Public Written Comments Submitted to PCAST

from, February 25, 2012 to May 10, 2012

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March 6th, 2012

The Honorable John Holdren
Co-Chair, President's Council of Advisors on Science and Technology
Director, Office of Science and Technology Policy
White House
[redacted]

Dear Dr. Holdren:

The National Center for Women and Information Technology (NCWIT) is pleased to provide the requested comments to you and the President's Council of Advisors on Science and Technology (PCAST) concerning unimplemented recommendations for K-12 computing and computer science education made in prior PCAST reports.

Specifically, two prior reports are relevant: the September 2010 Report, ***Prepare and Inspire: K-12 Education in Science, Technology, Engineering, and Math (STEM) for America's Future*** and the December 2010 Report, ***Designing a Digital Future: Federally Funded Research and Development Networking and Information Technology***. This letter seeks to reiterate the following recommendations as previously submitted by PCAST, and make suggestions for moving forward.

The September 2010 PCAST report, ***Prepare and Inspire: K-12 Education in Science, Technology, Engineering, and Math (STEM) for America's Future***, recommends a definition of K-12 "STEM Education" that includes computer science, a definition that is not yet in common use in federal and local STEM policy and education discussions:

"STEM education," as used in this report, includes the subjects of mathematics, biology, chemistry, and physics, which have traditionally formed the core requirements of many state curricula at the K-12 level. In addition, the report includes other critical subjects, such as computer science, engineering, environmental science, and geology, with whose fundamental concepts K-12 students should be familiar.

We noted how helpful it would be to explicitly mention computer science as a STEM discipline in our recent conversation with you on February 14th, 2012.

On page 50, the report further expands on the importance of K-12 computer science education:

Computer-related courses should aim not just for technological literacy, which includes such utilitarian skills as keyboarding and the use of commercial software packages and the Internet, but for a deeper understanding of the essential concepts, methods and wide-ranging applications of computer science. Students should gain hands-on exposure to the process of algorithmic thinking and its realization in the form of a computer program, to the use of computational techniques for real-world problem solving, and to such pervasive computational themes as modeling and abstraction, modularity and reusability, computational efficiency, testing and debugging, and the management of complexity.

The report goes on to m ention model-computing curriculum put forth by organizations such as the Association for Computing Machinery (ACM), the National Science Foundation (NSF) and the College Board. Although these efforts are progr essing they could bene fit from accelerated support from the W hite House. Other topics discussed included teacher preparation and the technology readiness of public schools.

The December 2010 P CAST report ***Designing a Digital Future: Federally Funded Research and Development Networking and Information Technology*** noted in Section 8.2 that:

NIT (Networking and Information Technology) pervades modern life. Every citizen – not just the NIT professional – needs to be fluent with information technology. The various dimensions of "NIT fluency" were the subject of a landmark 1999 National Academies study that has stood the test of time remarkably well. Fluency obviously involves a set of skills, such as using a word processor or spreadsheet, using the Internet to find information and resources, and using a database system to set up and access information. But fluency also involves a set of concepts and capabilities that have little to do directly with the use of a computer, but rather have to do with "computational thinking. Basic concepts of computational thinking include abstraction, modeling, algorithmic thinking, algorithmic efficiency and analysis, stepwise fault isolation, and universality. Basic capabilities include algorithmic expression, managing complexity, and evaluating information.

The report then went on to make this recommendation:

If Americans are to acquire proficiency in all levels of computing, their education must begin when they are children. Fluency with NIT skills, concepts, and capabilities; facility in computational thinking; and an understanding of the basic concepts of computer science must be an essential part of K-12 STEM education.

We hope pointing out these unim plemented PCAST recommendations is helpful to you. This letter is particularly timely in light of the release of the recent PCAST r eport, ***Engage to Excel: Producing One Million Additional College Graduates with Degrees in Science, Technology, Engineering, and Mathematics***, which states:

College level skills in mathematics and, increasingly, computation are a gateway to other STEM fields. Today many students entering college lack these skills and need to learn them if they are to pursue STEM majors.

Closing this gap will require coordinated action on many fronts. While some states allow computer science courses to count toward a secondary school core graduation requirement, most states that have specific course requirements for graduation count computer science courses only as electives. Many states also do not have a certification process for computer science teachers, and where certification processes do exist, such processes often have no connection to computer science content.

To reverse these troubling trends and prepare Americans for jobs in this high-wage, high-growth field, the Computing in the Core Coalition, of which NCWIT is a member, believes we must:

- Ensure computer science offerings are an integral part of the curriculum;
- Develop state computer science standards, curricula, and assessments;
- Improve access to underserved populations;
- Create professional development and teacher certification initiatives, including computer science teacher preparation programs in higher education;
- Form a commission on computer science education to bring states together to address the computer science teacher certification crisis; and,
- Establish an independent, rigorous evaluation of state efforts with reporting back to Congress and the administration.

Congressman Polis and Senator Casey have put forth these recommendations in the Computer Science Education Act as introduced in September 2011. The bill would also provide two-year competitive planning grants to states of at least $250,000 per state, as well as five-year competitive implementation grants to states to support their plans to increase and strengthen schools' capacity to offer effective computer science education.

At NCWIT, we believe we will never attract the necessary number of women and under-represented groups to computing if it's not taught in ways that are rigorous, inclusive and relevant to 21st century learners. The lack of computer science education in U.S. K-12 public schools is a national crisis and one we cannot continue to ignore. Please let us know how we can help.

Warm regards,

Lucinda M Sanders

Lucy Sanders
CEO and Co-founder, National Center for Women & Information Technology
Bell Labs Fellow

March 9, 2012

Submitted to Federal e-rulemaking Portal

Distinguished Co-Chairs of President's Council of Advisors on Science and Technology:
Dr. John P. Holdren
Assistant to the President for Science and Technology, and
Director, Office of Science and Technology Policy

Dr. Eric S. Lander
President and Director, Broad Institute of MIT and Harvard

Office of Science and Technology Policy
[redacted]

Re: Office of Science and Technology Policy, President's Council of Advisors on Science and Technology; Notice of Meeting: Partially Closed Meeting of the President's Council of Advisors on Science and Technology [Docket No. 2012–4223] 77 FR 10736. February 23, 2012.

Dear Drs. Holdren and Lander:

CropLife America (CLA) is pleased to provide comments to the Office of Science and Technology Policy's President's Council of Advisors on Science and Technology (PCAST) on the occasion of the meeting held on March 9, 2012 in which the Council is addressing the U.S. Department of Agriculture's science, technology, and innovation activities. We laud PCAST's objective to make policy recommendations in the many areas where understanding of science, technology, and innovation is key to strengthening our economy and forming policy that works for the American people.

CLA is the non-profit trade organization representing the nation's developers, manufacturers, formulators and distributors of plant science solutions for agriculture and pest management in the U.S. Our member companies produce, sell and distribute virtually all the crop protection technology products used by American farmers. CLA comments on issues that can have broad science and regulatory implications that may impact growers and our members. CLA and its predecessor organizations recently celebrated a 75th anniversary.

CropLife America appreciates U.S. Department of Agriculture (USDA) Secretary Vilsack's vision and leadership in articulating the significance of food and

agricultural research. CLA believes that federal funding for food and agricultural research, extension and education represents a top national priority and a necessary long-term national commitment. As a member of the National Coalition for Food and Agricultural Research (N CFAR) CLA believes that strong, consistent public funding for food and agricultural research and education conducted through a balance of programs of the USDA is critical to the continued discovery of new modern agriculture solutions. **Furthermore, the investment is critical to training students who will be the future experts in food and agricultural sciences in both the public and private sectors. We support USDA's leadership in research, extension and economics mission area, but the funding limitation severely impacts their ability to adequately address the grand challenges.**

To compliment private sector research, CLA supports the need for publicly funded research. We endorse coordination of research in public-private partnerships because there will be assurance that research is prioritized and relevant to American farmers and the environment. CLA members invest over $250 million for research and development for one pesticide to reach commercialization and the time required is now 10 years (CLA and European Crop Protection Association, 2010. The Cost of New Agrochemical Product Discovery, Development and Registration in 1995, 2000 and 2005-2008. R&D Expenditure in 2007 and expectations for 2010. Final Report, January 2010).

Several recent reports have summarized the need for increased federal government commitment to food and agricultural research and education.

- The challenges continue --including global food security and safety, human health, hunger, and environmental and economic sustainability (CAST. 2010. Agricultural Productivity Strategies for the Future: Addressing U.S. and Global Challenges. http://www.cast-science.org/publications/?agricultural_productivity_strategies_for_the_future_addressing_us_and_global_challenges&show=product&productID=29512011). In answer to those challenges, there is evidence that solutions are being provided through collaborative, high impact research of the highest scientific quality (Riley Memorial Foundation, 2011. Agriculture, Food, Nutrition and Natural Resources R&D Round Table. http://www.rileymemorial.org/rmf-round-table.html).

- The benefits from agricultural research continue to be a foundation for societal wellbeing and growth.
    - For example, the benefits from crop protection are vast. Today's U.S. farmer produces enough food to feed 140 people largely due to the availability and the choice of many agricultural tools such as seed, fertilizer and pesticides. Herbicides, insecticides and fungicides used in production of fruits, vegetables, and commodity crops in the U.S. have contributed to dramatic increases in productivity while enhancing the environment. Over 100 benefits case studies from both U.S. and global regions (http://www.croplifefoundation.org) indicate that without the use of crop protection products, more than 50% of crops were lost. Over the past 50 to 60 years, herbicide use has significantly increased crop yields, substituting for millions of additional acres that would otherwise be

required, and allowed for reduced tillage, reducing soil erosion by billions of pounds, which is a cornerstone of sustainable agriculture (Gianessi and Williams, 2011. Overlooking the obvious: The opportunity for herbicides in Africa. Outlooks on Pest Management, October 2011.). Similar science success stories abound in the agriculture sector.

- Food and agricultural research continues to pay off with nearly 50 percent average social rate of return to public investment (CAST, 2011. Investing in a Better Future through Public Agricultural Research. http://www.cast-science.org/publications/?investing_in_a_better_future_through_public_agricultural_research&show=product&productID=2963)
    - For example, safe crop protection products have been registered by the U.S. Environmental Protection Agency through a rigorous, science-based regulatory process. We must invest in crop protection research, innovative farming methods and new technologies to meet the unique challenges faced by agriculture and consumers worldwide who rely on it. Pesticides of reduced risk will continue to be registered and used in enhanced integrated pest management approaches in crop production. Seed and fertilizer will be improved. Adoption of precision agriculture is increasing rapidly. Precision application of crop protection products by growers includes use of many technologies including unique equipment, global positioning systems and geospatial information systems.

- A recent study summarizes private research and development. For crop protection chemicals, the cumulative effort of decades of crop protection research and development has produced effective, inexpensive solutions (Fuglie, Keith O., Paul W. Heisey, John L. King, Carl E. Pray, Kelly Day-Rubenstein, David Schimmelpfennig, Sun Ling Wang, and Rupa Karmarkar-Deshmukh. *Research Investments and Market Structure in the Food Processing, Agricultural Input, and Biofuel Industries Worldwide.* ERR-130. U.S. Dept. of Agriculture, Econ. Res. Serv. December 2011.).
    - Crop protection's benefits extend beyond agriculture into other sectors to create jobs, conserve environmental resources, help families save at the grocery store, and remain competitive in global trade
    - Crop protection benefits in the U.S. include:
        - The creation of 1,040,661 jobs that generate more than $33 billion in wages;
        - The reduction of fossil fuel use by 558 million gallons per year;
        - Increased yields which allow for an average of $98 billion of food to be exported annually, accounting for roughly 10% of all U.S. export revenues, while the U.S. imports less than $75 billion in food (*The Contribution of Crop Protection Products to the United States Economy. 2011. www.croplifeamerica.org/economic-impact*)

- In spite of a national and global imperative that food and agricultural research and education undergirds national security, public funding is declining (U.S. Department of Agriculture, Economic Research Service. 2010. Agricultural Research Funding in the Public and Private Sectors. http://www.ers.usda.gov/Data/AgResearchFunding/; American Association for the Advancement of Science. 2011. Chapter 27. Food, Nutrition, Agriculture, and Natural Resource Sciences in the FY 2012. P 267 – 276).

Notwithstanding these reports, we urge PCAST to also seek broad stakeholder input in any endeavor to study the science, technology and innovation in agriculture. Any evaluation of food and agricultural research priorities, science, and outcomes requires the perspectives and input of customers and stakeholders; not just from those conducting the research.

The return on investment from food and agricultural research will continue to advance. We cannot take modern agriculture or the research that supports it for granted. **CLA urges PCAST to recommend increasing public investment in U.S. food and agricultural research to ensure both U.S. and international food security. We trust that PCAST will recommend creative solutions and pathways to build that public investment, including new thinking on both partnership and leveraging opportunities between public agencies and within public and private collaborations.** The crop protection industry looks forward to assisting you.

We appreciate the opportunity to comment. If there are questions, please do not hesitate to contact me [redacted]

Sincerely,

Barbara P. Glenn

Barbara P. Glenn, Ph.D.
Vice President
Science and Regulatory Affairs

President's Council of Advisors on Science and Technology (PCAST) Webcast Question

From: Ahmet Yükseltürk [redacted]
Date: Fri, March 9, 2012 11:54 am
To: pcast@ostp.gov

Hi,

How US will cooperate with Russia, China and other countries to solve EHS issues?

Thank you.

--
Ahmet Yükseltürk
Bilkent University
[redacted]

STEM high school education with synthetic biology

From: "Schini, Rebecca" [redacted]
Date: Tue, March 20, 2012 9:46 am
To: "'pcast@ostp.gov'" <pcast@ostp.gov>
Priority: Normal

Good morning,

I am the chair for iGEM HS. This is an international competition for high school students in synthetic biology. I adapted the collegiate level competition to high school students in 2011. Last year, I held the competition for five Indiana teams. This year we have 40 teams from all over the globe, http://igem.org/Team_List?year=2012&division=high_school. I am speaking at NSF Noyce conference in May about being a leader as a Noyce scholar and the development of this competition as a way to challenge high school students. I would like the opportunity to speak with the PCAST committee my experience and the importance to challenge high school students in STEM.

As America becomes aware of the importance of STEM education and how educators should challenge their students, I would love to talk to the council about the importance for the development of these programs for high school students. Programs like iGEM HS are going to help colleges recruit a higher level of students in STEM. One of the students that competed last year received a full ride scholarship to Indiana University, the deciding factor IU gave was his involvement in iGEM HS. In the report “Engage to Excel”, PCAST stated the challenge to increase college enrollment in STEM. I would like to present the idea that programs like iGEM HS will help support this challenge and allow colleges the ability to receive a high quality of students.

I would like to share the experience of being a transition to teaching teacher and my involvement in increasing STEM in my school and the global impact iGEM HS possess.

I started my career as a microbiologist in a research environment for industry. I decided to become a teacher because I wanted to challenge myself. I am in my fifth year teaching in a high needs school in Greenfield, Indiana. I am a Project Lead the Way Master teacher for Biomedical Innovation. I have taken this curriculum and challenged my students to do research. Dr. Sylvester (Jim) Gates provided input on a research study for one of my research groups this year. I want my students to communicate with leading scientific researchers and potentially develop a mentor relationship with researchers in the field. Every research project is done under the guidance of myself and a fellow doctor or researcher in the field. While I am in Washington D.C.. please consider allowing me the opportunity to talk about the importance of building strong STEM programs in our high school system.

Sincerely,

Rebecca Schini

iGEM HS chair

PLTW BI Master Teacher

Science Teacher

Greenfield Central High School

[redacted]

From: Sylvis, Carol L. [redacted]
Sent: Friday, April 06, 2012 8:50 AM
To: Stine, Deborah D.
Cc: Sylvis, Carol L.
Subject: Call for STEM Help - Need Special Interest Rates for STEM College Students

Carol Sylvis
[redacted]

5 April 2012

Good Morning,

I am writing to plead for a reasonable interest rate for my son's college education. Please read on. At a time when there are so many headlines stressing the need for STEM students, why is it so hard for someone to help a STEM student get a good student loan? Could I recommend initiating special lower interest rate program for students willing to graduate with STEM degrees?

My son has been accepted into the University of Delaware Engineering Program and was accepted into the Honors Program. He received a $6,000 merit scholarship, and he was also able to obtain a $10,000 scholarship from my employer, Johns Hopkins Applied Physics Laboratory. I'm very proud. He wants to be an electrical engineer in the defense industry. However, even with this, it is quite a stretch for my son and our family.

Tuition and fees are approximately $42,000. I am divorced from his father (who doesn't feel he can assist financially), and have remarried. Unfortunately, this puts the financial burden on me, which amounts to approximately **20K** per year. I have two other younger boys who will need to attend college as well, and my current husband also has two children. Foreseeing loans of 20K per year, my son will have approximately 80K in college debt which I will need to co-sign.

My son, Bradley Swick, only qualified for a few thousand (total of $3,500) in subsidized and unsubsidized government grants. He is willing to take on the financial burden of repayment without hesitation, and that too makes me extremely proud, but also sad… sad that I can't help more, but also sad that the student loan interest rates are ridiculous even at a time when mortgage rates are much more reasonable, considering that our children are our future, it just makes no sense. It certainly doesn't seem to be where the priority is. I keep hearing that STEM needs to be a priority, so that our country can compete with the rest of the world and keep us at the top of world technology, but where is the break for kids trying to do that? Offering 11.76 interest rates is nothing but a deterrent to the next generation of our country. We need to provide breaks and or incentives for STEM students.

I am having difficulty finding a loan with a decent interest rate. I am doing everything possible to assist my son to live the American dream and give him an opportunity that I didn't have. I just want a decent interest rate. Is there anything I can do? I completed the FAFSA, and because I am remarried, I don't qualify for much. The quotes I am receiving are for rates between 6% (lowest with me being primary signer) to 11.76 and even higher in some cases. I have good credit (~700), but that doesn't seem to matter.

I am willing to cosign although that also puts me and my family in extreme financial difficulty. I just want my son to have a chance…. And by giving him a chance, we are also giving the country what they need more of -engineers who want to work in the defense industry. I am a concerned mother of a bright kid….a kid who is incredibly mature, responsible, has taken 9 AP classes and is ranked near the top of his class. I feel he deserves more than a huge interest rate that will start his adult life out being financially strapped. If you would like to get a real glimpse of who he is, invite him to meet you. You'd be amazed how mature and driven he is, and you'd also see exactly why I am writing this note. Sometimes you just have to advocate for what you believe in, and I'm taking the risk that someone out there will listen and provide guidance. Please advise if you have any insight on obtaining a reasonable loan to make this a reality for a kid that is definitely worth it. Please consider ***initiating special lower interest rates for students willing to graduate with STEM degrees?***

Below, is a link to a White House article that speaks about the importance of STEM. Also, attached below is my son's college admission essay.

http://www.whitehouse.gov/blog/2010/09/16/changing-equation-stem-education

Black Friday

Thanksgiving is a time to give thanks. After being thankful and eating a lot of food, thoughts turn to shopping. After some reflection, I came to the odd conclusion I could compare my desire to attend the University of Delaware with the Black Friday shopping craze.

If the University of Delaware were to have a Black Friday Sale… and if the door buster special item was acceptance, I'd be the first in line. That would be me with the pitched tent, snacks packed to make it through the night of waiting in line, and yes, that's me making friends to occupy my time during the long wait. You see, for me, getting the right education and attending the right college means far more than the enticing 50" LCD TV. Gaining entry into this establishment would provide me with a greater rush than getting the LCD TV that hundreds wish they'd gotten if only they had prepared a little better or had a bit more determination and patience. I've spent my past three years preparing for college, and now it is time to start the process.

Attending the University of Delaware would provide me with the unique opportunity to obtain an engineering and perhaps mathematics degree simultaneously, while also providing me the opportunity to further explore other areas of interest that I may not even know I have. If I were accepted into the Honors Program at the University of Delaware, I know I would be among an elite few, far more driven and focused than those waiting in line for the TVs during Black Friday, yet bursting with the same excitement of winning the chance at something awesome, in this case—a premier education. This excitement, however, won't wear off like that of the LCD TV that will be outshined by next year's model. My college experience will be unforgettable, undeniably my best investment and opportunity to create a successful future. I hope I am on the receiving end of The University of Delaware's door buster.

[redacted]

Very Respectfully,

Carol Sylvis
[redacted]

AKA
Proud Mom

"Education is the most powerful weapon which you can use to change the world." — Nelson Mandela

Written Statement from GE Global Research related to PCAST's April 16th discussion on the Advanced Manufacturing Partnership

From: "Azer, Magdi [redacted]
Date: Thu, April 12, 2012 7:46 pm
To: pcast@ostp.gov
Priority: Normal

Please accept the following written statement related to the Advanced Manufacturing Partnership (AMP). It is intended for submission to PCAST prior to their April 16, 2012 discussion of AMP. This statement represents the views of GE Global Research, acting as a representative of the General Electric Company.

Regards,

Magdi N. Azer, Ph.D.

Magdi N. Azer, Ph.D.
GE Global Research
Lab Manager, Laser & Metrology Systems Lab
Manufacturing Technologies

[redacted]
www.research.ge.com

[redacted]
GE Global Research

GE imagination at work

GE Global Research
Niskayuna, NY

Recommendations for Implementing a National Strategic Plan for Manufacturing

Abstract

The launch of the Advanced Manufacturing Partnership (AMP) has provided a unique opportunity to drive the competitiveness of U.S. manufacturing. With its emphasis on increasing government funding, fostering public-private partnerships, and building shared facilities and infrastructure, the U.S. will be well positioned to rebuild its manufacturing infrastructure. To maximize the impact of the National Network for Manufacturing Innovation (NNMI), it is essential to establish a healthy ecosystem of Innovative Manufacturing Institutes (IMIs) with participants from academia, government, and industry. This paper elaborates on four recommendations for structuring the NNMI to help small and medium enterprises (SMEs) introduce novel manufacturing technology into the U.S. manufacturing supply chain more rapidly. These recommendations include adopting a SEMATECH[1]-like collaboration model, providing broad access to state-of-the-art equipment, drawing the leadership for IMIs from industry, and leveraging IMIs as a training ground to develop an advanced manufacturing workforce. By focusing efforts toward solutions with broad impact, the NNMI will be poised to return the U.S. industrial base to its former position as a global manufacturing leader. This paper also provides a prioritized list of the technologies that the General Electric Company (GE) believes could be accelerated by the NNMI and which GE is committed to helping grow.

Introduction

Truly disruptive technology innovation occurs when multi-disciplinary teams concurrently work on product design, material development, and manufacturing innovation. This approach differs from the more traditional, and GE believes outdated, sequential approach of design, material selection, and manufacturing (see figure 1).

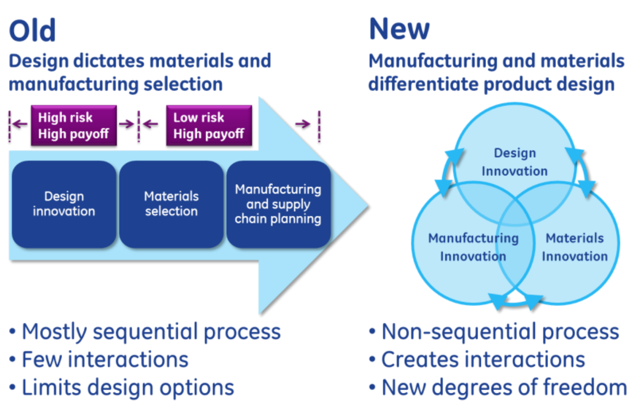

Figure 1 The contrast between traditional and disruptive innovation[2].

[1] SEmiconductor MAnufacturing TECHnology. In the context of the Advanced Manufacturing Partnership (AMP), using the term SEMATECH-like denotes that the National Network for Manufacturing Innovation (NNMI) should adopt the following attributes of SEMATECH: (a) focused research related to one topic (in this case manufacturing), (b) broad engagement with various sectors of the R&D community, including manufacturers, equipment suppliers, universities, research institutes, and the government, and (c) initially government subsidized, with the expectation that it will be funded solely by member dues in the future.

[2] *Re-inventing Industrial R&D*, Michael Idelchik, Industrial Research Institute (IRI) Summit, November 2011.

This approach to innovation is broadly applicable across many industries. At its core is the recognition that transformational R&D does not occur when design, materials selection, and manufacturing are decoupled. It occurs within the context of an ecosystem. As the Advanced Manufacturing National Program Office (AM-NPO) implements the recommendations of the President's Council of Advisors of Advisors on Science and Technology (PCAST) to create an integrated private-public advanced manufacturing initiative, it should view the NNMI similarly. Although the stated goal of PCAST has been to provide the funding and infrastructure to help small and medium enterprises compete globally, the AM-NPO can produce an even greater impact by considering how all enterprises, government, and academia can contribute toward improving U.S. manufacturing competitiveness. To do this, the following recommendations should be implemented.

1. Each Institute for Manufacturing Innovation (IMI) should focus its efforts toward addressing the fundamental technical barriers that prevent manufacturers from more broadly adopting specific new technologies. To accomplish this, each IMI should adopt an inclusive SEMATECH-like model that includes participants from each part of the manufacturing supply chain.

2. The equipment within an IMI should be made available to all companies so they can conduct manufacturing trials to reduce implementation risks and improve the productivity and competitiveness of their manufacturing operations. At the same time, companies that provide advanced technology equipment to the IMIs should be allowed to count these in-kind contributions toward membership or participation fees. This will ensure that IMIs always have access to state-of-the-art equipment.

3. The advisory boards that provide direction to an IMI should be comprised of individuals from industry, government, and academia, but their leadership teams should be recruited from industry and should have experience in the insertion of advanced manufacturing technology into production. Additionally, the NNMI should create a mechanism for collaboration, technology transfer, and best practice sharing between IMIs.

4. Working with community colleges and universities, IMIs should provide internships to train the future advanced manufacturing workforce. Furthermore, mechanisms should be created to allow private sector employees to co-locate at IMIs for long-term assignments designed to help them develop additional manufacturing expertise and actively participate in technology development and transition.

These recommendations align with the five objectives outlined in the National Science and Technology Council (NSTC) report, *A National Strategic Plan for Advanced Manufacturing*[3], Drawing from data provided by the National Science Board[4], this paper details how implementing these recommendations will increase collaboration between industry, government and academia and will provide the broadest possible impact to U.S. manufacturers.

[3] *A National Strategic Framework for Advanced Manufacturing,* National Science and Technology Council (NSTC), February 2012.
[4] *Science and Engineering Indicators Digest 2012,* National Science Board, December 2011.

Creating Partnerships

To accelerate insertion of new technology into production, GE Global Research launched a Pilot Development Center (PDC) in 2005. The goal of this center is to work with equipment suppliers to produce novel manufacturing equipment that is planned for transition to the production floor. Equipment is brought into the PDC, and it undergoes testing and pilot scale production trials to ensure it will operate as expected when placed in the factory.

As a result of PDC successes, GE, in partnership with the State of Michigan, and the Michigan Economic Development Council, launched its Advanced Manufacturing Technology Center (AMTC) in 2009. Rather than concentrating on discrete pieces of equipment, the AMTC focuses on building complete manufacturing cells which are required to scale technology from lab demonstrations into proven manufacturing processes. At present, the AMTC is focused on scale-up of three new processes, including advanced composite manufacturing. The AMTC relies on a strong partnership with the GE business units who will receive this technology. These businesses provide supply chain engineers to work side-by-side with researchers.

Recognizing that not every company has the resources required to build an AMTC, IMIs can help SMEs improve their level of technical sophistication and scale-up advanced manufacturing technology. In the process, all U.S. manufacturing enterprises will benefit, which is critical for global manufacturing competitiveness.

For SMEs to grow and be globally competitive, they need to understand the market opportunities and technical needs that their products and processes can address. By adopting a SEMATECH-like model for IMIs, SMEs will be able to work in close collaboration with large industrial enterprises, which source parts or equipment from the SMEs. This will enable SMEs to more efficiently gain an understanding of the requirements their products must satisfy. With this critical information, SMEs can most efficiently allocate their resources and shorten their development cycles.

The impact that IMIs can have is contingent upon the infrastructure and facilities that are placed in these institutes. While the federal government has stated its intent to help purchase the initial equipment for each institute, another way to ensure that IMIs continually upgrade their infrastructure is to incentivize production equipment manufacturers to place their latest equipment at IMIs. This can be accomplished by allowing equipment manufacturers to count these in-kind contributions toward their membership or participation fees. As an added benefit, institute employees will be able to provide direct feedback to the equipment manufacturers to help them improve their equipment for sale in the global marketplace.

Finally, with the increased emphasis universities are placing on technology transfer and commercialization, there should be a robust pipeline of university-initiated technologies that could be scaled up for insertion into the domestic supply chain.

Institute Governance and Technology Transfer

In the same way that IMIs should draw upon the unique skills of academia, government, and industry, it is equally important for each IMI's governing board to draw its membership from academia, government and industry. When it comes to day-to-day operation, however, the leaders for each institute and a number of their staff should be recruited from private industry, and they should bring demonstrated experience in the insertion of advanced manufacturing technology into production. If the expectation is that each IMI will be self-sufficient in five years, industry will need to see the fruits of its investment manifested in new capabilities. This is particularly important given the stated expectations that private industry should provide up to 50% of the funding to operate the IMIs. Drawing much of the institute's leadership team from industry is the best way to ensure that industry sees the benefit of engagement with IMIs and participates in these institutes on a long-term basis.

When the NNMI is created, it should also develop an effective policy for sharing know-how between IMIs. By simultaneously creating mechanisms to consistently transfer best practices and research findings between IMIs, industry will be able to derive even greater benefits. These mechanisms will also be important if the AM-NPO chooses to create virtual or distributed institutes versus co-locating the research activities of a particular IMI.

<u>Strengthening Workforce Skills</u>

As was pointed out in the NSTC report[2], 67% of companies surveyed in a recent industry association survey reported a serious shortage in the availability of qualified workers. This sentiment was reiterated at the AMP regional meeting that was held at MIT November 28, 2011. According to Jill Becker, CEO of Cambridge NanoTech, in order to develop and maintain the workforce required for her company to operate, Cambridge NanoTech has had to develop training programs itself[5]. Likewise, many large companies like GE have continued to use apprentice programs to build the skilled workforce of tomorrow. For example, GE Aviation in Lynn, Massachusetts has partnered with North Shore Community College (NSCC) for its apprentice program, and GE Energy in Schenectady, New York has partnered with Hudson Valley Community College's (HVCC) successful Manufacturing Technical Systems (MFT) program. This program provides trained manufacturing employees to the 19 companies that have partnered with HVCC, and it boasts a 95% placement rate prior to graduation[6].

The skills gap, however, is not limited to producing a production workforce. According to the National Science Foundation, the proportion of the science and engineering workforce older than 50 increased from 18% to 27% between 1993 and 2008[7]. As a result, it is equally important to place emphasis on replenishing the advanced manufacturing researchers that will be necessary to develop tomorrow's technology breakthroughs. The Advanced Manufacturing Partnership's IMIs are an ideal mechanism to create the next generation of skilled innovators, which is critical if the United States is going to continue to be a source of new ideas in the world.

There are two approaches to accomplish this goal. The first approach focuses on academic training. For example, graduate students with interest in manufacturing technology research could participate in short-term internships during their graduate studies. Funding for these internships could either come from the operating budgets of an IMI, or the National Science Foundation could allocate a portion of its Graduate Research Fellowship Program funding to sponsor fellowships at IMIs. At the undergraduate level, as the AM-NPO partners with universities to jointly develop manufacturing programs, they could structure co-ops or internships as part of a student's course of study.

The second approach involves creating mechanisms to allow private sector employees to co-locate at IMIs for long-term assignments. These assignments would be designed to help them develop additional manufacturing expertise. Conversely, IMIs would draw industry participants to their institutes to provide industrial experience in technology scale-up and insertion.

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[5] Advanced Manufacturing Partnership (AMP) Regional Meeting, November 28, 2011, Cambridge, MA. *Regional Panel 1: Advanced Manufacturing Success Stories.*

[6] Manufacturing Technical Systems (A.O.S), www.hvcc.edu/eit/mft/career.html

[7] National Science Board Science and Technology Indicators Digest 2012, pg. 3-6.

MATHEMATICAL ASSOCIATION OF AMERICA

May 15, 2012

John P. Holdren
Eric Lander
President's Council of Advisors on Science and Technology
White House
Washington, DC

Response to the PCAST Report to the President, *Engage to Excel*

Dear Dr. Holdren and Dr. Lander,

The Mathematical Association of America (MAA) strongly supports the fundamental message of the February 2012 report from the President's Council of Advisors on Science and Technology, *Engage to Excel: Producing one million additional college graduates with degrees in Science, Technology, Engineering, and Mathematics*. Appropriately, much of the focus of this report is on undergraduate mathematics education, which lies at the heart of all STEM education.

The PCAST report highlights the need to increase the number of students who obtain undergraduate preparation for careers in the STEM disciplines. It proposes some specific mechanisms for accomplishing this, including the need to draw on empirical evidence of what works. The report showcases the growing body of evidence for the effectiveness of using class time to actively engage students in thinking about the concepts they are learning, and for the effectiveness and power of student research programs to attract and motivate students toward STEM careers.

The report calls for more than just studying what works. It also points to the need to scale up successful programs to transform undergraduate science and mathematics education. Doing so will require partnerships that include universities, businesses, and government, and it will require the kind of national oversight and coordination and large scale program development that can be provided by the proposed Presidential Council on STEM Education.

MAA is the pre-eminent organization devoted to mathematics at the undergraduate level. Our efforts include a wide spectrum of programs: (1) outreach to precollege students and teachers, designed to attract and inspire talented students into STEM careers; (2) efforts to strengthen undergraduate mathematics programs, by promoting undergraduate research and broadening participation; (3) early-career faculty development; and (4) a full gamut of publications, meetings, and workshops that support faculty development through all career stages.

[redacted]

We hope that PCAST will now draw upon MAA's knowledge of what works in undergraduate mathematics education, and on MAA's experience in disseminating information through publications, meetings, and workshops. MAA is prepared to be an active participant as the PCAST recommendations are more fully developed and implemented.

In the attachment to this letter, we will comment on what the mathematical community in general and MAA in particular can offer toward the four overarching recommendations of the PCAST Report.

While we look forward to working with the proposed Presidential Council on STEM Education, we emphasize that the fundamental responsibility for implementing the recommendations that impact the mathematical sciences community must reside within this community. Our experience and the evidence we have and continue to collect give us the expertise and insight that are needed if the ambitious goals identified in the report are to be accomplished.

MAA anticipates partnering with federal agencies in large-scale development programs that implement prototype courses founded on research-tested student engagement strategies that can be adapted and adopted to improve student learning. By working together with colleagues in partner disciplines and coordinating outreach with other disciplinary societies, MAA believes we can catalyze widespread adoption of practices that will engage and inspire our future STEM leaders.

Sincerely,

Paul Zorn
President

David M. Bressoud
Past President

Michael Pearson
Executive Director

[Attachment]

[redacted]

Programs of MAA and other mathematical organizations that address the recommendations of the PCAST Report, *Engage to Excel*

1. **Catalyze widespread adoption of empirically validated teaching practices.**

The PCAST report begins its discussion of this recommendation with a call to educate undergraduate faculty in evidence-based teaching practices. The oldest and unquestionably the premiere program for informing new faculty about best teaching practices is MAA's Project NExT (New Experiences in Teaching). Started twenty years ago with a grant from ExxonMobil, it not only introduces new faculty to these best practices, it also provides an ongoing network of support via its active list servers and its lively reunions at national meetings. Through these networks, faculty learn how to deal with setbacks and unexpected situations and how to make best use of the resources at their disposal. Project NExT accepts about 80 new faculty per year. It has engendered a larger network of regionally based groups of new mathematics faculty, the Section NExTs, usually led by Project NExT alumni and reaching hundreds of young faculty each year.

In addition, MAA runs workshops at regional and national meetings on best teaching practices as well as summer workshops, under its PREP (Professional Enhancement Programs of the MAA) banner.

MAA has long been known for its publications on the teaching of undergraduate mathematics, reaching back to the 1950s when its Committee on the Undergraduate Program in Mathematics began to codify the standard mathematics curriculum that would be needed to prepare scientists and engineers. Its publication program continues regular reporting on research in undergraduate education and advice on implementing best practices. A decade ago, MAA published a series of reports under the title *The Curriculum Foundations Project*[1] that opened the dialogue between mathematics and its "partner disciplines"—including Engineering, Biology, Physics, and Chemistry—about what their students *really* need to take away from the courses taken in Mathematics.

This PCAST recommendation also talks about the need to develop metrics to evaluate STEM education. Part of this is embedded in *The Curriculum Foundations Project*. Before developing a metric, we need to know what it is we want to measure. Part of the job is to establish baseline data. MAA is gathering such data through its large-scale survey of mainstream Calculus I, the NSF REESE-funded project *Characteristics of Successful Programs in College Calculus* that is currently underway. MAA is also working with others in the field, such as Phil Sadler of the Department of Science Education at the Harvard-Smithsonian Center for Astrophysics whose *FICS-Math* project is helping to clarify the role of high school preparation in student success in college calculus.

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[1] Ganter, S. and Barker, W., eds. 2004. *Curriculum Foundations Project: Voices of the Partner Disciplines.* Mathematical Association of America. Washington, DC. The report from a second round of workshops is currently in progress.

2. **Advocate and provide support for replacing standard laboratory courses with discovery-based research courses.**

Discovery-based learning is not just for the science lab. For over twenty years, MAA has highlighted and promoted this approach to learning mathematics and has regularly published textbooks that employ this approach. Today it offers the second edition of Smith and Moore's *Calculus: Modeling and Application*, a direct descendant of their *Project CALC* (Calculus As a Laboratory Course), as well as Marshall, O'Dell, and Starbird's *Number Theory through Inquiry*, an IBL (Inquiry Based Learning) textbook that gives the students no answers, only questions. Students learn by discovering the answers to a carefully selected progression of questions.

MAA is now partnering with the Educational Advancement Foundation and its Academy of Inquiry Based Learning to promote IBL and to provide both materials and the supportive network that is needed for those who would implement it. The annual EAF meeting is a highly energized gathering of three- to four-hundred enthusiastic faculty who are implementing IBL.

3. **Launch a national experiment in postsecondary mathematics education to address the math preparation gap.**

The focus of this recommendation is on the mathematical preparation of students as they enter college. The "gap" appears to refer to the difference between what these students have learned and what they need to know to succeed in a STEM career. The call is to our colleges and universities to do a better job of preparing K-12 teachers of mathematics and to do a better job of enabling those who are not ready for college-level mathematics to overcome their deficiencies. MAA takes strong exception to PCAST's suggestion that these jobs could be done better outside of the mathematics department.

MAA and other mathematical organizations do recognize that there are serious issues here that need to be and are being addressed. MAA is part of the Conference Board of the Mathematical Sciences which currently is finalizing the *MET2 Report*, an update of its publication, *The Mathematical Education of Teachers*, that first appeared in 2001. This publication, which draws on our best knowledge of what makes for an effective mathematics teacher, lays out the role of mathematicians and mathematics departments in ensuring that teachers have the mathematical content knowledge needed for success in the classroom and that they get the support and continuing education needed to flourish.

MAA is very much aware of the problem of students who enter college unprepared for college-level work in mathematics. Several organizations are tackling this problem, most notably the Carnegie Endowment for the Advancement of Teaching that is working on its Statway program that prepares students for and assists them in successfully completing college-level statistics and the New Mathways program under development at the Dana Center at the University of Texas, Austin. Both AMATYC (American Mathematical Association of Two-Year Colleges) and MAA are monitoring these programs.

MAA recognizes the critical importance of the issues highlighted under this recommendation: the preparation of teachers and the need for programs that assist students to overcome deficiencies in pre-college mathematics. However, these issues are secondary to the thrust of the PCAST report, which is to attract students to and retain them in STEM majors. In 2010, we graduated 254,000 students with bachelor's degrees in STEM fields and an additional 75,000 with associate's degrees.[2] The additional one million degrees called for in the title of the PCAST report would occur over ten years, and therefore this report calls for a 30% increase, steep but not unreasonable. The United States has a plentiful supply of students who have completed an extensive amount of mathematics in high school. Each year, over 600,000 high school students complete a high school course in calculus.[3] Over half of all high school graduates, at least 1.6 million students per year, have completed a course at the level of Precalculus or higher.[4] MAA's study of the 300,000 students who enroll in mainstream Calculus I during the fall term shows that these are students who do well on the SAT/ACT mathematics exams, enjoy mathematics, and consider themselves good at it.[5]

There is a large pool of potential candidates for STEM careers, a fact that is underlined by the fact that the number of full-time freshmen intending to major in a STEM field (Biological Sciences, Computer Science, Engineering, Mathematical Sciences, or Physical Sciences) grew by 54%—from 276,000 in 2007 to 424,000 in 2011—in response to the current economic crisis and the sharp downturn in employment.[6] The challenge is to enroll these students in the foundational courses for the STEM disciplines and to retain them during the first year of college.

Nevertheless, MAA recognizes that there is a serious preparation gap. Many high school students who think they are well qualified in mathematics in fact have a lot of catching up to do. A third of the graduating class of 1992 who passed calculus in high school took precalculus in college.[7] One in six of the students from the graduating class of 2004 who passed calculus in high school took remedial mathematics in college.[8] Many of these students seek and are shut out of STEM majors. In addition, many students are discouraged by their first college calculus class. Student confidence in mathematical ability drops by half a standard deviation between the start and end of Calculus I.[9]

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[2] National Center for Education Statistics. *2011 Digest of Education Statistics*. Tables 298 and 301.

[3] Based on College Board data that 341,000 students took an AP Calculus Exam in 2011 and NCES data from the Educational Longitudinal Study of 2002 (ELS:2002) that 55% of those completing calculus in high school take the AP Calculus Exam.

[4] NCES Educational Longitudinal Study of 2002 (ELS:2002)

[5] Preliminary data from the MAA's national survey *Characteristics of Successful Programs in College Calculus*. See "The Calculus I Student" at http://maa.org/columns/launchings/launchings_05_11.html.

[6] Higher Education Research Institute. 2012. *The American Freshman*.

[7] NCES. National Education Longitudinal Study of 1988 (NELS:88)

[8] NCES. Educational Longitudinal Study of 2002 (ELS:2002)

[9] Preliminary finding from the MAA's national survey *Characteristics of Successful Programs in College Calculus.*

If we want to impact the pipeline of STEM majors, then we need to work on what is happening in calculus both in our high schools and in our colleges and universities. Our high schools, colleges, and universities recognize the problems with calculus instruction. The challenge is to better understand how and why such courses fail so many students, to disseminate knowledge of programs that work, and to assist in and coordinate the improvement of these courses. This is a current focus of MAA activities.

4. **Encourage partnerships among stakeholders to diversify pathways to STEM careers.**

MAA has always been active in working with NSF and the Department of Education. It has regularly travelled to Capitol Hill to educate our senators and congressmen about the issues of undergraduate mathematics education. We regularly work with corporations such as Exxon-Mobil and Intel and with concerned businessmen to improve the teaching and learning of college-level mathematics. There is much more that we could be doing. We welcome the assistance of PCAST in promoting and coordinating these partnerships that will enable us to scale up the approaches and programs that work and transform undergraduate mathematics education.

Mathematical Association of America
Testimony for the
President's Council of Advisors on Science and Technology
Friday, May 25, 2012

Those parts of this document in italics will not be read as part of the oral testimony.

Delivered by Michael Pearson, Executive Director of the MAA.

Dr. Holdren, Dr. Lander, and distinguished members of PCAST: we thank you for the opportunity to be here today.

The Mathematical Association of America was established in 1915. Our mission -- "to advance the mathematical sciences, especially at the collegiate level" -- and our activities align closely with the goals and purposes of the recent PCAST report, "Engage to Excel."

MAA's 20,000 members include university, college, and high school teachers; graduate and undergraduate students; pure and applied mathematicians; computer scientists; statisticians; and many others in academia, government, business, and industry.

For over 50 years MAA has shaped the undergraduate program in mathematics. We provide a wide range of resources for mathematics teaching and learning through our extensive publications and professional development programs. MAA meetings provide venues for faculty to share, collaborate, and learn from each other. Students use our meetings to present research results, interact with peers and faculty from around the country, and discover career opportunities.

In 10 days, Dr. Holdren will join us at our annual banquet where we recognize the top performers in this year's U.S.A. Mathematical Olympiad. The USAMO is the highest level of the MAA American Mathematics Competition, a program dedicated to strengthening the mathematical capabilities of our nation's youth. Approximately 350,000 middle and high school students participate in this program every year; in July, MAA will take six of these students to the International Mathematical Olympiad, in which we have participated since 1974. Last year, the U.S. team placed second among the 101 participating countries; all six members of the team were awarded gold medals. So, in addition to the challenges identified in "Engage to Excel," there are also stories of remarkable mathematical achievement.

MAA programs support development and testing of innovative approaches to mathematics education, including the preparation of future teachers. MAA promotes research-supported strategies for attracting and retaining STEM students: these include mentoring, community-building, inquiry-based learning techniques in the classroom, and engaging students in undergraduate research. *In this context, MAA acknowledges the critical role NSF plays across the STEM community in supporting the foundational work required to advance efforts to improve student learning at all levels.*

MAA's Committee on the Undergraduate Program in Mathematics makes recommendations that guide departments in designing undergraduate mathematics curricula. These recommendations, published as a guide roughly once a decade, have consistently insisted that mathematical sciences departments understand and address the diverse strengths, weaknesses, career plans, fields of study, and aspirations of mathematics students.

Quoting from a CUPM report:

> *From the scientific standpoint, one must take into account the extended mathematical needs of modern engineering and physical science. At the same time such sciences as econometrics, physiology, sociology, and genetics seem to demand, in part at least, entirely new mathematics.*

In fact, that quote comes from a 1955 report. The most recent report, published in 2004 and available at www.maa.org/cupm, echoes similar themes, though of course adjusted to reflect the dramatically different environment we now face.

Work on the next CUPM curriculum guide, due about 2014, is well underway.

MAA is dedicated, through its history and its mission, to the centrality of undergraduate mathematics in the STEM enterprise. We hope that these comments, together with our written response, will promote a robust and sustained discussion of how to leverage MAA's expertise in undergraduate mathematics to prepare and inspire students to pursue STEM majors and careers.

We welcome the opportunity to promote and facilitate adaptation and implementation of model programs, and look forward to working with PCAST, leadership at NSF, and other partners to carry this important work forward.

May 25th, 2012
Derek Shannon
Director of Business Development & Lab Coordinator
Lawrenceville Plasma Physics, Inc.

Hi, Ms. Stine-

An advance copy of my remarks is below and within the zipped folder, which also contains the scientific papers we mention and the PPRC collaboration agreement. I will have hard copies of the remarks per the instructions. Looking forward to it, thanks!

Best
Derek

Remarks as Prepared for the President's Council of Advisors on Science and Technology (PCAST)

May 25th, 2012

Derek Shannon
Director of Business Development & Lab Coordinator
Lawrenceville Plasma Physics, Inc.

Thank you to the Council for this opportunity. I want to first make the Council aware of the major scientific advances achieved by our dense plasma focus fusion research device in Middlesex, NJ; second, address how we hope federal energy programs will evolve in response; and third, share the news of an international scientific collaboration.

On March 23rd, 2012, we published in the journal Physics of Plasmas a report of the confinement of plasma with ion energy equivalent to 1.8 billion degrees C for a period of tens of nanoseconds using a dense plasma focus device. This achieved two out of three conditions-- temperature and confinement time-- needed not just for fusion energy, but for fusion energy using advanced, aneutronic fuels that have long been considered out of reach. We did all this with an innovative device costing less than one million dollars. If we are able to achieve the third condition, density, we could be on track to commercializing fusion within five years.

However, if our resources remain limited to the private sector, our chances of success may diminish, and we urge that federal energy policy evolve. This new promise for fusion shows we must not only preserve our existing investigations, but also expand the fusion energy program to include many more diverse contenders, especially aneutronic fusion and, in particular, the dense plasma focus device.

Finally, I want to announce that we reached a scientific publication collaboration agreement on May 20th, 2012 with Iran's lead fusion facility, the Plasma Physics Research Center. This agreement grew from the "Fusion For Peace" initiative that we proposed with Iranian and Japanese colleagues this spring.

[redacted]

Fusion reactions from >150 keV ions in a dense plasma focus plasmoid

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Using a dense plasma focus device with a 50 kJ capacitor charge, we have observed fusion reactions from deuterium ions with record energies of >150 keV, which are confined for durations of 7–30 ns in the cores of plasmoids with typical radii of 300–500 μm and densities $\sim 3 \times 10^{19}$ cm^{-3}. We have for the first time simultaneously imaged the plasmoid at high (30 μm) resolution and measured trapped ion energy and neutron anisotropy. The isotropy of the neutron emission as well as other observations confirms that the observed neutrons per pulse of up to 1.5×10^{11} are produced mainly by confined ions, not an unconfined beam. The conditions achieved are of interest for aneutronic fusion, such as with pB11 fuel. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.3694746]

I. INTRODUCTION

The dense plasma focus (DPF) device has long been known to be an efficient source of neutrons from fusion reactions and of MeV-energy ion and electron beams.[1,2] It also produces dense concentrations of hot plasma, or plasmoids.[3–5] However, there have been a number of key unresolved questions that are debated and which have major importance for the possibility of using the DPF as a future source of fusion energy. First, do the neutrons primarily come from high-energy ions that are confined in a dense plasmoid, or from an unconfined ion beam's collision with either background gas or a cool plasmoid? Second, are the high-energy ions present only in the beam, or are they also trapped and circulating in the plasmoids? Third, what are the typical dimensions of the plasmoids—centimeters, tens to hundreds of micrometers, or in between?

These questions are closely linked, since only trapped high-energy ions could produce large numbers of neutrons in the plasmoids. In addition, only plasmoids with relatively small volumes and masses could be heated to high average ion energies with the total energy available in the device. Researchers such as Brzosko, Bostick, and Nardi[6,7] have reported small plasmoids, radius <1 mm, with trapped ions with typical energy >50 keV and most of the neutrons coming from the confined ions, while others such as Kubes[8] have reported large plasmoids, radius >1 cm, with ions not confined or only partially confined (for a few orbits) and most neutrons from interactions with a beam.

These questions are of high practical interest, since if high-energy ions are trapped in the plasmoids, it is possible that with suitable conditions and fill gases, the energy released by fusion reactions could also be trapped, leading to ignition of the fusion fuel and high fusion yields. This would not be possible if the fusion reactions are mainly coming from a single pass of an ion beam.

Our experiments using a DPF with small-radius electrodes have given clear answers to these questions. We have observed a record 900 keV full-width half-maximum (FWHM) spread in neutron energies from deuterium reactions, which implies average ion energies as high as 160 keV for Maxwellian plasma, and higher if the high-energy ions are not yet thermalized. integrated charge-coupled device (ICCD) images, low anisotropy in neutron production, energy considerations, and the strong correlation of ion energy with fusion power all combine to demonstrate that >70% of the 10^{11} neutrons in the hottest shots are produced by ions confined in small plasmoids with core radii of 300–500 μm. We believe this result does not contradict other results obtained previously, such as by Kubes,[8] but is mainly the result of the relatively small radii of our electrodes, which lead to higher densities in the plasmoid and more effective heating of the ions.

A. The DPF—background of present work

The DPF is a compact and simple device first developed in the 1960s by N. V. Filippov in the USSR and by J. W. Mather in the USA and has been studied by dozens of groups over the last 45 years, resulting in a large and rich literature. It consists of two concentric cylindrical electrodes enclosed in a vacuum chamber. The chamber is evacuated to low pressure and then backfilled to several Torr with the fuel gas. A pulse of electricity with a rise time of 0.2–10 μs from a capacitor bank is discharged across the electrodes during operation.[4] In operation, the capacitors discharge in a several-microsecond pulse, the gas is ionized and a current sheath consisting of pinched current filaments forms and runs down the electrodes. When the sheath reaches the end of the inner electrode (the anode), the filaments pinch together in the center, forming dense, magnetically confined hot spots or plasmoids.[9,10] The plasmoids emit x-rays with energies from several keV to over 100 keV. X-ray pinhole images have demonstrated that the plasmoids can be tiny, with radii of hundreds of micrometers or less.[5,11–13] The plasmoids can have densities in the range of 10^{20}–10^{21} cm^{-3}. These densities were measured by a number of independent methods, including heavy ion and secondary product fusion,[14,15] CO_2 laser scattering,[16] and x-ray line intensities.[17] These plasmoids emit intense beams of accelerated ions and electrons.[18–20] Neutrons from fusion reactions are emitted from the device in large quantities (up to 10^{13}) per shot.

The role of the plasmoids in producing the fusion neutrons and the physical processes involved in their formation and maintenance have been hotly debated among DPF researchers for decades. The model that best fits all the existing data makes the role of the plasmoids central to neutron production. This model, initially developed by Bostick and Nardi,[4] and confirmed by observations of several groups over three decades, was elaborated into a more quantitative theory by one of the present authors.[21–26] In this model, the electron beam transfers part of its energy to the plasmoid electrons, which generate x-rays through collisions with nuclei. Through plasma instability (probably ion-acoustic), the electrons then transfer part of their energy to the ions, with a typical delay (in our experiments) of $\sim$20 ns. Ion collisions then occur, generating fusion reactions and neutrons.[26] The fusion reactions end when the ion and electron beams have exhausted the magnetic energy that confines the plasmoid, and partially or wholly evacuated the particles in the plasmoid.

The DPF routinely produces hard x-rays and γ-rays indicating the presence of Bremsstrahlung radiation from high-energy electrons colliding with nuclei.[23] Together with independent evidence, this indicated that the hot spots contained ions and electrons at very high energies in the range of interest for advanced fuel fusion.[10,16,17,23–26]

The Bostick-Nardi model[6] describes the DPF as operating by exploiting a series of natural instabilities in the plasma, with each instability further concentrating the plasma and the magnetic fields produced by the currents running through the plasma. In the past few decades, substantial advances have occurred in understanding the basic physics of such instabilities through experiments and observations of space plasma.

In the first instability, the current sheath moving through the plasma between electrodes breaks up into an array of filaments, increasing the density of the plasma and magnetic field strength by a factor of 10–20. The filamentary current sheath, driven by the interaction of its own currents and magnetic field, travels down to the end of the inner hollow electrode, where the filaments converge into a single central pinch region, further concentrating both plasma and magnetic fields. A third instability then kinks the single central filament like an over-twisted phone cord, forming a plasmoid, an extremely dense, magnetically self-confined ball of plasma only tens or hundreds of micrometers across. By this time, the density and magnetic fields of the plasma in this small region are much larger than those present at the start of the process, and a substantial fraction of the energy fed into the device is contained in the plasmoid. A fourth instability causes the magnetic fields at the center of the plasmoid to decrease, and these changing magnetic fields induce an electric field, which generates a beam of electrons in one direction and a beam of ions in the other. The electron beam heats the plasmoid electrons which in turn heat the ions, thus igniting fusion reactions. The energy is released in the ion and electron beams and in a burst of x-ray energy from the heated electrons in the plasmoid.

In addition to its very small size, simplicity, and ability to utilize the inherent plasma instabilities (rather than suppressing them), the DPF also has the advantage that it produces a plasmoid which is extremely dense. Such a dense plasmoid requires that the ions be confined for only a few thousand orbits, in contrast to the millions of orbits required in tokamaks or most other fusion devices. Thus the high stability of such devices is not required in the DPF, but rather only meta-stability.

II. EXPERIMENTAL APPARATUS

The experiments were performed with the "Focus Fusion-1" (FF-1) dense plasma focus at Lawrenceville Plasma Physics' laboratory in Middlesex, NJ.[26] This device is energized by a 113 μF, 12-capacitor bank. The cathode has a radius of 5 cm, and the anode has a radius of 2.8 cm, while in the present configuration both have a length of 14 cm, with a 2.8 cm-long ceramic insulator between them. The shots analyzed here were performed with charging voltages varying from 30 to 36 kV and peak current from 0.7 to 1.1 MA. For such relatively high currents, our electrodes are small, a choice based on theoretical indications that such small electrodes and the associated higher magnetic fields will allow denser and hotter plasmoids.[26] By comparison, mega-amp DPFs in Las Vegas[27] and Warsaw[8] have electrodes close to two and four times our radii, respectively. The fill gas was deuterium and the fill pressure was varied from shot to shot over a range of 10–24 Torr.

The current in FF-1 is measured by digitally integrating a Rogowski coil signal, while the number of neutrons generated are measured by three types of independent sets of instruments: a calibrated silver activation counter located 81 cm from the axis of the device; calibrated bubble detectors located at 90°, 12.5°, and 4° from the axis and on the axis in the direction away from the anode; and by integrating the signals from two time-of-flight (TOF) scintillator-photomultiplier tubes (PMTs) located at 11 m (near time-of-flight, NTF) and 17 m (far time-of-flight, FTF), at 90° from the axis. The rise time of the scintillator (25-mm-thick BC-404) is 2 ns and this is also the rise time of the PMTs. Out of 242 shots fired in the test period of September 1, 2010 to March 1, 2011, 44 shots had high signal-to-noise ratios in both the NTF and FTF detectors, and so they were selected for further analysis here.

In addition, in October 2011, we added a third inner time-of-flight (ITF) detector at an angle of 4° from the axis in the direction that the ion beam travels (downwards from the anode) at a distance of 1.2 m. This detector was shielded on all sides by 5 cm of lead to reduce the x-ray signal. We analyzed an additional 23 shots with similar conditions to the first set: charge voltage 33–40 kV, fill pressure 16–27 Torr, and peak current 0.8–1.0 MA. For these shots, we also had a vertical PMT (VPMT) located on axis above the anode, 32 cm from the tip of the anode.

III. DATA ANALYSIS

A. Time-of-flight data

Data from the TOF PMTs is measured at a 1 sample-per-ns rate by digital oscilloscopes. Figure 1 shows typical (inverted) NTF and FTF signals, showing the x-ray and later neutron pulse arrivals. To minimize shot and electromagnetic (EM) noise, the resulting data files are then averaged over a

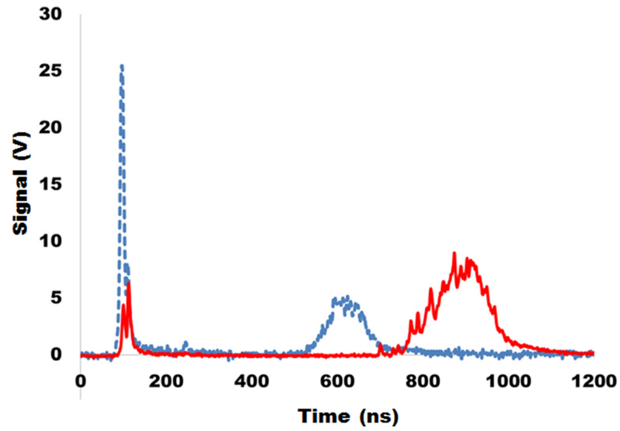

FIG. 1. Inverted data output for shot 11012403 from the Near Time of Flight PMT (dashed) and the Far Time of Flight PMT (solid) showing early x-ray peak and later neutron peak. The larger diameter FTF scintillator is more sensitive to neutrons. The timing of the data is shifted to compensate for photon time of flight and cable delays.

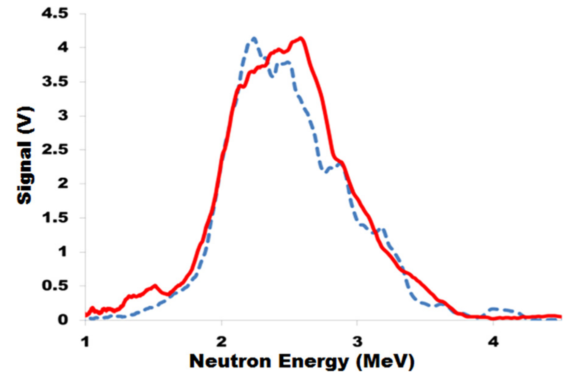

FIG. 2. Shot 11012403. PMT output for the NTF at 11 m (dashed blue) and FTF at 17 m (solid red) from the device axis plotted against neutron energy, determined from time-of-flight. The signals are recorded every nanoseconds and averaged over 20 ns. The amplitude of the NTF signal is magnified to match the peak height of the FTF signal. The FWHM of 960 ± 40 keV is a record for any DPF. Note the close agreement of the two signals.

20 ns window for the NTF and FTF signals and over a 5 ns window for the 1.2 m ITF signals.

For the first set of shots, observed with two TOF detectors, we have determined for each shot an average ion energy using the formula,

$$E_i = 2E(W^2 - \tau^2)/t^2,$$

where E_i is the mean ion energy, E is the neutron energy derived from the fusion reaction, t is the time required for a neutron of energy E to travel to the detector, W is the FWHM of the pulse at the detector, and τ is the duration of the neutron pulse at the origin of the pulse. This formula is an accurate fit (within 5%) to numerical values calculated by Bogdanov and Volosov[28] over a range in E_i from 2 to 100 keV assuming a Maxwellian plasma. For a non-Maxwellian distribution, the average energy is higher for the same W, so for the extreme case of a mono-energetic distribution, the same W results from ions at 220 keV, whereas a Maxwellian distribution gives 160 keV. By using the data from both the NTF and FTF, we can solve for both τ and E_i.

We have chosen to report the E_i for an assumed Maxwellian distribution only because these are the lowest and, therefore, most conservative values, not because we believe that the plasmoids are, in most cases, near-Maxwellian. Using these methods, we observed a broad range of E_i (see Table I) with mean $E_i = 72$ keV. Nine shots, 20% of the total, have $E_i > 100$ keV, and the hottest four shots have $E_i \sim 160$ keV. For ease of comparison with other results, we also give the range of the FWHM of the neutron energy spectra. Fig. 2 shows the TOF signals for one of the 4 hottest shots, shot 11012403, showing a FWHM of >900 keV, a record for a DPF.

(The largest FWHM previously reported, as early as 1978,[29] was 700 keV, or $E_i = 100$ keV.) For the same 44 shots, total neutrons averaged 4×10^{10} with a maximum of 1.1×10^{11} in one shot. While there is a large scatter in the results when plotted against peak current, pressure, or charging voltage, the nine shots with $E_i > 100$ keV occurred within a relatively narrow range of conditions, with charging voltage 32–35 kV, peak current 0.9–1.1 MA and for 8 of the 9 shots, fill pressure of 15–18 Torr, with 5 of the 9 shots occurring at 18 Torr. In addition, the upper envelope of the E_i vs. I distribution (the shots with the largest E_i for a given I) shows a clear increase of E_i with I (see Fig. 3).

When the total number of neutrons generated Y, the duration of the neutron pulse τ, and the neutron rate $P = Y/\tau$ are plotted against E_i, significant correlations are seen (see Fig. 4). For P, there is no correlation with E_i for $E_i < 40$ keV and P is in a relatively narrow range of $2.5–7 \times 10^8$/ns. But for $E_i > 40$ keV and most clearly for $E_i > 70$ keV, there is a

TABLE I. Distribution of average ion energies.

E_i (keV)	FWHM (keV)	Number of shots
0–20	0–320	6
20–40	320–450	7
40–60	450–560	4
60–80	560–650	9
80–100	650–720	9
100–150	720–880	5
>150	>880	4

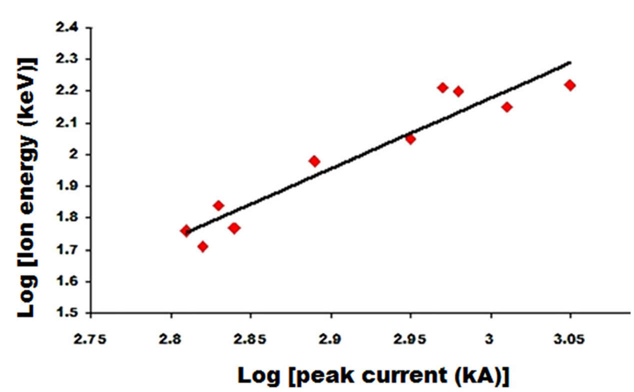

FIG. 3. Ion energy scales as I2 (upper envelope). Line is a linear fit to points with slope of $I^{2.2}$.

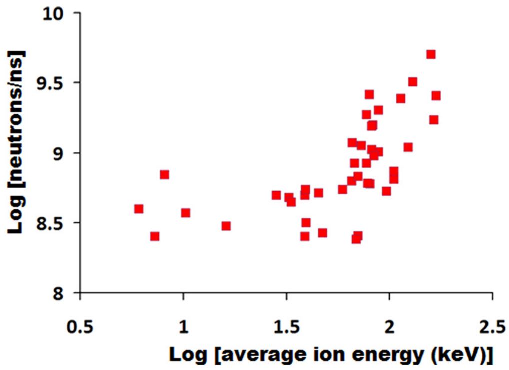

FIG. 4. Correlation between fusion power and average ion energy. Note correlation above around 40 keV and no correlation below that energy. Error bars omitted for clarity.

significant correlation. For the 32 shots with $E_i > 40\,\text{keV}$, $P = kE_i^{1.4\pm0.3}$, with correlation $r = 0.65$, significant at the 1% level. In the energy range from 40 to 170 keV, the reaction rate for $D + D \rightarrow n + {}^3He$ rises with $E_i^{1.17}$, so the results are consistent with the product $n'n{\cdot}V$ being independent of E_i, where n' is the number density of the hot ions, n the density of all ions in the region of neutron production, and V the volume of the region. Similar patterns are seen for Y and τ, with no correlation and a narrow range for $E_i < 40\,\text{keV}$ and a significant correlation for $E_i > 40\,\text{keV}$ (see Table II).

To confirm and refine the results that we obtained by using two TOF detectors, we carried out additional experiments with three detectors, using an additional TOF detector at 1.2 m, close to the axis (called the ITF detector). In these cases, we were able to determine τ more accurately, since at 1.2 m the neutrons have not had time to spread out as much as at 11 m. Here we calculated E_i using the ITF and FTF data.

When E_i is calculated in this way, the earlier results are broadly confirmed, but the distribution is shifted to still higher E_i. When these 23 shots are measured using NTF and FTF data, the mean E_i is 72 keV, but when calculated with ITF and FTF data, the mean E_i is 103 keV. With the 12 shots with $E_i > 100\,\text{keV}$, agreement between the two methods used to measure individual shots is closer, with 6 of these 12 shots having both measures in agreement within 20%. The "hottest" shot in this series had E_i of 170 keV, indistinguishable from the hottest 4 shots of the previous set.

The correlation of P with E_i is again observed with this second data set, using ITF measurements for τ. The relation here for the 22 shots with $E_i > 40\,\text{keV}$ is $P = kE_i^{1.8\pm0.3}$ is somewhat steeper than (but in adequate agreement with) that derived from the earlier data, and the correlation r is similar at 0.62.

TABLE II. Correlations of variables on E_i for $E_i > 40\,\text{keV}$.

Correlation on Log E_i	Slope	r
Log P	1.43 + 0.30	0.65
Log Y	0.83 + 0.27	0.51
Log τ	−0.56 + 0.22	0.42

There is thus convincing evidence that neutrons in FF-1 originate in regions that, in some shots, have ions with mean energy $E_i > 150\,\text{keV}$.

B. Neutron energy isotropy

Given these high ion energies, the key question is whether they are produced by an unconfined ion beam, with the energy spread perpendicular to the device axis generated by the divergence of the beam, or if instead they are produced by trapped ions that are circulating within a dense plasmoid. A significant experimental test that differentiates these two cases is to compare the mean neutron energy in the axial direction with that in the perpendicular direction (horizontal in the case of FF-1). For ions trapped in a plasmoid, we expect the neutron energies to be equal and thus the neutron anisotropy to be zero. However, if the neutrons are primarily produced by the axial ion beam, the average neutron energy in the direction of that beam will significantly exceed the mean energy perpendicular to the beam, so energy anisotropy will differ from zero.

We have used the axial signals from the ITF detector to measure the mean axial neutron energy and from the NTF and FTF to measure the mean perpendicular neutron energy (E_p). The mean neutron velocity and thus E_p can be measured directly from the difference in the peak arrival time at the NTF and FTF. The velocity derived and the timing information then yield the time of origin of the neutron pulse. That time, together with the measured time of arrival of the neutron pulse at the ITF detector, then yield the axial velocity and thus axial neutron energy (E_a).

For the 23 shots from October 2011, mean E_p is 2.25 ± 0.03 MeV and mean E_a is 2.65 ± 0.45 MeV. There is no statistically significant anisotropy. The much larger statistical error for E_a is due to the uncertainty in projecting back the time of origin of the neutrons from the NTF and FTF data, but the value measured is completely consistent with a stationary source value E_0, of 2.45 MeV. There is a significant difference between mean E_p and E_0, but it implies a mean bulk velocity of the neutron source of only 0.087 cm/ns. This would give the deuterons only 8 keV of energy, which is small compared to the up to 160 keV energy inferred from the TOF data. So this test is much more consistent with a neutron origin in trapped ions rather than in an unconfined axial beam.

C. Neutron flux anisotropy

A second key test of a beam vs. confined-ion origin for the neutrons is neutron flux anisotropy. Since a beam of deuterons will produce an anisotropic distribution of neutron flux while trapped ions will produce an isotropic flux distribution, measurement of neutron flux is a sensitive discriminator between the beam and trapped ion origins. Indeed such a test can put quantitative limits on the proportion of total neutron yield which is produced by a beam, if the beam energy is known.

We measured the mean ion energy in the beam (E_b) using the signal from a Rogowski coil located 31 cm from the end of the anode.[30] Since the ion beam is tightly

TABLE III. Neutron flux anisotropy ratio relative to 90°.

	Detector location (degrees from axis)		
E_i (keV)	12.5	4	0
<40	1.16 ± 0.21	2.42 ± 0.31	3.67 ± 1.32
40–100	0.82 ± 0.26	2.17 ± 0.38	1.04 ± 0.38
>100	1.10 ± 0.26	2.41 ± 0.24	1.95 ± 0.62

collimated and is not always exactly aligned with the axis, we succeeded in measuring the beam passing through the Rogowski coil in only 12 shots during May 2011. In these shots, the mean E_b was 320 keV, with the shots with highest yield having $E_b \sim 500$ keV. We can use this value as a rough indicator of the beam energy in other shots.

We compared the flux measured by bubble detectors at 12.5, 4, and 0° (a position directly below the bottom of the drift tube and anode), with that measured by bubble detectors located at 90° from the device axis. As shown in the first column of Table III, there is no statistically significant difference in flux between 12.5 and 90° for shots in any E_i group. We can compare the one-sigma upper limit for the anisotropy of the "hottest" shots of 1.36 with the anisotropy we expect if all the neutrons were produced by an unconfined axial beam colliding with a dense plasmoid near the anode's end.

For a beam energy of 500 keV, the expected anisotropy is 2.6, so we can set an approximate upper limit on the proportion of neutrons produced by a beam colliding with a plasmoid at 23%. Of course the data are also consistent with no anisotropy and thus none of the neutrons coming from an unconfined beam, although at least some neutrons must originate in this way.

The data also excludes the case that a major portion of the neutrons are generated by collisions of the ion beam with background plasma in the vacuum chamber or the 100 cm drift tube that extends below the chamber. Since the bubble detectors at 0° and 4° are necessarily located close to the plasma in the drift tube (at a distance of 8 cm in the case of the 4° detector), they are particularly sensitive to ions in the beam interacting with background plasma very near to their location. By comparison, the 90° detectors are located between 40 cm and 416 cm from the device axis. We took these differences into account by calculating the expected neutron flux from a beam of 500 keV interacting with the background plasma. From a beam that goes all the way down the drift tube, we expect a neutron flux of 1.6×10^{-22} n_pN neutrons/sr at 0° where n_p is the background plasma density and N is the number of beam particles, while at 90° we expect only 5.4×10^{-25} n_pN neutrons/sr from this same source or 300 times less flux. Thus given that the average flux ratio between 0° and 90° actually observed is only 2 (third column of Table III), we expect that no more than 0.3% of the neutrons observed at 90° can come from a beam that extends all the way down the drift tube. Indeed, there is evidence from the pattern of damage caused by ion beam erosion on the base of the vacuum chamber that most of the beam power is not close enough to the axis of the device to travel far down the drift tube.

A second possibility is the generation of neutrons from a beam that only traverses the 16 cm from the end of the anode to the bottom of the vacuum chamber, but is not close enough to the axis to go down the drift tube. In this case, we calculate that the neutron flux would be 4.2×10^{-25} n_pN neutrons/sr at the 12° detector at 28 cm from the anode tip and 7.5×10^{-26} n_pN neutrons/sr for the 90° detector. Thus we could expect a flux anisotropy ratio at 12° of 5.57 if all the neutrons were from the 16-cm long beam. This is far above the maximum of 1.36 anisotropy actually measured, so only about 8% of the neutrons could come from a beam-background interaction.

We thus conclude that at most 30% of the neutrons observed could have come from an unconfined beam and that thus at least 70% of the neutrons come from confined high-energy ions.

D. Timing of neutron emission and beams

It is useful to know when the neutrons are emitted relative to the time of beam generation. We record relatively hard x-rays with the NTF, filtered by 6 mm of copper, through a collimator which restricts the view to the plasmoid, excluding the region where the electron beam hits the anode. However, there is frequently more than one x-ray peak, so identification of a given peak with the beam is not easy. For this purpose, the signal from the VPMT, located above the anode, is relevant, as it is shielded by 14 cm of copper and 5 cm of steel, so is sensitive only to >1 Mev γ-rays generated by the electron beam, as well as to neutrons. The first peak from the VPMT therefore identifies the time of the beam emission.

Looking at the 11 shots in October 2011 with the highest charging potential of 40 kV, we found that the first peak from the VPMT corresponded closely in time with the first x-ray peak observed by the NTF with a time delay of 0 ± 8 ns.

We can then compare the time of beam emission with the peak of neutron emission, as observed in the second, much broader peak from the VPMT. For these 11 shots, the delay of the neutron emission is 26 ± 6 ns. Since the VPMT peak is broadened by scattering, it might appear a few nanoseconds late, so we can also use the time of origin of the neutrons projected back from the NTF and FTF peaks, as in Sec. III B of this paper. The results are similar, with a delay of 32 ± 17 ns, with the increased scatter due to the uncertainty in the back-projection of the neutron origin time.

Since the beam peak FWHM is only 8 ns, this data shows that the neutrons originate close to, but distinctly after the beam, again consistent with an origin of the neutrons from trapped ions, not an unconfined beam colliding with a target. However, the data does not exclude the possibility that the neutrons originate from beam ions that are trapped for tens of nanoseconds in the plasmoids. Nor do the data exclude the possibility that a subsequent smaller beam, after the main one, could be involved in the neutron production.

We show in Figure 5 x-ray data from NTF and x-ray and neutron signals from VPMT for a single shot 11101003,

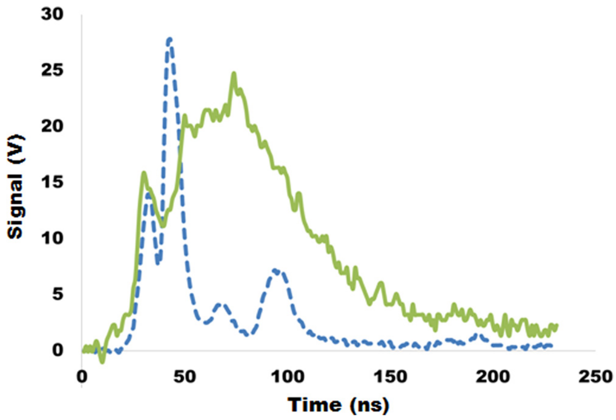

FIG. 5. Signals for shot 11101003 from near time of flight PMT (dashed blue), collimated to view only the region around the plasmoid, and VPMT (solid green), located on axis above the anode and shielded by 14 cm of copper and 5 cm of steel. Signals are corrected for light time of flight and cable delays to refer to origin. Note synchronicity of first peaks, showing electron beam generation. Second broad VPMT peak is for neutrons, broadened by scattering and delayed 13 ns by neutron time-of-flight.

which had the highest neutron yield of the series, 1.5×10^{11} neutrons.

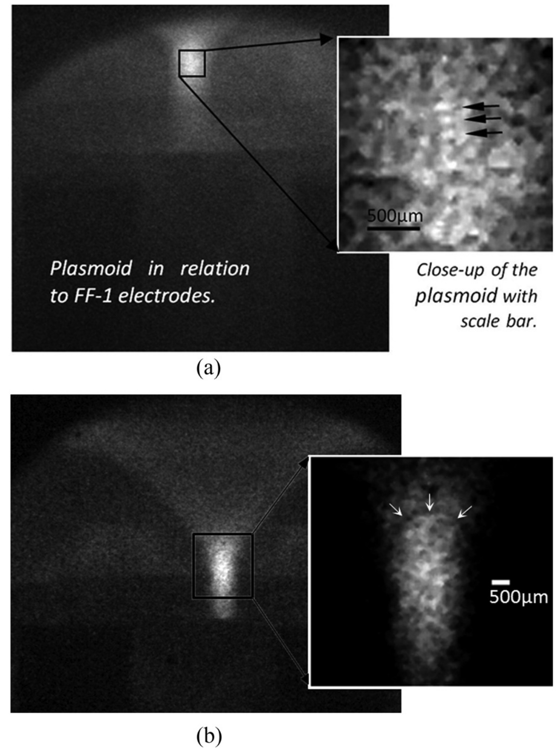

FIG. 6. (a) ICCD image of a plasmoid in shot 11012403. Note the filamentary structure, with nearly horizontal 30-μm radius filaments (arrows) wrapped in a 180-μm coil. Exposure 0.2 ns in visible and near-UV. This is the highest-resolution image of a DPF plasmoid yet obtained. (b) 0.2 ns ICCD image of shot 11100604, with a mean ion energy of 110 keV, also shows an approximately 500-μm radius plasmoid. Note shock wave above the plasmoid (arrows), showing sharp resolution of images.

E. Size and density of confined plasma

Given that the hot ions are confined, the next question is what is the size of the region in which they are confined? Images from the ICCD camera allow us to determine the upper limits for the volume of hot plasma in the plasmoid. Because of variability in the exact time of formation of the plasmoids from shot to shot, we observed the plasmoids only in some cases, such as shot 11012403, the same shot when we obtained the record neutron spectral width shown in Figure 2. Figure 6(a) shows the plasmoid formed on axis at a time within 2 ns of the peak x-ray emission and 52 ns prior to the peak of neutron emission. This is the highest-resolution image of a DPF plasmoid yet obtained. This image appears to show the plasmoid core consisting of a coil of plasma filaments. The bright filament is $\sim$60 μm in diameter and is wrapped in a coil that is 400 μm in diameter and 1.5 mm long. There is also a 500-μm radius halo of less dense filaments surrounding the inner core. This gives a maximum volume for the hot plasma of $\sim 1.2 \times 10^{-3}$ cm^3. This has to be considered an upper limit for the true volume of hot plasma for two reasons. First, the image was taken well before the peak of neutron production, so the plasmoid was still contracting at this time. Second, the image, taken in visible and UV light, shows the outermost layer of the hot plasma, so the inner, hotter layers have less volume.

Similar images with comparable volumes were obtained in several other shots, including shot 11100604 (Figure 6(b)), which also had a high E_i of 110 keV. Thus, in FF-1, the plasmoids are characterized by dense cores that are on the order of 500 μm in radius and 1-2 mm in length.

With either the Maxwellian assumption, for the known reaction rates for deuterons at a given temperature $T = E_i$, or for the assumption of mono-energetic ions confined in a cooler plasmoid, we find from the observed E_i and Y for the largest shots that the product n^2V is $\sim 4 \times 10^{35}$ cm^{-3}. Given the upper limit of V as about 1.2×10^{-3} cm^3, the lower limit for n is 3×10^{19} cm^{-3}.

We can use the amount of charge emitted in the largest measured ion beams as a minimum measure of nV, the total particle content of the plasmoid, assuming as we do that the beam originates there. Since the largest ion beams we have observed[30] have a total charge of 1.6 mC, nV is around 10^{16}, which makes n $\sim$ 4×10^{19} cm^{-3}, in agreement with our other estimate. We did not perform direct interferometric measurements of the density, but the agreement of the two indirect estimates gives us confidence that they are roughly accurate.

Since ions with 150 keV energy have velocities of 0.37 cm/ns, in 30–40 ns of confinement time, they can be expected to travel $\sim$10 cm or at least $\sim$30 orbits of the plasmoid. They are fully confined, but a high degree of stability is not required for the observed lifetime of the plasmoids. It seems unlikely, although not impossible, that the ions are in fact fully Maxwellian. For $E_i = 160$ keV and $n = 3 \times 10^{19}$ cm^{-3}, the thermalization time would be about 40 μs, much longer than either the 20 ns between the time of the last x-ray pulse and the peak of the neutron pulse, or the 30–40 ns duration of the neutron pulse.

To summarize, our results show that >70% of the neutrons observed in these shots originate in a plasmoid with n in the range of $3\text{-}4 \times 10^{19}$ cm^{-3}, with radii of about 500 μm and lengths of about 1.5 mm, confined ion average E_i up to 160 keV and lifetimes of 30–60 ns.

IV. DISCUSSION

It is useful to compare the thermal with the magnetic energy density in these plasmoids. In the case that electron energy is equal to ion energy, thermal energy density is $\sim 2 \times 10^{13}$ erg/cm^3. If we take the plasmoid magnetic field to be generated by a solenoid with ~10 turns and length 1.5 mm, as indicated in Fig. 6, for the peak current of 1 MA, B is ~80 MG and magnetic energy density is 3×10^{14} erg/cm^3 or about 15 times thermal energy density, so is sufficient to confine this hot plasma. In actuality, the average field in the plasmoid as a whole is necessarily less. A minimum estimate can be derived from the energy measured in the ion beams, which must derive their energy from the magnetic field energy stored in the plasmoid. Since the ion beam total energy is ~1 kJ for the largest shots, total electron plus ion beam energy must be ~2 kJ. For the volume of the plasmoids observed, this gives a minimum magnetic energy density of 1.7×10^{13} erg/cm^3, comparable to thermal energy density. Actual magnetic energy must be more than this, assuming less than 100% efficiency in beam generation.

The results reported here are broadly consistent with earlier reports by Nardi, Bostick, Brzosko *et al.*[6,7] of plasmoids with radii on the order of 100 μm, $n > 10^{21}$ cm^{-3} and highly energetic confined ions, as well as in the results reported by one of us (Lerner[23]) of plasmoids with $n > 10^{21}$ cm^{-3} and $E_i > 100$ keV. However, our present results go beyond this earlier work in that we have for the first time obtained high-resolution images of the plasmoid simultaneous with time-of-flight and anisotropy data showing the confinement of ~160 keV ions. In addition, we extend the results obtained earlier with total neutron yields of up to 2×10^9 in the case of Bostick, Nardi, Brzosko *et al.*[6,7] and 3×10^{10} neutrons for Lerner to the higher range of $>10^{11}$ neutrons/shot. We have also demonstrated the very clear and significant correlation of E_i with P. However, in these results, we have not yet duplicated the $n > 10^{21}$ cm^{-3} densities of the earlier work.

Our results contrast in some ways with those obtained by Kubes[8] with the PF-1000 machine, where that group observed much larger plasmoids with radii of 6-7 mm compared with our 500 μm, and lengths of 3–5 cm compared with our 1.5 mm. They also observed multiple neutron pulses with high anisotropy, and the majority of the neutrons being produced by unconfined beam-target interactions. We do not believe this to be a contradiction, as both our results and the earlier ones at Texas A&M were obtained on DPFs with small cathode radii of 5–8 cm. In contrast, the PF-1000 has a cathode radius of 20 cm and anode radius of 10 cm.

There are theoretical reasons[4] to believe that plasmoid radii increase with increased electrode radii, and therefore the use of smaller electrodes for the same peak current (higher initial magnetic field) increases both the density of the plasmoids and the total fusion yield for the same input current.

The conditions obtained in these experiments with deuterium are of interest for aneutronic fusion, such as pB11. At 150 keV, for example, the reaction cross section of the reaction $p+B_{11} \rightarrow 3\ He_4$ is almost triple that of DD, such that similar conditions would yield $\sim 4 \times 10^{11}$ pB11 reactions in the best shots.

Previous theoretical work has shown that there are effects at high magnetic fields that can reduce x-ray Bremsstrahlung with pB11 plasma.[26] Simulation[31] has also indicated promise that fusion power may at times exceed x-ray emission. We intend to test this soon.

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ORIGINAL RESEARCH

Theory and Experimental Program for p-B^{11} Fusion with the Dense Plasma Focus

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Abstract Lawrenceville Plasma Physics Inc. has initiated a 2-year-long experimental project to test the scientific feasibility of achieving controlled fusion using the dense plasma focus (DPF) device with hydrogen-boron (p-B^{11}) fuel. The goals of the experiment are: first, to confirm the achievement of high ion and electron energies observed in previous experiments from 2001; second, to greatly increase the efficiency of energy transfer into the plasmoid where the fusion reactions take place; third, to achieve the high magnetic fields (>1 GG) needed for the quantum magnetic field effect, which will reduce cooling of the plasma by X-ray emission; and finally, to use p-B^{11} fuel to demonstrate net energy gain. The experiments are being conducted with a newly constructed dense plasma focus in Middlesex, NJ which is expected to generate peak currents in excess of 2 MA. Some preliminary results are reported.

Keywords Dense plasma focus · Quantum magnetic field effect · Nuclear fusion · Aneutronic Fusion

Introduction

Controlled nuclear fusion using hydrogen-Boron-11 (p-B^{11}) fuel would constitute a transformative source of electricity with major advantages over any other known source of energy. No neutrons are produced in this reaction, $p + B^{11} \rightarrow 3\,He^4$, and the released energy is carried only by charged particles. This makes possible the direct conversion of the kinetic energy of these charged particles into electricity without going through the inherently expensive process of using heat to produce steam to run a turbine and generator. It thus opens up the possibly of drastically reducing the cost of electricity generation [1–3].

While a secondary reaction, $He^4 + B^{11} \rightarrow N^{14} + n$, does produce neutrons, they carry only 0.2% of the fusion energy and are low-energy neutrons, which are easily shielded. Thus this fuel makes conceivable the design of a generator that produces insignificant amounts of induced radioactivity, and no radioactive waste. These characteristics give p-B^{11} very significant operational advantages over deuterium–tritium (DT) fuel.

However, p-B^{11} presents two major technical challenges that have discouraged funding and research. First, the reaction requires average ion energies above 100 keV, considerably higher than the 40 keV envisioned for DT fuel, and the requirement for plasma density-confinement time product ($n\tau$) is also a factor of 45 times higher for net energy production. Second, the higher atomic charge of boron ions leads to the production of far greater amounts of X-ray energy than DT, and the emission of such X-ray energy cools the plasma, making plasma heating more difficult. We have taken steps to show how both of these technical challenges can be overcome using the DPF.

Dense Plasma Focus

The DPF is a compact and simple device first developed in the 1960s by N. V. Filippov in the USSR and by J. W. Mather in the USA and has been studied by dozens of groups over the last 45 years, resulting a large and rich literature. It consists of two concentric cylindrical electrodes enclosed in a vacuum chamber. The chamber is evacuated to low pressure and then backfilled to several

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torr with the fuel gas. A pulse of electricity with a rise time of 0.2–10 μs from a capacitor bank is discharged across the electrodes during operation [4]. In operation, the capacitors discharge in a several-microsecond pulse, the gas is ionized and a current sheath, consisting of pinched current filaments, forms and runs down the electrodes. When the sheath reaches the end of the inner electrode (the anode), the filaments pinch together, forming dense, magnetically-confined, hot spots or plasmoids [5, 6]. The plasmoids emit X-rays with energy from several keV to over 100 keV. X-ray pinhole images have demonstrated that the plasmoids are tiny, with radii of tens of microns or less [7–11]. The plasmoids have densities in the range of 10^{20}–10^{21}/cm^3. These densities have been measured by a number of independent methods including heavy ion and secondary product fusion [12, 13], CO_2 laser scattering [14], and X-ray line intensities [15]. These plasmoids emit intense beams of accelerated ions and electrons [16–19]. Fusion neutrons are emitted from the device in large quantities (up to 10^{13} per shot).

The role of the plasmoids in producing the fusion neutrons and the physical processes involved in their formation and maintenance has been hotly debated among DPF researchers for decades. The model that best fits all the existing data makes the role of the plasmoids central to neutron production. This model, initially developed by Bostick and Nardi [4], and confirmed by observations of several groups over three decades, was elaborated into a more quantitative theory by the present author [20–24]. In this model, the electron beam transfers part of its energy to the plasmoid electrons, which generate X-rays through collisions with nuclei. Through a plasma instability (probably ion-acoustic), the electrons then transfer part of their energy to the ions, with a typical delay (in our experiments) of $\sim$10 ns. Ion collisions, generating fusion reactions and neutrons, then occur [24]. When the ion and electron beams have exhausted the magnetic energy that confines the plasmoid, and partially or wholly evacuated the particles in the plasmoid, the fusion reactions end.

The DPF routinely produces hard X-rays and gamma rays indicating the presence of bremsstrahlung radiation from high-energy electrons colliding with nuclei [21]. Together with independent evidence, this indicated that the hot spots contained ions and electrons at very high energies in the range of interest for advanced fuel fusion [6, 14, 15, 22–24].

The Bostick-Nardi model detailed in [4] describes the DPF as operating by exploiting a series of natural instabilities in the plasma, with each instability further concentrating the plasma and the magnetic field produced by the currents running through the plasma. In the past few decades, substantial advances have occurred in understanding the basic physics of such instabilities through experiments and observations of space plasma.

In the first instability, the current sheath moving through the plasma between electrodes breaks up into an array of filaments, increasing the density of the plasma and magnetic field strength by a factor of 10–20. The filamentary current sheath, driven by the interaction of its own currents and magnetic field, travels down to the end of the inner hollow electrode, where the filaments converge into a single central pinch region, further concentrating both plasma and magnetic fields. A third instability then kinks the single central filament like an over-twisted phone cord, forming a plasmoid, an extremely dense, magnetically self-confined ball of plasma only tens of microns across. By this time, the density and magnetic fields of the plasma in this small region are tens of thousands of times larger than those present at the start of the process, and a substantial fraction of the energy fed into the device is contained in the plasmoid. A fourth instability causes the magnetic fields at the center of plasmoid to decrease, and these changing magnetic fields induce an electric field, which generates a beam of electrons in one direction and a beam of ions in the other. The electron beam heats the plasmoid electrons which in turn heat the ions, thus igniting fusion reactions. The energy is released in the ion and electron beams and in a burst of X-ray energy from the heated electrons in the plasmoid.

In addition to its very small size, simplicity, and ability to utilize the inherent plasma instabilities (rather than suppressing them), the DPF also has the advantage that the plasmoid is extremely dense. Such a dense plasmoid requires that the ions be confined for only a few thousand orbits, in contrast to the millions of orbits required in tokomaks or most other fusion devices. Thus the high stability of such devices is not required in the DPF, only meta-stability.

Quantum Magnetic Field (QMF) Effect

Lerner theoretically showed [22] that the problem of high X-ray emission with p-B^{11}could be mitigated through the use of the QMF effect. This effect, first pointed out in the 1970s [25], and studied in the case of neutron stars [26], involves the reduction of energy transfer from ions to electrons in the presence of a strong magnetic field. To apply the magnetic effect to the DPF plasmoids, which are force-free configurations, we first note that small-angle momentum transfer parallel to the field can be neglected in these plasmoids, since the ion velocity lies very close to the local magnetic field direction, and $\Delta p_{\parallel}/\Delta p_{\perp} \sim \sin^2\theta$, where θ is the angle between the ion velocity and the B field direction [22].

In a strong magnetic field, since angular momentum is quantized in units of $\hbar$, electrons can have only discrete energy levels, termed Landau levels (ignoring motion parallel to the magnetic field):

$$E_b = \left(n + \frac{1}{2}\right)\frac{e\hbar B}{mc} = \left(n + \frac{1}{2}\right) \cdot 11.6\,\mathrm{eV} \cdot B\,(\mathrm{GG}) \quad (1)$$

Since maximum momentum transfer is mv, where v is relative velocity, for $mv^2/2 < E_b$ almost no excitation of electrons to the next Landau level can occur, so very little energy can be transferred to the electrons in such collisions. Again ignoring the electron's own motion along the field lines, such a condition will occur when ion energy

$$E_i < \left(\frac{M}{m}\right)E_b \quad (2)$$

For $E_i = 300$ keV, this implies $B > 14$ GG for p, $B > 3.5$ GG for α, and $B > 1.3$ GG for ^{11}B. As will be shown below, such field strengths should be attainable with the DPF.

As calculated [22], for $T = T_i/E_b(M/m) < 1$, the coulomb logarithm can drop as low as 0.5 for the heating of electrons by ions, which can only heat electrons that are moving slower than the ions. For the heating of the ions by the much faster thermal electrons, with $T_e \gg 1$, quantum effects can be ignored and the coulomb logarithm is simply $\ln(2T_e)$. As a result, the ratio of these two coulomb logarithm terms can be as high as 20, which results in a similar value for T_i/T_e. This results in a reduction of X-ray emission by as much as a factor of four.

We have performed 0-D simulations of the plasmoid which include this QMF effect [24] which show that in this case fusion power can potentially exceed Bremsstrahlung emission by as much as a factor of 2, allowing ignition of the fuel and an 80% burn-up of the fuel in the plasmoid. While not fully realistic, the simulation is adequate to show the impact of the magnetic effect and the possibility for high fusion yields in which the energy emitted in the form of X-rays and ion beams exceeds the total energy input to the plasma by about a factor of two. Of course, this by no means guarantees that direct energy conversion efficiency will be high enough for a practical generator, but it does indicate that this is at least conceivable, and worth investigating experimentally.

The simulation, by its zero-dimensional character, assumes that the plasma in the plasmoid is homogenous. In addition the simulation assumes Maxwellian distributions for the electrons, and hydrogen and boron ions. Helium ions, produced by the fusion reaction, are assumed to cool to a Maxwellian distribution, but the fusion alpha particles are treated separately, as they are slowed by the plasma. In accordance with observation, it is assumed that the ions are all fully ionized.

This simulation also assumes that the plasma radius contracts during compression and then remains stable. Thus it is assumed that as fusion energy is released, countervailing forces prevent the rapid expansion of the plasmoid.

There are good experimental reasons for believing that this is as at least roughly the case, as we explain here. Half the fusion energy released in DD reactions is deposited in the plasmoids by the $d + d \rightarrow p + t$ reaction. In the plasmoids measured in, for example, Lerner [22], the additional pressure from this deposited energy would disassemble the plasmoids is a few ps, thousands of times shorter than their observed lifetime of tens of ns, unless the pressure was balanced by an increase in confining forces.

We intend to discuss the role played by centrifugal stabilization in the long lifetime of the plasmoids in a future paper.

Conditions in DPF Plasmoids

To see what the consequences of the QMF effect are for DPF functioning, we use a theoretical model of DPF functioning that can predict conditions in the plasmoid, given initial conditions of the device. As described by Lerner [20, 22, 23], and Lerner and Peratt [21], the DPF process can be described quantitatively using only a few basic assumptions. First, we assume that the magnetic energy of the field is conserved during the formation of the plasmoid, and that in a well-formed pinch, all the energy present in the field at the time of the pinch is trapped in the plasmoid. Second, plasma instability theory, as detailed in [20], shows that for optimal filament formation in the plasma chamber the following condition has to be satisfied.

$$\omega_{ce} = \omega_{pi} \quad (3)$$

where ω_{ce} is electron gyrofrequency and ω_{pi} is ion plasma frequency.

Third, we know that at the time the plasmoid begins to decay,

$$\omega_{ce} = 2\omega_{pe} \quad (4)$$

where ω_{pe} is the electron plasma frequency. This is due to the condition that when the synchrotron frequency exceeds twice the plasma frequency, energy can be radiated. At this point, the current begins to drop, and the change in the magnetic field sets up large accelerating potentials to sustain the current. This in turn generates the ion and electron beams that release the energy trapped in the plasmoid and initiate its decay, as well as start nuclear reactions. Finally, we assume that during compression the ratio B/n is a constant, as explained elsewhere [20].

From these basic physical relations, it is simple algebra to derive the plasma parameters in the plasmoid, not only for hydrogen [20], but for any gas or mixture of gases [21, 23]. The results are summarized here:

$$r_c = 1.32 \times 10^{-3}(\mu \cdot z)^{-2/3} r \quad (5)$$

$$B_c = 4z\left(\frac{\mu M}{m}\right) B \quad (6)$$

$$n_c = 3.7 \times 10^{10} \frac{\mu^2 z I^2}{r^2} \quad (7)$$

where B is peak field at cathode (G), B_c is the field in the core of the plasmoid, r is cathode radius (cm), r_c is the plasmoid core radius, n_c is plasmoid ion density, I is peak current (A), μ is average ionic mass and z is ionic charge.

The model [20] also allows us to describe the production of the electron and ion beams and the duration of the plasmoid. This is possible simply by equating the energy lost though the beams to the decay of the plasmoid B field. This allows the calculation of the accelerating potential, beam current and decay time.

$$\tau = 6.2 \times 10^{-6} \frac{r_c}{R_B} = 8.2 \times 10^{-9} \left(\frac{z}{\mu}\right)^{2/3} \frac{r}{R_B} \quad (8)$$

$$n\tau = \frac{304 \mu^{4/3} z^{1/3} I^2}{r R_B} \quad (9)$$

Here, τ is plasmoid decay time, R_B is the effective resistance of the beam, n_c is plasmoid density. However, a modification must be imposed here. For low I and thus low accelerating potentials, all the particles in the plasmoid are evacuated through the beam without carrying all the energy away. In this case the simple model will break down near the end of the plasmoid decay. However, for present purposes a suitable approximation simply reduces the plasma lifetime by the ratio of the accelerating potential to that needed to carry the entire plasmoid energy. To a good approximation this factor turns out to be I/1.4 MA. For $I > 1.4$ MA, this factor is unity.

These theoretical predictions are in good agreement with results that were obtained experimentally in 2001 with a 1.2 MA DPF [22]. If we use these equations to predict B_c we obtain 0.43 GG, in excellent agreement with the observed value of 0.4 GG. Similarly, the formulae yield $n\tau = 4.6 \times 10^{13}$ s/cm^3 as compared with the best observed value in [22] of 9×10^{13} and the average of 0.9×10^{13}.

For decaborane with $Z = 2.66$ and $\mu = 5.166$, with $r = 5$ cm, $I = 2.8$ MA these formulae yield $B_c = 11$ GG and $n\tau = 6 \times 10^{15}$.

This is of course a considerable extrapolation—a factor of 60 above the observed values in both B and $n\tau$. However, these conditions can be reached with relatively small plasma focus devices.

This is as far as the model in [20] takes us. We now turn to determining the fusion yield in the plasmoids, first elaborated in [21] but repeated here. It is clear that this yield is produced by two separate processes. In one process, the accelerated beam of ions collides with the background plasma in the plasmoid. In the second, the electron beam heats the electrons in the plasmoid, which in turn heat the ions, generating true thermonuclear fusion yield. The first is straightforward to calculate and gives the following result:

$$N' = 4\sigma(E_i) n_c \cdot r_c \cdot N_a = \frac{4\sigma(E_i) n_c \cdot r_c \cdot I_b \cdot \tau}{1.6 \times 10^{-19}} \quad (10)$$

$$N' = \frac{2.96 \times 10^{18} \cdot \sigma(E_i) \mu \cdot I^3 \cdot K}{R_B \cdot z} \quad (11)$$

where N' is the neutron yield from the beam-plasma interaction. Here, again, $K = (I/1.4 \times 10^6)$ does not exceed unity and $\sigma(E_i)$ is the reaction cross section. Note that the beam interaction yield is not strongly affected by atomic number.

The question of heating is more complex. If the electrons simply collided with the plasmoid electrons through Coulomb interaction, heating would be quite inefficient. However, H. Hora [27] has shown that, for a variety of plasma beam interactions, the electrons behave *as if* they have a cross section equal to a circle with radius equal to their Compton wavelength, hc/E rather the classical value of e^2/E. This of course increases the effective cross section by $1/\alpha^2$ or 2×10^4. The reason for this relationship is not entirely clear. It occurs only in plasma, since the cross sections of electrons in gas are well known and correspond to the classical result.

Using the Hora formula for cross section of relativistic electrons, we can easily calculate the fraction of beam energy that goes into heating plasma electrons:

$$d_c = \frac{E_i^2}{\pi \cdot h^2 c^2 n_e} \quad (12)$$

$$w = \frac{4 r_c}{d_c} = \frac{3.92 \cdot \mu^{2/3} \cdot z^{2/3}}{r \cdot R_B^2} \quad (13)$$

$$T_{e\,max} = 721\left(\frac{z}{1+z}\right) \text{keV} \quad (14)$$

$$T_{ef} = \frac{2.83 \times 10^6 \cdot \mu^{2/3} \cdot z^{5/3}}{r \cdot R_B^2 (1+z)} \quad (15)$$

Here, d_c is collision distance, w is the ratio of electron beam energy to heating energy, T_{emax} is the temperature for $w = 1$. We take half the peak temperature as T_{ef}, the average electron temperature of the plasmoid, although this ignores the nonlinearity of reaction rate with T. We thus find that the temperature increases nearly as the cube of atomic number of the gas involved. Since $n\tau$ increases as $z^{2.4}$, the $n\tau T$ product increases as approximately z^5. We thus see the model's strong prediction of fusion yield improvement with increasing μ and z.

In general, the electron–ion heating time is small compared with the duration of the plasmoid:

$$t' = \frac{1.56 \times 10^7 \mu \cdot T_e^{3/2}}{n \cdot z^2} = \frac{4.2 \times 10^{-4} \cdot T_e^{3/2} \cdot r^2}{\mu \cdot z^3 \cdot I^2} \tag{16}$$

$$\frac{t'}{\tau} = \frac{5.1 \times 10^4 \cdot T_e^{3/2} \cdot r \cdot R_B}{\mu^{-1/3} \cdot z^{7/3} \cdot I^2} \tag{17}$$

We thus find the thermonuclear yield to be:

$$N = f(T_i) n^2 \tau 8\pi r_c^3 = \frac{6.5 \times 10^5 \cdot \mu^{4/3} \cdot K \cdot I^4}{R_B \cdot z^{2/3}} f(T_i) \tag{18}$$

where $f(T_i)$ is the reaction rate. The increase in $n\tau$ is partially countered by the decrease in the radius of the plasmoid and thus the total mass involved, so exclusive of the increase in T, yield increases only as $z^{1.4}$, assuming a constant μ/z. But the strong increase in T generates an even sharper rise in yield. Since T increase with decreasing r, up to the point $w = 1$, smaller cathodes increase yield as well.

It should be noted that the thermonuclear yield, which should be observed as isotropic, scales as I^4 while the beam-plasma yield observed as anisotropic scales as I^3, so the degree of anisotropy will decrease with increasing current and total yield.

Control of Angular Momentum and Efficiency of Energy Transfer to the Plasmoid

The appropriate choice of cathode radius, peak current and fill pressure is not enough to ensure the efficient formation of a plasmoid that contains the full magnetic energy input to the device. In fact, in few of the existing DPF devices is the efficiency of energy transfer into the plasmoid very high, limiting yield to well below that predicted by the model described in the section "Conditions in DPF Plasmoids". For high efficiency, control of angular momentum is required, as first pointed out by Lerner and Blake [23].

The process of plasmoid formation involves the development of a kink instability in the current flow at the pinch and as such requires a certain amount of angular momentum. We here refer to total angular momentum, both of the magnetic field and of the particles. Another way of looking at this is that the axial field/azimuthal field ratio has to be sufficient for the kinking to occur. During the compression phase, angular momentum per unit mass is conserved, so this angular momentum can be derived from angular momentum present in the filament array at the time the compression begins. An approximate measure of the angular momentum per unit mass required can be obtained by the formula 0.5 $V_A r$, here V_A is the Alfven's velocity in the plasmoid and r is the plasmoid radius.

Angular momentum can be imparted to the plasma sheath during the rundown by the interaction of the inward flowing electron flows and any small initial axial magnetic field (e.g., the small axial component of the earth's magnetic field). The JXB force accelerates the electrons slightly in the azimuthal direction, creating an azimuthal component to the current. This in turn increases the axial magnetic field and thus the azimuthal acceleration of the electrons. In this way, a very small initial magnetic field (or small, random initial azimuthal component in the current created by irregularities in the electrodes) can be rapidly magnified. For example, given a ratio of axial to total magnetic field $B_0/B_T = \sin\theta$ then any initial axial field will be amplified so that at the end of the run down $\theta = \theta_i e^{V\tau/R}$, where τ is the run down time and R is the anode radius. Thus final angular momentum per unit mass is VR $\theta_i e^{V\tau/R}$ where V is the Alfven velocity at the anode radius at peak current. This is a simplified analysis, as in the real case B_T is rising rapidly during the early stages of the pulse. However, a numerical analysis using a realistic function for B_T shows a very similar result, as at later times, the magnitude of the initial axial field is very small compared with B_T, so the amplified field dominates, as in the simplified formula.

Since $V\tau$/r is proportional to L/R, the angular momentum is sensitively dependent on this ratio. If there is insufficient angular momentum, the plasmoid radius will be reduced in proportion to angular momentum and the total plasmoid energy and mass will be reduced as the cube of angular momentum. This sensitivity to initial very small angular momentum can in part explain the well-known shot-to-shot variability of plasma focus devices. Calculations show that if this natural amplification mechanism is relied on to provide angular momentum and the initial magnetic field is the earth's ambient field, L/R must be more than about 7 for high efficiency of energy transfer into the plasmoid. Indeed, in the best-performing DPF devices, this ratio exceeds 7 and can be as high as 17, implying that high V_A and longer τ are desirable.

The disadvantage of such long electrodes is their high inductance, around 20 nH. Since external inductance must exceed load inductance, total inductance in the system must be around about 45 nH. As Lee [28] has shown, these considerations lead to limitations on the total amount of current that can be fed into the DPF from a capacitor bank, as the pulse length must increase as capacitance does, unless the charging voltage becomes very high. The high inductance, by forcing up total bank energy, reduces the proportion of that energy that can be converted into the DPF magnetic field. So even if the efficiency of energy transfer from the magnetic field to the plasmoid increases, the total efficiency from capacitor bank to plasmoid does not necessarily increase.

The alternative to relying on amplification of the ambient magnetic field, is to inject angular momentum with a small artificial axial magnetic field, produced by a helical coil. While there have been previous efforts to stabilize DPF pinches with axial fields, these fields have been much greater than those contemplated here, generally thousands of G. If the model described here is valid, too much angular momentum will prevent the plasmoid from being formed and thus drastically reduce fusion yield. Only the optimal amount of field, of the order of a few G, will provide enough angular momentum to just balance the compressional pinch forces and form the largest possible plasmoid.

Viewed in another way, for a given electrode radius and length, the injection of angular momentum will greatly increase the angular momentum and thus the size of the plasmoid, and thus the energy yield from fusion reactions in the plasmoid. Approximately, fusion yield will increase as the third power of the amount of injected angular momentum.

Experiments with Focus Fusion-1

To test the above mentioned, and other theoretical predictions, we have constructed a new DPF facility (called Focus Fusion-1, or FF-1 for short) in Middlesex, NJ, with a 113 μF, 45 kV capacitor bank, which we expect will be able to achieve peak currents above 2 MA.

The design of FF-1 is based on the accumulated experience of the DPF field but represents an advance in two major ways. First, we expect that it will achieve a very high current with a very compact and relatively economical design by achieving a low external inductance of about 15 nH. With a capacitor bank total capacitance of 113 microfarads and a maximum charge potential of 45 kV, we expect the device to achieve a peak current of 2.2 MA using deuterium with 14-cm long anodes and as high as 2.8 MA using heavier gases and shorter anodes. Exclusive of the support structure, the entire device fits in a 2.5 × 2.5 × 1 m volume. Second, for these high peak currents, FF-1 has very compact electrodes, thus generating a high initial magnetic field. The cathode consists of 16 copper rods set at a radius of 5 cm and the anode is a hollow copper cylinder 2.8 cm in radius. At the highest peak current, the field at the anode surface will be around 200 kG, which we estimate is close to the highest field allowed by the mechanical strength of copper. These high fields will make possible high fill gas densities, which in turn will lead to high final densities in the plasmoids. Six different anodes ranging in length from 7 to 14 cm will be used, depending on the fill gas.

Figure 1 illustrates the vacuum chamber and the drift tube arrangement. The vacuum vessel is made of stainless steel SS304 with internal dimensions of 10 cm diameter and 30 cm height. It has been annealed to prevent it from acquiring a permanent magnetization, and thus complicating the axial field experiments. The drift tube is 100 cm long. A copper coil generates the axial *B*-field necessary for angular momentum injection. A knife edge consisting of 100 tungsten pins is placed around the anode close to the insulator and promotes the formation of filaments. The insulator is made of alumina ceramic. The chamber is initially evacuated using a Pieffer turbomolecular pump to ultra high vacuum levels. After this pump down, the deuterium gas is flowed into the chamber until the predetermined pressure is reached.

The experiment currently uses 13 diagnostic instruments to measure the various parameters of the plasma and the tiny plasmoid. We have listed the instruments by the parameter they are designed to measure. To measure the size and shape of the plasmoids we use:

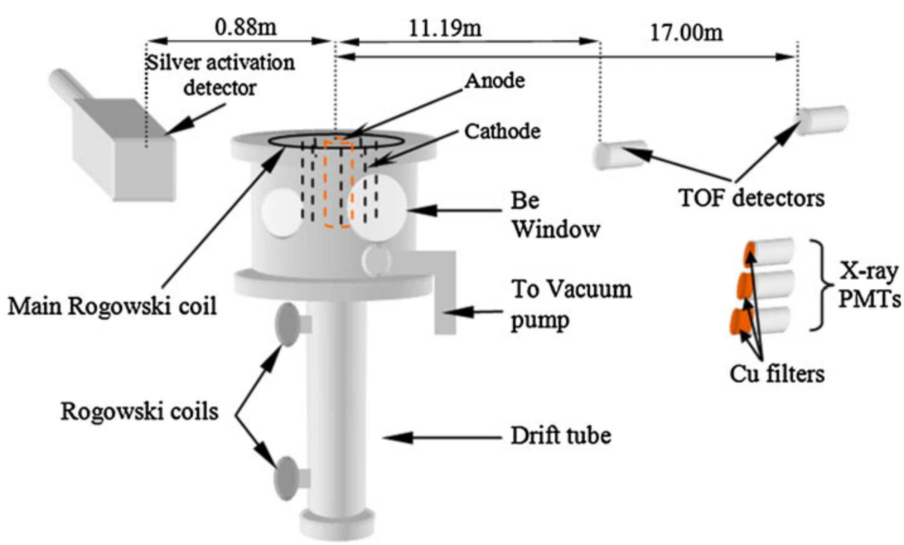

Fig. 1 Experimental setup of Focus Fusion-1

A 4PICOS Stanford Computer Optics ICCD camera with 0.2 ns minimum exposure time. The ICCD is sensitive to UV radiation down to 180 nm and thus should be able to observe radiation above the plasma frequency of the plasmoids for all deuterium experiments, although not for the heavier gases. In addition to its high temporal resolution, the ICCD currently has a spatial resolution of about 30 microns. We also use an X-ray pinhole camera.

To measure the electron energy distribution we use:

A set of three scintillators and PMT X-ray detectors each located behind a different thickness of copper filter—300 microns, 3, 6 mm. The ratios of the signals from the PMTs measure the average X-ray emission and can be fitted to a model of bremmstralung radiation to obtain the average electron energy with high time resolution. The detectors are shielded by a 5 cm lead brick from the emissions due to the collision of the electron beam and the anode, so that we are measuring X-rays from the plasmoids alone. The detectors are also shielded by copper sheaths from the RF pulse which arrives at the same time as the X-ray pulse.

The energy of the ions is measured by two neutron time of flight (TOF) detectors that consist of two scintillation detectors with PMTs placed at different distances—11 m for the near detector and 17 m for the far detector. The difference in the detection times of the two detectors measures the energies of the neutrons, thus allowing us to differentiate between the 14.7 and 2.5 meV neutrons from the D-T and D-D reactions. In addition, the spread in energies, indicated by the widening of the pulse with distance, gives us a measure of the ion velocities within the plasma. Since X-rays arrive first at the detectors, they produce a distinct signature and can be easily isolated from the neutron signal.

The TOF detectors can also be used to determine the density of the plasmoid. Since the DT neutrons can only be produced from tritium that is itself generated by DD reaction within the plasmoid, the ratio of DT to DD neutrons gives a direct measurement of the density of the plasmoid. In addition, if we know the volume of plasmoid from the pin whole camera, ICCD camera and the X-ray lens, and we know the electron temperature from the X-ray spectrometer, we can put these values together with a standard formula from the total amount of X-rays. We can then determine density using formula:

$$\text{Total X-ray Power}(P_x) = 1.6 \times 10^{-32} n_i^2 \cdot V \cdot T_e^{1/2} \tag{19}$$

The average ion energy can also be cross-checked given the density and volume of the plasmoid by the formula

$$N = n_i^2 V \tau \langle \sigma v \rangle \tag{20}$$

where N is neutron yield, 'V' is the volume, τ is confinement time, $\langle \sigma v \rangle$ is the reaction cross-section, n_i is the ion density In this manner every plasma parameter is obtained by at least two independent means and in most cases three.

Neutron measurements are made with two BTI bubble detectors, each calibrated by the manufacturer to ±25%. In addition, we have built a silver activation detector exactly following a previously calibrated design [29]. We have cross-calibrated the neutron detector with the bubble detectors and find them in agreement within 10%.

The ion beams are measured with two Rogowski coils built into the drift tube, one at 30 cm from the end of the anode, the other at 100 cm. The coils provide a measure of both the net current of the beams, and by time-of-flight calculations the energy distribution of the ions.

A main Rogowski coil built into the lower (ground) base plate records the dI/dt of the current through the anode and is integrated digitally to provide the current measurement. We have calibrated the current to within 5% by comparing the integrated current with a waveform generated by a detailed run-down simulation developed by Lee [28] for the measured capacitance, charging voltage and other characteristics of our device. The resulting calibration is also within 5% of that calculated from the inductance of the coil.

Finally, a HV probe measures the voltage on an individual spark plug.

Preliminary Experimental Results

So far, we have fired FF-1 over 500 times since it produced its first pinch on October 15, 2009. We have been somewhat slowed by the poor initial functioning of the switches, supplied by R. E. Beverly and Associates, which required extensive modification and rebuilding. However, we report here on some important preliminary observations which will be elaborated in future papers.

First, the fusion yield, as measured by the silver activation detector, depends sensitively on the time of the pinch. Much other DPF work has shown that the highest yields are obtained when the pinch occurs close to the quarter-cycle time of the device, when the maximum current would occur without the pinch. Here we define the pinch time as the time at which dI/dt has a minimum and thus the rate of energy transfer into the plasmoid is at a maximum. However, most researchers have found that the actual peak in yield occurs with a pinch time somewhat later than the quarter-cycle time, when the current is actually decreasing [30]. This is true for our FF-1 results as well, *but only if the axial magnetic field is absent.* When the field is present, we find that fusion yield increases significantly—by more than a factor of three—when the pinch time is exactly at the quarter cycle time (within ±3%).

As shown in Fig. 2, the results for shots at 10 torr D fill pressure tightly follow a steep scaling curve. All of the shots with the highest yield, and with pinch times between 1.78 and 1.86 μs—very close to the quarter-cycle time of 1.8 μs—were obtained with an additional axial field. In these particular cases, the field was about 1 gauss and was imposed by the magnetization of the vacuum chamber before we annealed the chamber to prevent such magnetization. No shots without the imposed axial magnetic field have such high yields or short pinch times. For those shots, the maximum yield occurs with pinch times >2.0 μs (thus for $R > 1.1$, where R is the ratio of pinch time to quarter-cycle time). The peak current in these shots varied between 630 and 720 kA.

The shots taken at higher current (around 1 MA) and with fill pressures of 18–24 torr show the same pattern, but with an increase in yield of about a factor of 4–5 at the same pinch times. This shot series demonstrated that the short-pinch time regime was not accessible without the additional axial field. Without this imposed field, when the fill pressure was reduced sufficiently for rapid run-downs and thus short pinch times, no pinch occurred.

An indication of the physical processes associated with these different yields is provided by the main Rogowski coil traces, which record the dI/dt of the current passing through the anode. For the long-pinch-time pulses (LPTs), those with $R > 1.1$, the characteristic fall in dI/dt at the time of the pinch is not smooth, but is interrupted by one or two large bumps, where the decline in current, and thus the transfer of energy into the plasmoid, is interrupted (Fig. 3). This phenomenon occurs in all the LPTs that we have observed. By contrast, all of the short-pinch time pulses

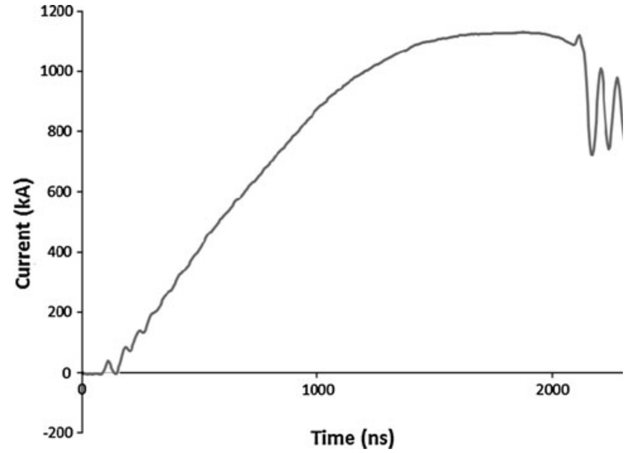

Fig. 3 Current vs time, shot 10011002, an LPT, with pinch process starting with negative dI/dt. Note the small bump in current before the pinch

(SPTs) have smooth decreases to the pinch (Fig. 4) and smooth increases in voltage.

The bumps characteristically precede the pinch maximum by only 30–50 ns. At this time, the current sheath has already converged onto the axis of the anode. We know this from our ICCD images, which show that the sheath is on the axis as early as 225 ns before the pinch (Fig. 5). So whatever physical process are causing the bumps, occur in the final stages of the formation of the plasmoid.

It is significant that the yields of the STPs exceed those obtained by other DPFs at the same current by about a factor of 6 (Fig. 6). Thus, the best yields obtained without the additional axial field are comparable to those obtained elsewhere, but the STPs obtained with the axial field have considerably higher yields than the historical DPF trend.

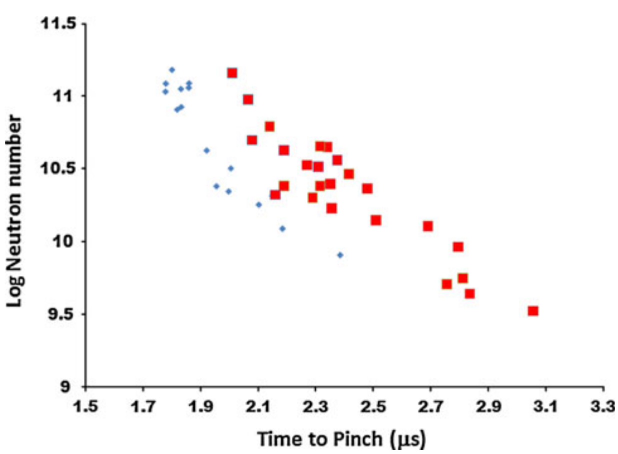

Fig. 2 Log neutron yield vs time to pinch. The *small dots* are shots at 10 torr fill pressure while the *large ones* are at 18–24 torr. *Error bars* are omitted for clarity and are 0.1 for log yield and extremely small—less than 5 ns—for time. Quarter-cycle time is 1.8 μs

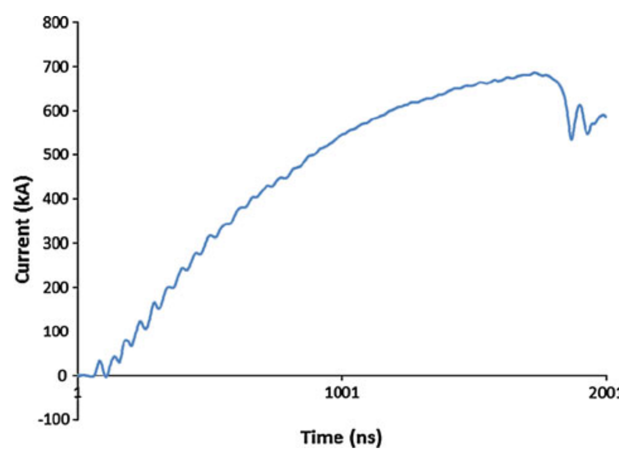

Fig. 4 Current vs time, shot 03301010, a SPT with pinch process starting with positive dI/dt. Note the smooth decline in current into the pinch

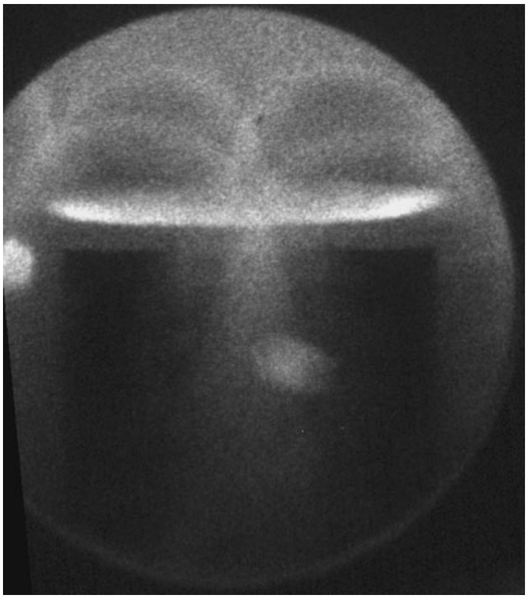

Fig. 5 ICCD image of end of anode at 225 ns before pinch, exposure time 0.2 ns. Note the convergence of the filaments at this time on the axis of the anode. The *circle* is the viewing window and the *bright horizontal ellipse* is the hole in the anode

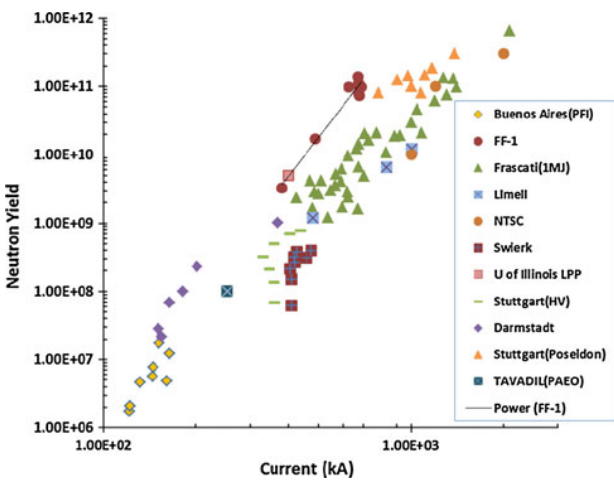

Fig. 6 FF-1 SPT results, *filled circles on line*, fall above the historic trend line of DPF results. Data is from M. Milanese and J. Pouzo [31], except for U of Illinois and FF-1. *Line* is power-law fit to FF-1 data

Comparison with Theory and Tentative Explanation of Results

We can compare these preliminary results with the yield predicted by the theoretical model described in this paper. Equations 11, 15 and 18 enable us to calculate a predicted yield based only on the peak current and the cathode radius of the device. Table 1 shows a comparison of the predicted yield with those actually observed for the STPs. As can be seen there is good agreement with these yield observations. We are in the process of comparing the other predictions of the model with observations.

Our results pose a number of questions that we can provide only tentative answers to at this time. Why are the yields much higher for the STPs than for the LTPs? Why are the STPs obtainable only with the imposed axial field? What is the significance of the bumps in the d*I*/d*t*?

It is reasonable to hypothesize that the two precursor bumps are caused by shocks which heat the plasma before the plasmoid is fully compressed, decreasing the amount of energy available for the plasmoid and possibly as well the amount of angular momentum. One likely time for such shocks to occur is in the final stages of the kinking process, when the coils of the kinking filament are approaching each other at high velocity. It is possible that with adequate injected angular momentum, due to the increased axial field, these shocks will be greatly decreased, as the coils will slide past each other in a spiral fashion, rather than colliding head-on. This would allow greater energy transfer other plasmoid and thus the higher yields. Of course, such a conclusion requires a good deal more evidence to be validated.

We note that, as described in the section "Control of Angular Momentum and Efficiency of Energy Transfer to the Plasmoid", the angular momentum is increasing exponentially with time. If a minimum amount is essential for the formation of the plasmoid, and thus for the pinch, the time needed to reach this minimum will be reduced if the initial axial field is greater. So an alternative explanation of the role of the axial field is that it allows this minimum to be reached before the pinch time, thus allowing the SPTs to take place.

The role of the precise timing of the pinch is less clear. Since the shocks occur before the pinch and presumably determine the energy transferred, the critical periods would logically be *before* the shocks, when the rapid fall in d*I*/d*t* just begins (in our hypothesis, with the start of the kinking process). In that case, the start of this fall in d*I*/d*t* occurs when the current is *rising* for all of the STPs and when it is *falling* or near zero for all of the LTPs. To be precise, all the STPs have $dI/dt > 10^{11}$ A/s at the time the pinch begins—a sudden shift to high negative d*I*/d*t*—while all the LTPs have $dI/dt < 3 \times 10^{10}$A/s at this time and the vast majority have $dI/dt < 0$. So the sign of dI/dt seems to be highly significant as well as its magnitude. The question then arises: why does the sign of d*I*/d*t* affect the shock process and how does it interact with the imposed axial field?

Tsybenko and Miklaszewkis [32] looked at the problem of pinch timing based on the observation that, in most DPFs, the maximum yields are slightly after the quarter cycle time. They hypothesized that a tangential discontinuity, which occurs when two adjacent parts of a

Table 1 Comparison of observed and predicted yield, SPTs

Shot no.	Fill pressure (torr)	Peak I (kA)	$Yield_{obs}$ ($\times 10^{11}$)	$Yield_{pred}$ ($\times 10^{11}$)	Pred. Obs
33003	10	674	1.05	1.54	1.45
33004	10	680	0.74	1.63	2.18
33005	10	675	0.77	1.55	1.99
33006	10	689	0.99	1.78	1.79
33007	10	627	1.03	0.94	0.9
33009	10	676	1.13	1.56	1.39
33010	10	674	1.4	1.53	1.09
31202	10	720	1.13	2.39	2.11
70605	7	488	0.2	0.167	0.83

cylindrical plasma are rotating at different frequencies, could set off instabilities that disrupt the pinch. They show that such an instability is suppressed if the current in the column is varying at a frequency comparable to the instability growth time—around 10 ns. However, in our observations the current varies over a time scale of 6–7 μs, so it is hard to see how this mechanism could be significant.

It is possible that the azimuthal potential induced by the d*I*/d*t* can add to or subtract from the angular momentum provided by the axial field coil to produce the optimal amount of angular momentum both for minimizing the shocks and forming the plasmoid, but at the moment a complete explanation of the data is not yet in hand. We expect that experiments now underway will greatly clarify the outstanding theoretical questions.

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