Proposal for Compact Toroid Injection in NSTX – Summary Report

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R. Raman

4 November 2008

During the past four years for the proposed plan to conduct CT injection research in NSTX, the fusion community has been made more aware of the need for this important research through three journal publications, a fourth invited journal paper which has been submitted to the journal, five conference talks, three presentations at Burning Plasma Meetings, an EPS poster presentation, and supporting presentations during NSTX Research Forums.

For this concept to become a useful tool for ITER and new magnetic confinement machines, the next step is to begin experiments on NSTX. All of the CT injection hardware continues to be stored in a preserved state at PPPL (Figure 1). A suitable lab space for initiating CT injection research at PPPL has been identified. A suitable port location for installing the CT injector on NSTX has also been identified (Figure 2).

Summarized below is a list of the important publications and presentations and the response to these presentations from the international fusion program, which clearly shows that the past four years have been quite productive in educating the fusion audience about the need for CT fuelling. The most critical comment I heard from a senior member of the ITER program was "Why have you not done any new experiments?" The DOE is in a very good position to benefit from this much needed research, which if initiated soon, would be unique in the world and it would allow NSTX to become a world leader in the area of advanced fuelling.

I was invited by a member of the Japanese Fusion Program to write a paper (a review article) in the area of Particle Control for the Journal of Plasma and Fusion Research. This article has now been submitted to the journal.

CT Injection Related Journal Publications

1. R. Raman, "Advanced fueling system for use as a burn control tool in a burning plasma device," Fusion Science and Technology, Vol **50**, 84 (2006)

2. R. Raman, "Advanced Fuelling System for Steady State Operation of a Fusion Reactor," Fusion Science and Technology, Vol **54**, 71 (2008)

3. R. Raman, "Advanced Fuelling System for ITER," Fusion Engineering and Design (2008) – accepted for publication, in press: doi:10.1016/j.fusengdes.2008.06.043

4. R. Raman, "Contribution to ITER of Self-Organizing Plasma Research in Particle Fuelling," – submitted to the Journal of Plasma and Fusion Research (September 2008) – invited journal paper

CT Injection Related Conference Papers (4 - 6 page papers)

R. Raman, "Fuelling Requirements for Advanced Tokamak Operation," **P1-071**, Proceedings of the 32st EPS Conference on Plasma Physics, 27 June to 1 July (2005) Tarragona, Spain – 4 page paper

R. Raman, T.R. Jarboe, H.W. Kugel, "Fuelling Requirements for Steady-State Spherical Torus Operation," *Proceedings of the 3rd IAEA Technical meeting on Spherical Tori*, 3-6 October 2005, St. Petersburg, Russia (2005). – 6 page paper

Burning Plasma Physics Meetings (Talks)

R. Raman, T.R. Jarboe, "Requirements for an Advanced Fuelling System, FESAC Panel Meeting," PPPL, 7 August (2007)

R. Raman, "Advanced fuelling system for use as a burn control tool," IEA Workshop (W60) on Burning Plasma Physics and Simulation, 4-5 June (2005) University Campus, Tarragona, Spain.

R. Raman, "Advanced fueling system for use as a burn control tool," US Burning Plasma Workshop, ORNL, Dec 8 (2005)

Conferences and Workshops

R. Raman, T.R. Jarboe, H.W. Kugel, "Fuelling Requirements for Advanced ST Operation," 13th International ST Workshop, 10-12 October (2007), Fukuoka, Japan - Talk

R. Raman, Advanced Fuelling system for use as a burn control tool in a burning plasma device, Session S5, 8th International Symposium on Fusion Nuclear Technology, Heidelberg, Sept 30 – Oct. 5 (2007) - Talk

R. Raman, Fuelling System for Steady State Operation of a Fusion Reactor, 8th International Conference on Tritium Science and Technology, 16-21 September (2007), Rochester, New York – This is the only poster presentation

R. Raman, "Fueling Requirements for Advanced Tokamak Operation," 6th International Symposium on Current Trends in International Fusion Research: A Review, 7-11 March 2005, Washington, DC, USA - Talk

Fuelling Requirements for Steady-State Spherical Torus Operation, R. Raman, T.R. Jarboe, H.W. Kugel, Joint meeting of The 3rd IAEA Technical Meeting on Spherical Tori and The 11th International Workshop on Spherical Torus, 3 to 6 October 2005, St. Petersburg, Russia (2005) – Talk

ITPA Meetings (Talks)

R. Raman, "Fueling requirements for steady-state, high bootstrap current fraction discharges," ITPA Meeting on Steady State and Energetic Particles Working Group, General Atomics, 8-10 October (2003)

R. Raman, "Compact toroid injection studies and extrapolation to ITER, ITPA Meeting on SOL and Divertor," Lisbon, Portugal, 8-12 November (2004)

Response from senior members of the International Fusion Program

- During the summary session of the 2008 IAEA FEC in Geneva, D. Stork, in summarizing the ITER and Fusion Technology related work, stated at least three times the lack of adequate fuelling related papers at the conference. He stated there were only two fuelling related papers. He said more research is needed in this area and highlighted the importance of fuelling for ITER.

- A supporting E-mail from Dr. Shimada, attached as the last page of this document (of the ITER Organization), states: *"From this viewpoint, your foresight and your longstanding efforts of developing Compact Toroid are very much appreciated, especially since the limitation of the presently available fuelling schemes has become obvious."*

- In the summary of the IEA Workshop on Burning Plasma Physics and Simulation, July 4-5, 2005, published in Fusion Science and Technology (Vol. 49, Jan 2006, pg 79) by A.J.H. Donne et al., in the area of Control and Diagnostics, they state, "In the field of *density control* it has been concluded that there is not much flexibility in the fueling of ITER." As a solution they state, "New *fueling techniques* should be tested on present devices. Given the prospects of CT injection, a test on a relatively large device is highly desirable. Pellet fueling from the high field side equatorial plane should be tested in plasmas with high edge temperatures and close to operational boundaries to judge its merits."

- The CT proposal has been endorsed by the ITPA Steady State Operations group, which in its November 2003 annual report, under section 9 – Other recommendations, stated *"R. Raman made a presentation on the injection of compact toroids (CT) for fuelling advanced scenarios. The approach appears interesting and a plan for developing this technique was proposed, the first step being a full test on NSTX, which appears essential before considering such a technique for ITER. The group is in favor of this proposal."*

Summary of the most Important Results in the Papers listed on Page 1

The 2006 Fusion Science and Technology paper describes the importance of localized core fuelling for steady-state operation of fusion reactors. Steady-state advanced tokamak and ST scenarios rely on optimized density and pressure profiles to maximize the bootstrap current fraction. Under this mode of operation, the fueling system must deposit small amounts of fuel where it is needed and as often as needed, so as to compensate for fuel losses, but not to adversely alter the established density and pressure profiles. Conventional fueling methods have not demonstrated successful fueling of AT-type discharges and may be incapable of deep fueling long-pulse edge-localized-mode–free discharges in ITER. The capability to deposit fuel at any desired radial location within the tokamak would provide burn control capability through alteration of the density profile. The ability to peak the density profile would ease ignition requirements, while operating ITER with density profiles that are peaked would increase the fusion power output. An advanced fueling system should also be capable of fueling well past internal transport barriers. Compact Toroid (CT) fueling has the potential to meet these needs, while simultaneously providing a source of toroidal momentum input.

The paper published in Fusion Sci. Technol. **54**, 71 (2008) describes the tritium related benefits of a CT fueller. Besides a simpler tritium fuel cycle offered by a CT fueller, as a result of the higher fuel burn-up fraction achieved due to core fuelling, the tritium throughput can be substantially reduced. This has the benefits of reduced tritium retention in the walls (by as much as 50% or more) and less tritium inventory on site. Both of these are very important for the early phase of ITER operations.

The paper published in Fusion Engineering and Design (2008) describes the CT fuelling requirements for ITER. It describes the amount of momentum a CT based fueller could inject in ITER. It provides a clear physics argument for the observed lack of metallic impurities from CT injection experiments. It presents a program plan for developing the CT fuelling concept on a time scale to impact ITER operations.

The invited paper submitted to the Journal of Fusion and Plasma Research, describes the advantages offered by STs for developing the CT fuelling concept. In an ST, because of the steep gradient in the toroidal field, the large plasma cross-section and the reduced magnitude of the toroidal field (compared to a tokamak with similar performance), the CT stopping location can be much more precisely established. This is important for establishing the CT penetration scaling laws for future machines. Other advantages of a CT fuelling system such as use in transport studies and reduced loop voltage plasma startup for ITER are also described. The roles NSTX and QUEST could play in developing the CT fuelling concept are described.

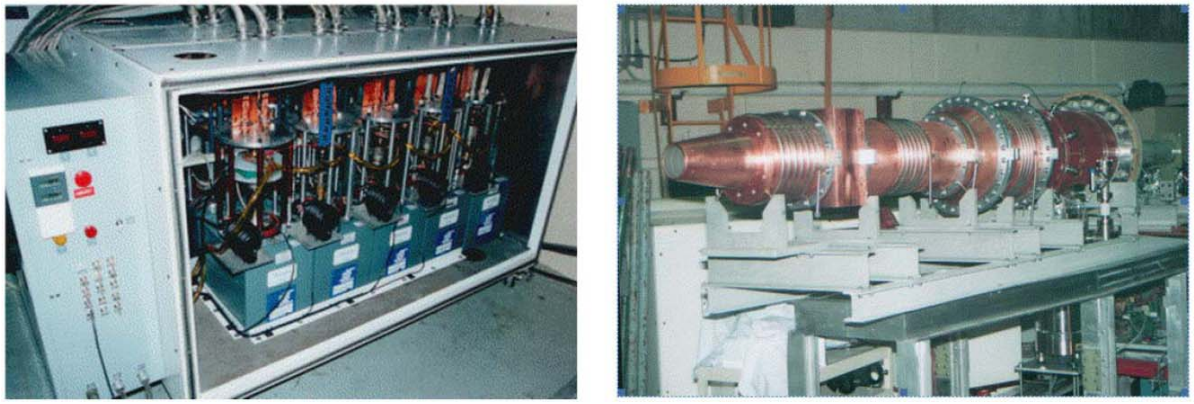

Figure 1: (Right) An assembled view of the CT injector. All plasma facing components are coated with state-of-the-art high quality coating of dense tungsten to reduce electrode erosion. It has shown clean metallic-impurity-free fuelling of TdeV. Shown on the left is the capacitor bank power supply used for forming the CT. A similar (but larger) capacitor bank (not shown here) is used to accelerate the CT. All these, including the vacuum systems and CT diagnostics are presently in storage at PPPL.

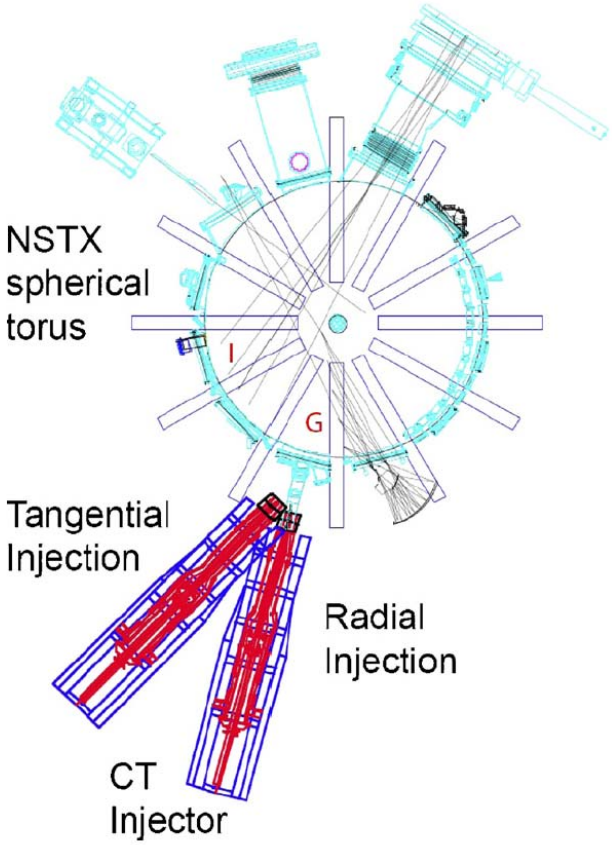

Figure 2a: Proposed layout of the CT injector (in storage at PPPL) on NSTX. The injection angle is variable, which facilitates momentum injection studies.

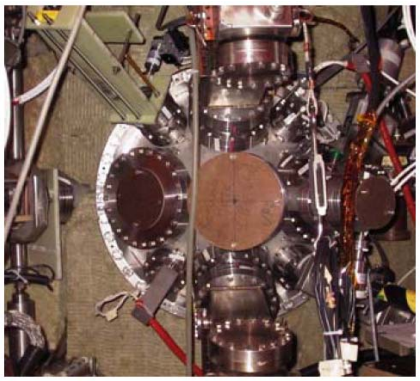

Figure 2b: Shown is the proposed CT injection port on NSTX. This is located on Bay G. This is the port in the middle of the figure. It is conveniently located on the same port as the soft x-ray system, which is needed for micro-second time scale resolution of CT propagation and dissipation inside NSTX. It is also very conveniently located next to the Thomson scattering system port, which is needed for precise mapping of the density deposition profile soon after CT injection.

Roger Raman

From: Shimada Michiya [Michiya.Shimada@iter.org]
Sent: Tuesday, October 02, 2007 1:17 AM
To: Roger Raman
Subject: encouragement letter

********** Encouragement Letter **********
Dear Dr. Raman,

In a fusion reactor, the number of actuators available for plasma control will be very much limited. The external heating power will be ~1/10 of the total heating power under the condition of Q ~ 50, the momentum input will be limited because of high neutral beam energy and high Q. Most of the plasma current (>80%) will be driven by bootstrap current, and the plasma shape parameters will be set to optimized values. Fuelling appears to be one of very few actuators available for a reactor.

Gas puffing will be inefficient, since the gas will be ionized in the scrape-off layer. Pellet injection will be more efficient, but the penetration into the plasma is rather limited (probably r/a > 0.7). Furthermore, the requirements for fulleing may have to be balanced against the influence on ELM behaviour. We need to develop fuelling schemes that enable deep and controllable penetration, which facilitates the control of the density profile and optimization of the fusion performance without causing excessive heat load on the plasma facing components.

Compact Toroid injection has characteristics that potentially fulfil the requirements of the fuelling scheme attractive for a reactor. Therefore research in this direction should be encouraged as much as possible. From this viewpoint, your foresight and your long-standing efforts of developing Compact Toroid are very much appreciated, especially since the limitation of the presently available fuelling schemes has become obvious. Unfortunately, the experiments of fuelling with Compact Toroid are still scarce, and the conceptual design of CT injector for the big ITER was not very compact.

I have two suggetions; one is an experiment on Compact Toroid fulling at a relevant fusion facility (eg NSTX) and the other is a conceptual design for the present ITER. Successful demonstration of fuelling with Compact Toroid in a well-diagnosed machine would be very encouraging. A 'compact' conceptual design of Compact Toroid injector for the present ITER would also make Compact Toroid more attractive.

Sincerely,
Michiya Shimada
Fusion Science and Technology Department
ITER Organization
