Need for Momentum Injection and Core Fueling in Reactor Grade Fusion Plasmas

[1]Roger Raman

[1]T.R. Jarboe, [2]J.E. Menard, [2]M. Ono

[1]University of Washington
[2]Princeton Plasma Physics Laboratory

This work is supported by US DOE contract numbers DE-FG02-99ER54519, DE-SC0006757 and DE-AC02-09CH11466

DOE Plasma Frontiers Workshop

Virtual Town Hall, August 12, 2015

OUTLINE

1. Present status and high-level description of research frontier

2. Importance of the scientific challenge

3. Summary of significance to fundamental plasma physics and needed facilities to achieve goal

Novel Actuators Would Improve Performance of Fusion Power Reactors

Compact Toroid (CT) injection has the potential to substantially improve the performance and efficiency of future reactor systems

- It will provide momentum injection capability for rotation, and rotation shear control &
- Deep fueling capability for density profile control, tritium fueling efficiency, and pressure profile control to improve bootstrap current fraction (deep fueling is also important to stellarators)

High-performance Tokamak and ST Plasmas Greatly Benefit from Plasma Rotation and Rotation Shear

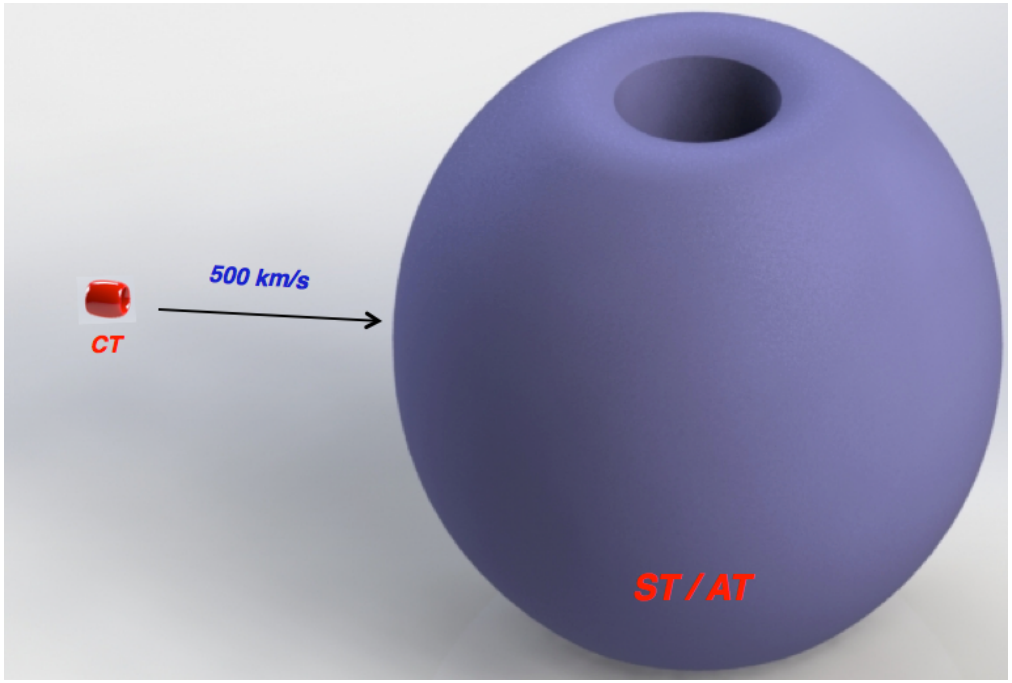
1. Neutral beams are the primary means for inducing plasma rotation and rotation shear in present devices
   - Improves energy confinement and sustains high beta discharges

2. Neutral beams also provide valuable core fueling in present tokamaks and STs
   - Reduces wall recycling by limiting cold edge fueling

ITER & DEMO Require Higher Beam Injection Energies to Penetrate to Plasma Core

1. Increased beam energy leads to significantly reduced momentum input per unit power
   - Momentum = Mass × Velocity, but Energy α Velocity^2
   - 5 MW 1 MeV D_2 NBI will inject just 1 N/s (ITER case), but at 100 keV it increases to 3.2 N/s (NSTX-U / DIIID Cases)
   - So, 1 MeV NBI largely injects energy, something that alpha heating can provide in reactors
2. Increased beam energy also leads to reduced core fueling per unit power
   - Again, because Energy α Velocity^2, the injected mass also substantially decreases with beam energy per unit power
   - 5 MW 1 MeV D_2 NBI will inject 0.06 Pa.m^3/s (ITER case), but at 100 keV it is 10 times larger (NSTX-U / DIII-D Cases), and contributes to important core fueling in high performance discharges
     - ITER pellet fueling system is designed for 200-500 Pa.m^3/s

Compact Toroid (CT) fueling has the potential to provide deep fueling and density and momentum profile control

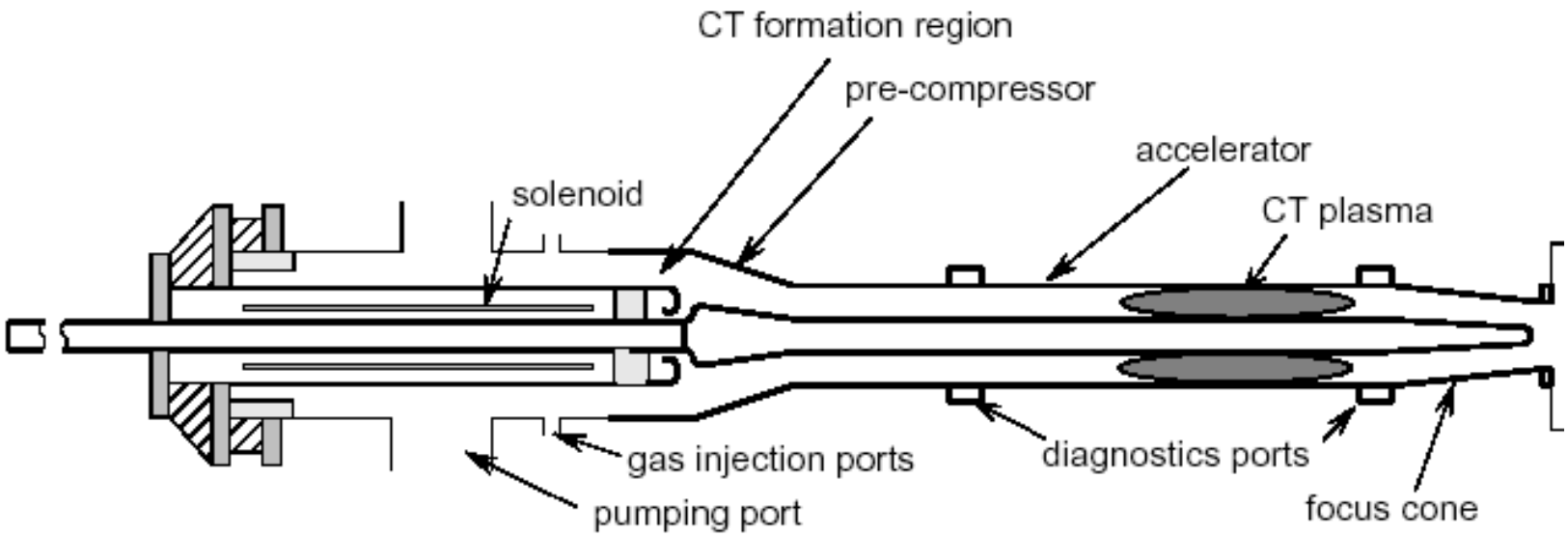


Variable penetration depth:
From edge to beyond the core

- Variation of CT size, speed, and angle can control deposition profile
- A fuelling system based on Compact Toroid injection has a simpler fuel cycle, without the need for tritium cryogenics, and should improve tritium usage and reduce tritium inventory in the fuel cycle
  - Deeper fueling would increase the tritium burn fraction

Perkins, Ho, Hammer, Nucl. Fusion 28, 1365 (1988)
R. Raman, Fusion Science and Technology, 54 (2008) 71

A CT Fueler forms and accelerates CTs in a coaxial rail gun in which the CT forms the sliding armature



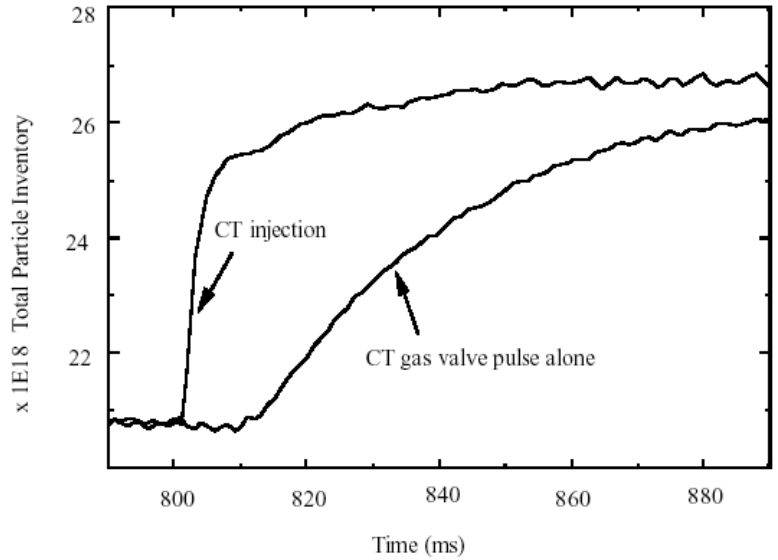
- Reactor Control System would control 4 CT Injector parameters to specify the fuel deposition location and the amount of deposited fuel
  - Amount of gas injected to form CT
  - CT solenoid current
  - Formation Voltage
  - Acceleration voltage

TdeV tokamak discharges beneficially fueled by CTs without causing any adverse perturbation

TdeV

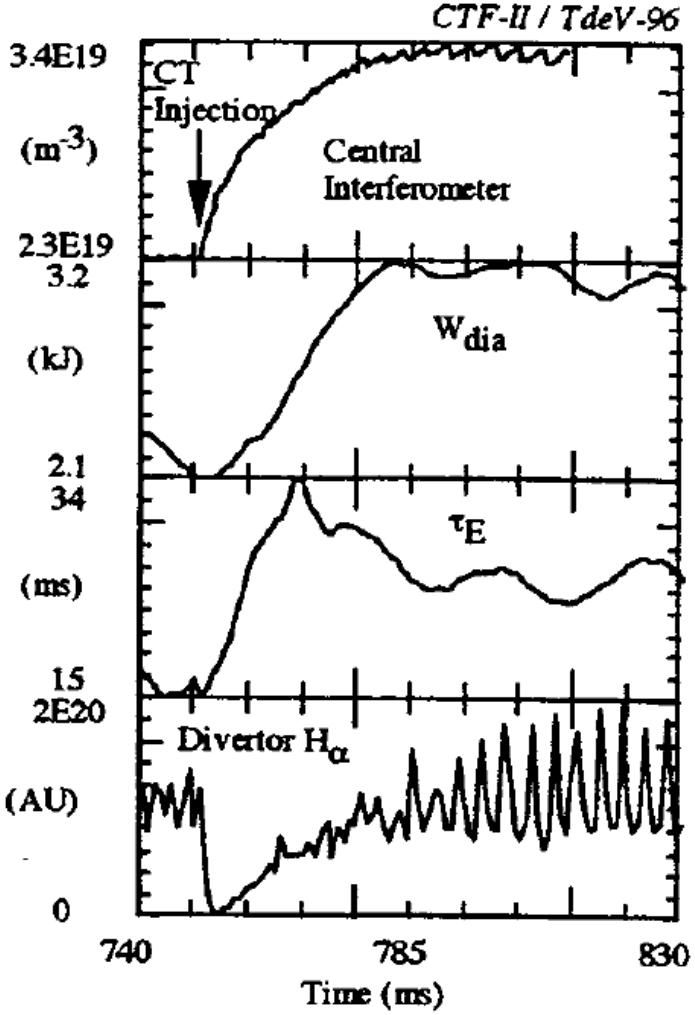
R/a = 0.86/0.25 m

B_T = 1.4 T, I_p = 160 kA



R. Raman et al, NF **37**, 967 (1997)

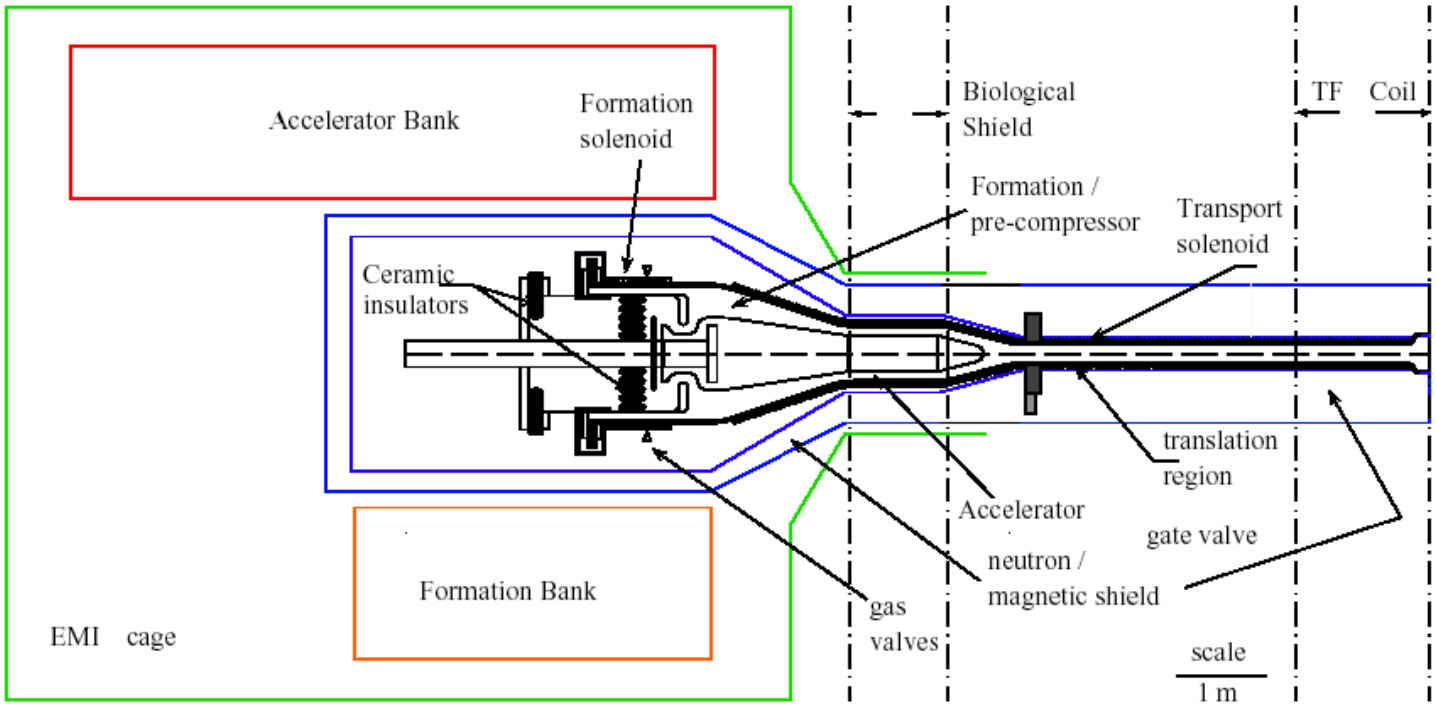
Localized core fueling not yet demonstrated



Edge fueling triggers improved confinement modes

Conceptual study for reactor-class device yields attractive design with efficient particle + momentum input

- < 1% particle inventory perturbation per CT [P_{CT} = 5 MW, V_{CT} = 500 km/s]
- 2 mg D_2 CT @ 20 Hz → same momentum as 100 MW NBI @ 1 MeV



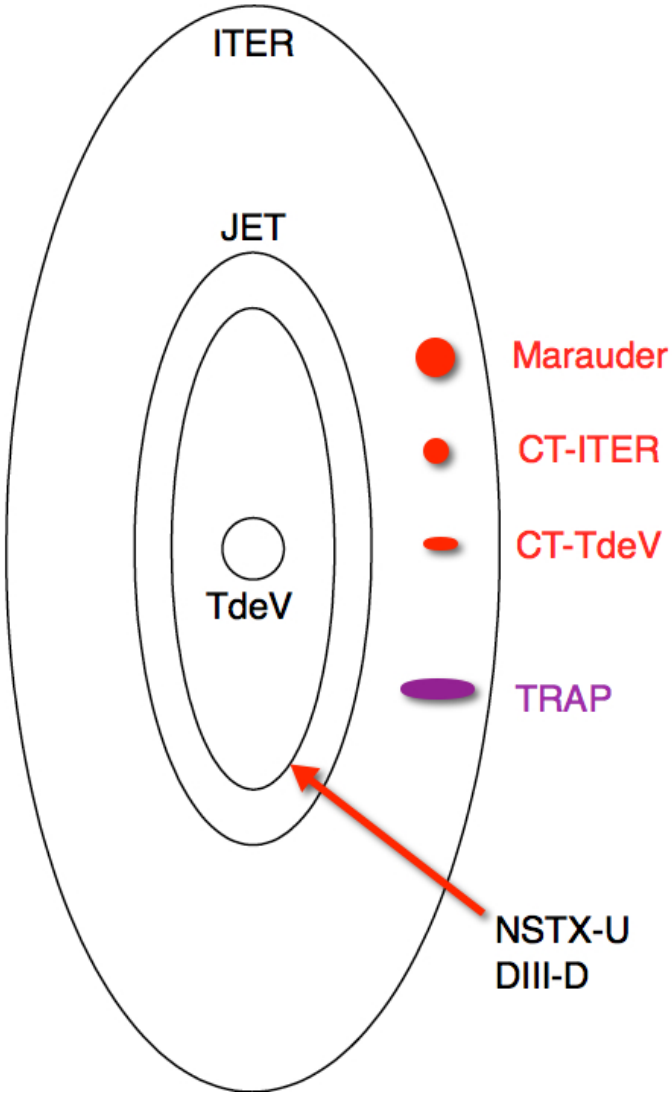
CT Injector Reactor Design Study Papers:
R. Raman and P. Gierszewski, ITER Task D315 (1997), Fusion Engin. & Design **39-40** (1998) 977-985
R. Raman and K. Itami, Journal of Plasma and Fusion Research, **76**, No. 10 (2000) 1079
R. Raman, Fusion Science and Technology, **50**, (2006) 84
R. Raman, Fusion Engineering and Design, **83** (2008) 1386
R. Raman, Fusion Science and Technology, **54** (2008) 71

Multiple injectors with different tangency would provide rotation shear control

Importance of the Scientific Challenge

- The past decade has seen impressive progress in the areas of generating, and sustaining high-performance plasma discharges
- These high-beta, high-confinement, and high-bootstrap current fraction discharges require neutral beam injection as a primary means to sustain the desirable reactor-relevant discharge parameters
- While the *Remarkable* Neutral Beam system is essential for near-term developments in fusion research, it does not extrapolate well to reactor grade systems
- CT injection technology is perhaps the only possible means to bridge the gap from present fusion systems to reactors, but over a decade of focused research and development is required to make this happen

New Generation STs (NSTX-U & MAST-U) are an Ideal Test-bed for Developing CT Fueling



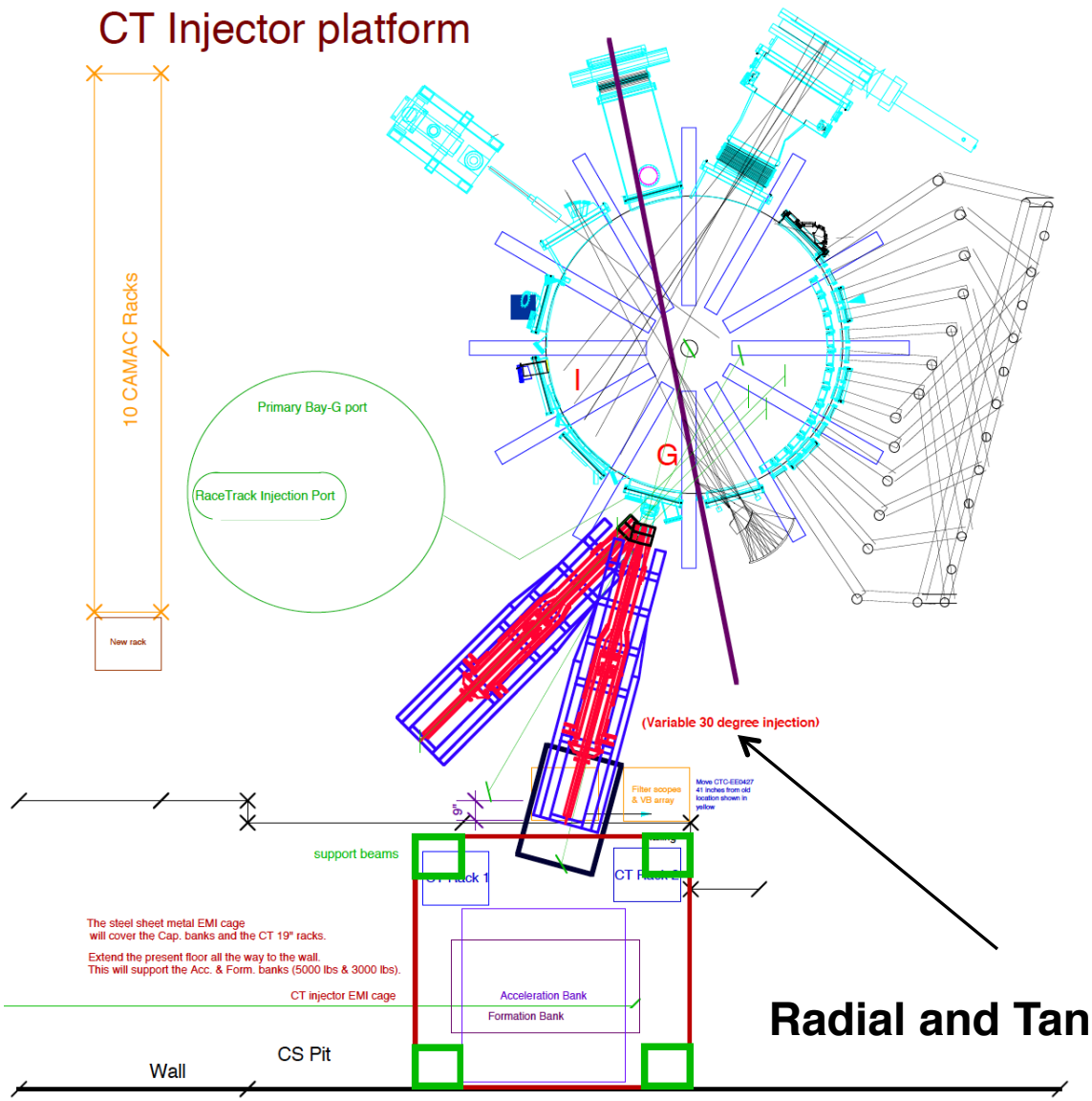
Approximate relative sizes of various target plasmas and CTs

- Compared to 1st generation tokamak devices used for CT fueling, STs have a large poloidal cross-section
  - Will allow a test of localized Fueling
- STs have low magnetic field
  - A low power (lower cost) CT injector is adequate
- STs have a steep gradient in B_T
  - The CT stopping position can be much more precisely determined
- NSTX-U / MAST-U have excellent diagnostics
  - Physics of CT penetration and dissipation, and magnetic reconnection, can be well diagnosed

Summary: Flexible Fueling System May be the Only Choice for Density Profile & Fusion Burn Control

- A flexible fueling system is all that a reactor device may be able to rely on to alter core plasma conditions (in addition to a some external current drive)
  - Ability to initially peak the density profile would ease ignition requirements
  - Deep fueling also needed for Wendelstein 7-X and LHD type Stellarators as they are projected to have hollow density profiles
- In a device with high bootstrap current fraction, optimized density and pressure profiles must be maintained
  - Fueling system must not adversely perturb established profiles
- Toroidal rotation, and rotation shear is necessary for maintaining MHD stability and operating at high beta, but ITER and AT/ST DEMO may have minimal momentum injection
  - Neutral beam torque may be too small or absent
  - alphas are isotropic

A CT Injector System has the Potential to Replace the NBI System in a Reactor Installation



NSTX-U is Capable of studying and developing CT injection in support of fusion reactors, while improving our knowledge on basic reconnection studies

Radial and Tangential CT Injection on NSTX-U

Summary of significance to fundamental plasma physics and needed facilities to achieve goal

- Generation of high-density, high-velocity, plasmoids with self-contained magnetic fields, and at high frequency provides a new experimental laboratory for studying fundamental magnetic reconnection physics
  - The interaction of this well-localized exotic magnetic structure with other “larger” target plasmas, or with themselves, will provide well-diagnosed laboratory conditions for improving our understanding of magnetic re-connection physics
- The large and well-diagnosed NSTX-U device that recently became operational is an excellent test bed for this wok
- The CT injector now in storage at PPPL is a system that could be used to begin this important developing work that helps both economical power generation from fusion and fundamental plasma physics research

Back-up Slides

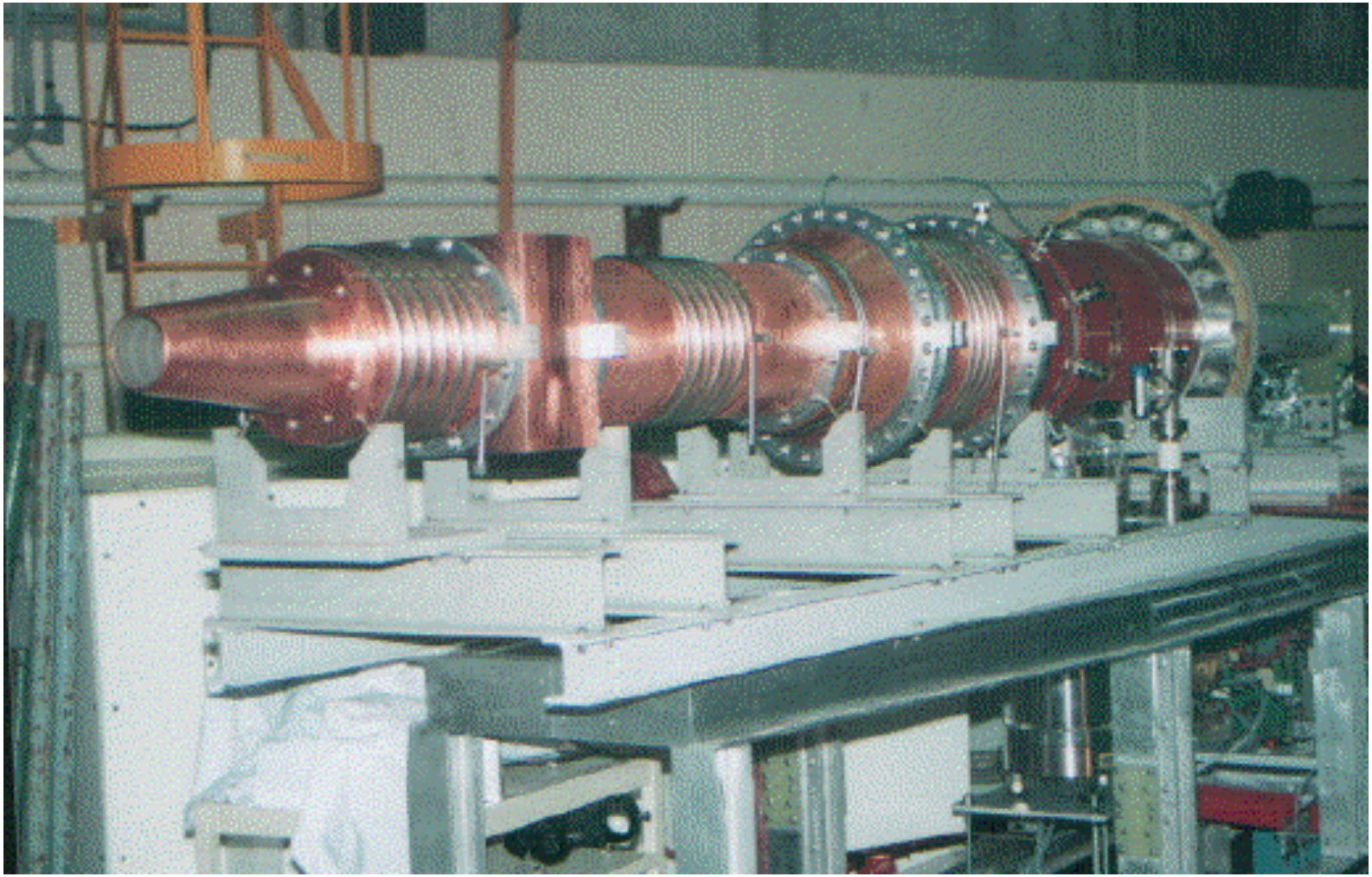
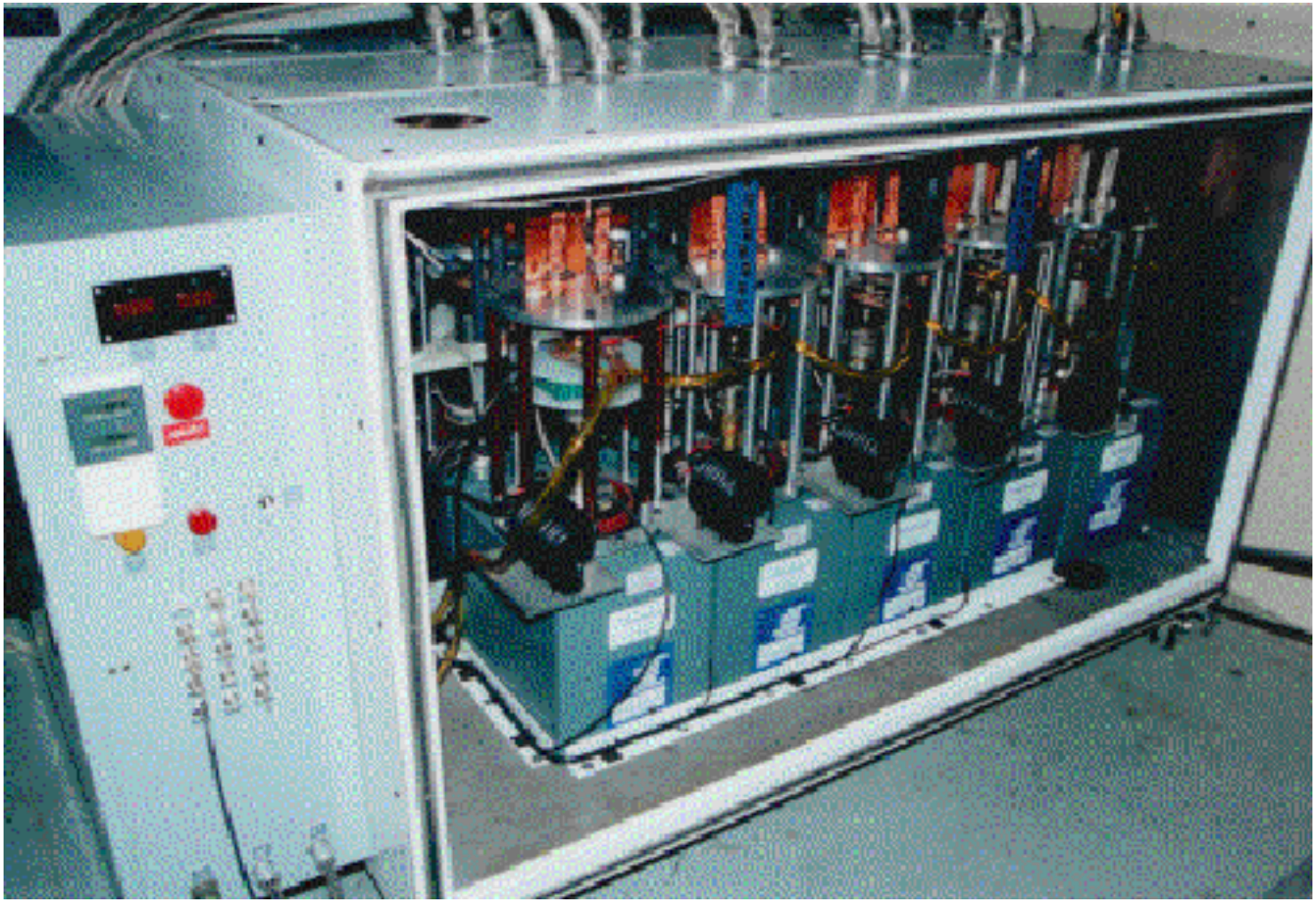
Advanced Fueling Needs Also Supported by ITPA and IEA

- ITPA Steady State Operations group (November 2003 annual report, under section 9 – Other recommendations) – stated *"The approach (injection of compact toroids for fueling advanced scenarios) 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."*

- 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 CTF-II Injector (in storage at PPPL)



The CT Formation bank power supply (110V AC input)