Simplifying the ST and AT Concepts

[1]R. Raman, [1]T.R. Jarboe, [2]J.E. Menard, [1]B.A. Nelson, [2]M. Ono, [2]T. Brown

[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

FESAC Strategic Planning Meeting
Gaithersburg, MD July 8-10, 2014

Economics & Device Reliability May Require Simplification of the ST and AT Concepts

1. Sustained Operation
   - Flexible fueling system to maintain optimized density profiles
   - Electron Bernstein Wave Current Drive for current profile control

2. Elimination of Components not needed for sustained operation provides greater flexibility in aspect ratio optimization
   - Solenoid Free Plasma Startup
     - Coaxial Helicity Injection (CHI)
     - Local Helicity Injection (LHI)
     - Electron Bernstein Wave Start-up (EBW)

Advanced Tokamak (AT) scenarios is the basis for future power plant operating conditions for both the ST and the Tokamak

The Advanced Tokamak (AT) is Characterized by Features Needed for a Viable Fusion Power Plant*

- The AT simultaneously obtains
  - Stationary state
  - High plasma pressure (MHD Stability)
  - High self-driven current (Bootstrap current)
  - Good particle and energy confinement (Plasma Transport)
  - Plasma edge that allows power handling (Divertor solutions)

***The Advanced Tokamak is a tough nut to crack!**

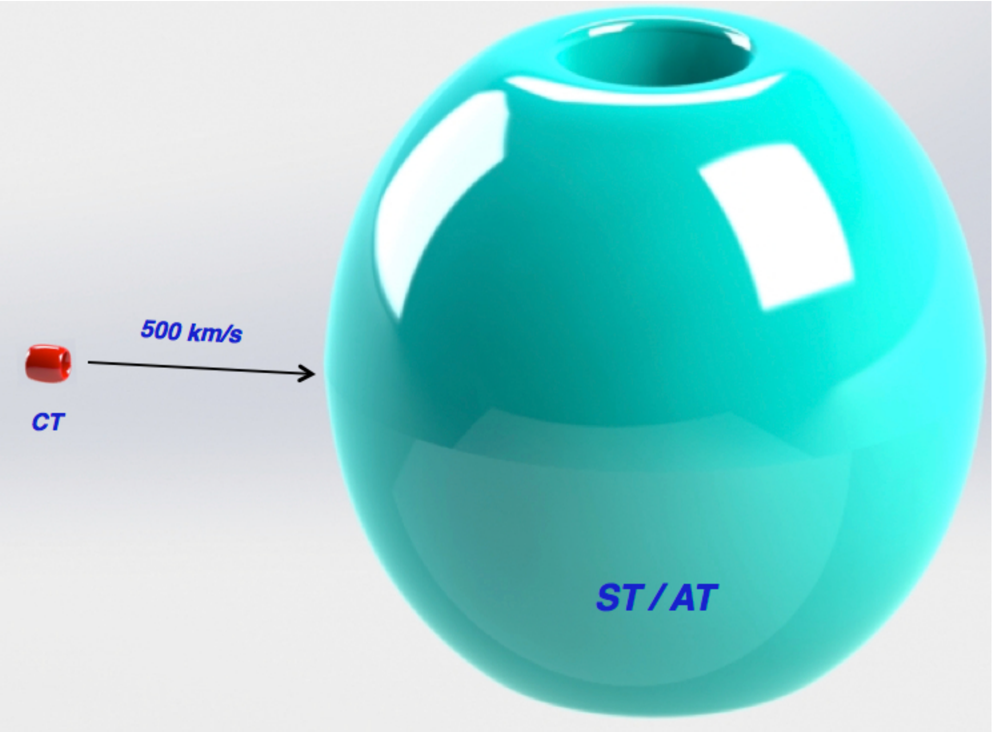
Flexible Fueling System May be the Only Choice for Density Profile & Fusion Burn Control

- A steady-state burning plasma device has no need for neutral beam injection for plasma heating & alphas are isotropic.
  - No momentum injection. (Toroidal rotation is necessary for maintaining MHD stability limits and to reduce transport)
- In a device with high bootstrap current fraction, optimized density and pressure profiles must be maintained.
  - Fueling system must not adversely perturb optimized density and pressure profiles
- In addition to a small fraction of external current drive a flexible fueling system is all that a burning plasma device may be able to rely on to alter core plasma conditions.
  - The 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

Proposed Initiatives are Identified in the ReNew Thrust 5

- Page 267: Active steady-state control *"How near optimal can the plasma profiles and bulk parameters be robustly maintained in sustained steady state?"*
- Page 270: *"Develop advanced fueling techniques, such as pellets or Compact Toroid injection capable of deep fueling in reactor-grade plasmas."*
- Page 269: *"Develop and test improved actuators. Examples include high-efficiency ECH and ECCD, with extension to higher density operation"*
- Page 270: *"Demonstrate burn control and control of the operating point thermal stability with sufficient flexibility to regulate power output to accommodate external demands"*
- Thrust 15: *"Create integrated designs and models for attractive fusion power systems"*

Compact Toroid Fueling



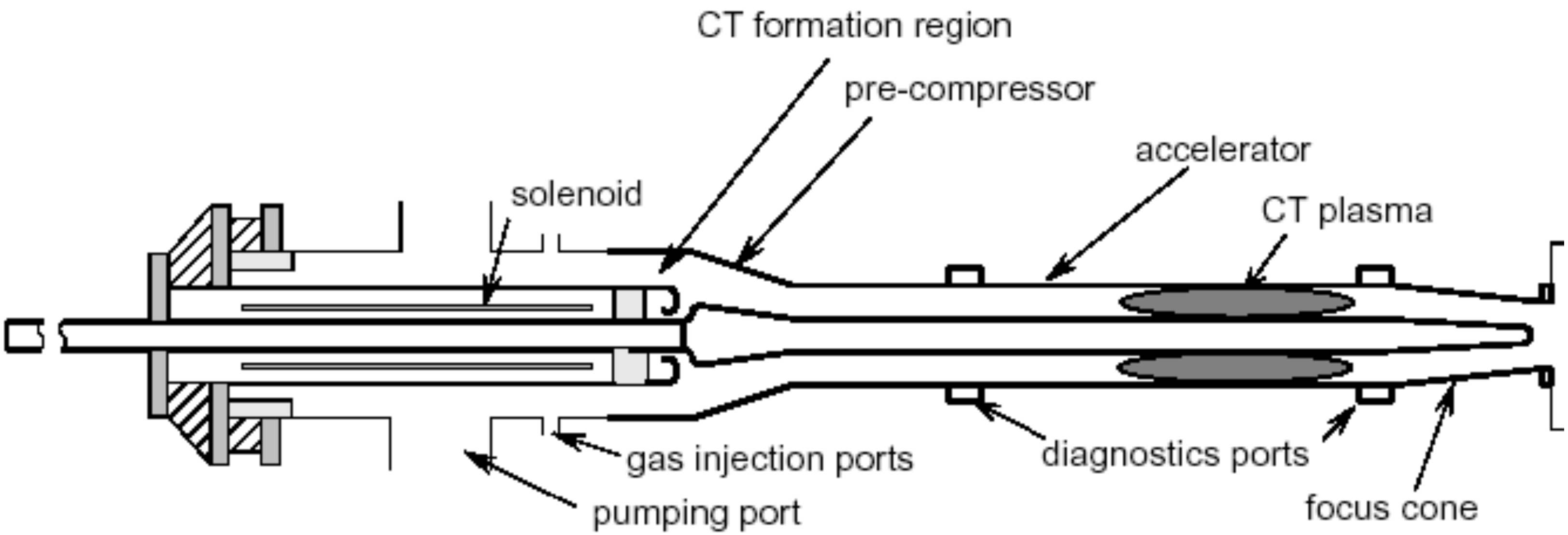
Variable penetration depth:
From edge to beyond the core

- Compact Toroid (CT) fuelling has the potential to meet these needs, while simultaneously providing a source of toroidal momentum input
  - Rotation important for transport and stability

- 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

*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



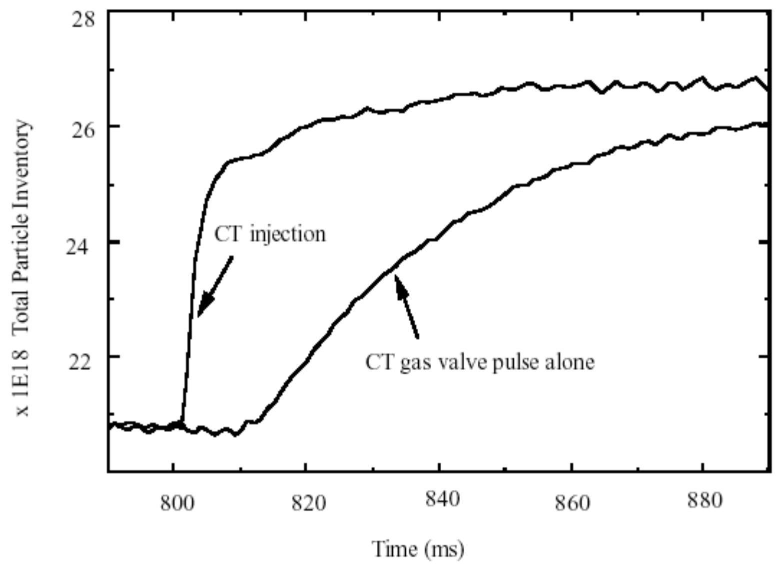
- Reactor Control System would control 4 CT Injector parameters to specify the fuel deposition location and the amount of deposited fuel
  - Amount of gas injected to form CT
  - CT solenoid current
  - Formation Voltage
  - Acceleration voltage

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

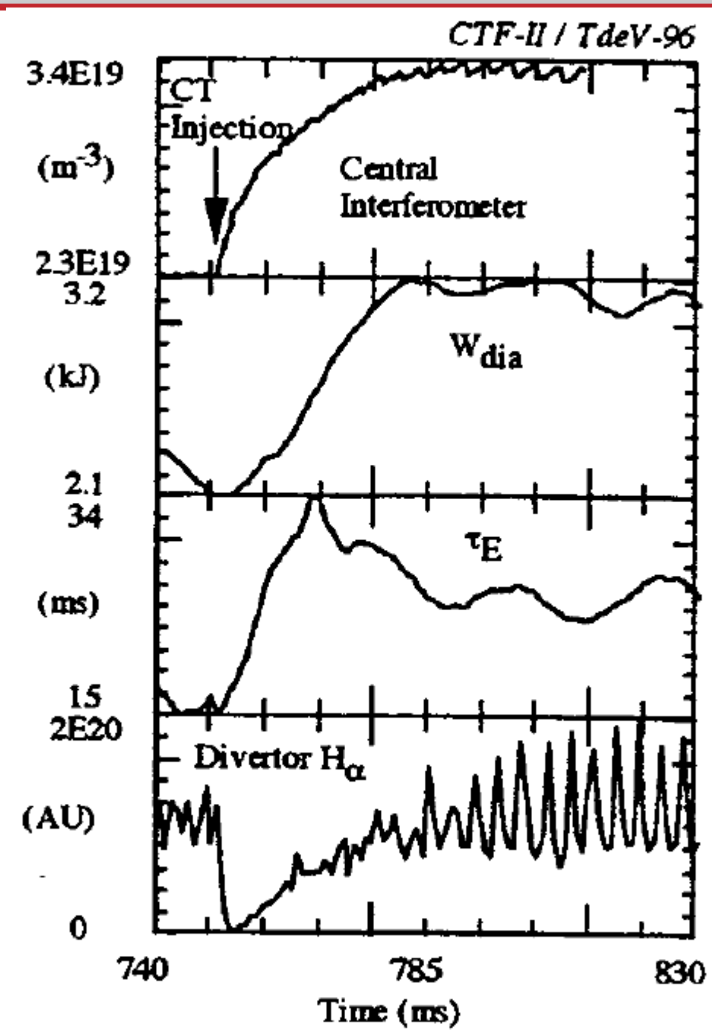
TdeV

R/a = 0.86/0.25 m

B_T = 1.4 T, I_p = 160 kA



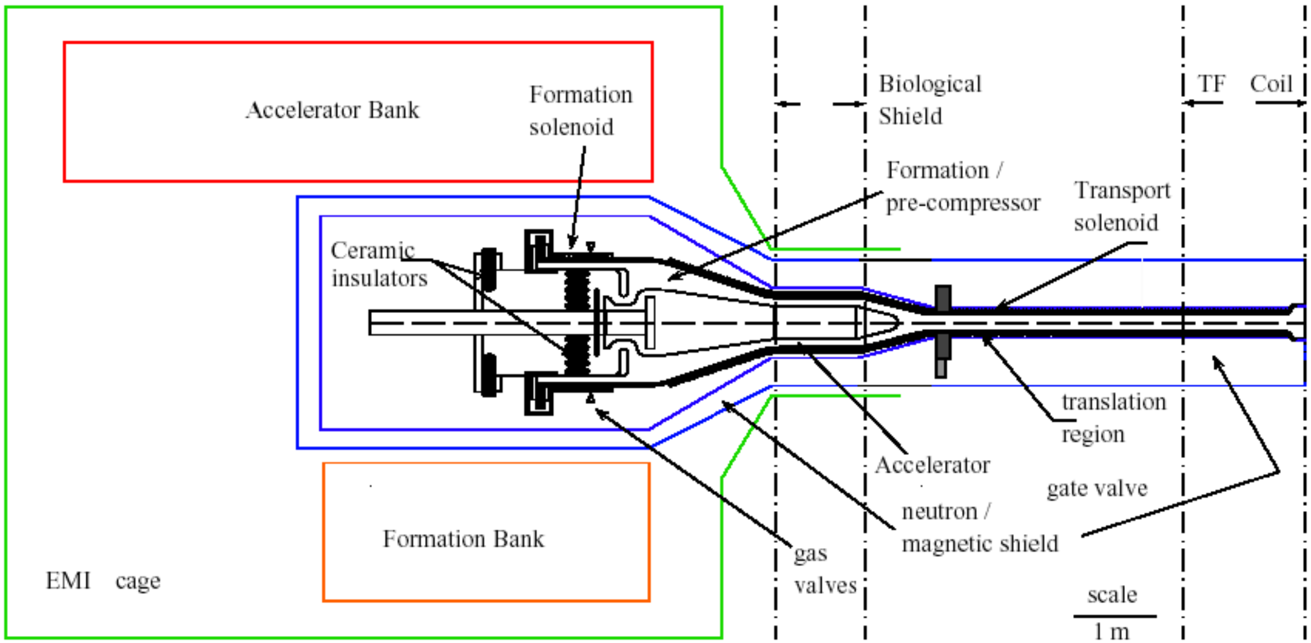
R. Raman et al, NF **37**, 967 (1997)



Localized core fueling not yet demonstrated

Edge fueling triggers improved confinement modes

Conceptual Study for Reactor-Class Device Yields an Attractive design

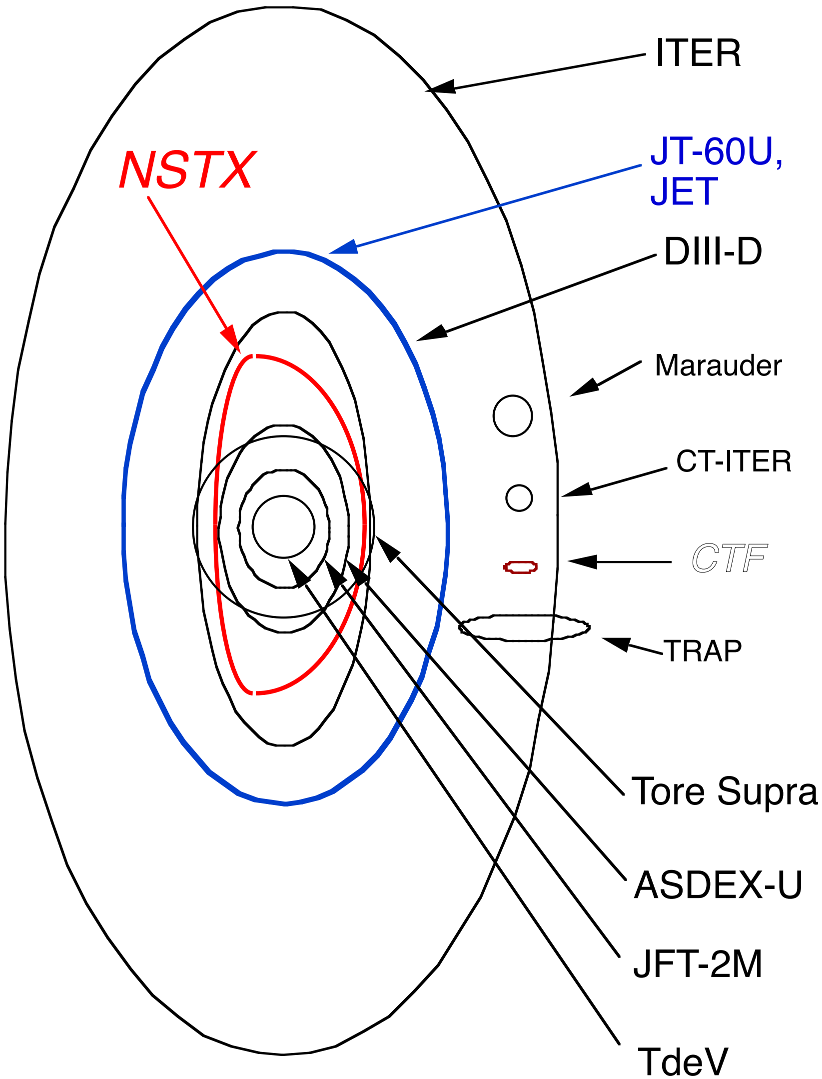


- < 1% particle inventory perturbation per CT pulse [P_{CT} = 5 MW, V_{CT} = 500 km/s]
- 2 mg D_2 CT @ 20 Hz imparts same momentum as 69 MW, 500 keV NBI source

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

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



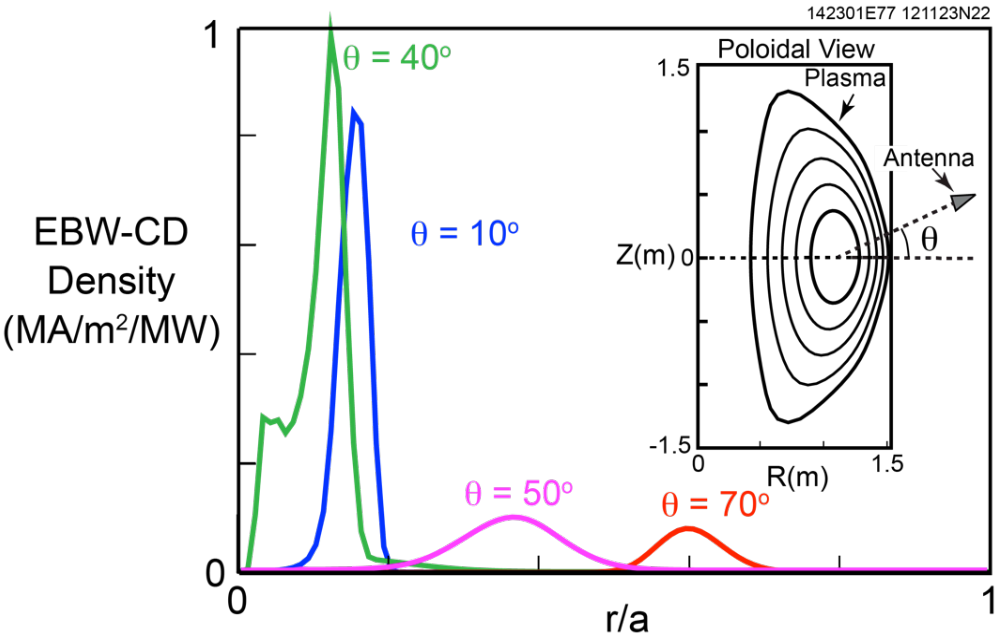
Approximate relative sizes of various target plasmas and CTs

- Compared to the 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 can be well diagnosed

Three Gyrotrons Would Provide Capability for both on-axis and off-axis Sustained CD

- EBW modeling for NBI H-modes predicts CD efficiencies ≤ 40 kA/MW:
  - 100% NI plasmas
  - Peak EBWCD density around 1 MA/m²/MW

EBWCD profiles



[G. Taylor, et al., Proc. 18th Joint Workshop on ECE and ECRH, Nara, Japan (2014)]

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."*

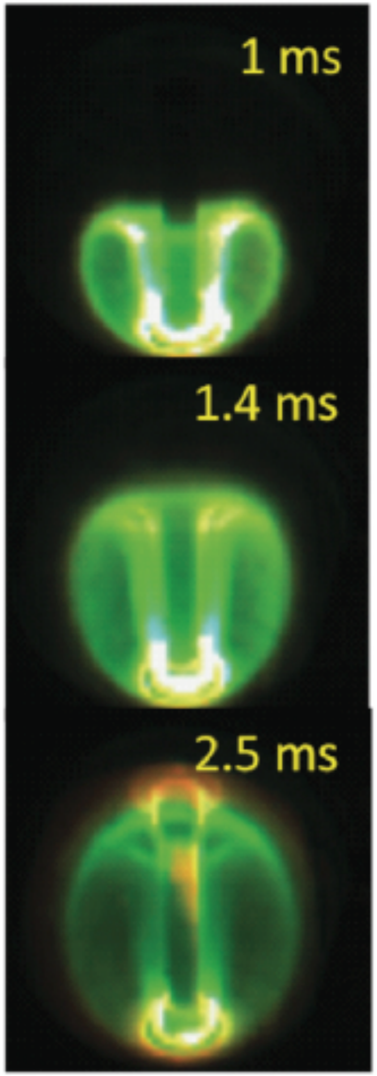
- As a solution they state, *"New fueling techniques should be tested on present devices. Given the prospects of CT injection, a test on a relatively large device is highly desirable. Pellet fueling from the high field side equatorial plane should be tested in plasmas with high edge temperatures and close to operational boundaries to judge its merits."*

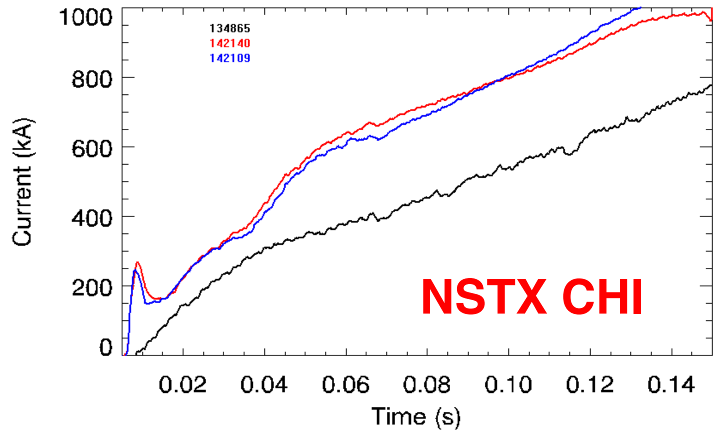
Solenoid-Free Start-up and Ramp-up

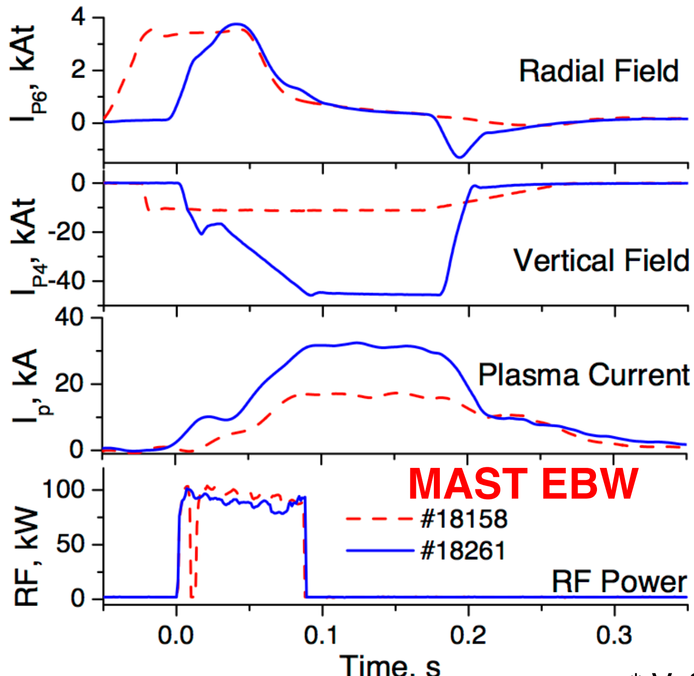
ReNew Thrust 16:
“Can plasma current be initiated and raised to high values without a solenoid”

NSTX / Pegasus / MAST Demonstrated Significant Progress in Transient CHI, LHI and EBW CD Start-up

NSTX CHI







Non-inductive Ramp-up of Start-up plasmas is a key program element for YRs 6-10

*EBW Start-up on MAST

Now produced 73 kA using 75 kW of ECH power

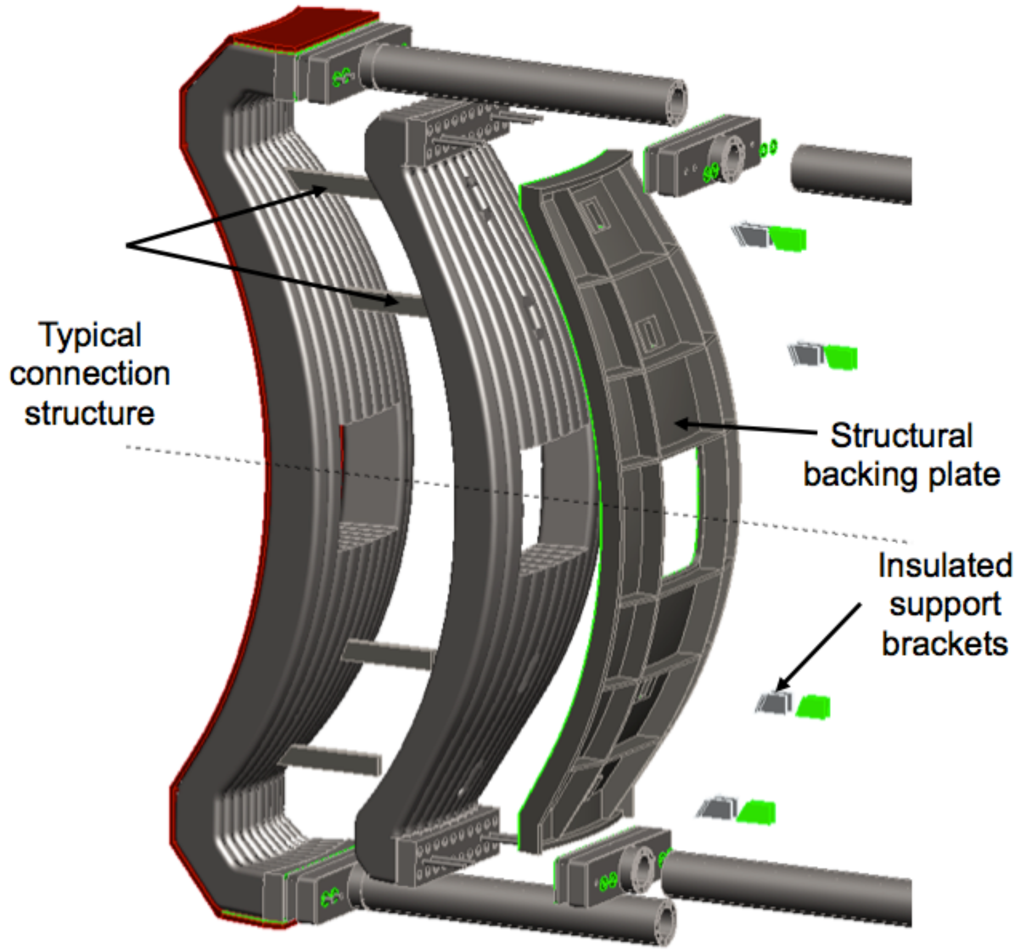
LHI Start-up in Pegasus Talk (by Fonck)

* V. Shevchenko, et al., Nucl. Fusion **50**, 022004 (2010)

CHI Design Studies for ST-FNSF have Identified Two Designs with > 2MA Start-up Current Generation Potential

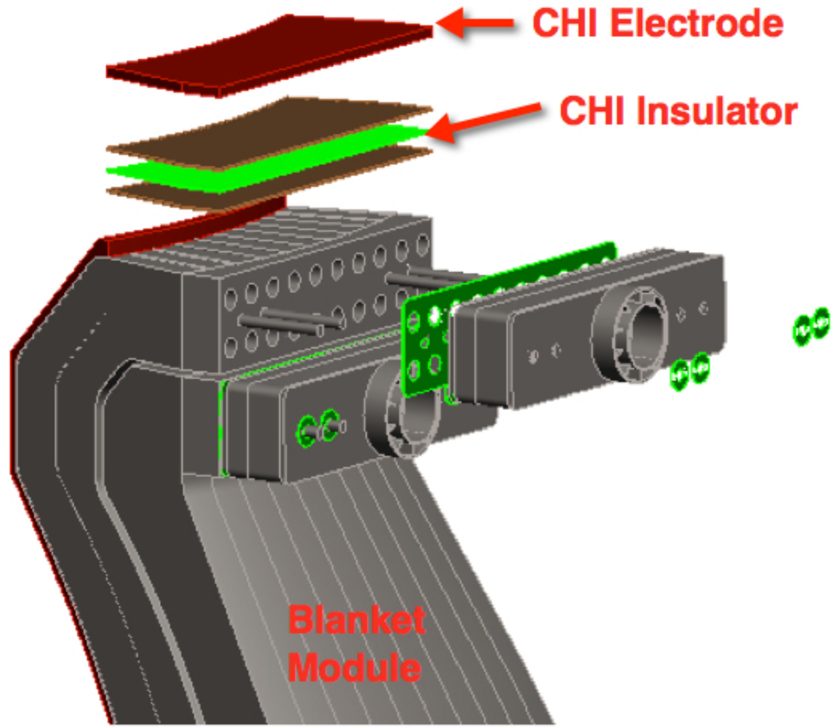
Concept – I (NSTX-like)

*Blanket modules and piping insulated from rest of vessel



Concept – II (DIII-D-like)

Toroidal electrode on top of blanket structure, analogous to CHI ring electrode previously used on DIII-D



*Insulator dose:
~10^9 Gy @ 6FPY < 10^{11} Gy limit

 * T. Brown, ST-FNSF designs * L. El-Guebaly, et al., MCNP Neutronics

5 year goal is to obtain physics validation for Solenoid-free plasma start-up, EBW CD, and Local CT Fueling

	YR 1	YR 2	YR 3	YR 4	YR 5
Transient CHI	200 kA	400 kA			
With 1MW ECH			400 kA High Te	Extend CHI to ~1 MA	
Full Non Inductive Ramp-up	Develop NI ramp-up in Inductive plasmas			Couple CHI to NBI CD	
LHI	Tests on Pegasus		Initial Tests on NSTX-U	High current Start-up	
1MW ECH (EBW Start-up) NSTX-U and MAST-U			Establish EBW Current Start-up, then couple to NBI		
EBW CD NSTX-U and MAST-U				Demonstrate 40 kA EBW CD	
CT Fueling Injector development	electrode shape	PS requirements	Size, velocity, density		
NSTX-U Fuelling					Localized Fueling
Multi-pulse Injector			Build 10 Hz power supply	Build 10 Hz injector	
Cost	\$0.5M CT	\$0.5M CT	\$1M CT, \$5M EBW	\$2M CT, 2M EBW	\$2M CT
Key Achievements	400 kA CHI Start-up		Off-line CT demonstration High T_e CHI	Start-up & Local Fueling physics validation	

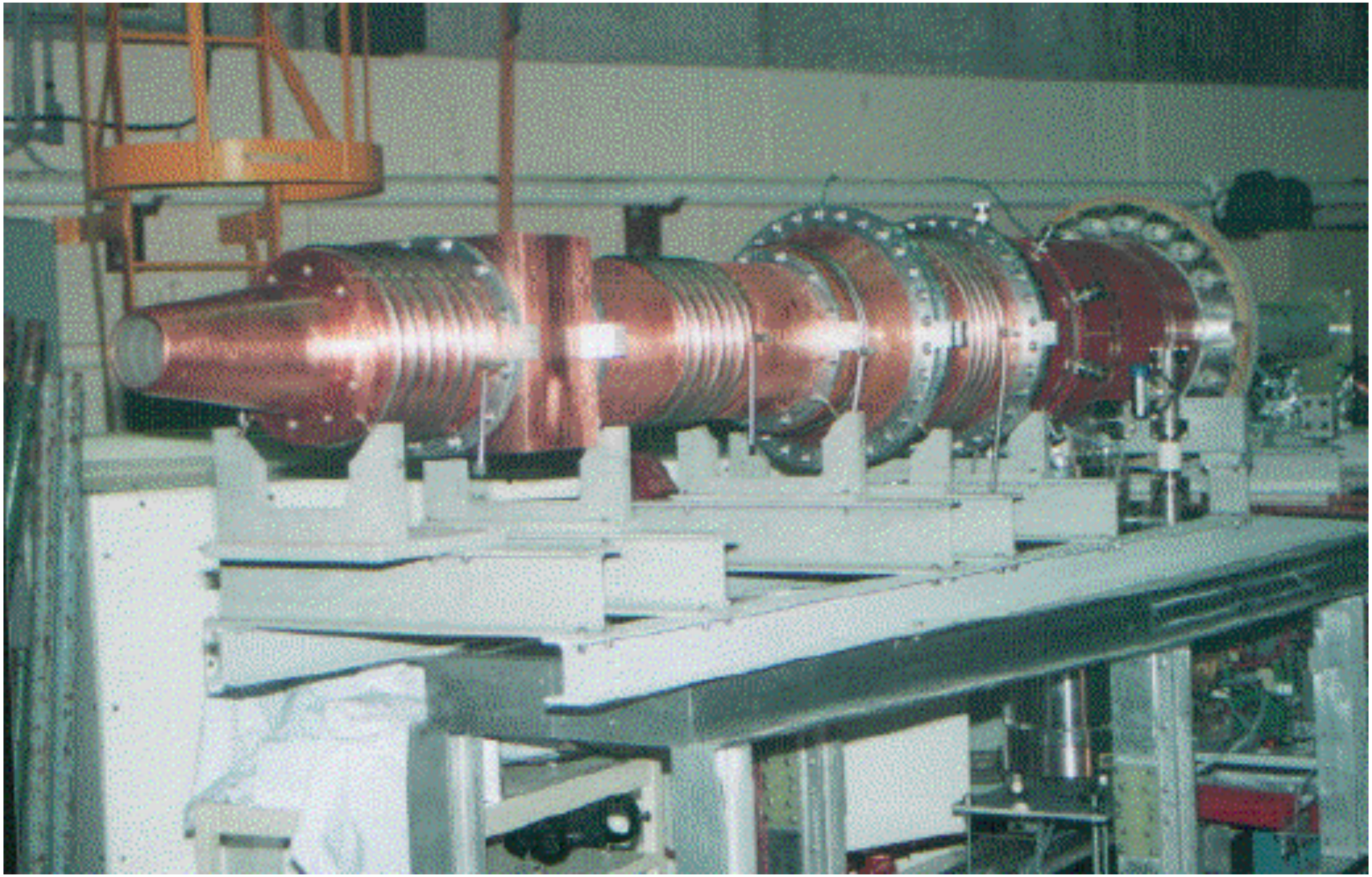
6-10 year goal is to obtain engineering validation for SFPS, Sustained EBW CD, and Density Profile Control

	YR 6	YR 7	YR 8	YR 9	YR 10
Transient CHI			Test high current CHI in Reactor elec. configuration		
With 2-3 MW ECH	Establish max I_p potential With CHI		Synergism With EBW		
Full Non Inductive Ramp-up	Couple CHI to NBI CD		Ramp CHI plasma to 1MA using NBI & RF		
LHI	400kA – 1MA tests		Couple to NBI. Test Reactor LHI designs		
1MW ECH (EBW Start-up) NSTX-U and MAST-U	Establish EBW Current Start-up limits.			Couple EBW to CHI, LHI plasmas	
EBW CD NSTX-U and MAST-U	Test current profile control		Demonstrate current profile control		
CT Fueling Injector development	Off-line tests with single pulse PS, then with 10 Hz PS, Limits on CT density				
NSTX-U Fuelling	CT scaling studies		Test density control	Density profile control	
Multi-pulse Injector		Build 20 Hz power supply, upgrade injector as needed			
Cost	$2M CT, 5M EBW	$2M CT, $5M EBW	$2M CT		
Key Achievements	Full Solenoid-free start-up and ramp -up			Current profile control	Density profile control

Large Tokamaks / STs Should Develop Back-up Options to Meet the Fueling and Burn-Control Requirements of an AT Plasma

- In a burning plasma device with only RF for current drive, a flexible fueling system may be the only internal profile control tool
  - A CT injector has the potential to deposit fuel in a ***controlled manner*** at any point in the machine
  - It also ***injects momentum*** for inducing plasma rotation, which is needed for reducing transport and increasing plasma stability limits
  - Deep fueling will increase tritium burn-up fraction and ***reduce tritium inventory*** in the fuel cycle. Also needed for Wendelstein 7-X, and LHD type Stellarators (Hollow n_e profiles)
- EBW can provide the balance of current drive not provided by bootstrap current drive
  - It is also needed for increasing T_e in helicity started plasmas, and can generate start-up current on its own potential and is expected to be synergistic with CHI and LHI
- Establishing SFPS capability would simplify the tokamak/ST configuration by eliminating an expensive component not needed for sustained operation
  - It will also provide greater flexibility in the selection of the device aspect ratio
- The projected 10 Year development effort is modest (~$30-$40M)
  - Year 5 would provide the physics validation for SFPS & small localized fueling
  - Year 6-10 would provide the demonstration of density and current profile control and the engineering demonstration for eliminating the solenoid

The CTF-II Injector (in storage at PPPL)



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