Motivation for Compact Toroid Injection in NSTX

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Assessment of the feasibility of using the CTF-II injector on NSTX

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NSTX Physics Meeting
Princeton Plasma Physics Laboratory
April 7, 2003

Chronology of collaborator Compact Toroid Fueling presentations at NSTX Research Forums

	U - Washington	*UC - Davis*
Dec. 1997	R.Raman-1st pres. ***Action:*** submitted proposal to DOE	D.Hwang-1st pres. ***Action:*** submitted proposal to DOE
Jan. 1999	R.Raman -2nd pres.	D.Hwang-2nd pres.
Jan. 2000	R.Raman - 3rd pres. (in Advanced Concepts)	
Jan. 2001	R.Raman - 4th pres. (in Heat., CD & Fueling) & 5th pres. (in Transport & Turbulence) ***Action:*** submitted 2nd proposal to DOE	
Nov. 2001	R.Raman - 6th pres. (in Boundary Physics)	
June. 2002 5yr Res. Plan. Meet.	R.Raman - 7th pres. (in Boundary Physics) R.Raman - 8th pres. (in Integrated Senario Dev.)	
July. 2002	***Action:*** submitted 3rd proposal to DOE. ***Result:*** *Approved by DOE for CT injector Relocation & Evaluation*	

The ability to inject CTs significantly expands NSTX experimental capability

- Precise H-mode initiation capability valuable for on-going XPs
- Electron Transport Barrier studies
- Clarification of the edge barrier seen during Neon injection
- Transport studies by isotopic impurity tailoring
- He ash removal studies
- Prompt density injection to avoid locked modes
- Reconnection studies - an important aspect of PPPL research
- Momentum injection studies for transport barrier sustainment
- Precise density profile control needed for NSTX SS discharges
- Local current injection to suppress NTMs
- Reduced divertor pumping requirements
- Possible extension of density limits
- Disruption mitigation by high-z plasma injection

Acknowledgements

For support during the past several years

Prof. Thomas R. Jarboe (Univ. of Washington)

Dr. Henry W. Kugel (PPPL)

Outline of Talk

- Description of a CT Injector
- Motivation for CT Injection
- Experimental results
- Proposed research plan on NSTX
- The CTF-II injector in storage at PPPL
- Summary and conclusions

A Compact Toroid (CT) is a self-contained toroidal plasma with embedded magnetic fields

Two types of CTs

- A Spheromak has comparable poloidal / toroidal fields and about 10% beta
  - Technology easily adaptable to high rep-rate operation
  - Electrode based CT formation requires attention to electrode tech.

- A Field Reversed Configuration (FRC) has only poloidal field (if it is not accelerated) and about 50% beta
  - Considerably challenging pulsed power technology
  - Inductive formation but CTs longer in length than Spheromaks

Very Early Work on CT Injection

- Perkins (LLNL) and Parks (GA) proposed concept for fueling

  -[Perkins, Ho, Hammer, NF 28, 1365 (1988) & Parks, Phys. Rev. Lett. **61**, 1364 (1988)]

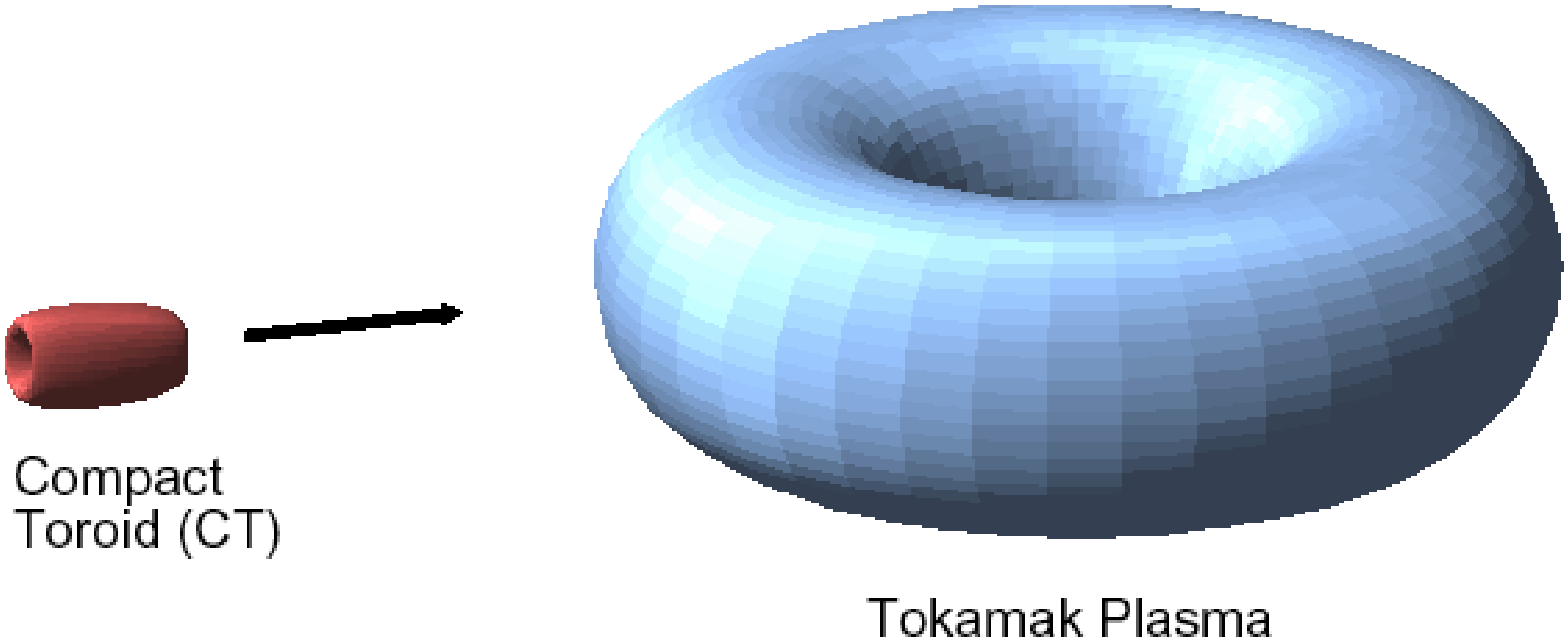
- Hammer and Hartman (LLNL) developed the accelerator concept

  -[Hammer and Hartman, Phys. Rev. Lett., **61**, 2843 (1988)]

- First tokamak fueling (CT size < Tok. size)

  -[Raman et. al,. Phys. Rev. Lett. **73**, 3101 (1994)].

A CT is accelerated to high velocity and injected into the target plasma to achieve deep fueling



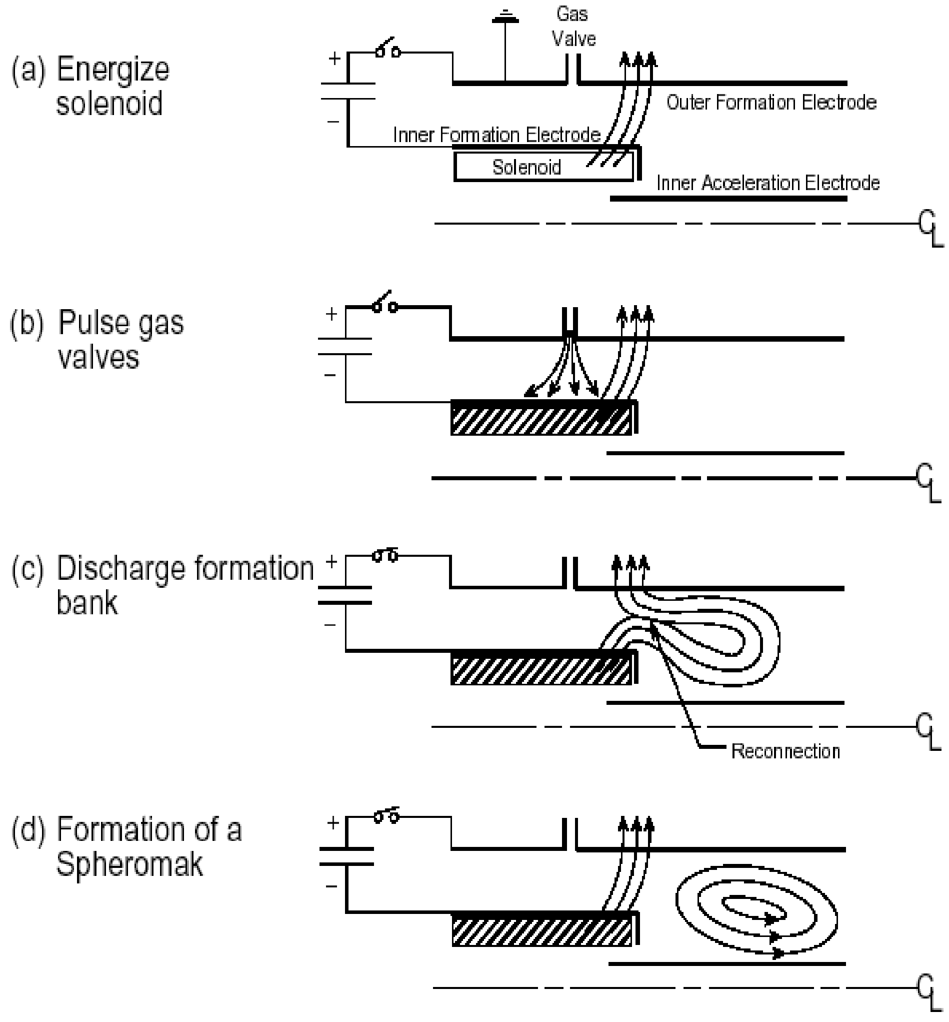
CT Penetration time: few μs

CT Dissociation time: < 100 μs

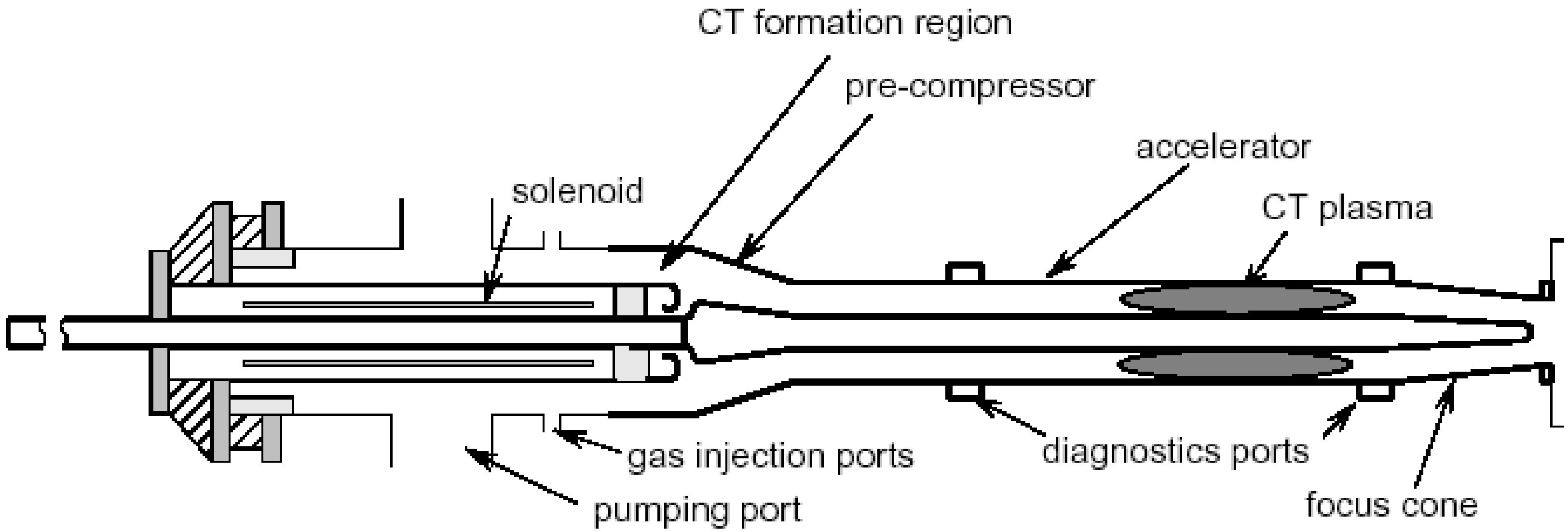
Density Equilibration time: 250 - 1000 μs

Variable Penetration depth: edge to beyond the core

CTs formed in a magnetized Marshall gun on fast (~10 μs) time scales



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



Raman et al., Fusion Techn., **24**, 239 (1993)

Amount of gas injected controls CT density

Applied voltage controls CT velocity

Control system specifies fuel deposition location for each pulse

CT Injection has the potential to meet future NSTX fueling needs

- Future NSTX high β, high bootstrap fraction plasmas require optimized profiles
- During high performance steady state non-inductive operation, <u>optimized profiles must be maintained</u>
- Fueling such discharges requires the prompt injection of small amounts of fuel <u>where needed and as often as needed</u>

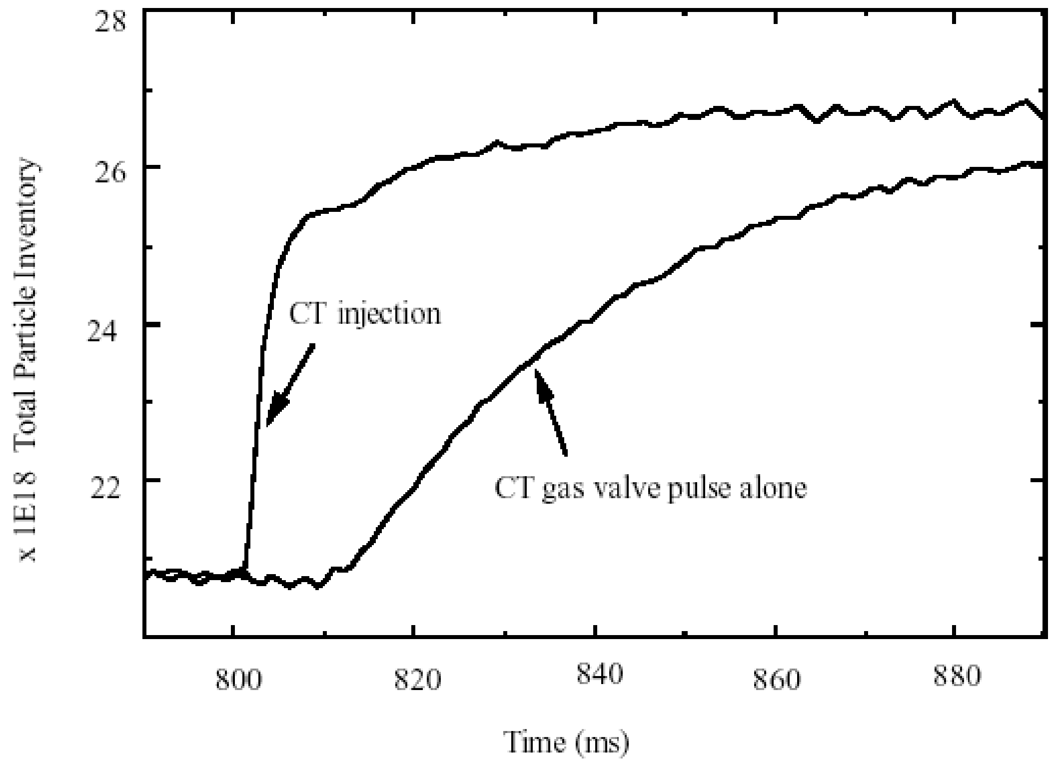
There is no existing fueling system to meet this requirement

IPPA goals relevant for CT Fueling

- 3.4.1.2 Fueling Technologies: "Develop systems and fueling techniques that are capable of providing a reliable, flexible particle source for controlling core plasma density and density gradients at acceptable fueling efficiencies; ..."

- Under the description of Section 3.4.1 Plasma Technologies: "The main issues for fueling technologies are to *understand and exploit advanced fueling physics (such as high field side launch) and demonstrate the performance (i.e., pellet speeds, density of compact toroids and repetition rates) required to effect adequate control of the density profile shape and high fueling efficiency*"

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



TdeV

R = 0.86m

a = 0.25m

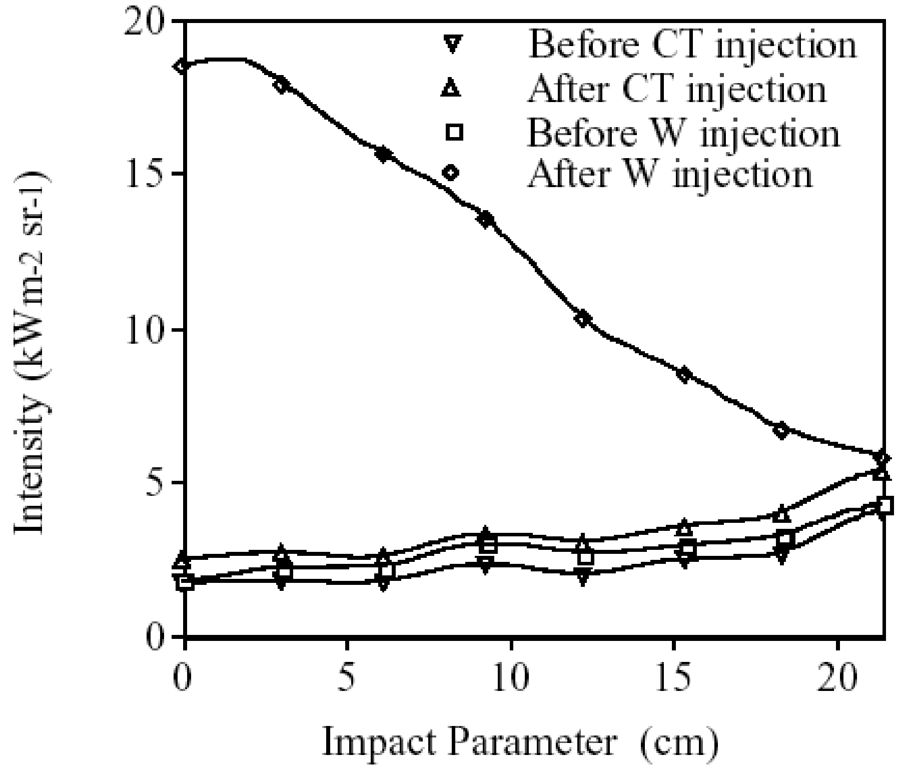
B_T = 1.4T

Ip = 160kA

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

No development work needed to beneficially add fuel to NSTX

No evidence for metallic impurity contamination of TdeV



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

Edge fueling of diverted discharges triggers improved confinement behavior

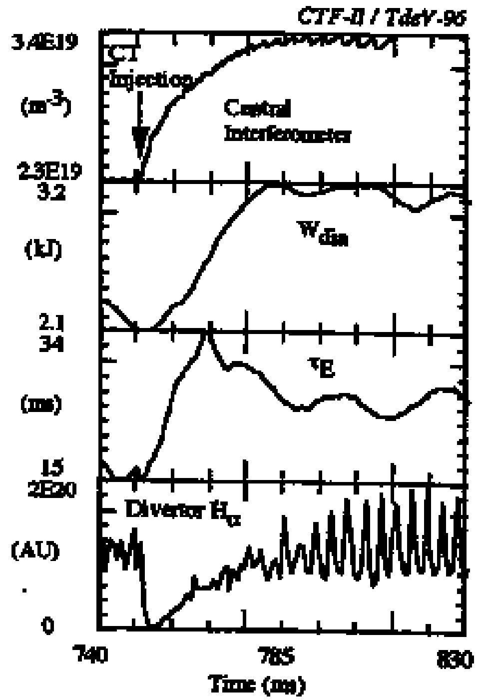


Figure 5: Example of improved confinement discharge from the CTF-II/TdeV96 run. $B_T = 1.5$ T, Ip = 170 kA, Te(0) = 900 eV, single null discharge. Beyond t = 785 ms, the oscillation amplitude in the divertor H_α signal increases.

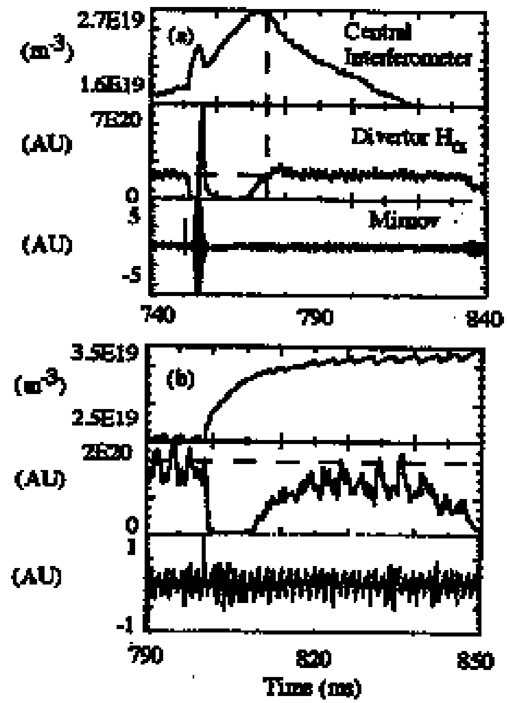
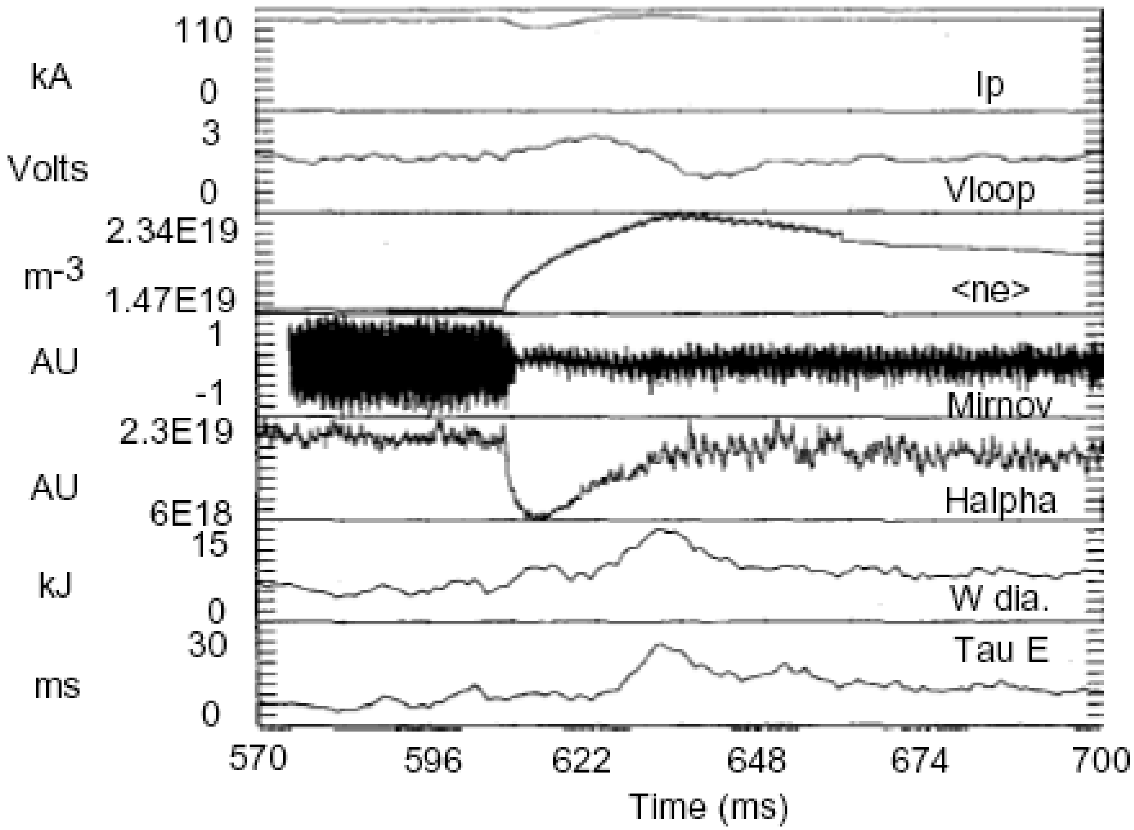


Figure 6: (a) The density signal continues to rise for as long as the H_α signal stays depressed. A single ELM is observed. (b) In this case, the H_α signal never quite reaches the pre-CT injection level while the density signal continues to gradually increase. No ELM feature is seen in this and in most CT injection discharges.

R. Raman et al., Proceedings of the 24th EPS Conf. p 293, 9-13 June 1997, Berchtesgaden, Germany 1997

Edge fueling of limited plasmas also shows a sharp reduction in Mirnov coil oscillations



CT induced confinement improvement also seen on STOR-M*

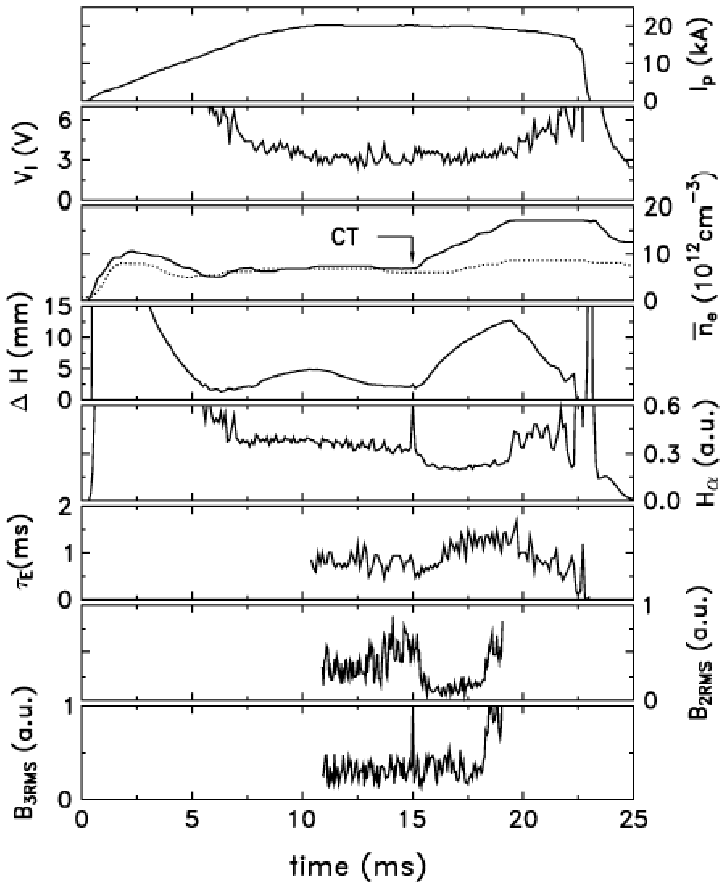


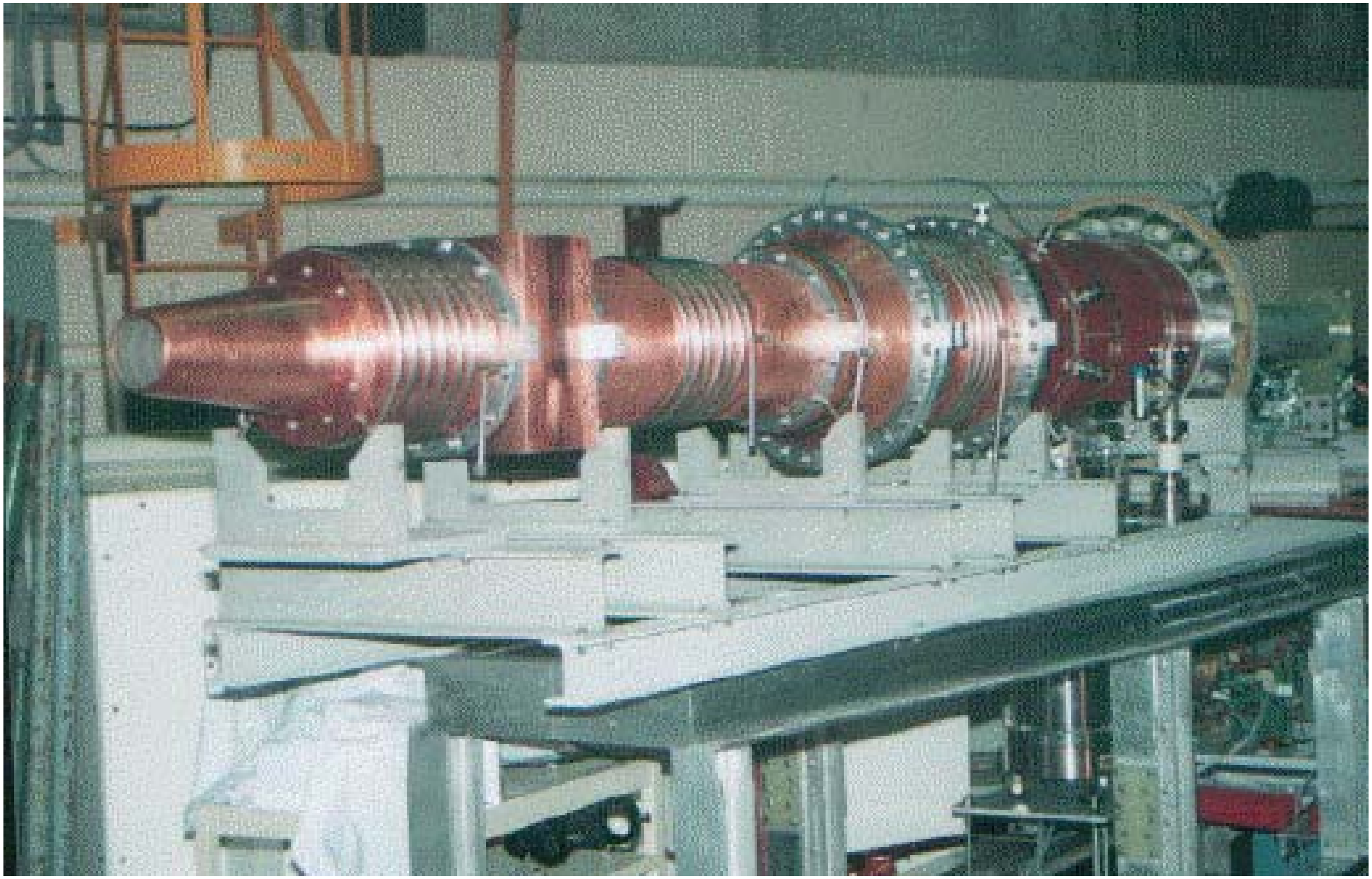
Figure 3. Tokamak plasma parameters during a discharge with CT injection at t = 15 ms. Shown are from top to bottom: plasma current, loop voltage, line averaged electron density, horizontal plasma position, H_α signal, energy confinement time, m = 2 Mirnov coil oscillations and m = 3 Mirnov coil oscillations. The dotted line shows the electron density with gas puffing in the injector, but without CT discharges.

STOR-M
R = 0.46 m
A = 0.12 m
Ip = 20 kA
B_T = 1T

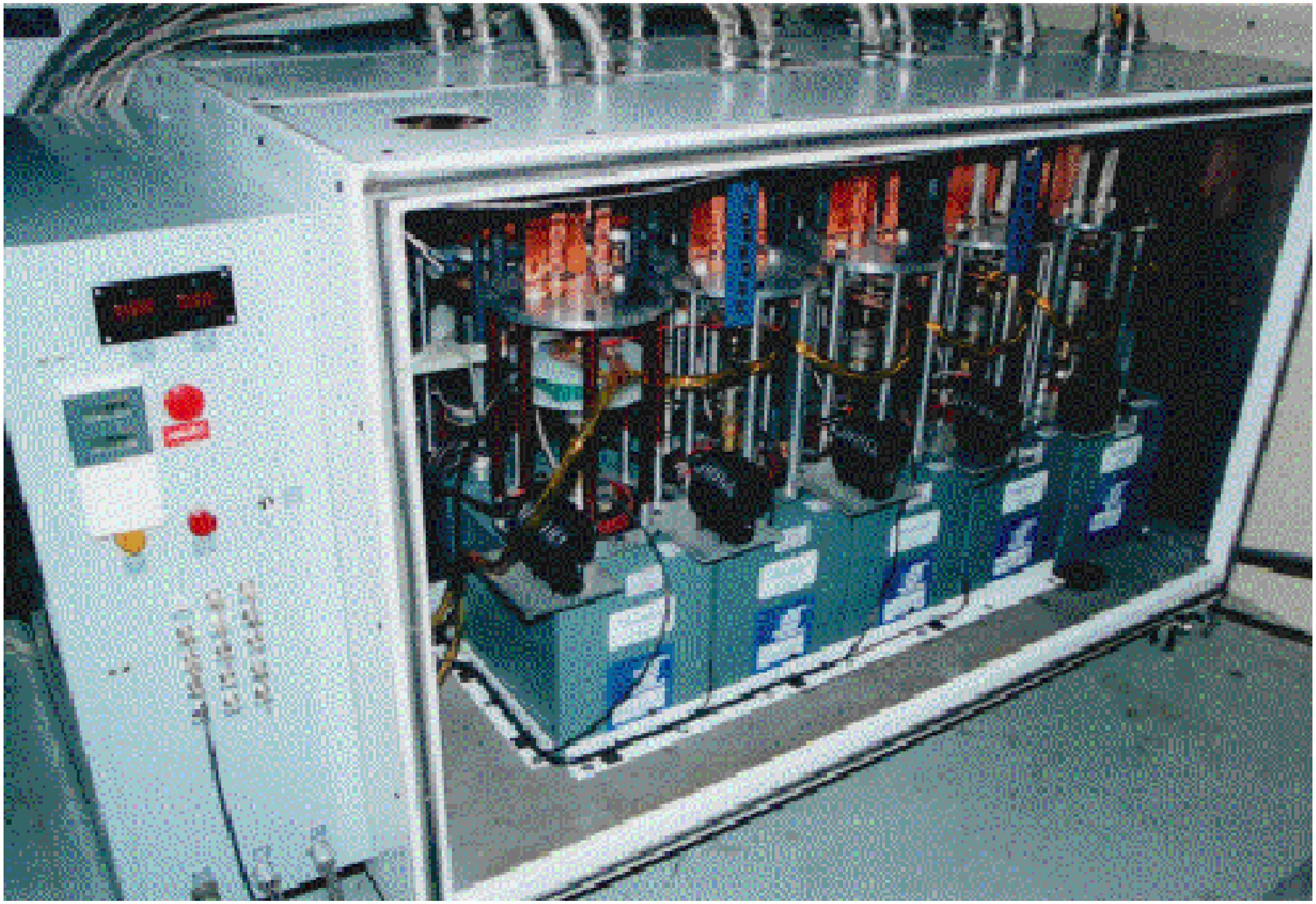
C. Xiao, A. Hirose, R. Raman, 2001,
Compact Torus Injection Experiments
in the STOR-M Tokamak,
Proc. of 4th Symp. on Current Trends in
International Fusion Research:
Review and Assessment
(Washington D.C., March 12-16, 2001,
in print)

* Recent similar results on JFT-2M

The CTF-II injector



The CT Formation bank power supply (110VAC input)

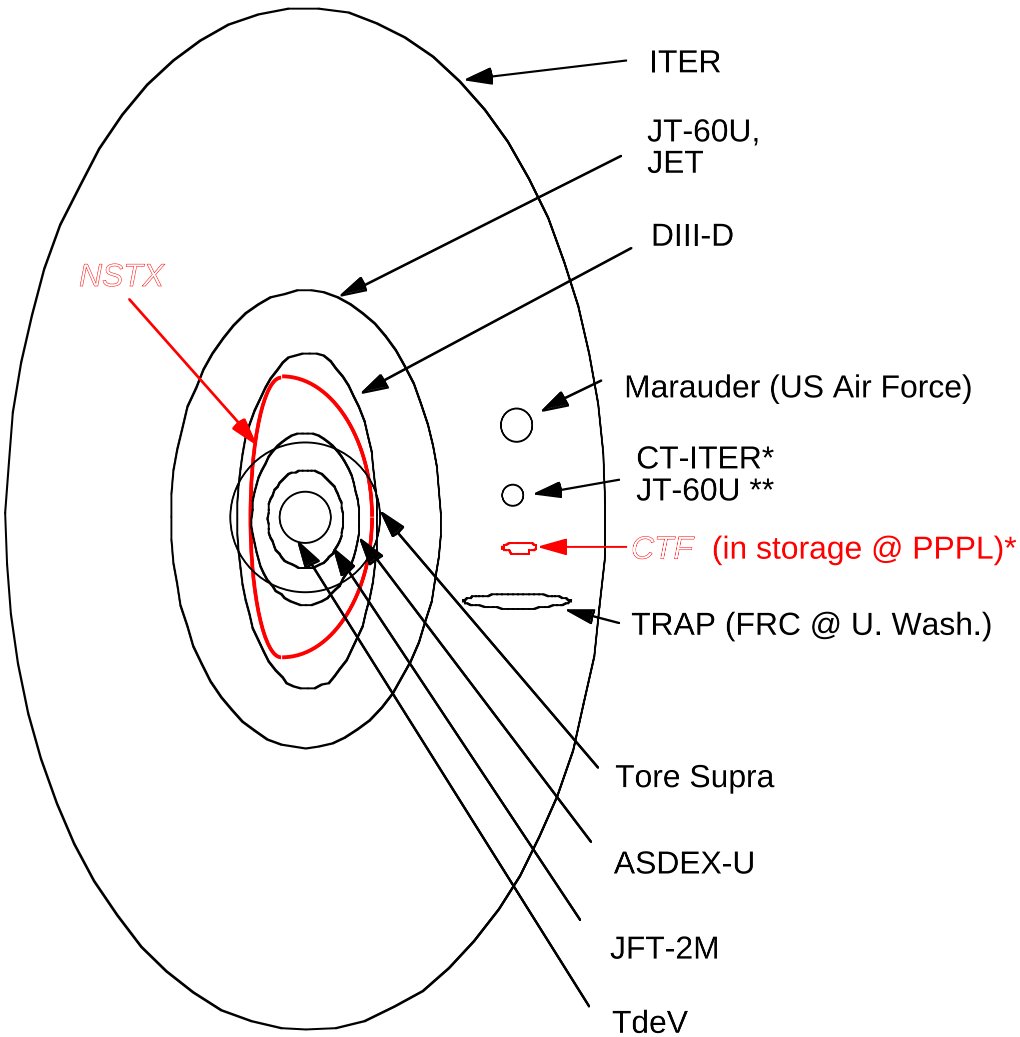


Two primary objectives for proposal

- Reliable initiation of H-modes and large surface area H-modes (during year-1)

- Establish CT parameters for controlled deep fuelling (during years 2 and 3)
  - Data needed for multi-pulse injector

Previous experiments too small to study localized core fueling



Relative sizes of various target plasmas and CTs.

A CTF sized CT will do far more localized fueling on a NSTX sized plasma

*R. Raman and P. Gierszewski, Fusion Engin. And Design, **39-40**, 977 (1998)

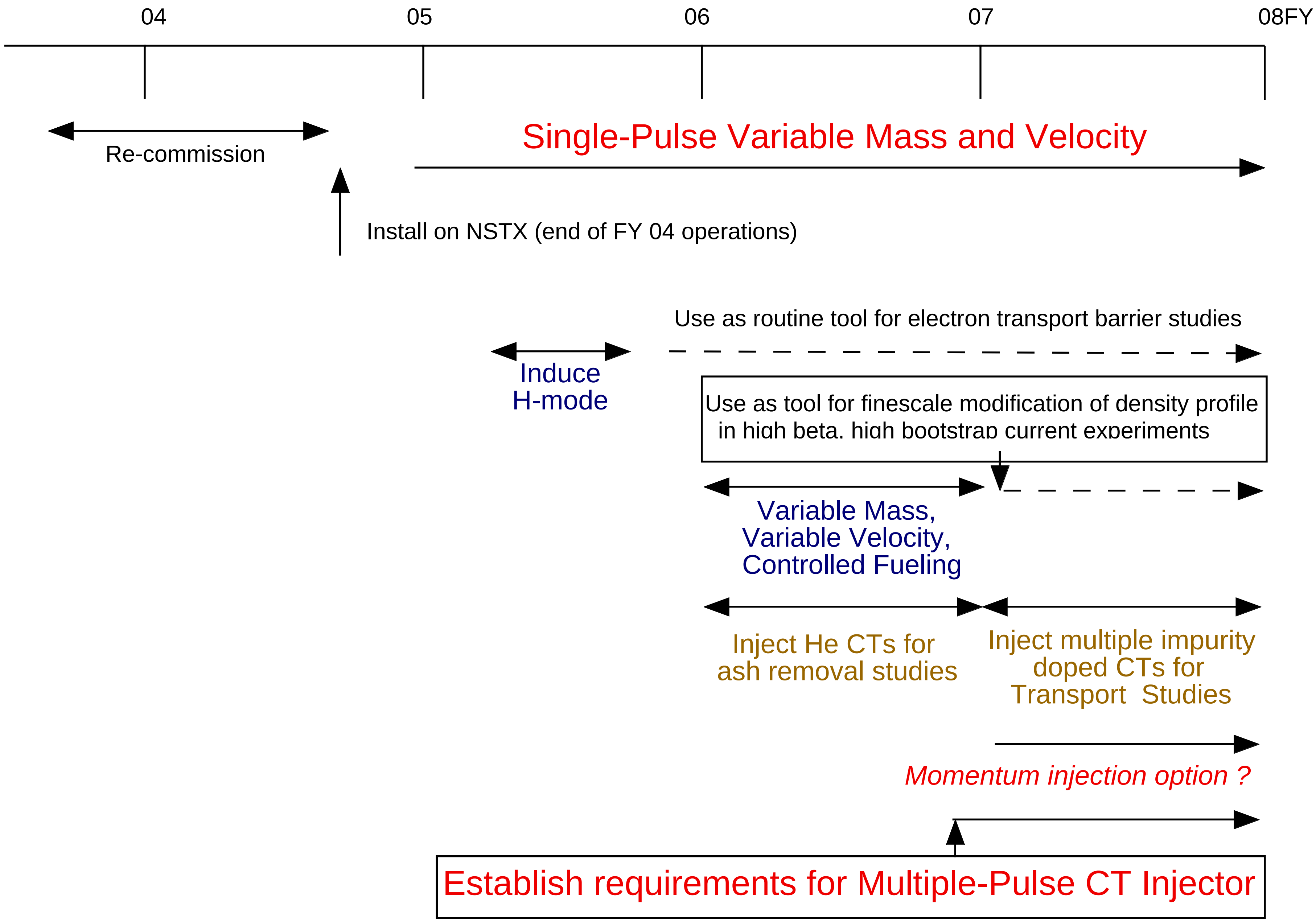
R. Raman and K. Itami, Journal of Plasma and Fusion Research, **76. 1079 (2000)

*Will cost >$1.5M and 2-yrs to build it from scratch

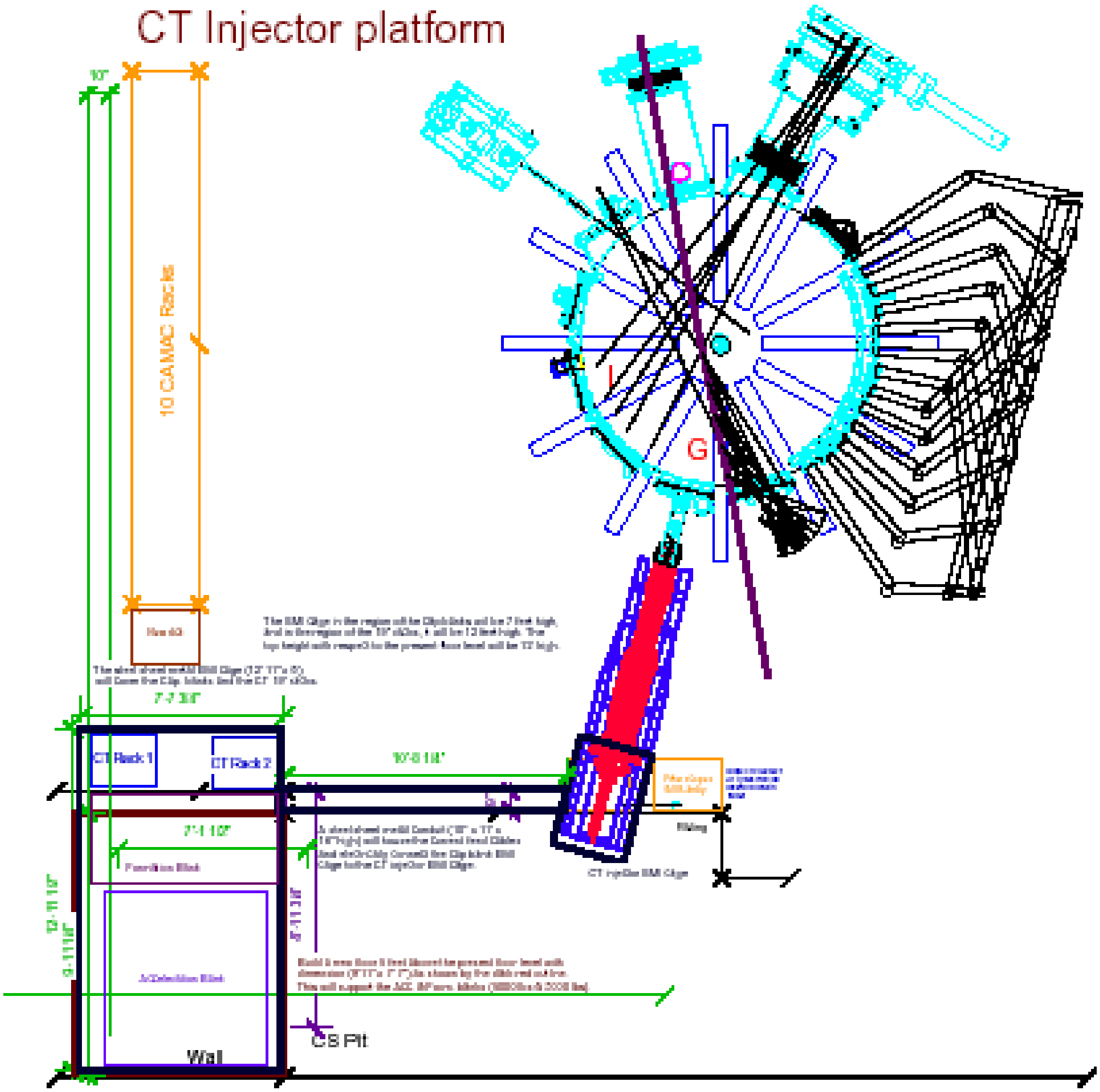
Secondary objectives

- Inject He CTs for He ash removal studies
- Inject Ne (or other impurity) doped CTs for transport studies
- Investigate capability for future tangential injection for momentum injection

CT Injection experimental plan on NSTX



Installation Concept



Boundary Physics 5-Yr program reviewer recommendations (Bruce Lipschultz)

- Comments on talk and program writeup (continued)
  - Cryopump justification and priority is not clear - make a decision
    - Cryopump is not obviously needed for density control per se.
    - However, *the ability to 'dictate' a specific density in a given shot may be worthwhile* - but has to be put in the context of progress in other areas.
    - **Other aspects of fueling need to be clarified as well (e.g. pellets vs CTs)**
  - Radial transport
    - Again, NSTX is in a potential position to make unique contributions
    - The basic diagnostic elements for attacking this are either there or in progress
    - A clear cohesive program bringing these diagnostics (and more importantly people) together is needed.
    - The effect on the wall (and impurities) may be very significant for an ST,

ST is a new class of plasma configuration, new technologies may be better suited to help the ST achieve its potential performance capability

	CT	**Pellet**
Particle invent. perturbation for deep fueling	Few % - will not destroy optimized profiles, allows precision fueling capability to adjust profiles	Typically 50% on DIII-D - large pellets needed to deposit small fraction of fuel in core
Penetration governing param.	$\alpha 1/B^2 \Rightarrow$ much easier penetration in ST as B^2 in NSTX is 2% of DIII-D	Te, fast electrons - similar to tokamak
Optimal injector location	Outboard mid-plane - tangential injection will impart momentum	'True'-Inboard mid-plane - improbable in a ST as even DIII-D does not use 'True' inboard mid-plane
Real time density feedback control capability	Yes - potential for fuel deposition location specification on each pulse using control system request	Improbable because large pellets fuel entire discharge and mechanical nature of injector.

Other remarks

- A reactor will not use NBI & Alpha power is isotropic $\Rightarrow$No momentum injection
- In a high β, high f_{BS} reactor some auxiliary current drive is needed

This leaves excellent density profile control as the method of choice to optimize reactor performance and to sustain transport barriers

Conclusions

- Excellent density profile control will enable STs to reach their highest potential
- Fueling SS discharges is much more difficult than fueling transient discharges. The needed fueling capability does not exist. Yet, the NSTX program plan calls for SS pulses with high beta and high bootstrap current drive
- The CT injection concept has the potential to meet this need, but data is needed from a single pulse injector
- The CT is also a source of momentum input and has the potential to sustain transport barriers
- A single pulse CT can make additional immediate contributions to the NSTX program
  - Precise H-mode triggering capability is useful for present XPs
  - Core injection of Neon will clarify transport issues
  - Injection of He CTs will enable He-ash removal studies