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Requirements For An Advanced Fueling System

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Reactor Fueling Requirements Not Adequately Addressed At Present

- Present systems may be inadequate
  - Pellets sizes are large & injection is shallow
  - No plan at present for density profile control

- Density profile control may be the ideal method for steady burn control

- Compact Toroid (CT) injection system has potential for density profile control and momentum injection
  - Brief summary
  - Open issues
  - Plans and suggestions

Flexible fueling system may be the only choice for burn control

- A burning plasma device has no need for neutral beam injection for plasma heating and alphas are isotropic → no momentum injection
- In a device with high bootstrap current fraction, optimized density and pressure profiles must be maintained → fueling system must not adversely perturb established density and pressure profiles
- Other than a system for current drive, a fueling system is all that a burning plasma system may be able to rely on to alter core plasma conditions and for burn control
  - Fusion power output scales as the square of density
  - Initial density peaking via. core fuelling provides more flexibility to reach ignition

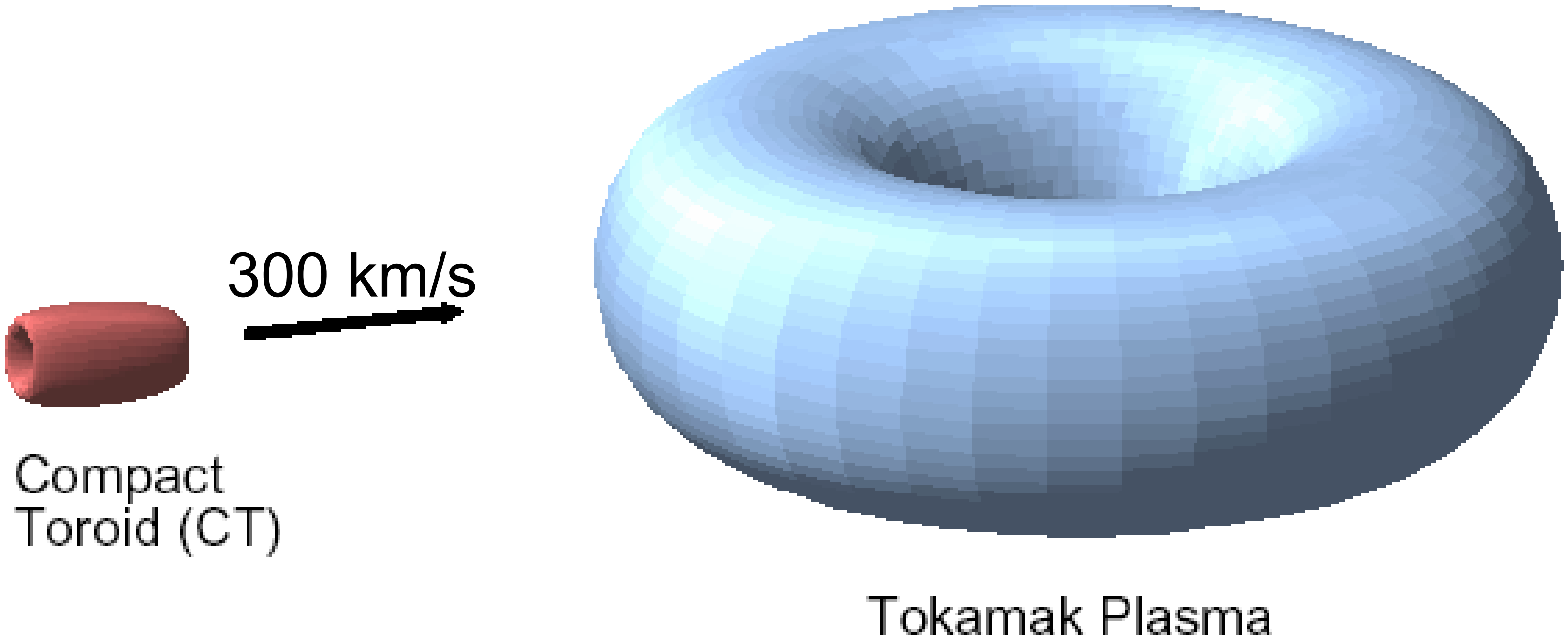
Fueling profiles from present systems

- Pellets (< 1km/s, HFS)
  - Large pellets increases density over a large radius
  - Capability of small pellets for profile control yet to be established

- Supersonic gas (~ 2-3 km/s)
  - Fuels from the edge with improved fueling efficiency
  - Capability for profile control not known yet

- Plasma jet (~ 30km/s)
  - Similar to supersonic gas, bulk fueling at present
  - Penetration into large cross-section plasmas not known

In a CT injection system a CT is accelerated to high velocity and injected into the target plasma to achieve deep fueling



CT Penetration time: few μs

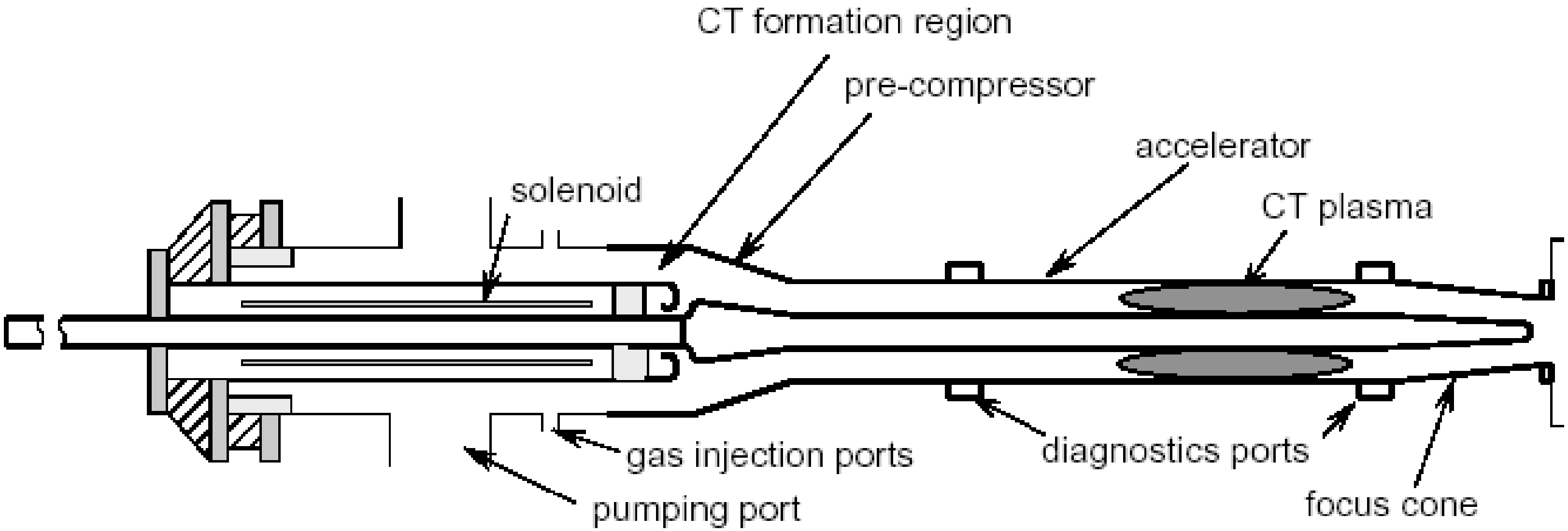
CT Dissociation time: < 100 μs

Density Equilibration time: 250 - 1000 μs

Variable Penetration depth: edge to beyond the core

Perkins, Ho, Hammer, NF 28, 1365 (1998), Parks, PRL, 61, 1364 (1988)

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



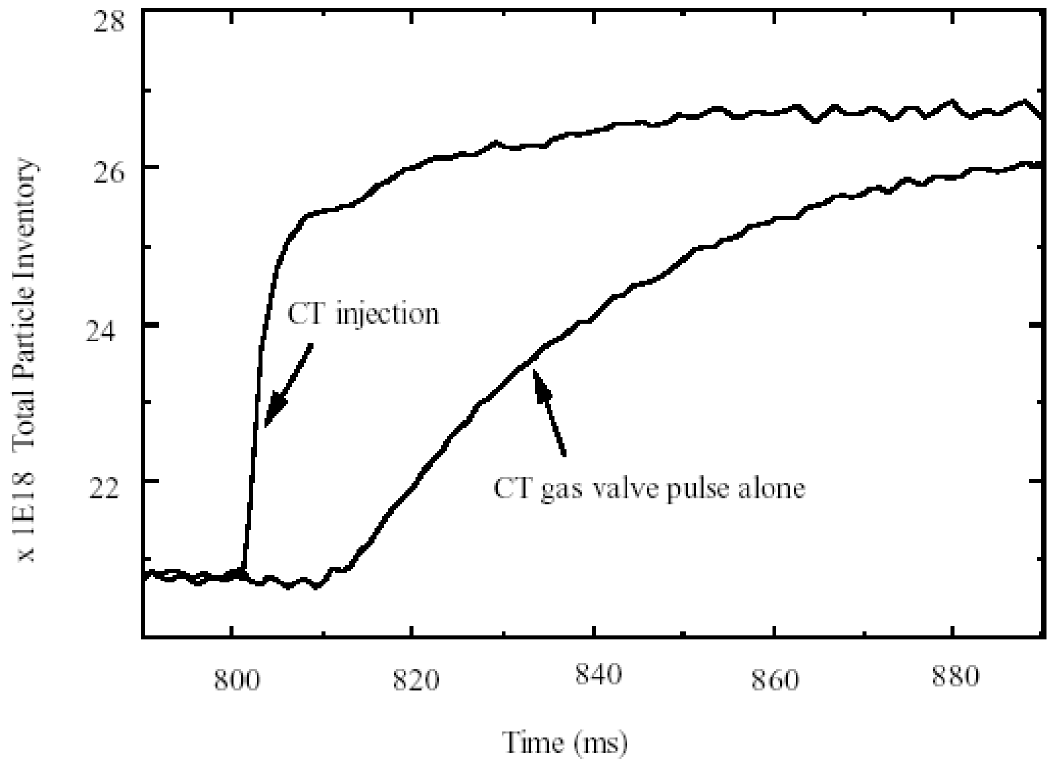
- Amount of gas injected controls CT density
- Applied voltage controls CT velocity

Control system specifies fuel deposition location for each pulse

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

Status of current work

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)

Edge fueling of diverted discharges triggers improved confinement behavior

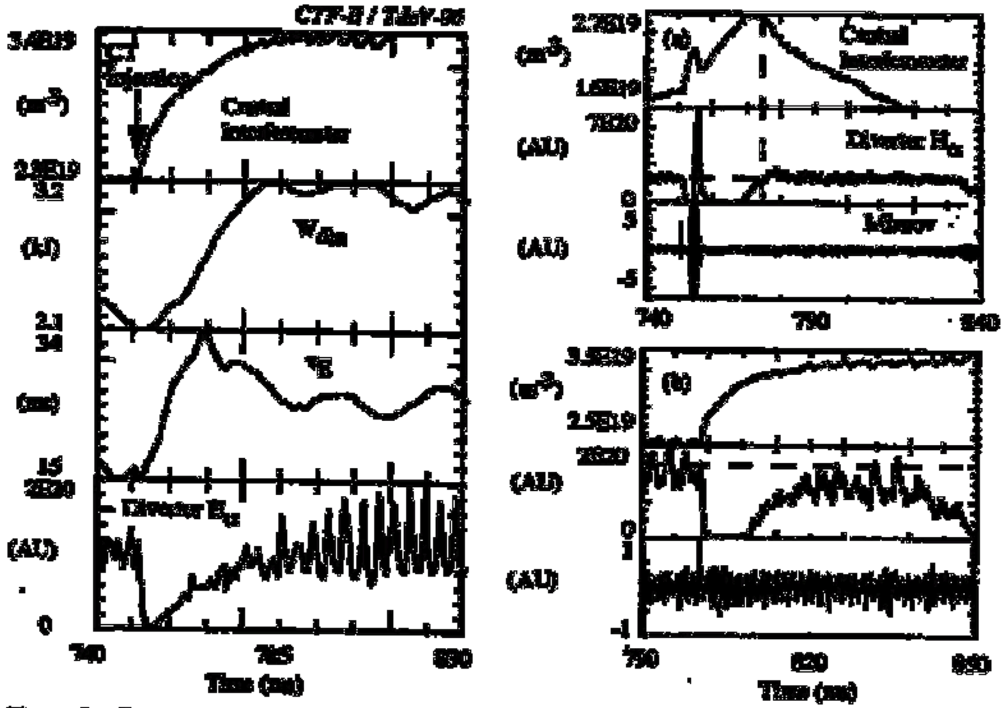


Figure 5: Example of improved confinement discharge from the CTF-II/TdeV96 run. B_T = 1.5 T, Ip = 170 kA, Te(0) = 900 eV, single null discharge. Beyond t = 785 ms, the oscillation amplitude in the divertor H_α signal increases.

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 regains 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

CT induced confinement improvement also seen on STOR-M*

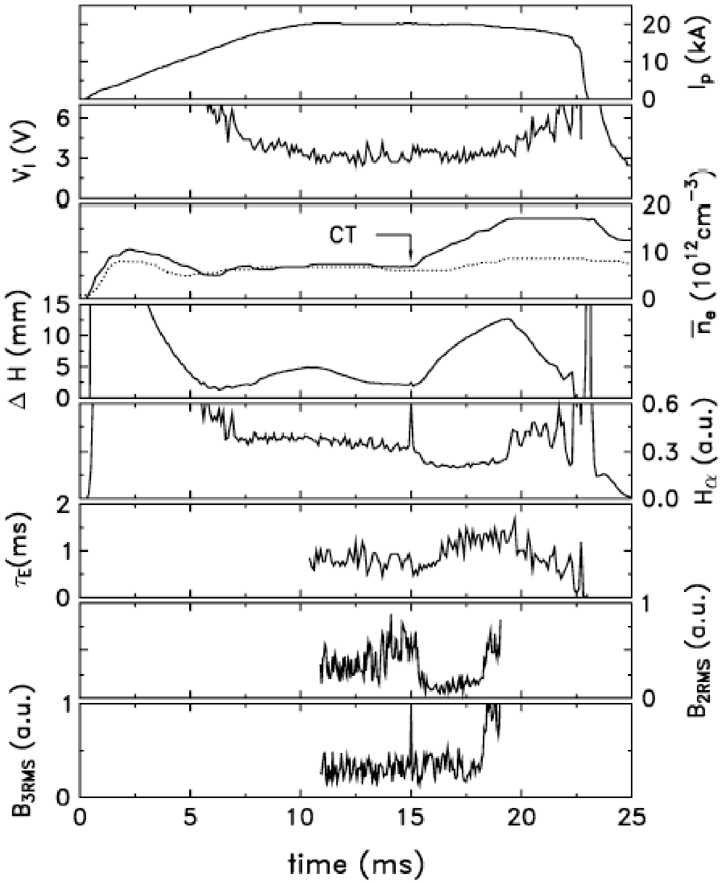


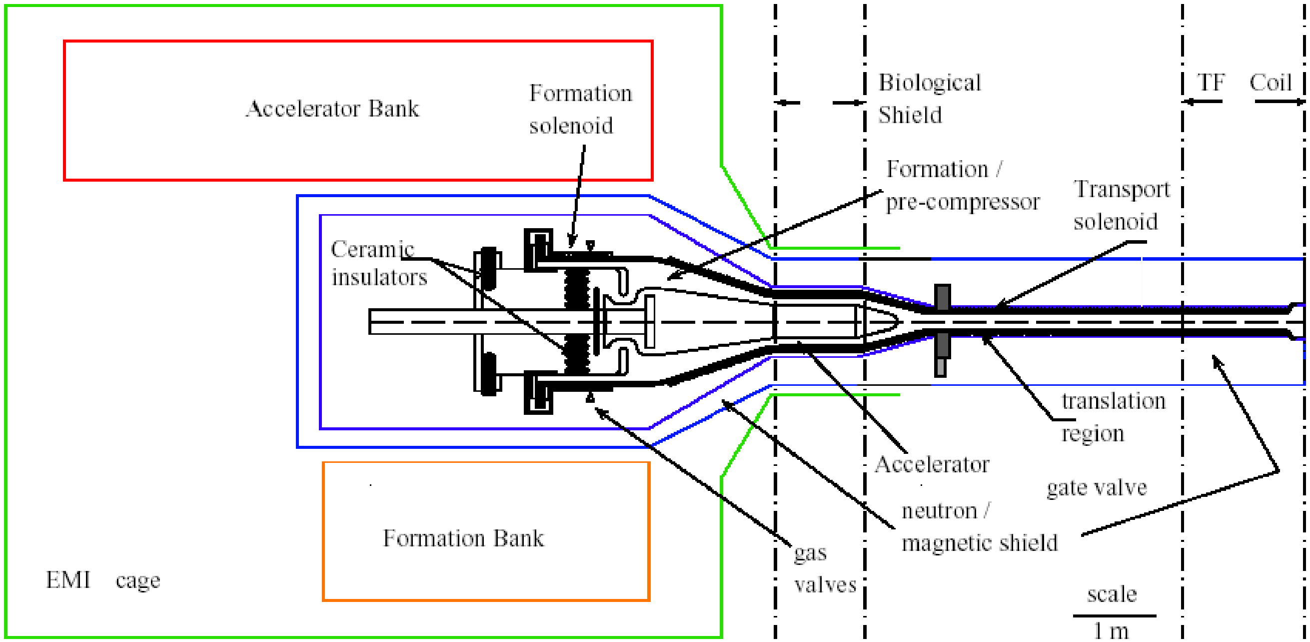
Figure 3. Tokamak plasma parameters during a discharge with CT injection at t = 15 ms. Shown are from top to bottom: plasma current, loop voltage, line averaged electron density, horizontal plasma position, H_α signal, energy confinement time, m = 2 Mirnov coil oscillations and m = 3 Mirnov coil oscillations. 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

Conceptual study of a CT system for ITER yields an attractive design

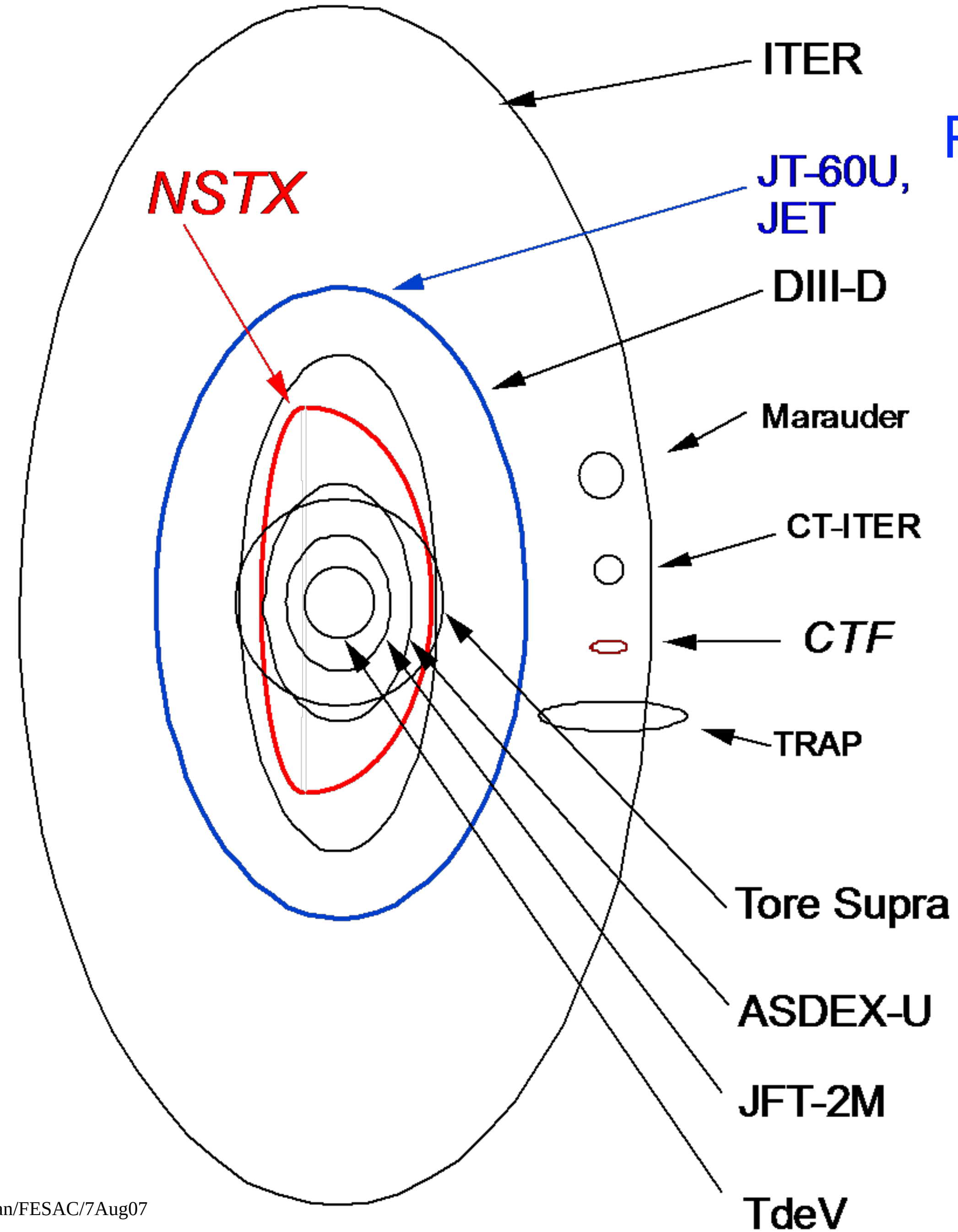


<1% particle inventory perturbation, 20 Hz operation

R. Raman and P. Gierszewski, ITER Task D315 (1997), Fusion Engin. & Design **39-40** (1998) 977-985

Open Issues

Previous experiments too small to study localized core fueling



Approximate relative sizes of various target plasmas and CTs.

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

- Steep B_T more precisely determines CT stopping location

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

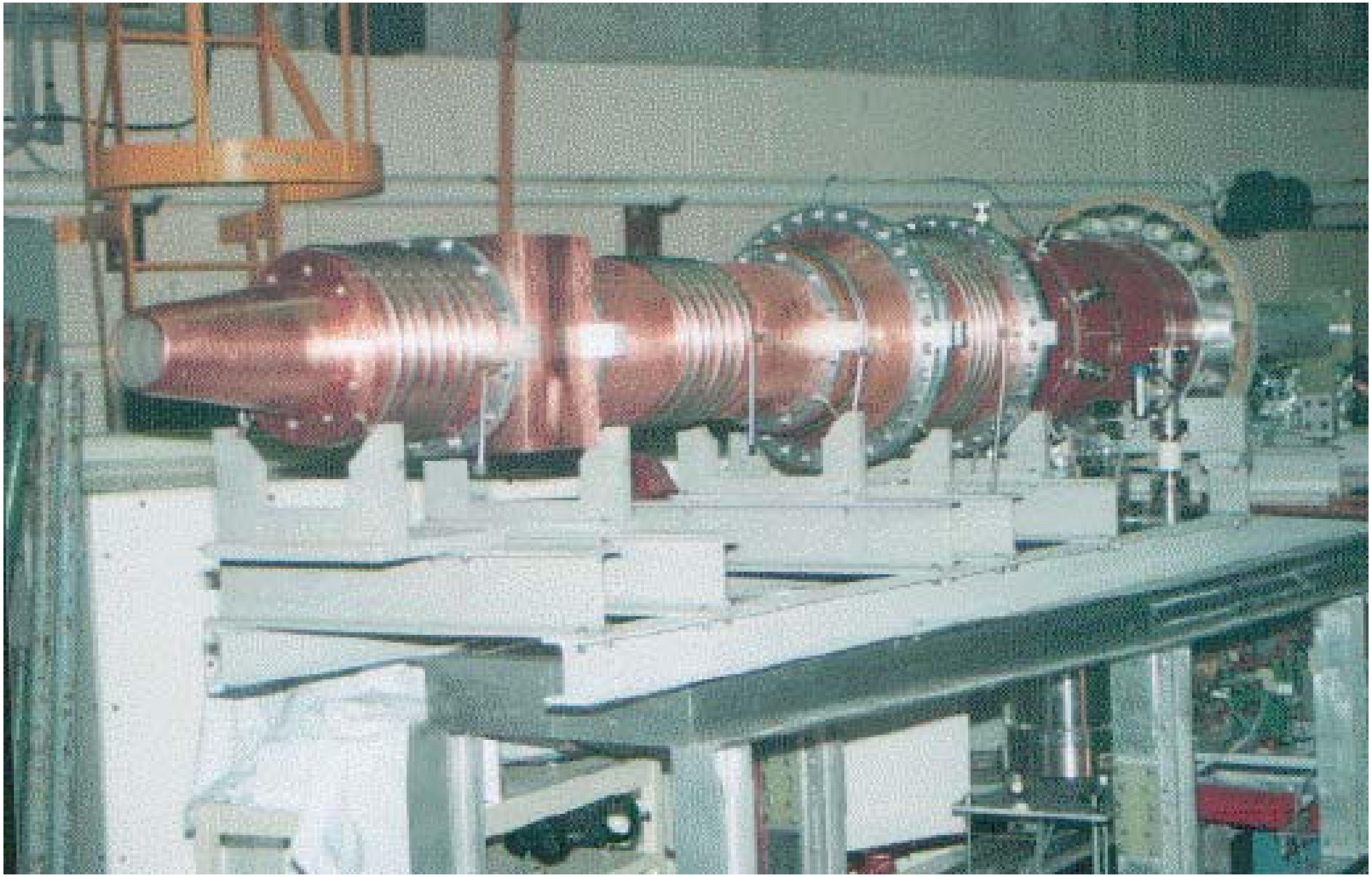
Proposed research Plan

- Injection into a large cross-section, low field device (eg., NSTX) - *using an existing injector*
  - Establish localized fueling (~ 2 yrs)
    - Transport studies
  - Establish momentum injection (~ 3 yrs)

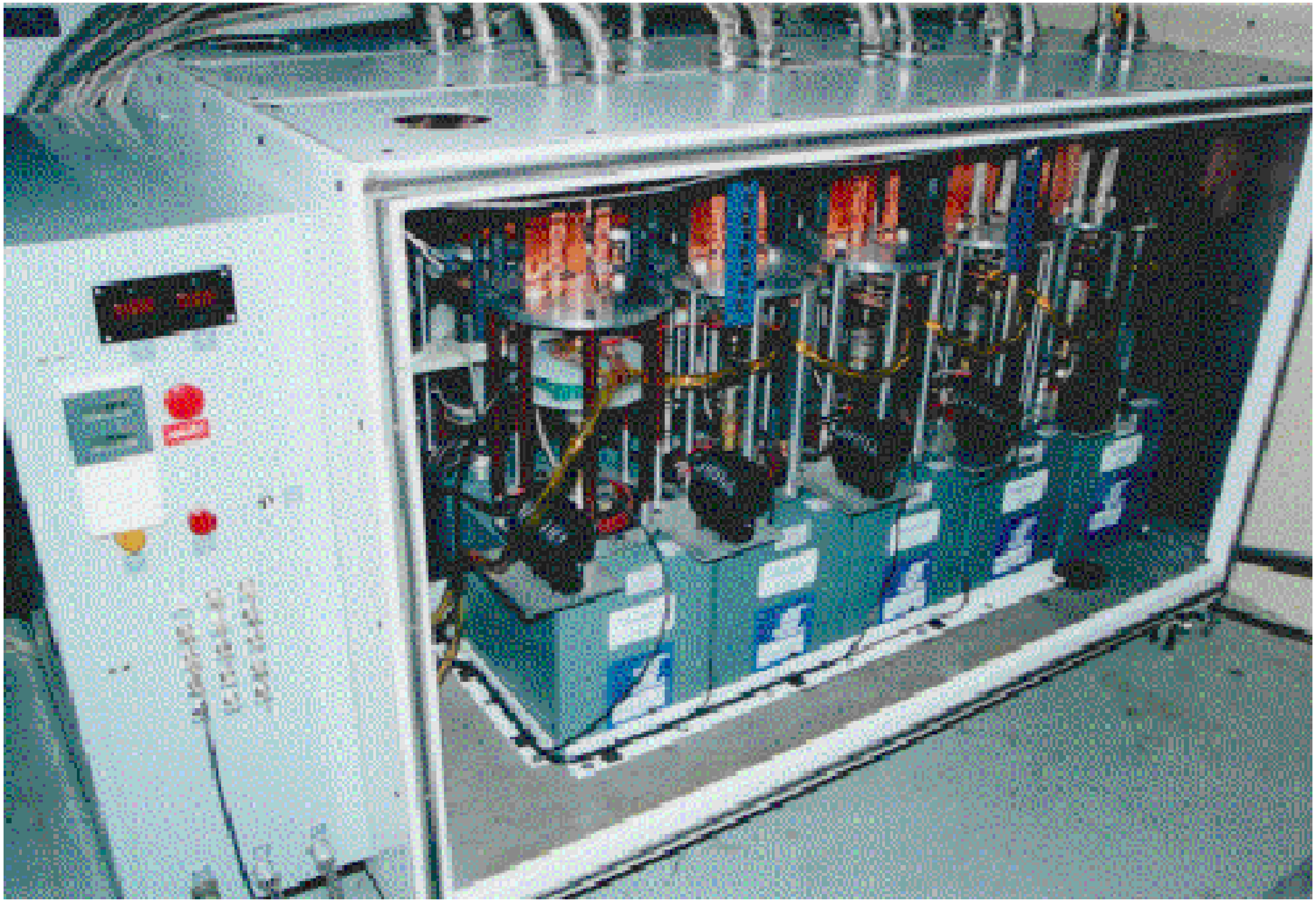
- Establish multi-pulse fueling
  - Requires injector modifications

- Larger scale experiments (DIII-D,JT-60U,JET)

The CTF-II injector (in storage at PPPL)



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



A CT injector could provide profile control 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
Optimal injector location	Outboard mid-plane - tangential injection will impart momentum	'True'-Inboard mid-plane - injection at an angle reduces penetration
Real time density feedback control capability	Yes - potential for fuel deposition location specification on each pulse using control system request - Also a source of momentum injection	Improbable because large pellets fuel entire discharge and mechanical nature of injector reduces fueling flexibility

Conclusions

- A CT injector has the potential to deposit fuel in a ***controlled*** manner at any point in the machine

- In a burning plasma device with only RF for current drive, a flexible fueling system may be the only internal profile control tool
  - Inject momentum for plasma beta and stability
  - Precise density profile control to optimize bootstrap current and to maintain optimized fusion burn conditions
  - Study core transport in present machines (He ash removal studies, ELM control)

- Large tokamaks should consider and develop backup options to meet the fuelling and burn control requirements of a burning plasma device
  - Large STs are an attractive target for developing CT fueling
    - **Steep B_T gradient, large crossection**

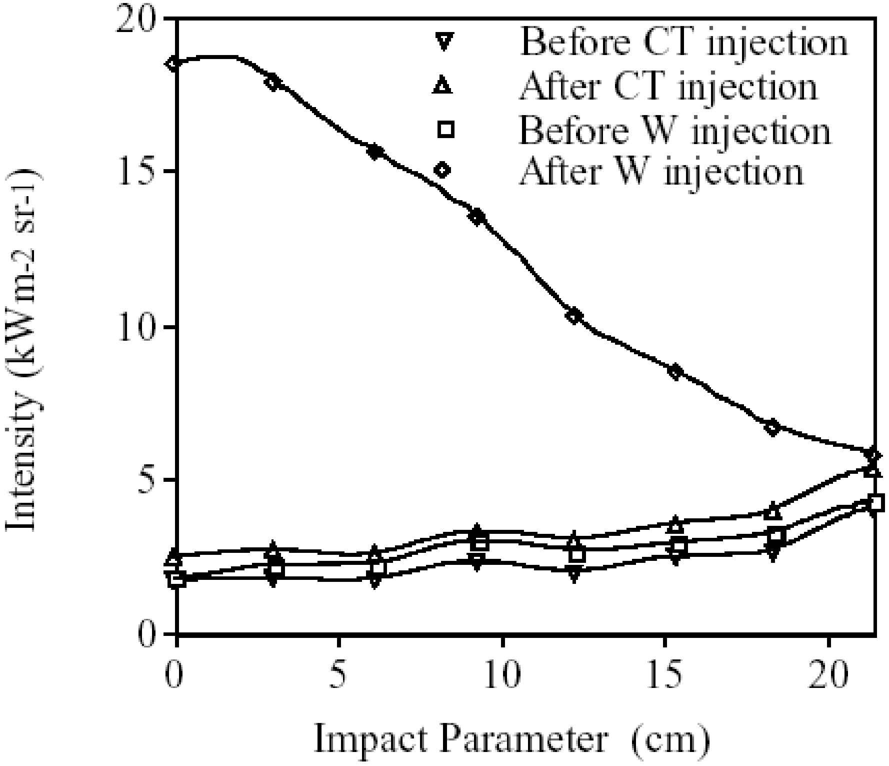
- A CT Test on NSTX has the short term potential for impacting the fusion development path
  - It has the potential to meet the needs of predictable, high-performance steady-state burning plasmas

ITER CT Injector parameters

CT radius	0.1 m
CT length	0.2 m
CT density (D + T)	9×10^{22} m^{-3}
CT mass	2.2 mg DT (2.6 T_2)
Fueling rate (D + T)	5.3×10^{20} / pulse
Fueling frequency	≤ 20 Hz
CT velocity	300 km/s
CT kinetic energy	100 kJ (120 kJ T2)
Momentum inj. rate	13.2 kg.m/s DT, 15.6 T_2,
Power consumption	8 MWe (10 T_2)

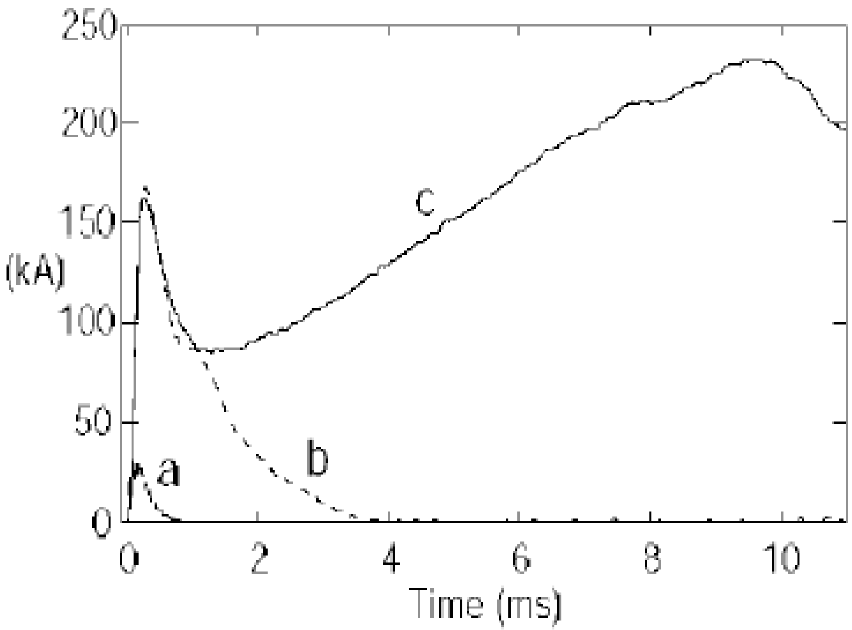
R. Raman and P. Gierszewski, ITER Task D315 (1997), Fusion Engin. & Design **39-40** (1998) 977-985

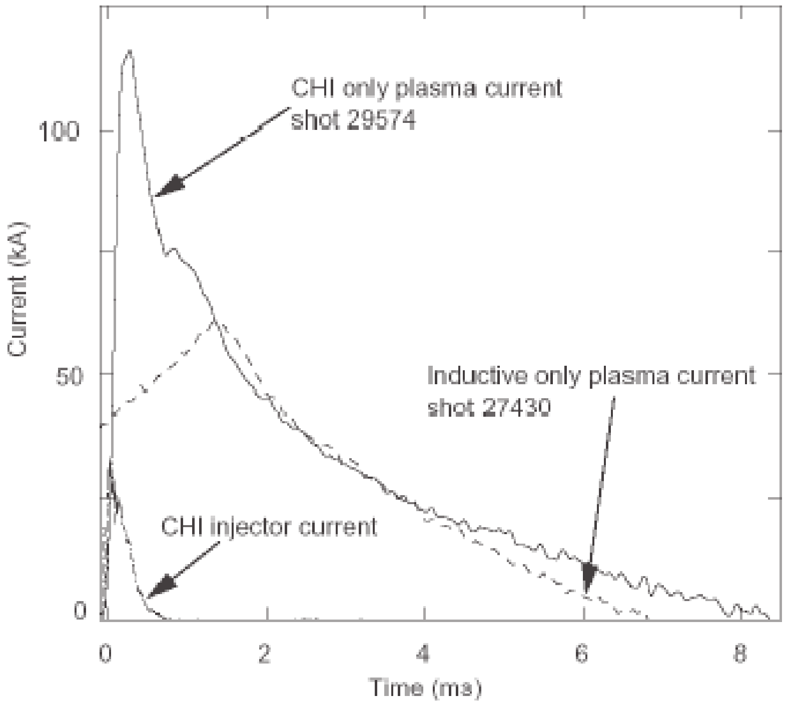
No evidence for metallic impurity contamination of TdeV



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

Inductive quality discharge produced by electrode discharge





Raman, et al., NF 45 (2005) L15-L19