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Compact toroid injection studies and extrapolation to ITER

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Outline of Talk

- Present deep fueling systems
- The CT injector
  - Description
  - Motivation for CT Injection
  - Experimental results
  - Extrapolation of a CT system for ITER

- Summary and conclusions
  - Possible research plan

Present deep fueling systems

- Pellets
  - Extensive (~25 yr) database
  - Improves performance in present machines (eg JET, PEP mode)
  - High field side injection at velocity < 1km/s

- Supersonic gas
  - Recent expts. in HL-1M, Tore Supra, W7-AS, others
  - Injects high density gas at high velocity (~2-3 km/s)

- Plasma jet
  - Recently used on Globus-M
  - Injects high density plasma at high velocity (~30km/s)

Fueling profiles from present systems

- Pellets
  - Density increases by ~10-50%for r/a 0.3 to 0.8 (Re: shot 90312 on DIII-D, L. Baylor et al, http://www.ornl.gov/fed/pellet/0rnlpell.html)
  - Large pellets increases density over a large radius
  - Capability of small pellets for profile control to be established
- Supersonic gas
  - Fuels from the edge with improved fueling efficiency
  - Large particle inventory perturbation in present experiments accompanied by plasma cooling
  - Capability for profile control not known yet
- Plasma jet
  - Similar to supersonic gas, bulk fueling at present
  - Penetration into large cross-section plasmas not known

Description of a CT injector

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)]

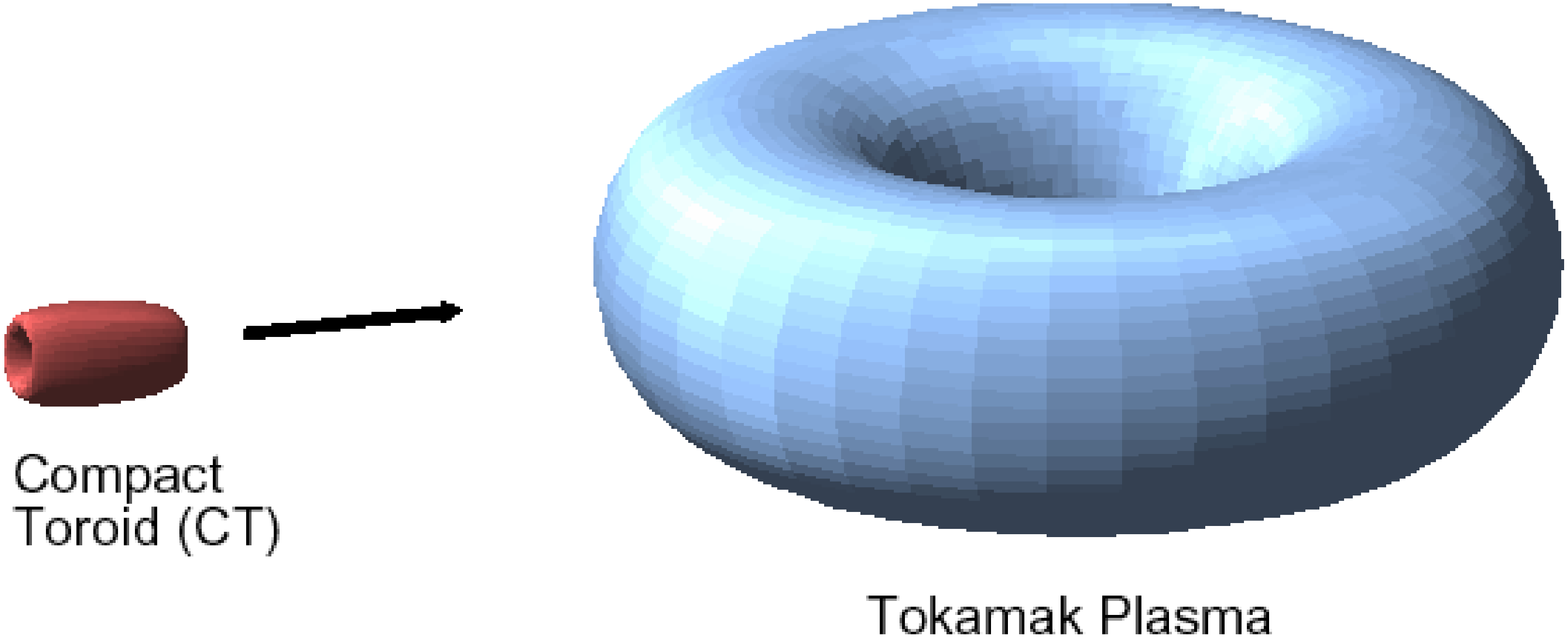
- Hammer and Hartman (LLNL) developed the accelerator concept

  -[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

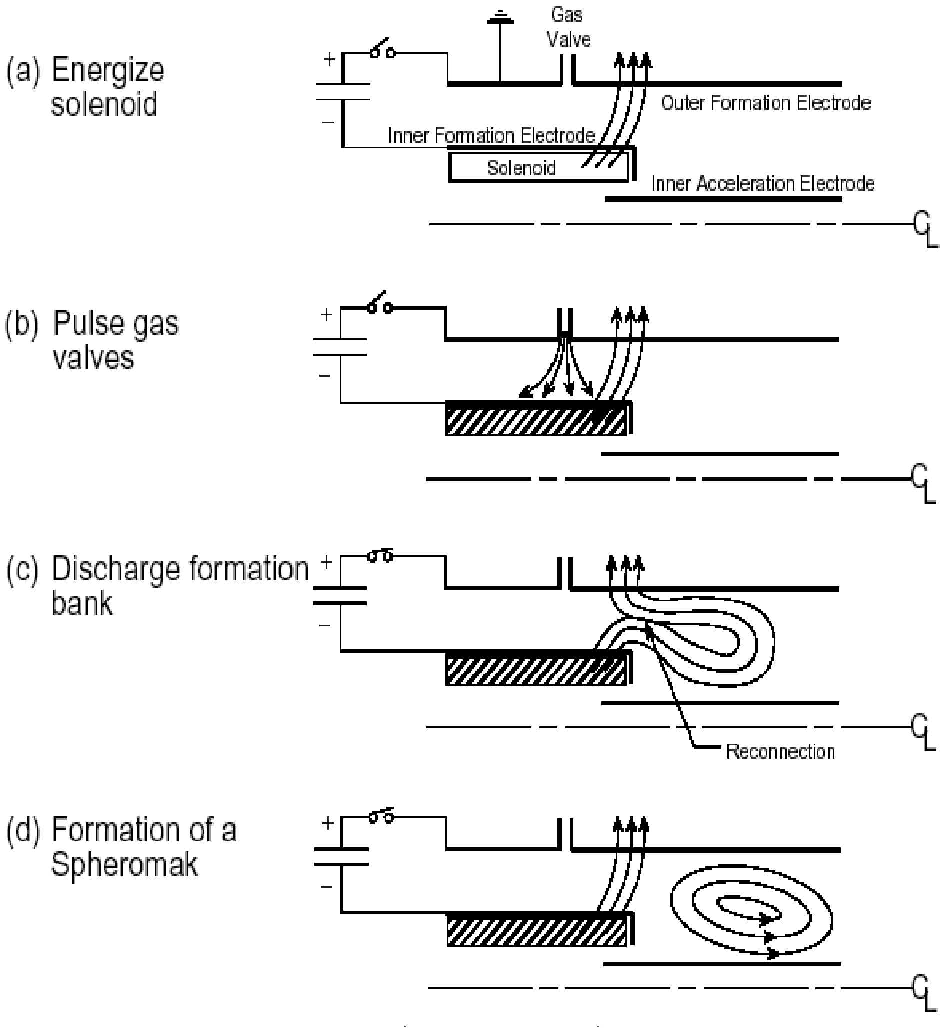
CT Dissociation time: < 100 µs

Density Equilibration time: 250 - 1000 µs

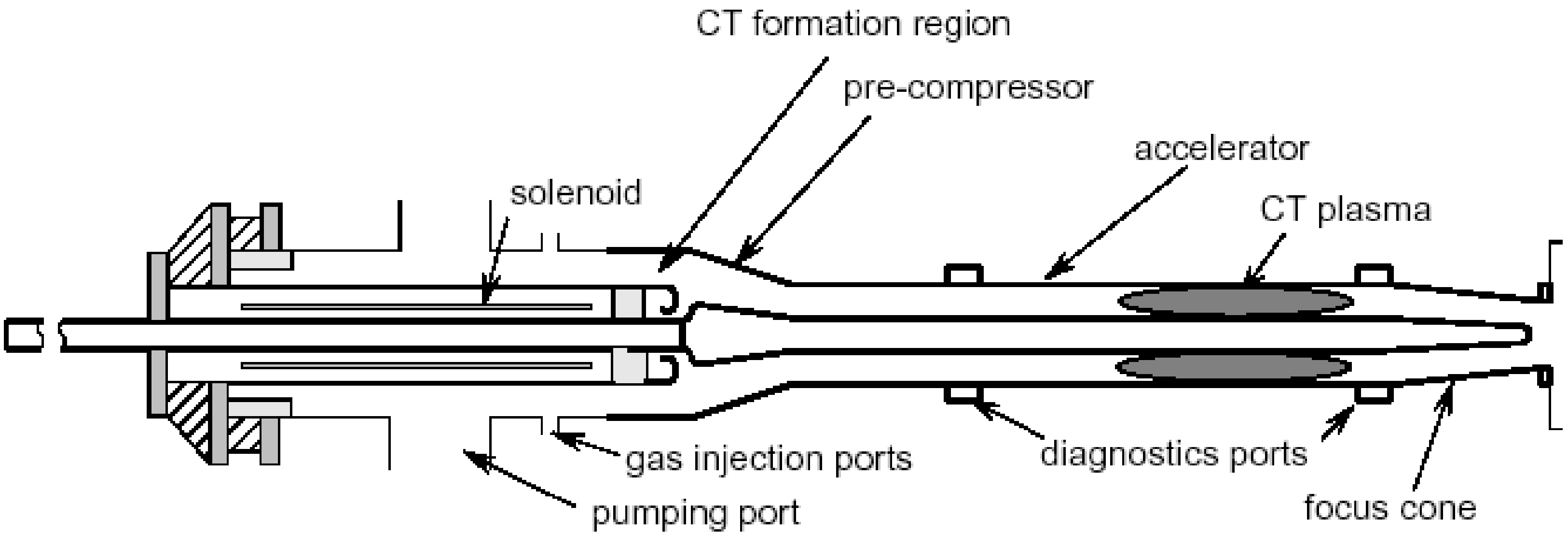
Variable Penetration depth: edge to beyond the core

Raman, ITPA meet., 8-12/11/04

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 high bootstrap current fraction, steady-state discharge fueling needs

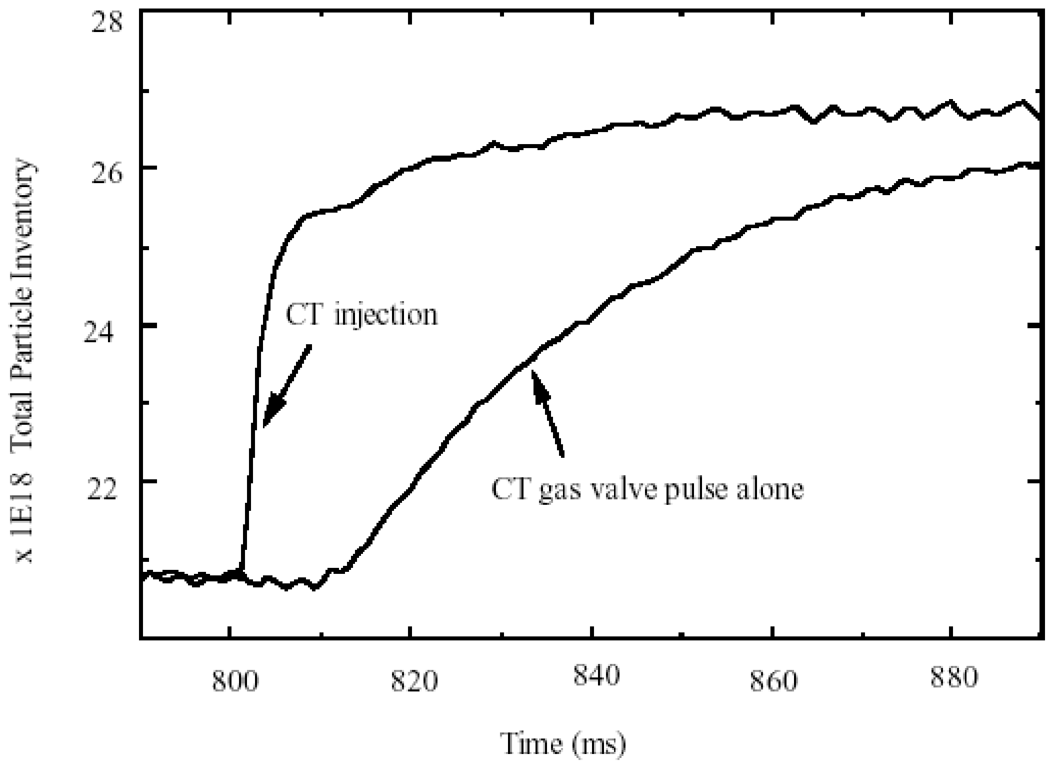
- Future high bootstrap fraction plasmas require optimized profiles
- During high performance steady state, optimized profiles must be maintained
- Fueling such discharges requires the prompt injection of small amounts of fuel where needed and as often as needed

IPPA (FESAC) goals relevant for CT Fueling

- 3.4.1.2 Fueling Technologies: "Develop systems and fueling techniques that are <u>capable of providing a reliable, flexible particle source</u> 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



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

TdeV

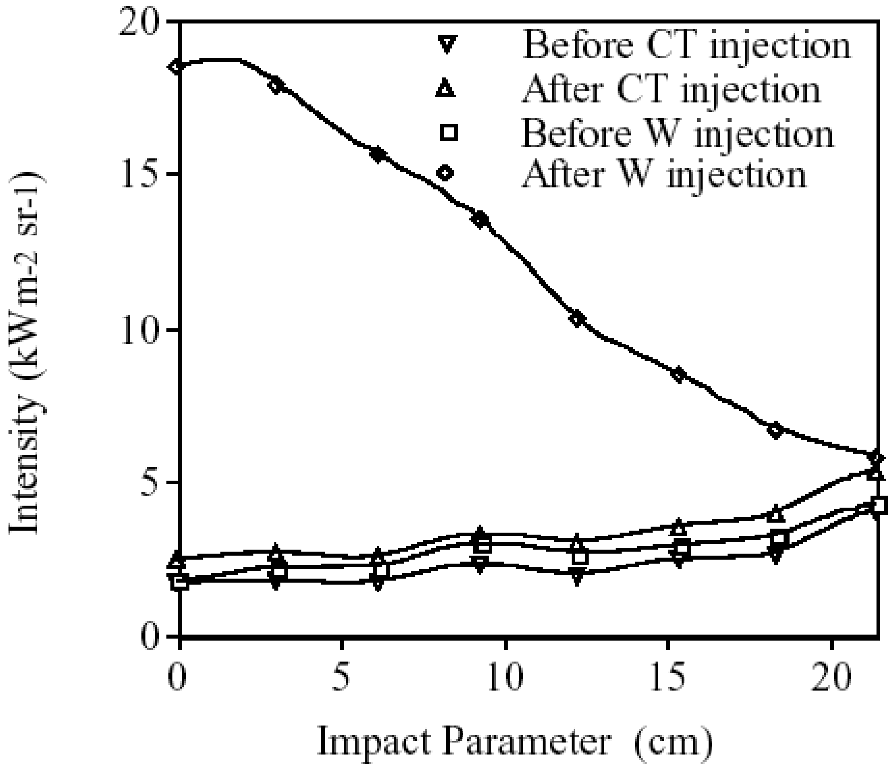
R = 0.86m

a = 0.25m

B_T = 1.4T

Ip = 160kA

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

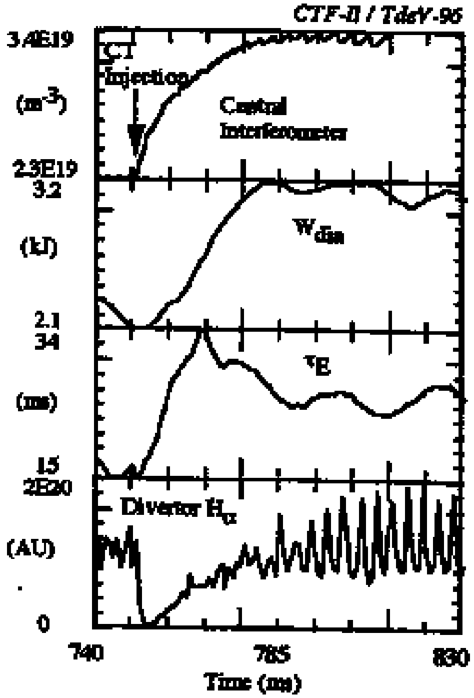


Figure 5: Example of improved confinement discharge from the CTF-II/TdeV96 run. $B_T = 1.5$ T, $I_p = 170$ kA, $T_e(0) = 900$ eV, single null discharge. Beyond $t = 785$ ms, the oscillation amplitude in the divertor H_α signal increases.

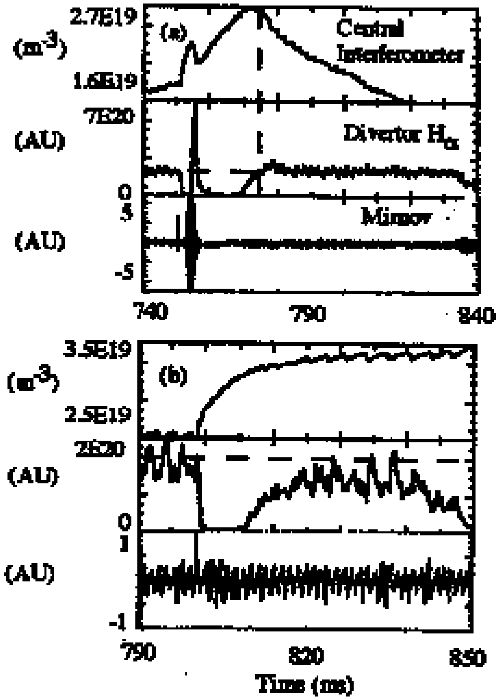
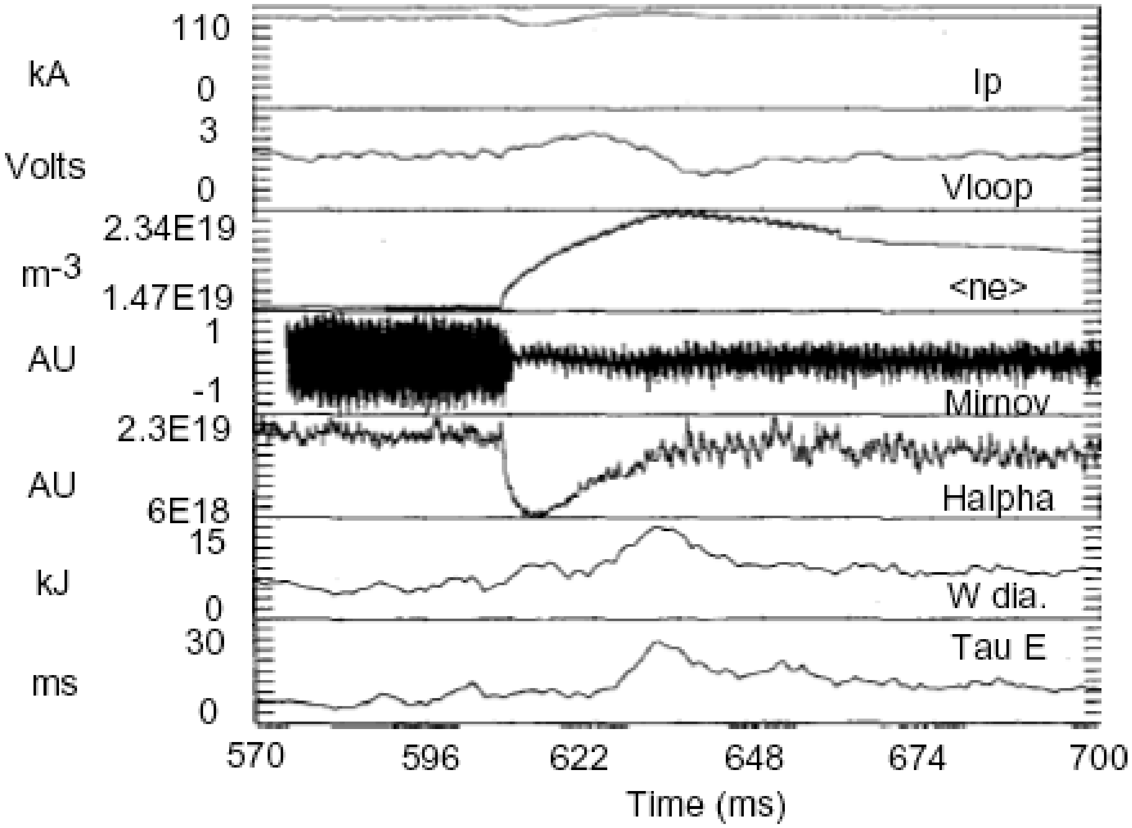


Figure 6: (a) The density signal continues to rise for as long as the H_α signal stays depressed. A single ELM is observed. (b) In this case, the H_α signal never quite reaches the pre-CT injection level while the density signal continues to gradually increase. No ELM feature is seen in this and in most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



Raman, ITPA meet., 8-12/11/04

Results from JFT-2M

Results from JFT2M

CT induced confinement improvement also seen on STOR-M*

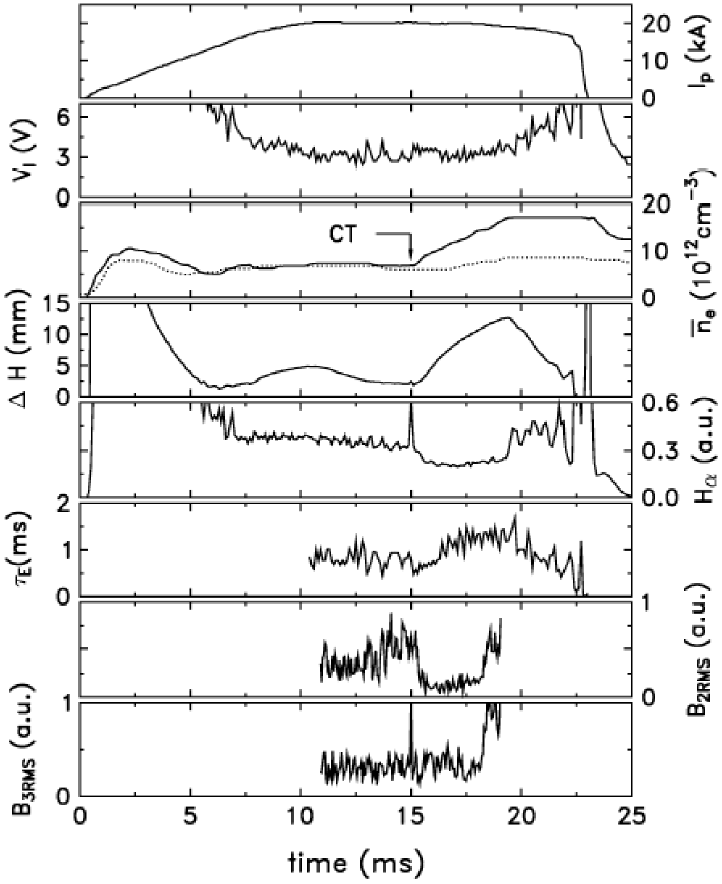


Figure 3. Tokamak plasma parameters during a discharge with CT injection at $t = 15$ ms. Shown are from top to bottom: plasma current, loop voltage, line averaged electron density, horizontal plasma position, H_α signal, energy confinement time, $m = 2$ Mirnov coil oscillations and $m = 3$ Mirnov coil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

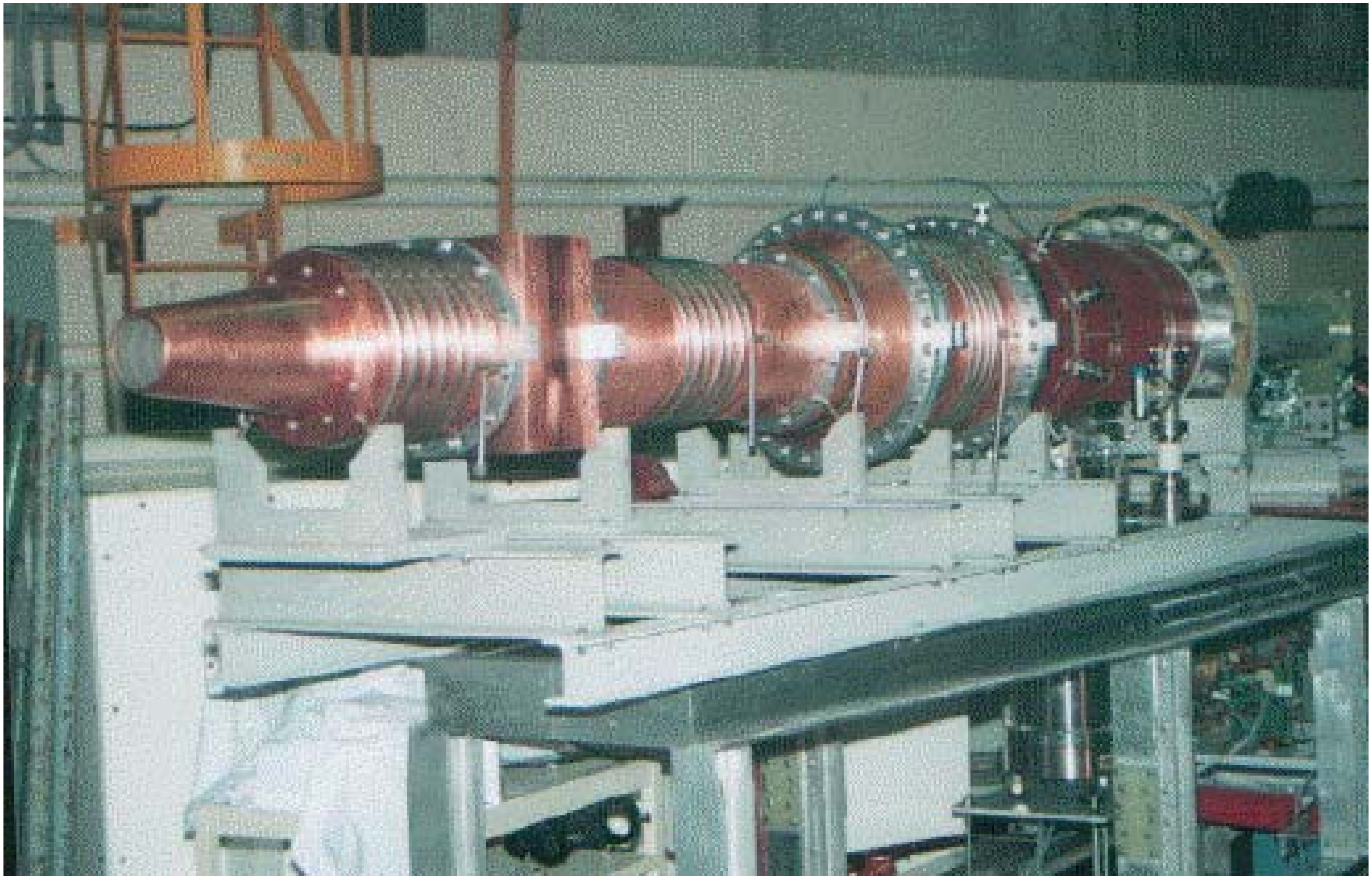
STOR-M
R = 0.46 m
A = 0.12 m
Ip = 20 kA
B_T = 1T

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)

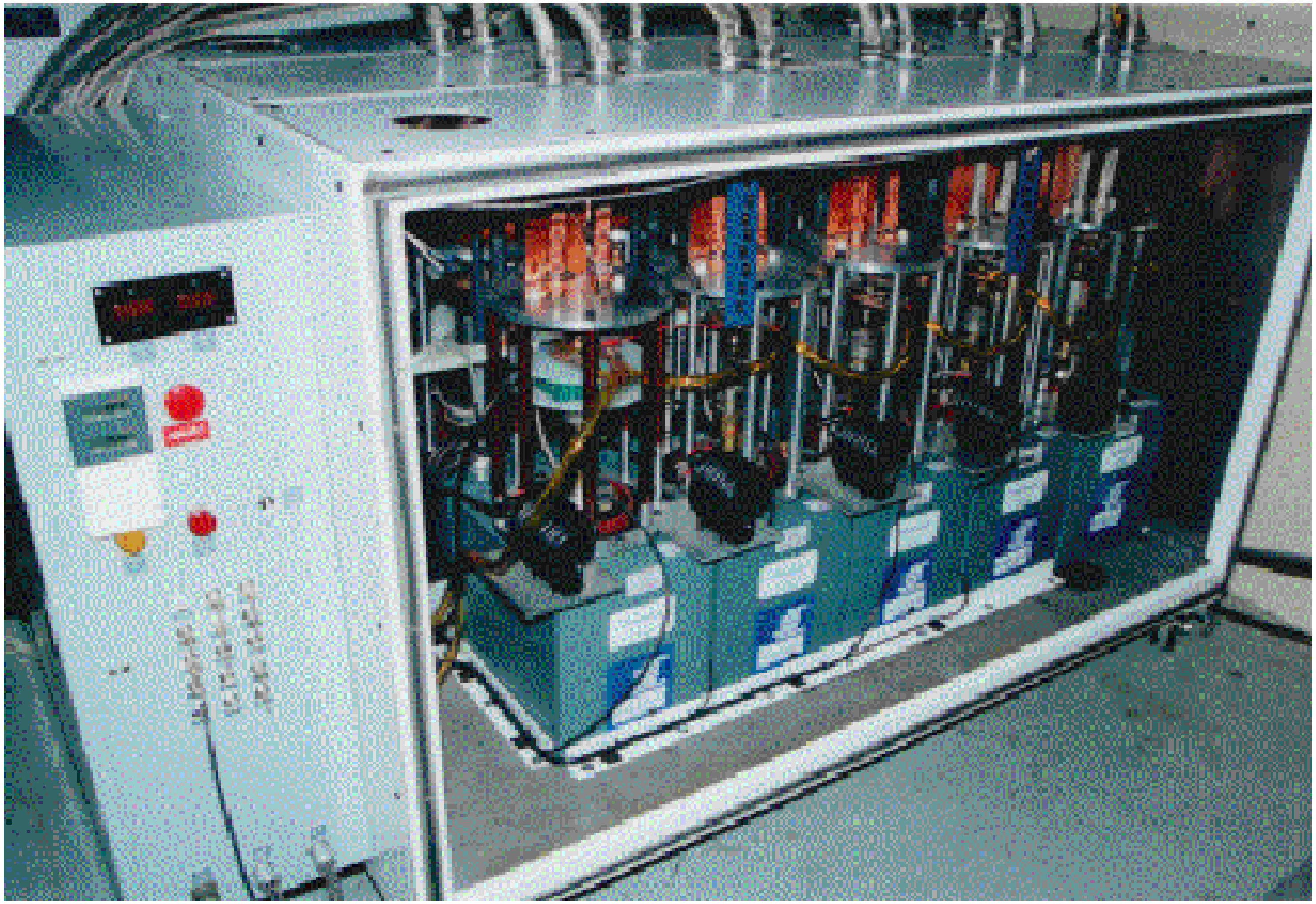
* Recent similar results on JFT-2M

Computational studies

The CTF-II injector

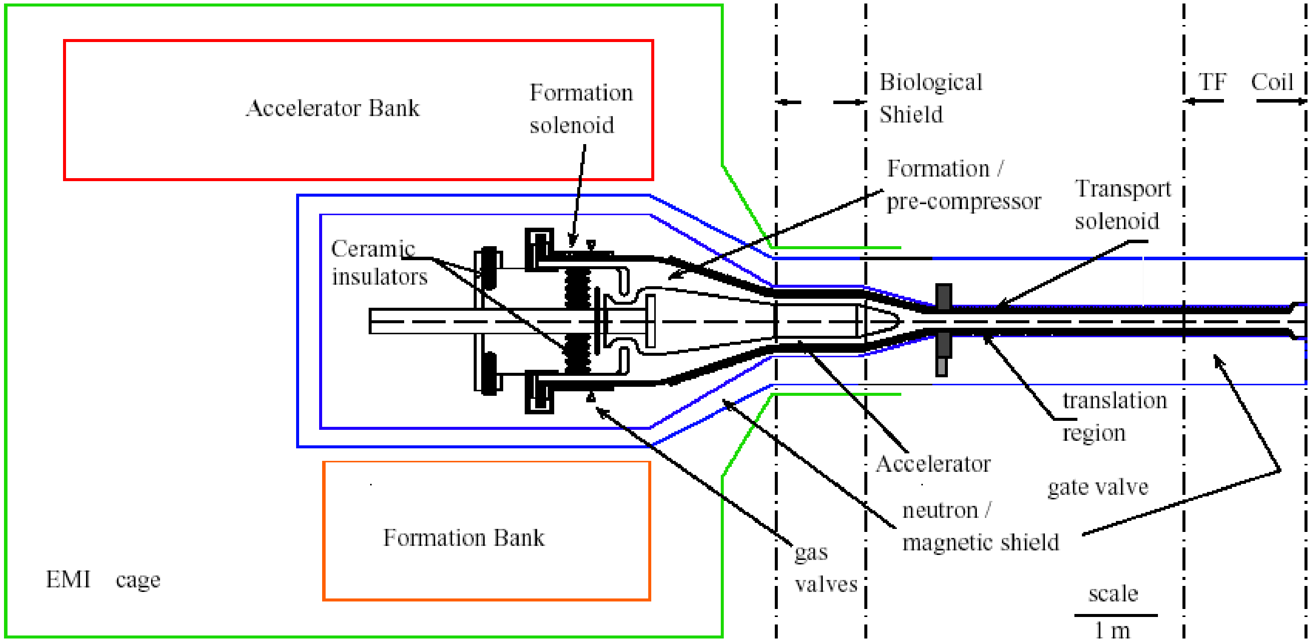


The CT Formation bank power supply (110VAC input)



Extrapolation to ITER

A CT injector could provide profile control capability for ITER



0.3% particle inventory perturbation, 20 Hz operation

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

ITER CT Injector parameters

Possible plan for CT fueling research

- Establish CT parameters for controlled deep fuelling (~2 yrs)
- Conduct expts. With rep-rate injector in high beta, high bootstrap fraction discharges
- Inject tangentially to demonstrate momentum injection

NSTX is an excellent candidate for CT fueling research

Simultaneous comparison of Pellet, Supersonic gas, Plasma jet, and CT injection is possible in NSTX

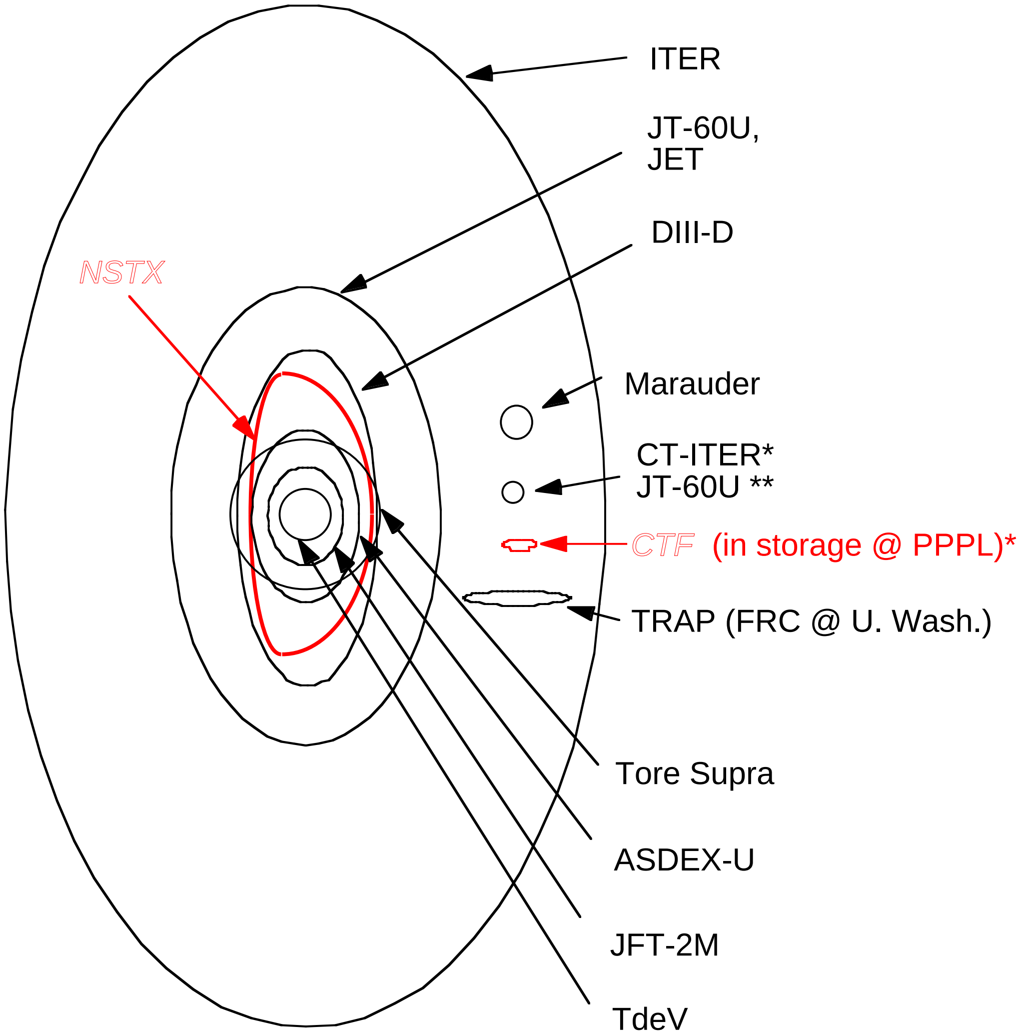
System	NSTX Operating Mode	Vel. (km/s)	Density (cm^{-3})	N_{inj}in 100ms	$N_{inj}/N_{ST\text{-}NSTX}$
Pellet ***(in 5yr plan)***	1 mm 2.7mm	~ 1 ~ 1	solid solid	5E19 1.0E21	7% [1] 140% [1]
Supersonic Nozzle(Fy04)	Mach 8	0.9to 2.4	5E17	2E20	28%* [2]
Plasma injector	plasma inj.	30	0.5to 1E16	0.5to 1E19	0.7to 1.4%[3]
CT ***(in 5yr plan)***	plasma inj. CT mode	50 300	0.5to 1E16 0.2to 1E16	0.5to 2E20 1 to 5E19	7 to 28%* 1.4 to 7%

[1] ORNL pellet calculator: http//www.ornl.gov/fed/pellet/Ornlpell.html

[2] V. Soukhanovskii's e-mail to R. Raman dated 5 Aug 2003

[3] Globus-M results: A.V. Voronin et al.,P-3.110 EPS 2003

Previous experiments too small to study localized core fueling



ITER

JT-60U,
JET

DIII-D

NSTX

Marauder

CT-ITER*
JT-60U **

CTF (in storage @ PPPL)*

TRAP (FRC @ U. Wash.)

Tore Supra

ASDEX-U

JFT-2M

TdeV

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

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
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

- Ignited reactors will not use NBI. Alpha power is isotropic ⇒No momentum injection
- In a high β, high f_{BS} reactor some auxiliary current drive that is needed, which leaves excellent density profile control as the method of choice to optimize reactor performance and to sustain transport barriers through momentum injection
- CTs could be used to fill the current hole with plasma density

Conclusions

- **Excellent density profile control will enable high bootstrap fraction, SS discharges to reach their highest potential**

- **A flexible fueling system for high performance discharges does not presently exist**
  - Inject momentum
  - Fill the current hole with plasma
  - Precise density profile control to optimize bootstrap current

- **Experimental and modeling effort will help understand improvements in performance that can be realized by a flexible fueling system**

- **NSTX fueling research involving supersonic gas injection, pellet injection, plasma jet injection and CT injection will facilitate an understanding of fueling optimization for ITER**