Fusion Research at the University of Saskatchewan - Tokamak and Dense Plasma Focus

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on behalf of

Plasma Physics Laboratory, University of Saskatchewan, Canada

***Supported by CRC, NSERC and Sylvia Fedoruk Center**

Part 1: STOR-M Tokamak Experiments

STOR-M Tokamak Research Program

Recent projects

- **Fuel Injecting**
  - **Compact torus (CT)**
  - **Repetitive CT injection**
- **Modification of Toroidal Flow Velocities in the STOR-M**
  - **Compact torus injection**
  - **Resonant Magnetic Perturbations (RMPs)**

Part 2: DPF U of S –I Experiments

DPF-U of S–I design and fabrication

- **Diagnostics**
  - **Faraday cup → ion beam detector**
  - **PIN diode → soft x-ray detector**
  - **Scintillator+ PMT → Hard x-ray measurement**

Ion beam energy and flux

Anomalous plasma resistance

Plasma heating and runaway charged particles

Part 1:

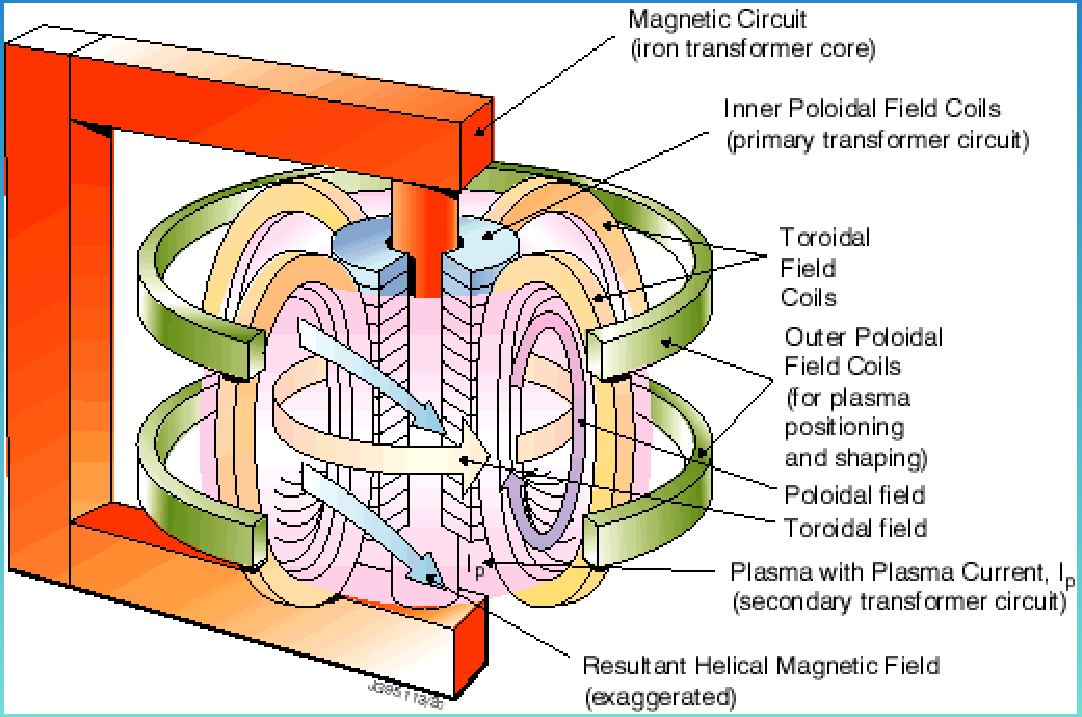
STOR-M Tokamak Experiments

Why Fusion?

- Resources
  - Depletion of the fossil fuel storage
  - Depletion of the fission fuel storage
- Environment
  - CO_2 emission must be reduced
  - Alternative energy resources (wind, solar, etc.)
- We need fusion energy
  - Abundant fuel supply
  - Low carbon footprints
  - Safe (Always subcritical, no runaways)

What is a tokamak?

- Bend solenoid to form closed magnetic field lines
- Drive plasma current
  - Heating
  - Help create helical field lines
- Vertical field for stability and shaping
- Additional heating (microwave, neutral beams, etc.)



Tokamak: Russian abbreviation for magnetic chamber

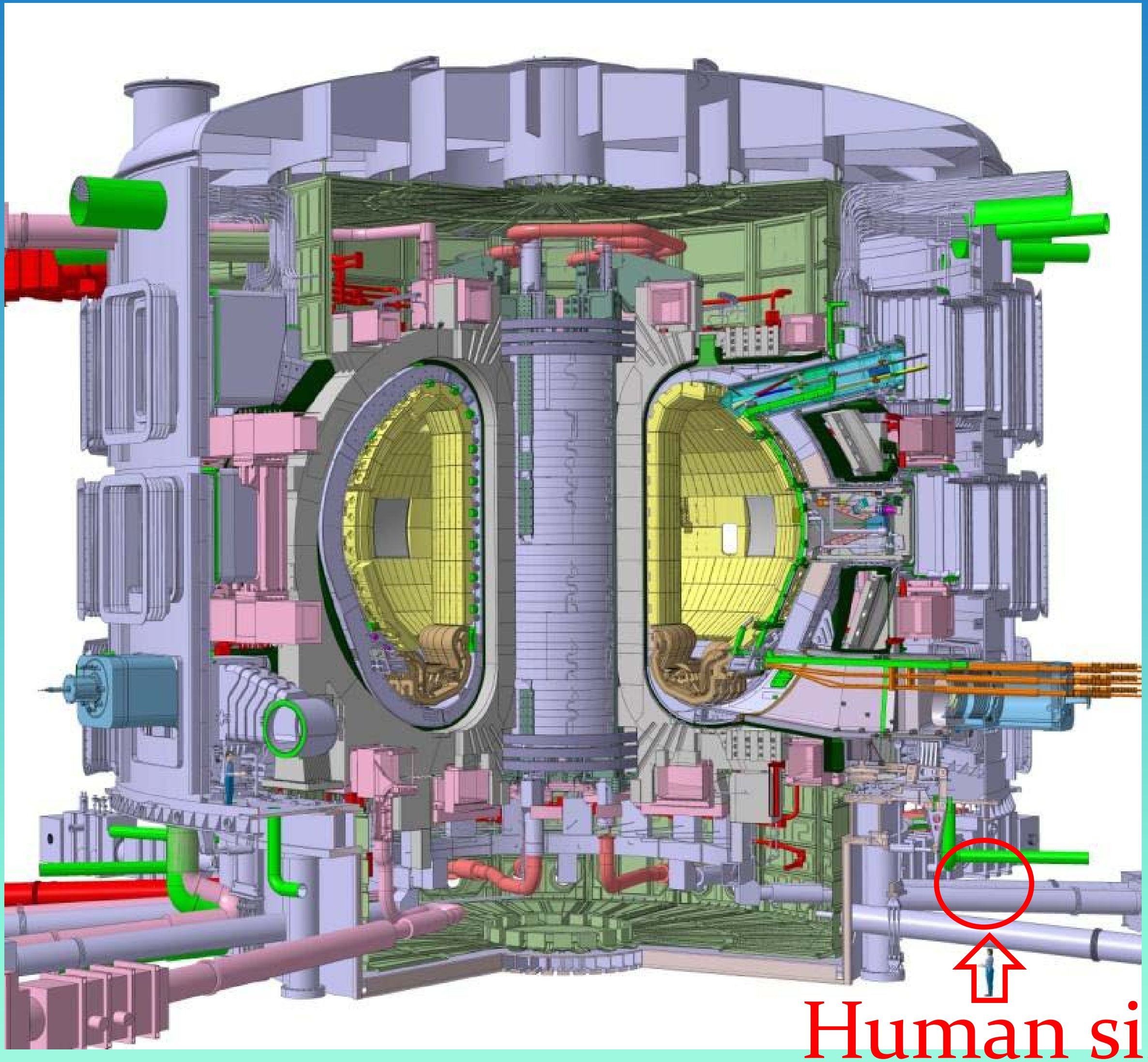
ITER Tokamak

- International Thermonuclear Experimental Reactor
- Largest tokamak in the world
- International collaboration with 7 partners
  - China, EU, India, Japan, Korea, Russia, USA
- Being built in Cadarache, France
- Will start operation in about 7 years
- Demonstrate net power gain

Q ≥ 10

ITER Tokamak

a = 2.0 m
R = 6.2 m
Q =10
P = 500 MW
73 MW heating



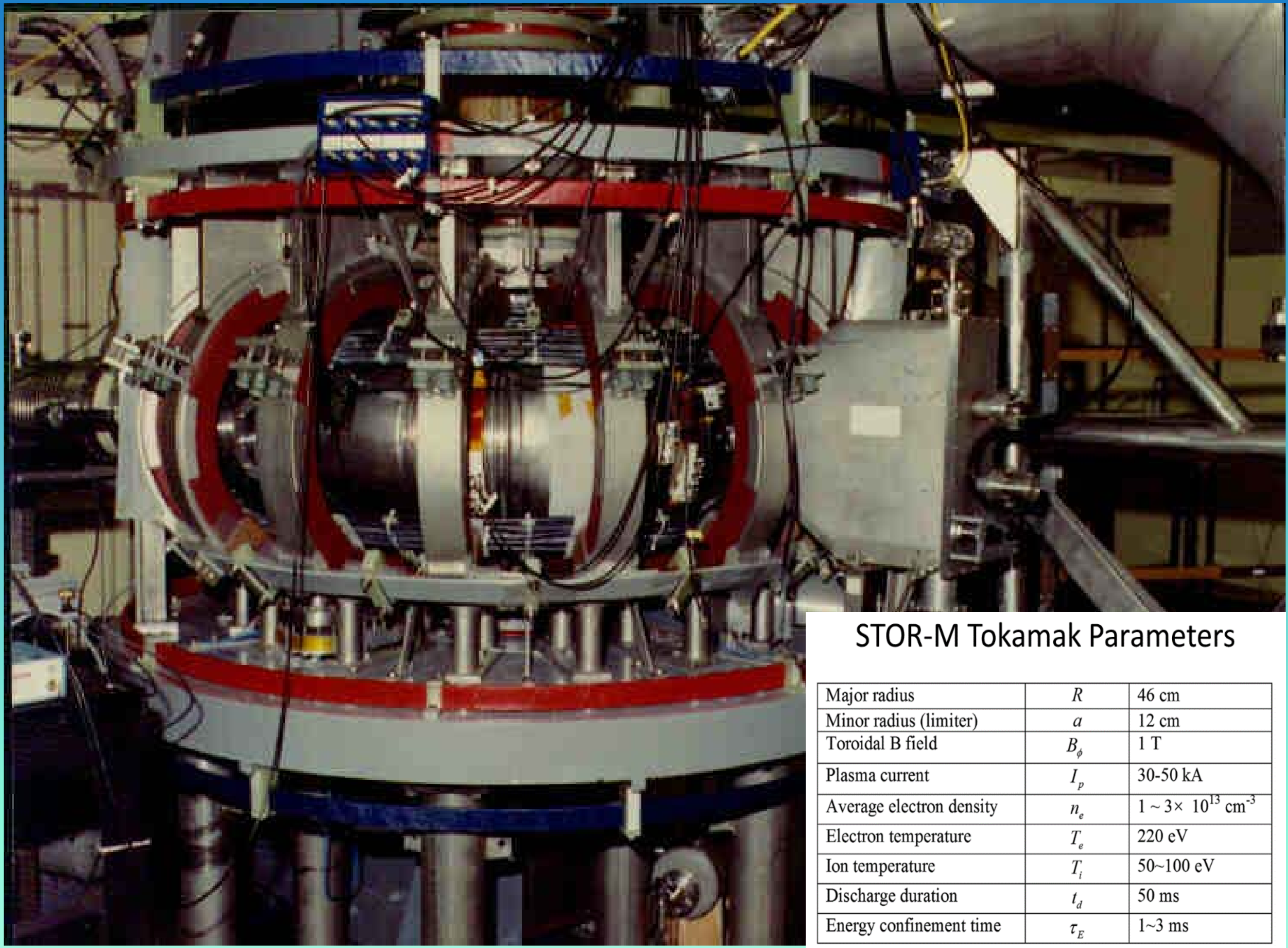
Plasma Physics Laboratory History

- Founded by Dr. Skarsgard in late 50’s
- First Canadian tokamak STOR-1M (early 80’s)
- STOR-M (built in 1987, still active)
- Compact torus injector added (90’s)
- Plasma processing (90’s)
- Dense Plasma Focus (2013)
- Both theoretical and experimental work

STOR-M Experiments

- Improved confinement induced by
  - Electrode/limiter biasing (early 1990's)
  - Turbulent heating
  - Compact torus injection
- Alternating Current operation (O. Mitarai)
  - First demonstrated on STOR-1M (a few kA plasma current)
  - Repeated on STOR-M (20 kA plasma current)
  - Repeated on JET (1 MA plasma current)
  - Repeated on HT-7 superconducting tokamak (quasi-steady state)
- Compact Torus Injector (mid 1990's until now)
- Resonant Magnetic perturbations (last few years)

STOR-M Tokamak Experiments



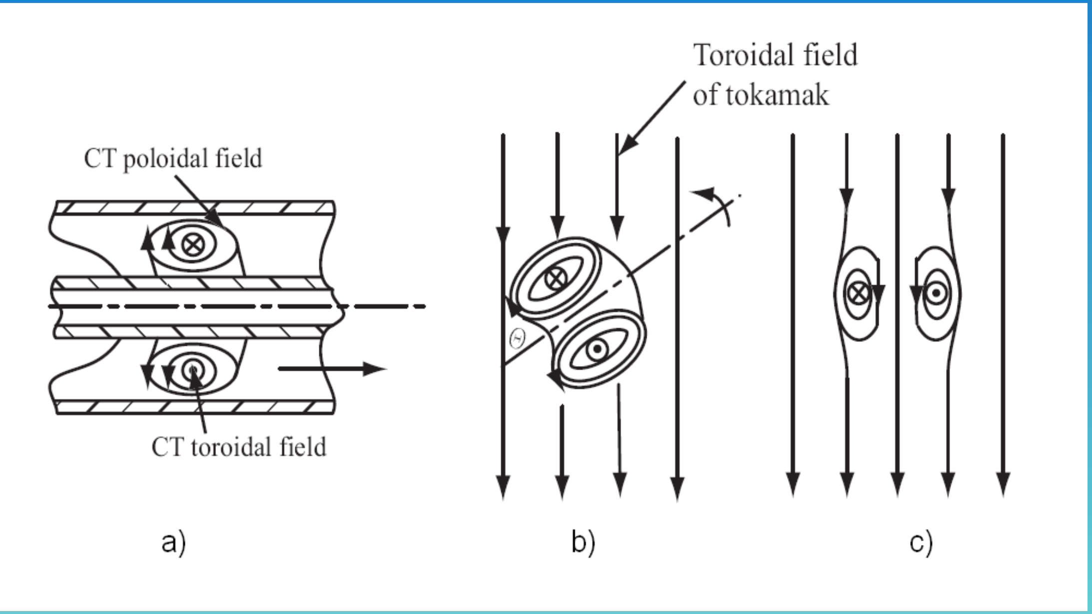
STOR-M Tokamak Parameters

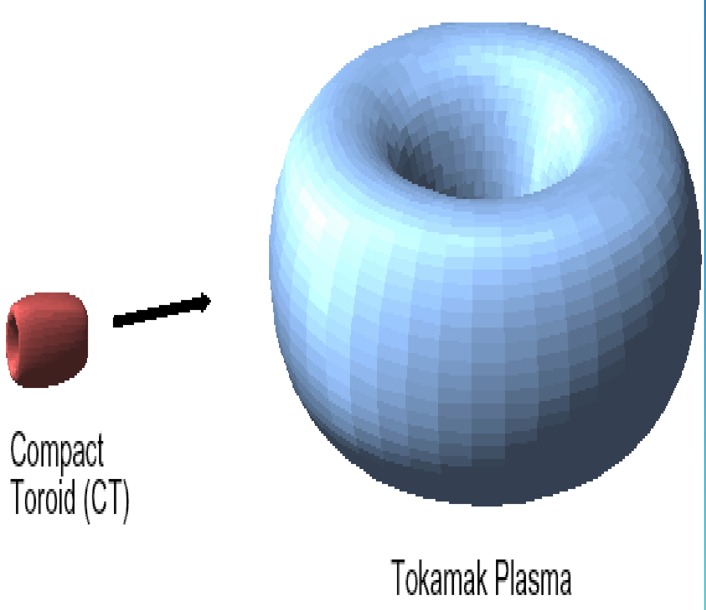
Major radius	R	46 cm
Minor radius (limiter)	a	12 cm
Toroidal B field	B_ϕ	1 T
Plasma current	I_p	30-50 kA
Average electron density	n_e	$1\sim3\times\ 10^{13}\ \mathrm{cm}^{-3}$
Electron temperature	T_e	220 eV
Ion temperature	T_i	50~100 eV
Discharge duration	t_d	50 ms
Energy confinement time	τ_E	1~3 ms

Fuel Injecting

- **Fueling**
  - **Current fueling technology is unable to directly fuel the reactor core.**
  - **Fuel recycling is complicated, also involving radioactive tritium**
- **Compact Torus (CT) Injection**
  - **Only candidate for deep fueling**
  - **Increase the burn rate**
  - **Momentum injection by tangential CT injection → Control flows (increase tolerance to error field)**

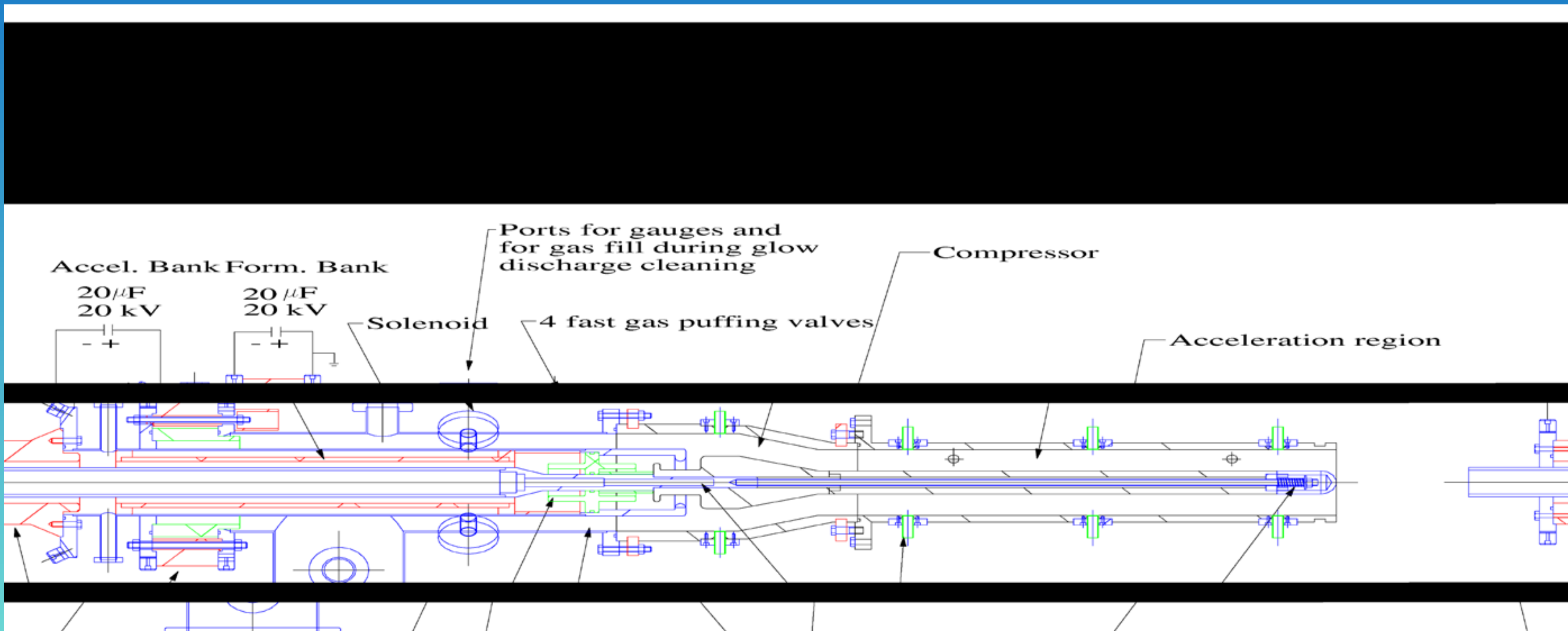
Compact Torus





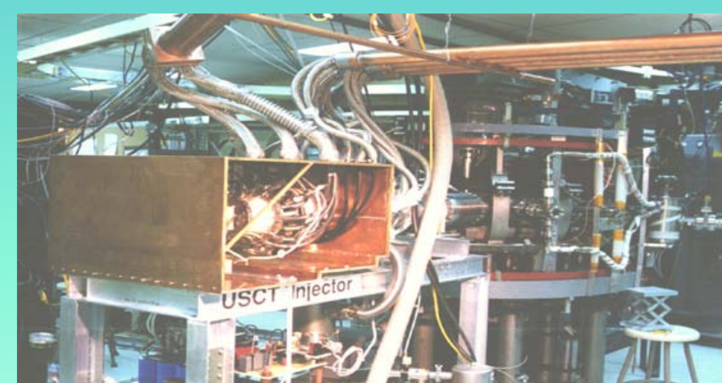
- **Magnetically confined robust plasmoid**
- **High in density, small in size**
- **Large acceleration, high velocity**
- **CT can be formed and accelerated in a coaxial gun**

CT layout



High voltage, high power, fast pulse discharges

- 25 kV, 20 μF banks
- Low inductance
- High current 150-220 kA
- 2.5 μs quarter cycle rising time



Penetration requirement

CT directional kinetic energy density must exceed the tokamak magnetic field energy density

$$\frac{1}{2} m_i n_{ct} v_{ct}^2 > \frac{B_{tok}^2}{2\mu_0}$$

n_{ct} : CT ion density
m_i : CT ion mass
v_{ct} : CT velocity
B_{tok} : tokamak toroidal magnetic field

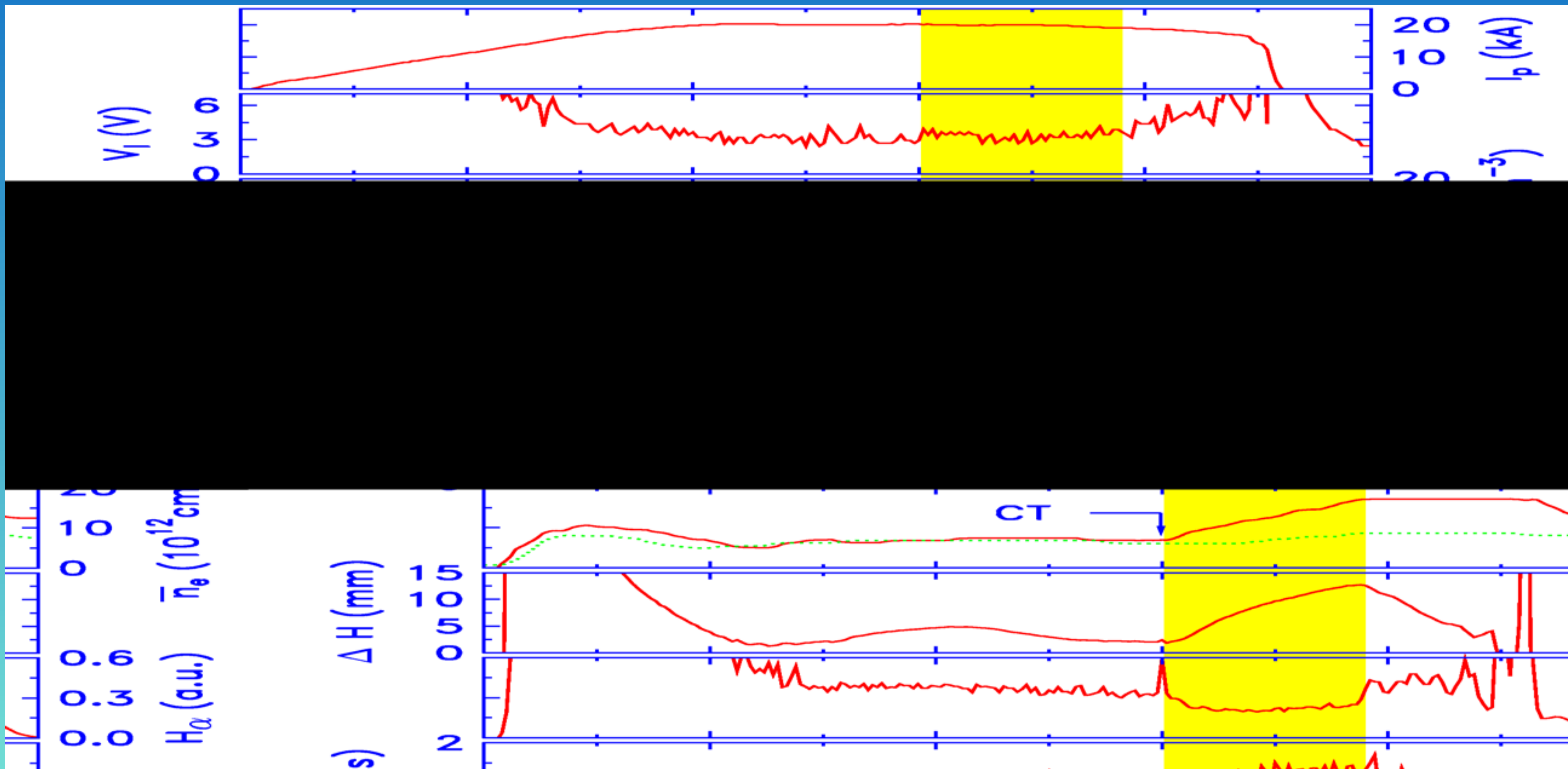
USCTI parameters:

$n_{ct} = 10^{15}\ \ \mathrm{cm}^{-3}$

$v_{ct} = 200\ \mathrm{km/sec}$

total mass $0.5\ \mu\mathrm{g}$

CT Induced Improved Confinement



- Density ↑
- H_α ↓
- MHD Fluctuations ↓
- Floating potential fluctuations ↓
- Energy confinement time ↑

Most clear signatures of improved confinement induced by CT injection

S. Sen, C. Xiao, A. Hirose, R.A. Cairns, PRL, 88, 185991, 2002

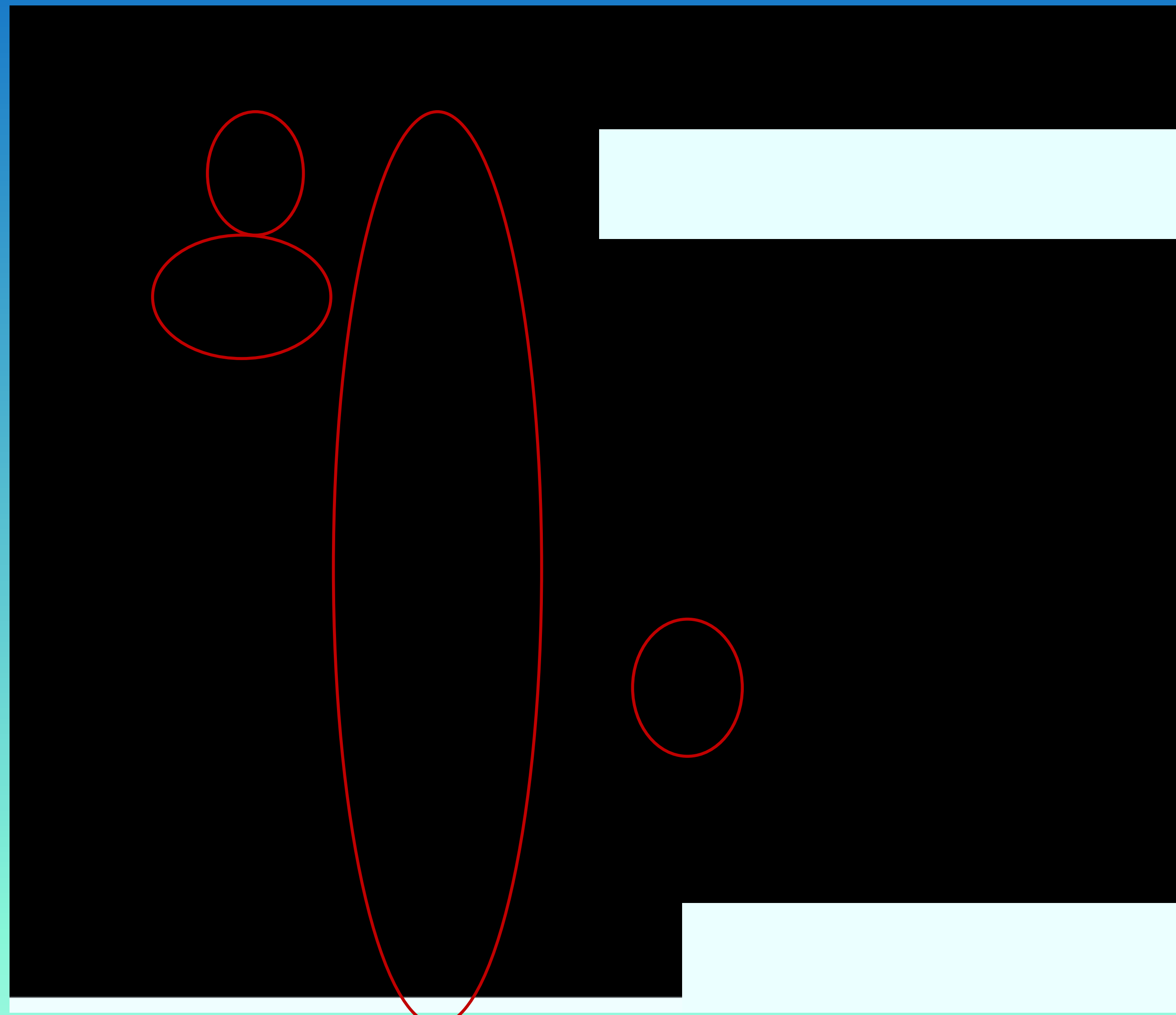
Repetitive CT operation

Storage Bank

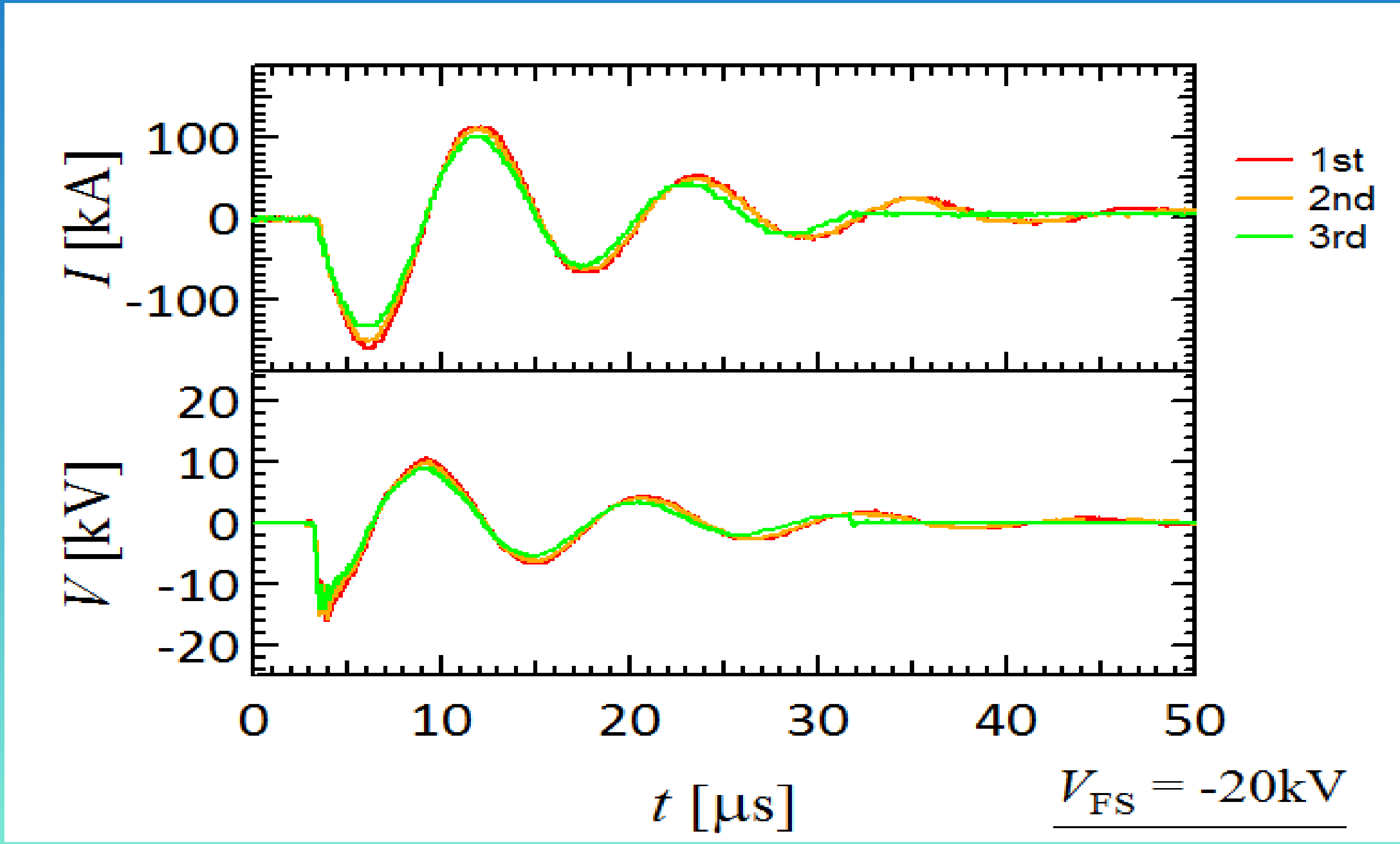
IGBT Stacks

Single Gate

Fast Bank



Discharge waveforms

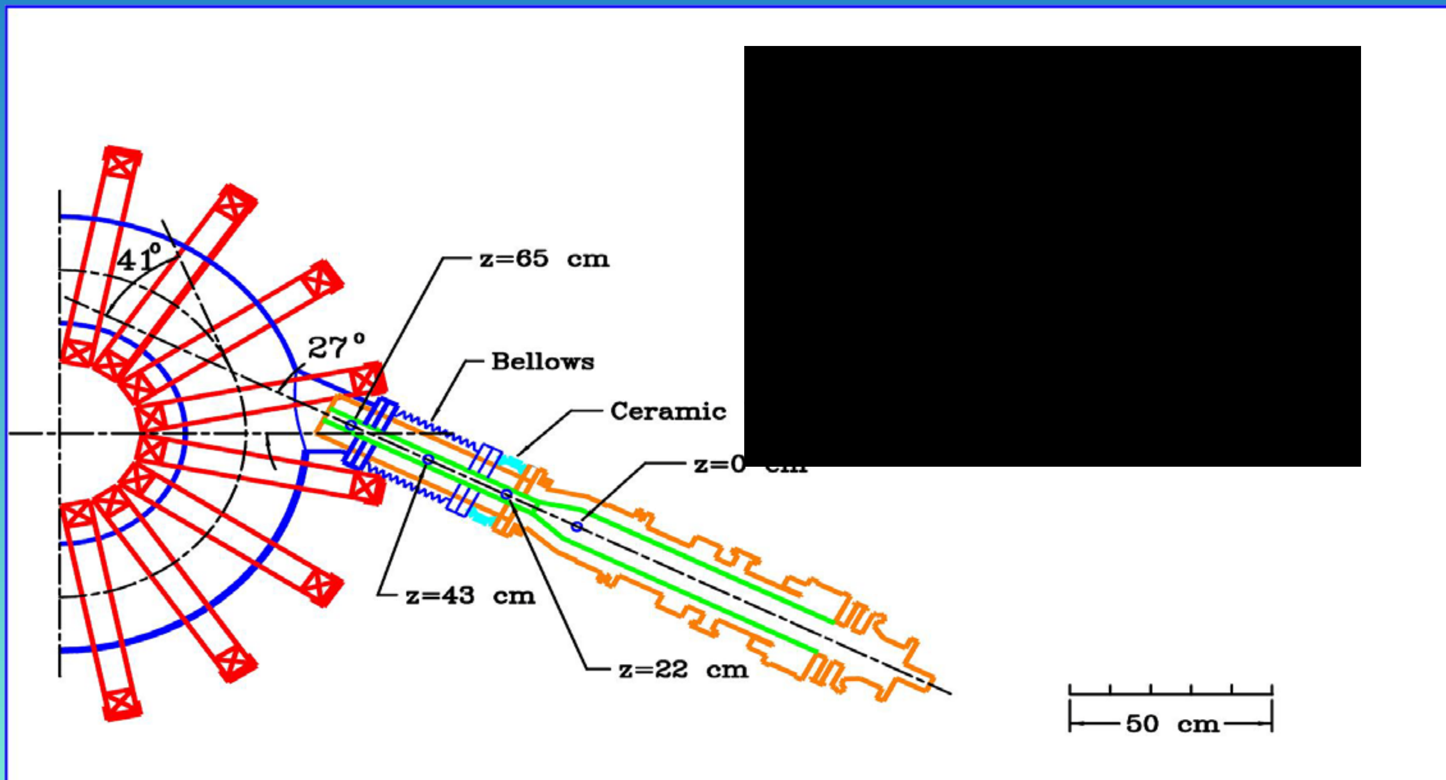


Record high repetitive rate of 10 Hz has been achieved!

Modification of toroidal flow velocities in the STOR-M Tokamak

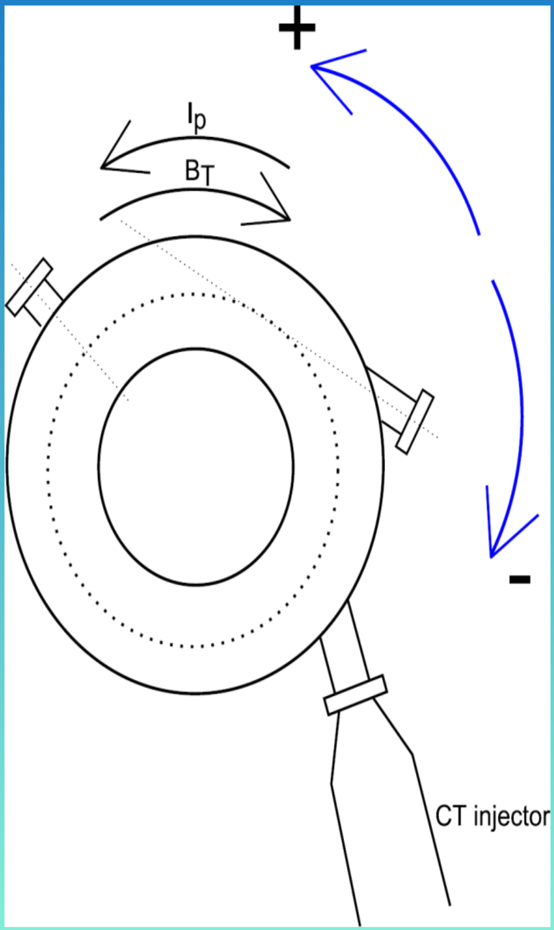
- **MHD instabilities (tearing mode or magnetic islands) interacts with the resistive wall or error field from coils**
- **If the plasma (or mode) does not rotate, those modes could be "locked' and grow quickly causing minor or major disruptions**
- **MHD instabilities degrade confinement**
- **Major disruptions in a fusion reactor → Huge thermal load on the first wall and Induces high voltage/current on coils and structures**

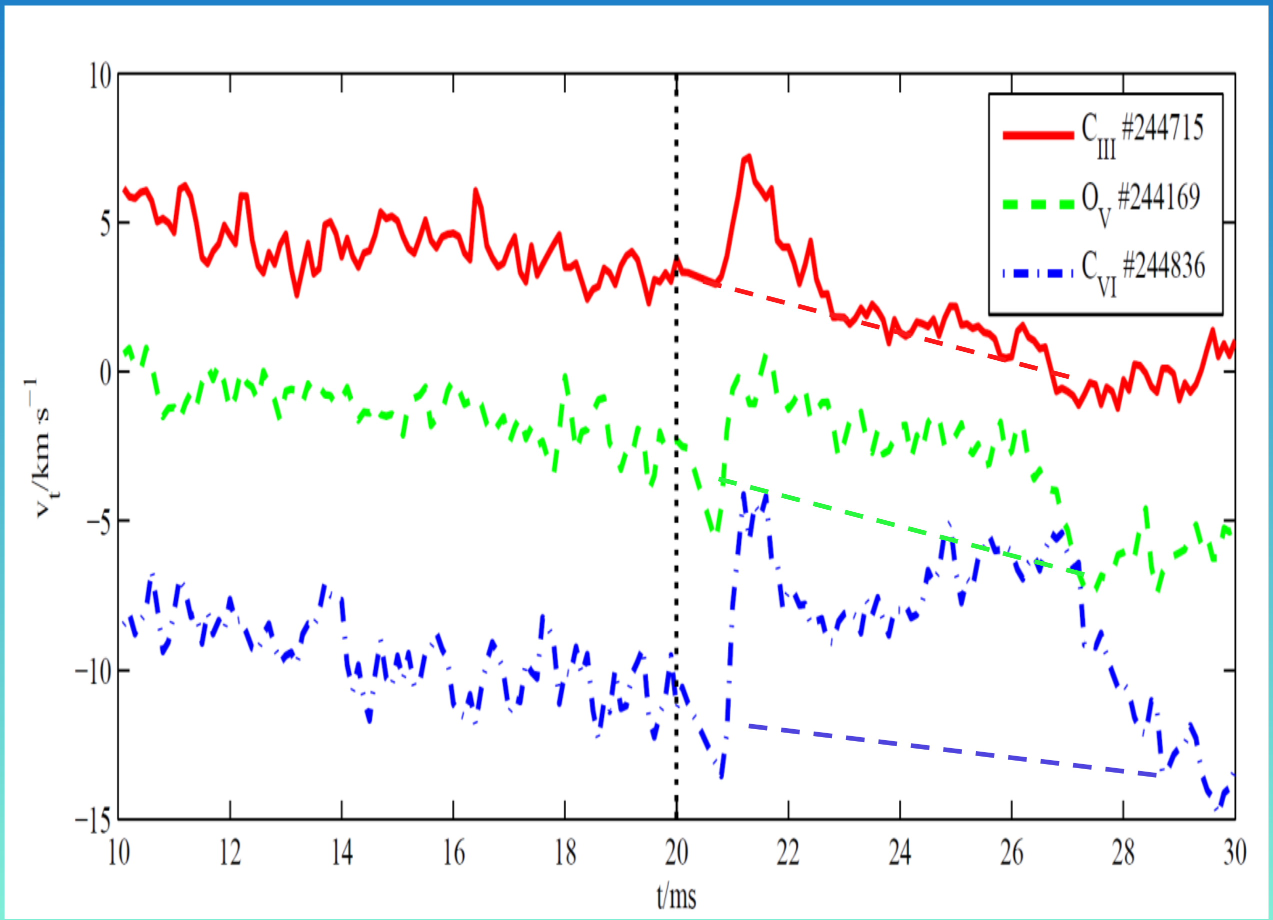
Tangential CT injection



Only Tangential CT injection experiment ever tested in the world

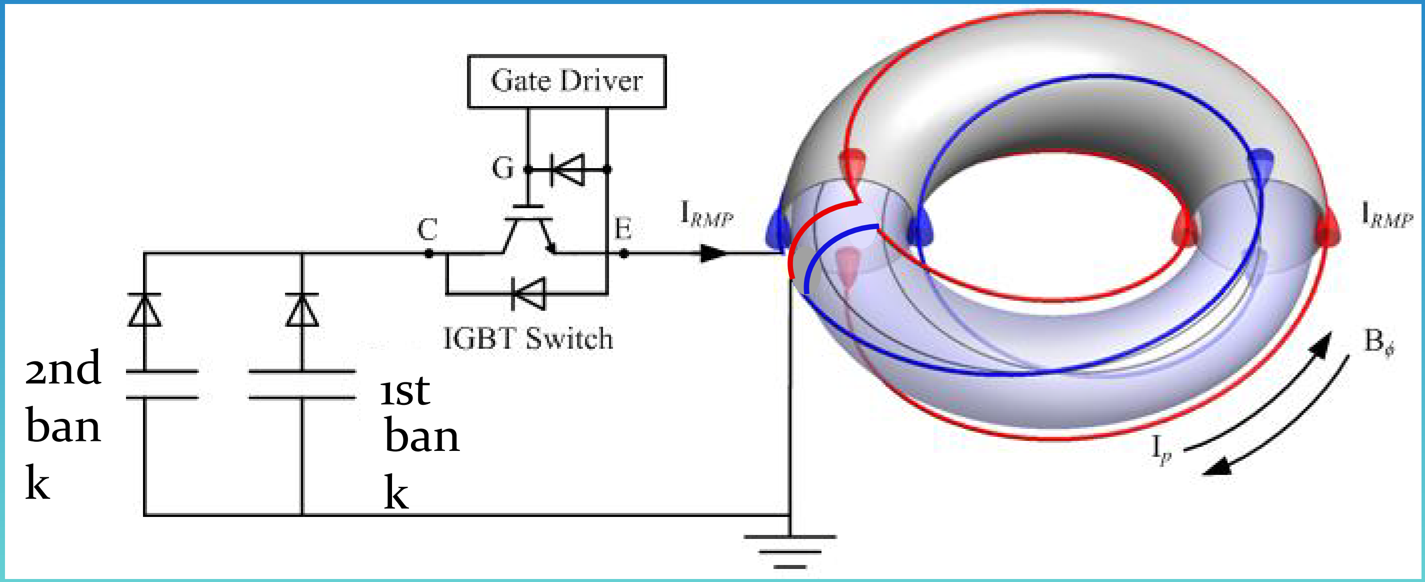
Flow modification by CT injection





First and only demonstration of momentum injection by CT injection

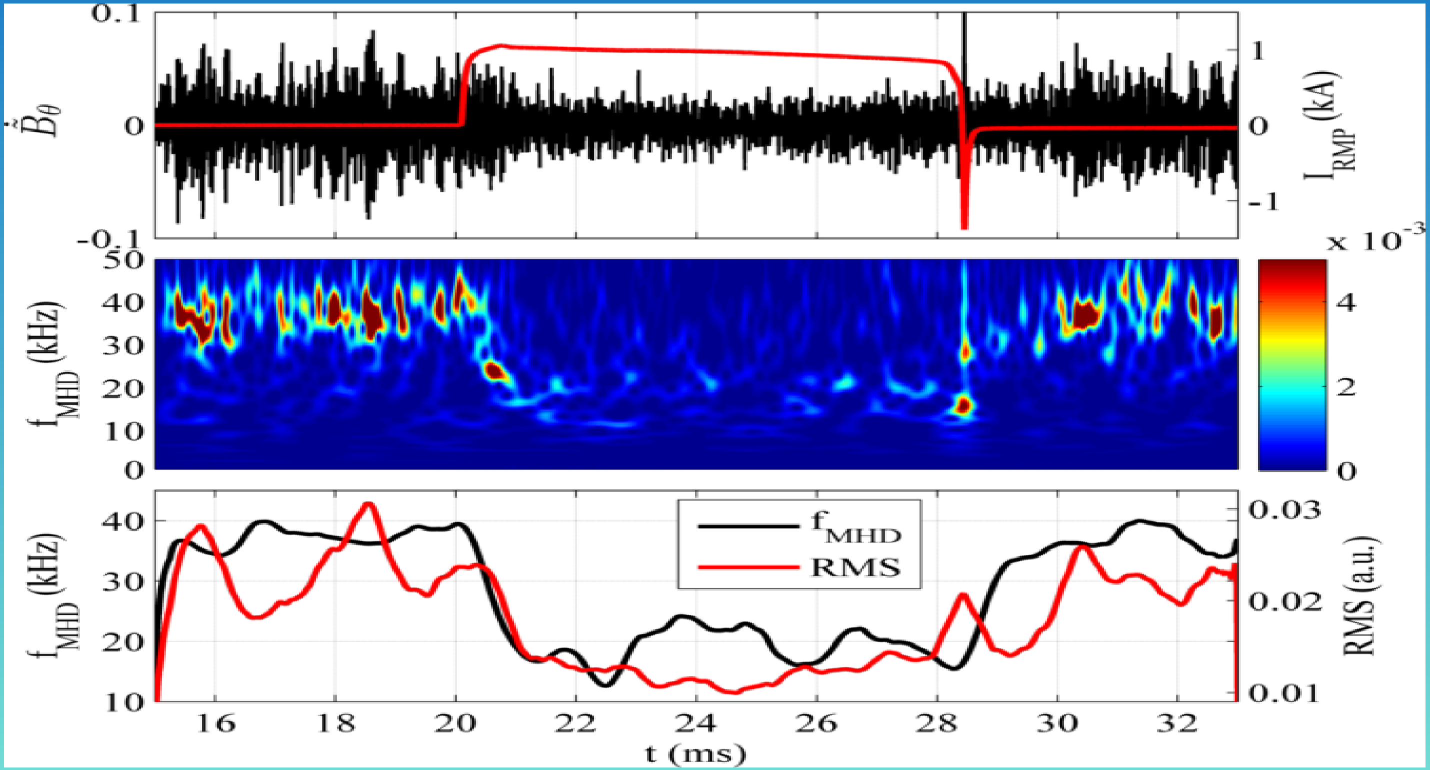
Experimental Setup -RMP



m/n=2/1 helical coils to suppress the dominant mode

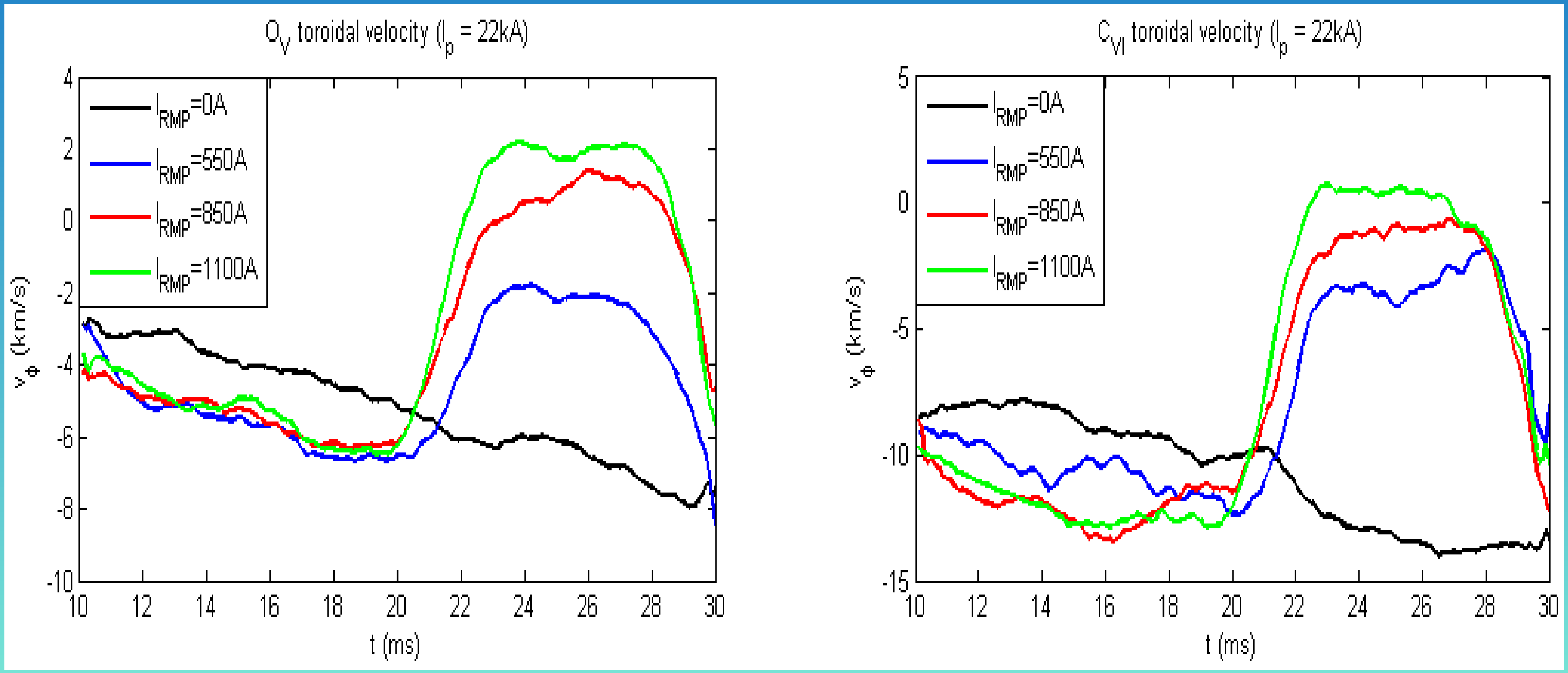
$$\tilde{B} = B_0 \exp\left[i\left(m\theta - n\varphi - \omega t \right) \right]$$

MHD frequency and amplitude



Results-Suppression

Modification of flow velocities by RMP

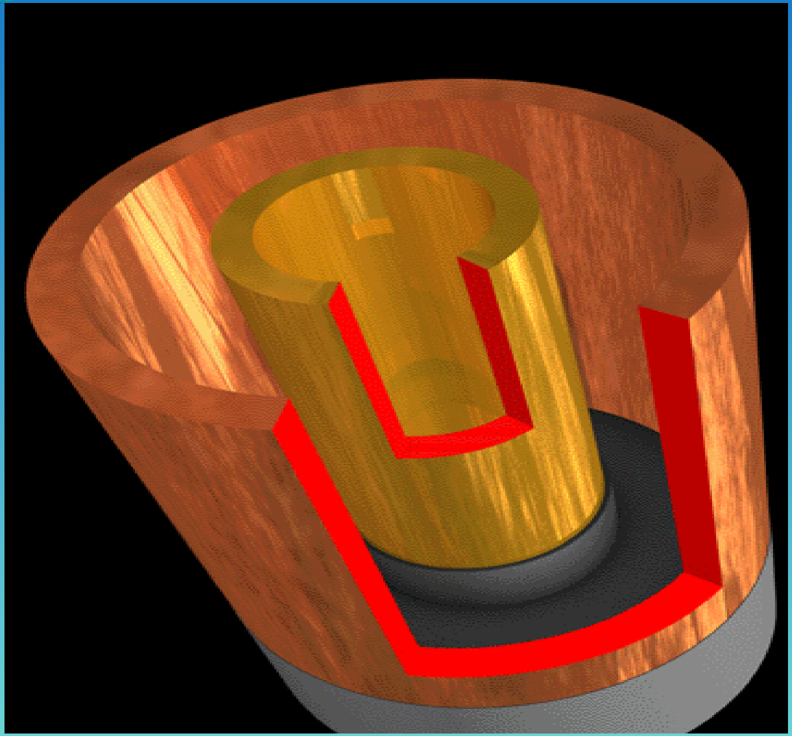


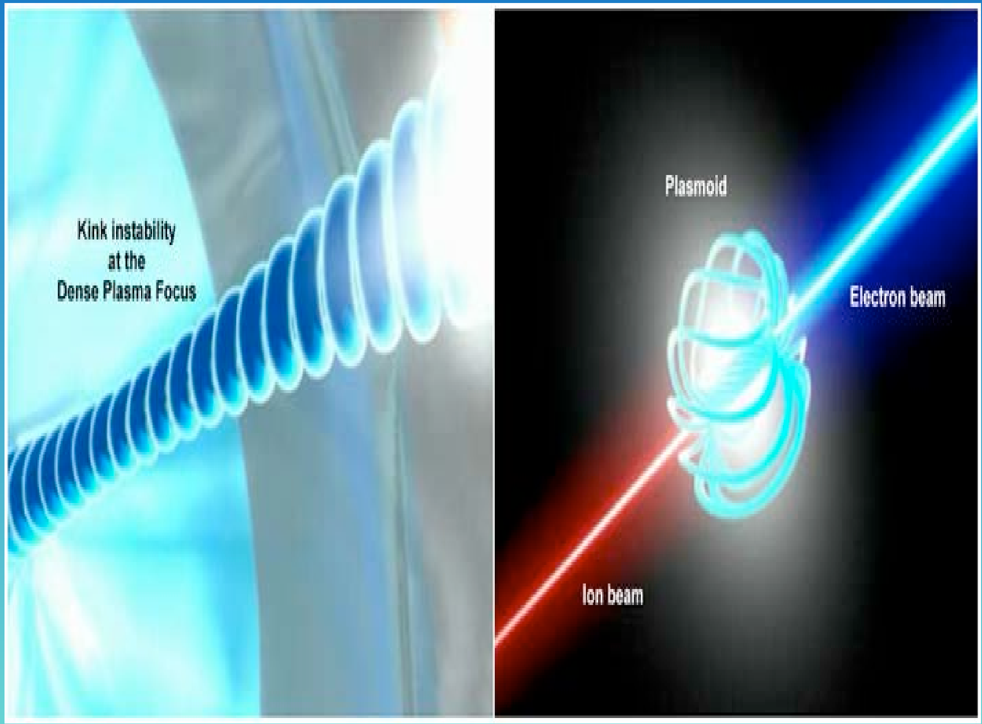
O_V and C_{VI} flow measurements at different RMP currents RMP was fired at 20ms for 8ms

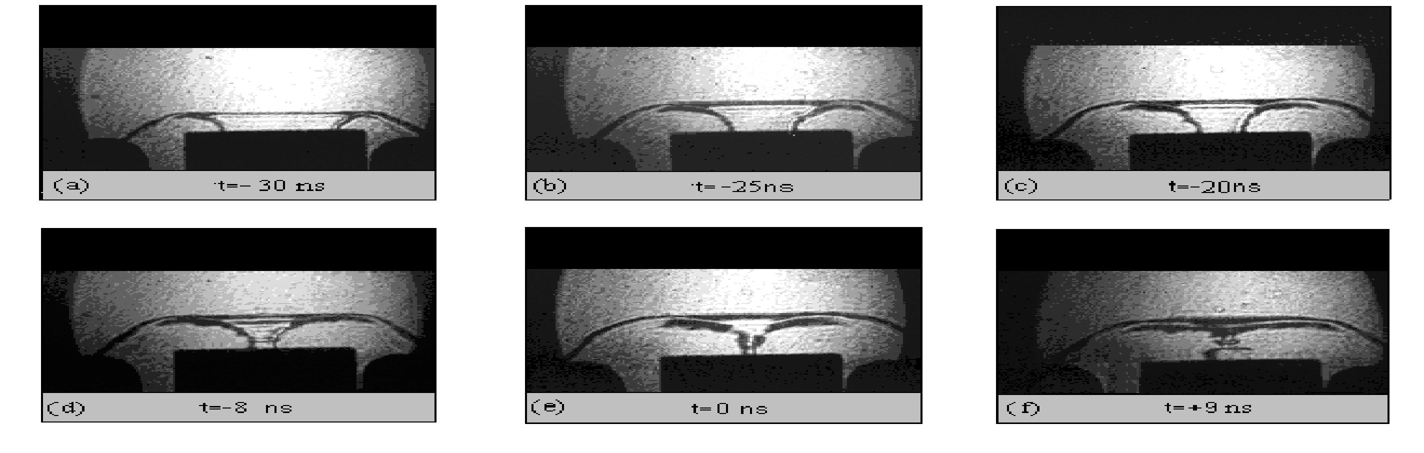
- **Co-current flow at SOL/edge (+ve, CCW)**
- **Counter-current flow at center (-ve, CW)**

Part 2:
DPF U of S–I Experiments

Dense plasma focus





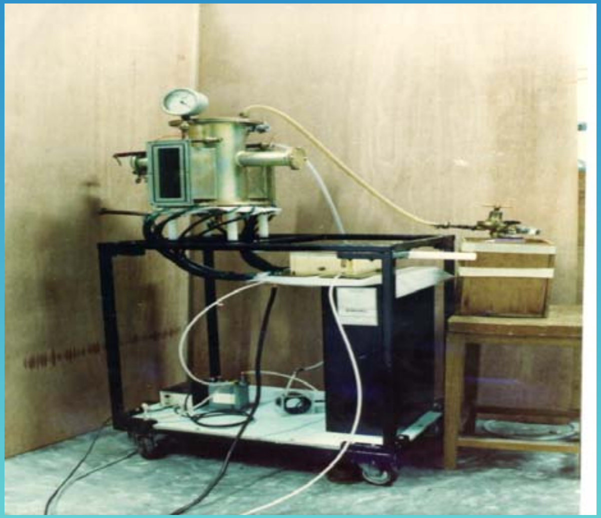


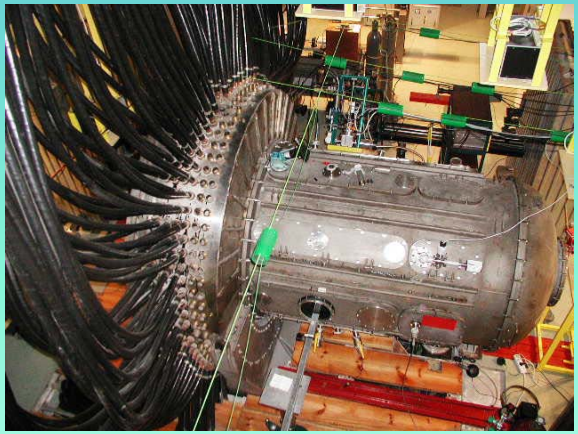
PLASMA FOCUS DEVICES (kJ-MJ)

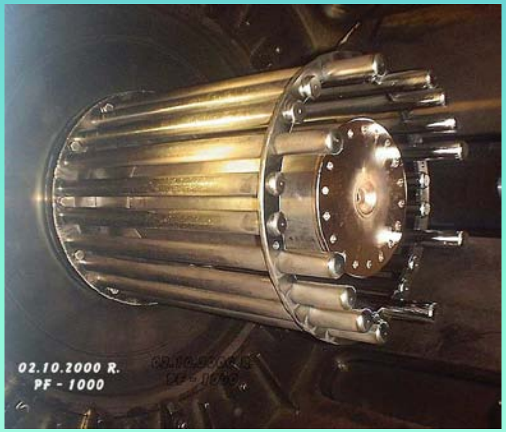
PF-1000, IPPLM, Warsaw

- **Charging voltage - U_0 = 20 - 40 kV**
- **Bank capacitance - C_0 = 1.332 mF**
- **Bank energy - E_0 = 266 - 1064 kJ**
- **Nominal inductance - L_0 = 15 7**

3 kJ Small Plasma Focus







Neutron yield scaling laws and neutron saturation problem

Early experiments show: $Y_n \sim E_o^2$

Prospect was raised in those early research years that, breakeven could be attained at several tens of MJ .

However quickly shown that as E_o approaches 1 MJ, a neutron saturation effect was observed; Y_n does not increase as much as expected, as E_o was progressively raised towards 1 MJ.

Fundamental reason for neutron saturation

constant dynamic resistance relative to decreasing generator impedance

IAEA Co-ordinated research program

IAEA Co-ordinated research project "Dense Magnetized Plasma"

8 countries: Poland, Russia, Italy, Singapore, China, Estonia, Romania, Republic of Korea

The main directions of applications developed are:

- **radiation material science;**
- **proton emission tomography;**
- **X-ray lithography;**
- **radiation enzymology;**
- **radiation medicine, etc;**

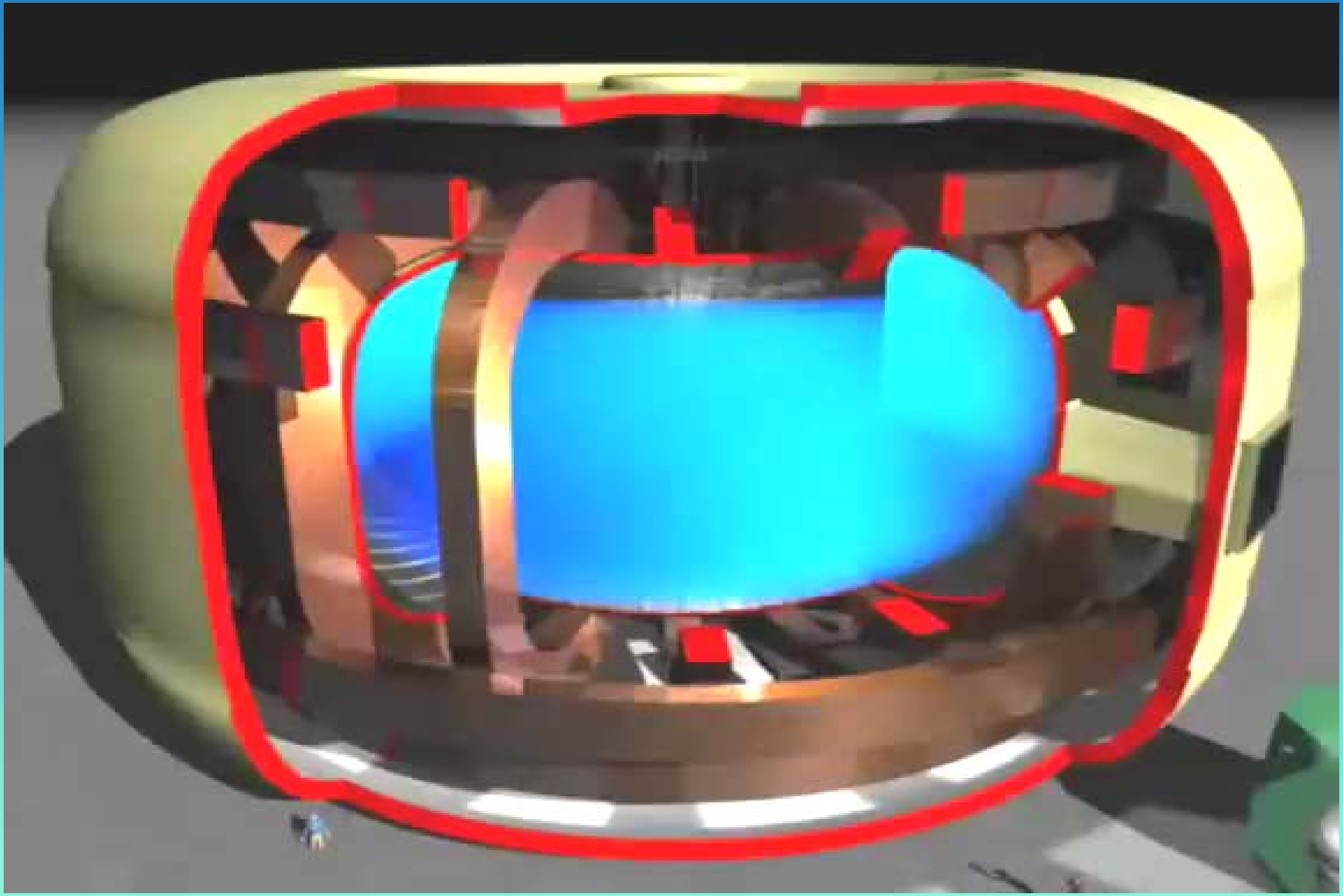
DPF device for Aneutronic Fusion

There are two main technical challenges to aneutronic fusion:

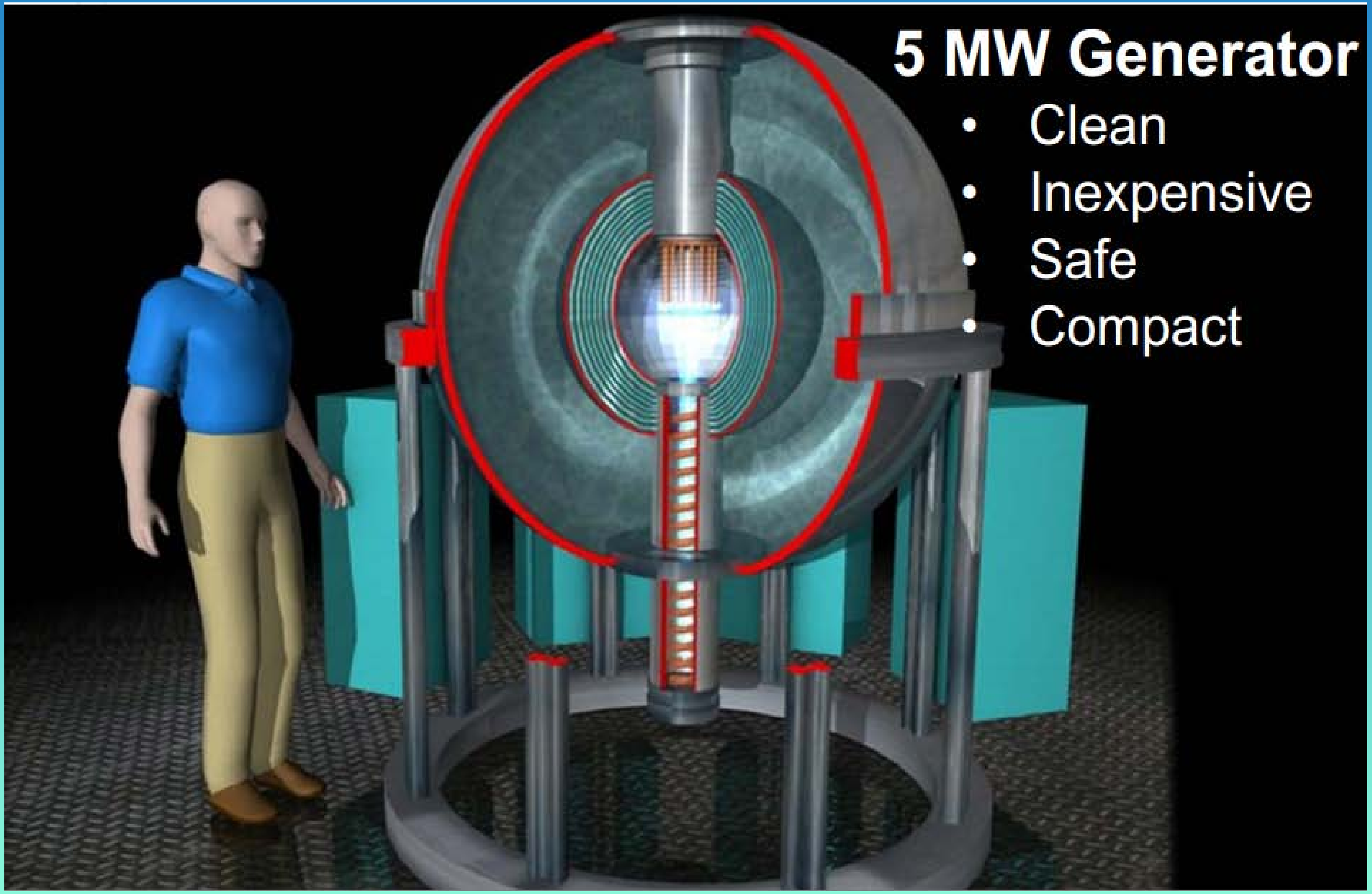
$$p + {}^{11}B \rightarrow 3\ {}^{4}He + 8.7\ MeV$$

- fusion ignition temperature is around 600 keV → Can be achieved by DPF
- Energy loss due to X-ray emission → Intriguing quantum mechanical effect

DPF device for Aneutronic Fusion



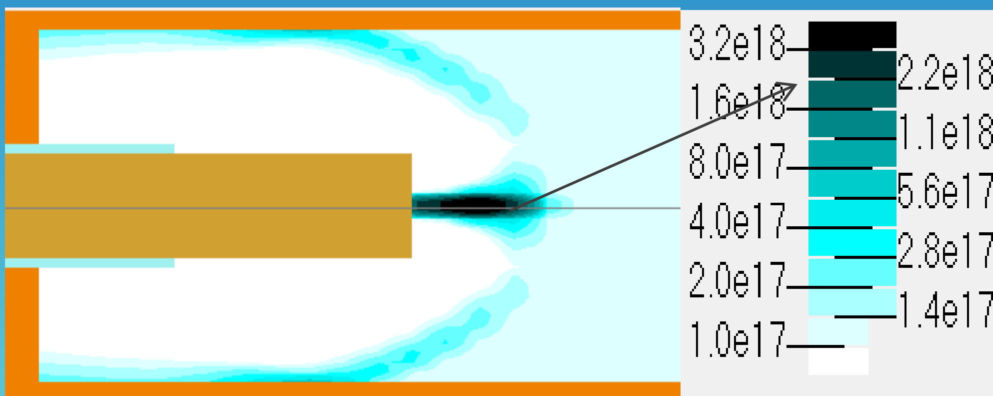
DPF power plant



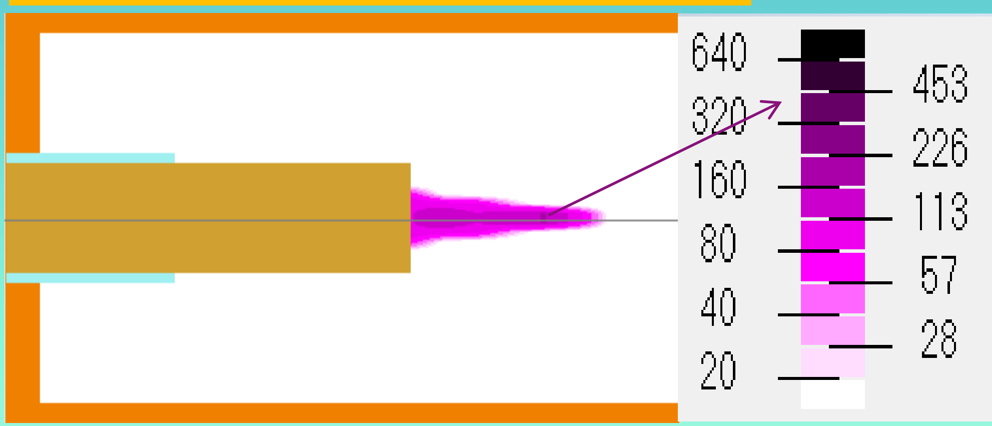
DPF U of S-I

Parameters of the 2 kJ DPF device DPF-UofS–I device

simulated plasma density (m^{-3})

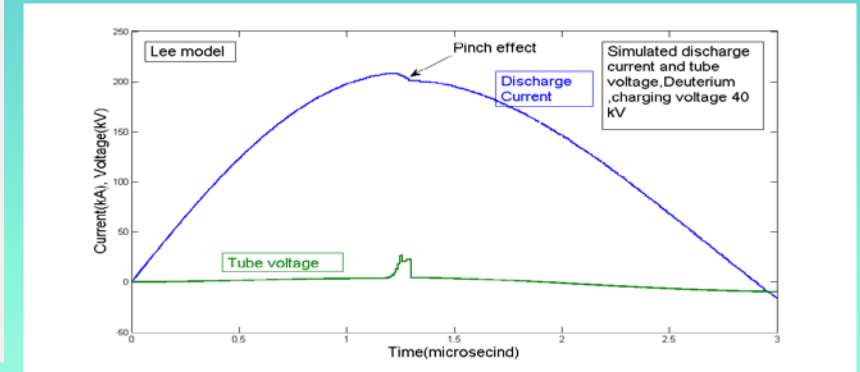


Simulated plasma temperature (eV)



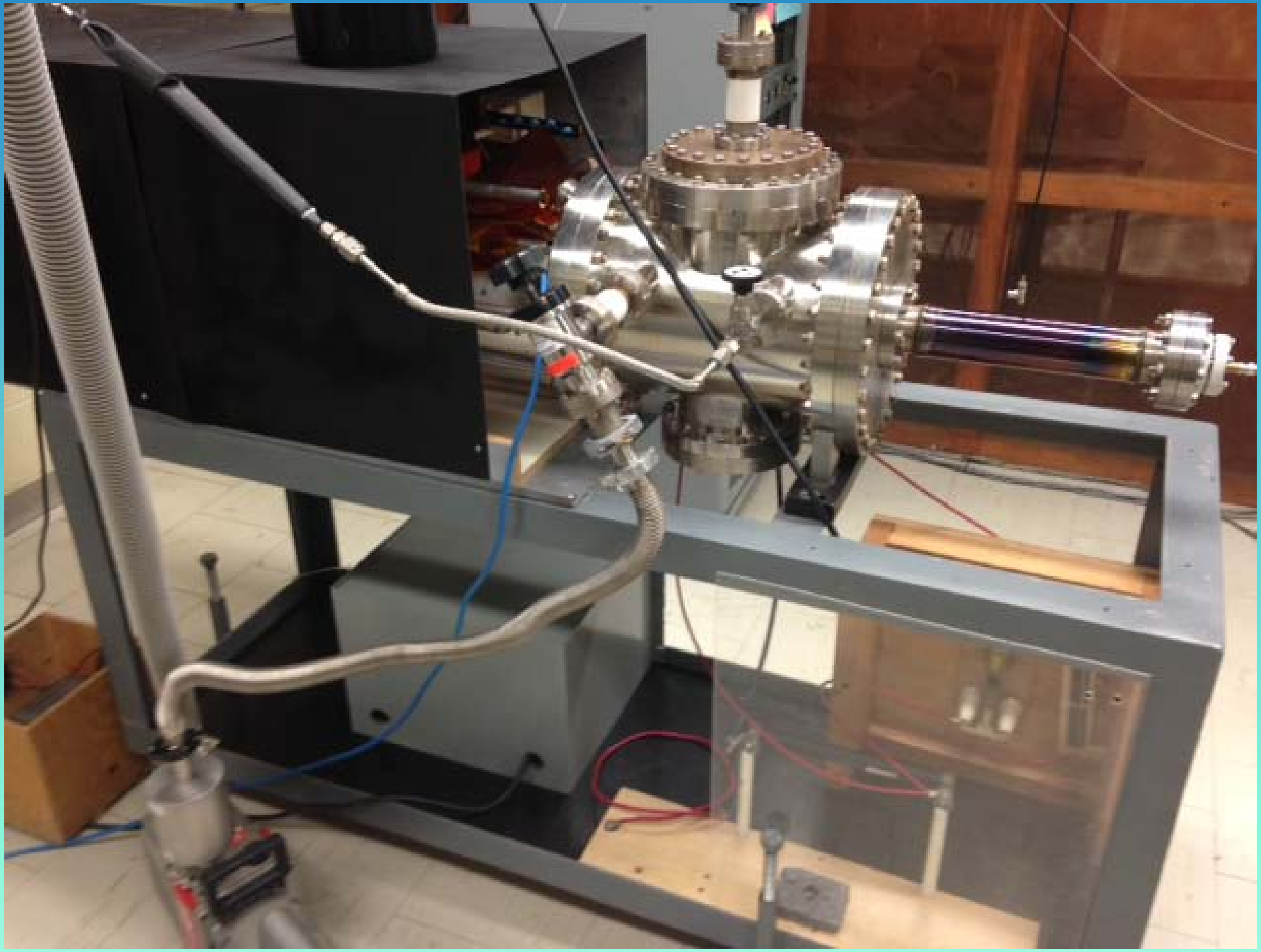
V.V. Vikhrev model, AIP Conference Proceedings 01/2006; 808(1):354-357. DOI: 10.1063/1.2159388

- **Capacitance = 5 microfarad**
- **Statics Inductance = 160 nH**
- **Charging Voltage = < 30kV**
- **Electrode Material = Copper**
- **Anode Radius = 15 mm**
- **Cathode Radius = 40 mm**
- **Insulator Material = Quartz**
- **Insulator Length = 30 mm**

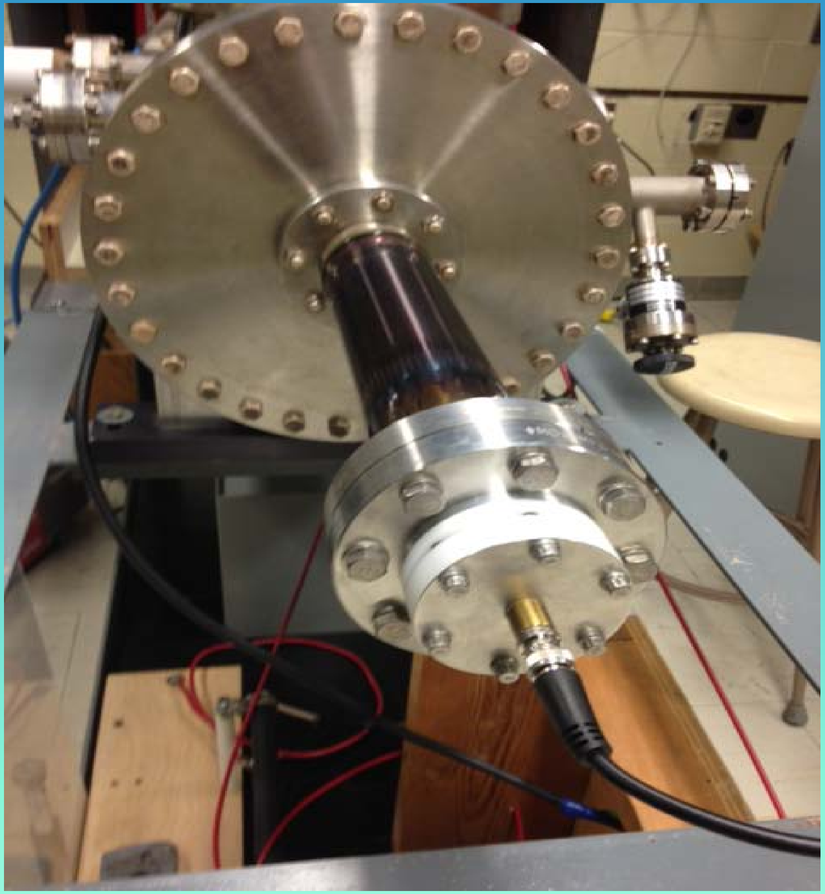


S. Lee, Radiative Dense Plasma Focus Computation Package: ADPF,http://www.plasmafocus.net; http://www.intimal.edu.my/school/fas/UFLF/

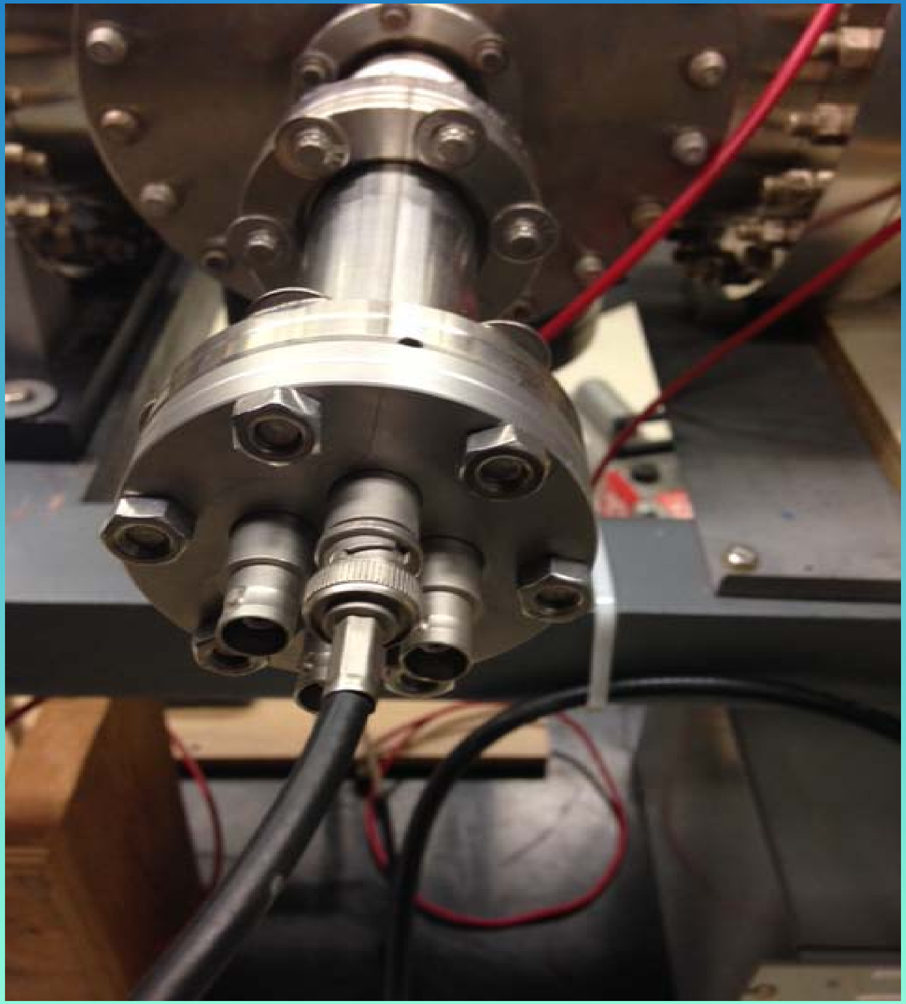
DPF-U of S–I



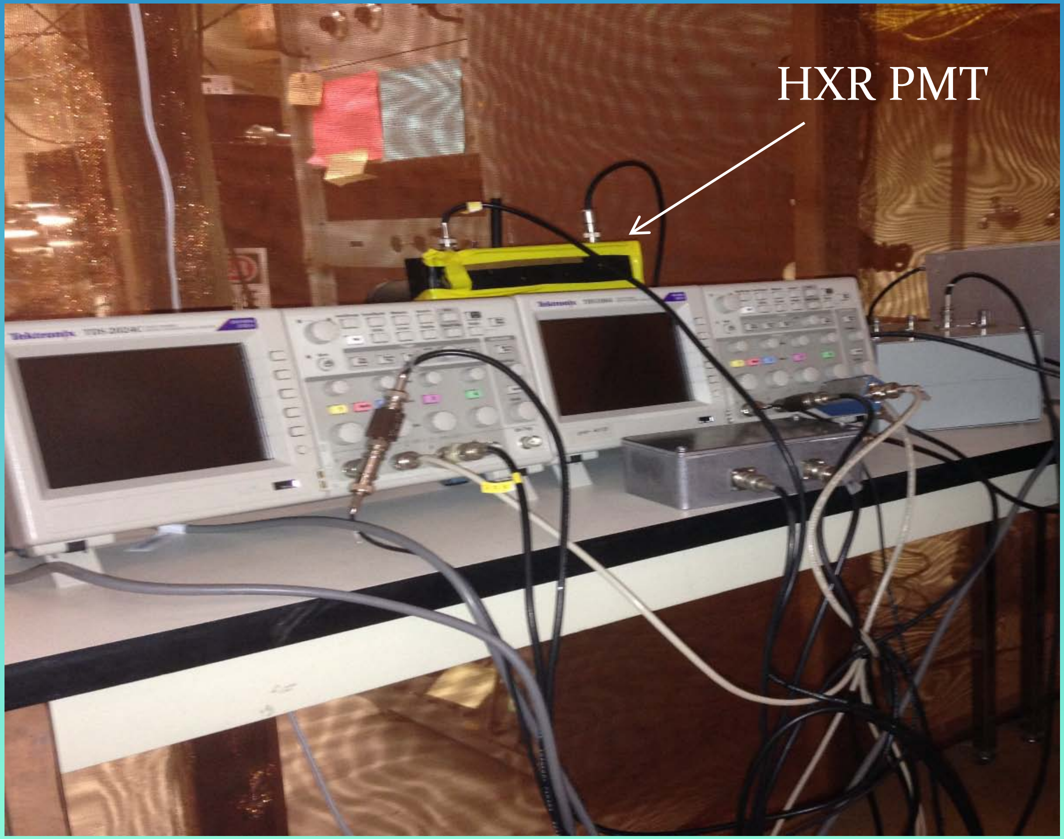
Faraday cup → ion beam detector



PIN diodes → soft x-ray detectors

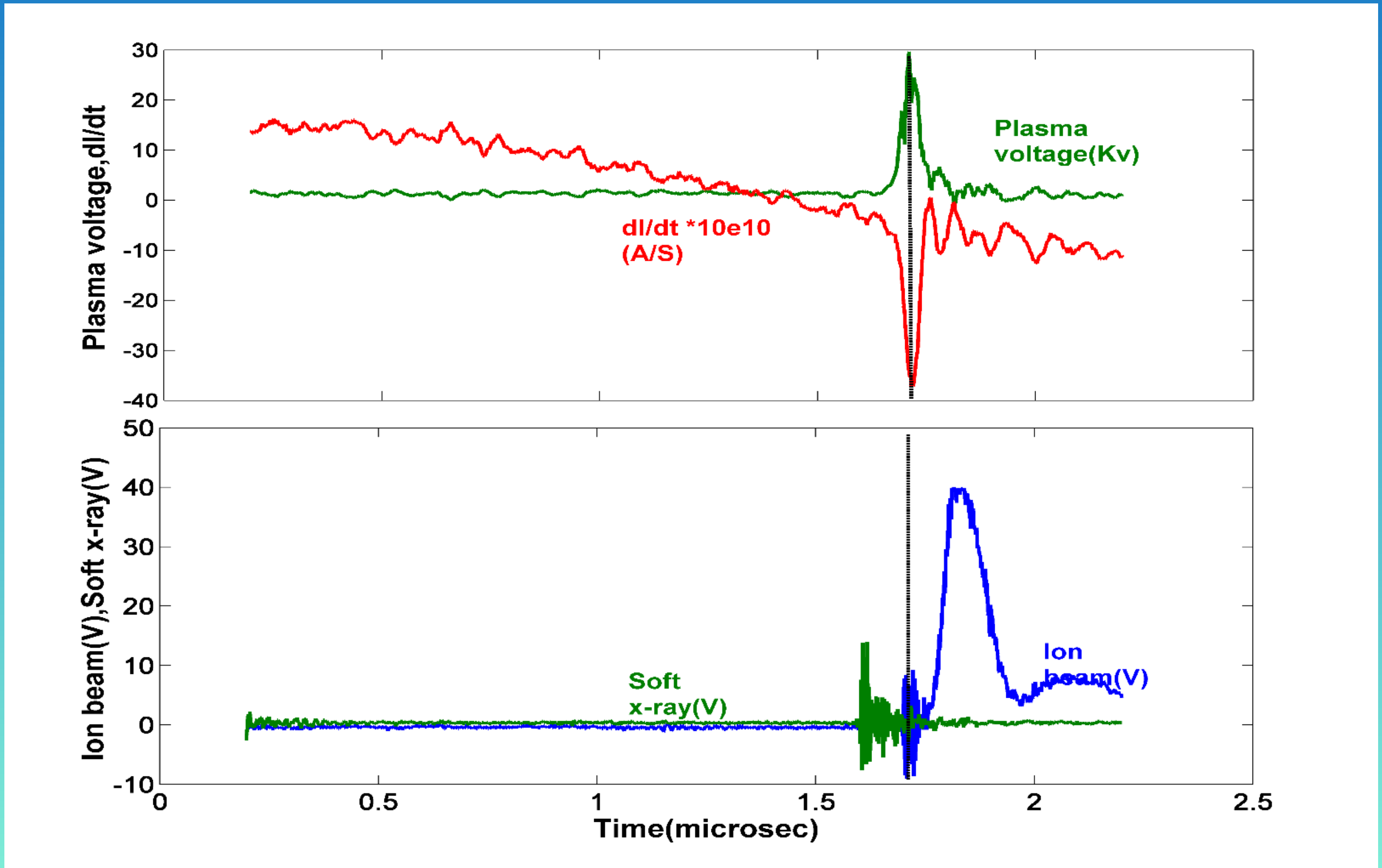


Faraday cage, HXR and oscilloscope



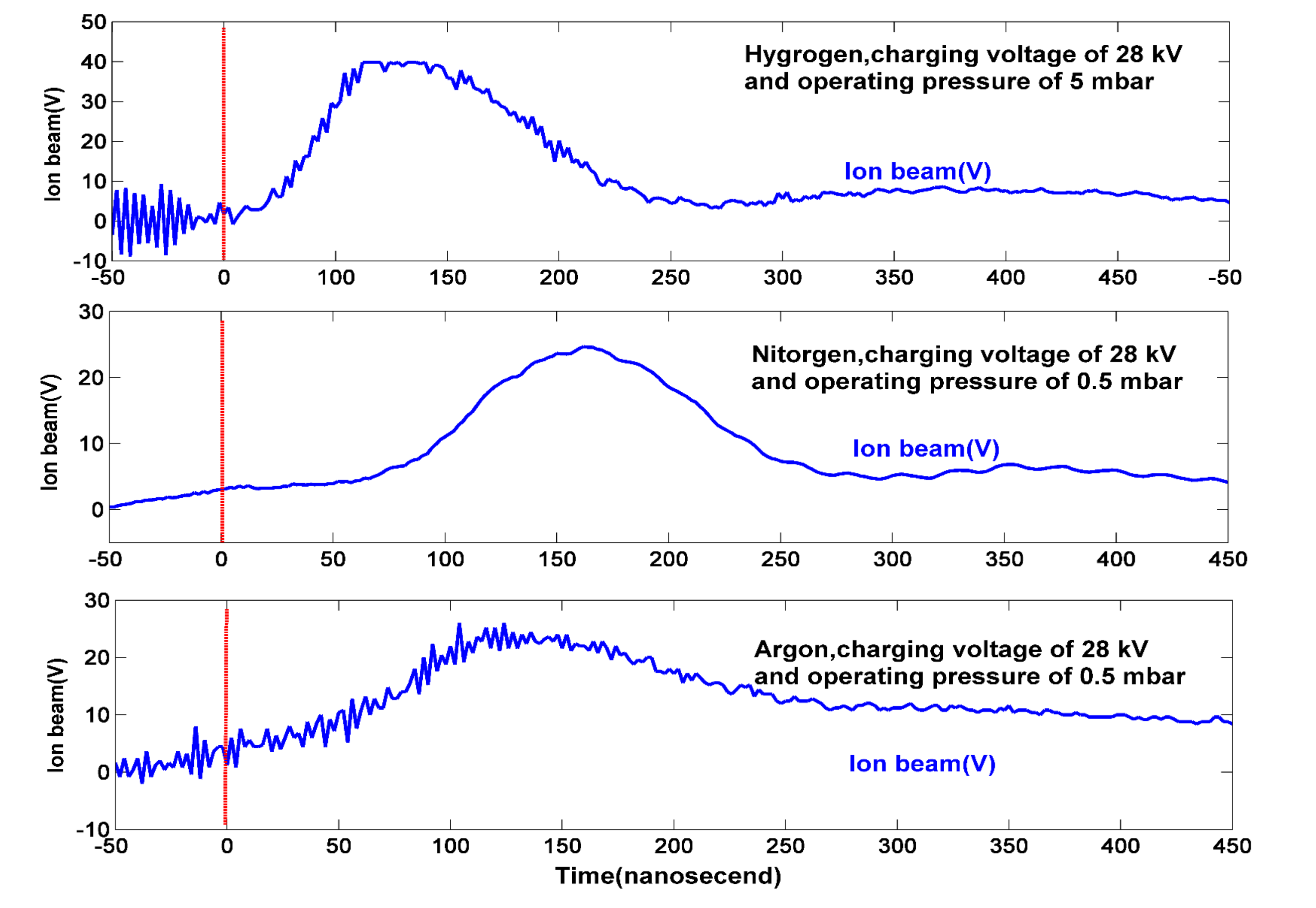
Ion beam emission from low-Z and high-Z DPF plasmas

plasma voltage, dI/dt , ion beam and soft x-ray signals Hydrogen gas

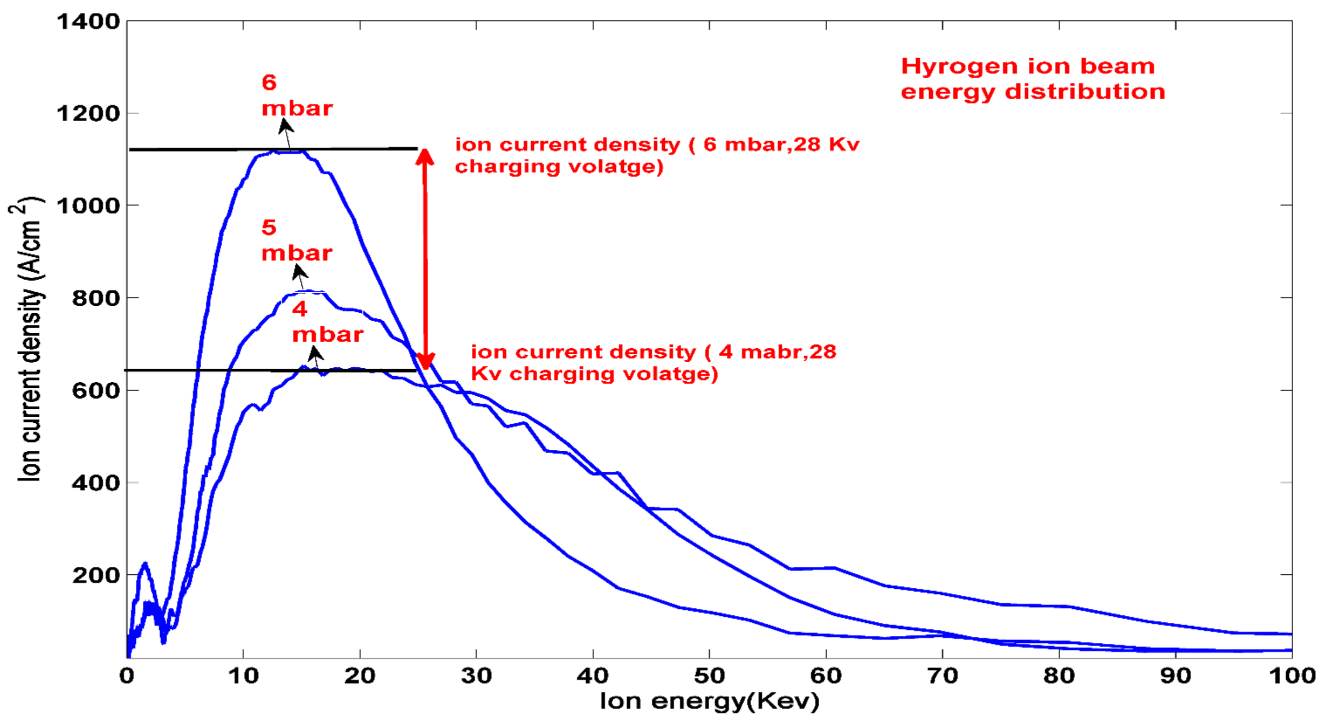


charging voltage of 28 kV and operating pressure of 5 mbar

Ion beam emission from Hydrogen, Nitrogen and Argon Plasmas

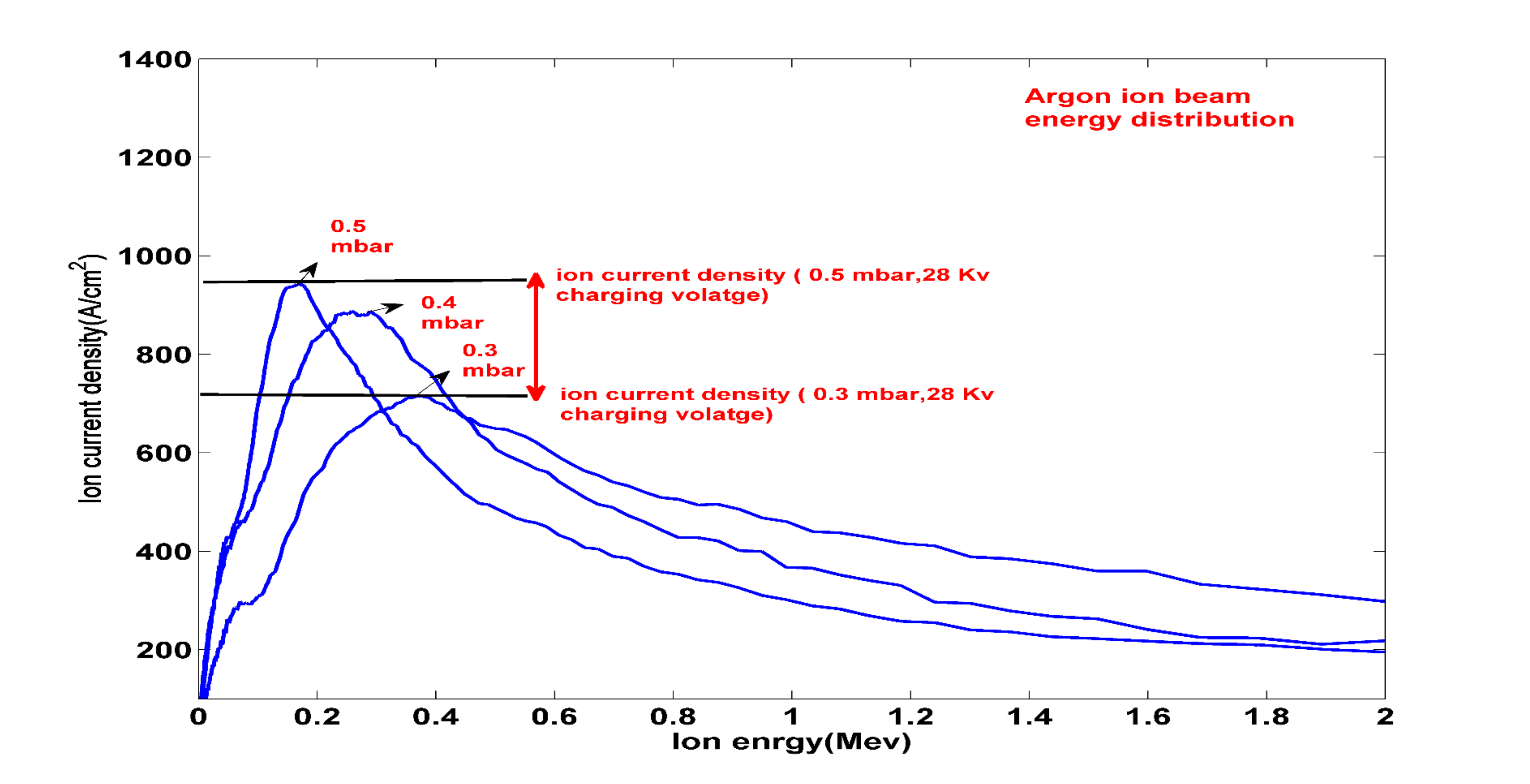


Energy distribution of ion current density (Hydrogen Plasma)



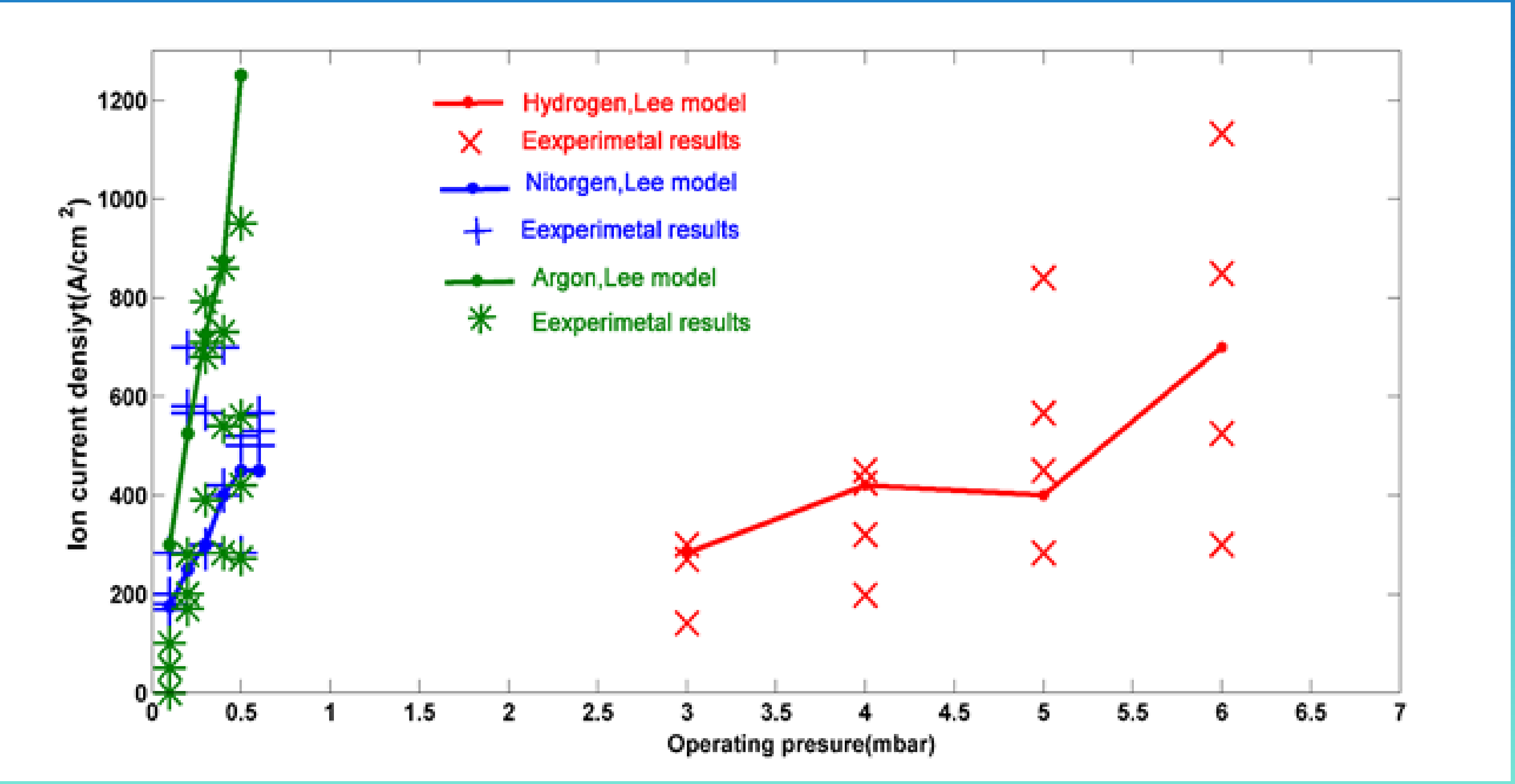
As pressure increases, the peak energy of ions decreases, put the current density increases (Bank voltage=28 kV)

Energy distribution of ion current density (Argon Plasma)



The peak ion current density occurs between 200 keV and 450 keV. Longer tail compare to Hydrogen and Nitrogen gases (Bank voltage= 28 Kv)

comparison of the measured peak ion beam current density with Lee model in high-Z and low-Z gases



Comparison the experimental results regarding the measured ion current density in three operating gases and different operating pressures with Lee model

Physics of Plasmas (1994-present) **20**, 062702 (2013); doi: 10.1063/1.4811650

Thank you