Recent Experimental Studies on the STOR-M Tokamak

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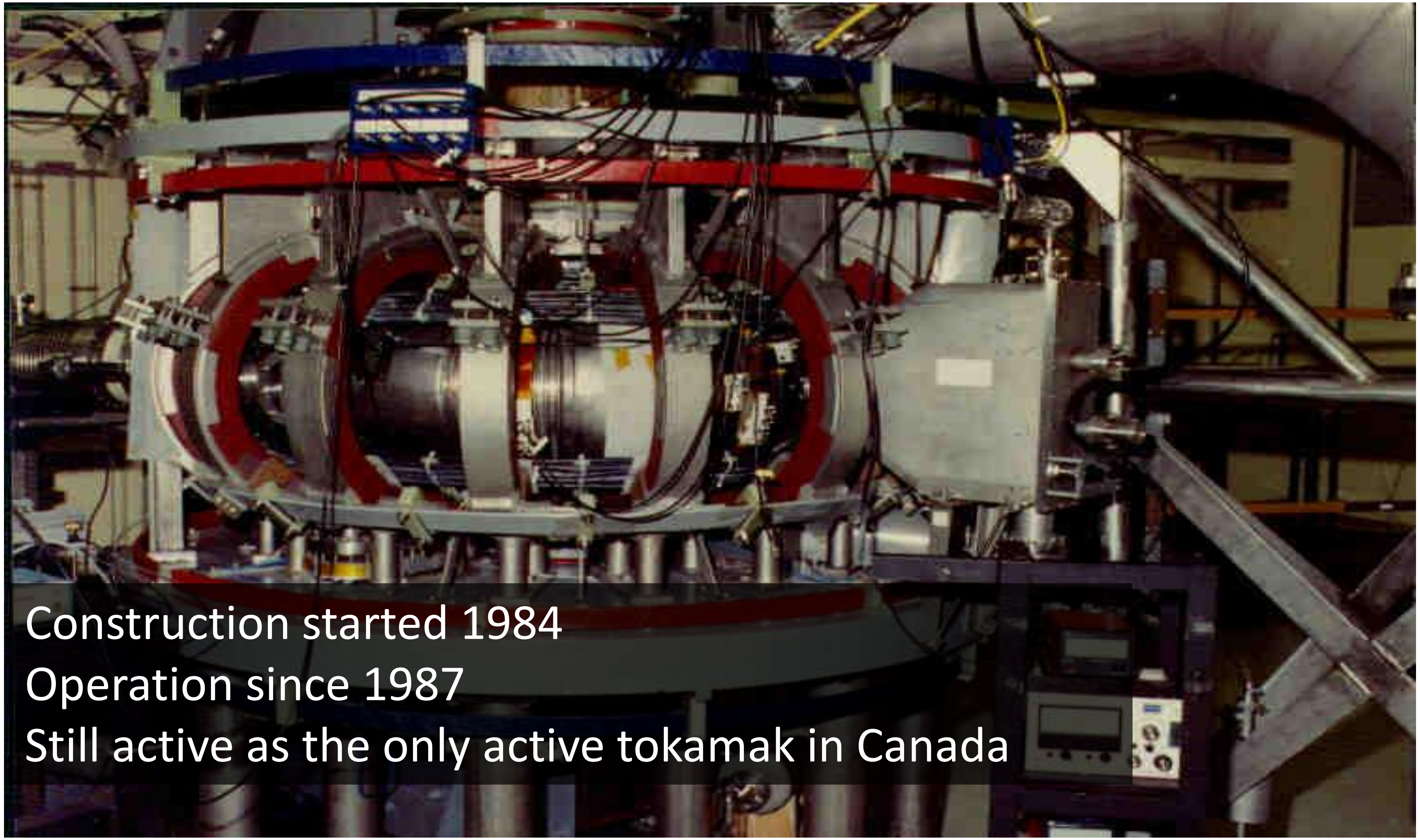
Outline

- STOR-M tokamak
- Compact torus fueling and repetitive operation
- Momentum injection by compact torus injection
- Effects of Li coating on the STOR-M discharges

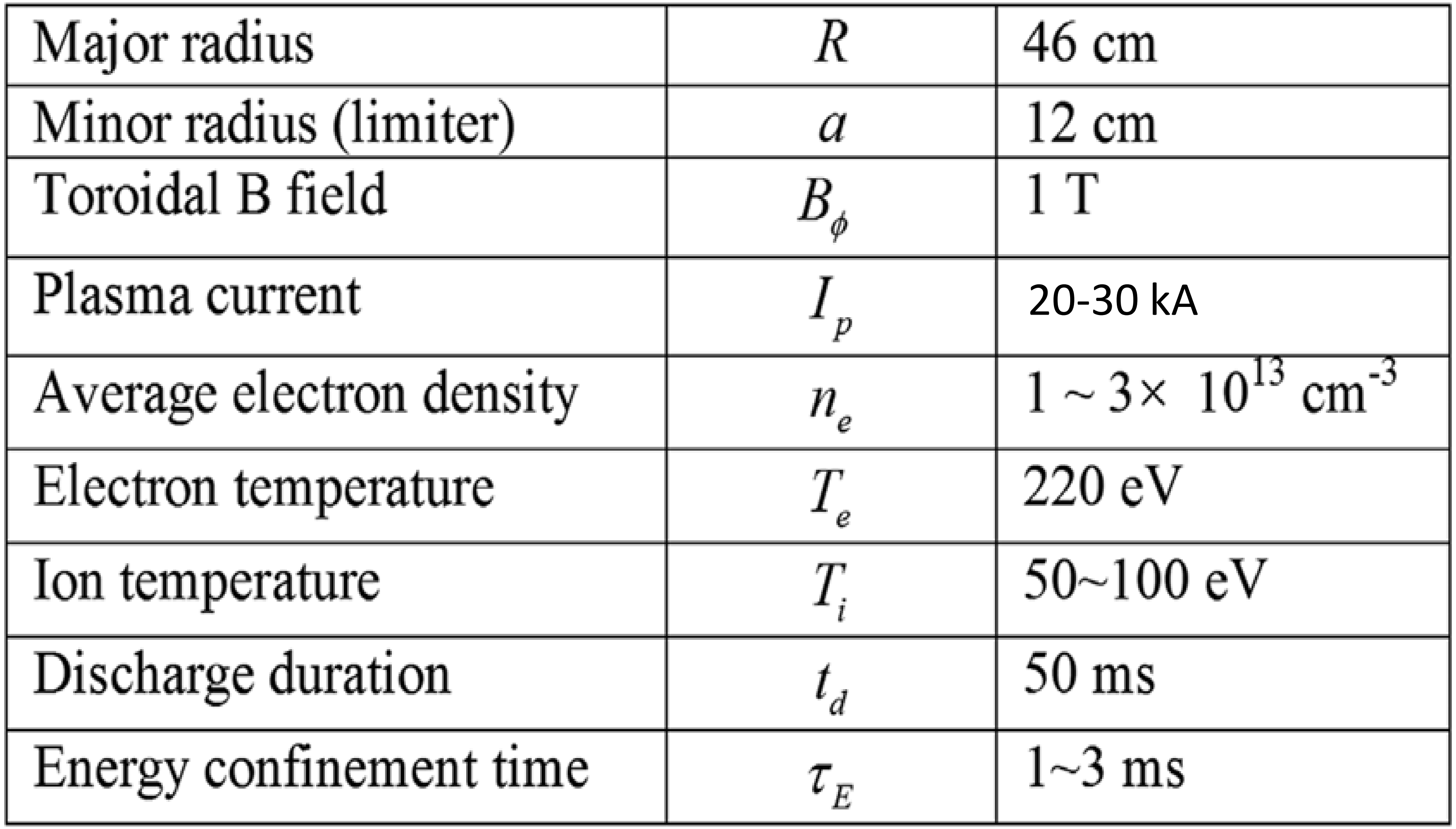
STOR-M Tokamak

STOR-M Tokamak



Construction started 1984
Operation since 1987
Still active as the only active tokamak in Canada

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	20-30 kA
Average electron density	n_e	$1 \sim 3\times\ 10^{13}$ 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

STOR-M Tokamak and Features

- Iron core tokamak
- Feedback position control
- AC (alternating current) capability
- Compact Torus (CT) injector
- Resonant Magnetic Perturbation (RMP) helical coils
- A host of diagnostics

Compact Torus and Fueling

Compact Torus (CT) Injection for Core Fuelling

- **Fuelling**

➢ Current fuelling technology (pellet injection and or gas puffing) is unable to directly fuel the reactor core

- **Compact Torus (CT) Injection**

➢ The only candidate identified by an ITER working group for deep fueling

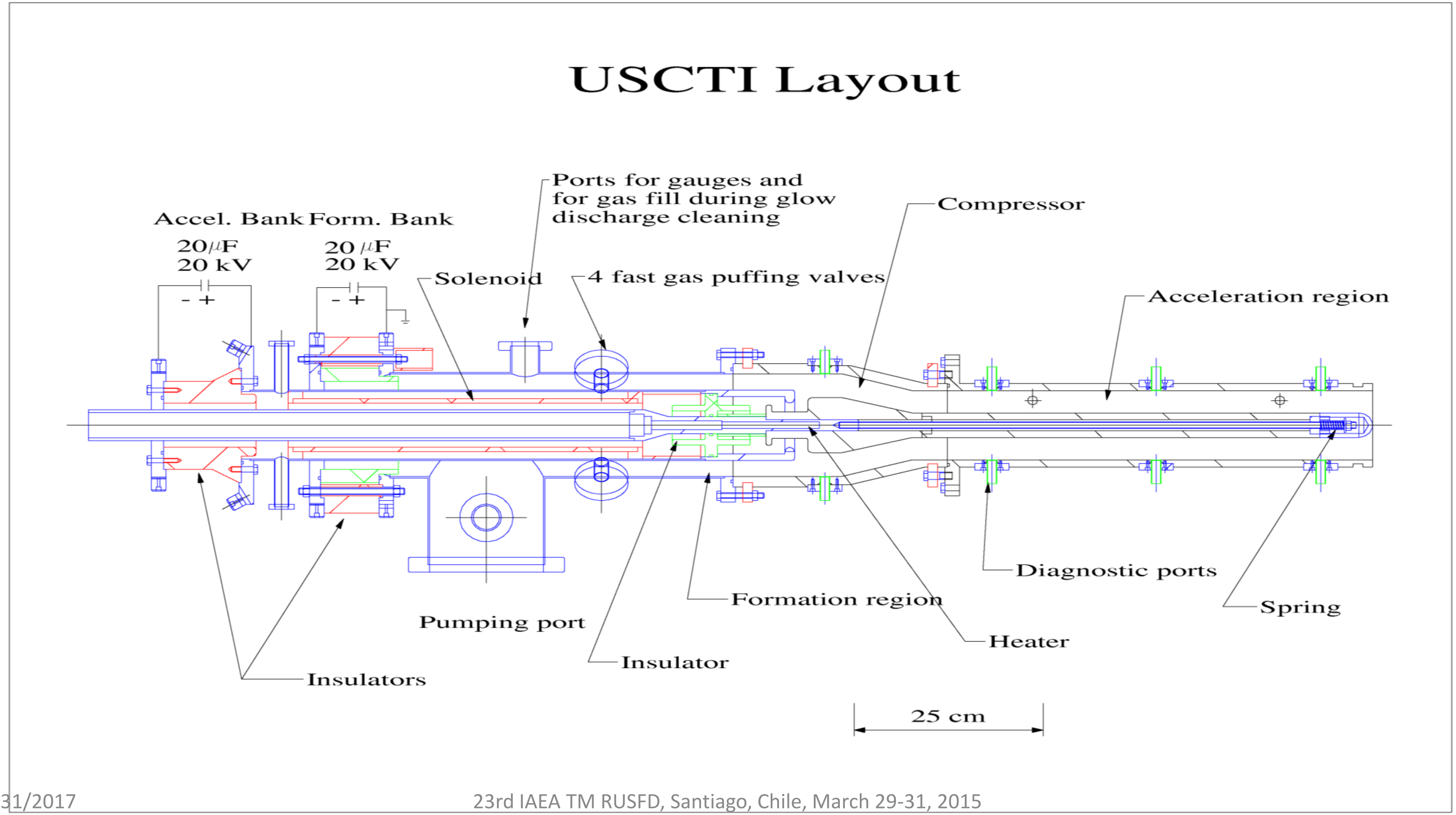
➢ Able to optimize pressure profile → increase bootstrap current

➢ Momentum injection by tangential CT injection → control plasma flows (increase tolerance to error field, suppress RWM, etc.)

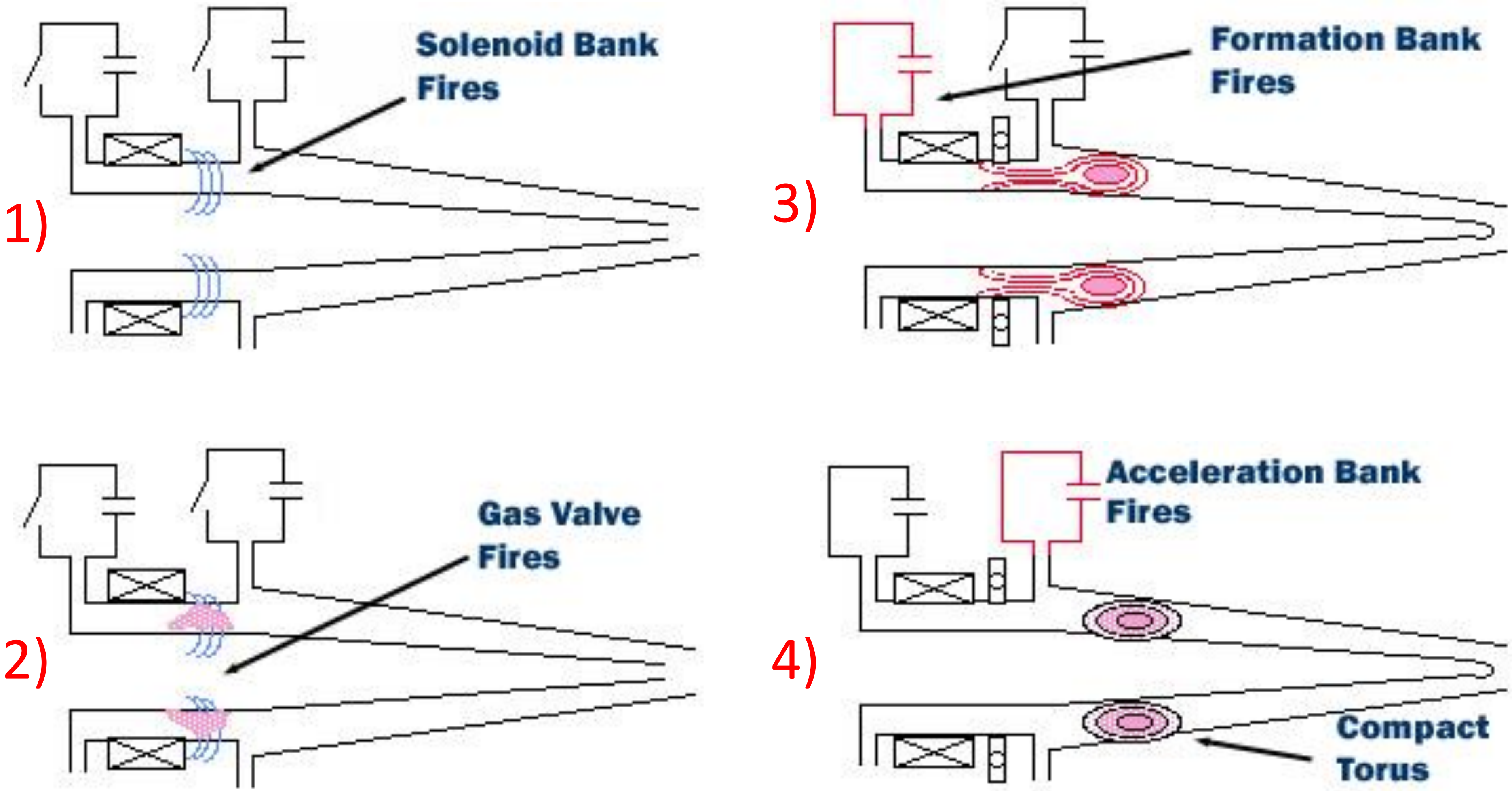
What is a Compact Torus (CT)?

- Magnetically confined robust plasmoid
- CT can be formed and accelerated in a coaxial gun
- High in density and small in size
- Can be accelerated high velocities (hundreds of kilometers per second)

University of Saskatchewan Compact Torus Injector

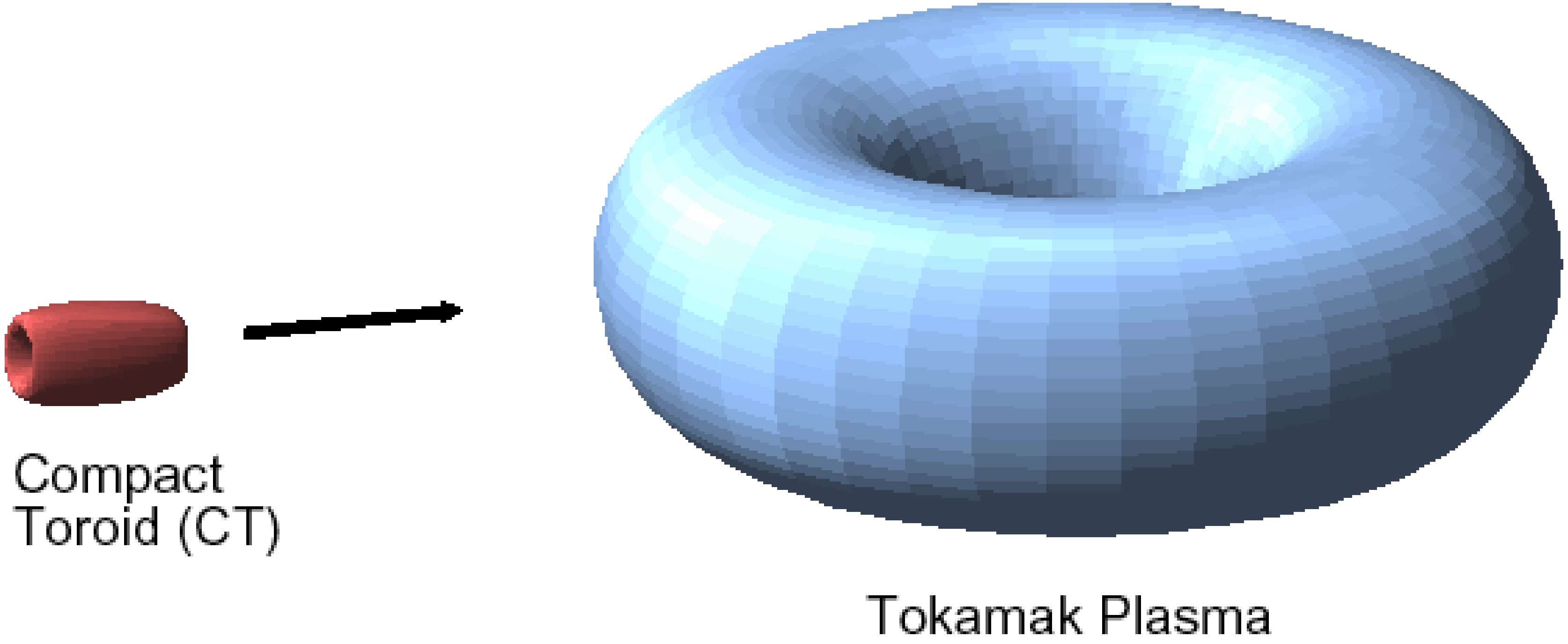


CT formation principle



Formed and accelerated in a coaxial gun via J×B force

CT penetration and fuelling



High density, small CT to fuel the tokamak core directly.

Repetitive operation is needed for steady-state operation of reactors.

Penetration requirement

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

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

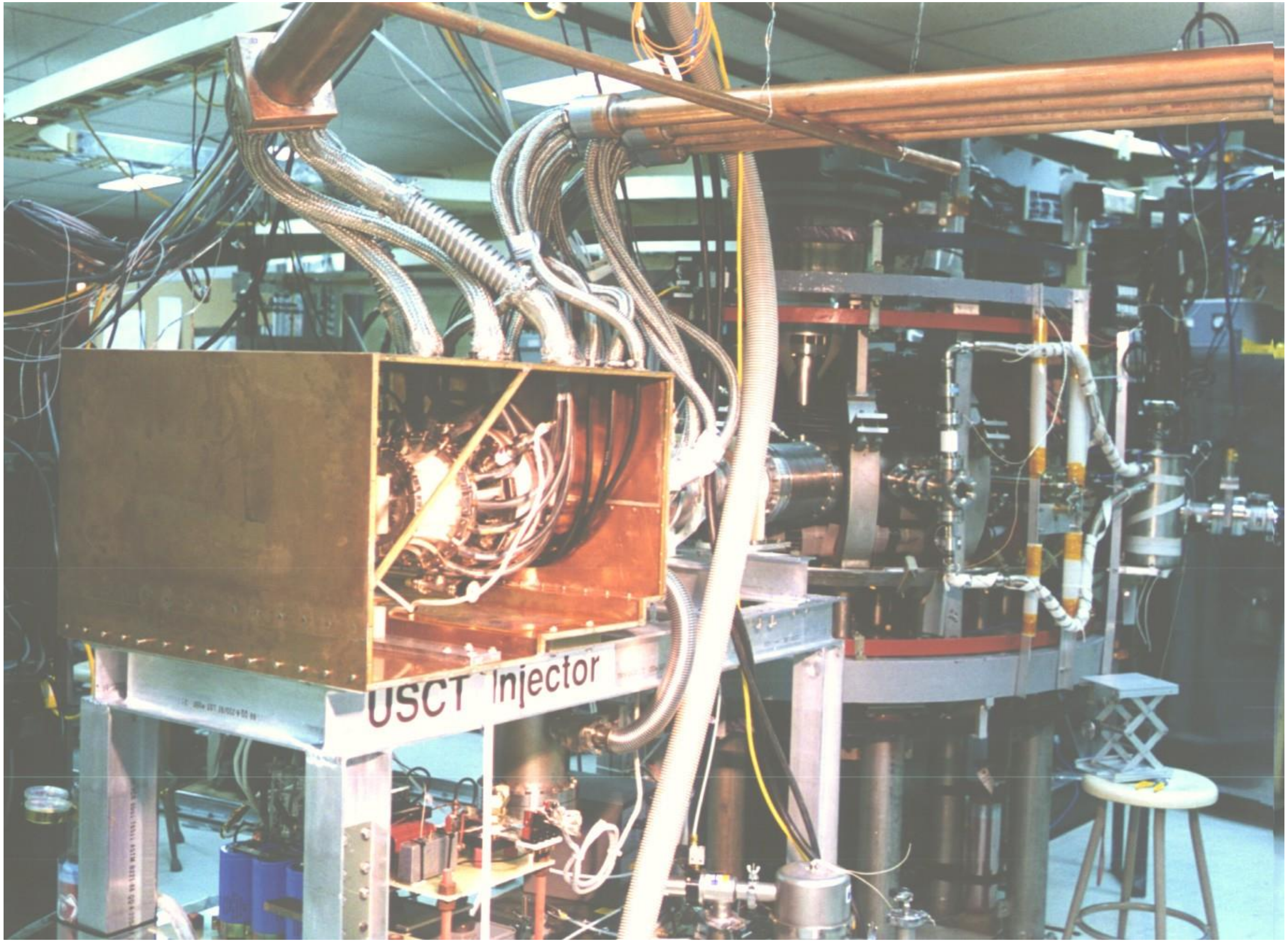
n_{ct} : CT ion density
m_i : CT ion mass
v_{ct} : CT velocity
B_{tok} : tokamak toroidal magnetic field

USCTI parameters:

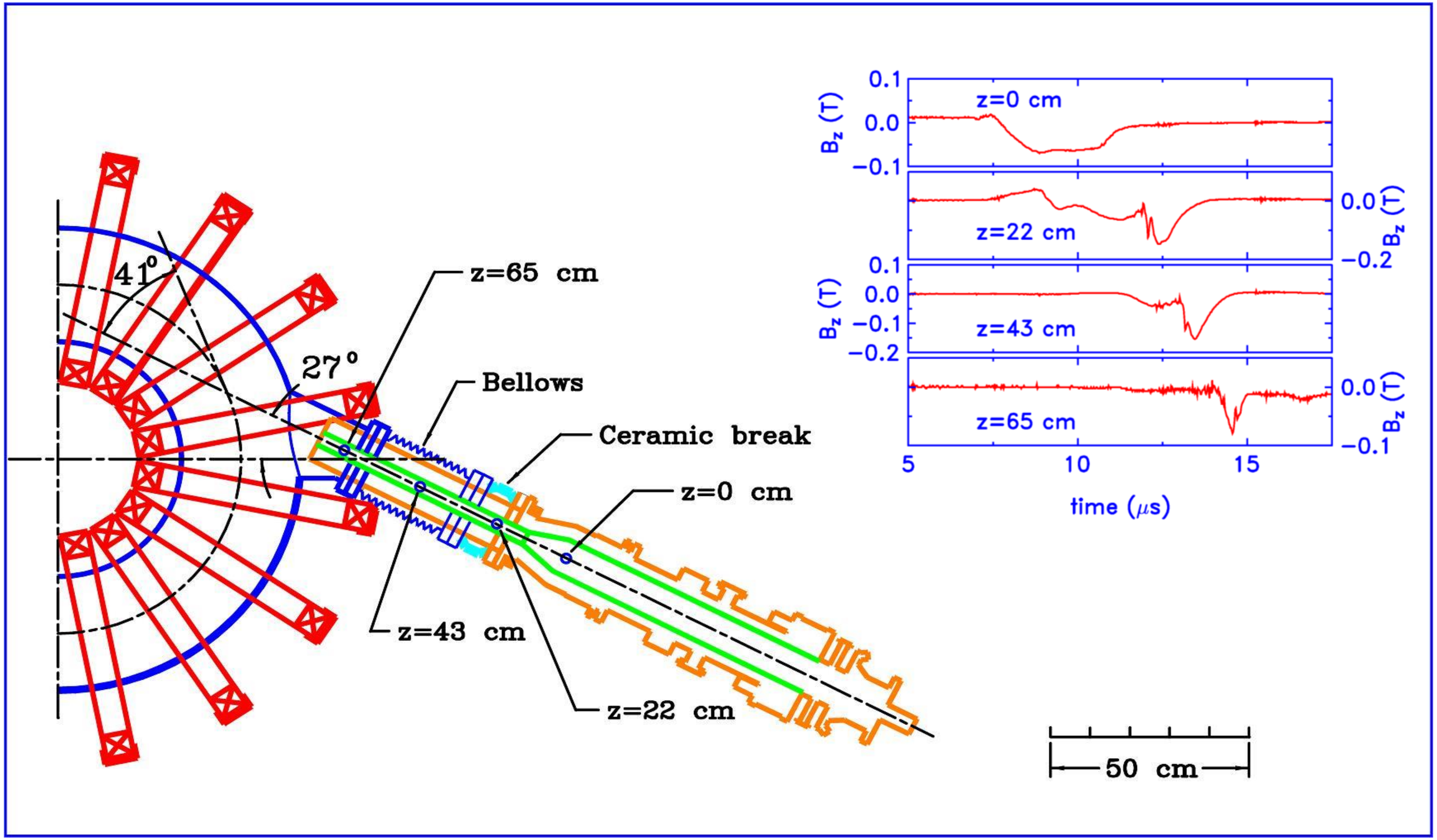
$n_{ct} = 10^{15}\ \ \mathrm{cm}^{-3}$

$v_{ct} = 200$ km/sec

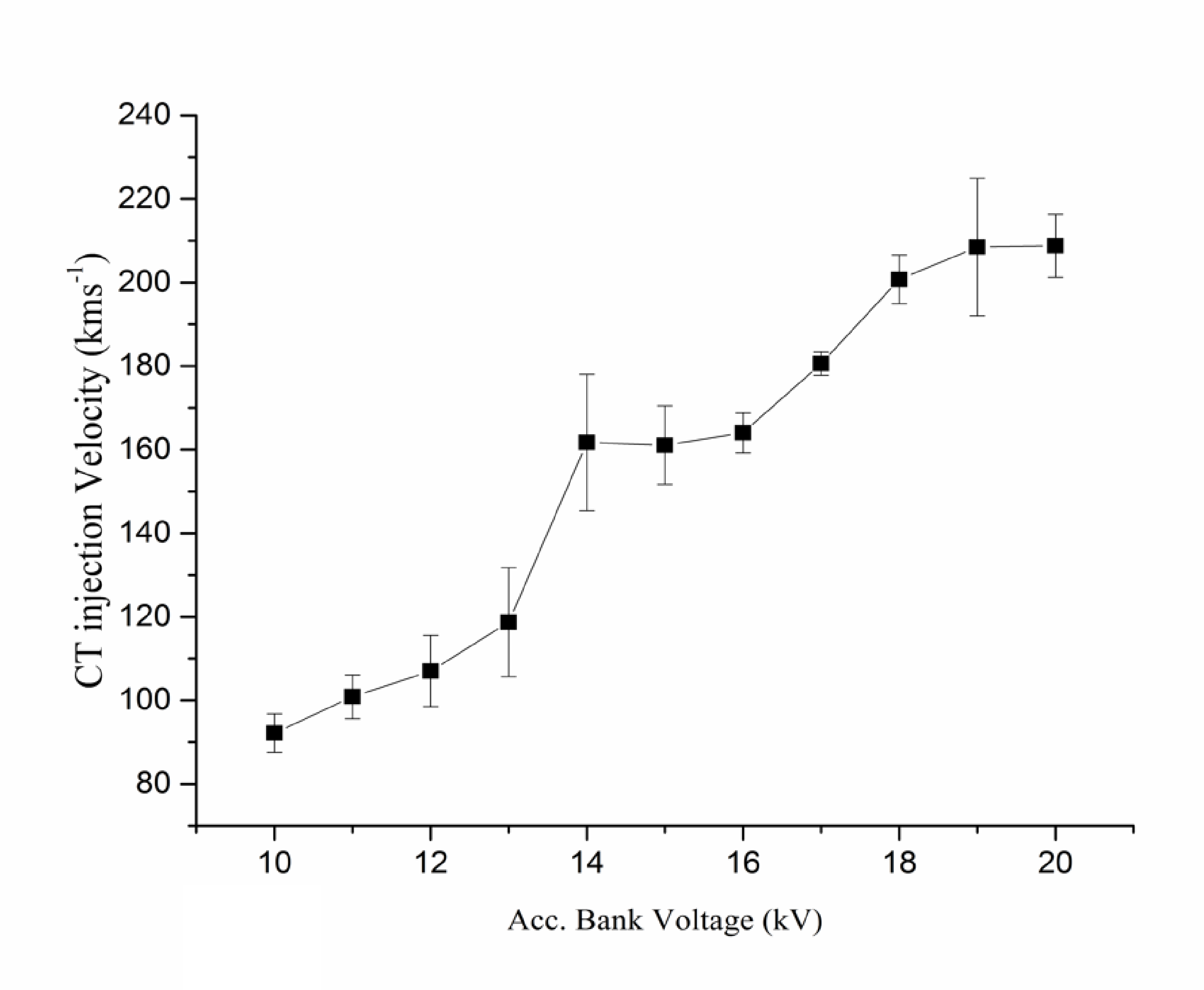
total mass 0.5 μg


USCT Injector

Injection Velocity Measurement



Injection Velocity Measurement



- CT velocity is measured by time of flight method
- CT velocity can be controlled by the acceleration bank voltage

Repetitive CT Operation

T. Onchi *et. al* IEEE-PS, 2015
DOI: 10.1109/TPS.2015.2499218
https://www.researchgate.net/publication/286509993

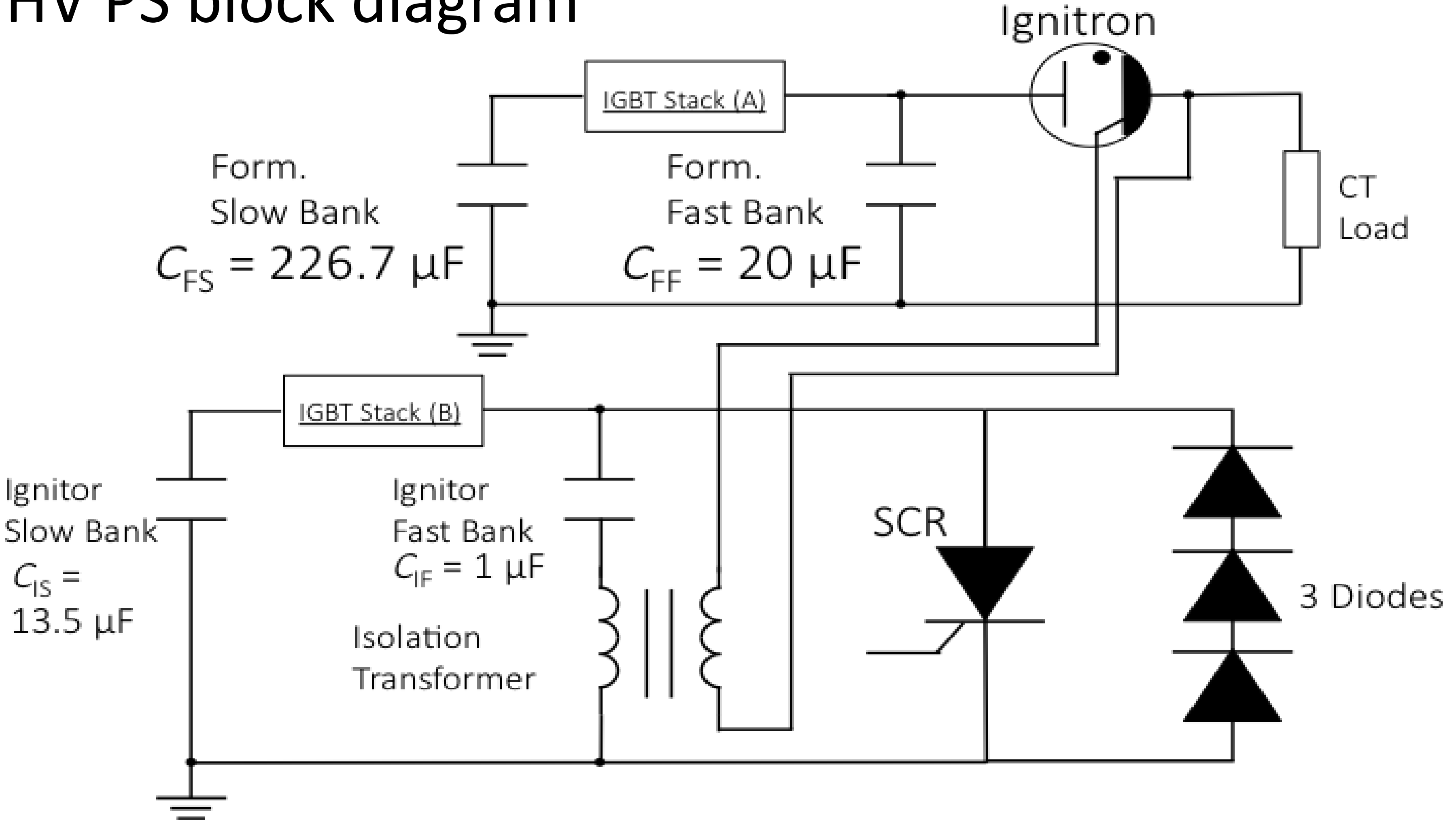
Repetitive CT injection

- The CT is produced through magnetic reconnection
- It can only be produced one at a time
- For steady stead reactor operation, repetitive CT operation is required.
- For multiple CT injection during STOR-M pulse duration (30-50 ms), 100 Hz is needed.

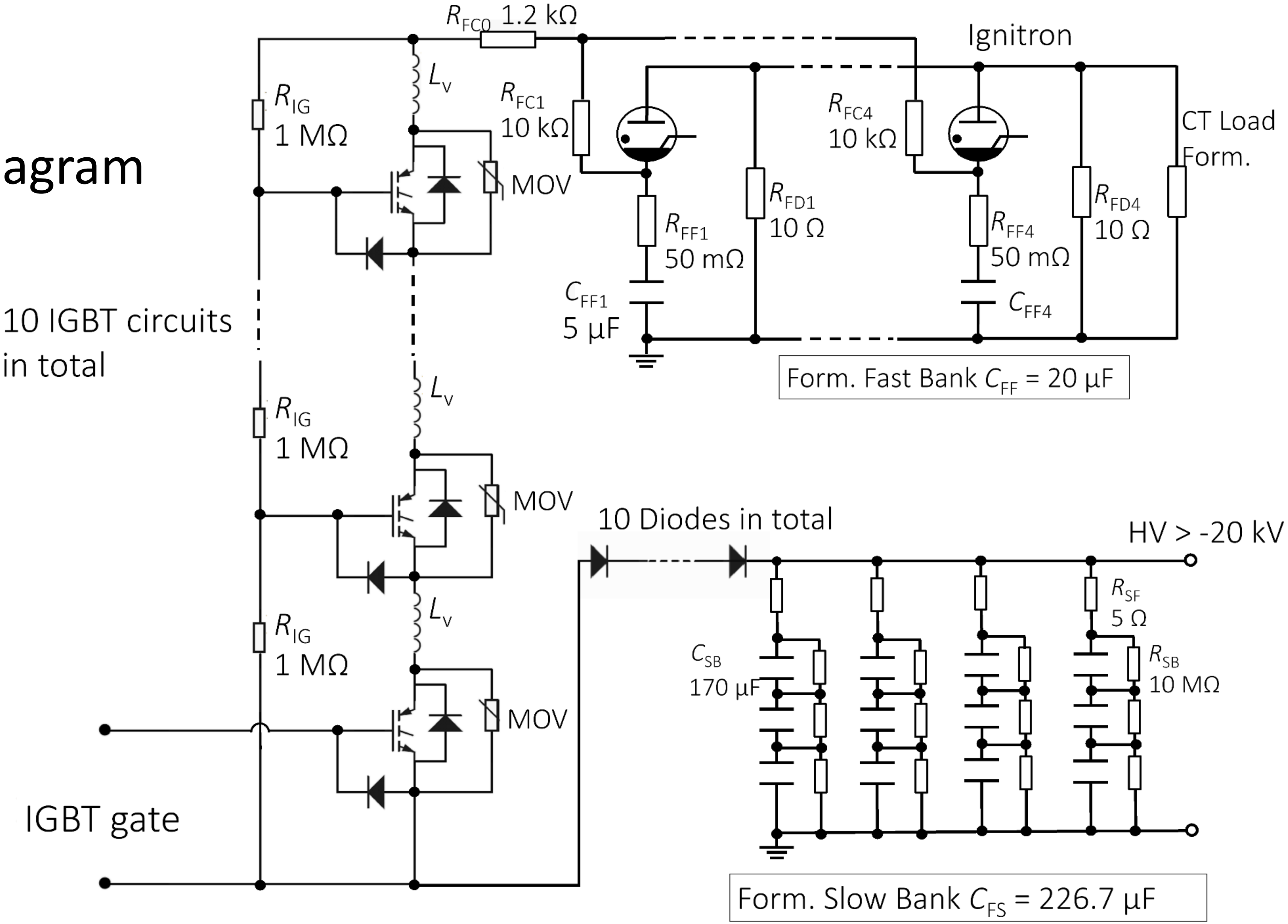
Repetitive CT Operation – Burst Mode

1. Store energy in slow capacitor banks (tens of seconds)
2. Charge fast banks quickly via a stack of IGBT gates (10-100 ms)
3. Discharge fast banks and create a CT (tens of μs)
4. Recharge fast banks and repeat the processes 2, 3, 4 until the voltage in the slow bank become too low

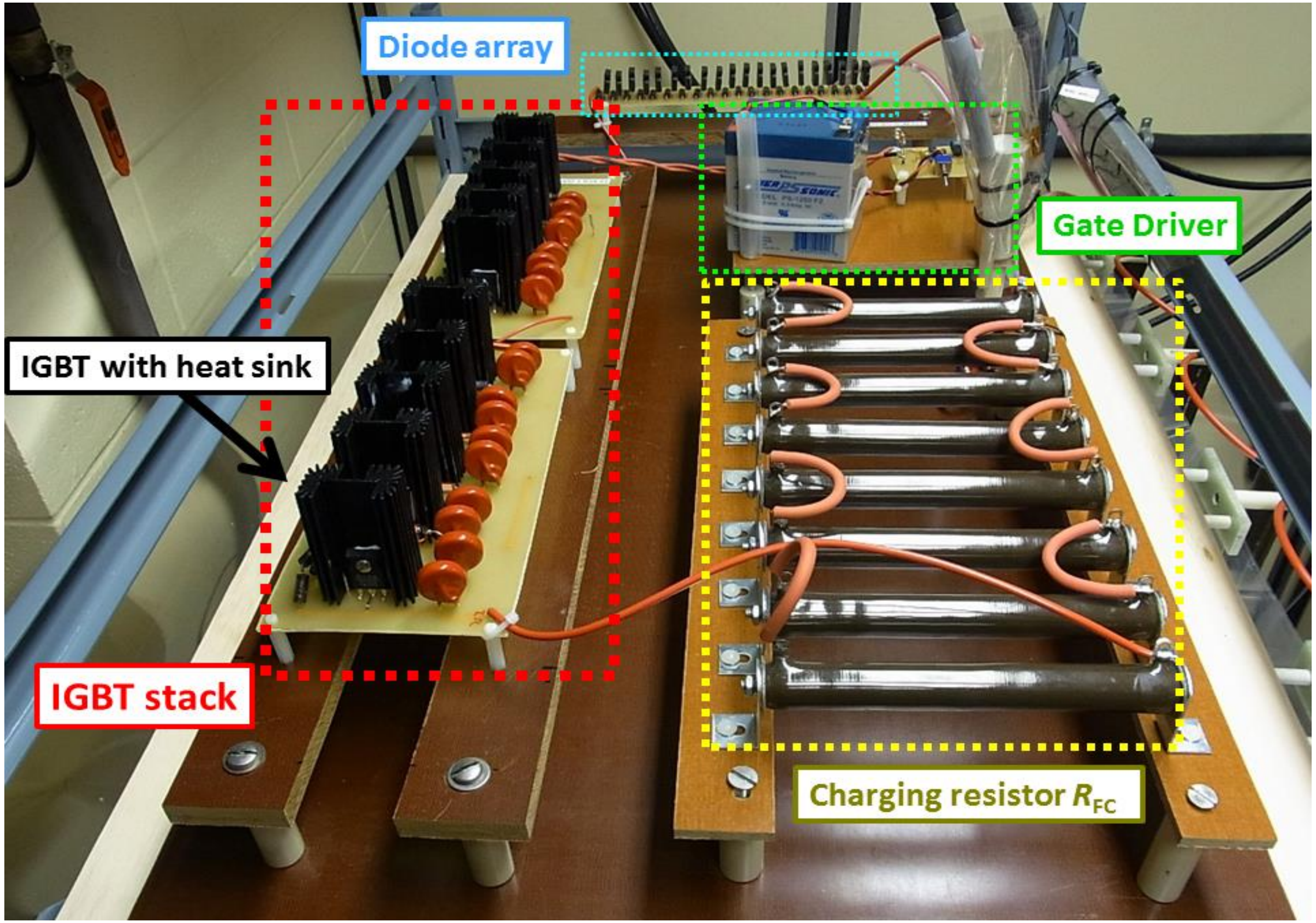
HV PS block diagram

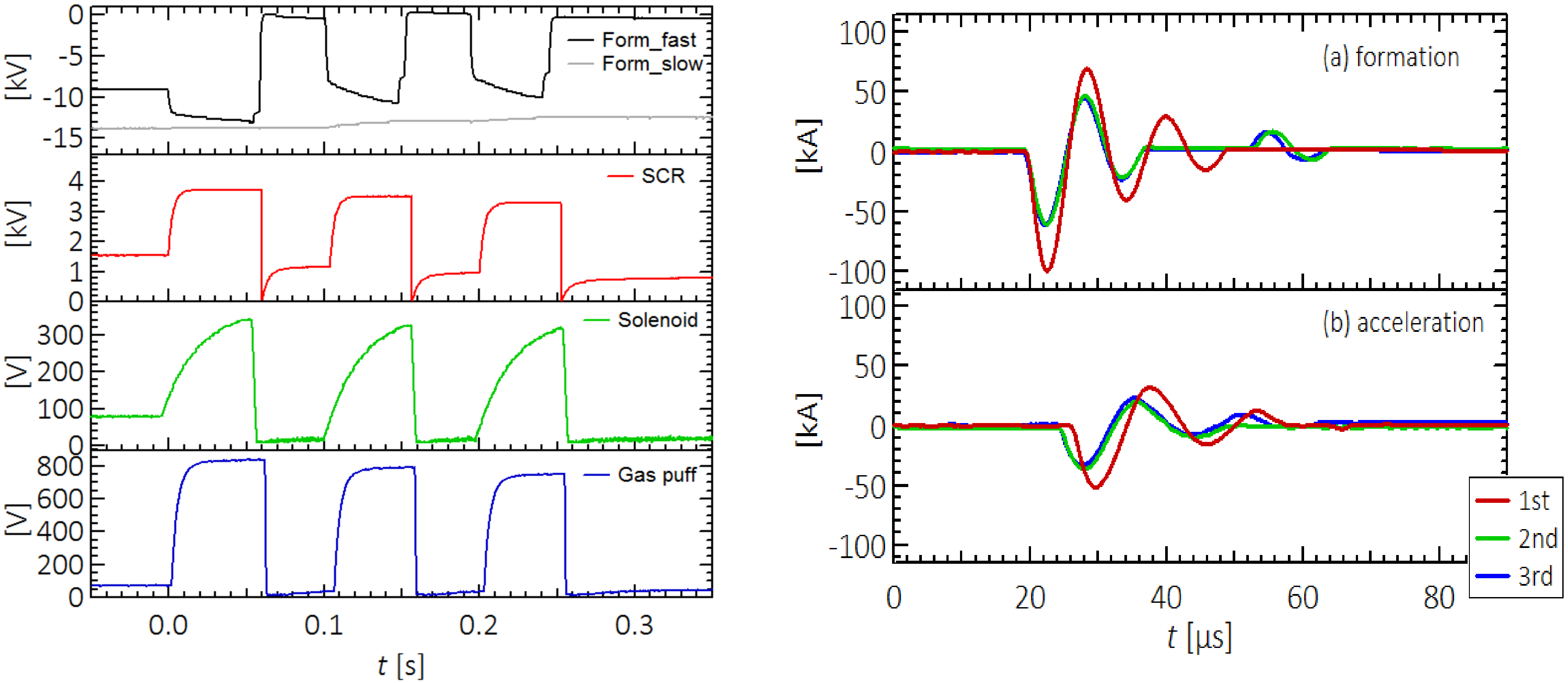


HV PS circuit diagram



Picture of fast charge reloading circuit





Example of repetitive CT operation at 10 Hz.

A system has been built and will be tested to charge the fast banks to the same voltages for all shots

Momentum Injection by CT Injection

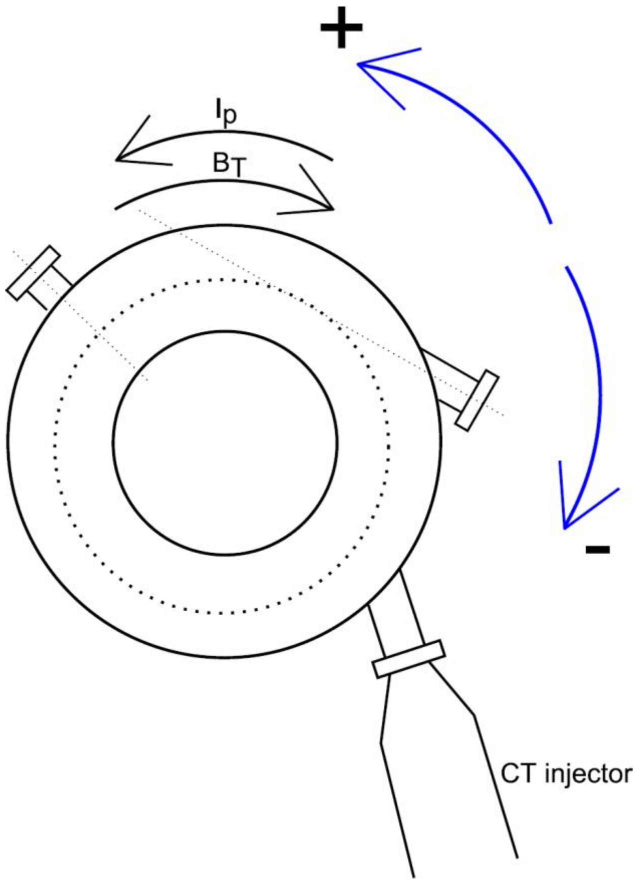
A. Rohollahi *et al* 2017 *Nucl. Fusion* **57** 056023

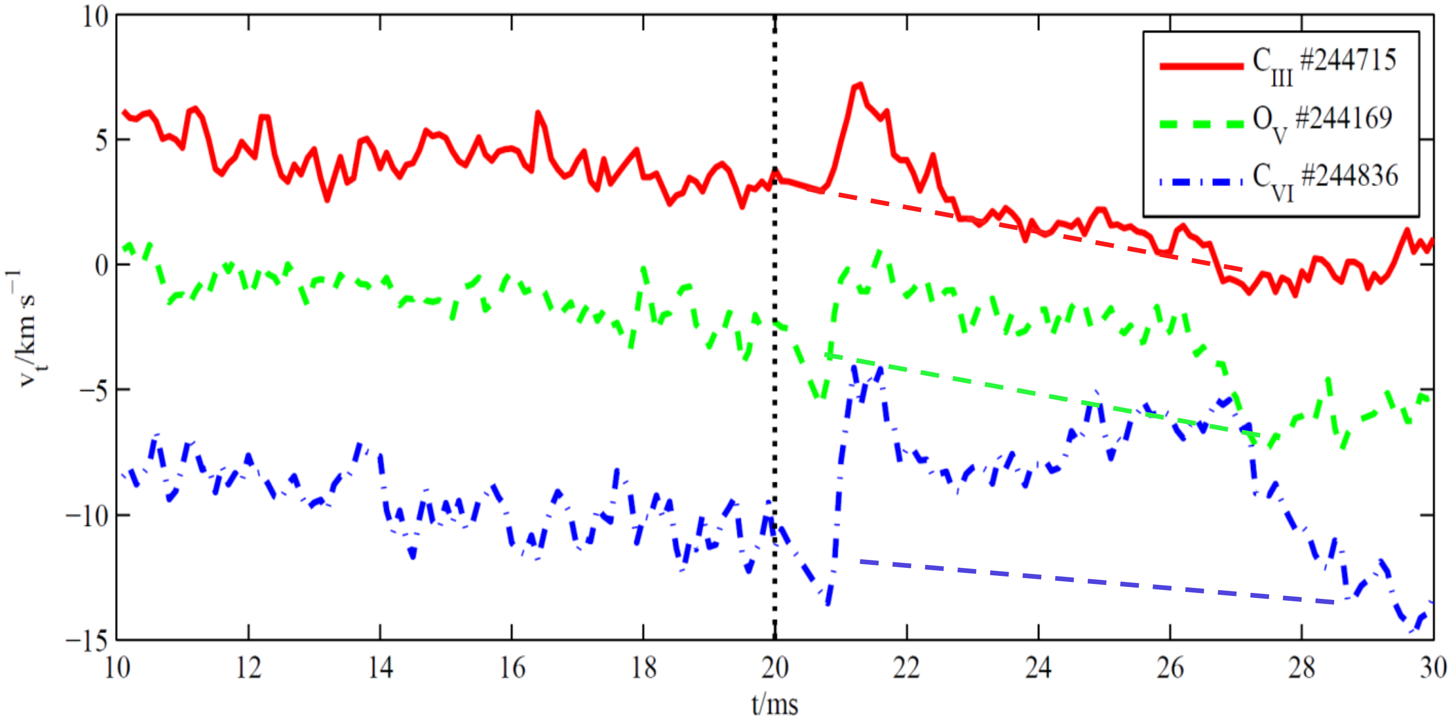
Momentum Injection CT

At the last IAEA-RUSFD meeting in Prague we reported

- RMP and co-current tangential CTI induced the change of plasma flow toward the current direction regardless of the intrinsic flow directions
- RMP and CTI both supressed MHD oscillations
- RMP does not have net momentum injection
- CT has a momentum 10 times the STOR-M toroidal rotation momentum

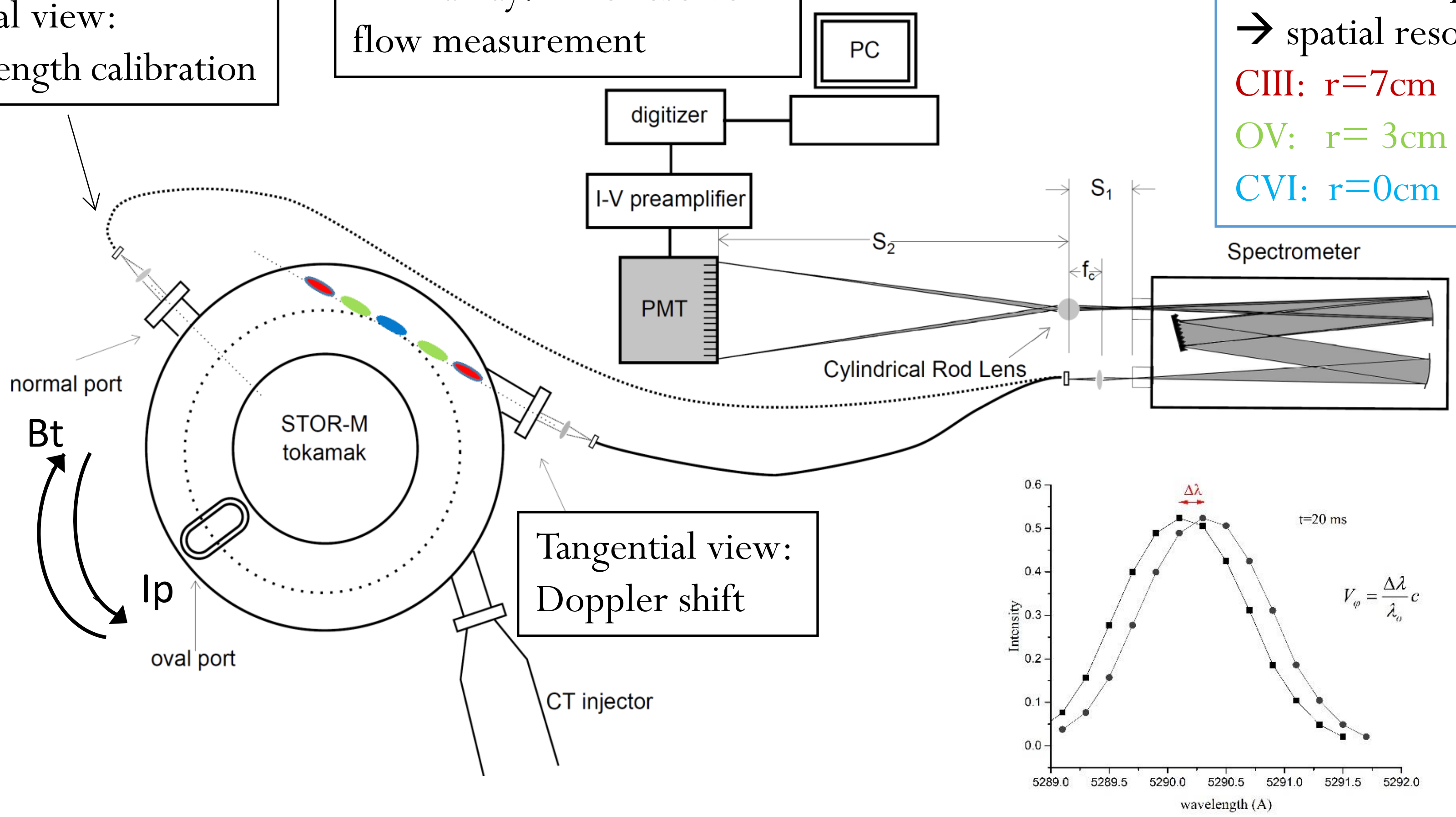
Flow modification by CT injection





IAEA-RUSFD 2015 slide-results

Ion Doppler Spectroscopy (IDS)



$$V_\varphi = \frac{\Delta\lambda}{\lambda_o} c$$

Normal view:
Wavelength calibration

PMT array: Time resolved
flow measurement

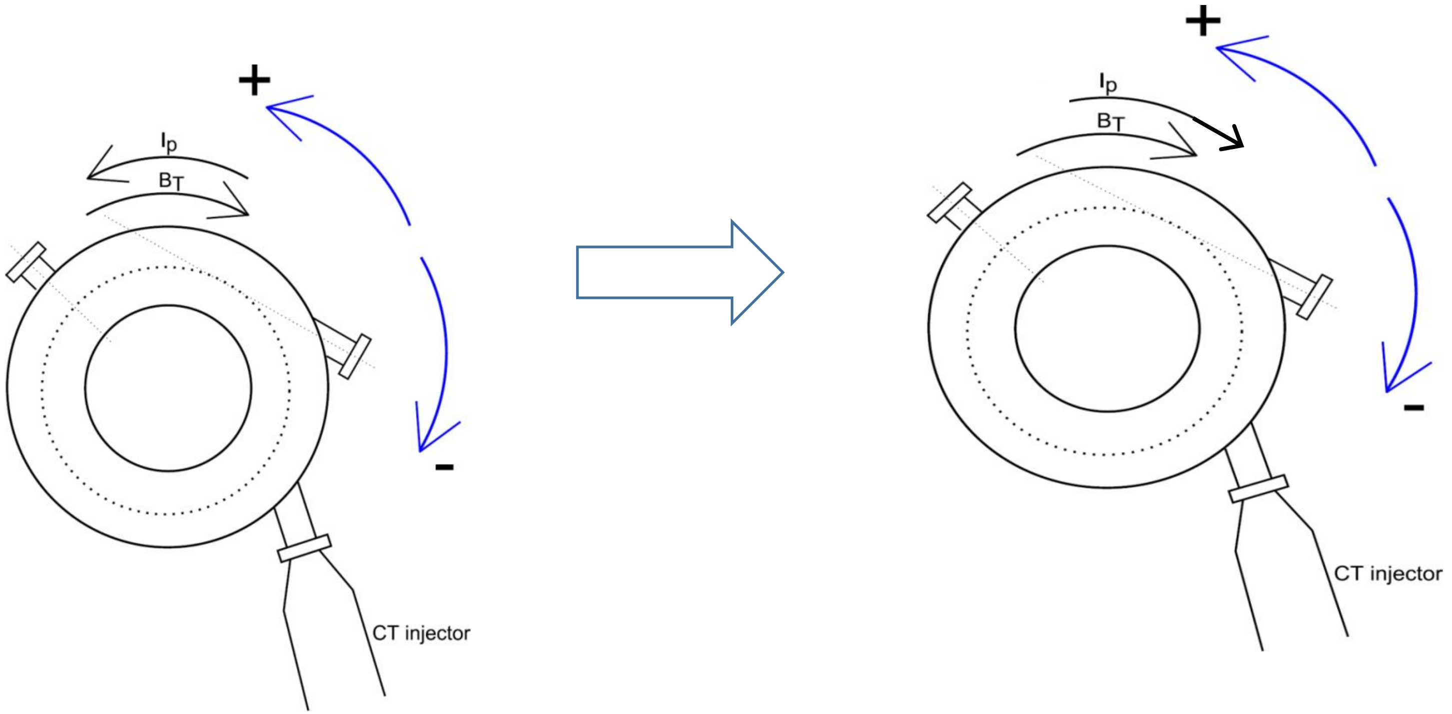
Choices of impurities
→ spatial resolution:
CIII: r=7cm
OV: r= 3cm
CVI: r=0cm

Tangential view:
Doppler shift

Reverse plasma current direction → Reverse intrinsic flow direction (along CT inj. Direction in the core plasma)

Momentum injection → speed up

MHD suppression → slow down

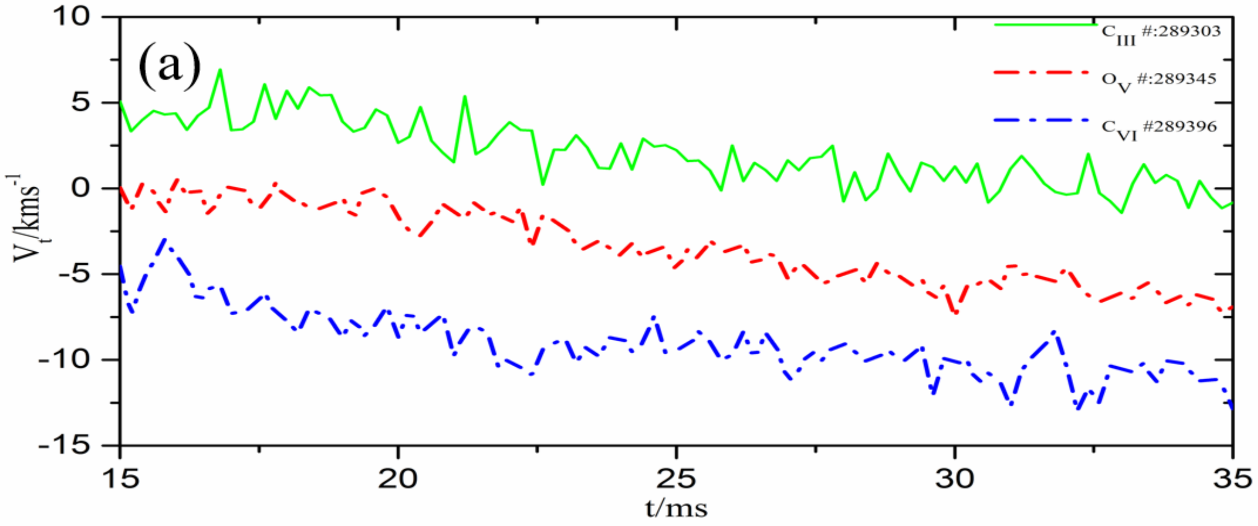


IAEA-RUSFD 2015 slide-plan

Toroidal Flow Measurement by IDS System

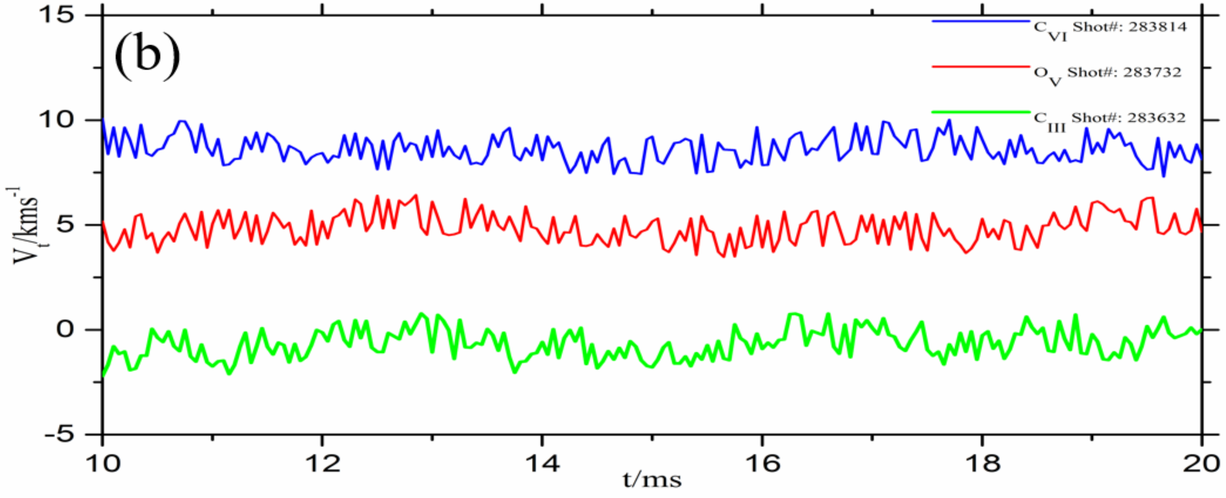
CCW Ip Current

- Core plasma: CW (anti-Ip)
- Outer plasm: CCW (co-Ip)

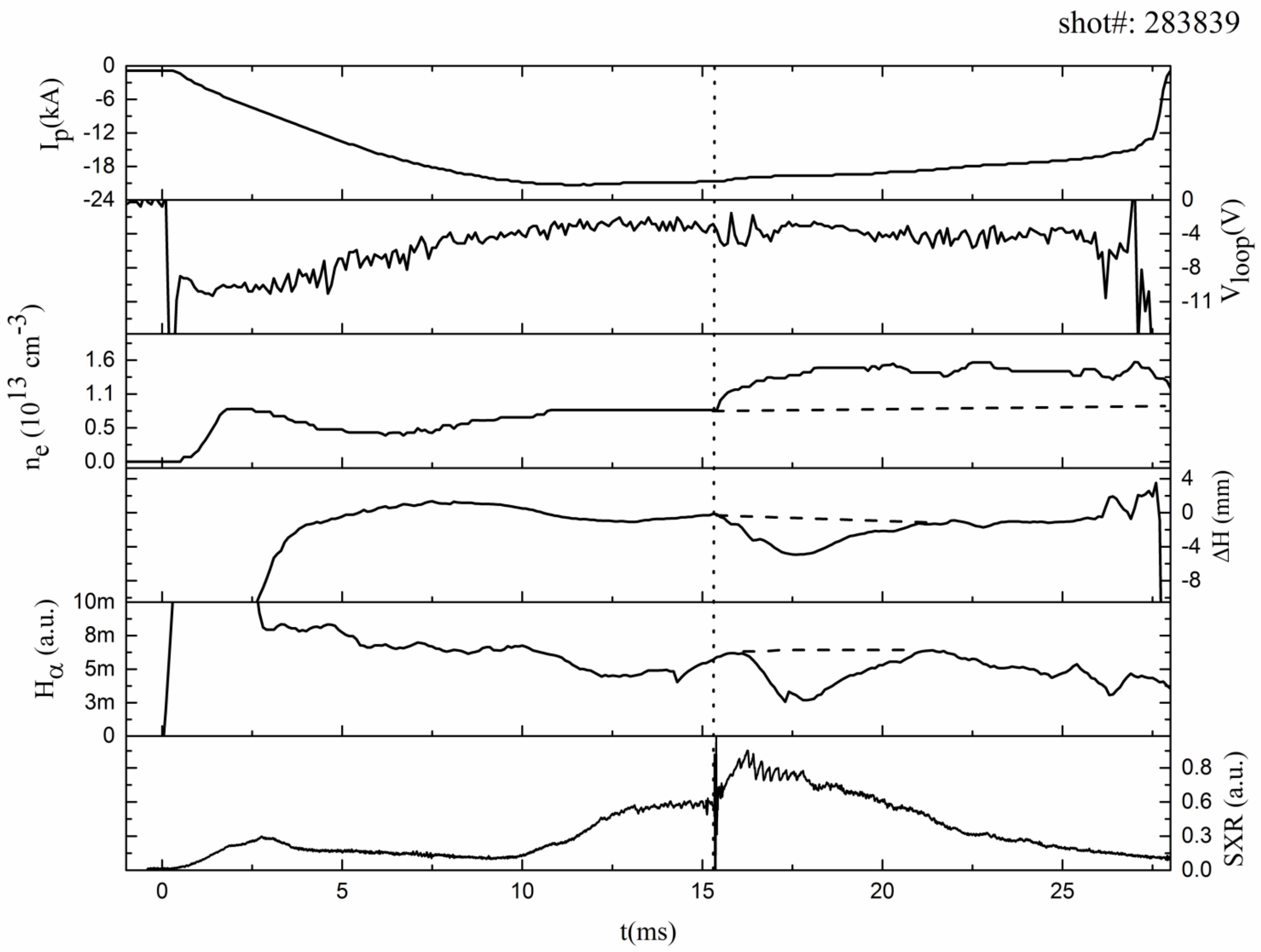


CW Ip Current

- Core plasma: CCW (anti-Ip)
- Outer plasm: CW (co-Ip)



Plasma Parameters after CTI



Density increase

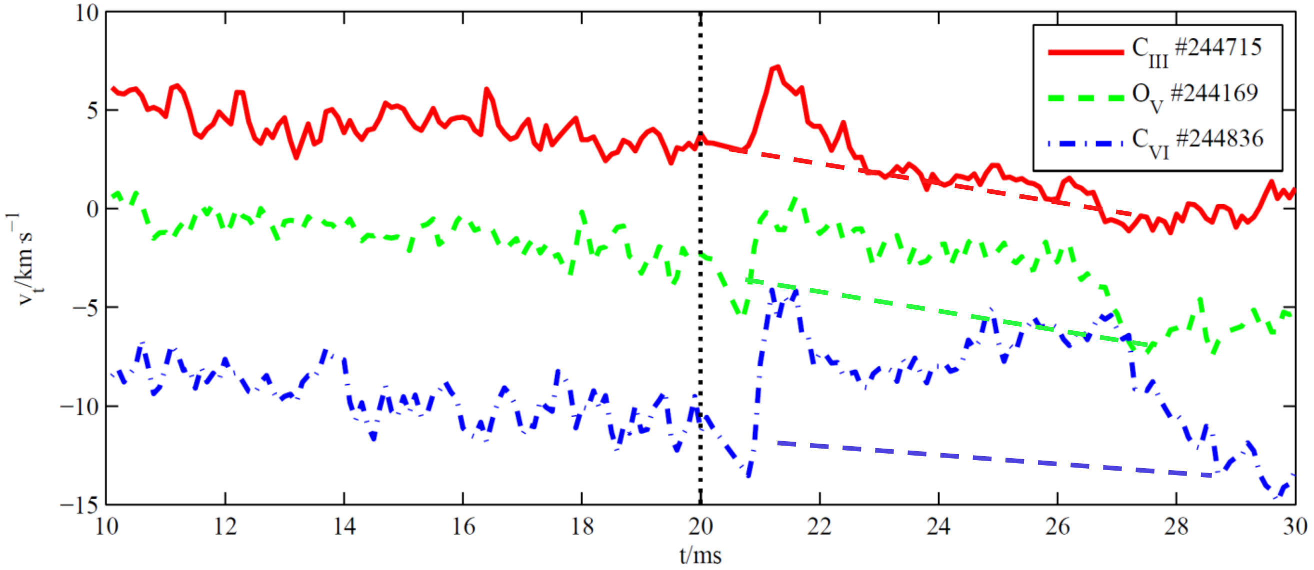
Hα reduction

Core channel

SXR increase

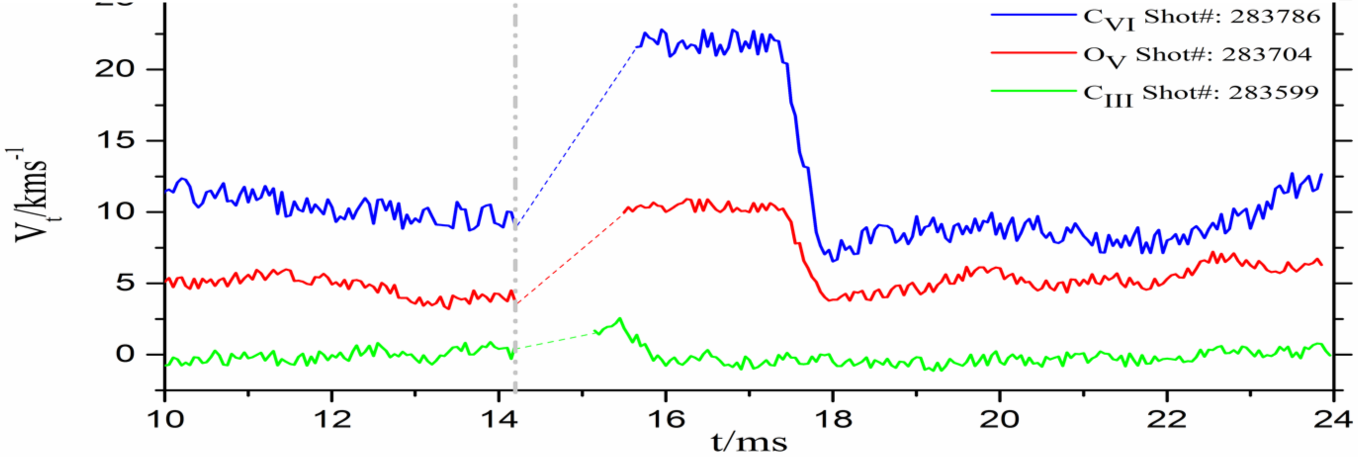
Effect of CTI on Toroidal Flow

CCW Current



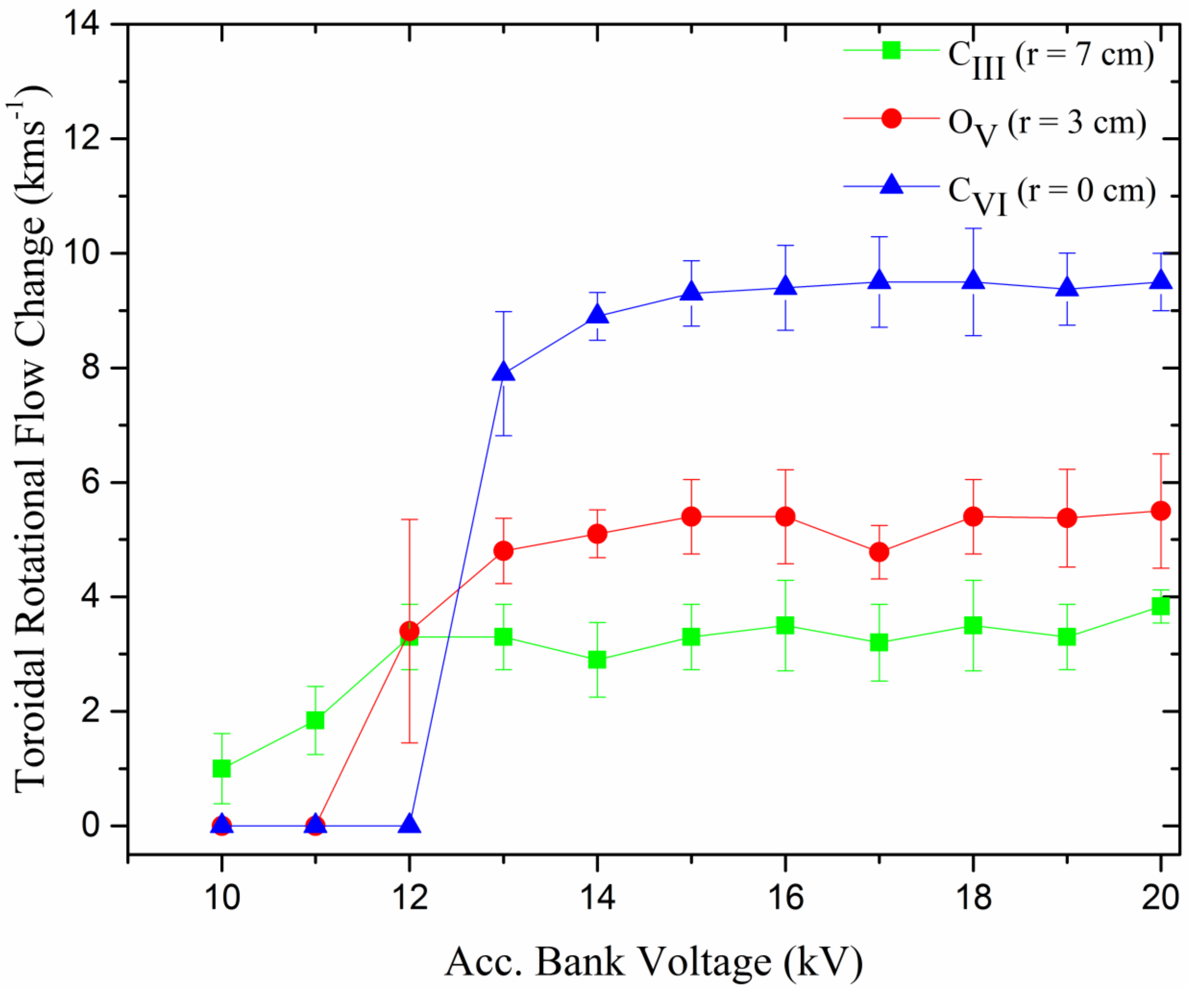
(a)

CW Current



(b)

Effect of CTI on Toroidal Flow

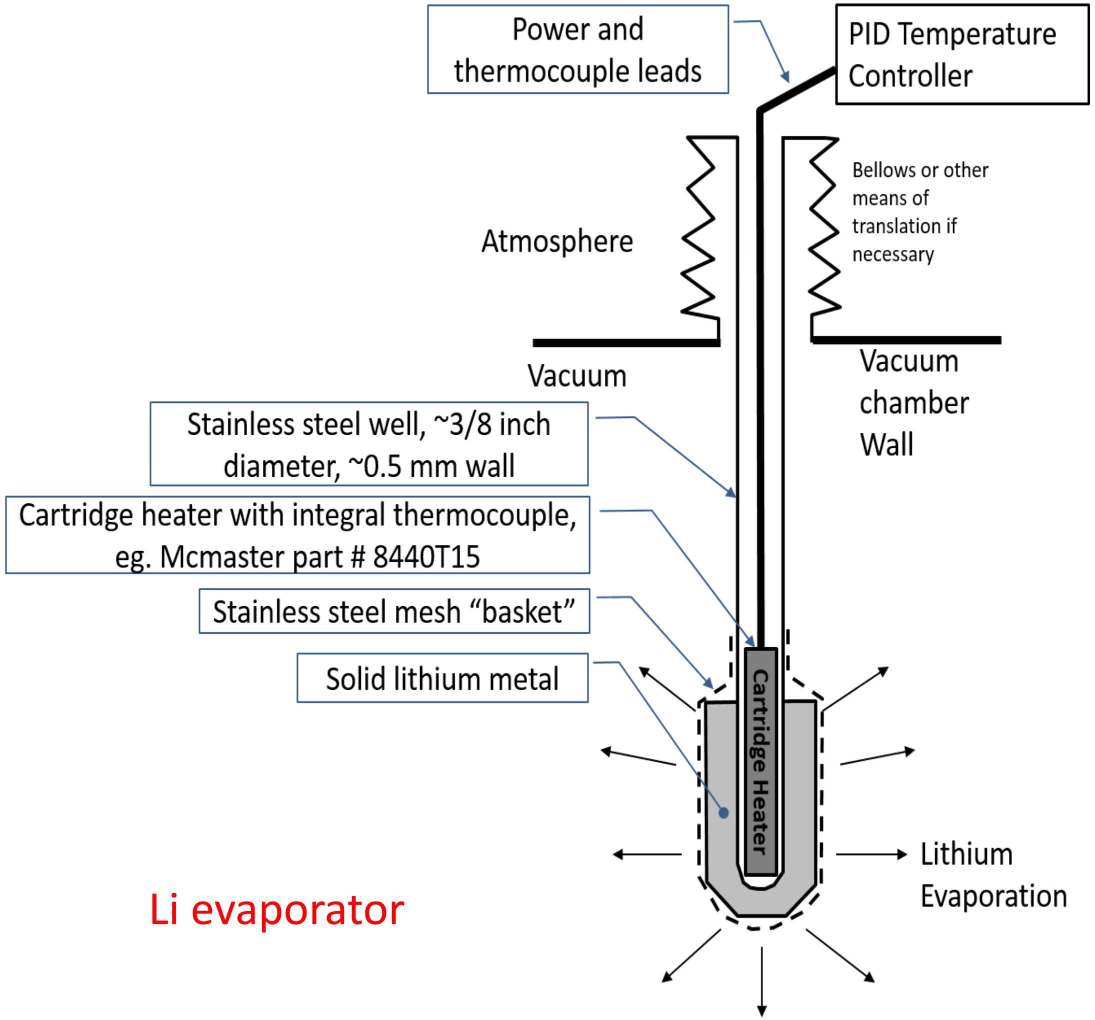


The threshold CT velocity for changes in flow velocity depends on the location of the impurity, perhaps reflecting CT penetration depth

Lithium Coating and its Effects on the STOR-M Discharge

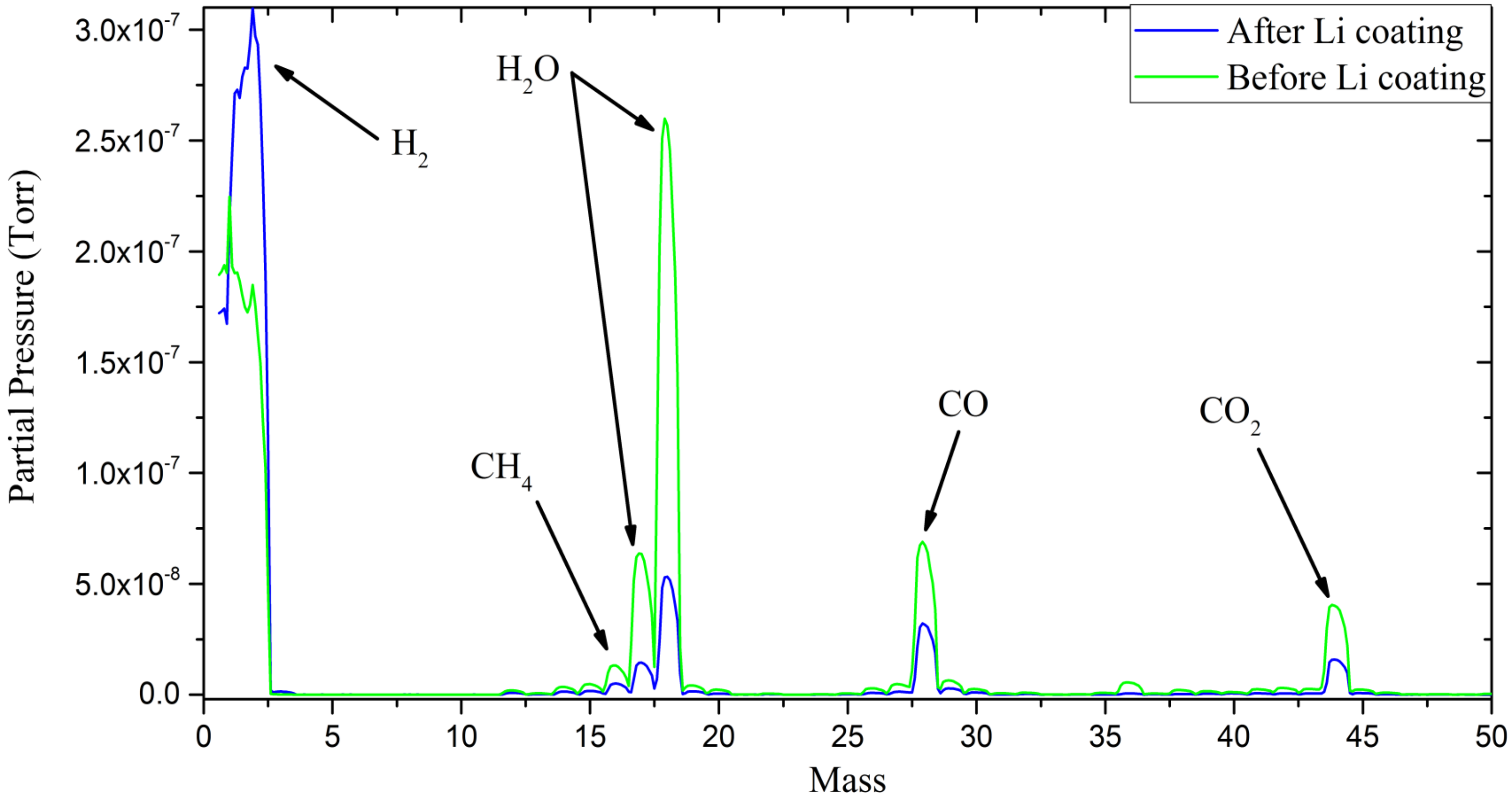
Li Coating of the Inner Tokamak Wall

- Lithium (Li) evaporator was provided by General Fusion Inc. in Burnaby, Canada.
- It has been used in STOR-M for two experimental campaigns
- Preliminary results have been obtained

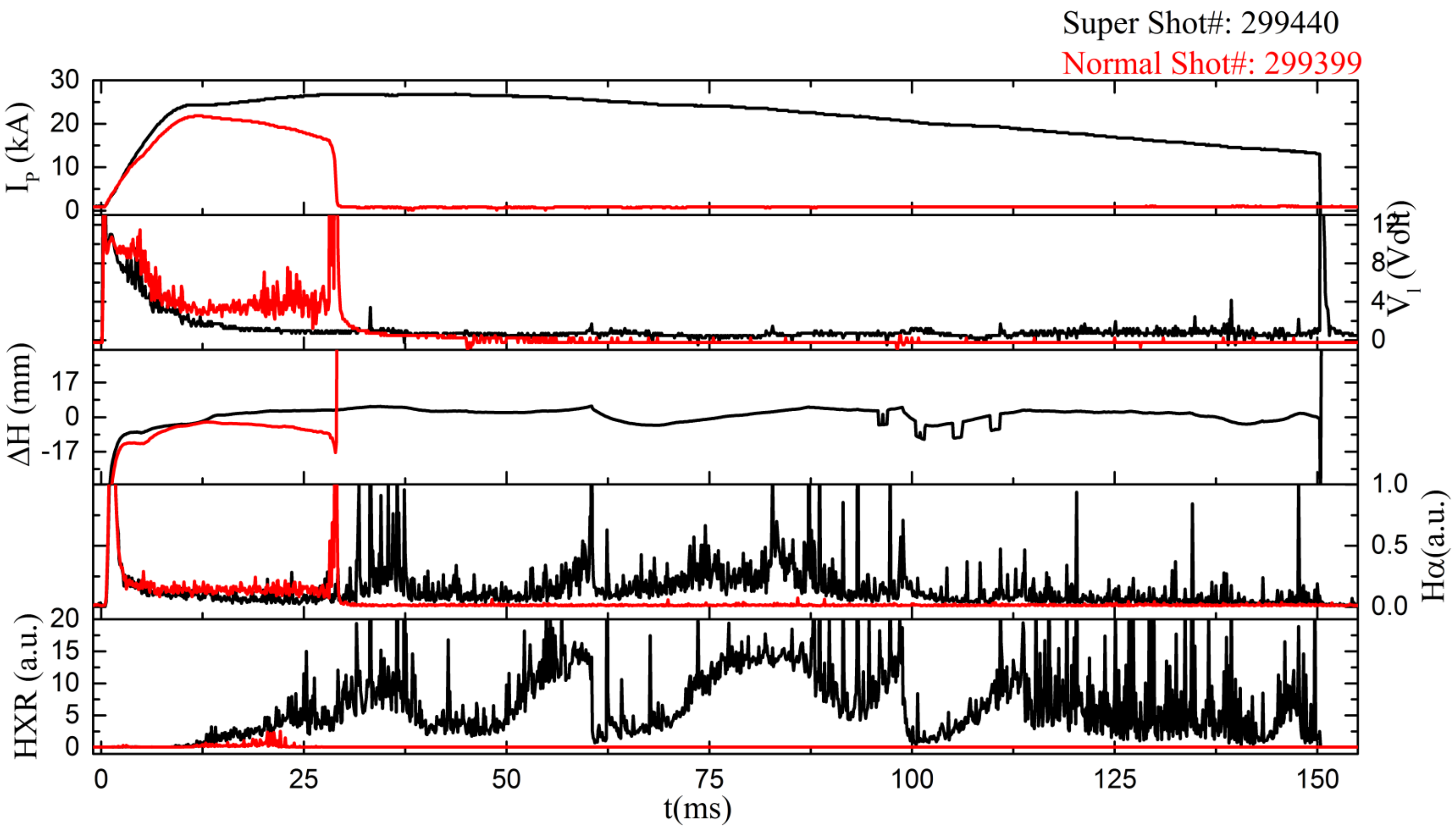


Li evaporator

Significant reduction of gaseous impurity in the chamber after Li coating



$P = 8.5\ \times 10^{-8}$ torr



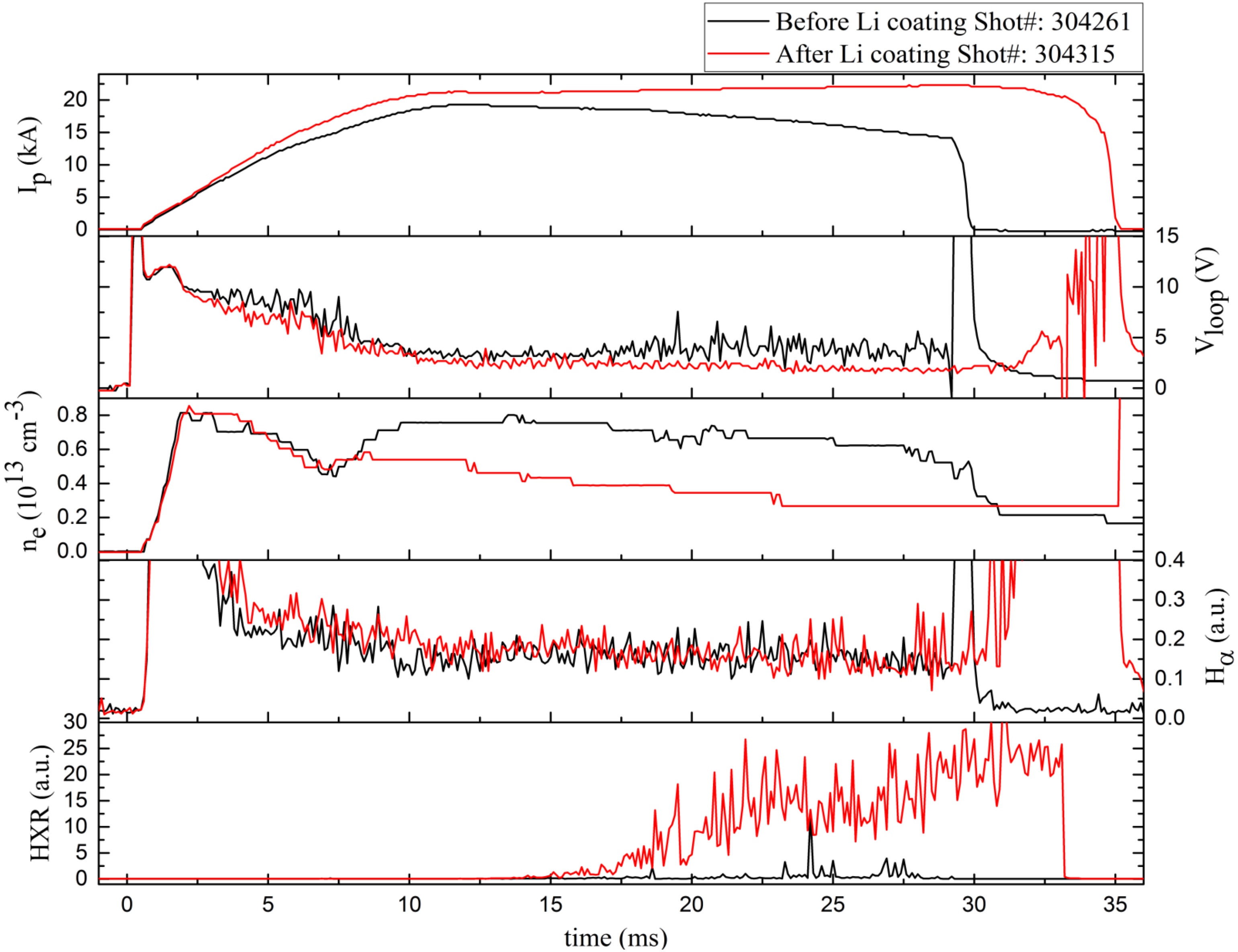
normal shot: terminated by gas puffing

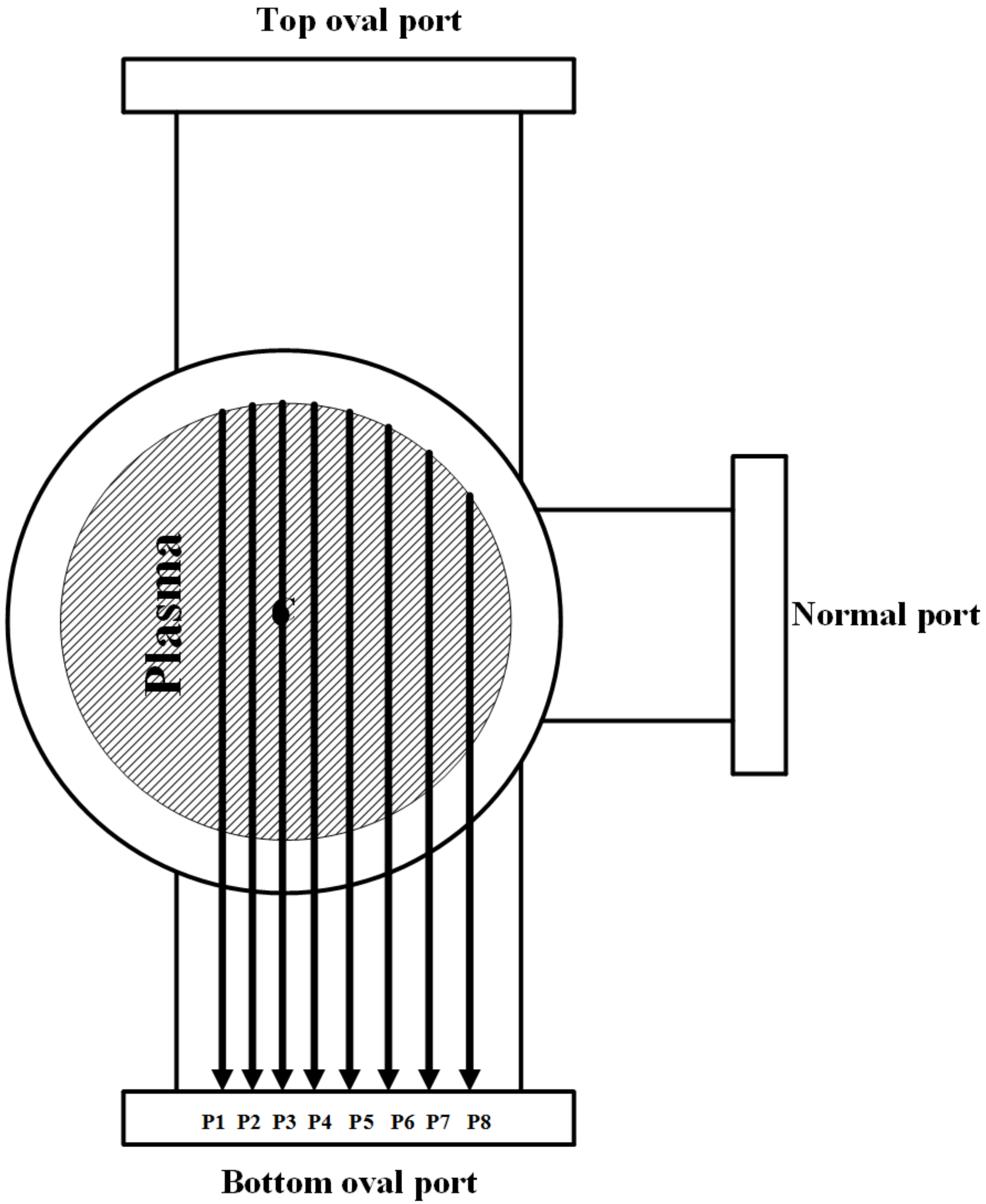
super shot after Li coating (without termination gas puffing).

- higher current, • lower loop voltage,
- high HXR (runaway electrons?), • terminated by disruption.

Plasma parameters after Li coating

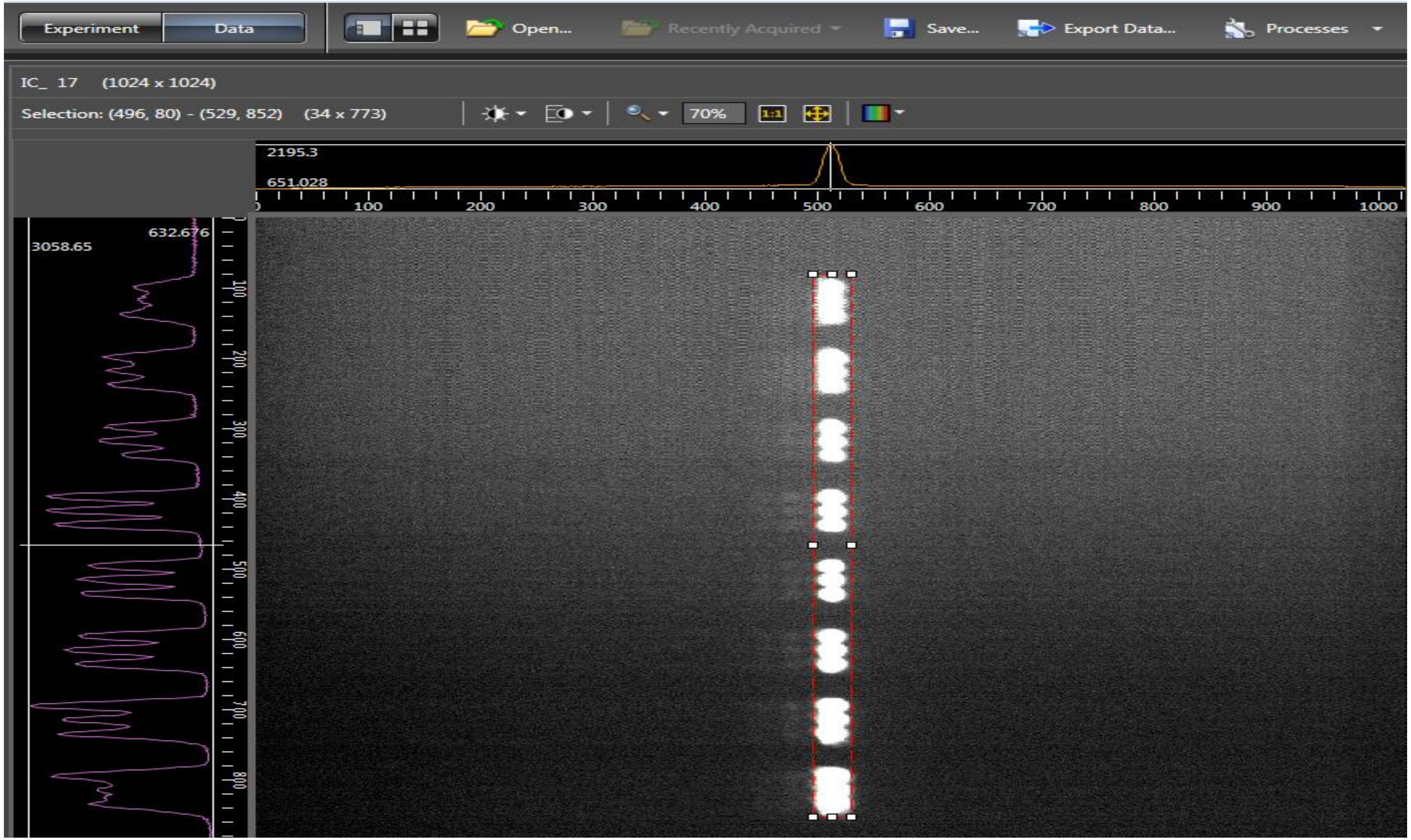
Li Coating





Impurity emission measurements

- 8-channel F.O. bundle
- Collimators at 8 vertical radial locations
- Imaging spectrometer
- ICCD camera



IC_ 17 (1024 x 1024)

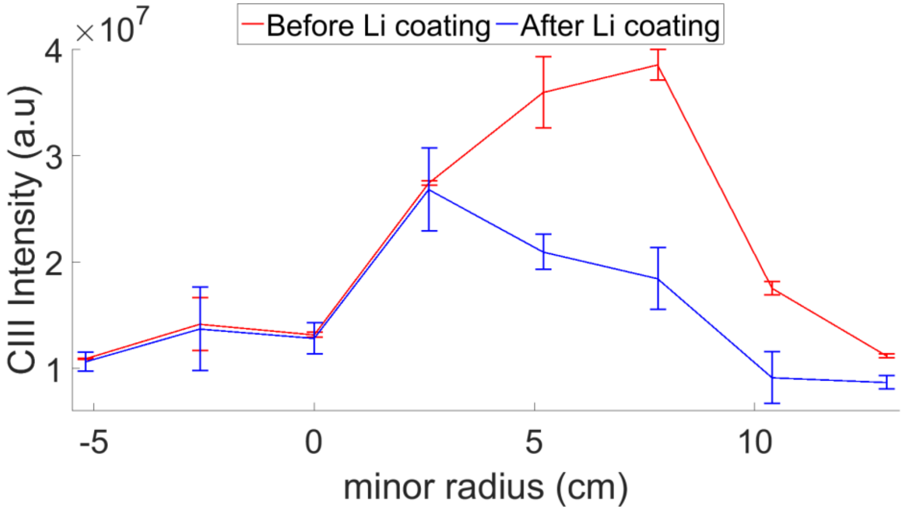
Selection: (496, 80) - (529, 852) (34 x 773)

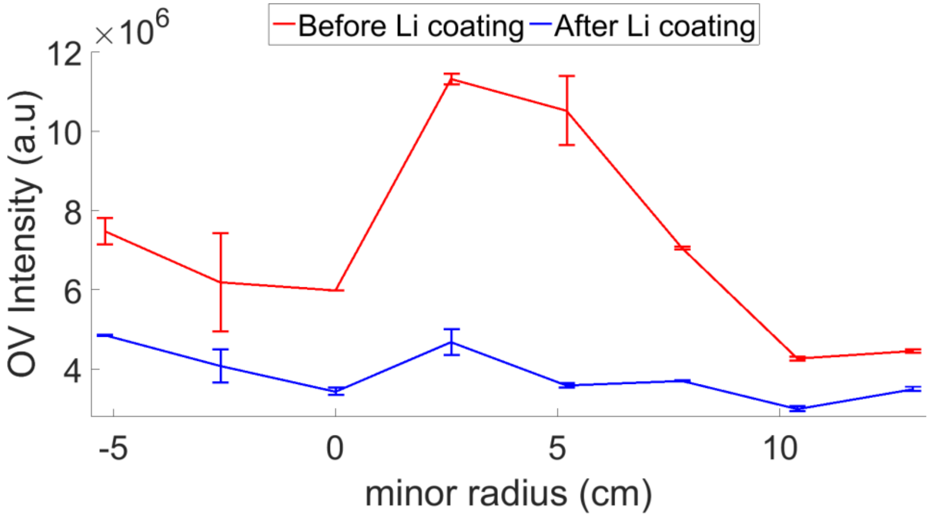
radius

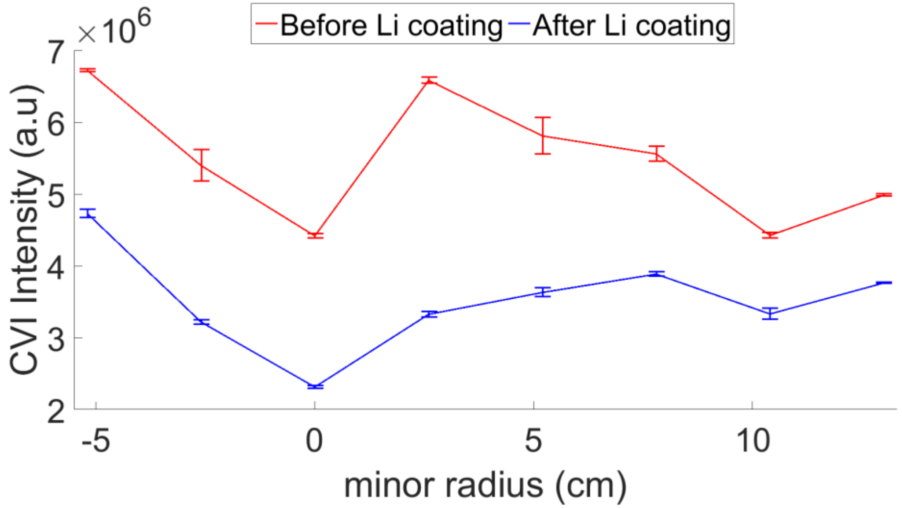
wavelength

Li Coating

Spectroscopy measurements of Plasma impurities





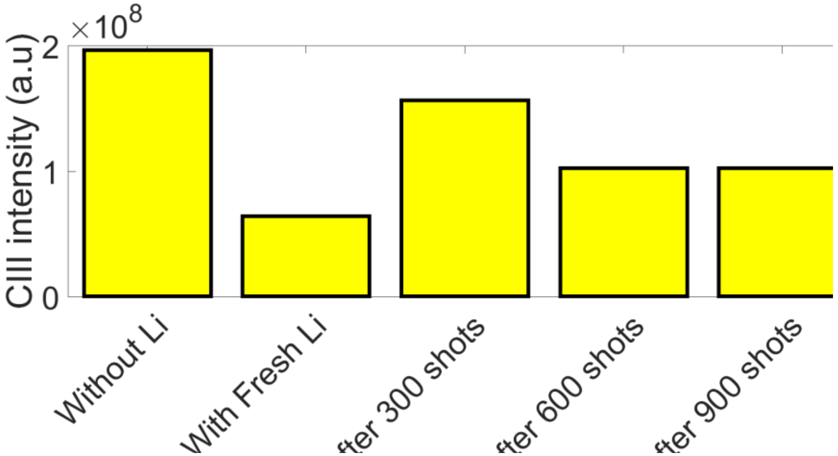


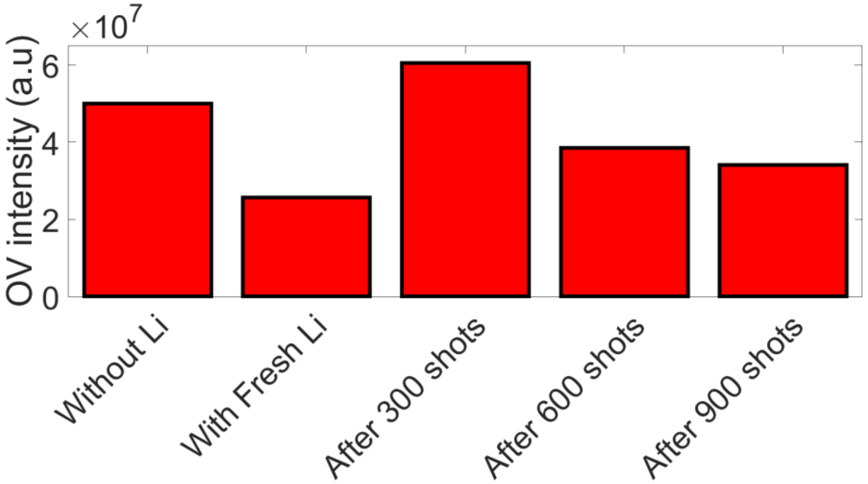
Immediately after Li coating

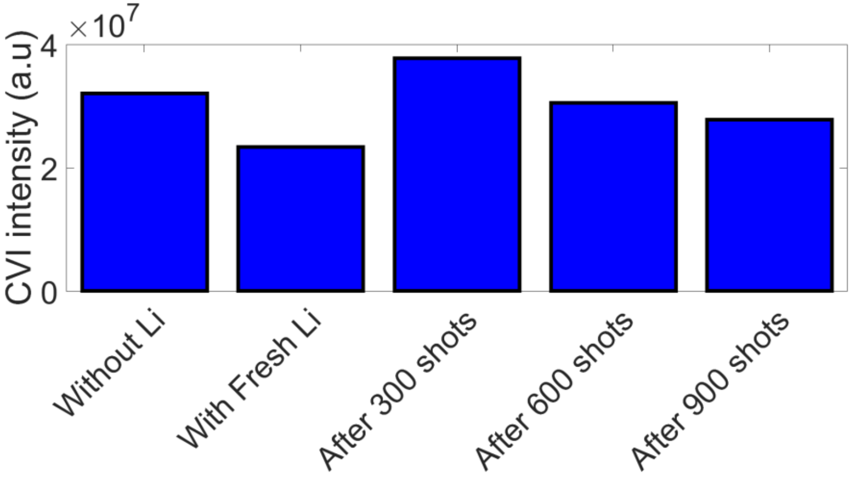
- All impurity emission level reduces

Li Coating

Evolution of Plasma Impurities after Tokamak Discharges



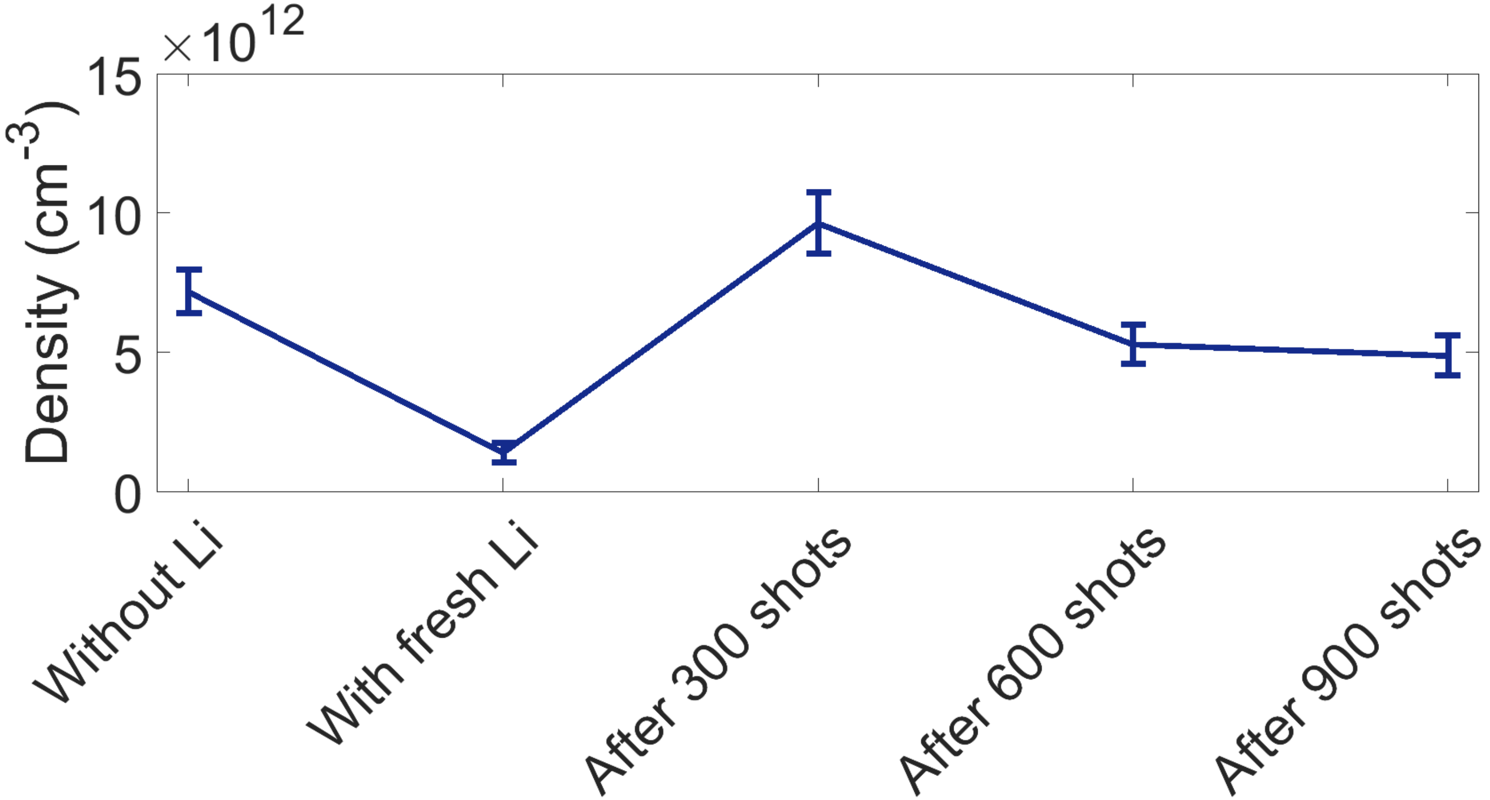




Impurity line emission summed over those at all 8 radial locations: reduced when freshly coated.

Li Coating

Plasma Density v.s. Number of Shots After Li Coating



Summary

- Repetitive CT operation up to 10 Hz has been achieved (and 100 Hz operation is planned)
- Tangential CT injection is able to control the toroidal flow velocities of the tokamak plasma through momentum injection
- Surface coating on STOR-M with Lithium has resulted reduced fuel recycling, reduced impurity radiation, increased plasma current and increase HXR emission.

Thank you!