# A space-charge-neutralizing plasma for beam drift compression

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# Overview

- Requirements of space-charge neutralization
- Neutralizing plasma channel
- Fabrication of cathodic arc plasma sources
- Development of a movable plasma probe array
- Achievements/conclusion

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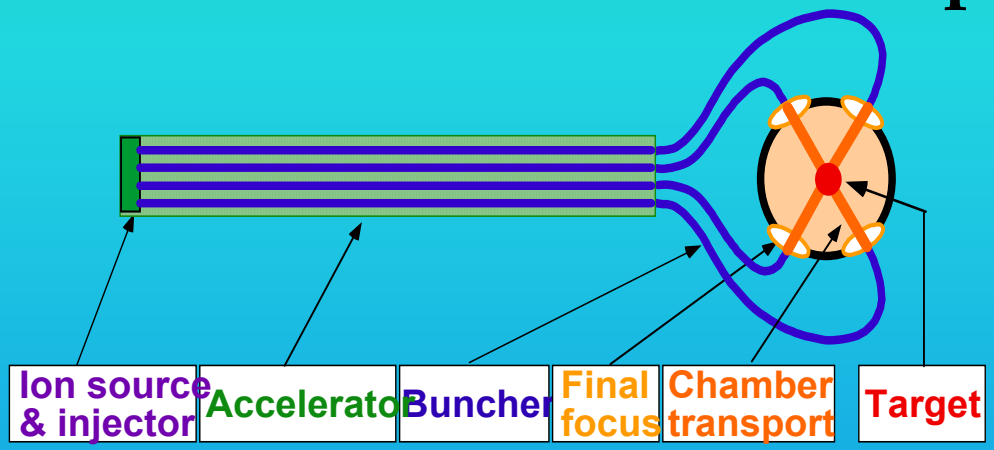
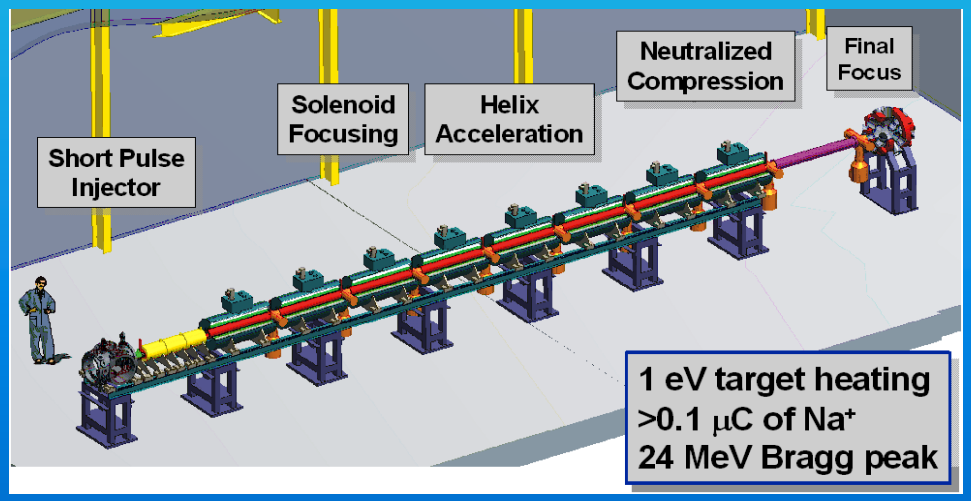
# The HIF Driver/WDM experiments require beam compressions

## to hit mm-sized spot with ns pulse



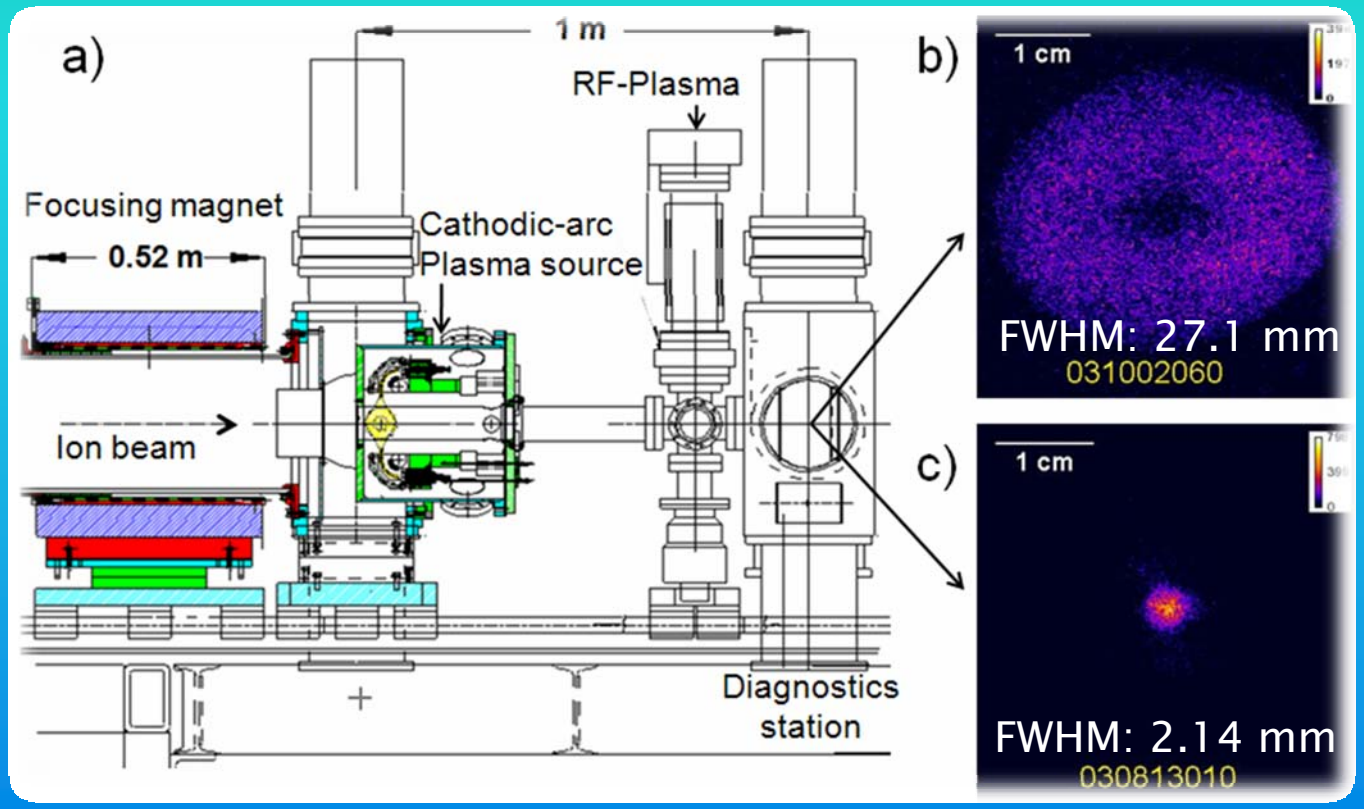




One concept of WDM facility

Examples

| | HIF Driver | WDM |
|---|---|---|
| Beam | ~40 kA (~4GeV) | ~200A (~23MeV) |
| Beam number | ~120 | 1 |
| Focal spot | 2 mm | 1 mm |
| Pulse length | ~10 ns | ~1 ns |

# Plasma electrons neutralized beam transport can provide ~mm spot



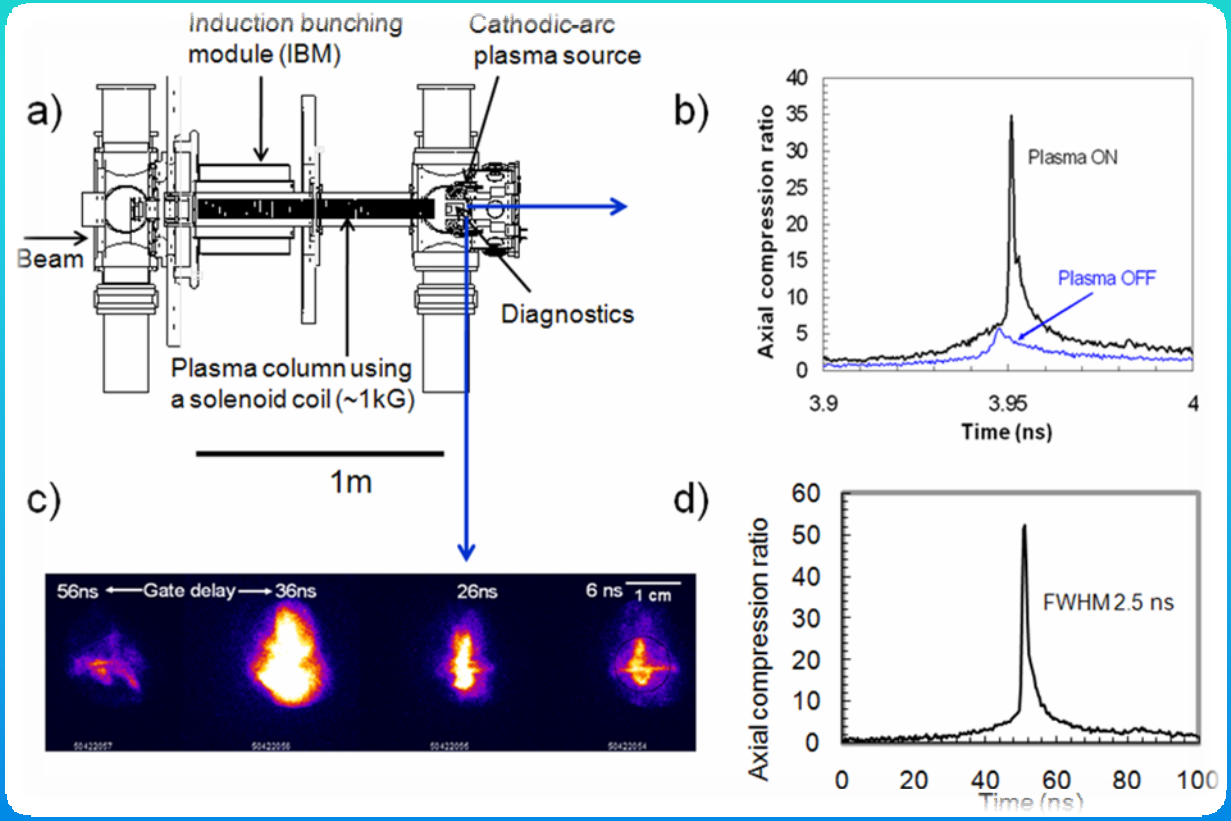

Typically,

$$\frac{n_p}{Zn_b} > 1$$

One of many examples: Roy et al NIMA 544 (2005) 225

In beam neutralization, electrons from a plasma or external source are entrained by the beam and neutralize the space charge sufficiently that the pulse focuses on the target in a nearly ballistic manner to a small spot.

# Longitudinal compression with neutralization can provide nanosecond pulse beam




Compressed pulse length

$$t_p = \frac{L}{v_L^{\,2}}\sqrt{\frac{2kT_L}{M}}$$

One of many examples: Roy et al PRL 95(2005) 23481

In neutralized drift compression beam is longitudinally compressed by imposing a linear head-to-tail velocity tilt to a drifting neutralized beam and producing a pulse duration of 2-3 ns.

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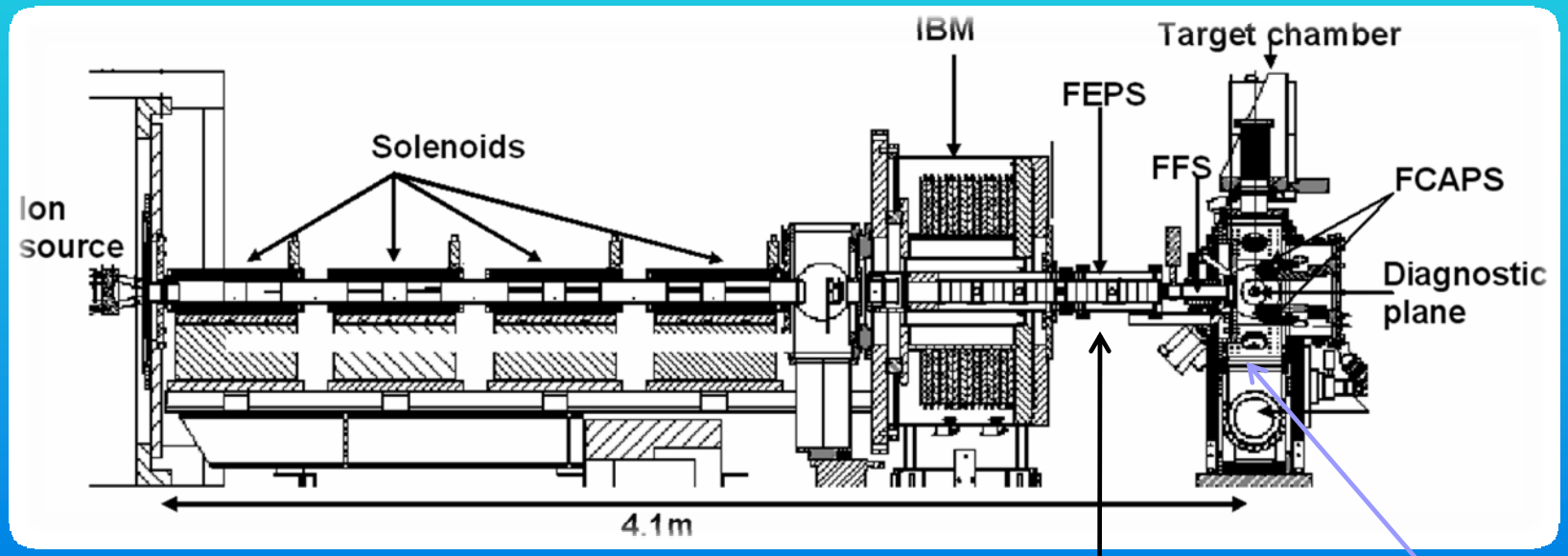
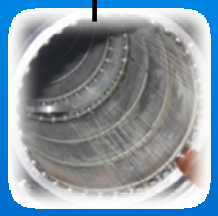
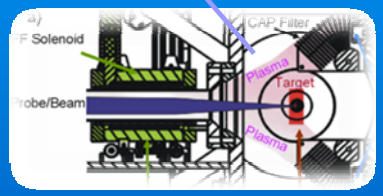
# A space charge neutralizing plasma channel for beam drift compression

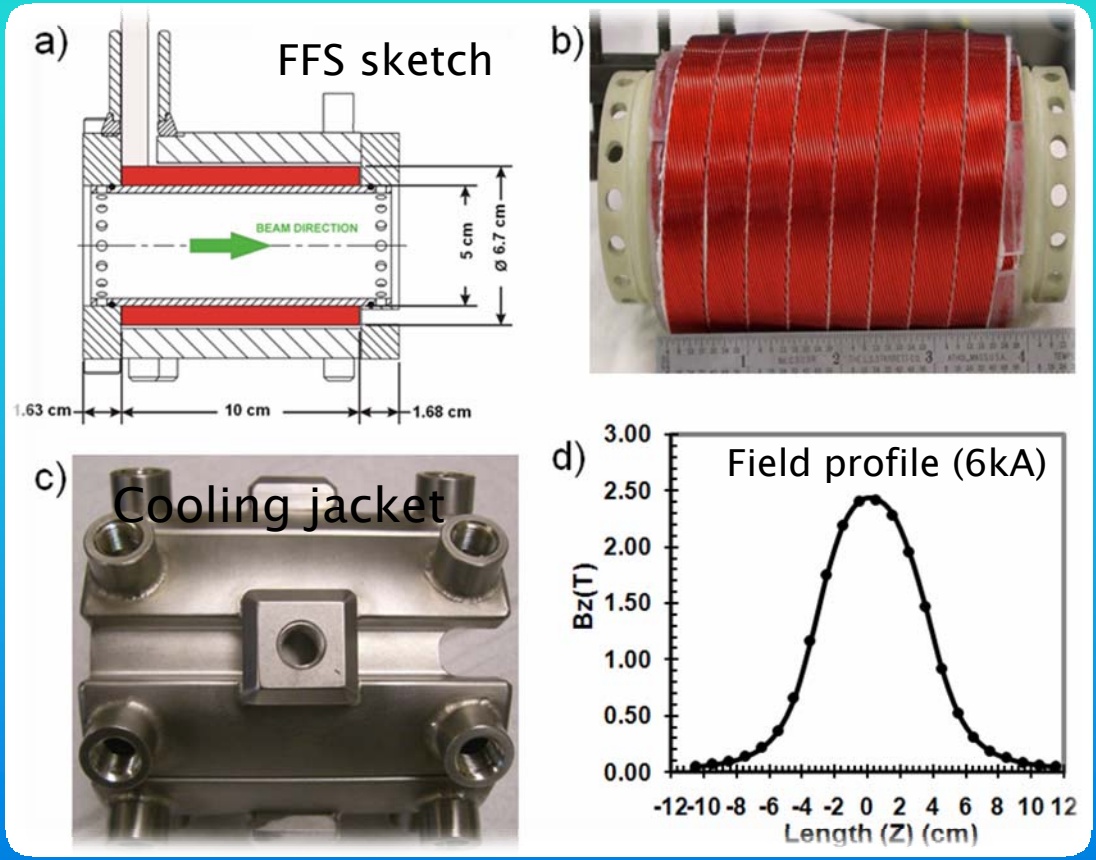
- A Ferro-electric plasma source (FEPS) injects plasma in the radial direction.
- A cathodic arc plasma source (CAPS) provides plasma near the target.
- A final focus solenoid (FFS) provides strong beam focusing field near the target, & its fringe field concentrates the CAPS plasma on axis near the target plane.



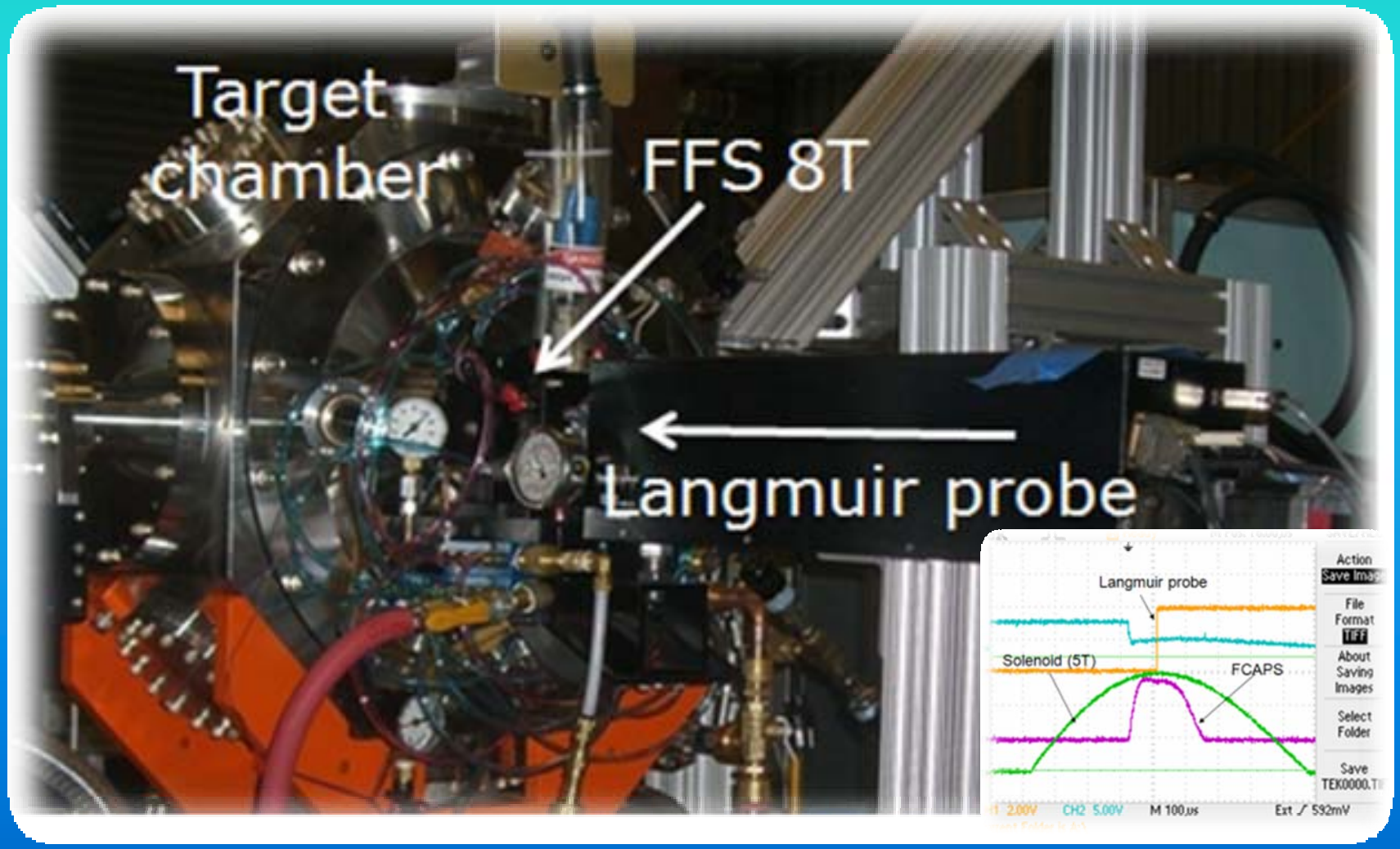


# A strong final focus magnet increases beam density near the target plane

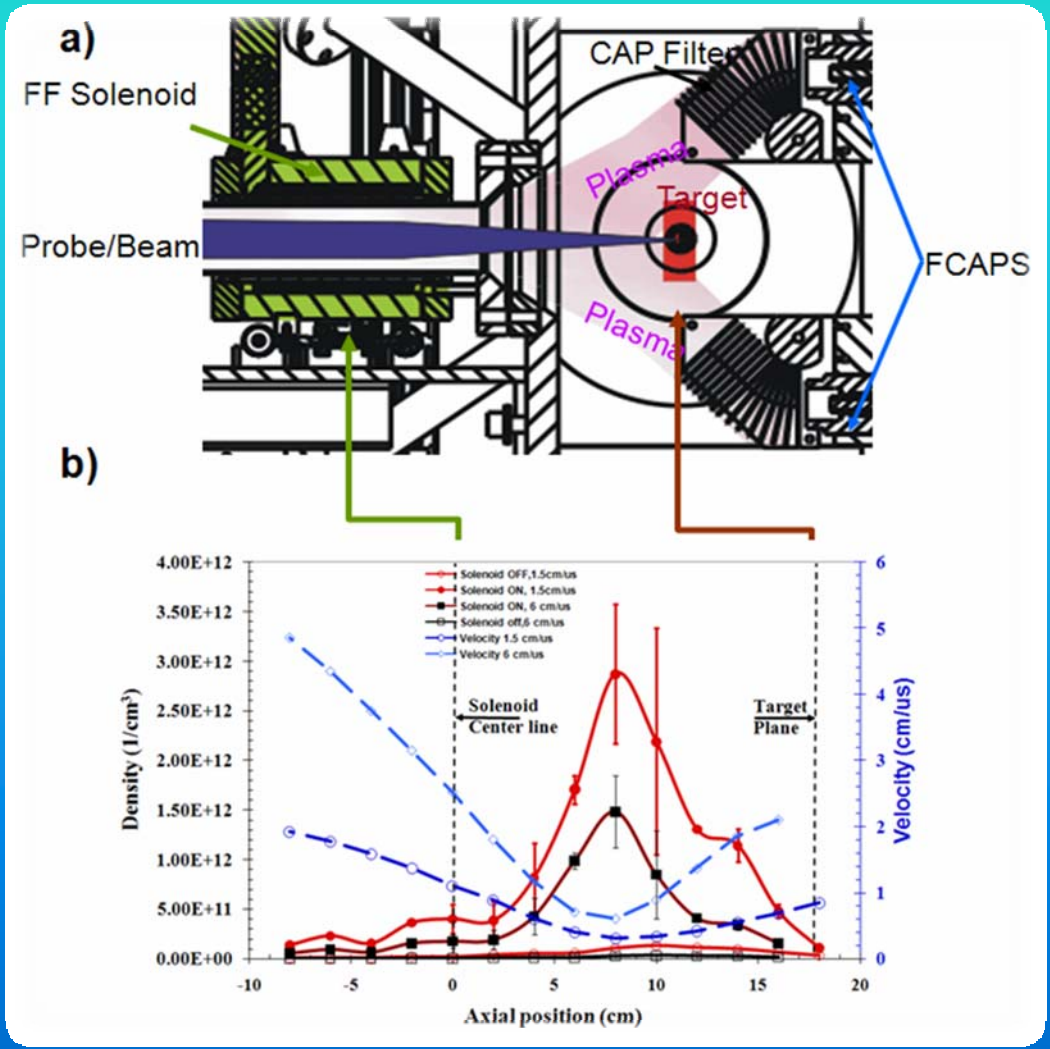



- 8T FFS magnet with 837-μs pulses & a peak current of 21.7 kA
- 1.5 kJ/pulse, which necessitates active cooling.

# Setup to measure axial plasma using single Langmuir probe

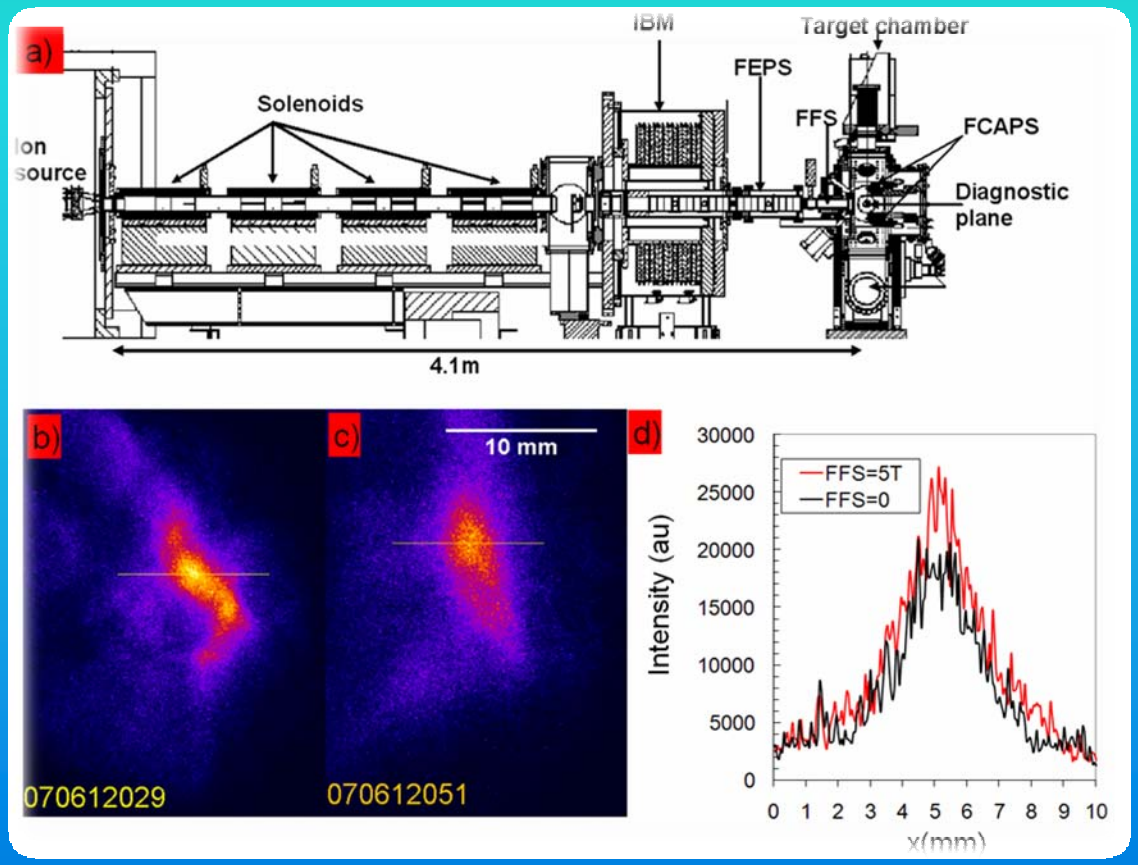


# The two-FCAPS provides a plasma density of $\leq 10^{12}$ /cm$^3$ when the FFS was powered.




- Maximum plasma density $\leq 2.8\times10^{12}$ /cm$^3$ between the gap of the FFS and the target plane, where the plasma electron velocity was lower due to the FFS field & Filter field.

# A higher plasma density may further decrease the focal beam spot size




| FFS | FWHM |
|---|---|
| 5T | 2.2 mm |
| off | 3 mm |
| IBM:25 kV<br>FCAPS: 1kV<br>FEPS:9kV | |

**Expected Beam peak density**

- ❑ **Compressed: ~$1.5\times10^{12}$ cm$^{-3}$**
- ❑ **Non-compressed ~$1.8\times10^{8}$ cm$^{-3}$**

❑ Expected beam deposition energy ≥ 18 mJ/cm$^2$
(60 fold and 1.3 mm edge radius, with 300 keV, 26 mA, 15mm edge radius input beam)

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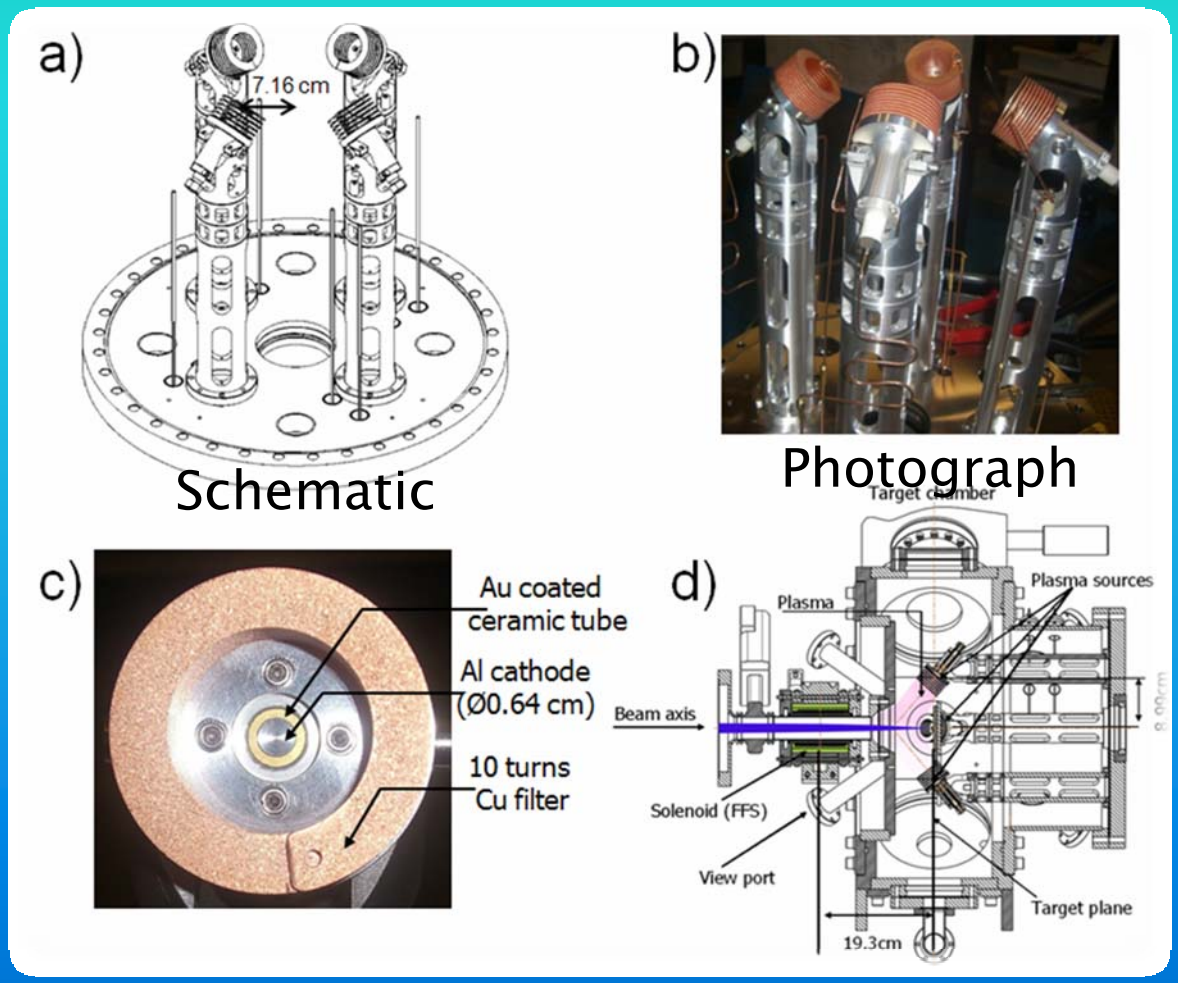
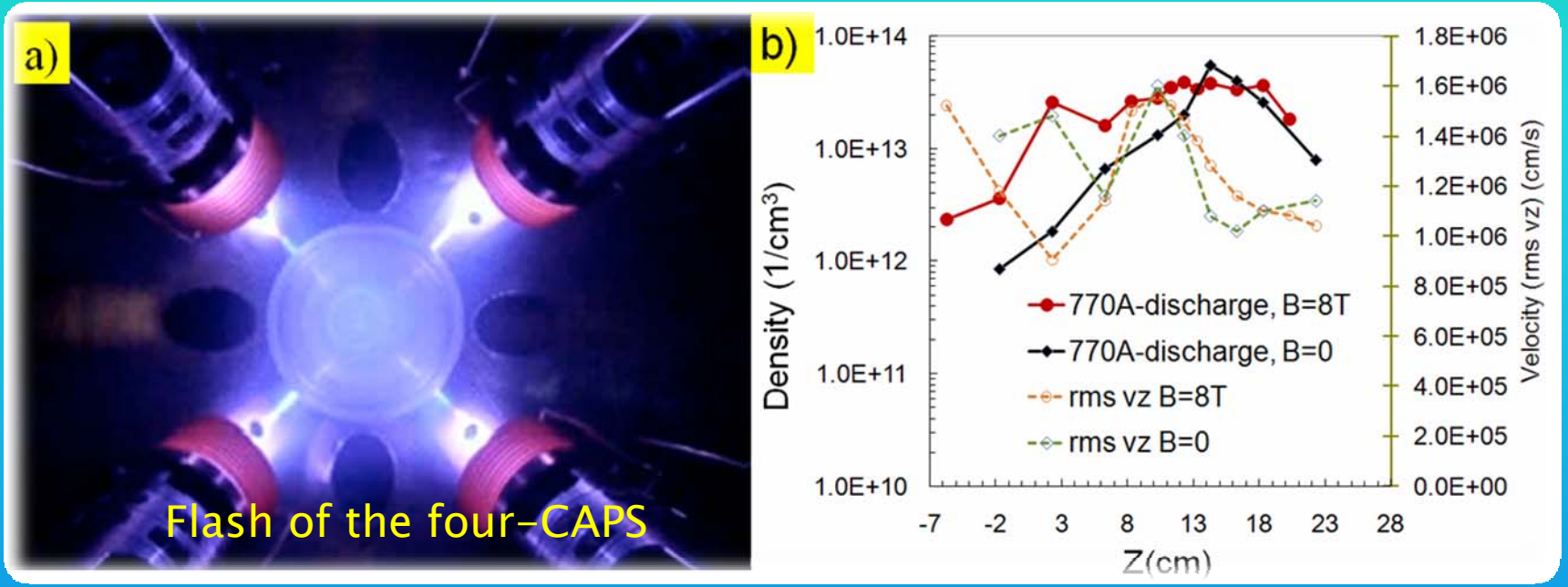
# FCAPS system with bent filter replaced by a CAPS system with straight filter

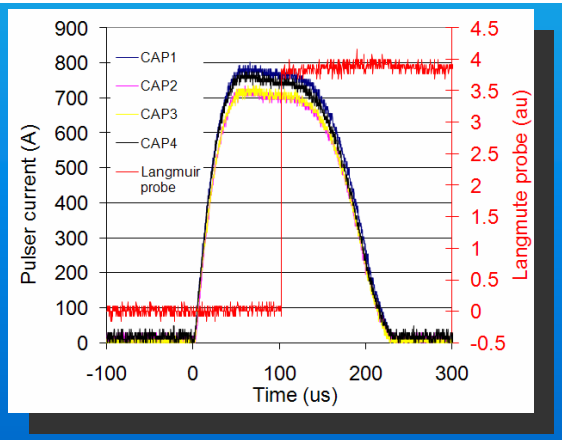



A cathode & filter

Target chamber

# The new four-CAP provides ~30 times greater plasma than the two-FCAPS with bent filters




- The calculated average velocities were considered for the FFS on or off, and for various axial locations. These calculated velocities were well matched with some measured velocities, measured using TOF.

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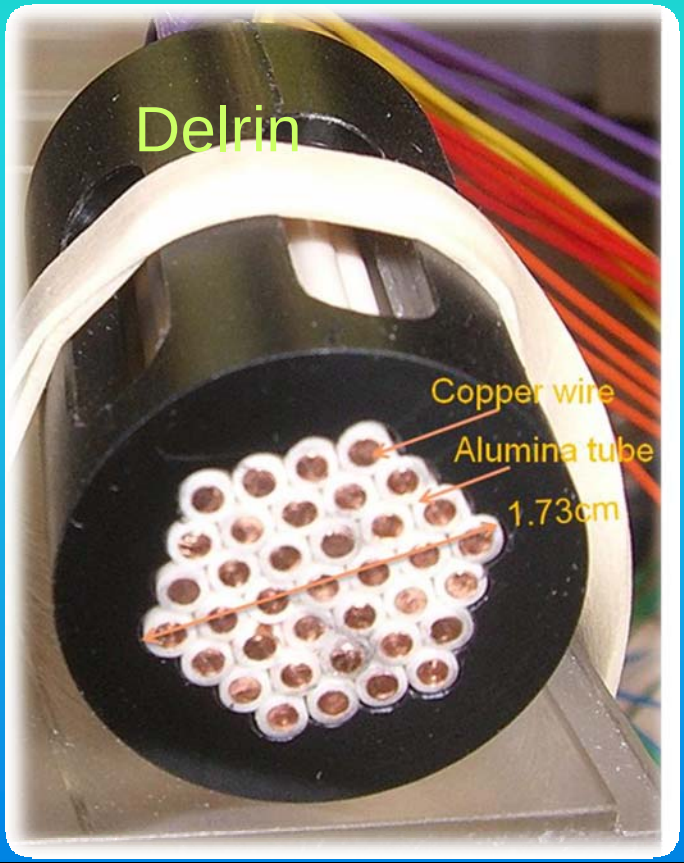
The single Langmuir probe has several drawbacks. It has a one to two mm droop within the 30 cm axial travelling distance, and the drive is along one axis only. In addition, the probe only covers an area of 1.46 $mm^2$. Also, the cross sectional area might provide error when the covering kapton insulation is coated for higher plasma discharges. Therefore, a new radial plasma probe was developed

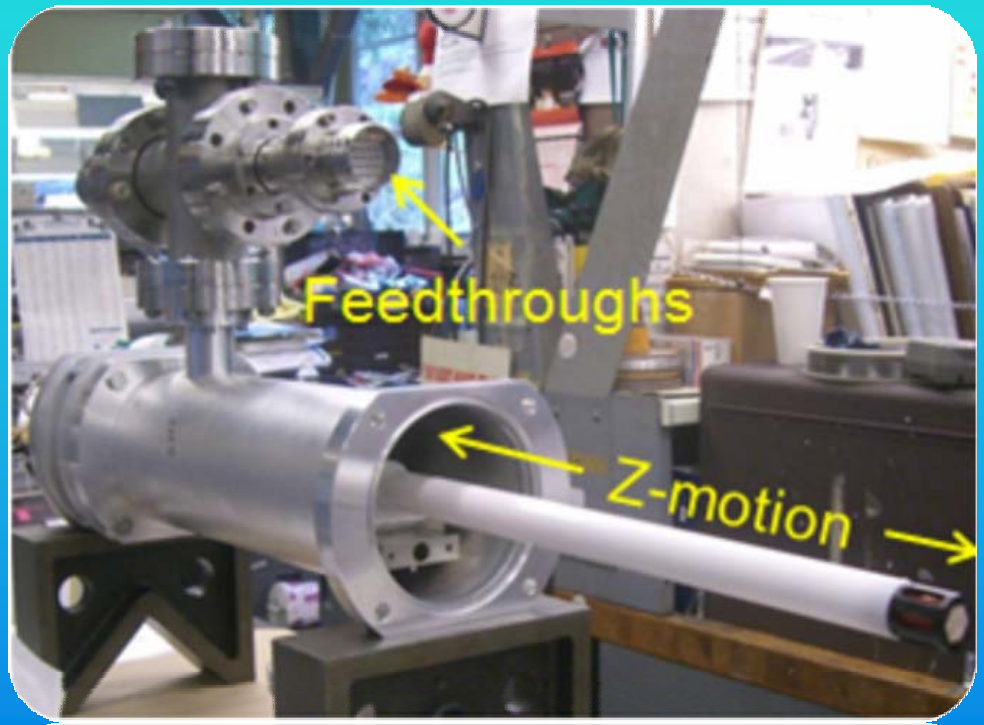
# An array of 37 collectors to measure radial and axial plasma distribution



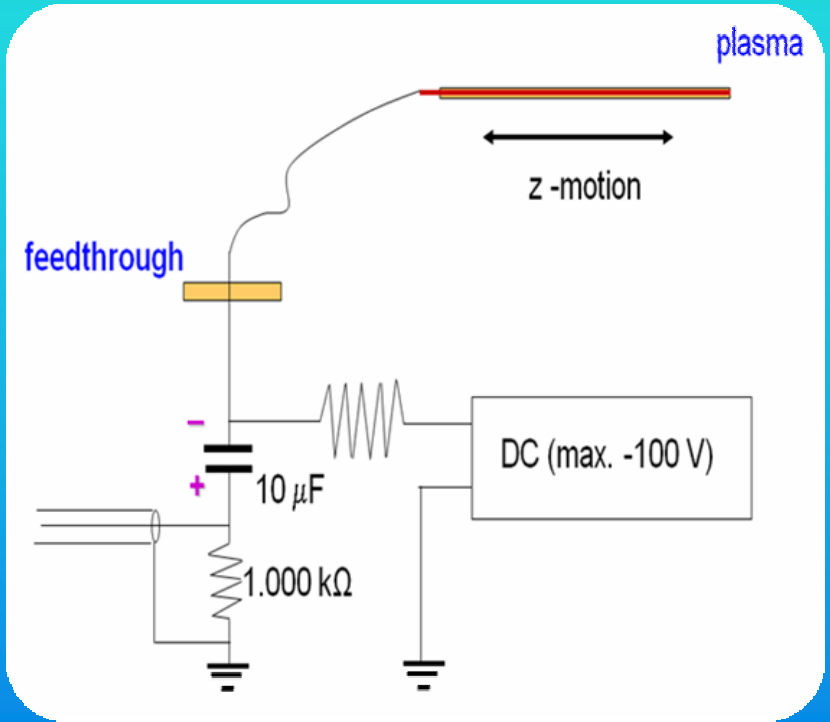

- 37 collectors
- Diameter 1.60 mm each,
- Center-to-center: 2.46 mm

| Name | Number |
|---|---|
| Number of collector | 37 |
| Collector material | Copper |
| Collector wire size | 24 Gauge (1.6mm diameter) |
| A collector area | 2.01 $mm^2$ |
| Collector shielding | Alumina tube |
| Alumina tube (each)<br>Outer diameter<br>Inner diameter<br>Length | <br>2.46 mm<br>1.64 mm<br>38.1 mm |
| Distance between wires | 2.46 mm (Center to center) |
| Total diameter of the probe (37 collectors) | 1.73 cm |
| Total probe area | 2.35 $cm^2$ |

# The axial drive unit of the probe array

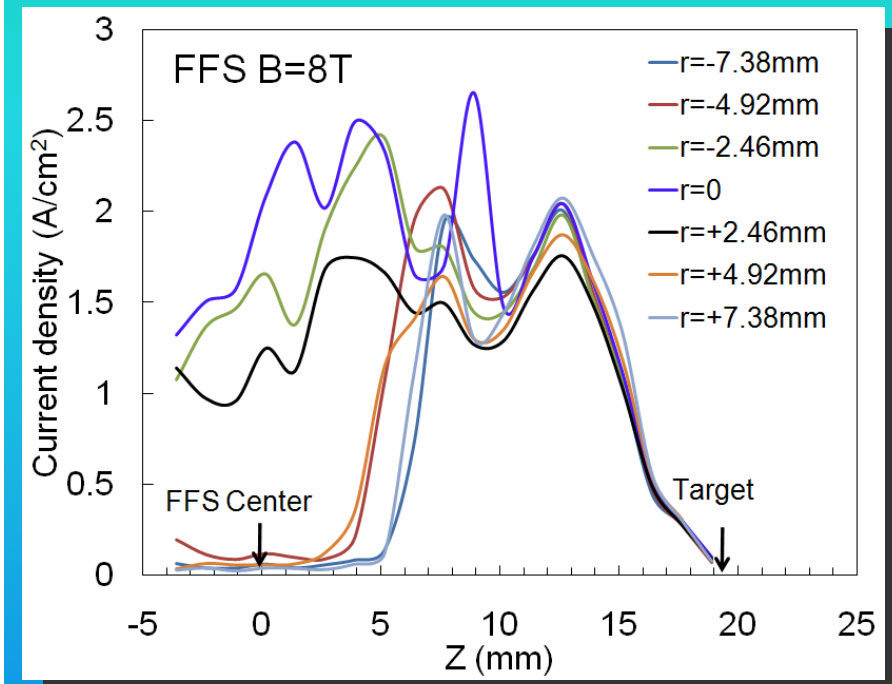


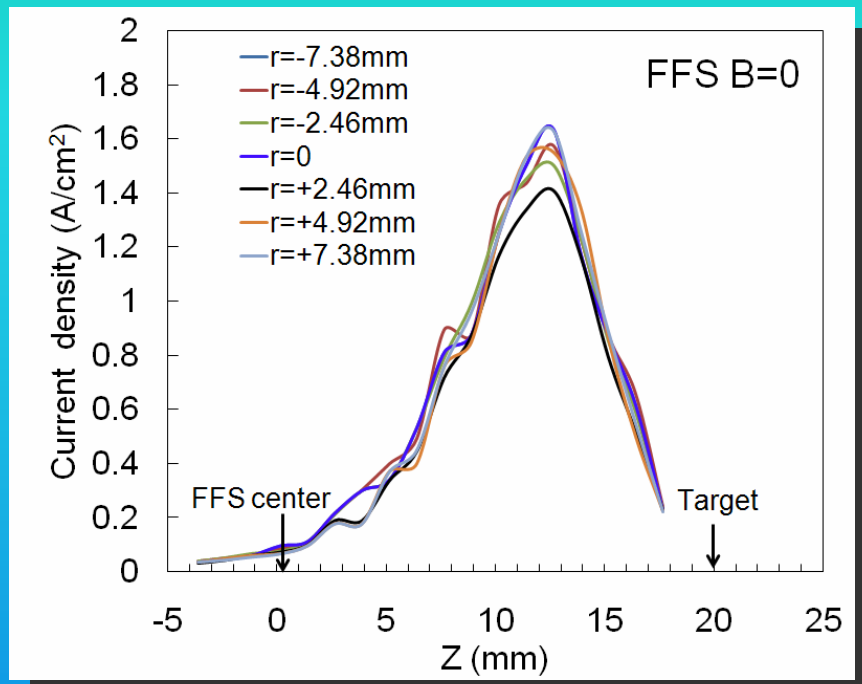

The precise 23.5 cm z-motion position was established using a fine position monitor



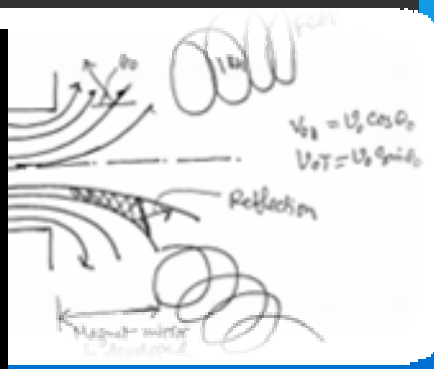

Circuit diagram for one collector, biased to 70 V for operation in the ion saturation mode.

# Plasma forms a thin column of diameter ~5mm along the 8T solenoid axis

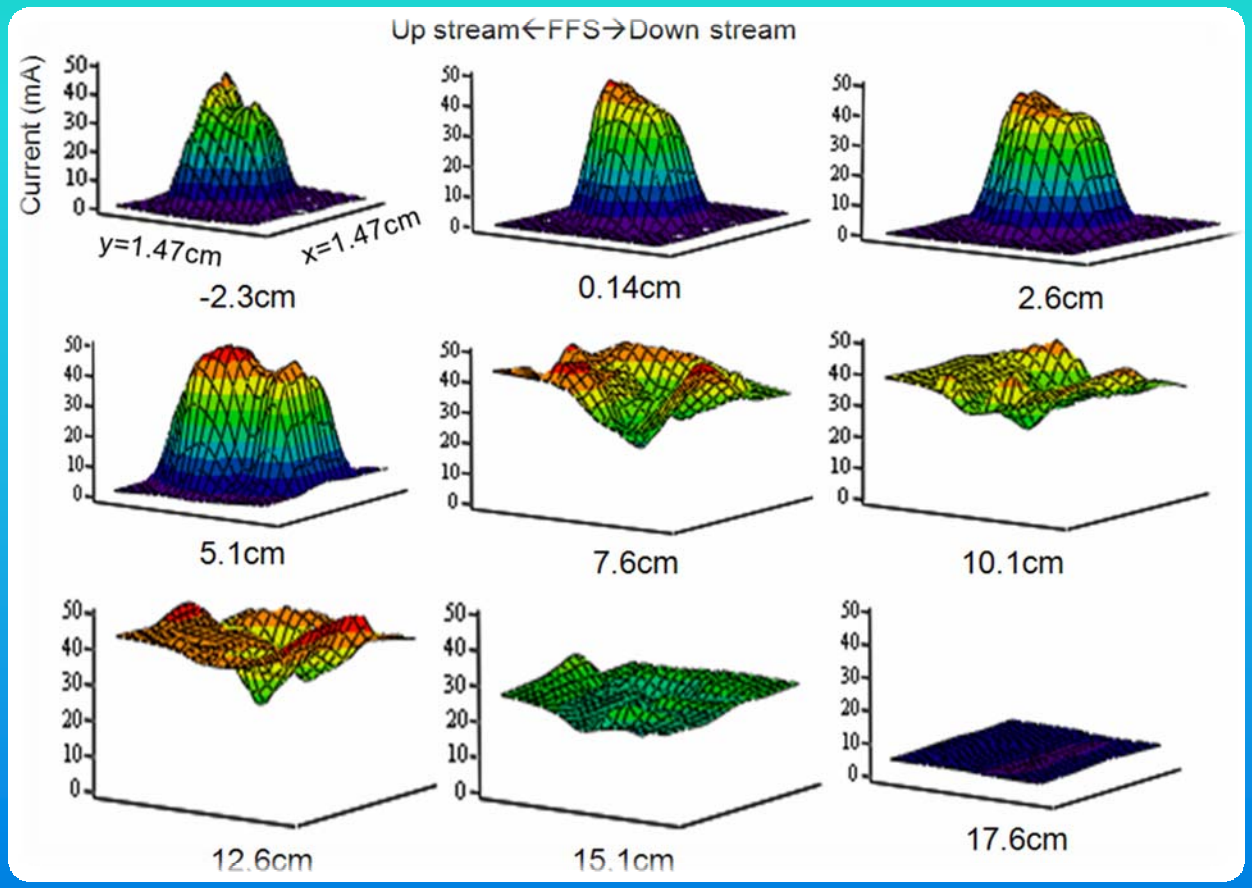


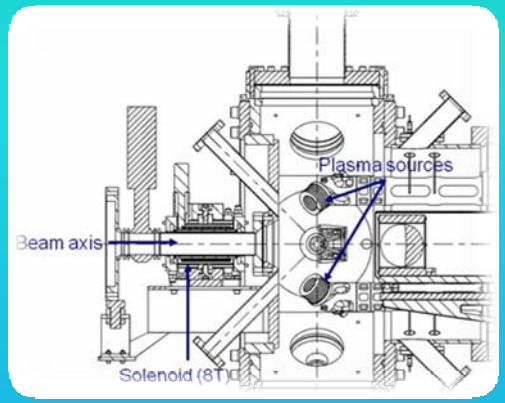




- Particles entering the FFS with minimum angles passed through the axis to the downstream end of the FFS with their axial velocity, $v_{0\parallel}=v_0\cos\theta_0$.
- Those particles with higher incident angles ($v_{0\parallel}=v_0\cos\theta_0$) to the beam axis, reflected back from where the adjacent field lines were dense and developed a magnetic mirror.

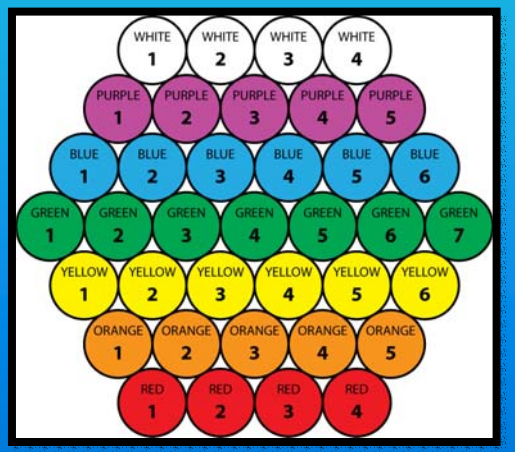


# Transverse & axial plasma distribution (surface plot) using the 37 collectors



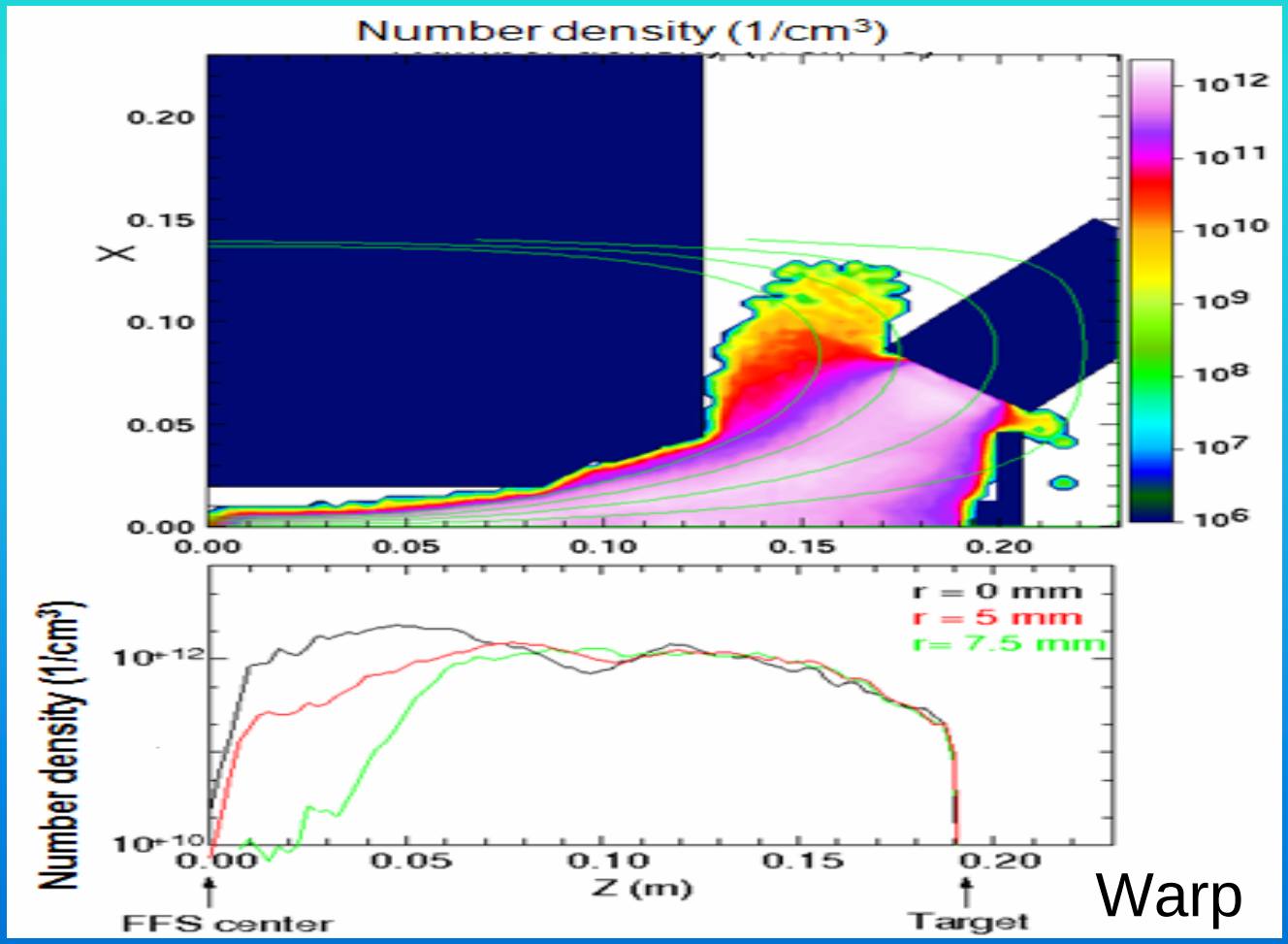

B=8T, 1CAPS:770A




37 collectors

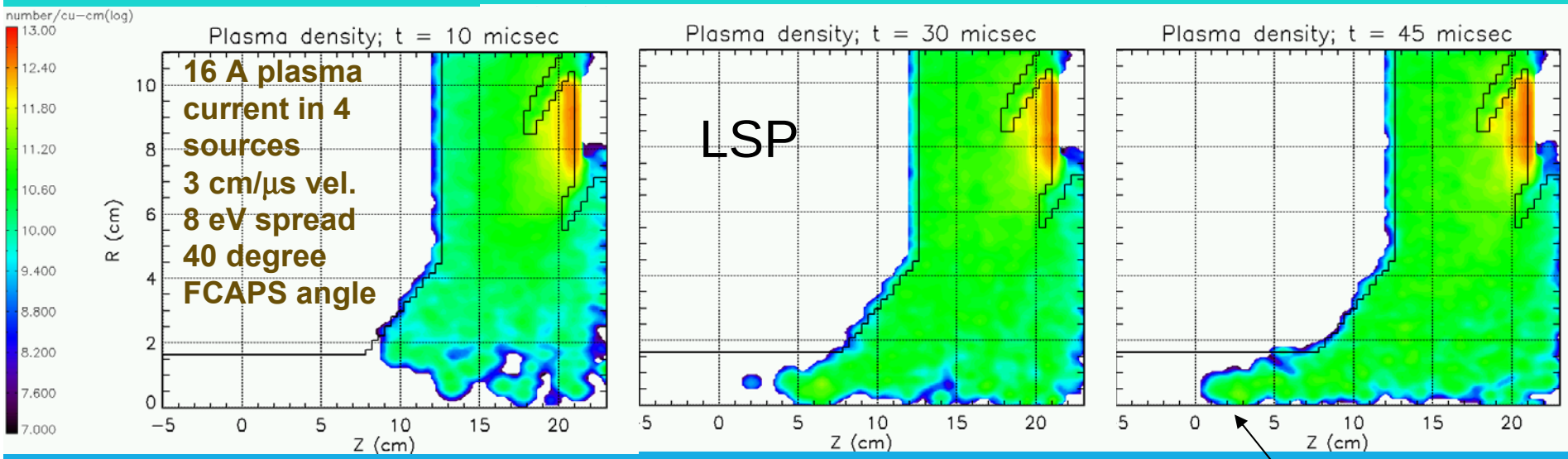
- The electrons mobility enhances the plasma diffusion.

# 3-D electrostatic PIC simulation shows qualitative agreement with experiment.




- with velocity of 3 cm/μs,temperature of 7 eV
- The density rapidly falls off, off-axis inside the solenoid.
- The peak density is ~10 smaller than experiment is due to a smaller injected plasma density out of the FCAPS.

# Electron mobility, space charge slows plasma drift into solenoid



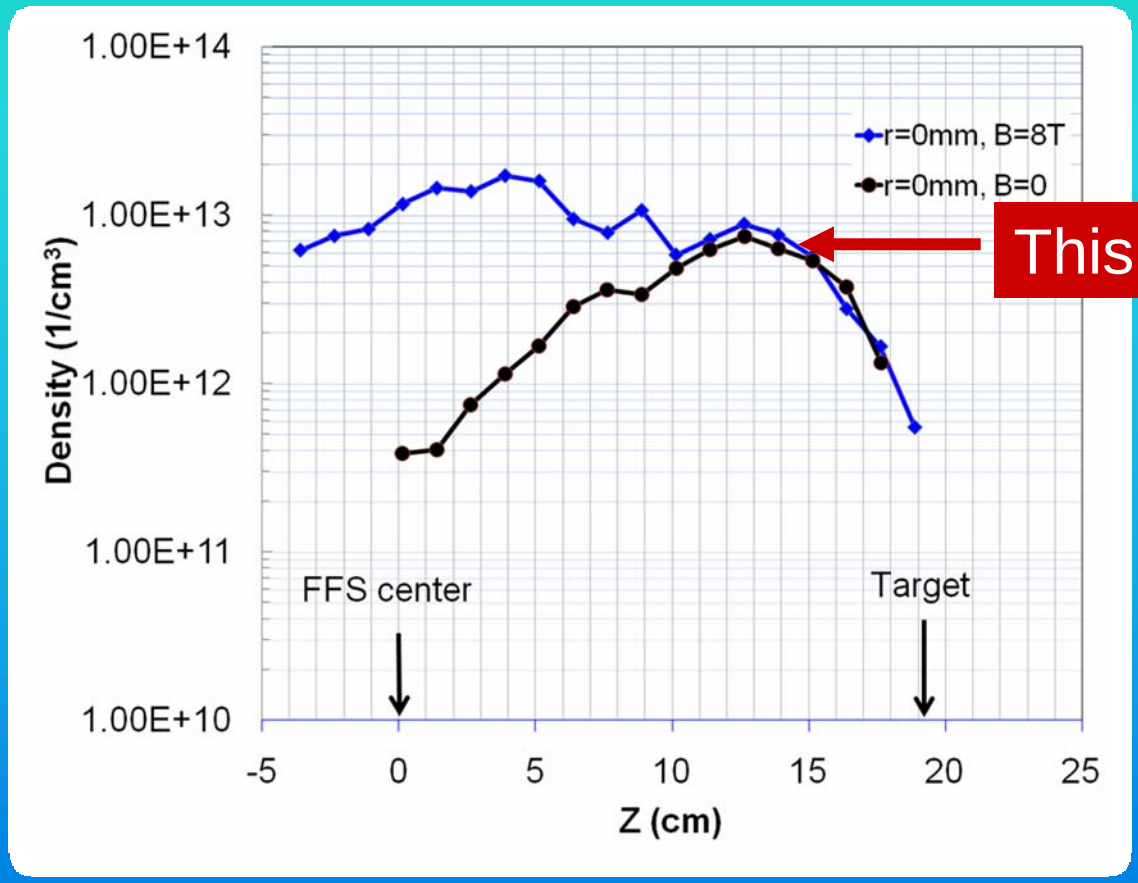

$10^{11}$ $cm^{-3}$ plasma slowly fills bore of solenoid

**Simulation parameters:**

- **3D cylindrical, period in θ (1/4 volume)**
- **8 T solenoidal fields calculated in time-dependent diffusion**
- **Full electromagnetic simulation with all Coulomb collisions**

**The 8T FF solenoid – much improved plasma source for transport!**

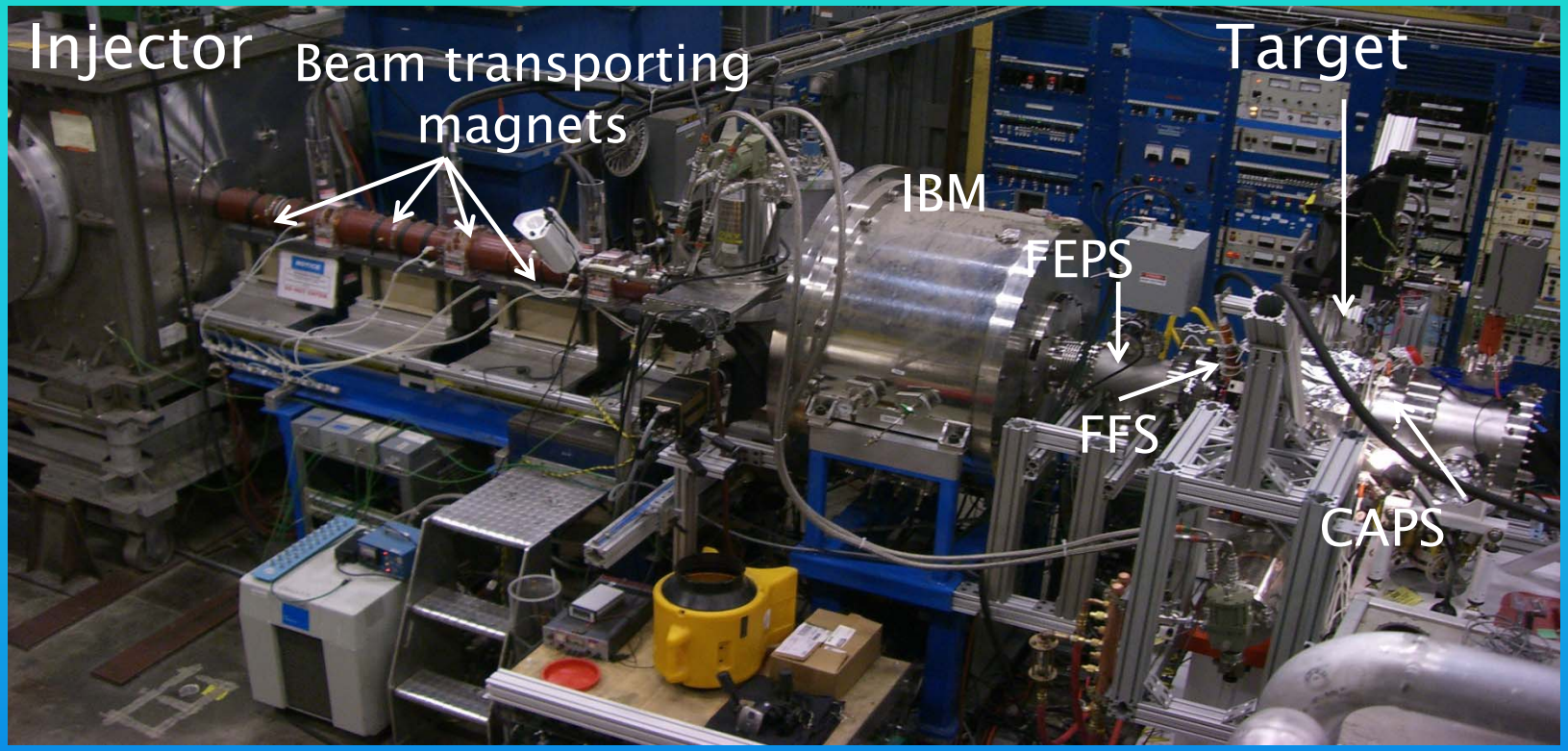
# The four-CAPS provides axial plasma of $\geq 10^{13}$ /cm$^3$ when the FFS was powered




This is the main result!

- The plasma (electrons & ions) drift into the bore using the diffusive B magnetic field map and the CAPS B field.
- The electrons mobility enhances the plasma diffusion.

# Integration of the plasma channel with beam drift compression experiments




Recently a beam profile of diameter ≤ 2.5 mm (at FWHM) was measured when the system operated for simultaneous radial and longitudinal compression.

# Summary

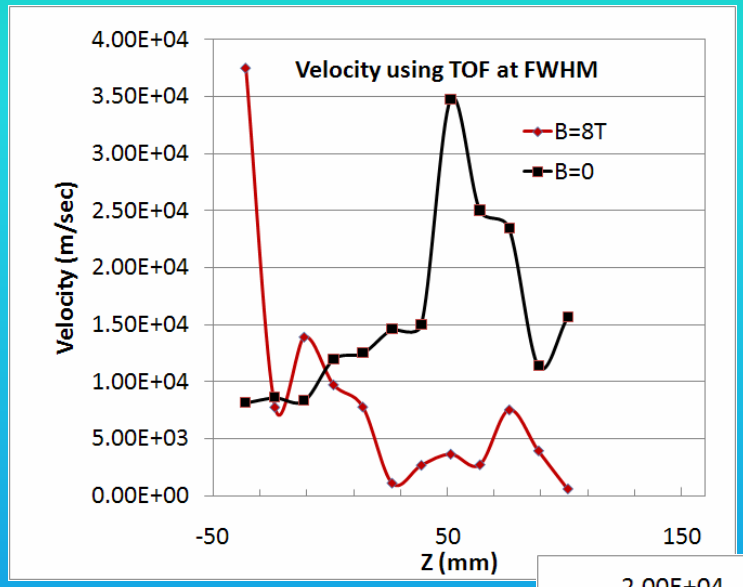
- We have successfully fabricated and operated four cathodic arc plasma sources, and the plasma was focused into a focusing solenoid with an 8 T field.

- A moveable plasma probe array with 37 collectors was developed to measure the radial and axial plasma distribution inside and outside of the solenoid.

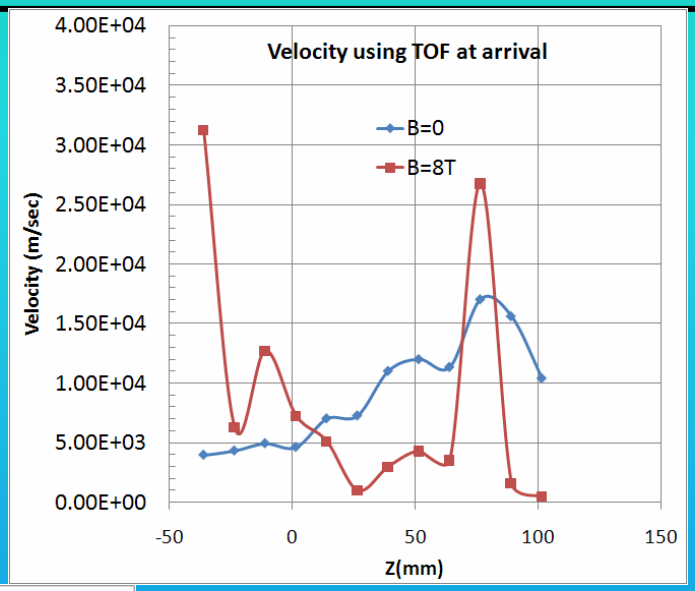
- A plasma electron density of $\geq 1 \times 10^{13}$ $cm^{-3}$ was achieved, and the plasma forms a thin column of diameter ~5 mm along the solenoid axis when the FFS is powered.

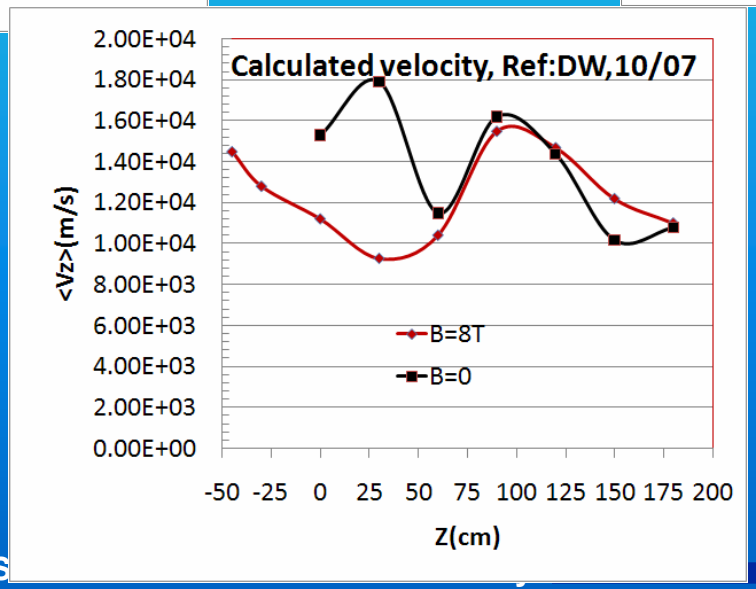
# Backup

# Conversion of plasma current to density depends on systematic velocity measurements

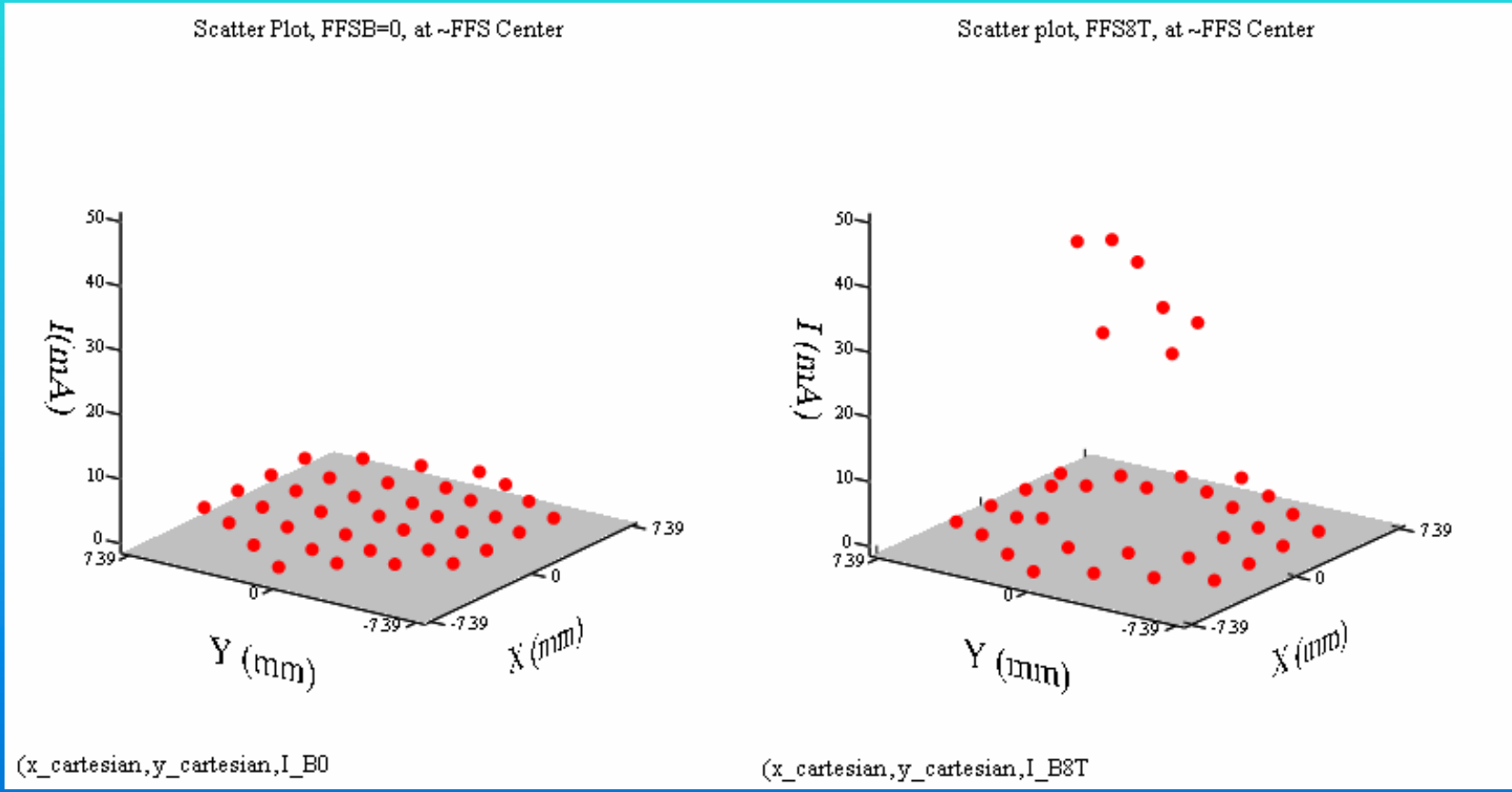



Measured velocity



# 37 collectors signals at the center of the FFS



# Plasma density: an example of conversion

Thumb tip (dice) radius $R_{th} := \frac{1.60}{2} \cdot mm$

$A_r := \pi \cdot R_{th}^2$

$A_r = 2.011\ mm^2$

Velocity (calculated) $v_e := 1.3 \cdot 10^4 \cdot \frac{m}{sec}$

Velocity (Measured) $v_{eM} := 5 \cdot 10^3 \cdot \frac{m}{sec}$

Charge of an electron $q_e := 1.6 \cdot 10^{-19} \cdot C$

Al+ charage state $Z := 2$

Plasma current
at the 5000mil drive (88.95 mm from the center of FFS solenoid) $I := 53.02 \cdot 10^{-3} \cdot A$

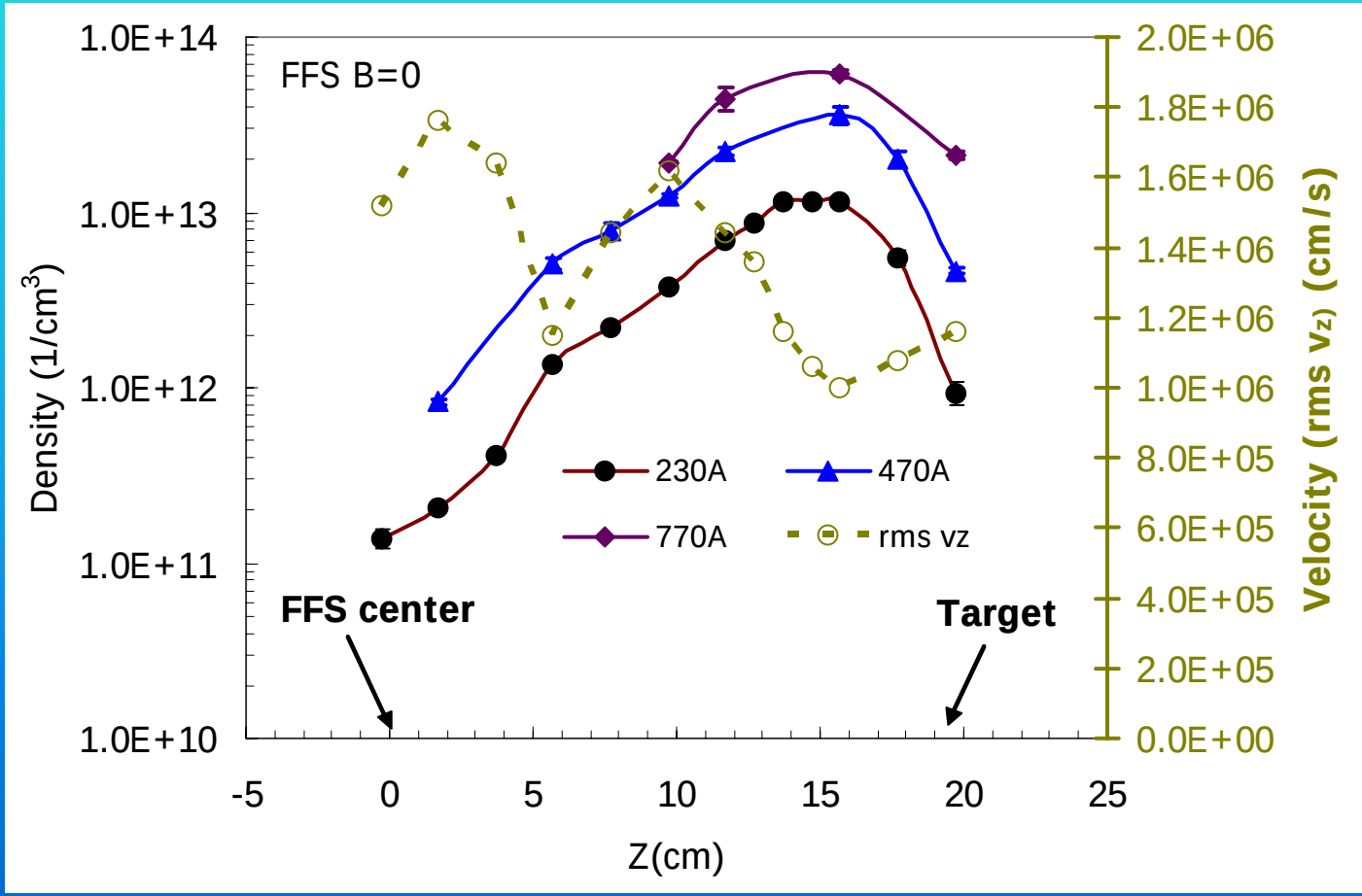
Number of particles $n_i(I, q, v, A, Z) := \frac{I}{A \cdot v \cdot q \cdot Z}$

$n_i(I, q_e, v_e, A_r, Z) = 6.339 \times 10^{12} \frac{1}{cm^3}$ (from calculated velocity)

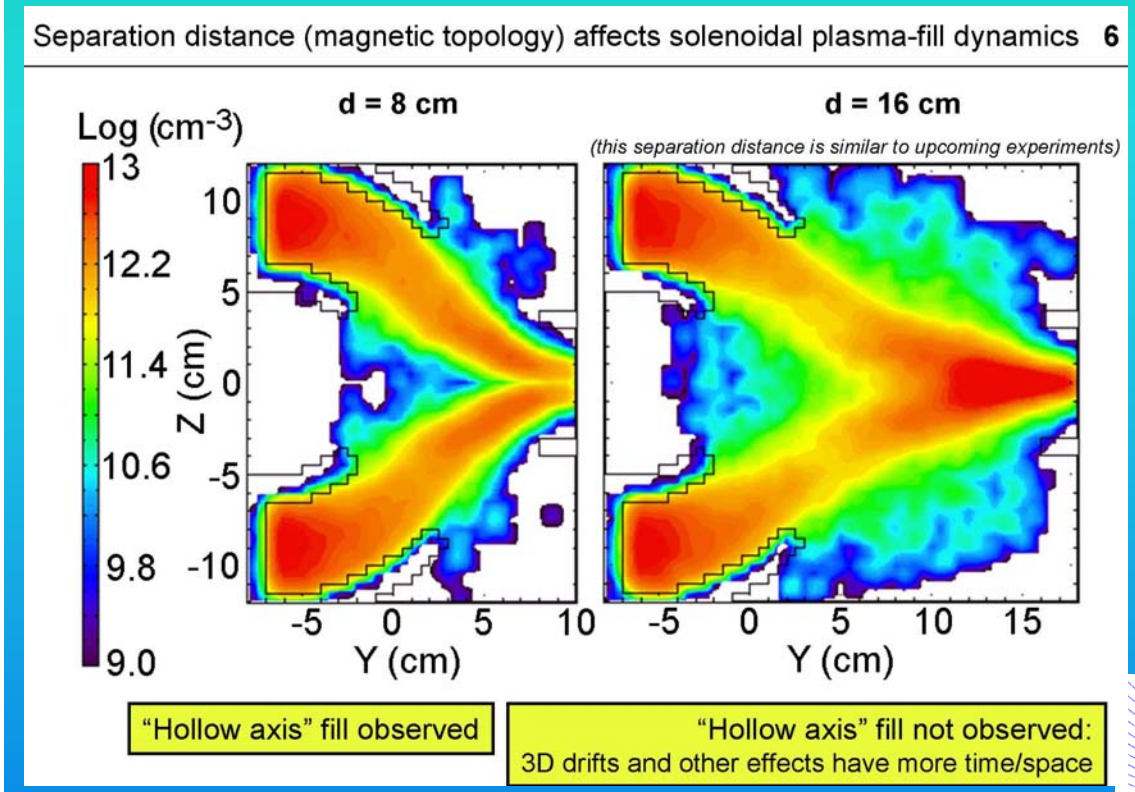
$n_i(I, q_e, v_{eM}, A_r, Z) = 1.648 \times 10^{13} \frac{1}{cm^3}$ (from measured velocity)

# Higher plasma density also measured by increasing cathode charging current

Examples of higher plasma density measurements with increasing cathodes current (FFS B=0 case).

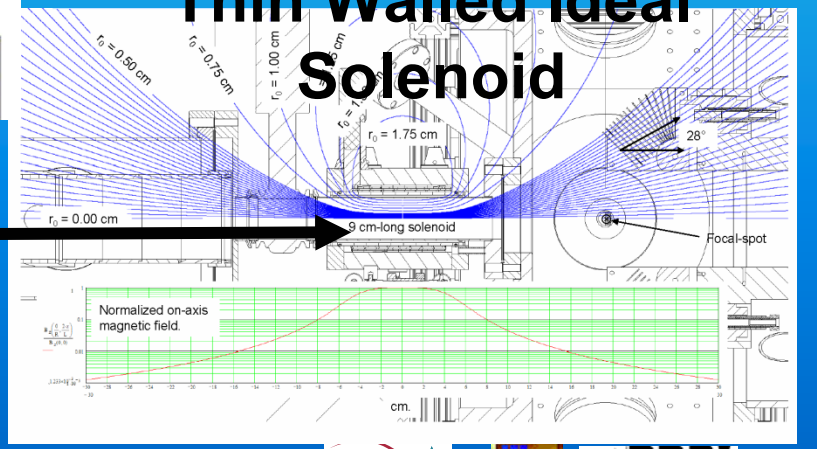


# A strong final focus solenoid increases beam density near the target plane



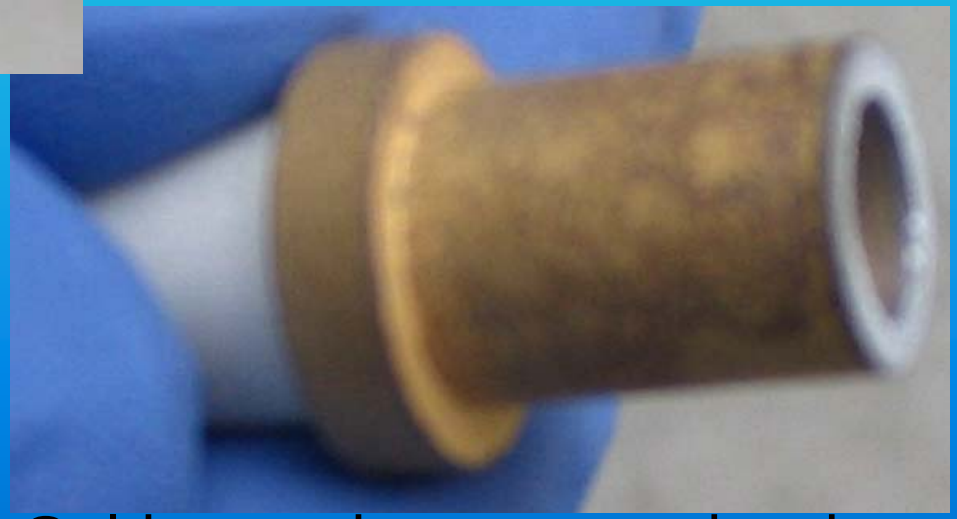

**Magnetic Field lines-Thin Walled Ideal Solenoid**

Beam



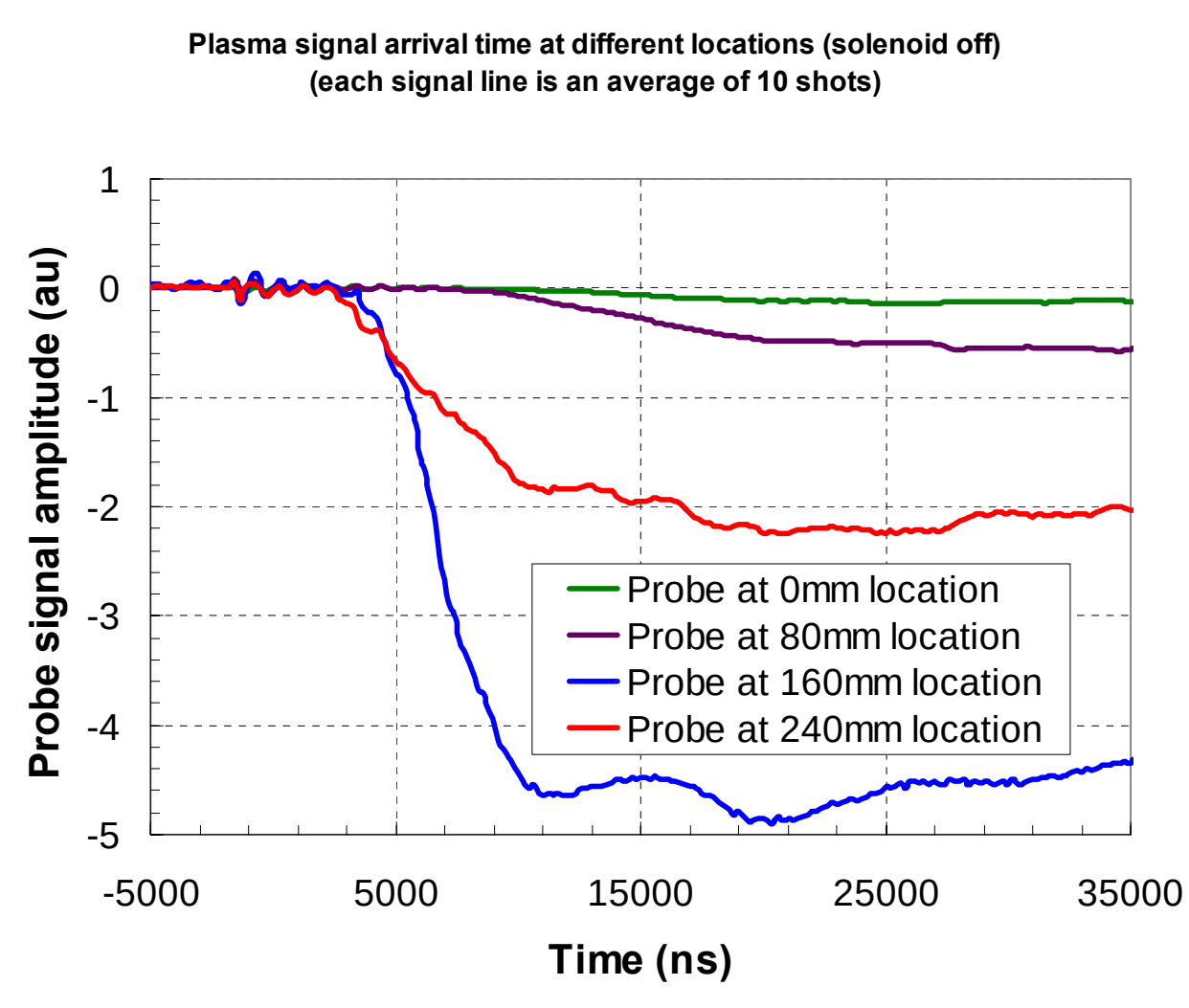
# Physical condition of a gold coated ceramic tube after

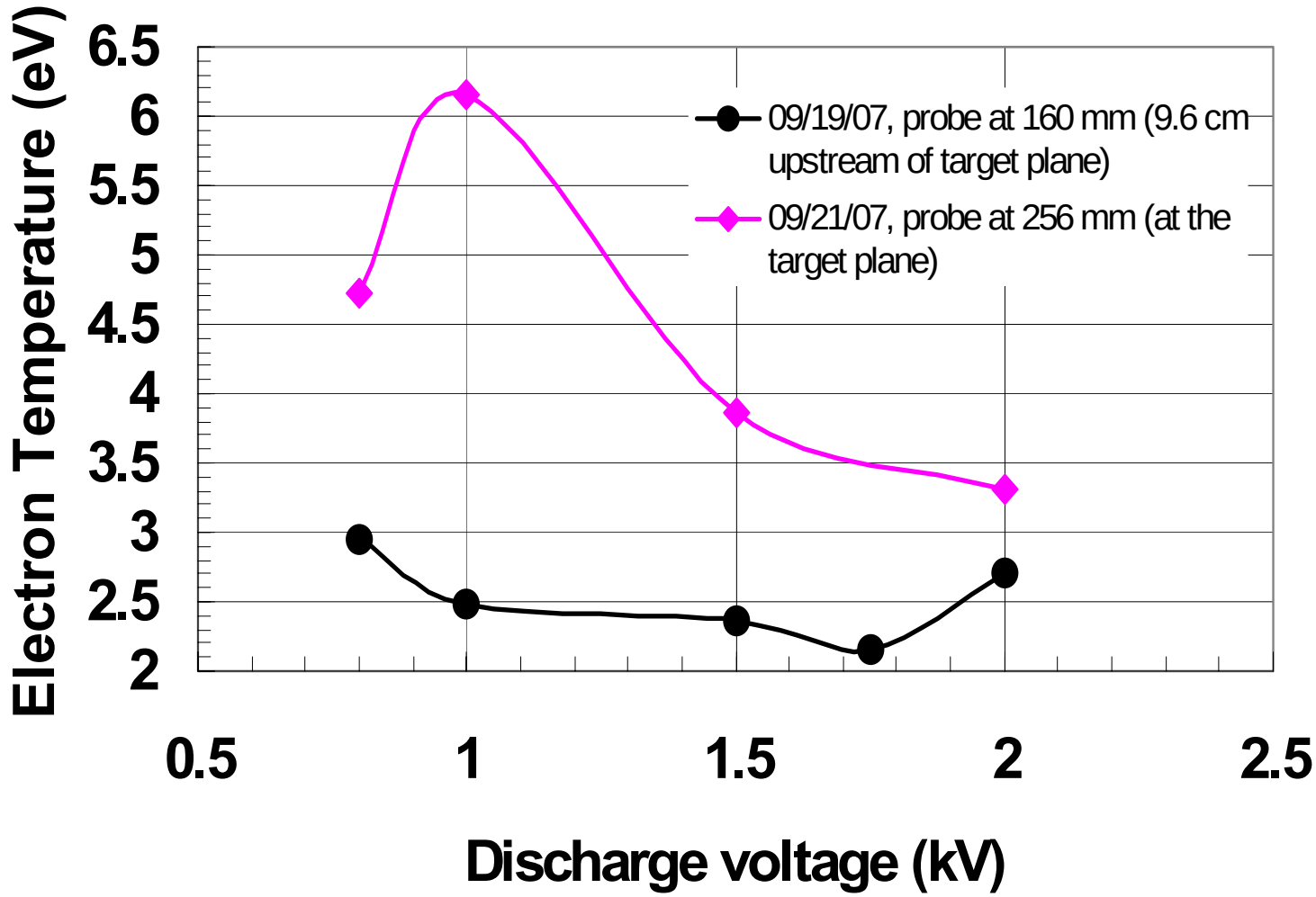
Gold coated area ceramic tube
: one side of FCAPS#4



Gold coated area ceramic tube
: Other side of FCAPS#4

# Velocity measurement to define density : Plasma signal arrival times for different Langmuir probe




A peak density of ~$10^{13}$/cm$^3$ was inferred assuming a velocity of $10^4$ m/s. This velocity was measured using time of flight method – studies of instrumental uncertainties are continuing.

# Electron temperature varies with discharge voltages and probe locations