# Plasma Source Development for the NDCX-I and NDCX-II Neutralized Drift Compression Experiments

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# Overview

- Plasma requirements for NDCX I and NDCX II.
- Ferroelectric plasma sources.
- Cathodic arc plasma sources.
- Filling a multi-Tesla solenoid with plasma.

# Plasma Source Requirements

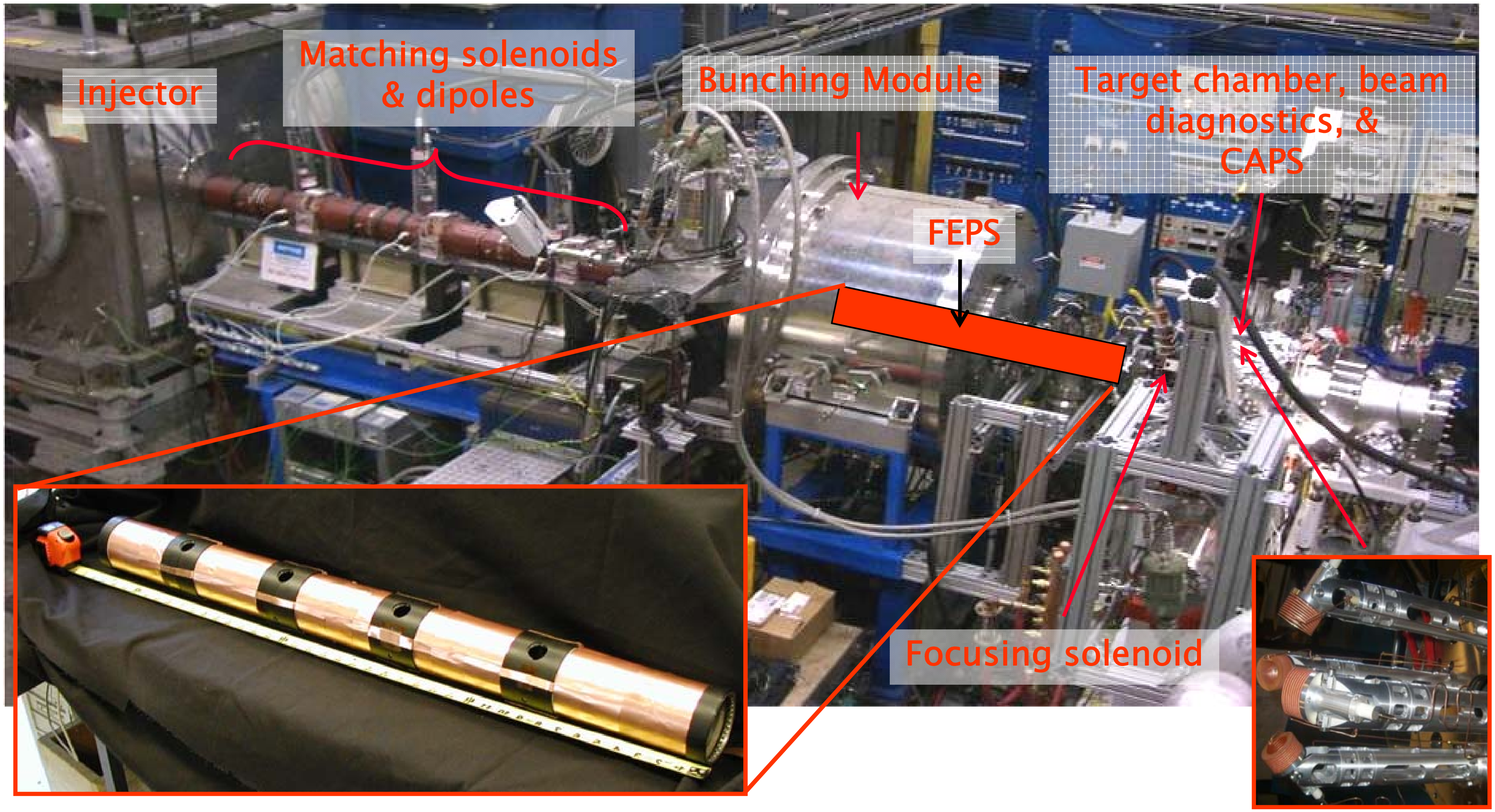
- Local plasma density should exceed the local beam density throughout the drift region.

  For NDCX-II:
  $n \sim 10^{11}$ cm$^{-3}$ at beginning of neutralized drift section.
  $n \sim 3\times10^{11}$ cm$^{-3}$ ~20 cm before focus (~30 ns before focus).
  Density up to $10^{14}$ cm$^{-3}$ at focus spot.

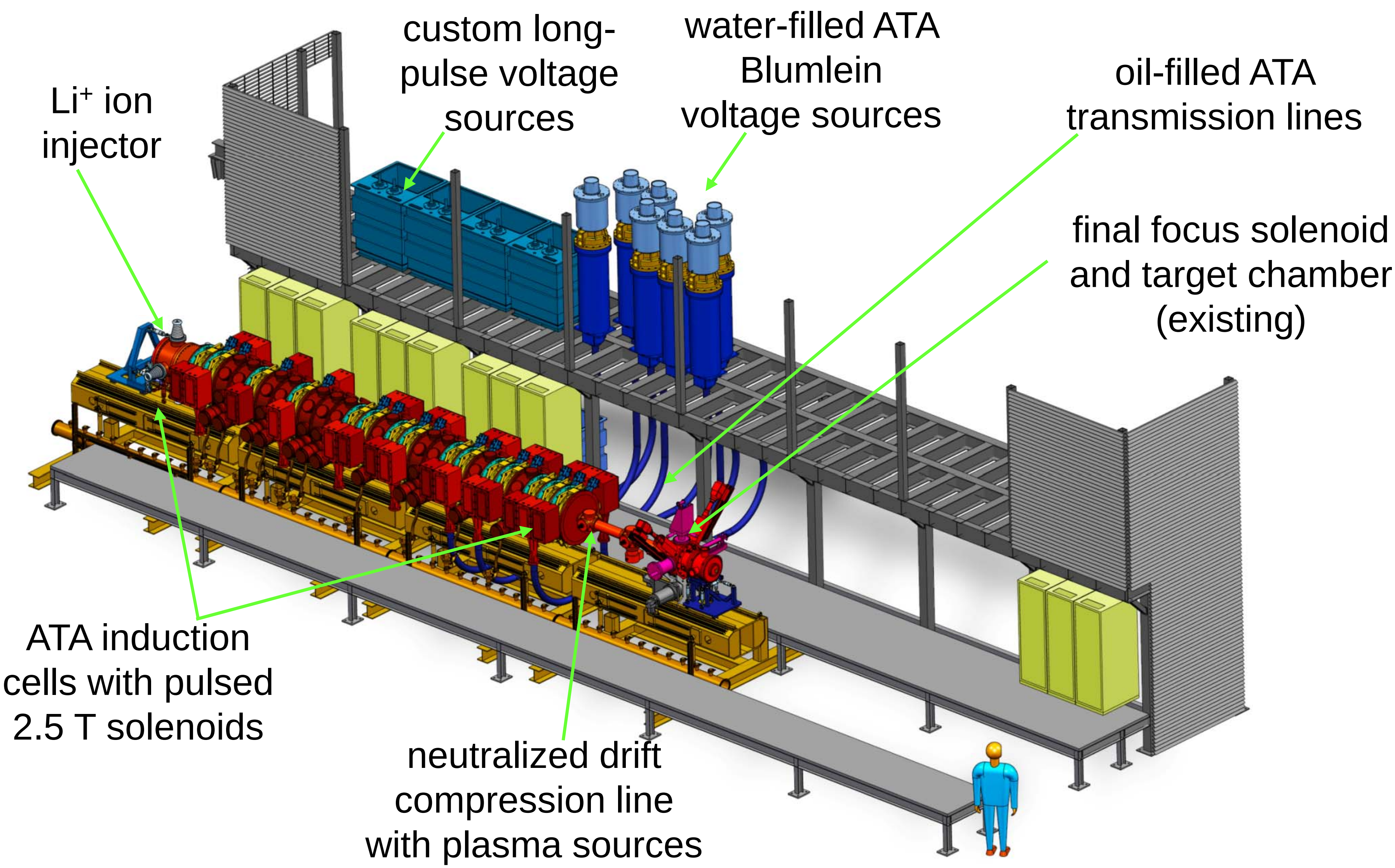
- Plasma sources should not employ electric or magnetic fields that would disturb the beam propagation.

- Plasma sources should not introduce so many neutrals as to interfere with the beam propagation by stripping or charge exchange.

# NDCX-I with a Ferroelectric Plasma Source (FEPS) and a Cathodic Arc Plasma Source (CAPS)



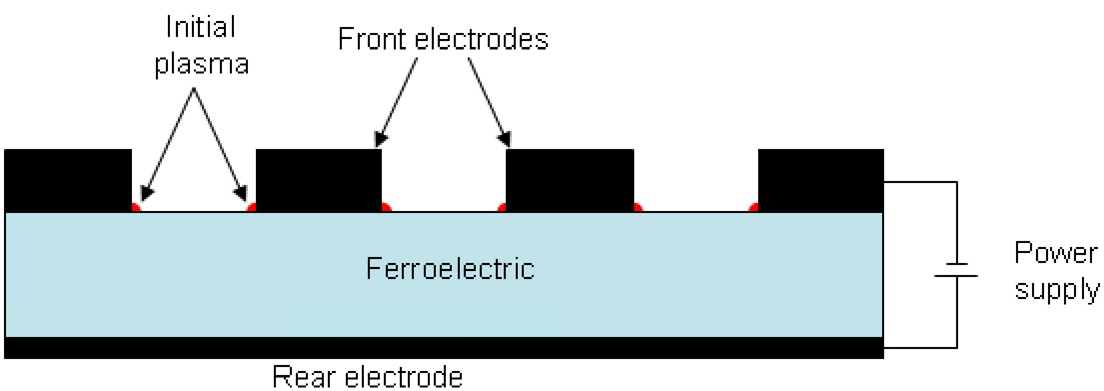
# NDCX-II Principal Systems

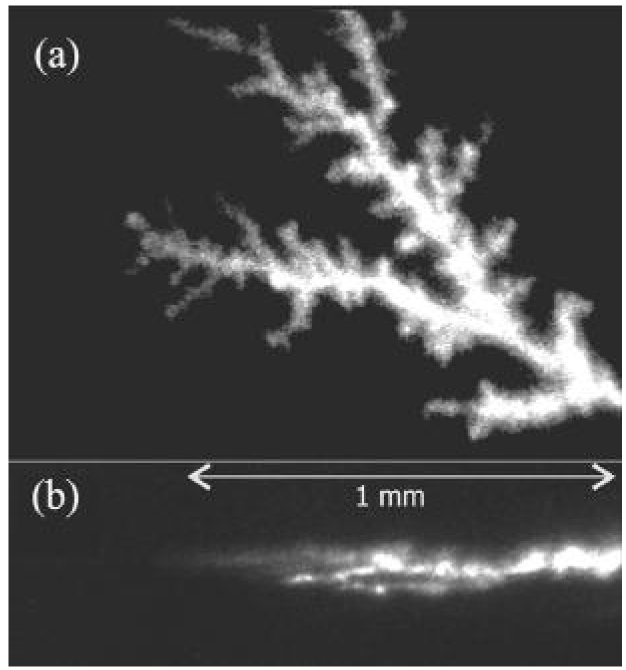


# High Dielectric Ferroelectric Ceramics

- Ceramics such as Lead Zirconium Titanate (PZT) and Barium Titanate ($BaTiO_3$) have relative dielectric coefficients of several thousand.
- Commonly used in transducers and high-power capacitors.

Ya. E. Krasik



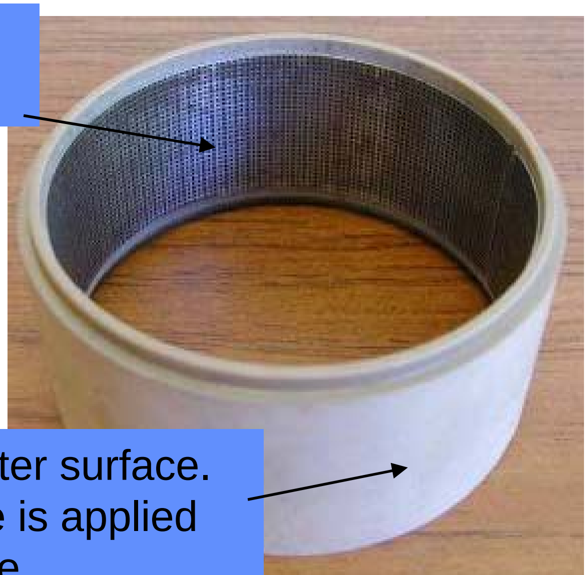

20 ns exposure

A high-dielectric ($\varepsilon/\varepsilon_0$ ~ 1000) ceramic produces a large polarization surface charge density when a high voltage is applied. The resulting large electric field creates a plasma on the mesh-lined surface.

# Barium Titanate (BaTiO3) Ferroelectric Plasma Source (FEPS) Design

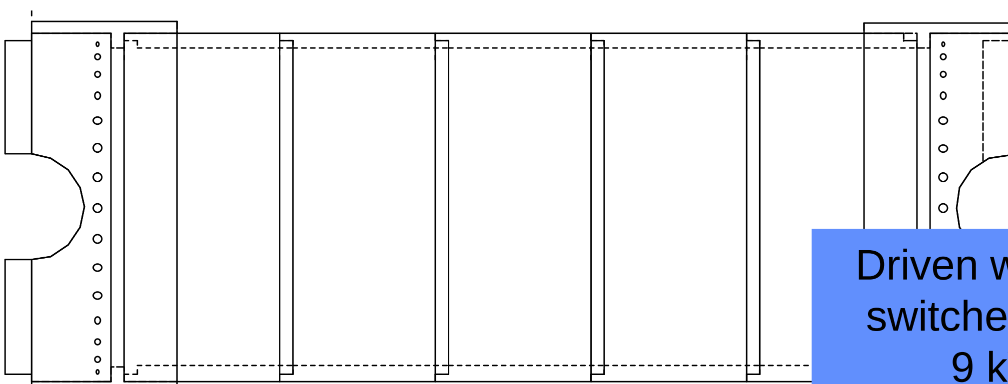
Grounded interior mesh

3.000” ID
3.300” OD
1.600” length



Metalized outer surface. High voltage is applied here.

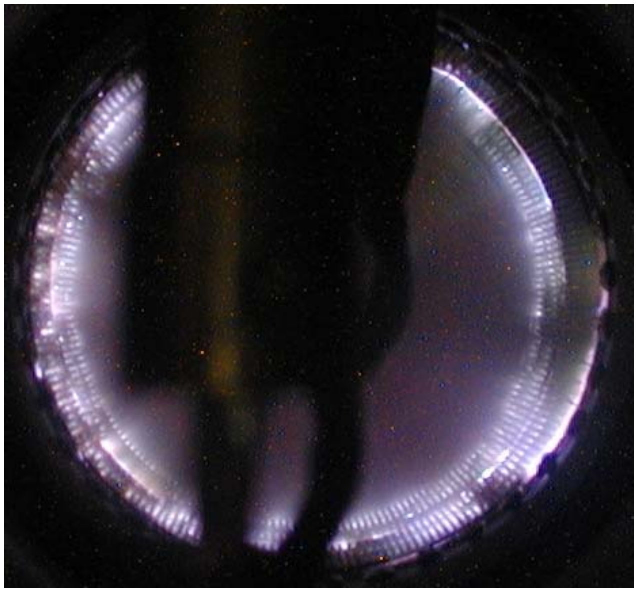
Coupling provides grounding and transverse access.



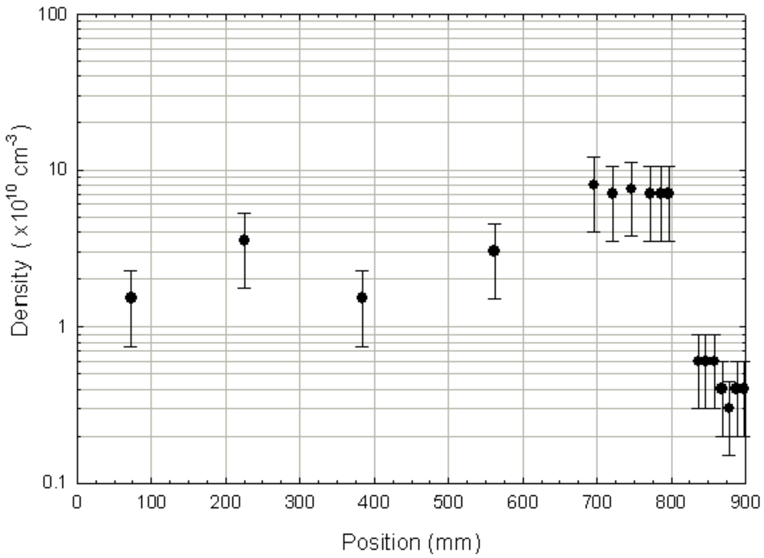
Driven with thyratron-switched capacitors.
9 kV, 500 A

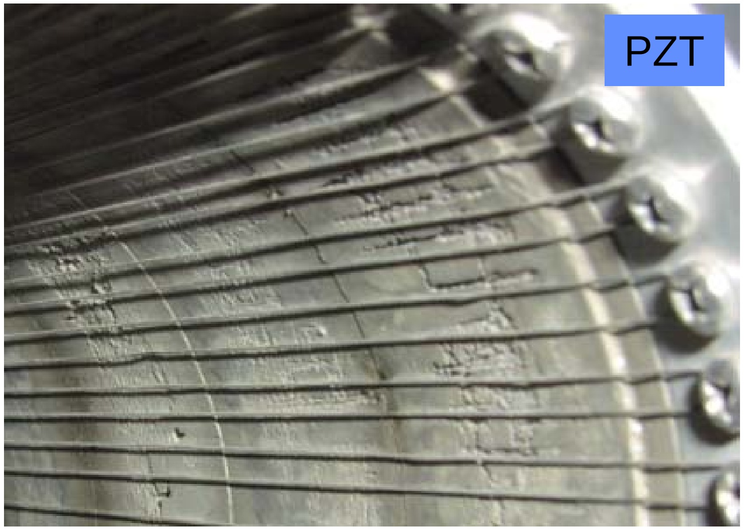
# FEPS Performance

- Uniform emission (8 shot average in photo)
- Plasma density mid $10^{10}$ $cm^{-3}$
- Plasma duration is ~ 10 $\mu$s
- Reliable for over ~$10^4$ shots
- Low gas loading
- Lead Zirconium Titanate (PZT) FEPS gives ten times more plasma, but PZT erodes quickly.



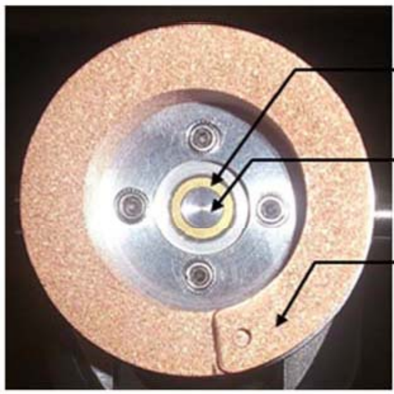
Langmuir probe measurements

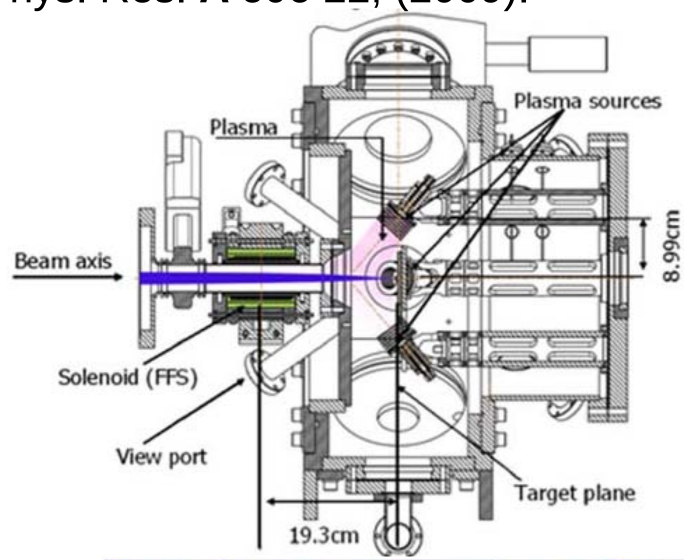


# Cathodic Arc Plasma Source (CAPS)

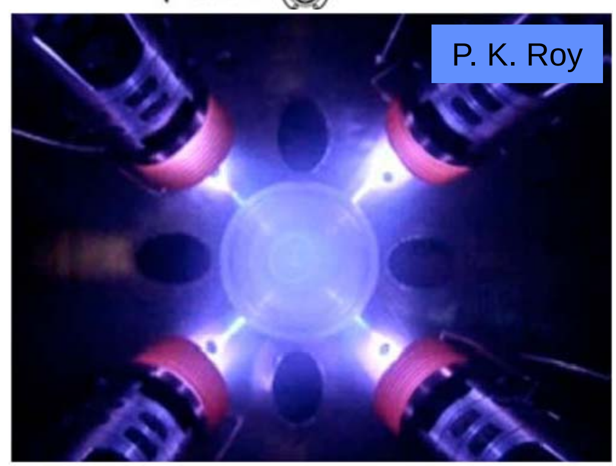
Developed by André Anders and collaborators.
HIF 2008 – P. K. Roy et al., Nucl. Instr. and Meth. in Phys. Res. **A 606** 22, (2009).



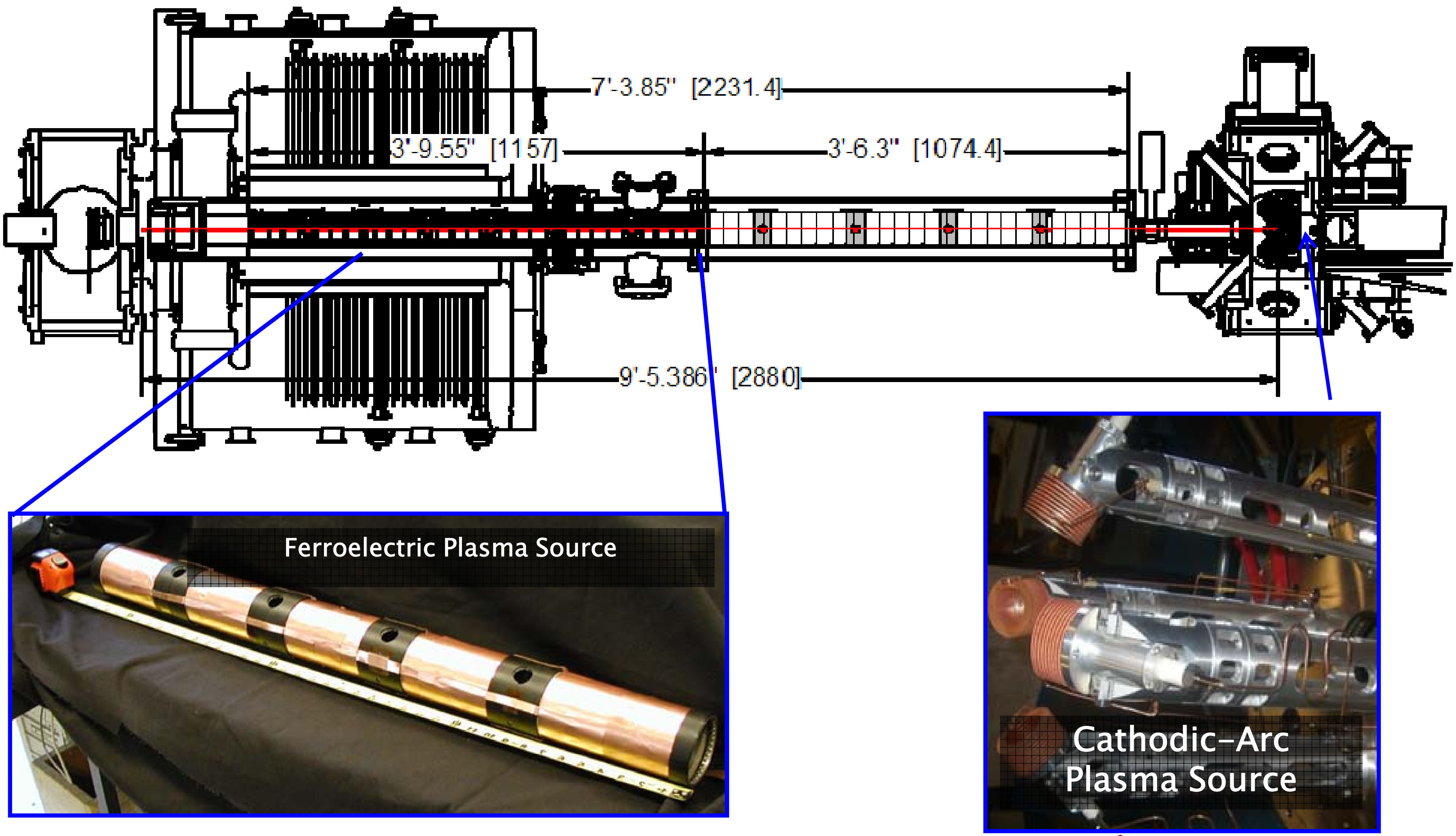




The four CAPS produce a plasma density of $10^{12}$ cm$^{-3}$ on the beam axis near the target spot and a plasma density of $10^{13}$ cm$^{-3}$ on the beam axis at the midplane of the 8 T Final Focusing Solenoid (FFS).

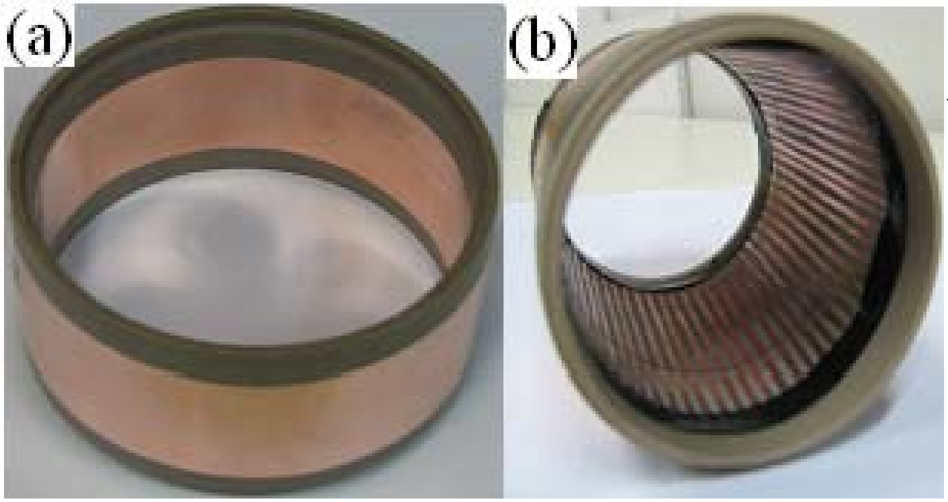
A 3 kV pulse drives 800 A peak current through each of the four sources.

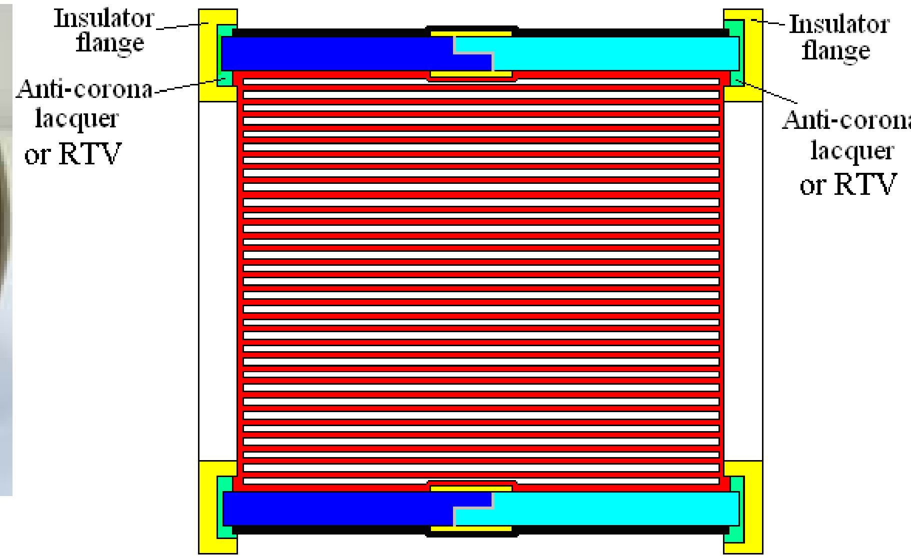


# NDCX-I Plasma Source Solutions Will Be Applied to NDCX-II



# Modifications Will Enable Increased FEPS Plasma Density for NDCX-II




100 μm copper “tape” strip electrodes with mm spacing are better than the perforated steel sheets at creating optimal conditions for plasma creation at the ceramic surface.

A spark gap or thyratron acting as a crowbar to shut off the pulsed high voltage increases the amount of plasma generated.

Collimated Faraday cup, wire probe, and microwave cutoff measurements give plasmas densities in the mid $10^{11}$ $cm^{-3}$ range.

# Modified Inner Electrode Design and Driver Crowbar Ensure Better Uniformity and Denser Plasma

0.1 μs exposure time, 7.5 kV charging voltage

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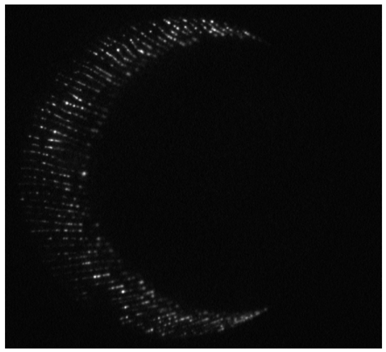
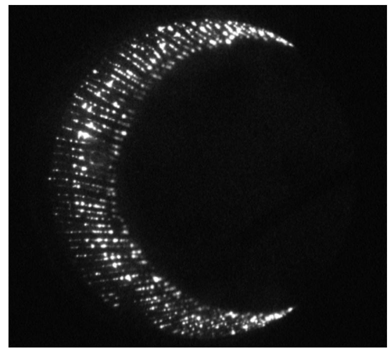
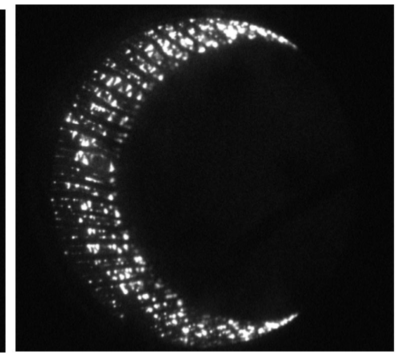


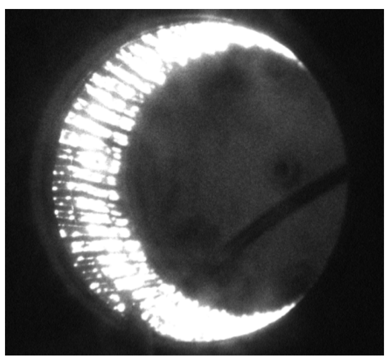
$\tau_d$ = 250 ns



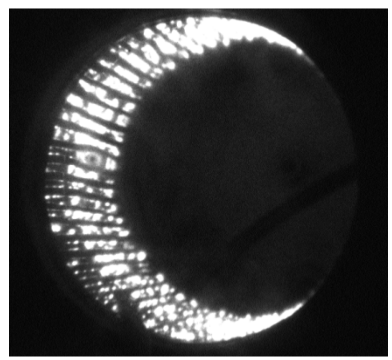
$\tau_d$ = 450 ns



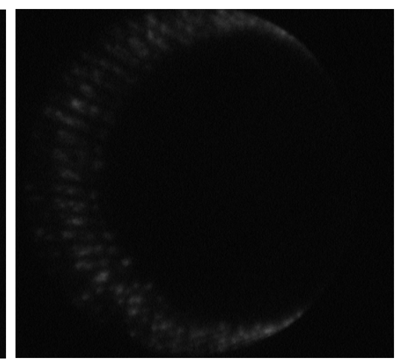
$\tau_d$ = 800 ns



$\tau_d$ =1100 ns
**Crowbar time**



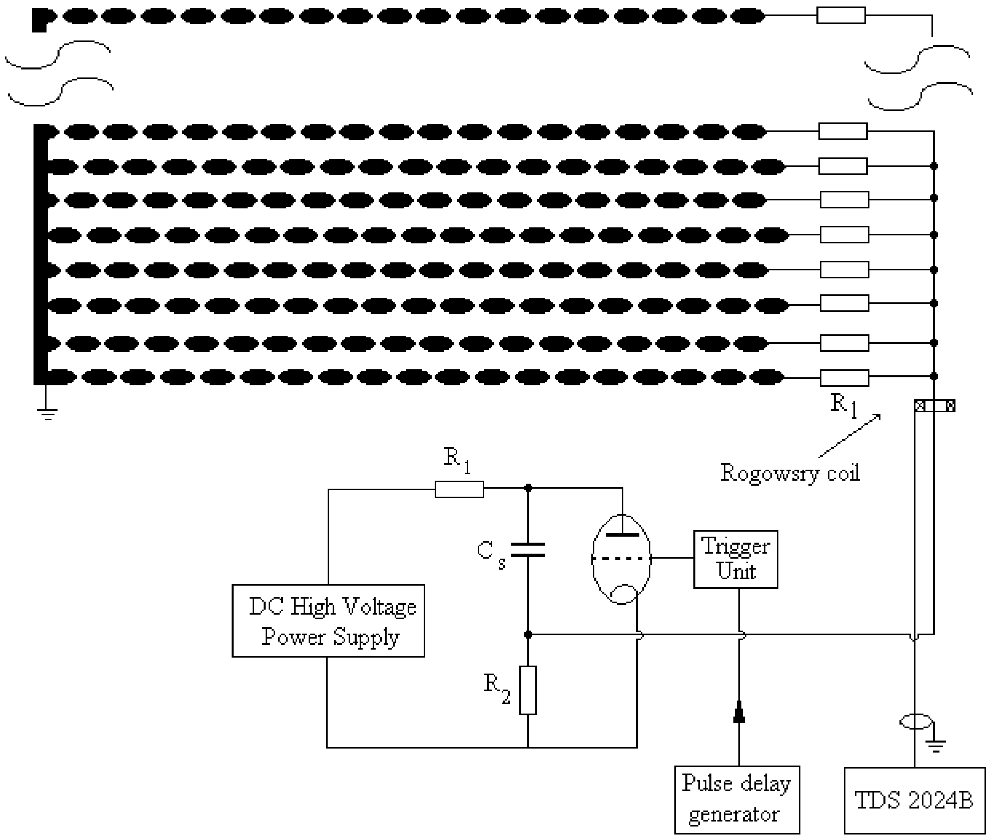
$\tau_d$ =1300 ns

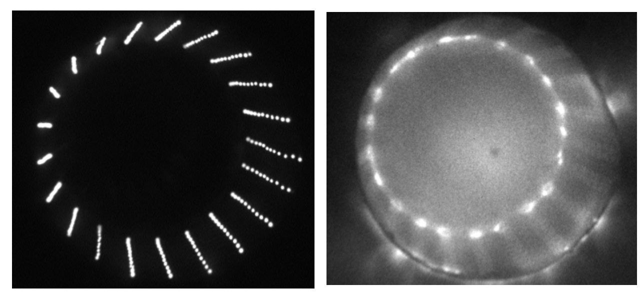


$\tau_d$ =1500 ns

Similar images with larger charging voltage and camera gain show reasonably uniform emission near the center.

# Flashboard Plasma Source is Being Tested



16kV, 4kA
Plasma density in the mid $10^{12}$ $cm^{-3}$ range

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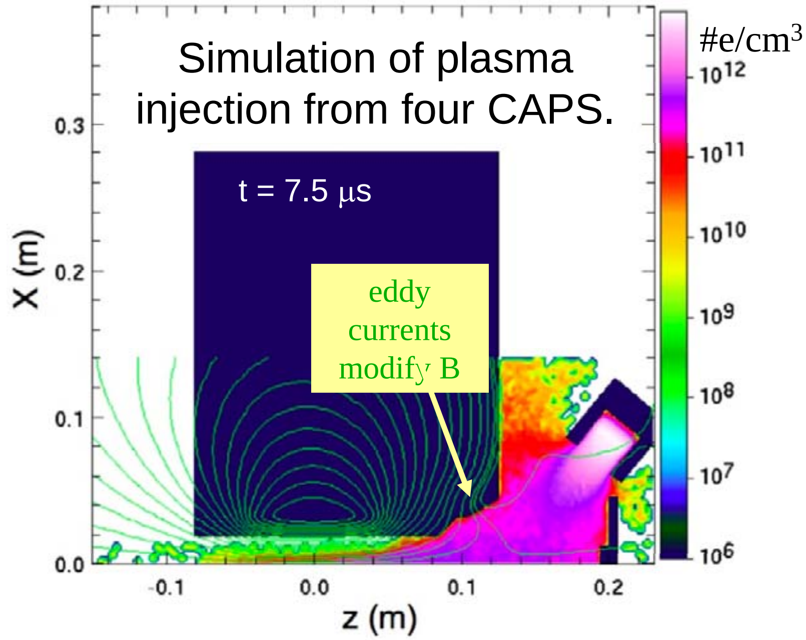
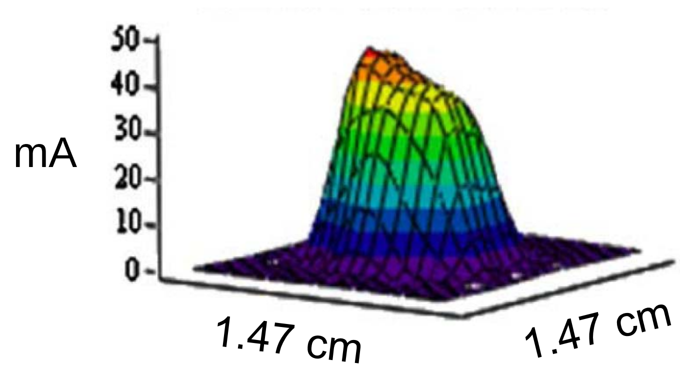
# Plasma Injected from CAPS into 8 T Solenoid is Concentrated Near the Beam Axis

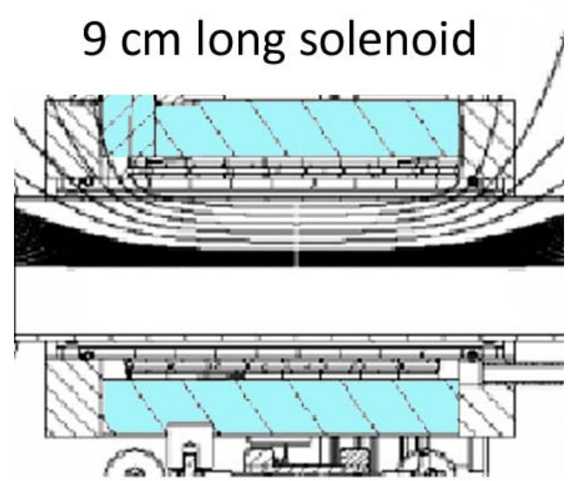



Ion saturation current measured on a hexagonal array of copper collector disks.

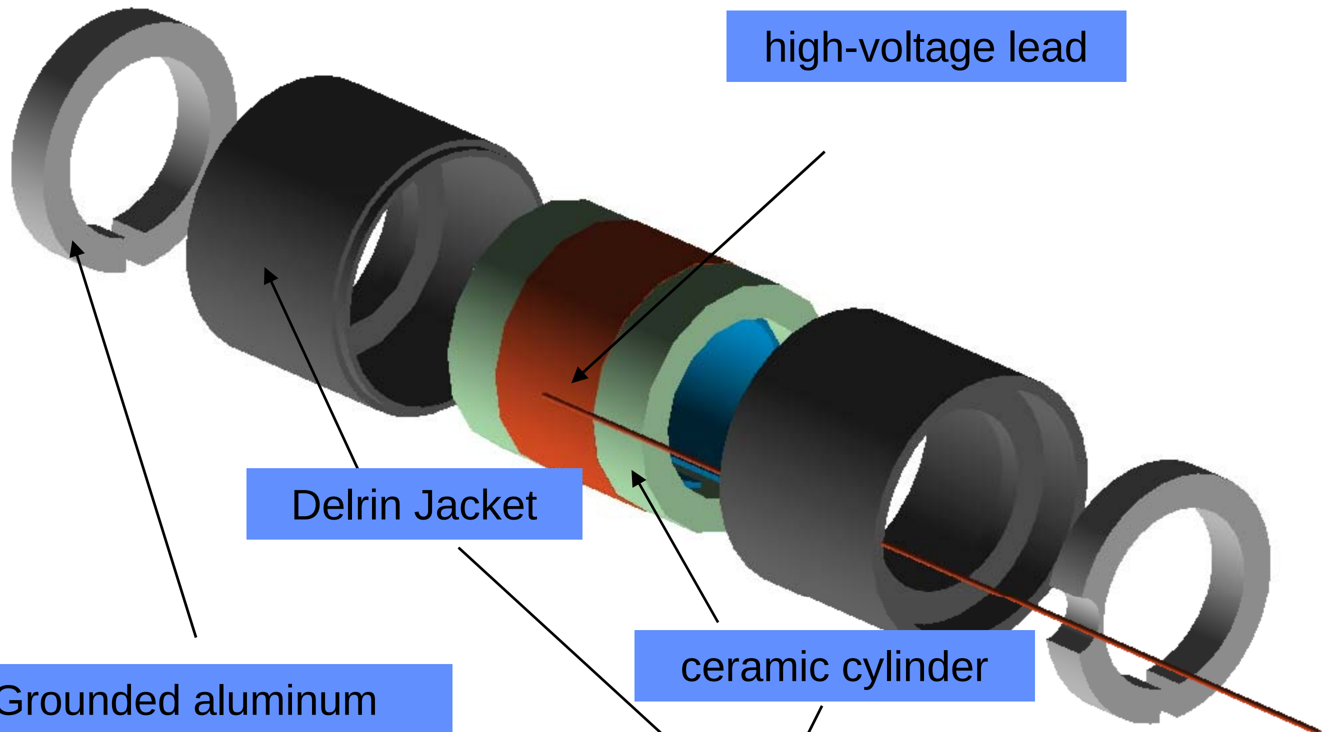


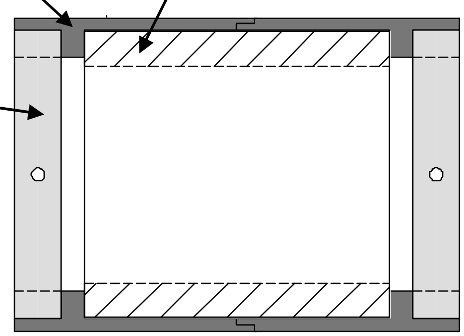

Plasma mostly flows along the magnetic field lines created by the CAPS filter coils, the 8 T solenoid, and the eddy currents.

The tendency to follow magnetic field lines, plus the effect of magnetic mirroring limits the amount of plasma at the solenoid midplane



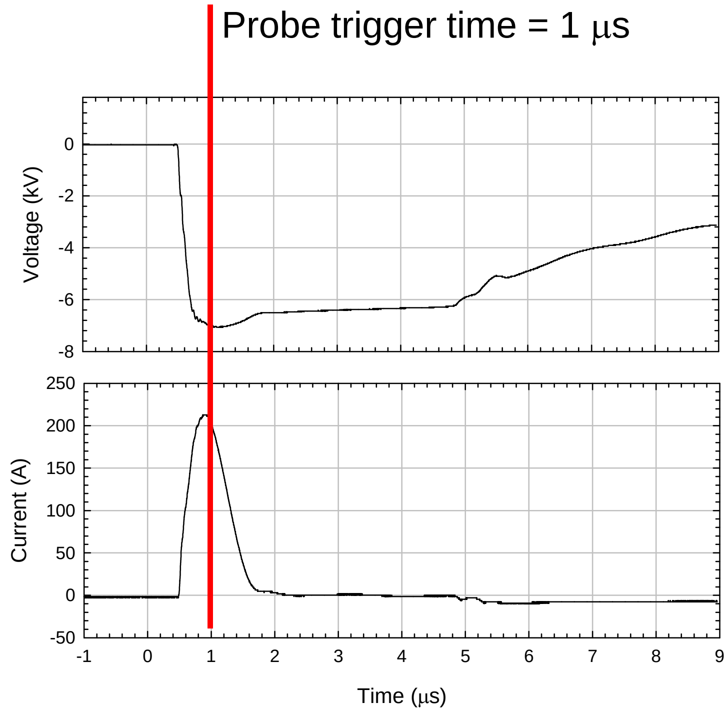
# “MiniFEPS” Was Designed to Create Plasma in 8 T Solenoid

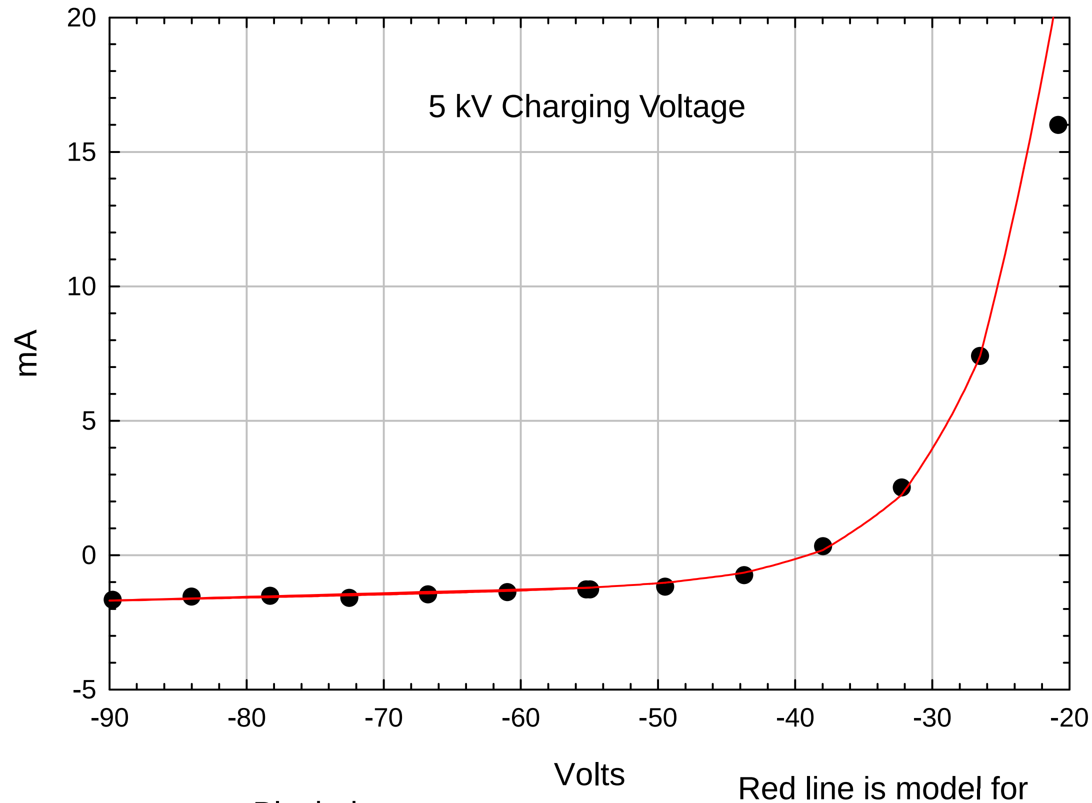


Conductors are slotted to prevent eddy current effects

# On-Axis, Centered Langmuir Probe Measurement Shows n = 2–6 x $10^{11}$ cm$^{s}$



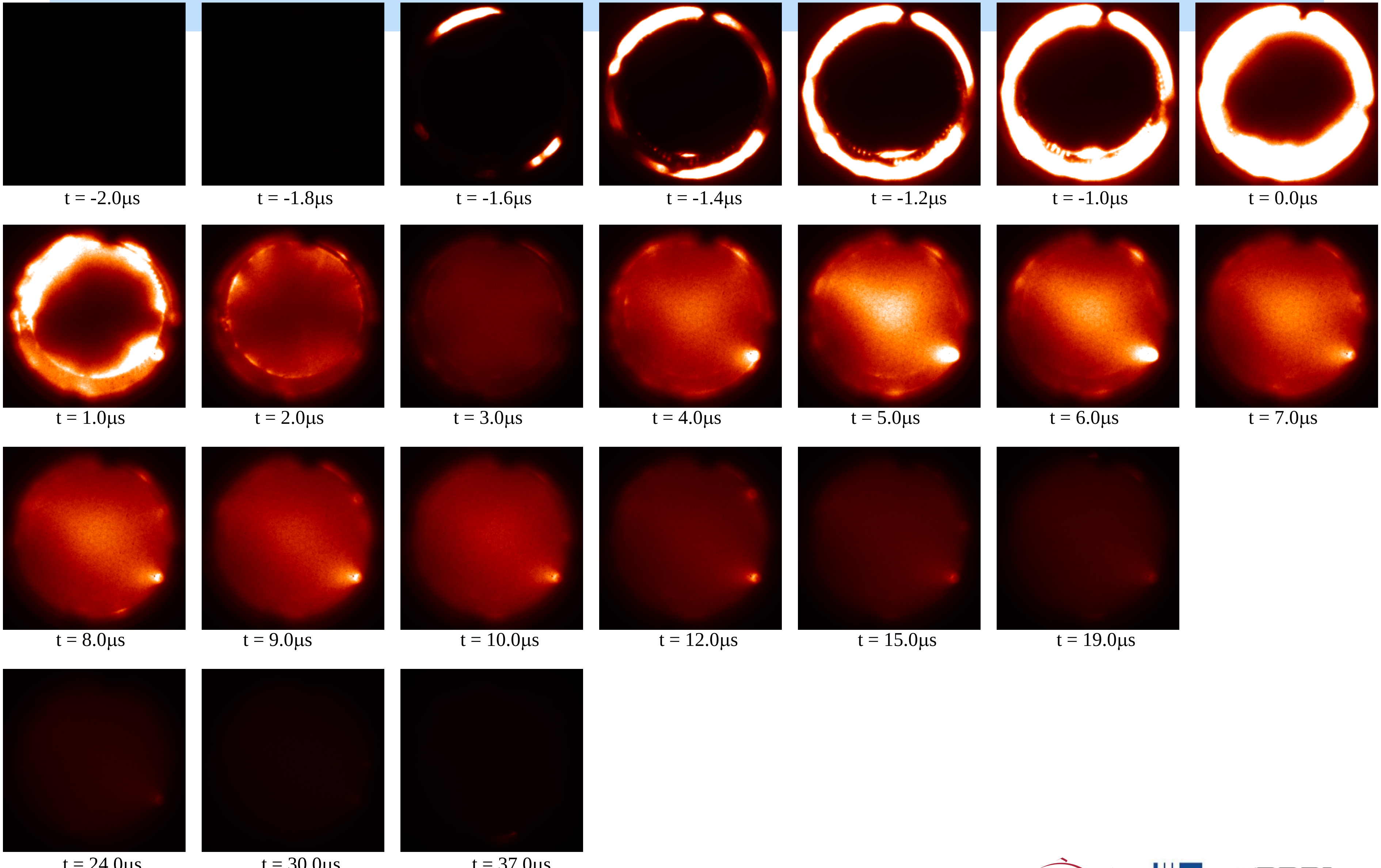




Black dots:
data
16 shot average

Red line is model for
$m_i$ = 138 amu
$kT$ = 6 eV
$n = 2 \times 10^{11}$ cm$^{-3}$

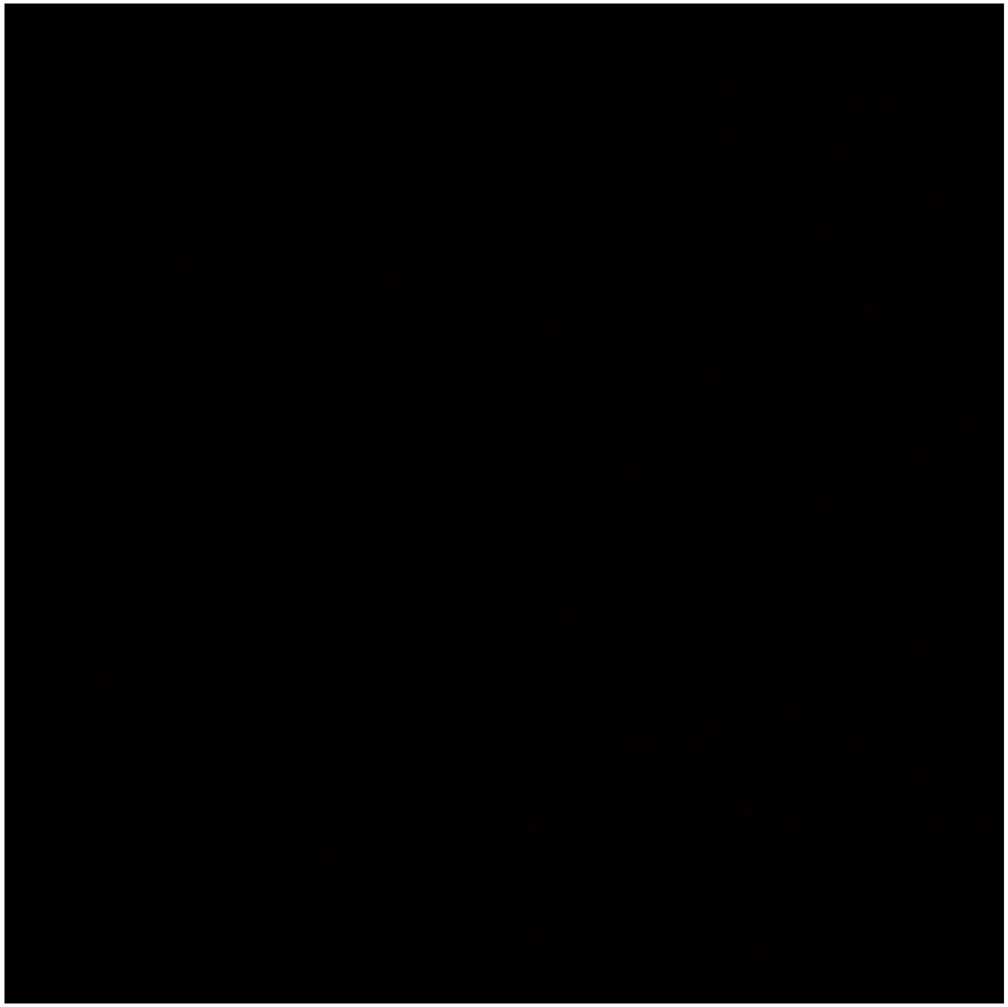
*Results are similar for 8 kV charging voltage but with $n = 6 \times 10^{11}$ cm$^{-3}$.*

# 8-Shot-Averages, 1 μs Exposure



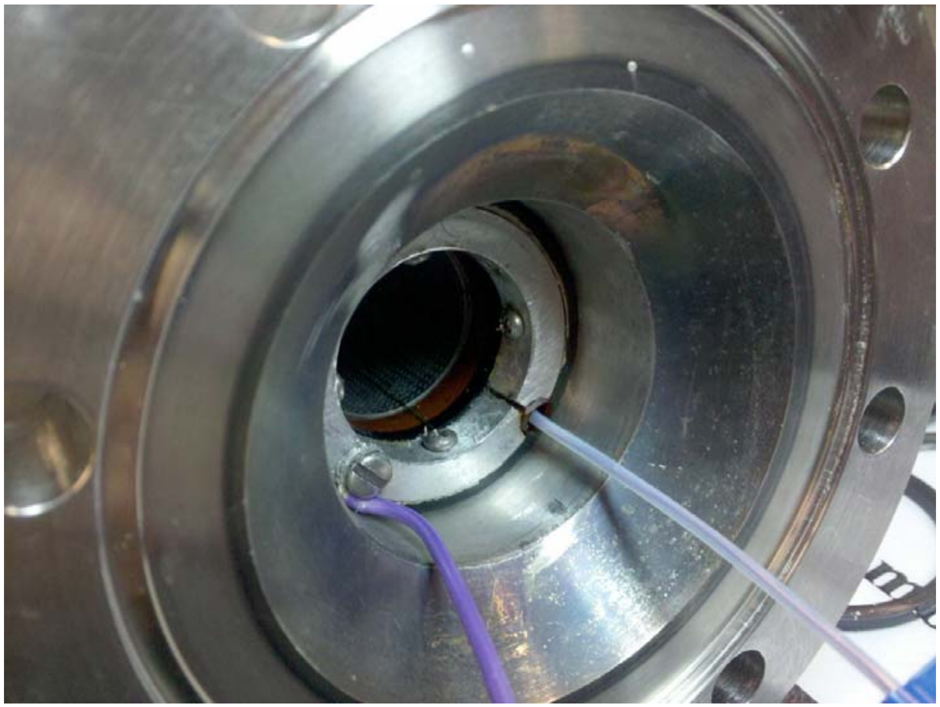
# Time Evolution of Short FEPS Discharge 8-Shot-Averages, 1 μs Exposure

Animated GIF

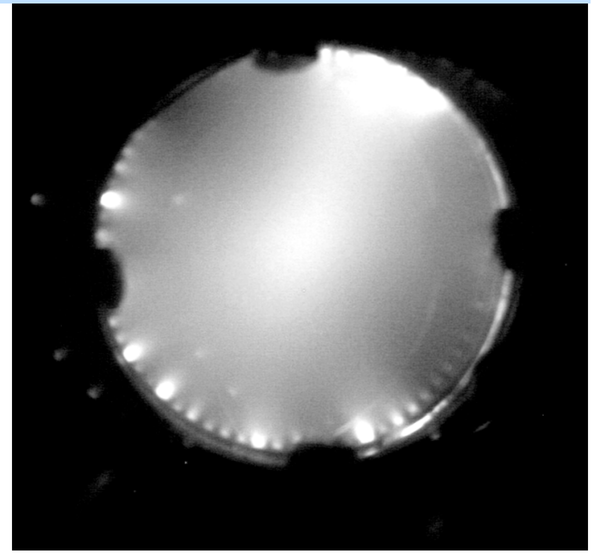


# miniFEPS Tested in 3 T Solenoid at LBNL

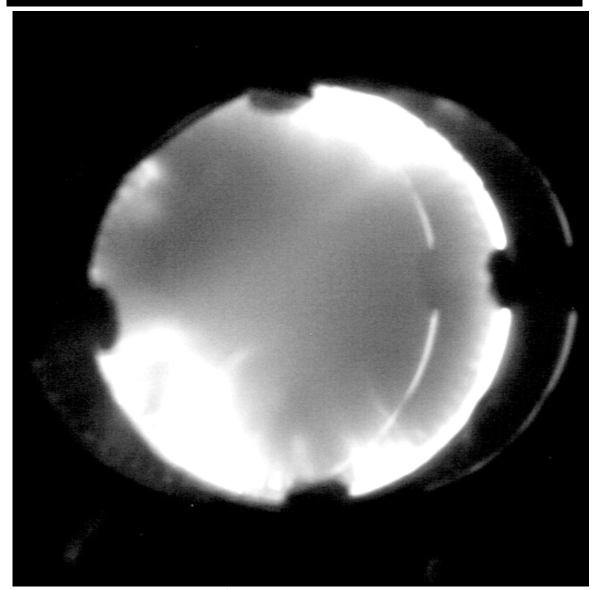
The plasma source is pulsed ($\mu$s timescale) at the maximum of the magnet pulse (ms timescale).



No B-Field →

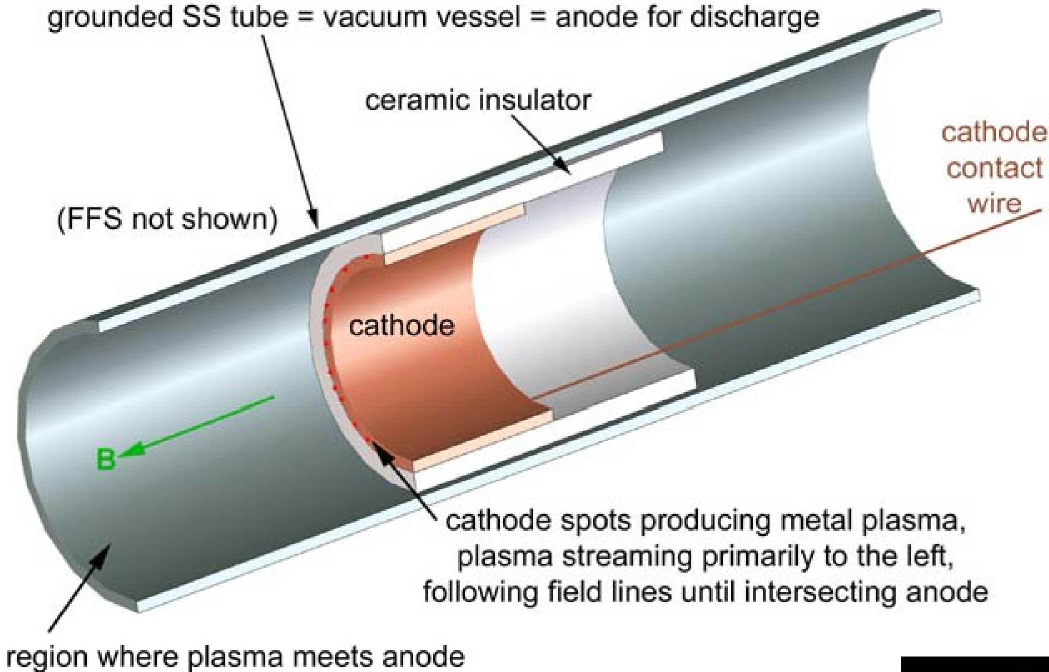


3T Field →



Heating from repeated magnet pulses caused melting of grease.

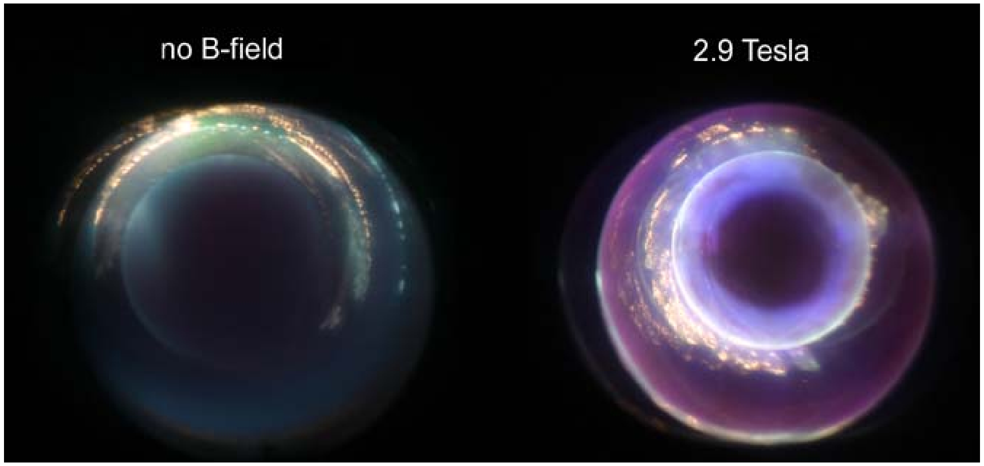
# Cathodic Ring Plasma Source




André Anders
Marina Kauffeldt
Efim Oks

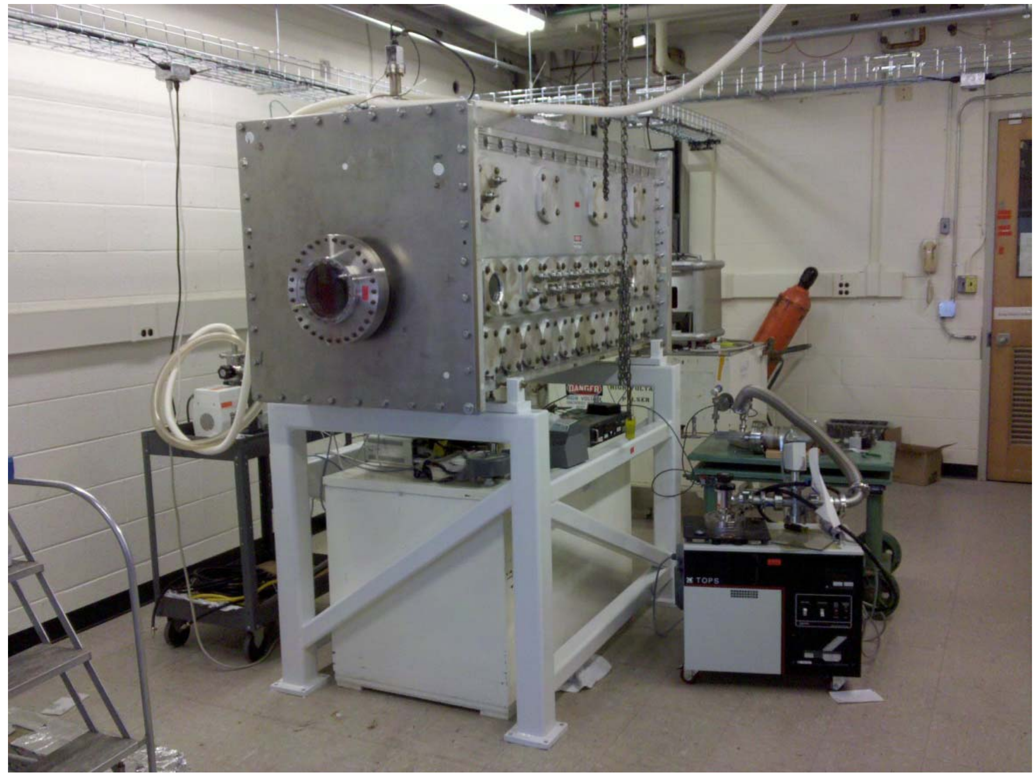
Conductors are slotted to prevent eddy current effects

1 kV charging voltage and 4.5 kA is needed to have many cathode spots around the circumference of the ring



# Test Stand at PPPL Will be Used for Development and Testing of Plasma Sources

- Testing of modified FEPS
- Testing of flashboard plasma source
- Conditioning of 2 m-long plasma source before installation on NDCX-II
- Development of high-density plasma sources such as laser ionized vapor or gas jet and laser ablation of a solid.



# Summary

- Ferroelectric (FEPS) and Cathodic arc (CAPS) plasma sources work well on NDCX-I and will therefore will be used on NDCX-II with modifications to ensure that the local plasma density exceeds the local beam density in the neutralized drift region.

- Compact FEPS and CAPS are being tested to see whether they can suitably fill the final-focusing strong solenoid with plasma.

- Development of high density plasma sources will continue in order to meet the demands of NDCX-II and future projects such as IB-HEDPX.