Plasma Sources for Beam Neutralization in NDCX-I and NDCX-II

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PRINCETON PLASMA PHYSICS LABORATORY

The Heavy Ion Fusion Science Virtual National Laboratory

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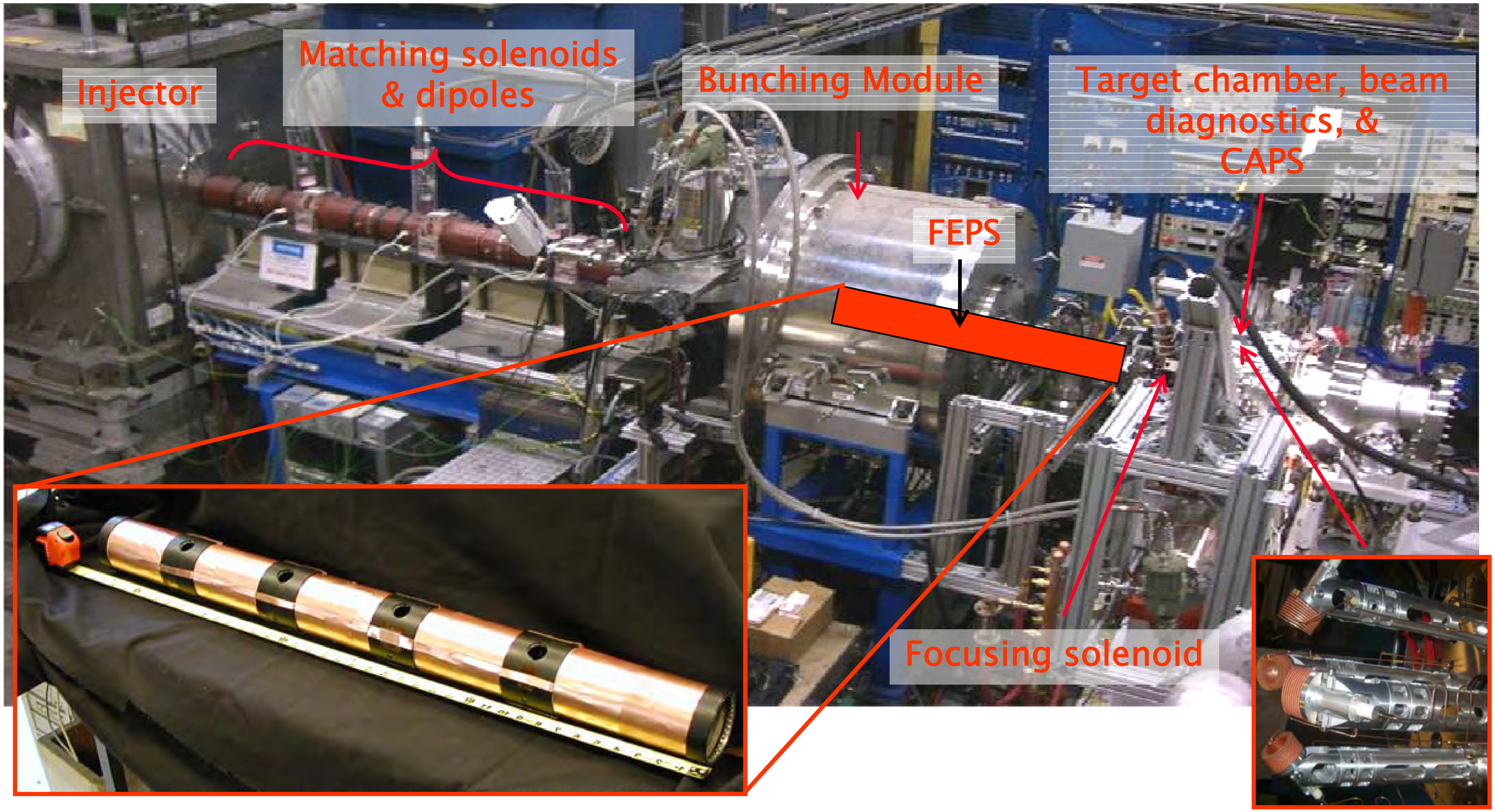
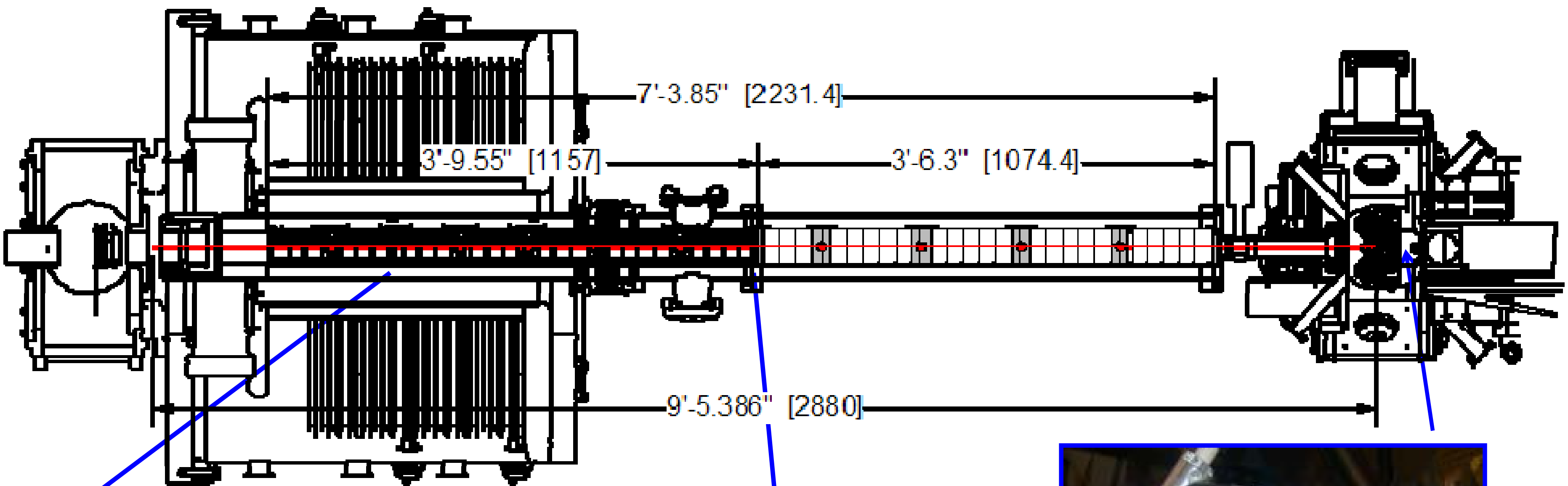
Plasma Source Requirements

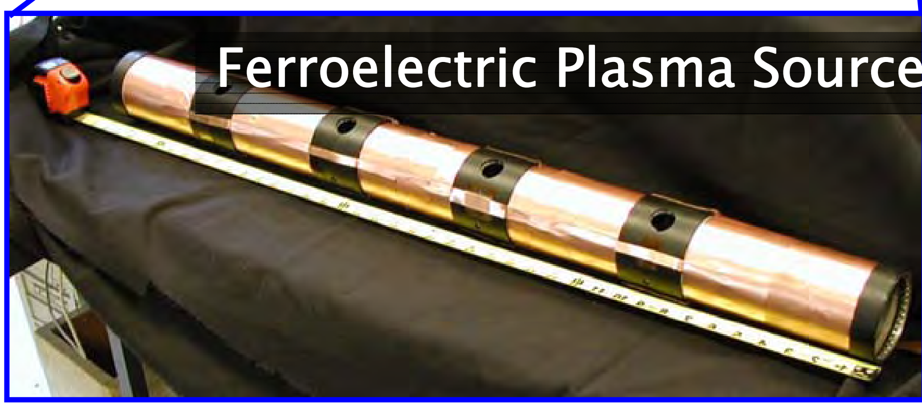
- Local plasma density should exceed the local beam density throughout the drift region.
  - For NDCX-II:
  - $n \sim 10^{11}\ cm^{-3}$ at beginning of neutralized drift section.
  - $n \sim 3 \times 10^{11}\ cm^{-3}$ ~20 cm before focus (~30 ns before focus).
  - Density up to $10^{14}\ cm^{-3}$ at 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.
- Plasma sources should not interfere with target diagnostics.

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

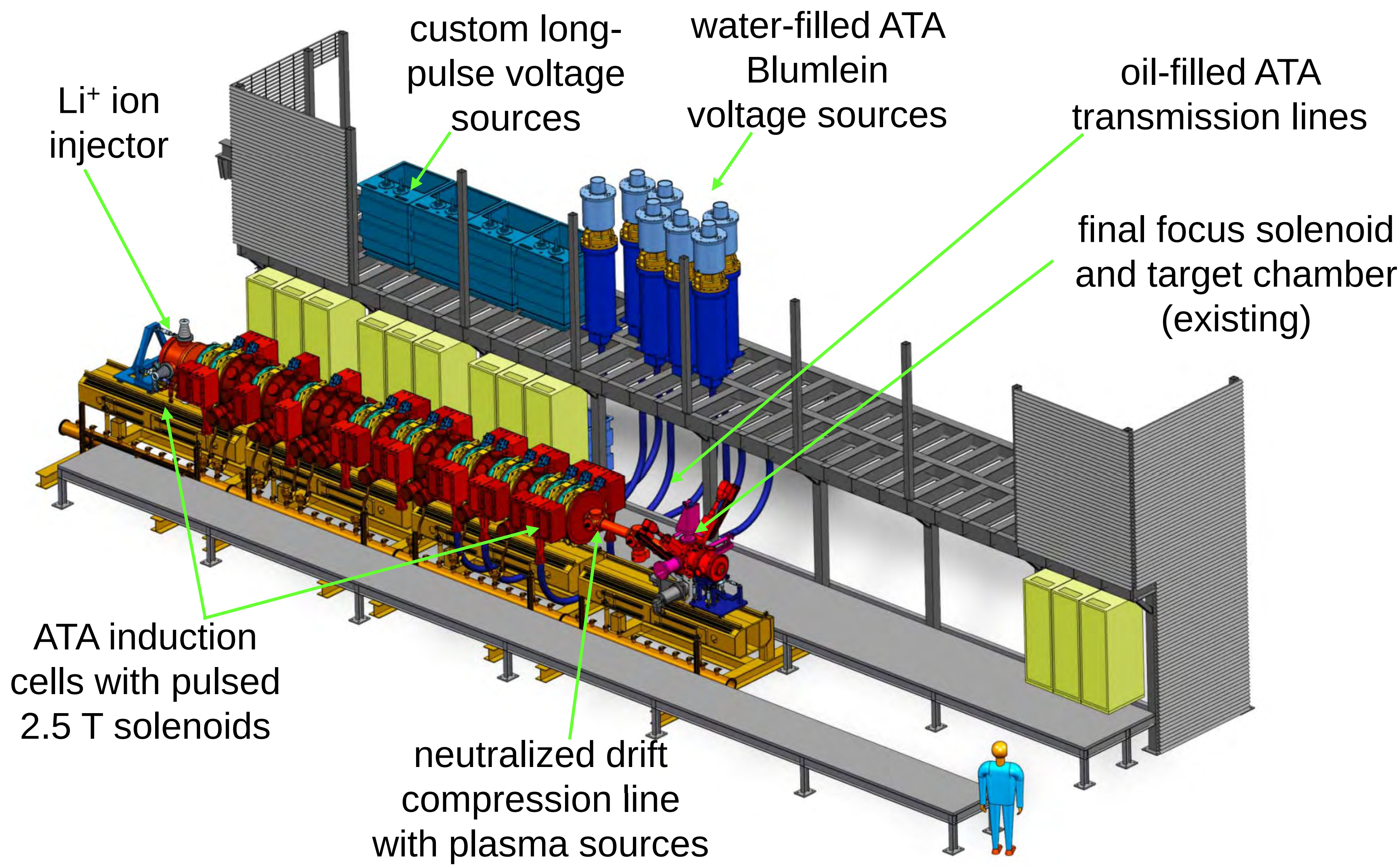


More Recent Layout of Downstream Section of NDCX-I





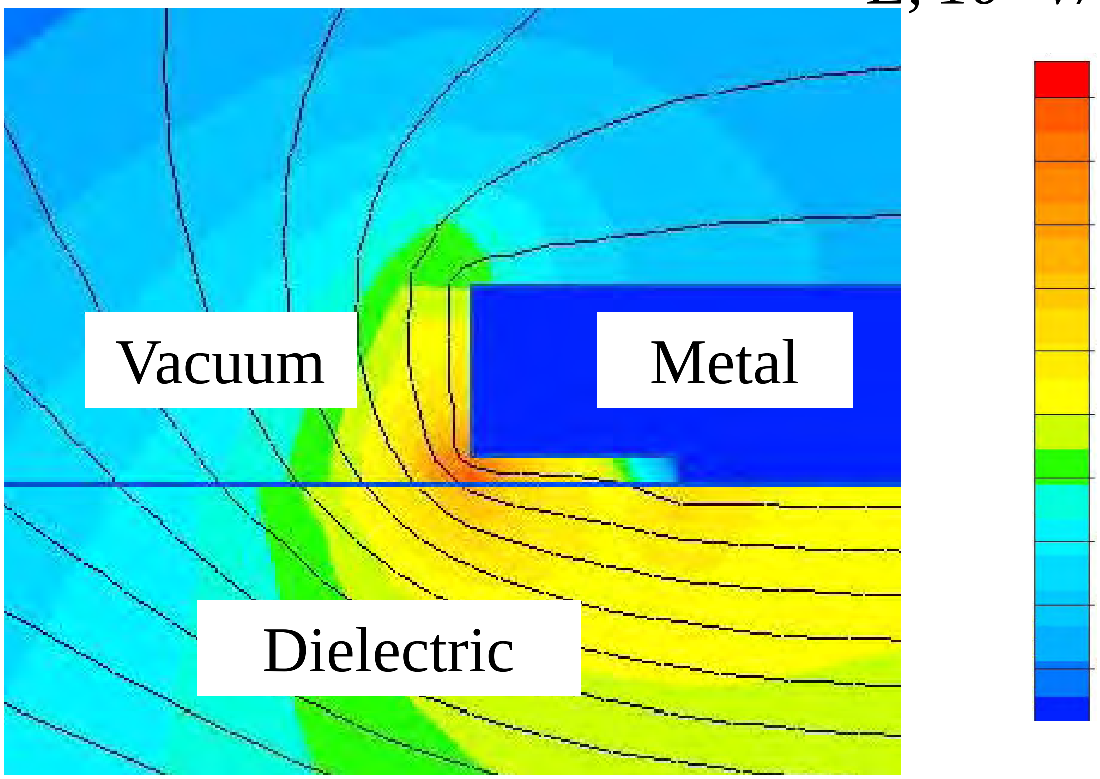
NDCX-II Principal Systems



A Material with a Large Dielectric Coefficient can be Used to Create Large Electric Fields

Electric field in triple point

E, 10^6 V/cm

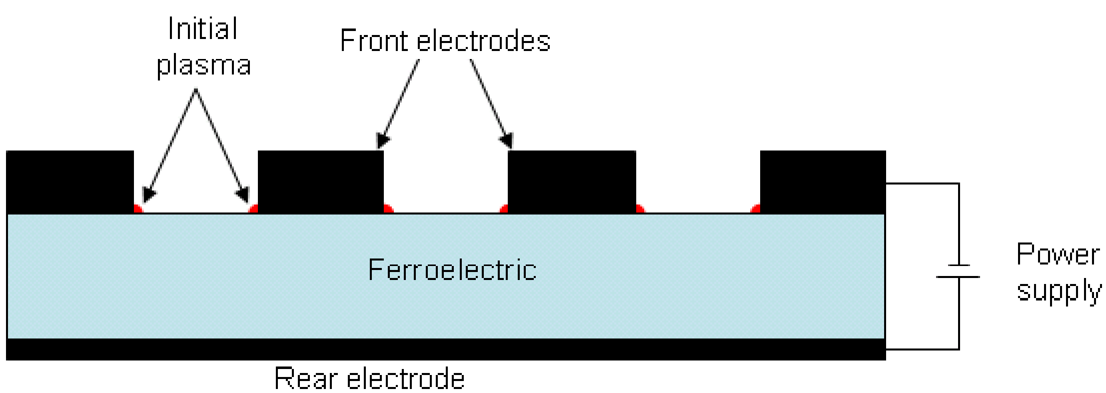


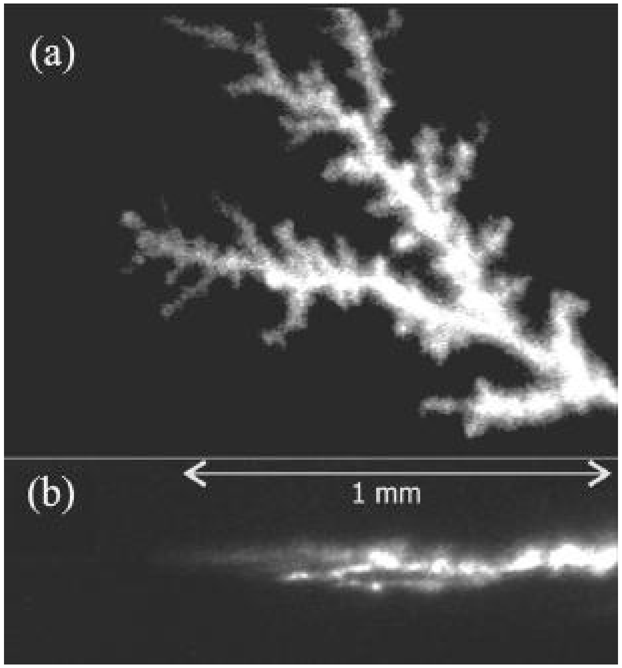
A high-dielectric ($\varepsilon/\varepsilon_0 \sim 1000$) ceramic produces a large polarization surface charge density when a high voltage is applied. The resulting large electric field creates a plasma on surface.

$$E_{tr} \approx \frac{\varphi_0}{d_{fer}} \times \varepsilon$$

Electrodes Can Be Placed on Ferroelectric Ceramics to Create a Large Area Plasma Source

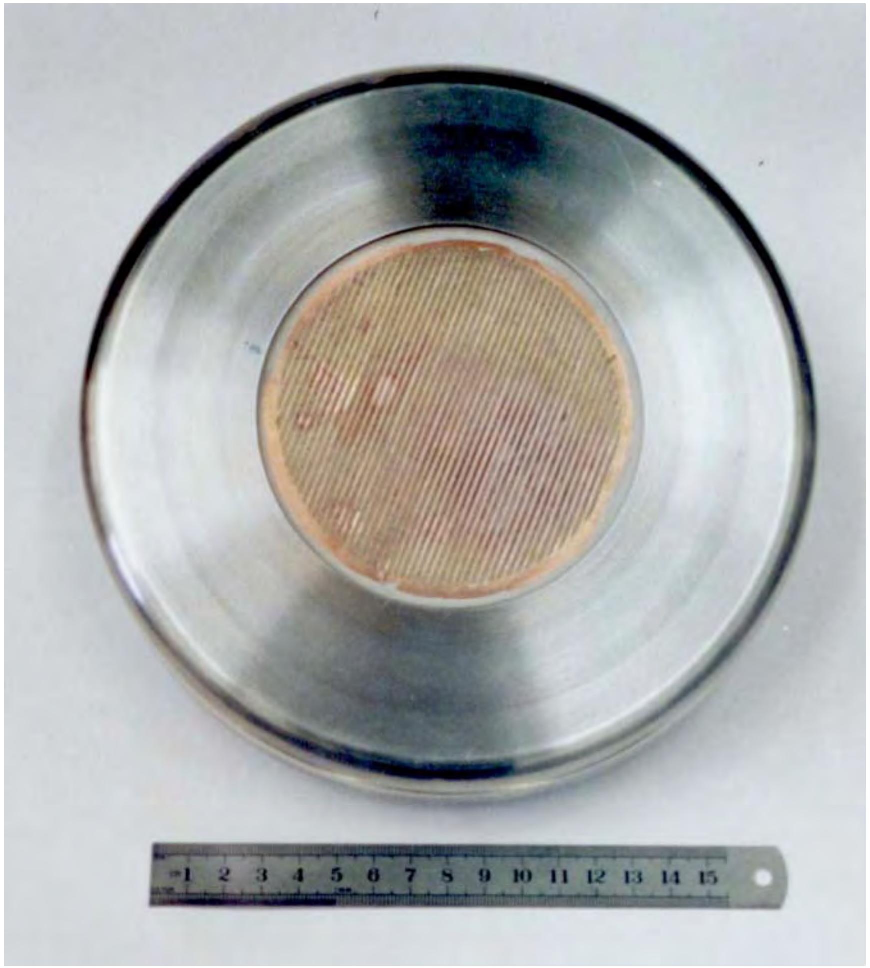
- Ceramics such as Lead Zirconium Titanate (PZT) and Barium Titanate ($BaTiO_3$) have relative dielectric coefficients of several thousand.
- Commonly used in transducers and high-power capacitors.

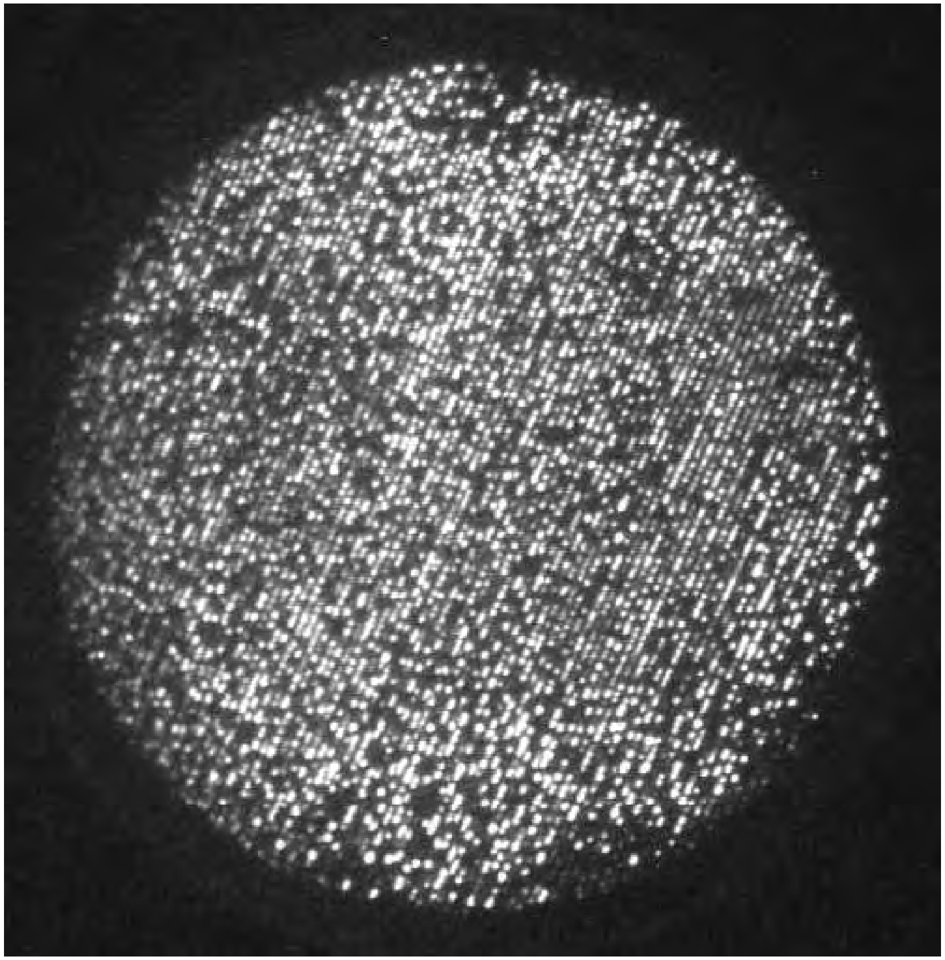




Ya. E. Krasik 20 ns exposure

Example of Plasma Produced on a Disk with Strip Electrodes





Main Processes Participating in Plasma Formation

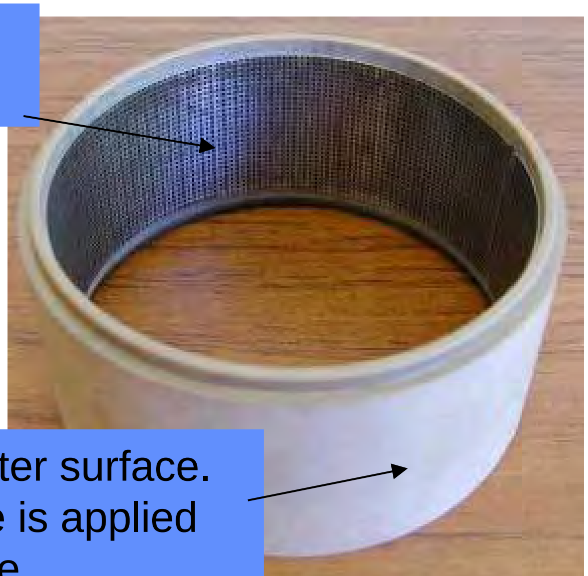
- Explosive plasma formation in triple points
- Avalanche of electrons along the insulator-vacuum interface
- Secondary electron and ion emission
- Gas desorption and ceramic ablation
- Ionization of the neutral cloud

Identified and studied by Krasik, Felsteiner, Haber and Kaganovich.

Barium Titanate ($BaTiO_3$) Ferroelectric Plasma Source (FEPS) Design

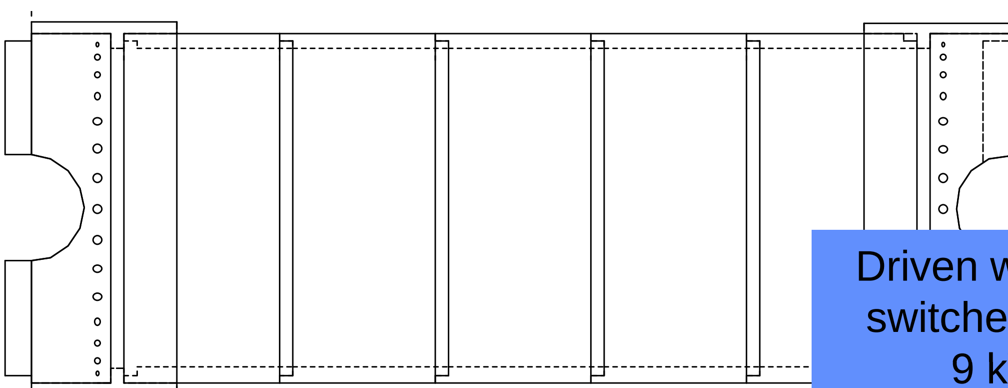
Grounded interior mesh

3.000” ID
3.300” OD
1.600” length



Metalized outer surface. High voltage is applied here.

Coupling provides grounding and transverse access.

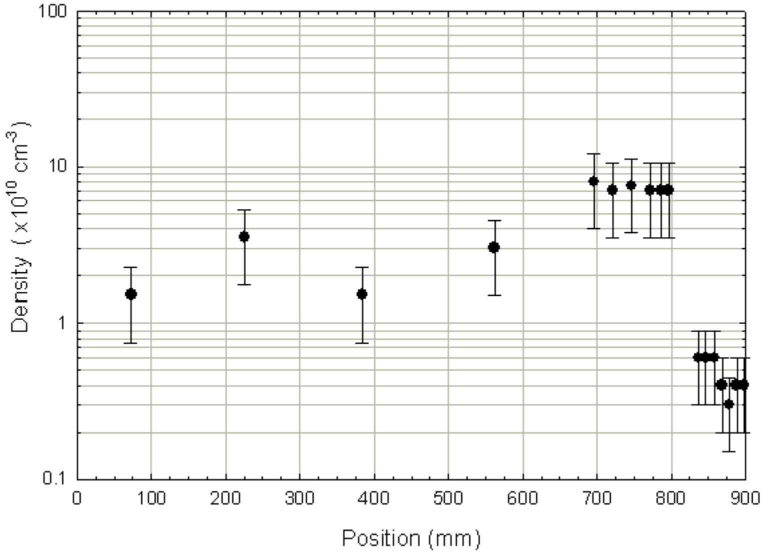


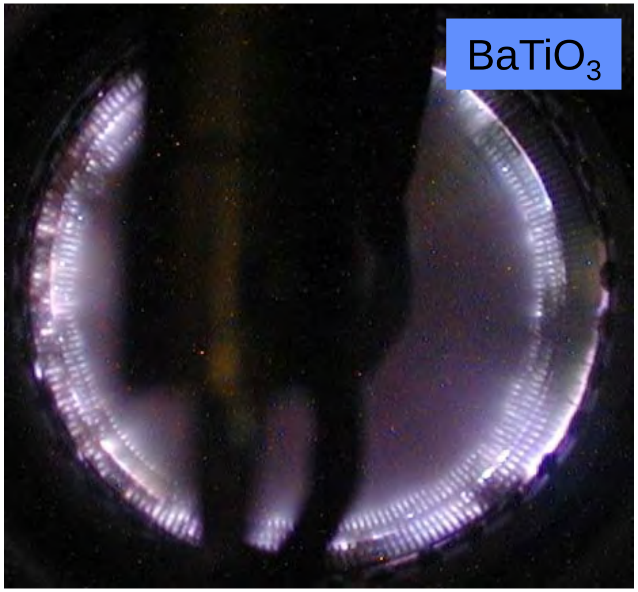
Driven with thyratron-switched capacitors. 9 kV, 500 A

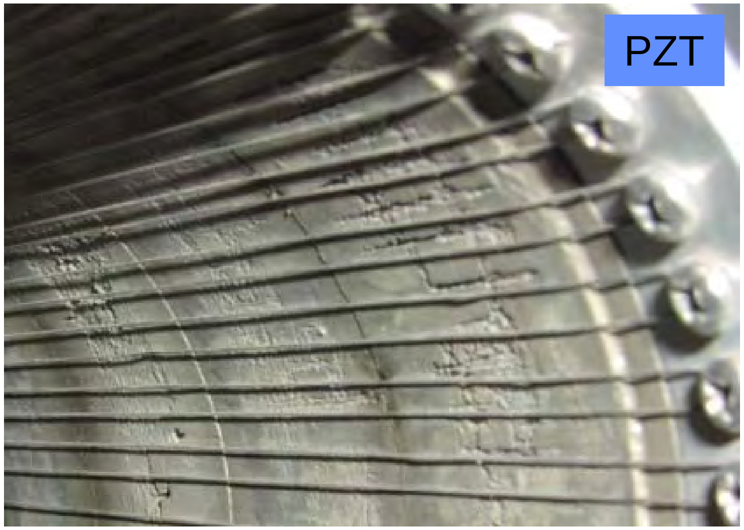
FEPS Performance

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

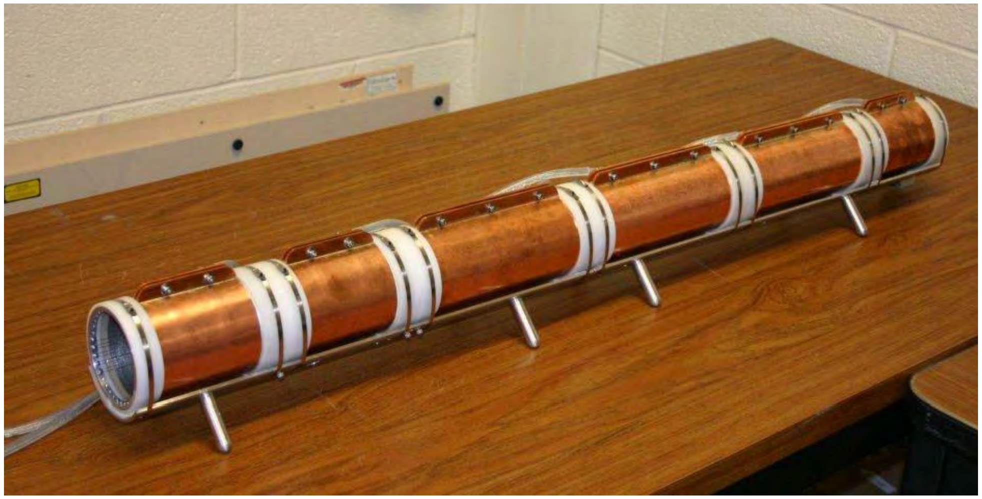
Langmuir probe measurements



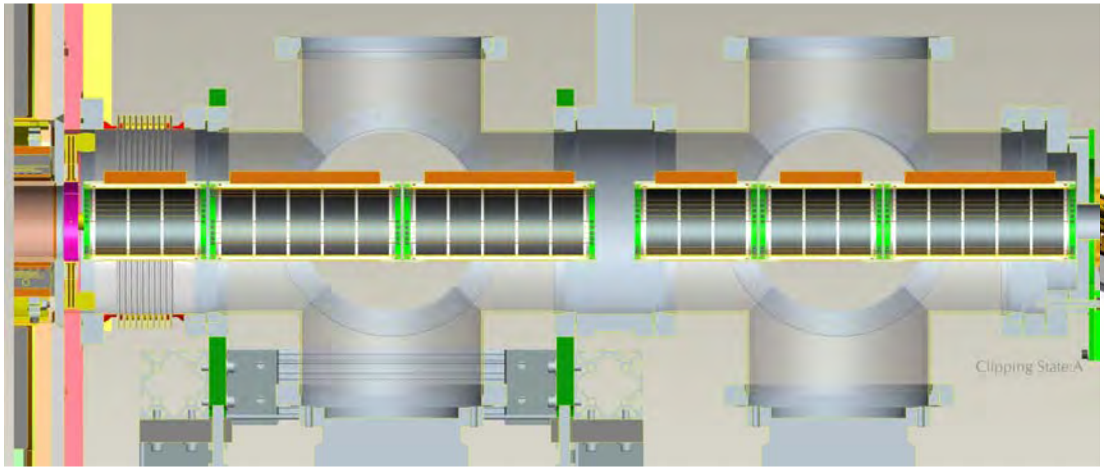


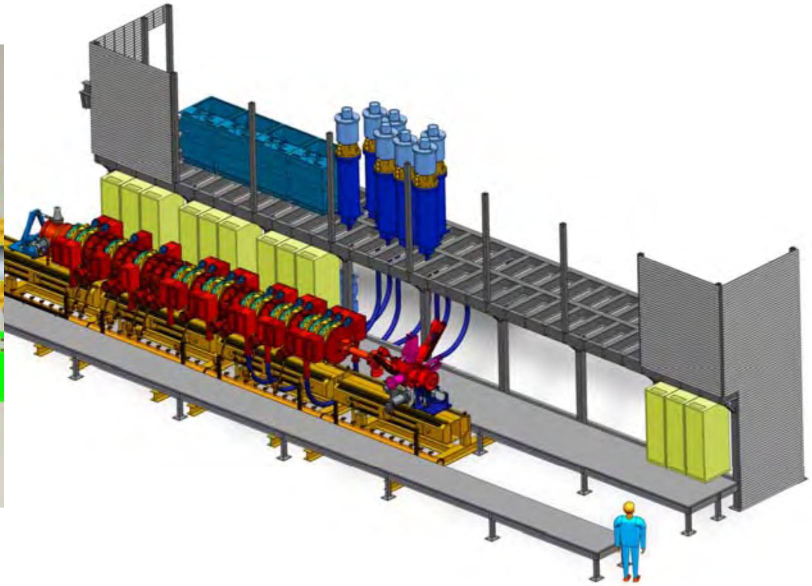


FEPS for NDCX-II



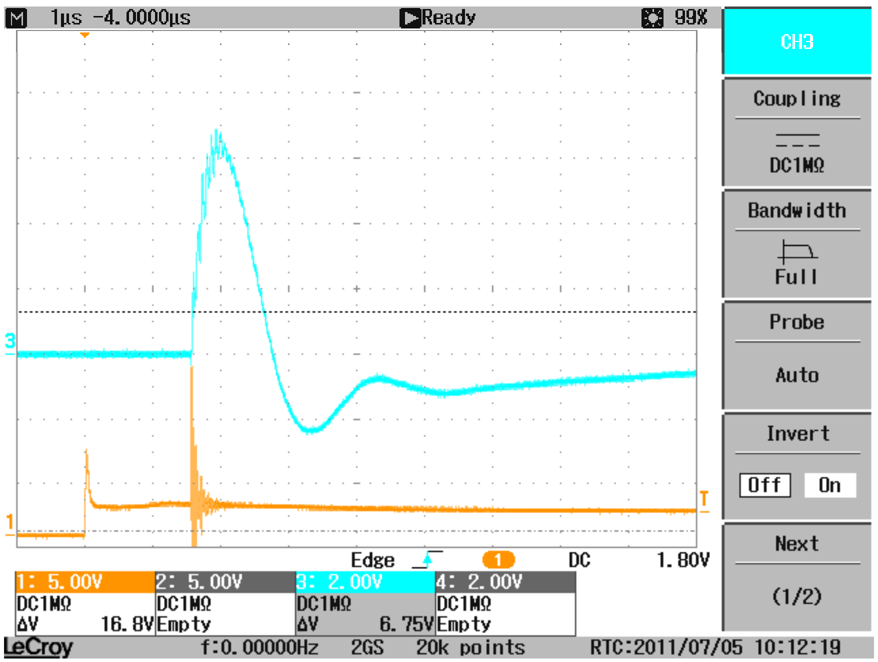
- Length of FEPS can be changed by changing individual modules.
- Each module has its own charging power supply, its own pulser, and its own trigger.
- Grounded cradle maintains alignment of the FEPS in the beam pipe.



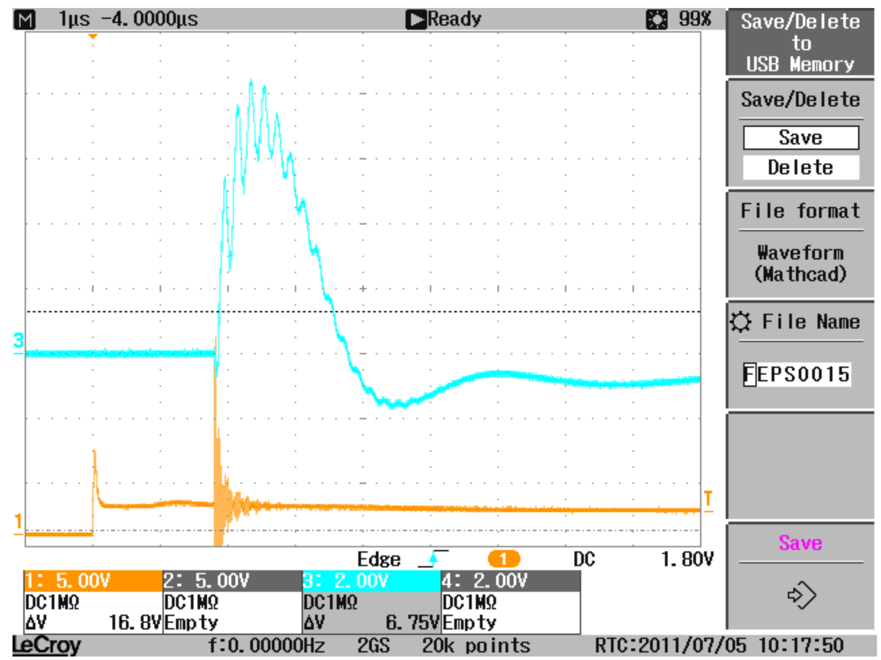


Current Through the FEPS is Sensitive to Cable Self Inductance, but there is Little Effect on Plasma

2 m coaxial cable

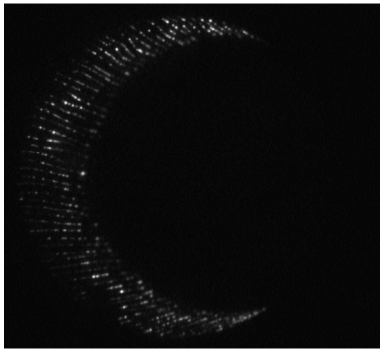


6 m coaxial cable

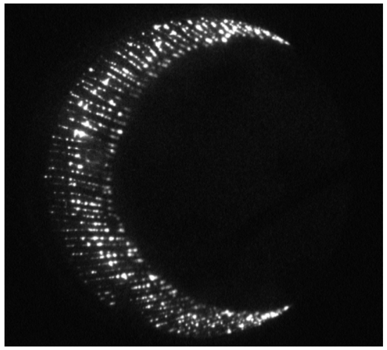


A Spark Gap Crowbar May Improve Uniformity and Plasma Density

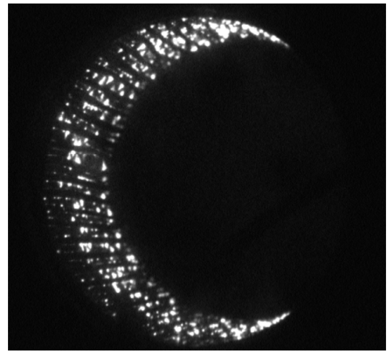
Ya. E. Krasik   0.1 μs exposure time, 7.5 kV charging voltage



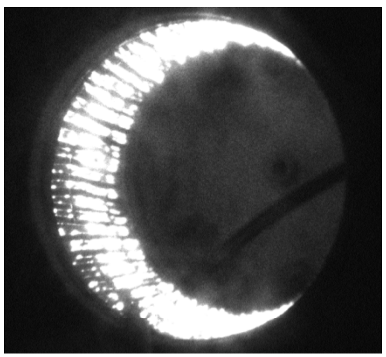
τ_d = 250 ns



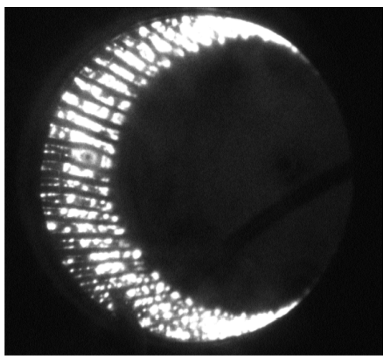
τ_d = 450 ns



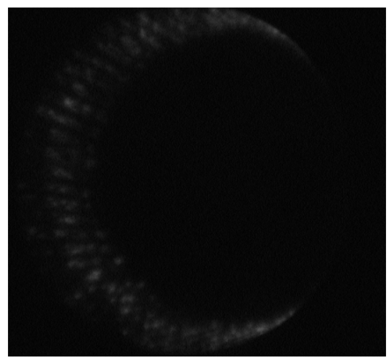
τ_d = 800 ns



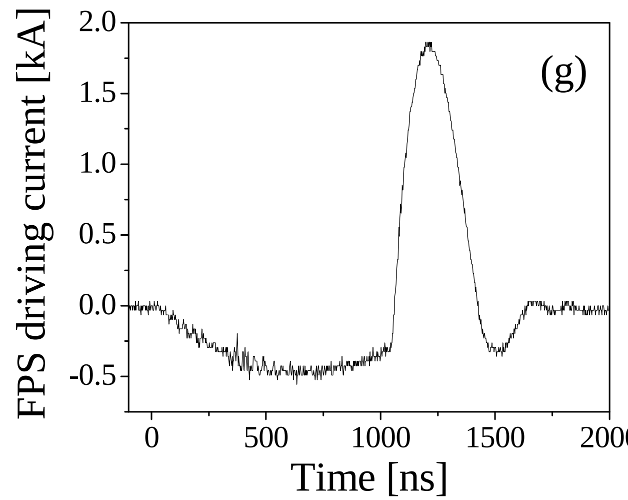
τ_d =1100 ns
Crowbar



τ_d =1300 ns

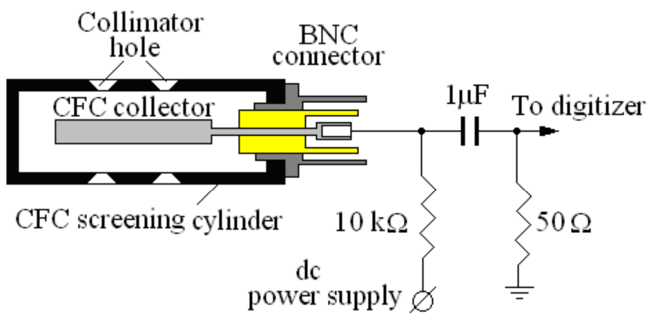


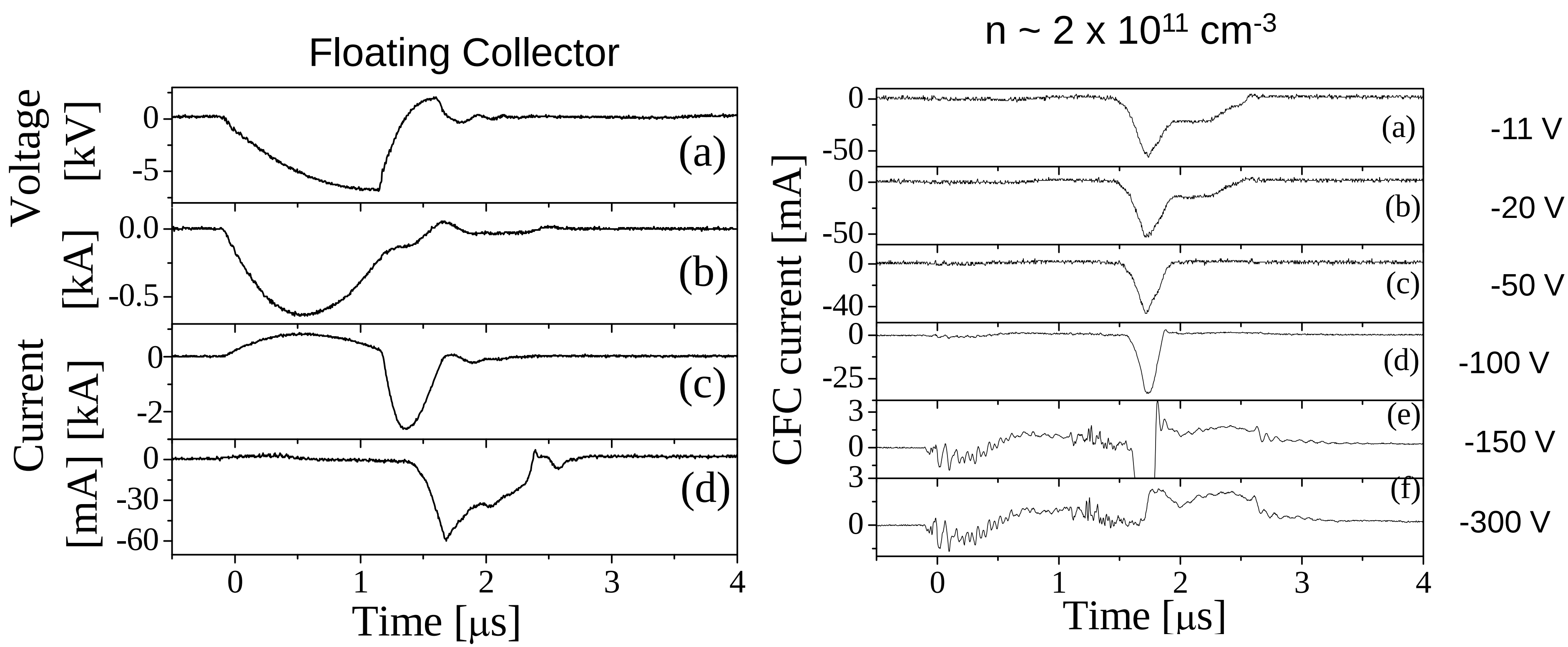
τ_d =1500 ns



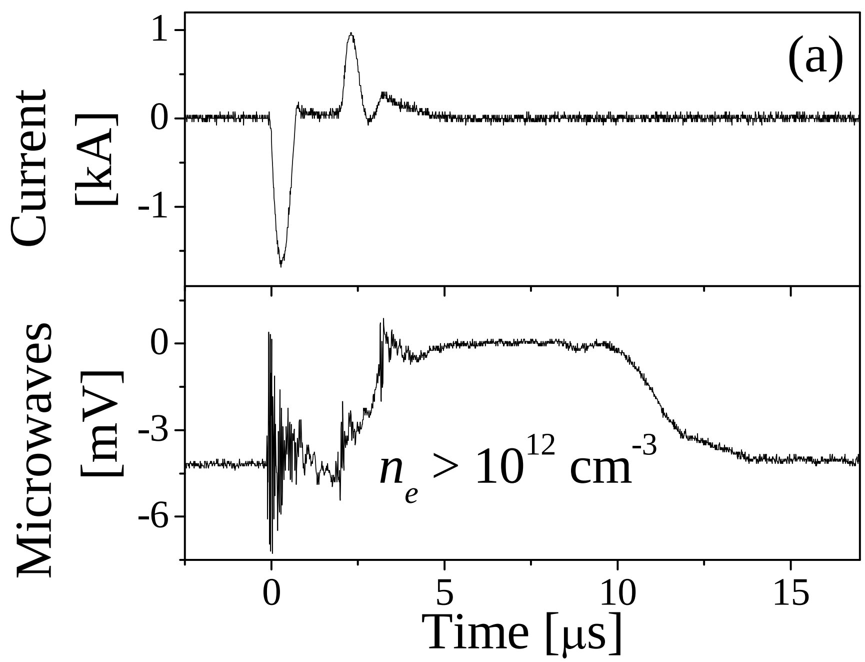
Similar images with larger charging voltage and camera gain show reasonably uniform emission near the center.

A Collimated Faraday Cup has been Used in Addition to Langmuir Probes

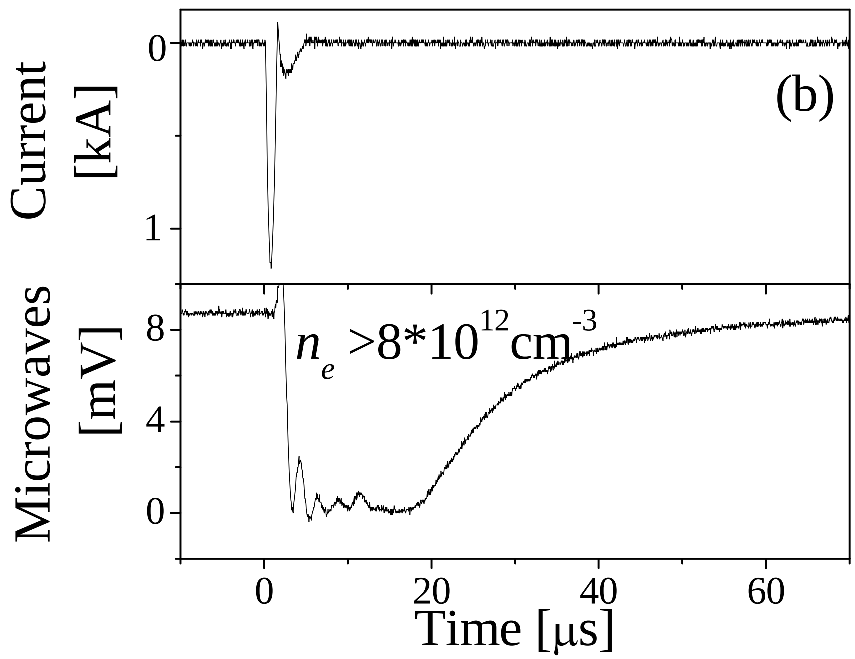




Microwave Cutoff Measurements Provide Another Measure of the Plasma Density



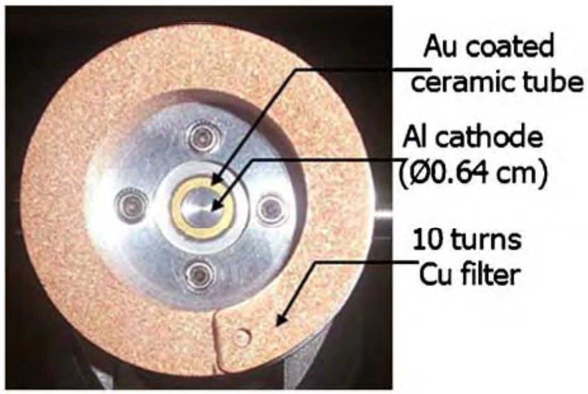
9 GHz

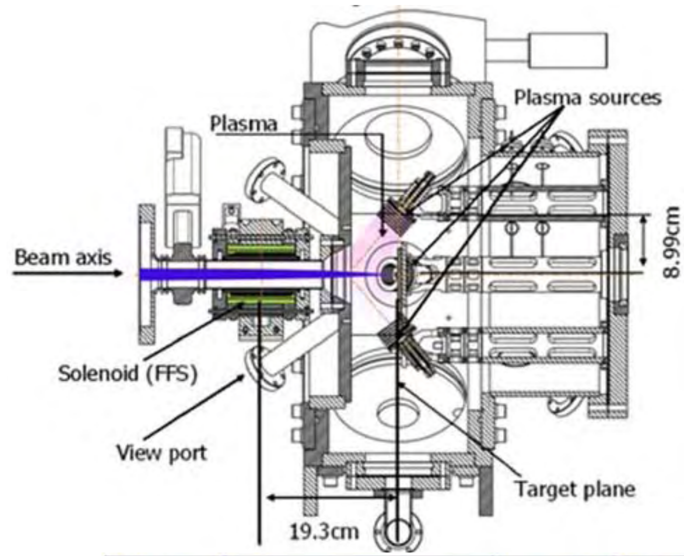


25 GHz

Cathodic Arc Plasma Source (CAPS)

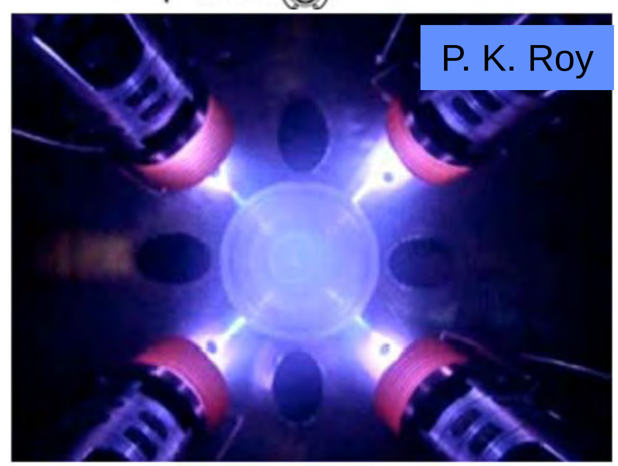
Developed by André Anders and collaborators.
HIF 2008 – P. K. Roy et al., Nucl. Instr. and Meth. in Phys. Res. **A 606** 22, (2009).



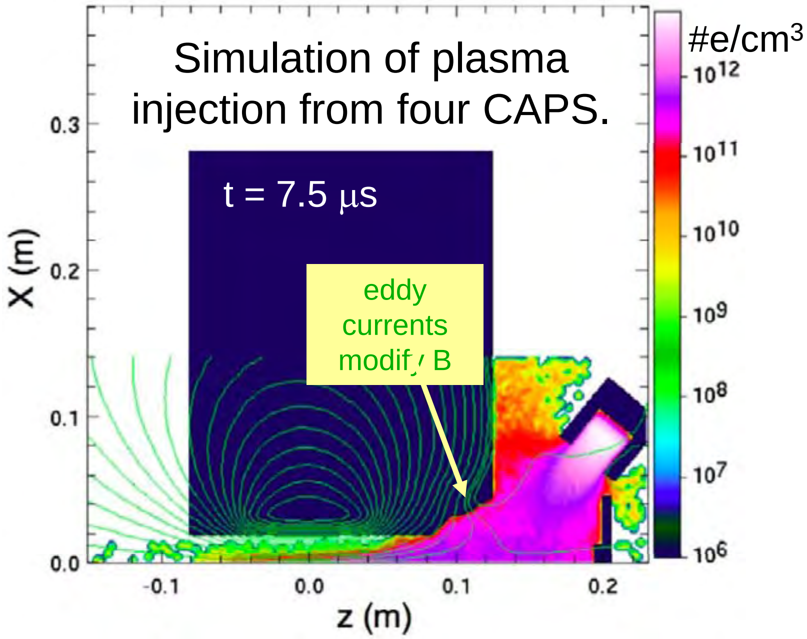


The four CAPS produce a plasma density of 10^{12} cm^{-3} on the beam axis near the target spot and a plasma density of 10^{13} cm^{-3} on the beam axis at the midplane of the 8 T Final Focusing Solenoid (FFS).

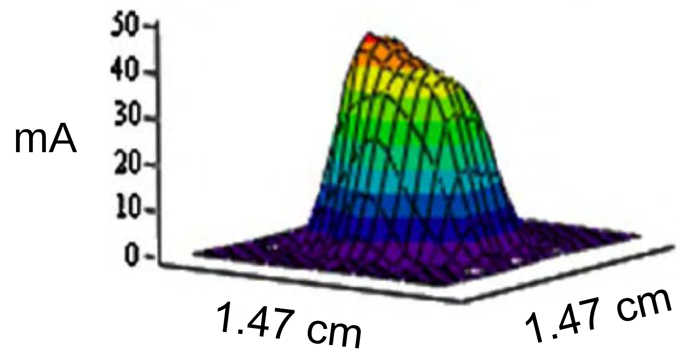
A 3 kV pulse drives 800 A peak current through each of the four sources.



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



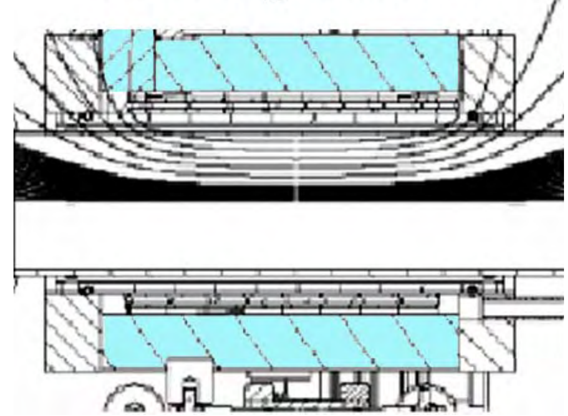
Ion saturation current measured on a hexagonal array of copper collector disks.



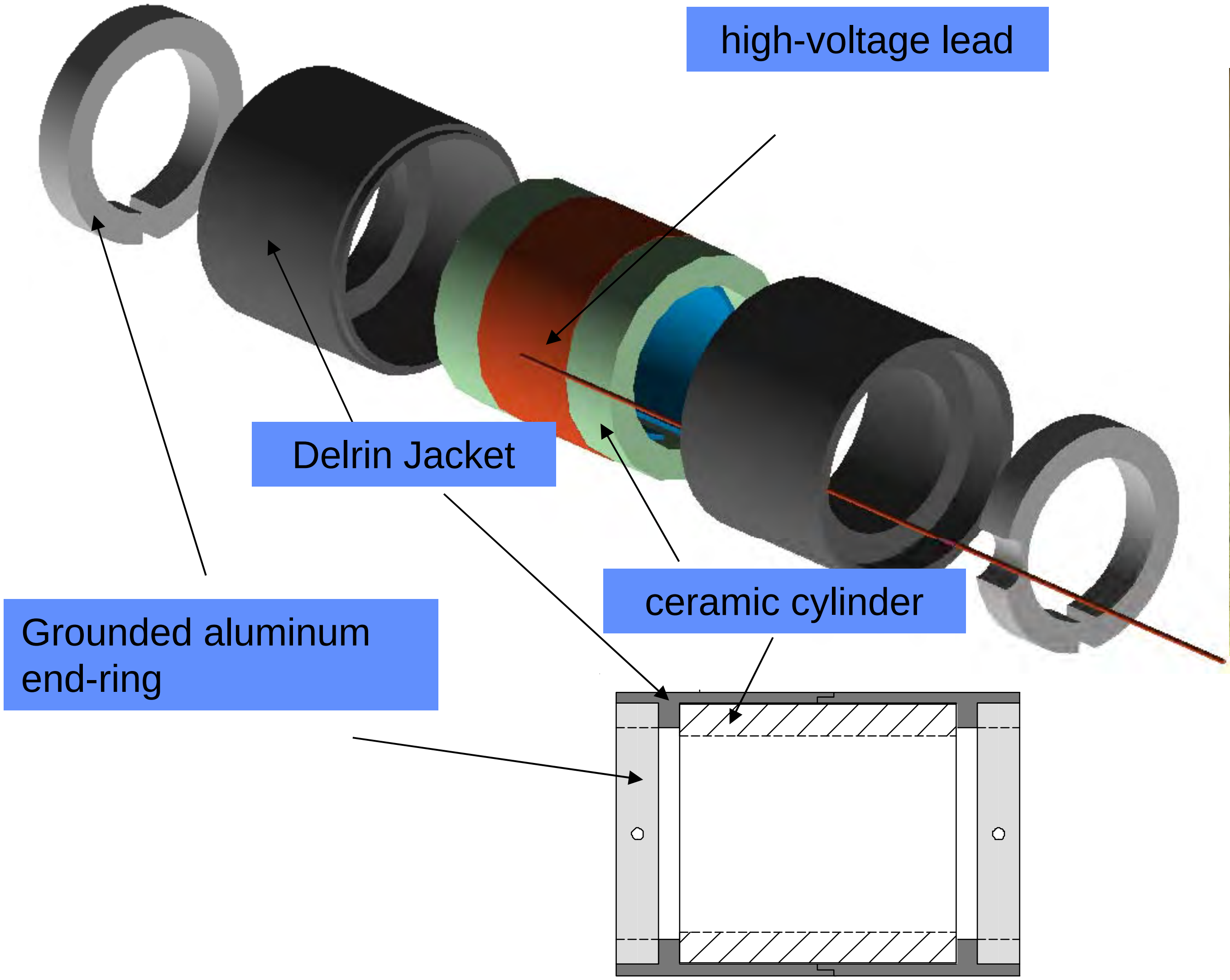
Plasma mostly flows along the magnetic field lines created by the CAPS filter coils, the 8 T solenoid, and the eddy currents.

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

9 cm long solenoid

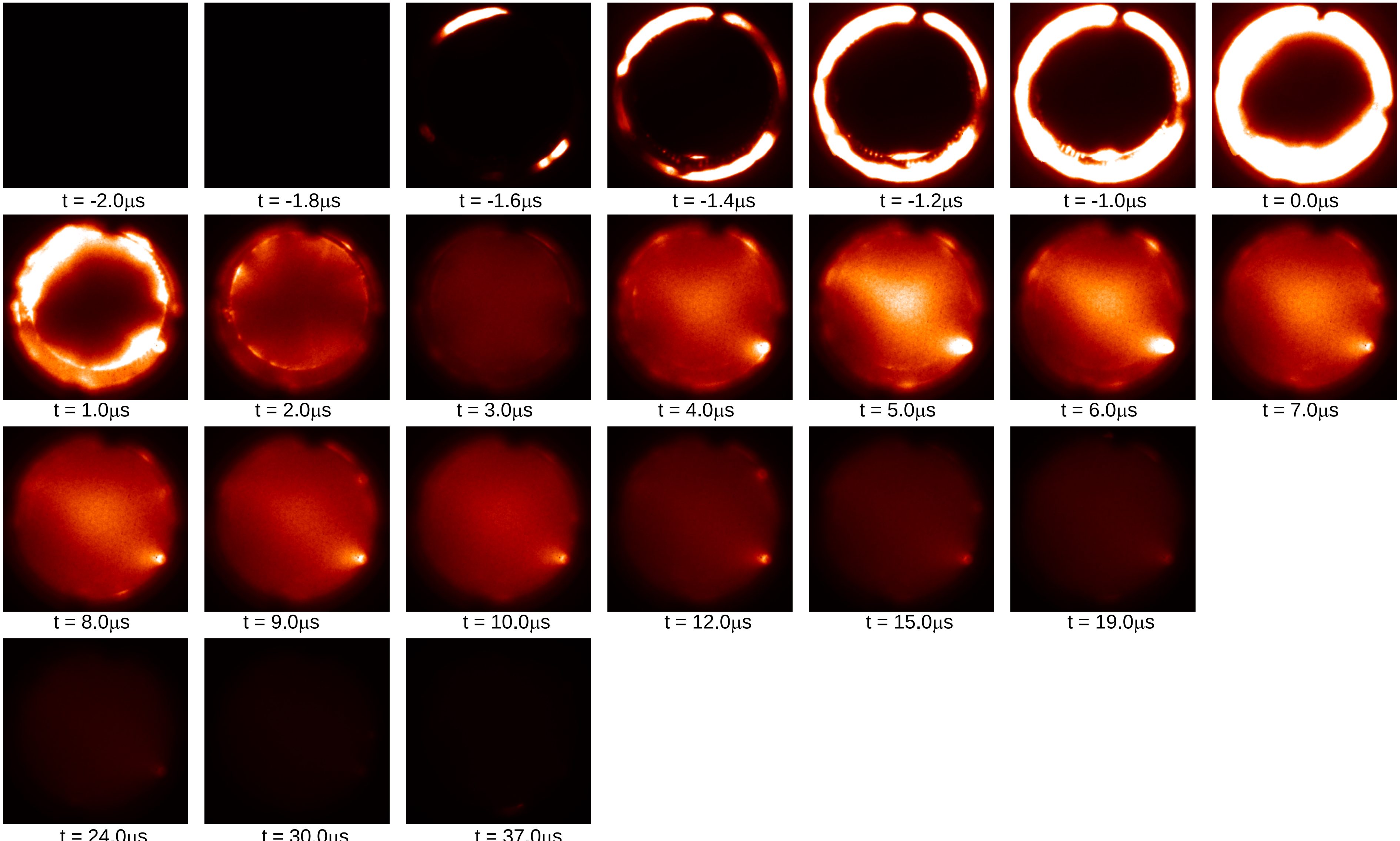


Compact FEPS was Designed to Create Plasma in 8 T Solenoid



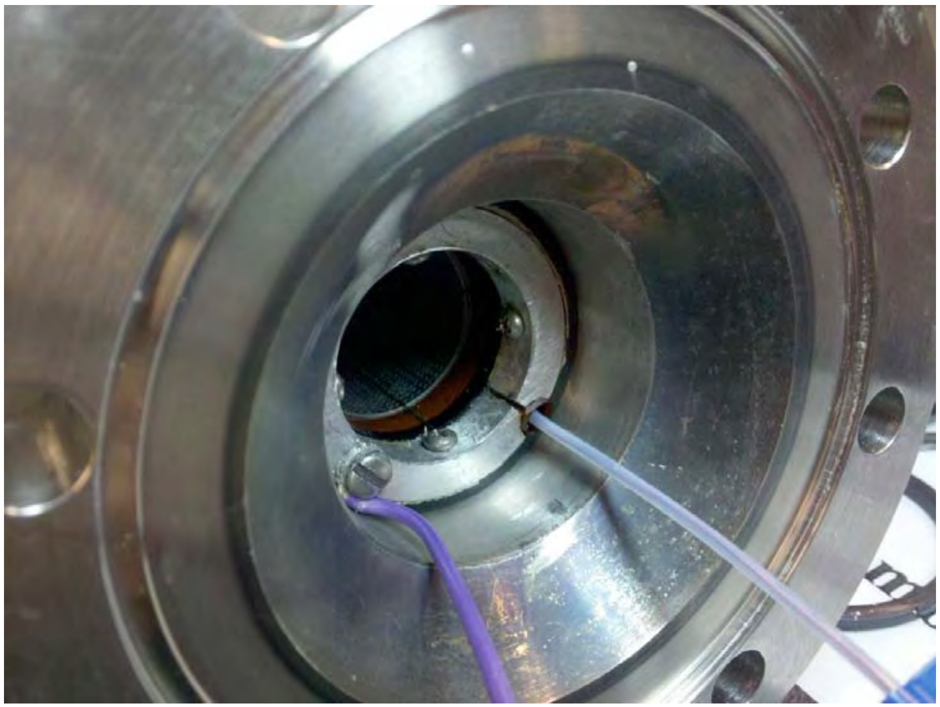
Conductors are slotted to prevent eddy current effects

8 Shot Average and 1 μs Exposure

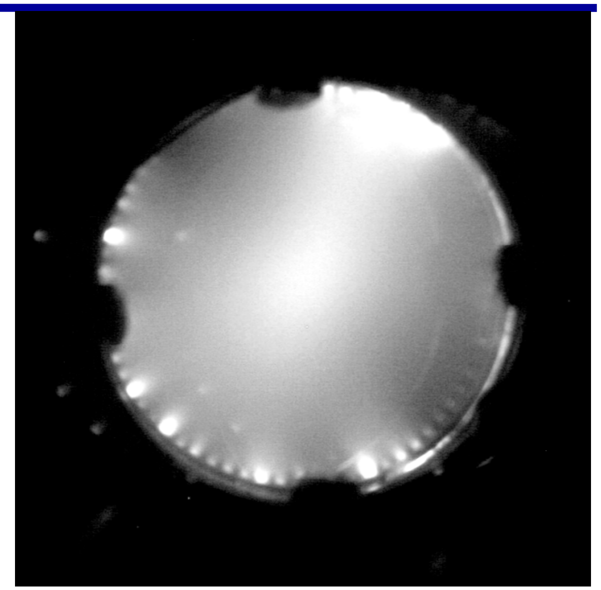


Compact FEPS Tested in 3 T Solenoid

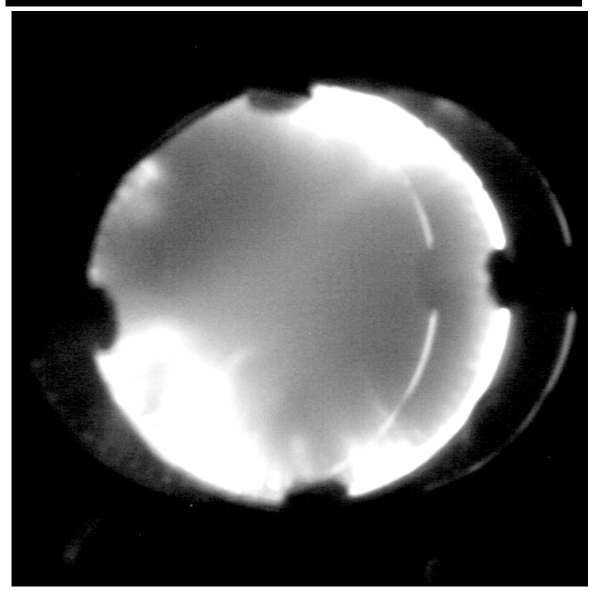
The plasma source is pulsed (μs timescale) at the maximum of the magnet pulse (ms timescale).



No B-Field →

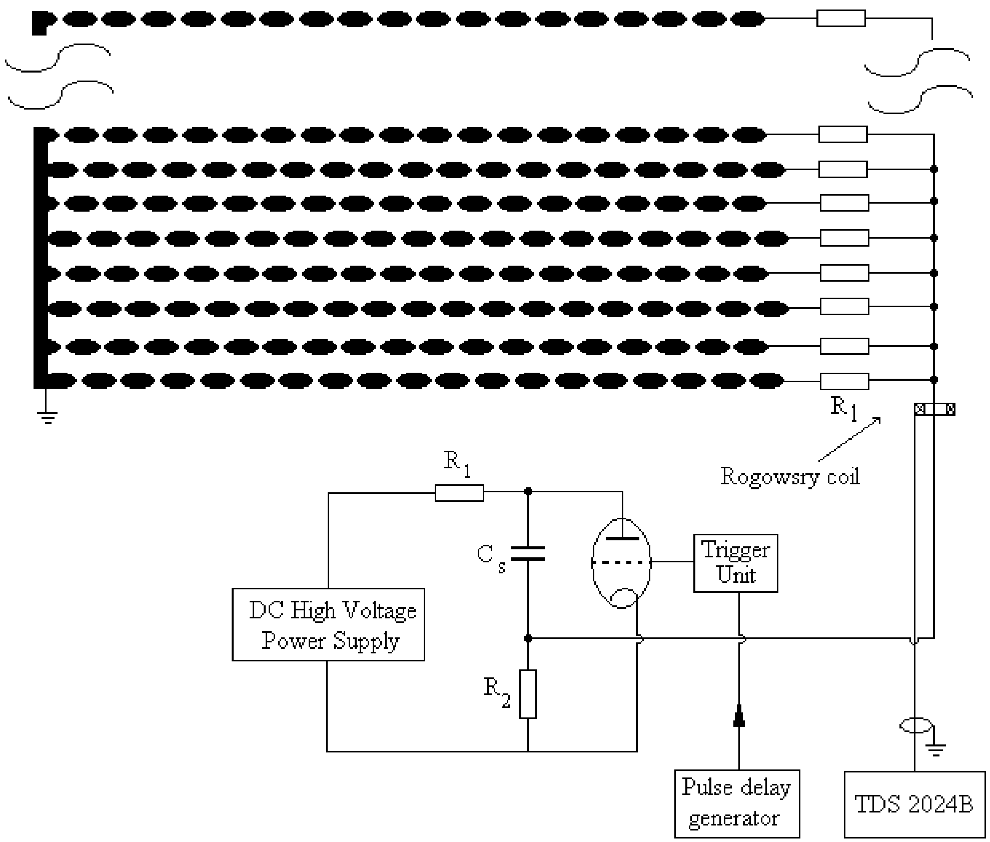


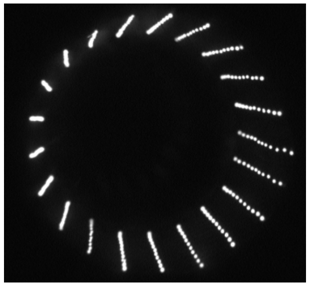
3T Field →

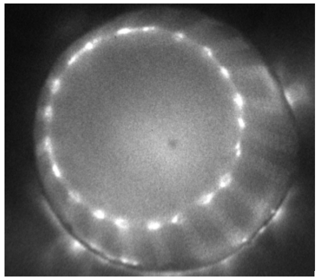


Heating from repeated magnet pulses caused melting of insulating Apiezon-L grease.

Flashboard Plasma Source is Being Tested



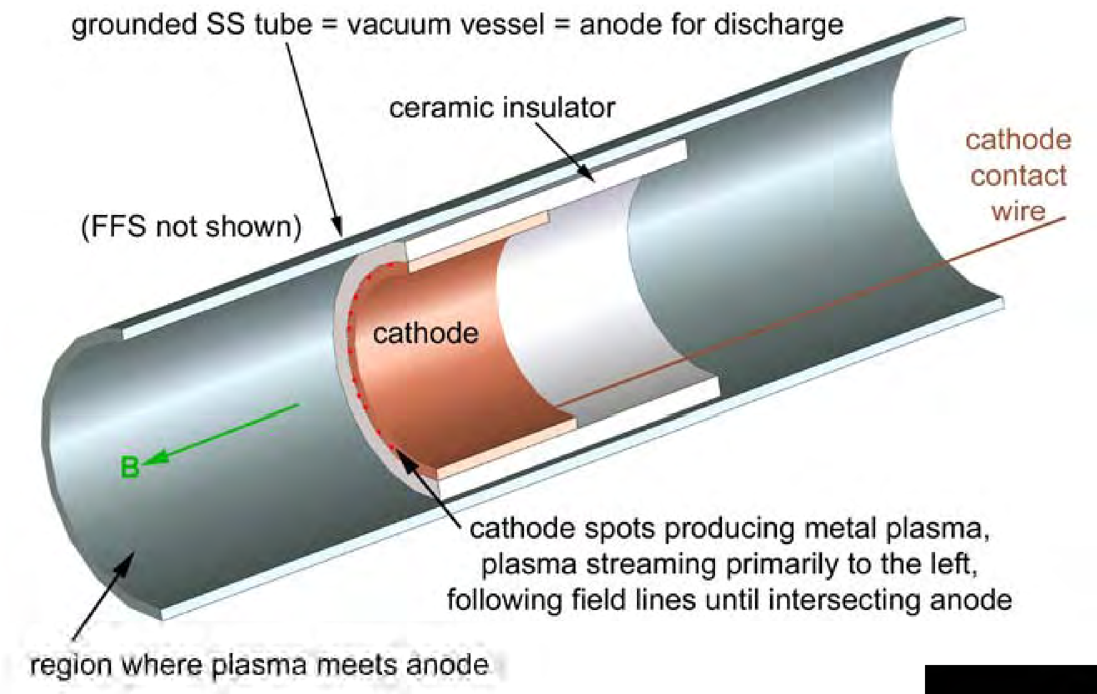




16kV, 4kA
Plasma density in the mid 10^{12} cm^{-3} range

Ya. E. Krasik

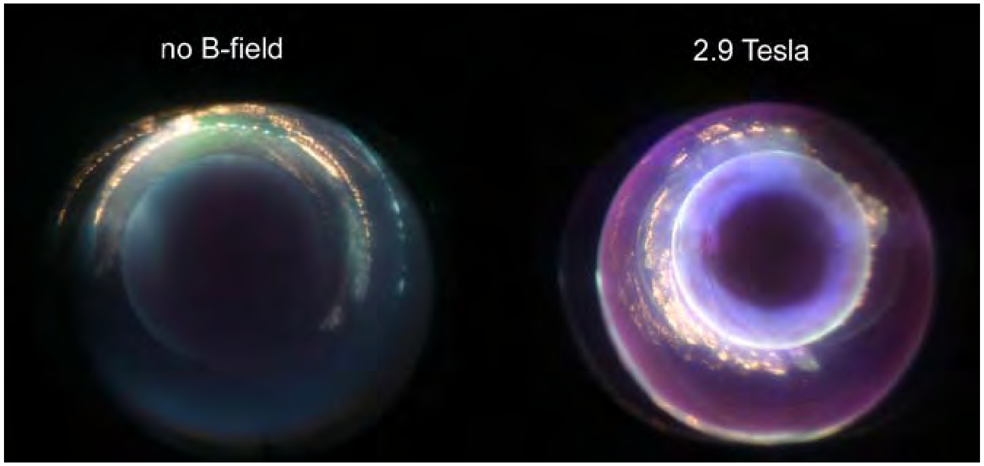
Cathodic Ring Plasma Source



André Anders
Marina Kauffeldt
Efim Oks

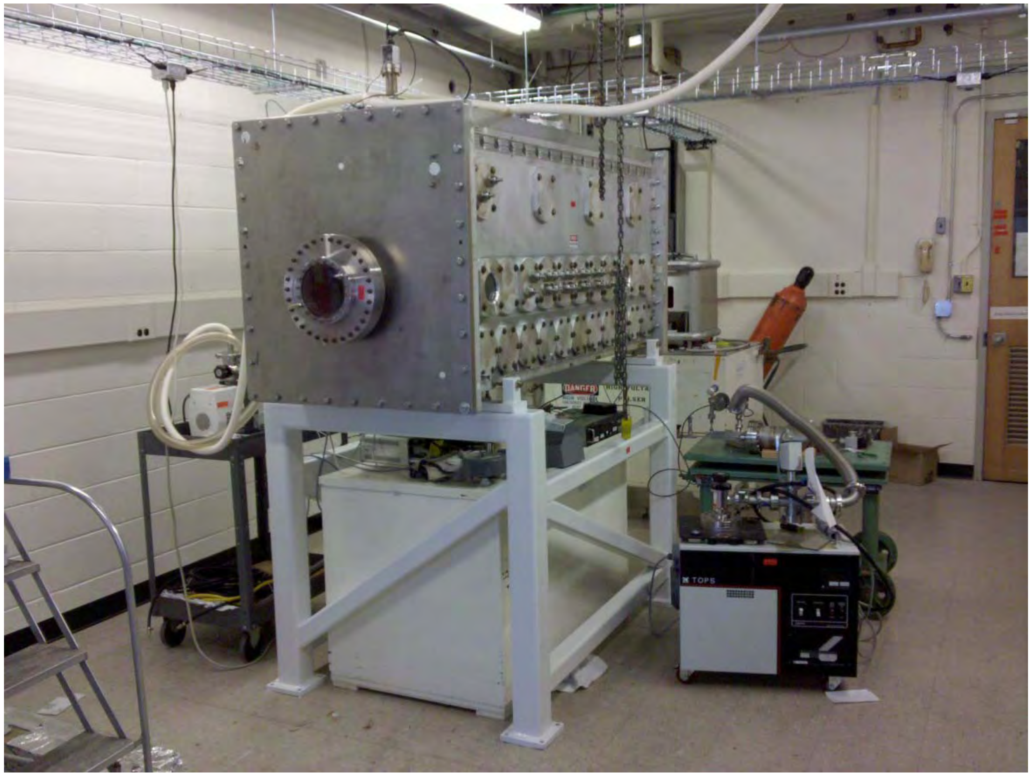
Conductors are slotted to prevent eddy current effects

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



Test Stand 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 to ensure that the local plasma density exceeds the local beam density in the neutralized drift region.
- Compact FEPS and CAPS might 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.