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ELECTRON-BEAM-GAS INTERACTION STUDIES FOR CODE VALIDATION*

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We report on a study of electron-beam-driven ionization and conductivity growth

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- ~70-kV electron beam injected into dry air at 20 mTorr to 20 Torr, and current densities from <10 A/cm^2 to >300 A/cm^2
- Highly-sensitive interferometer measured line-integrated electron density with sensitivity approaching 10^{-5} waves
- Global net current measured at the cell edge
- This work spans a range of conditions from those where ionization is purely due to the primary beam to those where ionization is dominated by plasma currents
- These experiments will resume later in 2015, supported by SNL
- This work built on, and is synergistic with, an variety of studies of both electron- and ion-beam-gas interaction at MV energies supported by SNL, AWE, and JFFI
  - Existing, AWE-funded program includes study ~1-MV electron-beam-gas interaction

An existing Febetron was retrieved, disassembled, and reconfigured for <100-kV operation

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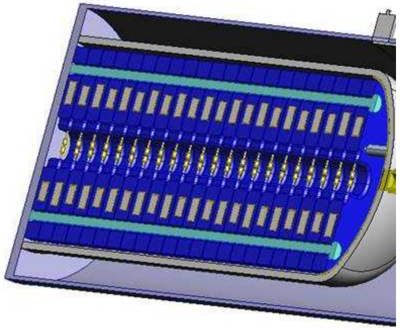
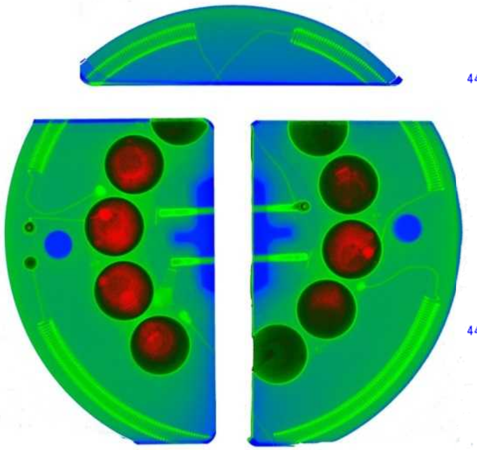
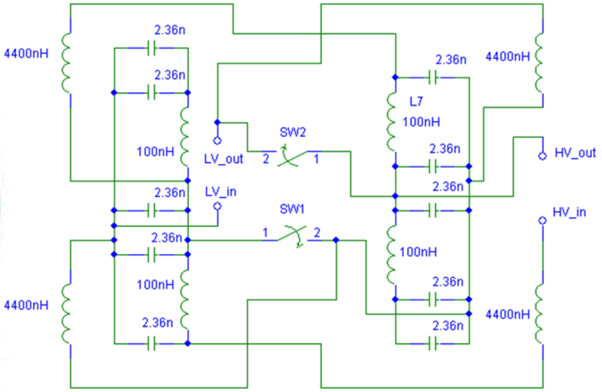
All but 6 pancakes removed

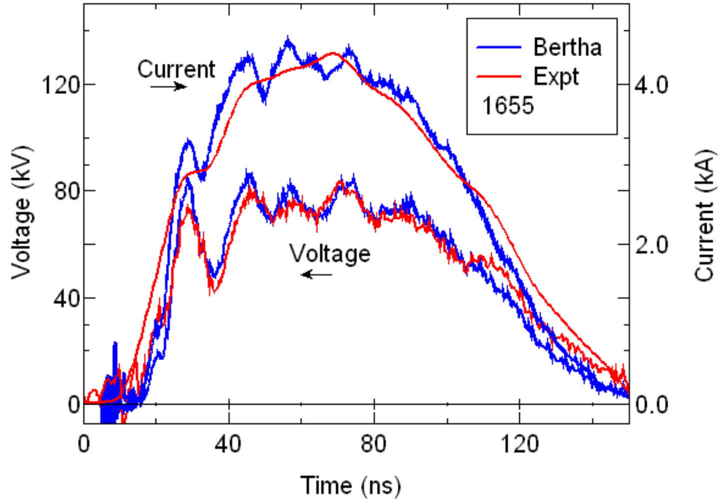


Pancake x-rayed and modeled by Ray Allen





Bertha model shows reasonable agreement



A small water-line generator could provide a more-tunable pulse

Experimental arrangement

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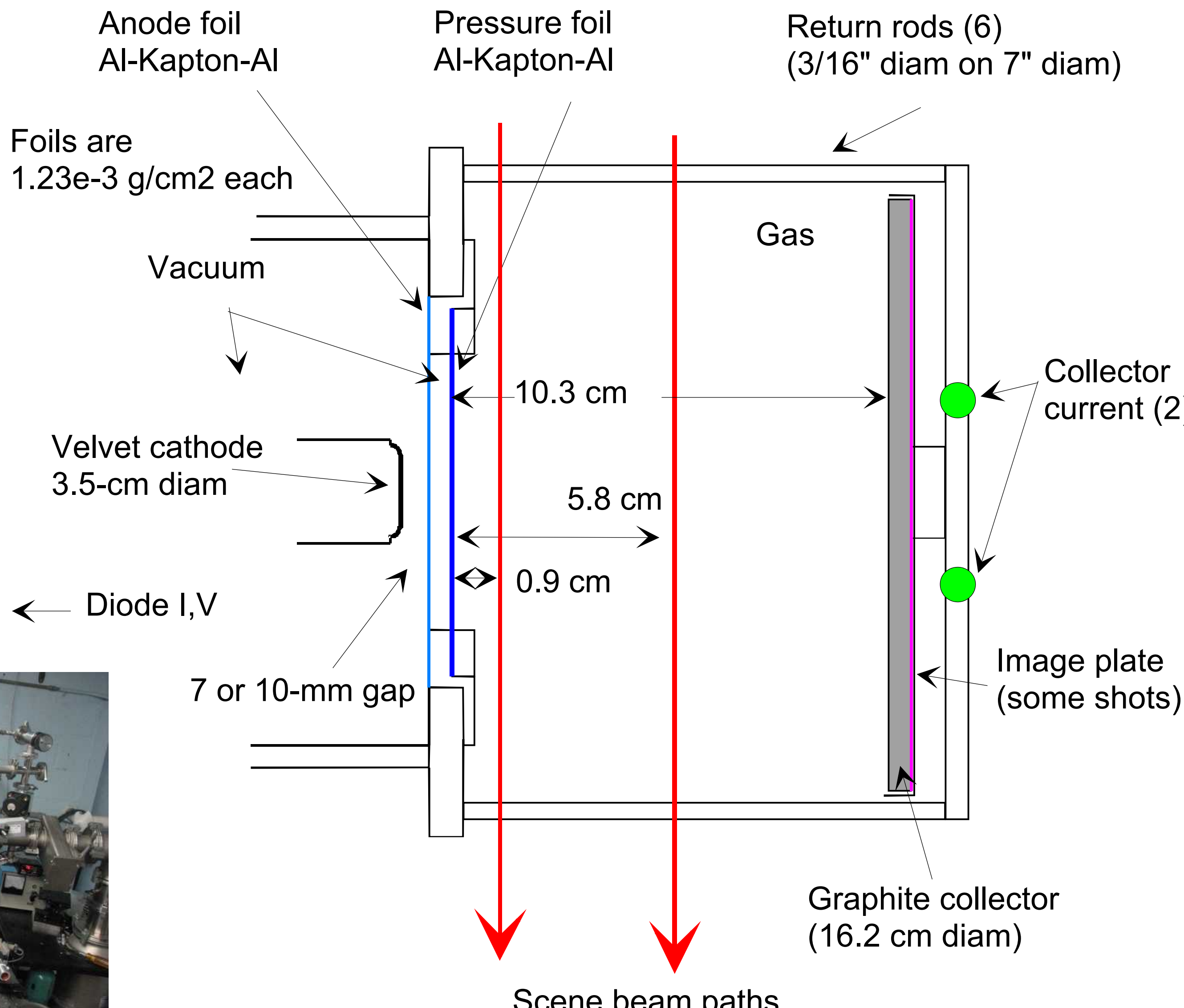

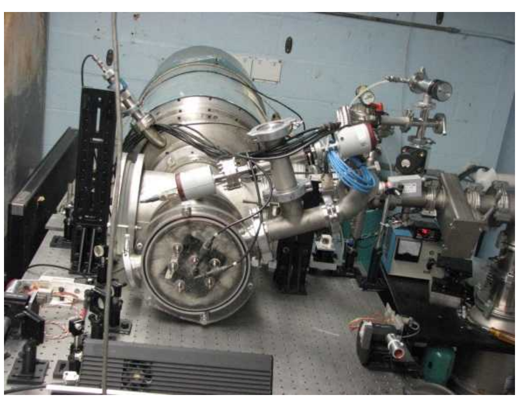

Electrical waveforms for medium and high current-density conditions

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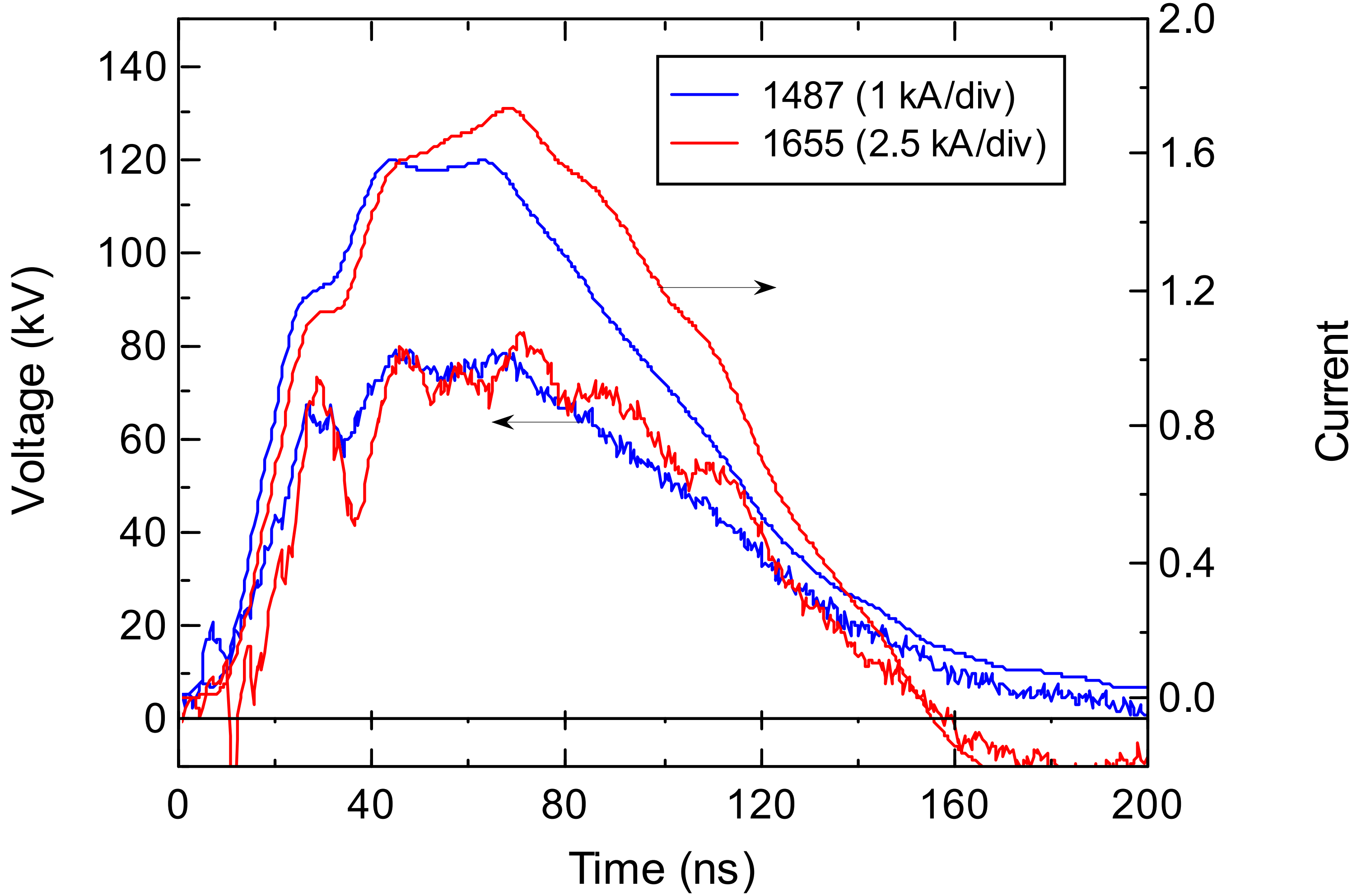
- Reasonable agreement with LSP impedance prediction



ITS calculates transmitted energy spectrum

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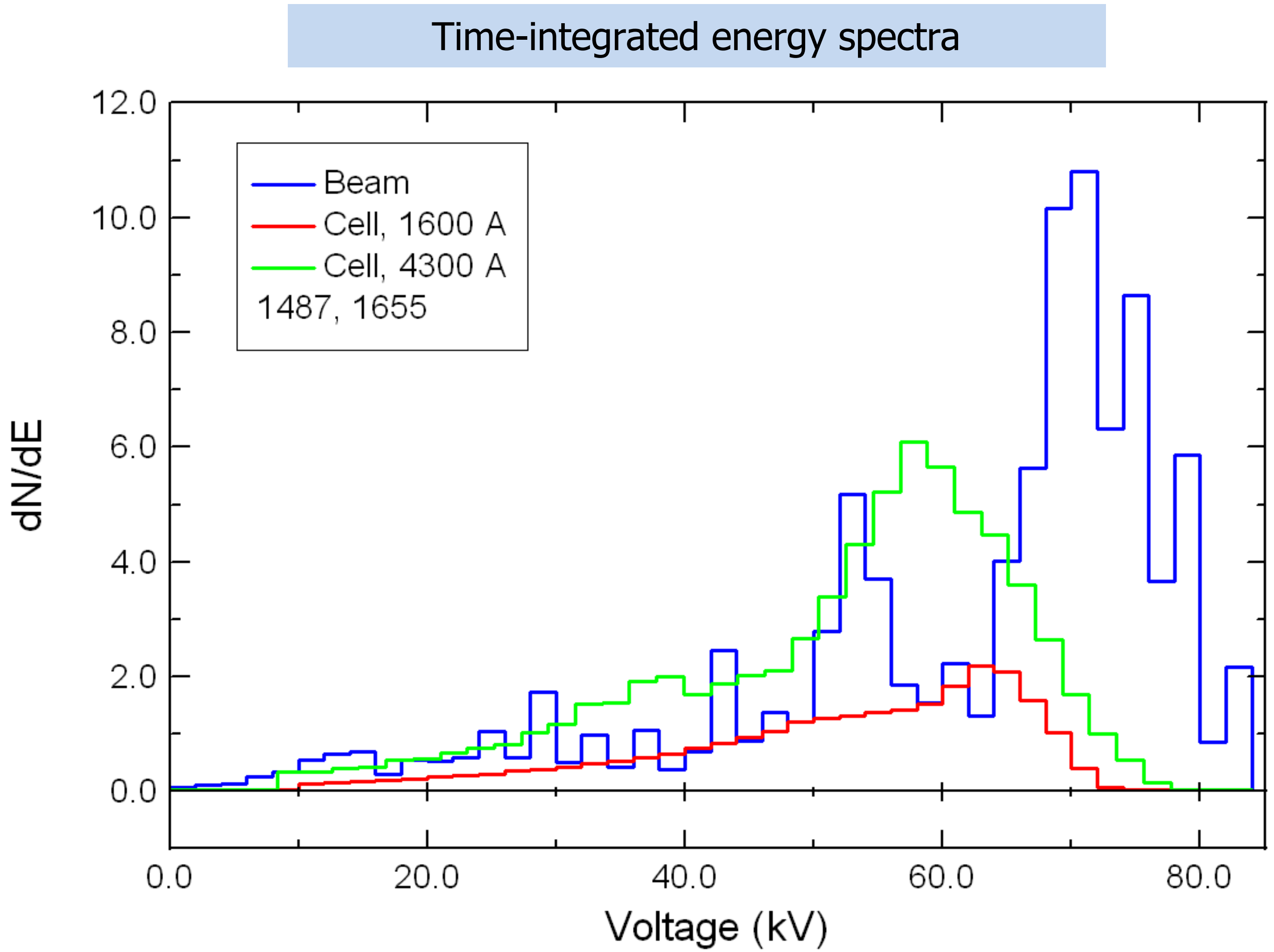

Image-plate distributions for all conditions fit by same functional form

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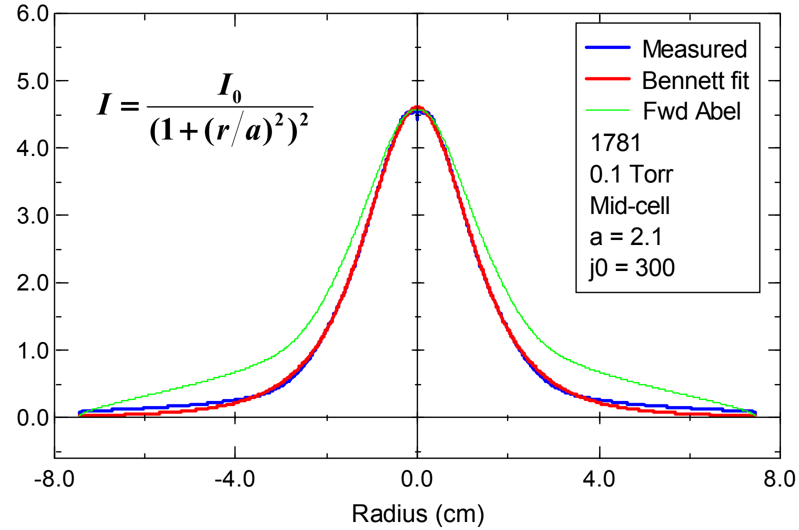
- Quasi-Lorentzian distribution
- Reasonable agreement with total transmitted current
- Forward-Abel transformed to compare with interferometry
- At high current density, variation in beam width with pressure at mid-cell



Summary

Distance from foil	Current	radius ***a***	Peak ***j***
1 cm	1600 A	3.1 cm	50 A/cm^2
6 cm (laser)	1600 A	4.4	25
10 cm (collector)	1600 A	4.4	25
1 cm, 0.1 Torr	4300	2.4	230
1 cm, 5 Torr	4300	2.5	200
6 cm, 0.1 Torr	4300	2.1	300
6 cm, 5 Torr	4300	3.1	140

Collector currents at medium current density show several pressure-dependent features

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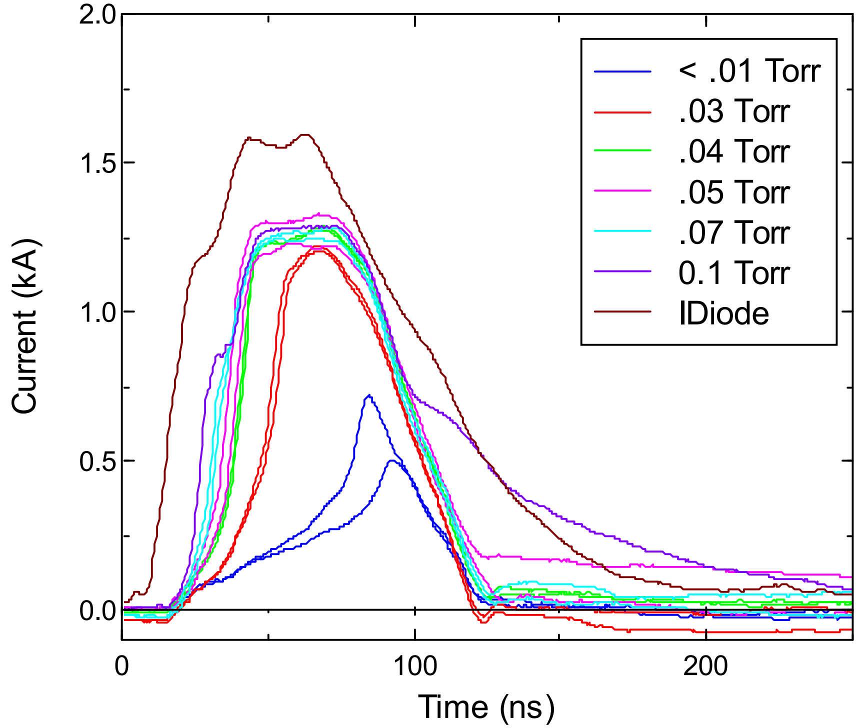
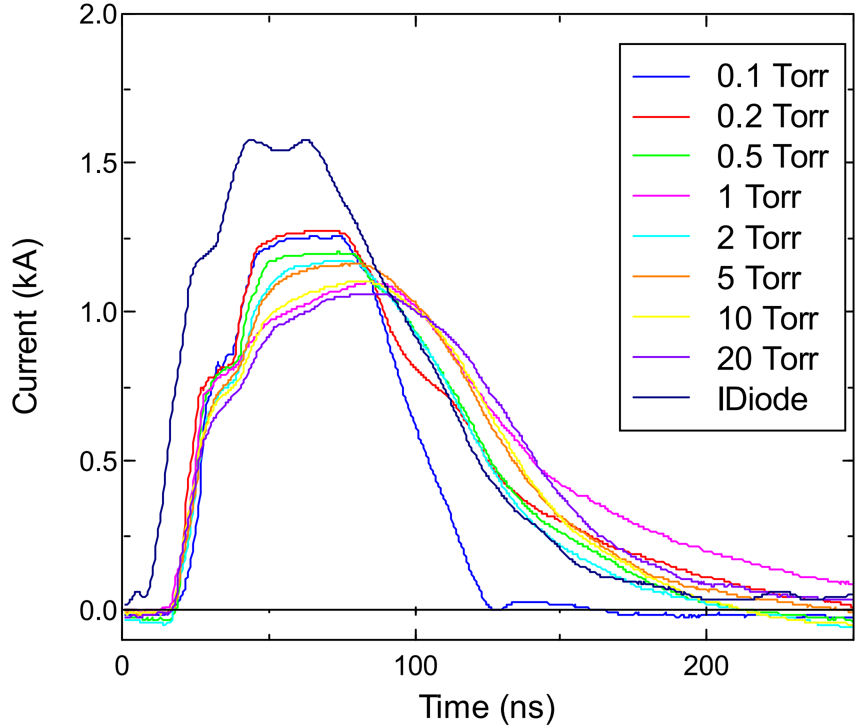
- Virtual cathode at low pressure
- Evidence for inductively-driven reverse current early in pulse
- Inductively-driven forward current at end of pulse

Low pressures



Higher pressures



These features become more pronounced at high current density

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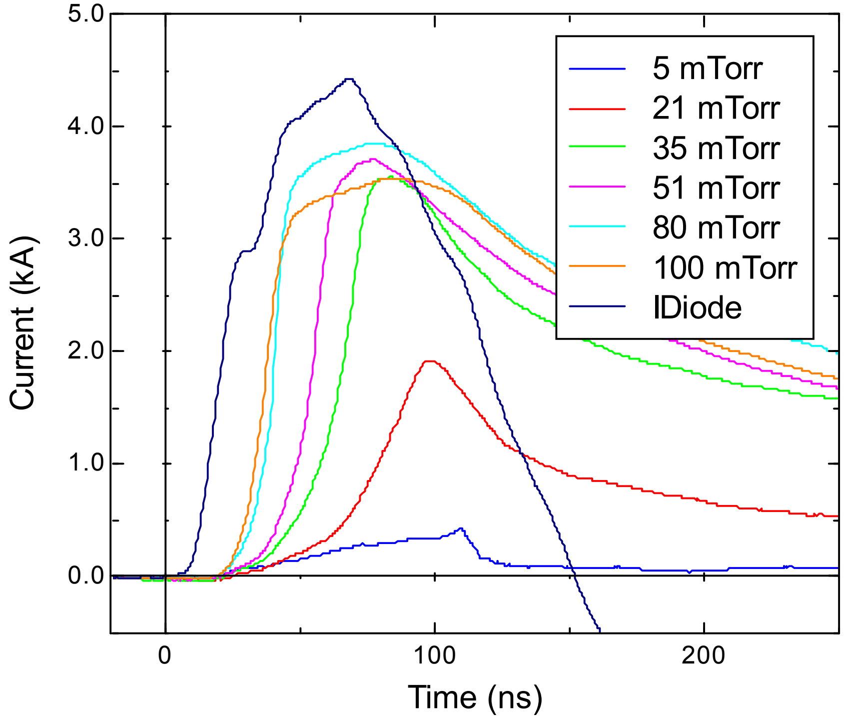
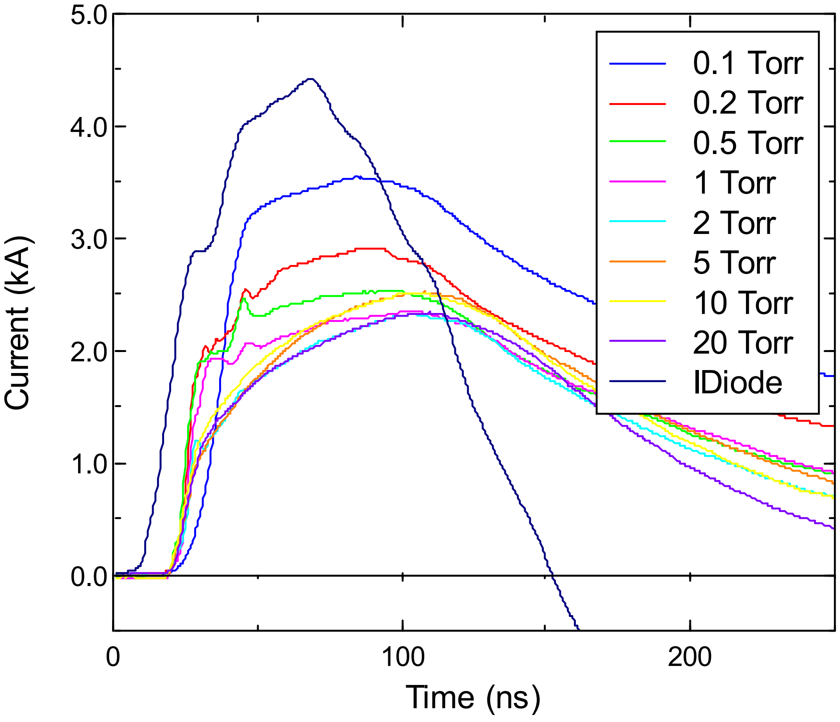
Low pressures



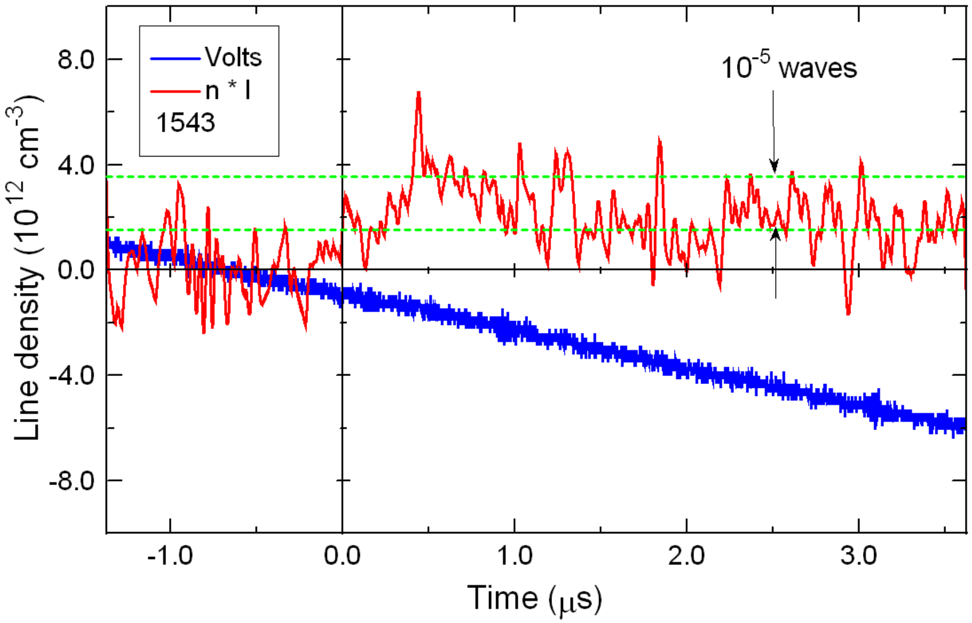
Higher pressures



- We were not able to measure the magnetic field inside the beam diameter
- Current at the cell wall is NOT the same as current in the plasma

High-sensitivity interferometer provides resolution approaching 10^{-5} waves

- Standard Mach-Zehnder configuration
- Synchronize experiment with zero-crossing of signal (highest sensitivity)
- Use polarization splitting to provide 2, opposite-polarity outputs and use differential detection
- Amplify differential output ~100x
- Carefully shield system from EM noise
- Once aligned, quite stable and straightforward to operate



The electron density falls more quickly at higher pressure
At low pressure, high-j, density rise during inductive tail

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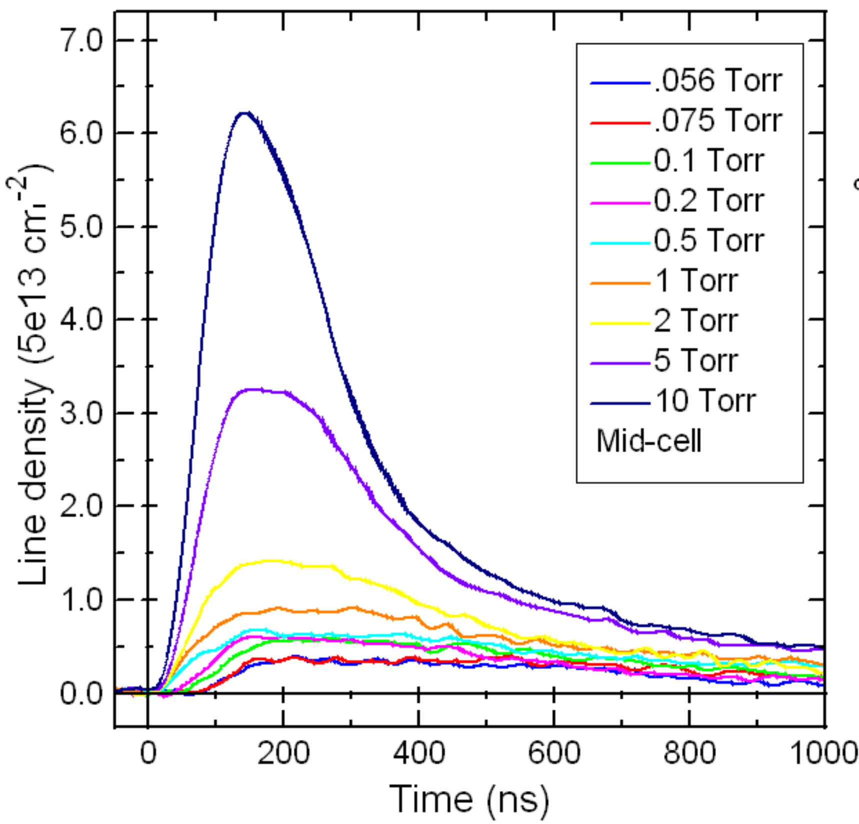
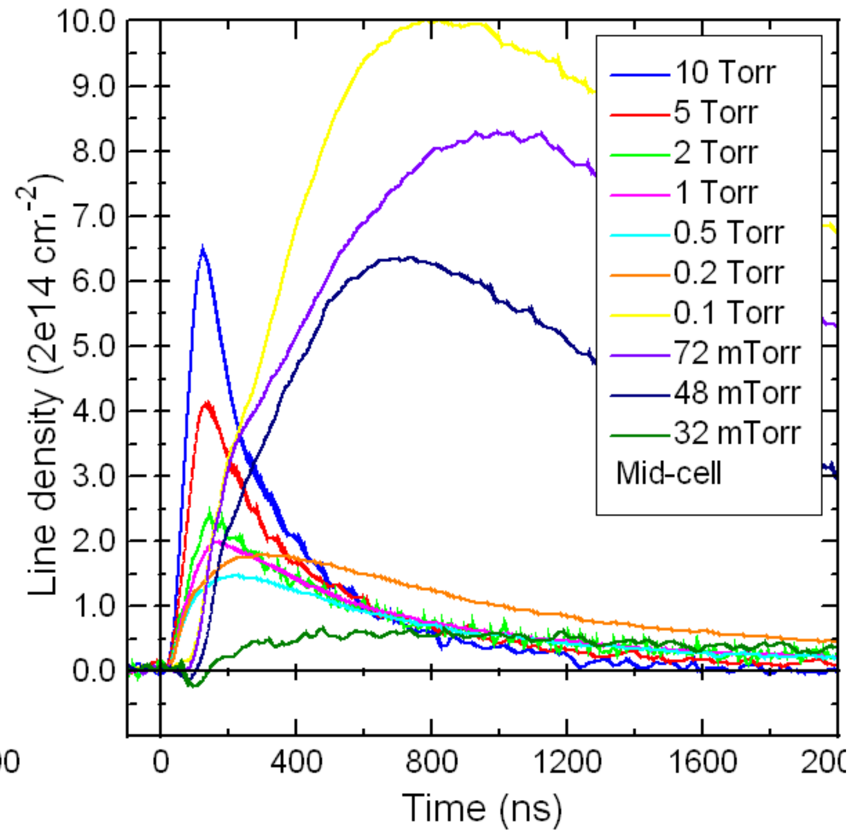
Medium-j (25 A/cm²)



High-j (300 A/cm²)



Radial profile flattens with time

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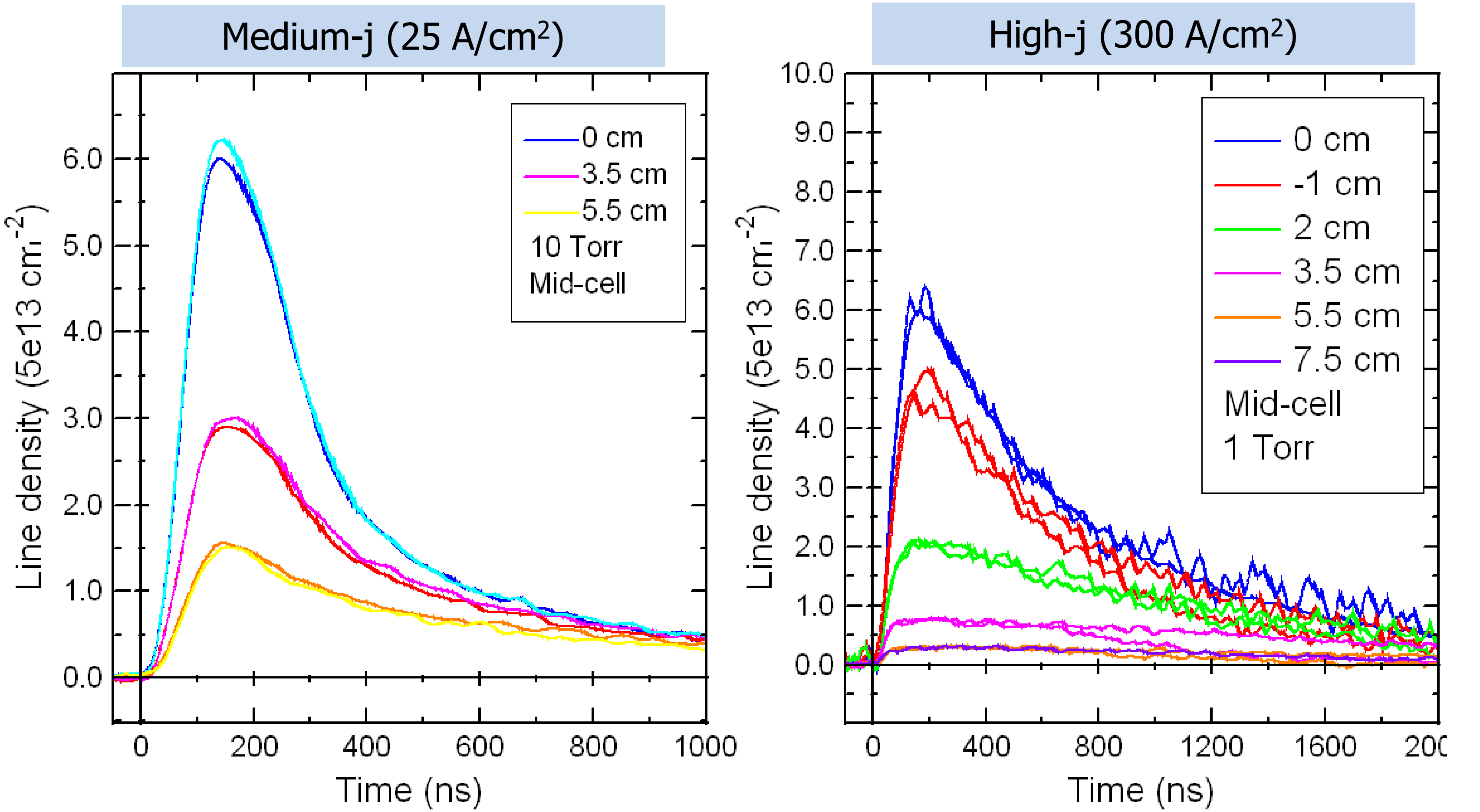

- Could we use an aperture to produce a well-defined beam shadow?
- Measurements outside beam could diagnose non-local effects

Peak densities at mid-cell location for different radial displacements on medium-j shots

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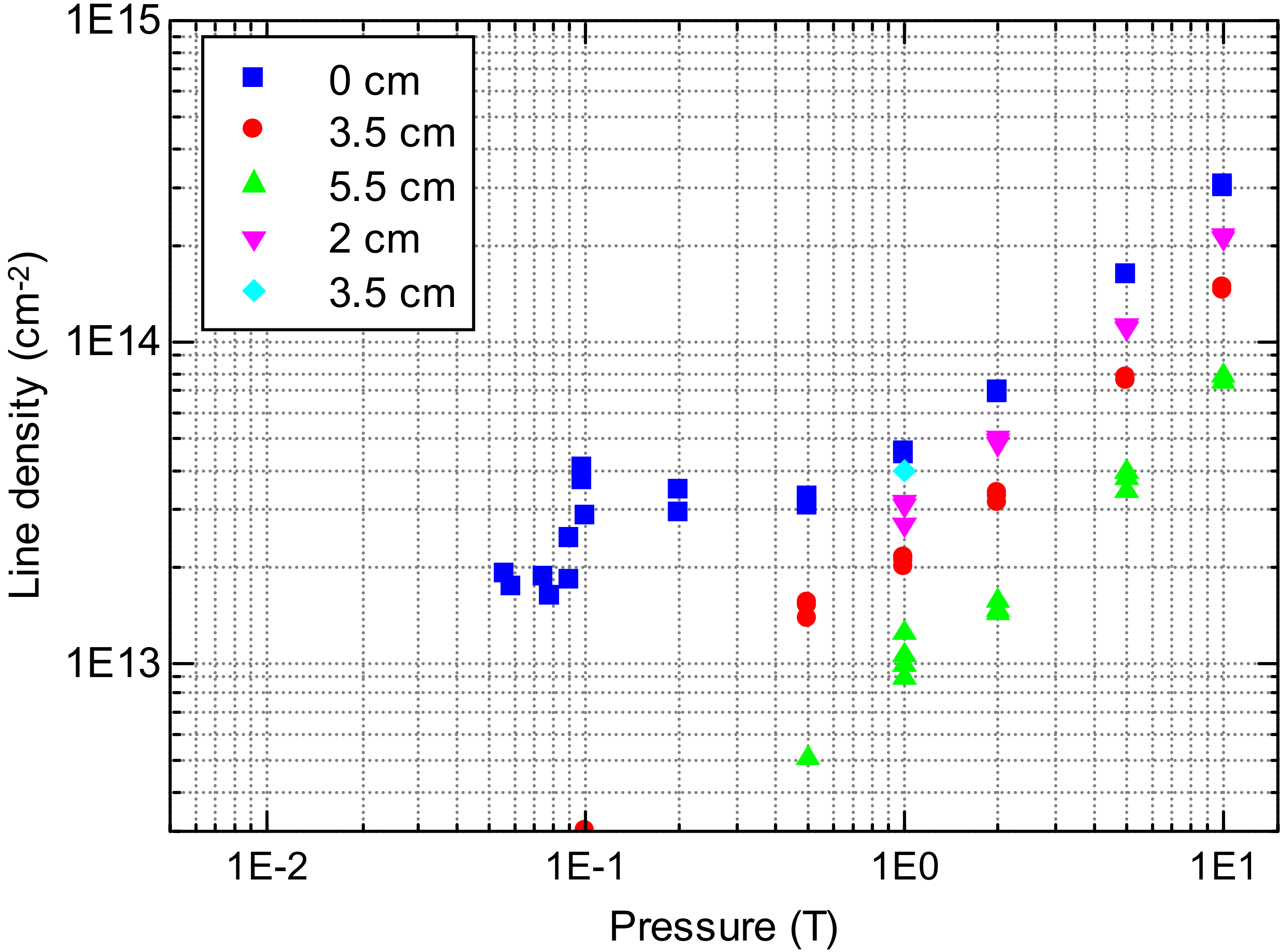

At high-current-density, dramatic increase in density on axis at low pressure

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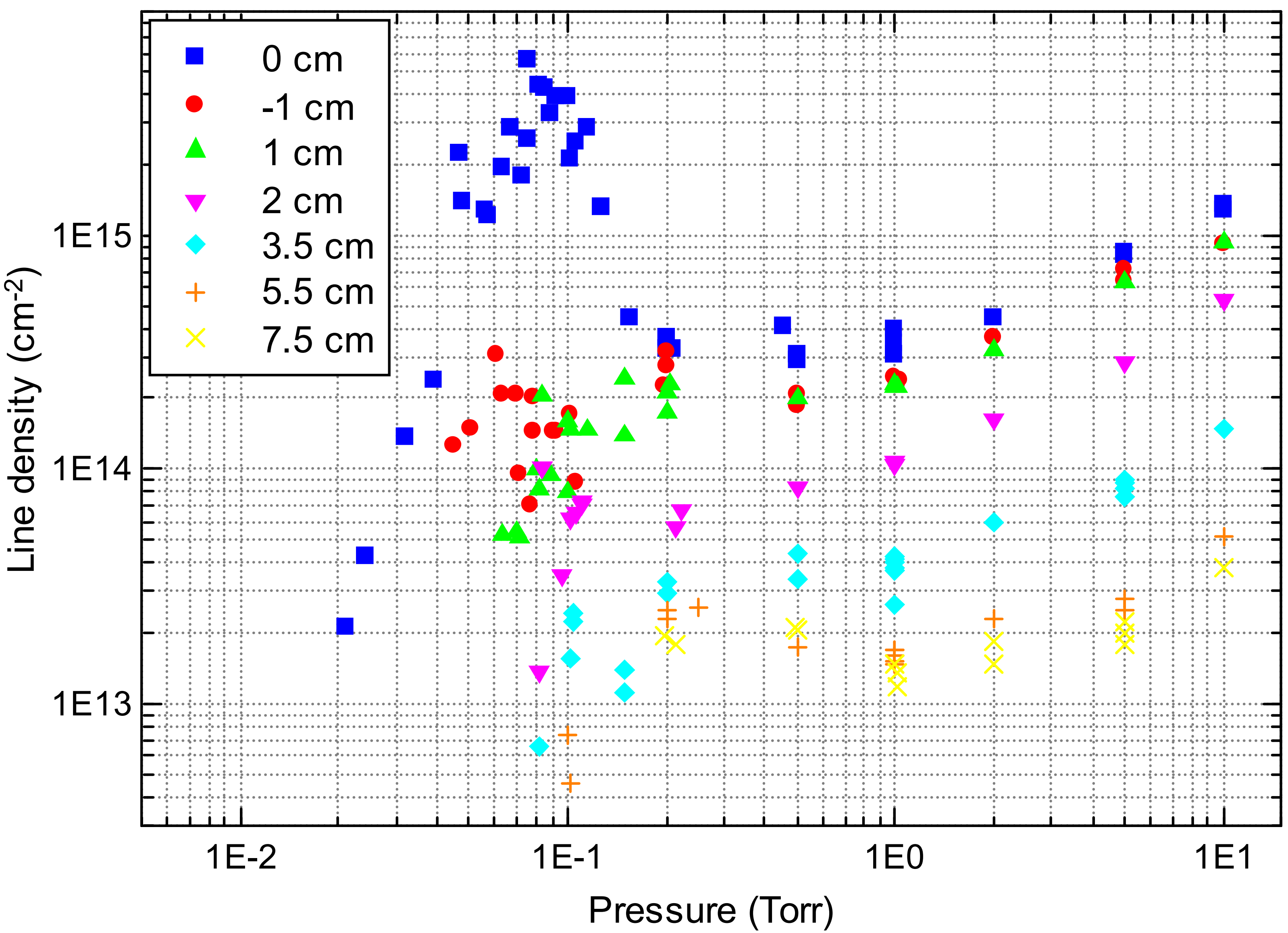

At high current density and/or low pressure, radial profile of density is narrower than beam

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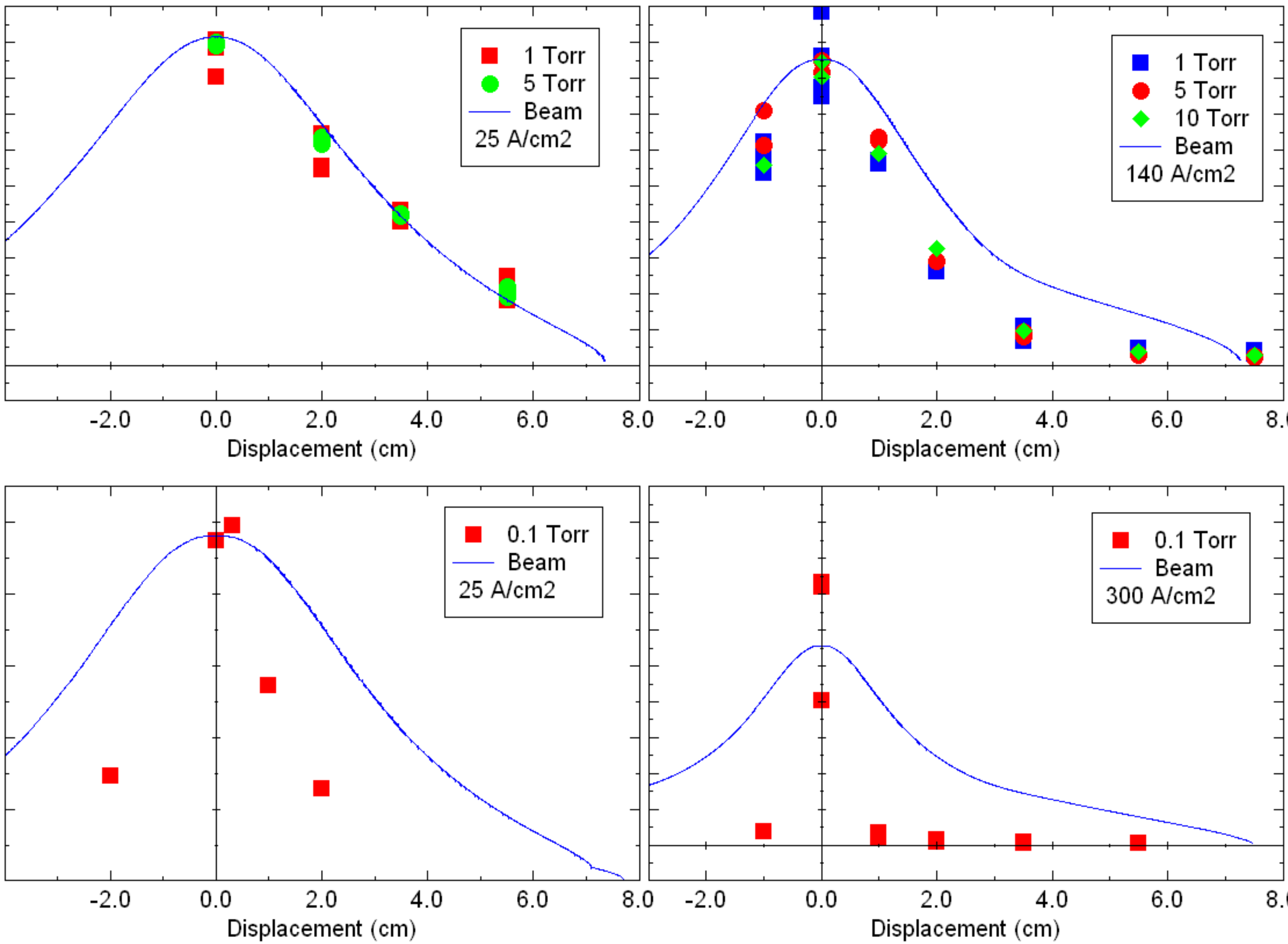
Forward-Abel-transformed beam profiles from image plates compared with peak densities



Very high ionization fractions inferred at low pressure (using rough approximation of 4-cm path length)

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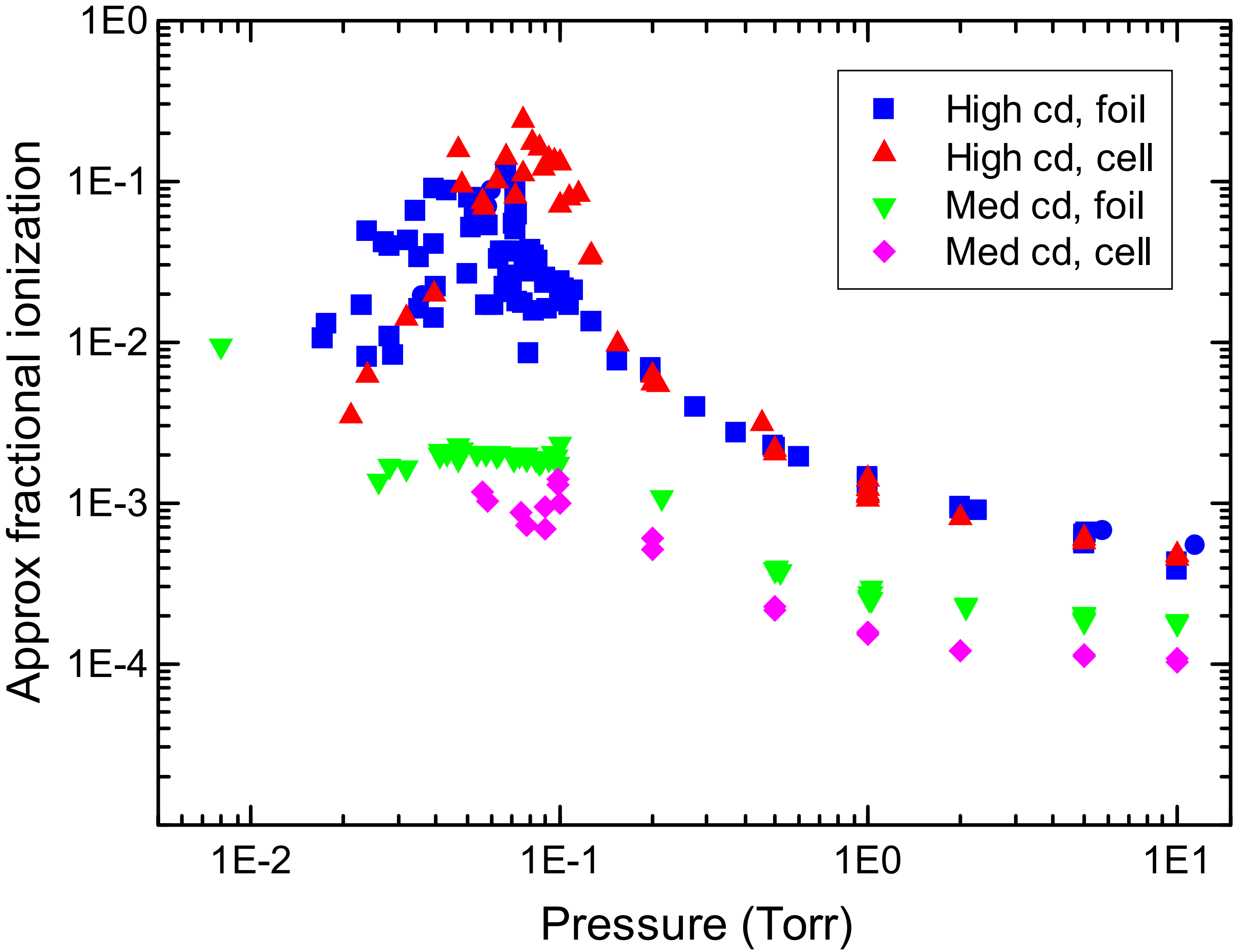

Moving up collector should increase axial electric field by increasing inductance and decreasing cell length

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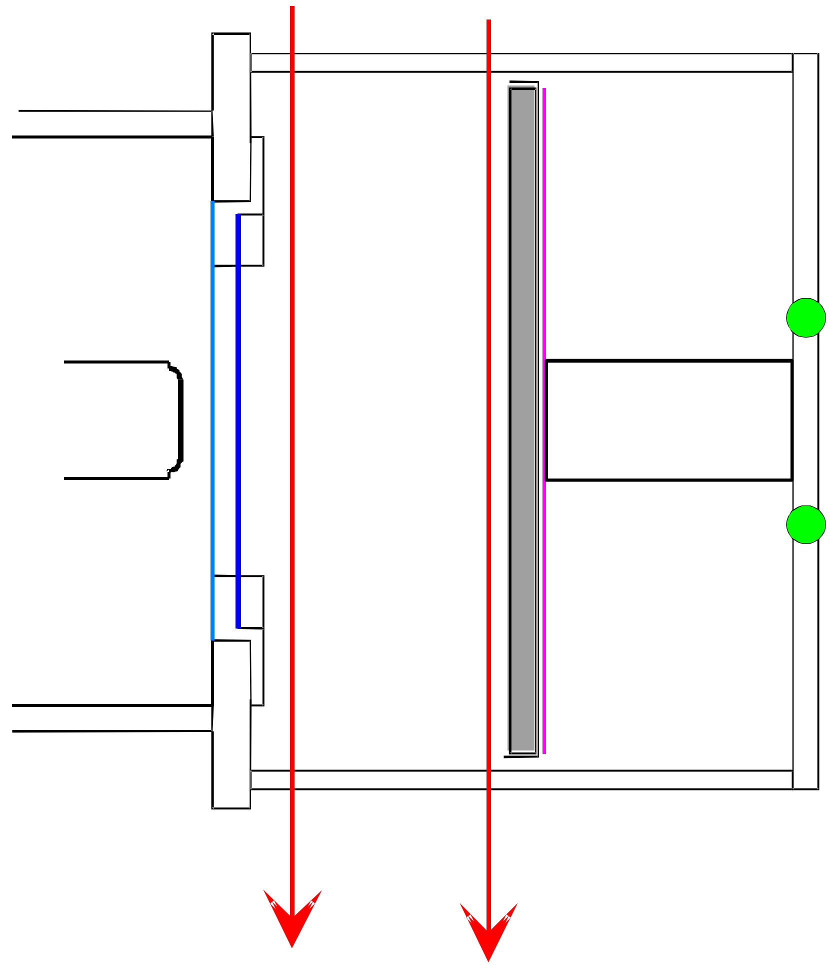
Distance to collector decreased from 11 to 4 or 5 cm

- Inductive field in beam acts to reduce current at pulse front and keep current flowing at tail
- Field is strongest on axis
- Inductive currents can connect to electrodes or just circulate in plasma
- External circuit inductance will tend to drive net current



Density increase at low pressure observed when collector moved up

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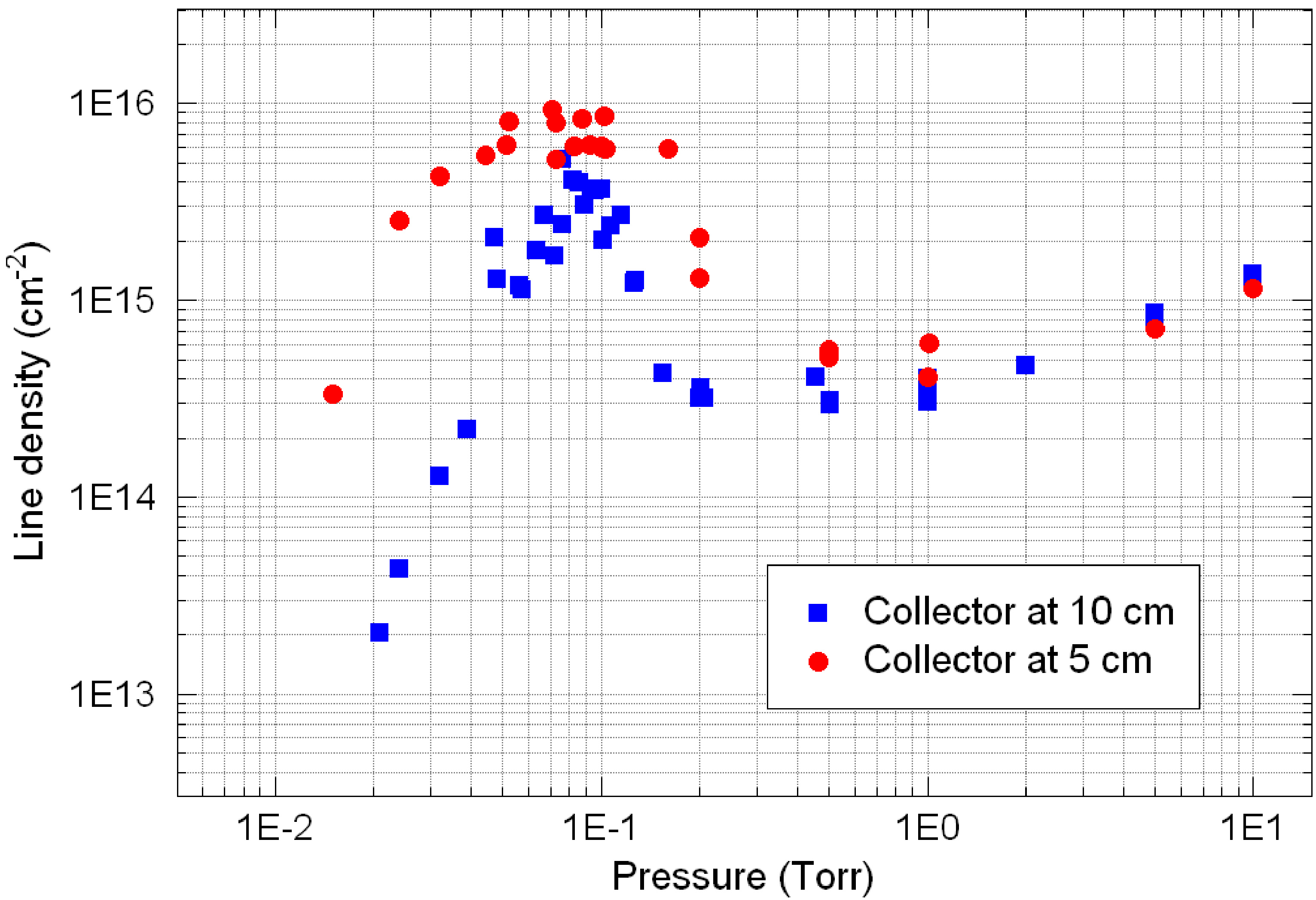
Peak densities at different collector and probe locations, high-j



Time-integrated photographs at different pressures
At low pressure, variation in late-time behavior is seen

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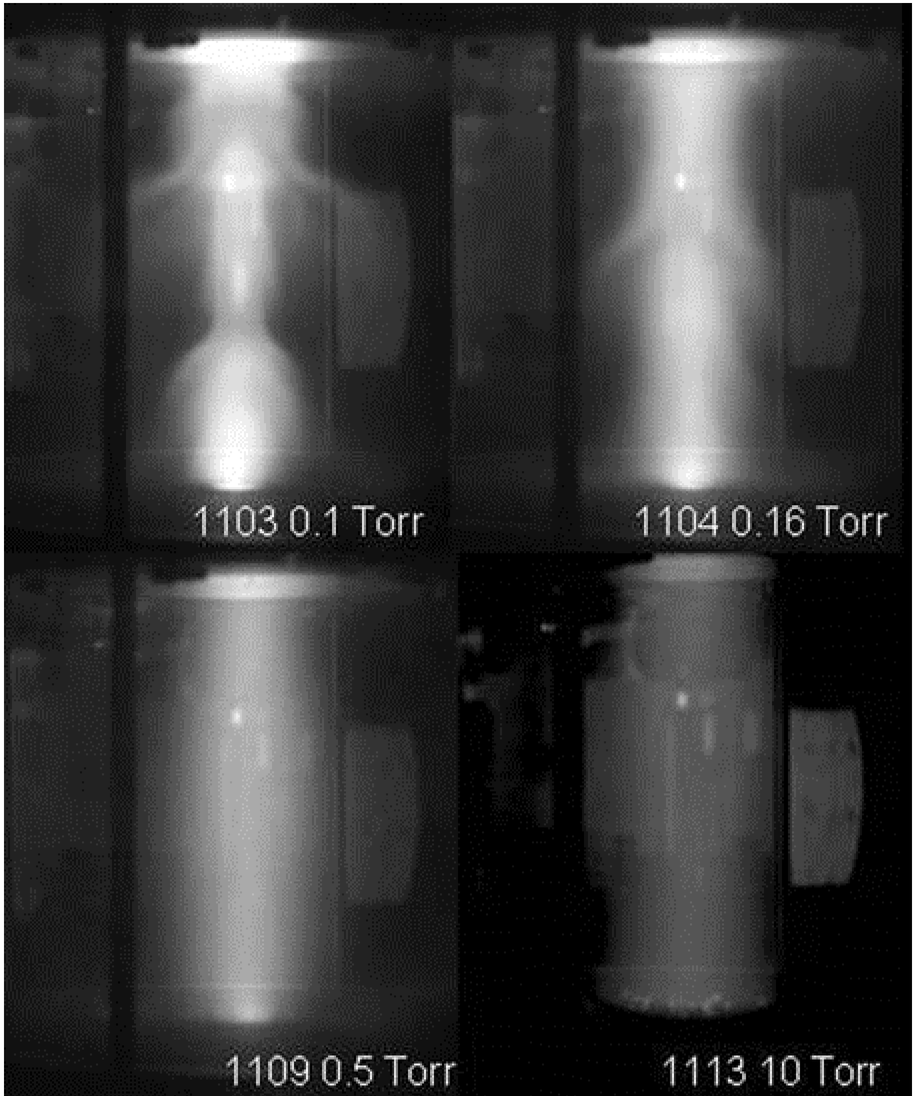
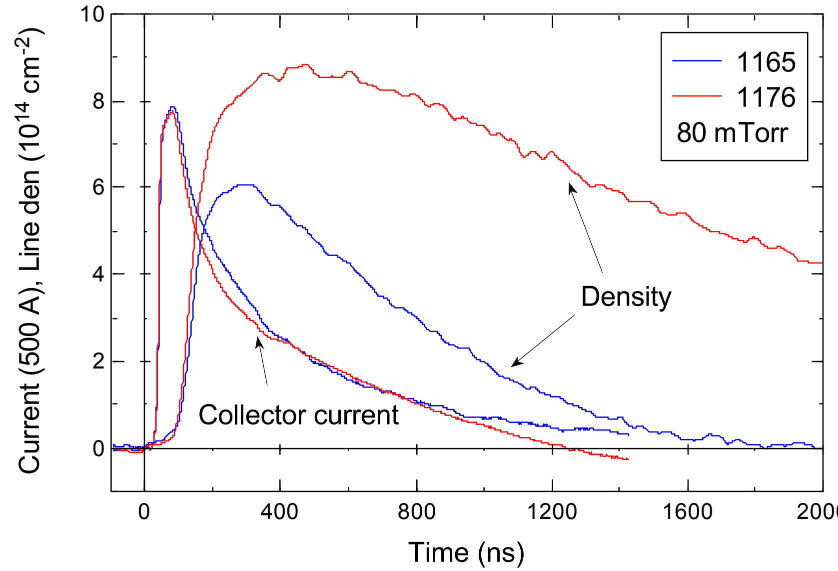
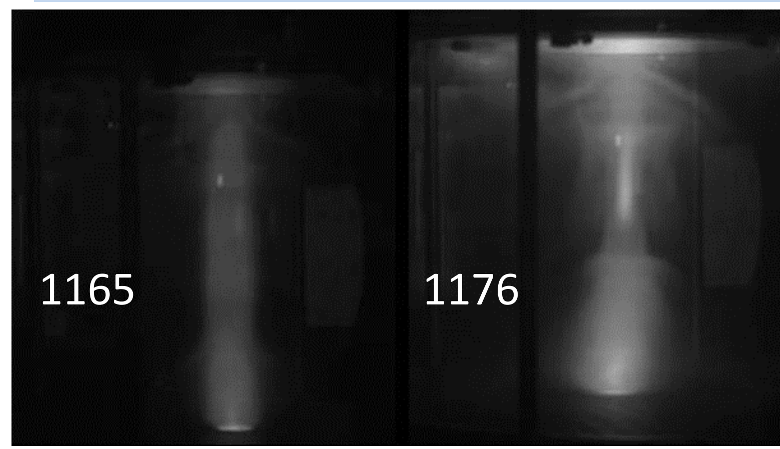




Nominally-identical shots at 80 mTorr



Time-resolved images possible in future

Conclusions

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- At low current density, ionization is purely collisional, with no plasma current.
- As the current density increases, the inductive electric field begins to drive a circulating plasma current, and additional ionization results. The increase in density is greatest on axis, both because the current density is highest there the inductive field is highest.
- As the beam current density increases still further, the increase in plasma density on axis becomes more pronounced, and a bright, narrow, luminous channel is observed, and the plasma conductivity is high enough that even the very weak inductive field late in time can drive additional plasma current. This results in very high peak densities, and close to full ionization. In this regime, the physics is expected to be very different, as electron-neutral collisions will no longer dominate.
- These results show that at sufficiently high beam current density and/or sufficiently low pressure, gas dynamics in the cell becomes a more complicated, coupled 2-D problem that shows dependence on the cell geometry and material.
- Future experiments will attempt to decouple some aspects of these dynamics.

Preliminary study showed feasibility of injecting 200-kV beam into NRL Space Chamber

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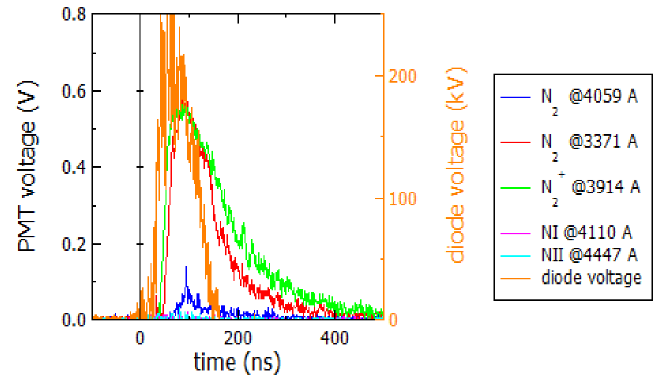
PMT signals in large chamber, 465 cm from injection



- Good propagation observed over 7 meters
- Ample light for spectroscopic measurements
- Possible future space-physics applications