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Electron-Beam-Gas Interaction Experiments at NRL

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Electron beams injected into low-pressure gas create a rich tapestry of physics

- Ionization by beam electrons
- Inductively-driven plasma currents
- Ionization by low-energy electrons from induced currents
- Dissociation
- Dissociative (fast) and radiative (slow) recombination
- Non-local effects and instabilities at low pressures

We are studying electron-beam-gas interaction for code development and validation

NRL PPD

- Lower-voltage (~70-100 kV), low-current (1-4 kA) electron beams at 10's to 100's A/cm^2
  - Febetron pulser
  - Hinshelwood, et al., ICOPS 2008 (Karlsruhe)
- Lower-voltage, higher-current (~50 kA) electron beams at several 100's A/cm^2
  - Newly-built table-top water line pulser
- Higher-voltage (~700 kV-1.5 MV), high-current (~800 kA-1 MA) electron beams at 2-10 kA/cm^2
  - Gamble II generator
- Gases are air or N_2 at 0.02 – 20 Torr
- Diagnosed using interferometry, spectroscopy, framing photography, and net-current measurement
- Results from all 3 sets of experiments are presented here

The Advanced Breakdown and Conductivity (ABC) model[1] extends nitrogen gas chemistry to high electron-beam current densities

NRL PPD

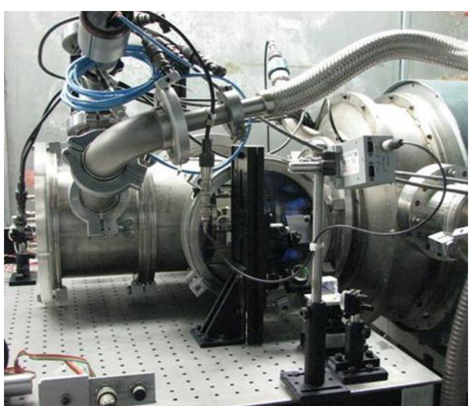
- NRL electron-beam gas-transport experiments span the regime of low (≤ 1 kA/cm^2) to high (≥ 10 kA/cm^2) current densities, often on one shot
- Previous models based on assumptions that the gas remains weakly-ionized and molecular[2-3] are appropriate for 1-kA/cm^2 and below
- NRL ebeam transport experiments at high beam current density J_b in 100-ns pulses are characterized by
  - a high degree of current neutralization $J_p \approx -J_b$
  - Joule heating $\eta_p J_p^2$ driving these plasmas to dissociation and high ionization
- Momentum- and energy-transfer physics are strongly affected by the state of the gas

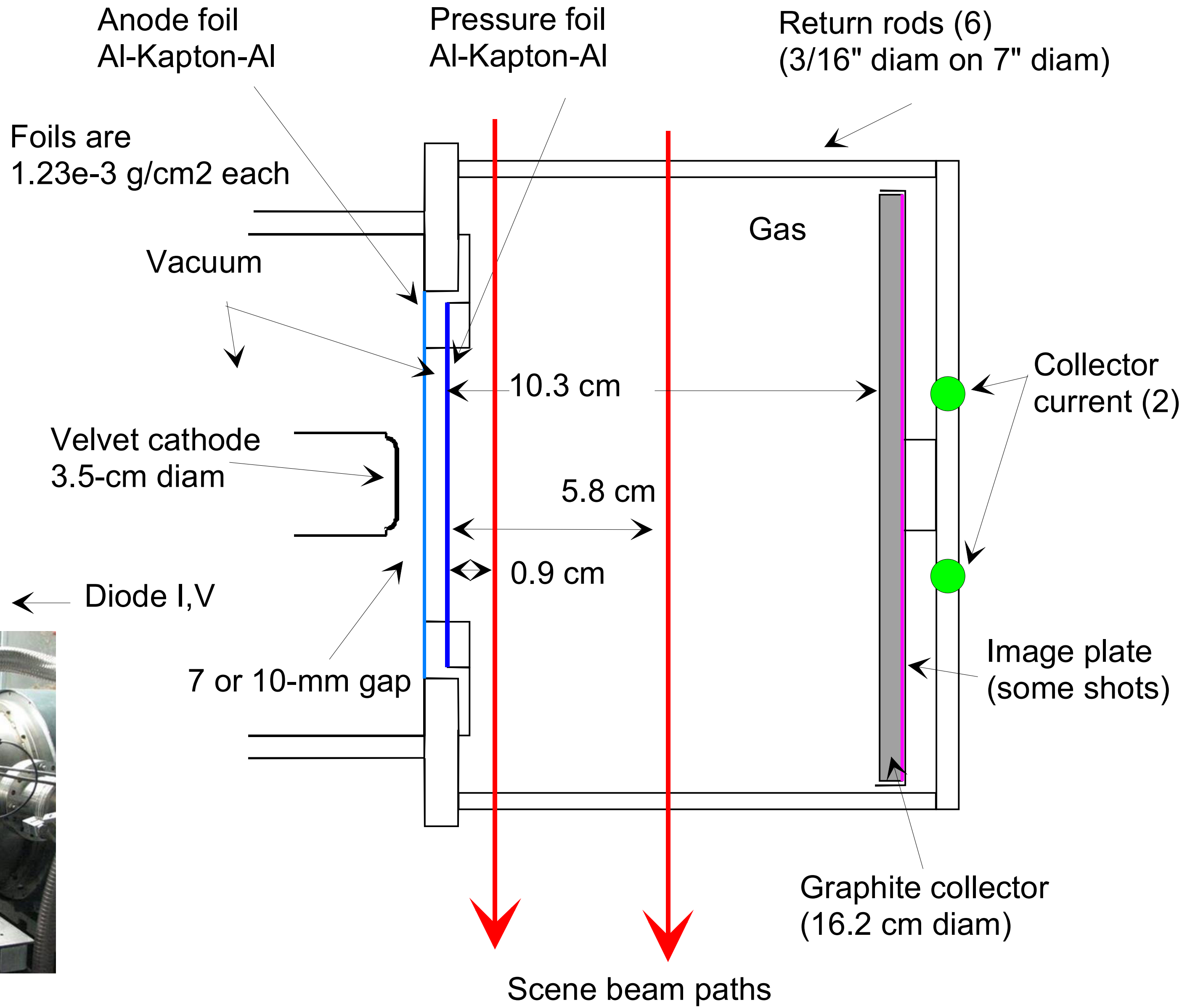
molecular/weakly-ionized	**atomic/strongly-ionized**
electron-neutral resistivity($\sim 1/n_e$)	electron-ion resistivity ($\sim 1/T_e^{3/2}$)
molecular excitation energy sinks	atomic excitation energy sinks
2-term electron-energy distribution	Maxwellian electron-energy distribution

1) J. Angus, *et al.*, to be published in Physics of Plasmas, #POP48751
2) D. McArthur and J. Poukey, PRL, 27, 26 (1971), and Phys. Fluids, 16, 11 (1973)
3) D. Welch, *et al.*, Phys. Plasmas 1 (1994)

Arrangement used in low-voltage experiments

NRL PPD

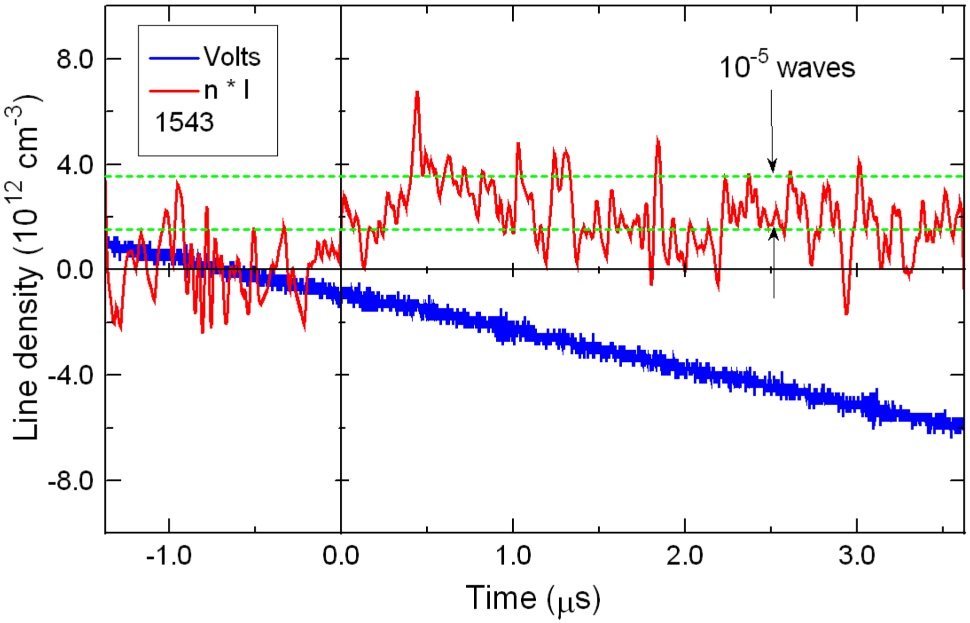




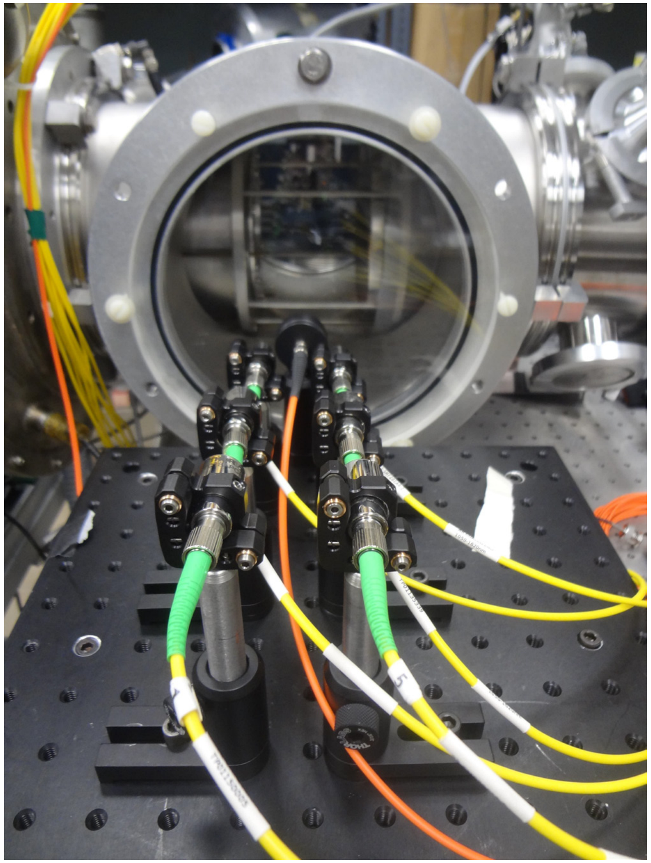
High-sensitivity interferometer provides resolution approaching 10^{-5} waves

NRL PPD

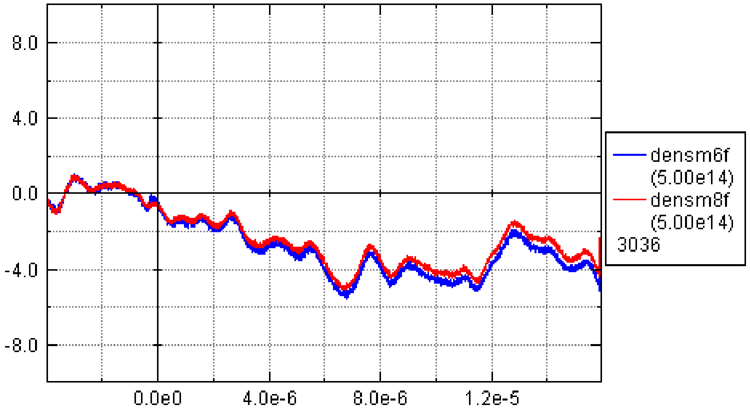
- Standard Mach-Zehnder configuration
- Synchronize experiment with zero-crossing of signal (highest sensitivity)
- Use polarization splitting to provide 2, opposite-polarity outputs and use differential detection
- Amplify differential output ~100x
- Carefully shield system from EM noise
- Once aligned,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

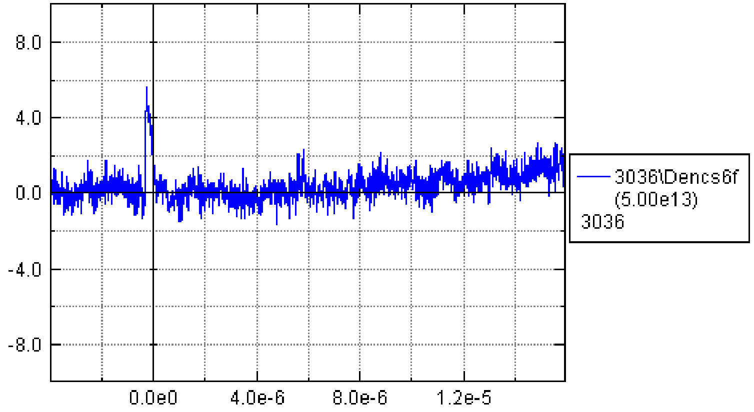


Fiber interferometer provides multiple lines of sight



Subtracting null signal gives ~2x10^{-3} waves resolution



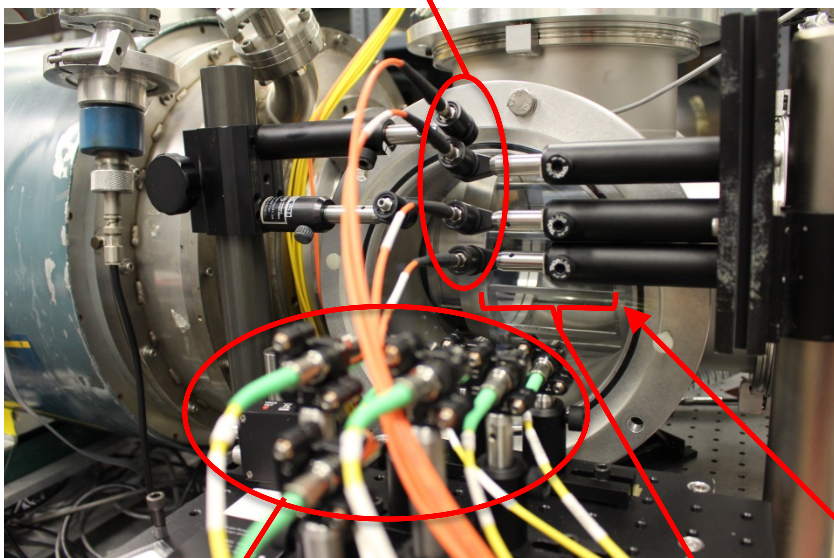


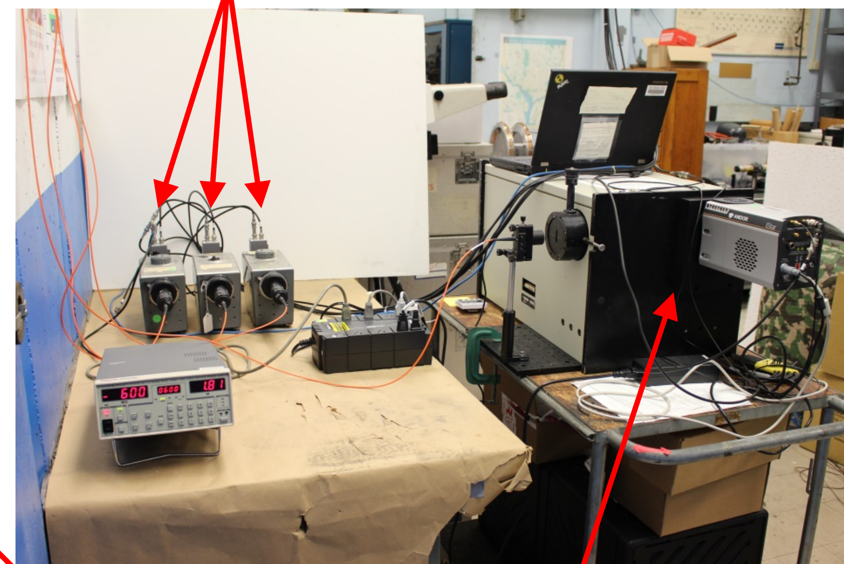
3 monochromators and an ICCD-coupled spectrometer used to measure light emitted by e-beam in dry air

NRL PPD

spectroscopy fibers and plasma-facing optics viewed 2.3 to 2.9 mm diameter spot across diameter at axial center of transport region

3 monochromators (intensity vs. time at a given wavelength) recorded N_2 at 3577 Å, N_2^+ at 3914 A, and either N I at 7442 Å and surrounding N I lines or N II at 5680 Å and surrounding N II lines





interferometer fibers and collimating optics

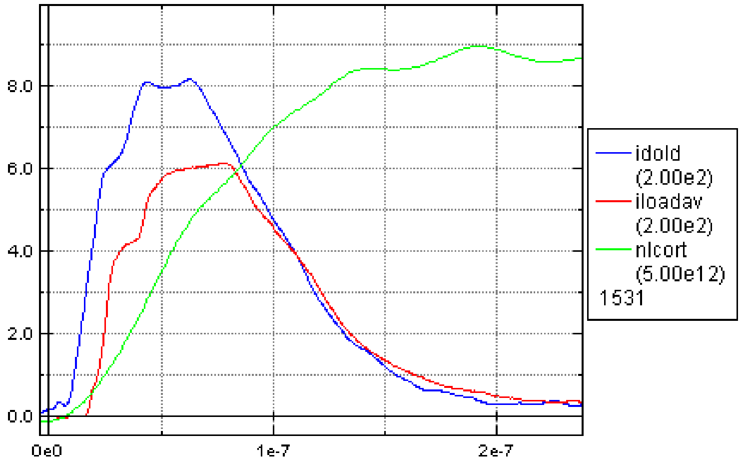
e-beam transport region

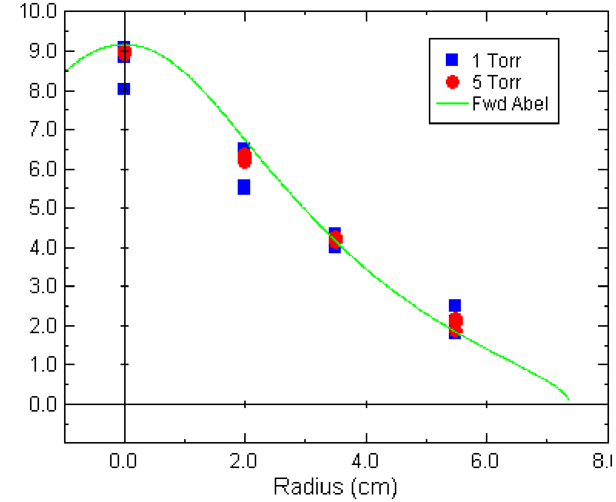
beam dump

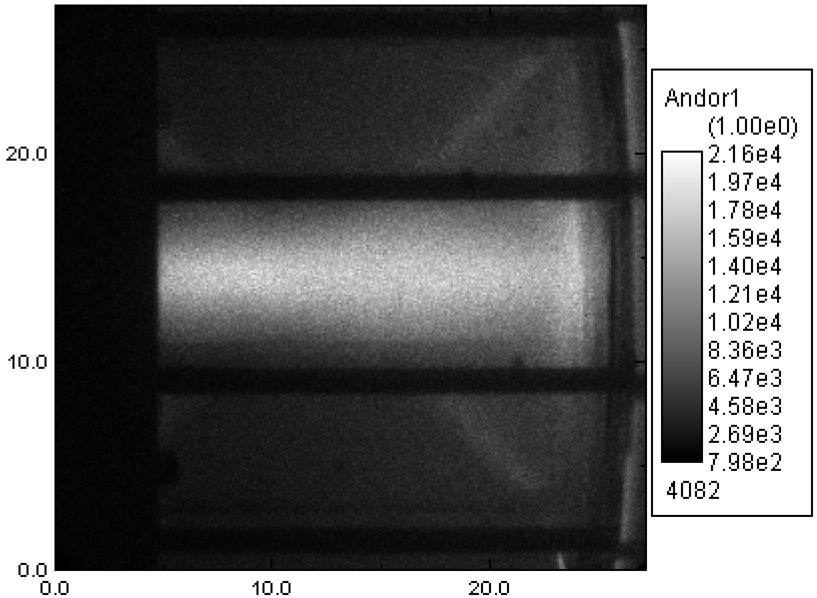
ICCD-coupled spectrometer (895 Å wide spectrum at a given time)

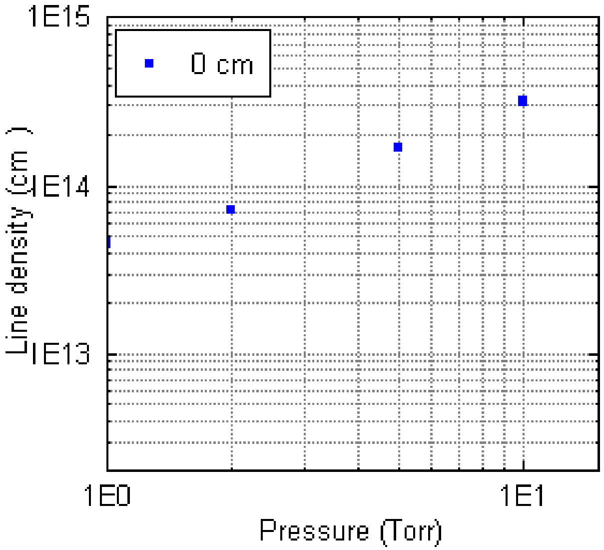
At 1 Torr and above, electron density scales with current density x gas density

NRL PPD



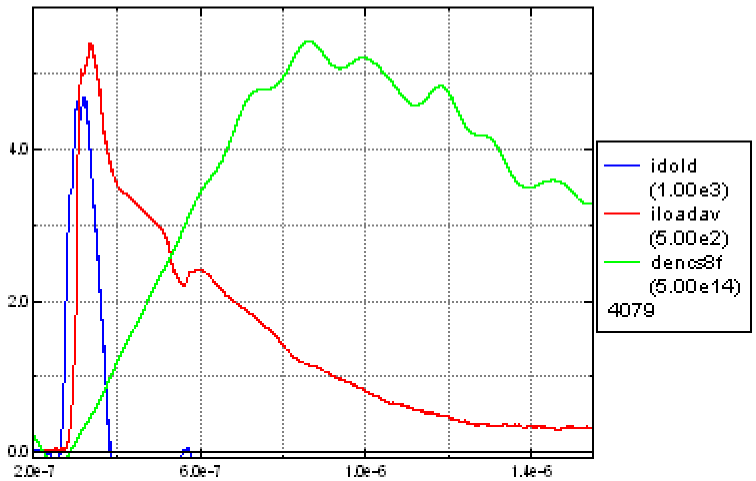


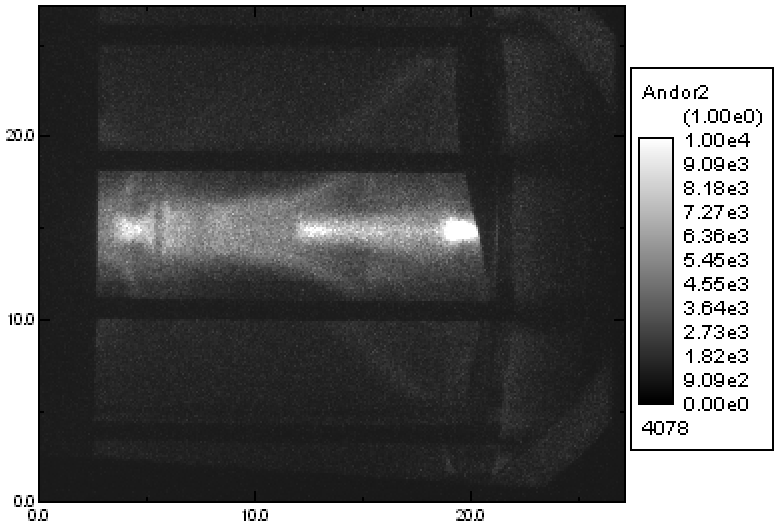




At 100 mTorr, large afterglow current leads to narrow, high-density channel

NRL PPD





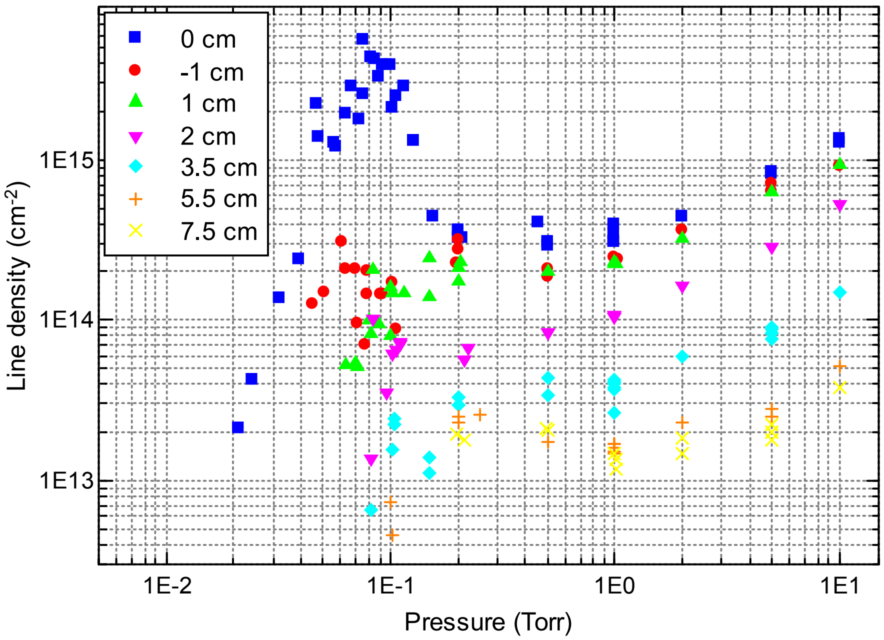
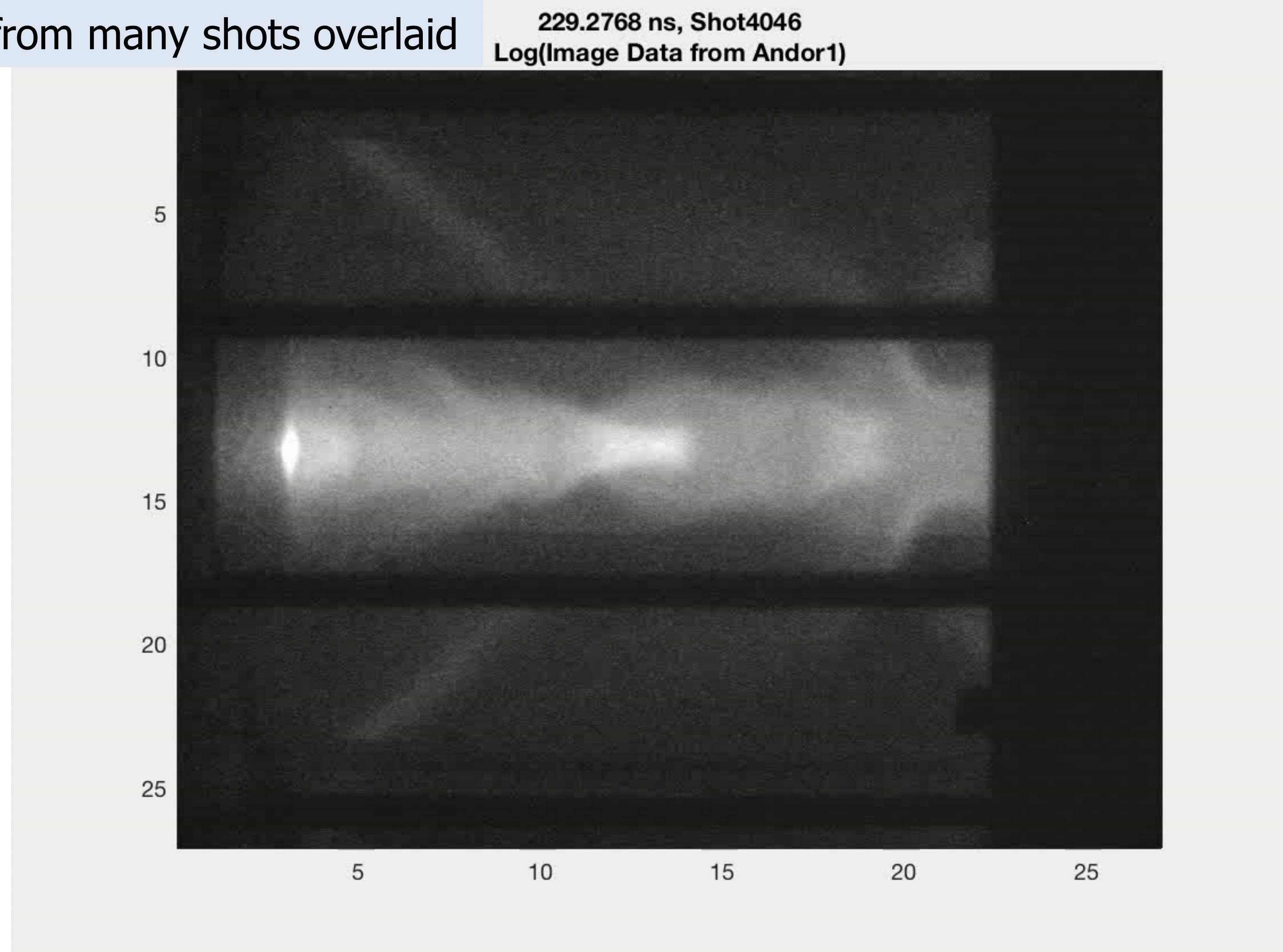


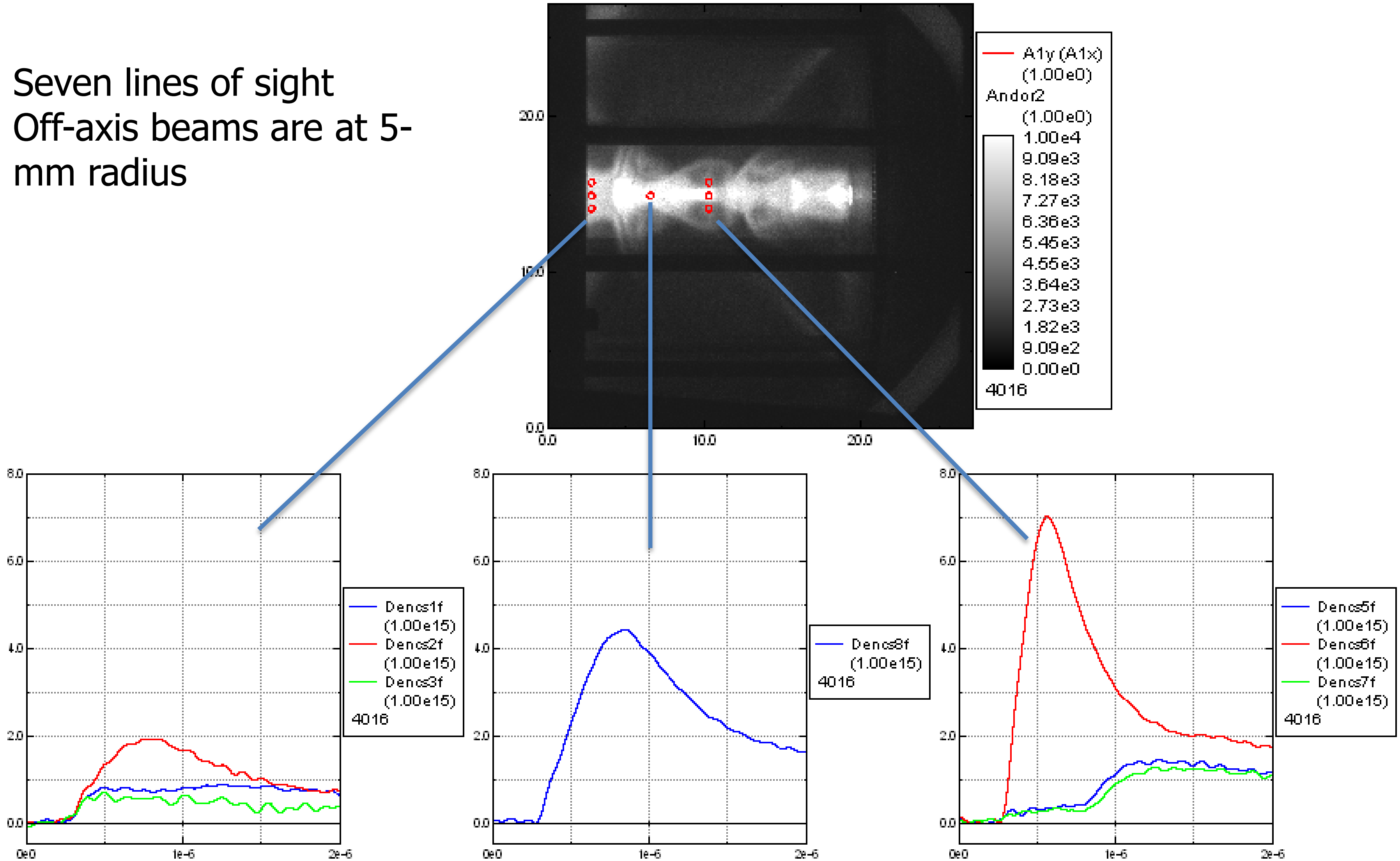
Image features show shot-to-shot reproducibility

Images from many shots overlaid



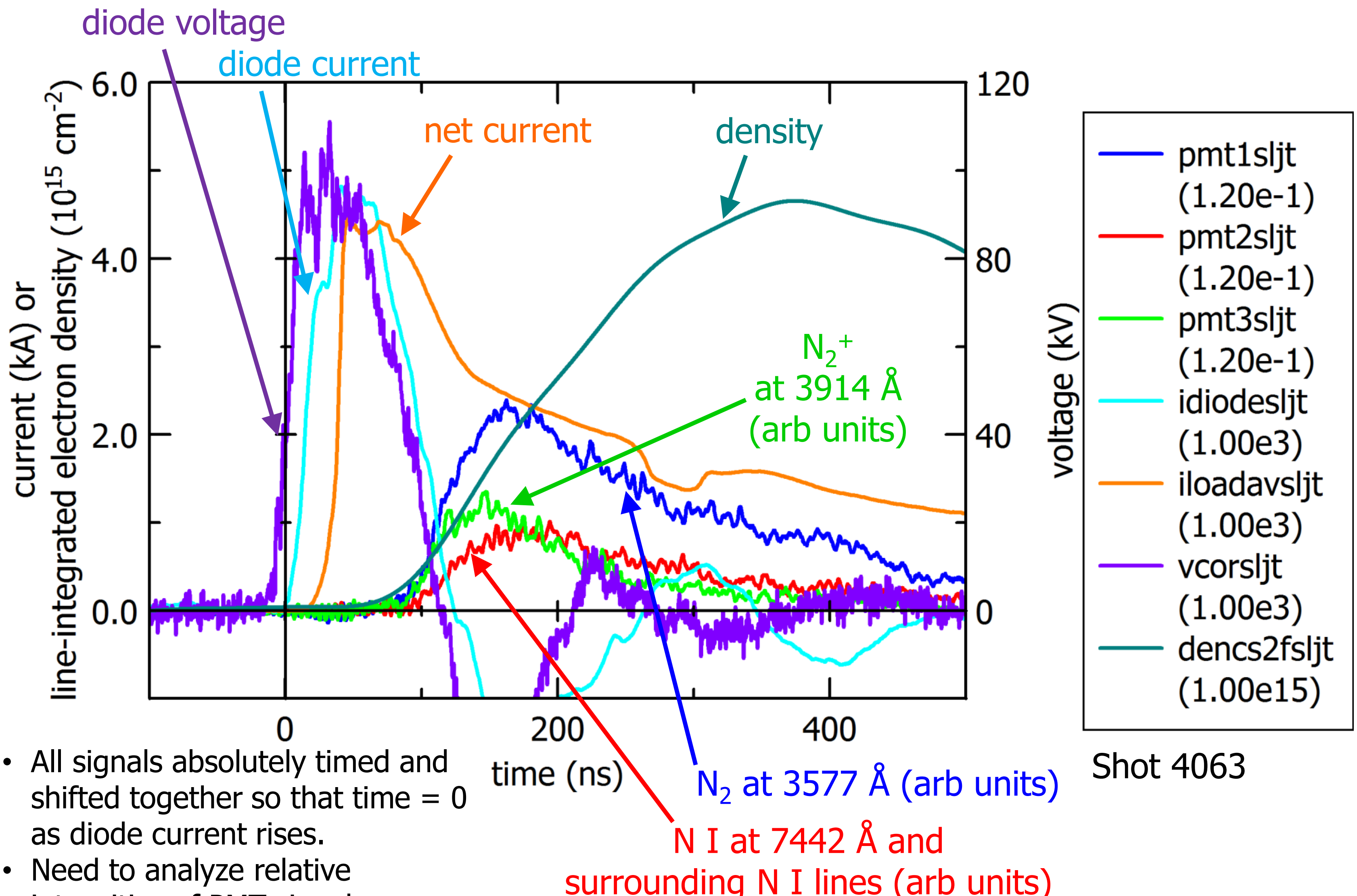
Density channel is very narrow and consistent with camera images

Seven lines of sight
Off-axis beams are at 5-mm radius



Time-dependent RAW SIGNALS at 100 mTorr

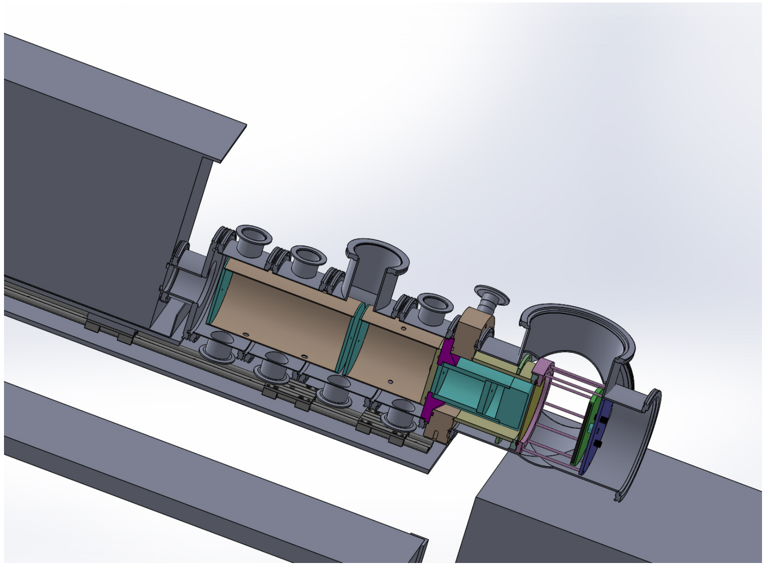
NRL PPD

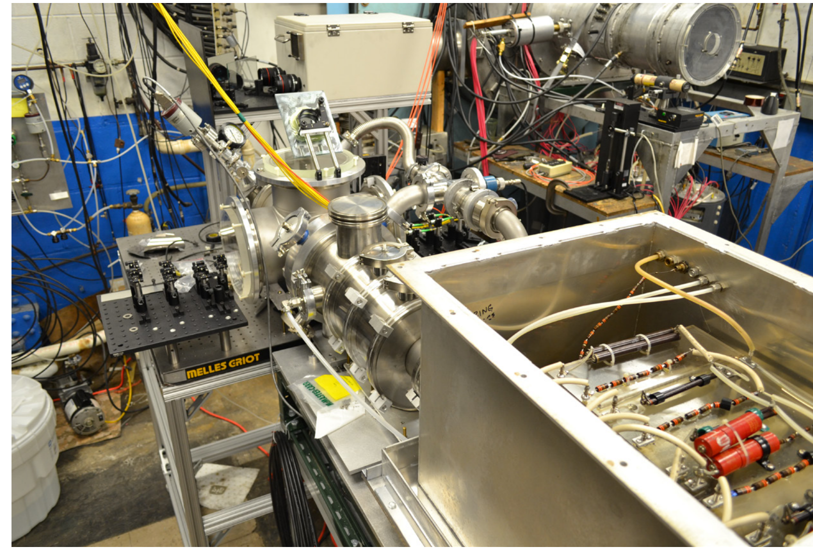


Shot 4063

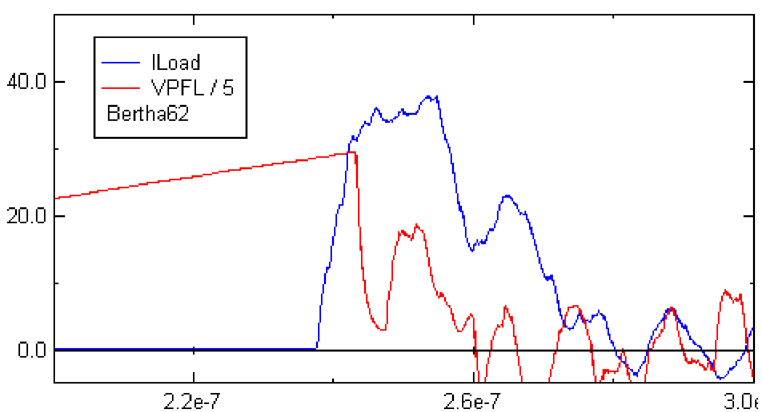
- All signals absolutely timed and shifted together so that time = 0 as diode current rises.
- Need to analyze relative intensities of PMT signals

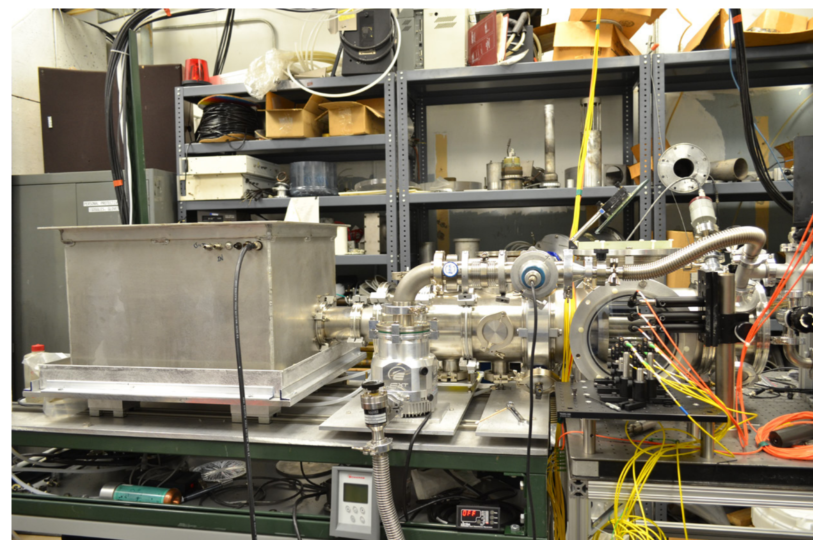
We have constructed a new water-line pulser to increase the injected current





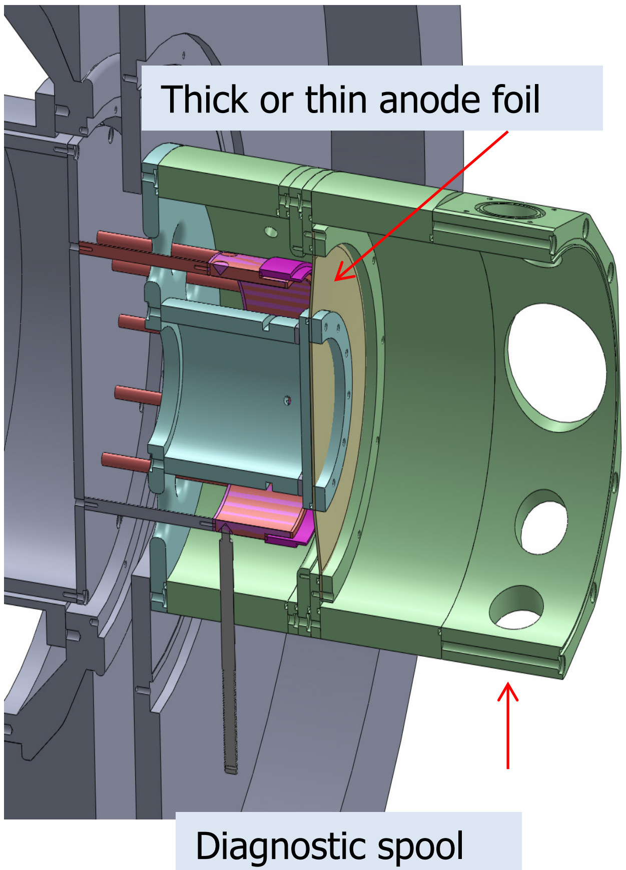
80 kV, 40 kA, 30 ns

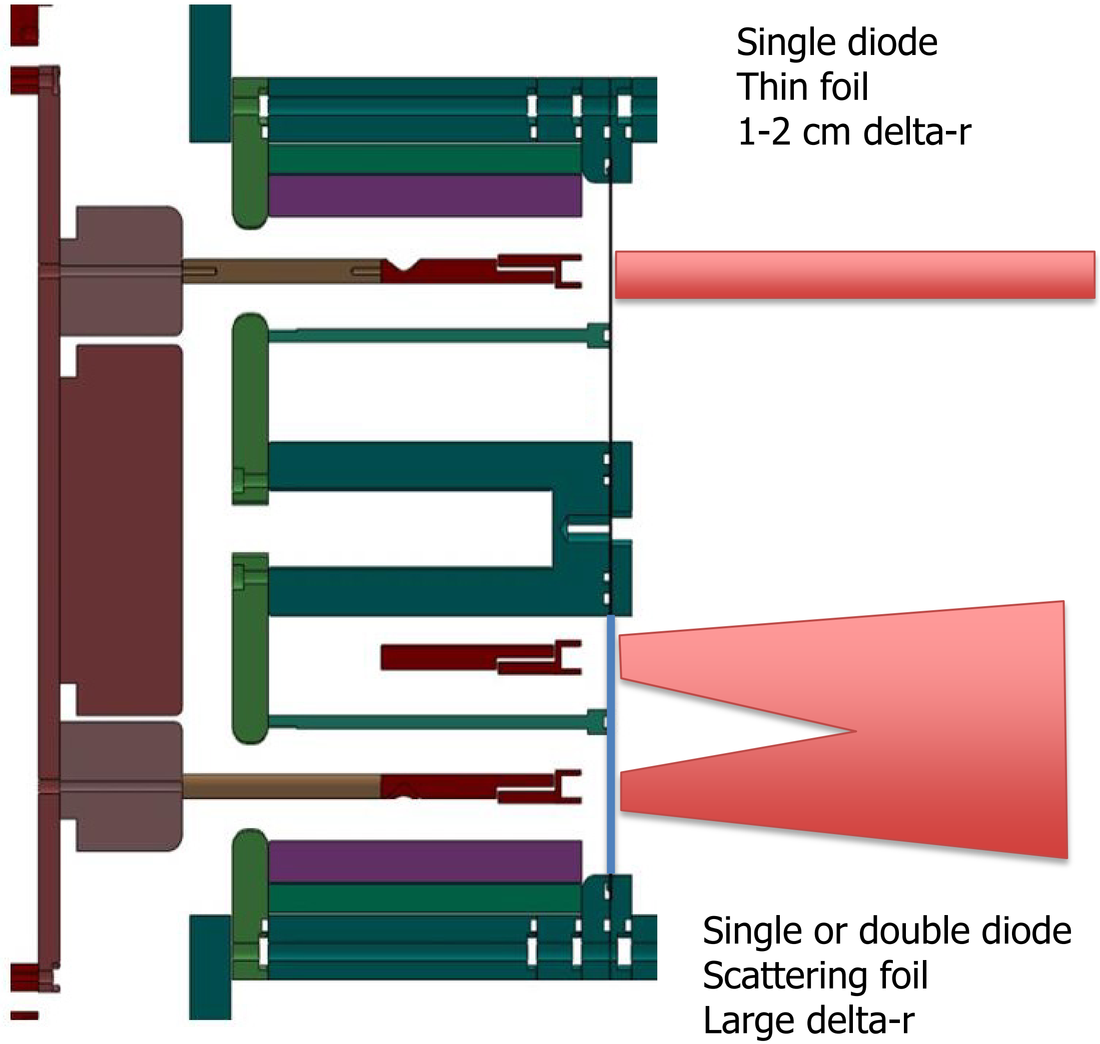




First data from new pulser

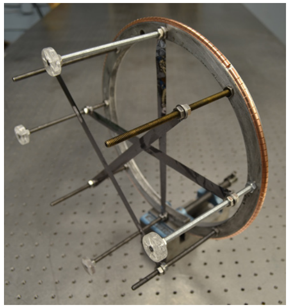
MV-level electron beams from the Gamble II generator are injected into nitrogen

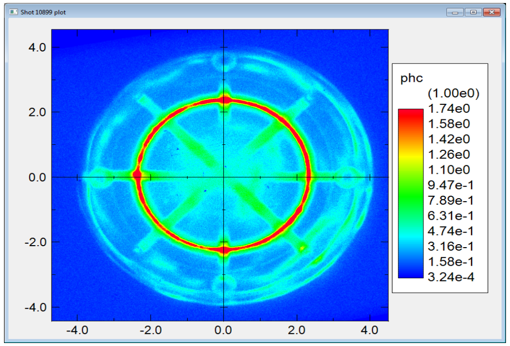


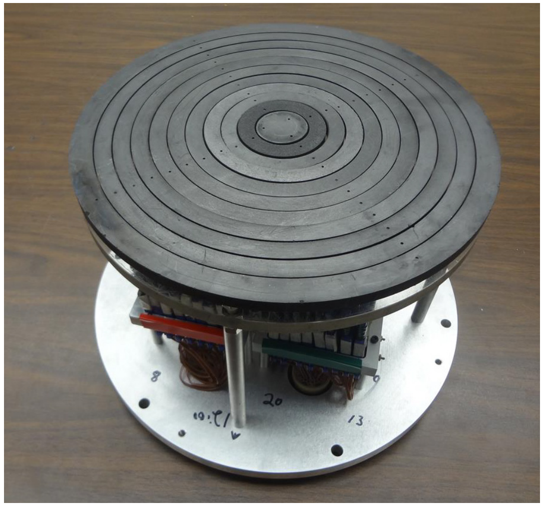


Diagnostics used on Gamble II experiments

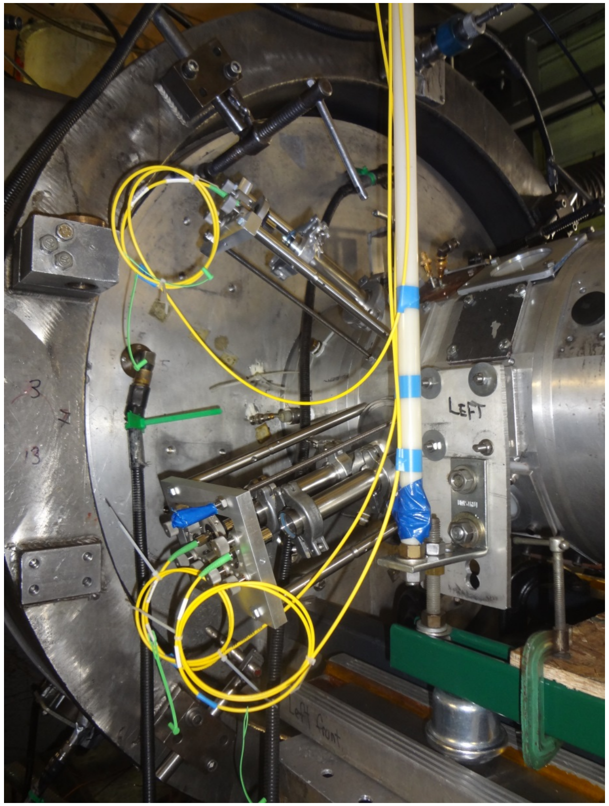
Beam characterized using x-rays (high current density) or calorimetry (lower current density)







Plasma diagnosed using interferometry, spectroscopy, and net-current measurement

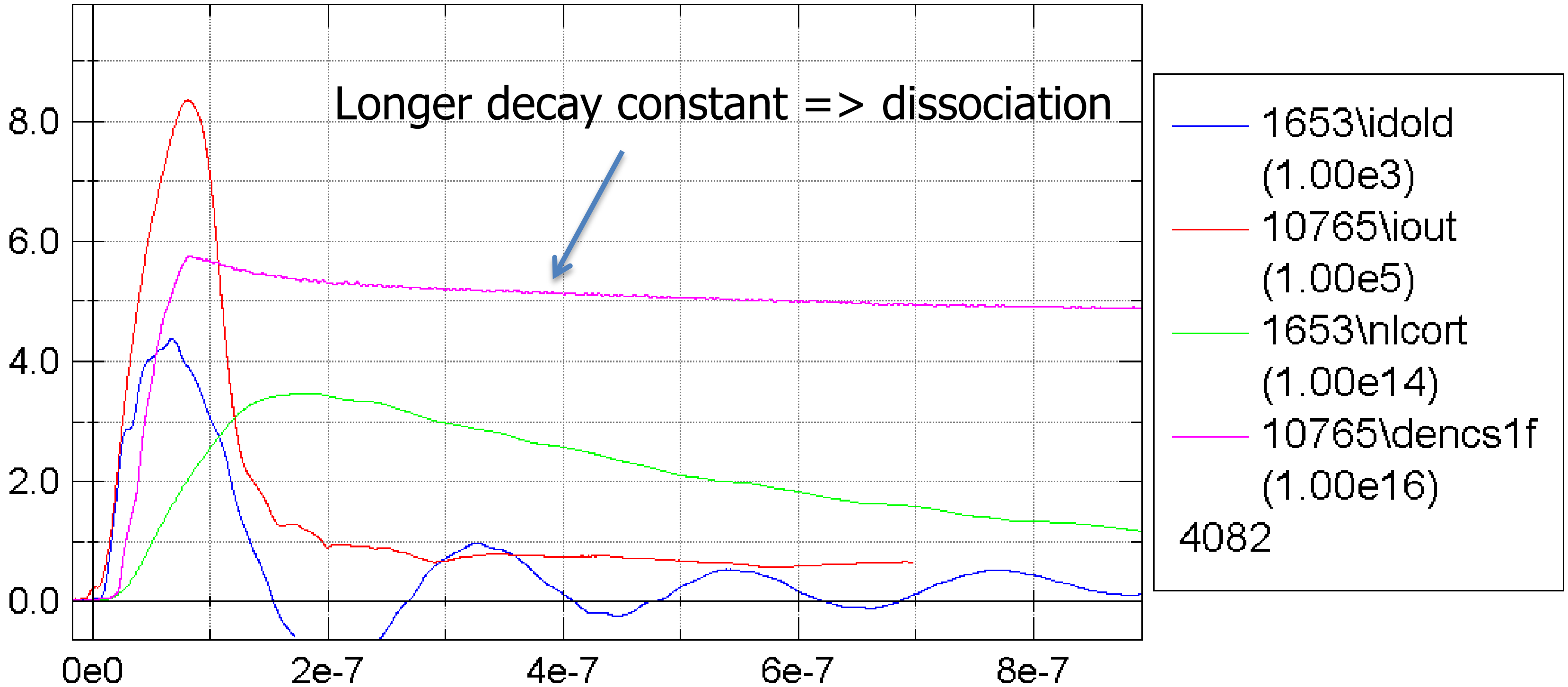


Under Gamble II conditions, 25X current density leads to 100X plasma density and dissociation

NRL PPD

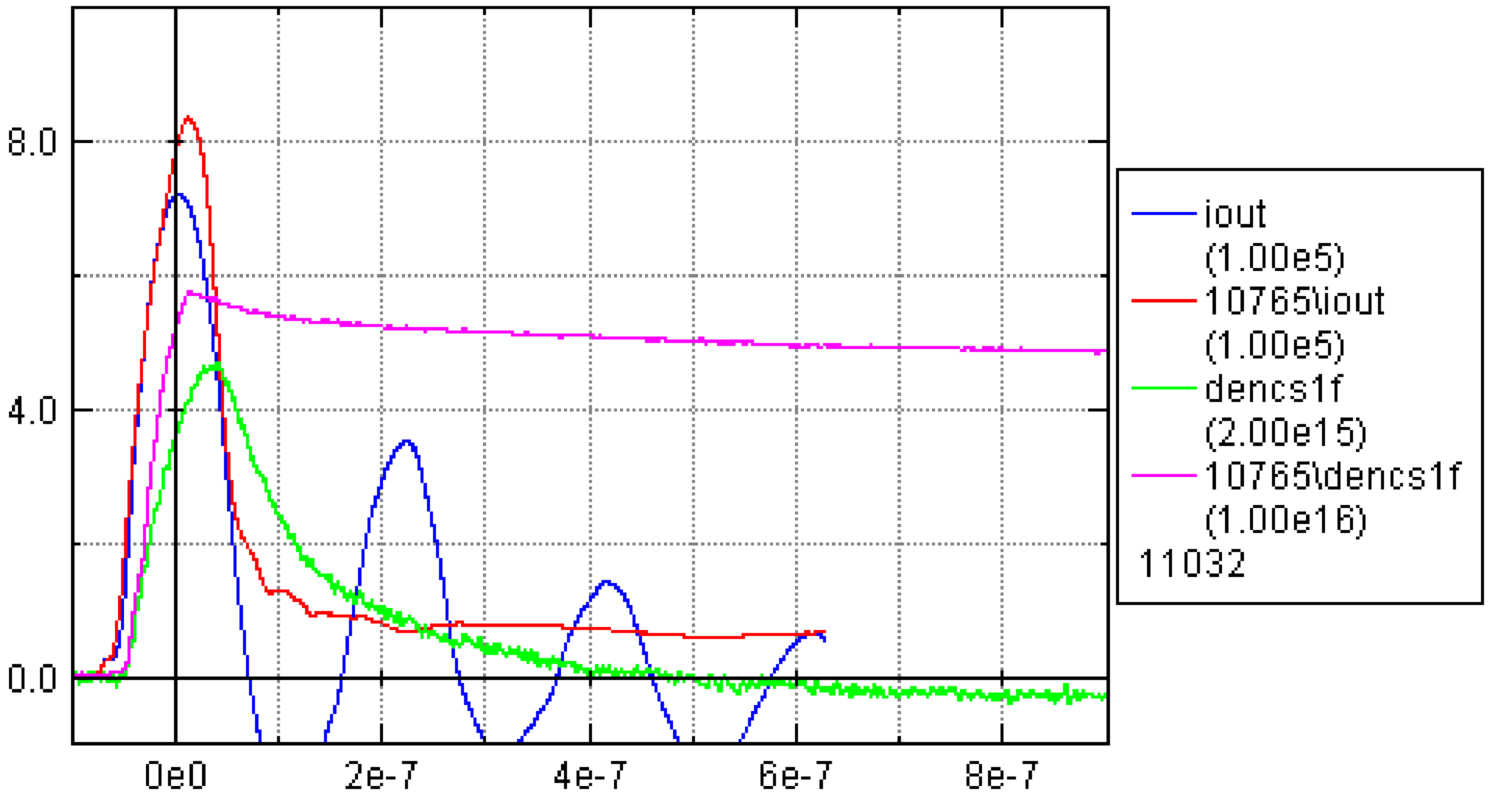
Febetron: ~15 cm^2, 300 A/cm2, 4-cm path length
Gamble II: ~60 cm^2, 7 kA/cm^2, 4-cm path length

1 Torr N2, tens of percent ionization



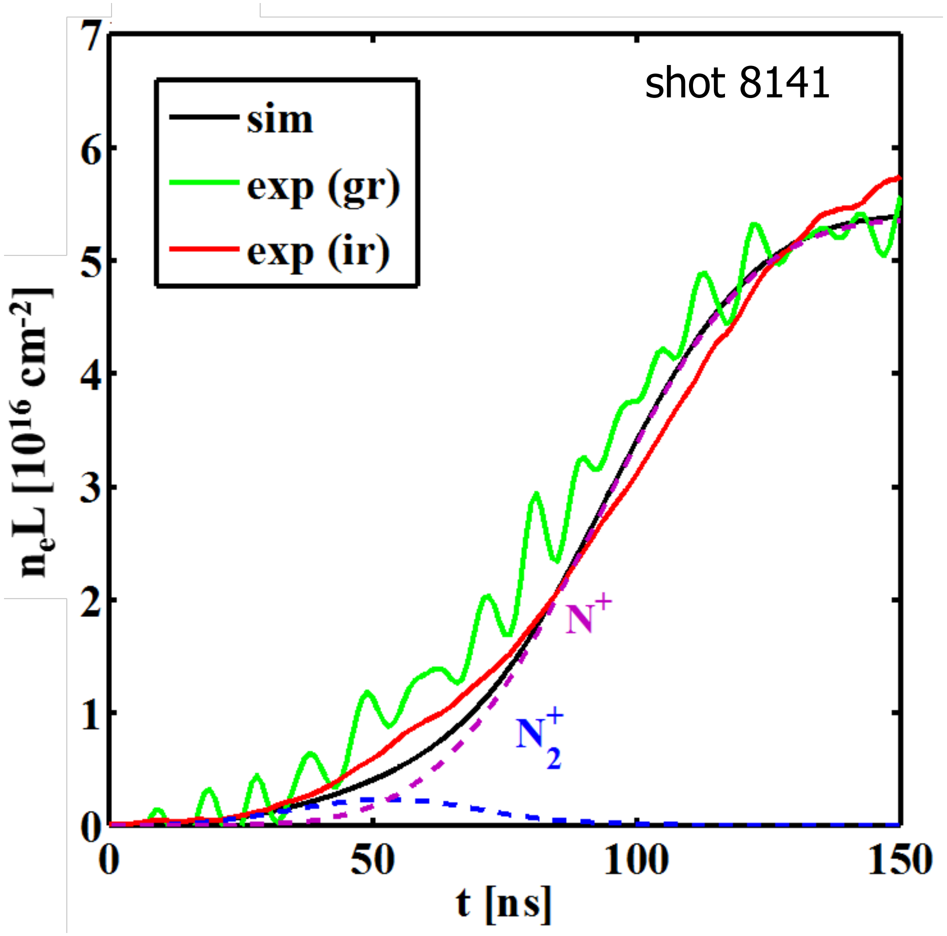
With a scattering foil, current density drops 5X and electron density drops 30X

Thin foil: ~60 cm^2, 7 kA/cm^2, 4-cm path length
Thick foil: ~450 cm^2, 1.5 kA/cm^2, 24-cm path length



ABC model does a good job of matching observed line density and measured net current

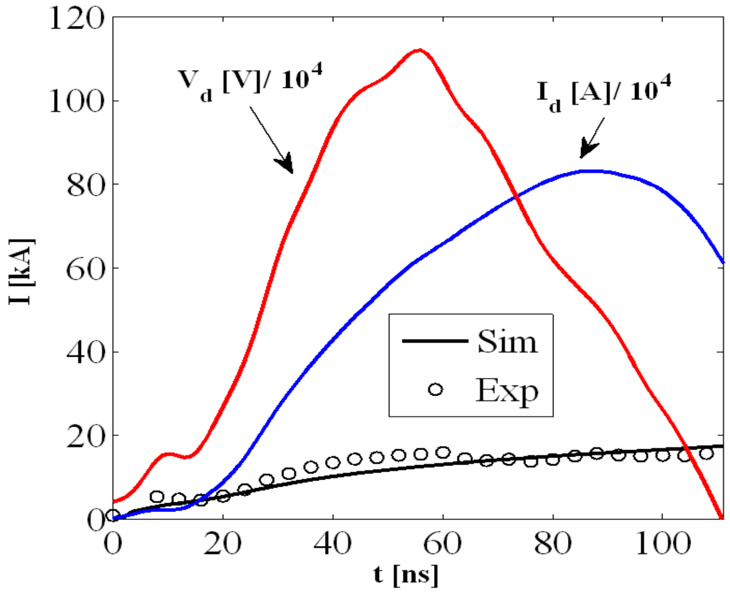
NRL PPD

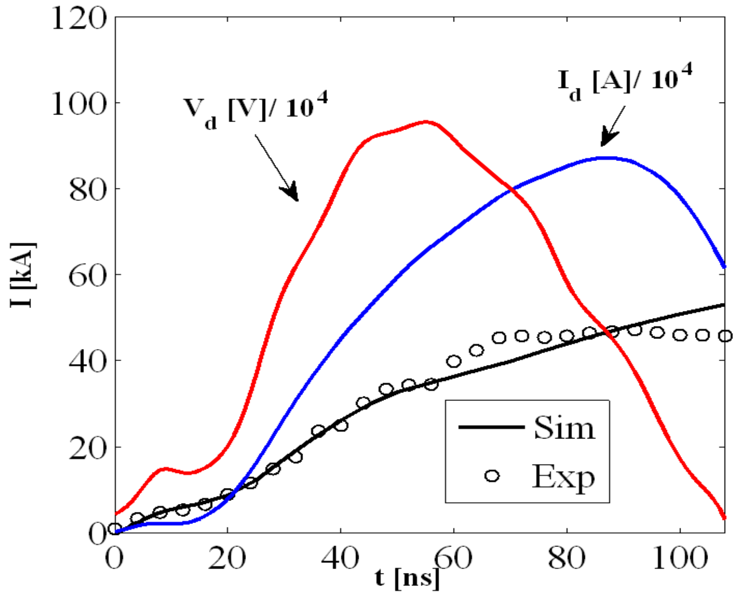


Add results modeling case with scattering foil

ABC model does a good job modeling net currents

NRL PPD

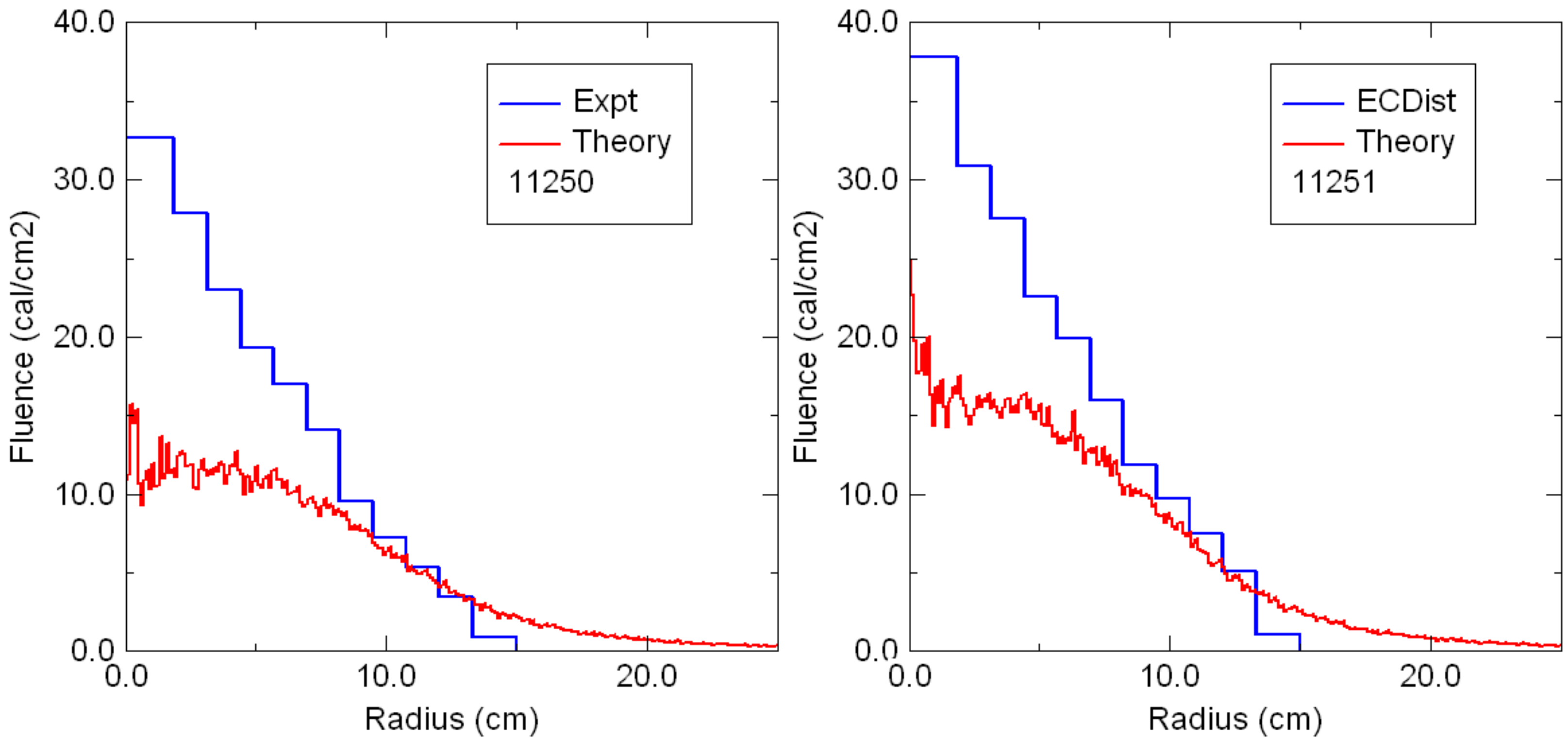




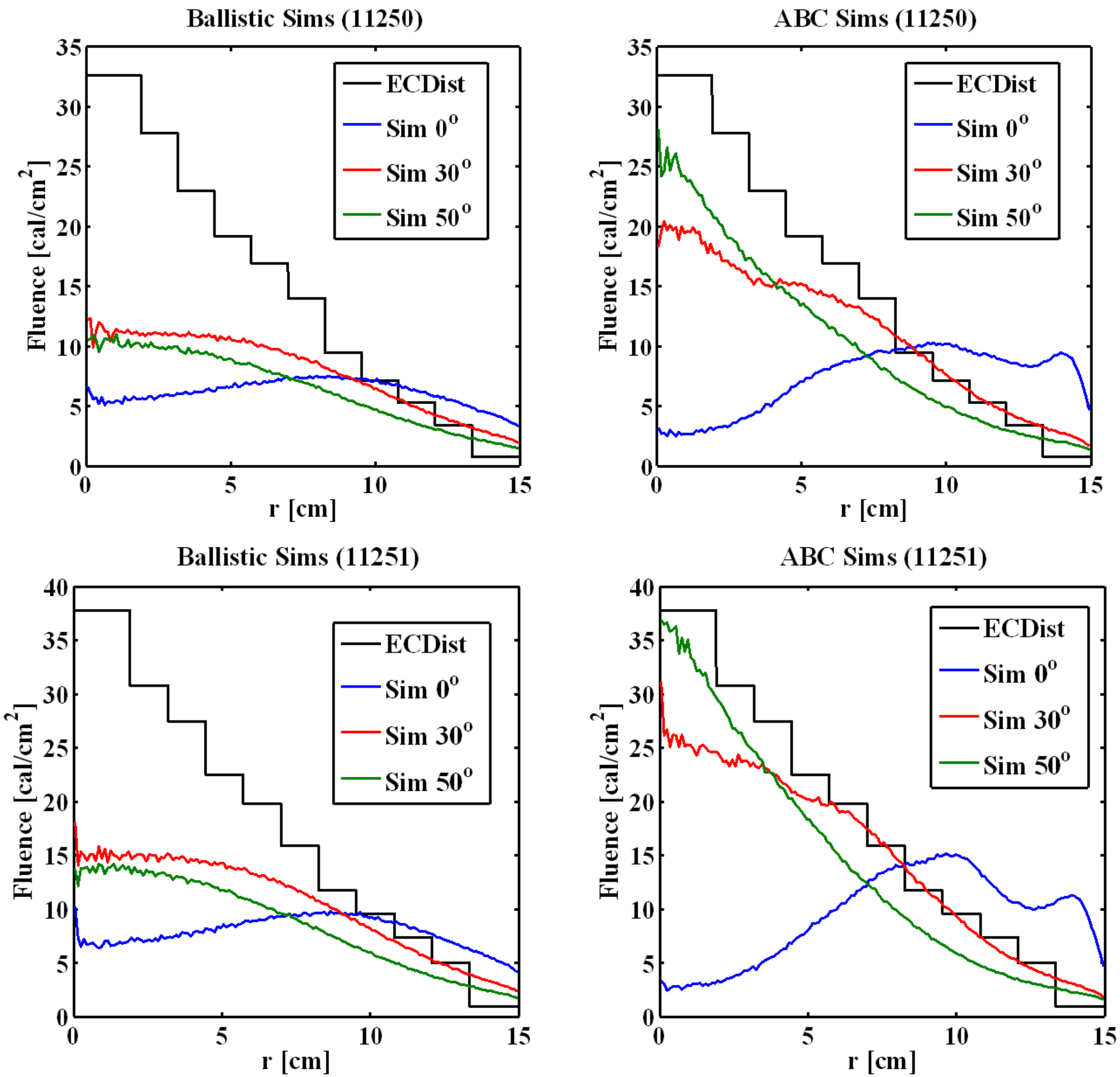
Shots with scattering foils demonstrate the existence of finite net currents

NRL PPD

- At low voltage with thicker (.1-mm) anode foil, no choice of entrance angles can match experimental results
- This suggests some "pinching" after the foil

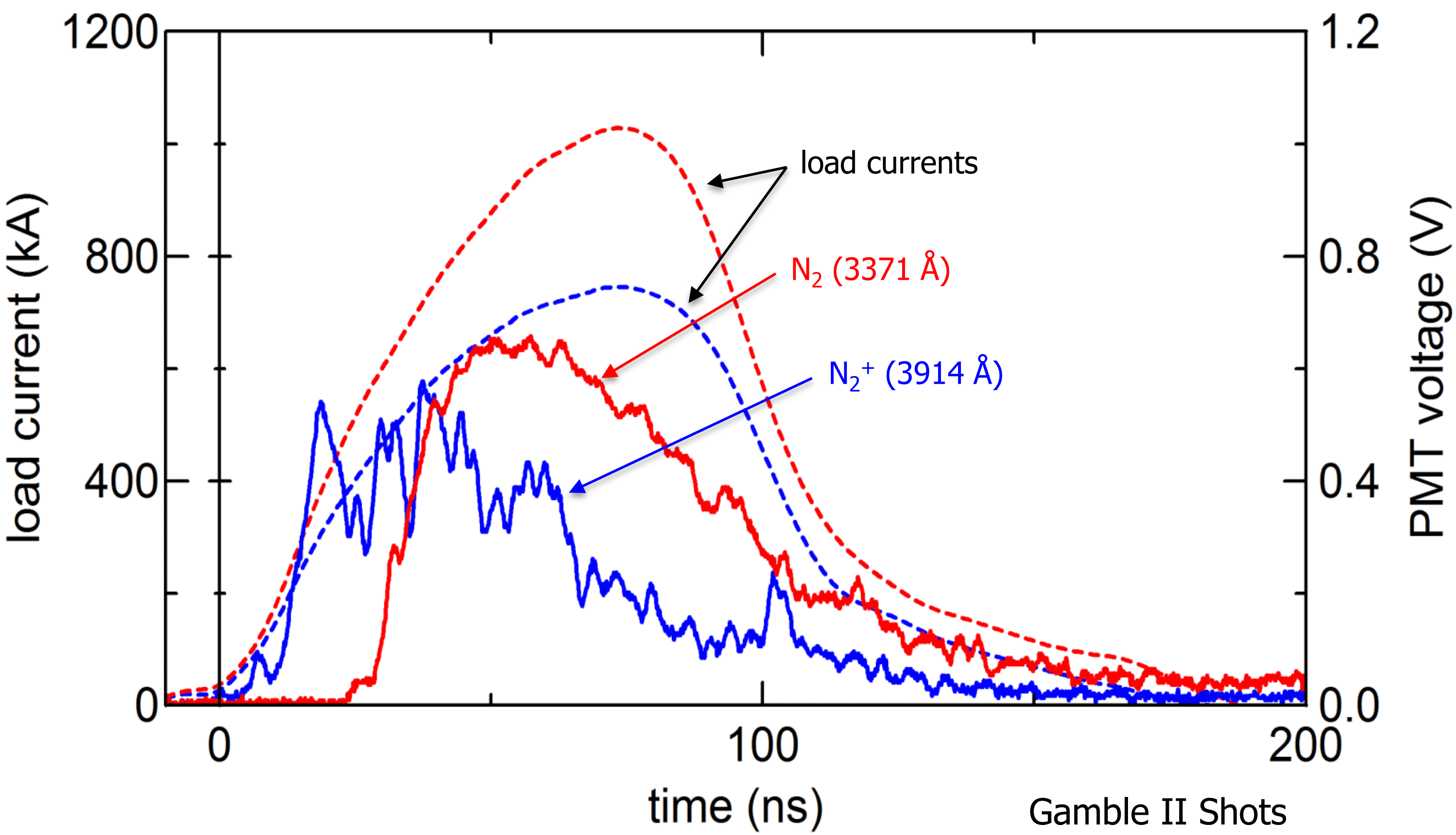


The ABC model can reproduce the observed beam profile



Time history of spectral lines recorded with monochromator on separate Gamble II shots

NRL PPD



Gamble II Shots
10759 & 10760

Conclusions

NRL PPD

- We have obtained gas-breakdown data over a range of conditions.
  - Low current density, higher pressure -> ionization is dominated by beam electrons, the ionization fraction is low, the gas remains diatomic, and electron-neutral collisions dominate
  - Higher current density where ionization is dominated by plasma current, ionization fraction is high, and the gas becomes dissociated
  - Lower pressure where the ionization is dominated by plasma current in the afterglow and kinetic effects become important
- The ABC model can reproduce the electron density and net current at both low and high current density, but cannot reproduce the observed ionization at low pressure, where a kinetic treatment is necessary
- We intend to pursue such a kinetic treatment in the future