SAND2023-05814C

U.S. NAVAL RESEARCH LABORATORY

Inductive Effects in Electron-Beam-Induced Excitation and Ionization of Air and Other Gases

Stuart L. Jackson, Eric R. Kaiser, David. D. Hinshelwood, Stephen B. Swanekamp, and Joseph W. Schumer
Plasma Physics Division, Naval Research Laboratory, Washington, DC, USA

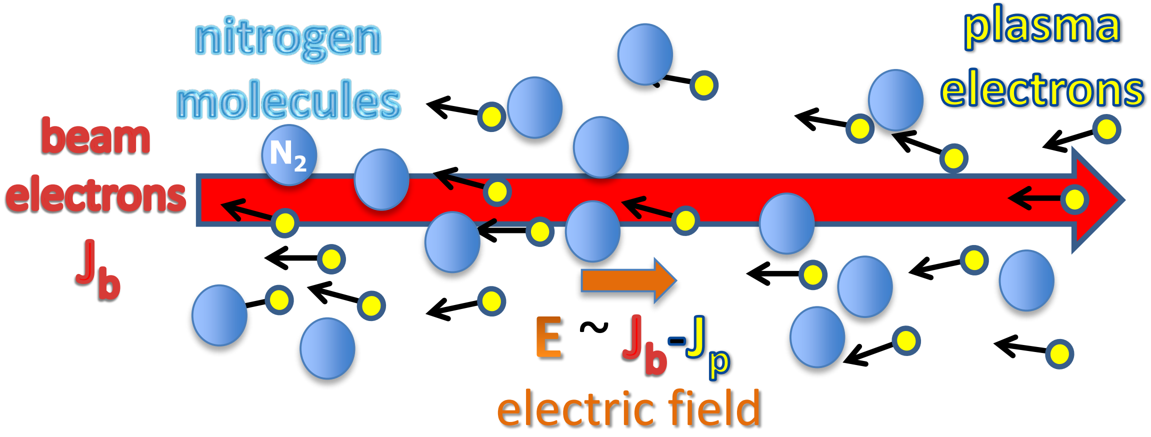
Nancy D. Isner
CTI, HII-Mission Technologies, Alexandria, VA, USA

Elaine L. Rhoades
Sandia National Laboratories, Albuquerque, NM, USA

Supported by the Naval Research Laboratory Base Program and Sandia National Laboratories (SAND2023-00081A). SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

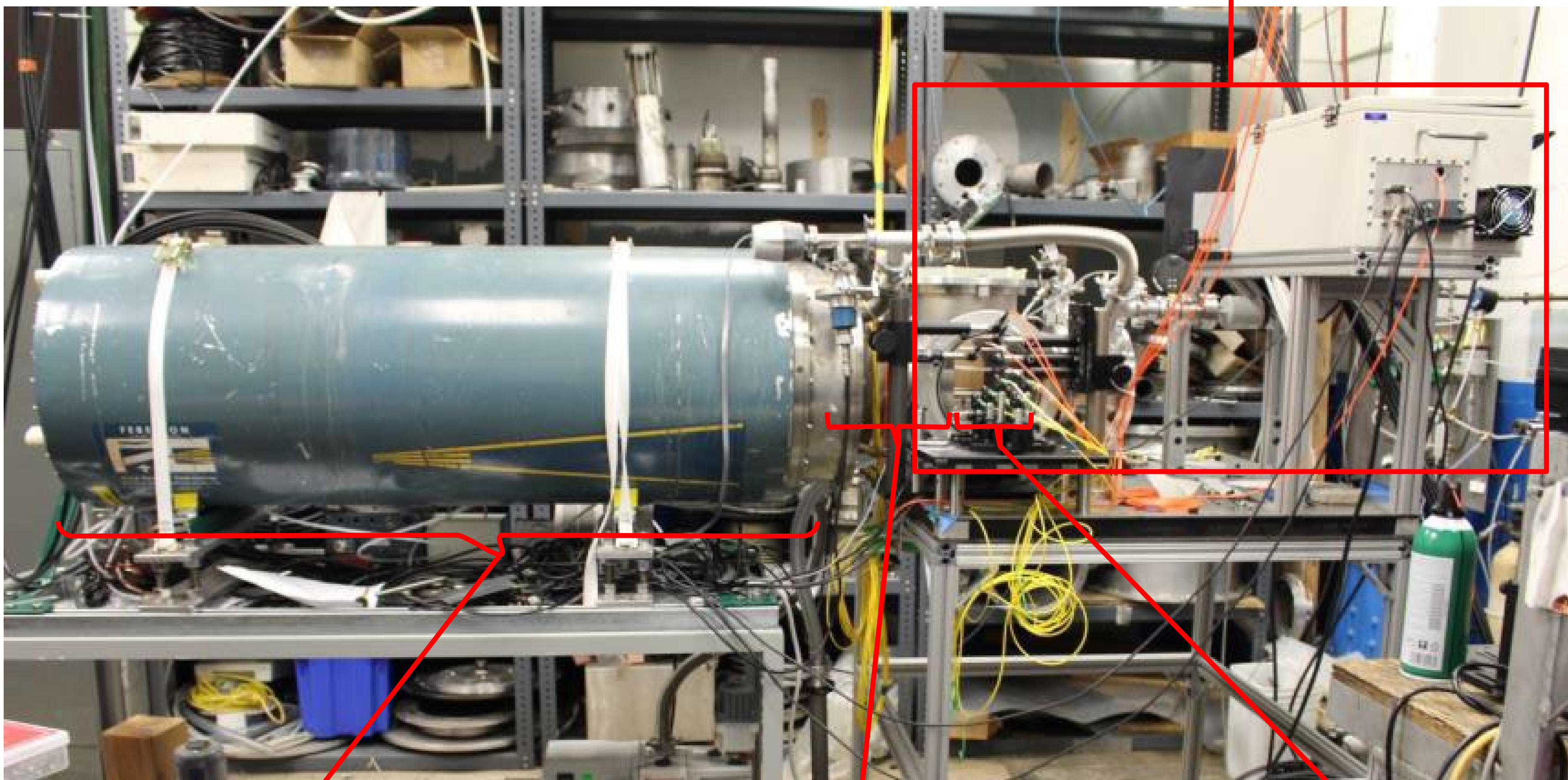
Abstract

An electron beam was produced in vacuum using a Febetron pulsed-power generator modified to produce a peak voltage of 100 kV, a peak current of 4.5 kA, and a pulse width of 100 ns. The beam electrons then passed through thin anode and pressure foils and transited a cavity filled with dry air or other gases, exciting and ionizing the gas along the way. Measurements from electrical, interferometric, spectroscopic, and optical imaging diagnostics were combined with circuit modeling to investigate the behavior of the beam at various pressures. At low gas pressures, the dynamics of the beam were strongly affected by the inductance of the cavity.



Laboratory arrangement for electron-beam-induced plasma chemistry experiments

diagnostics



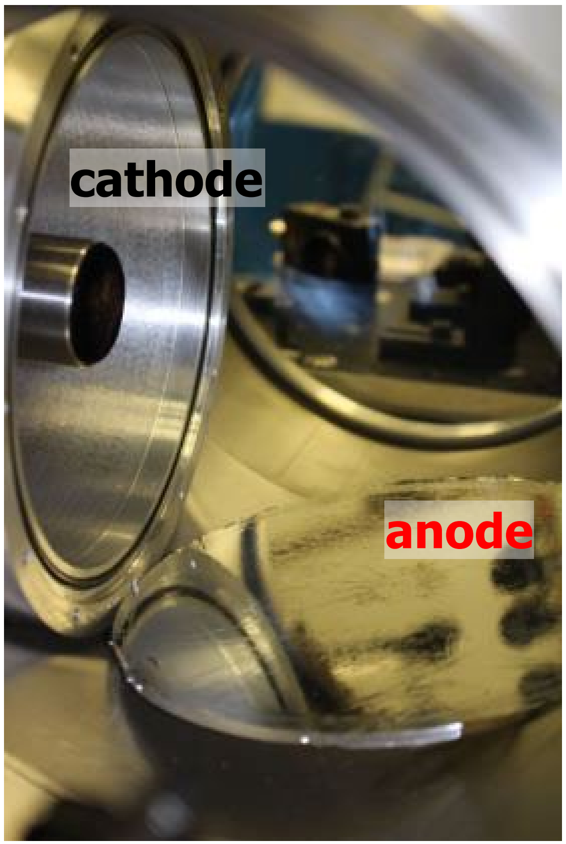
Febetron pulsed-power generator modified to 100 kV, 4.5 kA, 100 ns

vacuum section containing e-beam diode, 25 A/cm^2 to 300 A/cm^2)

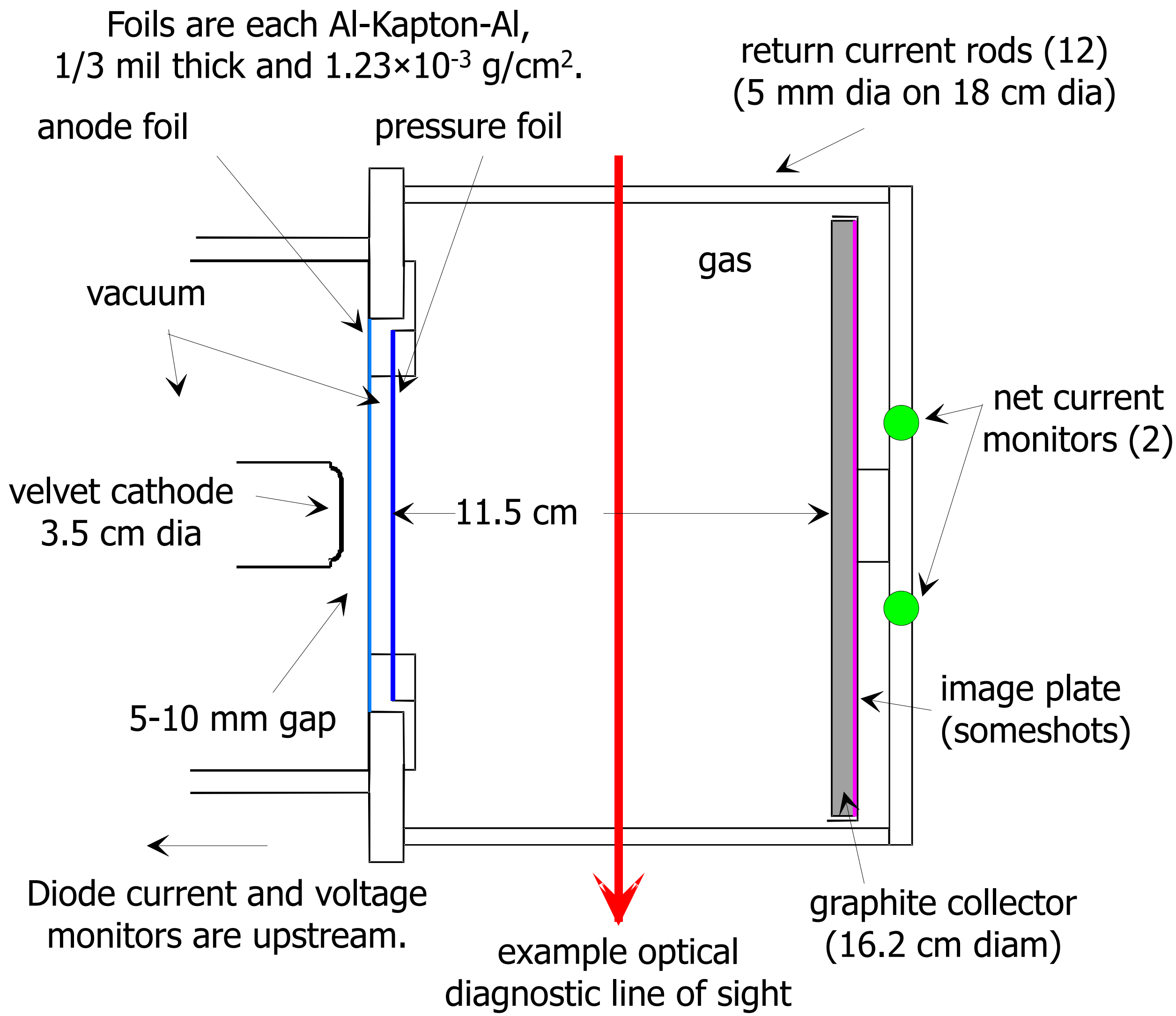
gas cell filled with dry air or nitrogen at 0.01 Torr to 10 Torr

Arrangement of e-beam diode and gas cell

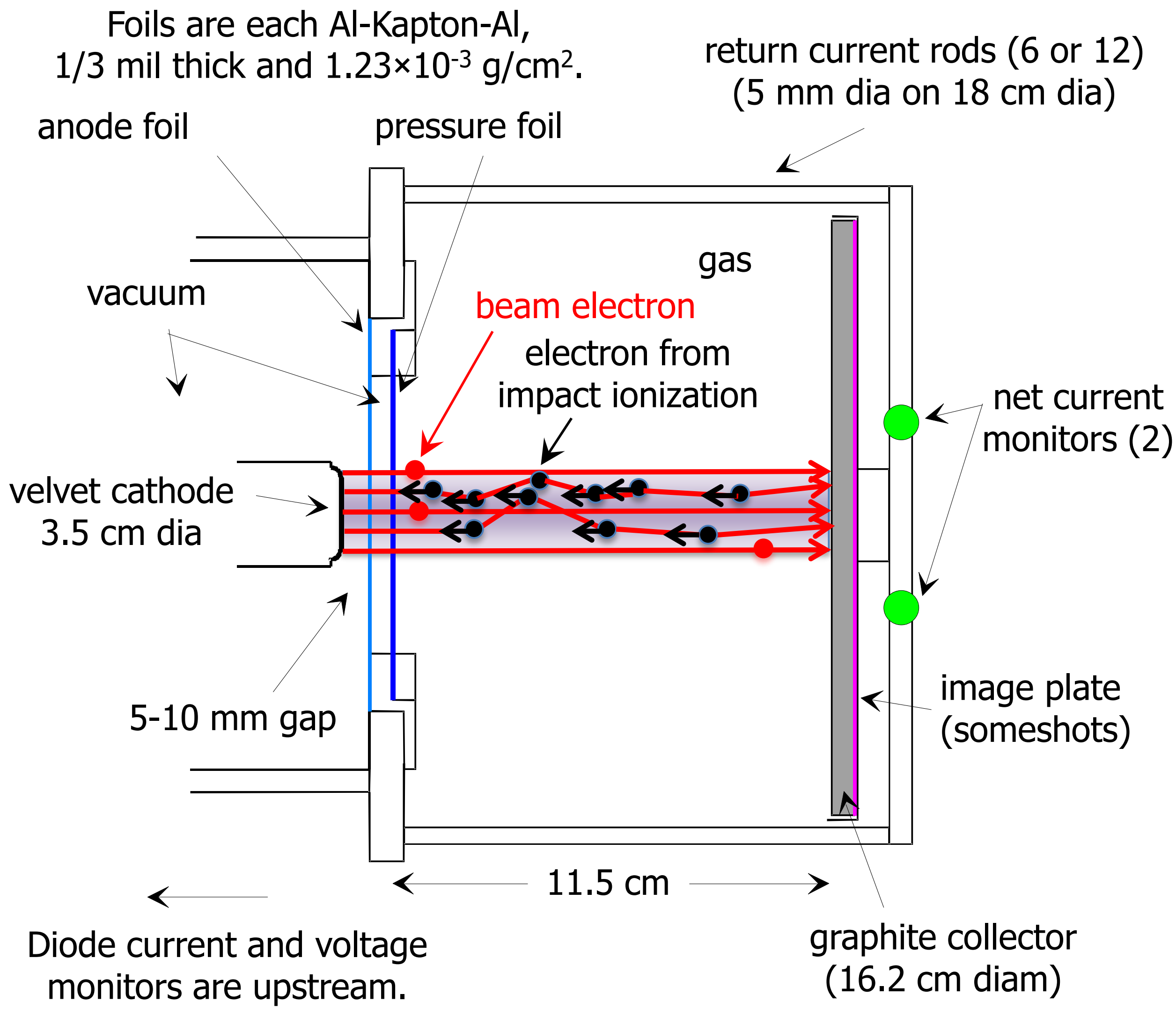
NRL PPD



Used cathode and anode



Time dependence of the ionization in the gas cell is determined by the pressure and inductance



- During the electron beam current pulse, a fraction of the beam current is canceled by counter-streaming electrons freed from the gas by beam-impact ionization
- The fraction of the beam current canceled depends on the gas pressure
- After the beam pulse ends, a decaying current continues to flow within the gas cell, due to its inductance
- Additional electrons are freed from the gas to carry this current and short the inductive electric field

Optical diagnostic arrangement

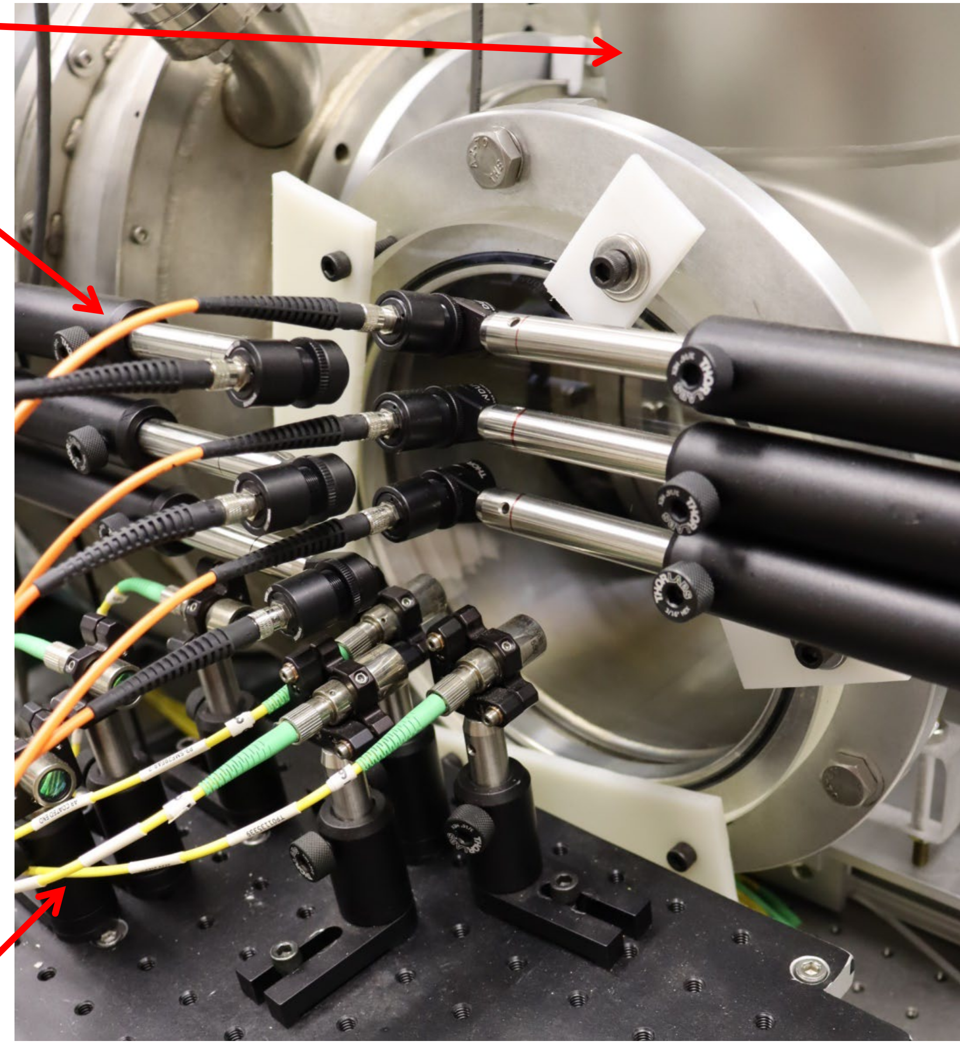
2 ICCD cameras (not shown) image gas cell through top window

6 spectrometers (orange optical fibers):

- Time-resolved monochromators (x3)
- Low-res, time-integrated survey spectrograph (new)
- Moderate res, time-gated spectrograph
- High-res, time-gated spectrograph (new)

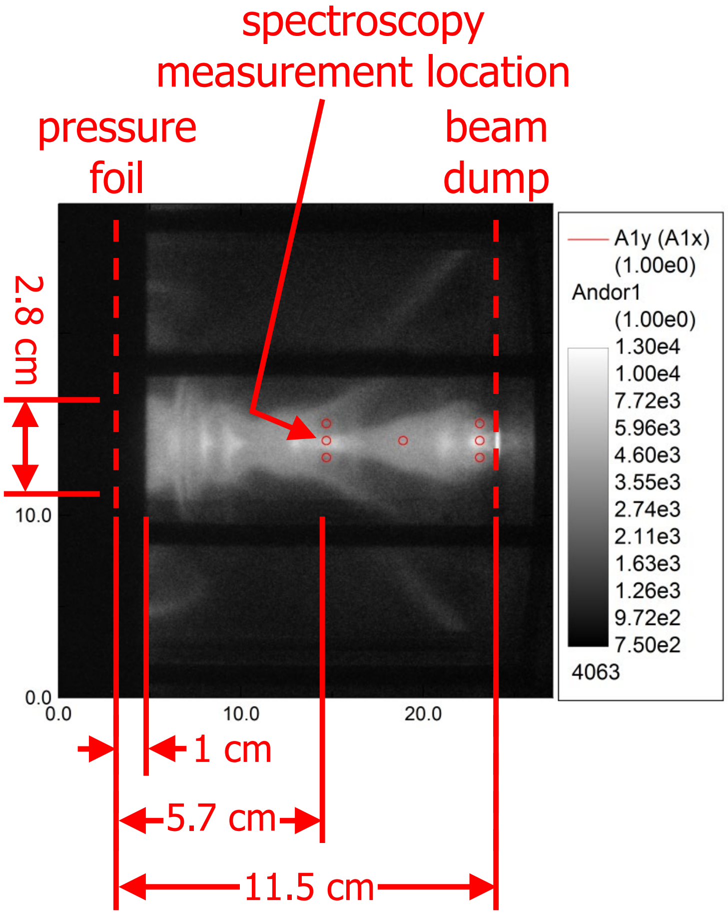
Each fiber is attached to a lens (in a black mounting tube) pointed to view across a diameter of the gas cell with 2.5 mm spatial resolution. All currently view the axial midpoint of the beam as it crosses the cell but each can be repositioned to another axial location (e.g., near the pressure foil or beam dump) by sliding the individual mounting posts.

Fiber interferometer (yellow optical fibers): currently viewing 3 axial locations



Fiber interferometer and visible-light cameras track electron density and record visible light emission

NRL PPD



Visible light image from ICCD camera with fiber interferometer views superimposed

- Fiber interferometer tracks line-integrated density at up to 7 locations
- Two ICCD cameras record visible-light emission at 2 times during pulse

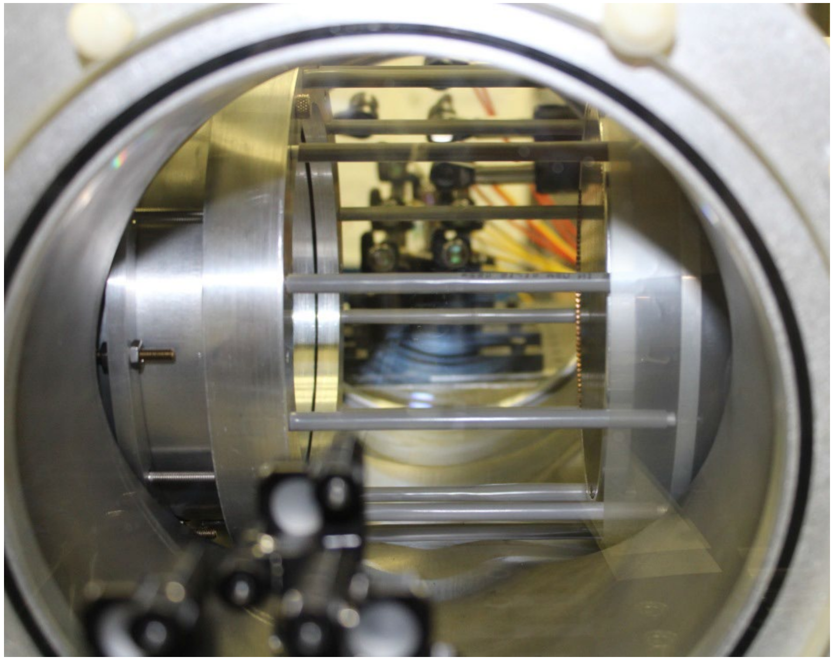
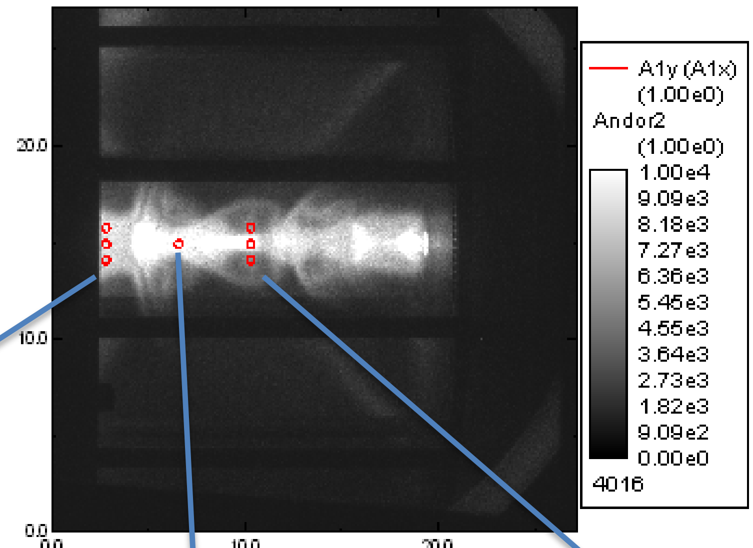


Photo of transport region, reversed to match visible light image. The beam is transported from left to right.

Flexibility of fiber interferometer allows measurement of density distribution in complex current channel[1]

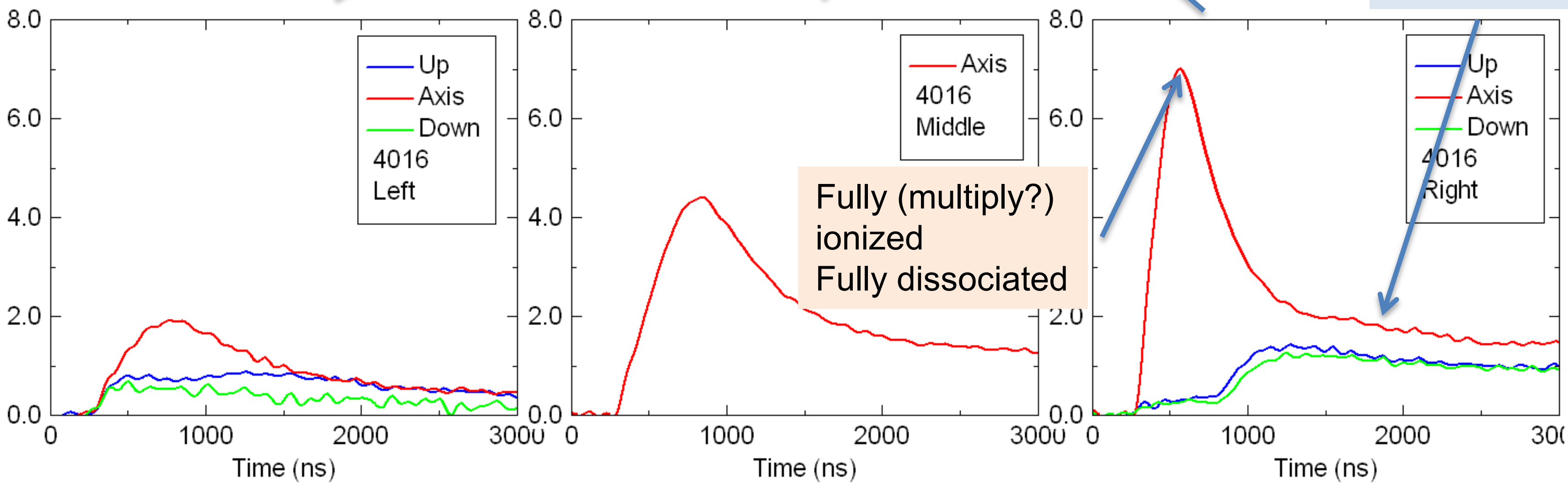
NRL PPD

- Seven lines of sight
- Off-axis beams are at 5-mm radius
- Image taken just after beam current pulse



10^{15} cm^{-2}/div

Diffusion masks recombination?

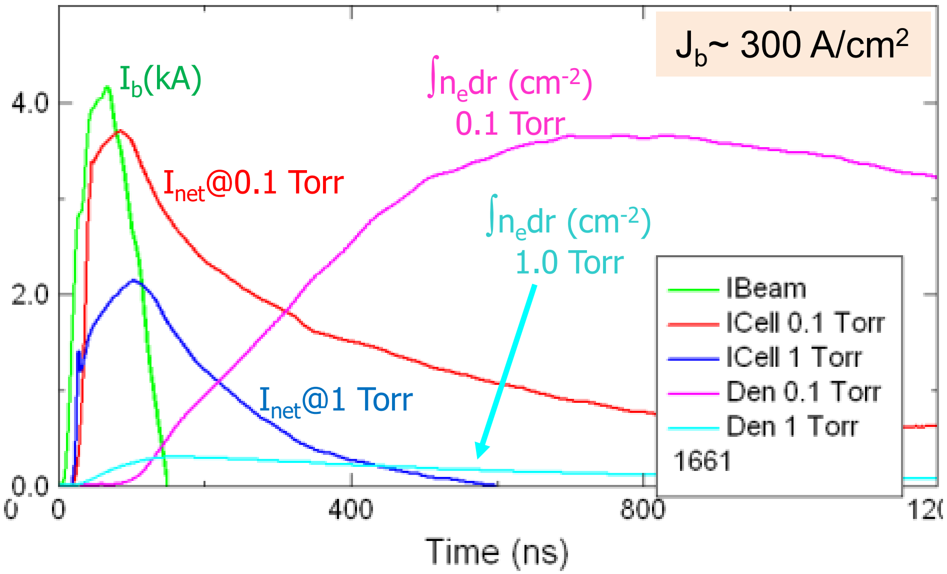


Fully (multiply?) ionized
Fully dissociated

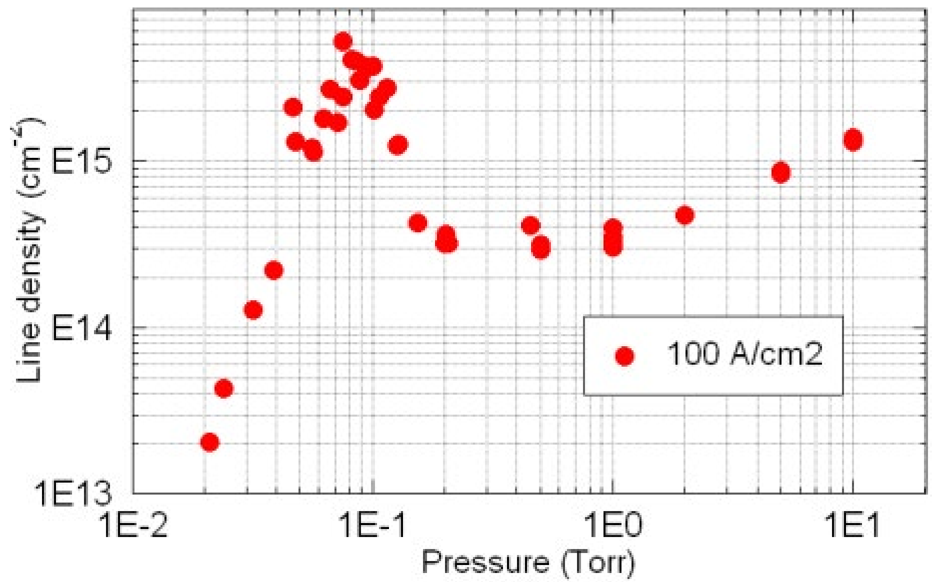
[1]D. D. Hinshelwood et al., EAPPC 2016.

The line-integrated plasma density induced by the e-beam has been measured for a range of pressures[1]

Comparison with P=0.1 and P=1 Torr



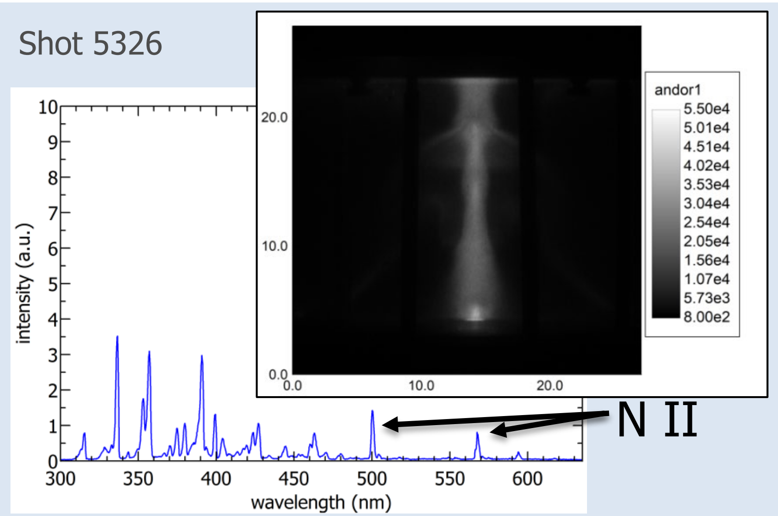
Peak electron densities vs. air pressure



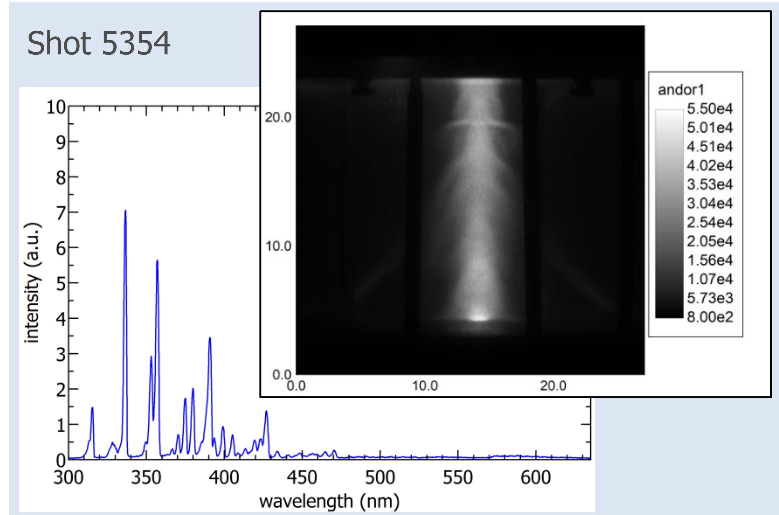
- In prior work, behavior of line-integrated density induced by e-beam in dry air over a range of pressures was observed to be quite complicated and indicated two regimes of interaction
  - A high pressure regime (p>1 Torr) where beam electrons collide with the gas, leading to significant ionization and current cancellation during the beam pulse
  - A low pressure regime (p<0.1 Torr) dominated by inductive effects where significant ionization does not occur until after the beam current begins to drop

[1]D. D. Hinshelwood et al., EAPPC 2016.

Enhanced atomic nitrogen emission near 100 mTorr corresponds to compact, high-density plasma

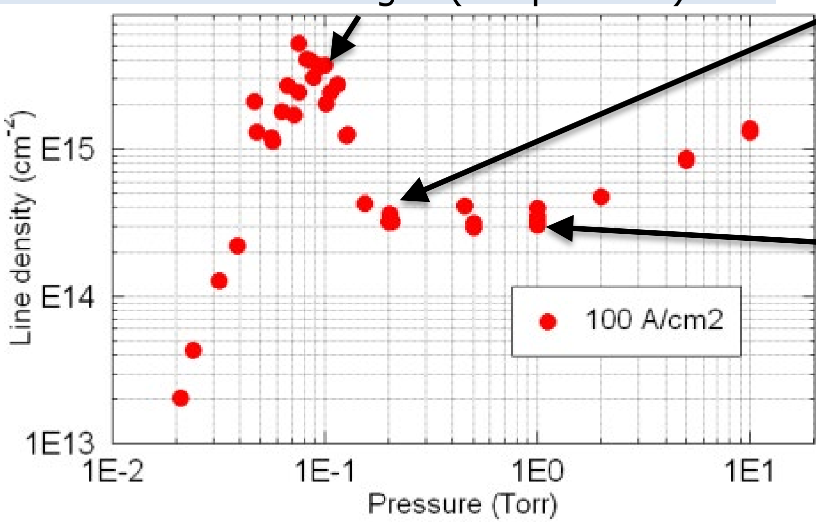


0.1 Torr nitrogen (low pressure)

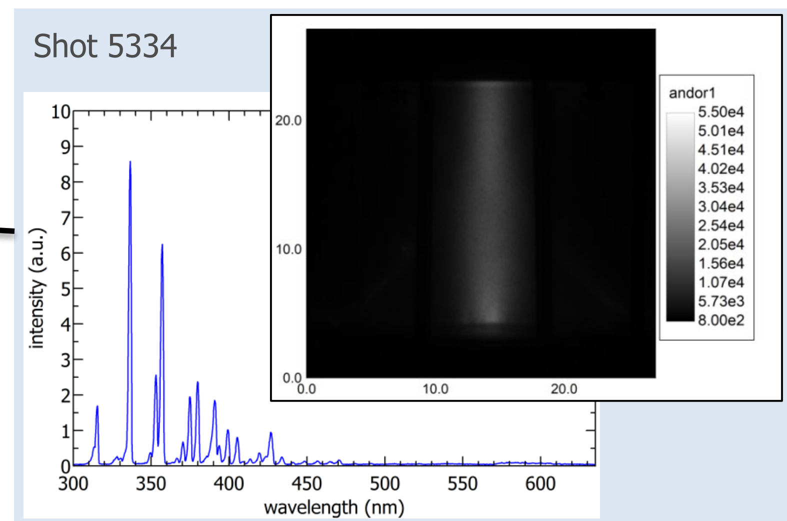


0.2 Torr nitrogen (intermediate pressure)

Note: Density plot is dry air at 100 A/cm^2; spectra and images are nitrogen at 300 A/cm^2.



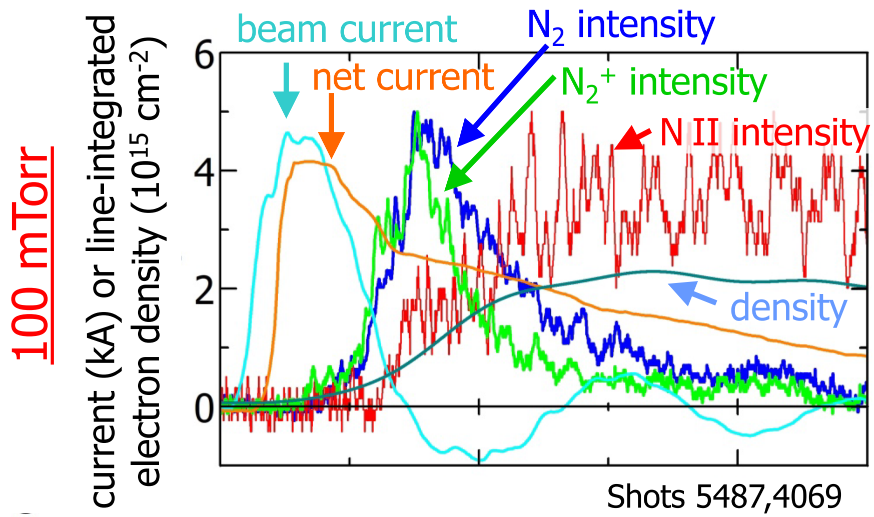
Peak electron densities vs. air pressure

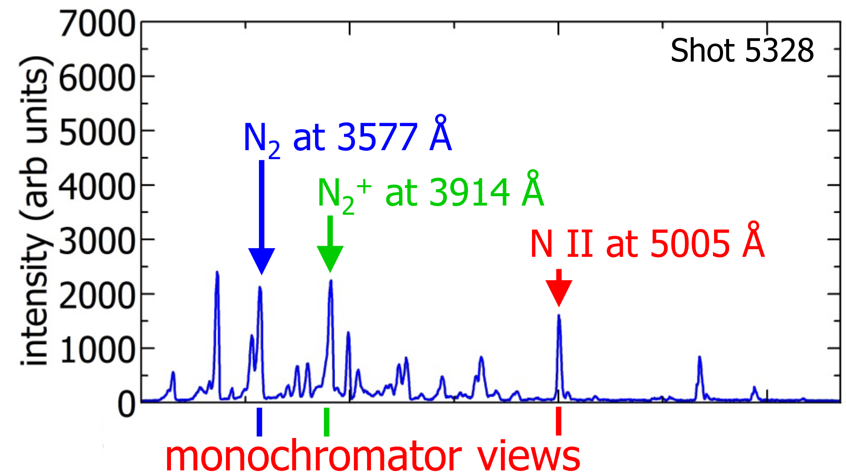


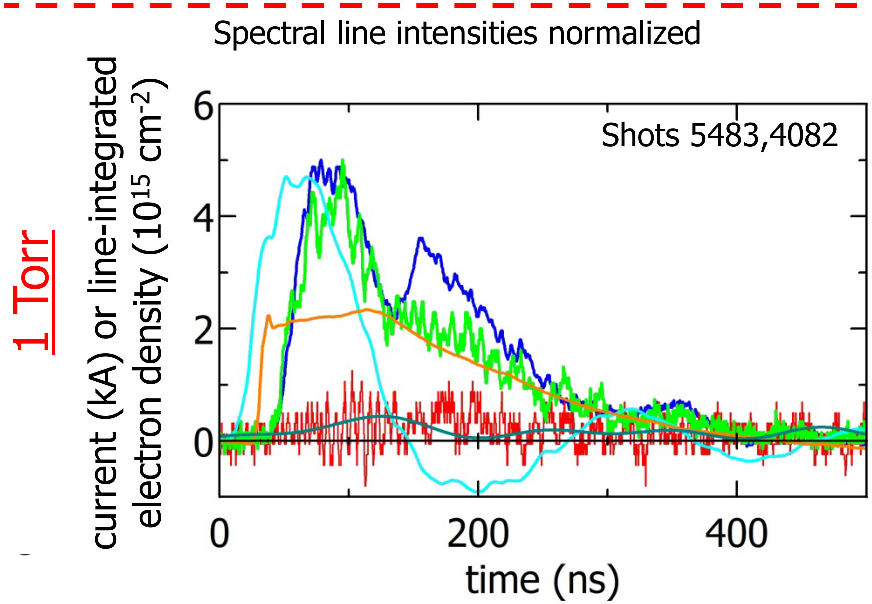
1 Torr nitrogen (high pressure)

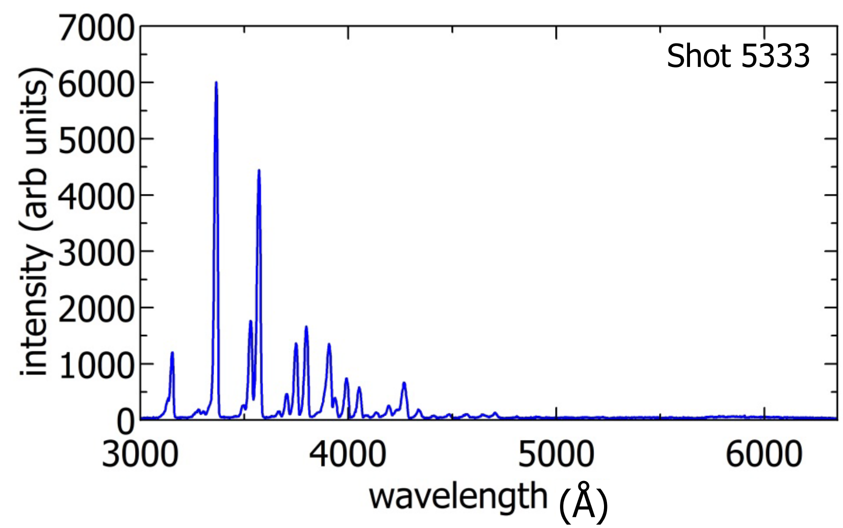
Time-dependent N_2, N_2^+, and N II line intensities recorded with monochromators and compared to electrical traces

NRL PPD





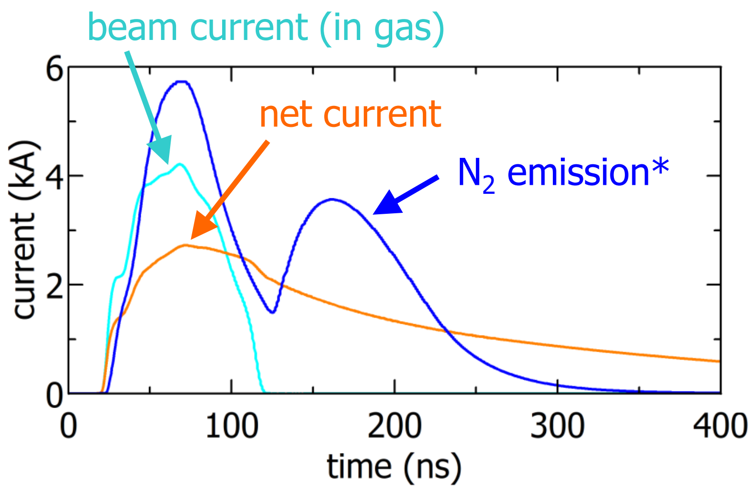




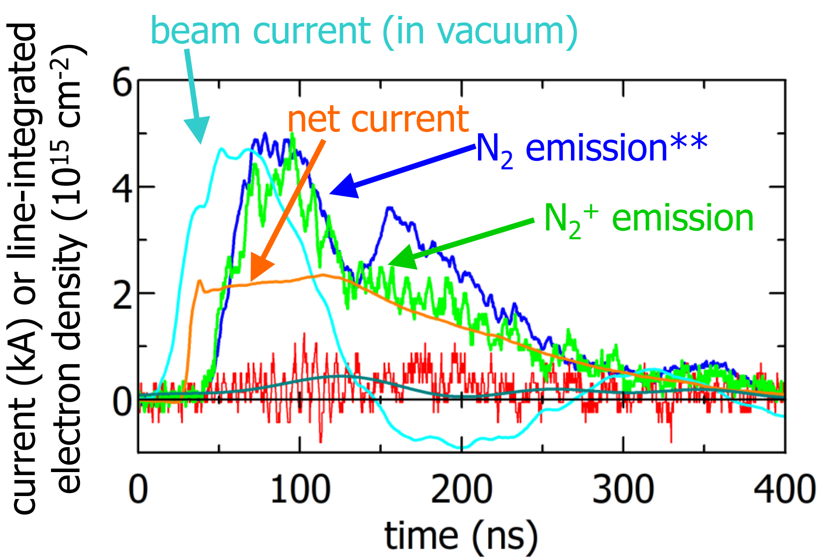
Spontaneous emission for second positive system of N_2 added to model for comparison with measurement

NRL PPD

Model at 1 Torr



Experiment at 1 Torr



Shots 5487,4069
Spectral line intensities normalized

- Rigid-beam model[1] used to simulate electron-beam-plasma system[2]
- Fluid-type model that solves first three moments of Boltzmann's Equation
- Simplified to 1D cylindrical coordinates and prescribed beam input parameters to drive the three governing equations
- Various plasma parameters are able to be tracked with model, such as line-integrated electron density, current, current density, electron energy, electric field, etc.
- Density of reactive species: model is currently tracking 26 different species and 60 different reactions
- Emission* calculated for 2nd positive system of N_2

$$N_2(C^3\Pi_u) \rightarrow N_2(B^3\Pi_g) + \frac{hc}{\lambda}$$

- Time dependence of this calculated emission compared to experimentally-measured emission** at 3577 Å for

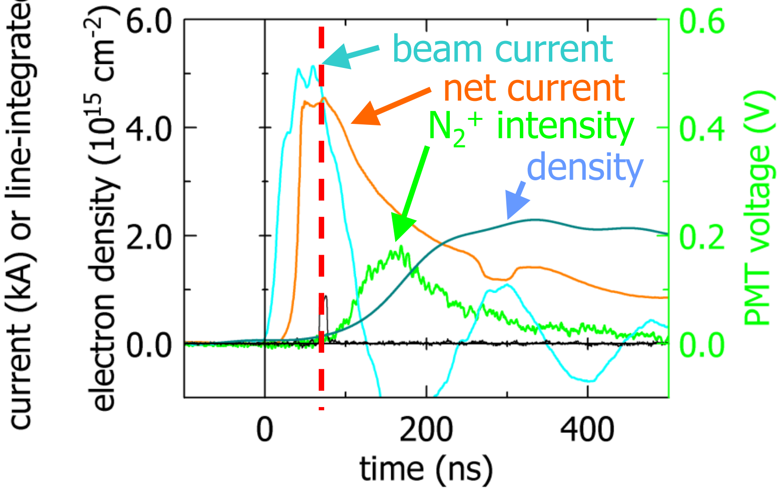
$$N_2(C^3\Pi_{u,\upsilon=0}) \rightarrow N_2(B^3\Pi_{g,\upsilon=1}) + \frac{hc}{\lambda}$$

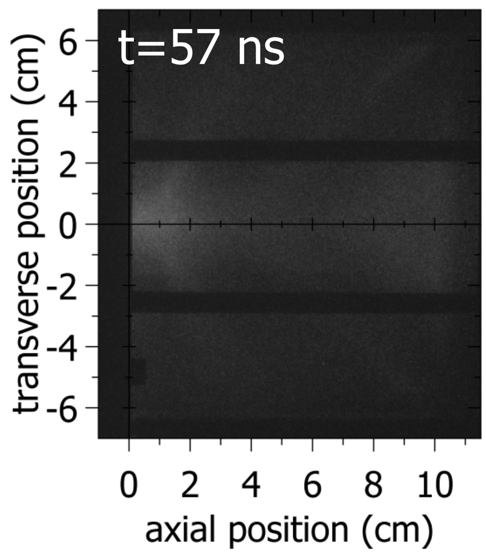
[1]A.S. Richardson et al., Phys. Plasmas 28, 093508 (2021).
[2]N. D. Isner et al., AO 1.2-02 (Monday PM Oral Session), this conference.

Time evolution: 0.1 Torr vs. 1 Torr, 10 ns exposure

NRL PPD

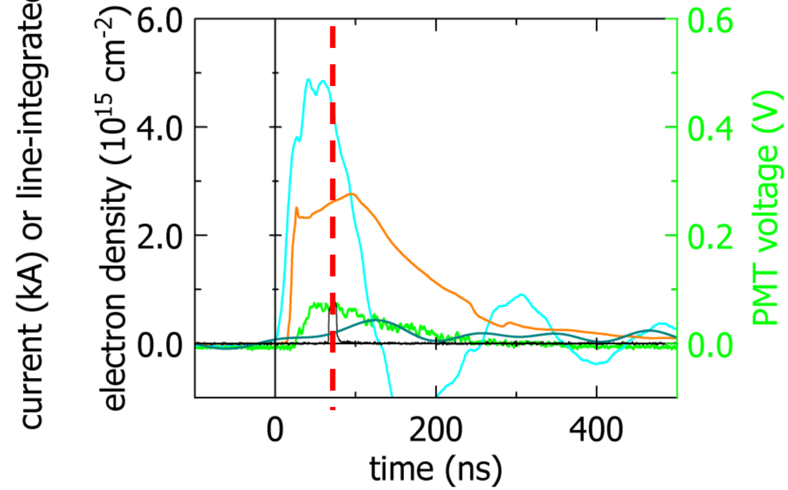
0.1 Torr

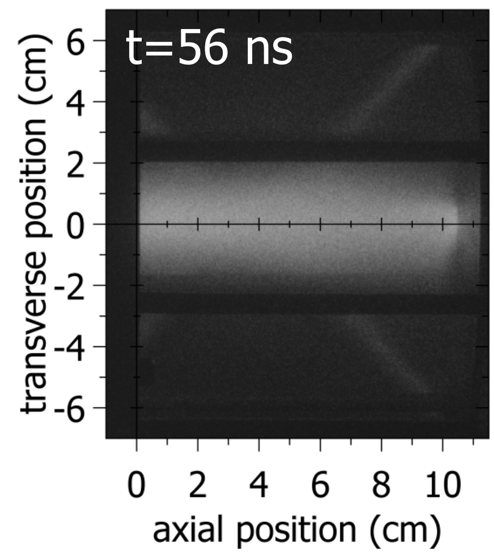




(Shots 4103 & 4069)

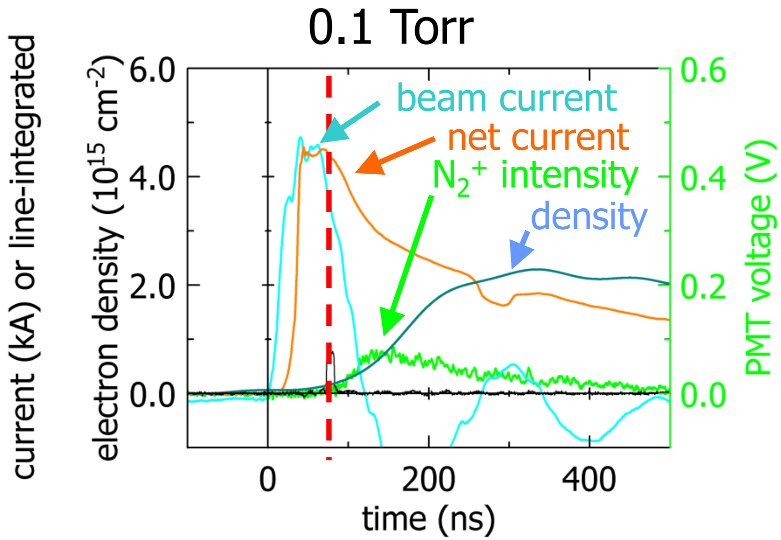
1 Torr

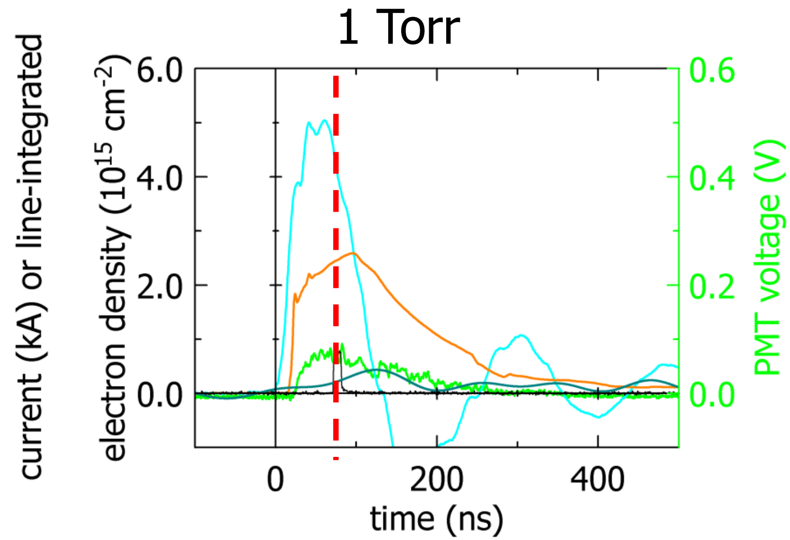


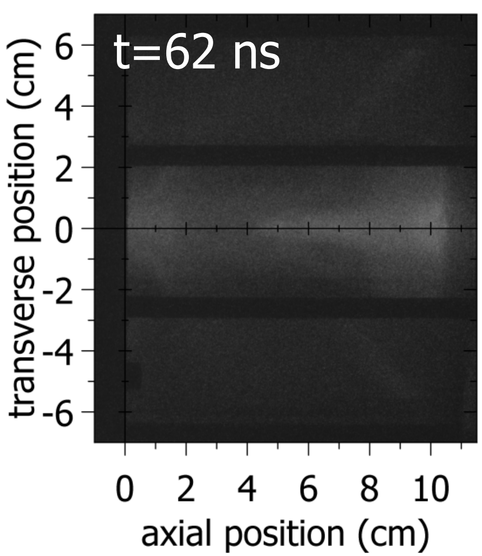


(Shots 4124 & 4082)

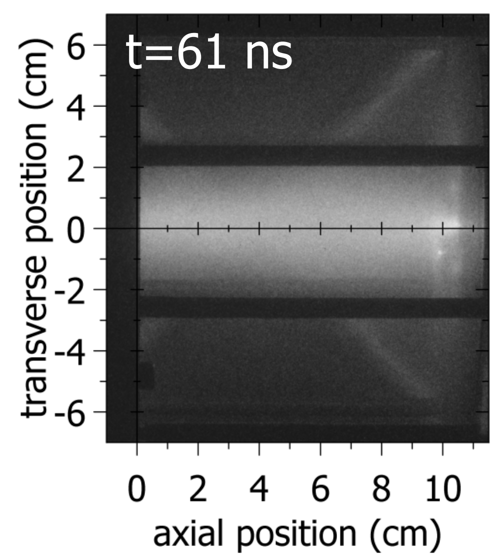
Time evolution: 0.1 Torr vs. 1 Torr, 10 ns exposure







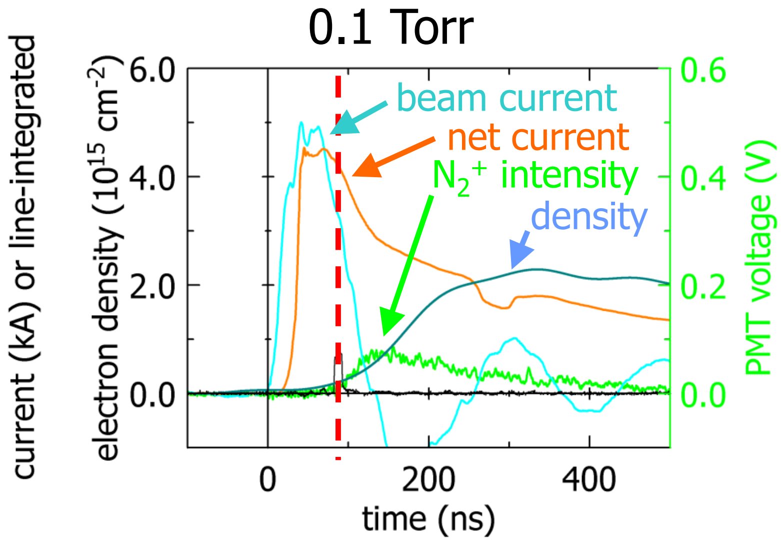
(Shots 4043 & 4069)

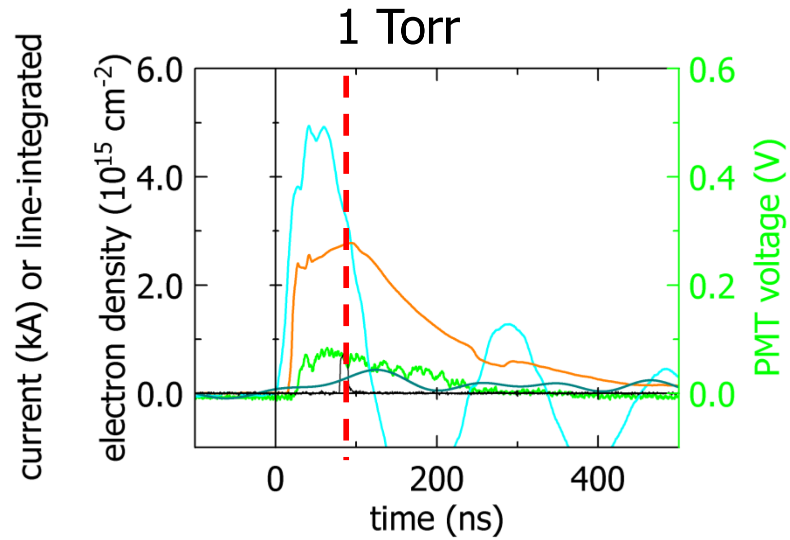


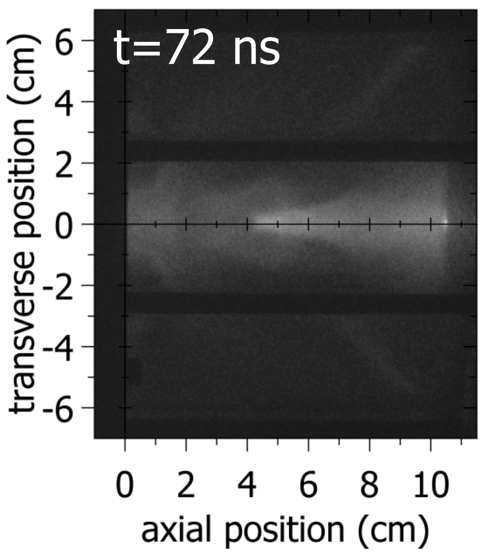
(Shots 4107 & 4082)

Time evolution: 0.1 Torr vs. 1 Torr, 10 ns exposure

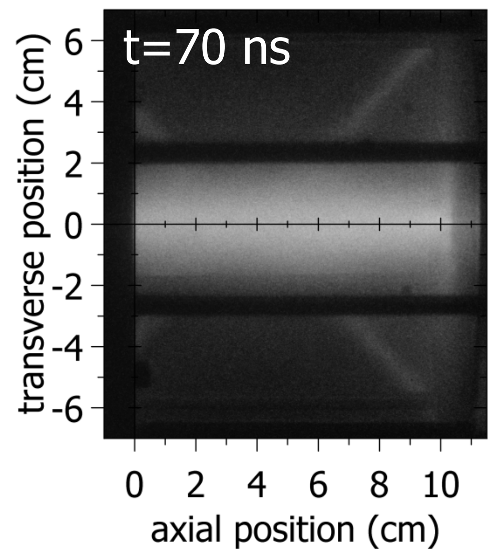
NRL PPD







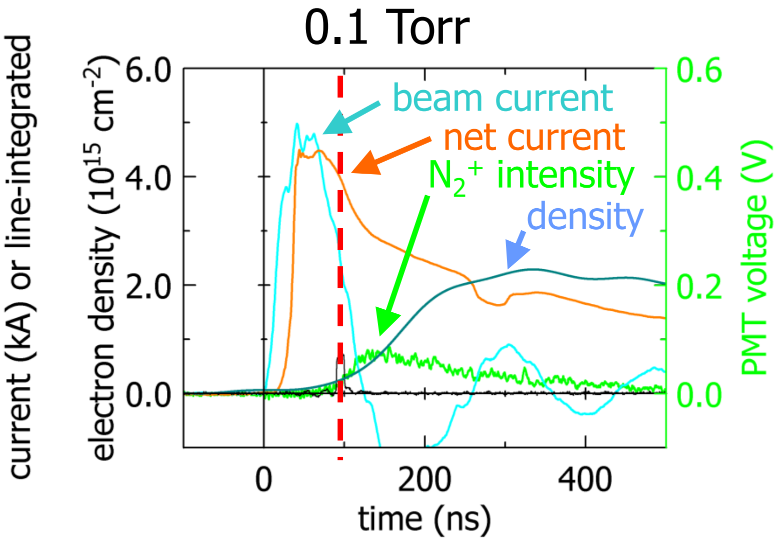
(Shots 4044 & 4069)

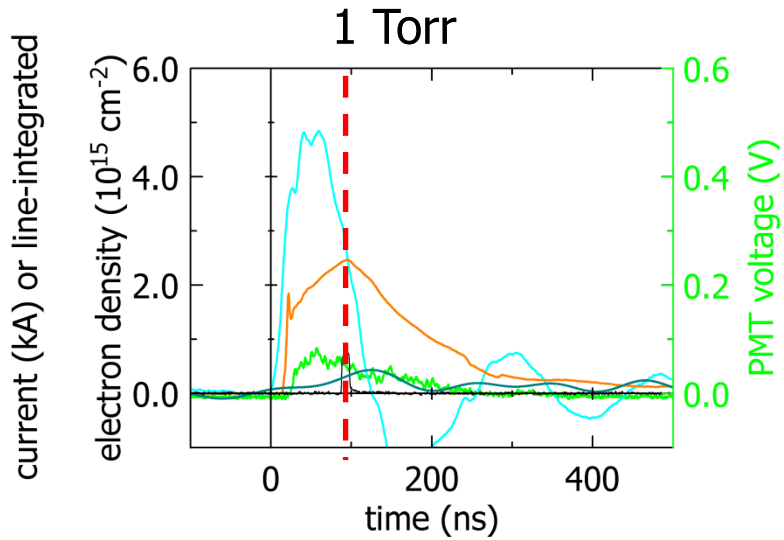


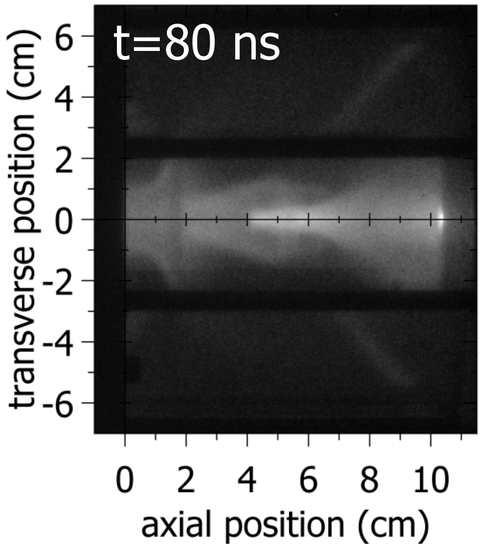
(Shots 4115 & 4082)

Time evolution: 0.1 Torr vs. 1 Torr, 10 ns exposure

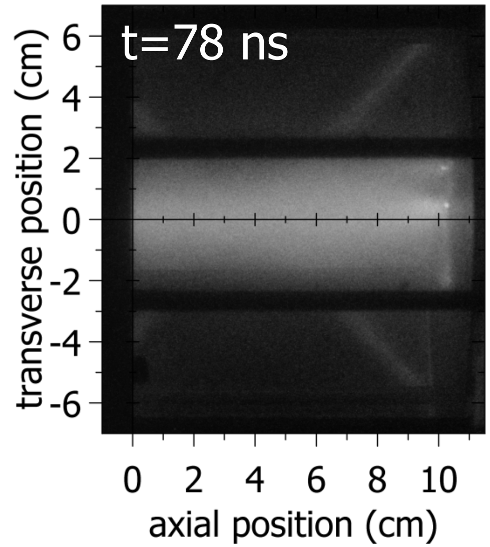
NRL PPD





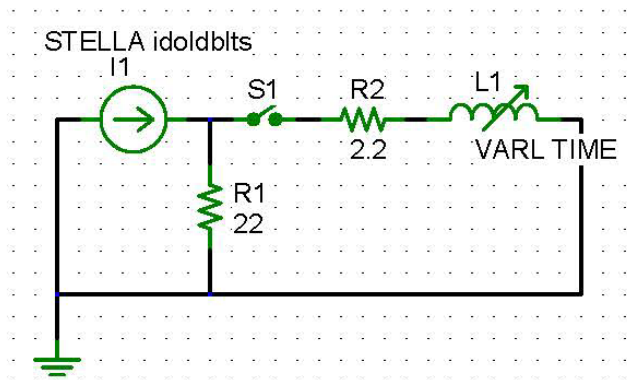


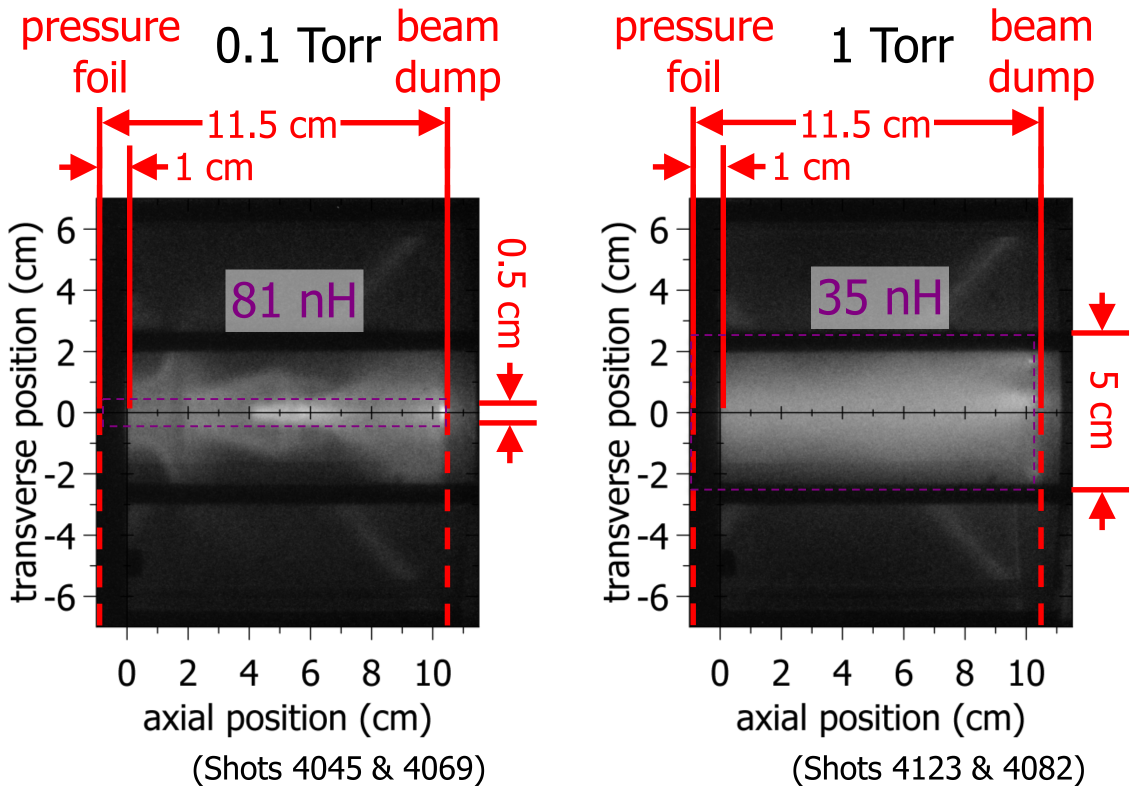
(Shots 4045 & 4069)



(Shots 4123 & 4082)

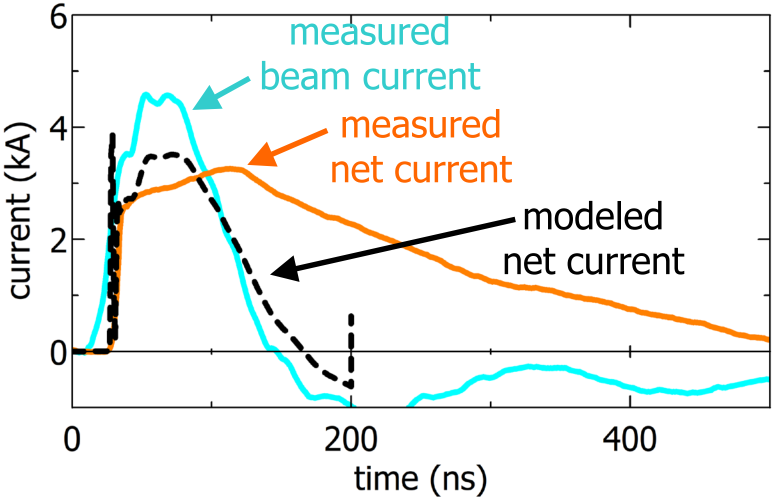
Circuit modeling extreme cases: 0.1 Torr vs. 1 Torr

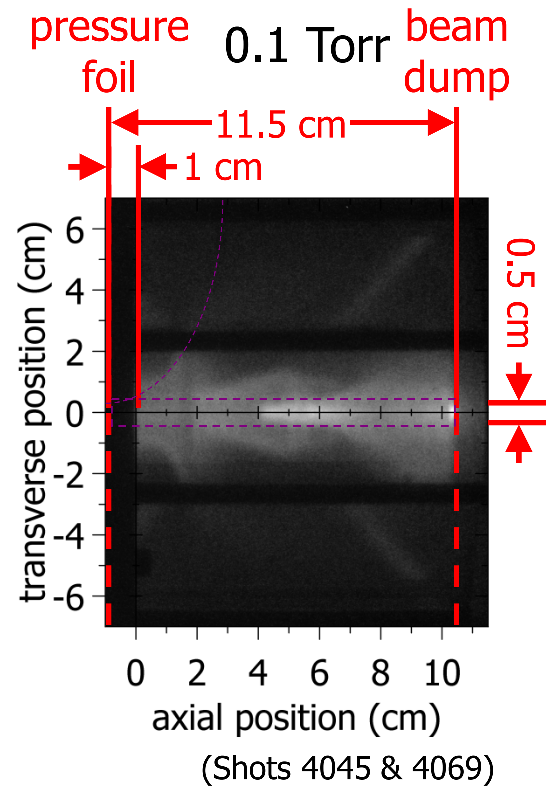




- CASTLE circuit model developed for e-beam through gas cell
  - Experimentally-measured e-beam current waveform as input to model
  - Simple circuit elements used in model, based on simplified geometry of e-beam through gas cell
- Two extreme cases modeled, as well as variable-inductance cases

Comparison of circuit models with experiment





- Net current at beam dump used to compare measured vs modeled
- Switch used at current corresponding to 35 kV when electrons begin to pass through foil and into gas cell
- Variable-inductance case approximates sweeping current path and begins to capture some features of net current waveform

Summary of inductive effects in electron-beam-induced excitation and ionization of air and other gases

- NRL has an established testbed for electron-beam-induced plasma chemistry experiments
  - A modified Febetron pulsed-power generator is used to drive a pulsed electron beam into a gas cell in order to understand the interaction between energetic electrons and air and other gases
  - Testbed allows for rapid data collection to support modeling efforts
- Measurements of electron density, and optical emission (images and spectra) induced in the air
  - Made at a small subset of pressures and current densities in air and nitrogen
  - Show that the interaction involves a complicated but repeatable blend of two physical regimes
- Circuit modeling has been used to investigate geometrical effects apparent in electrical measurements