Instrumentation Development for a Novel Local Electric and Magnetic Field Fluctuation Diagnostic

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On behalf of:

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58th Annual Meeting of the APS

Division of Plasma Physics

Oct. 31st – Nov. 4th, 2016

San Jose, California

Introduction

Electric and Magnetic Field Fluctuations are Underdiagnosed in Tokamaks

- $\tilde{E}$ measurements are integral to turbulent plasma physics because they provide information regarding:
  - $\tilde{E}_z \times \overrightarrow{B_\phi} = \tilde{v}_r$: cross-field transport
  - $\tilde{E}_r \times \overrightarrow{B_\phi} = \tilde{v}_\theta$: zonal flows, transport barrier

- Required for validation of tokamak core turbulence and transport models

- $\tilde{E}$ can be extracted from fluctuations in the Stark manifold

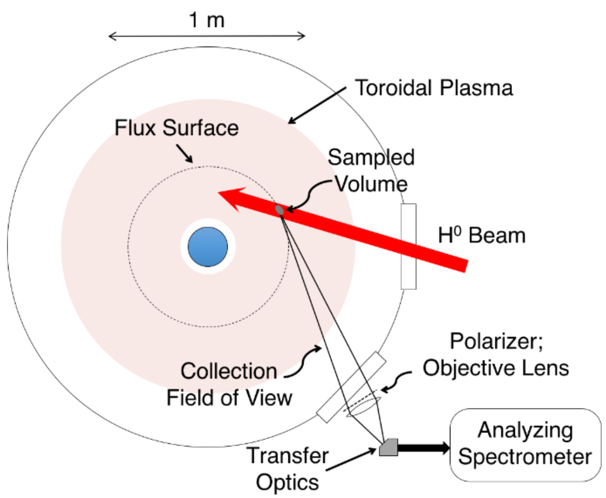
Local $\tilde{E}$ Results in Fluctuations in the Stark Manifold

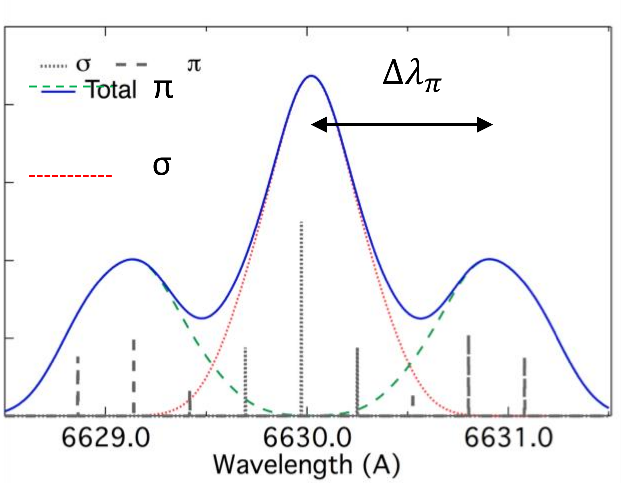
- The measured field is:

$$\boldsymbol{E}_{\text{tot}} = \boldsymbol{E}_{\text{plasma}} + \boldsymbol{v}_{\text{beam}} \times \boldsymbol{B}$$

  - For 80 keV beam, $B_T = 0.3\text{T}$
  - $E_{v\times B} \approx 1$ MV/m

- Two measurement methods:
  - $\tilde{E}_z \propto \widetilde{\Delta\lambda}_\pi$: measurement of separation of π lines
  - $\alpha\tilde{E}_r \propto \frac{\pi}{\sigma}$: line intensity ratio





Modeled MSE spectrum

1 H. A. Bethe & E. E. Salpeter. Quantum Mechanics of One- and Two-Electron Atoms. New York: Dover Publications, Inc., 1957.
2 H. Y-H. Yuh, PhD Thesis, MIT (1995).

$\tilde{E}$ and $\tilde{B}$ Measurement Validation Requires a High Performance DNB

- Diagnostic neutral beam requirements:
  - Low divergence, Low $T_{i\perp}$: limit peak broadening
  - High beam fraction at full energy
  - 80 kV: High energy for spectral splitting

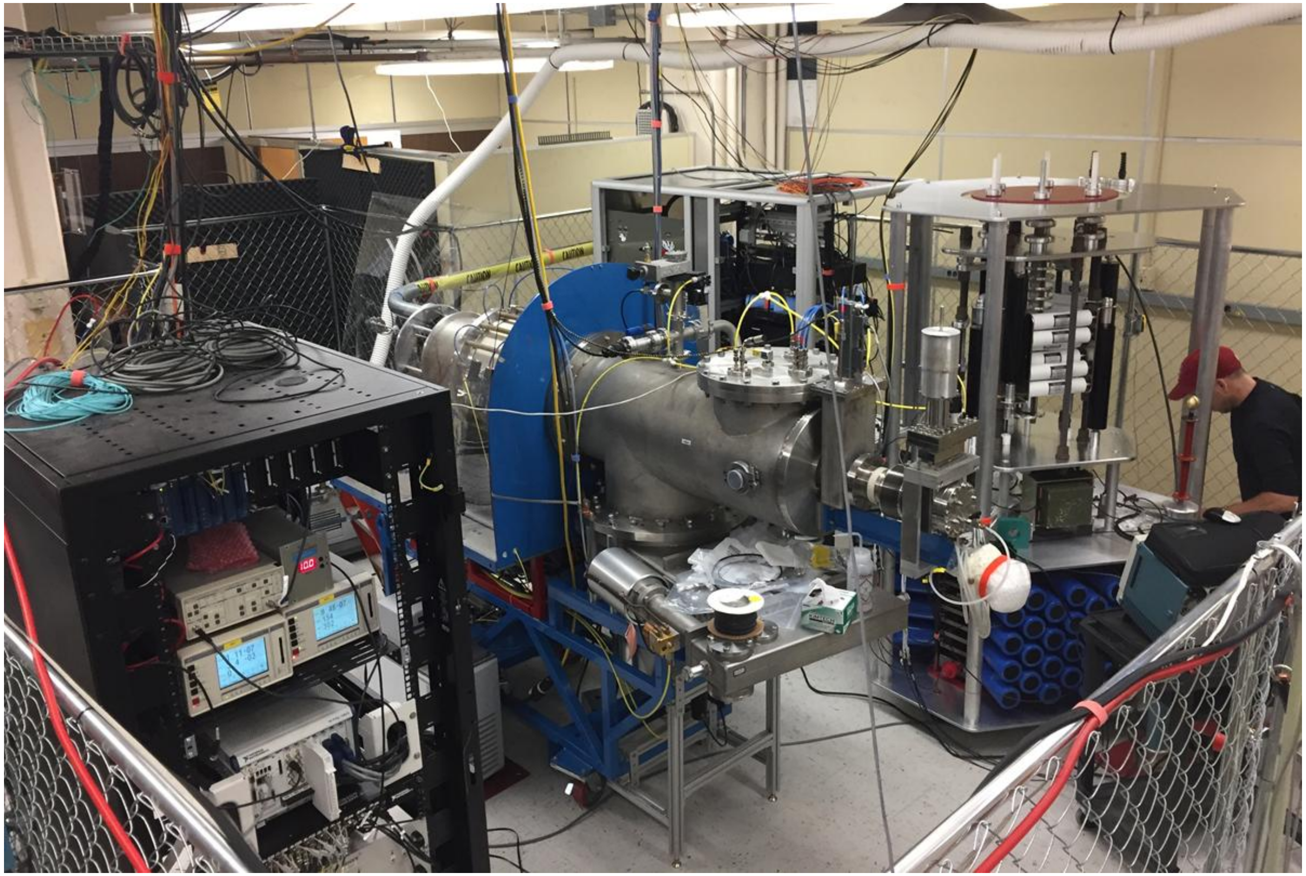
- Low ripple beam power supply
  - A novel three-phase resonant power supply
    - Well defined frequency components

- A novel high-speed, high-throughput spectrometer measures local $\tilde{E}$ up to 250 kHz
  - $U \cong 0.1\ cm^2$-ster
  - Spectral resolution $\cong 0.25$ Å
  - See poster by M.G. Burke

Diagnostic Beam

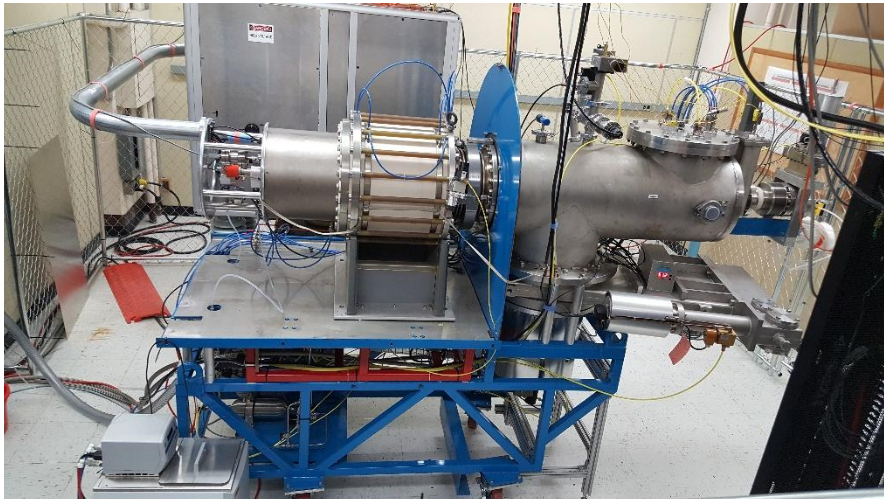
High Performance Beam Eases Field Fluctuation Measurements

- Beam produced by Culham for PPPL meets beam requirements
- Initial deployment will be on Pegasus



Diagnostic Requires High Energy, Low Divergence Beam

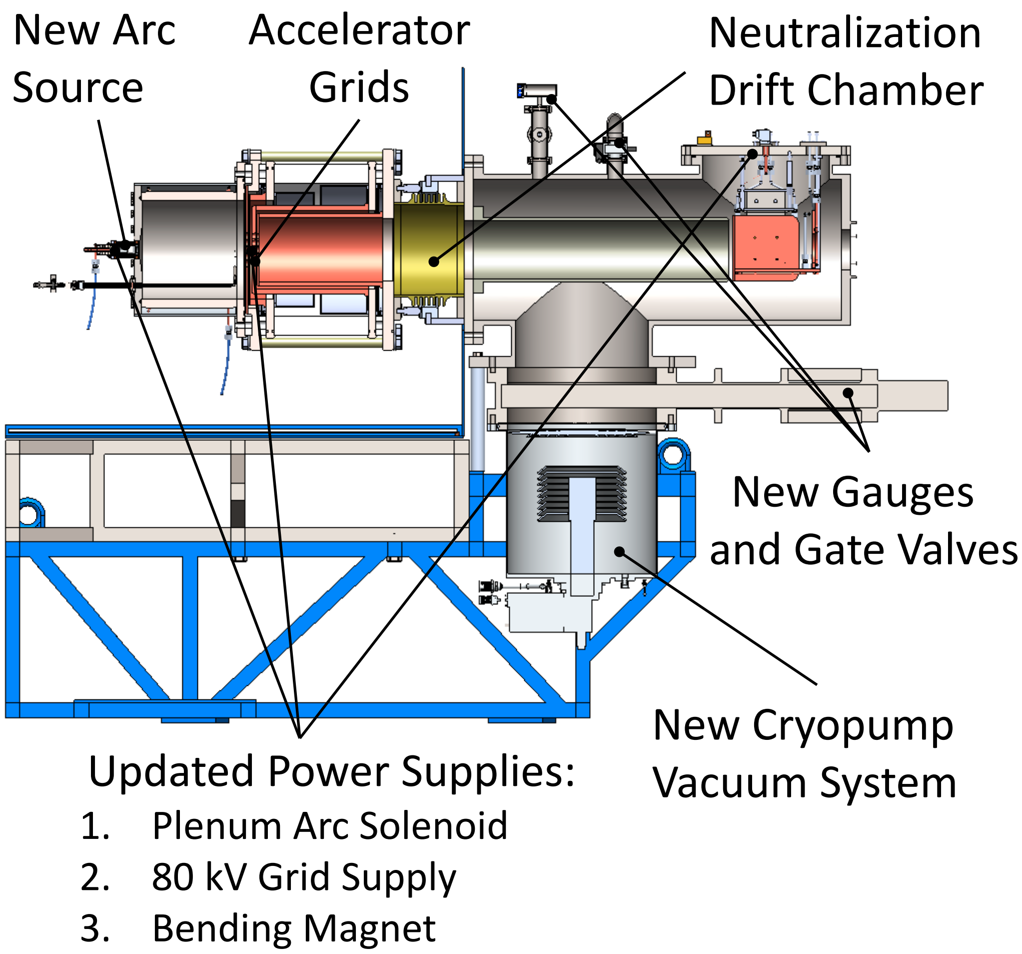
- Using DNB on loan from PPPL
  - H^0
  - Extracted Ion Current: 2-3 A
  - Full-energy J at focus: 3-6 mA/cm^2
  - Diameter ~ 9cm
  - Pulse Length ~ 100ms
- Favorable features
  - Low divergence: ≤ 0.47°
    - Mitigates divergence line broadening
  - High E_b ~ 60 – 80 keV
    - Maximizes MSE broadening
  - 90-95% ionization at full beam energy
    - New plasma arc source
    - Optimize signal at full energy component



J.R. Coupland et al, *Rev. of Sci. Instrum.* **61**, 472 (1990)
I.L.S. Gray et al, *IEEE* **1**, 149 (1989)

DNB Significantly Refurbished

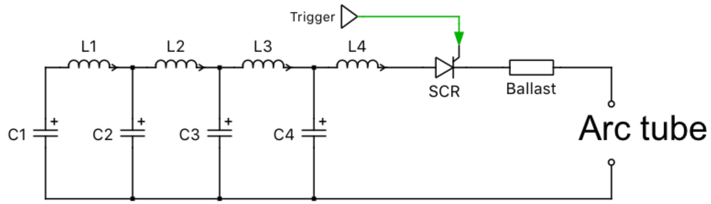
- New Active Arc Source
  - High full energy species fraction
- Vacuum System
  - All new seals and pump
- New Power Systems
  - Low ripple, 80kV power supply
  - Arc source power supply
- New Control Systems
  - NI FPGA and DAQ controlled with LabView



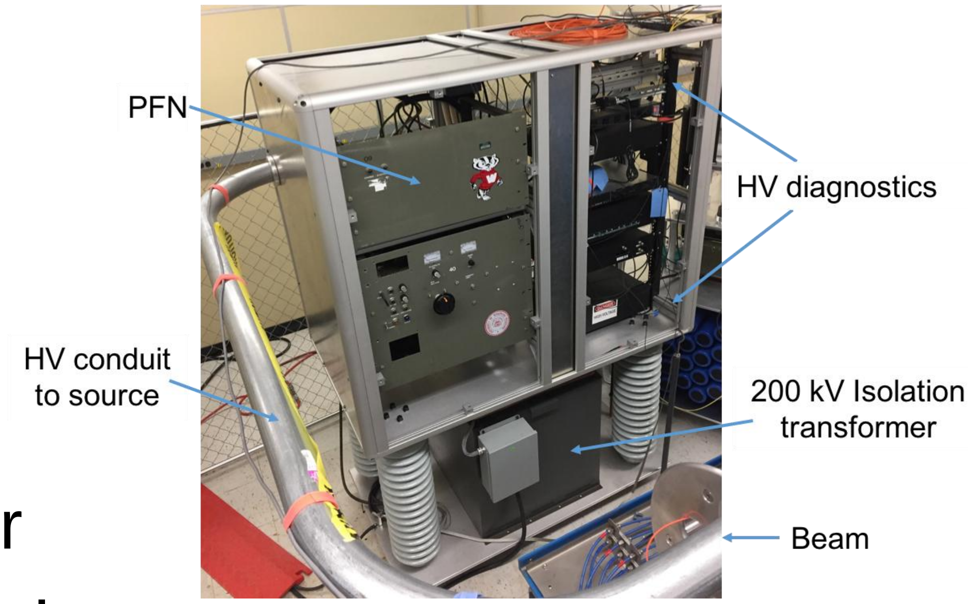
High Voltage Diagnostic Rack Commissioned

- Arc power supply
  - Pulse Forming Network (PFN)
- Sparker circuit
  - Tungsten electrode initiates breakdown at 2.5 kV
- Guide Field Power supply
- Gas valve power supplies
- HV diagnostics
  - Applied arc voltage and current
  - Langmuir probe measurements
- 200 kV Isolation transformer
- High voltage tests successful
  - 100 kV standoff

Arc PFN Circuit:



Arc PFN & High voltage Isolation Rack

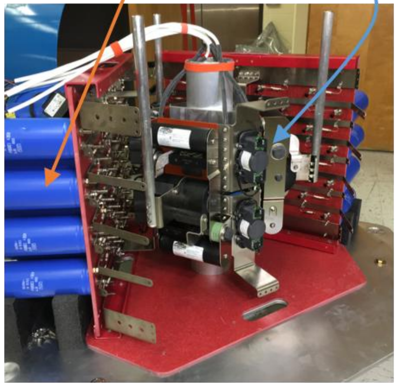


Novel Power Supply

80kV / 400kW Resonant Converter Implemented with IGBT Switches

- 35 kHz Base Switching Frequency
- 3 single phase transformers
- Fast Rise/Fall time (< 200usec)
- Low filter energy (1J)
- Low voltage ripple (±0.00025%)
- Low energy per cycle (2J)
- Low primary stored energy (120kJ)
- Gain is load dependent
- Excellent fault behavior
- FPGA Control
  - 40 MHz Base Frequency
  - Digital Control

3-phase resonant bridge & stored energy

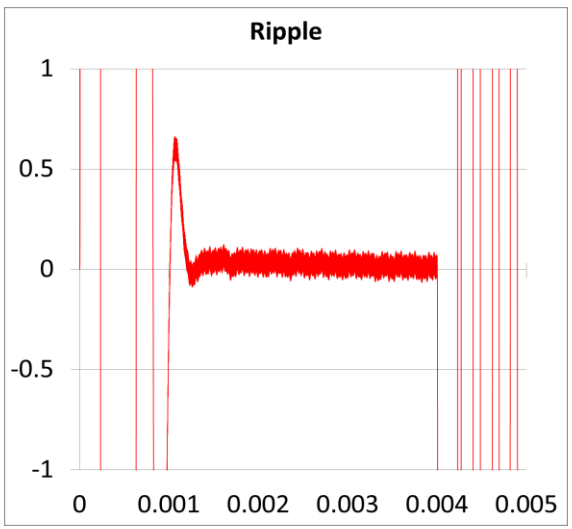


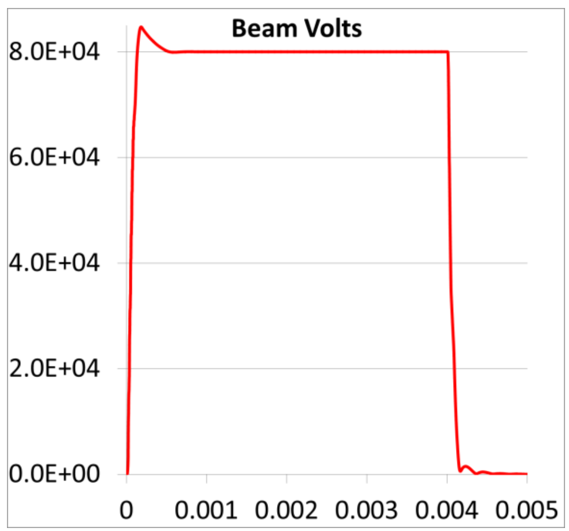
Assembled HV Power Supply

Low Ripple, 80keV High Voltage Power Supply Designed and Fabricated

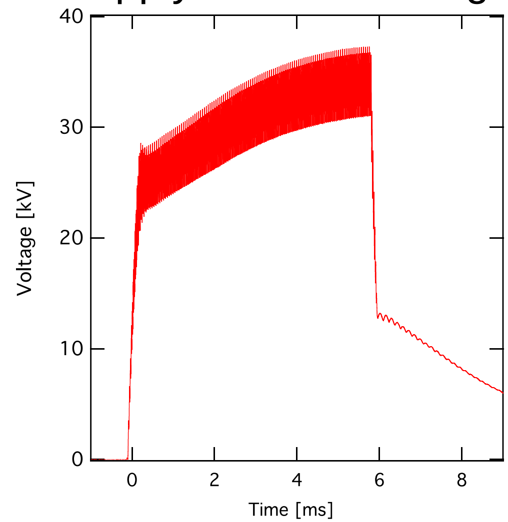
- New power system required for diagnostic development
- High energy, flat voltage power supply
- Resonant converter topology for low voltage ripple

Simulated Performance with PLECS





Initial Certification of Power Supply without filtering



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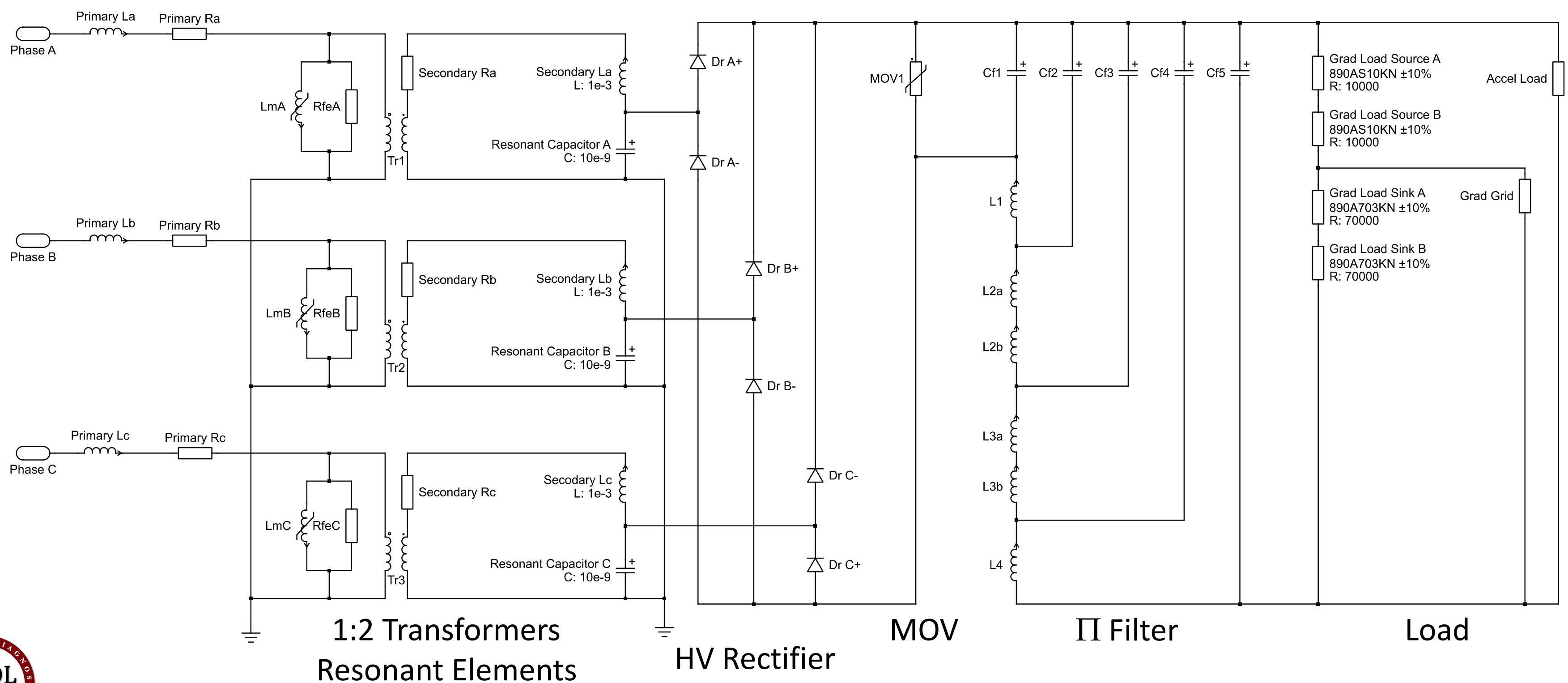
> 20x gain achievable in HV Section

- Resonant Converter High Voltage Section
  - 80kV at 5A with 1J of 80kV filter energy
  - Transformer leakage inductance (La/Lb/Lc) utilized for resonant circuit
  - Very fast ramp times < 200us to 80kV and no crowbar
  - Very low ripple ±0.2V or ±0.00025%



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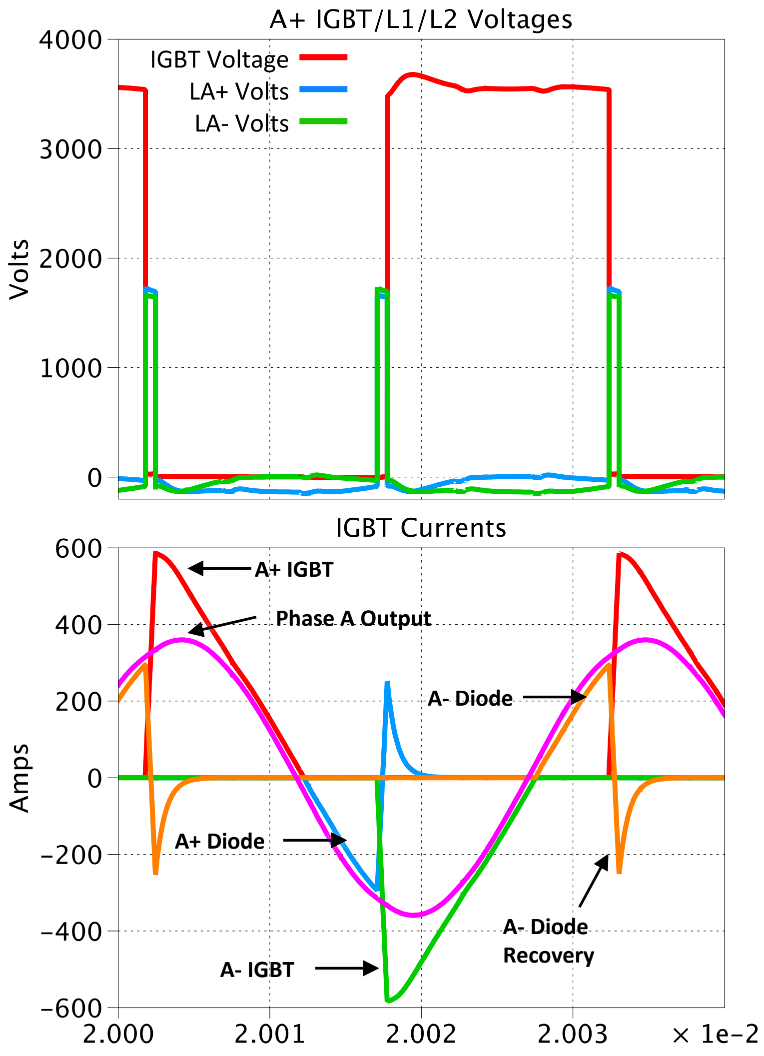
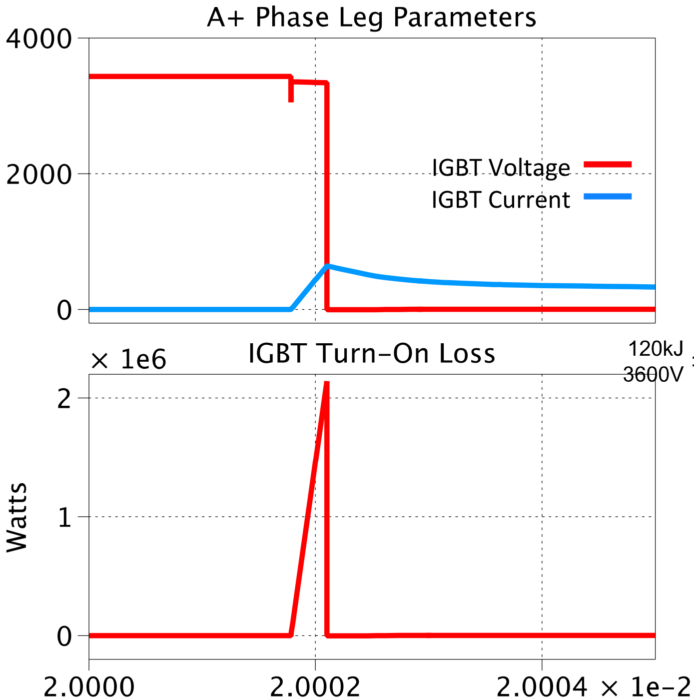
Zero Voltage/Zero Current Switching Provides Minimal System Losses

- What is ZVC/ZCS
  - Passive commutation
  - IGBT turn-off losses are zero
  - Diode commutation at zero voltage (with snubber)
  - Lower system losses allows higher frequency operation
  - Higher frequency allows for higher power density (lower energy per cycle)
  - What's not to like?
    - Lowest loss only at resonance
    - Turn-On losses can still be significant
    - Impedance imbalances cause trouble
    - Control difficult because of dynamic gain

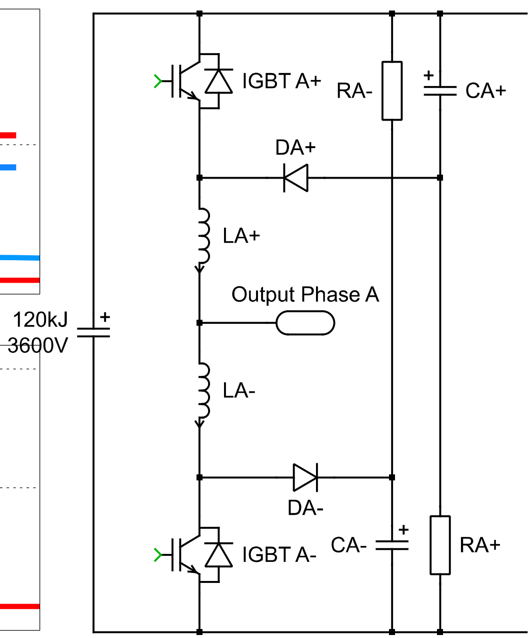


Multi-pole Bridge Snubber Minimizes Switching Losses

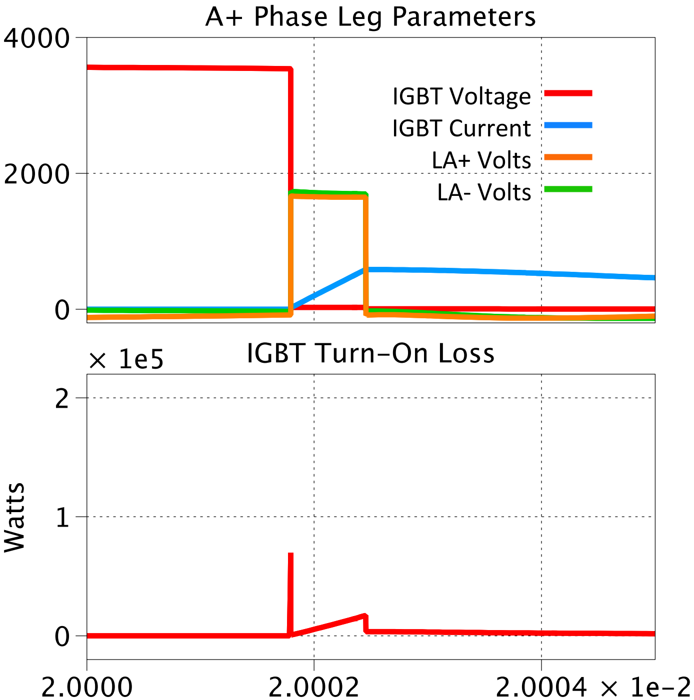
- Clamps device for ~ 400nsec
- Allows turn-on of IGBT at zero voltage
- Loss reduction enables access to higher switching frequencies



No Snubber



Phase Leg (1 of 3)



With Snubber

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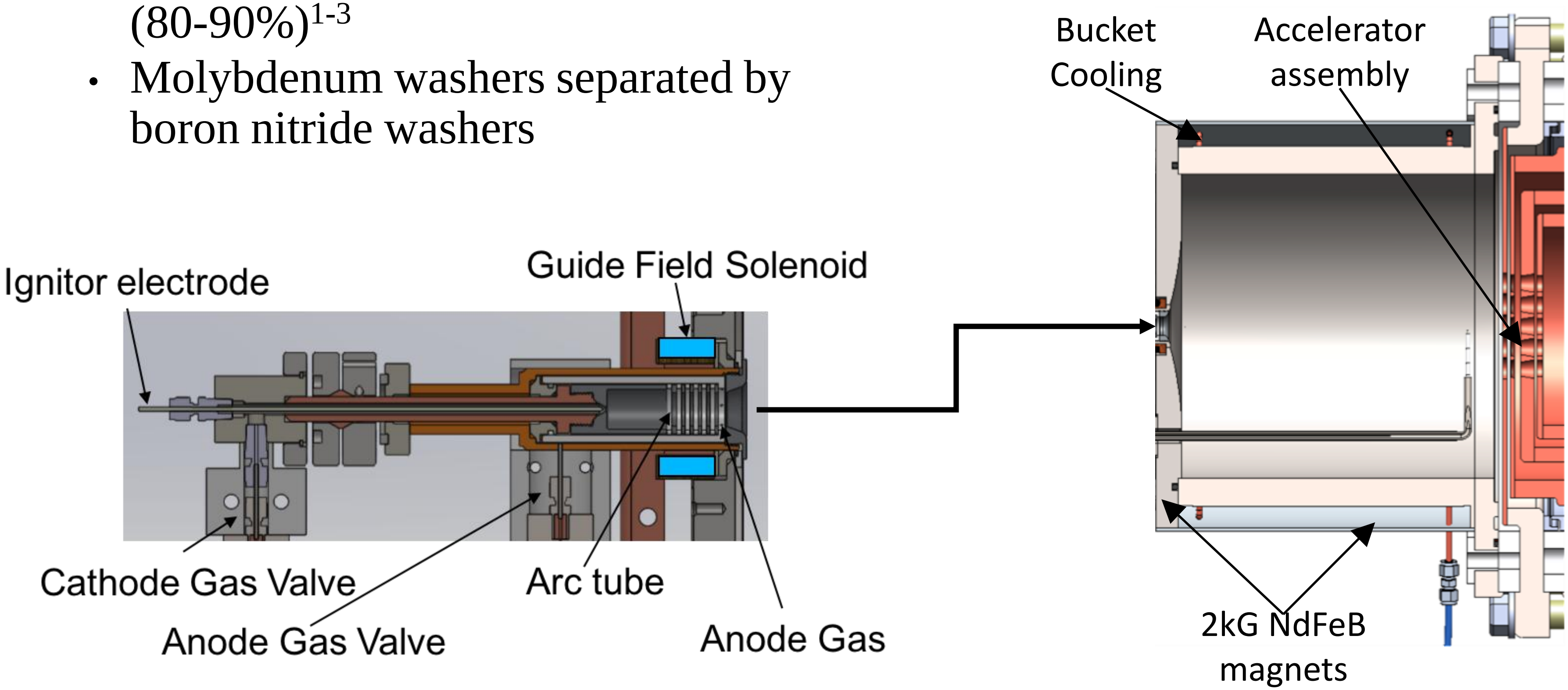
Source Plasma Characterization

New High Density Arc Plasma Deployed to Provide Optimal Species Mix

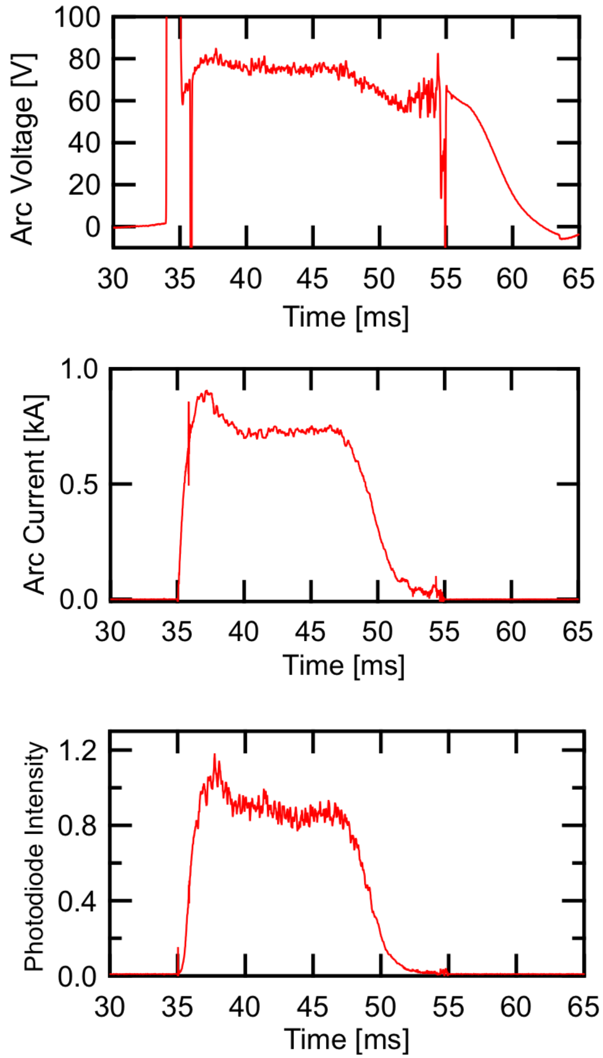
- Hot filament source replaced with washer stack arc source
  - Provides high ionization fraction (80-90%)[1-3]
  - Molybdenum washers separated by boron nitride washers
- Plasma expands into a bucket with multipole cusp fields



[1] Deichuli et al, *Rev. Sci. Instrum.* **79**, 02C106 (2008)
[2] Abdrashitov, et al, *Rev. Sci. Instrum.* **72**, 594 (2001)
[3] Korepanov, et al, *Rev. Sci. Instrum.* 75, 1829 (2004)

Shot Parameters for Typical Arc Discharge

- Arc Discharge
  - Breakdown initiated by 2.5 kV sparker
  - PFN discharges into the arc
  - ~10 ms pulse length
    - Potential to extend with new power supply
- Shot Parameters:
  - 80 V of arc voltage
  - ~800 A arc current
  - Plasma light intensity mimics arc current



Ion Source Needs to Match Grid Perveance Requirements

- Beam Extraction Requirements
  - Extracted Current at 80kV: 2.5 A
  - Grid Extraction area: 19 x 1.52 cm^2

    $\rightarrow j_{\mathrm{ext}} \approx 87$ mA/cm^2

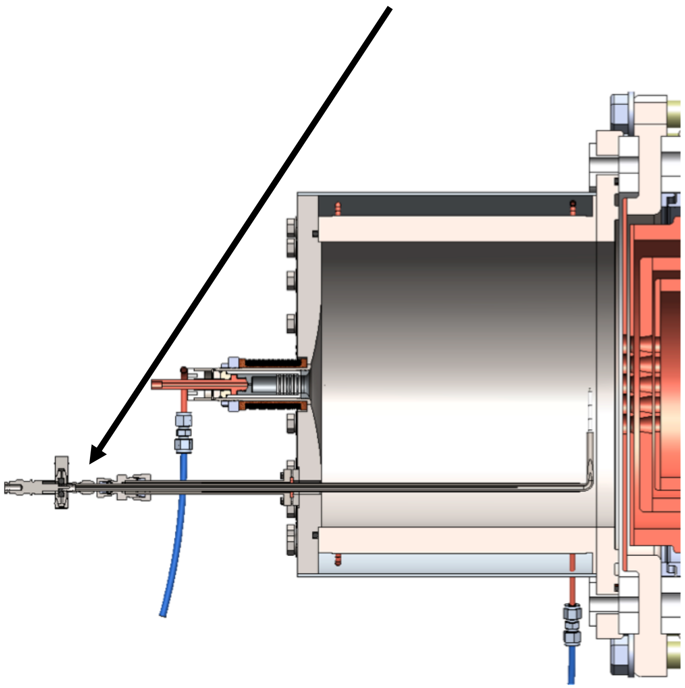
- Near the grids: $j_{\mathrm{plasma}} = n_e e v_B \rightarrow j_{\mathrm{ext}} = I_{\mathrm{ext}}/A_{\mathrm{ext}}$
  - Where $v_B = \sqrt{T_e / m_i}$

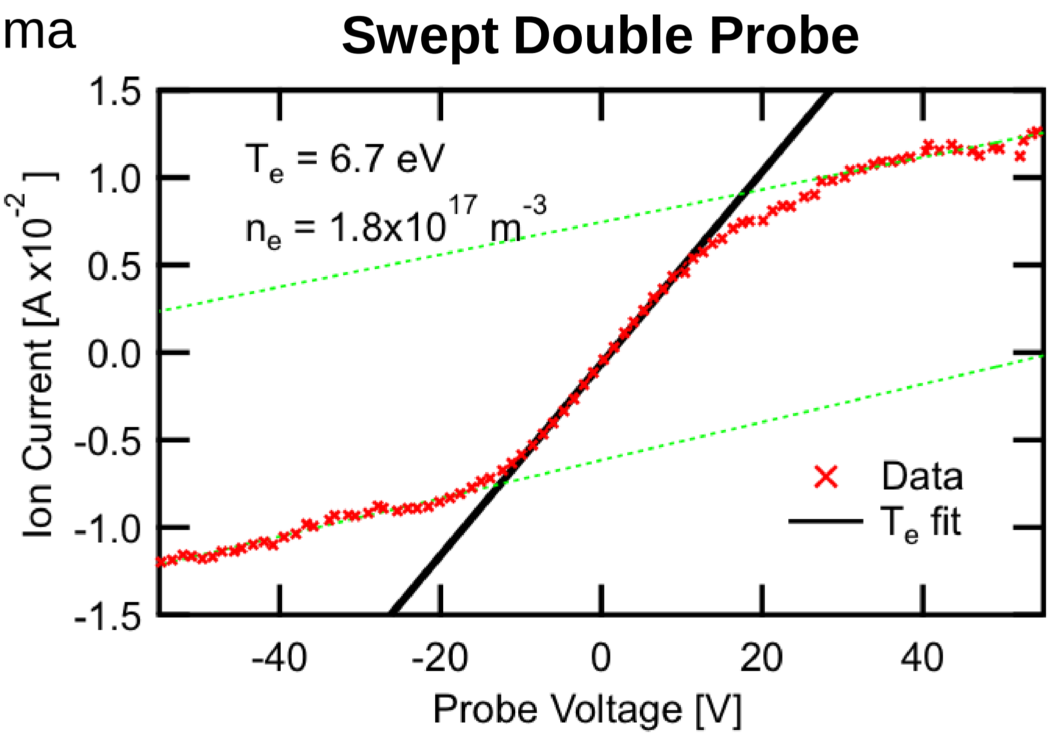
- Source Requirements to meet j_{ext} at the grids:
  - $T_e \gtrsim 4$ eV
  - $n_e \sim 2 \times 10^{17}$ m^{-3}

* N. Hershkowitz. "How Langmuir Probes Work." Plasma Diagnostics, 113-183. Academic Press, 1989.

Desired Operational Space Achieved

- A retractable and rotatable probe was designed for complete characterization of source plasma





*Johnson and Malter, Phys. Rev.. **80**, 58 (1950)*

Arc Performance Optimization

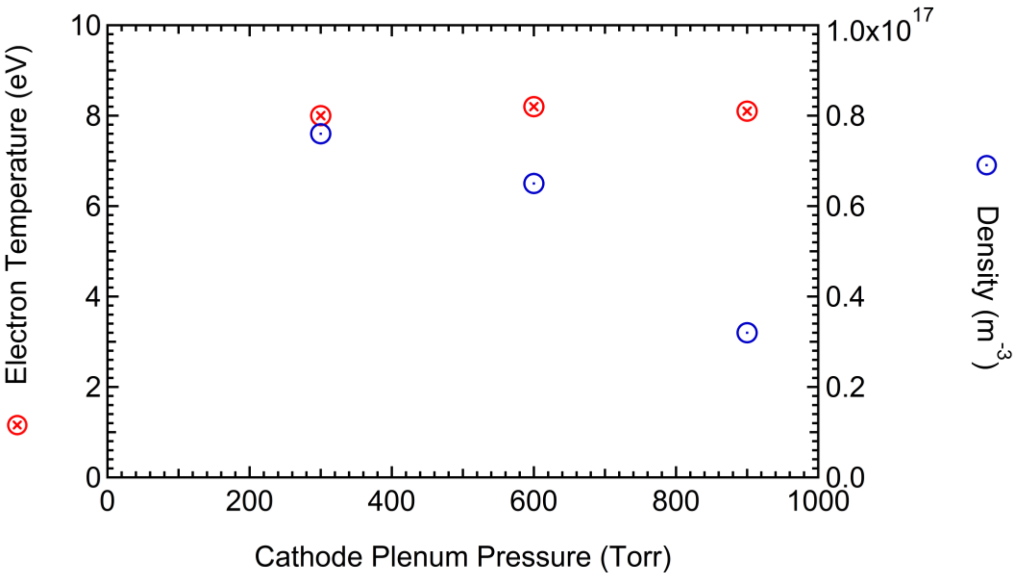
Stable Arc Discharge Required

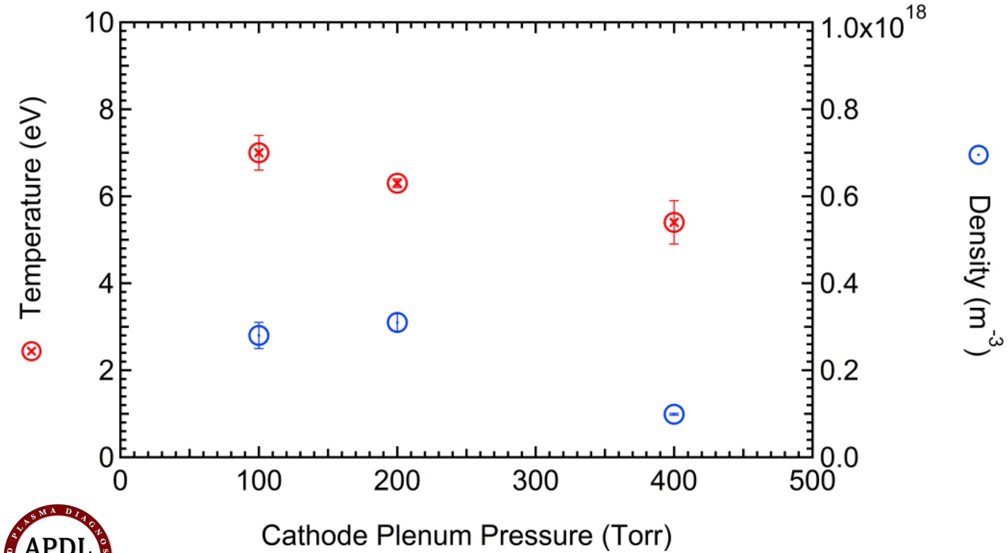
- $\widetilde{n_e}$ at the extraction plane may impact beam divergence

- Demonstrated ability to vary density
  - Match beam perveance

- Recent work has improved arc discharge stability
  - Additional hydrogen fueling at anode
  - Magnetic guide field strength

Cathode Gas Flow Rate Varies Plasma Source Parameters





Decreased cathode fueling increases plasma density while maintaining T_e

APDL

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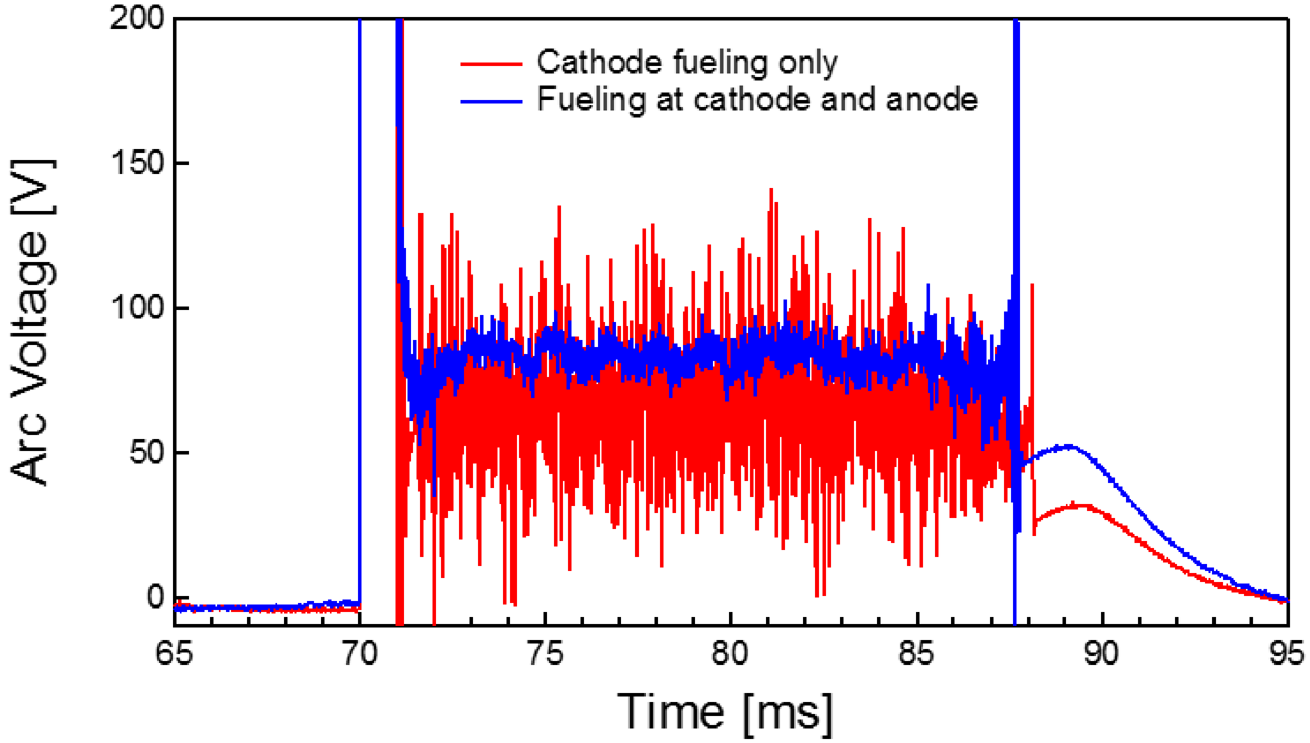
Anode Fueling Integral to Arc Stability

Voltage fluctuations in the arc reduced through gas feedthrough at the anode

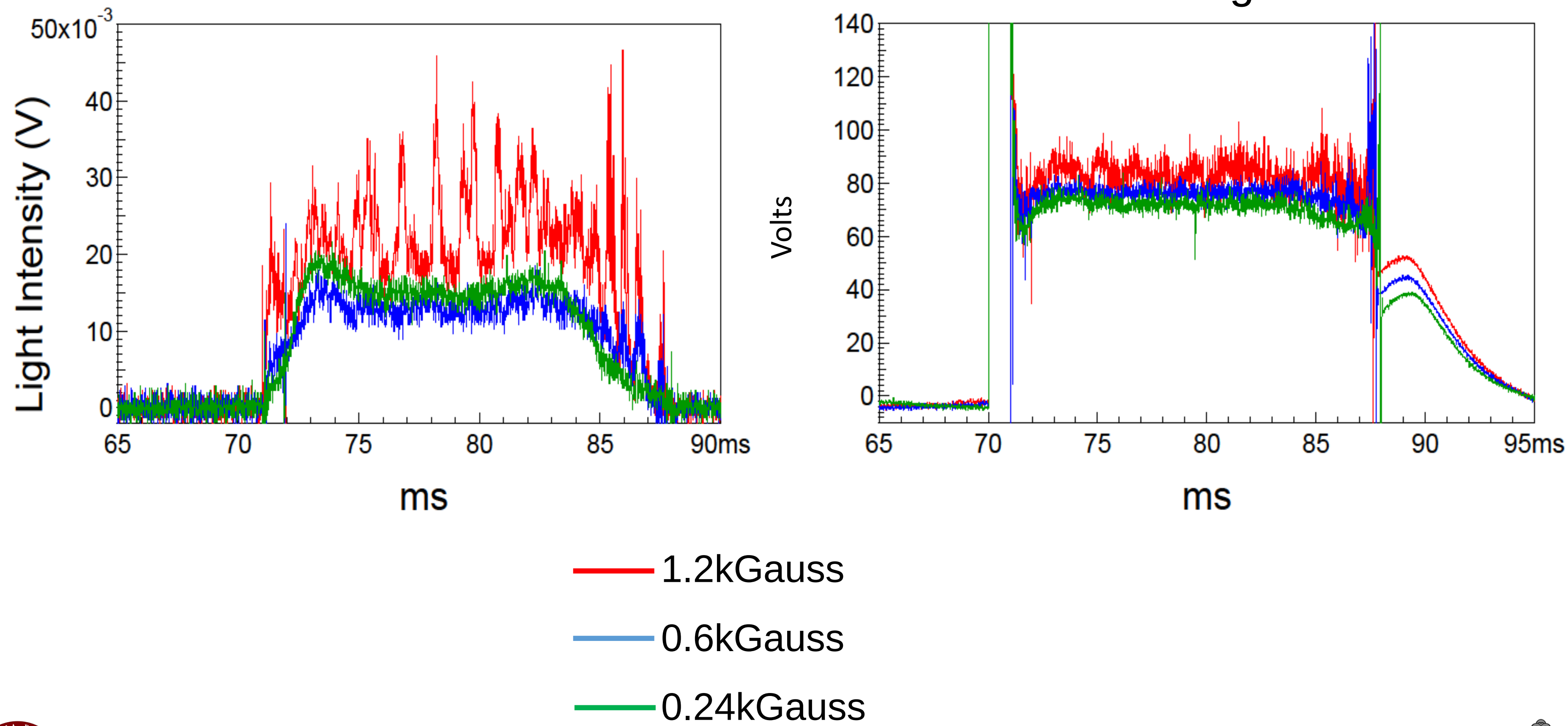


Arc Stability Modified by Strong Guide Field

- High guide field induces arc instability

Photodiode Detector

Arc Voltage



Validation of Electric Field Fluctuation Diagnostic Enabled by Optimized DNB

- A low-divergence, high energy diagnostic neutral beam (from PPPL) completely rebuilt
- New washer-stabilized plasma arc source gives required n_e at T_e~7 eV
- Source plasma stabilized by anode fueling
- A novel three phase resonant converter power supply has been designed and built for low ripple, constant voltage output
- Commissioning of HV PS to be followed by initial DNB operation

This research is supported by DOE Grant Number DE-FG02-89ER53296

Future Works

- Arc power and diagnostics rack tested successfully to 100kV
- High Voltage Power Supply testing in progress
  - Initial tests have achieved 36 kV
  - Test to 80 kV
  - Add filter network to reduce ripple
- Conditioning of accelerator grids to commence in short order
- Integration of new 80kV power supply after grid conditioning
- After conditioning, ion species mix and beam divergence measurements will determine arc discharge parameters