Instrumentation Development for a Novel Local Electric Field Fluctuation Diagnostic

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Advanced Plasma Diagnostics Lab
APDL

Introduction

Measurements of Electric Field Fluctuations are Desired for Validating Tokamak Core Turbulence and Transport Models

- $\tilde{E} = k_\perp \tilde{\phi}$ measurements are underdiagnosed in tokamaks and integral to turbulent plasma physics
  - Provides:
    - $\tilde{v}_r$: cross-field transport
    - $\tilde{v}_\theta$: transport barrier
- A novel high-speed, high-throughput spectrometer is being developed to measure local $\tilde{E}$ up to 500 kHz
  - U ≅ 0.1 cm^2-ster
  - Spectral resolution ≅ 0.5 Å
- A low-divergence, 80keV diagnostic neutral beam from PPPL is being refurbished to support the $\tilde{E}$ diagnostic
- A magnetized test chamber with $B_T > 0.5$ T and tokamak-like density planned for diagnostic testing

$\tilde{E}$ Levels Projected by Tokamak Fluctuation Scaling

- Estimate of drift wave fluctuations can be obtained from scaling relations of density and electrostatic potential fluctuations[1]:

$$\frac{\tilde{n}}{n} \sim \frac{e\tilde{\phi}}{T_e}$$

- Turbulence peaks at perpendicular wavenumbers of order unity inverse ion gyroradius at the local T_e

$$k_\perp \rho_s \sim \alpha$$

  - Various tokamaks have found α ranging from 0.1 – 1

- Taking $\tilde{E} \sim k_\perp \tilde{\phi}$:

$$\tilde{E} \approx \frac{\tilde{n}}{n} \frac{T_e}{e\rho_s} \alpha \approx \frac{T_e}{ea}$$

  - Where a is the plasma radius

[1] Wesson, J. Tokamaks. Oxford, UK: Clarendon Press, 2004.

Measuring $\tilde{E}$ is Challenging, but Possible Against Background Motional Stark Effect

Experiment	T_e(eV)	B(T)	a (m)	$\tilde{E}/E_{MSE}$
Pegasus - 1	100	0.15	0.3	$1x10^{-3}$
Pegasus - 2	300	0.3	0.35	$1.4x10^{-3}$
NSTX-U	~2000	1	0.6	$\sim 2.6x10^{-3}$
DIII-D	2000	2	0.7	$0.7x10^{-3}$

- Across devices $\tilde{E}/E_{MSE}$ ~ 0.1%

Two-point correlation can extract $\tilde{E}$, similar to present Turbulence Diagnostics

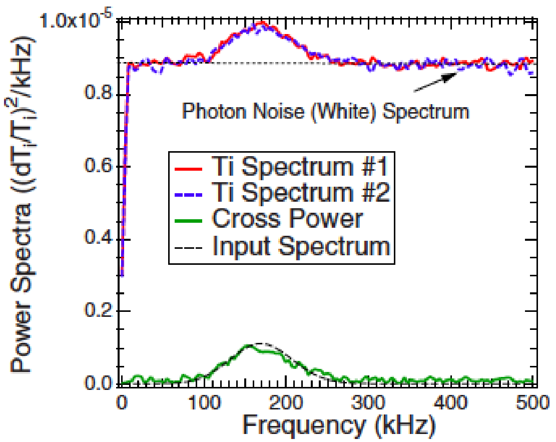
- $\tilde{T}_i$ and $\tilde{n}$ are known to be small:
  - $\tilde{T}_i / T_i \sim 10^{-2}$ (HF/UF-CHERS)[1]
  - $\tilde{n}/n \sim 10^{-2}$ (BES)[2]
- Anticipated $\tilde{E}/E_{MSE} \approx 10^{-3}$
  - Comparable to photon noise floor ~ 10^{-3}
- To extract E,
  - cross correlate with BES signal
    - Similar to UF-CHERS

$$\langle \tilde{E}_T \tilde{n}_T \rangle = \langle (\tilde{E}_p + \tilde{E}_\gamma)(\tilde{n}_p + \tilde{n}_\gamma) \rangle$$

$$\approx \langle E_p n_{p.}$$

  - Two-point cross-correlation of overlapping E signal

$$\langle E_{T_1} E_{T_2}, \approx \langle E_{p_1} E_{p_2},$$



[1] H.T. Evensen et al., Rev. Sci. Instrum. **66**, 845 (1995)
[2] R.J. Fonck et al., Phys. Rev. Letts **70**, 3736 (1993)
[3] G.R. McKee et al., Rev. Sci. Instrum. **79**, 10F528 (2008)

Measurement Technique

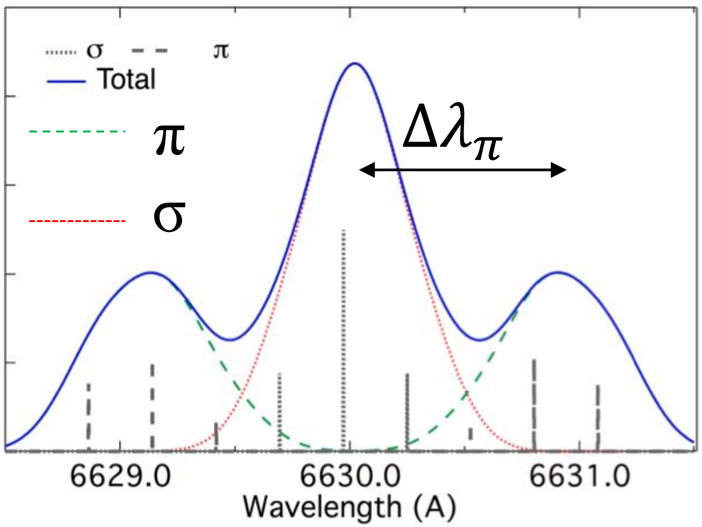
Local $\tilde{E}$ Results in Fluctuations in the Stark Manifold

- 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:
  - $\frac{\pi}{\sigma}$ line ratio
  - $\Delta\lambda_\pi$: separation of π lines



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).

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Analysis of Stark Multiplet Allows Measurement of $\tilde{\vec{E}}_{plasma}(t)$

- Midplane beam, sightline: linewidth changes

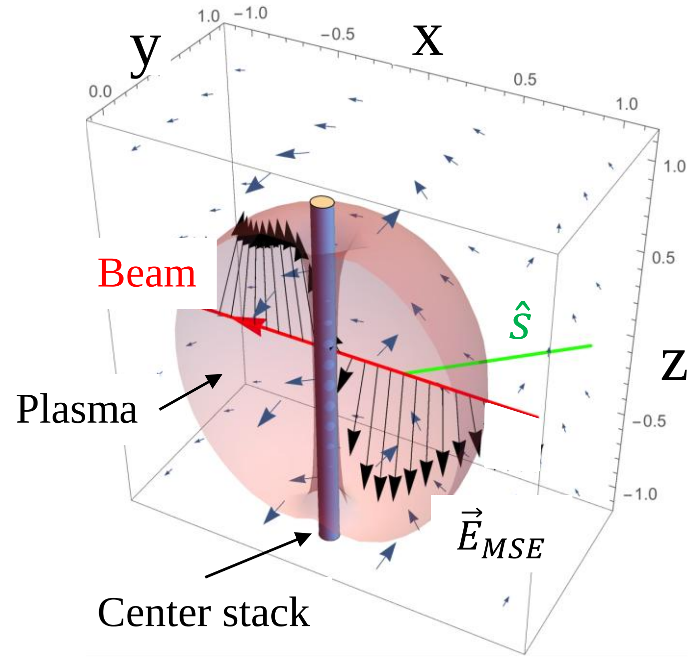
$$\widetilde{\Delta\lambda}_{Stark} \propto \tilde{E}_z$$

- Midplane beam, off-midplane sightline: Intensity ratio change

$$R = \frac{\sum I_\pi}{\sum I_\sigma} \propto \tilde{E}_R F(\tilde{n})$$

- First emphasis on line width measurement: insensitive to density fluctuations

Example: ST Geometry



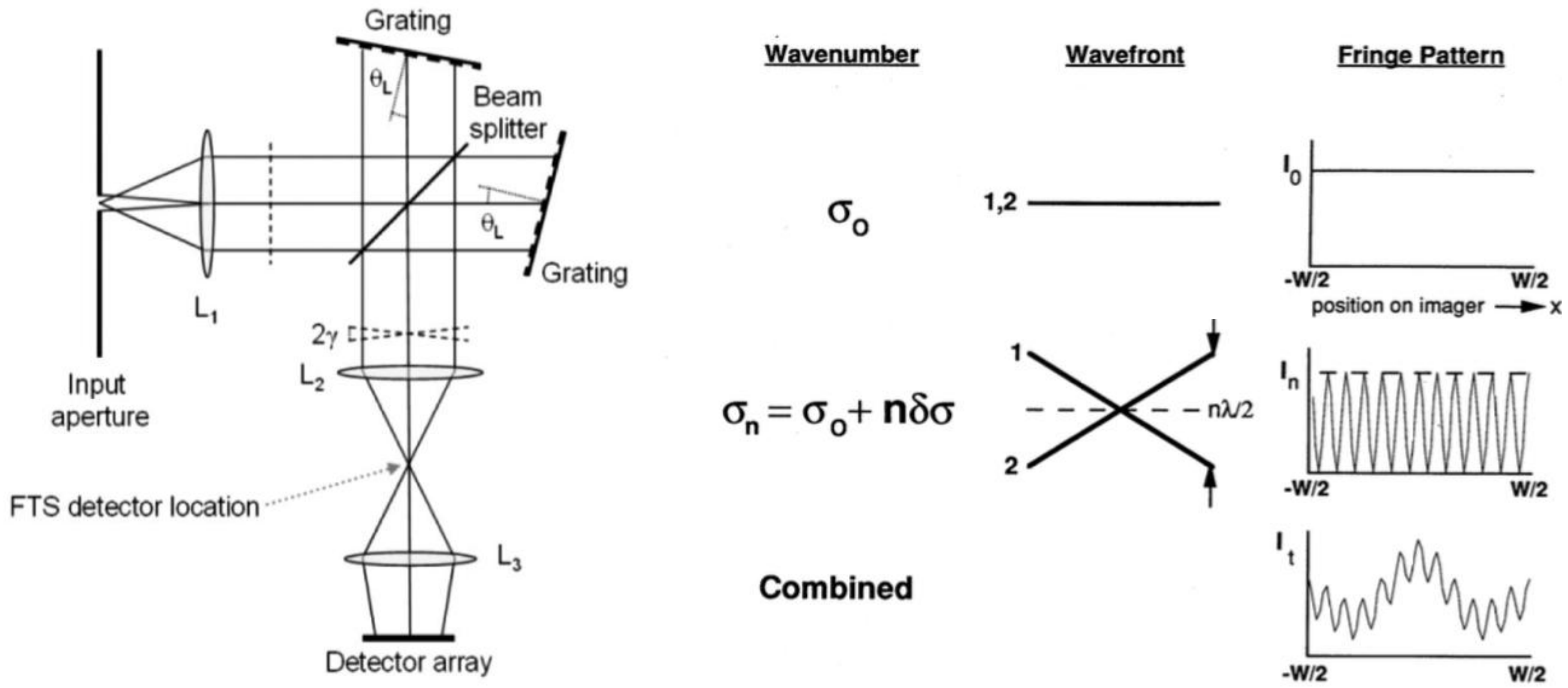
Spectrometer Requirements are Formidable for $\Delta\lambda_{\pi}$ Measurement

- Resolution:
  - Need ~ 8 spectral elements to resolve 2 gaussion π components
  - $\Delta\lambda_{\pi}$ ~ 4 Å giving a spectral resolution of 0.5 Å
    - $R = \frac{\lambda}{\delta\lambda} \sim 1.3\text{x}10^4$
- Etendue (optical throughput):
  - Matched to port availability and collection optics
  - U = 0.1 cm^2 – ster
  - 2 spatial points
- Compatible Detector System:
  - ~250kHz time response
- Mitigation of sightline-DNB broadening, low beam divergence, very good beam stability, high species fraction

H. Evensen, PhD Thesis, UW-Madison (1996)

Spatial Heterodyne Spectroscopy + New High-Speed 2D Detectors → Powerful Spectrometer Concept

- Self scanned, 2 beam interferometer



$$I(x) = \int_0^{\sigma} B(\sigma)(1 + \cos[2\pi(4|\sigma - \sigma_0|x \tan\theta_L)])d\sigma$$

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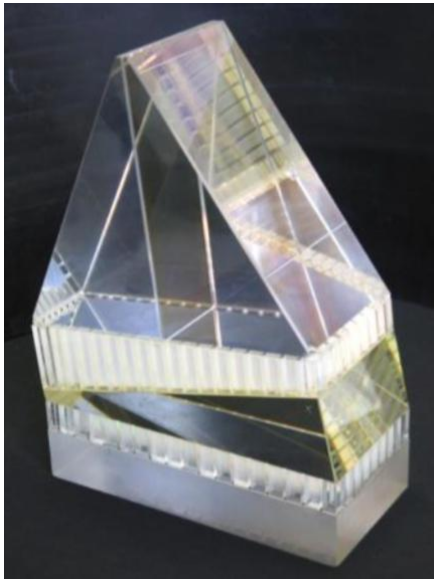
Spatial Heterodyne Spectroscopy Achieves High Resolution and Throughput

- SHS theoretical resolving power:
  - $R = \sigma/\delta\sigma \approx 2W/d$
  - For $\tilde{E}$: Need R~1x10^4
  - For W=50 mm only requires d=1/100 lines/mm
  - Resolution readily achievable with simple coarse gratings, compact size
- SHS throughput comparable to field widened Fourier Transform spectrometer
  - For $\tilde{E}$: need throughput of 0.05-0.1 cm^2str
  - $U = 2\pi\epsilon A/R$ = eta*0.015 ; eta ~1(no field widening) – 100 (field widening)
    - Required throughput readily achievable in SHS

DASH Interferometer



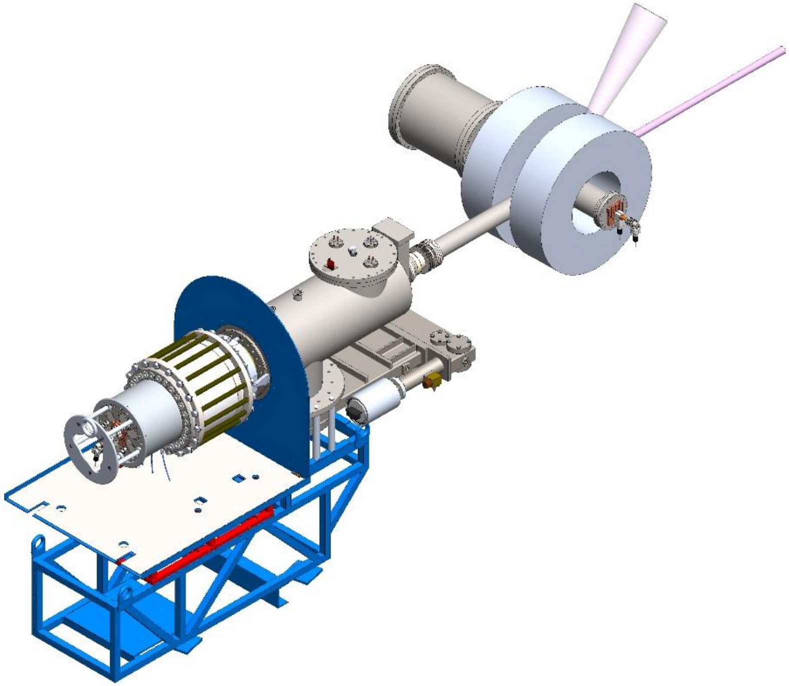
R≈5x10^4, U≈0.15 cm^2str

J. M. Harlander, C. R. Englert, D. D. Babcock, and F. L. Roesler, Opt. Express, OE, **18**, 2010.

Diagnostic Beam and Target Chamber

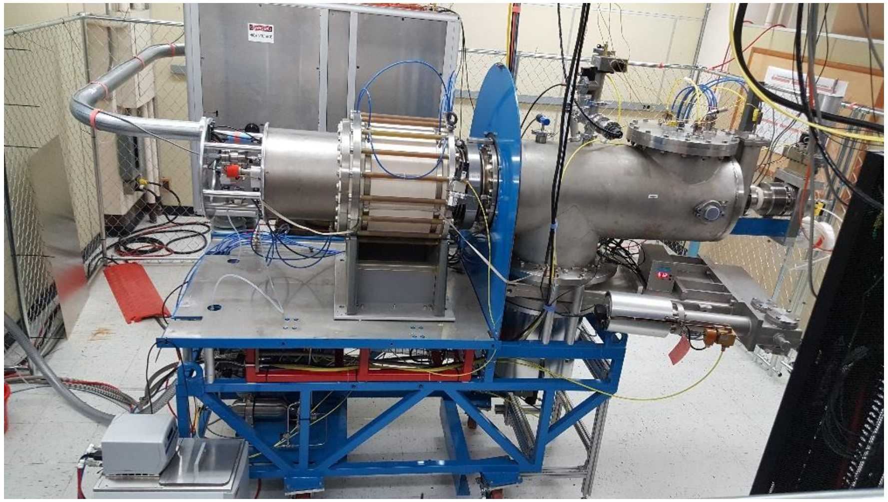
High Performance Beam Eases $\tilde{E}$ Measurement

- Beam produced by Culham for PPPL meets beam requirements necessary for E-field fluctuation measurements
  - Low divergence
  - High energy
  - High species fraction (new active arc source)
- Initial deployment will be on a magnetized target chamber



Diagnostic Requires High Energy, Low Divergence Beam

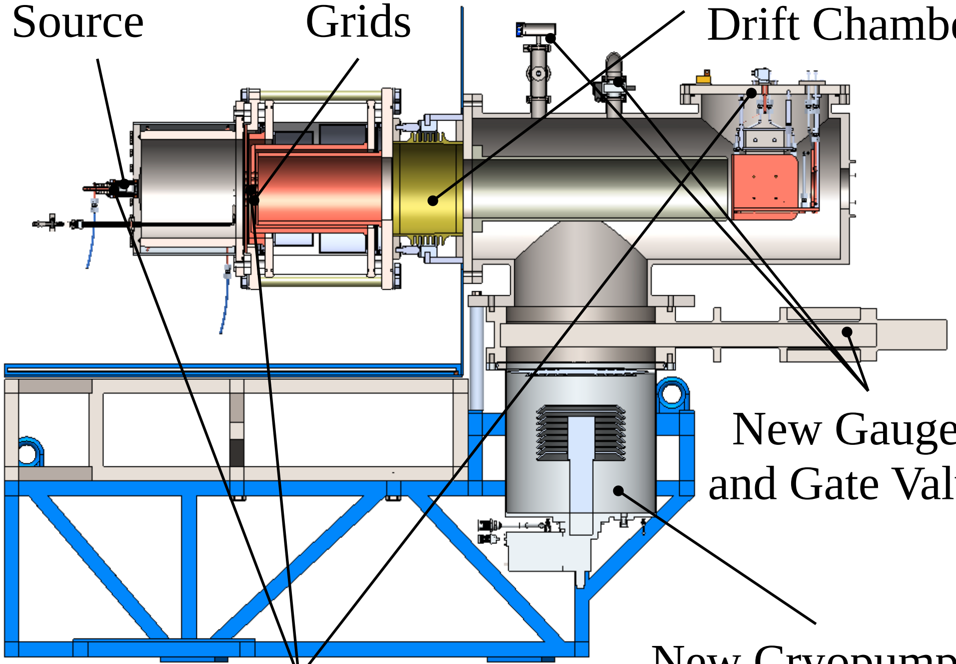
- Using DNB on loan from PPPL
  - H^0
  - Extracted Ion Current: 2-3 A
  - Full-energy J at focus: 3-6 mA/cm^2
  - Diameter ~ 9cm
  - Pulse Length ~ 100ms
- Favorable features
  - Low divergence: $\leq 0.47°$
    - Mitigates divergence line broadening
  - High E_b ~ 60 – 80 keV
    - Maximizes MSE broadening
  - 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)*

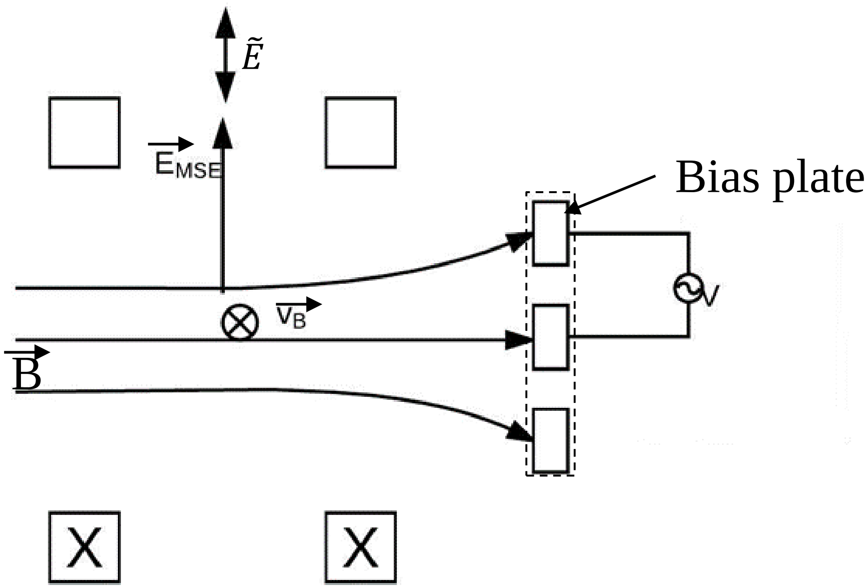
DNB Significantly Refurbished for $\tilde{E}$ Diagnostic Development

- 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

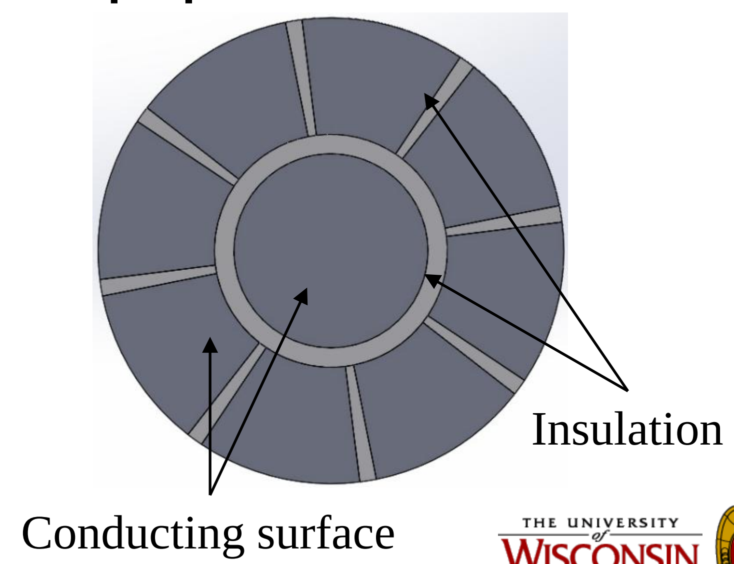


Target Chamber Designed to Induce Local $\tilde{E}$

- Bias plate at target chamber end used to induce fluctuations
  - Potential oscillations between conducting surfaces induces $\tilde{E}||E_{MSE}$
  - Oscillating the right/left sides induces $\tilde{E} \perp E_{MSE}$



Segmented plate allows parallel and perpendicular fluctuations



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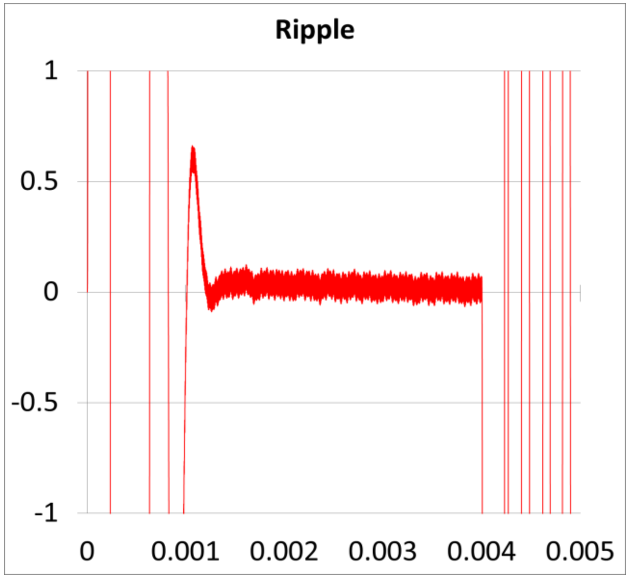
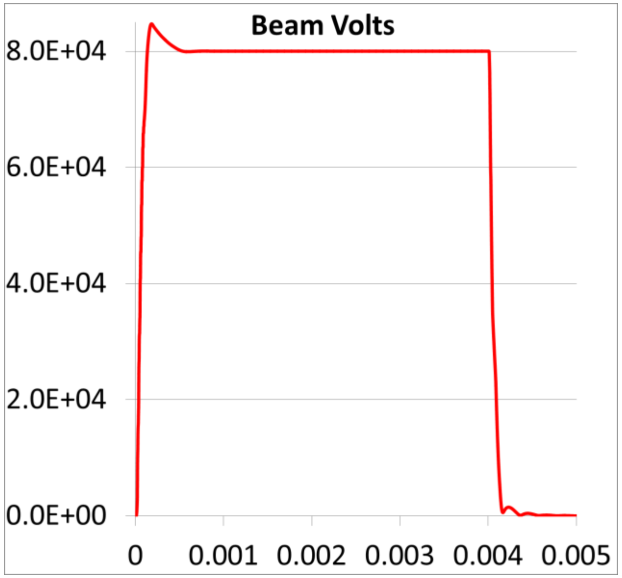
Novel Power Supply

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



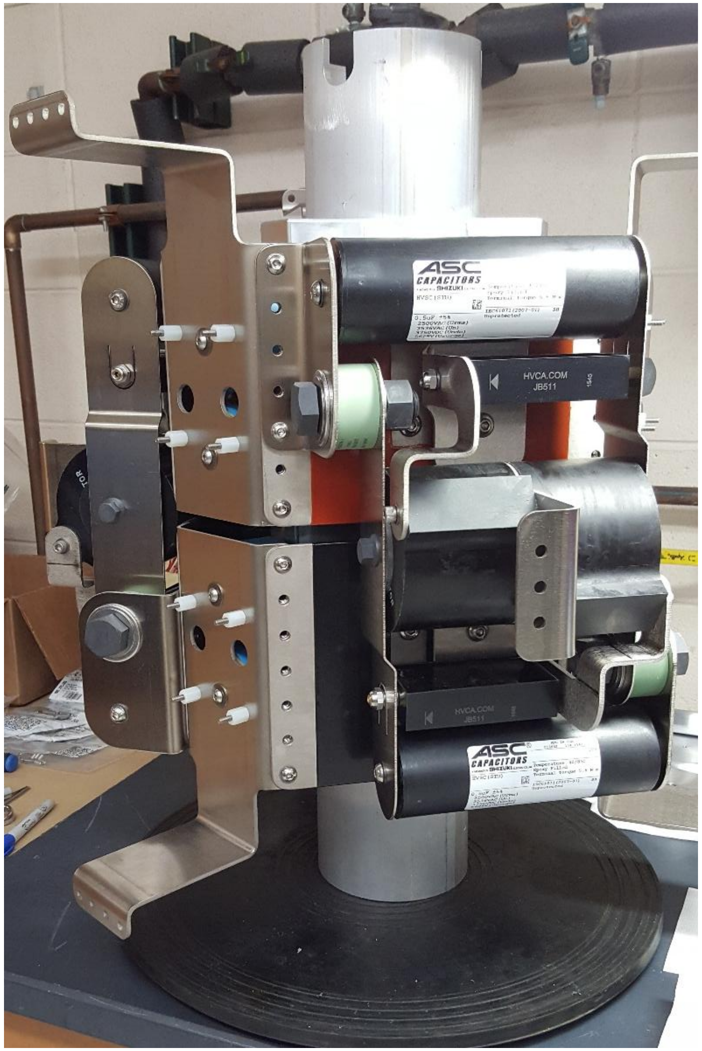


Assembled Power Supply

80kV / 400kW Resonant Converter Implemented with IGBT Switches

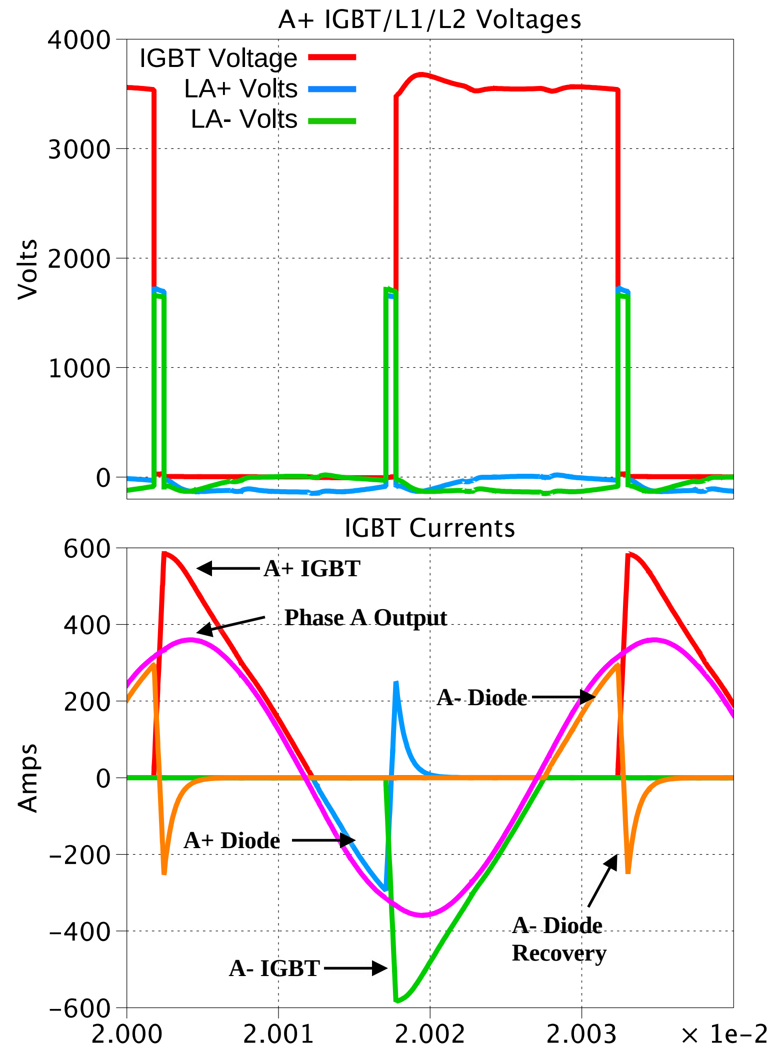
- Resonant Converter
  - 35 kHz Base Switching Frequency
  - 3 single phase transformers
  - Fast Rise/Fall time (< 200usec)
  - Low filter energy (1J)
  - Low voltage ripple (±0.00025%)
  - Low energy per cycle (2J)
  - Low primary stored energy (120kJ)
  - Gain is load dependent
  - Excellent fault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

400kW / 3600V 3-Phase Primary Bridge



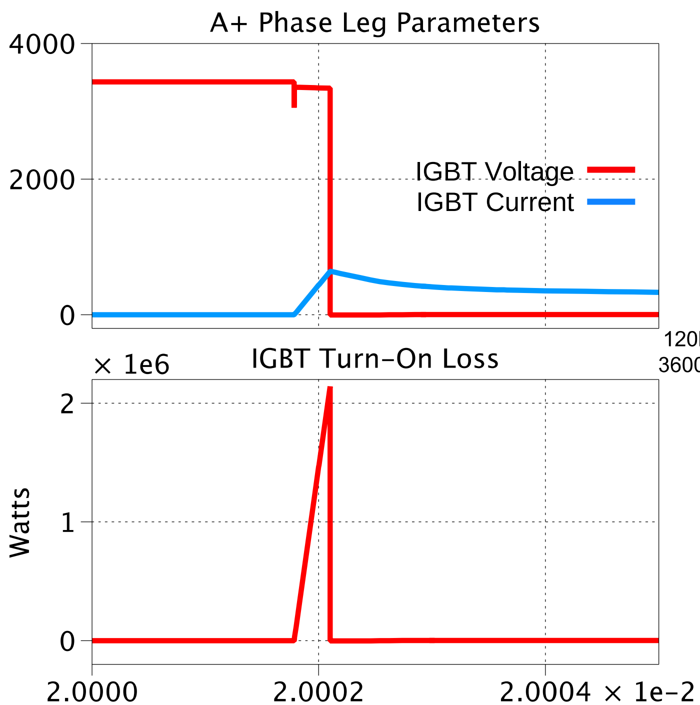
Zero Voltage/Zero Current Switching Provides Minimal System Losses

- 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

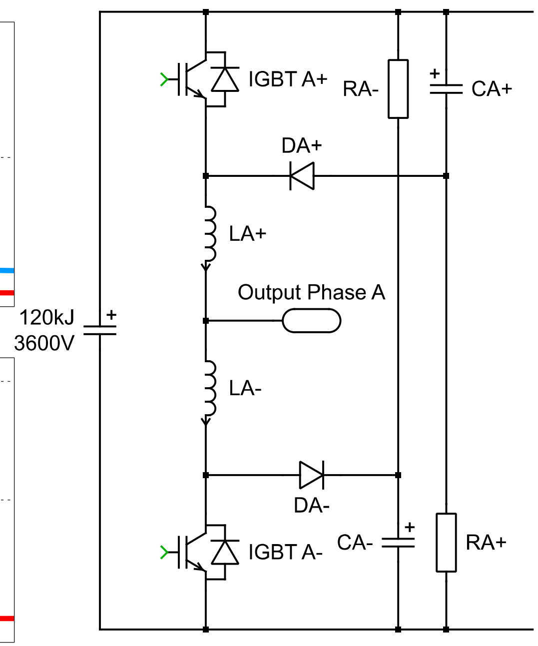


Multi-pole Bridge Snubber Minimizes Switching Losses

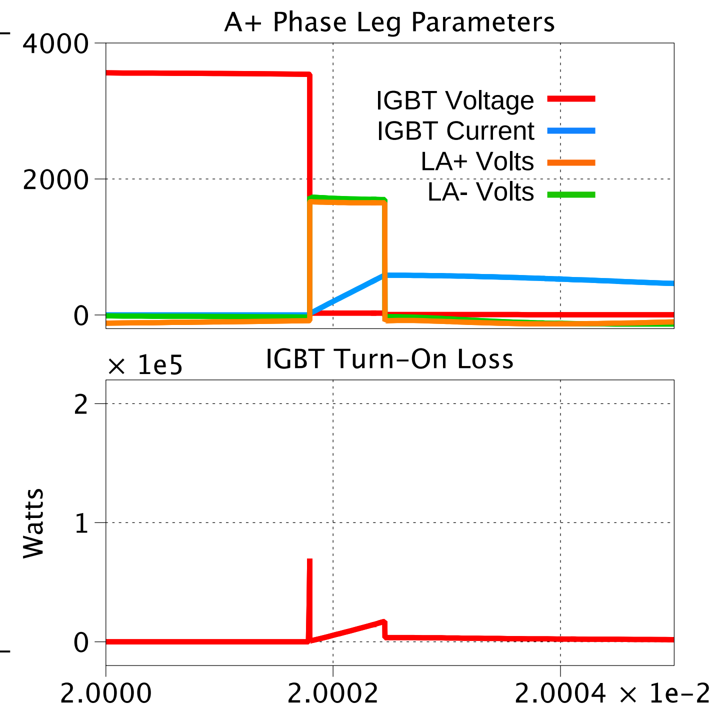
- Clamps device for ~ 400nsec
- Allows turn-on of IGBT at zero voltage
- Loss reduction enables access to higher switching frequencies



No Snubber



Phase Leg (1 of 3)



With Snubber

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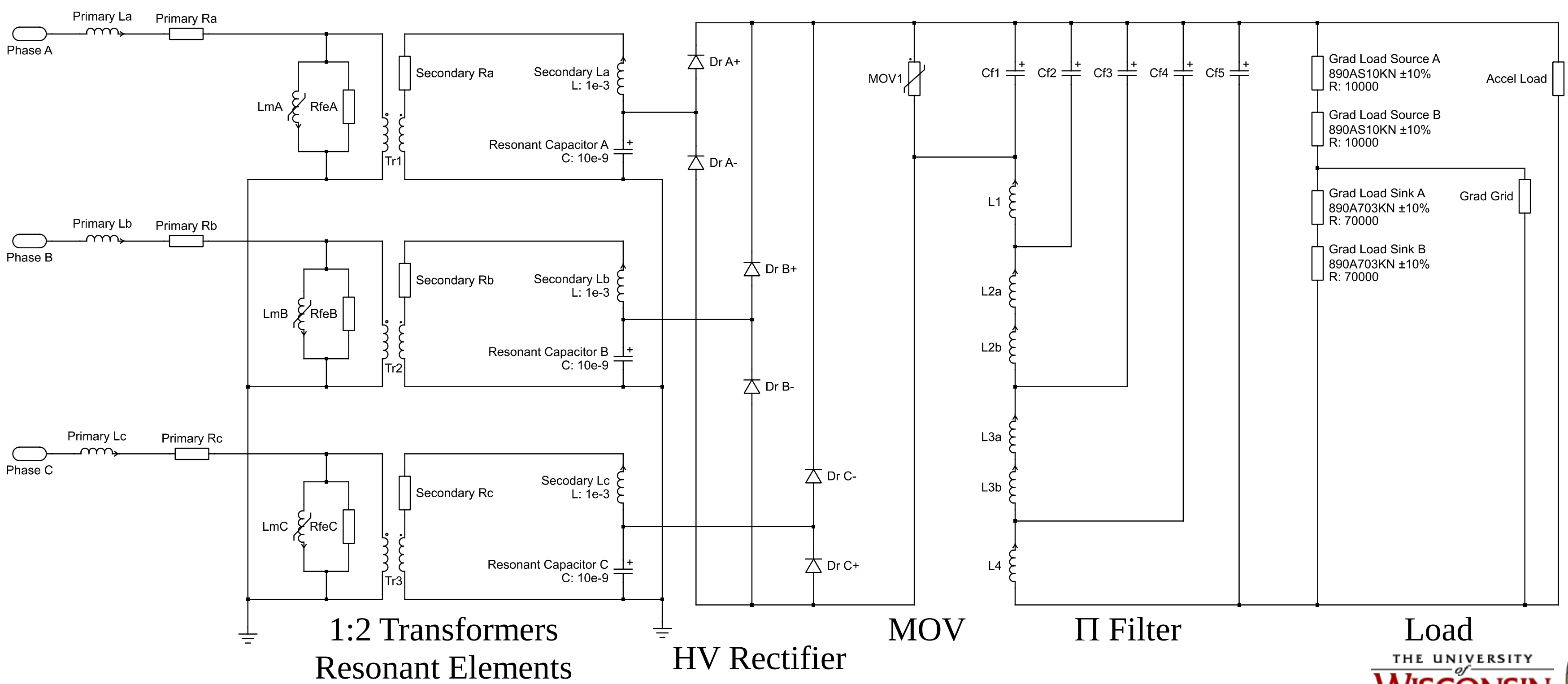
> 20x gain achievable in HV Section

- 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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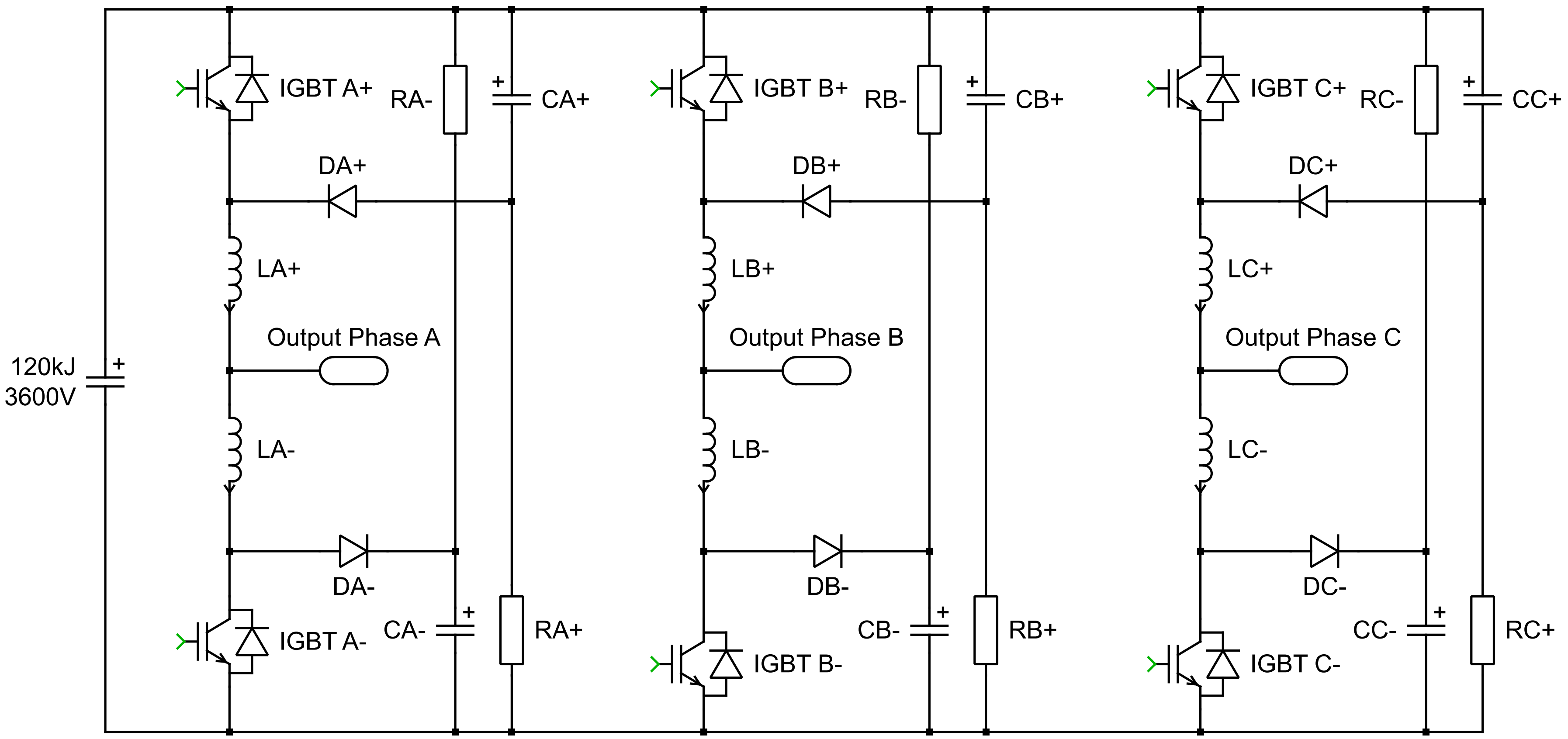
3600V Primary with Multi-Pole Snubber



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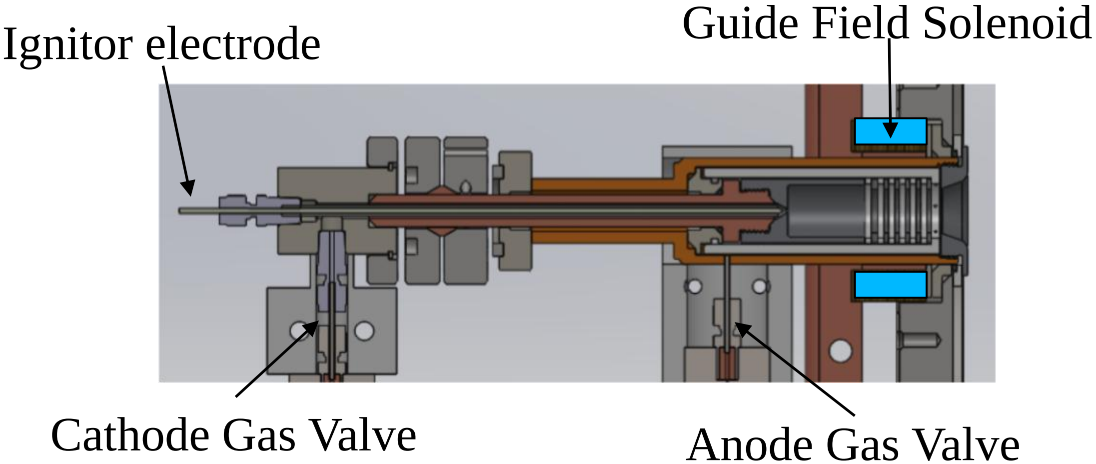
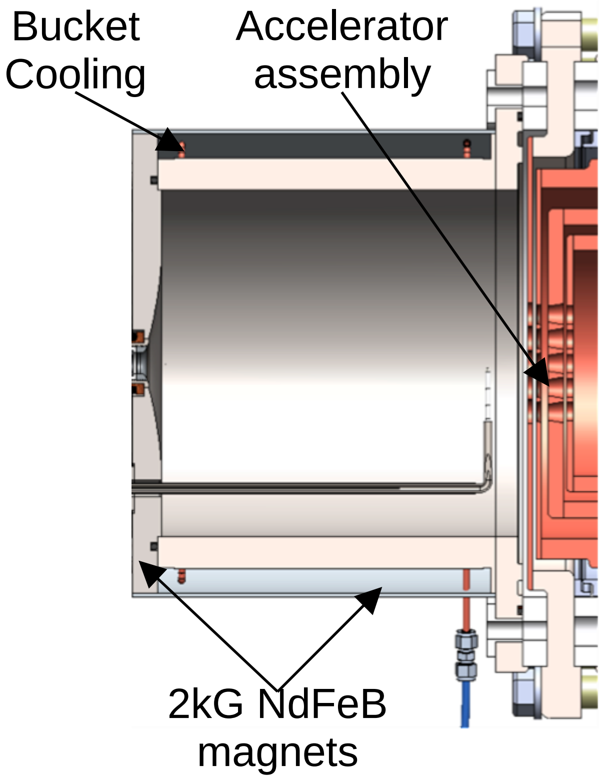
Source Plasma Characterization

New High Density Plasma Arc Source Provides Optimal Species Mix

- Hot filament source replaced with washer stack arc source
  - New arc parameters:
    - $T_e \sim 10$ eV
    - $n_e \sim 10^{22}$ m^{-3}
- Arc plasma provides high ionization fraction
  - 80-90% at full energy achieved with other arc source beams[1-3]



- 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)

Operational Space Mapped to Match Grid Perveance Requirements

- Beam Extraction Requirements
  - Extracted Current: 1-3 A
  - Grid Extraction area: 19 x 1.52 cm^2

$\rightarrow j_{ext} = 35 - 100$ mA/cm^2

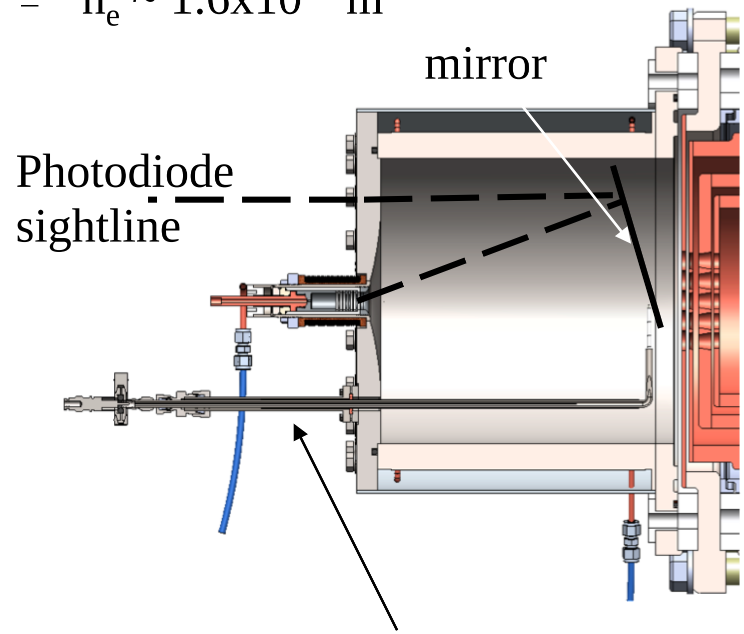
- At the grids:

$$j_{plasma} = n_e e v_B \rightarrow j_{ext} = I_{ext}/A_{ext}$$

$$n_e = \frac{I_e^*}{eA}\sqrt{\frac{2\pi m_e}{T_e}}\ (*) \qquad v_B = \sqrt{T_e / m_i}$$

- Swept Langmuir probe deployed to characterize plasma parameters

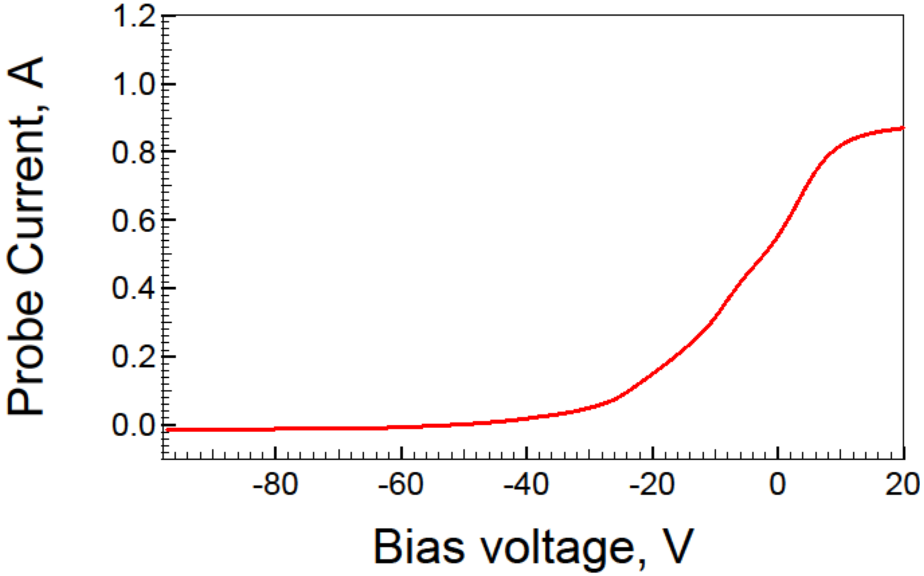
- Source Requirements to meet j_{ext} at the grids:
  - $T_e \sim 15$ eV
  - $n_e \sim 1.6\times10^{17}$ m^{-3}

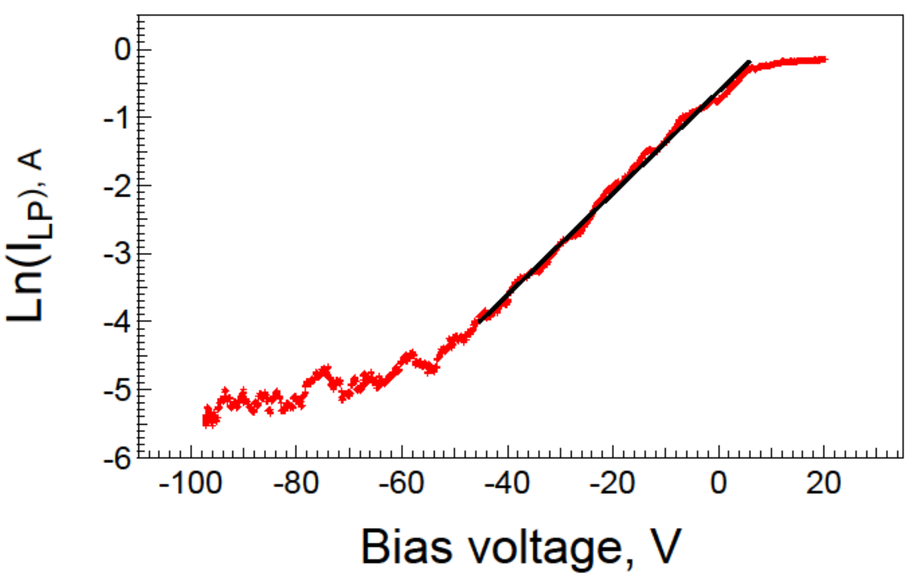


  - Retractable and rotatable probe designed for complete characterization of source plasma

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

Single Swept Langmuir Probe Traces Provide T_e and n_e Information





- $T_e \geq 14$eV allows for greater ionization and high species fraction
- $n_e \approx 6 \times 10^{17}$ m^{-3} densities (above those required) achieved easily
  - $j_{ext} \sim 350$ mA/cm^2, high but can be reduced with a grid if needed

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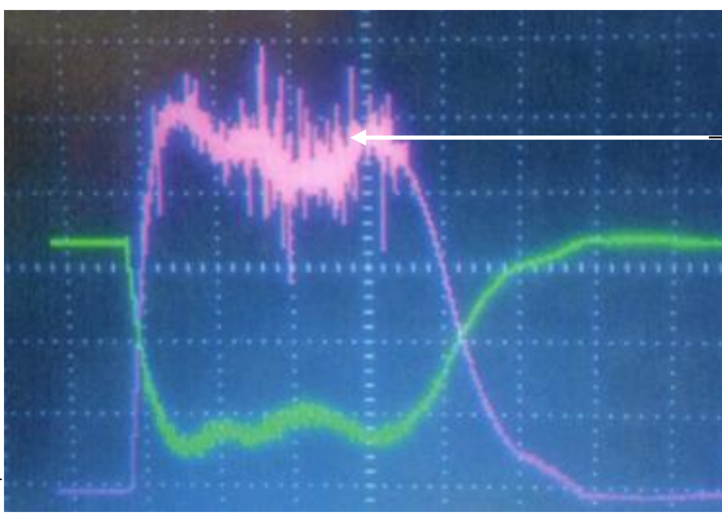
Desired Arc Operation Space Achieved

- Realized Arc Parameters
  - $T_e \sim 15$ eV
  - $n_e \sim 2 \times 10^{17}$ m^{-3}
- Shot Parameters:
  - Potential drop across the arc: 700 V
    - ~1.5kA arc current
  - Cathode plenum flow rate: 300 Torr-L s^{-1}
  - B_{GF}: 0.6kGauss

V_{arc} (pink) and Langmuir Probe I_{sat} (green) in 10ms arc discharge

800V



0V

0   20

ms

0

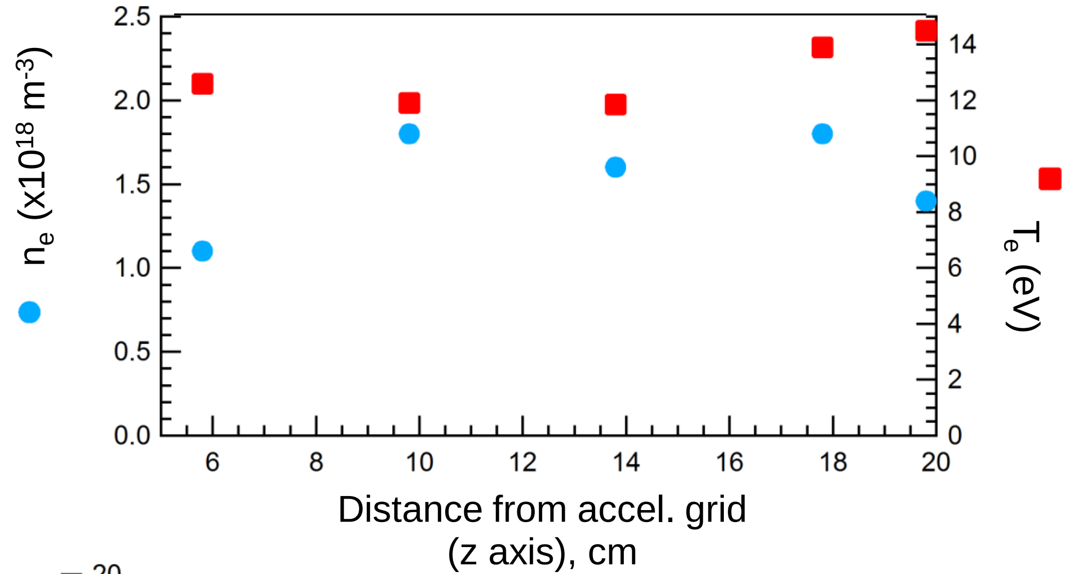
mA

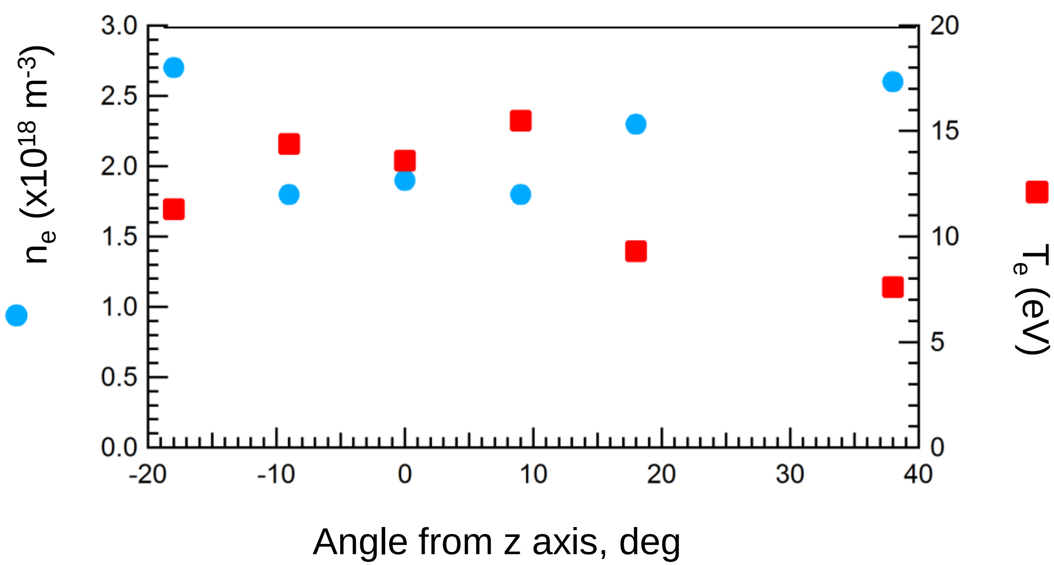
50

Voltage fluctuations on the arc do not correspond to fluctuations in ion saturation current

Measured T_e/n_e Profiles At Extraction Grid Spatially Uniform as Required

- Temperature spikes near the source, but remains stable in the bucket
- Density decreases near the grid





- Temperature decreases at the edge
- Density increases at the edge

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Arc Performance

100kV Testing of Arc Diagnostics Successful

- High voltage conditioning is still required for beam accelerator grids
- Integration of new 80kV power supply after grid conditioning

Additional Optimization of Arc Discharge May Be Needed for Diagnostic Performance

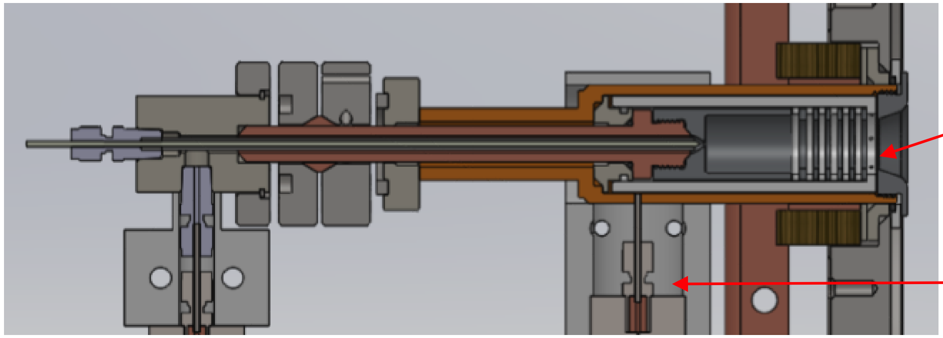
- Arc stability may affect beam divergence
  - $\widetilde{n_e}$ at the extraction plane may translate to beam divergence
  - Effect will be characterized when power supply is online

- Recent work has improved arc discharge stability

- Two major contributors:
  - Additional hydrogen fueling at anode
  - Magnetic guide field strength

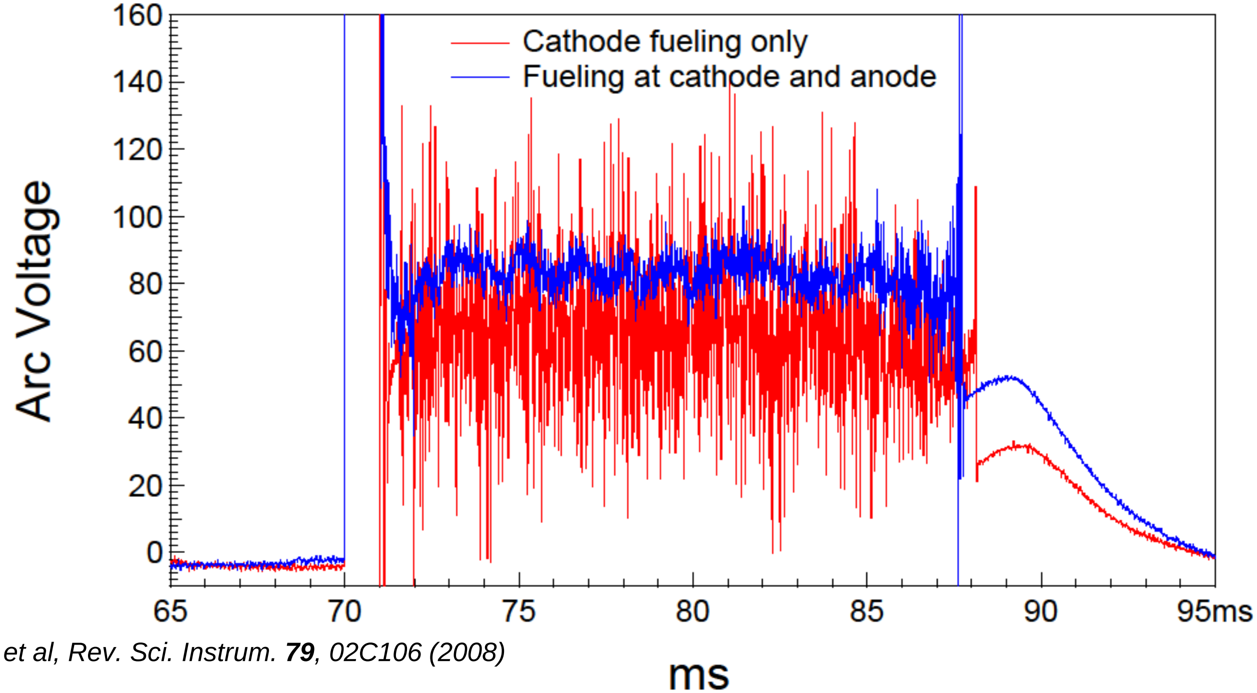
Arc Stability Increased by Hydrogen Fueling at Anode

- Hydrogen gas at anode reduces voltage fluctuations in the arc



Gas introduced radially via small holes in the last ceramic washer

Anode gas valve



[1] *Deichuli et al, Rev. Sci. Instrum.* ***79****, 02C106 (2008)*

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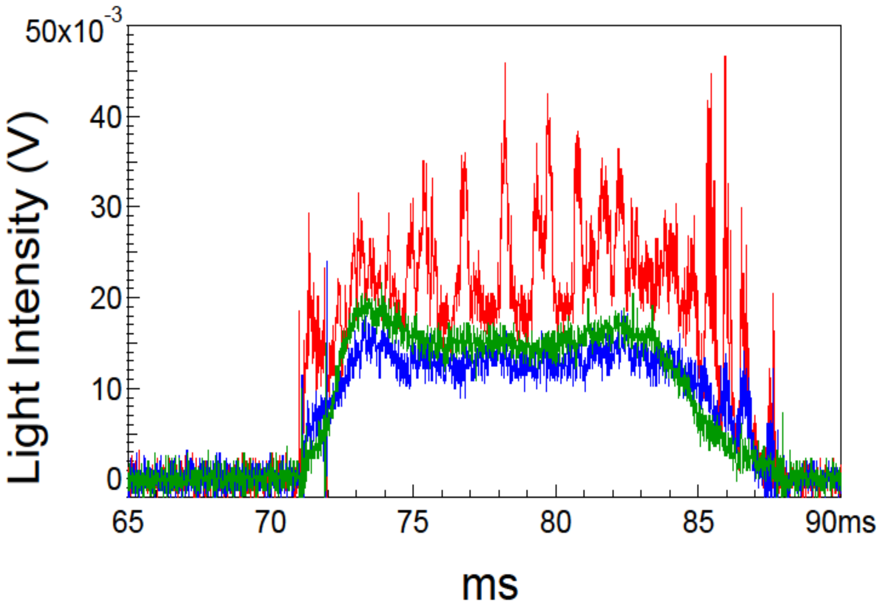
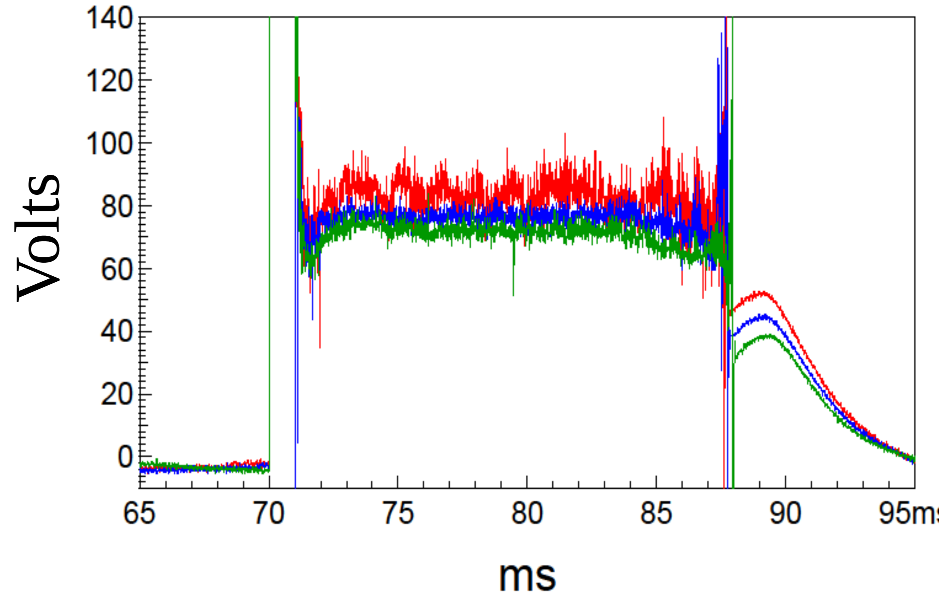
Arc Stability Modified by Strong Guide Field

- Increasing guide field induces voltage fluctuations in the arc

Photodiode Detector



Arc Voltage



Guide Field Strength

1.2kGauss
0.6kGauss
0.24kGauss

Measurements of Electric Field Fluctuation Possible with Novel Diagnostic

- $\tilde{E}$ measurements at 500 kHz possible via new Spatial Heterodyne Spectrometer and high speed 2D detector, providing a powerful, high resolution, high throughput, compact spectrometer concept

- A low-divergence, high energy diagnostic neutral beam (from PPPL) with new ion source being deployed to develop measurement

- A novel three-phase resonant converter power supply has been designed and built for low ripple, constant voltage output

- After conditioning, ion species mix measurements will determine necessity of quiet arc discharges.

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