Progress Toward a New Technique for Measuring Local Electric Field Fluctuations in High Temperature Plasmas

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PEGASUS Toroidal Experiment

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

- $\tilde{E} = k_{\perp}\tilde{\phi}$ measurements provide $\tilde{v}_r$ and $\tilde{v}_\theta$, currently under-diagnosed in tokamaks, and are quanities that provide information on cross-field transport ($\tilde{v}_r$), transport barriers ($\tilde{v}_\theta$), and other important turbulent plasma physics topics

- A novel high-speed, high-throughput spectrometer is being developed to measure local $\tilde{E}$ up to 500kHz
  - U≅0.01cm^2-ster
  - Spectral resolution≅0.25Å

- A low-divergence, 80keV diagnostic neutral beam (on loan from PPPL) is being installed on Pegasus to develop novel $\tilde{E}$ measurement

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Estimate of $\tilde{E}$ provided by Tokamak Fluctuation Scaling

- An estimate of drift wave fluctuation levels can be obtained from scaling relations between 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

- E-field fluctuations are measurable in fusion grade tokamaks plasmas

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

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$\tilde{E}$ in Fusion Grade Plasmas are Measurable Against Background MSE

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	$0.7x10^{-3}$

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$\tilde{E}$ Expected to be an Order of Magnitude Smaller than $\tilde{n}$ and $\tilde{T}_i$

- $\tilde{T}_i$ and $\tilde{n}$ are known to be small:

$$\tilde{T}_i/T_i \sim 10^{-2} \quad \text{(HF/UF-CHERS)}[1]$$
$$\tilde{n}/n \sim 10^{-2} \quad \text{(BES)}[2]$$

- Anticipated fluctuations for Pegasus are small:

$$\tilde{E}/E_{MSE} \approx 10^{-3}$$

- Photon noise floor ~ 10^{-3}

- UF-CHERS correlates with $\tilde{n}$ to extract turbulent signal

- To extract $\tilde{I}$, cross correlate with BES signal:

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

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

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Fluctuations in the Local Electric Field Results in Fluctuations in the Separation of the π components of the Stark Manifold

- The measured field is

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

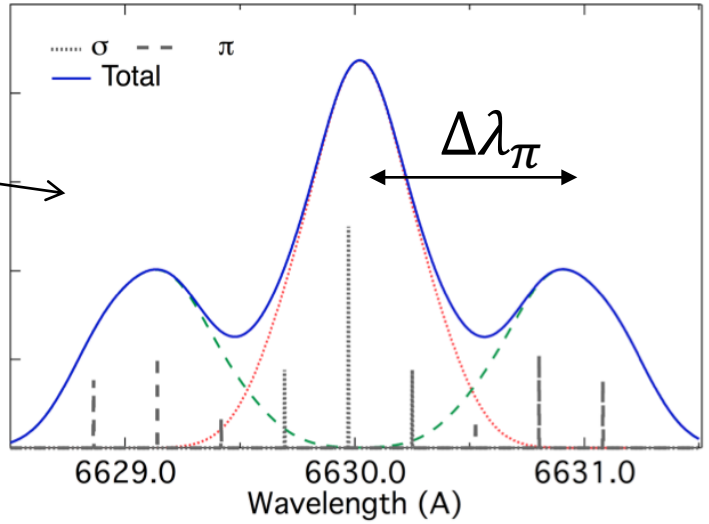
  - For 80 keV beam, $B_T = 0.3\text{T}$, $E_{v\times B} \approx 1$ MV/m

- Motional Stark effect splits H^0 Balmer-α into π ($\Delta m = 0$; parallel to E_{MSE}) and σ ($\Delta m = \pm 1$; perpendicular) components[1]

  - $\rightarrow \Delta\lambda^{\pi}_{H\alpha}(\text{Å}) = 0.277(\pm 2,\pm 3,\pm 4,\pm 8)E_{\text{tot}}\,[\text{MV/m}]$

  - $\Delta\tilde{\lambda}_{\pi} \rightarrow \tilde{E}_{Total} \rightarrow \tilde{E}_{plasma}$

- δv_{beam} information recorded in MSE spectra

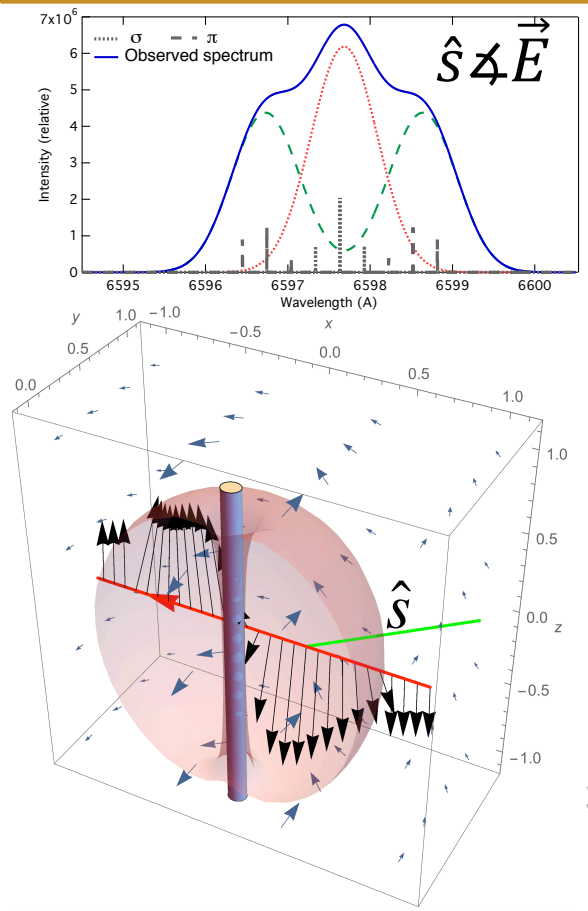


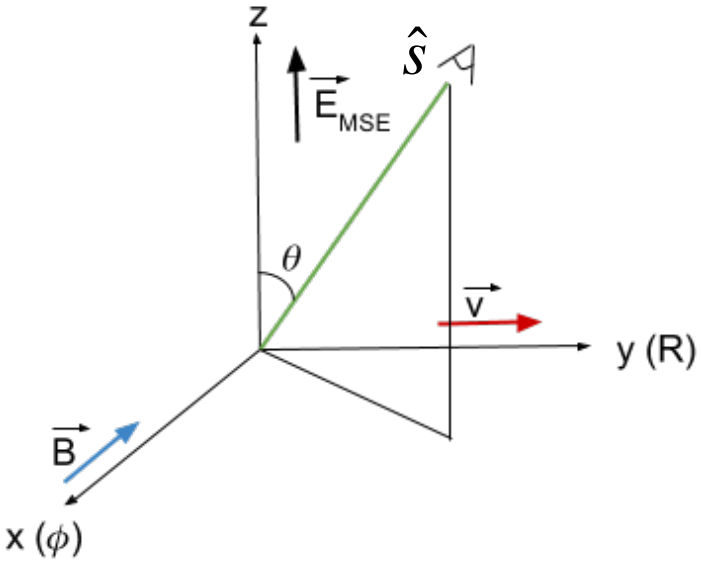
Modeled MSE spectrum for Pegasus

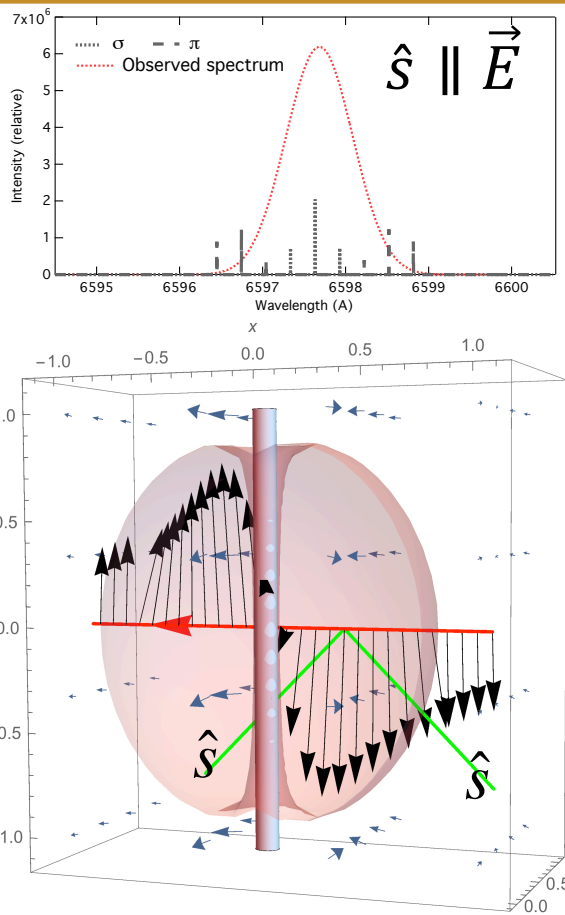
1 H. A. Bethe & E. E. Salpeter. Quantum Mechanics of One- and Two-Electron Atoms. New York: Dover Publications, Inc., 1957.

2 H. Y-H. Yuh, PhD Thesis, MIT (1995).

Sightline Geometry and Polarization Considered to Obtain $\tilde{E}_z$ and $\tilde{E}_r$







$\tilde{E}_z \rightarrow \tilde{v}_r$: Line-width

- midplane view multichannel spectrometer: $\Delta\lambda_\pi$

$\tilde{E}_r \rightarrow \tilde{v}_z$: Intensity ratio

- Off mid-plane radial view

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$\tilde{E}_r$ from Fluctuations of π and σ Intensity Ratio

- Intensity ratio function of upper state population density

$$R = \frac{\sum I_\pi}{\sum I_\sigma} = \frac{\sin^2\theta}{1+\cos^2\theta}\frac{n_\pi}{n_\sigma} = F\frac{\sin^2\theta}{1+\cos^2\theta}$$

- Intensity ratio fluctuates due to density fluctuations

$$\tilde{R} = R\left[\frac{\partial \ln F}{\partial \ln n_e}\frac{\tilde{n}_e}{n_e} + \frac{4\cos\theta}{\left(1+\cos^2\theta\right)\sin\theta}\tilde{\theta}\right]$$

- For electrostatic fluctuations, $\tilde{E}$ term ~2-5 x $\tilde{n}/n$

$$\tilde{R} = R\left[2.7\tilde{\theta} - 0.07\frac{\tilde{n}}{n}\right] \qquad \text{Drift Waves: } \frac{\tilde{n}}{n} \sim \frac{e\tilde{\phi}}{T_e}$$

- Reduce effect of $\tilde{n}/n$ further by multiple sightlines

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Spectrometer Requirements are Formidable

- Resolution:
  - Past practice (HF-CHERS), need ≥ 4 spectral elements (8 desired) to detect $\tilde{w}$
  - $\Delta w_{\text{total}} \sim 2$ Å giving a spectral resolution of 0.25 Å
- Etendue (optical throughput):
  - Matched to port and sightline availability on Pegasus
  - U = 0.01 $\text{cm}^2 - \text{str}$
- Compatible Detector System:
  - $\Delta t \sim 2$ μs
  - ≥ 8 spectral channels
- Mitigation of sightline-DNB broadening (Window Effect)

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

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

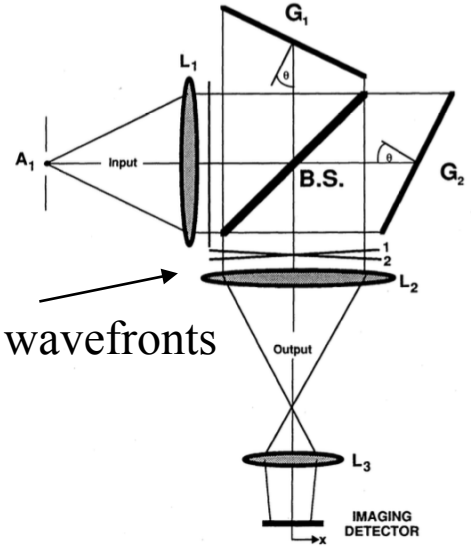
- Spatial Heterodyne Spectrometer
  - Self-scanned, 2-beam Michelson interferometer
  - Heterodyned to local λ_o to reduce sampling requirement
  - High throughput, high resolution, and compact!
  - Key spectrometer parameters:

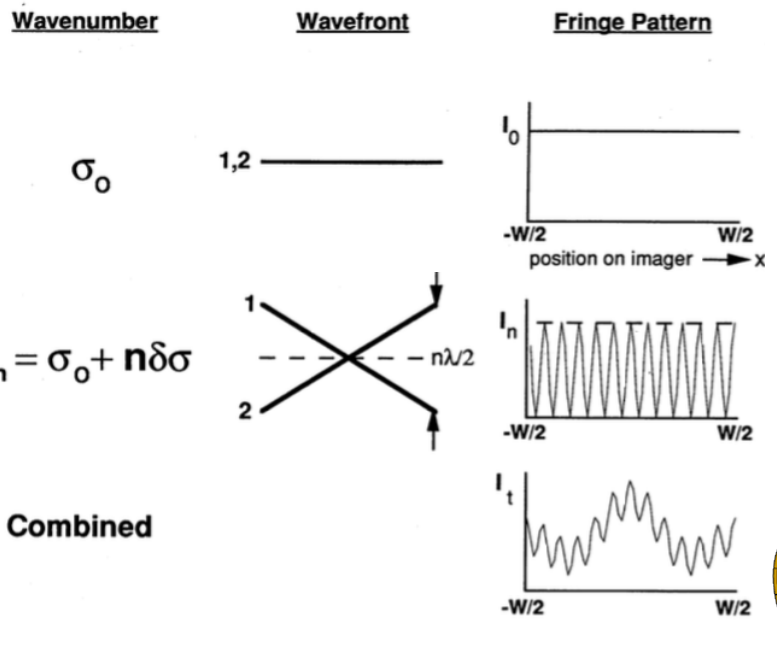
$$R = \frac{\lambda}{\Delta\lambda} \approx 30000$$

$$D_{lens,G} = \sqrt{\frac{2U_{sightline}R}{\pi^2}} \approx 8\ cm$$

  - Modest grating constant → $\frac{R}{D_G} \sim 300 l / mm$
  - Resulting output interferogram:
    - Fizeau fringes conjugate to grating face gives spatial interferogram of B(σ)

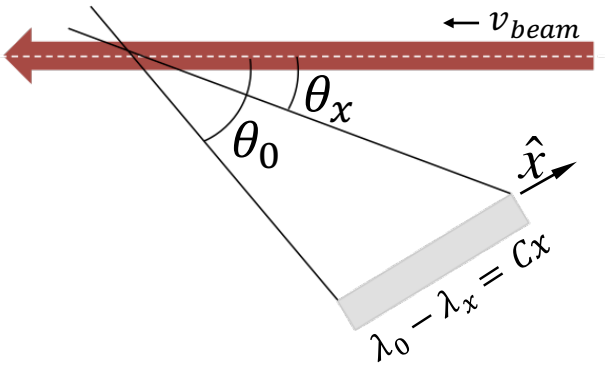
$$I(x) = \int_{-\infty}^{\infty} B(\sigma) d\sigma \cos[2\pi(4|\sigma - \sigma_o| x \tan\theta_L]$$

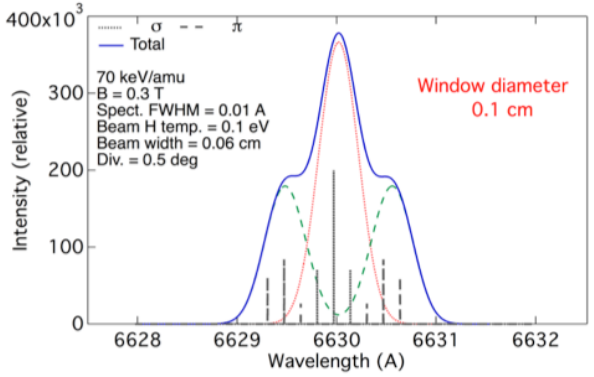


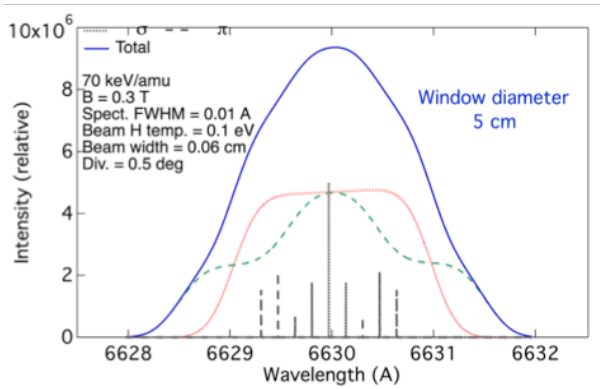


SHS Spectrometer Provides Built-In Mitigation of Sightline Doppler Broadening (Window Broadening)

- $\lambda_{H\alpha}$ shifts across window aperture due to varied intersection angle with respect to beam velocity → severely restricts spectral resolution at low $\vec{B}$







- SHS approach gives the ability to directly mitigate window broadening
  - Takes advantage of Fizeau fringe plane being conjugate with window
  - Phase shift due to window effect can be numerically removed from SHS interferogram
    - Window broadening effect manifests as a linear phase shift across the fringe pattern

$$\phi_w = 2\pi cx \longrightarrow \phi_{Total} = \phi_G + \phi_w$$

$$\longrightarrow I(x) = \int_{-\infty}^{\infty} B(\sigma)d\sigma + cos\phi_w \int_{-\infty}^{\infty} B(\sigma)d\sigma cos\phi_G - sin\phi_w \int_{-\infty}^{\infty} B(\sigma)d\sigma sin\phi_G$$

$$\phi_G = 4\pi(\sigma - \sigma_o)x \tan\theta_L$$

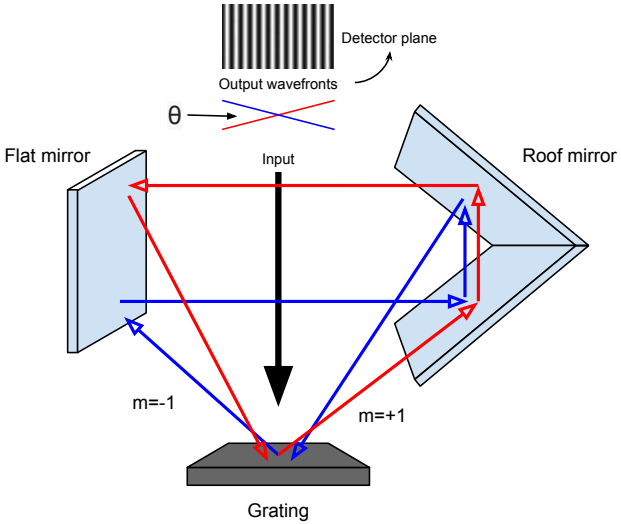
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New High-Speed CMOS Technology Allows for Fast Measurement of SHS Interferogram

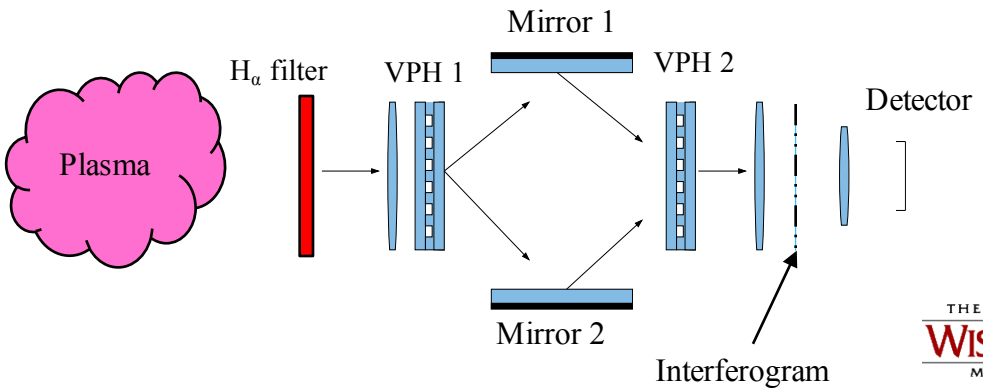


- High-speed Phantom v2512 FAST by Vision Research
  - 500 kHz
  - 160 x 80 pixels or 110 x 110 pixels
  - U_{camera} = 0.12 cm^2-str @ f/1
  - Allows for 2 spatial measurements
- QE ~ 50% over visible range
- Integrated DAQ
- In-line spectrometer concept separates plasma from detector utilizing new VPH grating technology

Practical SHS design 1: all-reflective



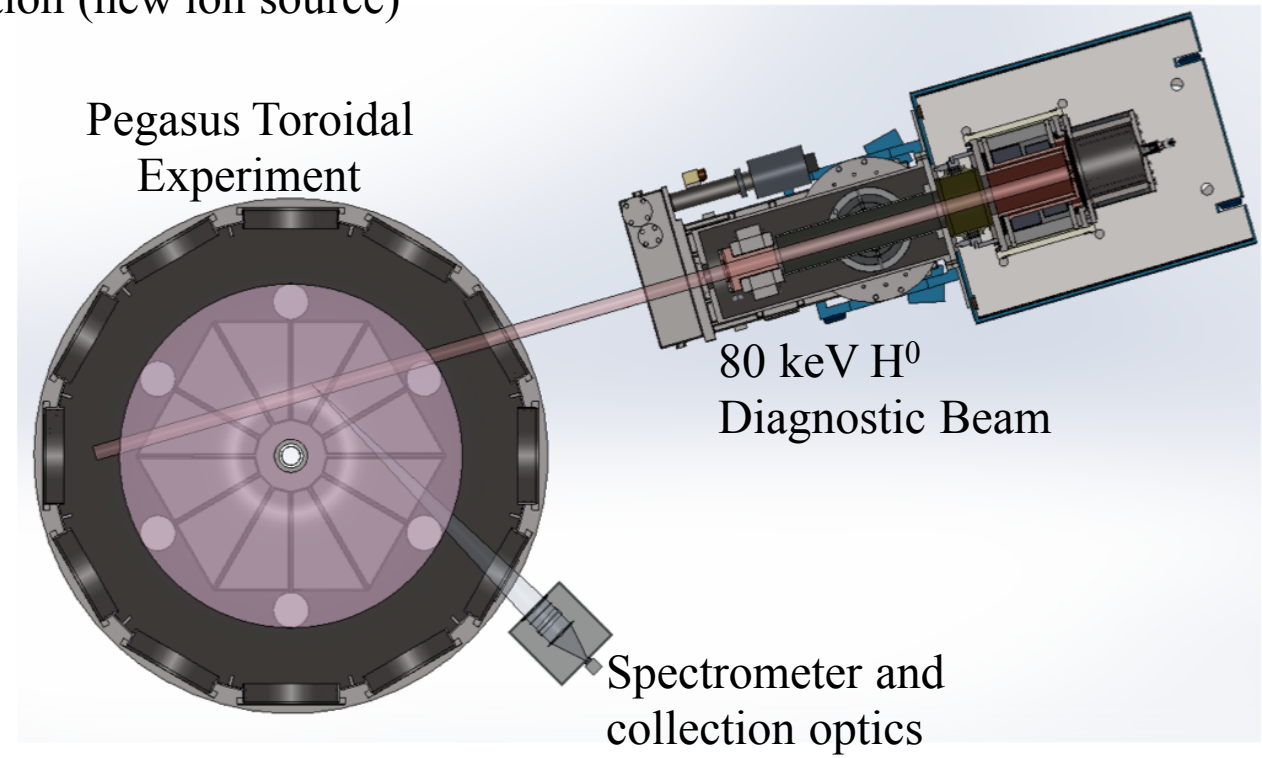
Practical SHS design 2: in-line



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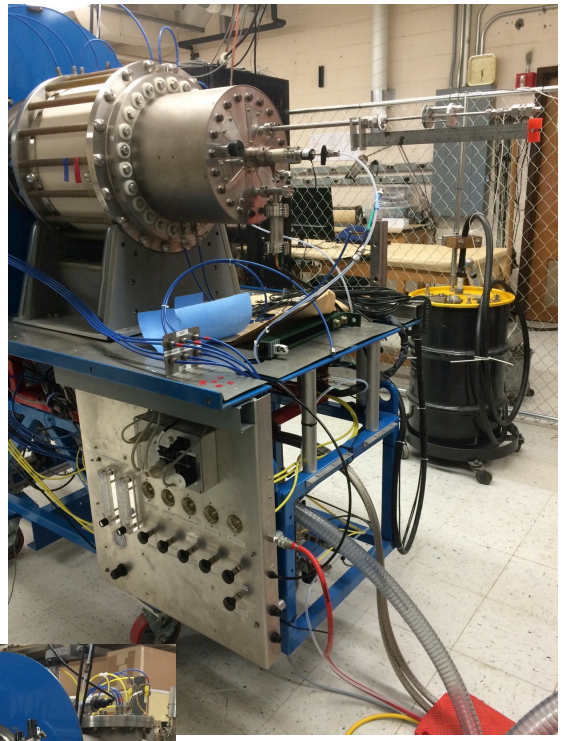
High Performance Beam Required for $\tilde{E}$ Measurement

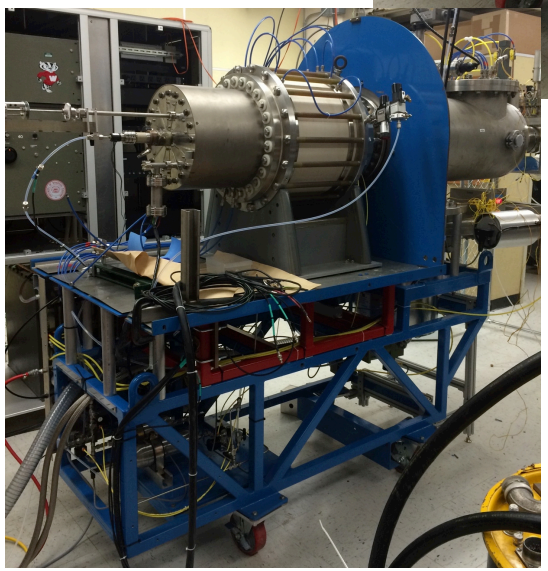
- Beam produced by Culham for PPPL meets beam requirements necessary for E-field fluctuation measurements
  - Low divergence
  - High Species Fraction (new ion source)
  - High Energy



Diagnostic Benefits from 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
- Features favorable for measurement
  - Low divergence: $\leq 0.47°$
    - Mitigates Divergence line broadening
  - High $E_b \sim 60 - 80$ keV
    - Maximizes MSE broadening
  - 90-95% ionization at full beam energy
    - New plasma arc source
    - Optimize signal at full energy component



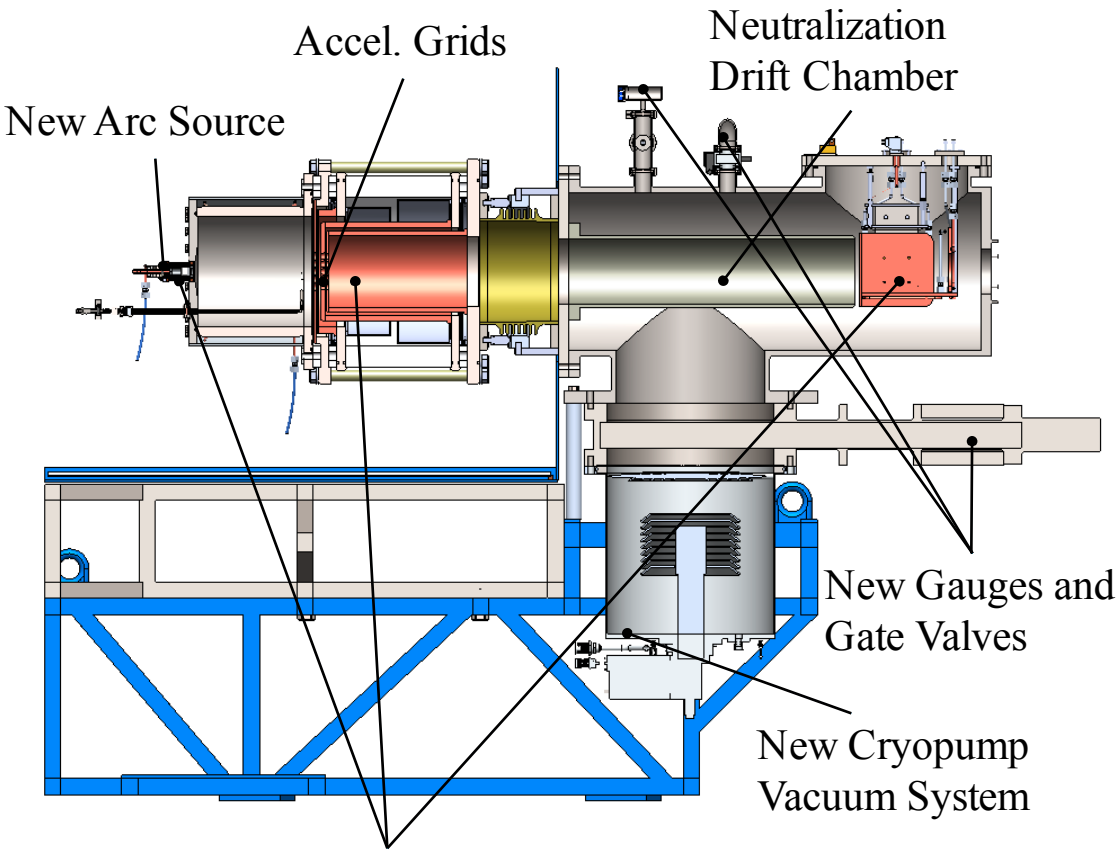


J.R. Coupland et al, Rev. of Sci. Instrum. ***61****, 472 (1990)*
I.L.S. Gray et al, IEEE ***1****, 149 (1989)*

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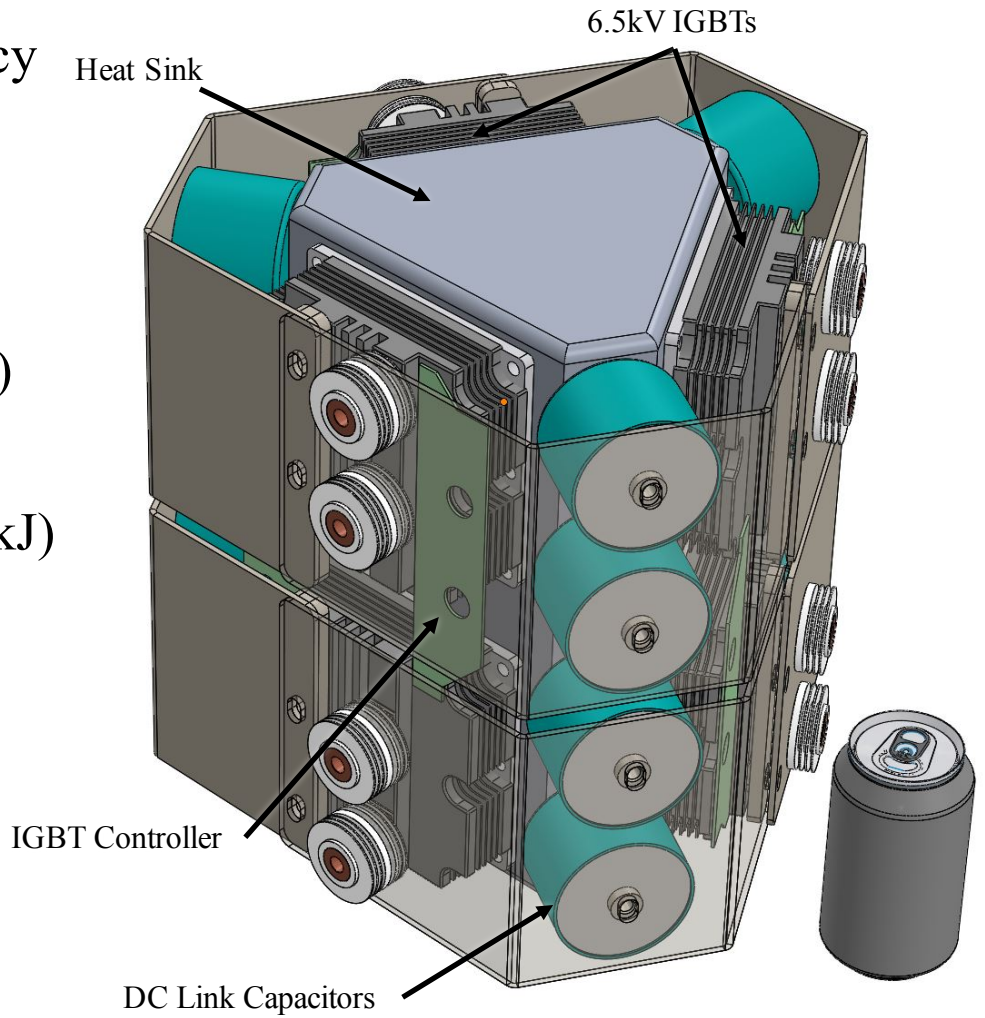
DNB Refurbishment and Upgrades

- Original DNB from PPPL
  - Transition to Pegasus required complete overhaul
- Vacuum System
  - All new seal and pump
- New Arc Source
  - High full energy species fraction
- New power systems
  - HV power supply components have been bid out
- New controls
  - NI FPGA and DAQ controlled with LabView



80kV / 400kW Resonant Converter

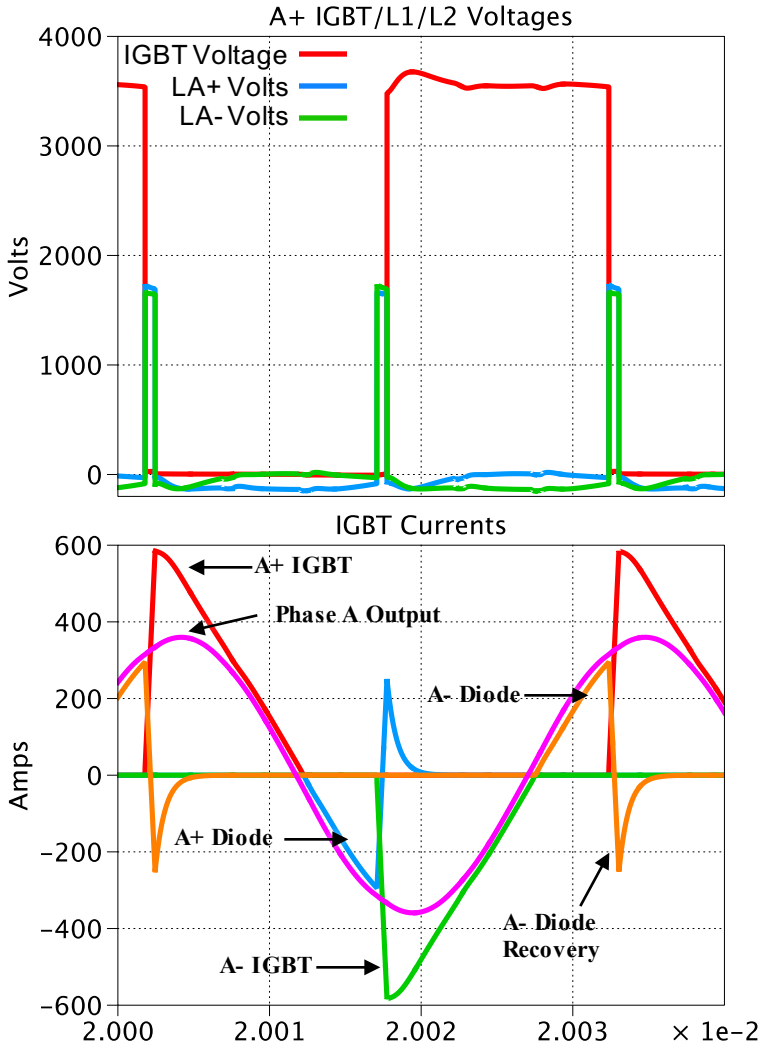
- Resonant Converter
  - 35 kHz Base Switching Frequency
  - 3 single phase transformers
  - Fast Rise/Fall time (< 200usec)
  - Low filter energy (1J)
  - Low voltage ripple (±0.00025%)
  - Low energy per cycle (2J)
  - Low primary stored energy (120kJ)
  - Gain is load dependent
  - Excellent fault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



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Zero Voltage/Zero Current Switching

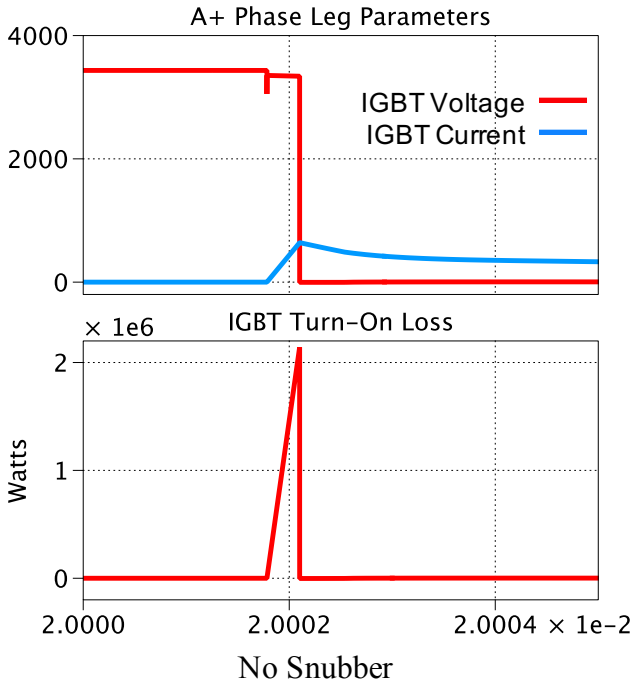
- What is ZVC/ZCS
  - Passive commutation
  - IGBT turn-off losses are zero
  - Diode commutation at zero voltage (with snubber)
  - Lower system losses allows higher frequency operation
  - Higher frequency allows for higher power density (lower energy per cycle)
- What's not to like?
  - Lowest loss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



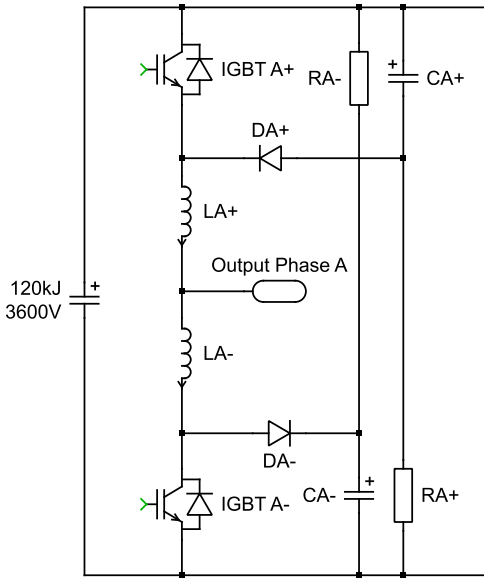
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Switching Losses Reduced ~100x

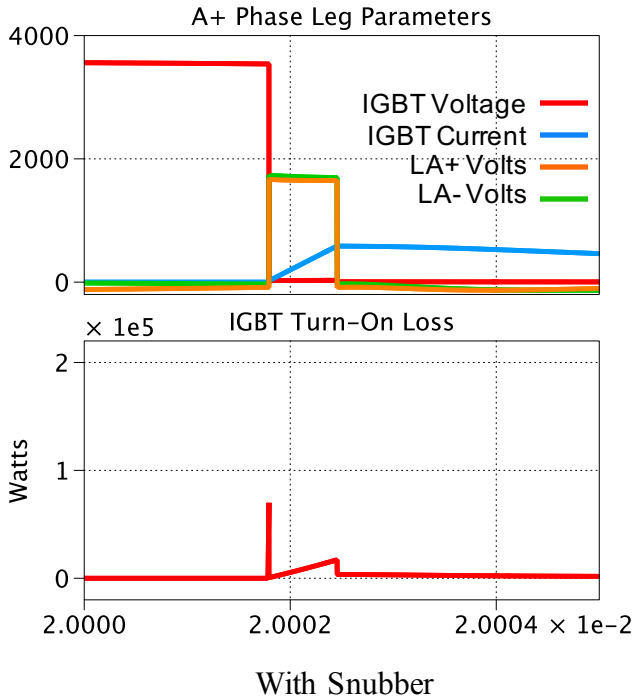
- Multi-pole Bridge Snubber
  - Clamps device for ~ 400nsec
  - Allows turn-on of IGBT at zero voltage
  - Loss reduction enables access to higher switching frequencies



No Snubber



Phase Leg (1 of 3)

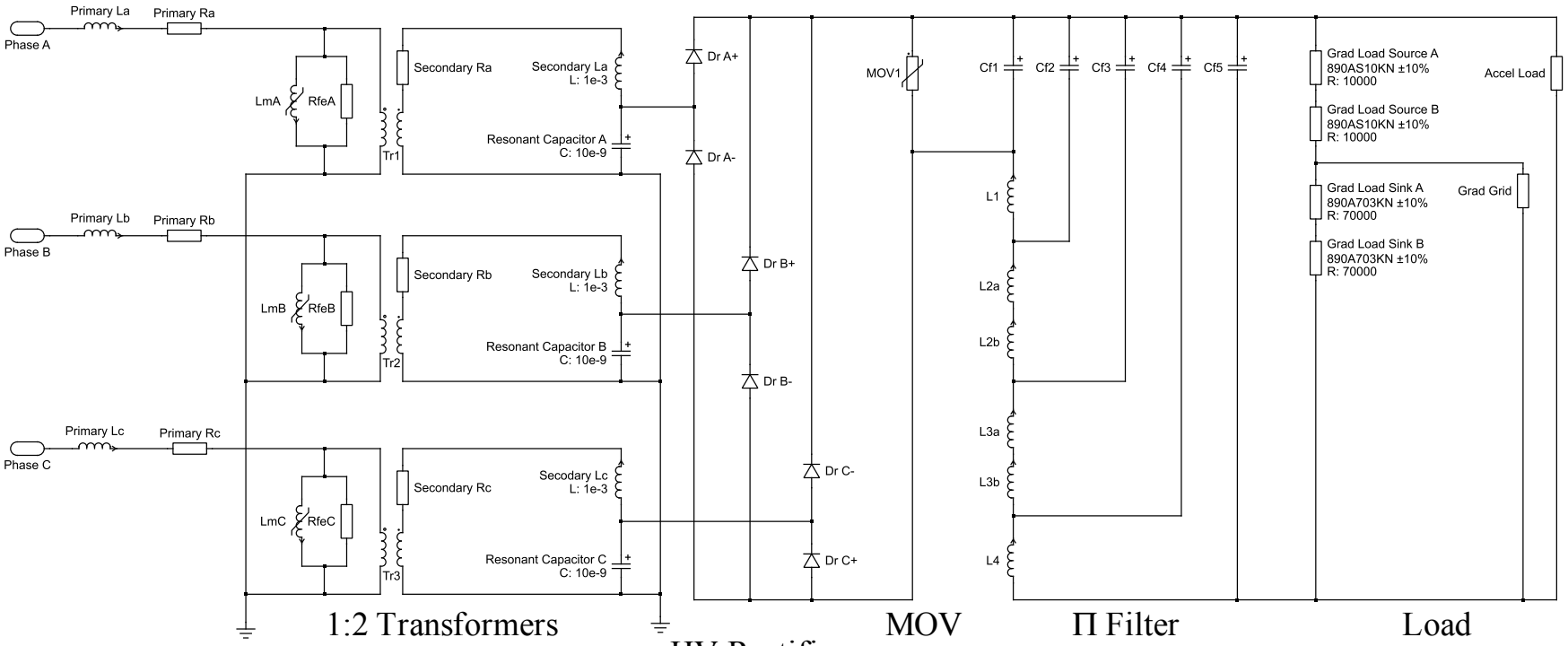


With Snubber

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> 20x gain achievable in HV Section

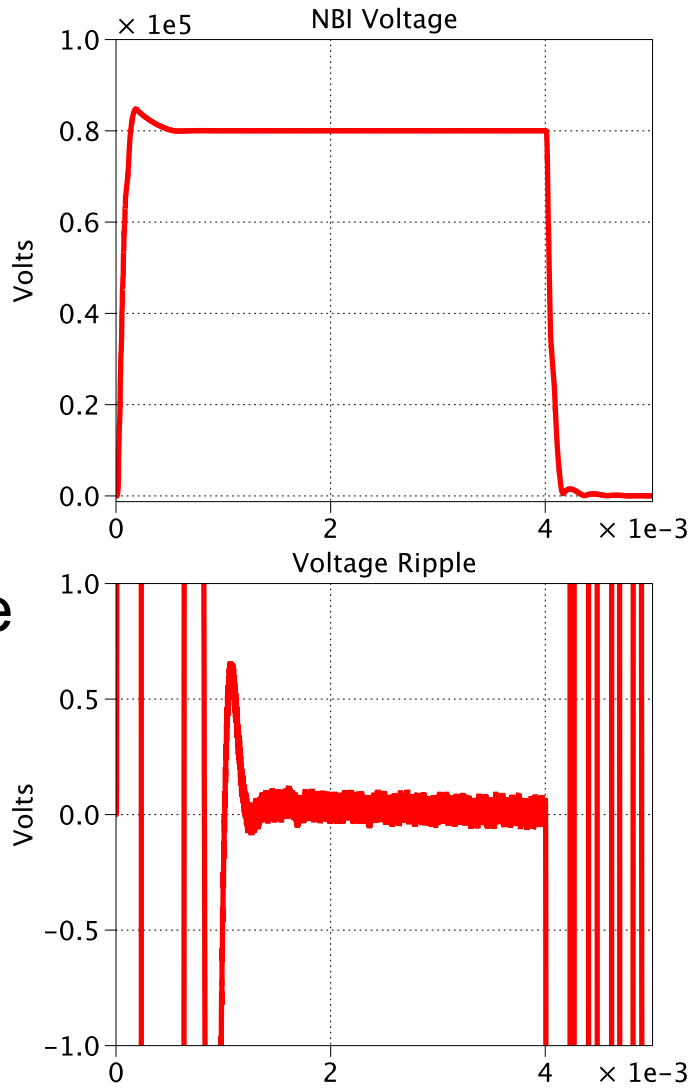
- Resonant Converter High Voltage Section
  - 80kV at 5A with 1J of 80kV filter energy
  - Transformer leakage inductance (La/Lb/Lc) utilized for resonant circuit
  - Very fast ramp times < 200us to 80kV and no crowbar
  - Very low ripple ±0.2V or ±0.00025%



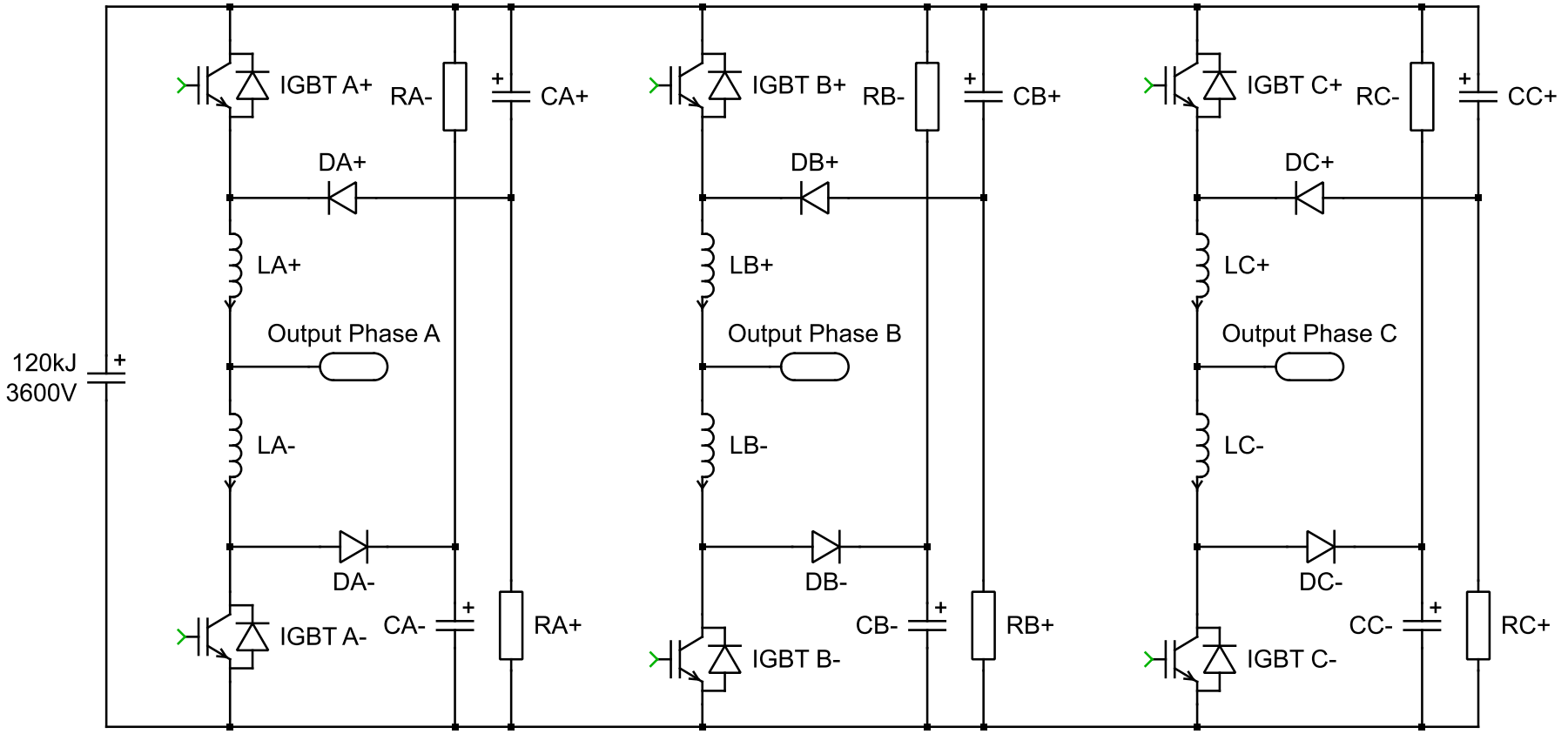
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Design and Assembly Progress

- PLECS modeling Complete
- Resonant Transformers and Capacitors in house
- Most Power Components In House
- Phase I FPGA Programming Complete
- FPGA Interface Awaiting Fabrication
- Bridge Topology Nearing Completion
- 120kJ Capacitor Bank in Fabrication

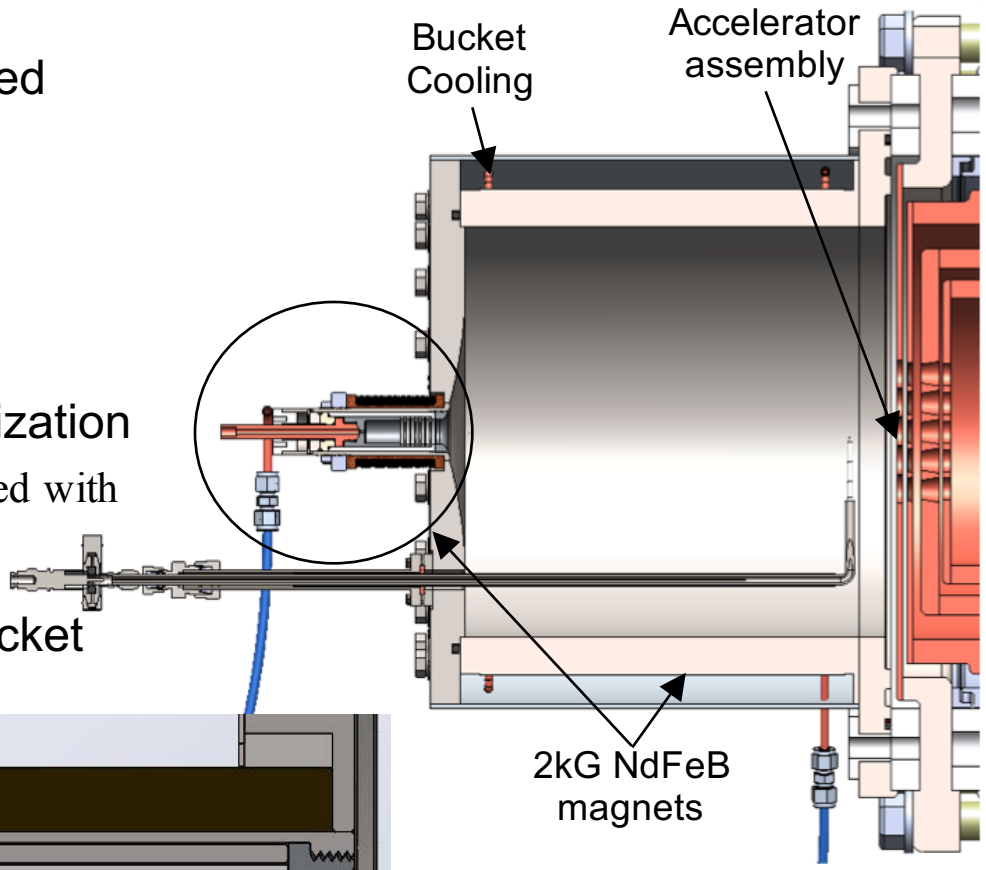


3600V Primary with Multi-Pole Snubber

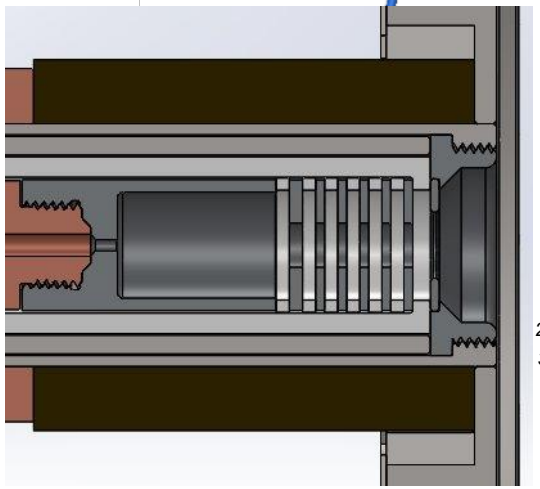


New High Density Plasma Arc Source Provides Optimal Species Mix

- Standard 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 near 100% ionization
  - Full energy fractions of 80-90% achieved with other arc source diagnostic beams[1-3]
- Plasma expands into a magnetic bucket with multipole cusp fields



New arc source design →



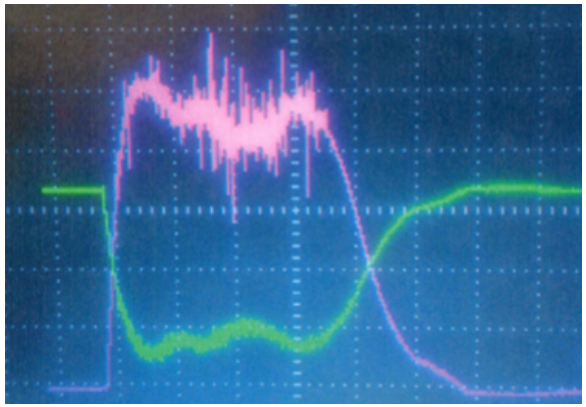
[1] *Deichuli et al, Rev. Sci. Instrum.* ***79****, 02C106 (2008)*
[2] *Abdrashitov, et al, Rev. Sci. Instrum.* ***72****, 594 (2001)*
[3] *Korepanov, et al, Rev. Sci. Instrum. 75, 1829 (2004)*

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Desired Operation Space Achieved

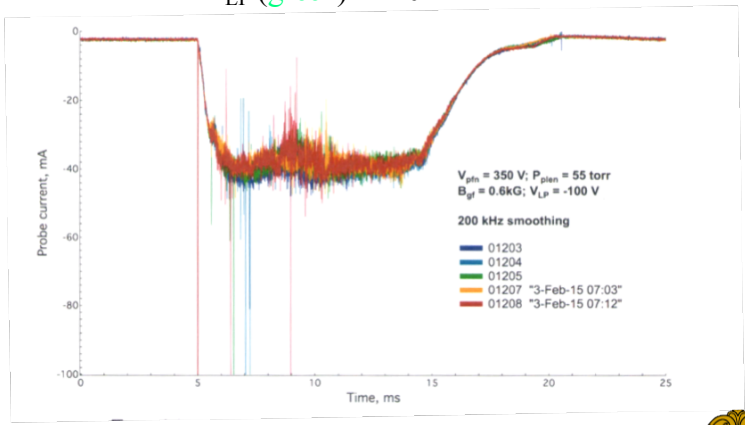
- Initial tests identified parameters yielding T_e and n_e desired for full-energy current density.
  - $T_e \sim 15$ eV
  - $n_e \sim 1.6 \times 10^{17}$ m^{-3}

- Further testing required:
  - confirmation of reliability and repeatability
  - measure beam species mix using a Czerny-Turner spectrometer



Shot Parameters:
Potential drop across arc: 350 V
Flow-rate ~ 300 torr L s^{-1} (5ms)
Bgf = 0.6 kG

Iarc (pink) ~ 1.5kA
I_{LP} (green) ~ -40 mA



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

    $\rightarrow j_{ext} = 34.7 - 104\ mA/cm^2$

- Source Requirements to meet j_{ext} at the grids:
  - $T_e \sim 15$ eV
  - $n_e \sim 1.6 \times 10^{17}\ m^{-3}$

- At the grids:

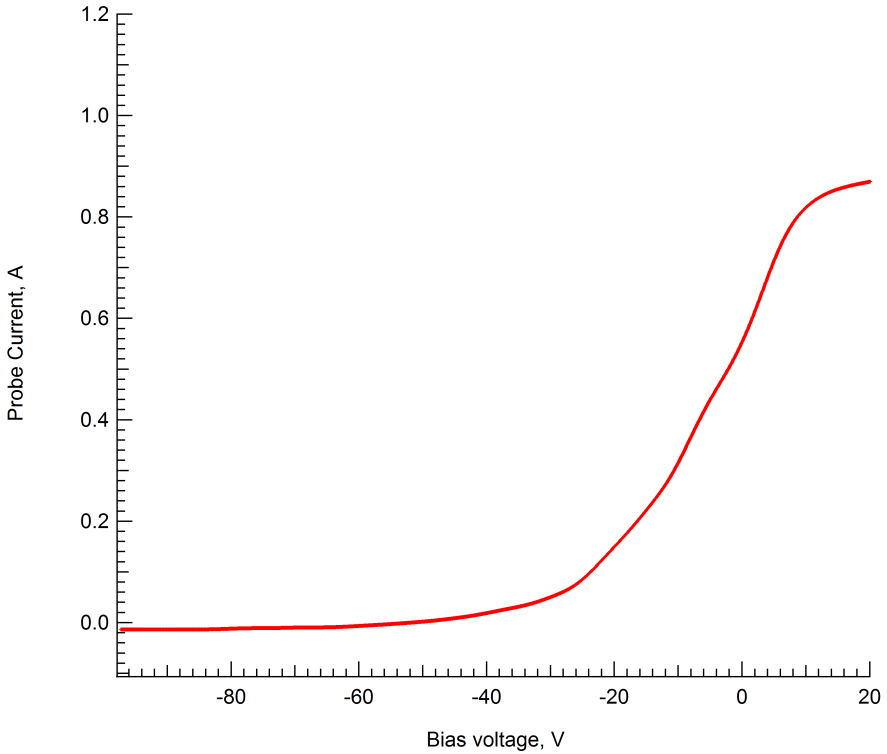
$$\boxed{j_{plasma} = n_e e v_B \rightarrow j_{ext} = I_{ext}/A_{ext}}$$

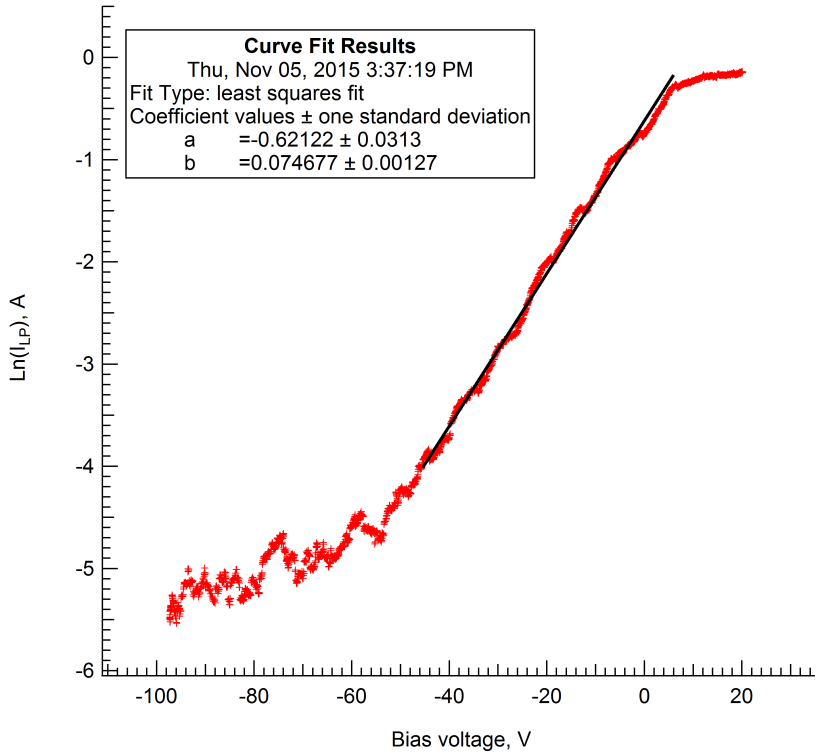
$$n_e = \frac{I_e^*}{eA}\sqrt{\frac{2\pi m_e}{T_e}} \quad (*) \qquad v_B = \sqrt{T_e / m_i}$$

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

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Single Swept Langmuir Probe Traces Provide T_e and n_e Information





- High T_e allows for greater ionization and good species fraction
  - Langmuir probe analysis:
    - From the $Ln(I_{LP})$ plot below:

$T_e \approx 1/b - a \approx 14.01$ eV

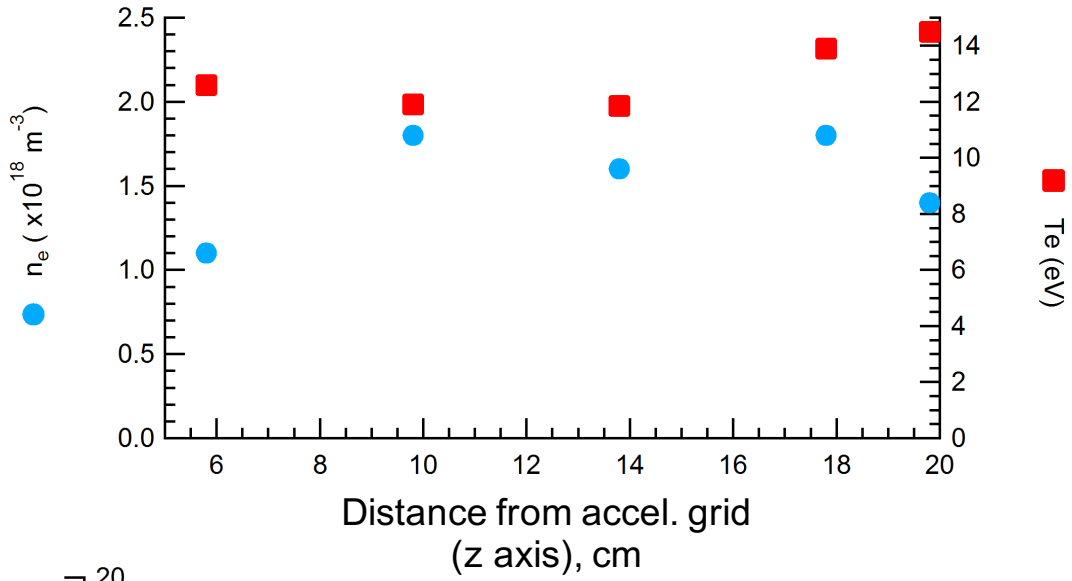
$n_e \approx 6.09 \times 10^{17}\ m^{-3}$ ⟵ Easily achieve densities above those required

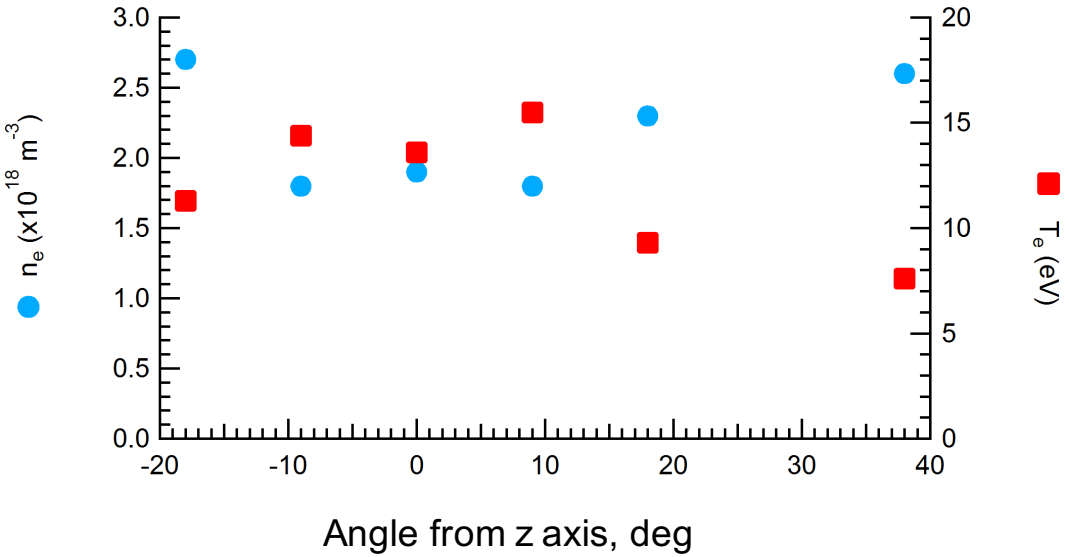
$j_{ext} \approx 357.4\ mA/cm^2$ ⟶ (Density required to match desired j_{ext}: $n_e \approx 1.8 \times 10^{17} m^{-3}$)

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Axial and Radial Profiles of Source Plasma Inside Bucket

- 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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Summary

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

- Design is scalable to fusion grade plasmas

- 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 developed

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