PEGASUS-III Experiment

Diagnostic Neutral Beam and Charge Exchange Recombination Spectroscopy Diagnostic for Studying Non-Solenoidal Tokamak Startup in PEGASUS-III

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Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

PEGASUS-III Experiment

Non-Solenoidal Tokamak Plasma Startup and Drive in PEGASUS-III

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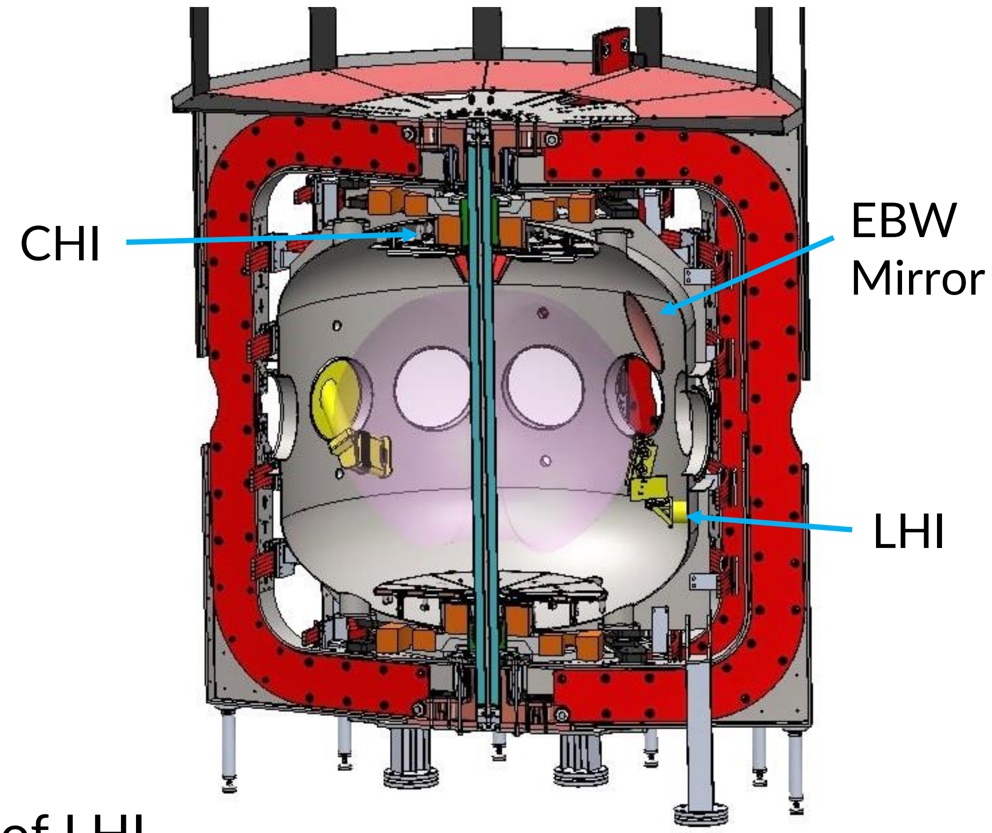
PEGASUS-III: Non-Solenoidal Current Drive (CD) Research and Development

Exploring Tokamak CD Techniques:

— Local Helicity Injection (**LHI**)

— Coaxial Helicity Injection (CHI)

— RF assist and sustainment (EBW)



Objectives

- Validate technology for MA-class plasma startup
- Build physics understanding of CD mechanisms
- Assess compatibility with NBI and RF sustainment
- Deploy internal diagnostics, critical for characterization of LHI

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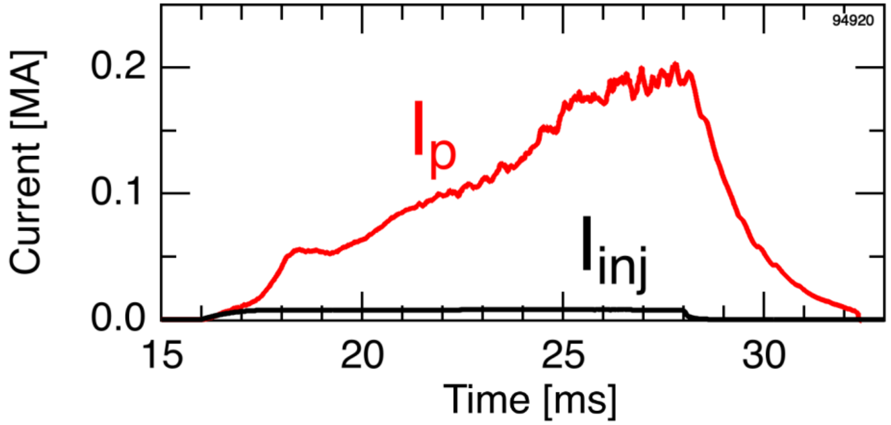
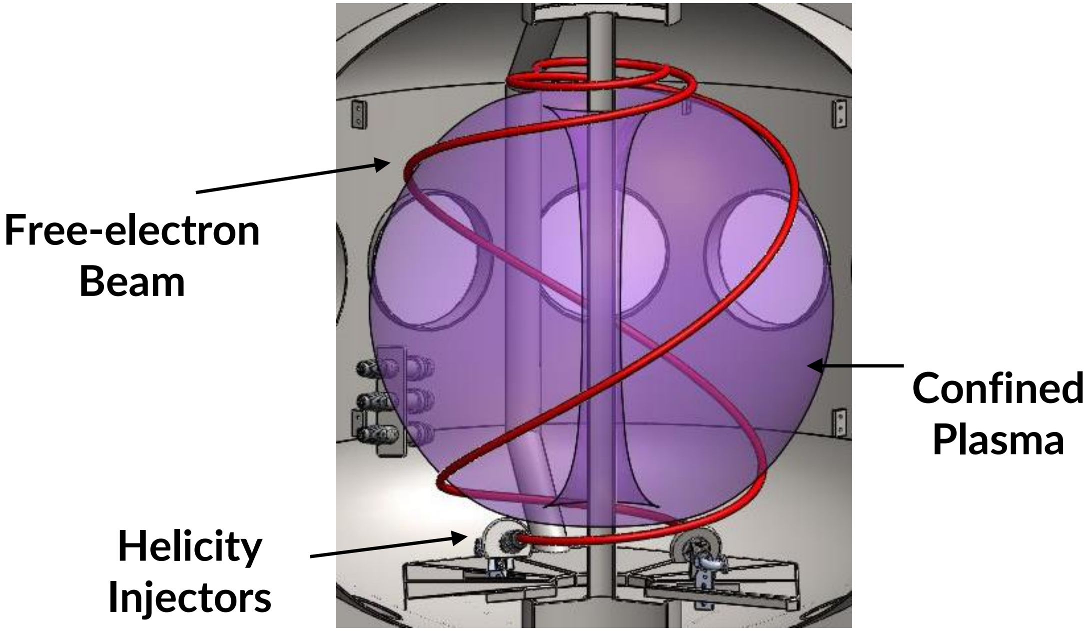
LHI Drives High I_p Plasmas with Compact Hardware

0.2 MA Plasma Initiated by LHI





- Routine startup from vacuum
- $I_p \leq 250$kA
- Demonstrated sustainment with Ohmic CD
- Port-retractable electrodes
- Flexible geometry

Essential features need evaluation for scaling:

- Equilibrium pressure profile
- Impurity sourcing, transport
- Predictive model
- Current density structure

Expanded Operating Space Will Advance Understanding of HI Startup and Current Drive

LHI Parameters

Parameter	PEGASUS	PEGASUS-III
ψ_{sol} [mWb]	**40**	**0**
$B_{TF,max}$ [T]	**0.15**	**0.58**
B_{TF} *Flattop* [ms]	**25**	**50–100**
I_p [kA]	≤200	≤300
I_{inj} [kA]	<8	~16
$\langle T_e \rangle$ [eV]	~100	~200
$\langle n_e \rangle$ [m^{-3}]	<1x10^{19}	~2x10^{19}

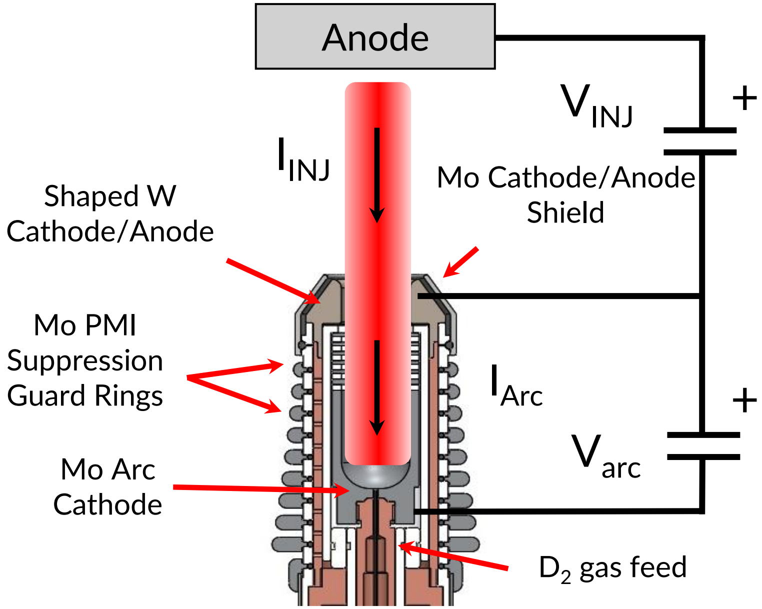
→ No solenoid, HI is primary startup and CD

→ New TF magnets enable higher B_{TF} to investigate confinement, I_p scaling

→ New power supplies: longer pulse lengths, greater I_p

Higher-performance enables:

- Higher T_e, higher charge state impurities
- Average densities $>1\times10^{19}$ m^{-3}
- Localized measurements with a DNB
- Majority $T_i(r)$ with active spectroscopy



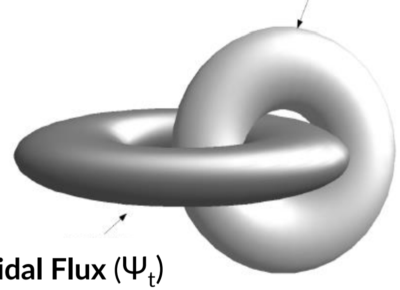
Injector Schematic

2x 4cm^2 Aperture LHI Array

LHI Plasmas are Generated by Taylor Relaxation of Edge-Injected Direct Current

1. Helicity, *K*, injected along open field lines into plasma volume by DC electrodes at plasma edge

$$K = \int_V \mathbf{A} \cdot \mathbf{B} d^3x$$



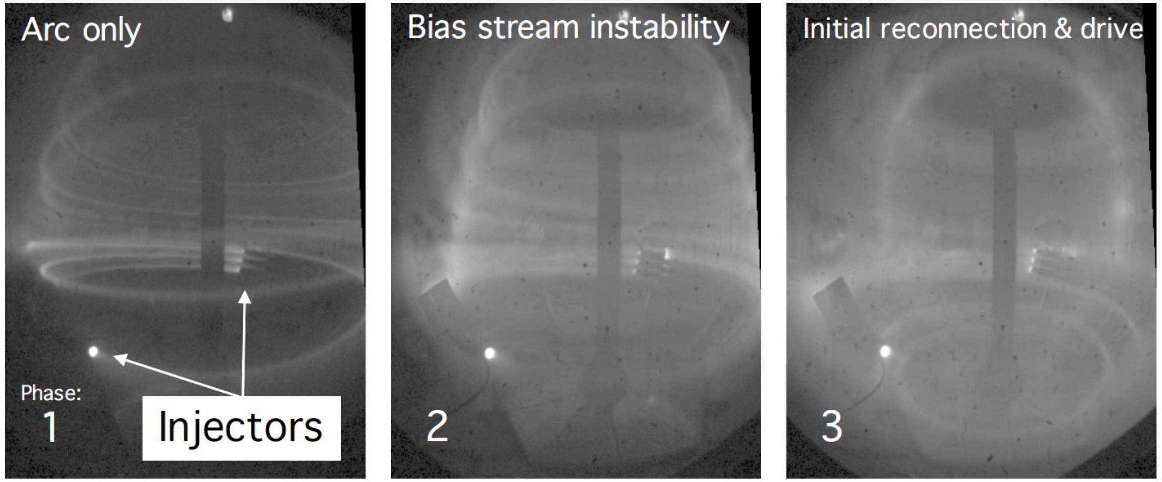
2. $J_{edge} >> J_{core}$, forms an unstable magnetic topology

$$\lambda \mathbf{B} = \mu_0 \mathbf{J}$$

3. System relaxes, transporting current to the core

$$\frac{dK_{tot}}{dt} = \underbrace{2\Psi \frac{d\psi}{dt}}_{\text{Induction}} \underbrace{-2 \oint_S dS(\phi \mathbf{B} \cdot n)}_{\text{Injection}} \underbrace{-2 \int_V dV(\mathbf{E} \cdot \mathbf{B})}_{\text{Dissipation}}$$

$$V_{LHI} = V_{inj} \frac{N_{inj} A_{inj} B_{inj}}{\Psi_t}$$



LHI Startup Phases

- Net I_p from effective loop voltage, $\boldsymbol{V_{LHI}}$
- LHI drives continuous magnetic reconnection events!

[1] D.J. Battaglia *et al.*, Nucl. Fusion **51** 073029 (2011) [2] J.M. Perry *et al.*, Nucl. Fusion **58**, 096002 (2018) [3] M.W. Bongard *et al.*, Nucl. Fusion **59**, 076003 (2019)

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Anomalous Ion Heating May Impact LHI Performance

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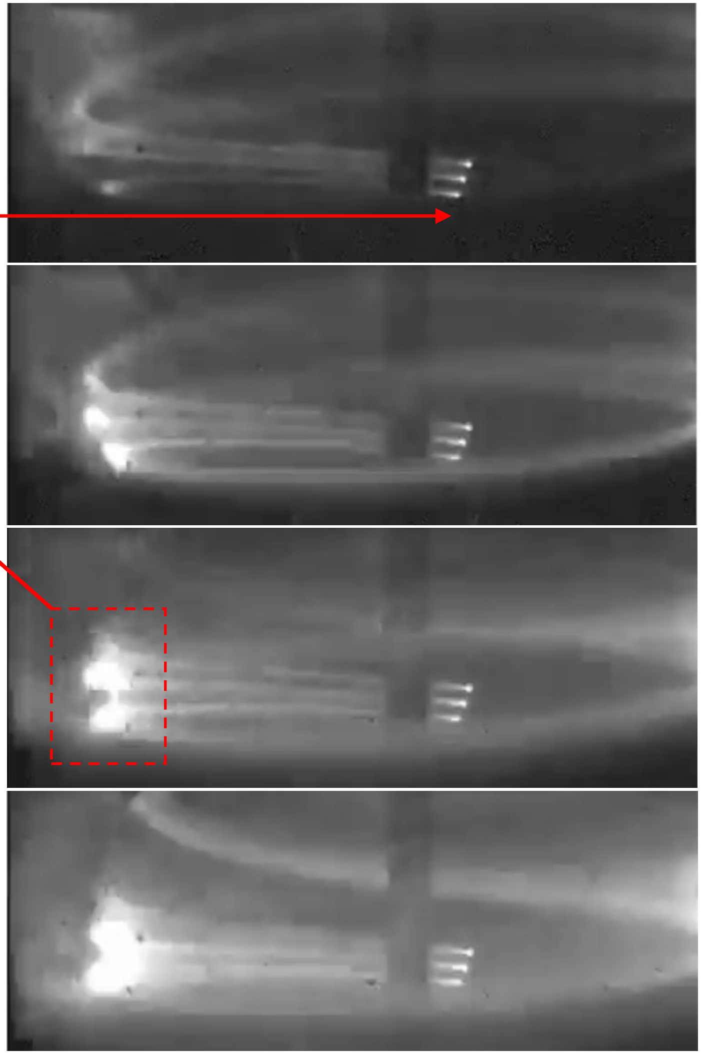
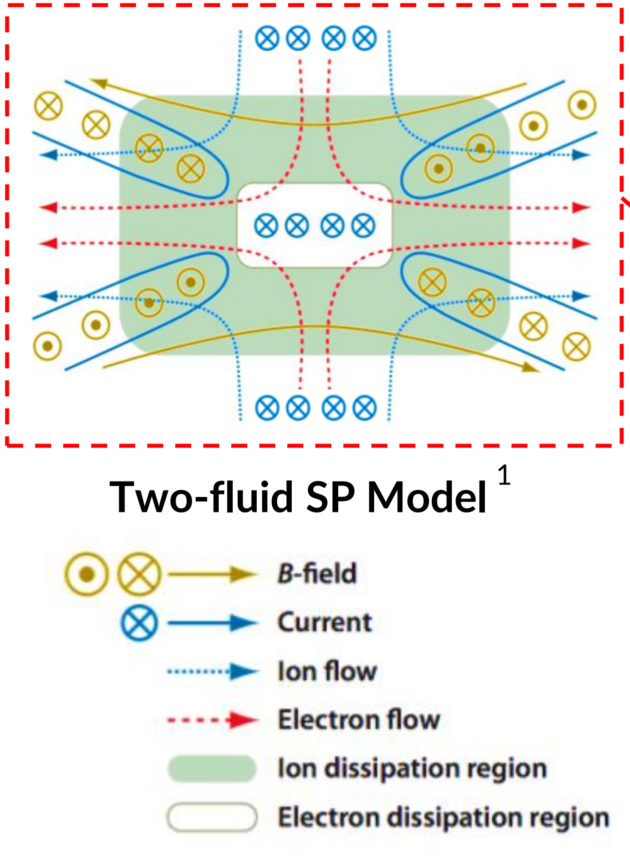
Magnetic Reconnection Heats Plasma and Drives Bulk Flow

3x Injector Array





Two-fluid SP Model [1]

Three Current Streams Merging Through Reconnection

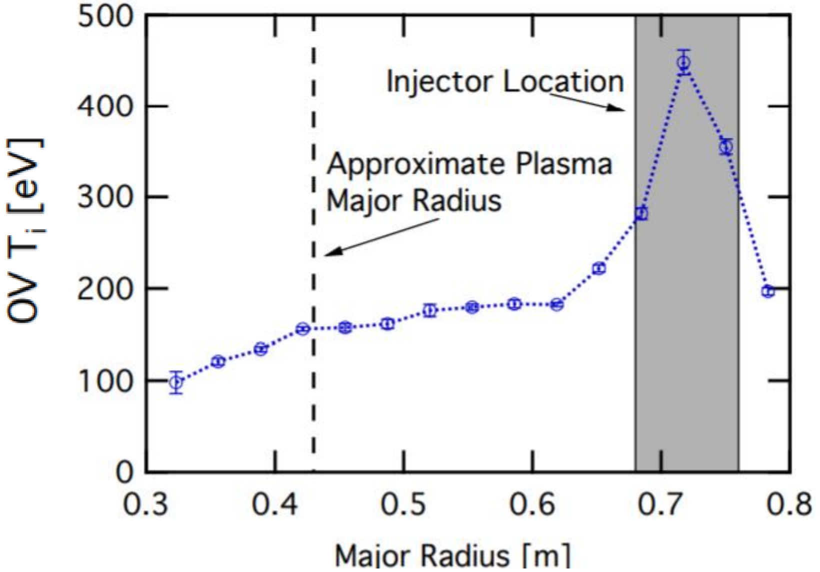
- In this regime, reconnection is described with a two-fluid Sweet Parker (SP) model
- Distance between opposing field lines approaches the ion inertial length
- Ions decouple from the reconnecting flux
- Two-fluid SP model predicts:
  - — Charge separation
  - — Increase in dissipation volume
  - — High rates of energy transfer
  - — Anisotropic heating

Reconnection heating suggests $\boldsymbol{P_{AUX}}$ for 0-D global power balance

[1] Zweibel and Yamada, Annu. Rev. Astron. Astrophys **47**, 291 (2009)

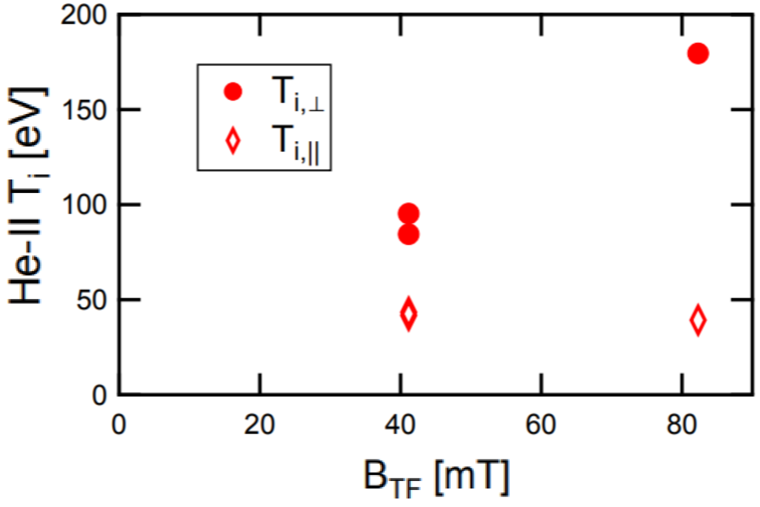
Reconnection-Heated Ions Contribute Pressure to Equilibrium and Impact Plasma Performance

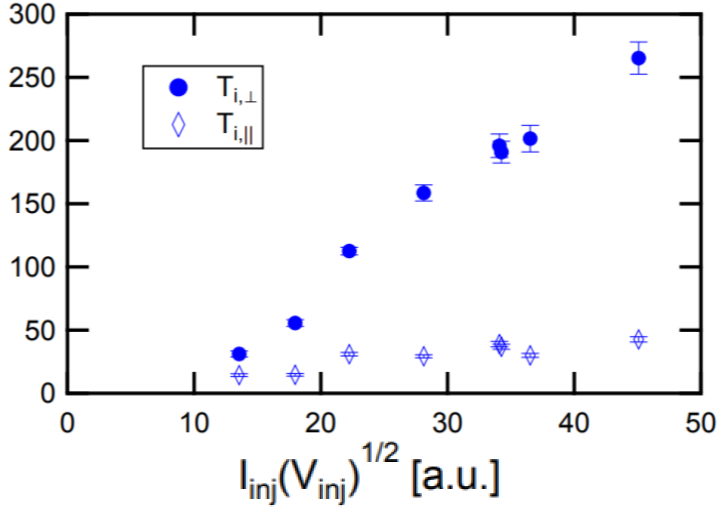
OV T_i Profile During LHI



- Magnetic reconnection preferentially heats ions
- From passive impurity measurements, $\boldsymbol{T_i \gg T_e}$ in edge
- Anomalously high T_i extends to the core, $\boldsymbol{T_i \geq T_e}$
- Anisotropic heating and scaling consistent with theory

He-II $T_{i,\perp}$ Scales with B_{TF} and Injector Parameters



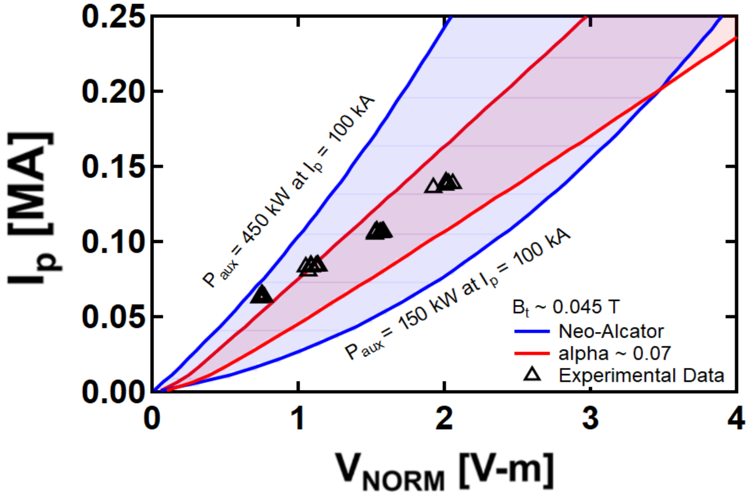


- Difficult to infer majority behavior from impurities
- If majority species $\boldsymbol{T_i \sim T_e}$, reconnection heating is comparable to Ohmic heating

[1] M.G. Burke *et al.*, Nucl. Fusion **57**, 076010 (2017)

Flow Shear and Electron Heating May Improve Confinement, I_p Scaling

LHI Scaling Assuming Linear Ohmic, Stochastic Confinement Regimes



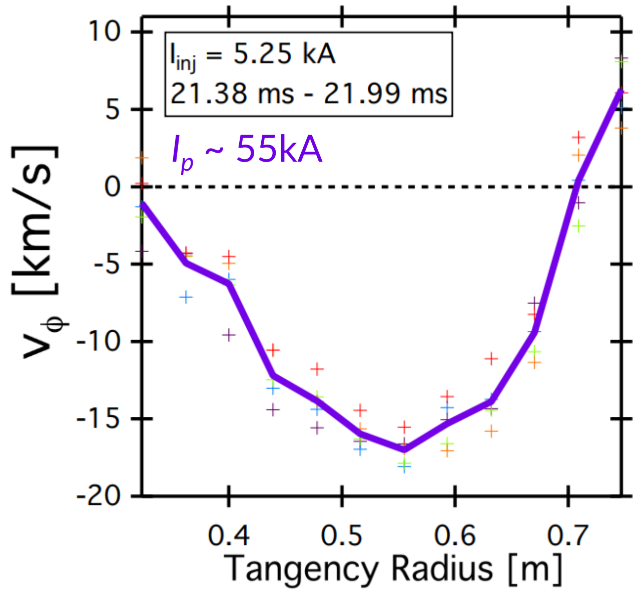
- Reconnection P_{AUX} must be considered to explain I_p trend with existing models
- At equilibrium, helicity input balances resistive helicity dissipation
- Increased P_{AUX} or improved confinement yields higher I_p

$$P_{in} = (V_{LHI} I_p + P_{aux})(1 - F_{rad})$$

$$P_{loss} = W/\tau_e \quad \text{or} \quad \sim n_e T_e v_{th_e}^2 \tau_c S^{-2\alpha}$$

- LHI bias can drive bulk flow shear
- Possible impact on transport
- Scaling with B_{TF}, I_p, and LHI parameters informs predictive model

He-II v_φ Displays Flow Shear Near Edge

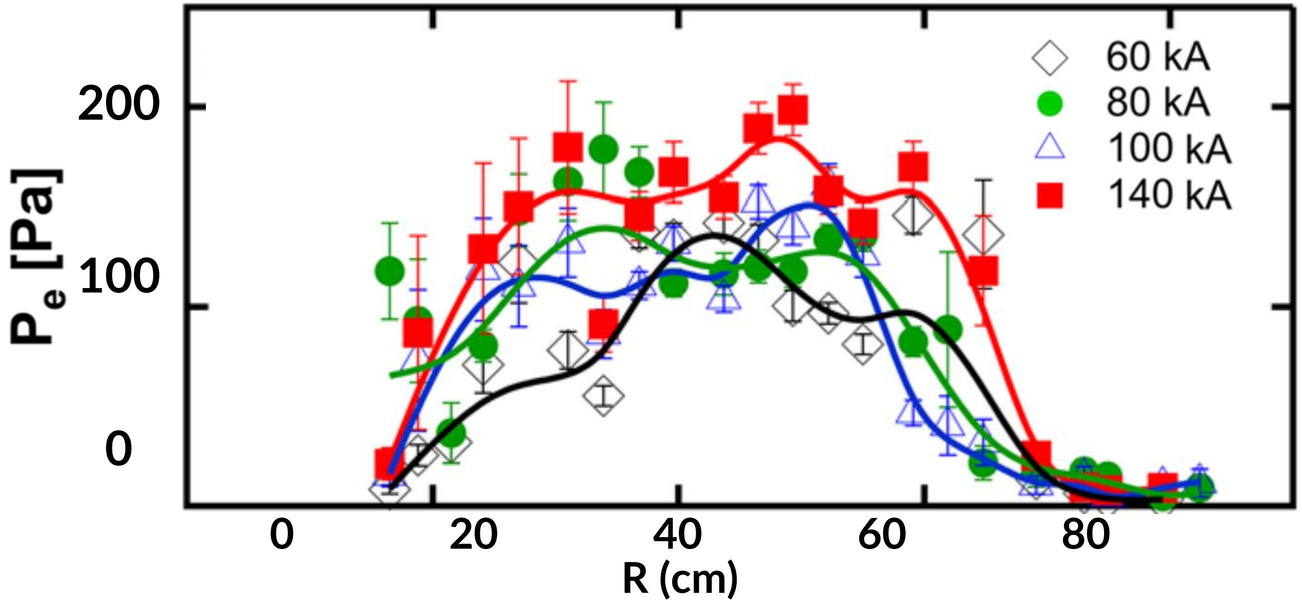


[1] M. G. Burke *et al.*, Nucl. Fusion **57**, 076010 (2017) [2] G. M. Bodner *et al.*, Phys. Plasmas **28**, 102504 (2021)

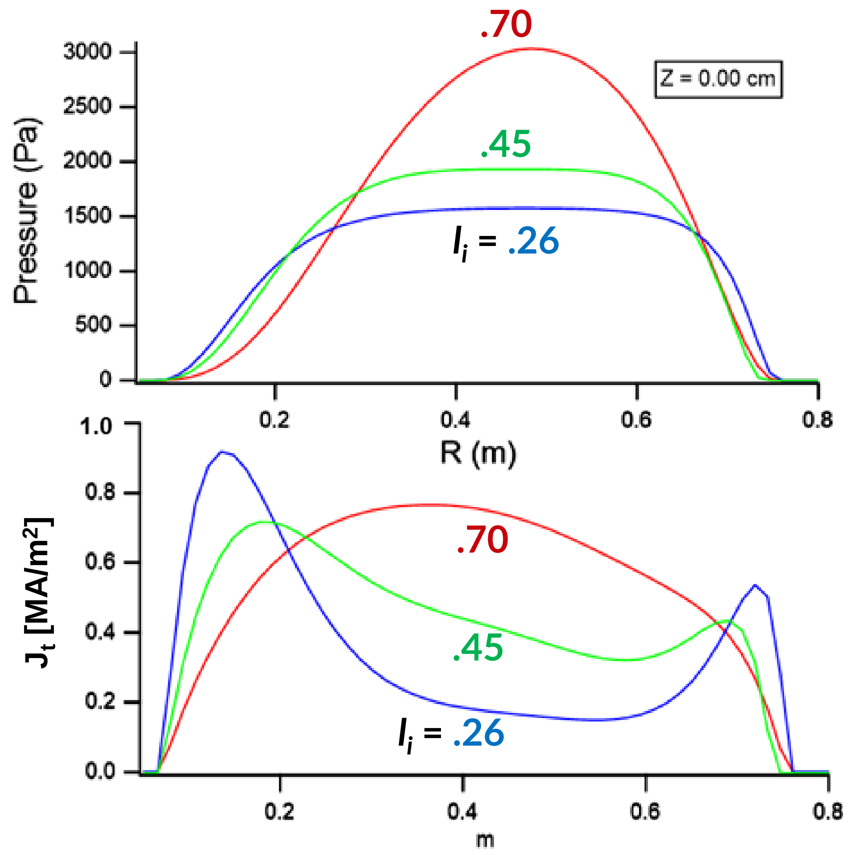
Majority T_i Necessary to Constrain Equilibria

- *P* and *J* profiles are ambiguous with external diagnostics alone
- KFIT equilibria modeled for assessment of diagnostics

Electron Pressure Profile Highly Dependent on V_{LHI}



l_i Scan of 300kA Plasma KFIT Projections



- If $p_i \sim p_e$, $\boldsymbol{p}_{total}$ may vary drastically with V_{LHI}
- Spatially localized majority T_i is <u>essential</u> for evaluating internal plasma parameters

[1] G. M. Bodner *et al.*, Phys. Plasmas **28**, 102504 (2021)

PEGASUS-III
Experiment

Majority $T_i(r)$ Diagnostic in Development

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DNB and ChERS Diagnostics Planned for PEGASUS-III

Refurbished DNB

- 60-80kV H^0 DNB ≤4A
- 3.3 to 4.5cm diameter within plasma

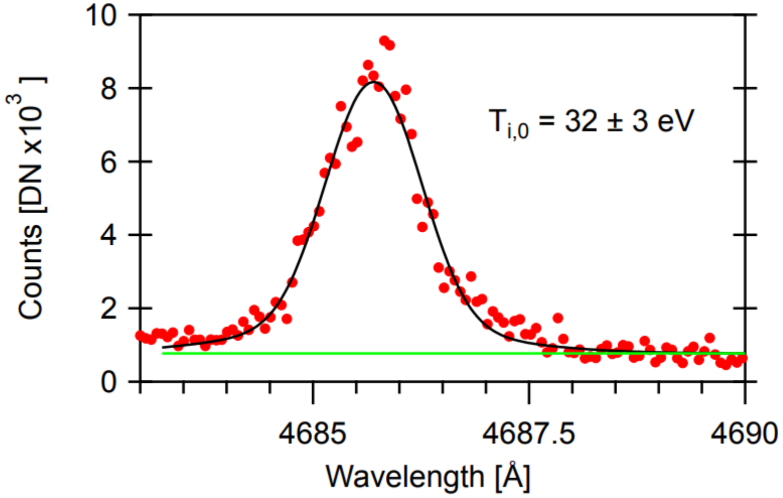
Impurity ChERS with repurposed Ion-Spectroscopy Diagnostic (ISD)

- Move sightlines to intersect DNB
- Inject helium as an impurity
- Observe 468.5nm line from He^{++}
- Fit for $T_i\,(r,t)$ and $v_\varphi\,(r,t)$ measurements

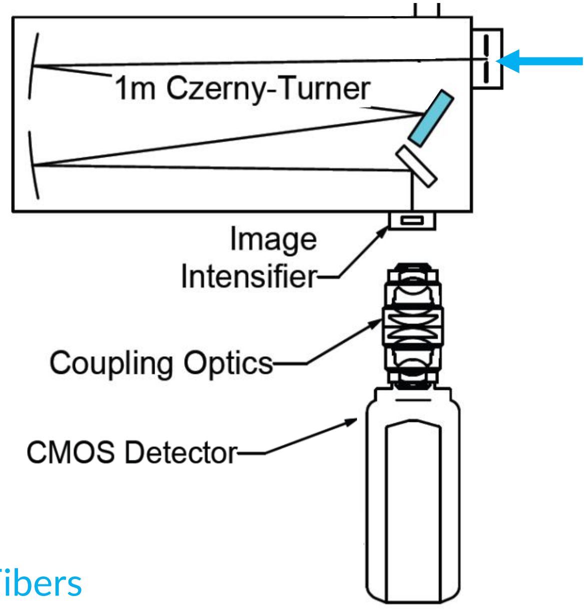
New Majority ChERS diagnostic proposed

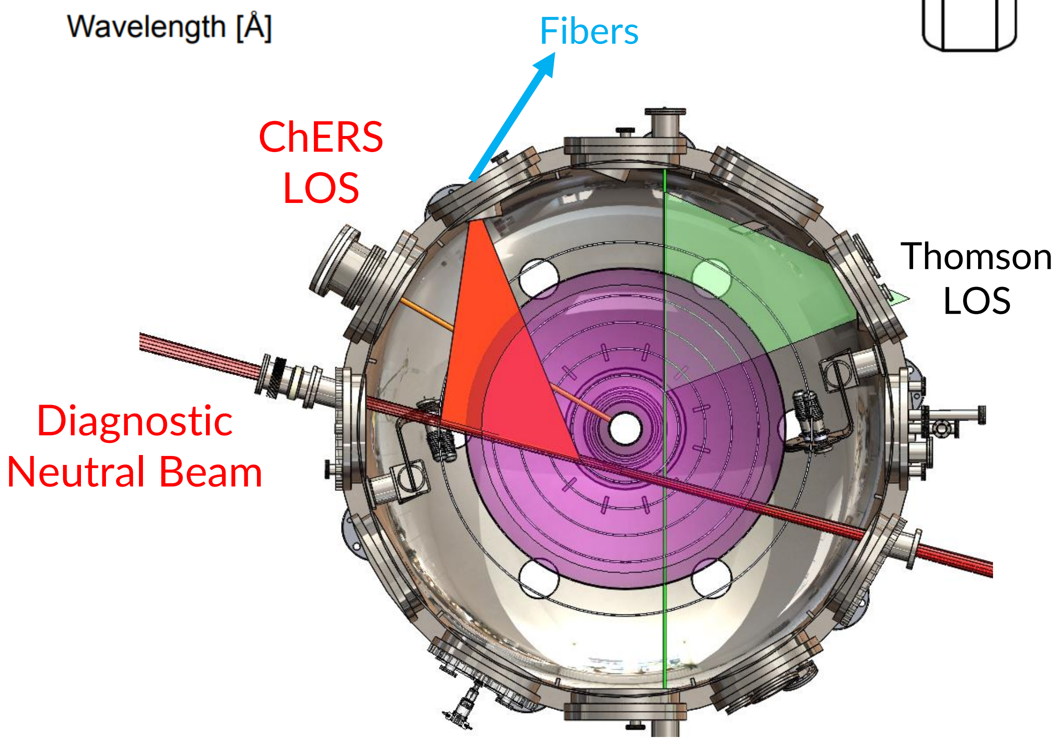
- Observe deuterium-alpha (Dα), 656.3nm
- **Measure equilibrium $T_i(r)$ in LHI**

Single Spatial Channel HeII T_i Fit



ISD Diagram





[1] M.G. Burke *et al.*, Nucl. Fusion **57**, 076010 (2017)

ChERS Diagnostics Examine Core Majority and Impurity Ion Velocity Distributions

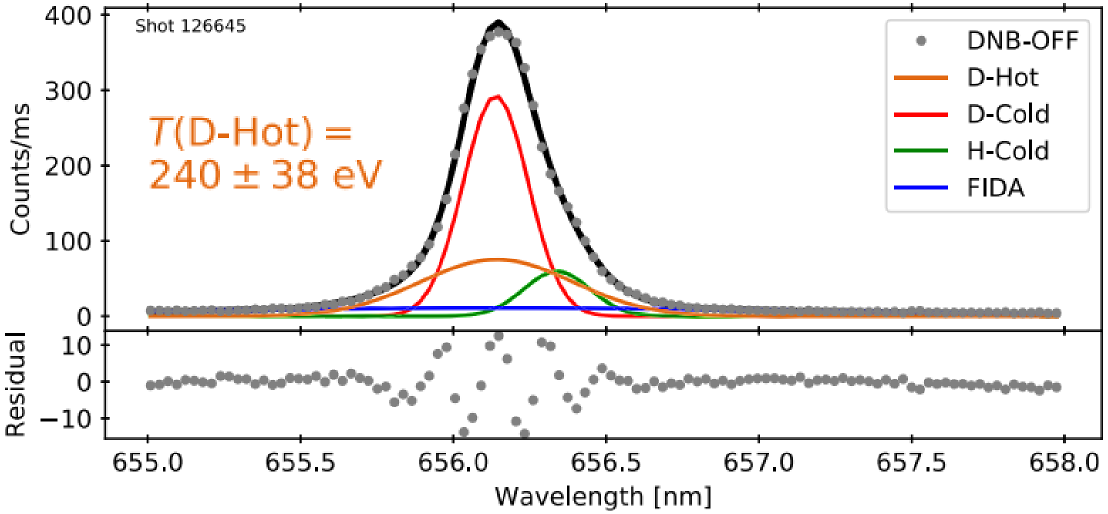
Charge Exchange Recombination Spectroscopy

- DNB neutrals donate electrons to plasma ions, forming "hot" neutrals in excited states

$$H^0 + A^{Z+} \rightarrow H^+ + A^{(Z-1)+}(n,l)$$

- Excited neutrals decay, emitting photons
- DNB illuminates a chord of plasma with signal
- Signal is subject to doppler shifting/broadening
- Each photon samples the local velocity distribution
- Signals fit for T_i and v_φ measurements

Example mChERS Data from TAE's C-2W
(Similar Plasma Parameters to PEGASUS-III)



Plasma parameters/stability impact measurement quality:

- Signal intensity proportional to ion density
- Low T_i → large overlap with background peak
- Signal and background must be constant through exposure

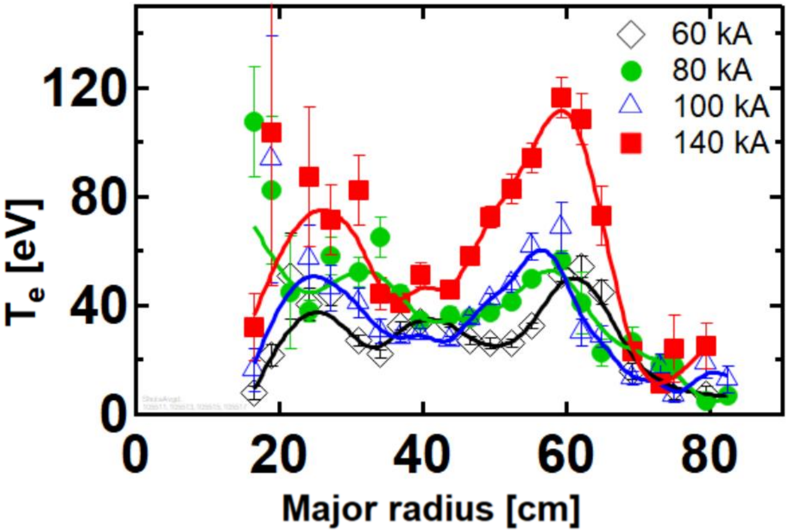
[1] Gupta *et al.*, Rev. Sci. Instrum. **92**, 073508 (2021); doi: 10.1063/5.0043826

Majority (Deuterium) ChERS in an LHI Plasma

Visible Imaging Shows
LHI Plasma Edges are Bright

LHI Phase **Ohmic Phase**

T_e Profiles in LHI



- Neutral fueling from injectors inherent to LHI
- Strong Dα radiation in edge
- Low-density plasmas, fewer photons, small signal
- Signal/Background ratio constrains dynamic range
- <u>Signal/Background most challenging aspect</u>

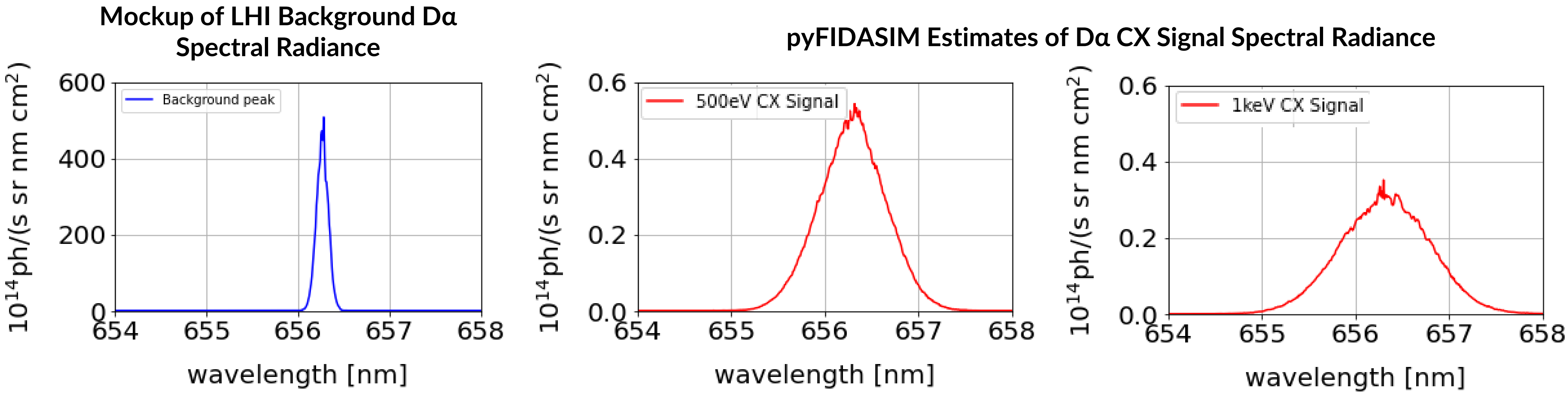
- Signal may be extracted with long, stable exposures
- DNB-ON exposure for charge exchange (CX) signal
- Subtract background, equivalent DNB-OFF exposure

mChERS Diagnostic requirements:

- 50ev < T_i < 2keV, ~10eV resolution
- ~1ms integration times
- Spatial binning < 1cm

G. M. Bodner *et al.*, Phys. Plasmas **28**, 102504 (2021)

Majority Charge Exchange (CX) Signal Evaluated with pyFIDASIM



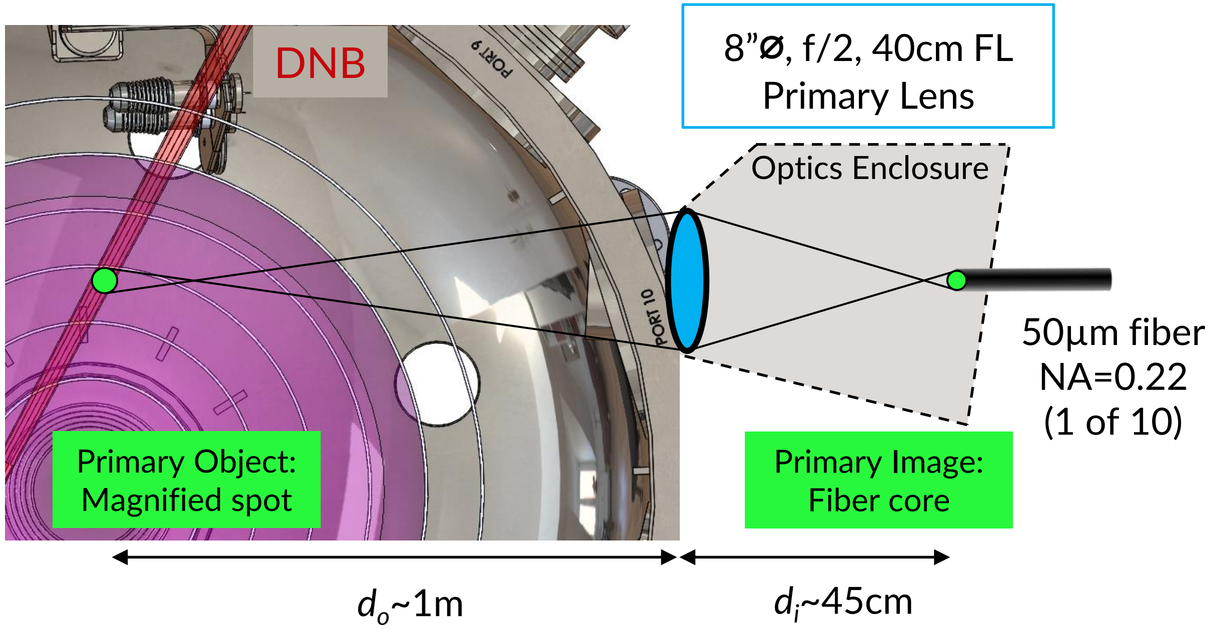
- Measured radiance used to predict Dα background peak in PEGASUS-III
- Instrumental broadening determines width of narrow peak
- Spectrometer FWHM of **0.1nm** needed for T_i resolution, also limits instrument broadening

mChERS Detector requirements:

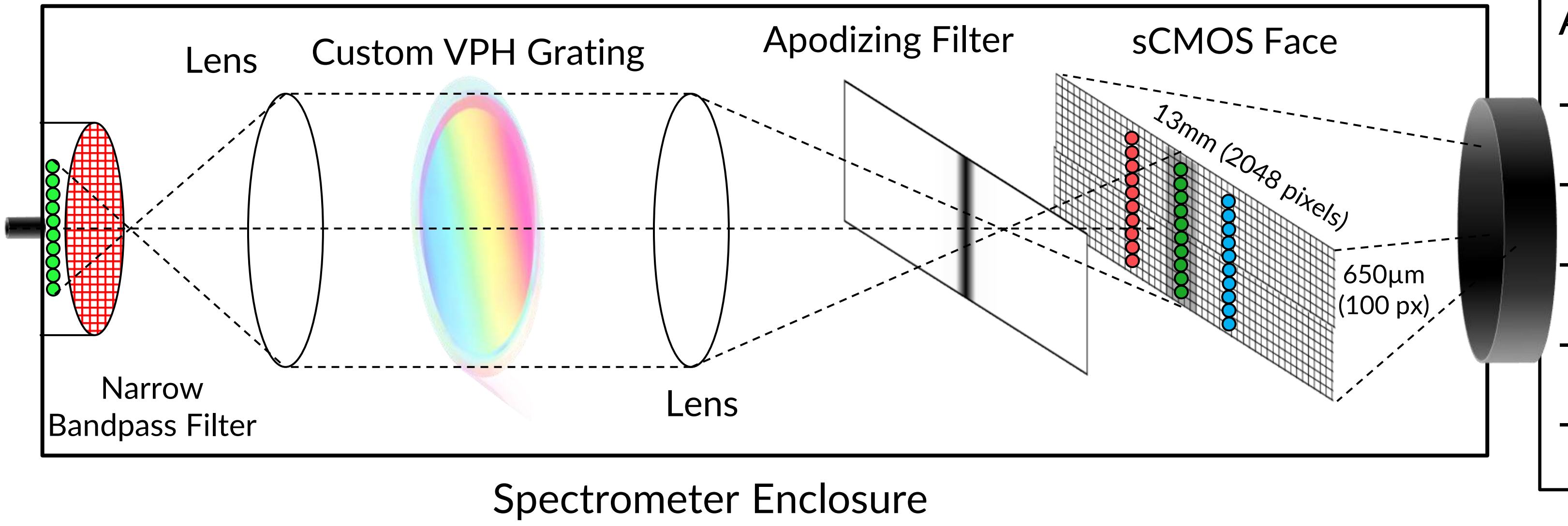
- Dynamic range > 100,000 to 1
- >1000fps for ~1ms measurements
- Sufficient area for multi-channel spectroscopy
- Minimal electronic noise

B. Geiger *et al.*, Plasma Phys. Control. Fusion **62**, 105008 (2020)

Conceptual Design of a Majority ChERS T_i Diagnostic



- Large lens maximizes collection
- 10 fiber array = spectrometer "slit"
- Dα bandpass filter reduces stray light
- Large lenses/grating match etendue of fibers
- Holographic grating maximizes efficiency, ~90%
- Bright background peak would saturate pixels
- Apodizing filter attenuates selected pixels' exposure



Andor Marana 4.2B-6 sCMOS

— 10 spatial channels at 1485fps

— Full vertical binning per channel

— High dynamic range, 34000 to 1

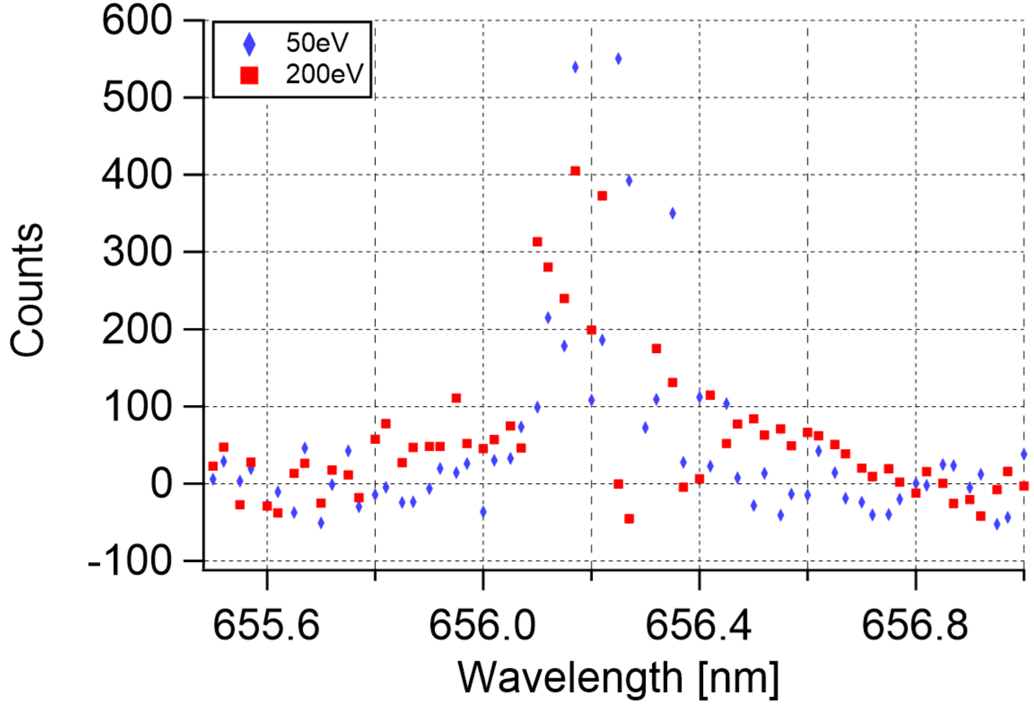
— Excellent quantum efficiency ~90%

— Low read noise, dark current

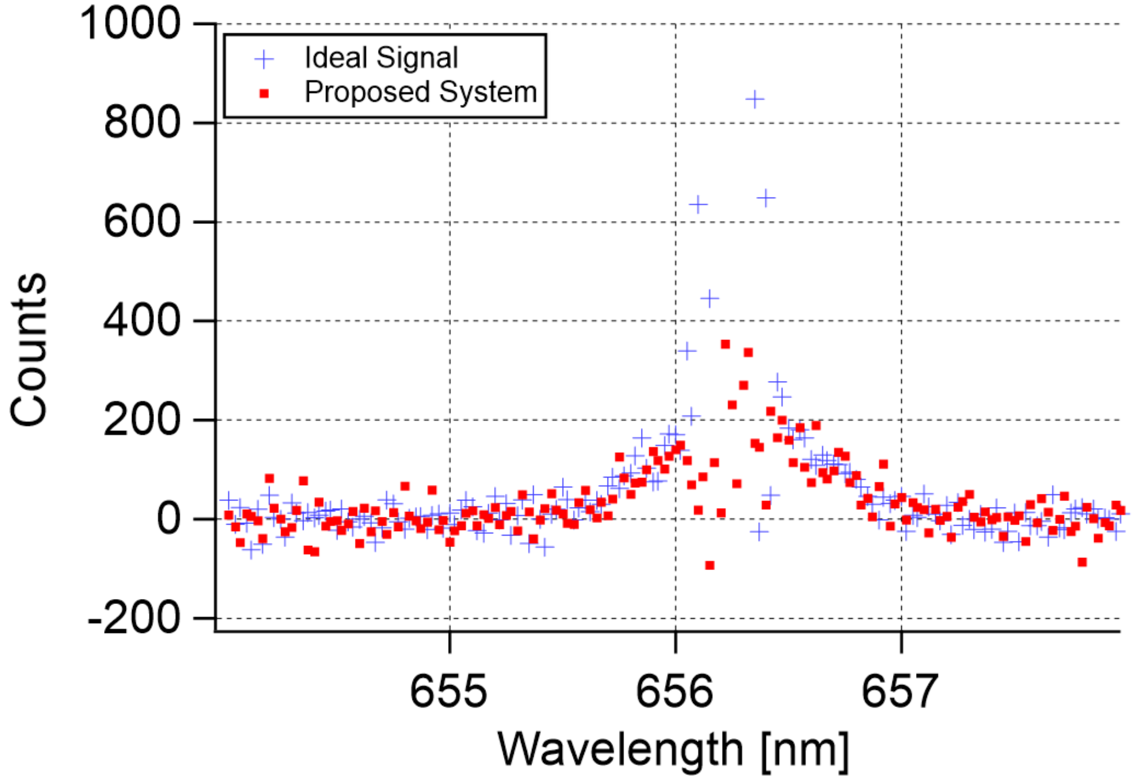
Modeling used to Evaluate Counts, T_i Resolution, Range

- 2.5A DNB, ~30% DNB attenuation, 50% photon efficiency
- n = 0.5x10^{19} m^{-3}, T_i =500eV, 700μs exposures
- Shot noise from signal and constant background
- Dark current, read noise applied
- Apodizing filter estimated, extends dynamic range ~10x

Low-T_i Signals Obscured by Background



500 eV Extracted CX Signal



- Low-T_i data appear distinguishable
- Further analysis needed to determine if practical

PEGASUS-III Experiment

Diagnostic Neutral Beam (DNB) Development Status

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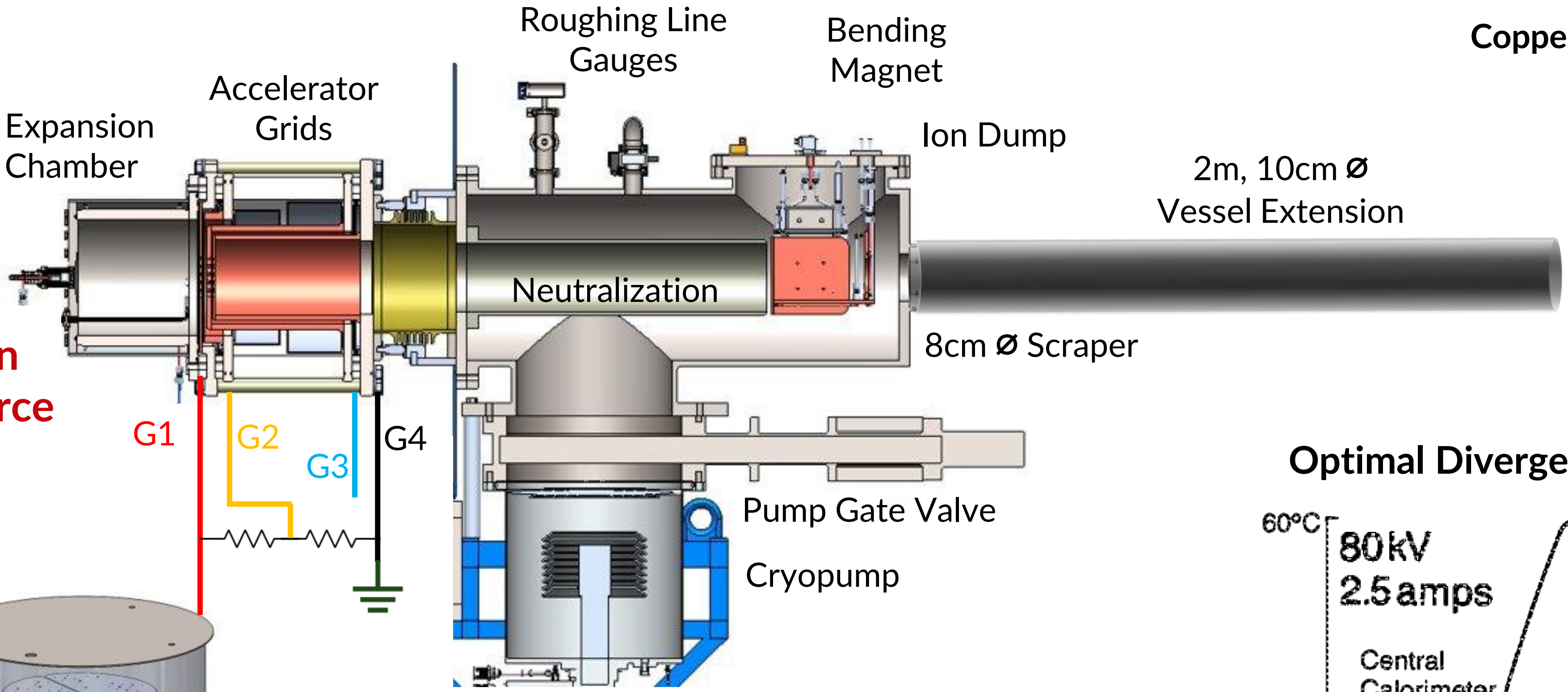
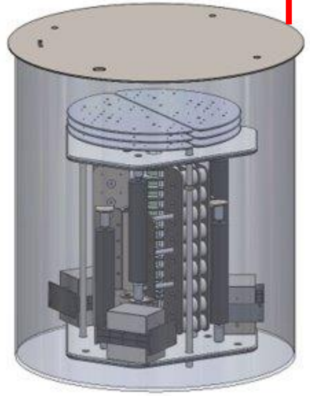
DNB Auxiliary Systems Installed, Ready for Extraction Test



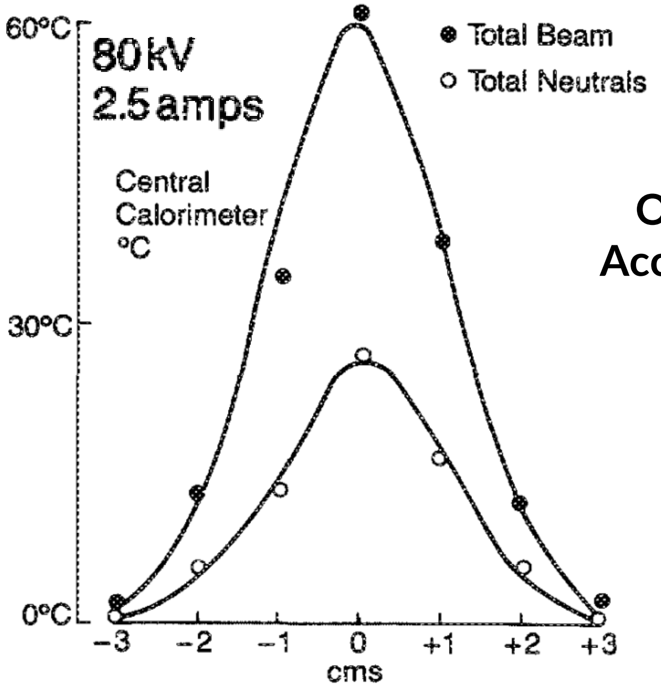


80kV 10ADC Power Supply

Copper Grid with Thermocouples: 2-D Calorimeter

- Accelerator grid power supply developed
- Fault protection system designed
- Preparing for DNB characterization

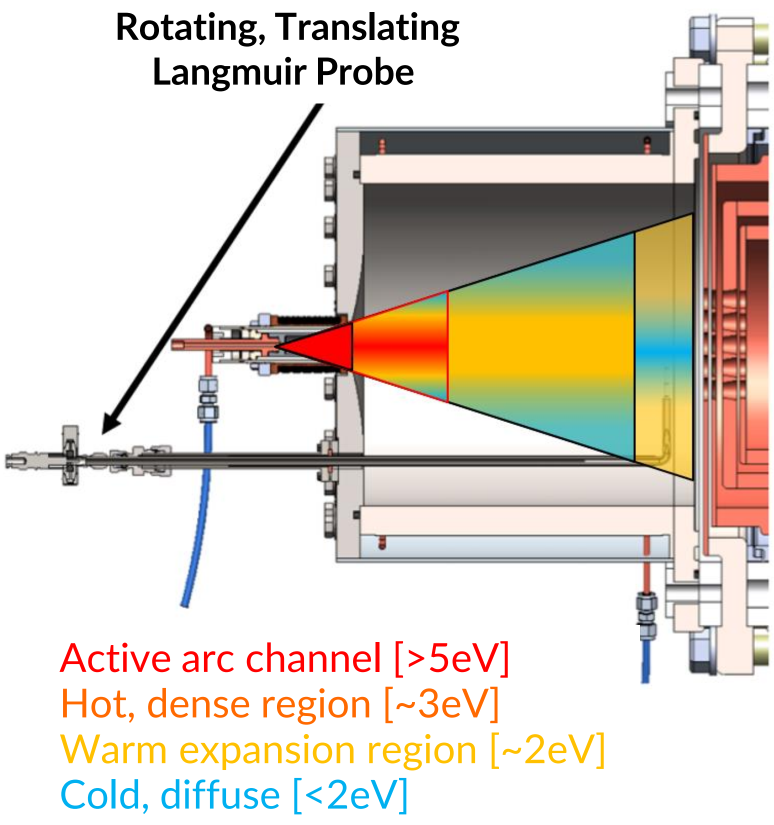
Optimal Divergence Profile [1]

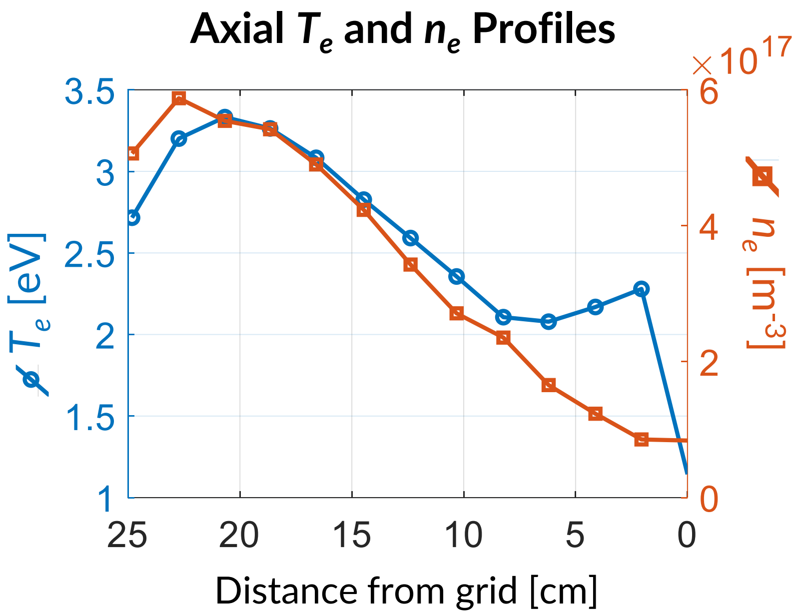


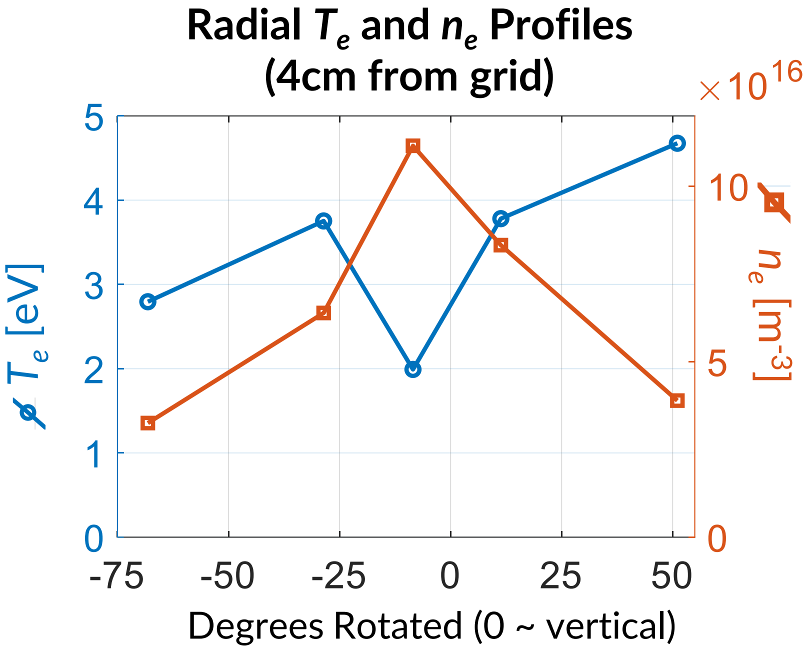
Original Acceptance Data

[1] Coupland *et al.*, Rev. Sci. Instrum. **61**, 472 (1990); doi: 10.1063/1.1141277

Arc-Plasma Ion Source Characterized



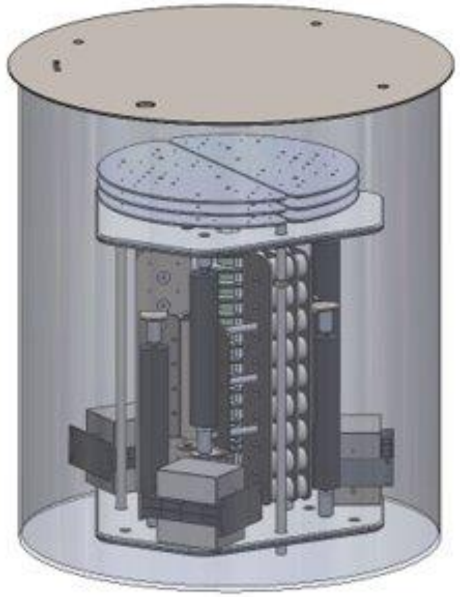




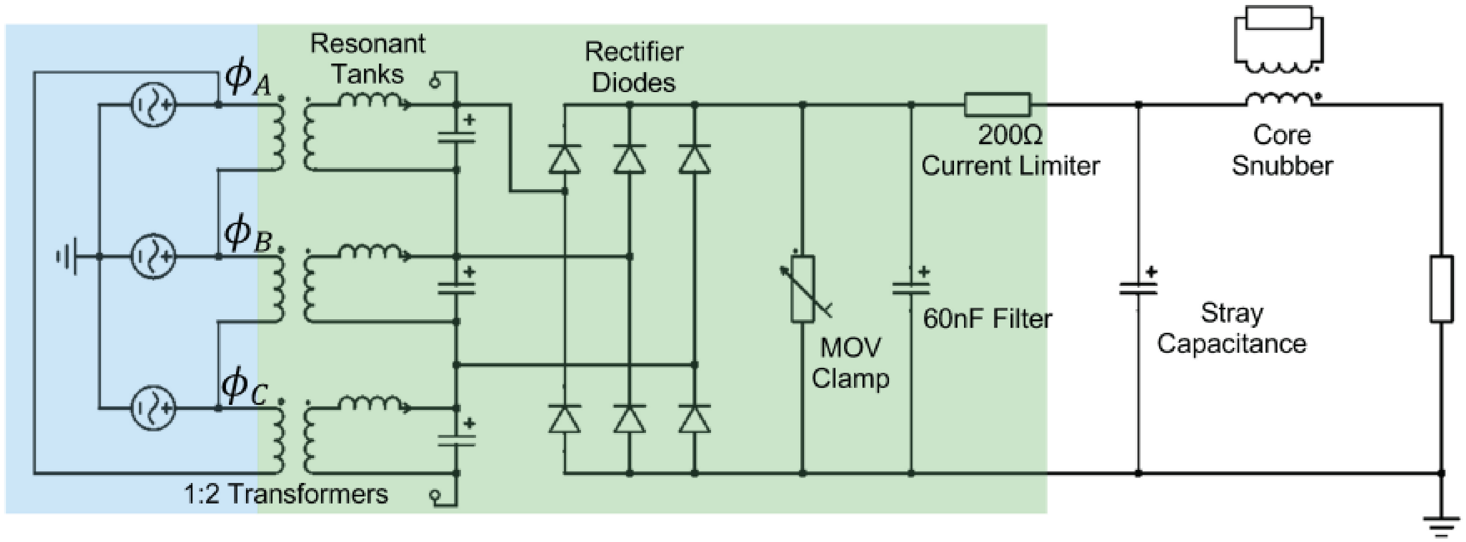
- Ion source optimized for high T_e, maximum stability
- ChERS measurements favor maximum current at ~40keV/amu
- Next, establish operating points for higher density
- Final step before HV extraction test

Programmable 80kV-10A-DC Power Supply Constructed

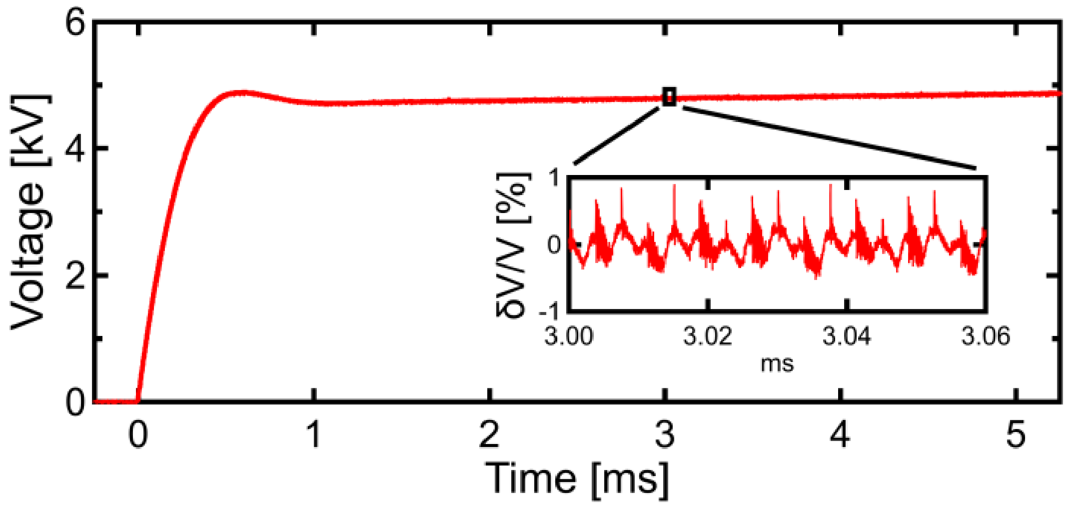
Power Supply in Steel Tank



Simplified Schematic



Demonstrated Low-Ripple DC Output



- RMS ripple < 0.2% demonstrated at 5kV
- <500μs ramp times
- Low stored energy in HV/filter stage
- HV system immersed in FR3 dielectric fluid
- Core snubber provides passive fault protection

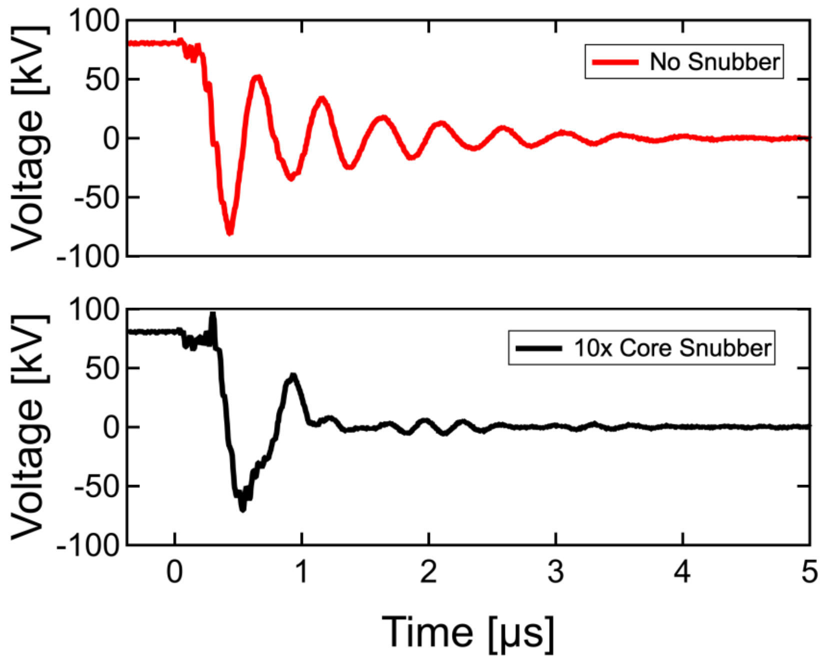
[1] M.W. Bongard *et al.*, IEEE Transactions on Plasma Science, doi: 10.1109/TPS.2022.3165694

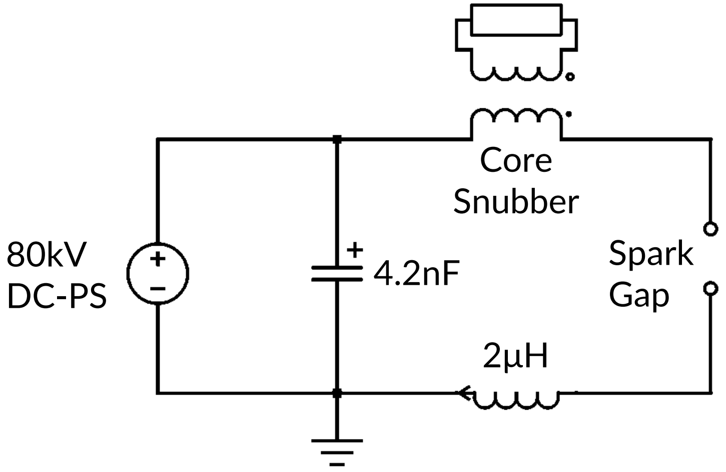
Fault Protection for Delicate, High-Voltage Load Designed

Prototype core snubber tested

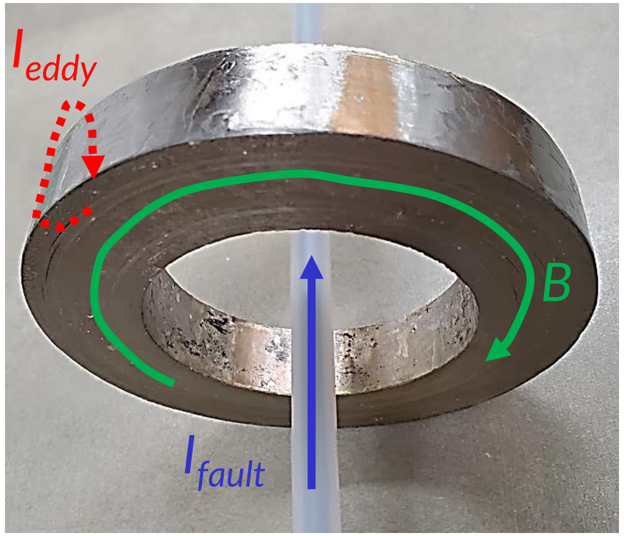
- Materials and toroid designs specified, procured
- Fault scenario replicated
- Energy dissipated at high dI/dt
- Data used to design full capacity system
- Dissipation capacity determined transmission stray C

Snubber Cores Dissipate Fault Energy

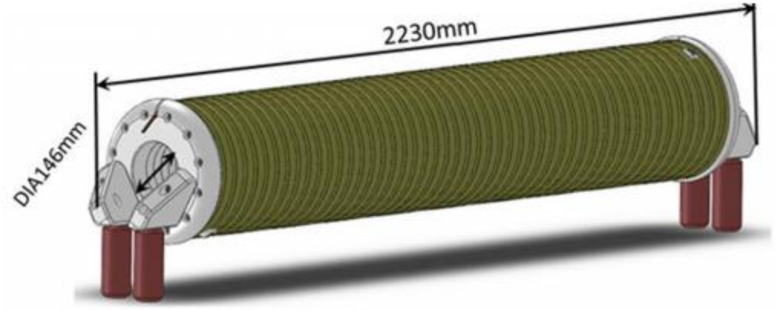




Core Snubber Test Circuit



Inspired by EAST Core Snubber



*Fei et al., Plasma Sci. Technol. **15**, 469 (2013)*

*Jiang et al., Rev. Sci. Instrum. **87**, 123302 (2016)*

DNB Timeline and Research Directions

DNB Commissioning 2023

- Commission 80kV PS, establish high density operation of ion source
- Finalize control code, test extraction of DNB
- Verify acceptable DNB parameters, plan for deployment, design mChERS diagnostic
- Deploy DNB and construct diagnostic

Research Directions

- Use helium injection, ChERS to determine T_i and v_φ profiles for LHI. scaling with B_{TF}, I_p, V_{LHI} vs. V_{inj}
- Develop mChERS system, determine majority T_i profile for LHI plasmas
- Study impact of ion heating on LHI performance, scaling with B_{TF}, I_p, V_{LHI} vs. V_{inj}
- Use T_i profile to refine understanding of LHI MHD equilibrium

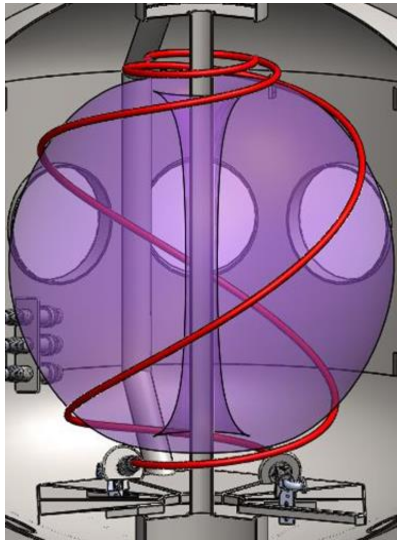
Summary

➢PEGASUS-III will advance understanding of non-solenoidal tokamak current drive, performance scaling of LHI

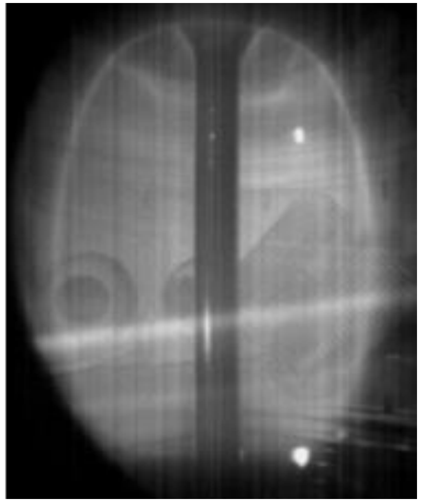
➢A DNB and diagnostics are being developed for spatially localized internal measurements of ion temperatures, bulk flow velocities

➢Internal measurements provide constraints on LHI equilibrium reconstructions, enable study of anomalous ion heating and bulk flow

LHI Array



Tokamak Plasma



PEGASUS-III Machine