Electron Temperature Measurements in the Pegasus Toroidal Experiment

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University of Wisconsin-Madison

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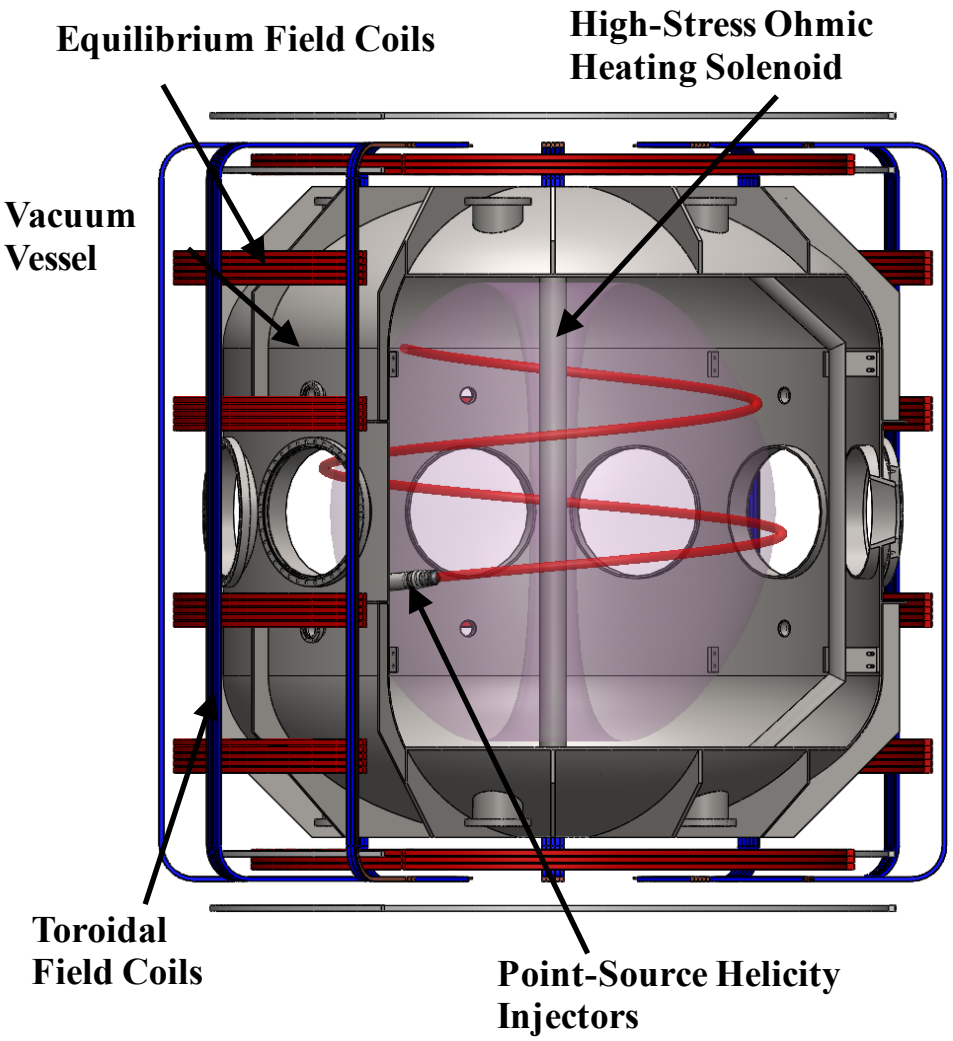


PEGASUS Toroidal Experiment

Electron Temperature Measurements Provide Insight Into Non-Solenoidal Startup

- Local Helicity Injection (LHI) in larger devices depends critically on confinement
- Begin quantifying confinement regimes using multi-point Thomson scattering on Pegasus ST
  - 12 radial positions, $0.15 < R_{maj} < 0.85$ m, $0.01 < T_e < 1$ keV
- T_e (r) in LHI discharges found to be similar to Ohmic profiles
- Peaked density and pressure profiles inconsistent with bulk stochastic transport
- Edge-localized MHD activity suggests dual-zone confinement regime
  - Warm, Ohmic-like core; Cool, stochastic edge

PEGASUS is a Compact Ultralow-A ST



Experimental Parameters

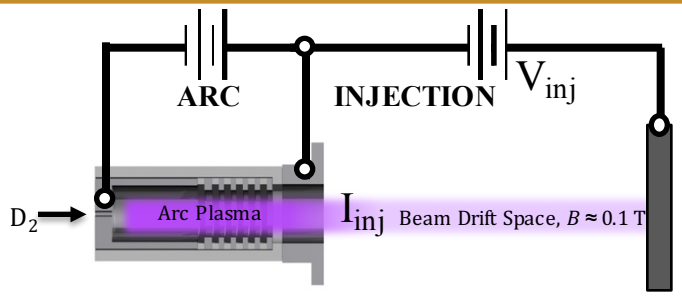
Parameter	Achieved
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	≤ .21
κ	1.4 – 3.7
τ_{shot} (s)	≤ 0.025
β_t (%)	≤ 25

Major research thrusts include:

- *Non-inductive startup and sustainment*
- *H-mode, ELMs at low aspect ratio*

LHI Provides Non-Solenoidal Startup, Depends Critically on T_e

- Local Helicity Injection (LHI) uses injectors localized to the plasma edge[1]



- Physics encapsulated in hierarchy of models:

1. Maximum I_p Limits[2]:

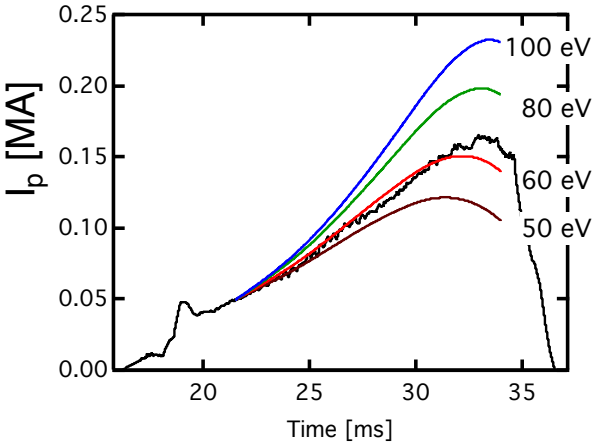
Taylor Relaxation

$$I_p \leq I_{TL} \sim \left(\frac{I_{TF} I_{inj}}{w}\right)^{1/2}$$

Helicity Conservation

$$I_p \lesssim \frac{A_p}{2\pi R_0 \langle \eta \rangle}\left(\frac{A_{inj} B_{\phi,inj}}{\Psi} V_{inj} + V_{IND}\right)$$

T_e-dependent terms



2. 0-D Power Balance Model for $I_p(t)$ [3]:

$$I_p[V_{LHI} - V_{IR} + V_{IND}] = 0; I_p \leq I_{TL}$$

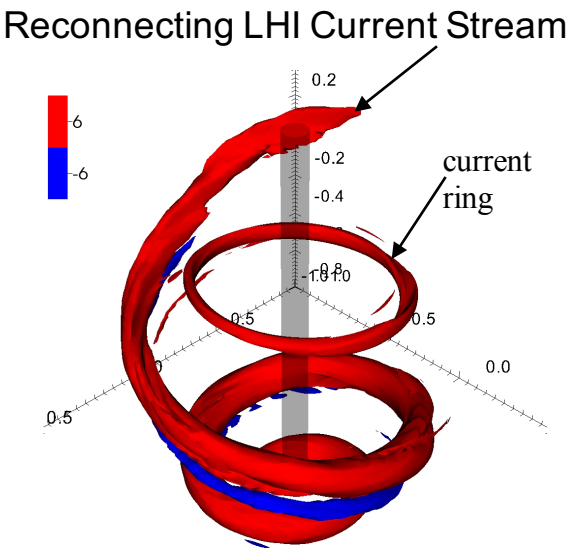
3. 3D Resistive MHD (NIMROD): *see below*

[1] *more info* ***Wed. 2pm****: J.M. Perry, PO6.00001*
[2] *D.J. Battaglia, et al. Nucl. Fusion* ***51*** *(2011) 073029. N.W. Eidietis, Ph.D. Thesis, UW-Madison, 2007.*
[3] *J.L. Barr, GP12.00116,* ***this session***

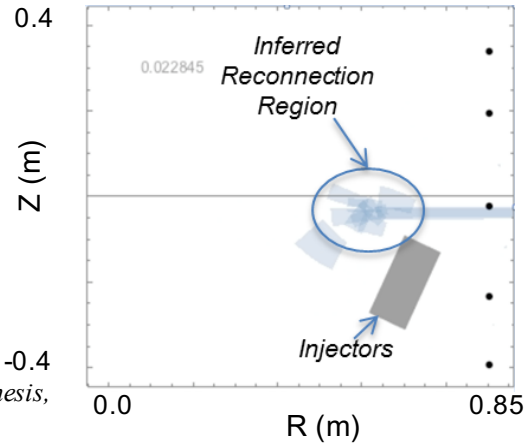
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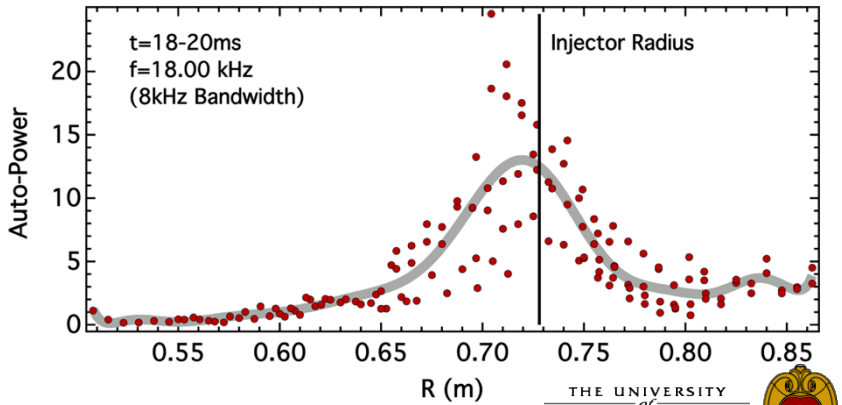
Measurements and Simulations Suggest Edge-Localized Reconnection

- 3D Resistive MHD simulations (NIMROD) predict current rings from reconnecting LHI streams[1]
- Measurements confirm maximum MHD signal localized near injector radius
- MHD analysis indicates streams localized to injector region during LHI drive[2]



[1] *J. O'Bryan, Ph.D. Thesis, UW-Madison, 2014.*
J. O'Bryan, et al., Phys. Plasmas ***19****, 080701 (2012)*





[2] *E.T. Hinson, Ph.D. Thesis, UW-Madison, 2015.*

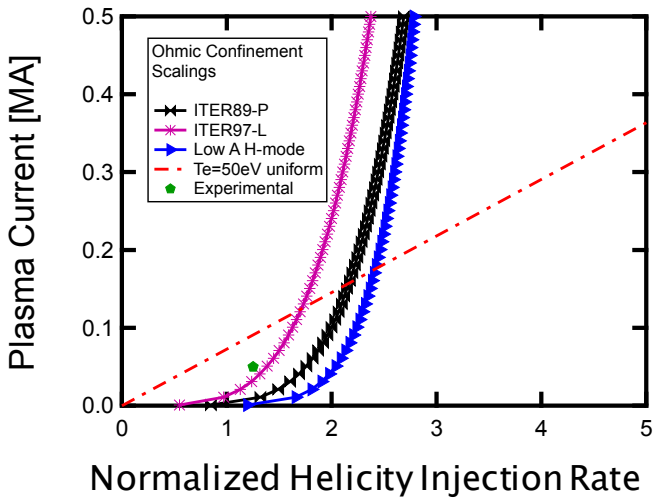
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Experiments on PEGASUS May Determine Dominant LHI Confinement Modes

- Edge localization of MHD suggests possible dual-zone confinement
  - Ohmic-like core
  - Stochastic edge
- For typical PEGASUS parameters, transport regimes separated by ~order of magnitude
- For L-mode confinement, I_p from LHI scales favorably with helicity injection rate

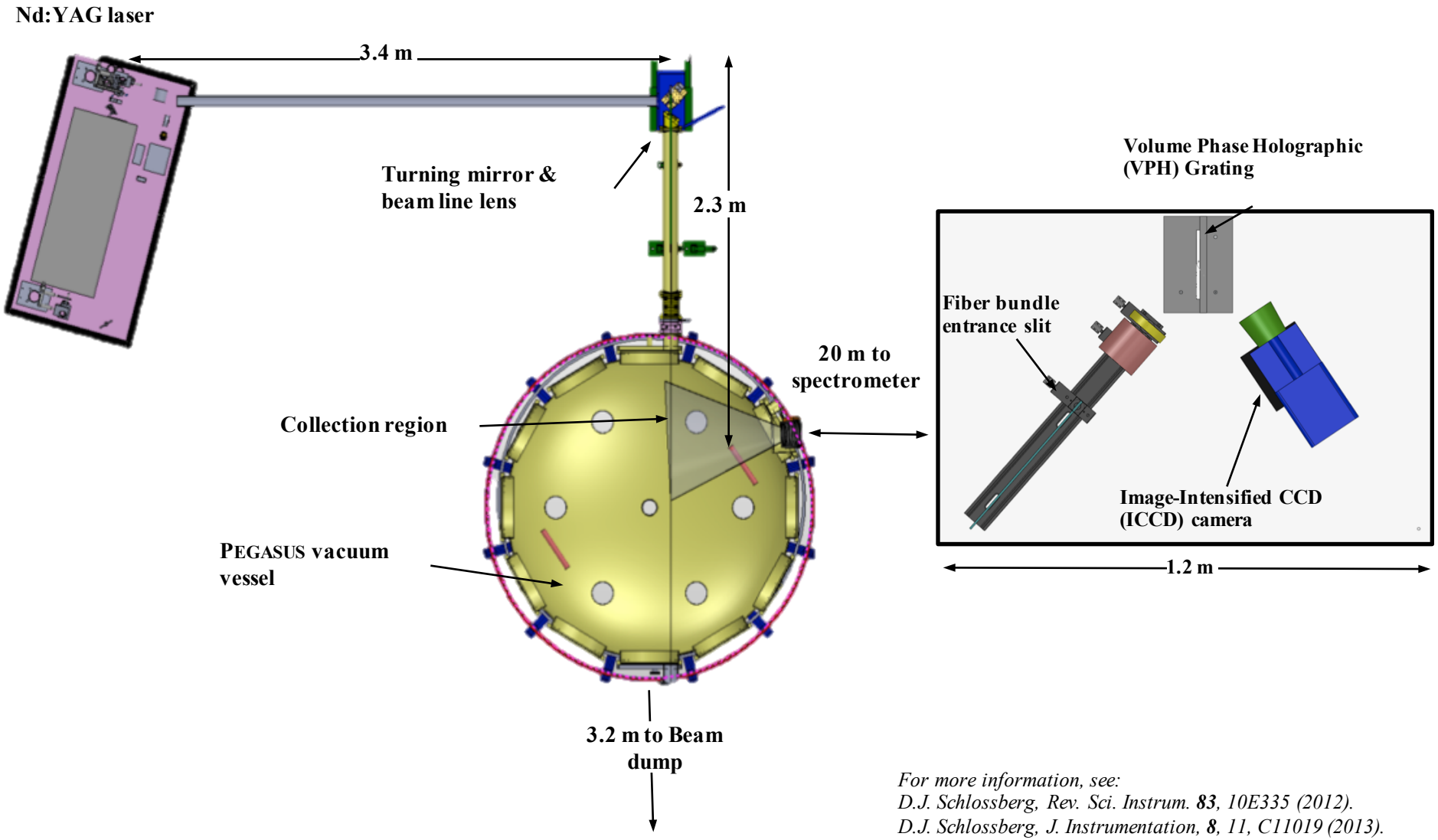
Warm Core	Cool Edge
OH-like confinement	Stochastic confinement
Low MHD	Large MHD

Transport	Approx. χ_e (m^2/s)
Classical:	0.2
Neo-classical (trapped):	20
Empirical (L-mode thermal):	200
Stochastic:	2000



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PEGASUS Thomson Scattering Uses Nd:YAG Laser, VPH Gratings, and ICCD

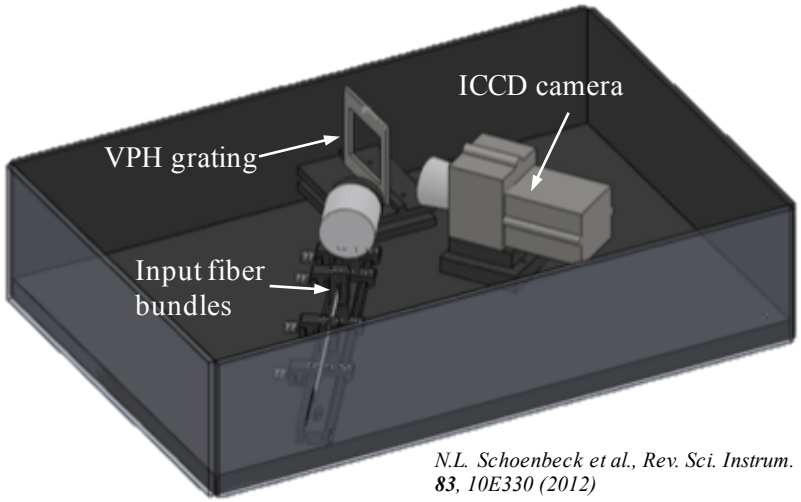


For more information, see:
D.J. Schlossberg, Rev. Sci. Instrum. ***83****, 10E335 (2012).*
D.J. Schlossberg, J. Instrumentation, ***8****, 11, C11019 (2013).*

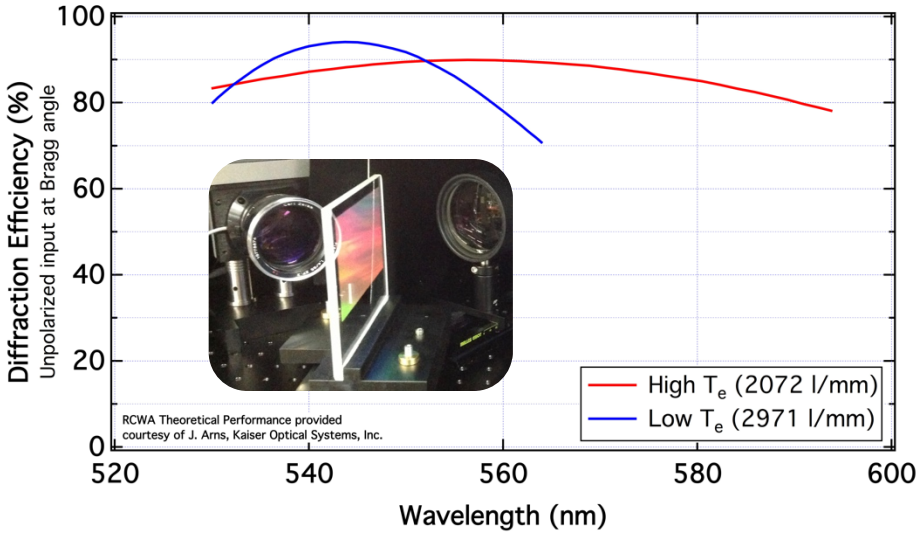
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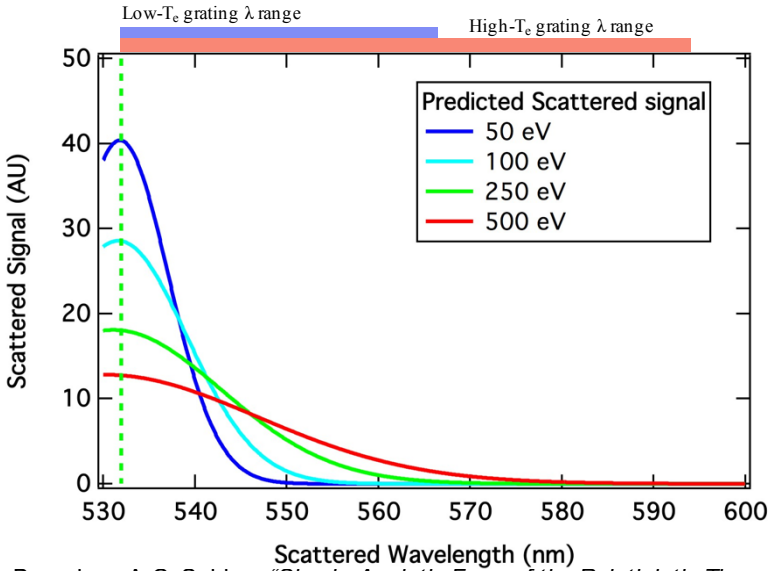
Spectrometers Employ VPH Gratings and ICCD cameras

- Custom achromatic entrance lens
- Kinematic mount provides easy interchange of gratings with different dispersions
- Image Intensified CCD (ICCD) detector
  - High quantum efficiency Gen 3 Intensifier
  - Fast gating capability to 1.2 ns



N.L. Schoenbeck et al., Rev. Sci. Instrum. ***83****, 10E330 (2012)*





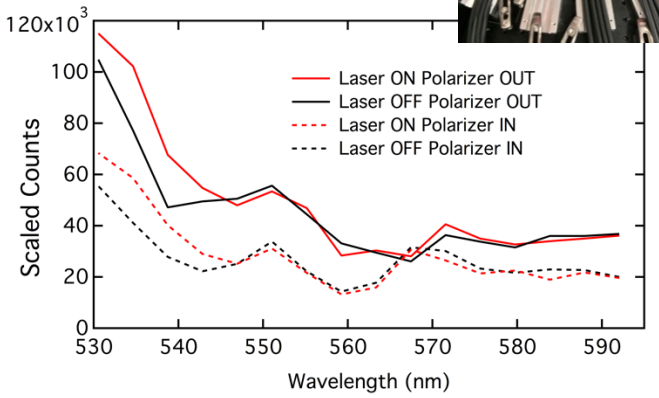
Based on: A.C. Selden, *"Simple Analytic Form of the Relativistic Thomson Scattering Spectrum,"* Phys. Lett. **79A**, 5,6 1980.

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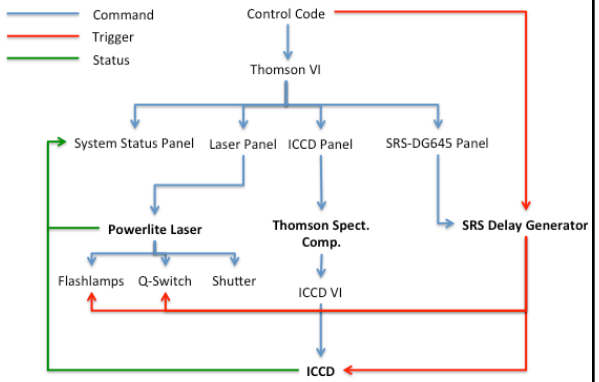
Upgraded PEGASUS MPTS System Delivers Improvements in Many Areas

Wire grid polarizers significantly reduce unwanted background

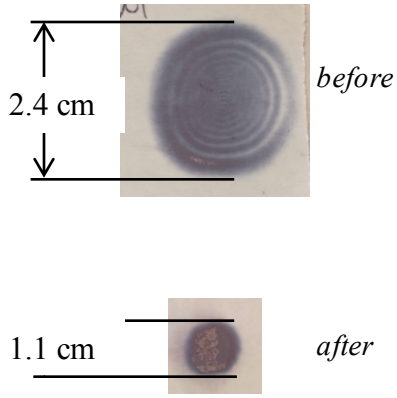




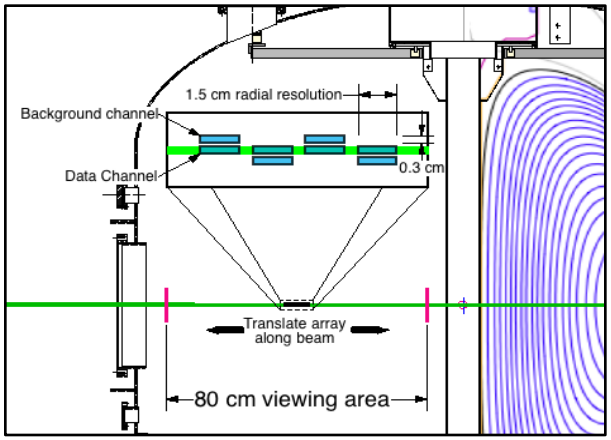
System automation increases reliability and system performance



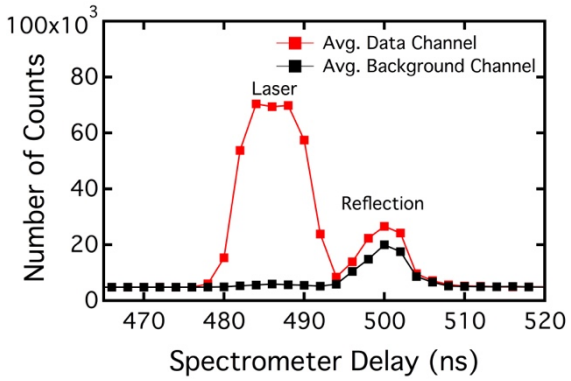
Optimized timing improves beam quality



New fiber bundle arrangement eases alignment



Collection time window optimized to capture scattered signal, reject stray light



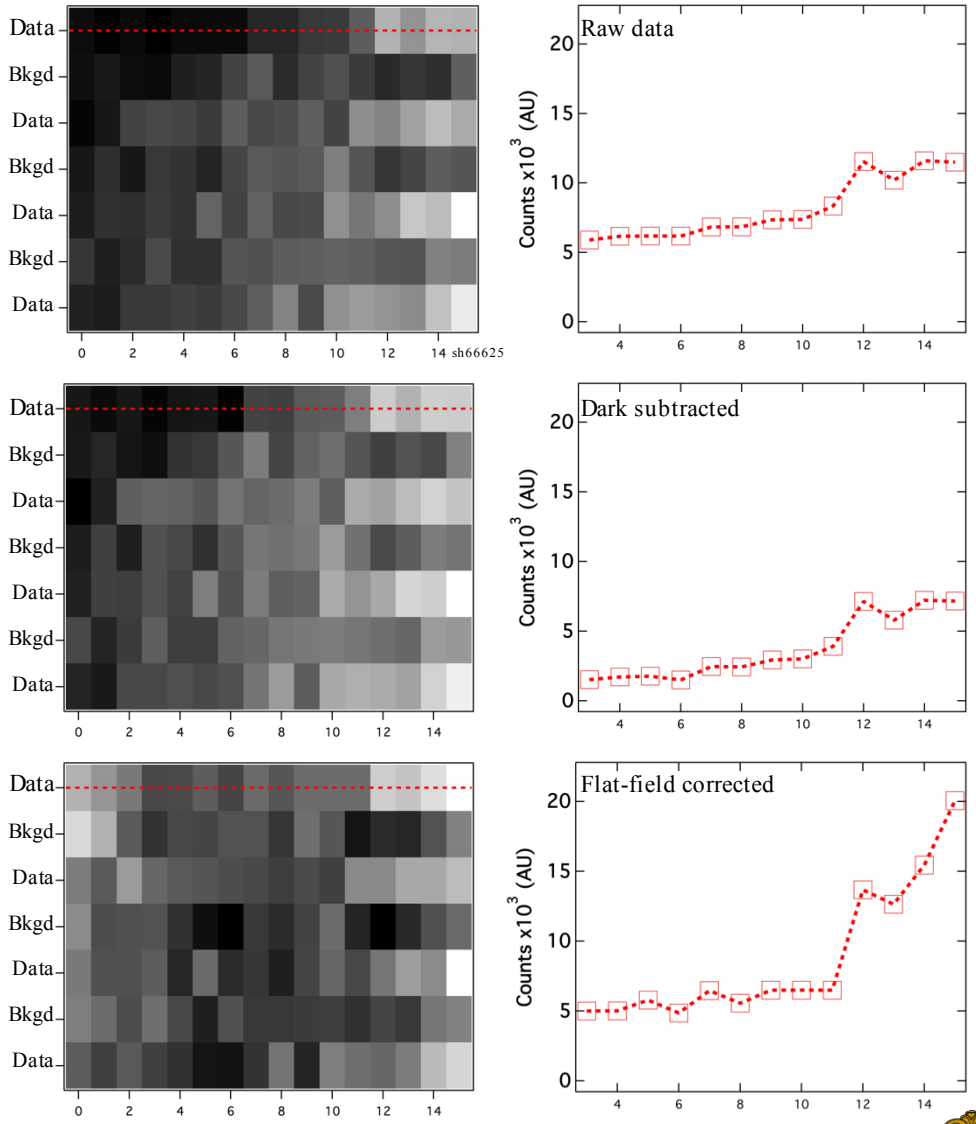
For more details see:

G.M. Bodner
GP12.00119
this session

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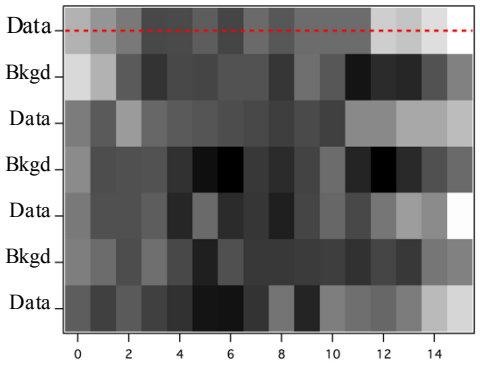
Thomson Analysis Consists of Sequential Image Processing Steps

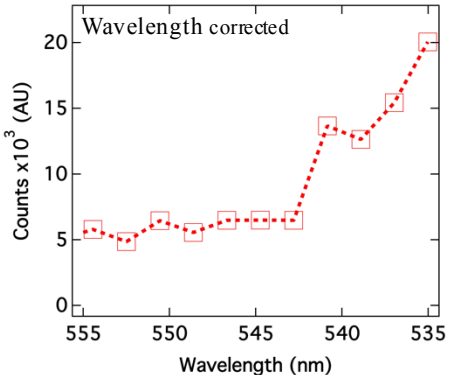
- **Single image** for each plasma shot
  - Each image contains 8 spatial channels (4 on-laser, 4 background)
- **Subtract a dark image** from plasma image to remove fixed pattern noise & offsets
  - Hot pixels
  - Camera readout amplifier offset
- **Correct for flat field** effects
  - Differing efficiencies vs. wavelength
  - Optical vignetting

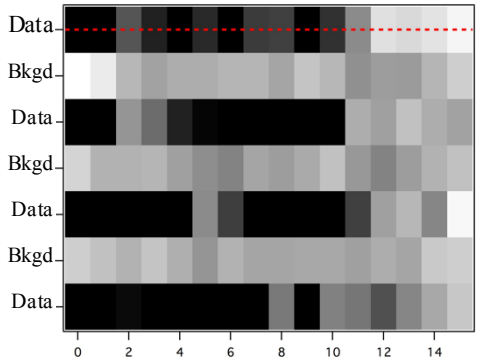


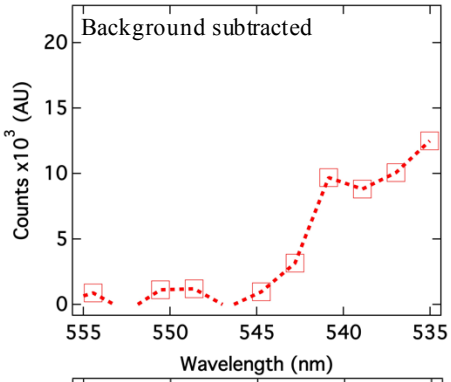
Gaussian Fits Used to Obtain Electron Temperatures

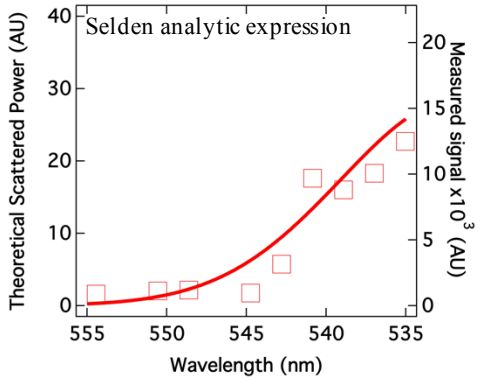
- **Correct λ mapping** for slit curvature
  - Use previous calibration with emission line lamps
- **Subtract background** channels from data channels
- **Gaussian fits** applied to obtain temperature
  - Refined analysis using Selden's analytic formula in development

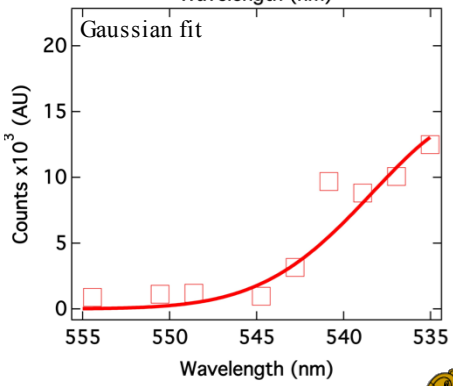








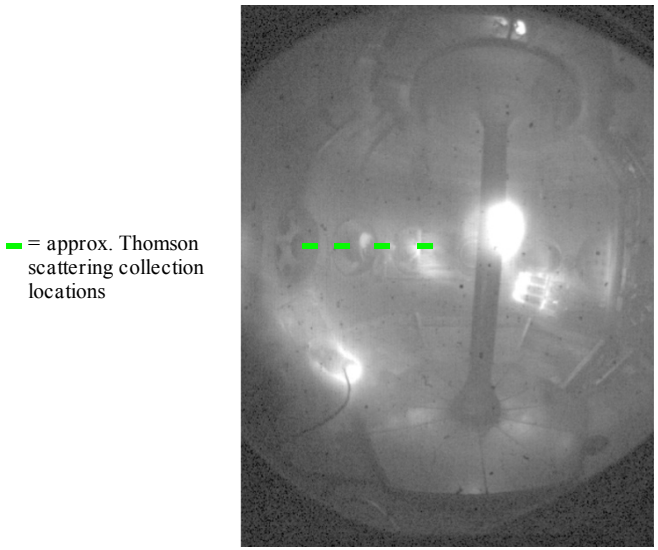


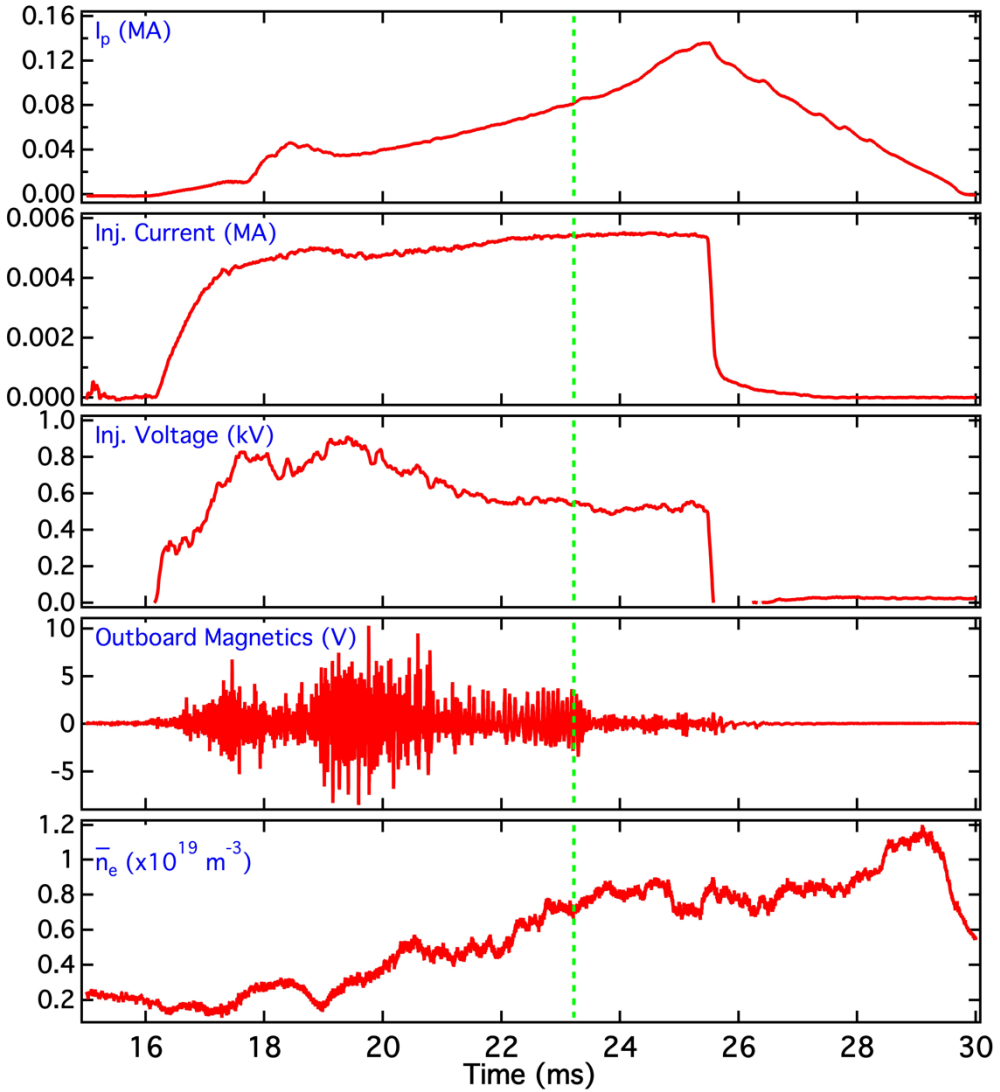


[1] A.C. Selden, Phys. Lett., **79A**, number 5, 6, Oct. 1980

LHI Plasmas with I_p~0.14 MA, I_{inject}~6.5 kA Diagnosed

- Plasmas highly reproducible
- Typically:
  - $B_T = 0.1$ T
  - $I_{inj,\,max} = 5.5$ kA
  - $V_{inj,\,max} = 900$ V
  - $t_{Thomson} = 23.225$ ms
  - $\bar{n}_e\,(t_{Thomson}) \approx 0.7 \times 10^{19}$ m^{-3}

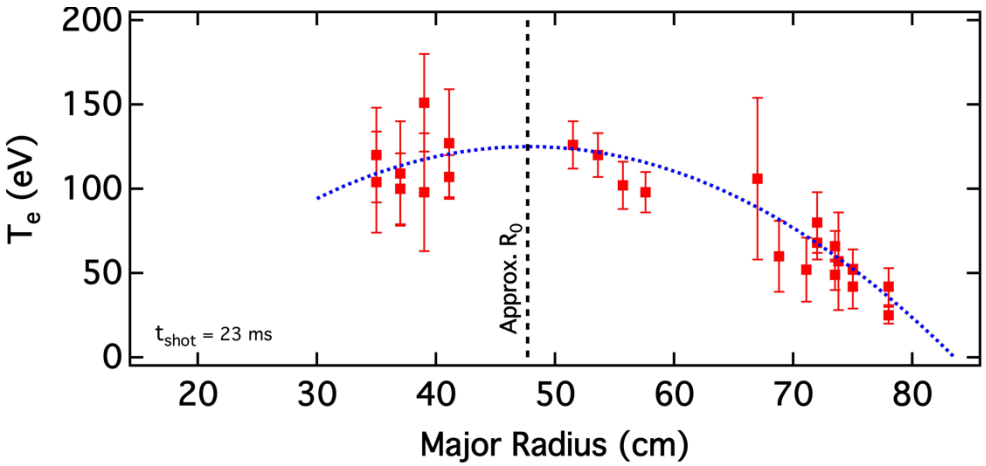


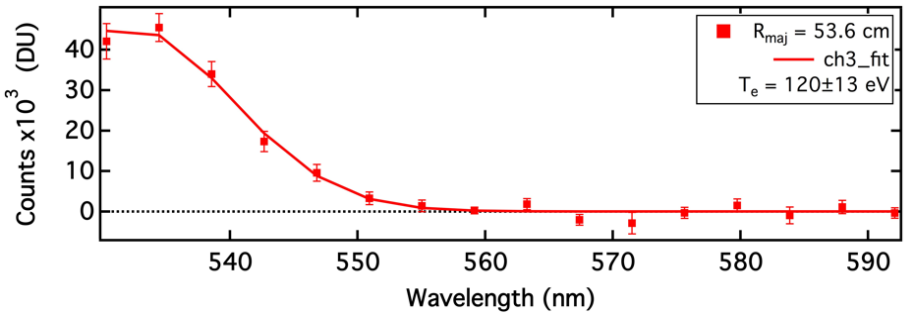


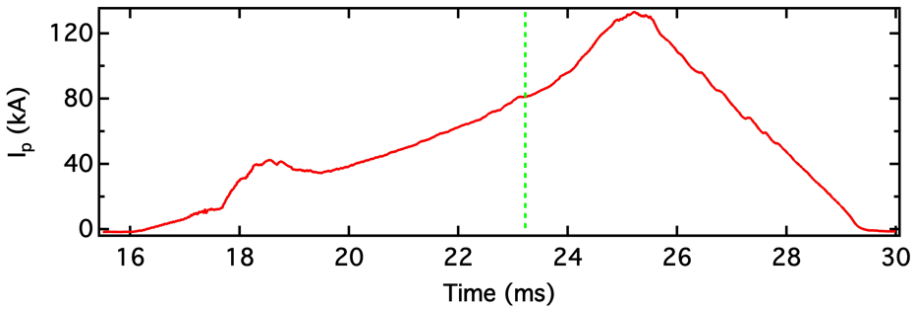
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First Measurements Show Peaked $T_e(r)$ During LHI Drive

- T_e measured at 16 radial locations during helicity injection drive
- >10 data and >10 background shots averaged at each radial location
  - Greatly increases SNR
- $t_{Thomson}$ ~1.75 ms prior to peak I_p
  - Bulk plasma still coupled to injectors



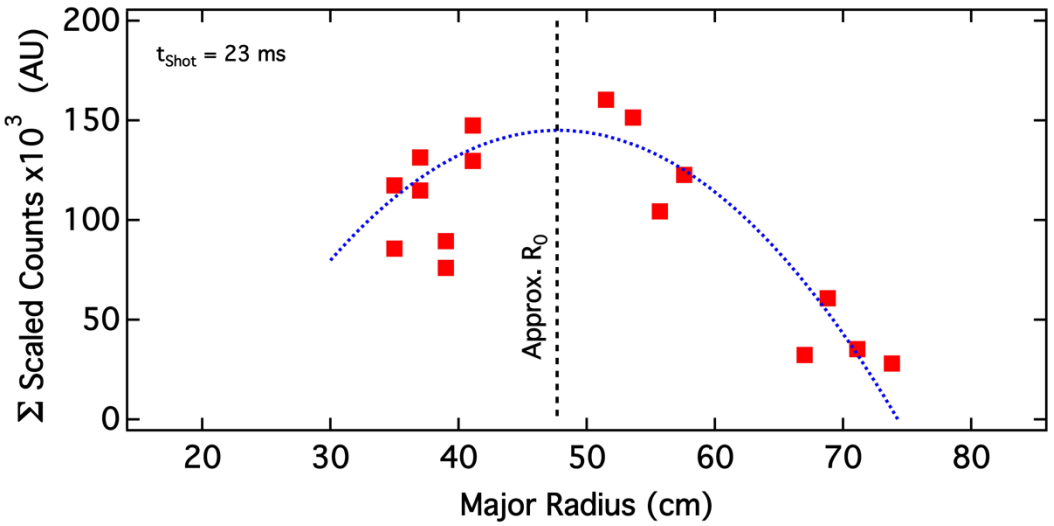


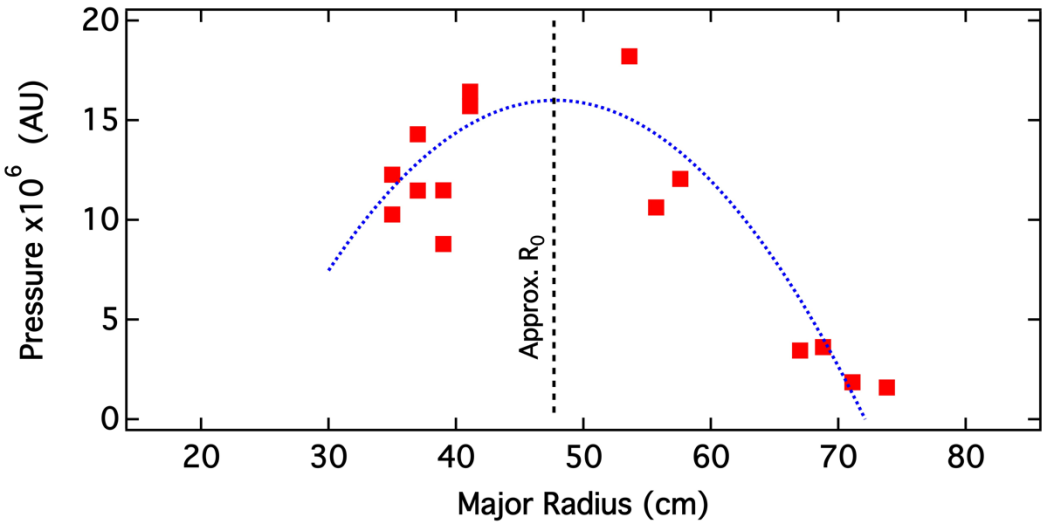


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Peaked Density and Pressure Profiles Suggest Ohmic-like Confinement

- Scattering at each location summed over λ
  - Ersatz for electron density
  - Profile peaks near plasma R_0
- Pressure profile estimated as $T_e(R) \times \Sigma \text{counts}(R)$
  - Peak p_e ~6x edge p_e
  - Peaked profiles inconsistent with bulk stochastic transport
  - Core heating could be from PF induction
- If scales favorably, *could provide excellent target for NBI coupling*

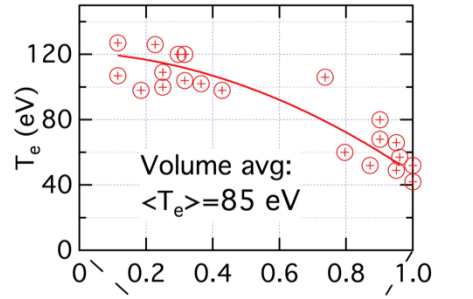


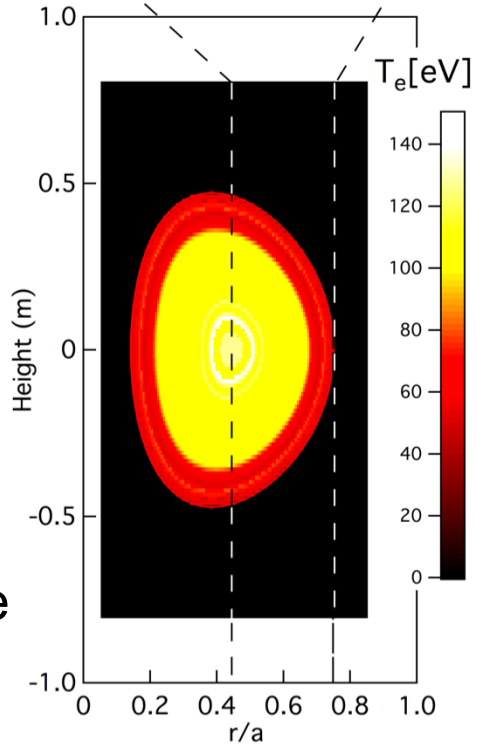


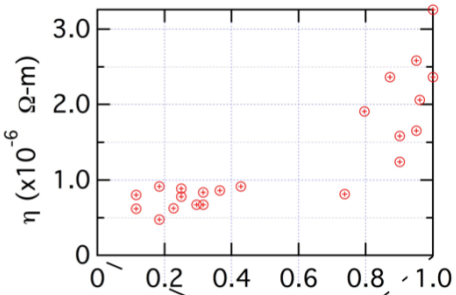
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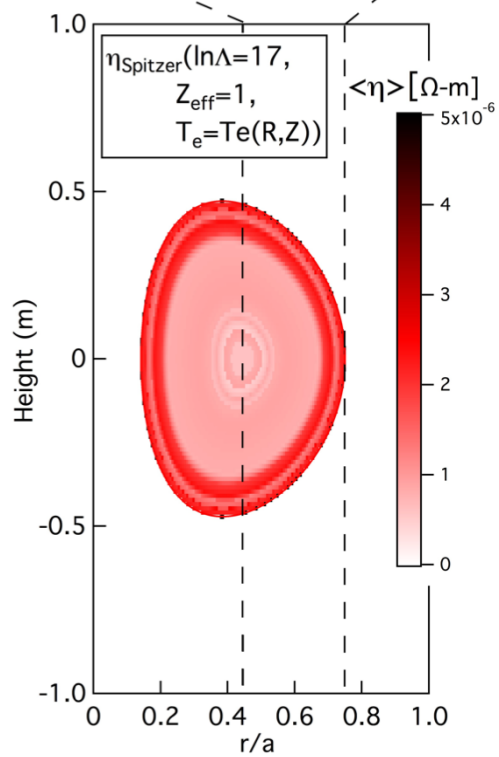
Mapping Measured T_e to Calculated Plasma Shape Provides $\langle T_e \rangle$ and $\eta_e(r)$

- Fast boundary reconstruction code estimates plasma edge[1]
- Simple geometric mapping gives averaged T_e:
  - Volume-averaged: $\langle T_e \rangle = 85$ eV
  - Uniform J(r): $\langle T_e \rangle \approx 76$ eV
    $\langle \eta_e \rangle = 1.3 \times 10^{-6}$ Ω-m
- Profiles suggest hot core, cool edge
  - Dual confinement regimes?







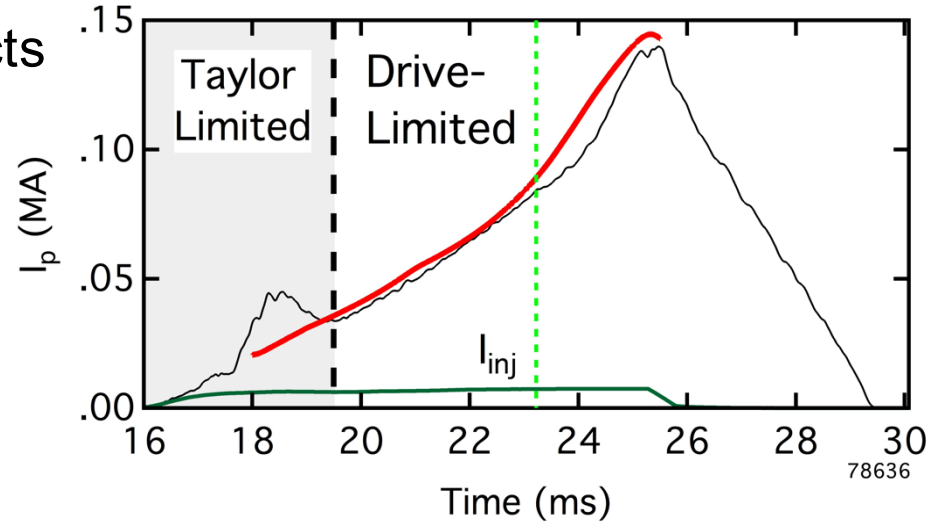


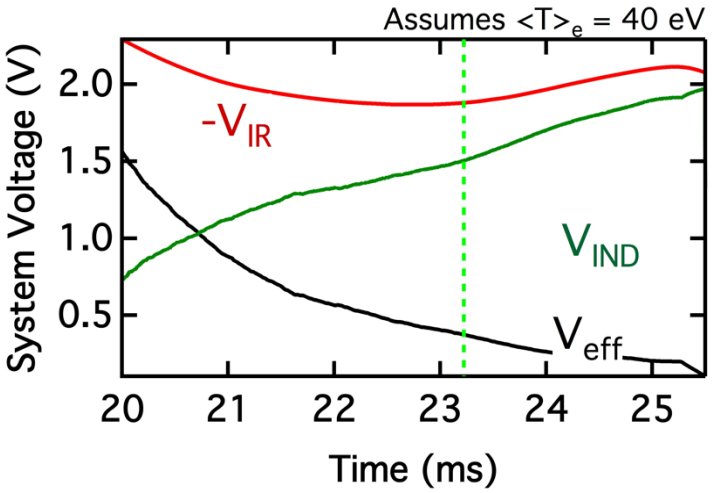
[1] J.L. Barr, ***this session*** GP12.00116

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0-D Power Balance Model Reveals Significant Inductive Drive at $t_{Thomson}$

- Power balance model for $I_p(t)$ predicts LHI discharge performance[1]
- Model represents plasma drive with inductive, helicity injection, and resistive terms
  - At $t_{Thomson}$, $V_{IND} > V_{eff}$
  - Inductive drive could provide core heating
- Understanding V_{IR} term critical to model accuracy
  - Strongly dependent on T_e



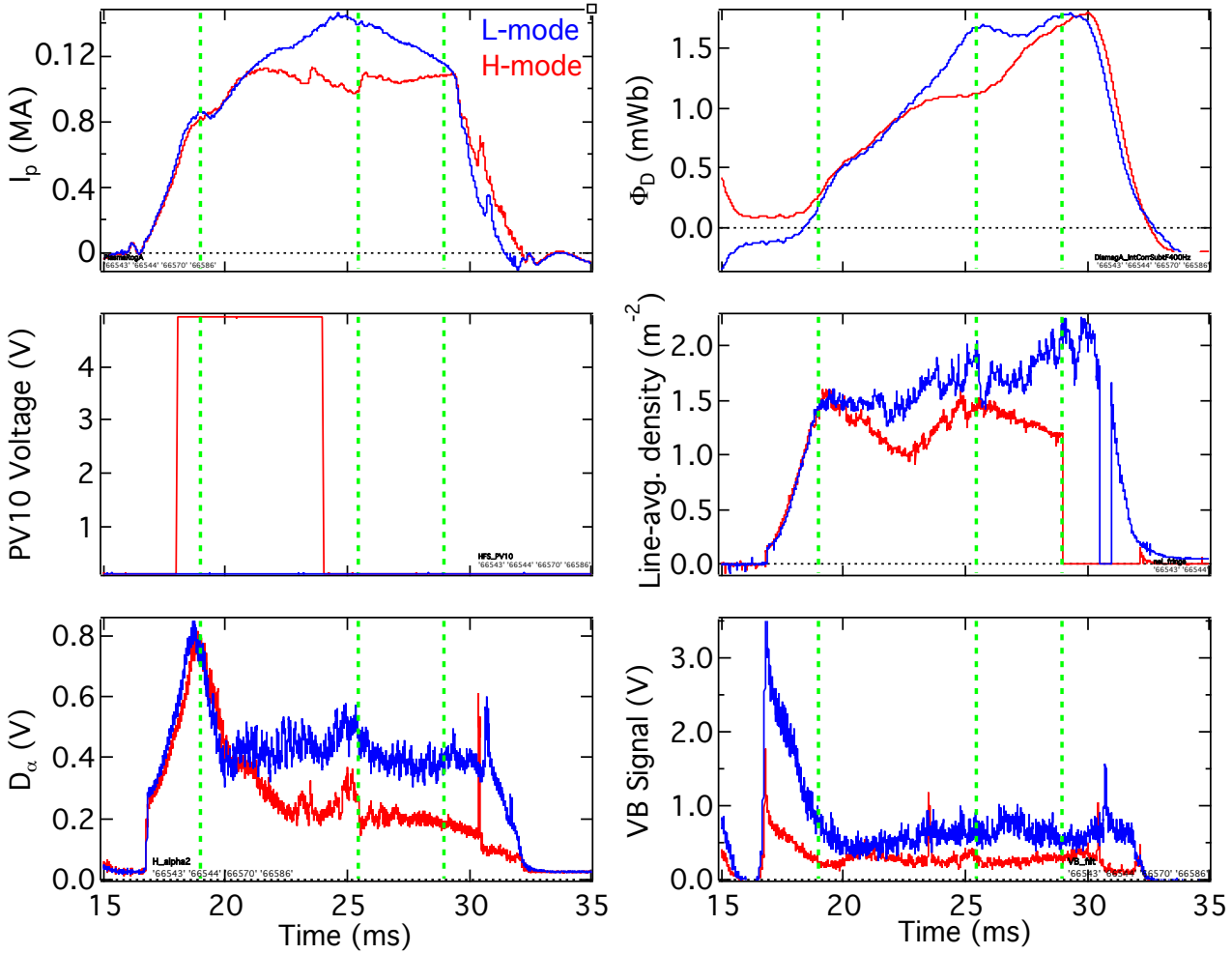


[1] *J.L. Barr,* ***this session*** *GP12.00116*

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L- and H-mode Electron Temperatures Investigated for I_p ~ 0.13 MA

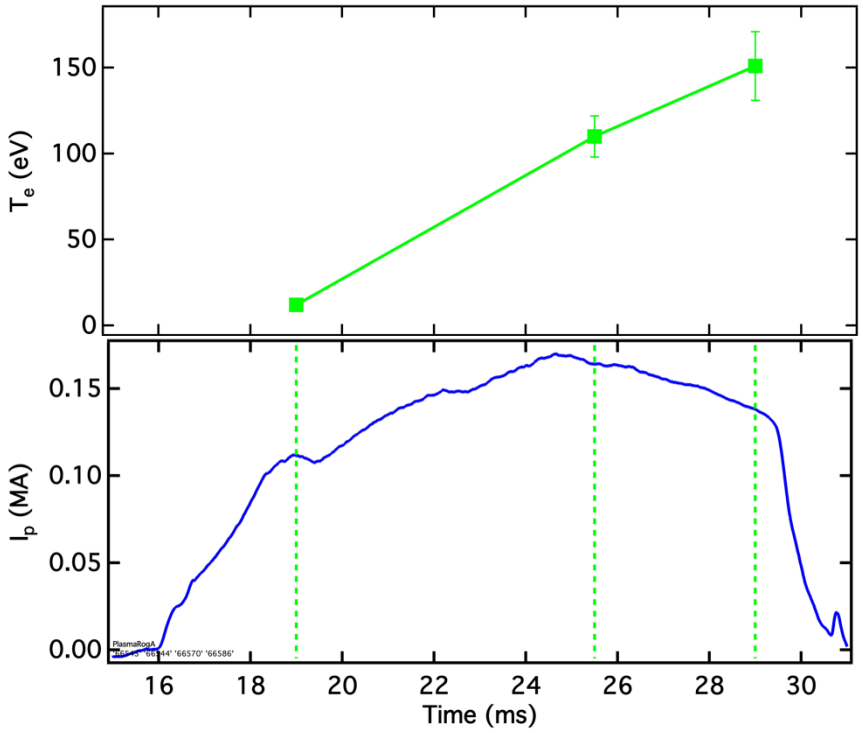
- Thomson data collected for L- and H-mode plasmas
  - $I_p = 130$ kA
  - $B_T = 0.1$ T
  - $\tau_{shot} \sim 20$ ms
- $R_{Thomson} = 35$ cm
- Time of Thomson collection window scanned from shot-to-shot *(dashed green line)*
  - Early phase
  - Mid-phase
  - Late phase

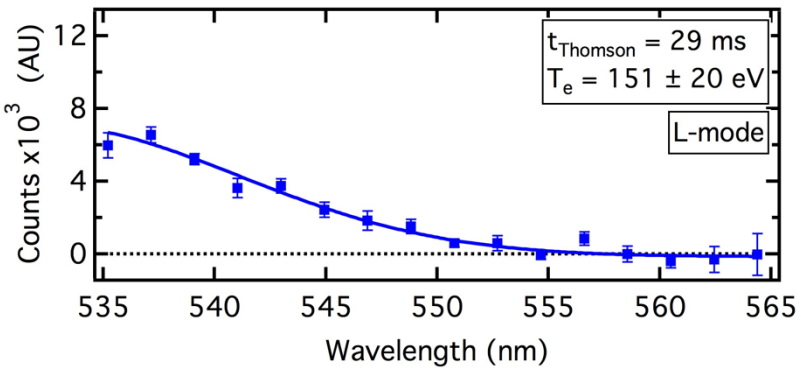


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L-mode Plasmas Exhibit Increasing T_e Throughout Discharge

- Position of 8-channel array spanned 32.9 cm < R_{maj} < 37.1 cm
- Data averaged over spatial points and multiple shots
- For initial analysis:
  - Spectral resolution $\Delta\lambda \approx 3$ nm
  - Due to ICCD camera software, binning restricted data collection to 7 spatial locations





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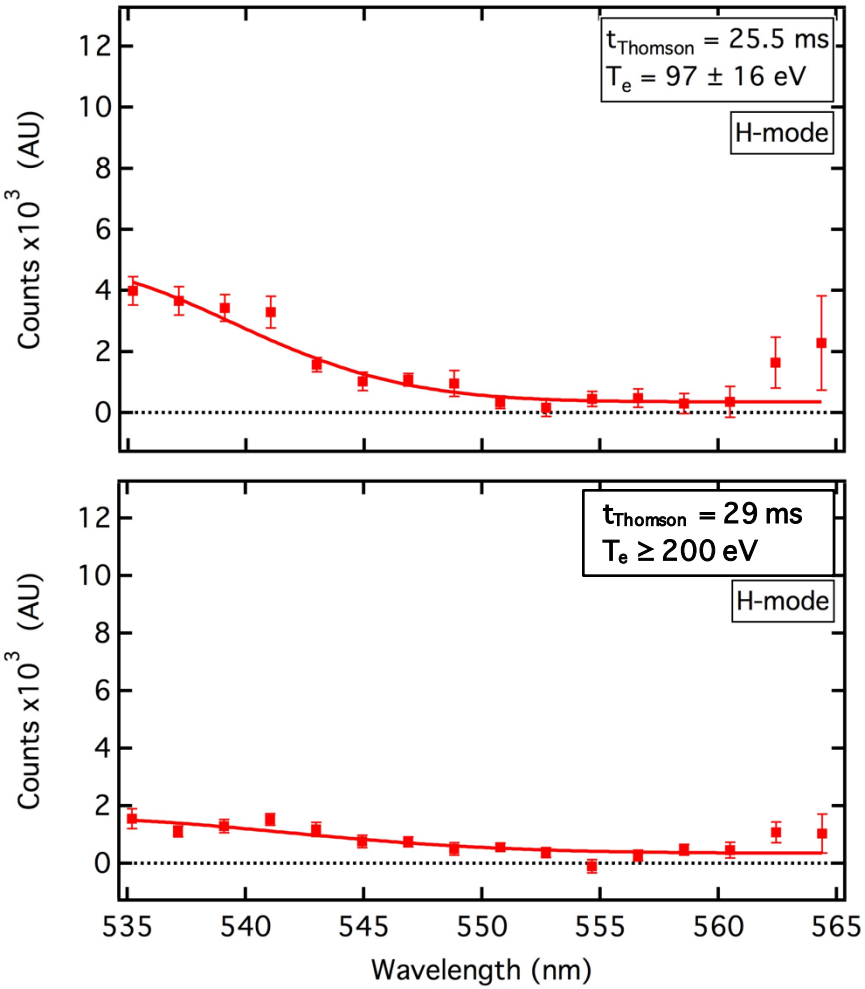
H-mode Spectra Indicate Temperatures Above Spectrometer Resolution

- TS spectrometer system designed with 2 interchangeable gratings:
  1. $10\ eV < T_e < 100\ eV$
  2. $100\ eV < T_e < 1000\ eV$

- Initial studies used low-T_e grating

- High-T_e H-modes scatter past grating-detector wavelength limit
  - Signal close to noise floor, may distort calculated T_e

- Future studies will install high-T_e grating for H-mode operations



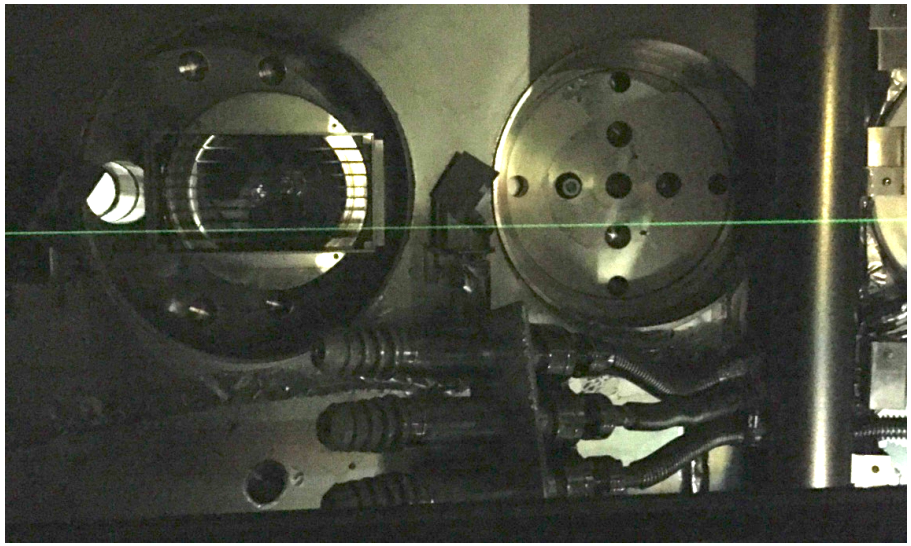
For more H-mode info,
THIS SESSION: *K.E. Thome GP12.00115, D.M. Kriete, GP12.00120*
Wed. 3pm: *M.W. Bongard PO6.00006*

THE UNIVERSITY of WISCONSIN MADISON

Future Directions

- Pursue confinement investigation of LHI discharges
  - Measure $T_e(r)$ dependence on V_{inj}, I_{inj}
  - Obtain $T_e(r,t)$ for typical LHI discharge
  - Use MPTS data to constrain LHI equilibrium reconstruction
  - Identify role of $T_e(r)$ in optimizing a discharge for handoff to P_{aux}

- Measure ultra-low aspect ratio H-mode plasmas
  - Pedestal characteristics
  - Core temperatures
  - T_e just prior and just after LH transition



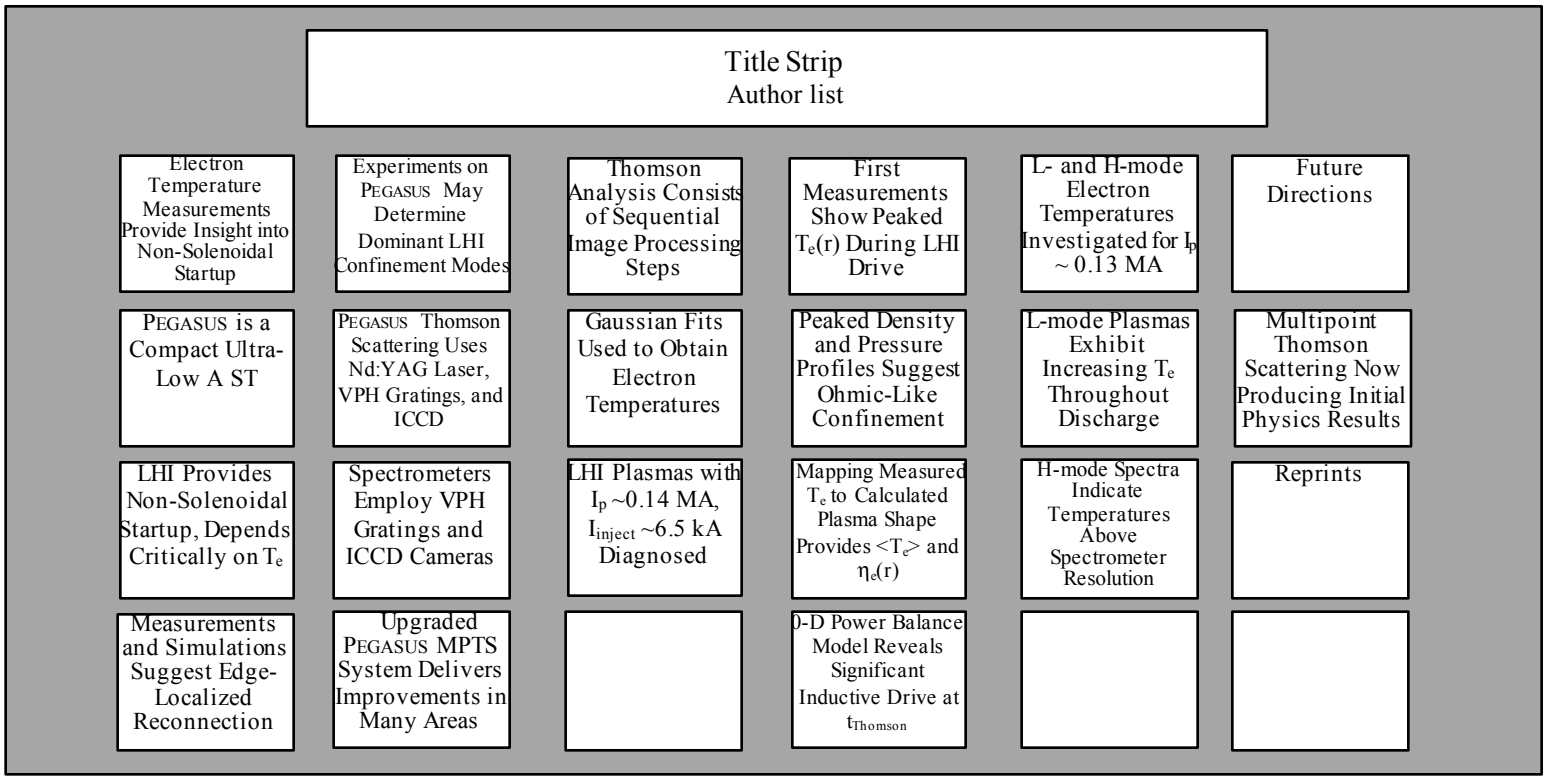
Multipoint Thomson Scattering Now Producing Initial Physics Results

- First measurements of $T_e(r)$ during Local Helicity Injection discharges
  - Peaked profiles inconsistent with bulk stochastic transport
  - Localized MHD suggestive of dual-zone confinement
  - If Ohmic-like confinement scales with V_{inj}, LHI plasmas provide excellent target for direct NBI coupling

- 0D power balance model for $I_p(t)$ shows significant inductive drive during Thomson collection time
  - Could provide source of core heating
  - Fast boundary reconstruction provides $\langle T_e \rangle$ and $\eta(r)$

- L- and H-mode plasmas display increasing T_e throughout discharge
  - L-mode $T_{e,max} \sim 150$ eV
  - H-mode $T_e > 200$ eV (will confirm with upgraded system)

Layout


Title Strip
Author list
Electron Temperature Measurements Provide Insight into Non-Solenoidal Startup
Experiments on PEGASUS May Determine Dominant LHI Confinement Modes
Thomson Analysis Consists of Sequential Image Processing Steps
First Measurements Show Peaked $T_e(r)$ During LHI Drive
L- and H-mode Electron Temperatures Investigated for I_p ~ 0.13 MA
Future Directions
PEGASUS is a Compact Ultra-Low A ST
PEGASUS Thomson Scattering Uses Nd:YAG Laser, VPH Gratings, and ICCD
Gaussian Fits Used to Obtain Electron Temperatures
Peaked Density and Pressure Profiles Suggest Ohmic-Like Confinement
L-mode Plasmas Exhibit Increasing T_e Throughout Discharge
Multipoint Thomson Scattering Now Producing Initial Physics Results
LHI Provides Non-Solenoidal Startup, Depends Critically on T_e
Spectrometers Employ VPH Gratings and ICCD Cameras
LHI Plasmas with I_p ~0.14 MA, I_{inject} ~6.5 kA Diagnosed
Mapping Measured T_e to Calculated Plasma Shape Provides $<T_e>$ and $\eta_e(r)$
H-mode Spectra Indicate Temperatures Above Spectrometer Resolution
Reprints
Measurements and Simulations Suggest Edge-Localized Reconnection
Upgraded PEGASUS MPTS System Delivers Improvements in Many Areas
0-D Power Balance Model Reveals Significant Inductive Drive at $t_{Thomson}$