PEGASUS-III Experiment

Investigating The Role of Impurities in Plasma Startup Via LHI on PEGASUS-III

C. Rodriguez Sanchez

S.J. Diem, R.J. Fonck, M.D. Nornberg, G.R. Winz

64th Annual Meeting of the APS Division of Plasma Physics, Spokane, WA

Presentation CP11.00050

17 October 2022

Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Poster Layout

US Legal
8.5 x 14”

US Letter
8.5 x 11”

12:1 scale Panel size: 8’ x 4’

Investigating The Role of Impurities in Plasma Startup Via LHI on PEGASUS-III

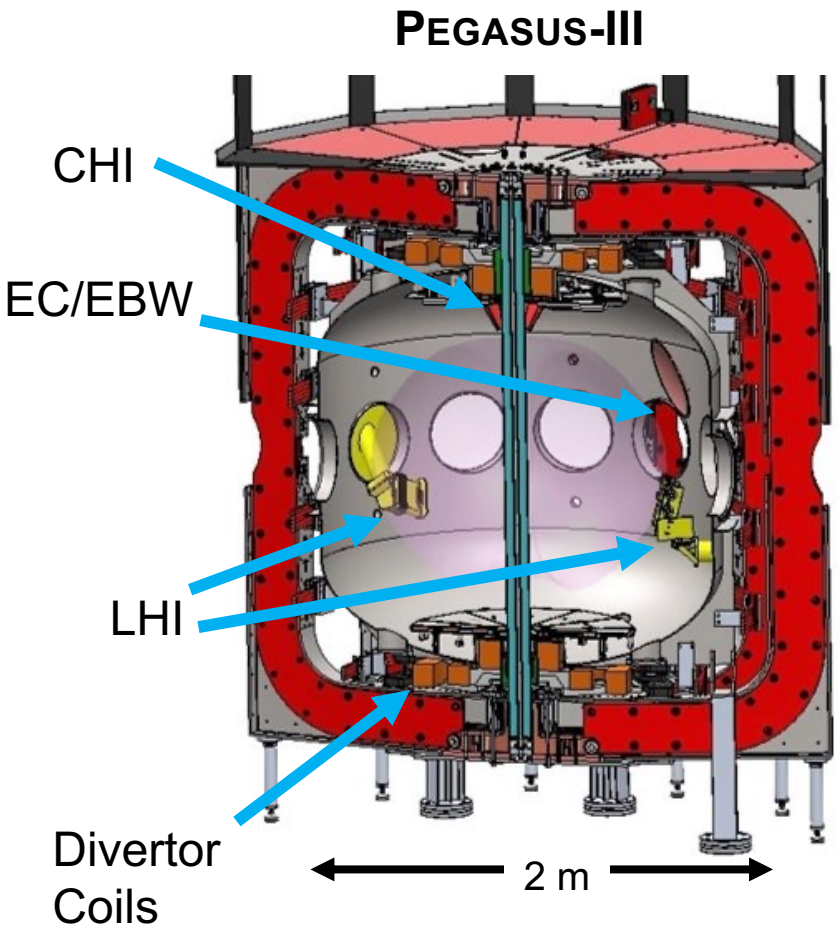
Tokamak Startup Via Local Helicity Injection	Diagnostic Development		Impurity Transport Modeling	Impurity Assessment on PEGASUS-III
PEGASUS-III: A Dedicated Non-Solenoidal Startup Experiment at low A	Impurity Content Can be Characterized by Looking at Different Parts of EM Spectrum	Impurity Studies will Utilize Multiple Diagnostics	Transport Code STRAHL is Used for Impurity Studies	LHI Impurity Sourcing, Concentrations and Effects on LHI Performance Will be Explored in PEGASUS-III
Predicting LHI Performance Needs Impurity Assessment	Impurity Species Monitored With VUV Spectroscopy	VUV Spectra Suggest Increased Impurity Influx During LHI	Initial Analysis With STRAHL for an LHI Discharge	Experiments will Investigate Impact of Impurity Transport in LHI Startup and Power Balance
Local Helicity Injection (LHI) is a Promising Non-Solenoidal Startup Technique	New AXUV Diagnostic Allows High Spatial and Temporal Resolution Measurements of P_{rad}	Clear Differences in P_{rad} are Observed Between Ohmic and LHI and Between Different B_T Levels	Reduced Impurity Transport Affects Charge-state Balance and Radiation Profile	Influence of Impurities on HI Tokamak Startup will be Studied in PEGASUS-III
Current Drive With LHI is Limited by Resistive Dissipation	Upgrades to VB Diagnostic Increase Throughput	Observed I_p Trends Motivate Measurements of Z_{eff}	Strong Impurity Transport May Explain Observed T_e Profiles	

Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Tokamak Startup Via Local Helicity Injection

PEGASUS-III: A Dedicated Non-Solenoidal Startup Experiment at low A

- Future power plants benefit from solenoid-free operations
  - Cost reduction
  - Increased space for shielding and blanket
  - Simplified design
- The new PEGASUS-III facility is a major upgrade to the PEGASUS ST
  - Removal of the Ohmic solenoid
  - Upgraded TF magnet assembly to deliver up to 0.6 T on axis
  - **Mission:** compare, contrast and combine startup techniques
    - Helicity Injection (LHI and CHI)
    - RF heating and current drive (EBW, EC)
- Impurity roles in plasma startup
  - Power balance
  - Limit current drive: $I_p \sim V/R$



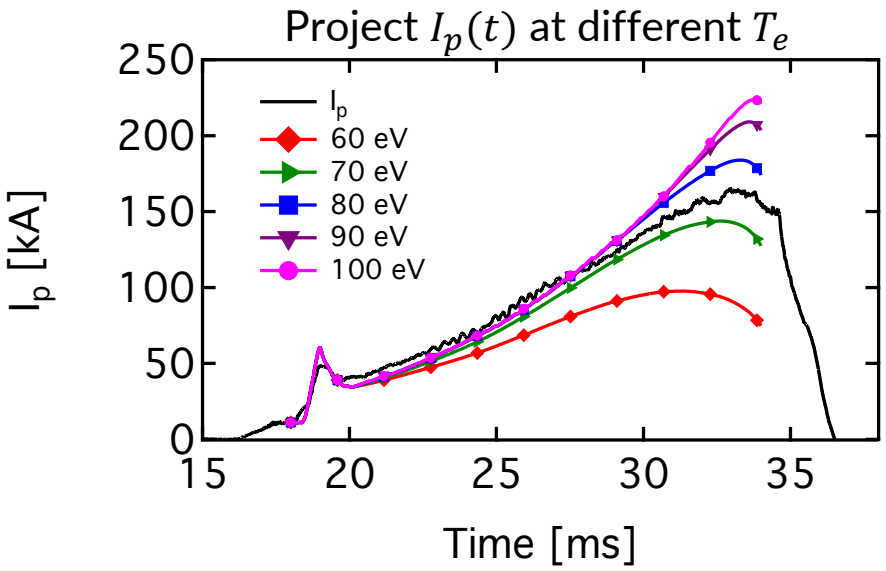
Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

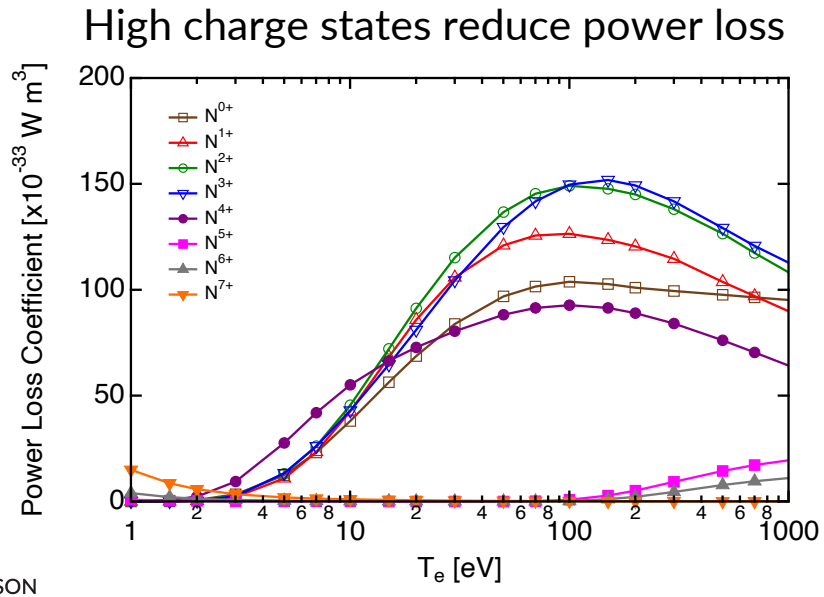
Predicting LHI Performance Needs Impurity Assessment

- Helicity input balanced by resistive dissipation

$$\dot{K}_{dis} \approx -\frac{2\pi R_0}{A_p}\langle\eta\rangle I_p \Psi \qquad \eta \propto Z_{eff} T_e^{-3/2}$$

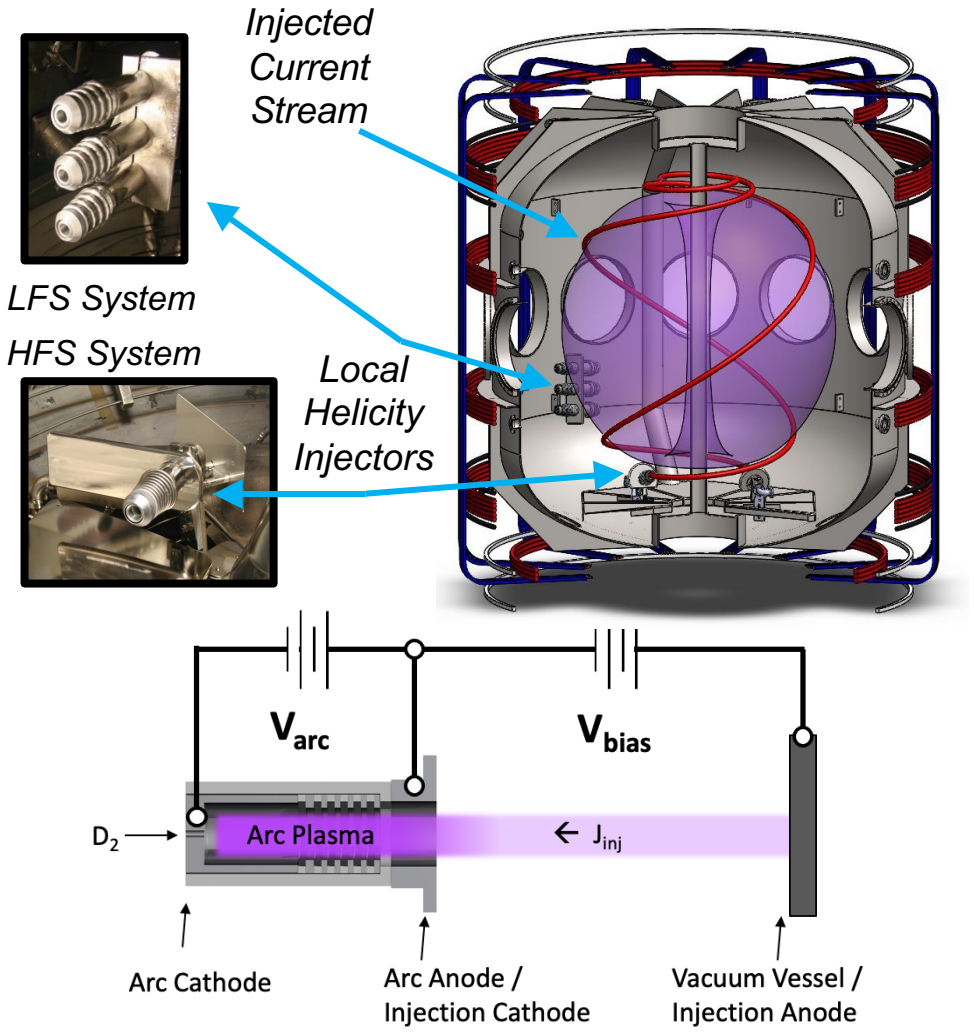
- Impurity concentration directly affects resistivity
  - Increased Z_{eff}
  - Plasma cooling
- LHI is useful if its target can couple to other CD
  - Acceptably low Z_{eff}
  - Power losses do not impact the power balance

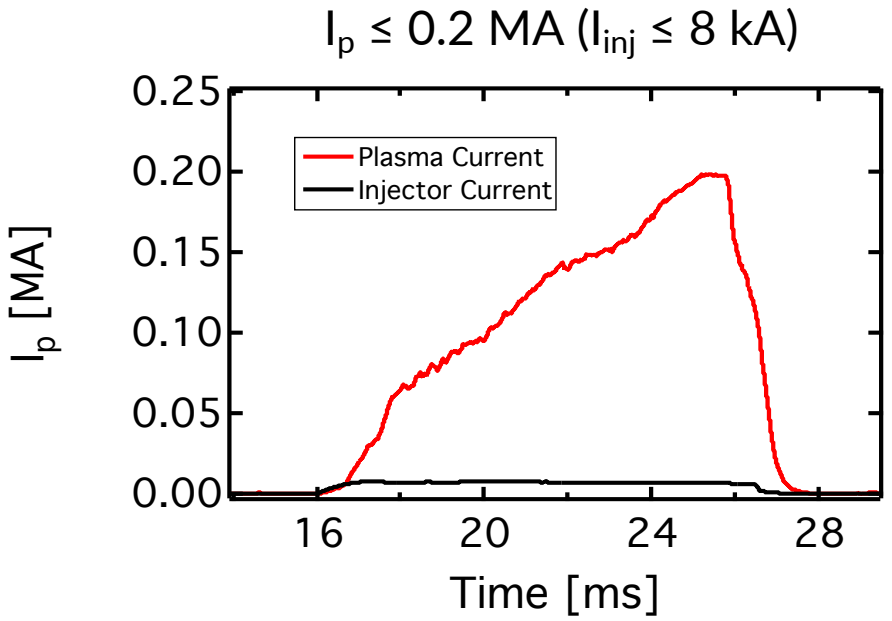




Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Local Helicity Injection (LHI) is a Promising Non-Solenoidal Startup Technique





- LHI provides solenoid-free startup
  - Edge current extracted from injectors at boundary
  - Relaxation to tokamak-like state via helicity-conserving instabilities
- Used routinely for startup on PEGASUS

Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Current Drive With LHI is Limited by Resistive Dissipation

$$K = \int \vec{A} \cdot \vec{B}\ dV \quad \Rightarrow \quad \frac{dK}{dt} = -2\,\frac{\partial \psi}{\partial t}\Psi - 2\int \phi \vec{B} \cdot \hat{n}\, dS - 2\int \eta \vec{J} \cdot \vec{B}\, dV$$

- AC Helicity Injection:

$$\dot{K}_{AC} = -2\,\frac{\partial \psi}{\partial t}\Psi = 2\mathrm{V}_{\mathrm{loop}}\Psi$$

- DC Helicity injection:

$$\dot{K}_{DC} = -2\int \phi \vec{B} \cdot \hat{n}\, dS = 2\mathrm{V}_{\mathrm{LHI}}\Psi$$

- Resistive Helicity Dissipation:

$$\dot{K}_{dis} = -2\int \eta \vec{J} \cdot \vec{B}\, dV \approx \frac{2\pi R_0}{A_p}\langle \eta \rangle I_p \Psi$$

- In Steady state, Source = Sink

$$V_{LHI} = V_{inj}\,\frac{A_{inj}B_{inj}}{\Psi}$$

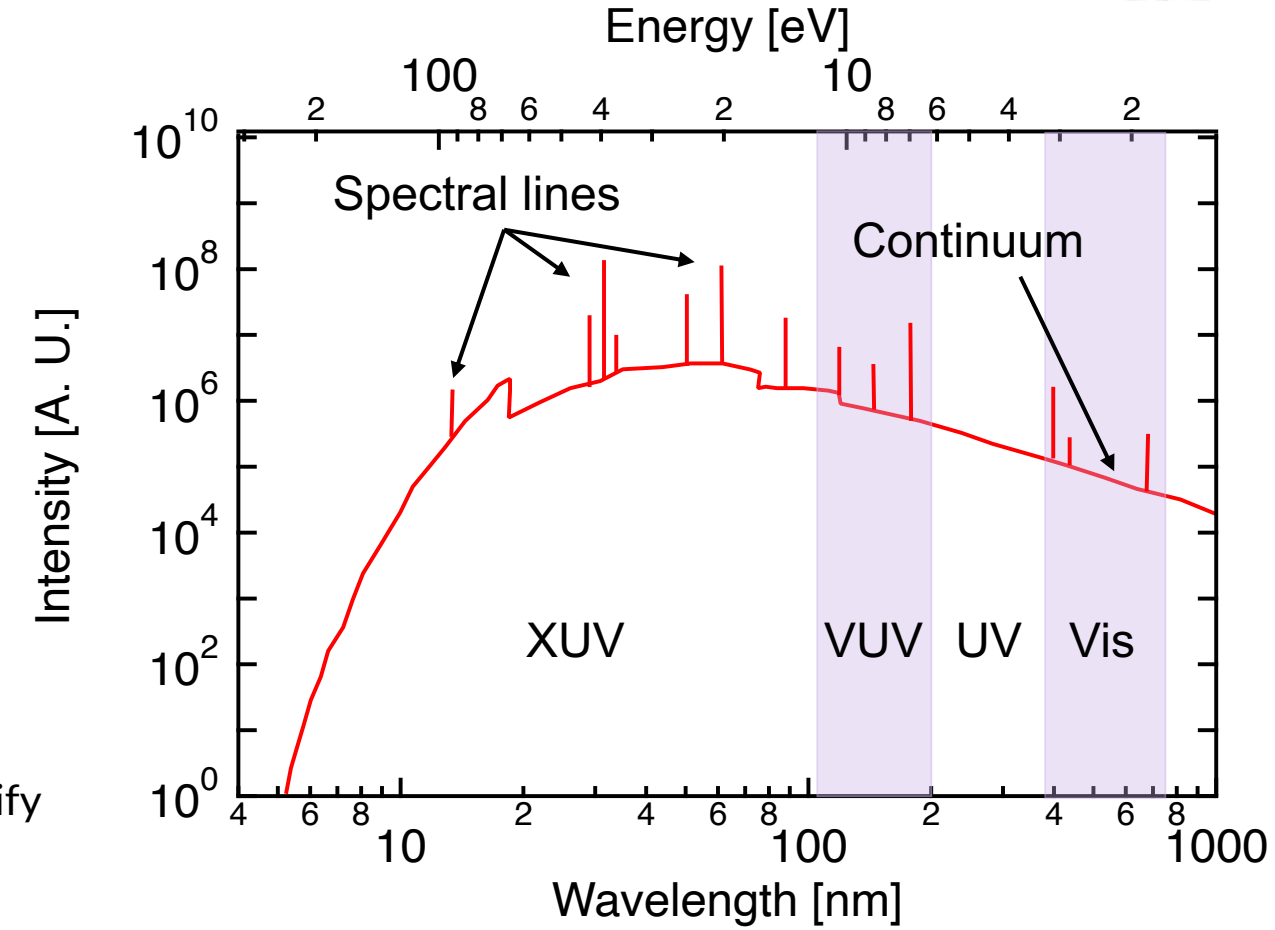
$$I_p \leq \frac{A_p}{2\,\pi R_0 \langle \eta \rangle}\left(V_{loop} + V_{LHI}\right)$$

Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Diagnostic Development

Impurity Content Can be Characterized by Looking at Different Parts of EM Spectrum

- Impurities increase EM radiation
  - XUV part contributes the most to power losses
- Bremsstrahlung emission
  - Continuum radiation
  - Electrons slow down after colliding with ions
  - Proportional to ion charge
- Line emission
  - Line emitted from transitions in electrons
  - Bright, resonant lines in the VUV are easy to identify

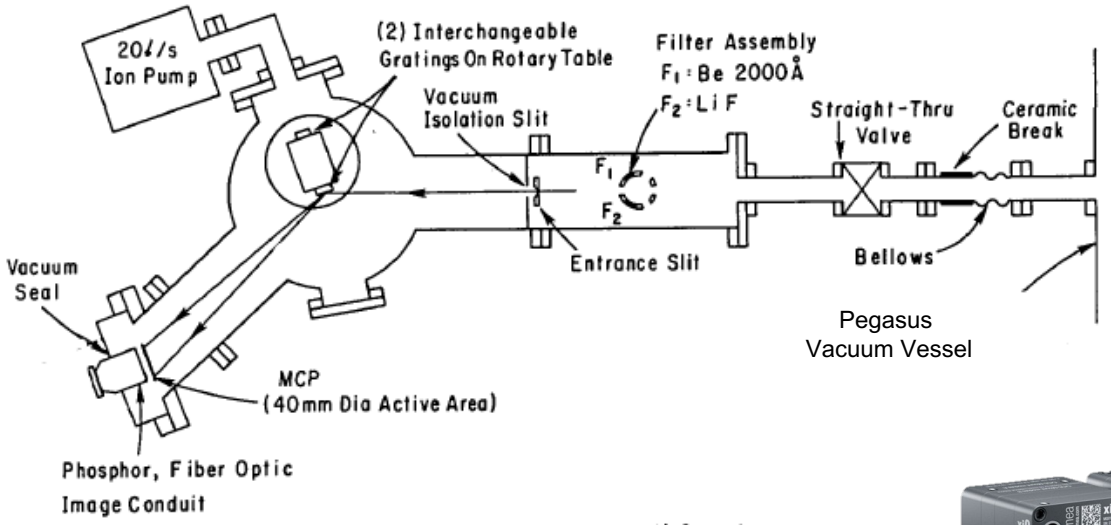


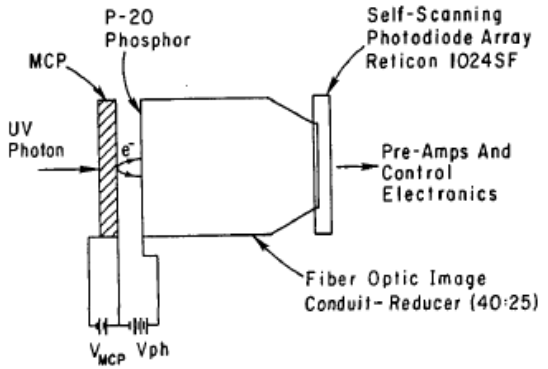
Inspired by: H.-J. Kunze, *Introduction to Plasma Spectroscopy* (Springer Berlin Heidelberg, Berlin, Heidelberg, 2009).

Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Impurity Species Monitored With VUV Spectroscopy

- SPRED VUV Spectrometer
  - Single line of sight at R_{tan} =20 cm
- Two interchangeable gratings
  - High resolution grating
    - Spectral Range 10 to 32 nm, resolution 0.04 nm
    - Useful for metallic lines like Mo, W and Ti
  - Low resolution grating
    - Spectral range 15.5 to 170 nm, resolution 0.3 nm
    - Coverage for Li-like to B-like low-z impurity lines
- CMOS image sensor
  - 2048 x 1088 Resolution
  - Temporal resolution ~ 1.5 kHz at 2048 x 120





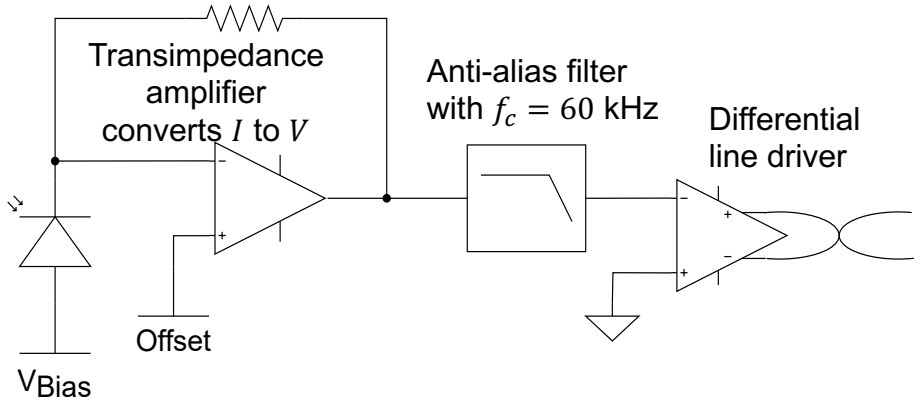
VUV to Visible imaging System

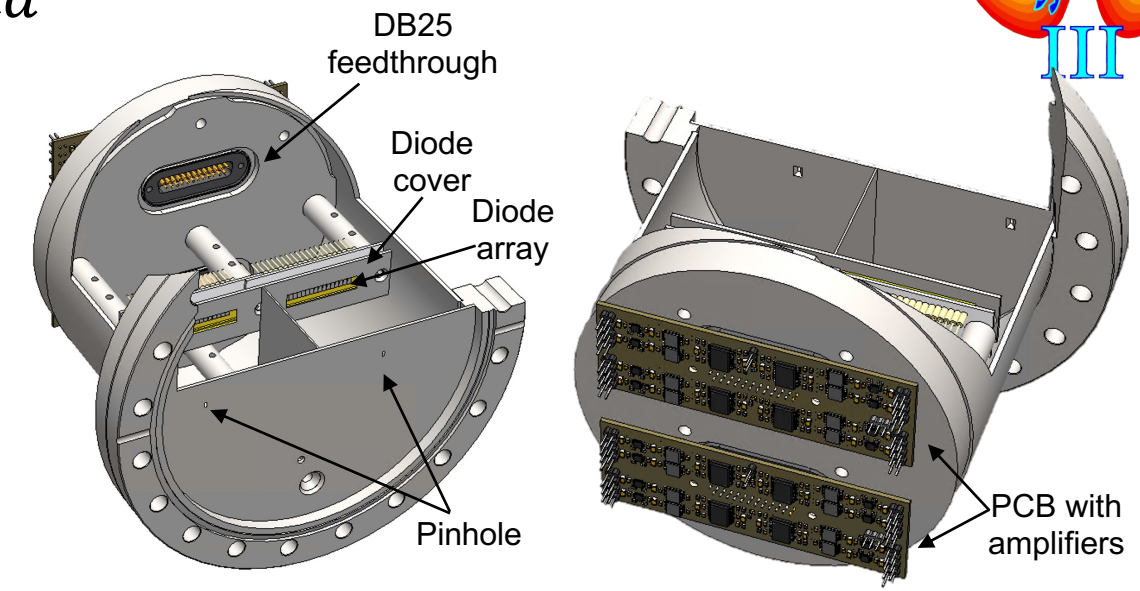
R. J. Fonck et al., Applied Optics 21.12, 2115 (1982)

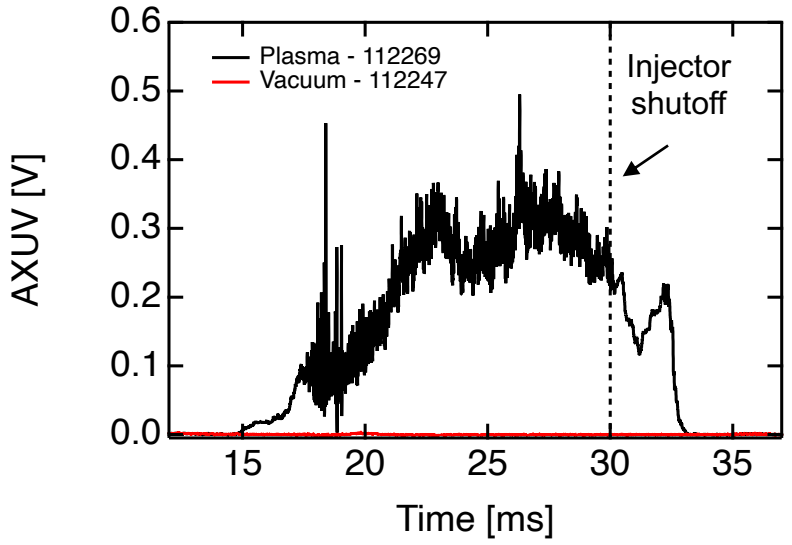
Department of
Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

New AXUV Diagnostic Allows High Spatial and Temporal Resolution Measurements of P_{rad}

- Two 16-channel AXUV16ELG photodiode arrays
  - 32 lines of sight
  - $R_{tan} \approx 9 - 90$ cm, ~ 2.5 cm spatial resolution
  - Onion inversion algorithm[1] to obtain $P_{rad}(R)$
- Three-stage amplifiers for high signal-to-noise ratio





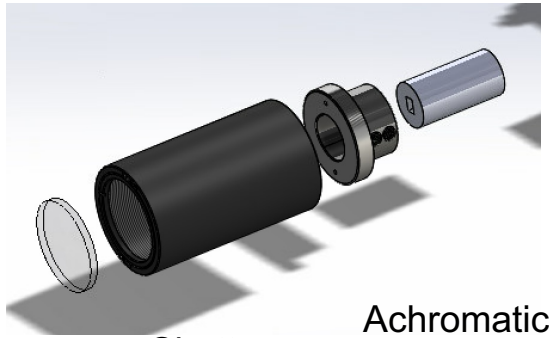


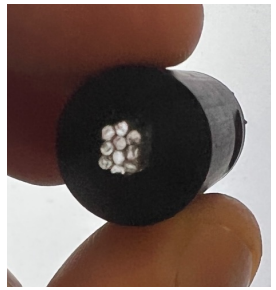
[1] C.J. Dasch, Applied Optics **31**, 1146 (1992).

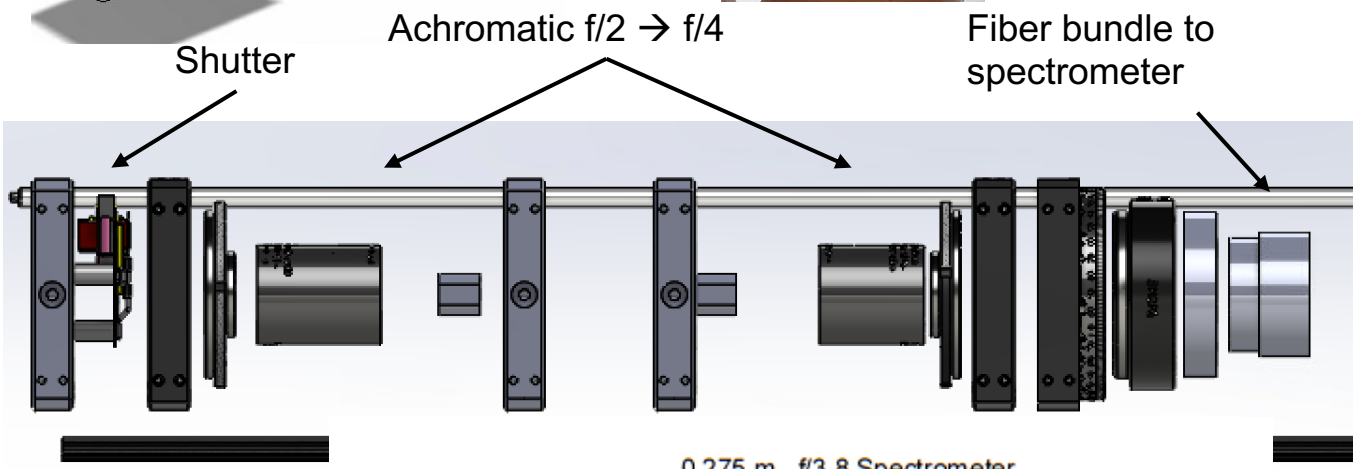
Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

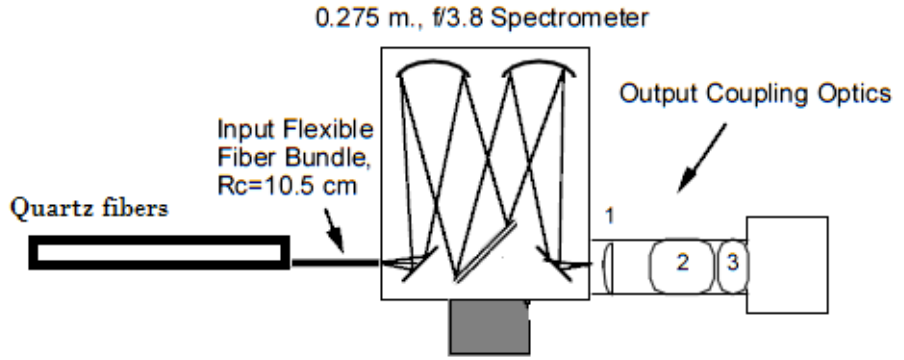
Upgrades to VB Diagnostic Increase Throughput

- Low radiance is expected for PEGASUS-III
  - $n_e \sim 1 \times 10^{19}$ m^3, $T_e \sim 100$ eV
  - $B_{brems} = \int \epsilon \, ds \sim 1 \times 10^{10} \frac{\gamma}{s} \frac{1}{\text{cm}^2} \frac{1}{\text{nm}}$
- Throughput to be increased by ~×10
  - Ten 1 mm f/2 fibers collect light
  - Introduced fast shutter (~ 2 ms)
  - Vertical binning of the full CCD
- Expected Counts (DN) ~ 20
  - $U = 1.4{\times}10^{-2}$ cm^2 sr (SpectraPro 275)
  - QE = 70%, G = 0.125 DN/photons
  - $\Delta\lambda \approx 1$ nm
  - $DN = B_{brems} \times U \times QE \times G \times \Delta t \times \Delta\lambda$







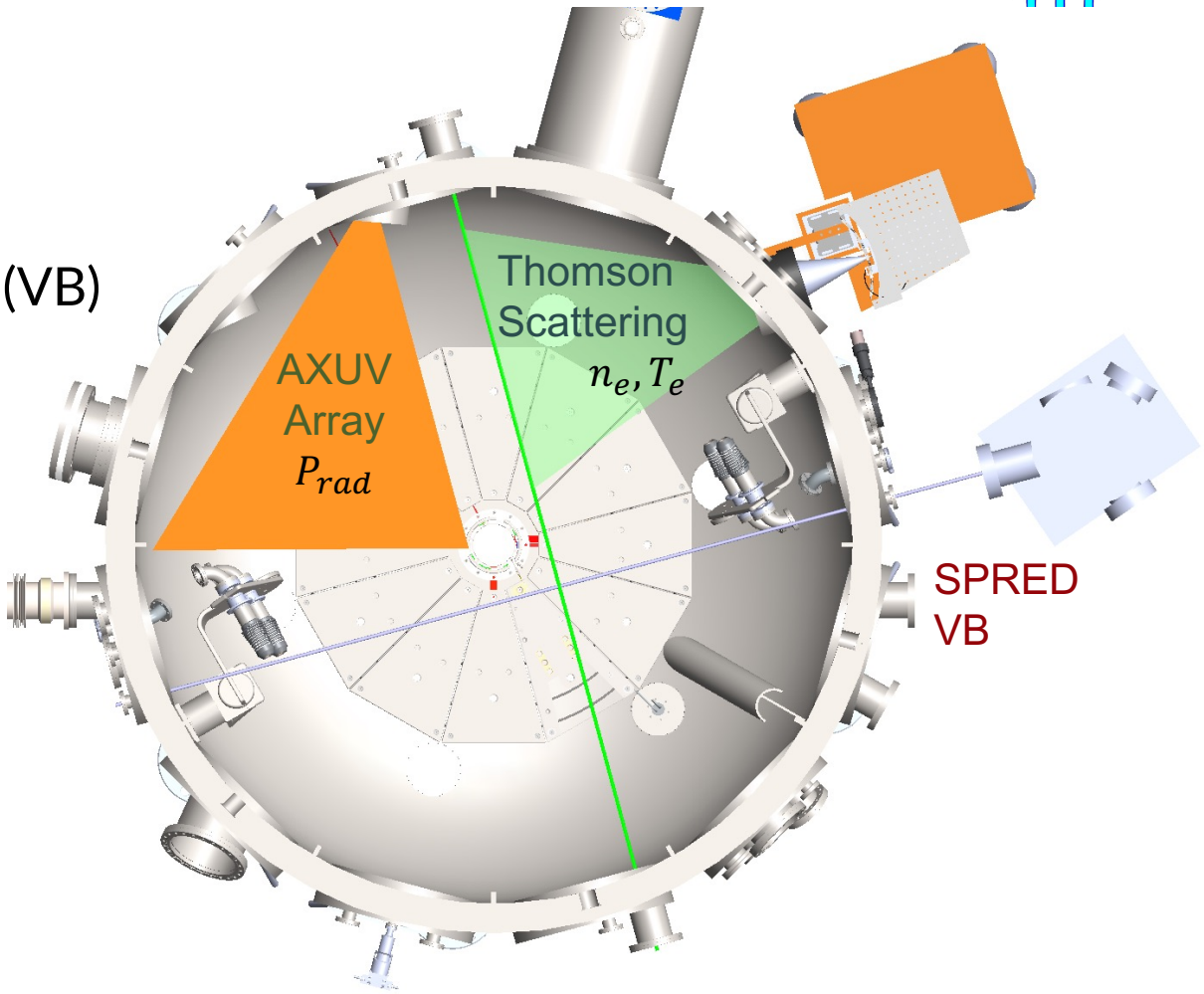


G McKee, UW-Madison NEEP (1995)

Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Impurity Studies will Utilize Multiple Diagnostics

- Species Identification with SPRED
- Z_{eff} measurements with Visual Bremsstrahlung (VB)
  - Needs n_e and T_e from Thomson Scattering
- AXUV radiometry for P_{rad}
- CHERS is under development*
  - Can directly measure impurity densities
- Impurity transport modeling with STRAHL



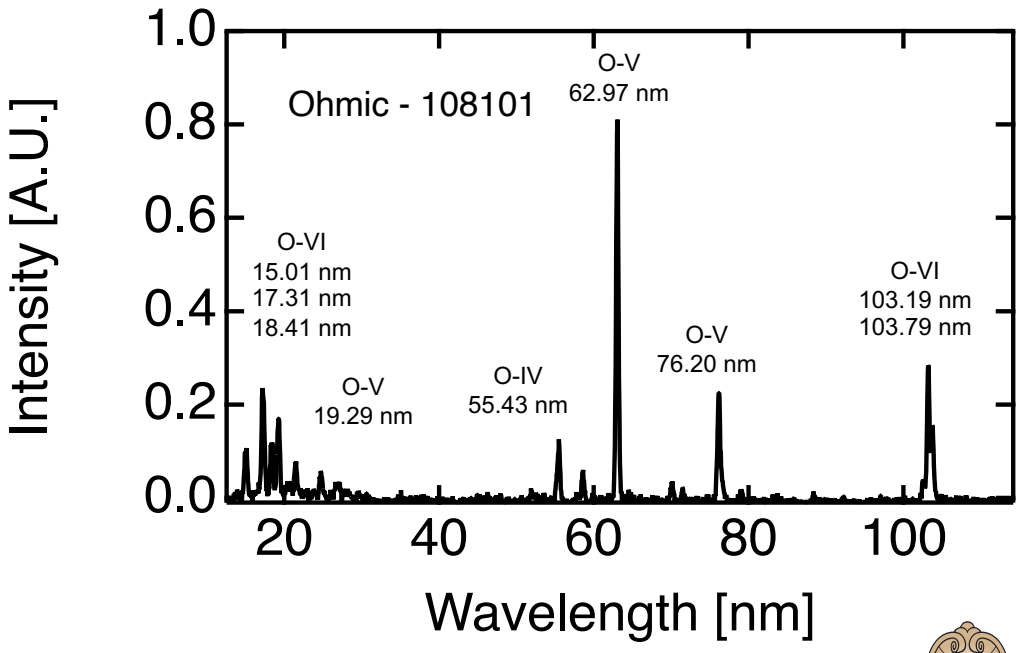
Department of
Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

*See A. K. Keyhani CP11.00052

VUV Spectra Suggest Increased Impurity Influx During LHI

Ohmic Discharge

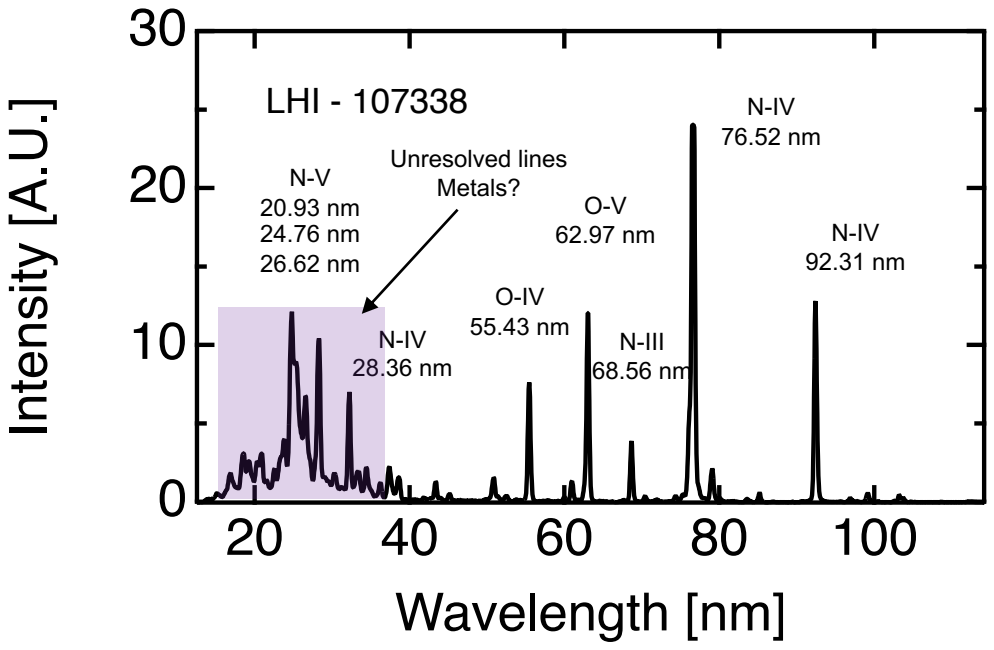
- Oxygen dominated
- Low intensity (100s counts)



LHI Discharge

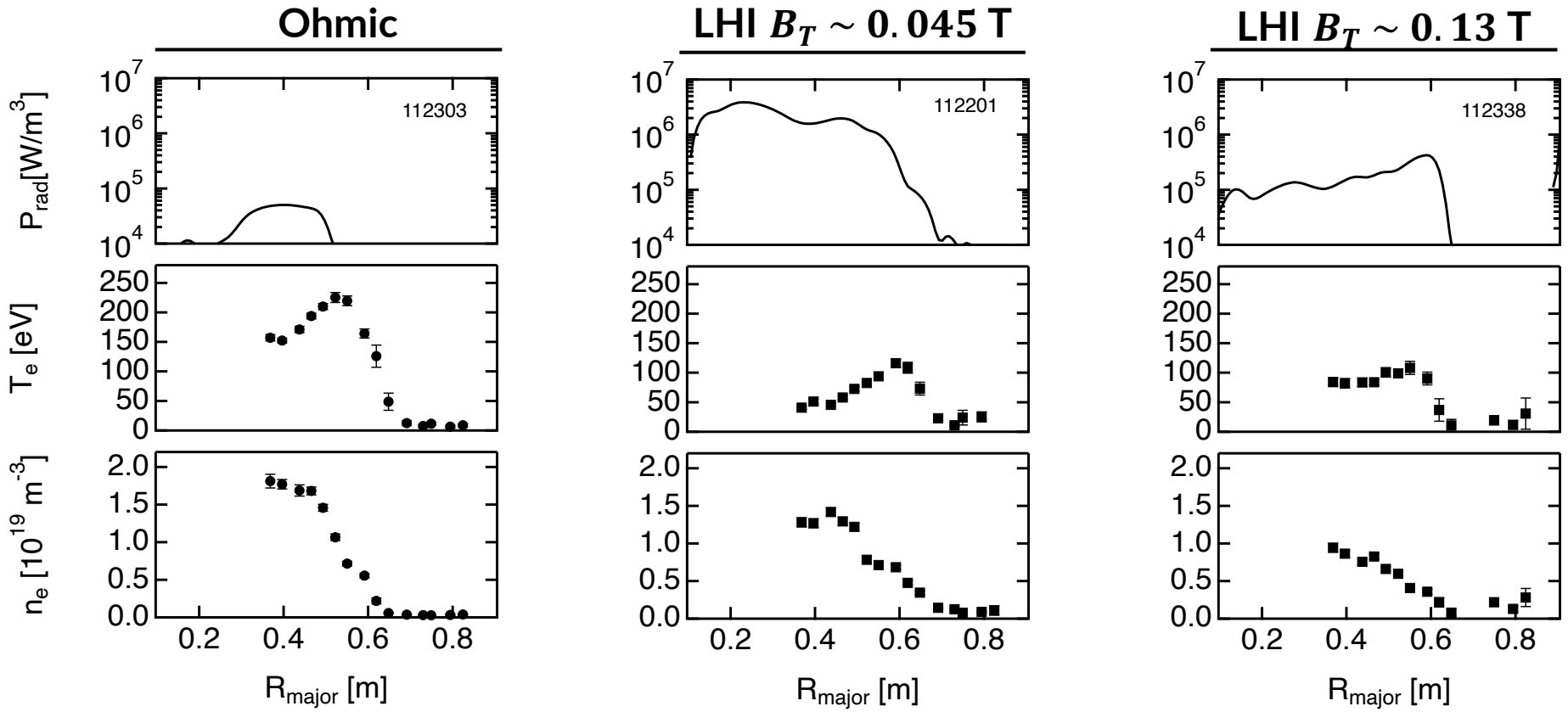
- Nitrogen and oxygen Identified
  - Possible sources are plasma material interaction
- Intensity is higher than Ohmic
  - At similar n_e and T_e, this suggest higher n_{imp}

$$\epsilon \propto n_e \, n_{imp} \langle \sigma(T_e) v \rangle$$



Department of
Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Clear Differences in P_{rad} are Observed Between Ohmic and LHI and Between Different B_T Levels



- AXUV diode sensitivity drops for photons with energies < 50 eV
  - Currently working on correction factor to account for change in diode response

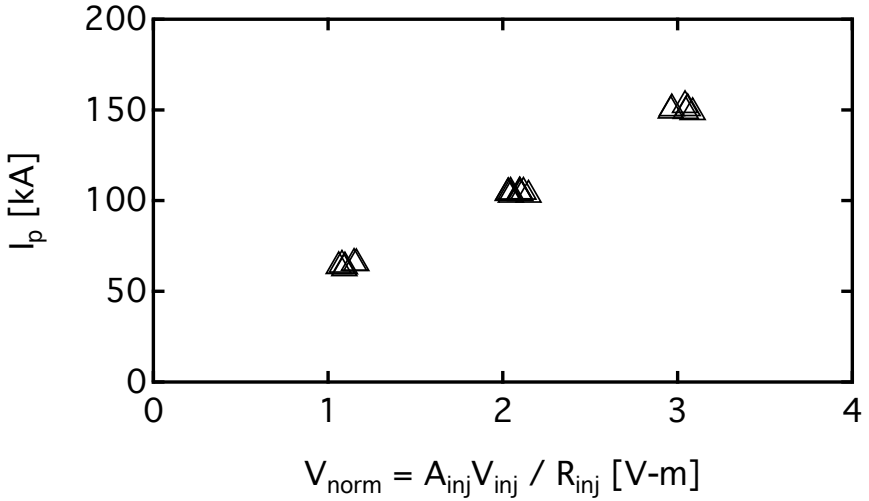
Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

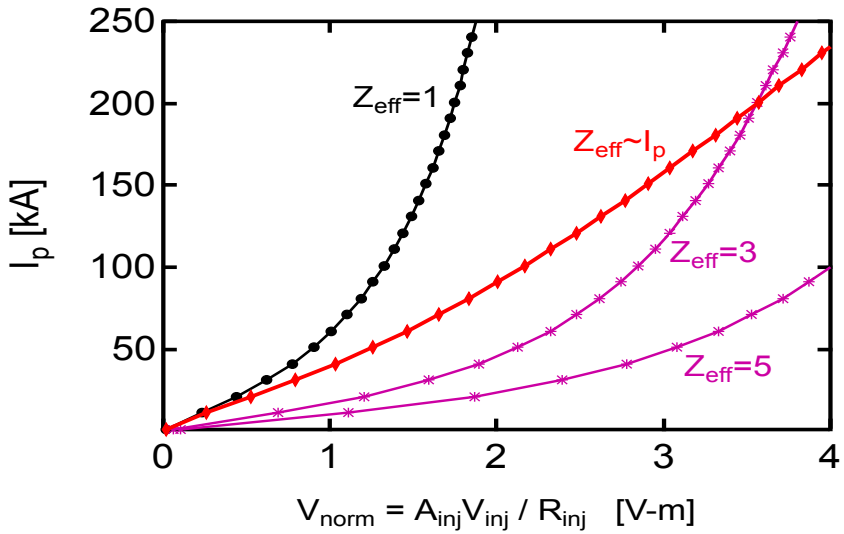
Observed I_p Trends Motivate Measurements of Z_{eff}

- $I_p \propto V_{LHI}$
  - Implies constant $\langle \eta \rangle$
  - Motivates efforts to determine Z_{eff}
- Bremsstrahlung continuum can be used to measure Z_{eff}

$$\frac{d\epsilon}{d\lambda} = 7.632\times10^{-15}\,\frac{n_e^2 g_{eff} Z_{eff}}{{T_e}^{1/2}\lambda} e^{-\frac{hc}{\lambda T_e}} \left[\frac{\gamma}{s}\,\frac{1}{\mathrm{cm}^3}\,\frac{1}{\mathrm{nm}}\right]$$

- Other sources of emission may complicate measurement:
  - Line radiation
  - Electron-neutral bremsstrahlung
  - Molecular hydrogen emission





Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Impurity Transport Modeling

Transport Code STRAHL is Used for Impurity Studies

- STRAHL[1] is an impurity transport code that solves the continuity equation
- Code outputs: impurity densities and emission
- 1-D cylindrical equation obtained if particle flux is averaged over a flux surface

$$\frac{\partial n_{I,Z}}{\partial t} = -\nabla \cdot \vec{\Gamma}_{I,Z} + Q_{I,Z} \quad \Rightarrow \quad \frac{\partial n_{I,Z}}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r} r \left(D \frac{\partial n_{I,Z}}{\partial r} - v n_{I,Z} \right) + Q_{I,Z}$$

- Impurity flux separated into diffusive and convective term
  - Diffusion is proportional to $\nabla n_{I,Z}$
  - Convection is proportional to $n_{I,Z}$

$$\Gamma_{I,Z} = D \nabla n_{I,Z} + v n_{I,Z}$$

- Radial label is related to the flux surface volume

$$r = \sqrt{\frac{V}{2\pi^2 R_0}}$$

- Sources/sinks couple neighboring states

$$Q_{I,Z} = -\left(n_e S_{I,Z} + n_e \alpha_{I,Z} + n_H \alpha_{I,Z}^{cx}\right) n_{I,Z} + n_e S_{I,Z-1} n_{I,Z-1} + \left(n_e \alpha_{I,Z+1} + n_H \alpha_{I,Z+1}^{cx}\right) n_{I,Z+1}$$

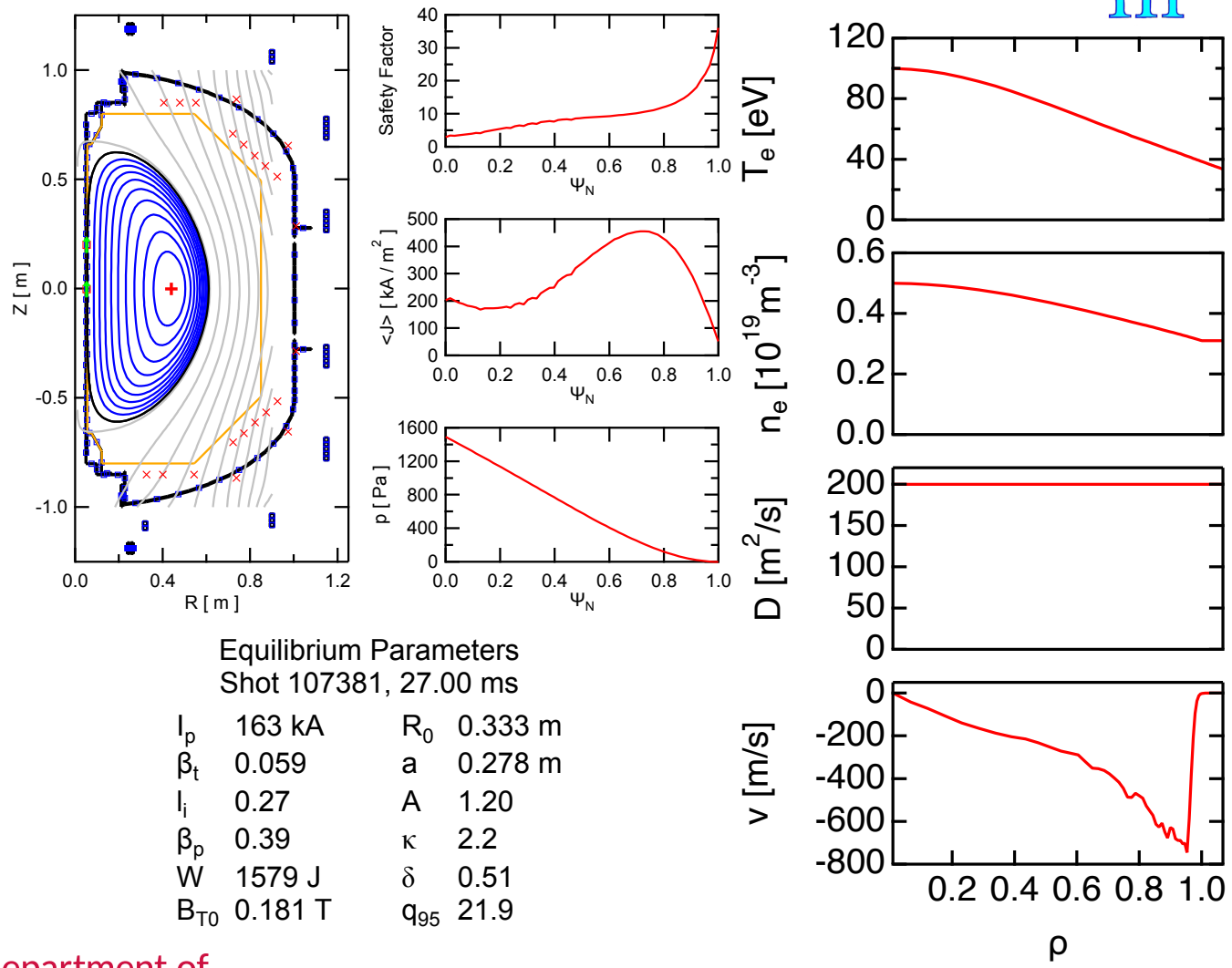
- Ionization ($S_{I,Z}$), recombination ($\alpha_{I,Z}$) and charge exchange ($\alpha_{I,Z}^{cx}$) rates obtained from ADAS[2]

[1] R. Dux, "STRAHL User Manual," IPP Report 10/30, 2006.
[2] H.P. Summers and M.G. O'Mullane, in *AIP Conference Proceedings* (2000), pp. 304–312.

Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Initial Analysis With STRAHL for an LHI Discharge

- Inputs to the code
  - Magnetic geometry from equilibrium reconstruction
  - Peaked background pressure profile
    - $T_{e0} = 100$ eV
    - $n_{e0} = 0.5 \times 10^{19}$ m^{-3}
  - Transport coefficients
    - $D \sim \frac{a^2}{\tau_E} \sim \frac{a^2}{\tau_p} \sim 200$ m^2 /s
    - Neo-Alcator scaling predicts $\tau_E \sim 0.5$ ms
    - $v = D \frac{1}{n_e} \frac{dn_e}{dr}$ if steady-state n_{imp} is assumed
  - Source rate chosen such that $\frac{n_{imp}}{n_e} \sim 1.5\%$
    - Localized at the plasma edge $\rho > 1$

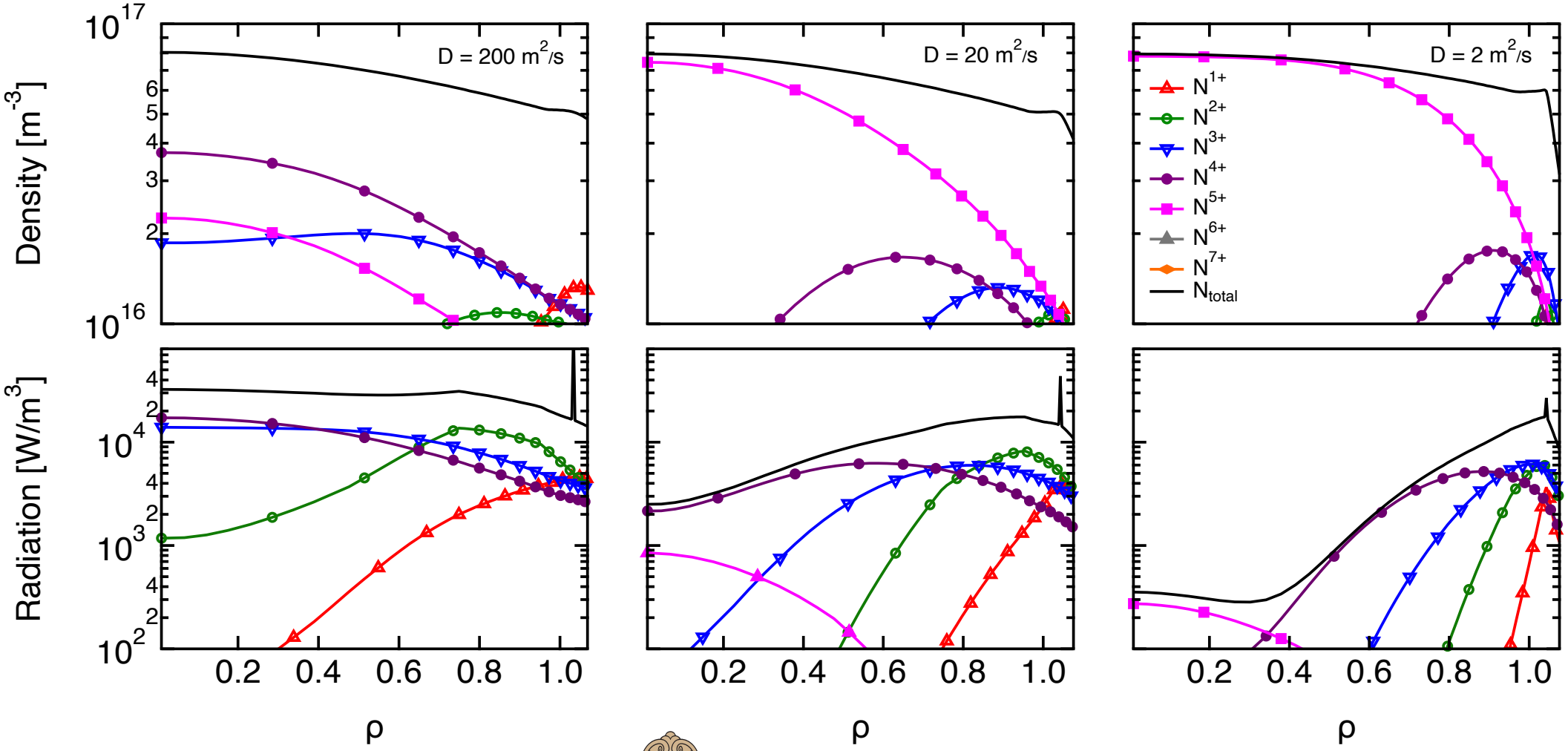


Equilibrium Parameters
Shot 107381, 27.00 ms

I_p	163 kA	R_0	0.333 m
β_t	0.059	a	0.278 m
l_i	0.27	A	1.20
β_p	0.39	κ	2.2
W	1579 J	δ	0.51
B_{T0}	0.181 T	q_{95}	21.9

Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

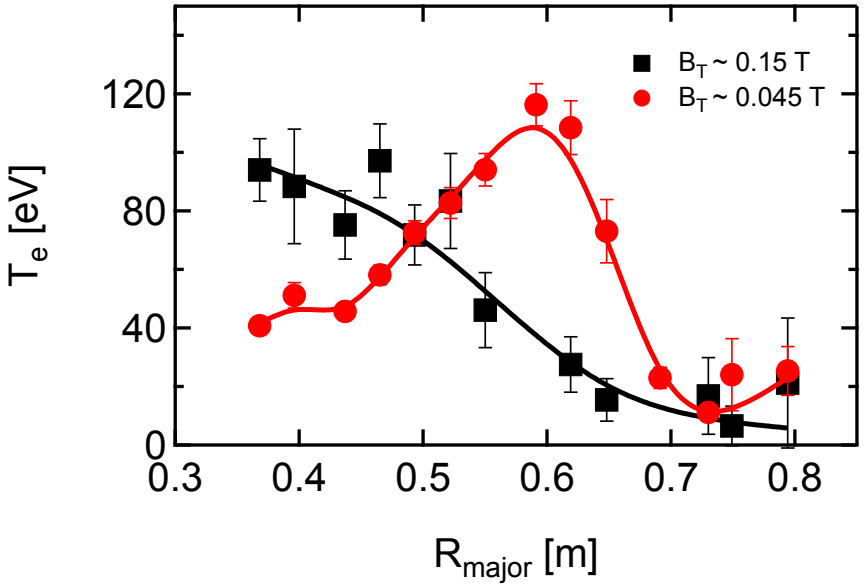
Reduced Impurity Transport Affects Charge-State Balance and Radiation Profile



Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Strong Impurity Transport May Explain Observed T_e Profiles

- LHI hollow current profiles → low core Ohmic heating [1]
  - $\eta J_0^2 \sim 10$ kW/m^3
- Strong transport leads to high core radiation
  - Low, highly radiative charge states can exist in the core
  - Flat radiation profile
  - $P_{rad,0} > \eta J_0^2$
- Reduced impurity transport → hollow $P_{rad}(R)$
  - Low charge states reside only at the edge
- Reduced transport expected at higher B_T
- In all cases $P_{rad} < P_{in}$



D [m^2/s]	$P_{rad,0}$ [kW/m^3]	$P_{rad,a}$ [kW/m^3]	P_{rad} [kW]
200	32.5	18.1	28.5
20	2.5	15.7	12.8
2	0.3	15.9	4.7

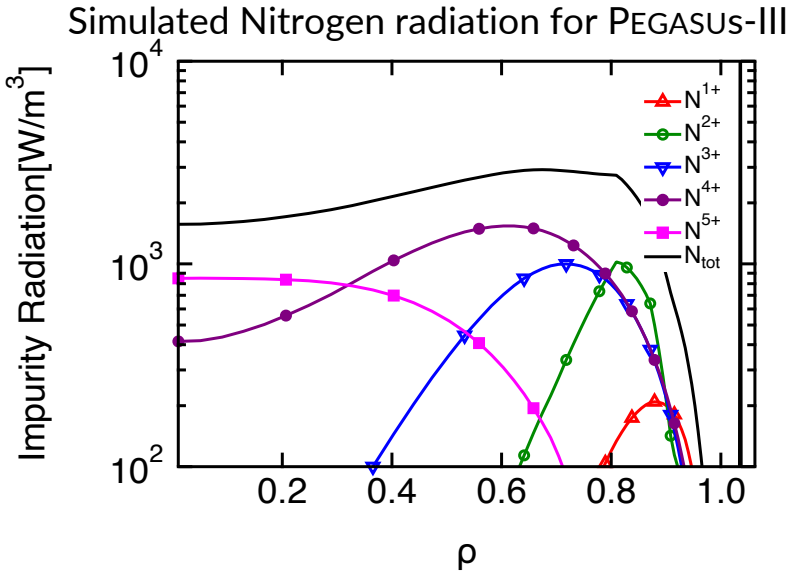
[1] G.M. Bodner et al., Physics of Plasmas **28**, 102504 (2021)

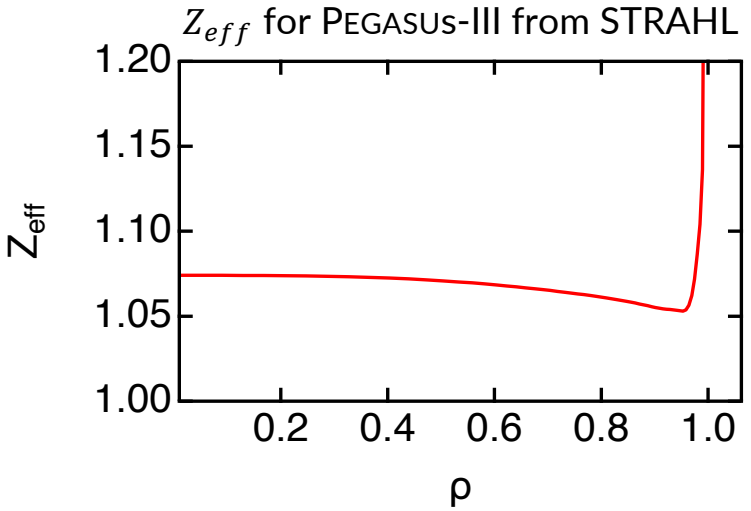
Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Impurity Assessment on PEGASUS-III

LHI Impurity Sourcing, Concentrations and Effects on LHI Performance Will be Explored in PEGASUS-III

- Experiments will characterize impurity sources from LHI
  - Cathode spots from injectors
  - Injector structures
  - Sputtering/ablation of wall materials due to electron beam
  - Combination of SPRED gratings allow to observe impurity lines
- Impurity concentration will be inferred through Z_{eff}
  - Simulations with STRAHL predict flat $Z_{eff}(R)$
  - Line-averaged Z_{eff} measurements with VB
- A more direct calculation of resistive dissipation and helicity drive
  - Helicity dissipated resistively
  - Needed for reliable I_p projections



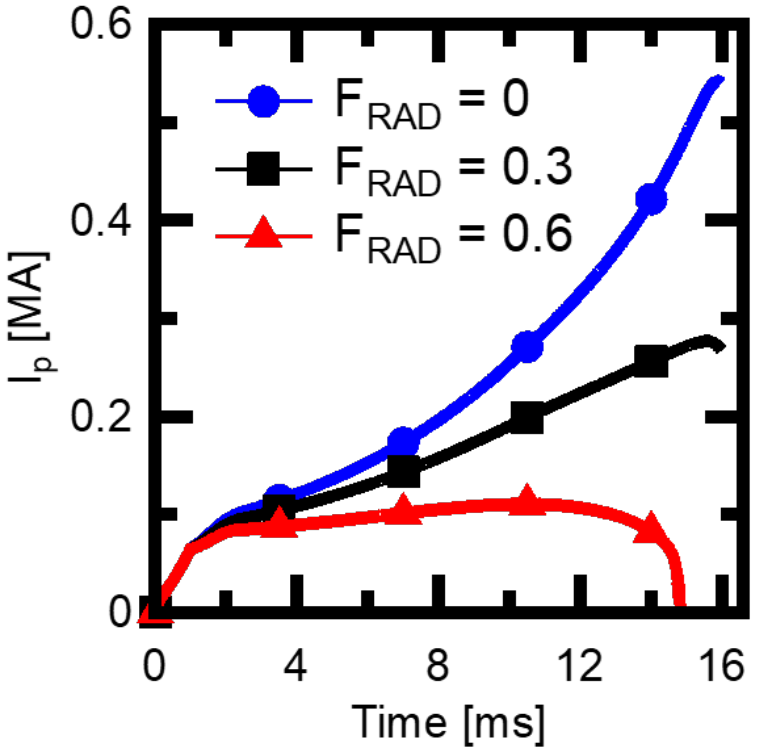


Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Experiments will Investigate Impact of Impurity Transport in LHI Startup and Power Balance

- Transport could play an important role in resistive dissipation
  - Possible cooling of T_e if high core radiation
- Changes in B_T may induce changes in transport
  - Evidence of improved transport at higher field seen on PEGASUS
  - New PEGASUS-III TF coils permit a wider B_T scan
- Transport determined from STRAHL and experiments
  - Use measured $P_{rad}(R)$ and Z_{eff} as constraint for STRAHL
- Radiation losses important for power balance

Projected I_p evolution on PEGASUS-III at different fractions of radiated power*



*See J. D. Weberski CP11.00049

Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Influence of Impurities on HI Tokamak Startup will be Studied in PEGASUS-III

- Impurity studies are needed for better LHI projections
  - Impurities affect helicity dissipation through changes in resistivity
    - Increase in mean ionic charge and cooling
  - Radiation power losses impact power balance
  - Accurate $I_p(t)$ projections require a model to scale helicity dissipation

- A suite of diagnostics and tools will be used to do an impurity assessment
  - Species identification with SPRED
    - New high-resolution grating will help to resolve previously unresolved lines
  - VB spectroscopy for Z_{eff}
    - Throughput of the diagnostic increased by ~10×
    - New spectral survey planned to find region free of line emission
  - AXUV radiometry for P_{rad}
    - New 32-channel designed, calibrated and ready for operations
  - Impurity Transport modeling with STRAHL

Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON