Ohmic Confinement Studies in the PEGASUS Toroidal Experiment

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53rd APS-DPP Annual Meeting

November 14-18, 2011

Salt Lake City, UT

PEGASUS Toroidal Experiment

Motivation for Study

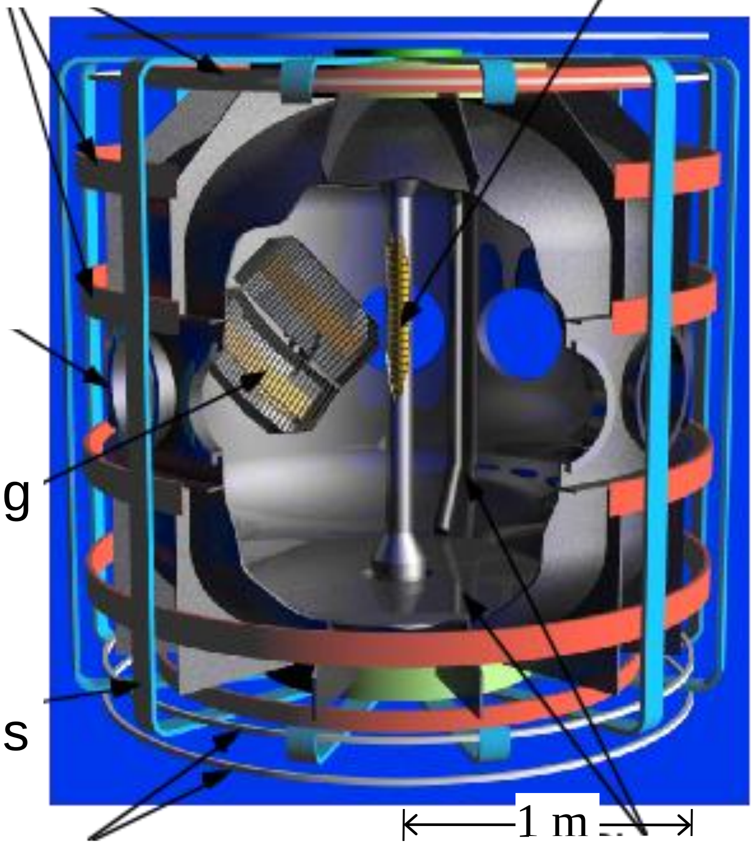
- Plasma performance is dependent on global recycling
  - Pegasus discharges indicate that a very low-recycling regime is obtained through the use of titanium gettering and cryogenic pumping
  - A significant increase in τ_p^* was observed with decreased wall pumping during systematic studies of wall conditioning

- Characterize Ohmically-driven modest current discharges' τ_e scaling
  - Will characterize future divertor operations' τ_e scaling
  - Will also characterize future Ohmically-driven discharges with helicity injection for added current drive's τ_e scaling

Outline

- Introduction to PEGASUS
- Measurements of Interest
- Description of Experiment
- Low and High Recycling Results
- Future Work and Conclusions

PEGASUS is a Compact Ultralow-A ST

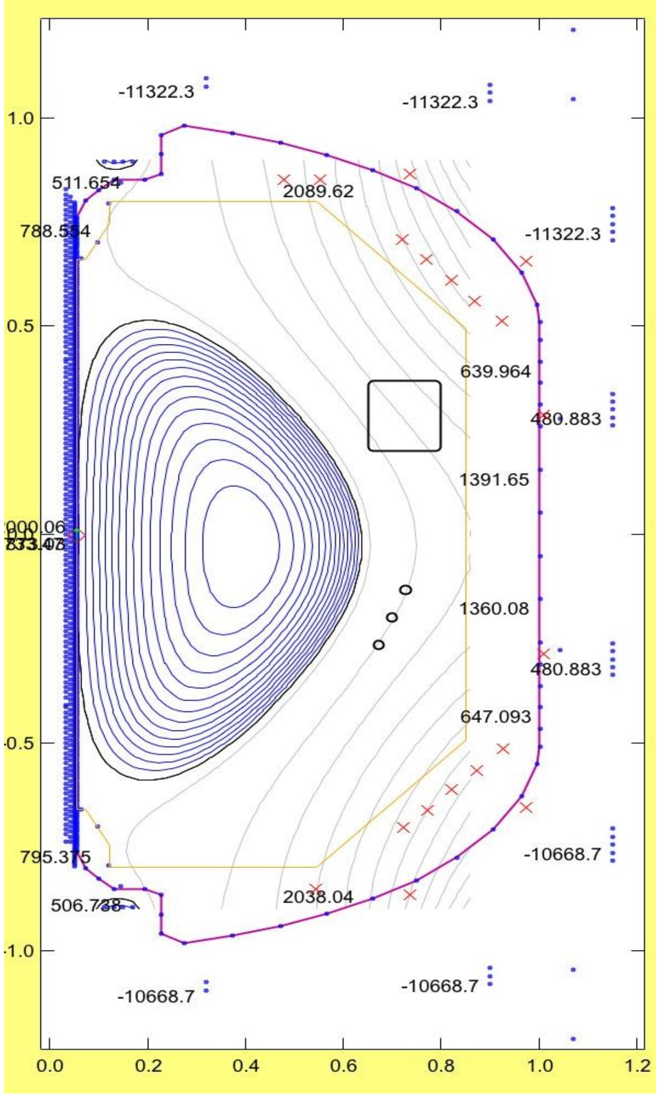


Experimental Parameters

Parameter	To Date
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	$\leq$ .22
I_N (MA/m-T)	6 – 12
l_i	0.2 – 0.5
κ	1.4 – 3.0
τ_{shot} (s)	$\leq$ 0.025
β_t (%)	$\leq$ 25
P_{HHFW} (MW)	0.2

Vacuum Conditions

- Pumping
  - Cryogenic Pump 5000 Torr·L/s for N_2
    - Removes N_2, O_2, H_2O
  - Titanium gettering covers >80% of plasma facing components
    - 0.045 to 0.15 grams Ti sublimated per hour
- Typical base pressures $<4\text{x}10^{-8}$ Torr
- Wall far from plasma
  - Limiter 15 cm from vacuum vessel



D_α Emission Used to Monitor and Understand Recycling

- D_α/H_α radiation results from collisional excitation of a deuterium/hydrogen atom from the plasma facing components (PFCs) when it interacts with the plasma
  - D_2 used as gas, but H_2 still present as an impurity

- Hydrogenic ionization rate is determined from D_α line intensities

- D_α line at 656.1 nm and H_α line at 656.3 nm

Importance of Recycling

- Both reflection of incident ions and neutrals and detrapping of previously trapped particles
  - Probability of backscattering ions is very low (inversely proportional to temperature)

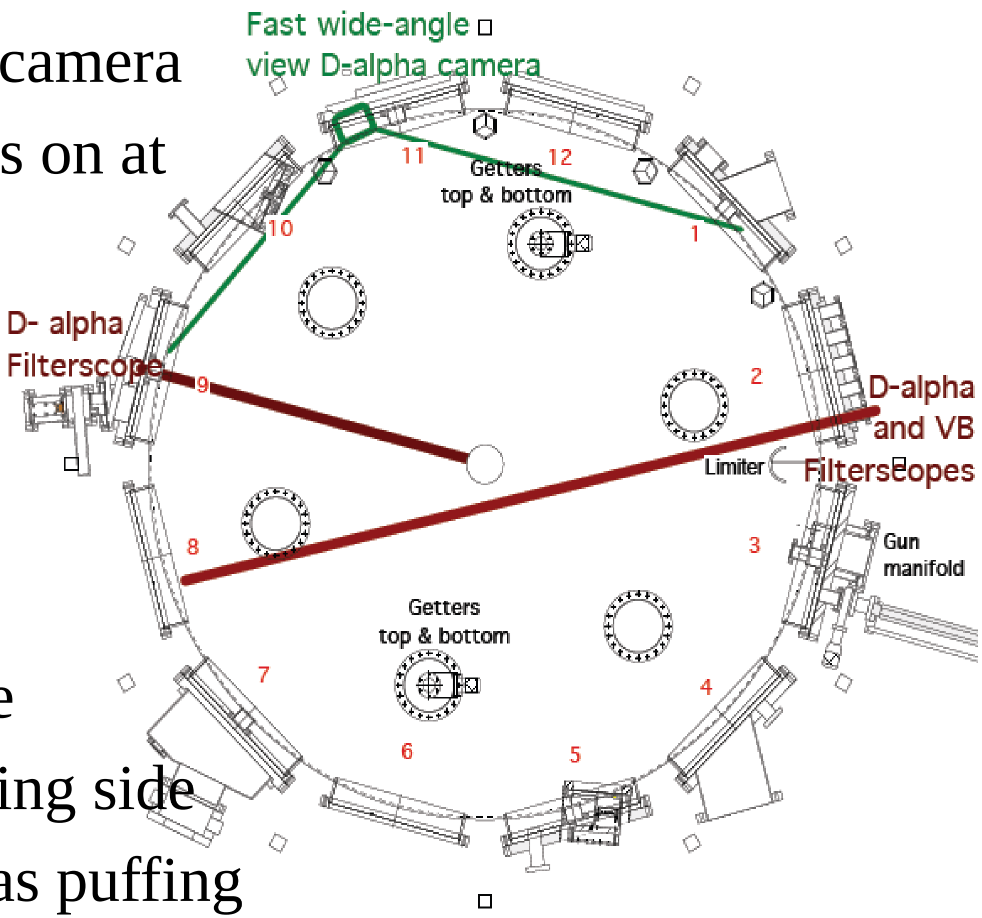
- Recycling coefficient, R, goes from 0 to 1 (high recycling)

- $R = \dfrac{particles\ reentering\ the\ plasma\ after\ interacting\ with\ the\ PFCs}{particles\ leaving\ the\ plasma}$

- Determine relationship between R and τ_e
  - CDX-U saw an increase in τ_e with reduced R, Majeski R *et al.* 2006 *Phys. Rev. Lett.* **97**, 075002

D_α emission monitored with wide-angle fast camera and filterscopes

- Fast wide-angle camera
  - MotionPro X4 5 kHz CMOS camera
  - Schott RG red glass filter, cuts on at ~610 nm
  - Fisheye F/4 8mm Sigma lens, 120^o machine view
- Two D_α filterscopes
  - Different sides of the machine
  - One located on main gas puffing side
  - Other located on additional gas puffing side



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Magnetic diagnostics used to calculate τ_e

- $$\tau_e = \frac{W}{I_p * V_{loop} - \frac{dW_k}{dt} - \frac{dW_m}{dt} - P_{RAD}}$$

- W, total energy, kinetic energy, W_k, magnetic energy, W_M, measured using KFIT equilibrium code
  - Time-evolving reconstructions performed to determine change in W_k and W_M

Name / Abbreviation	Type	Measures	Number
PlasmaRog	Rogowski Coil	I_p	2
Diamag	Diamagnetic Loop	Φ	2
NCFL / FL	Flux Loop	ψ_p	20
CFL	Centerstack Flux Loop	ψ_p	6
WFL / WL	Exterior Flux Loop	$\psi_p + \psi_{p,wall}$	6
PDX / P	Poloidal Mirnov Array	dB/dt, B, m	13
LowRes / LR	Poloidal Mirnov Array	dB/dt, B, m	7
HighRes / HR	Poloidal Mirnov Array	dB/dt, B, m	21
OTor / OT	Toroidal Mirnov Array	dB/dt, B, n	6
CTor / CT	Toroidal Mirnov Array	dB/dt, B, n	5

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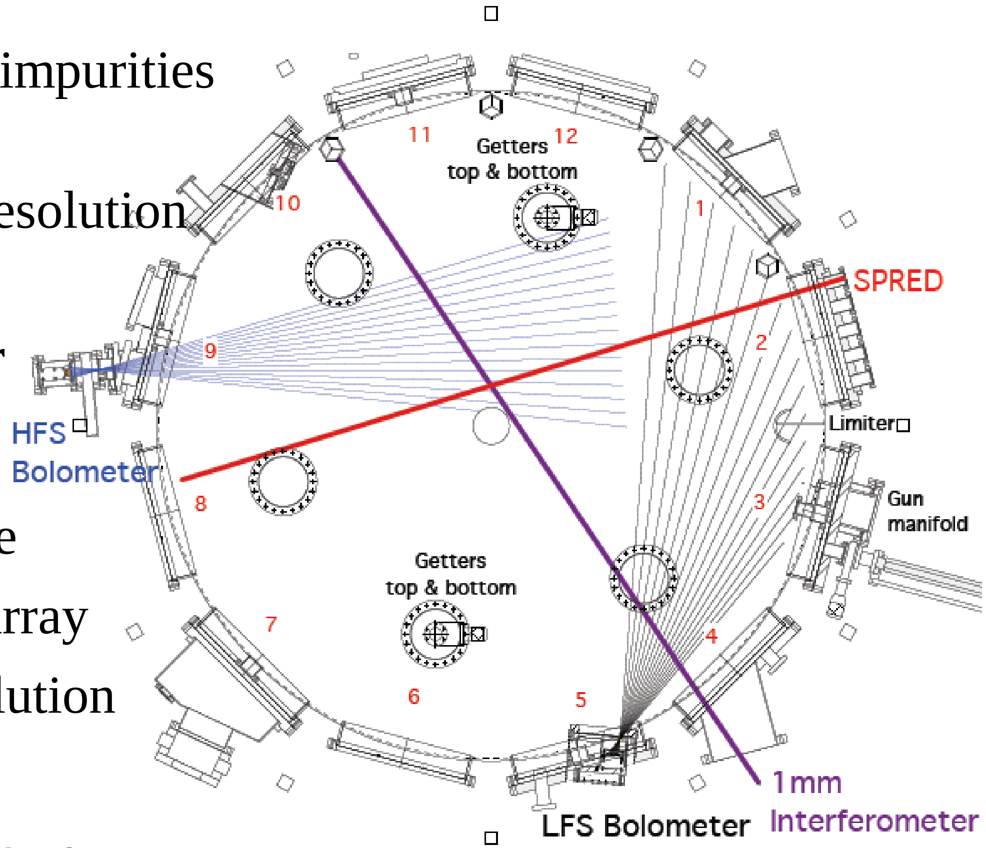
Estimate P_{RAD} via MIST

- SPRED VUV Spectrometer
  - Used to identify major sources of impurities and estimate T_e
  - 10-110 nm spectrometer, 200 μs resolution
- 2-16 channel AXUV Bolometer Diode Arrays
  - Used to estimate emissivity profile
  - One inboard array, one outboard array
  - Sensitive to photons, 0.4 ms resolution
- Michelson Heterodyne Microwave Interferometer
  - Used to estimate n_e



VB filterscope used to estimate τ_p^*

- Measure instantaneous density decay after external gas supply is terminated using
  - VB Filterscope
    - $I_{VB} \sim \frac{n_e^2}{\sqrt{T_e}} Z_{eff}$
    - $\sqrt{I_{VB}} \sim n_e$
  - Michelson Heterodyne Microwave Interferometer
    - Used for Comparison

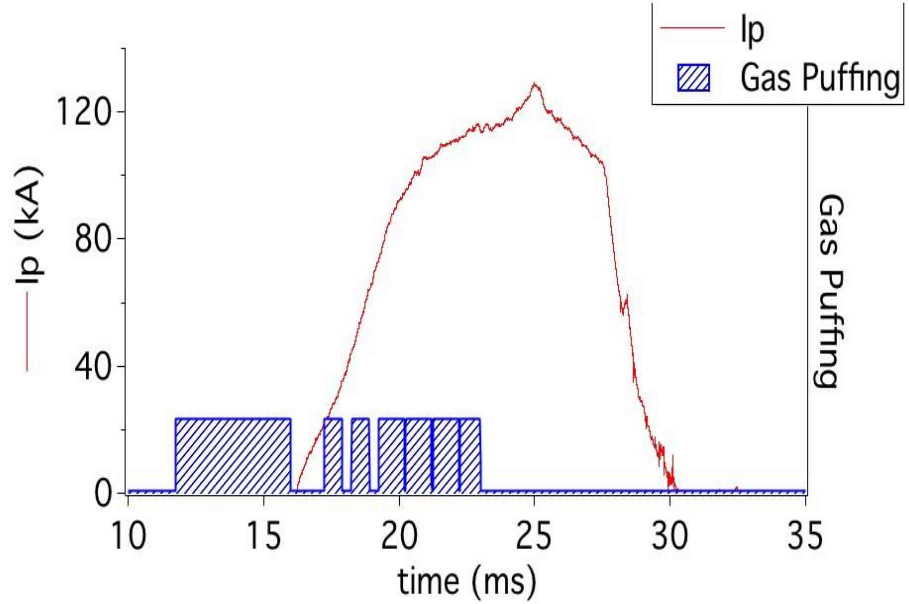
$$\tau_p^* = \frac{n_e}{\frac{dn_e}{dt}} = \frac{\tau_p}{1 - R}$$

$$\tau_p^* = \frac{\sqrt{I_{VB}}}{\frac{d\sqrt{I_{VB}}}{dt}}$$

Experiment: Transition from Low to Higher Recycling

- Started with well-conditioned machine
  - At least two weeks since last vent with titanium getters in use daily
- Established target discharge and then turned off gettering
  - **This is the reference “low” recycling plasma**
  - Removed gas puffing in I_p flat-top to observe instantaneous density decay

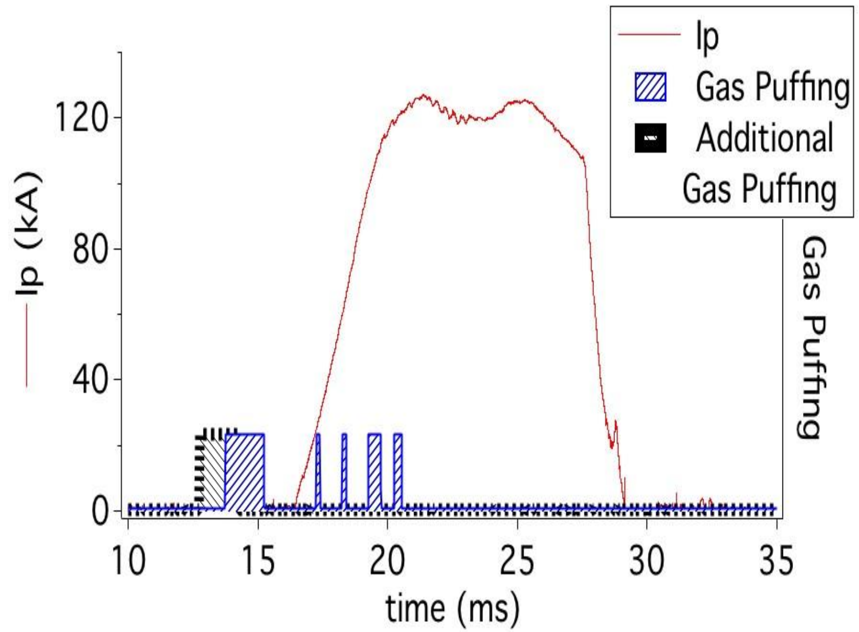
“Low” Recycling Reference Plasma



Experiment: Transition from Low to Higher Recycling Continued

- Progressive steps to passivate titanium on PFCs
  1. 7 seconds of D_2 gas puffing with pumps valved off
  2. 40 minutes of N_2 gas @ 100 mTorr backfill in vacuum vessel
  3. 20 minutes of N_2 gas @ 10 Torr backfill in vacuum vessel
     - **This is the reference "high" recycling plasma but NOT R=1**
  4. 20 minutes of N_2 glow
     - Cryogenic pump unavailable after
     - SPRED showed lots of Nitrogen impurities

"High" Recycling Reference Plasma



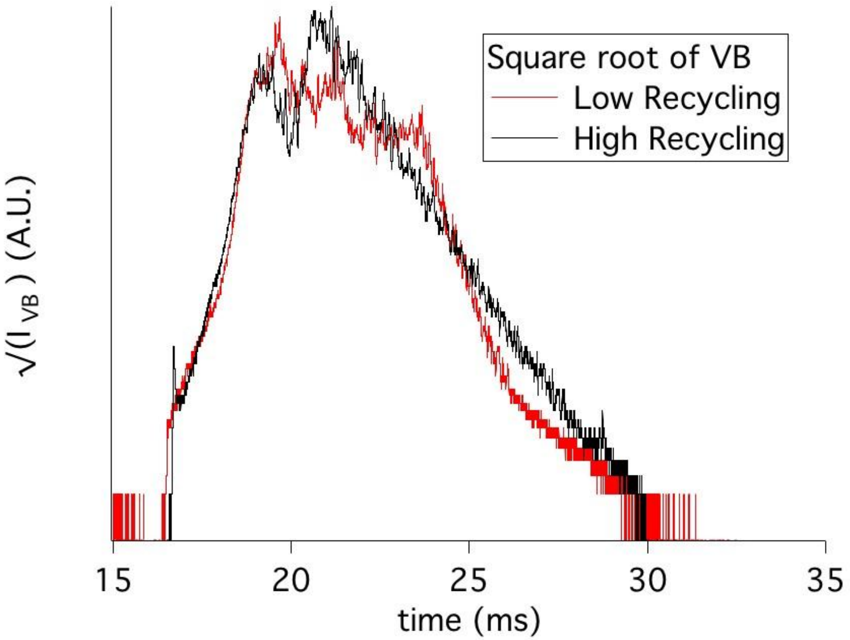
– Titanium still not completely passivated

τ_p^* Increases by a Factor of 4 from Low to High Recycling

- Measured using VB filterscope after external gas puffing is terminated

- Low recycling
  - $\tau_p^* = 2.8$ ms

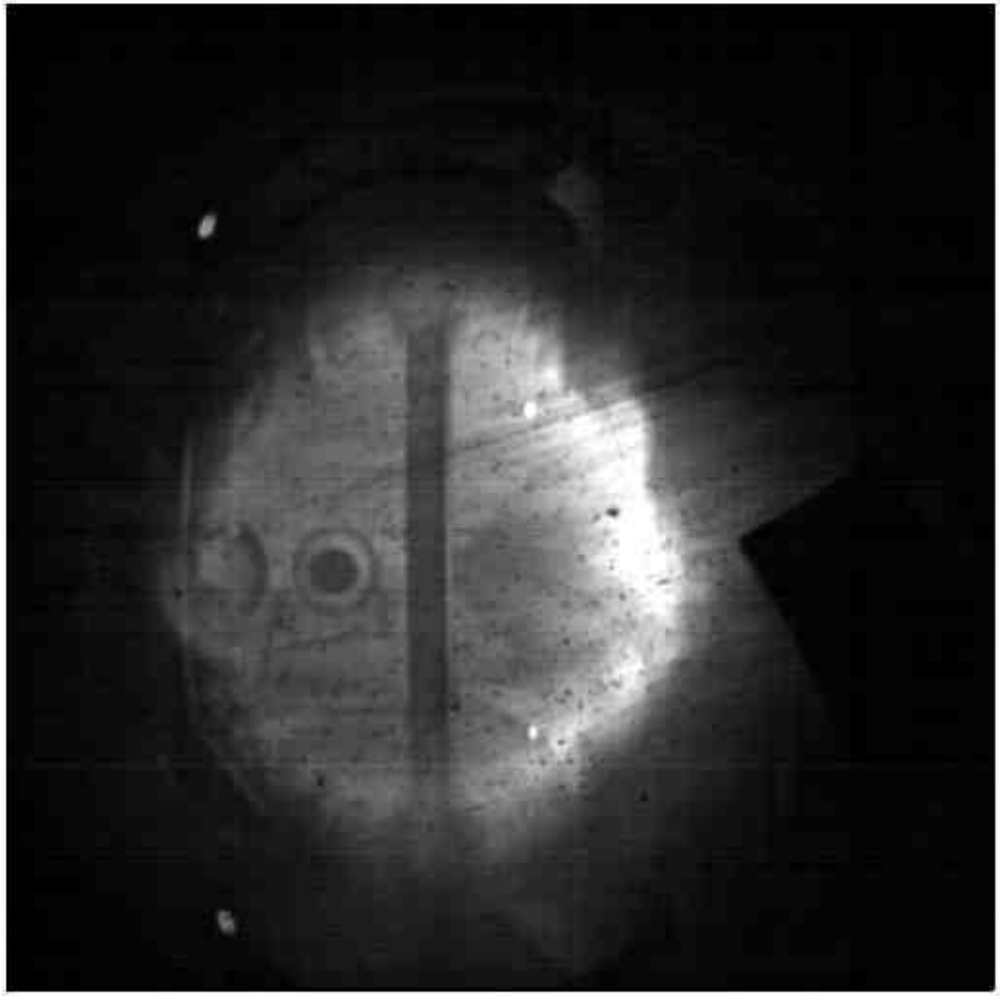
- High recycling
  - $\tau_p^* = 12$ ms



D_α camera used to observe locations of recycling

- 120º machine view shows
  - Divertor plates
  - Limiters
  - Plasma Guns
  - 4 Getters
  - Gas Puffing

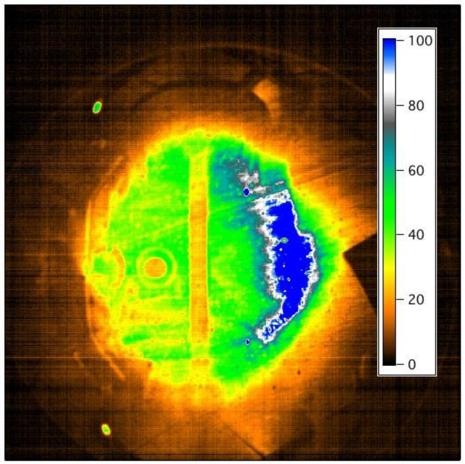
- Images shown with color scale to better illustrate



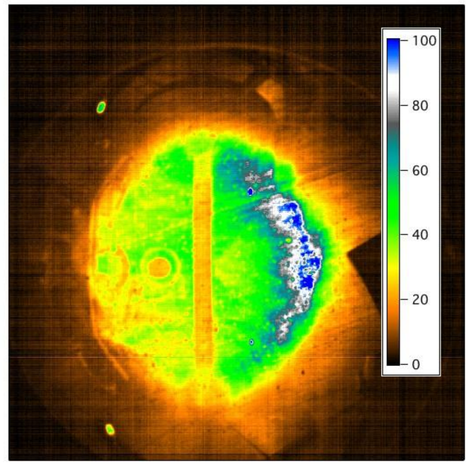
Low Recycling Plasma: D_α emission during I_p flat-top from camera

Puffing terminated at 22.75 ms

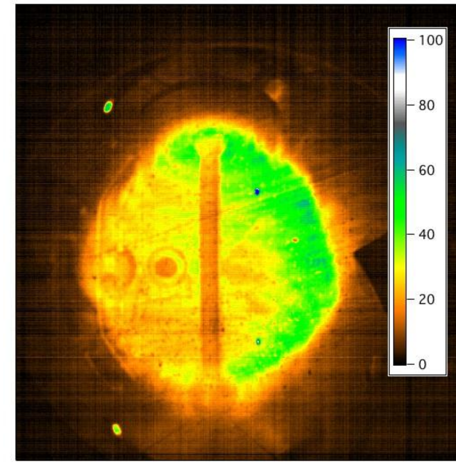
22.80 ms



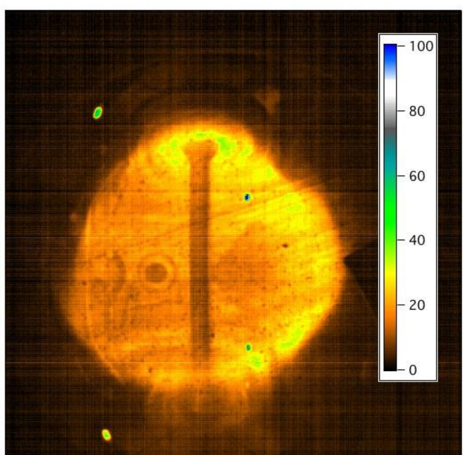
23.80 ms



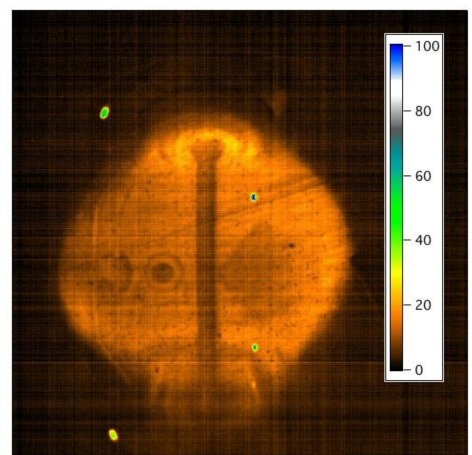
24.80 ms



25.80 ms



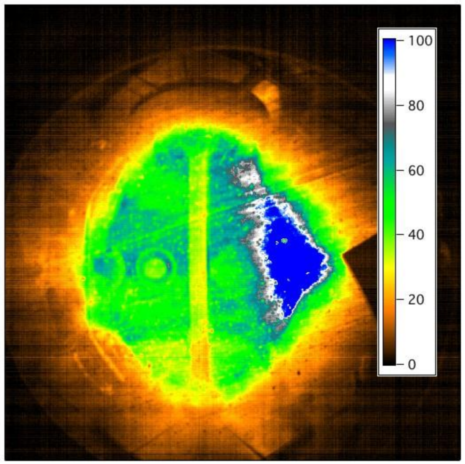
26.80 ms



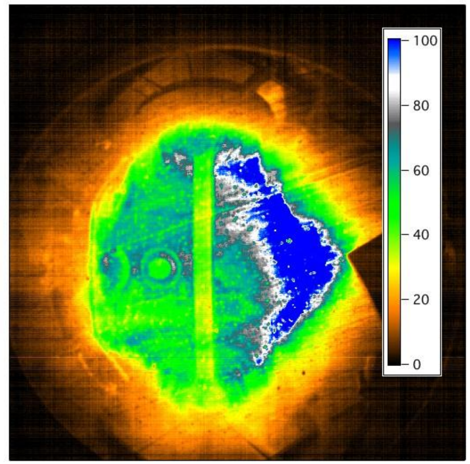
High Recycling Plasma: D_α emission during I_p flat-top from camera

Puffing terminated at 20.3 ms

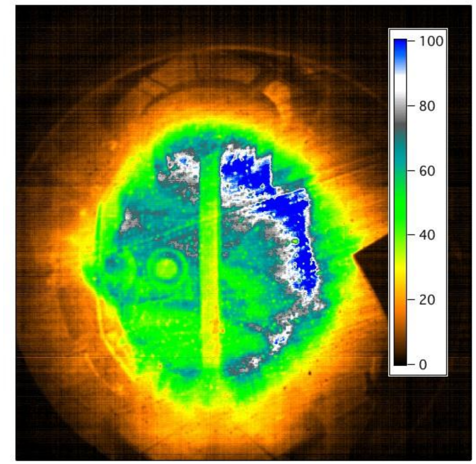
20.40 ms



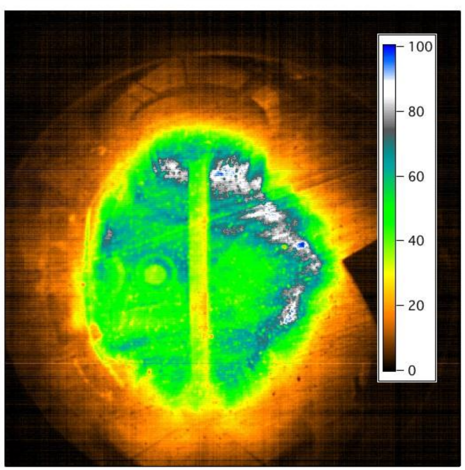
21.40 ms



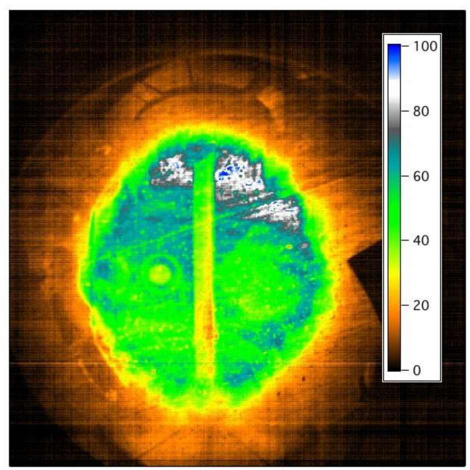
22.40 ms



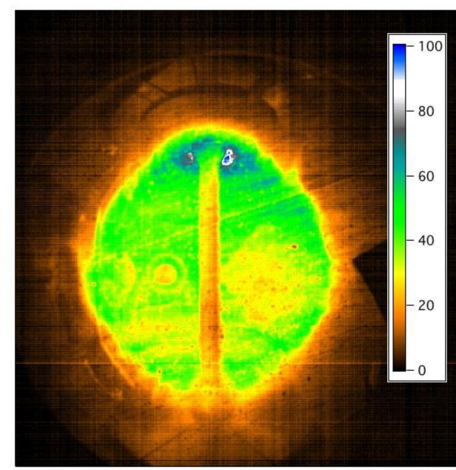
23.40 ms



24.40 ms

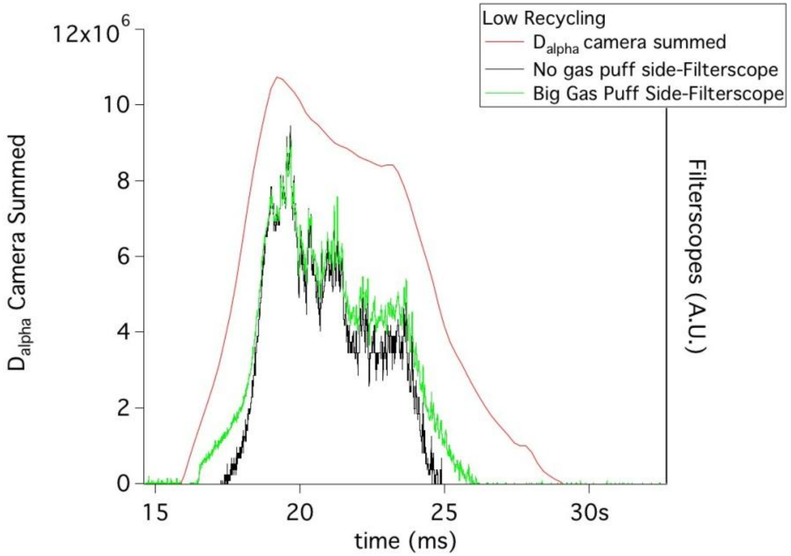


25.40 ms

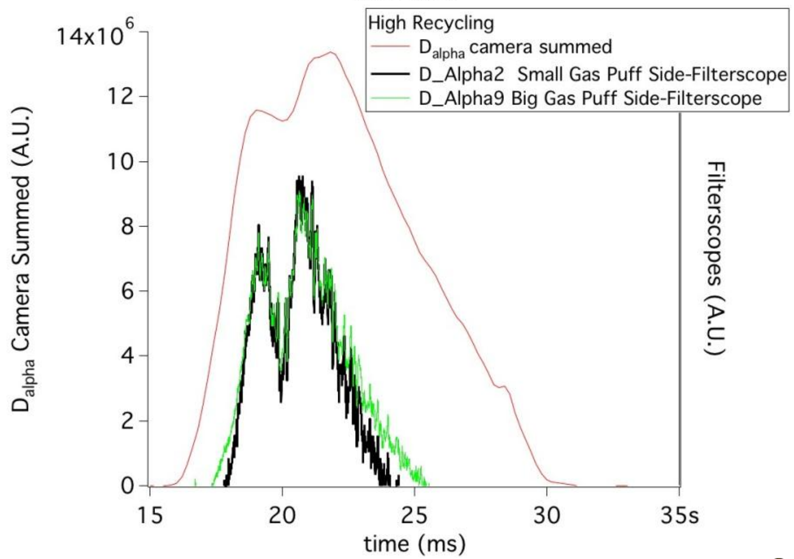


D_α signal from summed Camera and Filterscopes

- Low Recycling
  - Summed camera D_α profile closely matches the filterscopes' profile
  - After the last gas puff, D_α signal decays



- High Recycling
  - Summed camera D_α profile closely matches the filterscopes profile
  - First peak intensity comparable to low recycling results
  - Second peak is slightly higher than the first peak



K. E. Thome, 53rd APS-DPP, Salt Lake City, Utah, November 2011

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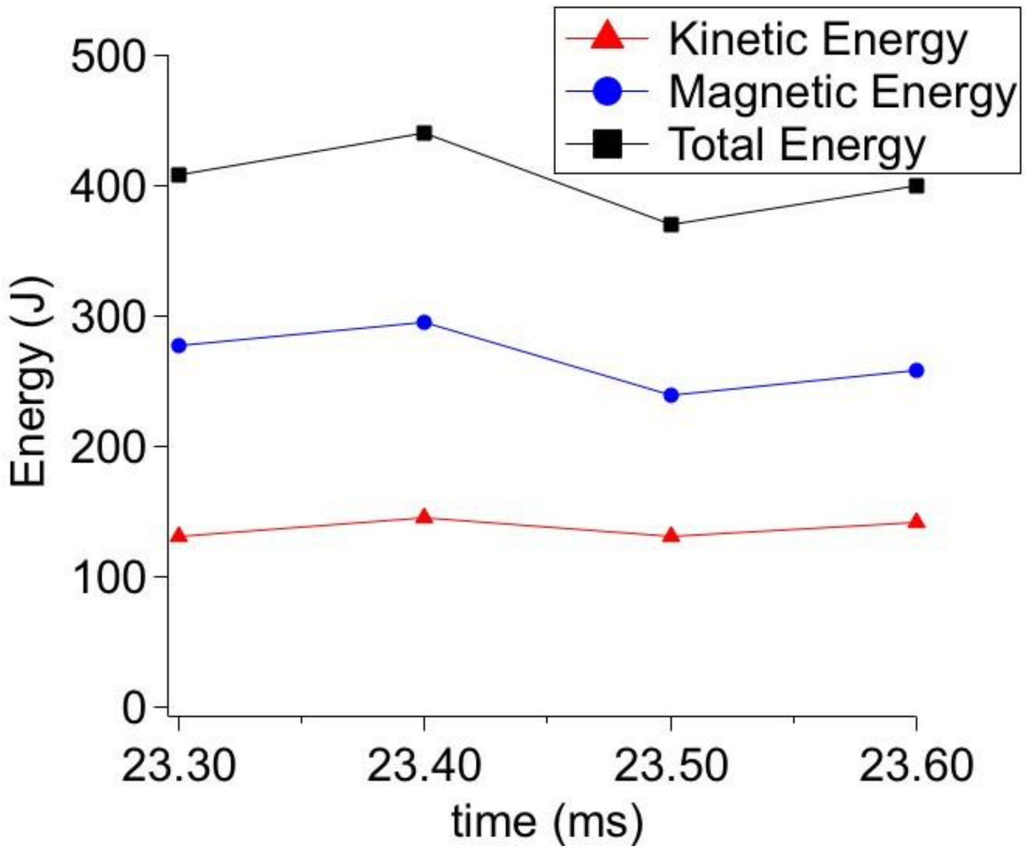
General Conclusions from D_α emission

- Recycling Locations
  - Recycling occurs mostly at LFS edge, location of main gas puffing
  - Some recycling occurs on the top divertor plate
    - Particularly for high recycling
- Only slight increase in D_α emission in high recycling as compared to low recycling
- Particles in high recycling plasma stay in the plasma longer
  - Particles in low recycling plasma are ionized for 2 ms after last gas puff
  - Particles in high recycling plasma are ionized for 4 ms after last gas puff

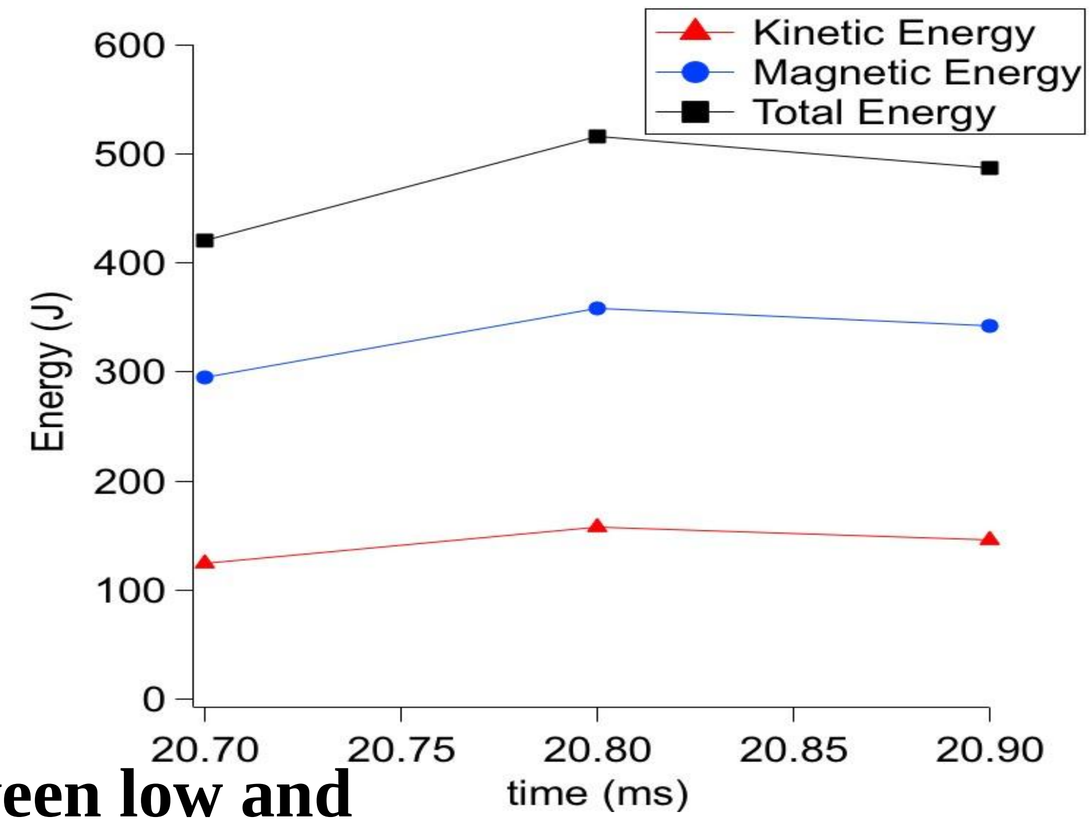
Low Recycling Energy Confinement

- τ_e measured during I_p flat-top before gas puffing is terminated
- $\frac{dW_k}{dt} \approx \frac{dW_M}{dt} \approx 0$
- P_{RAD} is extremely small
- τ_e is 0.95 ms



High Recycling Energy Confinement

- τ_e measured during I_p flat-top and before gas puffing is turned off
- $\frac{dW_k}{dt} \approx \frac{dW_M}{dt} \approx 0$
- P_{RAD} is extremely small
- τ_e is 1.05 ms
- **τ_e did not change between low and high recycling**



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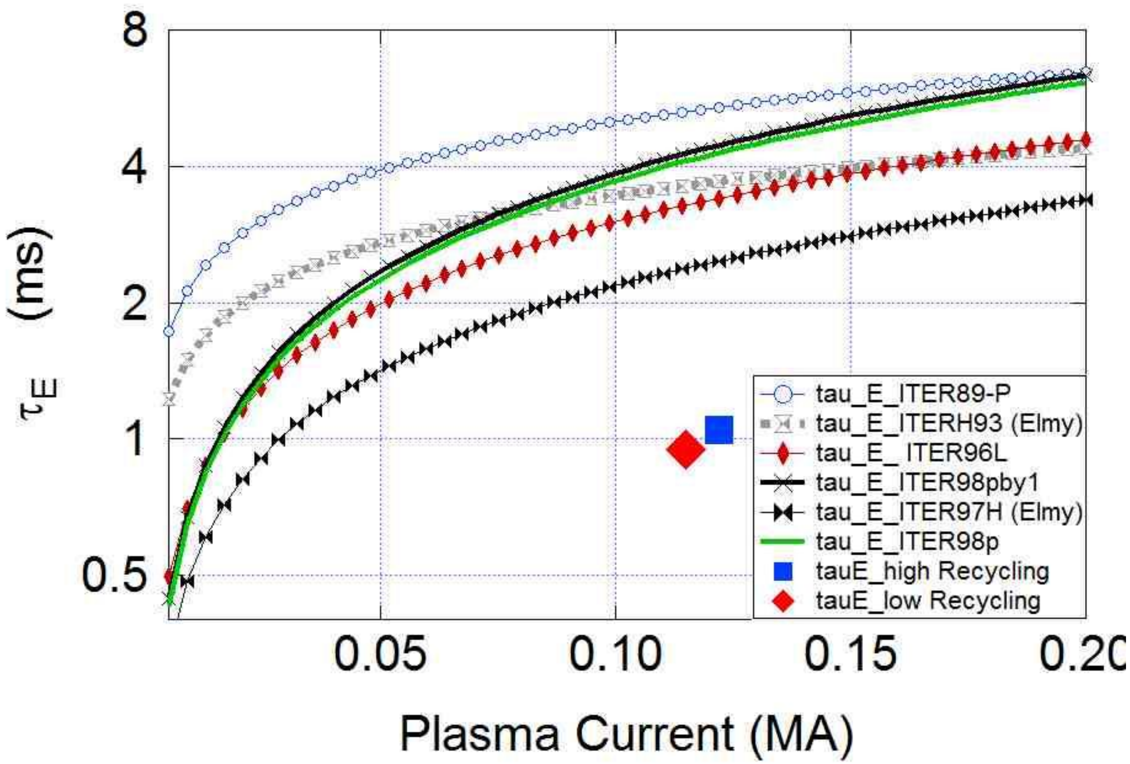
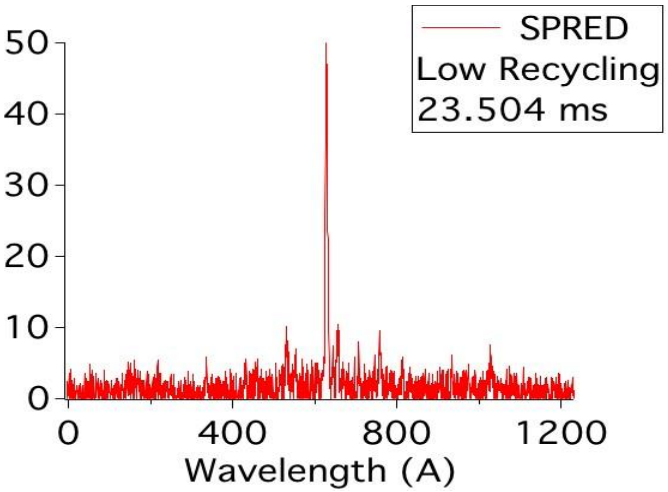
Pegasus L-mode τ_e compared with scaling laws

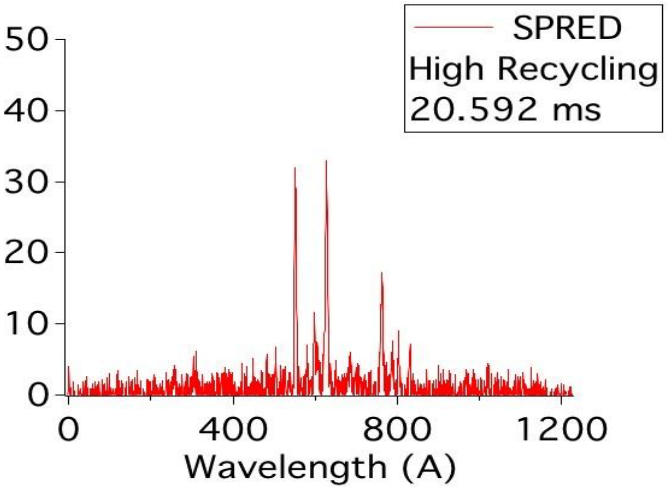
- Measured τ_e a factor of 2 smaller than predicted using scaling laws
  - P_{RAD} negligible
  - Not corrected for charge exchange losses, expected to be significant
  - Will put on new bolometers that include charge exchange



Impurities identified via SPRED

- Impurities
  - Very low signal levels
  - Only Oxygen and Deuterium lines
  - Comparable levels between low and high recycling
    - But measured at different times during discharge
- T_e estimated using line intensity ratios for MIST





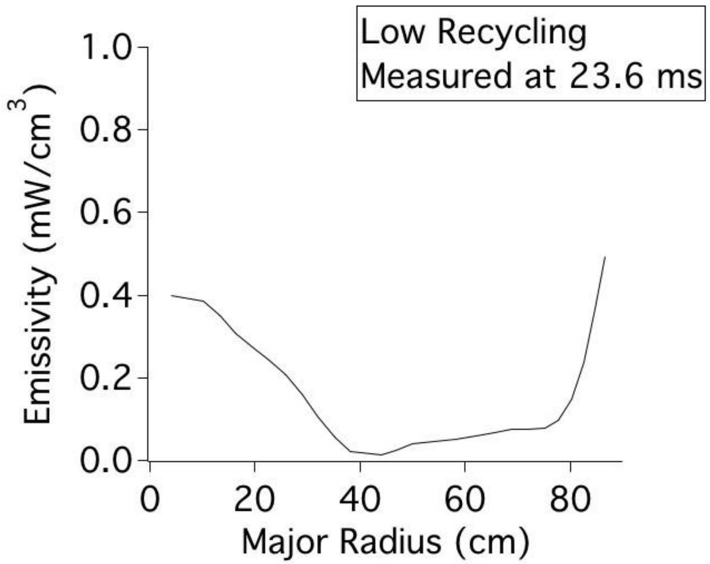
P_{RAD} and Z_{eff} estimated via Bolometers

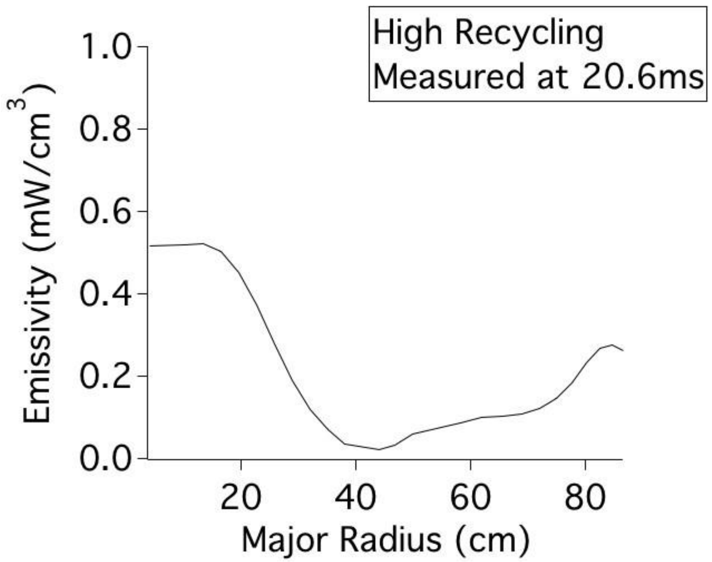
- Very low signal levels

  0.4 to 0.6 mW/cm^3 maximum
  - Maximum used as input for MIST

- Hollow profile
  - Also somewhat asymmetric
  - Possibly enhanced at edges due to reflections

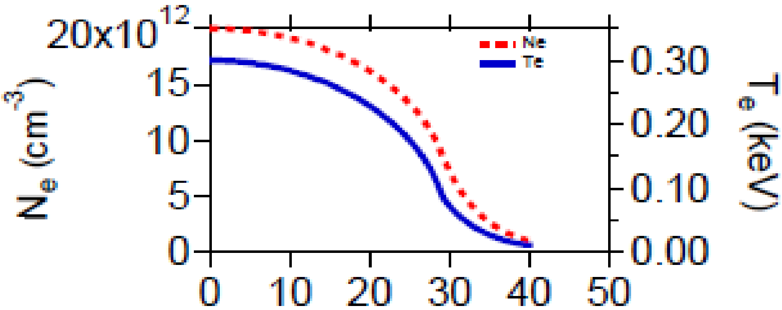
- In the future will measure charge exchange losses

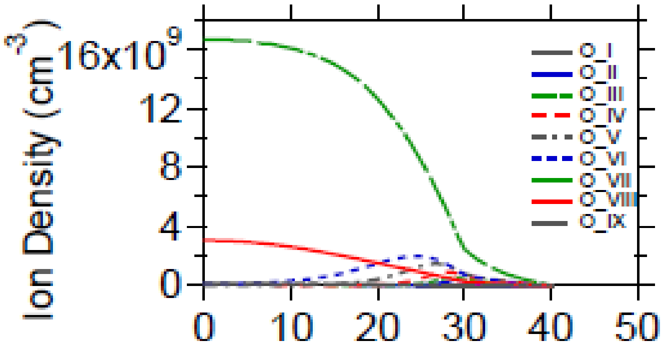


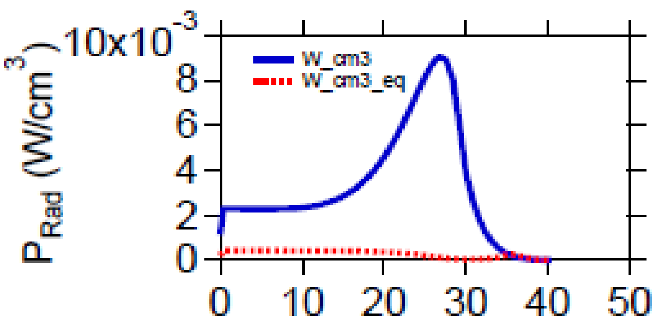


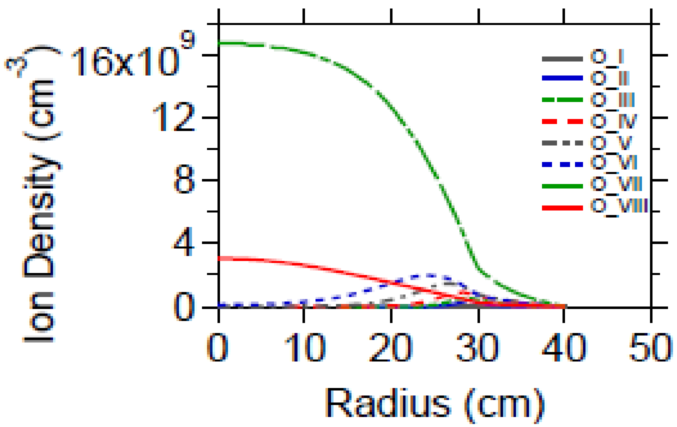
Impurity Transport Code used for Z_{eff} and P_{RAD}

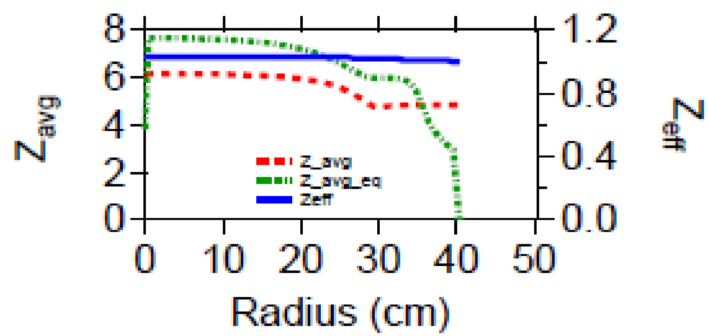
Oxygen:
rmajor=35.5 rso=30.0
te0=0.30 tea=0.020 tex=2.0 tey=0.5
ane0=2.0e13 anea=0.5e13 anex=2.0 aney=0.5
llitene=1 llneut=1 llnzze=1 llnq=1 llramx=1 llemr=1 llem=1
lprnq=1 lprnqz=1 lptpwr=1 lptnzz=1
NUCZ=8 FRACZ0 = 0.001
DAC=2.0E5 CVNE=1.0 SOFLX=5.0 LRNDEP=1











Estimate of Recycling Coefficient

- If $\tau_e \sim \tau_p$ using
  - $\tau_{eL} \approx \tau_{eH} \approx 1.0$ ms
  - $\tau^*_{pL} \approx 2.8$ ms
  - $\tau^*_{pH} \approx 12$ ms
  - R_L=0.6 and R_H= 0.9

$$\tau_p^* = \frac{\tau_p}{1 - R}$$

- However, if $\tau_{eL} \approx \tau_{eH}$ are both off by a factor of 2, as predicted by scaling laws probably due to charge exchange losses
  - R_L=0.3 and R_H= 0.8

Future Work: Ohmic Operations and Diagnostic Improvement

- Ohmic Operations
  - Vary n_e and I_p and measure τ_e to determine scaling
  - Attempt to fully passivate titanium gettering
- Diagnostic Improvement
  - Michelson Interferometer
  - Multi-point Thomson Scattering
  - T_i (R,t)
  - Bolometer Diodes
    - Will measure charge exchange losses

Future Work Continued: Future Experiments

- Apply knowledge of fueling and confinement to achieve high β_T at $I_p/I_{TF} > 2$

- Add separatix operations via new divertor coils
  - H-mode may be possible
  - H-mode via EBW (proposed for future)

- Add additional current drive via helicity injection
  - Explore confinement for higher I_p with Ohmic heating following helicity injection

Conclusions

- Pegasus Ohmic L-mode plasmas are very low recycling with R=0.6 using measured τ_e and R=0.3 using predicted τ_e
  - They have very little Oxygen Impurities
  - They have very low radiation levels
  - $Z_{eff} \approx 1.0$ using MIST
- τ_e was measured using KFIT time-evolving reconstructions and MIST to estimate P_{RAD}
  - τ_e was 1.0 ± 0.05 ms for both the low and high recycling plasmas
  - Difference between measured τ_e and predicted τ_e scalings is probably due to charge exchange losses not currently taken into account

Reprints

- See http://pegasus.ep.wisc.edu/

- Work supported by US DOE Grant DE-FG02-96ER54375