

Global energy confinement studies on the Pegasus Toroidal Experiment

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Abstract

Recent studies have shown low-recycling walls significantly enhance L-mode energy confinement [1]. Discharges on Pegasus suggest a low-recycling regime is obtained using Titanium gettering and cryogenic pumping. When the external gas supply is terminated during an established discharge, tangential H_α and visible light signals drop to 5% of their initial levels within 5 ms. Effective particle confinement is measured using the density decay rate and its effect on energy confinement on Pegasus is explored. Initial global energy confinement times of $\tau_e = 2 – 4$ ms were calculated for $I_P \sim 0.15$ MA L-mode discharges. Scans of plasma current and line-averaged density are used to benchmark τ_e measurements against empirical L-mode scaling laws. These initial τ_e measurements indicate the H-mode power threshold as given by the ITPA04 scaling [2] can be exceeded in diverted Ohmic discharges on Pegasus.

[1] Majeski, R. *et al* Phy. Rev. Letters **97** 07002/1-4
[2] Takizuka, T. *et al* Nuc. Fusion **46** A227-233

*Work supported by the US Department of Energy Grant DE-FG02-96ER54375

An accurate measurement of τ_e is important for future Pegasus experiments

- **Helicity injection experiments**
  - Good τ_e is an indication closed flux surfaces have formed
- **Accessing high β regime**
  - Requires good energy confinement
  - H-mode access may be possible on Pegasus
  - Low recycling walls suggest Pegasus can achieve enhanced L-mode energy confinement

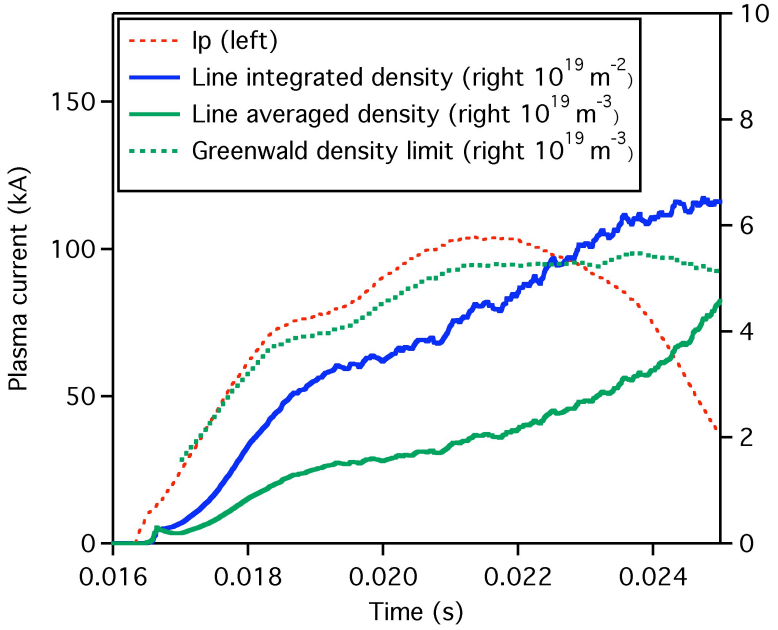
Suite of diagnostics used to constrain τ_e calculation

Diagnostic	Capability	Measures	Status
Core Flux Loops	6	V_L, B_{pol}	Operational
Wall Flux loops	6	Vessel currents	Operational
Int. Flux loops	20	B_r	Operational
Rogowski Coils	2	I_p	Operational
Diamagnetic Loop	2	B_t	Operational
Bp, Mirnov Coils	56	B_r , B_z & MHD activity	Operational
VUV (SPRED)	Central Chord	Relative impurity monitor	Operational
Interferometer	Single Chord	n_{el}	Operational
High Res. Camera	5000 fps	Plasma shape / position	Operational
Filterscopes	Central Chord	Oxygen, Carbon, VB, Da	Operational
Tangential SXR PHA	Single Chord	$T_e(t)$	Operational
Tangential Bolometer Array	32 Chords	P_{rad}	Operational
Tangential VB Array	20 Chords	$Z_{eff}(R,t)$, $n_e(R,t)$	Operational
2-D SXR Camera		Internal Shape / q(R)	Testing

$\bar{n}_e$ necessary for comparison to τ_e empirical scaling relations

Heterodyne microwave interferometer provides single midplane line integrated density measurement

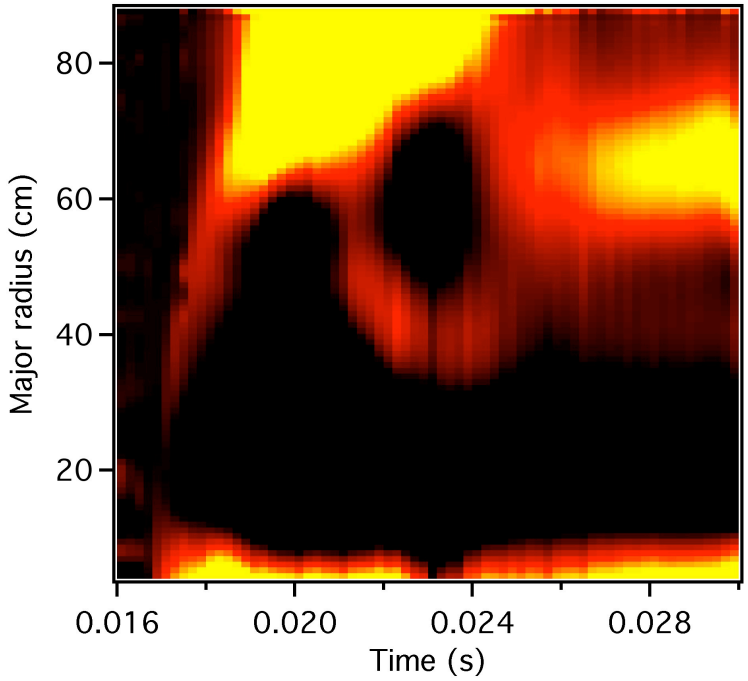
Low density discharge



- Compact, stable, inexpensive and easy to align
- 1 MHz IF signal digitized for post-shot processing
- Four midplane chords available
- Designed by UCLA

P_{rad} measurement important for power balance calculations

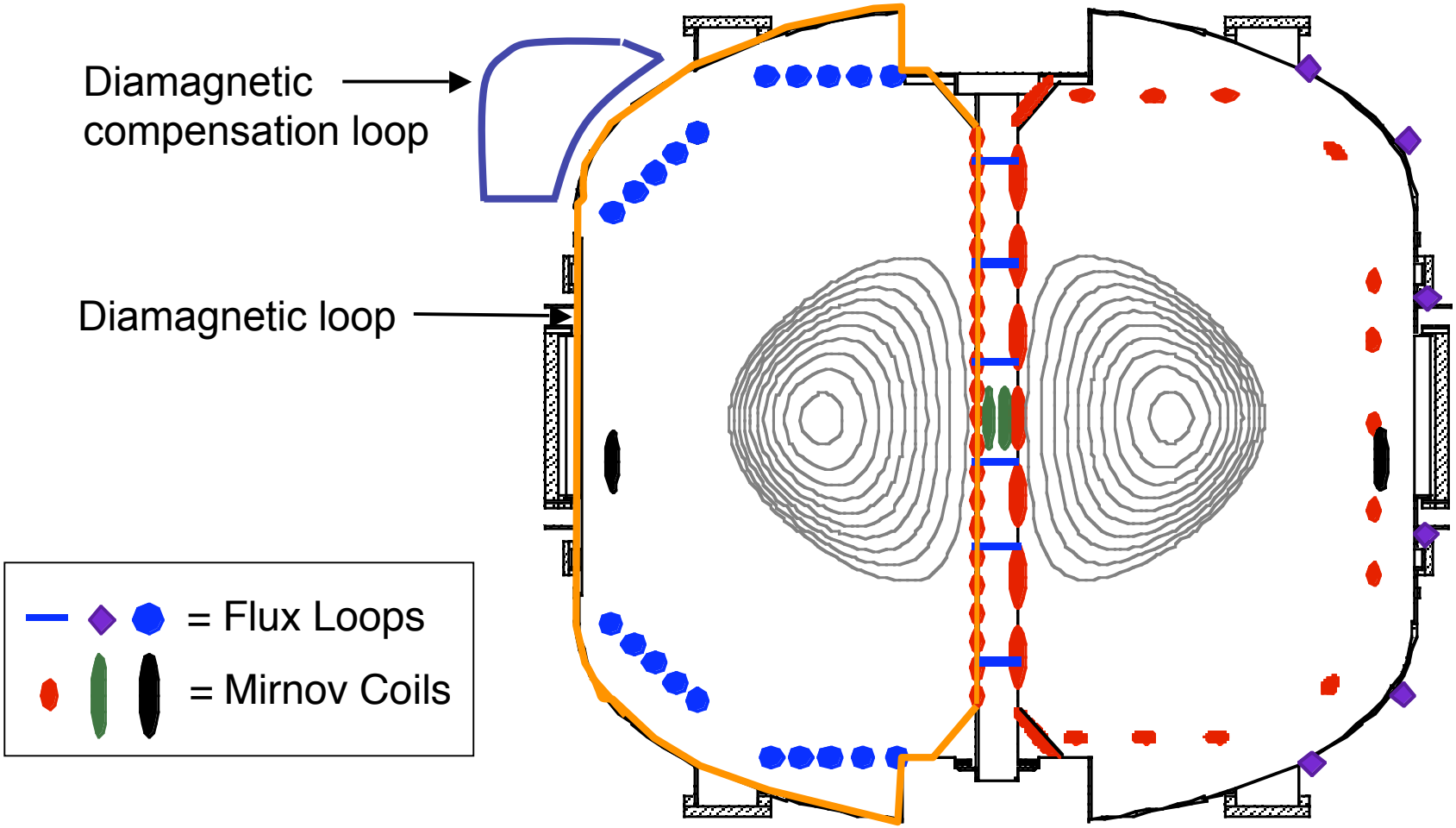
Two 16-channel AXUV silicon photodiode detectors spatially and temporally resolve mid-plane radiative power loss.



Shot 38731 Relative emissivity

- Integrated Photodiode Array and Pre-amp Assembly
- Responds to visible light through soft x-rays
- Spatial resolution ~ 2 to 4 cm
- Temporal resolution of 200 ms

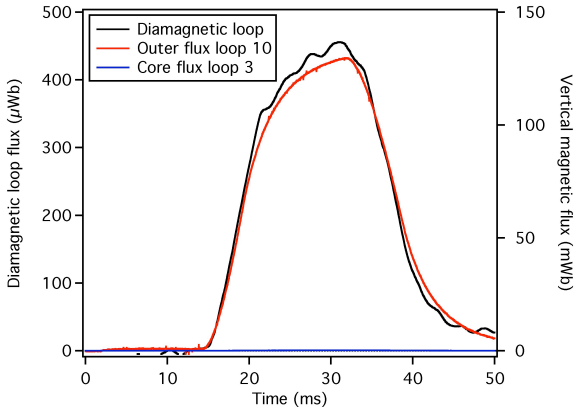
Magnetic diagnostics sufficient to constrain global parameters in equilibrium reconstructions



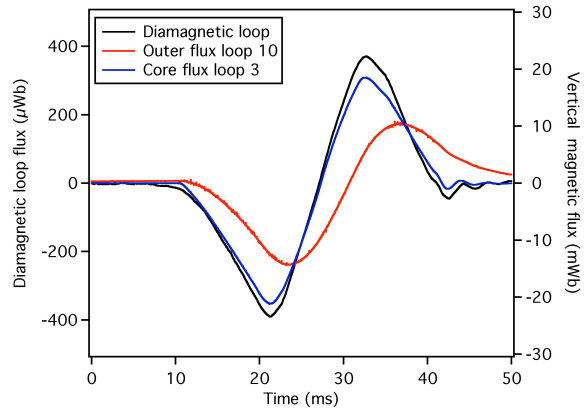
Vacuum field subtraction adequately compensates for B_v and B_r diamagnetic loop pickup

- B_r and B_v pickup due to misalignment of coils and diamagnetic loop
- Pickup on the order of plasma paramagnetic field
- Programmable power supplies provide good shot repeatability
  (< 1% deviation)
- Net vertical and radial field from plasma ~ 5% of vacuum fields

EF field only

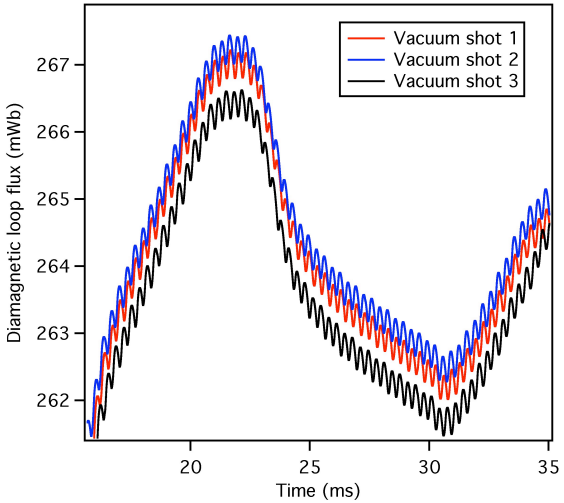


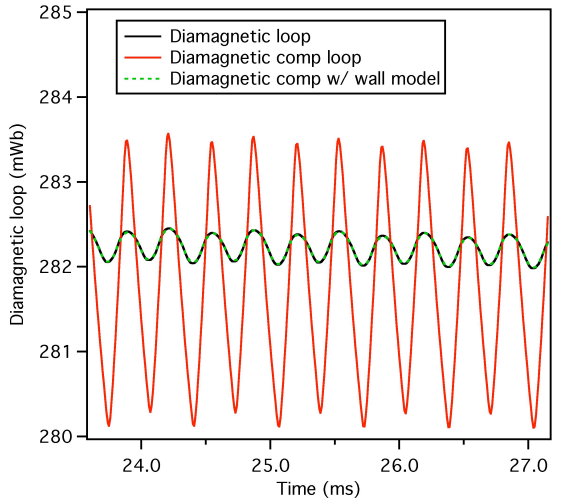
OH field only



Toroidal flux model required to compensate for vacuum B_t pickup in diamagnetic loop

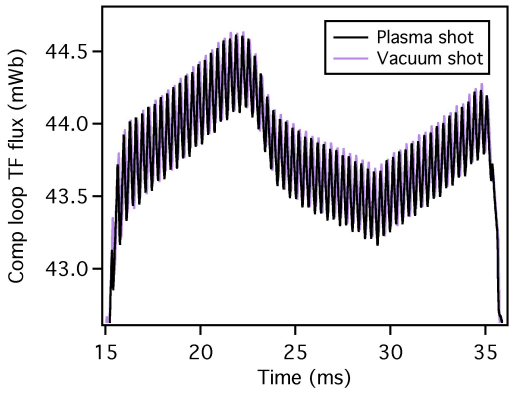
- Vacuum TF flux >> flux from plasma
- 1 % shot to shot deviation in TF flux ≈ plasma signal (1 mWb)
- Switching ripple not repeatable and ≈ 10 % of plasma signal
- Use external loop or TF current to compute TF flux
- Requires single pole flux penetration model for conductive wall ($\tau \sim 0.5$ ms)





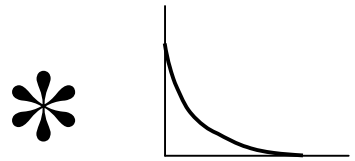
Flow chart of diamagnetic loop compensation calculations

Compensation loop signal

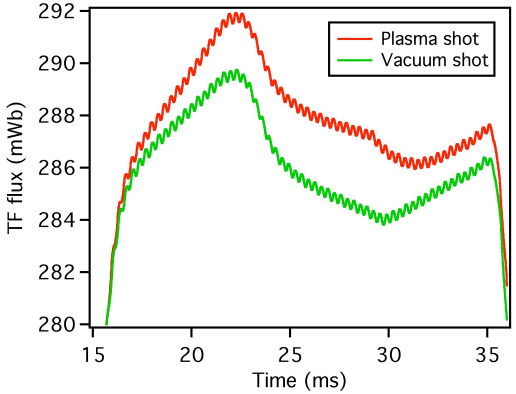


Subtract vacuum shot from plasma shot

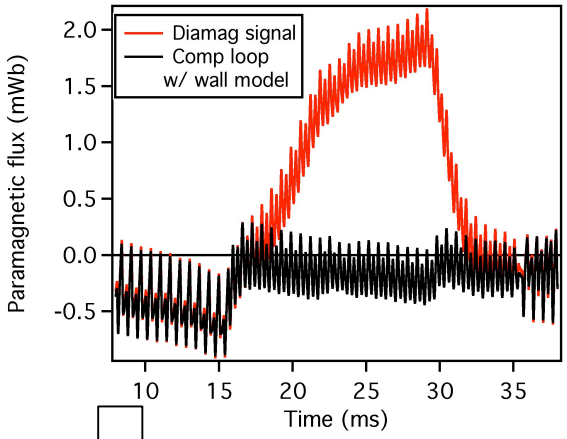
Convolve with single pole (low pass filter) wall model



Diamagnetic loop signal



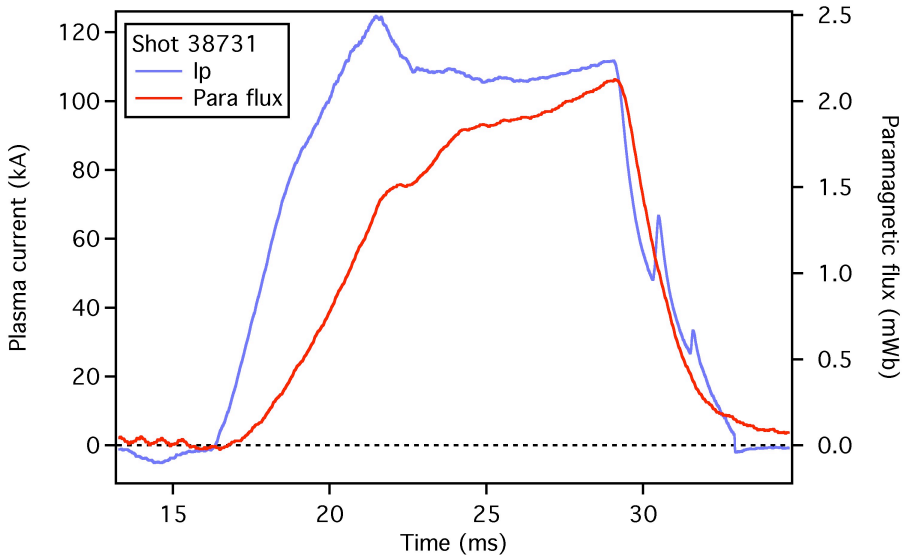
Subtract vacuum shot from plasma shot



Pegasus plasmas are paramagnetic

Subtract compensation loop signal from diamagnetic loop signal

Measurement accurate to within 5%



- Paramagnetic → large toroidicity ($B_T \sim B_p$) inherent to low-A geometry
- Measurement constrains W_k in equilibrium reconstructions

Energy confinement time is calculated using equilibrium reconstructions

$$\tau_e \equiv \frac{W_k}{P_{loss}}$$ Energy confinement time

$$P_{in} = P_{loss} + \left(\frac{dW_k}{dt} + \frac{dW_M}{dt} \right)$$ Power balance

where $P_{loss} = P_{rad} + P_{th,loss}$ and $P_{in} = V_{loop} I_p$

$$\tau_e = \frac{W_k}{P_{in} - \left(\frac{dW_k}{dt} + \frac{dW_M}{dt} \right)}$$

W_k and W_m calculated throughout discharge using equilibrium reconstructions

Magnetic measurements included in initial τ_e equilibrium reconstructions

I_p	0.11 MA
B_{T0}	0.17 T
R	0.30 m
a	0.25 m
A	1.2
κ	1.4
q_{95}	15.5
q_0	2
β	2.5 %
β_p	14 %
W_k	230 J
W_m	437 J

High field, low β discharge

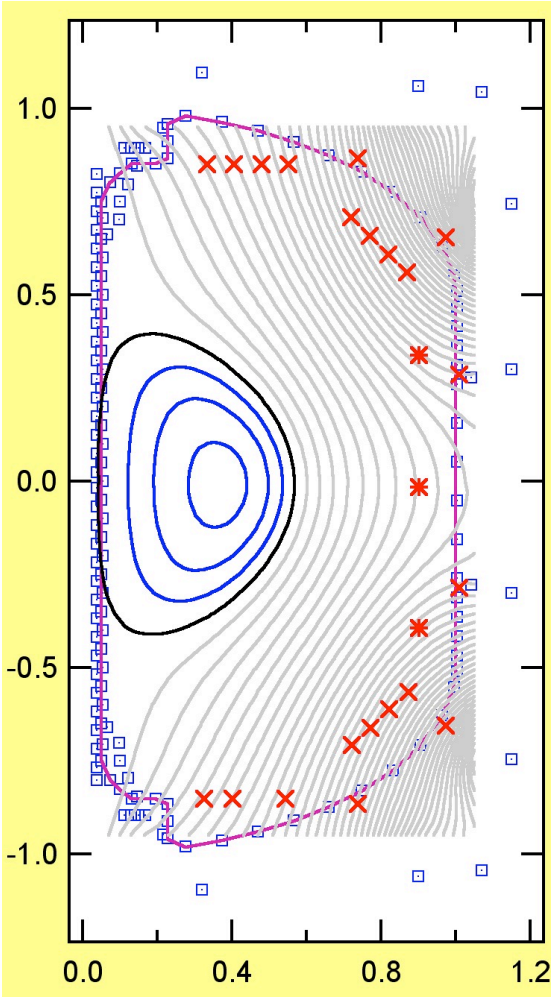
Shot 38731

at 29 ms

Magnetic measurements included in reconstruction

- Flux loop
- Mirnov
- Coil or wall element

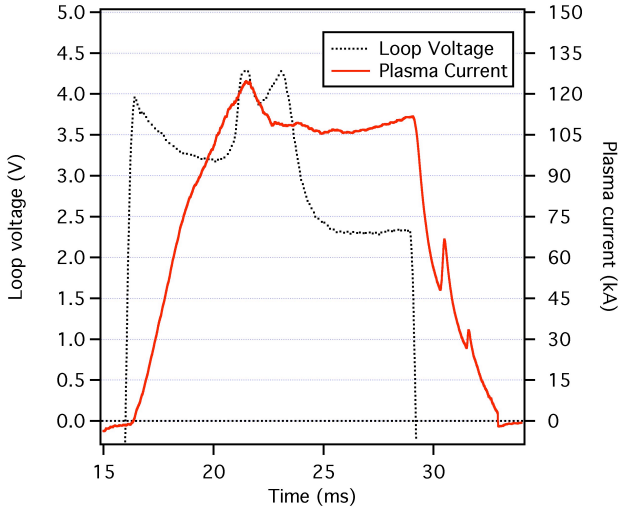
Reduced χ^2: 1.3

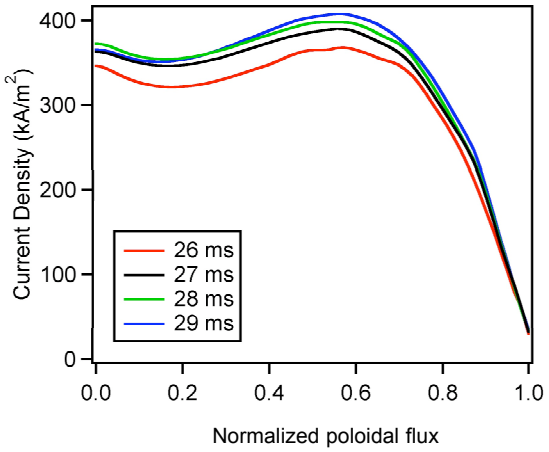


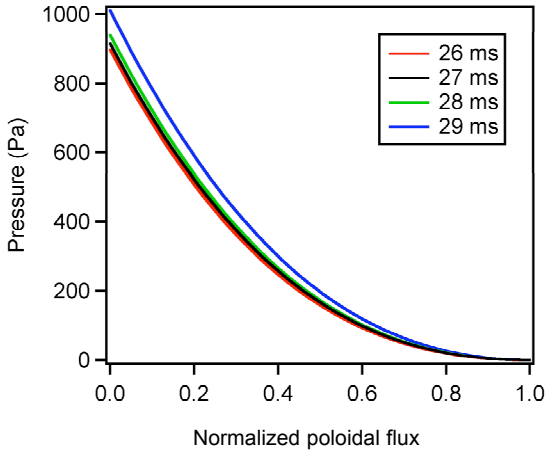
Quasi-static discharge with a 3 ms flattop is a good target for an accurate τ_e calculation

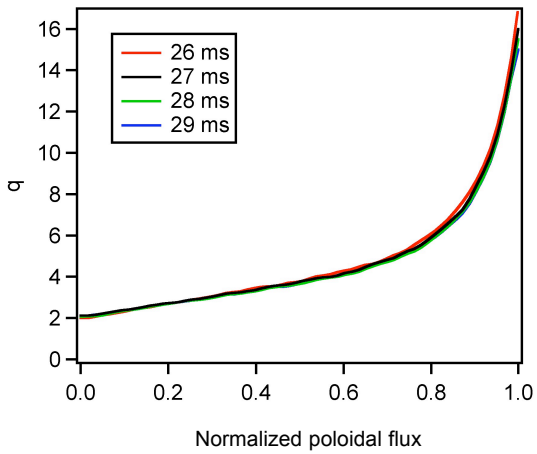
Shot 38731 reconstruction

- Profiles evolving slowly over last 3 ms
- $\frac{dW/dt}{P_{in}} \approx 10\%$



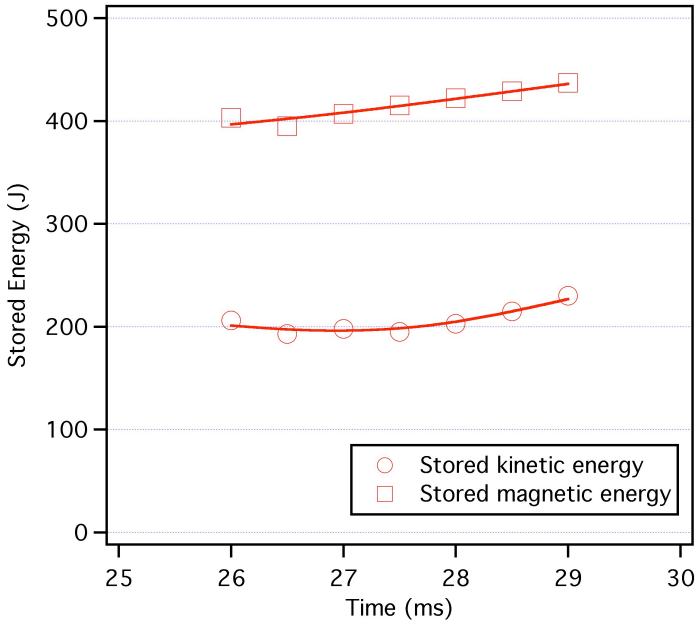




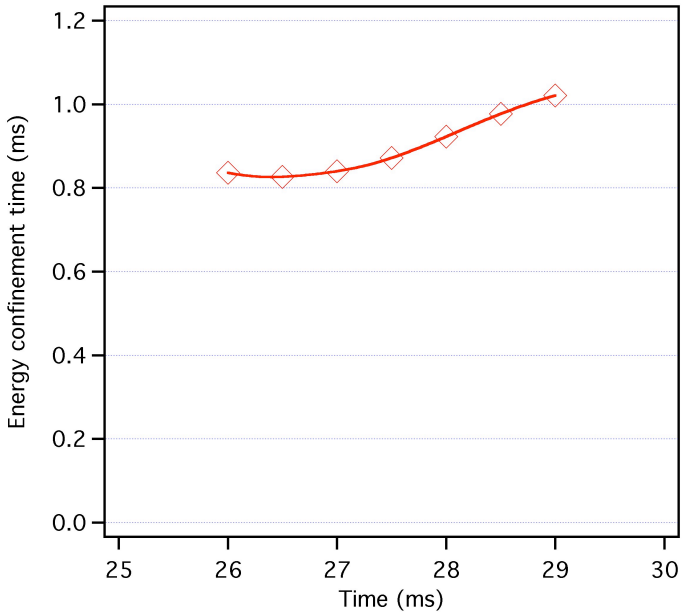


Energy confinement improves during flattop period

Stored Energy



Energy Confinement Time



X-ray emission spectrum suggests the plasma core temperature increases during this period

Empirical scaling relations greater than calculated τ_e

Assume T_{e0} = 150 eV, T_{i0} = 75 eV, n_{e0} = 4 x 10^{19} m^{-3}

$\bar{n}_e$ = 2 x 10^{19} m^{-3} (40 % Greenwald limit)

$$\tau_{e\,ITER\,97L} = 0.037 I_p^{0.74} B_T^{0.20} \kappa^{0.67} R^{1.69} \varepsilon^{0.31} \bar{n}_e^{0.24} M_{eff}^{0.26} P_L^{-0.57} = 2.6\ ms$$

$$\tau_{e\,98y,2} = 0.00562 I_p^{0.93} B_T^{0.15} \kappa^{0.78} R^{1.97} \varepsilon^{0.58} \bar{n}_e^{0.41} M_{eff}^{0.19} P_L^{-0.69} = 2.5\,ms$$

$$\tau_{e\,START\ ohmic} = \tau_{e\,neo-Alcator}\left(0.86\sqrt{A/(A-1)}\right) = 1.7\ ms$$

Low recycling walls may lead to improved L-mode τ_e

- Many tokamaks observe improved τ_e with reduced wall recycling*
- Titanium gettering is an inexpensive and easy wall conditioning technique
- Using inter-shot Ti gettering in Phase II operations improved ohmic flux consumption
  - Phase I (60 mV -s) discharges reproduced in Phase II (30 mV-s)

*Majeski, R. *et al* Phy. Rev. Letters **97** 07002/1-4
Strachan, J.D. Nucl. Fusion **34** 1017 (1994)

Inter-shot Ti gettering reduces wall recycling on Pegasus

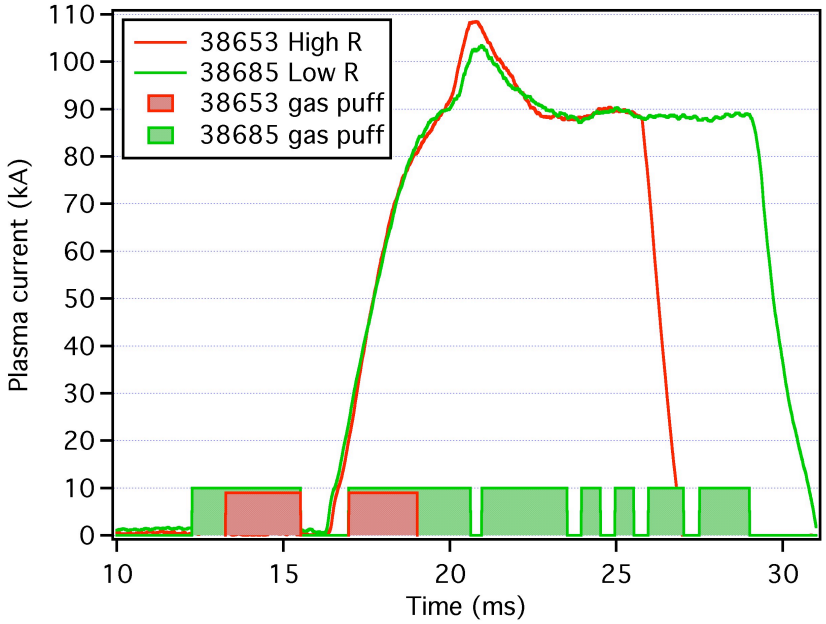
Wall conditioning

- 50 hour He glow, 8 hour gettering after vent
- Titanium gettering between shots (> 50,000 T•L/s pumping)
- Cryogenic pump (< 5×10^{-9} Torr)

Evidence of reduced wall recycling with gettering

- Discharges require more fuel
- Lower loop voltage required to drive similar plasmas
- Reduction in impurity line radiation

Discharges with low recycling walls require more fueling and lower loop voltage

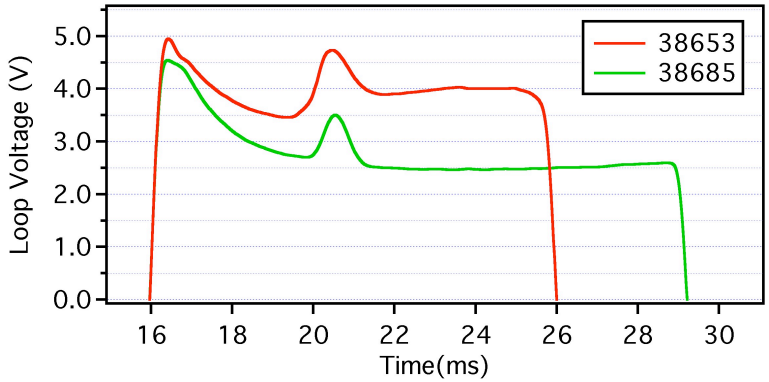


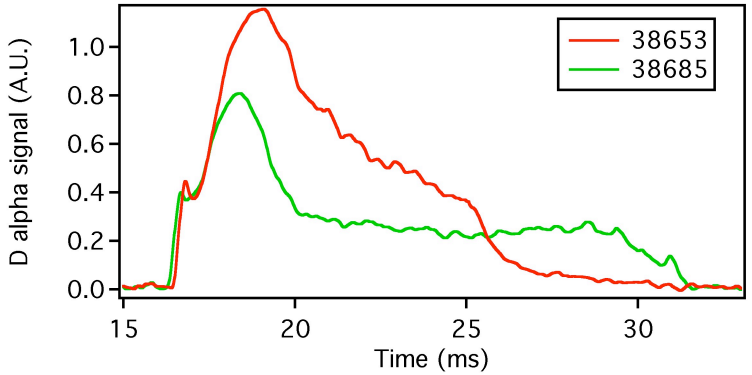
Shot 38653

High wall recycling
(Pacified Ti gettered walls)

Shot 38685

Low wall recycling
(Ti gettering between shots)

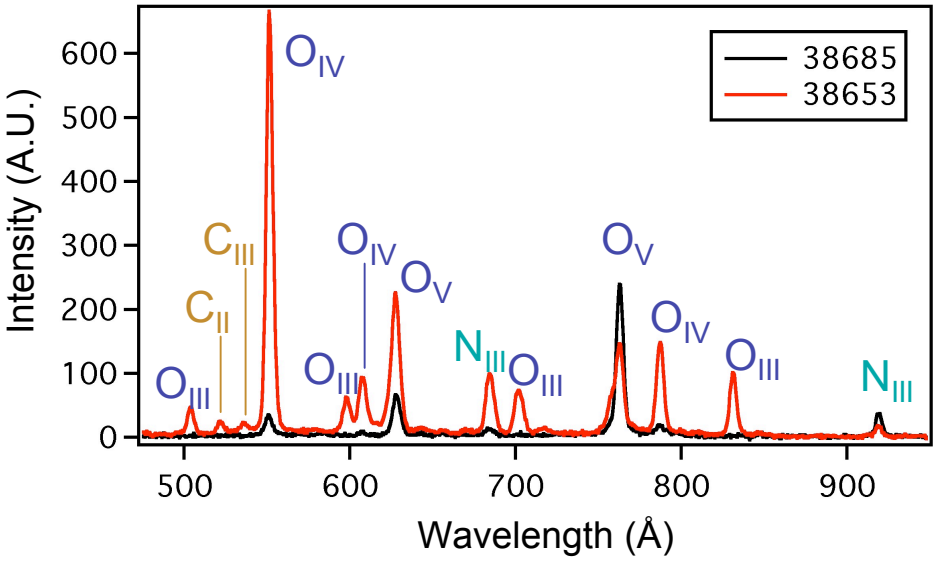




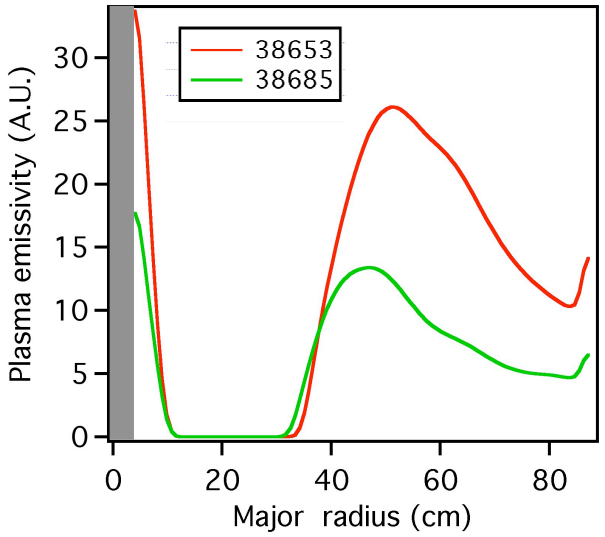
Discharges with low recycling walls have reduced P_{rad} and impurity content

- Bolometer measurements show radiated power is about twice as large with high recycling walls
- SPRED spectrum suggests hotter plasma and reduction of C impurities with gettered walls

VUV Spectrum at 25 ms



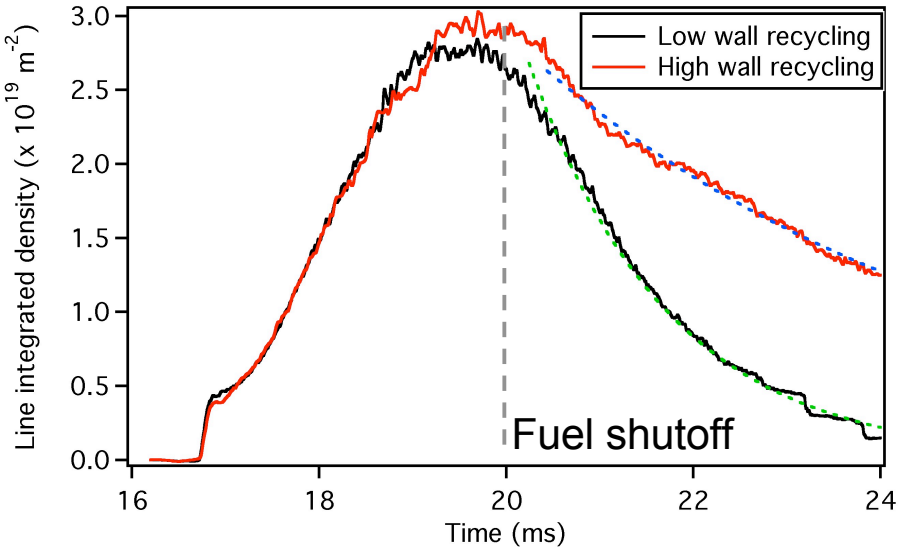
Relative emissivity at 25 ms



Effective particle confinement three times lower with gettered walls

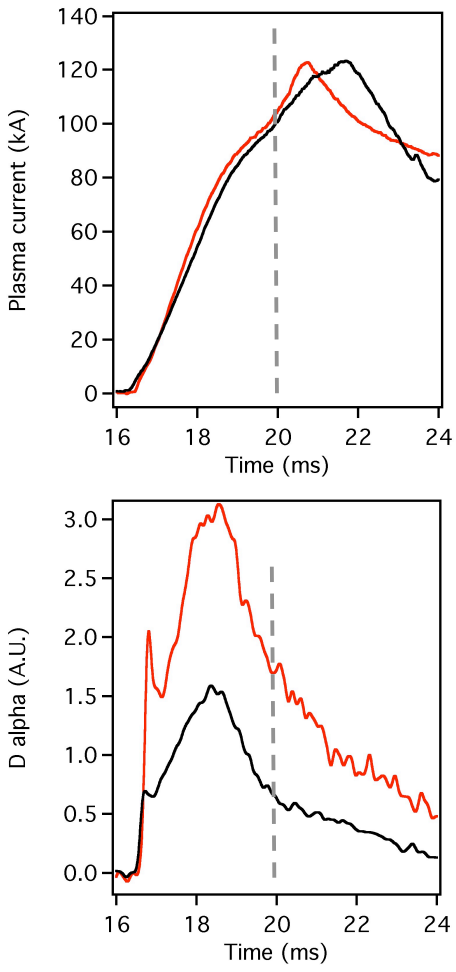
Effective particle confinement time: $\tau^*_p = \tau_p / (1\text{-}R)$

Measure density decay rate after fuel shutoff



High R: τ^*_p = 4.9 ms Low R: τ^*_p = 1.5 ms

Can assume τ_p similar for both conditions, thus τ^*_p is an indirect measurement of R



H-mode power threshold in STs exceed traditional scaling relations

- NSTX, START, Globus - M and MAST → H-mode ops
  - P_{thr} > empirical scaling relations
- ITPA study* incorporating low A P_{thr}

$$P_{thr} = 0.072 |B|_{out}^{0.7} n_{20}^{0.7} S^{0.9} \left(\frac{Z_{eff}}{2} \right)^{0.7} F(A)^{0.5 \pm 0.5}$$

$$\text{where } F(A) = 0.1A / \left(1 - \left[2/(1+A) \right]^{0.5} \right)$$

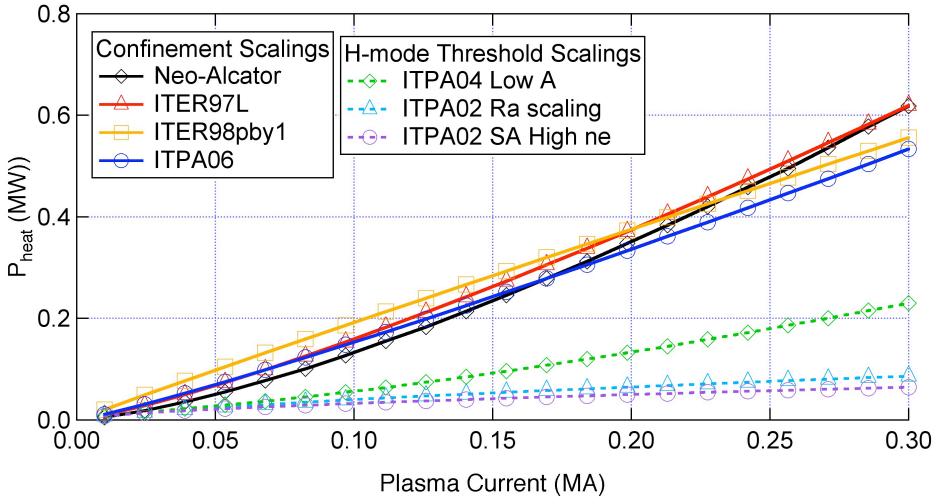
- START - 800 kW P_{thr} w/ I_p > 200 kA
  - Pegasus is a similar size, but at lower field

* Takizuka, T. *et al* Nuc. Fusion **46** A227-233

H-mode operations may be possible on Pegasus

- Self-consistent η model with τ_e & P_{thr} scaling relations
  - $P_{heat} > P_{thr}$ for typical Pegasus operations
- Achieve high ohmic heating in high I_p ops
  - Gun + ohmic ops → $I_P > 200$ - 300 kA
- HHFW → 2 MW heating

B_T	.17 T
n_e / n_G	0.8
R, a	0.35, 0.30 m
κ,δ	1.5, 0.15
Z_{eff}	2
T_i / T_e	0.5



SN and DN plasma on Pegasus

- Power threshold is minimized in diverted plasmas
- Divertor coils installed for SN or DN operations

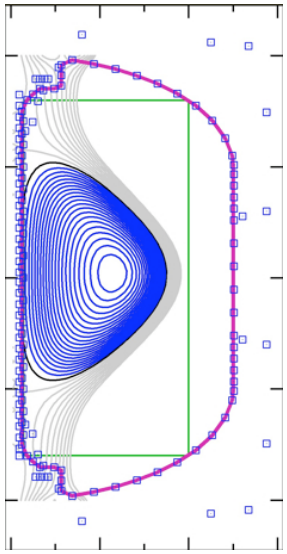
Equilibrium calculations

I_p = 130 kA

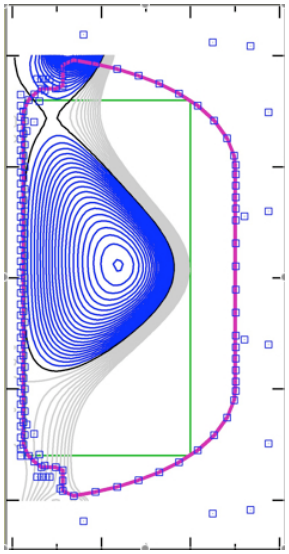
B_{T0} = .17 T

q_0 = 2

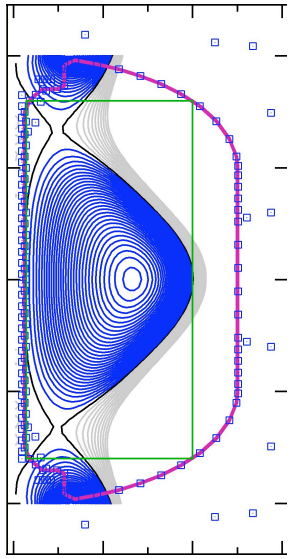
P_0 = 1.5 kPa



Divertors off



Upper Divertor
12 kA



Both Divertors
16 kA

Summary

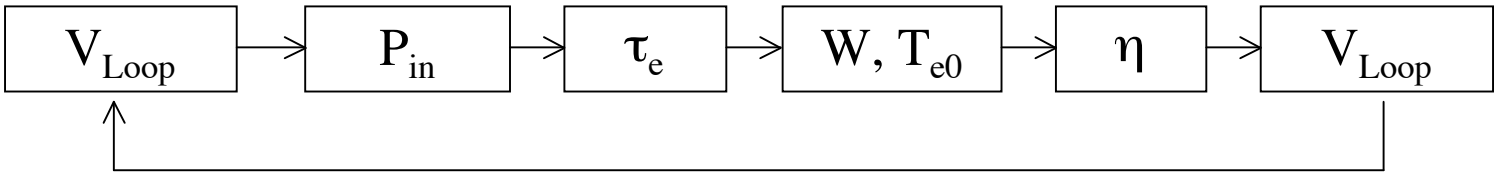
- **Diagnostics sufficiently constrain τ_e measurement**
  - Diamagnetic loop compensation method accurate to within 5%
  - Diagnostics needed for comparison to global empirical scaling relations nearing completion
- **Evidence of low recycling walls on Pegasus**
  - About 60% more heating power is required to sustain a discharge with pacified walls
  - Factor of three improvement in τ_p^*
- **H-mode operations may be possible on Pegasus**
  - Ohmic heating power exceeds P_{thr} empirical scaling relations
  - Achieve START H-mode conditions with high I_p or HHFW



Reprints



Self-consistent plasma model



Assume parabolic density and temperature profile

$$n_e(\rho) = n_{e0}\left(1-\rho^2\right)^{\alpha_n} \text{ and } T_e(\rho) = T_{e0}\left(1-\rho^2\right)^{\alpha_T}$$

$$W_k = \int \frac{3}{2}\left(n_e kT_e + n_i kT_i\right)dV = 3k\left(1+\frac{T_i}{T_e}\right)\left(1+\alpha_n+\alpha_T\right)n_{e0}T_{e0}V$$

$$n_{e0} = \left(\frac{\bar{n}_e}{n_G}\right)\left(\frac{I_p(MA)}{\pi a^2}\right)\left(\alpha_n+1\right)$$

Assume Spitzer resistivity