Abstract

Present experimental campaigns on the Pegasus Toroidal Experiment are concerned with accessing q- and β-limits in an ultra-low aspect ratio plasma. To date, Pegasus plasma are heated only with an OH solenoid, but an additional HHFW heating system is scheduled for operation in the near future. For A ~ 1.15-1.4, R(0) ~ 0.2-0.4 m, κ ~ 1.5-2, I(p) ≤ 0.15 MA, and B(t) ≤ 0.07 T, plasmas are being limited by a global m/n =2/1 mode, as observed on both external and internal diagnostics. Due to low shear in these discharges, the mode persists over a large volume of the plasma. Magnetic equilibrium reconsructions of these plasmas show β(t) ≤ 25 % with no instabilites due to beta yet observed. Efforts to overcome the 2/1 mode include; 1.)Raising the electron temperature, T(e), by raising the plasma current density, adding volt-seconds to the OH power supply, and RF heating, and 2.) rainign the plasma q-profile with increased toroidal magnetic field. Preliminary auxiliary heating with a HHFW RF system has begun. This system supplies bulk T(e) heating with ≤ 0.5 MW of power.

Supported by U.S. DoE grant No. DE-FG02-96ER54375

2001 Program Overview

Developing understanding of limits of operation at very low-A and low-TF

- Gain capability to explore high-β_t, low-q_a regimes

• Facility Development

- Increasing Ohmic drive capability; I_p up to 150 kA
- New internal hardware and
- Diagnostics and analysis tools
- Initial operation of HHFW heating system

• Experimental Campaign

- Improved plasma formation control
- Extension of higher I_p capability
- Documentation of equilibrium parameters at very low-A
- Identification of factors hindering access to low B_t, high I_p
  - *V-sec availability*
  - *Demonstrate access to external kink limit at low-*β_N

• Developing tools necessary for equilibrium and stability analysis

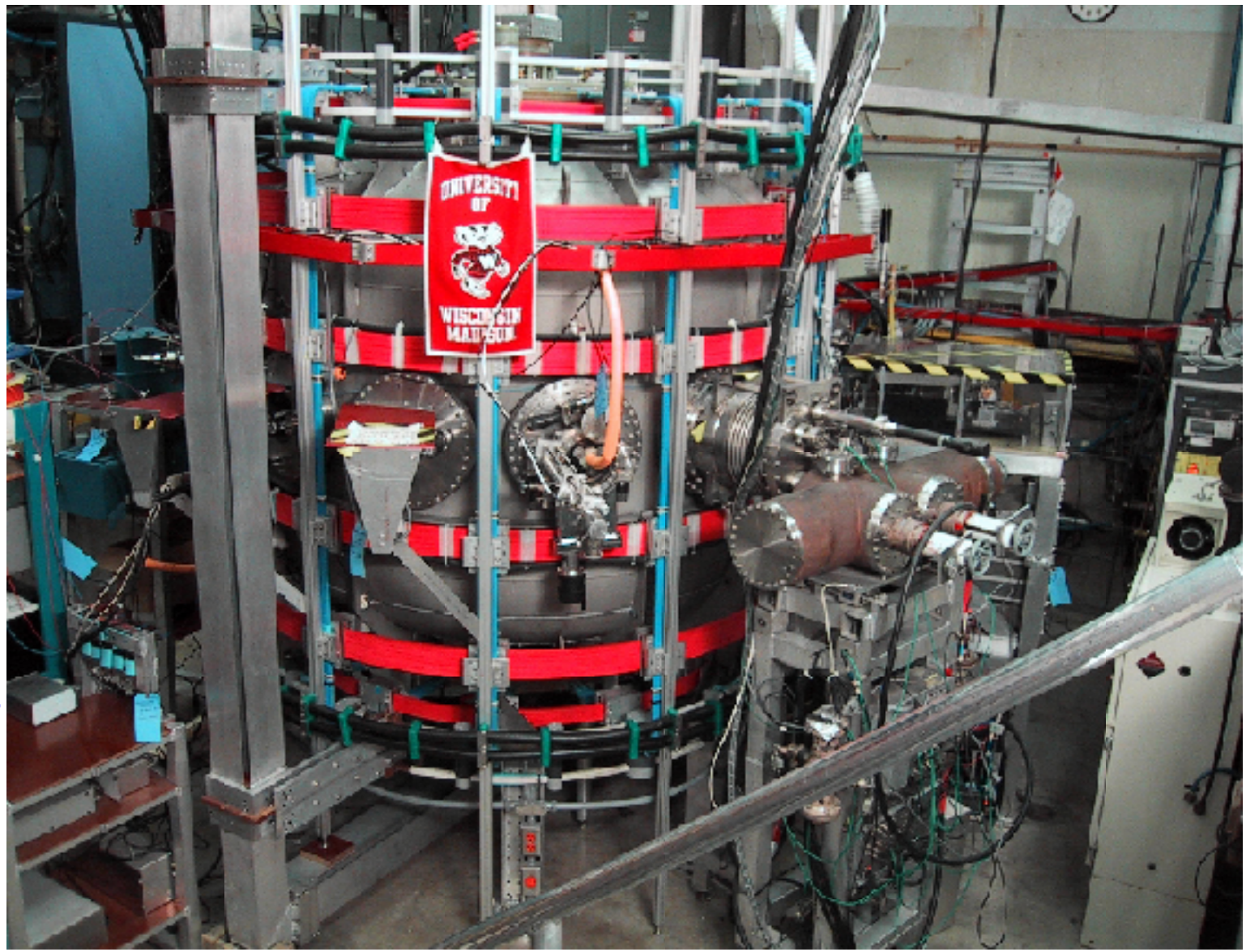
- Increased V-sec
- High power RF heating
- Increased B_t with fast rampdown

PEGASUS is a Mid-Sized University ST

Design Parameters

A	1.1 - 2.0
R	0.2 - 0.45 m
I_p	0.1 - 0.3 MA
B_t	< 0.30 T
K	~ 1.5 - 3.7
Δt_{pulse}	30 - 40 msec
β_t	*O*(1)
β_N	> 5
I_N	> 10
Heating and Sustainment	Inductive* + RFCD (HHFW, EBW)

* NHMFL: $B_{solenoid}$ = 10 - 14 T



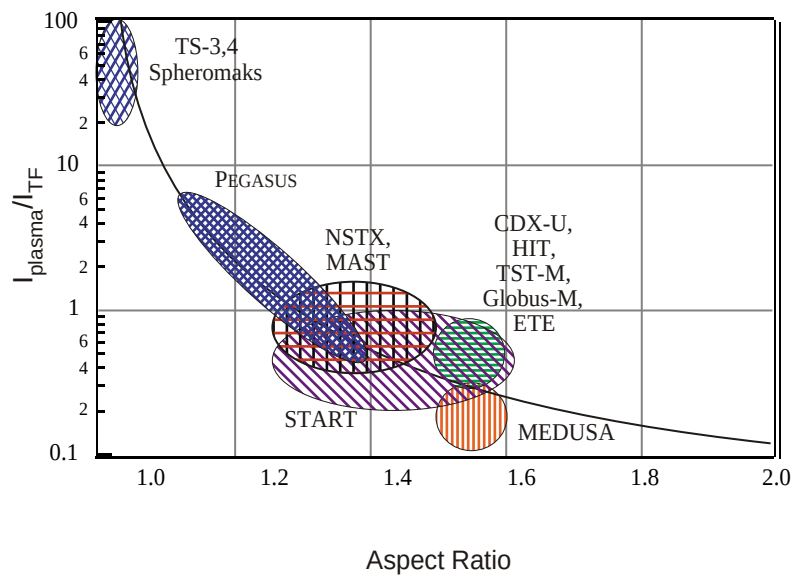
Role of the PEGASUS Experiment

Pegasus Toroidal Experiment
University of Wisconsin-Madison

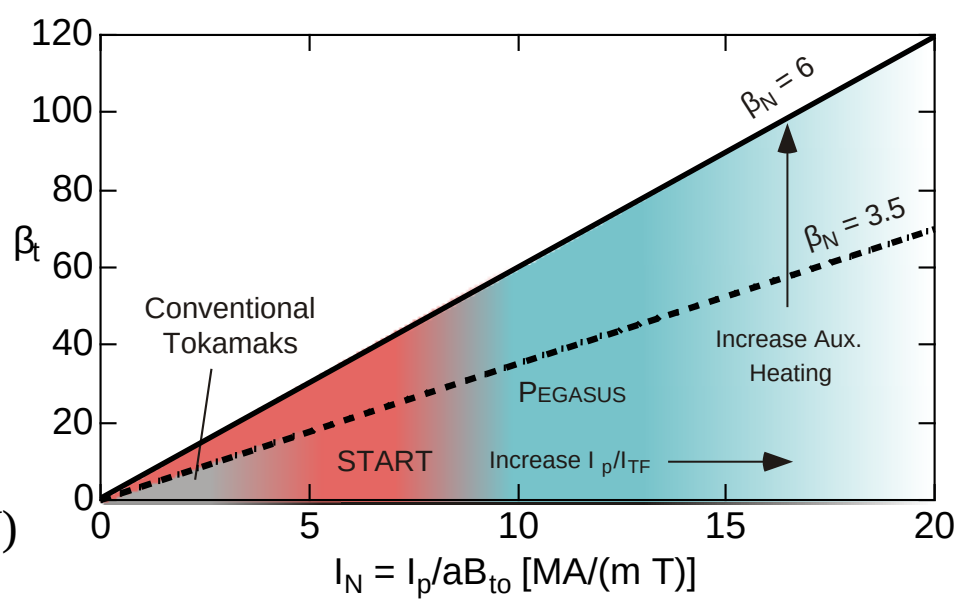
Mission Statement

An extremely low-aspect ratio facility exploring quasi-spherical high-pressure plasmas with the goal of minimizing the central column while maintaining good confinement and stability.

- **Physics of A ≈ 1 plasmas as an Alternate Concept (low q)**
  - Extreme toroidicity (A → 1)
  - Very high TF utilization (I_P/I_{TF}) > 3
  - Stability at very low TF (β ≈ 1)
  - Relaxation stability at tokamak/spheromak boundary
  - RF heating and CD schemes (HHFW, EBW)
  - Trade-offs: CD, recirculating power, and A ≈ 1, low-TF operation



- **Contribute to development of the ST (high q)**
  - Stability limits for A → 1 (vs. I_p/I_{TF}, q_ψ, N_e, β_t, β_{pol}, κ, A, etc.)
  - β limit dependencies
  - Access high β_t at extreme I_N w/o conducting shell
  - Confinement A < 1.3
  - New startup schemes (e.g., plasma gun, EBW)



Machine Hardware Upgrades

- **Extensive interior hardware installation in 2001 campaign**

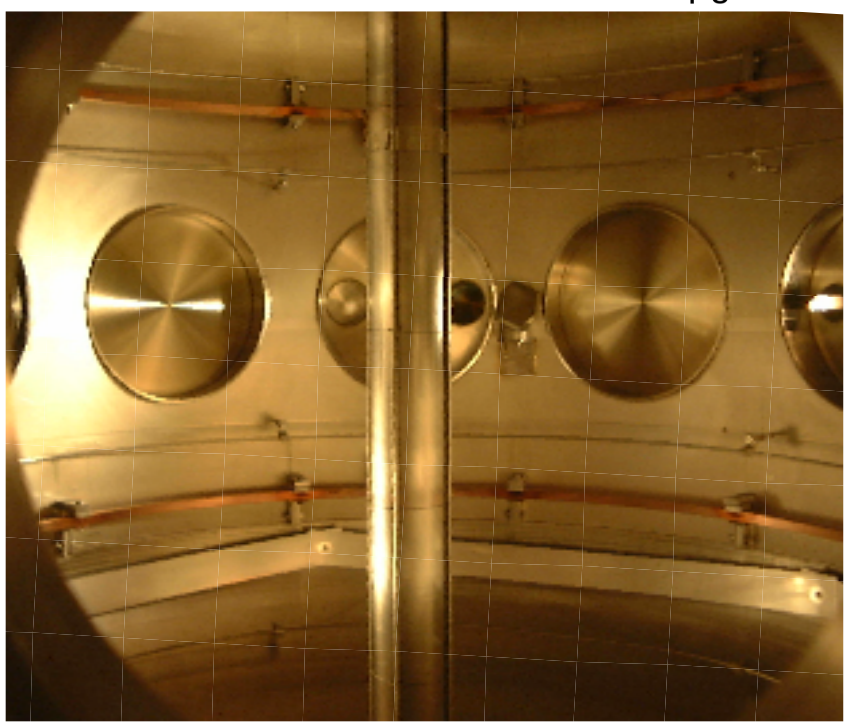


Recent Hardware Upgrades to Machine

- **Major Opening in Fall/Winter 2000 for facility upgrades**

(Poster RP1.040; B. Lewicki)

Internal View of PEGASUS Before Upgrade

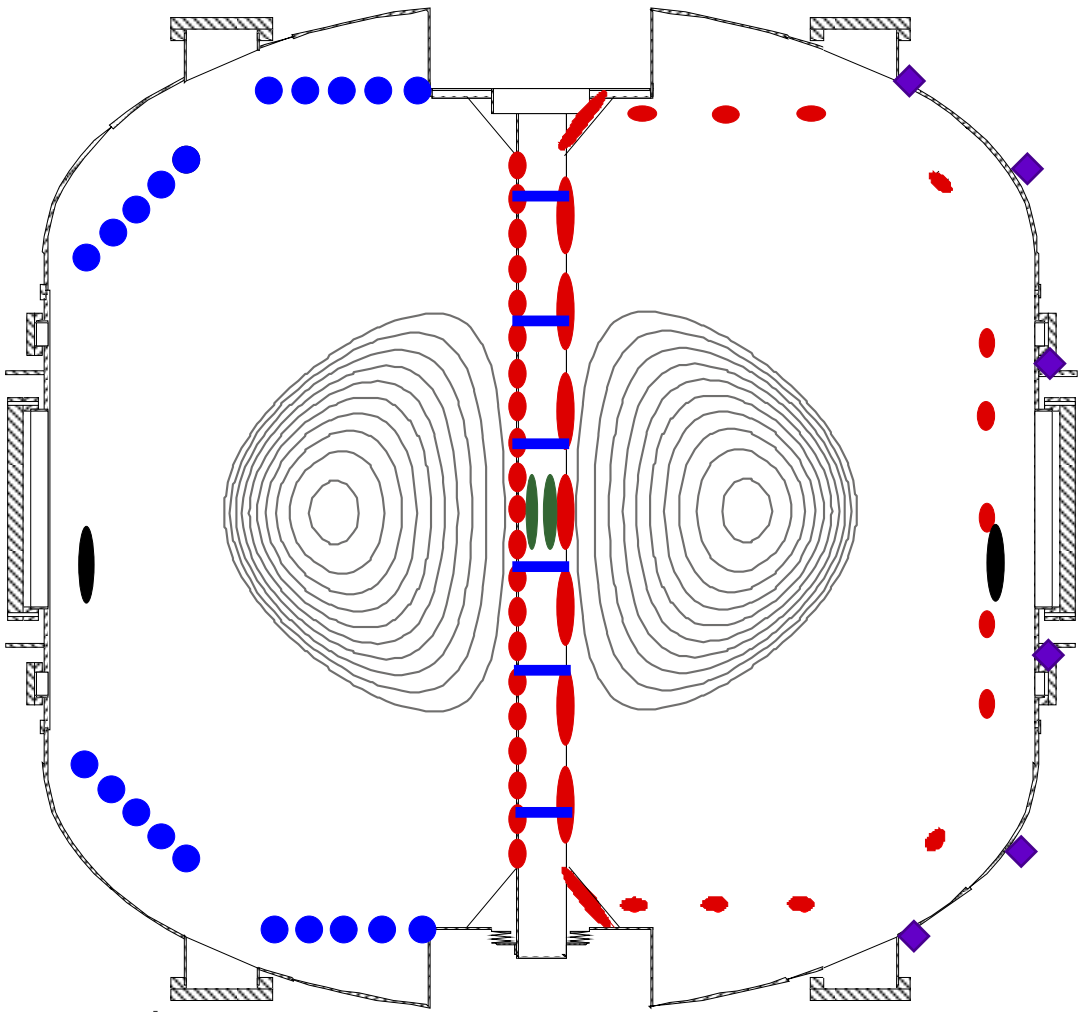


- **Internal diagnostics installed**
  - Flux loop and B_{pol} arrays
  - Extensive centerstack magnetics
  - Diamagnetic loop
  - New Rogowski coils
- **HHFW and EBW antennae installed**
  - P_{RF} = 1-2 MW available for HHFW
  - Fully steerable EBW/ECH antenna
- **Improved power deposition hardware**
  - Divertor plates
  - High-power outer limiter
  - New centerstack shield / cone structure
- **Data acquisition system**
  - Upgraded to GPIB/CAMAC

Addition of Magnetic Diagnostics

Pegasus Toroidal Experiment
University of Wisconsin-Madison

Current Magnetics Arrangement



Not shown:
- Plasma Rogowski Coils (2)
- Diamagnetic Loops (2)
- Diamagnetic Compensation Loop
- Internal B_{tan} Coils (15) [constrain wall currents]

Before Upgrade

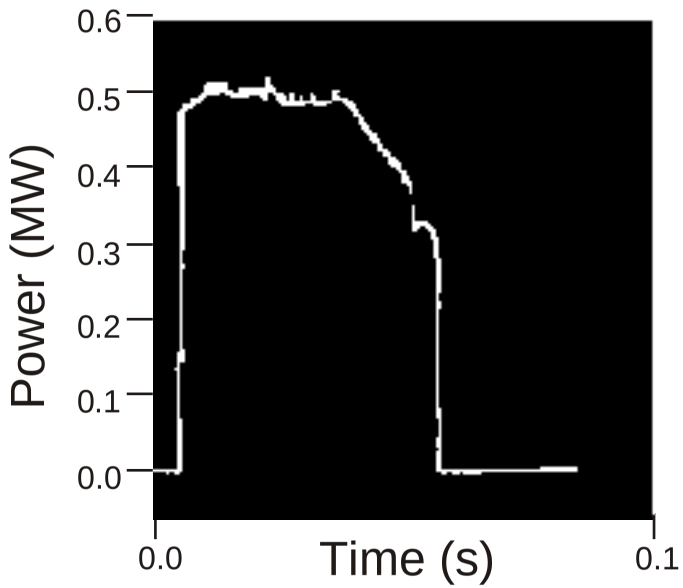
- Poloidal Mirnov Coils	(13)
- Flux Loops	(6)
Total	(19)

After Upgrade

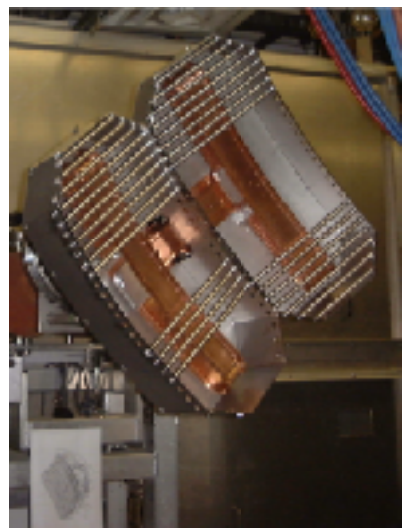
Flux Loops	(26)
Poloidal Mirnov Coils	(22 + 21)
LFS Toroidal Mirnov Coils	(6)
HFS Toroidal Mirnov Coils	(7)
External Wall Loops	(6)
Total	(88)

Initial Operation of HHFW Heating System

- **HHFW system installed and heating tests underway**
  - *P_{RF} = 1-2 MW available; sufficient to access high β_t regime*
  - Initial loading tests give an impedance of about 1 Ohm
  - Up to 100 kW injected into vessel (Poster RP1.037 by P. Probert)



RF forward power results from
~ 50 ms test into dummy load

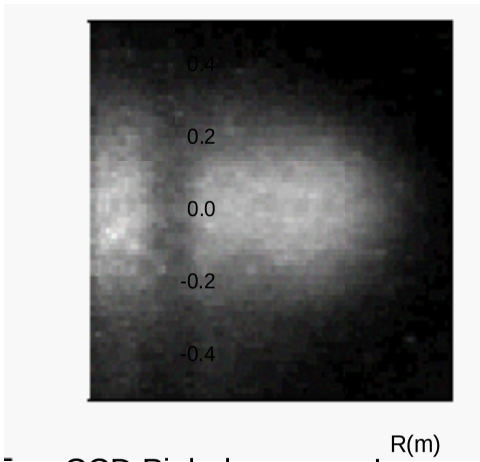


- **HHFW Startup and CD applications:**
  - Startup assist via preheating and/or current profile "freezing"
    - *Startup plasma phase: 40% single pass absorption*
    - *High β plasma phase: 100% single pass absorption*
  - CD possible with present power supply and new antenna

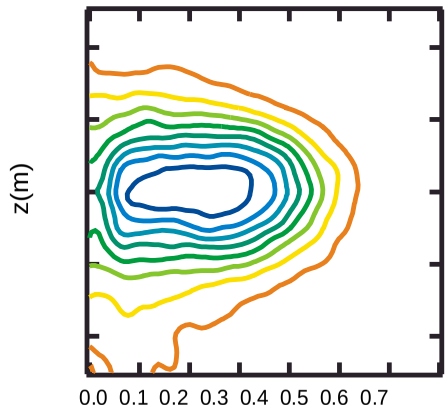
Diagnostics on PEGASUS

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Pinhole SXR Camera (Poster RP1.036; K. Tritz)

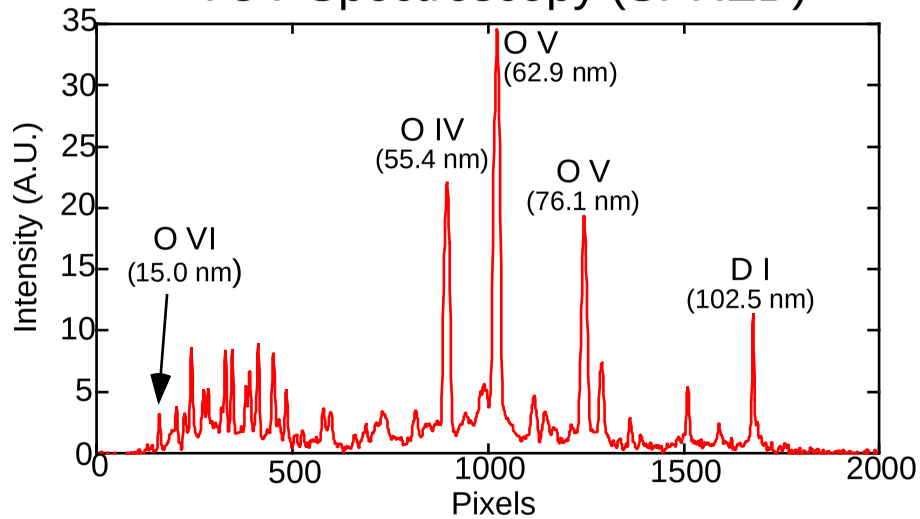


CCD Pinhole camera Image

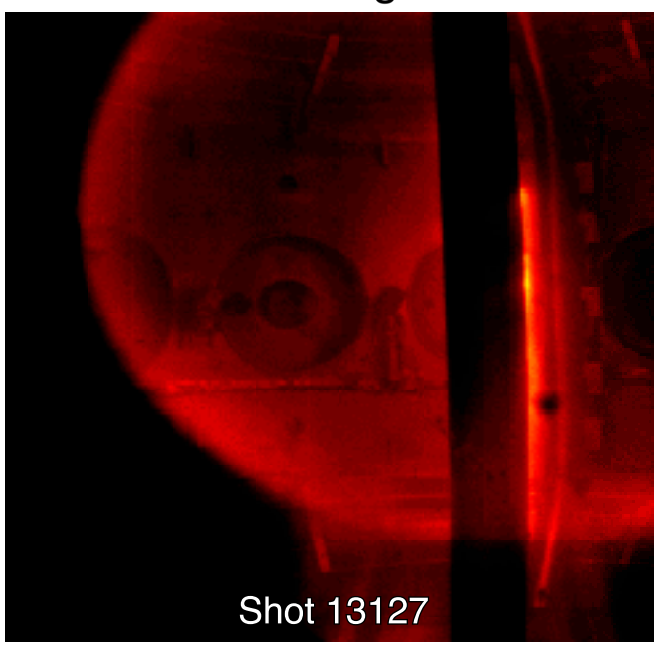


Contour plot of X-ray Intensity

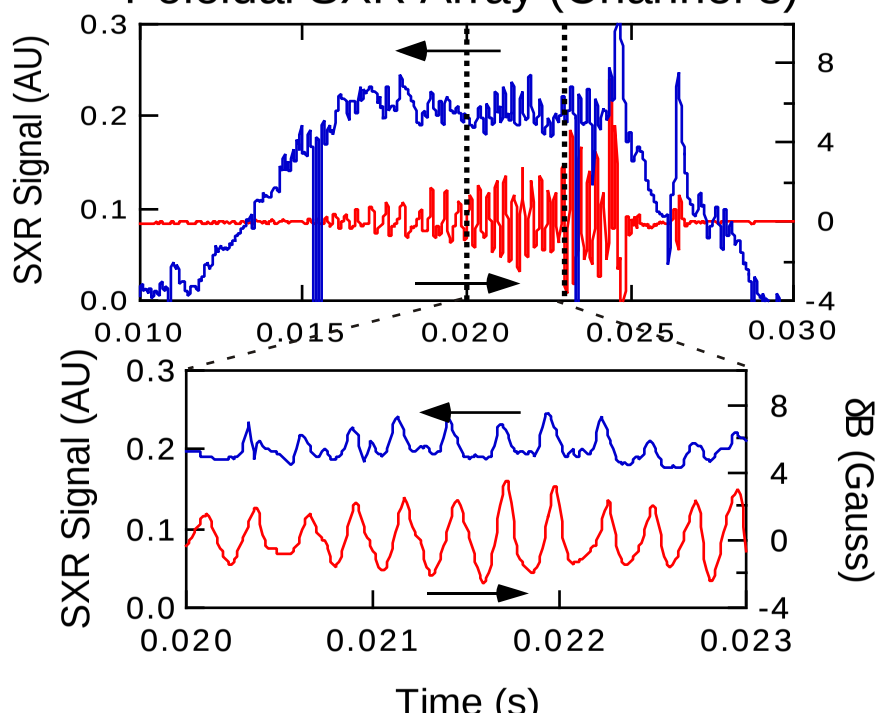
VUV Spectroscopy (SPRED)



Fast Framing Camera



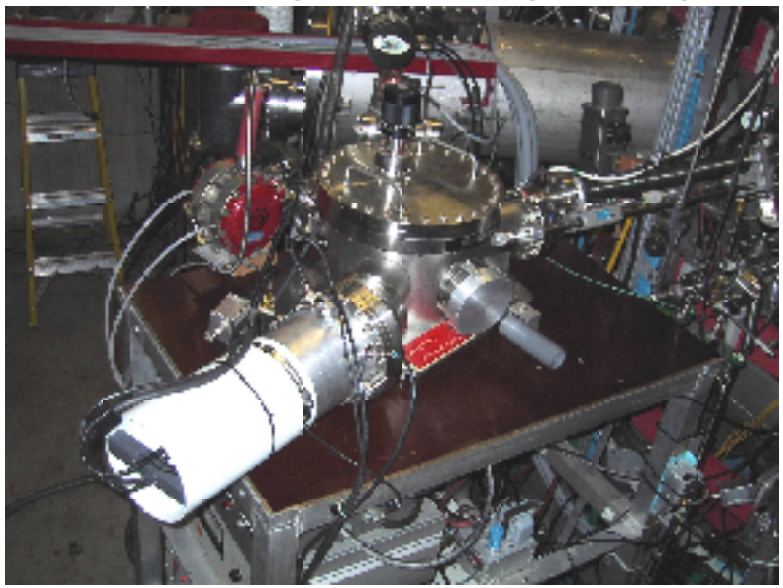
Poloidal SXR Array (Channel 8)



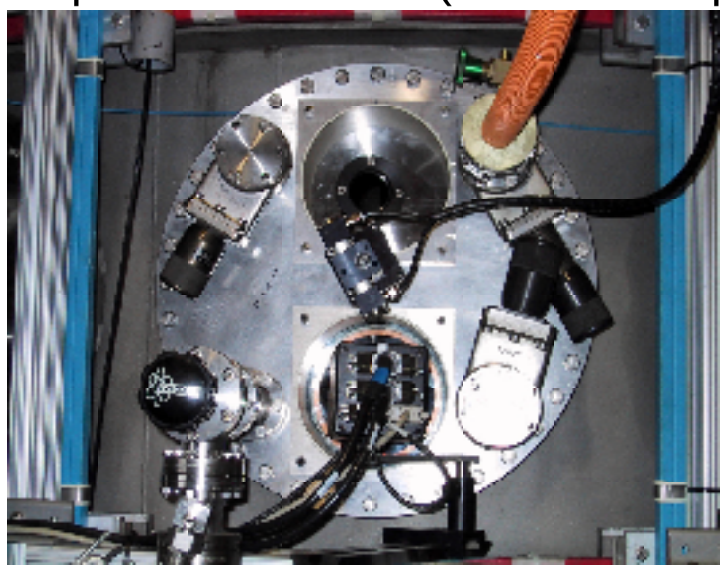
Diagnostics on PEGASUS

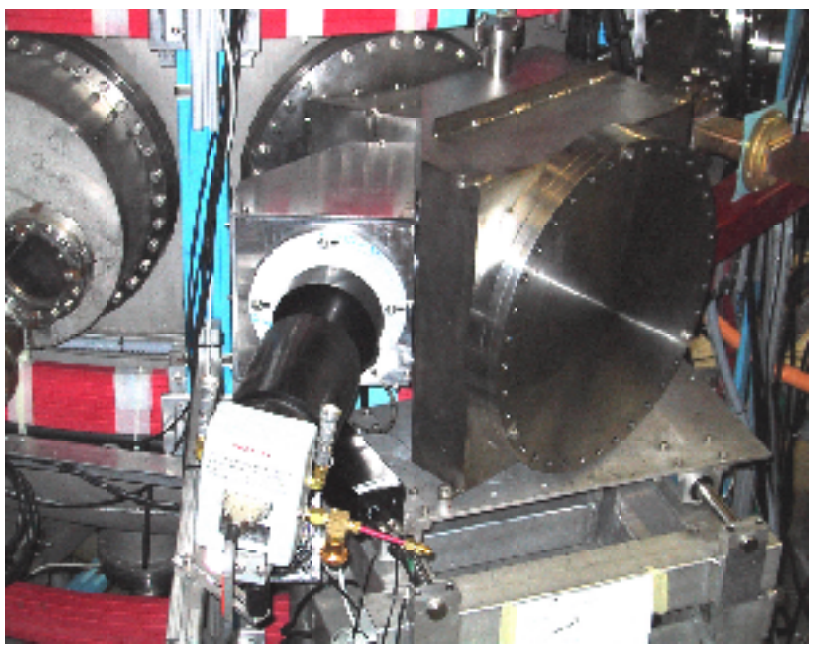
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SPRED (Plasma Impurities)

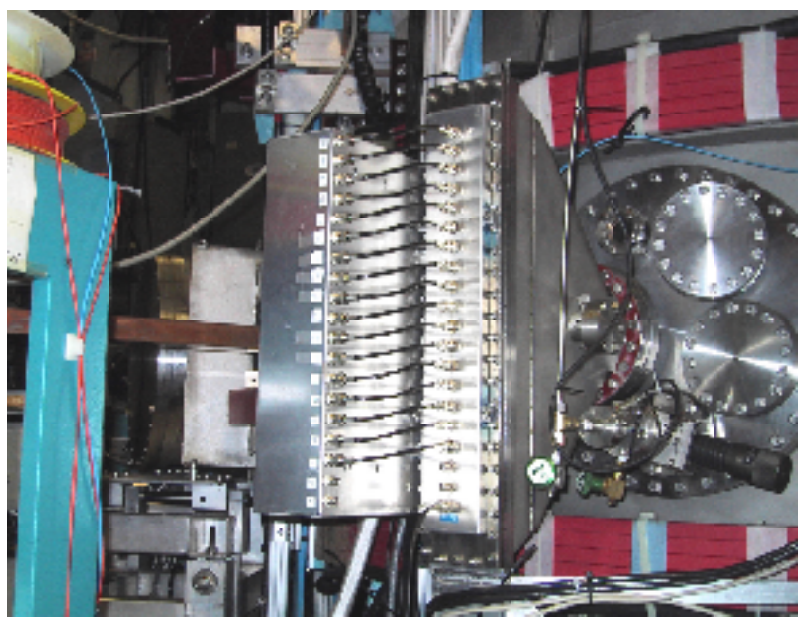


1000 fps CCD Camera (Plasma Shape)





SXR Pinhole Camera (j(R) profiles)



Poloidal SXR Diode Array (Internal MHD)

Diagnostics on PEGASUS

Pegasus Toroidal Experiment
University of Wisconsin-Madison

• Presently operating diagnostics

Diagnostic	Capability	Measures
Core Flux Loops	(6)	V_L , Ψ_{pol}
Wall Flux loops	(6)	Vessel currents
Int. Flux loops	(20)	Ψ_{pol}
Rogowski Coils	(2)	I_p
Diamagnetic Loop	(2)	Φ_{tor} / β_p
B_p, Mirnov Coils	(56)	B_r , B_z / MHD activity
VUV (SPRED)	central chord	Impurity monitor
Filterscopes	central chord	Oxygen, Carbon, D_α
Interferometer	single chord	$N_e l$
High Res. Camera	1000 fps	Plasma shape/position
2-D SXR Camera		Internal Shape/ j(R)

• Near-future diagnostics

Diagnostic	Capability	Measures	When?
Poloidal SXR Diode Array	(19)	MHD Activity	Winter 2001
Tangential CCD PHA	single chord	$T_e(t)$	Winter 2001
Tangential Bolometer Array	~20 chords	P_{rad}	Winter 2001
Ross Filters	single chord	$T_{e0}(t)$	Winter 2001
2-Color X-ray	single chord	T_e	Winter 2001
Tangential VB Array	~20 chords	$Z_{eff}(R,t)$, $N_e(R,t)$	Summer 2002
DNB		$N_e(R,t)$, $T_e(R,t)$, j(R)	Proposed
EBW Radiometer		$T_e(t)$	Proposed

Status of Ohmic Plasma Operation

- **Routine high-stress solenoid operation**

- **Startup at low B_t in presence of conducting walls**
  - Induced wall currents modeled
  - Wall currents routinely included in equilibrium runs

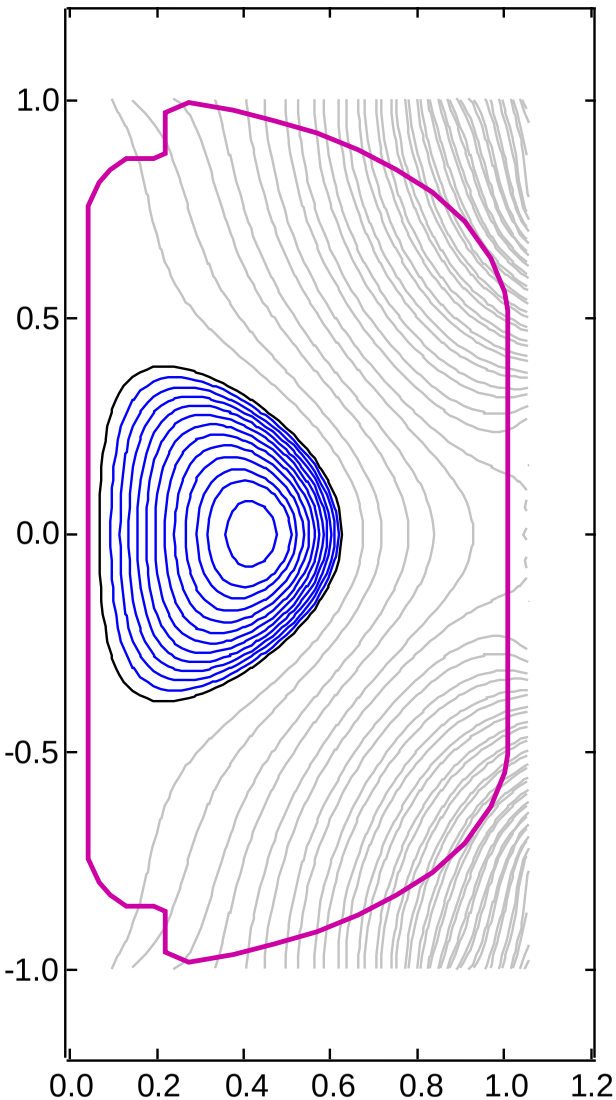
- **Plasmas show low-A characteristics**

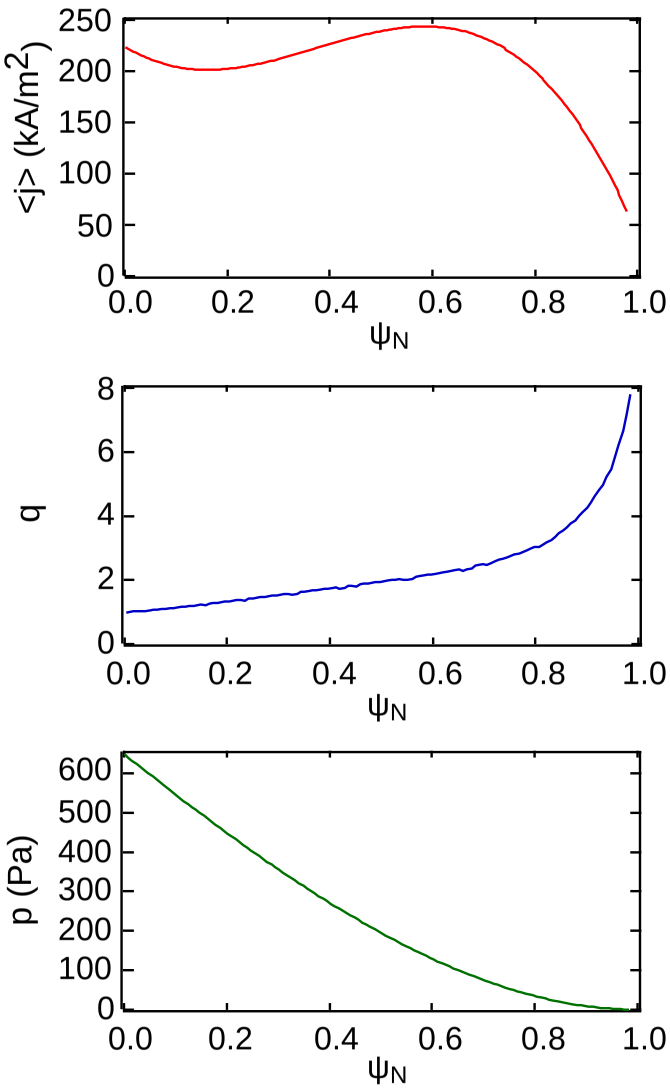
- *High* β_t	$\beta_t \sim 25\%$
- *High* β_N	$\beta_N \sim 5$
- *High TF utilization factor*	$I_p/I_{TF} \sim 1.2$
- *High normalized current*	$I_N \sim 8$
- *High density*	$n_e \sim n_{GW}$
- *MHD*	*2/1, 3/2, IREs, double tearing modes*

- **Extension of operating space**
  - Increasing ohmic drive capability; I_p up to 150 kA
  - Density control and fueling (fast gas puffing)
  - Pulse length extension (up to 30 ms)
  - Wall conditioning (Ti gettering, DC GDC)

Magnetic Equilibrium Reconstruction Used as Primary Analysis Tool

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University of Wisconsin-Madison





Shot 12445

I_p	78.3 kA
B_t (axis)	0.048 T
R_0	0.337 m
β_t	18%
a	0.282 m
l_i	0.40
A	1.20
q_0	0.98
κ	1.4
q_{95}	5.9

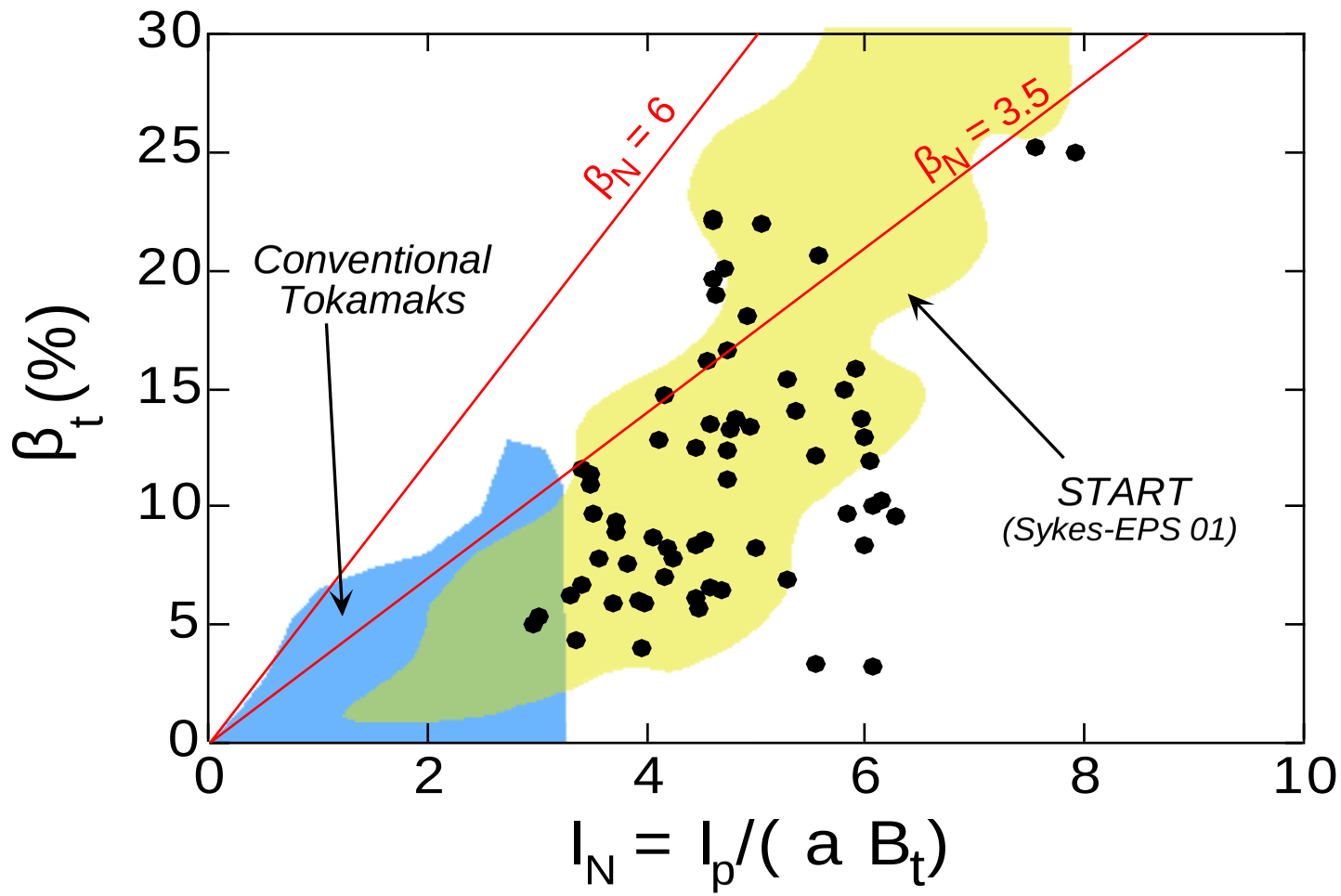
Constraints: Rogowski Coil
18 Flux Loops
3 B_p Coils
Diamagnetic Loop

Poster RP1.035 by S. Diem

PEGASUS is Accessing High-β_t ST Regime

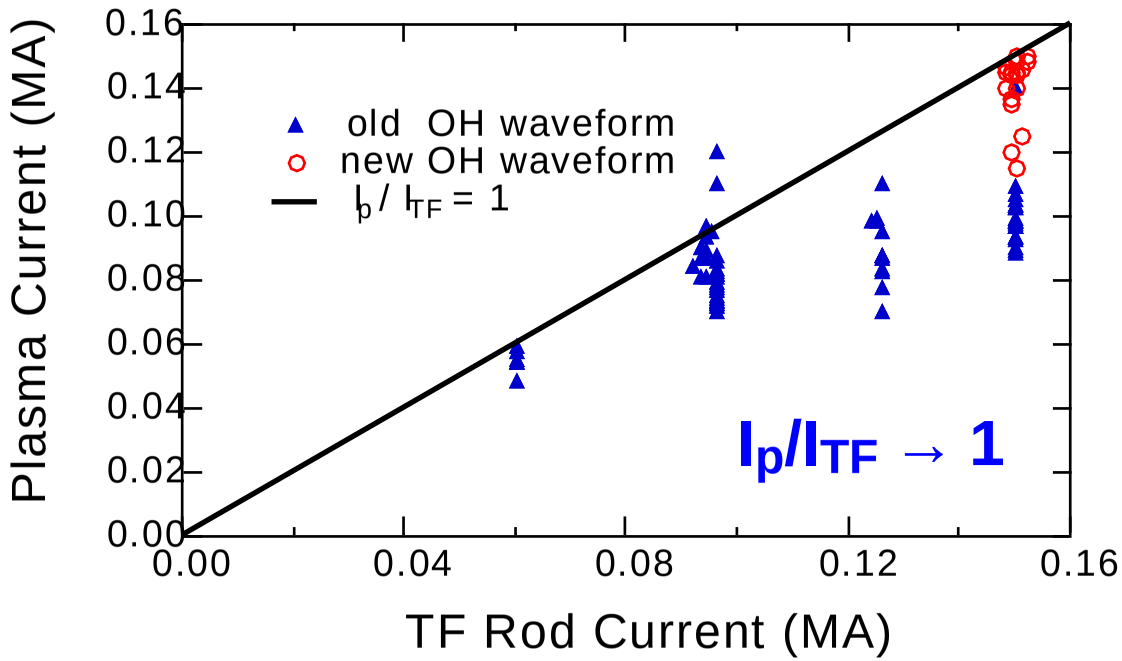
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- **High β_t attained at high density, low-TF**
  - *Ohmic heating only; constant TF*
  - *Highest β_t, I_N at low TF*

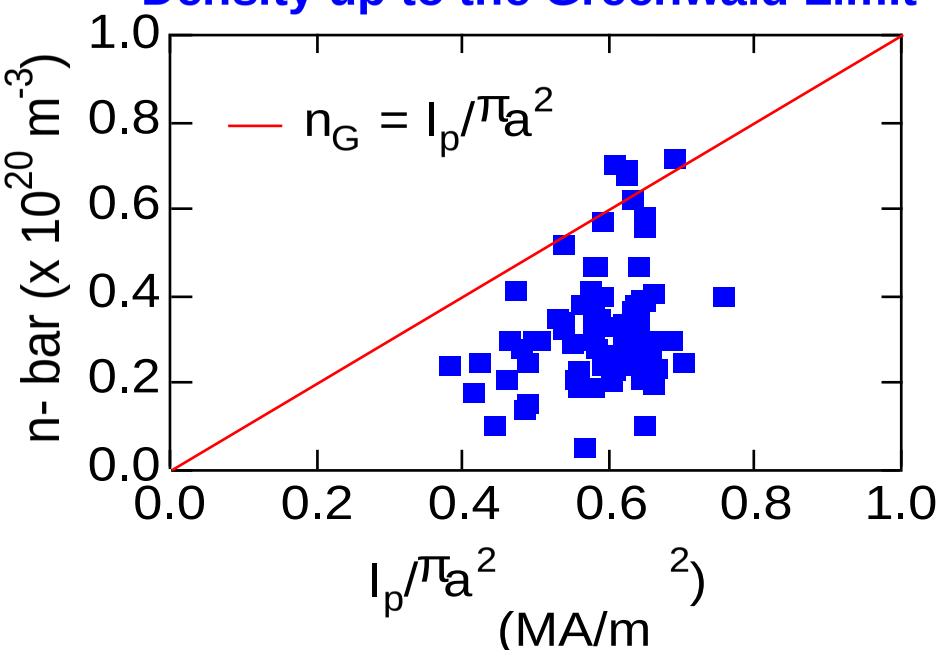


High Density, Low-l_i, Low-TF Operation

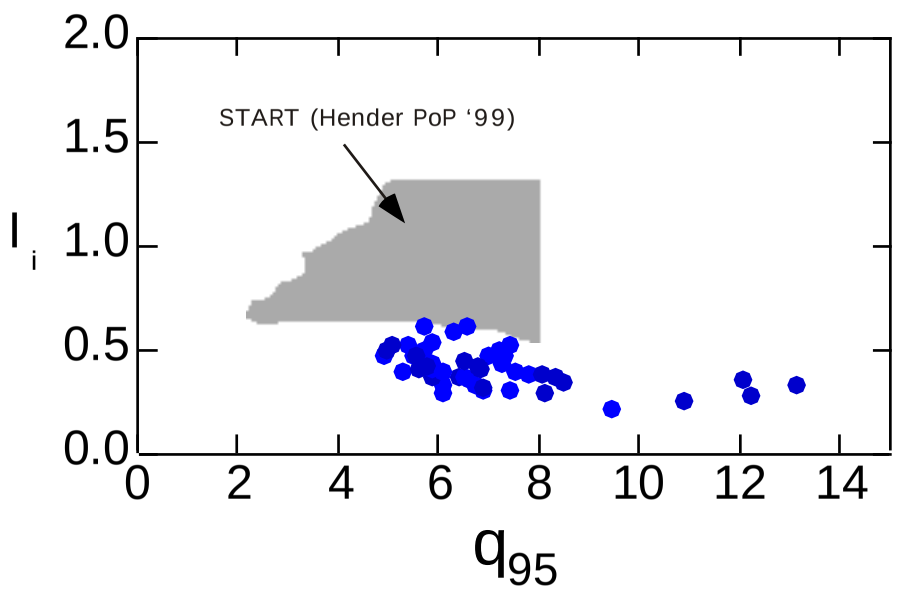
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Density up to the Greenwald Limit

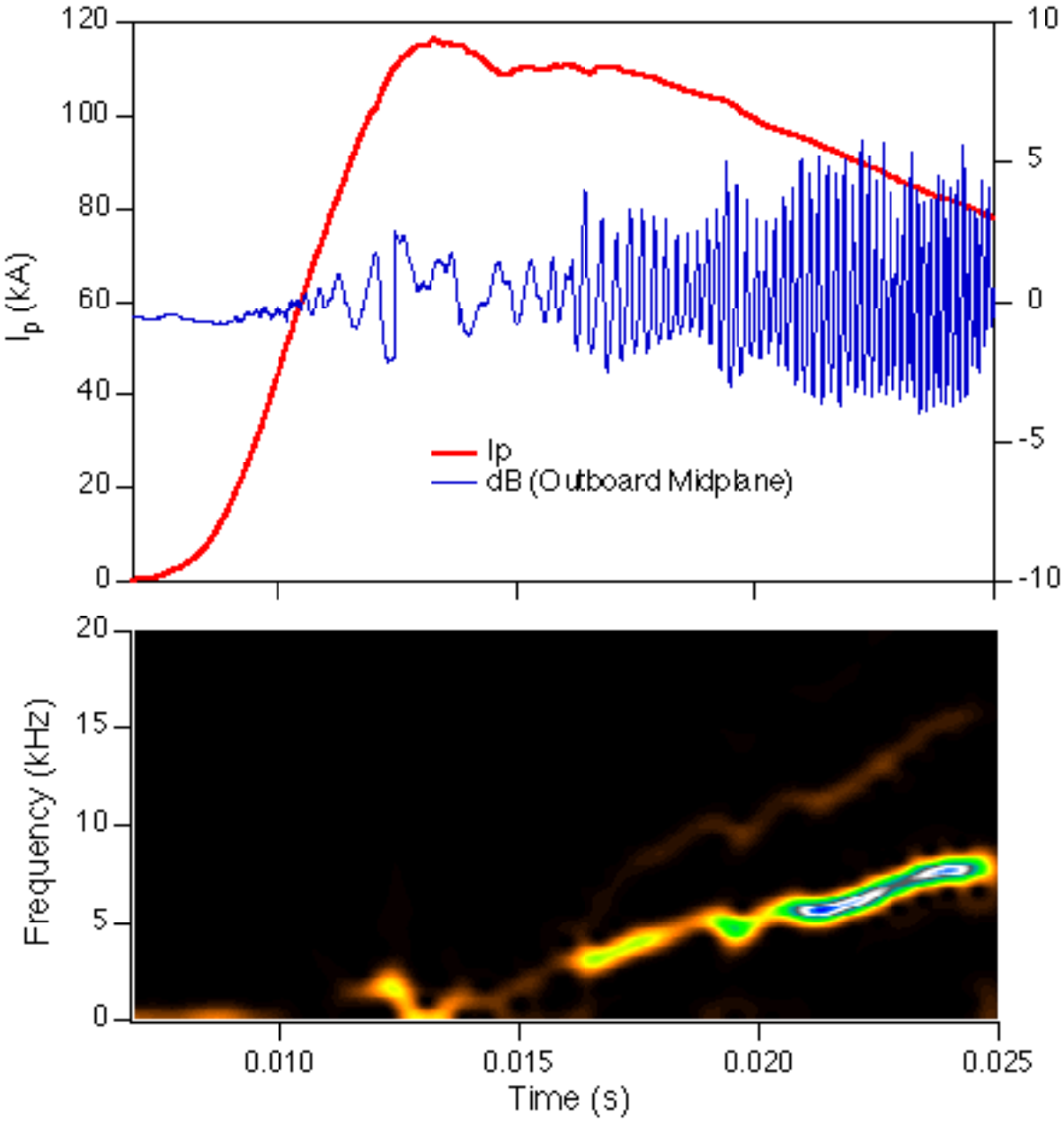


Low l_i; increases during current relaxation



Significant MHD is Observed During Discharge Evolution

Pegasus Toroidal Experiment
University of Wisconsin-Madison



- A rotating 2/1 mode is present
  - Observed in most discharges
  - Mode rotates in electron diamagnetic direction
  - Frequency is 5-10 kHz
- A lower frequency mode is often observed during the current ramp
- IREs and double tearing modes also observed

Poster RP1.034 by G. Garstka

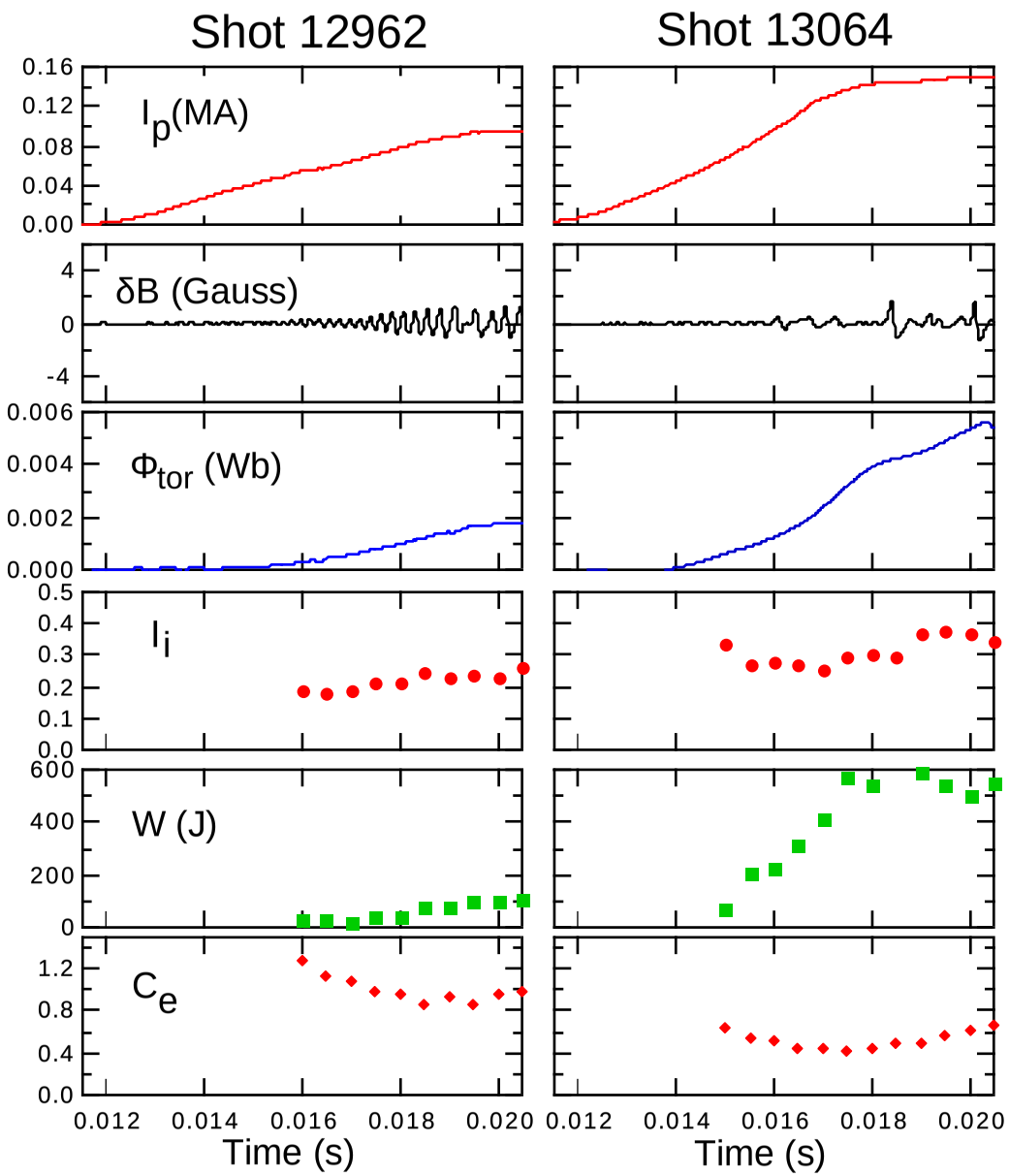
High-β, low-q Operational Limits

- **Evaluating role of MHD on access to low-TF, OH regime**
  - Use flux consumption analysis for quantitative comparison
    - Ejima Coefficient, C_e = high poor use of Ohmic V-sec
    - Ejima Coefficient, C_e = low efficient use of V-sec

- **Large Scale MHD Present ⇔ Reduced Ip, C_e ~ 1**
  - Internal modes appears to limit I_p in these cases
  - Mode is a large 2/1; observed when q_0 drops below 2
  - Appears to correlate with a large low-shear interior region with $q \leq 2$
  - Improvement expected with higher TF start-up

- **External Kink Observed ⇔ Max Ip, C_e ~ 0.5**
  - External kink and/or V-sec limit at highest I_p, B_t cases
  - Appears as q_{95} approaches 5; higher than typical tokamak
  - Improvement expected with increased V-sec and discharge control

Characteristics of OH Plasmas to Date

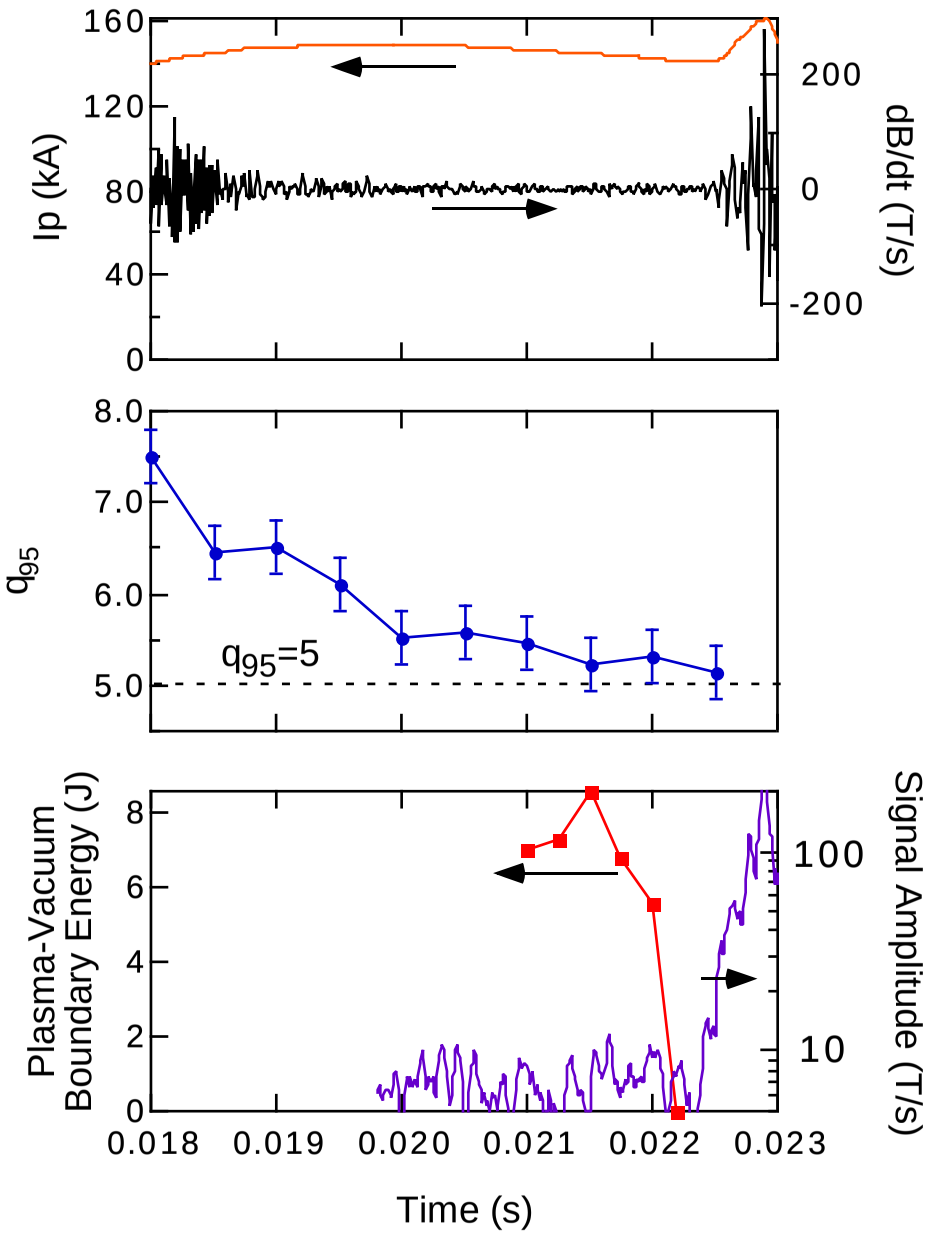


- With 2/1 Mode
  - *plasma current reduced*
  - *high C_e*
  - *Kinetic energy low*

- Without 2/1 Mode
  - *plasma current maximum*
  - *low C_e*
  - *Kinetic energy high*

Theoretical Analysis Suggests Kink Instability

Pegasus Toroidal Experiment
University of Wisconsin-Madison



- Observed disruptions are associated with edge q-limits
  - Oscillations not observed until $q_{95} \approx 5$
- Calculated plasma-vacuum boundary energy approaches zero as oscillations begin
  - Negative value indicates instability to external kink
  - Calculations made with DCON and VACUUM

Poster RP1.034 by G. Garstka

Facility Upgrades to Further Study of low-q_{95}, high-β_t Plasmas

Pegasus Toroidal Experiment
University of Wisconsin-Madison

- **Goals require increased control of plasma conditions**
  - *Density control and shot reproducibility = between-shot gettering*
  - *Improved equilibrium field control*

- **Suppression of large internal MHD modes**
  - *Increasing I_p ramp time = increased V-sec from ohmic solenoid*
  - *Attain higher $T_e(0)$ during formation = increased B_T*
  - *HHFW heating = increased RF power operation*
  - *Maintain q(0) > 2 during plasma formation = increased B_T*

- **Control onset of suspected external kink modes**
  - *Maintain I_p ramp time = increased V-sec from ohmic solenoid*
  - *Maintain high q95 during formation = increased B_T w/rampdown*
  - *Controlled gas puff for edge cooling = continuous gettering*
  - *Separatrix operation = energize divertor coils*

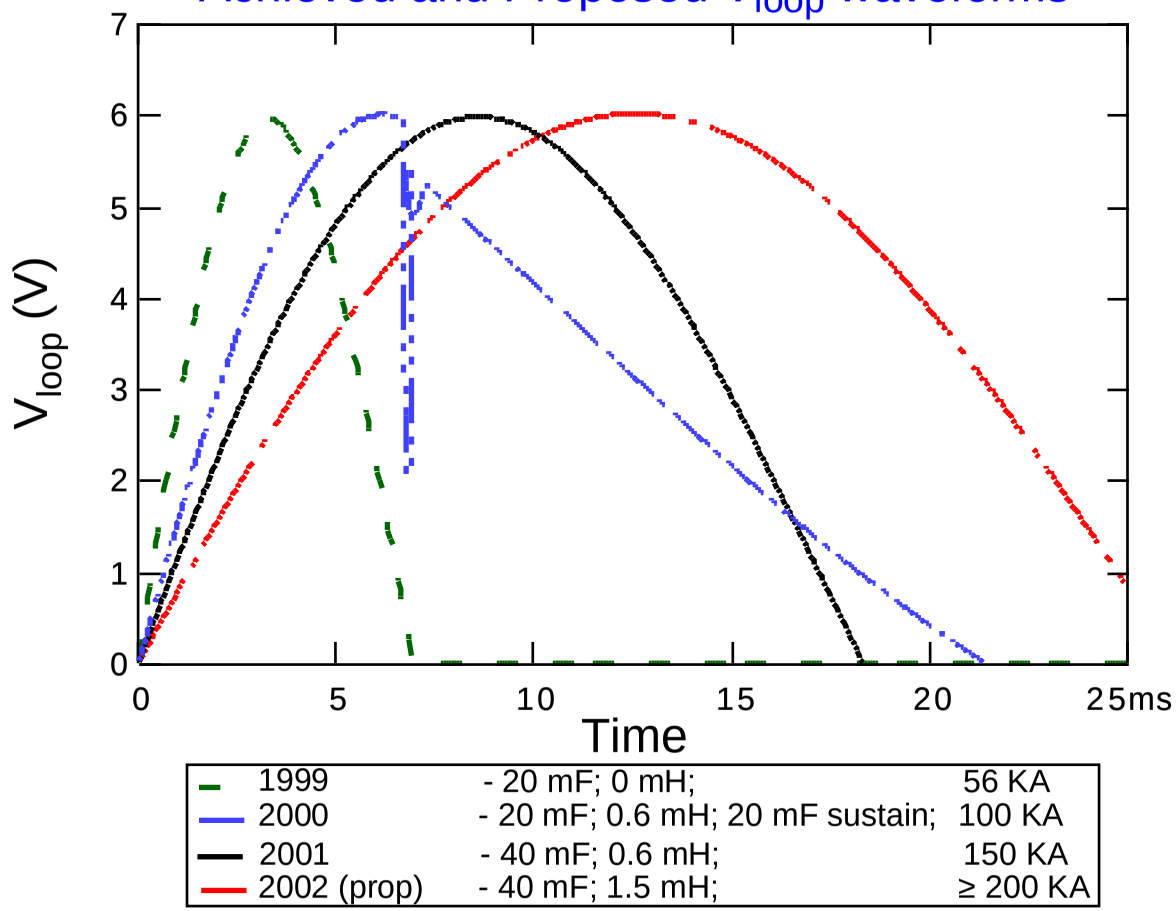
- **Access to very high β_T regime**
  - *Increase $T_e(0)$ during formation = increased B_T w/fast-rampdown*
  - *Increase I_p and N_e = increased V-sec*
  - *High-power HHFW heating = increased RF power operation*

- **Proposed long-term improvements to add control flexibility**
  - *Programmable internal radial position coils and divertor coils*
  - *EBW heating tests*
  - *Possible plasma gun startup*

Extension of OH Power Supply will Provide Increased Volt-Seconds

- **Increased Volt-second delivery planned**
  - *Increasing V-sec throughout project has given access to increasing Ip, Te, Ne, etc.*
  - *V-sec on Pegasus limited by power supply capabilities, not solenoid*
  - *Addition of a high-power inductor gives simple V-sec increase*
    - *should provide access to Ip ≥ 0.2 MA*

Achieved and Proposed V_{loop} waveforms



TF Coils with Rapid Ramp-down and Increased B_t in Fabrication

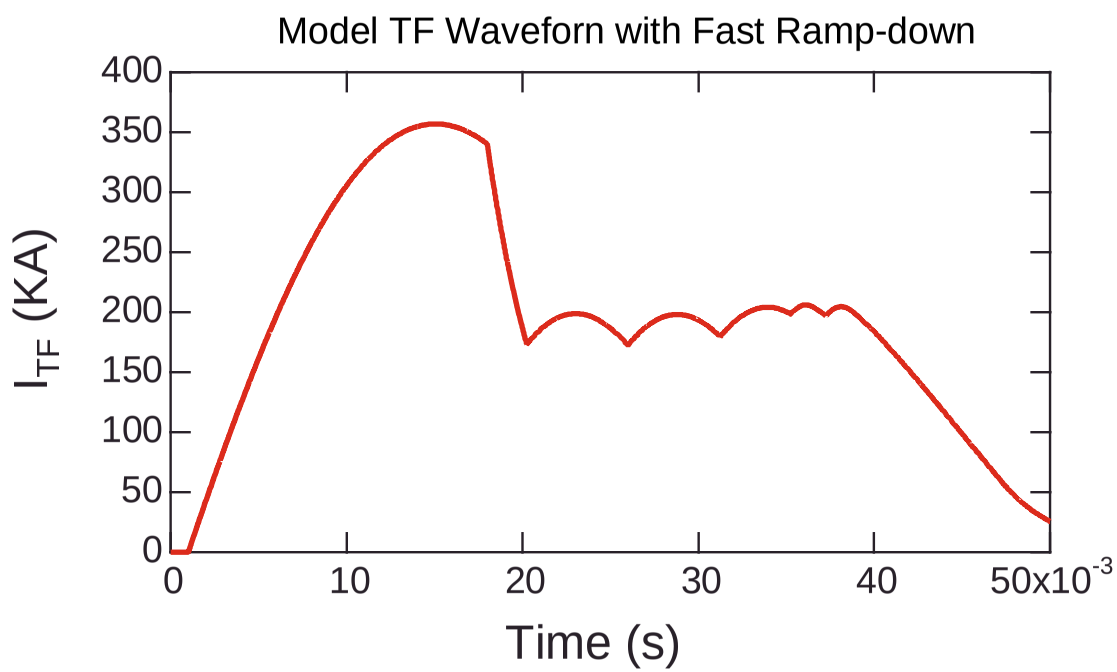
Pegasus Toroidal Experiment
University of Wisconsin-Madison

- **Provide B_T increase of 2-3 (0.15 - 0.3T) during formation**
  - *Support faster I_p ramp w/o large-scale MHD*
  - *Improved T_e evolution for lower resistivity*

- **Allow rapid decrease in B_t during shot**
  - *Access low-q_{95} and/or high β_t regimes starting with well-formed, hot plasma*
  - *New 12-turn low-inductance TF center rod assembly fabricated*



New 12-Conductor TF Center-rod Assemblies



Summary

- **Pegasus upgraded its diagnostic capability in 2001 Campaign**
  - *Extensive magnetic diagnostics installed*
  - *Tools for equilibrium and stability analysis developed further*
  - *Internal hardware modified to handle future high power operation*

- **Plasmas to date show low-A characteristics**

- *High* β_t	$\beta_t \sim 25\%$
- *High* β_N	$\beta_N \sim 5$
- *High TF utilization factor*	$I_p/I_{TF} \sim 1.2$
- *High normalized current*	$I_N \sim 8$
- *High density*	$n_e \sim n_{GW}$
- *MHD*	*2/1, 3/2, IREs, double tearing modes*

- **Future work will concentrate on extending high-β, low-q regime**
  - *Increased* B_t *for startup control*
  - *Increased V-sec for further discharge evolution; proposed* $I_p \geq 200$ *kA*
  - *HHFW heating for MHD control and high* β_t