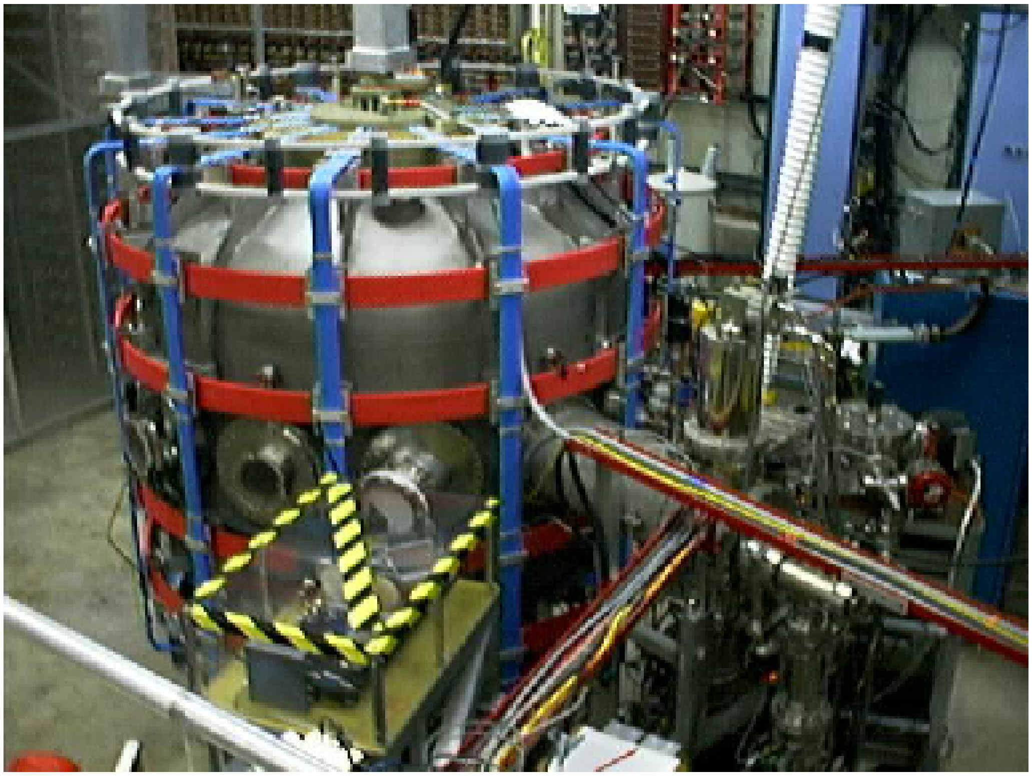
Recent Results from the PEGASUS Toroidal Experiment

G.D. Garstka

for the PEGASUS Group

University of Wisconsin–Madison U.S.A.

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.

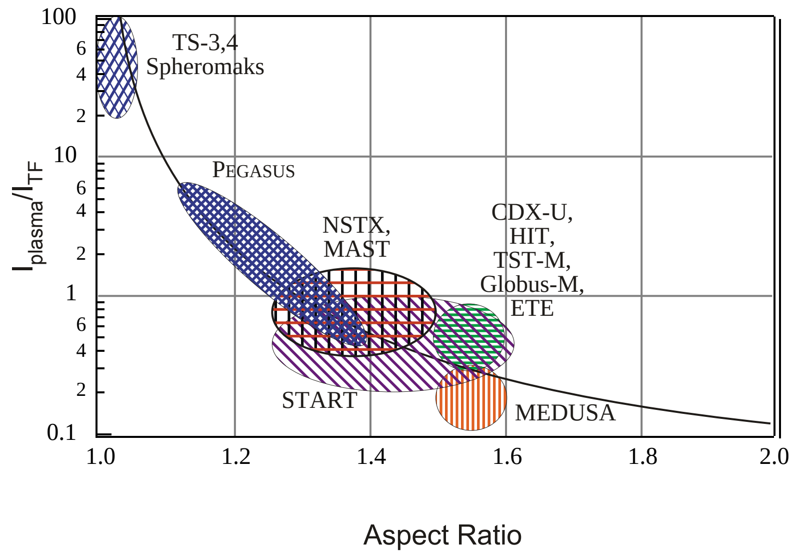


*Supported by U.S. DoE grant No. DE-FG02-96ER54375

Role of the PEGASUS Experiment

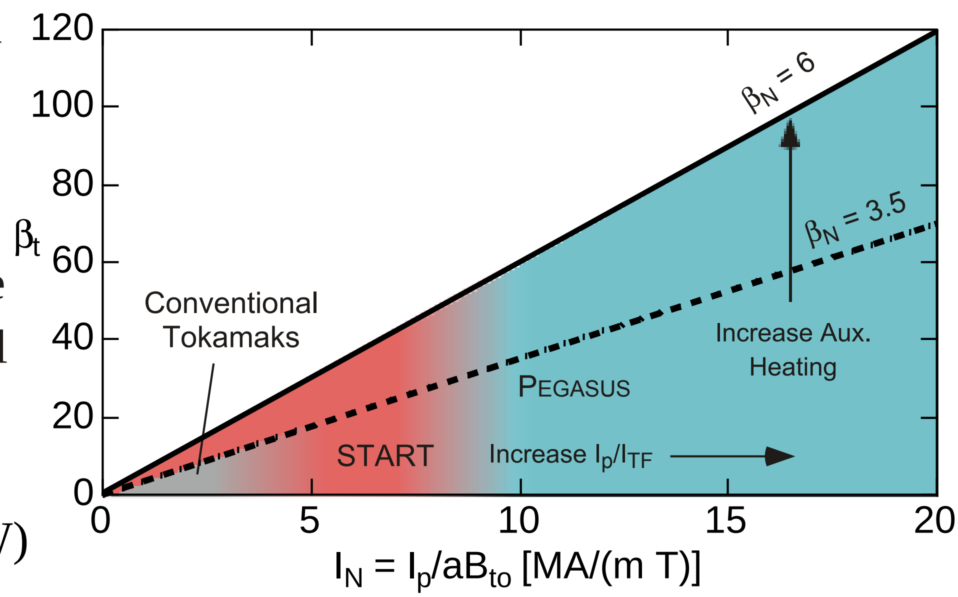
- **Physics of A ≈ 1 plasmas as an Alternate Concept (low q)**

  - 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



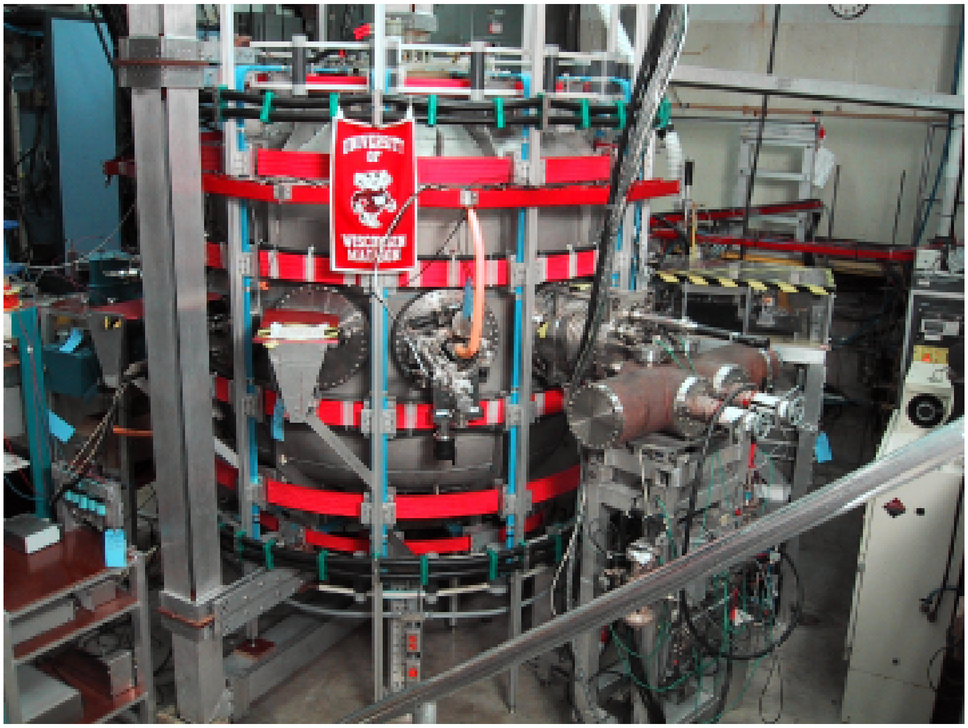
- **Contribute to development of the ST (high q)**

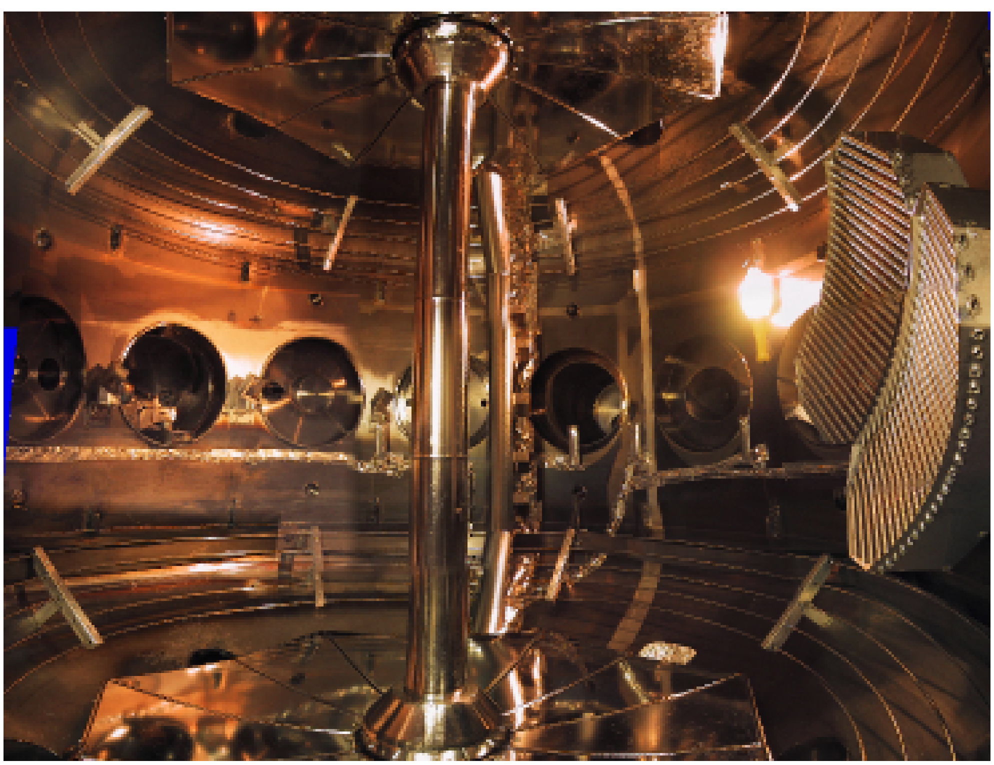
  - Stability limits for A → 1 (vs. I_p/I_{TF}, q_ψ, N_e, β_t, β_{pol}, κ, A, etc.)
  - β limit dependencies
  - Access high β_t at extreme I_N w/o conducting shell
  - Confinement A < 1.3
  - New startup schemes (e.g., plasma gun, EBW)



Pegasus is a Mid-Sized University ST

- High-Stress Solenoid Allows Exploration of A $\rightarrow$ 1 Regime





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
κ	~ 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

Mid 2001: 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**

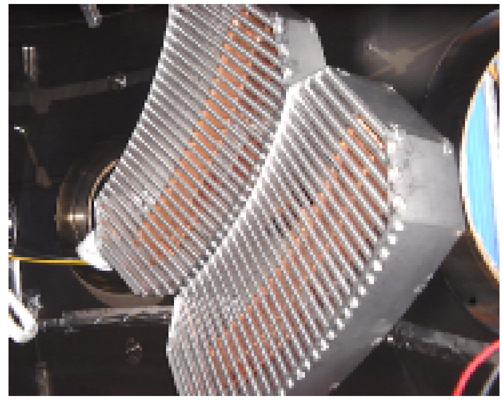
- *High β_t*	$\beta_t \sim 25\%$
- *High β_N*	$\beta_N \sim 5$
- *High TF utilization factor*	$I_p/I_{TF} \sim 1.2$
- *High normalized current*	$I_N \sim 8$
- *High density*	$n_e \sim n_{GW}$
- *MHD*	2/1, *IREs, double tearing modes*

- **Extension of operating space**
  - Increasing ohmic drive capability; I_p up to 140 kA
  - Density control and fueling (fast gas puffing)
  - Pulse length extension (up to 30 ms)
  - Wall conditioning (Ti gettering, DC GDC)

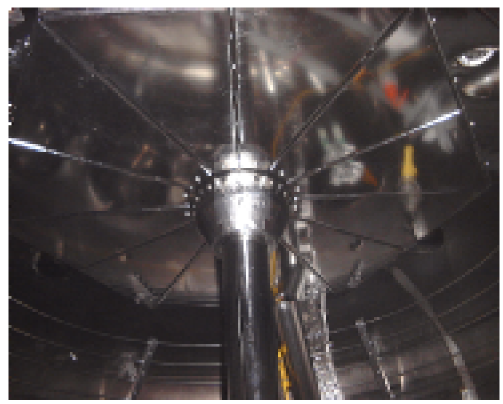
- **Major upgrades**
  - Extensive internal magnetics
  - New plasma-facing components
  - HHFW antenna installed and tested up to 100 kW
  - Several new diagnostics coming online

Major Machine Modifications to Upgrade Internal Hardware

- **Extensive internal diagnostics installed**
  - Flux loop and B_{pol} arrays
  - Extensive centerstack magnetics
  - Diamagnetic loop and new Rogowski coils



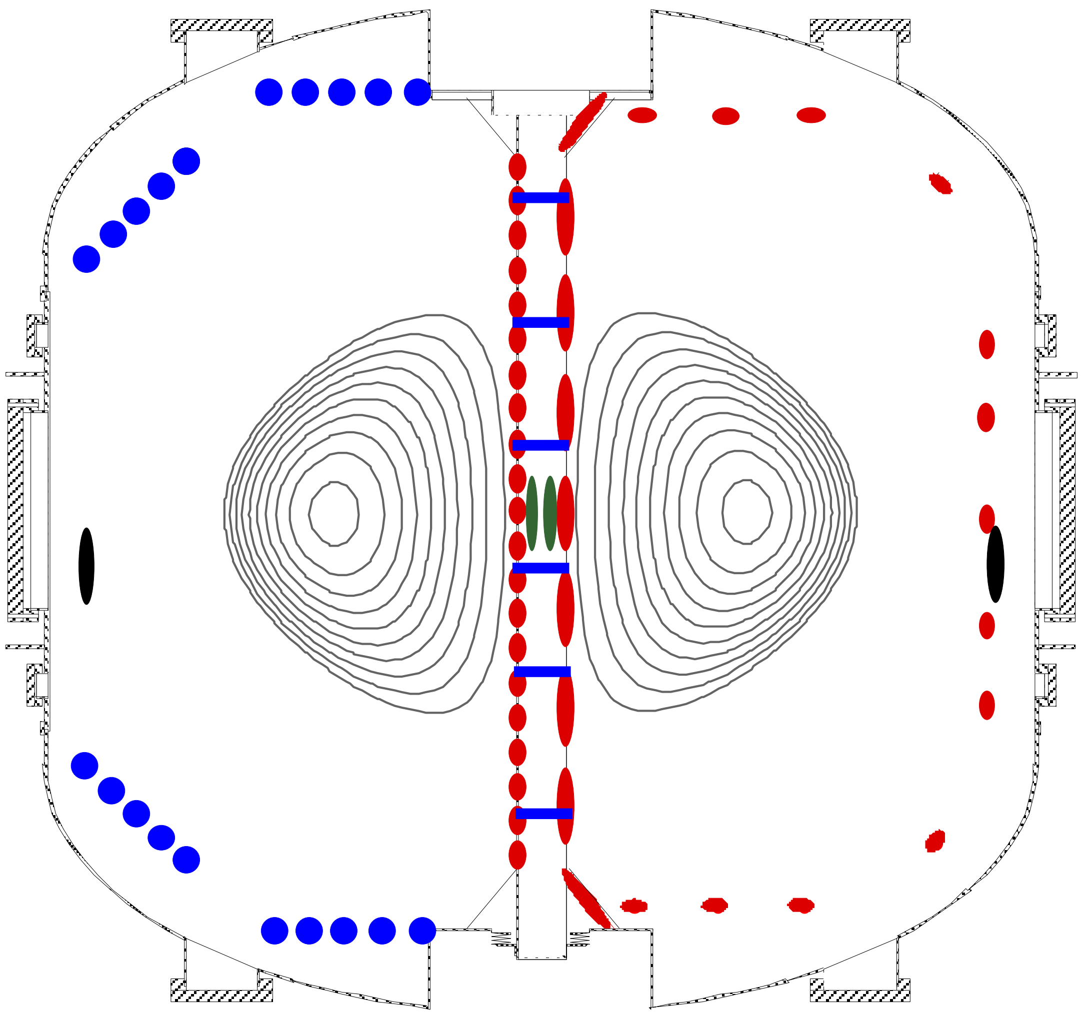
- **HHFW and EBW antennae installed**
  - P_{RF} = 1-2 MW available for HHFW
  - Fully steerable EBW/ECH antenna



- **Improved power deposition hardware**
  - Divertor plates
  - High-power outer limiter

- **Near-Future Modifications to further improve performance**
  - New toroidal field center rod assembly
    - *Low inductance 12-turn $\Rightarrow$ rapid B_t decrease during shot*
    - *Increased TF, up to 0.3T $\Rightarrow$ increased startup stability*
  - Increased Volt-seconds from high-stress solenoid
    - *Power supply improvements*
  - Commission high power HHFW system for heating

New magnetics diagnostics installed in 2001

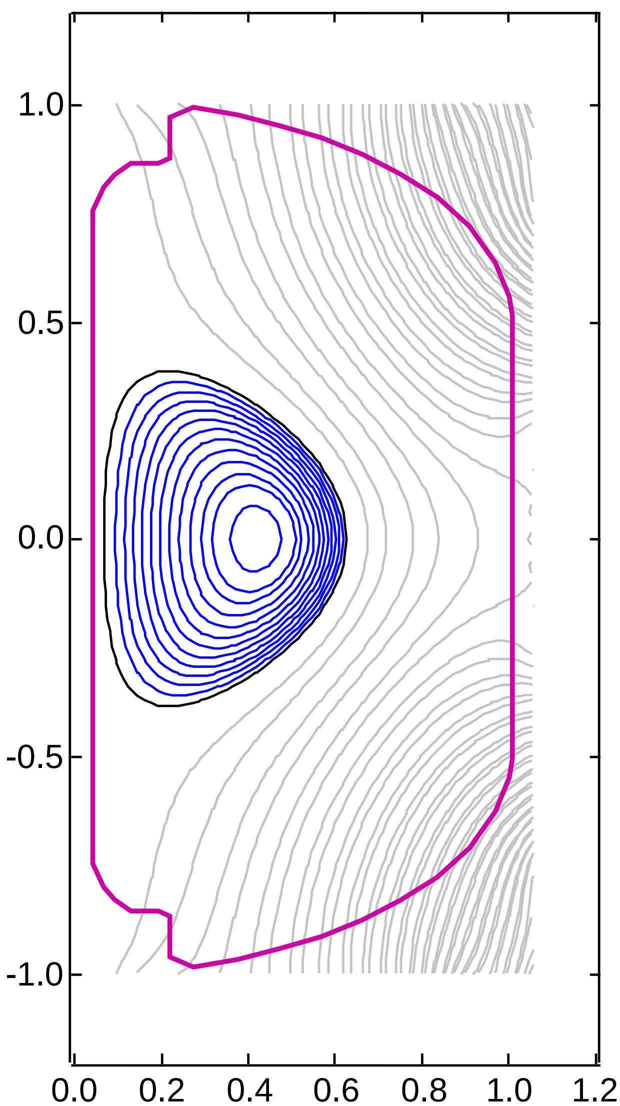


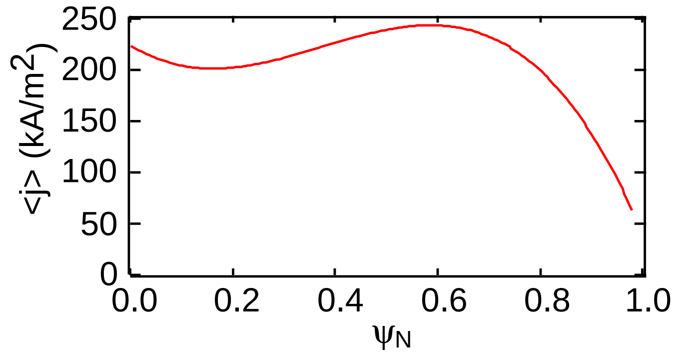
- Flux Loops (26)
- Poloidal Mirnov Coils (22 + 21)
- LFS Toroidal Mirnov Coils (6)
- HFS Toroidal Mirnov Coils (7)

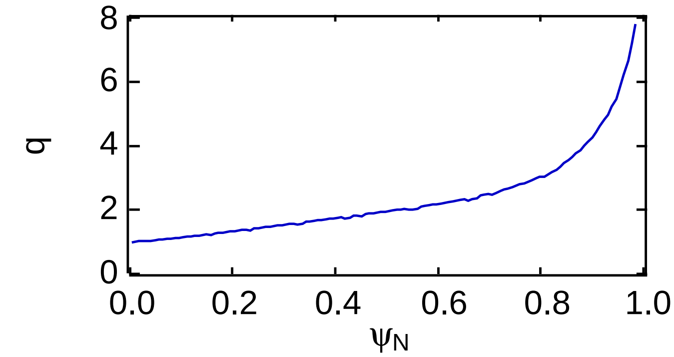
Not shown:
- Plasma Rogowski Coils (2)
- Diamagnetic Loops (2)
- Diamagnetic Compensation Loop
- External Wall Loops (6) [constrain wall currents]
- Internal B_{tan} Coils (15) [constrain wall currents]

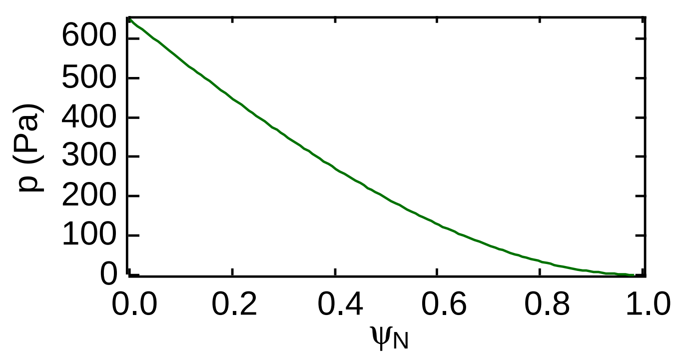
Magnetic Equilibrium Reconstruction Used as Primary Analysis Tool

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_{98}	7.8





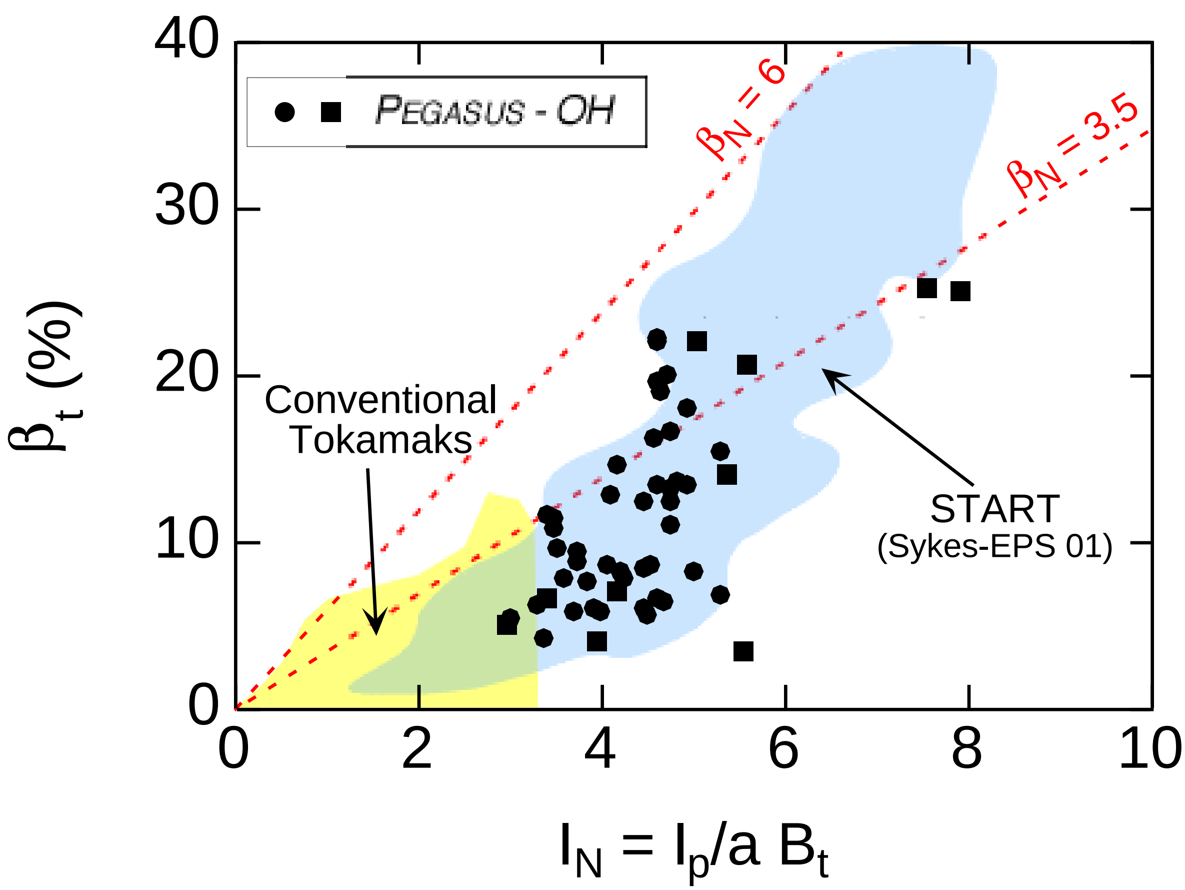




Constraints: Rogowski Coil
18 Flux Loops
3 B_p Coils
Diamagnetic Loop

Pegasus is Accessing High-β_t ST Regime

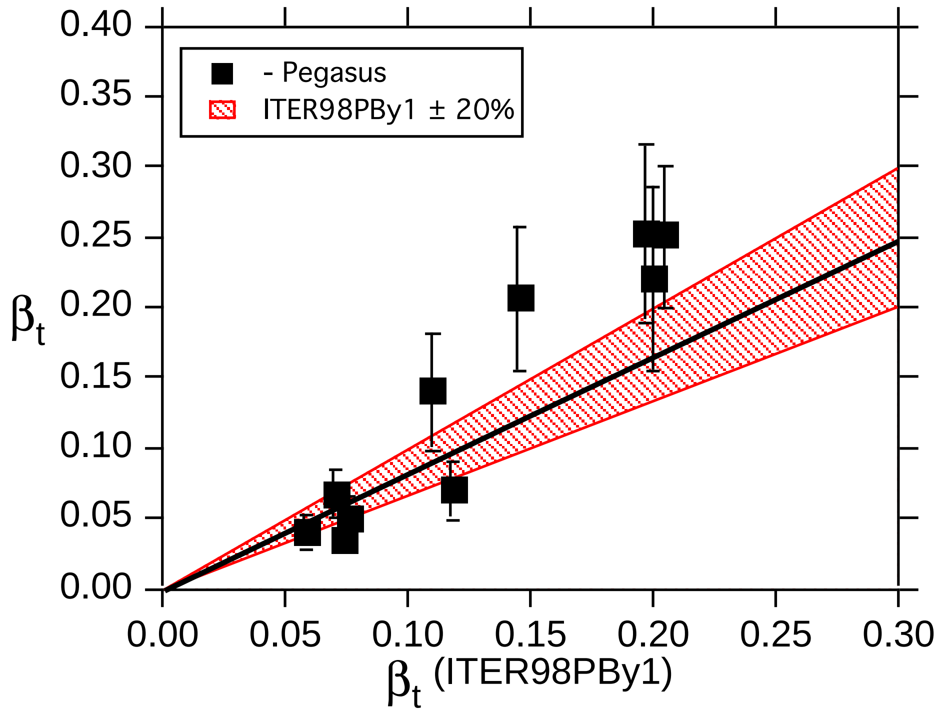
- **High β_t attained at high density, low-TF**
  - *Ohmic heating only; constant TF*



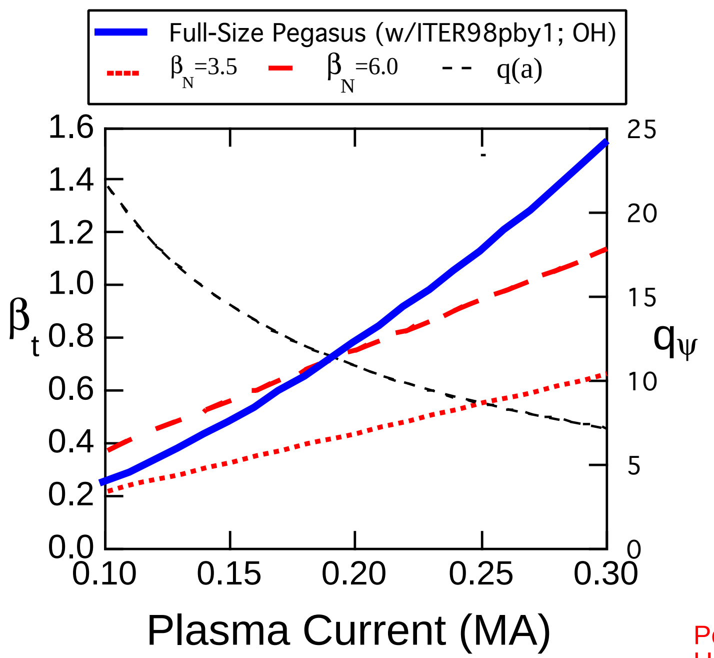
- **Tools to move further under development**
  - *Additional MHD diagnostics*
  - *Increased V-sec*
  - *Increased, t-variable TF*
  - *HHFW heating*
  - *Density control*

Estimates of β_t Consistent with START Confinement

- **β_t estimated from magnetic equilibrium reconstruction**

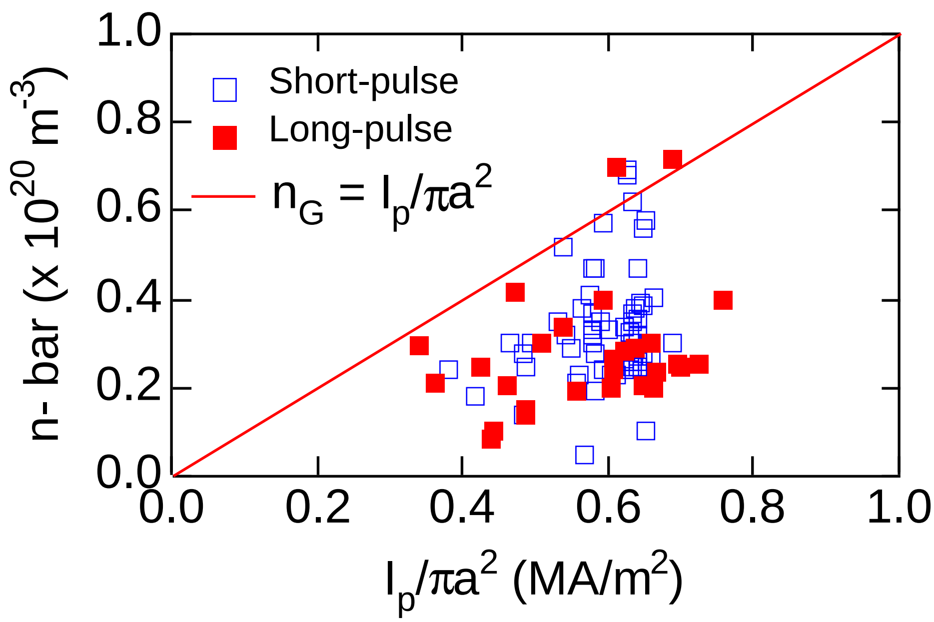


- **High β_t accessible at full OH power; higher T_e with aux heating**

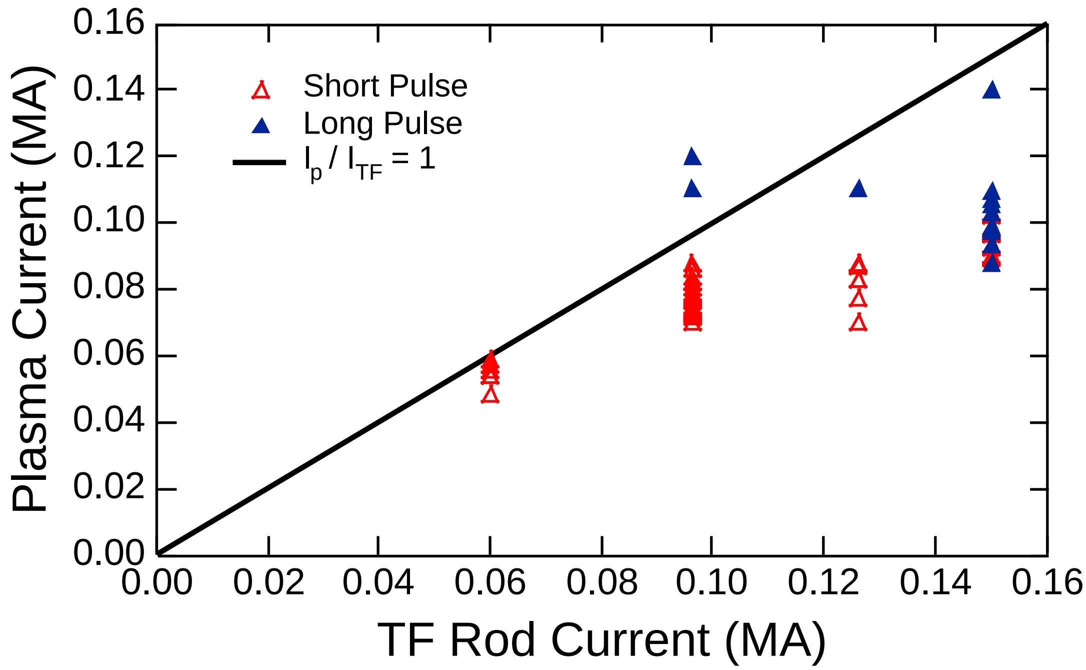


High Density, Low-TF Operation

- **Density Approaches the Greenwald Limit**

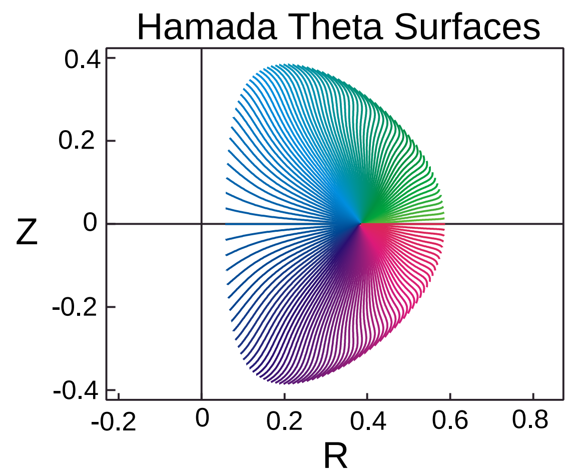


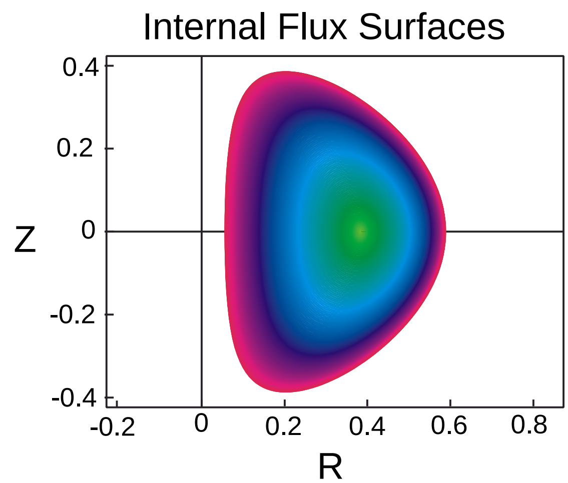
- **$I_p/I_{TF} \rightarrow 1$ at lower TF settings**
  - *MHD modes limit I_p ramp rate $\rightarrow$ high I_p/I_{TF} only at low TF*
  - *Present limits on I_p/I_{TF}: ramp rate, MHD, V-sec*

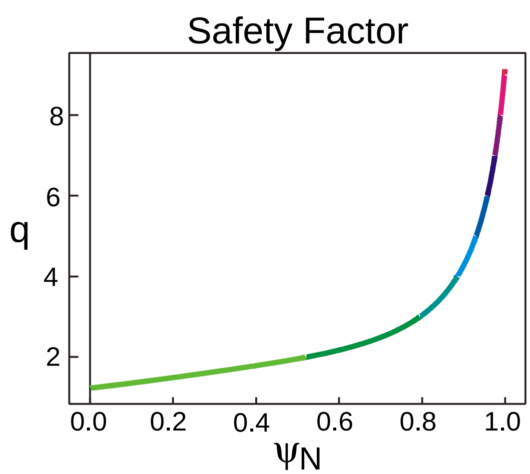


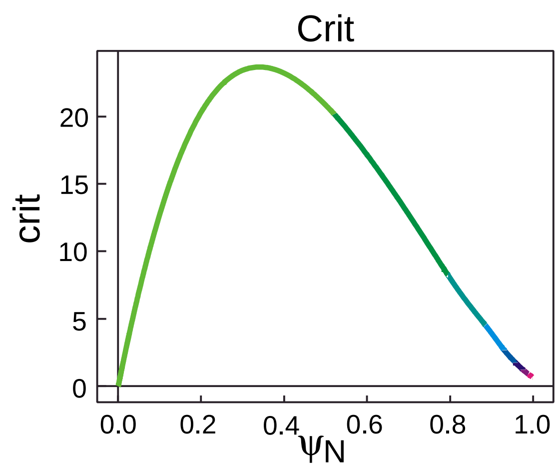
DCON is being implemented to map stability space and analyze individual equilibria

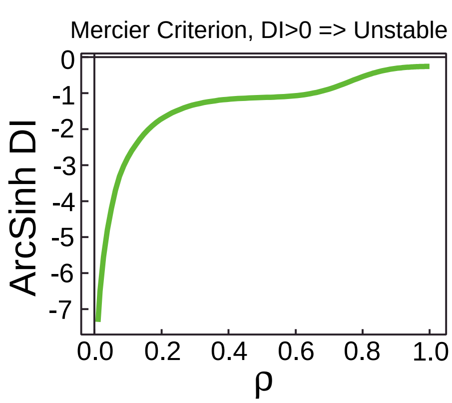
- Shot 12445, 18% β_t

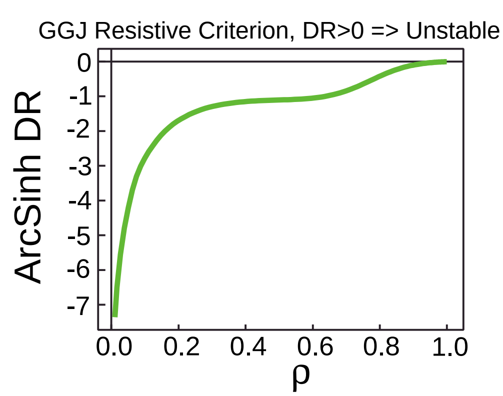


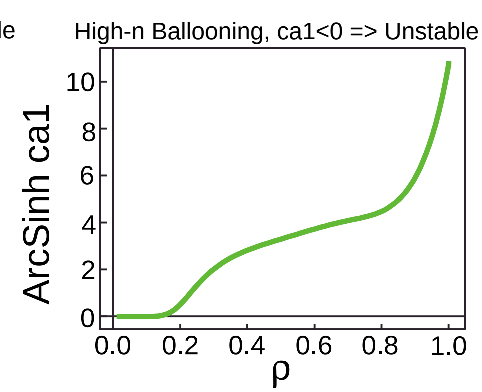






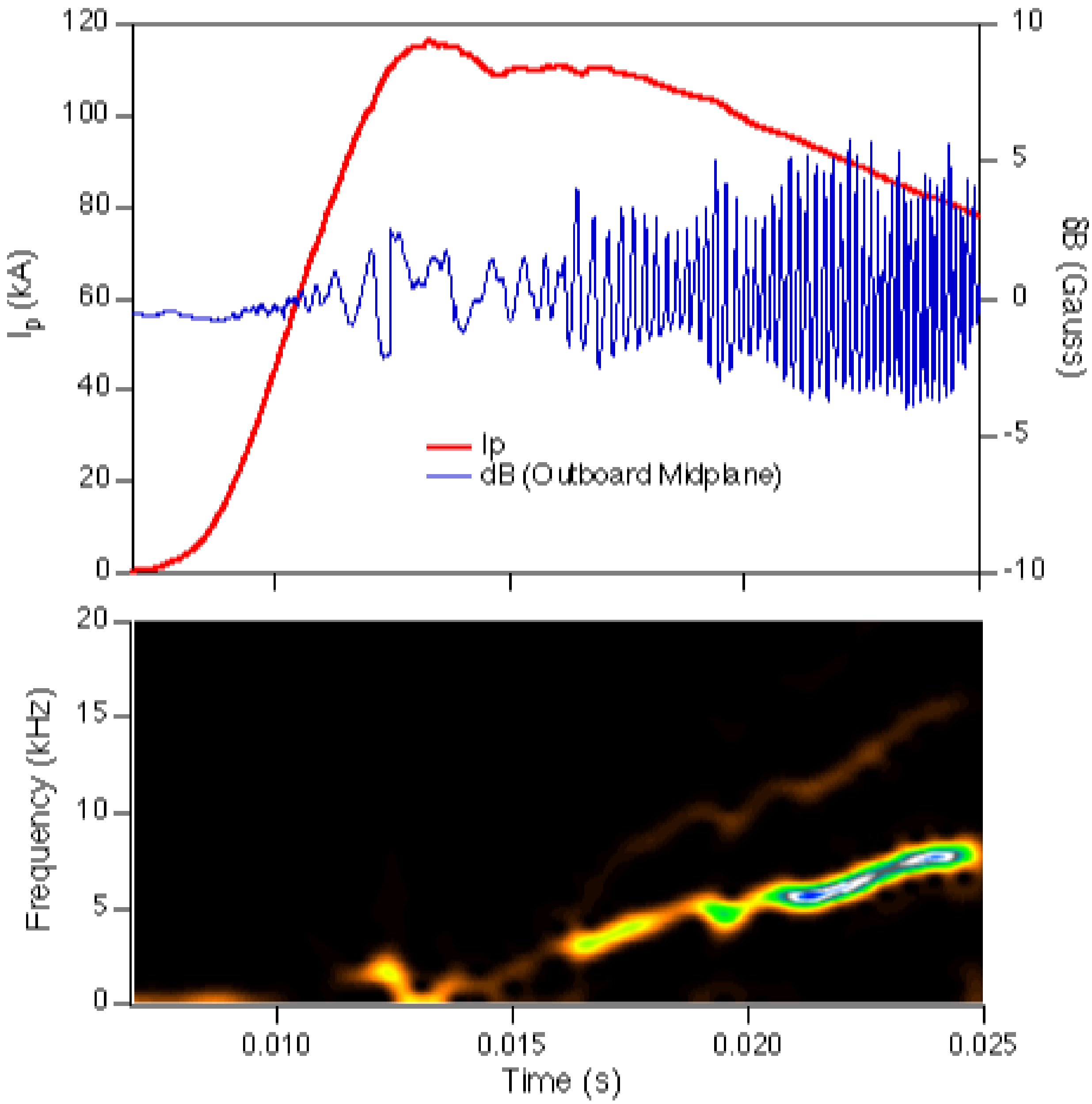






Significant MHD is observed during discharge evolution

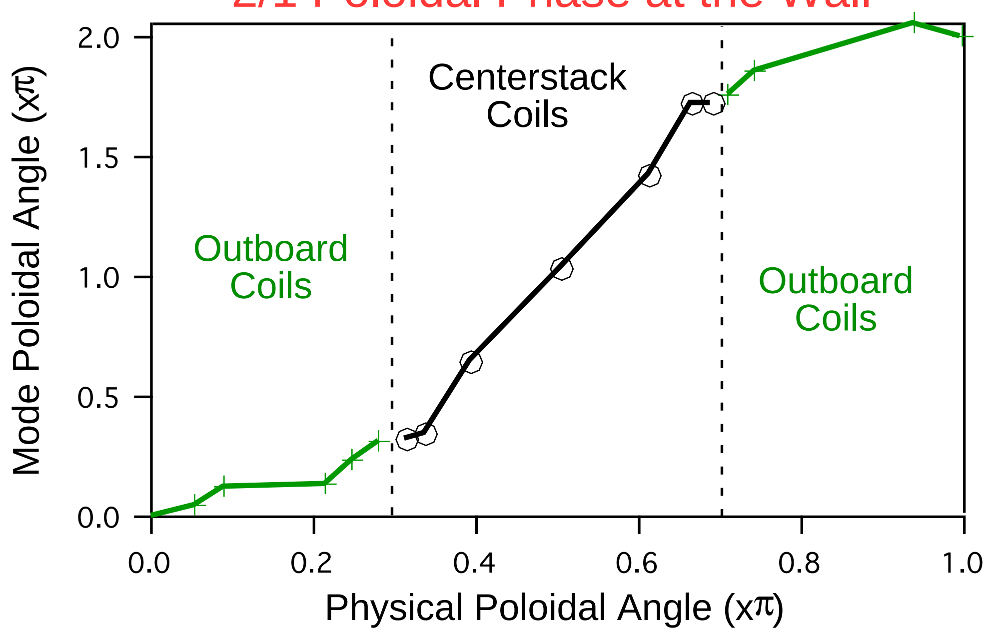
- A rotating 2/1 mode is present in most discharges studied
  - Mode rotates in electron diamagnetic direction
  - Frequency is 5-10 kHz
- A lower frequency mode is often observed during the current ramp
- IREs and double tearing modes also observed

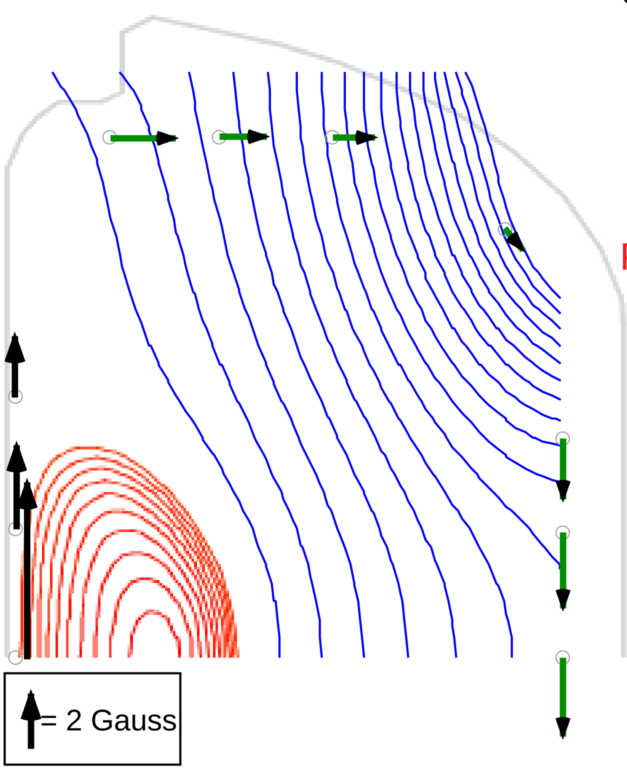


2/1 mode structure is poloidally asymmetric

- Poloidal and toroidal phase analyses clearly indicate mode is m=2/n=1
- Toroidicity of mode is seen in large phase shifts along centerstack
  - Roughly 1.5 wavelengths observed across 120º poloidally
- Mode is strongest on the low-field side
  - As plasma grows, LFS signal increases and HFS signal decreases

2/1 Poloidal Phase at the Wall



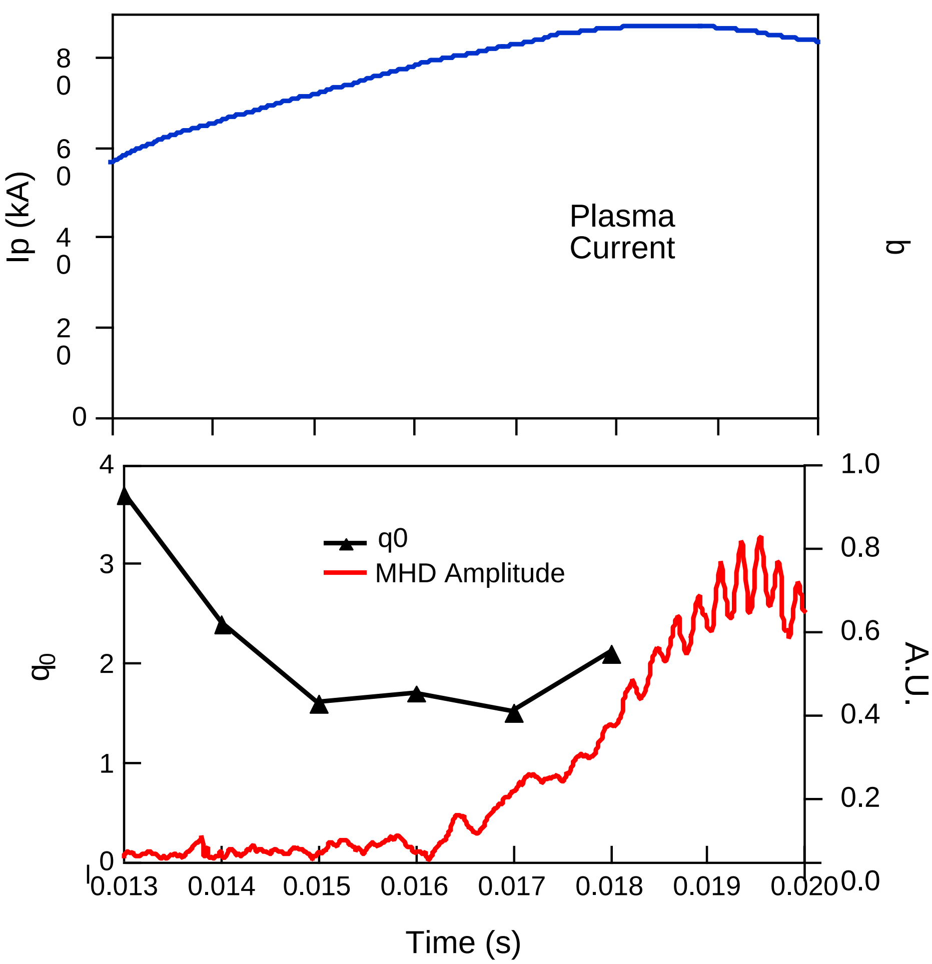


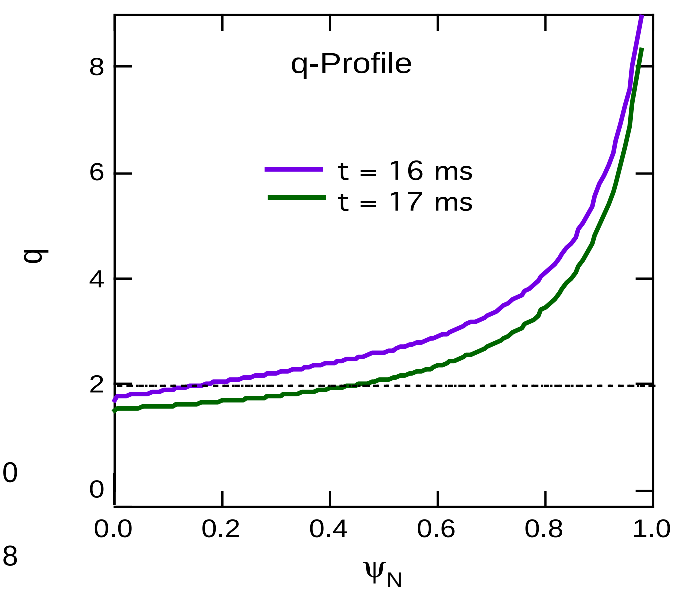
Perturbed Field Magnitude
at the Wall

2/1 Mode appears and grows after $q_0 = 2$

- Consistent with observed helicity of the mode

- Central q presently inferred from Equilibrium fit
  - 2D SXR camera will constrain q_0

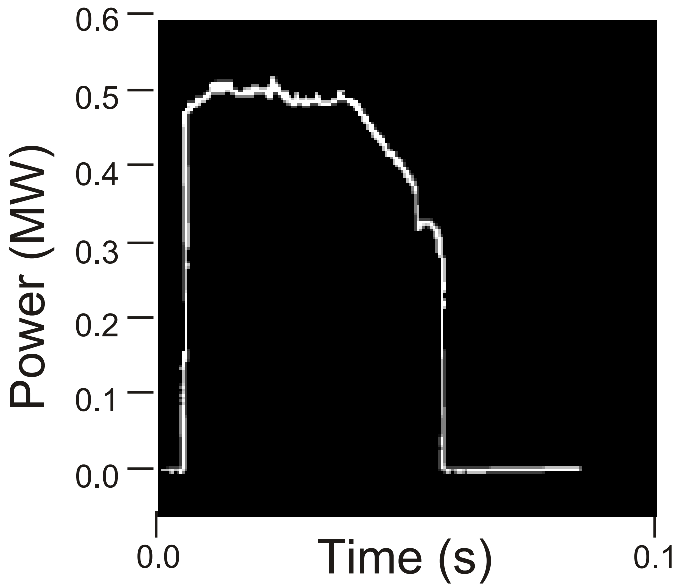




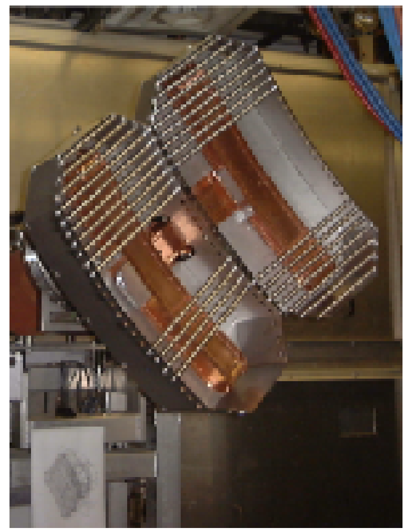
- In general, strong MHD activity appears to relate to I_p limits
  - Relative roles of MHD and V-sec limits under study

RF Startup and CD Techniques for High β Access

- **HHFW system installed and heating tests underway**
  - P_{RF} = *1-2 MW available; sufficient to access high* β_t *regime*



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



  - Initial loading tests give an impedance of about 1 Ohm
  - Up to 80 kW injected into vessel

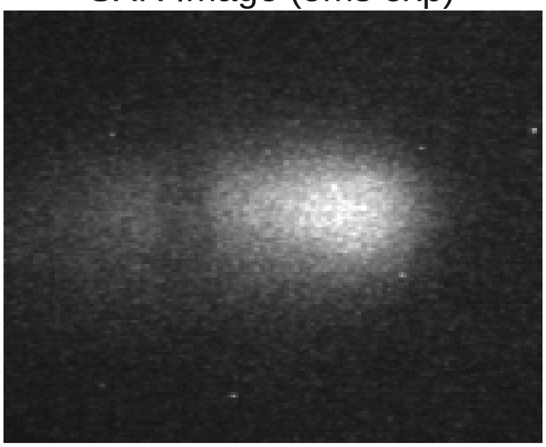
- **HHFW Startup and CD applications:**
  - Startup assist via preheating and/or current profile "freezing"
    - *Startup plasma phase: 40% single pass absorption*
    - *High β plasma phase: 100% single pass absorption*
  - CD possible with present power supply and new antenna

- **EBW heating and CD to be tested for application to high β, A → 1 plasmas**

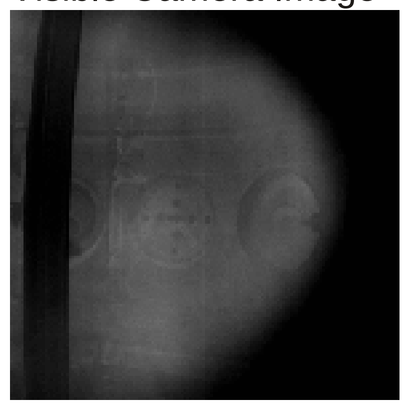
SXR Camera Provides q(0) Constraint in Equilibrium Reconstruction

- **Tangentially viewing Soft X-ray camera provides measure of internal plasma flux surface shape**
  - Internal plasma shape strongly dependent on current distribution
  - SXR image added to measurements fitted in magnetic reconstruction
  - Initial data may give constraint on allowed q(0)

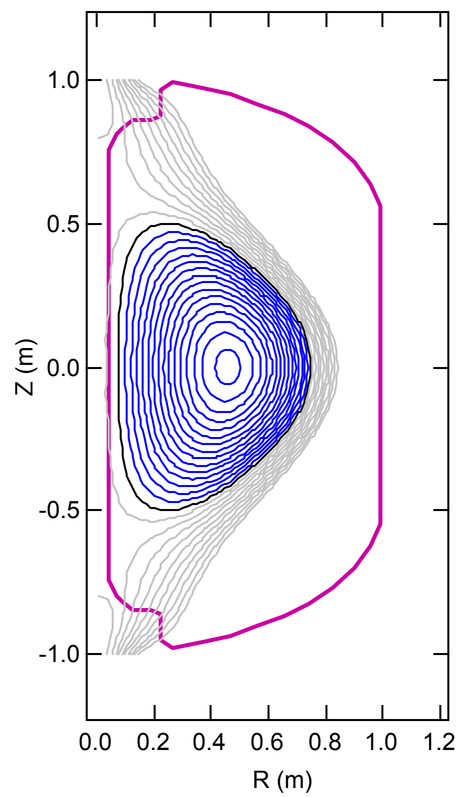
SXR Image (5ms exp)



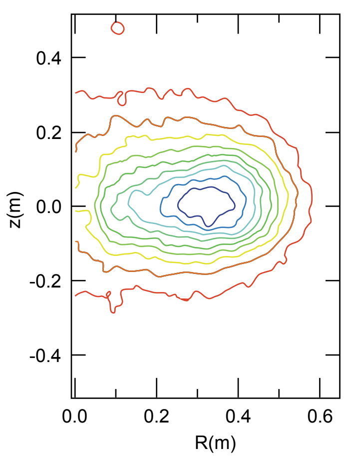
Visible Camera Image



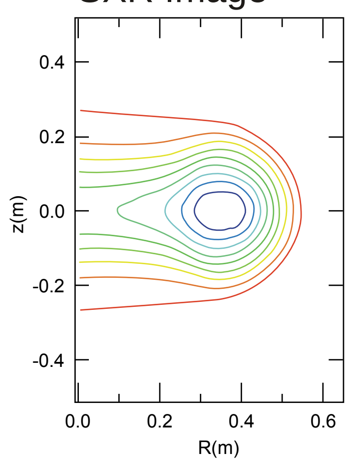
Shot 9639 (t = 18 ms), Frame 13



SXR Image Contour Plot



Calculated SXR Image



- Center-weighted fit gives q(0) ≈ 1.8
  - *Analysis development in progress*

Summary

- Primary goal is to explore the A $\rightarrow$ 1 regime
  - Tokamak/Spheromak Overlap: How close can A $\rightarrow$ 1 and maintain good stability and confinement?
  - Geometry (A, κ, separatrix) and current profile (ℓ_i, q_o, q_ψ) influence on the stability limits?
  - Tradeoffs between A ≈ 1 and current drive requirements?

- Ohmic campaigns have demonstrated low-A phenomena
  - $I_p/I_{TF} > 1$, $I_N \approx 8$
  - $\beta_t \approx 25\%$, $\beta_N \approx 5$
  - $N_e \approx N_{GW}$
  - Formation at very low B_t (~ 0.04 T)
  - MHD activity: 2/1 mode, double tearing, IRE
  - Presently limited by MHD activity and available V-sec

- New capabilities are rapidly coming online
  - New magnetics diagnostics and PFCs installed
  - HHFW antenna testing during plasma ops
  - Upgrades for OH and TF in Fall 2001

    Increased I_p, T_e, q(0,t) to control MHD
  - Several new diagnostics in development

PEGASUS Staff

- Merger of Research & Education Missions of UW

- **Pegasus Personnel - Experiment Team:**

Staff: (full)
G. Garstka
B. Lewicki
B. Ford
G. Winz

(part)
R. Fonck
P. Nonn (+ MST)
P. Probert (+ HSX)

Graduates:
R. Schooff
C. Ostrander
E. Unterberg
A. Sontag
K. Tritz

Undergraduates:
S. Diem
M. Reinke
J. Boerner
T. Reinecke
D. Schuster
R. Lawson
S. Schwab

- **Associated Theory (CPTC)**

J. Callen
C. Hegna
K. Comer

PEGASUS has Benefited Greatly from Contributions from Members of the Fusion Science Community:

- **Collaborations**

NHMFL:	Solenoid design, fab., tests
	Stress Analyses; VV construction; Theory (MHD, RF…); Future expts.
PPPL:	RF; Power Engr.; DNB assistance
UCLA:	μwave interferometer
MST:	Engineering; diagnostics; e-gun j sources

- **Contributions**

NHMFL	Magnets
General Atomics	Vacuum Vessel, Iron core
PPPL	Capacitors; diagnostics; CAMAC
LANL	Caps; Ignitrons, RF systems
MST	Ross diodes; iron core; caps, etc.
HSX	EF cap bank
LLNL	Caps; DNB power system
ORNL	Thomson scattering
Westinghouse	High-E cap bank
UW SC Lab:	TF hex conductor

Plasma Diagnostic Set

- Presently operating diagnostics

Diagnostic	Measures
Core Flux Loops	V_L
Ext Flux loops	Vessel currents
Int. Flux loops	Equilibrium
Rogowski Coils	I_p
Diamagnetic Loop	Toroidal Flux / β_p
B_p, Mirnov Coils	Equilibrium / MHD activity
VUV (SPRED)	Impurity monitor
Filterscopes	Oxygen, Carbon, D_α
Interferometer	$N_e\ell$
High Res. Camera	Plasma shape/position

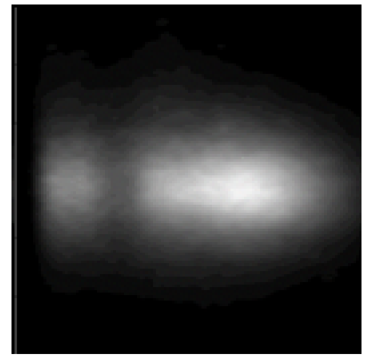
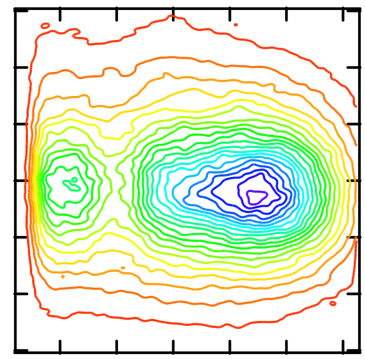


Image from 2D SXR Camera



Constant emissivity surfaces

- Near-future diagnostics

Diagnostic	Measures	When?
Tang. SXR Camera	Plasma shape/equilibrium	Summer 2001
SXR Array	Internal MHD	Summer 2001
Bolometer Array	P_{rad}	Fall 2001
VB Array	$N_e(R,t)$	Fall 2001
Ross Filters	T_{e0}	Summer 2001
2-Color X-ray	T_e	Fall 2001
Wall Pickup Coils	Vessel currents	Winter 2001
DNB	$N_e(R,t)$, $T_e(R,t)$, j(R)	?
EBW Radiometer	$T_e(t)$	?