Plasma Formation Studies and Plans for the PEGASUS Toroidal Experiment*

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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.

- Explore the extreme limit of low-aspect ratio physics

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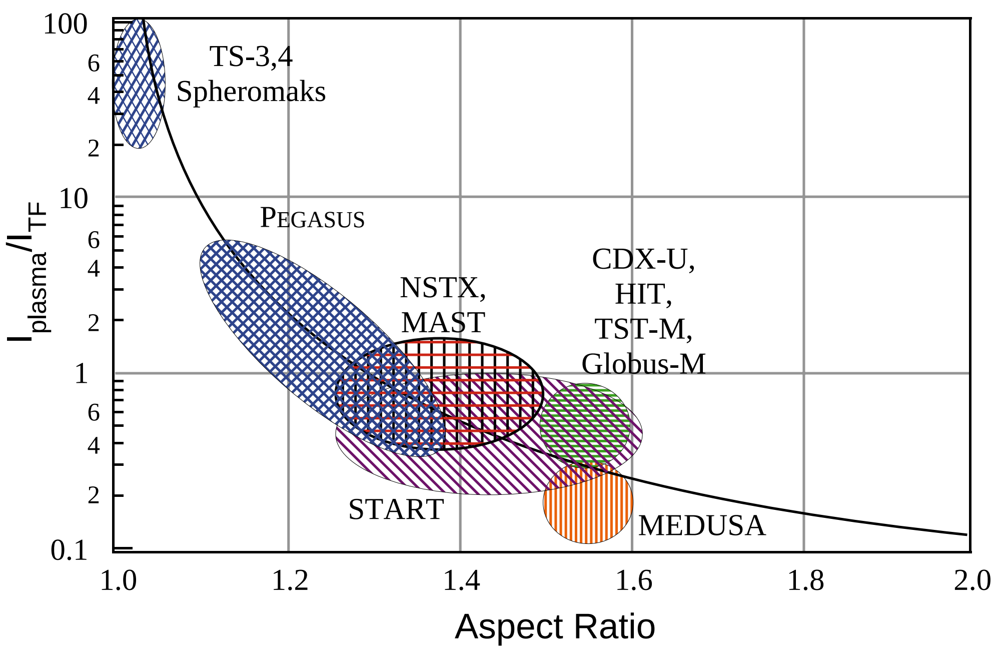
Role of the PEGASUS Experiment

- **Contribute to development of the Spherical Torus (High q_ψ)**
  - *Extreme toroidicity ($A \rightarrow 1$)*
  - *Current limits and disruptivity*
  - *β limit dependence on A, κ, etc.*
  - *Confinement with aux. heating at $A < 1.3$*
  - *New startup schemes (e.g., plasma gun current injection)*

- **Address physics of $A \rightarrow 1$ as an Alternate Concept (Low q_ψ)**
  - *Very high TF utilization (I_P/I_{TF}) > 3;*
  - *Trade-offs: CD, recirculating power, and $A \approx 1$, low-TF operation*
  - *MHD equilibrium and stability at very low TF ($\beta \approx 1$)*
  - *Explore RF heating and CD schemes (HHFW, EBW)*

$A \rightarrow 1 \Rightarrow$ smaller centerstack, less recirculating power and waste



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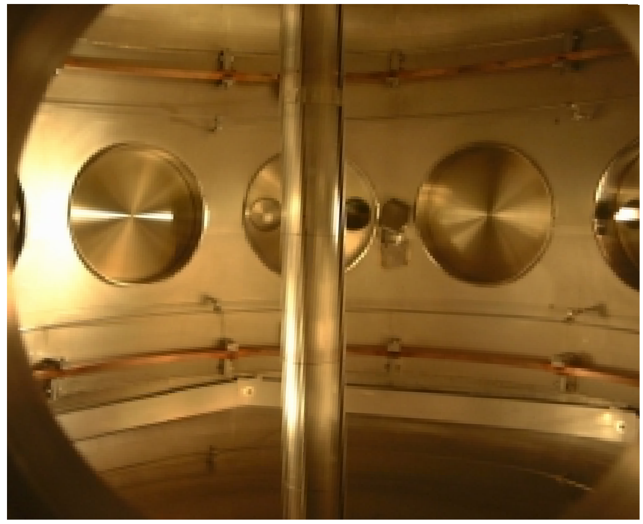
PEGASUS Operates at Ultra-Low A via Reinforced, High-Stress Solenoid



PEGASUS Operational Parameters

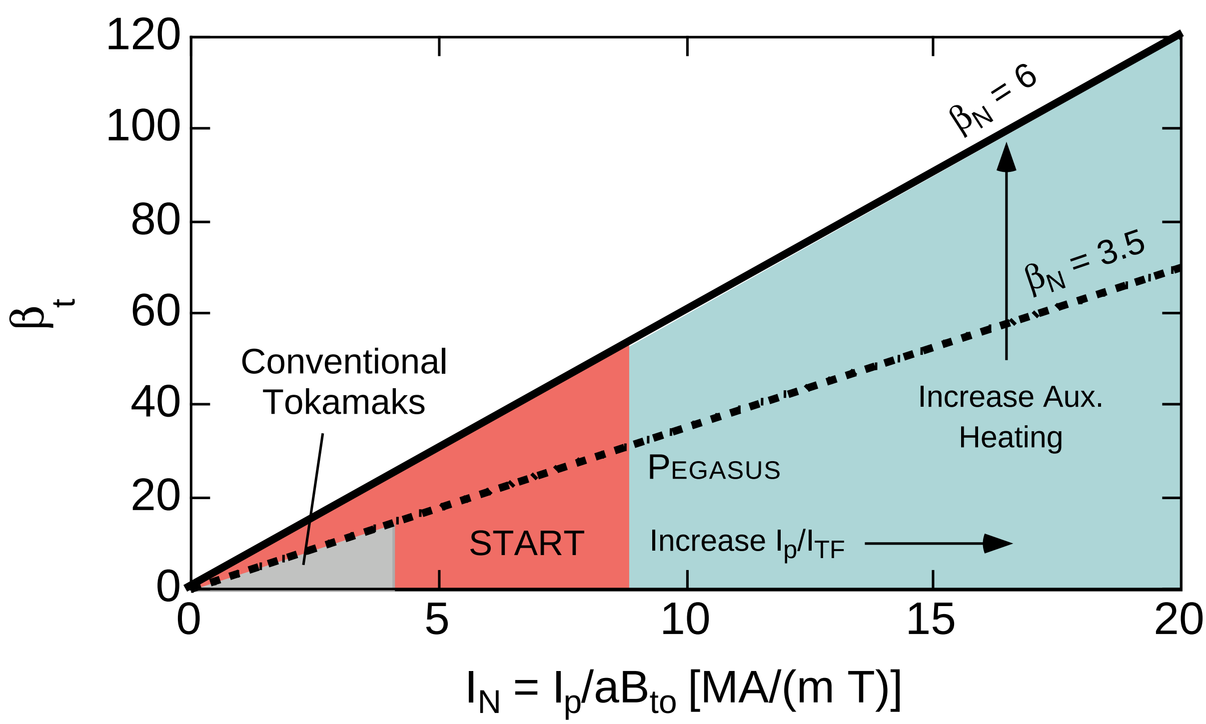
Parameter	Present	Full
A	1.16 - 1.3	1.1 - 2.0
R	0.2 - 0.3 m	0.2 - 0.45 m
I_p	0.1 MA	0.1 - 0.3 MA
B_t	$\leq$ 0.1 T	$\leq$ 0.15 T
κ	~ 1.5 - 3.0	~ 1.5 - 3.7
Δt_{pulse}	3 - 8 msec	30 - 60 msec
β_t	0.03 - 0.2	*O*(1)
β_N	1 - 5	> 5
I_N	~ 2 - 6	> 10
Heating and Sustainment	Inductive*	Inductive*+ RFCD (HHFW, EBW), Plasma Guns

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

Goals of the PEGASUS Toroidal Experiment:

- **Primary Goals:**
  - *Plasma stability limits at high I_p/I_{TF}, low A, high κ*
  - *Operational limits (in terms of q_ψ, density, β, κ, A, etc.) for $A \rightarrow 1$*
  - *Demonstrate access to high β_t at extreme I_N without a close-fitting conducting shell.*

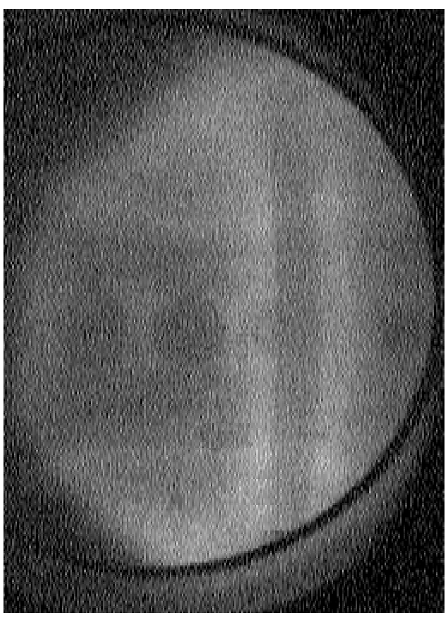
- **Secondary Goals:**
  - *Test relaxation stability at tokamak/spheromak boundary*
  - *Measure global confinement characteristics for varied A, κ, etc.*
  - *Evaluate the need for external CD as $A \rightarrow 1$*
  - *Evaluate plasma guns for startup and j(R) modification*
  - *Initial studies of startup, heating, and CD via EBW launch*



First Campaign: Plasma Formation Studies

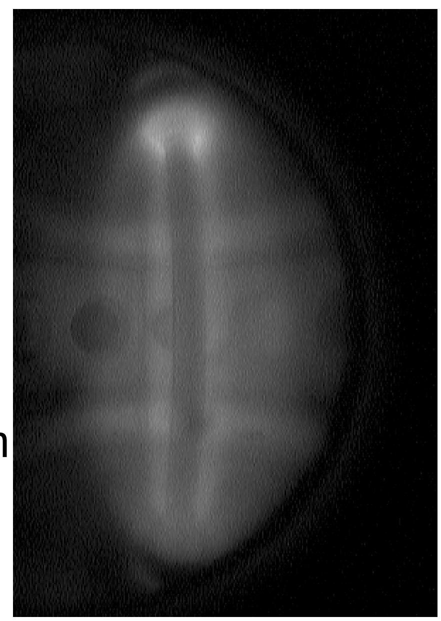
- **Demonstrated efficient startup and startup at low B_t in presence of conducting walls**
  - *Critical for low TF, high β mission for Pegasus*
  - *Induced wall currents are reasonably understood and accounted for*
  - *Startup achieved at B_{to} ~ 0.05 T, startup at 2 V possible at full field*

- **Accessed a variety of plasma geometries**



R = 0.34 m
a = 0.29 m
A = 1.17
$\kappa \approx 1.8$

R = 0.2 m
a = 0.15 m
A = 1.3
$\kappa > 3$



Geometric Plasma Properties Estimated from Visible Images

Startup Plasmas Show ST Characteristics

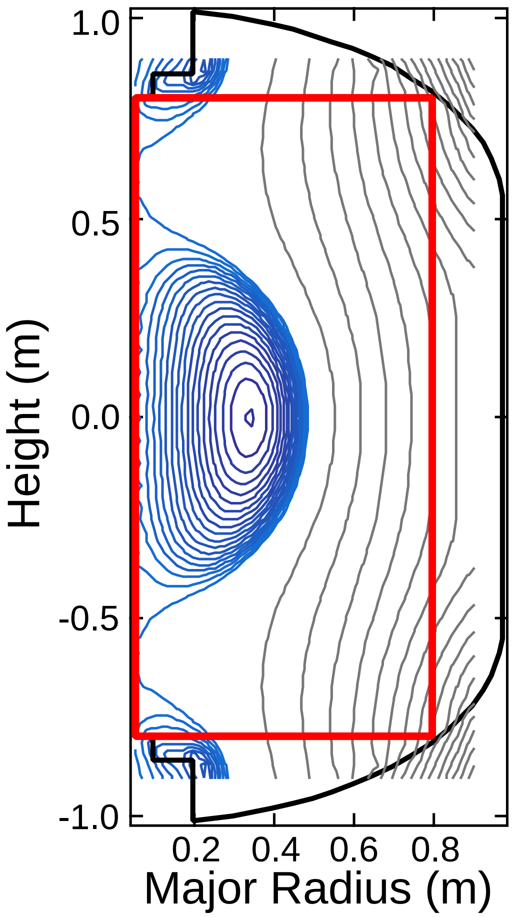
- **ST-like behavior observed:**
  - *Fast plasma current ramps (20 - 100 MA/sec)*
  - *High natural elongation*
  - *MHD: IRE's and tearing modes observed*

- **Initial plasmas beginning to access low TF, high β_t regime**

- *High β_t, normalized β*	$\beta_t \sim 20\%$, $\beta_N \sim 5$
- *High density*	$n_e \sim n_G$
- *High TF utilization factor*	$I_p/I_{TF} \sim 1$
- *High normalized current*	$I_N \sim 6$

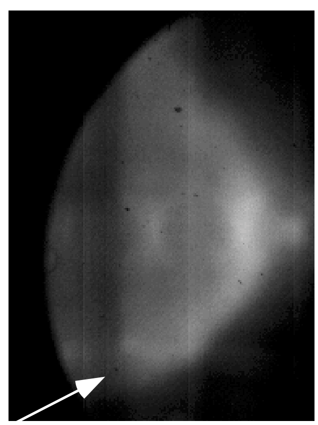
- **Full power, long pulse operation anticipated by OH completion**
  - *Pulse extended from ~ 5 to 30 ms*
  - *I_p raised from 0.1 to 0.3 MA*

Moderately High β_t Accesible in OH Plasmas



Shot 4699

R	= 0.27 m	I_P	= 0.065 MA
a	= 0.22 m	β_{pol}	= 0.6
A	= 1.22	l_i	= 0.35
κ	= 2.1	β_t	$\approx$ 0.22
I_{TF}	= 0.09 MA	β_N	= 4.9
q_a	$\approx$ 7	q_0	$\approx$ 1.5

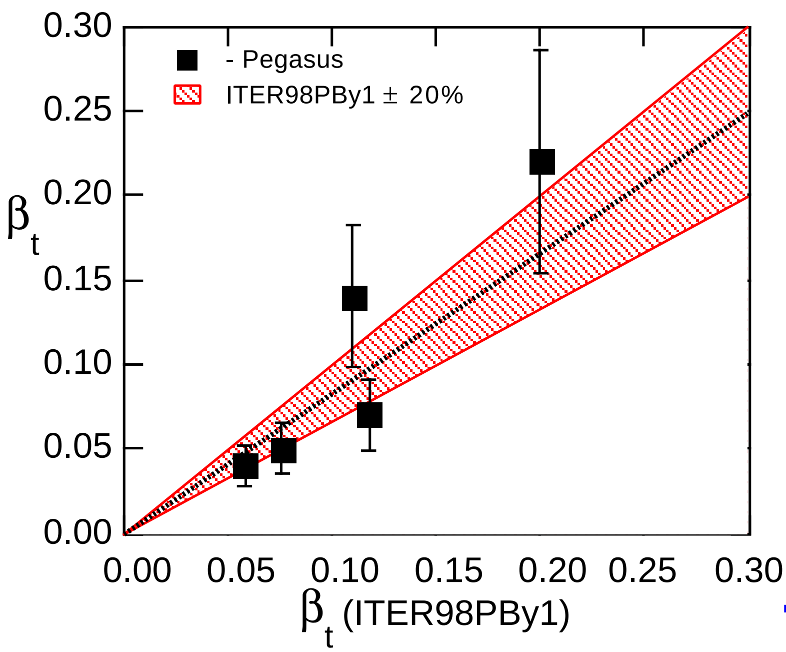


Ohmic Solenoid

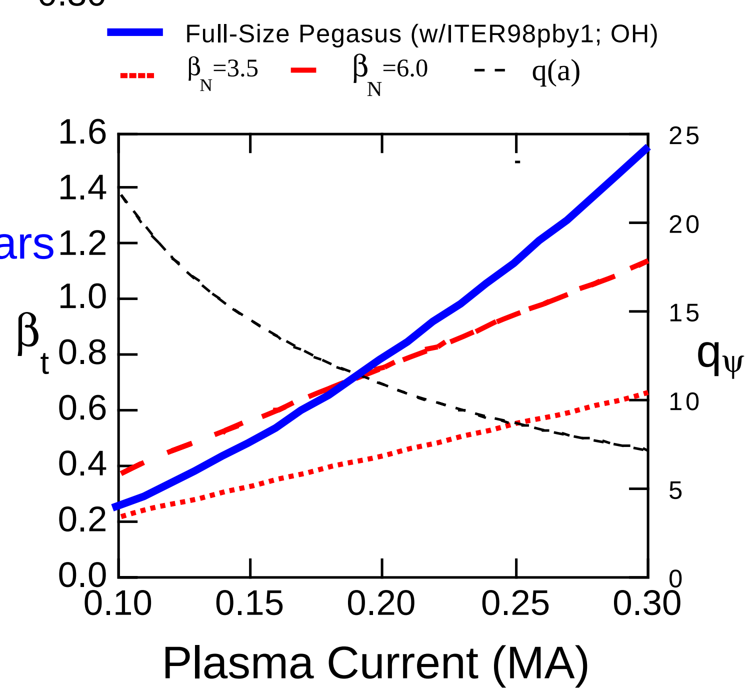
- Equilibrium reconstruction using 6-8 B_p coils & 4-6 fluxloops
- Visible image used to constrain position and size
- Density, spectroscopy and confinement consistent with fit pressure

First Results: Promising for Full-Power Operation

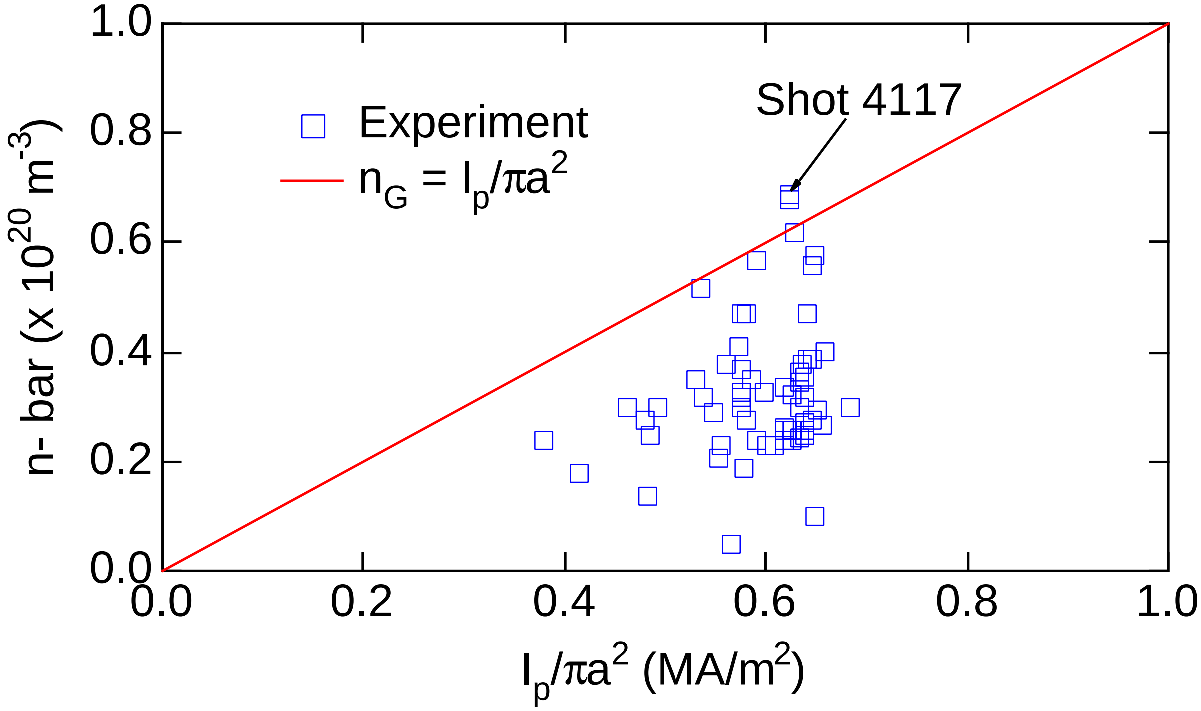
- Estimates of β_t consistent with START scaling
  - *Experiment β_t estimated from magnetic equilibrium*
    - Min. diagnostics, P_{Rad}, Z_{eff}, τ_{pulse}, etc. → large uncertainties
  - *0-D confinement model with ITER98PBy1 τ_E scaling for expected β_t*

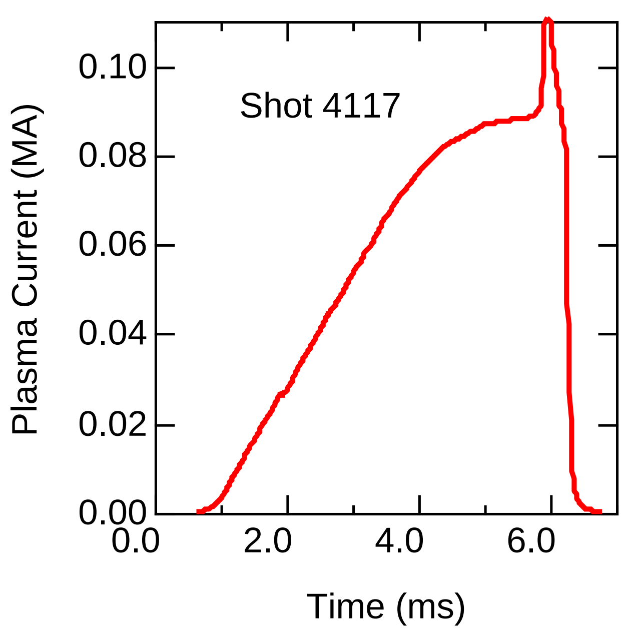


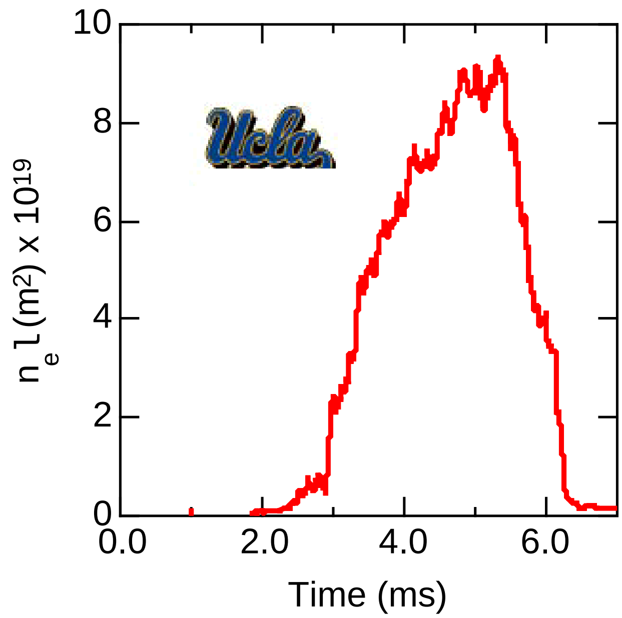
- Intereseting plasma regime appears accessible with OH only
  - *Lower collisionality and challenge stability limits with more flexible shapes via auxiliary heating*



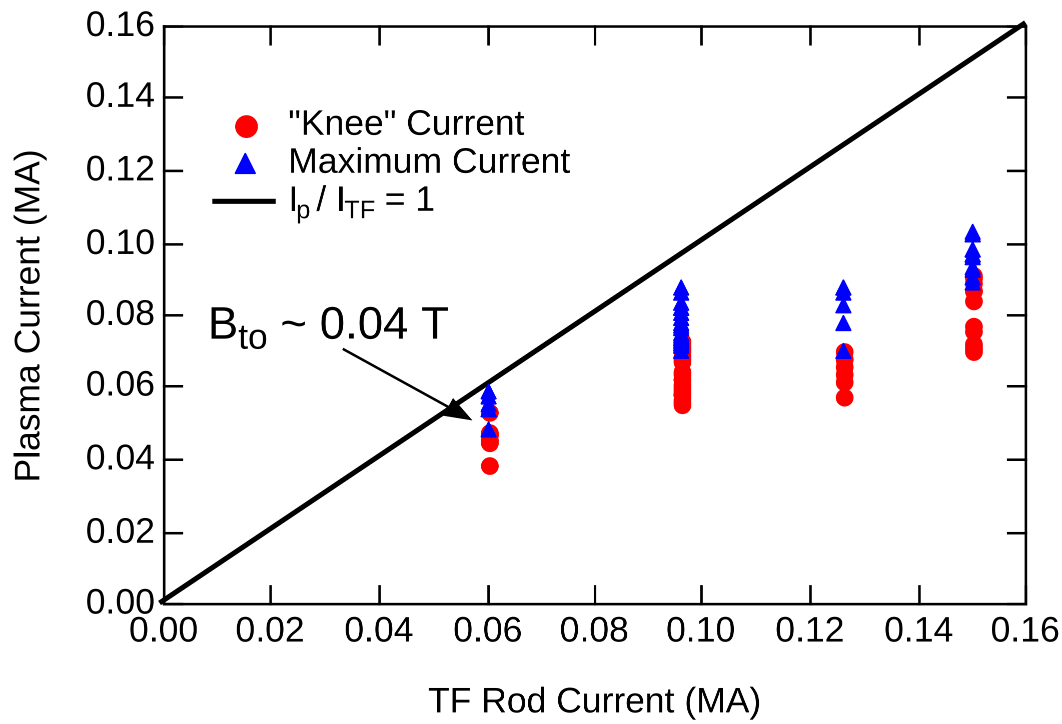
Plasma Density Approaches Greenwald Limit



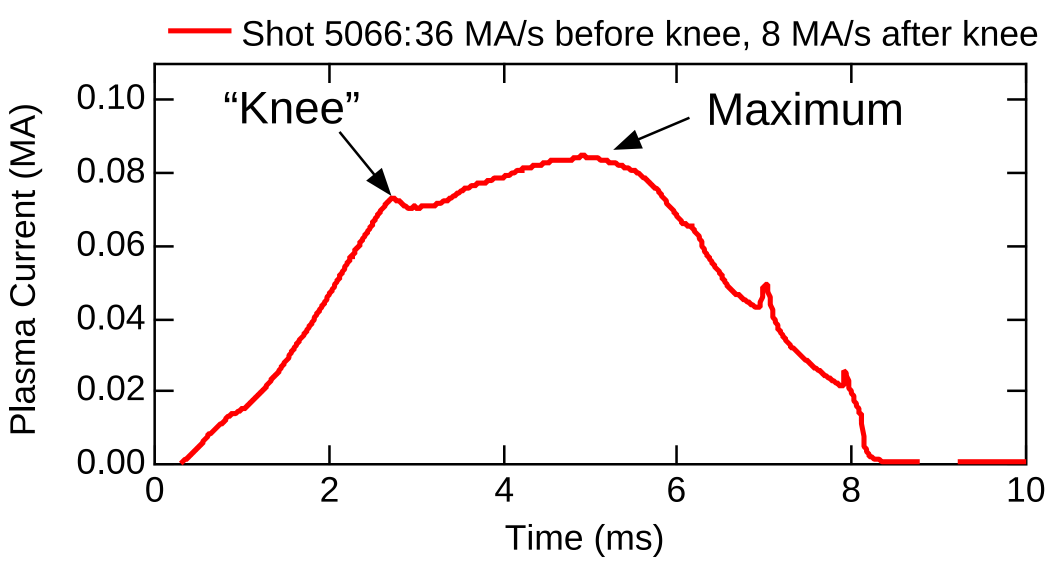




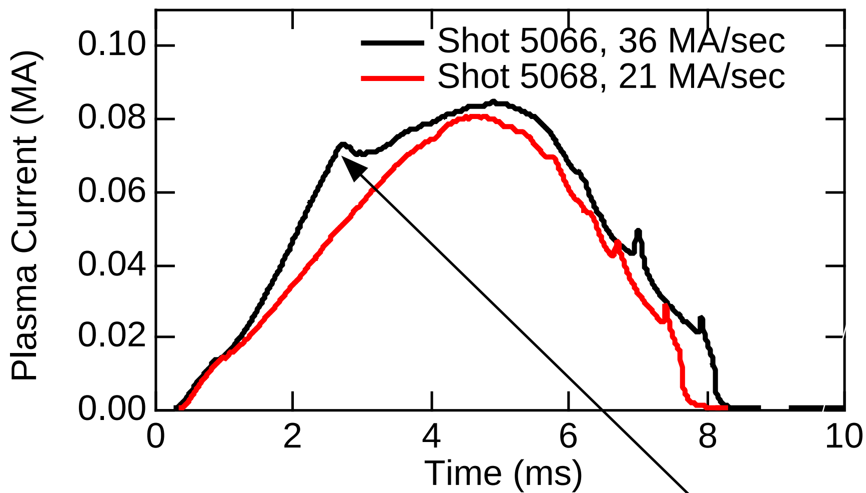
$I_p/I_{TF} \rightarrow 1$ at Lowest TF Settings



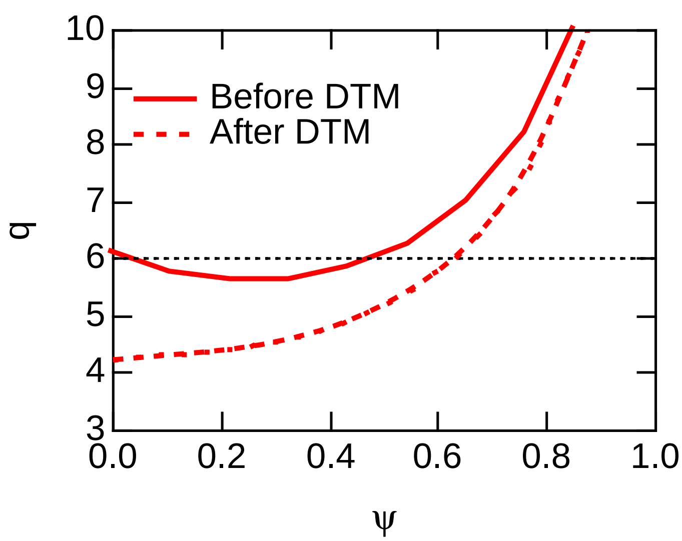
- **Present limits on I_p/I_{TF}: ramp rate and pulse length**
- **Tearing modes limit I_p ramp rate $\rightarrow$ High I_p/I_{TF} only at low TF**



Double Tearing Modes Limit Plasma Current Ramp Rate

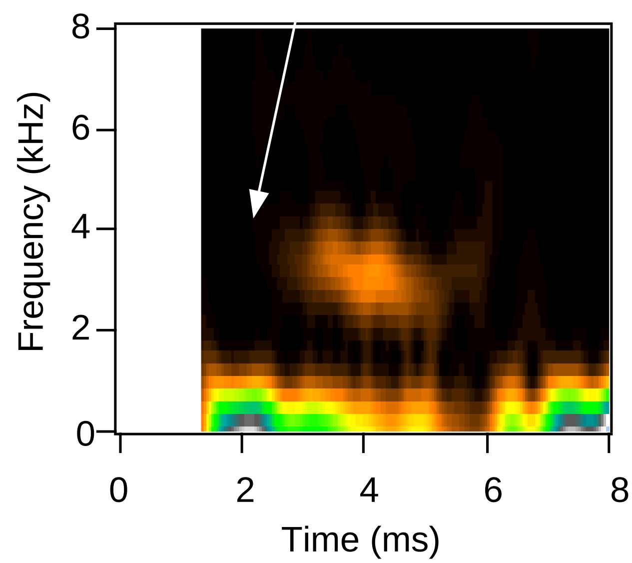


Similar events on MEDUSA identified as DTM's with internal j(r) measurements



q profile flattens and current penetrates into the core after the DTM

Shot 5066: m=2 mode after “knee” in plasma current



m = 2 activity observed on Mirnovs and interferometer

- **I_p ramps up to 30 MA/sec are stable**

PEGASUS Research Program Overview

- **Low-q/low-TF stability studies in full power OH plasmas**
  - *Full power, large OH plasma development*
  - *Low-q limits @ $A < 1.3$*
  - *Limits of I_p/I_{TF} operation*
  - *Loading and coupling tests for HHFW antenna*
  - *j(R) via SXR imaging tests*
  - *Test separatrix/divertor operation*
  - *Tests of plasma gun injection*

- **High β stability and high power RF auxiliary heating**
  - *MHD stability limits: shaping, profiles, configuration effects*
  - β_t *limits with auxiliary heating and DC TF*
  - *Confinement evaluation*

- **Exploration of high β stability at high and low edge q**
  - *Kink and ballooning stability limits*
  - *Tokamak/spheromak stability boundary with TF rampdown*
  - *Tests of EBW heating*

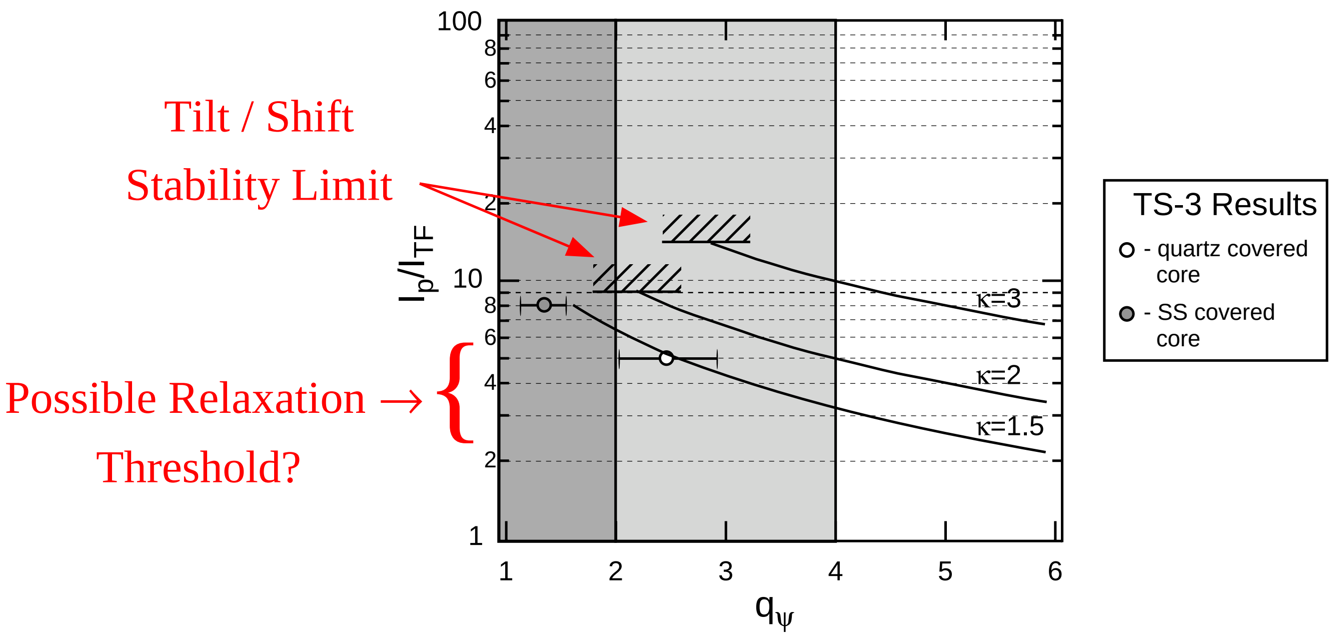
- **Status: Feb 2000**
  - *Ending maintenance period: OH power supply completion*
  - *Operations expected early March*

Investigate Tokamak-Spheromak Transition

- **Determine limit of low TF operation**
  - *As TF → 0, a transition from a stable tokamak configuration to a unstable spheromak-like plasma is expected*
  - *This transition defines the lower limit of B_t*
  - *Explore transition behavior with geometry, j(R), β, etc.*

- **Taylor relaxation may occur at lower I_p/I_{TF}**
  - *$\lambda a > 2.4$ ($\lambda = j_{||}/B_{tot}$) suggests the onset of relaxation and/or increased MHD in PEGASUS for $I_p/I_{TF} \geq 2$*
  - *The above relation assumes a cylindrical geometry - torodicity may increase the I_p/I_{TF} limit for PEGASUS*

- **PEGASUS expected to be tilt/shift stable at relaxation threshold**

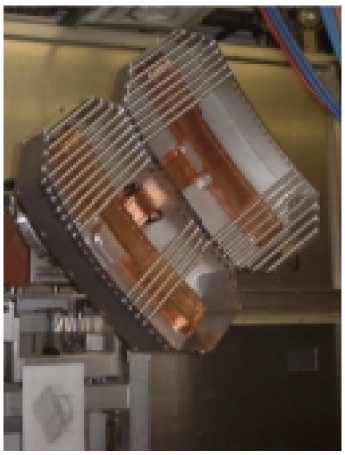


- **Takes advantage of new, low-inductance TF centerstack**

Development Activities Continuing

- **OH power supply development near completion**
  - *Step-down transformer for impedance matching and double-swing*
  - *Longer pulse, more flexible waveform control*

- **RF heating system development continuing**



  - *1-2 MW HHFW heating system*
  - *First-generation antenna fabricated; install Spring 2000*
  - *0.5 MW tested into dummy load*

- **Internal hardware upgrades due during RF install**
  - *More complete centerstack protection and upper/lower limiters*
  - *Increased coverage with magnetics diagnostics*

- **Next-generation centerstack in fabrication**
  - *Low inductance TF circuit*
  - *Ramp down power supply in development*

- **Advanced diagnostics in design**
  - *j(R,t) from SXR 2-D imaging and Li pellet injection (PPPL help)*
  - $T_e(t)$ *from EBW radiometer*
  - N_e *profiles from beam fluorescence*
  - *Tilt angle from Reflectometry (UCLA)*

Summary

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

- Starting to access interesting low TF, ST regime
  - $I_p = 0.1$ *MA*
  - $n_e \sim n_G$
  - $\beta_t \sim 20\%$, $\beta_N \sim 5$
  - *Startup up at 60 kA of TF rod current* ($B_{to} \sim 0.05$ *T*)
  - $I_p/I_{TF} \approx 1$, $I_N \sim 6$
  - *Completion of OH will allow for longer pulses, higher* I_p

- Near-term goals concentrate on exploration of low-TF ohmic operation
  - *High field utilization*
  - *Equilibrium and stability as A $\rightarrow$ 1*
  - *Initial RF operation*

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