Abstract

The PEGASUS Toroidal Experiment is exploring current and pressure limits in the high β_t, low-q operating space at near-unity aspect ratio. The first limit of interest is the external kink boundary that will define the accessible low-q, high I_N space. Initial operations were characterized by high β_t at very low toroidal field ($B_t \leq 0.07$ T) but were limited both by 2/1 tearing modes in the resistive, low-shear interior and by power-supply-waveform control capability. The experiment has been modified to avoid these limits with increased, time-variable TF, increased V-s, and improved position and shape control. The modifications allow for greater flexibility in q(r,t) tailoring and should provide access to the external kink boundary. Equilibrium and stability (DCON) modeling project stable equilibria approaching $I_p/I_{tf} \sim 3$ ($I_N \sim 20$). The initial campaign with the upgraded facility is focused on first suppressing the internal MHD activity and then challenging kink limits by achieving the modeled parameters.

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

Outline

- **Pegasus is a mid-size ST built to explore A $\rightarrow$ 1**

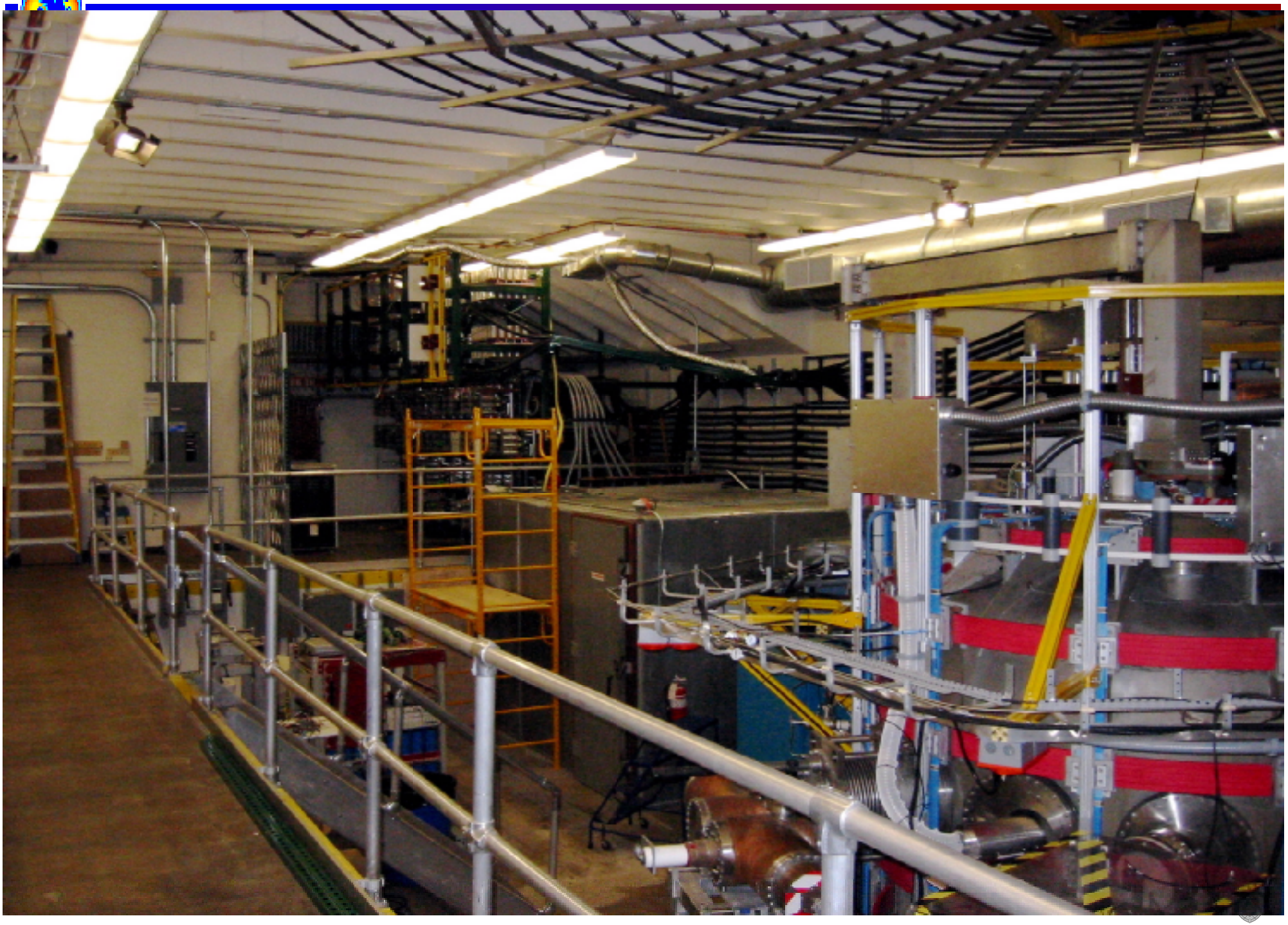
- **Commissioning of new facility began May 2004**

  - Facility rebuild almost complete
  - Full PF and TF systems commissioned
  - Low power OH ops began
    - *Divertor PS used on OH coils for systems shakedown and low power ops (limited V_{loop} and V-sec)*
  - Full power OH ops to begin winter 2004

- **Ops focused on internal mode suppression in prep for high I_N campaigns**

  - New capabilities exploited to overcome I_p/I_{tf} ~ 1 limit
    - *Full OH flux, non-inductive start-up, higher TF(t), and variable PF capabilities used*
    - *Goal: suppress mode and access low-q operational space*
  - High I_N campaigns planned to prelude high-β_t mission of PEGASUS
    - *Access to I_p/I_{tf} ~2 modeled without ideal instabilities*
    - *I_p/I_{tf} ~3 (I_N ~ 20) modeled as upper limit to field utilization*

Competely Rebuilt PEGASUS Facility



Mission: Explore Plasma Limits as A→1

PEGASUS is 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

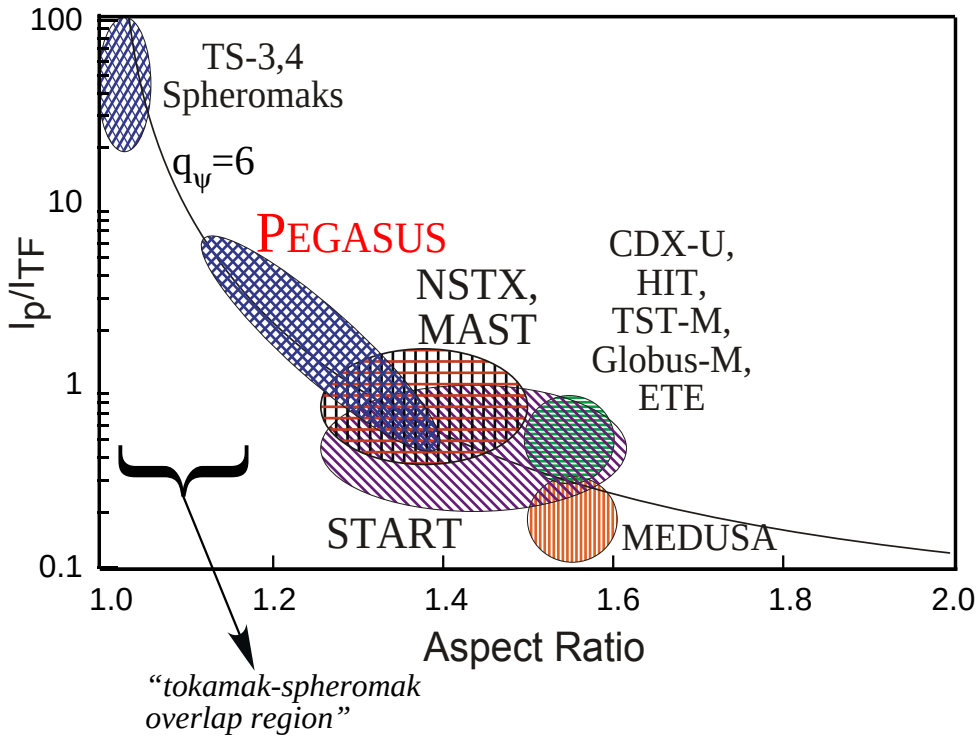
PEGASUS Goals

- Stability and confinement at high I_p/I_{TF}
  - *Extension of tokamak studies*
- Limits on β_t and I_p/I_{TF} (kink) as A→1
  - *Overlap between the tokamak and the spheromak*

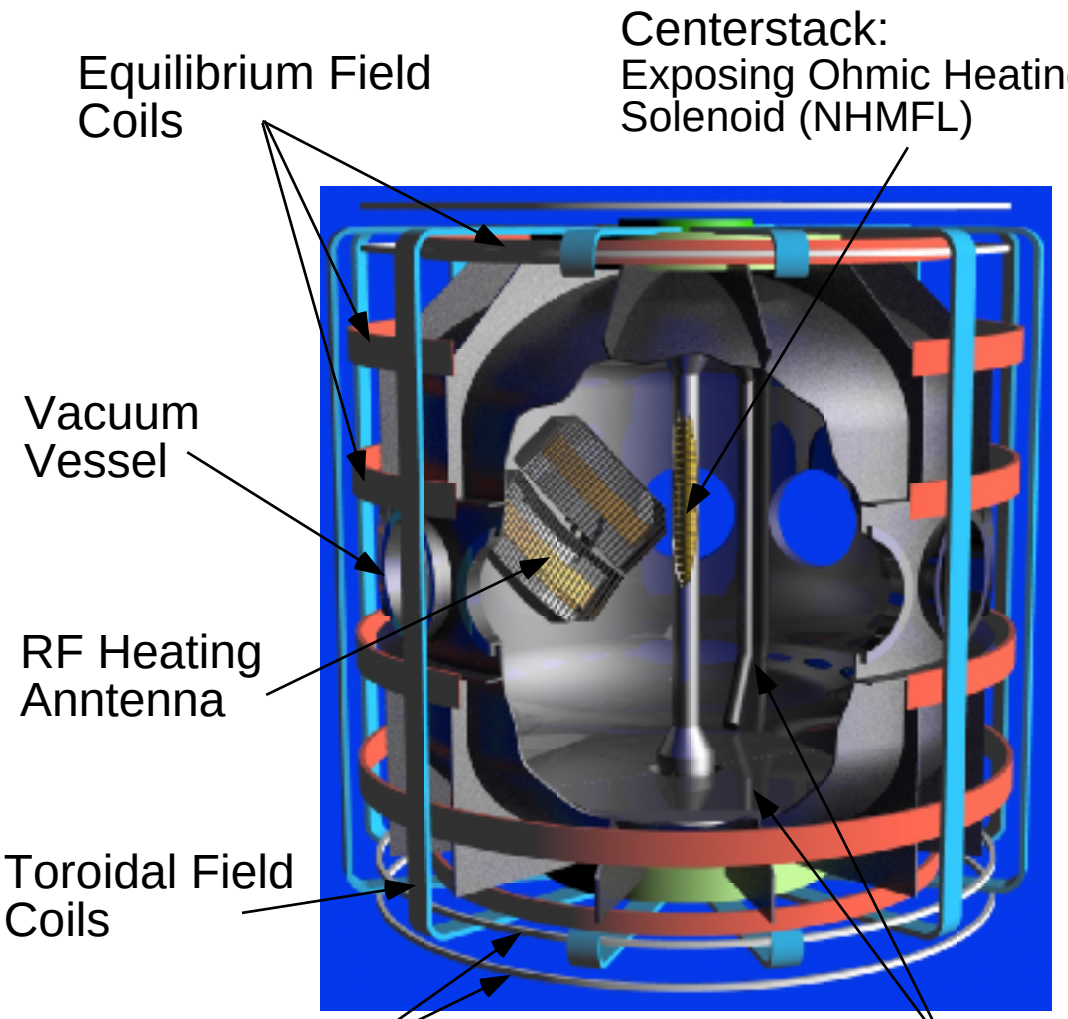
Future Emphases

- Support ST movement to next stage
  - *EBW tests for heating and CD (w/PPPL)*
  - *Noninductive startup techniques*
  - *Novel divertor designs (w/UTexas)*
  - *CT fueling tests (w/UCD)*
  - *High pressure gas puff for deep fueling*
  - *Diagnostics*

I_p/I_{tf} → figure of merit
for access to low-A physics



PEGASUS is a University-Scale, Mid-Sized ST

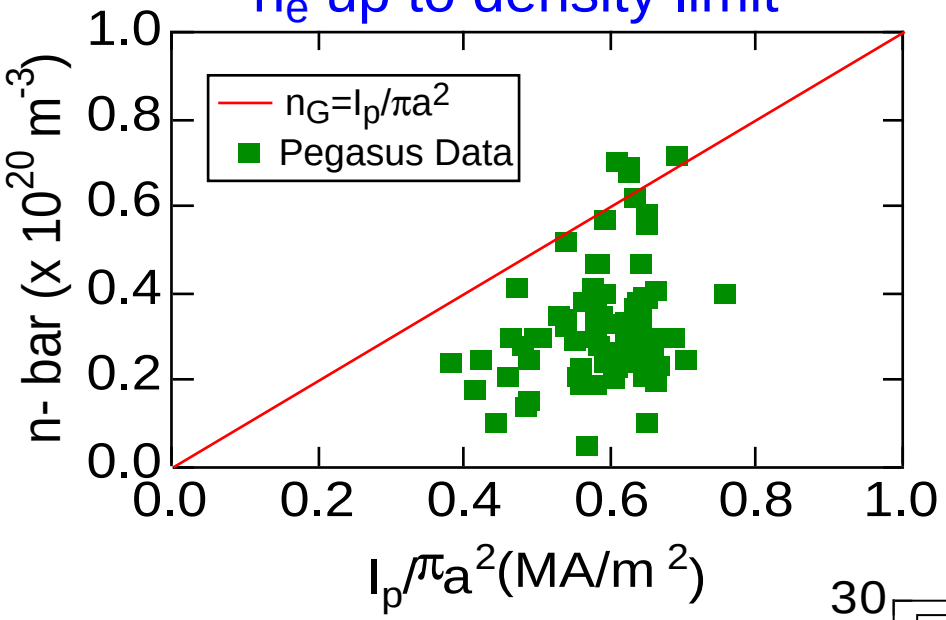


Experimental Parameters

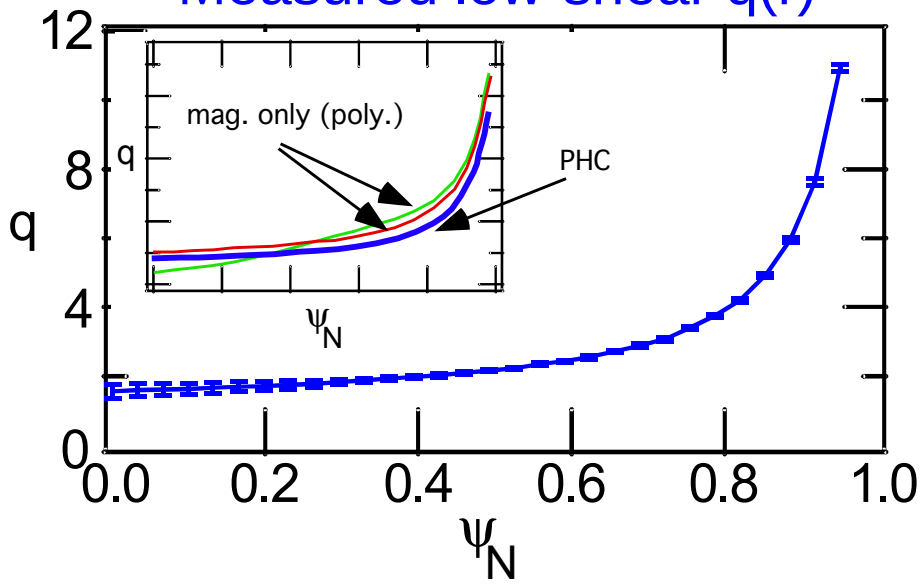
Parameter	Achieved	Phase II Goals
A	1.15-1.3	1.12-1.3
R (m)	0.2-0.38	0.2-0.45
I_p (MA)	≤ 0.16	≤ 0.30
I_N (MA/m-T)	6-8	15-20
RB_t (T-m)	≤ 0.03	≤ 0.1
κ	1.4–3.7	1.4–3.7
τ_{shot} (s)	≤ 0.02	≤ 0.05
n_e (10^{19} m^{-3})	1-5	≤ 10
β_t (%)	≤ 20	> 40
P_{HHFW} (MW)	0.2	1.0

Phase-I Demonstrated Low-A Characteristics

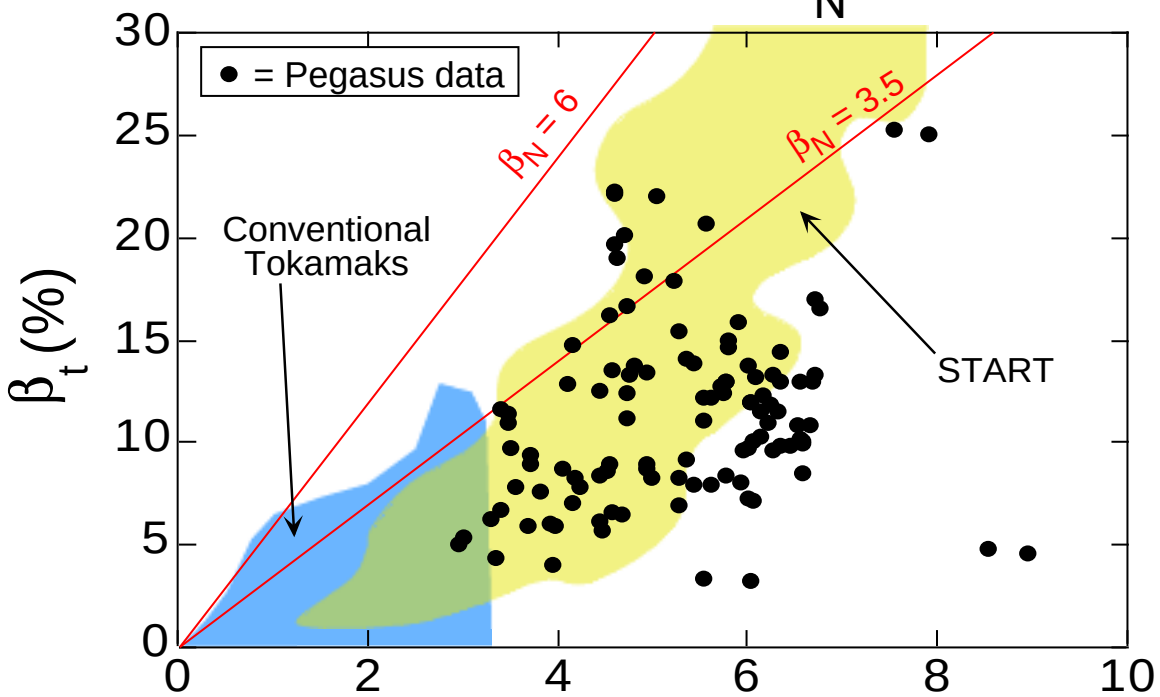
$\overline{n_e}$ up to density limit



Measured low-shear q(r)

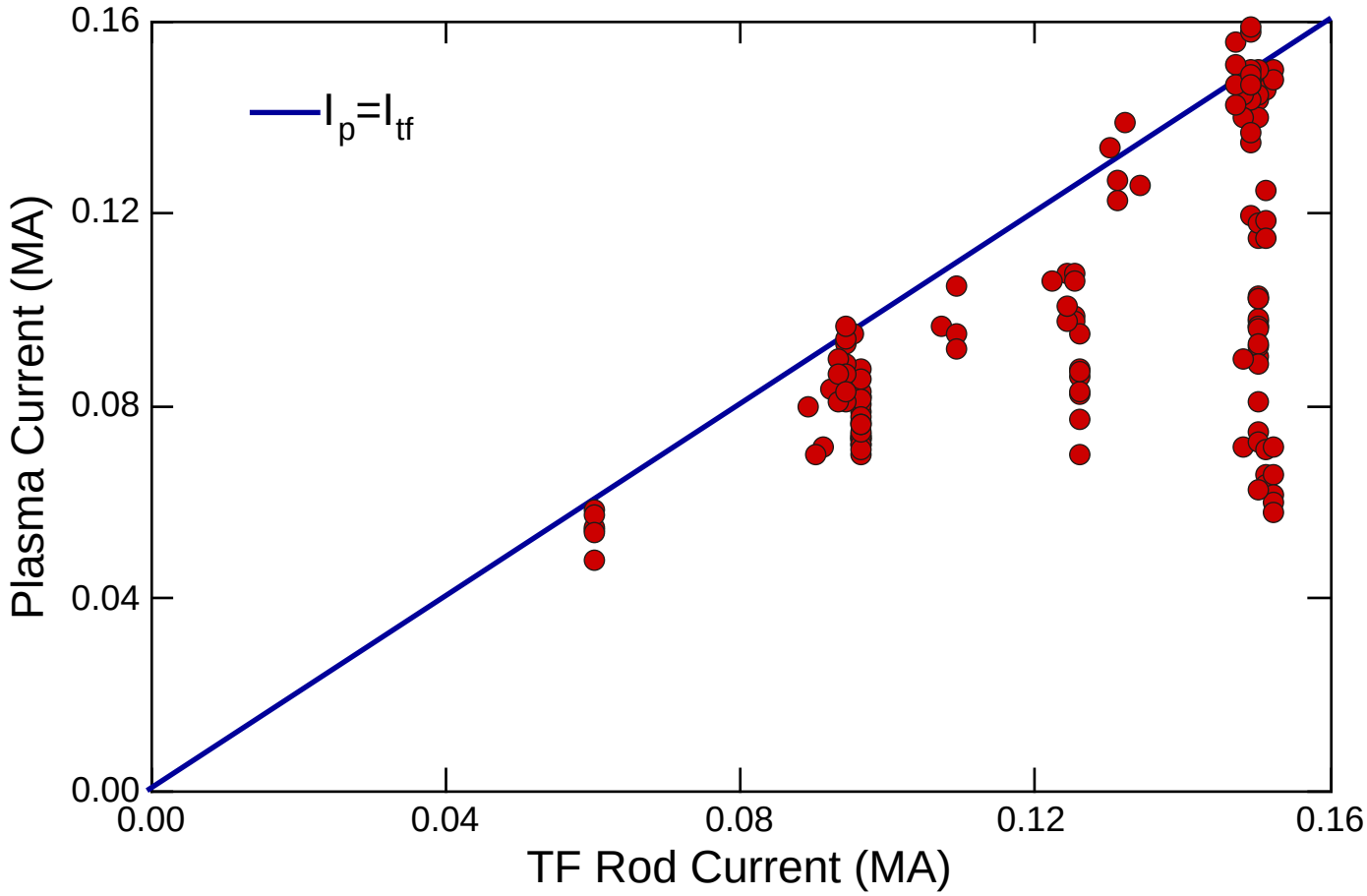


Low-field, OH-only discharges → high I_N & β_t



Phase-I, Toroidal Field Utilization Exhibited a “Soft Limit”

- Maximum $I_p \approx I_{TF}$
- Soft limit due to 2 factors:
  - *Large internal tearing modes*
  - *Reduced V-sec as TF decreases*



Two Factors Contributed to Phase-I Soft Limit

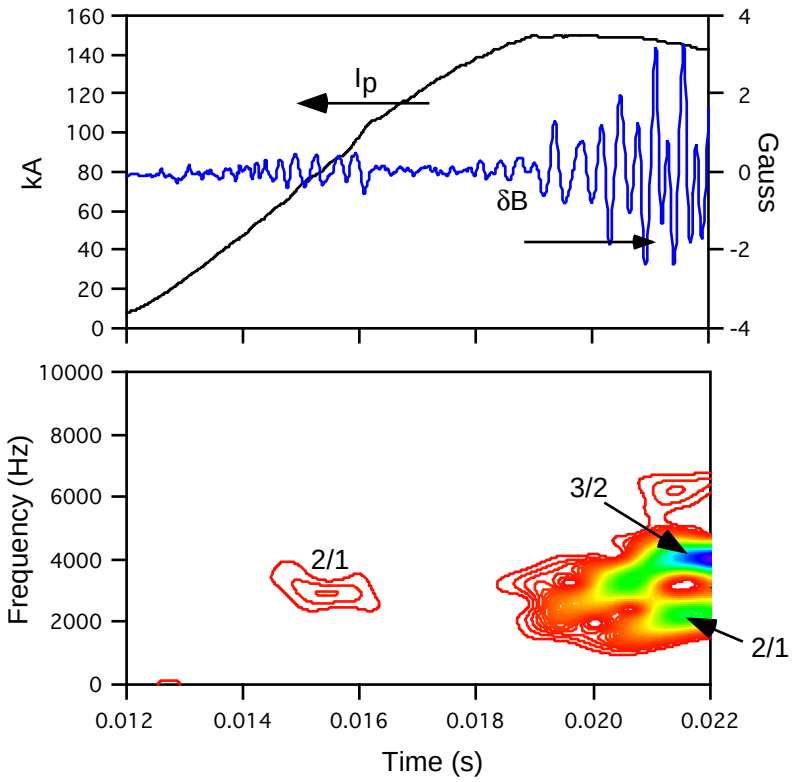
Large resistive MHD instabilities degraded plasma as TF ↓

- low B_t and fast $dI_p/dt \rightarrow$ early appearance of low-order q=m/n
  - *fixed sine-wave loop voltage*
- high resistivity early
- ultra-low A $\rightarrow$ low central shear

$\Rightarrow$ Result: rapid growth of tearing modes and large saturated island widths

- *Most common modes: m/n=2/1, 3/2*
- *Leads to decreased C_E, I_p*

- $I_p/I_{TF} \approx 1 \Rightarrow q_0 \approx 1.5$ - 2



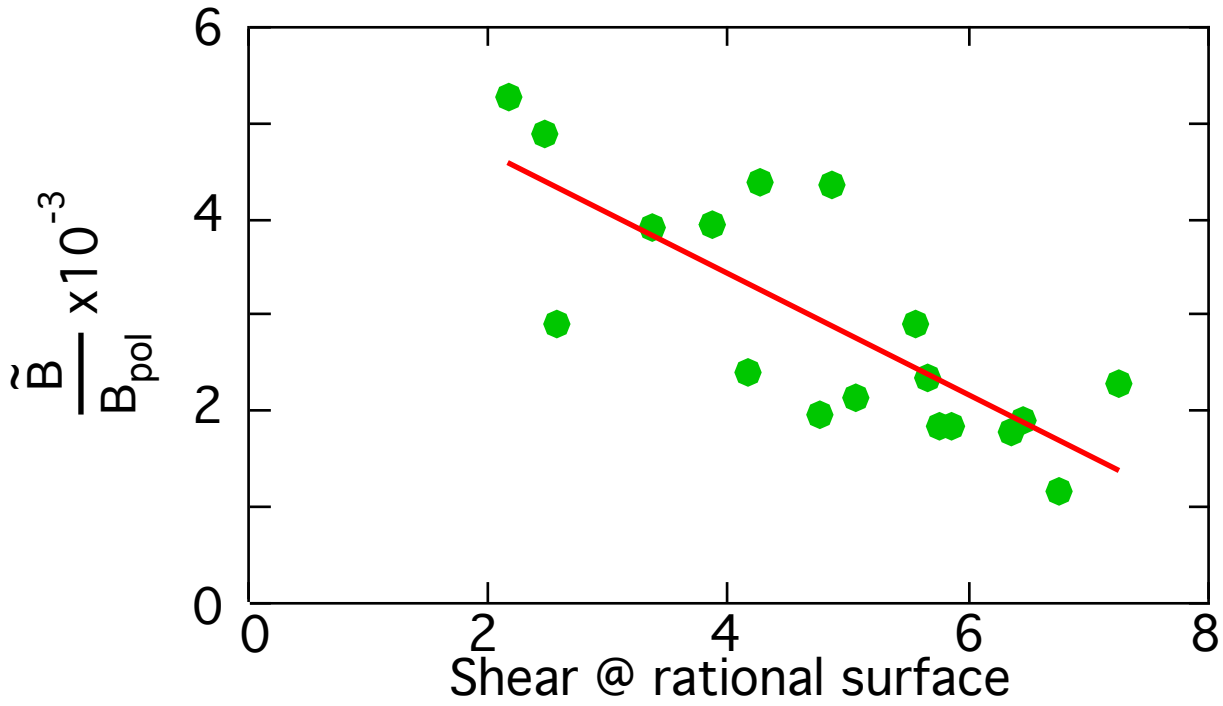
Reduced effective Volt-seconds as TF ↓

- reduced toroidal field $\rightarrow$ delayed startup
- delayed startup + fixed sine V_{loop} waveform $\rightarrow$ reduced effective V-s

Manipulation of Phase-I q(r) Reduced Mode Amplitude

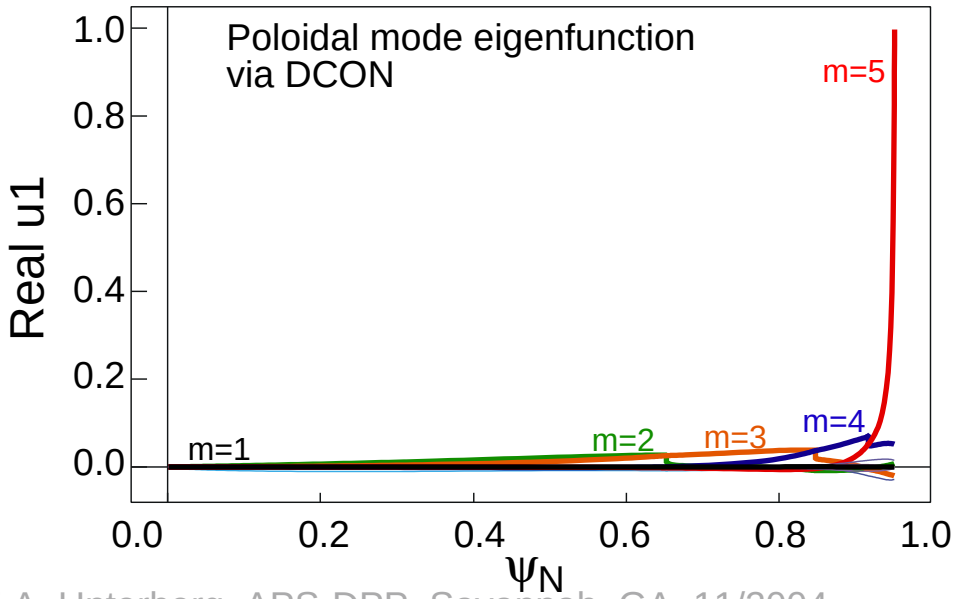
- Discharge tailoring → plasmas with reduced MHD activity
  - Increased W, I_p
- Increased shear, increased q_0 ⇒ delay tearing onset
- MHD amplitude decreased with increasing shear

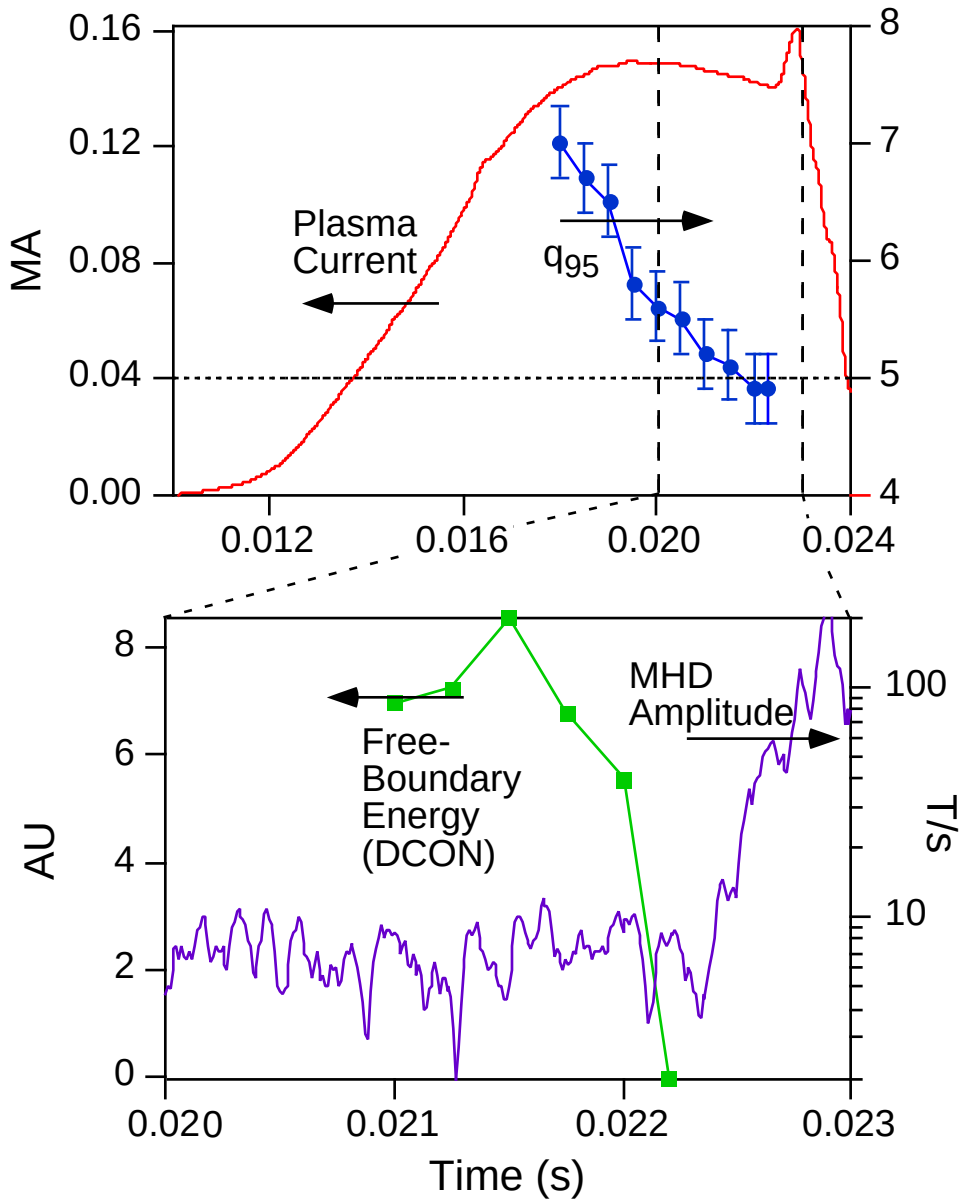
⇒ Access higher toroidal field utilization via higher q_0, T_e, shear



Phase-I Observed a High q_{95} External Kink Limit

- High I_p plasmas often disrupted
- q_{95} = 5 observed preceding disruption
  - ℓ_i=0.5 at this time
- DCON analysis ⇒ unstable to n=1 external kink
  - m=5 most unstable mode
- Consistent with theory expectation





Upgrades Almost Complete for All Coil Sets

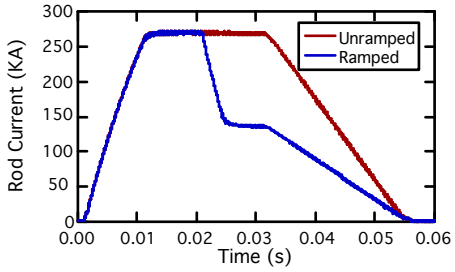
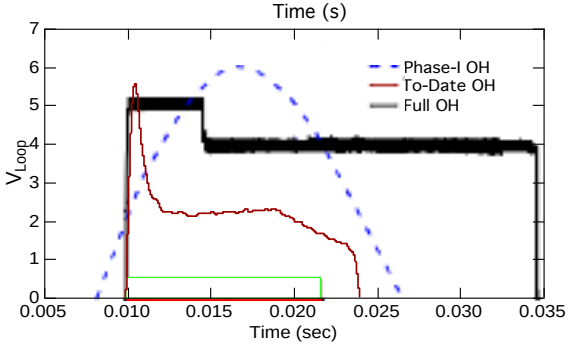
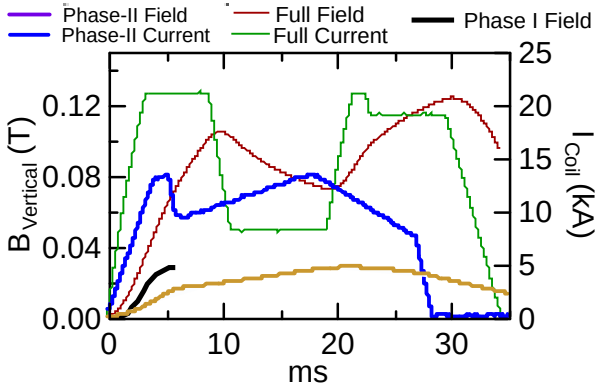
System	Phase I	Phase II	Example Waveform
Toroidal Field	• 60 turns • Quasi-DC • 150 kA-t max	• 12 turns • Fast time-variable • 450 kA-t max	
Ohmic Heating	• Half-sine Waveform • ±40 KA	• Programmable Waveform • ±50 KA	
Equilibrium Field	• Monolithic coil set • 2 Resonant banks • Waveform constrained by startup concerns • No divertor	• 5 Independent coils • Programmability • Evolution free from startup constraints • Divertor installed	

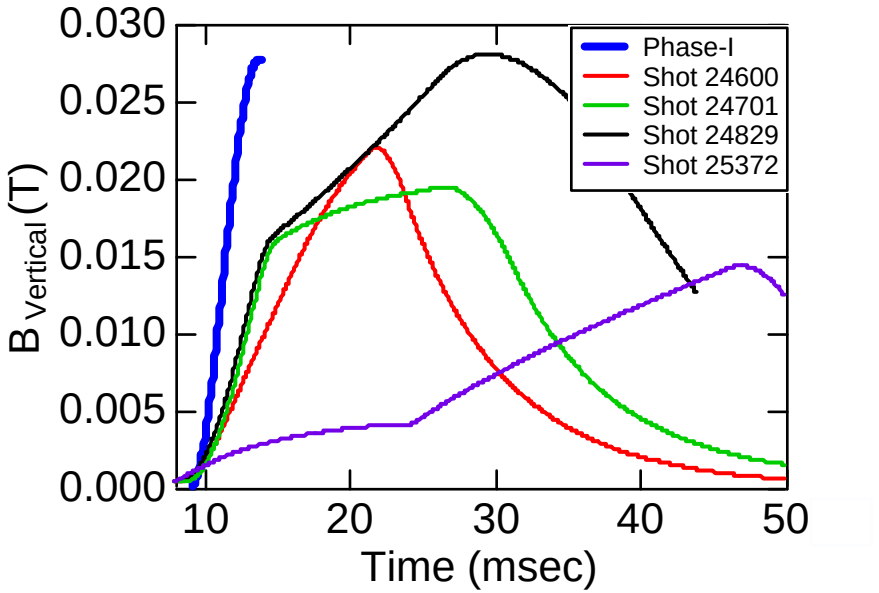


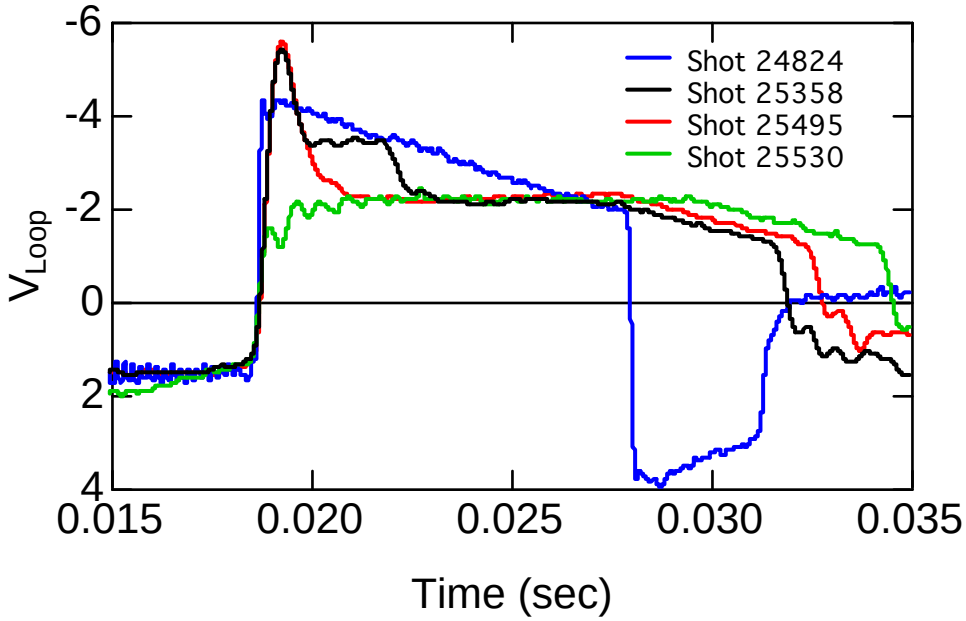
ABB IGCT
2.8kV@4kA
Steady-State
~ 50 cm long

- PS use IGBT and IGCT solid-state high power switches
  - *Switches arranged in an H-bridge*
  - *Assistance from HIT-II at UWash.*
- For details see Poster PP1.019-B.T. Lewicki et al.

Phase-II Shakedown Expanded Ops Capability

- High variablity in vertical field
  - *removed limitation of Phase-I ops*
  - *allows for position/shape control*
- V_{loop} variablity
  - *Phase-I ops = half sinewave*
  - *allows for waveform control to manage V-sec*
  - *current OH flux < 30 mV-sec*
  - *final OH flux = 90 mV-sec*
- Combined capability = high experimental flexibilty





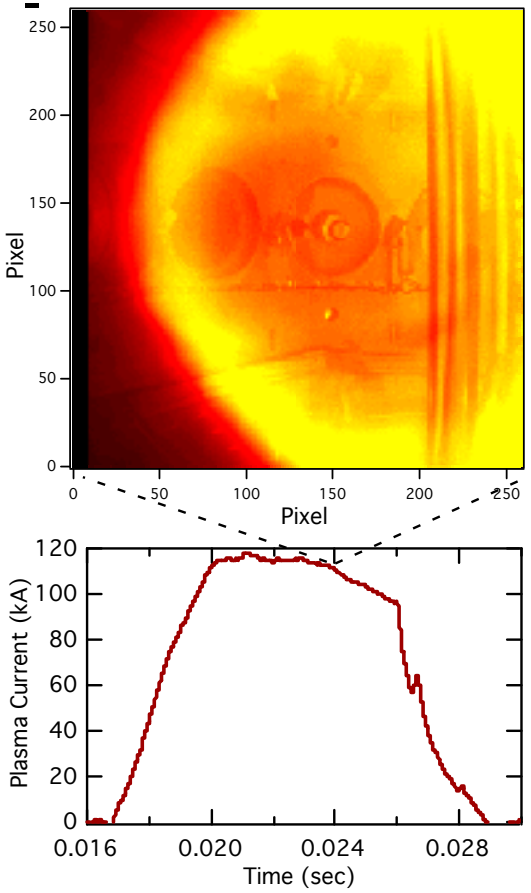
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Phase-II Capability Allows Varied Plasma Shapes

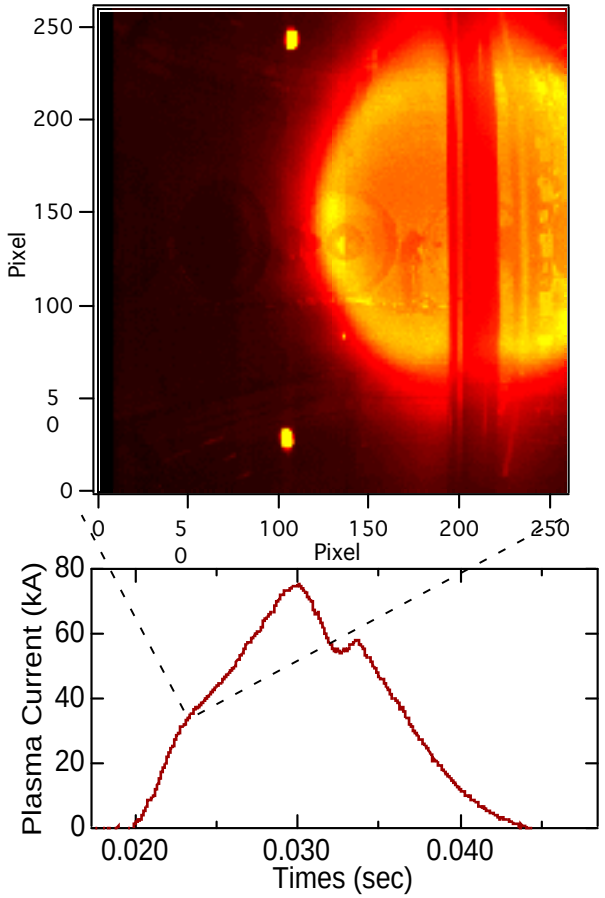
- Phase-II shakedown variability of facility creates wide-range of plasmas
  - *plasma shaping/position control demonstrated with new EF coils*
  - *variable I_p ramps demonstrated with controlled V_{loop} and V-sec*

- Plasma-run scenarios developed to exploit these capabilities

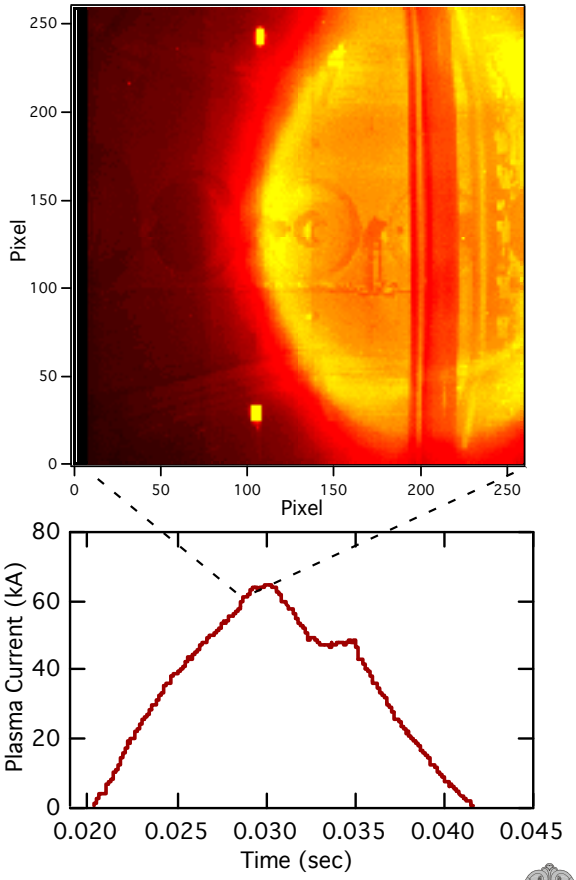
Shot 24825: Full-sized Plasma



Shot 25521: Small-a Start-up Plasma

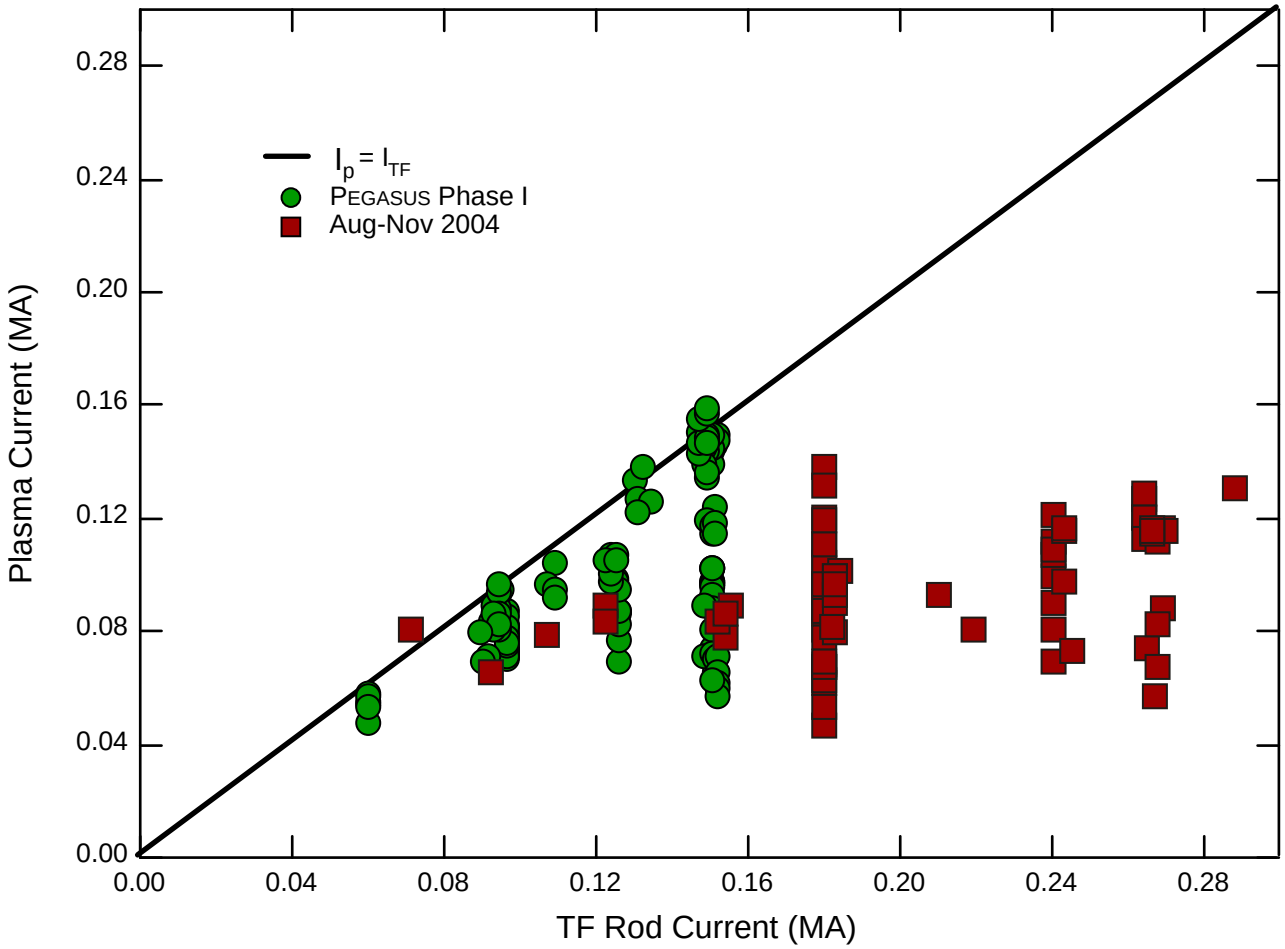


Shot 25551: High-κ Plasma



Phase-II Shakedown has Expanded Operating Space

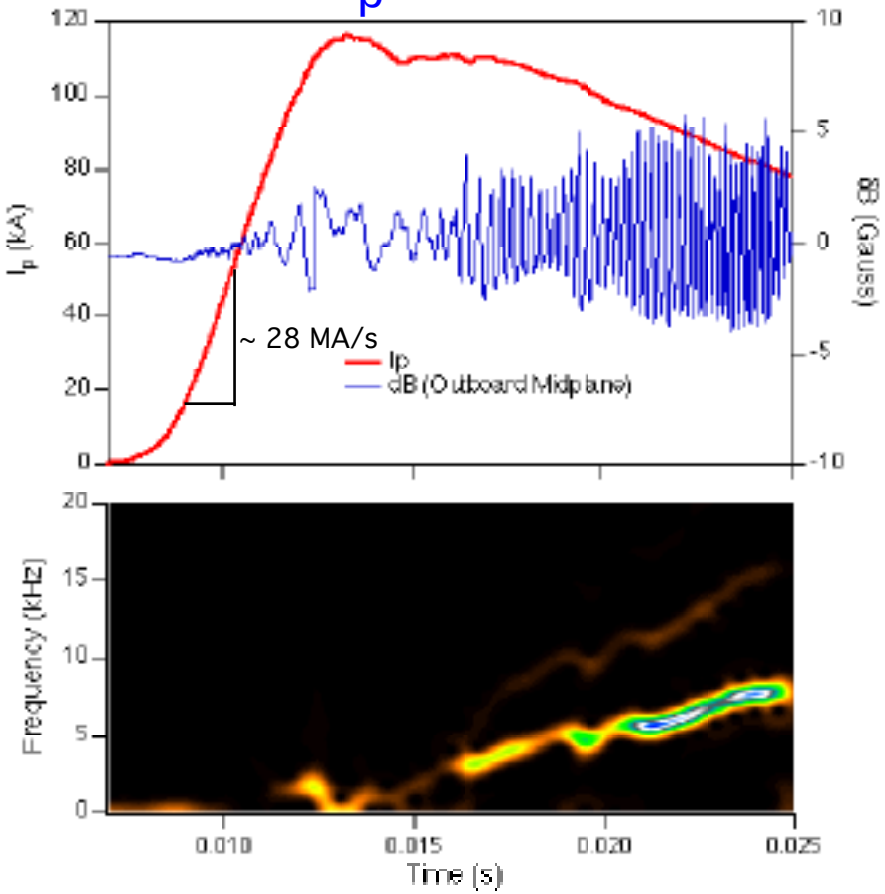
- Higher TF allows extension of ops
- Limited OH flux: Not challenging to I_p limit
  - *Full OH should allow expansion*



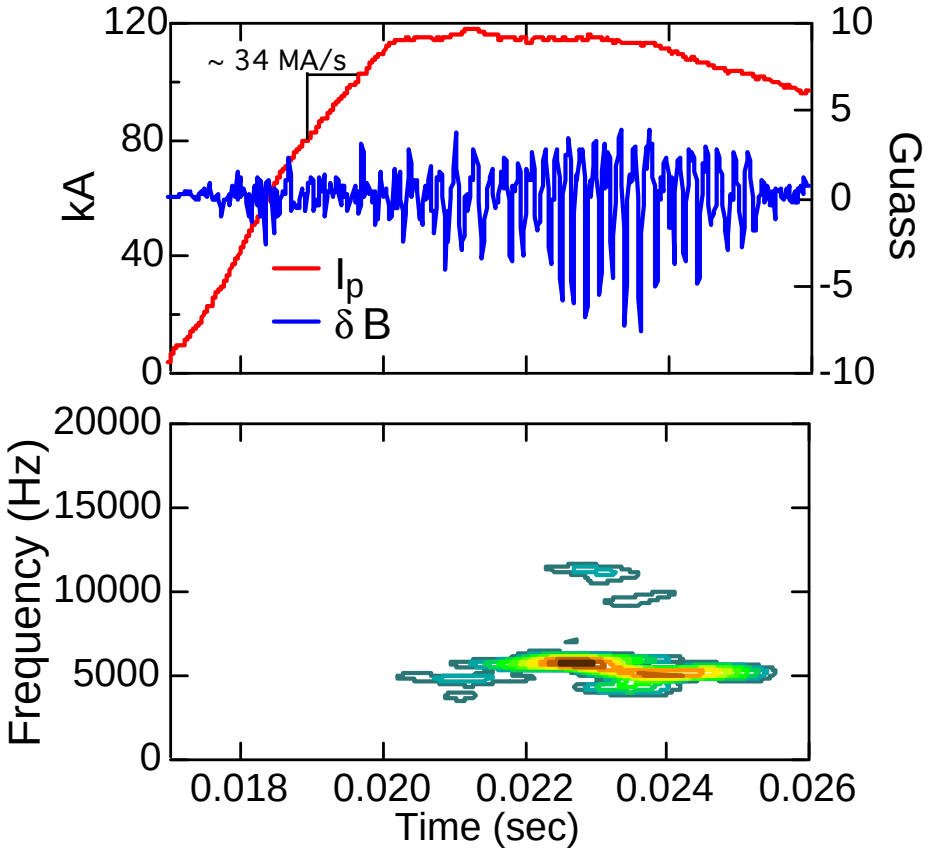
Current Ops have Similar Traits to Phase-I

- Plasma current has comparable characteristics
  - I_p *ramp-rates are similar*
  - *matching maximum* I_p
- Mode activity shows similar qualities
  - *similar frequency*
  - *similar* δB

Phase-I: I_p and mode activity

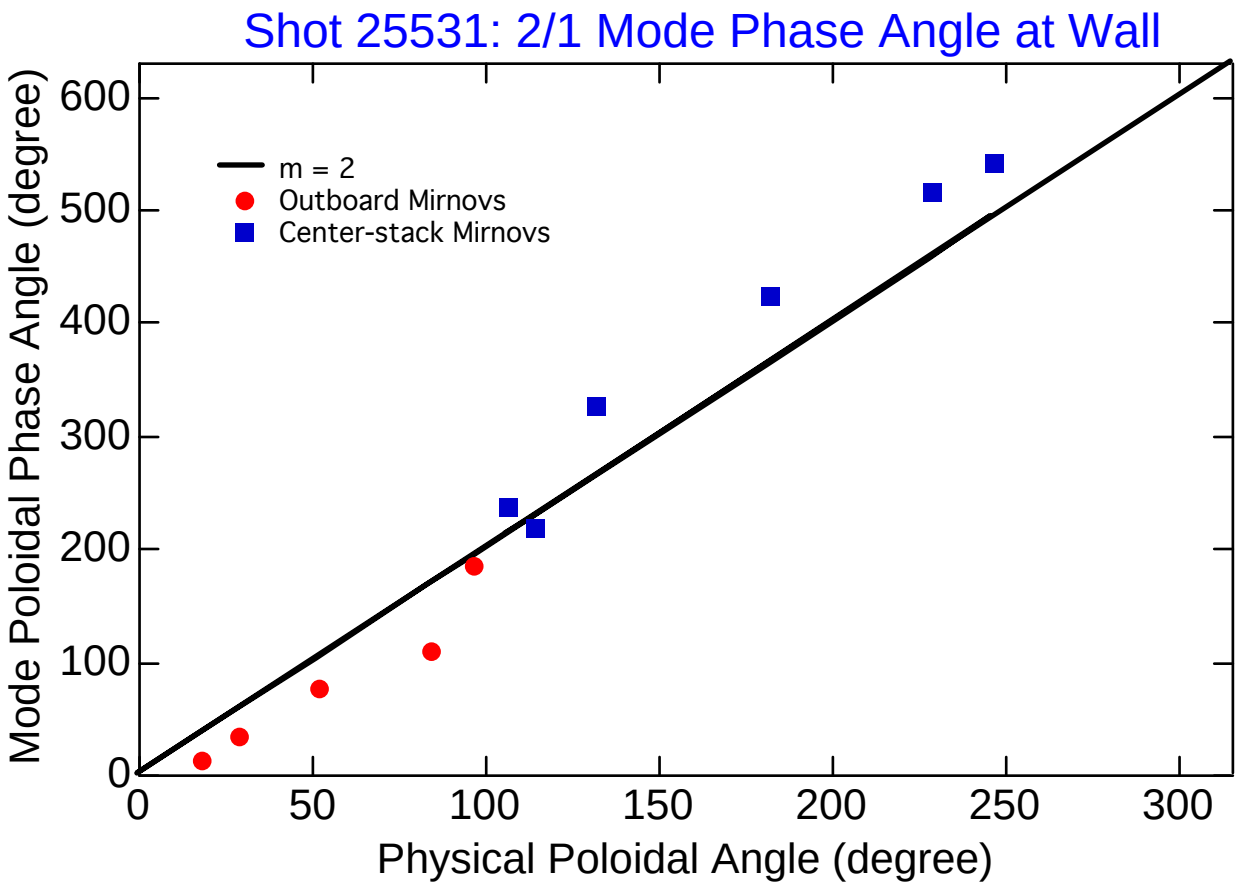


Phase-II Ops: I_p and mode activity



Mode Mitigation Experiments Have Begun

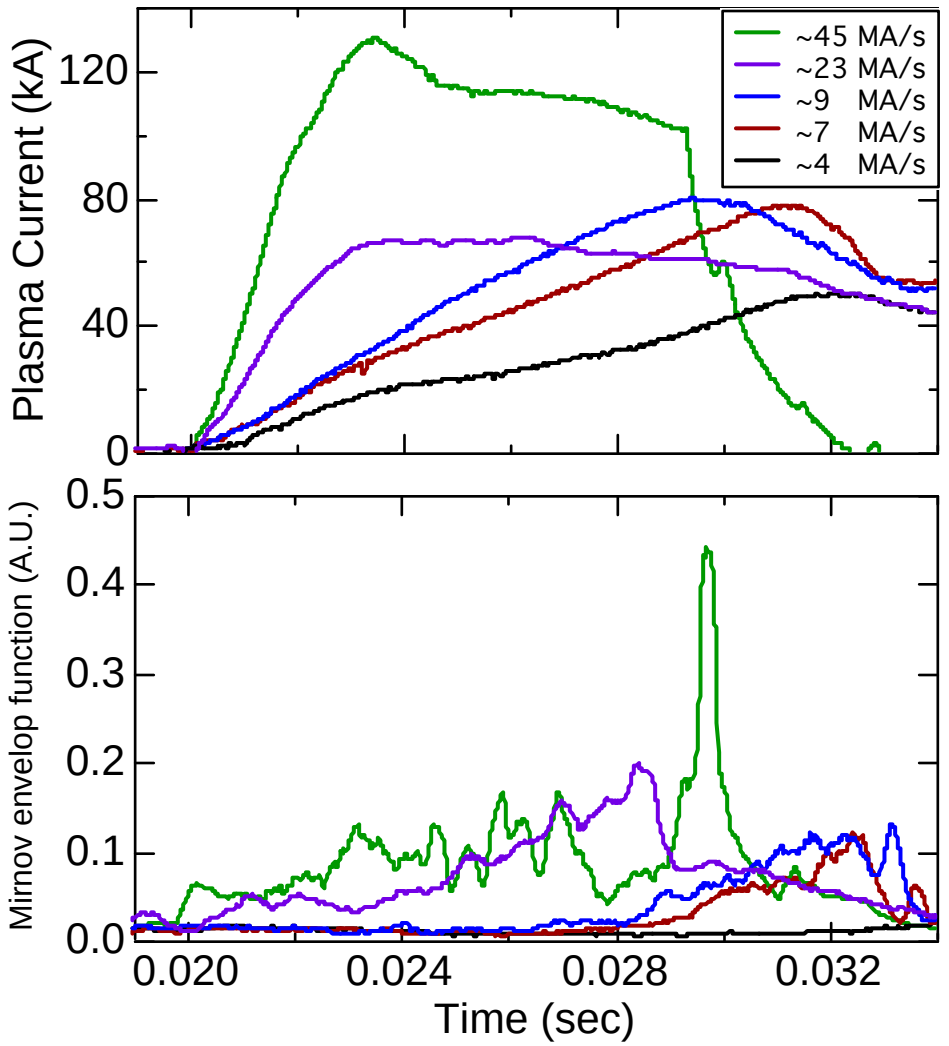
- Experiments in internal mode suppression have begun
  - *mode has again been classified as m=2/n=1*
- Initial experiments used higher TF magnitude
  - *mode seen with TF* $\Rightarrow \sim 1.75\ I_{tf}$(Phase-I)



I_p Ramp-rate Varied to Affect Current Profile

- Initial experiments to lower ramp-rate
  - *Allows current diffusion*
    $\Rightarrow$ less hollow J(r)
  - *Allows T_e to be greater before q=2 surface enters plasma*
- Ramp-rate effects mode activity
  - *Envelop function of Mirnov signal decreases with decreased ramp-rate*
- Ip ramp-rate experiment limited at present by OH PS
  - *Full OH capability will allow further I_p ramp-rate scenerio development*

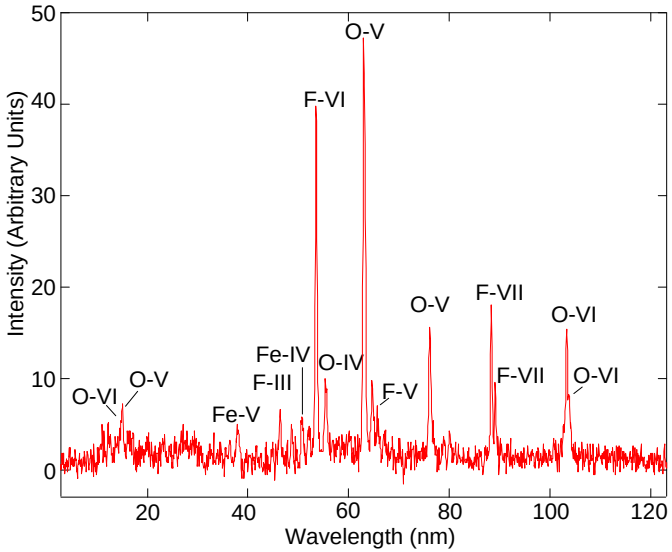
Varied I_p ramp-rates & respective envelop functions



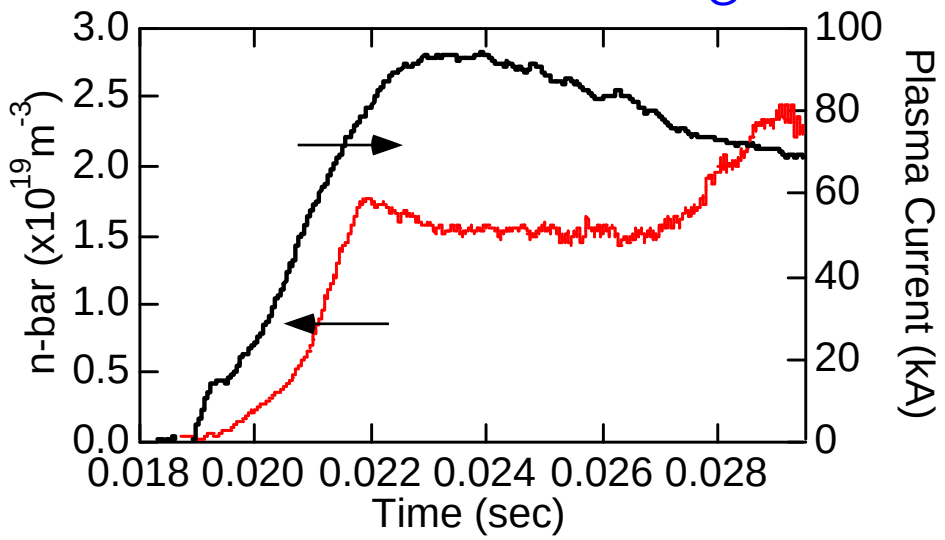
Campaign Planned with Additional Diagnostics

- 2/1 mode mitigation experiments to commence with re-commissioned diagnostics
  - *Temperature (Ross Filter & PHA) and density (IF) measurements coming online*
  - *SXR Array for internal mode activity*
- Re-commissioning already giving insight
  - *Interferometer shows low density plasmas*
  - *SPRED shows impurity content of discharges*
- For details see Poster PP1.016-M.P. Kozar et al.

SPRED: discharge impurity content



Line avg. density ~ 0.6 n_G



Near-term Experimental Plans

Finish installation of full OH PS

- Current PS limited to < 30 mV-sec
  - *allowed initial systems shakedown and IGBT development*
- Full installation will allow ~ 90 mV-sec and use IGCT technology

Begin campaign of high I_N, low-q operation

- Use final OH and plasma gun on developed MHD-quiescent discharges
- Goal is to reach $I_p/I_{tf} \sim 3$ ($I_N \sim 20$)
  - *modeled as interesting physics regime*

Develop campaign of plasma gun hand-off to OH

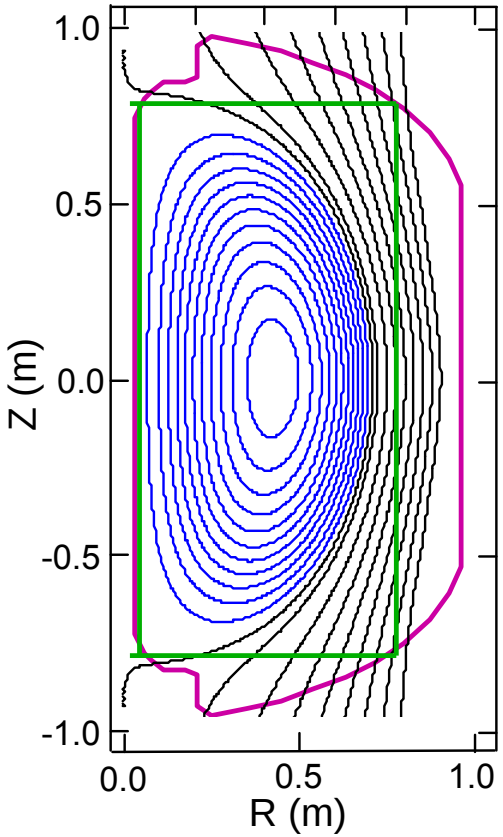
- Develop run scenario with non-inductive start-up technique
- Goal is to conserve V-sec for use later in the discharge

DCON: Stable $I_p/I_{tf} > 1$ Equilibrium

- DCON modeling used to develop interesting ops spaces for future run campaigns

- "zero"-β equilibria showing $I_p/I_{tf} = 1.93$

Flux Plot

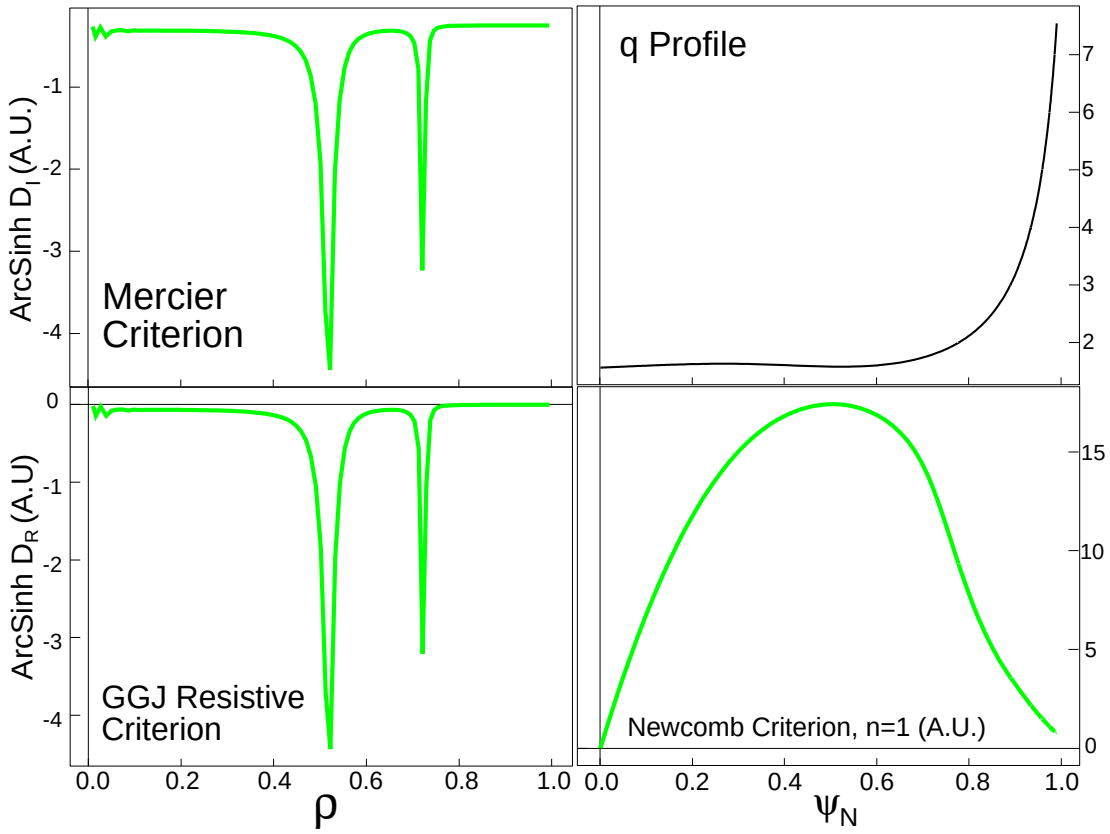


Equil. Parameters

I_p	290000
I_N	12
I_p/I_{tf}	1.93
ℓ_i	0.59
q_0	1.5
R_0	0.39
a	0.34
Elongation	2.2
q_{95}	4.8

- Predicted Stable with DCON

$D_I, D_R > 0$ => Unstable

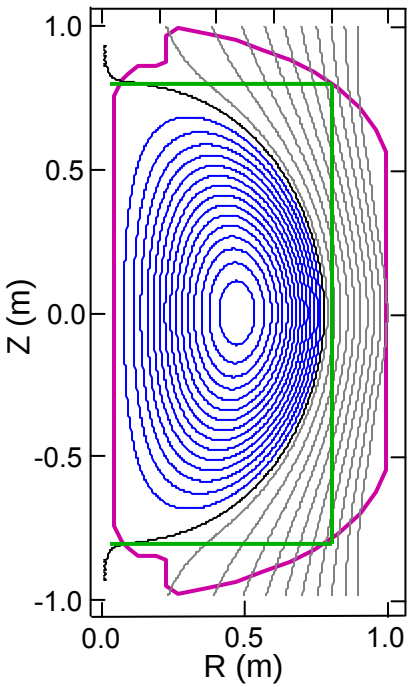


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I_p/I_{tf} ~ 3, I_N ~ 19 Modeled

- High-I_p/I_{tf}, "zero"-β Equilibria

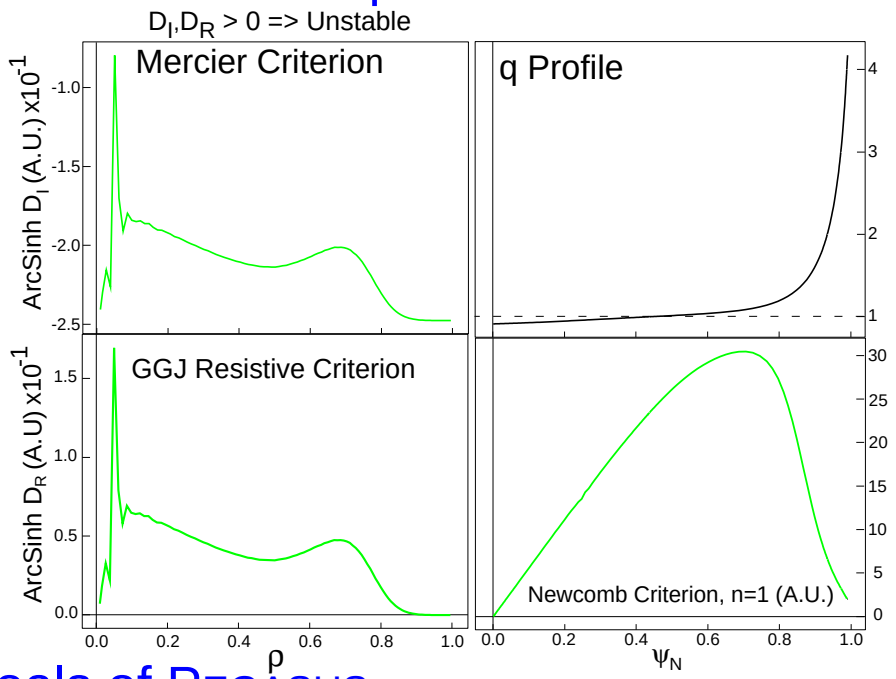
Flux Plot



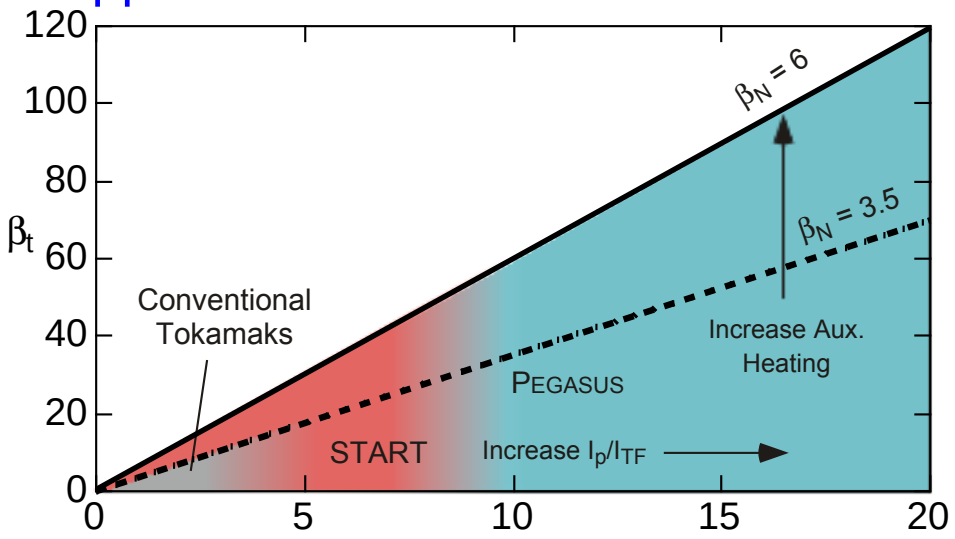
Equilibria Parameters

I_p	296000
I_{tf}	90000
l_N	18.9
l_i	0.68
q_0	0.91
R_0	0.41
a	0.36
Elongation	1.98
q_{95}	2.3

- DCON Output



- Approaches Phase II Goals of PEGASUS



Planned Upgrades to Facility

OH modifications and upgrades

- Long pulse ops
  - *full OH swing limits pulse length*
  - *pre-chill center-stack* $< 0°C$
- Active feedback control
- For details see Poster PP1.019-B.T. Lewicki et al.

Non-inductive start-up techniques

- 6-gun plasma array
  - *allows for* $I_p \sim 30$ *kA before OH flux is started*
- For details see Poster PP1.020-N.W. Eidietis et al.

Diagnostics

- 2D SXR camera for current profile
- EBW Radiometer for electron temperature
- For details see Poster PP1.016-N.W. Kozar et al.

Summary

- **PEGASUS is a mid-size ST built to explore A $\rightarrow$ 1**
- **Commissioning of new facility began May 2004**
  - Facility rebuild almost complete
  - Full PF and TF systems commissioned
    - *PF coils $\rightarrow$ 400 kA-turns*
    - *TF coil $\rightarrow$ 288 kA rod current*
  - Low power OH OPS began
    - *OH coils limited to V_{loop} ~ 4 V peak and ~ 30 mV-sec*
  - Full power OH OPS begin winter 2004
- **OPS focused on internal mode suppression in prep for high I_N campaigns**
  - New capabilities exploited to overcome I_p/I_{tf} ~ 1 limit
    - *Full OH flux, non-inductive start-up, higher TF(t), and variable PF capabilities used*
    - *Goal is to suppress mode enough to access low-q operational space*
  - High I_N campaigns planned to prelude high β_t mission of PEGASUS
    - *Access to I_p/I_{tf} ~2 modeled without ideal instabilities*
    - *I_p/I_{tf} ~3 (I_N ~ 20) modeled as upper limit to field utilization*

Reprints