Performance and Stability Limits at Near-unity Aspect Ratio in the PEGASUS Experiment*

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Long Beach, California

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This Session

- GO1 15 Sontag - Equilibrium and Stability Analysis

Poster Session - Thursday Afternoon

- RP1 33 Unterberg - Characteristics of OH Plasmas
- RP1 34 Garstka - MHD Analysis
- RP1 35 Diem - Magnetic Reconstruction & Stability
- RP1 36 Tritz - q(0) via SXR Imaging
- RP1 37 Probert - HHFW
- RP1 38 Ostrander - $T_e(0,t)$ via Multi-Color SXR
- RP1 39 Schooff - $T_e(R,t)$ via CCD/PHA
- RP1 40 Lewicki - Facility Development

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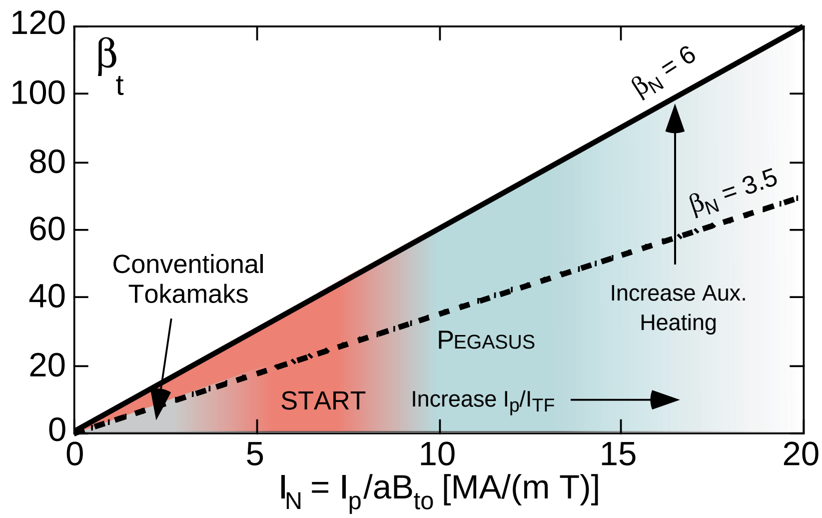
Role of the Pegasus Experiment in the Fusion Science Program

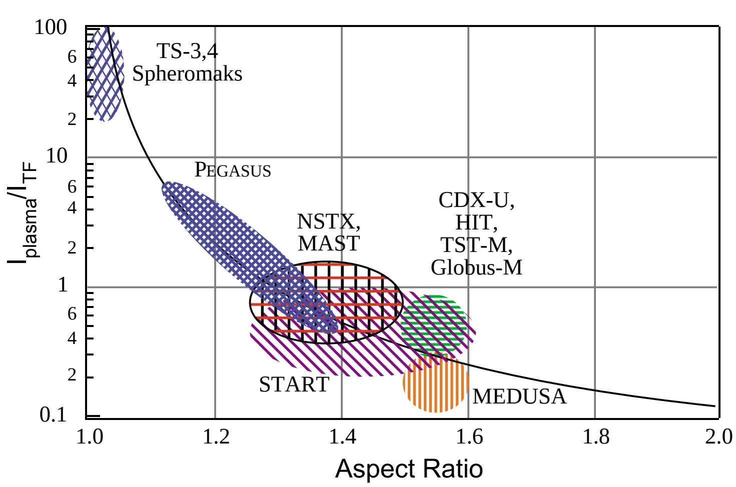
An extremely low-aspect ratio facility exploring quasi-spherical high-pressure plasmas with the goal of minimizing the central column while maintaining good confinement and stability.

- **Plasma properties in Spherical Torus as A → 1**
  - β and I_p limits, disruptivity, and confinement dependence on A, κ, etc.
  - New startup schemes (e.g., plasma gun current injection, EBW/ECH)

Extend ST stability studies to high I_N



- **Physics of A → 1 plasmas as an Alternate Concept**
  - MHD equilibrium and stability at very low TF (β ~ 1)
  - Explore RF heating and CD schemes (HHFW, EBW)



High TF utilization (I_P/I_{TF} > 3)
⇒ Tokamak-Spheromak overlap

Program Developments in 2001 Campaign

- **Developing understanding of limits of operation at very low A and low TF**
  - Gain capability to explore high-β_t, low-q_a regimes

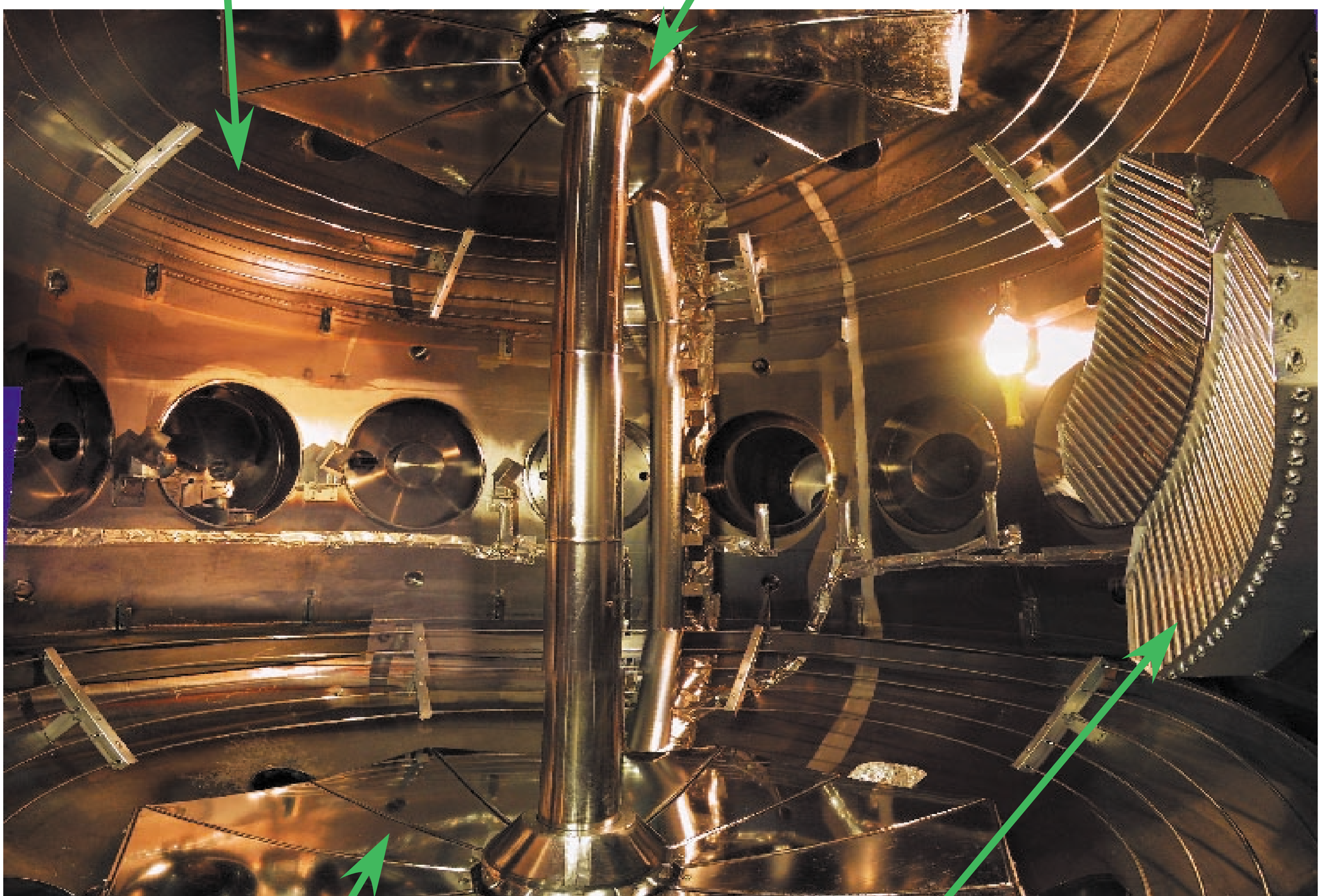
- **Facility development**
  - Increasing ohmic drive capability: I_p up to 150 kA
  - New internal hardware and pfc's
  - Diagnostics and analysis tools
  - Initial operation of HHFW heating system

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

- **Identify paths for next campaign**
  - Increased V-sec
  - High power RF heating
  - Increased B_t with fast rampdown

Facility Upgrades Installed in Major Opening in Fall/Winter 2001

- Internal diagnostics installed
  - Flux loops; B_{pol} arrays; Centerstack magnetics; New Rogowski coils



- Improved plasma facing components
  - Divertor plates
  - High-power outer limiter
  - New centerstack shield / cone structure
- HHFW and EBW antennae
  - $P_{RF\text{-}HHFW} \approx 1$ MW
  - Steerable EBW/ECH antenna

Increasing Diagnostic Capabilities Deployed

- Presently operating

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)	5000 fps	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)

- Primary analysis tools operational

Equilibrium Code	R, a, ℓ_i, β, κ, etc.
DCON	Stability analysis

- Near-future

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 chord	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 chord	$Z_{eff}(R,t)$, $N_e(R,t)$	Summer 2002
DNB		$N_e(R,t)$, $T_e(R,t)$, j(R)	Proposed
EBW Radiometer		$T_e(t)$	Proposed

PEGASUS Allows Access to Interesting Low-A Regime

- **Routine high-stress solenoid operation**

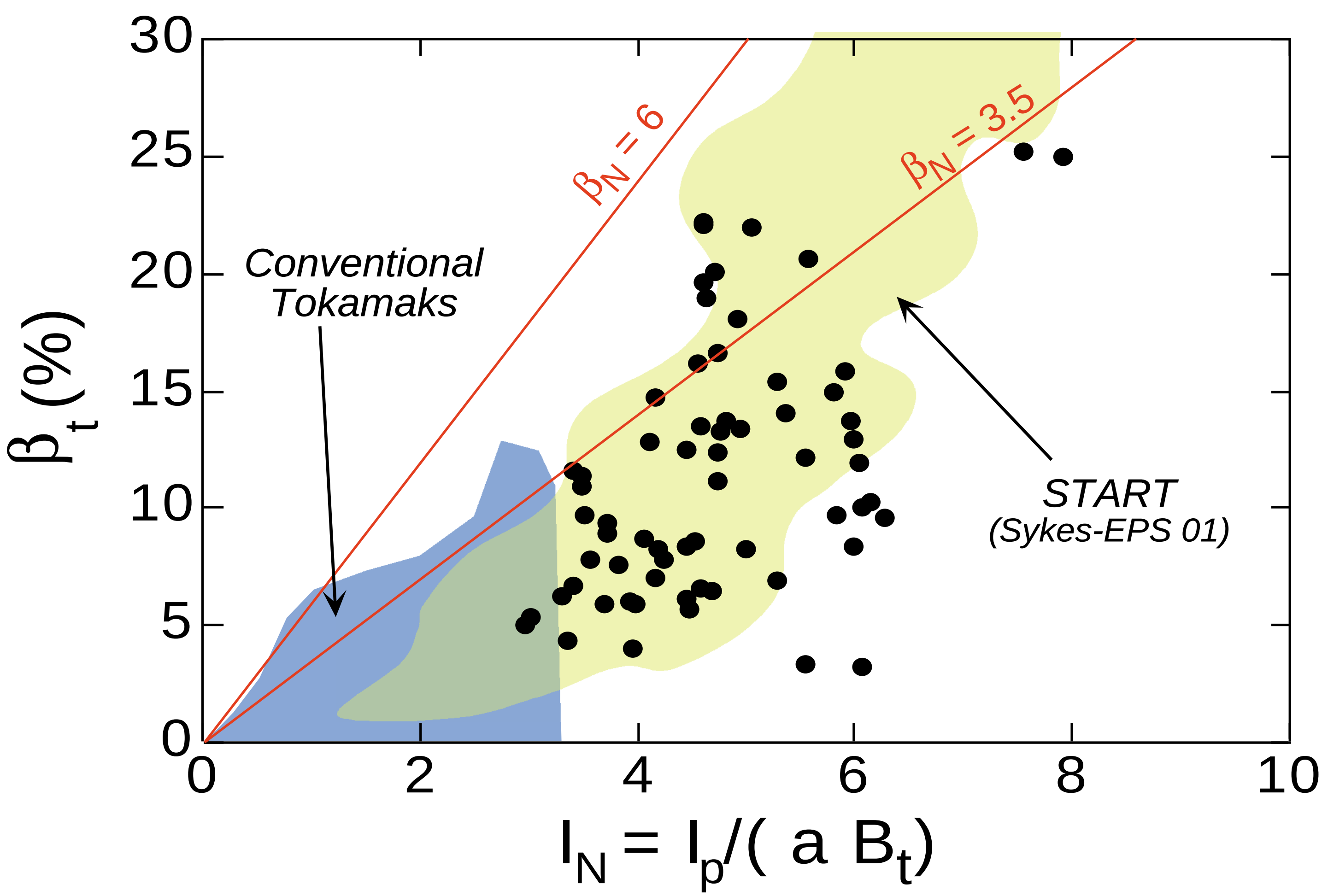
- **Startup at low B_t in presence of conducting walls**
  - Induced wall currents modeled
  - Wall currents routinely included in equilibrium runs

- **Plasmas show low-A characteristics**
  - *Low A* — $A \sim 1.16$
  - *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, double tearing modes, IREs, external kink*

- **Identification of factors hindering access to lower B_t**
  - V-sec availability
  - Large-scale MHD activity

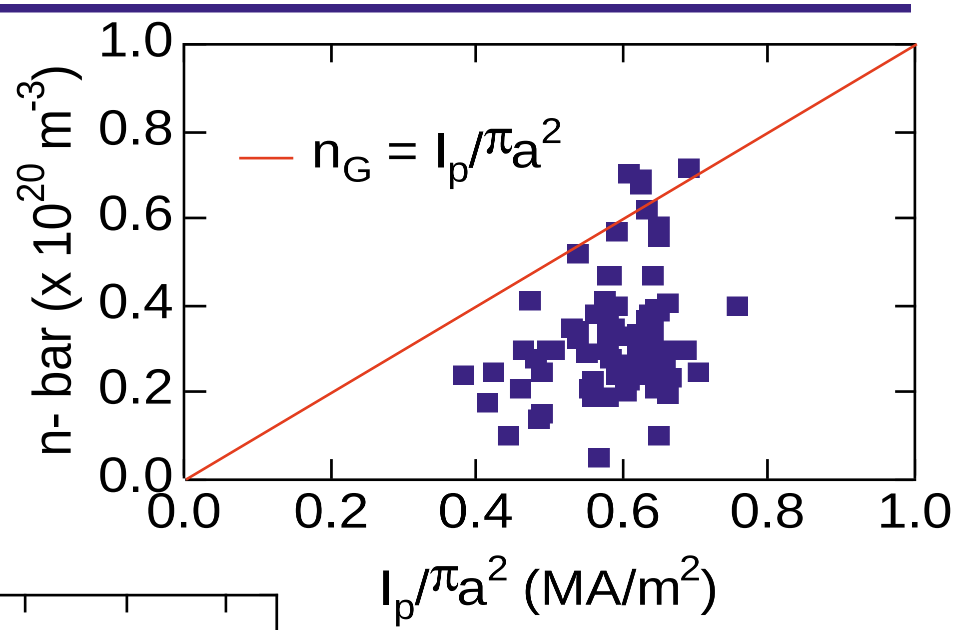
PEGASUS Accesses High-β_t ST Regime

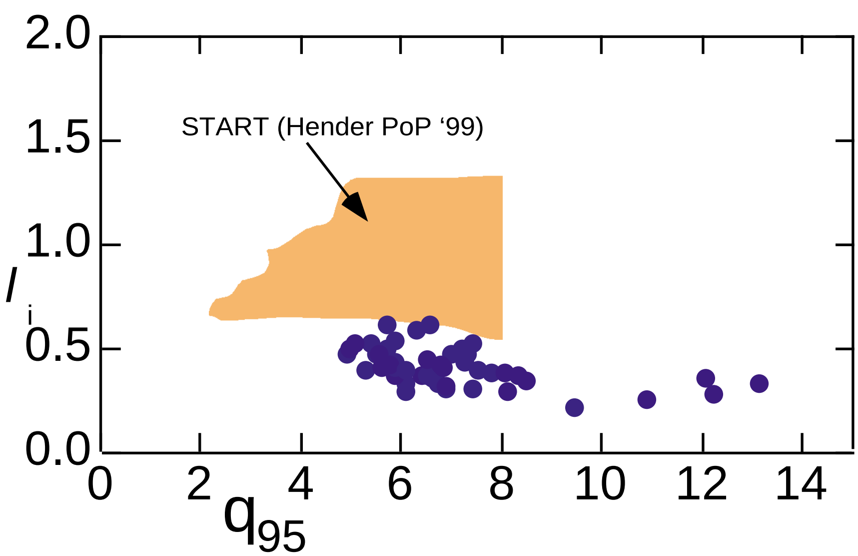
- **High β_t attained at high density, low-TF**
  - *Ohmic heating only; constant TF*
  - *Highest β_t, I_N at low TF (~0.05 T)*
  - *So far, limited by discharge evolution*



High Density, Low l_i, Low-TF Operation

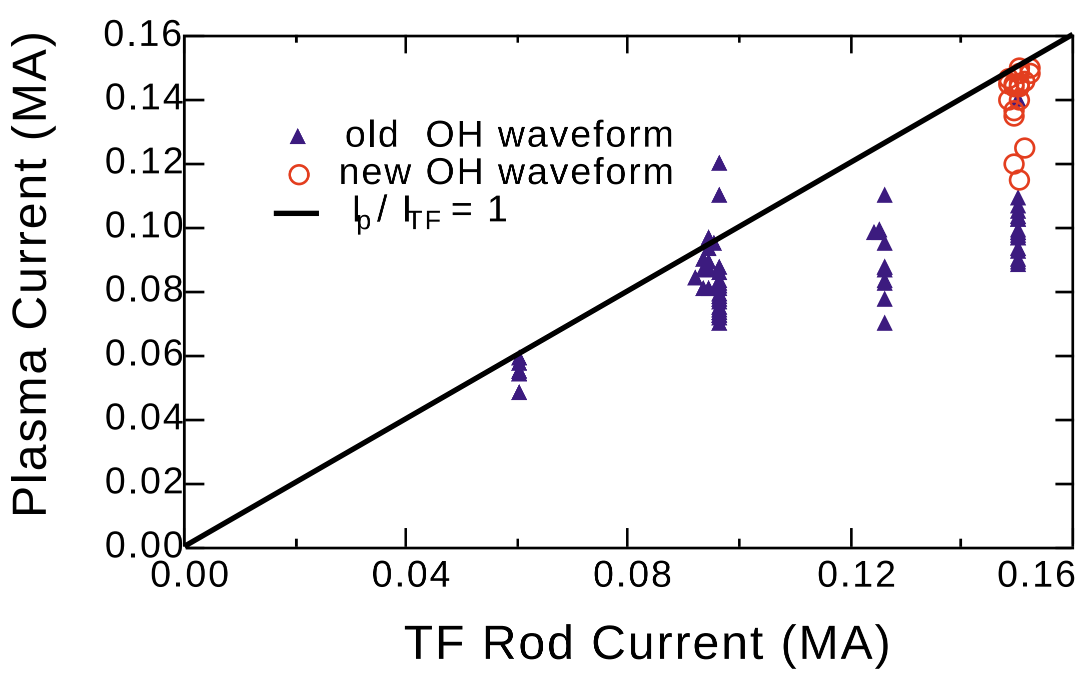
Density up to the Greenwald Limit





Low l_i; increases during current relaxation

$I_p/I_{TF} \rightarrow 1$



MHD Activity Appears to Hinder Access to low-TF, high-β_t regime

- **Access to high I_p/I_{TF}, low-q_{95}, high β_t regimes requires identification and suppression**

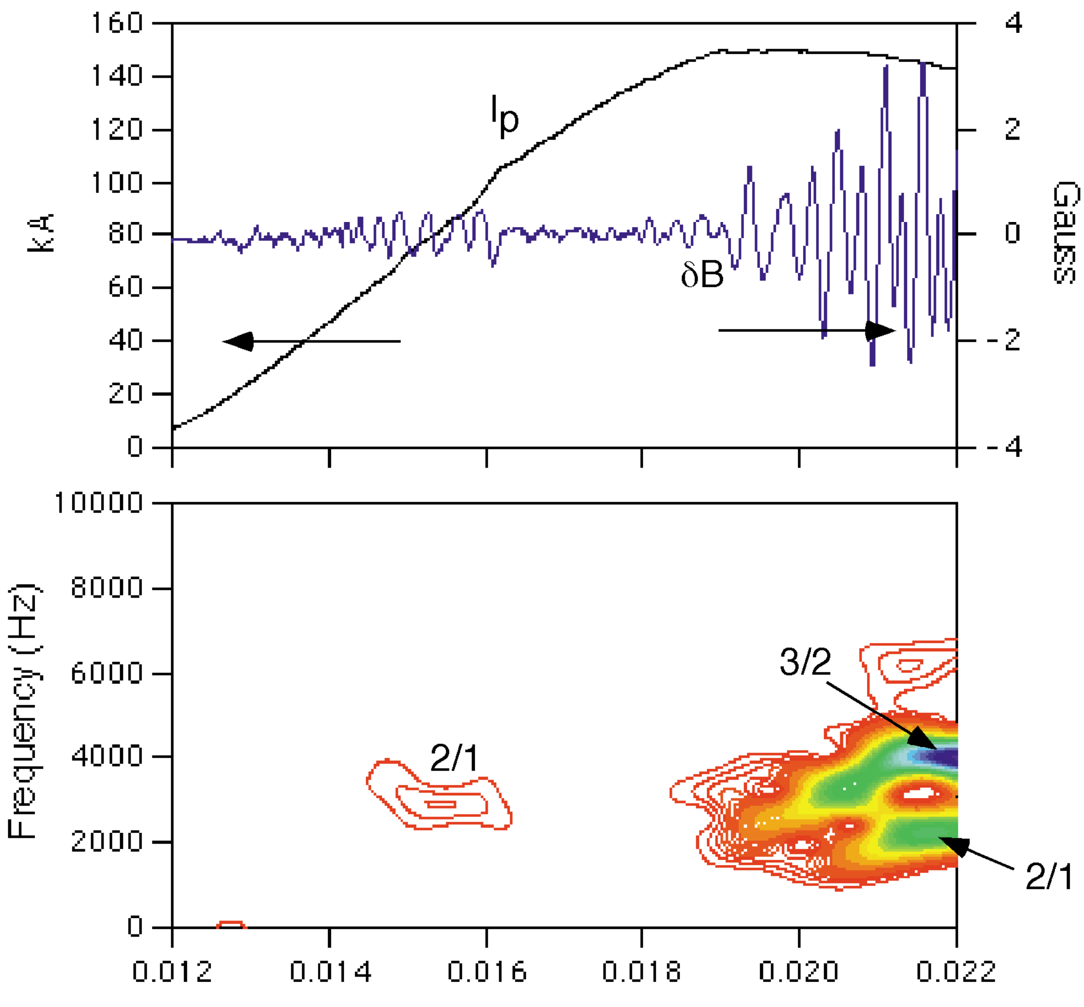
- **Evaluating role of MHD on access to low-TF OH regime**
  - Correlate appearance with estimated q(0,t) evolution
  - Use flux consumption analysis for quantitative comparison
    - Ejima Coefficient, C_e = high $\Rightarrow$ poor use of Ohmic V-sec
    - Ejima Coefficient, C_e = low $\Rightarrow$ efficient use of V-sec

- **Large Scale Internal Resistive MHD $\Leftrightarrow$ Reduced I_p, $C_e \sim 1$**
  - 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 <u>large low-shear interior region</u> with $q \leq 2$

- **External Kink Observed $\Leftrightarrow$ max I_p, $C_e \sim 0.5$**
  - External kink and/or V-sec limit at highest I_p, B_t cases
  - Appears as q_{95} approaches 5; higher than typical tokamak

Higher-Current Discharges Exhibit a Variety of MHD activity

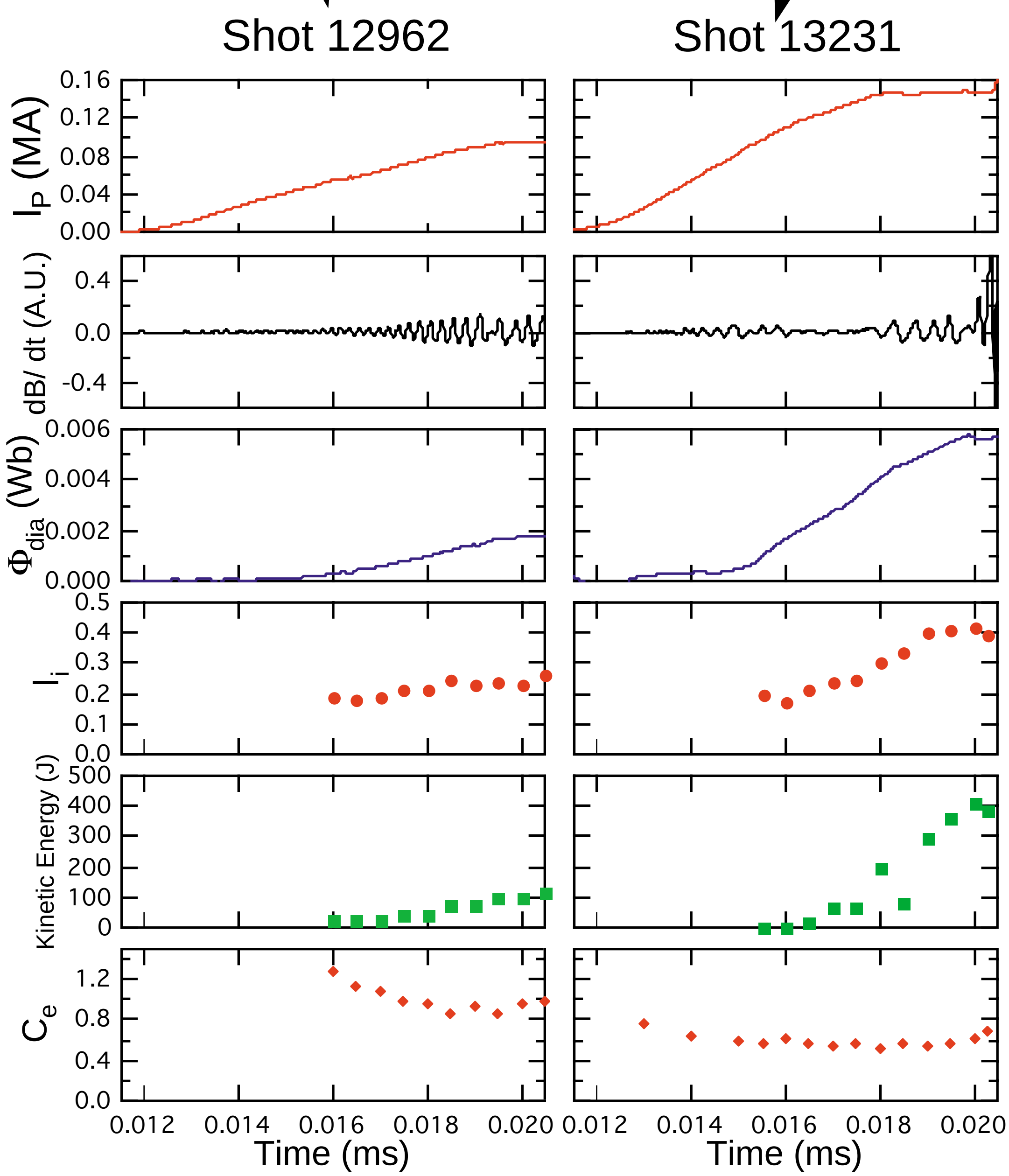
- 2/1 mode is observed but disappears
  - Pass through q(0) ≈ 2 region
- A 3/2 mode appears after a quiescent period
  - Correlated with q(0) dropping below 1.5



- Higher I_p accessed by discharge tailoring
  - Increased loop voltage
  - Edge cooling through aggressive gas puffing

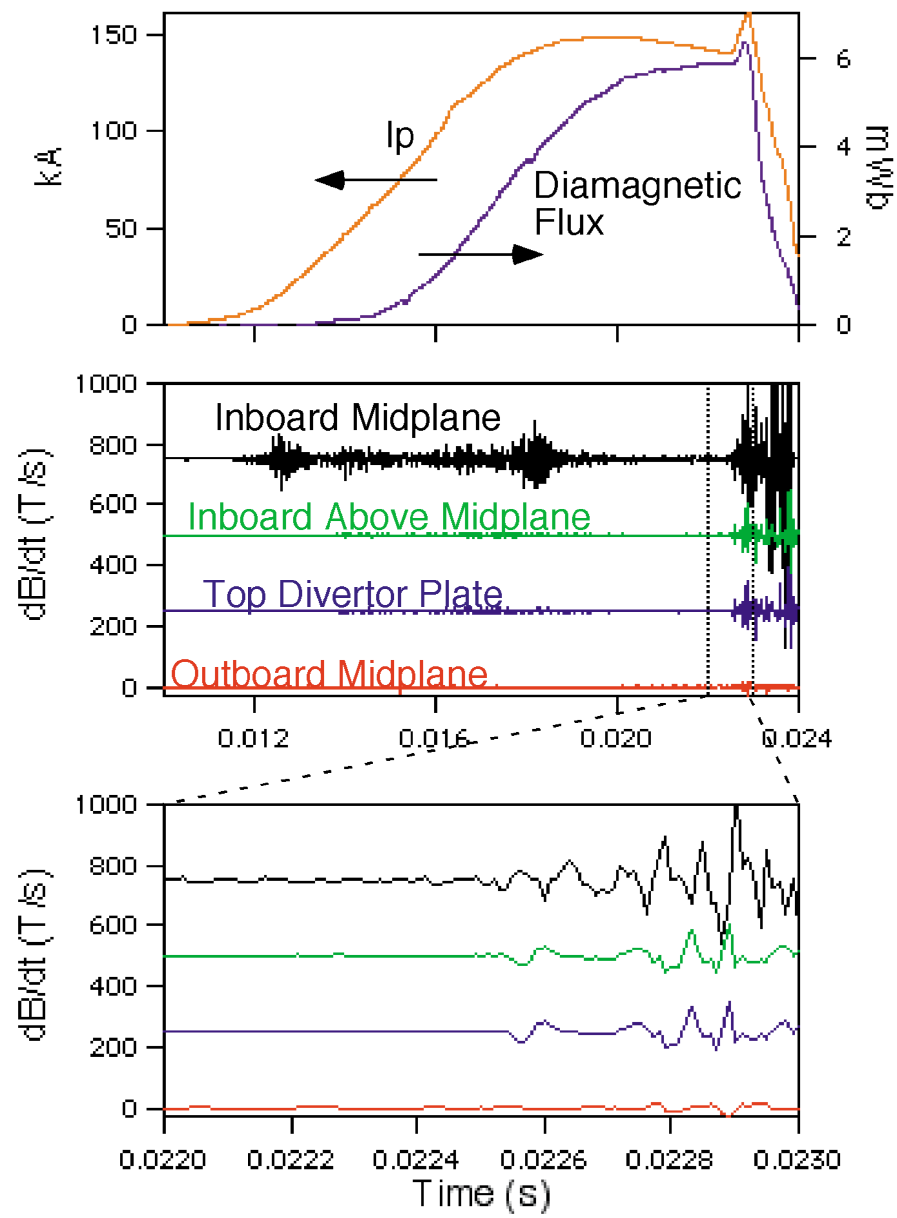
Large 2/1 MHD Activity Degrades Plasma Evolution

- With 2/1 Mode
  - *I_p reduced*
  - *High C_e*
  - *Low stored energy*
- Without 2/1 Mode
  - *Max I_p achieved*
  - *Lower C_e*
  - *Kinetic energy high*
  - *Onset of 3/2 mode*



Starting to Challenge External Kink Limits

- Higher-I_p discharges often terminate in abrupt disruptions
  - Precursor fluctuations observed on Mirnov coils
  - Lower-I_p shots have IREs, followed by gradual plasma termination

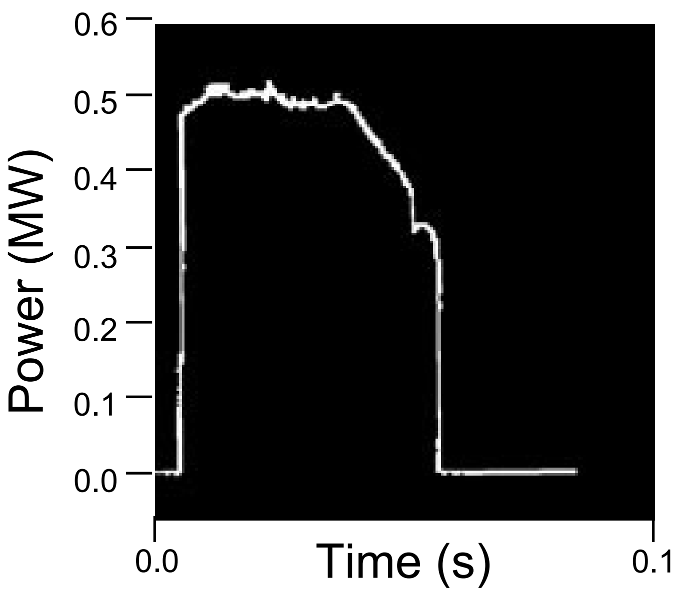


- Observed disruptions are associated with edge q-limits
  - Oscillations not observed until $q_{95} \approx 5$

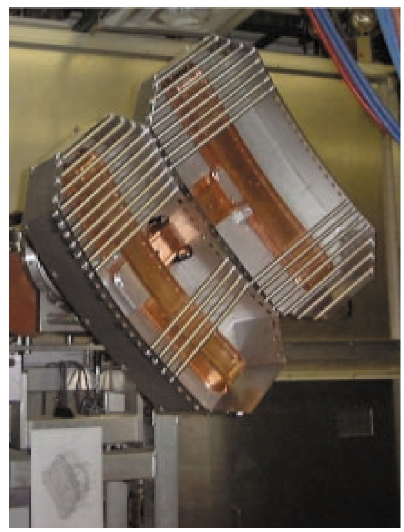
- Consistent with theoretical understanding of ideal kink stability
  - DCON & VACUUM: Plasma-vacuum energy $\rightarrow$ 0 as fluctuations begin
  - As A$\rightarrow$1, stable q_a increases

HHFW Heating Provides New Tool

- **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
  - $P_{RF} \approx$ 100 kW to date (Poster RP1.037 by P. Probert)



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



- **HHFW applications:**
  - MHD control: electron heating; reduce resistivity earlier
  - 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

Facility Upgrades Will Increase Access to low-q_{95}, high β_t Plasmas

Goals:

- **Increased control of plasma conditions**
  - *Density control, reproducibility, improved equilibrium field control*
- **Suppression of large internal resistive MHD modes**
  - *Increased I_p ramp time*
  - *Attain higher $T_e(0)$ during formation*
  - *Maintain $q(0) > 2$ during formation*
- **Control onset of suspected external kink modes**
  - *Maintain I_p ramp time*
  - *Maintain high q_{95} during formation*
  - *Edge control: edge cooling, shear, etc.*
- **Access to very high β_T regime**
  - *Increase I_p, N_e, T_e*
  - *Improved access to low-B_t regime*

Tools to achieve goals in near future:

- *Between-shot gettering*
- *Increased V-sec*
- *Increased B_T w/fast-rampdown*
- *Increased RF power*
- *Energize divertor coils*

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

Summary: Progress in Development and Understanding Plasmas at Very Low A & B_t

- **Facility and analysis developments ⇒ increased capability**
  - Internal hardware, wall conditioning, field programming
  - Magnetics diagnostic array and equilibrium analysis

- **Plasma equilibria show low-A characteristics**
  - $\beta_t \sim 25\%$ $\beta_N \sim 5$
  - $I_p/I_{TF} \sim 1.2$ $I_N \sim 8$
  - $n_e \sim n_{GW}$ $A \approx 1.16$
  - *2/1, 3/2, double tearing modes, IREs, external kink*

- **Access to low-B_t, low-A operation: configuration and physics**
  - V-sec capability can limit access to interesting physics
  - Large internal modes (2/1, 3/2) degrade plasma evolution
    - *Susceptible due to large, low shear region and low Te?*

- **Evidence of access to external kink emerging**

- **Next campaign: focus on MHD control and challenge limits**
  - High power RF heating
  - Increased B_t with fast rampdown
  - Increased V-sec
  - Separatrix operation

- **Pegasus Personnel - Experiment Team:**

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