Status and Plans for the PEGASUS Toroidal Experiment

R. J. Fonck for the Pegasus Team

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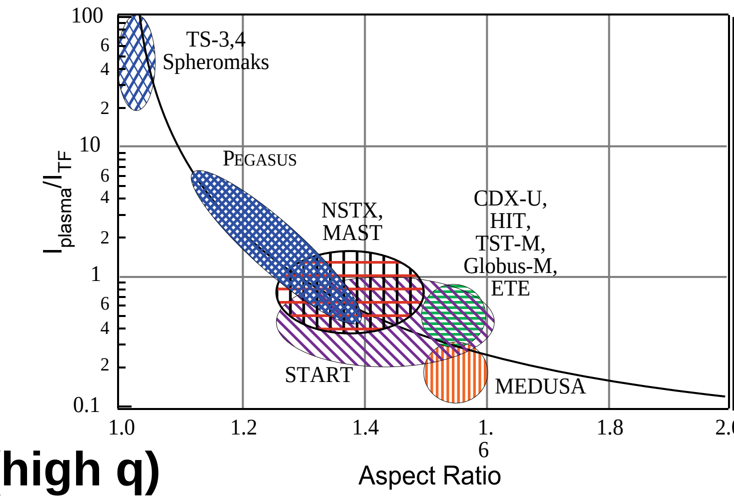
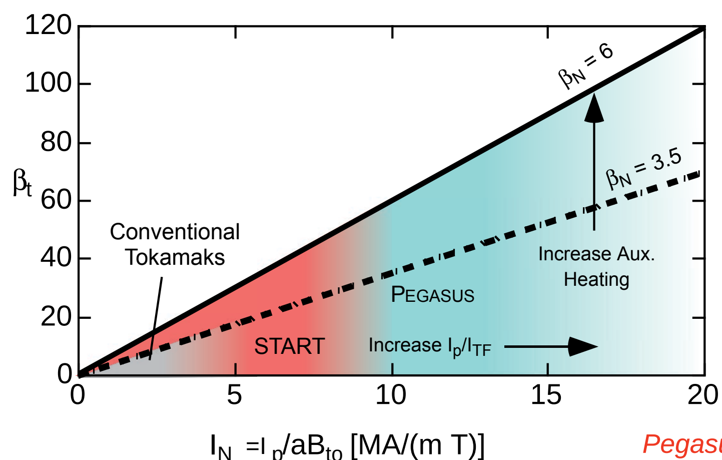
Role of Pegasus in the Fusion Community

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 <u>Alternate Concept</u> (low q)**
  - Extreme toroidicity ($A \rightarrow 1$)
  - Very high TF utilization (I_P/I_{TF}) > 3
  - Stability at very low TF ($\beta \approx 1$)
  - Relaxation stability at tokamak/spheromak boundary
  - RF heating and CD schemes (HHFW, EBW)
  - Trade-offs: CD, recirculating power, and $A \approx 1$, low-TF operation



- **Contribute to development of the ST (high q)**
  - Stability limits for $A \rightarrow 1$ (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 spherical torus

- Achieved Parameters:
  - $R = 0.2 - 0.45$ m
  - $B_t \leq 0.07$ T
  - $\kappa = 1.5 - 3.7$
  - $\langle n_e \rangle = 1 - 5\times10^{19} m^{-3}$
  - $A = 1.15 - 1.3$
  - $I_p \leq 0.15$ MA
  - $\Delta t_{pulse} = 10 - 30$ ms
  - $\beta_t \leq 20\%$
- High-strength solenoid magnet is enabling technology

PEGASUS Experiment Group

- **Pegasus Personnel - Experiment Team:**

Staff:
G. Garstka
B. Lewicki
B.Ford
G. Winz
R. Fonck
P. Nonn (+ MST)
P. Probert (+ HSX)

Graduate Students:
C. Ostrander
N. Eiditis
A. Sontag
K. Tritz
E. Unterberg

Undergraduates:
S. Diem
M. Reinke
R. Slowoski
R. Curtiss
B. Wilson
J. Boerner
A. Norseck
C. Putre
R. Radel
T. Wagner

- **Associated Theory (CPTC)**

J. Callen
C. Sovinec
C. Hegna

Vacuum vessel interior hardware

Pegasus diagnostic set

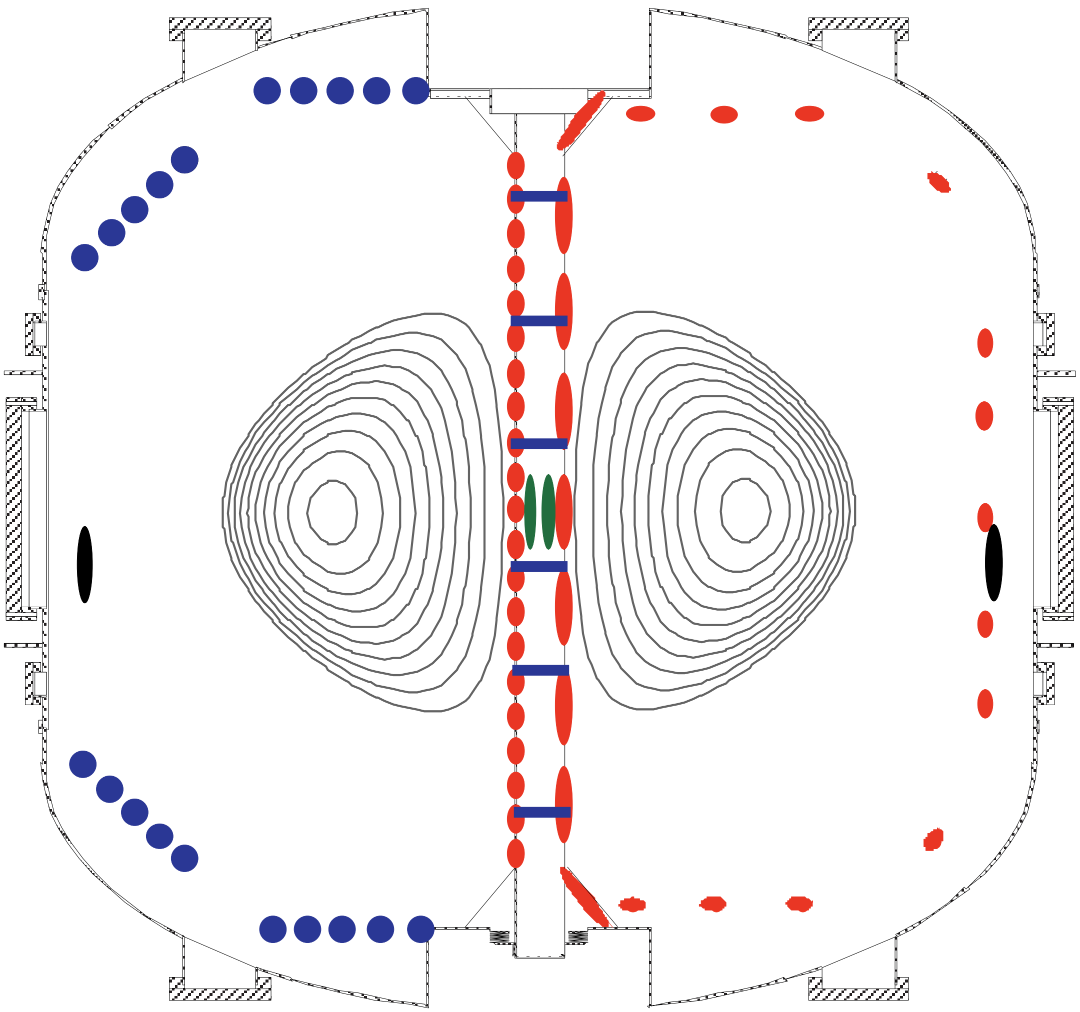
- Presently Operating Diagnostics

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, VB, D_α
Interferometer	single chord	$N_e l$
High Res. Camera	1000 fps	Plasma shape/position
2-D SXR Camera		Internal Shape/ j(R)
Poloidal SXR Diode Array	(19)	MHD Activity

- Near-Future Diagnostics

Diagnostic	Capability	Measures	Status
Tangential CCD PHA	single chord	$T_e(t)$	In Development
Tangential Bolometer Array	~20 chords	P_{rad}	Testing
Ross Filters	4 chords	$T_{e0}(t)$	Testing
2-Color X-ray	4 chords	T_e	Testing
Tangential VB Array	~20 chords	$Z_{eff}(R,t)$, $N_e(R,t)$	Testing
DNB		$N_e(R,t)$, $T_e(R,t)$, j(R)	Proposed
EBW Radiometer		$T_e(t)$	Proposed

Magnetics diagnostics installed in 2001



Flux Loops (26)

Poloidal Mirnov Coils (22 + 21)

LFS Toroidal Mirnov Coils (6)

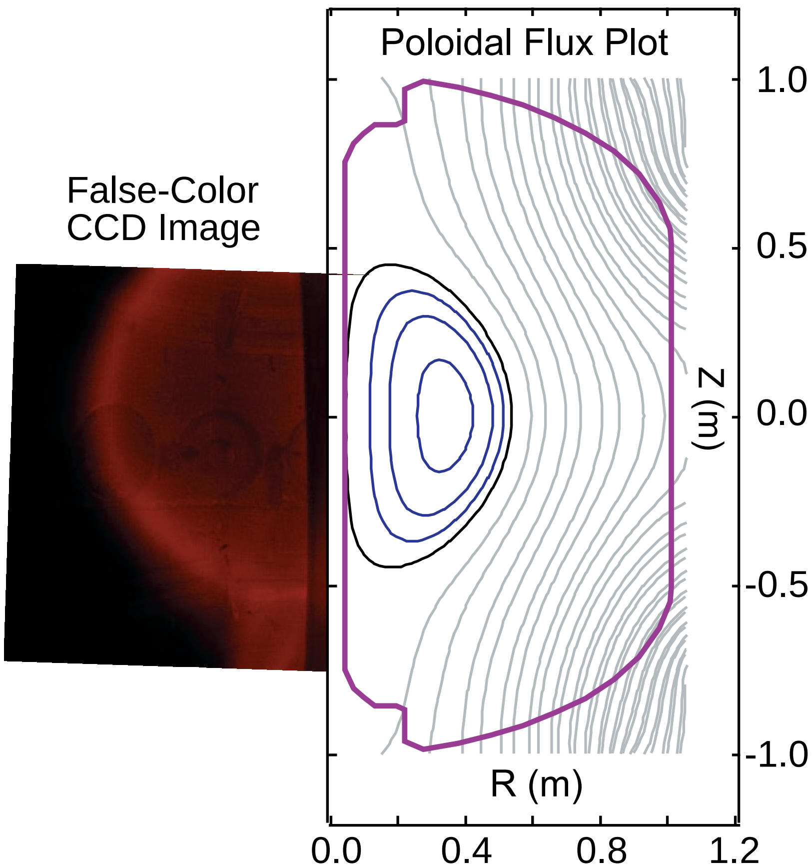
HFS Toroidal Mirnov Coils (7)

Not shown:
Plasma Rogowski Coils (2)
Diamagnetic Loops (2)
Diamagnetic Compensation Loop
External Flux Loops (6)
Internal B_{tan} Coils (15)

Equilibrium reconstruction is a primary analysis tool

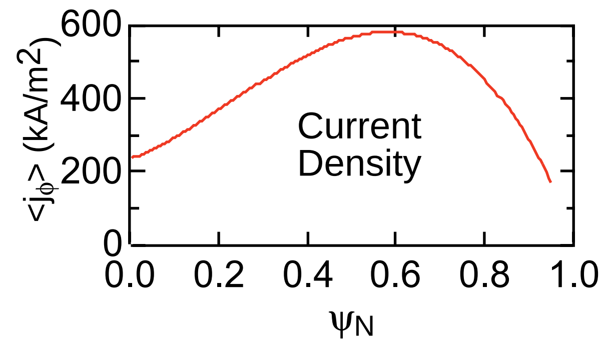
- A new equilibrium code has been developed for Pegasus
  - Robust, cross-platform, easy incorporation of new diagnostics
- Uses a two-step iterative method to determine equilibrium
  - Gauss-Seidel multigrid relaxation to solve Grad-Shafranov equation
  - Levenberg-Marquardt method to minimize χ^2
- Benchmarked against existing codes
- Sample reconstruction:

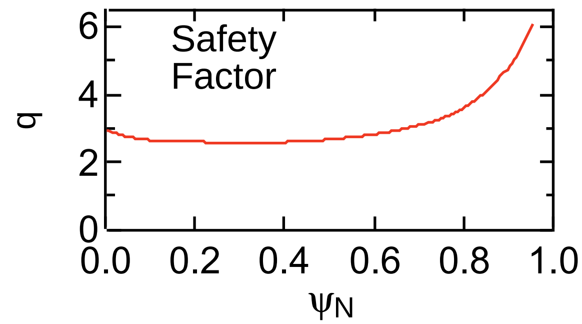
False-Color CCD Image

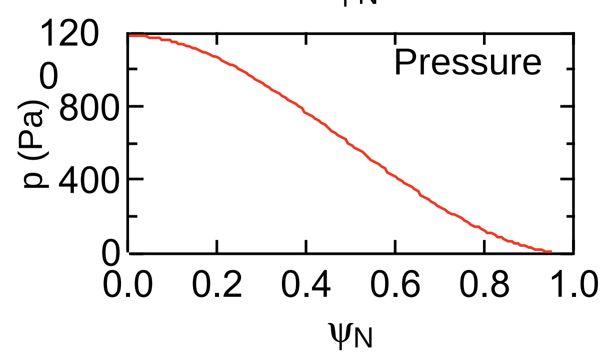


Fit Results

I_p	151.4 kA
R_0	0.305 m
a	0.249 m
A	1.22
κ	1.8
RB_t	0.003 T-m
β_t	16%
l_i	0.35
q_0	2.8
q_{95}	6.2

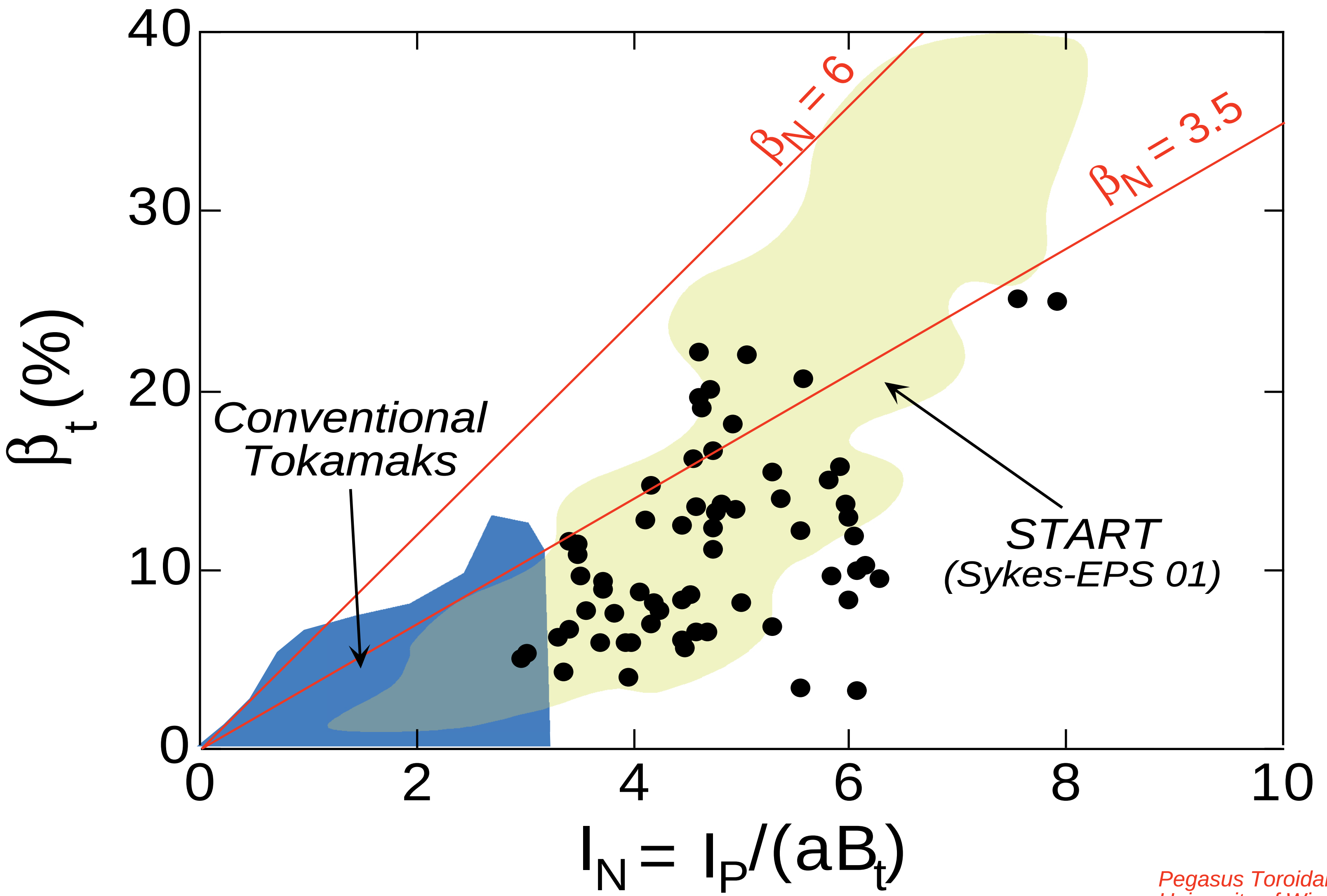




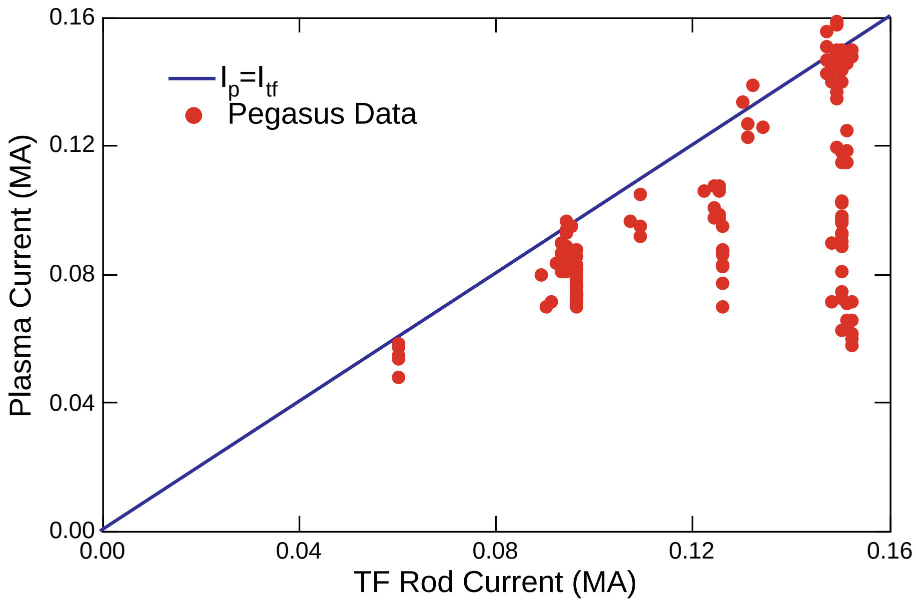


PEGASUS is Accessing High-β_t ST Regime

- High β_t achieved at high density and low toroidal field
    - All results achieved with ohmic heating only
    - Highest normalized currents achieved at low field



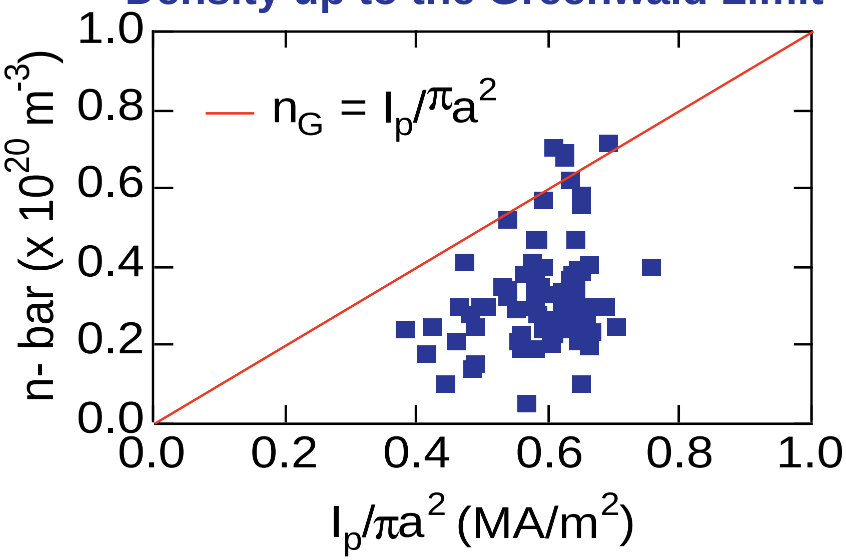
Low-TF, High Density, Low-l_i Operation



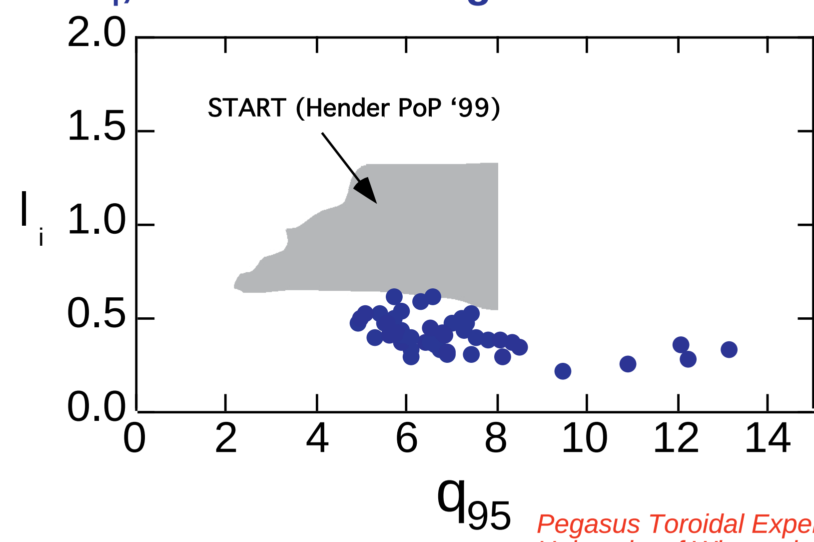
TF utilization: "soft" limit at $I_p \approx I_{TF}$

- Increased V-s consumption required for breakdown at lower TF
- Large-scale resistive MHD during current ramp (exacerbated by low l_i?)

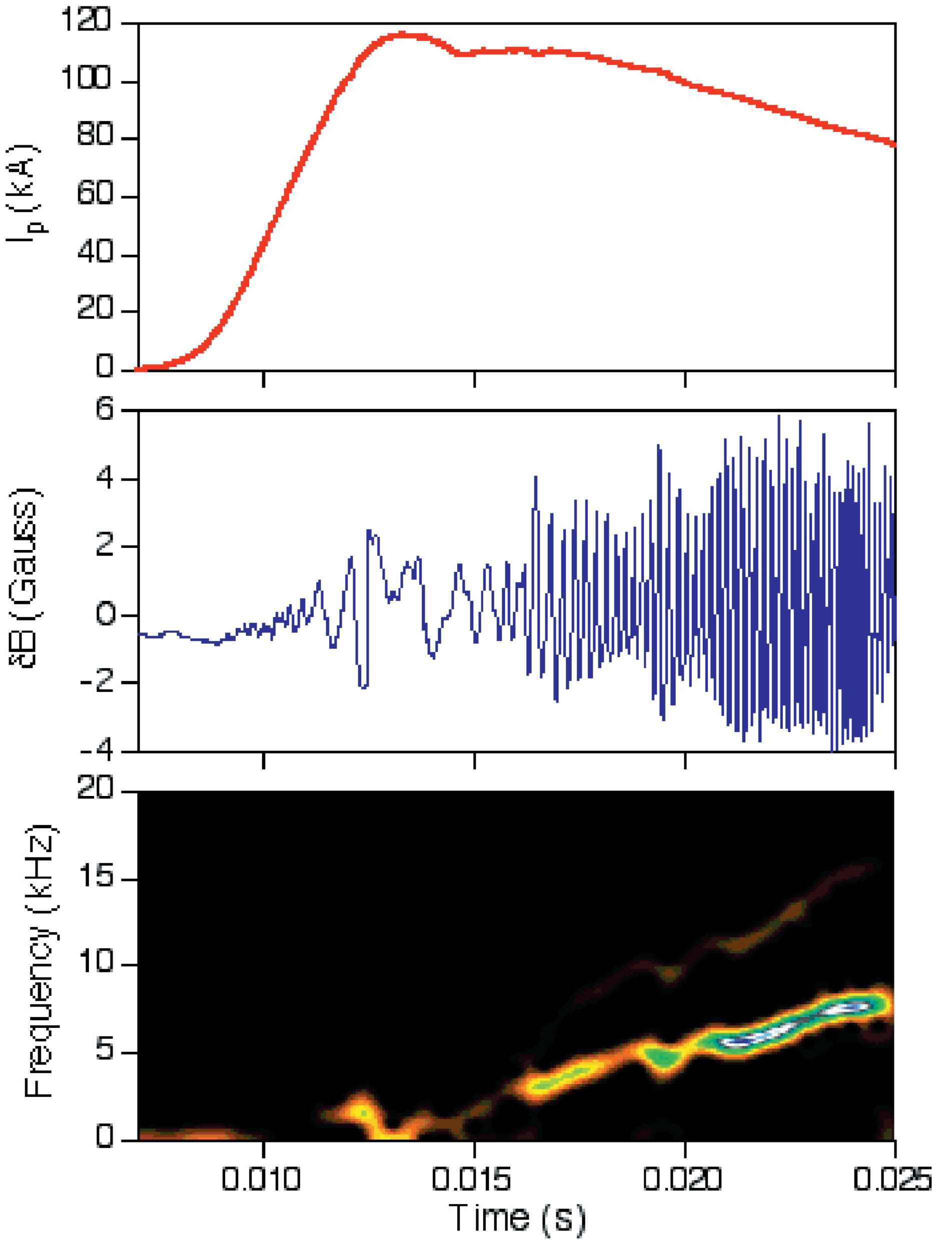
Density up to the Greenwald Limit



Low l_i; increases during current relaxation

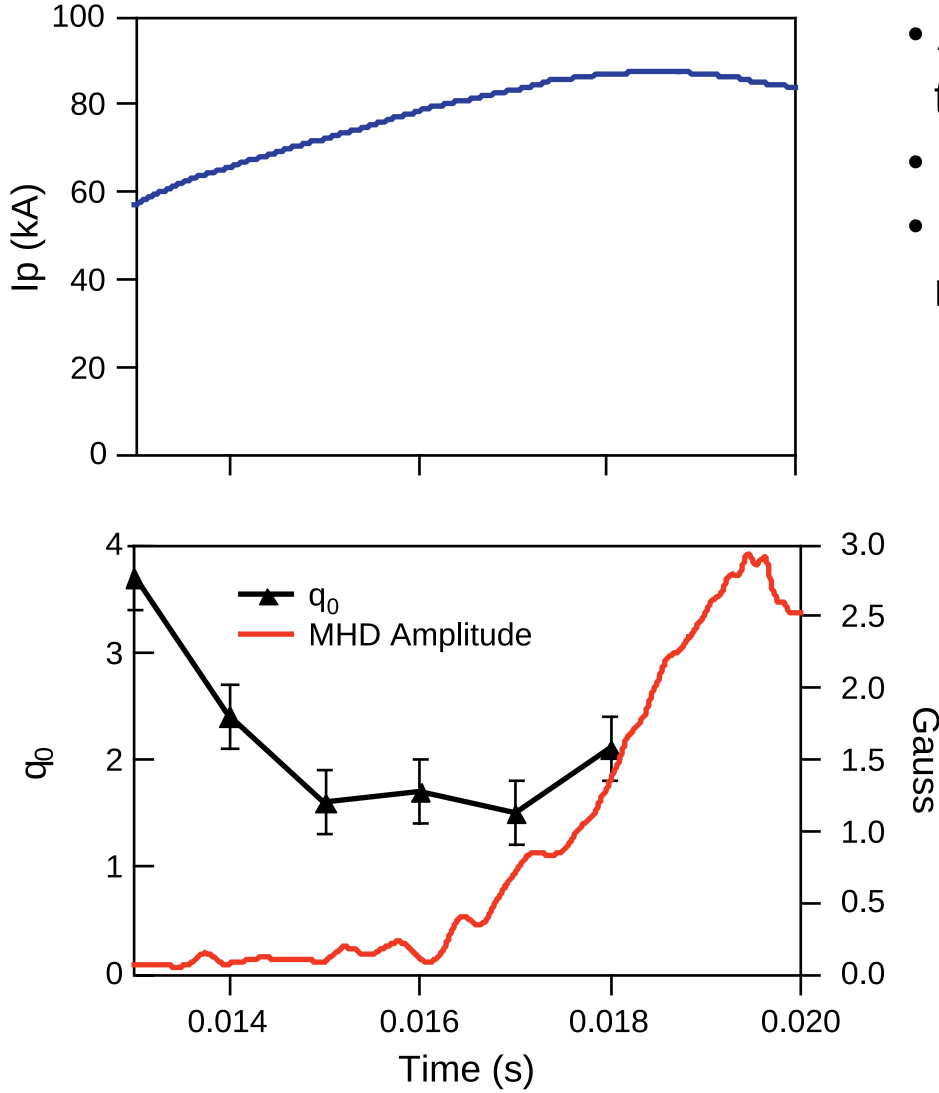


A dominant feature has been a rotating m/n=2/1 mode

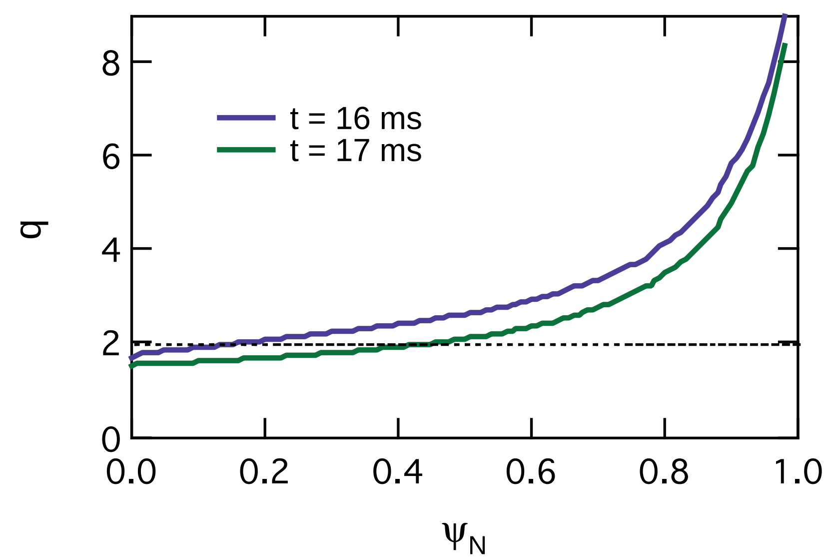


- Mode present in all significant discharges
- Rotates in electron diamagnetic direction
  - Mode is likely magnetic island
- Frequency is typically 2-10 kHz
  - No evidence of mode locking
- Little shear stabilization of island growth
  - Central shear is nearly zero

2/1 mode not observed until $q_{min} < 2$



- Consistent with observed helicity of the mode
- A large region of low shear exists about the q=2 surface
- Central q inferred from Equilibrium fit
- In general, strong MHD activity appears to relate to I_p limits



External kink modes observed in highest-current shots

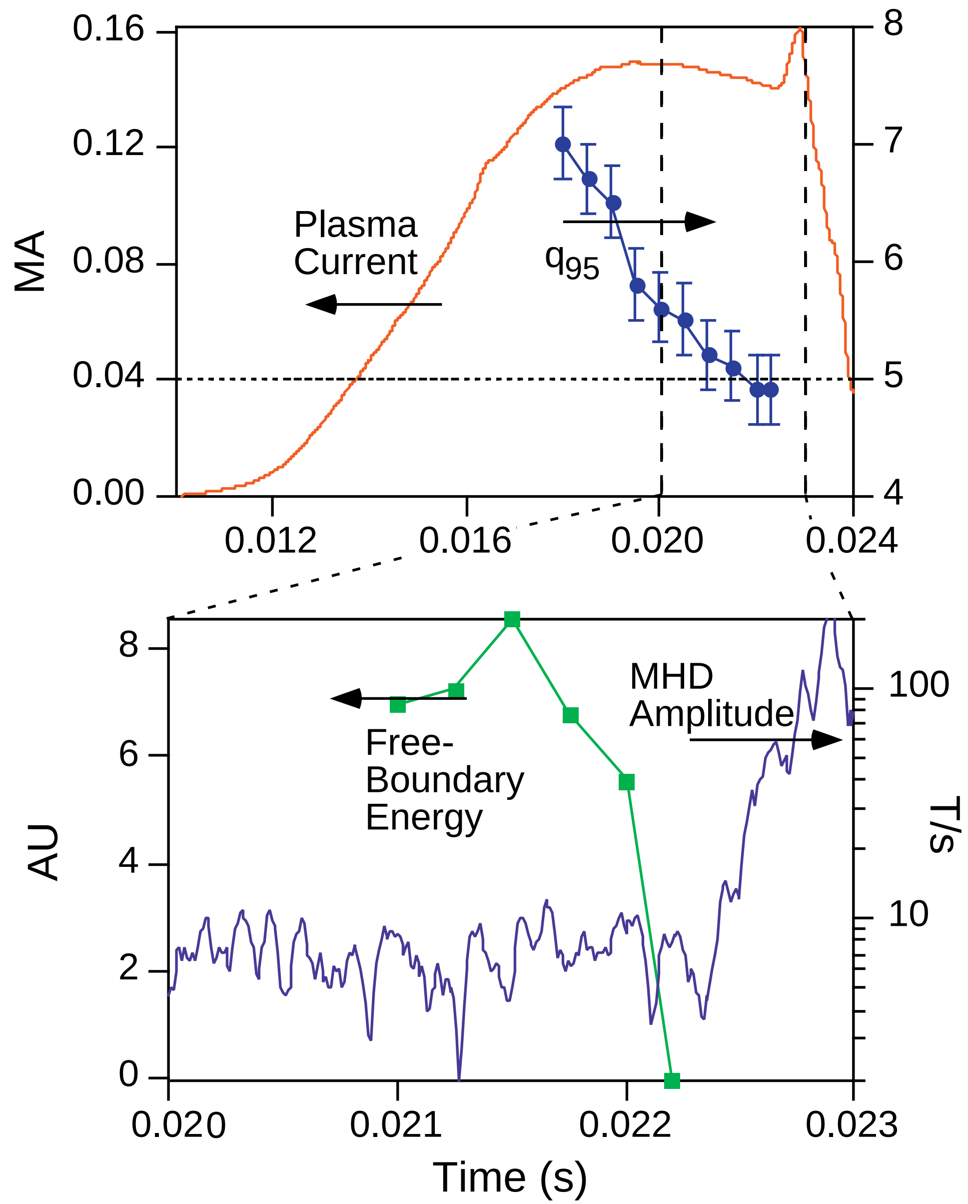
- Higher-current discharges (150 kA class) often terminate in abrupt disruptions
  - Lower-current shots have IREs followed by gradual plasma termination

- n=1 fluctuations are observed on Mirnov coils immediately prior to disruption
  - Dominant frequency is roughly 10 kHz
  - Mode observed a few 100 μs before IRE

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

- Calculated free-boundary energy (DCON) approaches zero as oscillations begin
  - Negative value indicates instability to external kink

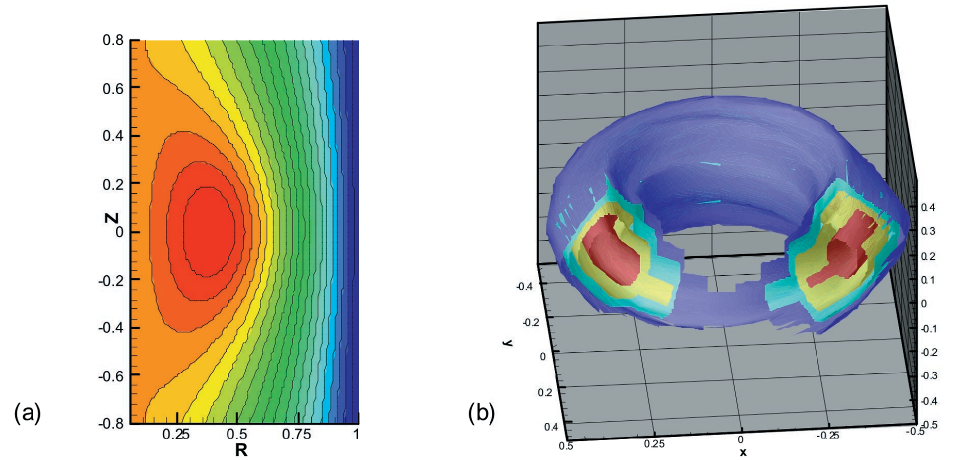
- Consistent with theoretical understanding of ideal kink stability at near-unity A
  - As $A \rightarrow 1$, unstable q_a increases
  - Roles of finite β, low l_i under study



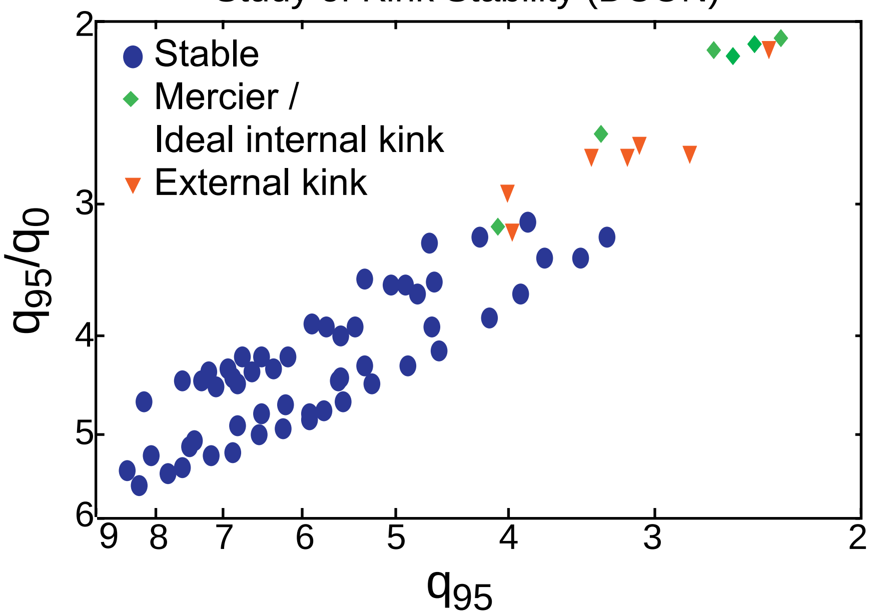
A variety of computational tools are being implemented

- Equilibrium code
- Wall currents code
- Energy confinement code
- DCON: ideal stability analysis
- TSC: predictive discharge modelling
- GATO: instability growth rates
- NIMROD: resistive MHD analysis

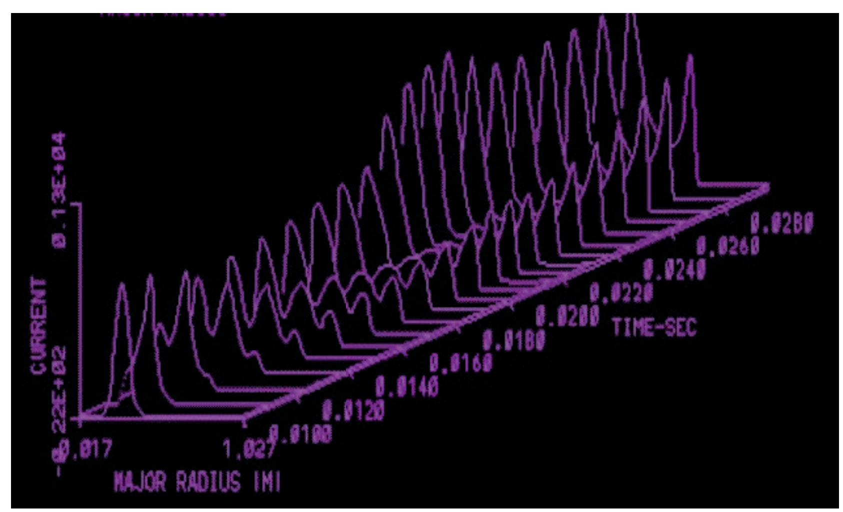
Preliminary Model of Resistive Stability (NIMROD)



Study of Kink Stability (DCON)



Evolution of J(r) during TF rampdown (TSC)



Planned upgrades will allow further study of low-q high-β plasmas

- **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 programmable V-sec from ohmic solenoid*
  - *Attain higher $T_e(0)$ during formation = increased B_T, improved position control*
  - *HHFW heating = increased RF power operation, improved position control*
  - *Maintain $q(0) > 2$ during plasma formation = increased B_T*

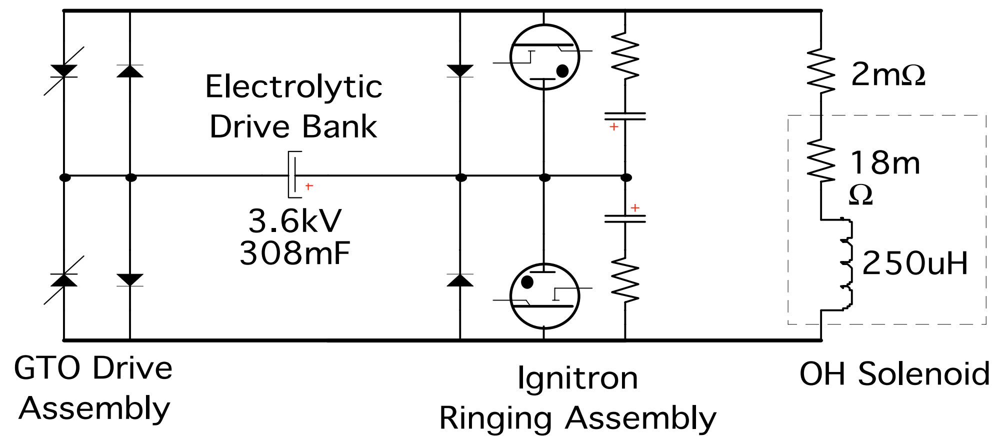
- **Control onset of suspected external kink modes**
  - *Maintain I_p ramp time = increased programmable V-sec from ohmic solenoid*
  - *Maintain high q_{95} during formation = increased B_T w/rampdown*
  - *Controlled gas puff for edge cooling = continuous gettering*
  - *Separatrix operation = energize 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*

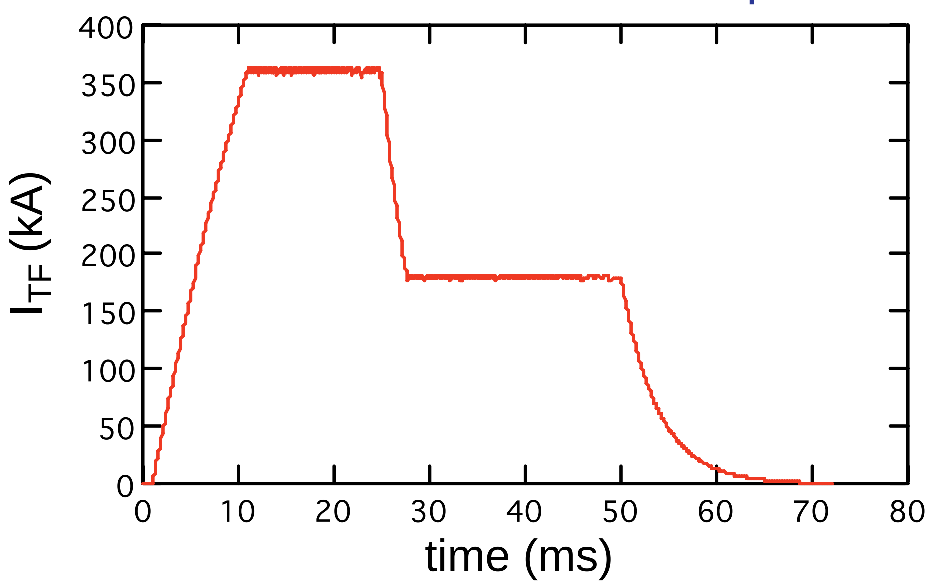
New power supplies will provide dramatically improved control over plasma evolution

- Bipolar switching supplies replacing resonant L-C systems to provide flexible waveform control
  - *TF: much higher I_{rod} and fast rampdown capability w/ new center rod*
  - *OH: near full use of available flux and programmable V_{loop} control*
  - *EF: programmable position control*

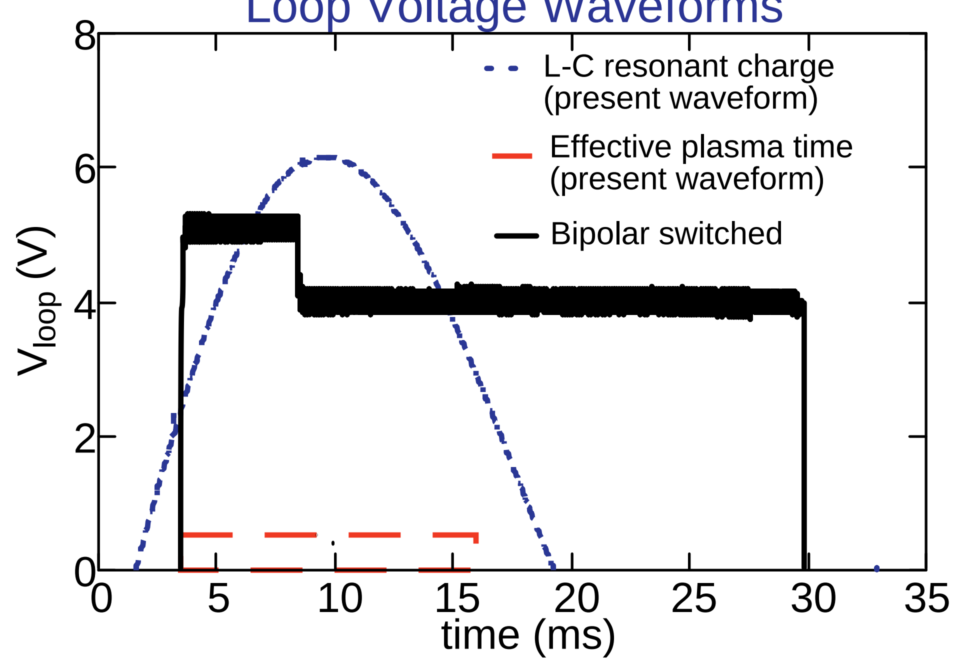
Four Quadrant Ohmic Switch



TF Waveform with Fast Rampdown



Present and New Loop Voltage Waveforms



Status & Project Plans for next 3-years

- **Renewal proposal submitted to continue for another 3 years**
  - *Year 1: Tool development and MHD suppression*
    - Programmable EF control; Increased V-sec; $B_{TF}(t)$
    - Lab reconfiguration
  - *Year 2: I_p limits; access high β_t, low B_{TF} regime*
    - Internal MHD suppression thru q(0,t) and resistivity manipulation
    - Vary external mode onset thru edge cooling and shear control, plus geometry and l_i evolution
  - *Year 3: Stability boundaries documentation*
    - Increase stored energy through increased Δt_{pulse}, I_p, T_e, N_e, and P_{aux}
    - Documentation and parameter scans in tokamak-spheromak transition region

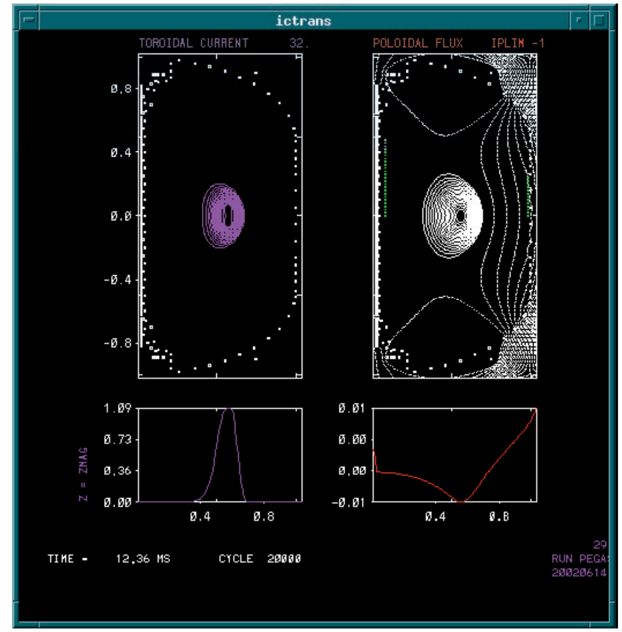
- **Have started ~11 month down period for renovation and upgrades**
  - *Lab reconfiguration or possible move to new high-bay area*
  - *Front-loading proposed major upgrades to present down period*
    - Uograded OH power system ⇒ 2-3 times effective V-sec
    - New EF power system ⇒ active radial position and shape control
    - Low-inductance TF system ⇒ time-variable TF

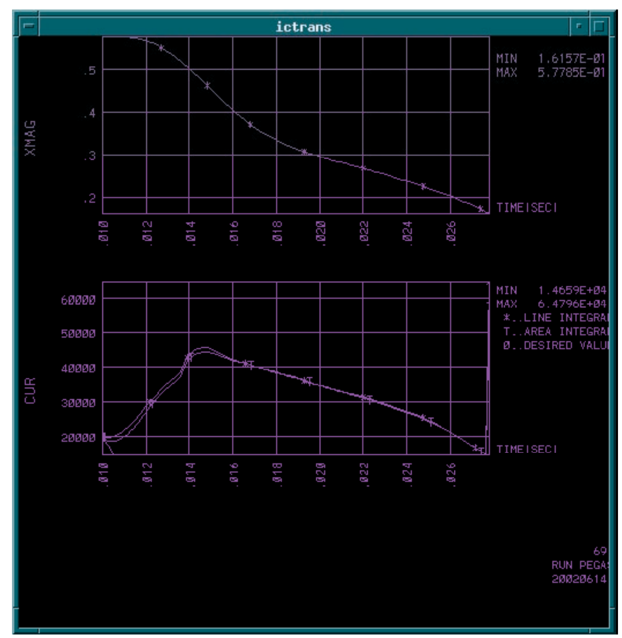
Relation to NSTX and ST PoP Program

- **Present program is mainly complementary**
  - *Explore extreme in A; tokamak-spheromak transition region*
  - *Expand ST database for stability limits, etc.*
  - *Appropriate role for CE component of ST PoP program*

- **Interested in developing future interactions with NSTX program…**
  - *EBW tests*
    - *500 kW, 2.45 GHz system feasible*
    - *Hoping to explore PPPL-ORNL-UW collaboration*
  - *Diagnostic developments*
    - *Tangential X-ray imaging*
    - *Low-field j(r) measurements*
  - *Move to tests of startup and non-inductive ST techniques*
    - *e.g., ECH, EBW, HHFW, external coil induction-compression, etc.*
  - *Fueling with spheromak injection into diamagnetic plasma (UC-Davis)*
  - *Here to explore any and all ideas...*

TSC: induction-compression startup with external coils





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

- **Facility and analysis developments ⇒ increased capability**
- **Plasma equilibria show low-A characteristics**
  - *β_t ~ 25%* *β_N ~ 5* *$n_e \sim n_{GW}$*
  - *I_p/I_{TF} ~ 1.2* *I_N ~ 8* *$A \approx 1.16$*
  - *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 T_e?*
  - Evidence of access to external kinks at low l_i
- **Proposed direction: access & document low-q, high β_t @ A →1**
  - Characterize tokamak-spheromak overlap regime
  - Improved plasma control to manipulate MHD onset
    - *Increased I_p; position/shape control; $B_{TF}(t)$*
  - Separatrix operation for edge q control and possible H-mode