Abstract

The central solenoid of a spherical torus (ST) offers limited Ohmic flux, which exacerbates the limitations of this heating and current drive technique. The design of a scalable non-solenoidal (NS) startup technique is desired to expand the operating space of the ST and to provide a path to NS operation for STs and tokamaks. Pegasus employs a two-part NS startup technique of DC helicity injection and poloidal field induction. DC helicity injection is used to create a target plasma at the outboard midplane by injecting current along helical field lines. The current filaments relax to a tokamak-like magnetic topology with I_p determined by magnetic helicity conservation. A prototype system capable of injecting up to 2kA has been used to create target plasmas with toroidal current up to 20kA. Poloidal field induction has been used to ramp the target to 30kA and provide a target suitable for coupling to other CD techniques.

*The research was performed under appointment to the Fusion Energy Sciences Fellowship Program administered by Oak Ridge Institute for Science and Education under a contract between the U.S. Department of Energy and the Oak Ridge Associated Universities.

*Work supported by U.S. D.O.E. Grant DE-FG02-96ER54375.

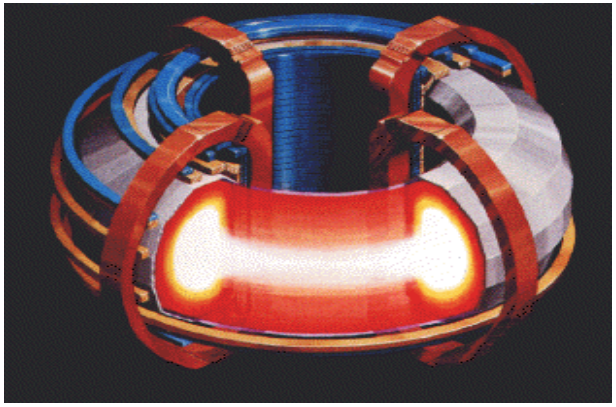
Nonsolenoidal Start Up is Desired for Current Carrying Fusion Systems

- Ohmic solenoid has been primary start up device in tokamak, spherical torus, and other magnetic confinement devices
  - Simple, mutual induction drives I_p
  - Relatively efficient
  - Small error fields
  - *Pulsed power operation*
- Engineering constraints
  - Large heat and neutron flux
    - Cryogenic cooling and massive shielding
  - Imbedded solenoid design
    - Cross-field stresses
  - Larger machine size & operating/electricity costs

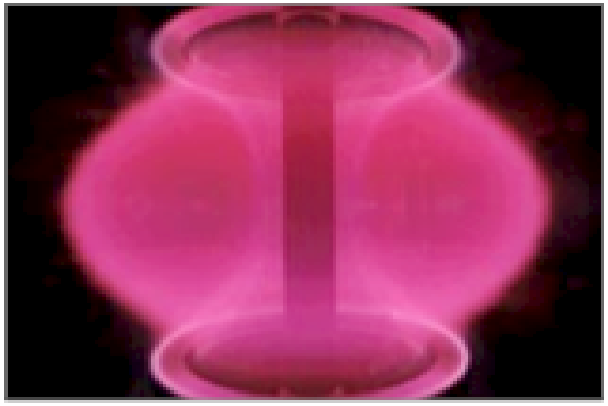
*~Nishio, S., et al., J. Plasma and Fusion Res., **78**, 1218 (2002)*

Solenoidal Start Up is a Particularly Acute Problem for STs

- Small solenoid offers limited V• s
  - Toroidal field coil construction & cooling difficult
  - Shielding increases machine size for low-A operations
- NS Startup offers long pulse high Ip operating space
  - Frees ohmic system from;
    - Initial ionization
    - Current ramping
    - Heating
  - Full exploration of ST physics



General Tokamak schematic



ST: START has a smaller central solenoid

Pegasus is a ULART: an Ultra Low Aspect Ratio Tokamak

Central Solenoid

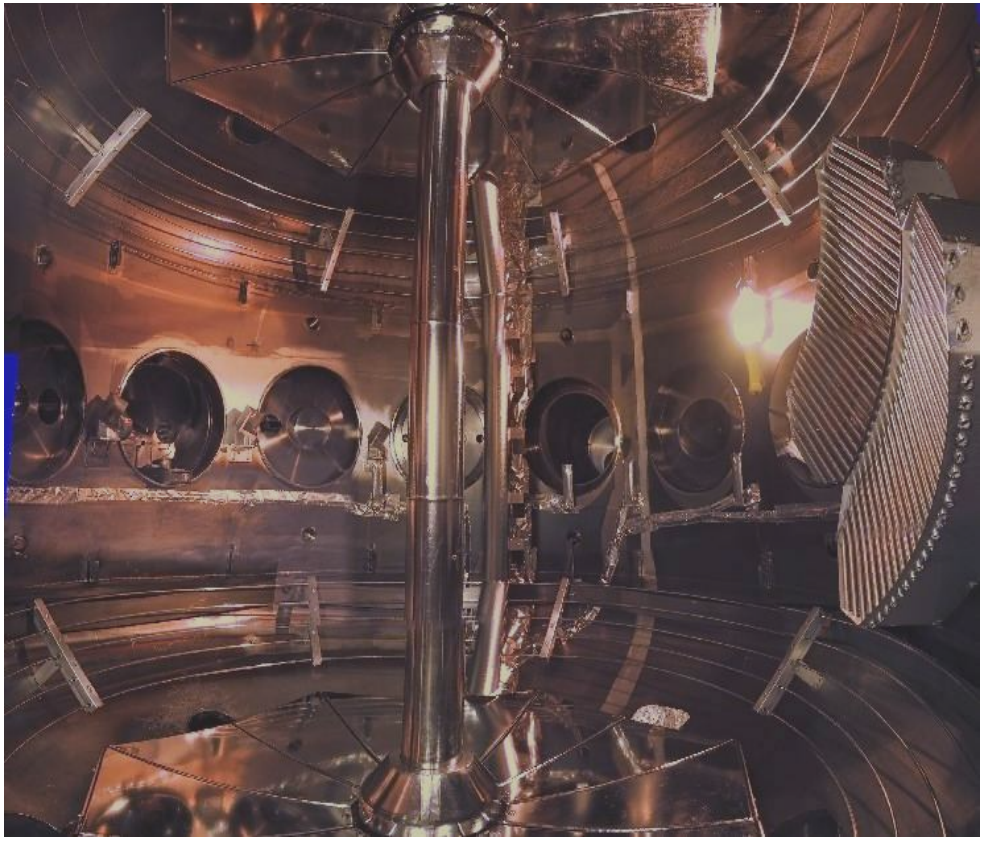
- 11cm diameter
- B_{max} = 14T
- ~30-90$mV \cdot s$ available

Pegasus is flexible

- PF programming
- Wide operation range
- Large ports

Experimental Parameters

Parameter	Achieved
A	1.15-1.3
R (m)	0.2-0.38
I_p (MA)	≤ 0.19
I_N (MA/m-T)	6-14
κ	1.4–3.7
τ_{shot} (s)	≤ 0.02
β_t (%)	≤ 27



Pegasus Explores a Combination of Helicity Injection and Poloidal Field Induction

DC Helicity Injection

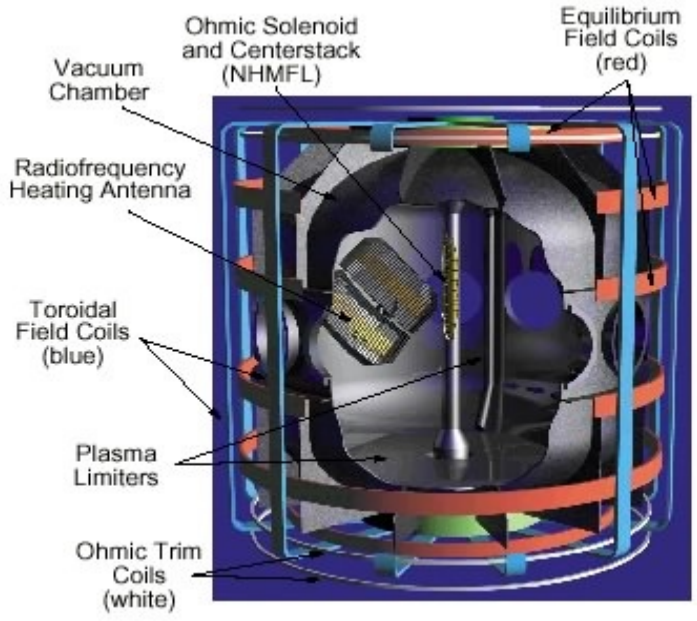
- Injects current along **B**
- Relaxes to a tokamak-like structure
  - Helicity conservation & magnetic reconnection

Advantages:

- Point source DC injection
  - "Match Lighting" startup
    - Neutron damage minimized
- Potential Scalability
  - Only vacuum access
  - Pegasus ports accessible
- Several-step startup
  - Aid with RF heating, NBI, etc

Poloidal Field (PF) Induction

- PF induction creates a V_{Loop}



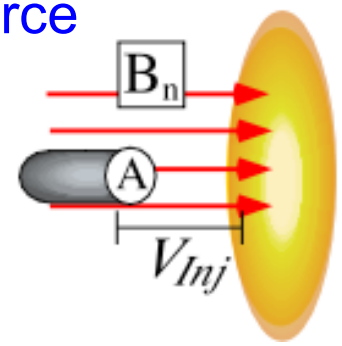
Advantages:

- EF coils used to drive Ip
- Coils external
- Pegasus PF coil sets flexible

DC Helicity Injection Sustains a Plasma Current

- DC Helicity injection rate for a point source
  - *Constant B across injector*

$$K\acute{\imath}_{Inj} = 2\,\grave{O}_A \mathrm{F}\,\mathbf{B}\times d\mathbf{a} = 2V_{Inj}B_nA_{Inj}$$



where $B_n \approx B_{Tor}$ &

$$B_v = \frac{\mu_o I_{\rho o \delta}}{(2\pi R_{Gun})}$$

- The helicity dissipation is related to I_p
  - *All dissipation is resistive, a simple tokamak geometry*

$$\int_V \mathbf{E}\cdot\mathbf{B}\,dt \;\text{Þ}\; \grave{O}_V \mathrm{h}\,\mathbf{J}\times\mathbf{B}\,dt = \mathrm{h}\;I_p(2\mathrm{p}R)B_o$$

where $B_o = \frac{\mu_o I_{\rho o \delta}}{(2\pi R_o)}$

- Helicity injection can sustain a plasma current

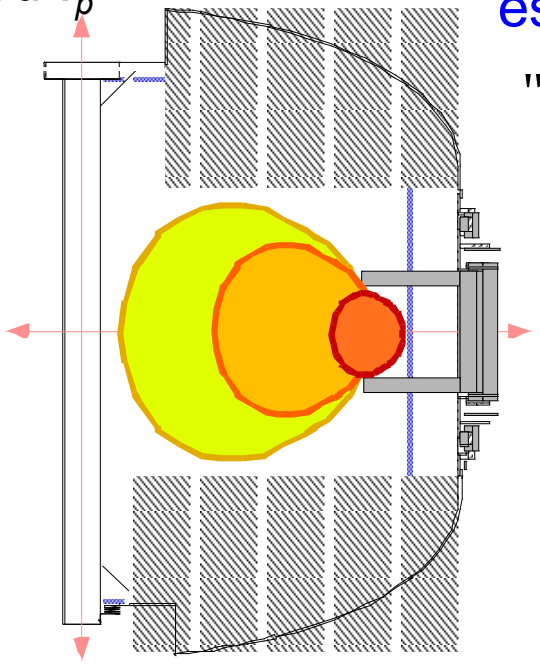
$$I_p = \frac{\varsigma_{Iv\varphi} B_v A_{Iv\varphi}}{\eta(2\pi P)\,B_o} \Rightarrow \frac{\varsigma_{Iv\varphi} A_{Iv\varphi}}{\eta\,(2\pi P_{\Gamma\upsilon\nu})}$$

$$\varsigma_{\substack{\Lambda o o \pi \\ \varepsilon\phi\phi}} = \frac{V_{Inj}A_{Inj}}{(\pi a^2)}\,\frac{P_o}{P_{\Gamma\upsilon\nu}}$$

- Note: I_p depends on R_{Gun} not R_{plasma}

Closed Flux Tokamak Formation Requires the Satisfaction of Multiple Constraints

- Helicity conservation
- Radial equilibrium
  - B_v *for relaxed* I_p
- Flux closure:
  - $B_v < B_p$

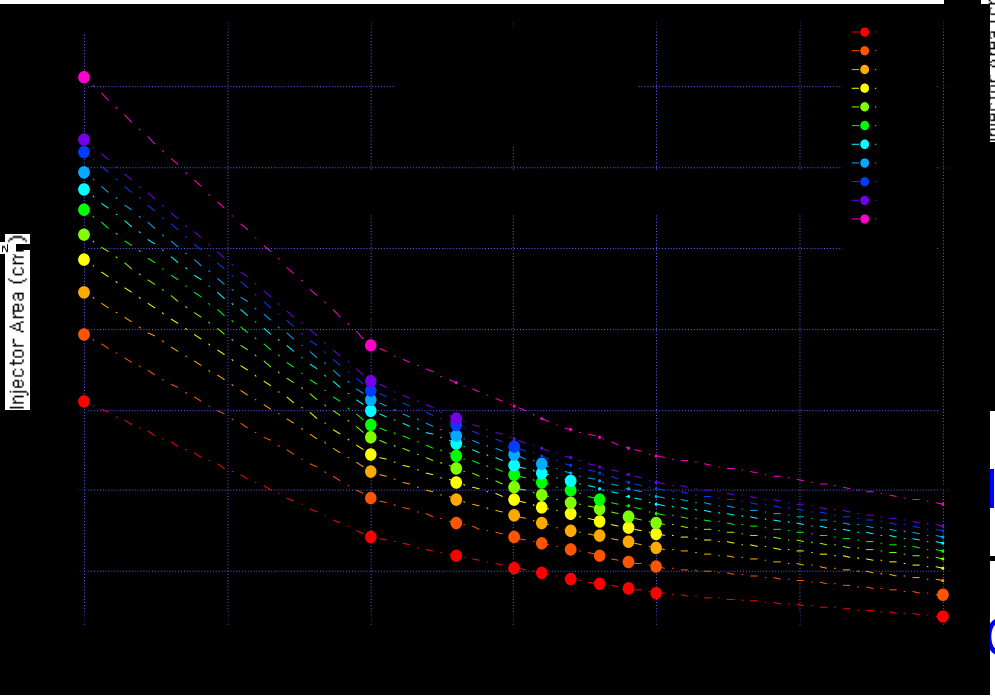


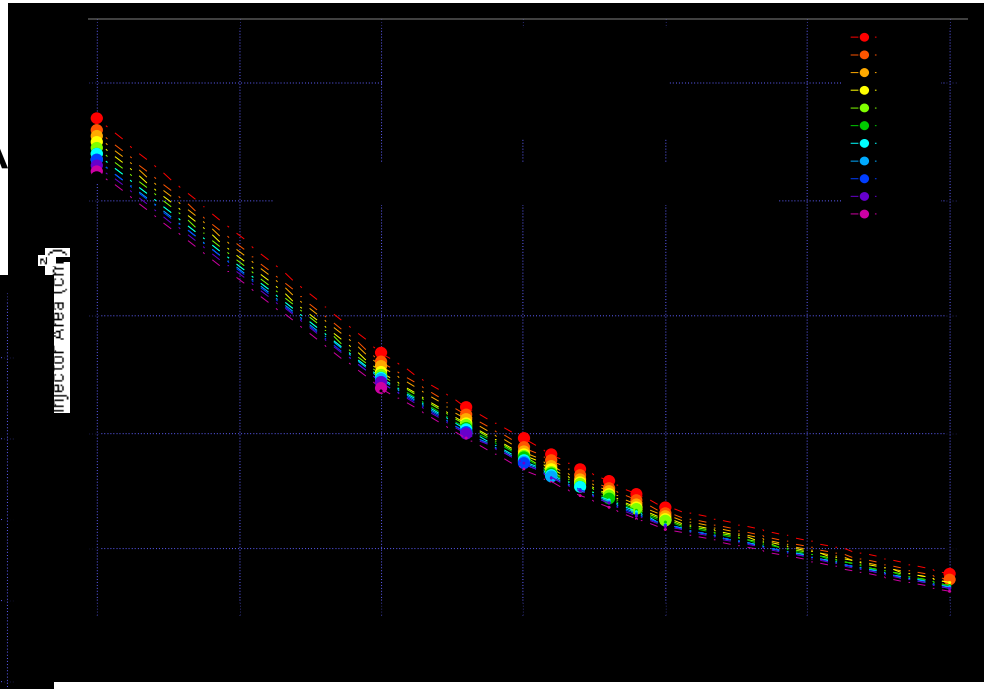
- All self-consistent with □ estimates
  - Simplifying assumptions:
    - closed circular flux surfaces
    - Edge q > 3 (basic kink stability)
    - Injector location R_{Gun} = 0.7m
    - V_{inj} ~ 600V
    - 100% helicity conservation
    - radial force balance

Use Simple Helicity 0-D Confinement Estimates to Define Gun Design

Confinement estimates obtain self-consistent plasma parameters using $V_{eff} I_p$

- Te ~ 50eV, n ~ 10^{18}, Ip ~ 5-100kA
- τ_e estimates empirically derived



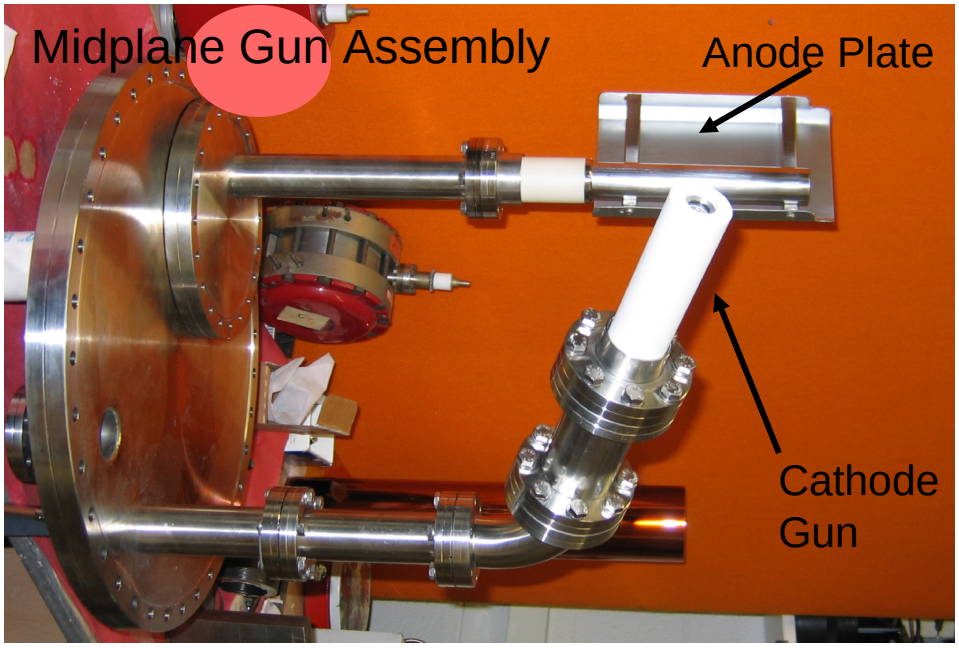


ITER_98p
- *Consistent w/most tokamaks & ST's*

Connor-Lackner-Gottardi (CLG)
- *provides region of uncertainty*

Experimentally, Washer-Stack* Guns Provide a Source of DC Helicity





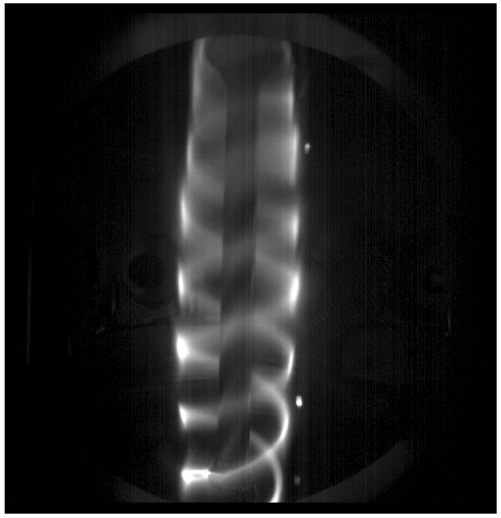
- Direct current source along **B**
- Low impurity content
- Scalable to larger size & other experiments
- Controllable by current feedback loop
- Significant power per device (1-2 MW)

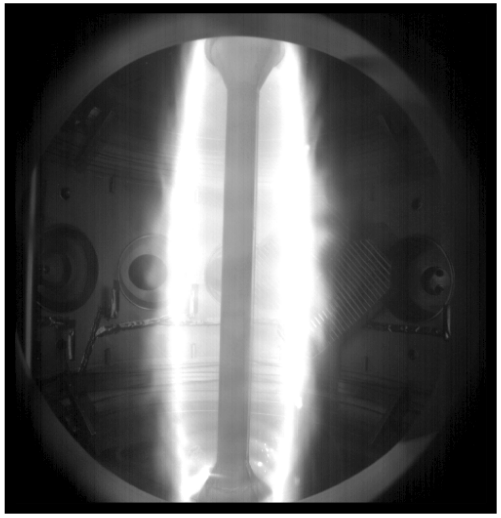
** Originally designed and provided by MST*

Divertor Guns Demonstrate Proof of Concept on Pegasus

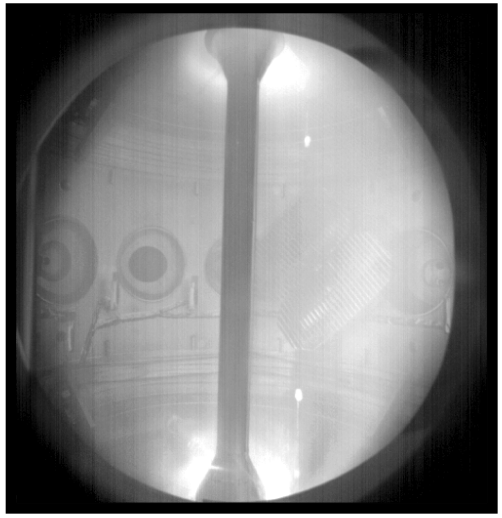
- At low I_{inj} and/or high pitch angle, helical current filaments form
  - $M = I_p/I_{inj}$ = Geometric stacking

- At low fields ($B_\square \approx 0.01$ T, $B_\square \approx 0.005$ T), tokamak-like relaxation occurs
  - M >> Geometric stacking





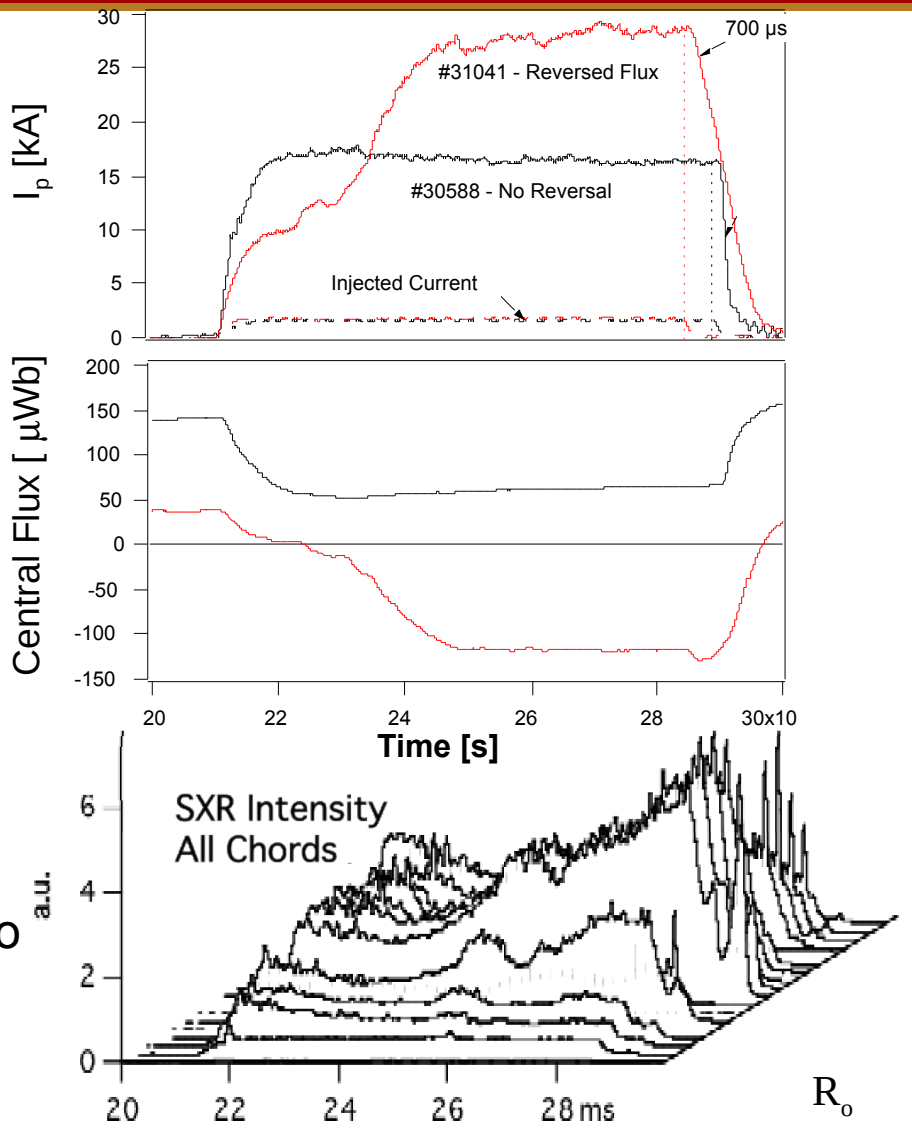




(1a) Filaments (1b) Sheet (2) Relaxed

Plasma Measurements Suggest Formation of Closed Flux-Surface Plasmas

- I_ϕ increase > 50 %
  - Max observed < 50kA
- Core flux-reversal
- τ_{Decay} increase > 400 %
  - w/o reversal ≈ 160 μs
  - w/ reversal > 700 μs
- Radial force balance ~satisfied
  - B_v required (for 30 kA, R=0.4 m):
  - $\ell_i = 0.5: 0.0072\ T$
  - $\ell_i = 0.0 : 0.0054\ T$
  - Applied B_v: 0.005 T
- Increased core heating observed
  - O-V (114 eV) to O-IV (77eV) line ratio
    - Te > 50 eV
  - SXR Emission peaks at midplane
    - Midplane signals decay slower



Comparison of V_{eff} & decay V_{surf} indicates that helicity balance determines maximum current drive

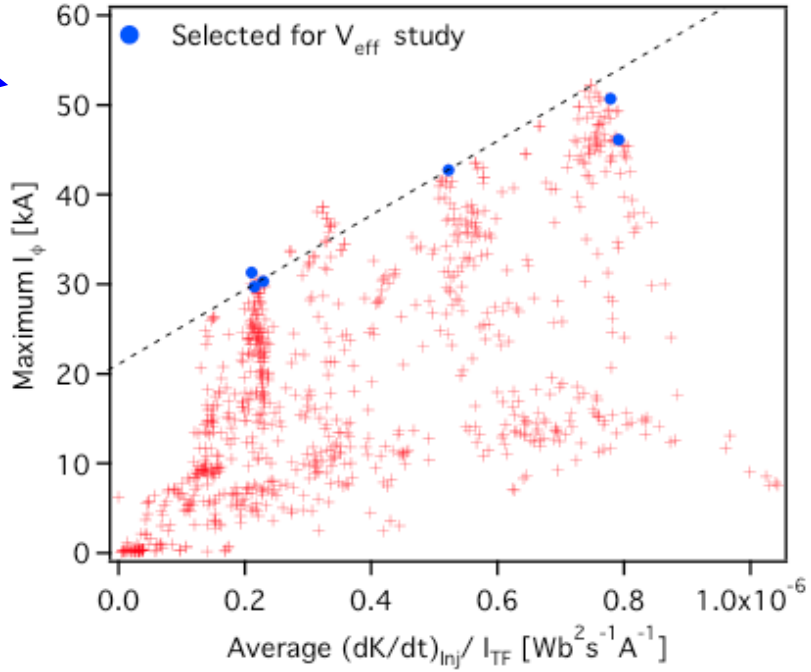
- Max I_ϕ offset linear to injected dK/dt
- dK/dt limiting I_ϕ?
  - Compare V_{eff} & decay V_{loop}
- Decay V_{Loop} estimated by V_{surf}
  - Measured by center column flux loo

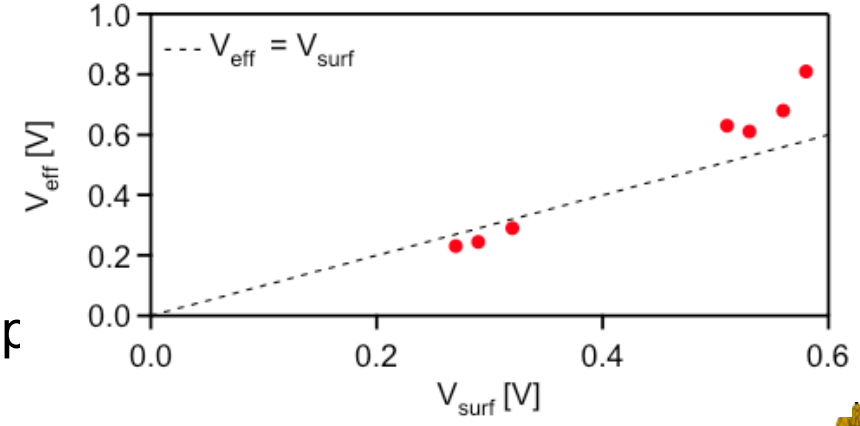
Guns (2) — TF at gun

$$V_{eff} \approx V_{inj} \frac{N_{inj} A_{inj} B_{Tinj}}{A_p B_{Tp}}$$

Plasma X-section area — TF at plasma centroid

- $V_{eff} \approx V_{surf}$ indicates:
  - Helicity efficiently transported into p
  - Current drive limited by dK/dt



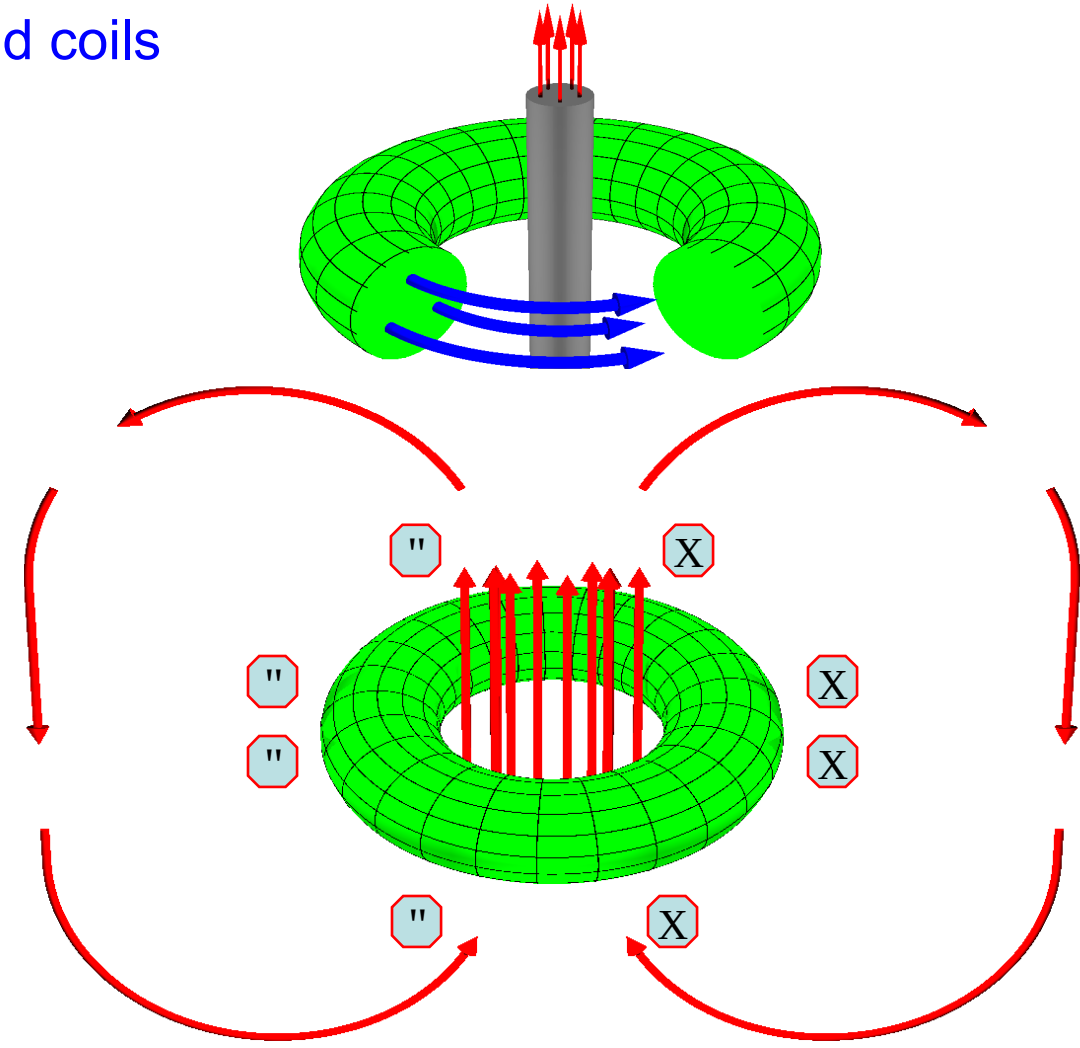


Poloidal Field Coils can Drive Plasma Current

- All tokamaks use poloidal field coils
  - Null formation
  - Plasma shaping
  - Radial Stability

- Ramp PF coil currents to drive plasma current

- For given magnetic field V• s determined by central plasma torus area



PF Induction is a Nonlinear Process

- Conceptually simple, analytically intractable
- The plasma loop voltage determined by a simple circuit equation;

$$V_{Loop} = \Lambda_\iota \frac{\delta I_\pi}{\delta \tau} + \frac{1}{2} \frac{\delta \Lambda_\iota}{\delta \tau} I_\pi + I_\pi R$$

Plasma Resistance

- $B_{v,}$ applied for radial equilibrium, must be self-consistently satisfied.
- Need complex modeling (TSC) to include nonlinear processes
  - 1-D modeling in anticipation of running TSC
    - Use well characterized evolution values for ohmic induction
    - C_E ~0.5, Spitzer Resistivity, etc…

Some Basic Plasma Assumptions

- Linearly increasing Ip (5kA→100kA)
- Circular cross-section
  - R_o & a grow to fill vacuum and maintain edge stability (q>3)

- Plasma parameters evolve linearly in time (n_e, T_e…)
- Basic confinement and wall modeling develop coil programming scenarios
- Independent control to maintain necessary B_v and V_{Loop}

- Preliminary Ejima analysis (C_E≈0.5) approximates possible plasma currents
  - Wall code examines coil capabilities for scenario
  - Initial plasma currents of 5&10kA show ~60-75kA final Ip

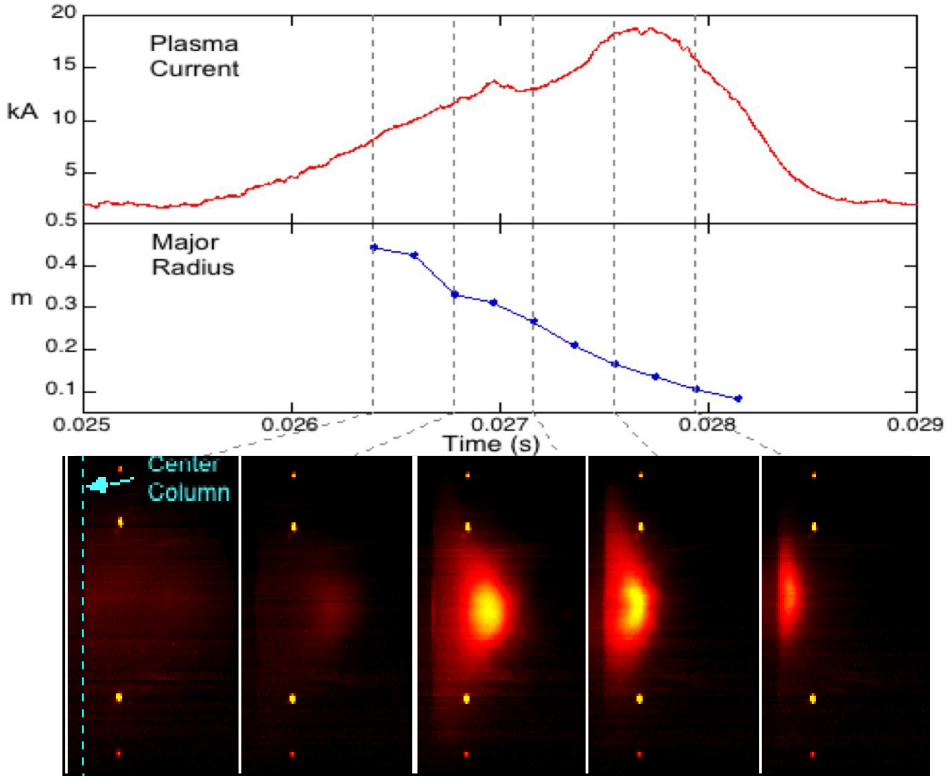
- Does not include coupled dynamic wall or plasma response

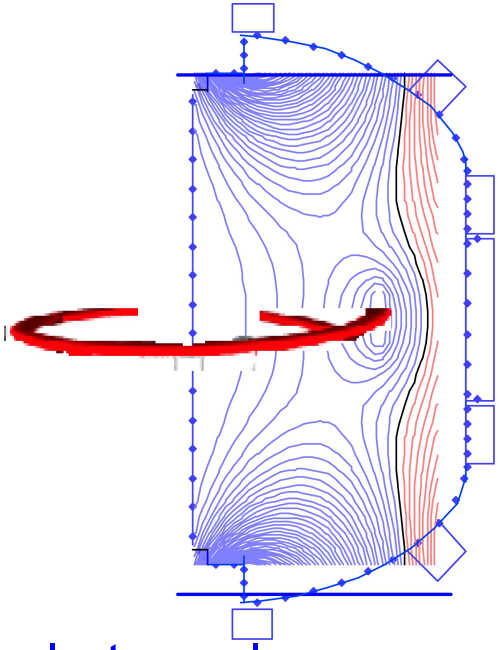
Design considerations for an outboard gun system

- Recall: For a given η, V_{inj}, A_{inj}, $I_p \sim \frac{1}{R_{Gun}}$
- Edge q > 3 calculations show larger possible I_p for smaller R_o
- Start-up is a 2 part process
  - Initiation : want maximum I_p
  - Evolution : want maximum induction possibilities
- Goal is to optimize the system
  - Divertor region not optimal startup location
  - Midplane port design more scalable
  - Central plasmas have fewer available V• s
  - Edge plasmas cannot be large or have high initial I_p
    - require more growth
- Divertor and outboard midplane regions represent wide experimental range for DC helicity injection in Pegasus

PF Induction Tests on Midplane Show Promising Results

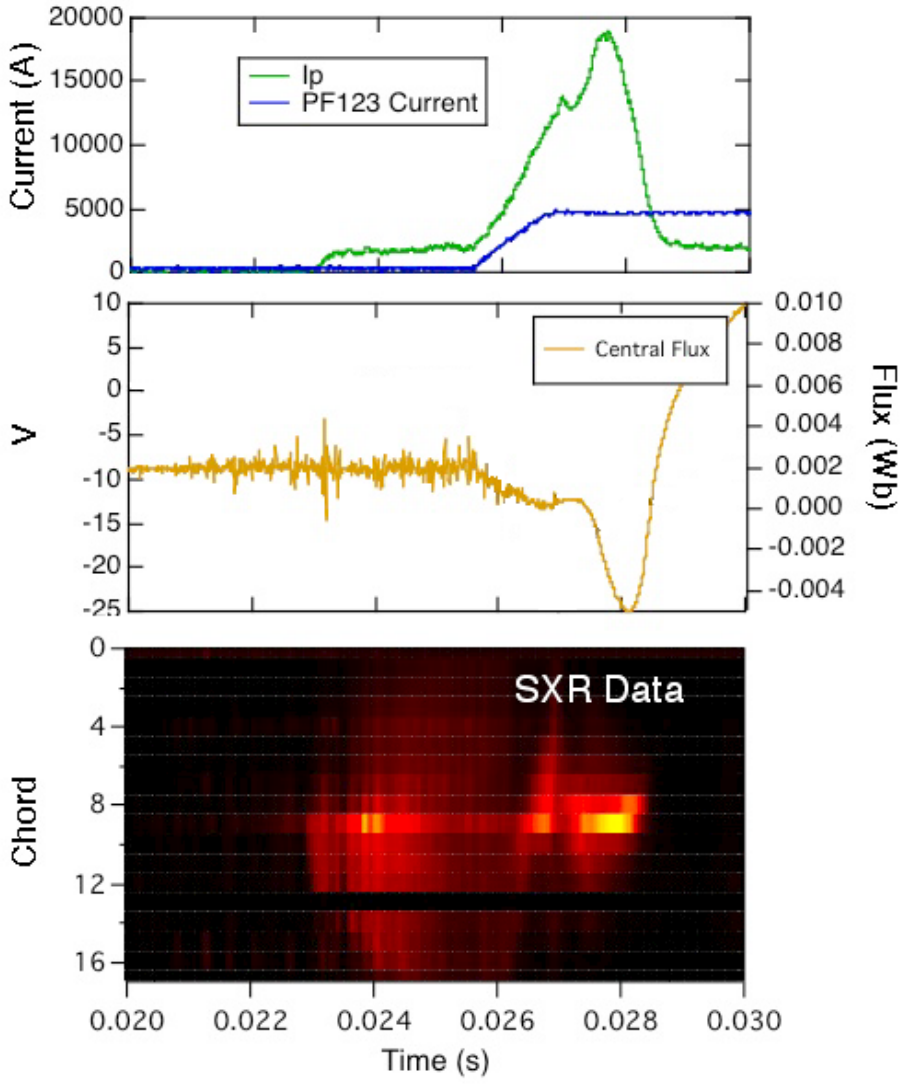
- 1 kA gun on midplane
  - R=0.7 m
  - Current returns to separate anode - *not vessel*





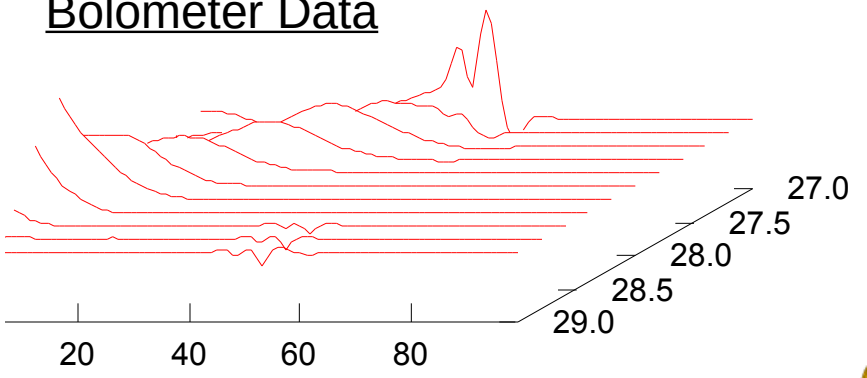
- Single turn plasma produced
  - Kink unstable
- Poloidal fields ramped in
  - OH-free PF induction
  - 1kA→18kA
  - Plasma moves radially inward

Single Turn PF Test Drives a Small Plasma



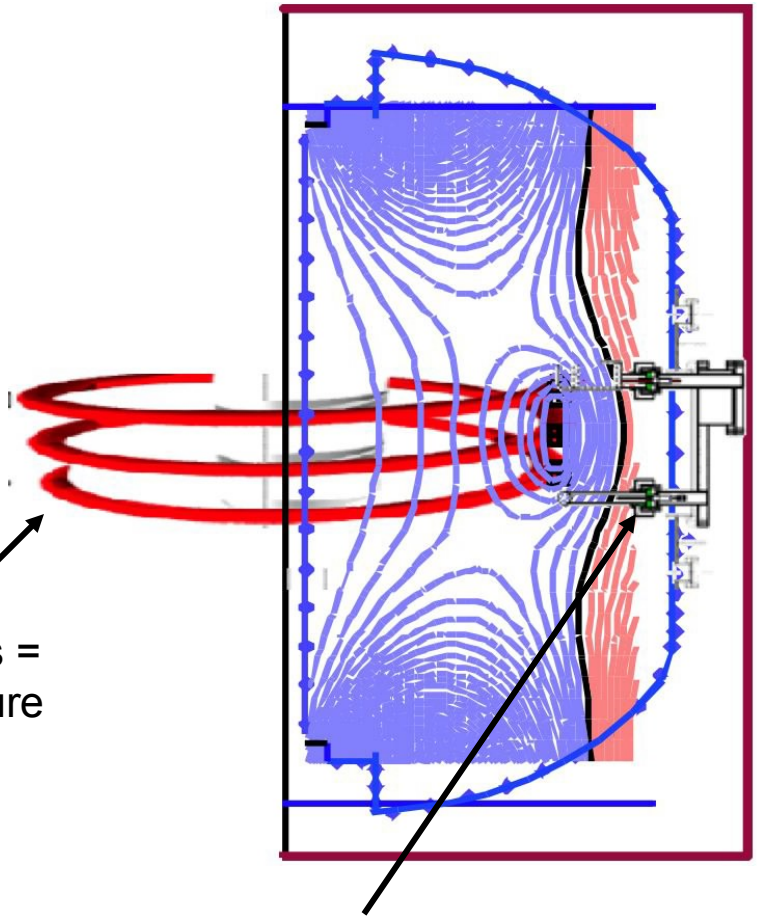
- Diagnostics indicate flux closure
  - SXR: increased signal
  - VUV: O-V > O-IV
  - Central flux: reversal observed
  - Bolometry: centrally-peaked radiation moving toward centerpost

Bolometer Data



2nd Experimental Campaign: Helicity Assisted PF Induction

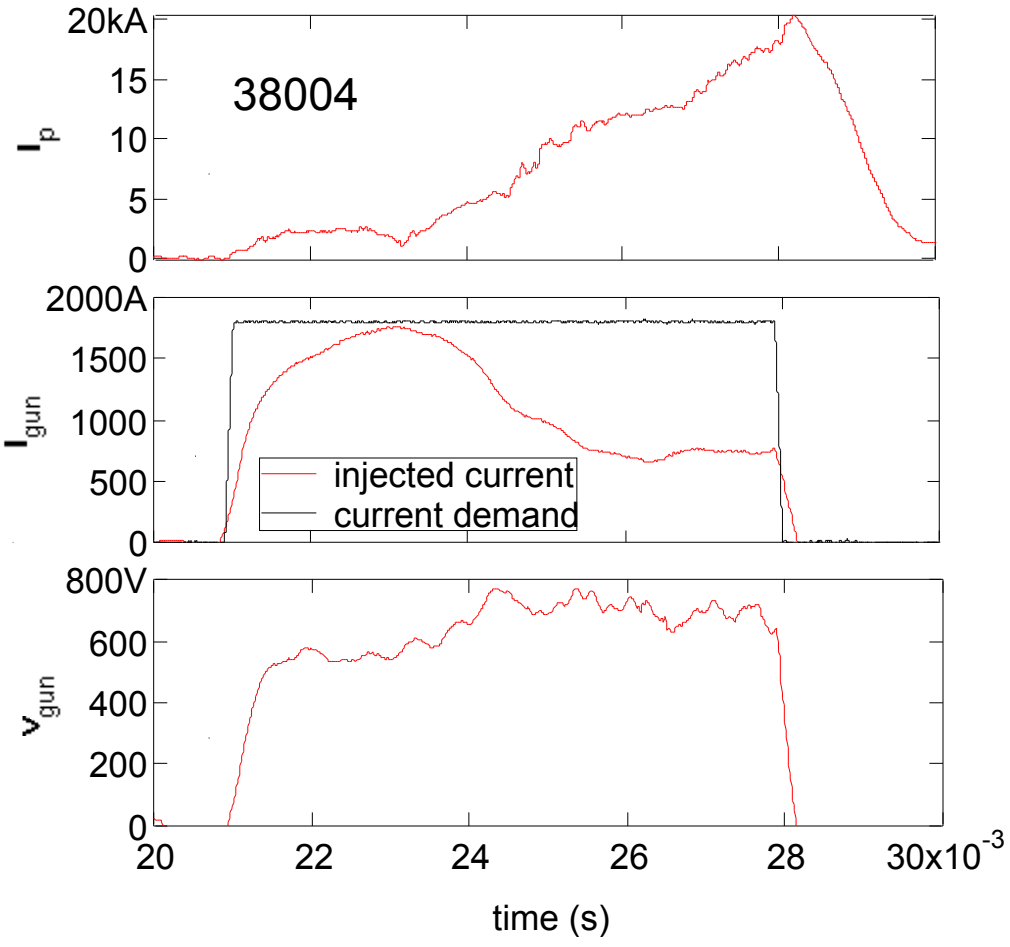
- Initial target: 5 kA plasma
  - q > 3
  - Self-consistent conditions satisfied
- Install assembly at midplane
  - 2 kA gun
  - R=0.7 m
  - 2b = 0.3 m
- Design for 3 turns
  - TF=20 kA
  - B_v = 16 Gauss
    - Radial force balance for 5 kA
- Field reversal likely
  - Wall code shows closed FS
  - Helicity balance calculations OK



Midplane Gun Used to Create Relaxed Discharges

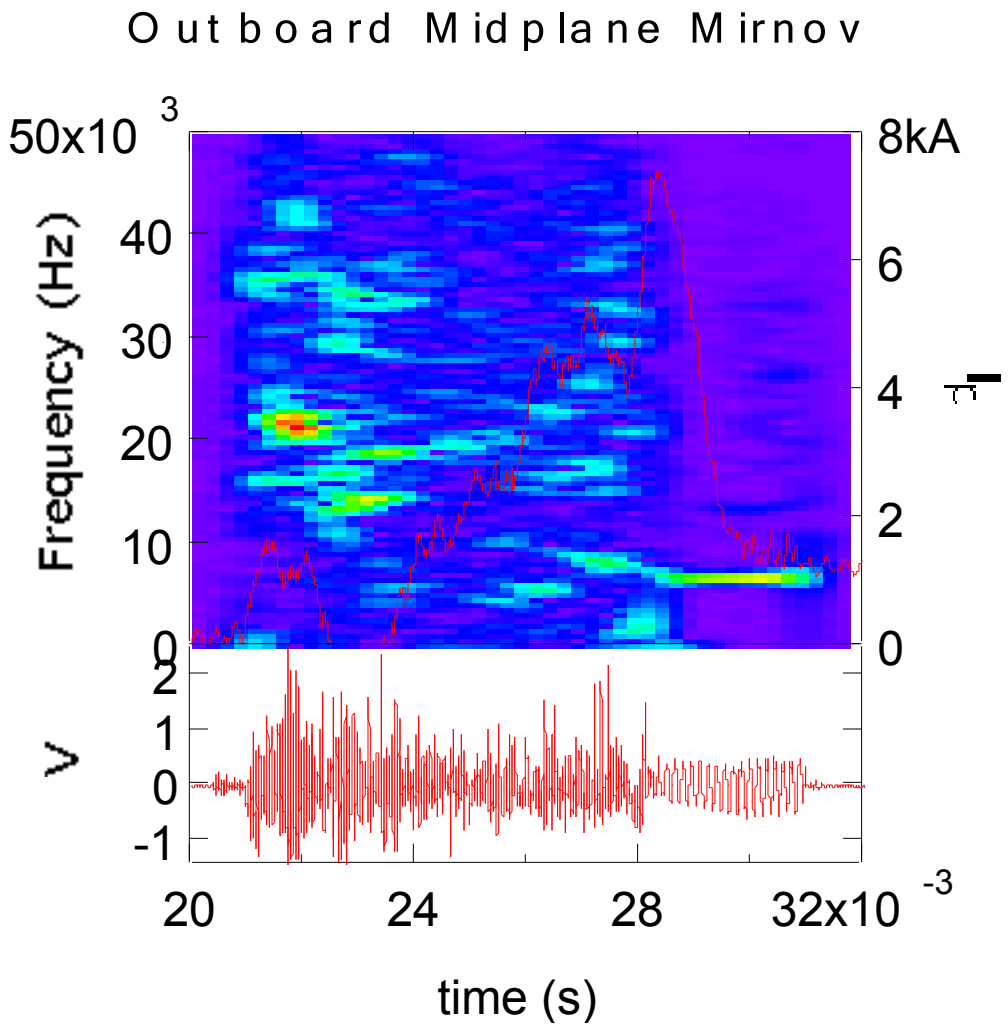
- Driven current is limited by power supply voltage
  - higher voltage may allow more injected helicity
- I_p = 20 kA for I_{gun} = 750 A
  - M = 26
  - static fields
- Tokamak-like discharge with

  R = 0.4 m observed after gun turns off
  - I_p decay much longer than I_{gun} decay



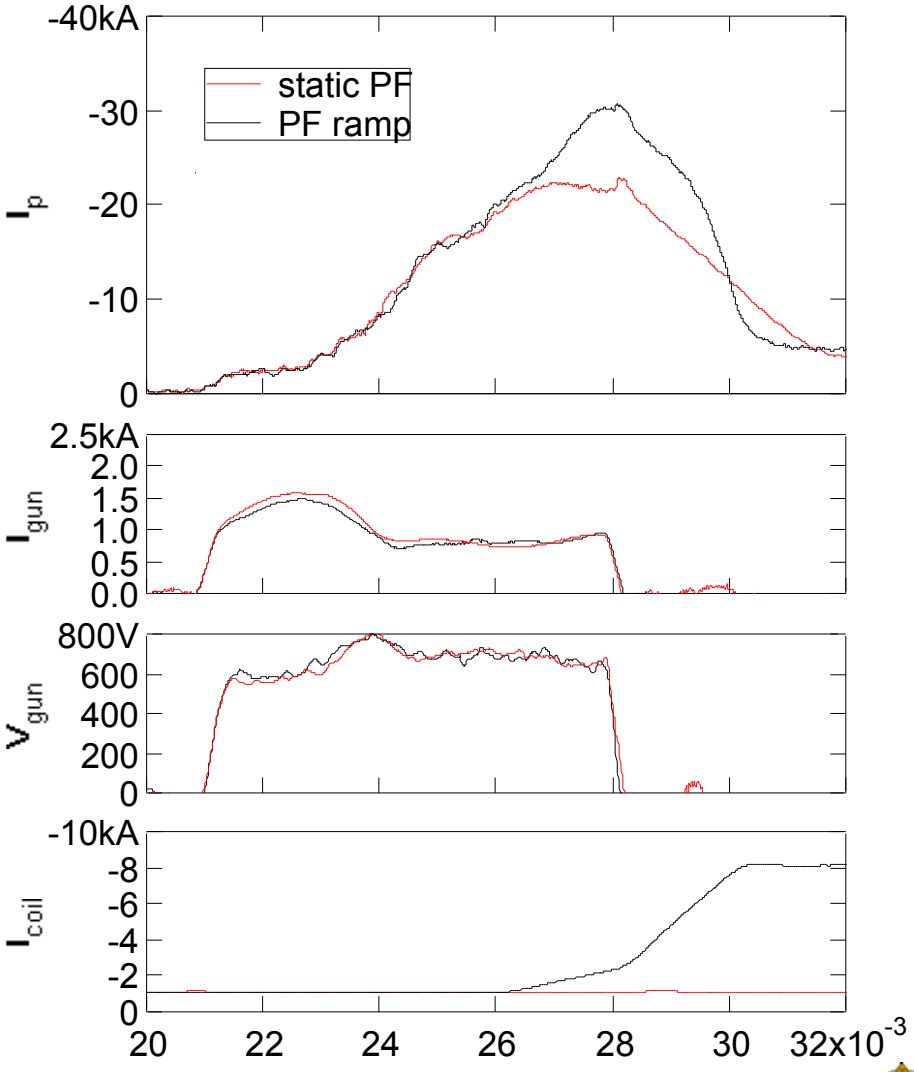
Coherent MHD After Gun Shut-Off Indicates Flux Closure

- 22 kHz mode present during unrelaxed phase
  - less coherent activity during relaxation
- 7 kHz mode appears while plasma is in decay phase
  - similar frequency to typically observed TM in Pegasus
- Mode decreases in amplitude and duration with lower pre-fill pressure and higher I_p
  - hotter discharge?



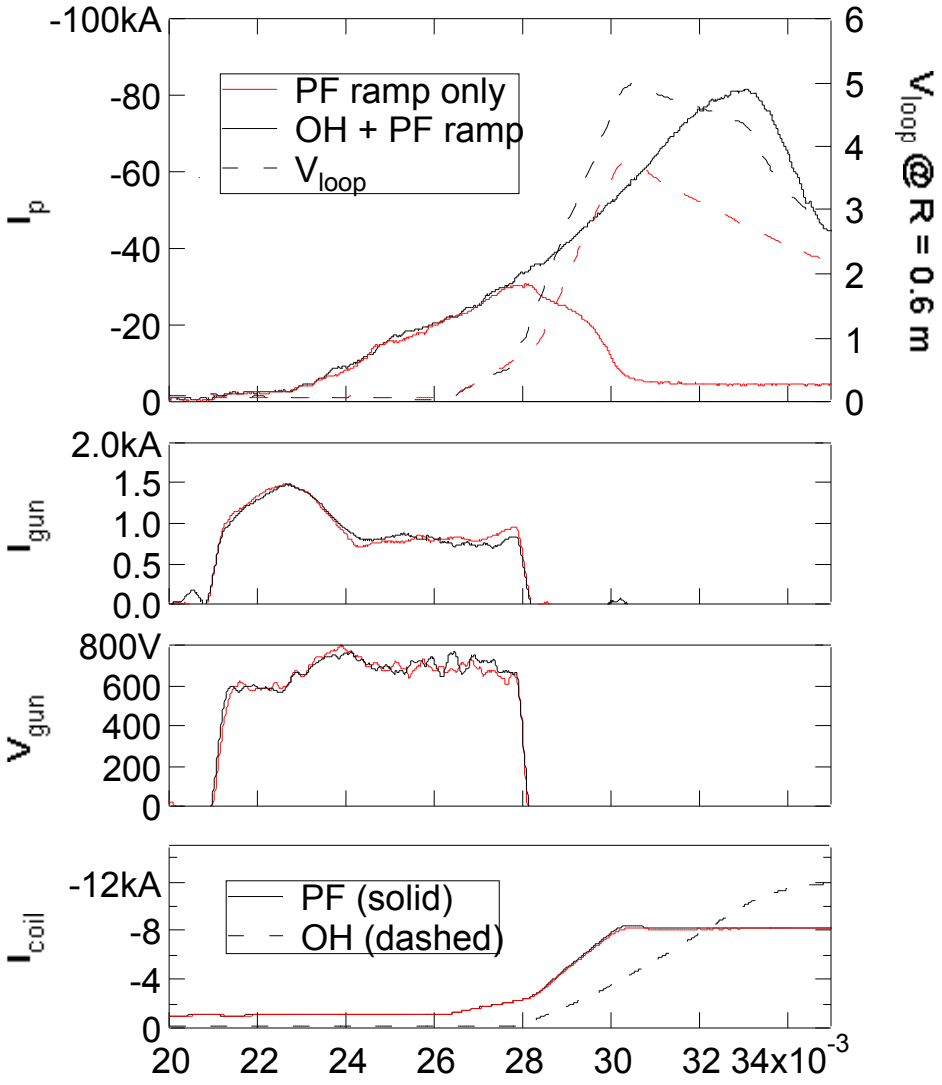
PF Induction Enhances I_p

- PF induction before gun shut off increases I_p by ~ 50%
  - limited by radial force balance
  - high B_v during injection causes plasma detachment from gun
- Fast PF ramp after gun off drives plasma into core
- PF induction insufficient to sustain midplane gun discharge in this configuration
  - possibly more effective with higher target current
  - next generation, high-power gun array will give further test



OH Induction Able to Ramp Up Midplane Gun Discharge

- Additional V_{Loop} does not affect radial force balance
- OH plasma still moves in radially, but much more slowly
- Handoff much easier than with divertor guns
  - large R gives longer decay time
- Operations halted to install higher power guns
  - all results to date with simple prototype single gun
  - high power gun array being installed 11/07



High Power Gun Array Being Installed

- 3-gun array at single toroidal location
  - 3x current of prototype
  - still use single anode
  - broad scrape-off should allow simultaneous injection
- High-voltage power supply in design
  - should allow more injected helicity
- Initial tests 12/07
  - existing power supplies
  - optimize gun configuration

⇒ New array & power supplies should easily give > 100 kA relaxed gun plasma

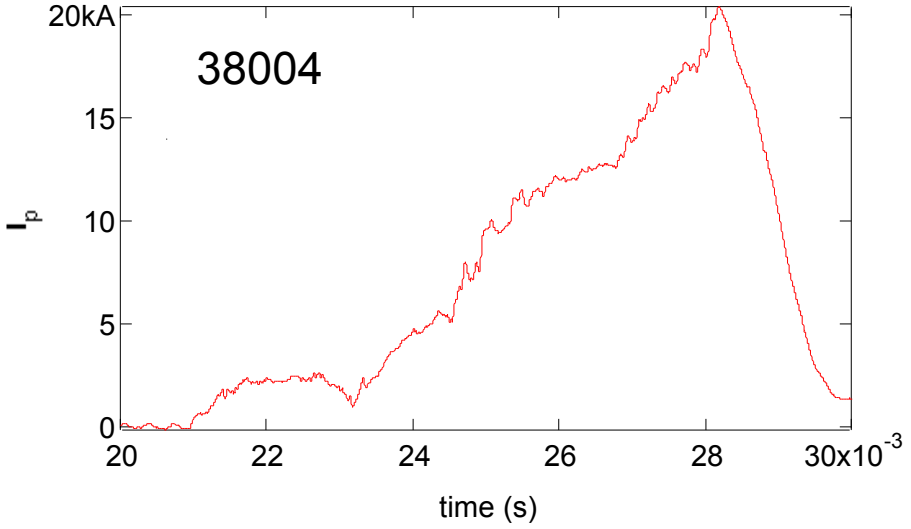


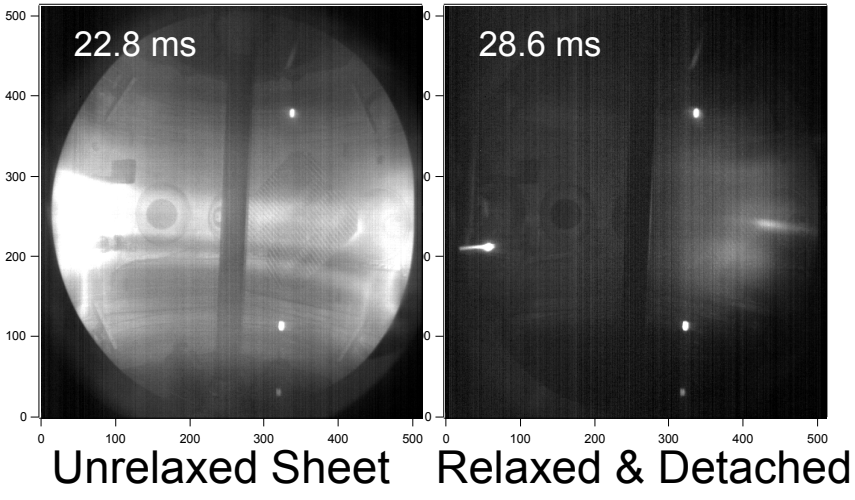
Future Work

- Expand target formation space
  - Vary size, current, and radial location of plasma
  - Reconstructions & Stability analysis (DCON)
    - Does the helicity, equilibrium, and energy balance as expected?
- Helicity consumption/efficiency analysis
  - How does helicity penetrate with different compression techniques?
  - Is 1-D model accurate-enough?
  - Can we benchmark compression processes against TSC and NIMROD models?
  - Does initial target state effect final compressed state?
- Process optimization in Pegasus
  - Describe physics that optimize/classify operating regimes in Pegasus
  - *What tradeoffs are acceptable, given a set of experimental goals?*
  - Can we extrapolate our understanding to 100-200kA design?
    - *Create scalable procedure, NSTX*

Midplane Gun Successfully Creates Relaxed Discharges

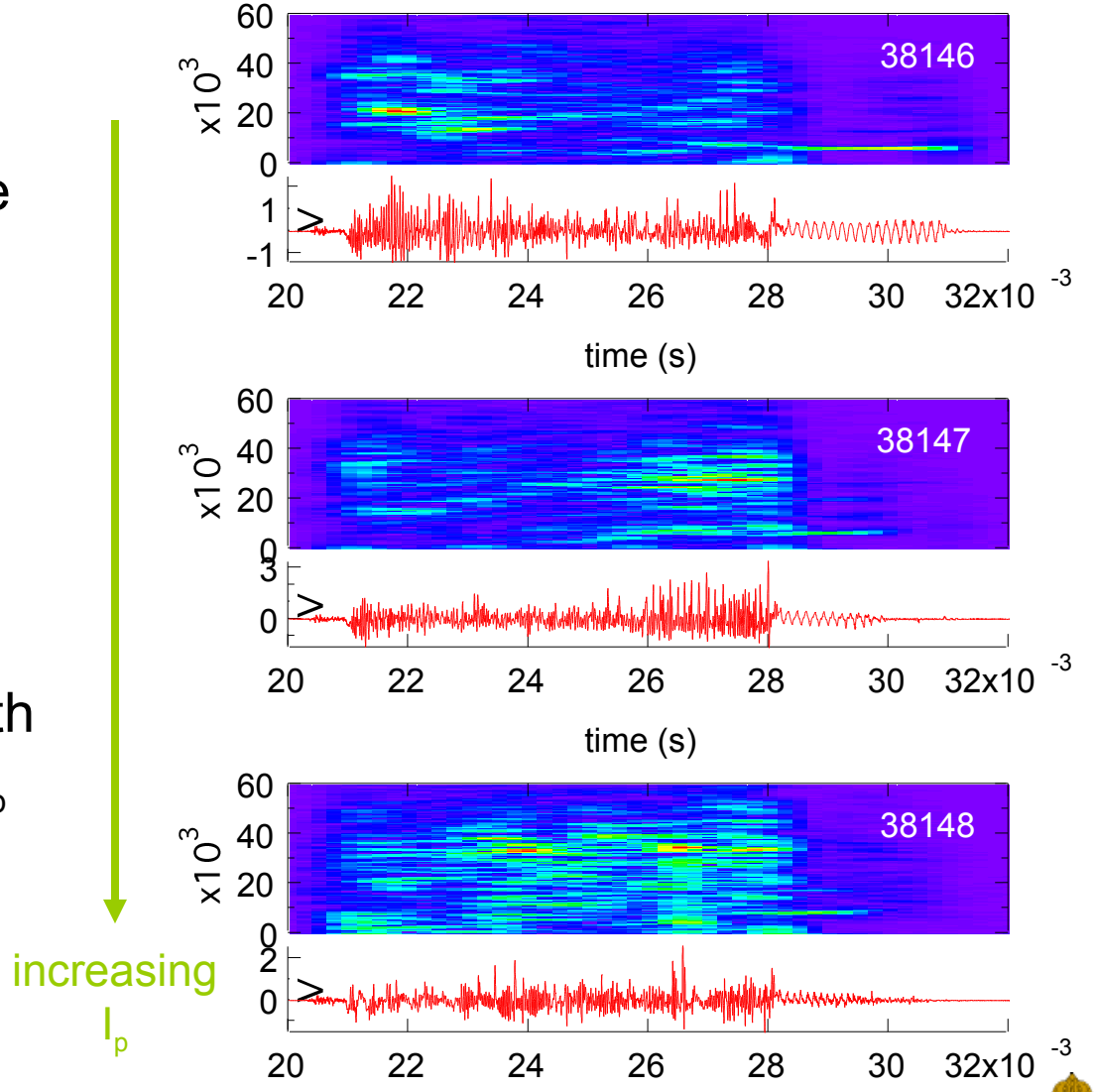
- Discharge evolution similar divertor gun plasmas
- Unrelaxed sheet plasma w/geometric current multiplication until 23 ms
  - then 4 MA/s ramp until gun shut-off
- Relaxed ST-like discharge observed after guns turn off





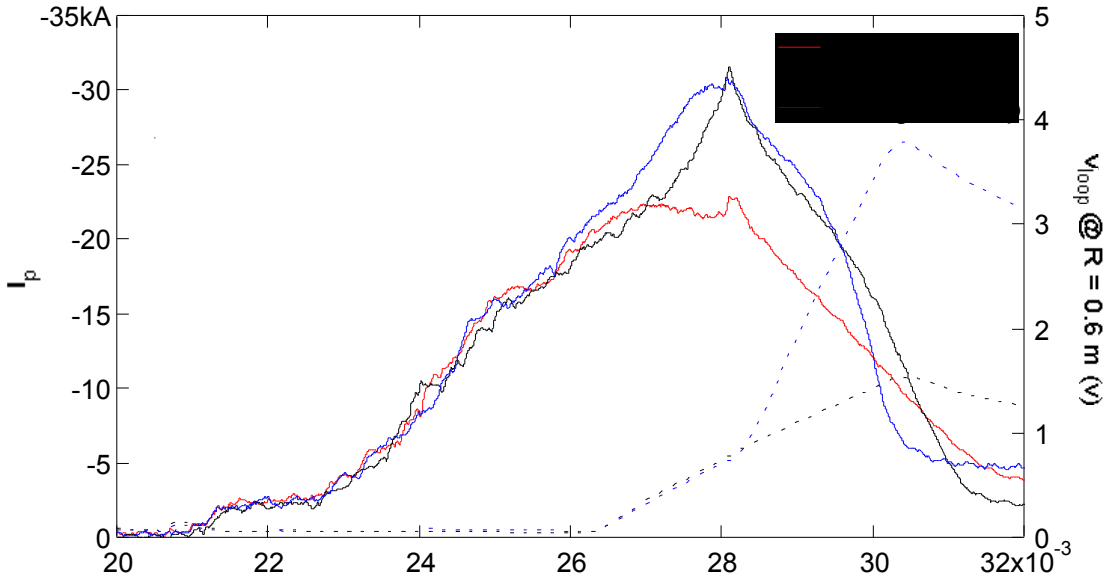
Coherent MHD After Gun Shut-Off Indicates Flux Closure

- 7 kHz mode appears while plasma is in decay phase
  - outboard midplane Mirnov
- Mode decreases in amplitude and duration with lower density and higher I_p
  - hotter discharge?



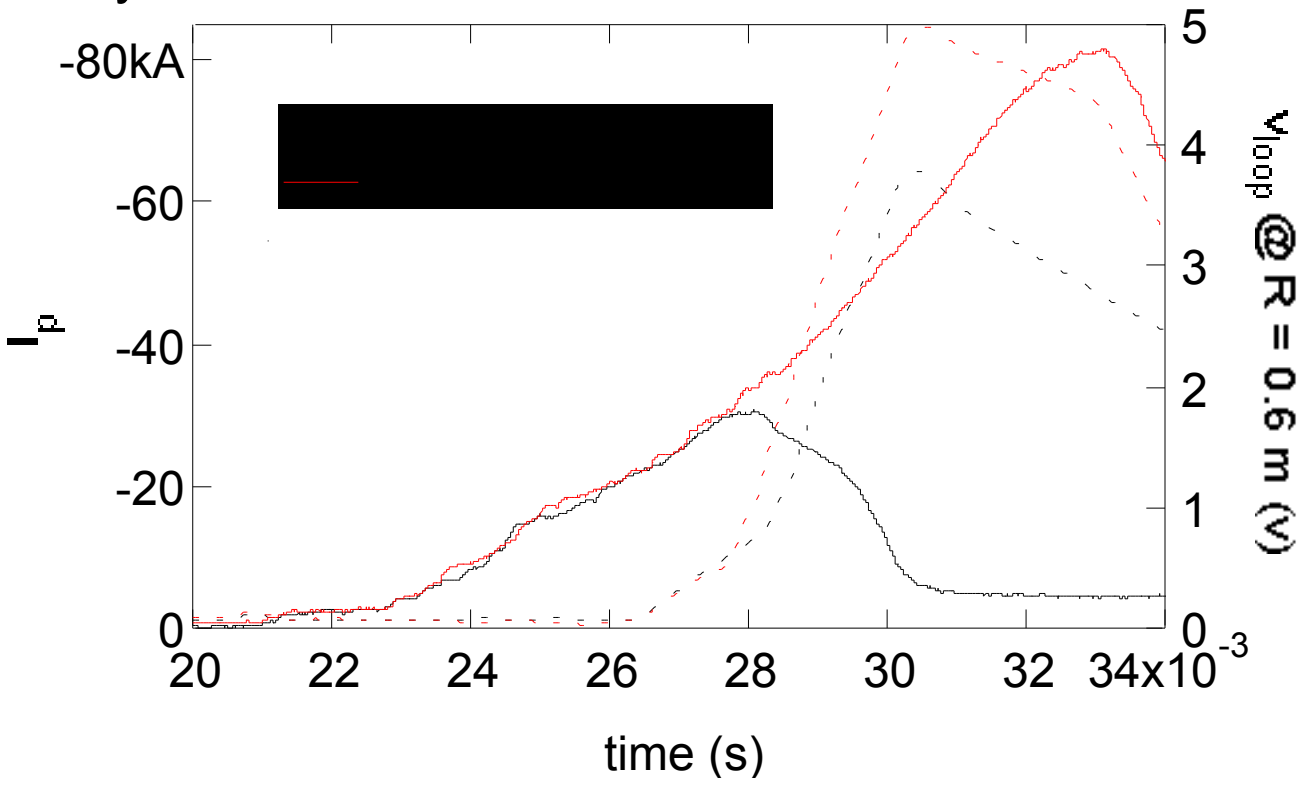
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- PF induction insufficient to sustain midplane gun discharge in this configuration



OH Induction Able to Ramp Up Midplane Gun Discharge

- Additional V_{Loop} does not affect radial force balance
- OH plasma continues to move in radially, but much more slowly



η Has a Subtle Dependence on Various Plasma Parameters

- $\eta = m_e/(n_e e^2 \tau_c)$
  - 1st order depends on mass, density, & momentum loss-time of electrons
    - Often Spitzer resistivity is quoted where simple electron electron collision times are used for τ_c,

$$\eta_{sp} = 2.8 * 10^{-8}/T_e^{3/2} \ (\Omega \bullet m)$$

  - Even in the simple Spitzer estimation plasma shaping, confinement times, and power radiation can dramatically effect the plasma temperature

  - We estimated upper bounds on the DC Helicity injection parameters (A_{inj}, V_{inj}, and R_{Gun}) using various established scaling laws at multiple machine locations

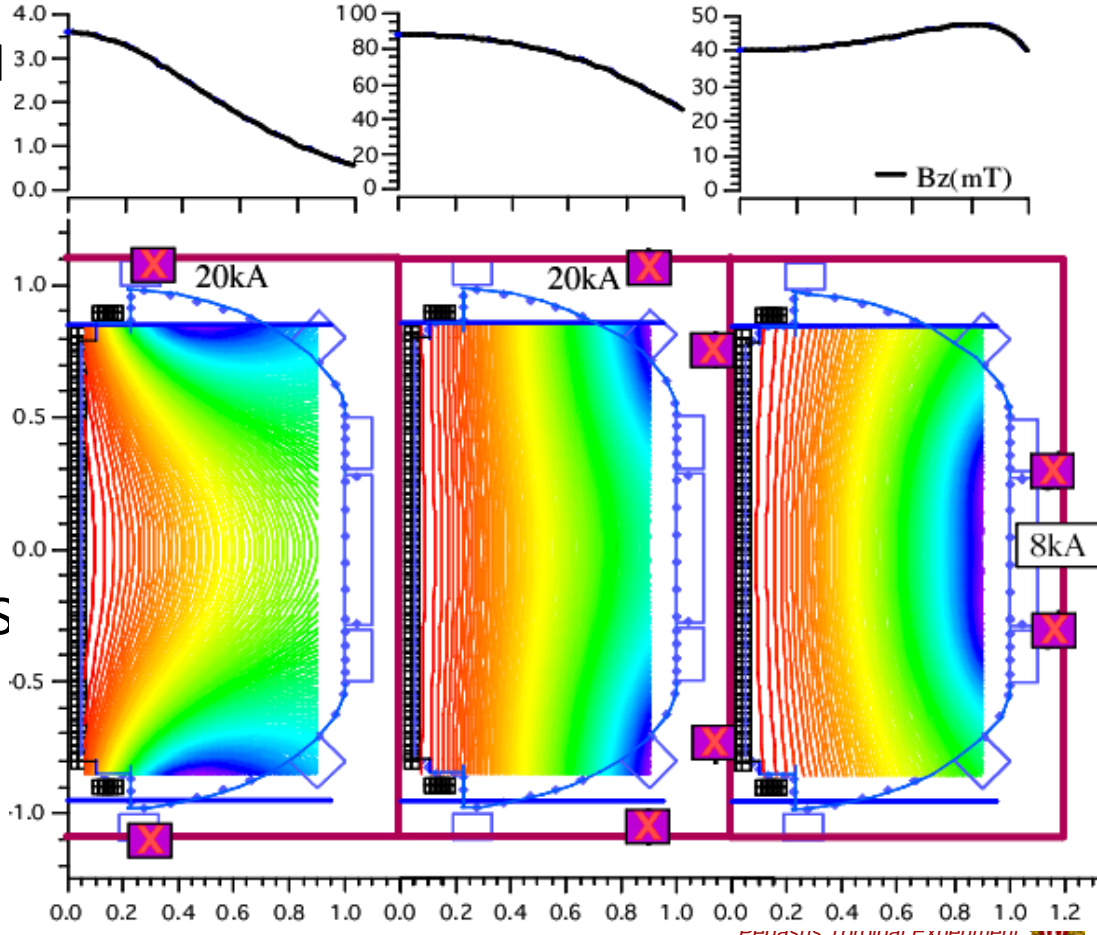
1-D Poloidal Field Approximations

- Static vacuum field modeling explores capabilities of PF coil set
- Resistive vacuum vessel modeled as 91 axis-symmetric current filaments
  - Found by integrating coupled circuit eq,

$$\bar{M} \cdot \frac{d\bar{I}}{dt} + \bar{R} \cdot \bar{I} = \bar{V}$$

  - M determined by self & mutual inductance between coils
  - *Similar technique used by NS*

**Y. Ono 20th IAEA 2004 IC/P6-35*



Confinement Code

- Basic confinement scaling looks at plasma's stored power (energy confinement)

$$\Pi_{in} - \Pi_{out} = \frac{W}{\tau_E}$$

- Where the stored plasma energy is calculated using assumed profiles in density and temperature

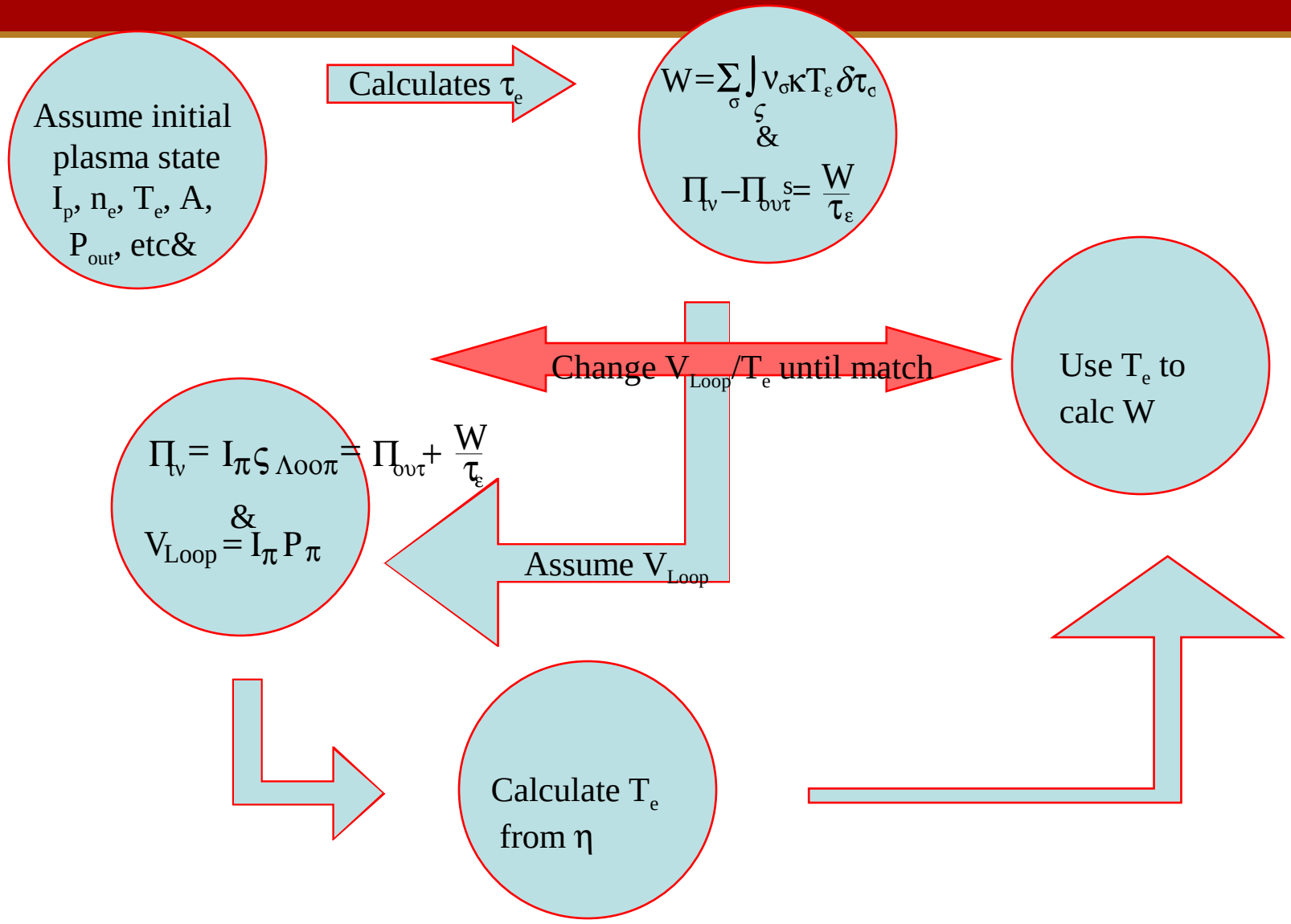
$$W = \sum_{\sigma} \int_{V} n_{\sigma} k T_{\sigma} \, dV_{\sigma}$$

- τ_e is empirically derived from multiple sets of machine data and classified by each machine
- P_{out} is determined by setting a radiative power fraction to estimate losses
- Code iterates V_{Loop} -> T_e until a self consistent solution is found, from which R_p, η, q_{edge}, etc can be determined

$$\Pi_{in} = I_{\phi} V_{Loop} = \Pi_{out} + \frac{W}{\tau_E} \quad \& \quad V_{Loop} = I_{\phi} R_{\phi}$$

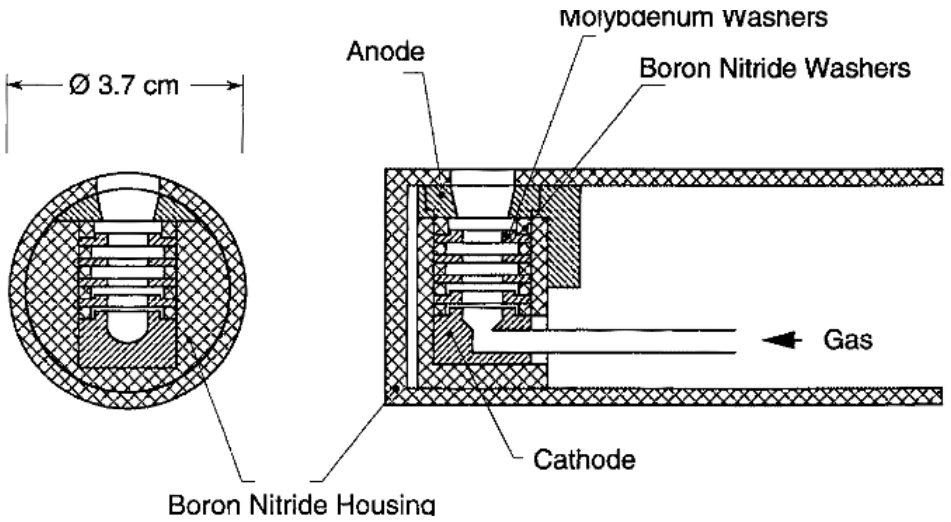
where the resistance incorporates T, and Z_{eff}

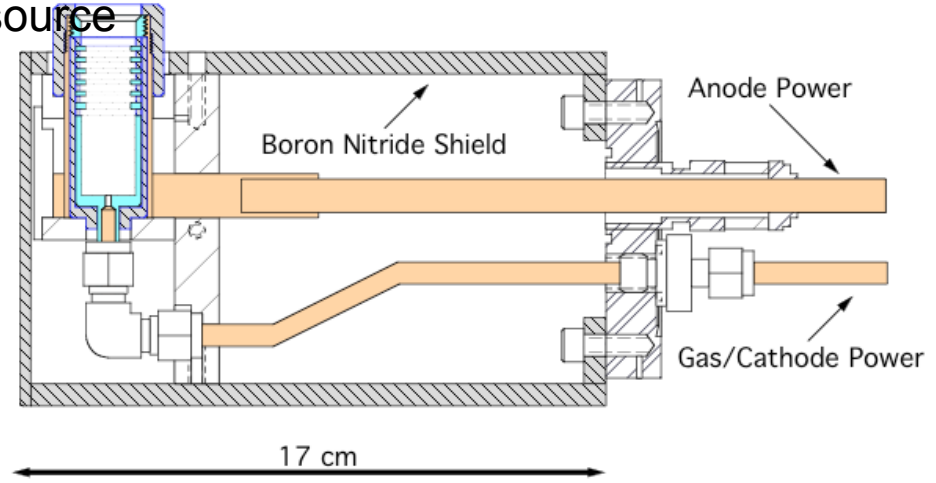
Confinement Diagram



Plasma Guns are a Source of DC Hinj

- Mo anode & cathode separated by Mo & BN washers
- D_2 fed independently via dual gas/cathode line
- BN housing
- Relatively clean plasma source
  - Internal arc formed
  - Anode of arc is cathode of electron source
  - Small aperture area
- Typical parameters:
  - I_{arc} = 1-2 kA
  - I_{inj} = 1-2 kA
  - V_{inj} < 900 V
  - δt_{arc} = 0.01 s (set by heating)





KFIT Equilibrium Reconstructions

MHD equilibrium determines global plasma parameters

Magnetic diagnostics provide fitting contraints

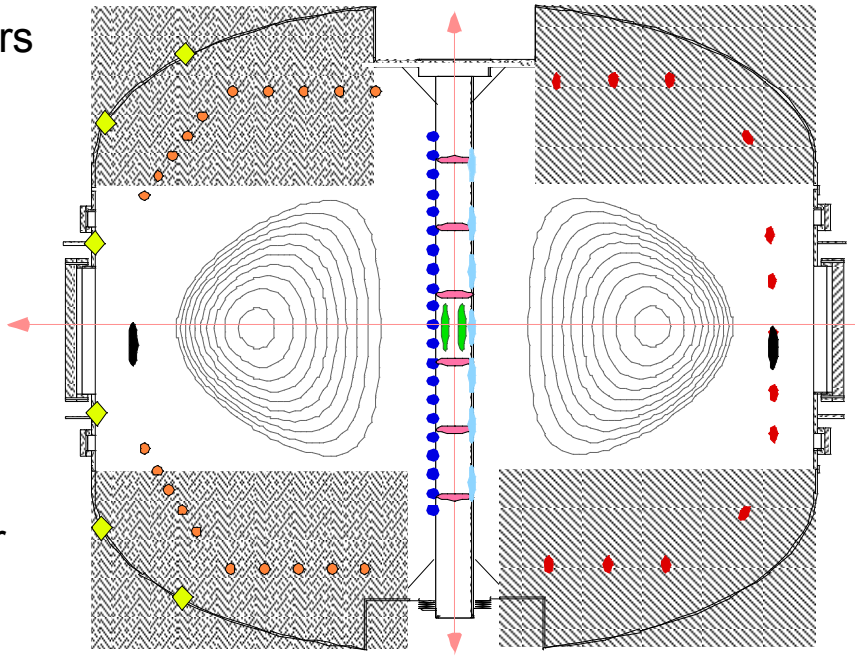
- An array of flux loops and Bdot coils on inboard and outboard sides

Induced vacuum vessel currents are taken into account

- Wall currents on the order of plasma current
- Axisymmetric current filament model for 1st order correction
- Wall currents constrained by wall loops

Iterative process: Grad-Shafronov solution decoupled from $\chi 2$ minimization

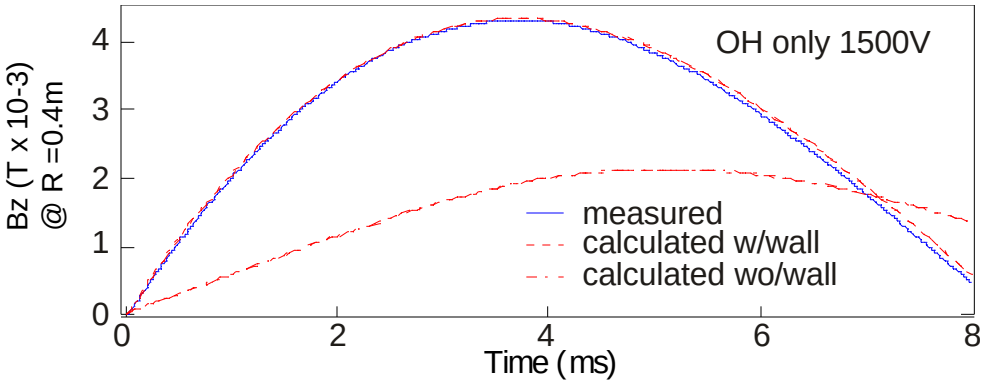
- IGOR Pro routine interfaced to an ANSI C G-S solver
- Guass-Seidal 2-D grid relaxation
- $\chi 2$ minimized via Levenberg-Marquardt method

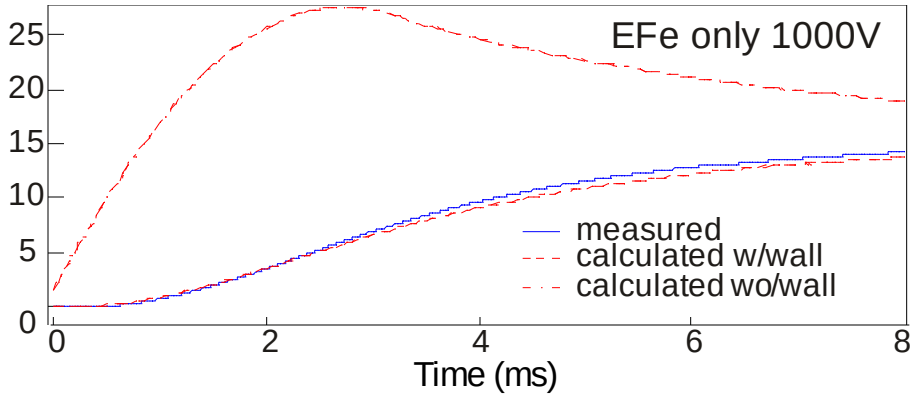


Fluxloops	20
Poloidal Mirnovs	13
LFS Toroidal Mirnovs	6
Wallloops	6
HFS Toroidal Mirnovs	7
Core Flux Loops	6
High Res Mirnovs	21
Low Res Mirnoves	7

Wall Model Calibrated with B Probe Measurements

Predicted OH and EF coil values match measured data well

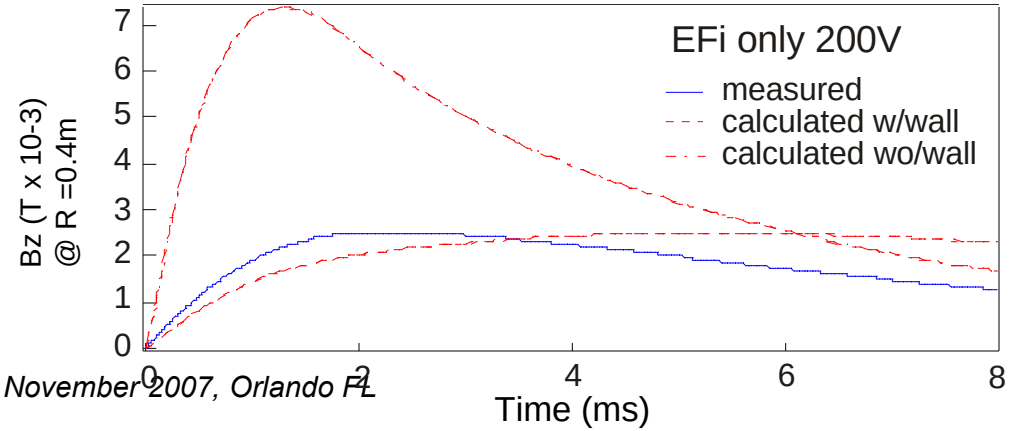




Predicted values for internal trim coils show more deviation

" Port structures with time varying inductance couple strongly to internal coils

" Model provides low order correction



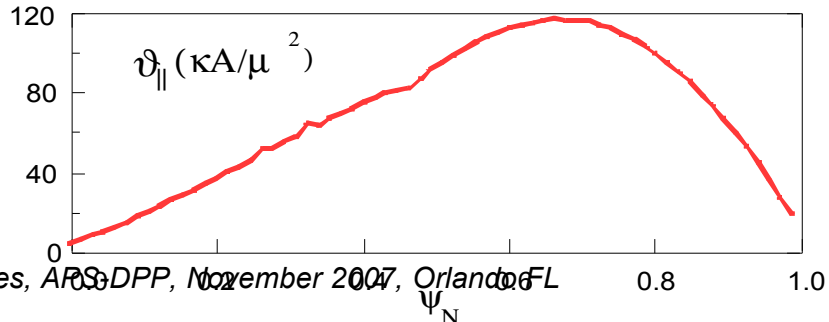
Gun Reconstructions: During Current Injection

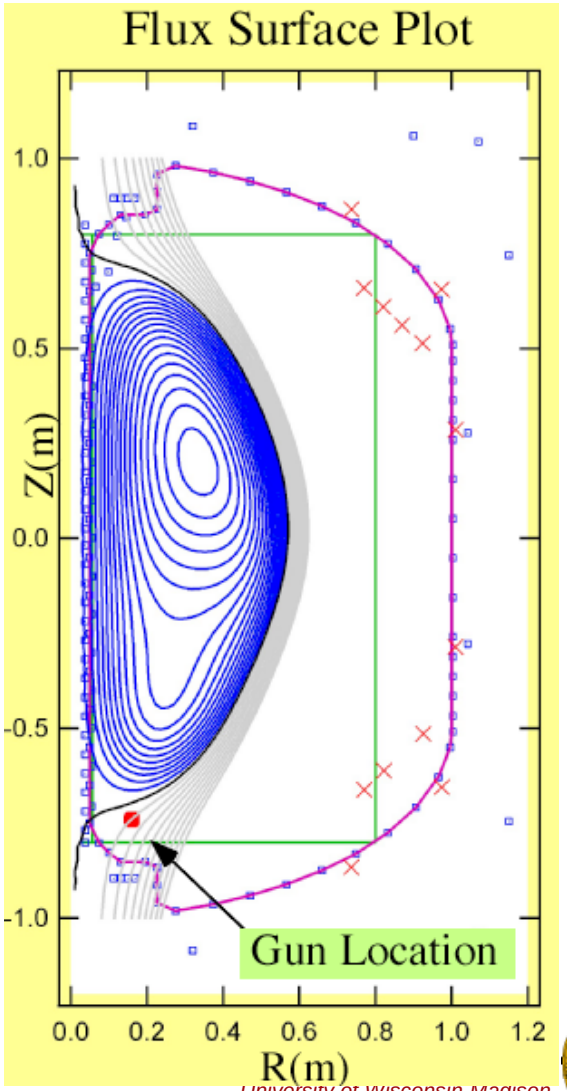
- GS solver assumes closed flux surfaces
  - Open field line current ignored to 1st order
    - reconstruction results only approximations
  - Post gun phase there are no external currents
    - reconstructions reliable

I_π	45.6 (κA)
Xo	0.335 (m)
Zo	0.201 (m)
l_i	0.225
a	0.252 (m)
K	2.49
θ0	2.074
θ_{99}	8.18

c plasma parameters:

- Flux surfaces vertically asymmetric
- Magnetic axis off center
- Highly Elongated
- High edge q
- Extremely hollow current profile





Flux Consumption Analysis

- Accounting technique for flux lost to dissipative processes
  - Resistive heating
  - Breakdown
  - Vessel currents
  - Transport
  - Current channel formation
  - MHD activity
  - Radiation

$$\Phi_{TOT} = \Phi_{ext} + \Phi_{int}^{ind} + \Phi_{dis}^{ind}$$

Φ_{TOT} = Total flux from coils

Φ_{ext} = flux generated by plasma, but external to it

$$\frac{1}{2} L_{ext} I_p + \int_0^{\tau} \delta\tau' \Lambda_{\varepsilon\xi\tau}(\tau') \frac{\delta I_\pi(\tau')}{\delta\tau}$$

* L_{ext} is difficult to calc

Φ_{int}^{ind} = internal plasma flux

$$\frac{1}{2} L_i I_p + \int_0^{\tau} \delta\tau' \Lambda_l(\tau') \frac{\delta I_\pi(\tau')}{\delta\tau}$$

*L_i is calc d from plasma reconstruction

Φ_{dis}^{ind} = flux used by dissipative processes

$$L_R I_p = C_E m_0 R_o I_p$$

* Dissipative processes are given this form to define the Ejima coefficient

$$C_E = \frac{1}{m_0 R_o I_p} \left(\Phi_{TOT} - F_{ext} - F_{int}^{ind} \right)$$

*dimensionless number
(0=no resistive losses)