The PEGASUS Toroidal Experiment: Recent Results and Future Plans

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University of Wisconsin-Madison

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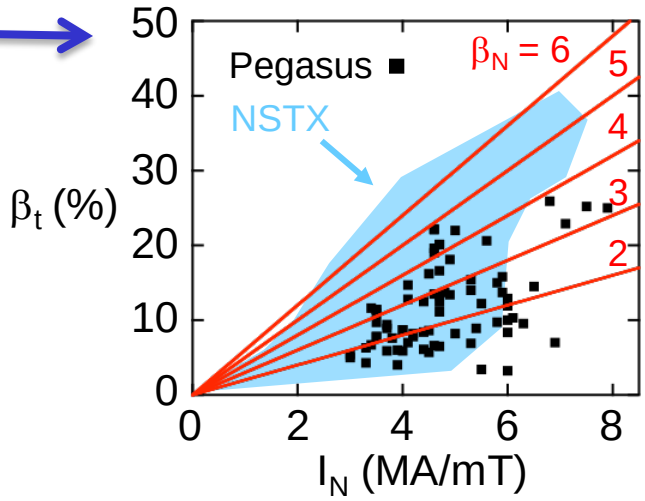
PEGASUS Toroidal Experiment

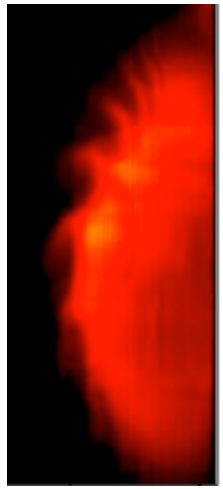
PEGASUS Overview Abstract

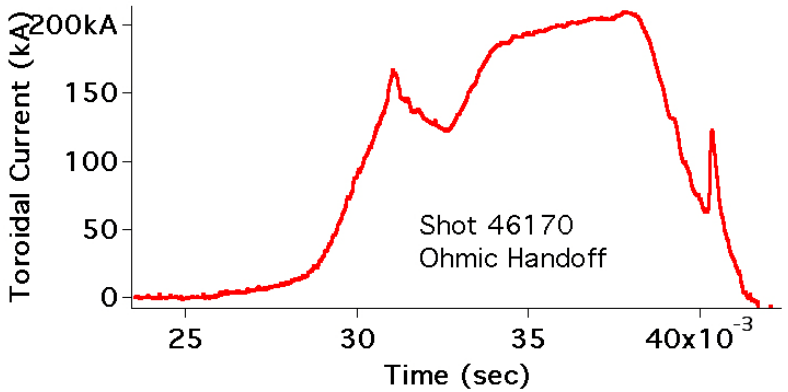
- The PEGASUS program is:
  - developing non-solenoidal startup and growth techniques for tokamaks,
  - exploring plasma stability at near-unity aspect ratio.
- Helicity injection from localized current sources in the plasma periphery produced $I_p > 0.17$ MA, consistent with a simple theory invoking helicity balance and Taylor relaxation constraints.
- Future efforts will concentrate on accessing $I_p = 0.3$ MA to test theory to the point where parallel conduction losses dominate the helicity loss rate. Plasma growth following startup will be pursued via Higher Harmonic Fast Wave heating (0.8 MW available) and/or Electron Bernstein Wave heating and current drive (0.5-1.0 MW EBW proposed). Proposed upgrades in support of these programs include a new centerstack for increased TF, divertors for separatrix-limited operation, and long-pulse capabilities.
- Plasma stability is dominated by peeling-like modes at large J/B and large-scale low-m,n=1 core activity.
- The new capabilities will provide core and edge J(R) manipulation to stably access the unique high I_N, high-β_T regime at $A \approx 1$.

PEGASUS is studying low-A physics and developing non-solenoidal startup techniques

- Determining limits to I_N, β_t
  - High I_N, β_t accessed through j(R) manipulation and/or fast TF ramps
  - Tokamak-spheromak overlap
- Peeling modes observed
  - Driven by high $(j_{\|}/B)_{edge}$
  - Can explore ELM physics
- Non-inductive startup via point current sources
  - DC helicity injection
  - Target plasmas couple to outer-PF induction & Ohmic solenoid drive

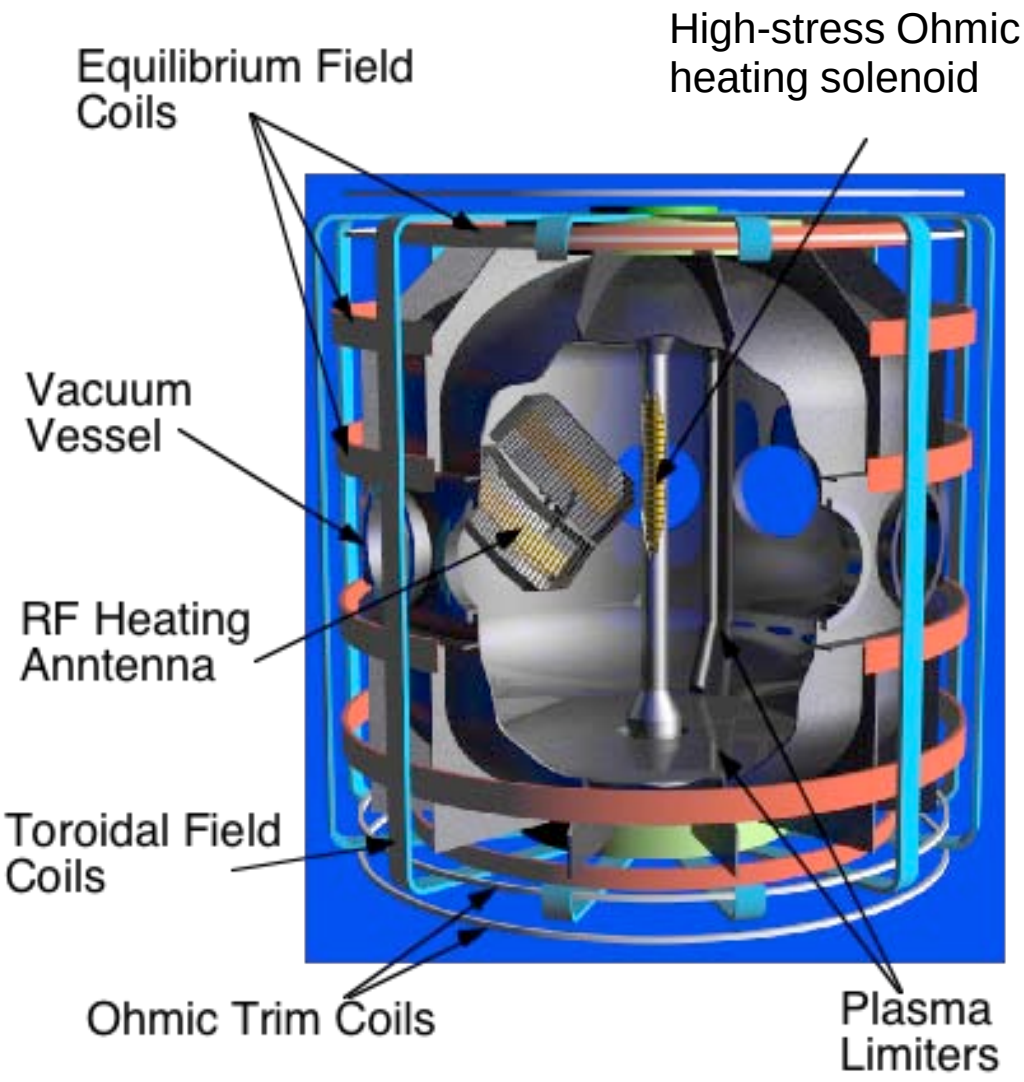






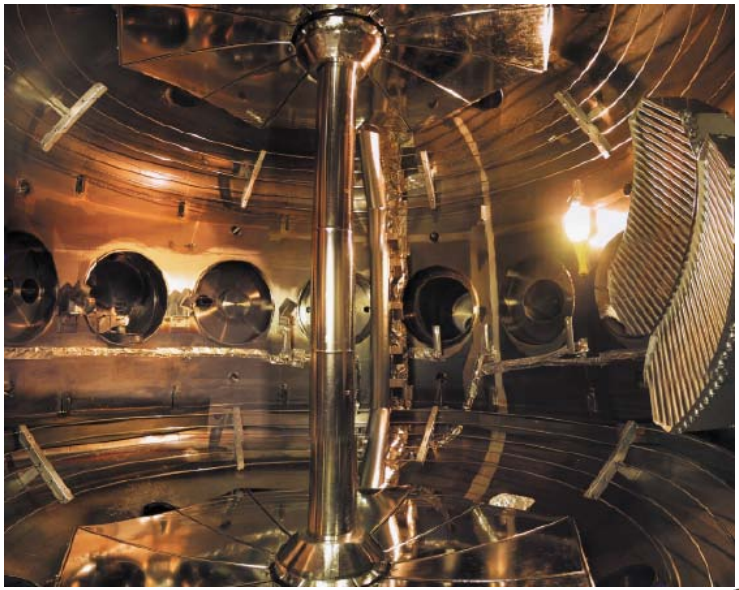
Work supported by U.S. DOE Grant DE-FG02-96ER54375

Pegasus is a Compact Ultralow-A ST



Experimental Parameters

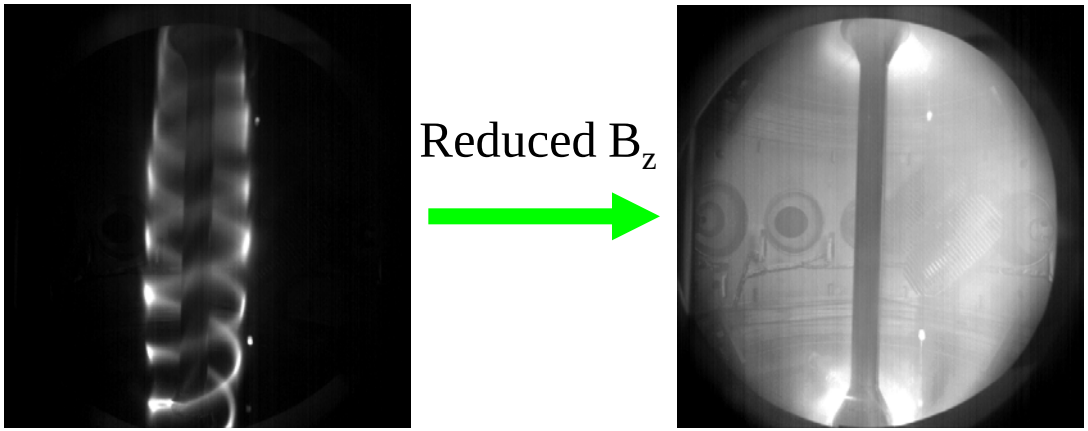
Parameter	To Date
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	≤ .21
I_N (MA/m-T)	6 – 12
l_i	0.2 – 0.5
κ	1.4 – 3.7
τ_{shot} (s)	≤ 0.025
β_t (%)	≤ 25
P_{HHFW} (MW)	0.2



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Local Plasma Current Sources + Helical Vacuum Field Give Simple DC Helicity Injection Scheme

- Current is injected into the existing helical magnetic field
- High I_{inj} & modest B $\Rightarrow$ filaments merge into current sheet
- High I_{inj} & low B $\Rightarrow$ current-driven B_θ overwhelms vacuum B_z
  - Relaxation via MHD activity to tokamak-like Taylor state w/ high toroidal current multiplication



B_T=10 mT, B_z = 5 mT

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Magnetic helicity injection is current drive

Magnetic helicity: linkage between magnetic fluxes

$$K \equiv \int \mathbf{A} \cdot \mathbf{B} \, dV$$



K is conserved in magnetized plasmas, decaying on resistive timescales.

In tokamaks, K is proportional to the product $I_{TF}I_p$. Increases in K correspond to increases in I_p.

Driving current on magnetic field lines is helicity injection

DC helicity injection startup on PEGASUS utilizes localized washer-gun current sources

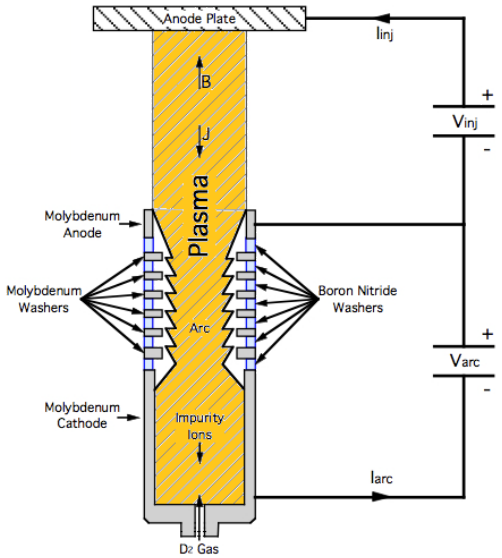
- Plasma gun(s) biased relative to anode:
  - Helicity injection rate:

$$\dot{K}_{inj} = 2V_{inj}B_N A_{inj}$$

V_{inj} - injector voltage

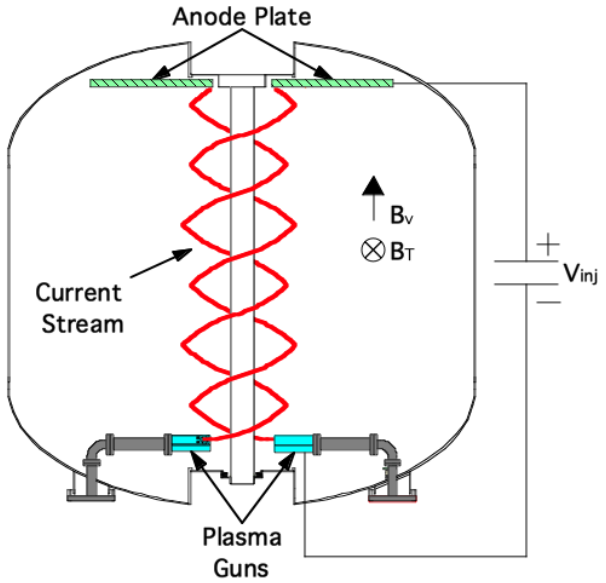
B_N - normal B field at gun aperture

A_{inj} - injector area

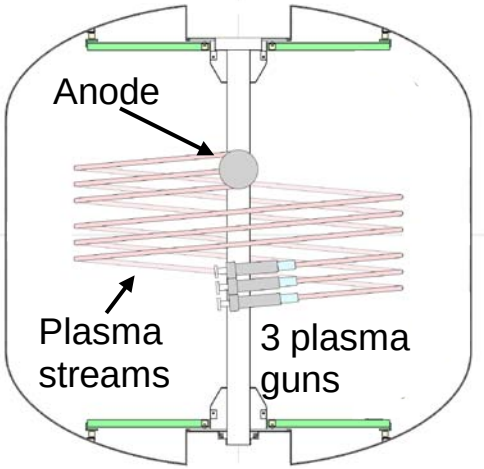


Simplified illustration of a plasma gun for helicity injecton

Divertor injection



Midplane injecton



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Driven helical filaments can relax to an axisymmetric tokamak-like state

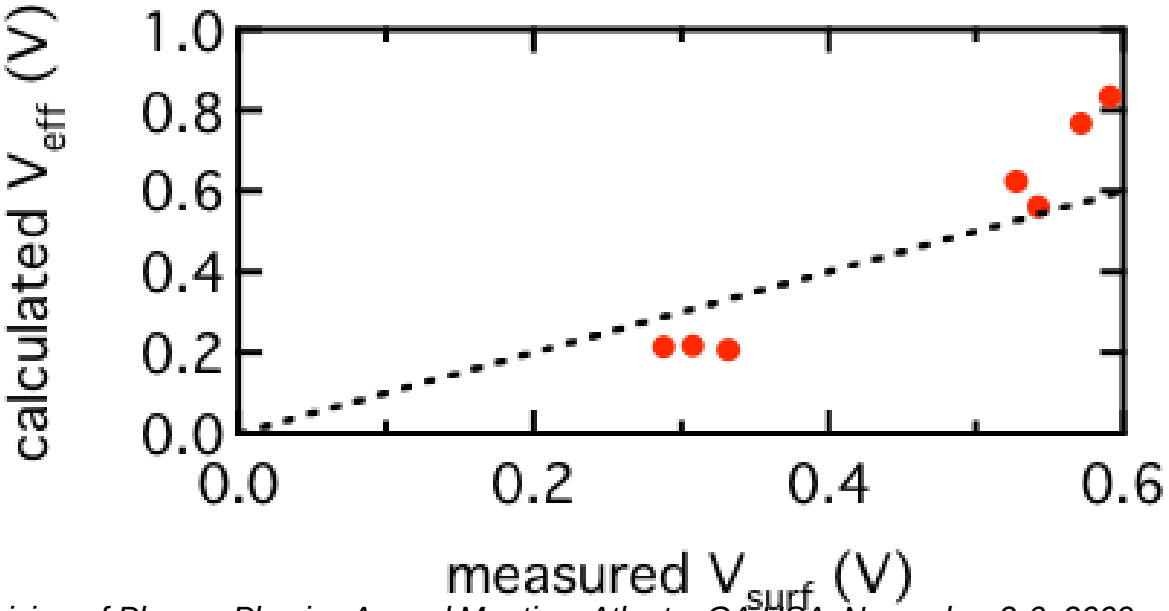
- Driven helical filaments are strongly unstable
  - Relax into the axisymmetric tokamak-like state
- Tokamak-like equilibrium satisfies a set of conditions
  - Radial force balance
  - Helicity/power balance
  - Kink stability: edge q > 3
  - Taylor relaxation current limit
- Max I_p is determined by helicity injection rate and the Taylor relaxation limit, related to magnetic geometry
  - Scales with I_{TF}, I_{bias}, and the width *w* of the driven layer

For more details, see poster PP8.00086, by D. Schlossberg, *et al.*

Helicity Balance Provides One Limit on Current I_p

- Far below relaxation current limit: max I_p occurs when dK/dt balances resistive decay
- Decay V_{loop} estimated with V_{surf}
- $V_{eff} \approx V_{surf}$ indicates:
  1. Injected helicity gets into the plasma
  2. Maximum driven current limited by dK/dt

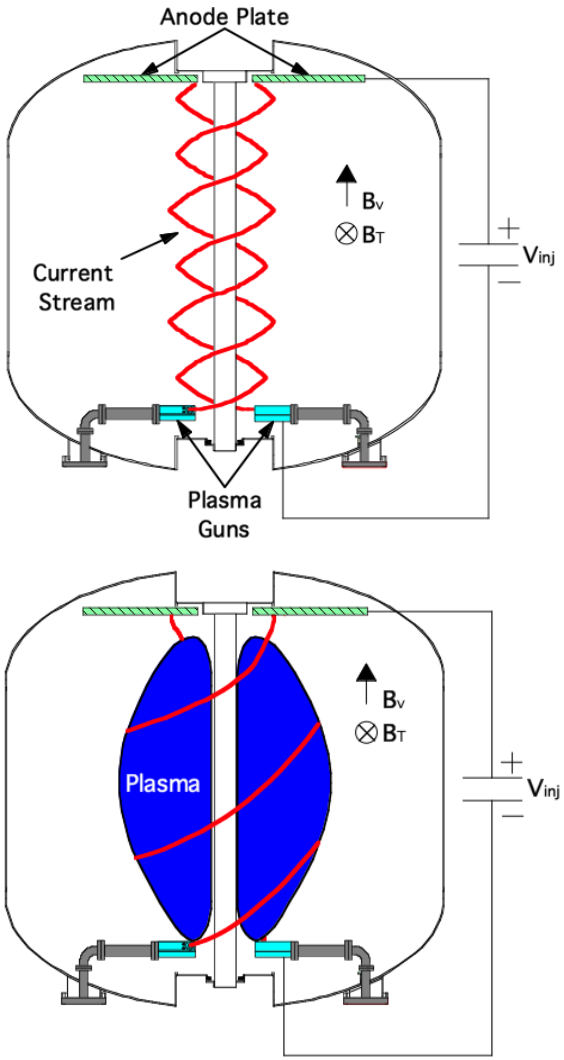
This study used only static-field divertor-gun discharges (no induction drive)



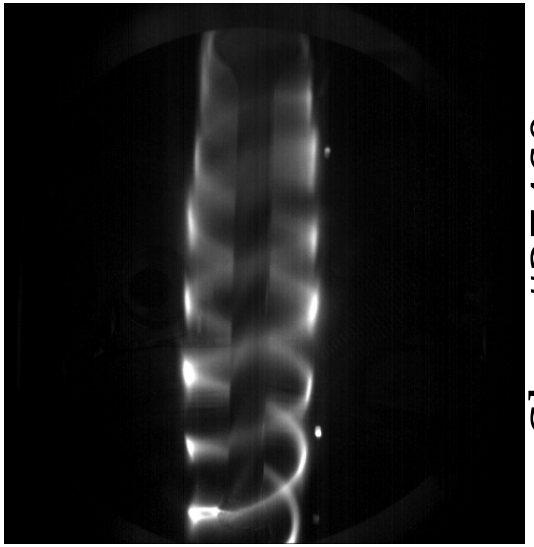
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Divertor-gun system used in initial PEGASUS helicity injection experiments

- Two divertor-mounted guns as shown.
- The gun-driven filaments could relax to form a tokamak plasma.
- Divertor-gun-driven discharges were generally far below the relaxation limit.



Filaments



Shot #37460

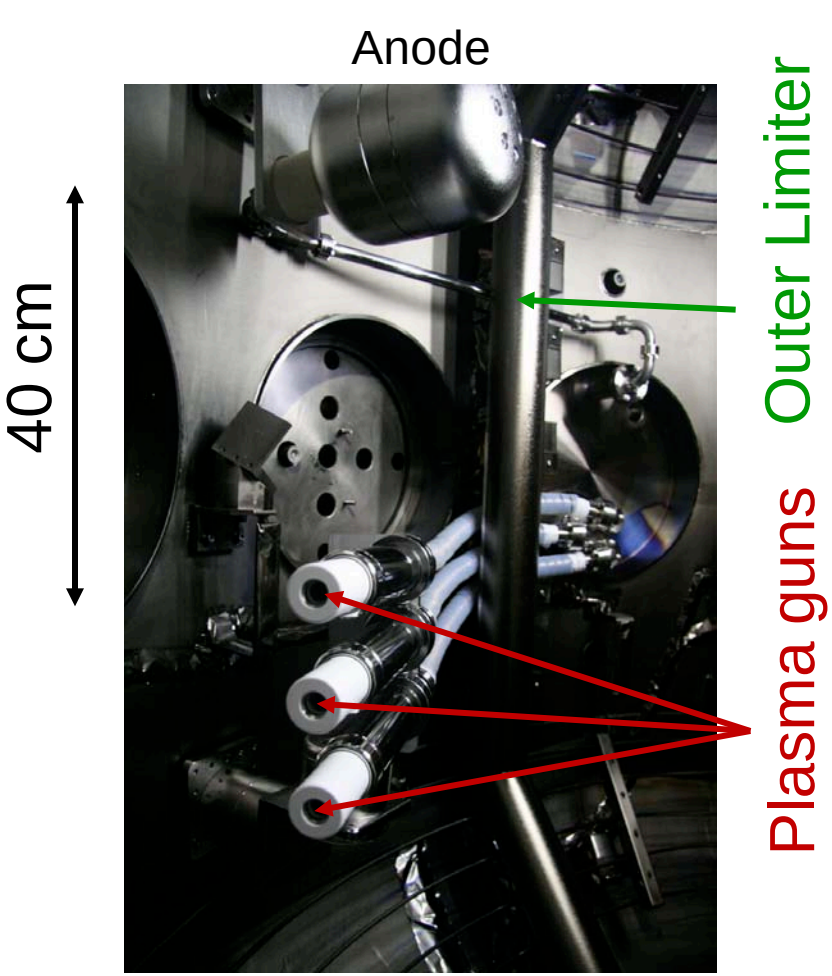
Relaxed State

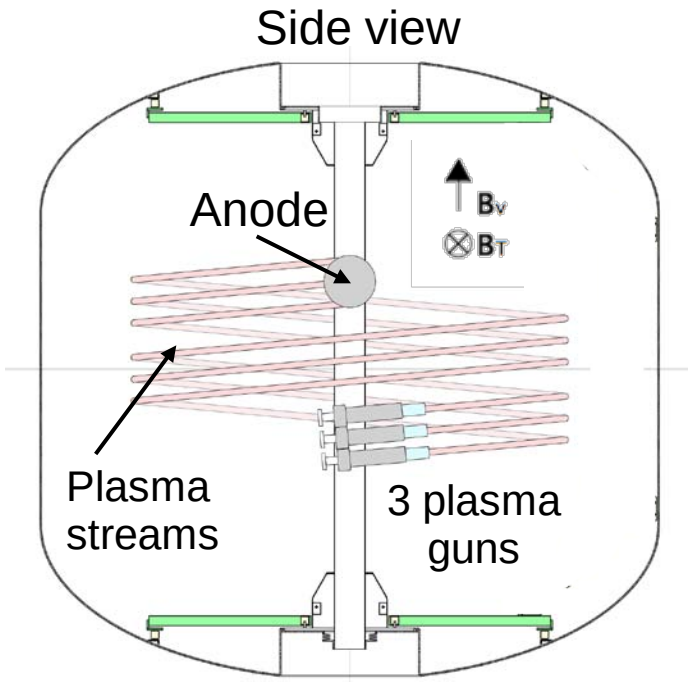


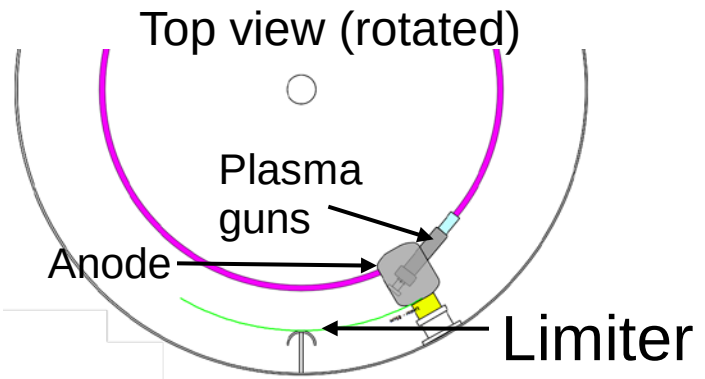
Shot #37222

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Outer-midplane helicity injection system effectively tests “port-plug” HI concept







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Taylor relaxation criteria also limits the sustainable I_p for a given magnetic geometry

Helicity balance in a tokamak geometry:

$$\frac{dK}{dt} = -2\int_V \eta \mathbf{J}\cdot\mathbf{B}\, d^3x - 2\frac{\partial\psi}{\partial t}\Psi - 2\int_A \Phi\mathbf{B}\cdot d\mathbf{s} \quad \Rightarrow \quad I_p \le \frac{A_p}{2\pi R_0\langle\eta\rangle}\left(V_{ind} + V_{eff}\right)$$

- Assumes system is in steady-state (dK/dt = 0)
- I_p limit depends on the scaling of plasma confinement via the η term

$$V_{eff} \approx \frac{N_{inj}A_{inj}B_{\phi,inj}}{\Psi}V_{bias}$$

Taylor relaxation of a force-free equilibrium:

$$\nabla\times B = \mu_0 J = \lambda B \qquad \lambda_p \le \lambda_{edge} \quad \Rightarrow \quad \frac{\mu_0 I_p}{\Psi} \le \frac{\mu_0 I_{inj}}{2\pi R_{inj} w B_{\theta,inj}} \quad \Rightarrow \quad I_p \le \left[\frac{C_p}{2\pi R_{inj}\mu_0}\frac{\Psi I_{inj}}{w}\right]^{1/2}$$

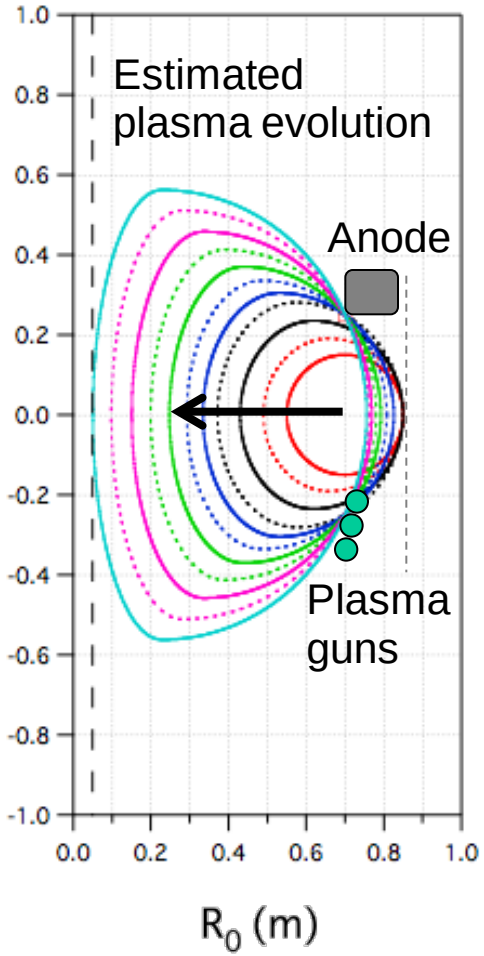
Assumptions:

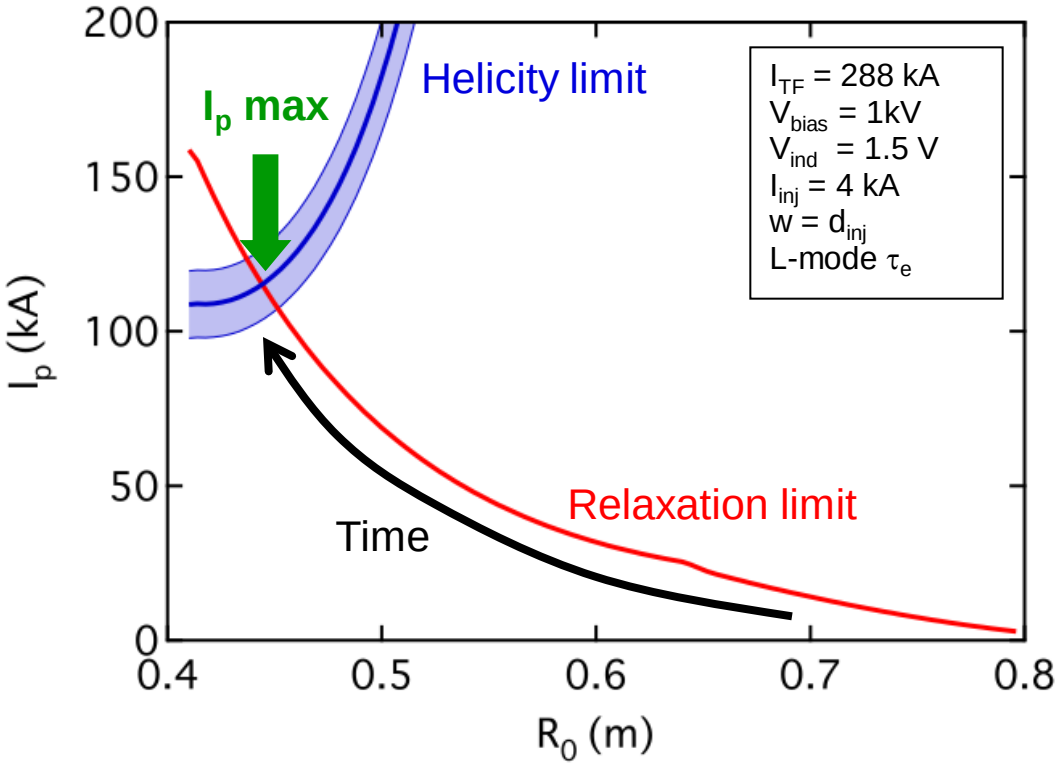
- Driven edge current mixes uniformly in SOL
- Edge fields average to tokamak-like structure

A_p Plasma area
C_p Plasma circumference
Ψ Plasma toroidal flux
w Edge width

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Maximum I_p achieved when helicity and relaxation limits are satisfied simultaneously

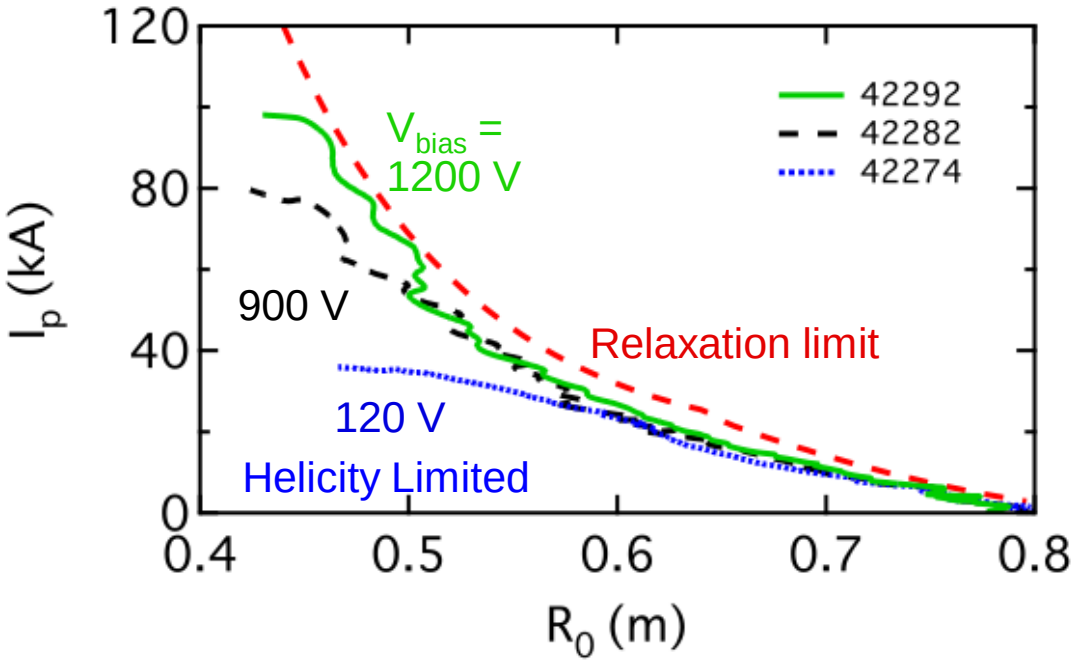




These particular parameters require a B_v ramp, for both radial force balance and some induction.

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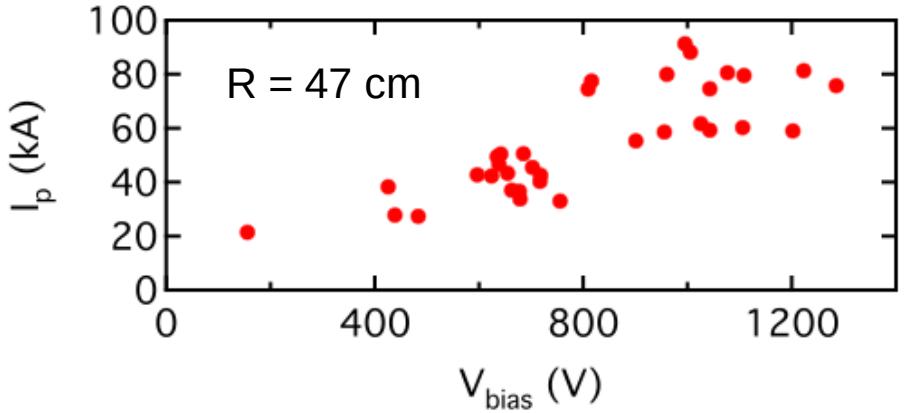
Sufficient helicity injection is required to drive the plasma up to the relaxation limit



$$\dot{K}_{DC} \propto V_{bias} \propto Z_{inj}$$

High dK/dt with modest I_{bias} requires high impedance Z_{inj}

Max I_p increases with V_{bias}



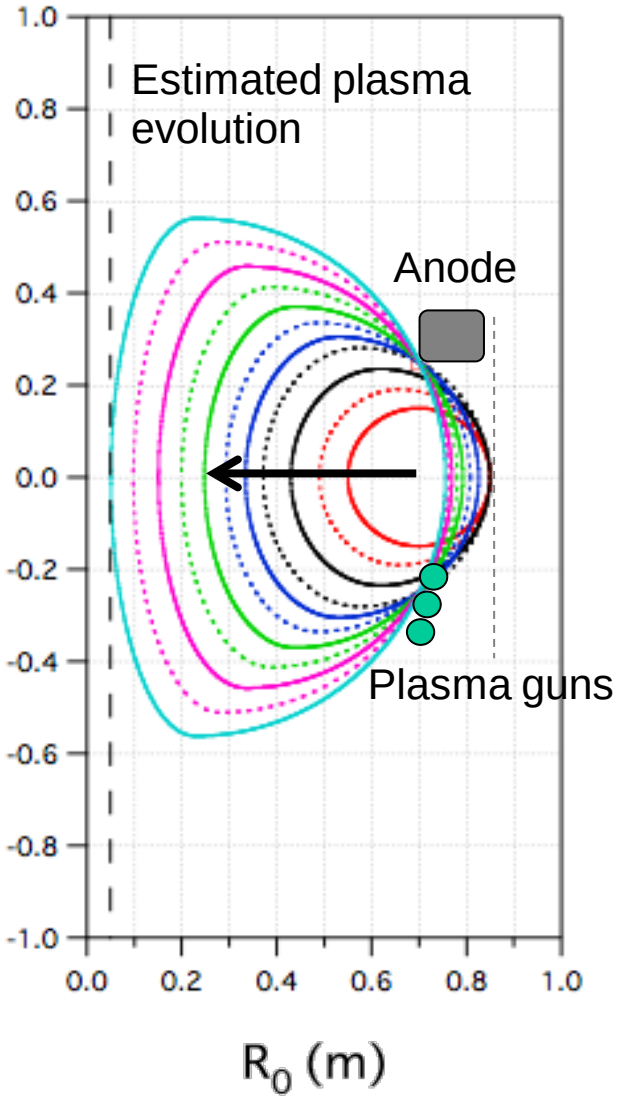
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Midplane-driven plasmas evolve inward

Forms as small circular outboard plasma

As the helicity content increases, plasma expands into high-field region

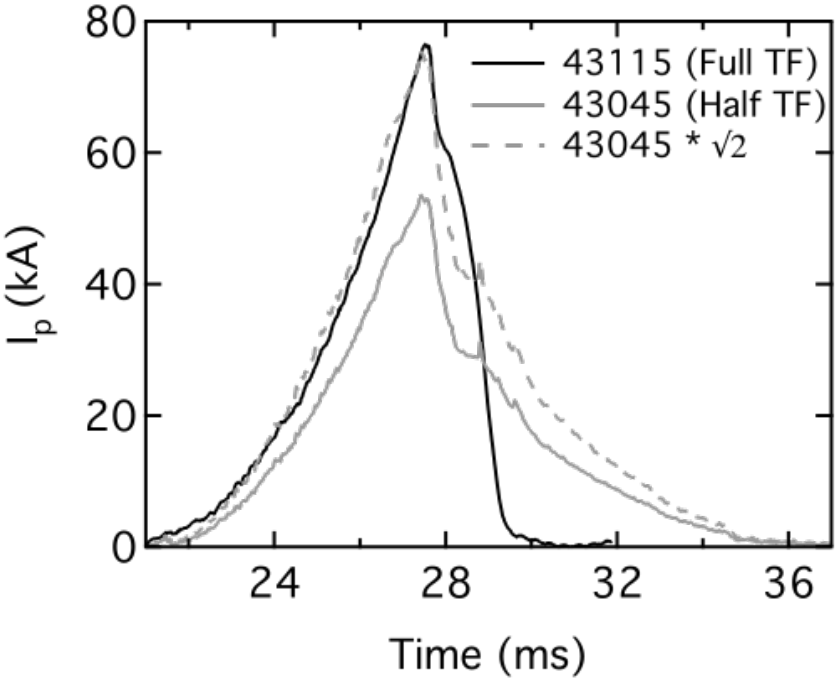
Maintaining radial force balance may require vertical field ramps

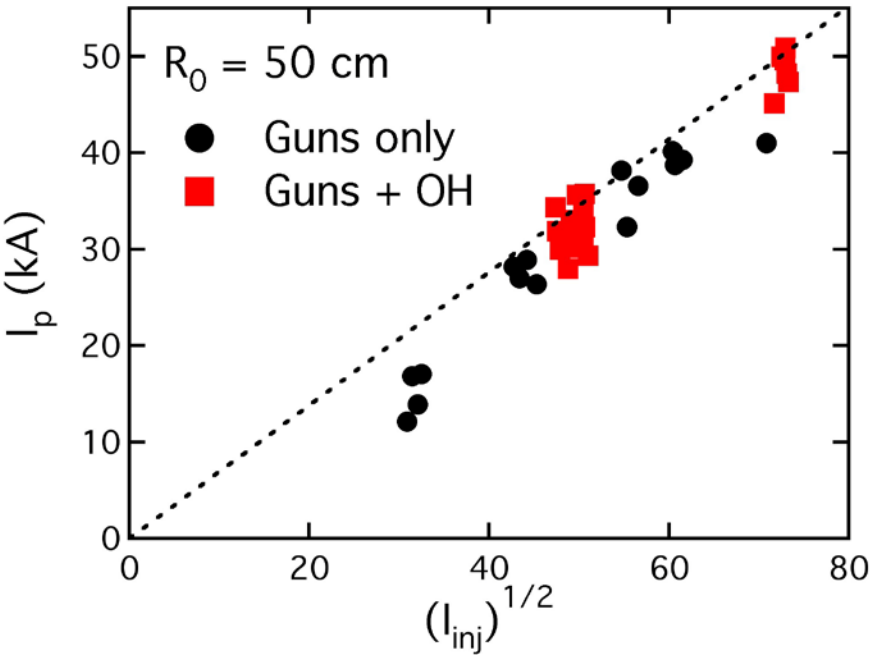


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Experiments confirm relaxation limit scalings with I_{TF} and I_{bias}

- The relaxation limit I_p scales with $(I_{TF}I_{bias})^{1/2}$
- Experimental plasma currents follow these scalings:

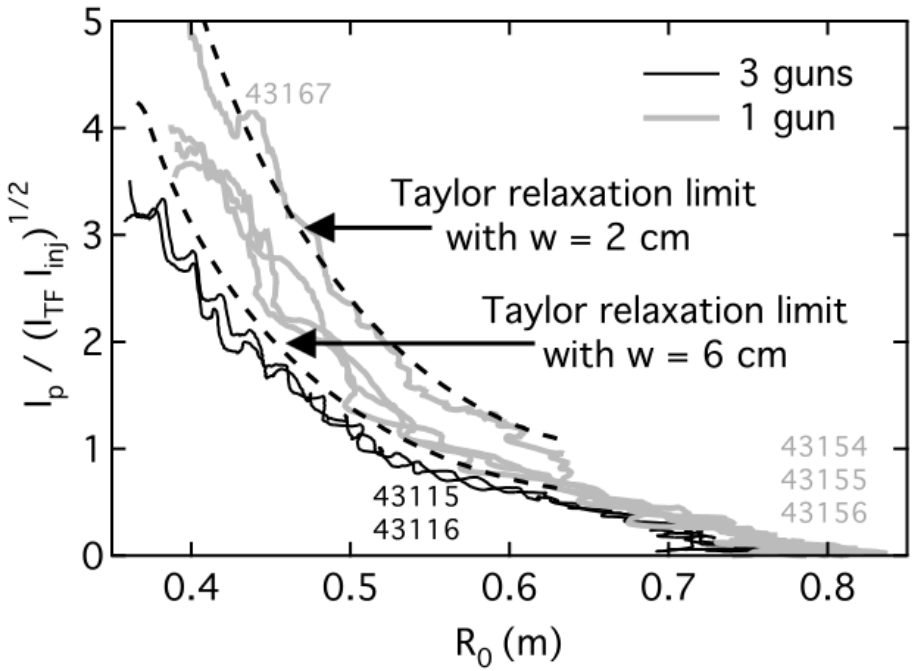


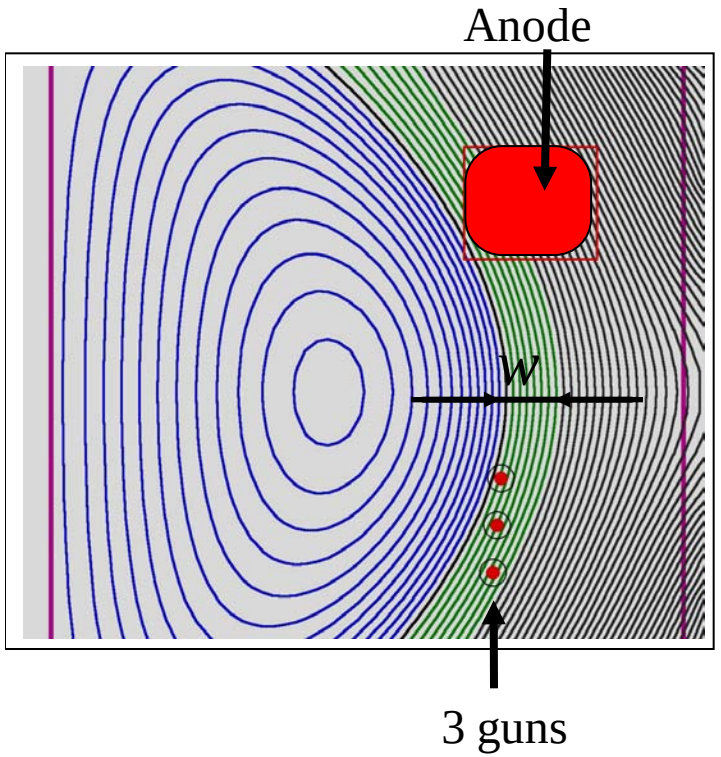


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Experiments demonstrate dependence on the width of the driven current layer

- Relaxation current limit scales as $w^{-1/2}$
- One-gun discharges had higher limits than corresponding three-gun cases, indicating the gun array was misaligned:

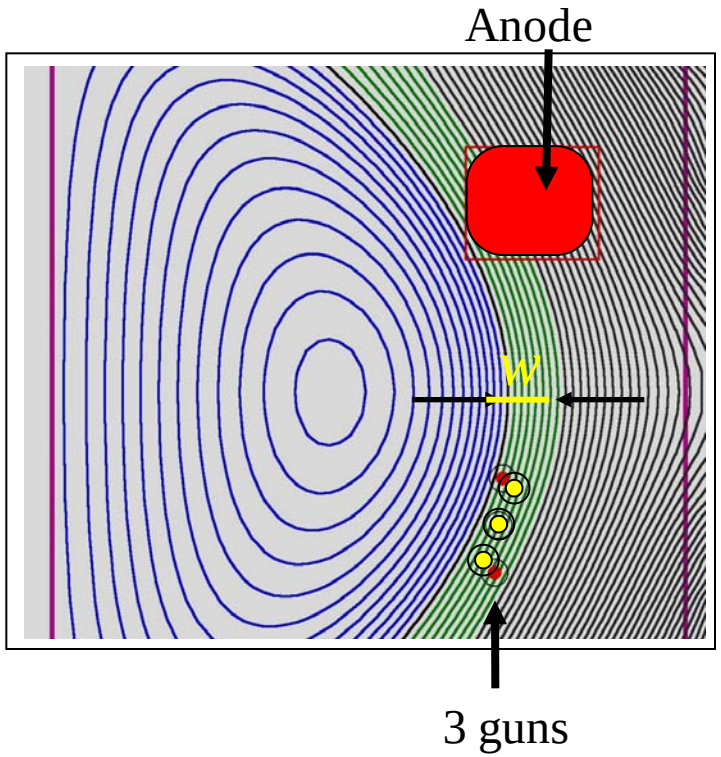


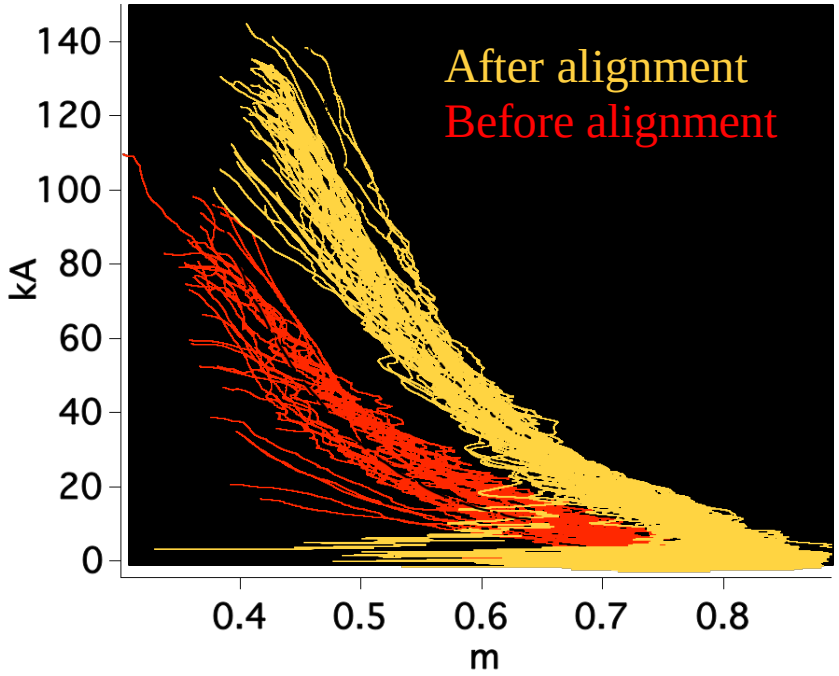


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Gun array was realigned, significantly improving plasma performance

- Changing the tilt of the gun array increased the max I_p by a factor of 1.5-1.7, implying a factor-of-3 change in *w*.
- In this configuration, have achieved I_p > 170 kA.

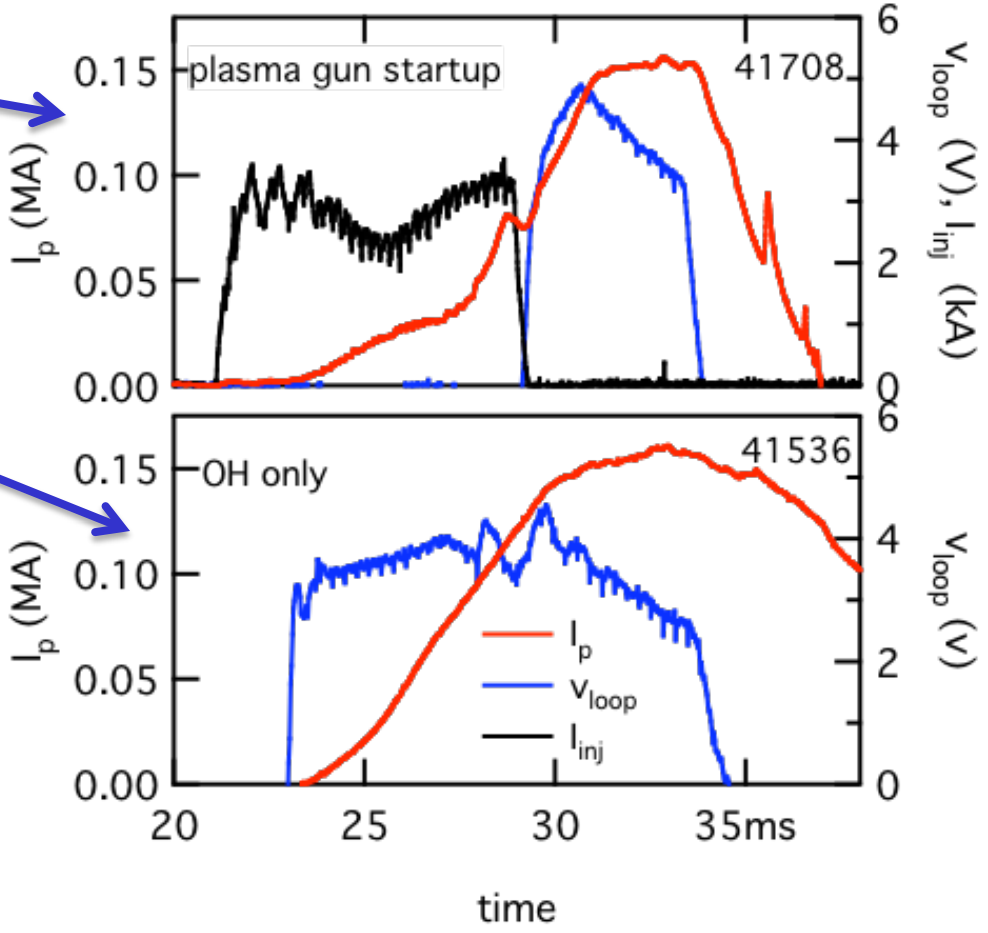




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Plasma gun startup provides a robust target plasma for Ohmic handoff

- Handoff to Ohmic
  - Gun-driven target ~80 kA
  - Most pre-OH current is captured by the OH drive
- Corresponding OH-only
  - Gun startup saved ~ 50% flux
- Will couple high-I_p targets to double-swing OH ramp

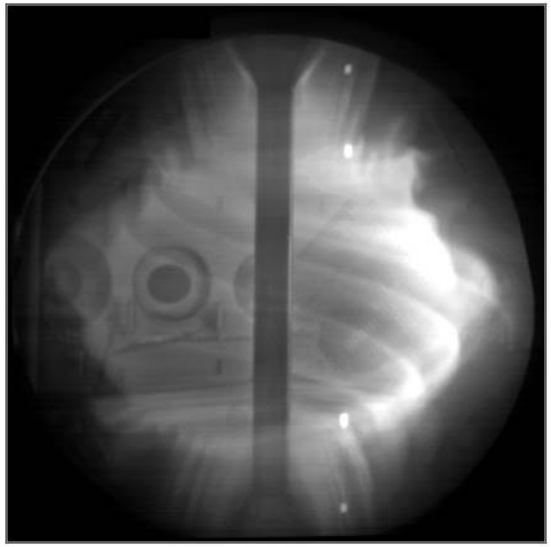


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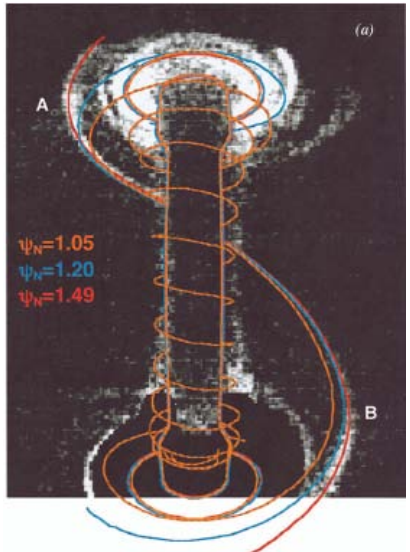
Peeling-mode studies are in progress

- Filamentary edge instabilities consistent with peeling modes
  - Nonlinear phase: explosive detachment and radial acceleration
- Direct comparison to theory requires accurate equilibria
  - Probes measure $B_z(R,t)$ and pressure in the plasma edge
  - Local equilibrium code KFIT is being modified, with basis functions that can capture the experimentally constrained profiles
- ITER-relevant physics accessible at low cost by operating at very low aspect ratio
- For more details, and progress toward testing the theory, see Poster PP8.00087 by E.Hinson, *et al.*, this session.

Observed Filaments are Similar to ELMs

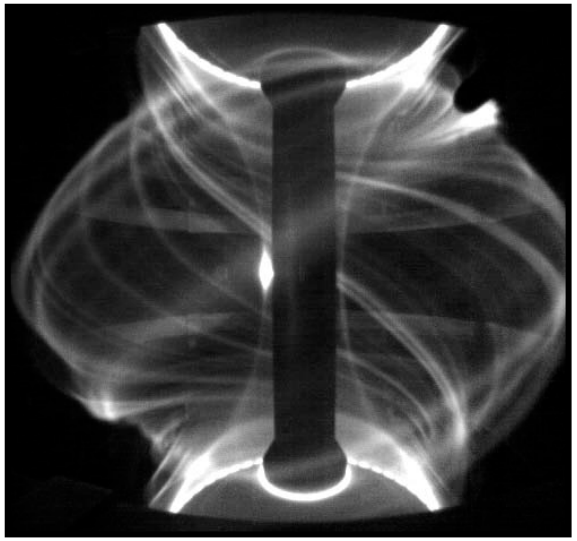


PEGASUS



Maingi, Phys. Plasmas **13**, 092510 ,2006

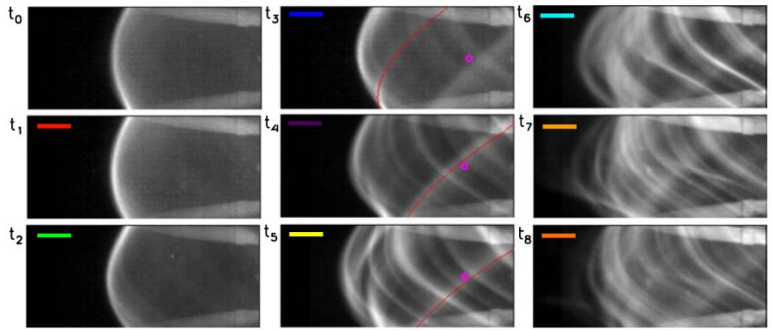
NSTX



Kirk, Plas. Phys. Controlled Fus. **49**, 2007

MAST

- Filamentary, field-aligned structures
  - Present under conditions of high $\langle j_{edge}/B \rangle$
- PEGASUS: L-mode edge assumed
  - However, may still manifest same instability



Scannell, Plas. Phys. Controlled Fus. **49**, 2007

Near-unity A Maximizes Peeling Drive

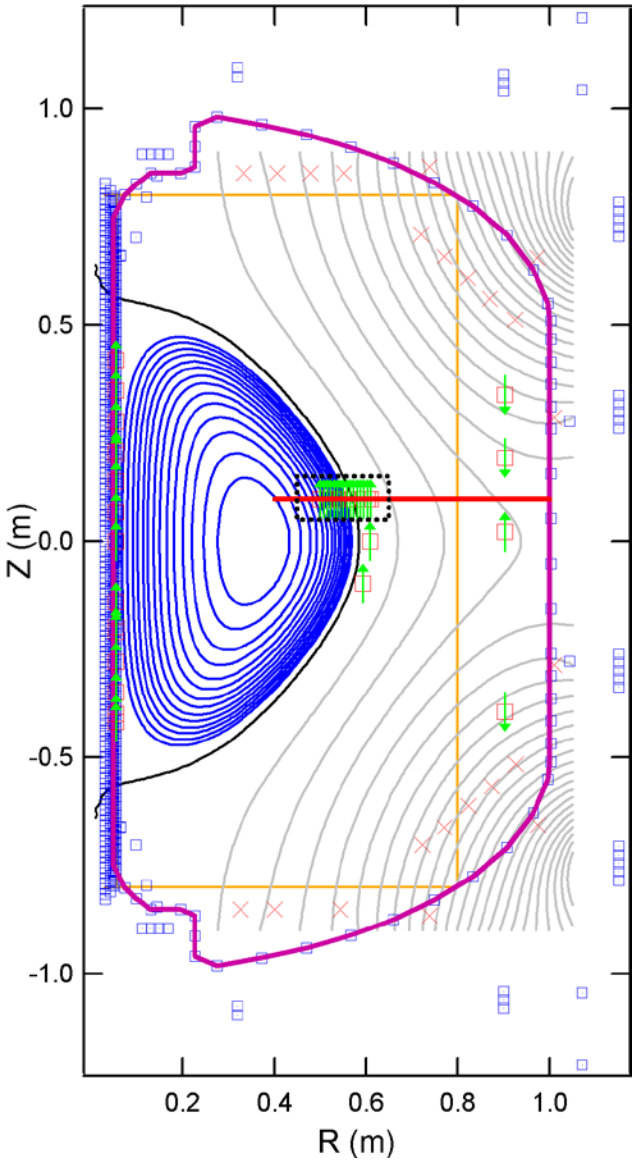
Device	J_{edge} (MA/m²)	$B_{\varphi,0}$ (T)	J_{edge}/B
PEGASUS	~ 0.1 – 0.2	0.1	**~ 1**
DIII-D*	1 – 2	2	**0.5 – 1**

*: Thomas, Phys. Plasmas **12**, 056123 2005

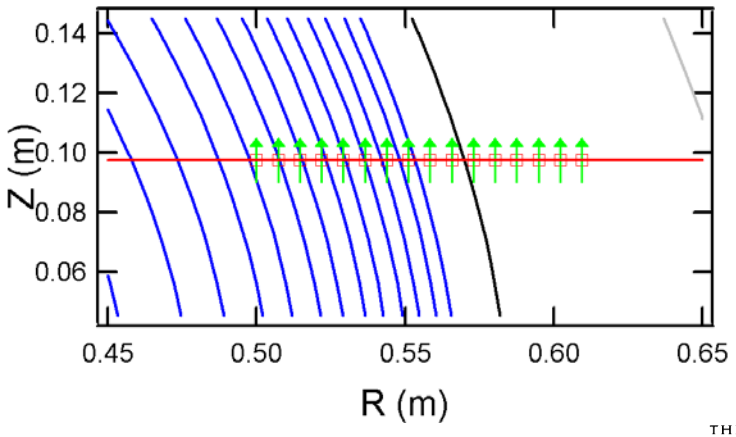
- PEGASUS operations at A → 1 lead to naturally high j_{edge}/B
  - Comparable to larger machines in H-mode
- However, *source* of peeling drive different
  - Large machines: H-mode p' → j_{BS}
  - PEGASUS: Large dI_p/dt (≤ 50 MA/s) → transient skin current
- Low-A geometry enables ITER-relevant research

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Accurate Stability Analysis Requires Local Measurements of J_T and p'



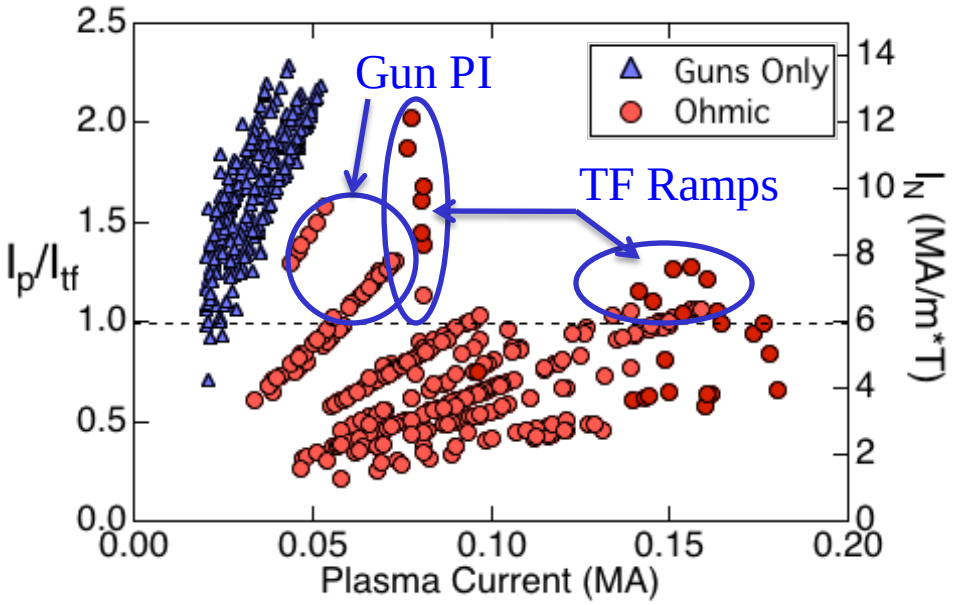
- Comparing experiment to peeling-mode theory requires accurate edge profiles:
  - Need both edge p(ψ) and j(ψ) profiles
- PEGASUS: measurements using probes
  - Hall-effect array constrains j(ψ)
  - Langmuir array constrains p(ψ)

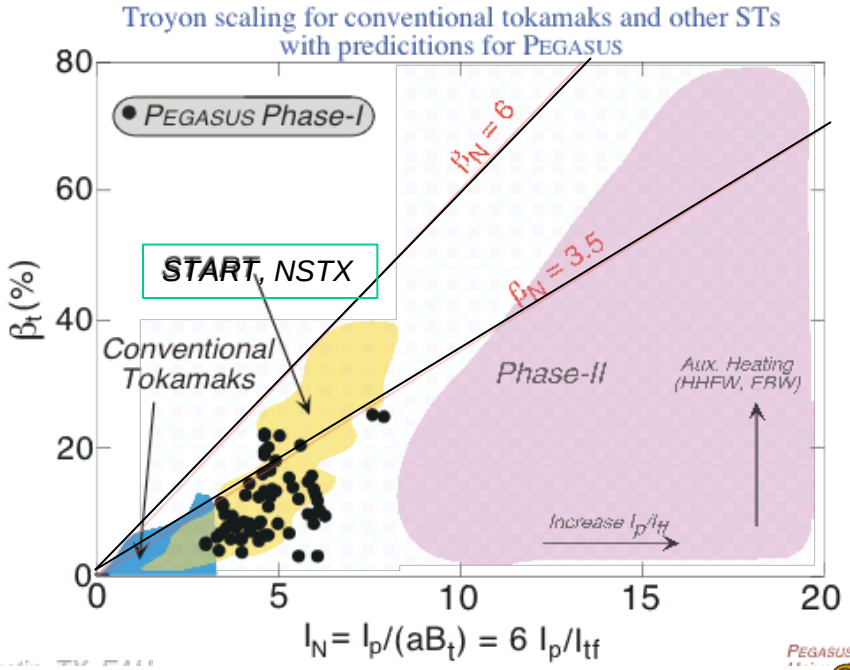


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High β_T at A≈1 accessible at high I_N

- High I_N requires current drive and current profile control
- Developing startup and current drive techniques, to support overall ST program and enable high-β studies
- Future devices need non-solenoidal current drive anyway, PEGASUS simply needs current drive solutions now

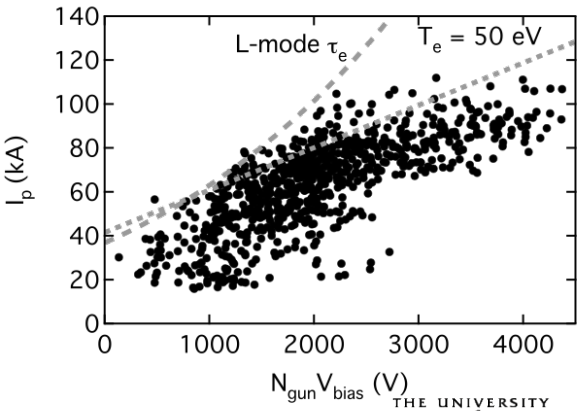




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Further development of gun startup needed to achieve high I_p

- PEGASUS near-term goal is 0.3-0.4 MA
  - Allows characterization of confinement/dissipation in driven plasma
  - Enables access to high I_p/I_{TF}, high β regimes
- This requires:
  - Increase TF: increase Taylor limit, improve confinement
  - Increase gun current: increase Taylor limit
  - Bigger/improved plasma guns: higher helicity injection rate
  - Test augmenting the guns with shaped electrodes
- Outstanding issues:
  - What sets the bias impedance Z_{inj}?
  - Is the confinement/dissipation stochastic?
  - What sets the width *w* of the driven region?

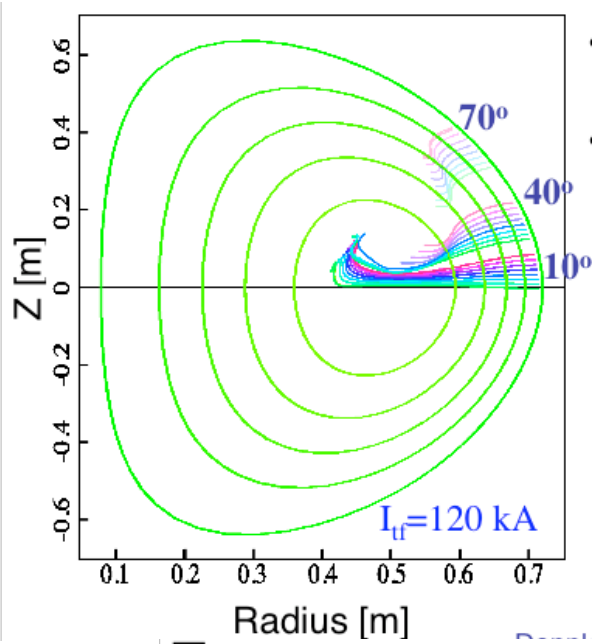


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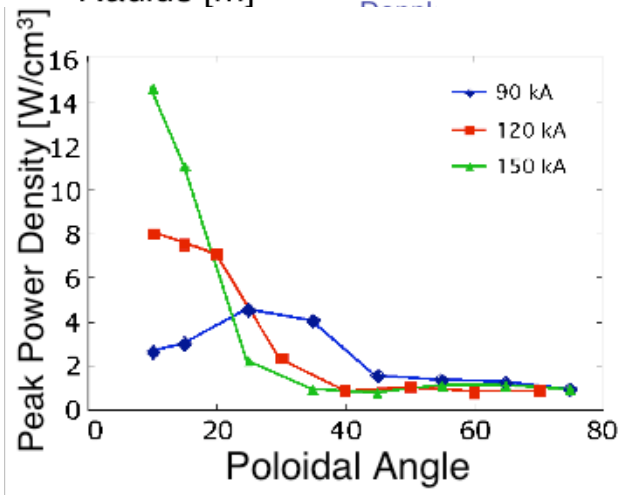
Non-solenoidal startup with RF and/or helicity injection in PEGASUS

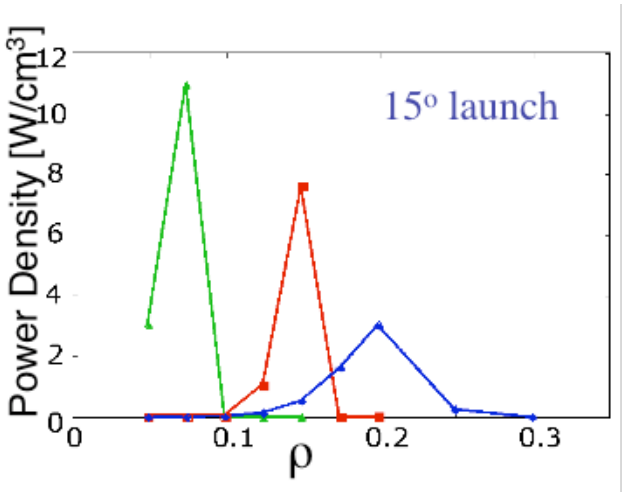
- Two RF systems to be available: HHFW and EBW
- HHFW: Two-strap antenna, 0.8 MW, 8-18 MHz
- EBW planned for next year: 0.5-1.0 MW @ 2.45 GHz
  - 2.45 GHz enabled by very low field at low-A
- Enables comparison of non-solenoidal startup scenarios:
  - Helicity injection + outer-PF induction
  - EBW heating + outer-PF induction
  - Helicity injection + EBW heating + outer-PF induction
- Enables non-solenoidal sustainment on PEGASUS:
  - RF heating, possible bootstrap overdrive
  - Intermittent helicity injection

Midplane-launched EBW damps near magnetic axis and gives optimal heating



Ray-tracing and power deposition calculations by S. Diem using GENRAY and CQL3D.





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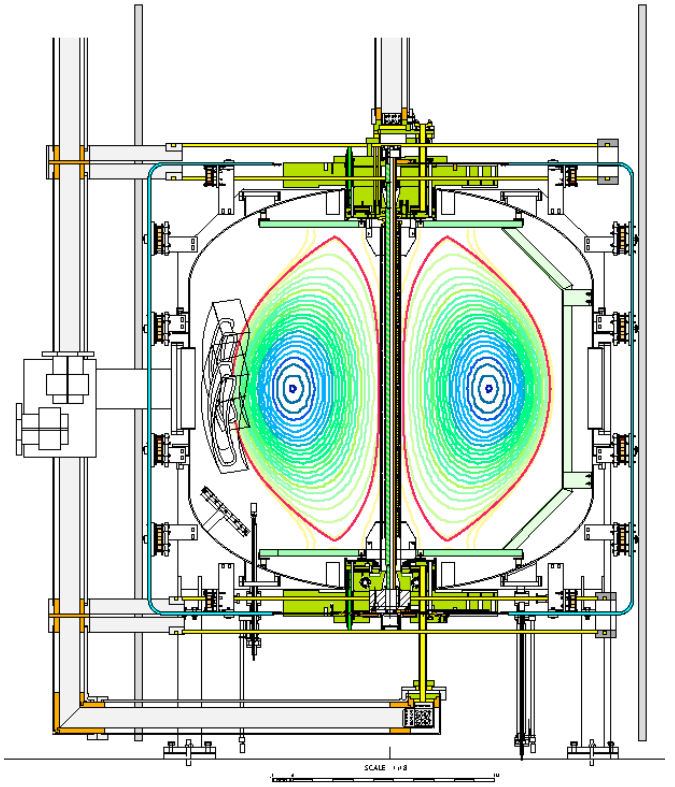
PEGASUS Summary: Creating High-I_p Non-Solenoidal Discharges & Studying Edge Stability

- Exploration of high I_N, β_t space facilitated by j(r) tools
  - $I_p/I_{TF} > 2$, $I_N > 14$ achieved; extend operation to high I_p, n_e for high β_t
- Making progress with non-solenoidal startup
  - $I_p \sim 170$ kA using helicity injection and outer-PF rampup
  - Using understanding of helicity balance and relaxation current limit to guide hardware and operational changes
    - Adding RF systems: develop startup and sustainment scenarios
    - Outstanding physics questions: λ_{edge}, Z_{inj}, confinement, *etc.*
  - Ultimate goal is 0.3-0.4 MA non-solenoidal current
- Able to rigorously test Peeling-Ballooning theory
  - Edge measurements constrain equilibrium reconstructions
  - Can compare stability calculations to experimental observations

Proposed PEGASUS Facility Modifications

- Magnetic and power systems reconfiguration
  - Increase TF by factor of 2
  - Activate divertor coils
  - Deploy existing PCS
  - Helicity injection supply development
- Internal hardware modifications
  - Install passive conducting plates
  - Optimize gun geometry
  - Install enhanced guns and/or electrodes
  - Install internal radial position coils
- Improved core and edge diagnostics
  - Multi-point Thomson scattering
  - Poloidal SXR array
  - Ion spectroscopy: flows and T_i
  - Visible brehmsstrahlung

Present Configuration



Near-term planned physics campaigns

- Continue and extend non-solenoidal current drive studies
  - Test understanding of relaxation current limit
  - Study confinement/dissipation, bias impedance, driven layer width
  - Use additional tools as they become available: RF, increased TF, *etc*
  - Target is 0.3-0.4 MA non-solenoidal plasma current
- Rigorously test peeling-mode theory
  - Use current-profile and pressure-profile constraints
  - Use divertor coils to add shear
- Explore non-solenoidal sustainment
  - Enables high-I_N, high-β_T studies

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