The PEGASUS Toroidal Experiment: Recent Results and Future Plans

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15th International Spherical Torus Workshop

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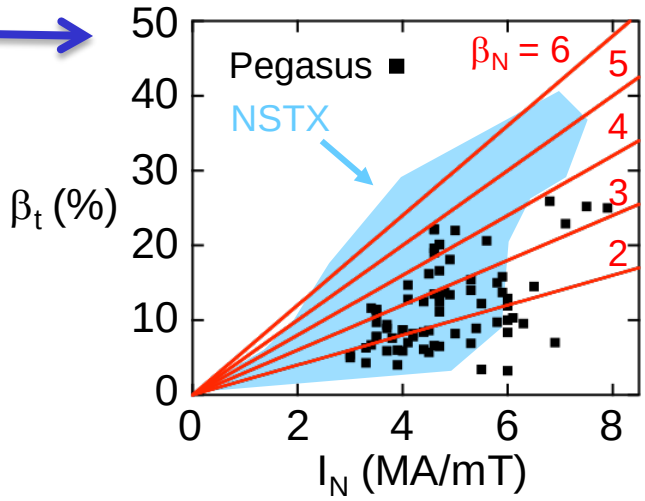
Madison, WI USA

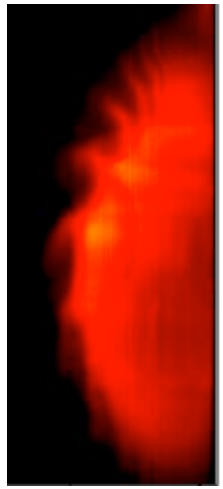


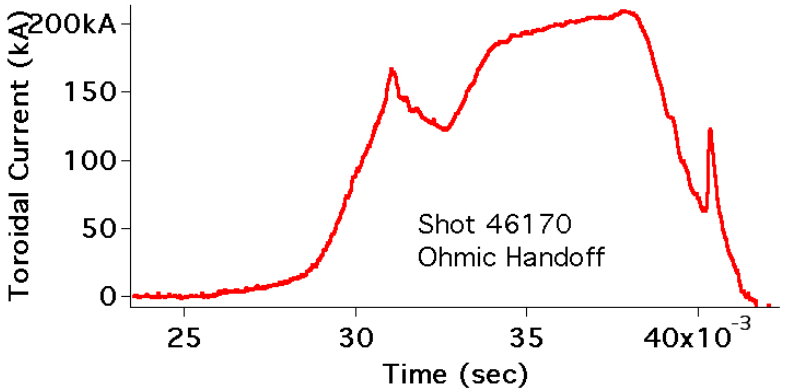
PEGASUS Toroidal Experiment

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





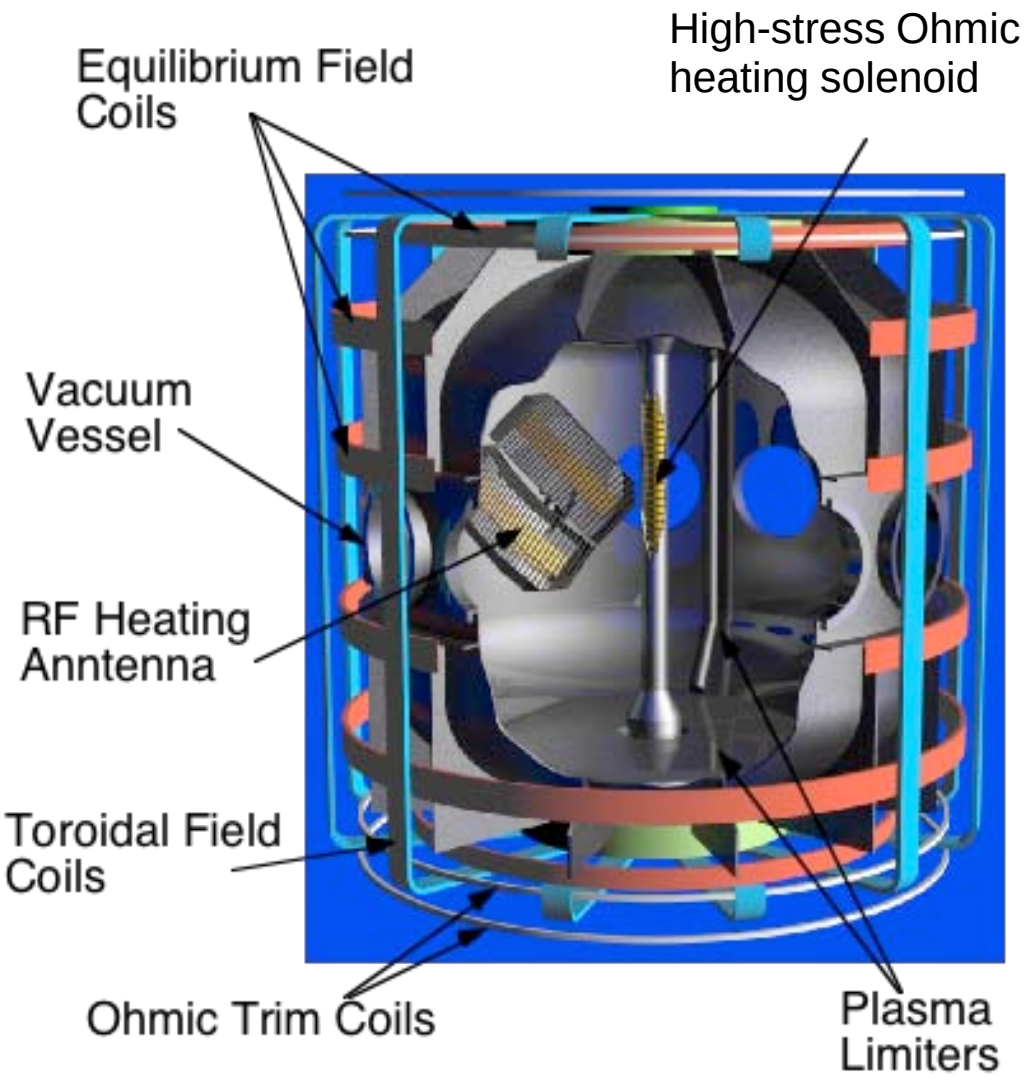


Work supported by U.S. DOE Grant DE-FG02-96ER54375

PEGASUS Overview Outline

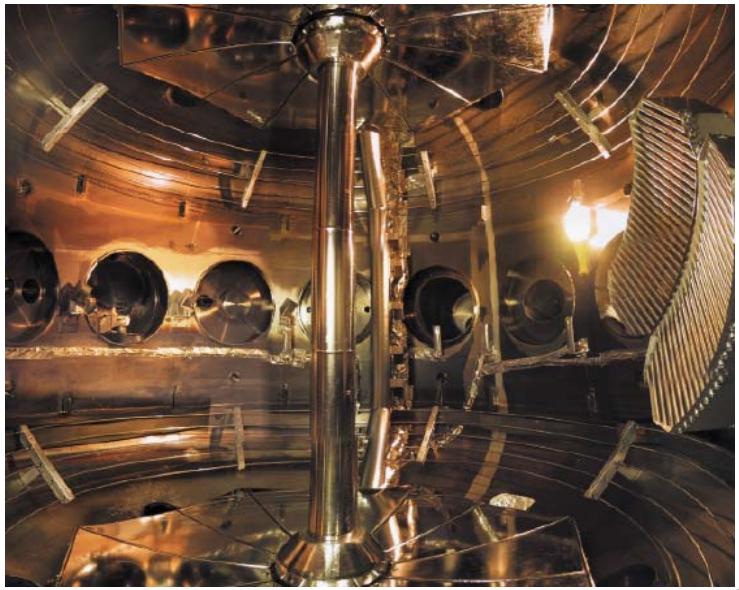
- The PEGASUS Toroidal Experiment
- Non-solenoidal startup
- Peeling mode studies
- Future: Guns & RF startup & growth
- Summary

Pegasus is a Compact Ultralow-A ST



Experimental Parameters

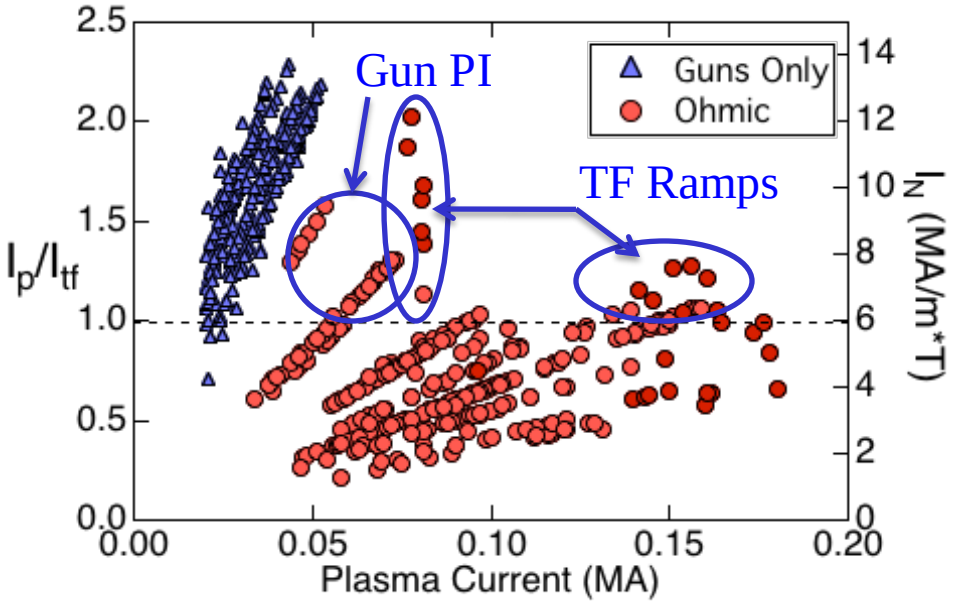
Parameter	To Date
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	≤ .21
I_N (MA/m-T)	6 – 12
l_i	0.2 – 0.5
κ	1.4 – 3.7
τ_{shot} (s)	≤ 0.025
β_t (%)	≤ 25
P_{HHFW} (MW)	0.2

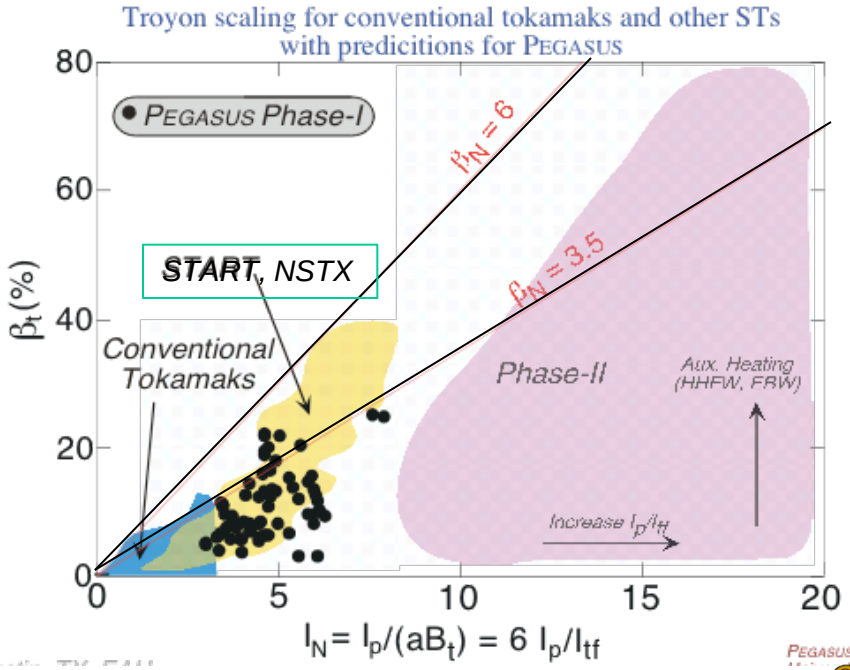


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High β_T at A≈1 accessible at high I_N

- 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



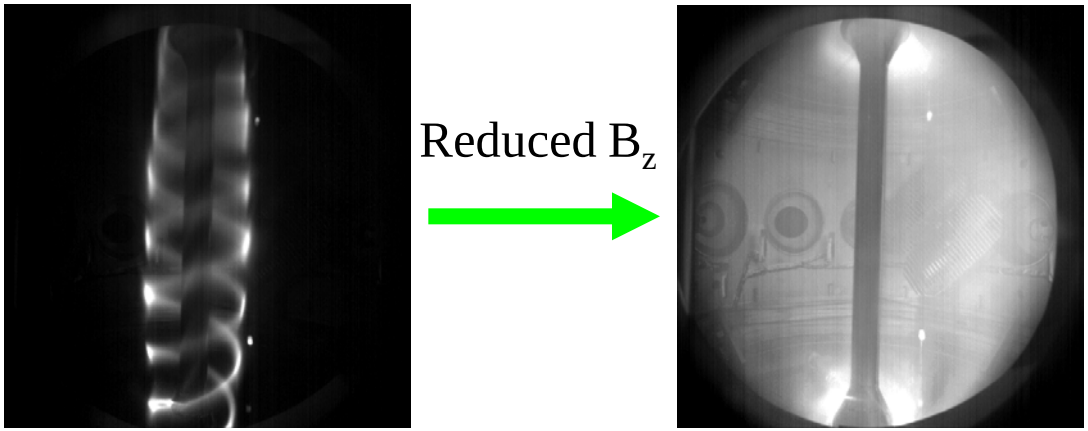


PEGASUS Overview Outline

- The PEGASUS Toroidal Experiment
- Non-solenoidal startup studies
  - Plasma gun system description
  - Limits on the driven toroidal current
- Peeling mode studies
- Future: Guns & RF startup & growth
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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 open 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:

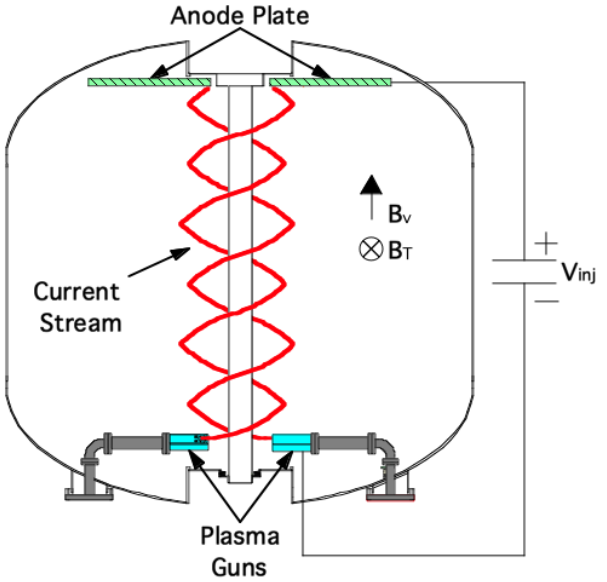
$$\dot{K}_{inj} = 2V_{inj}B_N A_{inj}$$

V_{inj} - injector voltage

B_N - normal B field at gun aperture

A_{inj} - injector area

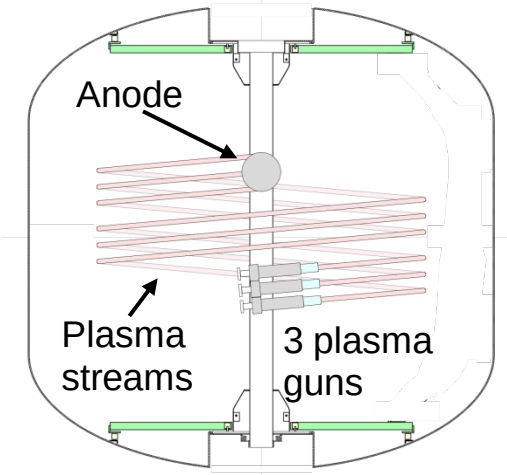
Divertor injection



- Plasma guns have geometric flexibility

- Gun-based system can be scaled to larger devices, such as NSTX

Midplane injecton



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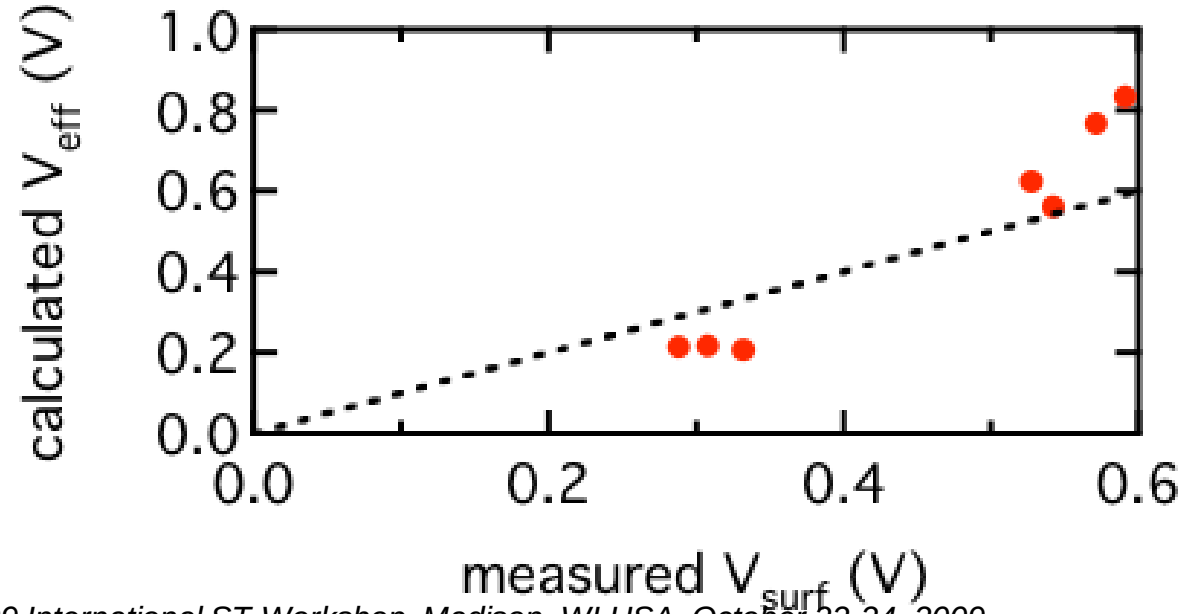
Driven helical filaments can relax to an axisymmetric tokamak-like state

- 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

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)



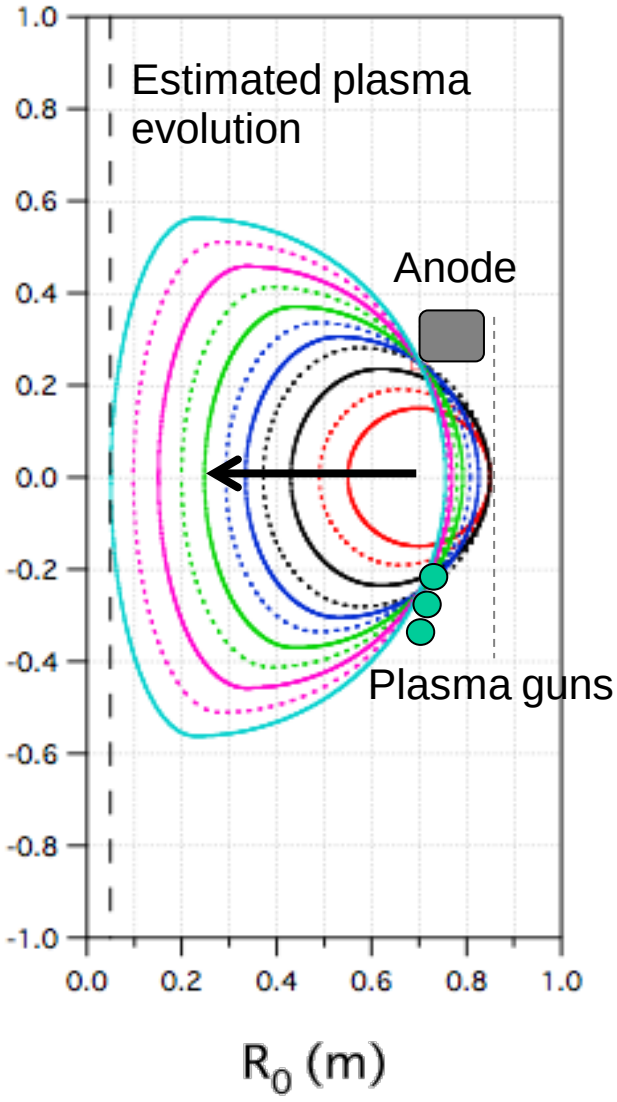
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Midplane-driven plasmas evolve inward

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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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:

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

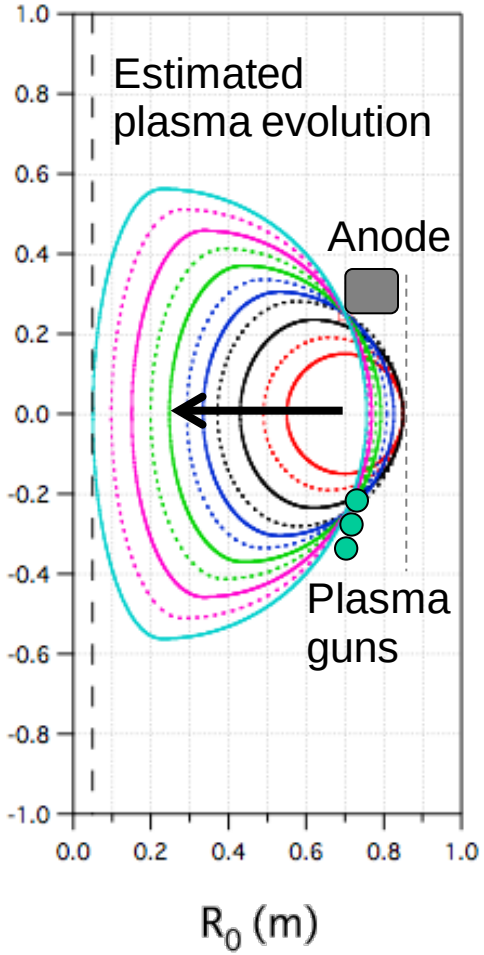
Assumptions:

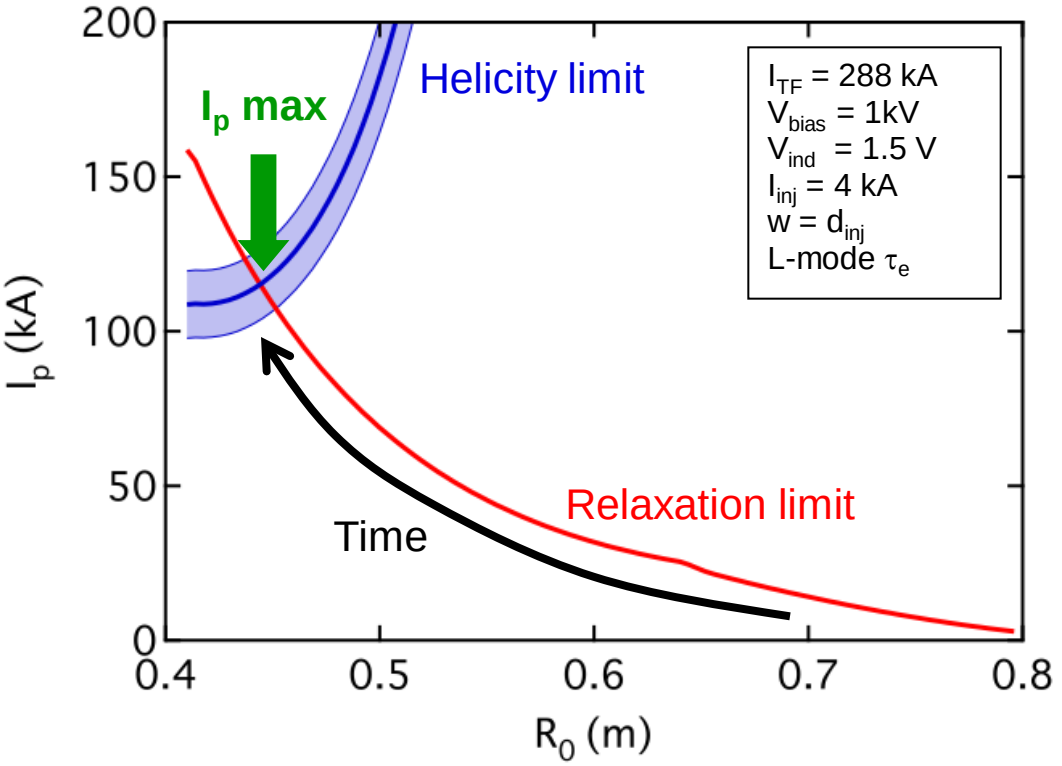
- Driven edge current mixes uniformly in SOL
- Edge fields average to tokamak-like structure

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

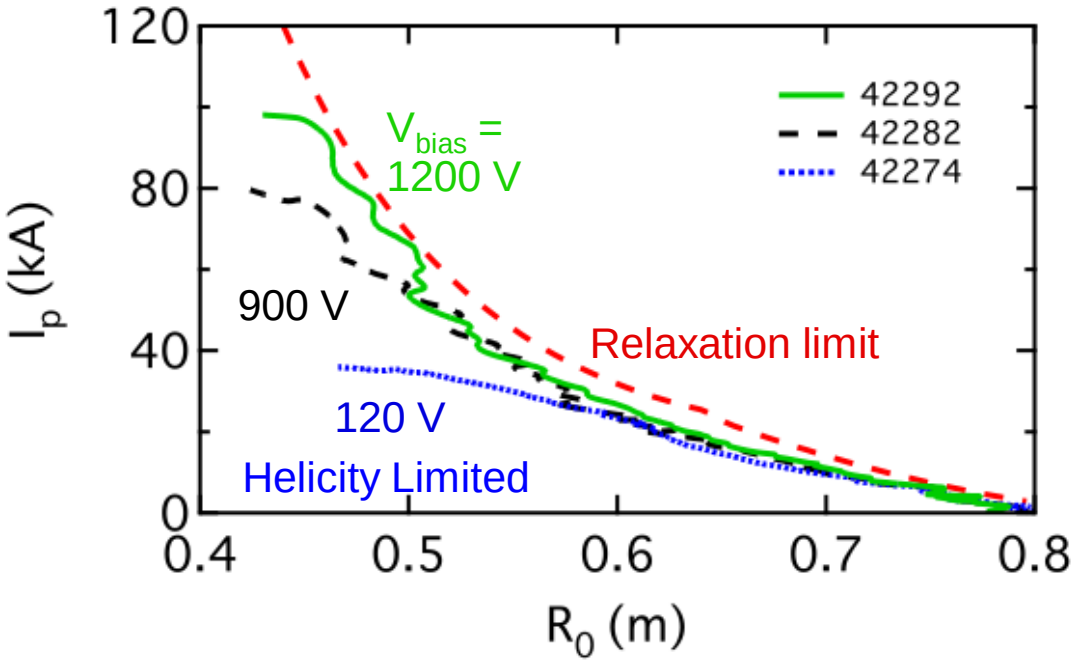




These particular parameters require a B_v ramp, both for radial force balance and some induction.

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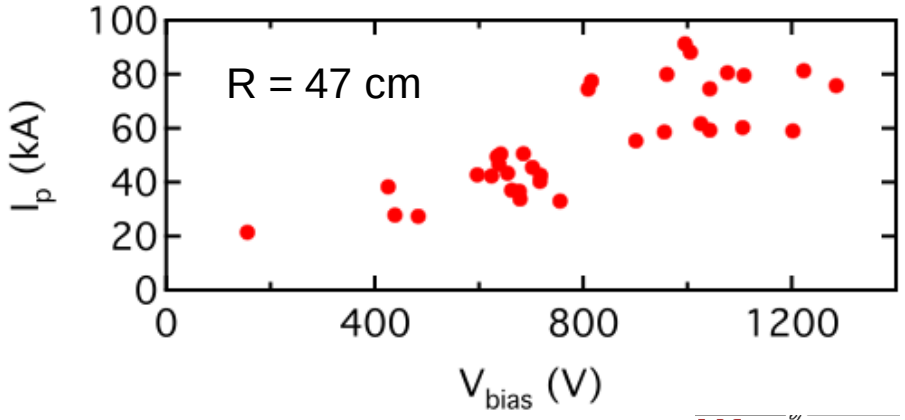
Sufficient helicity injection is required to drive the plasma up to the relaxation limit



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

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

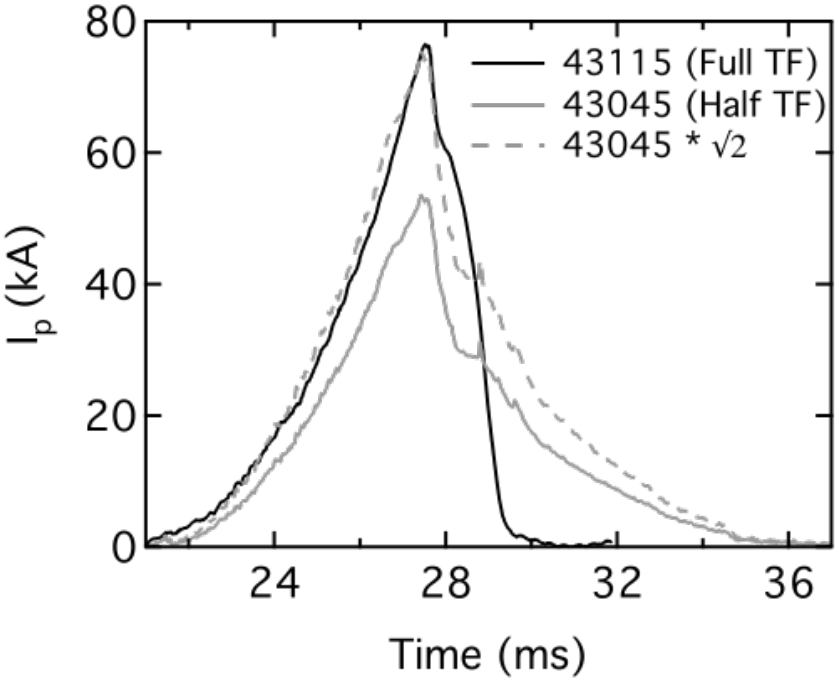
Max I_p increases with V_{bias}

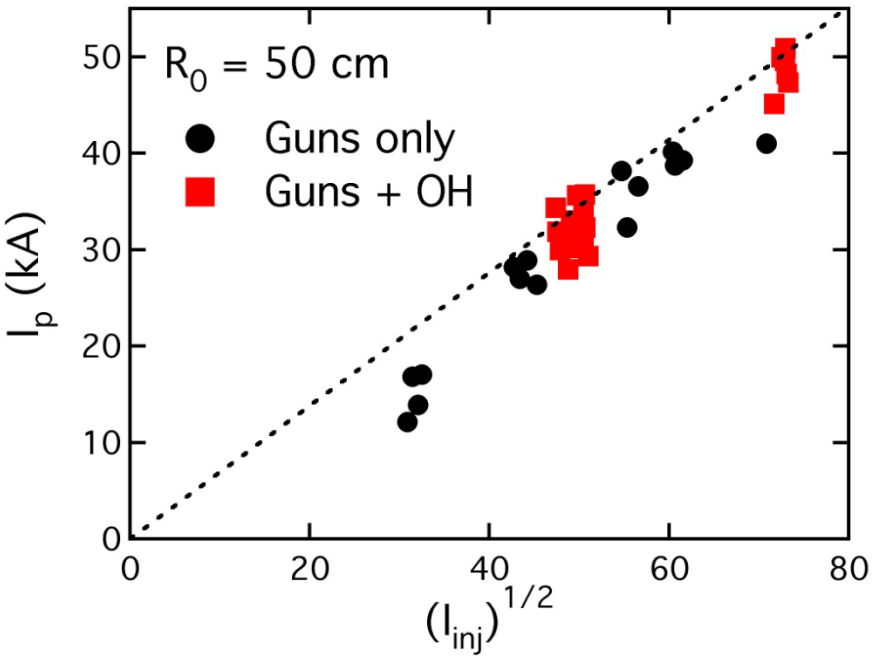


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Experiments confirm relaxation limit scalings with I_{TF} and I_{bias}

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

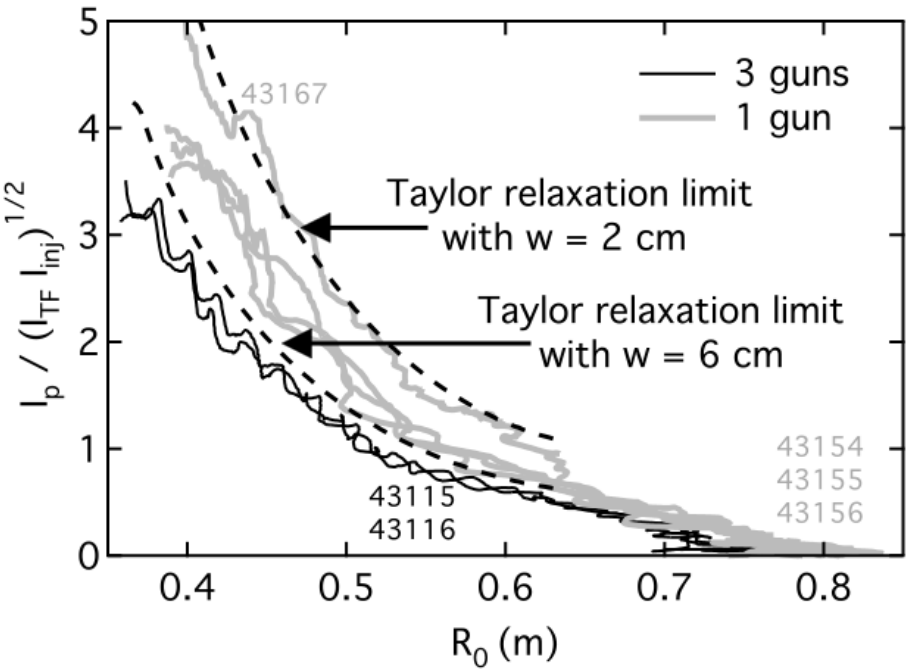


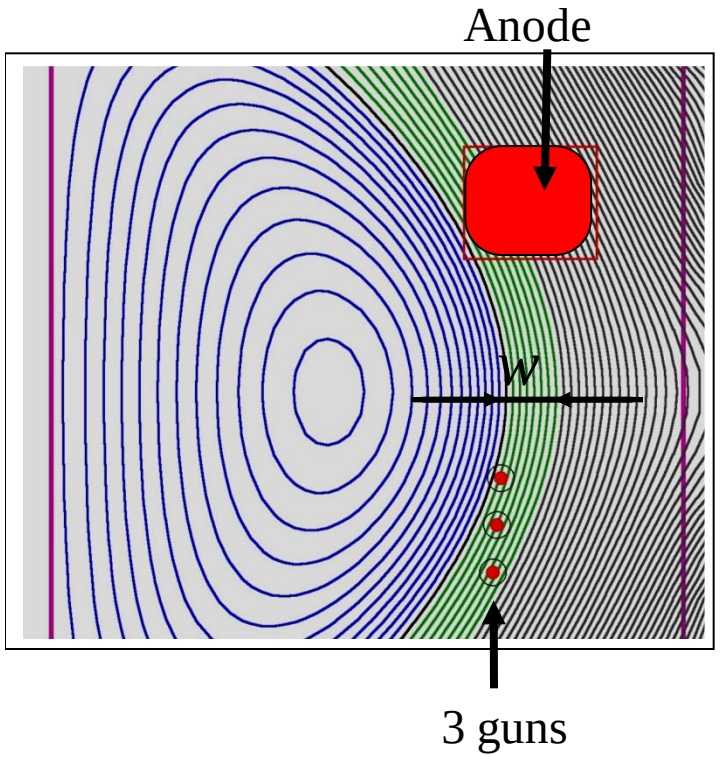


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Experiments demonstrate dependence on the width of the driven current layer

- 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:

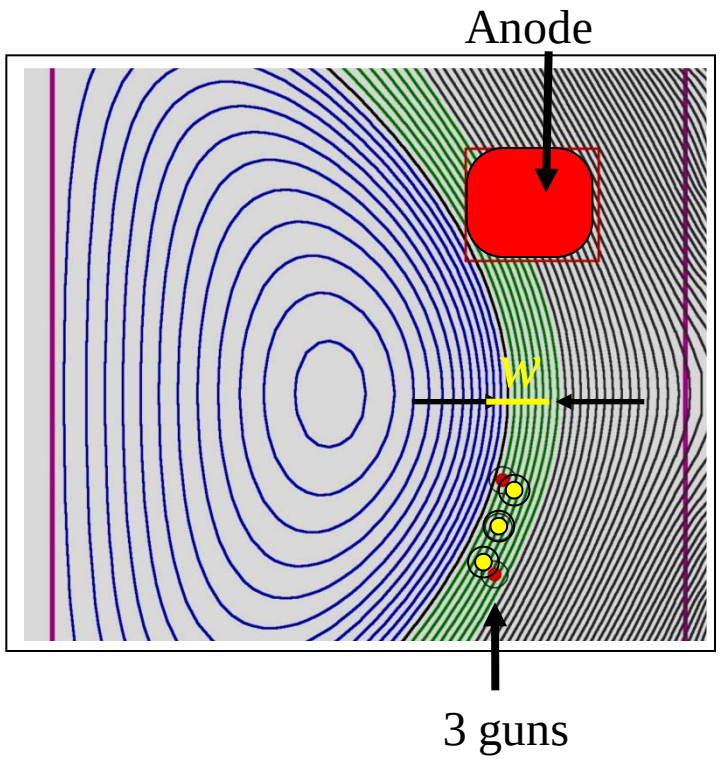


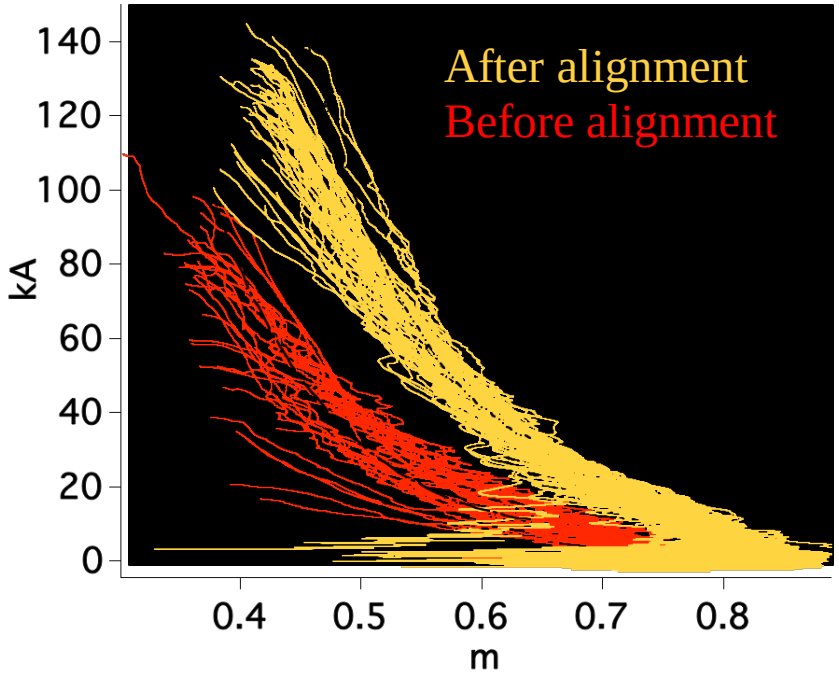


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Gun array was realigned, significantly improving plasma performance

- 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.

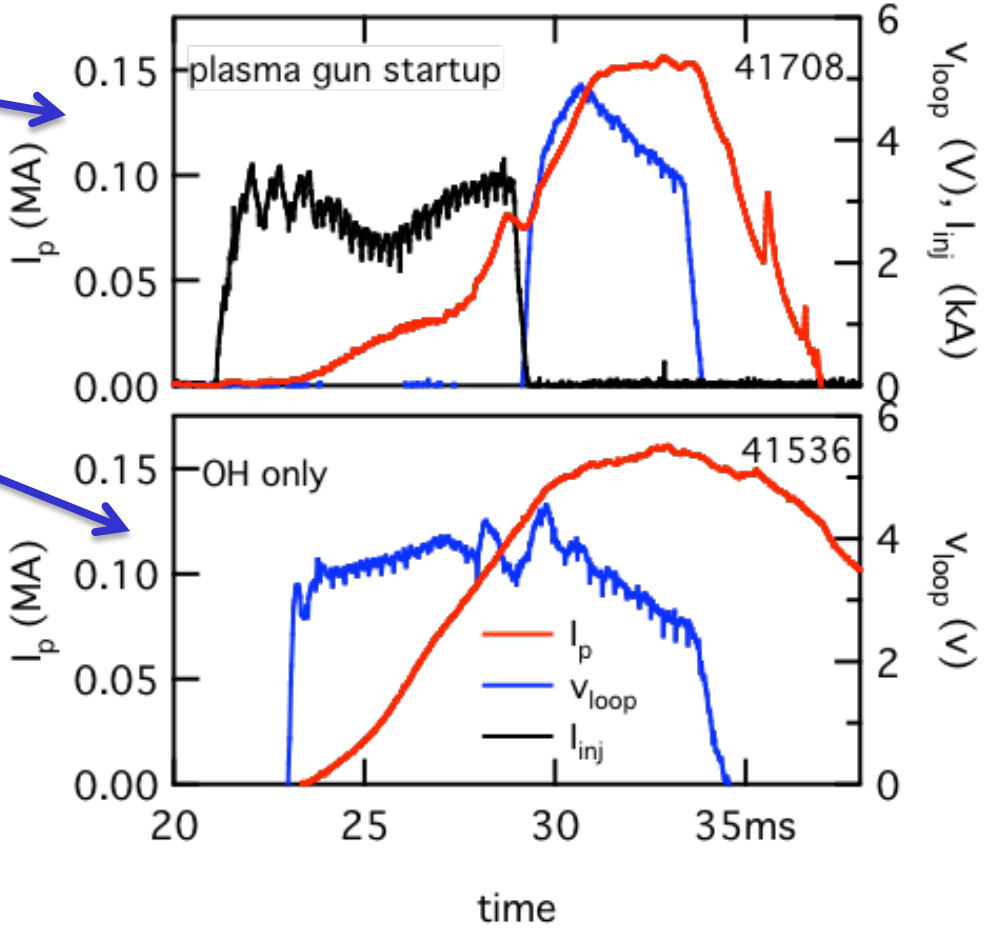




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Plasma gun startup provides a robust target plasma for Ohmic handoff

- 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



For more details, see D. Schlossberg's talk at 2:15PM today

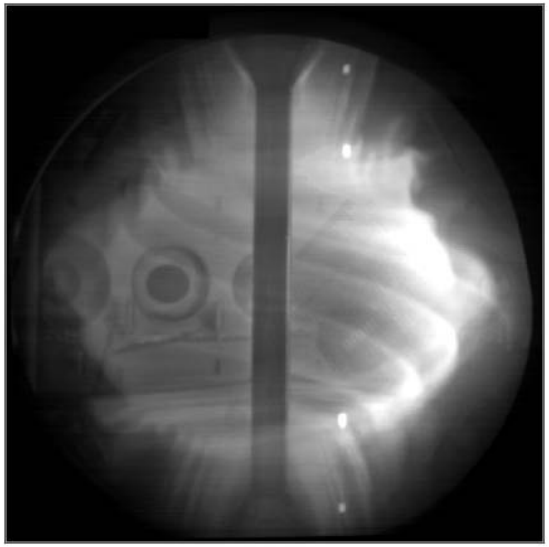
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PEGASUS Overview Outline

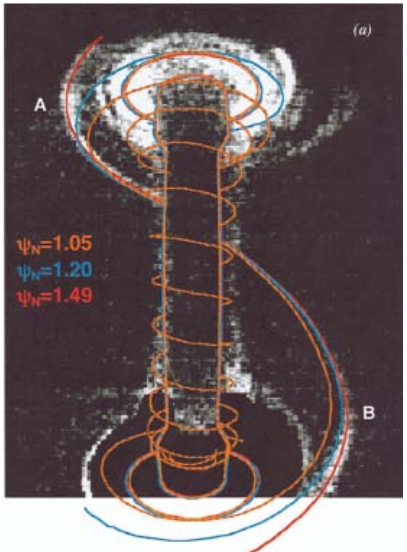
- The PEGASUS Toroidal Experiment
- Non-solenoidal startup studies
- Peeling mode studies
  - Characterization of the modes
  - Measuring $J_T(R)$ and $p(R)$ to test theory
- Future: Guns & RF startup & growth
- Summary

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Observed Filaments are Similar to ELMs

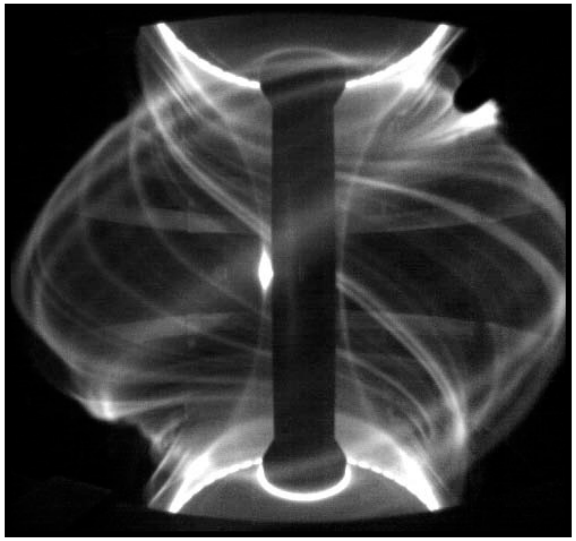


PEGASUS



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

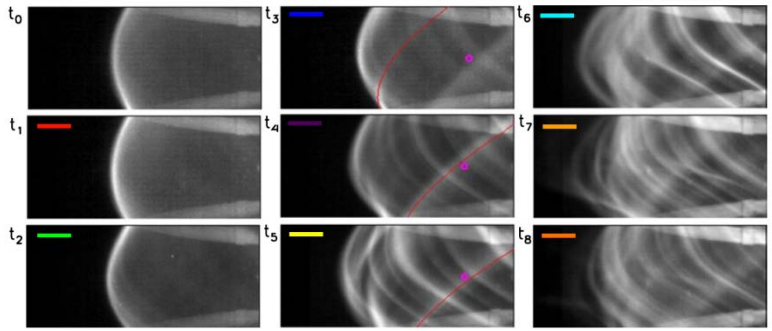
NSTX



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

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Near-unity A Maximizes Peeling Drive

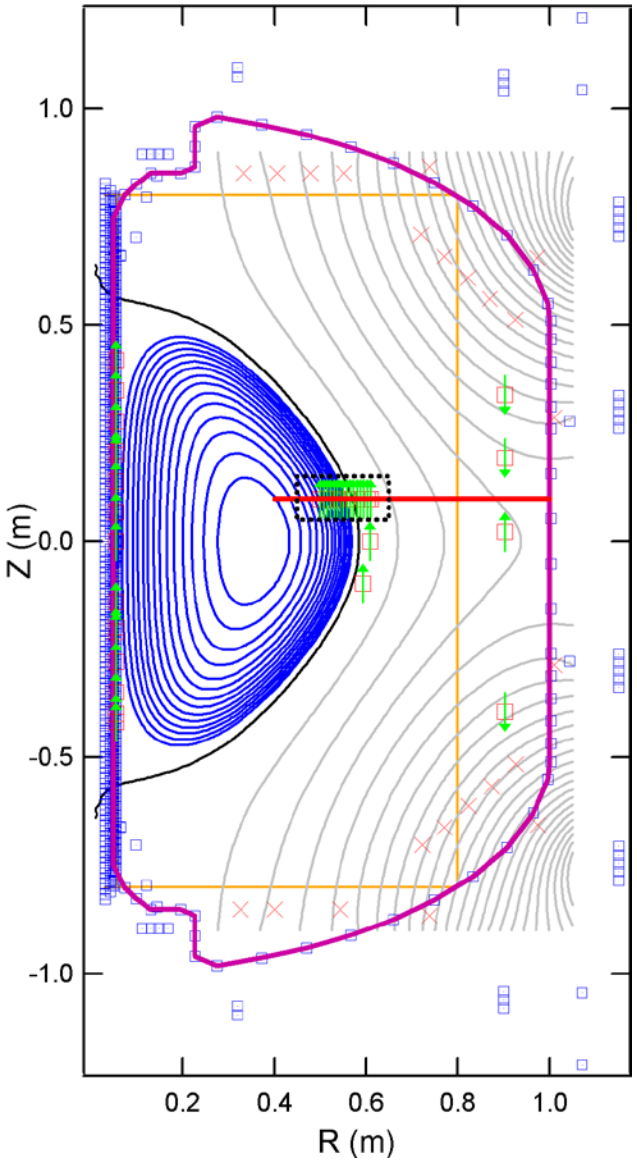
Device	J_{edge} (MA/m²)	$B_{\varphi,0}$ (T)	J_{edge}/B
PEGASUS	~ 0.1 – 0.2	0.1	**~ 1**
DIII-D*	1 – 2	2	**0.5 – 1**

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

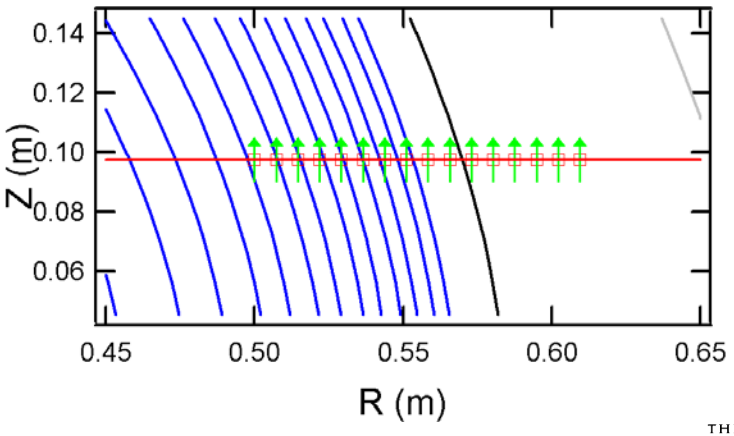
- PEGASUS operations at A → 1 lead to naturally high j_{edge}/B
  - Comparable to larger machines in H-mode
- However, *source* of peeling drive different
  - Large machines: H-mode p' → j_{BS}
  - PEGASUS: Large dI_p/dt (≤ 50 MA/s) → transient skin current
- Low-A geometry enables ITER-relevant research

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Accurate Stability Analysis Requires Local Measurements of J_T and p'

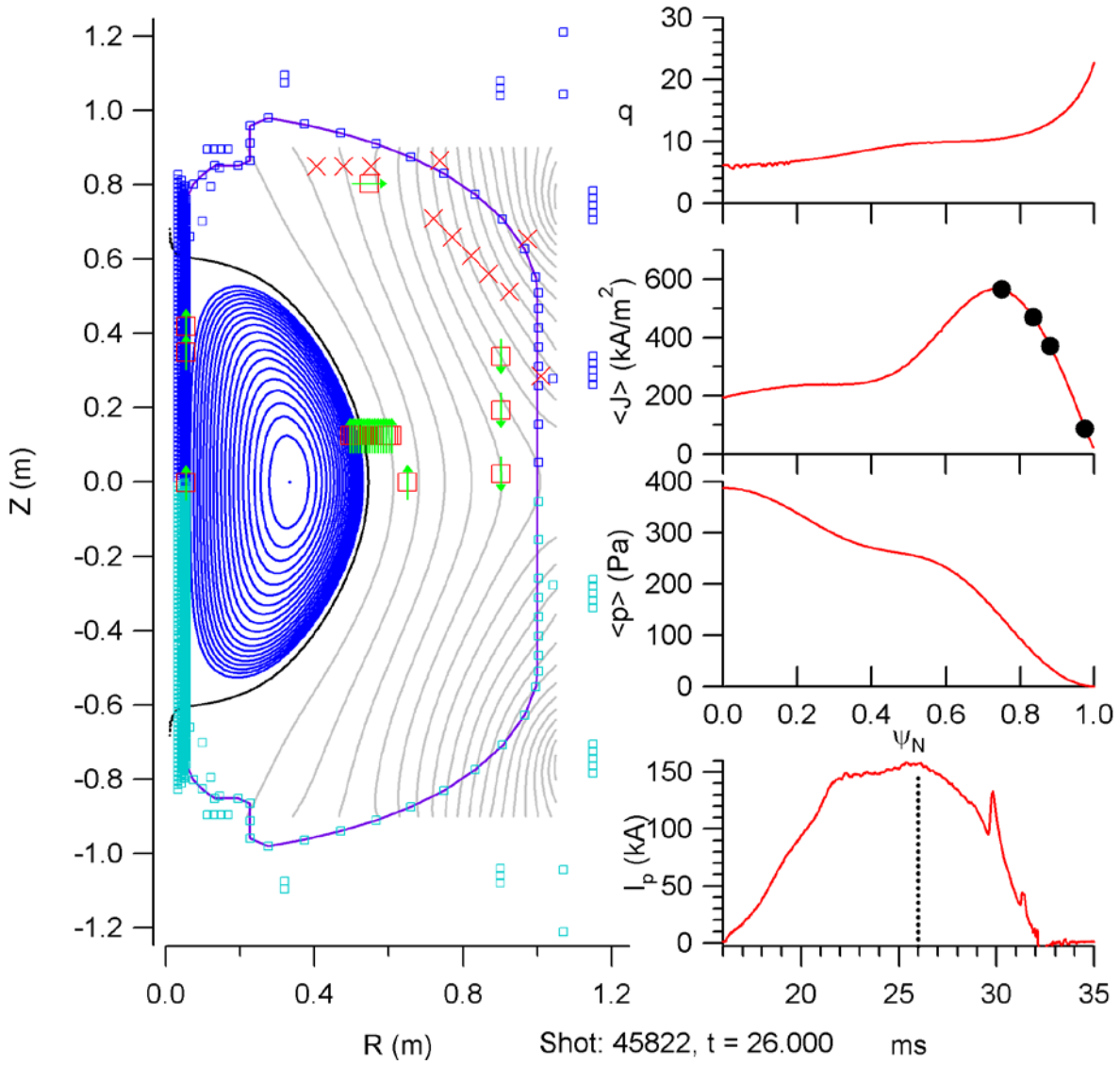


- Comparing experiment to peeling-mode theory requires accurate edge profiles:
  - Need both edge p(ψ) and j(ψ) profiles
- PEGASUS: measurements using probes
  - Hall-effect array constrains j(ψ)
  - Langmuir array constrains p(ψ)



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Initial Internally Constrained Equilibrium



- KFIT* using 5 point cubic spline basis set
- Better basis set is being implemented

*Sontag, A., et. al., Nuclear Fusion, **48,** 095006 , 2008

I_p	157 kA
R_0	.30 m
a	.24 m
A	1.2
κ	2.2
ℓ_i	.25
β_p	.10
β_t	.02
q_0	6.1
q_{95}	17

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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 M. Bongard's talk tomorrow at 10:40AM

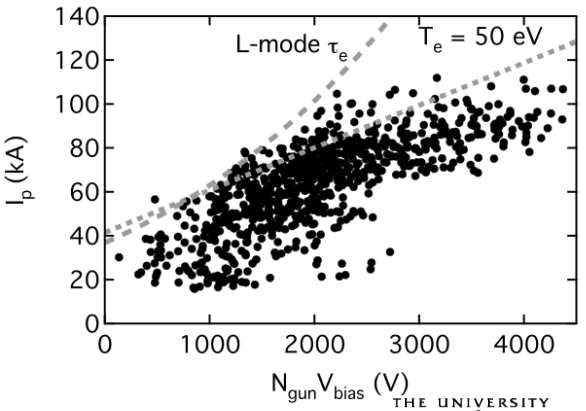
PEGASUS Overview Outline

- The PEGASUS Toroidal Experiment
- Non-solenoidal startup studies
- Peeling mode studies
- Future: Guns & RF startup & growth
  - High-I_p non-solenoidal startup and growth
  - Implementation of RF systems (EBW, HHFW)
  - High-I_N, high-β_T studies
- Summary

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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?

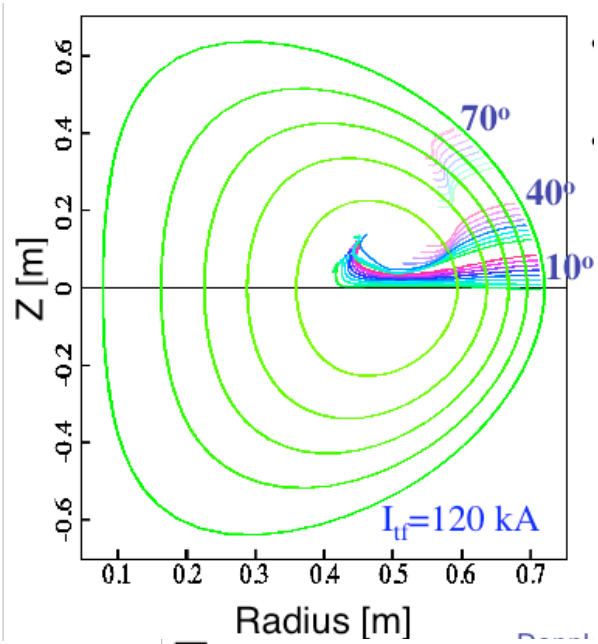


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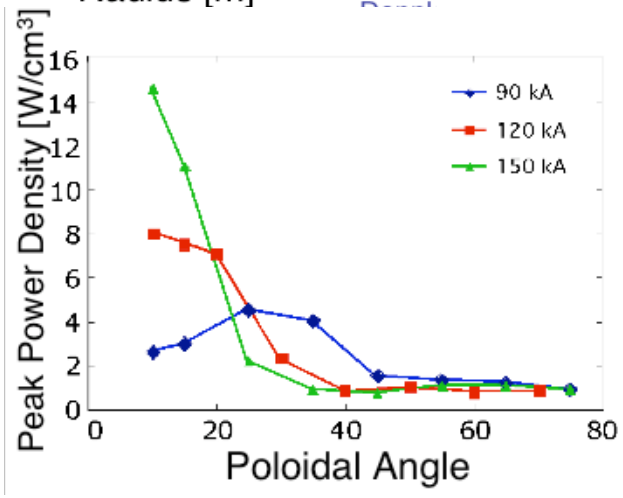
Non-solenoidal startup with RF and/or helicity injection in PEGASUS

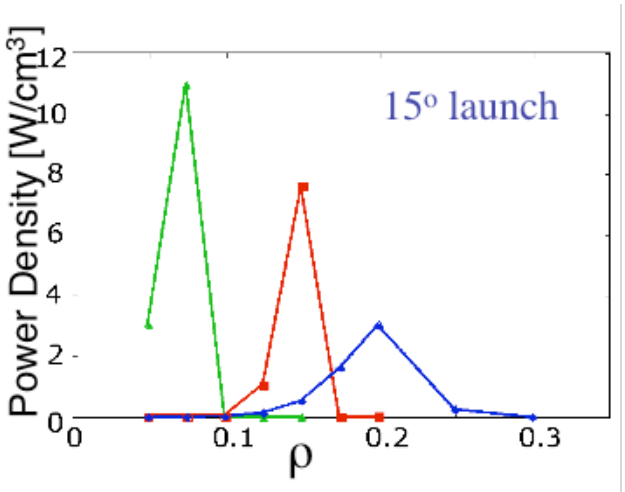
- Two RF systems to be available: HHFW and EBW
- HHFW: Two-strap antenna, 0.8 MW, 8-18 MHz
- EBW planned for next year: 0.5-1.0 MW @ 2.45 GHz
  - 2.45 GHz enabled by very low field at low-A
- Enables comparison of non-solenoidal startup scenarios:
  - Helicity injection + outer-PF induction
  - EBW heating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



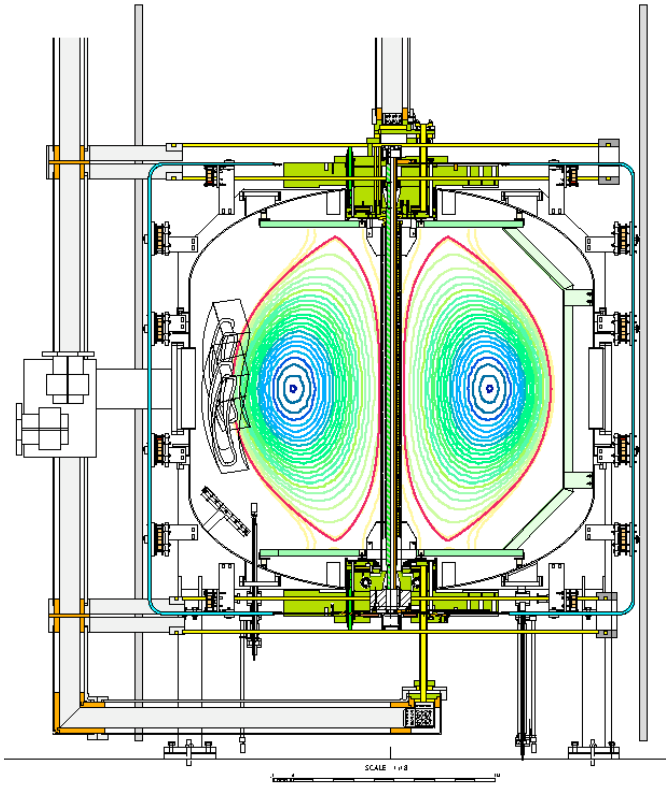


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Proposed PEGASUS Facility Modifications

- 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

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