Recent Results and Plans for the Pegasus ST Experiment

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STCC Meeting, PPPL

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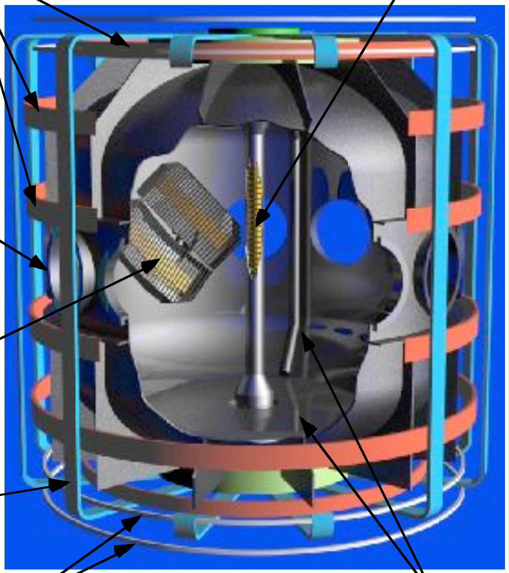

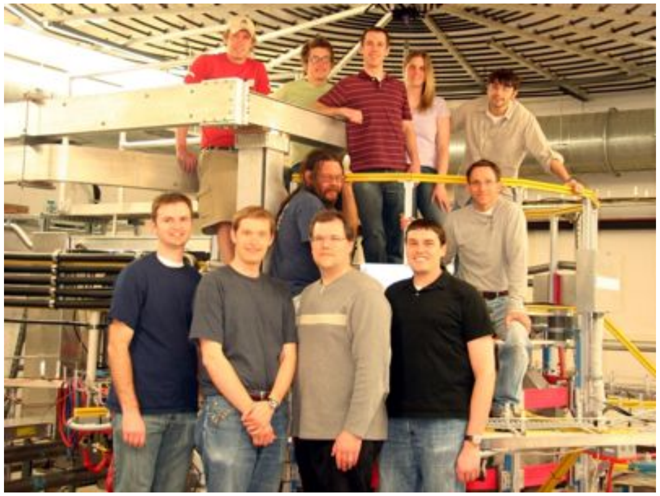

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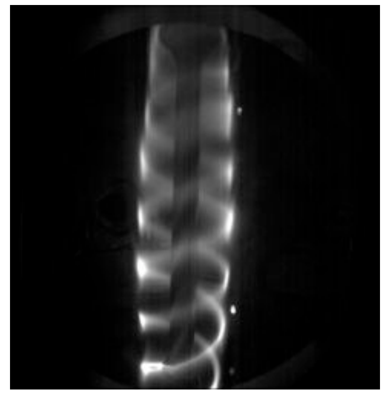
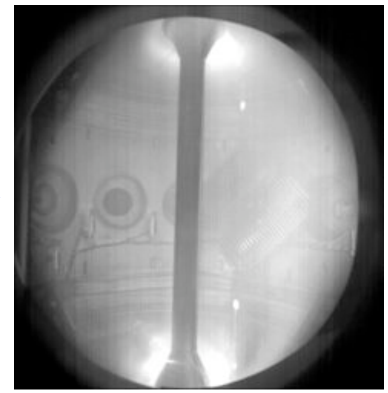
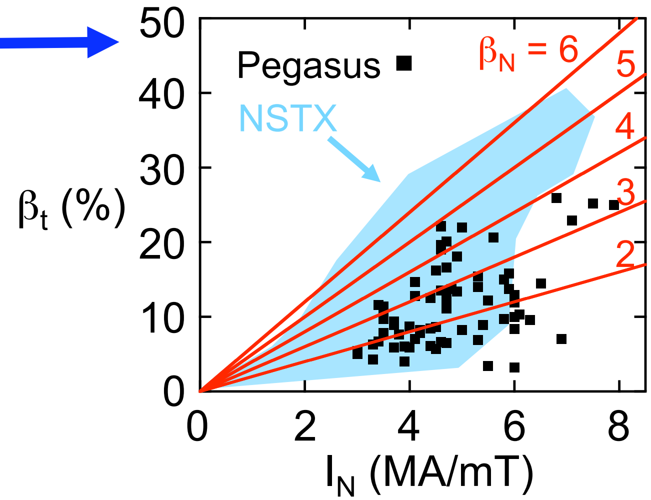
PEGASUS is studying MHD at low aspect ratio & developing non-solenoidal startup techniques

- Non-inductive startup via point current sources
  - Non-solendoidal startup and rampup is critical for STs (FESAC TAP report)
  - DC helicity injection
  - Coupled to outer-PF induction and Ohmic drive

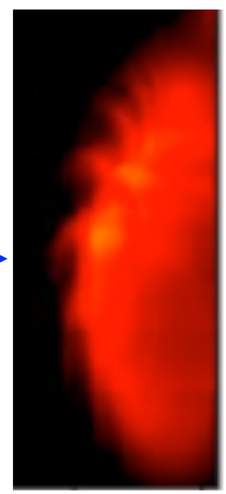




- Determining limits to I_N, β_t
  - High I_N, β_t accessed through j(R) manipulation, fast TF ramps
  - Tokamak-spheromak overlap



- Edge filamentary structures observed
  - Peeling modes?
  - Possibly due to high $(j_{||}/B)_{edge}$

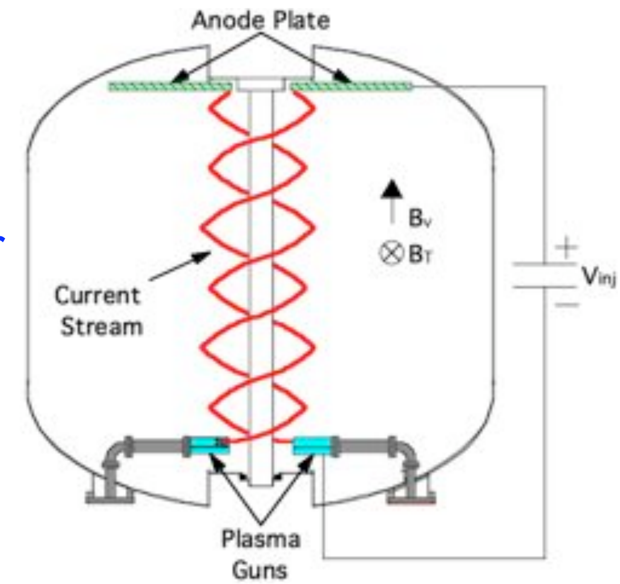


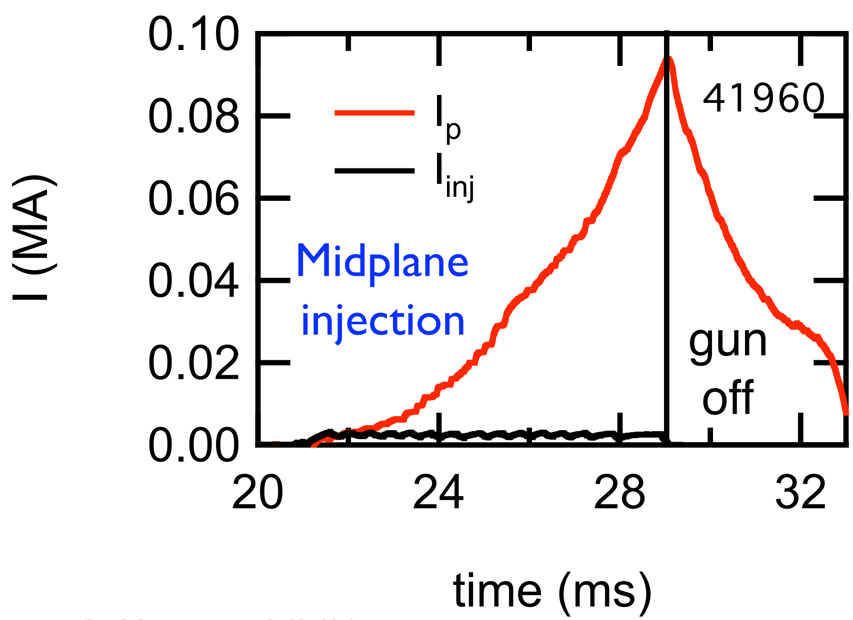
- Planned PEGASUS activities

Point-Source DC Helicity Injection May Provide Viable Non-Solenoidal Startup Technique

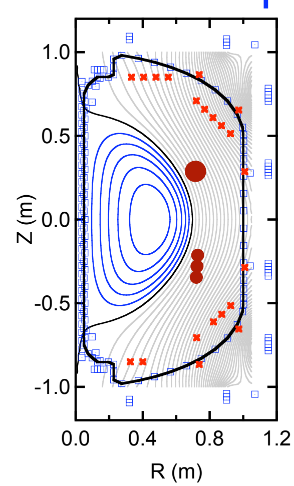
- Plasma guns provide localized, point-current source at plasma edge
- Technique appears to be flexible & scalable to larger currents & devices
- Up to 0.1 MA plasma current to date

Divertor injection





Midplane injection

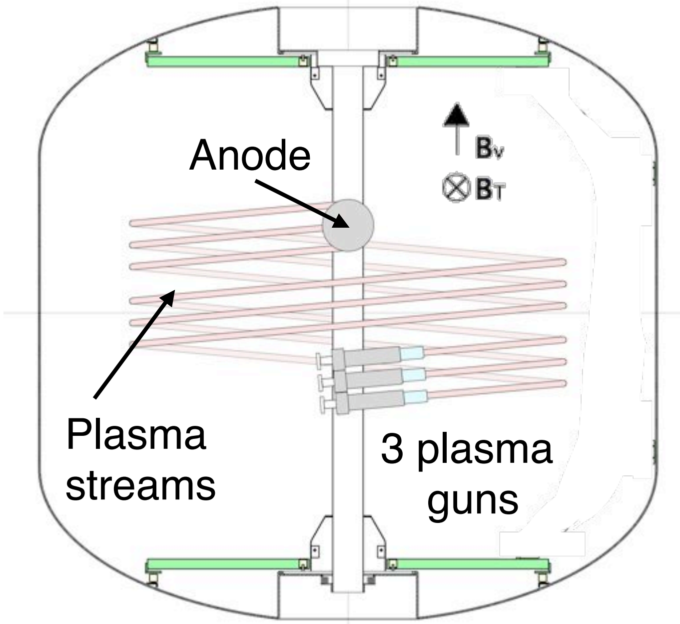


At gun shut-off:

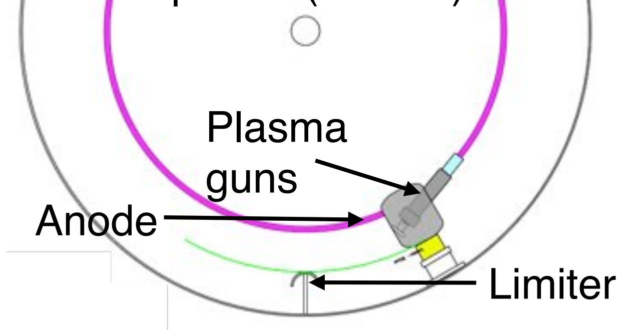
I_p = 94 kA
R_0 = 0.45 m
ℓ_i = 0.35
κ = 1.6
β_p = 0.22
W_{tot} = 350 J

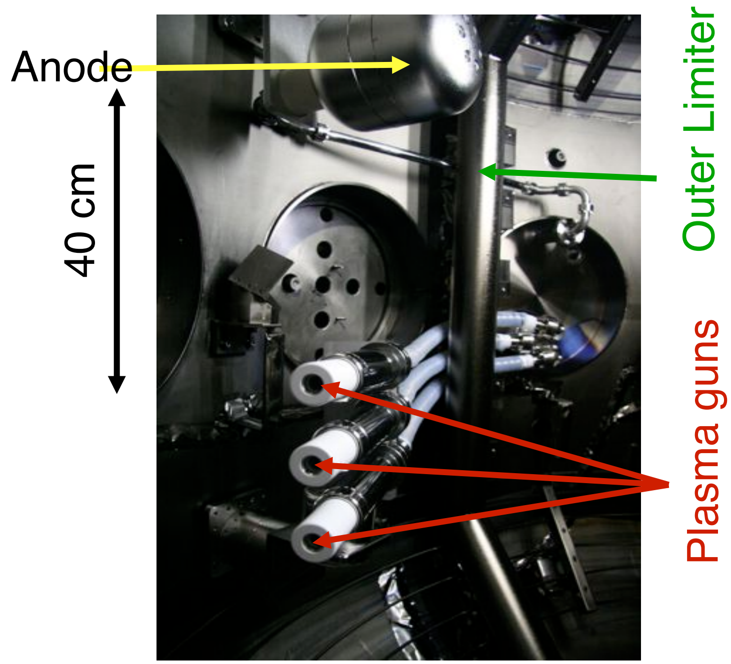
Outboard gun system ≈ "port-plug" design for point-source injection

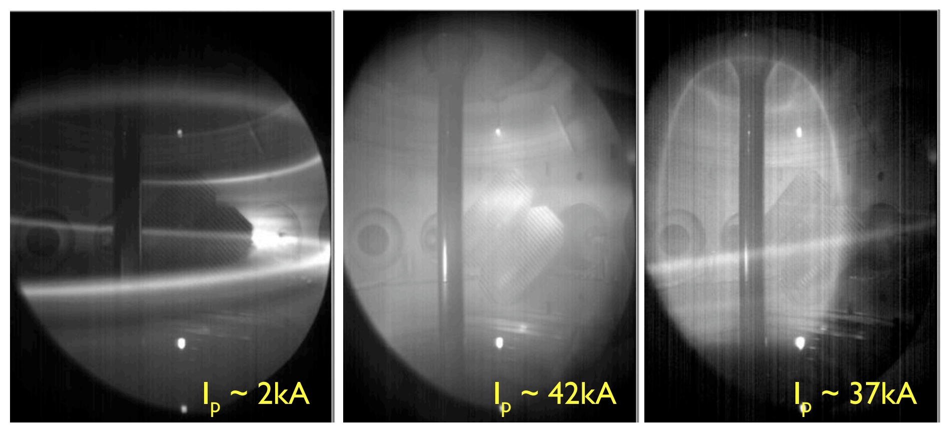
Side view



Top view (rotated)







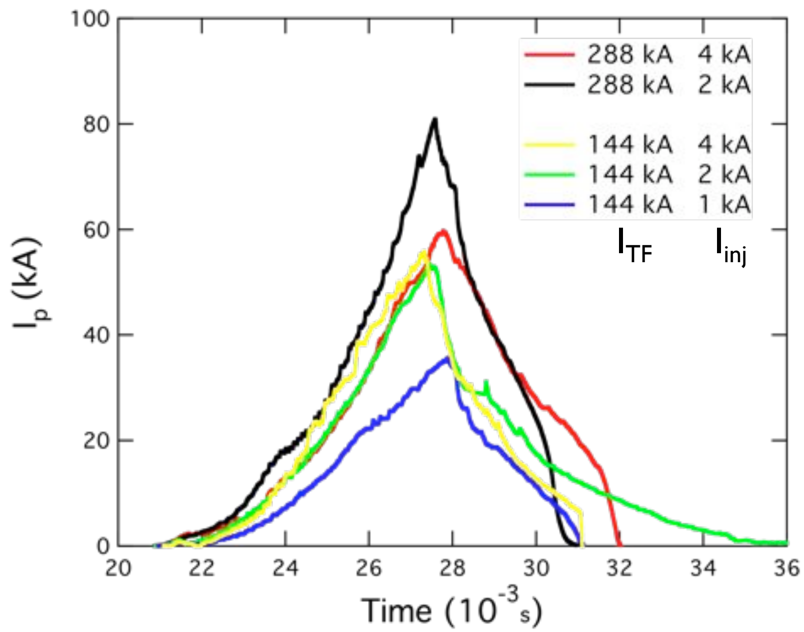
Current Filament only | Gun-driven Phase | Post-gun Decay

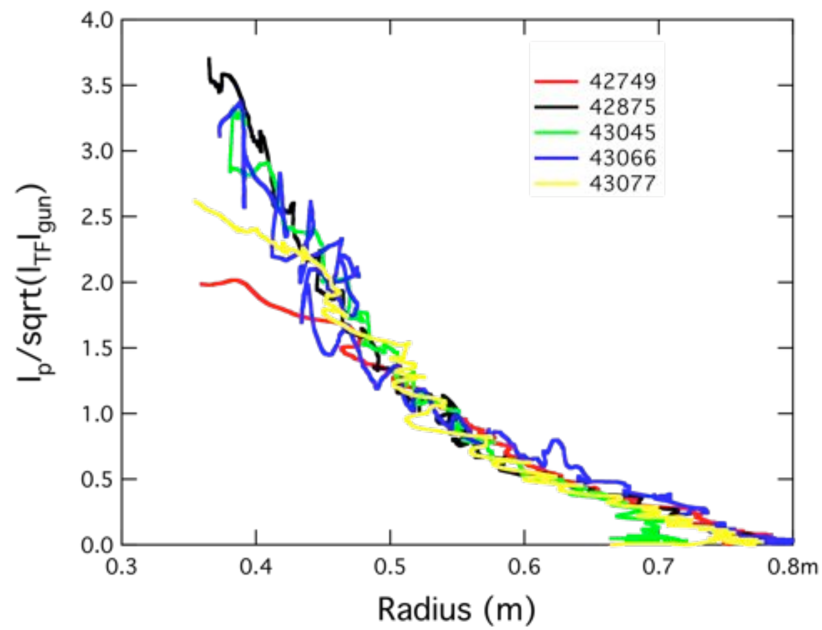
Pegasus Toroidal Experiment
University of Wisconsin-Madison

Recent Experiments Beginning to Test Simple Model for Maximum Ip

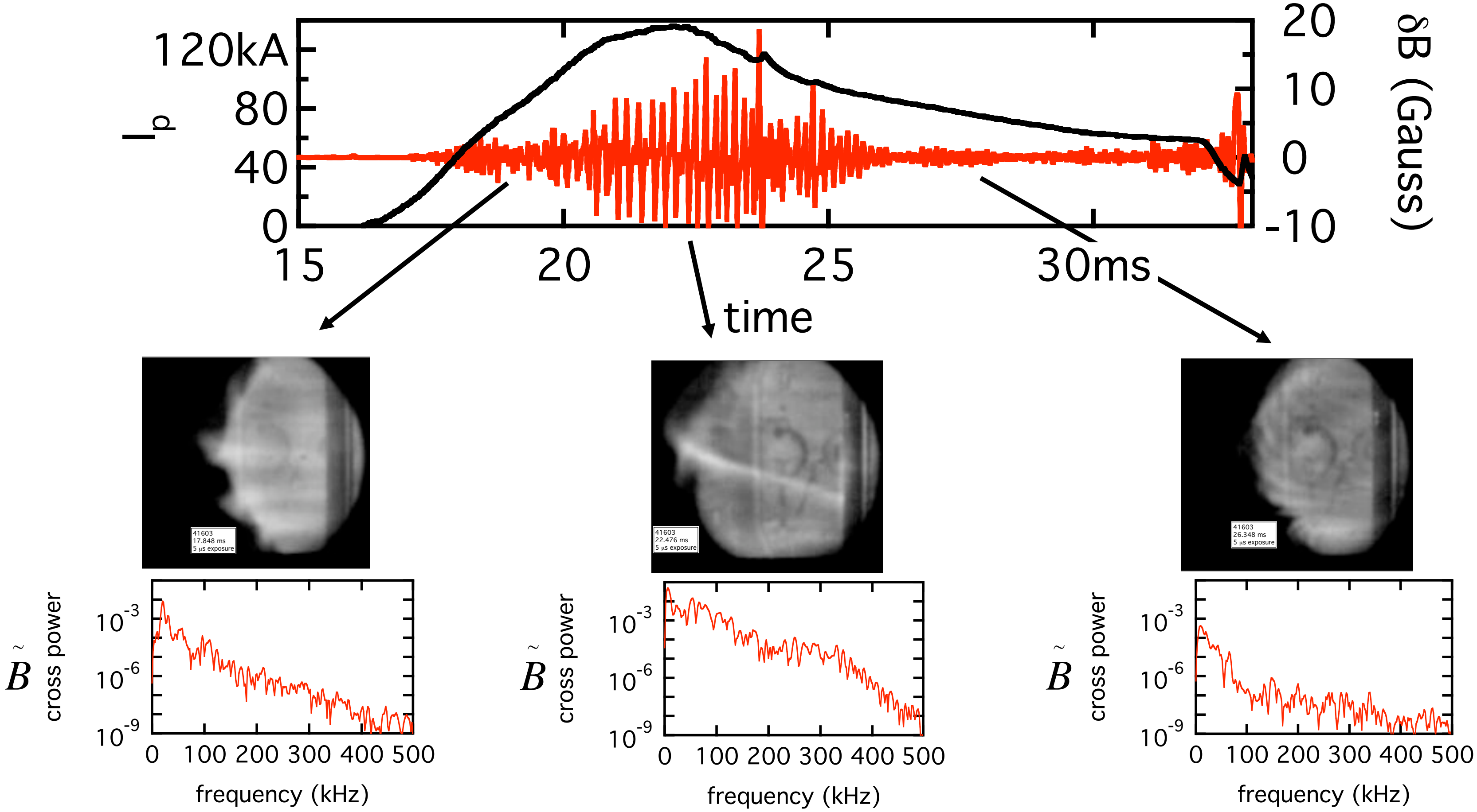
- Relaxation limit suggests: $$I_p \le \left[\frac{C_p}{2\pi R_{inj}\mu_0}\frac{\Psi I_{inj}}{w}\right]^{1/2} \sim \sqrt{I_{inj} I_{TF}}$$

- Vary I_{gun}, I_{TF} under ~ constant conditions
  - Max I_p scales as expected, provided sufficient helicity input available





Coherent Edge Fluctuations Have Strong Electromagnetic Component



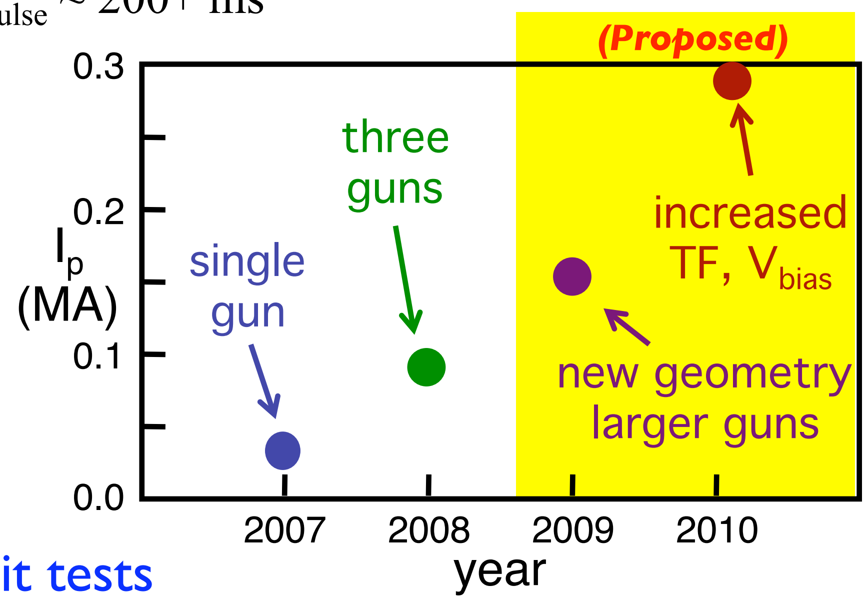
- peeling-like structures @ hi j/B
- Spatial coherence 50-150 kHz
- observed only w/probe at plasma edge

- large 2/1 TM dominates
- visible distortion of edge
- seen on all Mirnovs

- peeling suppressed via I_p rampdown?
- Intermittant turbulent banding; mostly electrostatic

Proposed Pegasus Research Program: Address Several Areas of ST Focus

- Non-solenoidal startup & growth via HI, current sources
  - Model for scaling point source injection startup to larger scale
    - *Combine w/CHI concepts to optimize I_p*
  - Extend non-solenoid startup to ~0.3MA
  - Couple to growth, sustainment; target = t_{pulse} ~ 200+ ms
    - *HI, HHFW, PF, bootstrap, EBW(?)*
  - Develop technically robust approach
    - *Deploy to NSTX in future*



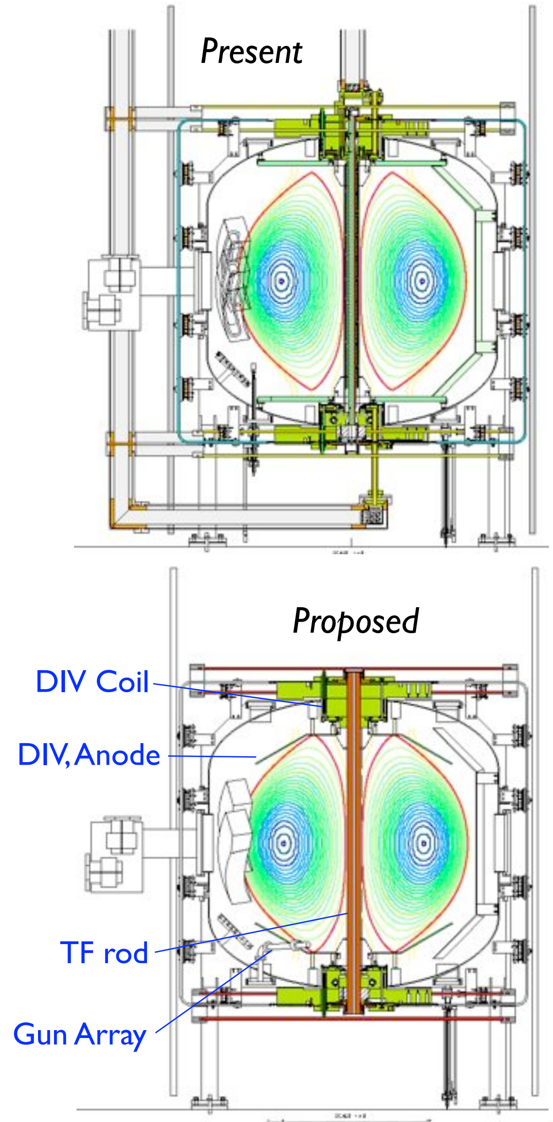
- Edge characteristics; Peeling modes
  - Edge j(ψ), P(ψ) profiles via probes
  - Add separatrix for local shear & H-mode

- Coupled HI-OH CD for high I_N, β_t limit tests
  - Achieve high I_p/I_{TF} with broad j(r) at $I_p \geq 0.15$ MA

- Use plasmas for Li Divertor test concepts?

Proposed Future Program: Modest Facility Modifications

- Magnetic and power systems reconfiguration
  - Remove OH solenoid; new TF rod assembly
    - *Increase TF x 5 ($B_t \sim 0.64T$)*
  - Larger Divertor coils
  - Reconfigure for longer pulse operation
- Flexible Helicity Injection system
  - New high-voltage boost power supplies
  - Integrated plasma gun test/development facility
- Sufficient core and edge Diagnostics
  - Multi-point Thomson scattering
  - Edge current and fluctuation probes
  - Insertable gun diagnostic station
  - (Future) DNB/CHERS for $T_i(r)$ and J(r)



Pegasus Contributes to the National ST Science Program

- Exploration of high I_N, β_t in tokamak-spheromak 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
- Helicity injection startup and growth development
  - $I_p \sim 0.1$ MA achieved with simple outboard midplane 3-gun array
  - Goal: ~0.3 MA non-solenoidal target & hand-off to RF heating & growth
- Edge instabilities, especially at high j_{edge}/B
- Future contributions proposed
  - Optimized HI concepts for large facility deployment
    - *Startup and growth to NB target plasmas*
  - Detailed tests of Peeling-ballooning theory
  - Fully nonsolenoidal operation
  - Concept tests for next generation: Li divertor, etc?

Reprints at: http://pegasus.ep.wisc.edu/Technical_Reports

Achieved I_p depends on helicity, relaxation, and tokamak constraints

Helicity balance in a tokamak geometry:

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

- I_p limit depends on the scaling of plasma confinement via the η term

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

Requirement from Taylor relaxation:

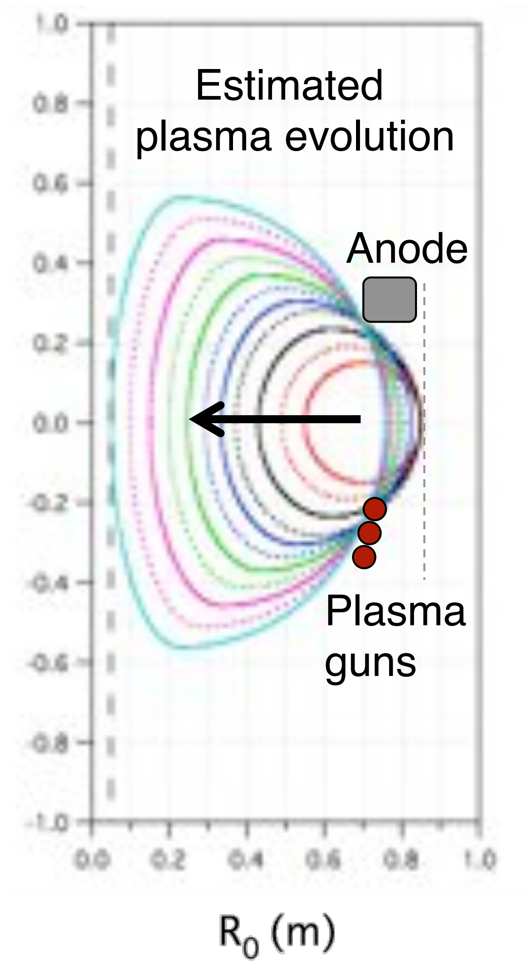
$$\frac{\mu_0 j}{B} = \lambda_p \le \lambda_{edge} \Rightarrow \frac{\mu_0 I_p}{\Psi} \le \frac{\mu_0 I_{inj}}{2\pi R_{inj} w B_{\theta,inj}} \Rightarrow I_p \le \left[\frac{C_p}{2\pi R_{inj}\mu_0}\frac{\Psi I_{inj}}{w}\right]^{1/2}$$

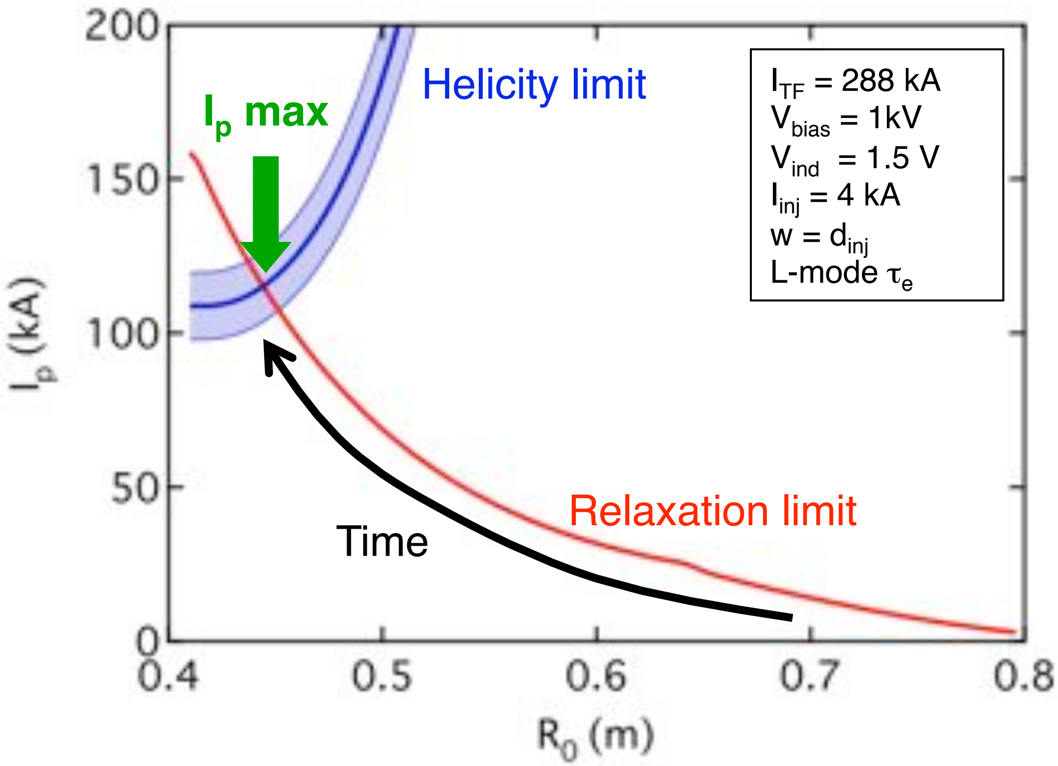
- Assumes edge current mixes uniformly in SOL
- Edge fields average to tokamak-like structure

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

Radial force balance.
Overall stability (e.g., q ≥ 3)

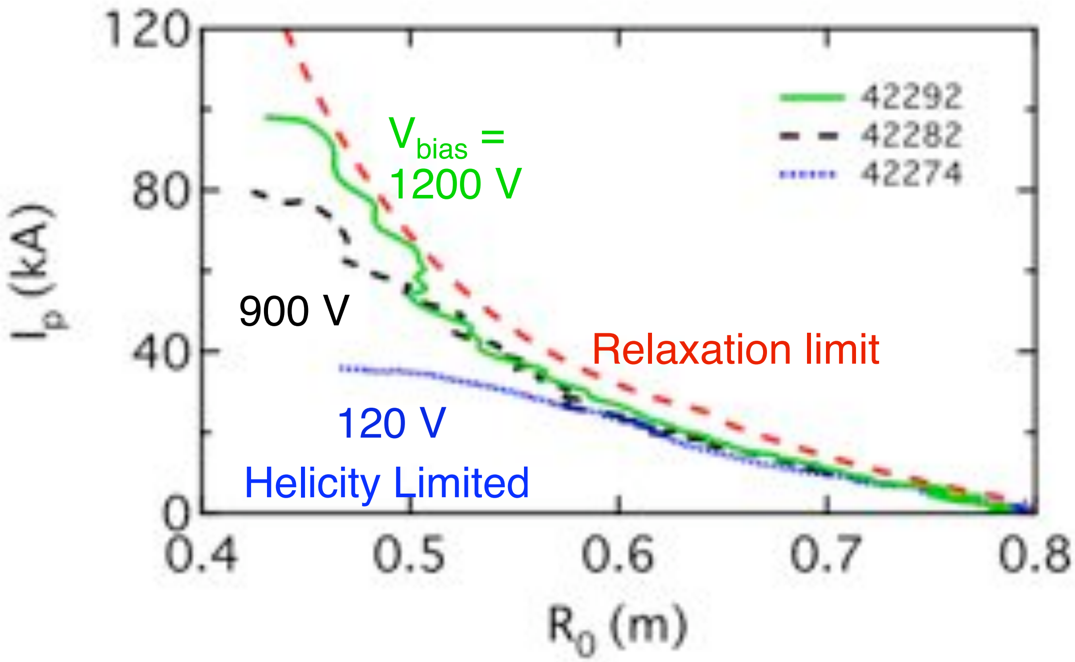
Maximum possible I_p reached when helicity and relaxation criteria are satisfied simultaneously





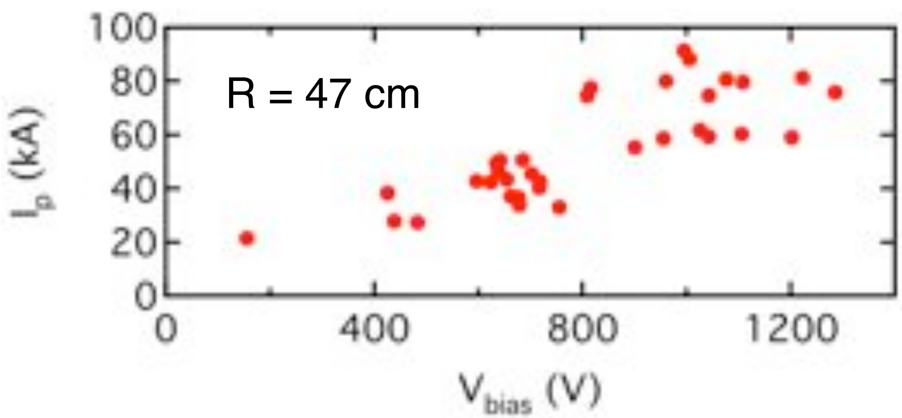
- Radial force balance requires an outer-PF ramp
- Total "loop voltage" from relaxation and PF ramp

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



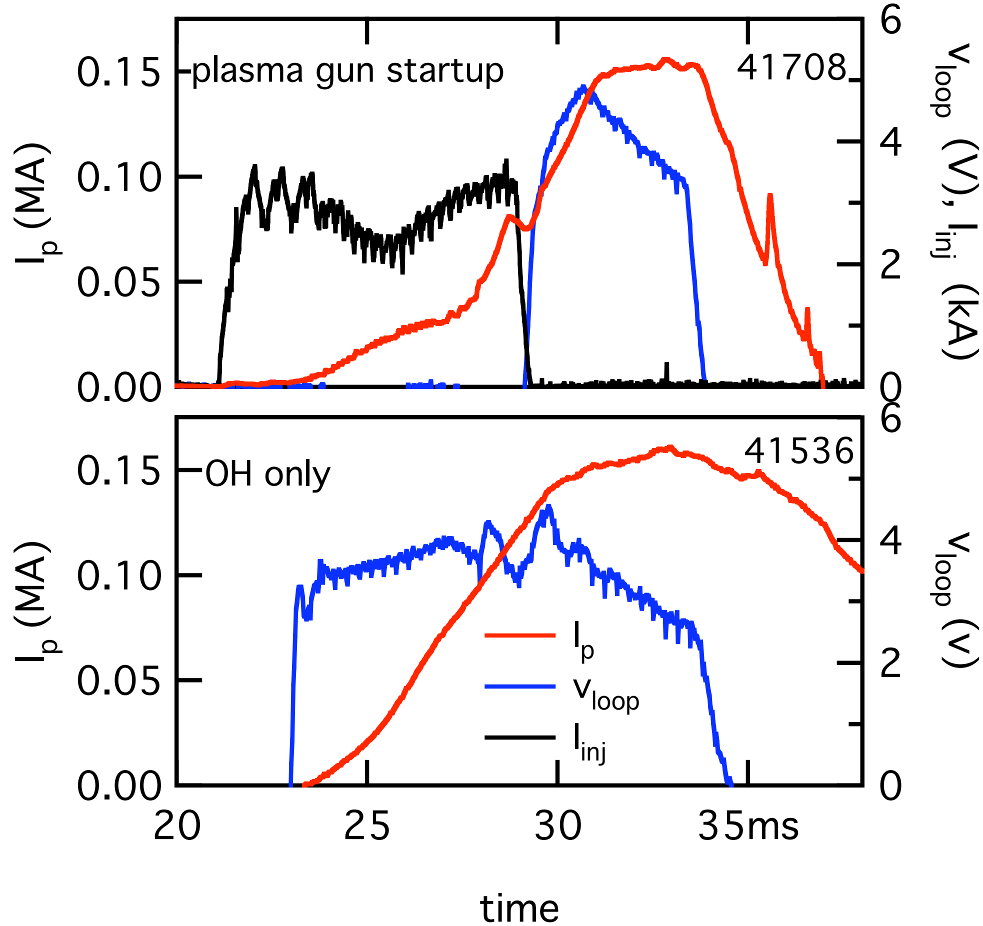
$$\dot{K}_{DC} \propto V_{bias} \propto Z_{inj}$$

- I_p increases with V_{bias}, helicity injection rate:



Plasma Gun Startup Provides Robust Target Plasma

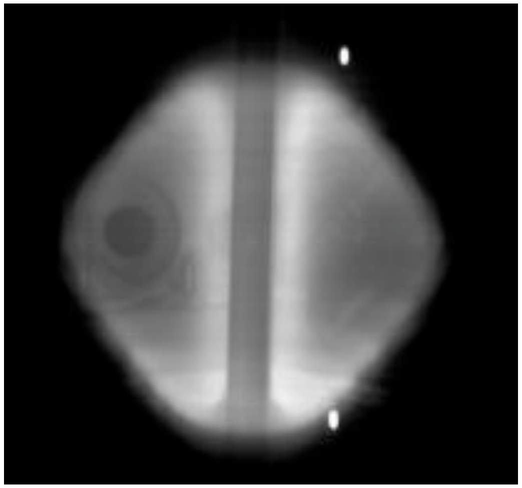
- 3-gun target then OH drive
  - pre-OH plasma ~80 kA
- Equivalent I_p with 1/2 OH flux swing
  - ~ 50% flux savings
- Need to assess target suitability for other CD means



Edge Filaments Observed in Most Discharges

- Localized to edge
  - large tearing modes also observed which cause entire plasma to wobble
- Appear early in discharge & exist throughout shot
  - individual modes last less than 100 μs
- Uncorrelated with I_p saturation
- Can be delayed by manipulating size and/or shape?

Larger Startup
- sharp edge



Smaller Startup
- strong filaments

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