Predictions for non-solenoidal startup in Pegasus with lower divertor helicity injectors

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APS-DPP Meeting
New Orleans, LA
Oct. 26-31, 2014



PEGASUS
Toroidal Experiment

Abstract

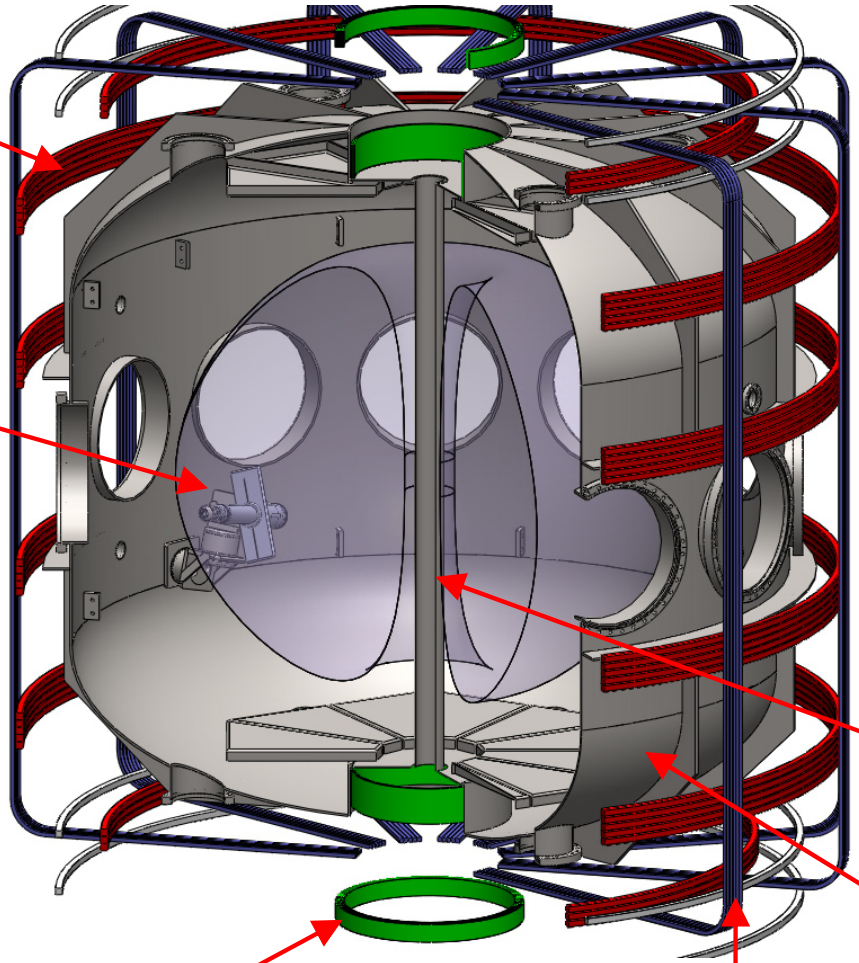
Non-solenoidal startup in Pegasus has focused on using arrays of local helicity injectors situated on the outboard midplane to leverage PF induction. In contrast, injector assemblies located in the lower divertor region can provide improved performance. Higher toroidal field at the injector increases the helicity injection rate, providing a higher effective loop voltage. Poloidal flux expansion in the divertor region will increase the Taylor relaxation current limit. Radial position control requirements are lessened, as plasma expansion naturally couples to injectors in the divertor region. Advances in cathode design and plasma-facing guard rings allow operation at bias voltages over 1.5kV, three times higher than previously available. This results in increased effective loop voltage and reduced impurity generation. Operation of helicity injectors in the high field side elevates the current requirements for relaxation to a tokamak-like state, but these are met through the improved injector design and increased control over the poloidal field structure via the addition of new coil sets. These advances, combined with the relocation of the injectors to the divertor region, will allow access to the operational regime where helicity injection current drive, rather the poloidal induction, dominates the discharge – a prerequisite for scaling to larger devices. Initial estimates indicate that plasma currents of 0.25-0.30MA are attainable at full toroidal field with 4 injectors of $2cm^2$ each and 8kA total injected current.

Local Helicity Injection provides robust start-up on the PEGASUS ST

Equilibrium Field Coils

Local DC Helicity Injectors





High-stress Ohmic heating solenoid

Vacuum Vessel

Divertor Coils

Toroidal Field Coils

Plasma Parameters

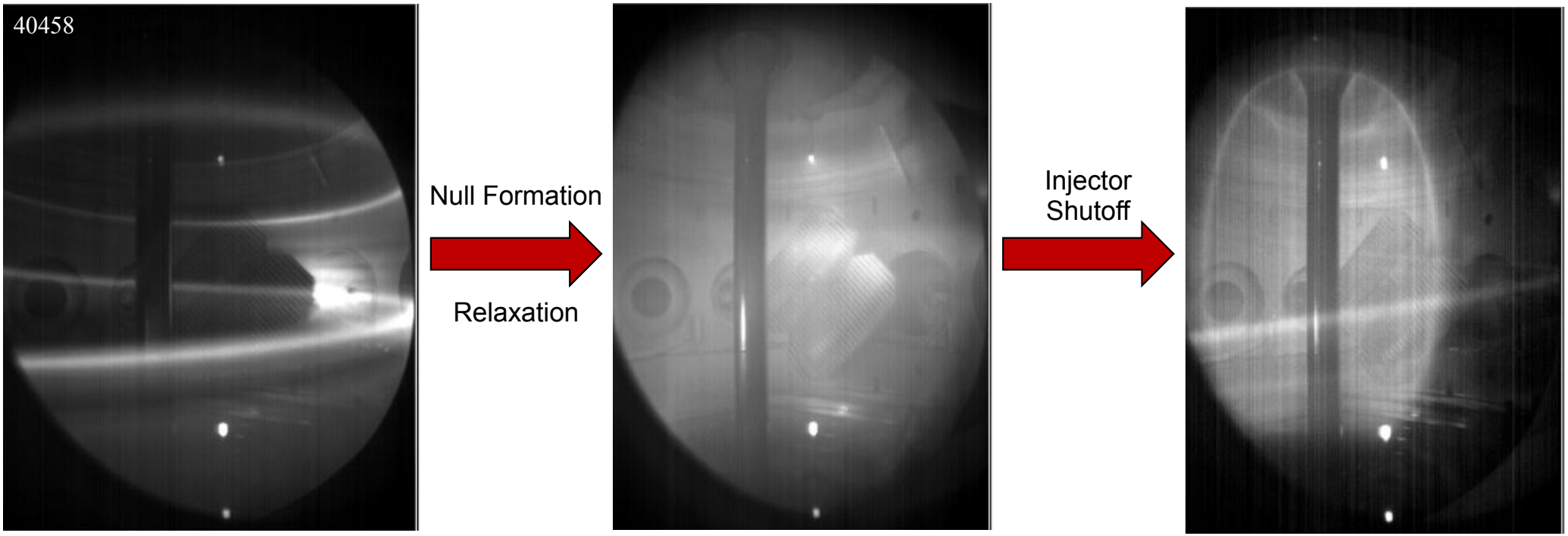
I_p	$\leq$ 0.18 MA
τ_{shot}	$\leq$ 0.025 s
B_T	0.15 T
A	1.15 – 1.3
R	0.2 – 0.45 m
a	$\leq$ 0.4 m
κ	1.4 – 3.7

Injector Parameters

I_{inj}	$\leq$ 6.5 kA
V_{inj}	$\leq$ 2.5 kV

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Local helicity injection offers scalable non-solenoidal startup



- Current injected along helical vacuum field
  - Local, active current sources
- MHD relaxation, tokamak-like state
  - Constrained by helicity, Taylor relaxation limits
- Tokamak plasmas produced after injector shut off
  - Couples to alternative current drive sources

Battaglia *et al.*, Nucl. Fusion **51**, 073029 (2011)

Helicity injection drives toroidal current

Total helicity K in a tokamak geometry: $K = \int_V (\mathbf{A} + \mathbf{A}_{vac}) \cdot (\mathbf{B} - \mathbf{B}_{vac})\, d^3x$

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

Resistive dissipation | Inductive drive | DC helicity injection

$$\dot{K}_{DC} = -2\int_A \Phi \mathbf{B}\cdot d\mathbf{s} = 2V_{inj}B_{\perp}A_{inj} \quad \Rightarrow \quad V_{eff} \approx \frac{A_{inj}B_{\phi,inj}}{\Psi}V_{inj}$$

- Effective loop voltage (V_{eff}) driven by
  - Injector area (A_{inj})
  - Field at injector (B_{inj})
  - Injector bias voltage (V_{inj})
  - Plasma toroidal flux

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Taylor relaxation criterion also limits the total sustainable I_p for a given plasma geometry

- Considering force-free equilibrium:

$$\nabla \times B = \mu_0 J = \lambda B$$

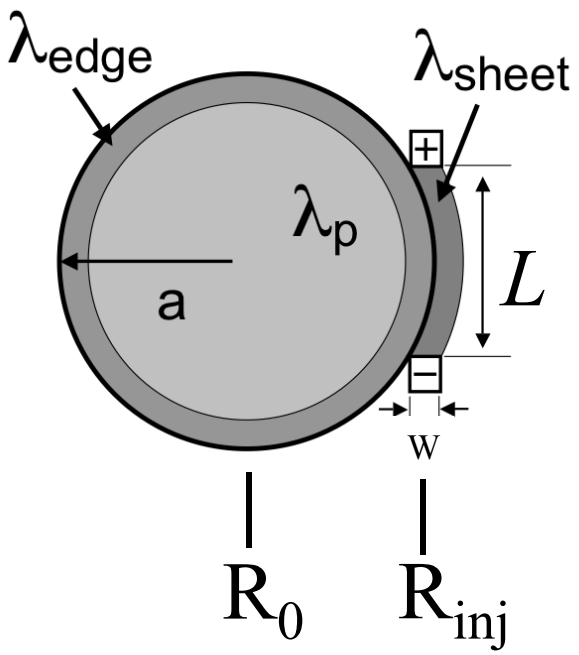
- Current penetration via Taylor relaxation requires:

$$\overline{\lambda}_{edge} > \overline{\lambda}_{plasma}$$

- Averaging $\overline{\lambda}_{edge}$ over the plasma surface area gives Taylor relaxation current limit[1]:

$$I_p \leq \left[\frac{C_p}{2\pi R_{inj}\mu_0} \frac{\Psi I_{inj}}{w} \right]^{1/2}$$

- Current limit increased by high I_{inj}/w
  - w=current channel width at midplane
  - May manipulate w through flux expansion in highly shaped plasma



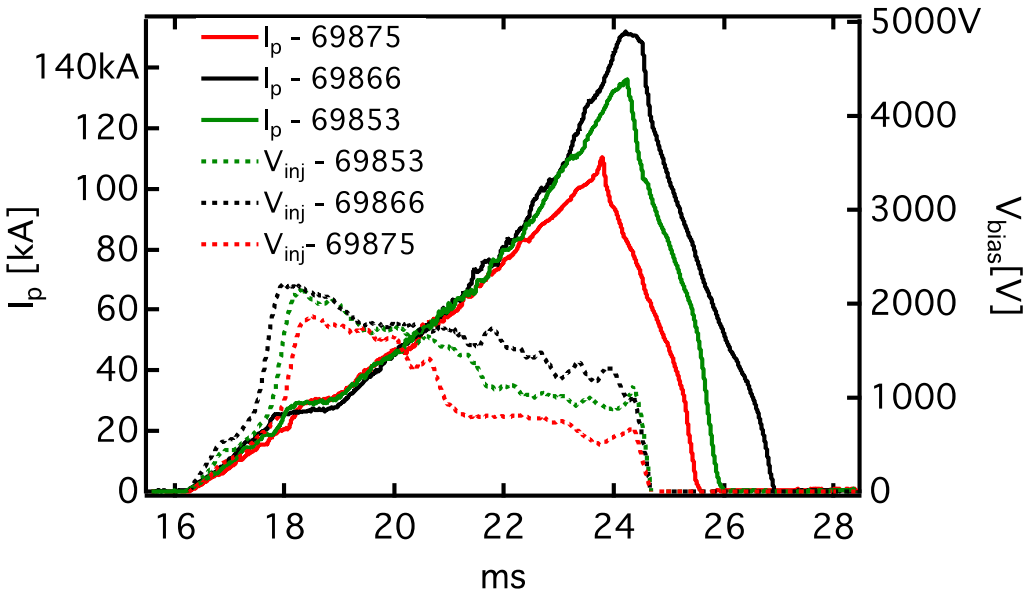
A_p, A_{inj} : Plasma, injector area
C_p : Plasma circumference
Ψ : Plasma toroidal flux
w : Edge current channel width

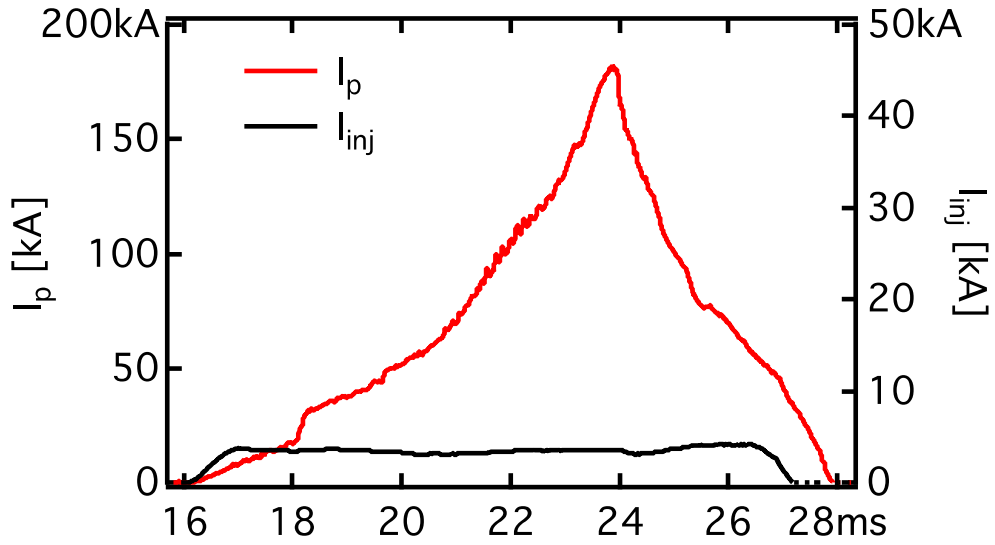
1 Holcomb, C.T. et. al., Phys. Plasmas **13**, 2006

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I_p increases with helicity drive; up to 0.18MA achieved to date

- Top: Increasing V_{eff} yields higher I_p
  - Improved injector design
    - higher V_{inj} → higher V_{eff}
  - Inductive drive is still dominant late in time
- Bottom: I_p>0.18MA with I_{inj}<5kA
  - Achieved with 3 outboard injectors

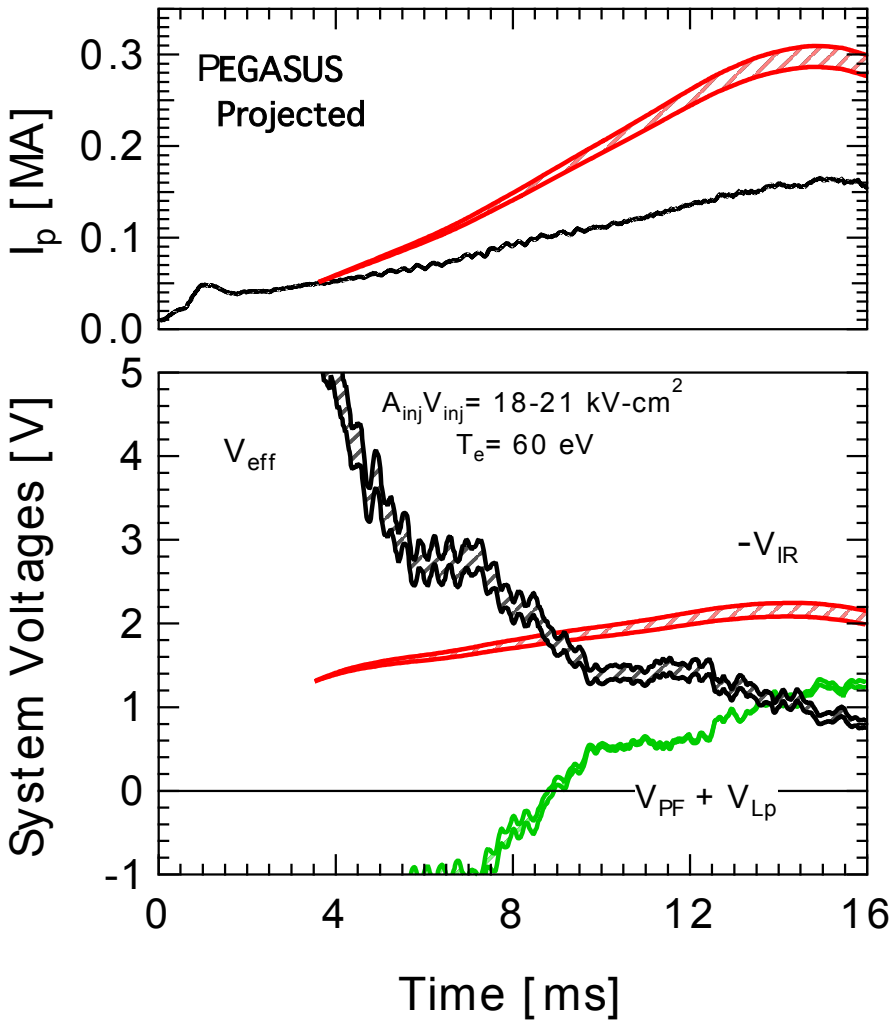




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Increased V_{eff} needed to test predictive understanding of LHI to larger scale

- 0-D energy balance model motivates need for more V_{eff}
  - Inductive drive (from poloidal field and geometric evolution) is dominant late in shot
  - PF induction a limited effect; need more helicity drive to move forward
  - Must seek more V_{eff} from increased:
    - A_{inj}
    - V_{inj}
    - B_{inj}
- Goal: I_p>0.3MA in Pegasus to explore the regime where drive from LHI exceeds inductive drive
  - Will emulate physics regime for NSTX-U



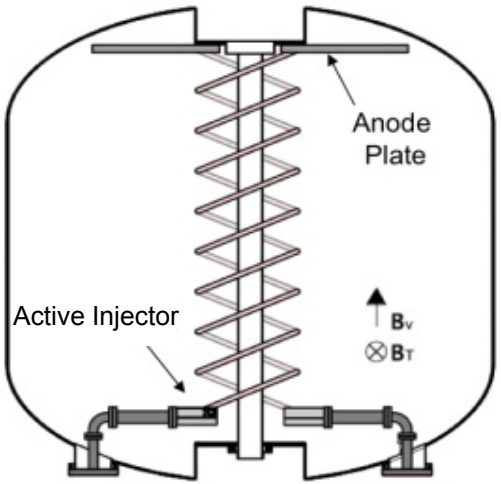
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Divertor injectors: increased V_{eff} and reduced inductive drives

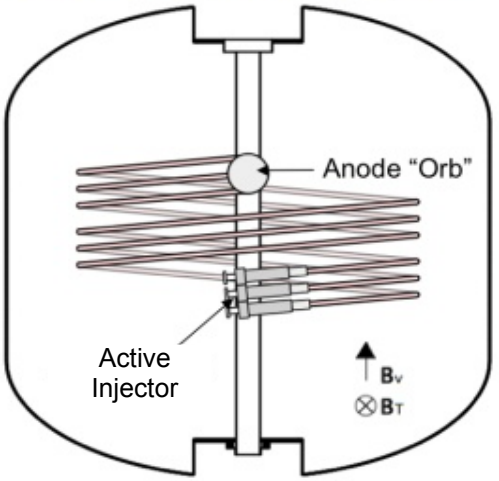
- Benefits of injectors in lower divertor:
  - Lower R_{inj} increases B_{inj}
    → increased V_{eff}
  - Poloidal flux expansion
    → increased Taylor limit
  - Plasma couples passively to injectors
    → Relaxed radial position requirements

Inboard Injection

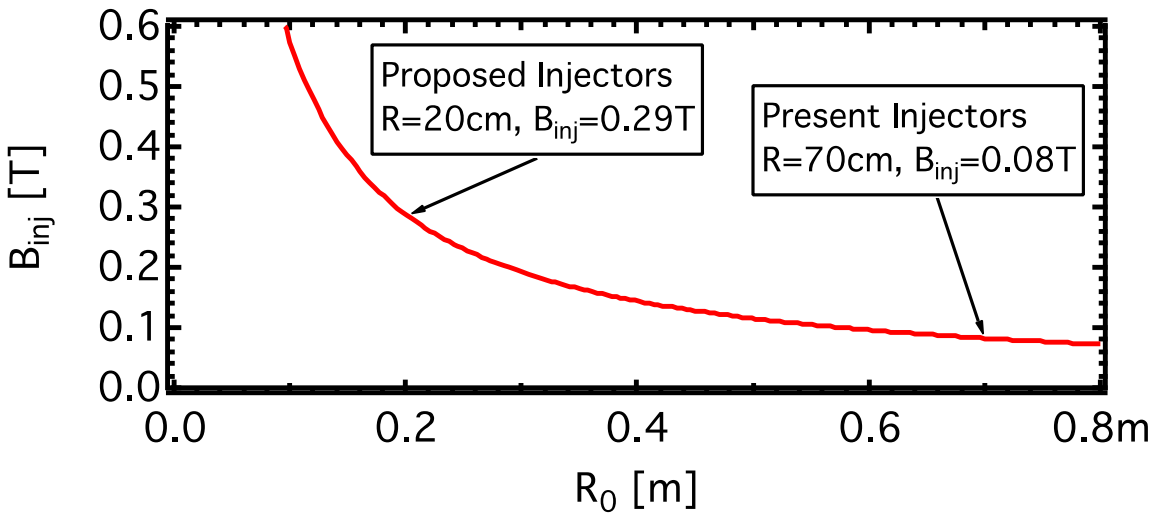


R_{inj} = 20cm, Z_{inj} = -75 cm

Outboard Injection



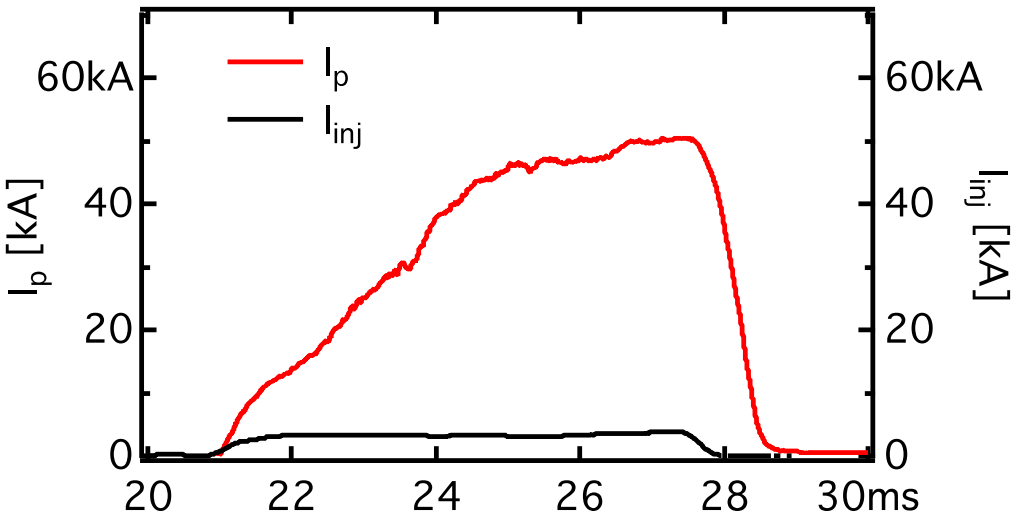
R_{inj} = 70 cm, Z_{inj} = -20 cm



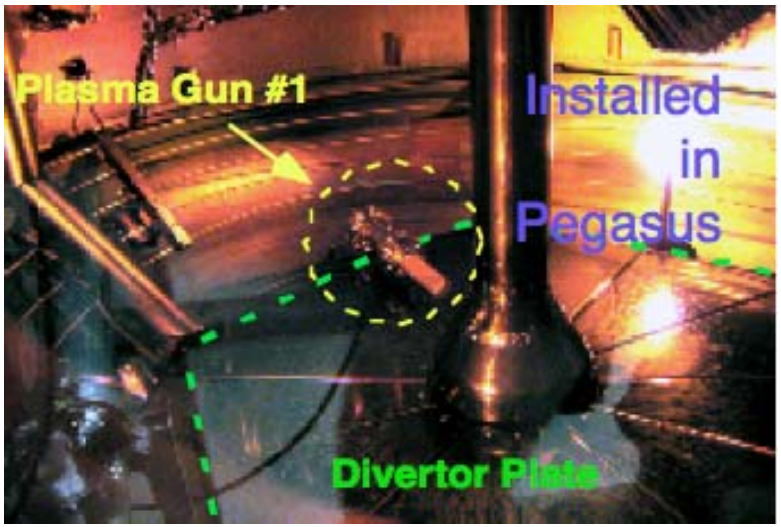
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Early tests demonstrated viability of divertor injector operation

- $I_p \approx 50kA$ with $I_{inj} \approx 3kA$
  - I_p limited by helicity input rate
  - Stable coupling to injectors
  - Tokamak-like current decay after injector shut-off
  - Verified helicity conservation



- Limitations of early test:
  - $I_{TF} < 10\%$ max I_{TF} due to geometric constraints
  - $V_{inj} \leq 600V$
  - Large PMI and impurity fueling from injectors

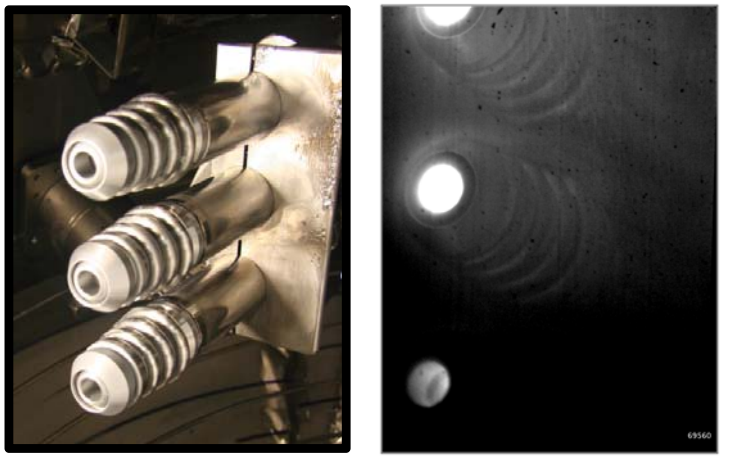


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Injector technology development projects to high current, full field operation

- Cathode design geometry mitigates PMI, reducing impurities
  - Clean operation of high power injector near
- Shield ring “pagoda” improves voltage standoff
- Local scraper limiter reduces density at injector
- Independent power systems for each injector set
- Improved divertor coils provide control of localized field pitch at injector

“Pagoda”-style injectors with quiescent operation



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<T_e> and injector parameters set I_p

- T_e determines operating space, informs injector design requirements
  - Steady state I_p set by injectors parameters, plus T_e
  - Motivates understanding confinement of LHI discharges
- At steady state, Ohm's law sets I_p
  - Plasma resistance dissipates helicity
  - Assume Spitzer resistivity
- Normalized effective loop voltage is a useful figure of merit for drive
  - $\mathbf{V_{norm} = (NAV/R)_{inj}}$

$$V = I_p \cdot \Re_{Sp}$$

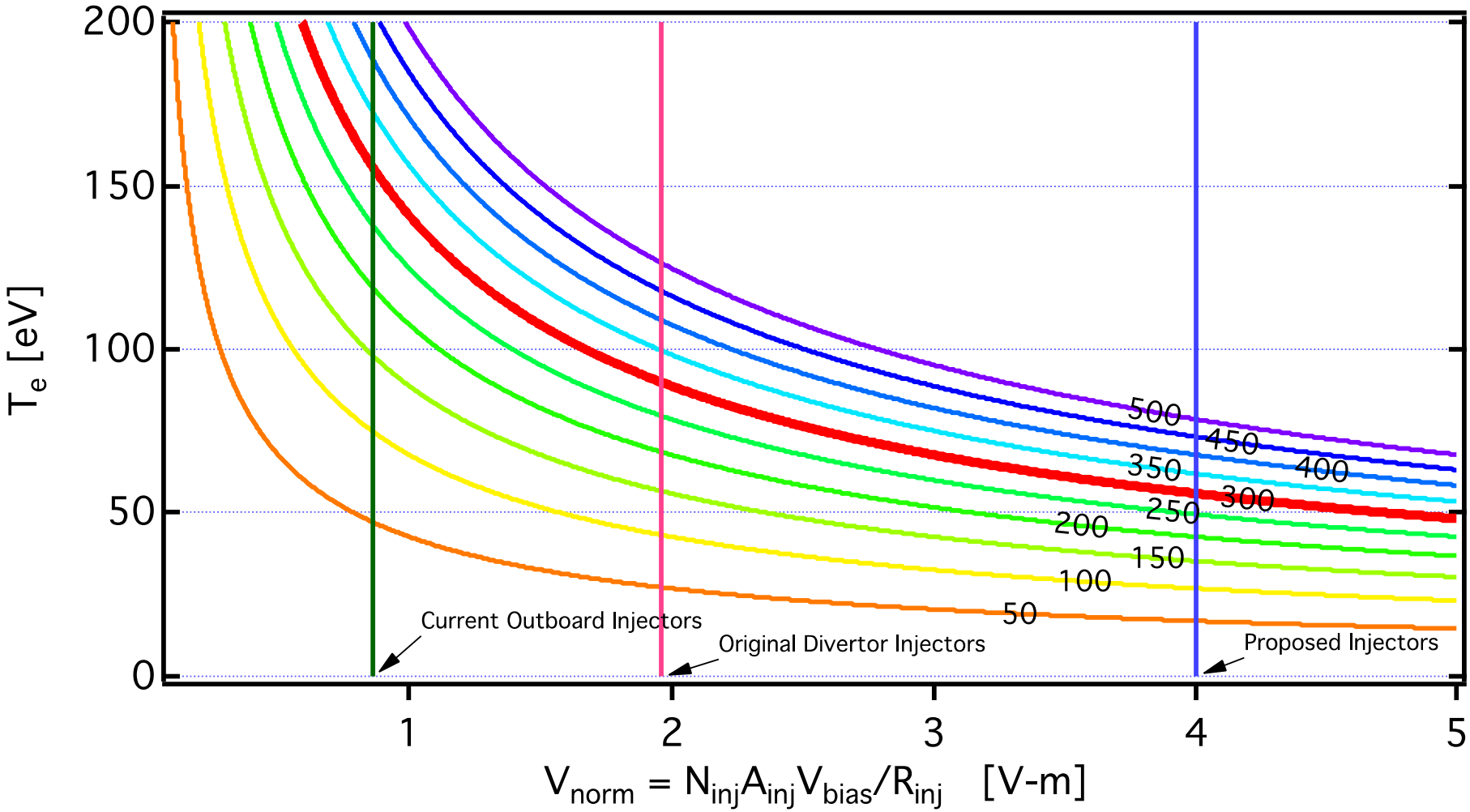
$$V_{eff} = \frac{N_{inj} A_{inj} V_{bias} B_{TF,inj}}{\Psi_{TF}}$$

$$\Rightarrow I_p \propto \underbrace{\left(\frac{N_{inj} A_{inj} V_{bias}}{R_{inj}} \right)}_{V_{norm}} \cdot T_e^{3/2}$$

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Projections of steady state I_p for given $\langle T_e \rangle$ and V_{norm}

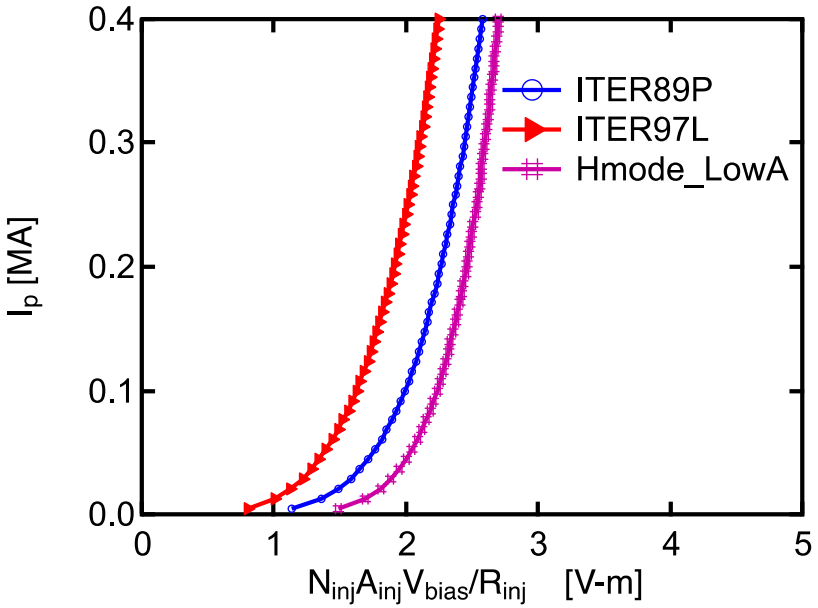
Contours of plasma current in kA as a function of average electron temperature and normalized drive voltage



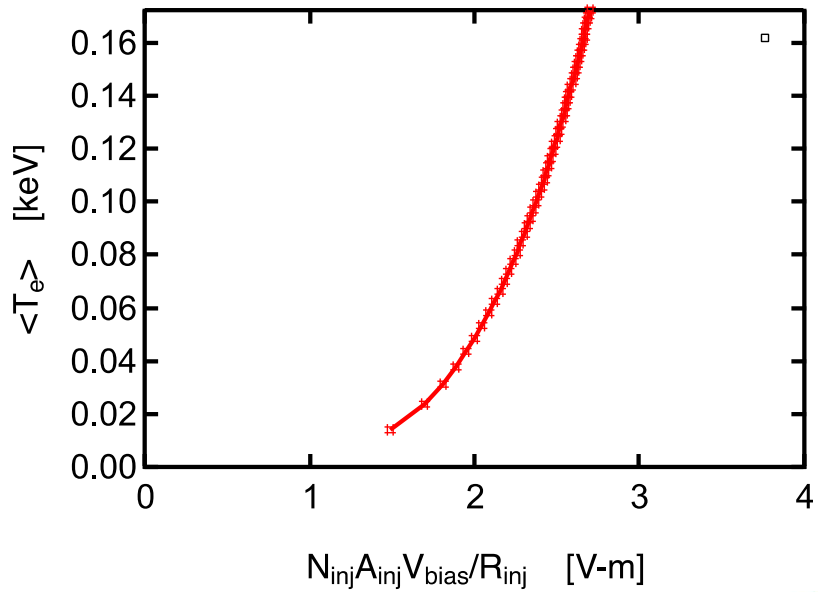
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Estimating I_p via Ohmic confinement (optimistic)

- Standard Ohmic confinement models represent a likely best case
  - Predicts I_p=300kA and $\langle T_e \rangle$ = 120eV for V_{norm}=2.7V-m



- Plasma shape and size effect required V_{norm}
  - Lower injector requirements for larger, more elongated plasmas
  - Expect to operate with R_0=0.3m, κ=2.5

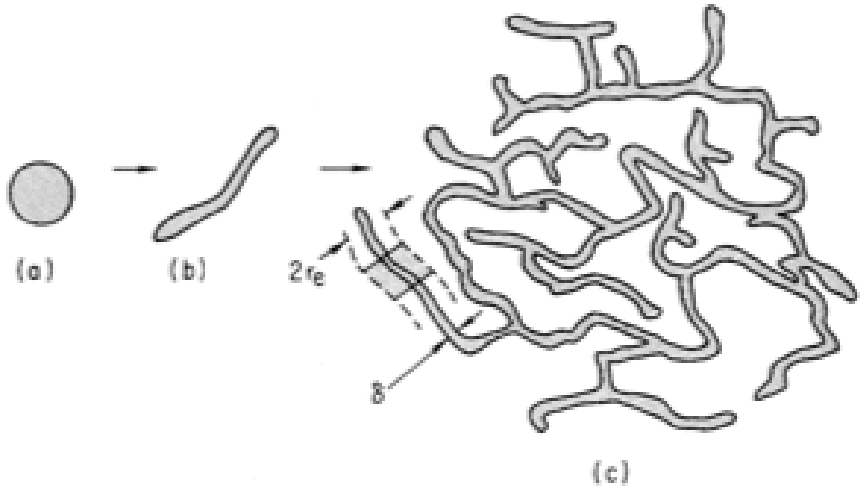


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Estimating I_p via fully stochastic confinement (pessimistic)

- Stochastic field lines result from magnetic island overlap
  - Field line diffusion results in enhanced energy loss
- Model as random walk of field lines
  - Collisionless ($\lambda_c > L_m$)
    - Step size: $\delta_r = L_m(\delta B_r/B)$
  - Collisional ($\lambda_c < L_m$)
    - Step size: $\delta_r = \lambda_c (\delta B_r/B)$
  - Pegasus LHI: $\lambda_c \sim L_m$
    - Approximately collisional

Below: Random walk of field lines leads to stochastic spreading of a flux tube. Image credit Rechester and Rosenbluth, PRL 1978.



$$\chi_{collisional} = \frac{\delta_r^2}{\Delta t} = v_{||} L_m \left(\frac{\delta B_r}{B_{tor}} \right)^2$$

$$\chi_{collisionless} = \frac{\delta_r^2}{\Delta t} = v_{||} \lambda_c \left(\frac{\delta B_r}{B_{tor}} \right)^2$$

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Estimating I_p using stochastic confinement scaling

- Can scale I_p from past results
  - Relations between I_p, V_{eff} and Te
    - Equate P_{in} to energy loss rate
    - Relate R_{Spitz} to T_e
    - Set $V_{eff}=I_pR_{Spitz}$

  → Ip = f(V_{eff}), self-consistent T_e

$$P_{in} = I_p V_{eff}; \quad \frac{W}{P_{in}} \sim \tau_E \sim \frac{a^2}{\chi_{stoch}}$$

$$\Rightarrow I_p \sim \frac{V_{eff}^{5/2}\left(\kappa a^2\right)^{7/2}}{R^{5/2}\left(\frac{\delta B_r}{B_{tor}}\right)^{3/2}}$$

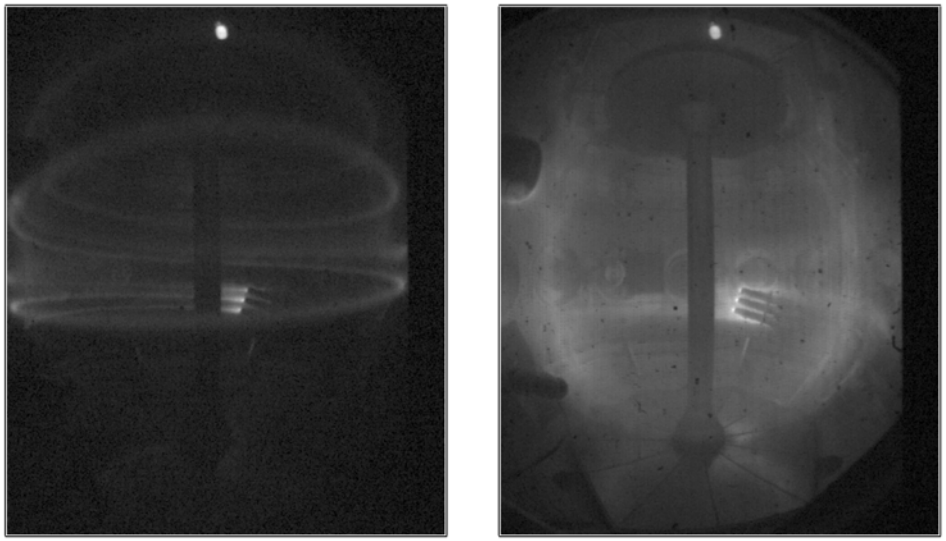
- Wide range of predicted I_p due to uncertain scaling of magnetic fluctuations with Lundquist number, S
  - $\alpha=0$ → $I_p \approx 300$kA
  - $\alpha=1/4$ → $I_p \approx 120$kA
  - Global stochasticity estimate is likely worst case scenario

$$\left(\frac{\delta B}{B}\right) \sim S^{-\alpha}; \quad \alpha = 0, \frac{1}{4}, \frac{1}{2}$$

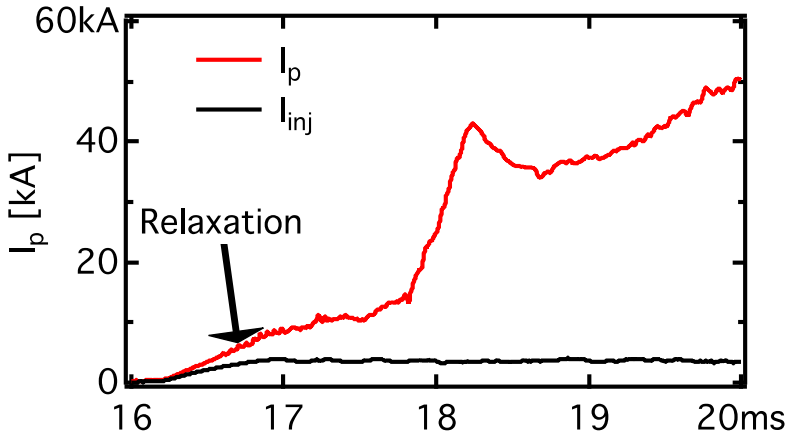
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LHI requires relaxation to tokamak-like state

- Initially, injected current streams along vacuum field
- Current streams deform poloidal field
- With sufficient I_{inj}, formation of poloidal field null
- Taylor relaxation to lowest energy state
  - Tokamak-like plasma formed
  - Now $I_p >> I_{inj}$ possible



Left: Current filaments follow vacuum field.
Right: null formation and relaxation to tokamak-like plasma.
Bottom: Plasma current rises during relaxation.

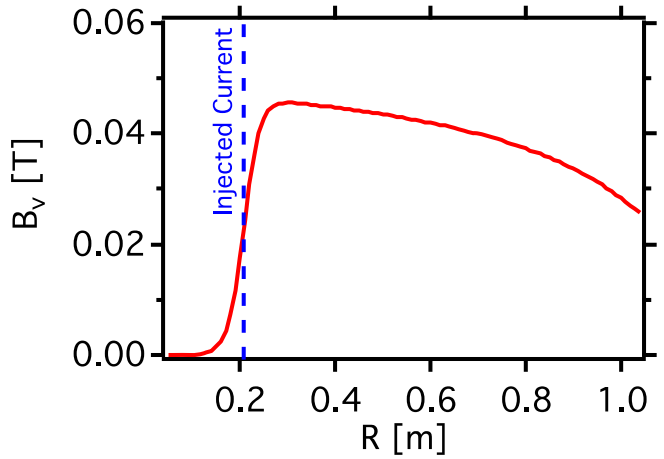


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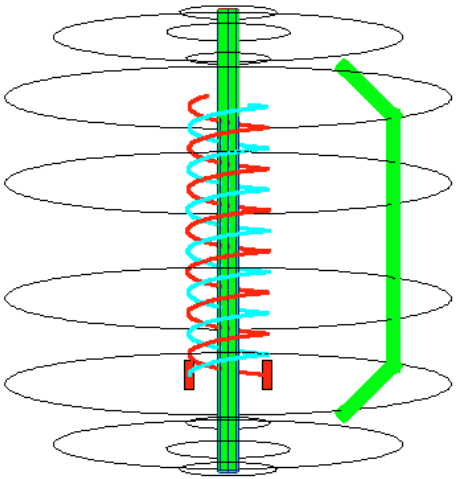
Conditions for relaxation

- Null formation: $B_v \approx 0$ locally
  - Field of current streams cancels vacuum field: $B_{v,streams} = -B_{v,vac}$
  - $B_{v,streams}$ set by:
    - I_{inj}
    - windup factor (toroidal transits of current stream)
  - Higher B_v/B_{tor} raises pitch, lowering windup factor
  - Low $B_{v,vac}$ favorable for relaxation
- Injector geometry sets minimum pitch
  - Current streams must clear opposite injector

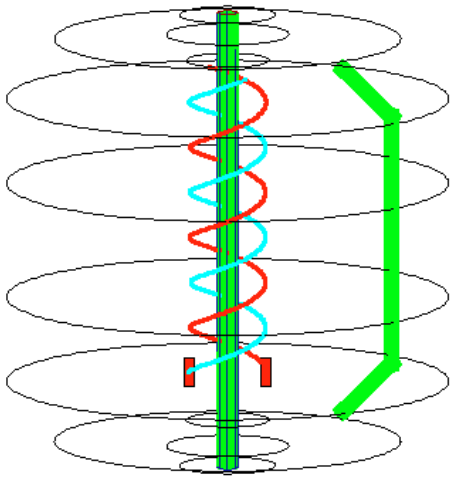
Injected current must create vertical field null, triggering relaxation



High Windup



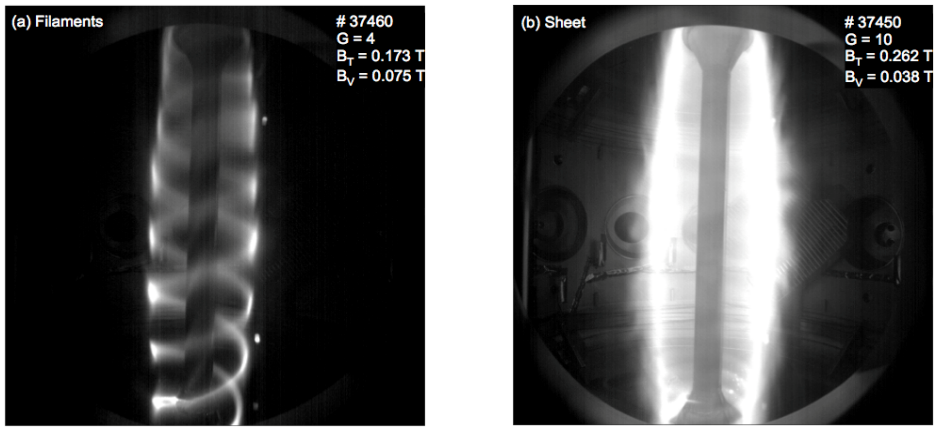
Low Windup



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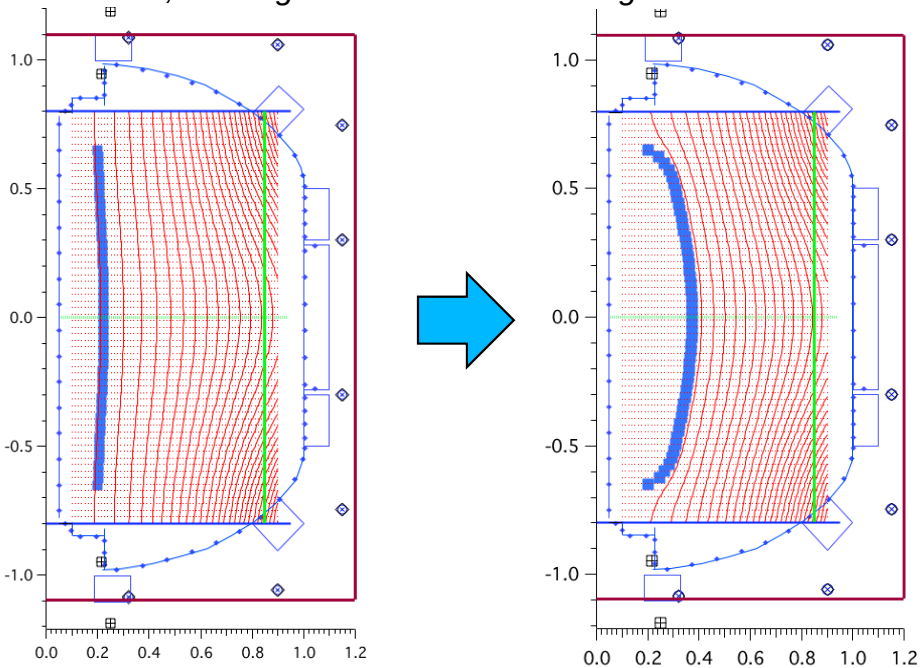
Modeling null formation in 2D

- Current filaments modeled as a continuous sheet (3D→2D)
  - Stream merger supported by observation



Above: current streams merge into continuous sheet. Below: self field of current sheet deforms poloidal field structure, causing sheet to bow out to larger radius.

- Injected currents deform poloidal field
  - Current sheet bows outward, following field lines
  - Windup factor reduced at larger R
    - More I_{inj} needed to achieve vertical field null



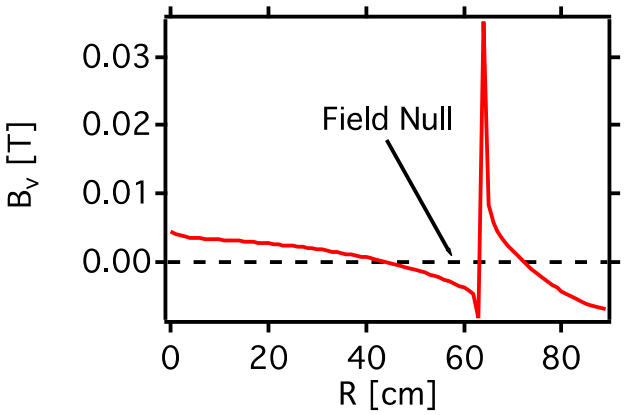
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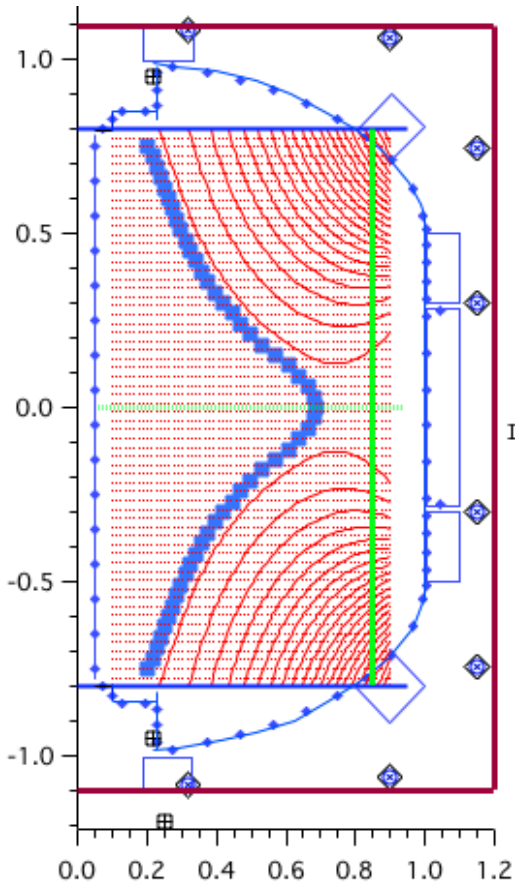
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Null formation with divertor injectors

- Clearance requirement:
  - $\frac{B_V}{B_{tor}} \geq \frac{\Delta z_{inj}}{2\pi R_{inj}}$
  - At low R_{inj}, must raise B_v or lower B_{tor} to maintain clearance
  - Small injector height (Δz_{inj}) favorable

- High B_v renders null formation difficult
  - Use divertor coils to boost B_V locally
  - Run mid-plane coils negative to assist null formation
  - Null achieved on outboard side





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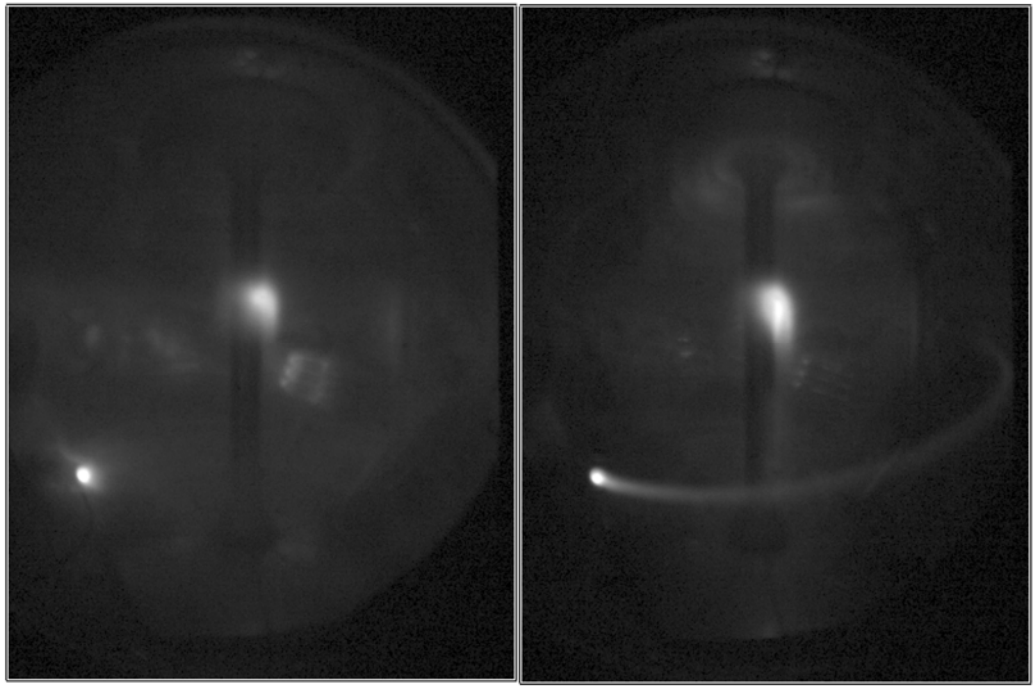
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Alternately, use outboard injectors for start-up, then transition to divertor injectors

- Outboard injectors create relaxed plasma easily
  - No clearance issue
  - B_v/B_{tor} favorable
- Transition to divertor injectors after relaxation
  - Raise B_v as I_p grows
  - Current stream clears injectors
- Similar to handoff from LHI to ohmic drive
  - LHI/Ohmic handoff already demonstrated

Plasma position requirements: must remain coupled to injectors

- Injectors adjacent to LCFS:
  - Coupled to plasma → current drive
- LCFS far from injectors:
  - Decoupled → no current drive
- Outboard injectors require large plasma
  - Lose connection easily
- Inboard (divertor) injectors couple passively
  - plasma growth maintains connection



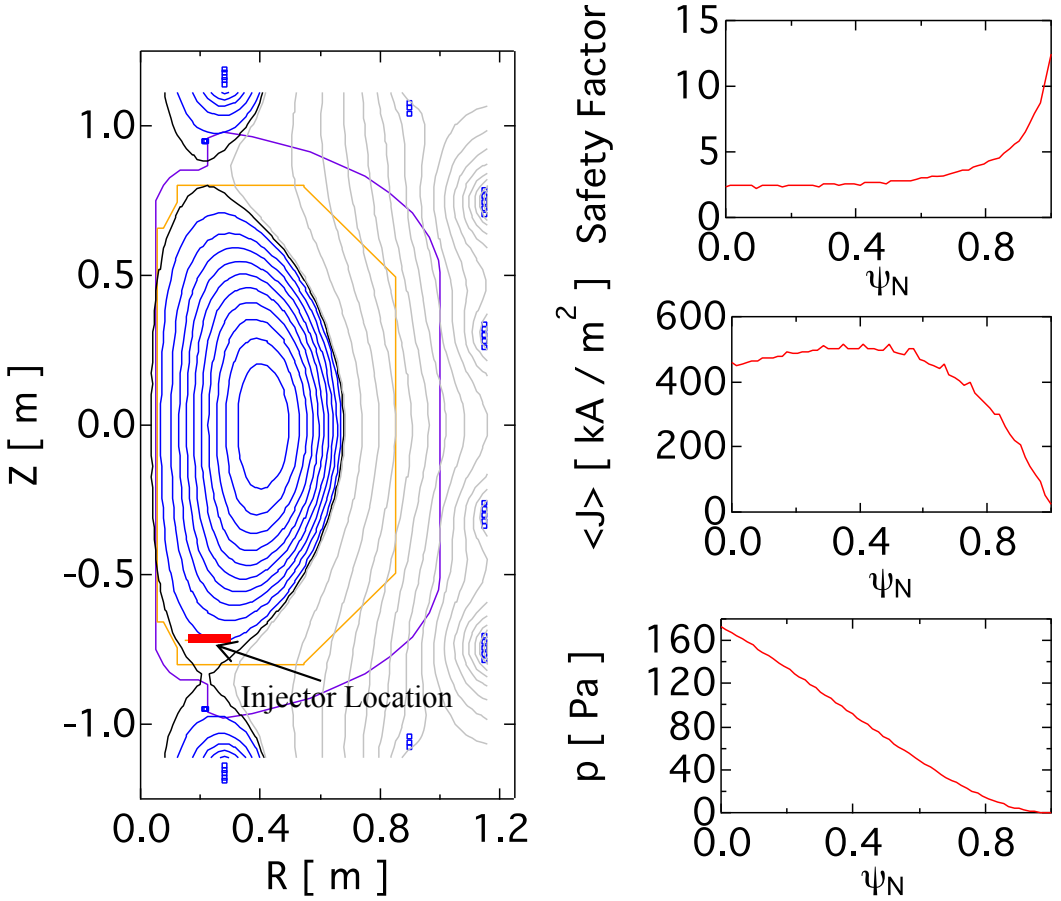
Coupled *Decoupled*

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Design point: plasma current of 0.3MA

- Predictive Grad-Shafranov solutions
  - Show plasma shape compatible with injector position
  - Inform operational scenario
- Injector location at bottom of plasma
  - Reduced sensitivity to radial position
  - Furthest inboard position for maximum current drive



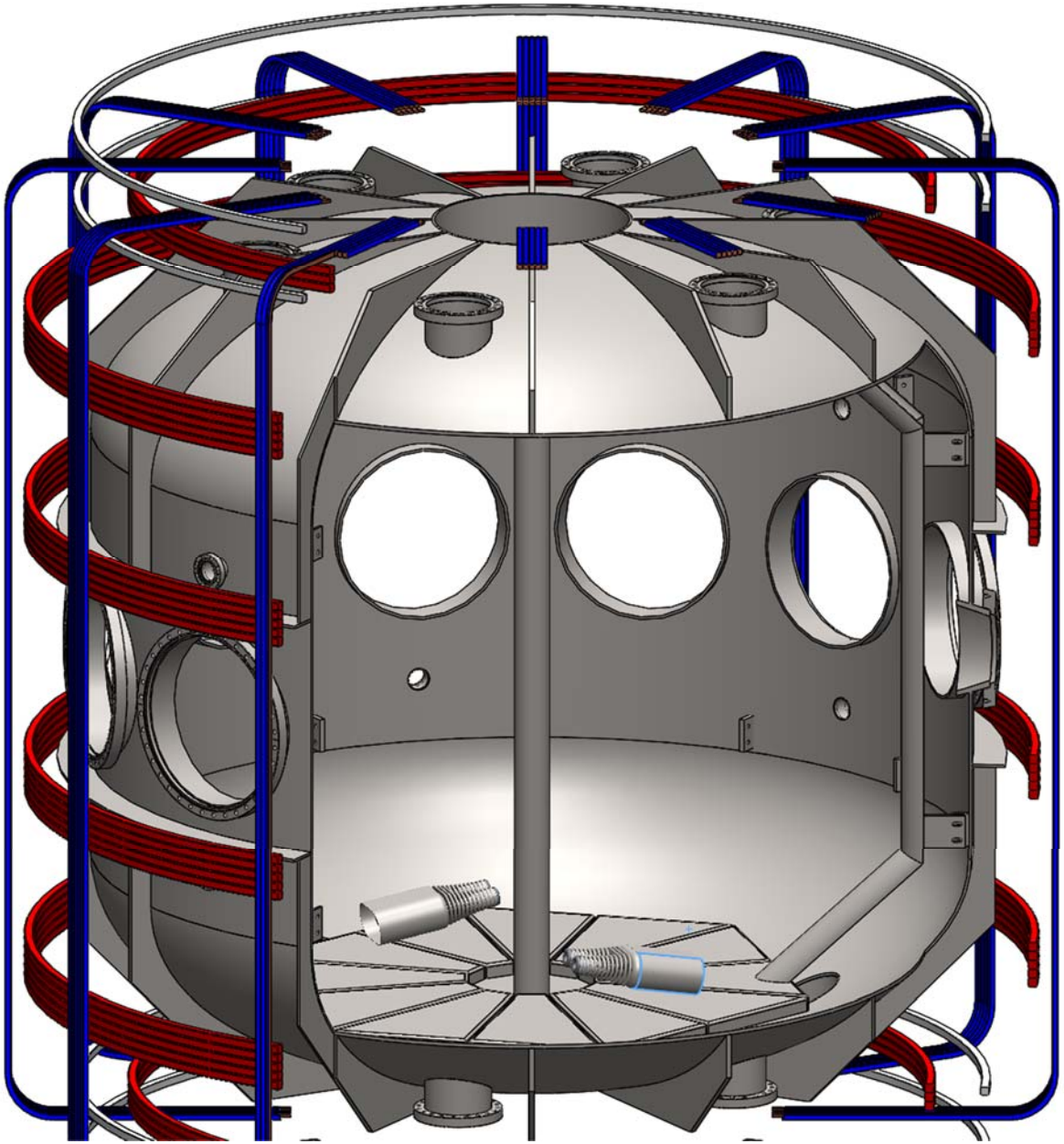
Equilibrium Parameters
Shot 0, 0.000 ms

I_p	325 kA	R_0	0.369 m
β_t	0.0068	a	0.301 m
ℓ_i	0.49	A	1.23
β_p	0.014	κ	2.4
W	3682 J	δ	0.36
B_{T0}	0.144 T	q_{95}	7.94

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2 sets of 2 injectors mounted to lower divertor plate



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Conclusions

- Divertor helicity injectors bring new challenges
  - Null formation at full field
  - Geometric windup constraints
- Wide range of predicted plasma current due to uncertainty in confinement behavior motivates a high power divertor LHI experiment
  - Understanding the confinement for LHI critical to scalability as startup technique
- Potential for very high performance
  - Goal of $I_p \geq 0.3MA$
  - 4 injectors, $I_{inj}=8kA$, $V_{inj} \geq 1000V$, $R_{inj}=20cm$