Non-Solenoidal Startup via Local Helicity Injection and Edge Stability Studies in the Pegasus Toroidal Experiment

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17th International Spherical Torus Workshop

York Plasma Institute
York, UK
Sept. 16-19, 2013



PEGASUS Toroidal Experiment

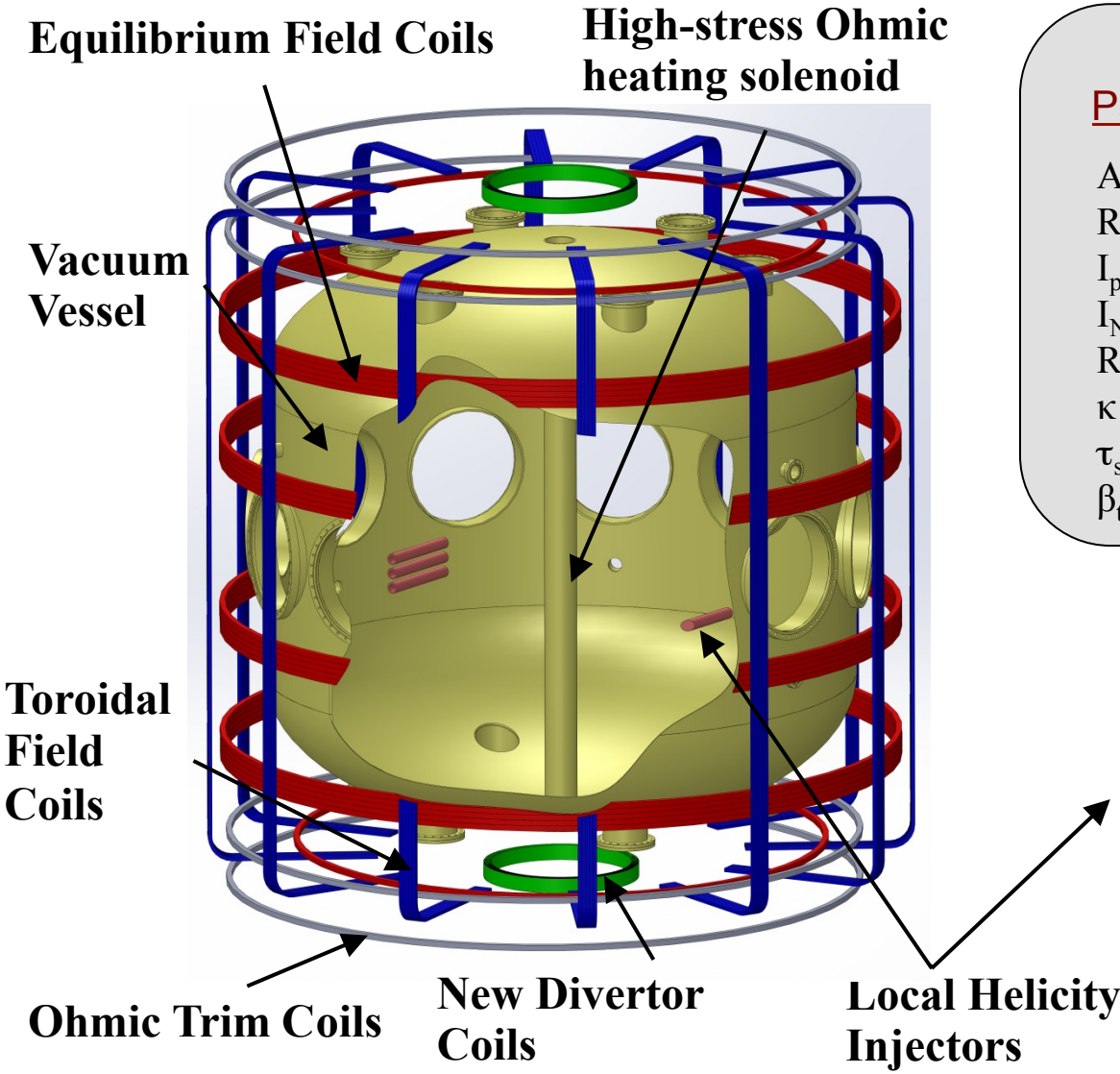
Exploiting Unique Aspects of the ST to Advance Fusion Energy Science

- Non-solenoidal startup: Increasing ST/tokamak attractiveness
  - Local Helicity Injection produces tokamak plasmas using edge current drive
    - Predictive understanding through helicity conservation, Taylor relaxation constraints
  - Progress in current injector development, basic understanding, and predictive capabilities
  - Technique should be applicable to any tokamak, not just ST

- Edge physics: Stability, pedestal, ELM dynamics
  - Low-A naturally provides access to peeling instability underlying ELMs
    - Simplified diagnostic access → unique $J_{edge}(t)$ measurements
  - Extension to ITER-relevant peeling-ballooning physics via H-mode operation

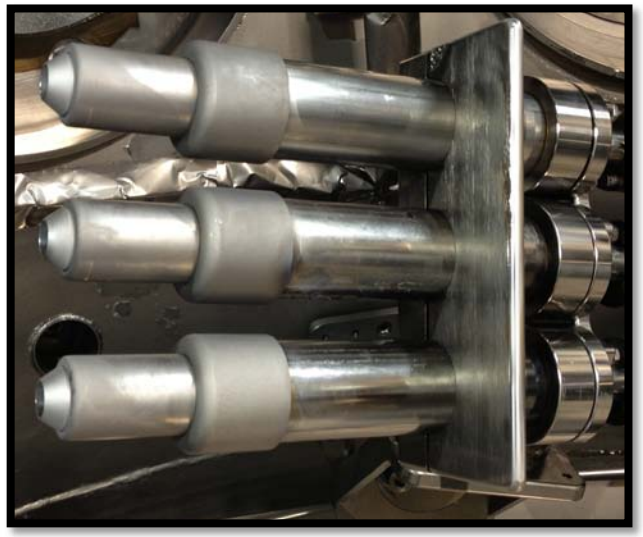
- Testing boundaries of tokamak stability at ultimate geometric limit
  - High β_T, toroidal field utilization I_p/I_{TF} as $A \rightarrow 1$

Pegasus is a Compact, Ultralow-A ST



Experimental Parameters

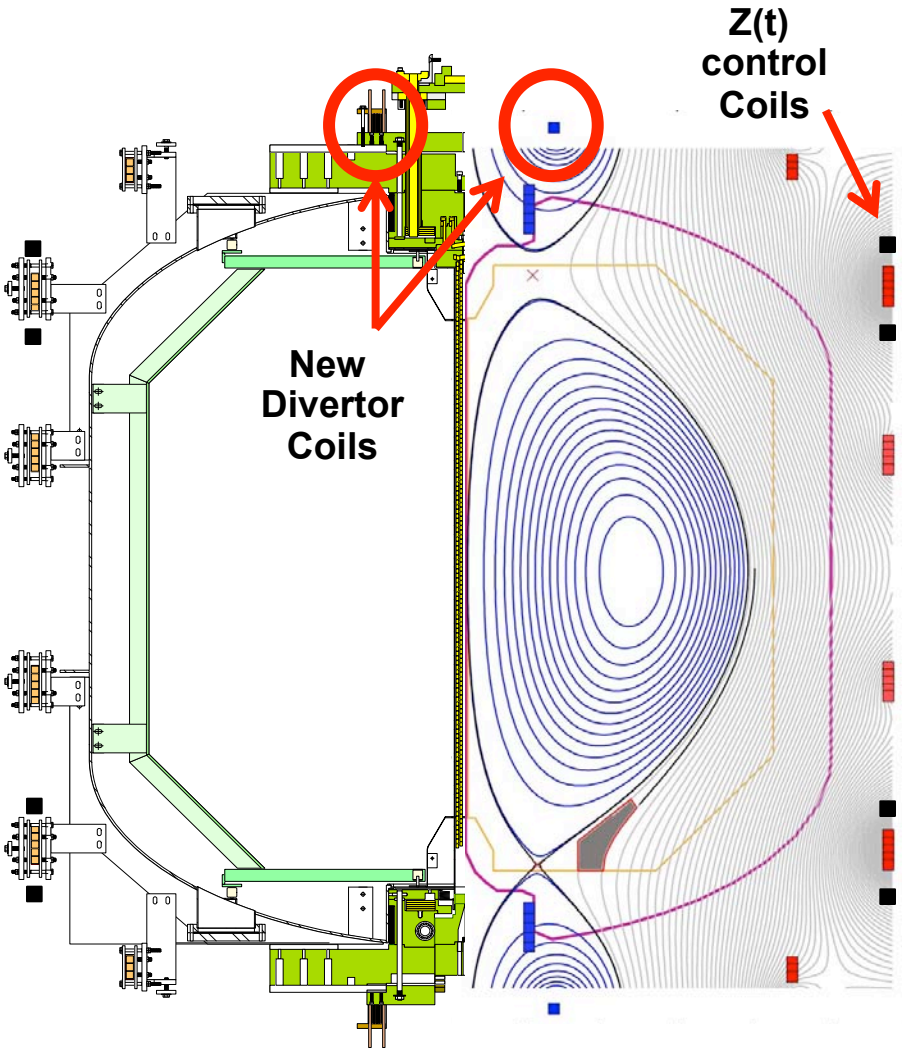
Parameter	Achieved	Goals
A	1.15 – 1.3	1.12 – 1.3
R(m)	0.2 – 0.45	0.2 – 0.45
I_p (MA)	≤ .23	≤ 0.30
I_N (MA/m-T)	6 – 14	6 – 20
RB_t (T-m)	≤ 0.06	≤ 0.1
κ	1.4 – 3.7	1.4 – 3.7
τ_{shot} (s)	≤ 0.025	≤ 0.05
β_t (%)	≤ 25	> 40



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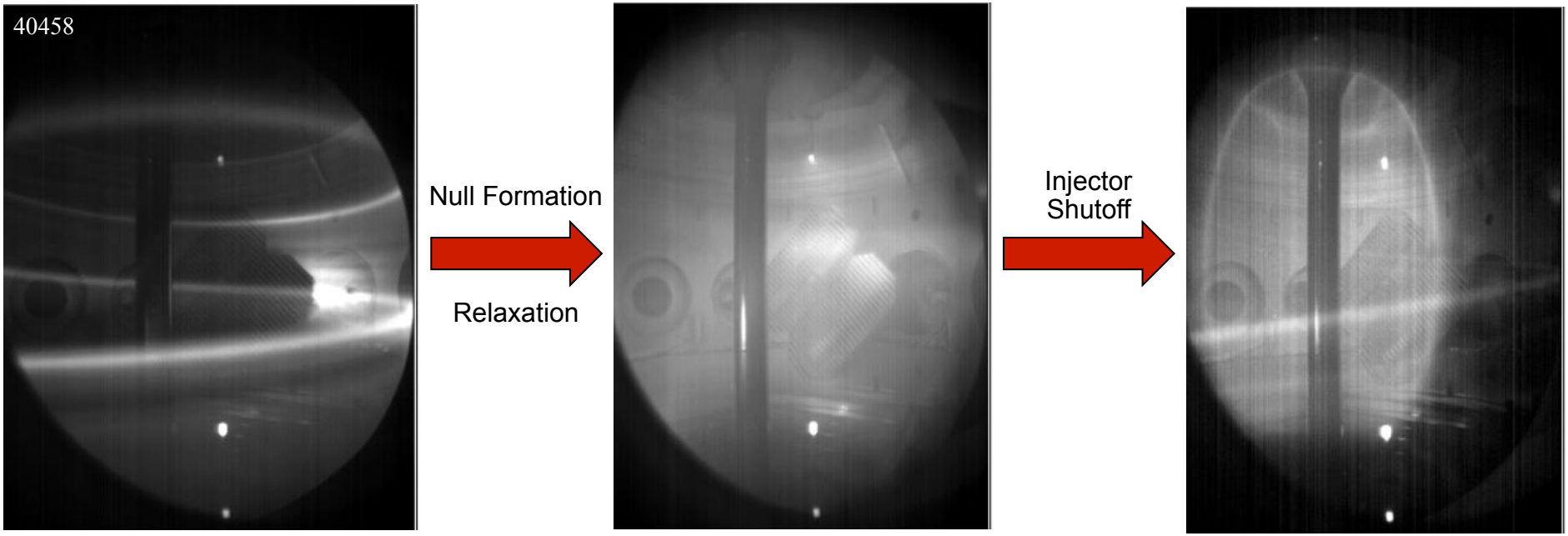
Device Upgrades Support Expanded Helicity Injection, Edge Physics Studies

- Helicity Injection Systems
  - Injector material, design optimization: *reduced PMI*
  - Active fueling control
  - Multi-aperture injector array for high-I_p startup
- Power Supplies, Heating, Fueling
  - New helicity injection power: *2.2 kV, 14 kA supply*
  - Centerstack fueling*: LHI fueling and H-mode access*
- Expanded PF Coil Set and Control
  - New PF coils, power systems: *vertical control*
- Diagnostic Deployment and Improvements
  - Multipoint Thomson Scattering
  - High-speed $T_i(R,t)$: *Anomalous reconnection heating*
- New divertor coils → *separatrix operation*
  - Exploit H-mode operating regime
  - Flux expansion to optimize LHI startup



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Local Helicity Injection Offers Scalable Non-Solenoidal Startup



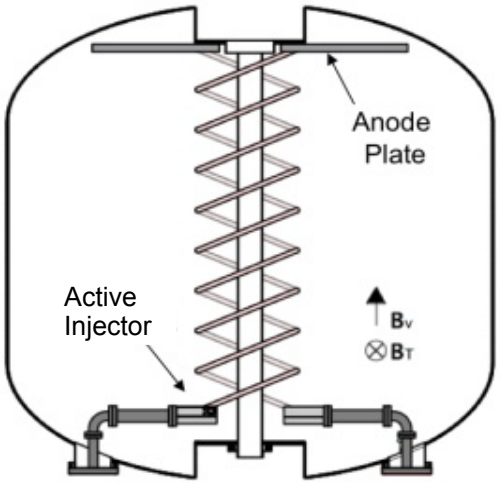
- Current injected along helical vacuum field
  - Local, active current sources
- MHD relaxation, tokamak-like state
  - Constrained by helicity, Taylor relaxation limits
- Tokamak plasmas produced after injector shut off
  - Couples to alternative current drive sources

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

Helicity Input Provided by Edge-Localized Sources

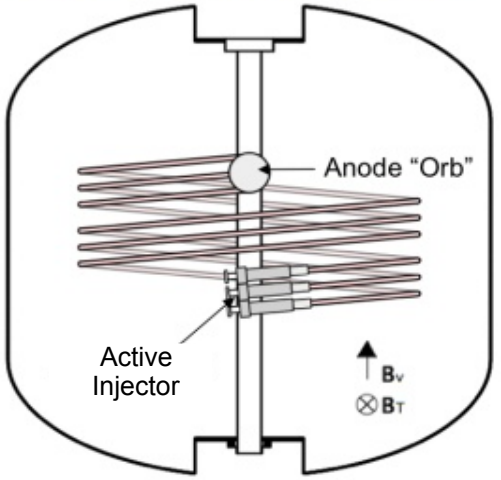
- Flexible injector geometry
- Active arc plasma injectors provide initial current windup, relaxation
- Either active injectors and/or separate electrodes can provide further growth, sustainment

Inboard Injection*

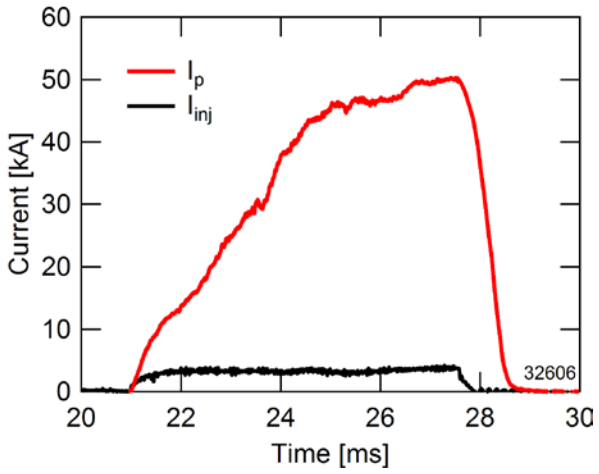


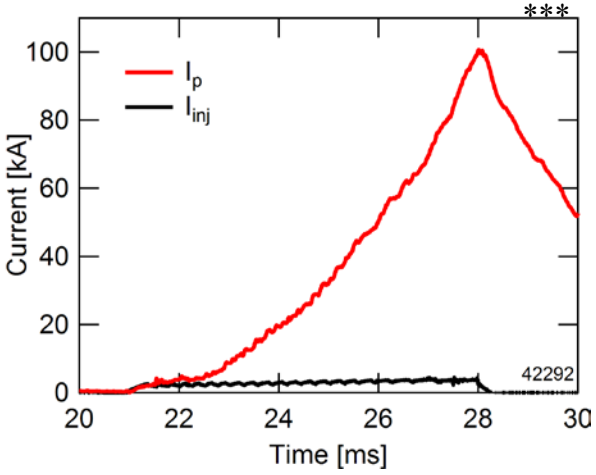
R_{inj} = 16 cm, Z_{inj} = -75 cm

Outboard Injection**



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





*: Eidietis *et al.*, J. Fusion Energ. **26**, 43 (2007)
: Battaglia *et al.*, Nucl. Fusion **51, 073029 (2011)
***: Battaglia *et al.*, Phys. Rev. Lett. **102**, 225003 (2009)

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Helicity Balance, Taylor Relaxation Criteria Determines Maximum Achievable Ip from LHI

Helicity balance in a tokamak geometry:

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

- Helicity injection can be expressed as an effective loop voltage
- I_p limit depends on plasma confinement via resistivity η

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

Taylor relaxation of a force-free equilibrium:

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

Assumptions:

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

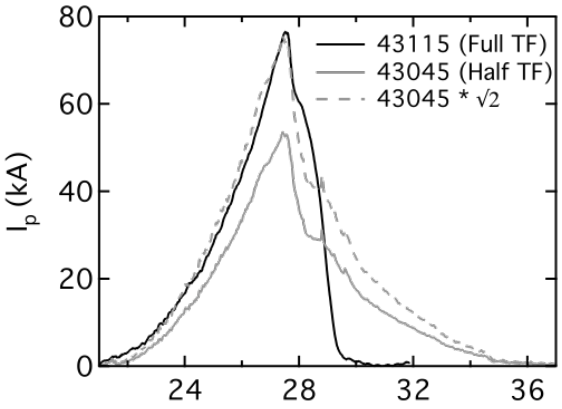
A_p, A_{inj} : Plasma, injector area
C_p : Plasma circumference
Ψ : Plasma toroidal flux
w : Edge current channel width

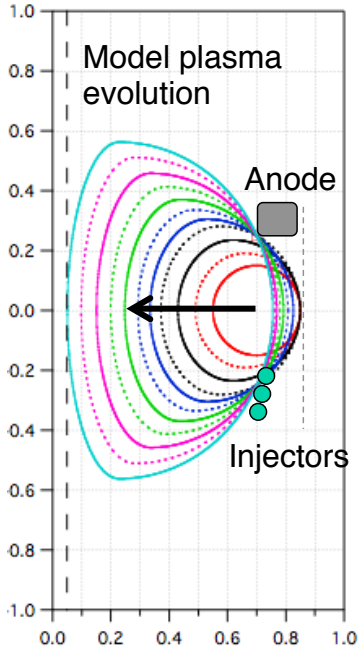
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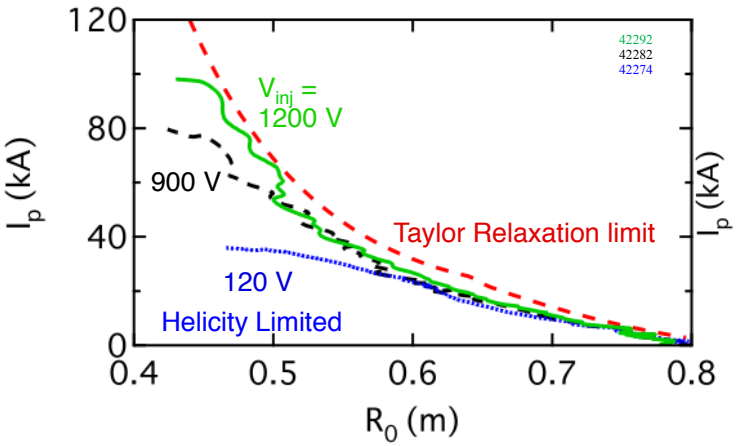
Maximum I_p Follows Taylor Limit Scaling, With Sufficient Helicity Injection Input Rate

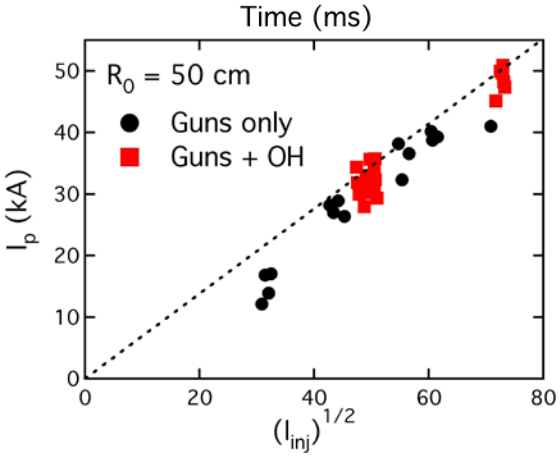
- Low-field-side helicity injection gets current drive from
  - Helicity input
  - Induction due to geometry evolution and poloidal field increase
- With sufficient helicity input rate, $I_p(R,t)$ trajectory approaches Taylor relaxation limit
  - Expected scalings with I_{inj} and I_{TF} confirmed
  - A hard limit as long as in MHD turbulent state

$$I_{p,max} \propto \sqrt{I_{TF} I_{inj}}$$





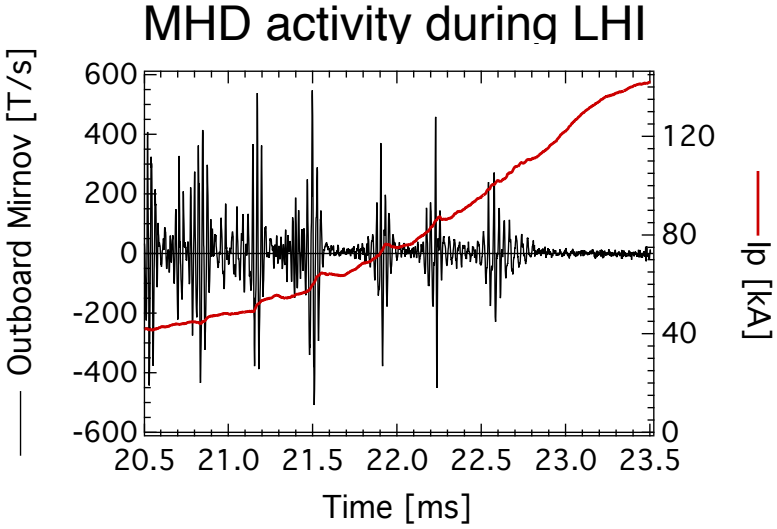




Battaglia *et al.*, Nucl. Fusion **51**, 073029 (2011)

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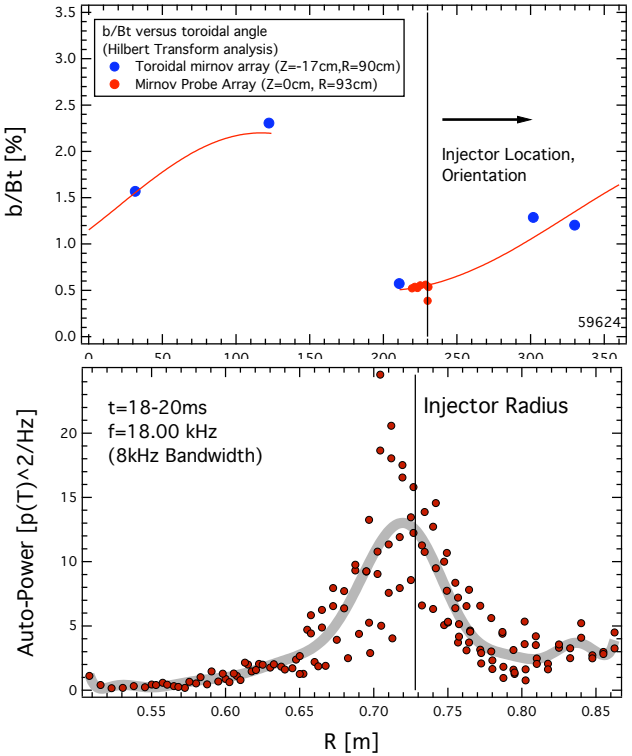
LHI Dynamics: Bursts of MHD Change Plasma Paramters and Magnetic Topology



- With each burst…
  - ℓ_i decreases → I_p increases
  - R_0 decreases → plasma expands
  - $B_{\phi,0}$ increases → q_0 increases
  - Slight drop in E_k and E_m
  - Little change in poloidal flux at plasma edge
  - Decrease in the total trapped poloidal flux

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

- n = 1 bursts appear to represent singly line-tied kink activity
  - Localized near injector radius
  - Amplitude toroidally asymmetric



Barr *et al.*, APS-DPP 2012

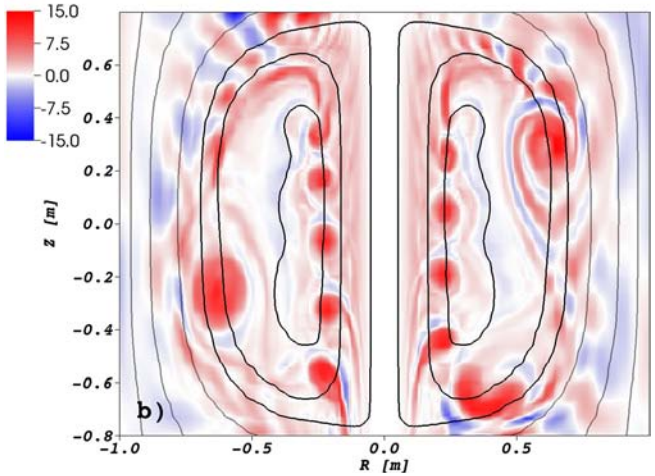
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NIMROD Simulations Indicate Complex Physical Dynamics during LHI

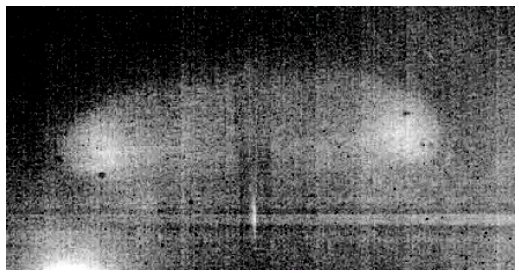
- NIMROD simulations of LHI with HFS injectors in divertor region
  - Current channels maintain after relaxation
  - Channels reconnect and inject current rings into interior region
  - Synthetic diagnostics show MHD signatures similar to experiment

- Experiment shows supporting features
  - Similar MHD bursts
  - Negative voltage spikes
  - Hints of ringlets

NIMROD LHI simulation. Contours of I = j/B (red) and poloidal flux (lines) *[O'Bryan Phys Plas.**19**, 2012]*

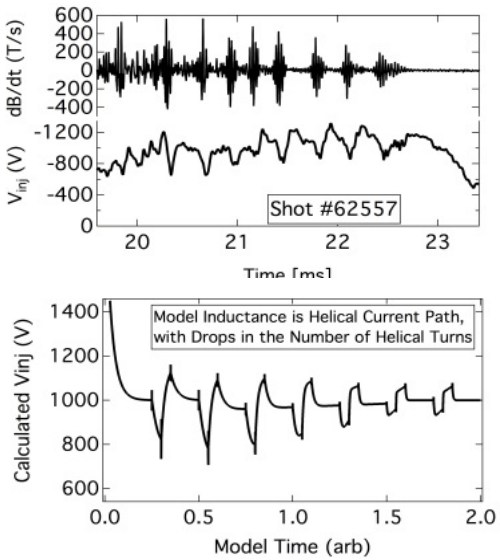


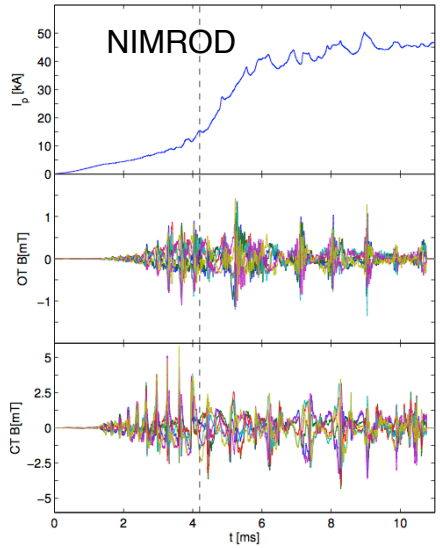
Fast camera image of axisymmetric plasma ring, formed at an LHI-MHD burst



(top) MHD activity and V_{inj}(t

(bottom) Calculated V_{inj} transients from finite-length helix inductance model.

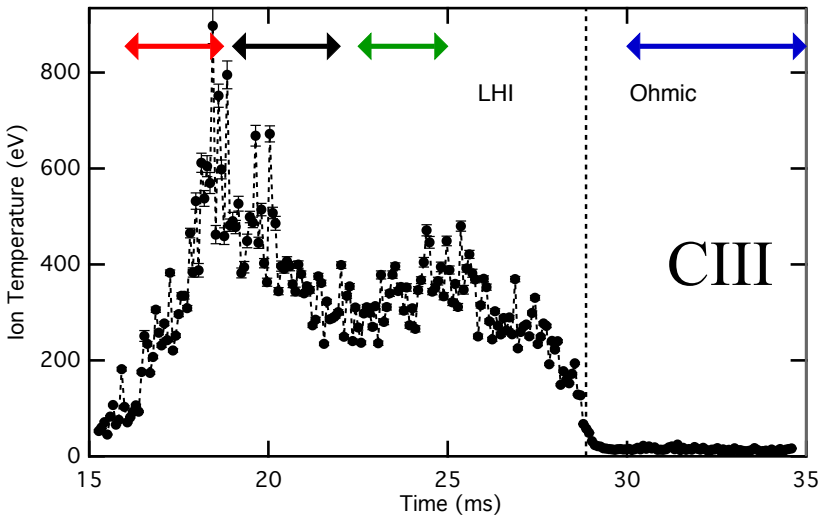


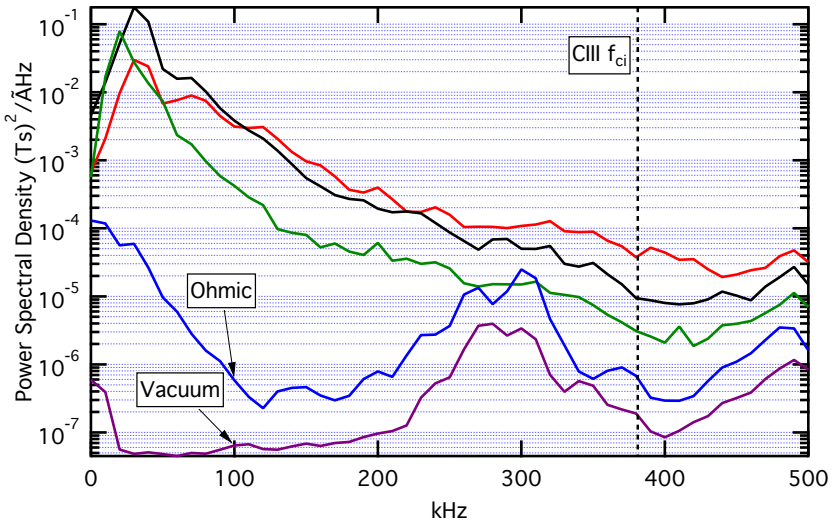


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Strong Impurity Ion Heating Correlated with MHD Activity During LHI

- Correlated with magnitude of n = 1 and high frequency burst activity on multiple line species
- $T_i > T_e$; Ion $T_\perp > 2\ T_\parallel$ is often observed
  - Similar phenomenon observed in MST** during magnetic reconnection
- Consistent with suggested ion cyclotron heating due to reconnection events
  - LHI MHD spectra shows power in IC resonance region
    - Much less so during Ohmic phase
  - High toroidal correlation at high frequencies when T_i rising rapidly
  - Need to measure ion mass dependence, down to working gas





*: Burke *et al.*, Rev. Sci. Instrum. **83**, 10D512 (2012)
: Magee, *et al*. Phys. Rev. Let. **107, 065005 (2011)

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Projection to Higher I_p and Larger Facilities Requires Science and Technology Progress

- Injector requirements
  - Impurity control for injectors in plasma SOL
  - Extension to longer pulse length
  - Large-area electron injections, with active waveform controls
  - Reasonable (cost-effective, simple, etc.) power systems
  - Since past ISTWS, have explored variety of injectors and power system designs

- Conservation laws and Taylor theory describe limits of operation, but not how to get there
  - Need description of the time-evolving startup scenario
  - Required helicity input rate depends on plasma evolution
  - Injector impedances determine helicity input rate and power requirements

- For FNSF, NXST-U, etc., need to test in regime where drive from LHI dominates
  - ~ 0.3 MA startup in Pegasus (also consistent with Pegasus program needs)

Injector Technology Evolved to Increase Helicity Injection Capabilities, Mitigate PMI



1. Circular beveled Mo faces



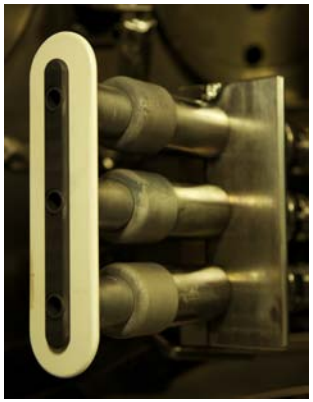
2. "Slot" Mo faces with BN caps



3. "Slot" caps with BN raised ~1 cm Above Mo faces



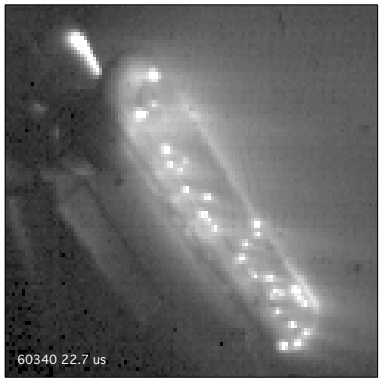
4. 3-Inj, two-piece Mo electrode with ***local scraper limiters***



5. One-piece C electrode with local limiters



6: Mo electrode raised off the BN limiter



7: Injector Inj / Mo Electrode with ***piezoelectric gas control***



8: Mo backing plate: impurity control



9: ***(3) Frustum injectors*** + 1st generation ***gas-effused electrode***

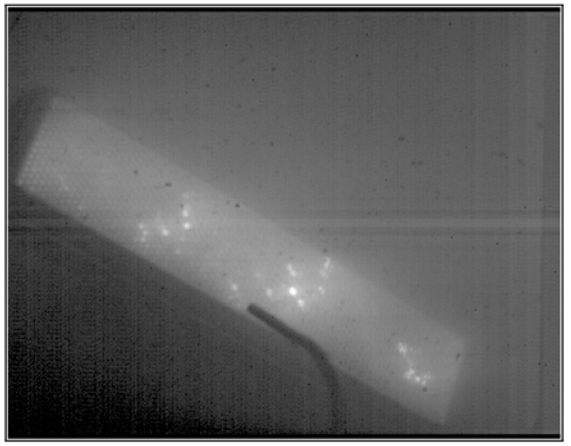


10: (3) Frustum injectors + ***large area gas-effused electrode***

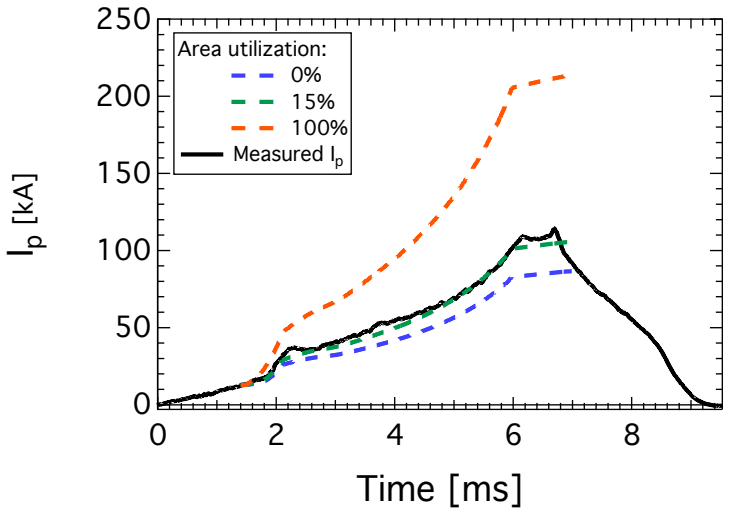
RJF, 2013 ISTWS, York, UK

Gas-Effused Passive Electrode Subject to Hot Spots and Reduced Effective Area

- Initial results from simple passive small injector assembly motivated test of large-area electrode
  - ~ 50 cm^2 Mo plate with uniform gas flow through ~ 2mm holes
  - Relies on hollow cathode formation from immersion in plasma SOL
  - Matched PF evolution, fueling



- Operation space was narrow
  - Difficult to get and maintain uniform illumination of plate through discharge
  - Presence of random cathode spots suggested non-uniform current emission
    - 0-D analysis suggested effective area for HI was << geometric area



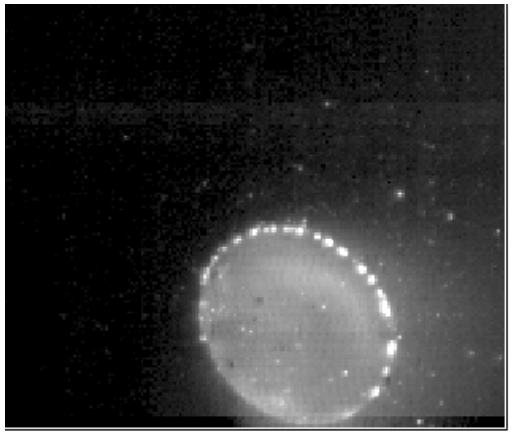
- Conclusion: not useful as robust tool for high helicity injection rate
  - However, this design did solve the problem of compact gas manifold design for a compact multi-arc injector system

Injector PMI Virtually Eliminated via Frustum Cathode Design

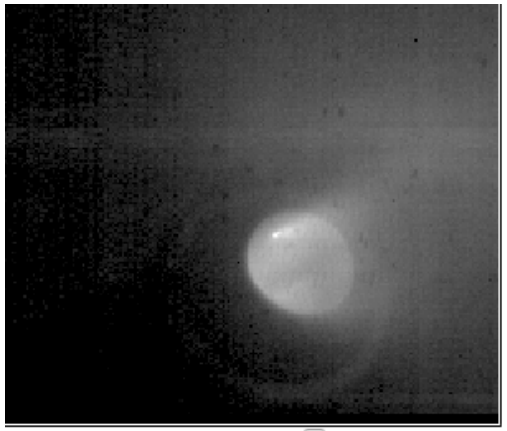
- Injectors are prone to generation of cathode hot spots
  - Cathode spots concentrate I_{inj} to small area and lower helicity input
  - Spots migrate to BN insulators and eject impurities
    - Uncontrolled fueling

- Cathode spot effects mitigated by frustum cathode design
  - Higher A_{inj} at same I_{inj} reduces generation
  - Cathode spots that do emerge migrate up the cone and extinguish
  - Virtually eliminates impurities ($Z_{eff} < 1.5$) and excess fueling during LHI

Concave Cathode

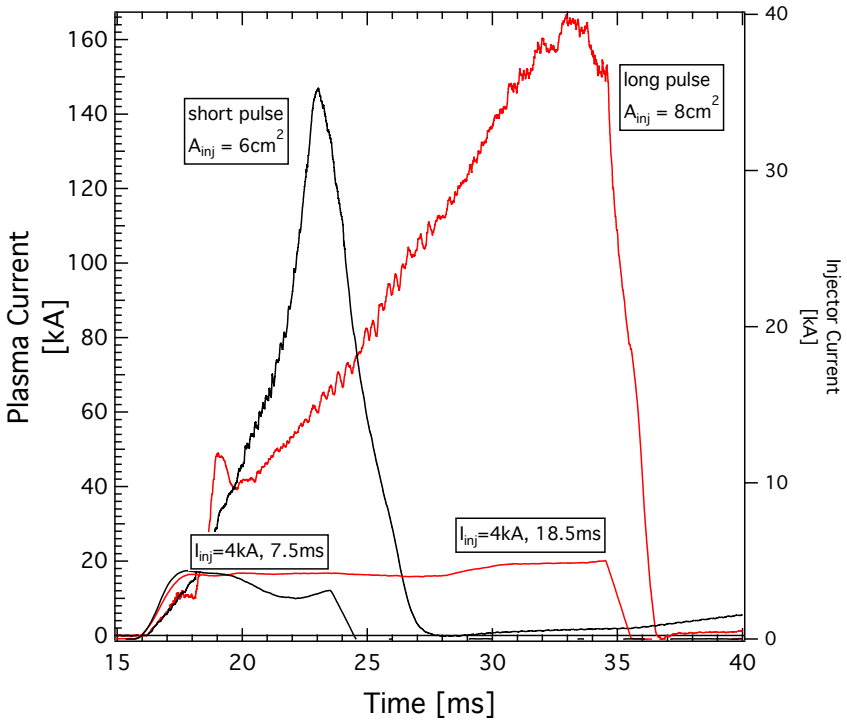


Frustum (Convex) Cathode



Longer Pulse Startup Demonstrated

- Arc injector upgrades support pulse extension
  - IGBT switched arc power supplies to minimize heat load and extend pulse length
    - Replaced long-used PFNs
  - Programmable Piezo-valve gas injection
- Enabled > doubling of startup pulse length
  - Varied I_p ramp rate for enhanced stability
  - A modest increase in inductive drive terms
  - Including HFS fueling

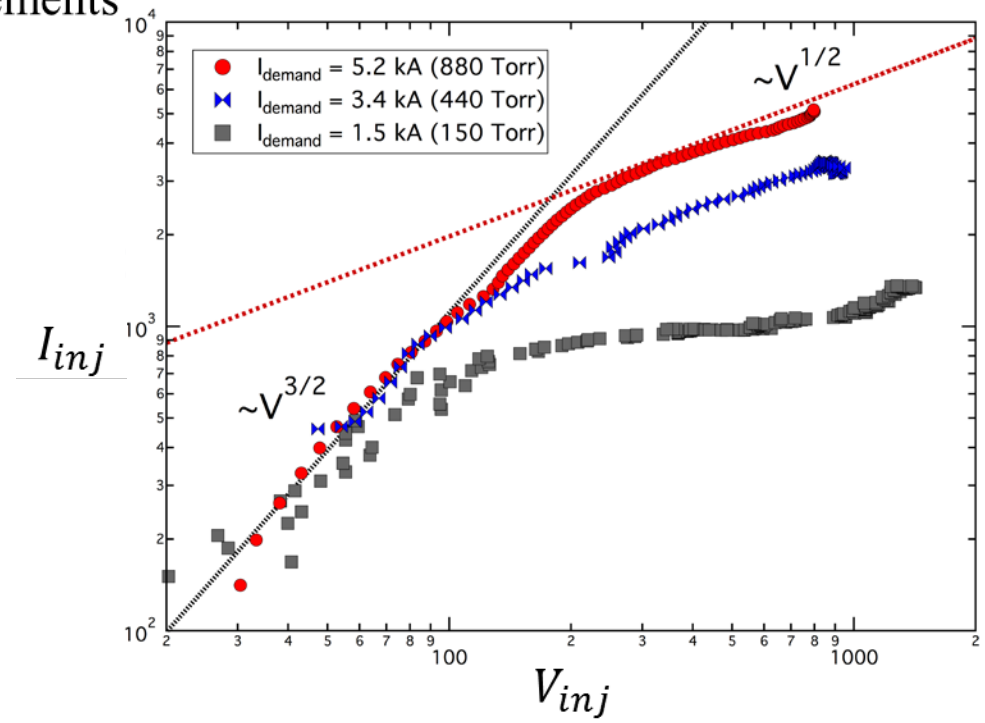


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Source Impedance Governed by Space Charge and Magnetic Current Limits

- Predictive impedance models required to design future startup systems
  - Taylor limit $\propto \sqrt{I_{inj}}$; Helicity input $\propto V_{inj}$
  - Z_{inj} couples $I_{inj}, V_{inj} \rightarrow$ power requirements
- Two distinct regimes evident in active source I-V characteristics
  - Double-sheath space-charge limit
    - Low I_{inj}, V_{inj}
    - $I_{inj} \propto V^{3/2}$
  - Alfvén-Lawson magnetic current limit
    - High I_{inj}, V_{inj}
    - $I_{inj} \propto V^{1/2}$
    - Sheath expansion may also contribute

I-V characteristics of arc plasma current injector for varied fueling rates.



Hinson *et al.*, APS-DPP 2012

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LHI: 0-D analysis Lumped Parameter model useful for projections

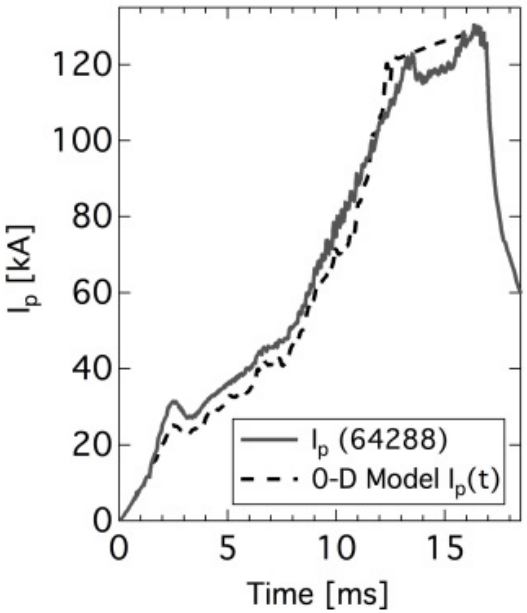
- Lumped parameter circuit model uses energy conservation in time-evolving plasma geometry:

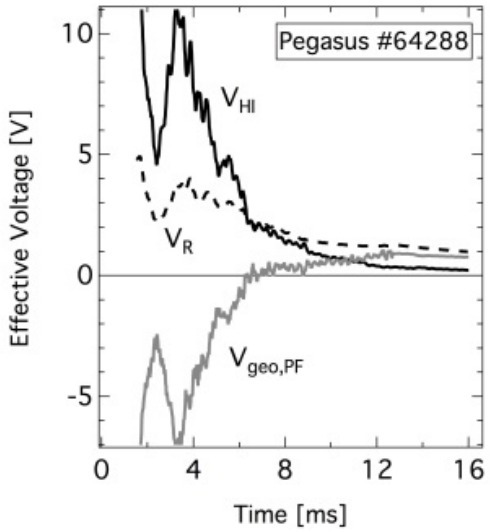
$$I_p\left[V_{eff} + V_{PF} - V_R - V_L\right] = 0$$

$$V_L = L_p\dot{I}_p + \frac{1}{2}I_p\dot{L}_p$$

  - Specify $R_0(t)$ and $I_p(0)$ as input
  - Use analytic descriptions for shape, l_i, radial force balance, etc.
  - LHI input as $V_{eff}(t)$ from helicity conservation

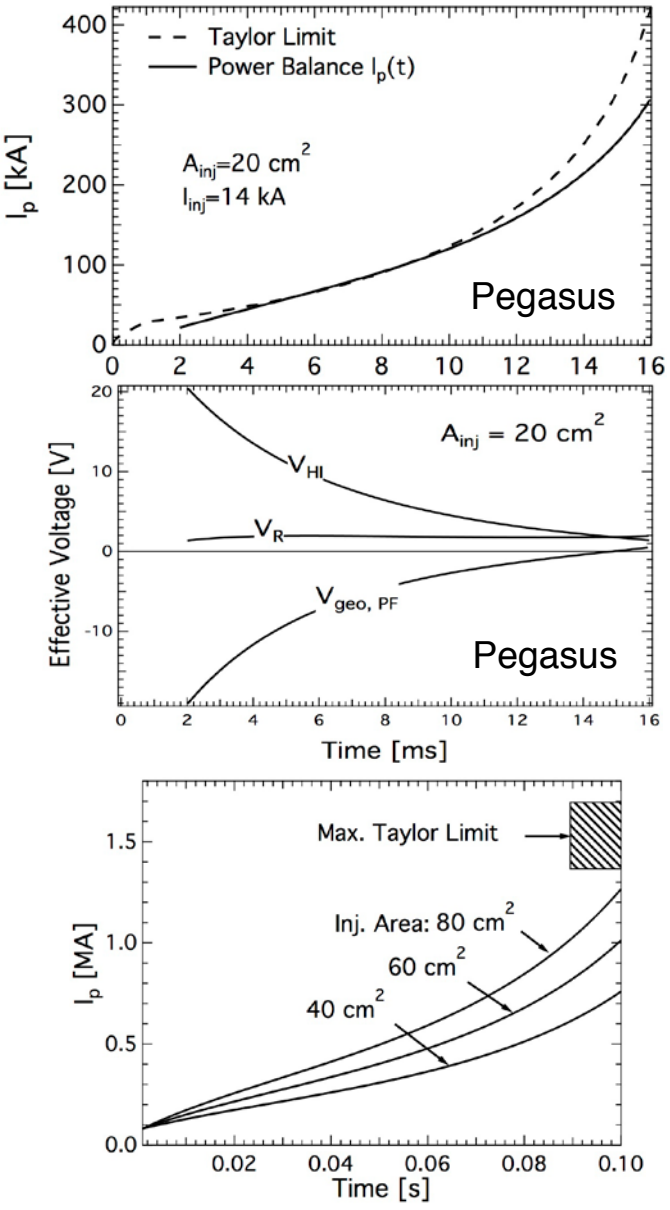
- Gives a reasonable reproduction of Pegasus discharge using LHI- startup
  - Most drive comes from geometric/poloidal induction
    - Not yet a rigorous test of the LHI V_{eff} term





0-D Model Guides Design for High-Ip Startup Systems for Pegasus and NSTX-U

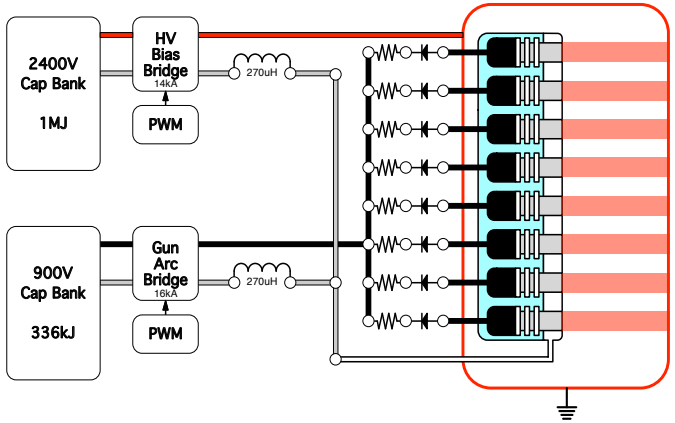
- Estimates needed LHI input rate
  - Determines needed injector parameters
  - For $V_{inj} \sim 0.8$ kV, $I_{inj} \sim 14$ kA, need injection areas of 15-80 cm^2
- Need to test regime where helicity drive dominates induction drive
  - Pegasus ~ 0.3 MA case emulates NSTX-U ~ 1 MA startup (NSTX-U estimate only approximate)
  - Also tests regime where tokamak confinement may deviate from stochastic
- Additional issues arise for larger machines
  - Injector heat loads in long pulse
  - Higher B_t may require reduced aperture sizes for injector beamlets



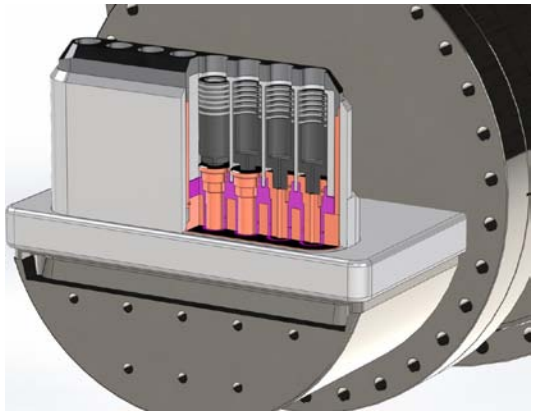
Large Area Injector via Compact Integrated Arc Injector Array for High-I_p Startup

- Simple monolithic power systems support multi-injector array
  - Single power systems for internal plasma arcs and extraction bias
  - Tested with 3-gun assembly on Pegasus
  - Programmable IGBT controlled Arc current demonstrated for active heat and current control

- Integrated 8-injector array presently in fabrication
  - Designed to test access to $I_p \sim 0.3$ MA
  - 8 arc chambers in monolithic assembly
  - Gas distribution using staggered-hole plate array in base
  - 16 cm^2 array will prototype NSTX-U design

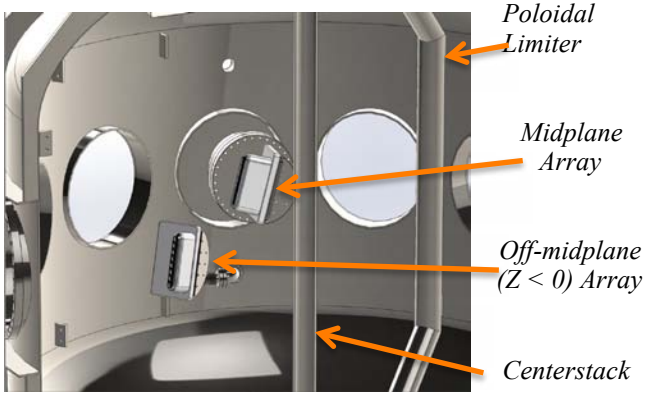


8-injector array power systems



Integrated 8-injector Assembly

Variable Array Locations



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Exploiting Unique Aspects of the ST to Advance Fusion Energy Science

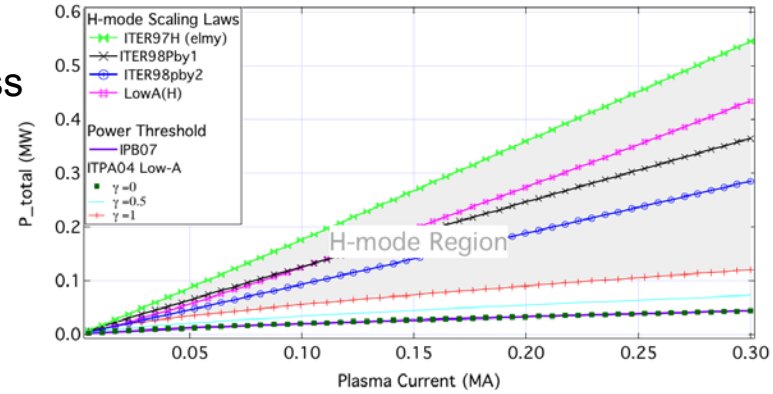
- Non-solenoidal startup: Increasing ST/tokamak attractiveness
  - Local Helicity Injection produces tokamak plasmas using edge current drive
    - Predictive understanding through helicity conservation, Taylor relaxation constraints
  - Progress in current injector development, basic understanding, and predictive capabilities
  - Technique should be applicable to any tokamak, not just ST

- Edge physics: stability, pedestal, ELM dynamics
  - Low-A naturally provides access to peeling instability underlying ELMs
    - Simplified diagnostic access → unique $J_{edge}(t)$ measurements
  - Extension to ITER-relevant peeling-ballooning physics via H-mode operation

- Testing boundaries of tokamak stability at ultimate geometric limit
  - High β_T, toroidal field utilization I_p/I_{TF} as $A \rightarrow 1$

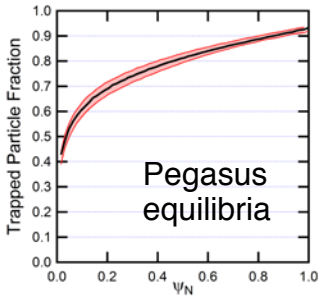
Operation at A ~ 1 Offers Ready Access to Advanced Tokamak Physics

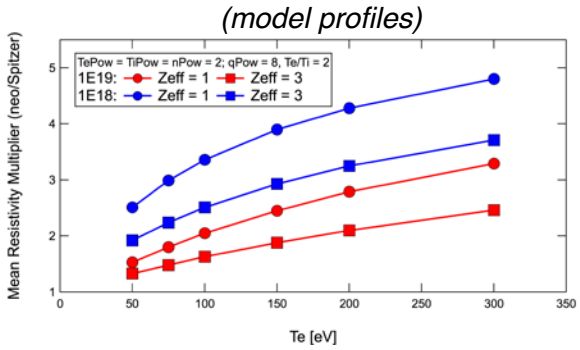
- Very low B_t at modest I_p = very low P_{th} for H-mode access
  - High edge shear = separatrix not necessarily needed
  - Easy access with ohmic heating only
  - ***BUT*** need hot edge => centerstack fueling



H-mode power threshold and ohmic confinement scalings for PEGASUS.

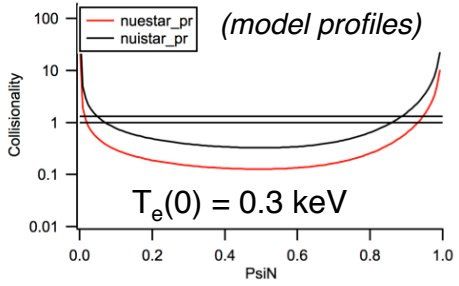
- Short connection lengths and very strong trapping = neoclassical effects at low T_e
  - High particle trapping fractions
  - Strongly non-Spitzer resistivity
  - Bootstrap current possible





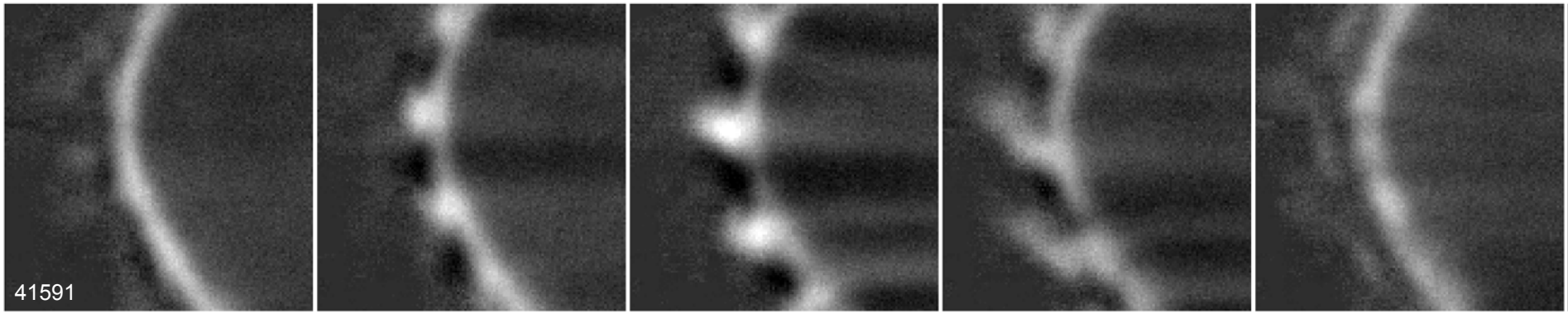
- High j_{edge}/B_t plus H-mode pedetal = Peeling mode and peeling-ballooning modes accessible

- With short pulse and low $\langle T_e \rangle$, easy diagnostic accessibility
  - e.g., probes in pedestal region



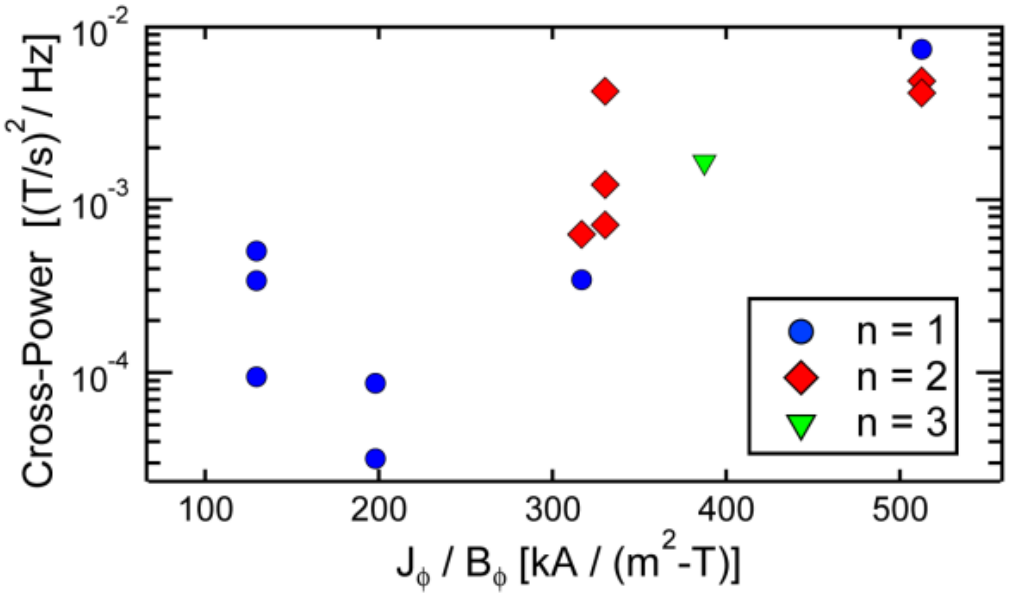
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Pegasus Peeling Mode Features Match Empirical and Theoretical Expectations



0-9 μs 11-20 μs 22-31 μs 33-42 μs 44-53 μs

- Short lifetimes with high poloidal coherence
- Detachment, radial propagation of filaments
- High-m, low-n structure
- Mode amplitude increases with theoretical drive J/B

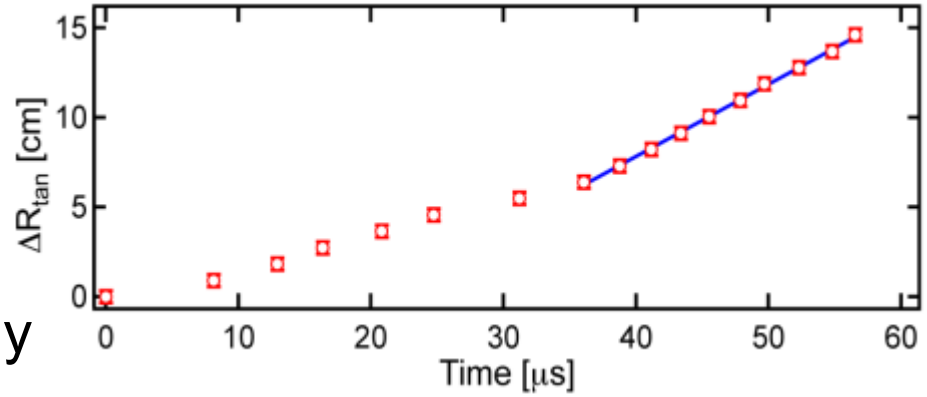


Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

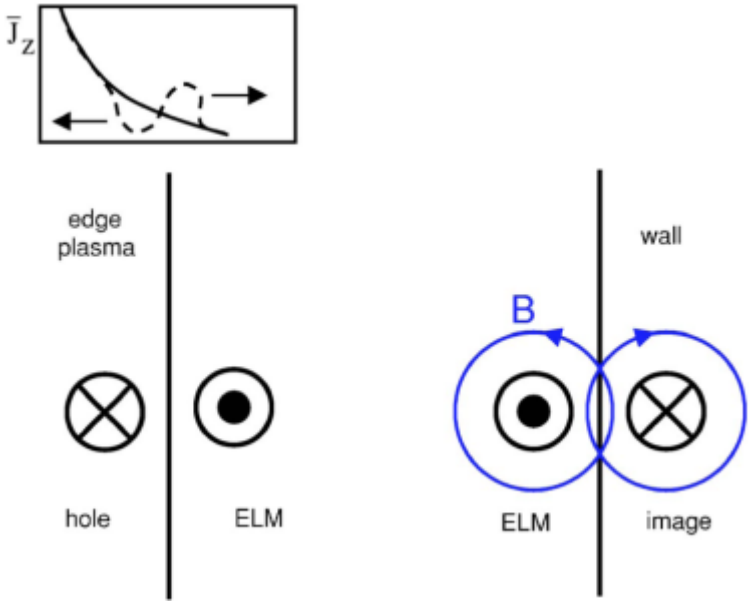
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Filament Radial Motion Qualitatively Consistent with Electromagnetic Blob Transport

- Trajectory of detached filament tracked with 275 kHz imaging
- Magnetostatic repulsion* plausibly contributes to dynamics
  - Current-hole **jxB** drives a_R
  - Transition at ~35 μs comparable to healing time of current hole
- Measured v_R comparable to that expected from EM blob models**
  - $v_R \sim 4$ km/s; $v_{R,IB} \sim 8$ km/s
  - Agrees to O(1) accuracy of theory



Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)



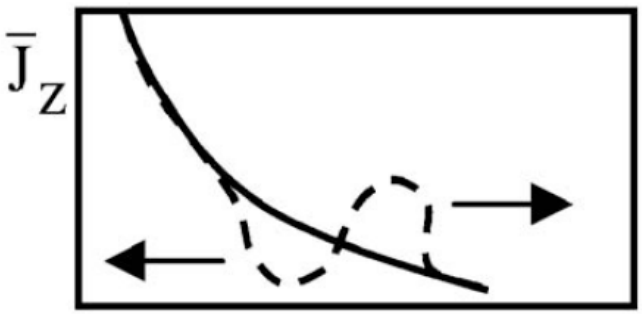
*: Myra, Phys. Plasmas **14**, 102314 (2007)

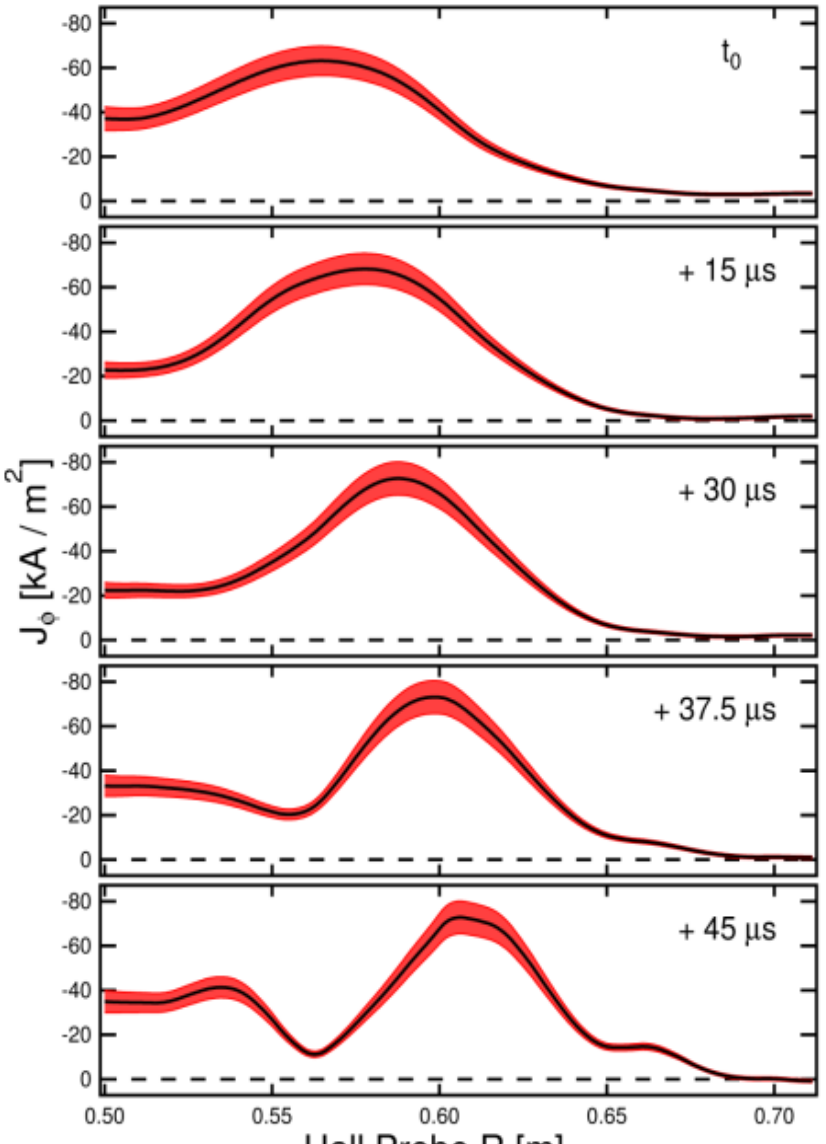
: Myra *et al.*, Phys. Plasmas **12, 092511 (2005)

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J_{edge} Dynamics Measured on ELM Timescales

- Peeling mode filament forms from initial "current-hole" J_{edge} perturbation*
  - Validates formation mechanism hypothesized by EM blob transport theory**
- Filaments carry current $I_f \sim$ 100-220 A
  - $I_f < 0.2$ % of I_p, similar to MAST ELMs
- Radial motion qualitatively consistent with transient magnetostatic repulsion
  - Measured v_R consistent with available analytic models***





: Myra, Phys. Plasmas **14, 102314 (2007)

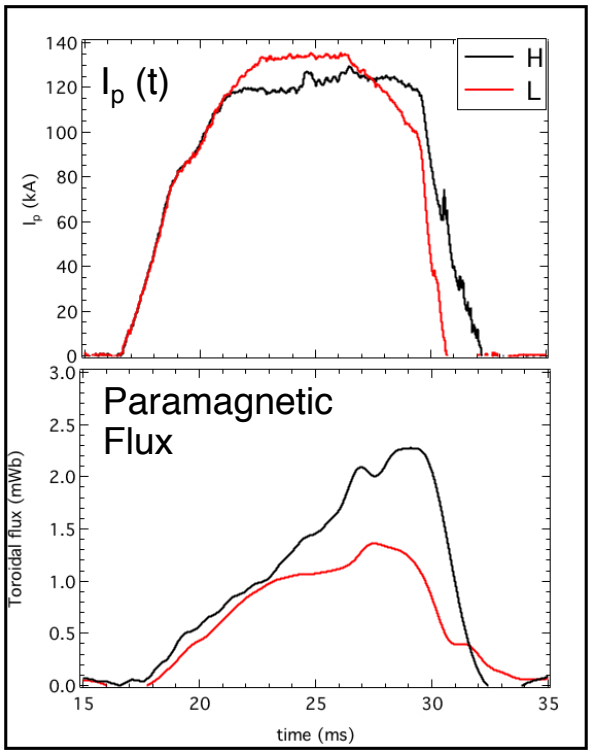
***: Myra *et al.*, Phys. Plasmas **12**, 092511 (2005)

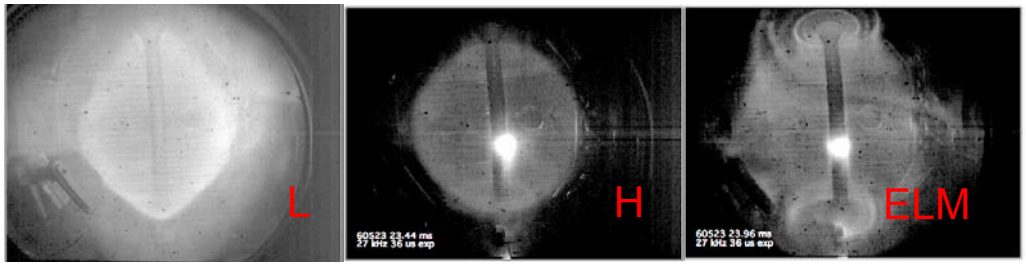
*: Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

H-mode Plasmas Routinely Obtained in Pegasus

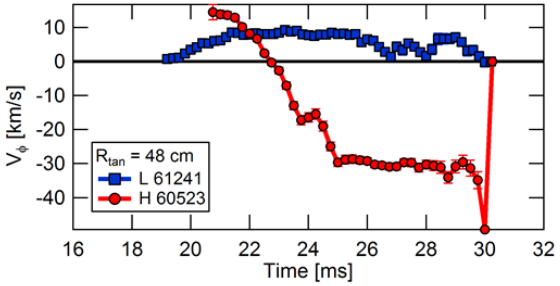
- Obtained with centerstack fueling
  - Ohmically heated
  - Limited or diverted
- Standard H-mode signatures
  - Reduced D_α emission
  - Edge pedestal between ELMs
  - Type I, III ELMs suggested
  - ~ Doubling of stored energy
  - Toroidal flow reversal
  - T_e increase

Increased W_{stored} in H-mode





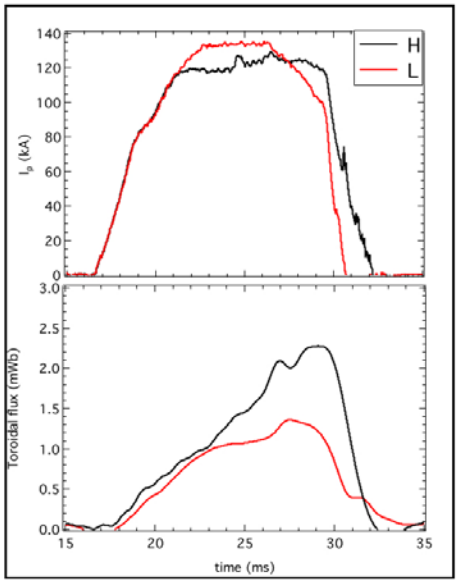
Rotation reversal during H-mode:

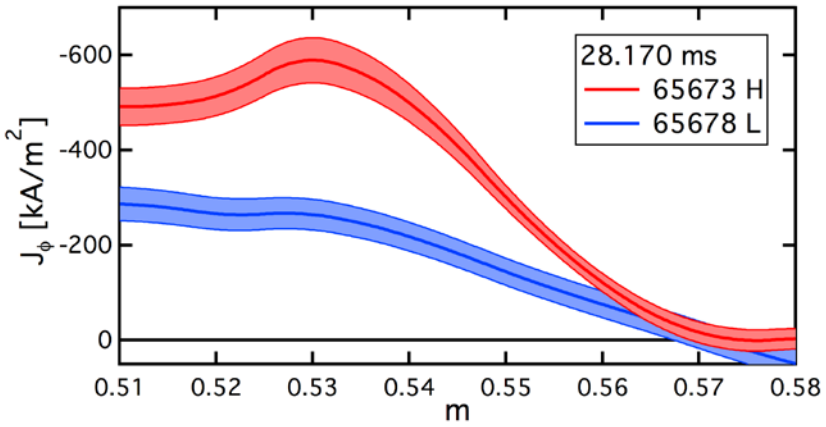


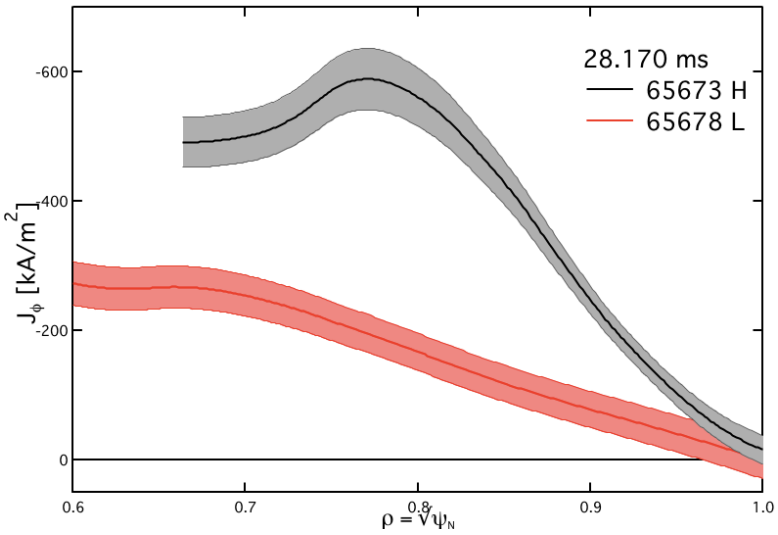
Edge Current Pedestal Observed in H-Mode

- Internal B measurements from Hall array* yield local $J_\phi(R,t)$**
  - Map to ψ_N only approximate
- Current gradient scale length significantly reduced in H-mode

  $L \rightarrow H$: $6 \rightarrow 2$ cm





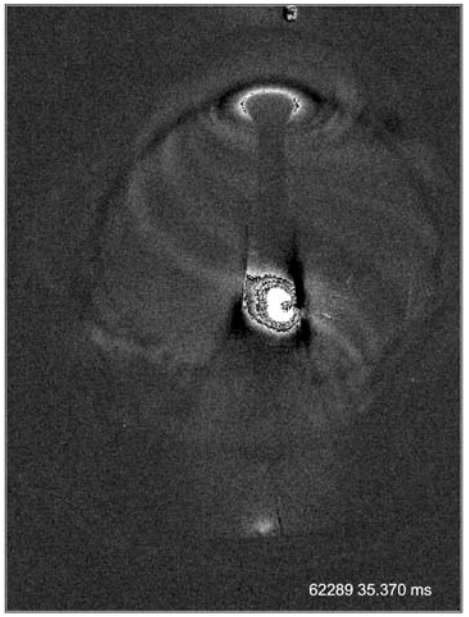


*: M.W. Bongard *et al.*, Rev. Sci. Instrum. **81**, 10E105 (2010)
: C.C. Petty *et al.*, Nucl. Fusion **42, 1124 (2002)

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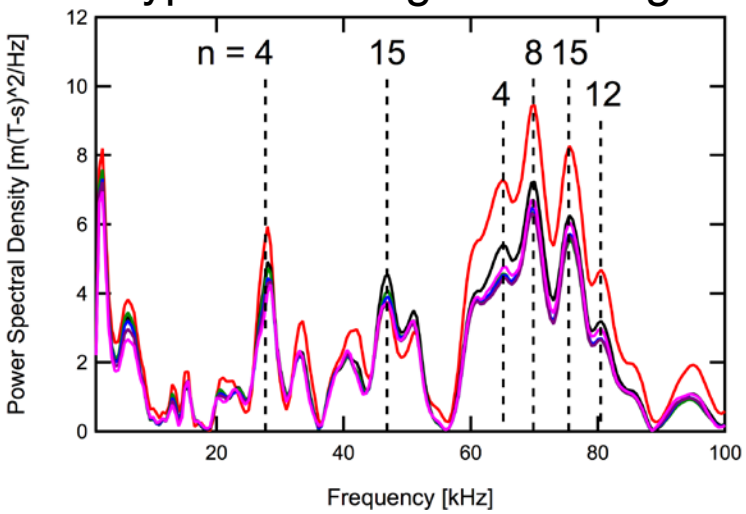
Type I and Type III ELMs Have Different Magnetic Signatures

- ELMs are evident in Pegasus H-modes
  - Type I ELMs are infrequent and violent
  - Type III more ubiquitous and less perturbing
  - Standard filamentary structures observed

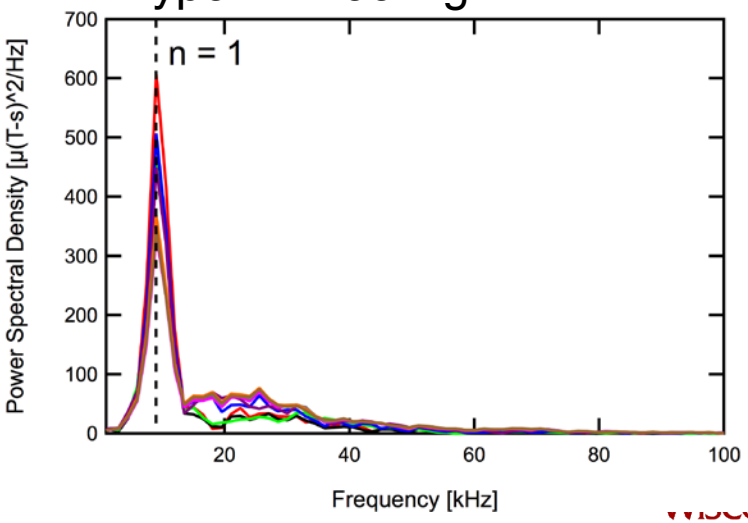


- Toroidal mode spectra suggest different modes at play

Type I: Peeling-Ballooning?



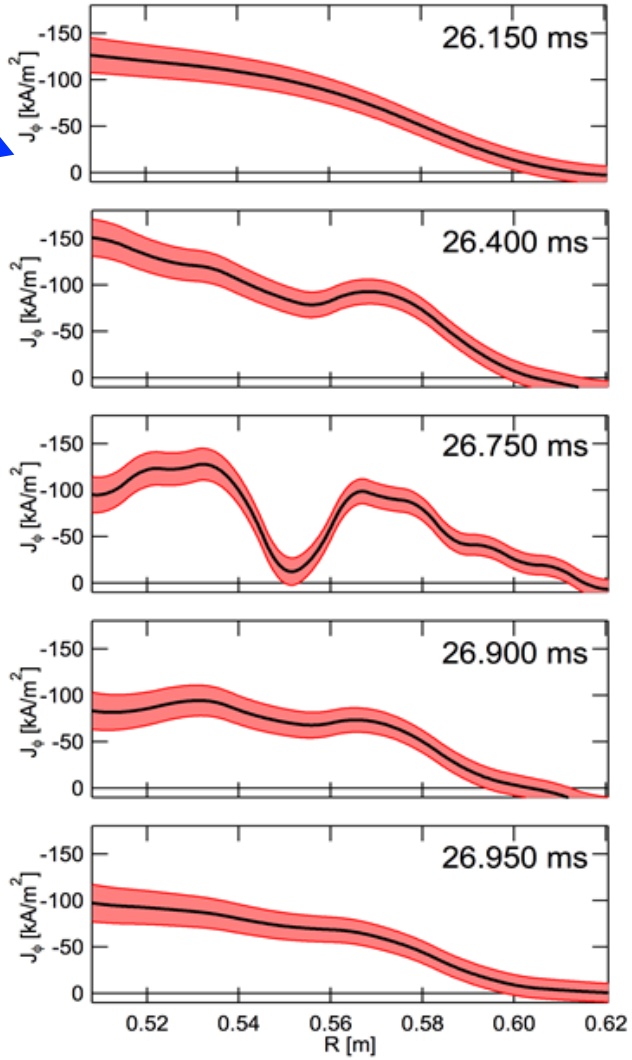
Type III: Peeling



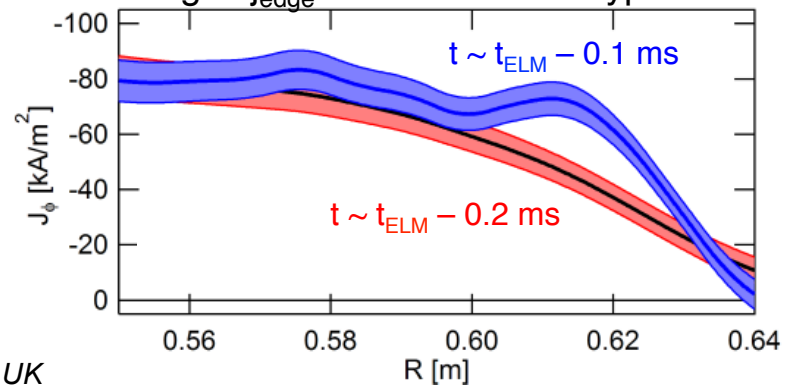
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$J_{edge}(r,t)$ ELM Dynamics Observed

- J(R,t) profiles measured through Type III ELM cycle
  - n=1 precursor
  - Current-hole perturbation accompanies pedestal crash
    - Similar to Peeling modes seen previously with I_p ramps
    - Rapid recovery of edge pedestal
- Pedestal peak in j(R) evolving before Type I ELM
- Proof-of-principle of test of ELM nonlinear dynamics
  - More detailed measurements in progress to confirm these



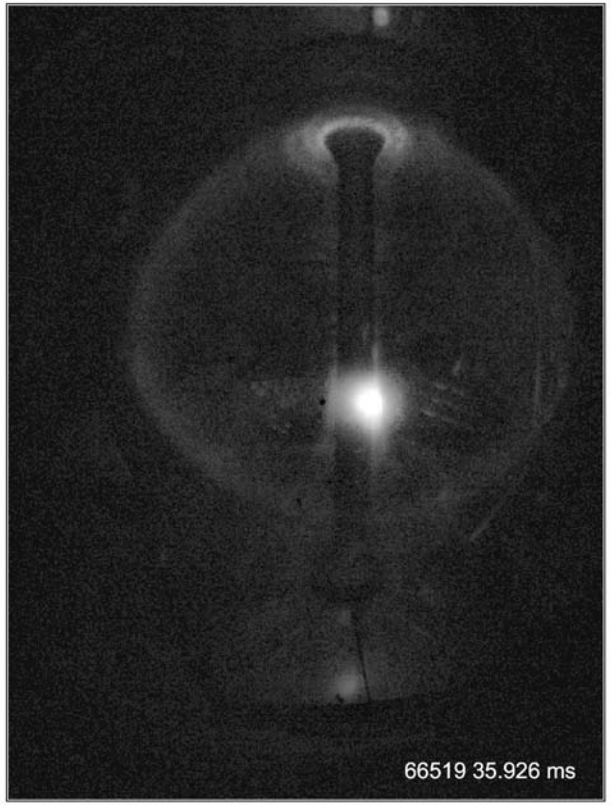
Peaking in j_{edge} ~0.1 ms before Type I ELM?



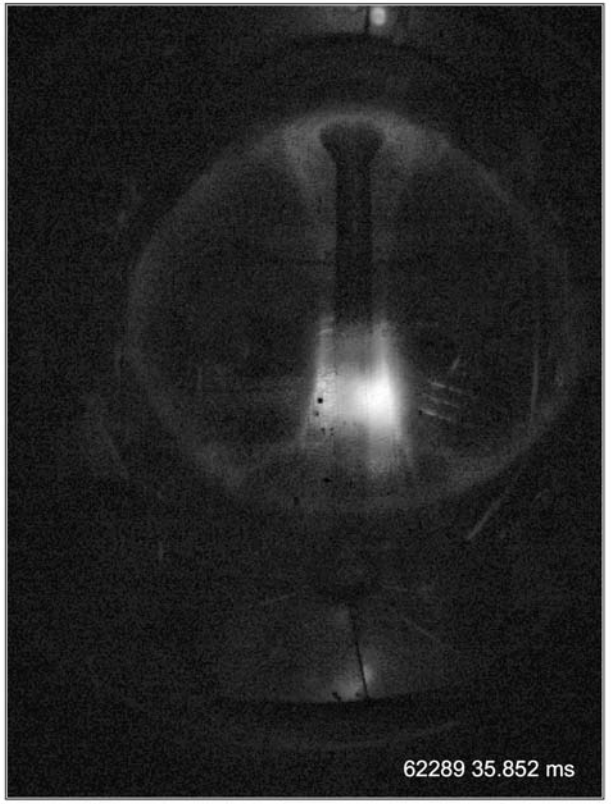
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Divertor Coils Activated to Access Standard Separatrix-Limited H-modes

Non-diverted:
Centerstack Limited



Diverted:
Separatrix Limited

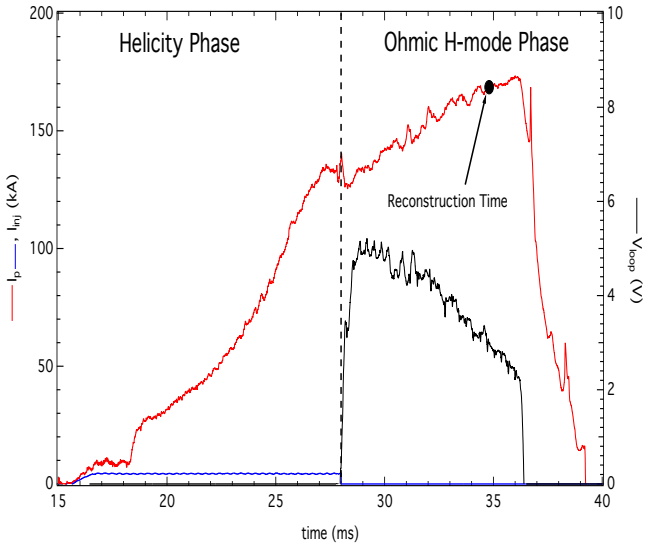


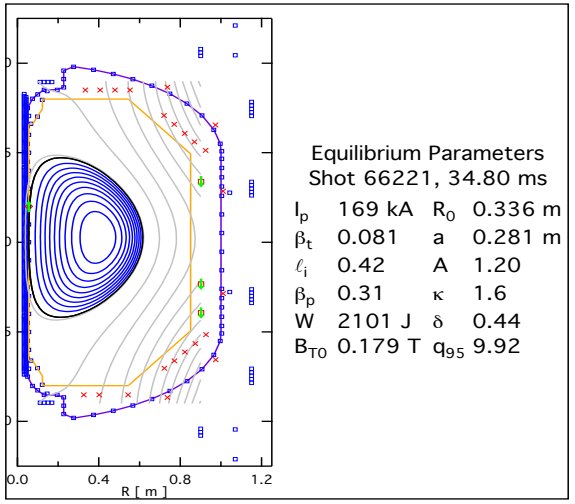
- Initial results show no significant difference between diverted and non-diverted

LHI Startup Compatible with Consequent High-Quality OH H-mode

- High-Ip, long-pulse H-mode plasmas desirable for Pegasus goals
  - Confinement and edge stability studies
  - Attaining high β_t regime

- Need additional current drive
  - LHI-initiated discharge readily couples to ohmically-driven H-mode



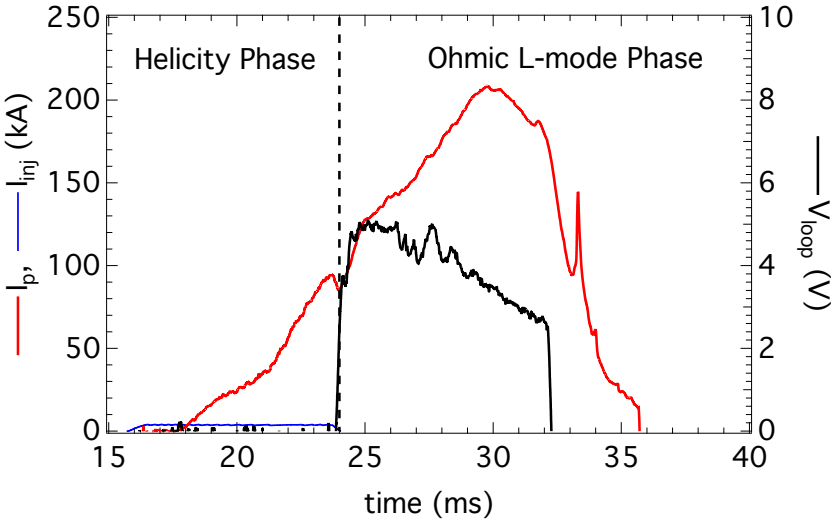


- But, more difficult to raise Ip in ohmic phase since injector redesign
  - May be influenced by density/fueling and/or residual MHD activity

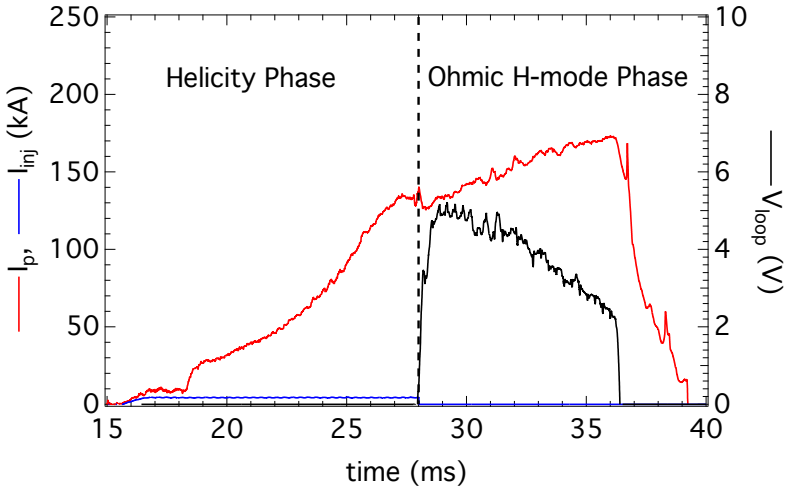
- High I_p, long-pulse operation awaits new integrated LHI assembly and power systems upgrades

Anecdotal Evidence: Increased Trapping Effects with Cleaner, Hotter Plasmas?

- Flat-cathode Current Injectors
  - Significant impurity fueling
  - Increased I_p with available V-sec



- Frustum-cathode Current Injectors
  - No impurity fueling
  - Much harder to raise I_p with available V-sec



- So far, harder to raise I_p in ohmic phase with
  - Indications that trapping may be giving rise to increased resistivity?
  - May be influenced by MHD and density/fueling
- High I_p, Longer-pulse operation requires increased current drive capability
  - Awaits new integrated LHI startup system, plus future power systems upgrades

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Studies at Near-Unity Aspect Ratio in Pegasus Advance Fusion Energy Sciences

- Significant progress with non-solenoidal startup of ST
  - Increasing understanding of HI physics to project towards MA-class startup
    - Helicity balance, relaxation current limits determine ultimate I_p
    - Complex MHD drives J(R,t) and reconnection-driven ion heating
    - Sheath and magnetic current limits govern injector impedance
    - Lumped parameter energy model useful for prediction forward
  - Developing advanced edge current sources for increased helicity injection

- Leveraging low-A regime to test edge stability theory
  - Peeling mode characteristics consistent with theory
    - Onset, spatial structure, MHD virulence consistent with ideal MHD
    - Nonlinear dynamics: filament creation / propagation from J_{edge} current-hole
  - ITER-relevant ELM stability tests of peeling-ballooning modes

- LHI J(R,t) control and H-mode access support high-β studies of tokamak limits
  - Enhanced divertor coils for separatrix operation