Progress in Nonsolenoidal Startup via Local Helicity Injection in the Pegasus Experiment

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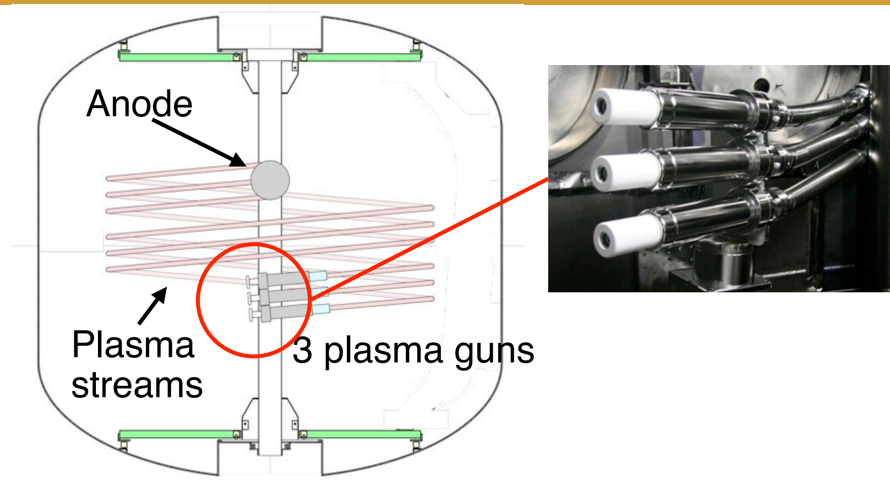
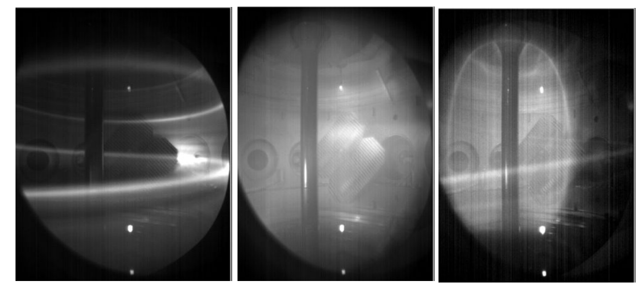
PEGASUS
Toroidal Experiment

Local Helicity Injection uses LFS Injection Plus Poloidal Induction for ST Startup

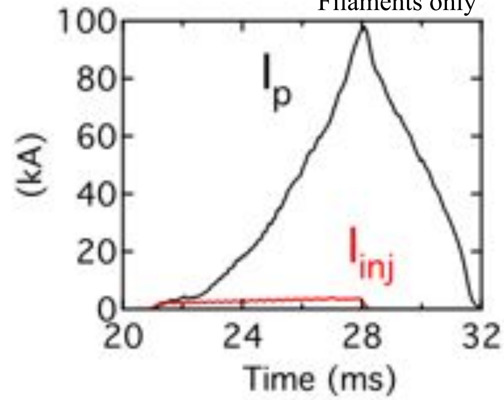
- Flexible injector geometry
- Startup sequence:
  - PF field weakened by current streams
  - Relaxation to tokamak-like state
  - Rapid inward expansion and growth in I_p at low A
  - Poloidal field induction adds to current growth
- Goal:0.3 MA non-solenoidal I_p
  - To extrapolate to next level/NSTX-U
  - Issues: j_{edge}, Z_{inj}, confinement, injector technology, etc.



PEGASUS shot #40458: two midplane guns, outer-PF ramp



I_p=2-3 kA Filaments only | I_p=42 kA Driven plasma | I_p=37 kA Guns off Decaying



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Local Helicity Injection Offers Scalable Nonsolenoidal Startup

- Inject Helicity for I_p startup using electron current source at the tokamak plasma edge
  - Helicity balance via resistive dissipation losses:

$$I_p \le \frac{A_p}{2\pi R_0 \langle \eta \rangle}\left(V_{ind} + V_{eff}\right) \qquad V_{eff} \approx \frac{A_{inj} B_{\phi,inj}}{\Psi_T} V_{bias}$$

  - Max I_p via relaxation to Taylor (constant λ) state:

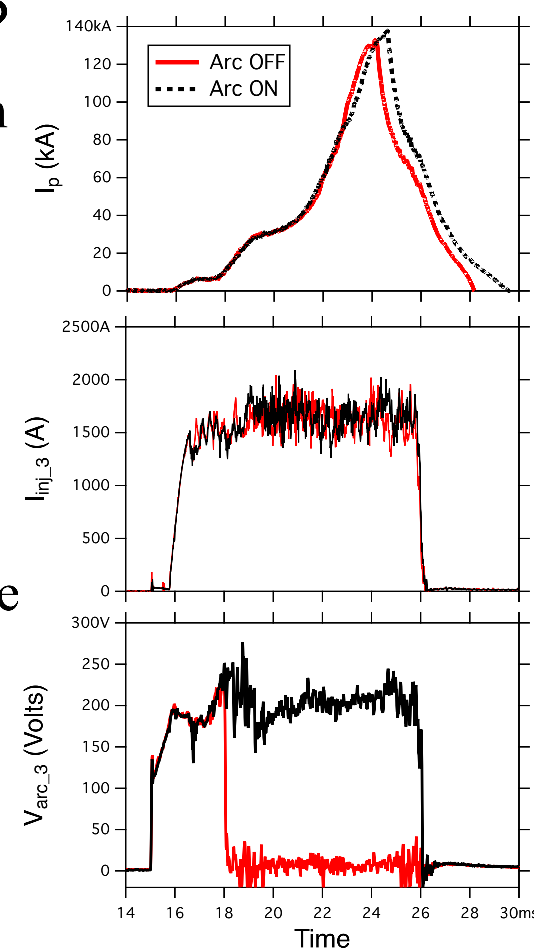
$$I_p \le \left[\frac{C_p}{2\pi R_{inj} \mu_0} \frac{\Psi_T I_{inj}}{w}\right]^{1/2}$$

A_p	Plasma area
C_p	Plasma circumference
Ψ_T	Plasma toroidal flux
w	Edge current channel width

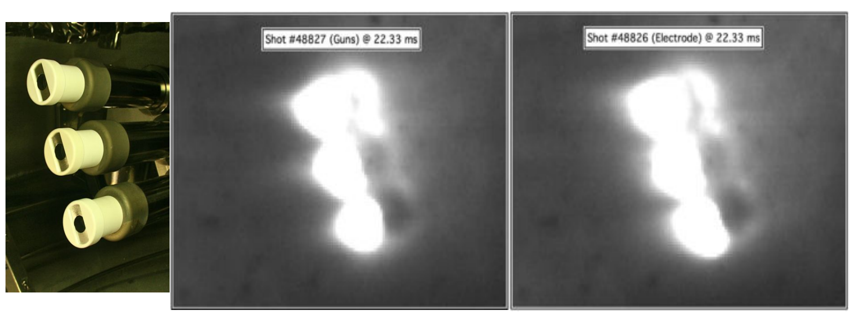
- **Maximizing I_p requires:**
  - Large helicity input rate: **High A_{inj}, V_{inj}**
  - High relaxation limit: **High I_{inj}, & B_{TF}, low *w***

Exploring Passive Injectors to Increase Area for Higher Helicity Injection Rates

- Mitigate cost/complexity of producing high electron current: passive current sources?
  - Step 1: Form tokamak-like state with active arc gun
    - I_{inj} ~ 2-4 kA; A_{inj} ~ 4-6 cm^2
  - Step 2: Increase I_p via electrodes in edge plasma
    - I_{inj} ~ 12 kA; A_{inj} ~ 60 cm^2



- First tests are promising
  - Arc current off after relaxation to tokamak-like state
  - $I_p(t)$ is the *same*



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Gas-Fed, Large-Area Electrode May Mitigate Requirement for Arc Sources

- Need to spread I_{inj} across large area
  - Effective area of metallic electrode = small → low HI rate

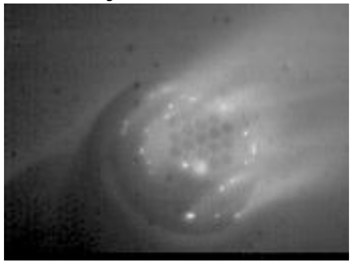
Single arc source with integrated large-area passive electrode

Small cathode spots emit current from simple metallic electrode

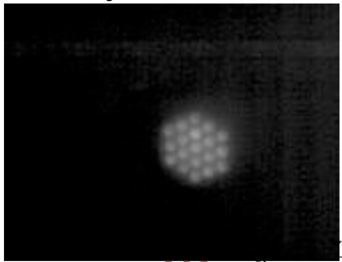
- Gas-fed hollow cathode electrode to provide required large-area source of charge carriers
  - In edge of tokamak plasma

Perforated electrode (no plasma arc) with beveled edge to avoid electrode-BN arcing

I_{inj} = 2 kA



I_{inj} = 0.5 kA



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Predictive Impedance Models Required to Project to Future Startup Systems

- Injector impedance couples Helicity and Relaxation limits
  - Defines power requirements

- Double-sheath space-charge limits I_{inj} at low I_{inj}, V_{inj}

$$J_e = \frac{4}{9}\varepsilon_o \sqrt{\frac{2e}{m_e}} \frac{V^{3/2}}{(\chi \lambda_{De})^2}$$

- Magnetic current limit at high $I_{inj} > I_A$ and $V_{inj} > 10\ kT_e/e$

$$I_{AL}^{e} = 1.65 \frac{4\pi m_e v_e}{e\mu_o} \equiv 1.65 I_A = 56\sqrt{V_{inj}}$$

  - For uniform current density
  - Sheath expansion can also contribute here

- So far, implies impedance dominated by local processes
  - Influence of background plasma not clear

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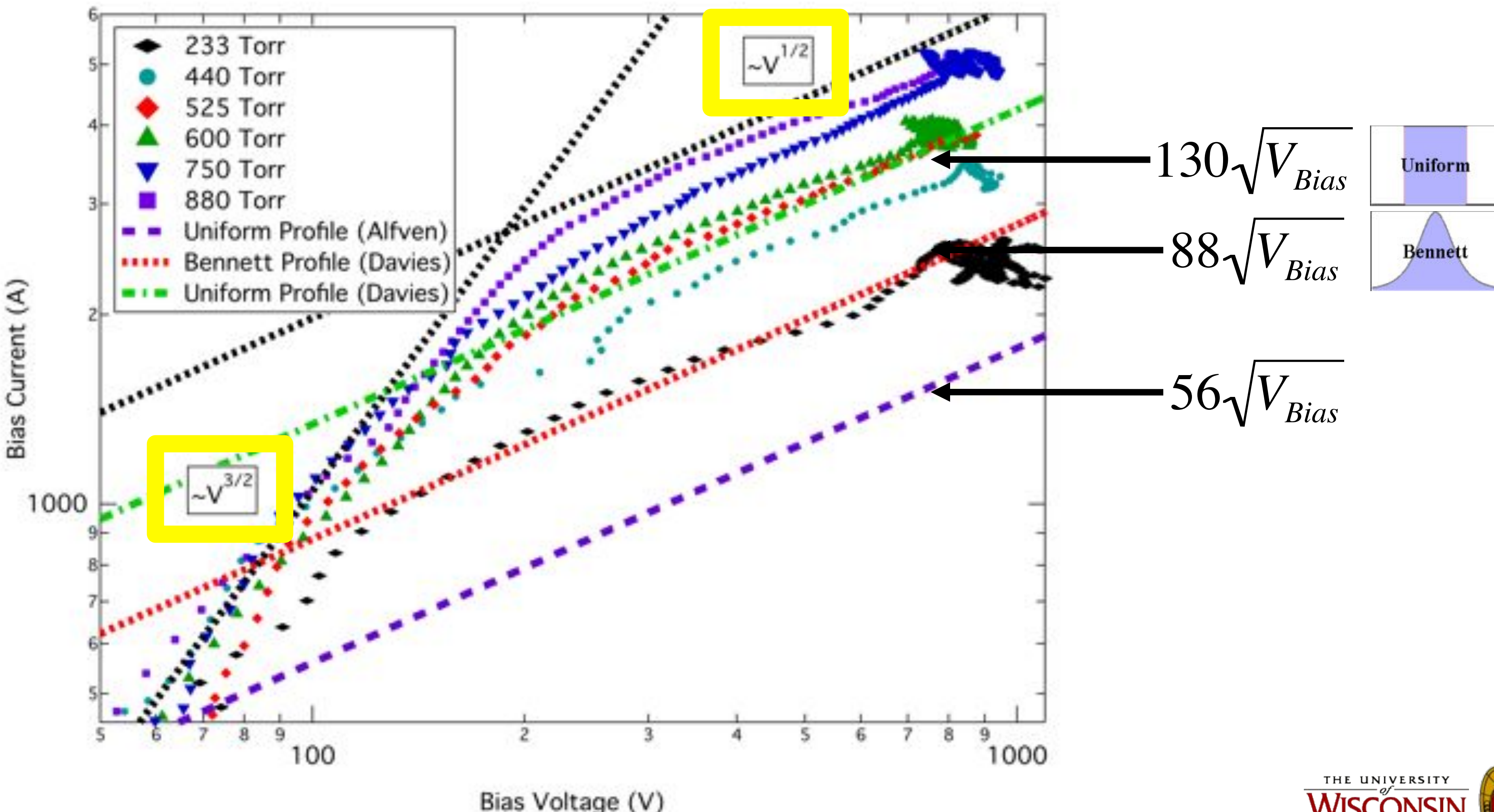
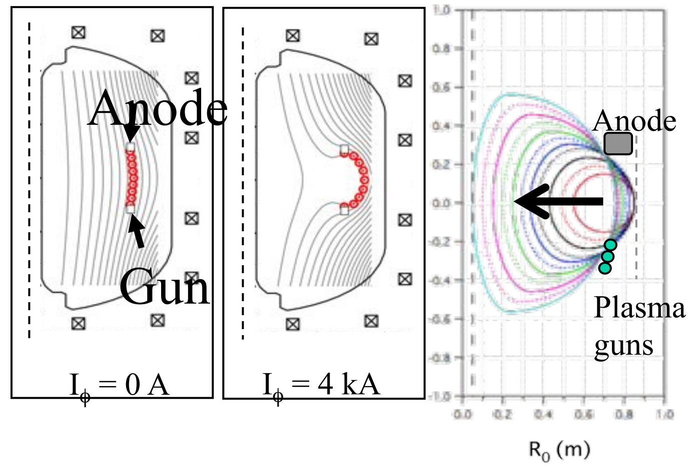
Magnitude, Scaling of Data Consistent with Sheath and Magnetic limits

- Magnetic limit is expected at currents of order I_A
- Suggests current profile is changing with density

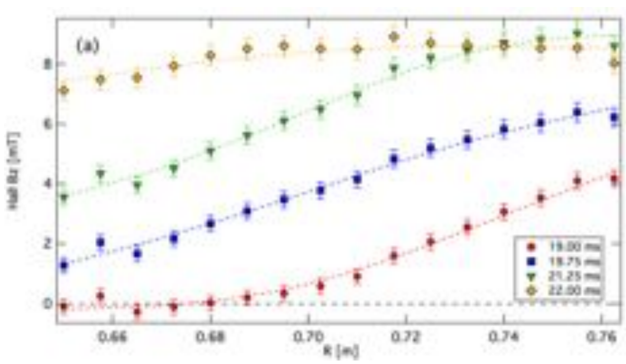


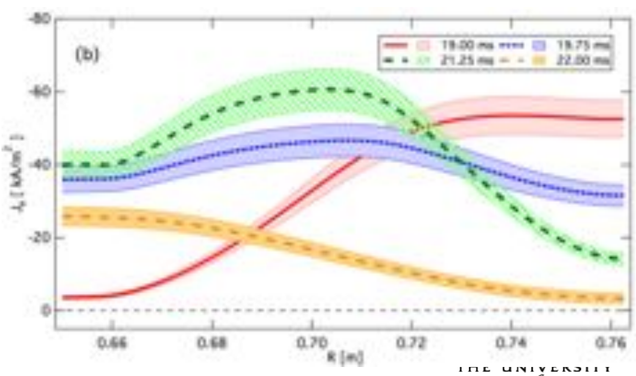
HI Physics: Poloidal Null Formation During Relation to Tokamak Verified

- (a) $B_z(R,t)$ shows expected* poloidal null formation
- (b) $J_T(R,t)$ shows core current buildup
  - Plasma moves inward (red -> green)
  - J = typical peaked tokamak profile after detachment (yellow)



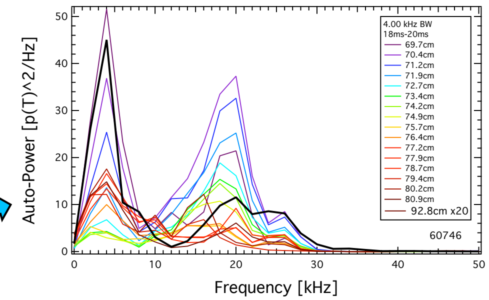
*D. J. Battaglia, et al., Nucl. Fusion, 51, 073029, 2011



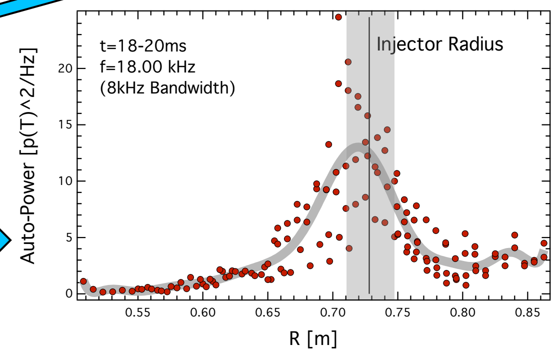


HI Physics: n=1 Mode Correlates with Rise in Plasma Current

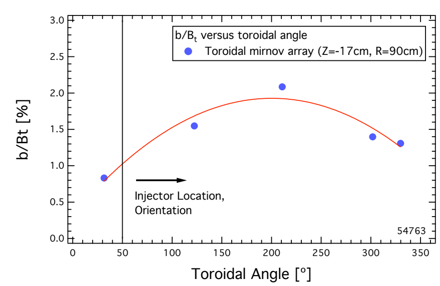
- Bursty and continuous n=1 mode coincident with rises in I_p
  - Similar to that seen in HI-driven spheromaks and tokamaks
  - n=1 MHD power peaked at 16 kHz

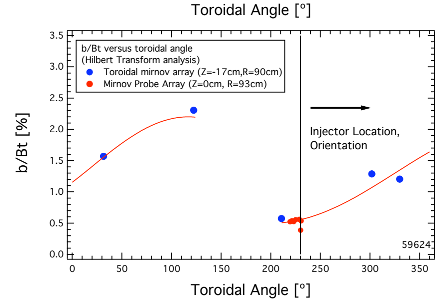


- Power peaked at current injector radius
  - From internal $B_z(R,t)$ measures



- Toroidally asymmetric
  - Follows injector location
  - Tentatively: line-tied kink mode





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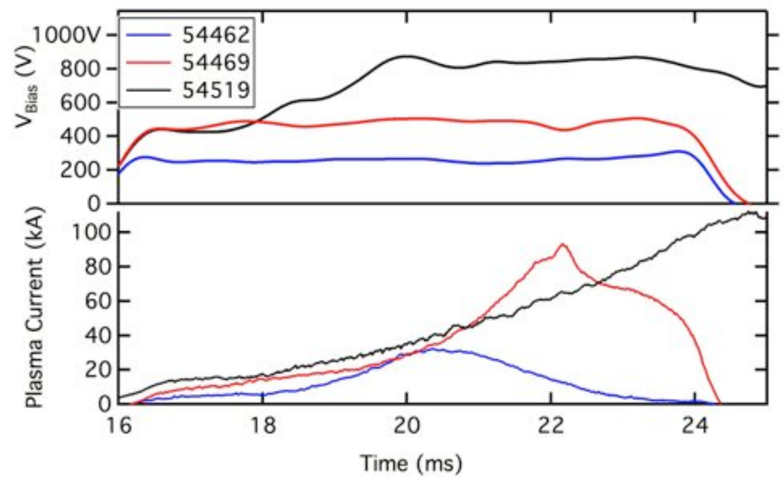
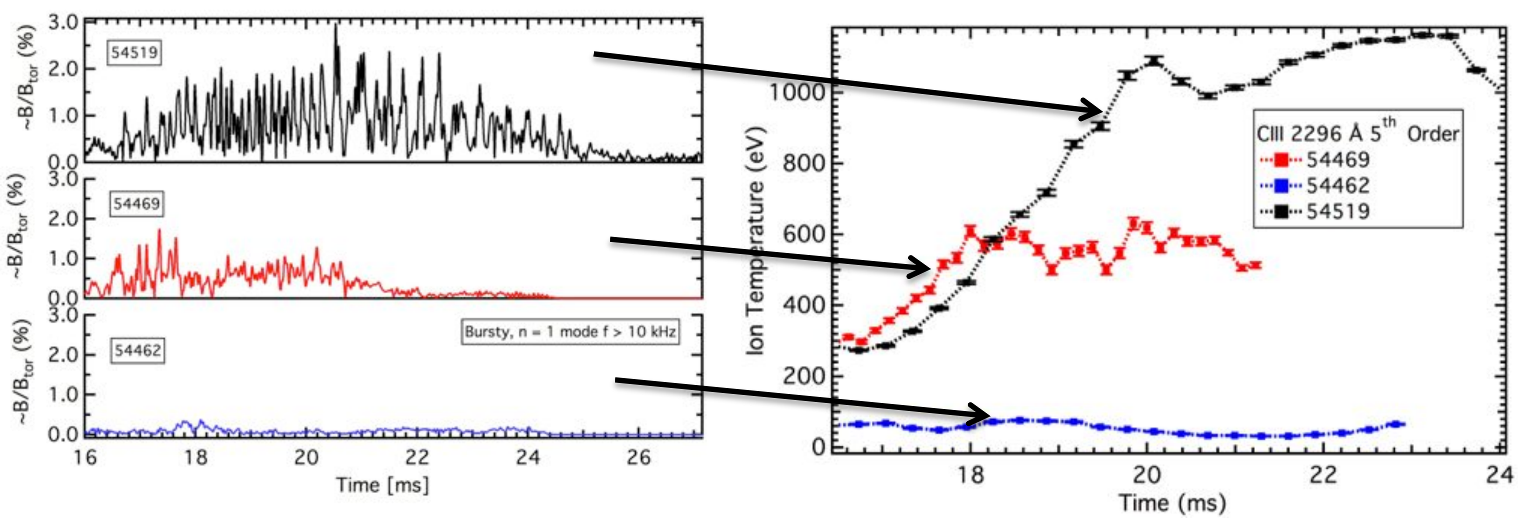
HI Physics: Strong Ion Heating Correlates with MHD Amplitude and Power Input

- Strong ion heating observed via impurity lines during helicity injection
  - Radially integrated spectroscopy
  - VUV spectroscopy: $T_e \sim 50$ eV or so



- Heating correlates with n = 1 activity

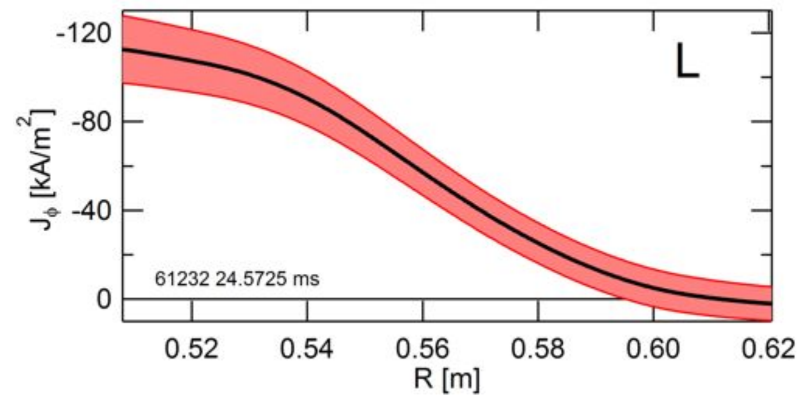
- $T_{i\perp} > T_{i\parallel}$
  - Similar to that seen on MST with large reconnection during sawtooth crash

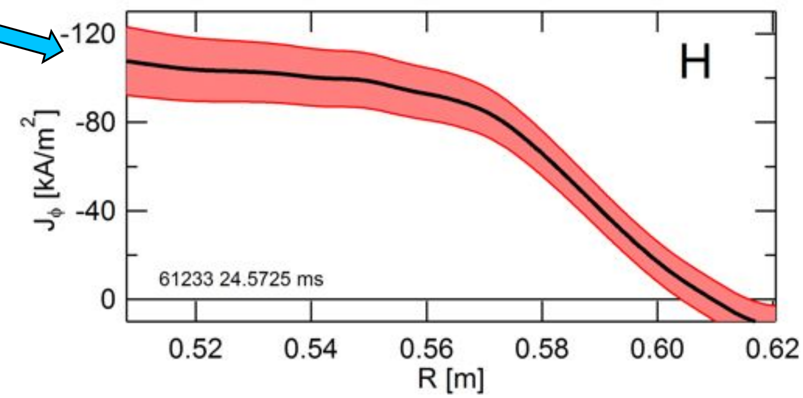


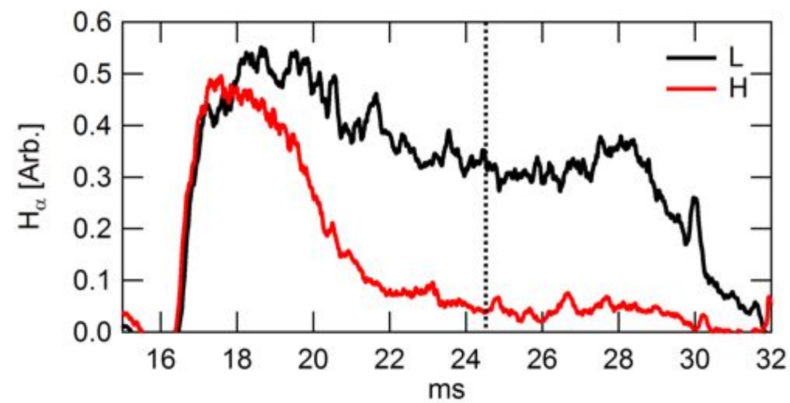
Access to Ohmic H Mode may help Startup and Consequent Current Drive

- Ohmic H-mode via centerstack fueling
  - $I_p \sim 0.12$ MA
- **Pedestal in j(R,t) observed**
  - Internal B measurements from Hall array* yield local $J_\phi(R,t)$**
- Gradient scale length significantly reduced in H mode
  - L → H: 6 → 2 cm

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







Summary: Progress in Developing Local Helicity Injection for ST Startup

- Local current sources support non-solenoidal startup of ST and other confinement devices
  - NSTX-U class power systems deployed on Pegasus
  - Preliminary: gas-fed electrodes may be combined with plasma arc sources to drive high I_p

- Arc source impedance, and helicity injection rate, appear to be governed by sheath effects and magnetic current limits

- Plasma properties during helicity injection similar to other reconnecting plasmas
  - N=1 MHD activity related to current buildup
  - Current buildup and poloidal null formation
  - Anomalous ion heating during reconnection

- Ohmic H-mode attained: should aid startup studies
  - J(R,t) pedestal and perturbations during ELM readily observed

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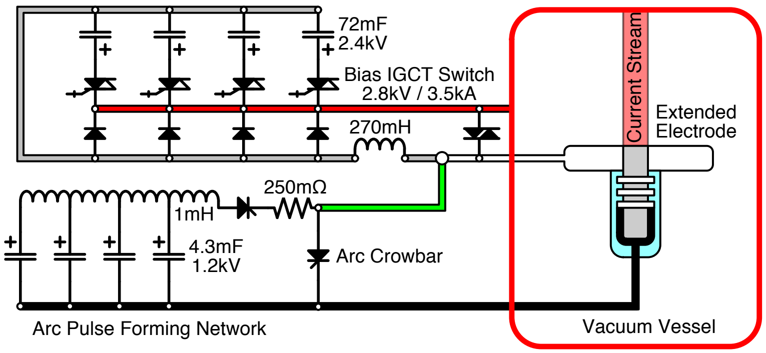
Related Posters for Details

- NP8.00060: *Bongard*: **Non-solenoidal Startup and Pegasus Program**
- NP8.00061: *Barr*: **MHD and Helicity Injection on Pegasus**
- NP8.00062: *Hinson*: **Injector Impedance Studies**
- NP8.00063: *Burke*: **Ion Heating and Flow Measurements on Pegasus**
- NP8.00064: *Thome*: **Plasma Fueling and H-mode Access in Pegasus**
- NP8.00065: *Schlossberg*: **Thomson Scattering and Plans for Confinement Studies**
- NP8.00066: *Schoenbeck*: **Multipoint Thomson Scattering System for Pegasus**
- NP8.00067: *Shriwise*: **New Pegasus Divertor Design for Helicity Optimization**
- NP8.00068: *Perry*: **Power Systems and Magnetics Upgrades**
- NP8.00069: *O'Bryan*: **Simulation of current-filament dynamics and relaxation in Pegasus**
- PP8.00024: *Redd*: **Design Considerations for Local Helicity Injection on NSTX-U**

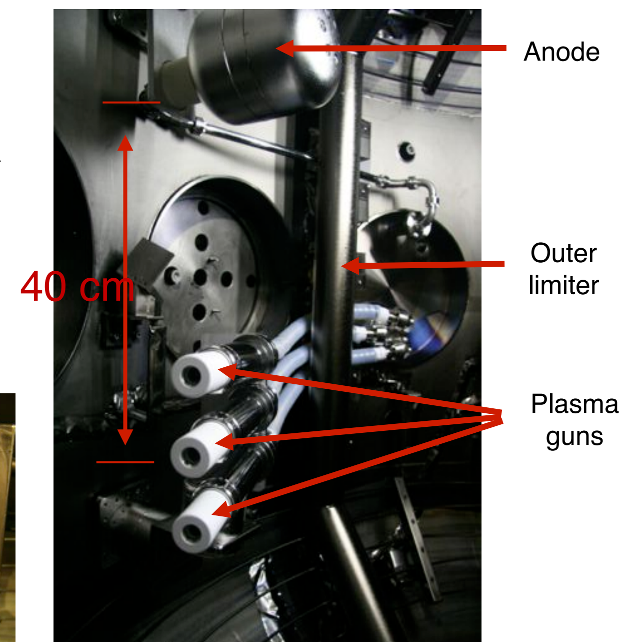
Extras

Power Systems and Current Injectors Being Developed to Test Startup to High I_p

- New power systems deployed
  - NSTX-U class power level
  - Bias: $I_{inj} \leq 14$ kA @ $V_{inj} \leq 2.2$ kV
  - Arc: Simple PFN



- Injectors under development
  - **Active**: plasma-arc current sources
    - Intense beam ~ 1 kA/cm^2
  - **Passive**: large-area electrodes
    - Metallic electrodes to develop insulation designs
    - Gas-fed designs under test



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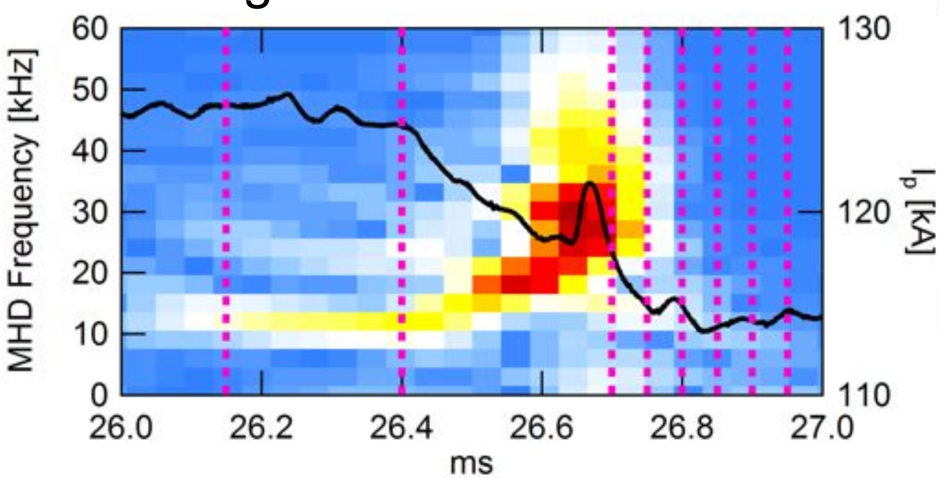
J_{edge} ELM Dynamics Observed

- J(R,t) profiles measured throughout single Type III ELM
  - n = 1 EM precursor
  - ~10% I_p loss, negligible $\Delta\Phi$
- Current-hole perturbation accompanies pedestal crash
  - Similar to peeling modes in Pegasus*
- Rapid recovery to H-mode pedestal following event



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