NSTX-U

NSTX-U is sponsored by the
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Fusion Energy Sciences

Reduced Model for Direct Induction Startup Scenario Development on MAST-U and NSTX-U

D.J. Battaglia, A.J. Thornton, S.P. Gerhardt, A. Kirk, L. Kogan, J.E. Menard

NSTX-U / Magnetic Fusion Science Meeting
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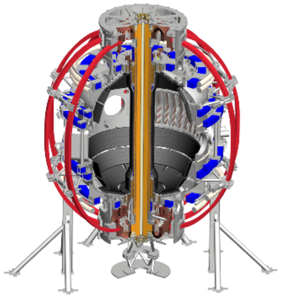
PPPL



Motivation

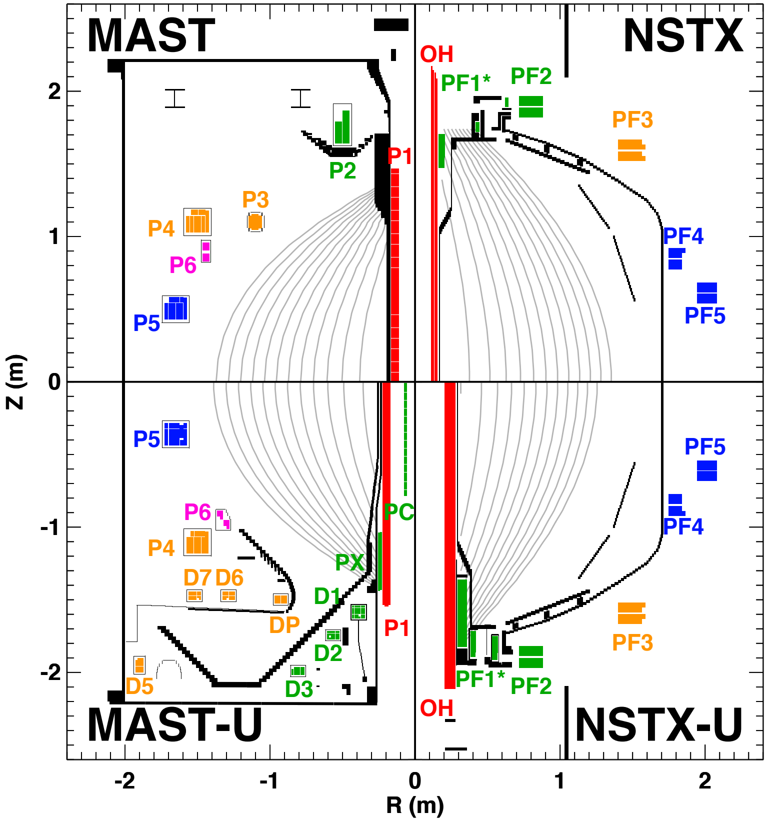
- Develop tools to assist MAST-U in achieving first plasma and reliable startup scenarios
  - MAST dabbled in inductive startup, but the scenarios are not directly transferable to MAST-U
  - MAST-U will probably use 7 – 12 coil sets during startup
    - Lots of flexibility and knobs to adjust … it's good to have a plan
- Use the tools for interpreting and optimizing startup on NSTX-U
  - Startup scenario used in 2016 still needs some tweaking
  - Provide a tool for P.O.'s to redesign / fix startup
- Provide data and analysis that supports ITPA efforts to develop startup models for ITER

Outline

- Startup on NSTX(-U) and MAST(-U)
- Reduced model for breakdown phase
- Reduced model for early burn-through phase
- Predictive modeling
- Summary

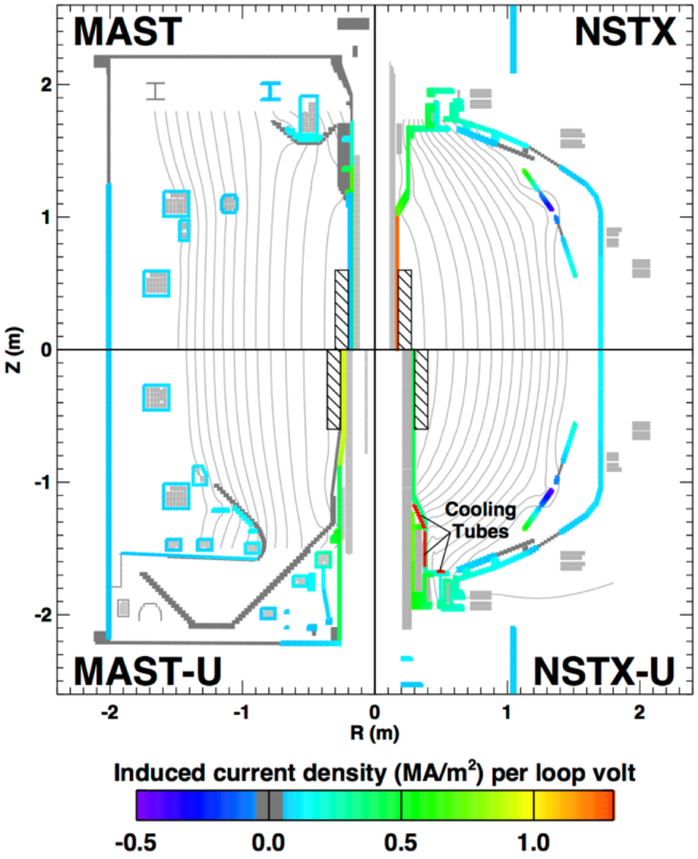
Position of coils and passive elements in the 2D axisymmetric model for the four devices

- **Central solenoid**
  - Gray contours show solenoid fringe field
  - Precharge adds confining field
- **Nulling coils**
  - Null solenoid fringe field
  - Fast current swing to confining field to improve passive vertical stability
- **Equilibrium coils**
  - Unipolar coils add confining field but degrade passive vertical stability
- **Divertor coils**
  - Cancel radial field of solenoid fringe field but degrade passive vertical stability
- **Passive conducting elements**



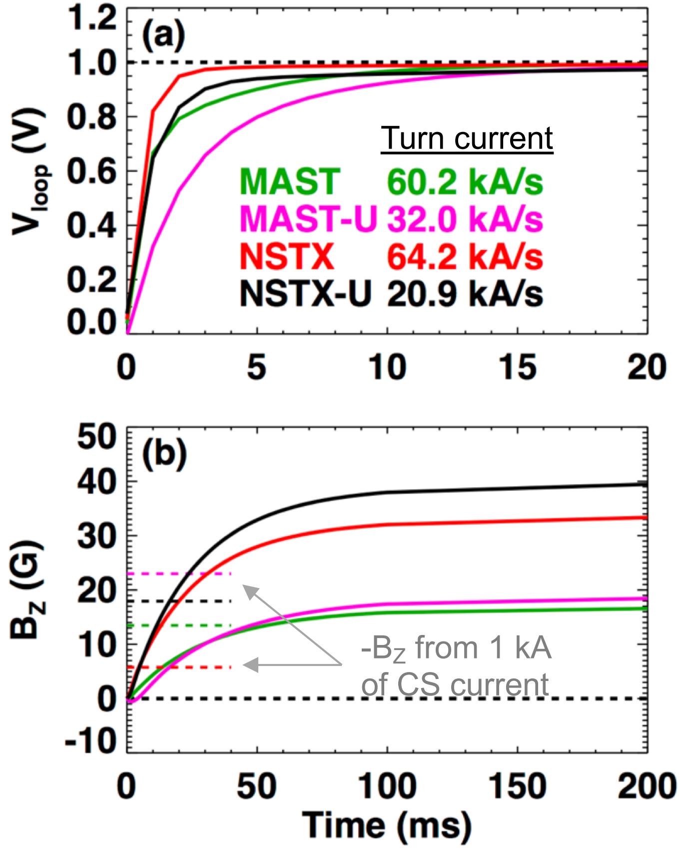
Induced currents are a significant fraction of the total magnetic fields during startup

- Figure shows current induced by one loop volt within ROI
  - Gray flux surfaces due to induced currents (no coil currents)
  - Field in deconfining direction ($+V_{loop}$)
    - Radial field degrades passive vertical stability
    - More of an issue for NSTX than MAST
- Induced current in copper cooling tubes on NSTX-U is 15 – 30 MA/m^2



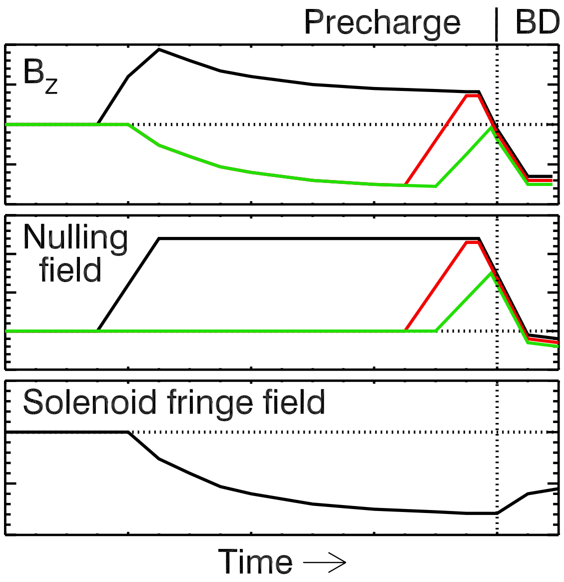
Devices have different induced current properties

- Apply step function of dI_{CS}/dt
  - Smaller dI_{CS}/dt with larger solenoid radius
- Time constant of V_{loop} impacted by inboard structures
  - MAST(-U) has more conductive inboard structures for inductive baking
- Longer time constant of B_Z increase impacted by outboard structures
  - NSTX(-U) structures closer to plasma
  - Must be considered when setting solenoid precharge strategy



NSTX(-U) and MAST(-U) have different constraints and capabilities for precharge and pre-ionization (PI)

- NSTX: Long prefill, exclude null during solenoid precharge
  - Enables real-time vessel pressure feedback
  - Pre-ionization: ECH (~ 6 kW) & filaments
- MAST: Short prefill, minimize precharge of solenoid and nulling field
  - Nulling field from D-coils with restrictive I^2t limits
  - MAST-U scenarios aim to "ramp through" null as opposed to using "the kiss" (MAST)
  - Emissive filaments are only planned routine PI
    - May use Thomson laser and/or NBI (used on MAST)



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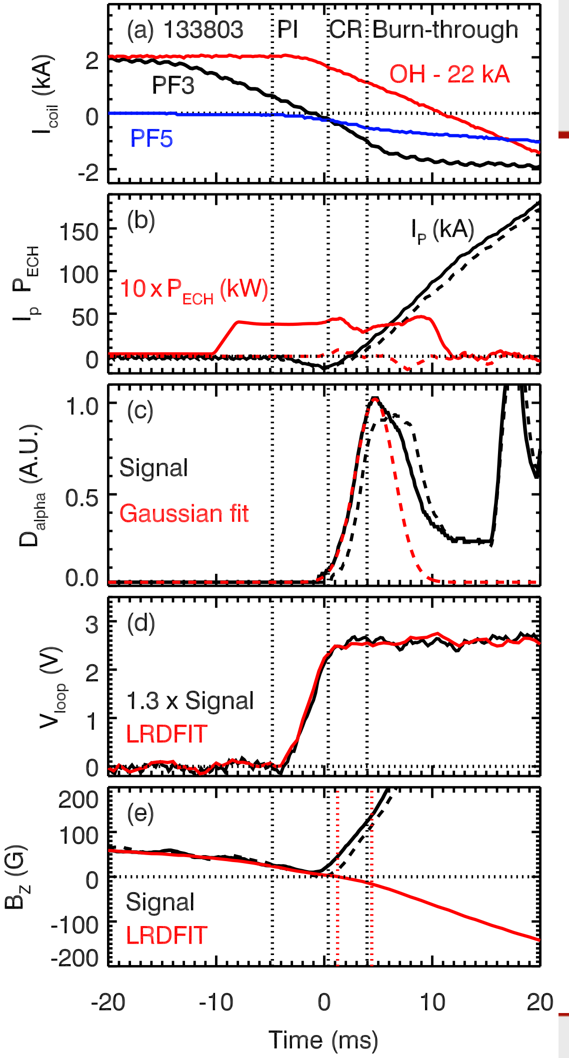
Example of startup on NSTX

- Breakdown divided into two phases
  - Pre-ionization (PI) where increase in density and I_p is not detected
    - Evolution dictated by electron-neutral collisions
  - Current ramp (CR) where I_p increases from zero to about 20 kA
    - Increase detected on magnetics, D_α
    - Evolution influenced by electron-ion collisions
  - Ends near D_α peak when $n_N \sim n_e$
    - Equalization within plasma region (20% of vessel vol.)
    - Metric: B_Z inboard = 125 Gauss

- Small impact of ECH PI when prefill near target of 40 μTorr
  - Dashed lines in (b), (c), (e) from no ECH shot



Goal: Develop a reduced model using vacuum field calculations to determine early evolution of I_p

- Initial breakdown is typically related to the Townsend avalanche theory
  - Exponential increase in charge carriers proportional to the difference in the ionization rate and the loss rate

$$dN_e/dt = N_e\, v_{De}\, (\alpha - 1/L)$$

Where L is the connection length of the open field line

  - Inverse neutral ionization length depends on the neutral pressure (P) and the applied parallel electric field (E)

$$\alpha = A\, P\, exp(-B\, P/E)$$

Where A and B are Townsend coefficients

- Electrons can achieve a constant velocity due to ion-neutral collisions or constantly accelerate (run away) at large E/P along open field lines
  - Lloyd, B. *et al. Nucl. Fusion* **31,** 2031–2053 (1991)

$$\mathbf{v}_{De} = \eta_{br} \frac{E}{P}$$

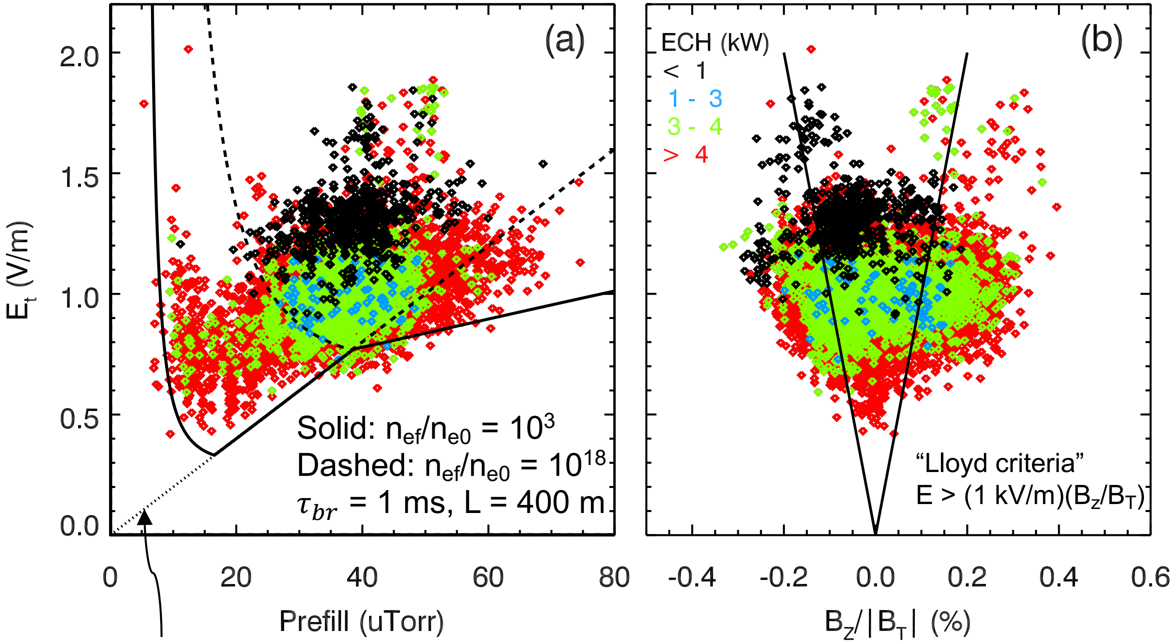
Constant

$$\mathbf{v}_{De} = \left(\frac{eEL}{2m}\right)^{1/2}$$

Run-away when E/P $\gtrsim$ 20 kV/Torr

Database of NSTX discharges indicates minimum L ~ 400 m

- Average fields for 1 ms prior to detection of plasma field
  - E, B fields at IWL + 5 cm
- ECH expands conditions for initiation
  - Points colored by ECH power
    - No ECH (black) all require E above runaway threshold
  - Little change once P_{ECH} > 4 kW
    - Consistent with density saturation observed on other devices



Runaway threshold
E/P > 20 kV/Torr

$$n_{ef}/n_{e0} = exp(\tau_{br}\, v_{De}\, (\alpha - 1/L))$$

Experiments & modeling have shown that breakdown evolution is slower than Townsend process on tokamaks

- Slower evolution can be partially recovered assuming an effective connection length < helical connection length
  - Cross-field transport, 3D fields, neutral-screening, impurities can enhance loss rate
  - Lower bound on L set by α > 1/L
    - NSTX: L_{eff} > 400 m
    - Factor 5 smaller than field line tracing in Hammond, K.C. et al. Nucl. Fusion (2018)

- Recent high-fidelity calculations demonstrated that perpendicular E field from charge separation limits the parallel E field at large density
  - Yoo, M.-G. *et al. Nat. Commun.* **9**, 3523 (2018).

$$E_{self} \sim \sqrt{\frac{n_e\, k\, T_e}{\epsilon_0}}\, \gamma \sin\theta$$

Maximum self-generated parallel field where gamma is a geometry parameter and theta is field line pitch (0 is pure toroidal)

As seen on "PPPL Today" today

Min-Gu Yoo wins "Young Scientist in Plasma Physics" award

Min-Gu Yoo, a postdoctoral fellow in PPPL's Theory Department, received the Korean Physical Society's "Young Scientist in Plasma Physics" award at the society's conference on April 24 in Daejon, South Korea. Yoo has worked at PPPL for the past year after earning a doctorate in nuclear engineering from Seoul National University, from which he graduated with dual bachelor's degrees in physics and nuclear engineering.

He received the Young Scientist award for his graduate research on the process that converts a neutral gas to a plasma in the doughnut-shaped fusion reactor called a tokamak. Yoo was first author of a paper on the subject published online in Nature Communications last August. "I am very happy. It is my honor to get this award," Yoo said.

Yoo's research shows the limitations of previous theories on how a gas becomes ionized. One major theory, the Townsend "avalanche theory," holds that ionization occurs when electrons are accelerated by an electric field, collide with gas molecules and free more electrons, causing an avalanche that allows the gas to become electrically conductive. Yoo found that the the
on the Korea Superconducting Tokamak Advan
developed an alternative theory that the gas b
electric field between charged particles. Yoo c

Yoo now works with Weixing Wang and other p
code aimed at understanding the physics of th

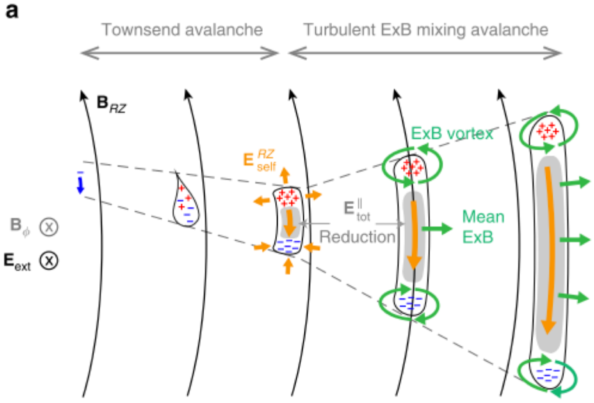
nature COMMUNICATIONS

ARTICLE

DOI: 10.1038/s41467-018-05839-5 OPEN

Evidence of a turbulent ExB mixing avalanche mechanism of gas breakdown in strongly magnetized systems

Min-Gu Yoo[1], Jeongwon Lee[2], Young-Gi Kim[1], Jayhyun Kim[2], Francesco Maviglia[3], Adrianus C.C. Sips[4,5], Hyun-Tae Kim[4], Taik Soo Hahm[1], Yong-Seok Hwang[1], Hae June Lee[6] & Yong-Su Na[1]



Reduced model requires a method for relating time-dependent vacuum field calculations to L_{eff}

- Average E and B fields over a 2D rectangular ROI
  - Use Townsend equations to derive change in I_p normalized to n_e

$$\frac{1}{e\,n_e}\frac{dI_p}{dt} = S_{ROI}\,v_{De}^2\left(A\,P\,exp\left(-B\frac{P}{E_{avg}}\right) - \frac{1}{L_{avg}}\right)cos\,\theta_{avg}$$

S: H_{ROI} x W_{ROI}

v_{De}: Use constant or runaway velocity

- Define the average connection length as a combination of the vertical and radial loss rates
  - Similar to a previous strategy for experiments on VEST
  - A.Ejiri et al., Nucl. Fusion (2018)

$$L_{CZ} = \frac{1}{2}\frac{H_{ROI}}{\langle|B_Z|/|B_T|\rangle} = \frac{\mu_0 I_{TFrod}}{4\,\pi}\frac{H_{ROI}}{\langle R|B_Z|\rangle}$$

$$L_{CR} = \frac{1}{2}\frac{W_{ROI}}{\langle|B_R|/|B_T|\rangle} = \frac{\mu_0 I_{TFrod}}{4\pi}\frac{W_{ROI}}{\langle R|B_R|\rangle}$$

$$L_{avg} = \left[L_{CZ}^{-2} + L_{CR}^{-2}\right]^{-1/2}$$

Assume ROI limited on inner wall, up/down symmetric

The ROI for averaging the vacuum fields changes with time and favors a highly elongated shape

At each time point, find 2D ROI that maximizes …

$$\frac{1}{e\,n_e}\frac{dI_p}{dt} = S_{ROI}\, v_{De}^2 \left(A\, P\, exp\left(-B\frac{P}{E_{avg}}\right) - \frac{1}{L_{avg}} \right) cos\,\theta_{avg}$$

$$L_{CZ} = \frac{\mu_0 I_{TFrod}}{4\,\pi}\frac{H_{ROI}}{\langle R|B_Z|\rangle} \qquad L_{CR} = \frac{\mu_0 I_{TFrod}}{4\pi}\frac{W_{ROI}}{\langle R|B_R|\rangle}$$

$$L_{avg} = \left[L_{CZ}^{-2} + L_{CR}^{-2}\right]^{-1/2}$$

$$\mathbf{v}_{De} = \eta_{br}\frac{E_{avg}}{P} \quad \text{or} \quad \mathbf{v}_{De} = \left(\frac{eE_{avg}L_{avg}}{2m}\right)^{1/2}$$

if E_{avg}/P > 20 kV/Torr

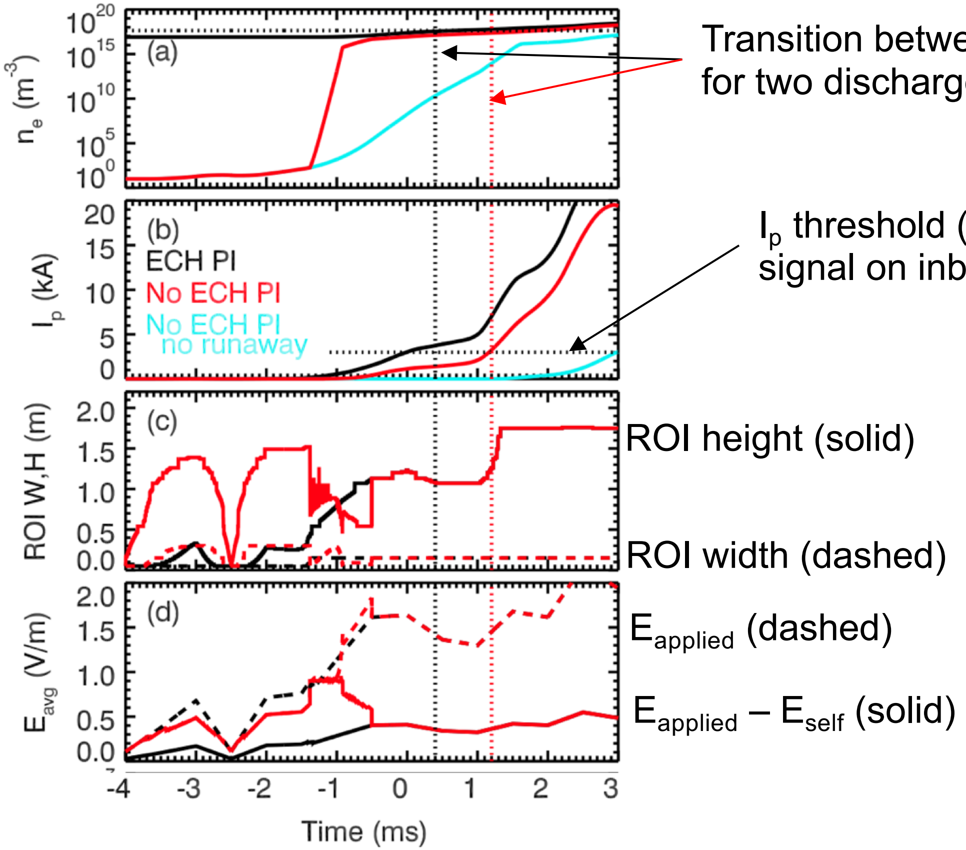
Then use the average quantities within optimum ROI to evolve plasma density to the next time point

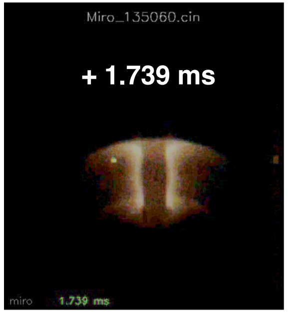
- L_{avg} largest when $L_{CZ} = L_{CR}$
  - Rectangle with κ ~ 2 that aligns with the field curvature
- Chosen ROI is usually more elongated (κ ~ 5)
  - Maximize E and minimize B pitch angle (B_ϕ/B_θ)
  - Favors regions where E_{avg}/P larger than run-away threshold
  - Loss rate dominated by L_{CR}
- Bigger ROIs encompass more charge carriers
  - But, decrease L_{eff}

Reduced model derived from time-dependent vacuum field calculations

Initial $n_e = 10^{17}\ m^{-3}$ (PI)
Initial $n_e = 10\ m^{-3}$ (No PI)
Initial $n_e = 10\ m^{-3}$ and $v_{De} = \eta_{br} \frac{E_{avg}}{P}$ only

- Model matches 1 ms delay between ECH and no ECH cases
  - Runaway regime critical for reproducing small delay
- Important to include E_{self}, but restrict it to be 75% or less of applied E
  - Starts to make a difference when $n_e > 10^{16}\ m^{-3}$
  - ECH case does not enter runaway regime





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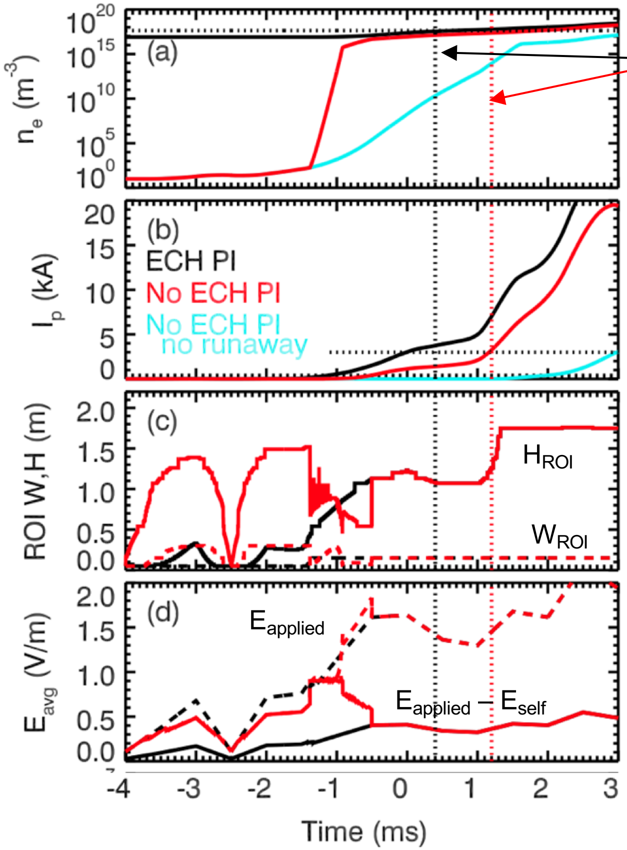
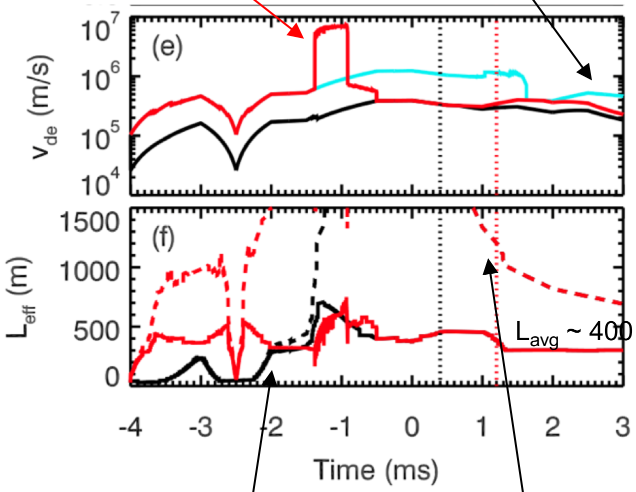


Transition between PI and CR phases for two discharges shown earlier

Brief runaway

Ad-hoc e-i effect added to reduce v_{De} when n_e > 10% of n_N



L_{avg} (solid) << L_{CZ} (dashed)

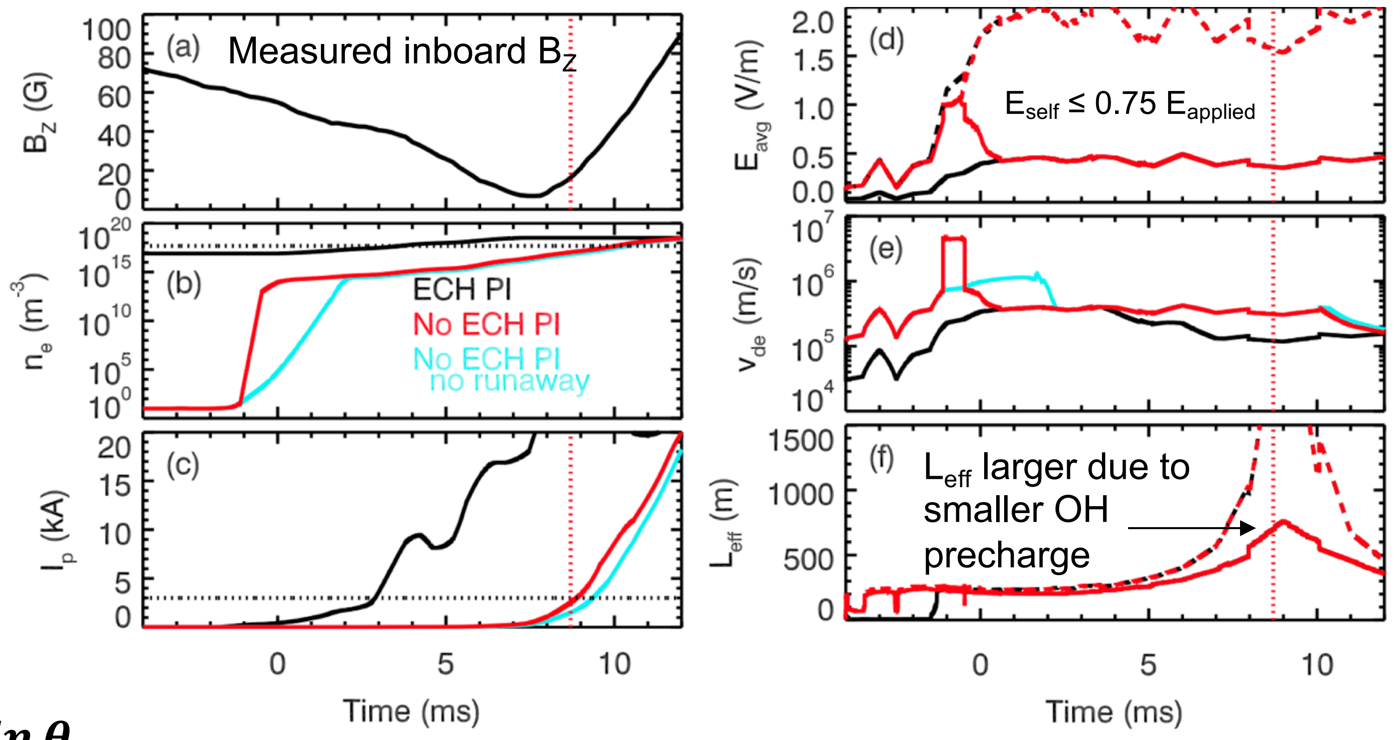
Discharge with long evolution provides additional support that self-produced E fields oppose applied field

- Lower I_{OH} without changing PF current
  - No ECH PI

- Slow evolution reproduced only when using E_{self}
  - Independent of runaway regime
  - E_{self} becomes important at $n_e \sim 10^{13}$ due to larger pitch angle
  - E_{self} limited to 75% of $E_{applied}$

$$E_{self} \sim \sqrt{\frac{n_e\, k\, T_e}{\epsilon_0}}\ \gamma \sin\theta$$

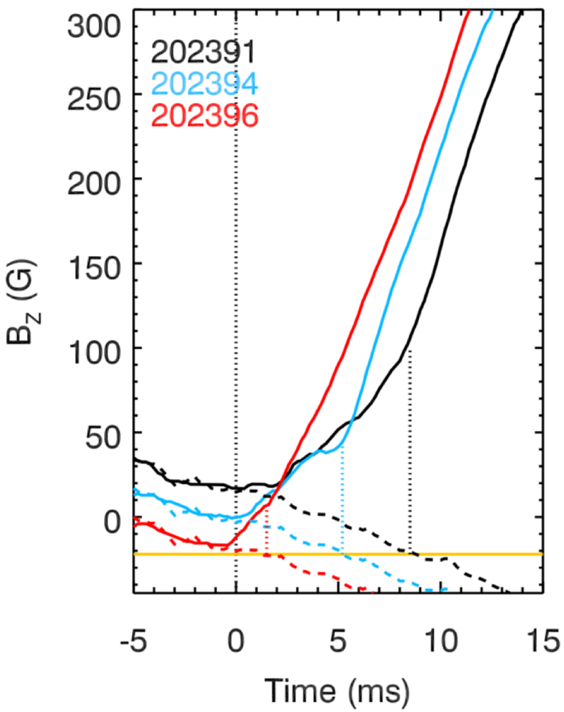
$\gamma = 0.08$



Operations on NSTX-U demonstrated initiation of discharges with large error fields + ECH

- First discharges on NSTX-U scanned PF precharge to move null timing earlier
  - Solid: plasma shot
  - Dashed black: vacuum shot
    - Dashed colored: shifted vacuum shot

- Initiation occurs near t=0 despite large range of B_Z
  - ECH PI facilitates breakdown without a good field null
  - L_{eff} is large enough to sustain an avalanche
    - Rate of initial increase depends on E_{self}
  - Inflection in dI_p/dt occurs when B_Z is sufficiently negative to provide equilibrium field



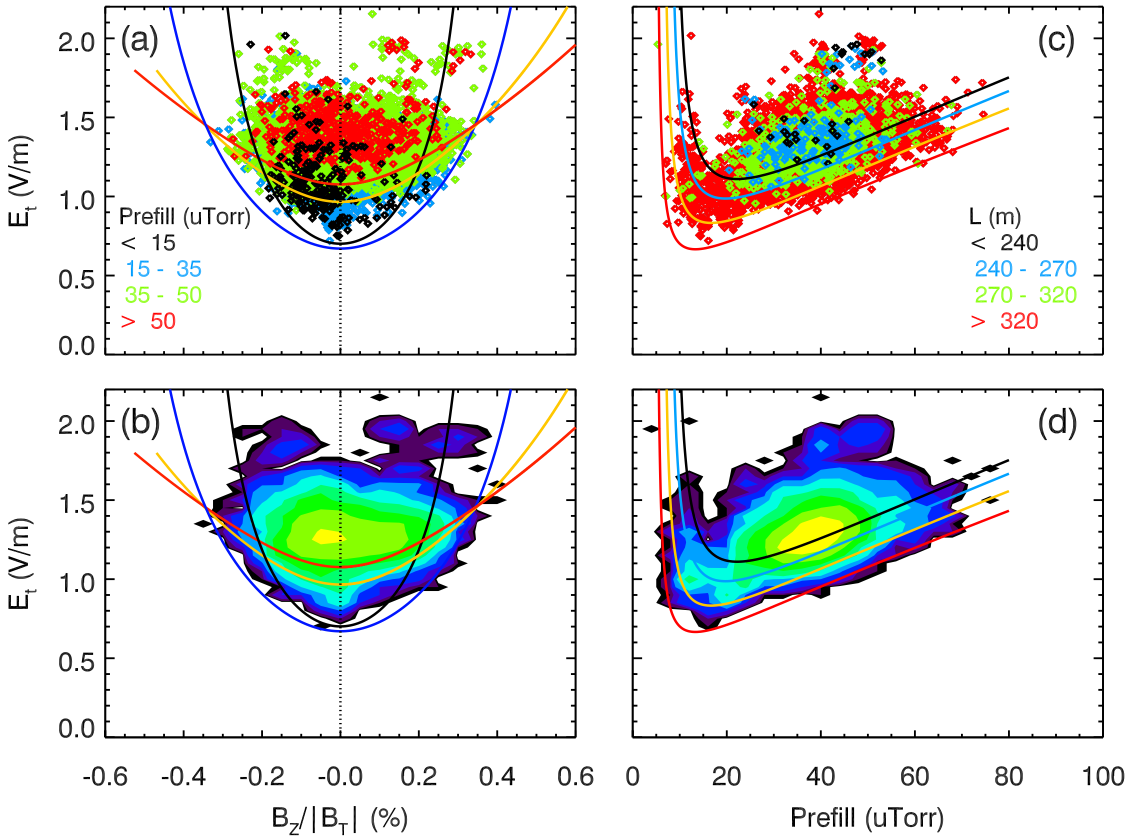
Database consistent with assumptions of reduced model

- Examine 1 ms prior to $B_{Z,plasma}$ = 15 G (I_p ~ 3 kA)
- Contours are 4 x E_{min}
  - Ionization rate > loss rate

$$E_{min}[\text{V/m}] > \frac{1.25 \times 10^4 \, P[\text{Torr}]}{\ln(510 \, P[\text{Torr}] \, L[\text{m}])}$$

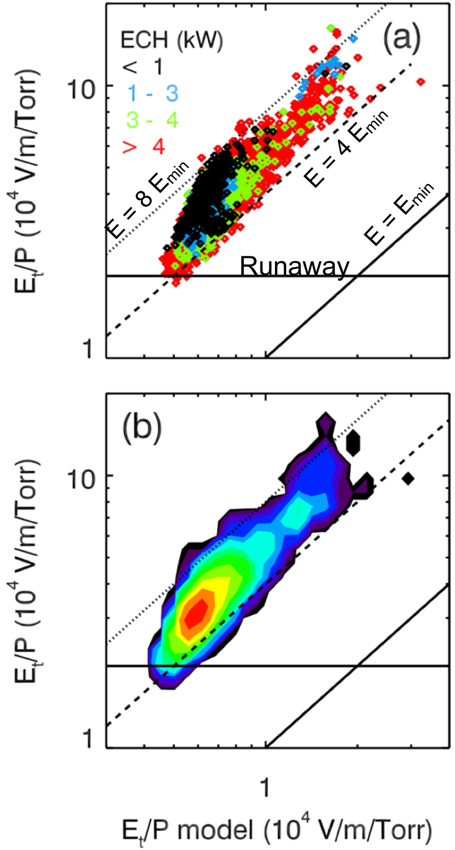
- Use relationship between measured B_Z and L_{eff}
  - H_{ROI} = 1.8 m

$$L_{eff} = \left[\left(\frac{2}{H_{ROI}} \frac{B_{Z,mirnov}}{B_T} \right)^2 + \left(\frac{1}{400 \text{ m}} \right)^2 \right]^{-1/2}$$



Summary of breakdown model

- Use Townsend avalanche equations
  - Assume E_{self} limits E field available to drive electrons along helical field
    - Ad-hoc limitation that $E_{self}/E_{applied} < 0.75$
    - Limits density evolution once density is $10^{10} - 10^{16}$ m^{-3}
  - $E/P > 4 \times E_{min}/P$ (see figures →)
  - Runaway regime leads to rapid initiation without pre-ionization



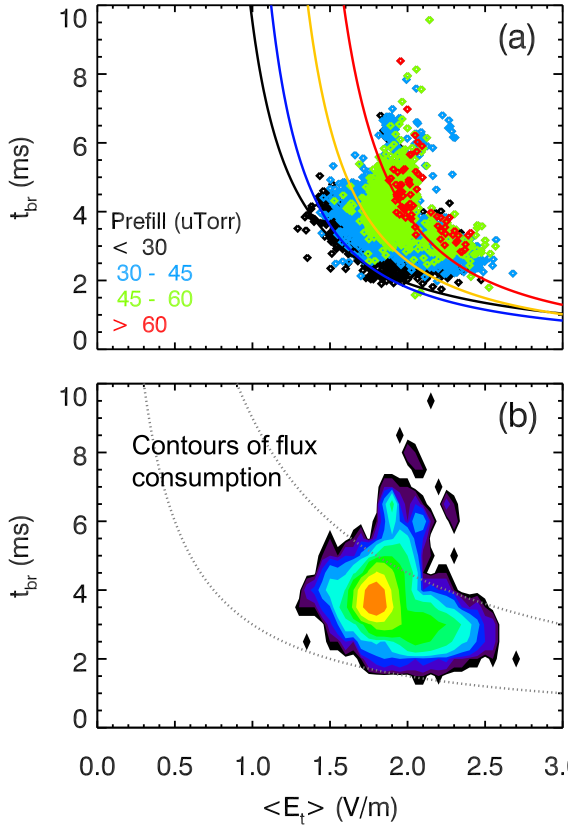
- Time-dependent vacuum field calculations used to compute field quantities (E_{avg}, L_{eff})
  - Average over a 2D rectangular ROI
  - Boundaries chosen to maximize rate dI_p/dt
  - Optimum ROI typically has large elongation
    - Loss rate dictated by radial field (curvature)
    - Height of field null matters a lot more than width

Evolution of I_p in CR breakdown phase depends on electron-ion collisions

- CR phase: $0.01 < n_e/n_{N0} < 0.5$
  - Ionization process clamps T_e ~ 10 eV
  - e-i collisions become more frequent then e-n
  - Field lines transition from open to closed
  - Ends with $B_{Z,plasma}$ ~ 115 G, I_p ~ 20 kA, D_α peak
    - $n_e \sim n_N$ (in plasma region)

- Electron drift velocity set by neoclassical or Spitzer resistivity
  - Lines: Z = 1, T_e = 10 eV, no neoclassical enhancement, $E = E_{ext}/4$, L_{eff} = 400m, n_{ef}/n_{e0} = 30

$$t_{br} = \frac{Z\,(n_{ef}/n_N)\ \ln(n_{ef}/n_{e0})}{\left(1-(r/R)^{1/2}\right)^2}(0.083)\ \frac{P}{E\,(\alpha-1/L)}$$



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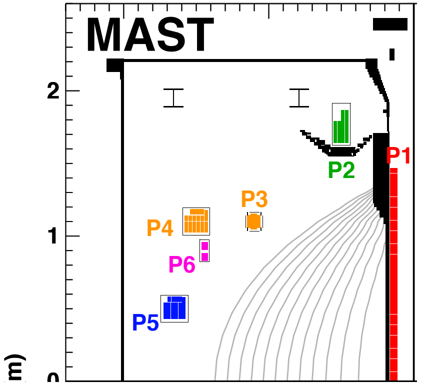
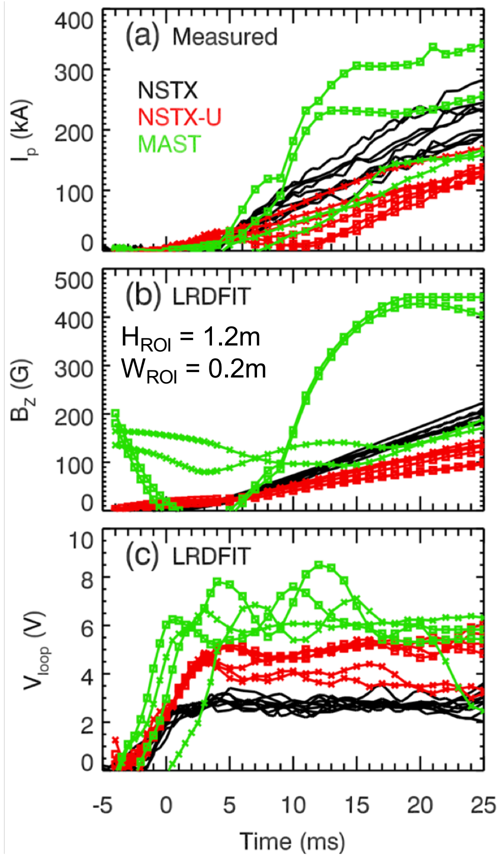
Database of time-dependent vacuum field calculations for developing semi-empirical models for ramp-up

- **NSTX** used a consistent breakdown scenario for a decade of operations
- **NSTX-U** had two primary scenarios
  - 8 kA solenoid precharge (X's)
  - 20 kA solenoid precharge (squares)
- **MAST** had two flavors of scenarios
  - Cap bank on P3s for a rapid flux swing
  - No P3, P2s reduce B_Z (no field null)

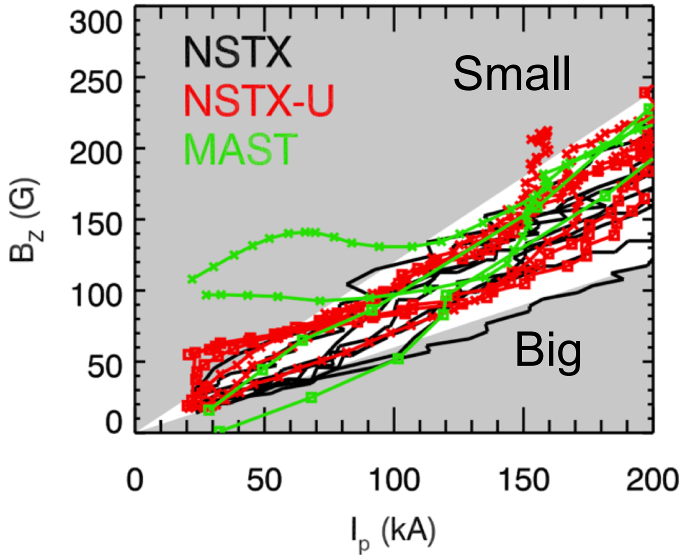




Semi-empirical model developed for equilibrium field

- I_p and B_Z must increase self-consistently
  - Startup scenarios use feed-forward currents

- B_Z/I_p similar for all three devices
  - Low-A equilibrium have a weak dependence on R due to scaling of elongation



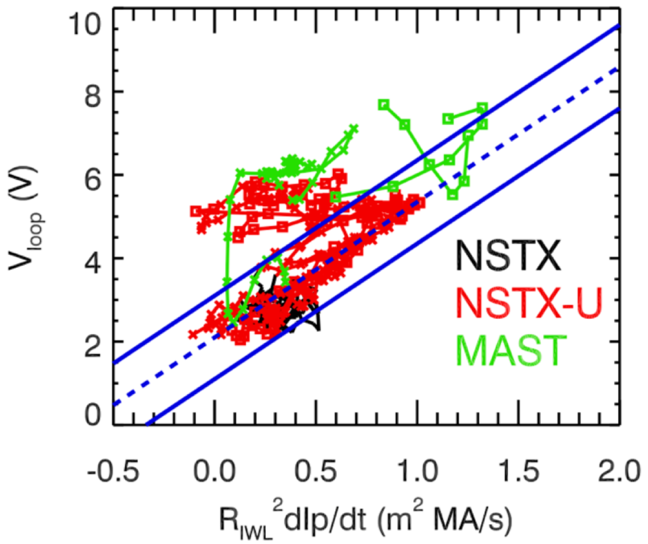
B_Z/I_P (G/kA) = 0.9 ± 0.3

Sufficient V_{loop} must be provided for desired I_p ramp rate

- Min V_{loop} scales linearly with inductive voltage (dI_p/dt)
- Best model has largest J near IWL
  - Force-free equilibrium where J ~ B ~ B_T
  - Inductance of a solenoid scales as R^2/h
    - Height of solenoid = 1.2 m
  - Resistive voltage (V_r) constant at 2.1 V

$$V_s = 3.9\frac{R^2}{h}\frac{dI_p}{dt} + V_r$$

- Consistent with scaling of flux consumption during ramp-up on STs
  - Favors bigger plasmas (smaller B_z/I_p)



$$\Delta\psi_s \sim 0.4(R/a)\mu_0 I_p R$$

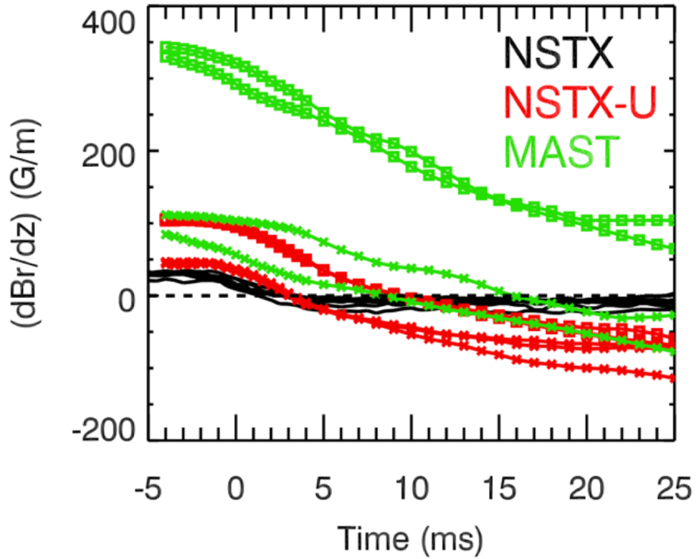
Gryaznevich, M., Plasma formation in START and MAST spherical tokamaks. *Nucl. Fusion* **46**, (2006).

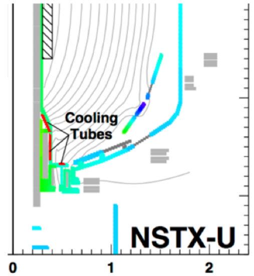
Vertical stability is an important aspect of the ramp-up scenario

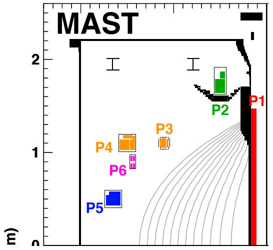
- Poloidal field must have sufficient curvature to maintain passive vertical stability
- Estimated by considering change in BR from a small shift in plasma boundary

$$\frac{1}{S}\oint \frac{dB_R}{dZ}\cdot \hat{R}\, dS > 0$$

  - Assume rectangular 2D boundary
  - Magnitude is sensitive to choice of boundary, but general trend is less sensitive
- Some scenarios challenged vertical stability
  - NSTX-U with large V_{loop}: induced large currents in copper cooling tubes
  - MAST with PF2: hard to get a complete null







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NSTX-U: Switching cooling tube material from copper to Inconel enables larger dI_p/dt

Solenoid precharge is 24 kA

$B_{T0} = 0.65$

dI_p/dt = 10 MA/s

2016 wall model

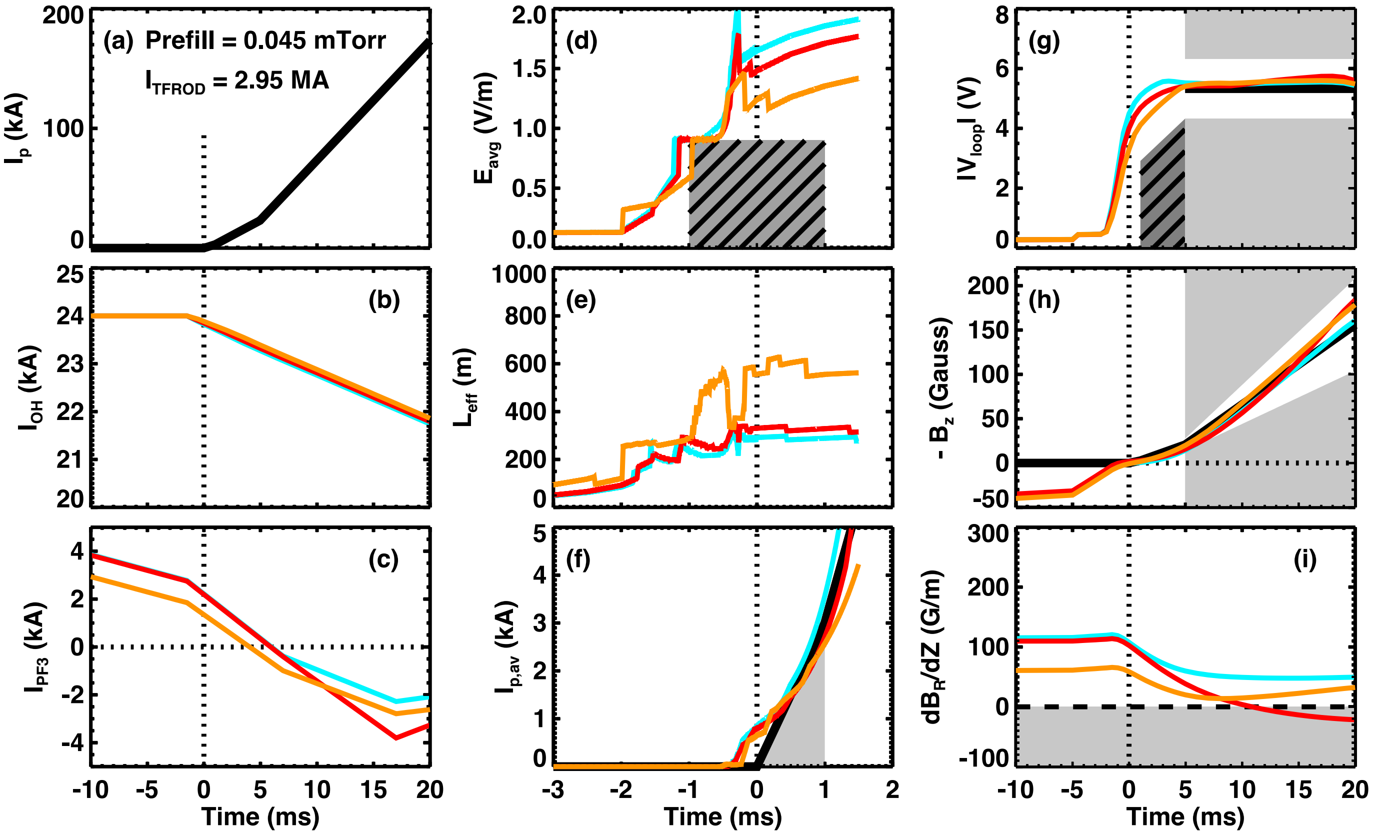
Difficult to get passive vertical stability

Switch cooling tubes to Inconel

Now have some headroom in vertical stability

Then add PF2

Reduce early V_{loop}



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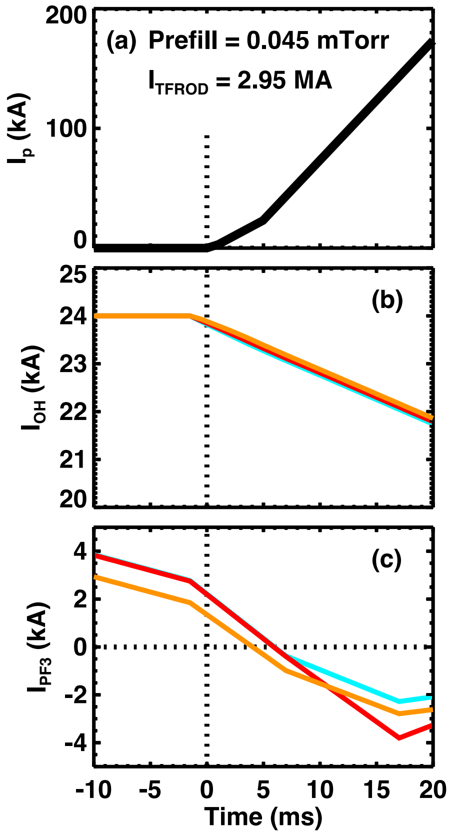


Input parameters:
Prefill, TF rod current and target dI_p/dt

Assume I_p = 20 kA at end of breakdown phase

Length of breakdown phase set by assumption on minimum V_{loop}

Solenoid, PF3 and PF2 currents are input into vacuum field model (LRDFIT)

NSTX-U: Switching cooling tube material from copper to Inconel enables larger dI_p/dt

Solenoid precharge is 24 kA

B_{T0} = 0.65

dI_p/dt = 10 MA/s

2016 wall model

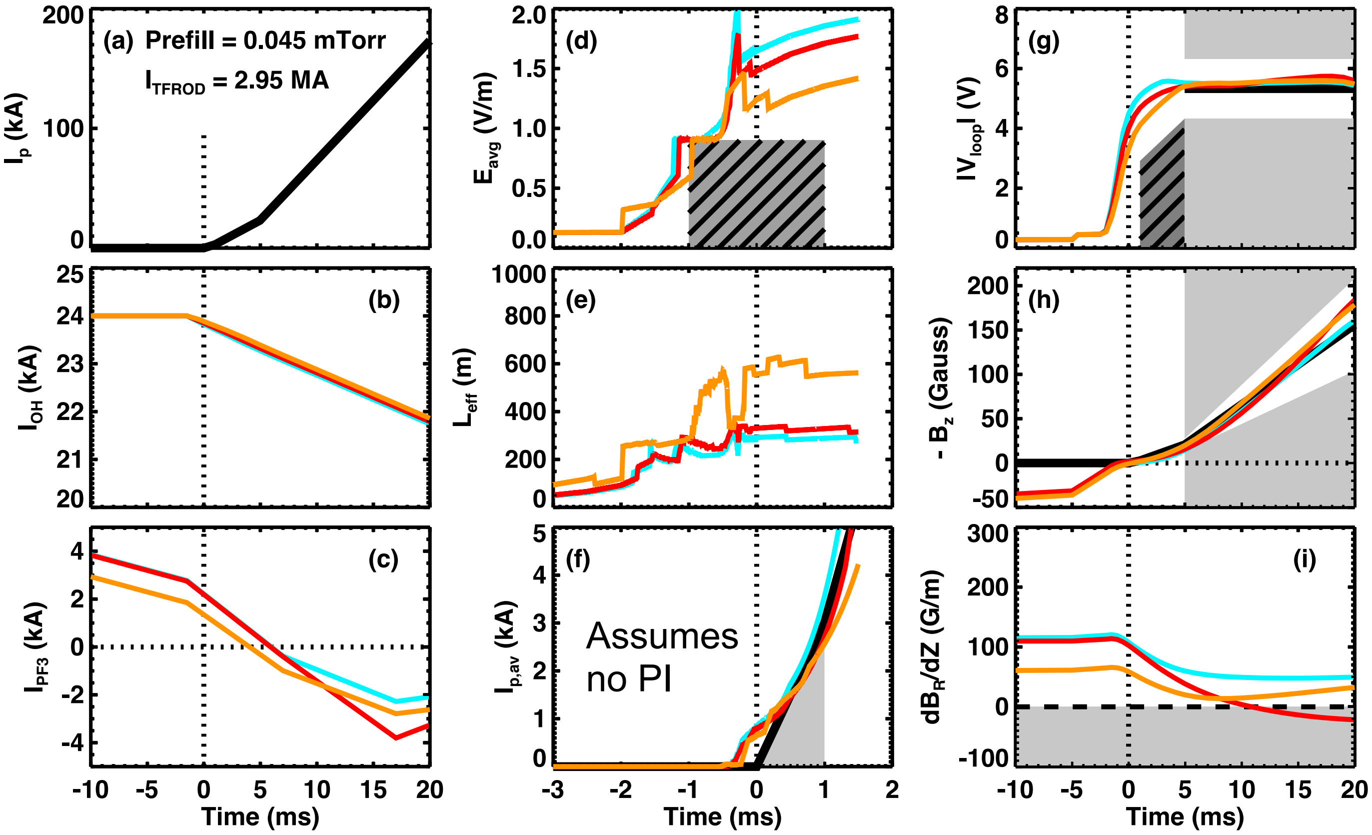
Difficult to get passive vertical stability

Switch cooling tubes to Inconel

Now have some headroom in vertical stability

Then add PF2

Reduce early V_{loop}



MAST-U scenarios: head room on optimizing null, but operate near voltage limits on many coils

Using first operation limits

Scenario using 6 D-coil sets

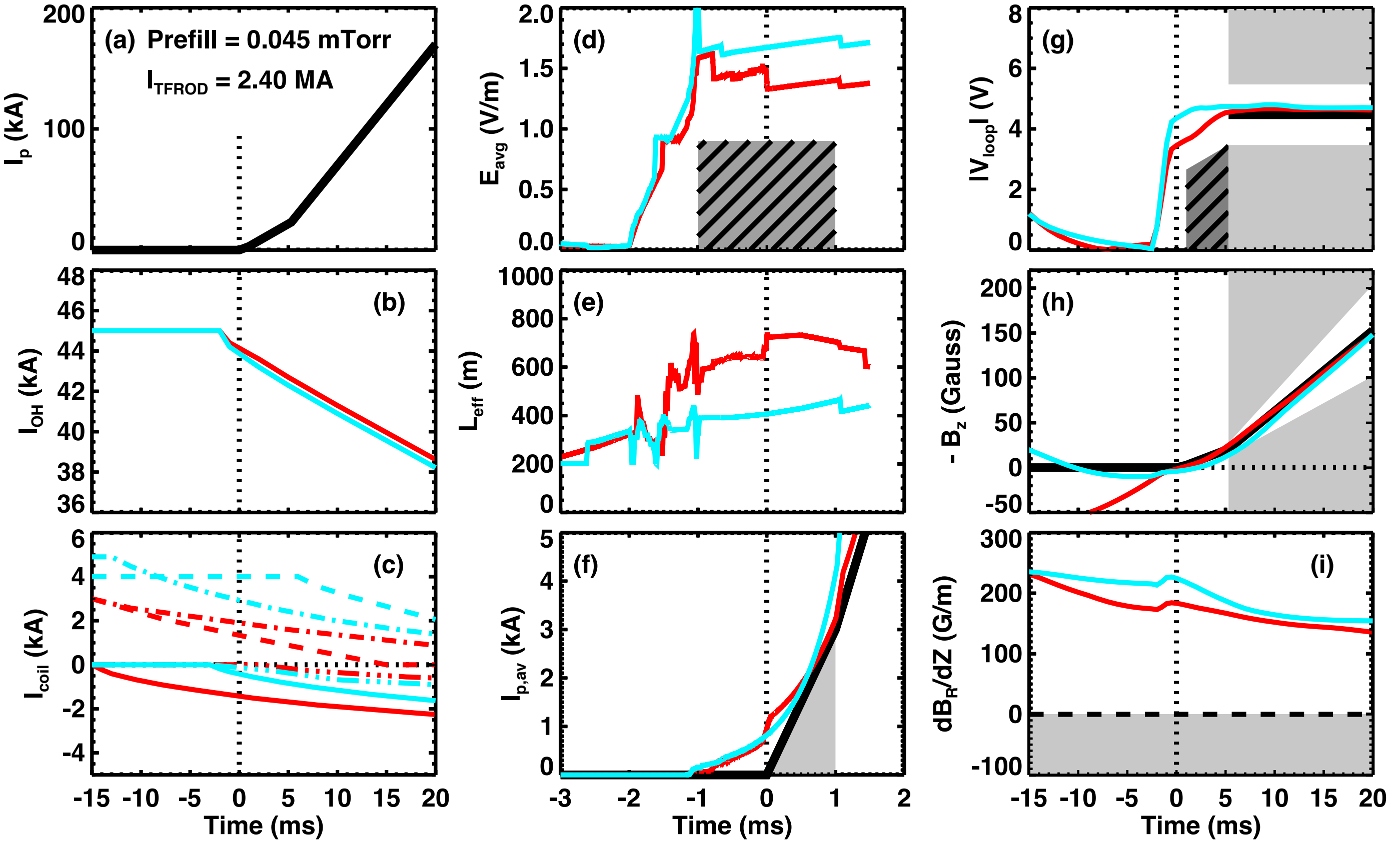
Headroom in all parameters

Scenario minimizes I^2t heating of D-coils

Scenario using 3 D-coil sets

At I,V limits on most PF coils

Hard to exclude null prior to breakdown



Summary

- A reduced model using time-dependent vacuum field calculations has been developed for NSTX-U and MAST-U
  - Provides fast simulation framework for designing feed-forward currents and understanding technical limitations to the scenarios
  - NSTX-U I_p ramp rate limited by vertical stability from induced currents in polar region
  - MAST-U I_p ramp rate limited by available voltage on PF supplies
- Reduced model for breakdown in good agreement with NSTX database
  - Townsend model with two elements not typically included:
    - Runaway regime accelerates the breakdown with no PI and
    - Drift velocity of electrons reduced by a self-produced E field
  - Breakdown region is close to IWL where loss rate is dictated by the field curvature
- Semi-empirical equilibrium and stability constraints on ramp-up developed using shared database of NSTX, NSTX-U and MAST results

Future work

- Database and detailed analysis of select discharges support ITPA efforts toward developing startup models
- Couple model into Simulink control framework
  - Plasma equilibrium and stability could be directly solved, at larger computational expense
- Pursue further experiments and high-fidelity modeling to challenge and improve reduced model