Predictive Modeling of Halo Currents in Disruptions and Disruption Mitigation Scenarios

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ASTRACT

Predictive Modeling of Halo Currents in Disruptions and Disruption Mitigation Scenarios, D.A. Humphreys, A.G. Kellman, *General Atomics*, D.G. Whyte, *UCSD*, S. Ishida, G. Kurita, *JAERI*.

The success of recent models of disruption halo currents [1] and post-thermal quench radiation power balance [2] offer the hope of accurately predicting halo currents expected in disruptions mitigated by massive gas injection. Such an ability to reliably predict halo currents in rapid shutdown scenarios is of great importance in the design of next-generation tokamaks. The method is illustrated in application of an extensively validated semi-analytic model to prediction of halo currents expected in unmitigated and mitigated disruptions in the JT-60SU device design and the DIII-D tokamak experiment. Implications of specific halo current predictions and the general method itself are discussed.

[1] Humphreys, D.A., Whyte, D.G., "Classical Resistivity in a Post-Thermal Quench Disrupting Plasma," Phys. of Plasmas **7 (**2000) 4057
[2] Whyte, D.G., Humphreys, D.A., "Measurement of Plasma Electron Temperature and Effective Charge During Tokamak Disruption", Phys. of Plasmas **7** (2000) 4052

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OVERVIEW

- Models of halo current evolution and radiation energy balance during disruptions now allow accurate prediction of halo currents when mitigated by massive impurity injection.
  - → Ability to accurately predict mitigated levels of disruption halo currents allows design of next-generation tokamaks for realistic disruption loads;
  - → Method illustrated with JT-60SU design/analysis;

- Halo model accurately reproduces core and halo current evolution given:
  - → Pre-disruption equilibrium and machine geometry;
  - → Post-thermal quench core and halo resistivity (i.e. T_e and Z_{eff});

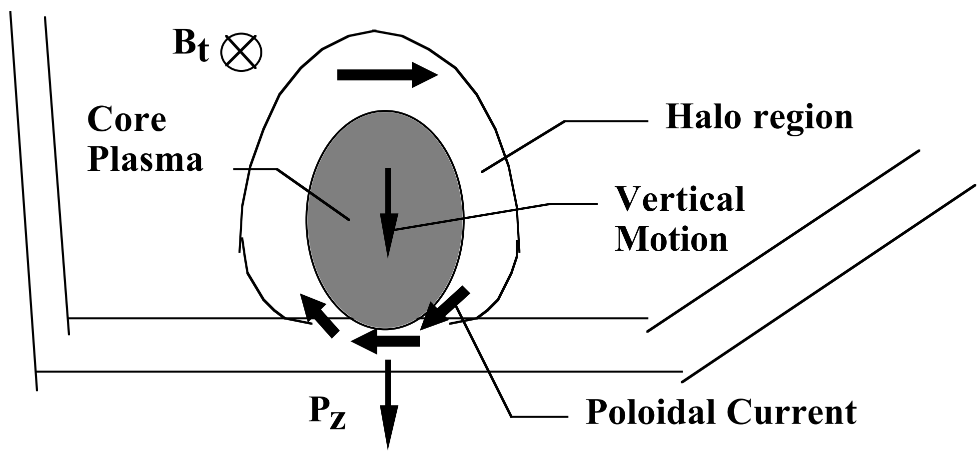
- KPRAD model of energy balance including detailed imurity line radiation data and ohmic input provides accurate prediction of post-thermal quench core and halo resistivity for:
  - → Massive injection of impurities to quench plasma;
  - → Appropriate for massive gas or liquid jet disruption mitigation scenarios;
  - → Massive He gas puff mitigation approach demonstrated on DIII-D;

Poloidal Halo Currents Driven During Disruption Can Produce Large Electromagnetic Forces on In-Vessel Components and First Wall

- Force-free halo current includes:
  - → Both toroidal and poloidal components;
  - → Both axisymmetric (n=0) and nonaxisymmetric (n≠0) components.

- Stress normal to first wall (arising from poloidal halo currents flowing in first wall):

$$P_z \cong \frac{I_{h(pol)} B_t}{\mathbf{2}\pi R} \quad \left[\frac{N}{m^{\mathbf{2}}}\right]$$

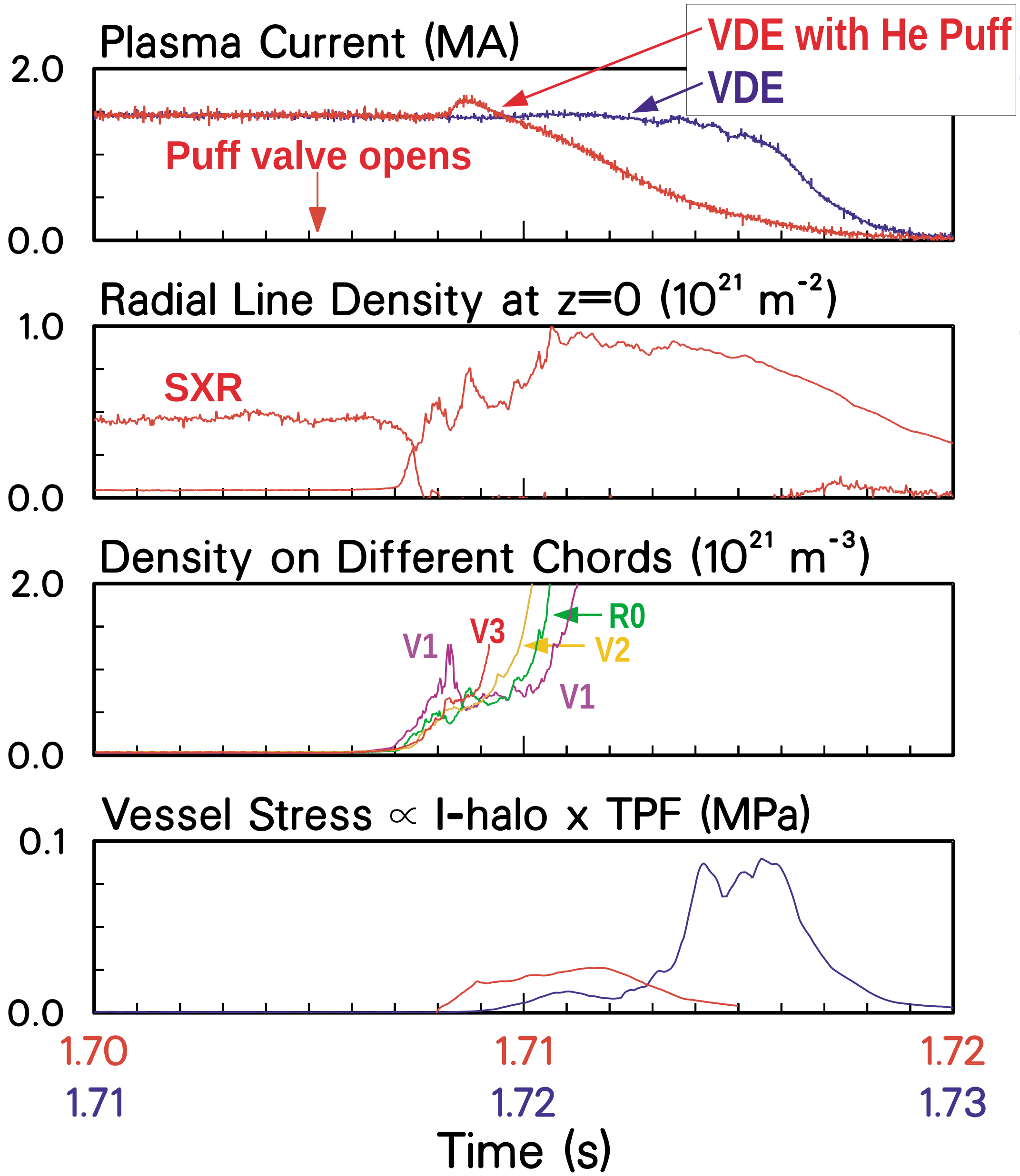


- Design of high-performance tokamaks requires assessment of expected disruption halo current forces:
  - → Predictive capability required…

Disruption Loads Can Be Significantly Mitigated by Massive Injection of Impurities

- (Pete's vugraf)

Massive Helium Gas Puff Reduces Halo Currents and Avoids Runaway Electron Generation



Total of 3400 T-l injected in ~10 ms from reservoir of Helium at ~ 1000 PSI

Current quench start ~3 ms after Helium Puff

Thermal quench and large density rise start ~ 2.2 ms after puff valve opens

No evidence of runaway electrons

Rapid penetration of helium to plasma core results in density increasing linearly all across plasma to $1 \times 10^{21} m^{-3}$

Force on vessel due to halo current and toroidal peaking factor of halo current reduced

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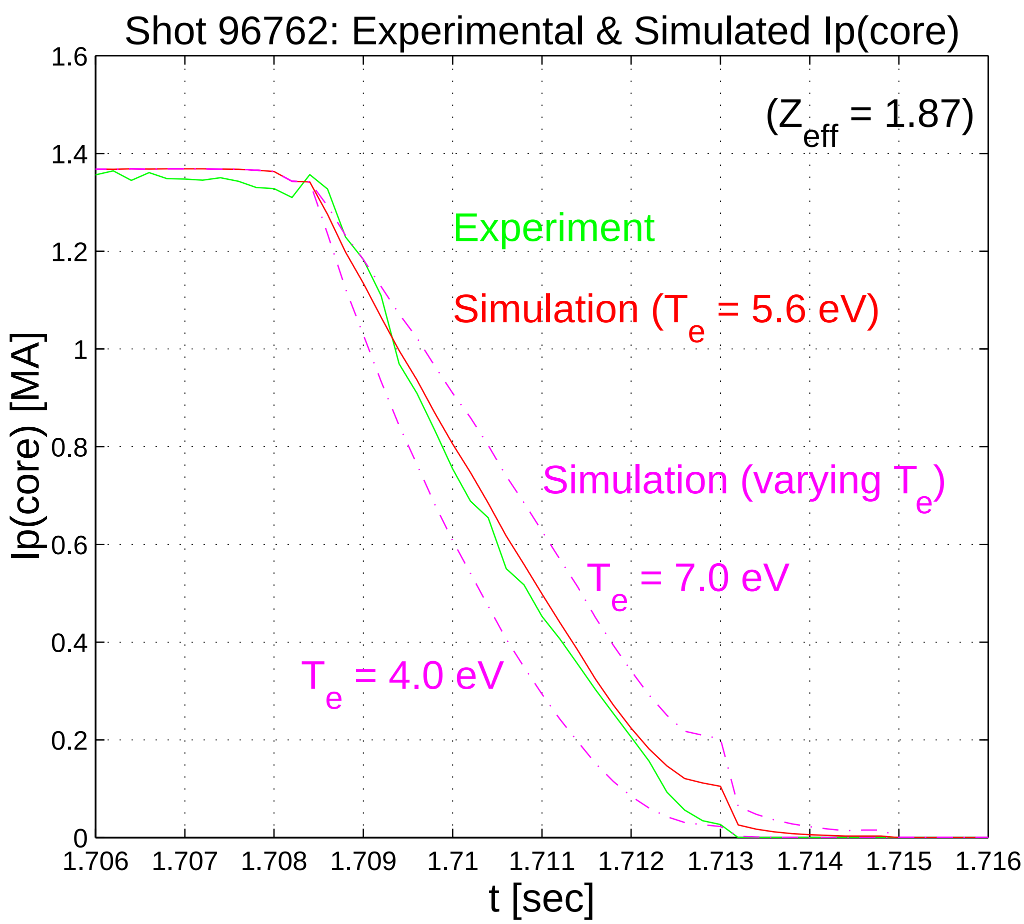
Core/Halo Models Accurately Predict Currents Given Equilibrium/Machine Geometry & Actual Core/Halo Resistivities

- Simulation of DIII-D massive He gas puff experiment;
- Core and halo plasma current calculations assume fixed Spitzer resistivity throughout; include resistive dissipation, core→halo induction; effect of dynamically varying plasma shape, convection.
- Refs: Whyte, Humphreys; Phys. Pl. **7** (2000) 4052
  Humphreys, Whyte; Phys. Pl. **7** (2000) 4057

Circuit Model Accurately Reproduces Decay of Core Current Using Measured T_e and Z_{eff}

- Measured core T_e = 5.6 ± 0.4 eV and Z_{eff} =1.87 ± 0.08



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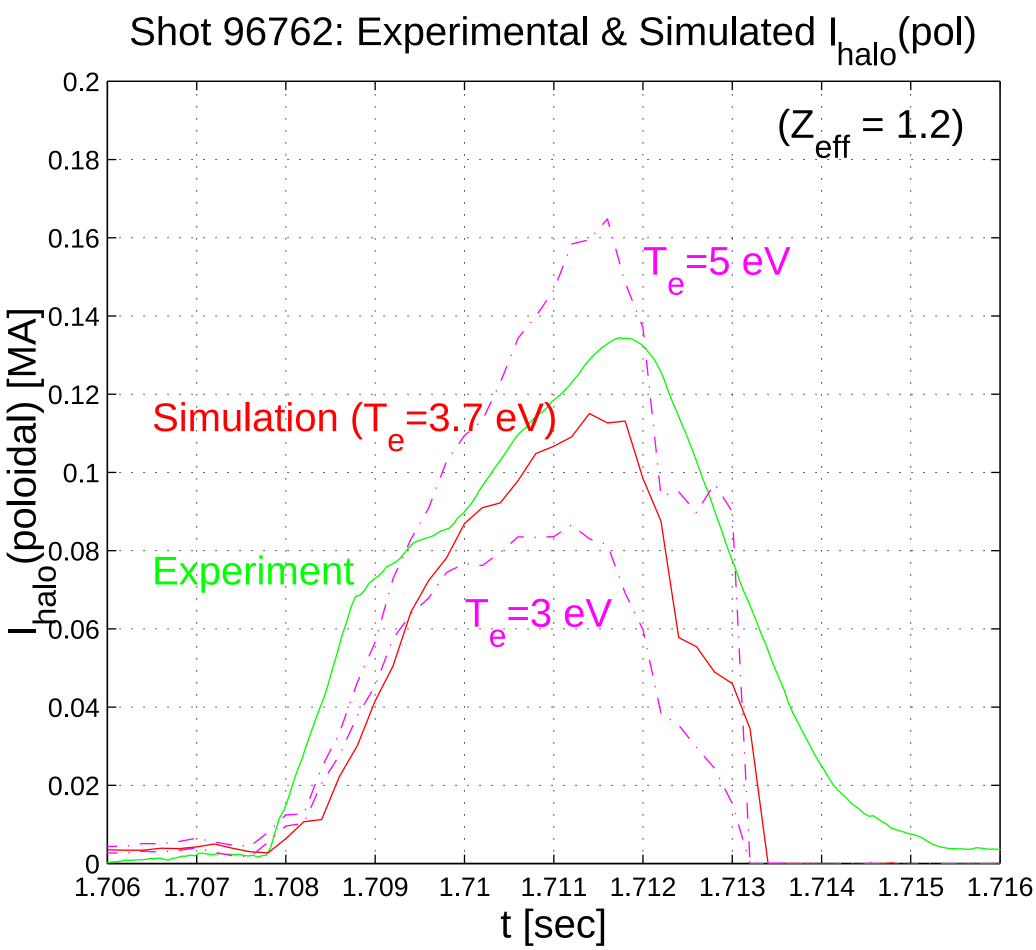
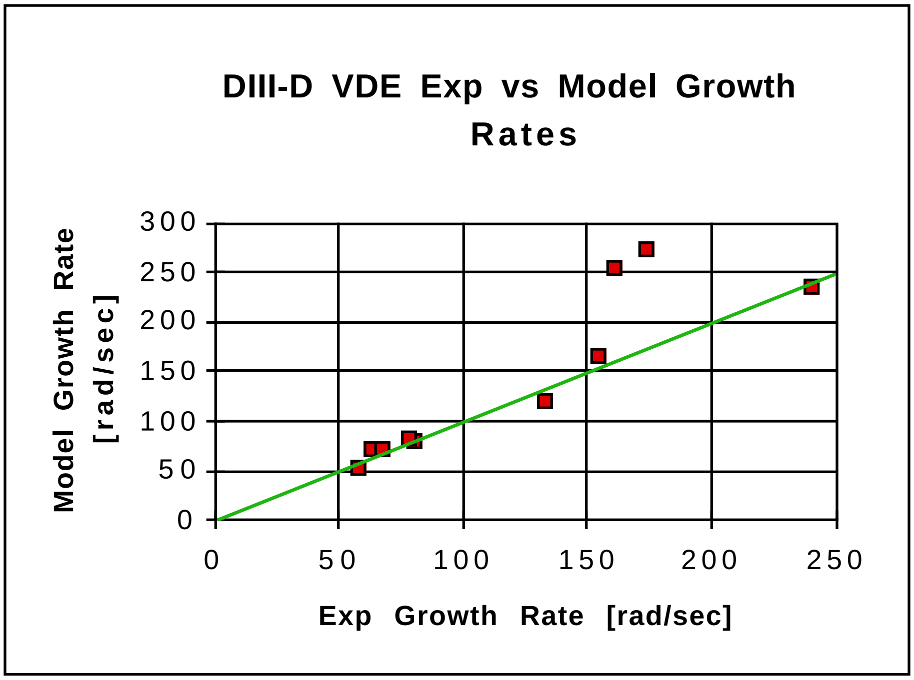
Halo Current Model Accurately Reproduces Halo Evolution Using Measured T_e , Z_{eff}

- Measured halo $T_e = 3.7 \pm 0.2$ eV and $Z_{eff} = 1.2 \pm 0.15$



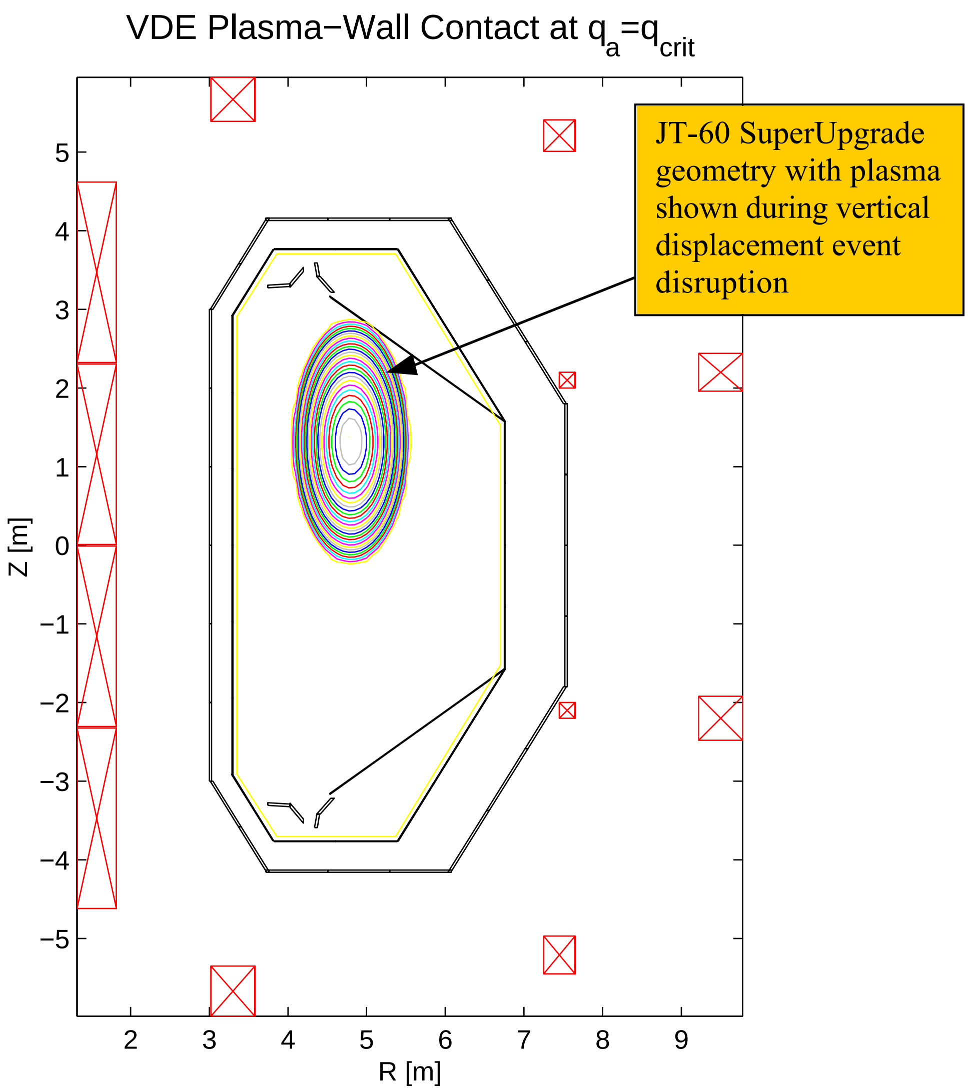
Equilibrium+Machine Geometry Allow Determination of Plasma Vertical Growth Rate

- Growth rate, and thus motion due to vertical instability, is accurately predictable from equilibrium + geometry:



Electromagnetic Model of Machine Geometry Allows Determination of Detailed Plasma Vertical Motion History During Disruption

- Illustration of simulated vertical displacement event disruption for JT-60SU device design:



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Halo Width History Inferred from Equilibrium+Machine Geometry

- (Discuss geometry/empirical observation, algorithm for determination, show JT60SU geom during VDE…)

Mitigation Scenarios Allow Predictive Calculation of Post-Thermal Quench T_e , Z_{eff}

- (Excerpts from Dennis Whyte's PowerPoint presentation)

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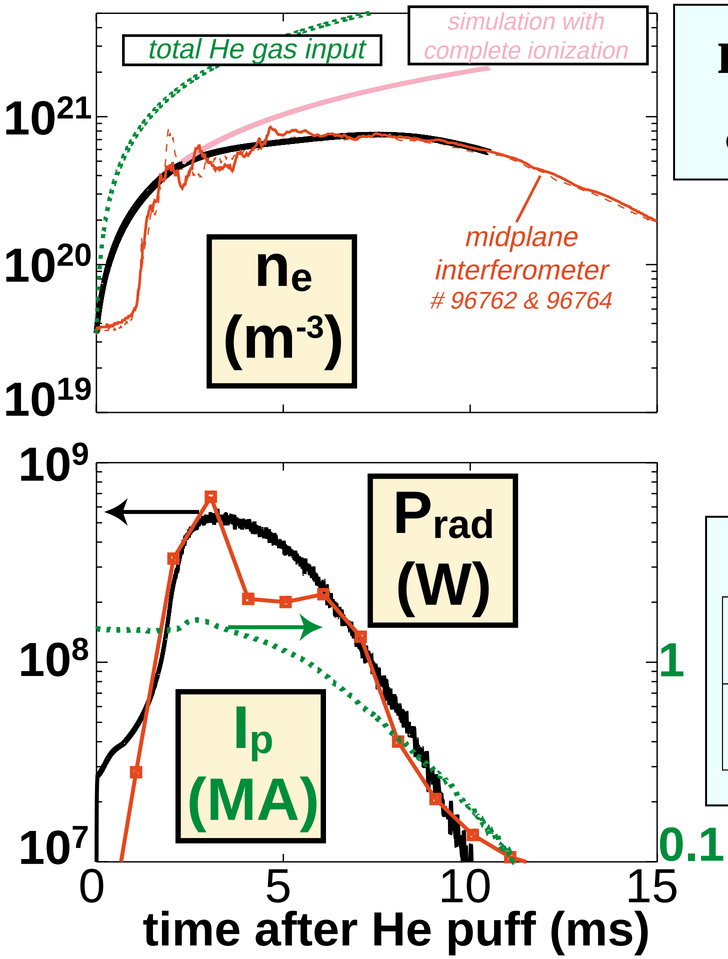
KPRAD predicts all the important features of the massive He gas puff on DIII-D

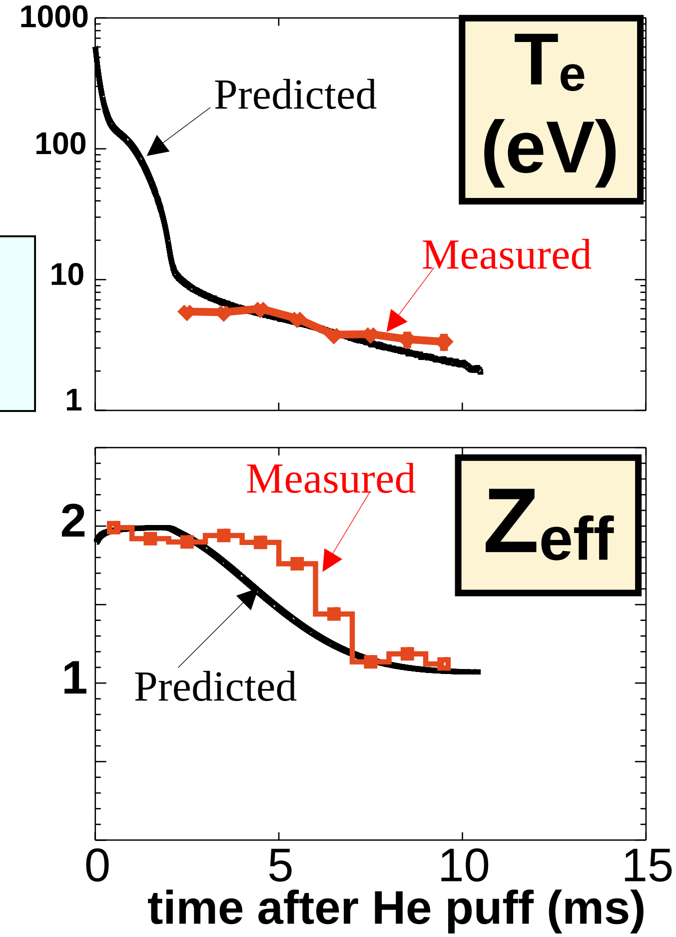


n_e saturation at ~ 10^{21} m^{-3}

T_e Z_{eff} & η agree

Energy radiated

KPRAD	Measured
2.15 MJ	1.95 MJ



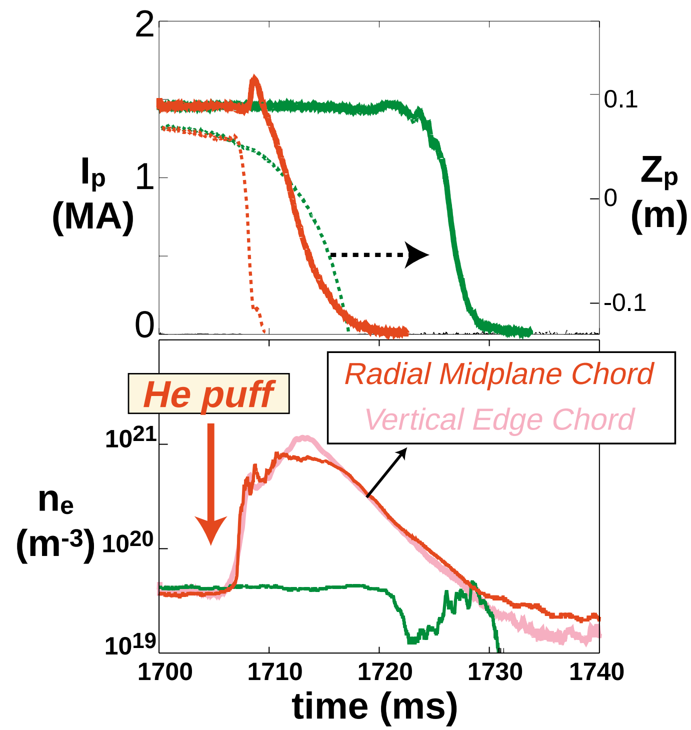
Cooling produces no seed runaways.

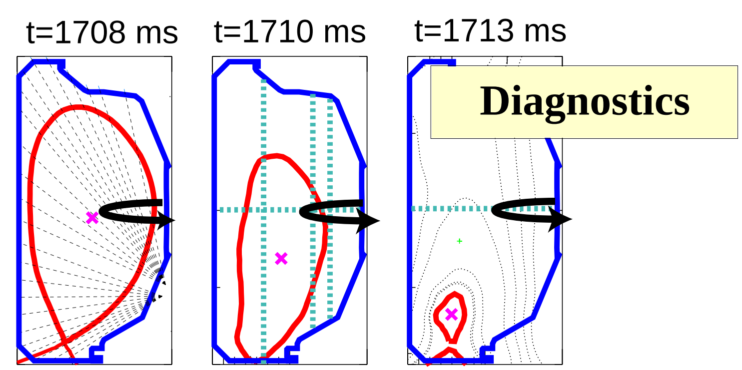
Massive Helium gas puff increases n_e uniformly to ~10^{21} and mitigates a DIII-D triggered VDE

	No puff	He puff
Gas injection	-----	10^{23} in ~10 ms
Peak I_{halo} (MA)	0.30	0.13
TPF	~2	1.2
Vessel movement (mm)	1.5 mm	< 0.9 mm
W_{floor} (MJ)	0.73	< 0.05
W_{rad} (MJ)	1.38	1.95

Reduced I_{halo}

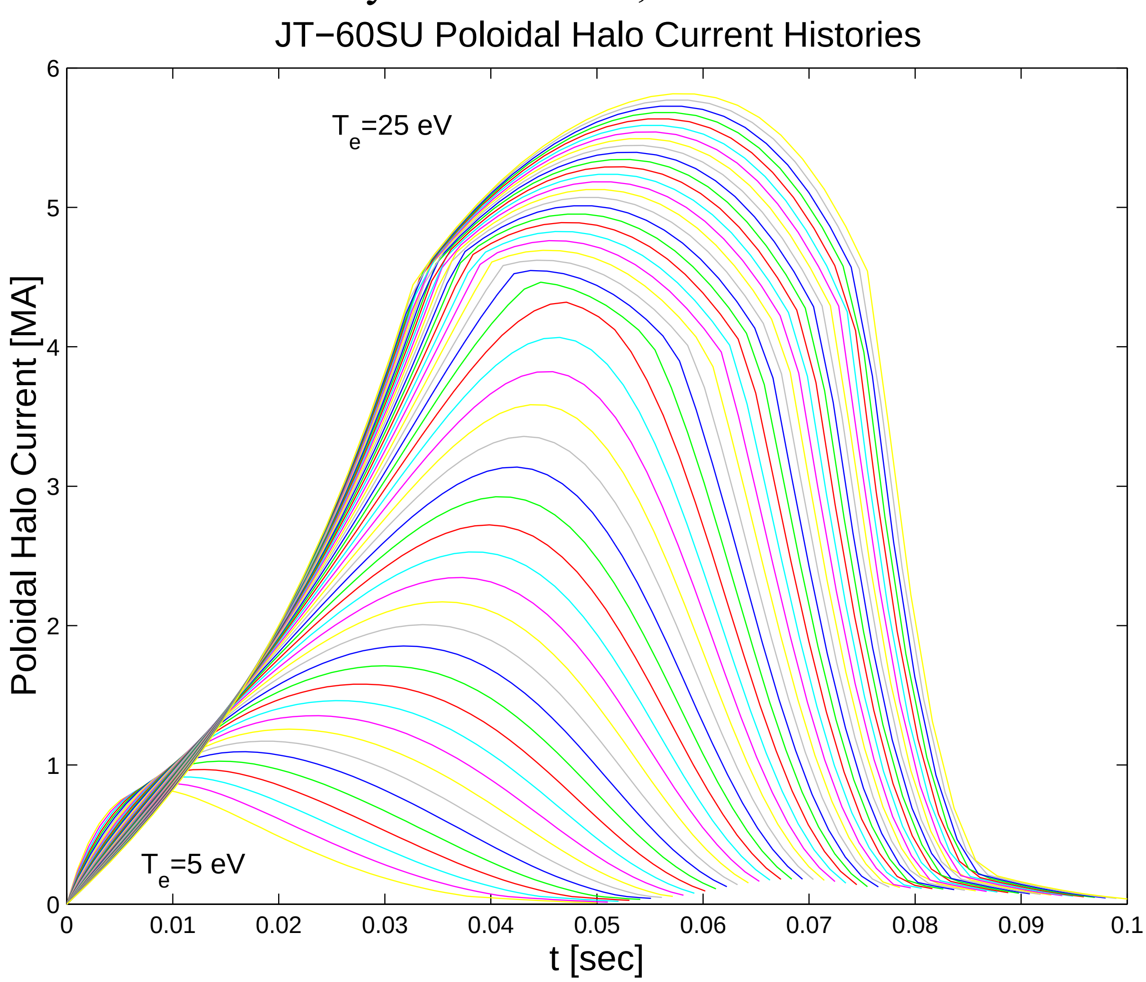
Radiation mitigation of divertor heat flux





Halo Current Model Allows Rapid Calculation of Scoping Studies to Determine Range of Expected Loads: JT-60SU Design Study

- Core and halo temperatures varied from $T_e = 5 \rightarrow 25$ eV;
- Growth rate fixed at $\gamma_Z = 50$ rad/sec;
- Time histories show result for no MHD triggering:
  - ⇒ Triggering of MHD at q_e=1 results in saturation of peak halo current for $T_e > 17$ eV;
  - ⇒ Triggered MHD stops $I_{h(pol)}$ evolution at discontinuity in derivative;



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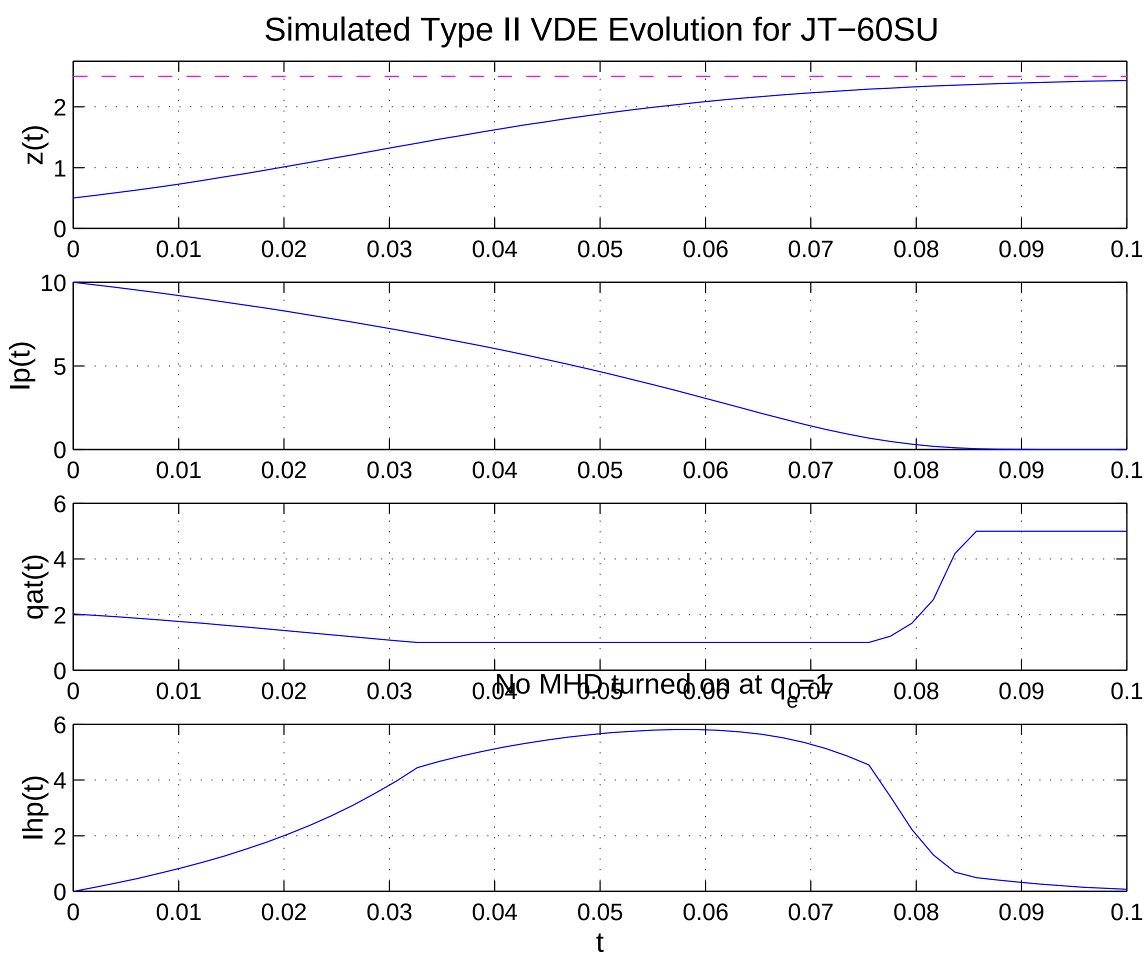
JT-60SU Disruption Simulations Show Key Features of VDE Dynamics: Plasma Vertical Motion, Core Current Decay, Halo Current Evolution

Largest Halo Current Case in Scoping Study:

- Core and halo temperatures T_e = 25 eV (Z_{eff}=1.5);
- Vertical growth rate γ_z=50 rad/sec;

⇒ High vertical growth rate relative to core current decay rate causes q_e to drop to unity, producing large halo current (“Type II VDE”):



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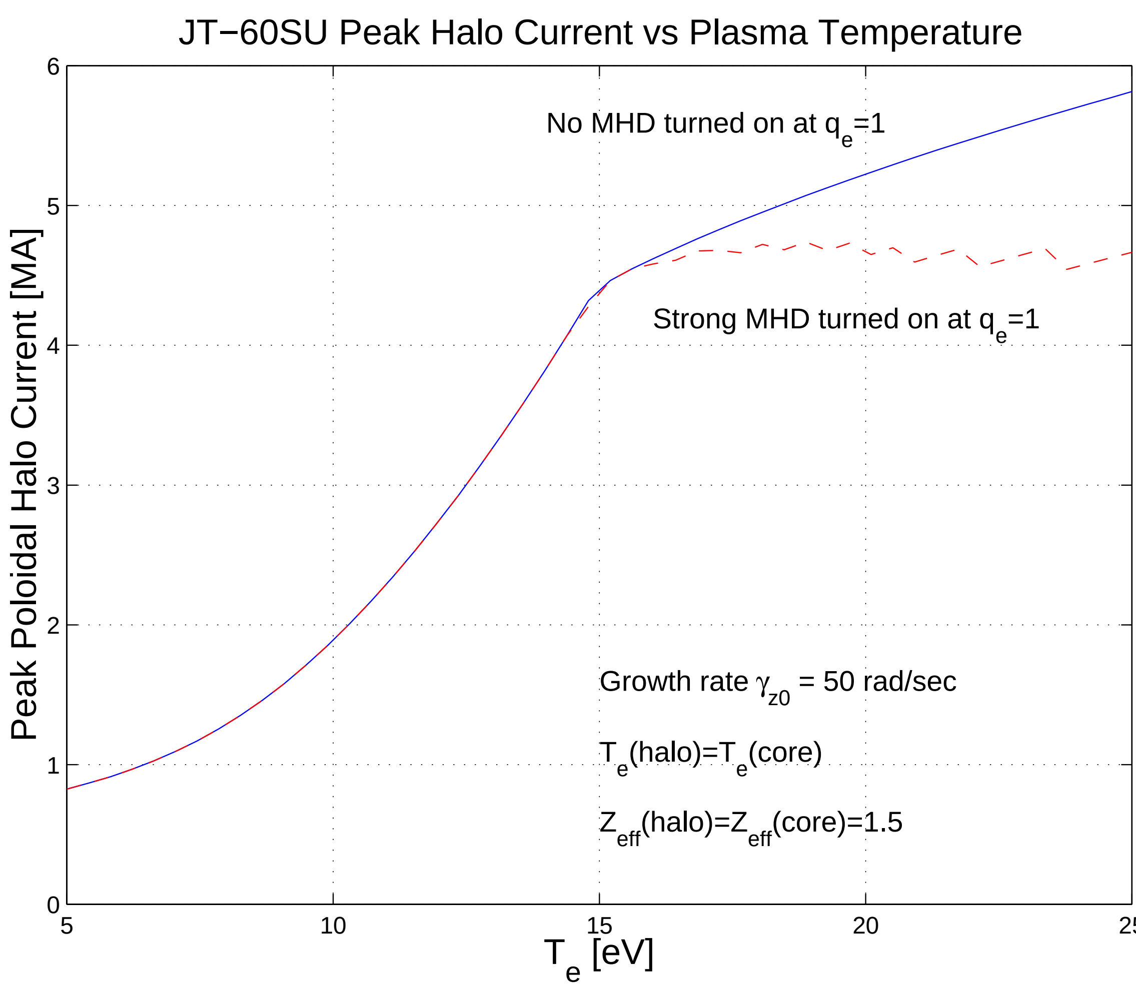
Simulations of JT-60SU VDE Using γ_z=50 rad/sec Show Maximum Poloidal Halo Current I_h ~ 4.7 MA [I_p=10 MA]

- Core and halo temperatures varied from T_e = 5→25 eV:

- Effect of strong MHD modes destabilized at q_e=1 (observed in DIII-D and Alcator C-MOD) produces maximum peak halo current I_h(peak) ~ 4.7 MA



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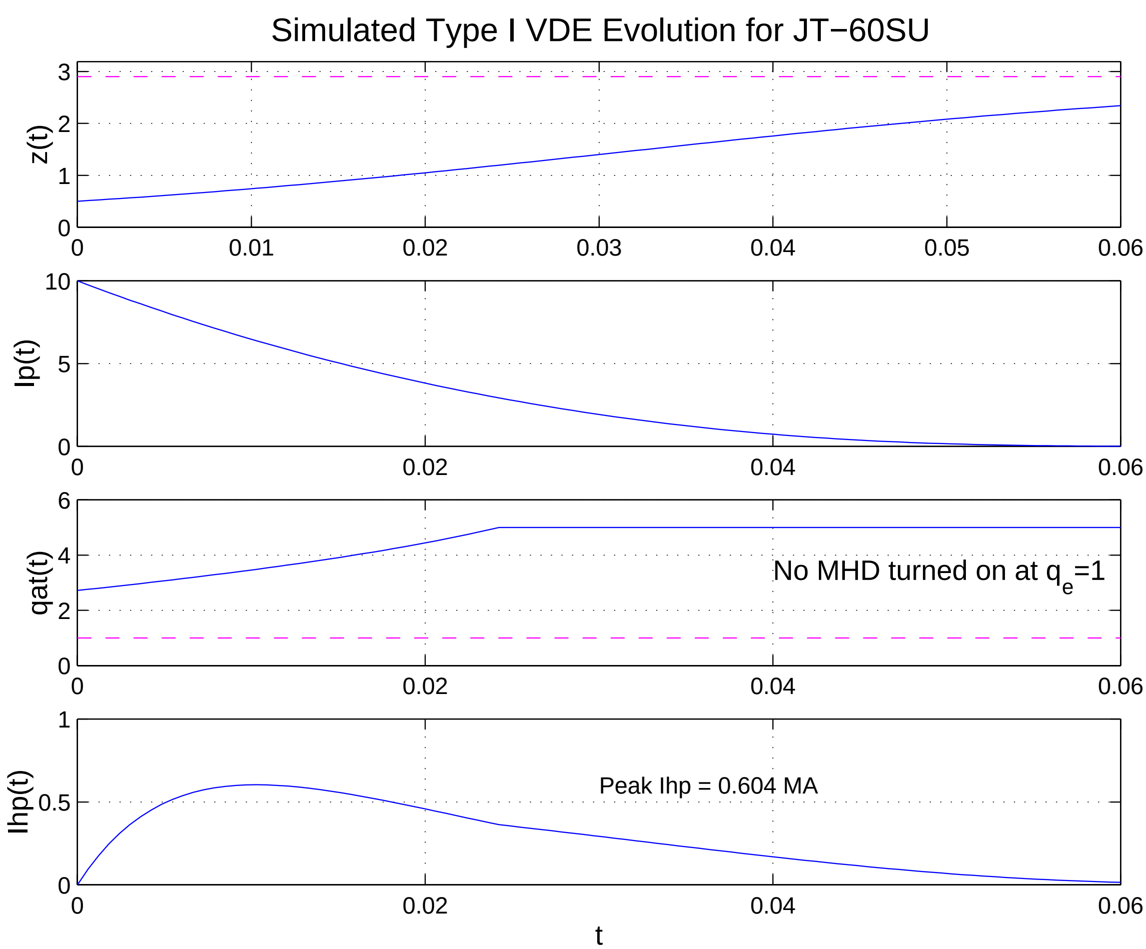
Fully Predictive Capability for Mitigation Scenarios Allows Assessment of Expected "Safe Shutdown" Loads in JT-60SU

- Massive He gas puff for mitigation: post-thermal quench T_e=5 eV, Z_{eff}=1.5 assumed for core and halo;

- Peak halo current falls from unmitigated value of 4.7 MA to 0.60 MA due to He mitigation:



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CONCLUSIONS

- Capability now exists to predict halo currents expected in disruptions mitigated by massive impurity injection;

- Fully predictive capability is enabled by models accurately describing key physics effects in disruption mitigation scenarios:
  - → Halo current model which includes principal effects and accurately reproduces experiment;
  - → KPRAD radiation energy balance model which includes all important effects in disruption mitigation scenarios and accurately reproduces experiment;

- Accuracy of models demonstrated in DIII-D massive He gas puff disruption migitation experiments in DIII-D using measured T_e and Z_{eff} for both core and halo (and Spitzer resistivity):
  - → KPRAD accurately predicts plasma T_e and Z_{eff} for both core and halo;
  - → The halo model accurately predicts detailed evolution of core and halo currents;

- Use of predictive simulation of disruption mitigation scenarios demonstrated with analysis of JT-60SU disruption halo currents:
  - → Unmitigated peak poloidal halo current = 4.7 MA;
  - → Peak poloidal halo current when mitigated by He gas puff = 0.60 MA;

Analytic Halo Model Assumes Current is Driven by dI_p/dt and Poloidal Flux Change $d\Phi_h/dt$

- Circuit equation for toroidal halo current I_{ht} :

$$L_{heff}\dot{I}_{ht} + R_{heff}I_{ht} = -M_{hp}\dot{I}_p^{core} - \frac{\mathbf{1}}{q_h}\frac{d}{dt}\left(B_t\pi\kappa a_h^2\right) + \dot{\Psi}_{ext} \quad ,$$

↑ dI_p/dt (resistive+convective) ↑ $d\Phi_h/dt$

- Force-free constraint in halo means peak poloidal halo current is determined by halo safety factor q_h at time of peak toroidal halo current:

$$I_{hp} = \frac{I_{ht}}{q_h}$$

- Halo currents are increased by higher vertical growth rate relative to current decay rate, which results in lower q_h at time of peak toroidal halo current.

- Approximate solution for VDE's:
  → Type I VDE ⇒ vertical growth rate $\gamma_{zeff} << I_p$ decay rate γ_{p0} ⇒ Halo safety factor remains high:

$$I_{hp}(pk) \approx I_{p\mathbf{0}}\, f_Q \frac{\gamma_{p\mathbf{0}}}{\gamma_{h\mathbf{0}}}(\mathbf{1} - e^{-\frac{\gamma_{h\mathbf{0}}}{\gamma_{p\mathbf{0}}}})\; q_{cq}^{-\mathbf{1}}(\mathbf{1} + \frac{\gamma_{zeff}}{\gamma_{p\mathbf{0}}})$$

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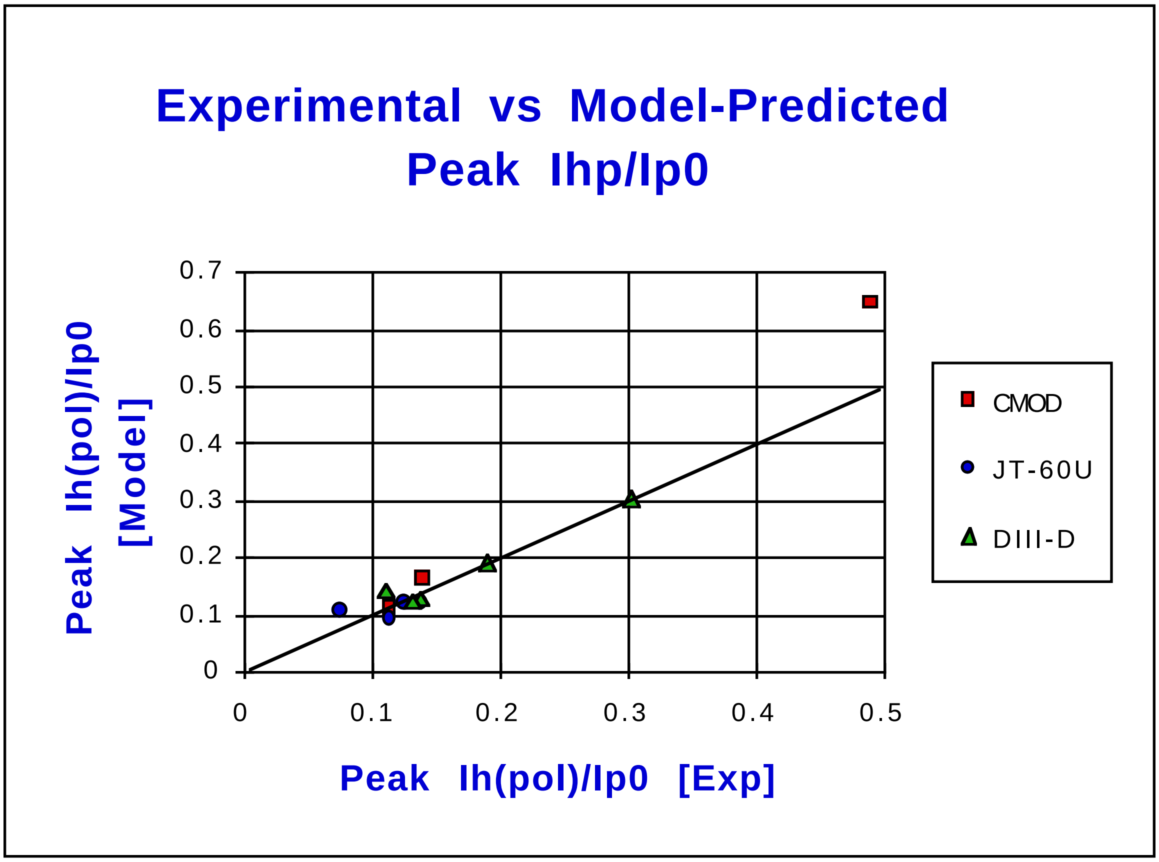
Analytic Model Reproduces Peak Halo Current Scalings in Alcator C-MOD, JT-60U, and DIII-D VDE's



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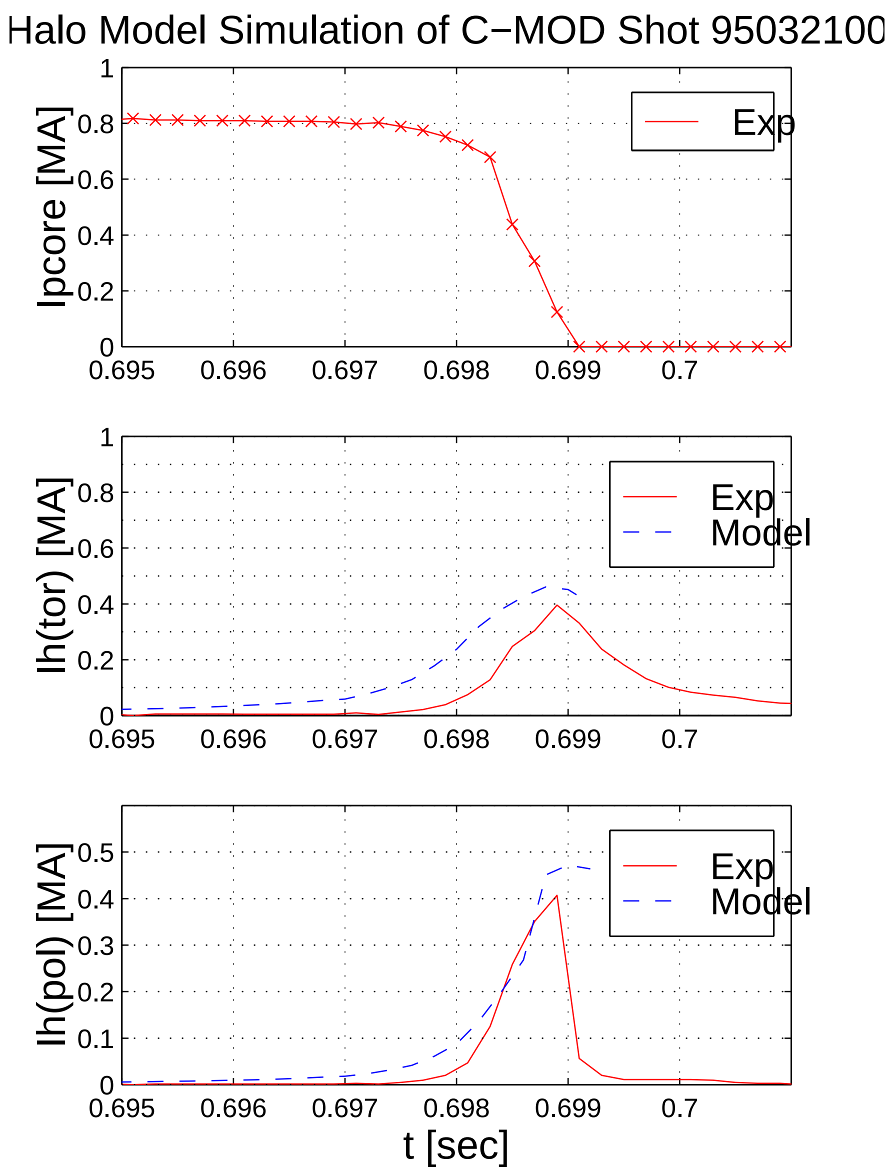
Model Accurately Reproduces Detailed Evolution of Halo Currents in Alcator C-MOD VDE's



- T_e(halo)=10 eV, Z_{eff}(halo)=1.0, w_{halo}=0.1 m assumed for simulation

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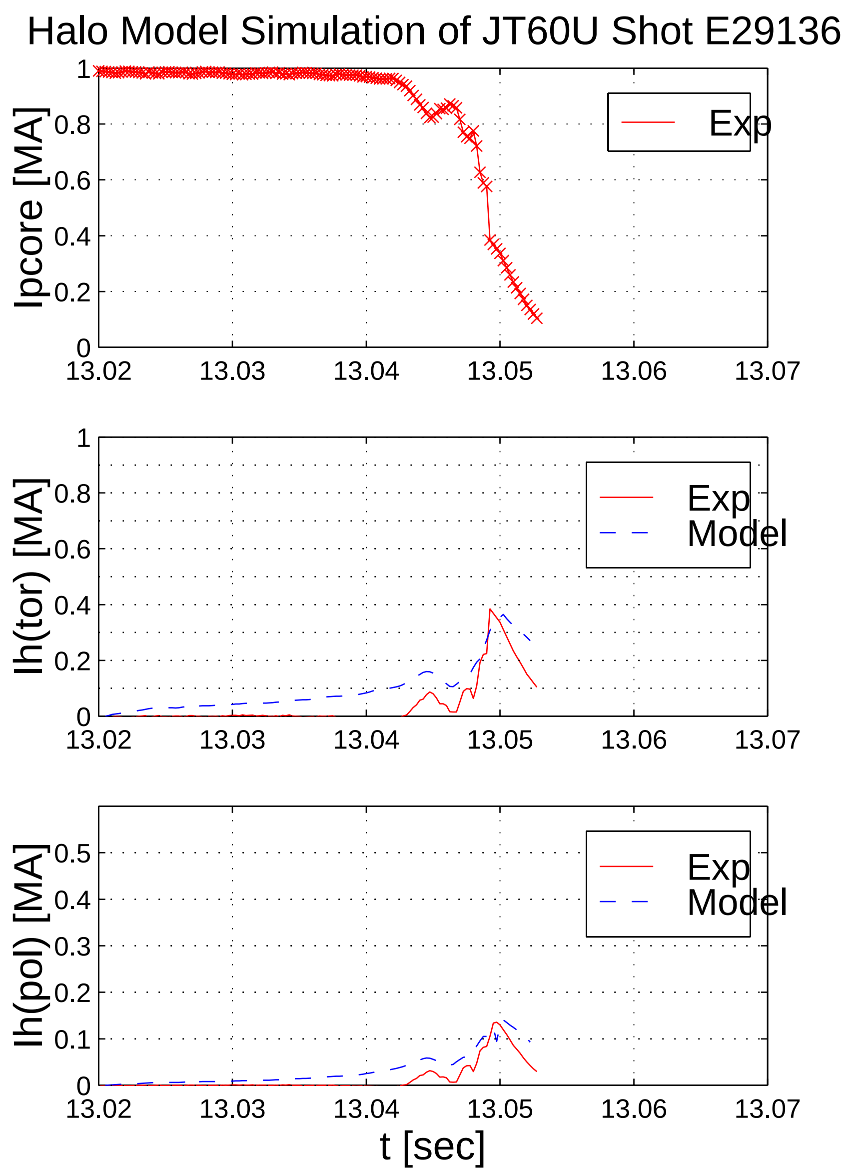
Model Accurately Reproduces Detailed Evolution of Halo Currents in JT-60U VDE's



- T_e(halo)=4 eV, Z_{eff}(halo)=1.0, w_{halo}=0.1 m assumed for simulation

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