A Diffusive Model for Halo Width Growth During VDEs

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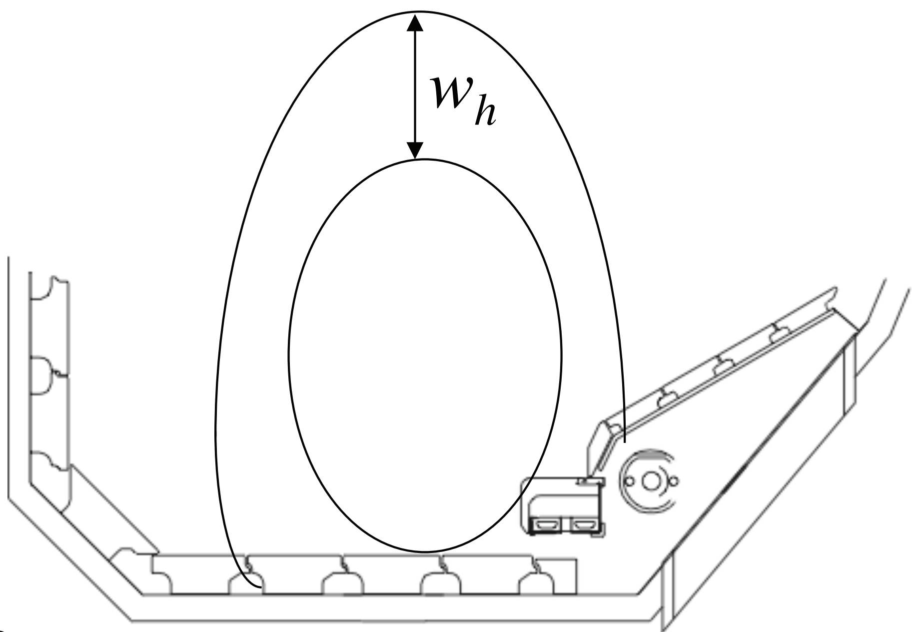
General Atomics



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Abstract

The electromagnetic loads produced by halo currents during vertical disruption events (VDEs) impose stringent requirements on the strength of ITER in-vessel components. A predictive understanding of halo current evolution is essential for ensuring the robust design of those components. That evolution is primarily governed by two quantities: the halo region width and resistivity. A diffusive model of halo width growth during VDEs has been developed that provides one part of a physics basis for predictive halo current simulations. The diffusive model was motivated by DIII-D observations that VDEs with cold post-thermal quench plasma and a current decay time much faster than the vertical motion (Type I VDE) possess much wider halo region widths than warmer plasma VDEs where the current decay is much slower than the vertical motion (Type II). A 2-D finite element code is used to model current diffusion during selected Type I and Type II DIII-D VDEs. The model assumes a core plasma region within the LCFS diffusing current into a halo plasma filling the vessel outside the LCFS. LCFS motion and plasma temperature are prescribed from experimental observations. The halo width evolution produced by this model compares favorably with the experimental measurements of Type I and Type II halo width evolution. Supported by the US Department of Energy under DE-FC02-04ER54698.

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Outline

1. A physics basis for predictive halo current simulation is important for the robust design of tokamak in-vessel components
2. Halo current evolution is very sensitive to the halo region resistance, which is a function of halo T_e , Z_{eff} and halo width
3. Experimental evidence indicates halo width evolution resembles a magnetic diffusion process
4. A 2-D finite-element model of toroidal current diffusion during vertical disruption events (VDEs) has been developed that produces halo width evolution in good agreement with experimental data

This diffusive halo width growth model provides one part of a physics-based, fully predictive model for halo current evolution

Motivation: Physics Model of Halo Region Evolution Important for Robust In-vessel Component Design

- **Open field line halo currents flowing through vessel during a VDE create potentially damaging JxB forces**

- **Robust design of tokamak in-vessel components requires accurate modeling of these forces**

- **JxB forces sensitive to evolution of halo width (w_h) and resistivity (η_h)**

- **No physics-based model for evolution of intrinsic halo properties in present integrated disruption simulations (TSC, DINA)**
  - Large uncertainty extrapolating data from existing devices to ITER & future devices

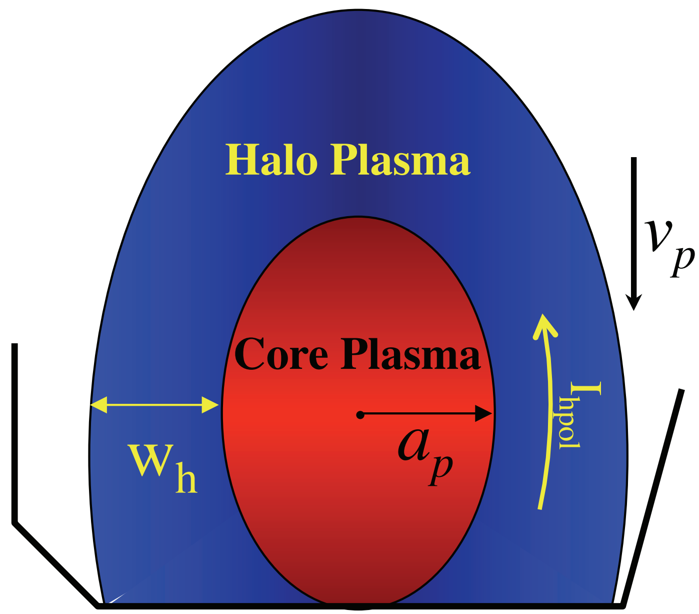
DIII-D divertor tile broken by halo forces

Toroidal Current Transfer from Core to Halo Region Sensitive to Relative Decay Rates

- **Transfer ∝ ratio core/halo decay rates: γ_p / γ_h**

$$\gamma_p / \gamma_h \propto \left(\frac{w_h}{a_p}\right)\left(\frac{\eta_p}{\eta_h}\right)$$

Wider $\mathbf{w_h}$ ⇒ Higher I_{halo}
Narrower $\mathbf{w_h}$ ⇒ Lower I_{halo}



Modeling halo current evolution requires knowledge of

$\underbrace{Z_{eff}, T_e,}_{\eta}$ & w_h

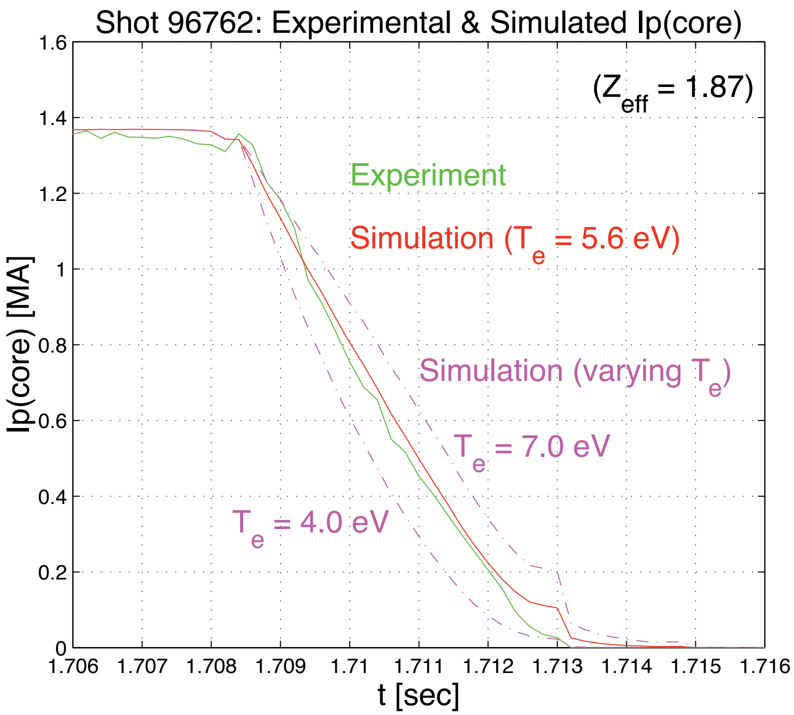
Discussed in this poster

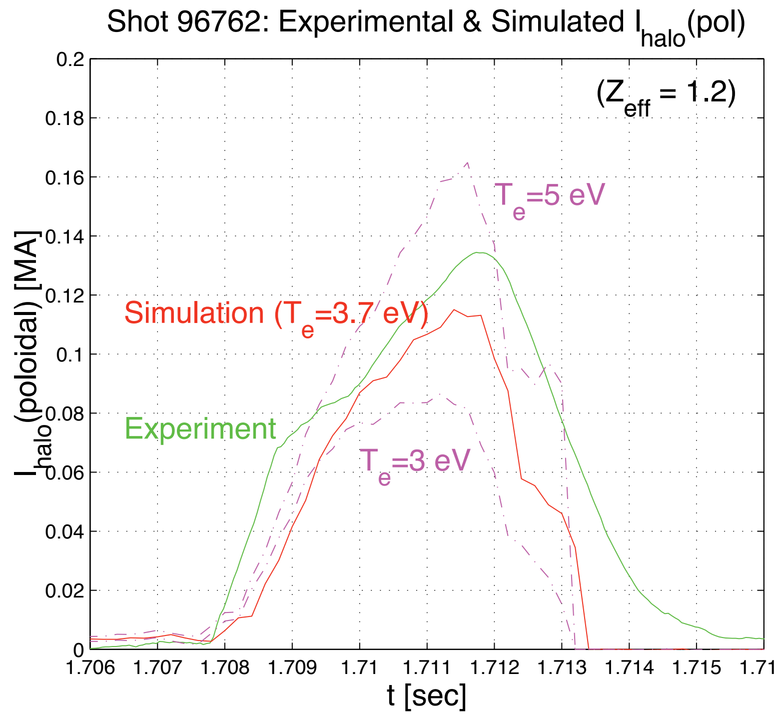
D.A. Humphreys & A.G. Kellman, Phys. Plasmas **6**, 2742 (1999).

Lumped Parameter Model can Accurately Describe Core/Halo Current Evolution if η's & w_h Specified from Experiment

- **He massive gas injection induced VDE enables post-CQ T_e measurements**
  - Using SPRED measurement of XUV He free-bound recombination continuum

- **Model *very sensitive* to halo resistance (w_h, T_e, Z_{eff})**





D.A. Humphreys & A.G. Kellman, Phys. Plasmas **6**, 2742 (1999).
D.G.Whyte, T.C.Jernigan, D.A.Humphreys, et al., J. Nucl. Mater **313**, 1239 (2003).

VDEs Divided into Two Limiting Classifications

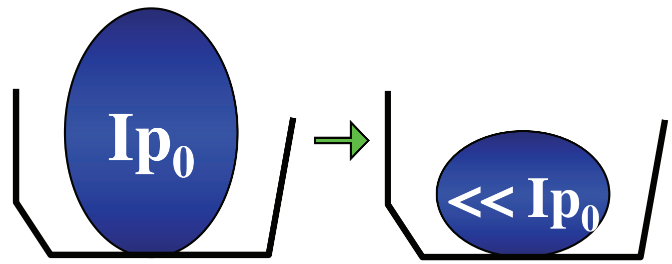
- **Type I (cold core)**

  Slow vertical motion relative to current decay ($\gamma_z / \gamma_p << 1$)

  → core circumference ~constant as I_p decreases

  → halo q remains high

  ⇒ **lower $I_{hpol} = I_{htor}/q_{halo}$**



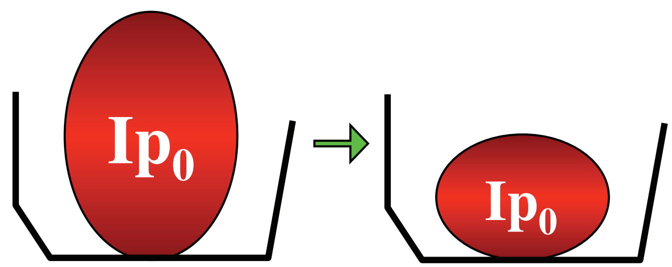
- **Type II (hot core)**

  Fast vertical motion relative to current decay ($\gamma_z / \gamma_p >> 1$)

  → I_p ~constant as core circumference decreases

  → halo q decreases to ~1

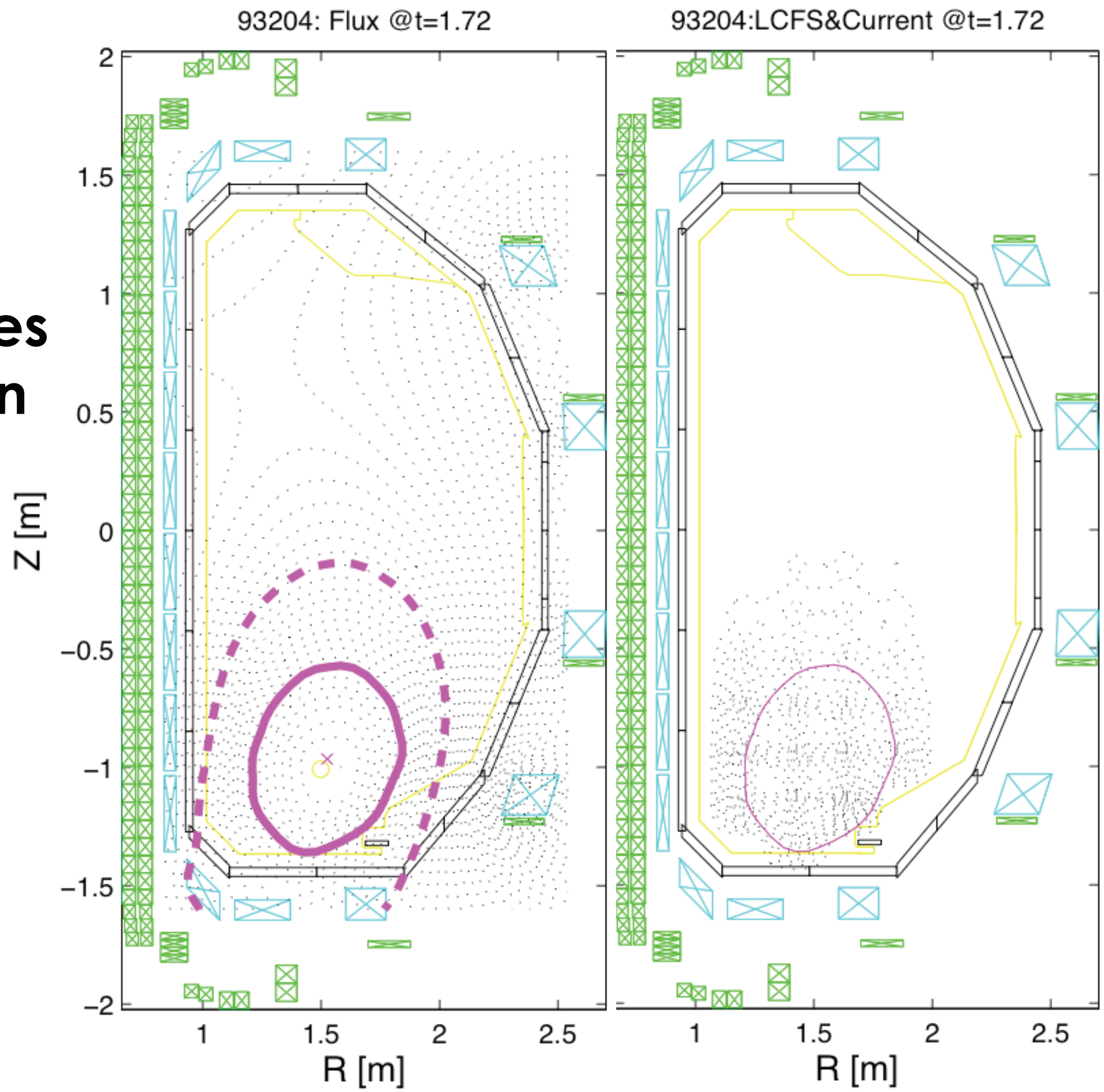
  ⇒ **higher $I_{hpol} = I_{htor}/q_{halo}$**



These two limits display very different w_h evolution

Measuring w_h: JFIT Reconstructs Current Distribution During CQ, Also Identifies w_h

- **Performs constrained fit to magnetic measurements**
  - Flux loops, poloidal field probes, Rogowski loops
- **Variety of basis function choices available for current distribution on grid**
  - Uniform-current elements
  - SVD principal components
- **Variety of solution methods for constrained fitting**
  - Simple linear (SVD inversion)
  - Nonlinear least squares
  - Constrain current to be positive everywhere

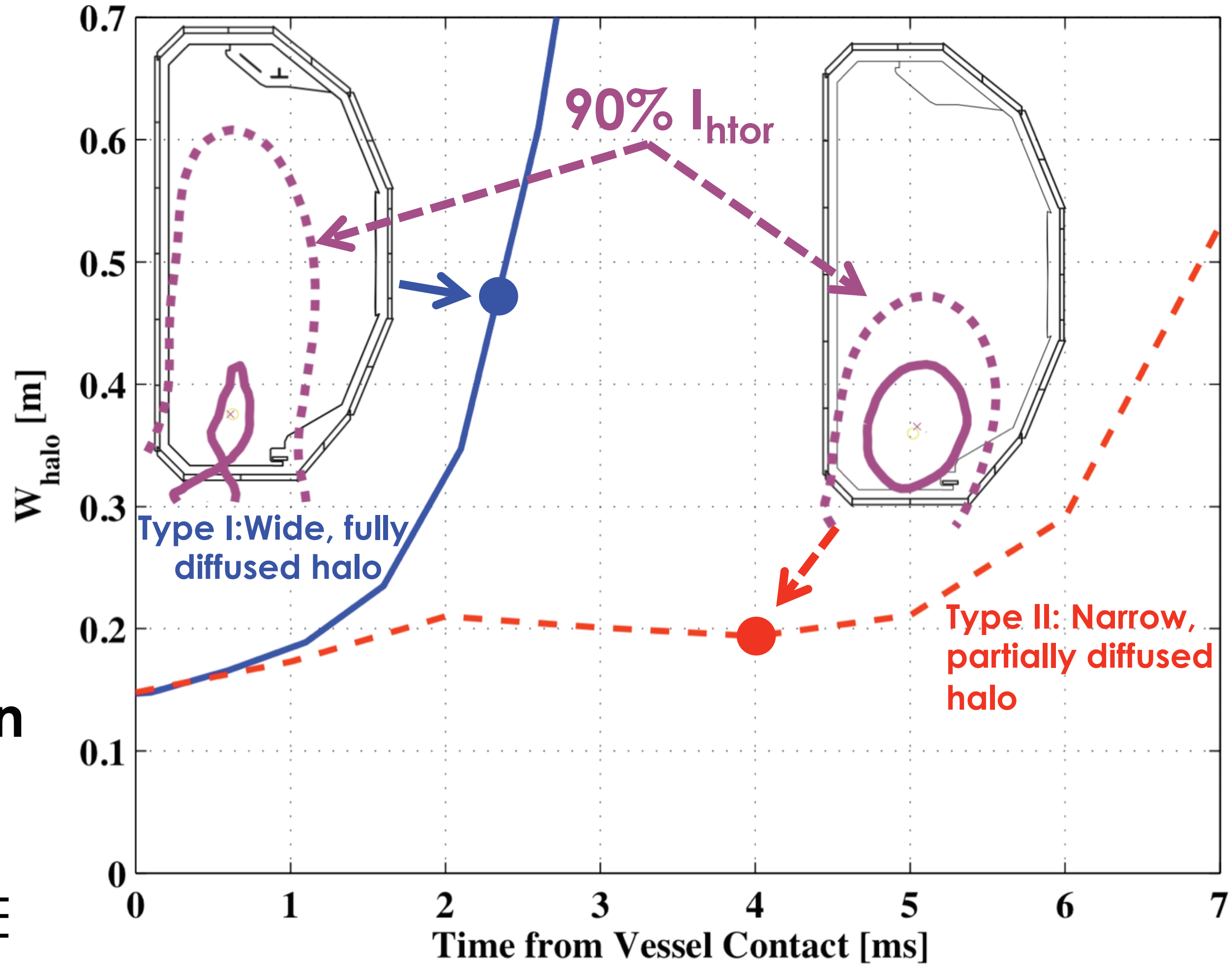


JFIT Reconstructions Display Large Variation in w_h by VDE Type

- **JFIT halo width**

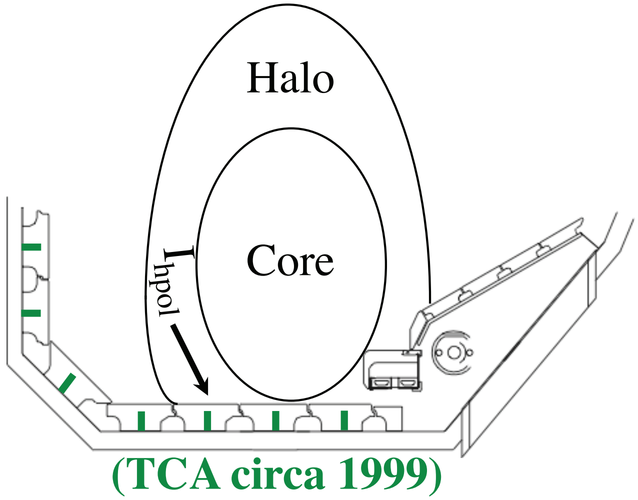
$$w_h^{JFIT}(t) \equiv \frac{1}{I_h^{tor}} \int_{A_{halo}} J_h^{tor}(t)(r - r_{core})\,dRdZ$$

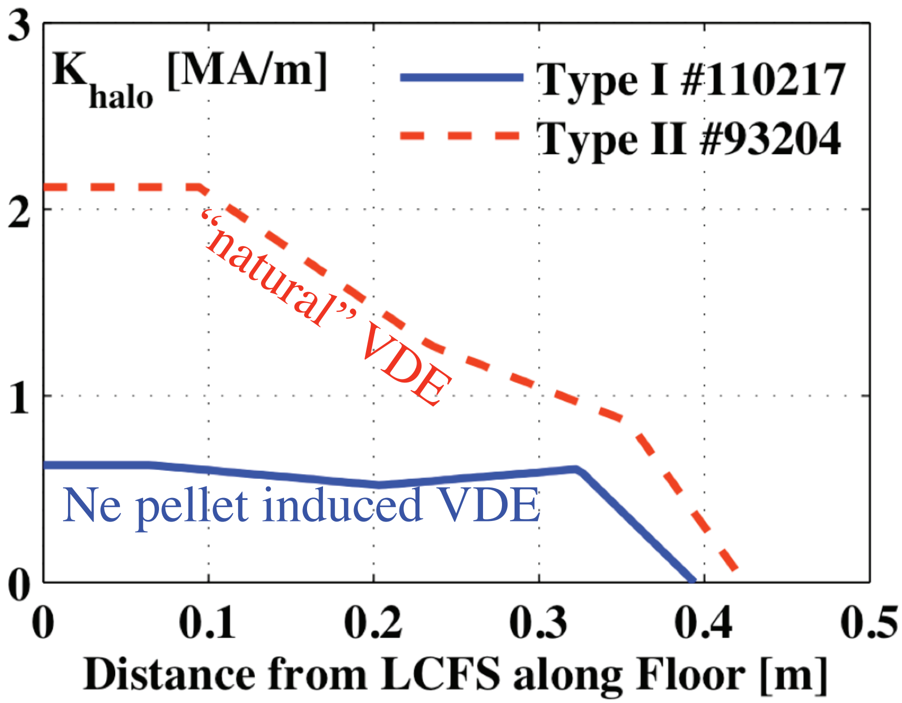
- **Type I VDE w_h >> Type II**
  - Type I: w_h=0.62 m
  - Type II: w_h=0.20 m
- **Primarily vertical expansion**
  - Not easily measured by tile diagnostics
  - Observable as post-VDE "bounce" in Z_p estimators



Measuring w_h: DIII-D Tile Current Array (TCA) Measurements Show w_h Varies With VDE Type

- Shunts measure I_{hpol} through isolated tiles
- High poloidal & toroidal resolution (~7x5)
- Decommissioned 2006, re-commissioned 2009 at reduced resolution (2x5)





- **Type I**
  Broad, even profile ➔Large w_h
- **Type II**
  Peaked, narrow profile ➔ Small w_h

Halo Width Evolution Suggests Diffusive Process

- **Magnetic diffusivity $\lambda_m = \eta/\mu_0$**

$$\nabla^2 \mathbf{A} = \frac{1}{\lambda_m}\frac{\partial \mathbf{A}}{\partial t}$$

- **Type I → cold halo → higher κ → wide halo**
- **Type II → hot halo → lower κ → thin halo**

- **Assumes ubiquitous plasma in "vacuum" region into which current can diffuse**

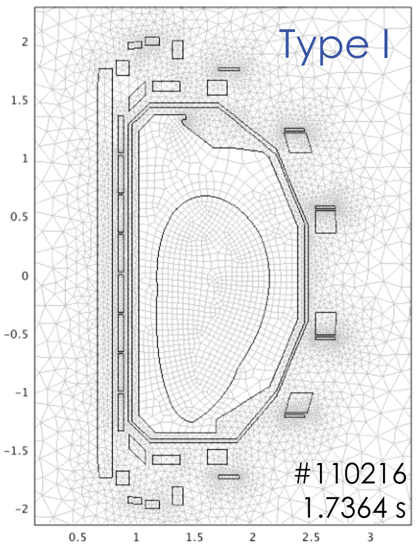
2-D Finite-element Model of Toroidal Current Diffusion During VDE Developed to Test Diffusion Hypothesis

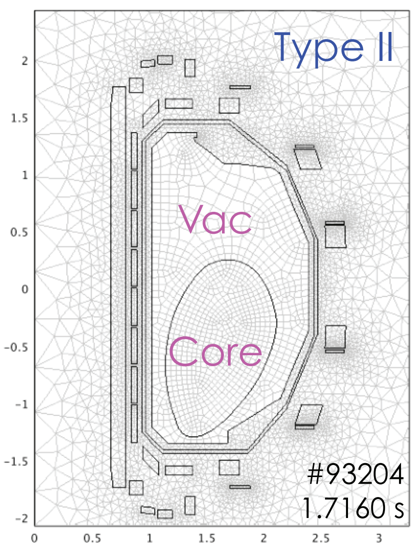
- **Finite element models of Type I, Type II VDE**
  - Implemented in Comsol Multiphysics
  - Solves magnetic diffusion equation on dynamically deforming mesh

- **Simulation begins at start of CQ**
  - Vertical displacement already in progress
  - LCFS compressing against floor

- **LCFS motion prescribed from JFIT measurements**
  - No Grad-Shafranov force balance enforced

- **Assumes static T_e in core & vacuum regions, initially uniform J in core**
  - T_e derived from best fit to lumped parameter model

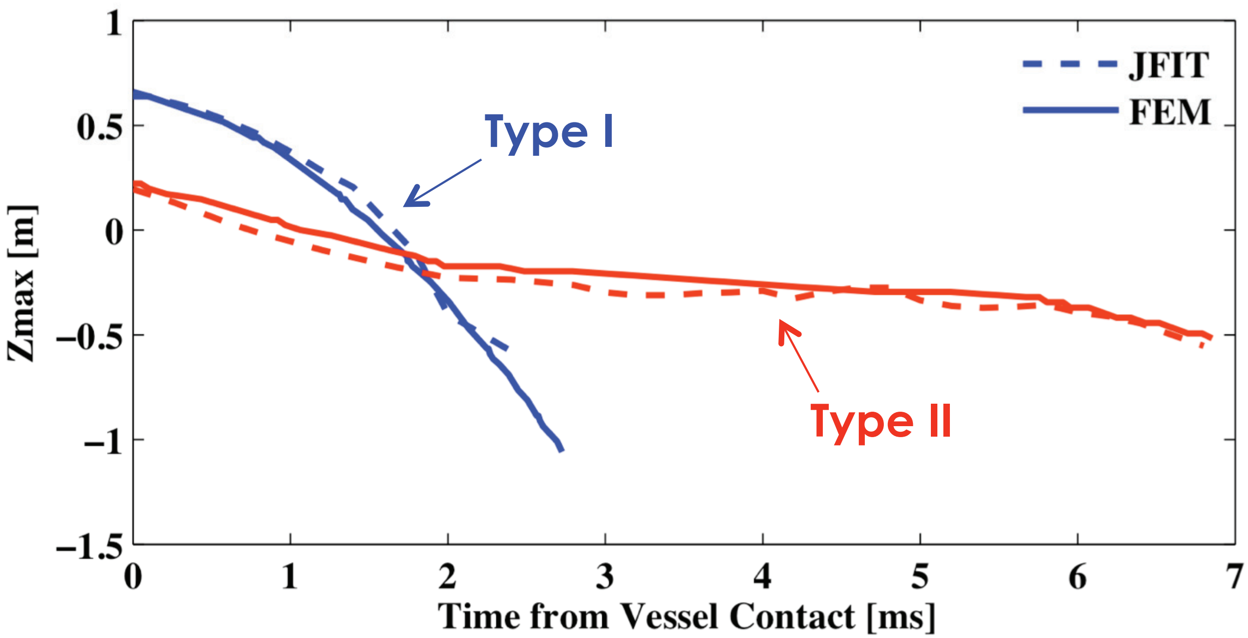


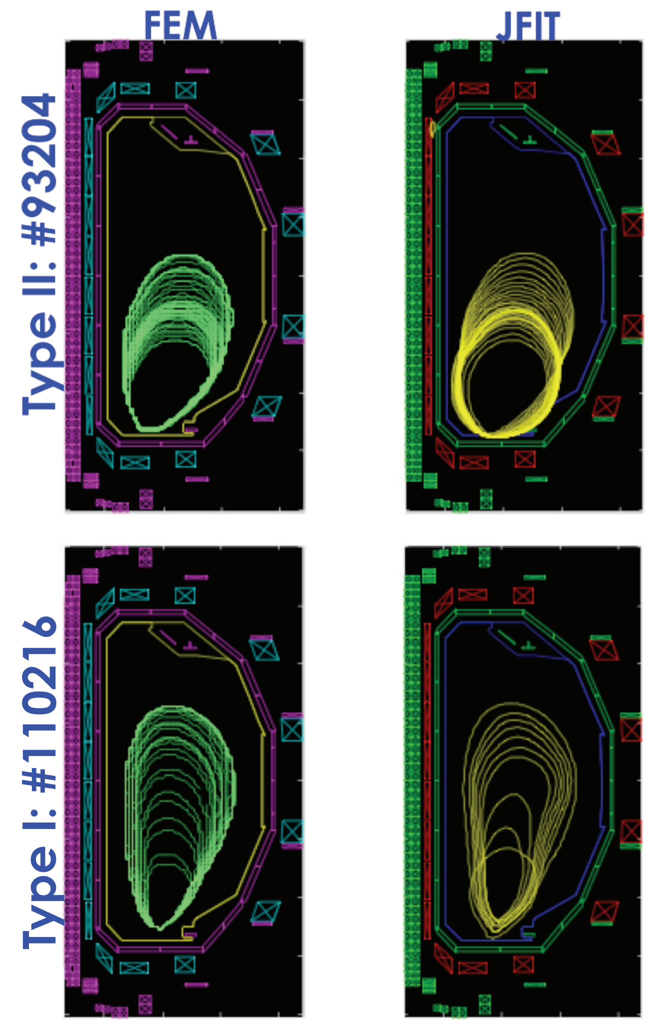


LCFS Motion Based Upon JFIT LCFS Evolution

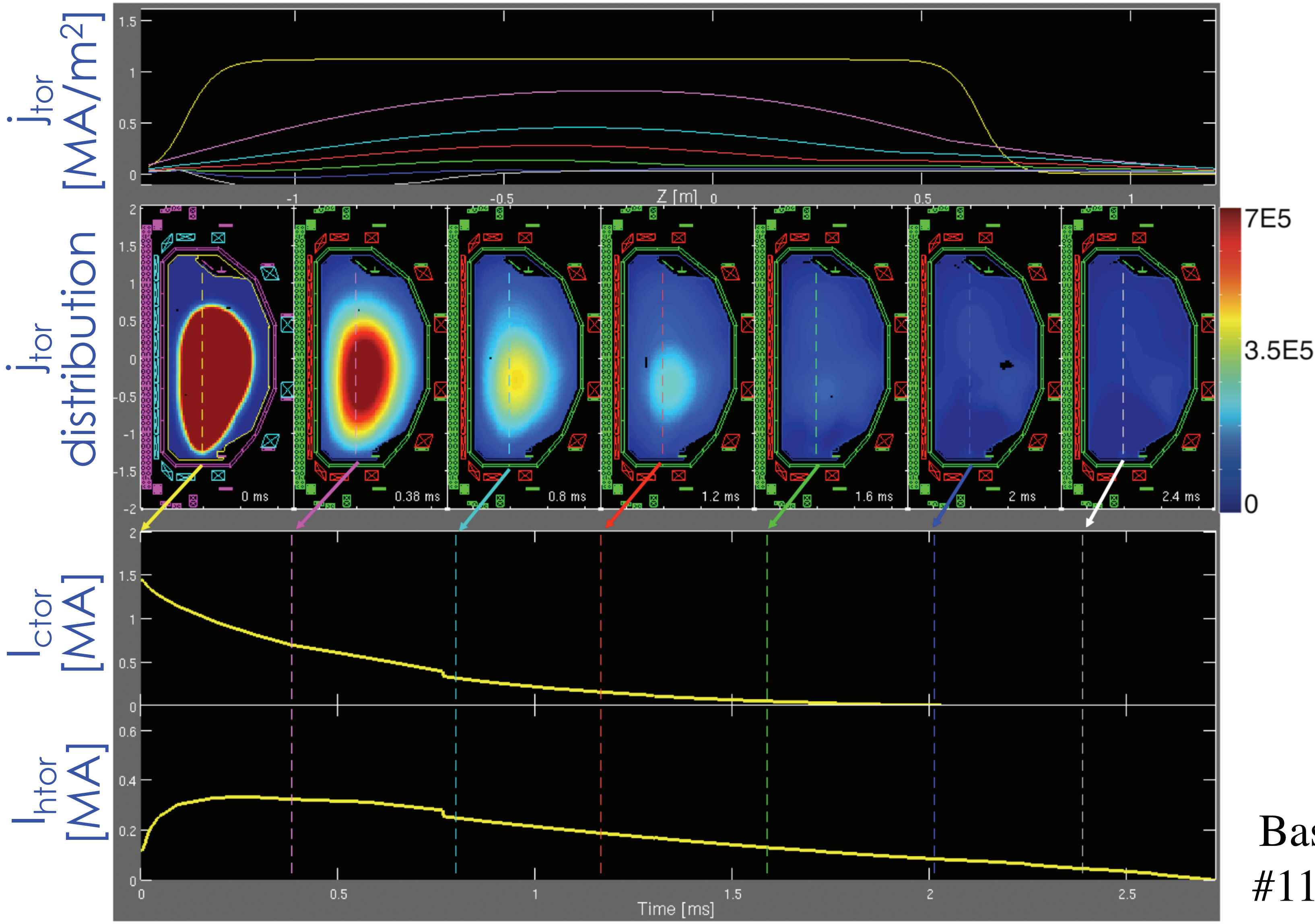
- **Complicated deformed mesh algorithm makes matching exact motion difficult**

- **Emphasis placed upon matching LCFS z_{max}**
  - Fastest changing point in geometry



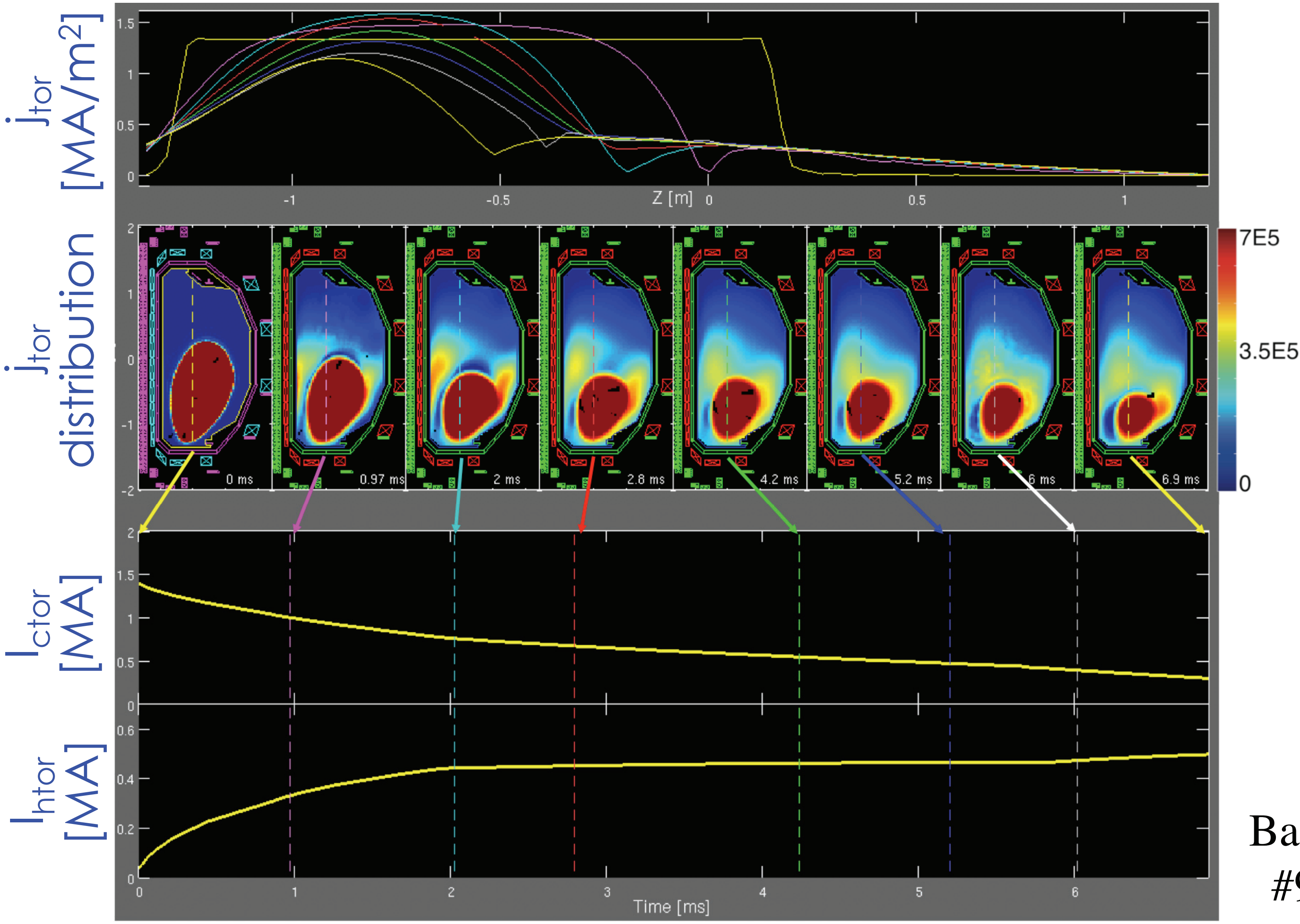


Type I VDE Model Evolution



Based on
#110216

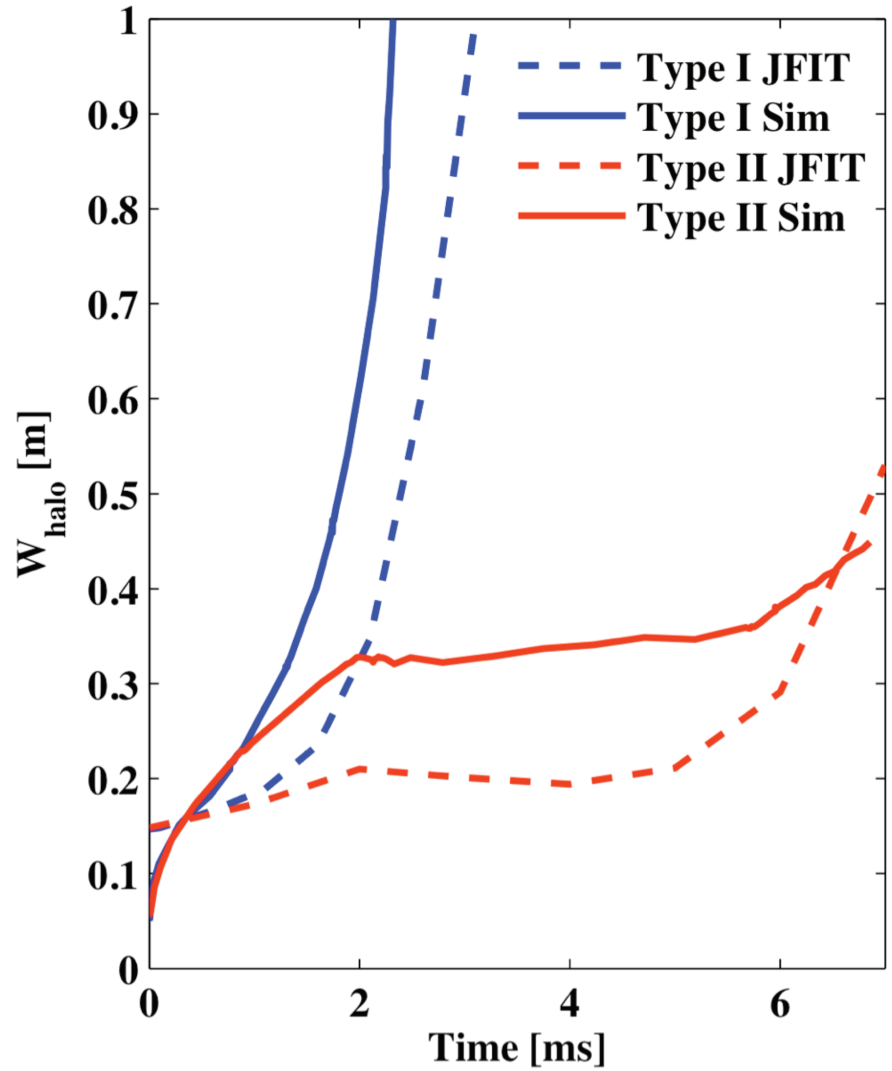
Type II VDE Model Evolution



Based on #93204

Diffusion Model Displays Qualitative Agreement With Experimental w_h Evolution

- **Clear difference between Type I, Type II w_h evolution**
- **Good match to late Type I growth rate**
- **Captures w_h "flattop" in Type II evolution**
- **Majority of discrepancy occurs during early expansion (<1 ms)**
  - Initial conditions, constant T_e assumption may be too simplistic
  - Addition of poloidal current diffusion (toroidal field diffusion) to model should slow initial growth & give better match to I_h & I_{core} evolution



Summary

- **Predictive simulations of halo current evolution require halo resistivity and width, but no physics basis for these exists**
  - Extrapolation to ITER & future devices problematic
- **Experimental evidence indicates that halo width evolution is governed by magnetic diffusion**
  - Growth rate strongly dependent upon VDE type
- **2-D FEM model of toroidal current diffusion during VDE produces w_h evolution in good agreement with experiment**
  - Assumes ubiquitous plasma outside LCFS

Paired with model for halo resistivity, this work can provide a physics basis for predictive simulations of halo forces in ITER and future devices