IDENTIFICATION OF INTERMEDIATE n IDEAL MHD KINK-PEELING MODES WITH ELMS IN DIII-D H-MODE DISCHARGES

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GENERAL ATOMICS

BACKGROUND

- **ELMs first observed in ASDEX H Mode (F. Wagner, et al., Phys. Rev. Lett., 49, 1408, 1982)**
- **Several explanations have been proposed:**
  - **Unstable low n Ideal MHD peeling modes**
    - » **driven by the Pfirsch Schluter current from the steep p'_{edge} in H Mode (A.D. Turnbull et al., J. Comp. Phys., 66, 391, 1986)**
    - » **β threshold for instability arises from large p'_{edge}**
  - **High n ideal MHD ballooning modes (P. Gohil et al, Phys. Rev. Lett., 61, 1603, (1988)**
    - » **Onset of ELMs correlated with p'_{edge} reaching the simple circular cross section estimate for the ballooning limit**
  - **Low n Ideal MHD peeling modes driven by edge current density gradients (J. Manickam Phys. Fluids B4, 1901, 1992)**

None of the explanations has held up to detailed scrutiny

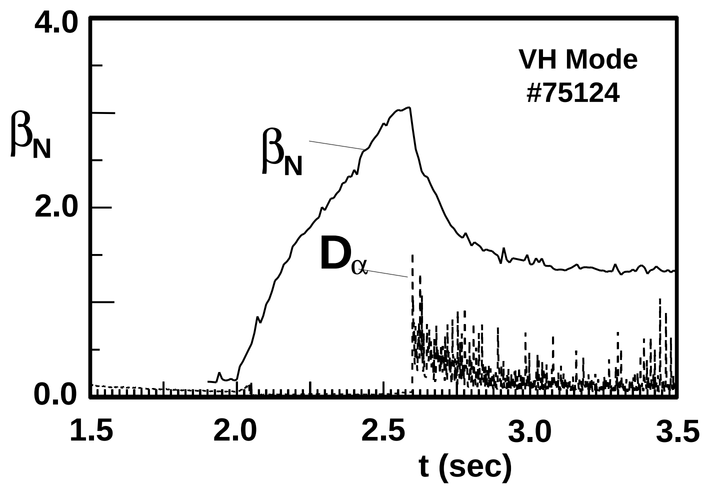
This work presents a more complete model for ELMs

ELMs result from a complex interaction between ballooning and low n kink peeling mode stability with the latter driven partly by the edge p' and partly by the bootstrap current density

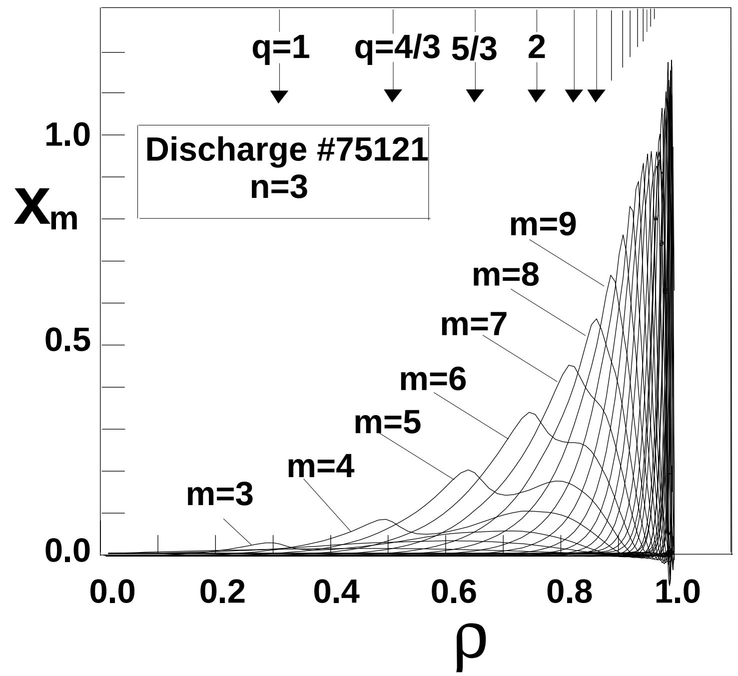
HIGH PERFORMANCE VH MODE AND NCS H MODE DISCHARGES ARE TERMINATED BY A LARGE ELM

- **Termination has been identified as a low to intermediate n MHD peeling mode** **(E.J. Strait, et al., EPS 1993, Vol. 1, p211, 1994)**

High performance termination by first large ELM



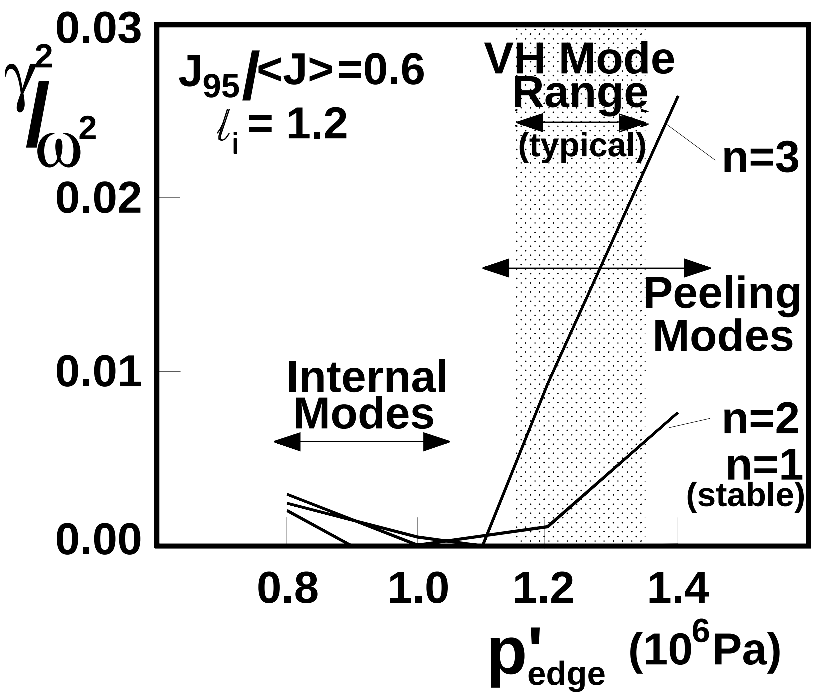
Calculations predict edge n=2,3,4 modes driven by j_{edge} and p'_{edge}



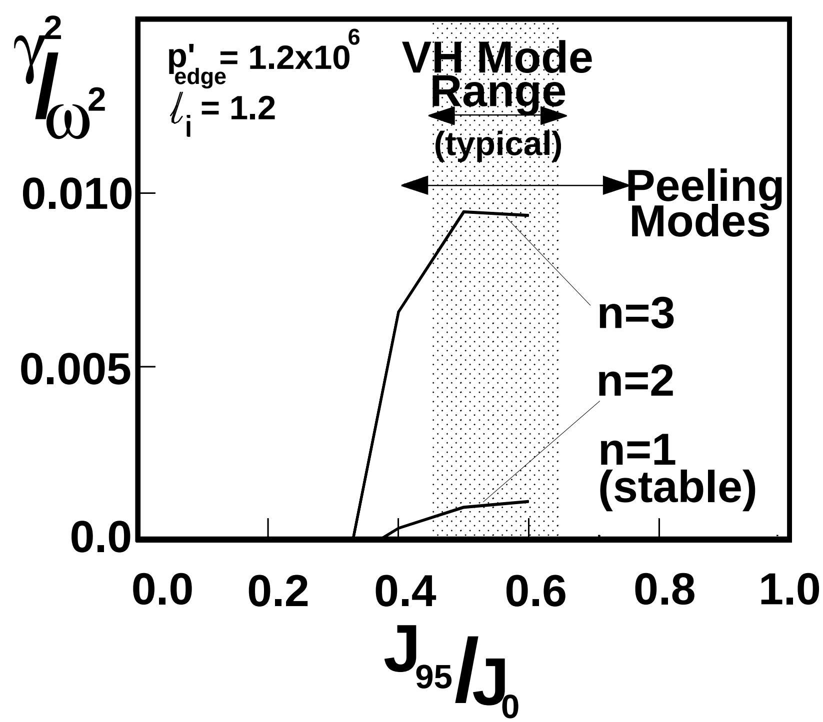
GENERAL ATOMICS

VH MODE TERMINATION EVENT IS DRIVEN BY COMBINATION OF j_{edge} and p'_{edge}

Instability threshold for p'_{edge}



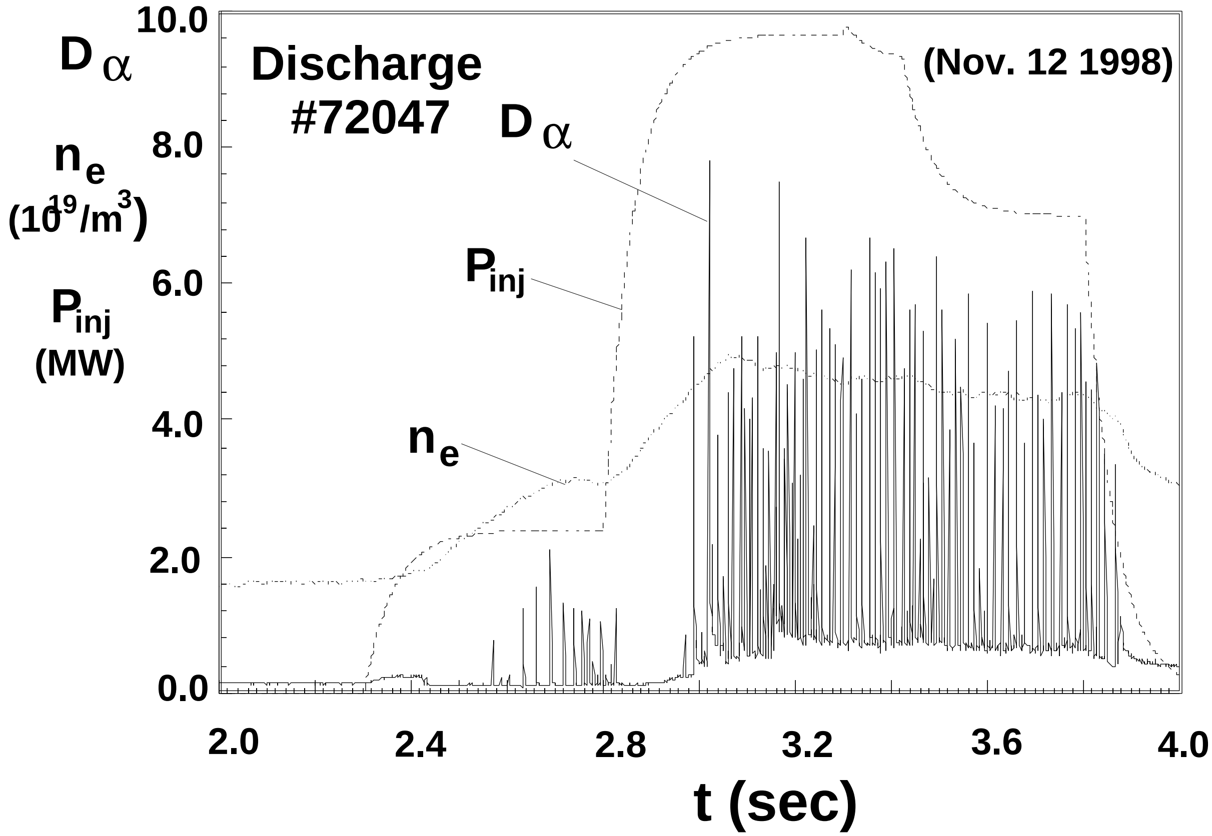
Instability threshold for j_{edge}



GENERAL ATOMICS

PREVIOUS ATTEMPTS FAILED TO IDENTIFY ORDINARY TYPE I ELMS IN ELMING H MODE AS LOW n MHD INSTABILITIES

- **Equilibria reconstructed for Discharge #72047 at 2688 msec**
  - **GATO calculations predicted stability for n = 1 through 5**



GENERAL ATOMICS

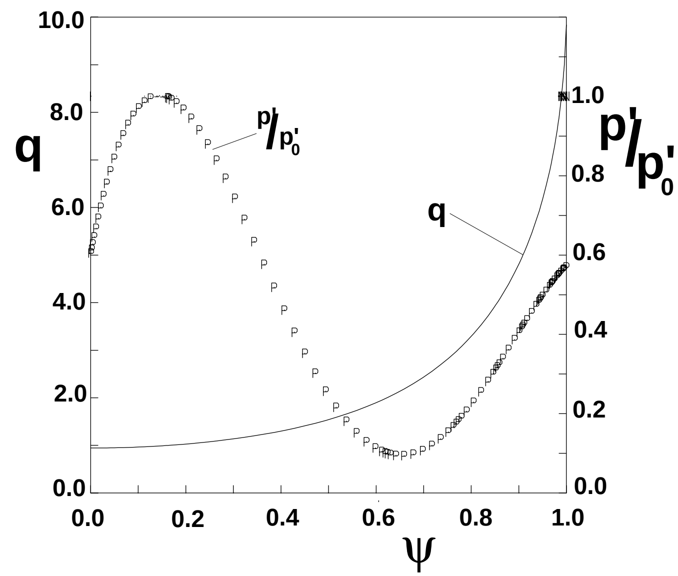
PREVIOUS CALCULATIONS FOR ELMING DISCHARGES COULD NOT ADEQUATELY RESOLVE THE EDGE CURRENT PROFILE

- **Equilibrium diagnostics available were:**
  - **Thomson and CER ⇒ pressure profile**
  - **Magnetics ⇒ plasma boundary**
  - **Single MSE channel ⇒ current profile**

⇒ **Simple polynomial fits to p' and f = rB_T yielded smooth profiles with reasonable χ^2**

Safety Factor and Pressure profiles

(Discharge #72047.2688)



GENERAL ATOMICS

IMPROVED EQUILIBRIUM RECONSTRUCTIONS ALLOW ELMS TO BE IDENTIFIED AS LOW n KINK MODES IN DIII-D

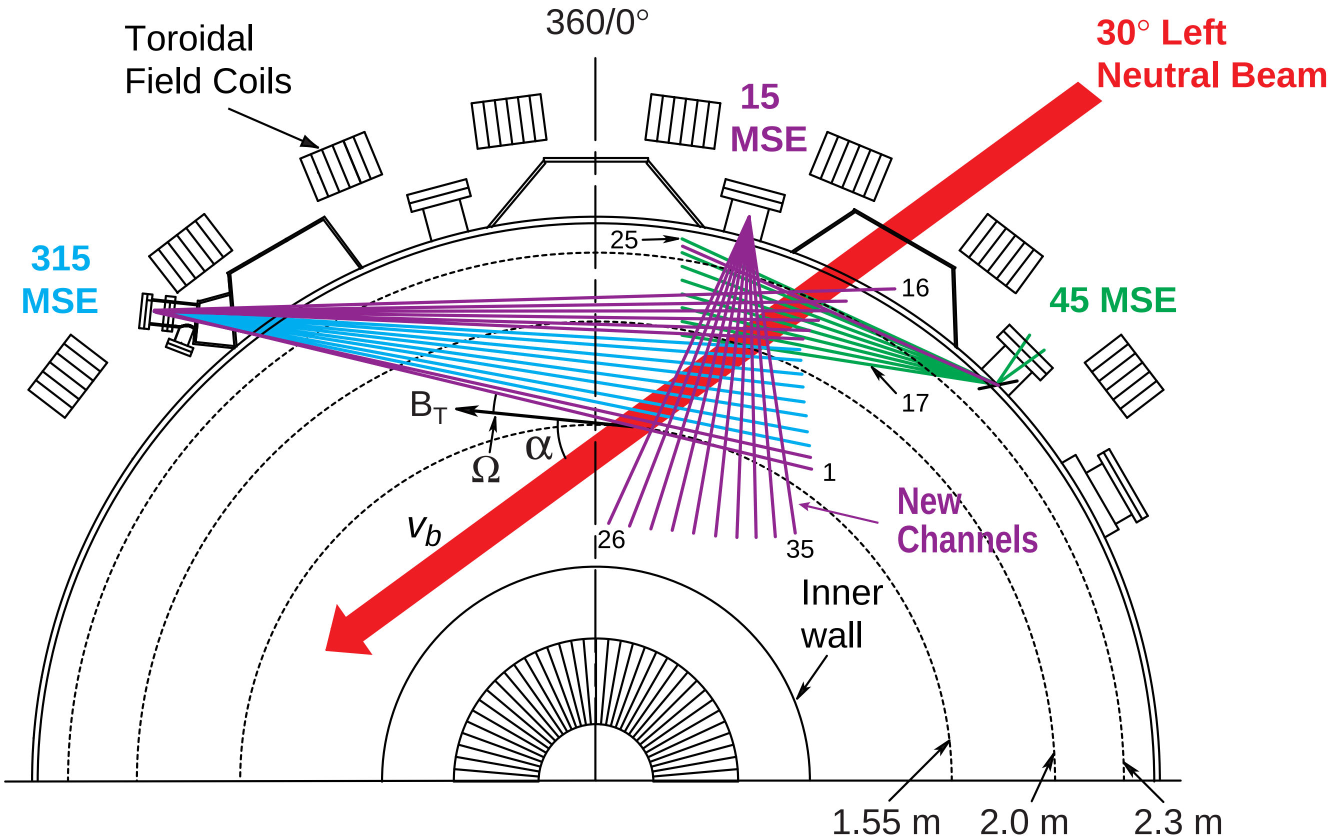
- **Three critical improvements over previous attempts:**
  - **improved diagnostics:**
    - » **36 MSE channels**
    - » **upgraded magnetics**
  - **improved fitting of the edge pressure:**
    - » **hyperbolic tangent fit or**
    - » **spline fit with appropriate knots near the edge**
  - **constraint that j_{edge} be consistent with ballooning stability**

⇒ **require consistency between edge bootstrap current and p'_{edge}**

GENERAL ATOMICS

NEW 36 CHANNEL MSE DIAGNOSTIC PROVIDES DETAILED INTERNAL CURRENT PROFILE INFORMATION

- **Multiple viewing angles allow resolution of E_r and B_z:**
  - **Internal j is well resolved**



GENERAL ATOMICS

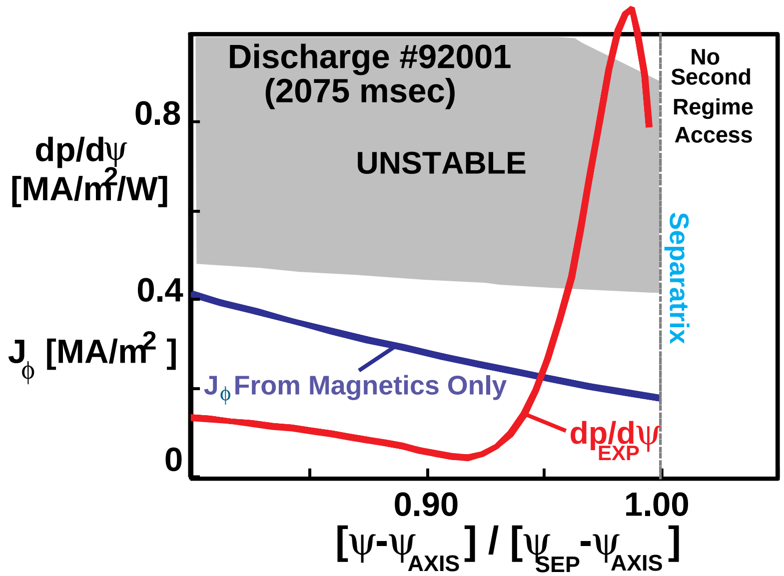
MORE REALISTIC EQUILIBRIUM RECONSTRUCTION PROCEDURE FOR EDGE PRESSURE AND CURRENT IS CRUCIAL

- **Accurate fit to H mode edge pressure ⇒ large edge gradient**

  ⇒ **Strong variation in p' near edge needs to be accurately reproduced**

- **Large p'_{edge} with simplest fit using magnetics data only**

  ⇒ **edge predicted to be unstable to ballooning modes**

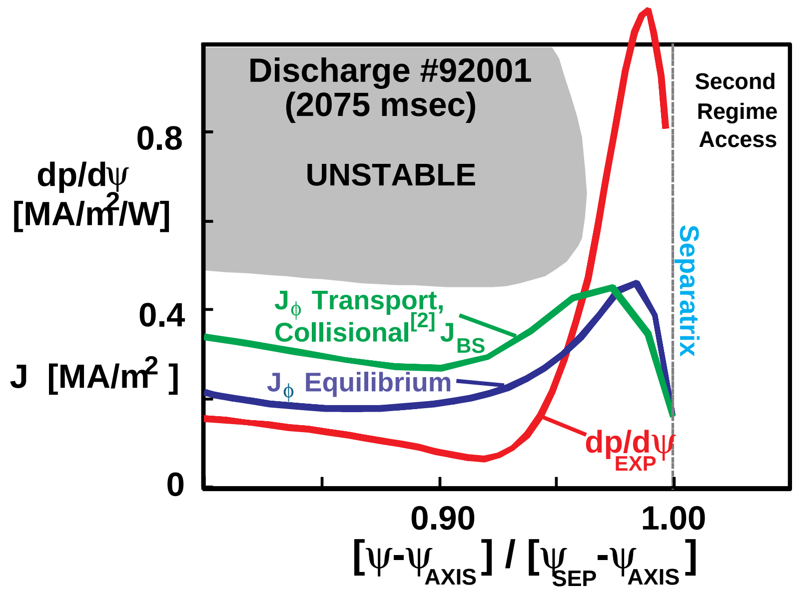


GENERAL ATOMICS

ADDITIONAL CONSTRAINT REQUIRING BOOTSTRAP ALIGNMENT IS NECESSARY TO RESTORE CONSISTENCY WITH BALLOONING

- **Edge j profile is still ambiguous since the edge MSE system cannot resolve E_r and B_z sufficiently:**
  - ⇒ **A significant variation in j_{edge} is still consistent with the MSE and magnetics data**

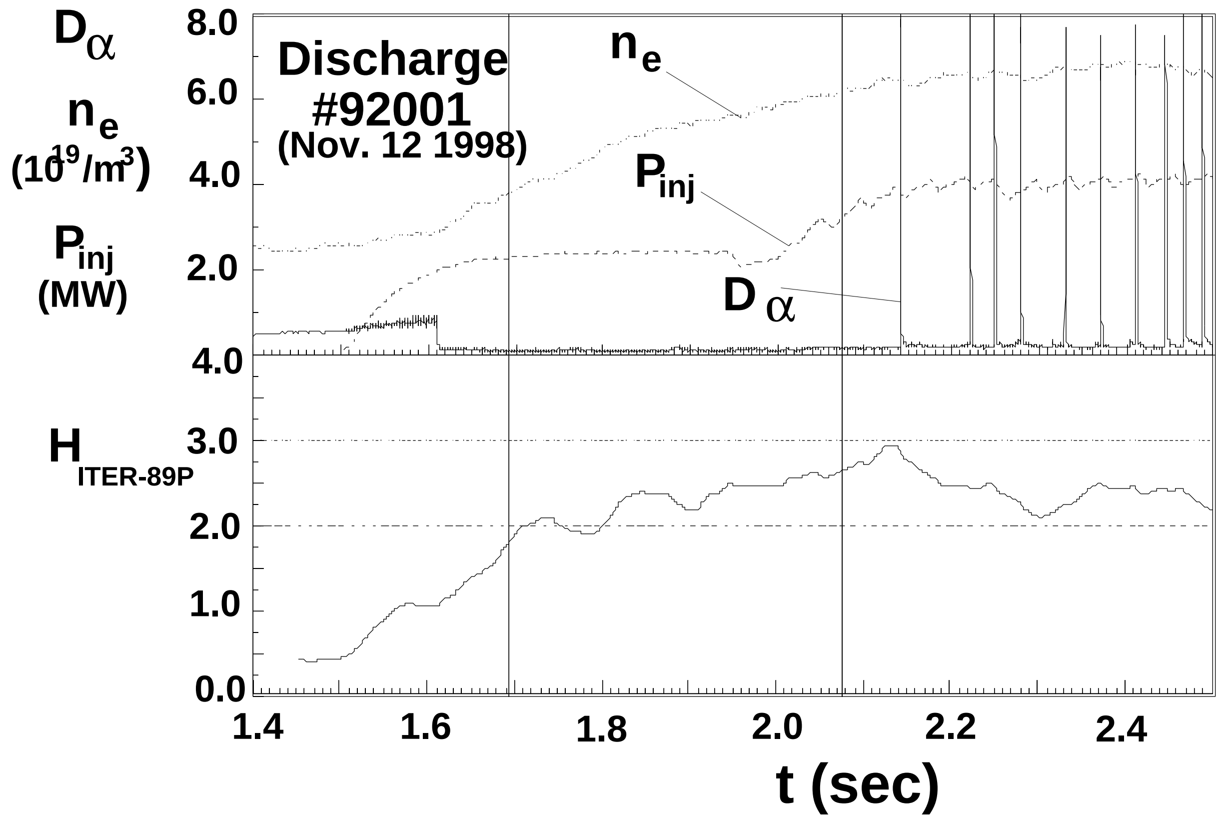
- **Constraining j_{edge} to be aligned with the calculated neoclassical bootstrap current from the large p'_{edge} opens access to the second stability region for ballooning modes:**
  - ⇒ **restored consistency of the measured p'_{edge} with ballooning stability**



GENERAL ATOMICS

PLASMA IS PREDICTED UNSTABLE TO LOW n KINK - PEELING MODE BEFORE TYPE I ELM FOR DISCHARGE #92001

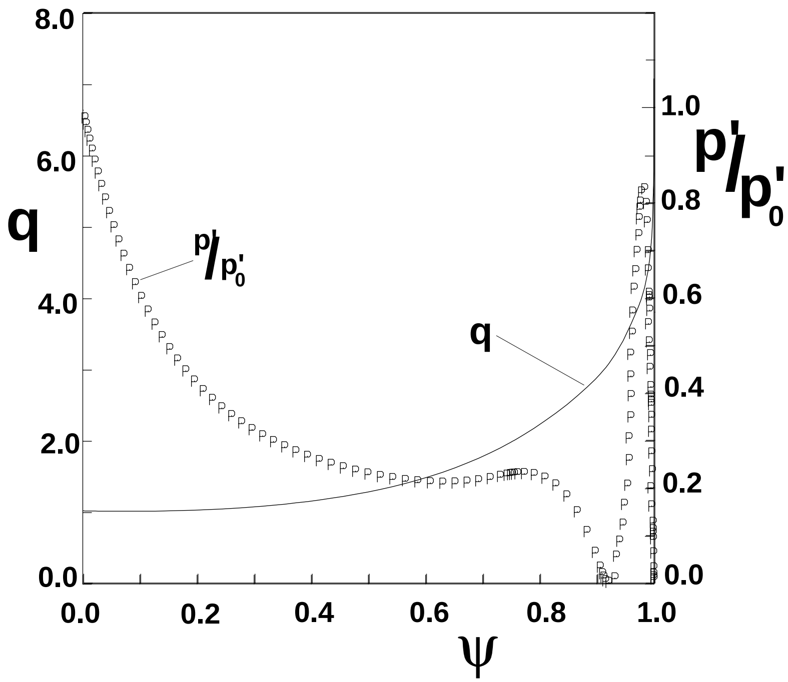
- **Equilibrium and low n (n = 1 through 5) stability analysis performed at 1693 msec and 2075 msec**



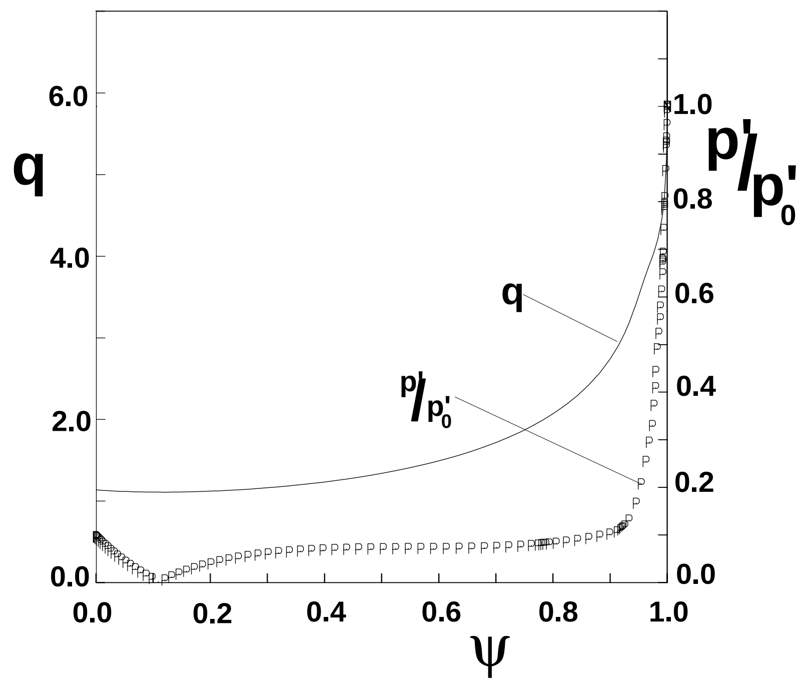
GENERAL ATOMICS

PROFILES FOR DISCHARGE #92001 SHOW A LARGE P'$_{edge}$ IN ELM FREE PERIOD AND JUST BEFORE THE ELM

- **ELM Free Period**



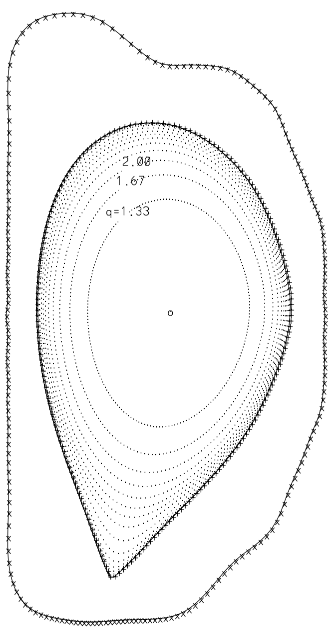
- **Just before ELM**



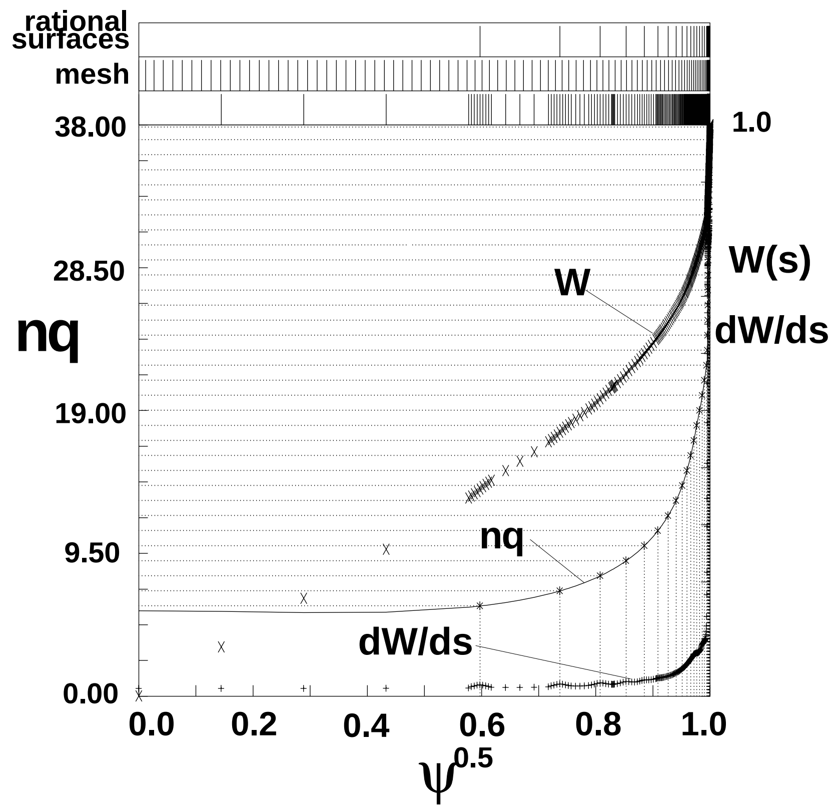
GENERAL ATOMICS

STABILITY CALCULATIONS INCORPORATE ESSENTIAL DETAILS OF CURRENT PROFILE AND THE PLASMA AND WALL SHAPE

- Realistic DIII-D wall:
  - Plasma boundary set within 10^{-4} of separatrix
  - Up-down asymmetry



- Mesh packing used to resolve the edge



GENERAL ATOMICS

STABILITY CALCULATIONS FOR n=1 AND n=2 SHOW COMPLETE STABILITY

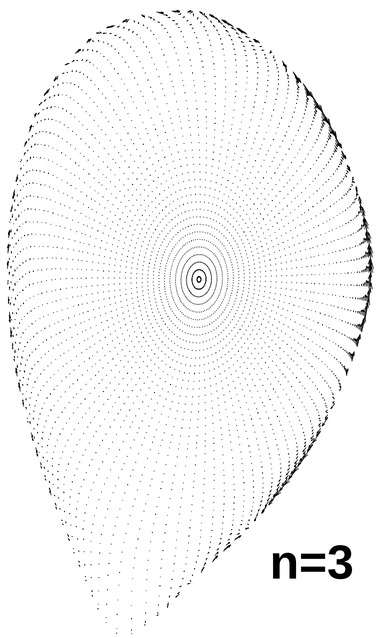
- **Best fit to equilibrium data at 1693 msec yields $q_0 = 1.02 \pm 0.1$**
  - **Unstable to n = 1 quasi-interchange mode**
    - » **increasing q_0 to 1.05 $\Rightarrow$ stable to n = 1 with or without wall**
  - **Stable to n = 2 with or without a wall**

- **Best fit to equilibrium data at 2075 msec yields $q_0 = 1.13 \pm 0.1$**
  - **Stable to n = 1 with or without a wall**
  - **Stable to n = 2 with or without a wall**

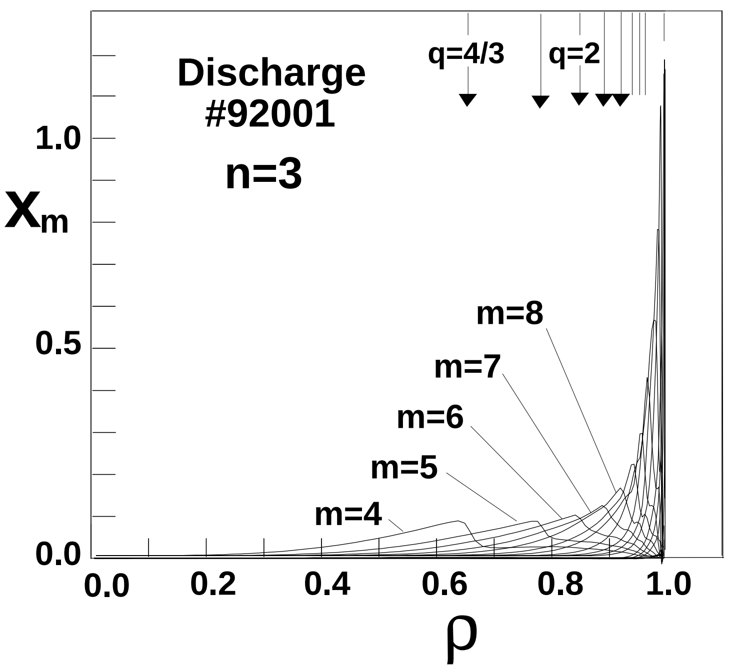
GENERAL ATOMICS

UNSTABLE IDEAL n=3 MODE JUST BEFORE TYPE I ELM IS A KINK-PEELING MODE

- **Mode displacement**



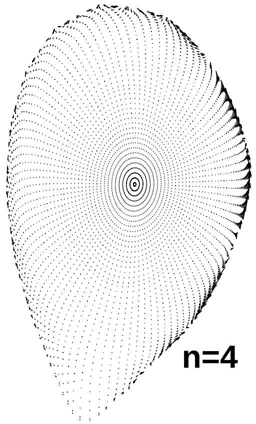
- **Fourier decomposition**

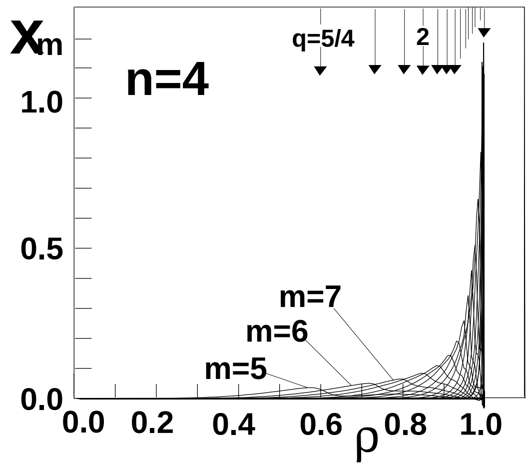


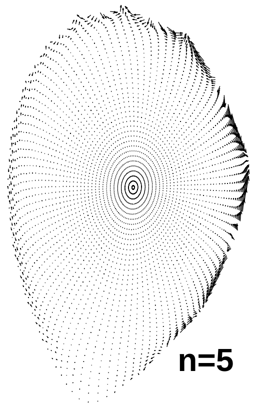
GENERAL ATOMICS

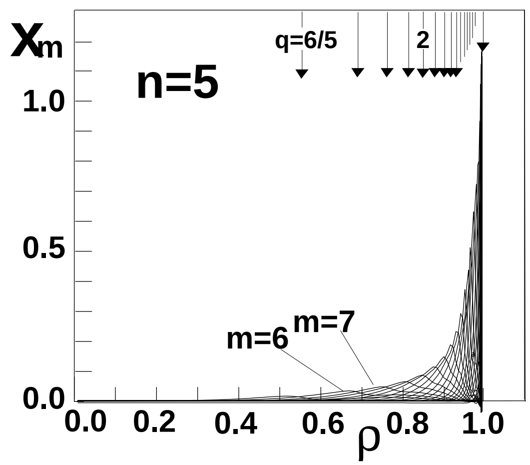
UNSTABLE IDEAL n=4 AND n=5 MODES ARE ALSO KINK-PEELING MODES

- **Mode displacement**
- **Fourier decomposition**









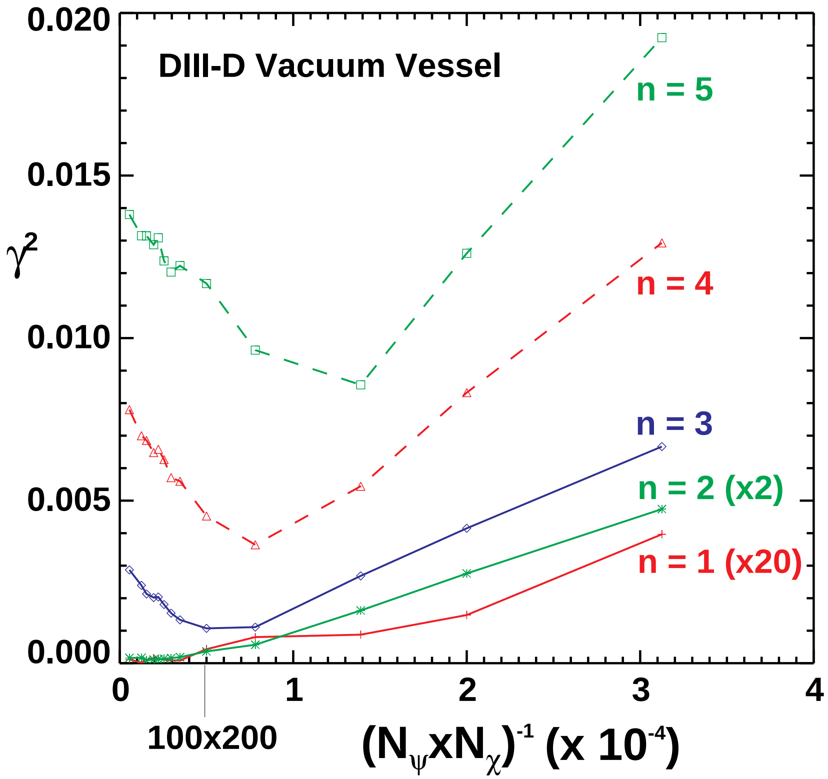
GENERAL ATOMICS

MESH CONVERGENCE STUDIES SHOW COMPUTED n=3,4, AND 5 UNSTABLE MODES ARE WELL RESOLVED

- **Convergence from stable side typical for unstable peeling modes**
  - **marginally unstable n=2 mode at extremely high resolution**
    - » **sensitive to small variations in equilibrium => can be ignored**

- **n=3,4,5 modes are well converged at $N_\psi x N_\chi$ = 100x200**

- **Mesh Convergence**



GENERAL ATOMICS

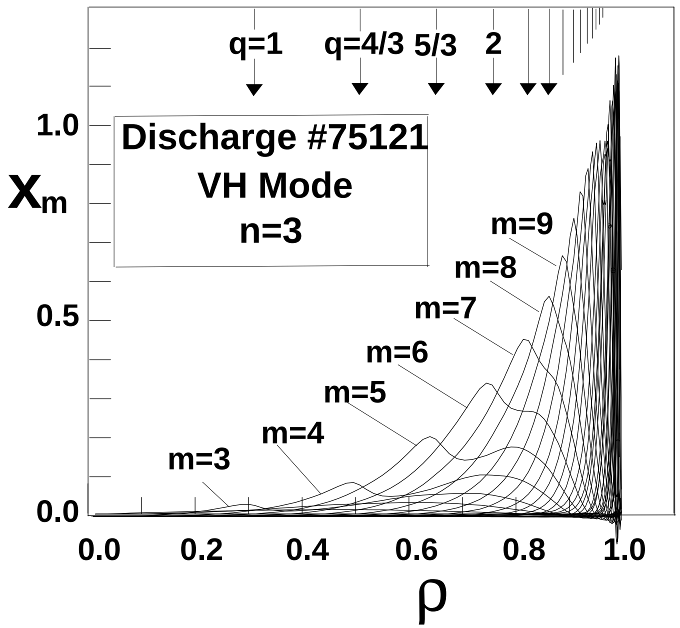
RESULTS ARE CONSISTENT WITH INTERPRETATION OF VH TERMINATION EVENT AS A LARGE BROAD ELM

- **VH Mode termination and Type I ELM instabilities are both low to intermediate n 'peeling' modes with considerable 'ballooning mode' structure**
  - $\Rightarrow$ **partly pressure driven and partly current driven**

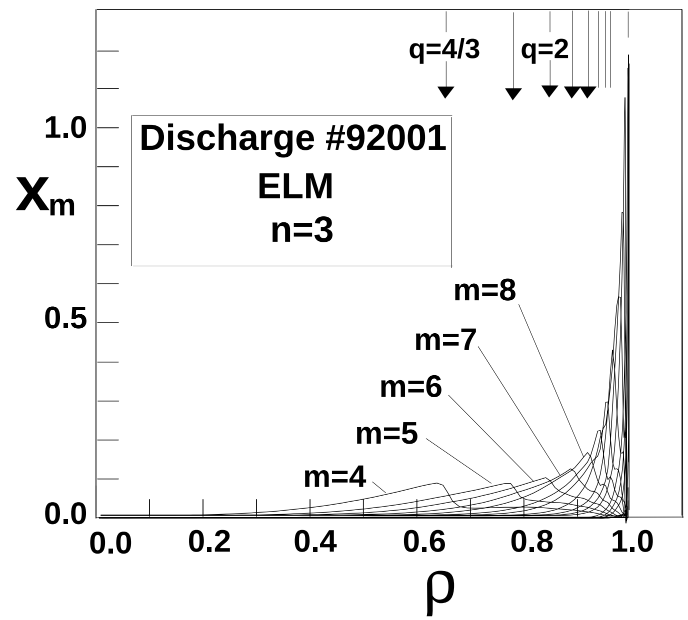
- **VH Mode termination is similar but is lower n and has a broader radial extent**
  - $\Rightarrow$ **more dangerous**
  - $\Rightarrow$ **leads to irreversible collapse of high performance phase**

ELM IS MORE RADIALLY LOCALIZED THAN VH MODE TERMINATION INSTABILITY

- **VH Termination:**
  Discharge #75121 n=3



- **ELM:**
  Discharge #92001 n=3



CAUTIONARY REMARKS

- **Ordinary Type I ELM instability is not always found from calculations:**
  - stability depends sensitively on j_{edge}
  - requirement of 'reasonable' alignment of j_{BS} and j_{edge} in order to impose consistency with ballooning stability does not fully constrain j_{edge}
    - » j_{edge} depends on the fraction of the full collisionless bootstrap current j_{BS} that is used
    - » j_{BS} is reduced by collisional effects
    - » full alignment of j_{BS} and j_{edge} may not always be realized in individual discharges

- **Some recent high performance NCS discharges, however, have steep VH-Mode like edge pressure gradients but the ELMs behave more like standard Type I ELMs:**
  - First ELM does not terminate high performance
  - Stability calculations find no low n modes (n = 1,2,3, and 4) unstable
    - $\Rightarrow$ Shape is important: See posters by Lao and Rice and talks by Osborne and Ferron

SUMMARY

- Identification of Type I ELMs in standard ELMing H Mode discharges requires careful equilibrium reconstruction:
  - Internal current profile measurements
  - Accurate representation of edge pressure profile
  - Consistency between reconstructed profiles and observed ballooning mode stability ($\Rightarrow j_{edge} \sim j_{bootstrap}$)

- Calculations are consistent with the view that the VH Mode termination event is a large ELM at lower n and not as radially localized as the standard Type I ELM

- The results suggest the following model:
  ELMs result from a complex interaction between ballooning and low n kink peeling mode stability:
  - ballooning stability determines p'_{edge}
    - » if first regime limited $\Rightarrow$ high n mode????
    - » if second regime access $\Rightarrow$ low or intermediate n mode????
  - low or intermediate n mode is driven partly by the edge p' and partly by the bootstrap current density

GENERAL ATOMICS