Measurement of Edge Currents in DIII–D and Their Effect on the Pedestal

by
D.M. Thomas

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GA:

A.W. Leonard
R.J. Groebner
T.H. Osborne
P.B. Snyder
L.L. Lao
D. Sundstrom
J. Peavy

LLNL:

T.A. Casper

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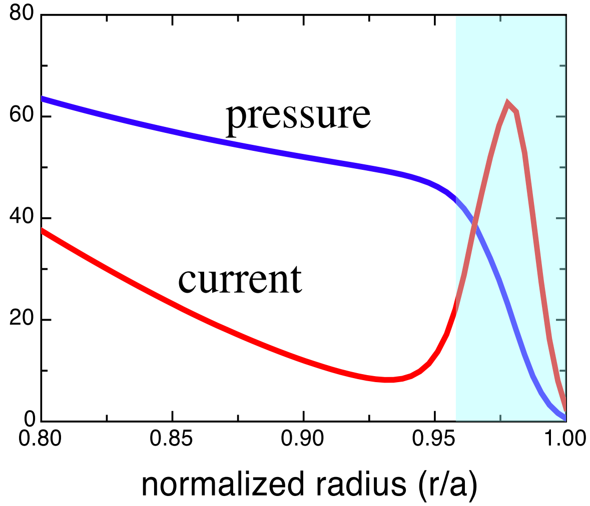
Overview

- The edge current density j(r) is measured to assess its influence on pedestal stability and confinement
  - Use Lithium beam, Zeeman effect to determine local magnetic field profile
  - Calculate the current structure using Ampere's law
- Data from H-mode experiments show evidence for an edge current peak. Peaks reside near the edge, coincident with the edge pressure gradient as predicted by theory. Peaks are of the right magnitude to agree with bootstrap current calculations
- Pre-ELM equilibrium reconstructions using this detailed current information are marginally unstable to low/medium-*n* modes, consistent with linear peeling-ballooning theory

A successful ELM/ Pedestal model requires accurate knowledge of the edge current density



- Pedestal height is directly related to core confinement, fusion performance
- Stability of the pedestal is determined by pressure and a local current
- Current itself is driven by pressure gradient (BS + P-S currents)
  - feedback driven limit on pedestal height
- We have evolved a successful ELM and pedestal model based on peeling-ballooning modes P. Snyder, 19th IAEA, P.O.P. 9,2002
  - Quantitative pedestal stability limits and mode structures
  - Model has been verified against experiment
  - Predictive, if we knew the current distribution

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In toroidal geometry, the parallel current consists of multiple terms

$$j_{\parallel} = j_{\parallel OHMIC} + j_{\parallel P-S} + j_{\parallel BS} + j_{\parallel CD}$$

- The edge current is dominated by Ohmic early on, <u>pressure driven</u> terms later:

$$j_{\parallel P-S} = -\frac{RB_{\phi}}{B}\frac{dp}{d\psi}\left(1-\frac{B^2}{\langle B^2\rangle}\right)$$

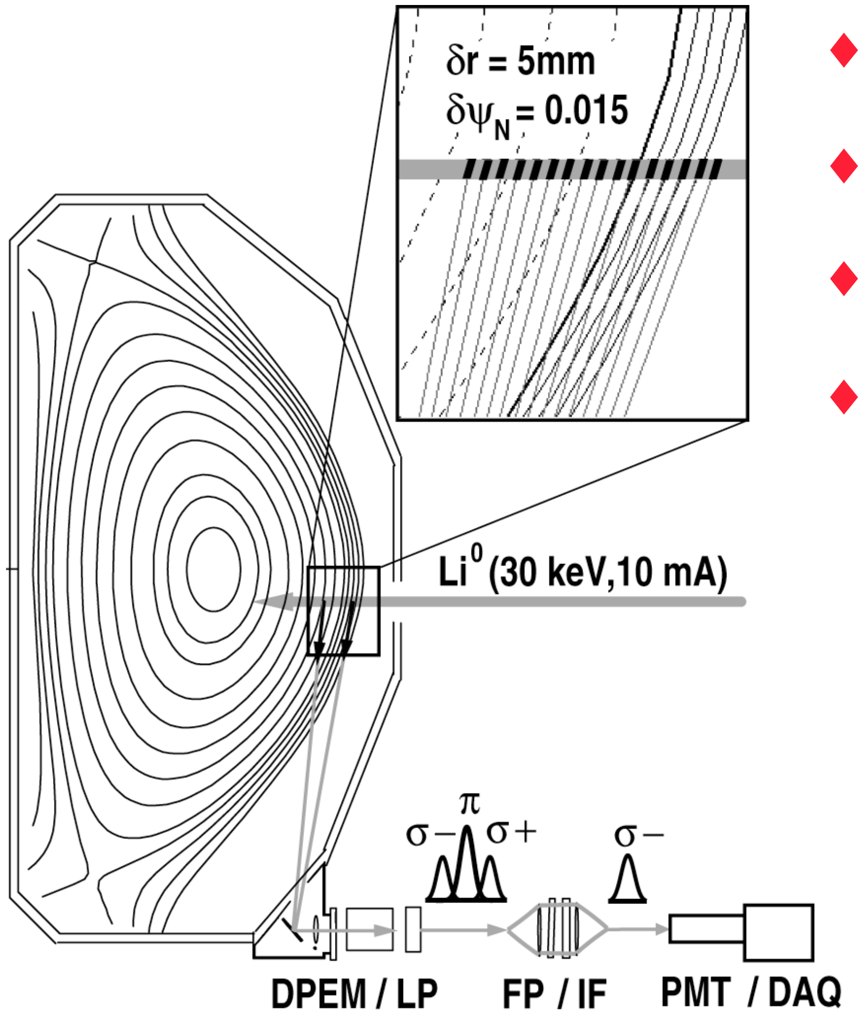
$$j_{\parallel BS} = \frac{\varepsilon^{1/2} n\mathrm{T}}{B_{\theta}}\left[\alpha\frac{dn_e}{d\psi} + \beta\frac{dT_e}{d\psi} + \gamma\frac{dT_i}{d\psi}\right]$$

- Currents play dual role in edge stability:
  - o Stabilize ballooning (pressure-driven) mode.
  - o Destabilize peeling (current driven) modes.

Lithium beam can be used to provide an accurate edge j(r) determination

- We use one of the Zeeman components of the ^{6}Li 670.8 nm 2S-2P resonance line.
  - Quantum-mechanical effect, line has well determined splitting and polarization characteristics in a B field.
- Measurement is purely a B-field effect.
  - 2S-2P state separation ensures no Stark mixing
  - No electric field sensitivity or ambiguity
- Strategy: inject lithium beam, analyze the polarization of emitted radiation in edge region, relate to B, infer $j_{\phi}(r)$.
- Small beam + large excitation rate
  - Good signals, good spatial localization.
  - Beam penetration sufficient for H-mode edges.

We have installed a 32 channel LIBEAM polarimeter system on the DIII-D Tokamak



- Good tangency to flux surfaces for wide variety of discharges
- This resolution is required by need to identify localized structure in B_{POL}
- Select the $\sigma-$ line with narrowband filter
- Measure ratio of CP to LP using dynamic polarimetry to identify field component along viewchord B_{VIEW}:
(D.M.Thomas, RSI 74,3, 1541 (2003).

$$B_{VIEW}(R,z) = |B| \cos(\alpha)$$

1) Use as EFIT constraint
2) Solve directly using Ampere's Law:

$$\mu_0 j_{TOR} = \frac{\partial B_R}{\partial z} - \frac{\partial B_z}{\partial R} = F\left(B_{VIEW}, \frac{\partial B_{VIEW}}{\partial R}\right)$$

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A profile of B_{VIEW} is determined from the polarization measurements

- **Bview ~ Bpol (fraction of a percent, depending on discharge)**
  - Use EFIT lBl values at view locations to calculate Bview from cos(α)
  - Negligible errror (<0.1%)introduced

- **Individual channels are calibrated using equilibria from ohmic discharges (negligible edge current)**
  - Use NBI blips for full kinetic treatment in EFIT
  - Process corrects for individual variations in etalon filters
  - Yields calibration factor for each channel

- **Use companion shots to correct for background light in filters**
  - Background is unpolarized, but can affect Bview calculation due to specific method of determining polarization ratio
  - Important at low light levels

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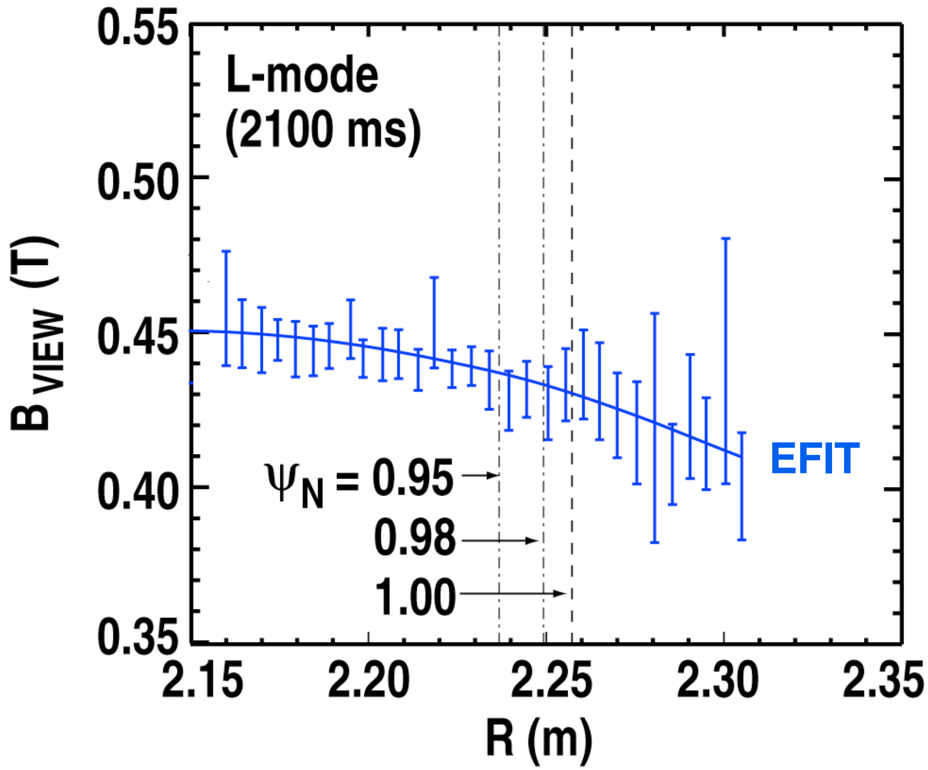
L-Mode: measurements show little structure in edge poloidal field

- Field profiles are easily determined in L-mode
  - Small statistical error, due to low density, modest attenuation
  - Good data region covers most of edge
  - Typically get very good agreement between the measured B_{VIEW} profile and that calculated from an EFIT reconstruction



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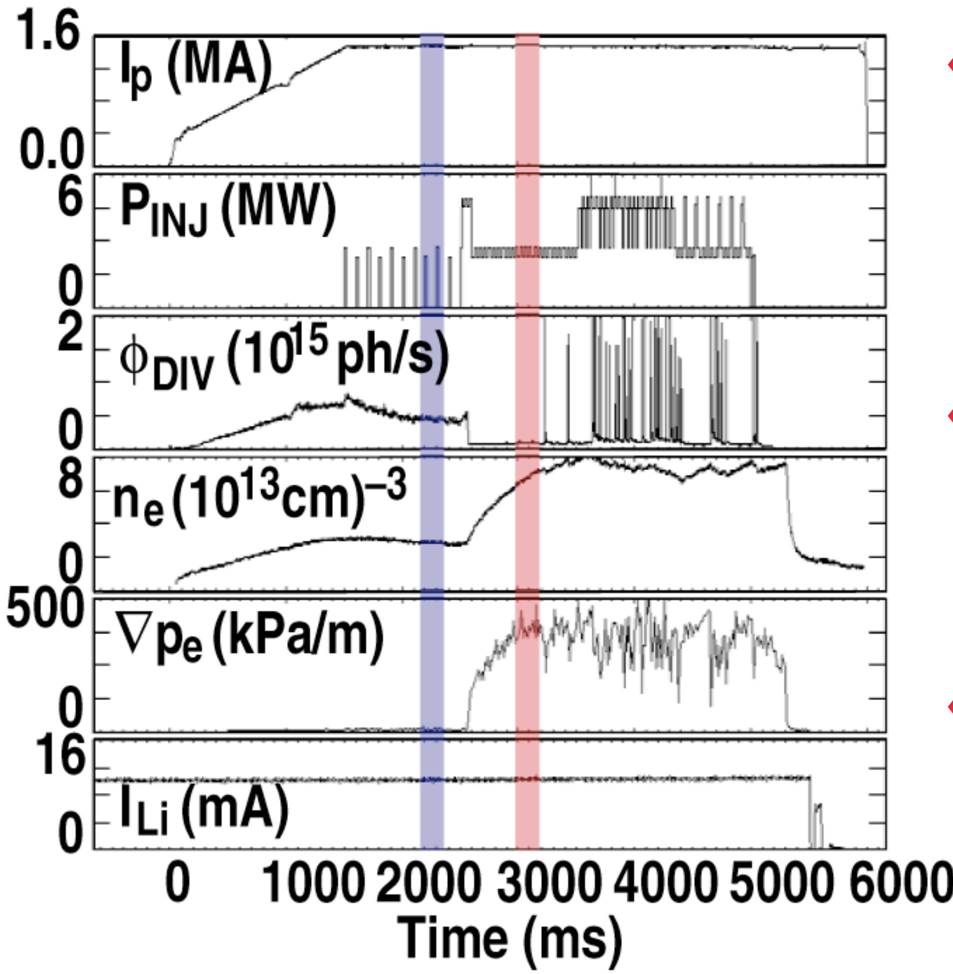
Measurements during high edge pressure gradient experiment reveal local B_{VIEW} changes



- The L-H transition is followed by an extended ELM-free period where the pedestal pressure rises to very high values
- The pedestal pressure growth is then limited by intermittent giant Type 1 ELMS
- We concentrate on evolution of currents during long ELM-free H-mode, compare to L-mode

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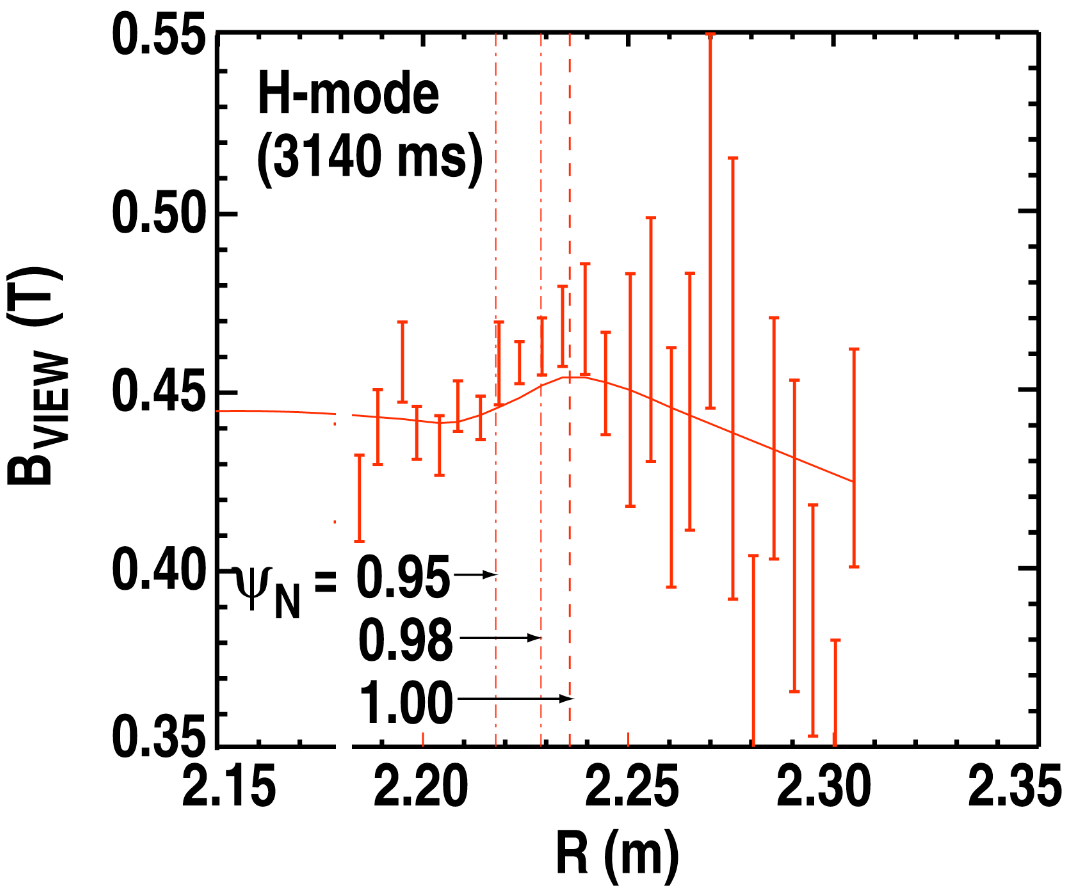
Local magnetic field profile changes substantially during ELM free H-mode phase

- Divergence in B_{VIEW} profile near edge => current peaking



- Error bars increase due to lower signal levels

=> Decreased time resolution

- Still have a 'sweet spot'- a range of R which have small statistical errors

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The local current density may be estimated directly from the measurement

- A straightforward approach is to recast Ampere's law

$$\mu_0 j_{TOR} = \frac{\partial B_R}{\partial z} - \frac{\partial B_z}{\partial R}$$

using known spatial calibration and estimate of flux shape $\tan\theta_B = (B_R/B_z)$ in region of interest (from EFIT) Thomas,RSI 75,10,4109(2001)

- This allows us to derive a simple parameterization for $J_{TOR}(r)$ in terms of B_{VIEW}, $d(B_{VIEW})/dR$, $\tan\theta_B$ and its derivatives.

$$u_0 j_{TOR} = f\left\{ B_{VIEW}, \frac{dB_{VIEW}}{dR}, \tan^2\theta_B, \frac{\partial \tan\theta_B}{\partial z}, \frac{\partial \tan\theta_B}{\partial R} \right\}$$

- The main uncertainty: error taking derivatives of data

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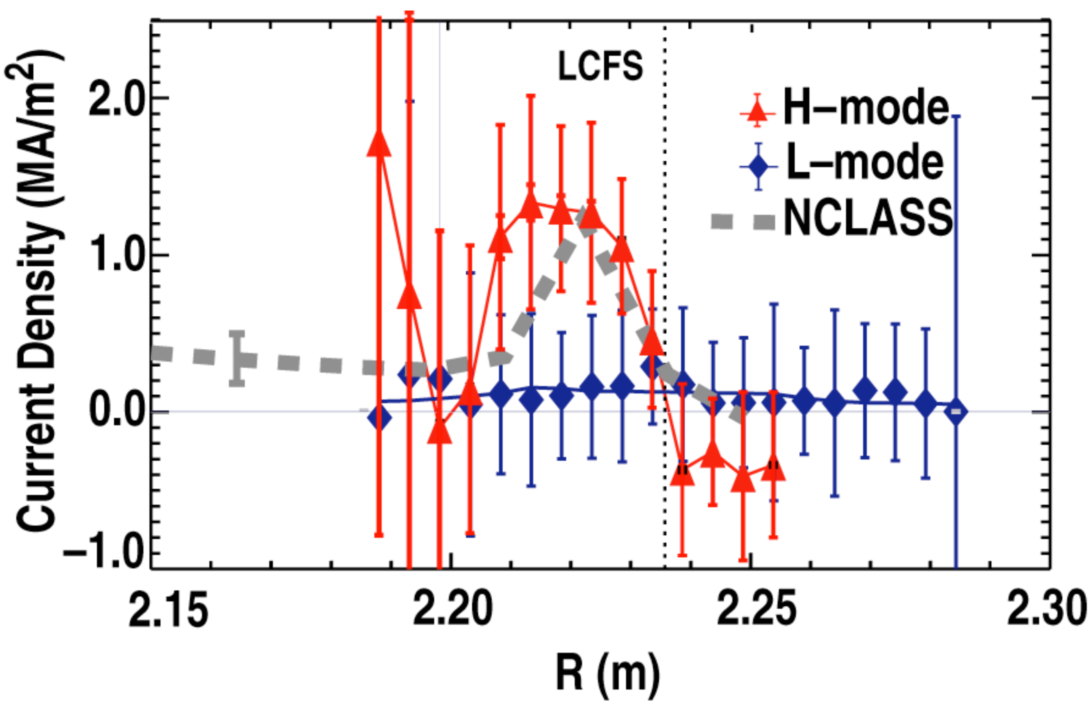
The calculated toroidal current compares well with model predictions

- Comparison with kinetic EFIT prediction based on measured pressure profiles
- EFIT current shape constrained by NCLASS bootstrap model in edge
- Good qualitative agreement

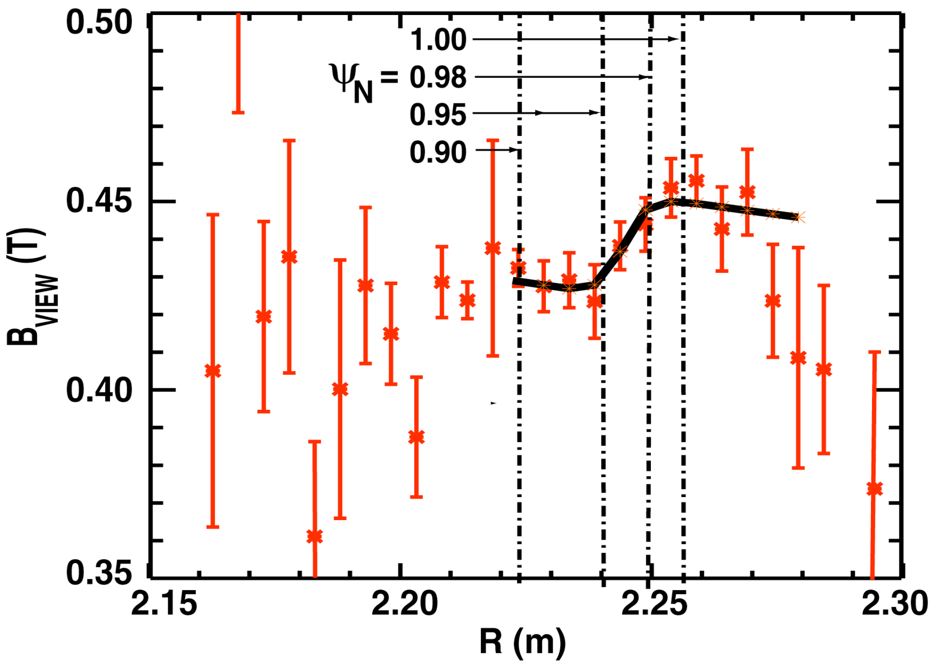
Thomas et al., PRL 93,6,065003 (2004)



B_{VIEW} fitting model improves J_ϕ evaluation

- **We use a modified tanh model for fitting the measured profiles:**

$$B_{FIT} = A_0 \tanh\left(\frac{R - A_1}{A_2}\right) + \frac{A_3}{R - A_4} + A_5$$

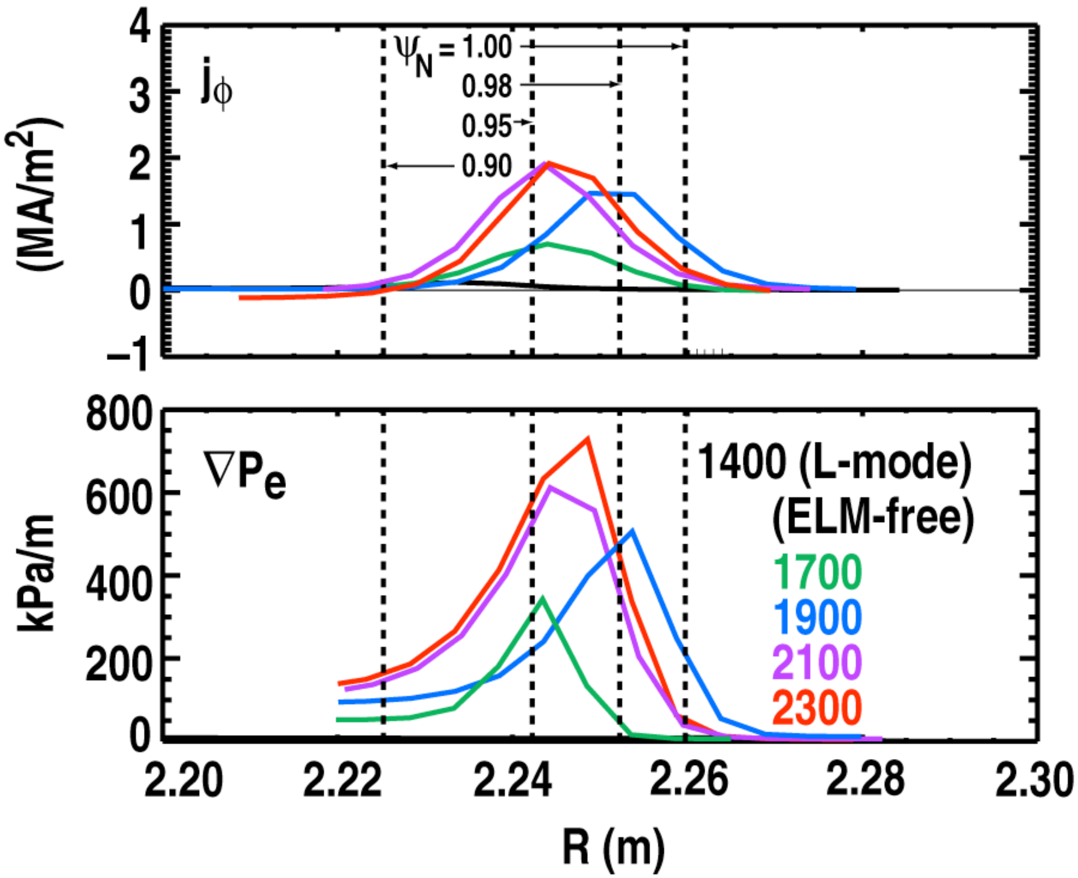


- **Edge pressure is already well characterized using tanh formalism**
- **Emphasizes changes between L and H-mode**
- **Gives good fits to data in relevant range**

- **This results in a modified $sech^2$ form for the edge current**
  - **Reasonable parameterization for Jr shape, allows self consistent comparisons. Avoids numerical derivative errors**

The measured currents are located near the peak of the edge pressure gradient

- Exactly as expected from the model for current generation
- Time evolution also follows pressure gradient growth



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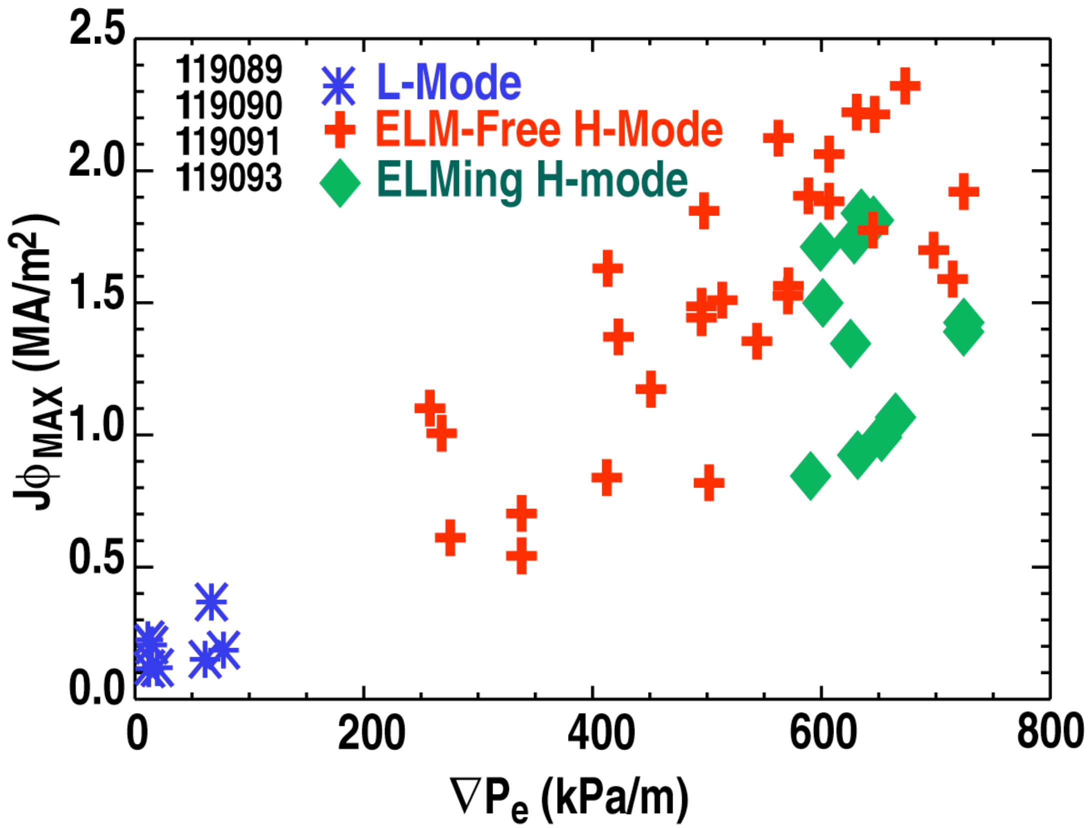
Measured currents grow monotonically with evolution of edge pressure gradient



- Evidence for saturation of current at highest pressures prior to ELMing phase
- Currents in ELMing phase systematically lower (but averaged over ELM cycles)
- Try to follow through ELM cycle, but time resolution still an issue

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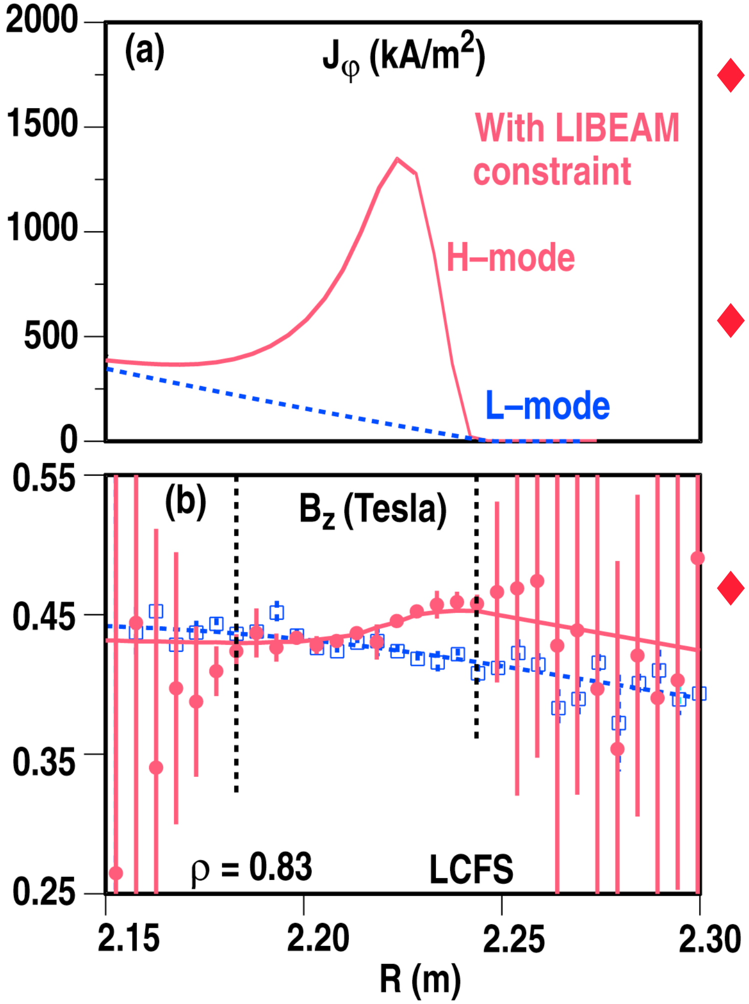
Equilibrium Reconstructions and LIBEAM

- **Important for two reasons:**
  - **Tests of <u>stability models</u> require best possible equilibria**
  - **Tests of specific bootstrap models also need good equilibria**
    - **To provide accurate mappings for requisite diagnostics**

- **Use our measurements with EFIT, CORSICA in two ways:**
  - **May compare the predictions of various equilibria with measurement by comparing calculated field and current profiles**
  - **May use the measurements as a constraint on equilibrium solutions, similar to the way MSE values are handled**

LIBEAM data can be used to strongly constrain EFIT reconstructions



- The LIBEAM magnetic field data are used as constraints on EFIT equilibrium solutions along with magnetics and MSE
- The resulting calculated Bz profiles from EFIT are plotted as solid (H) and dashed (L) lines
- The resulting calculated toroidal current for the two cases. Again, H-mode profile shows a clear peak in the current density near the separatrix, with a peak value in excess of 1MA/m^2

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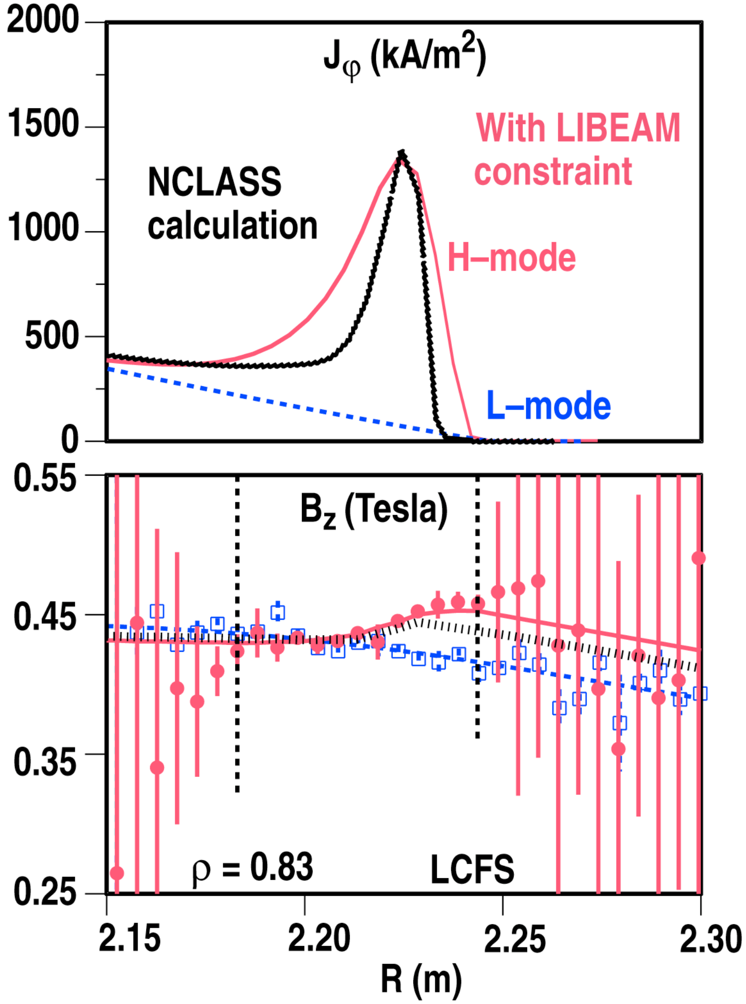
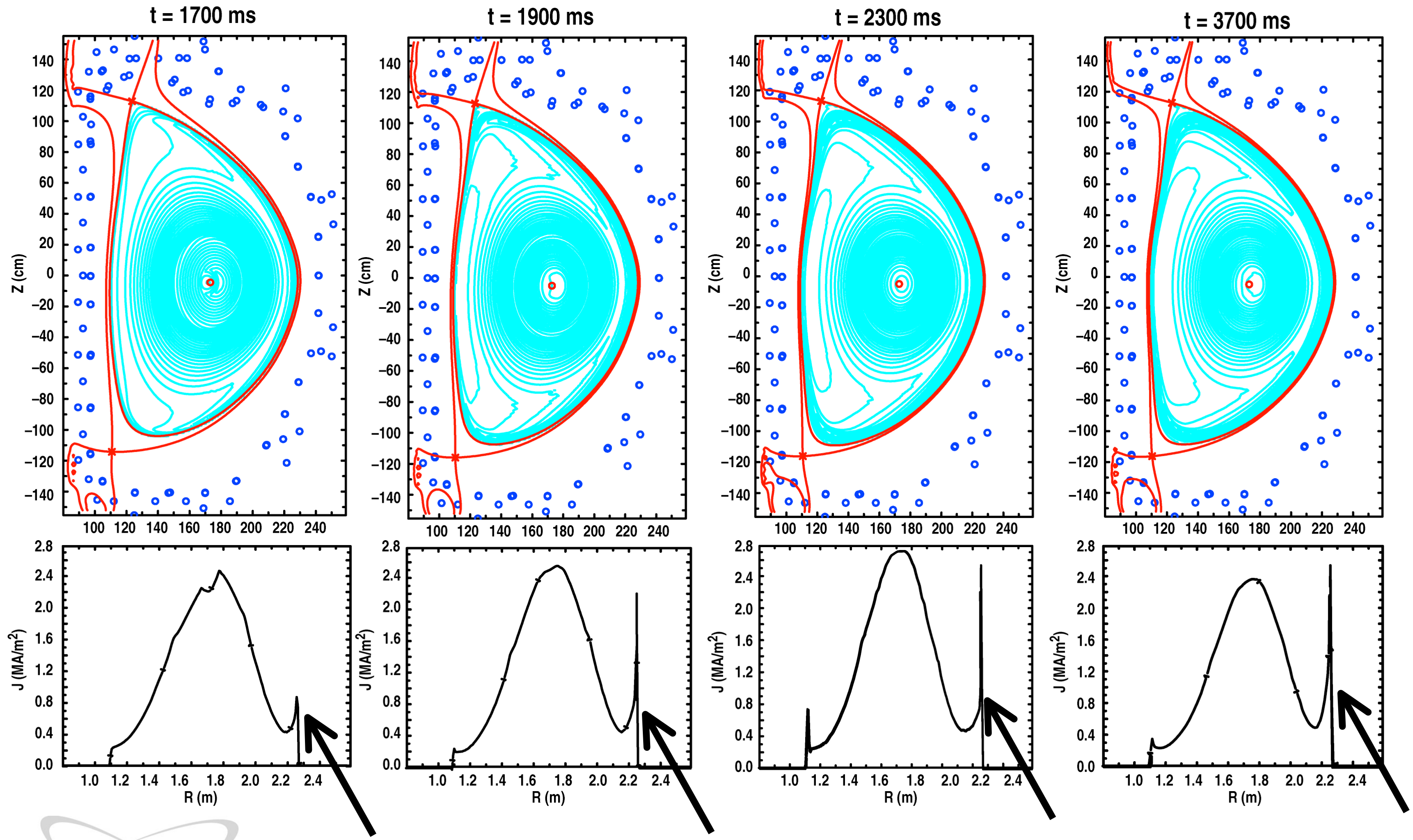
Resulting current density agrees well with neoclassical calculation



- Compare the current density from **lithium beam constrained solution (red curve)** with a calculated bootstrap current constraint
- The black dashed curve is from an equilibrium reconstruction whose edge jϕ constrained by a bootstrap current calculated using the NCLASS model
- Measurement somewhat wider than prediction

CORSICA reconstructions also show growth of edge current peak during ELM free phase

Current Contour Plots---ELM-Free phase **ELMing phase**



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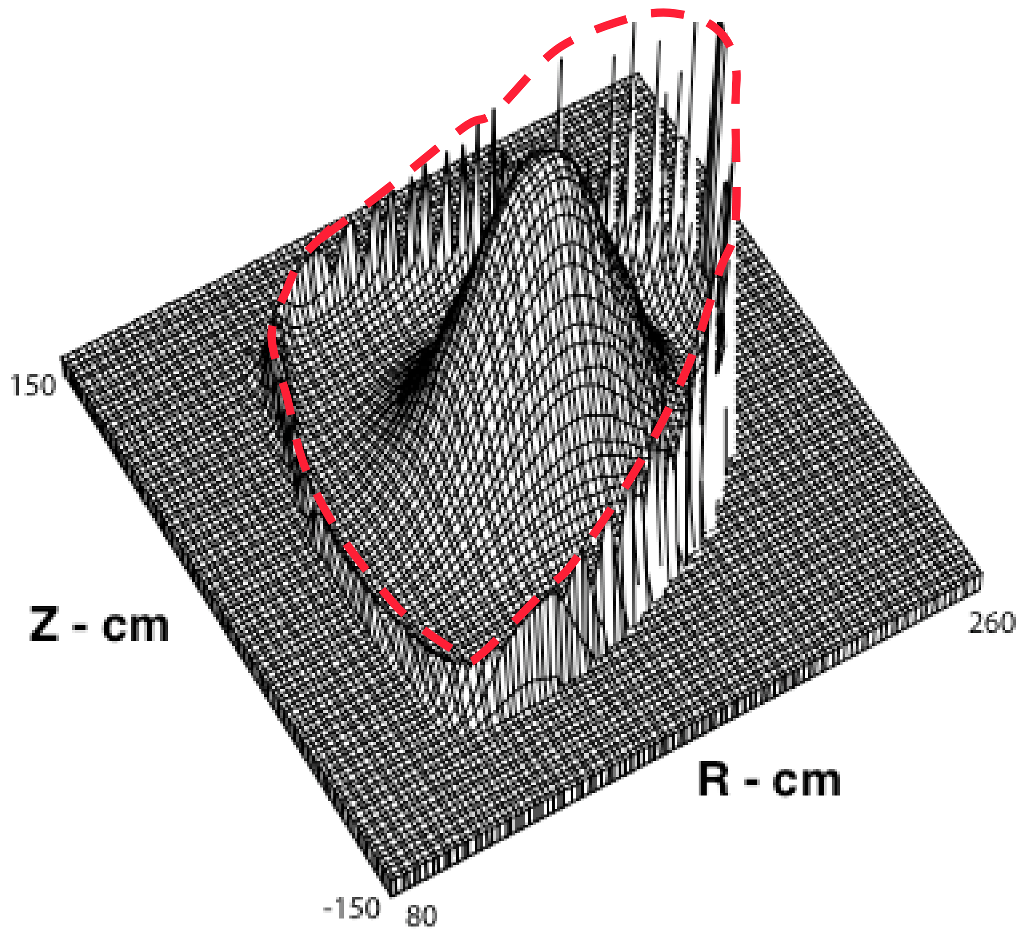
CORSICA current structure at end of ELM-free period is extremely peaked

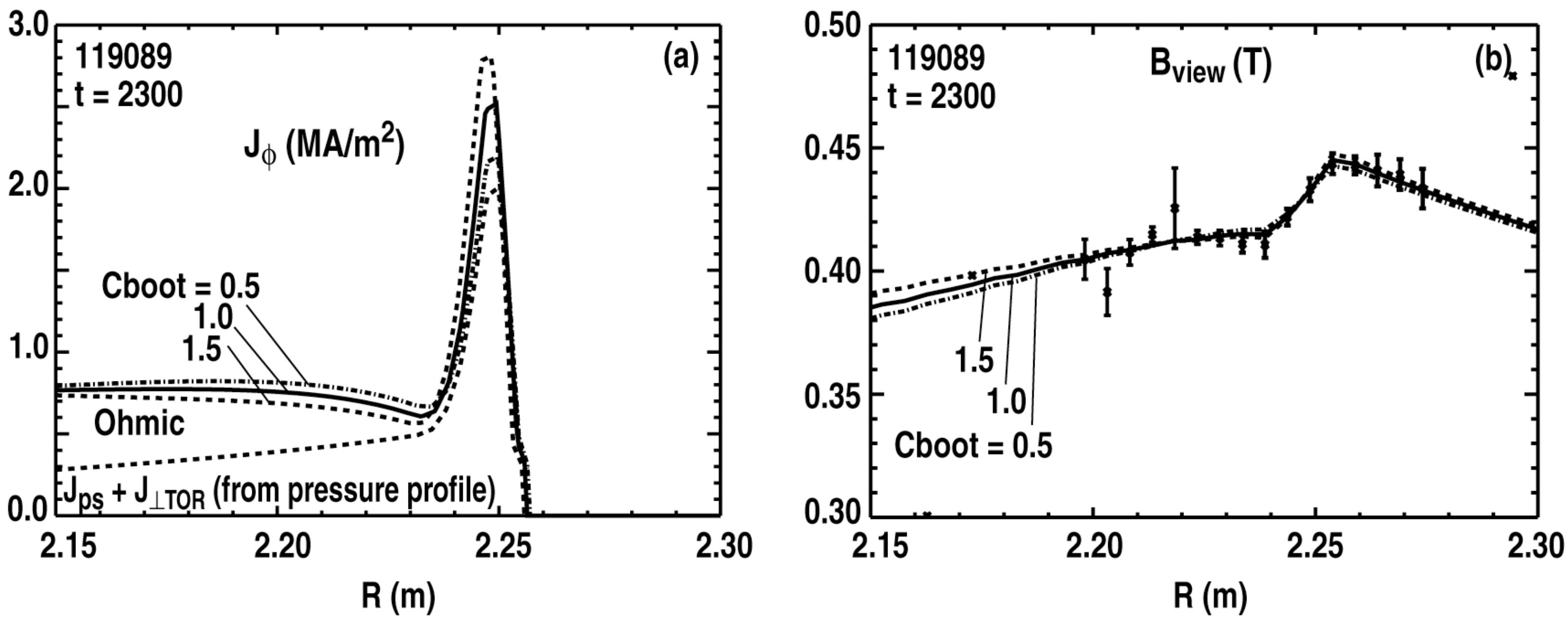


2D current density distribution -- 119089 at 2300ms

- Particularly on outside midplane, where Pfirsch-Schluter and Bootstrap components are additive.
- Poloidal structure is just an artifact of grid size in equilibrium solver

High edge current equilibria represent a special challenge

- For kinetic fits current shape calculated in G.S. solution is **dominated by shape of pressure profile**
  - Bootstrap current can be smaller locally than $J_{P\text{-}S}$
  - Libeam values are consistent, but weakly constraining fit
  - Neeed to be careful on mapping, parameterization…



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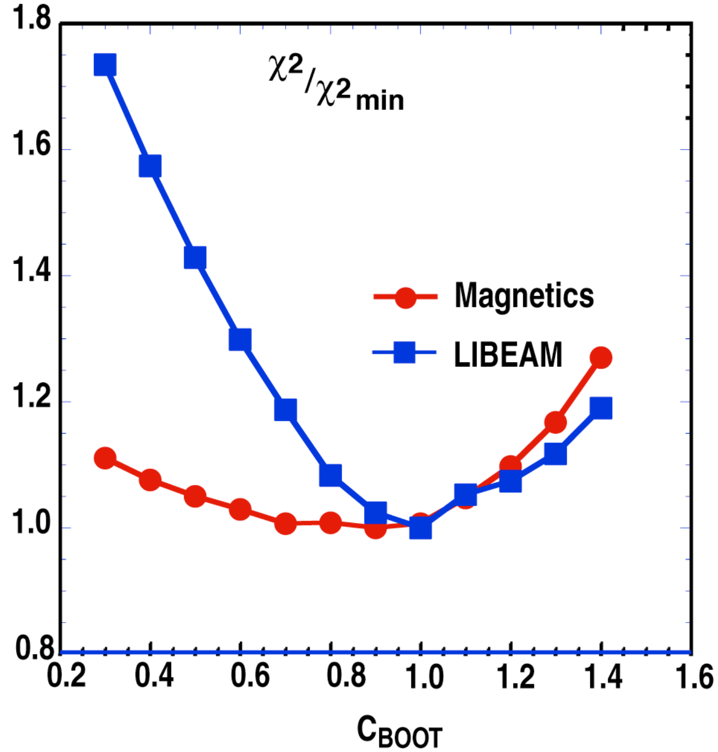
CBOOT ~1 consistent with measurement

- **Ran a series of full kinetic equilibria where Sauter bootstrap model was assumed and used to scale edge current density peak by a factor C_{BOOT}. A shallow minimum around C_{BOOT} = 1 is found for both magnetics and LIBEAM data.**



- **Indicates that our assumptions about J_{BS} for stability modeling are valid**

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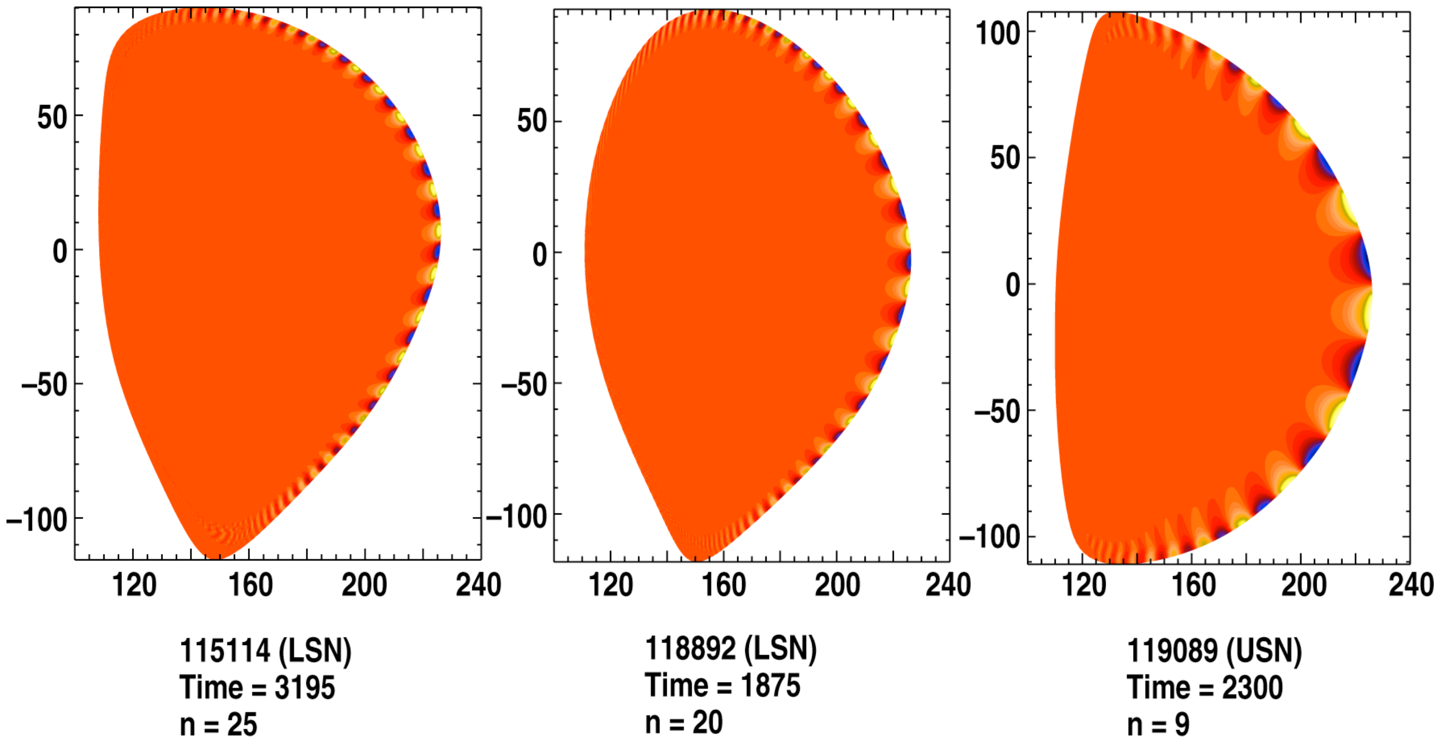
These late ELM-free equilibria are marginally stable to low/medium *n* modes (ELITE, Snyder,P.O.P, 2003)



- **Consistent with the approach to an ELMing state expected from the stability model, where lower and lower *n* modes become successively unstable as current and pressure increases**
- **The radial depth of the ELM correlates with the depth of the most unstable mode** **Leonard, P.O.P. 2003, Wade, paper CI2A.002, this conference.**

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Conclusions

- B_{POL} measurements using LIBEAM have confirmed the existence of a large localized current in the region of the edge pressure gradient
  - ELM-free H-mode - see evidence for 1- 3 MA/m^2 at time of peak ∇p. Also seen in QH-mode, VH-mode
  - Spatial location and evolution of the current peaks is coincident with ∇p_e to within the mapping uncertainty. Clearly pressure driven
  - ELMing phase average current is somewhat lower
- Can use Ampere's law to interpret j_ϕ directly from measurement
  - Amplitude is consistent with the measured pressure profile and a collisional bootstrap current with C_{BOOT} = 1
  - Justified in using existing bootstrap assumptions for stability studies

Conclusions

- **The measured profiles have been used in equilibrium reconstructions**
  - **Excellent agreement between measured and calculated poloidal field profiles**
  - **Kinetic fits - find large Pfirsch-Schluter currents, weakly dependent on J_{BOOT} or LIBEAM constraints**
- **ELITE stability calculations using the resulting equilibria indicate toroidal modes in the medium to low (10-25) n range are marginally stable shortly before the first ELM crash**
  - **Consistent with linear PB model predictions for ELM approach**
- **Future work:**
- **Variation of bootstrap models in gradient region w/ rapid n,T, ν* changes**
- **Investigate inter-elm behavior of current.** Snyder, paper JI2.005, this conference.

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