Status of BOUT++ Simulations

X. Q. Xu

Lawrence Livermore National Laboratory

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2011 BOUT++ Workshop

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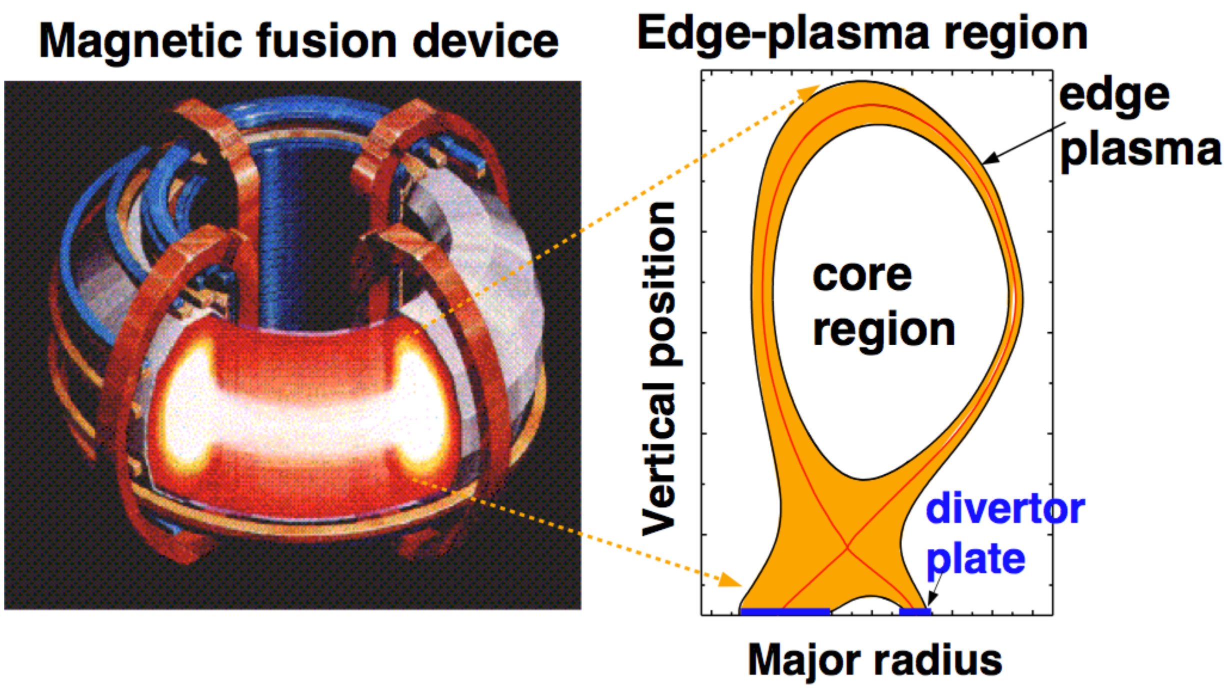
Tokamak edge region encompasses boundary layer between hot core plasma and material walls

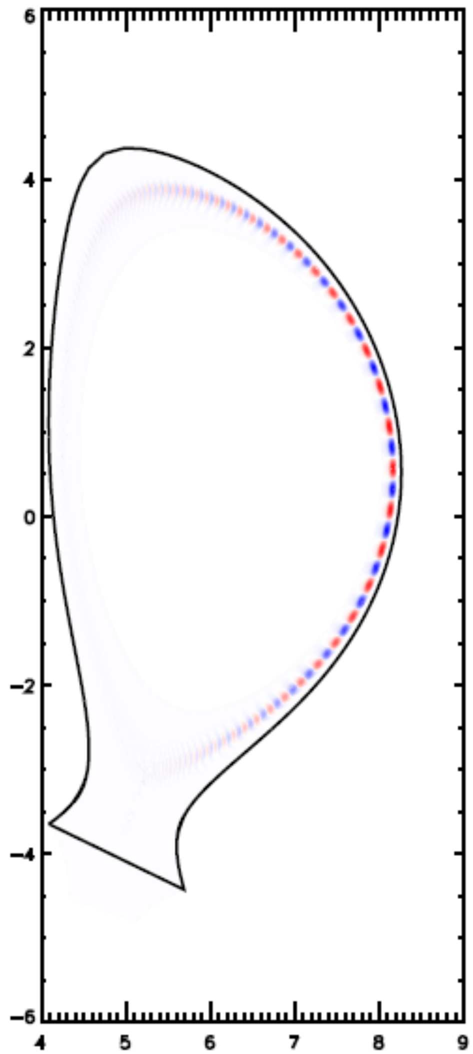
- Complex geometry
- Rich physics (plasma, atomic, material)

- Sets key engineering constraints for fusion reactor
- Sets global energy confinement



BOUT (BOUndary Turbulence) was originally developed at LLNL in late 1990s for modeling tokamak edge turbulence*

- **Boundary Plasma Turbulence has a different characters than in the core and play an important role in the core confinement**
- **BOUT is an unique code to simulate boundary plasma turbulence in a complex geometry**
  - **Observed large velocity shear layer**
  - **Proximity of open+closed flux surface**
  - **Presence of X-point**
- **BOUT/ BOUT++ codes has being applied to DIII-D, C-MOD,NSTX, MAST, ITER senarios, ⋯**



** X.Q. Xu and R.H. Cohen, Contrib. Plasma Phys. 38, 158 (1998)*
Xu, Umansky, Dudson & Snyder, CiCP, V. 4, 949-979 (2008).

BOUT++ is a successor to BOUT, developed in collaboration with Univ. York*

BOUT++
Boundary Plasma Turbulence Code

Original BOUT, tokamak applications on boundary turbulence and ELMs with encouraging results

BOUT-06: code refactoring using differential operator approach, high order FD, verification

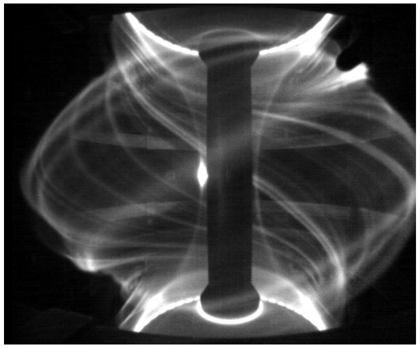
BOUT++: OOP, 2D parallelization, applications to tokamak ELMs and linear plasmas

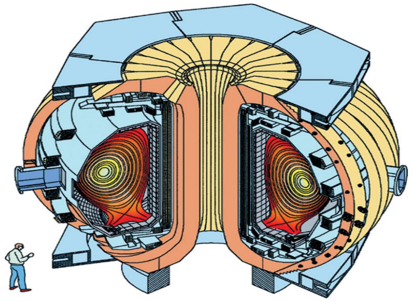
- ✓**Gyro-fluid extension**
- ✓**RMPs**
- ✓**Neutrals & impurities**
- ✓**Preconditioner**
- ✓**Massive concurrency**

2000 2005 2011

•**Umansky, Xu, Dudson, et al., , Comp. Phys. Comm. V. *180 , 887-903 (2008).***
Dudson, Umansky, Xu et al., Comp. Phys. Comm. V.180 (2009) 1467.
Xu, Dudson, Snyder et al., PRL 105, 175005 (2010).

BOUT and BOUT++ have been products of broad international collaborations





GENERAL ATOMICS

Argonne NATIONAL LABORATORY

ILLINOIS INSTITUTE OF TECHNOLOGY

THE UNIVERSITY of York

THE UNIVERSITY OF CALIFORNIA UCLA

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BERKELEY LAB

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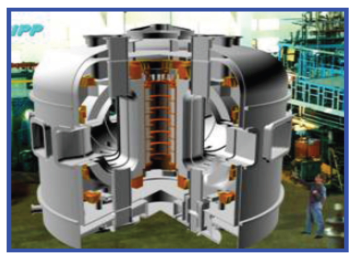


Institute of plasma Physics
Chinese Academy of Sciences

MIT PSFC

THE UNIVERSITY of WISCONSIN MADISON

ifts 浙江大學聚變理論與模擬中心

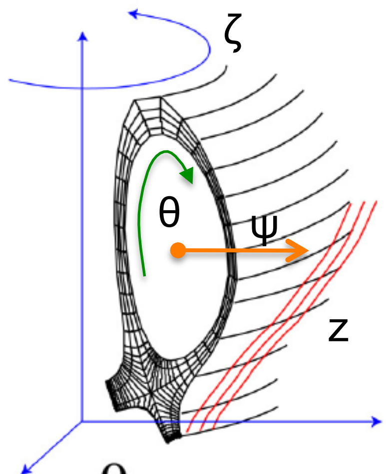
Institute for Fusion Theory and Simulation, Zhejiang University

北大聚变模拟中心

Fusion Simulation Center, Peking University

Fusion Energy Sciences

BOUT++ utilizes a coordinate system aligned with the magnetic field for computational efficiency.



Field-aligned coordinates

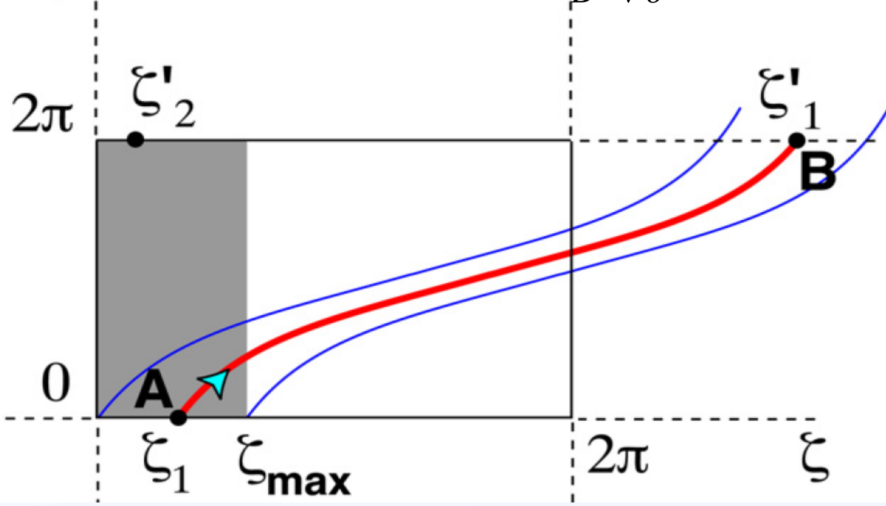
$$x = \psi - \psi_0,$$

$$y = \theta,$$

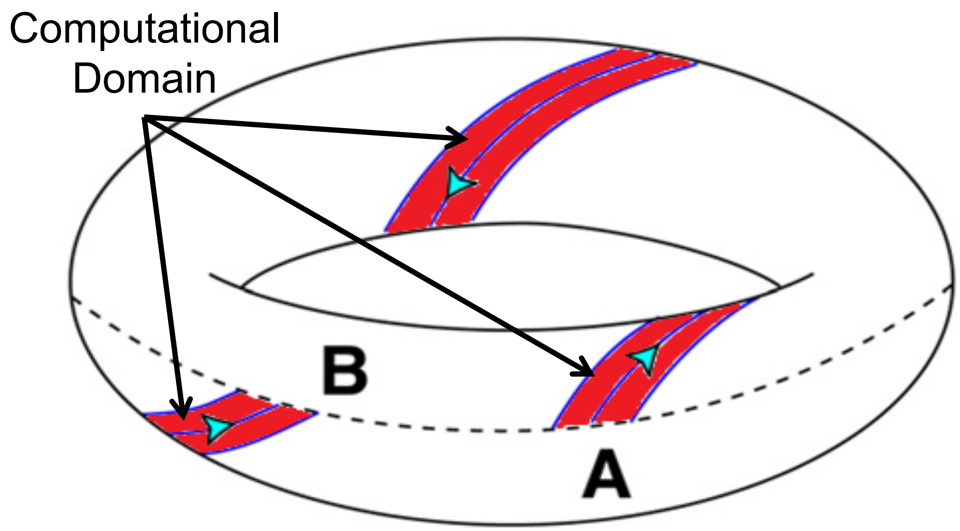
$$z = \zeta - \int_{\theta_0}^{\theta} \nu(\psi,\theta)\, d\theta$$

where ν is the local safety factor given by:

$$\nu(\psi,\theta) = \frac{\vec{B}\cdot\nabla\zeta}{\vec{B}\cdot\nabla\theta}$$



In most simulations, only a fraction of the torus is simulated



The y-periodicity requires a twist-shift condition due to the field-aligned system

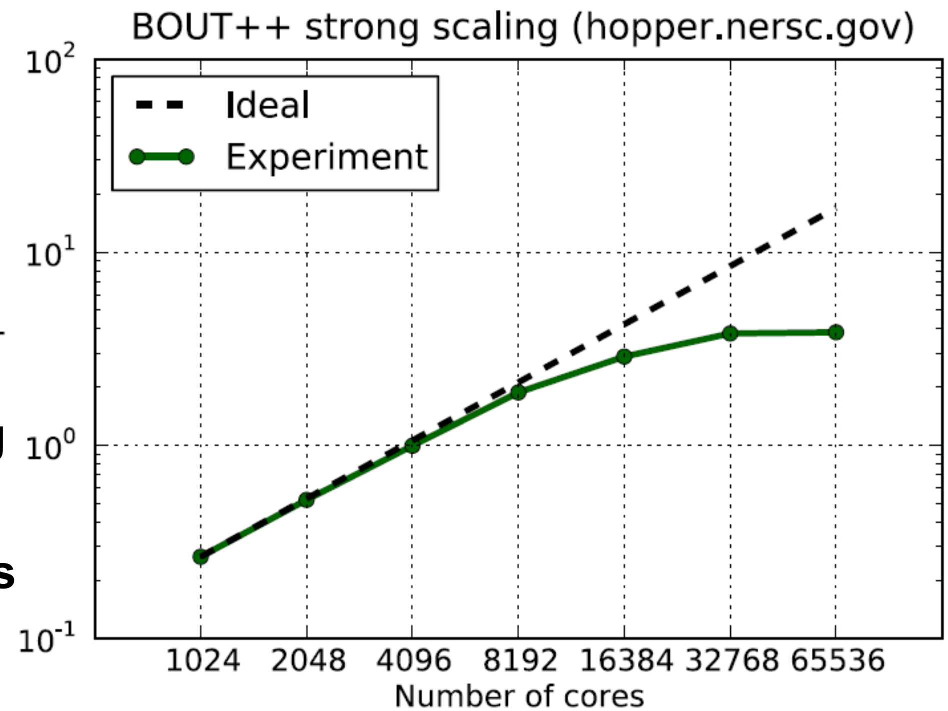
$$F(x, y = 2\pi, z_0) = F(x, y = 0, z_1)$$

$$z_1 = \left(z_0 + \oint \nu dy\right) \mathrm{MOD}\ z_{max}$$

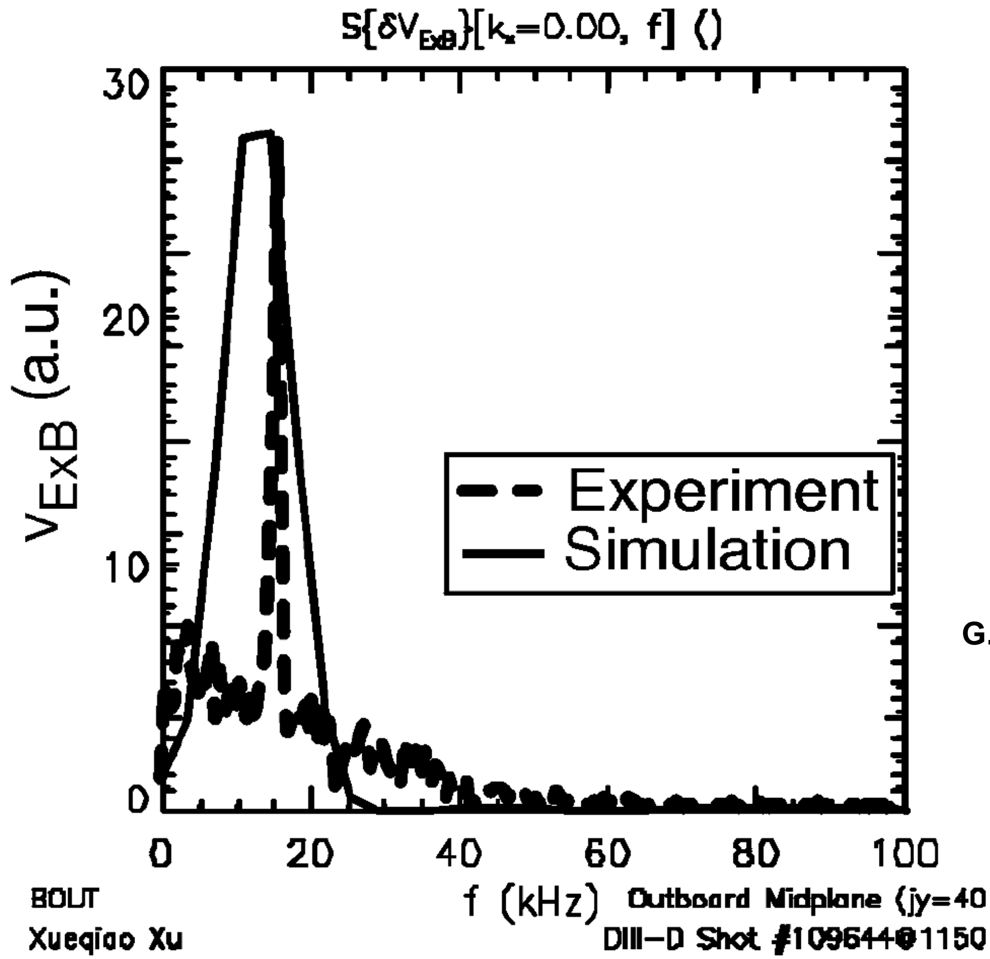
BOUT++ Code can be run at high concurrency

- **Direct numerical simulation of plasma turbulence**
  - **Fluid equations based on Braginskii equations for N_i, T_e, T_i, $V_{||e}$, $V_{||i}$, and ϖ**
  - **Time integration by implicit ODE solver CVODE and PETSc**
  - **Parallel implementation with MPI**
- **BOUT++ provides an object-oriented framework in C++**
  - **Modular!!!**
- **MPI parallelization allows ideal strong scaling to hold up to *10,000* cores!**
- **Multi-developer version control allows for efficient development**

P Narayanan et al. Performance Characterization for Fusion Co-design Applications". In: Proceedings of CUG (2011).

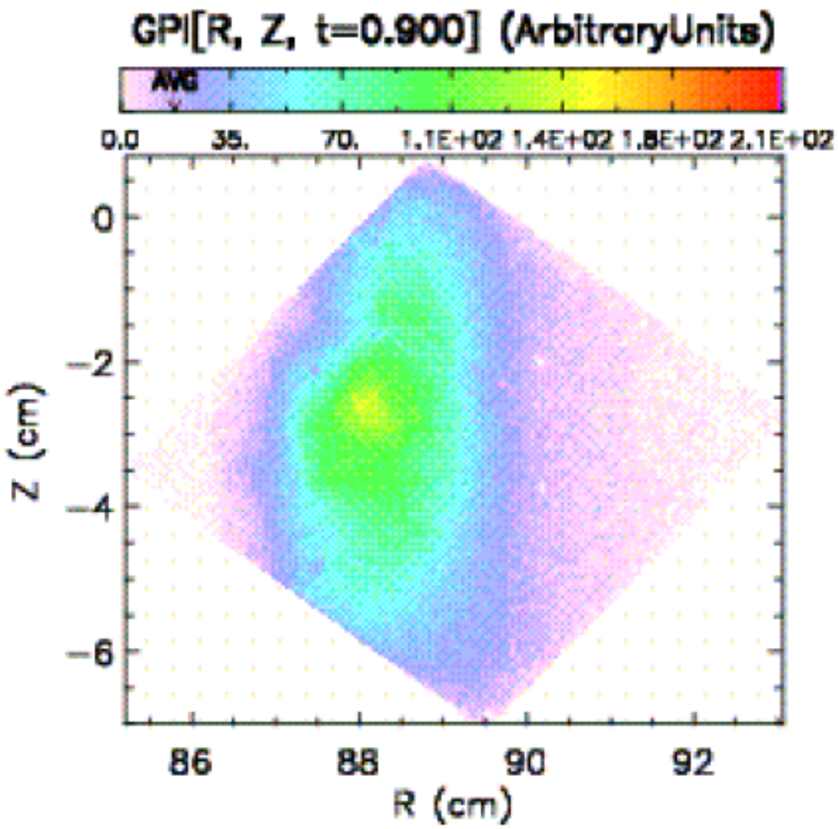


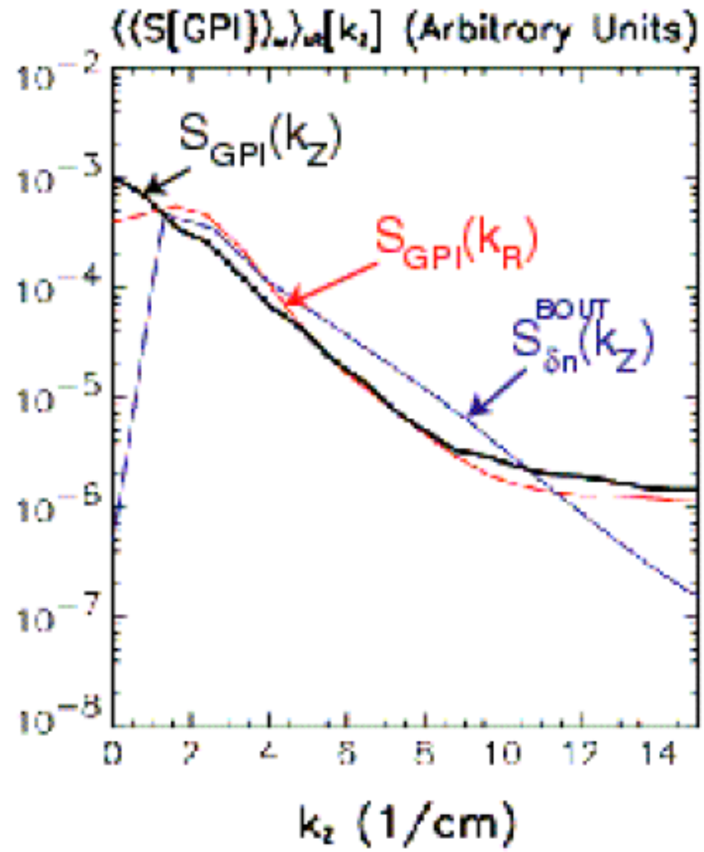
A comparison of a GAM *ExB* oscillation observed in a BOUT simulation of experimental discharge (109644) and a comparison with BES measured turbulence poloidal velocity spectrum



G. R. McKee, PoP, Vol. 10, 1712 (2003)

Spectrum of the GPI data is compared with that of the BOUT simulation

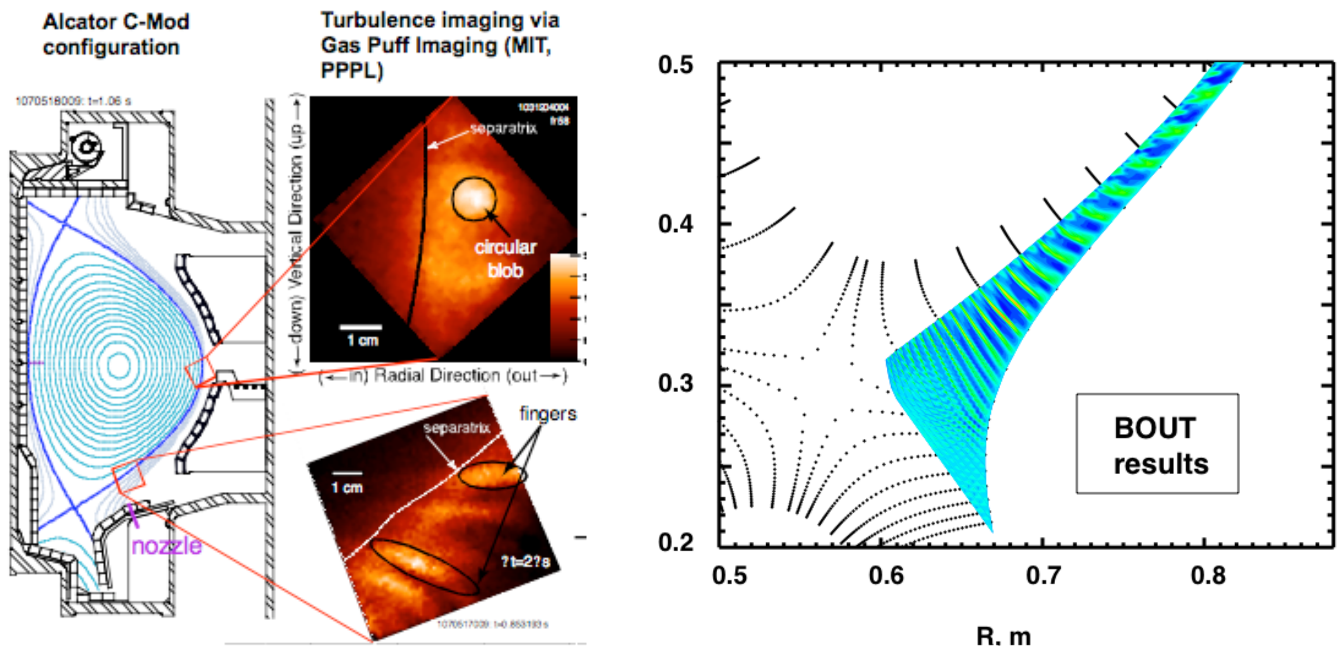




W.M.NEVINS, X.Q.XU, et. al. , ***in 19th IAEA Fusion Energy Conference, Lyon (France) 14-19 October 2002, IAEA-CN-94/TH/P3-07.***

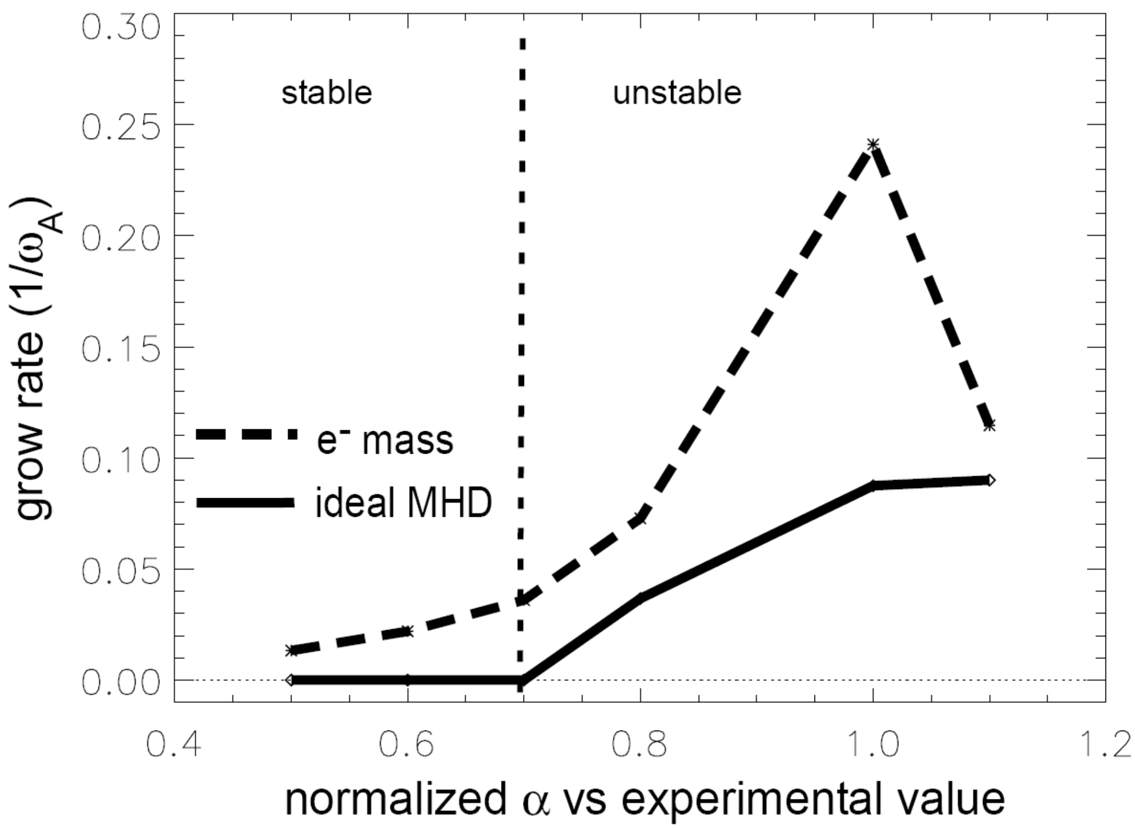
9

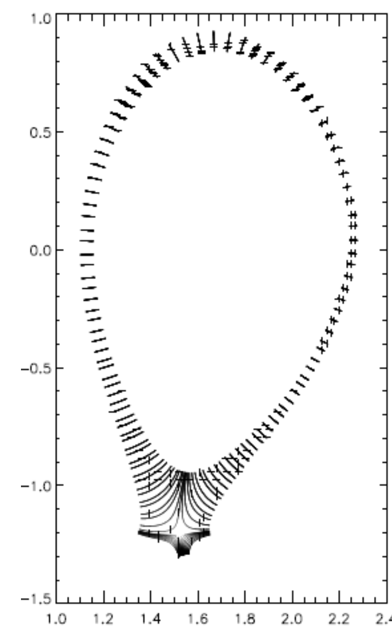
Structure of density blobs in X-point region is distinctly different from that at outer mid-plane



- **Blobs at outer midplane are more or less “round”**
- **Blobs near x-point are radially elongated**
- **Consistent with recent x-point GPI measurements at C-Mod**
- **Radial fingers are caused by flux tube squeezing**
- **Apparently turbulence drive is from outer mid-plane**

Extended BOUT++ code to magnetic X-point geometry and plasma shear flow
BOUT++ simulations for DIII-D ELMy H-mode: shot #131997 at reduced $J_{||}$

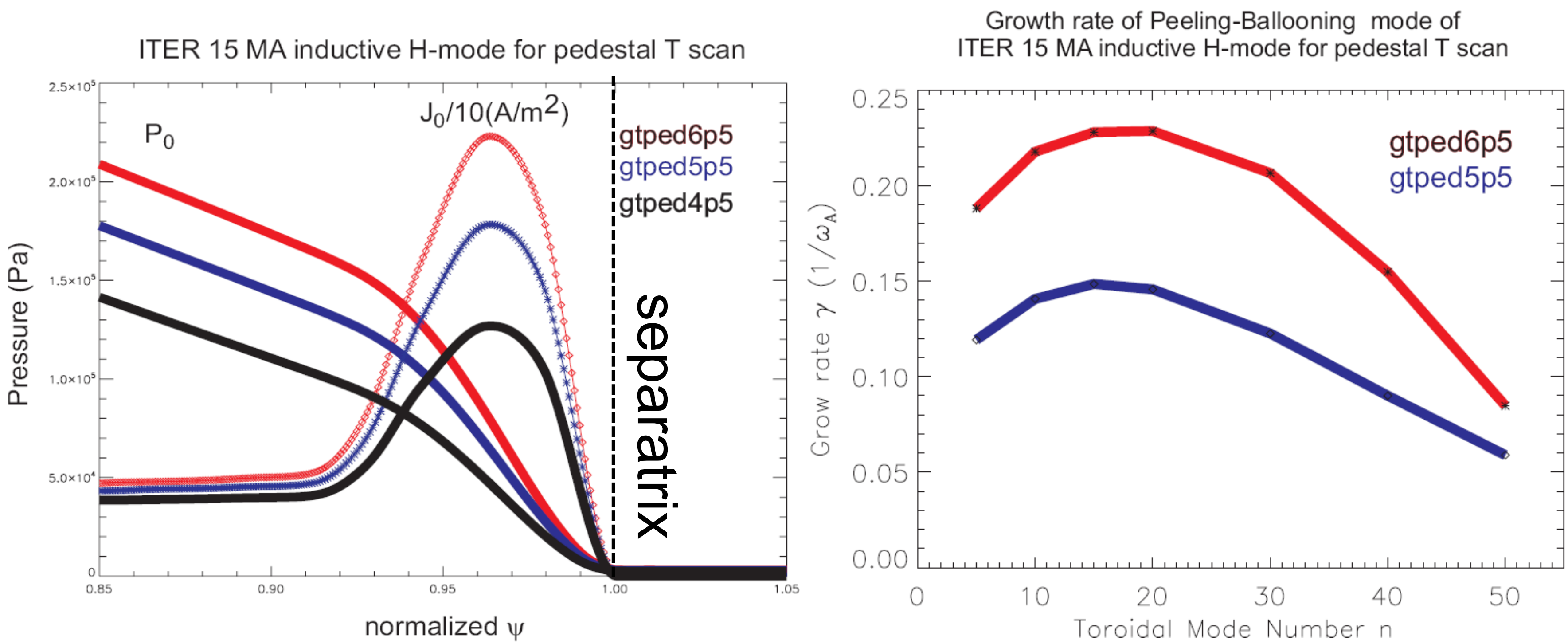




- ✓Ideal MHD stability boundary is consistent with infinite-n BALLOO code
- ✓Inclusion of e^- inertial eliminates the stability boundary

BOUT++ simulations for one of the latest designs of the ITER 15 MA inductive ELMy H-mode scenario (under the burning condition)

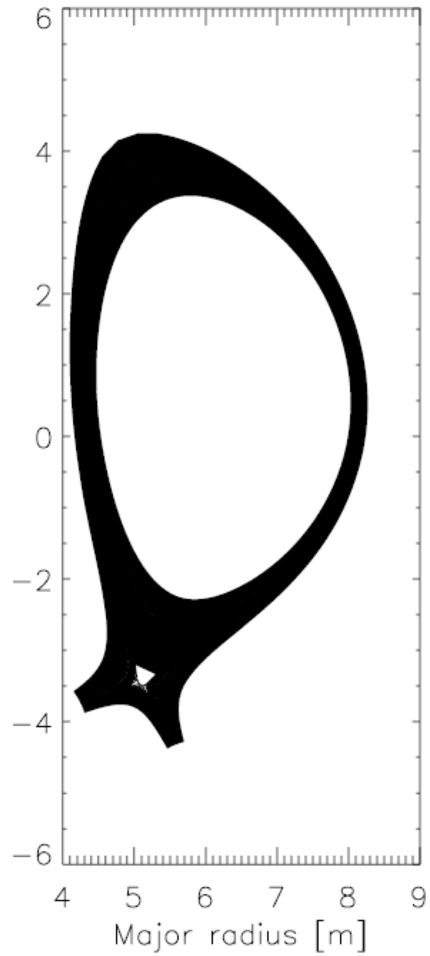
- **Simulations starting from equilibrium generated by the CORSICA code.**

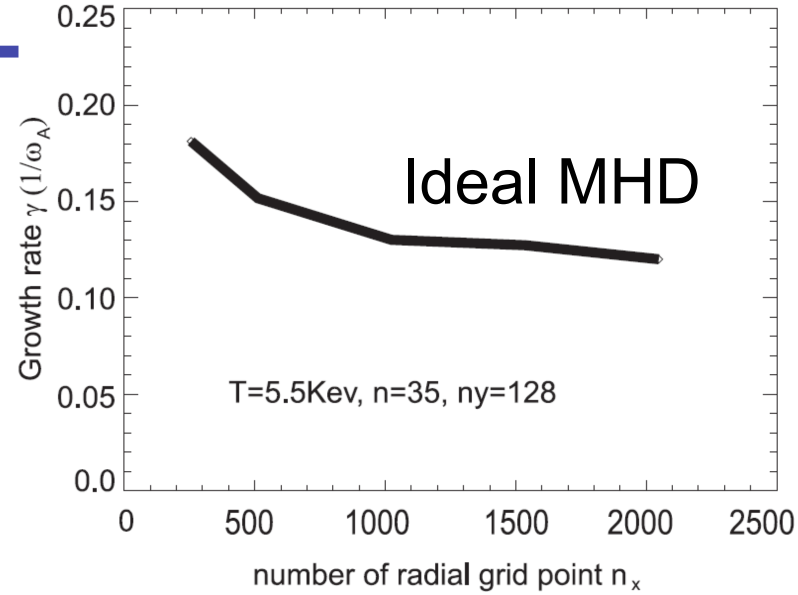


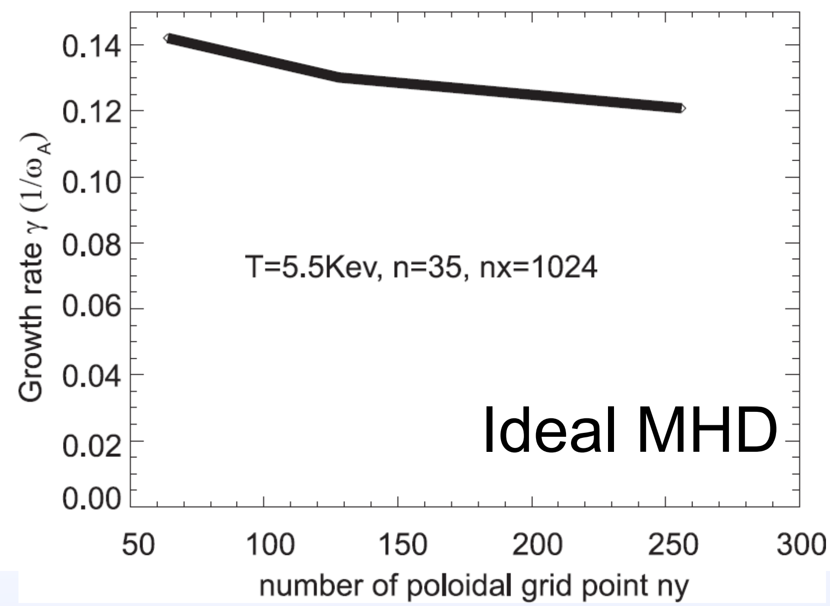
- **Marginal unstable pedestal case, T_{ped}=5.5keV, n_{max}=15**
- **The calculations impact previous ITER ELMy H-mode scenario design as it was based on the pedestal height T_{ped}=4keV**

BOUT++ simulations for one of the latest designs of the ITER 15 MA inductive ELMy H-mode scenario

It is numerical challenge to simulation ITER divertor geometry, requiring high resolutions nx > 1000, ny>100, even for linear mode.



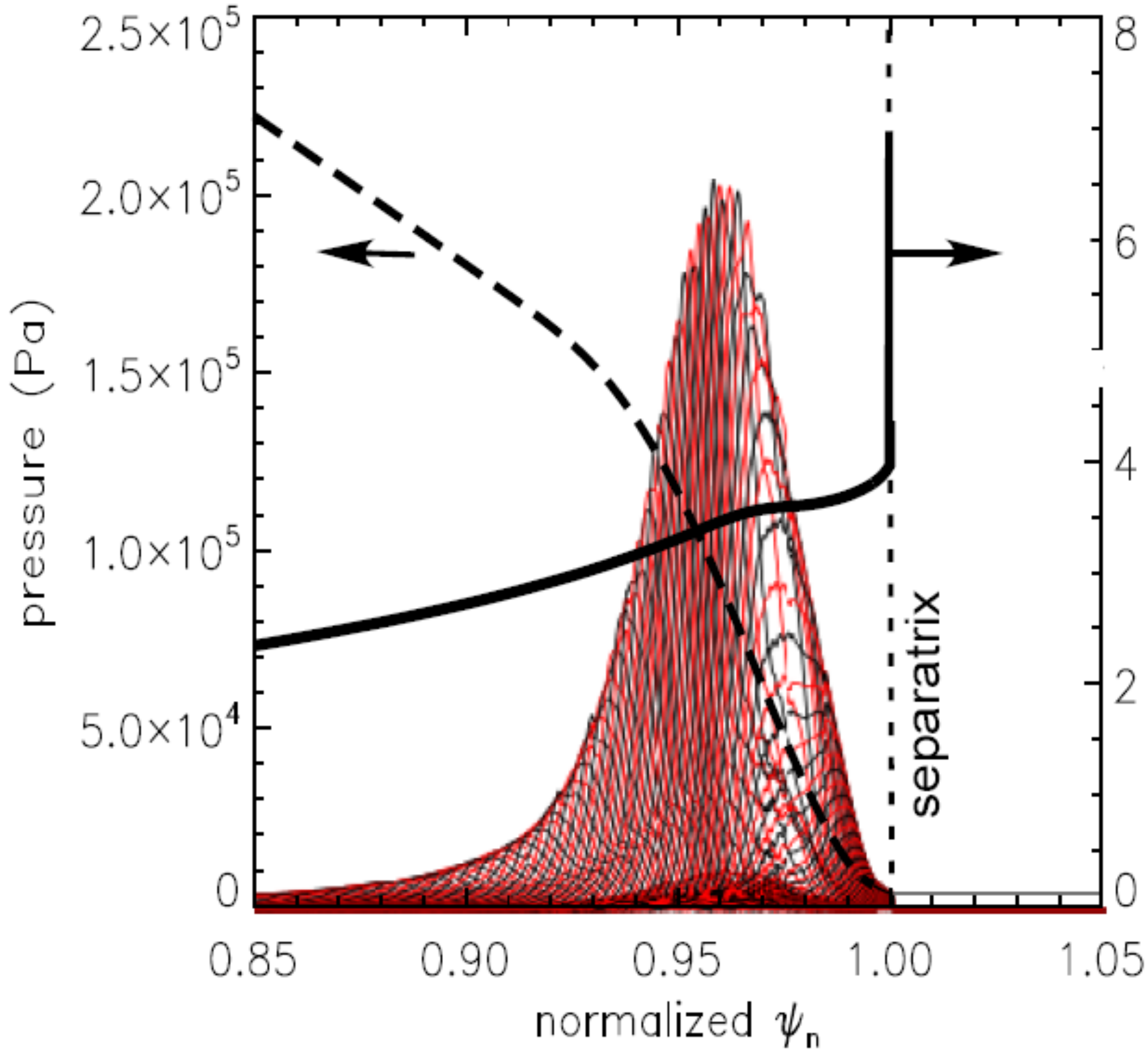


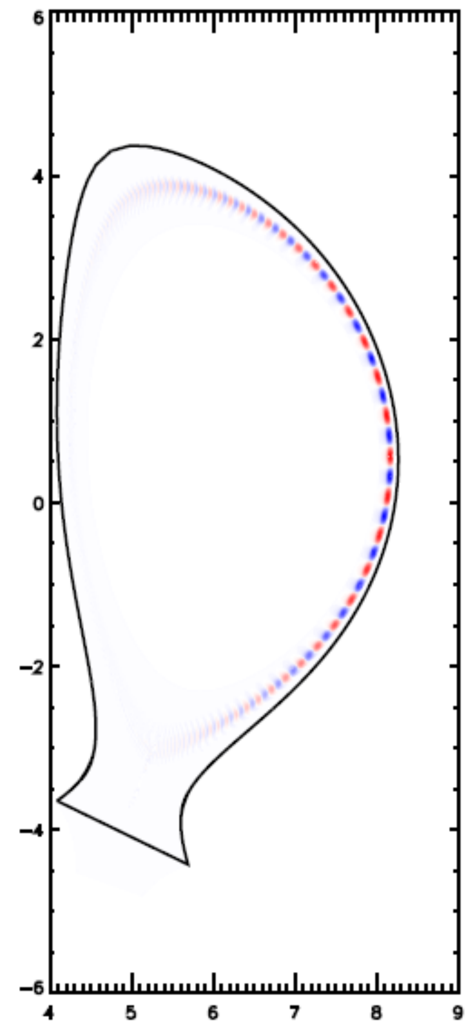


china eu india japan korea russia usa

Fusion Energy Sciences

BOUT++ simulations show radial and poloidal mode structures and for the ITER 15 MA inductive ELMy H-mode scenario





Nonlinear simulations of peeling-ballooning modes with anomalous electron viscosity in ELM crashes

Perturbed pressure Contours from Nonlinear P-B modes

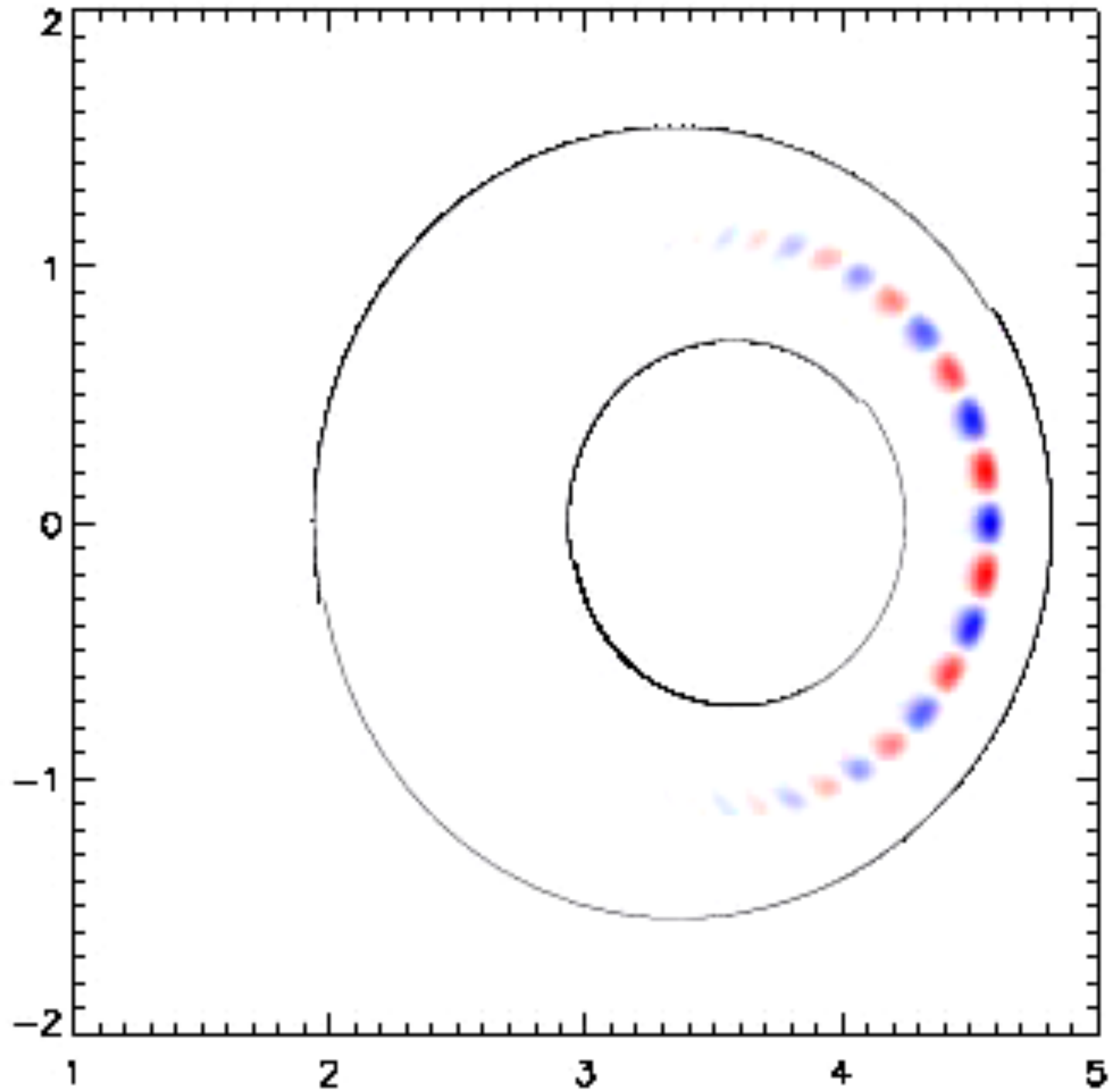
512x64x64,

$S=10^8$ & $S_H=10^{12}$

Pressure fluctuation

$2\mu_0\delta p/B^2$

contours-- poloidal cross section



Pressure Profile from BOUT++ Nonlinear P-B modes

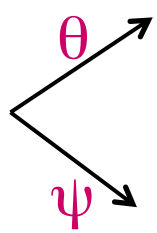
512x64x64,

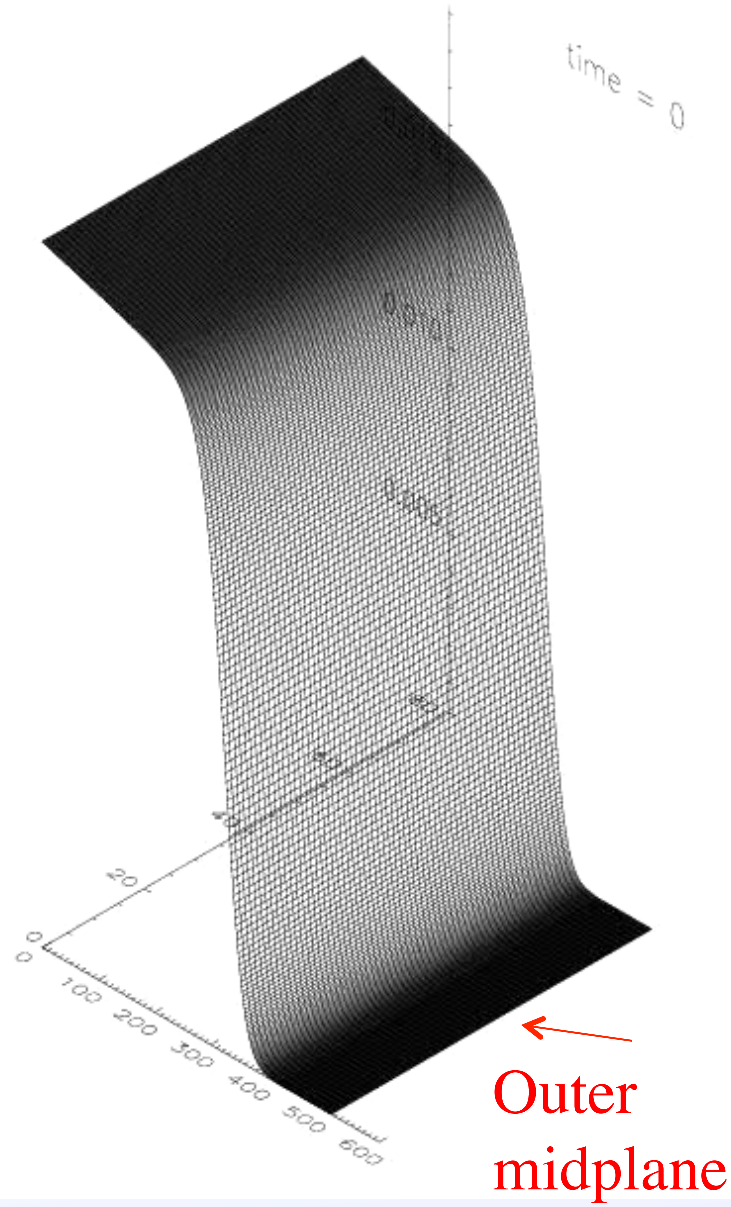
$S=10^8, S_H=10^{12}$

Pressure profile:

$2\mu_0 \langle P \rangle / B^2$ $\quad P=P_0+\langle \delta p \rangle$

pressure vs. radius and poloidal angle





Perturbed pressure Contours from nonlinear P-B modes

512x64x64,

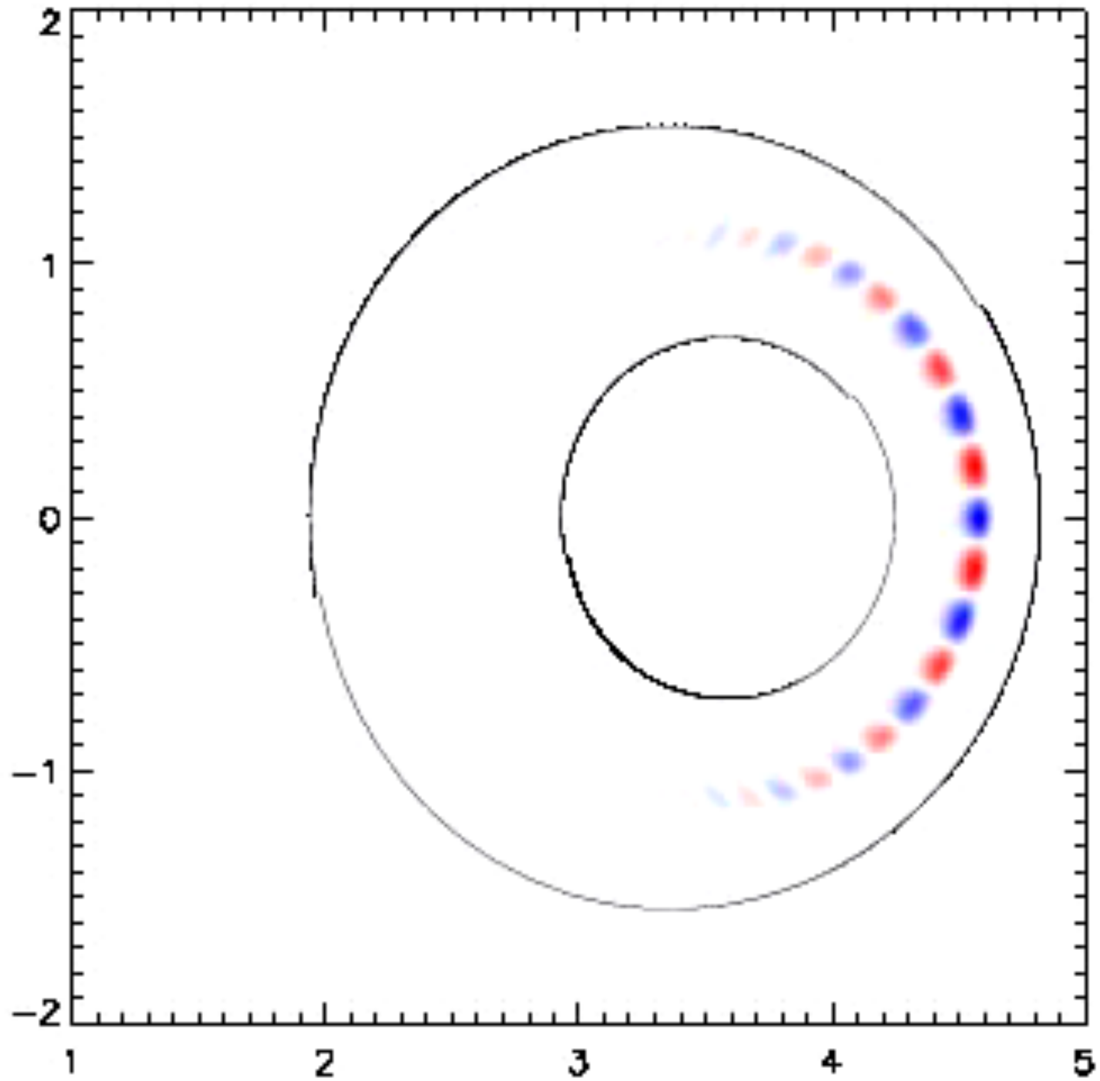
$S=10^5$ & $S_H=10^{12}$

Pressure fluctuation

$2\mu_0\delta P/B^2$

contours-- poloidal

cross section



Pressure Profile from Nonlinear P-B modes

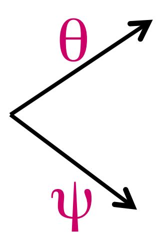
512x64x64,

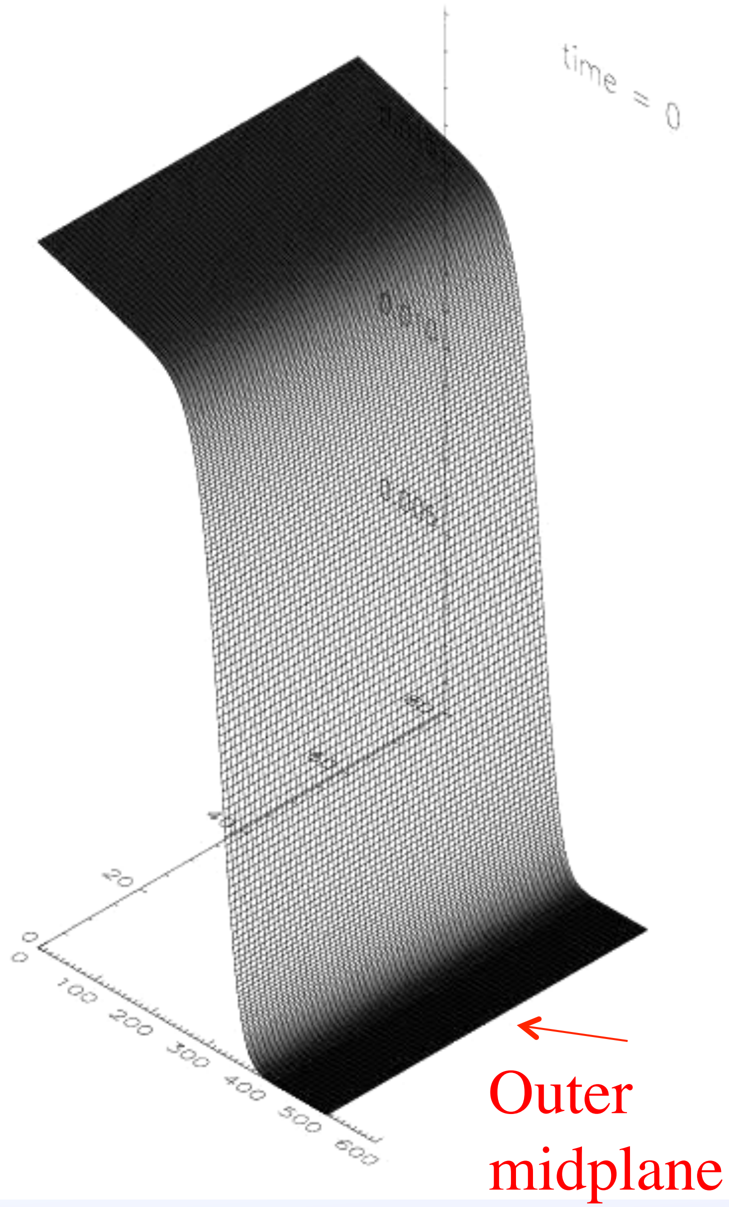
$S=10^5$ & $S_H=10^{12}$

Pressure profile:

$2\mu_0\langle P\rangle/B^2$ $P=P_0+\langle\delta p\rangle$

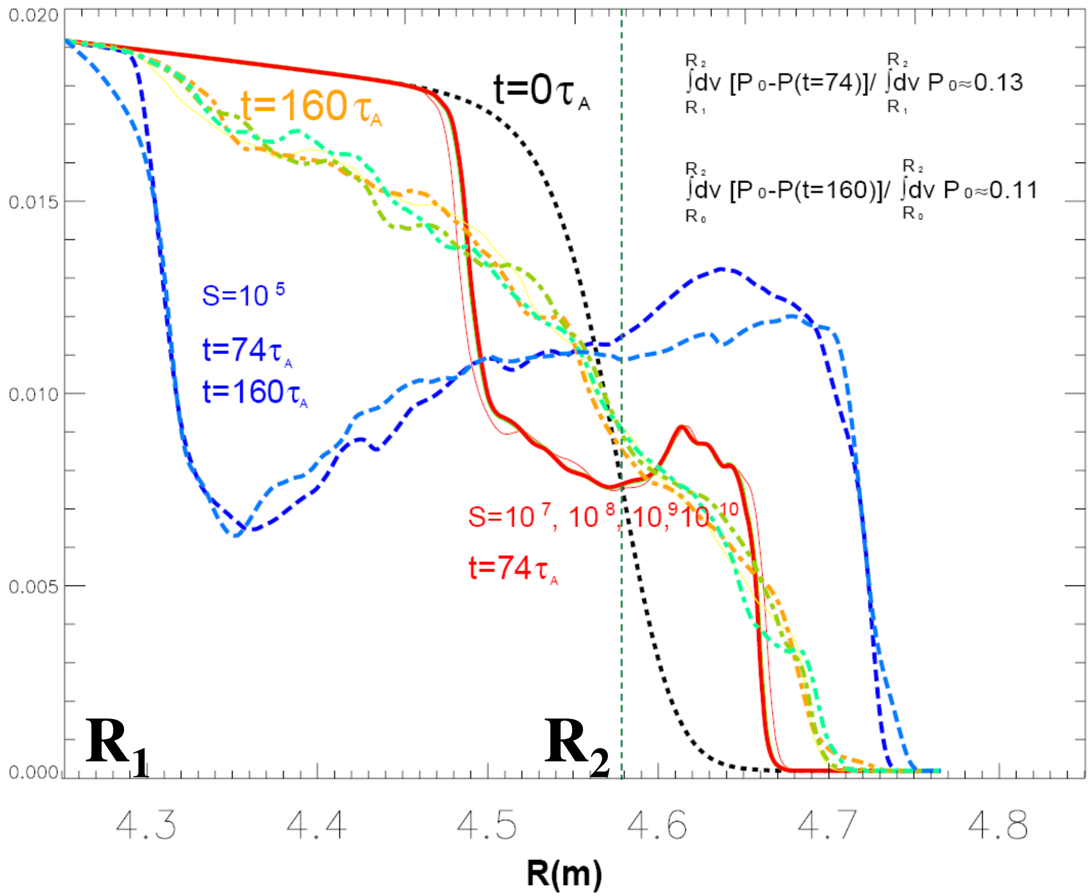
pressure vs. radius and poloidal angle





Flux-surface-averaged pressure profile $2\mu_0 <P>/B^2$ vs S with $S_H=10^{12}$

low S -> large ELM size, ELM size is insensitive when $S>10^7$



ELM size= $\Delta W_{ped}/ W_{ped}$

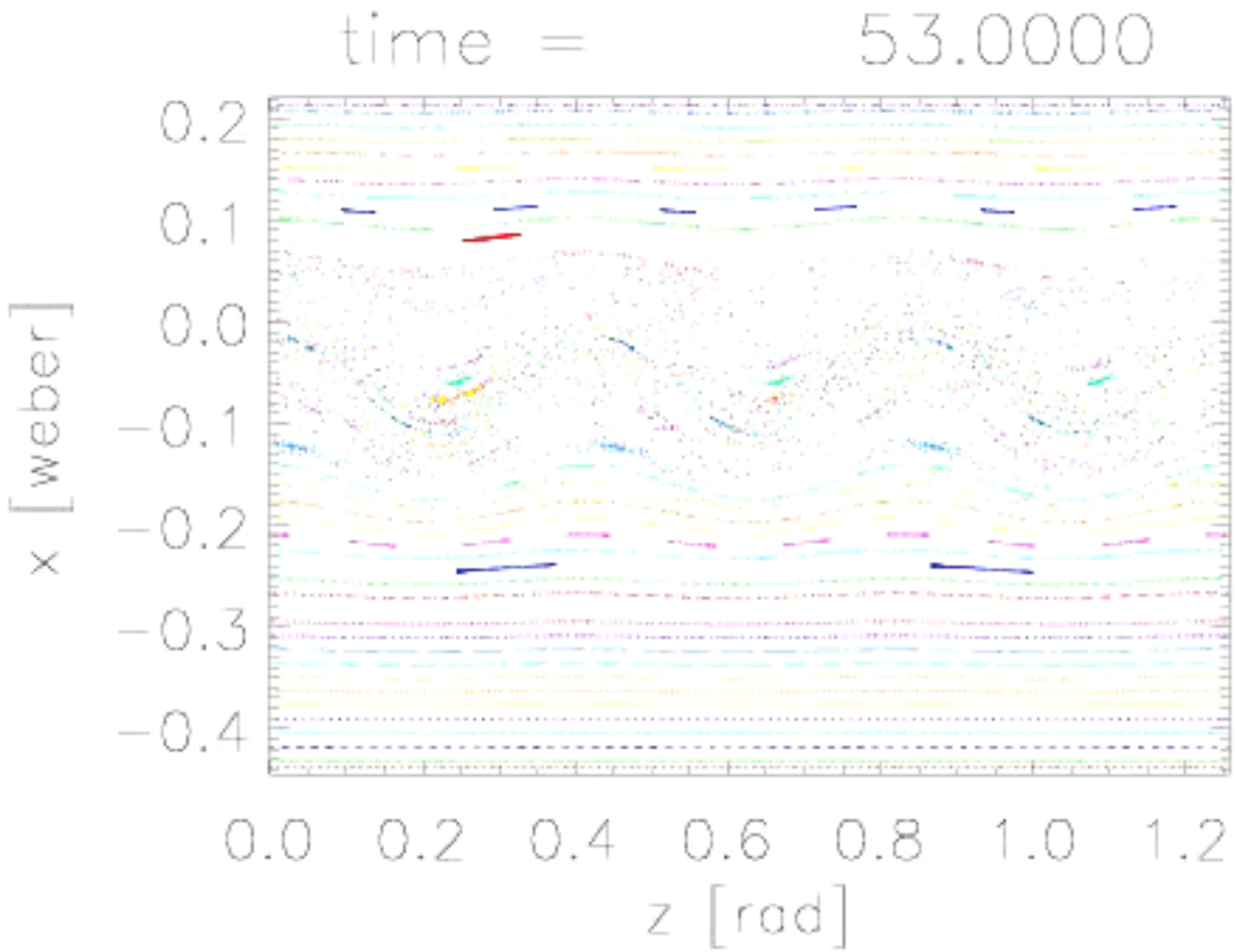
ΔW_{ped}= the ELM energy loss

W_{ped} =pedestal stored energy

(1) a sudden collapse: P-B modes -> magnetic reconnection -> bursting process

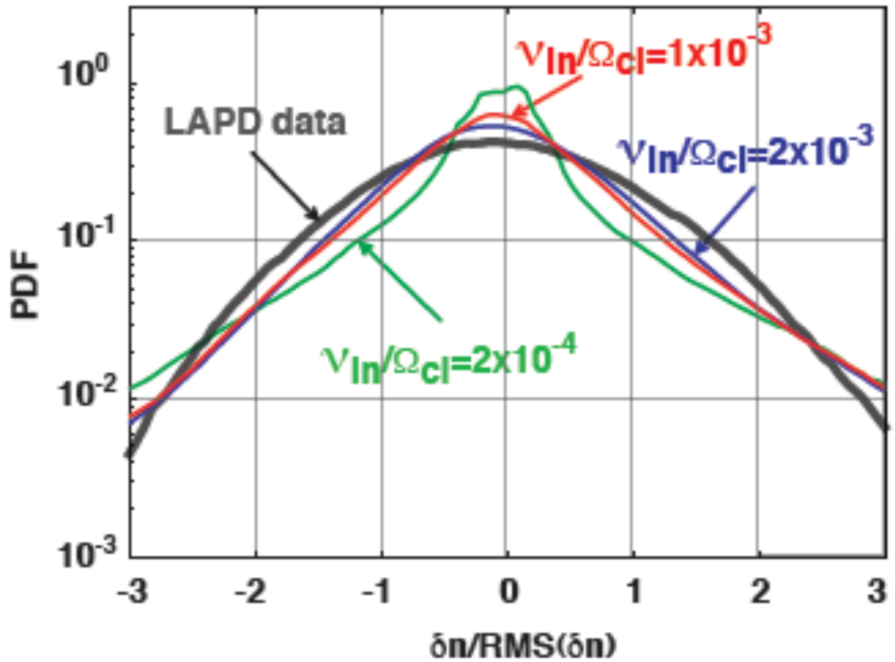
(2) a slow backfill as a turbulence transport process

For lower S (10^6), the reconnection region grows and the pedestal collapse becomes much larger.

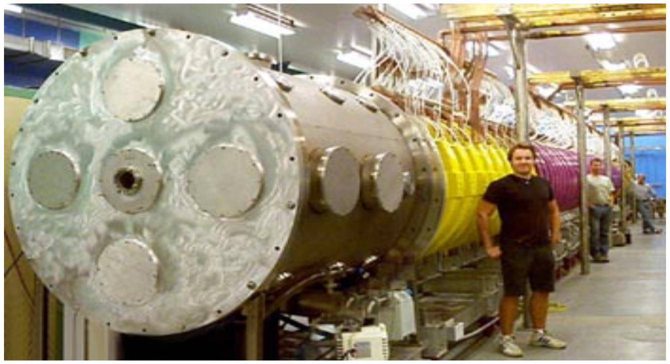


Calculated fluctuations amplitude is within factor ~2 from LAPD data, qualitatively in reasonable agreement

PDF of δn/n is in semi-quantitative agreement with experimental data

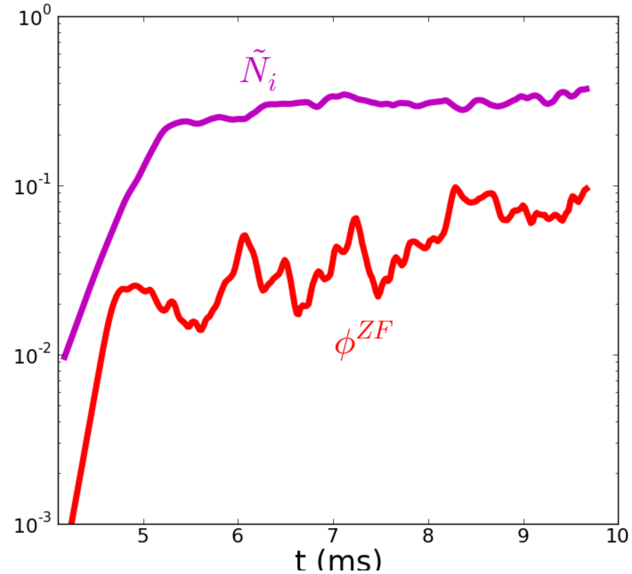


✓If neutral density is taken too low => PDF shape becomes different from expt.

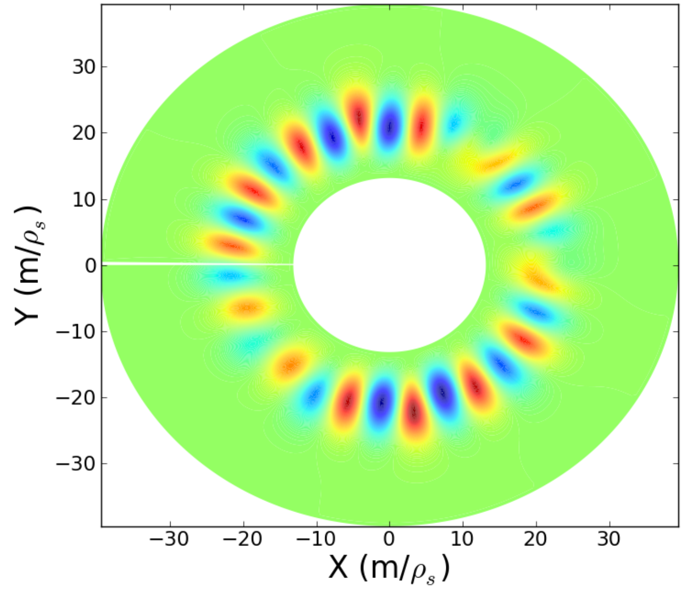


M.V.Umansky, APS invited talk 2010

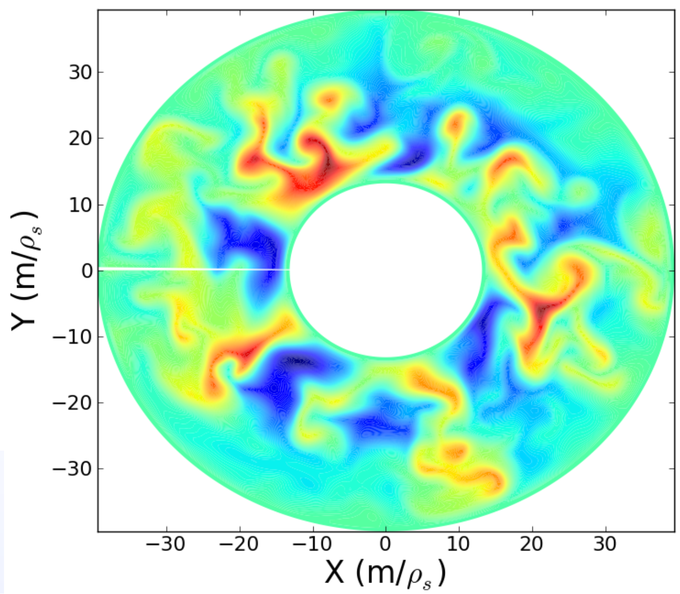
Nonlinear BOUT++ Simulations Grow by Linear Drift Wave Instability and Saturate by Nonlinear Interactions

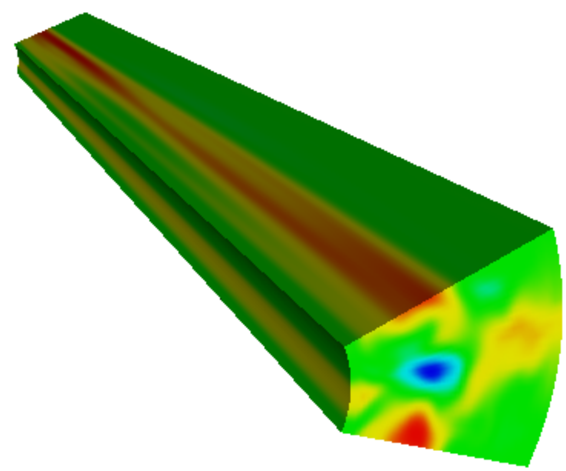


Most Unstable Linear Mode



Non-Linear Saturated Turbulence





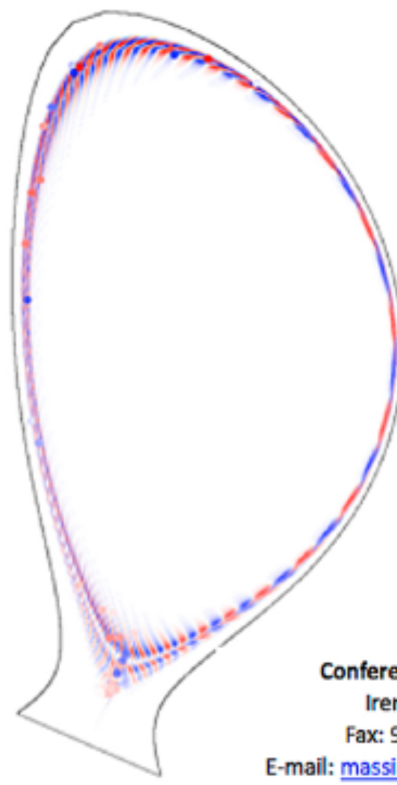
One mission of the workshop is to promote effective collaboration within the BOUT community and beyond

Workshop Theme

The mission of the workshop is (1) to prepare researchers to use and further develop the BOUT++ code for edge turbulence, transport, and ELM simulations of magnetic fusion devices; and (2) to promote effective collaboration within the BOUT community and beyond.

Workshop Format

This 3 day workshop covers tutorial lectures for the basics of the BOUT++ code and tools used by BOUT++, special lectures on gyrofluid models, resonant magnetic fields, preconditioners, and topical applications by present BOUT++ users/developers. Some sessions will include an associated lab exercise using Linux machines.



Conference Contacts
Irene L. Massiatt
Fax: 925-424-6401
E-mail: massiatt1@llnl.gov