INTRODUCTION TO

UC San Diego

DMITRI M. ORLOV
JULY 25, 2022
ITER INTERNATIONAL SCHOOL - 2022

with contributions from
M. Baldwin, E. Bass, F. Beg,
J. Boedo, C. Holland, E. Hollmann,
X. Jian, J. Kleissl, S. Krasheninnikov,
R. Perillo, C. Tsui, G. Tynan, R.
Smirnov

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BEST COLLEGES U.S.News & WORLD REPORT RANKINGS

- The University of California, San Diego is a public research university.
- UC San Diego was established in 1960 near the pre-existing Scripps Institution of Oceanography.
- UC San Diego offers over 200 undergraduate and graduate degree programs, enrolling 33,343 undergraduate and 9,533 graduate students.
- UC San Diego spent $1.354 billion on research and development (FY2019), ranking it 6th in the nation.
- UC San Diego faculty, researchers, and alumni have won 27 Nobel Prizes, 3 Fields Medals, 8 National Medals of Science, 8 MacArthur Fellowships, and 3 Pulitzer Prizes.

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THE CENTER FOR ENERGY RESEARCH WAS ESTABLISHED AT UC SAN DIEGO IN 1972 TO DEVELOP SOLUTIONS FOR THE GROWING CHALLENGES OF ENERGY SUPPLY AND UTILIZATION IN OUR SOCIETY.
WE ARE NOW ONE OF UCSD'S LARGEST ORGANIZED RESEARCH UNITS.

Sol Penner,
1974-90

Forman Williams,
1990-2006

Farrokh Najmabadi,
2006-15

Farhat Beg,
2015-19

Jan Kleissl,
2019-present

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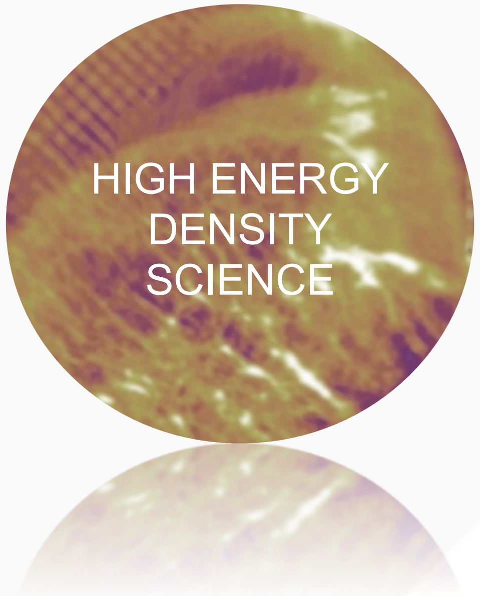
At the Center for Energy Research (CER), our mission is ***to create solutions*** for the growing challenges of energy ***supply***, ***distribution***, and ***utilization***.

CER fosters interdisciplinary research, develops visibility and recognition as a ***leading institution in energy studies***, and ***advances educational programs in energy technologies***.



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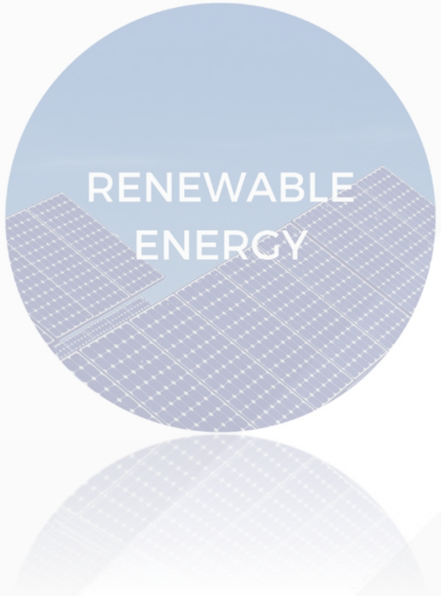
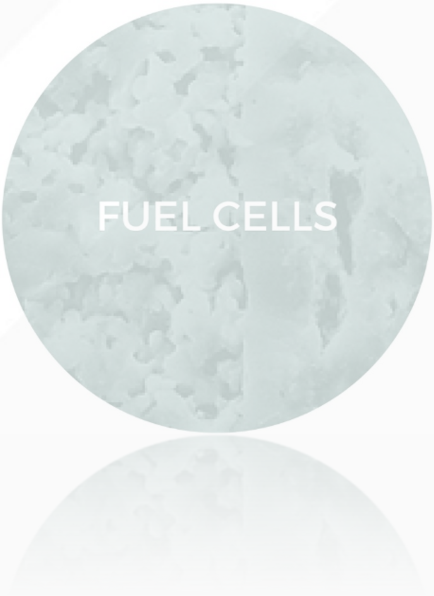
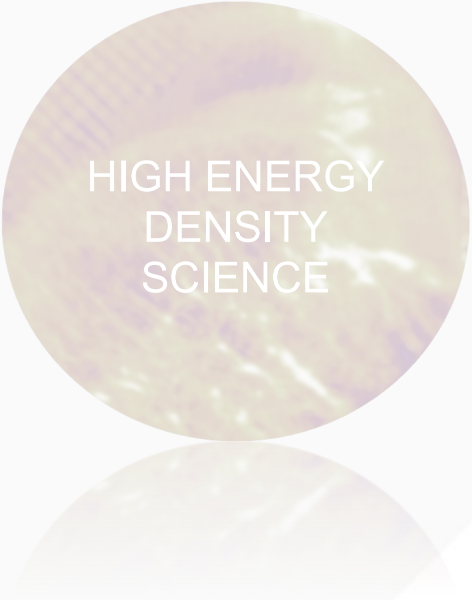
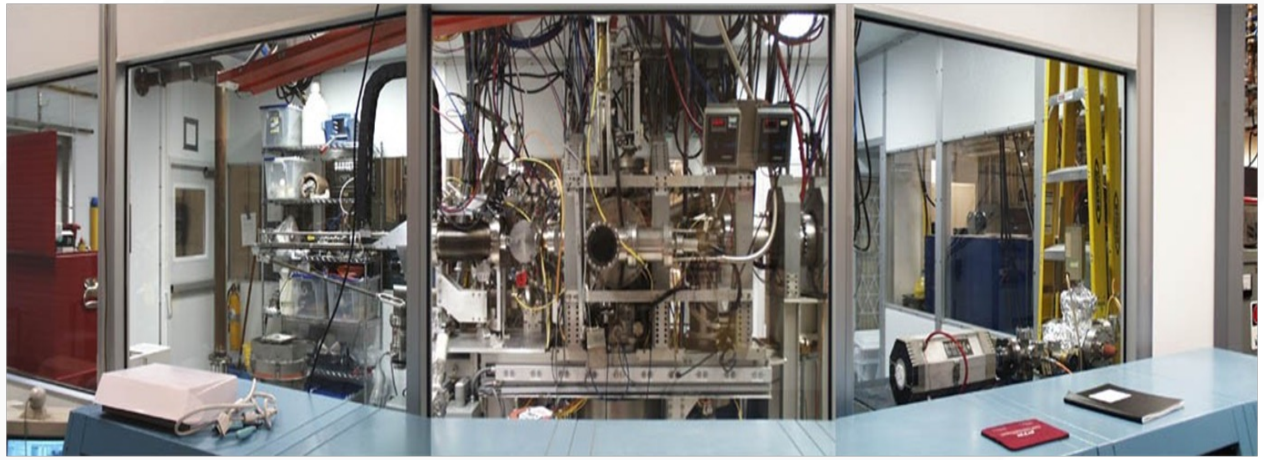


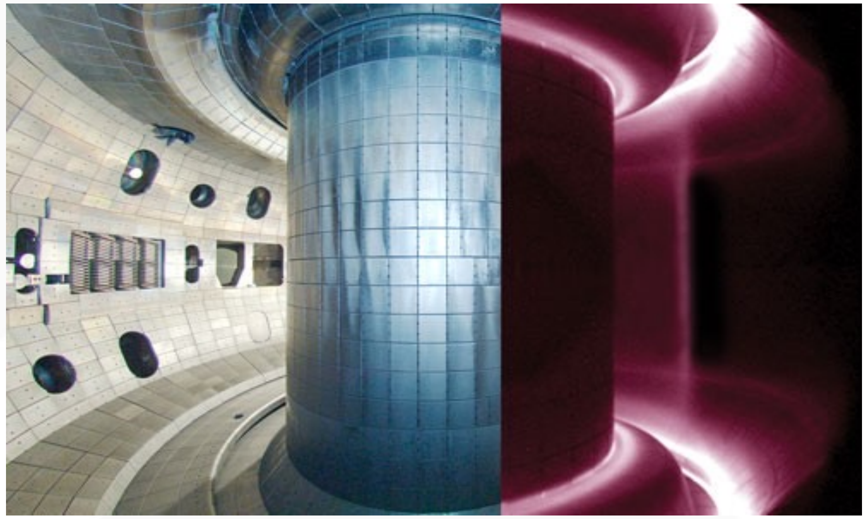


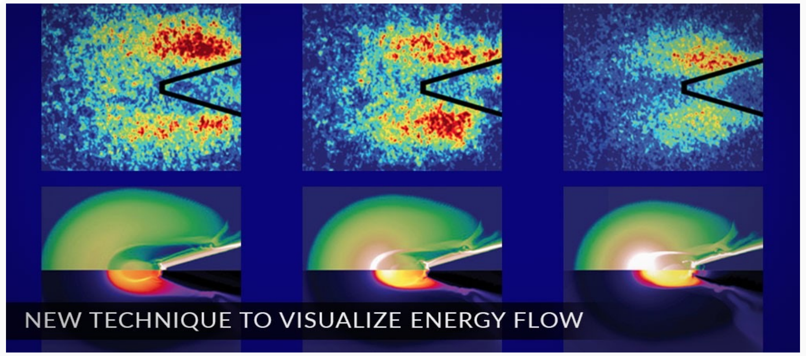


UCSD CER KEY RESEARCH AREAS

- **PISCES Program**
- **DIII-D Tokamak Collaboration**
- **TCV Collaboration**
- **Tokamak Theory and Modeling**
- **Center for Matter under Extreme Conditions**
- **Center for Momentum Transport and Flow Organization**







NEW TECHNIQUE TO VISUALIZE ENERGY FLOW

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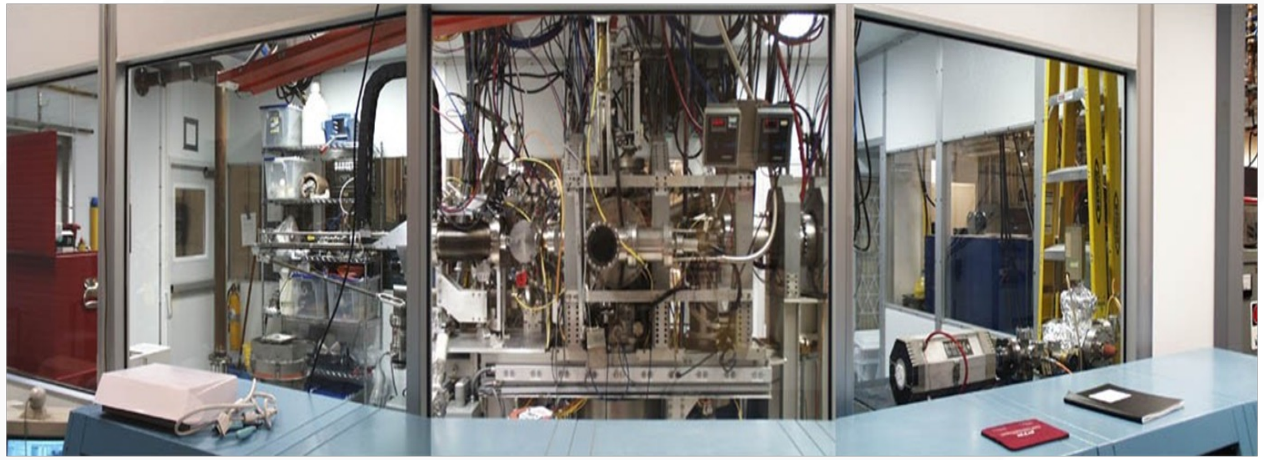

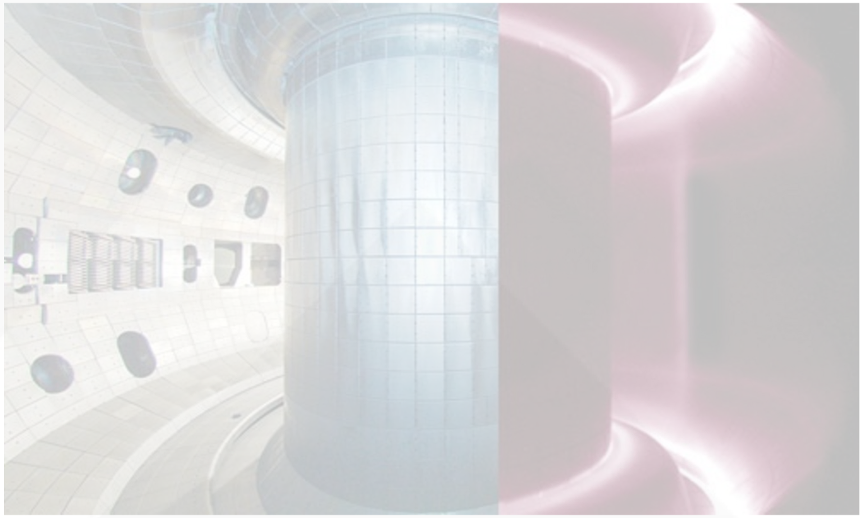

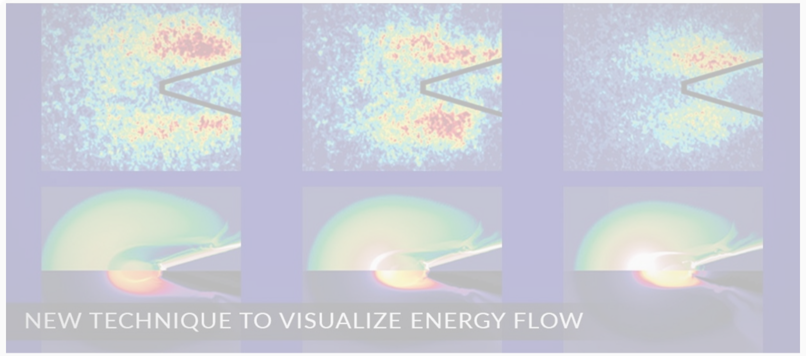
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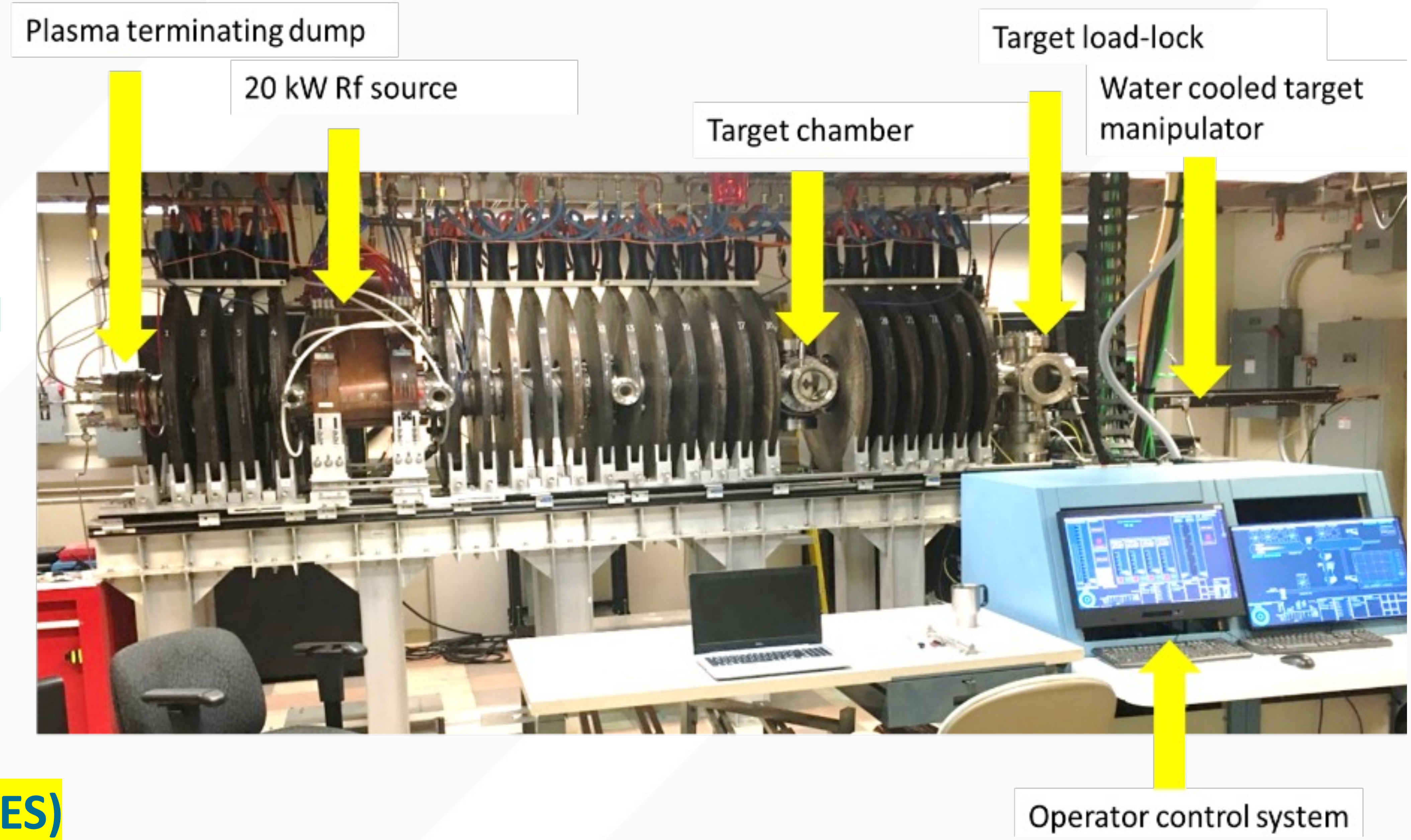
BURNING PLASMA RELEVANT FUSION MATERIALS RESEARCH AT PISCES

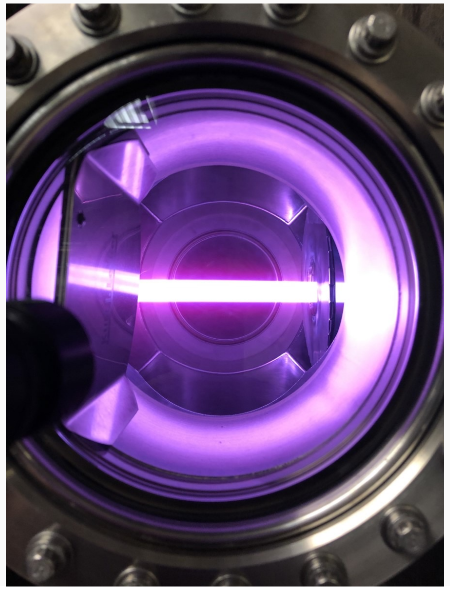
PISCES-Rf - a new high flux helicon PMI platform that replaces PISCES-B is now operational.

Liquid cooled MPEX style RF source assembly installed on CSDX



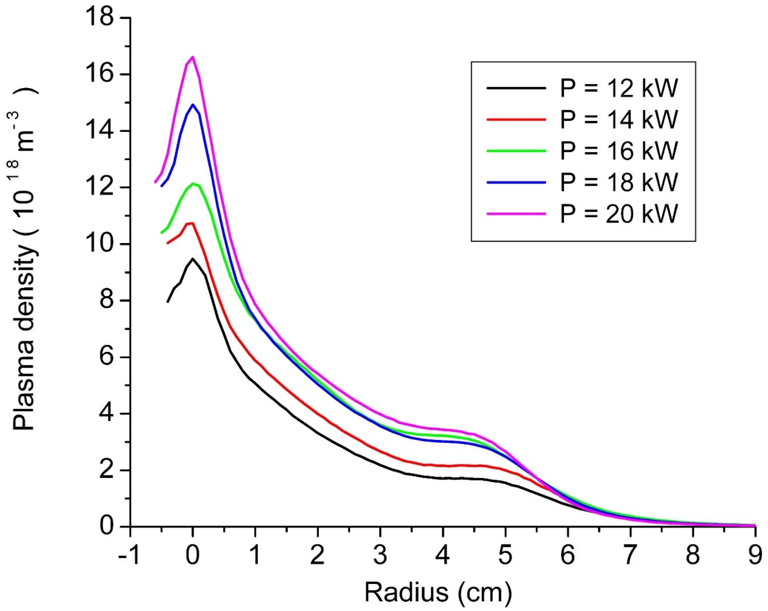
G Tynan , MJ Baldwin (PISCES)

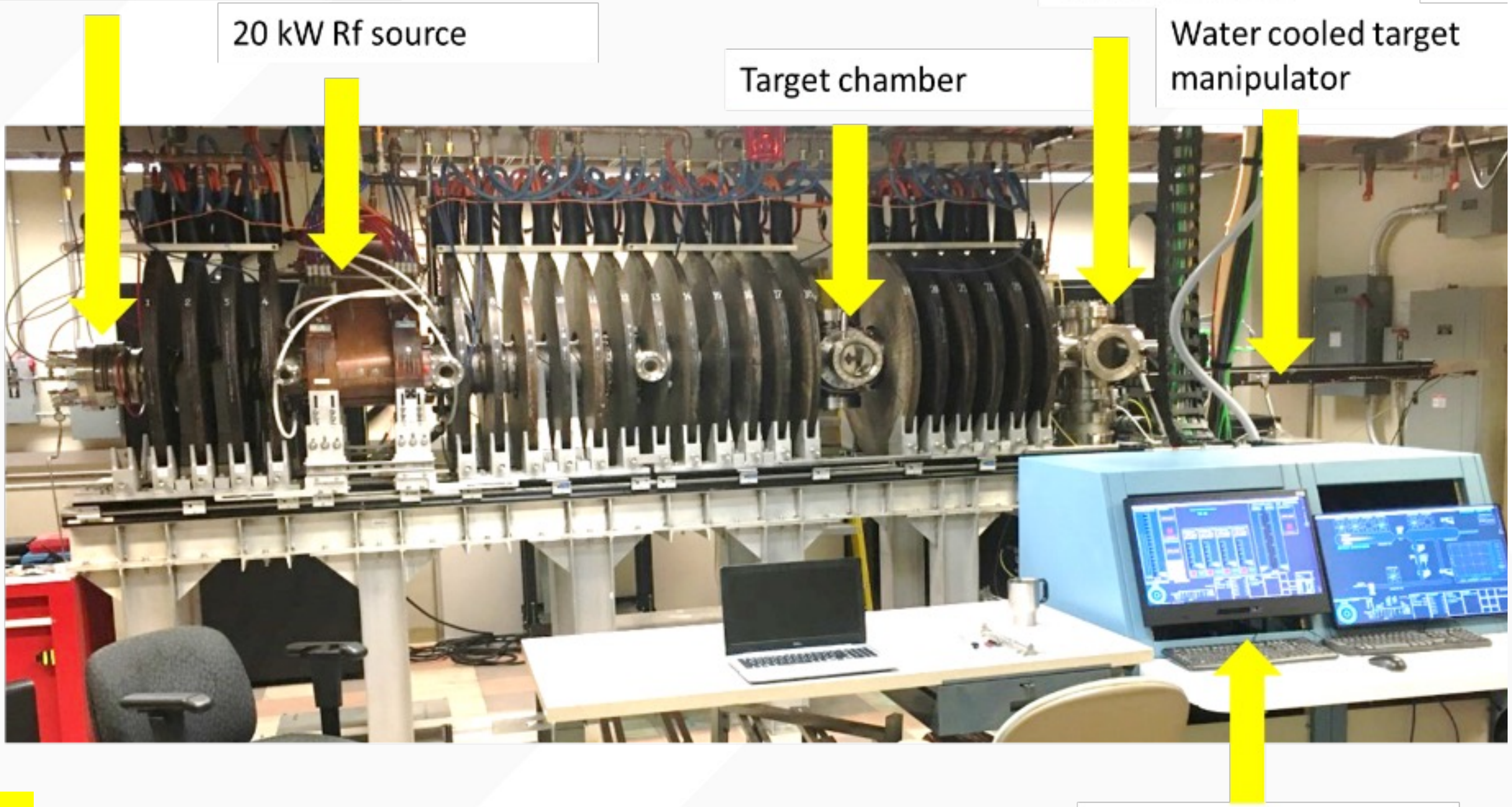
AT 20 KW RF POWER, PISCES-RF CAN PRODUCE HIGH DENSITY H_2 ,D_2 & HE PLASMAS >10^{19} M^{-3}



Electron temperature ~3 – 6 eV

Target peak Particle flux ~ 10^{23} $m^{-2}sec^{-1}$





Plasma terminating dump

20 kW Rf source

Target chamber

Target load-lock

Water cooled target manipulator

Operator control system

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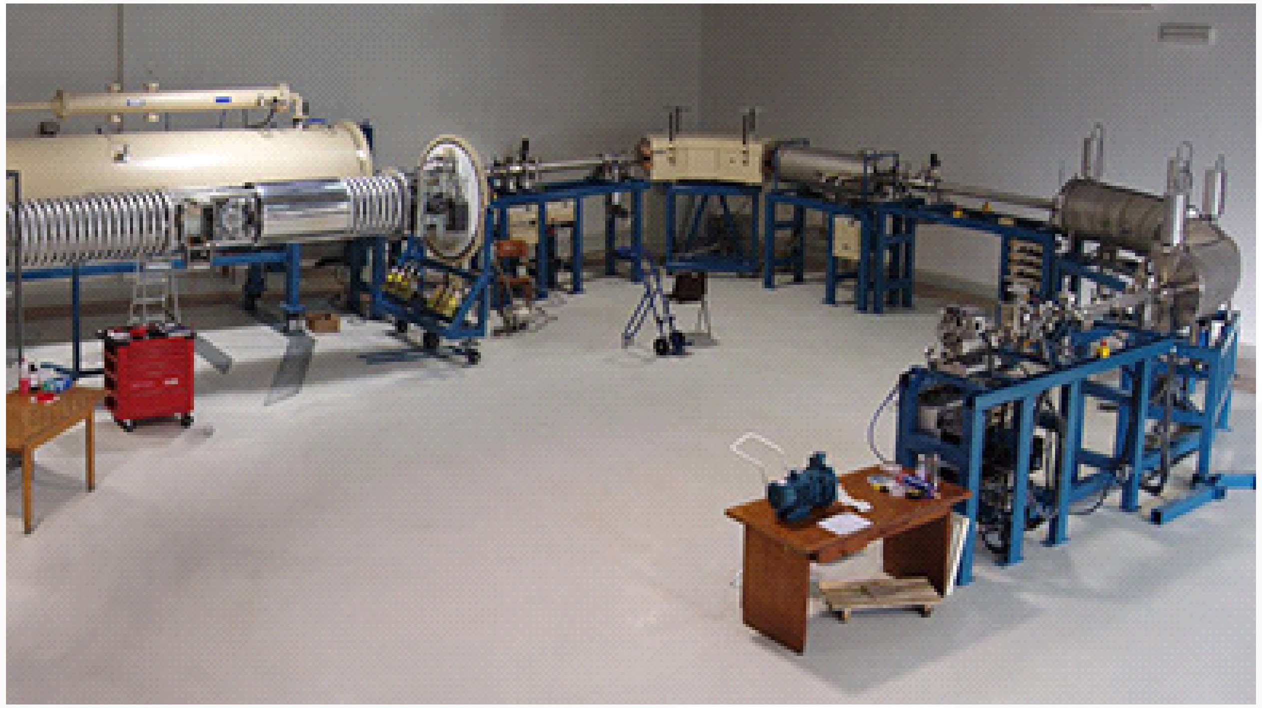
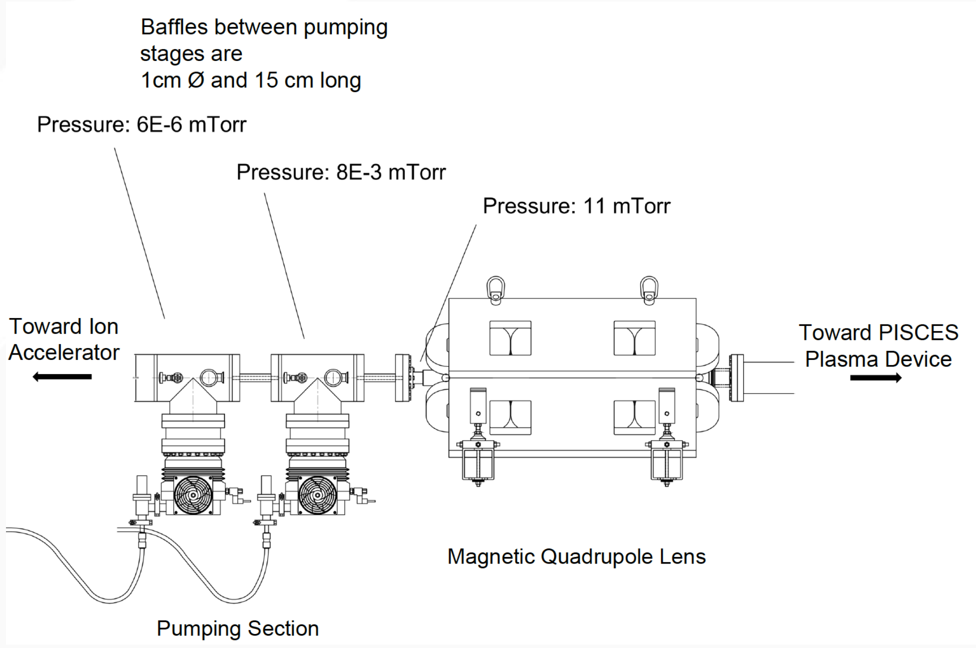
A NEW 3 MV PELLETRON W/ DIFFERENTIAL PUMPED ION FLIGHT TUBE TO PROVIDE HEAVY ION DAMAGE TO PISCES-RF PMI TARGETS.



9SDH-2 3 MV Pelletron for the production of simultaneous heavy ion damage in the first several microns of B-PMI targets



Differential pumping section and magnetic quadrupole focusing lens.

Base line focus for damaging W: ~100 nA of 20 MeV W^{6+} ions on target during PMI.

SRIM calcs. suggest a maximum of about 1.6 $\times 10^{-2}$ dpa/s peak damage ring at a depth of ~1.2 um over 4 mm dia spot is possible.

- Estimate end-of-life dpa for ITER (1 dpa) in targets in as little as 1 h of operation, and a full power year load for a hypothetical DEMO (30 dpa/y) in as little as a few days.

- By defocusing further, and/or derating the ion source, the lowest damage rate can be $\times 10^{-8}$ dpa/s, below the rate expected for an actual working fusion device.

G Tynan , MJ Baldwin (PISCES)

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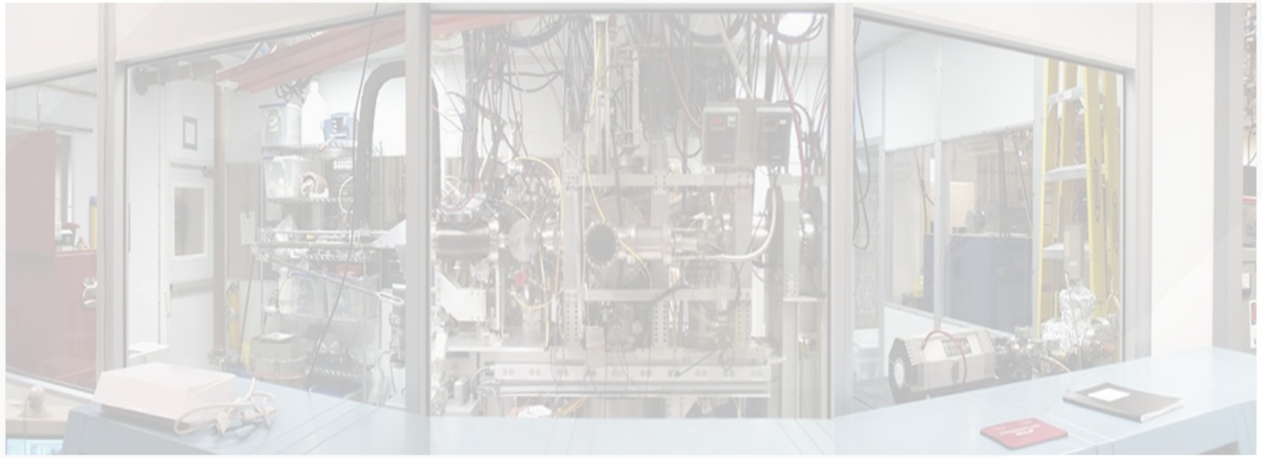

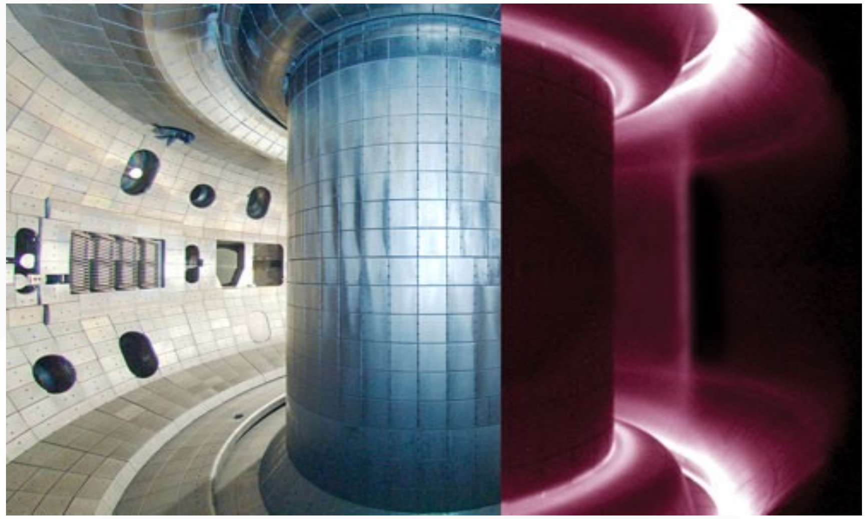

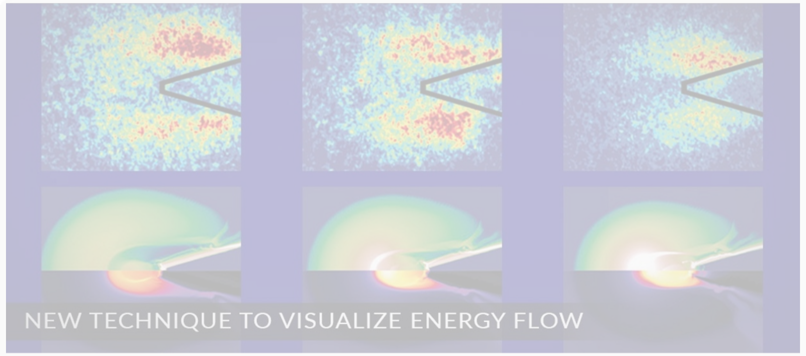

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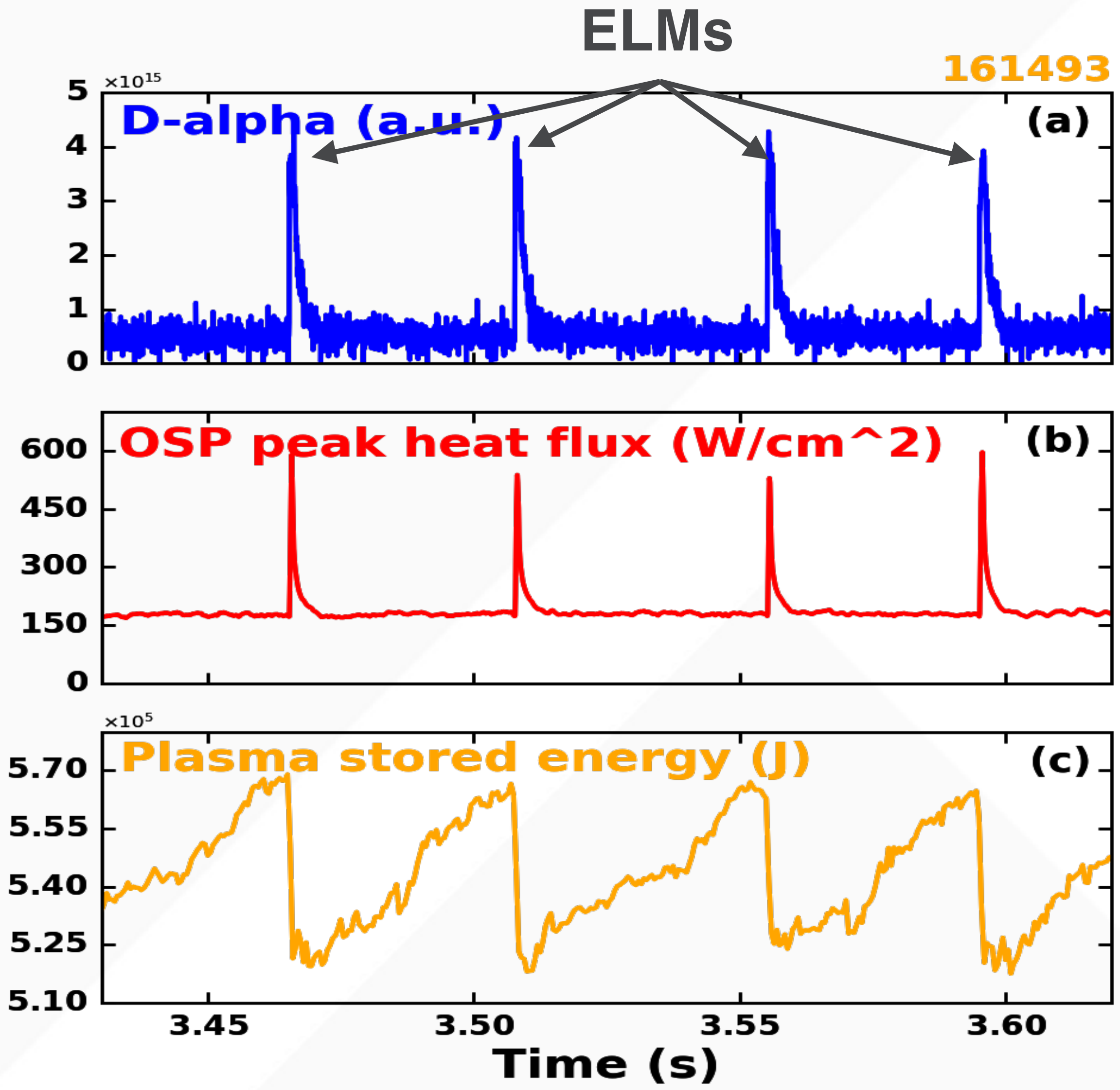
EDGE-LOCALIZED-MODES POSE A CONCERN FOR FUTURE MACHINES WALLS

- **Edge-localized-modes, or ELMs, are fast (~1-2 ms) plasma instabilities that occur in high-confinement (H-mode) plasmas[1].**

- **ELMs remove particles and impurities from the core but carry a significant fraction, up to 10%, of the plasma stored energy (Fig 1c), leading to power loads to the divertor targets that can compromise material's integrity[2].**

- ***At UCSD, we study ELM transport in the SOL and in the divertor with experiments and simulations; in particular, we evaluate various ELM types and their impact to both primary and secondary divertors[3].***



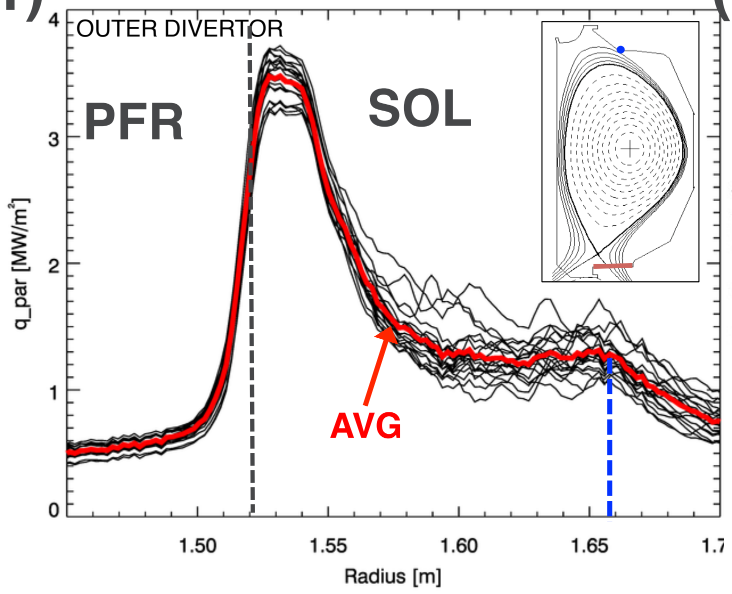
[1] Hill, JNM, 1997
[2] Pitts, JNM, 2011
[3] Perillo, NF, 2021

J Boedo, R Perillo

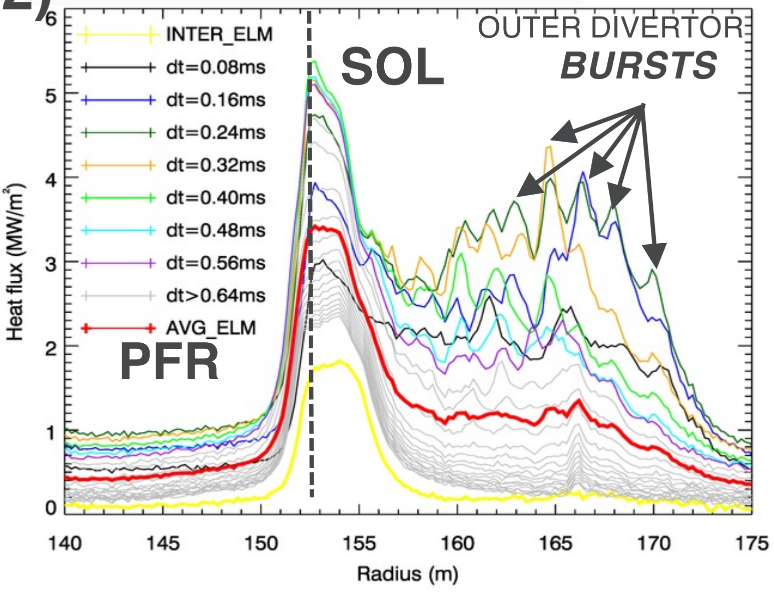
A SIGNIFICANT FRACTION OF ELM POWER IS DEPOSITED TO THE FAR-SOL

- **Up to ~40% of the ELM power gets deposited to the far-SOL region of the divertor, resulting in a plateau in the conditionally-averaged ELM heat flux profile (Fig 1).**
- **Such plateau is due to heat flux bursts that extend radially throughout the divertor. These structures have instantaneous peak heat flux comparable to that at the strike-point (Fig. 2).**
- **The experimental profile can be reproduced by ~85% with the parallel-loss-model[1] (PLM) by adding fast filaments (Fig. 3).**
- ***This supports a concept where the ELM can fragment, leading to fast, smaller filaments that carry a significant fraction of the ELM to regions far from the strike-points (Fig. 4).***

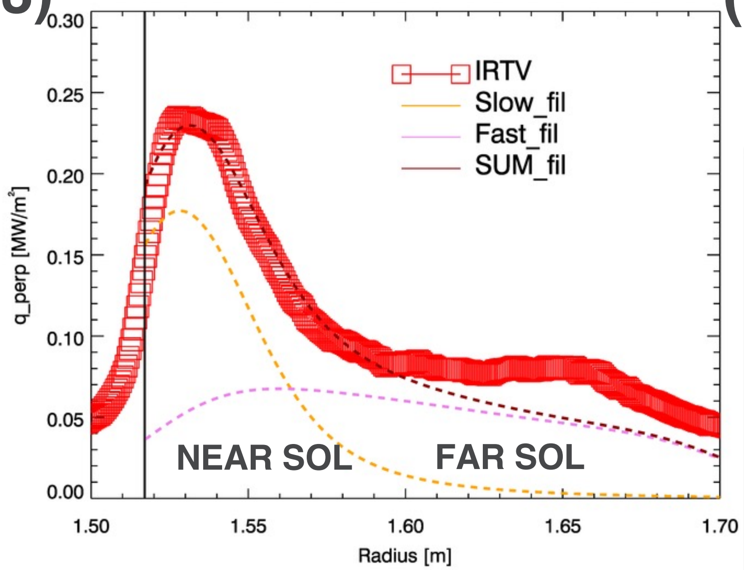
(1) AVERAGE OVER 30 ELMs



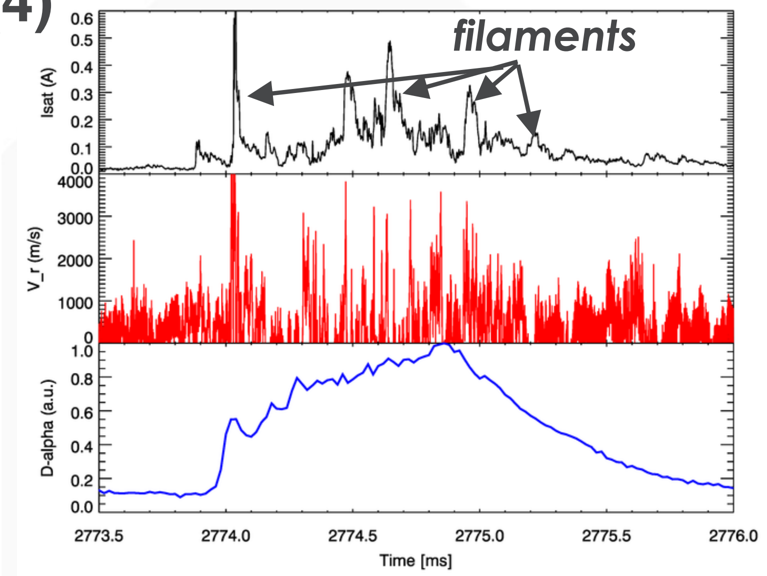
(2) SINGLE ELM EVOLUTION



(3) EXP-MODEL COMPARISON



(4) SINGLE ELM STRUCTURES



[1] Fundamenski, PPCF, 2006

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ELM PLASMA REACHES THE SECONDARY INNER DIVERTOR

- **ITER will have a secondary XPT in the vicinity of the upper wall (Fig.1)[1].**

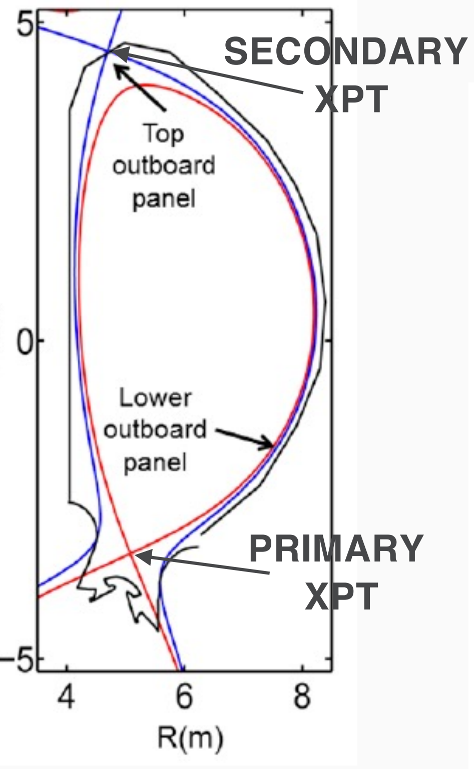
- **We have evaluated the power flux to the secondary divertor at DIII-D for different types of ELMs, and the main findings are:**

1) ELM plasma reaches the secondary inner target, although magnetically isolated from the outer one, when dRsep is < 1cm (Fig. 2).

2) Peak heat flux are comparable between secondary inner and outer targets (Fig.2).

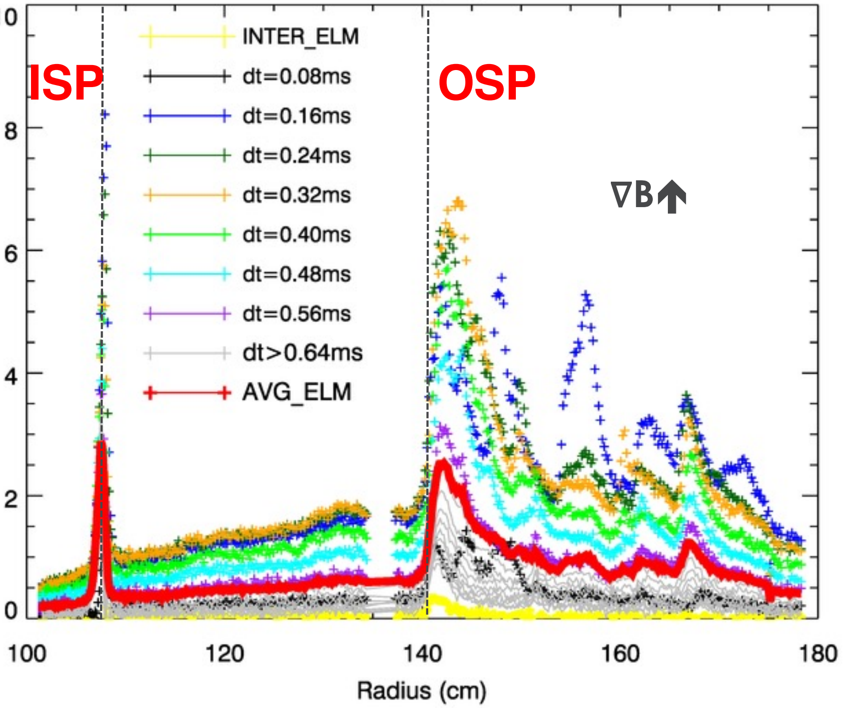
3) *The ELM contribution to the total time-averaged heat flux is ~85% for type-I and 8% for grassy-ELMs[2], highlighting the latter as a promising ELM regime in future machines (Fig. 3).*

(1)

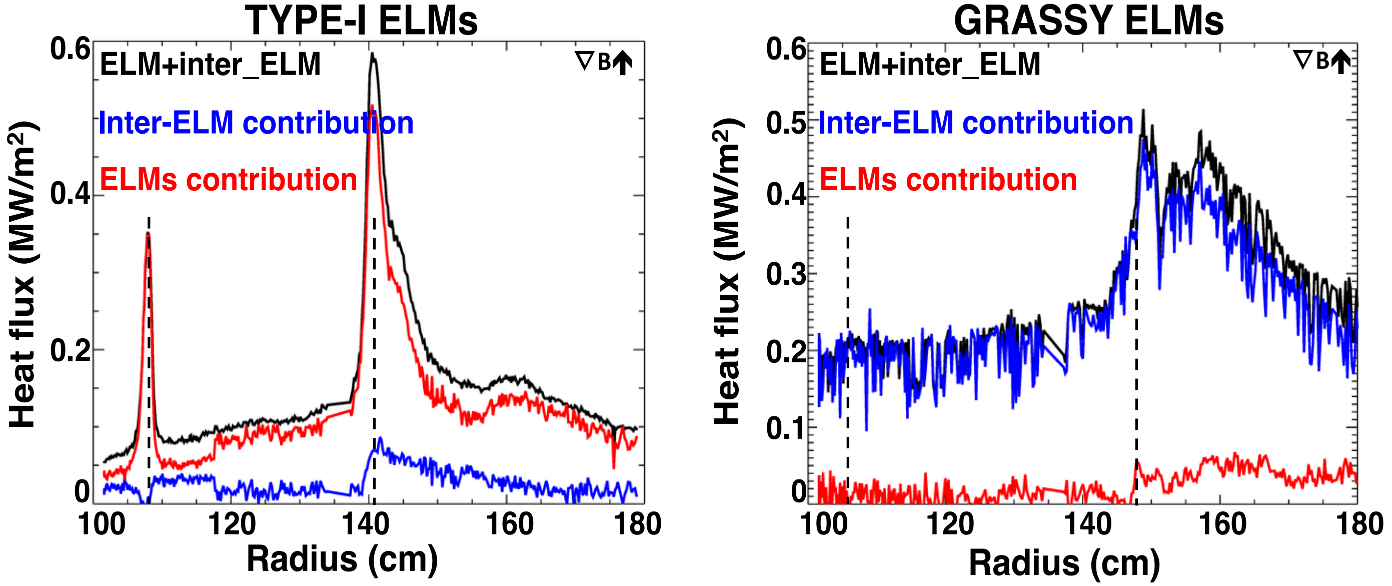


(2)

SINGLE ELM TO SECONDARY DIVERTOR



(3) TIME-AVERAGED HEAT FLUX TO THE SECONDARY DIVERTOR



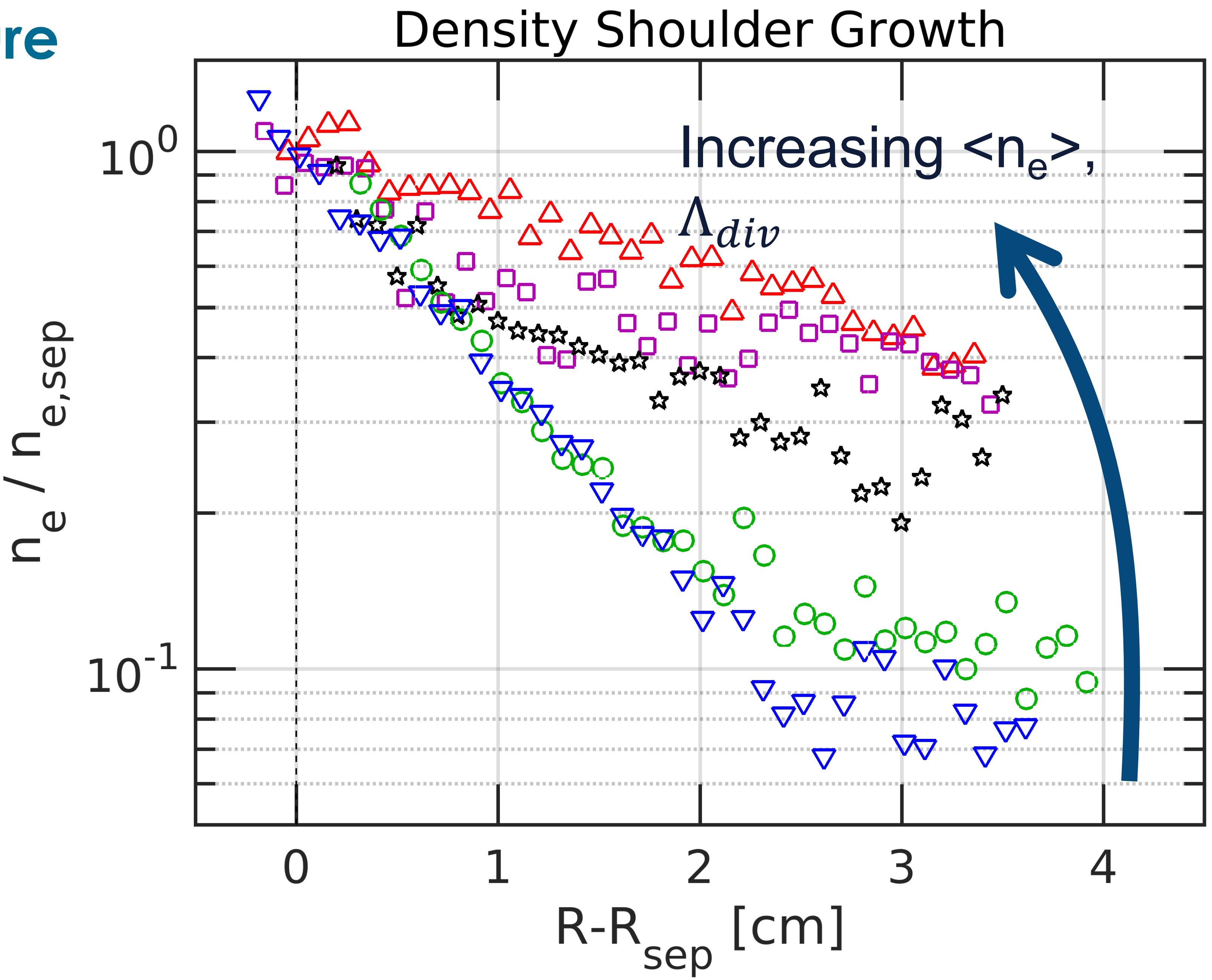
[1] Pitts, JNM, 2011
[2] Perillo, PoP, 2022

J Boedo, R Perillo

DENSITY SHOULDER GROWTH WITH INCREASING <N_E>

- Tokamak SOL density profiles often exhibit a two-layer structure
  - [McCormick, LaBombard]
- Shoulder gets broader and/or flatter with Increasing <n_e> and collisionality Λ_{div}
- Changes prediction of main-chamber plasma fluxes
  - Causes first wall erosion, impurity sputtering
- If there are no ELMs and no density shoulder in ITER, the first wall will last longer, saving around $100 million
  - [Richard Pitts personal communication 2022]

n_e at the outer-midplane



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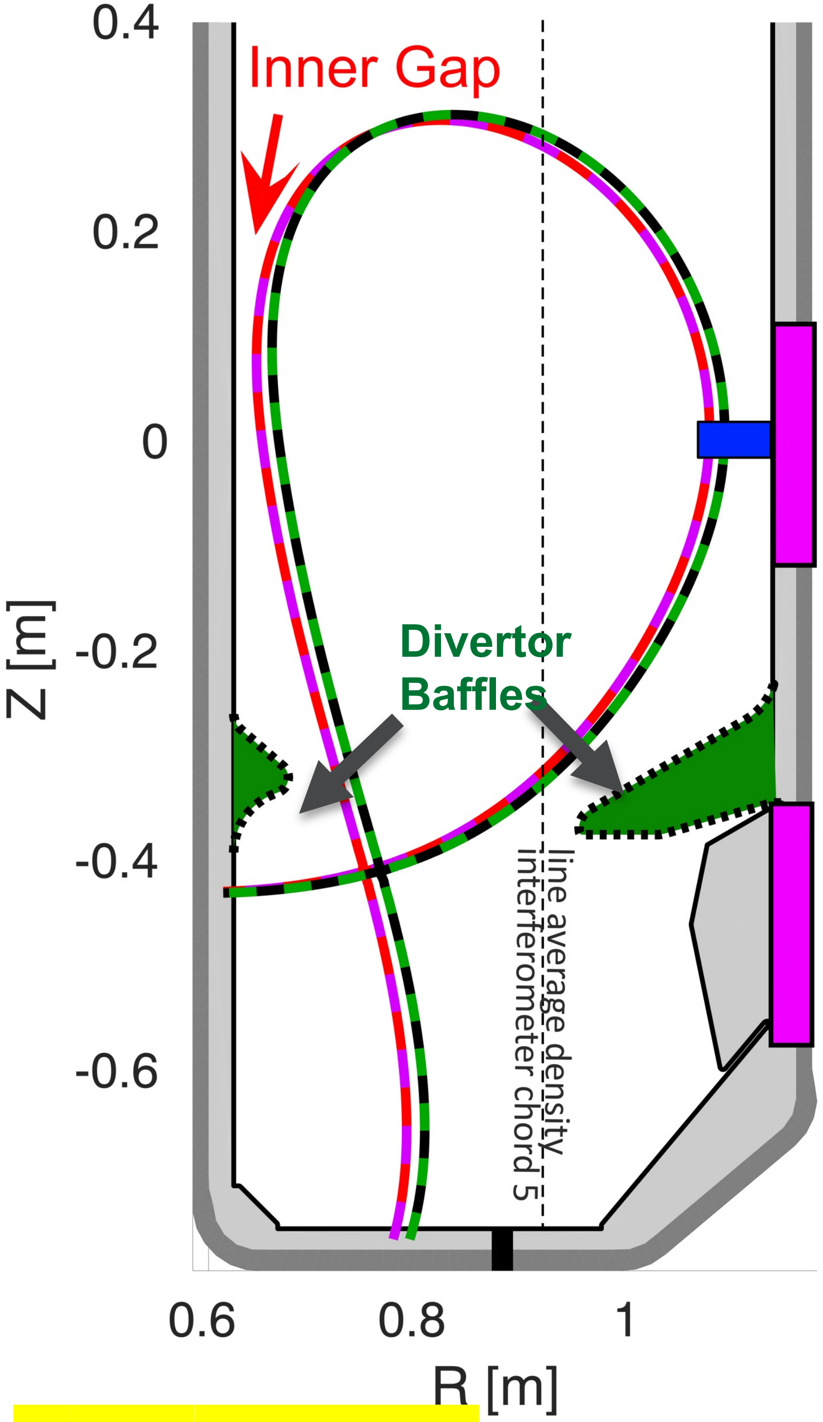
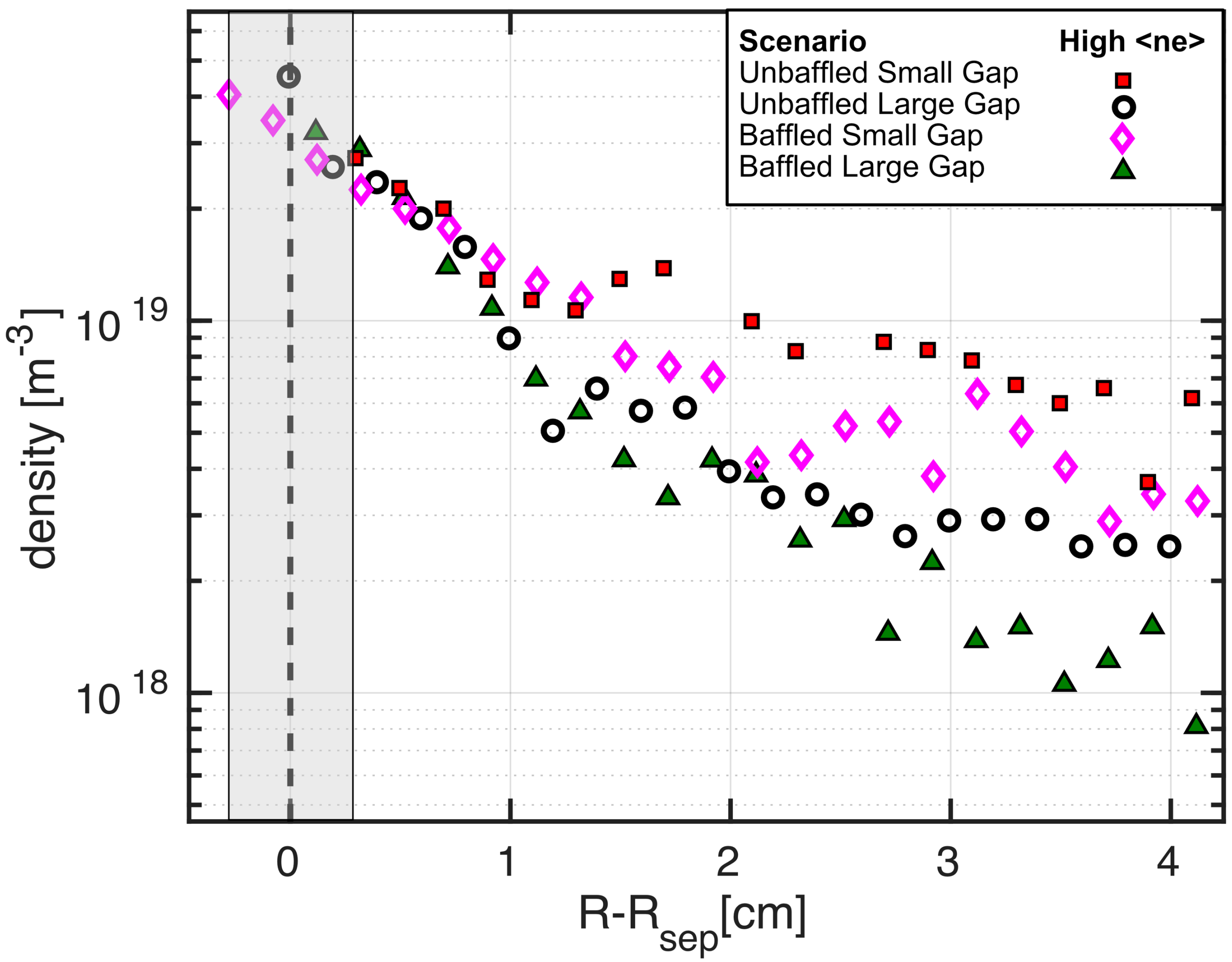
MAIN-CHAMBER NEUTRALS ALSO CONTRIBUTE TO SHOULDER CREATION





- **4 identical cases (same $\langle n_e \rangle$) except inner wall gap and divertor baffles**
- **Shoulder strongest when divertor baffles removed (neutrals escape into main-chamber) and when the inner gap is reduced (increases recycling in main-chamber)**

- **Shoulder growth does not occur when main-chamber neutral sources are minimized (Baffled Large Gap scenario)**
- **Good news for ITER? – divertor designed to block neutrals, already designed for wide main-chamber gaps.**

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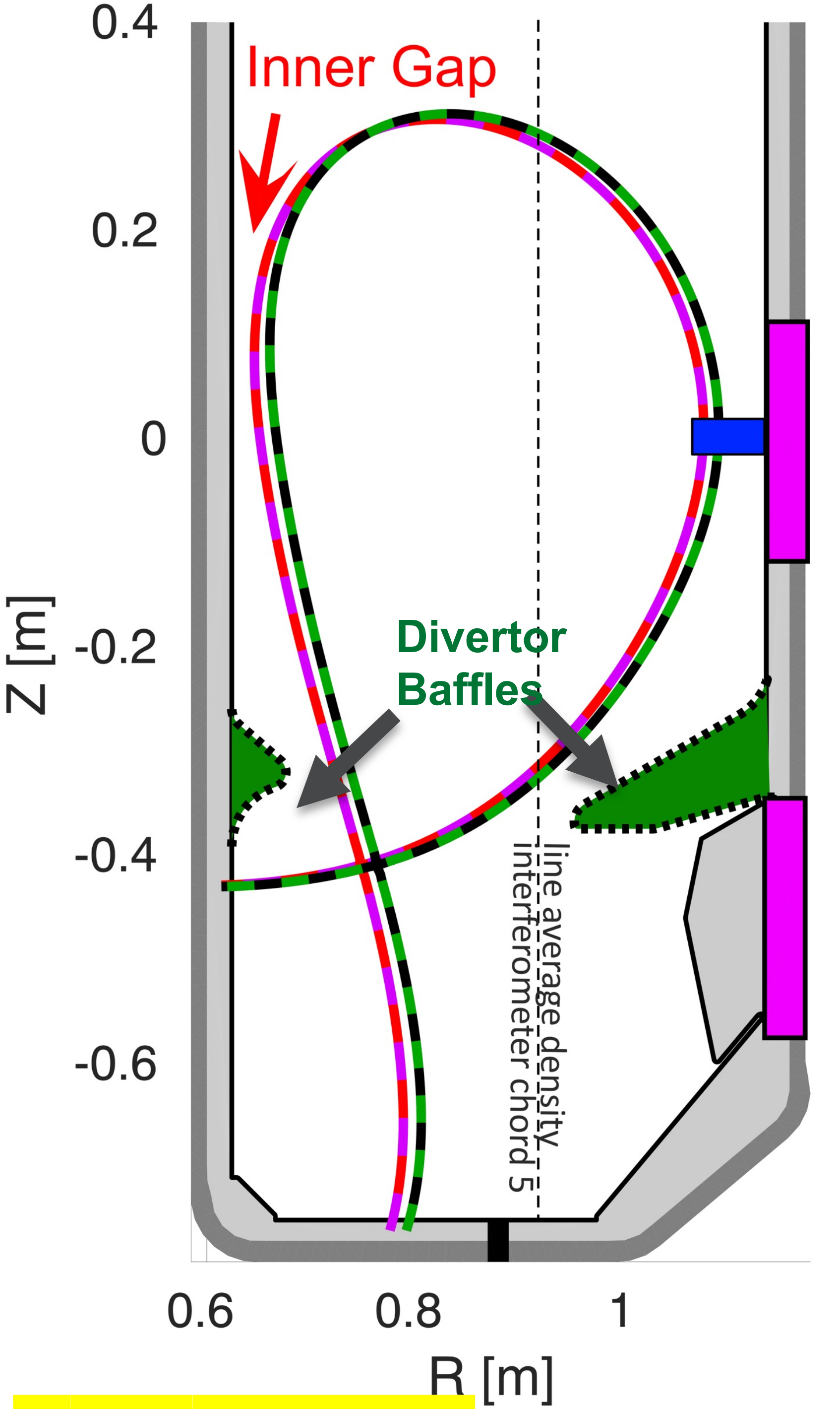
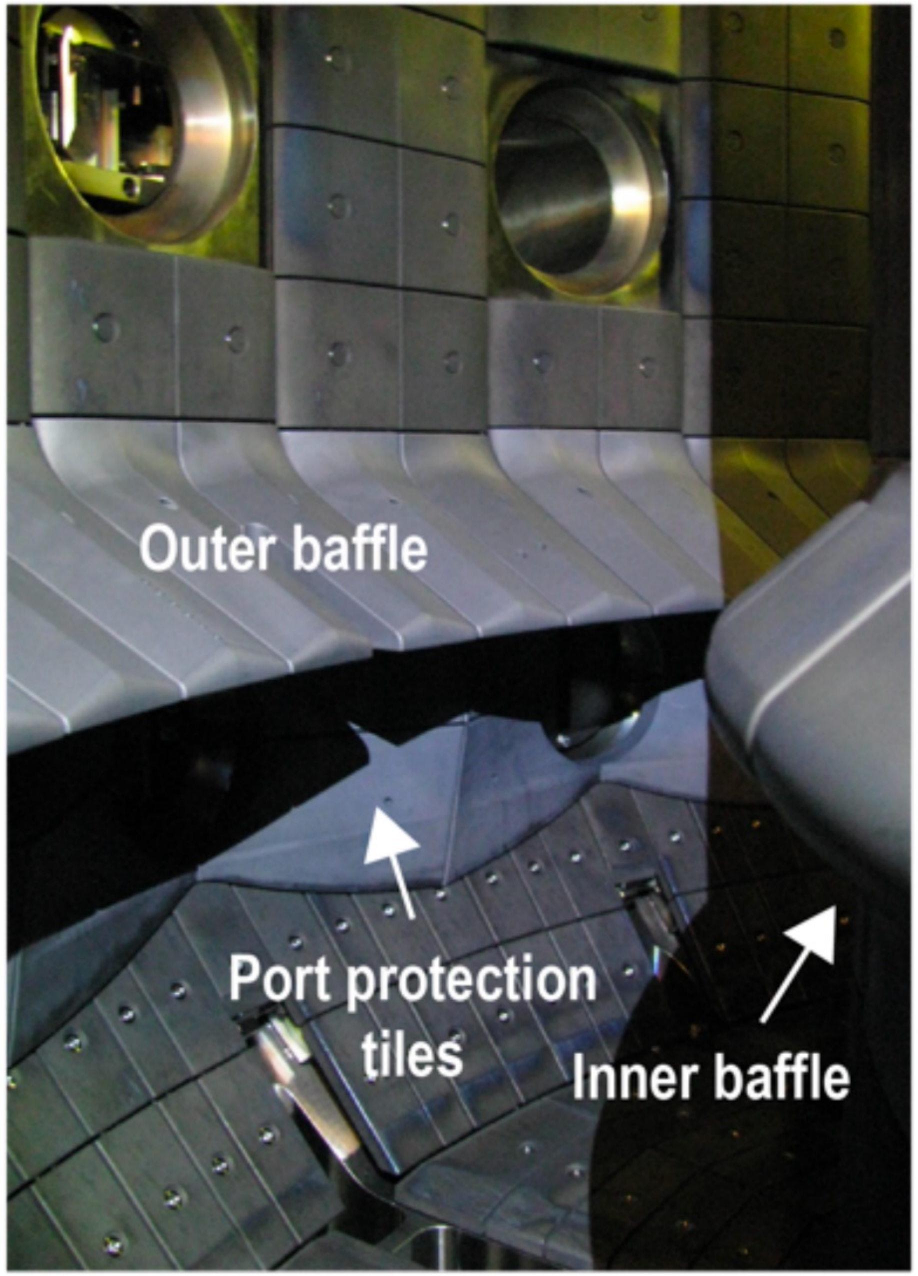
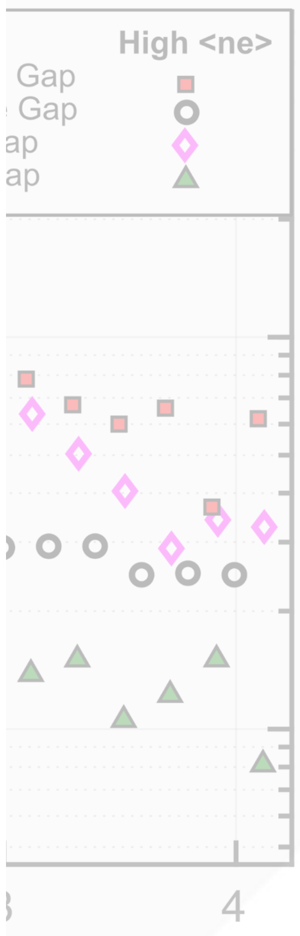
MAIN-CHAMBER NEUTRALS CONTRIBUTE TO SHOULDER AMPLITUDE







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occur when main-chamber neutral
ffled Large Gap scenario)
ertor designed to block neutrals,
already designed for wide main-chamber gaps.

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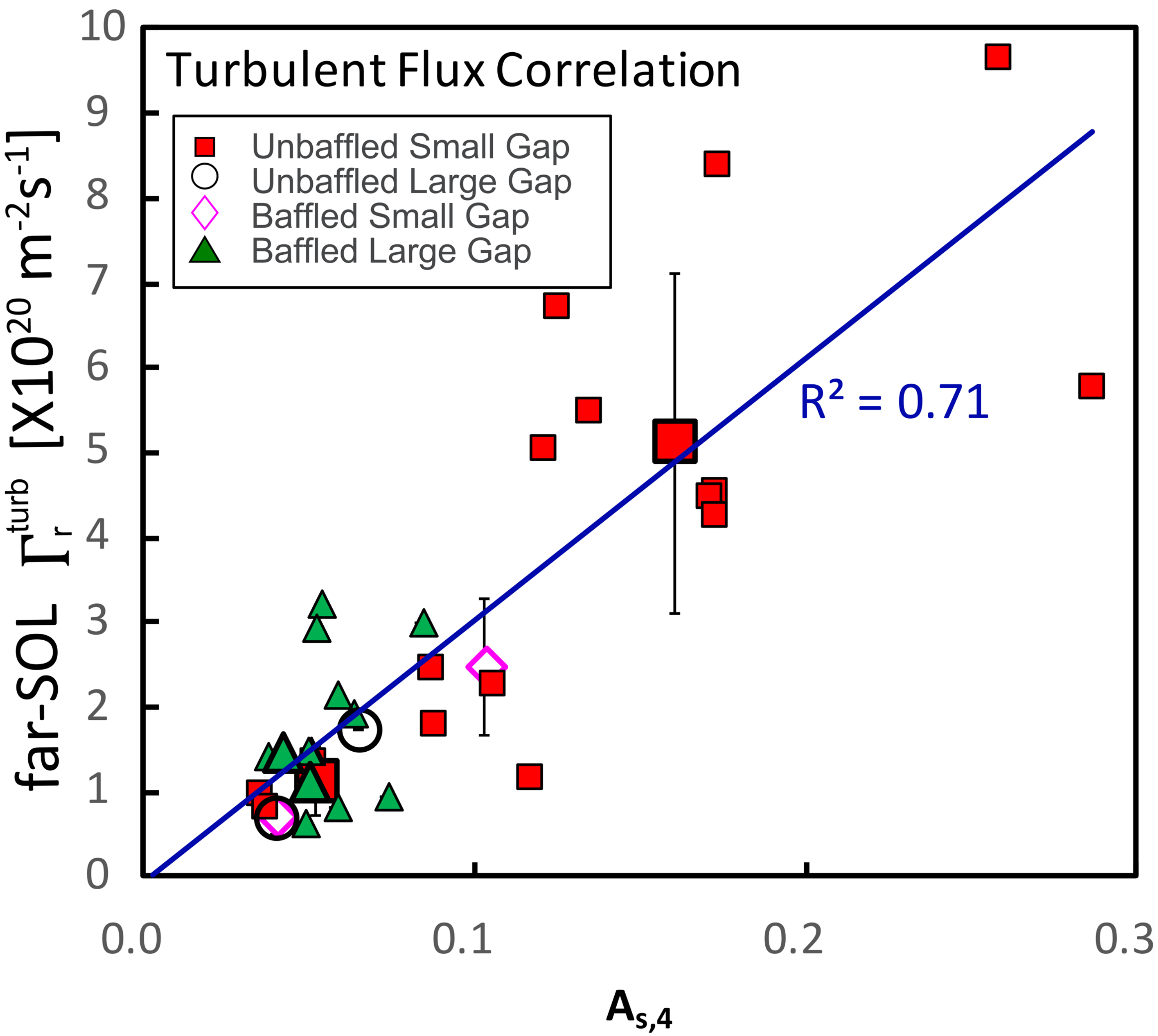
TURBULENT FLUX CORRELATES WITH SHOULDER AMPLITUDE

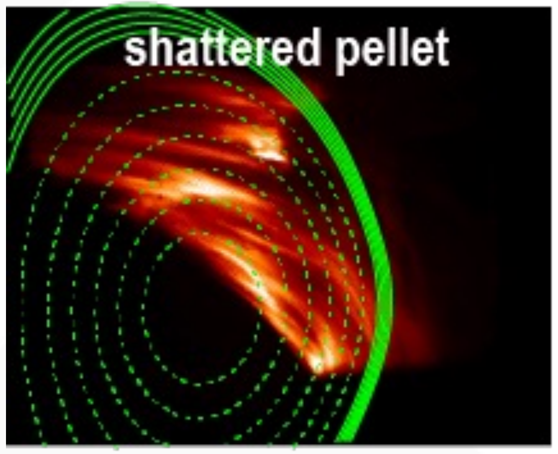


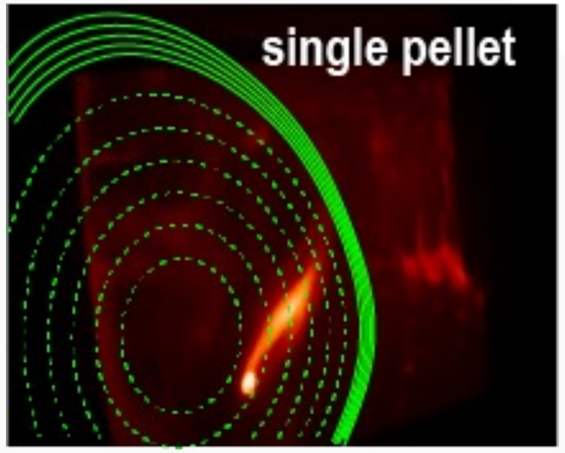
- **Radial turbulent flux (at midplane) correlates with shoulder amplitude**
  - **Not with $\langle n_e \rangle$ (full density scan in Baffled Large Gap scenario)**
- **Turbulent flux is needed for shoulder creation but not only component.**

C Tsui, J Boedo

UCSD WORK ON DISRUPTION MITIGATION FOR ITER

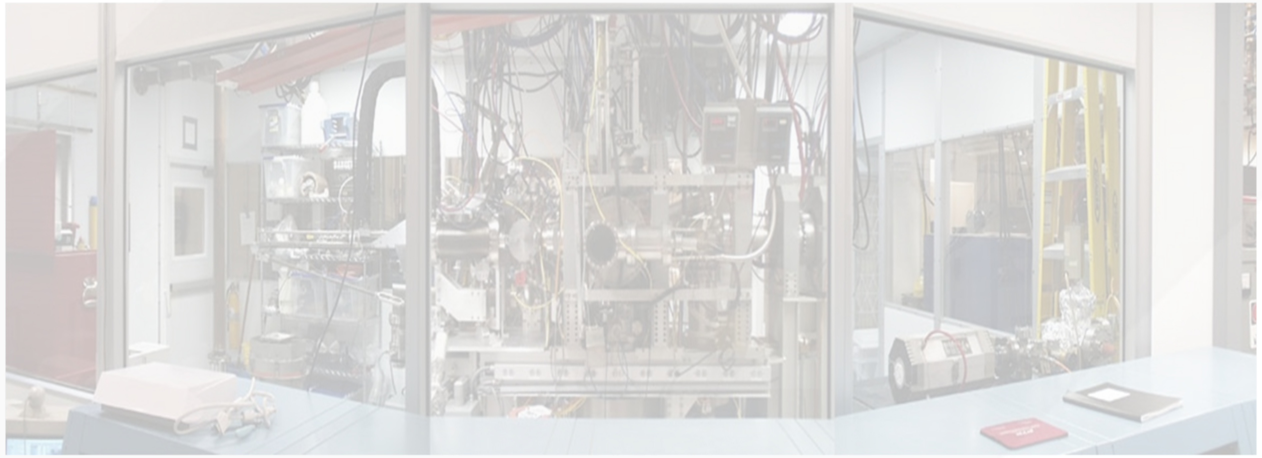
- Disruptions are global instabilities which can rapidly (~1 ms) release stored plasma thermal and magnetic energy into wall.
- Can generally be avoided:
  - Operate away from performance boundaries (I_p, β_N, n_e)
  - Good control system.
  - Disruption ”early warning system” with “soft landing” (ramp down of power) to avoid disruptions.
- Some disruptions may be unavoidable in future tokamaks:
  - Control system power supply failure.
  - Wall tile breaking.
  - Burning plasma acting in unpredicted manner.
- DIII-D research is working on last resort rapid shutdown techniques to safely shut down discharge in rare event of unavoidable disruption.
- Most present methods involve rapid injection impurities by different methods (gas, shattered cryogenic pellets, etc).
- Research focuses on optimizing impurity injection scheme to best mitigate wall damage from various channels:
  - Conducted heat loads to divertor
  - Induced current JxB forces on wall
  - Runaway electron beam strikes to wall

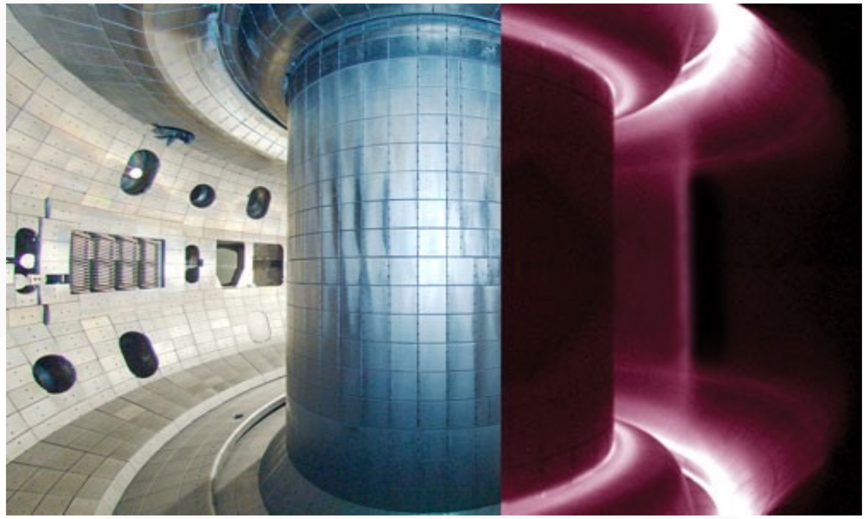




E Hollmann

UCSD CER KEY RESEARCH AREAS





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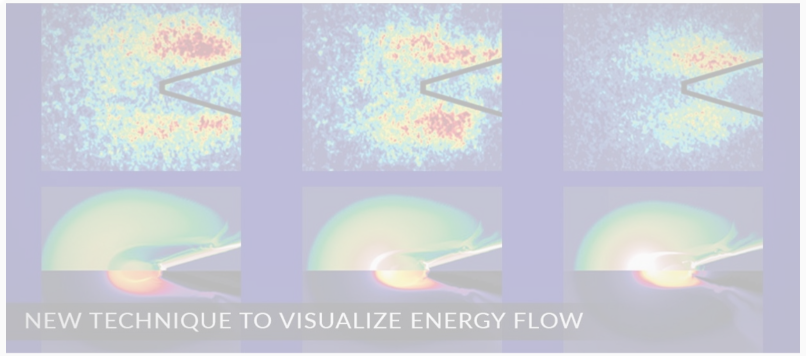

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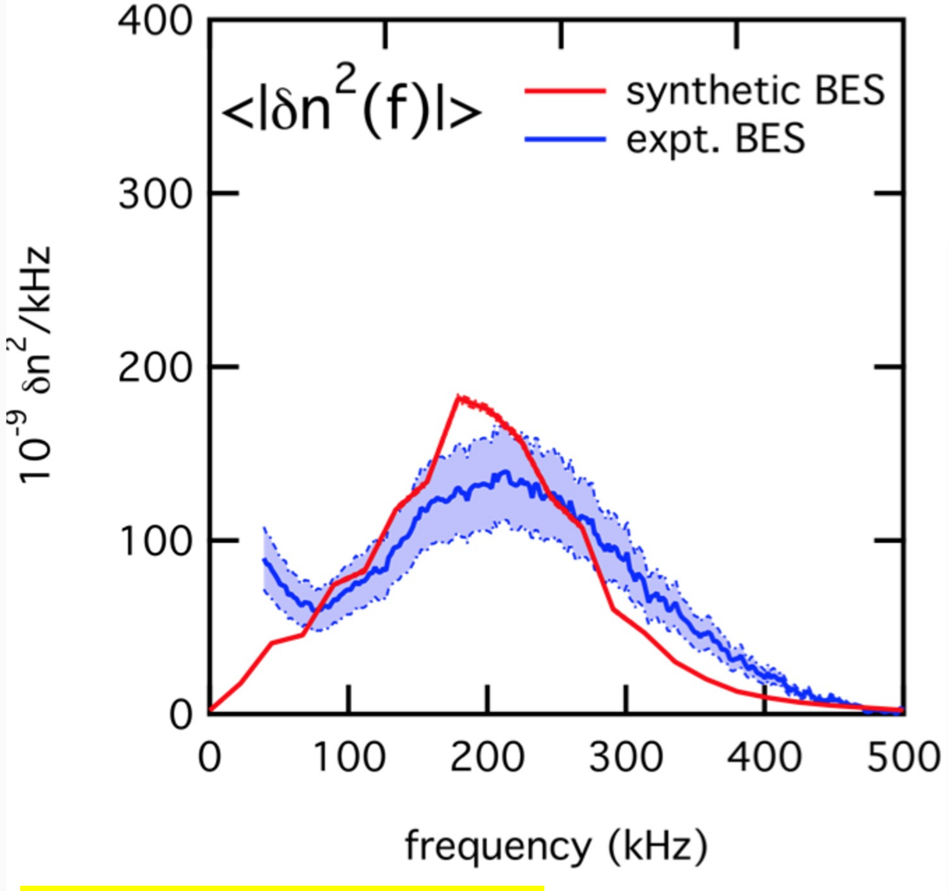
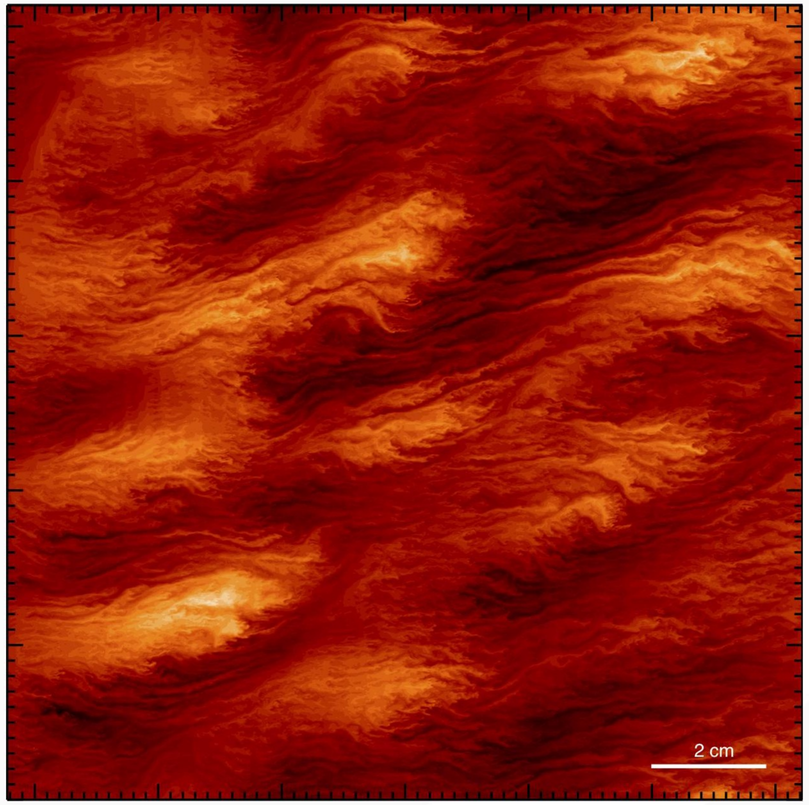
COLLABORATIONS WITH TEAMS AROUND THE WORLD TO DEVELOP, VALIDATE, AND APPLY PREDICTIVE MODELS OF FUSION PHYSICS

- Significant focus on studying turbulent transport in tokamaks

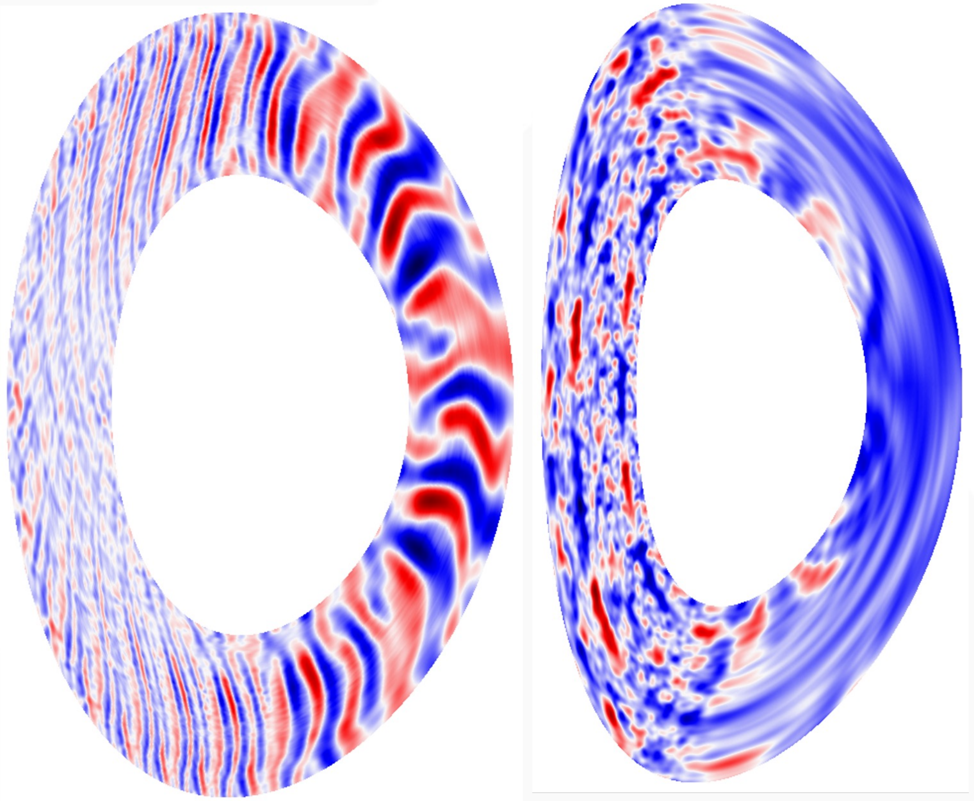
Developing synthetic diagnostics to enable quantitative code-experiment comparisons (Holland *et al*, PoP 2009)



Massively parallel simulations to understand how turbulence at different scales drive transport (Holland *et al*, NF 2017)



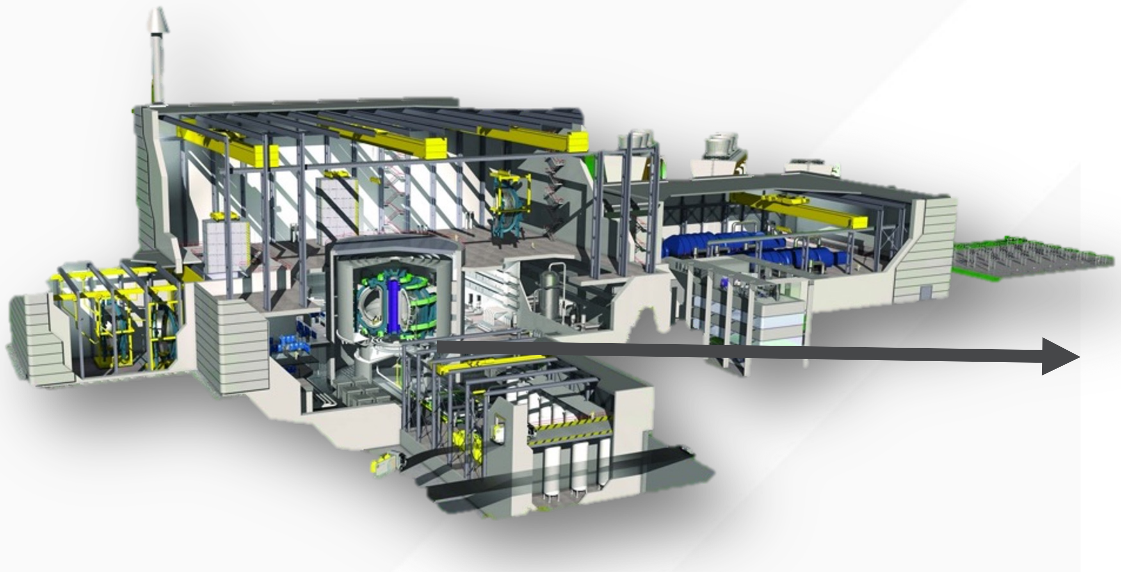
Predicting how turbulence structure and transport changes in different operating scenarios (Jian *et al*, PRL 2019)

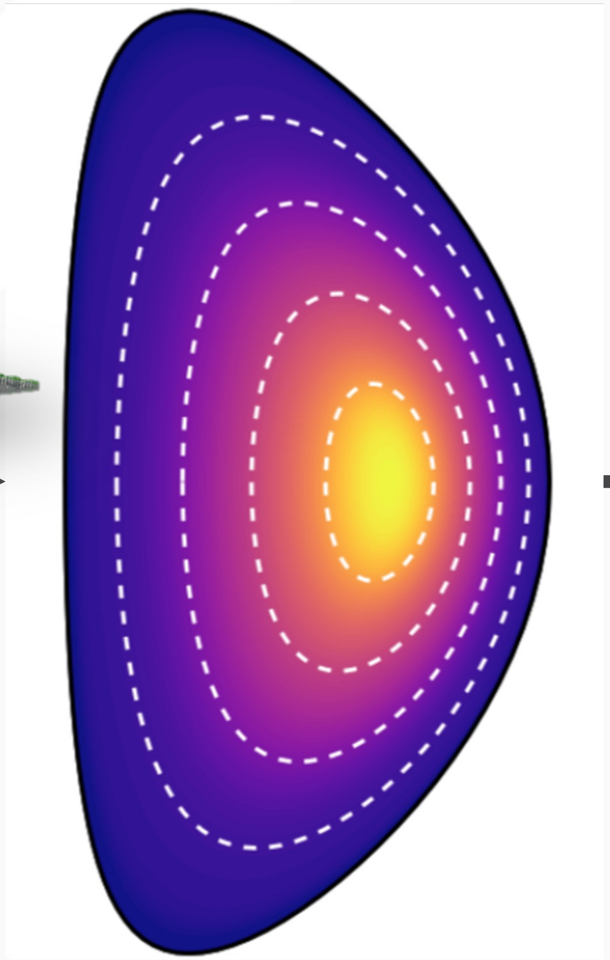


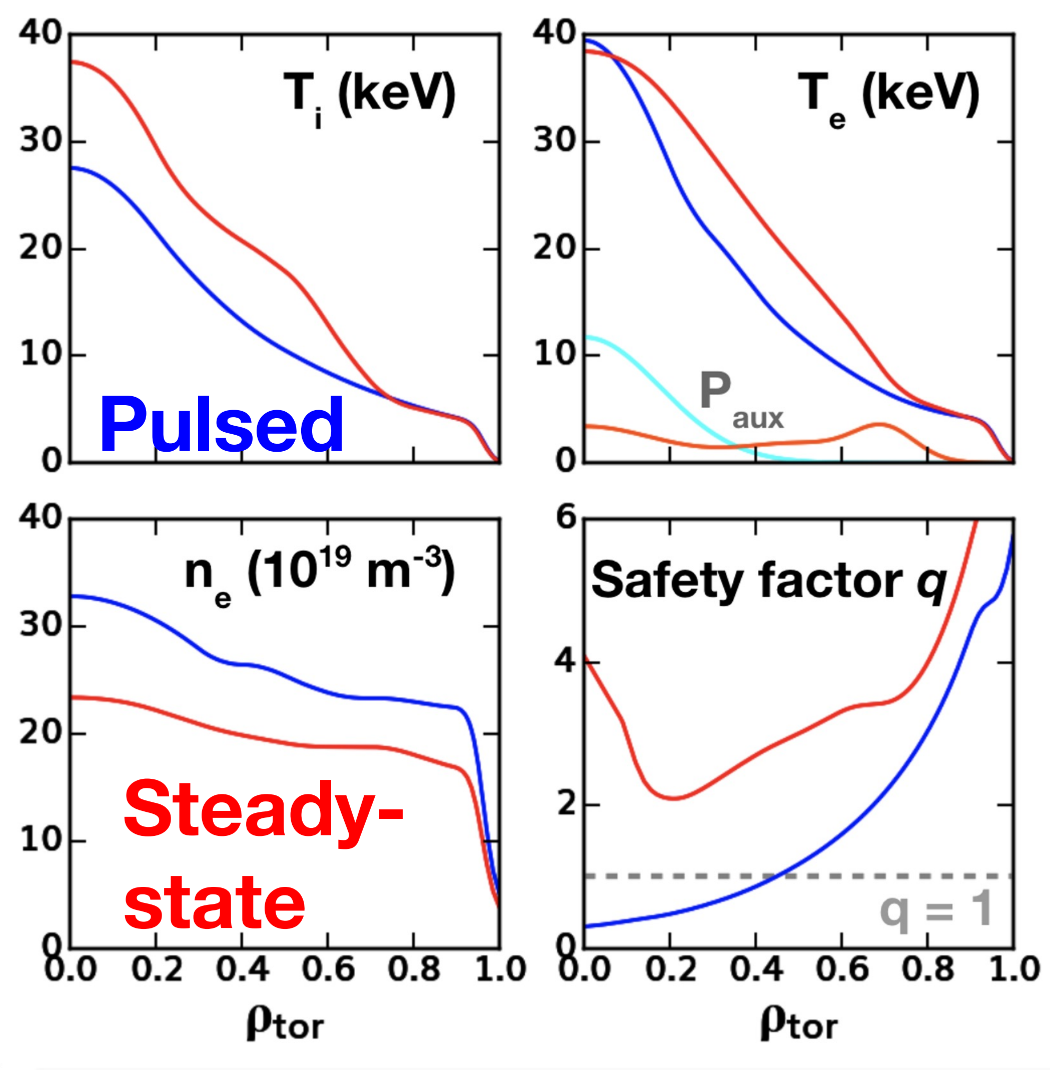
C Holland, X Jian

FUTURE WORK WILL HAVE INCREASED EMPHASIS ON APPLYING THESE MODELS TO ACCELERATE DEVELOPMENT OF FPP CONCEPTS

- Work to be carried out as part of Advanced Tokamak Modeling (AToM) SciDAC project research plan https://atom.scidac.io/



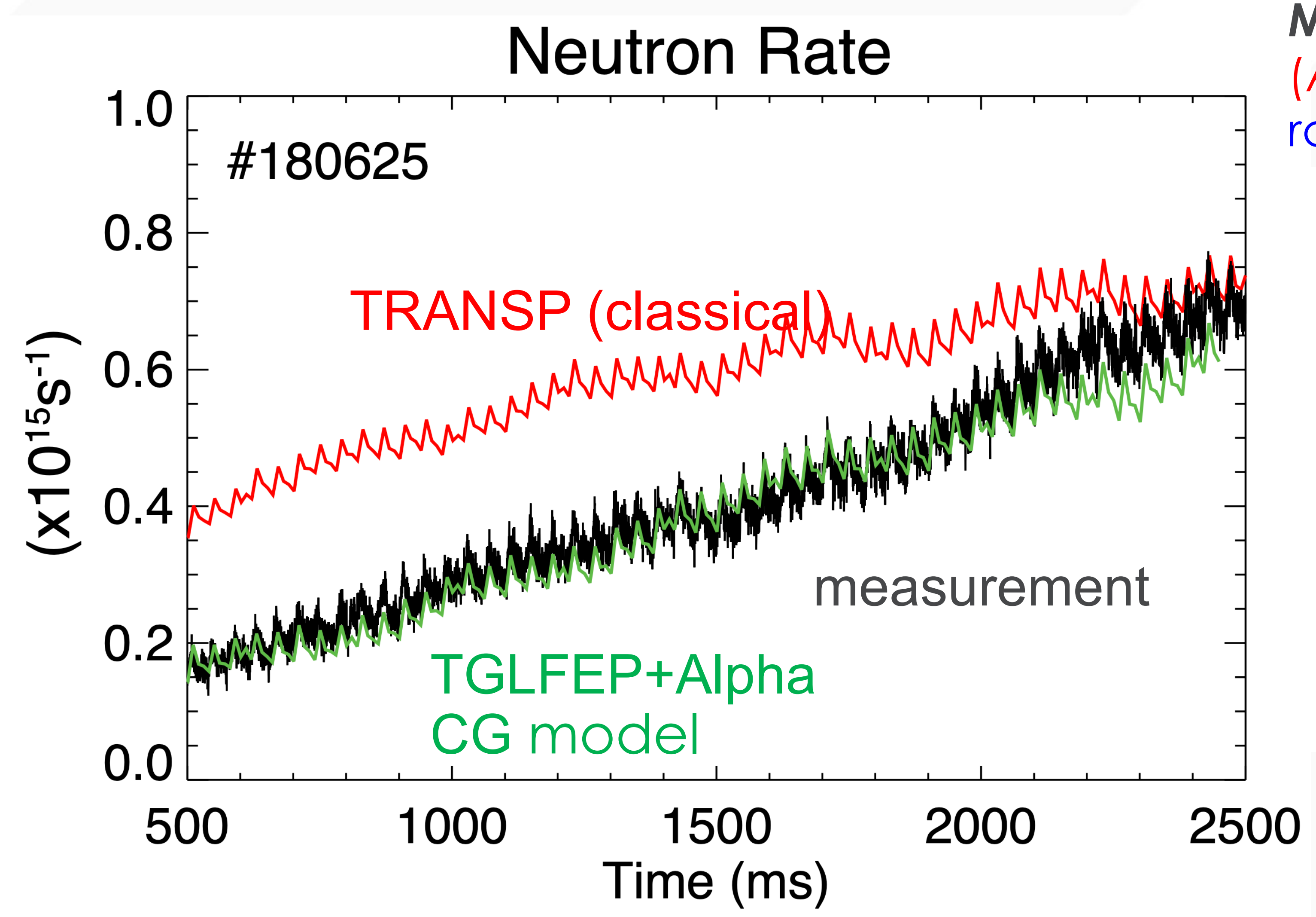




Scoping of inductive/pulsed and steady-state compact FPP concepts (Holland *et al*, 2021 APS-DPP)

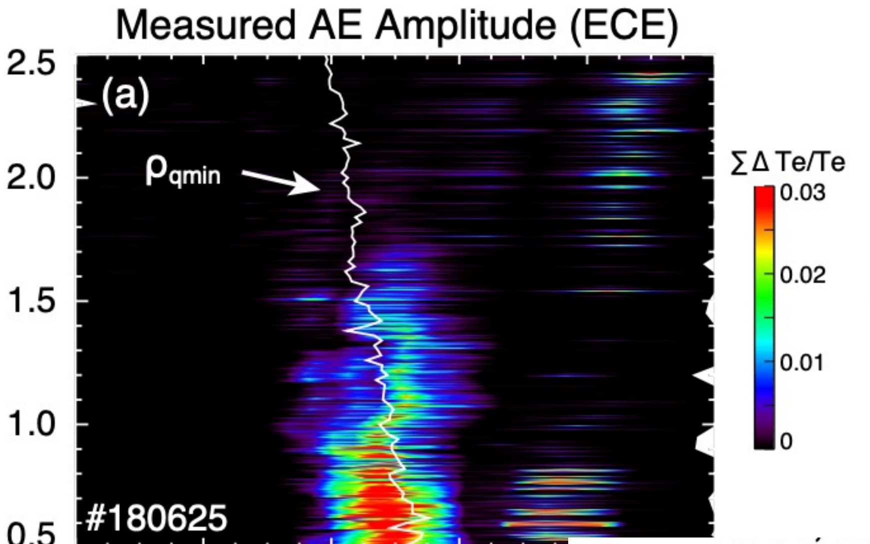
C Holland, E Bass, D Orlov, X Jian

CRITICAL-GRADIENT ALFVÉN-EIGENMODE (AE) TRANSPORT CAN PRODUCE SPECTACULAR AGREEMENT WITH DIII-D EXPERIMENTS

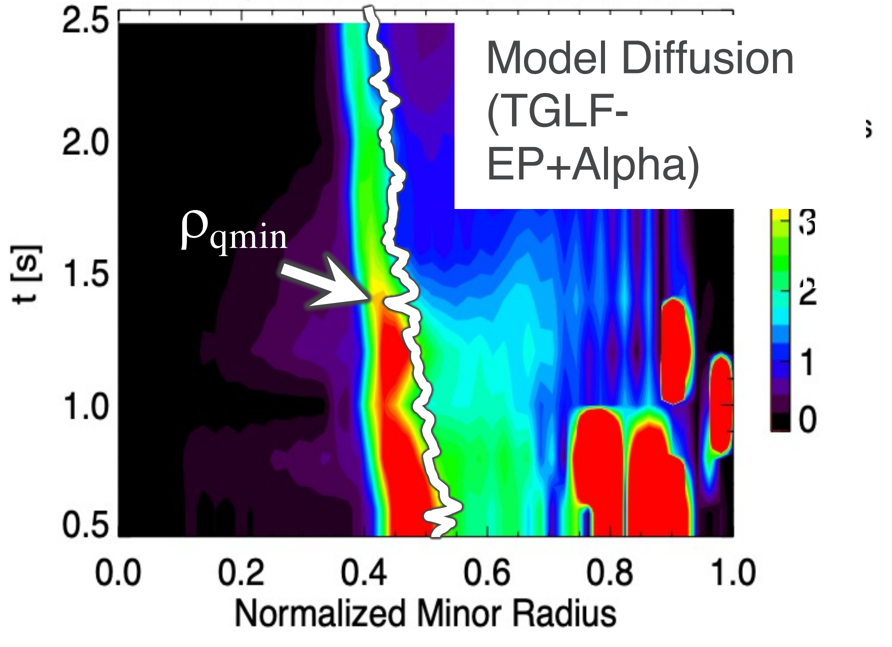


current ramp up, decreasing $q_{\min}$

Measured neutron deficit from **classical** (AE-free) prediction goes to zero as current ramps up and $q_{\min}$ goes down.



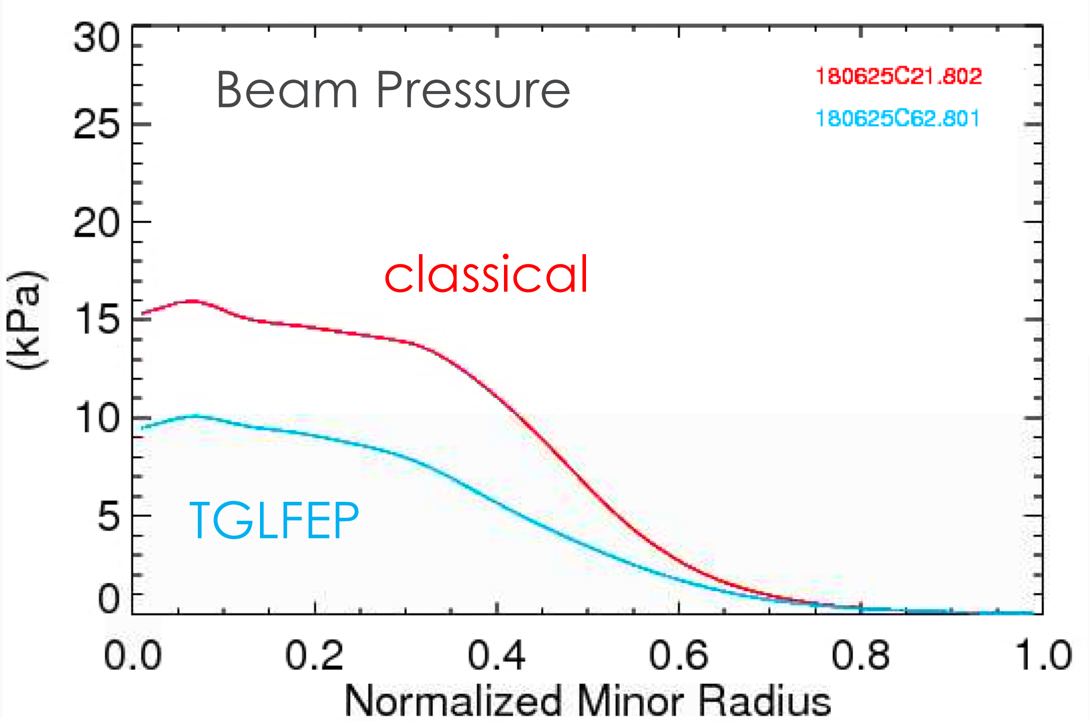
Model diffusion mirrors **AE activity**

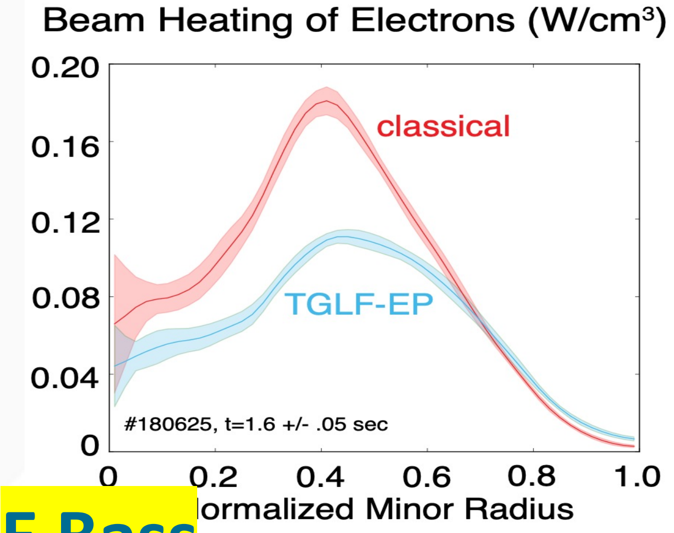


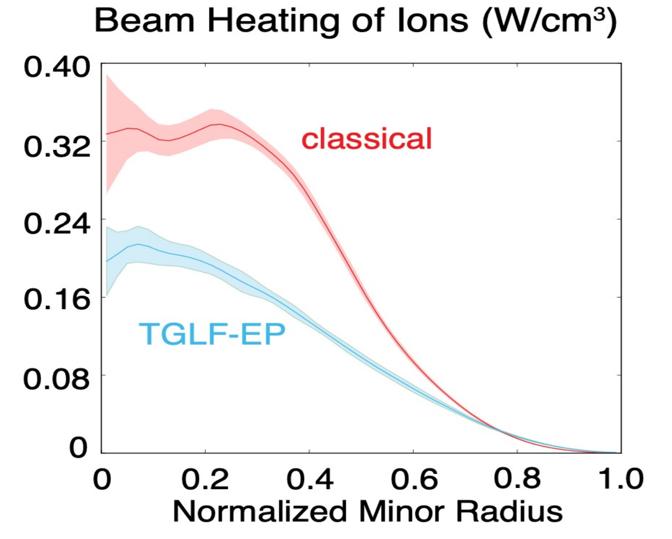
E Bass

PREDICTED EP DIFFUSION CHANGES BEAM ION AND ELECTRON HEATING, MATCHES THERMAL TURBULENCE PREDICTIONS TO EXP.

- TGLF-EP+ALPHA shows large reduction in beam pressure due to AE-induced transport → affects power deposition → affects TGLF T_i profile prediction

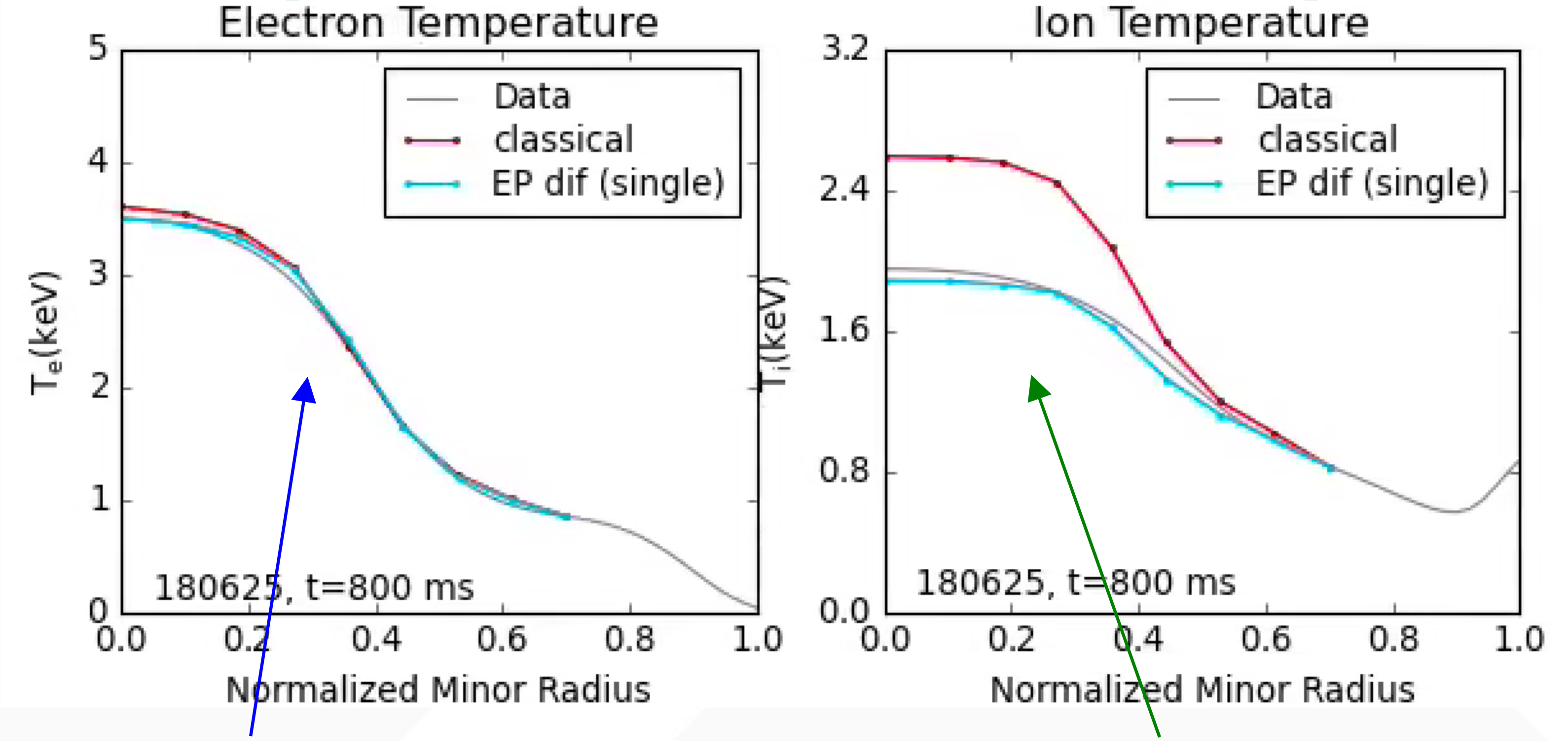






E Bass

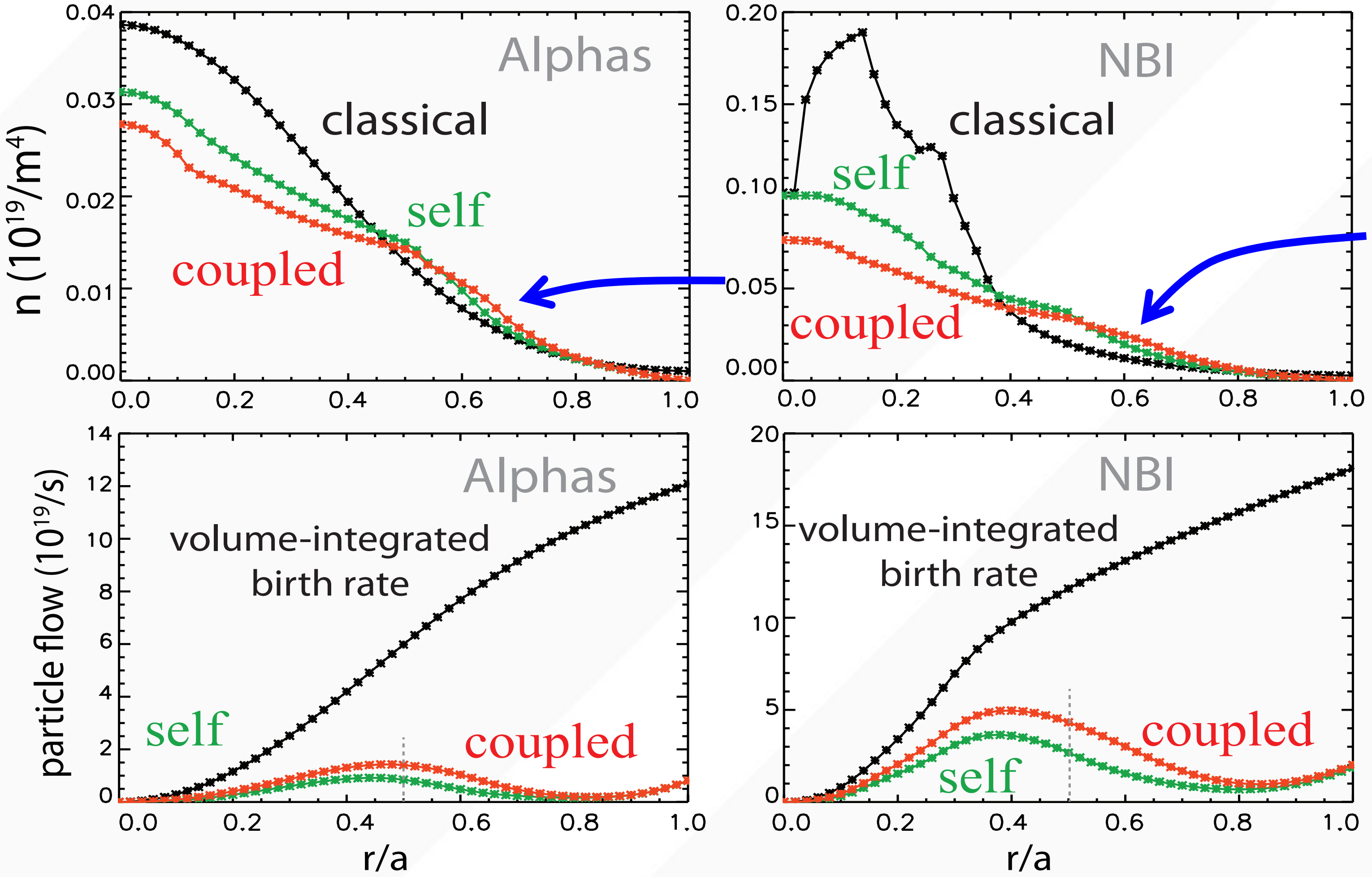
TGLF Profiles
(microturbulence prediction)



Electron profiles are in stiff regime in this case:
e^- power flux goes down but profile is unchanged

Ion turbulence is not stiff → **prediction changes**

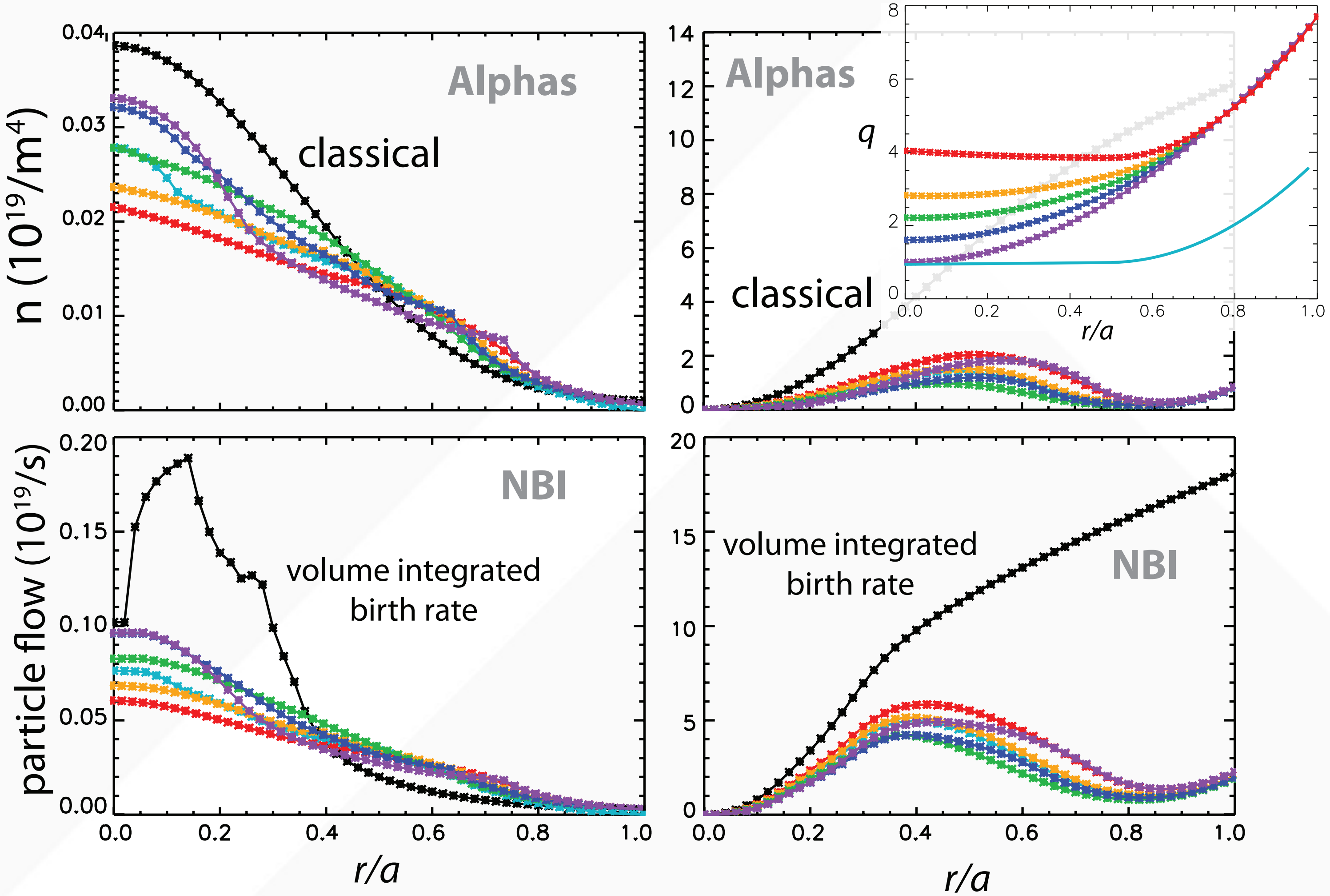
A TWO-SPECIES CRITICAL-GRADIENT MODEL USED TO PREDICT ALPHA PARTICLE AND BEAM ION TRANSPORT IN ITER SCENARIOS



Mid-core AEs redeposit EPs to the outer radii where there energy is absorbed.

Coupled drive means alphas drive beam-ion transport and vice versa

Coupled transport with various q profiles



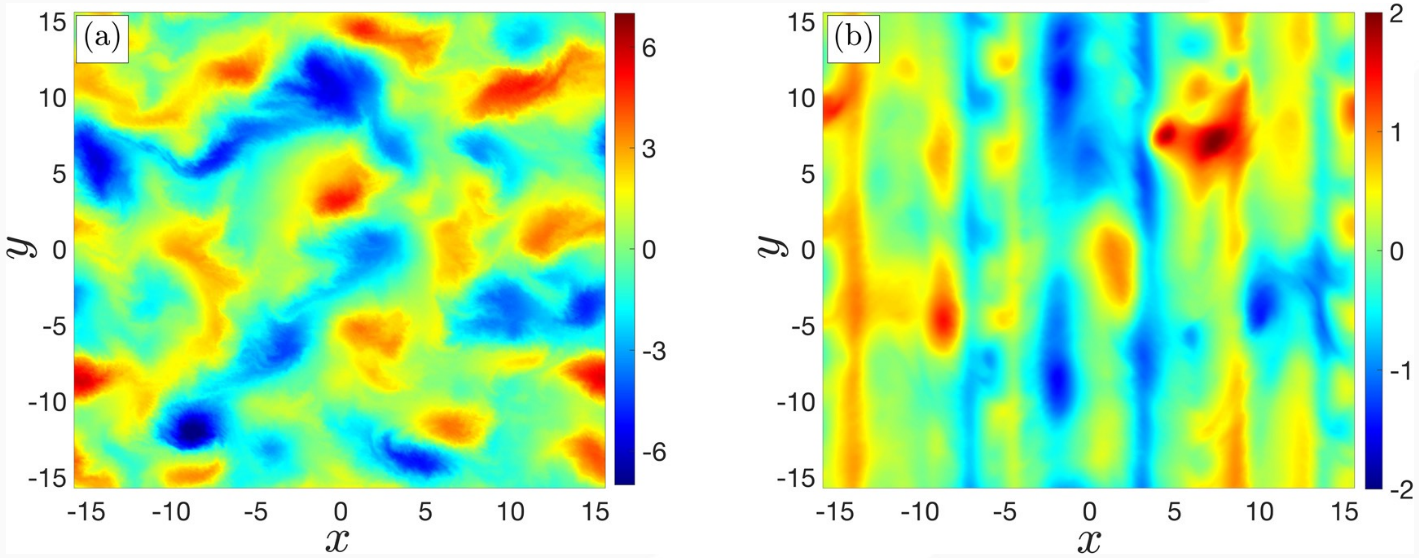
Base case (as above) has moderate EP redistribution.

Reduced current (increased q) → higher EP transport.

Reduced penetration (increased core shear) → lower EP transport

E Bass

DRIFT-WAVE TURBULENCE AND ZONAL FLOW



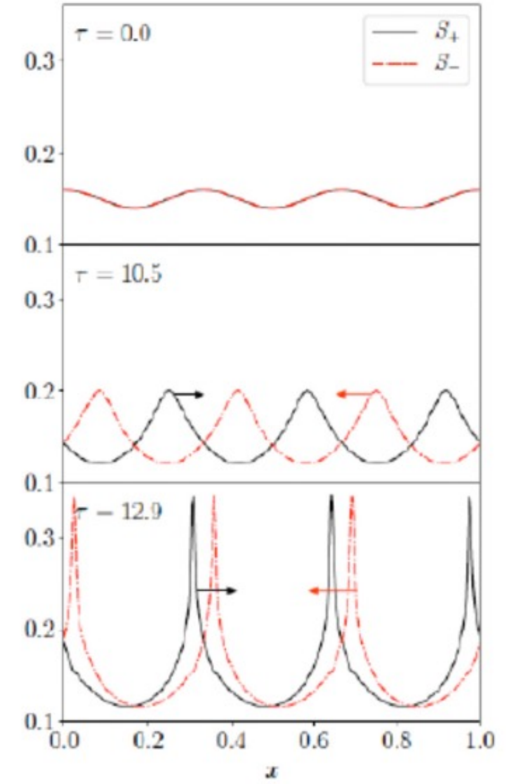
Trapping of the drift-wave eddies at the extrema of self-generated zonal flow (right) reduces anomalous cross-field plasma transport, which becomes strong in the absence of zonal flow (left)

Nonlinear interactions of drift-waves and zonal flows can be described by coupled equations describing the group velocity, U, and the enstrophy amplitude, S, of the drift wave packets:

$$\frac{\partial S}{\partial \tau} + \frac{\partial}{\partial x}(US) = 0,$$

$$\frac{\partial U}{\partial \tau} + U\frac{\partial U}{\partial x} = \frac{\partial S}{\partial x},$$

Collapsing solutions for the case of two counter propagating drift wave packets →



S Krasheninnikov, R Smirnov (Applied Plasma Theory Group)

DIVERTOR PLASMA DETACHMENT

- The reduction of the heat load on divertor targets in both ITER and future fusion reactors require the reduction of plasma particle flux, Γ_{div}, on the targets (so-called divertor plasma detachment)
- From the energy and particle balance in the scrape off layer plasma

$$Q_{SOL} = Q_{imp} + E_{ion}\Gamma_{ion} + \gamma T_d \Gamma_d$$

$$\Gamma_{ion} = \Gamma_{div} + \Gamma_{rec}$$

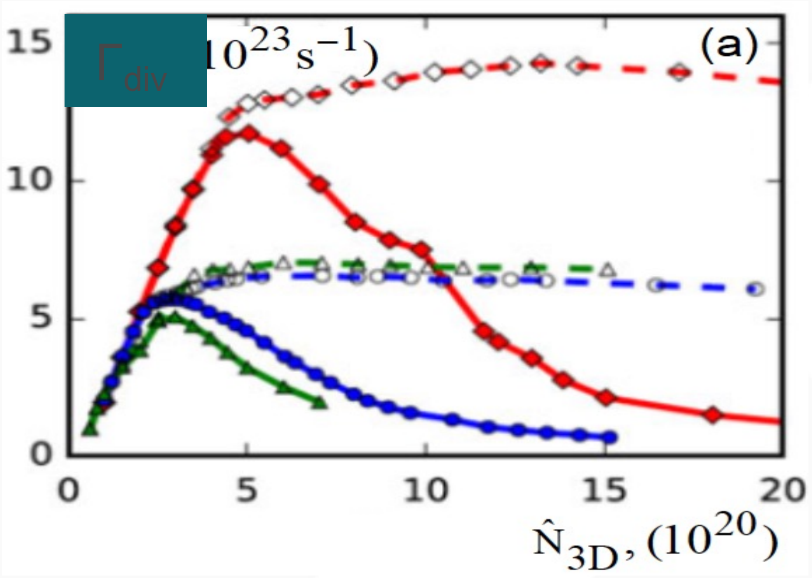
Q_{SOL} – heat flux into SOL, E_{ion}~30 eV – H ionization cost, Qimp – impurity radiation, Γ_{ion} and Γ_{rec} are ionnizationsource and recombination sink

- For small T_d, we find

$$\Gamma_{div} = \left(Q_{SOL} - Q_{imp}\right) / E_{ion} - \Gamma_{rec}$$

- Which shows that the reduction of plasma particle flux on the target is only possible by either increase of impurity radiation or by plasma recombination

- 2D numerical SOLPS simulations fully confirm these conclusions:



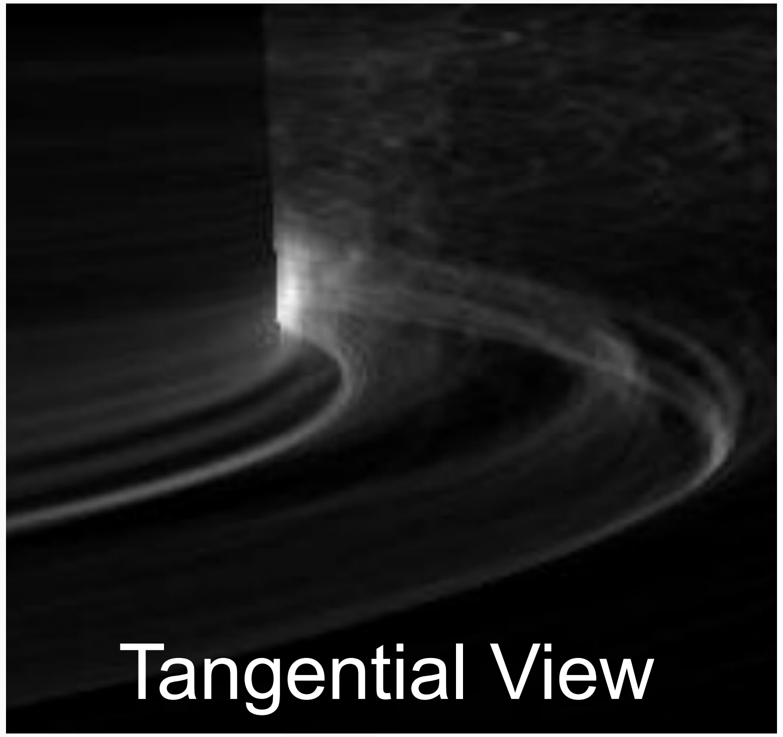
— Q_{SOL}=8 MW, Q_{imp}=0
— Q_{SOL}=8 MW, Q_{imp}=4 MW
— Q_{SOL}=4 MW, Q_{imp}=0

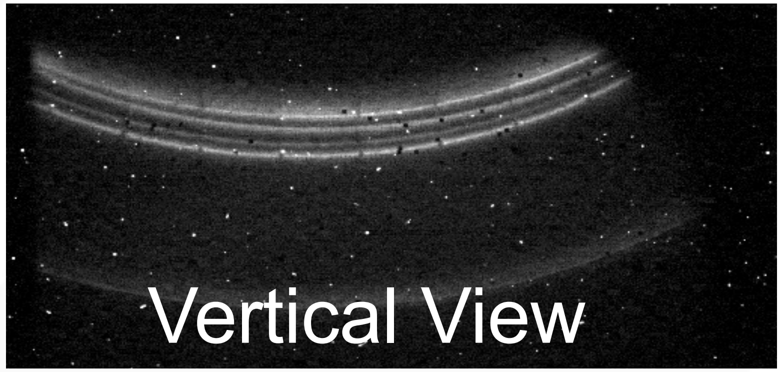
dashed – w/o, solid - with volumetric plasma recombination

S Krasheninnikov, R Smirnov (Applied Plasma Theory Group)

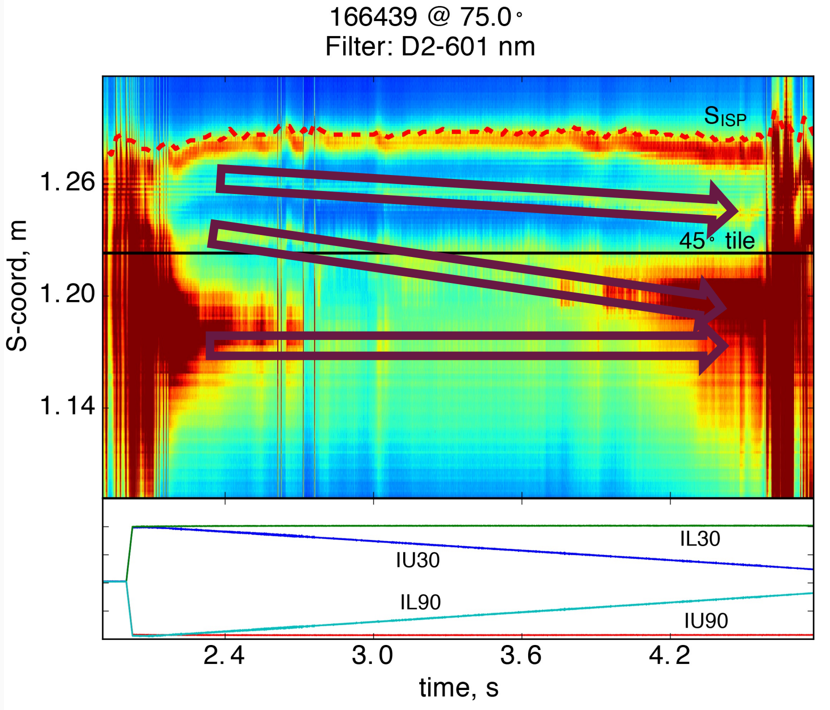
RMP ELM SUPPRESSION AND ITS LINK TO THE DIVERTOR HEAT AND PARTICLE FLUXES

- **Resonant Magnetic Perturbation (RMP) ELM control in ITER may result in toroidally asymmetric divertor heat and particle flux distributions**
- **Reduction of heat and particle flux asymmetries via:**
  - **rigid toroidal rotation of RMP fields**
    - may be limited due to mechanical and thermal stress on the coils and divertor components
  - **current modulation in a subset of the ITER ELM coils (toroidal perturbation spectra)**


Tangential View


Vertical View

- **DIII-D I-coil quartet ramp experiments were used to validate plasma response model predictions for footprint topology: vacuum TRIP3D, single and 2 fluid M3D-C1, MARS, ideal non-linear VMEC, nonlinear JOREK and NIMROD.**


166439 @ 75.0°
Filter: D2-601 nm

D Orlov

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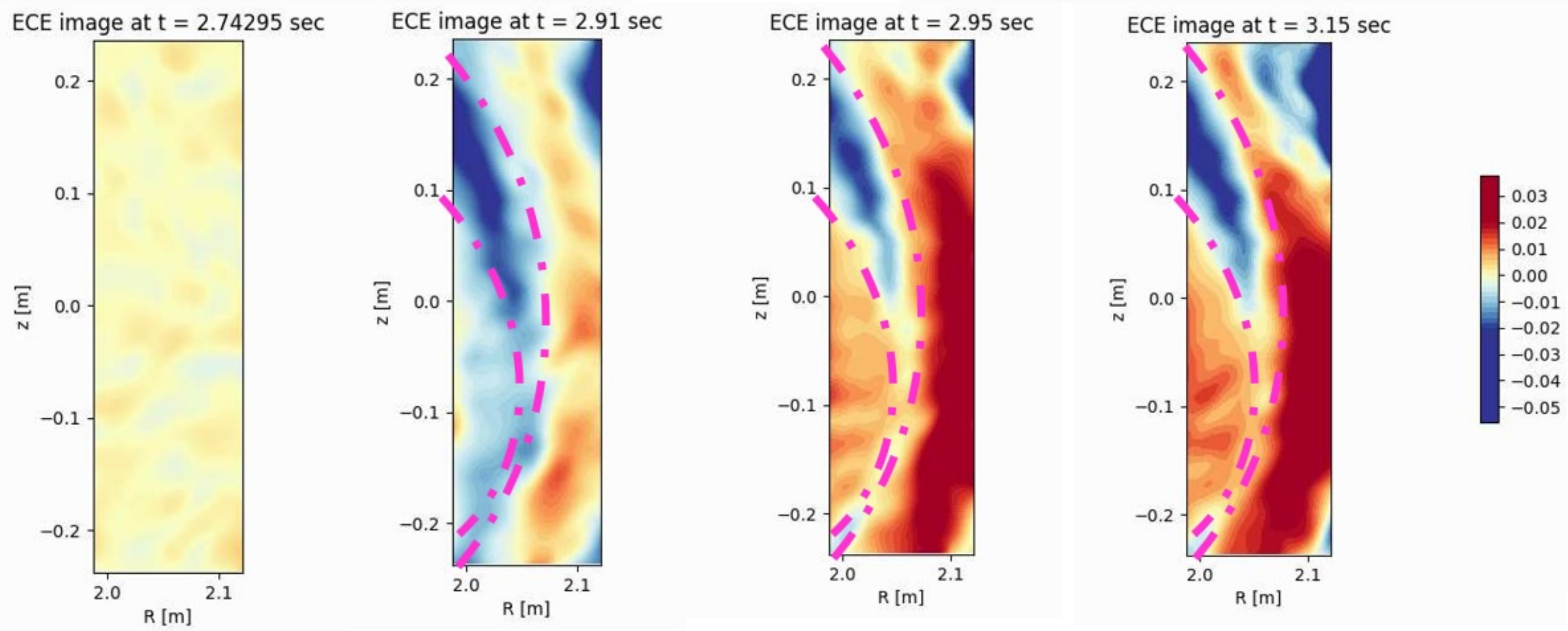
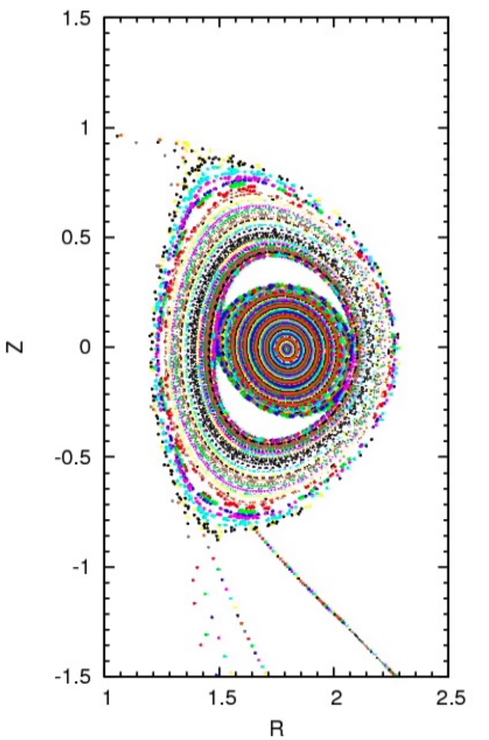
BENCHMARKING RMP RESPONSE MODELS AND TRANSPORT SIMULATIONS IN KSTAR PLASMAS

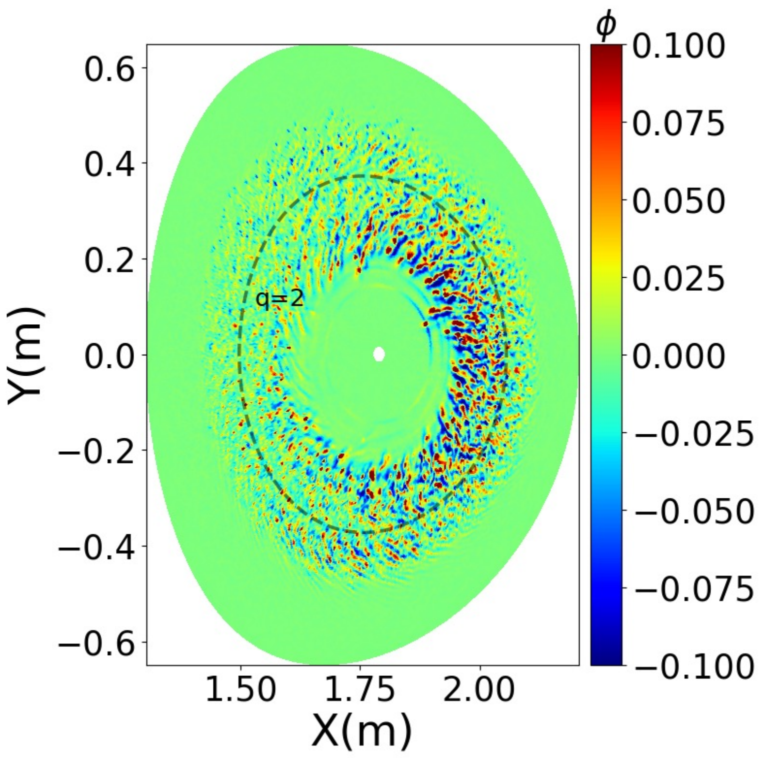
Fluctuation measurements for KSTAR L-mode IWL discharge make it an ideal case for studying large island transport

KSTAR mode locking experiment provide test of linear and nonlinear RMP response models in M3D-C1 and NIMROD. Plasma response calculations show island structure similar to experimental measurements

GTC simulations using axisymmetric equilibrium find ITG-driven microturbulence, providing a baseline for studying effects of large magnetic islands

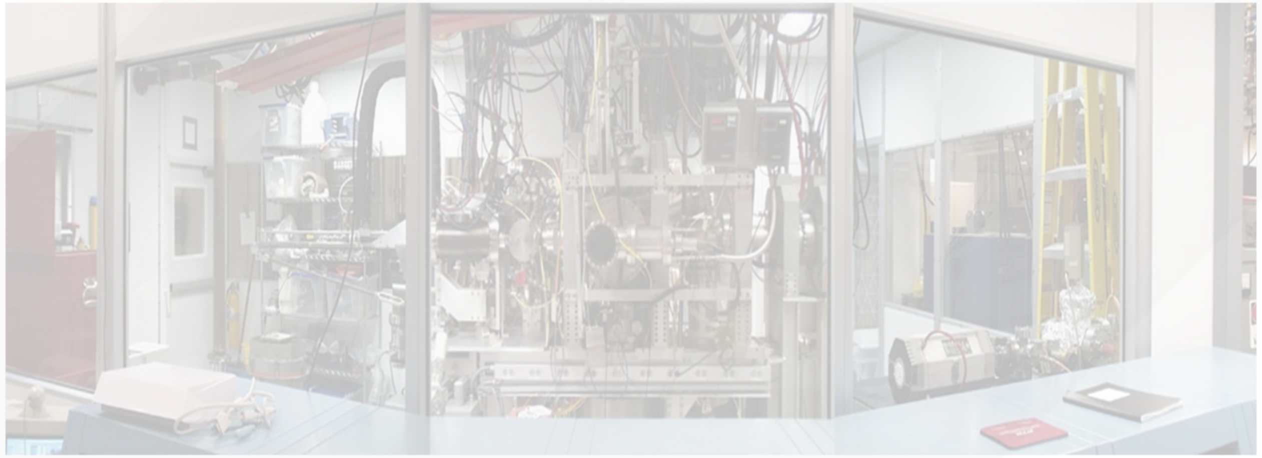


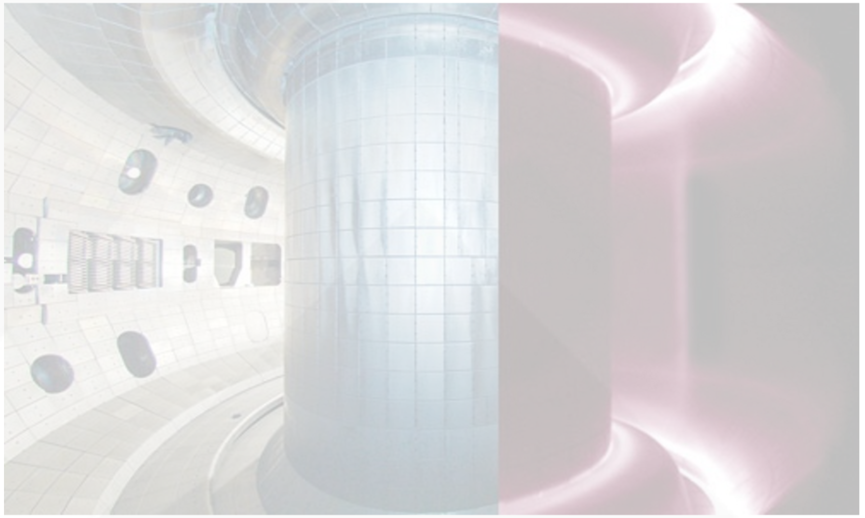




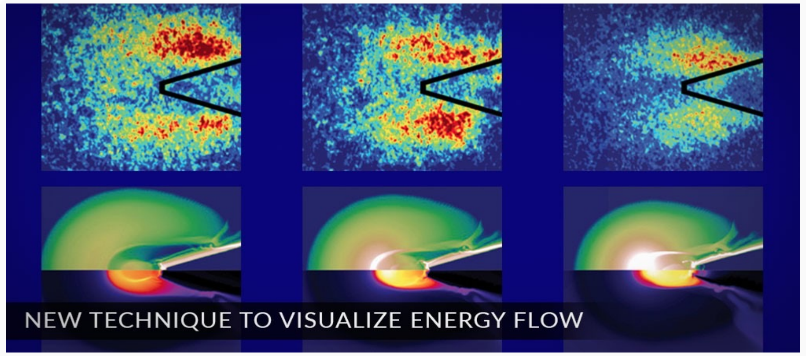
D Orlov and LPT RMP team

UCSD CER KEY RESEARCH AREAS



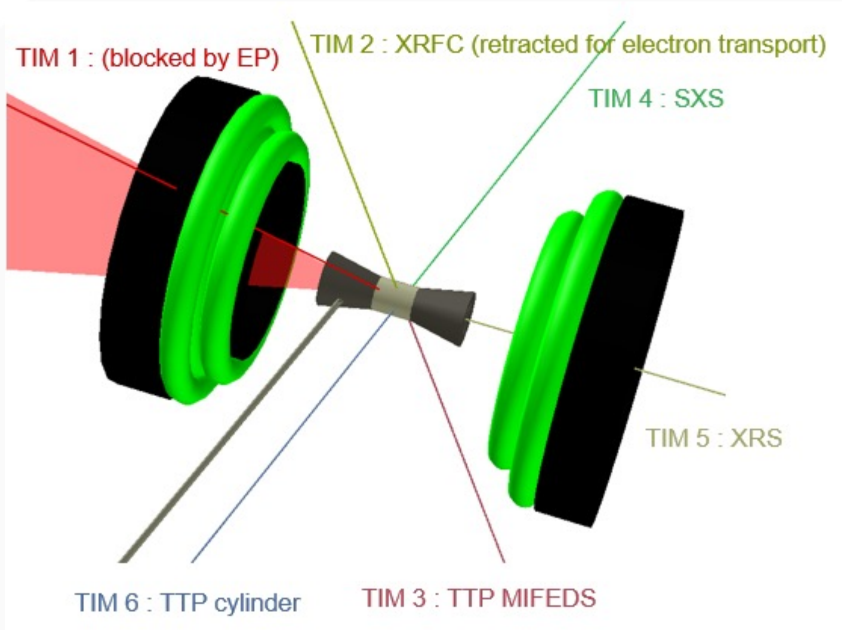


- PISCES Program
- DIII-D Tokamak Collaboration
- TCV Collaboration
- Tokamak Theory and Modeling
- Center for Matter under Extreme Conditions
- Center for Momentum Transport and Flow Organization

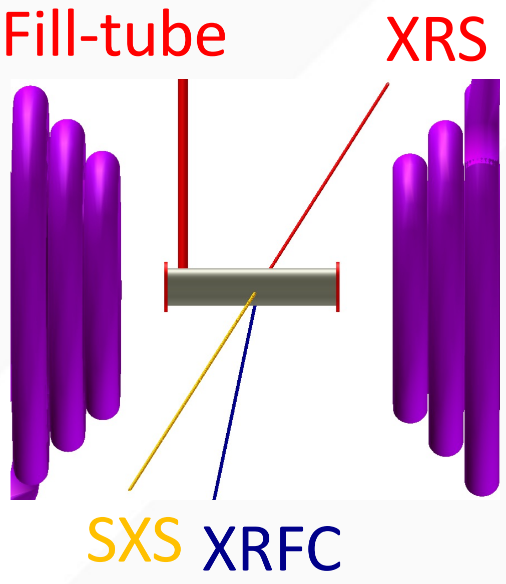


CER
Center for Energy Research

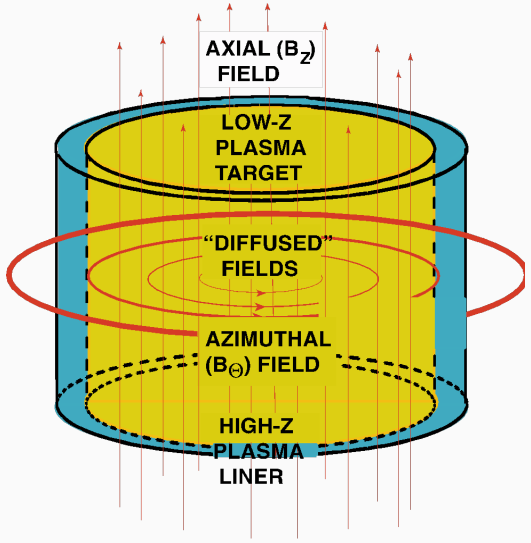
RESEARCH ON HIGH ENERGY DENSITY SCIENCE AND FUSION IN THE CENTER FOR MATTER UNDER EXTREME CONDITIONS



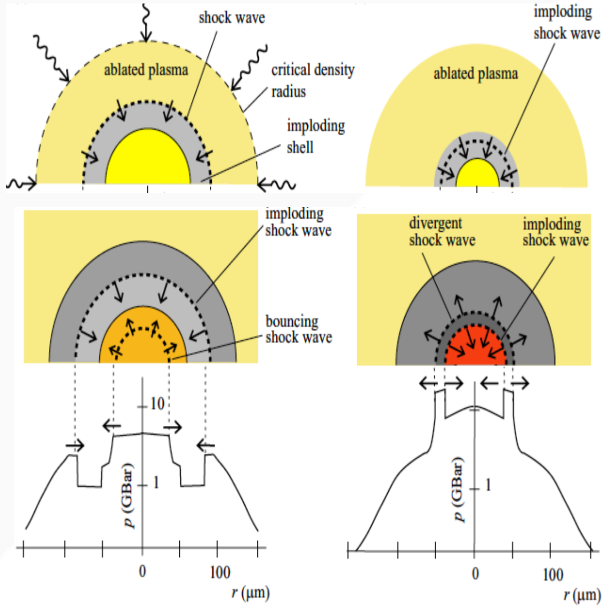
Fast Ignition 2.0



MagLIF



Liner on target Z-pinch



Shock ignition

CMES does fundamental research on four fusion concepts

Why fast ignition?

- Higher gain and lower ignition threshold
- Less stringent symmetry requirement
- Stand off distance is challenging

Magnetized Implosions: What Happens to the Compressed Plasma in Presence of Strong Magnetic Fields?

F Beg (Center for Matter under Extreme Conditions)

FUSION AND ASTROPHYSICAL PLASMA PHYSICS GROUP PROJECTS

Avalanching and turbulence spreading

How does turbulence and turbulent mixing propagate and penetrate stable regions?

Zonal flow scale selection and staircase formation

Why do zonal flow patterns select the scale they do? What are the consequences?

Flow pattern formation in linear devices CSDX

How do azimuthal (zonal) and axial flows interact and compete for free energy?

Cosmic ray acceleration

- How are high energy cosmic rays accelerated? How do plasma physics processes accelerate a simple nucleon to the energy of a home run baseball in flight?

L → H transition

What is the physics of the forward and back transitions to/from the remarkable good confinement state of H-mode?

Elasticity in turbulent spinodal decompositions

What determines the size of the blobs formed? What properties does the spinodal decomposition turbulence have?

P Diamond (FAPP)

Welcome to

UC San Diego

*Stuart Collection
https://stuartcollection.ucsd.edu/