Innovative Confinement Concepts, Waves and Energetic Particles SOL and Divertor Research

26th IAEA Fusion Energy Conference

By David N. Hill

Assistance:
R. Buttery, X. Chen, J. deGrassie, C. Greenfield, H. Guo, A.W. Leonard, T.C. Luce, R. Maingi, C. Paz-Soldan, C. Petty, R. Pinsker, W.M. Solomon, O. Schmitz, V. Soukhanovskii, D. Thomas, Z. Unterberg, and M. Van Zeeland

October 22, 2016

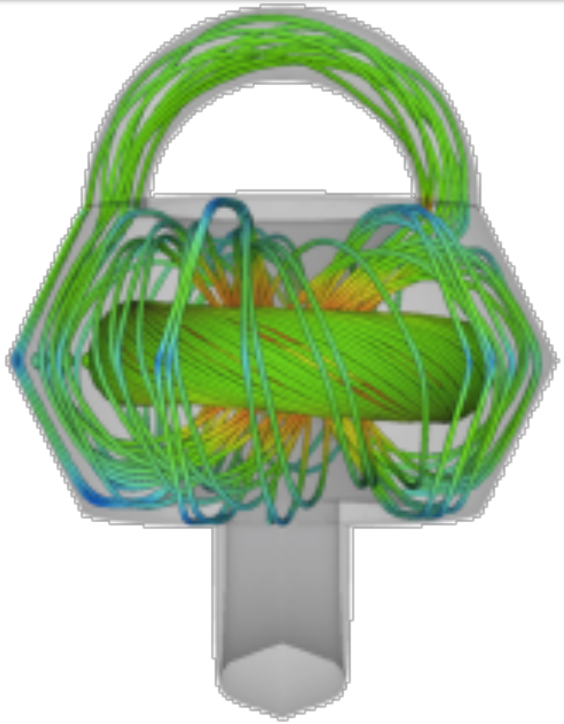
Significant Advances for ITER Operation and Fusion Energy Reported During This Meeting

- ICC (16 papers)
  ST, FRC, Spheromak, Pinch

- EX-W (56 papers)
  Wave-plasma interactions, current drive & heating, and EPs

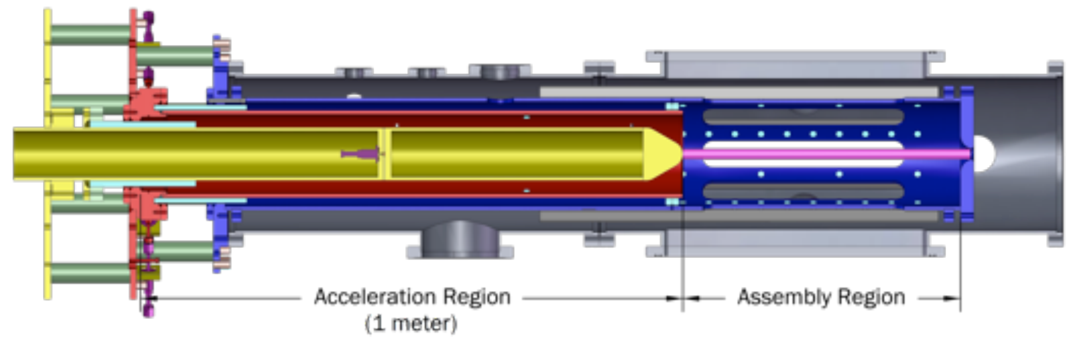
- EX-D (61 Papers)
  Plasma-material interactions, divertors, limiters, and SOL

Novel approaches to fusion are progressing



Spheromak

HIT-SI (Washington) demonstrates sustainment of spheromak plasmas with oscillating injector



Z-Pinch

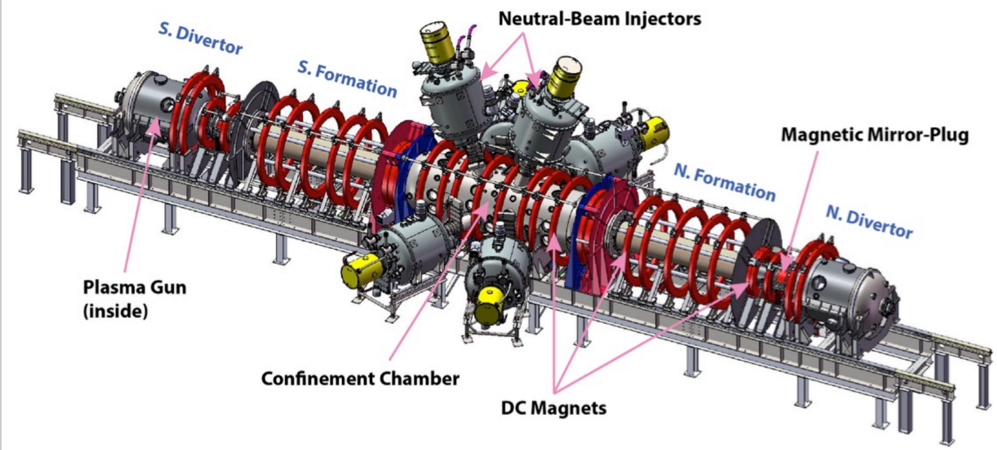
ZaP-HD (Washington)

Significant Z-pinch shear-flow stabilization observed: modeling points toward sustained, stable Z-pinch configurations

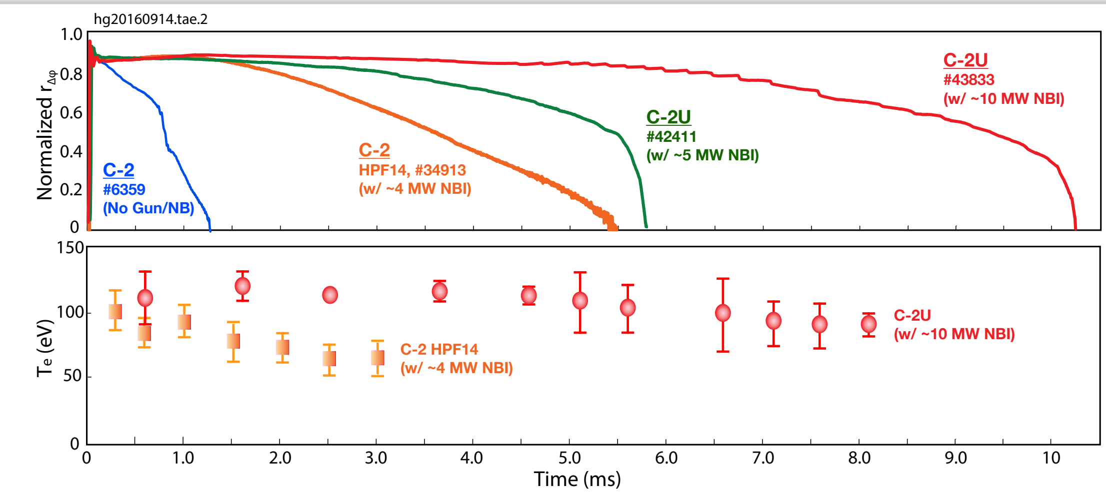
T. Jarboe, EX/P3-33
A. Hossack, EX/P3-42
U. Shumlak, EX/P3-32

Field-Reversed Configuration Sustained via 10 MW Neutral-Beam Injection on the C-2U Device

- Upgraded C-2U device
- Advanced beam-driven FRC state produced via ~10 MW NBI
- Key FRC plasma parameters (e.g. radius & T_e) ware sustained for >5 ms
- Significant improvement in transport and confinement



C-2U Device at Tri Alpha Energy

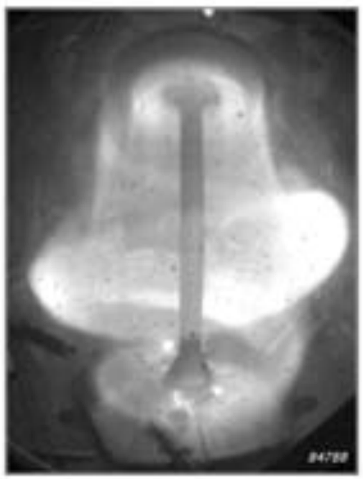


Time evolutions of normalized plasma radius & electron temperature in C-2 / C-2U experiments

H. Gota, EX/P3-41
T. Asai, EX/P3-37

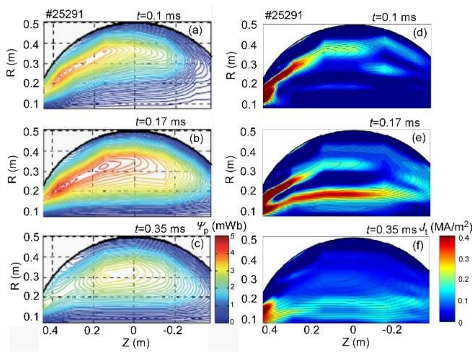
Small-scale Spherical Tokamak Experiments Address Non-solenoidal Startup and Sustainment

Pegasus



Localized helicity injection
(also: β➔1 in high normalized current regime)

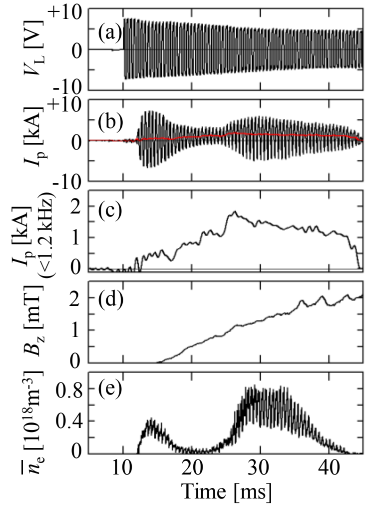
HIST



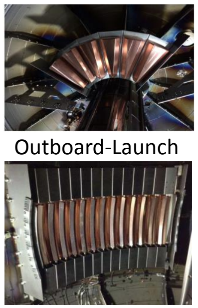
Coaxial Helicity Injection

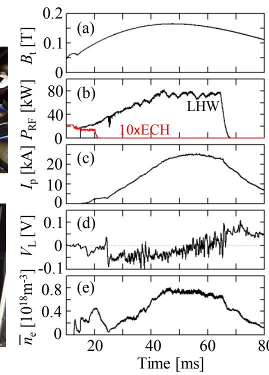
TST-2

DC current drive by AC Ohmic operation



Startup using CCC antennae





- **400 kA generated by merging compression in MAST**

IAEA FEC 2016

R. Fonck, OV/5-4
Y. Takase, OV/5-5

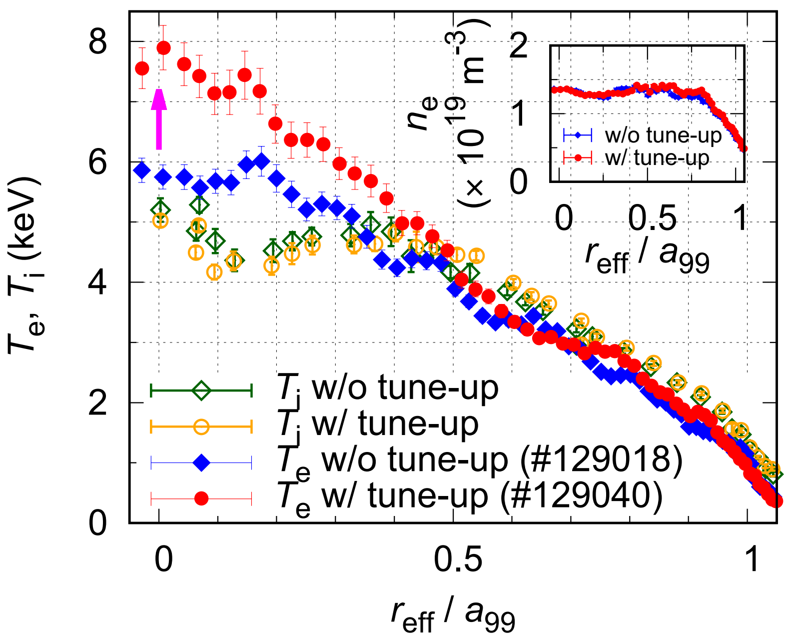
EX-W: Wave-Plasma Interactions, H&CD, Energetic Particles (> 50 papers)

- **Wave-particle interactions, Heating and Current Drive**
  - Electron Cyclotron and EBW
  - LHCD: high density operation and edge coupling
  - ICRF: better reactor-relevant schemes and antenna design
- **Energetic Particle Transport**
  - Multimode effects result in stiff fast-ion transport
  - Progress in understanding instability drives
  - Current and Fast Ion profiles strongly effect the fast ion losses
- **Significant Progress on Runaway Electron Mitigation**
  - Recent/planned shattered pellet experiments (ITER baseline mitigation) address key issues
  - Expanding studies of Runaway Electrons to provide physics basis for control

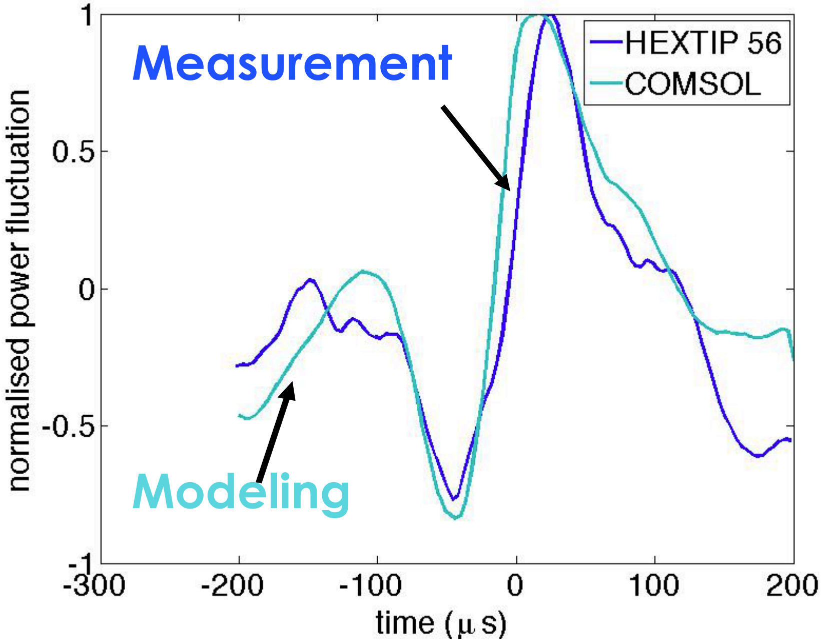
Modeling Advances Facilitate Optimized Applications Using Electron Cyclotron Waves

- **High T plasma achieved on LHD with optimized aiming through upgraded ray-tracing code.**

LHD



TCV data – TORPEX simulation



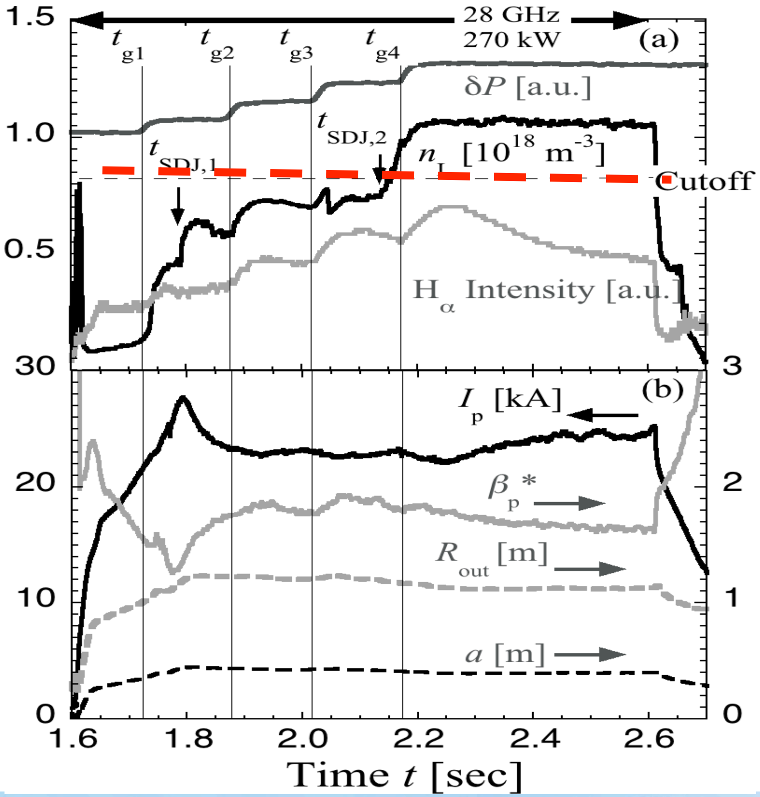
- **NTM stabilization sensitive to beam broadening by edge fluctuations.**
- **EC modeling matches measured scattering by edge turbulence: important first step**

Tsujimura, *EX/P8-2*
Goodman, *EX/P8-28*

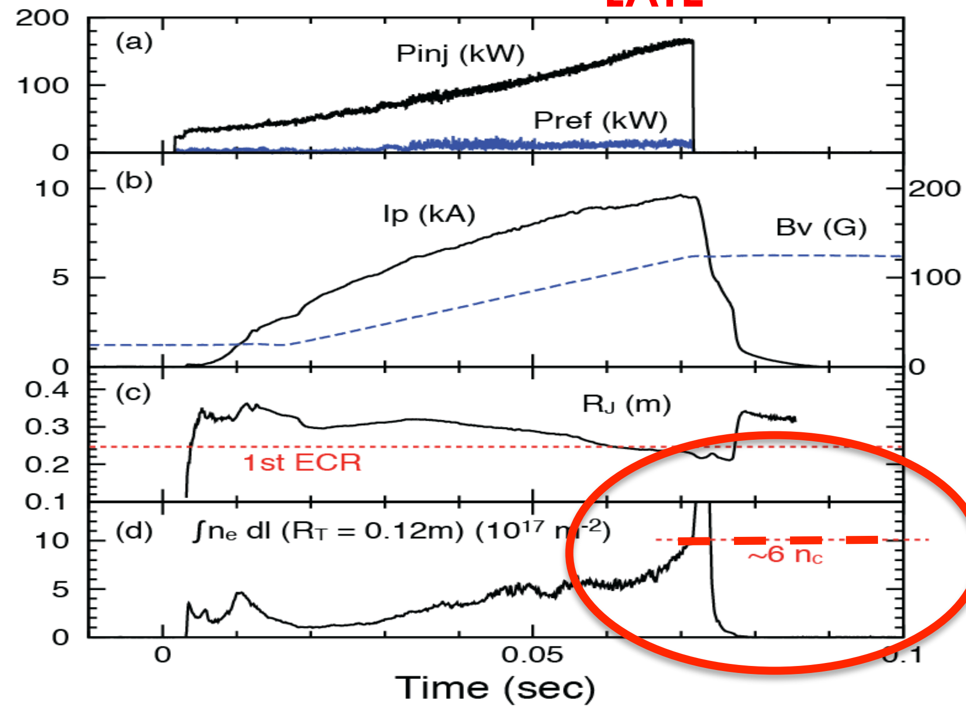
Heating of Overdense Plasmas by Electron Bernstein Waves Is Effective in Low |B| Devices

- **Non-inductive startup achieved via O to X to Bernstein mode conversion: > 6x cut-off.**

QUEST tokamak



LATE

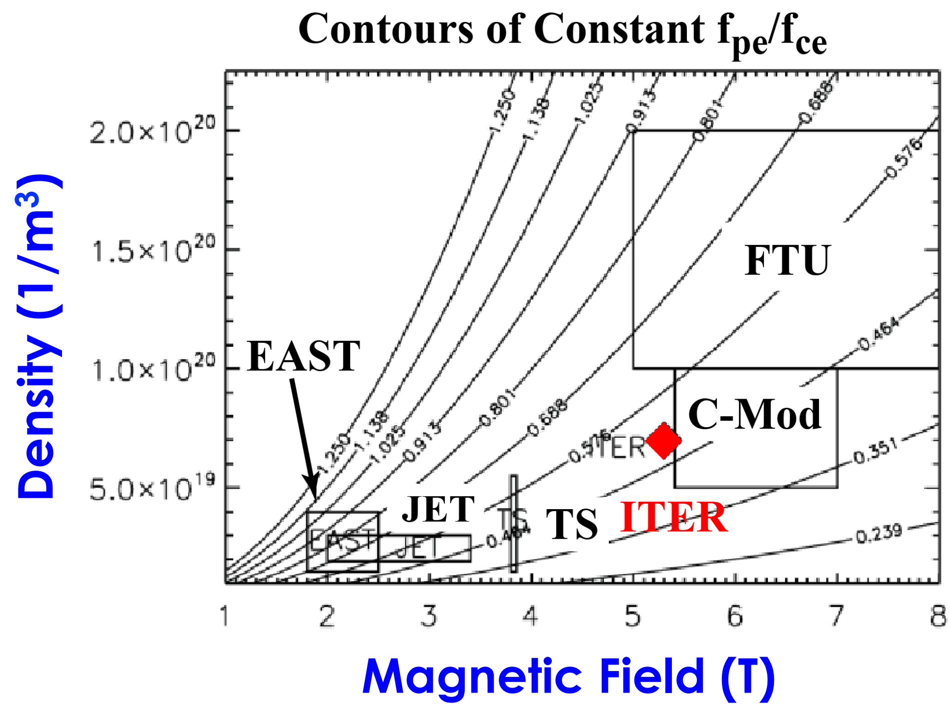


- **Non-inductive startup and current sustainment achieved with dual frequency (8.2/28 GHz) injection**

Tanaka *EX/P4-40*
Idei *EX/P4-50*

Improved Understanding of LHCD Efficiency Increases Confidence in Application to ITER

- **LHCD applied on conventional, superconducting & spherical tokamaks**
  - C-Mod: Edge absorption studies
  - EAST: efficiency vs. frequency
  - FT-2: Parametric decay
  - HL-2A: Passive-active multijunction launcher
  - TST-2: LH startup
- **Wave physics organized and understood by f_{pe}/f_{ce}**
- **All experiments observe loss of current drive at sufficiently high density**
  - Parametric instabilities
  - Collisional absorption
  - Scattering from density fluctuations

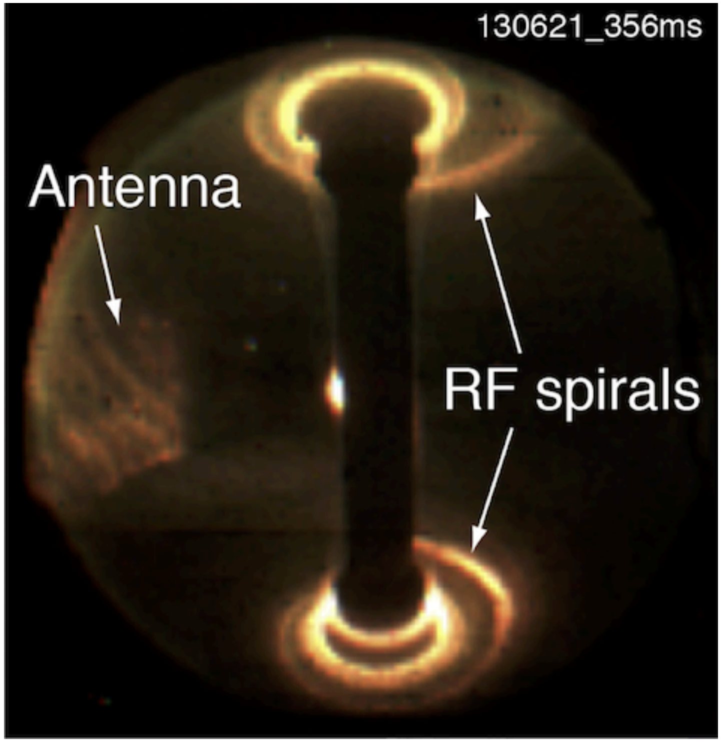


Ekedahl P7-34
Ejiri P4-48, Lashkul P7-41
B.J. Ding EX/P7-5
Wallace EX/7-1

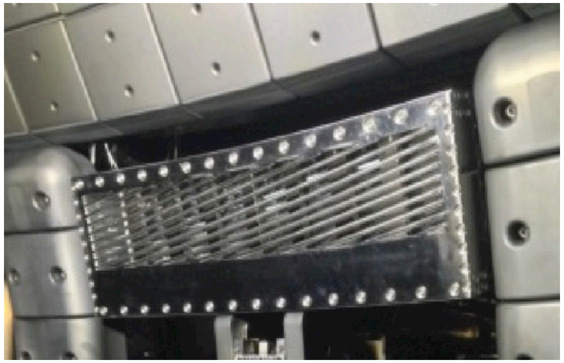
Coupling of High Harmonic Fast Waves Presents Significant Challenges

- Significant power can be coupled directly to divertor: may be explained by strong RF fields in SOL plus rectification in the divertor

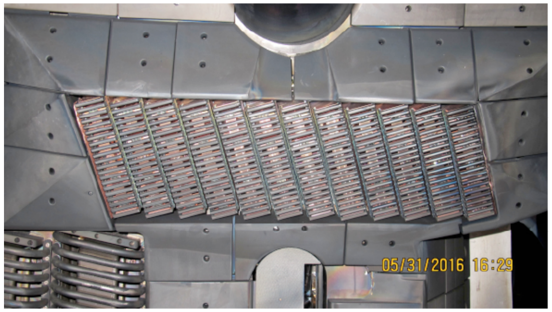
NSTX



KSTAR



DIII-D

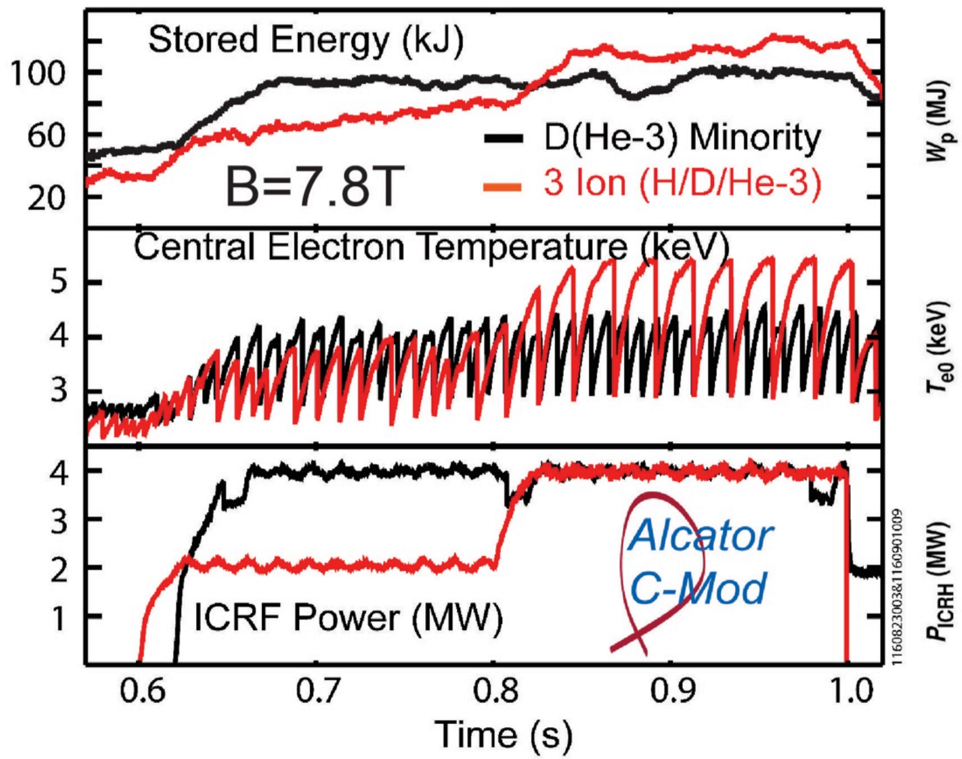


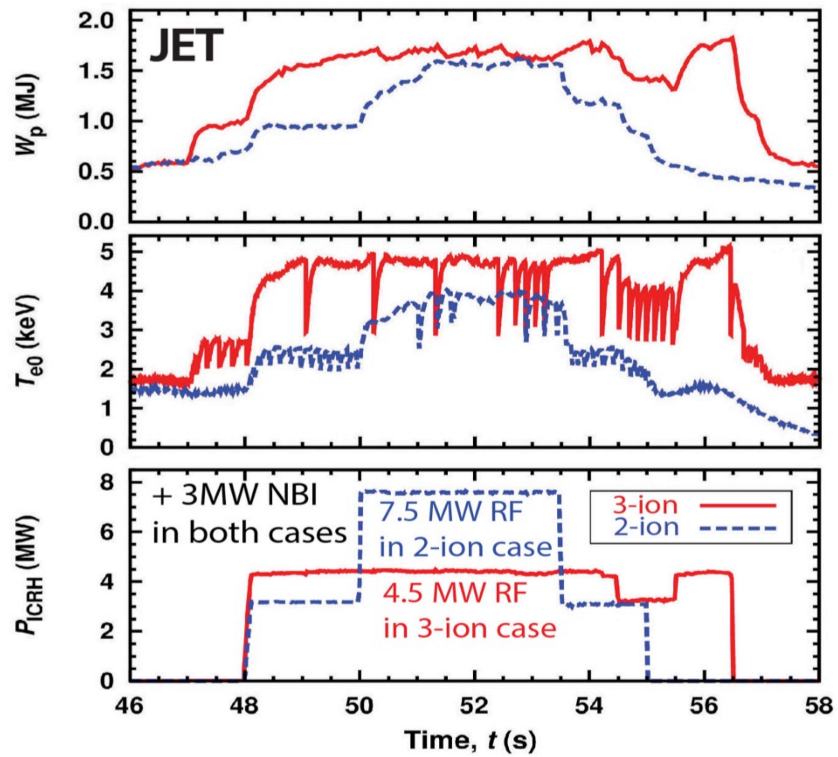
- High-harmonic fast wave coupling also explored in conventional tokamaks as potential current drive scheme (DIII-D, KSTAR)

Perkins EX/P4-42
Pinsker EX/P3-22, Oh OV2-4

Three-Ion ICRF Absorption Scheme Shown to Provide Effective Heating

- **~50% more efficient than D(He^3) in C-Mod**
- **Potential ITER applications:**
  - mimic fusion-born alphas in non-active phase
  - Use during D-T operation with Be

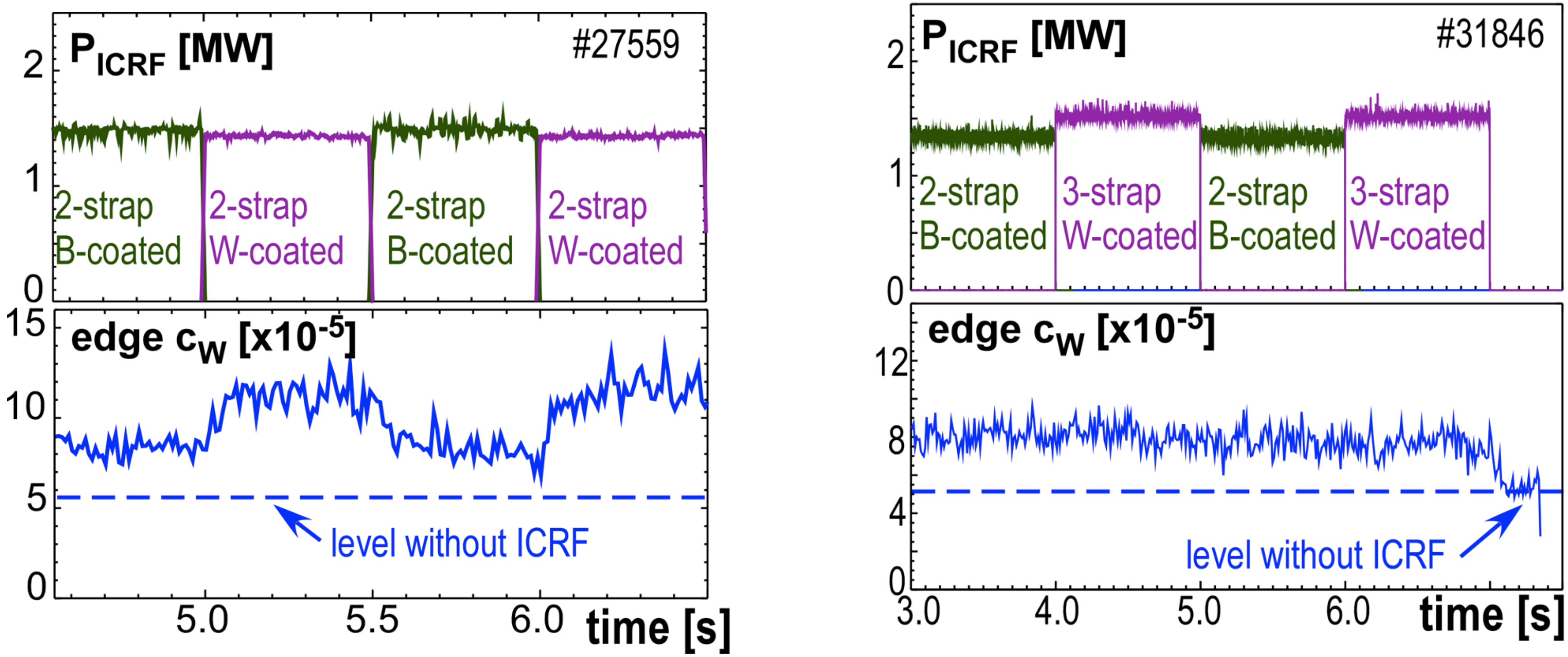




Wright P3-5, Litaudon OV1-3, Ongena P5-12

Improved Antenna Design Mitigates Impurity Generation with ICRF

AUG: 3-strap antenna designed to reduce rf interaction at the antenna reduces W input

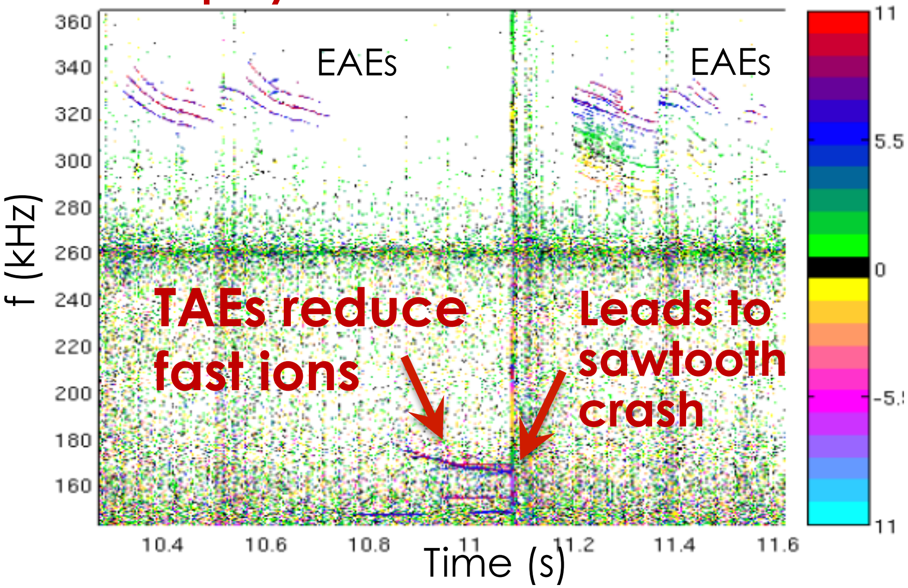


- **IShTAR: linear facility characterizing ICRF antenna-plasma interactions**

Noterdaeme P6-26
Crombe P6-48

Significant Fast Ion Transport & Losses Result From Interplay of Energetic Particle Driven Modes

Interplay of Sawteeth and AEs in JET[1]



- **JET shows chain of energetic particle transport[1]:**

TAE → sawtooth → Edge AE fast ion losses

1 Sharapov EX/P6-8

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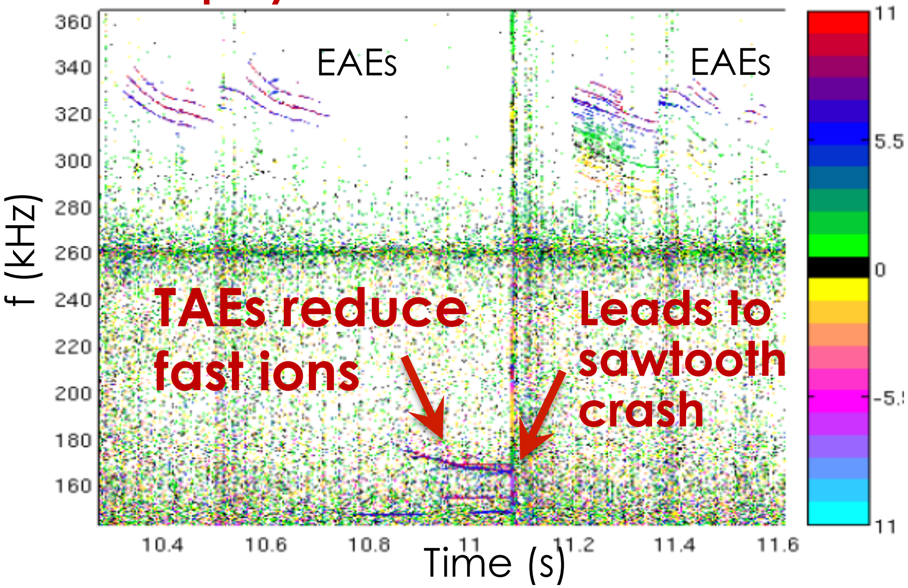
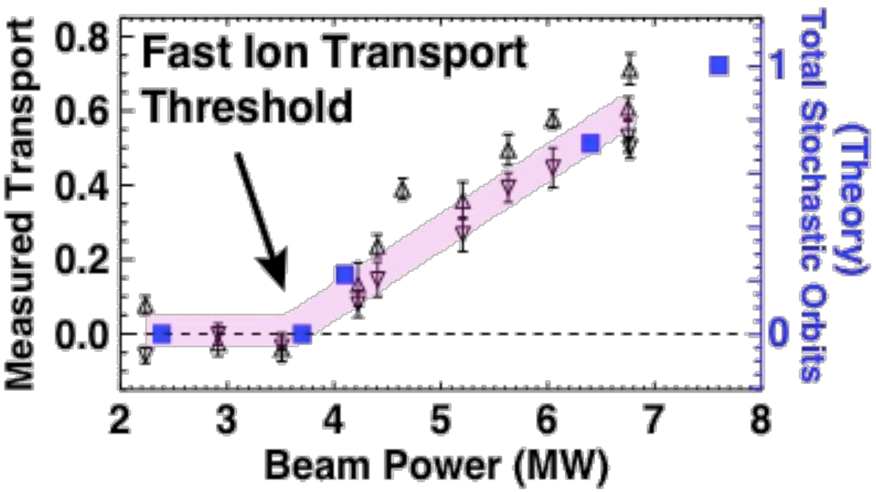


- **JET shows chain of energetic particle transport[1]:**

  TAE → sawtooth → Edge AE fast ion losses

- **DIII-D finds critical gradient behavior as multiple FI modes overlap[2]**

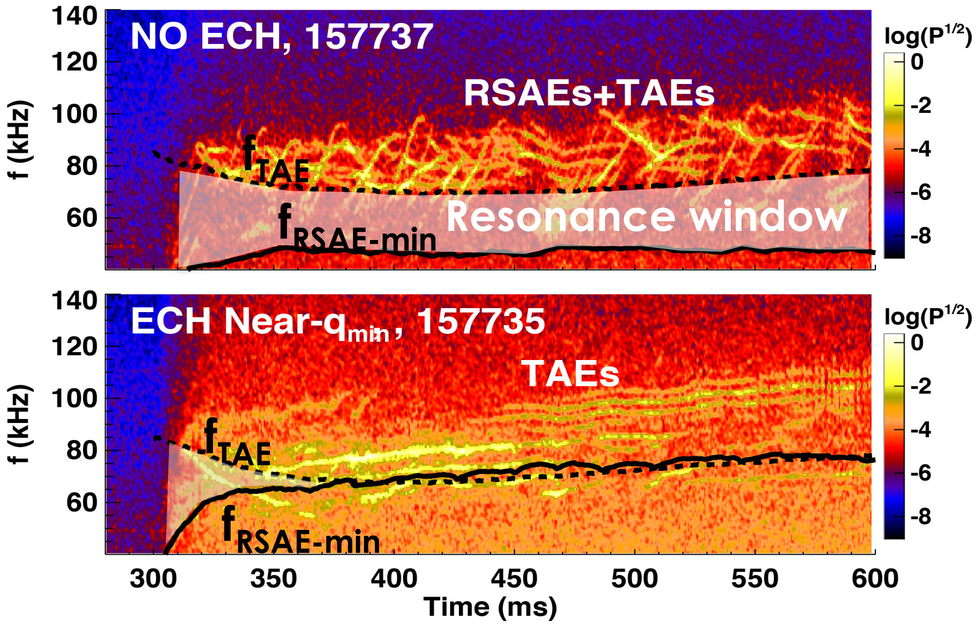


1 Sharapov EX/P6-8 2 Collins EX/P6-2

Key Progress in Understanding Drives and Influences of Energetic Particle Instabilities

- **DIII-D: Higher T_e closes resonance window for Reverse Shear AEs[1]**

ECH modification of RSAEs in DIII-D[1]



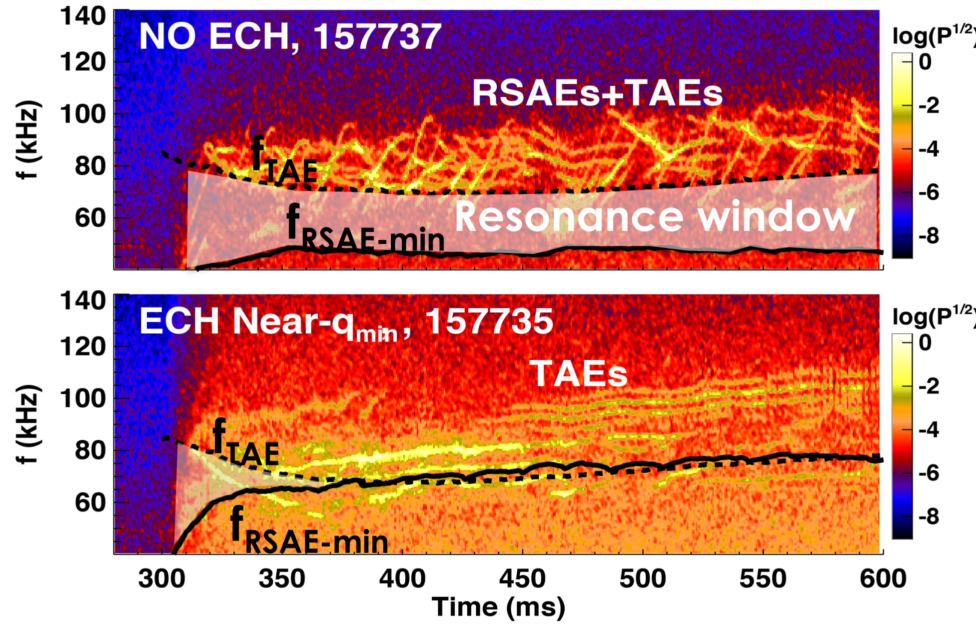
1 Van Zeeland EX/P3-24

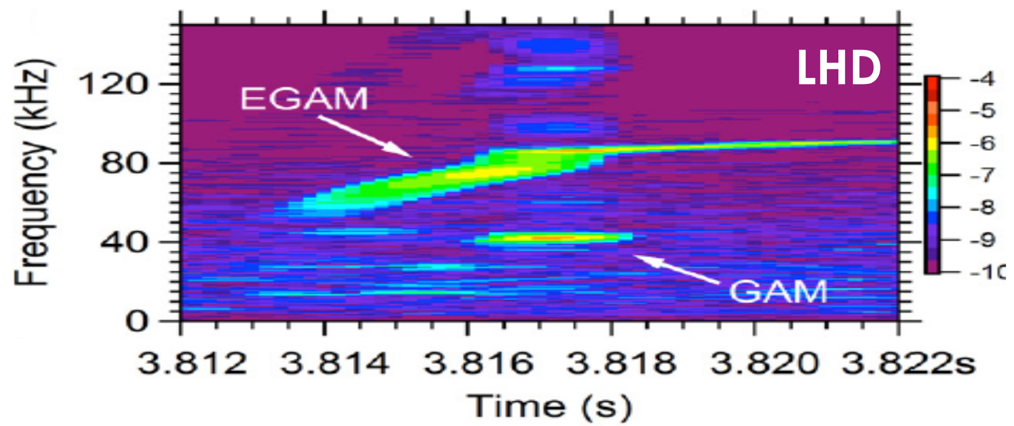
Key Progress in Understanding Drives and Influences of Energetic Particle Instabilities

- **DIII-D: Higher T_e closes resonance window for Reverse Shear AEs[1]**
- **LHD: EGAM observed to drive intense GAM via nonlinear**

GAM drives zonal flow and may alter transport

ECH modification of RSAEs in DIII-D[1]

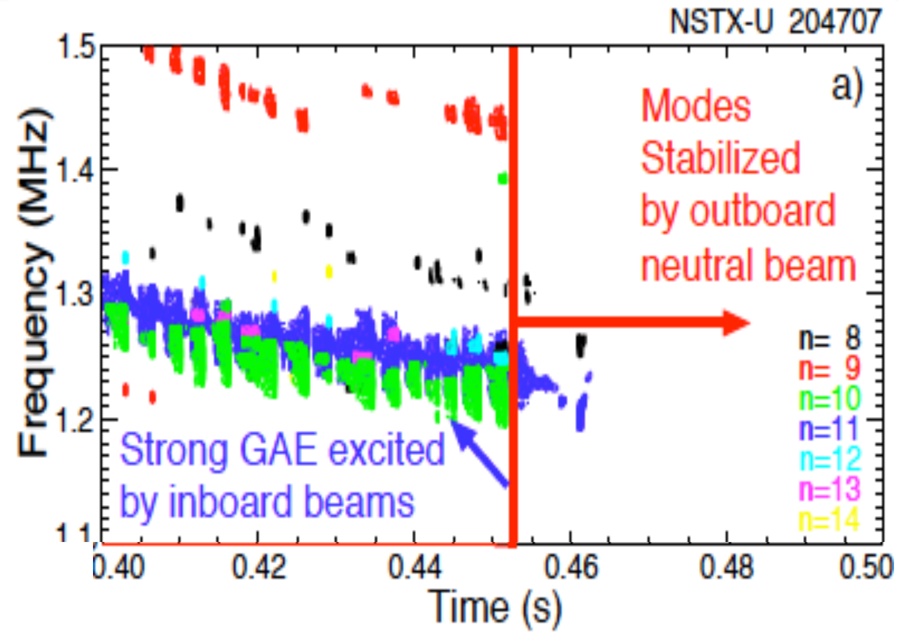




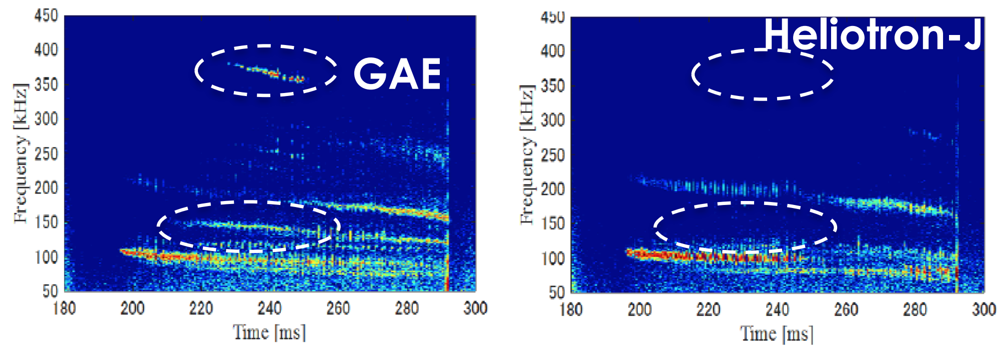
1 Van Zeeland EX/P3-24 2 Takeshi EX/P8-1

Energetic Particle & Current Distributions Are Central to Understanding and Control of Fast Ion Losses

- **New off axis beam in NSTX-U reduces fast ion gradient to stabilize GAE[1,2]**
  - Validates HYM code predictions



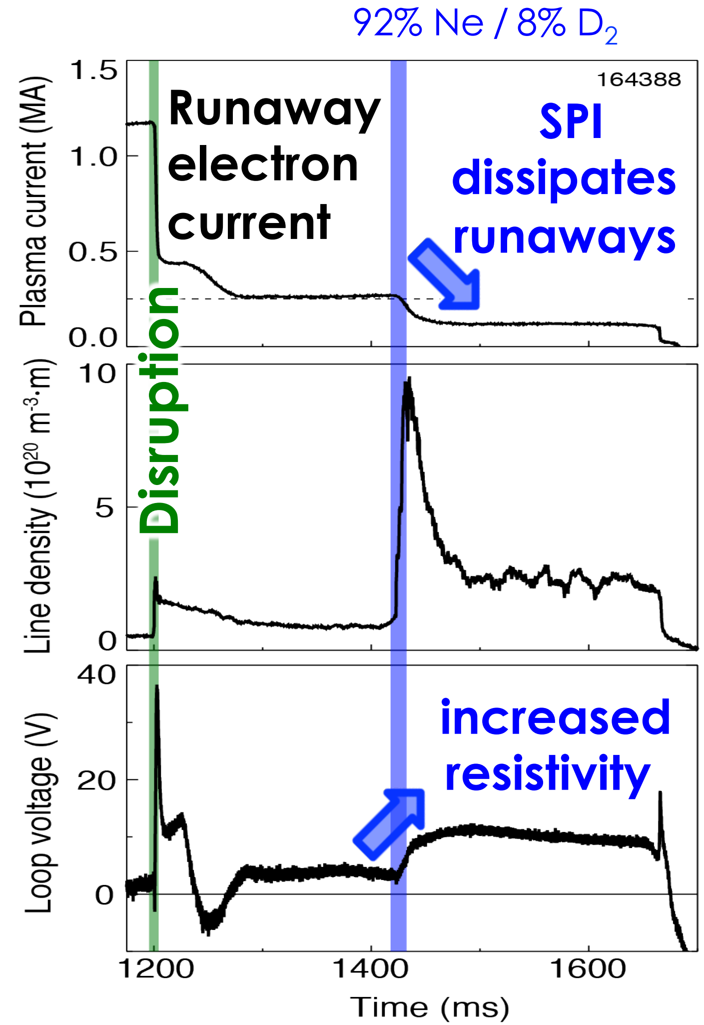
- **Heliotron-J: ECCD alters magnetic shear to stabilize GAE activity[3]**



1 Fredrickson EX/P4-4
2 Gorelenkov Postdeadline
3 Nagasaki EX/P8-19

Promising Runaway Electron Dissipation Techniques Developed on DIII-D and HL-2A

- **DIII-D: Neon Shattered Pellet Injection results in significant dissipation**[1] →
  - Dissipation depends on impurity species, but not strongly on injection technique



1. Shiraki, et al. EX/9-2

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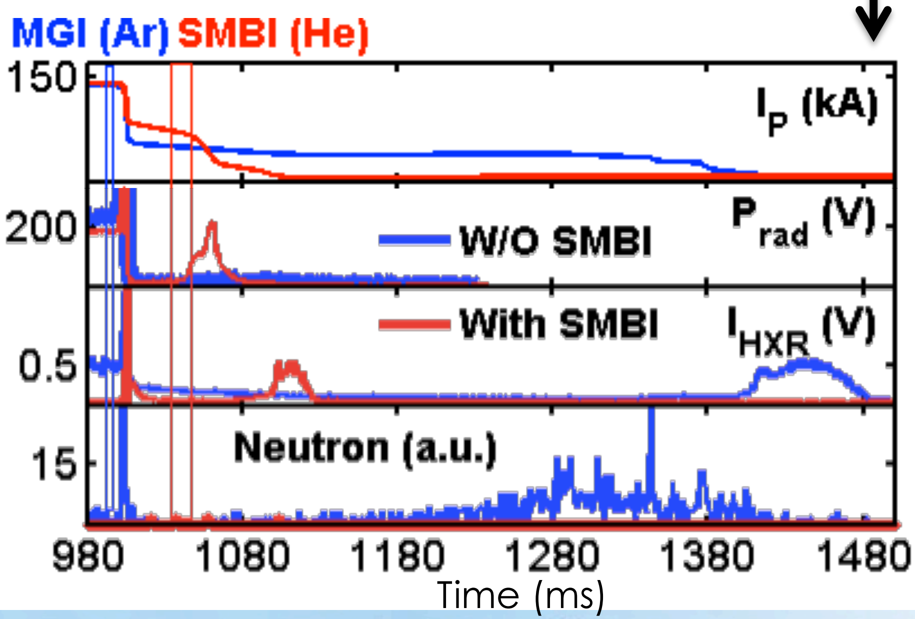
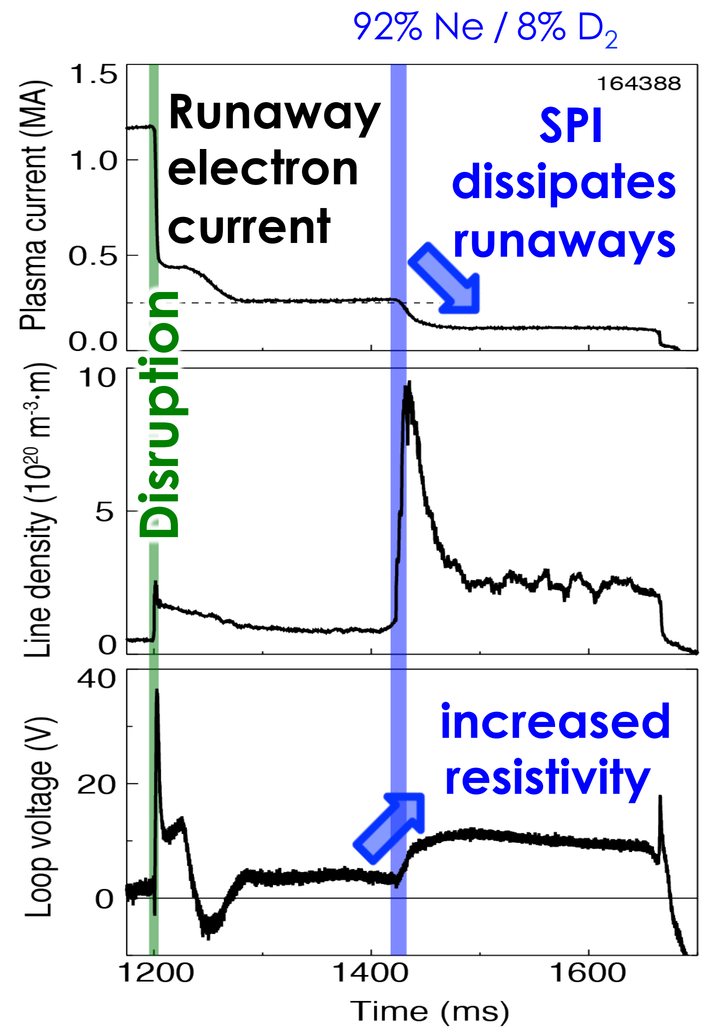
  - Dissipation depends on impurity species, but not strongly on injection technique
- **HL-2A: Supersonic Molecular Beam scatters REs by MHD oscillations**[2]





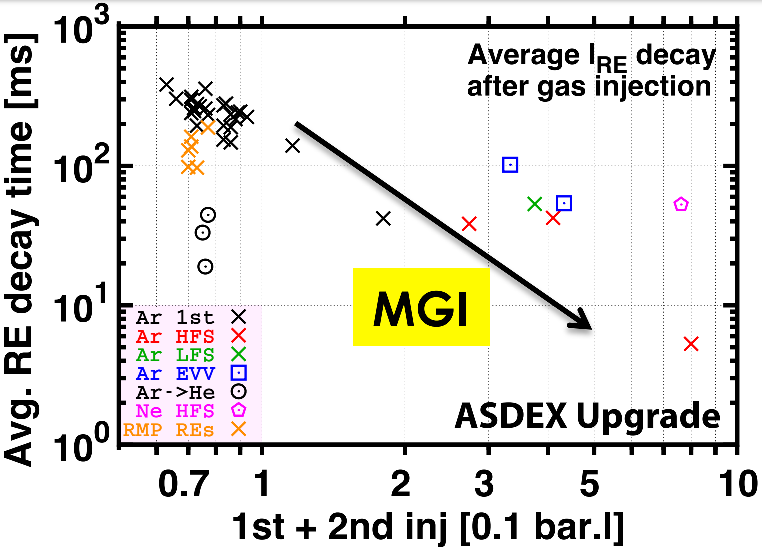
1. Shiraki, et al. EX/9-2
2. Liu, et al. EX/9-3

EuroFusion Tokamaks Demonstrate Various Runaway Electron Control & Mitigation Techniques

Newly developed scenarios for reliable RE generation on AUG and TCV[1]

- **AUG: Increased MGI quantity increases RE dissipation**
  - LFS vs. HFS injection identical

- **TCV: Full conversion of pre-TQ Ohmic current into RE current**



1. Martin, et al. EX/P6-23 2 Papp, et al. EX/9-4

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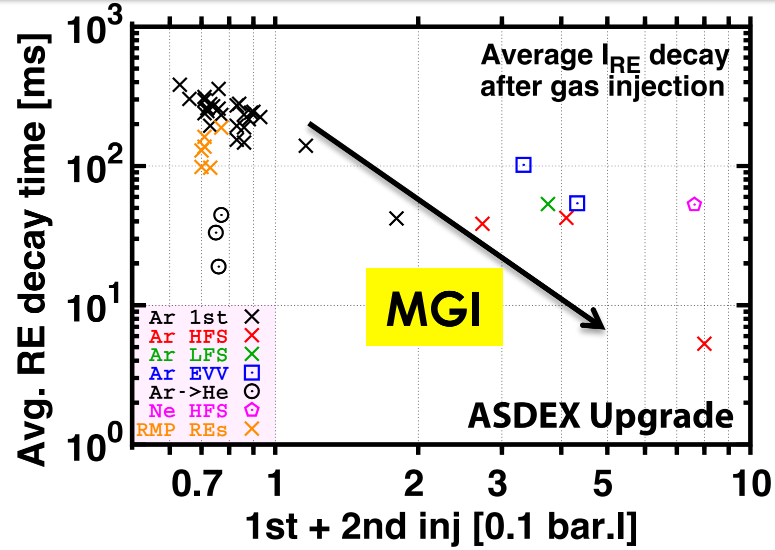
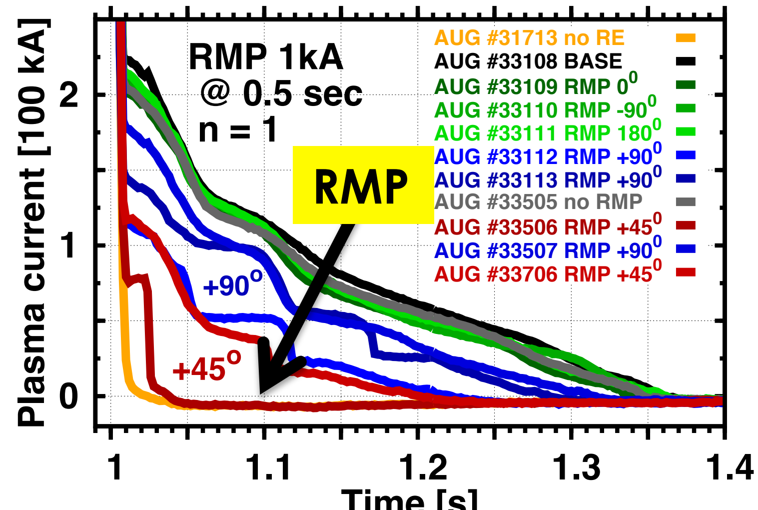
- **TCV: Full conversion of pre-TQ Ohmic current into RE current**
- **AUG: Applying pre-TQ n=1 RMP field inhibits RE generation**[2]

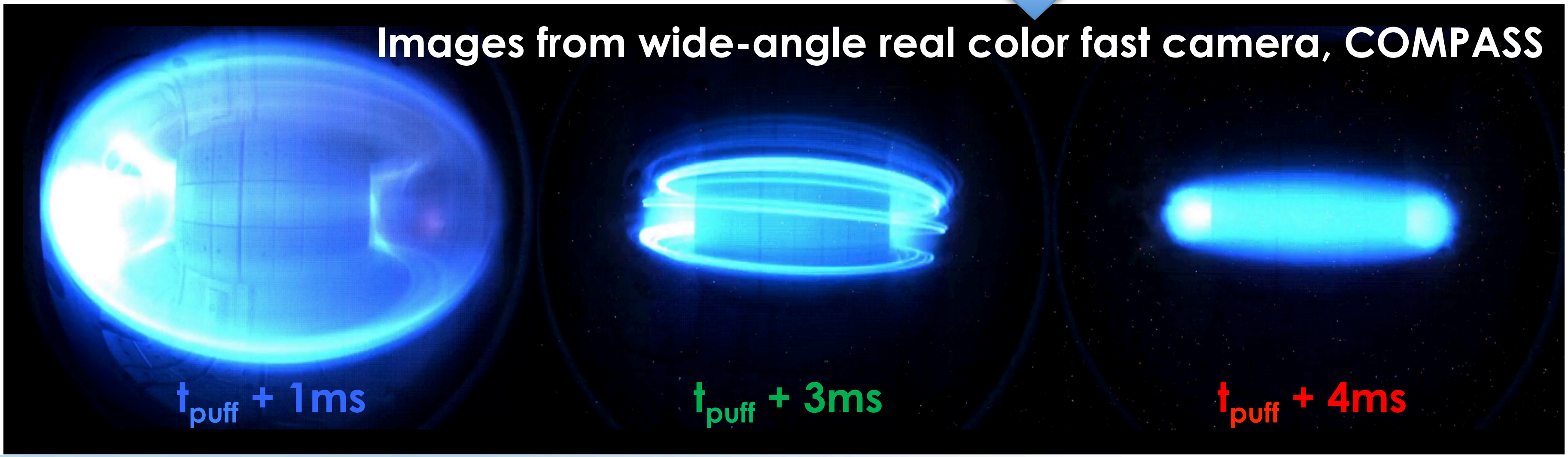




1. Martin, et al. EX/P6-23 2 Papp, et al. EX/9-4

Runaway Physics and Control Progressing Worldwide

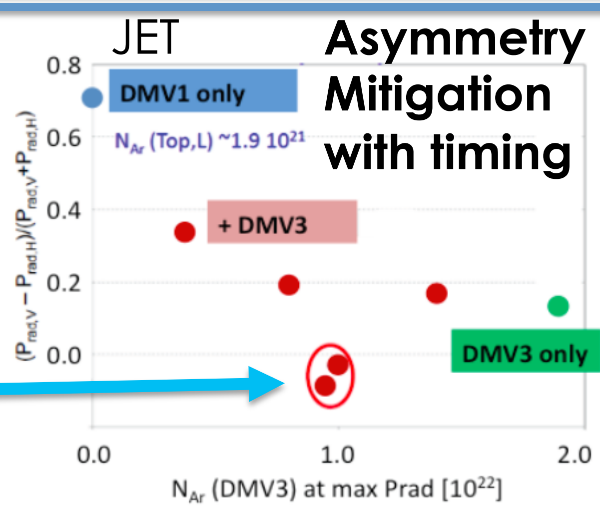
- **Control of beam will be necessary for controlled dissipation**
  - FTU: Ip/Vloop control achieved, spectrum studied
- **Characterization of distribution function is enabling validation**
  - FT-2: DeGaSum deployed to understand HXR emission from Res
  - DIII-D: Gamma ray imaging resolves spatial distribution
- **Important role of MHD being investigated in RE seed formation**
  - Compass: Filamentary structure underlines MHD role

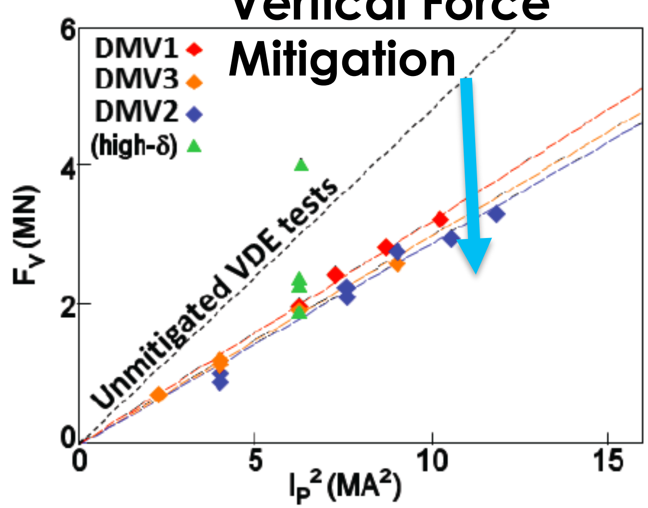


1.Esposito EX/P8-27
2. Carnevale EX/P8-22
3. Shevelev EX/P7-42
4. Mylnar EX/P6-34

Disruption experiments show path to control thermal and vessel forces with high-Z mitigation

- **JET system can reduce both radiation asymmetry and vessel forces**



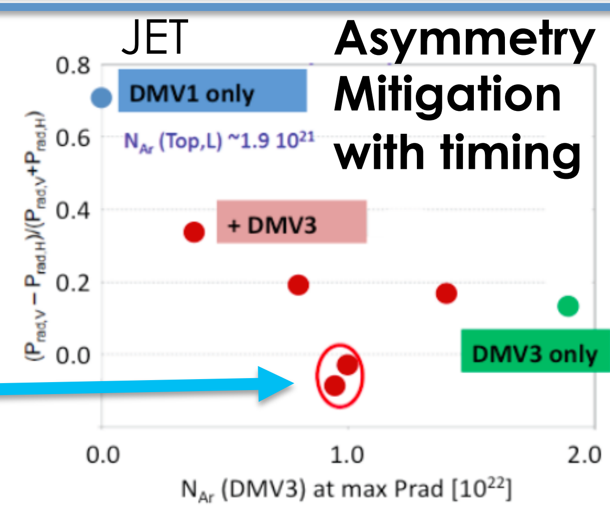


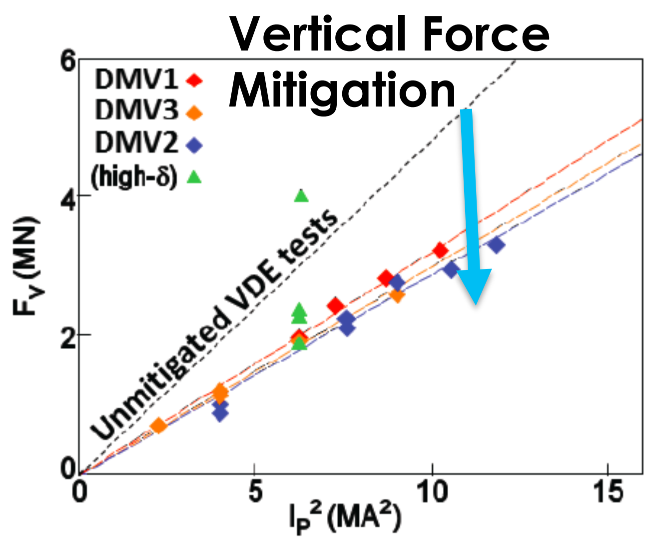
1. Joffrin EX/9-1

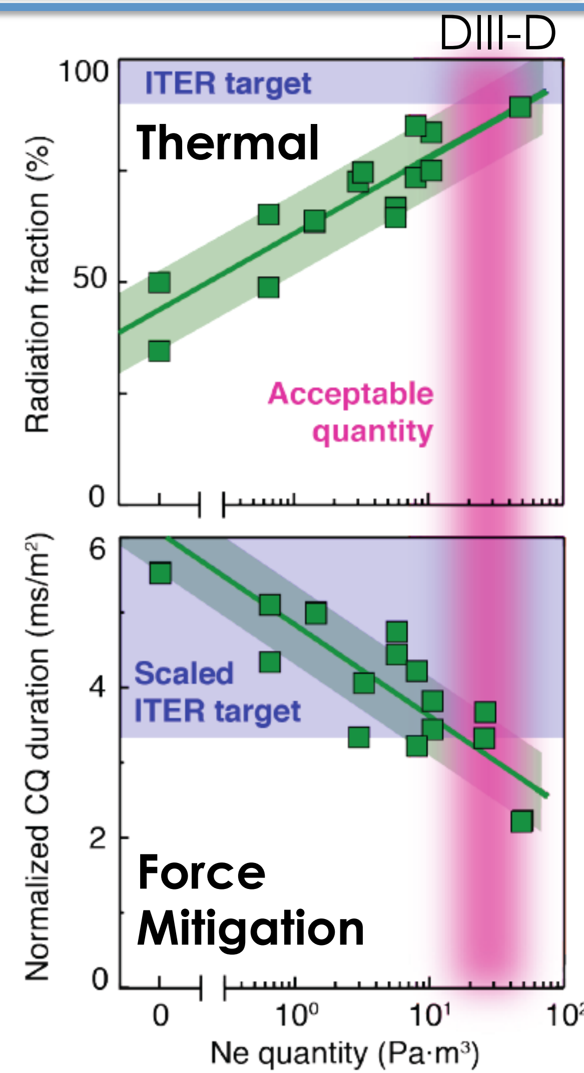
2. Commaux EX/9-2

Disruption experiments show path to control thermal and vessel forces with high-Z mitigation

- **JET system can reduce both radiation asymmetry and vessel forces**
- **Shattered pellet injection allows tuning of disruption properties**

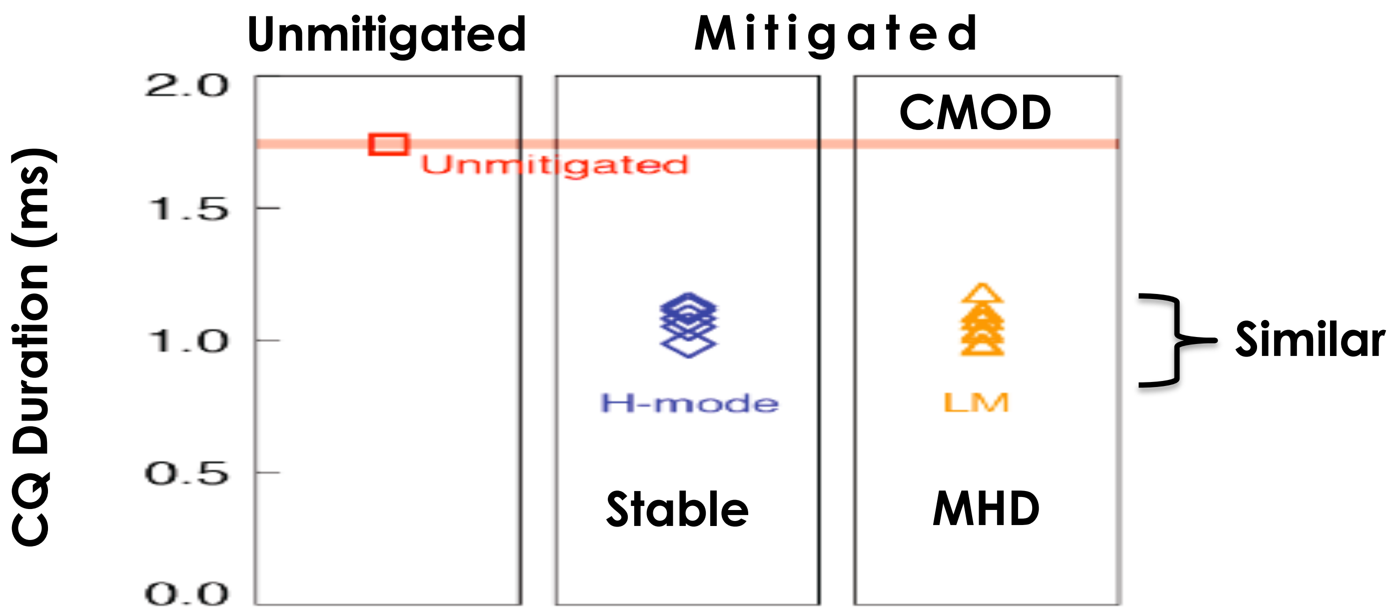






1. Joffrin EX/9-1
2. Commaux EX/9-2

Disruption mitigation found to remain effective despite pre-existing MHD modes



- **Disruption loads equally mitigated with or without MHD modes**
  - Also observed on DIII-D

Conclusions obtained from healthy plasmas are still applicable to ITER

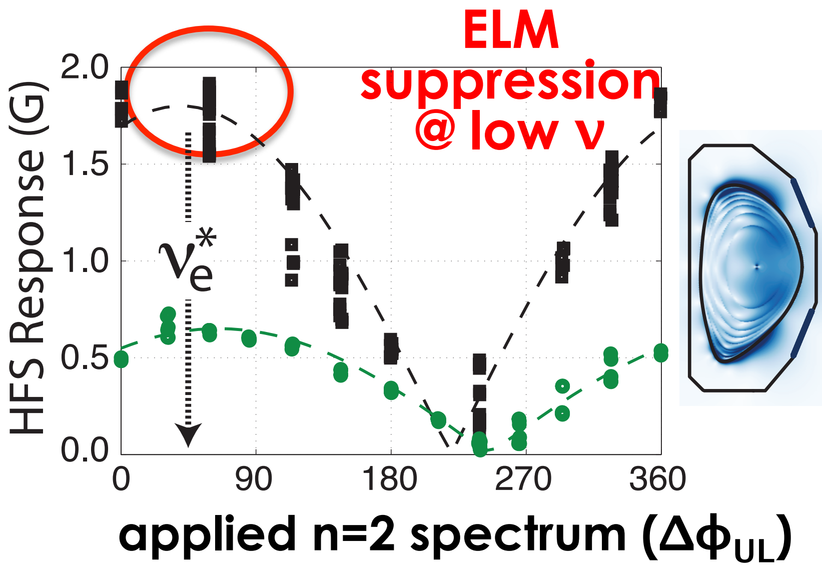
1. Shiraki EX/P3-20

EX-D: ELMs, Divertors, Materials (> 60 papers)

- **ELMs and their Control**
  - ELM suppression
  - 3D effects on the boundary
  - ELM heat flux
- **Divertor Heat Flux**
  - Edge transport
  - Divertor detachment and control
  - Core-edge integration
- **Plasma Facing Components**
  - Tungsten operation experience
  - Fuel retention in Be/W
  - Alternative PFCs

New Understanding of Plasma Response Extends RMP ELM Suppression to Full W Wall and Long Pulse

- **DIII-D**: resonant field amplification at low collisionality ν_e^* yields suppression



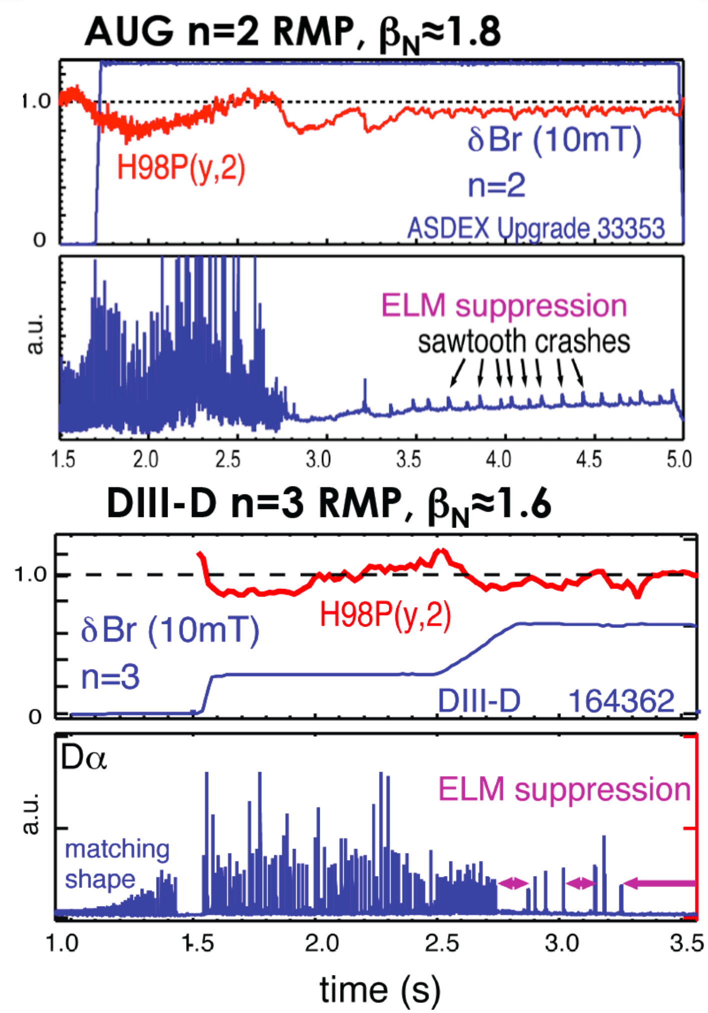
Paz-Soldan, EX/1-2
Y.-K. Oh, OV/2-4
Y. Sun, EX/P4-7
Kallenbach, OV/2-1
B. Wan, OV/2-2
Nazikian PD/1-2

New Understanding of Plasma Response Extends RMP ELM Suppression to Full W Wall and Long Pulse

- **DIII-D: resonant field amplification at low collisionality ν_e^* yields suppression**

- **ASDEX-Upgrade obtained full ELM suppression with full W wall matching DIII-D collisionality and shape**

➡ Demonstrates reliability for extrapolation towards ITER



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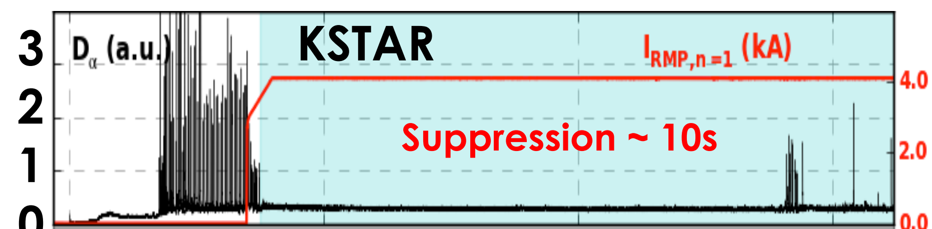
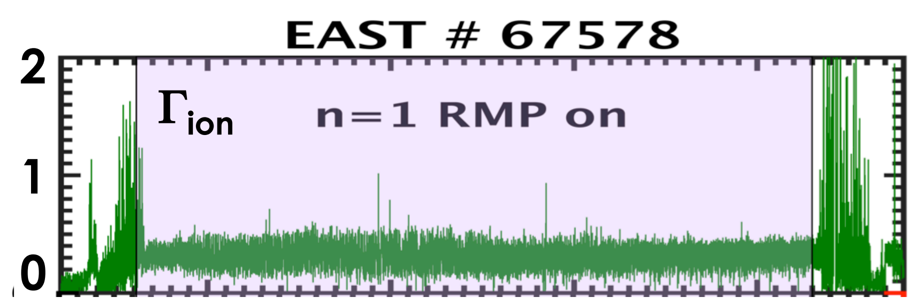
- **Full RMP ELM suppression was obtained for >10s at KSTAR and ~20 s at low rotation on EAST**





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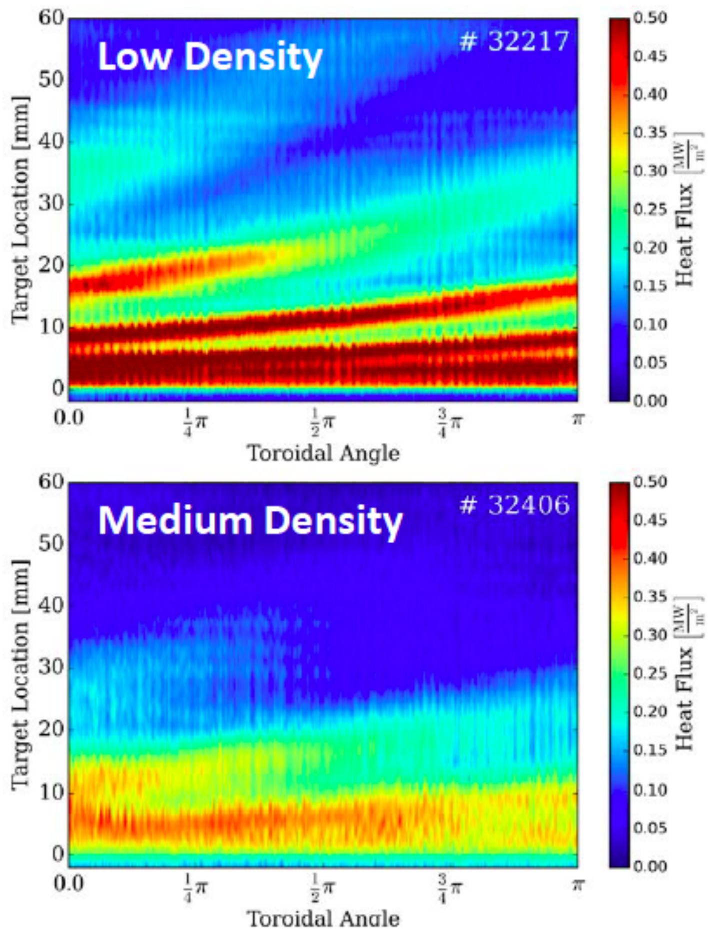
Y. Sun, EX/P4-7
Kallenbach, OV/2-1
B. Wan, OV/2-2
Nazikian PD/1-2

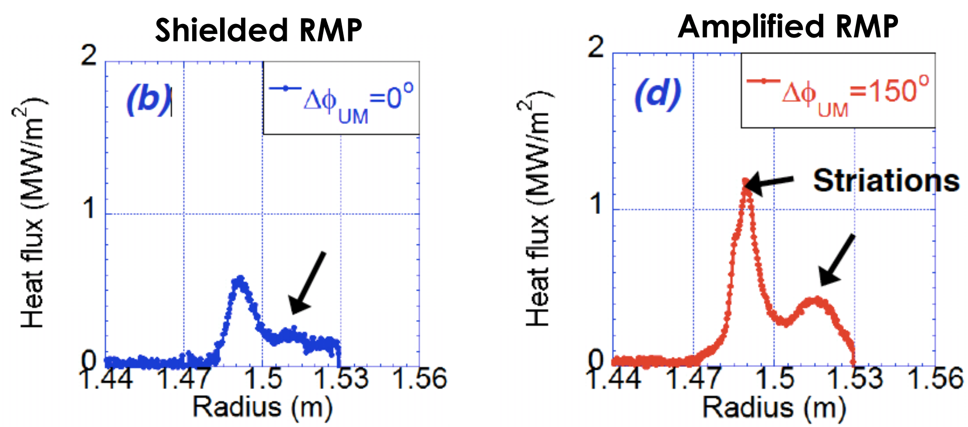
3D Divertor Fluxes Can be Controlled and Mitigated by Density and Applied RMP Spectrum

- **ASDEX-Upgrade:** Striated heat flux pattern vanishes with density

i



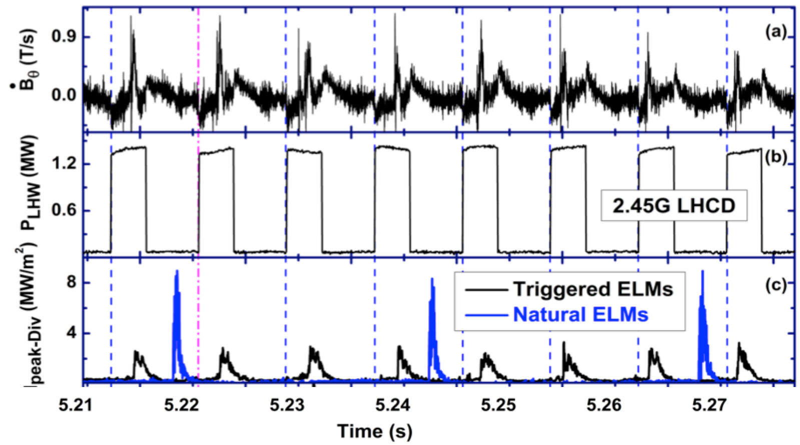
- **DIII-D:** 3-D temperature lobes and inter-ELM heat flux striation vanish at detachment transition
- **KSTAR:** Link between plasma response and strike line striation was demonstrated



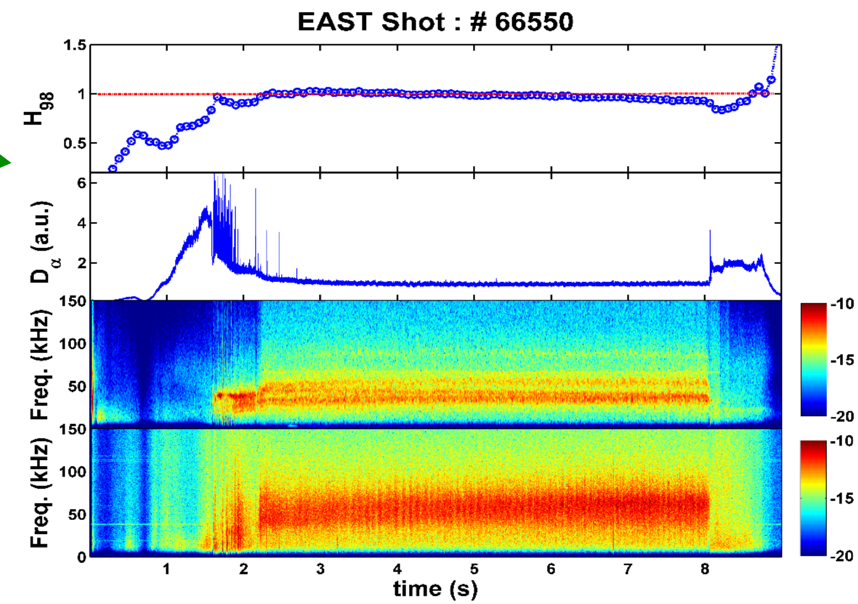
J.-W. Ahn, EX/P4-30 B. Sieglin, EX/7-3 Ra
A. Briesemeister, EX/7-3 Rb

Alternative Approaches to ELM Control Are Being Developed

- **EAST:** Lower hybrid used to pace ELMS and reduce peak heat flux



- **EAST:** New "*no-ELM*" regime with steady LH heating observed at low ν*, with new EM continuous mode



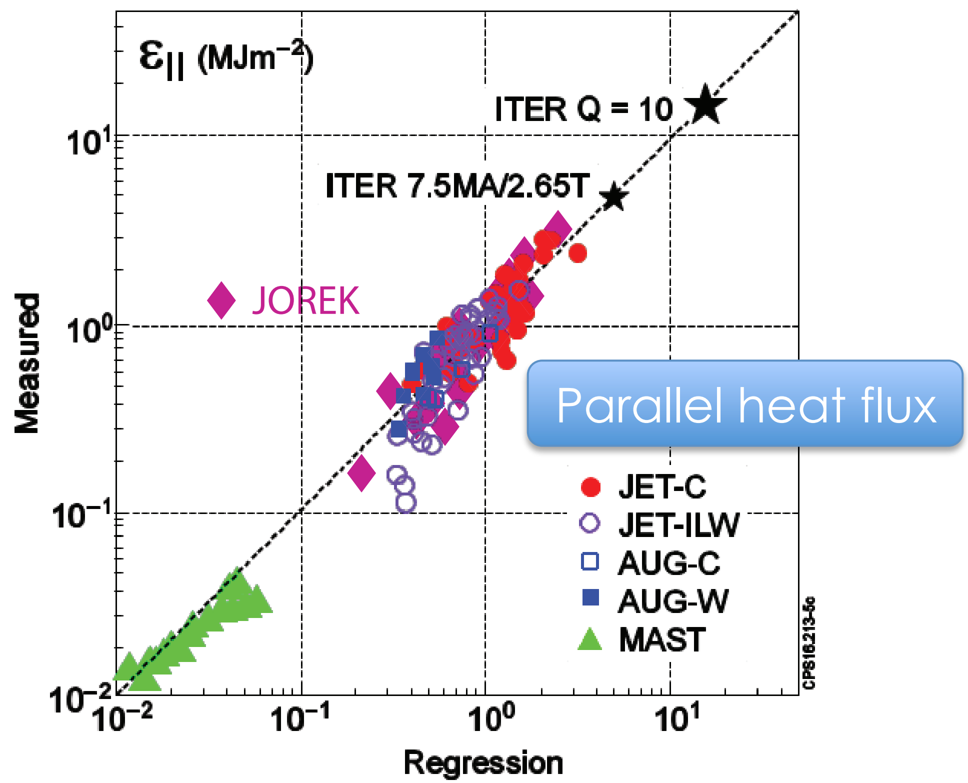
- **DIII-D** ITER baseline: D2 pellets or Li granules pace ELMs *but heat flux reduction not observed at constant ν**

G. Xu, EX/10-2
A. Bortolon, EX/10-1

New ELM Divertor heat flux Scaling Projects to smaller ELMs in ITER

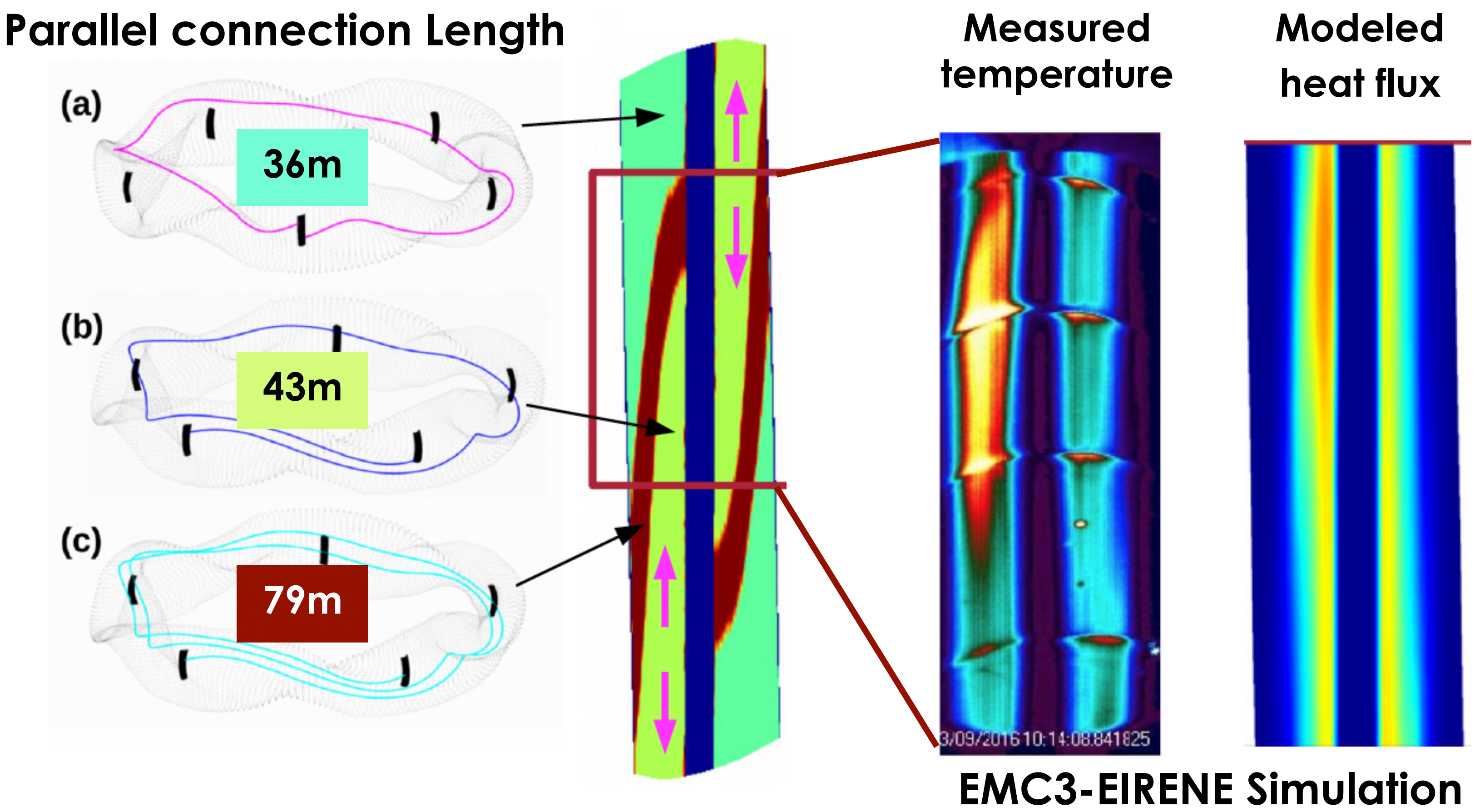
- **Peak ELM heat load proportional to machine size and pedestal pressure**
- **Projection for ITER significantly lower than previous estimates (10x reduction)**
- **ELM simulation with JOREK reproduces empirical scaling**

$$\varepsilon_{||}\left(MJ/m^2\right) \propto R^{1.0} n_{e,ped}^{0.75} T_{e,ped}^{0.98} \left(\Delta W/W\right)^{0.5}$$



Litaudon,OV1-4
Pamela TH/8-2

Measured PFC temperature profile shapes agree qualitatively with modeled heat flux in helical scrape-off layer of Wendelstein 7-X



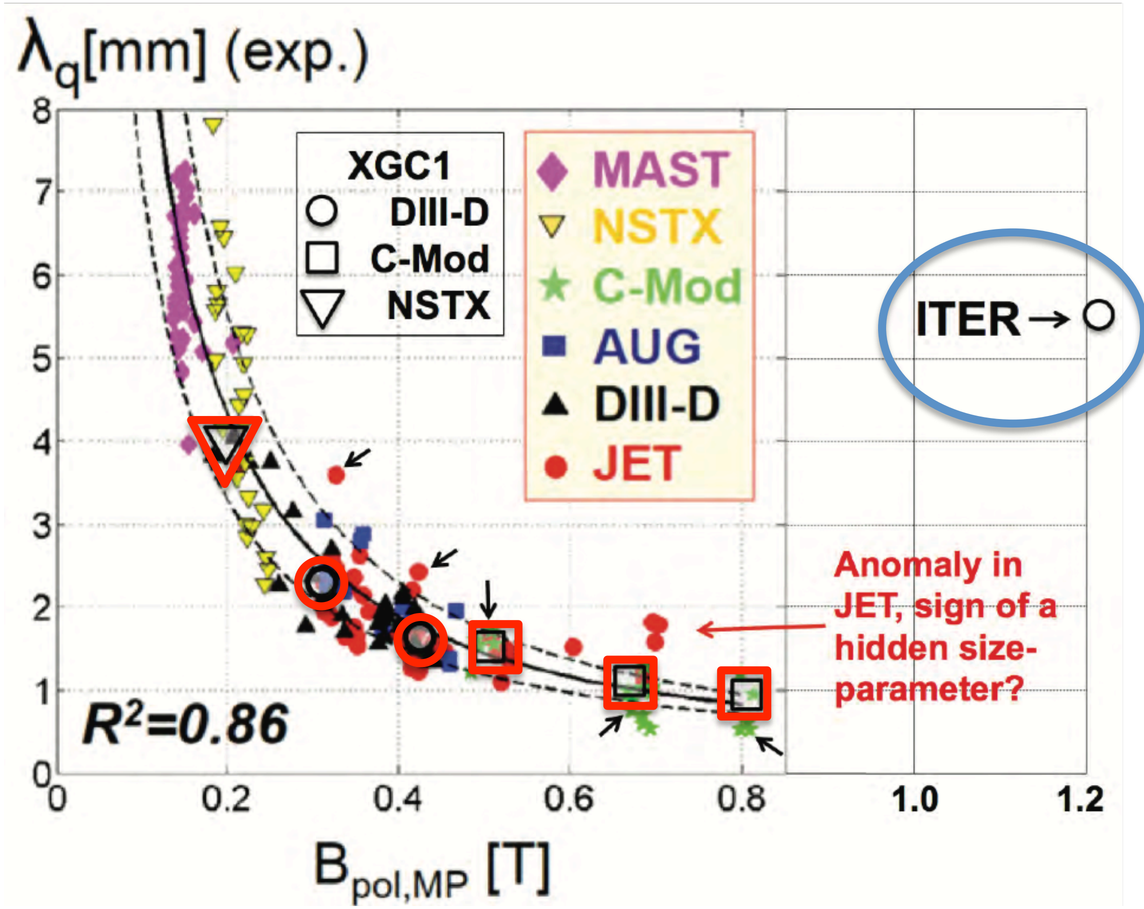
- **Highest heat flux for longest connection length**
- **Lowest heat flux at tangency points**

[F. Effenberg, Th/P6-11] [G. Wurden, EX/P5-7] [S. Boszhenkov, EX/P5-11]

Kinetic Simulation With Turbulence Predicts Broader Divertor Heat Flux Profile for ITER

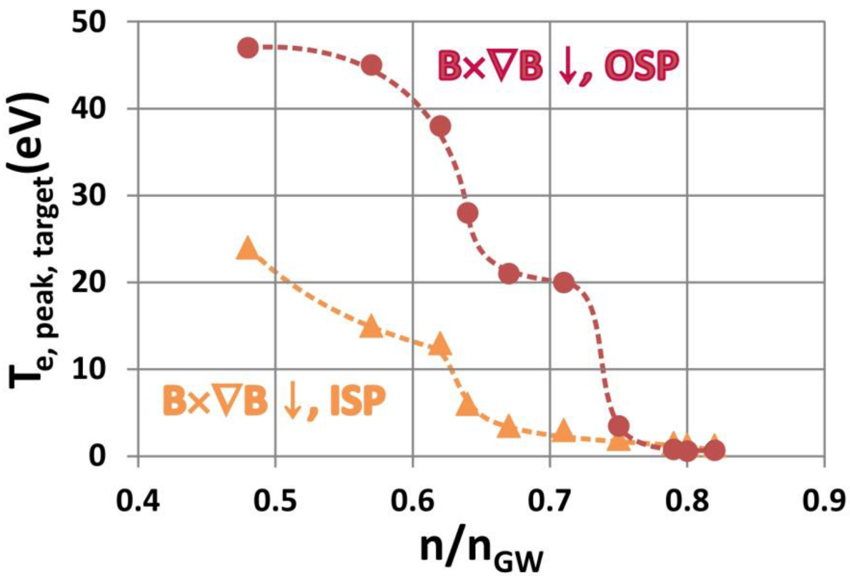
Divertor Heat Flux

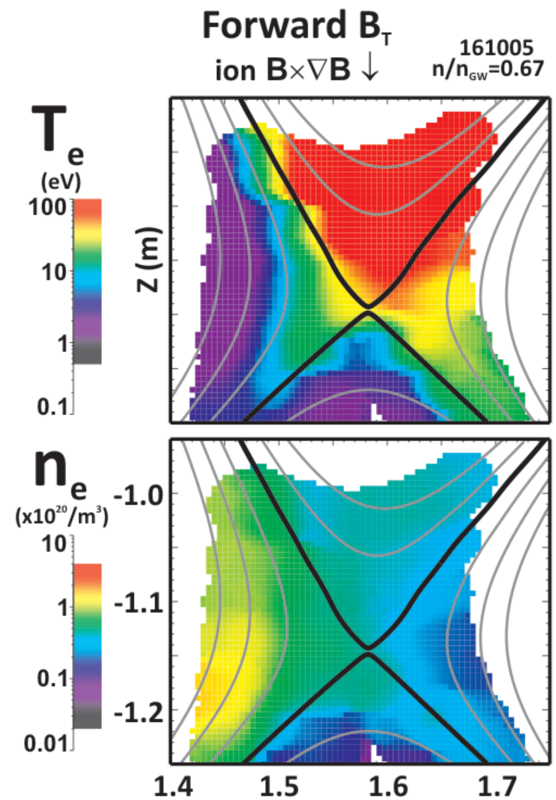
- XGC1: Kinetic code reproduces ITPA heat flux width scaling
- Size scaling of electron turbulence expected to broaden heat flux in ITER



New 2d Measurements Show Importance of Drifts On Asymmetries and Detachment Threshold

- ∇B drift into divertor: Asymmetric T_e, n_e and detachment



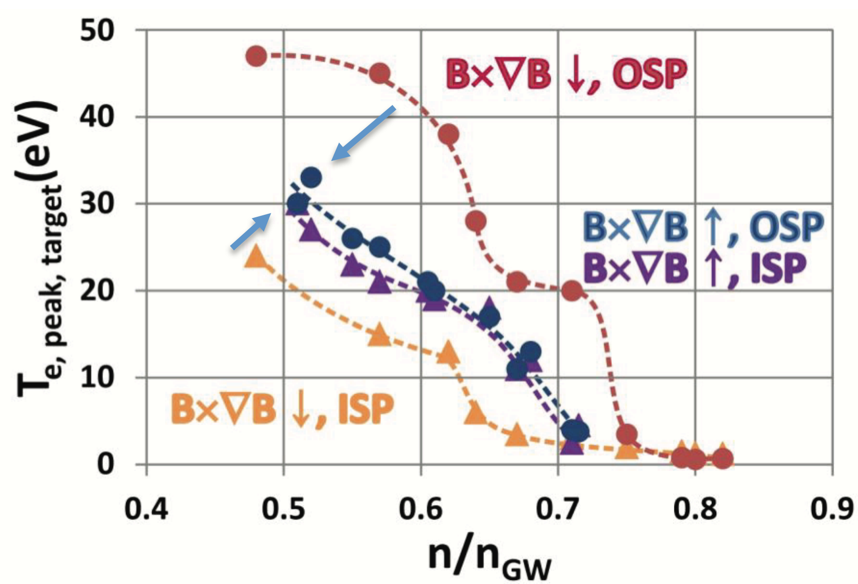


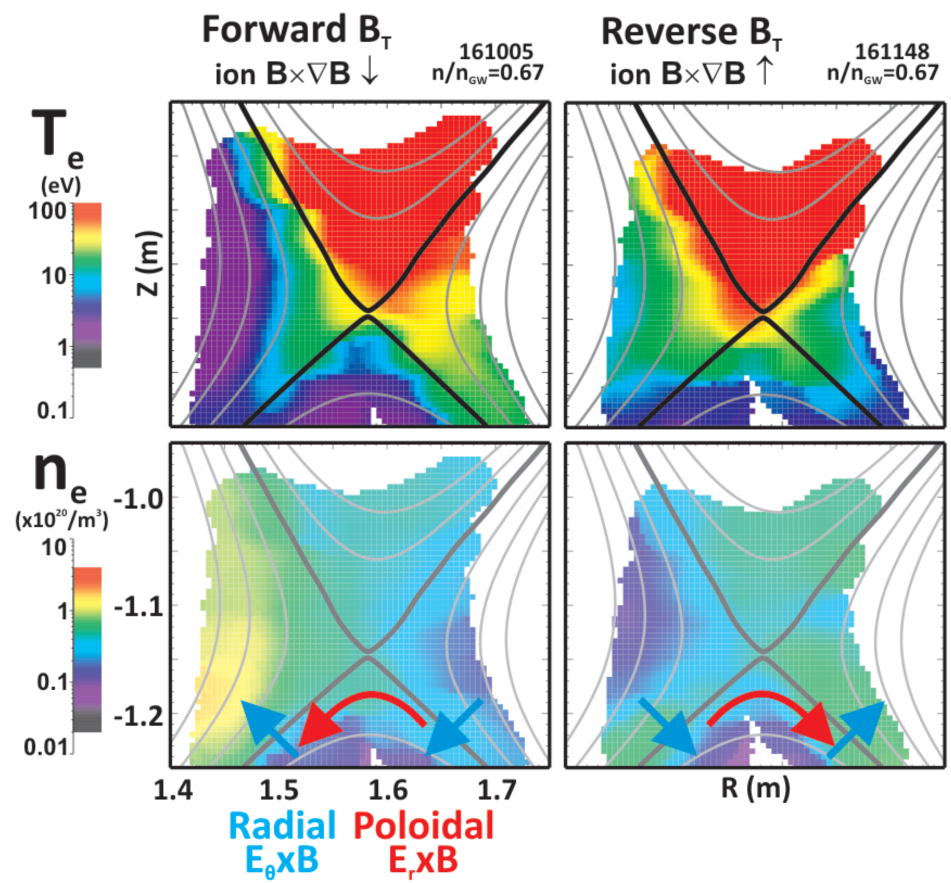
- Major features are reproduced in models when drifts are included

McLean EX/2-1   Churchill TH/P6-10   Wischmeier PD

New 2d Measurements Show Importance of Drifts On Asymmetries and Detachment Threshold

- ∇B drift into divertor: Asymmetric T_e, n_e and detachment
- ∇B drift out of divertor: Symmetric T_e, n_e and detachment





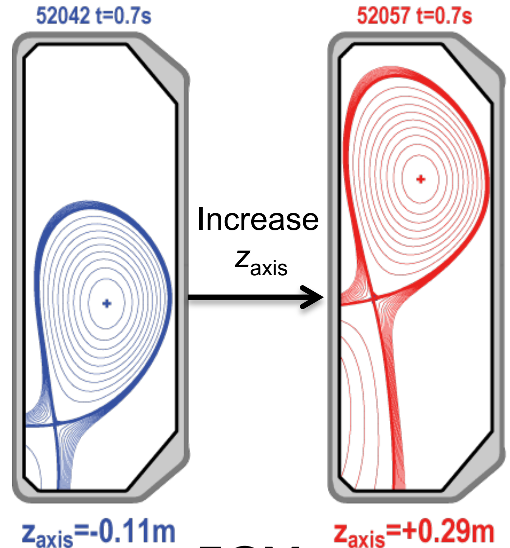
- Major features are reproduced in models when drifts are included

IAEA FEC 2016

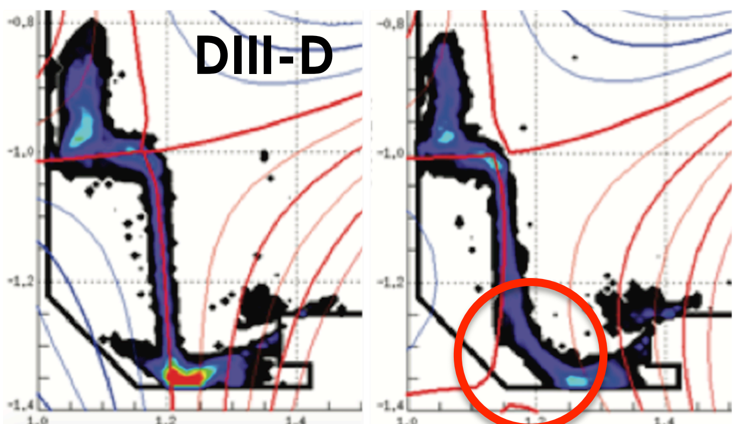
McLean EX/2-1 Churchill TH/P6-10 Wischmeier PD

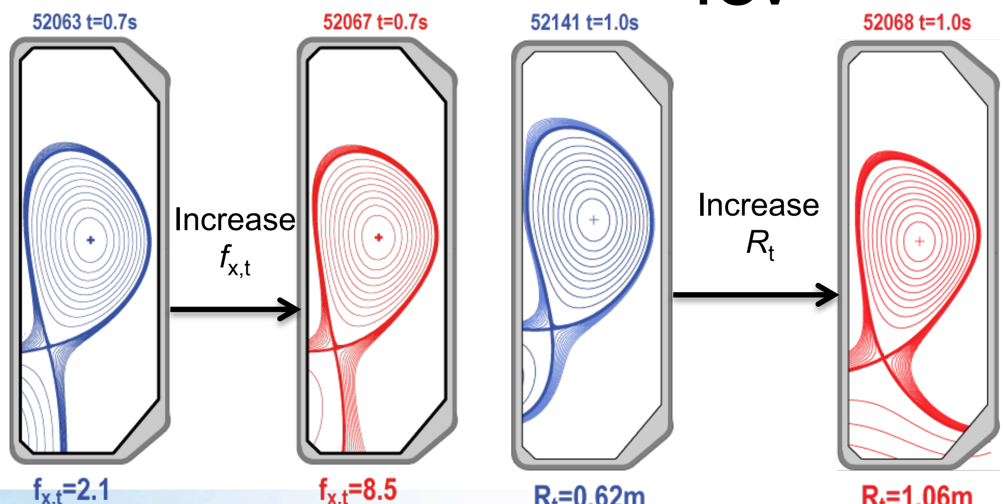
Flexible Shaping Exploited to Test Impact of Divertor Geometry on Detachment

- **Detachment onset measured with R_{maj} , flux expansion, $L_{||}$ and flaring variations**
- **Access to deep detachment without X-point degradation in X- and Super-X divertor**
- **Large database for 2D model validation**



TCV





Reimerdes EX/2-3

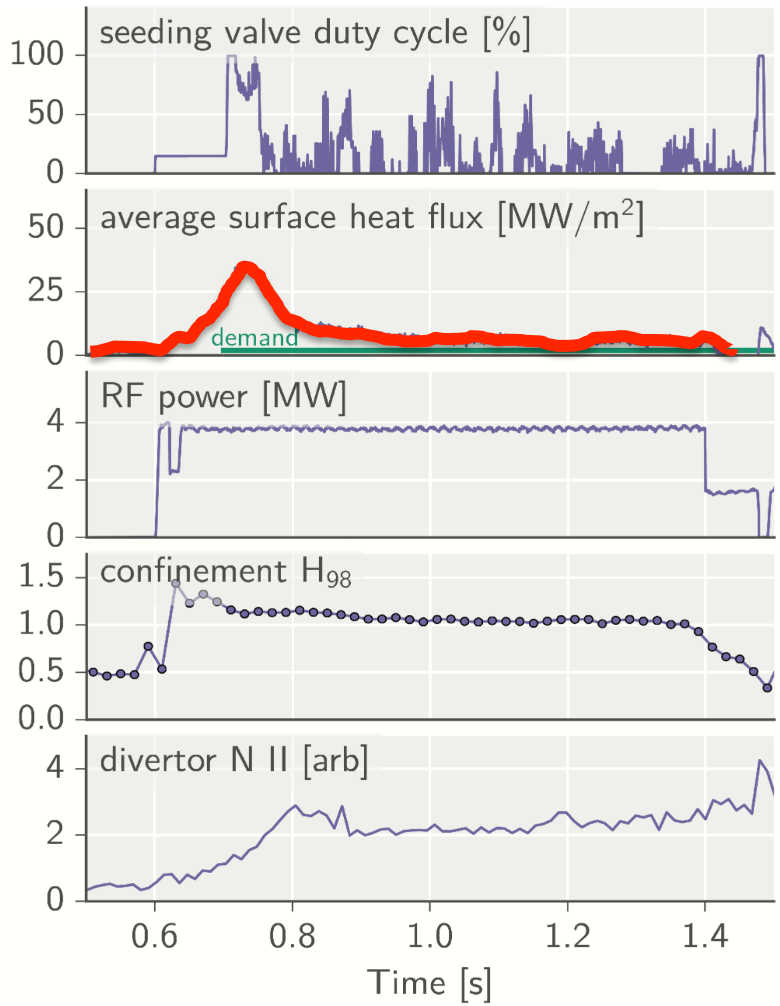
Covele EX/P3-28

New Real-time Divertor Measurements Increase Options for Heat Flux Control

- **C-Mod: Real-time measurement of divertor heat flux and controlled by nitrogen injection**
- **DIII-D: Direct measurement of divertor T_e by Thomson scattering**
- **AUG: Nitrogen seeding more effective than neon due to higher divertor compression**

A remaining issue is control of fast divertor transients by slower gas puff and recycling response

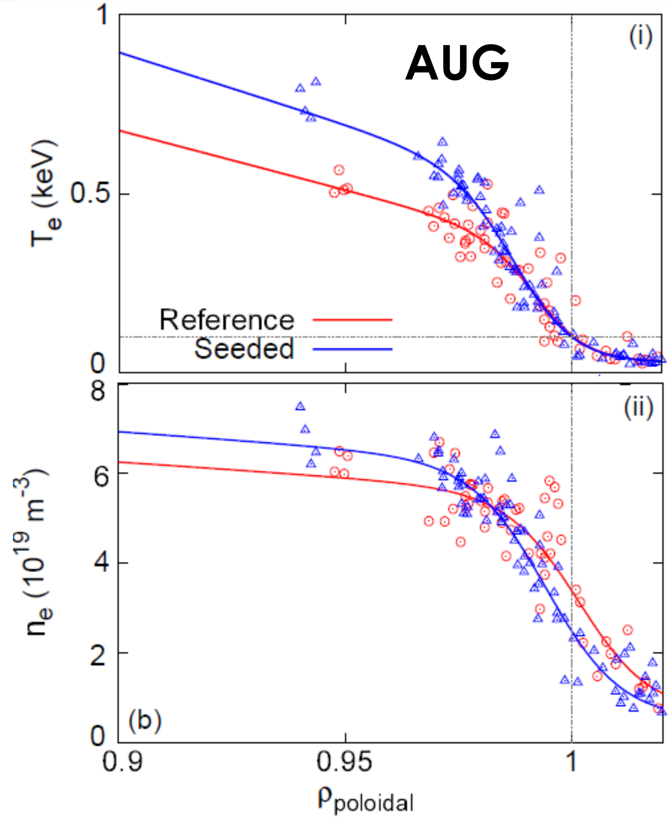
C-Mod



Bruner EX/P3-7 Reimold EX/P6-22
Eldon EX/P3-29

Impact of Boundary Plasma Conditions on Pedestal Performance Is Being Quantified

- **AUG:** N seeding leads to improved pedestal temperature
- **C-Mod:** Balanced DND exhibits steep profiles and good impurity screening on the high-field side, favorable for inside launch hardware
- **DIII-D:** D_2 gas puffing at high power improves pedestal stability and confinement in DND hybrid plasmas



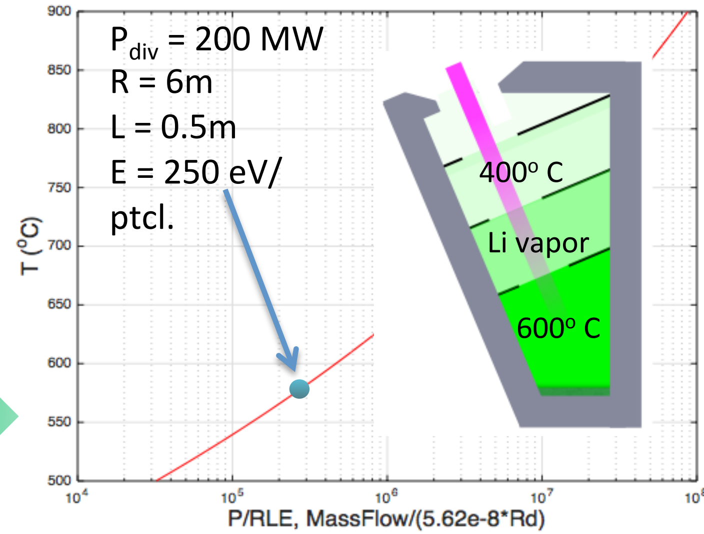
- **NSTX:** Edge electron particle and thermal diffusivity drop by >95% and 80% respectively in high triangularity, high elongation lithium enhanced NSTX H-modes

Kallenbach, OV/2-1 Petrie, EX/P3-27
Dunne, EX/3-5 Maingi, EX/P4-38
LaBombard, EX/P3-6

Alternative PFCs for Fusion May Include Liquid Lithium and Tin

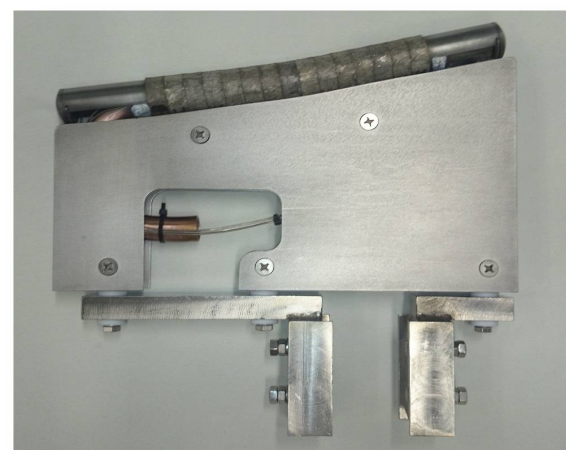
Lithium:

- **Operation with liquid Li/W Limiters in T-10 led to strong suppression of W accumulation in the plasma center**
- **Lithium vapor in equilibrium with 600° C liquid in CPS can detach DEMO divertor, with modest Li efflux**



Tin:

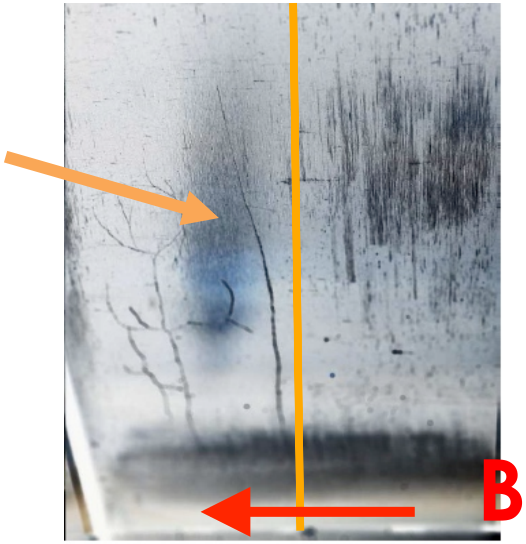
- **Corrosion-compatibility of liquid Sn with Mo and W was demonstrated at temperatures up to 1000° C.**
- **The new Tin cooled liquid limiter has been installed on FTU and first experiments will start in Autumn 2016**



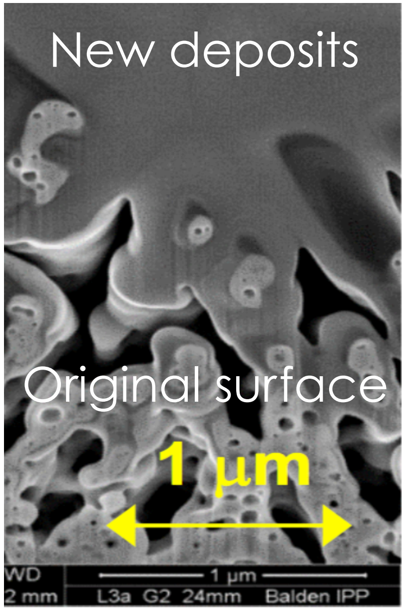
Lyublinski, EX/P8-37   Goldston, PD/P-9
Mazzitelli, EX/P8-21

AUG "Massive W Divertor" Showed Cracking After Operation, Little Change in Surface Morphology

- Cracks normal to B-field.
- FEM calculations: vertical tile cuts may avoid cracks



- He exposure to pre-treated nanostructure surface shows only smooth overcoat layer



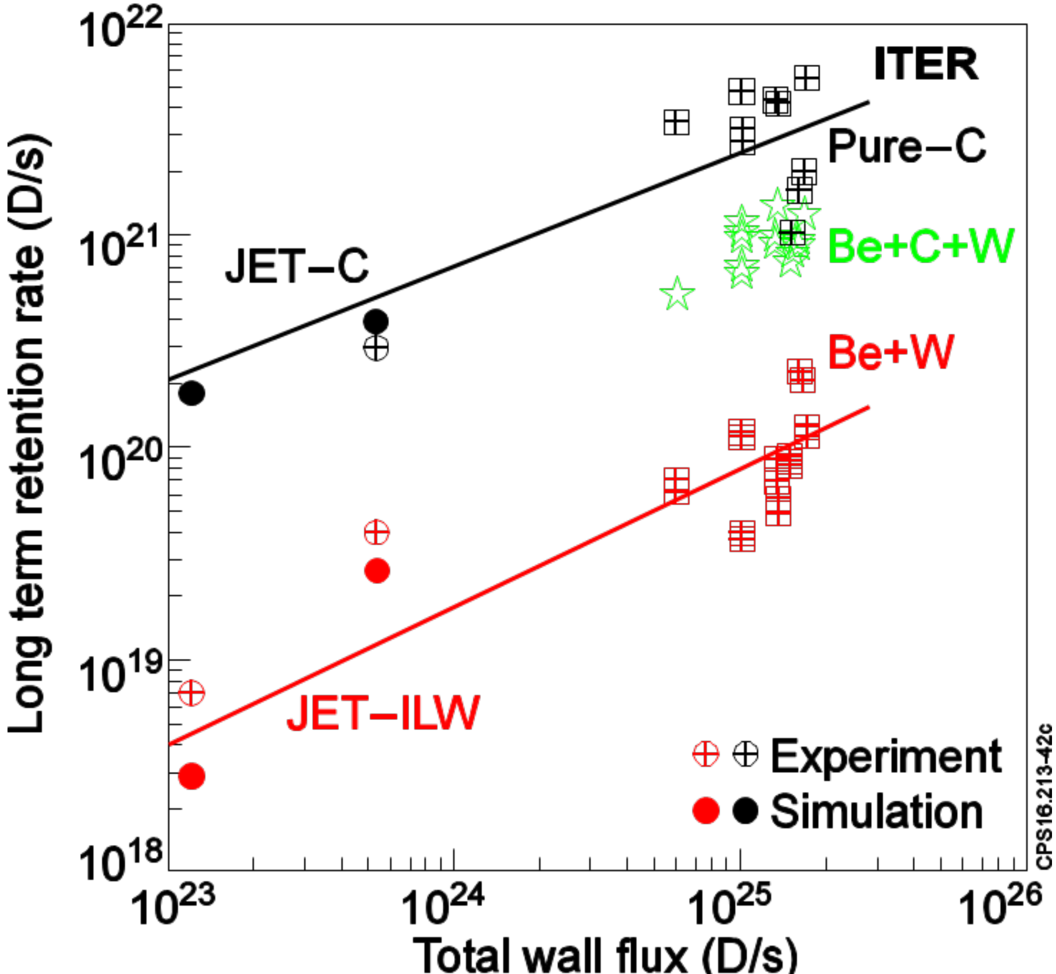
Progress on structural material R&D, but higher ductility tungsten remains challenging

Stoller MPT/1-1 Kallenbach OV2-1
Hakola EXP6/21

JET-ILW Hydrogenic Retention Studies Are Advancing Predictive Capability and Wall Designs

- **Hydrogenic retention reduced more than an order of magnitude**

- **Well reproduced by models**

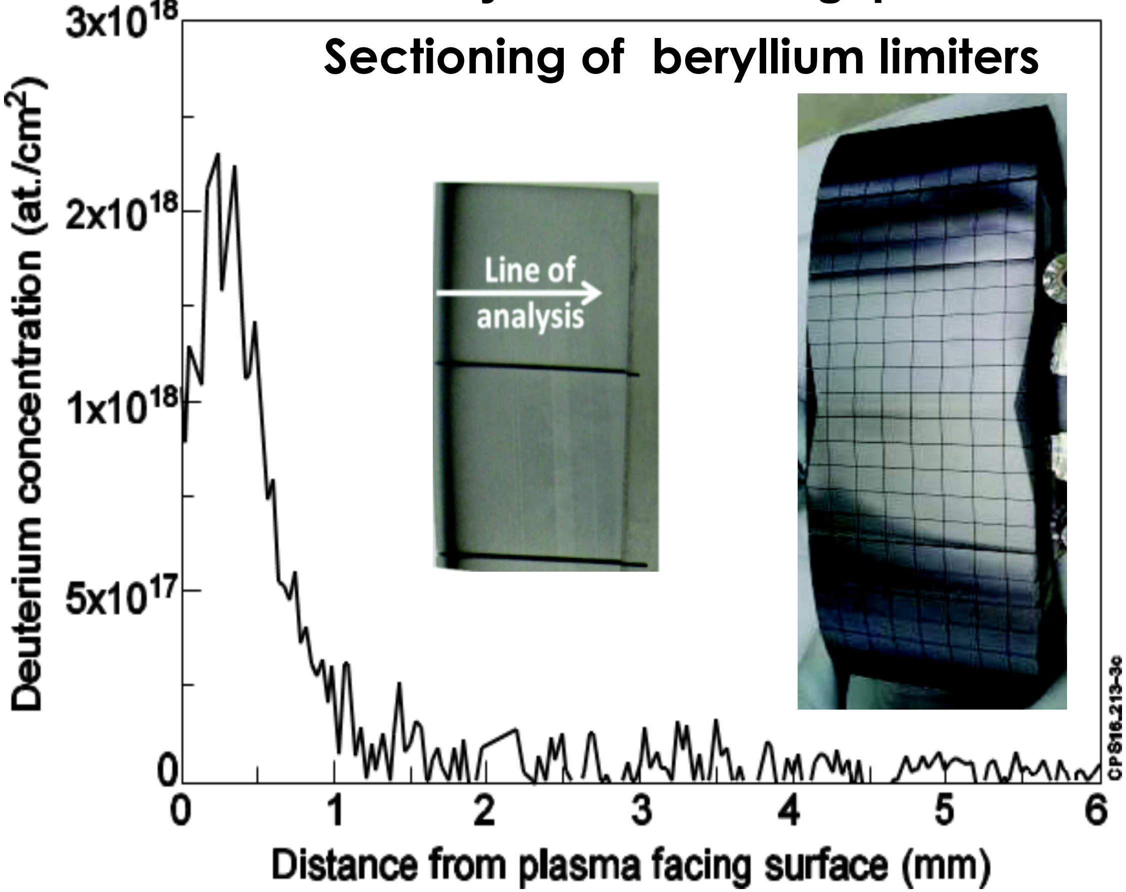


[Schmid et al NF 2015]

JET-ILW Hydrogenic Retention Studies Are Advancing Predictive Capability and Wall Designs

- Hydrogenic retention reduced more than an order of magnitude
- Well reproduced by models
- Fuel retention in Be castellation gaps show Low contribution (3%) to global fuel inventory
- High fraction of co-deposited D retained after high temperature bake

Fuel analysis in narrow gaps



Litaudon OV/13, Hakola EX/P6-21

Onward Towards ITER and Fusion Energy!