FUSION FOR ENERGY

Summary EX (part 2)

Gabriella Saibene
(Fusion for Energy)

Dedicated to Mario Gagliardi (15.09.1982 – 01.05.2021), dear colleague, friend and brilliant fusion engineer

DISCLAIMERS

I apologize in advance for including just a fraction of the contributions presented at the Conference, in the Experimental area (full inclusion is Mission Impossible)

I also apologize for any error in interpretation of your results: in case, please contact me after the conference and I will rectify them for the Nuclear Fusion paper (gabriella.Saibene@f4e.Europa.eu)

On the way to an ITER plasma

DG Bigot [OV 1-1] identified the validation of ITER Research Plan as central for its effective execution

IRP → required R&D entrusted to the plasma fusion communities, in particular

1. Divertor (and wall) load controls → ELM suppression
2. Effective disruption detection and **mitigation**
3. Development of plasma scenarios with required performance (Q and Pfus), compatible with ITER constraints (actuators PFC lifetime, ...).


ITER TECHNICAL REPORT

ITR-18-003

ITER Research Plan within the Staged Approach (Level III – Provisional Version)

ITER Organisation


ITER TECHNICAL REPORT

ITR-20-008

Required R&D in Existing Fusion Facilities to Support the ITER Research Plan

Alberto Loarte

Results at this conference

The results presented at this conference show remarkable progress in all major priority areas for ITER (and beyond).

This conference has also highlighted the importance of experiment design driven by modelling (predict first)

Two main takes:

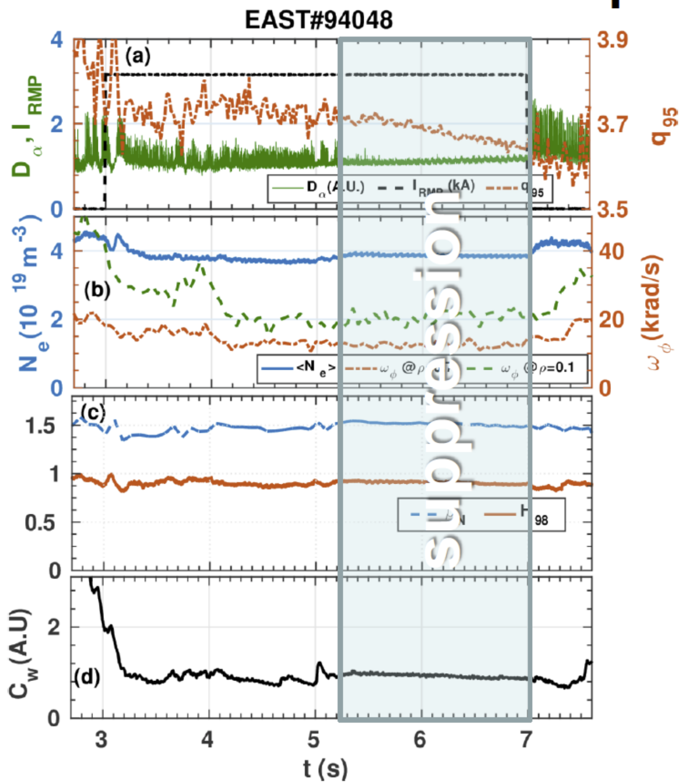
1. Scenarios supporting the development of integrated performance as required in ITER have been established in many machines, and using different approaches and actuators
2. At the same time, new ideas emerge opening active lines of research (disruption mitigation one of those)

ELM suppression with RMP - EAST

A Loarte Y Sun
EX4/4

ELM suppression by n = 4 RMP in EAST

Demonstrated in EAST for first time and in low input torque plasmas



- ❑ Conditions similar to high Q **ITER H-modes**
  - ➢ **low torque** T_{NBI} → **0.44 N·m** (< 0.9 N·m **ITER 33 MW-NBI equivalent)**
  - ➢ q_{95} ~ 3.65, $\nu_{*e,ped}$ ~ 0.5, β_N ~ 1.5
  - ➢ T_i ~ T_e ~ 1.5-2 keV
- ❑ **No drop in energy** confinement
  - ➢ Small density pump out
  - ➢ Low W concentration during RMP application

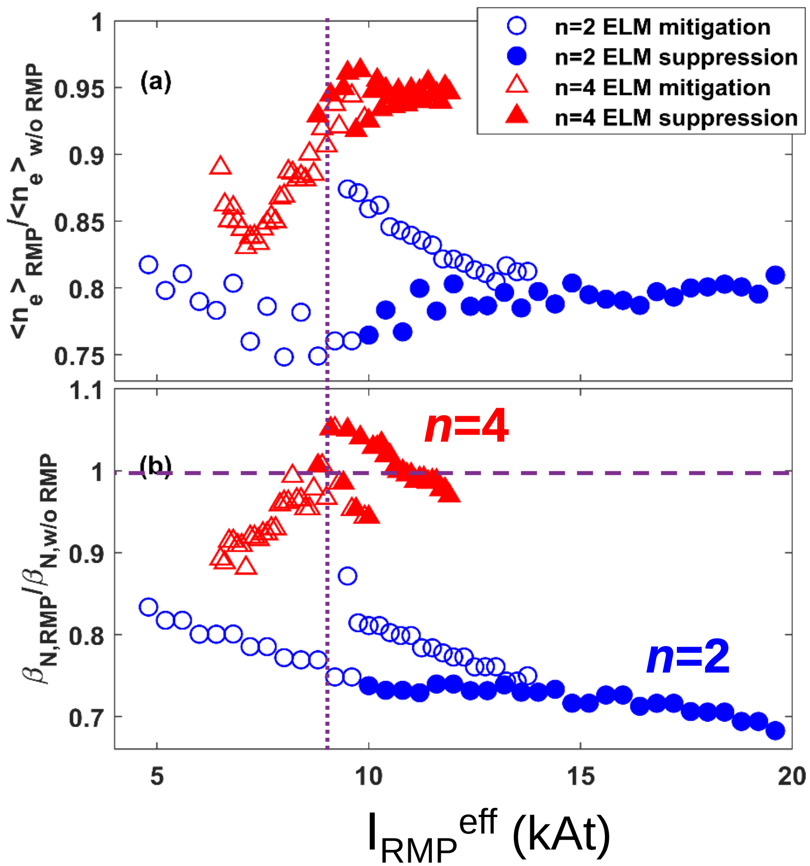
28th IAEA Fusion Energy Conference – Y. Sun and A. Loarte – 13 – 5 – 2021

Page 8

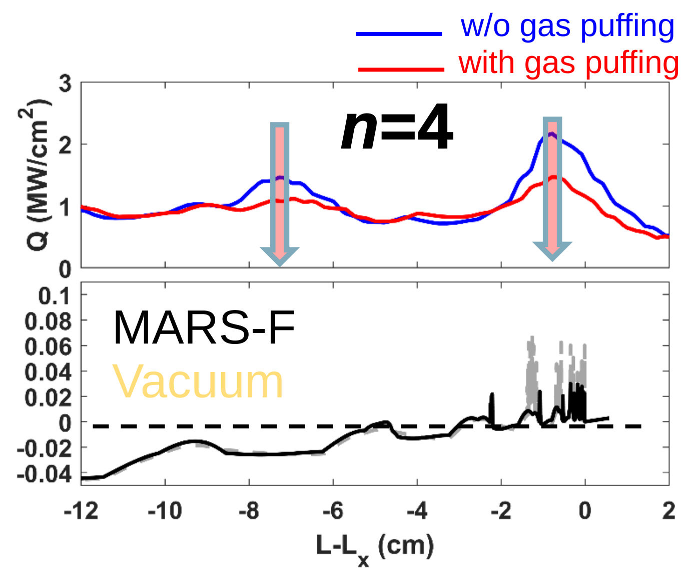
Optimum ITER high Q scenario integration of ELM Suppression with *n* = 4 RMP in EAST

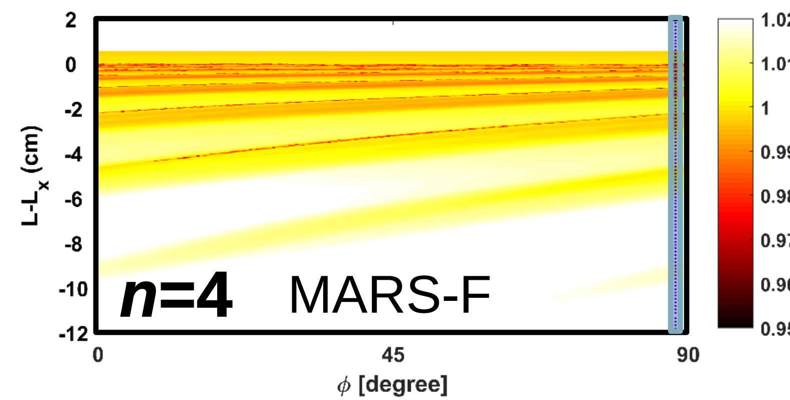
A Loarte Y Sun EX4/4

- ❑ High energy and particle confinement maintained



- ❑ Good control of divertor power fluxes (separatrix + off-separatrix)





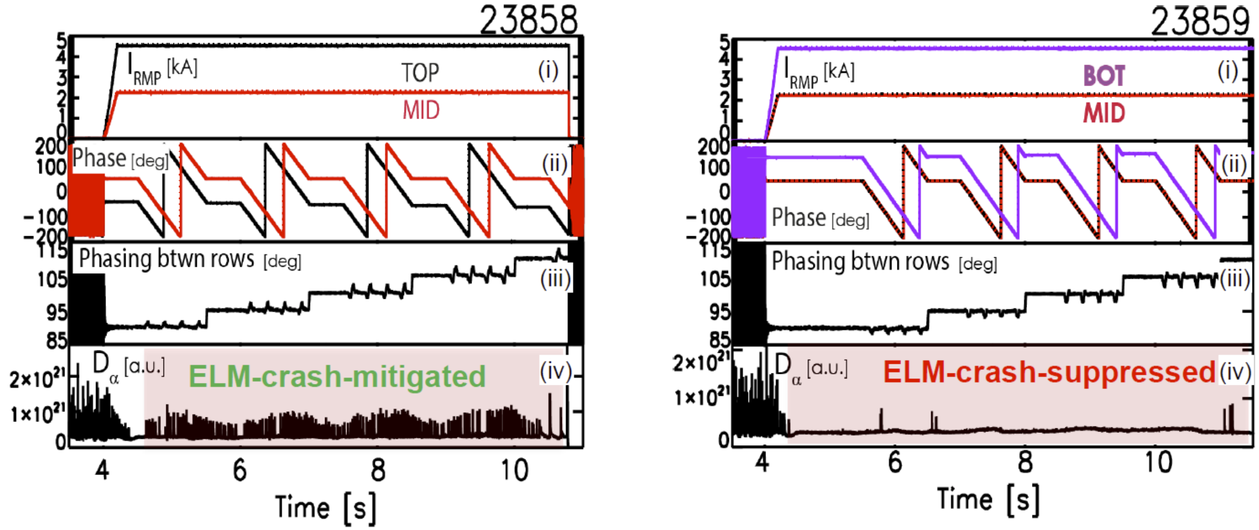
ELM suppression with RMP - KSTAR

FUSION FOR ENERGY

Optimized coupling with RMP fields leads to ELM suppression

S W Yoon OV 2-3

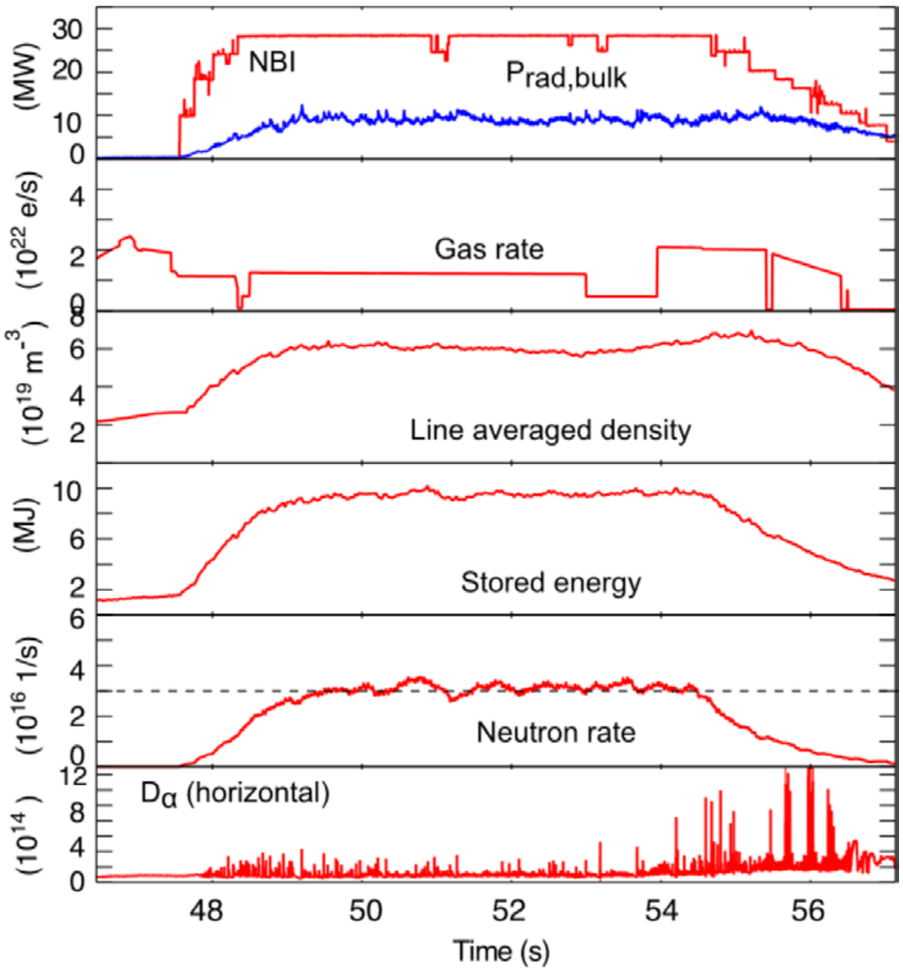
Evidence of up/down asymmetric coupling difference for RMP ELM suppression, showing a meritorious use of Mid/Bot, instead of Top/Mid



- **Potentially critical information for ITER RMP operation**
- **Much more reduced level of Bottom row was found to be sufficient, suggesting a weak coupling of top-row in 3-row IMCs**

Stationary Scenarios for the DT phase achieved: baseline route -

Baseline: 3 MA/2.8 T (q_{95}=3.1)

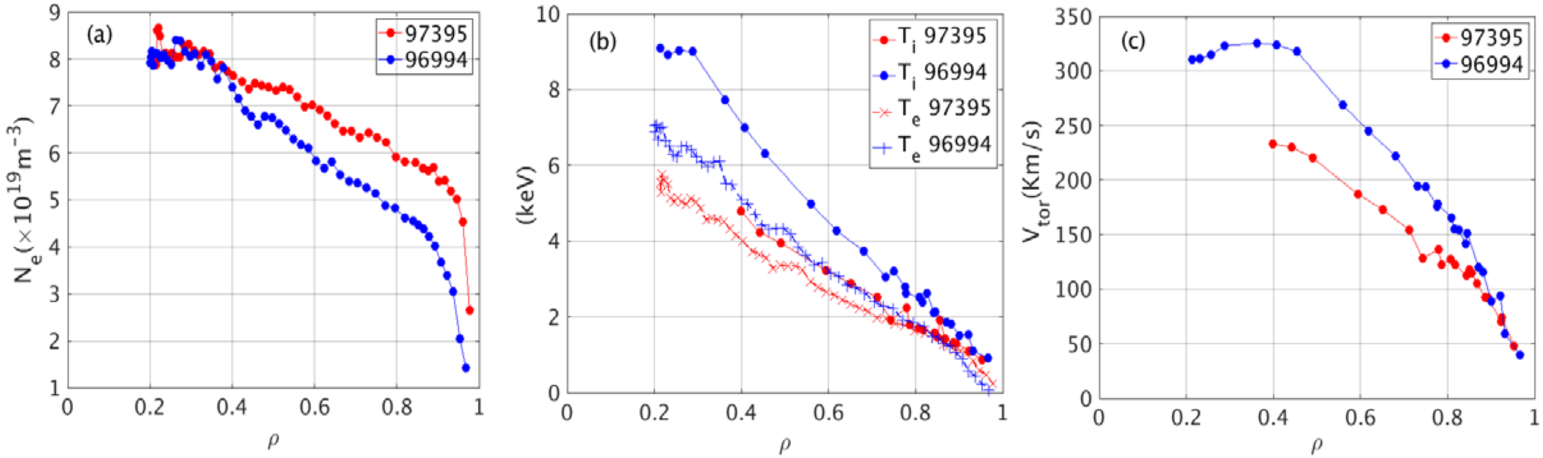


- $H_{98}(y,2)$ = 1.05, β_N = 2.2, β_p = 0.9, f_{GLD}~ 0.7
- Improvement wrt Type-I ELMs plasmas
  - Reduced gas puff + Pellets (45Hz): high confinement
  - Inclusion of small Ne quantities provides stability [C. Giroud IFE/P4-12]
- Long phases with high frequency (200-400Hz) small ELMs
- Core radiated power stable
- Divertor in 'attached' conditions

J Garcia EX 1-2 and E de la Luna EX 3-2

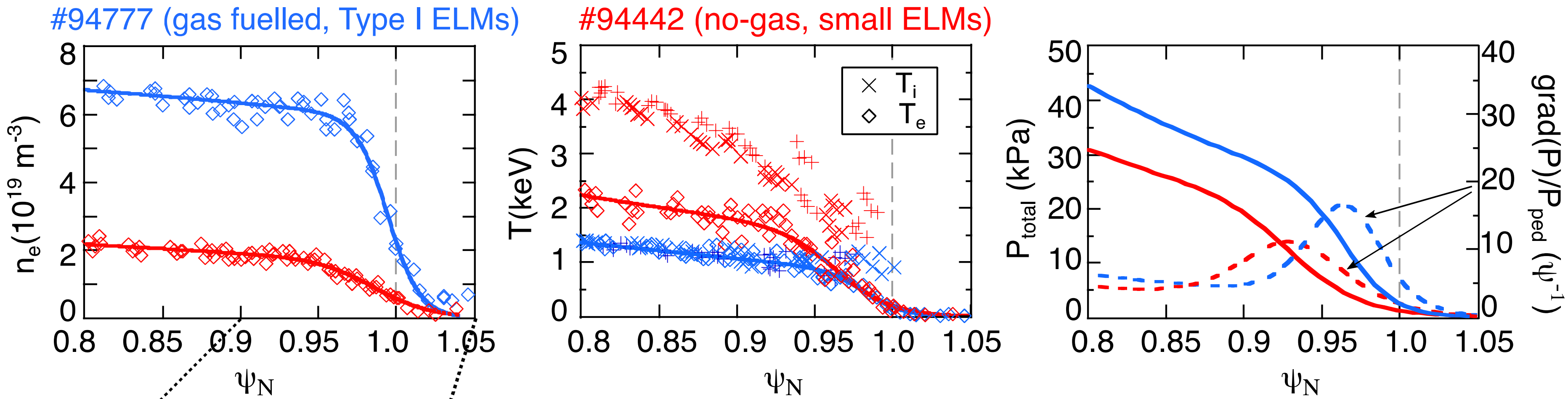
Differences between small and Type-I ELMs plasmas at same input power – J Garcia EX 1-2

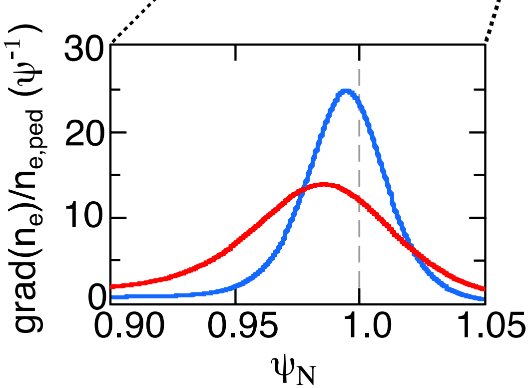
Type-I ELM: only gas   Small ELM: gas+pellets+Ne



- Compared to type-I ELMs, small ELMs pulses are characterized by:
  - Higher density peaking
  - Wider pedestal at the same pedestal top pressure
  - $T_i/T_e>1$ including the pedestal top
  - Higher rotation and rotation shear (close to ITER predictions) [C. Chrystal NF 2020]
  - Higher DD neutron rate

Wider density pedestal and high T_i^{PED} correlated with the onset of small ELMs





- Compared to the ELMy H-mode plasma, the discharge with small ELMs has:
  - similar P^{PED} (lower n_e^{PED}, but higher T_e^{PED}, T_i^{PED})
  - wider n_e and P_e pedestal width, significantly lower maximum ∇n_e & ∇p_e.
  - position of maximum gradient shifted inwards (due to wider width) → improved pedestal stability

E de la Luna, EX 3-2

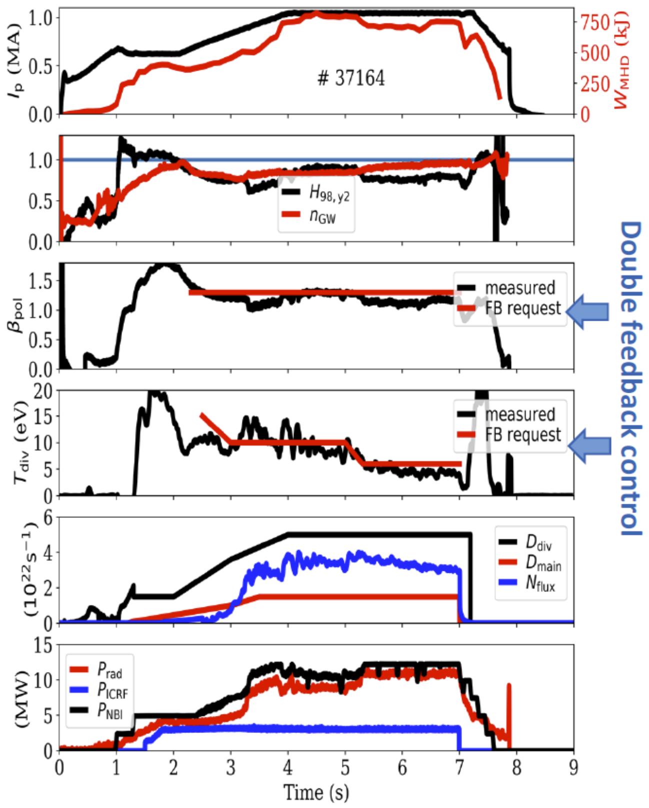
ELMs mitigation scenarios

FUSION FOR ENERGY

Extensive studies of ”natural” small ELM regimes in Asdex-U, including I-modes, EDAs and QCE. U Stroth [OV2-2]

QCE: high-power discharge without any large ELM

ASDEX Upgrade IPP



An integrated scenario at DEMO relevant separatrix parameters

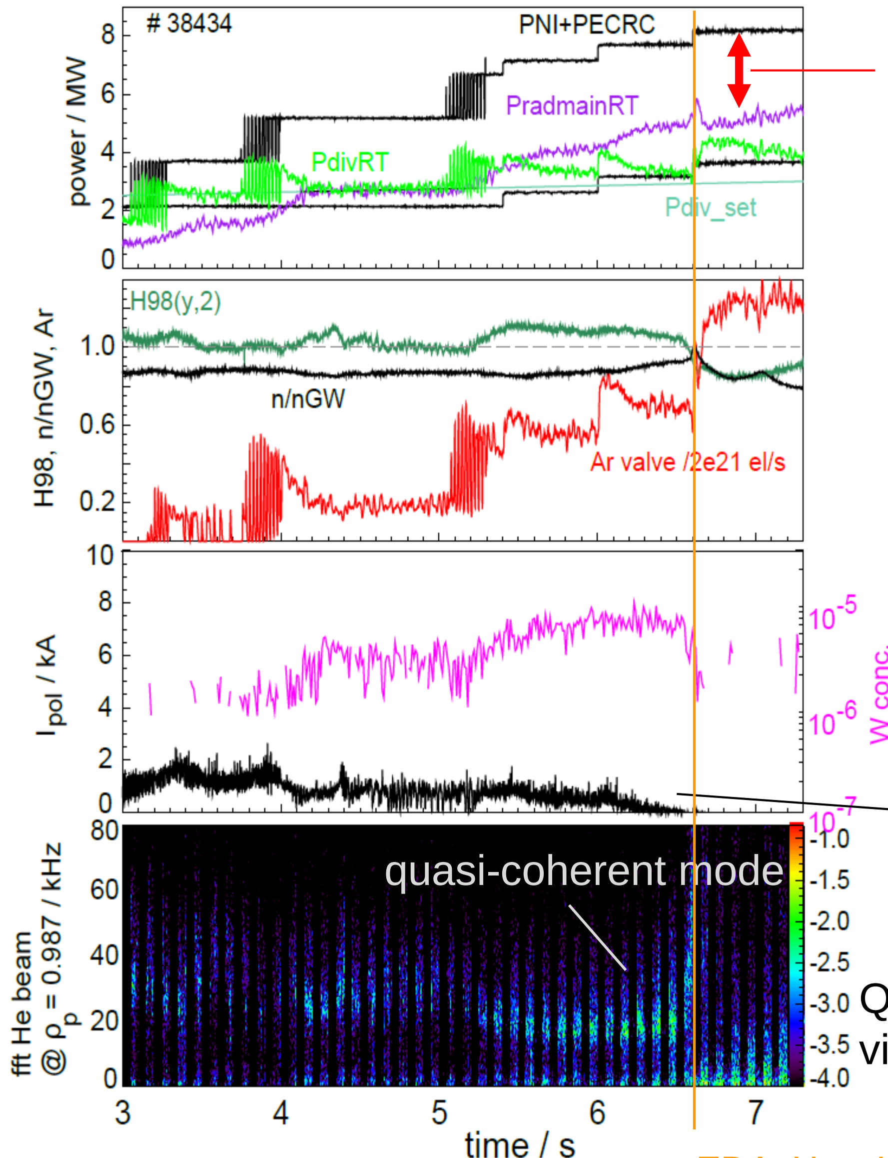
- High power (15 MW), partially detached divertor, close to H-mode confinement
- Quasi continuous transport by small (type II) ELMs
- Power fall-off length 4 times larger than between ELMs in H-Mode

→ poster by M. Faitsch et al.

[M. Faitsch et al. NME 2020]

TU WIEN EPFL SWISS PLASMA CENTER

Integrated no-ELM scenario in AUG:
EDA H-mode extended to high power by controlled Ar seeding



power to divertor controlled via Ar seeding

quite narrow power window in Psep for L- EDA - ELMy

very good performance: $H_{98}>1$,
$n/n_{GW}=0.9$, $\beta_N = 2$,
integration with detachment shown with Ar+N

low tungsten concentration < 10^{-5}

completely ELM-free

QCM @ 20-30 kHz provides full ELM suppression via MHD-stable pedestal

EDA H → L-mode due to radiation event

A Kallenbach EX 2-5

FUSION FOR ENERGY

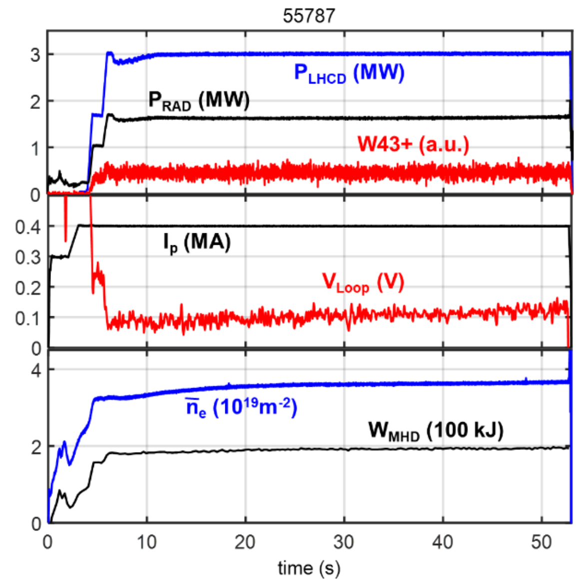
WEST experiments demonstrate very long plasmas with W divertor [Bucalossi OV 2-1]

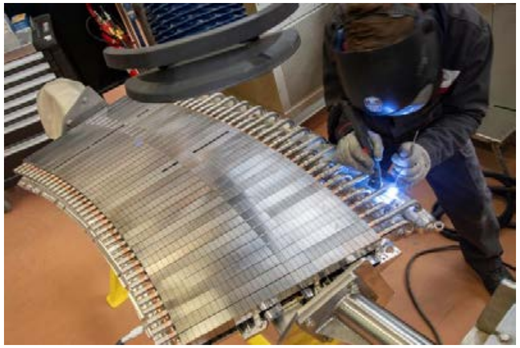
Long pulse discharges with duration 30 s – 1 min routinely performed in Phase I

- **9 MW of combined ICRF/LHCD power coupled, without W accumulation**
- **Wall monitoring system for RT metallic PFC protection implemented**
- **No failure on ITER-grade PFU prototypes (from CN, EU and JPN) but evidence of damages after several hours of plasma at moderate heat fluxes:**
  - ✓ Optical hot spot observed for the first time as predicted by modeling
  - ✓ **Cracks and local melting observed at moderate heat flux on misaligned PFUs** from 0.3mm - 0.8mm → crucial issues for safe operation in ITER and divertor lifetime

Phase II with the full ITER-grade divertor aiming at 1000s plasmas to start in summer 2021

- **456 PFUs manufactured and reception tests competed → assembly ongoing**
- **Main thrusts for phase 2:**
  - ✓ Combined high heat flux/high particle fluences studies
  - ✓ Towards steady-state H-mode operation in full W device



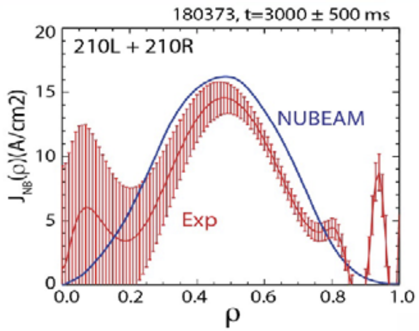


Off-axis NB injection in DIII-D

Improved actuators (off-axis NB) for profile & q control in DIII-D

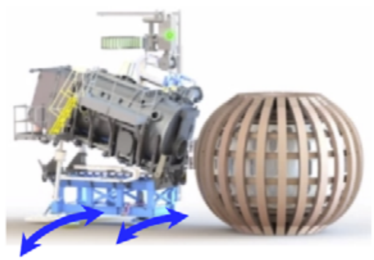
M Fenstermacher [OV 1-3]

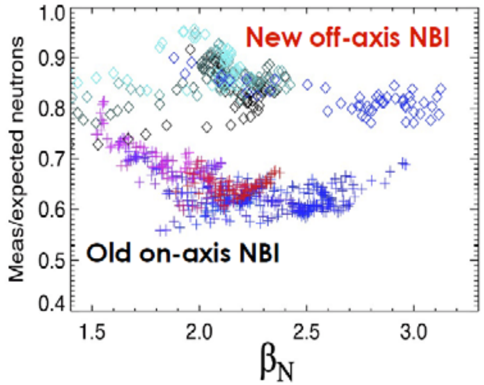
Performance of High-q_{min} Plasmas Improved by Increased Off-Axis NB Power Reducing AE Drive and Fast Ion Losses



- Reduced beam pressure gradient at ρ_{qmin} gives higher thermal pressure and ratio of neutrons/ TRANSP(classical)

- New off-axis NBI current drive matches simulations





- Recovered up to 25% of neutrons ratio (35% with added ECCD)
- 10% higher confinement, 15% higher β_N

Optimization to classical fast ion confinement possible in steady state reactor scenarios

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

B. Grierson (poster), P/1, Tues AM

acher, DIII-D Overview, 2020 IAEA FEC

C. Collins (oral), EX/8 Sat AM

4

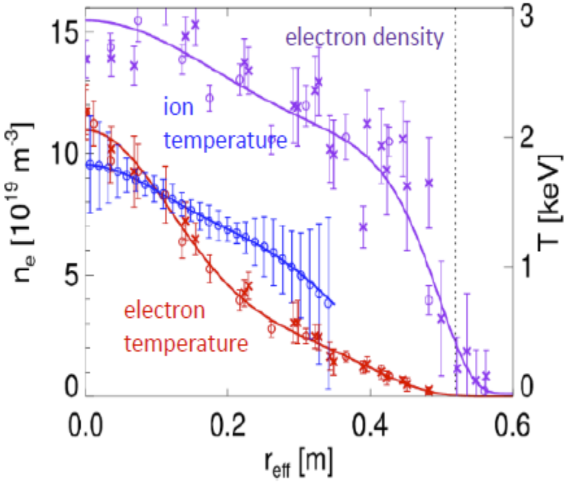
W7-X high density plasmas with ECH only

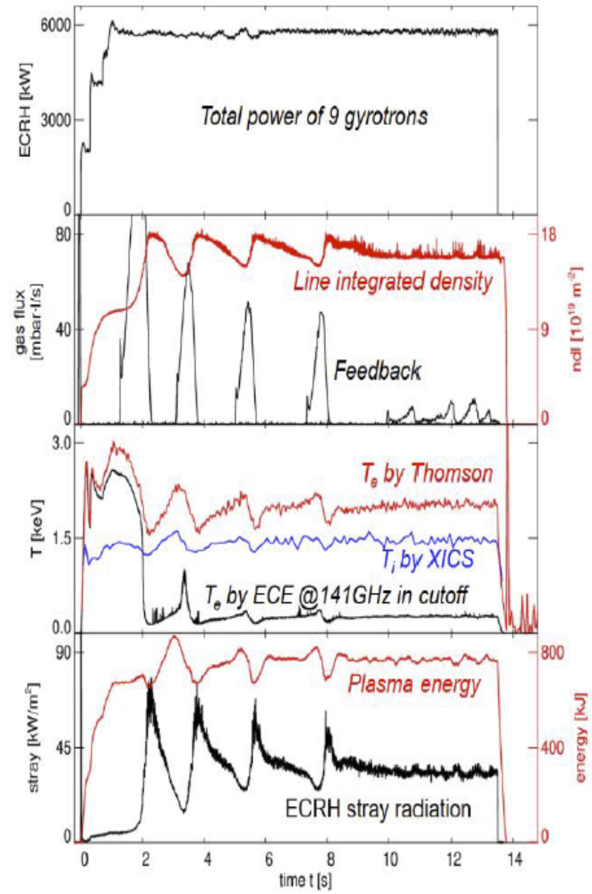
FUSION FOR ENERGY

Multi-pass EC 2nd harmonic O-mode key for sustained high n plasmas

High density operation

O2 ECRH operation with 6 MW sustained a density of 1.4 10^{20} m^{-3}, where strong electron ion coupling could be achieved.





H O Laqua, P6 6

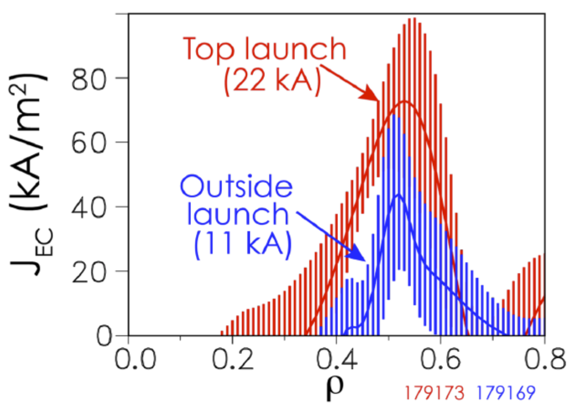
ECCD optimization

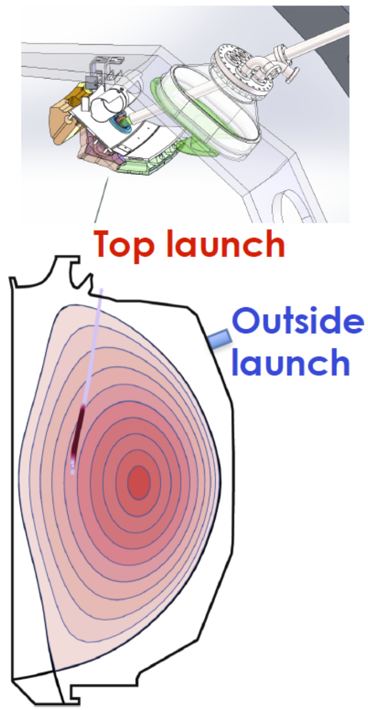
EC HFS vertical injection in DIII-D reaches predicted high CD efficiency

Xi Chen [EX 1-1]

Doubling of Off-axis ECCD Achieved on DIII-D via Reactor-relevant 'Top Launch ECCD' Approach

- **New top launch ECCD system is installed on DIII-D to allow experimental validation**
- **Experiments tested main tenets of top launch ECCD**
  - Geometry allows selective wave interaction with high $V_{||}$ electrons having high CD efficiency
  - Long absorption path compensates for inherently weak damping at high $V_{||}$





Experimental validation of new ICRH schemes

H + He_3 ICRH heating in JET

3^{rd} harmonic D in AUG

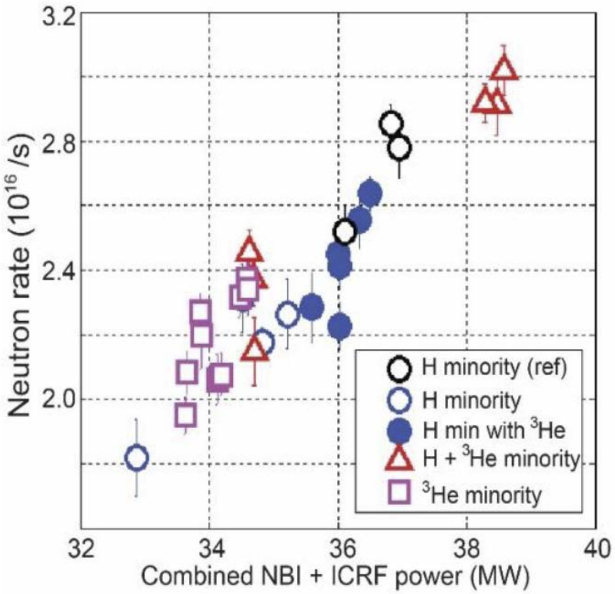


***Figure 4** Neutron rate as a function of ICRF+NBI power in discharges with different ICRF schemes*

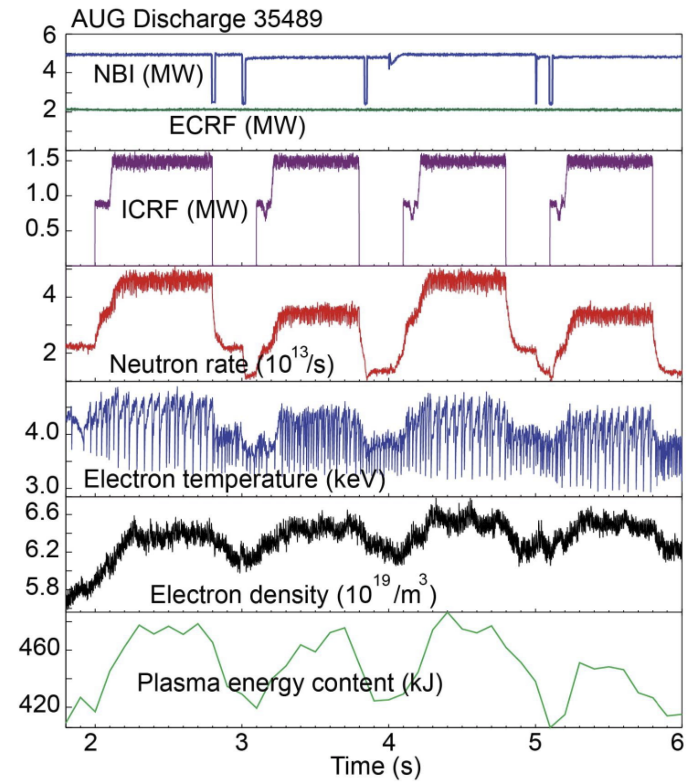


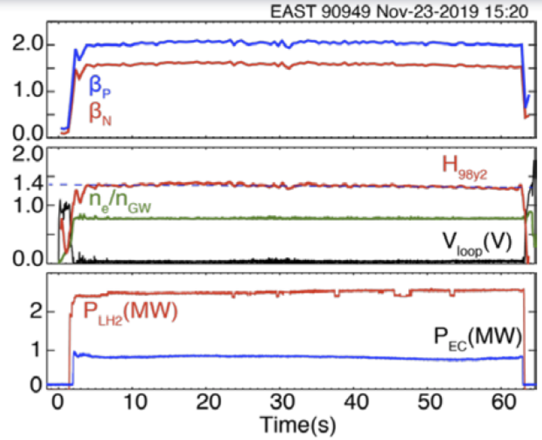
***Figure 8** Plasma parameters for AUG discharge 35489 with 3rd harmonic ICRF heating of D with synergy with D NBI. Different NBI injectors were used for each ICRF phase.*

JET – Hybrid scenarios with combined NB and ICRH heating

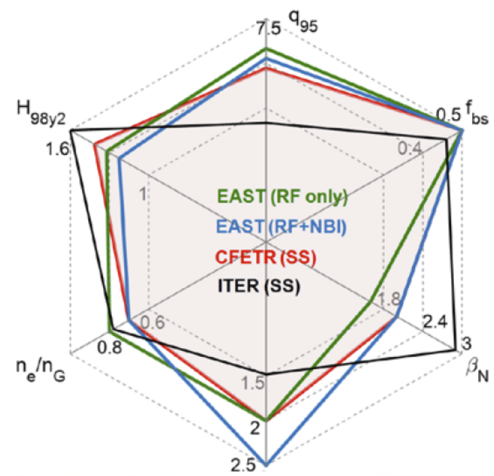
Pure e-heating steady state H-mode with W divertor achieved in EAST

– B N Wan [OV 1-4]

EAST demonstrated high β_P long pulse H-mode operation with high f_{bs}



- **A 60s steady-state high β_P H-mode discharge achieved by optimizing core and edge compatible integration.**
  - β_p~2.1, f_{bs}~0.5, H_{98}>1.3, small ELMs
  - eITB (T_e>T_i), zero torque, low rotation



- **Fully non-inductive high β_P regimes close to 1GW CFETR performance obtained by Improving confinement**
  - Higher β_p
  - Higher density gradient
  - Reduced fast ion losses

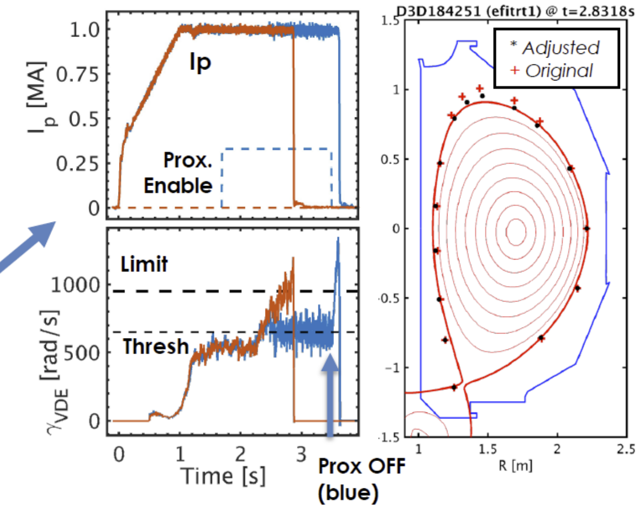
Disruption prevention

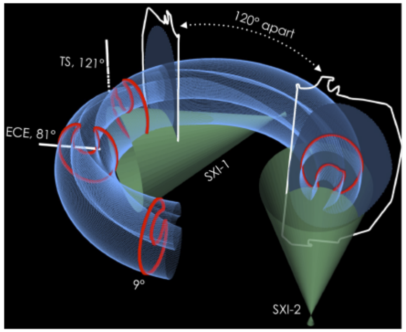
J Barr EX-5

Also F Felici EX-P4-21

Development and Experimental Qualification of Novel Disruption Prevention Techniques on DIII-D

- **DIII-D Disruption Free Protocol:**
  - *Initiative for qualifying comprehensive disruption prevention tools in DIII-D*
- **Novel real-time proximity-to-Instability controller for avoidance of stability limits**
  - Applied for robust VDE prevention
- **Novel soft-landing technique generates warm, helical core after thermal quench**
  - Significantly slow current quench
- **Rigorously qualifying emergency shutdown for disruption avoidance**
  - Transitioning to limited for emergency shutdown significantly improves chances of success





DIII-D NATIONAL FUSION FACILITY

J. Barr/ITER FEC 2020/May 14th, 2021

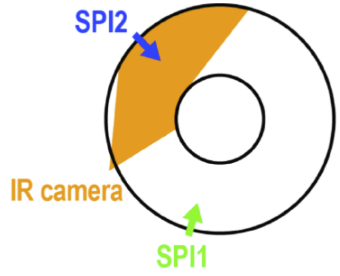
GENERAL ATOMICS

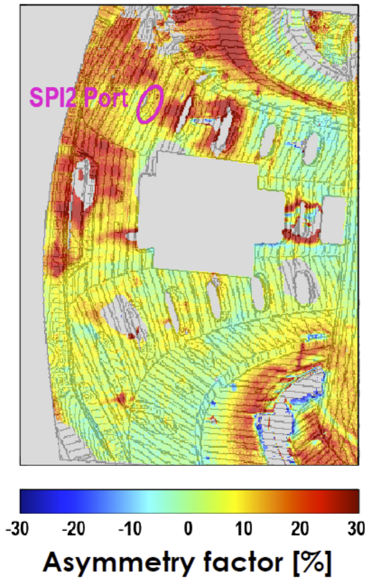
D Shiraki EX-5-2 Ra

Collaboration DIII-D, Eurofusion, JET and Oak Ridge Nat Lab

TQ radiation asymmetry due to localized injection source is observed experimentally and in extended-MHD simulations

- **Asymmetries observed from comparing first-wall IR thermography for different SPI systems**
- **Radiation peak is broadly centered around SPI port**
  - Due to rapid localized injection, rather than MHD heat flux
- **Estimated TQ toroidal peaking factor = 1.9 +0.5/-0.3**
  - Consistent with DIII-D NIMROD simulations[1]
- **Close to ITER surface melt limit[2] (peaking factor ~ 2)**
  - Not yet known if multiple SPIs reduce peaking





[1] C. Kim, et al., This conference
[2] M. Sugihara, et al., Nucl. Fusion **47** (2007) 337

9 DIII-D NATIONAL FUSION FACILITY D. Shiraki/IAEA-FEC/May 14, 2021

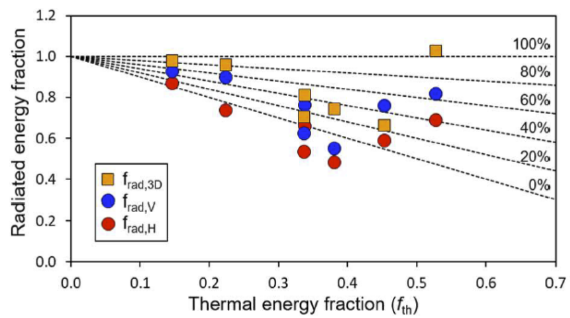
SPI characterization - JET SPI

S Jachmich

EX-5-1 Ra

Radiation efficiency

- Vary P_{NBI} to scan f_{th} (W_{th}=0.3-1.5MJ for W_{mag}~3 MJ)
  - Pellet: 80% Ne (Ne=2.4×10^{22} atoms + D-shell)
- Axisymmetric weighted is significant lower than 100%



- Fast cameras show large helical structure: SPI-location

- Emis3D code to determine helical structure fitting best the LOSs of the bolometers
- Assumes Gaussian toroidal distribution using $P_{rad,V}$ and $P_{rad,H}$ as boundaries

➢ *Difference in W_{rad} measured by 2 bolometers → radiation asymmetries*

➢ *Toroidal peaking ~2.2*

Radiated energy fraction: $\langle f_{rad} \rangle = W_{rad,H} / (W_{mag}+W_{th}-W_{coupled})$

Thermal energy fraction: $f_{th} = W_{th} / (W_{mag}+W_{th}-W_{coupled})$

R. Sweeney et al, 62nd APS DPP meeting, 2020

iter china eu india japan korea russia usa | Stefan Jachmich *et al*, 28th IAEA Fusion Energy Conference, May-2021 | IDM UID: xxxxxx | Page 8

RE mitigation

FUSION FOR ENERGY

Paz Soldan

EX-5-2 Rb

DIII-D and JET

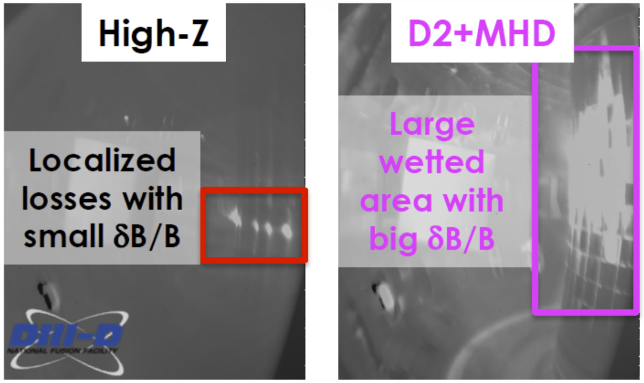
New Approach to Runaway Electron Mitigation Demonstrates Safe Termination of MA-Level RE Beams

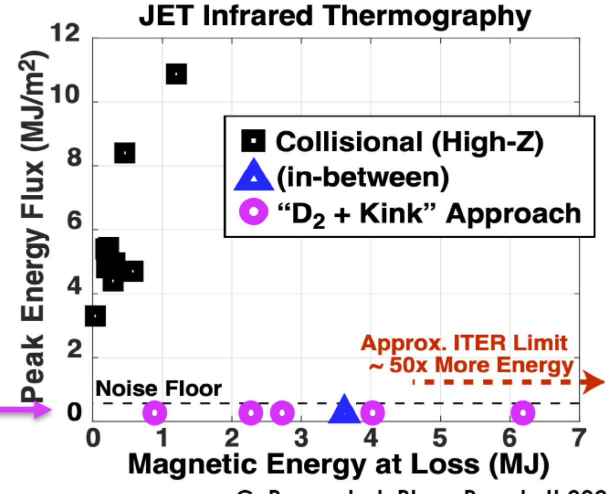
Approach involves

1. Deuterium Injection
2. Excite Current-Driven MHD (big δB/B)
3. "Disruption of RE beam" → sub-ms loss

Safe RE Termination Achieved By:

- Low-Z: recombines background plasma → accelerates Alfvenic MHD
- Large dB/B: REs lost to wall over large wetted area → disperse kinetic energy
- Current converts back into Ohmic bulk → Magnetic energy dissipates benignly





New Approach Avoids First Wall Heating Despite High RE Energy

DIII-D NATIONAL FUSION FACILITY EUROfusion

EX/5-2b

C Paz-Soldan/IAEA-FEC/2021-05

C. Reux et al, Phys. Rev. Lett 2021
C. Paz-Soldan et al, Plas. Phys. Contrl. Fus 2019

RE mitigation

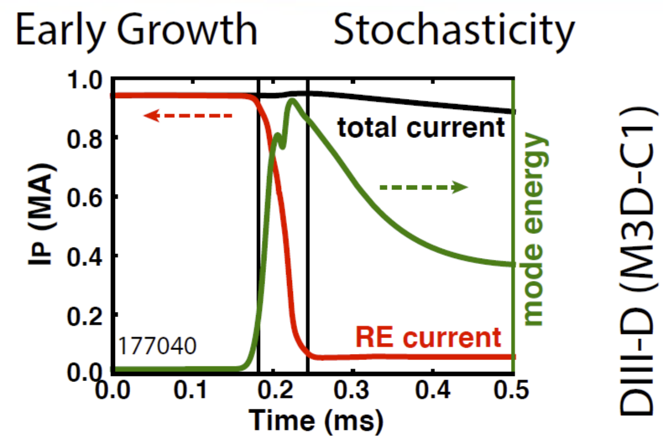
Paz Soldan

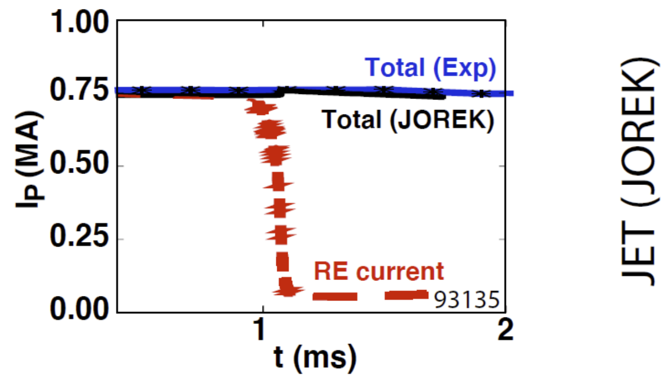
EX-5-2 Rb

Extended MHD Modeling Reproduces RE → Ohmic Current Transfer in DIII-D and JET

- **M3D-C1 and JOREK with RE fluid model deployed**
- **Near-total stochasticity found in both simulations**
- **Prompt loss of REs drives current transfer to the bulk**
- **Dissipation of magnetic energy into line radiation**
  - … Not back into RE energy

Ideal Scenario for Magnetic Energy Handling





C. Liu et al, Phys. Plasmas (in preparation, 2021)
V. Bandaru et al, Plas. Phys. Contrl. Fus. 2021

Operation recovery after SPI

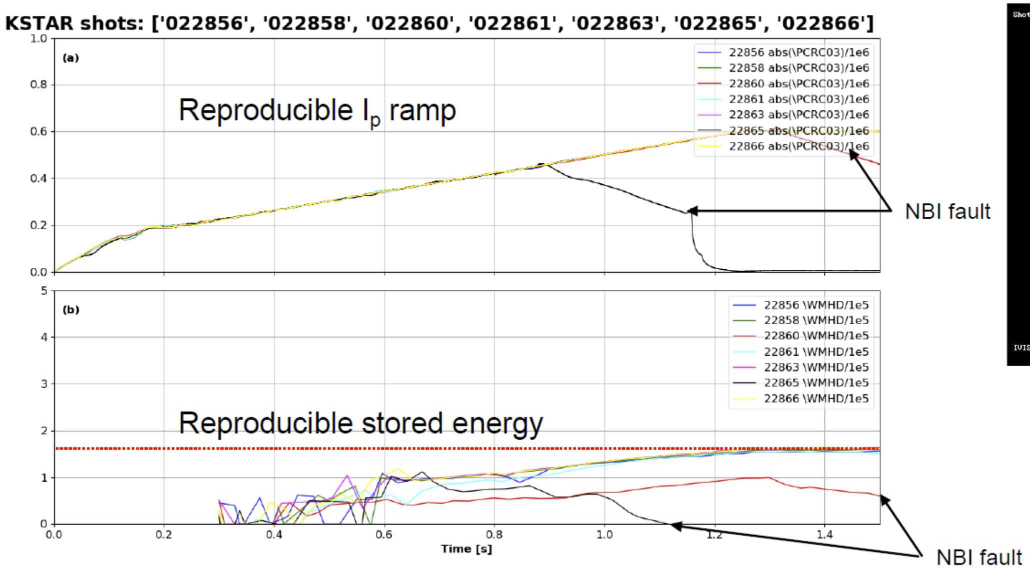
FUSION FOR ENERGY

B_T Compatible – intershot cleaning with ECWC in KSTAR - S W Yoon OV 2-3

KSTAR

21

Electron cyclotron wall cleaning can be
a good solution for wall recovery from massive material injection.



ECWC

Ne:D=0.05:0.95 (all 7 mm SPI pellets except 4.5 mm pellet of #22856)

X2 harmonic EC-assisted start-up at B_T=1.8 T + X2 harmonic ECWC

- #22856 (SPI) → #22857 (ECWC) → #22858 (SPI) → #22869 (ECWC) → #22860 (NBI fault) → #22861 (SPI) → #22862 (ECWC) → #22863 (SPI) → #22864 (ECWC) → #22865 (NBI fault) → #22866 (SPI)

Conclusion

The scientific and technical content of the material presented in this conference is remarkable, with quality and coherence of the fusion community work increasing consistently.

ITER is becoming a reality (not only buildings, with all my respect to buildings) and this helps towards channeling ideas and resources to sustain the ITER Research Plan .

Performance & reproducibility of ELM control and suppression, pedestal control, disruption mitigation, additional heating, .. is impressive . Modeling is now guiding experiments, not only interpreting results.

The holy grail of the integrated scenarios, as necessary for ITER success, seems to me much nearer than ever before.