Integrated modelling of disruptions and their mitigation

IIS2025 14th ITER International School

Integrated Modeling in Magnetic Fusion Plasmas

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Di Hu

Special thanks to F.J. Artola, C. Liu, E. Nardon, D. Bonfiglio, M. Kong

and the JOREK team

北京航空航天大學

BEIHANG UNIVERSIYT

Contents

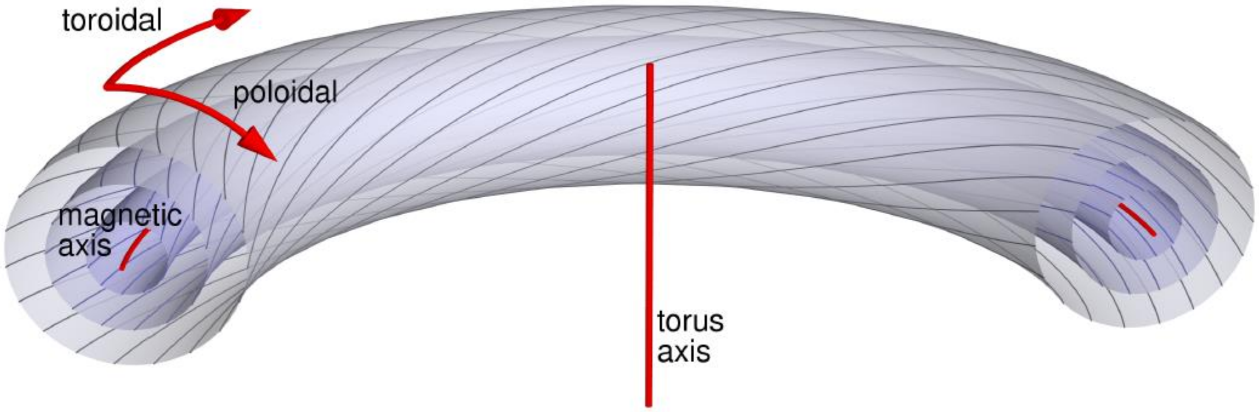
- Introduction： tokamak, disruptions & their mitigation
- Importance of the integrated modelling
- Components of the integrated modelling
- Case studies of disruption mitigation simulations
  - TQ mitigation & associate seed RE transport modelling in ITER
  - VDE & sideway forces during the CQ
  - RE current mitigation by passive coils
- Conclusion & discussion

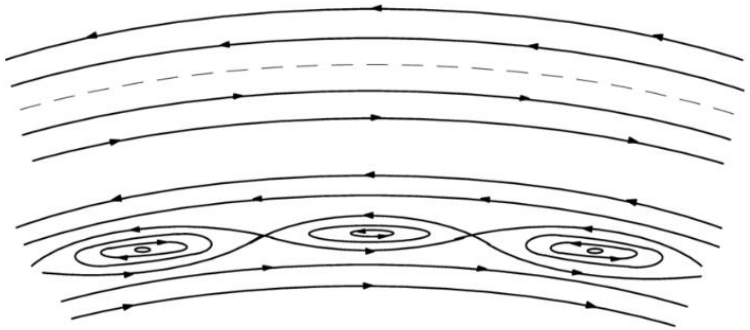
The tokamak confinement…

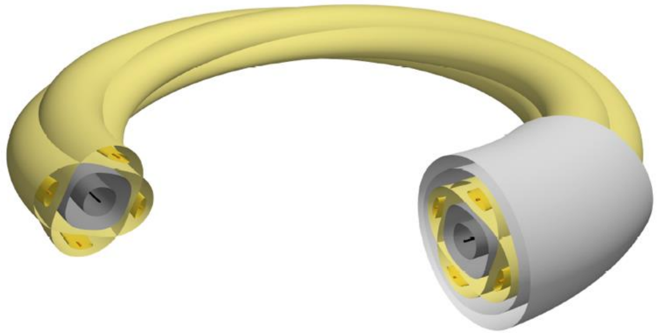
- Tokamak is currently the most successful magnetically confined plasma configuration, due to its good toroidal **symmetry**.

- Such symmetry could be broken by inherent or externally driven helical perturbation.

- With large aspect-ratio & single helicity, the nested flux surfaces “tear” into helical magnetic islands.



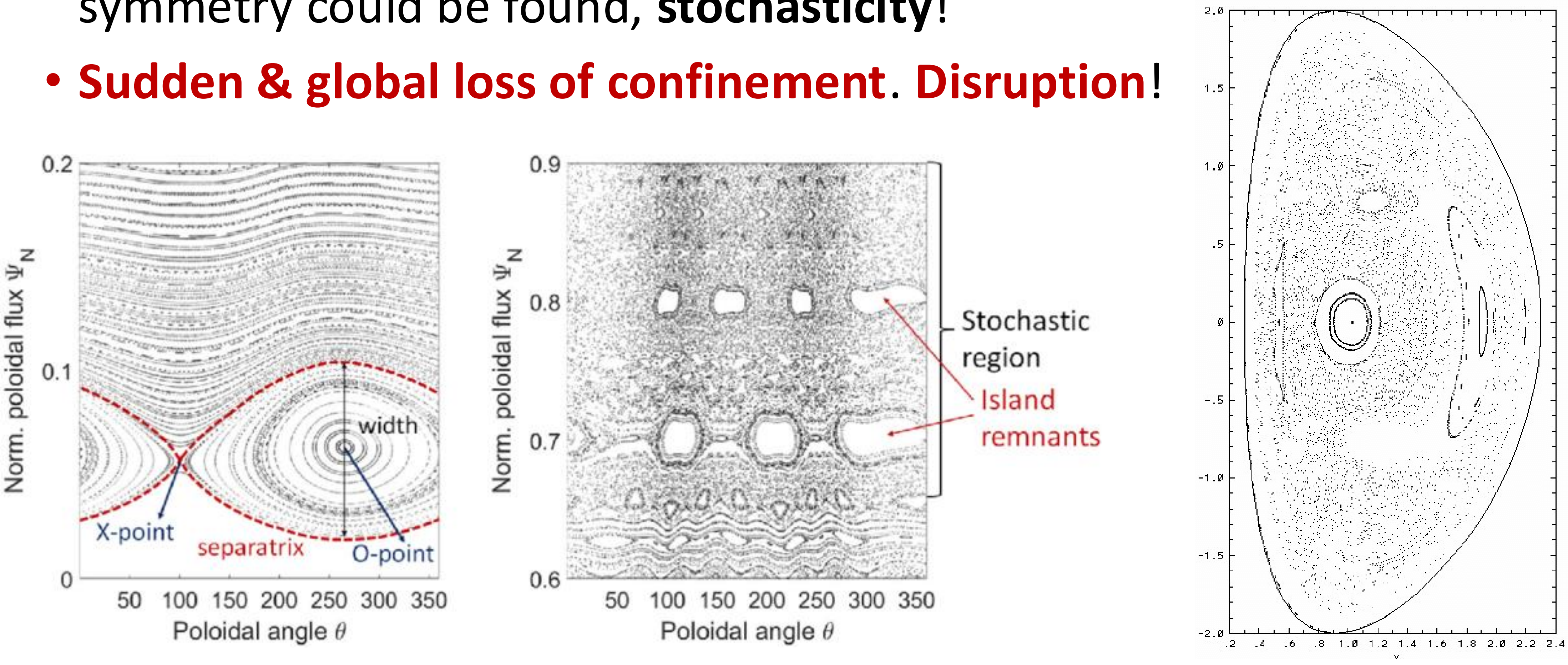




Matthias Hölzl, 2010, “Diffusive Heat Transport across Magnetic Islands and Stochastic Layers in Tokamaks”, Technische Universität München

… and its loss

- In the presence of magnetic perturbation with **multiply helicities**, no symmetry could be found, **stochasticity**!
- **Sudden & global loss of confinement**. **Disruption**!

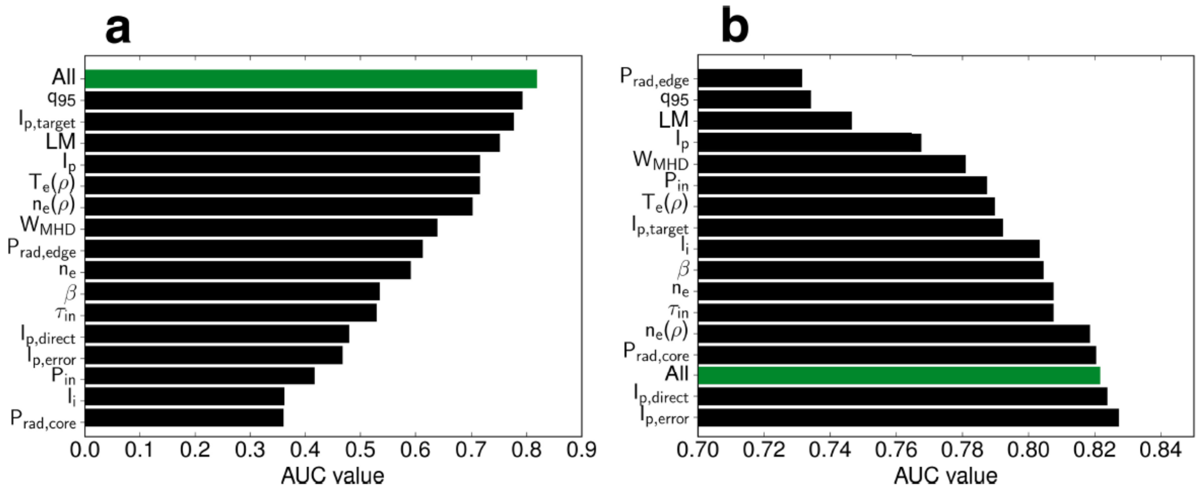


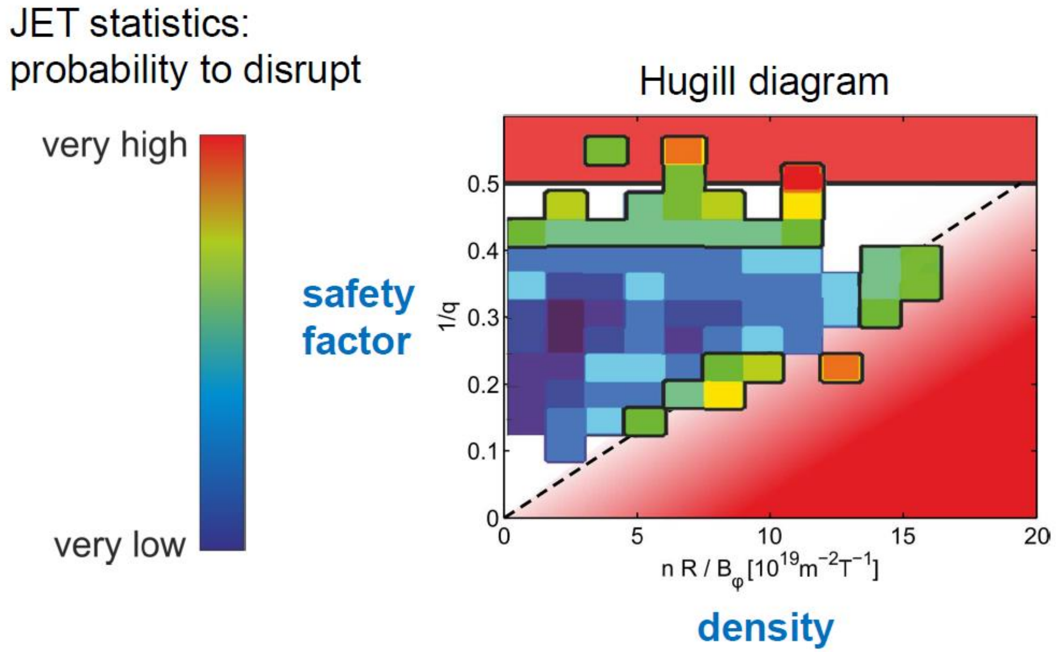
E.G. Kostadinova et al., J. Plasma Phys. (2023), vol. 89, 905890420; W. Park et al 2003 Nucl. Fusion 43 483

The disruption limits

- Empirically there are three **statistical** limits to disruptions
  - $q_{95} \geq 2$, associated with external kink instabilities
  - $\beta_N = \frac{\langle\beta\rangle}{I(MA)/a(m)B(T)} \leq 3.5\%$, associated with pressure driven ballooning and kink
  - $n < n_{GW} \equiv I(MA)/\pi a^2(m^2)$, associated with edge cooling and ensuing tearing

- Modern disruption prediction uses neural networks to explore stability boundaries in multi-dimensional space

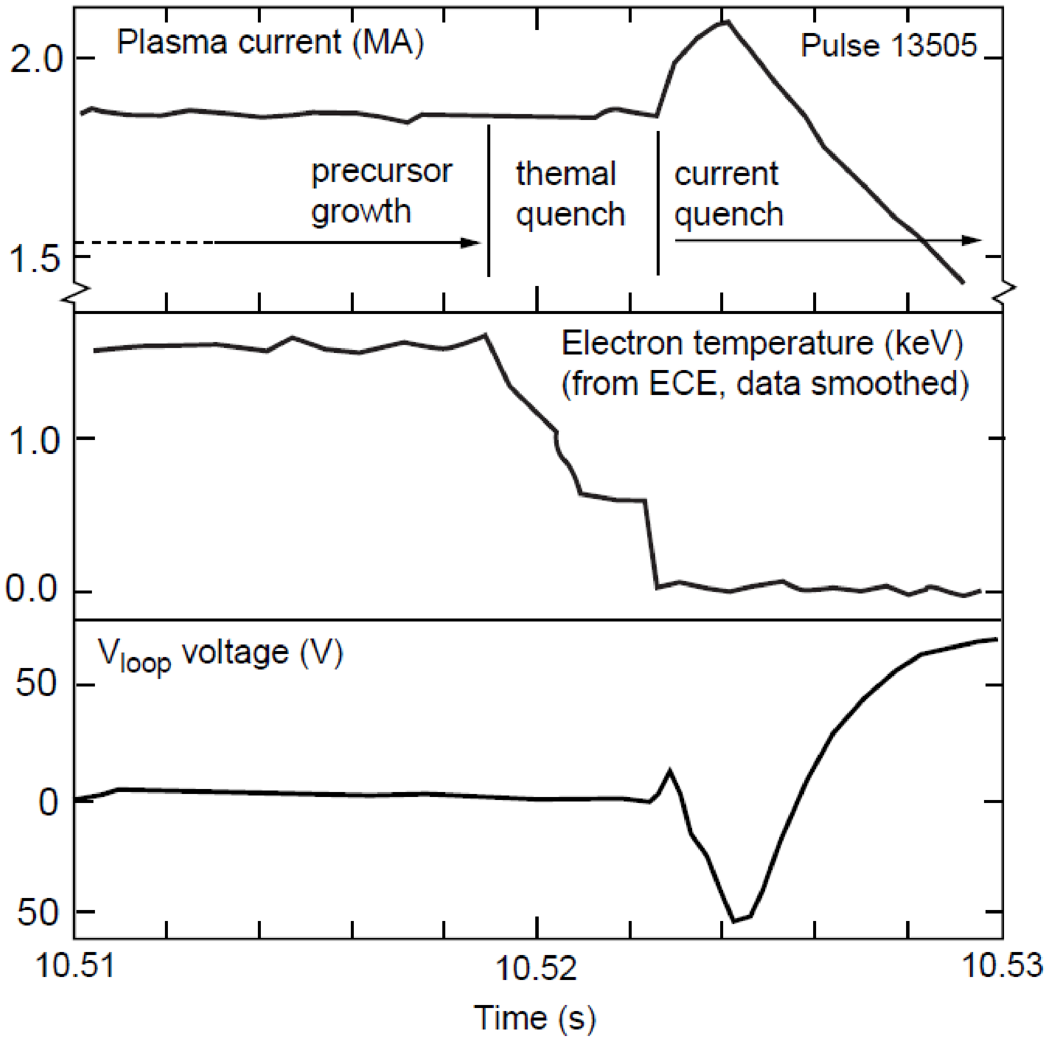




J. Kates-Harbeck et al., Nature (2019); P. de Vries, Nuclear Fusion 2009

Disruption in tokamaks

- The disruption occurs in several phases.
- **The precursor phase** *usually* see increased precursor mode activity and gradual confinement degradation.
- The **Thermal Quench (TQ)** sees the rapid loss of thermal energy.
- The **Current Quench (CQ)** is a result of the TQ as the cold plasma becomes resistive, hard to maintain the current, thus the magnetic energy.



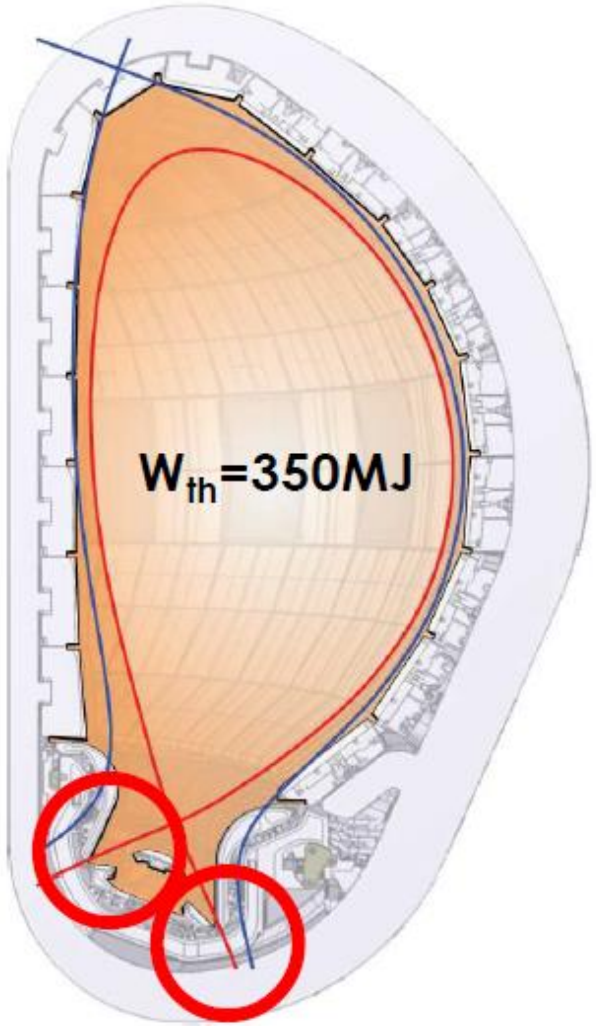
J.A. Wesson et al., Nucl. Fusion 29 (1989) 641

Consequences, thermal load

- The temperature increase of a semi-infinite 1D uniform material exposed to **constant heat flux** q_s for Δt time is:

$$\Delta T(\Delta t) = \frac{2}{\sqrt{\pi}b}\Delta Q(\Delta t) = \frac{2}{\sqrt{\pi}b} q_s\sqrt{\Delta t}, \qquad b = \sqrt{\kappa\rho c}$$

- The temperature rise is proportional to the energy impact ΔQ apart from the material dependent parameters.
- ΔQ itself is independent of materials, the wall damage threshold depends on the material.



Courtesy of E. Nardon

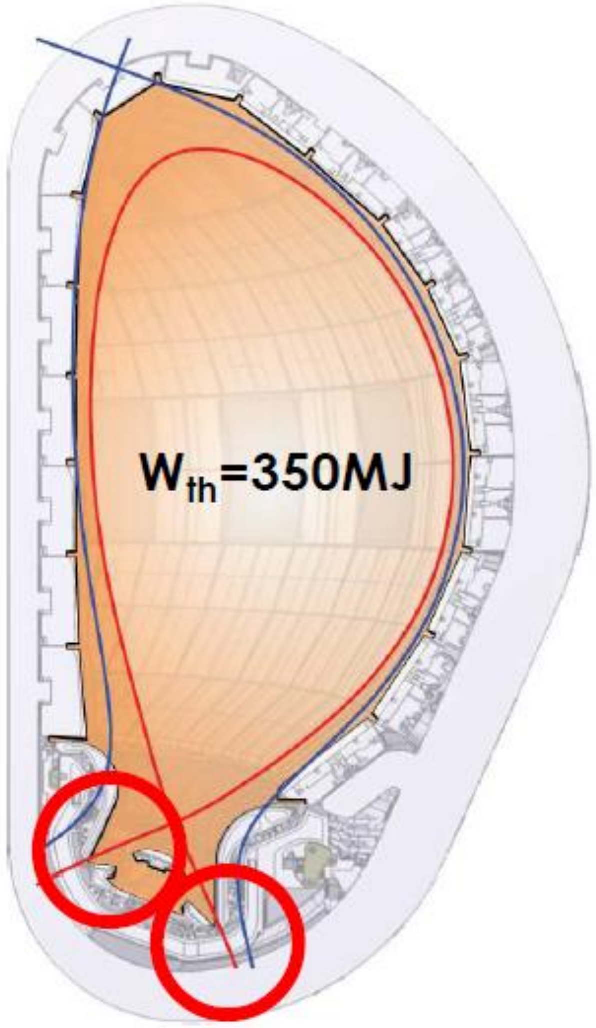
Consequences, thermal load

- What if the heat flux q_s is not a constant?
- The heat transfer is analogous to a 1D random walk.
- Consider $q_s(t)$ as a series of heat packets continuously arriving at the boundary of the 1D semi-infinite material, which then commit random walks with step length determined by the heat conductivity.
- The fundamental solution for such random walk is

$$\Phi(x,\Delta t) = \frac{1}{\sqrt{\pi\alpha\Delta t}} e^{-\frac{x^2}{4\alpha\Delta t}}$$

- The summation of all heat packet distribution at $x = 0$ is proportional to

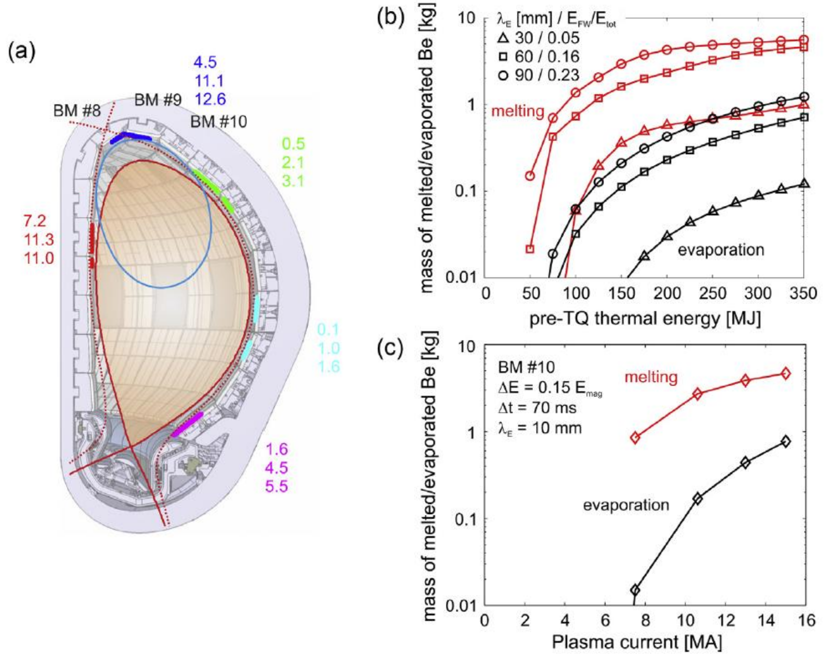
$$\Delta Q(t) = \frac{1}{2}\int_{t_0}^{t} \frac{q_s(t')}{\sqrt{t-t'}} dt'$$

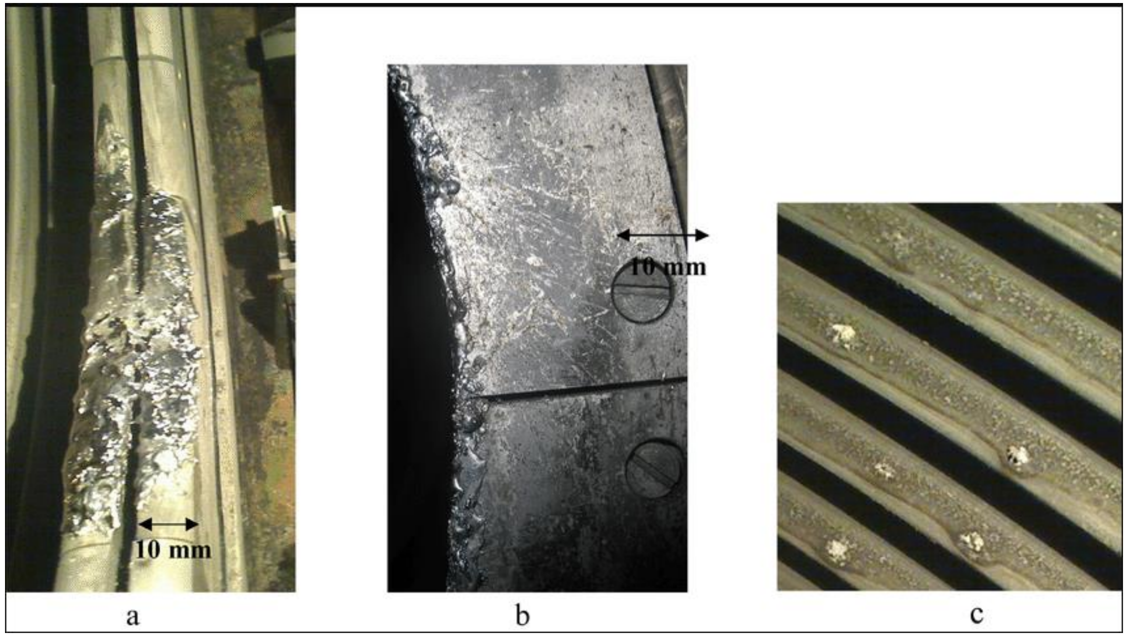


Courtesy of E. Nardon

Consequences, thermal load

- Disruption could be characterized by the sudden and global confinement loss of the plasmas.
- Such confinement loss could result in **rapid and localized** energy deposition on the device, resulting in irrevocable damage.

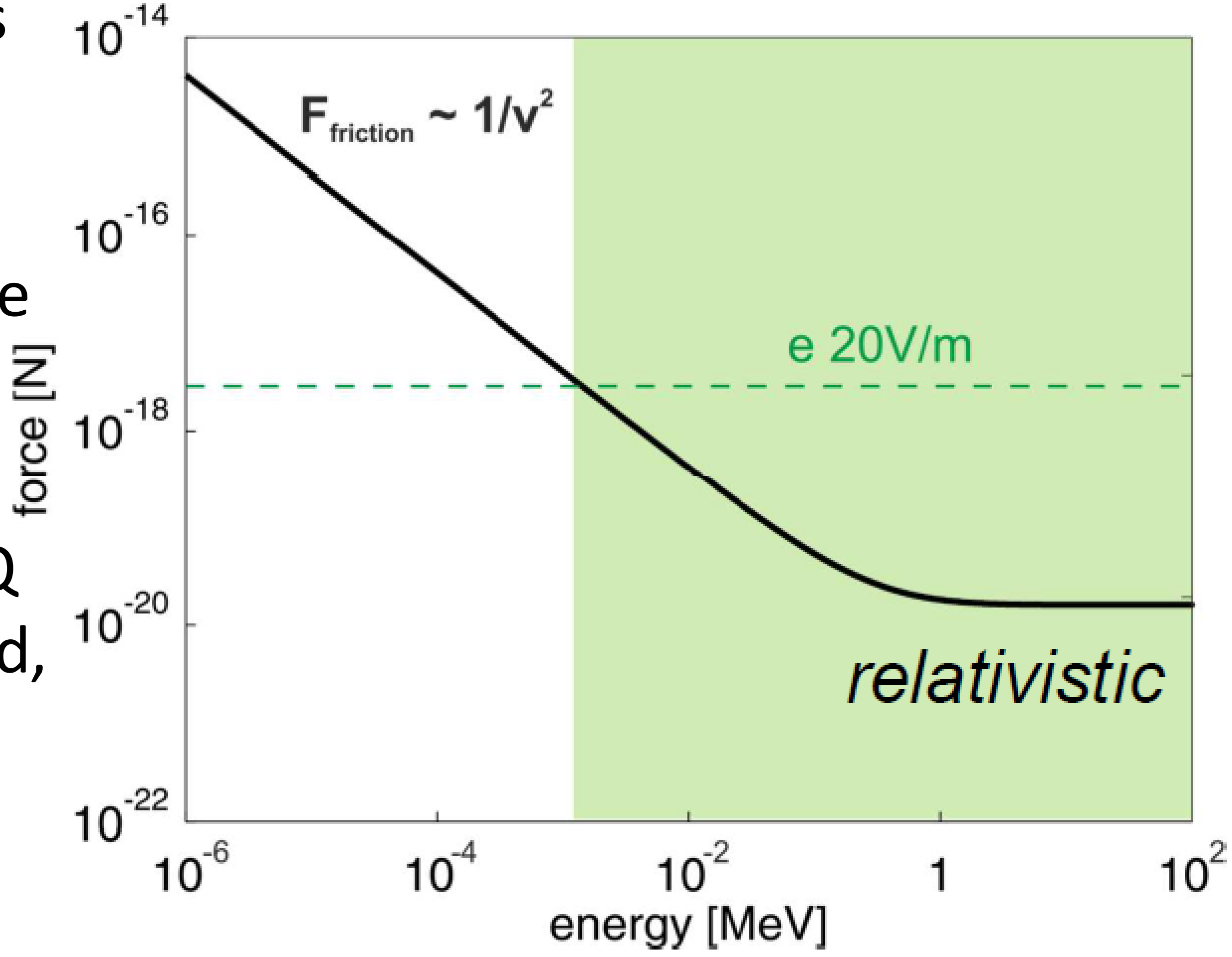




M. Lehnen et al., Journal of Nuclear Materials 463 (2015) 39–48; V.P. Budaev et al., Nuclear Materials and Energy 12 (2017) 418–422

Consequences, runaway electrons

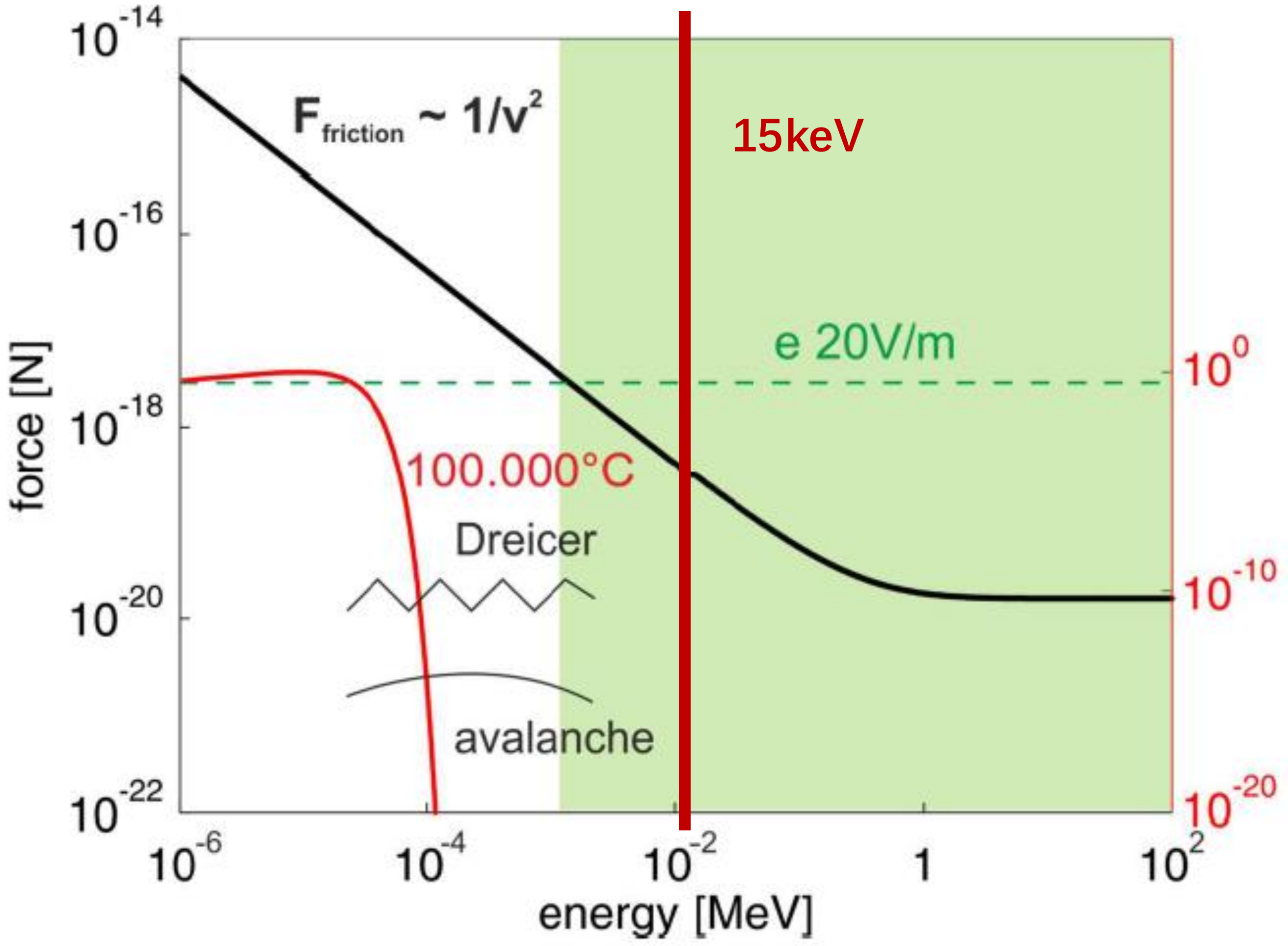
- The collision drag force depends on the electron velocity.
- With higher energy & velocity, the drag force decreases, but the electric acceleration does not.
- “Runaway” could occur in the momentum space during the CQ due to the inductive electric field, until other physics set in.
- Runaway electron (RE) is one of the direst issue of disruption.



Courtesy of E. Nardon

Consequences, runaway electrons

- Several ways to create new REs:
  - Dreicer
  - Avalanche
  - Hot-tail
  - Tritium decay
  - Compton scattering
- The avalanche could be most dangerous due to its **exponential feature**......



Courtesy of E. Nardon

RE plateau during CQ

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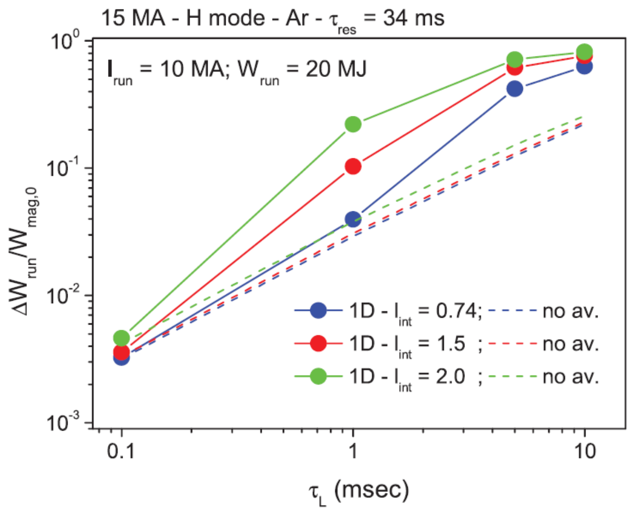
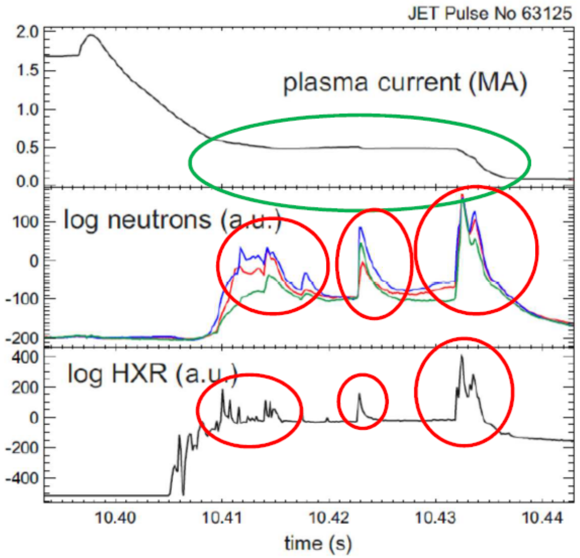
- The REs could become the **dominant current carrier** via avalanche, forming the RE plateau.
- Such plateau could not be maintained indefinitely.
- Significant **energy conversion** could occur as the RE current loss control and hit the wall eventually.





runaway plateau

fast loss events
driven by instabilities

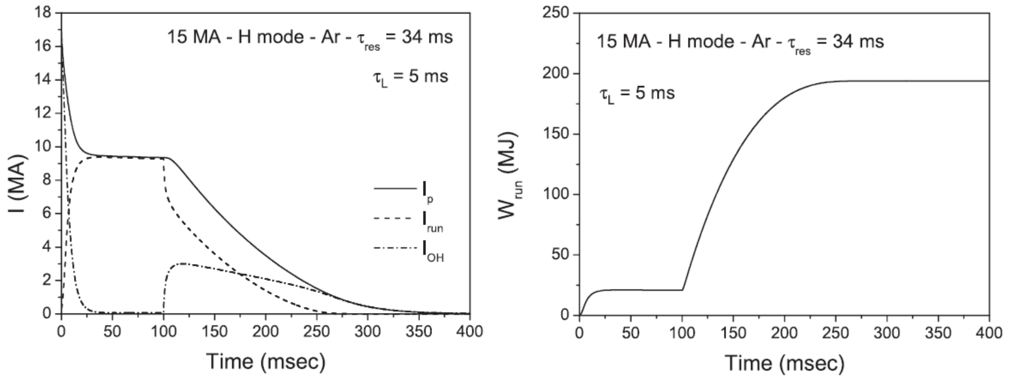
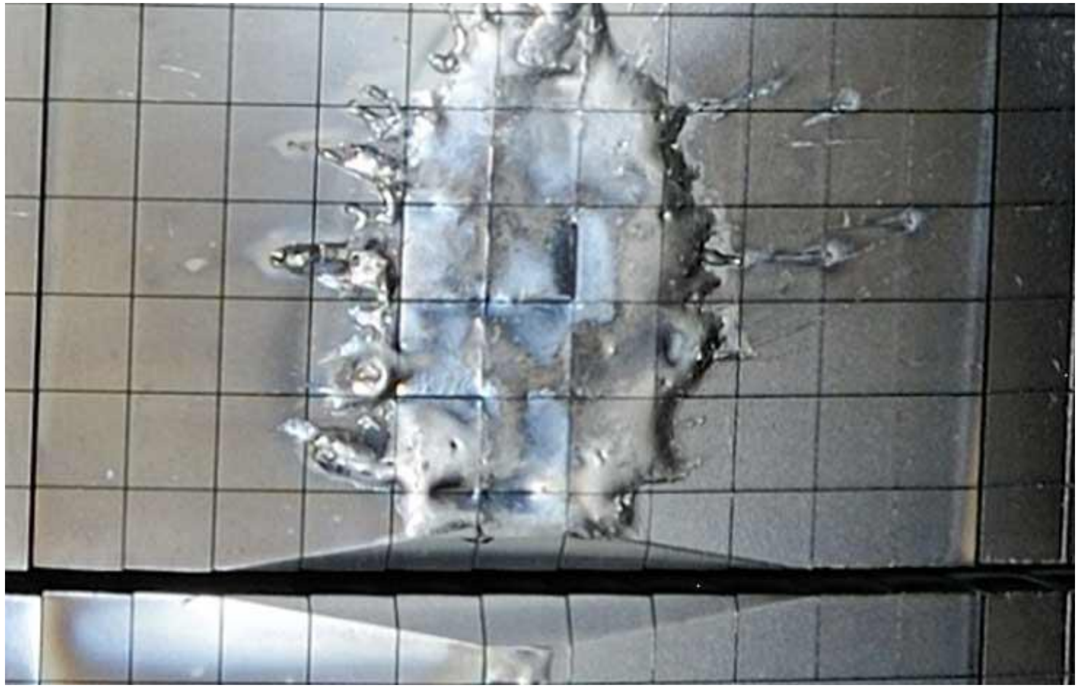


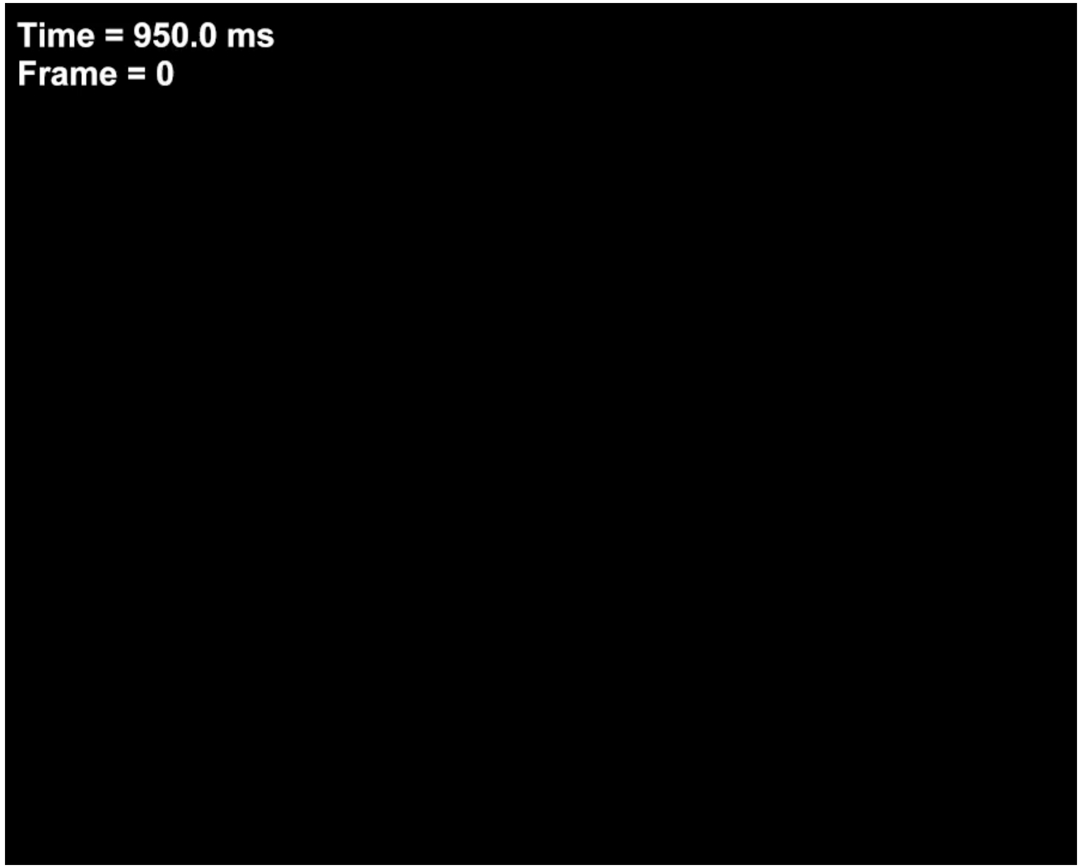
Figure 29. For a 15 MA H-mode disruption with Ar injection and $\tau_{res} = 34$ ms: left: time evolution of the total plasma current, runaway current and ohmic current during the current quench and termination phases of the disruption. The termination phase starts at 100 ms and $\tau_L = 5$ ms. Right: time evolution of runaway kinetic energy gain.

J.R. Martín-Solís et al 2017 Nucl. Fusion 57 066025

Consequences, runaway electrons

- Upon losing control, the RE current impacts the first wall in asymmetrically. Other geometric effects deteriorate the asymmetry.
- Could result in localized energy deposition, even breaching of VV.

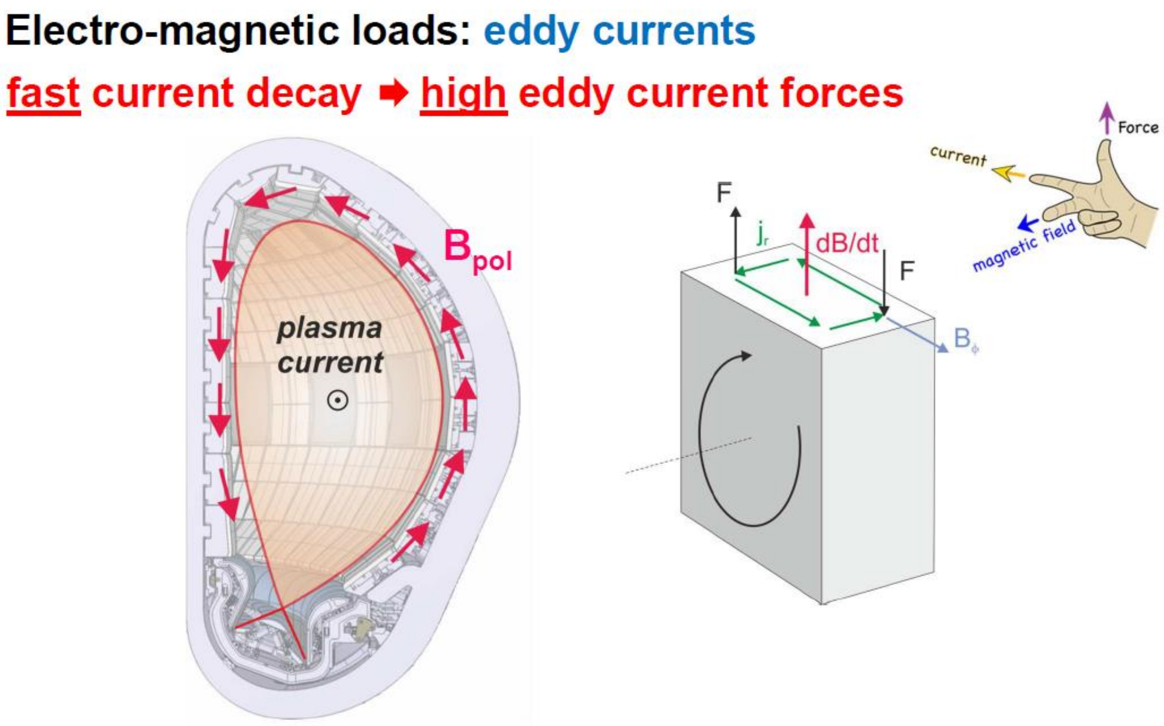


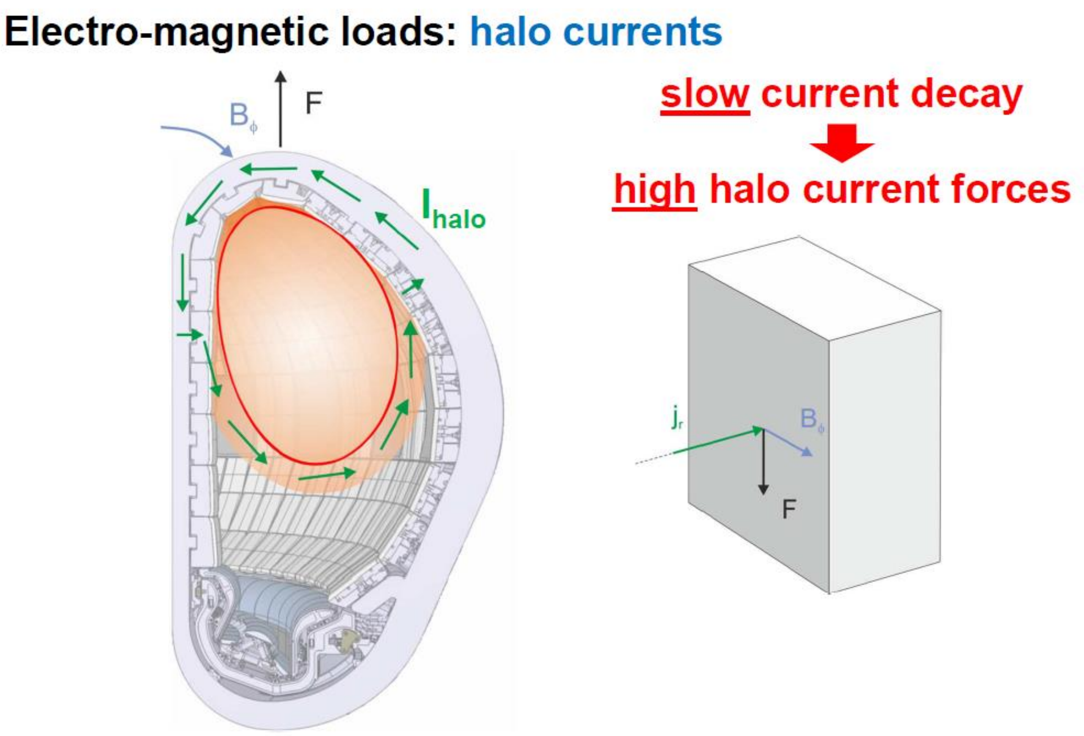


G. F. Matthews et al., Phys. Scr. T 167, 014070, 2016; J. Caloud et al., REM2024, 2024/05/27

Consequences, EM load

- Eddy current and plasma-wall sharing current could be induced in the conducting vessel during the CQ, bringing 2D & 3D $\boldsymbol{J} \times \boldsymbol{B}$ force with it.

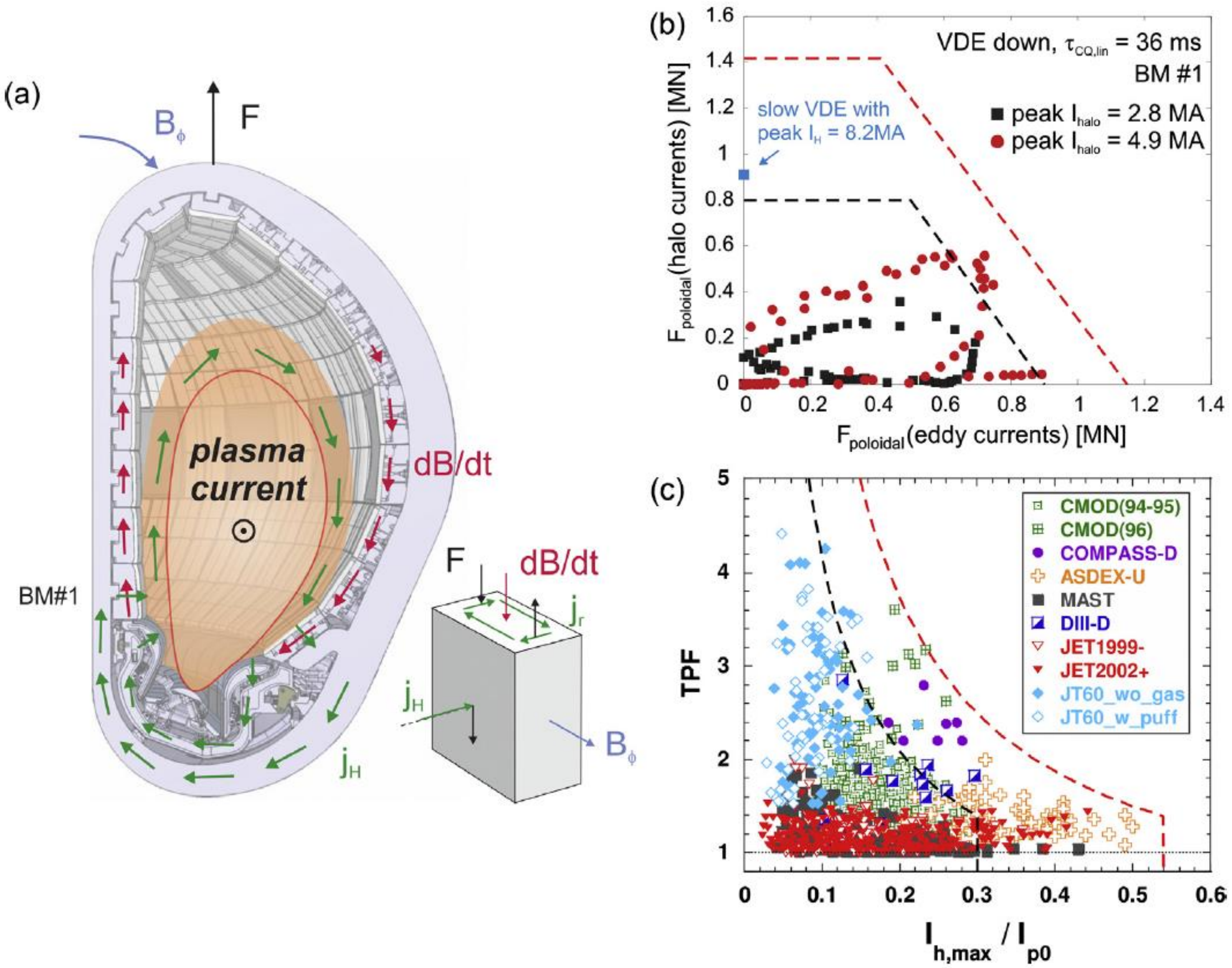




Courtesy of E. Nardon

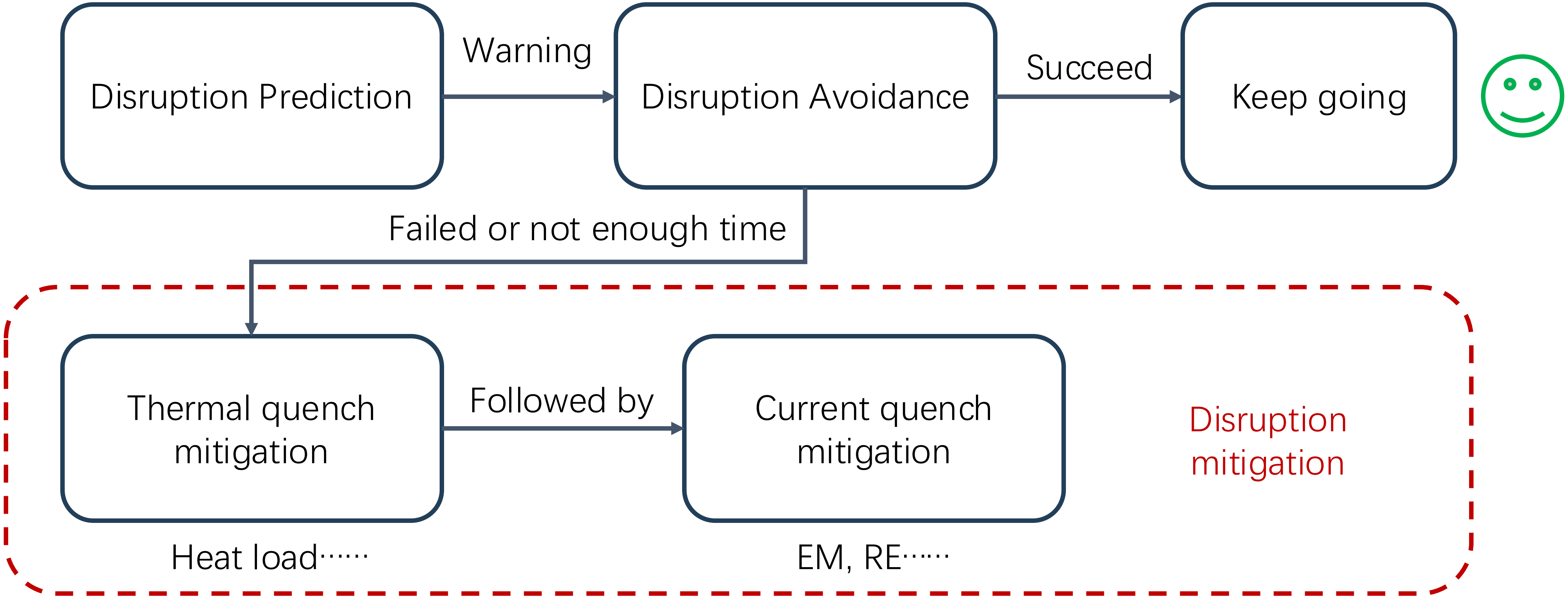
Consequences, EM load

- Vertical displacement of the plasma and the current sharing between the plasma and the device could result in significant asymmetric **electro-magnetic (EM) load……**
- The above various disruption consequences make their mitigation a **multi-dimensional** problem with a lot of constraint……



M. Lehnen et al., Journal of Nuclear Materials 463 (2015) 39–48

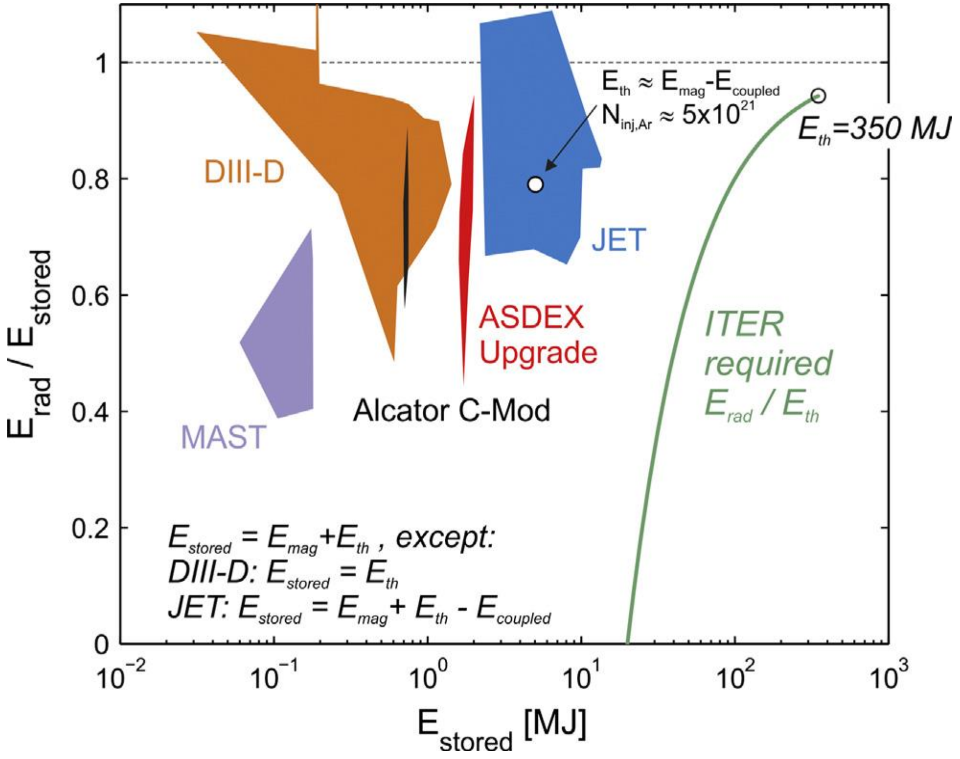
How to deal with it?



Running a high-performance discharge without disruption mitigation is like **driving without airbags**!

Disruption mitigation

- Disruption mitigation systems (DMSs) have been devised to avoid localized energy deposition, including Massive Material Injection (MMI), passive coils etc.. **The more uniform the energy deposition, the better**!



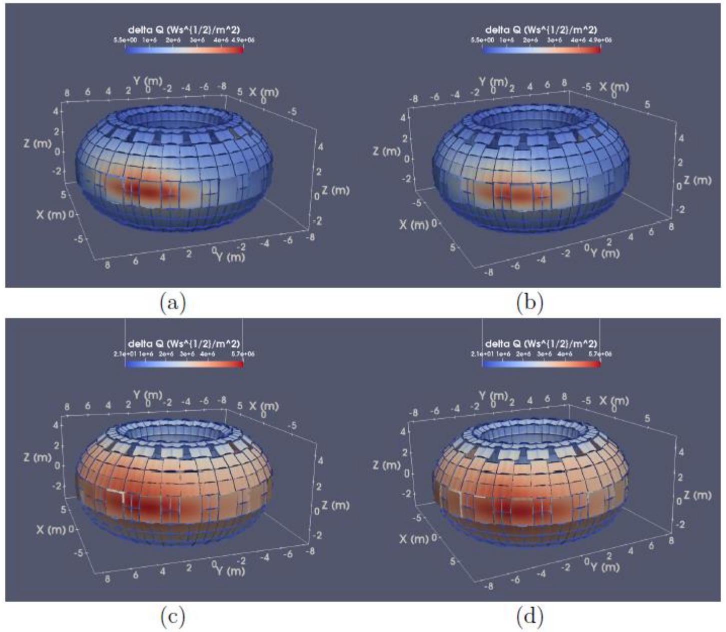
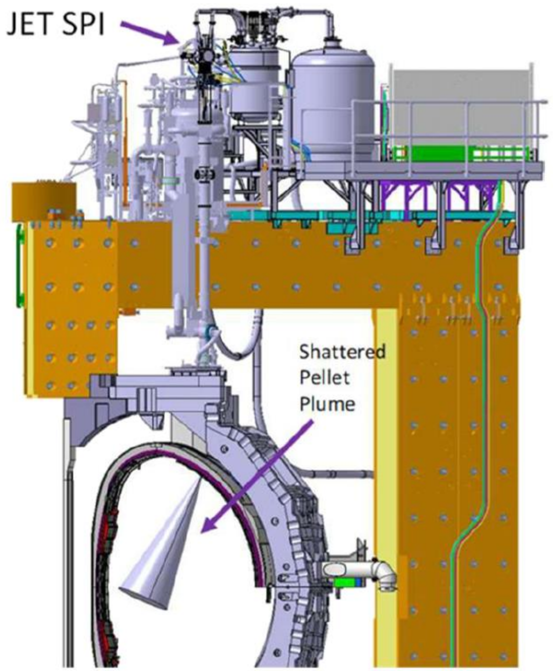


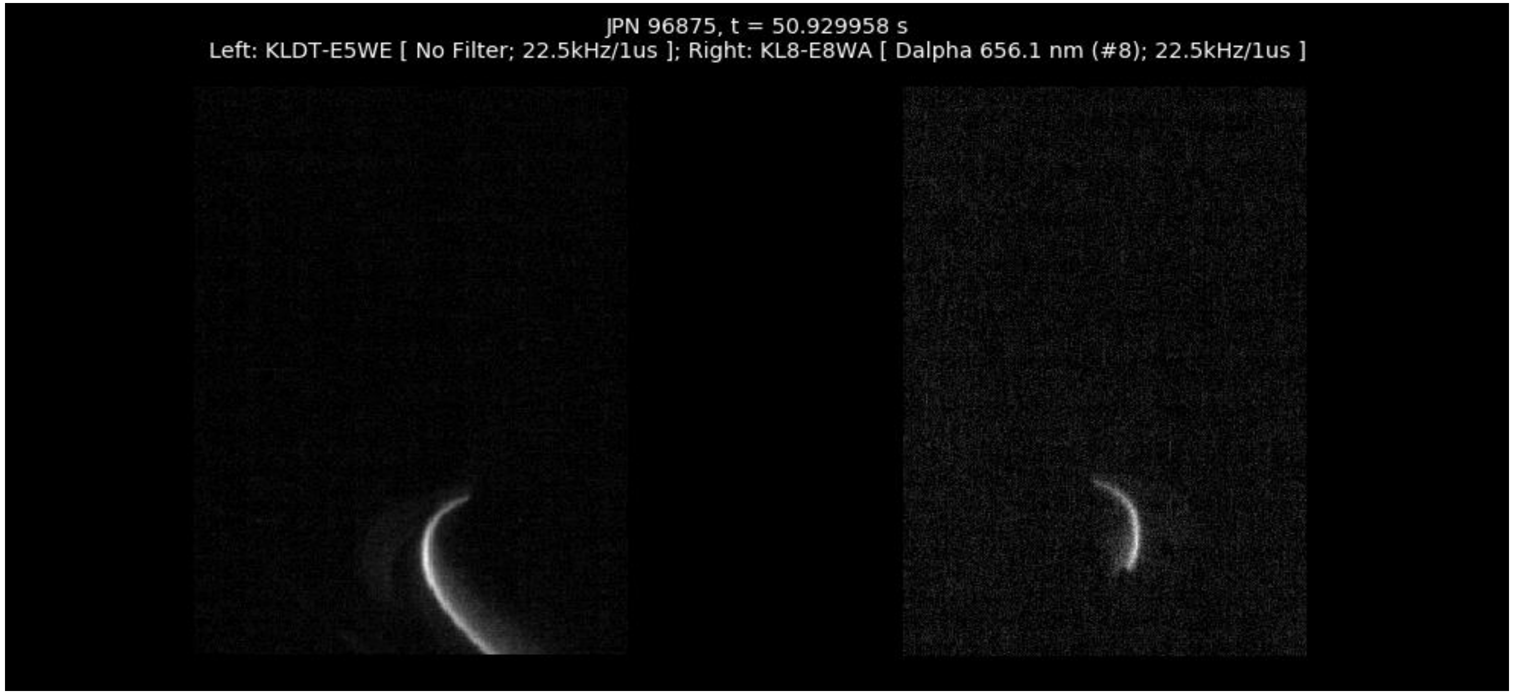
Figure 14. The first wall energy impact of DH-QP-dt0 calculated using Eq. 4 at (a) $t = 2.06ms$ looking at port EQ-08, (b) $t = 2.06ms$ looking at port EQ-17, (c) $t = 5.64ms$ looking at port EQ-08 and (d) $t = 5.64ms$ looking at port EQ-17.

Lehnen M. et al 2015 J. Nucl. Mater. 39-48 463; D. Hu et al., Nucl. Fusion 64 (2024) 086005

Disruption mitigation

- Among the MMIs, the Shattered Pellet Injection (SPI) enjoys **better penetration**, beneficial for core material delivery, thus **enhanced heat flux symmetry** as well as **helping with RE control** during the CQ.
- Other MMI in active study, Massive Gas Injection, Shell Pellet etc..

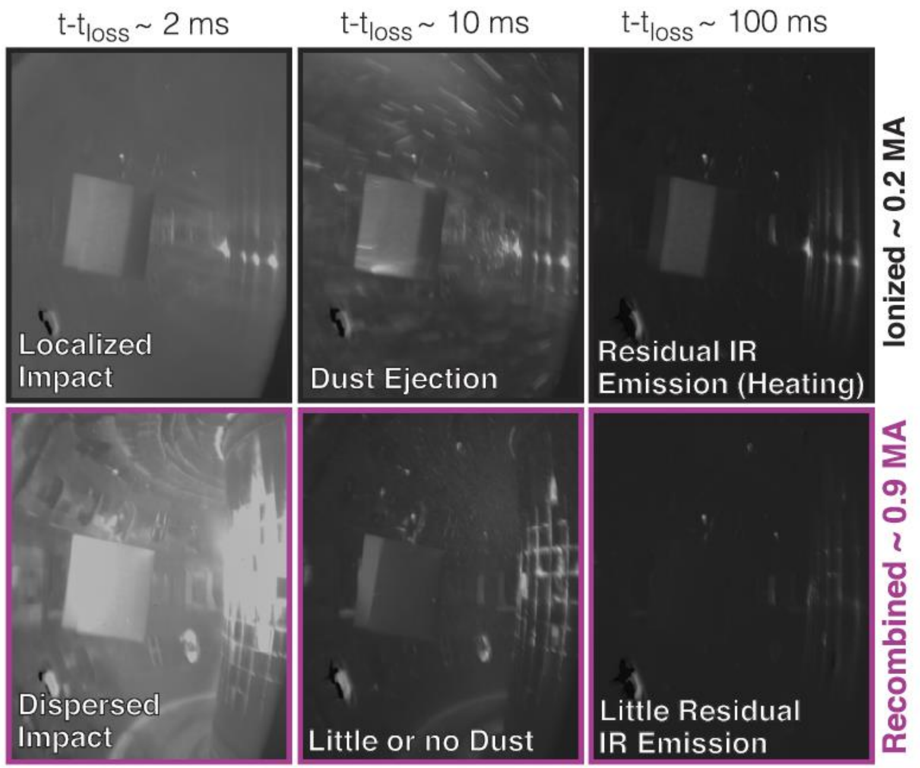


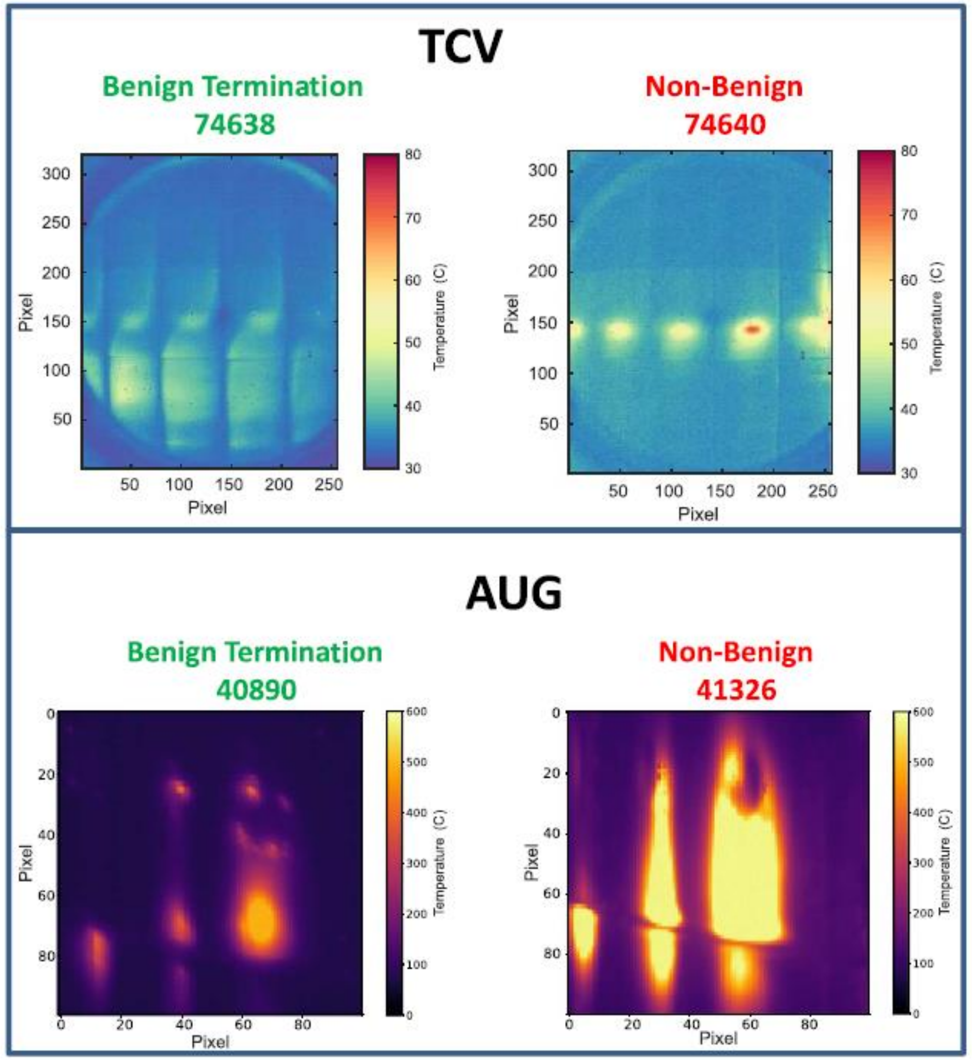


L.R. Baylor et al 2021 Nucl. Fusion **61** 106001; U.A. Sheikh *et al* 2021 Nucl. Fusion 61 126043;

Disruption mitigation

- Multiply layers of defense: safely terminate the RE current even if the SPI failed to prevent its formation

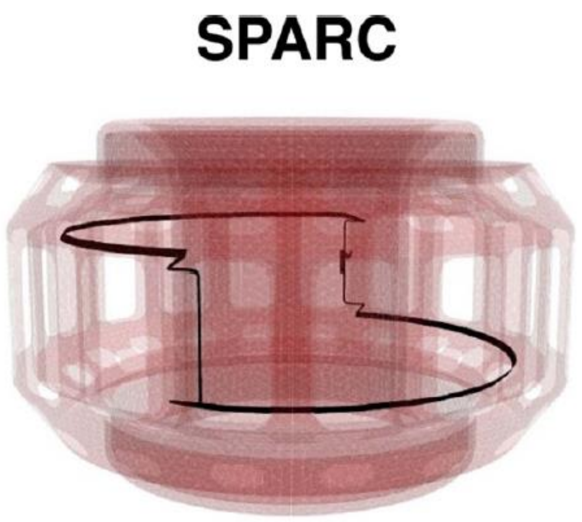


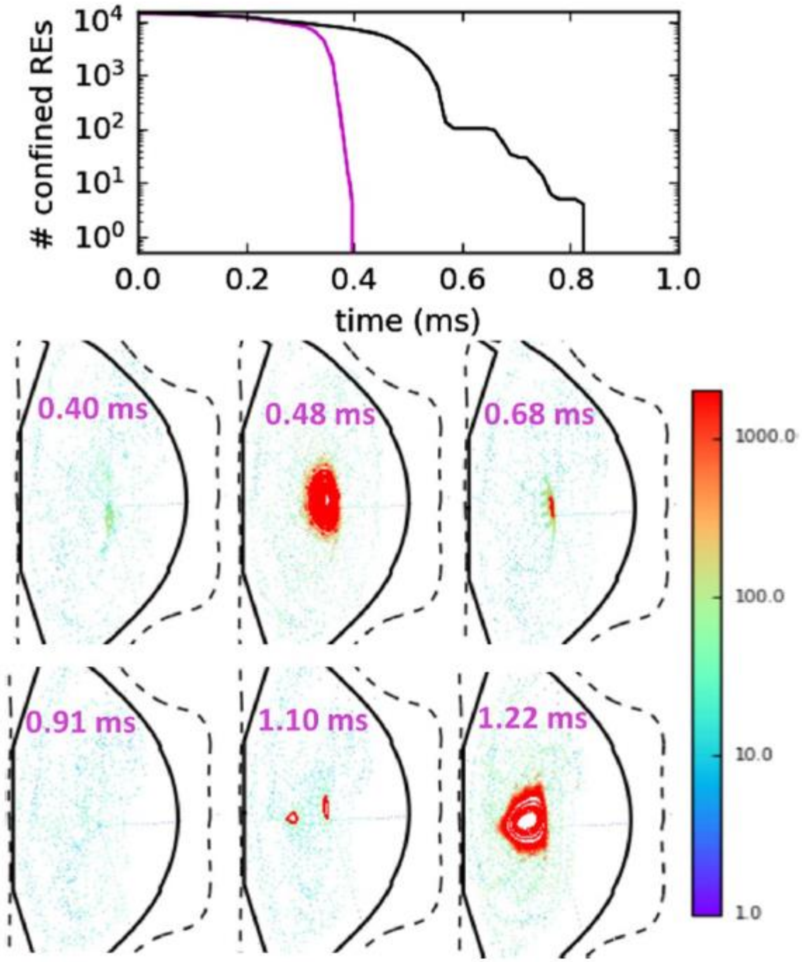


C. Paz-Soldan et al 2021 Nucl. Fusion 61 116058; U Sheikh et al 2024 Plasma Phys. Control. Fusion 66 035003;

Disruption mitigation

- The passive coil is also one of promising RE mitigation scheme being designed, helping to break flux surfaces during the CQ and prevent RE avalanche.





V.A. Izzo et al., Nucl. Fusion 64 (2024) 066003

Contents

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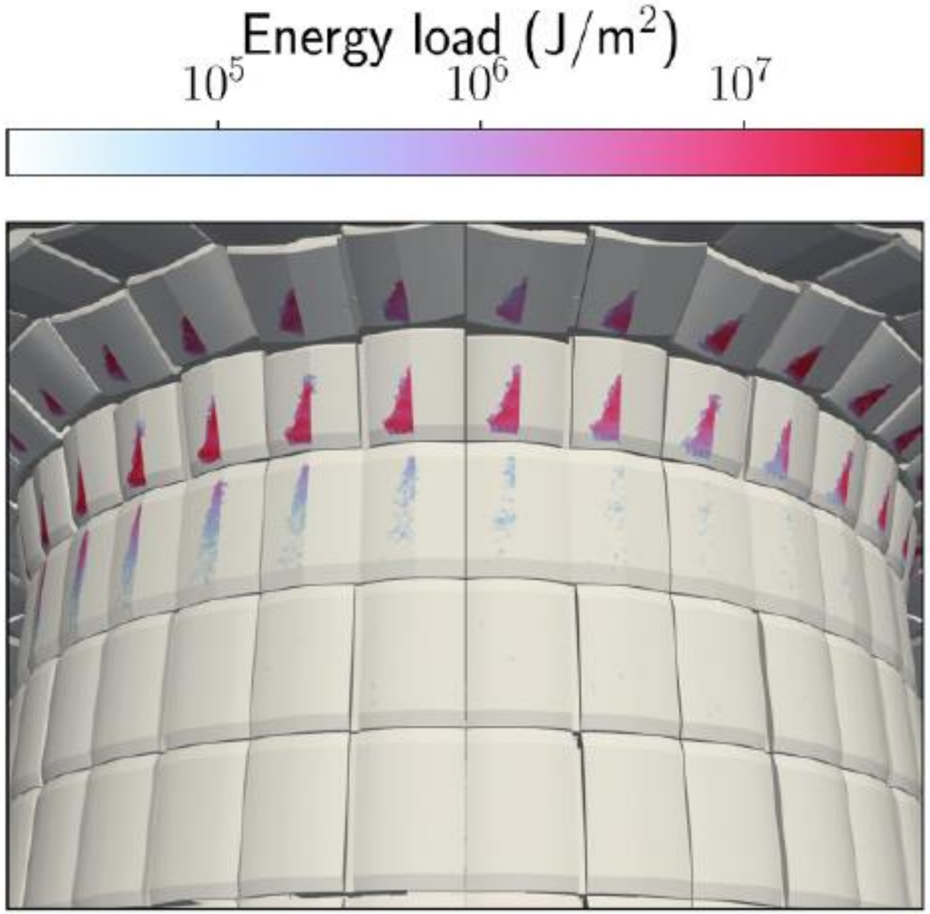
Importance of integrated modelling

- Modeling of disruption and its mitigation is of great importance for future high-performance devices.
- Integrated modelling **provides crucial extrapolation** for safe operations regarding the level of disruption loads and the DMS efficiency.
- Also **helps to analyze disruptions in existing machines** where direct diagnostics are hard due to temporal or spatial resolution limit.

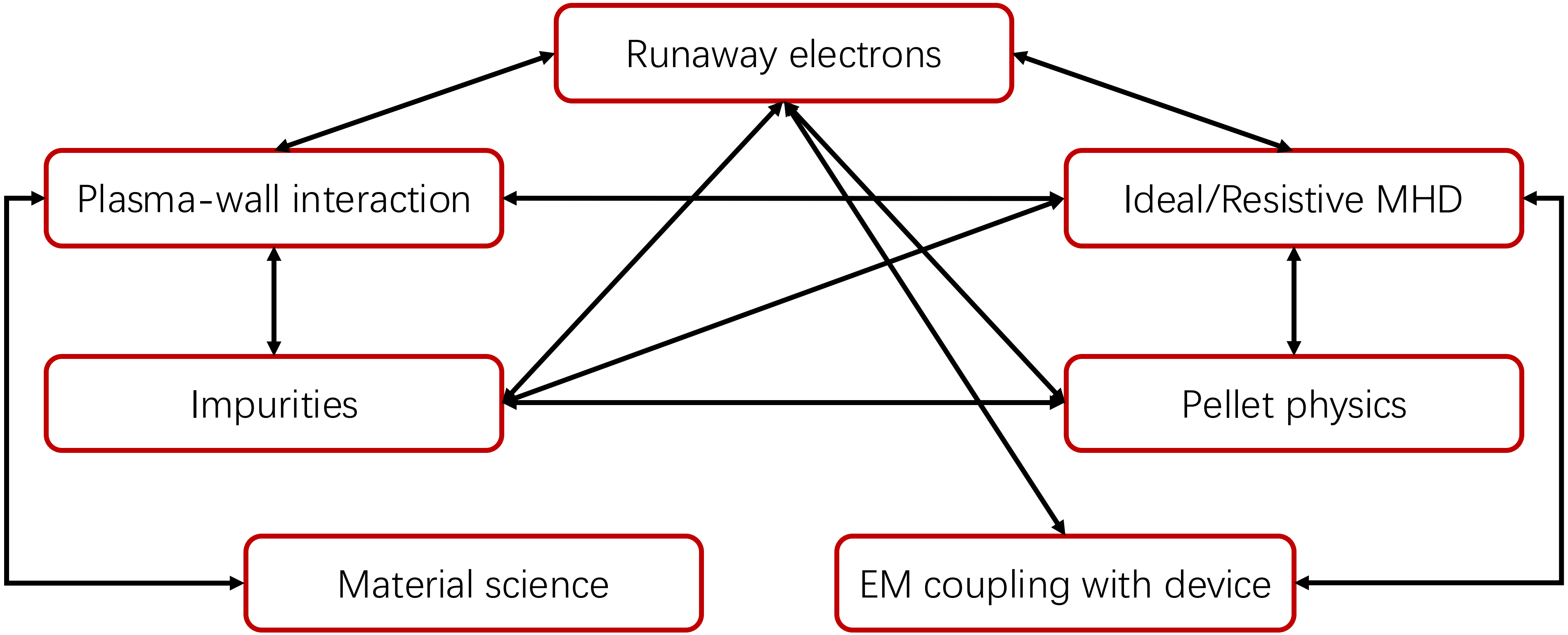
RE load for ITER



V. Bandaru et al, Nucl. Fusion 64 (2024) 076053

Importance of integrated modelling

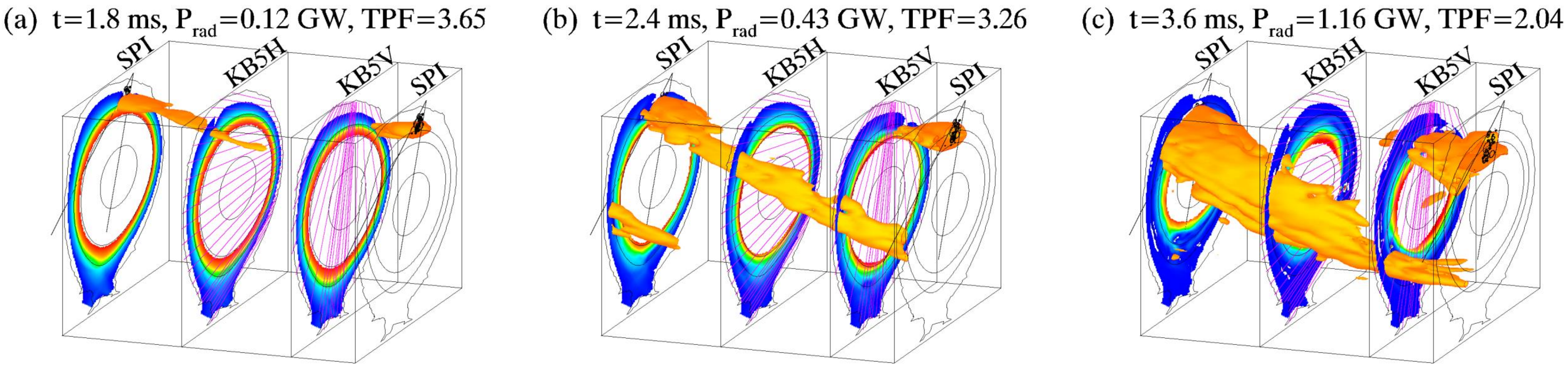
- Difficulties in disruption modelling arise from its multi-physics nature.



- Strongly coupled and inseparable. **Integrated modeling needed!**

Modelling validation

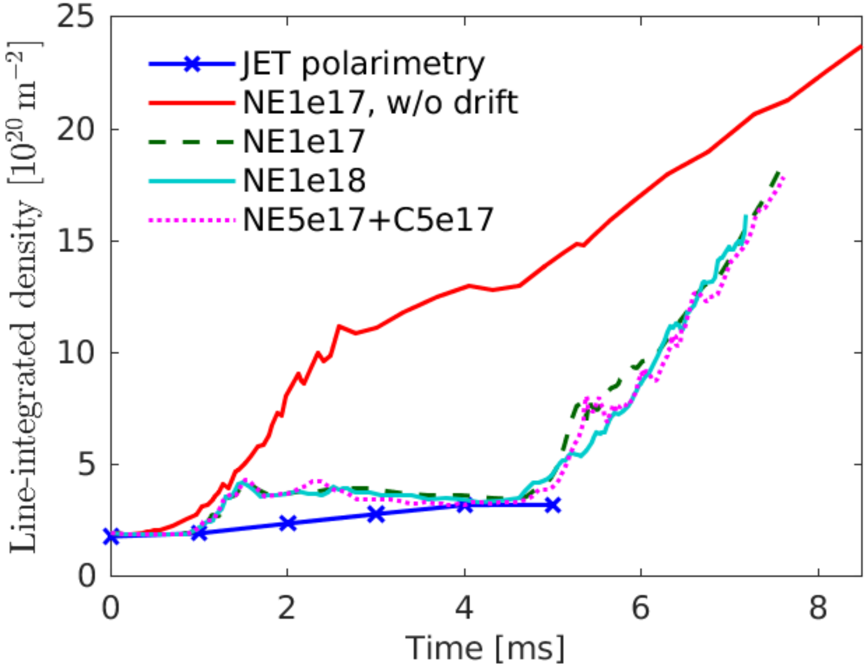
- The validation of the integrated modelling is of utmost importance, since we rely on their extrapolation power. For this, synthetic diagnostics are developed to facilitate comparison with experiments.

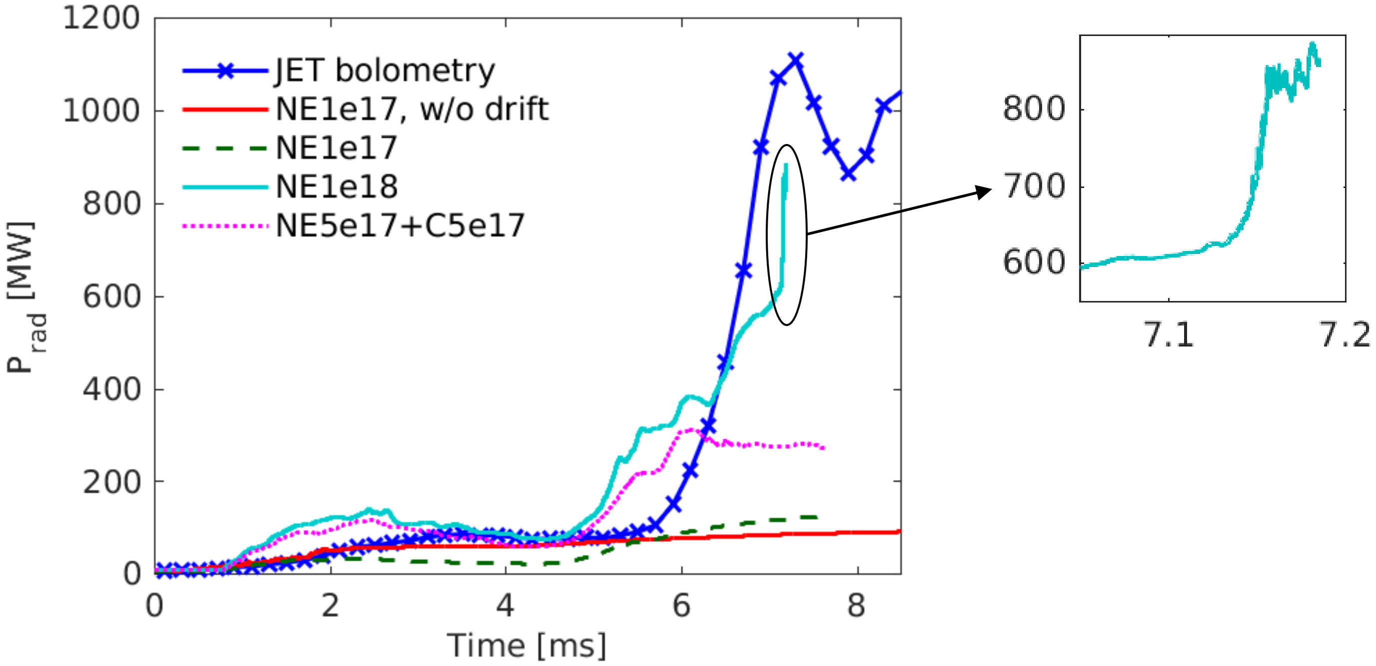


D. Bonfiglio et al, to be submitted

Modelling validation

- Comparison to experimental diagnostics help to identify the key physics that should be kept in the integrated modelling





- Density overestimated without considering drifts (red curve in the left plot)
- Background Ne concentration plays a key role in triggering TQ onset and radiation peak

M. Kong et al. NF 64 (2024) 066004

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Multi-physics and multi-scale coupling

- The coupling is multi-scale, will try to introduce most important ones

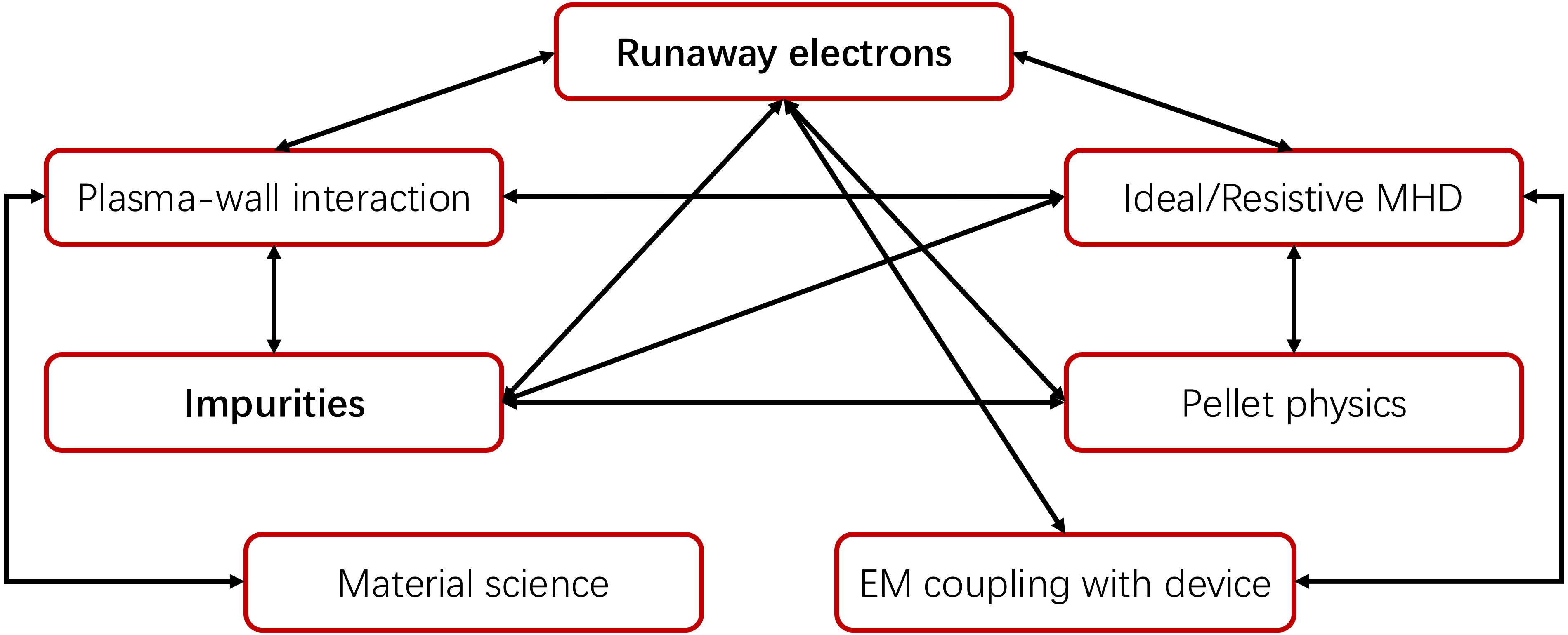
Fast

$\sim 10^{-8} s$	Runaway electrons
$\sim 10^{-6} s$	Ideal MHD
$\sim 10^{-5} s$ - $\sim 10^{-4} s$	Atomic physics; Pellet physics, Plasma-wall interaction
$\sim 10^{-3} s$	Resistive MHD
$\sim 10^{-1} s$	VDE, external current responses, EM load
$\sim 10^{6} s$	Material damage by prolonged radiation

Slow

Components of disruption modelling

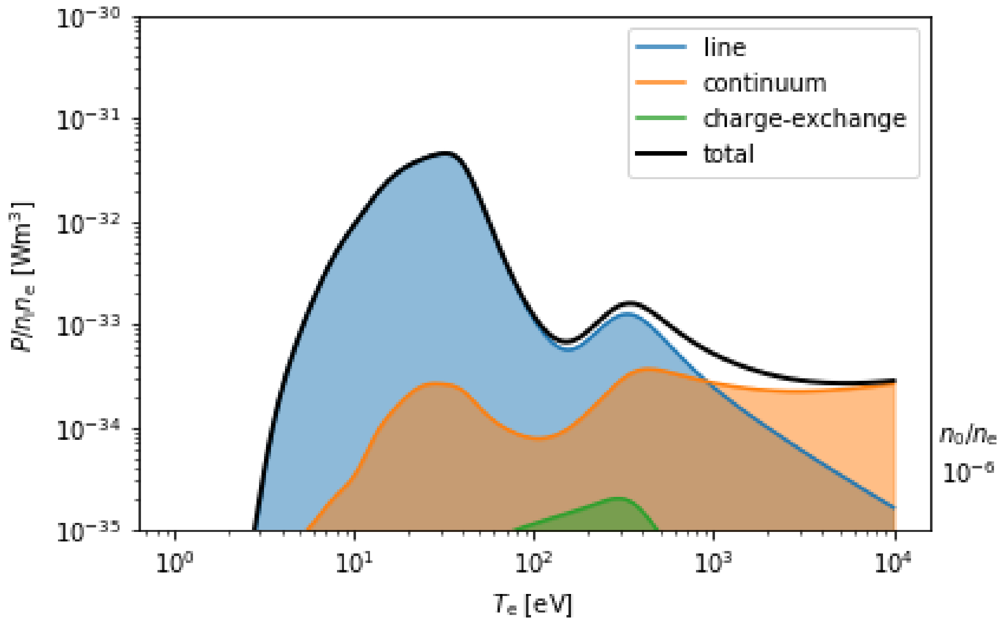
- Will try to introduce most important ones, beginning with impurity related ones.

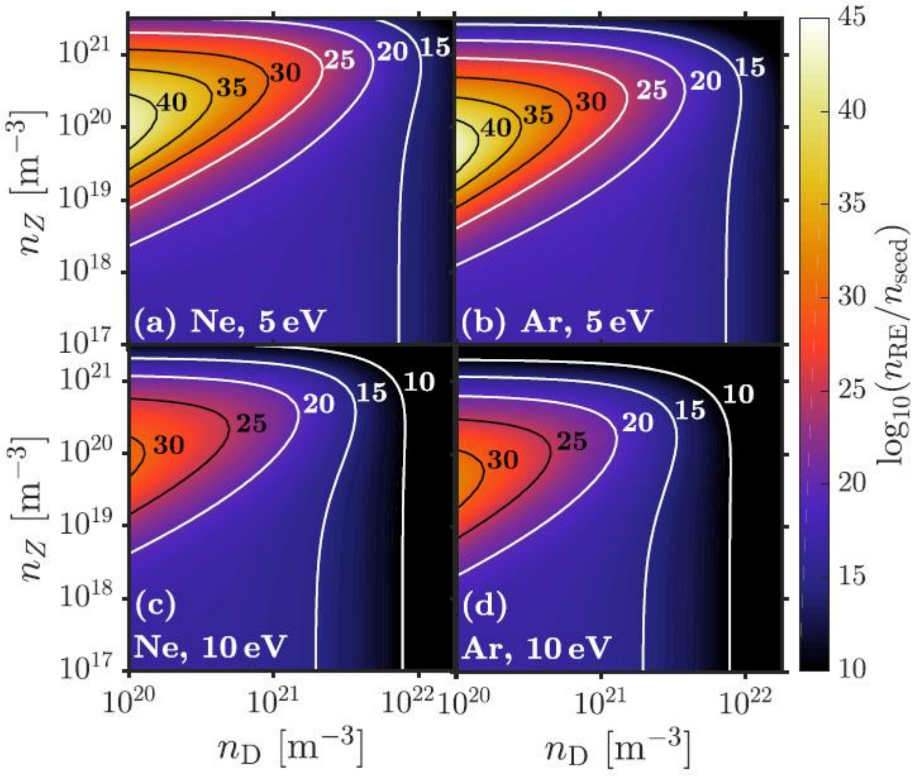


Impurity coupling to MHD & RE

- The impurity couples to the rest of the physics mainly via ionization/radiation and changing the collision.

$$P_{rad} = n_e n_{imp} L_{rad}(n_e, T_e) = n_e \sum_{i=0}^{Z} n_{imp}^{i+} (L_L^{i+}(n_e, T_e) + L_R^{i+} \times (n_e, T_e) + L_B^{i+}(n_e, T_e)). \quad (6)$$

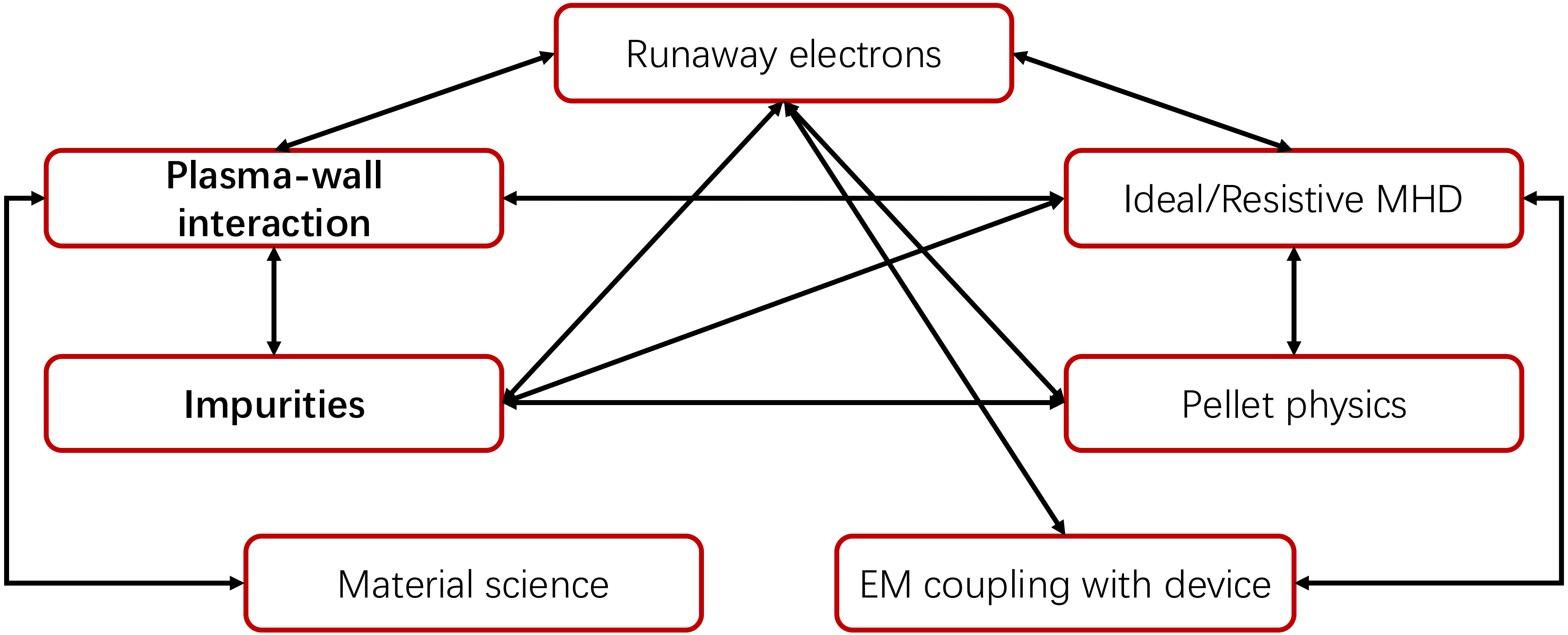




D Hu *et al* 2021 Plasma Phys. Control. Fusion 63 125003; L. Hesslow *et al* 2019 Nucl. Fusion 59 084004;

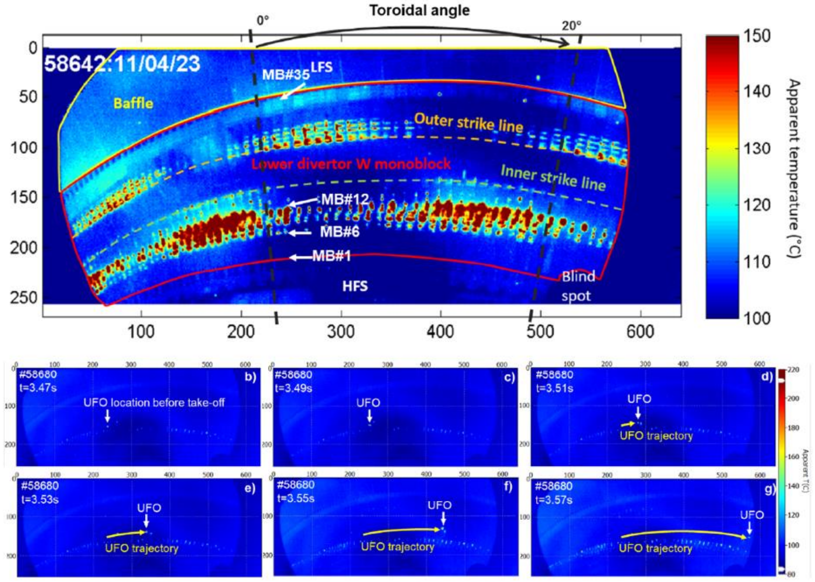
Components of disruption modelling

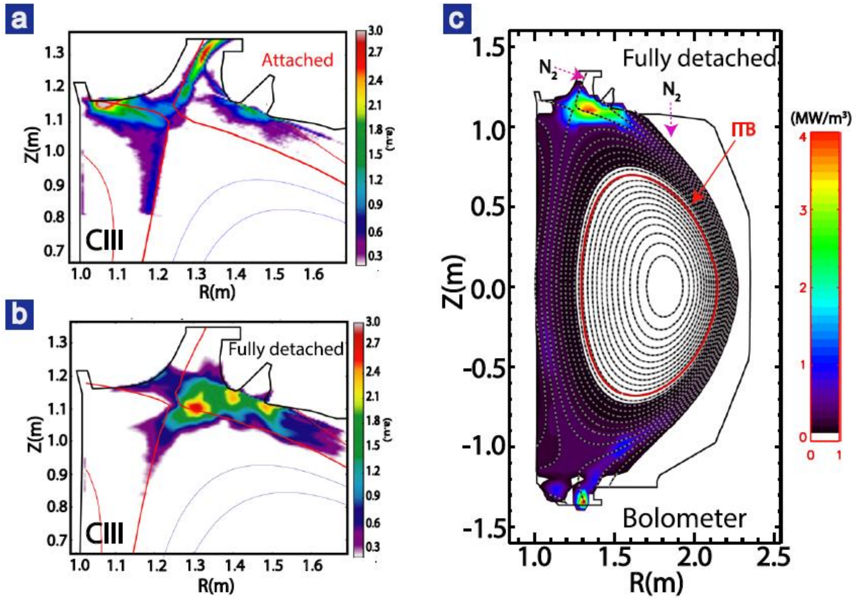
- Impurities are inevitably induced into the plasma core.



Impurity & plasma-wall interaction

- The accumulation of wall/divertor impurities might triggers disruptions.
- Intentional massive impurity injection is also used for TQ mitigation
- Impurities also play significant role in RE collision and avalanche.
- Local heat flux results in more impurity release……

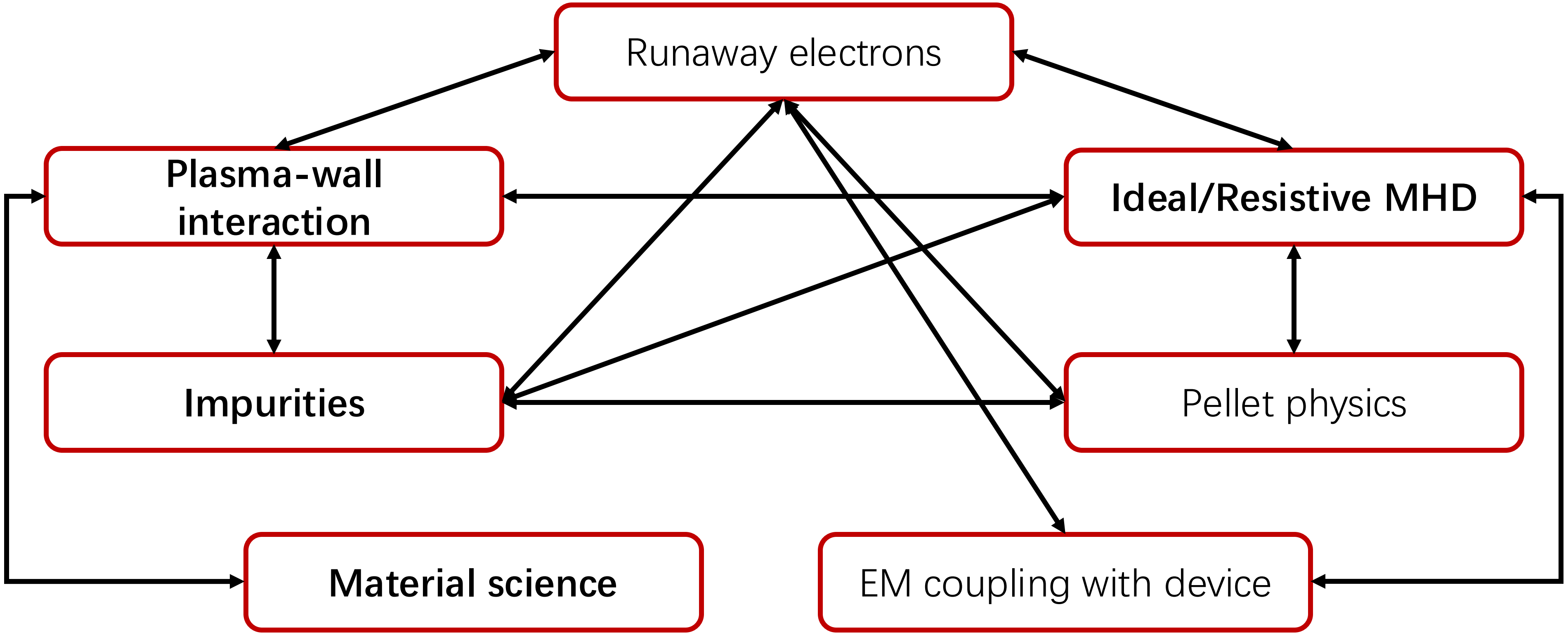




J. Gaspar et al Nuclear Materials and Energy 41 (2024) 101745; L. Wang et al NATURE COMMUNICATIONS | (2021) 12:1365;

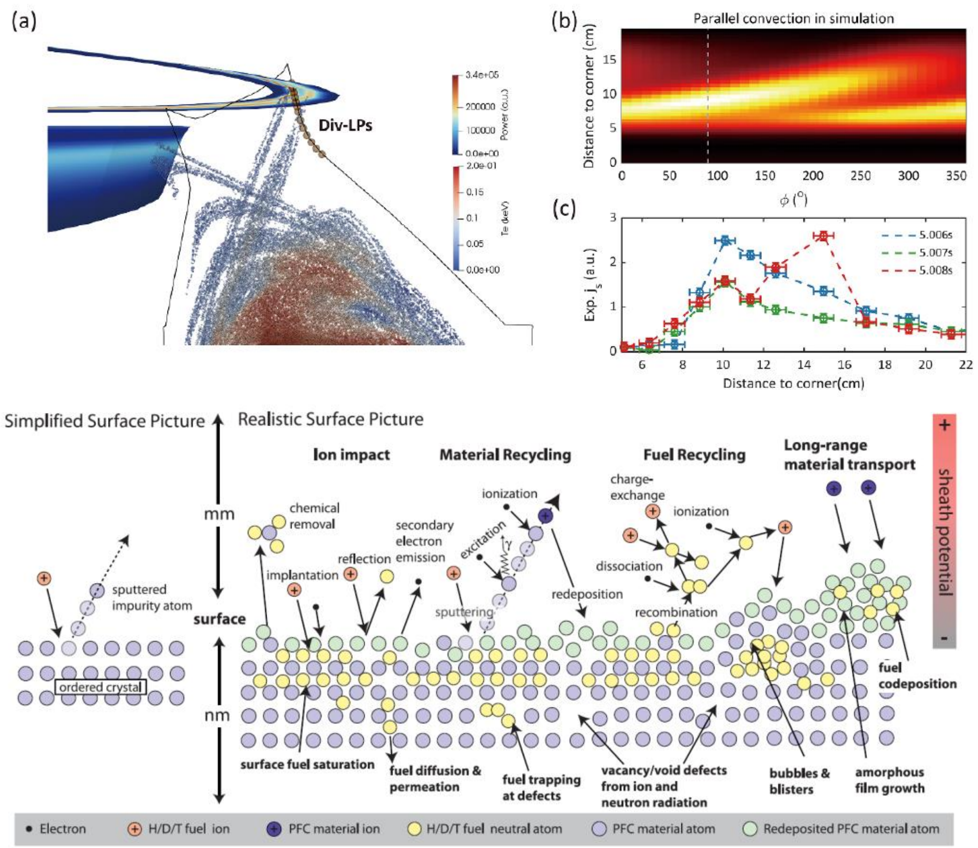
Components of disruption modelling

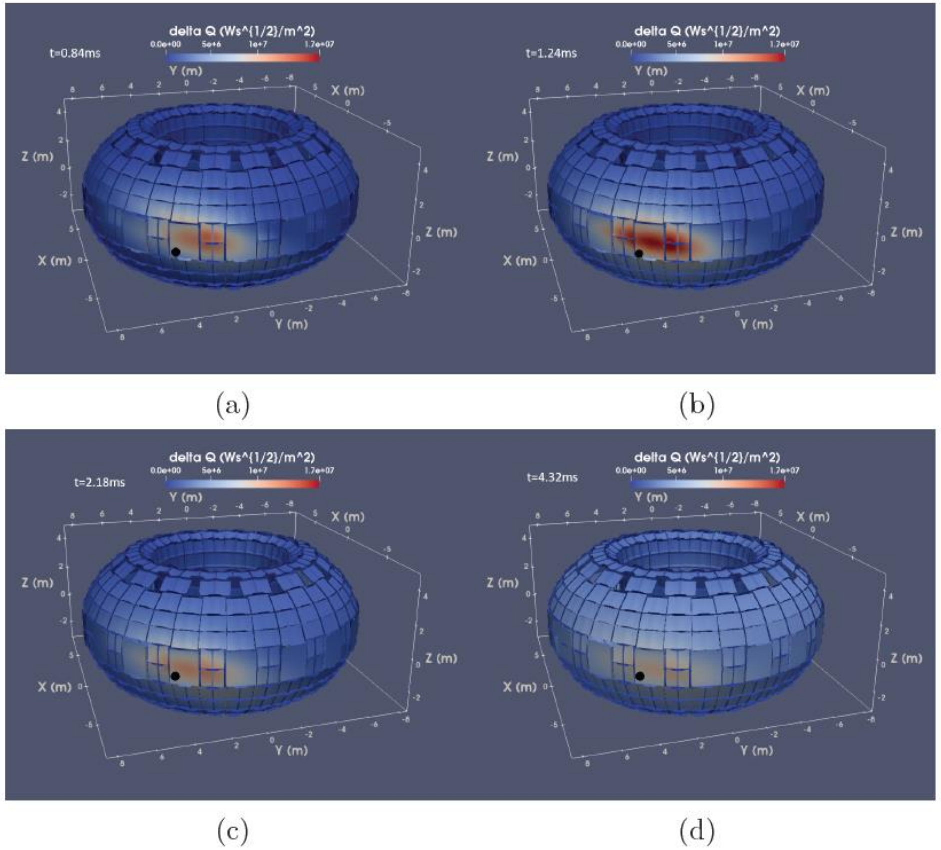
- The core physics and the material physics couple to each other through the plasma-wall interaction.



Coupling to the material

- The plasma-facing-components (PFCs) serve as important boundary condition for the impurity release.

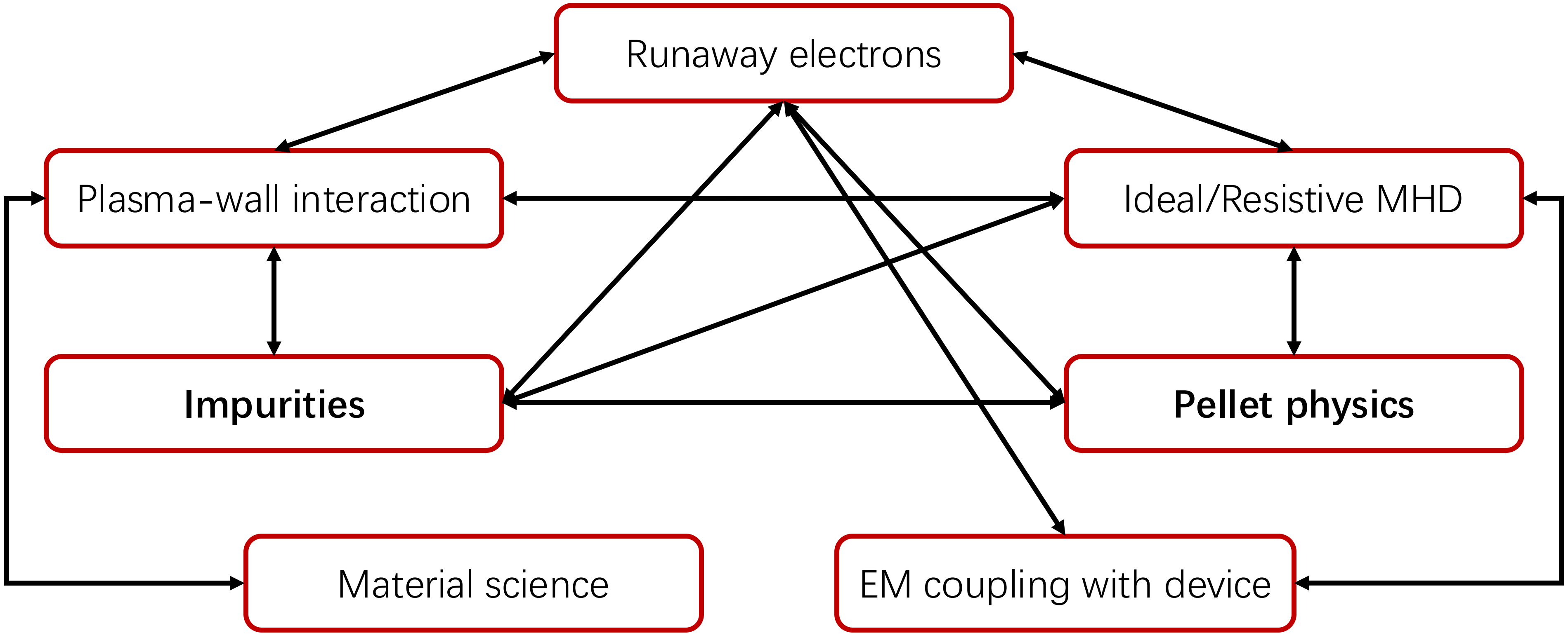




W. Xia et al., Nucl. Fusion 65 (2025) 056028; B.D. Wirth et al. MRS Bulletin 36, 216–222 (2011)

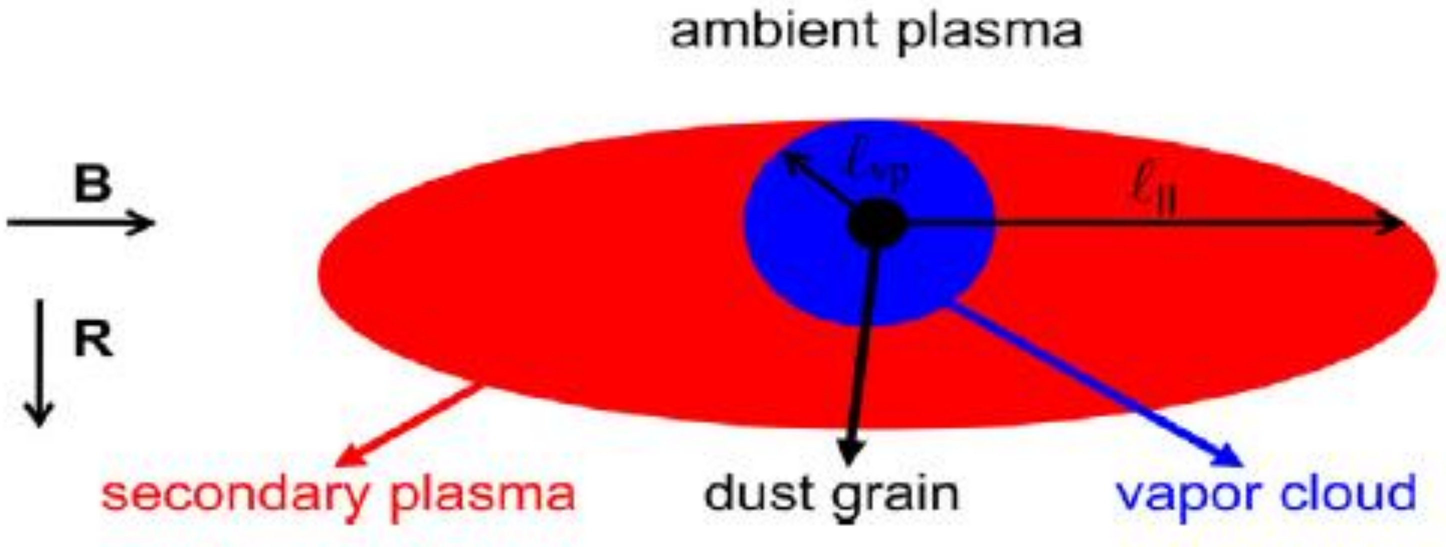
Components of disruption modelling

- Impurities could also be introduced intentionally.



Pellet ablation

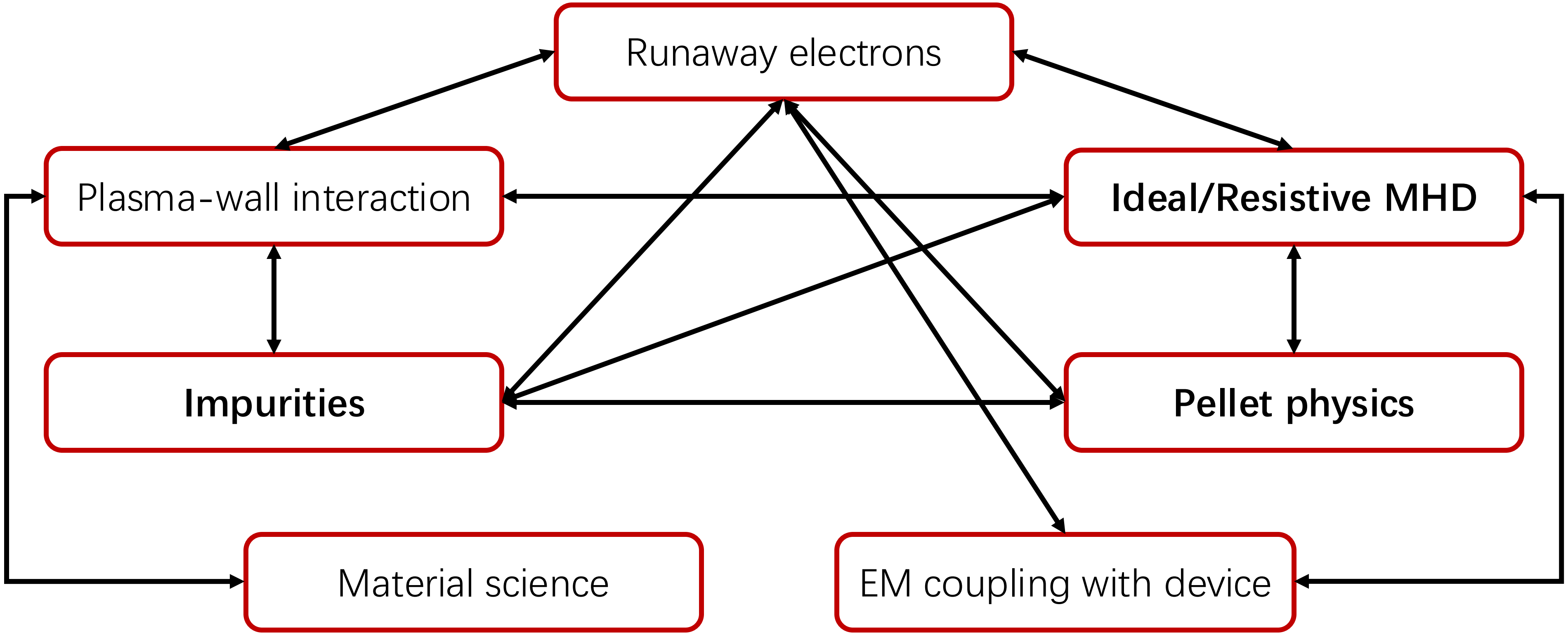
- The active introduction of impurities (via SPI) during the TQ mitigation is strongly coupled to the pellet physics.
- The ablation strongly depends on the small-scale pellet physics.
- Plasmoid drift, rocket effect…… all important to impurity deposition



S.I. Krasheninnikov *et al* Journal of Nuclear Materials 463 (2015) 869–872;

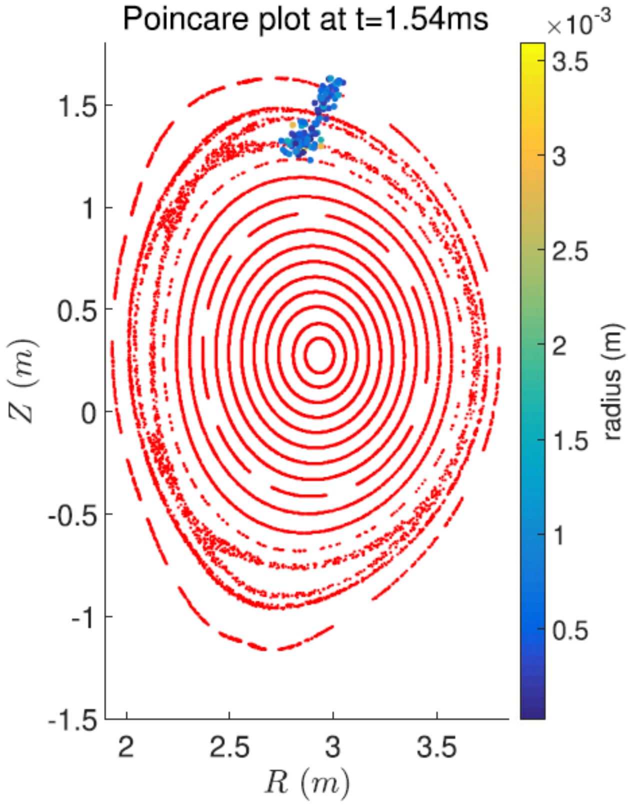
Components of disruption modelling

- Impurity induced cooling drive resonant mode via helical current perturbation. MHD modes in turn transport the impurities.

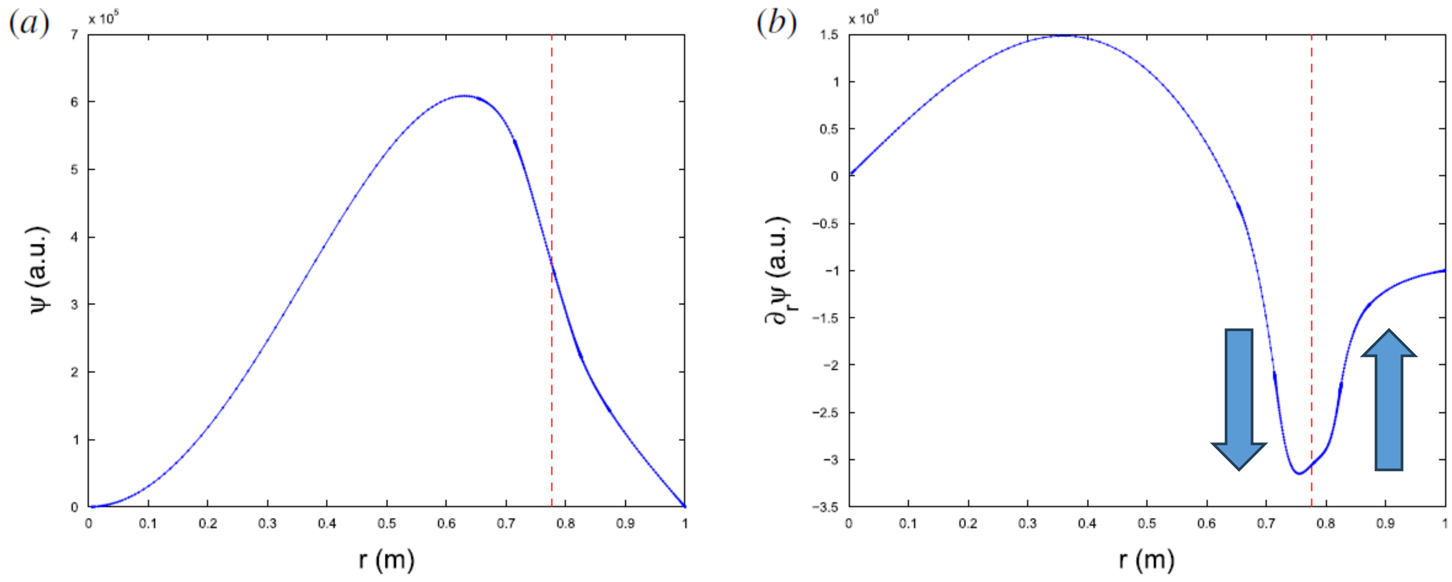


MHD destabilization by cooling

- Localized cooling caused by dilution & radiation prompt current contraction & helical current perturbation, destabilizing resonant modes.



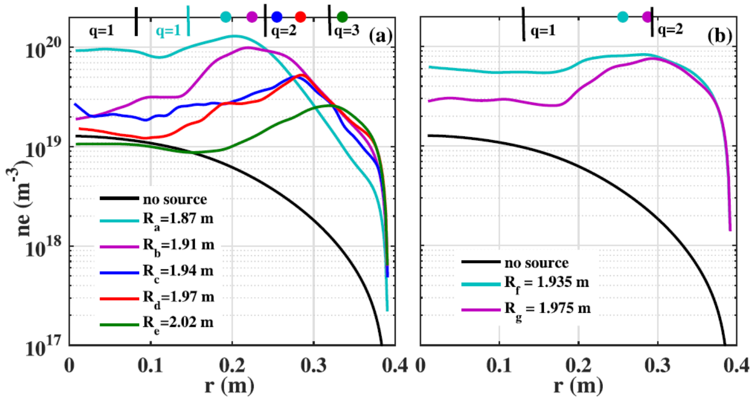
$$\frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial \Psi^*}{\partial r}+\frac{1}{r^2}\frac{\partial^2\Psi^*}{\partial\theta^2}=-j^*(\Psi^*)+2k\bar{F}-k^2(r^2-r_s^2)P(\Psi^*),$$
$$j^*(\Psi^*)\equiv(1+k^2r_s^2)P(\Psi^*)+T(\Psi^*).$$

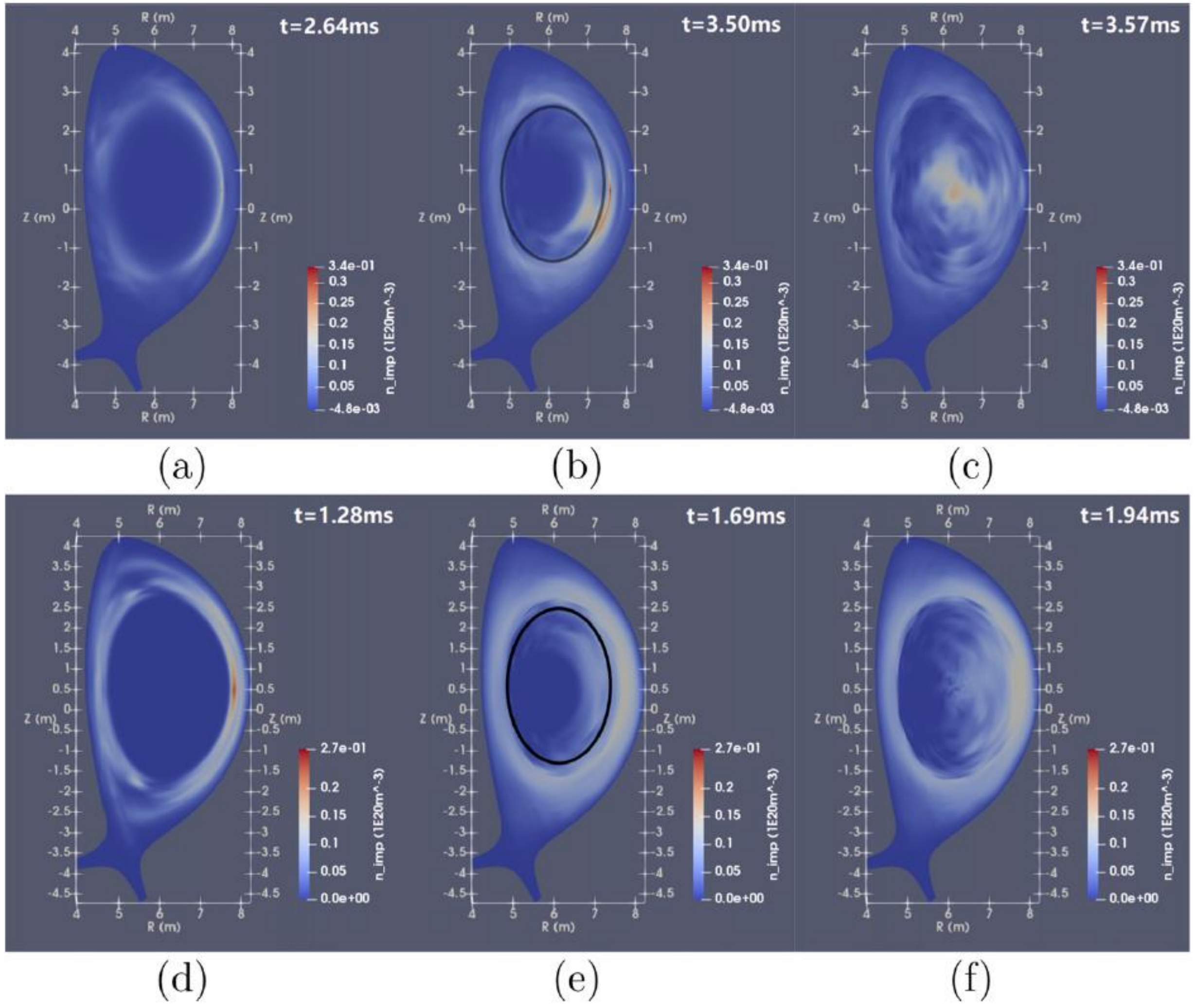


D. Hu *et al* Nucl. Fusion 61 (2021) 026015; D. Hu & L.E. Zakharov, J. Plasma Phys. (2015), vol. 81, 515810602;

MHD transport of impurities

- The MHD mode would in turn result in impurity transport.
- The transport strongly depends on the **mode structure** & the **impurity deposition** profile, hence the injection penetration exhibit nonlinear behavior.

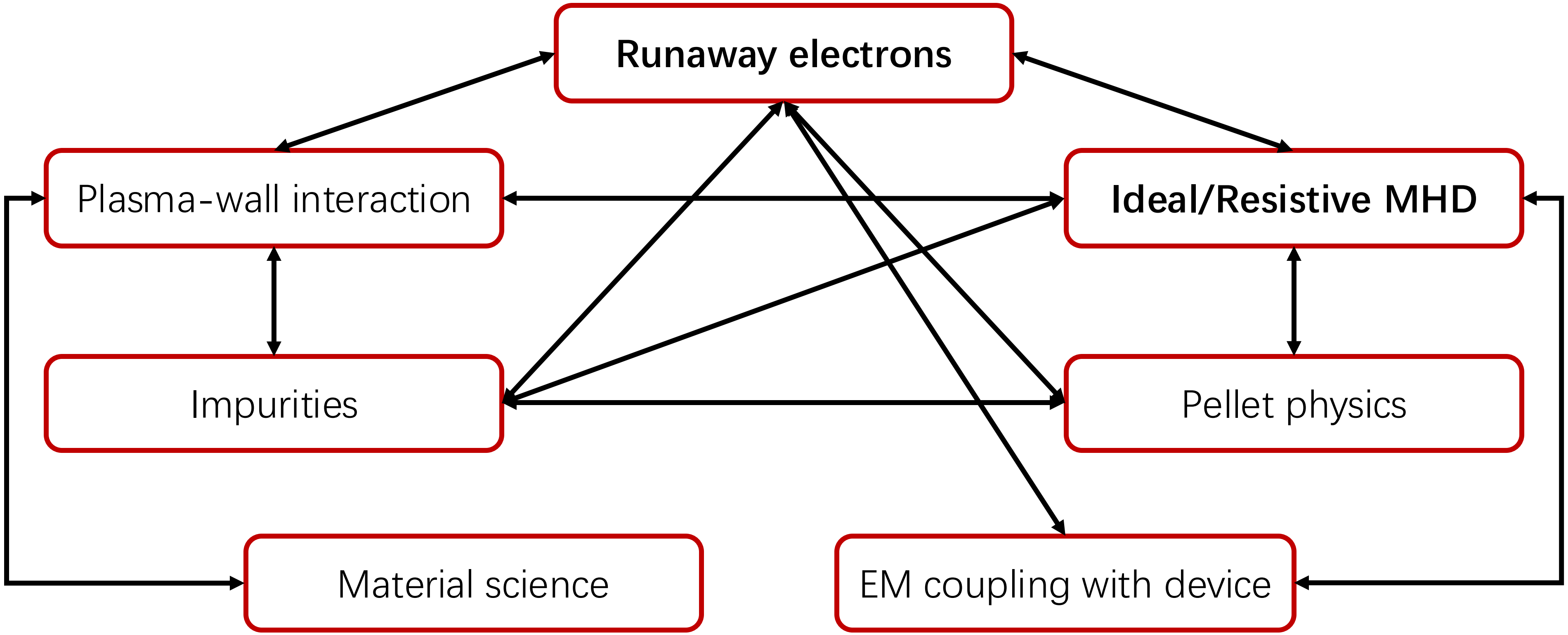




D. Hu et al 2021 Nucl. Fusion 61 026015; S. L. Hu *et al* Phys. Plasmas 30, 112509 (2023);

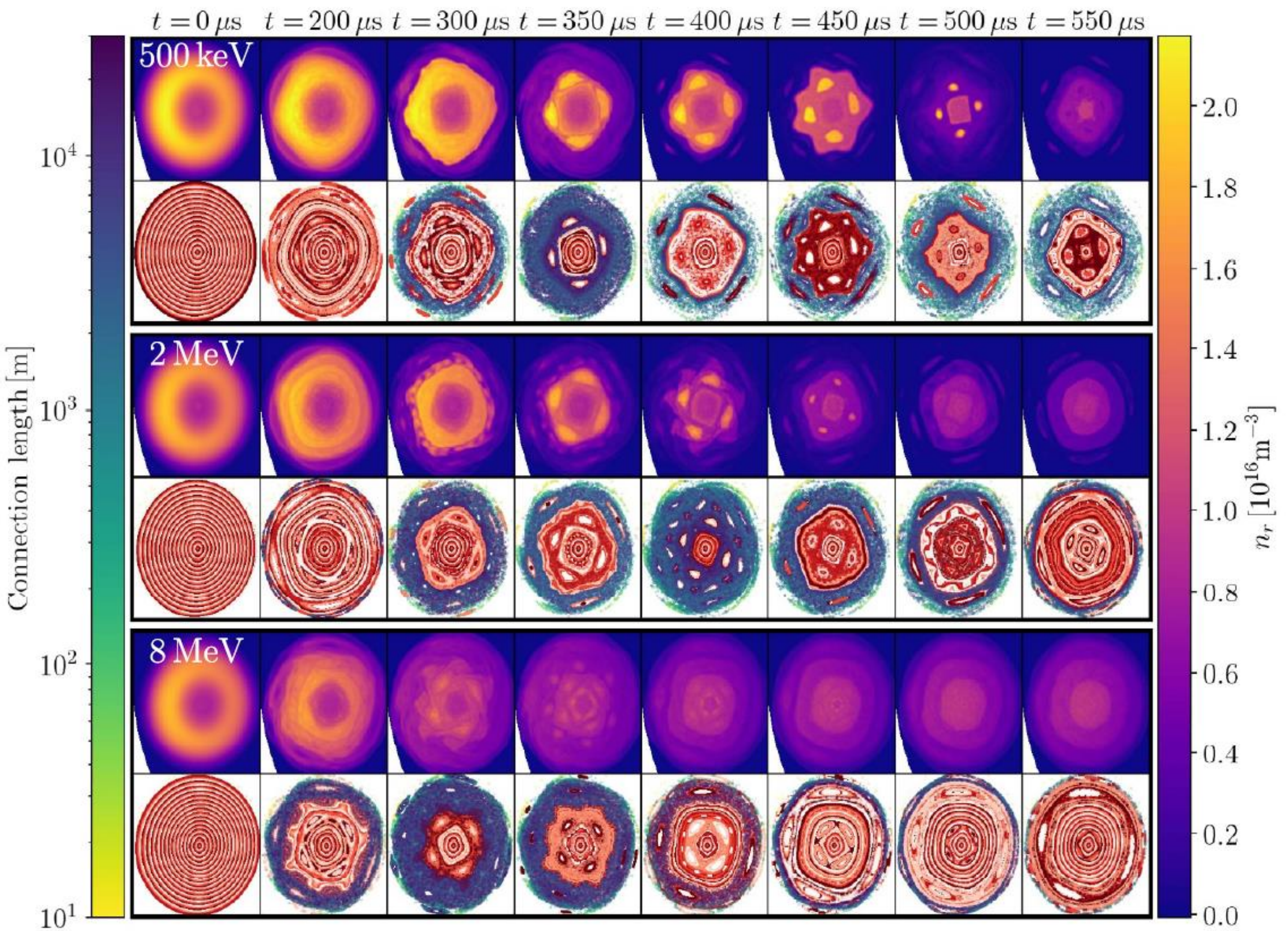
Components of disruption modelling

- RE could be come the dominant current carrier……



RE physics & MHD coupling

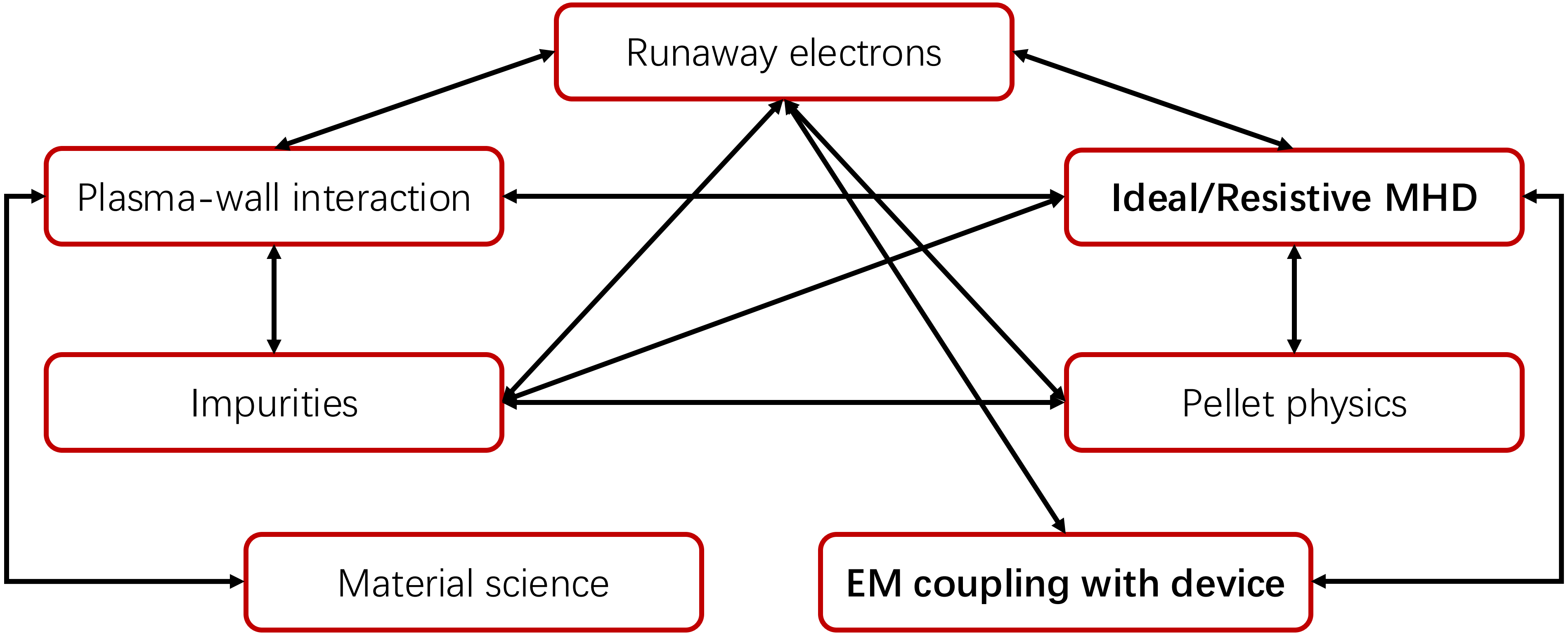
- RE dynamics could affect macroscopic stability once they become the **dominant current carrier**.
- The MHD stability is directly coupled to the RE dynamics.
- The field line perturbation in turn affects the RE dynamics.
- Could also couples to external current response: RMP, wall current, passive coils……



H. Bergström et al 2025 Plasma Phys. Control. Fusion 67 035004

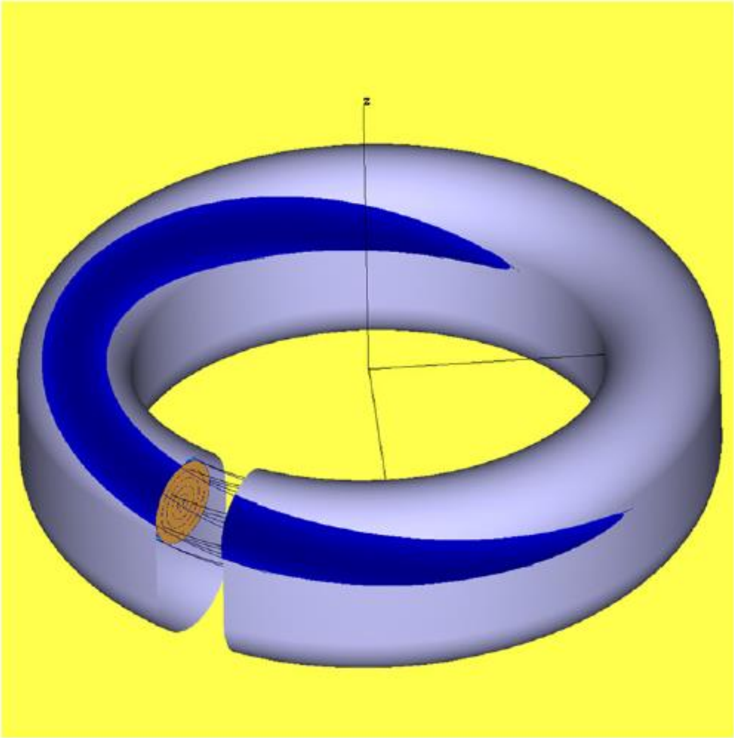
Components of disruption modelling

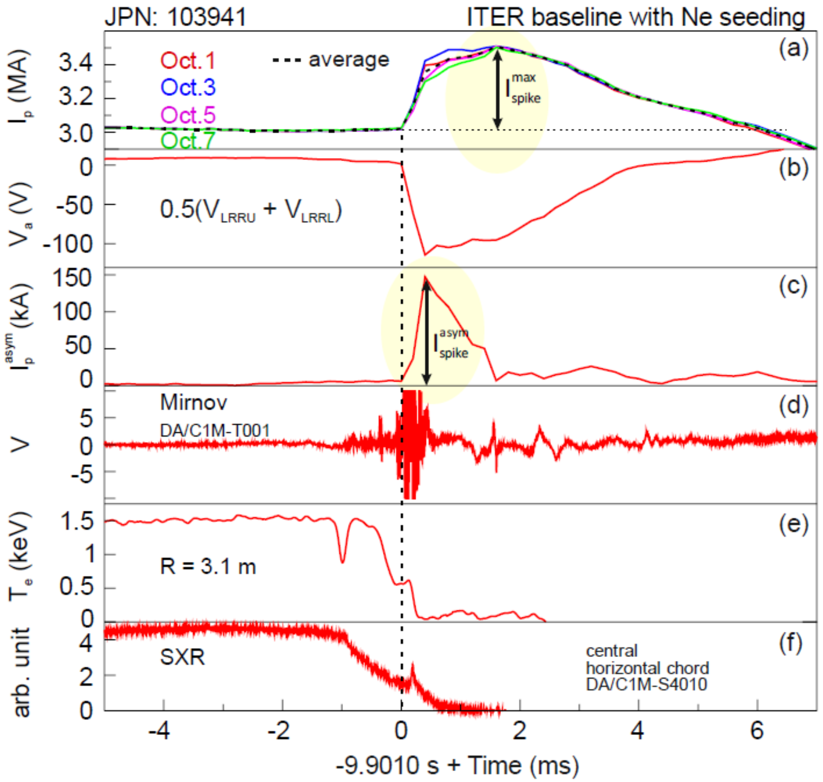
- During the current quench, strong current coupling between the plasma and the wall could occur.

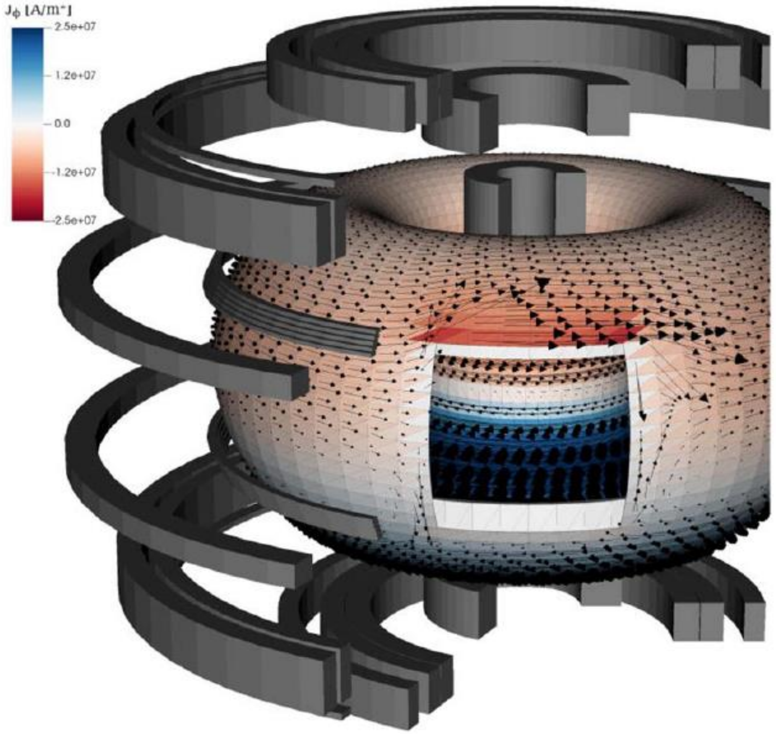


Coupling to the device

- During the CQ, significant coupling between the plasma current and the wall/coil current could occur. Could have impact on the plasma stability.



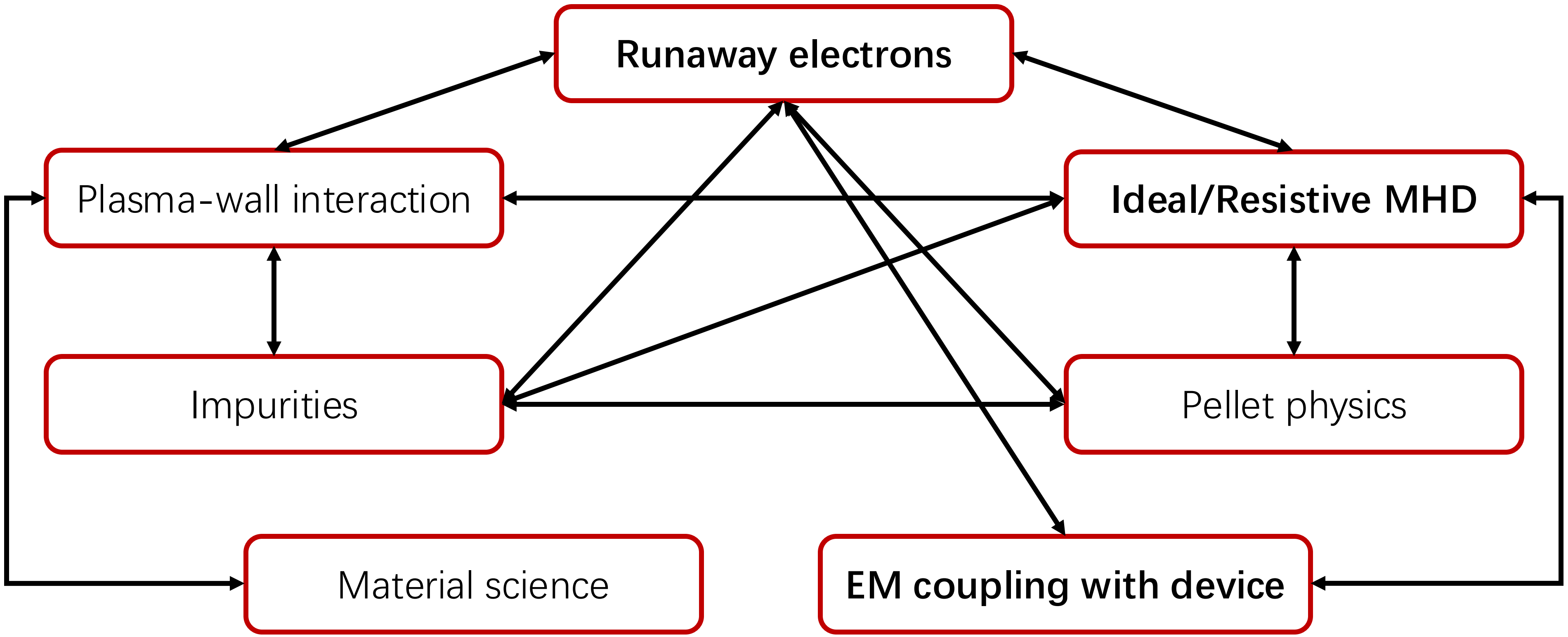




L.E. Zakharov et al 2021 Physics of Plasmas 19, 055703 (2012); Sergei Gerasimov|RT03+REM, EPFL 2- 6 June 2025;
F J Artola et al 2024 Plasma Phys. Control. Fusion 66 055015; M. Hoelzl et al 2024 Nucl. Fusion 64 112016

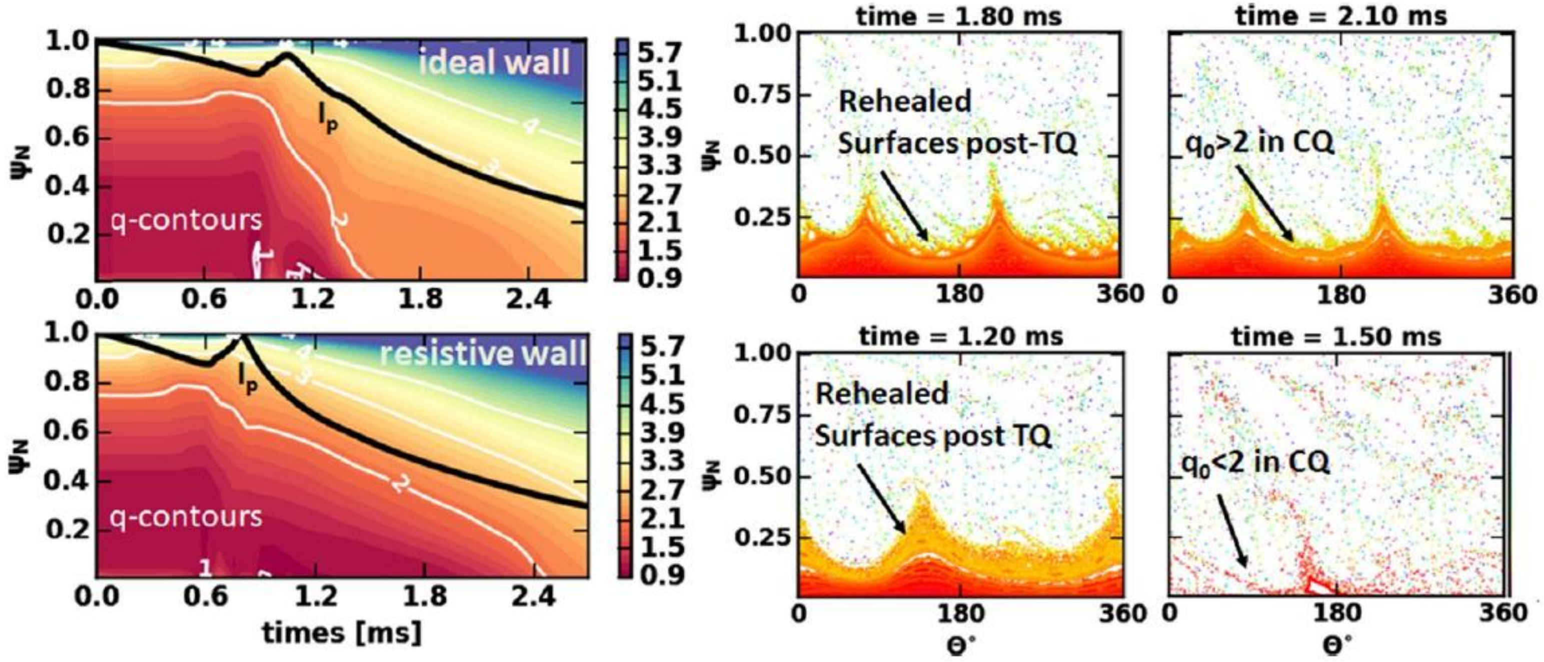
Components of disruption modelling

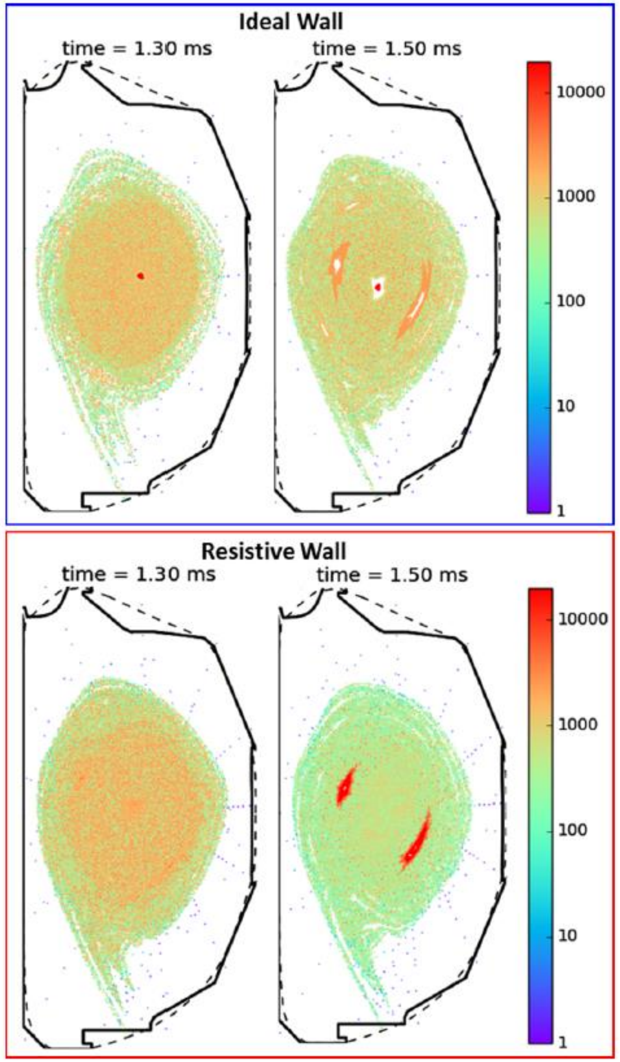
- Adding the runaway electrons into the recipe and the dynamics becomes more complicated……



Coupling to the device

- The coupling to the passive coil and the conducting wall could significantly alter the MHD instability during the CQ phase, thus strongly impact the RE mitigation efficiency.





V.A. Izzo et al., Nucl. Fusion 64 (2024) 066003

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Progress & Challenge

- Several examples of integrated disruption modelling is chosen to highlight both its **progress** and **challenge**.
- The examples correspond to three most significant concerns of disruption mitigation: the **heat load** mitigation during the thermal quench, the **EM load** during the current quench, and the **runaway electrons**.
- Those are but a few examples among a sea of ongoing disruption integrated modelling works.

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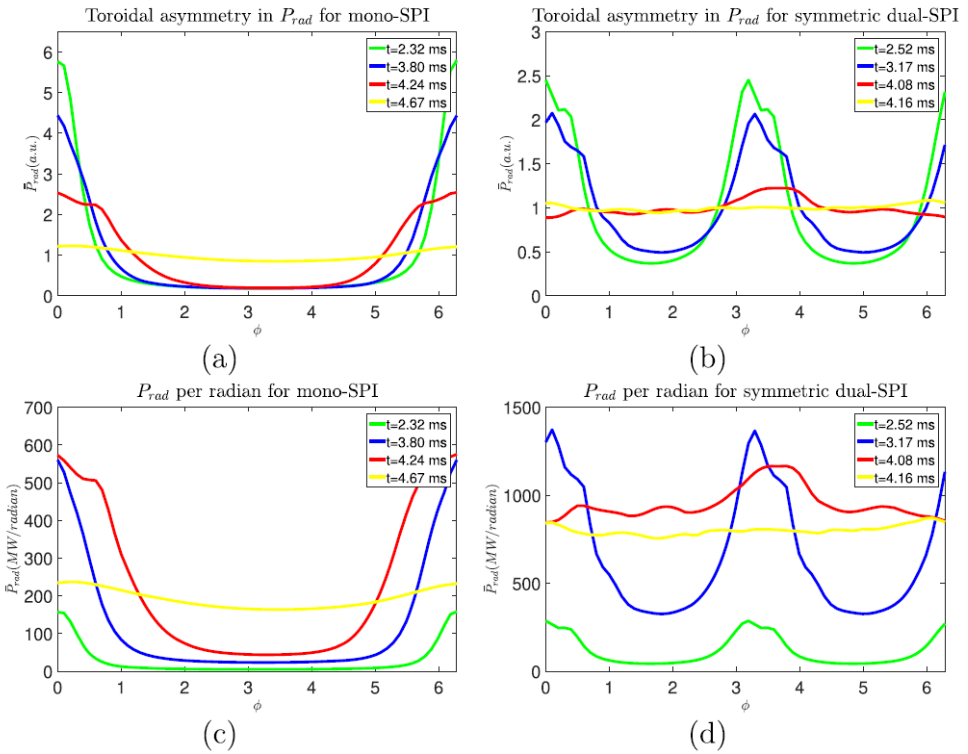
Modelling of TQ mitigation & RE loss

- One of the major concern of SPI as a disruption mitigation is the **radiation asymmetry** during the TQ mitigation. Already substantial investigations into the radiation power density and its asymmetry <u>within the plasma</u> by various codes.

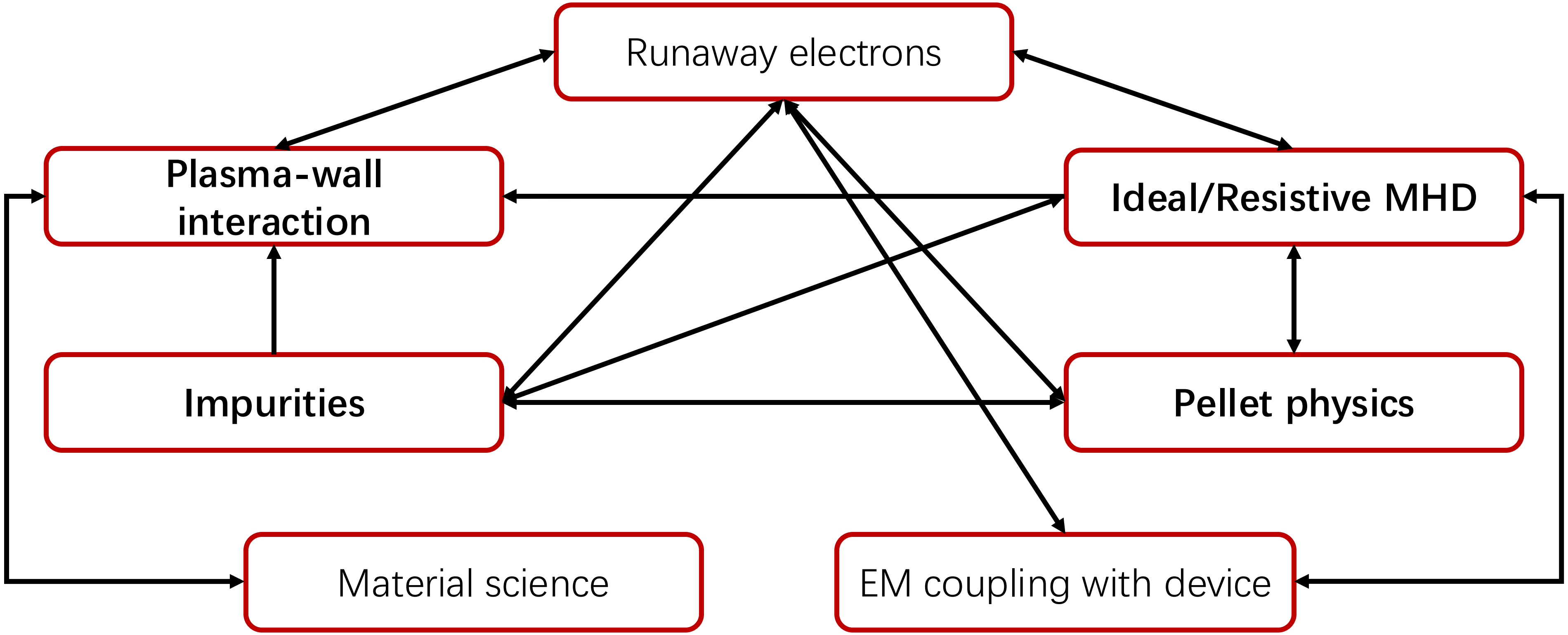
- The ultimate criterion, however, is the temperature rise on the first wall, which could be characterized by the so-called **energy impact**.
- 3D non-linear simulations need to be coupled with ray-tracing post-processing tools to obtain the first wall energy impact.
- The RE seed transport during the TQ mitigation is also of great interest.



D. Hu *et al* 2021 *Nucl. Fusion* **61** 026015

The coupling scheme

- In this particular case, the couple occurs between the MHD, the pellet, the impurity and the wall

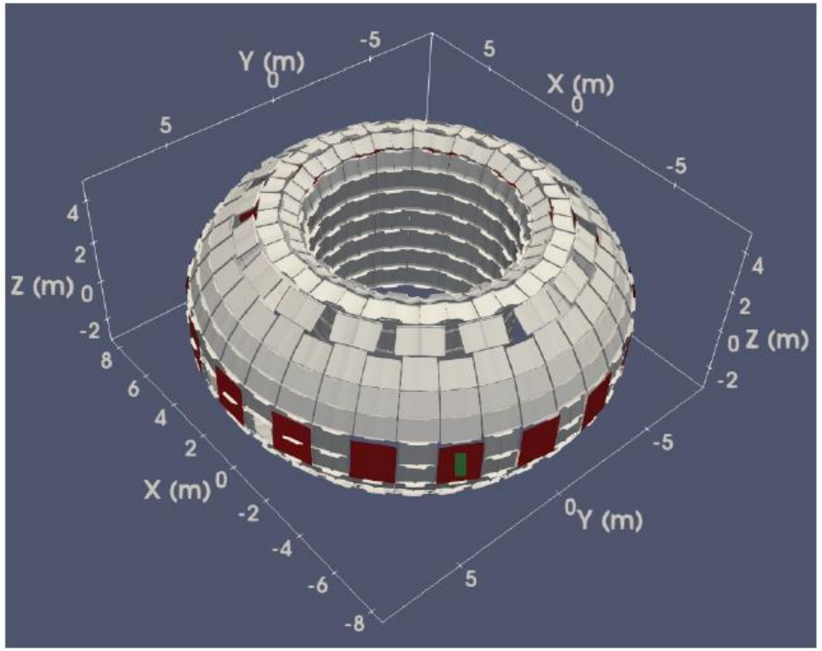


Coupling to IMAS

- The JOREK result is coupled via the Integrated Modelling & Analysis Suite (IMAS) to raytracing tools such as RaySect/CHERAB to obtain the wall heat flux & energy impact.
- A variety of SPI & plasma parameters are scanned, transparent plasma assumed.

Notation	Equilibria	Neon	Hydrogen	Frag.	Delay	Tor. Angle
BH-FP-dt0 (case 1)	baseline	$2 \times 2.5 \times 10^{22}$	$2 \times 1.8 \times 10^{24}$	300	$0ms$ (Asymm.)	180°
DH-FP-dt0 (case 2)	degraded	$2 \times 2.5 \times 10^{22}$	$2 \times 1.8 \times 10^{24}$	300	$0ms$	180°
DH-QP-dt0 (case 3)	degraded	$2 \times 2.5 \times 10^{22}$	$2 \times 4.5 \times 10^{23}$	100	$0ms$	180°
DH-QP-dt1 (case 4)	degraded	$2 \times 2.5 \times 10^{22}$	$2 \times 4.5 \times 10^{23}$	100	$1ms$	180°
DH-QP-dt0-ff (case 5)	degraded	$2 \times 2.5 \times 10^{22}$	$2 \times 4.5 \times 10^{23}$	1000	$0ms$	180°
DH-QP-dt0-120 (case 6)	degraded	$2 \times 2.5 \times 10^{22}$	$2 \times 4.5 \times 10^{23}$	100	$0ms$	120°
DH-QP-stg (case 7)	degraded	2×0	$2 \times 5 \times 10^{23}$	100	$0ms$	180°
		$+2 \times 2.5 \times 10^{22}$	$+2 \times 4.5 \times 10^{23}$	100	(Staggered)	

TABLE I. The injection parameters for the SPI considered in this study. Note that for BH-FP-dt0 there exists an asymmetry between the plumes although they are injected at the same time.

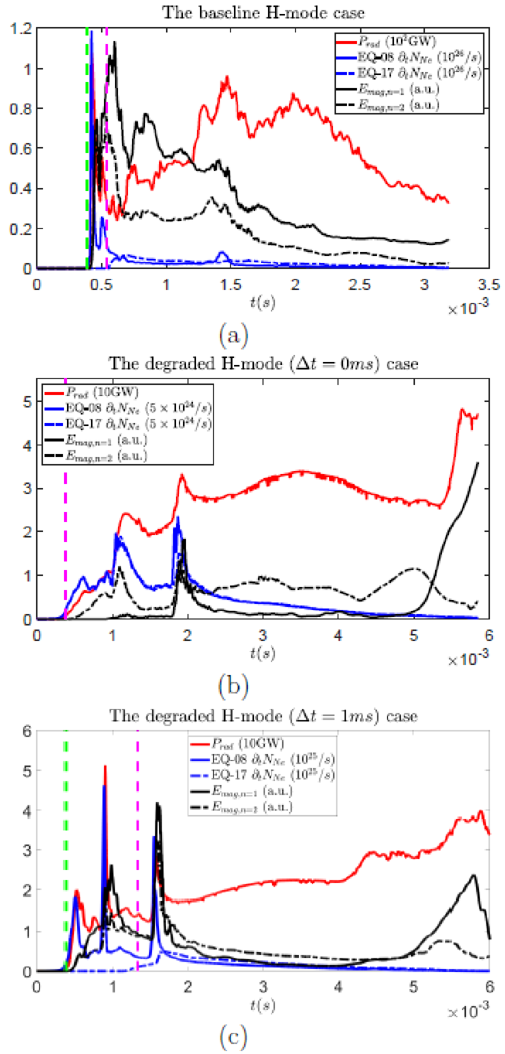


D. Hu *et al* Nucl. Fusion 64 (2024) 086005

The radiation, ablation & MHD

- Strong correlation between the radiation peaks, the ablation peaks and the MHD peaks. A positive loop.
- Despite stronger total radiation power in the later TQ phase, its asymmetry is milder, thus posing a weaker challenge to disruption mitigation.
- Even the baseline case which shows strongest local energy impact, the tungsten melting threshold is not reached.

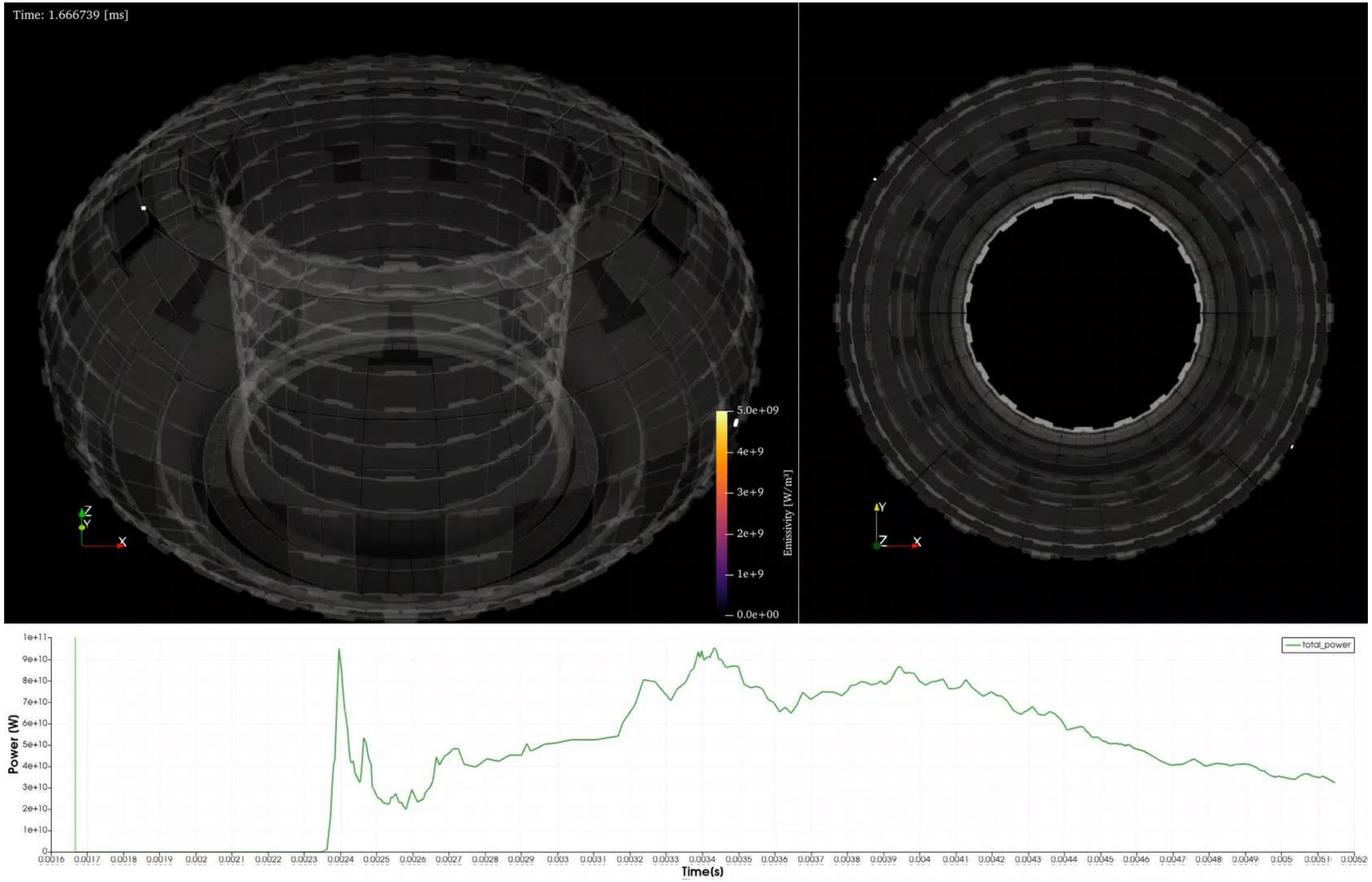
Case #	Assim. Ne	Assim. H	f_{rad}	t_{TQ} (90%-20%)	Max. ΔQ
BH-FP-dt0	9.91×10^{21}	6.40×10^{23}	49.4%	$2.0ms$	$25.4MWs^{1/2}/m^2$
DH-QP-dt0	2.53×10^{22}	4.40×10^{23}	89.8%	$4.4ms$	$5.7MWs^{1/2}/m^2$
DH-QP-dt1	2.15×10^{22}	3.58×10^{23}	86.3%	$4.2ms$	$14.9MWs^{1/2}/m^2$



The emissivity within the plasma

- The emissivity reconstructed from the JOREK simulation by RaySect/Cherab tools integrated in IMAS
- Apparent rotating helical structure reproduced by the simulation/visualization, consistent with the JET footage despite different devices.

Courtesy of
Koyo Munechika



Degraded H-mode heat load

- The RaySect/CHERAB toolset projects the radiation power density onto the realistic ITER first wall to obtain the radiative **heat flux**.
- The time convolution of such heat flux provides the so-called "**energy impact**", proportional to the wall temperature rise.

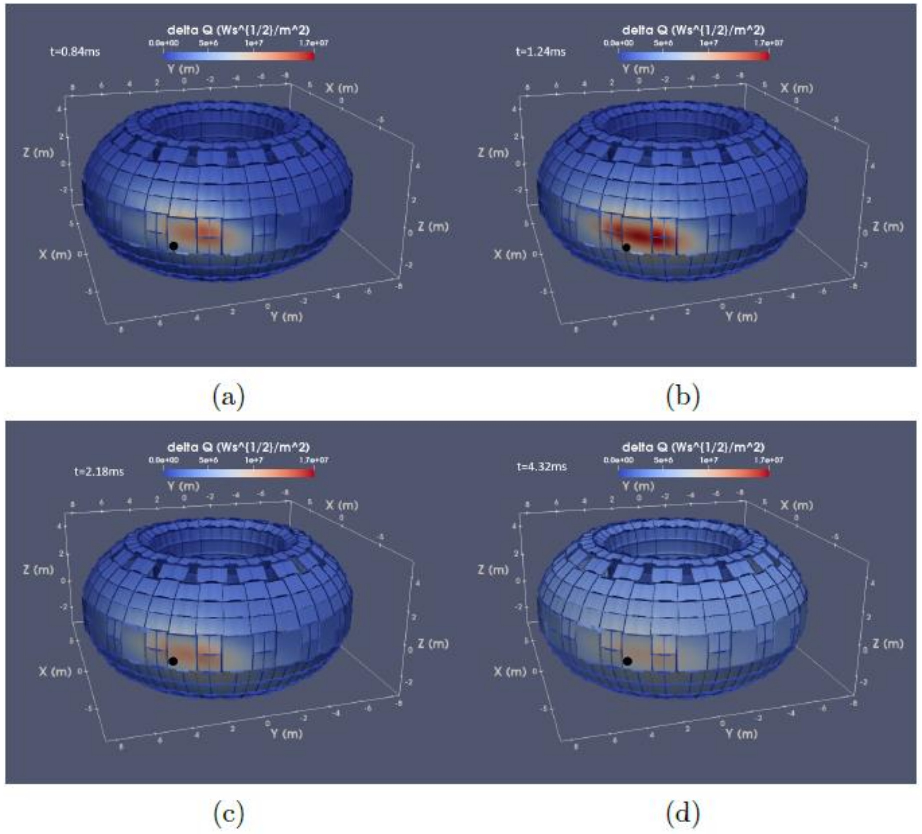


FIG. 14. The first wall energy impact of DH-QP-dt0-ff calculated using Eq. 4 at (a) $t = 0.84ms$, (b) $t = 1.24ms$, (c) $t = 2.18ms$ and (d) $t = 4.32ms$ looking at port EQ-08. The EQ-08 port is marked by the black dots.

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Quick summary of the results

- Fragments entering the baseline H-mode pedestal result in **significant plasmoid drift** and accompanied MHD, undermining the mitigation efficiency.
- Reasonably good mitigation for degraded cases, **the tungsten tiles would not melt under any circumstances**, and **the SS plate melting is acceptable**.
- The rocket effect has not been considered in those studies.

Notation	Assim. Ne	Assim. H	f_{rad}	t_{TQ}(90%-20%)	Max. ΔQ
BH-FP-dt0	9.91×10^{21}	6.40×10^{23}	49.4%	2.0ms	$25.4MWs^{1/2}/m^2$
DH-FP-dt0	$\sim 1.1 \times 10^{22}$	$\sim 8.0 \times 10^{23}$	~76.5%	~3.1ms	$16.0MWs^{1/2}/m^2$
DH-QP-dt0	2.53×10^{22}	4.40×10^{23}	89.8%	4.4ms	$5.7MWs^{1/2}/m^2$
DH-QP-dt1	2.15×10^{22}	3.58×10^{23}	86.3%	4.2ms	$14.9MWs^{1/2}/m^2$
DH-QP-dt0-ff	2.82×10^{22}	5.54×10^{23}	81.3%	2.4ms	$16.6MWs^{1/2}/m^2$
DH-QP-dt0-120	$\sim 2.5 \times 10^{22}$	$\sim 4.4 \times 10^{23}$	~84.5%	~4.4ms	$11.6MWs^{1/2}/m^2$
DH-QP-stg	9.64×10^{21}	8.92×10^{23}	78.4%	7.91ms	$5.9MWs^{1/2}/m^2$

Table 2, The neon and hydrogen assimilation, radiated fraction, TQ time and maximum local energy impact for all cases considered in this section. The tilde signs indicate the estimated results extrapolated from the nearly-finished simulation results. Almost all of the non-radiative thermal energy loss in the DH-QP-stg case occurs during the H injection phase.

TQ mitigation simulation

- JOREK coupled with Raysect/CHERAB is used to investigate the MHD and the radiation characteristics during dual-SPIs into ITER H-modes.
- Strong **plasmoid drift** and accompanied MHD could occur due to local over-pressure for the baseline H-mode case, resulting in density expulsion and premature energy loss. **Detrimental to the TQ mitigation efficiency**. **Could be avoided by considering the neon mixture and precursor confinement loss**.
- Radiation asymmetry could arise from SPI configuration or inherent MHD. The asymmetry is stronger in the early phase.
- **The energy impact would not exceed the W limit**. Although **it could exceed the SS limit**, **it won't result in significant mass loss** thus is acceptable. Whether repeated exposure would cause minor cracks in W tiles remain to be investigated.

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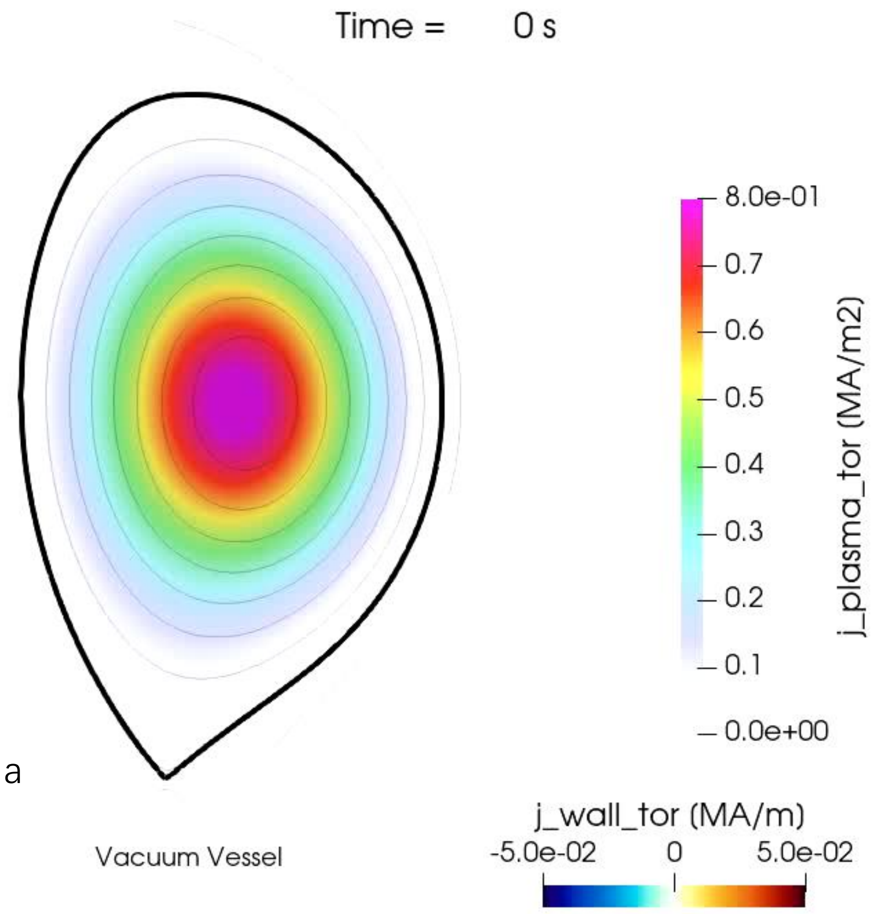
VDE simulation

- Elongated plasmas → vertical instabilities
  - ➢ Feedback control on vertical position needed

G. Laval et al, The Physics of Fluids, v.17, n.4, **1974**, p.835-845

JOREK simulation of a JET VDE



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Tools of VDE modelling

with different

- **Plasma models**
  - 2D / 3D
  - Evolutionary equilibrium / reduced MHD / full MHD
- **Wall models**
  - 2D / 3D
  - Thin / volumetric

Code/Framework	Plasma model	Wall model
DINA (ITER load reference code)	2D evol EQ. + 1D transport	2D Toroidal filaments
TSC	2D MHD + 1D transport	2D Toroidal filaments
CarMa0NL-CARIDDI	2D evol EQ.	3D volumetric
M3D	3D full MHD	2D thin
NIMROD	3D full MHD	2D thin
M3D-C1	3D full MHD	2D volumetric
M3D-C1-CARIDDI (1-way coupling)	3D full MHD	3D volumetric
JOREK-STARWALL (upgrading to full MHD)	3D reduced MHD	2D thin
JOREK-CARIDDI (full coupling)	3D reduced MHD	3D volumetric
Other tools: ANSYS, CREATE_NL, INDEX, PROTEUS, MAXFEA, CEDRES++...		

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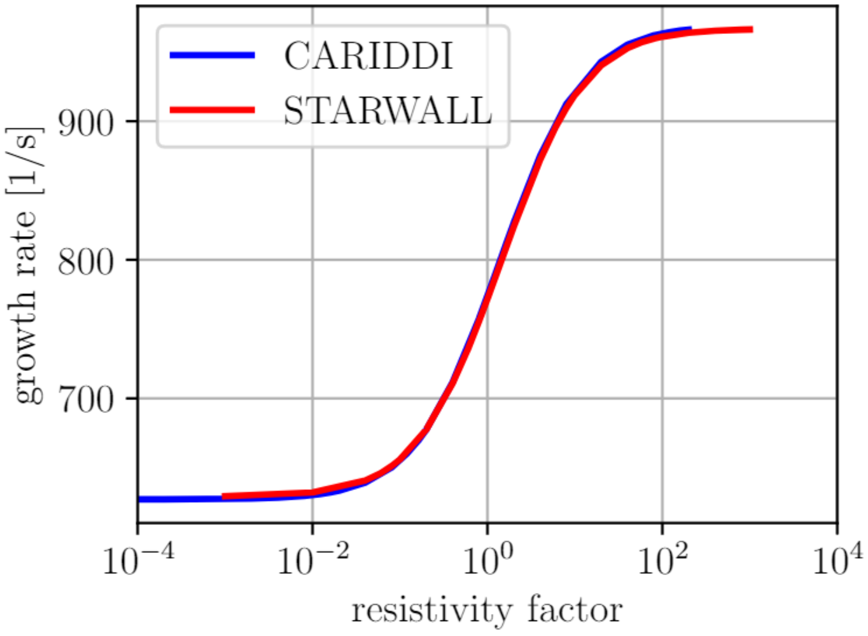
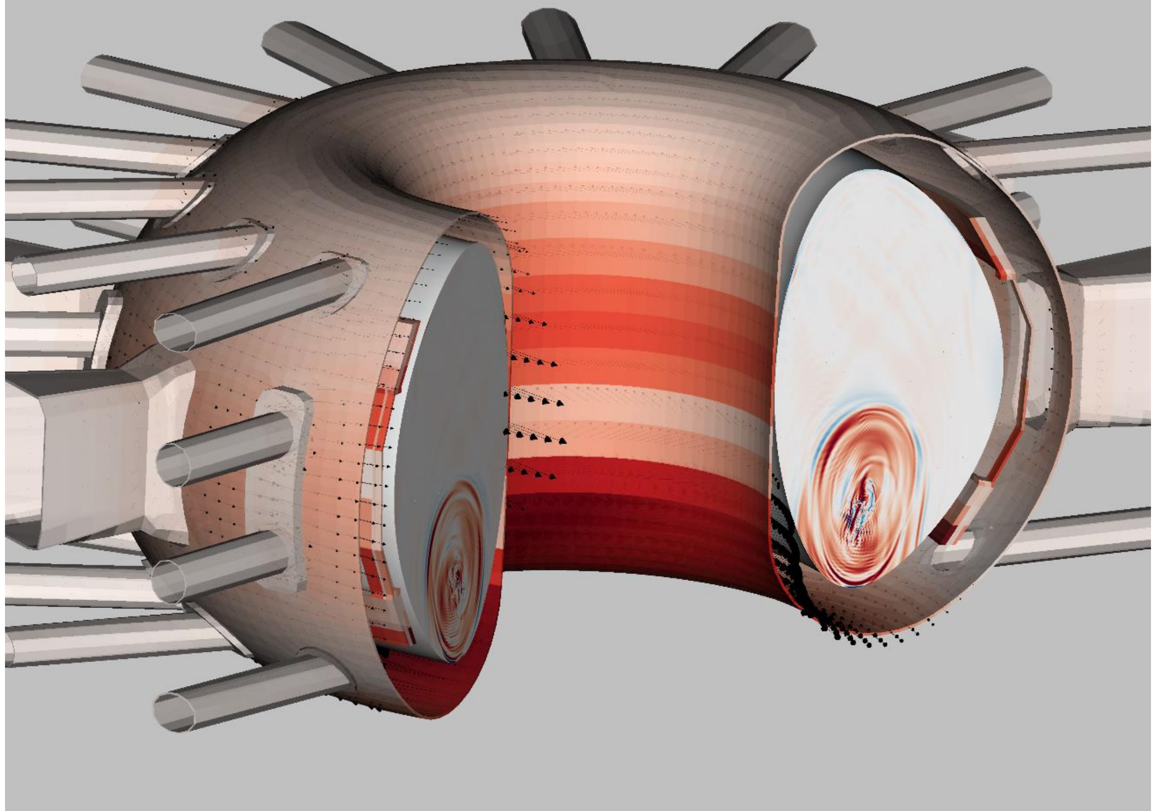
Tools of VDE modelling

Example: *JOREK-CARIDDI* coupling for 3D plasma/ 3D wall model
[N. Isernia & N. Schwarz, Phys. Plasmas 30, 113901 (2023)]

Growth rate of 2/1 tearing mode .vs. wall resistivity



Self-consistent JOREK-CARIDDI simulation of a 3D VDE with a 3D wall



Halo current coupling still missing

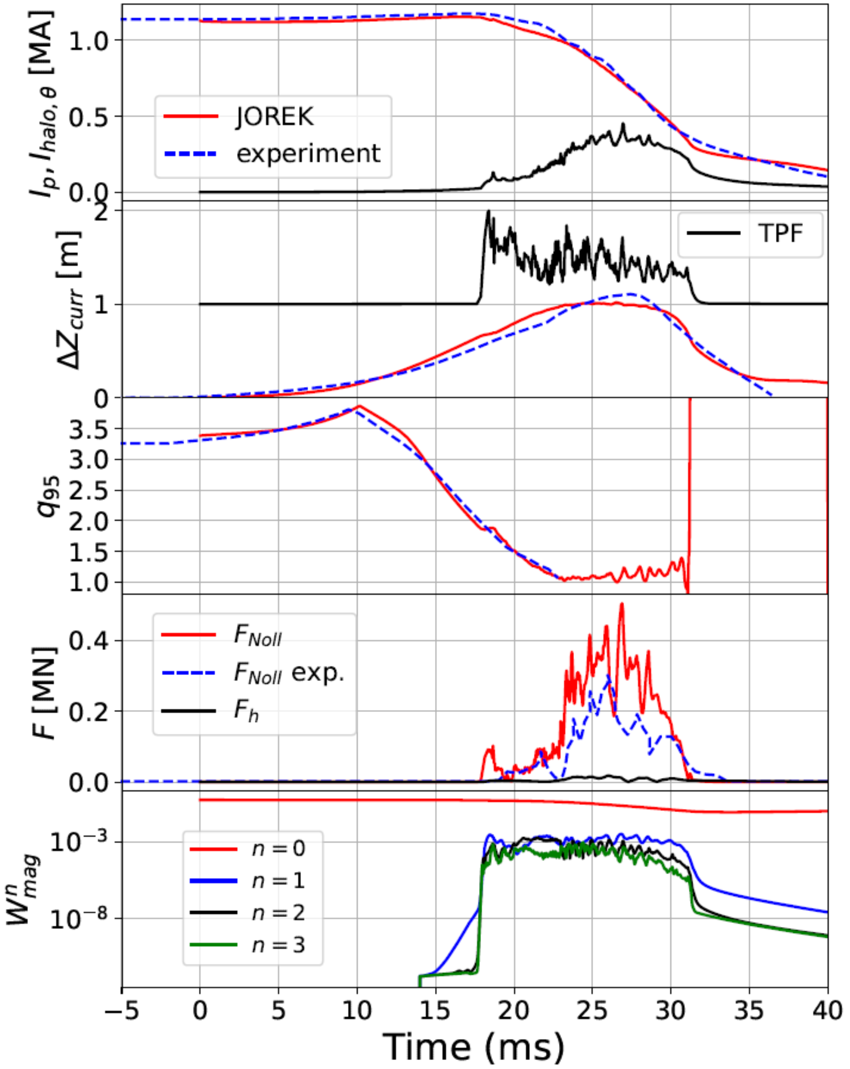
Validation activities (JOREK-JET)

*3D code validation – **Sideways force***

- **Realistic parameters & time-scales**
  I_p is not constrained
- **<u>Model simplifications</u>** (to reduce memory consumption)
  - ➢ Reduced MHD (ψ, u, j, w, T)
    $\rho = \rho_0$; $v_\parallel = 0$; Dirichlet B.C.s;
  - ➢ $n \in [0,3]$

Allow calculating accurate preconditioner for iterative solver

+ Implicit time-stepping → **Large time steps (~1 μs)**



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Validation activities (JOREK-JET)

*3D code validation – **Sideways force***

- **Simulated sideways force (F_h) is an order of magnitude smaller than Noll's force**

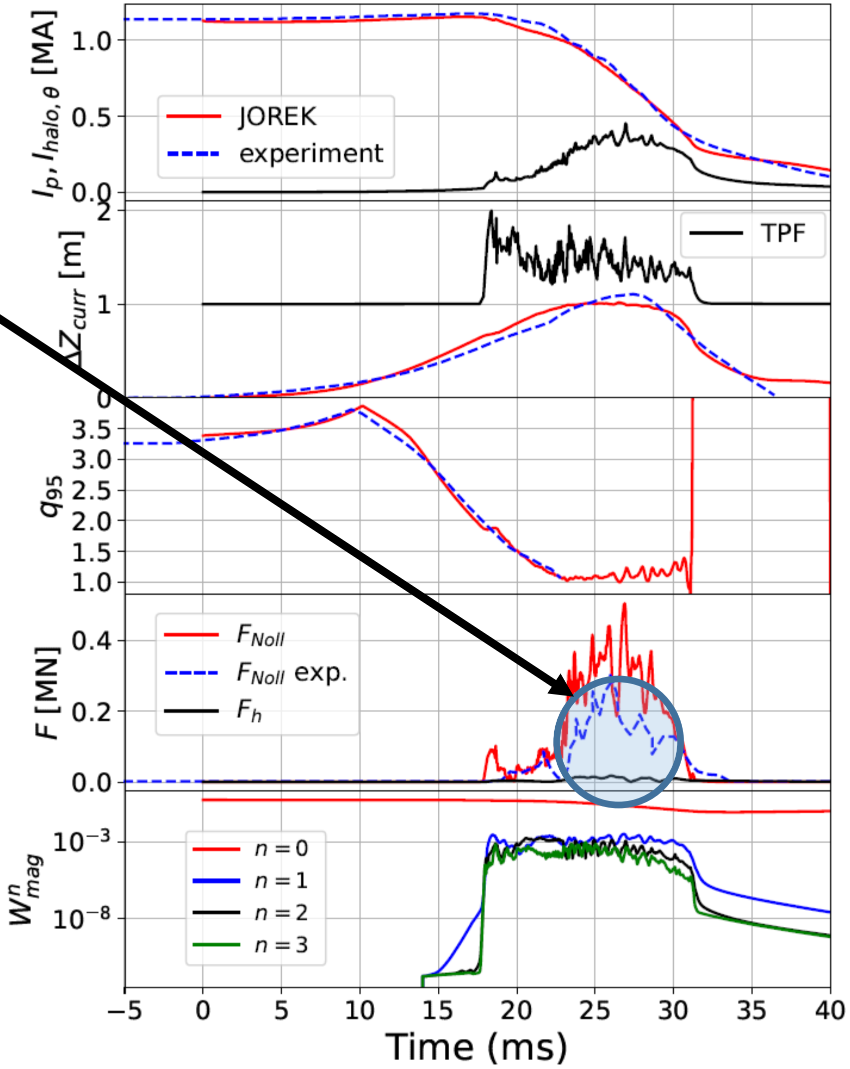
- A source & sink model [V. Riccardo, (2000) *NF,* **40** 1805] predicts

$$F_h \sim \pi a_w B_\phi \Delta I_p^{n=1} \sim F_{Noll}$$

+ inhomogeneous wall resistivity

- **The JORECK-STARWALL coupling is such that $\Delta I_p^{n=1} = 0$**

- Other models could also explain the JET force
  - ATEC model [Roccella, 2016 *NF* **56** 106010]
  - Hiro current model [Zakharov, (2012) *PoP* **9** 055703]



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VDE modelling discussion

- Several codes are available with different plasma and wall assumptions
- 3D plasma/ 3D wall frameworks start to become available
- 2D plasma models
  - ➢ Need artificial constraints when $q_{95} \leq 2$ (from 3D codes or experiments)
  - ➢ Can be directly applied if $q_{95} > 2$ (e.g. mitigated disruptions)
- 3D plasma models (needed for heat and EM load distribution)
  - ➢ Further validation and benchmarking needed
  - ➢ SOL and PWI physics typically disregarded, must be taken into account despite difficulties
  - ➢ Long time scales in future devices → use of re-scaling techniques
  - ➢ Code development needed to recover JET’s sideways force in JOREK

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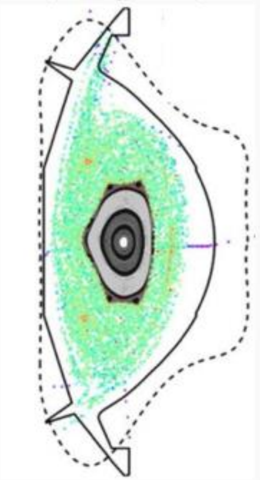
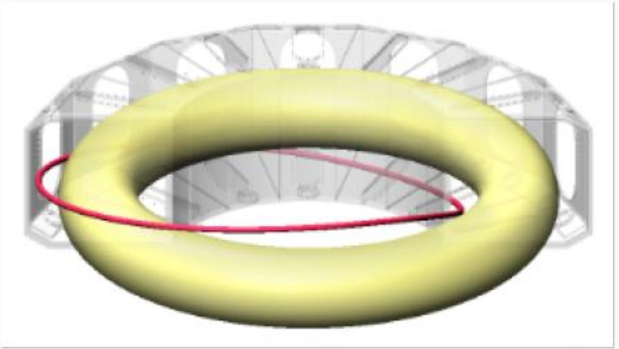
Modelling of TQ mitigation & RE loss

- One promising RE current depletion scheme is using the passive coils.
- Fast responding, strong induced external helical current helping to break flux surfaces.
  - Induced current can be $\sim$10% of initial I_p.
  - Coil responds immediately to a current quench, in accordance with Faraday's law.
- Passive coil has been selected as one of the major RE mitigation methods in SPARC and STEP
- One J-TEXT case is selected as the modelling target, where previous simple coupling between the coil and the non-RE plasma **failed to reproduce** experimental observation.
- Something is amiss……. **Coupling to the REs**?



NIMROD simulation of magnetic stochasticity formation in presence of REMC



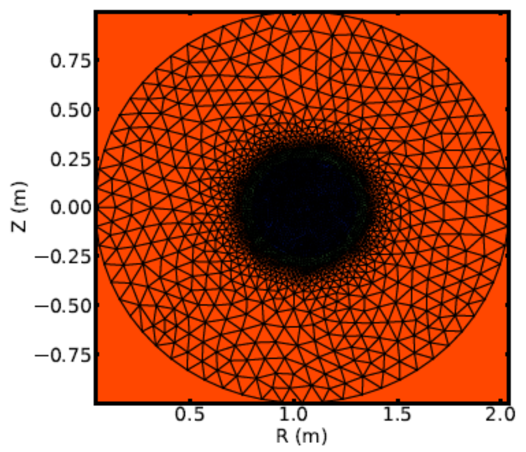
Helical coil ($n = m = 1$) installed on J-TEXT

H.M. Smith, A.H. Boozer, and P. Helander, Phys. Plasmas 20(7), 072505 (2013); R.A. Tinguely, et al., Nucl. Fusion 61(12), 124003 (2021)
A.F. Battey, et al, Nucl. Fusion 64(1), 016010 (2023); V.A. Izzo, et al., Phys. Plasmas 32(4), 042507 (2025).

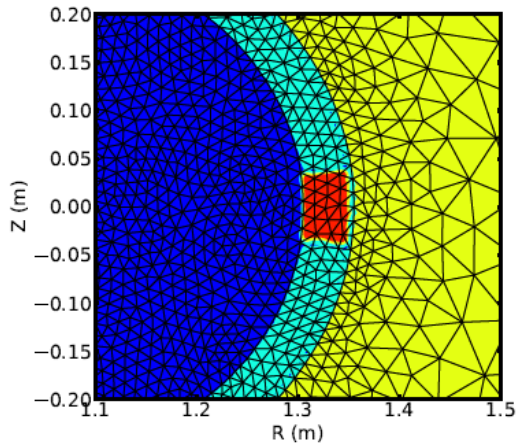
M3D-C1 grids

- A low-resistivity channel can be embedded in M3D-C1 resistive wall to model the passive coil, capturing the coupling between the plasma and the coil currents
  - Coil current can be controlled in the simulation to match results from experiments or other codes (COMSOL, ThinCurr)
- Avalanche growth of RE current and its impact on MHD instabilities is included.
  - Coil current affects both equilibrium and perturbed fields

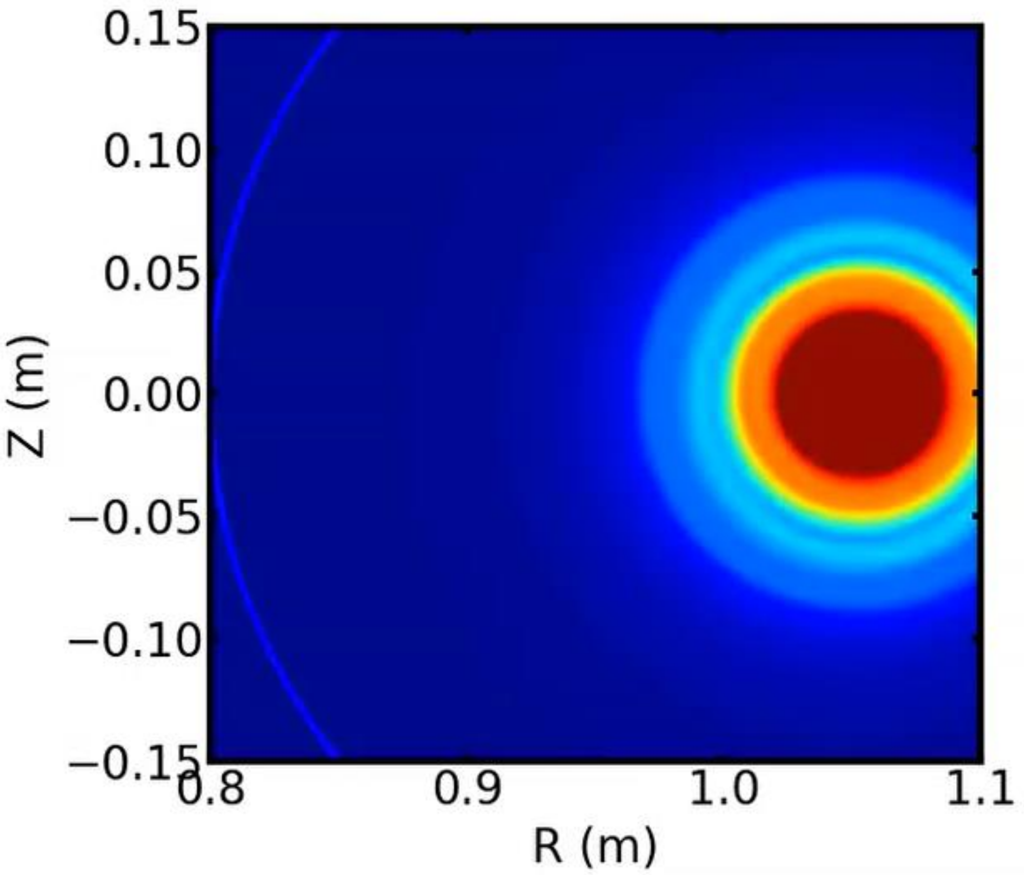
Multi-region mesh used in M3D-C1 simulation

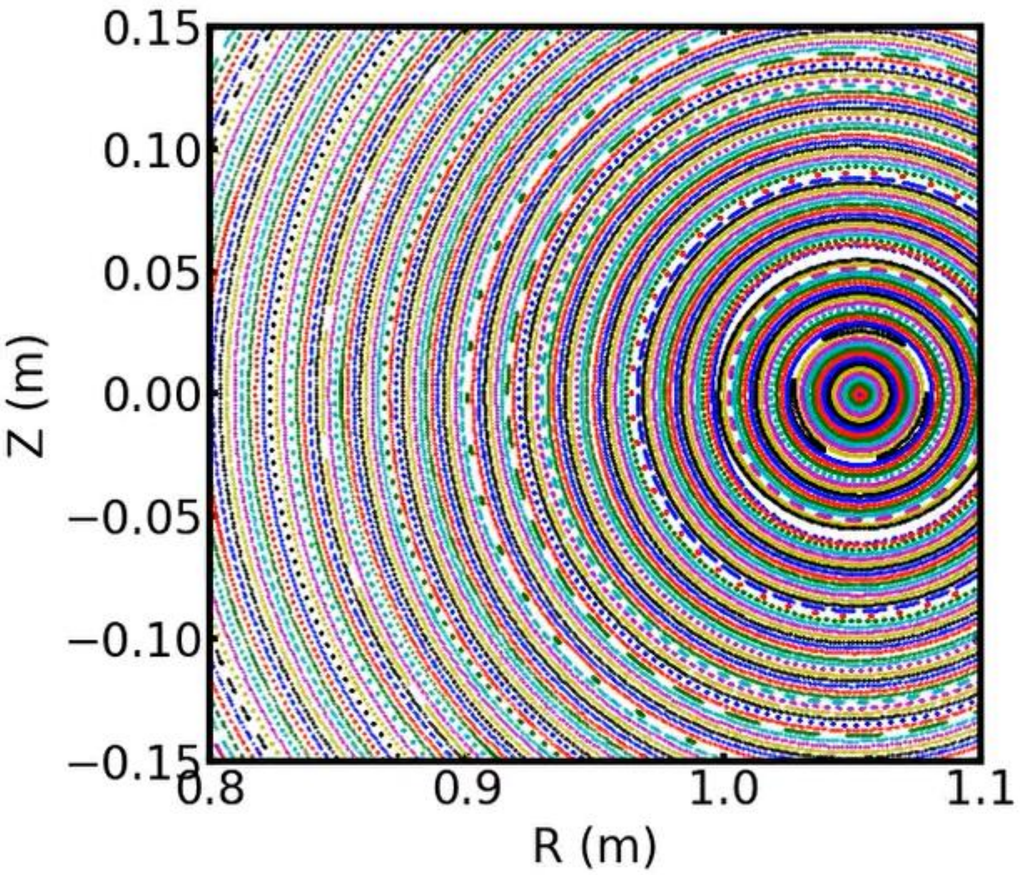


Low resistivity channel in resistive wall region



Tearing modes and RE transport

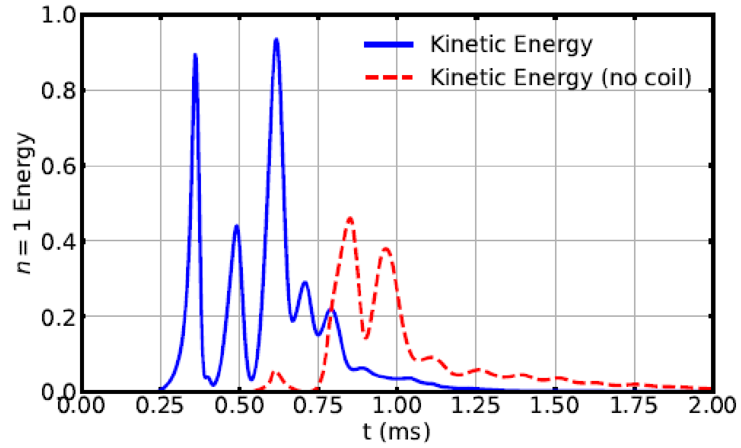




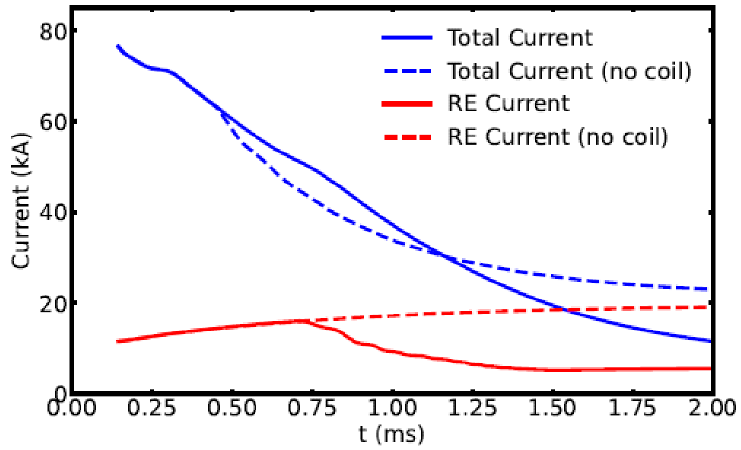
Coil-MHD synergy

- Peaked current profile (RE avalanche, Ohmic diffusion) → MHD
  - Passive coil provides seed perturbation for MHD modes to grow earlier and bigger
  - Transported REs forms a new frontier at separatrix between open and closed fluxes, triggering new instabilities
- After shifting of plasma towards HFS, $\delta\mathbf{B}$ from coil and MHD modes help maintain field stochasticity and a channel of RE loss to wall

Evolution of MHD kinetic energy

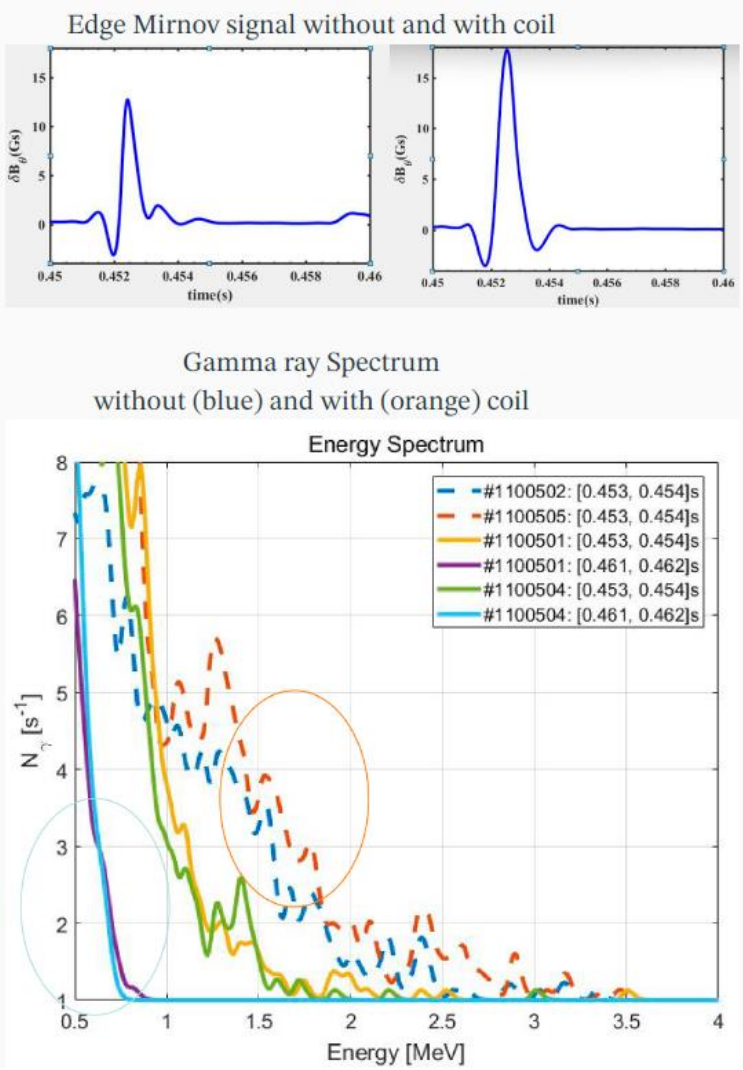


Evolution of total and RE current

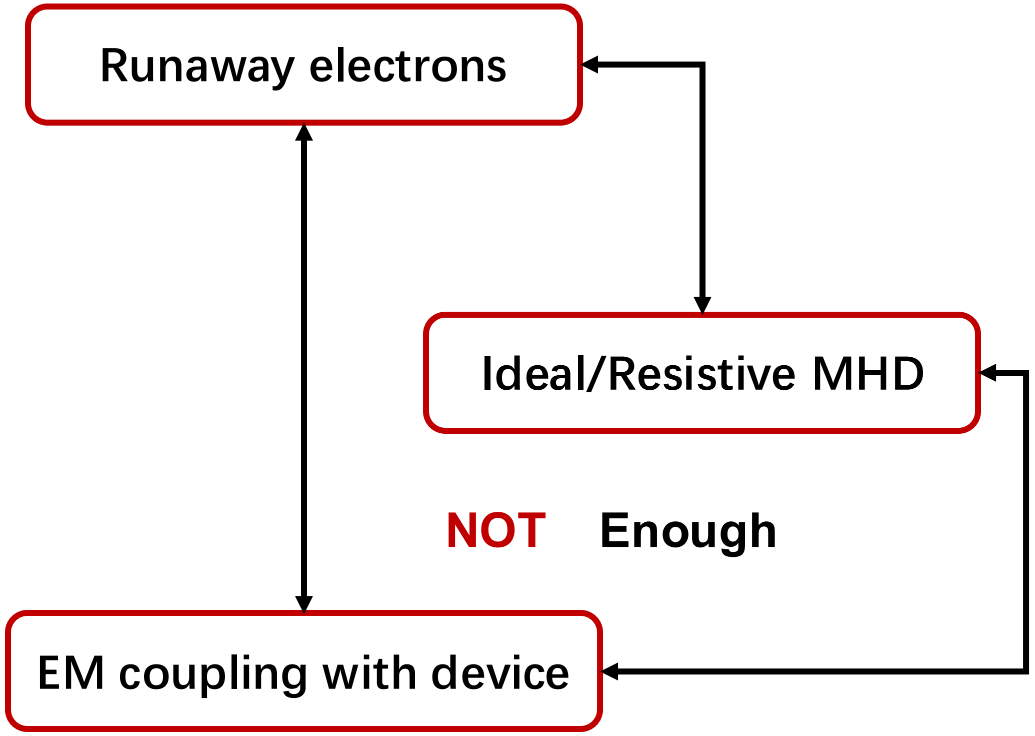


Experimental evidence

- Magnetic perturbation from Mirnov at edge shows fluctuations in shots w/o and with coil, indicating excitation of MHD modes in both cases.
  - δB about 30% larger in the coil-enabled shot
- RE became more energetic in the coil-enabled shot, according to gamma-ray spectrum
  - Parallel electric field $\boldsymbol{E}_{\parallel} = \eta(\boldsymbol{J} - \boldsymbol{J}_{\boldsymbol{RE}})$ is stronger for coil-enabled case (due to loss of RE) , which helps RE acceleration.



Discussion



- The helical coil installed in J-TEXT illustrated successful mitigation of RE plateau. However, there is a discrepancy with simulation modeling **if only considering magnetic perturbations from coils**.
- J-TEXT CQ simulation shows that MHD instability in presence of **RE current plays pivotal role** of forming magnetic islands and stochastic fields, and facilitating RE transport. The passive coil plays a **supporting role** of amplify the mode growth and maintain field stochasticity.
- **Integrated modelling is essential**!

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Contents

- Introduction： tokamak, disruptions & their mitigation
- Importance of the integrated modelling
- Components of the integrated modelling
- Case studies of disruption mitigation simulations
  - TQ mitigation & associate seed RE transport modelling in ITER
  - VDE & sideway forces during the CQ
  - RE current mitigation by passive coils
- Conclusion & discussion

Discussion

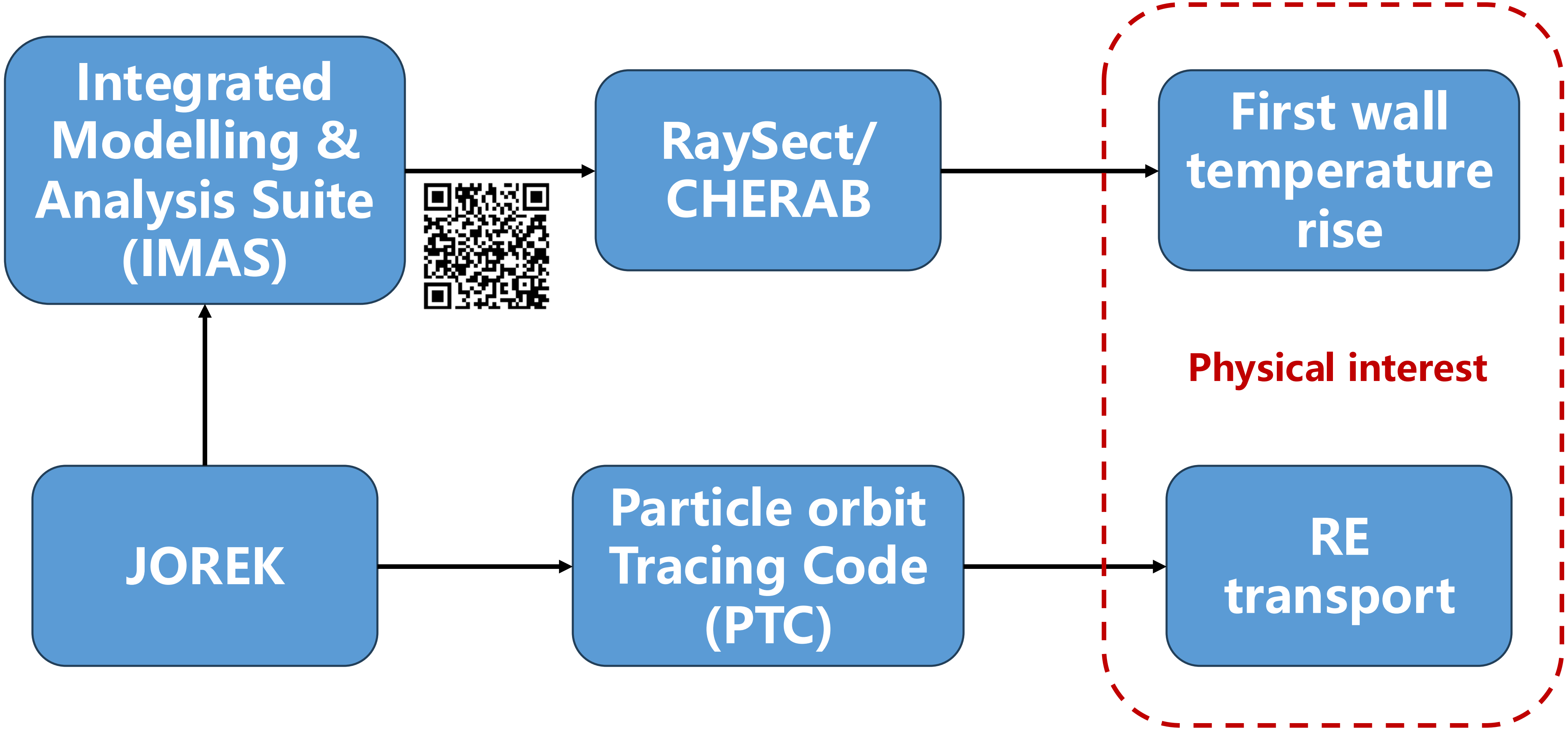
- **Integrated modelling of disruption is essential** for future devices.
- The modelling of disruption and its mitigation are inherently difficult due to their **multi-scale** and **multi-physics** nature, but also important.
- The various physics involved could be **strongly coupled and inseparable**, hence the importance of integrated modelling.
- Significant progress has been made regarding the disruption modelling, with specialized numerical tools coupled to each other or through the integrated modeling platform.
- Several examples have been shown to demonstrate the high-fidelity capability of modern integrated modelling tools, as well as their limitation and challenges.

Discussion

- One natural question: is it always better to add in yet another physics? Would there be an end to the addition of the integrated model?
- Where does one stop? When should one be happy?
  - Physics estimation, order of magnitude analyses……
  - Numerical verification……
  - **Experimental validation**……
- The integrated modelling of disruption is ongoing work and faces many challenges, but crucial for the safe operation of future high-performance devices such as ITER.

Backup Slides

The code dependency



D. Hu *et al* Nucl. Fusion **64** (2024) 086005;

Simulation setup

We consider two kinds of equilibria: the baseline and the “degraded” H-mode. The latter represents the H-L back transition in the precursor phase. The thermal energy is 370MJ and 190MJ respectively

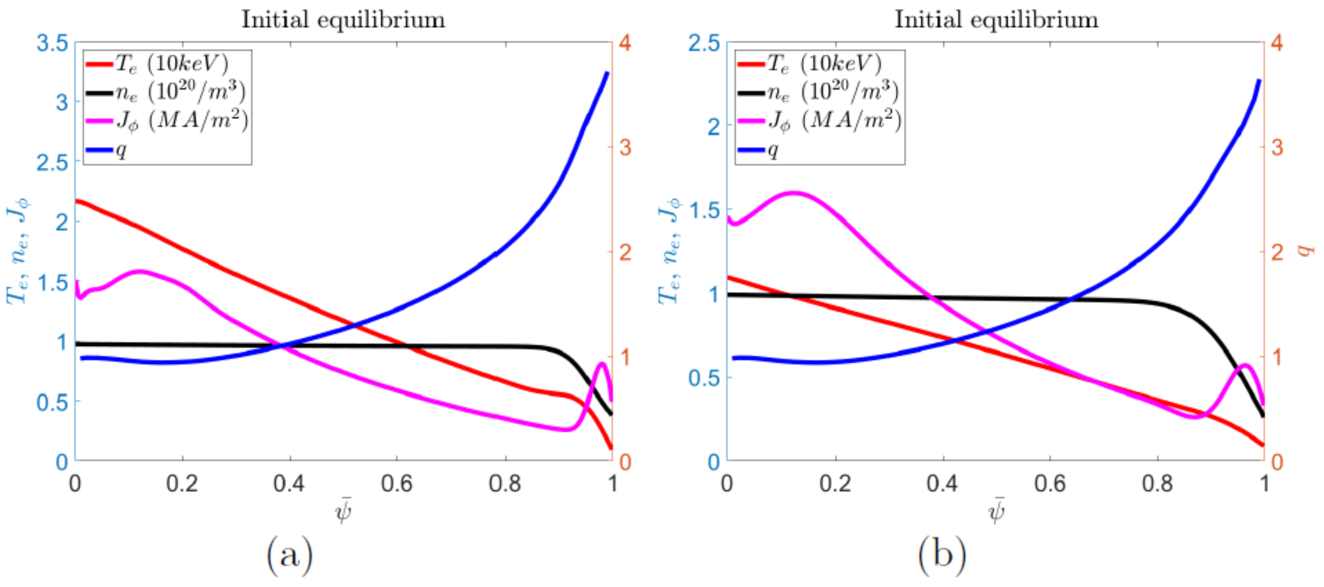
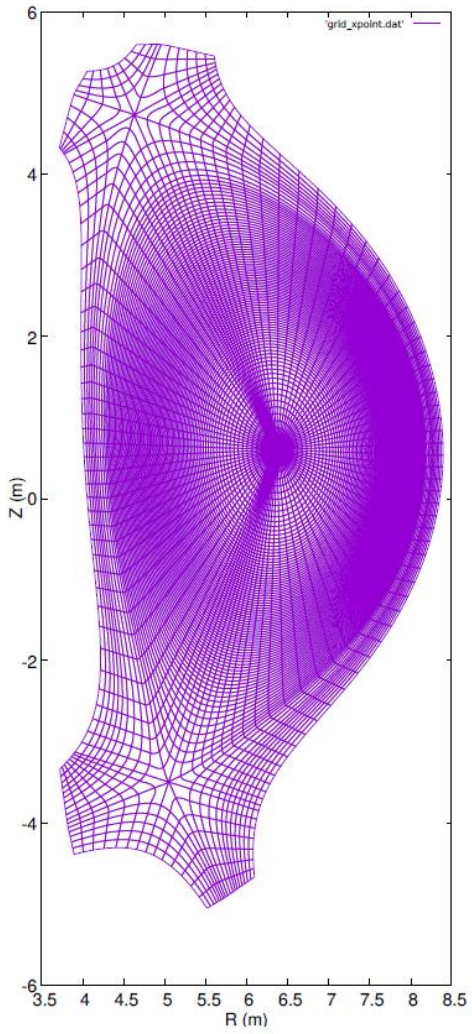


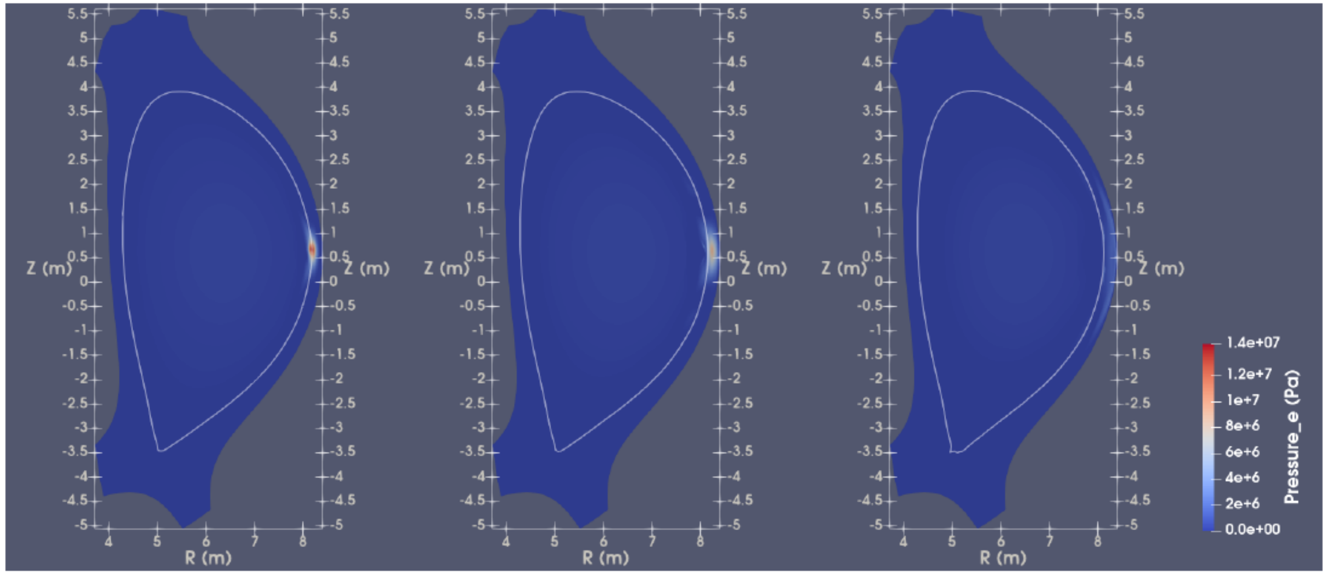
Figure 1. The initial equilibria of (a) the baseline H-mode and (b) the degraded H-mode, $\bar{\psi}$ is the normalized poloidal flux.



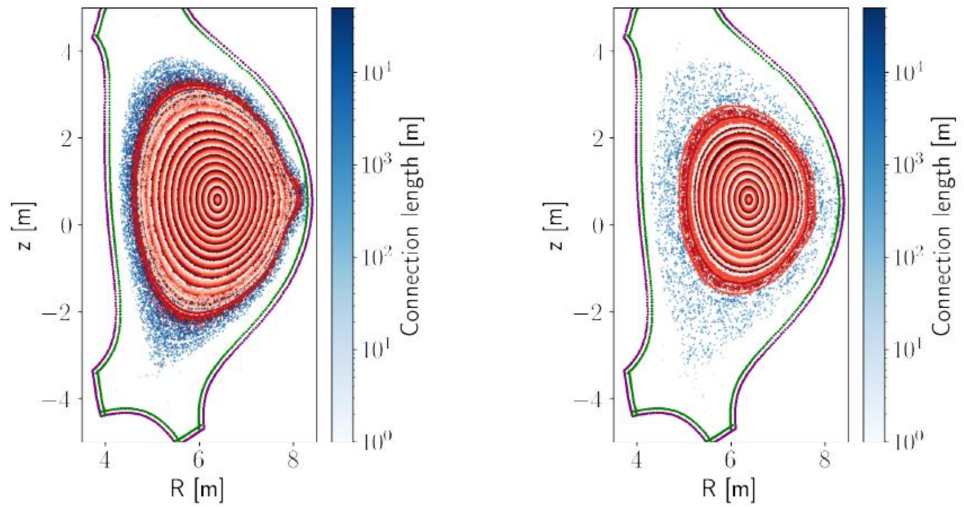
D. Hu *et al* Nucl. Fusion **64** (2024) 086005

Plasmoid drift & MHD

- Local over-pressure close to the fragment plume could occur as soon as the fragments arrive on the pedestal for the baseline H-mode case, drive polarization and plasmoid drift along major radius.
- The drift motion is accompanied by edge stochasticity and heat flux.
- **Direct SPIs into "healthy" H-mode might be challenging。**



(a) (b) (c)



(a) (b)

D. Hu *et al* Nucl. Fusion 64 (2024) 086005

The energy impact threshold

- The ITER window SS plate melting threshold is about $13MJm^2s^{-1/2}$
- The beryllium threshold is about $28MJm^2s^{-1/2}$
- Exceeding the melting threshold is acceptable under certain circumstances. Exposing the ITER SS window plate under $22MJm^2s^{-1/2}$ heat pulse results in 1-2 micrometers of surface roughening, without significant mass loss.

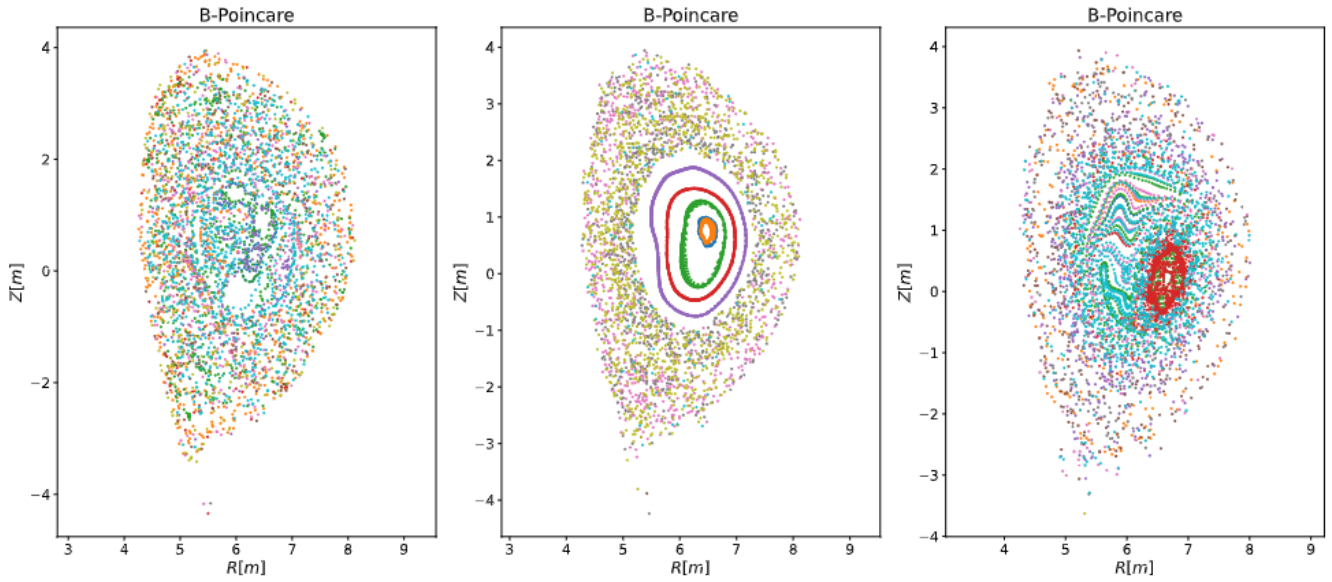
Table 1. Material data (at 1000°C) and energy impact for selected target materials.

Material	Heat conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)	Heat penetration coefficient ($\mathrm{kW\,s^{1/2}\,m^{-2}\,K^{-1}}$)	Temperature change (K)	Energy impact ($\mathrm{MW\,s^{1/2}\,m^{-2}}$)
Graphite (EK98)	49	13	1300	15
CFC (N11)	90	16	1300	18
Tungsten	110	16	2400	38

A Herrmann, Plasma Phys. Control. Fusion 44 (2002) 883–903; R.A. Pitts et al. J. Nucl. Mater. 463 (2015) 748–752

PTC simulation based on JOREK results

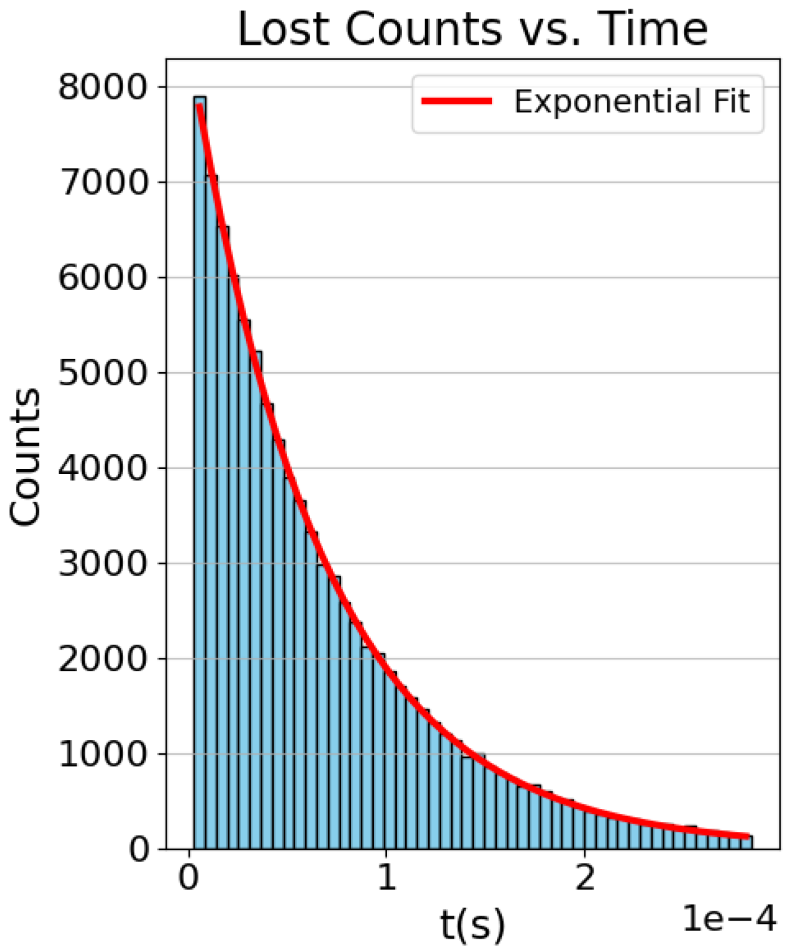
- A few characteristic time slices are chosen to be used as the background field for test particle transport simulations.
- In general, we found the RE characteristic loss time to be smaller than the evolution time of the stochastic field.
- The transport is directly linked to the stochasticity, as expected.



(b) t=4.839ms (c) t=7.139ms (d) t=8.433ms

Characteristic loss time

With sufficiently stochastic magnetic field (DH-QP-dt1, **4.839ms**):



The RE loss exhibit good **exponential feature**

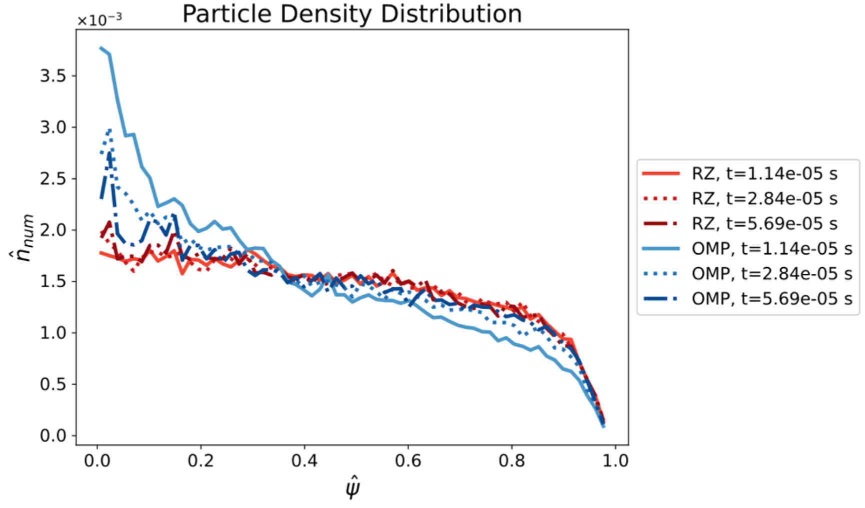
RE loss rate：

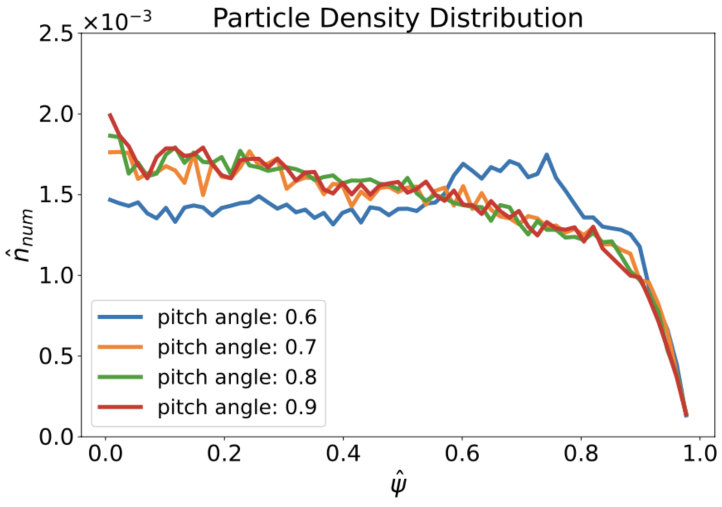
$$\mathrm{N}_{loss}(t) = -\frac{dN(t)}{dt} = \frac{1}{\tau} \cdot N_0 \cdot \exp\left(-\frac{t}{\tau}\right)$$

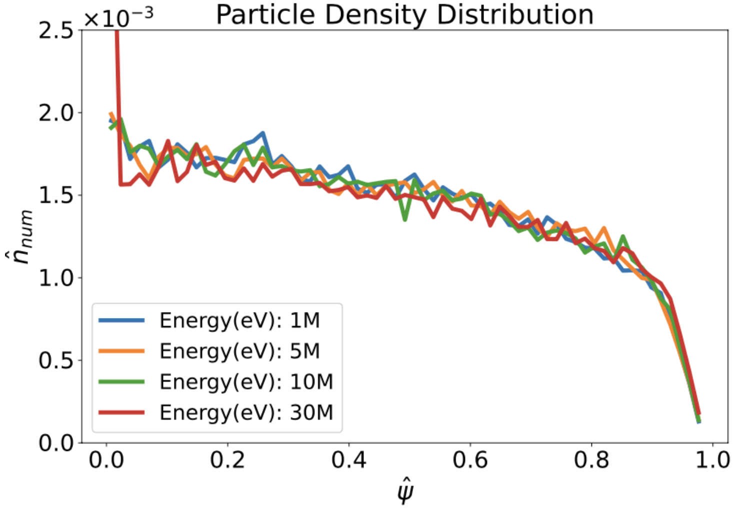
The characteristic loss time $\tau = 6.6547 \times 10^{-5} s$. This timescale is much shorter than the MHD evolution time. The fitting coefficient：$R^2 = 0.9996$

Self-similar RE profile

- With sufficiently stochastic field (DH-QP-dt1, 4.839ms) , the RE density profile evolves towards a **self-similar** one, consistent with the exponential RE loss. The characteristic timescale to reach such a profile is about $50\mu s$. Faster than the MHD evolve time.
- **Independent of pitch angle and energy so long as passing.**
- Depends on the level of stochasticity.







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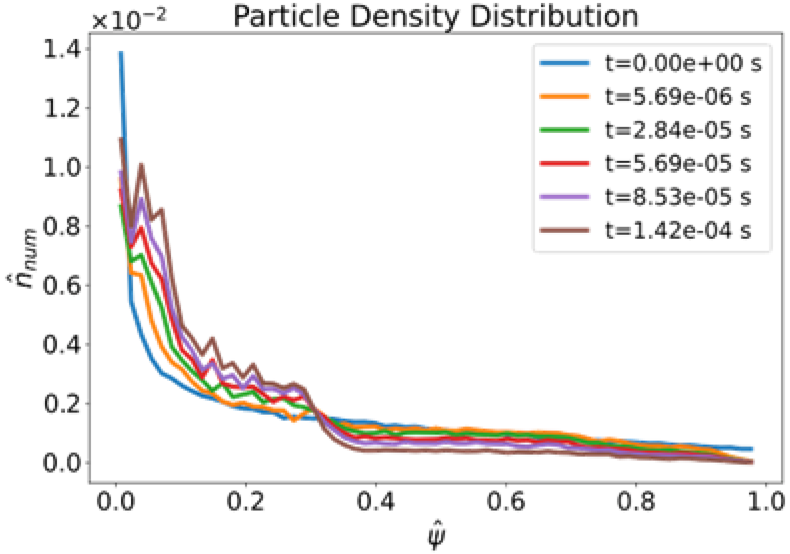
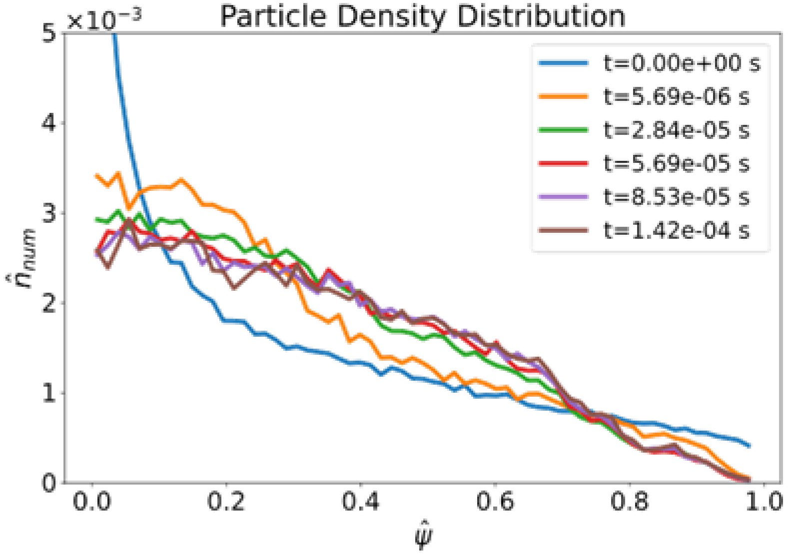
Self-similar RE profile

- Partially healed flux surfaces break such self-similar profile…….
- Pitch angle = 0.9, $E = 5MeV$, a): DH-QP-dt1, 7.139ms; b): DH-QP-dt1, 8.433ms
- The normalized RE core profile becomes more peaked as the RE confinement there is relatively better.



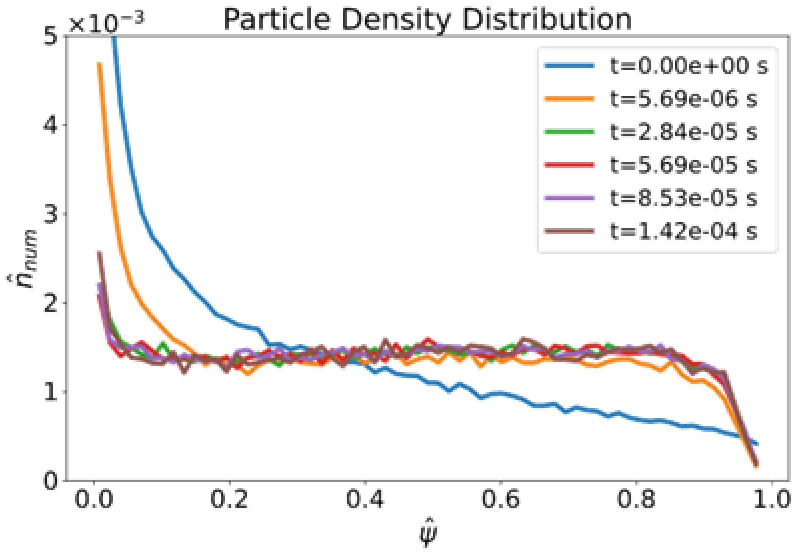
(a)



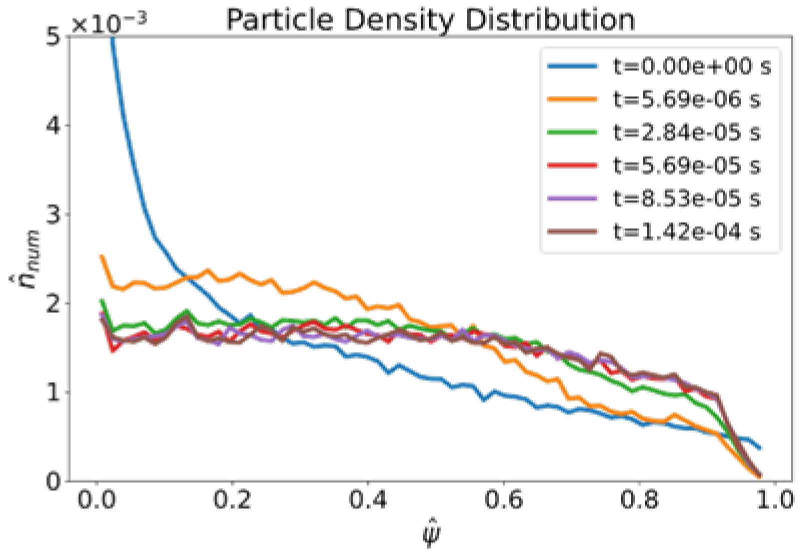
(b)

Self-similar RE profile

- The exact shape of the self-similar profile **depends on the magnetic field**.
- Pitch angle = 0.9, E = 5 MeV。(a): DH-QP-dt0, 9.499ms; (b): DH-QP-dt0-120, 4.863ms, both cases with sufficiently stochastic magnetic field。
- Despite the difference in the ultimate profile, both cases reach their respective self-similar profile.



(a)



(b)

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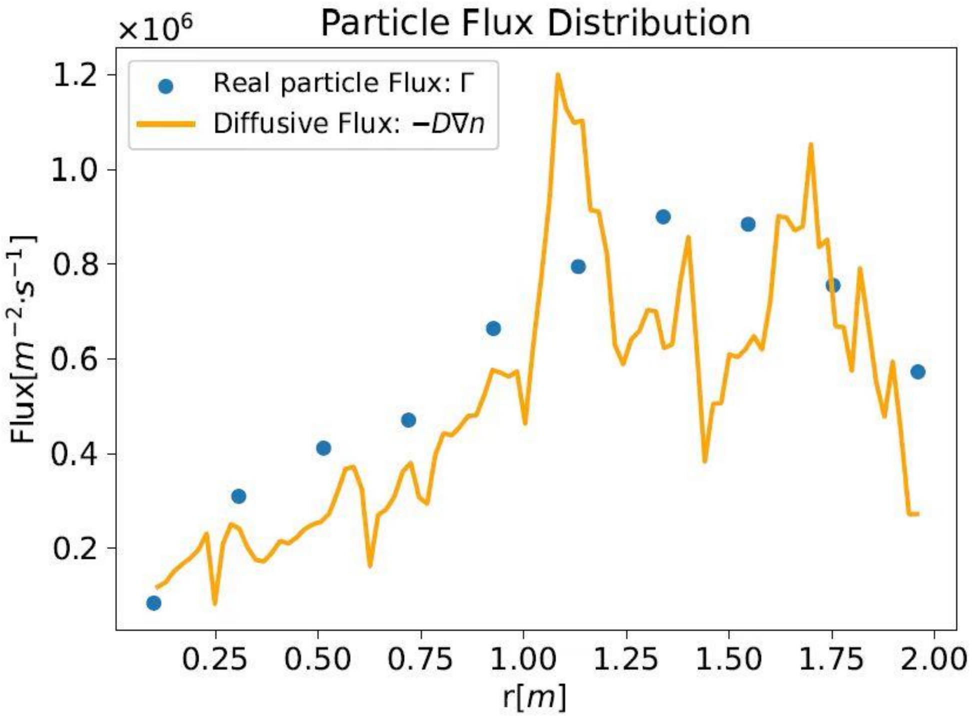
The diffusive RE flux

Tracing the variance of the Poincare points, one could extract the RE transport coefficients [1] ：

$$K_{r_0} = \frac{\mu_r - r_0}{\tau}, \qquad D_{r_0} = \frac{\sigma_r^2}{2\tau},$$

It is found that the **diffusive flux** $\Gamma = -D\nabla n$ reproduce the general trend and order of magnitude of the total particle flux.

Some deviation might be due to the noise in ∇n.



[1]K. Särkimäki, et al, Confinement of passing and trapped runaway electrons in the simulation of an ITER current quench, Nucl. Fusion 62 8 (2022) 086033

RE transport simulation discussion

- The RE density profile exhibit **self-similar feature** during their transport within sufficiently stochastic magnetic field. This coupled with the exponential density decay suggest a transport eigen-mode.
- The self-similar profile is mostly **independent of the RE energy, initial distribution and pitch angle** (so long as they are passing), but **depends on the stochastic field**. The convergence time to this self-similar profile is faster than the MHD evolution time.
- The total RE flux could be explained by a pure **diffusive flux** relatively well, given that the field is sufficiently stochastic. The statistical diffusion coefficient reproduce the trend predicted by the RR model.
- **Future challenges: RE coupling to the MHD once they becomes dominant current carrier, the high momentum orbit drift……**

When do VDEs occur?

Unmitigated disruptions

Conduction / convection dominate energy loss

Major disruptions

Plasma instability (e.g. locked mode)
↓
Thermal quench
↓
VDE
↓
Current quench

Hot VDEs

Loss of vertical control
↓
VDE
↓
Thermal quench
↓
Current quench

→ **Case used for next example**

Mitigated disruptions

Radiation dominates energy loss

Impurity injection
↓
Thermal quench (Radiative collapse)
↓
Current quench + **VDE**

F.J. Artola t al., 49th EPS, Bordeaux 3-7 July 2023

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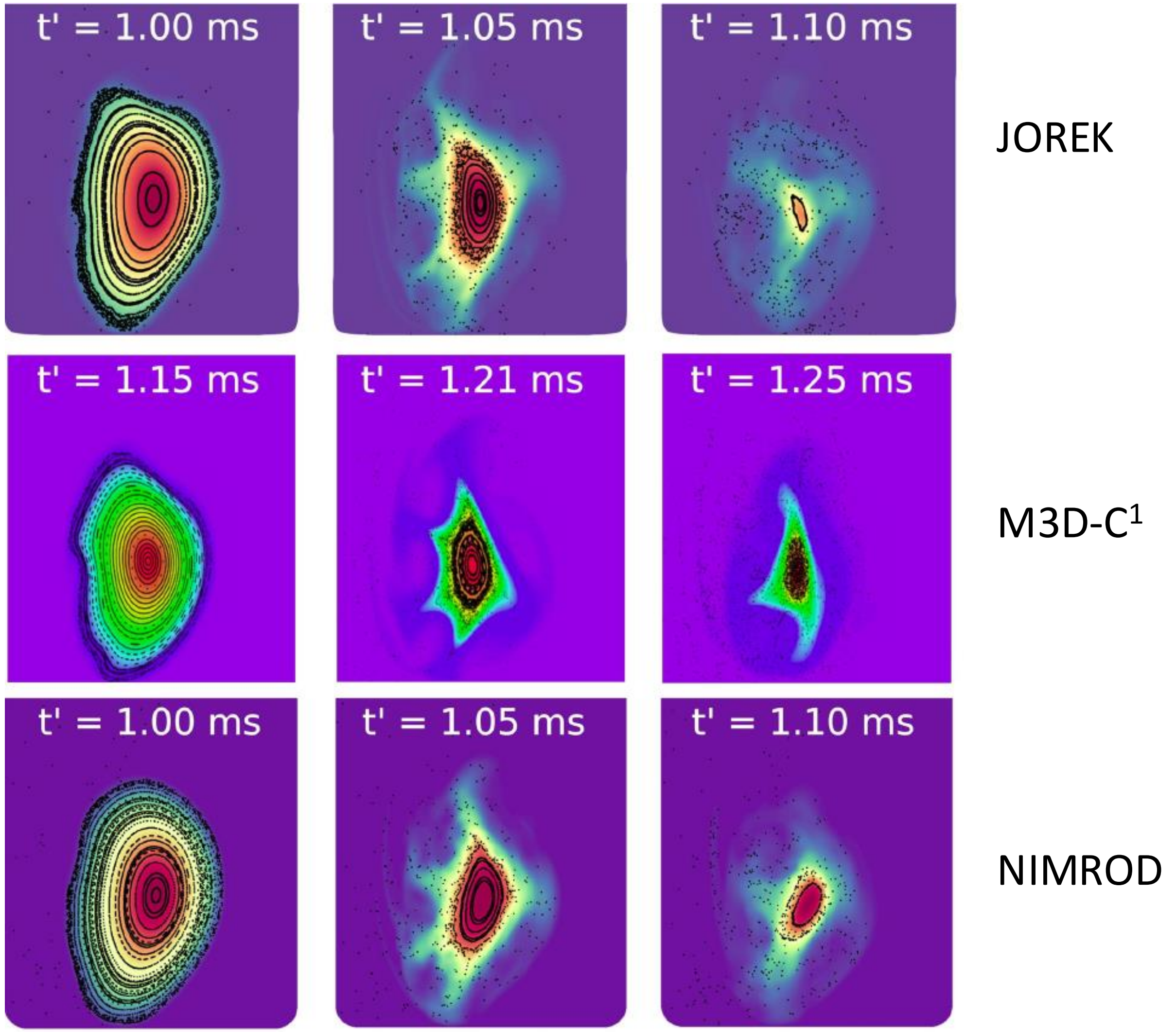
Benchmark activities

Examples of 2D benchmarks (not a complete list)

- Miyamoto, et al, *"Inter-code comparison benchmark between **DINA and TSC** for ITER disruption modelling"*, Nucl. Fusion 54 083002 (2014)
- Isernia, N., et al. "*Cross-validation of analytical models for computation of disruption forces in tokamaks.*" Plasma Physics and Controlled Fusion 61.11 (2019)
- Krebs, I. et al, *"Axisymmetric simulations of vertical displacement events in tokamaks: A **benchmark of M3D-C1, NIMROD, and JOREK**"*, Phys Plasma 27, 112505 (2020)

3D benchmark - Artola, F.J. *"3D simulations of vertical displacement events in tokamaks. A benchmark of M3D-C1, NIMROD and JOREK"*, Phys Plasma 28 052511 (2021)

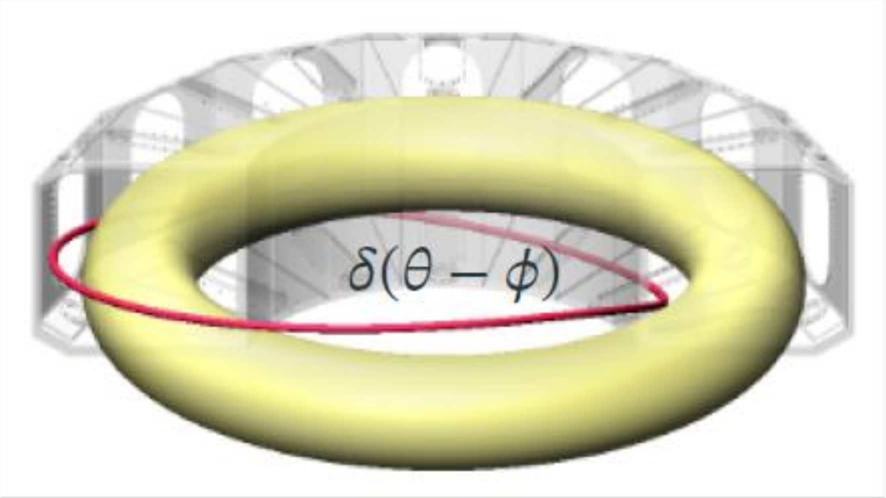


<u>Pressure heat map during the TQ induced by a VDE</u>

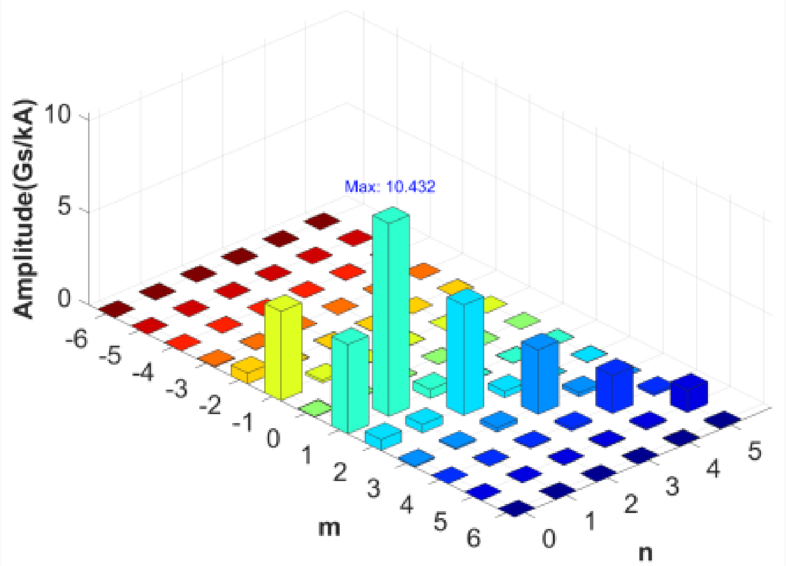
F.J. Artola t al., 49th EPS, Bordeaux 3-7 July 2023

Modelling challenge

- Simply coupling the external coil to a non-RE current plasma fails to produce significant stochasticity again after the flux surfaces healed.
- Something is amiss…… **the coupling to the RE current carrier?**



Helical coil ($n = m = 1$) installed on J-TEXT



Spectrum of $\delta\mathbf{B}$ calculated from helical coil

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Fluid representation of the RE current

- The RE current could be represented as a separate fluid, provided the current carrier momentum is not too high.

$$\frac{\partial n_{RE}}{\partial t} + \nabla \cdot \left[n_{RE} \left(c\boldsymbol{b} + \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2} \right) \right] = S$$

$$nm \left[\frac{\partial \boldsymbol{V}}{\partial t} + (\boldsymbol{V} \cdot \nabla)\boldsymbol{V} \right] = e n_{RE} \boldsymbol{E} + (\boldsymbol{J} - \boldsymbol{J}_{\boldsymbol{RE}}) \times \boldsymbol{B} - \nabla p$$

$$\boldsymbol{E} + \boldsymbol{V} \times \boldsymbol{B} = \eta (\nabla \times \boldsymbol{B} - \boldsymbol{J}_{\boldsymbol{RE}})$$

$$\boldsymbol{J}_{\boldsymbol{RE}} = -e n_{RE} \left(c\boldsymbol{b} + \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2} \right)$$

P. Helander, D. Grasso, R.J. Hastie, et al., Phys. Plasmas 14, 122102 (2007);
C. Liu, C. Zhao, S.C. Jardin et al., Plasma Phys. Control. Fusion 63(12), 125031 (2021).