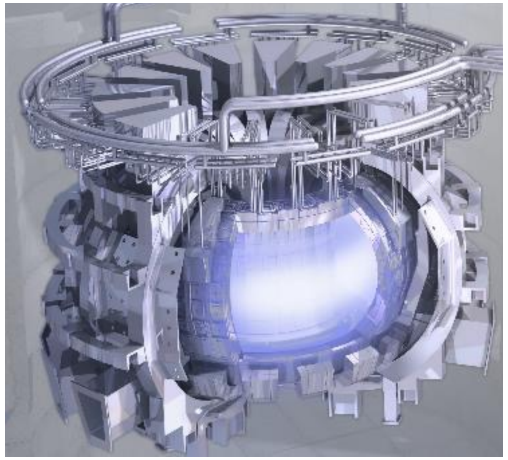
Integrated simulations of disruption mitigation and runaway electrons in ITER and DEMO Project: [INDEXBA]



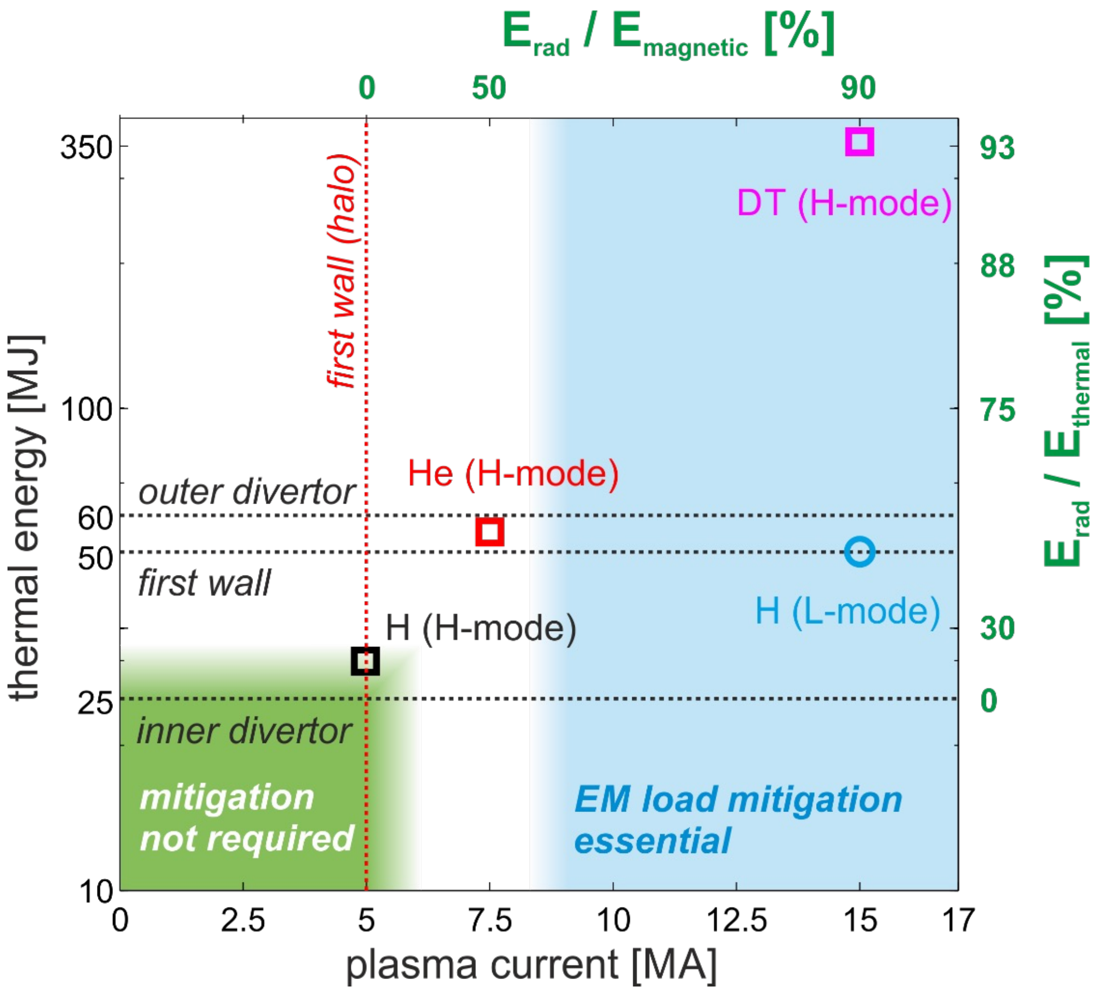
A. Matsuyama and Y. Yamamoto

QST Rokkasho Institute

IFERC-CSC Workshop on JFRS-1 Projects, May 13 2022@MS Teams

Disruption Mitigation System is a key plant to ensure successful operation in ITER and beyond

- FIG: ITER parameter range and the tolerance to the disruption loads



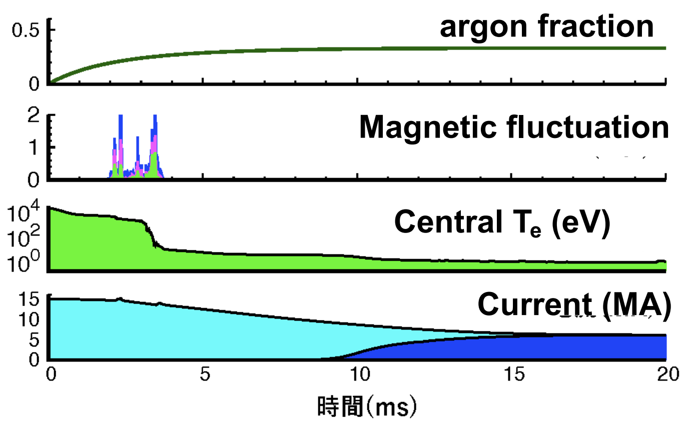
Disruption mitigation will be commissioned from early operation and is even essential for the routine operation towards mission goal (Q=10).

The ITER Research Plan:
ITR-18-003
https://www.iter.org/technical-reports

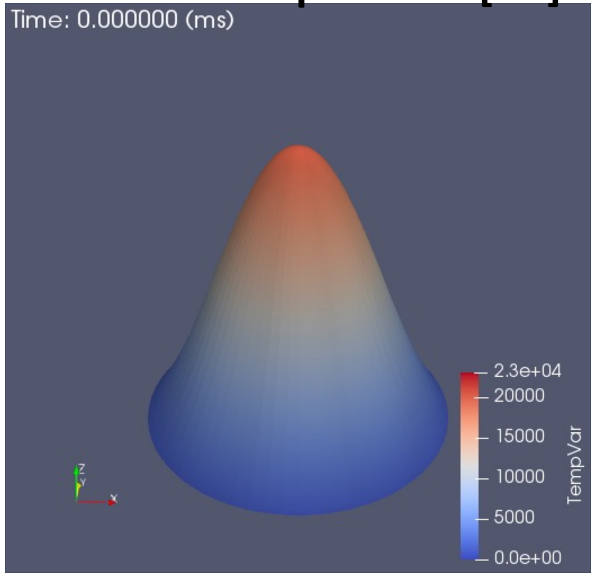
Early results of INDEX project: MHD simulation of runaway electrons

- Disruption mitigation that is not optimized is even harmful because it drives significant runaway generation

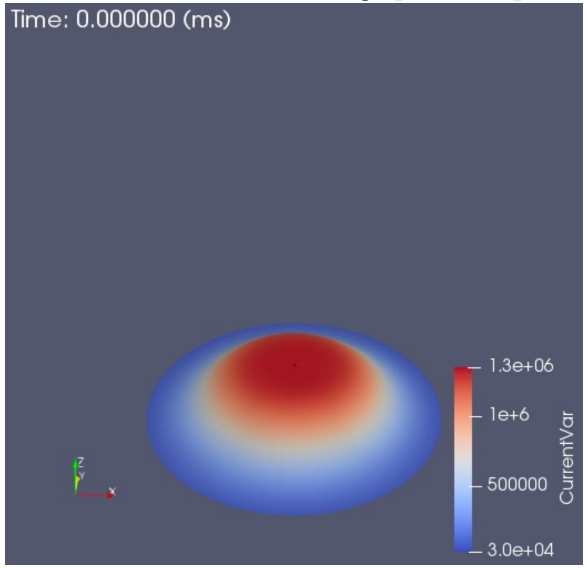
Radiative cooling ⇨ **Unstable j profile** ⇨ **T_e collapse**



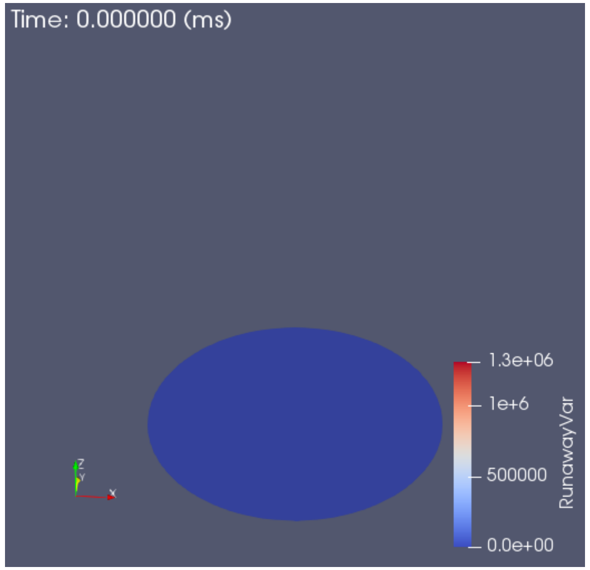
Electron Temperature [eV]



Current density [A/m²]



Runaway Electrons [A/m²]



EXTREMe code [Matsuyama+ IAEA-FEC2018 TH/4-2], a pioneering code for runaway electron fluid model

Focus of this project – History of the JA disruption project

- **BA phase1:** IFERC-CSC Helios [DISRUPT] – JFRS-1 [INDEX]

  Simulation of the phenomenology, thermal quench, vertical displacement events, runaway electron generation, etc.

  – Matsuyama+ IAEA-FEC2018 TH/4-2 (oral)

- **BA phase II:** IFERC-CSC JFRS-1 [INDEXBA] + DEMO design activity (DDA)

  Focus is placed on designing the mitigation scheme towards ITER and DEMO

  – Matsuyama+ IAEA-FEC2020 TH/P3-12 (poster)

→ Direct link to ITER DMS Task Force and JA-EU Joint DEMO design activity

Outline

1. Disruption simulations in support of the physics validation of ITER Disruption Mitigation System

2. Development of runaway electron simulation for EU-JA Joint Activity on Characterization of RE wall loads in DEMO

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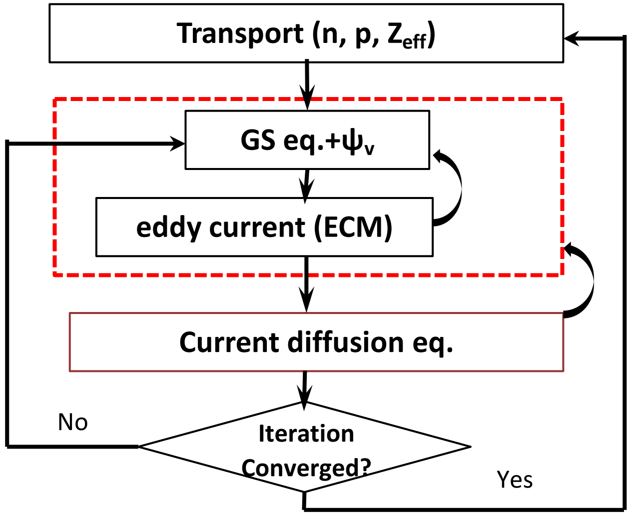
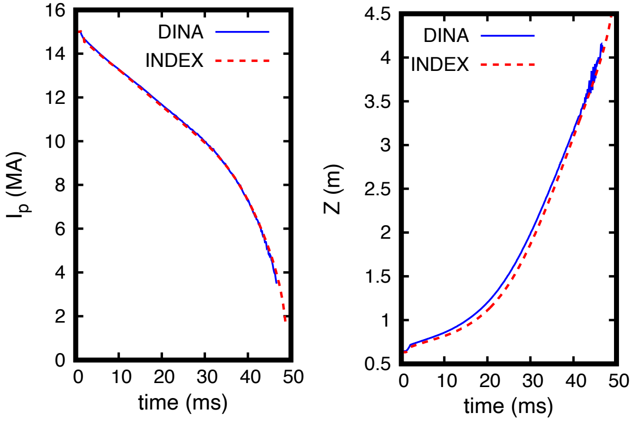
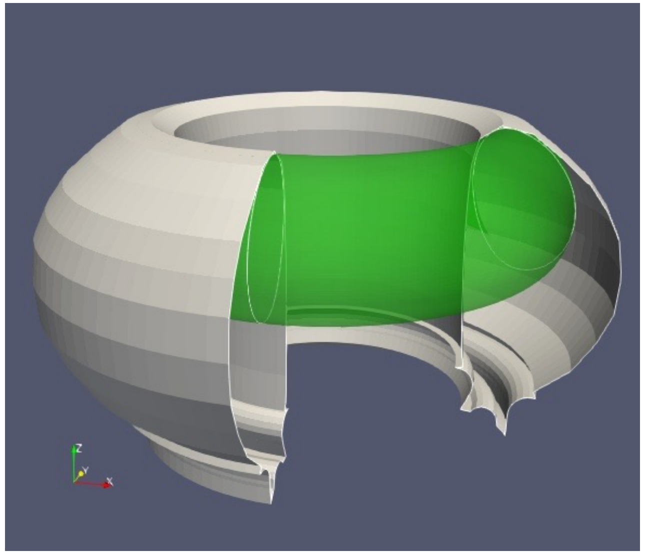
INDEX (Integrated Numerical Disruption EXperiment code)

- **Core plasma model:** 1.5D tokamak model coupled to the external circuit model for the PF/CS coils + eddy currents → Self-consistent VDE + Current Quench model



Benchmark with DINA code for ITER upward VDE



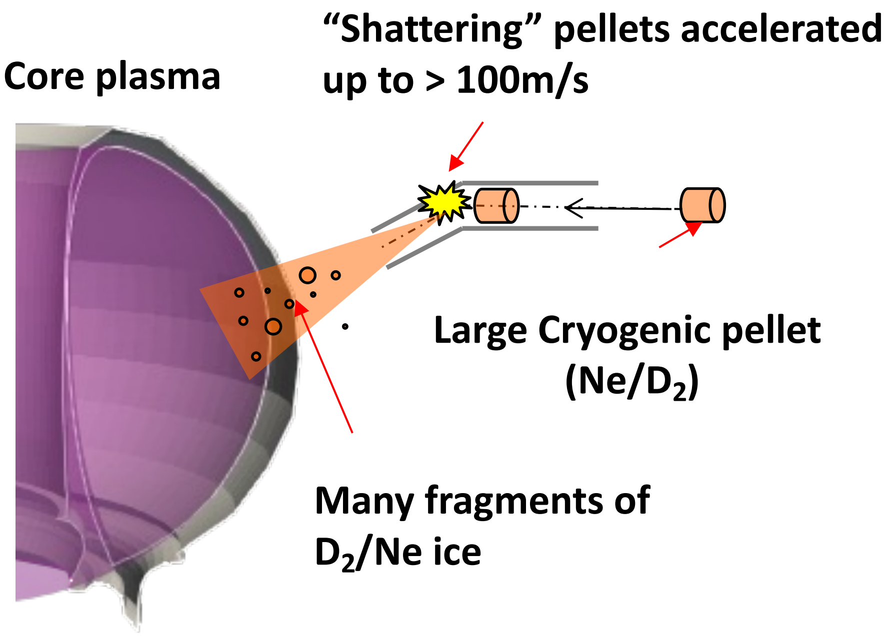


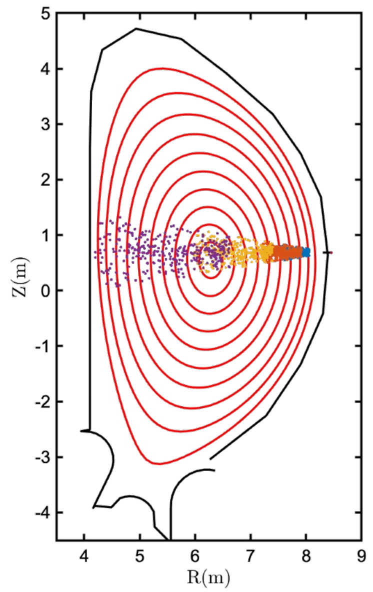
INDEX (Integrated Numerical Disruption EXperiment code)

DEMO DESIGN JOINT SPECIAL TEAM

- **Core plasma model:** 1.5D tokamak model coupled to the external circuit model for the PF/CS coils + eddy currents → Self-consistent VDE + Current Quench model

- **Actuator:** Particle tracking to model the Shattered Pellet Injection (SPI) → Forced thermal quench by radiation



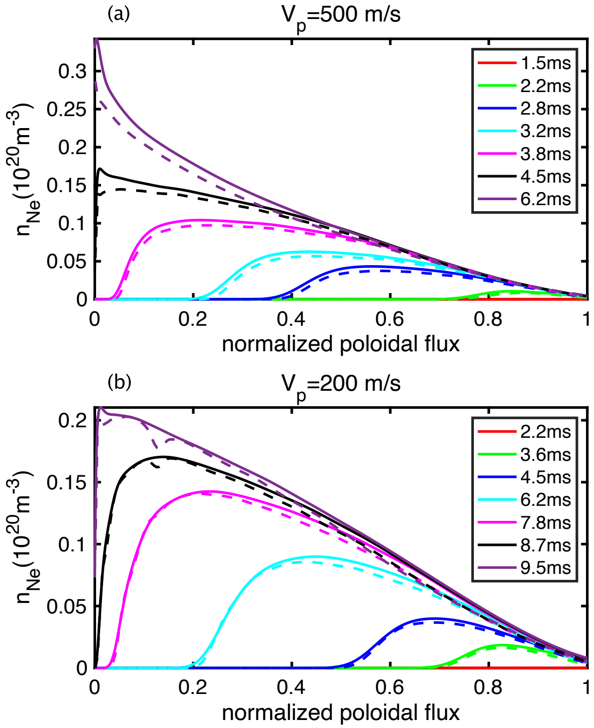


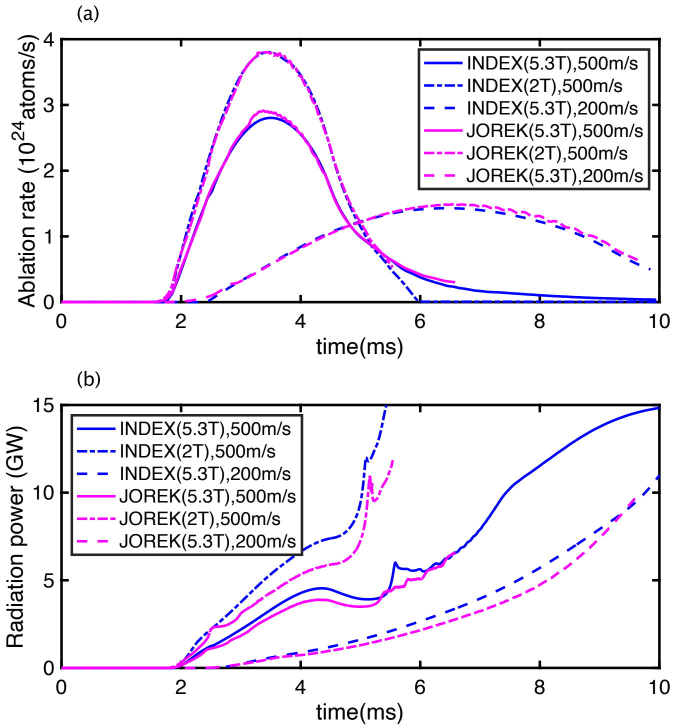
Update the position of fragments → Give the density and temperature → Calculating the ablation rate → the pellet surface recession

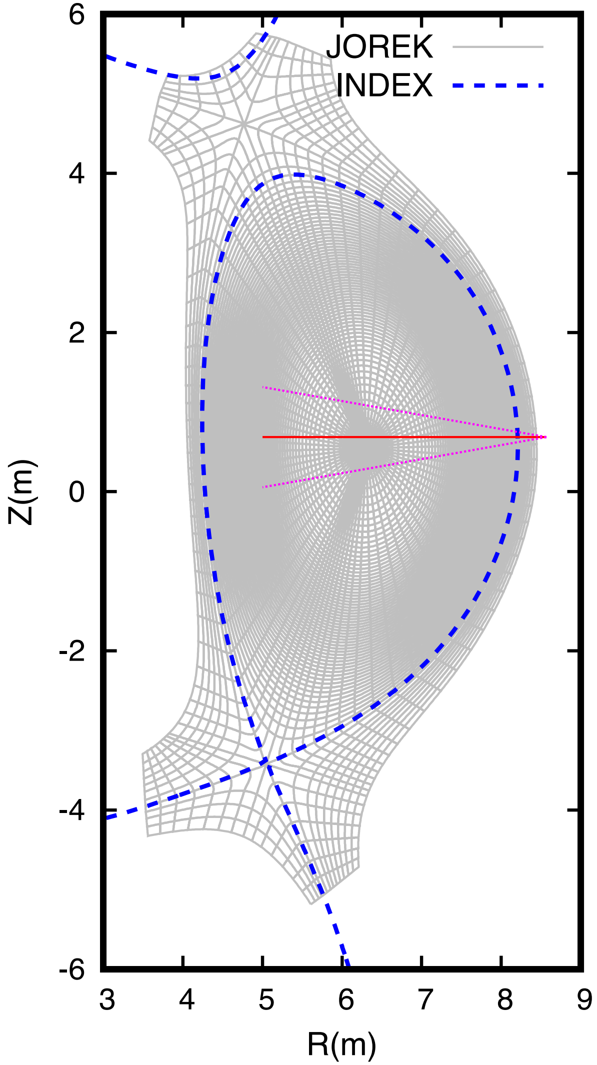
Calculating the ablation rate → Get surface averaged particle source → Update plasma prof. and 2D equilibrium

Recent progress on the project – Code verification with JOREK simulations

- Successful code benchmark with JOREK Axisymmetric SPI simulation [Hu+, NF2018/2021] for 5% Neon / 95% Hydrogen injection into ITER 15 MA Hydrogen L-mode case
  - Contributing to ITER DMS design validation







[Matsuyama+, submitted to PPCF]

Recent progress on the project – Assessment of key trends in ITER

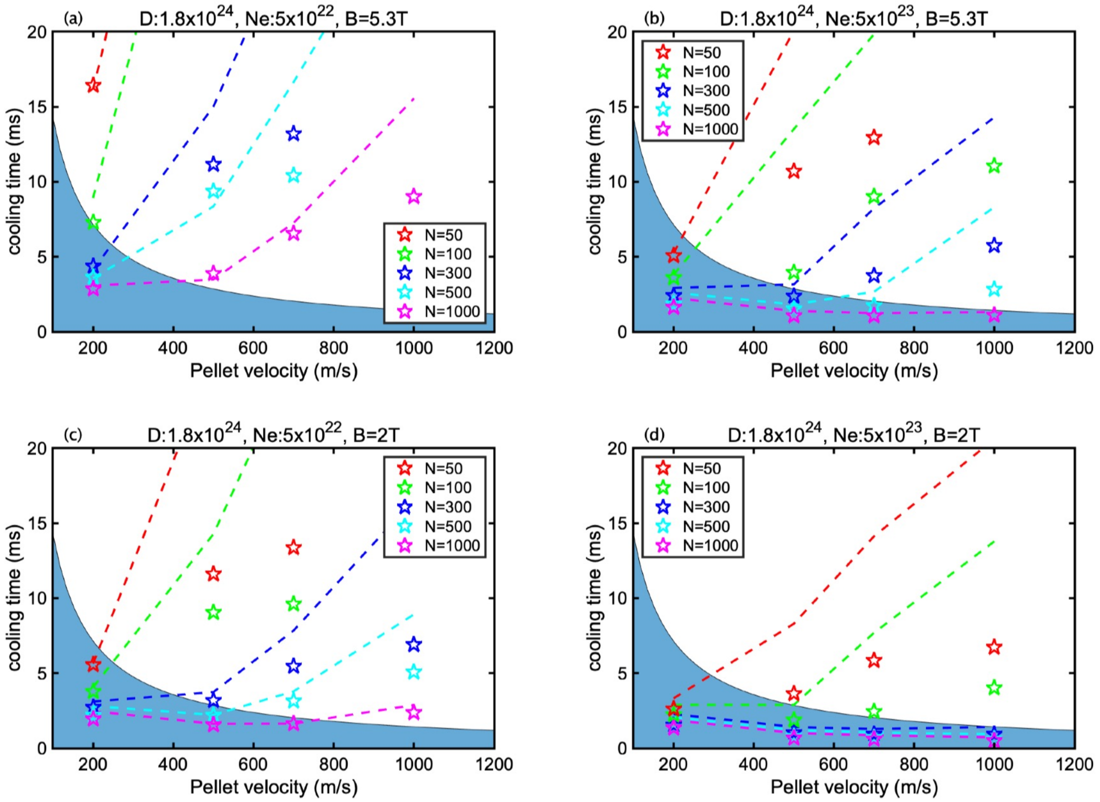
DEMO DESIGN
JOINT SPECIAL TEAM

- Optimizing ITER SPI parameters (injection velocities, magnetic field, shard sizes…)
  - Contrary to gas injection, the cold front that destabilizes the tearing mode happens behind the SPI plume
  - <u>Moderate cooling desirable for avoiding fast transition to RE currents</u> can be achieved with large shard sizes and higher injection velocity with a relatively small neon quantities
- More work on the pellet and SPI physics is on-going for direct contribution to ITER

Symbol: INDEX prediction

Line: 0D analytical model

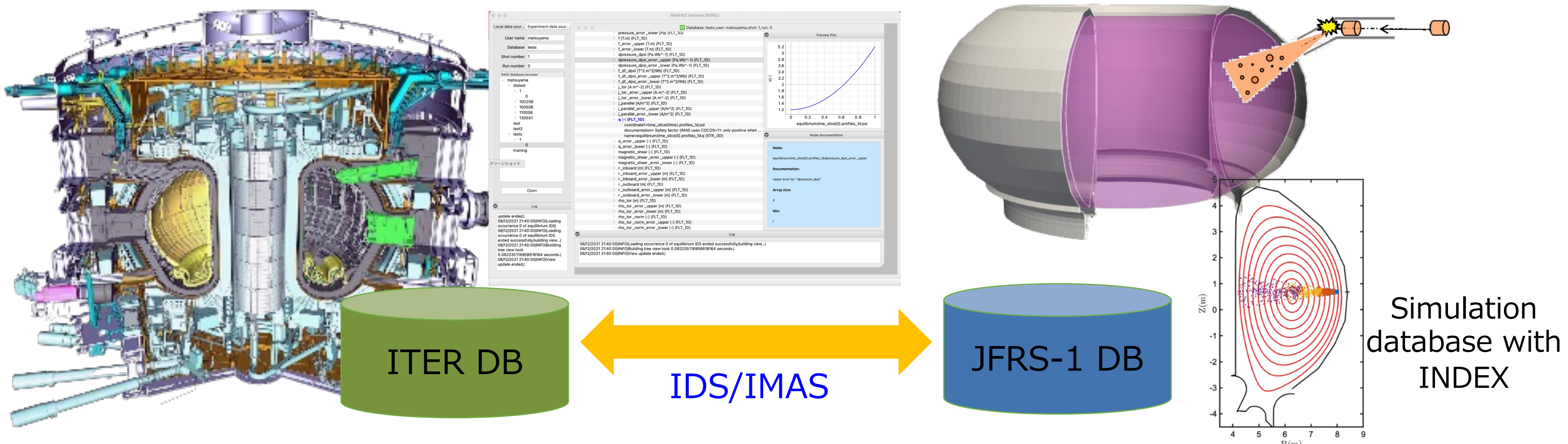
Large N -> Small shards



[Matsuyama+ submitted to PPCF]

IMAS implementation – Adapting the INDEX code to ITER standards

- Plasma Theory and Simulation Group (PTSG) of QST is responsible for the implementation of the task agreement with IO: “ITER DMS simulations with the code INDEX” (12/2020-12/2022)
  - The scope of the work is to provide IO with modelling of Shattered Pellet Injection (SPI) into plasma discharges to support the definition of design parameters of the Disruption Mitigation System (DMS).
- The prototype of the IMAS interface is underdevelopment with support from IFERC-CSC.
  - Simulation data will be provided to IO through IMAS infrastructure by the end of TA



Outline

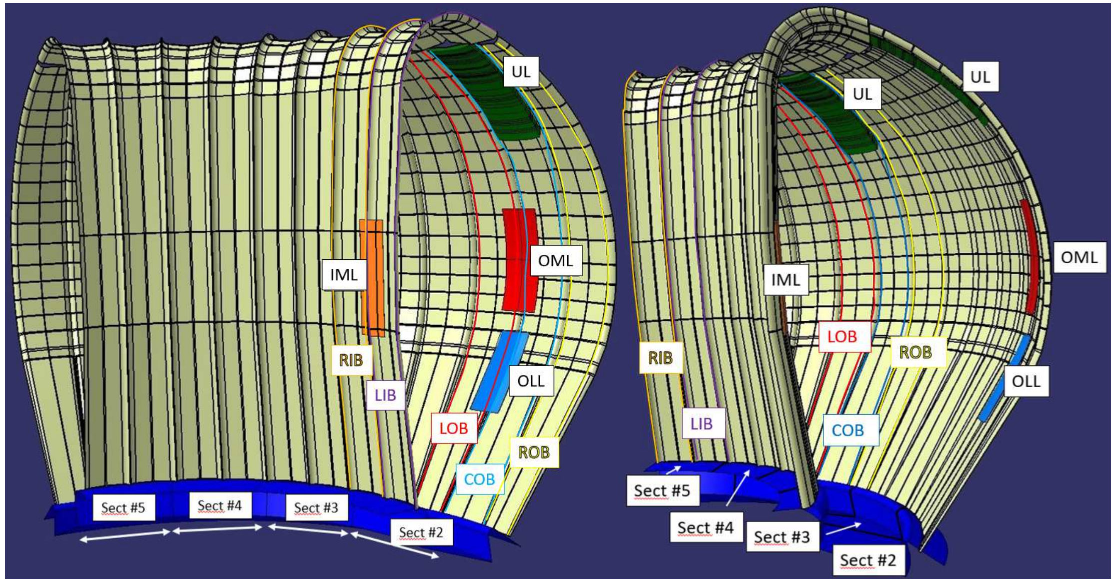
1. Disruption simulations in support of the physics validation of ITER Disruption Mitigation System

2. Development of runaway electron simulation for EU-JA Joint Activity on Characterization of RE wall loads in DEMO

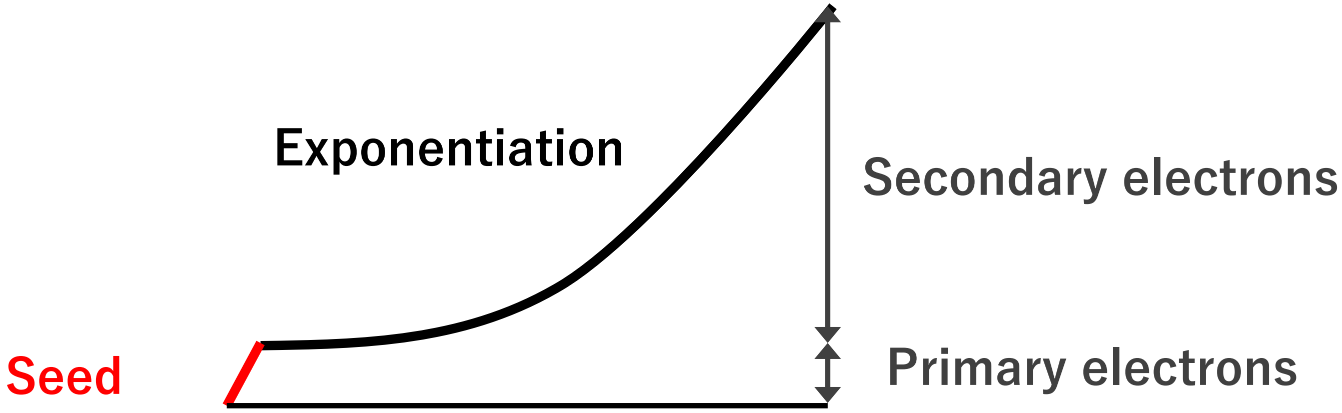
Disruption Load Specification is a key element for DEMO design

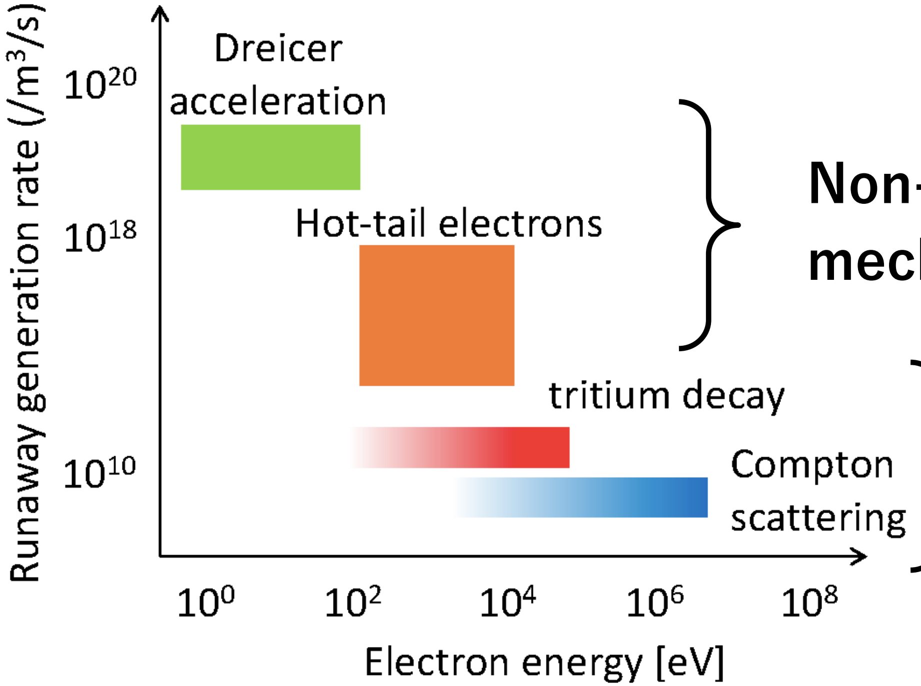
- Analysis of plasma transients, taking into account both unmitigated and mitigated disruption loads, will provide valuable database for DEMO design study
  - These data is essential from early phase of the DEMO design: safety, commissioning, operation scenario, in-vessel components design, etc.

- **DEMO design activities for IFERC Project Task 1-2**: “Evaluation of plasma facing components (PFC) heat loads during transients”
  - A strategy will be proposed to allow protection of the first wall against all the foreseeable and unforeseen plasma transients, via the installation of discrete and possibly sacrificial limiters.



RE generation mechanisms in tokamak plasmas





Fast cooling: (τ_{source}=0.1ms)
Slow cooling: (τ_{source}=1ms)

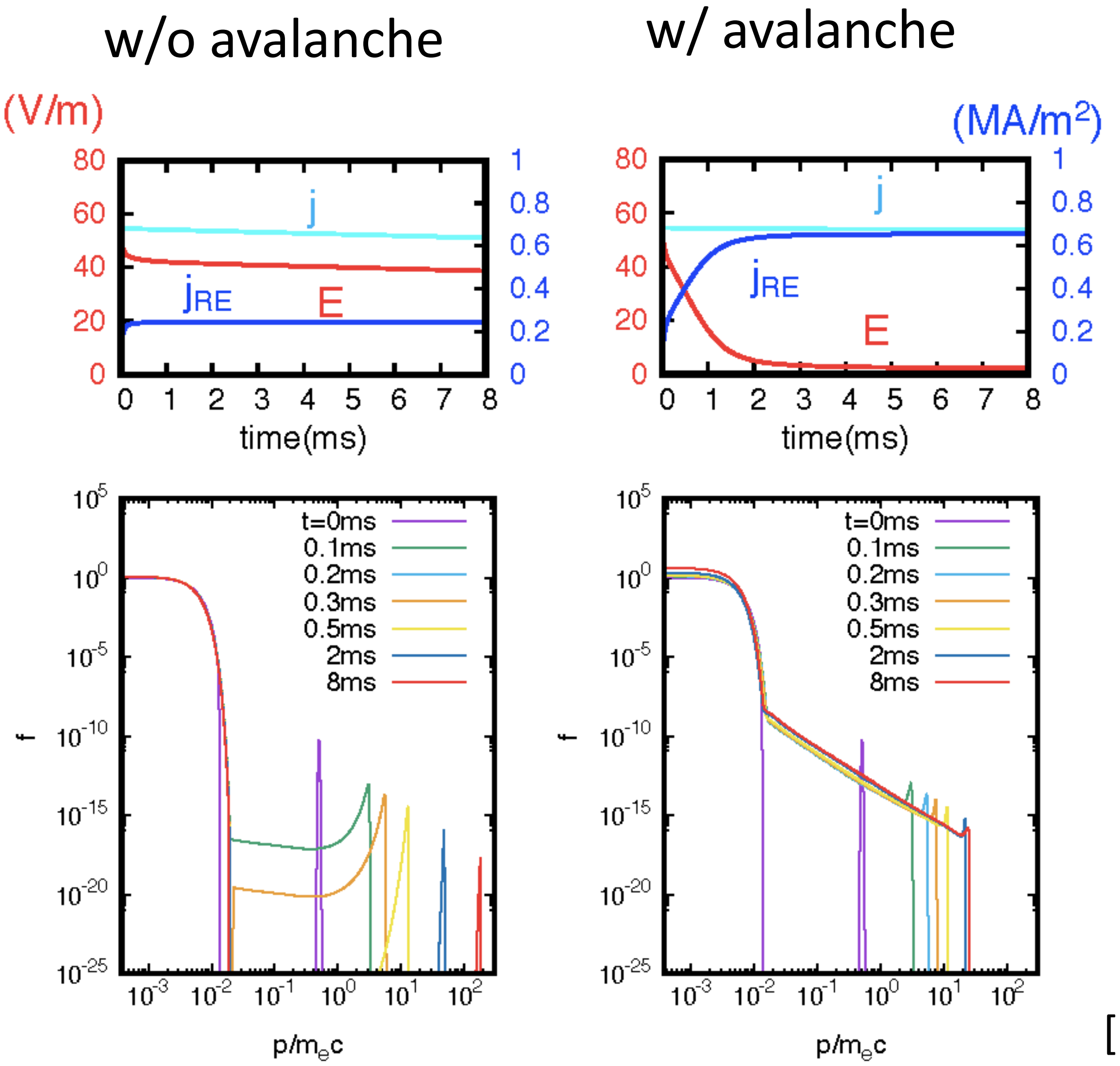
Non-steady mechanisms

Deformation of distribution function during TQ

Steady source (nuclear phase):

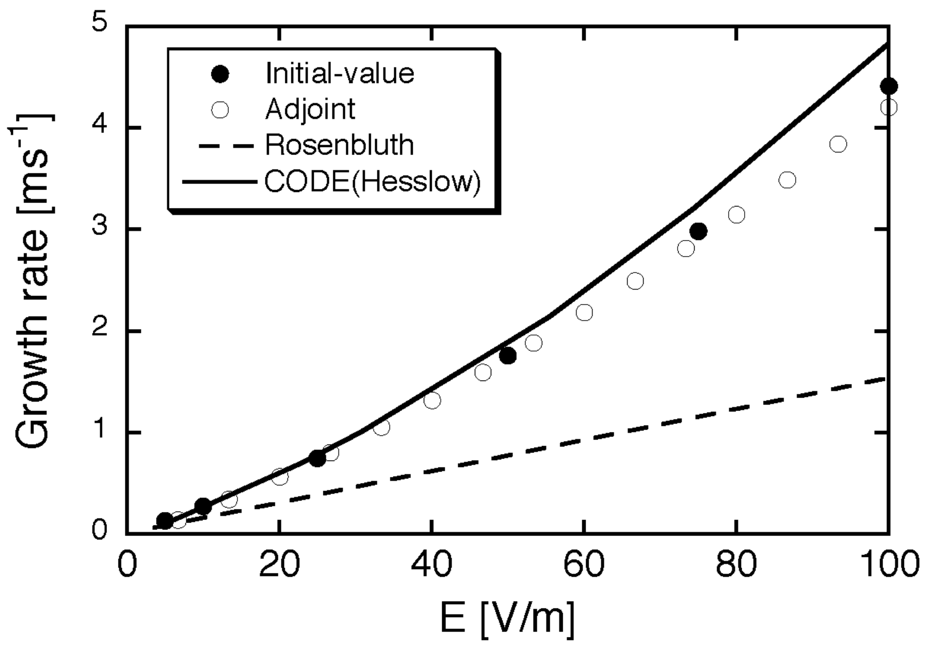
Important for ITER and DEMO

Kinetic simulations of runaway electron generation by avalanches



Benchmark of avalanche growth rate using JFRS-1

T_e = 10 eV, n(D) = n(Ar^{1+}) = $10^{20} m^{-3}$

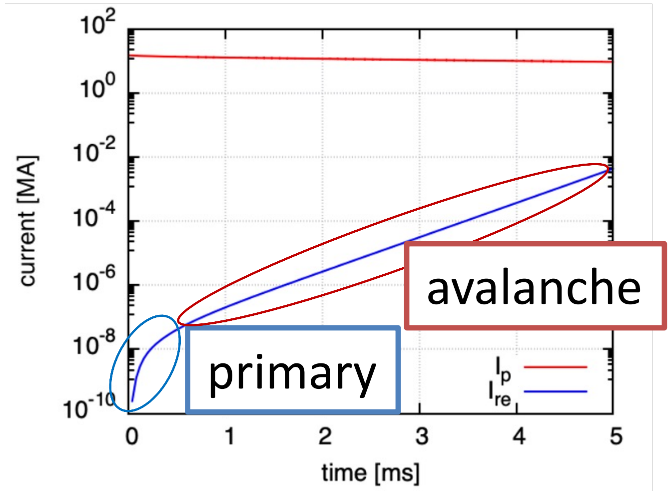


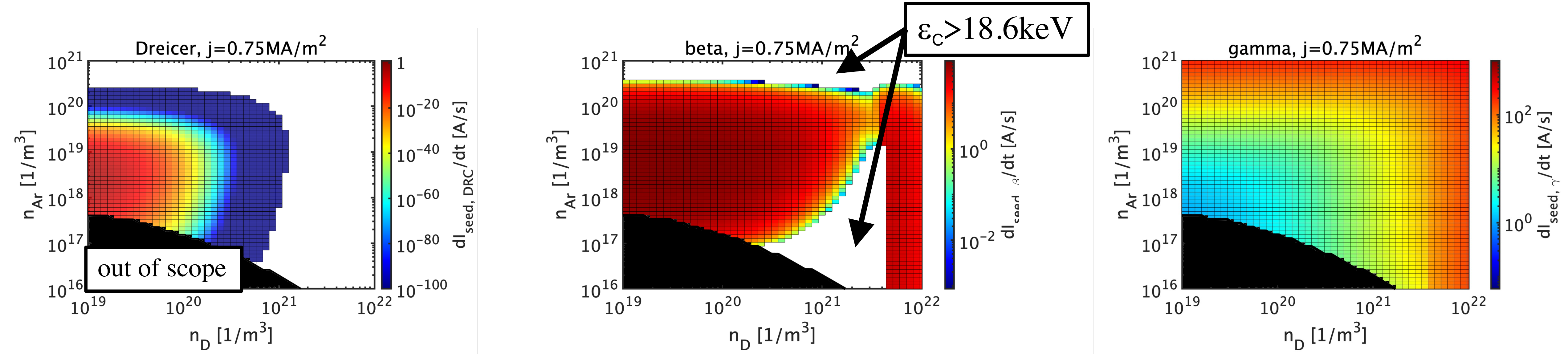
→ These kinetic benchmark is used to refine simplified RE model [Matsuyama & Yagi, PFR2017] for integrated simulations

[Matsuyama, JPSJ Autumn meeting 2020]

Simplified RE generation model has been integrated into INDEX

- Include the primary RE source (Dreicer, tritium decay and Compton scattering) and the avalanche.
- The avalanche growth rate and the critical energy are evaluated with the partially screened model [Hesslow+, JPP2018;NF2019].
- Dreicer process is less important in low-T and high-n plasmas.
- No RE source from tritium decay for ε_c>18.6keV.
- RE source from Compton scattering mainly depends on the number of free and bounded electrons.

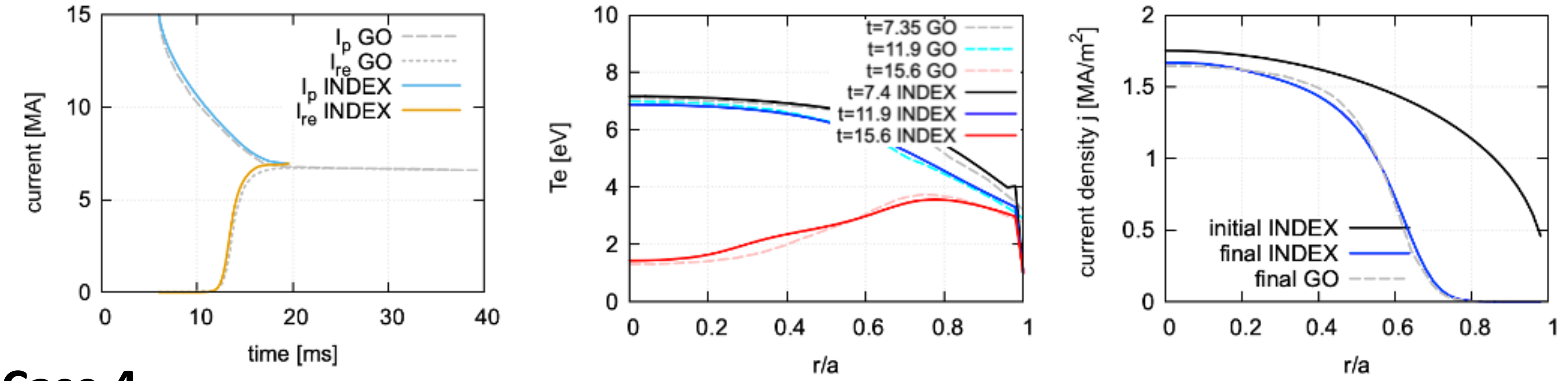




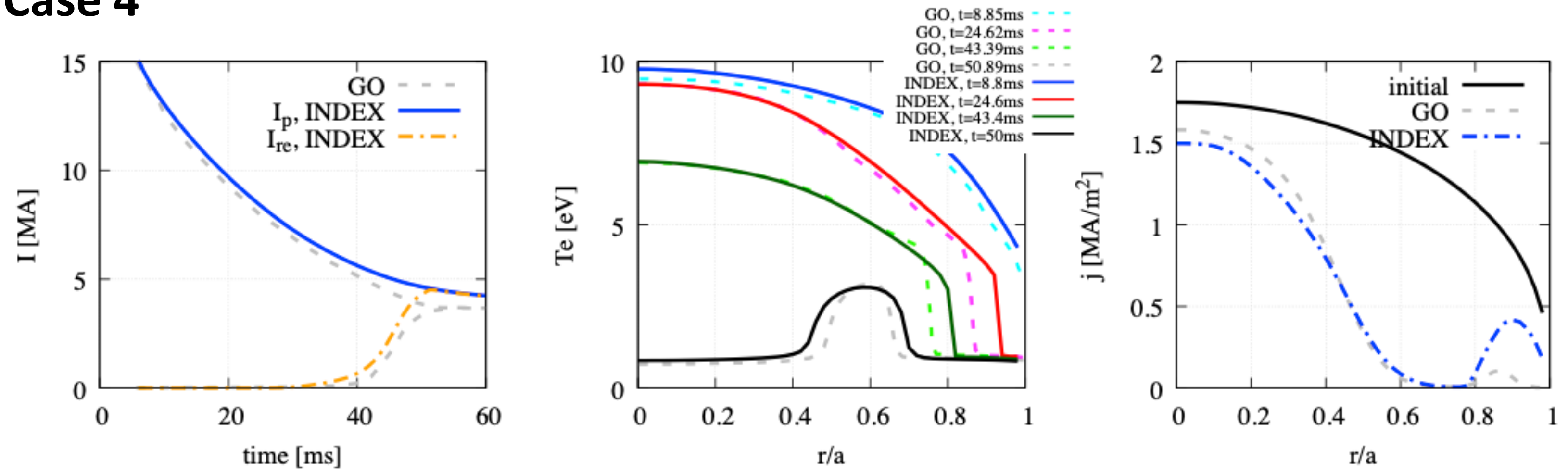
Comparison of RE generation in DT plasmas between INDEX and GO

- Code benchmark with GO code [Vallhagen JPP2020]
  - The same scenario was used to benchmark with JOREK [Vandaru DMS TF meeting 2020]

Case 1



Case 4

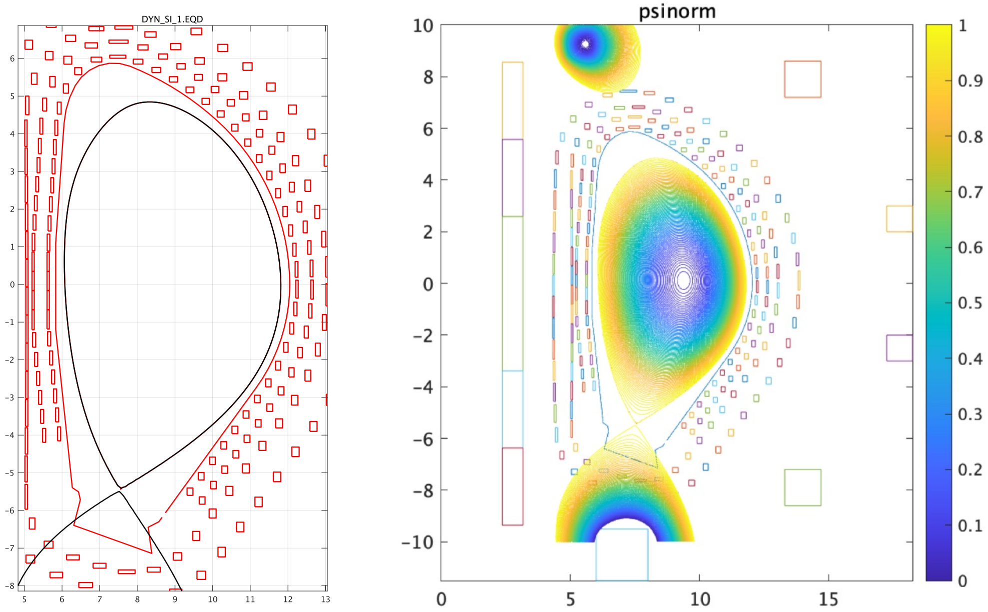


Case	n_D/n_{D0}	n_{Ne}/n_{D0}	I_{RE} [MA]
1	0	1	6.7
2	3	0.03	0
3	40	0.08	7.3
4	7	0.08	3.7

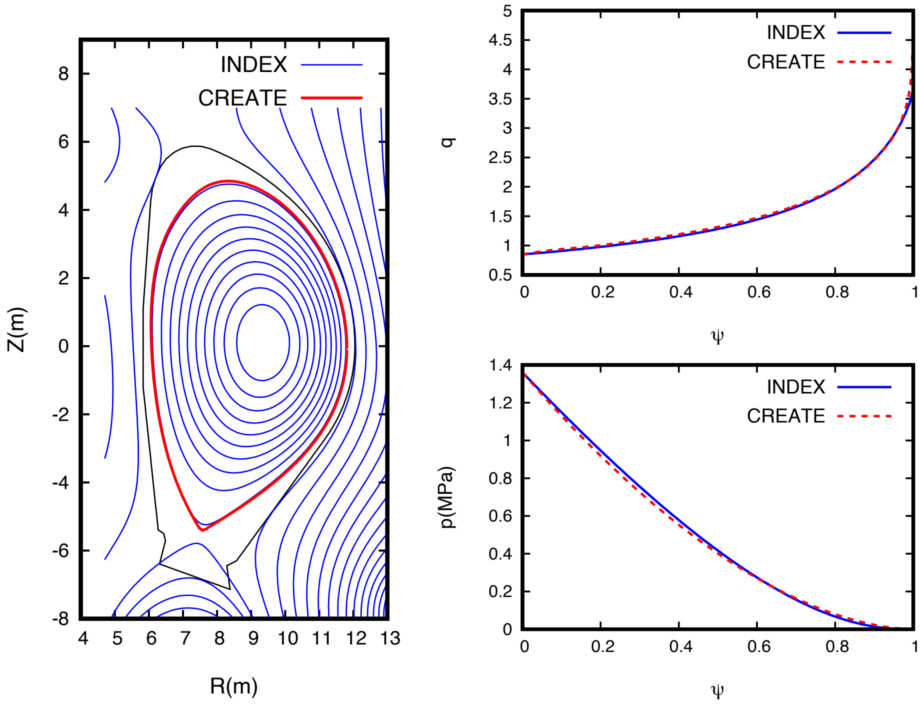
Common Reference Data Developed for Disruption Load Assessment due to VDE & REs

- Free-boundary equilibrium of EU-DEMO was well benchmarked between CREATE-NL and INDEX.
  - Max. Difference in PF/CS coil currents only about 80 kA (less than 1% of max. I_{coil} ~ 20 MA)
  - Plasma shaping, pressure profile, and safety factor profiles well reproduced

2D MODEL by CREATE_NL (DYN_SI_1.EQD)



Reproduced initial Equilibrium by INDEX

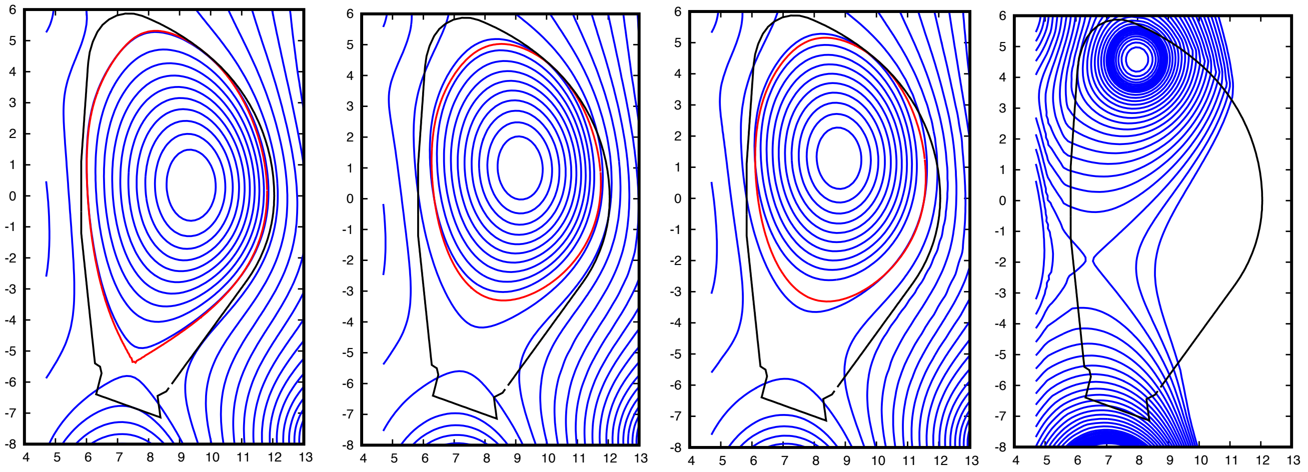


Good agreement in plasma dynamics between INDEX and CREATE

- Wall contact point was compared between INDEX and CREATE using 2D flux map provided after last meeting
  - Good agreement for both first touching and final termination point *– Good ref. for wetted area analysis!*
  - Exact agreement at intermediate step is not expected because of the model difference for plasma parameters (different evolution of β_p and l_i)

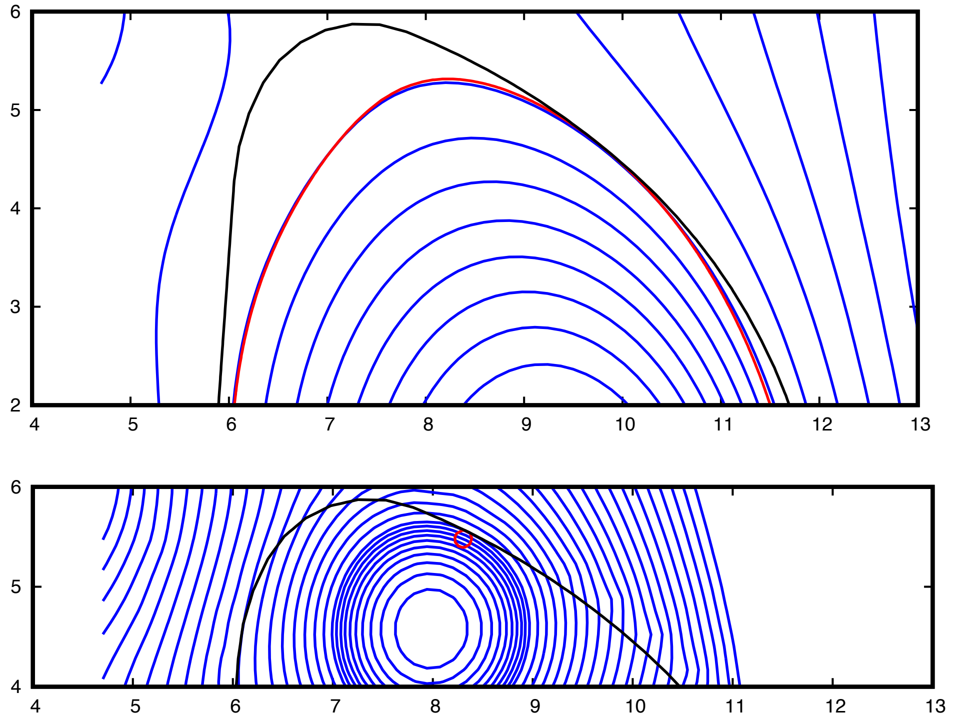
Event (INDEX, CREATE)

First touch (FT) **TQ start** **TQ end** **Termination**



309ms 540ms 545ms 590ms

Time frame of INDEX simulation



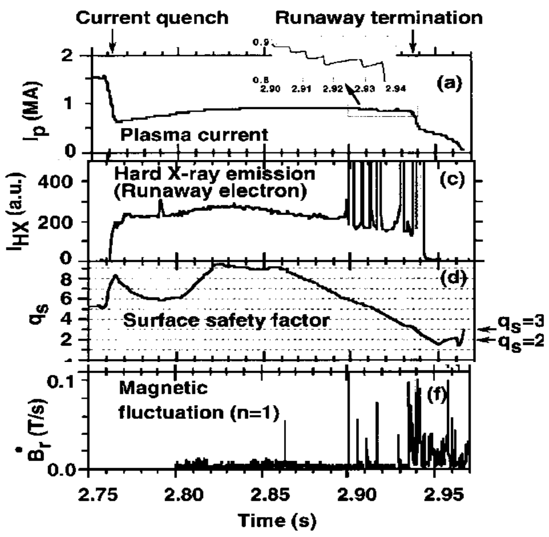
Future work: RE beam simulation during Vertical Displacement Events

DEMO DESIGN
JOINT SPECIAL TEAM

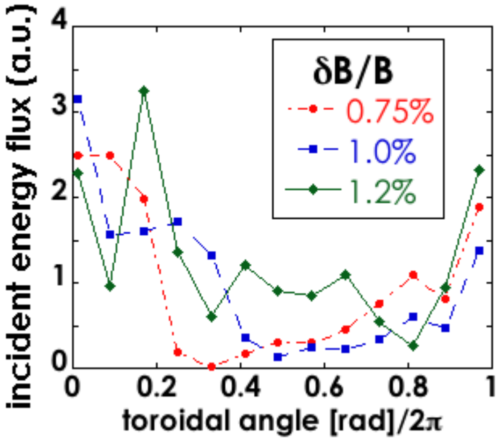
Workplan

FY2021		FY2022	FY2023-2024
Code adaptation	Scenario of RE wall impact	Orbit loss analysis	Assessment of machine protection
✓ **Implement RE model to INDEX** ✓ **Compare VDE simulations between JA and EU**	✓ VDE analysis with RE beam ✓ Identify low-n MHD unstable scenario of RE beam	✓ RE orbit analysis with MHD modes ✓ Evaluate energy deposition pattern	✓ Workflow applied for sacrificial limiter design ✓ Disruption mitigation scenario development

JT-60U [Tamai+ NF2002]

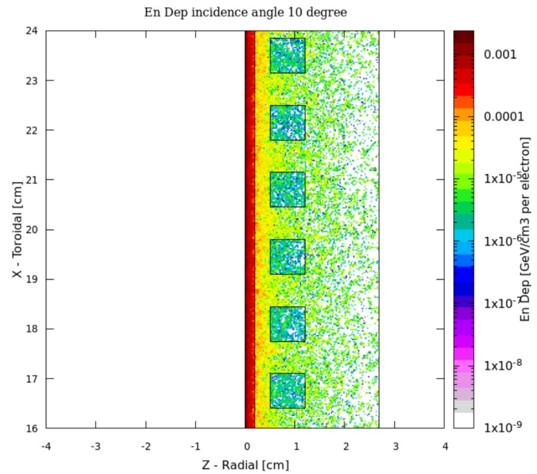


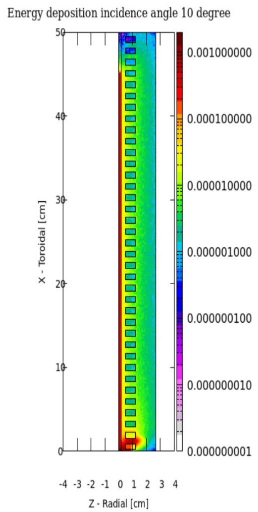
RE energy flux due to external kink in ITER div config. [Matsuyama+, PSI2013]



Volumetric energy deposition modeling by FLUKA

[Courtesy of F. Subba & L. Singh]





Summary: Progress on disruption analysis for ITER and DEMO through Project [INDEXBA] and related collaboration

1. Disruption simulations in support of the physics validation of ITER Disruption Mitigation System
   - QST has made a key contribution to physics validation of ITER DMS with close collaboration with IO. The project gains much benefits from the support by IFERC-CSC project (computational resources, IMAS development, and other technical supports…)
2. Development of runaway electron simulation for EU-JA Joint Activity on Characterization of RE wall loads in DEMO
   - Joint work has been launched with focused effort and the code adaptation (model development, code benchmark, simulation setup, etc.) has been progressed in FY2021. More results are expected in FY2022 by completion of collaborative workflow for the characterization of RE wall loads, which addresses a critical issue on tokamak DEMO design.