"Kick-off" of the E-TASC TSVV Task 9 project:

"Dynamics of Runaway Electrons in Tokamak Disruptions"

E. Nardon*, 12/01/21

*With some slides borrowed from M. Hoelzl!

Objectives of the meeting

- Give everyone an overview of the project proposal and context
- Brainstorm on the important questions and how to address them
- Define precise plans (“tasks”) for next year, form working groups for each task

Agenda

- Tuesday 12/01/21, 9-12am
  - Introduction, general scope of the project, organization
  - Brainstorming, free discussion
  - Status and plans for model validation

- Friday 15/01/21, 9-12am
  - Status and plans for code development
  - Status and plans for code application to RE avoidance/mitigation by massive material injection in ITER and DEMO
  - Status and plans for searching alternative solutions to the RE issue

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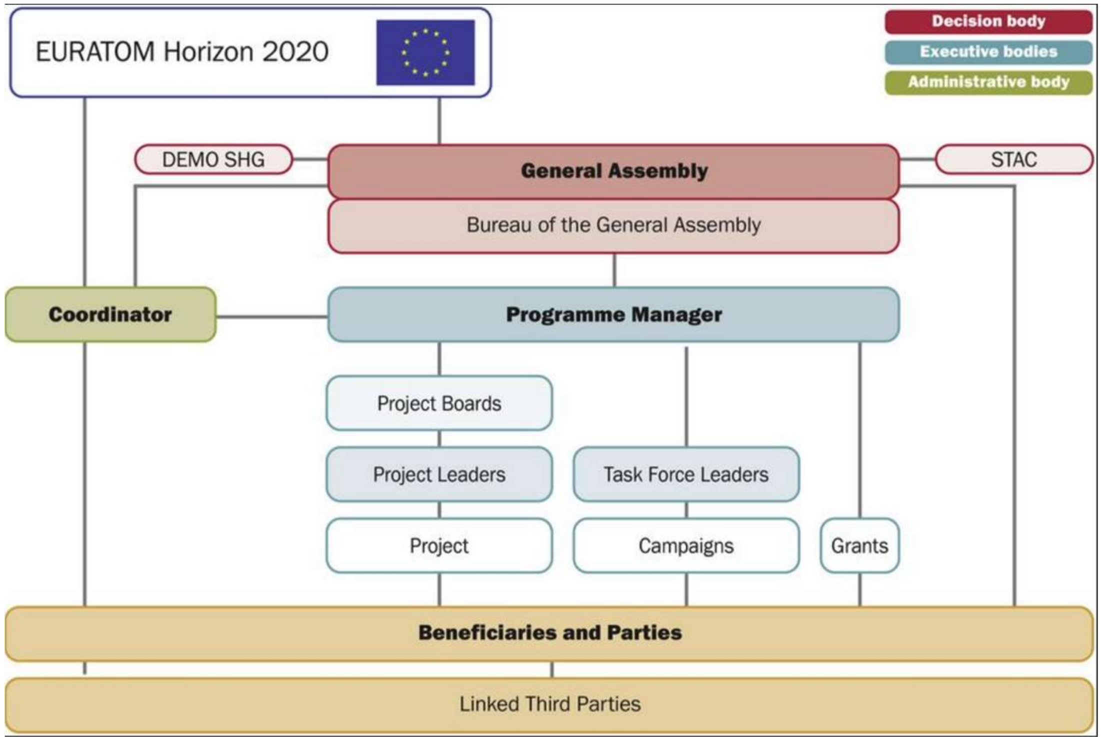
Some context: EUROfusion v2.0



- New European Framework Program 2021-2027
- EUROfusion re-structured
- General Assembly (GA) takes all major decisions
- The budget proposed by the European commission was cut by ~20% → affects the "funding rates" for all activities
- Official approval of E-TASC TSVV projects is a topic for the GA at the end of February

"Old names"

Fusion Science Department	ITER Physics Department
Tokamak and Stellarator Exploitation, Theory, Simulation, Verification & Validation (TSVV)	
TE (Tokamak Exploitation & TSVV)	JET1 + JET4 + MST1 + MST2 + PFC + CD
SA (JT-60SA Exploitation & TSVV)	SA
W7X (W7-X Exploitation & TSVV)	S1 + part of S2

WP TE Task force leaders: Emmanuel Joffrin, Marco Wischmeier + Deputies

https://wiki.euro-fusion.org/wiki/WPTE_wikipages:_Tokamak_Exploitation_Work_Package

- call for proposals (closed)
- call for manning (not clear when)

E-TASC (European Theory And Simulation Coordination)

- E-TASC is the new "home" for theory and simulation
- Governed by E-TASC Scientific Board (SB)
- TSVV: Theory and Simulation Validation and Verification projects
  - 14 topics (“Tasks”)
  - Running for five years (2021-2025)
  - Follows a phase (2019-2020) with 4 “pilot projects”, including the one on *“Modelling of electron runaway in tokamak disruptions in the presence of massive material injection”* led by Ola Embreus (https://users.euro-fusion.org/iterphysicswiki/index.php/TSVV-thrust1a)
- ACH: Advanced Computing Hubs
  - Up to 5
  - Support for TSVVs and other EUROfusion activities
  - Not yet clear where and when; slow ramp-up expected
- EnR: Enabling Research projects
  - For more “blue sky” research
  - Limited funding, likely only about 4 accepted

« Details » which remain to be clarified concerning TSVV projects

- Funding rate
- Official starting date
- ACH contributions
- Mobility budget and procedures
- Rules for endorsement / clearance on the EUROfusion pinboard
- …

TSVV Tasks

Dep.	WP	#	Title
FSD	TE	1	Physics of the L-H Transition and Pedestals
FSD	TE	2	Physics Properties of Strongly Shaped Configurations
FSD	TE	3	Plasma Particle/Heat Exhaust: Fluid/Gyrofluid Edge Codes
FSD	TE	4	Plasma Particle/Heat Exhaust: Gyrokinetic/Kinetic Edge Codes
FSD	PWIE	5	Neutral Gas Dynamics in the Edge
FSD	PWIE	6	Impurity Sources, Transport, and Screening
FSD	PWIE	7	Plasma-Wall Interaction in DEMO
FSD	TE	8	Integrated Modelling of Transient MHD Events
FSD	TE	9	Dynamics of Runaway Electrons in Tokamak Disruptions
FSD	TE	10	Physics of Burning Plasmas
FSD	PrIO	11	Validated Frameworks for the Reliable Prediction of Plasma Performance and Operational Limits in Tokamaks
FSD	W7X	12	Stellarator Optimization
FSD	W7X	13	Stellarator Turbulence Simulation
FTD	DES	14	Multi-Fidelity Systems Code for DEMO

An overview on our proposal

Team and ppy's

	Beneficiary	2021	2022	2023	2024	2025
E. Nardon	CEA	0,5	0,5	0,5	0,5	0,5
Y. Peysson	CEA	0,2	0,2	0,2	0,2	0,2
C. Reux	CEA	0	0,5	0,5	0,5	0,5
PhD/Postdoc	CEA	0	0,5	0,5	0,5	0
T. Fülöp	Chalmers University	0,5	0,5	0,5	0,5	0,5
I. Pusztai	Chalmers University	0,5	0,5	0,5	0,5	0,5
M. Hoppe	Chalmers University	0,5	0	0	0	0
PhD/Postdoc	Chalmers University	0	0,5	0,5	0,5	0,5
C. Sommariva	EPFL	0,5	0,5	0,5	0,5	0,5
O. Linder	IPP Garching	0,5	0,5	0	0	0
G. Papp	IPP Garching	0	0	0,5	0,5	0,5
K. Särkimäki	IPP Garching	0,5	0,5	0	0	0
Postdoc	IPP Garching	0	0	0,5	0,5	0,5
E. Hirvijoki	Aalto University	0	0	0	0,5	0,5
S. Olasz	*CER Budapest*	*(0,5)*	*(0,5)*	*(0,5)*	*(0)*	*(0)*
ACH resources		1,6	1,6	1,2	1,2	1,2
Total		5,3	6,3	5,9	6,4	5,9

Main objectives

- To develop a set of self-consistent, robust and validated models with different levels of complexity to simulate Runaway Electron (RE) dynamics and mitigation in the presence of Shattered Pellet Injection (SPI) and 3D fields

- To apply these models in order to seek RE avoidance and mitigation methods for future tokamaks, in particular ITER and DEMO

Work Packages (WPs)

- WPM: project Management
- WPC: Code development
- WPV: code Validation
- WPA: code Application to Massive Material Injection (MMI)
- WPO: search for Other (non-MMI) possible solutions to the RE issue

WPM: project Management (E. Nardon, T. Fülöp)

- Set up wiki page and mailing list
- Organize regular remote progress meetings of the whole project team (every 2 or 3 months)
- Form topical sub-groups with a specific leader and with more frequent interaction
  - Connected to tasks in the work plan
  - To be decided at this meeting and updated when needed
- Organize an annual general meeting to review progress and make plans for the following year
  - Will be open to external guests, e.g. international RE experts, members of other TSVV projects, members of the ITER Organization, …
- Write an annual report reviewing the status of the project and describing plans for the next year

WPC: Code development

- Task C1: Develop and verify DREAM
- Task C2: Implement a model for collisions and for the synchrotron radiation reaction force for test electrons in JOREK
- Task C3: With the help of JOREK, develop a model for transport associated to magnetic stochasticity during the TQ, for use in ASTRA and DREAM
- Task C4: Implement a pellet model in DREAM
- Task C5: Implement a model for the interaction between REs and pellets in JOREK
- Task C6: Implement a model for the RE beam “companion plasma” in DREAM
- Task C7: Implement a model for the RE beam “companion plasma” in JOREK

- Task C8: Implement synthetic RE diagnostics in JOREK
- Task C9: IMAS integration
- Task C10: Implement a PIC RE model in JOREK

WPV: code Validation

- Task V1: Push the validation of ASTRA, ETS and DREAM regarding RE generation during disruptions
- Task V2: Create a validation-oriented database on RE generation during disruptions
- Task V3: Validate JOREK regarding RE generation in MMI experiments
- Task V4: Validate JOREK regarding RE beam termination modelling and the effect of D2 SPI on it

WPA: code Application to MMI

- Task A1: Assess operational boundaries related to RE generation in ITER and DEMO using the “baseline” RE avoidance strategy based on SPI
- Task A2: Further investigate the use of pure D2 SPI for fast plasma dilution before the TQ
- Task A3: Use JOREK to seek benign RE beam termination scenarios in ITER, possibly making use of a pure D2 SPI onto the RE beam

WPO: search for Other (non-MMI) possible solutions to the RE issue

- Task O1: Use LUKE to assess the possibility of RE avoidance with waves
- Task O2: Study RE-driven instabilities

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    - ETS, ASTRA
    - DREAM
    - JOREK
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Timeline for WPV (code Validation)

Task	2021	2022	2023	2024	2025	Key contributors
V1: Push the validation of ASTRA, ETS and DREAM regarding RE generation during disruptions			Publication			T. Fülöp, M. Hoppe, I. Pusztai, O. Linder, G. Papp, S. Olasz, Chalmers PhD/postdoc, ACH resources
V2: Create a validation-oriented database on RE generation during disruptions			Cases used for Task V1 present in database			ACH resources, C. Reux, G. Papp, S. Olasz, O. Linder
V3: Validate JOREK regarding RE generation in MMI experiments			JET simulations with test particles and the RE fluid model Publication	ASDEX Upgrade simulations with test particles/RE fluid model Publication	Simulations with self-consistent kinetic REs Publication	E. Nardon, K. Särkimäki, IPP postdoc, E. Hirvijoki
V4: Validate JOREK regarding RE beam termination modelling and the effect of D_2 SPI on it				JET experiments simulated Publication		C. Reux

Status and plans concerning the validation of JOREK

- The effort on **simulations of MMI-triggered disruptions** with JOREK has intensified in the last few years
  - ITER SPI: D2 [1] and Ne+D2 [2]
  - ASDEX Upgrade D2 SPI [3]
  - JET SPI (Ar [2], Ne+D2 [4], D2 [5]) and MGI (D2 [5] and Ar [6])
  - KSTAR D2 SPI [8]

- REs typically not included in the simulations, we first try to understand and validate the « MHD part »
  - But we did do some test particle studies for JET cases [9-11]

[1] E. Nardon et al. 2020 Nucl. Fusion 60 126040

[2] D. Hu et al. 2020 Nucl. Fusion (accepted)

[3] M. Hoelzl et al. 2020 Phys. Plasmas 27 022510

[4] D. Bonfiglio et al., EFPW 2020

[5] M. Kong et al., presented by E. Nardon at ITPA MDC meeting, October 2020

[6] E. Nardon et al., 2017 Plasma Phys. Control. Fusion 59 014006

[7] E. Nardon et al., REM 2020

[8] S. Lee et al. presented by E. Nardon at ITPA MDC meeting, October 2020

[9] C. Sommariva et al. 2018 Nucl. Fusion 58 016043

[10] C. Sommariva et al. 2018 Nucl. Fusion 58 106022

[11] K. Särkimäki et al. 2020 https://arxiv.org/abs/2006.03726

- Simulations usually find that the MMI triggers a big MHD crash leading to a large drop of the temperature

- However:
  - The TQ is typically incomplete (the temperature drops down to ~100 eV, not ~10 eV)
  - The Ip spike is typically much smaller than in experiments
  - Detailed match to measurements has not been shown

⇒ Cannot consider model as validated yet

- A difficulty is that simulations can be very long (several weeks), and many run into numerical issues during the TQ

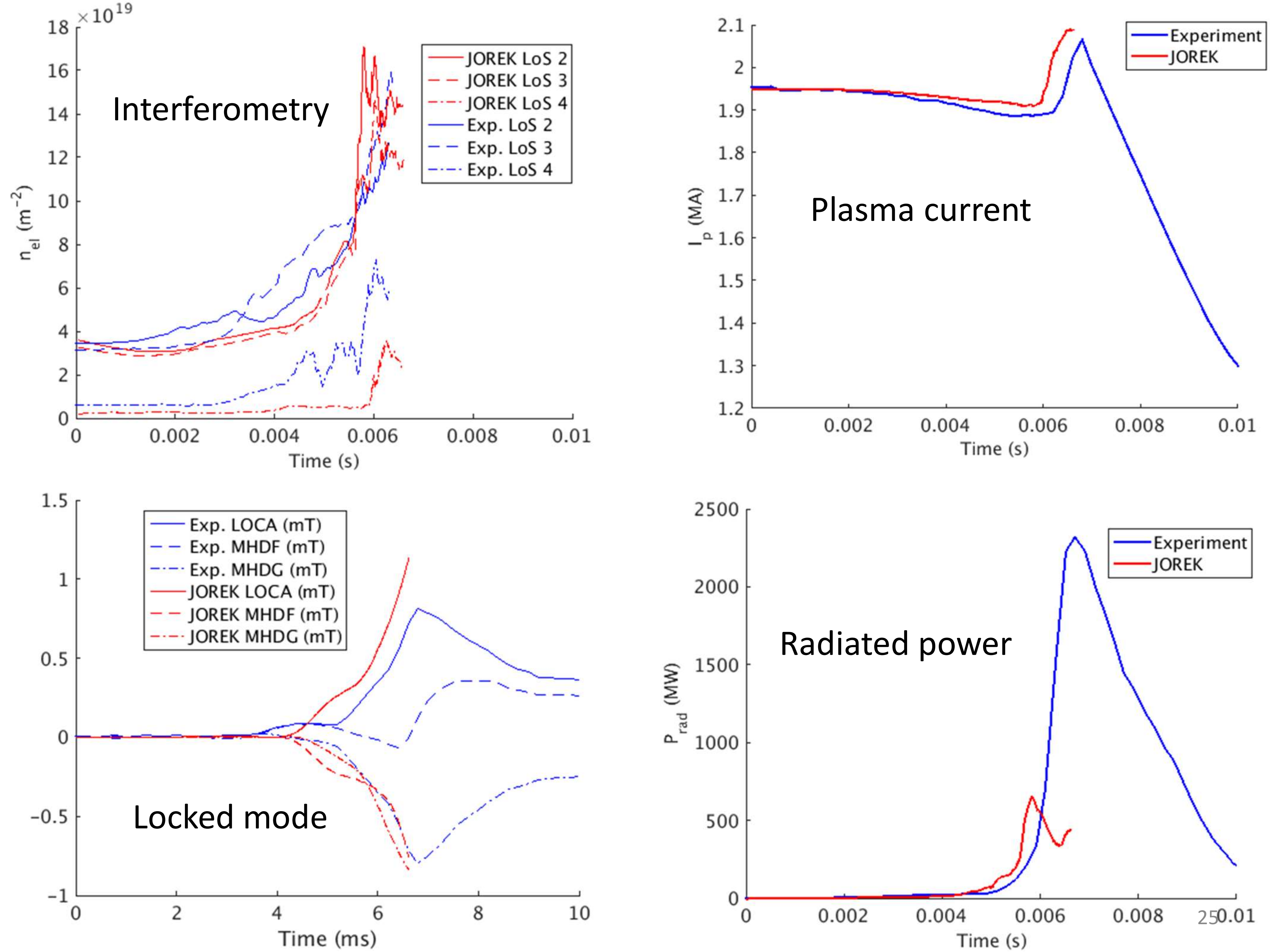
- In the last few years, I have been working on simulating JET pulse 85943
  - Argon MGI leading to disruption and formation of a RE beam
  - Part of a Bt scan leading different RE currents

- Use synthetic interferometry diagnostic to constrain the Ar source (not described self-consistently in JOREK)

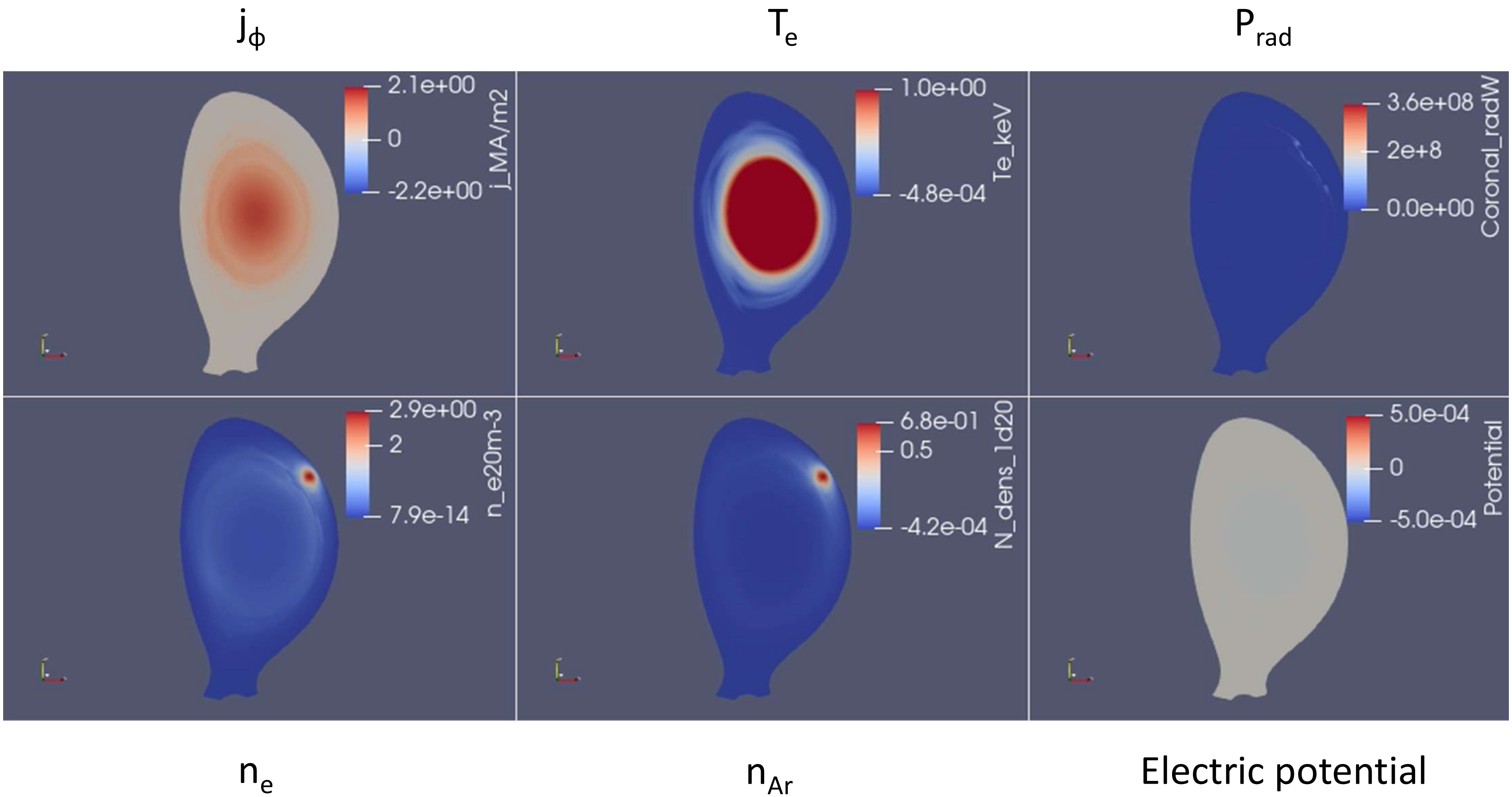
- Try to validate by comparing:
  - Ip
  - Radiation (synthetic bolometry)
  - Magnetic perturbations (synthetic saddle loops)

- Some results presented at the REM one year ago. Simulations were unrealistic in several respects:
  - Argon source at outer midplane instead of top
  - No Ohmic heating
  - Resistivity scaled up by a factor 10
  - Large viscosity (which furthermore scaled like $T_e^{-3/2}$)

- Current simulations have:
  - An argon source at the top
  - Ohmic heating
  - A realistic resistivity with a cut-off at high temperature
  - A smaller viscosity (independent of T_e)



Interferometry
×10^19
n_el (m^-2)
Time (s)
JOREK LoS 2
JOREK LoS 3
JOREK LoS 4
Exp. LoS 2
Exp. LoS 3
Exp. LoS 4
Plasma current
I_p (MA)
Time (s)
Experiment
JOREK
Locked mode
Time (ms)
Exp. LOCA (mT)
Exp. MHDF (mT)
Exp. MHDG (mT)
JOREK LOCA (mT)
JOREK MHDF (mT)
JOREK MHDG (mT)
Radiated power
P_rad (MW)
Time (s)
Experiment
JOREK



- More details soon!

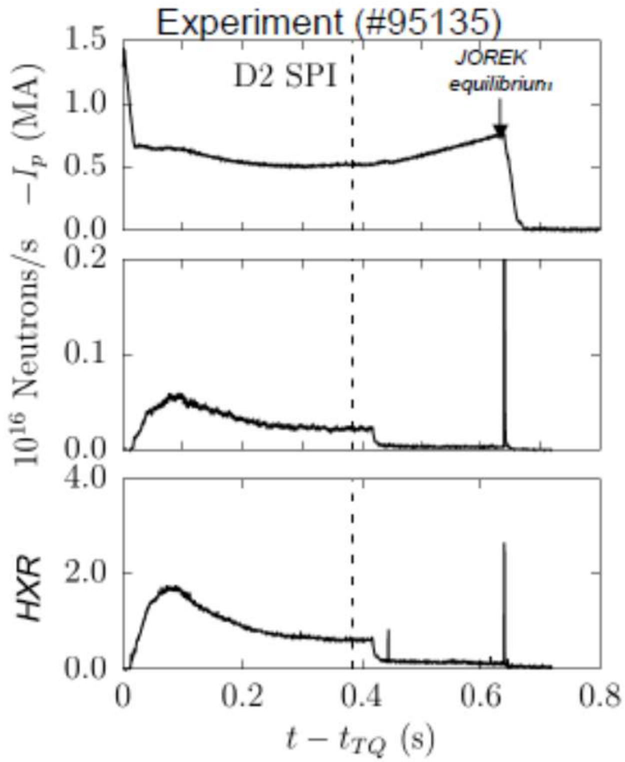
- Plans for 2021 concerning JOREK simulations of MMI-triggered disruptions:

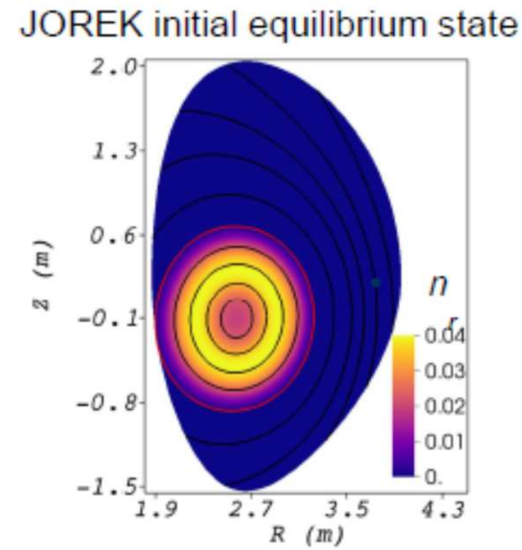
  - "Push" simulations of 85943 and their analysis and comparison to experimental data
    - Try to run through the TQ and into the CQ
    - Scan input parameters and spatial resolution
    - Try to understand the dynamics!
    - Investigate field line / test electron dynamics (Konsta?)
    - Re-run simulations including a self-consistent RE fluid
    - Improve the MGI model (impurity source in the SOL, temperature-dependent diffusivity, recycling, …)

  - Validate and analyze other cases, in particular JET SPI cases (ongoing simulations by D. Bonfiglio and M. Kong)

  - Note: some JOREK developments planned within TSVV 8 should help
    - "Mode families" should make calculations faster
    - Improved finite elements treatment of grid axis should suppress numerical issues there

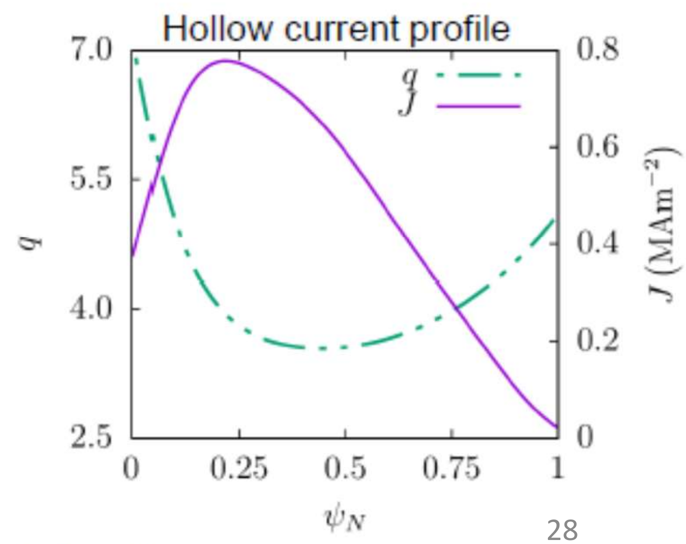
RE-fluid model to simulate benign RE beam termination in JET





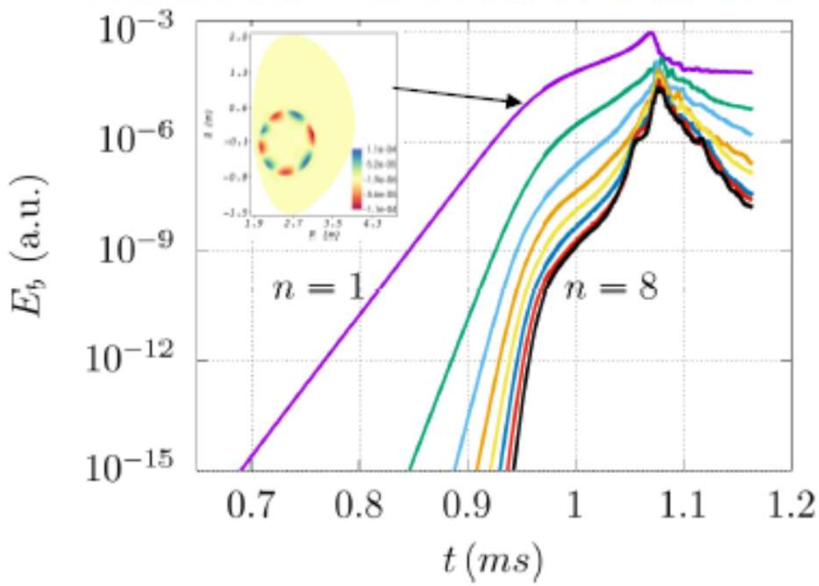
- D_2 2^{nd} injection expels most of the Argon-impurities via recombination ==> leads to current rise
- Subsequent fast MHD crash and all REs are lost
- No wall damage (benign termination)

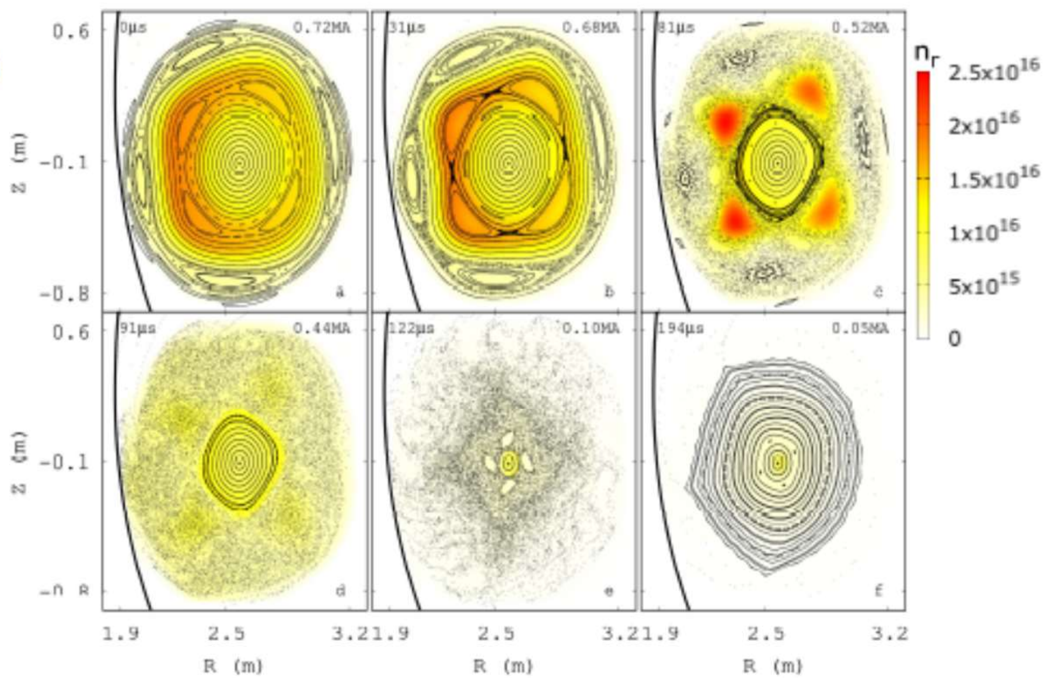
[Bandaru et. al. Phys. Rev. E 99, 063317 (2019)]
[Reux et. al. Phys. Rev. Lett. , Submitted]



[V Bandaru, M Hoelzl, C Reux et al, PPCF (submitted)]

MHD mode growth; outer (m,n)=(4,1) dominant



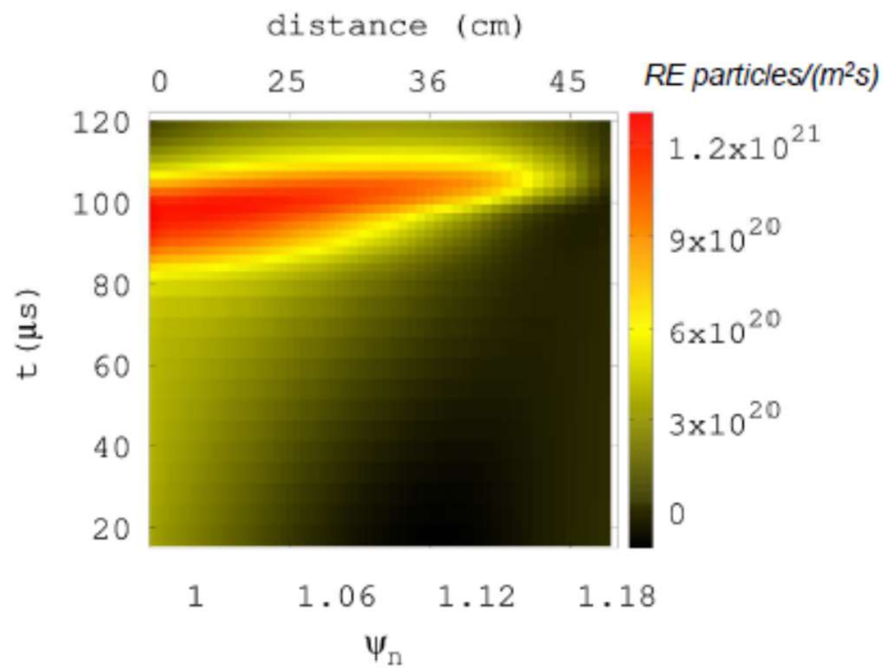


Stochastization causes the loss of ~95% of the REs in the simulation

[V Bandaru, M Hoelzl, C Reux et al, PPCF (submitted)]

RE deposition on the wall

Toroidally averaged RE flux



- Most of the REs are lost in ~20 μs (similar to experiment)
- Distributed RE losses partly explain the benign nature of the termination

Bandaru et. al. PPCF (in preparation)

[V Bandaru, M Hoelzl, C Reux et al, PPCF (submitted)]

- Plans (2021-2025) concerning JOREK simulations of D2 SPI into RE beam and associated benign termination:

  - Validation on JET data
    - Simulate not only the termination, but also the D2 SPI and argon purge effect
    - Simulate a set of cases with varying parameters leading to more or less benign terminations
    - Validate using bolometry, spectroscopy, …
    - In our proposal, this task is on C. Reux with a milestone in 2024
    - Associated code development task: "Implement a model for the RE beam companion plasma in JOREK", also on C. Reux, with a milestone in 2023
    - Will benefit from S. Sridhar's PhD work [S. Sridhar et al 2020 Nucl. Fusion 60 096010]

  - Application to ITER
    - Task on E. Nardon with a milestone in 2024

- Plans for 2021?

About the validation database

- Objectives and characteristics?
  - At a minimum: store reference data from our validation cases (simulation input and output, experimental measurements)
  - Maybe also:
    - Store ITER simulation data
    - Store experimental data for many pulses and machines
  - Format? IMAS
  - Relation to existing RE databases?

- Team and leader?
  - We asked for 0.5 ppy/year from the ACHs for this task

- How to get started? My proposal for the short term:
  - We list cases that we have been simulating recently / are planning to simulate and which would make sense to have in the database
  - We list the relevant quantities to be stored in the database and check if that can be done with IMAS (if not, discuss with IMAS team)
  - We wait for ACH support to actually set up and fill in the database