Highlights of WPSA modelling during FP8

G. Falchetto CEA, IRFM (France)

Acknowledgements: G Giruzzi, T Bolzonella and WPSA modelers

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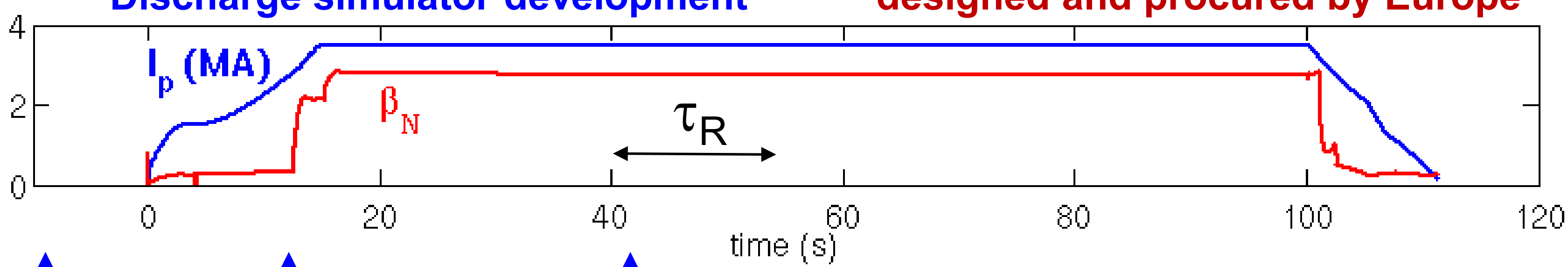
Preparing controllable high-β long-pulse scenarios

Integrated scenario modelling
Discharge simulator development

Machine enhancements
designed and procured by Europe



EC wall conditioning

breakdown and ramp-up

EDICAM wide-angle camera

high-β long-pulse sustainment & control

edge Thomson Scattering

- **pumping/fuelling** — **Cryopumps**
- **edge, divertor** — **divertor VUV**
- **turbulence**
- **fast ions** — **FILD**

- **ELM** — **Pellets**
- **NTM**
- **RWM**
- **disruptions & VDE** — **MGI**

➢ Modelling in support to the enhancements and diagnostics procured by EU, including control actuators

WPSA modelling aims and FP8 strategy

Focus: sustainment and control of high-β long-pulse discharges in various plasma regimes

Coherent studies were performed aimed at **preparing a sound basis for the scientific exploitation of JT-60SA** :

- advanced modelling connected with the scientific programme priorities;
- identification of the characteristics of diagnostics and actuators to be developed in view of an efficient research programme;
- development and validation of operation oriented tools.

Next talks

The required simulation tools were devised and systematically developed and modelling studies carried out :

- global discharge simulation (with fast 0D simulators)
- integrated scenario modelling of discharge phases
- wall conditioning
- breakdown and current ramp-up
- flat-top sustainment and control (core/edge profiles, fast ions, power loads)
- control and mitigation of instabilities and disruptions

G. Giruzzi et al., Plasma Phys. Contr. Fusion 62 (2020) 014009

WPSA modelling activities in FP8

2014-2018
Coordinator M Romanelli

Activity	Title
SA.M.A01	Pedestal stability assessment
SA.M.A02	Flat-top phase scenario modelling
SA.M.A03	Full core/edge scenario modelling (C)
SA.M.A04	Full core/edge scenario modelling (W)
SA.M.A05	Integrated modelling of transient phases
SA.M.A06	Modelling of fast ion distribution and MHD

2019-2020
Coordinator T Bolzonella

Activity	Title
SA.M.A01	MHD and control modelling
SA.M.A02	Scenario, transport and edge modelling
SA.M.A06	Fast ion modelling

> 20 articles
~ 50 conference & workshop contributions

Highlights on EU physics studies for JT-60SA within WPSA in FP8

G. Giruzzi et al., PPCF 62 (2020)
+ 2020 modelling reports

Discharge simulation and integrated scenario modelling

- **Global discharge simulations**, producing time evolution of all the physical quantities, including magnetic equilibrium and radial profiles, are better done by **fast simulators**: systematic analyses were carried out with the **METIS** code.

  JT-60SA Research Plan v4.0 Sept 2018

- More accurate modelling can be performed for a phase of the discharge with **integrated modelling codes**, as **ASTRA, CRONOS, JINTRAC** and TOPICS (JA) : the **flat-top stationary phase** of the reference scenarios : H-mode, hybrid, advanced was addressed and more recently the **ramp-up** phase.

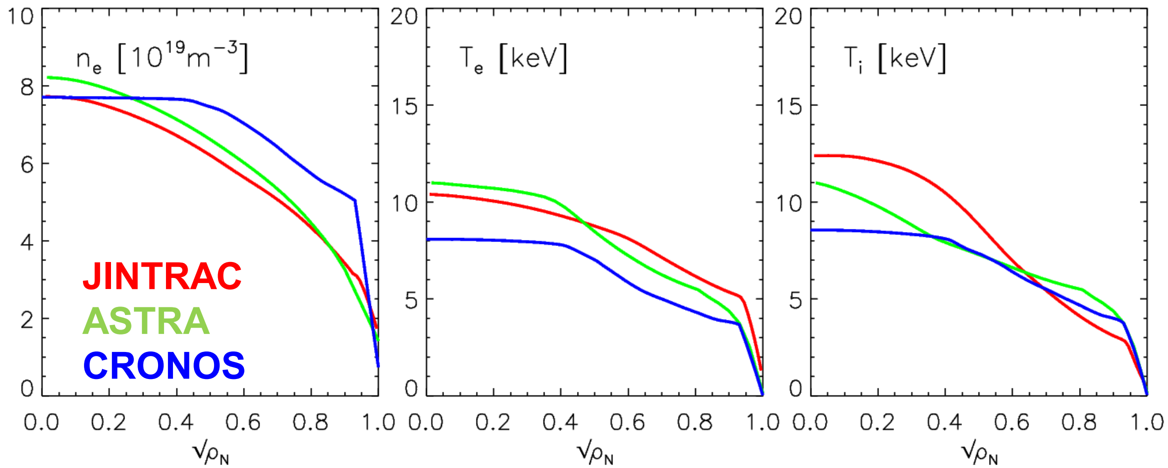
  J. Garcia et al. NF 2014
  N Hayashi et al. NF 2017
  L Garzotti et al. NF 2018

  J Morales et al. PPCF 2021

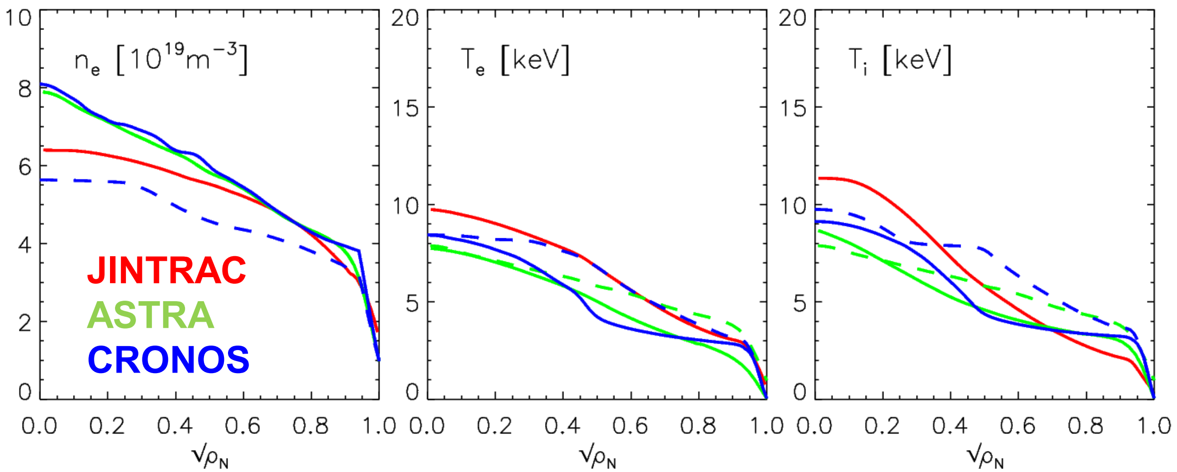
- A procedure was first devised for the validation an benchmark of the EU and JA IM codes, based on JT-60U and JET discharges representing the main scenarios. Simulations performed with a variety of embedded models (transport, pedestal, rotation, scalings) provided predictions of comparable accuracy.
- The validated modelling framework has then been applied to more complex predictive JT-60SAmodelling eg the formation of an ITB and its control by ECCD, RMP, ripple and NTV effects.

EU JT-60SA Scenario Modelling highlights

Modelling of reference scenarios **flat-top phases** with **ASTRA/CRONOS/JETTO** and various transport models.



Scenario 2



Scenario 4

ASTRA (solid: Bohm/g.-B., dashed: GLF23)
CRONOS (solid: CDBM, dashed: TGLF)

➔CDBM provides accurate, or in some cases, conservative estimates of the electron and ion temperatures

J. Garcia et al., Nucl. Fusion 54 (2014)

Integrated scenario modelling and turbulence modelling

A series of simulations of **scaled-down versions of the main operational scenarios for JT-60SA**, has been performed with the **JINTRAC suite** :

- parameter scans for scenario 2 (sawtoothing ELMy H-mode) at half field, half current
- study of the sensitivity to various NBI configurations for scenario 4.2 (hybrid) at half field and half current.
- modelling of **the Initial Research Phase I and II scenarios** **Fig. 3-4 JT-60SA Research Plan**

The simulations have been catalogued and can be used as a basis for the preparation of experiments, the modelling of diagnostics and further studies on fast particle physics, divertor physics or general MHD stability.

All the simulations were performed, using a self-consistent scheme whereby the MHD stability of the pedestal is checked during the simulations by means of the HELENA and MISHKA equilibrium and stability codes and the pressure in the external transport barrier is automatically adjusted in order to clamp it at the peeling-ballooning stability boundary.

Modelling session Thu 18th 9AM **Garzotti et al**

- The effect of plasma shaping on tokamak microstability has been investigated by means of the gyrokinetic code GS2 for both low and high β JT-60SA scenarios.

O Beeke, M Romanelli submitted to Nucl Fus.

Current ramp-up phase

Optimization of ECRH assisted current ramp-up for hybrid scenario has been investigated using **CRONOS** integrated modelling framework.
The CRONOS simulations, encompassing the computation of neoclassical resistivity by NCLASS code, turbulence transport by CDBM or TGLF, ECRH power and current deposition by the ray tracing code REMA, were validated using JET and TCV data in L-mode. Then, current ramp-up phases for JT-60SA scenario 4.2 were simulated with the validated models.
The main result is **the assessment of the ECRH power and power deposition location** required to access to the safety factor profile typical of advanced hybrid scenario.

A significant amount of off-axis ECRH power, depending on the current ramp-up rate, is required to maintain q >1 across the entire plasma radius. The optimal ECRH deposition location, allowing for high central Te, is found to be close to ρ=0.33.

J Morales et al., "L-mode plasmas analyses and current ramp-up predictions for JT-60SA hybrid scenario", Plasma Phys. Contr. Fusion 63 (**2021**) 025014.

Modelling session
Thu 18th 9AM

Flat-top plasma sustainment: density control

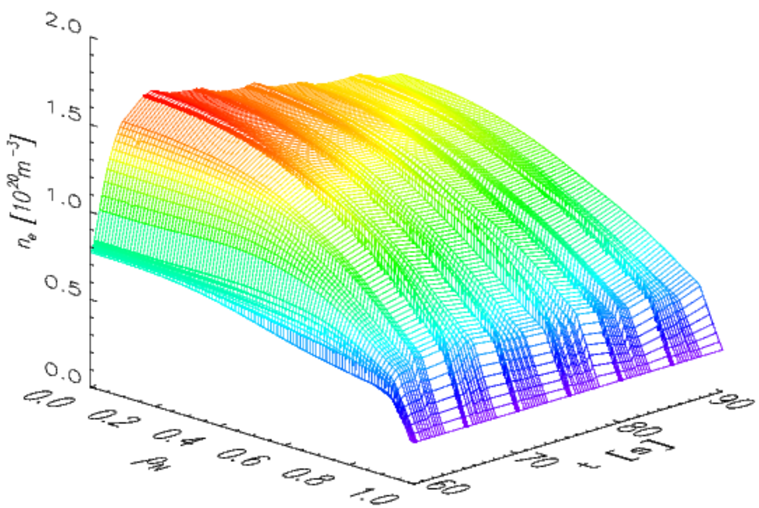
Density control is a key ingredient for long pulse regimes, in particular for access to high-density scenarios, close to the Greenwald limit.
A key actuator of such control will be the pellet fuelling system.

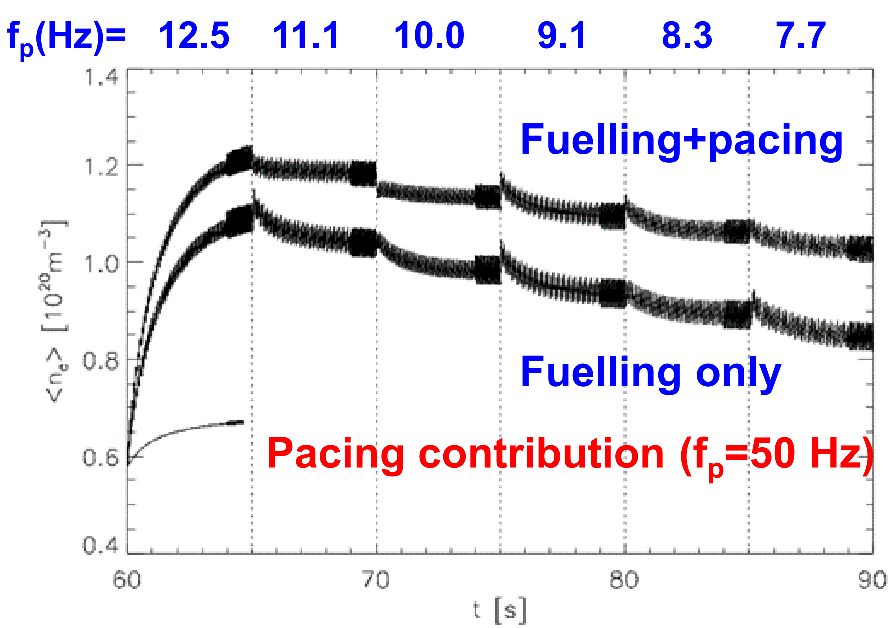
Detailed modelling of pellet ablation, using the HPI2 code, was carried out in order to determine the optimum pellet injection location and parameters for all the reference scenarios and optimise the system design.

Simulations were performed with the integrated modelling suite **JINTRAC**, appropriately set up for JT-60SA simulations, in conjunction with **HPI2**, in order to assess the feasibility of combined fuelling and ELM pacing.

L. Garzotti, et al.

Density and ELMs controlled by pellets





Modelling with **JINTRAC**
and pellet ablation module **HPI2**

- pellets speed: 400 m/s (HFS injected)
- **fuelling** pellets: 6.5 10^{20} atoms, frequency 7.7 - 12.5 Hz
- **pacing** pellets: 0.8 10^{20} atoms frequency 50 Hz

→ high-density scenarios, approaching Greenwald limit, accessible and controllable

L. Garzotti, P. Lang et al.

Flat-top plasma sustainment: power loads and radiation

The second key element for long pulse regimes is the control of power loads on the divertor during the strong heating phase, which can be attained by divertor radiation associated with controlled impurity seeding strategies.

Systematic studies of the relevant scenarios, in a simplified geometry, have been performed by means of the **COREDIV** code, both for C-PFC and W-PFC.

R. Zagórski K. Gałązka (2016-2018)

Simulations combining the core, SOL, and divertor have been performed using JINTRAC coupled to the edge code EDGE2D and the EIRENE Monte Carlo code for the neutrals, for a scenario similar to Scenario 5-1, but at reduced heating power.

M. Romanelli NF 2017

A **comparison between COREDIV and EDGE2D-EIRENE** modelling approaches has been made for scenario 3 (C wall).

The C radiation in the SOL and the power delivered to the divertor target, computed by the two codes agree within 10%. Importantly, the different plasma conditions close to the targets have a severe impact on detachment: EDGE2D-EIRENE exhibits full detachment when the electron density at the separatrix is increased to 3.6 10^{19} m^{-3} whereas COREDIV could not correctly assess it. Here, **the dominant factor is the employed neutral model.**

Edge, radiation and detachment control

High-density scenario simulated by **EDGE2D-EIRENE** code.

P_{aux}= 30 MW, $\langle n_e \rangle = 9 \times 10^{19}\ m^{-3}$

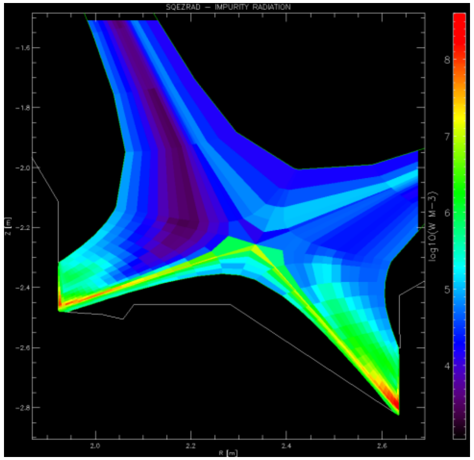
$n_e^{sep} = 3.6 \times 10^{19}\ m^{-3}$

Greenwald fraction ~0.8

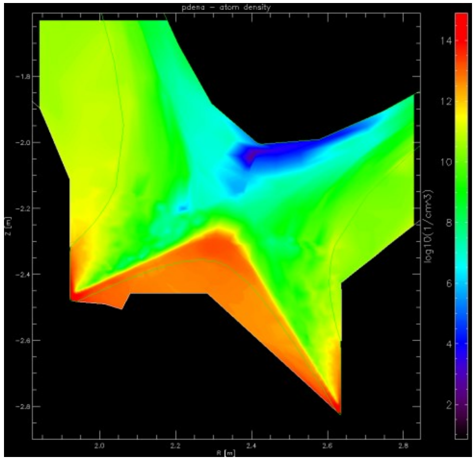
Based on previous systematic analysis by **COREDIV** code

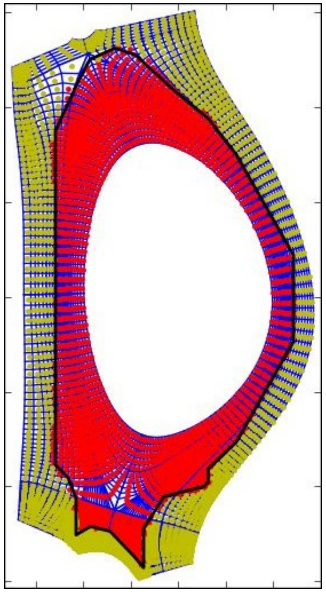
K. Gałązka, M. Romanelli et al.

Carbon radiation



Neutrals density

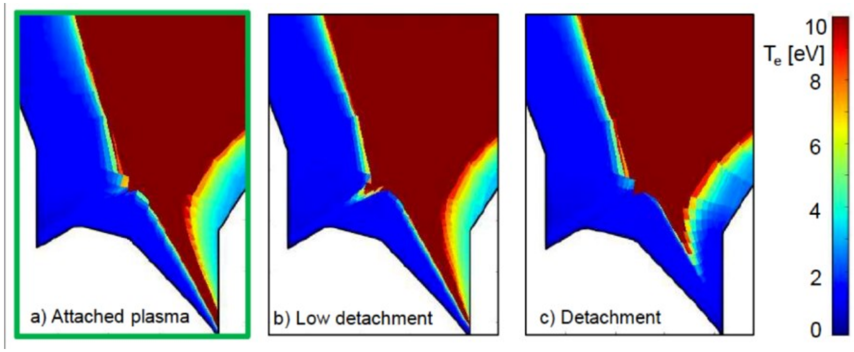


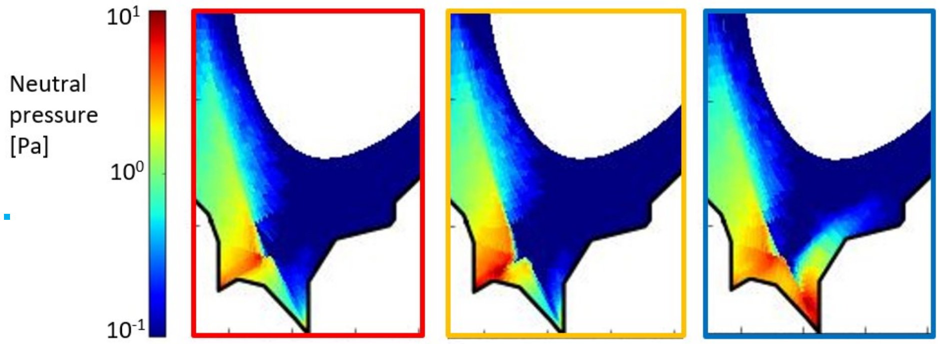


SOLEDGE2D-EIRENE

- High asymmetry level between inner and outer divertor
- Validated transport model predicts attached plasma at outer divertor with using standard input parameters

L. Balbinot, P. Innocente et al.





Edge/divertor modelling

Modelling session
Thu 18th 10AM

- Power exhaust modelling of JT-60SA **Scenario 2 with C wall** was performed with **SOLEDGE2D-EIRENE** code. Cases with only C impurities as well as with **Ar or Ne puffing** have been explored. A minimum density providing reasonable operational plasma parameters has been found in both cases (Zeff < 4).

  L Balbinot, P Innocente

- Simulations were performed using **SOLPS-ITER** code (w/o drifts) for the **W-PFC** future JT-60SA phase. Divertor conditions in **Scenario 3 with metallic (W) wall and N injection** have been assessed, leading e.g. to the identification of driving mechanism(s) for detachment. This study confirmed the compatibility of Scenario 3 with a metallic wall using nitrogen seeding as extrinsic radiative impurity. **G Rubino M Wischmeier et al**
- Sophisticated edge/SOL/divertor simulations were performed by means of the SONIC code (JA), extended to include multiple impurity species and impurity–impurity interaction, such as the physical sputtering of C by seeding impurities. This allowed comparative simulations of the radiation patterns with C and injected Ne, Ar, or mix.

- A **comparison to the SONIC** simulations was started in 2020. **S Wiesen et al**

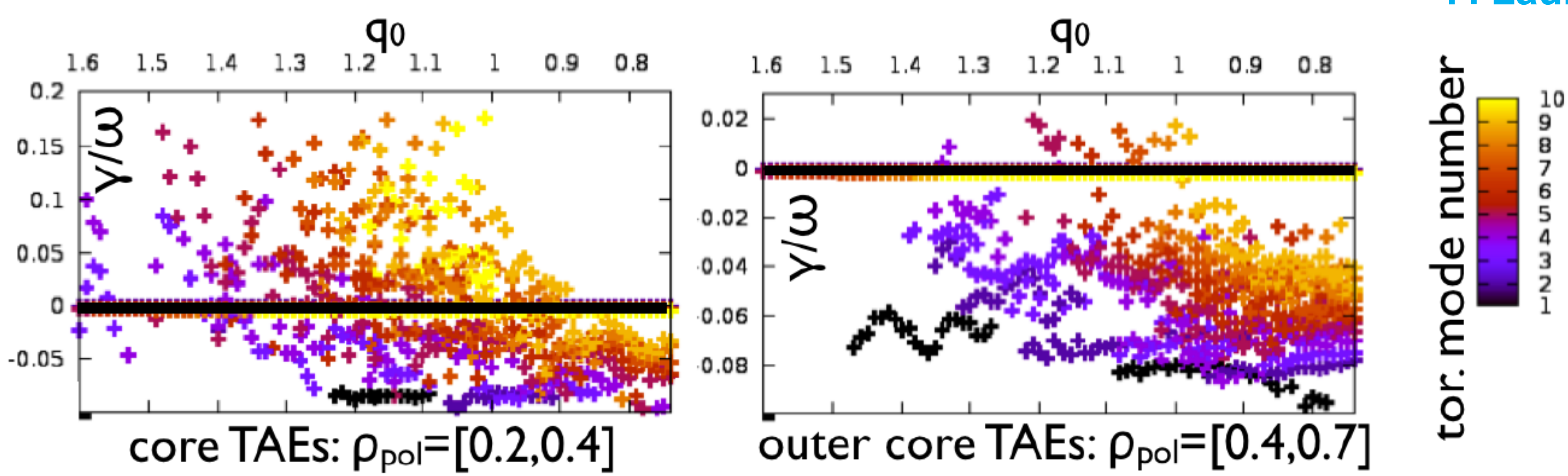
Energetic Particle physics studies

- **JT-60SA will be a key experiment for burning plasma /EP physics : ideal machine**
  - High **fast ion content** in **high-β** scenarios, due to 34 MW NBI heating
  - Experiment before ITER with **super-Alfvénic beam** (N-NBI at 500 keV)

- **Crucial input on physics models and code validation for:**
  - particle **birth/deposition** and confinement properties in **3D**
  - stability boundary for **EP-driven instabilities (Alfvén Eigenmodes)**
  - predicting their **non-linear saturation** amplitudes and **resonance overlap**
  - transition from **diffusive EP transport** to onset of **EP avalanches** →

Scan of q_0 → AE growth rates for hybrid scenario (LIGKA workflow):

P. Lauber et al.



Fast ion modelling

Modelling session
Thu 18th 11AM

Analysis of fast ion instabilities during flat-top and current ramp-up phases of the advanced scenario 4 was performed using **ASPACK** package, aiming at identifying and characterising the spectra of Alfvén Eigenmodes (AEs). **R Coelho et al**

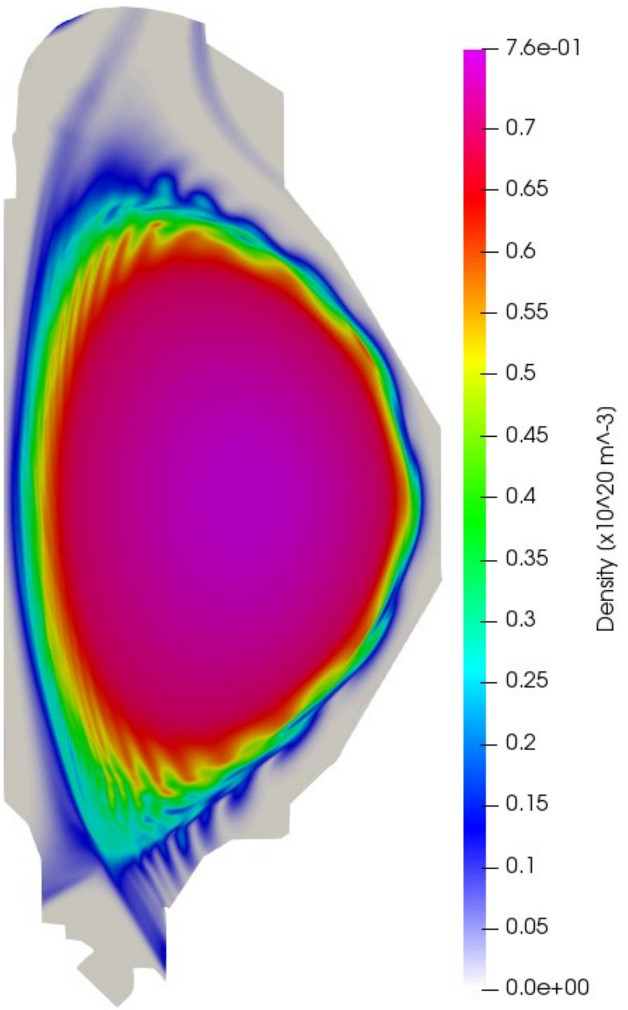
A new interface between the MHD-kinetic MEGA and the gyrokinetic **LIGKA/HAGIS** codes has been developed, bridging the EU and JA energetic particle tools. As LIGKA/HAGIS package is embedded in IMAS framework, this will allow the comparison of EP distribution functions with ASCOT and of stability results with ASPACK towards the **final target of understanding and predicting several aspects of linear and non-linear EP physics.** **Ph Lauber et al**

In support of the EU FILD diagnostic procurement, the **fast ion distribution** has been computed with the **ASCOT** suite of codes in complex situations, e.g., **in the presence of 3D perturbations**. **Taina Kurki-Suonio, M Vallar, P Vincenzi**
The magnetic fields for different scenarios were calculated from the geometries and currents in the poloidal and toroidal field coils, together with the corresponding equilibria, followed by the reconstruction of the fully 3D first wall and a numerical model for the neutral beam injectors extending all the way to the grounded grid. The magnetic perturbation from the geometries and currents in the Error Field Correction Coils (EFCC) were calculated, and also plasma response was included in the evaluation of the fast ion distribution.

First-principle ELM simulations

- First-principle simulation of non-linear ELM dynamics is fundamental to gain insight into the conditions for the access to no-ELM or small-ELM regimes or for active ELM control.

- Non-linear simulations were performed with the 3D MHD code **JOREK** for H-mode scenarios, for ballooning mode numbers n=4–22 and various plasma resistivity values.
  Simulations start with a collapsed pedestal, which then builds on, until a ballooning mode becomes unstable and the ELM crash is produced.



Large **ELM crash** simulated with n=8
(energy loss ~12% of the total plasma energy content)

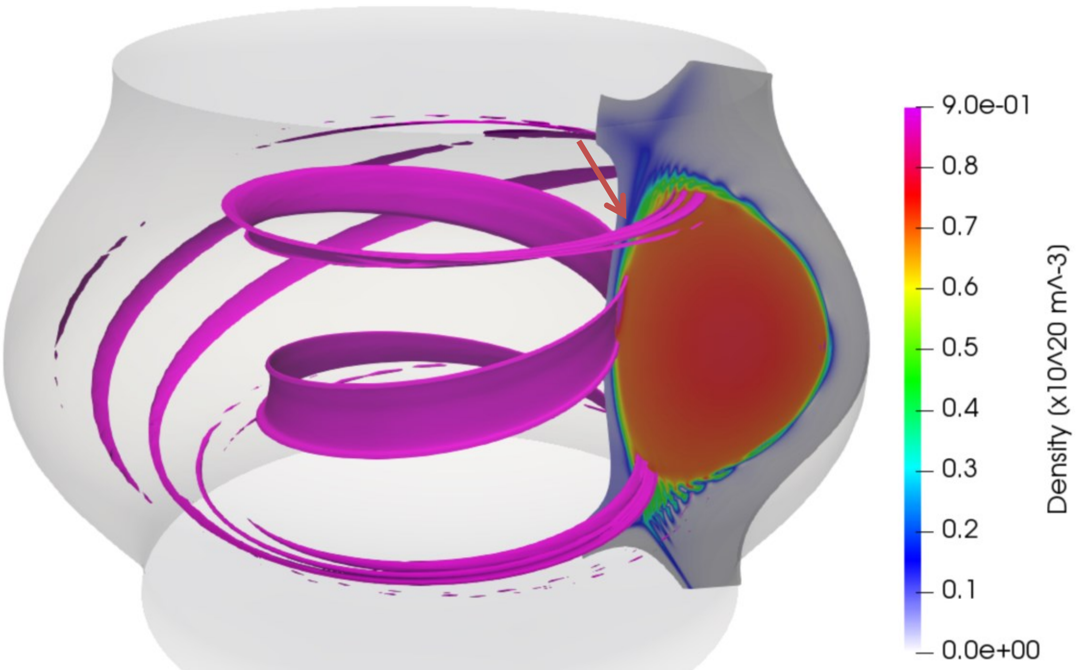
S. Paméla et al.

(H-mode, ITER-like scenario 4.1)

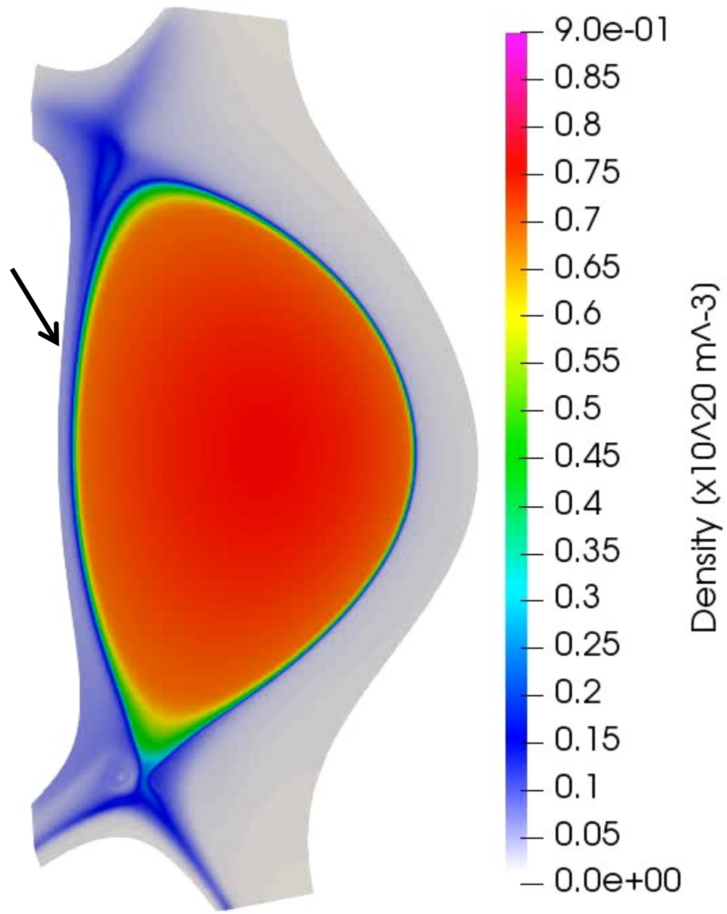
ELM control by pellets

Modelling session
Tue 16th 4PM

- Control of the ELM amplitude and frequency by pellet injection was modelled with **JOREK** including the **NGS pellet ablation module**, in support of the EU project for the procurement of the JT-60SA pellet injector.



Pacing pellet density perturbation simulated by **JOREK** with the **NGS** pellet ablation model



JOREK simulation of JT-60SA by S. Futatani (UPC)
Pellet injection from HFS

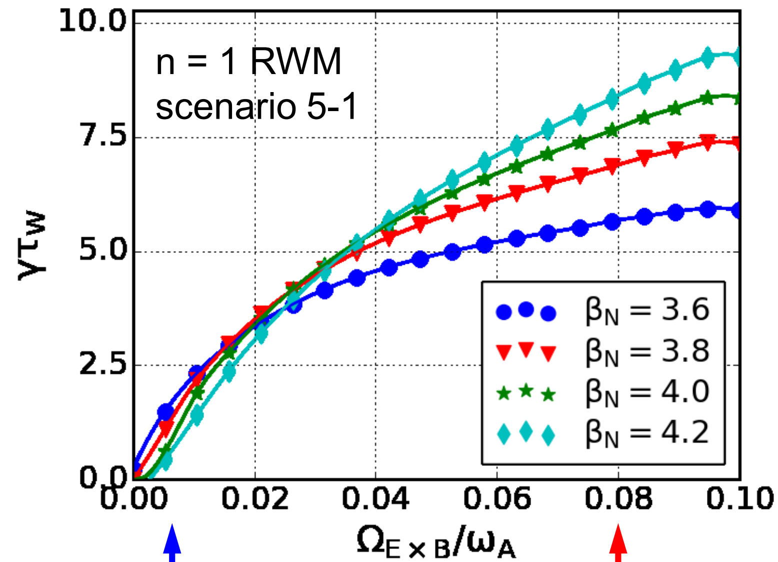
S. Futatani et al.

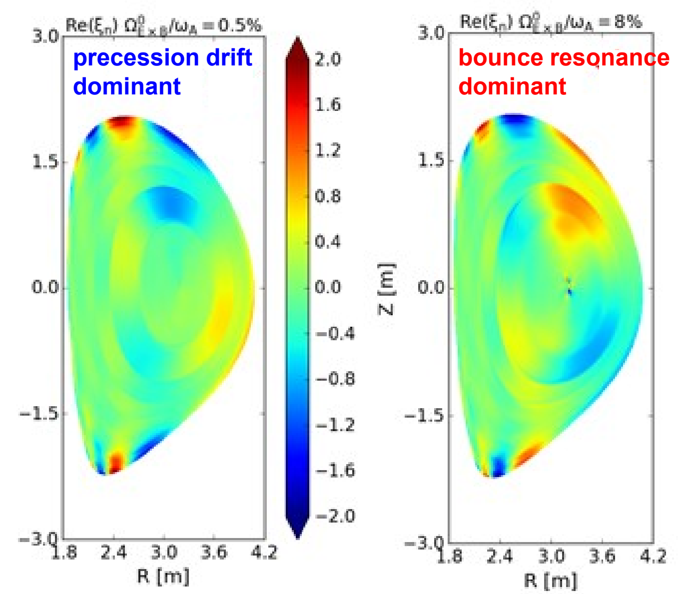
High-β MHD: kinetic and rotation effects on RWM

RWM stability with drift-kinetic contribution

- **MARS-K** code computation for high-β scenario
- thermal ions and electrons included
- strong stabilisation with respect to fluid model:
  - **precession drift** resonance dominant a low rotation
  - **bounce resonance** dominant at high rotation

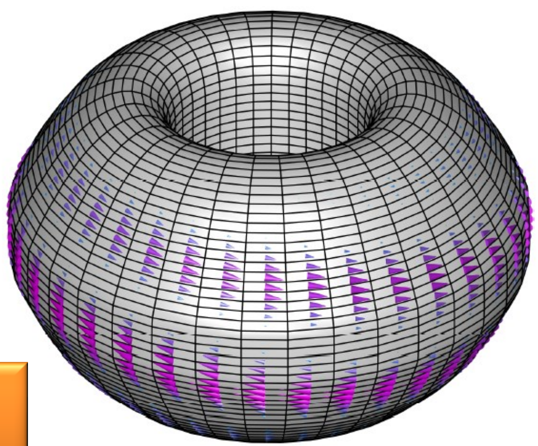
→ complex β_N dependence of growth rate





3D effects and control issues → CarMa code

- **n=1 eigenmode** on an axisymmetric surface at the stabilising plate position
- **control** strategies studies with **in-vessel coils**



L. Pigatto et al.

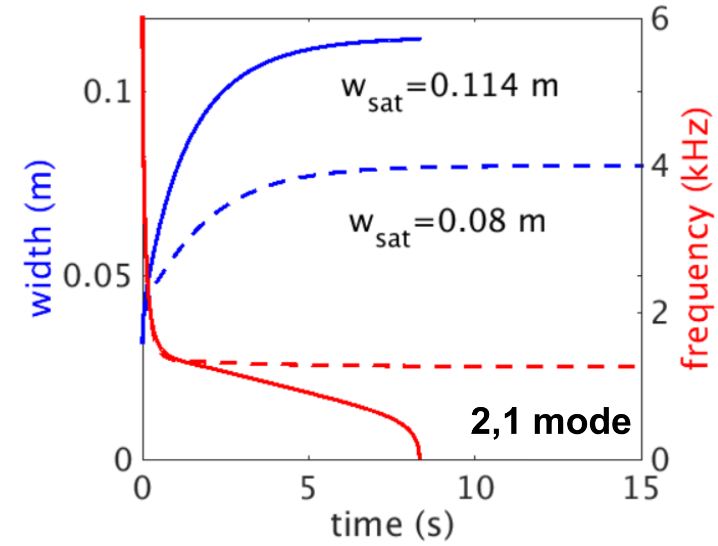
Modelling session Tue 16th 4PM

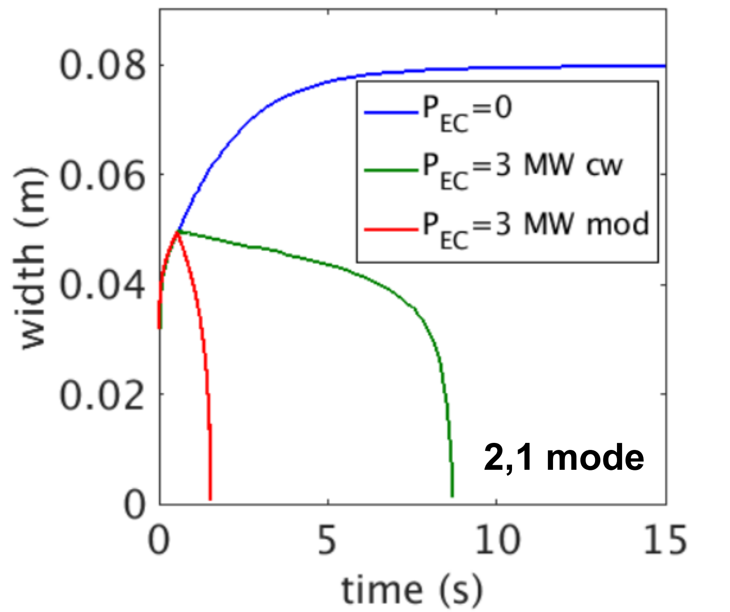
High-β MHD: Neoclassical Tearing Modes

- NTMs expected in virtually all JT-60SA scenarios at nominal heating power (→ high β) and will be **controlled by ECCD**
- Effect of ECCD with the actual antenna configuration computed by the **Generalized Rutherford Equation**
- **Mode rotation** is modelled including e.m. torque due to the eddy currents and viscous torque

  → 3,2 or 2,1 modes can **lock** in a few seconds
- Depending on the mode saturation width, **3-7 MW of modulated ECCD** power can suppress the modes or reduce their amplitudes

S. Nowak et al.





FP9 : WPSA Code Management strategy

- Establish reliable modelling codes, workflows and <u>operation related tools</u> for routine use in the scientific exploitation starting in 2023
- Modelling support to the enhancements and diagnostics procured by EU, including control actuators
- Specific focus on modelling the first operation phase scenarios: Initial research phase I and II, in H and D, with C-PFC and reduced power (! Divertor not actively cooled)

	Phase	Expected operation schedule		Annual Neutron Limit	Remote Handling	Divertor	P-NB Perp.	P-NB Tang.	N-NB	NB Energy Limit	ECRF 110 GHz & 138 GHz	Max Power
Initial Research Phase	phase I	2021 (5M)	H	-	R&D	USN Carbon	0	0	0	0	1.5MWx5s	1.5MW
		2023 (2M)				LSN Carbon Div. Pumping	3MW	3MW	10MW	23MW x 14s duty = 1/30	1.5MWx100s + 1.5MWx5s	19MW
	phase II	2023-2024 (6M)	D	3.2E19			6.5MW	7MW				26.5MW
		2024-2025										
	phase III	2025-2027								Real Injection : ~ 26MW x 2-3 sec limited by divertor cooling		
Integrated Research Phase	phase I	2029 - 2031	D	4E20		LSN Actively cooled Carbon Div.Pumping	13MW			20MW x 100s 30MW x 60s duty = 1/30	7MW x 100s	37MW
	phase II	2033 -	D	1E21		LSN Actively cooled Tungsten-coated Carbon Div.Pumping						

Publications
in 2014-2020

https://iterphysicswiki.euro-fusion.org/index.php?title=WPSA_publications

Publications /1

1. J. Garcia et al., *"Physics comparison and modelling of the JET and JT-60U core and edge: towards JT-60SA predictions"*, Nucl. Fusion **54** (2014) 093010.
2. P. Bettini et al., *"Advanced computational tools for the characterization of the dynamic response of MHD control systems in large fusion devices"*, *IEEE Transaction on Magnetics*, **51** (2015) 7204105.
3. S. Mastrostefano et al., *"Three-dimensional analysis of JT-60SA conducting structures in view of RWM control"*, Fusion Eng. Des. **96–97** (2015) 659.
4. C. Gleason-González et al., *"Simulation of collisional effects on divertor pumping in JT-60SA"*, Fus. Eng. Des. **109–111** (2016) 693
5. R. Zagórski et al., *"Numerical analyses of JT-60SA scenarios with the COREDIV code"*, Nucl. Fusion **56** (2016) 016018.
6. K. Gałązka et al., *"Numerical analyses of JT-60SA with tungsten divertor by COREDIV code"*, Plasma Phys. Contr. Fusion **59** (2017) 045011.
7. N. Cruz et al., *"Control-oriented tools for the design and validation of the JT-60SA magnetic control system"*, Control Engineering Practice **63** (2017) 81.
8. G. Giruzzi et al., *"Physics and operation oriented activities in preparation of the JT-60SA tokamak exploitation"*, Nucl. Fusion **57** (2017) 085001.
9. N. Hayashi et al., *"Transport modelling of JT-60U and JET plasmas with internal transport barriers towards prediction of JT-60SA high-beta steady-state scenario"*, Nucl. Fusion **57** (2017) 126037.
10. M. Romanelli et al., *"Investigation of sustainable high-beta long-pulse scenarios in JT-60SA C-wall"*, Nucl. Fusion **57** (2017) 116010.
11. R. Zagórski et al., *"Numerical analyses of baseline JT-60SA design concepts with the COREDIV code"*, Nucl. Fusion **57** (2017) 066035.

Publications /2

12. N. Aiba, S. Pamela et al., *"Analysis of ELM stability with extended MHD models in JET, JT-60U and future JT-60SA tokamak plasmas"*, Plasma Phys. Contr. Fusion **60** (2018) 014032.
13. L. Garzotti et al., *"Analysis of JT-60SA operational scenarios"*, Nucl. Fusion **58** (2018) 026029.
14. K. Gałązka et al., *"Multiple impurity seeding for power exhaust management in JT-60SA with carbon divertor"*, Contrib. Plasma Phys. **58** (2018) 751.
15. L. Pigatto et al., *"Resistive Wall Mode physics and control challenges in JT-60SA high β_N scenarios",* Nucl. Fusion **59** (2019) 106028.
16. J. Vega et al., *" Assessment of linear disruption predictors using JT-60U data"*, Fusion Eng. Des. **146** (2019) 1291.
17. D. Corona et al., *" Plasma shape control assessment for JT-60SA using the CREATE tools"*, Fusion Eng. Des. **146** (2019) 1773.
18. **G. Giruzzi et al., *"Advances in the physics studies for the JT-60SA tokamak exploitation and research plan"*,** Plasma Phys. Contr. Fusion **62** (2020) 014009.
19. J. Morales et al., *"L-mode plasmas analyses and current ramp-up predictions for JT-60SA hybrid scenario"*, Plasma Phys. Contr. Fusion **63** (2021) 025014.
20. V. Ostuni et al., *"Tokamak discharge simulation coupling free-boundary equilibrium and plasma model with application to JT-60SA",* Nucl. Fusion **61** (2021) 026021.
21. G. Rubino et al., *"Assessment of Scrape-Off Layer and divertor plasma conditions in JT-60SA with tungsten wall and nitrogen injection"*, Nuclear Materials and Energy **26** (2021) 100895.
22. A. Louzguiti et al., *"Modeling of AC losses and simulation of their impact on JT-60SA TF magnets during commissioning",* *to appear in* IEEE Trans. on Applied Superconductivity (2021)

Conferences / 2014-2015

1. P. Bettini et al., "Advanced computational tools for the characterization of the dynamic response of MHD control systems in large fusion devices", 16th Biennial Conference on Electromagnetic Field Computation (CEFC), Annecy (France), 25-28 May 2014.
2. J. Garcia et al., "Analysis of JT-60SA scenarios on the basis of JET and JT-60U discharges", 41st EPS Conf. on Plasma Physics (EPS 2014), Berlin (Germany), 23-27 June 2014.
3. P. Bettini et al., "Three-dimensional electromagnetic analysis of JT-60SA conducting structures in view of RWM control", 28th Symp. on Fusion Technology (SOFT 2014), San Sebastián (Spain) 29 Sept.-3 Oct. 2014.
4. S. Mastrostefano et al., *"Three-dimensional electromagnetic analysis of JT-60SA conducting structures in view of RWM control"*, 28th Symp. on Fusion Technology (SOFT 2014), San Sebastián (Spain) 29 Sept.-3 Oct. 2014.
5. L. Garzotti et al., *"Modelling of JT-60SA Operational Scenarios"*, 19th Joint EU-US TTF meeting, Culham (UK) 8-11 Sept. 2014.
6. J. Garcia et al., *"Heat and Particle Physics analysis in advanced tokamak plasmas from JET and JT-60U"*, 8th IAEA Techn. Meeting on Steady State Oper. of Magn. Fus. Devices, Nara (Japan), 26-29 May 2015.
7. L. Garzotti et al., *"Modelling of JT-60SA Operational Scenarios"*, 8th IAEA Techn. Meeting on Steady State Oper. of Magn. Fus. Devices, Nara (Japan), 26-29 May 2015.
8. R. Zagórski et al., *"Numerical analyses of steady-state and inductive JT-60SA scenarios with the COREDIV code"*, 8th IAEA Techn. Meeting on Steady State Oper. of Magn. Fus. Devices, Nara (Japan), 26-29 May 2015
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14. L. Pigatto et al., *"Resistive Wall Mode physics in JT-60SA high β_N scenarios"*, 43rd EPS Plasma Physics Conf. (EPS 2016), Leuven (Belgium), 4-8 July 2016
15. G. Giruzzi et al., *"Physics and operation oriented activities in preparation of the JT-60SA tokamak exploitation"*, 26th IAEA Fusion Energy Conference (FEC 2016), Kyoto (Japan), 17-22 Oct. 2016
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