Modelling needs to support the ITER Research Plan and role of HPC

Alberto Loarte on behalf of the Science Division
Science, Controls, and Operation Department
ITER Organization

With many contributions from Science Division members and collaborators

Outline of talk

- ☐ Introduction and overview of ITER Construction Status
- ☐ Overview of ITER Research Plan and staged approach
- ☐ ITER modelling needs
- ☐ Role of HPC to support ITER Research Plan
- ☐ Conclusions

Introduction and Overview of Construction Status

ITER mission goals

ITER shall demonstrate scientific & technological feasibility of fusion energy:

- ➢ Pulsed operation:

Q ≥ 10 for burn lengths of 300-500 s inductively driven current

→ Baseline scenario 15 MA / 5.3 T

- ➢ Long pulse operation:

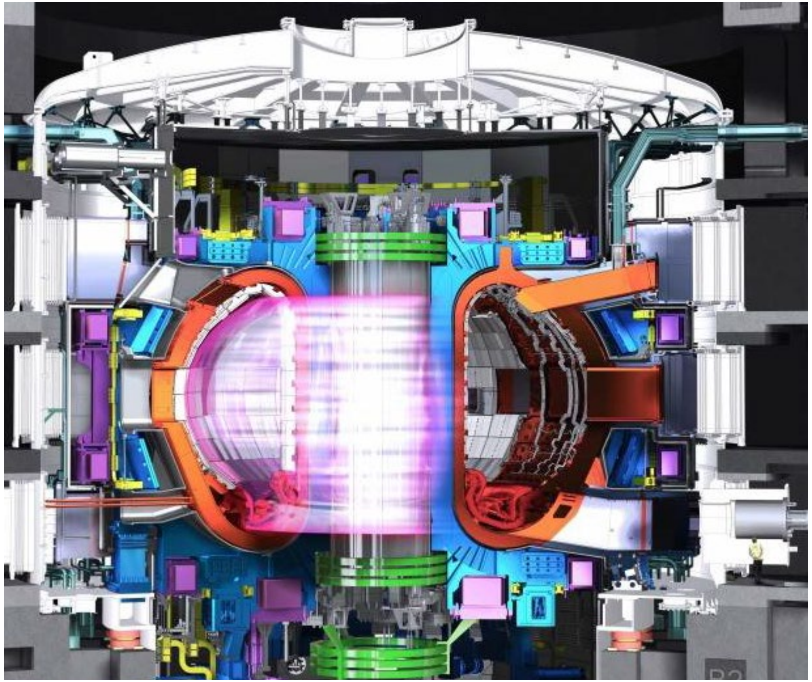
Q ~ 5 for long pulses up to 1000 s

→ Hybrid scenario ~ 12.5 MA / 5.3 T

- ➢ Steady-state operation:

Q ~ 5 for long pulses up to 3000 s, with fully non-inductive current drive

→ Steady-state scenario ~ 10 MA / 5.3 T

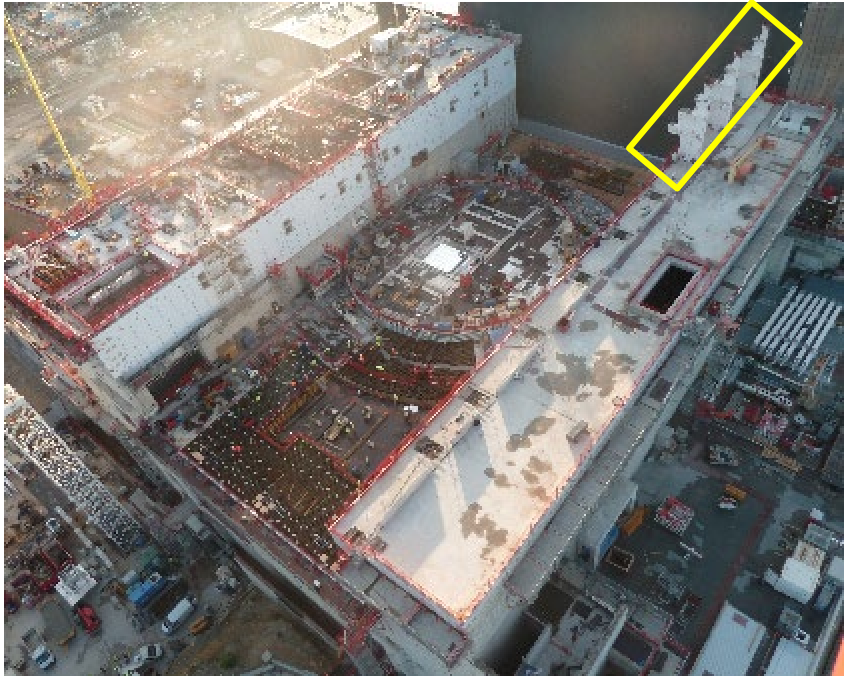


The ITER Research Plan describes the strategy to achieve these goals

Progress on ITER Assembly and Commissioning

- ☐ Despite the challenges of the pandemic major progress in construction in 2020
- ☐ Tokamak building Crane Hall completed
- ☐ The Project has received all of the large components and tools required for assembly of the first tokamak sector
- ☐ Cryostat Assembly has begun → Start of Assembly Celebration
- ☐ The first 2 (out of 6) poloidal field coils are on-site being cold-tested
- ☐ Commissioning of some of the fundamental plant systems is underway or in preparation

Tokamak Building Construction: Crane Hall Enclosed



September 2019

June 2020

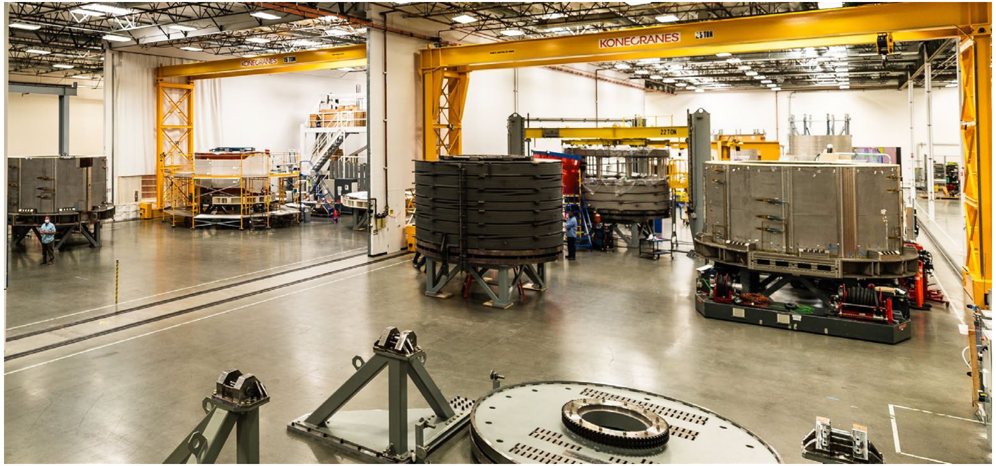
Successful Cryostat Base Installation + further work


Start of Assembly Ceremony July 2020

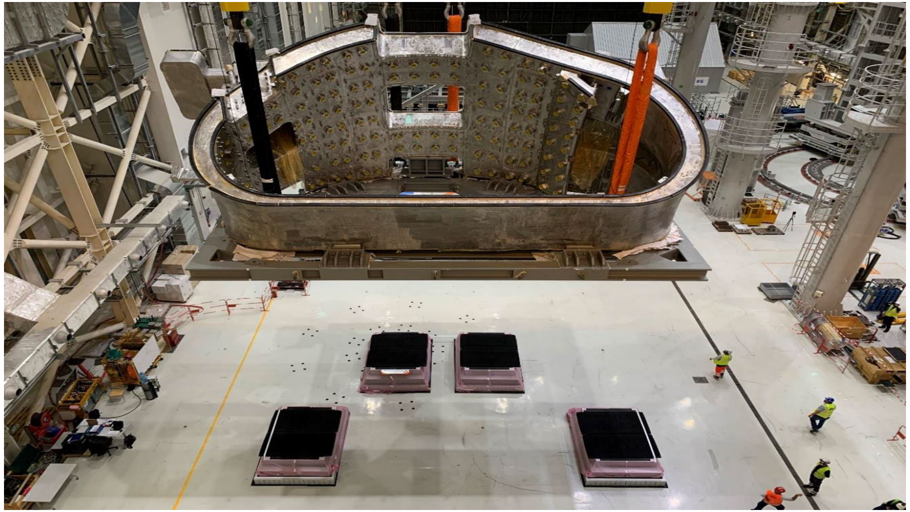
Poloidal Field Coils On-site and CS on the way

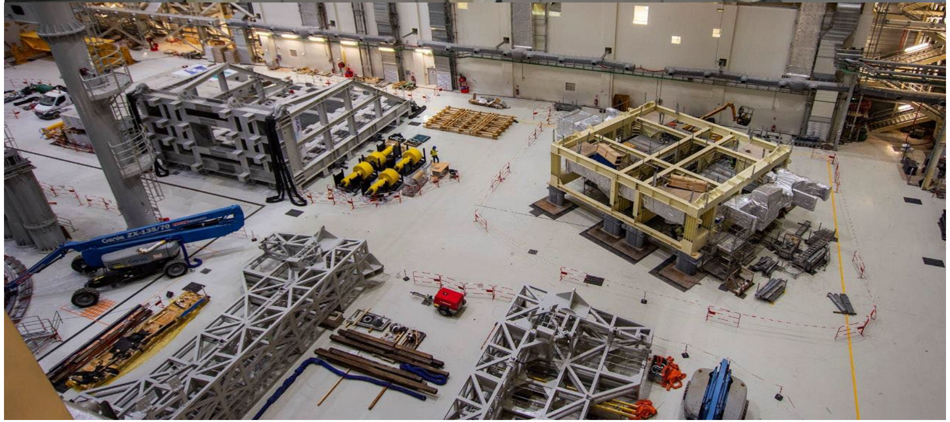
- The divertor coils PF6 and PF5 are fabricated and undergoing cold tests

- Central Solenoid Module 2 is Ready for Testing
- Module 1 to be shipped to ITER site soon



First Vacuum Vessel Sector + 4 TF coils on-site



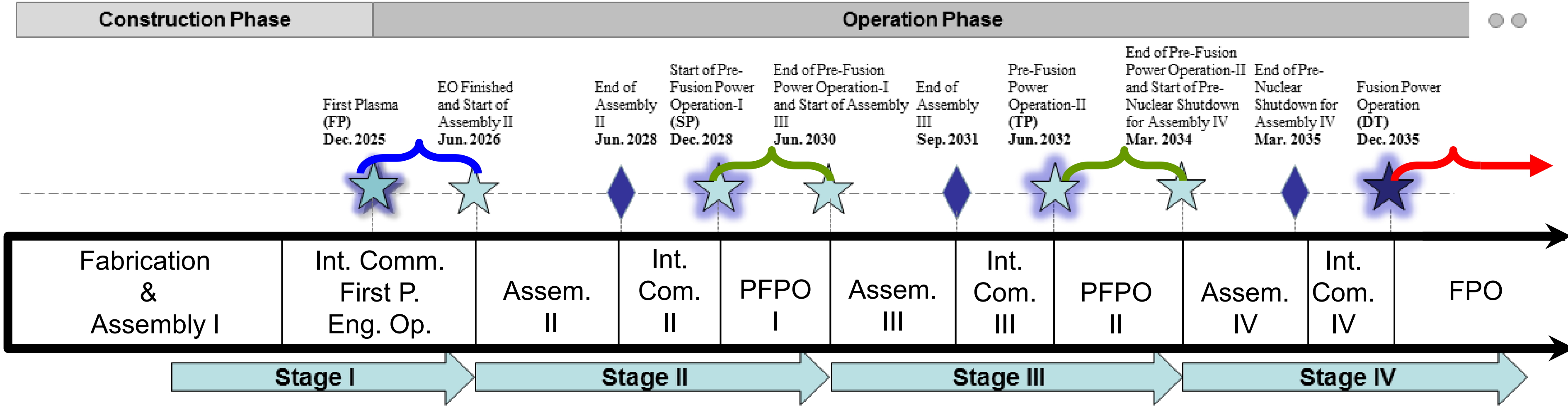


- Vacuum Vessel Sector 6 passed He leak tests – Metrology and magnetic diagnostic installation on-going
- Sector 7 95 % complete

Overview of ITER Research Plan (IRP) and staged approach

ITER Research Plan (IRP)

- ☐ **R&D Strategy to achieve project's goals with distinct phases :**
  - ➢ **Integrated Commissioning, First Plasma, Engineering Operation**
  - ➢ **Pre-Fusion Operation phase (H/He)**
  - ➢ **Fusion Power Operation (D and DT) → Achievement of high Q goals**



Construction Phase

Operation Phase

First Plasma (FP) **Dec. 2025**

EO Finished and Start of Assembly II **Jun. 2026**

End of Assembly II **Jun. 2028**

Start of Pre-Fusion Power Operation-I (SP) **Dec. 2028**

End of Pre-Fusion Power Operation-I and Start of Assembly III **Jun. 2030**

End of Assembly III **Sep. 2031**

Pre-Fusion Power Operation-II (TP) **Jun. 2032**

End of Pre-Fusion Power Operation-II and Start of Pre-Nuclear Shutdown for Assembly IV **Mar. 2034**

End of Pre-Nuclear Shutdown for Assembly IV **Mar. 2035**

Fusion Power Operation (DT) **Dec. 2035**

Fabrication & Assembly I

Int. Comm. First P. Eng. Op.

Assem. II

Int. Com. II

PFPO I

Assem. III

Int. Com. III

PFPO II

Assem. IV

Int. Com. IV

FPO

Stage I

Stage II

Stage III

Stage IV

Integrated Commissioning-First Plasma-Engineering Operation

1. Integrated Commissioning

- ❑ Integrated commissioning of:
  - ➢ Plant systems (central control systems, power supplies, cooling/baking, vacuum, cryogenics etc.)
  - ➢ Magnet systems to level required for FP (nominally 50% maximum current)
  - ➢ ECRH, diagnostics, fuelling, GDC, PCS systems
- ❑ Magnetic diagnostic calibration

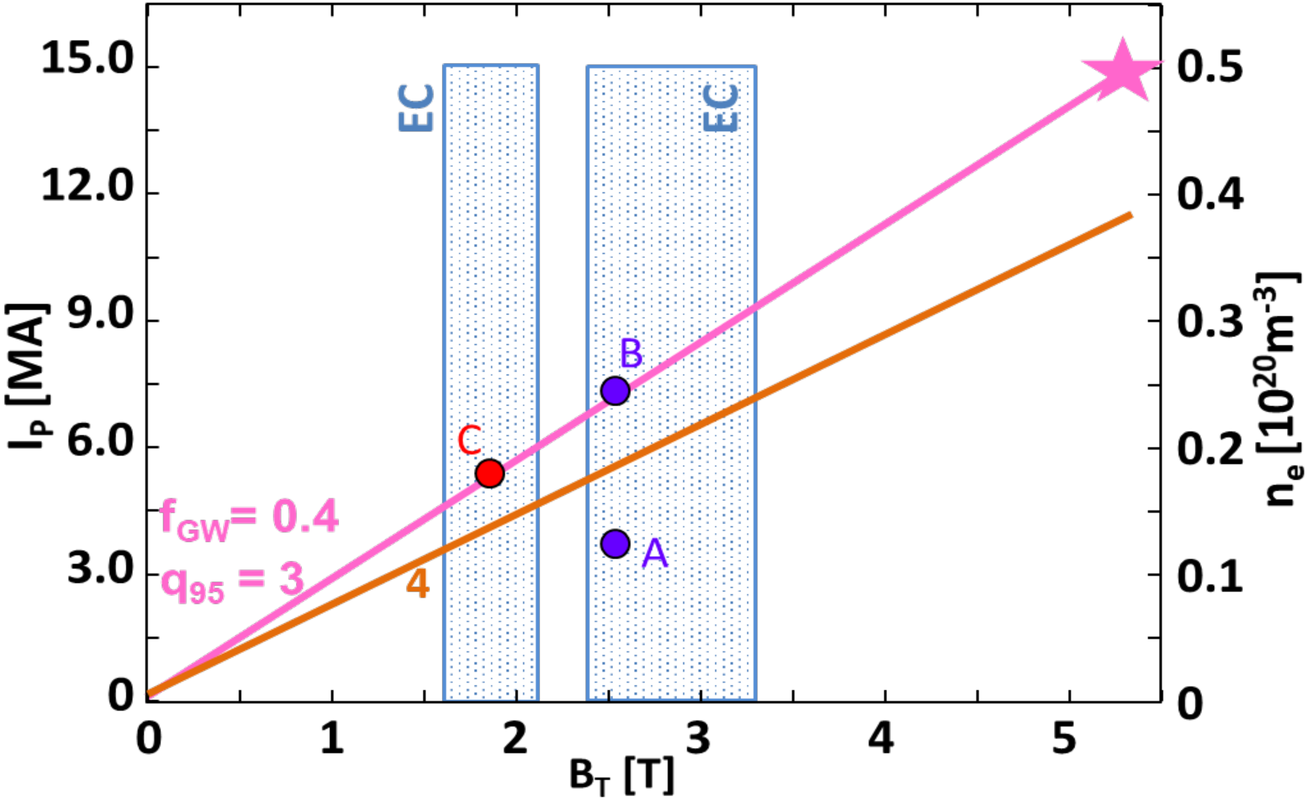
2. First Plasma

- ❑ 100 kA/ 100 ms milestone with ECH assisted start-up (P. de Vries, NF 2019)

3. Engineering Commissioning

- ❑ Performance tests of all Magnet systems to full current
- ❑ Definition of strategy to align plasma facing components
- ❑ Studies of Ohmic start-up (for 1.8 T)

PFPO-I

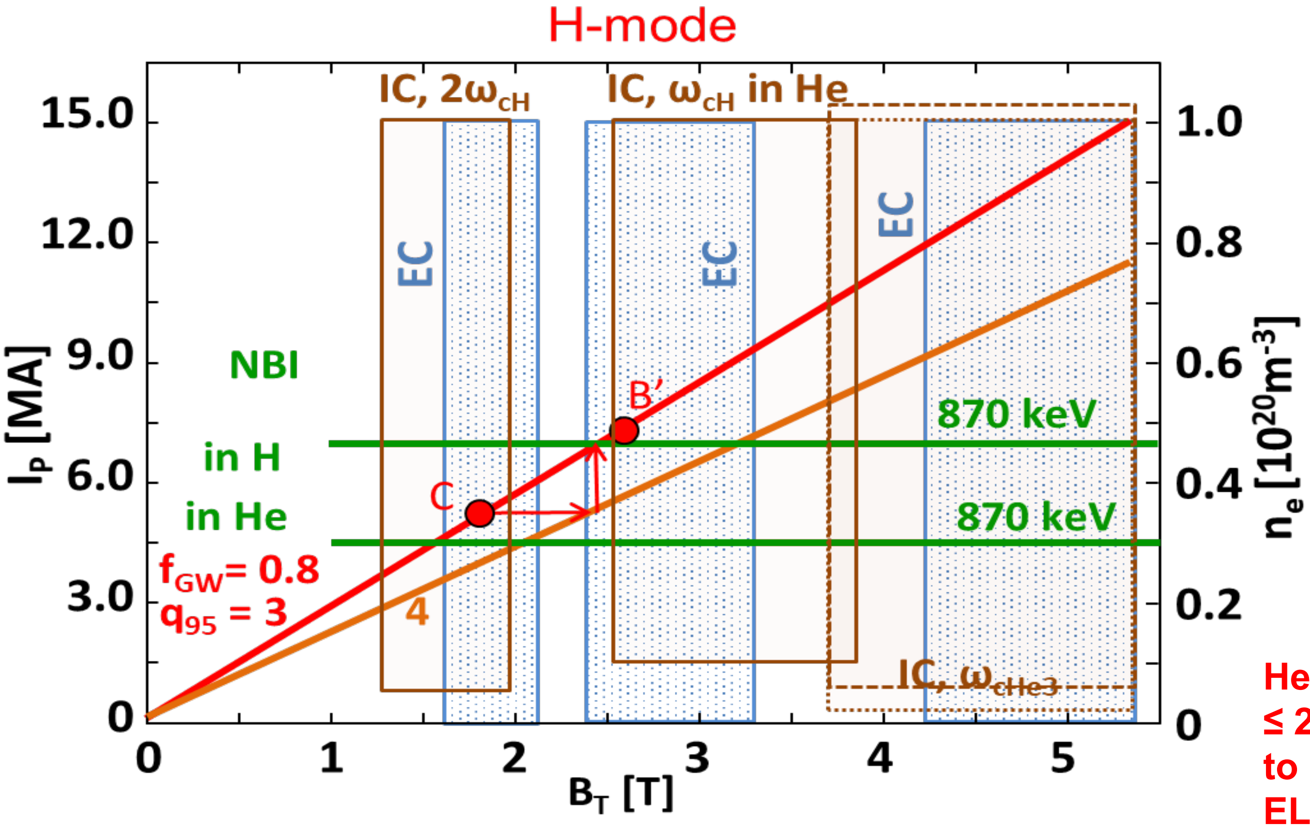


- **A.** 1st divertor plasma
3.2 MA / 2.65 T

- **B.** q_{95}=3 plasma
7.5 MA / 2.65 T
  - L-mode in PFPO-I

- **C.** 1st high confinement
5 MA / 1.8 T

PFPO-II

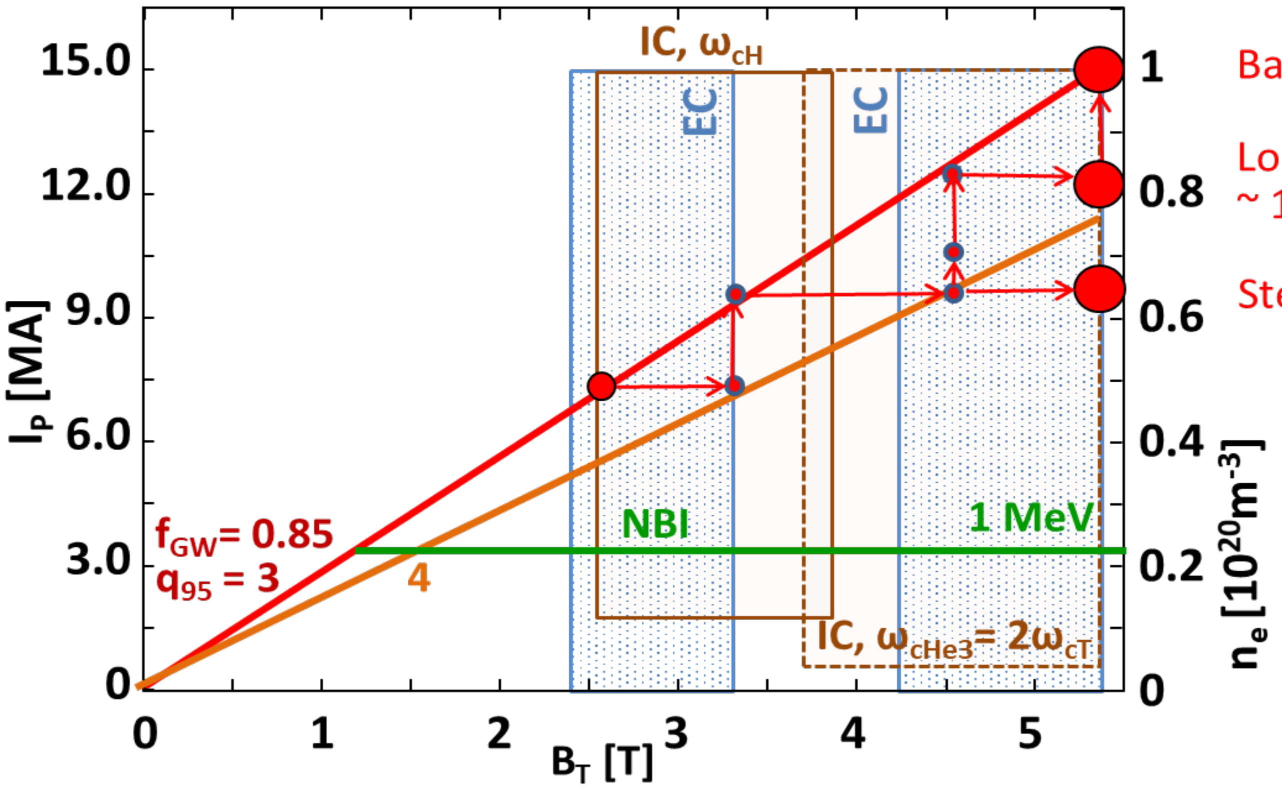


- **C.** *q_{95}=3 plasma*
  5 MA / 1.8 T
  - *H-mode*
- **B'.** q_{95}=3 plasma
  7.5 MA / 2.65 T
  - H-mode

Plasma species	$P^{H\text{-mode}}$ (MW) $n_e = 0.5\ n_{GW}$
H	58
He	38

He H-modes are robust $P_{aux}/P_{LH} \leq 2.0$ → uncertain extrapolation to DT (fuelling, PWI, pedestal, ELM control, …) → R&D required

Fusion Power Operation (D/DT)



Baseline 15 MA / 5.3 T

Long pulse hybrid
~ 12.5 MA / 5.3 T

Steady-state ~ 10 MA / 5.3 T

ITER modelling needs

ITER modelling needs

ITER modelling needs are wide → many (but not all) need HPC support

- ☐ IMAS framework
- ☐ Modelling of ITER scenarios
  - IRP refinement and development of control strategies (Q = 10 & Q =5 examples)
  - Assessment of scenarios (Fast particle stability, T-control, ...)
- ☐ Experimental data analysis
  - Synthetic diagnostics to prepare analysis and assess diagnostic performance
  - High level diagnostic analysis including measurement consistency
- ☐ Detailed modelling of specific plasma processes (usually HPC-supported)
  - Disruption and Disruption Mitigation (MHD simulations, Power fluxes and impact on materials, …)
  - ELM control (MHD simulations, Fast particle losses, Power fluxes, …)
  - …..

Framework for ITER modelling and Analysis (IMAS)

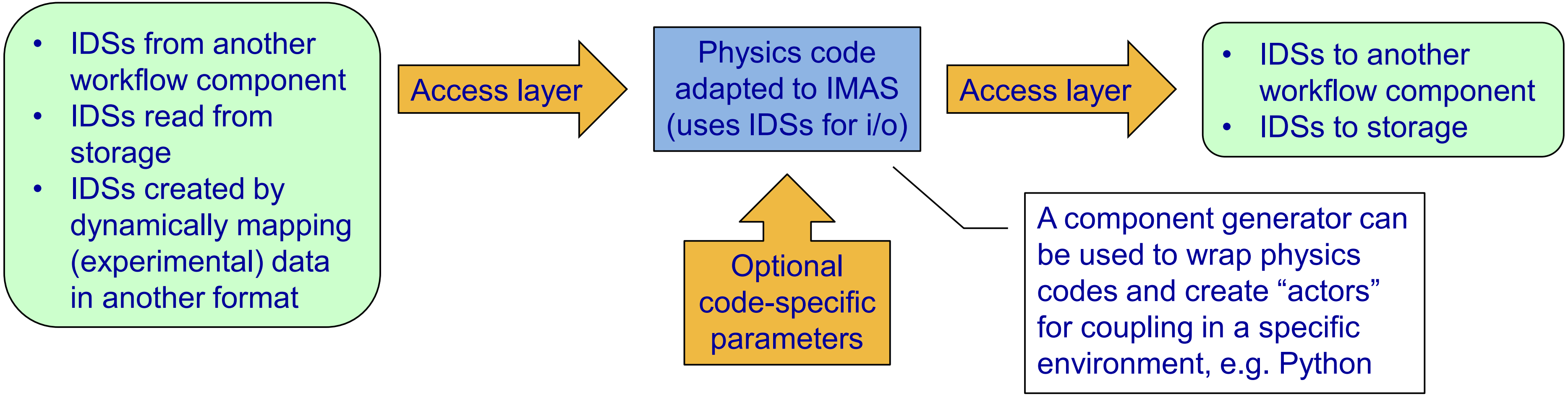
- The Integrated Modelling & Analysis Suite (IMAS) is the framework that will be used for all physics modelling and analysis at ITER
- Uses a modular approach that builds around a standardized data representation that can describe both experimental and simulation data for any device
- Inclusion of machine description data allows development and validation of machine-generic components and workflows within ITER Members' programmes before application on ITER
  - Allows ITER Members to contribute to (and benefit from) developments including:
    - High Fidelity Plasma Simulator and its components
    - Data processing and analysis tools
- Tutorials are available at https://imas.iter.org

Data Model

- Data Dictionary defines structuring and naming of data
  - Same data structures used for both experimental and simulation data
  - Applicable to all devices (includes Machine Description data) – not restricted to ITER
  - Uses a tree structure (allows re-use of names)
  - Automated definition of data structures for all supported languages
    - C/C++, Fortran, Python, Java and Matlab
  - Well-defined lifecycle procedures allow collaborative evolution of Data Model
- Interface Data Structures (IDSs)
  - Standardised entities for use between software components and storage
    - Examples include plant systems (*diagnostics, heating systems*) and physics concepts (*equilibrium, core plasma profiles*)
  - Contains traceability information (provenance) and self-description information
  - Supports modularity and facilitates interchange of components from contributors

Using Interface Data Structures (IDS) to couple codes

- ☐ The IMAS Access Layer makes coupling codes using IDSs straightforward, even if they are written in different languages
  - – Currently support: Fortran, C++, Python, Java, MATLAB
- ☐ This is the basis upon which modular workflows such as plasma simulators and data processing chains will be created



- IDSs from another workflow component
- IDSs read from storage
- IDSs created by dynamically mapping (experimental) data in another format

Access layer

Physics code adapted to IMAS (uses IDSs for i/o)

Optional code-specific parameters

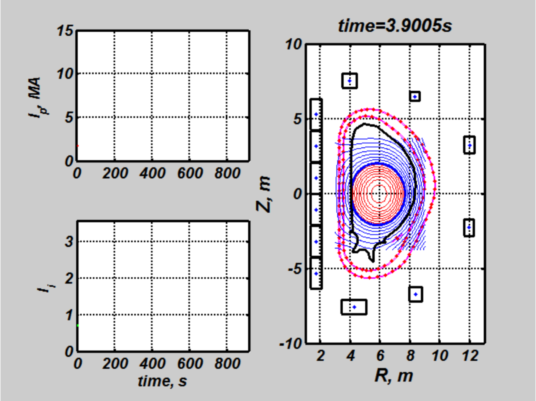
Access layer

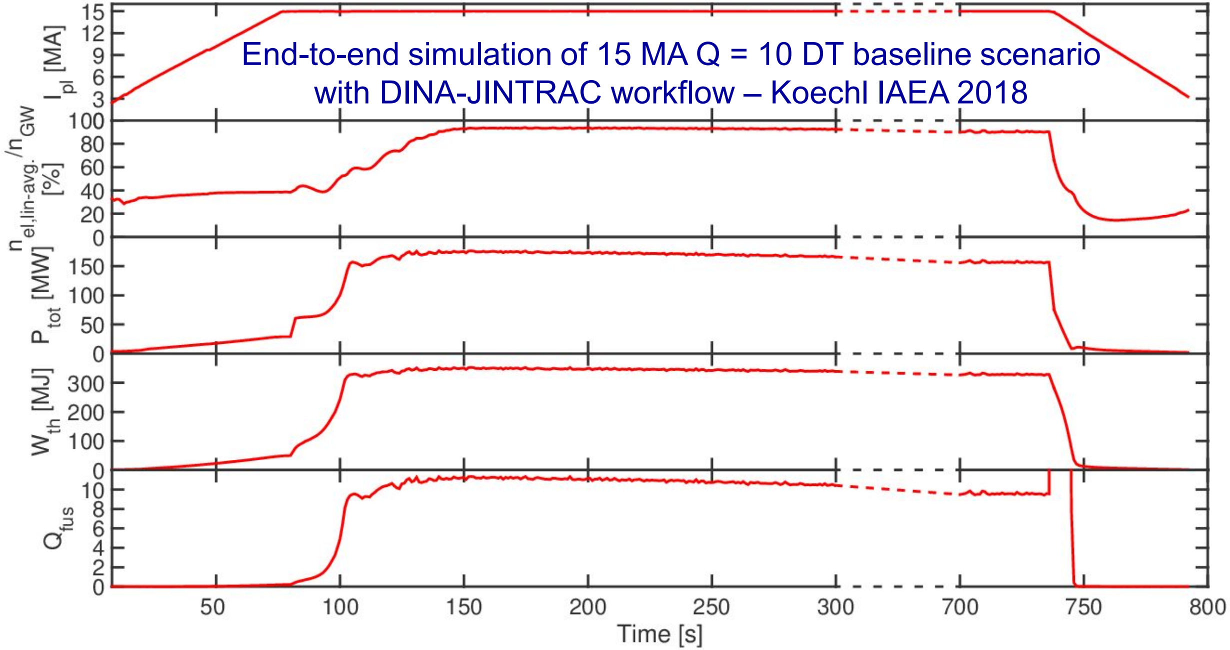
- IDSs to another workflow component
- IDSs to storage

A component generator can be used to wrap physics codes and create “actors” for coupling in a specific environment, e.g. Python

Integrated physics assessment of Q = 10 DT scenario - I

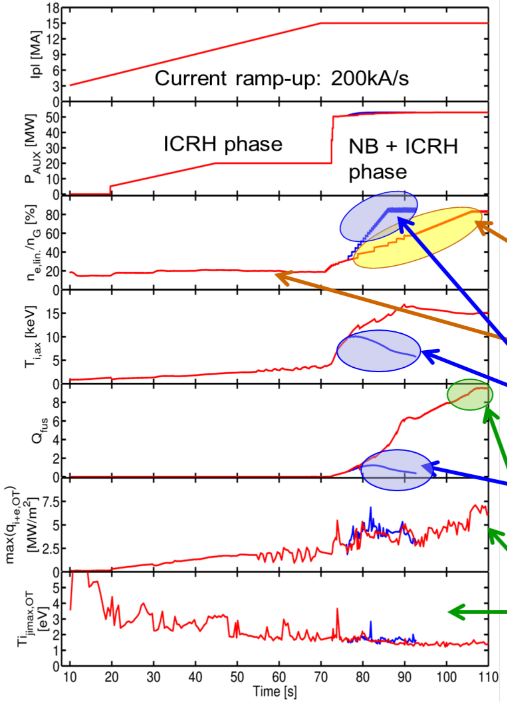
- Free-boundary equilibrium code DINA and the JINTRAC suite of codes adapted to IMAS and used to simulate the 15 MA / 5.3 T DT Q=10 ITER baseline scenario
- Scenario assessed for entire evolution from early ramp-up phase (from X-point formation) until late ramp-down phase (to X-point-limiter transition) by integrated simulations:
    - Core, edge, and SOL transport
    - Power Fluxes to PFCs
    - Impurity dynamics
    - Time-dependent free-boundary plasma geometry
    - Pedestal pressure by self-consistent edge MHD stability analysis




End-to-end simulation of 15 MA Q = 10 DT baseline scenario with DINA-JINTRAC workflow – Koechl IAEA 2018

Integrated physics assessment of Q = 10 DT scenario - II

- JINTRAC integrated modelling used to optimized self-consistent fuelling and control of divertor conditions in stationary and transient phases (L-H and H-L)



E. Militello-Asp IAEA 2016

Fine-tuning of gas & pellets to:
- avoid full divertor detachment
  - Single pellet can derail the plasma!
- provide enough fuelling to reach Q=10

A Greenwald density fraction < 35% to be expected in L-mode at 20MW.

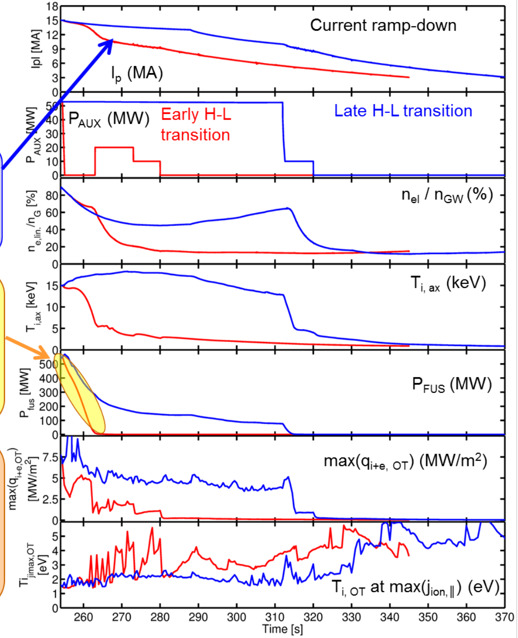
Too high fuelling during the L-H transition cools off the plasma and thwarts the build-up of α heating.
- The plasma returns to L-mode!

Q ~10 reached keeping the target power loads and temperatures permissible with Ne seeding.

The current ramp-down from 3 to 15MA takes ~85-120s depending on when in the ramp the H termination takes place.

In the case of fast P_{AUX} switch-off the H-mode termination takes ~10-15s
- This is slow enough for the vertical control systems to keep the plasma stable.

Keeping the target power loads and temperatures down to avoid W sputtering but simultaneously avoiding triggering a MARFE needed careful adjustments of Ne seeding.
- Real-time system advisable!

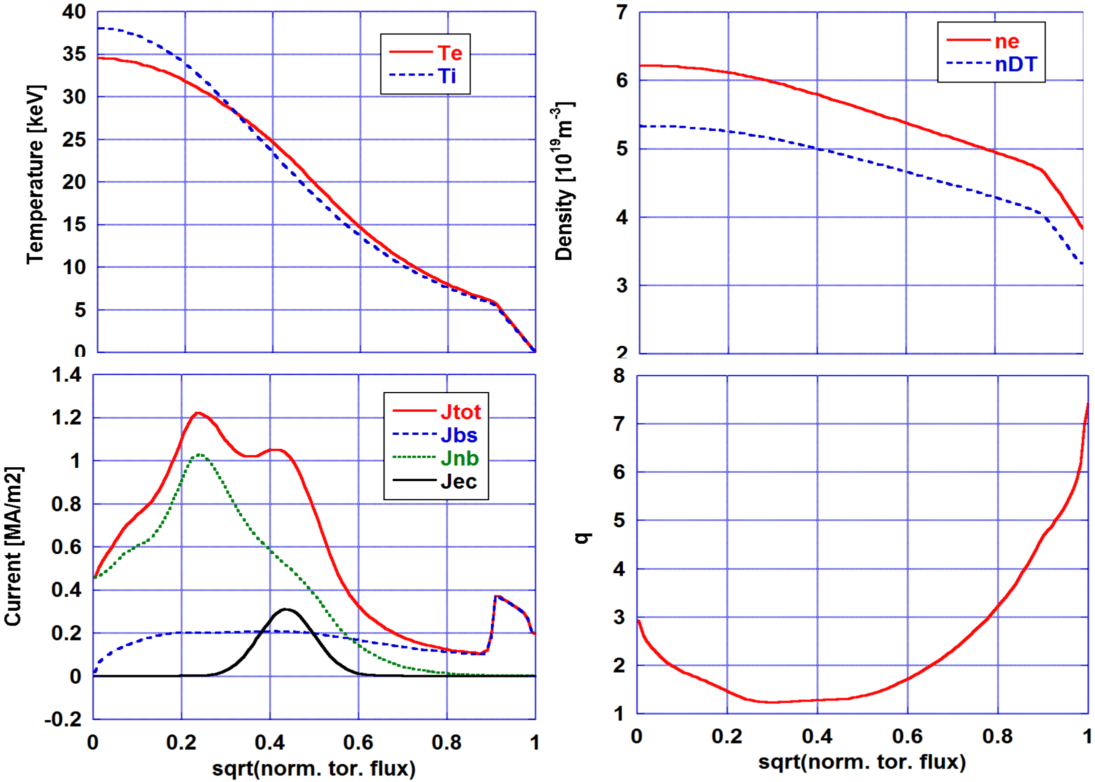


Q = 5 steady steady-state plasma at 10 MA

❑ Conditions identified by 1.5-D ASTRA modelling

- ✓ EPED1+SOLPS used for pedestal and boundary

- $Q=5.02$, $f_{GW}=0.69$
- $H_{98}=1.52$, $\beta_N=3.02$
- $q_{min}=1.23$
- Relatively high $l_i(3)$~0.87 mainly due to 40 MW NBI (+ 20-30 MW ECH)

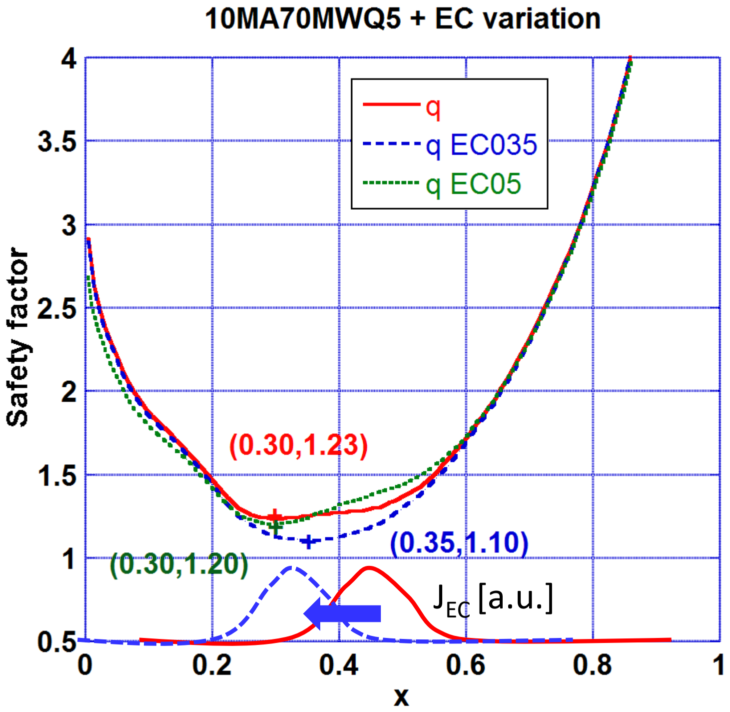


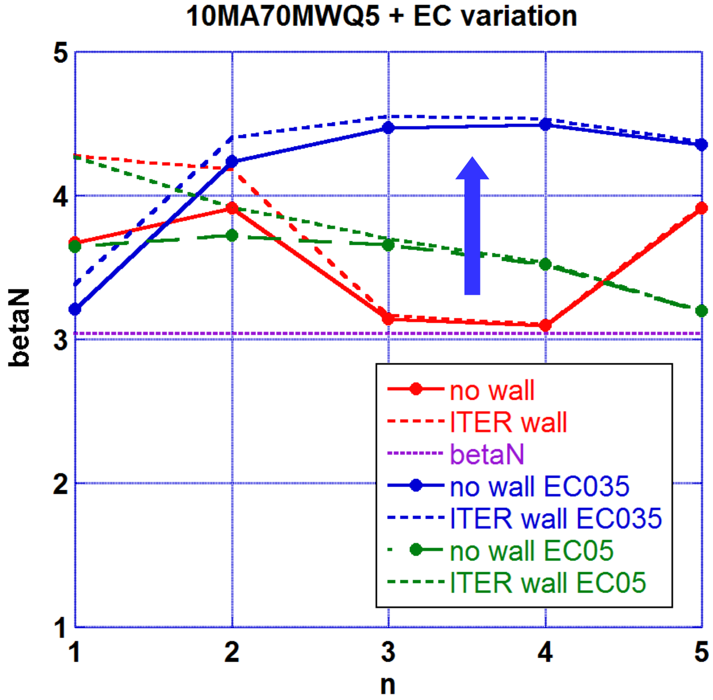
Polevoi – NF 2020

Stability Analysis for Q = 5 plasma

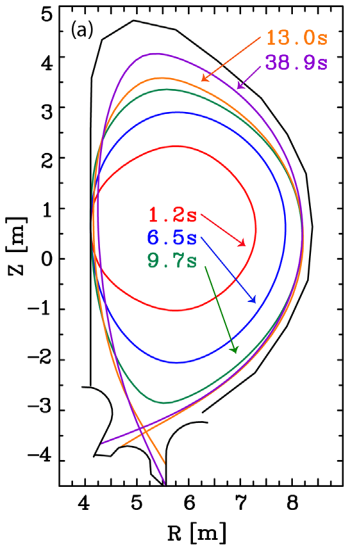
- KINX stability analysis shows that low-n (=1-5) ideal MHD modes ($\beta_N < \beta_{N,limit}$) by varying the ECCD location (ρ_{ECCD}=0.35 is ok)

Details is in Polevoi – NF 2020



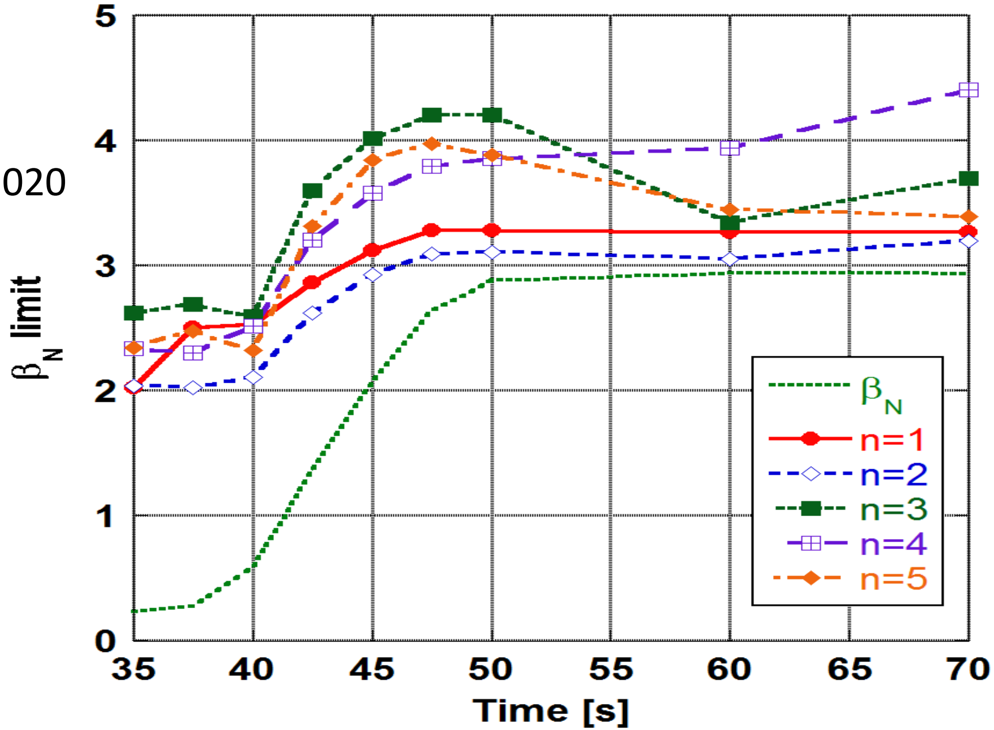


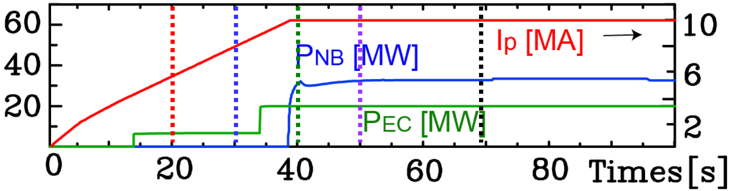
Optimization of access to Q = 5 steady state



- ☐ HCD waveform design strategy to avoid ideal MHD limits during the ramp-up and access to Q = 5 steady-state

S.H. Kim APS 2020
Sub. NF



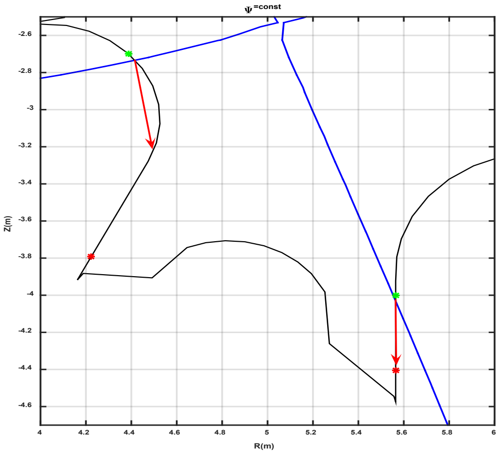


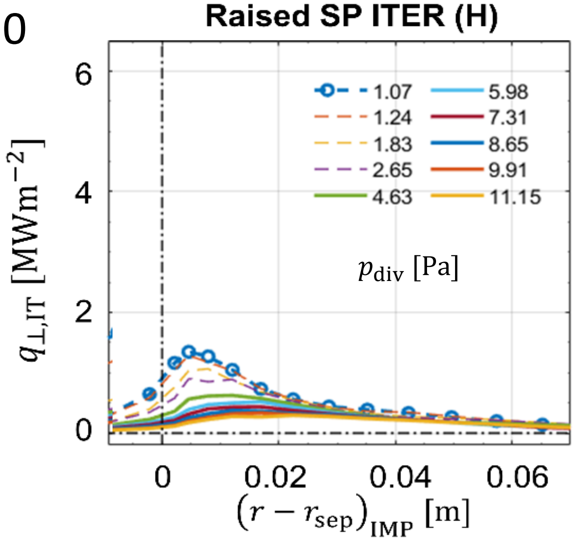
Scenarios (Scenario Phases) for T removal

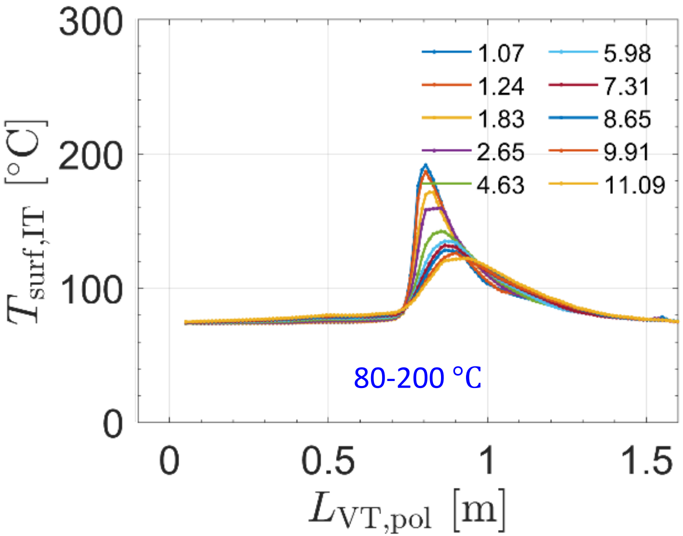
❑ Edge plasma modelling to assess operational strategies for T removal

- ➢ Be deposition expected to occur dominantly on high field side together with T co-deposited
- ➢ Operation with raised strike point considered to remove T (by surface heating)
- ➢ SOLPS-ITER used to assess effectiveness of strategy → not viable because T_{surf} is too low

J.S. Park AAPPS-DPP 2020





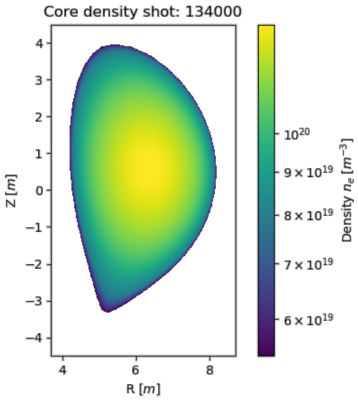


Synthetic Diagnostics

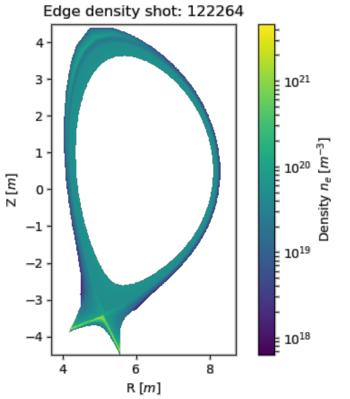
- Synthetic diagnostics modelling required for
  - Diagnostic design including performance assessments
  - Development of control algorithms
  - Development of data processing and analysis workflows
- Example for ITER Visible Spectroscopy Reference System (VSRS)

B. van den Boorn, M. de Baar, M. de Bock

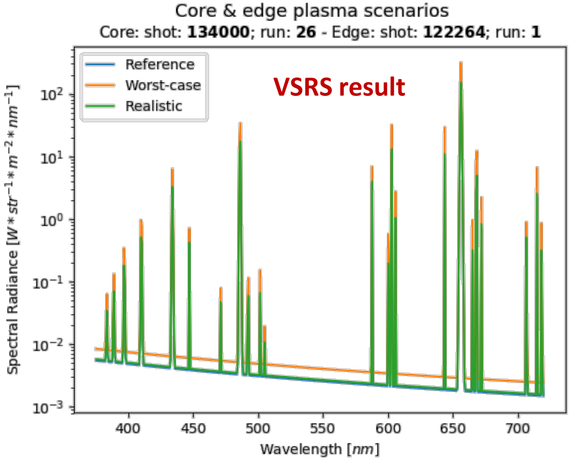
- Main VSRS measurements → Line-averaged Z_{eff} and n_e
- Synthetic diagnostic data from IMAS scenario simulations


Core density shot: 134000

`equilibrium`
`core_profiles`


Edge density shot: 122264

`edge_profiles`


Core & edge plasma scenarios

Core: shot: **134000**; run: **26** - Edge: shot: **122264**; run: **1**

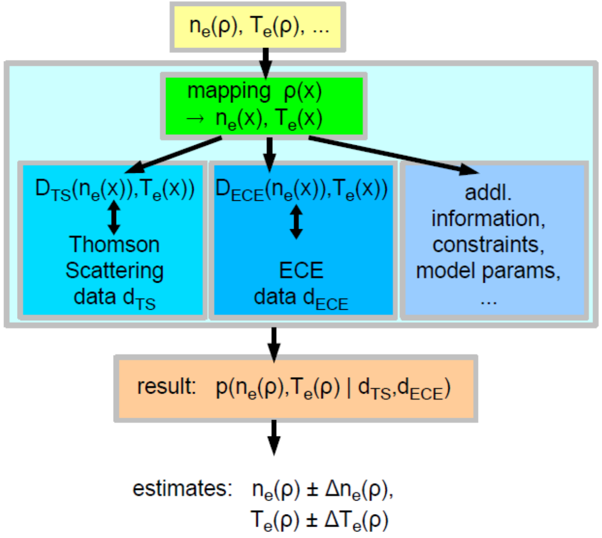
VSRS result

`vsrs`

High level diagnostic analysis

- ❑ High level diagnostic analysis being developed for ITER
  - ➢ Best measurement for plasma parameters from set of diagnostic
  - ➢ Systematic evaluation of errors and identification of diagnostics issues

Bayesian probability approach



$n_e(\rho)$, $T_e(\rho)$, ...

mapping $\rho(x)$ $\rightarrow n_e(x), T_e(x)$

$D_{TS}(n_e(x)),T_e(x))$ ↕ Thomson Scattering data d_{TS}

$D_{ECE}(n_e(x)),T_e(x))$ ↕ ECE data d_{ECE}

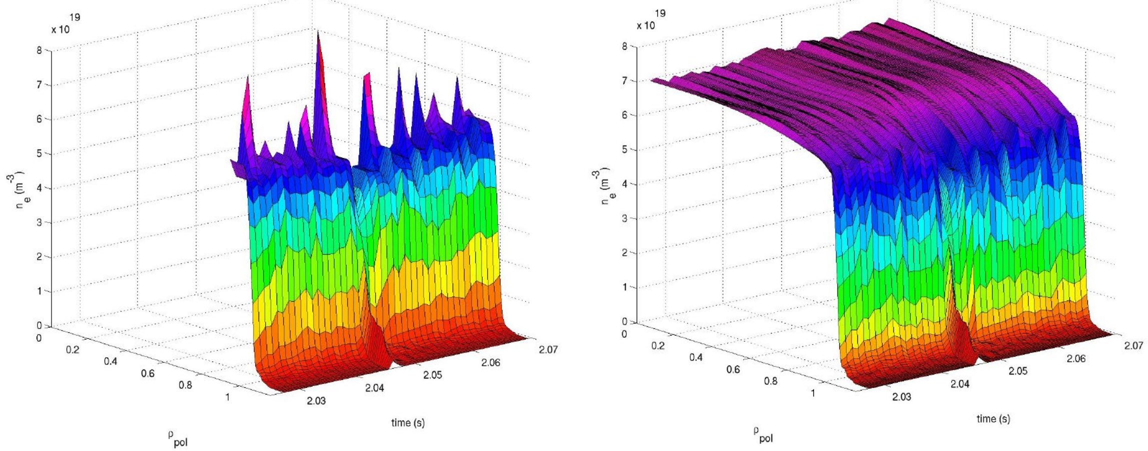
addl. information, constraints, model params, ...

result: $p(n_e(\rho),T_e(\rho) \mid d_{TS},d_{ECE})$

estimates: $n_e(\rho) \pm \Delta n_e(\rho)$,
$T_e(\rho) \pm \Delta T_e(\rho)$

Li-beam + Interferometer density measurement during Type I ELM in ASDEX Upgrade

(R. Fischer IAEA TM 2019)



HPC support to IRP

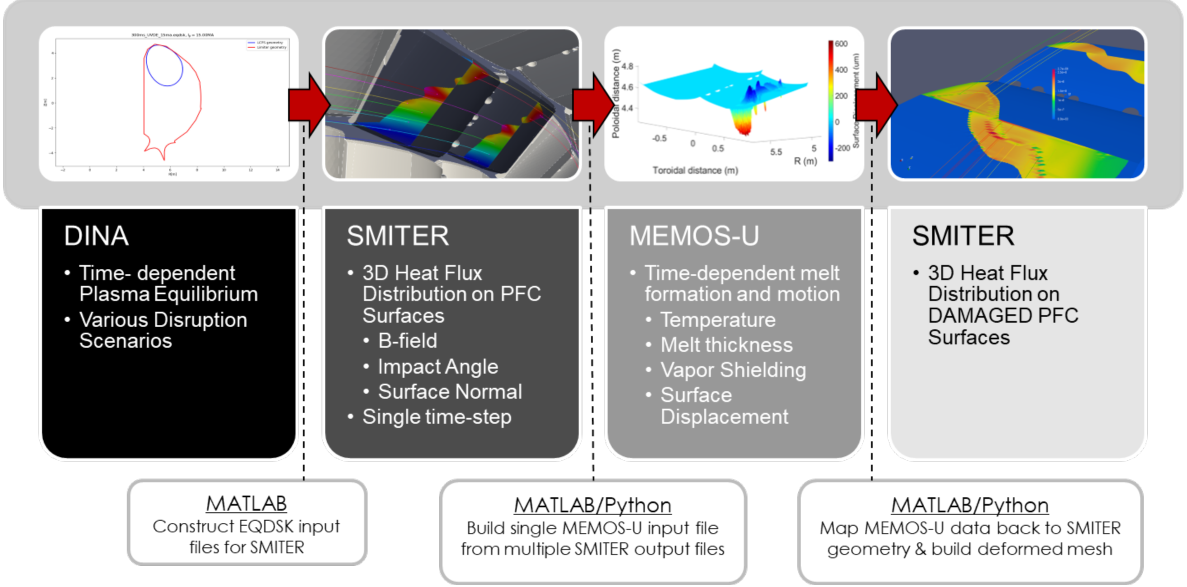
- Detailed modelling of specific physics processes impacting IRP development strategy
  - Disruption EM and Thermal loads on VV and in-vessel components
  - Disruption mitigation
  - ELM control and associated scenario issues

- Support to integrated modelling and data analysis
  - Development of neural networks to accelerate physics models to overcome bottlenecks
  - Increase parallelization of models in integrated modelling for HPC simulations (e.g. H&CD workflow)

Disruption EM and Thermal loads on VV and in-vessel components

- ❑ **Prediction of disruption loads is very important but predictions will need to be validated as part of IRP before operating at 15 MA → validation strategy needs to be defined with low risk to components**

Energy Deposition Analysis: Workflow (J. Coburn AAPPS-DPP 2020)



DINA
- Time- dependent Plasma Equilibrium
- Various Disruption Scenarios

SMITER
- 3D Heat Flux Distribution on PFC Surfaces
  - B-field
  - Impact Angle
  - Surface Normal
- Single time-step

MEMOS-U
- Time-dependent melt formation and motion
  - Temperature
  - Melt thickness
  - Vapor Shielding
  - Surface Displacement

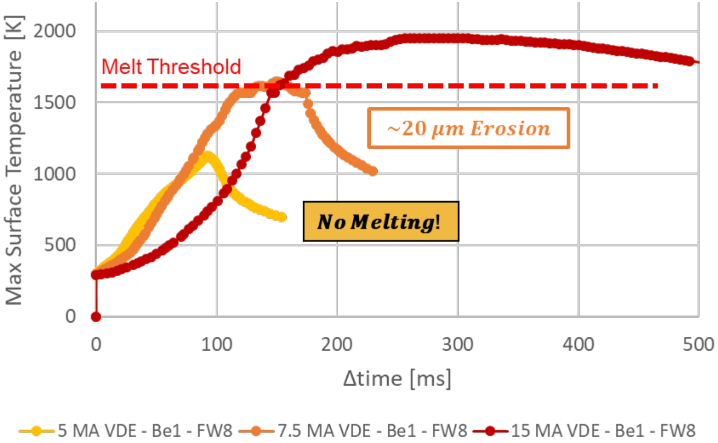
SMITER
- 3D Heat Flux Distribution on DAMAGED PFC Surfaces

MATLAB
Construct EQDSK input files for SMITER

MATLAB/Python
Build single MEMOS-U input file from multiple SMITER output files

MATLAB/Python
Map MEMOS-U data back to SMITER geometry & build deformed mesh

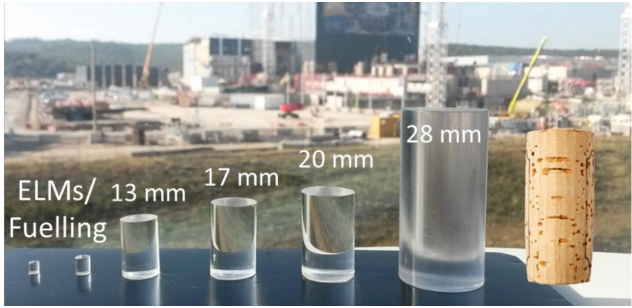
VDE Melt Results from MEMOS-U - FW8



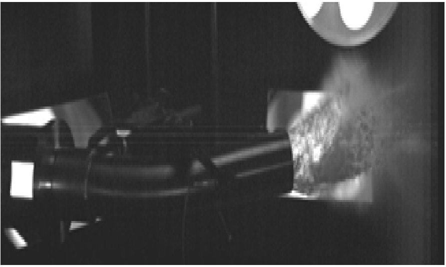
5 MA VDE - Be1 - FW8	7.5 MA VDE - Be1 - FW8	15 MA VDE - Be1 - FW8
Δt = 105 ms	Δt = 175 ms	Δt = 400 ms
E_{dep} = **45 MJ**	E_{dep} = **122 MJ**	E_{dep} = **593 MJ**

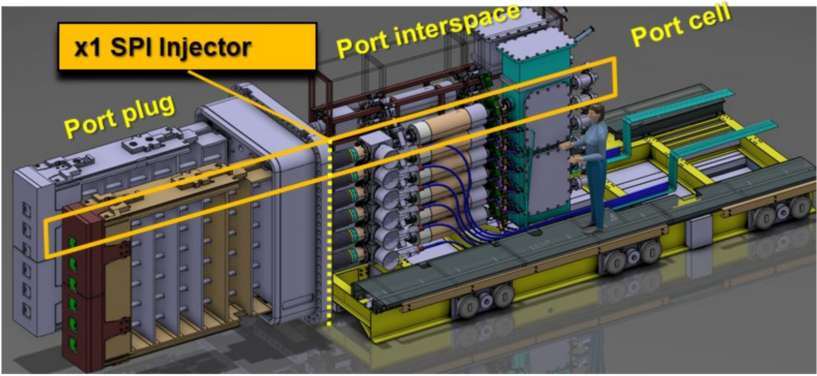
Disruption Mitigation

- ☐ **Effective disruption mitigation essential for IRP → highest priority R&D**
- ☐ **Concept:**
  - **Dissipating thermal and magnetic energy → radiation**
  - **Preventing runaway electron formation → increasing plasma density**
- ☐ **Technique:**
  - **Injection of Ne, (Ar) and D_2 through Shattered Pellet Injection**



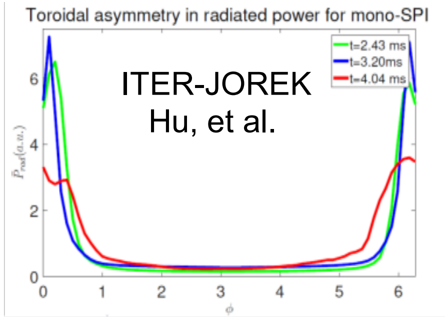
Lehnen IAEA FEC 2018



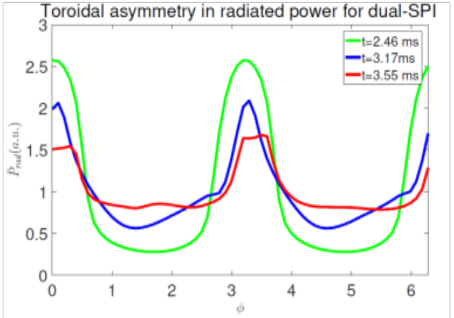


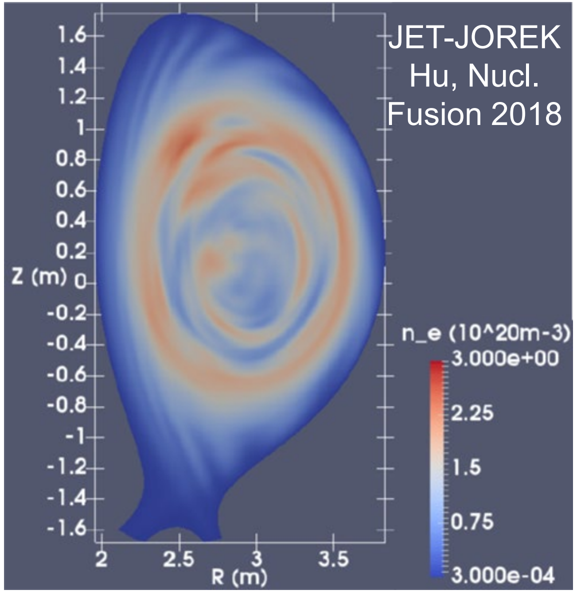
Disruption mitigation modelling support for ITER

- Large amount of material → impact of injection from multiple locations
- Effectiveness of pellet fragment sizes for various mitigation missions
- Concept of runaway electron avoidance and runaway energy dissipation



ITER-JOREK
Hu, et al.





JET-JOREK
Hu, Nucl.
Fusion 2018

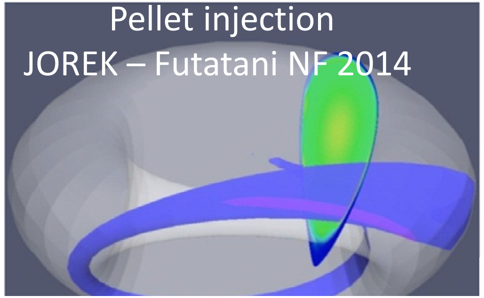
3D MHD JOREK modelling of JET SPI

Density distribution determined by injection + MHD → critical for runaway electron avoidance

Large experimental and modelling effort coordinated by ITER DMS Task Force

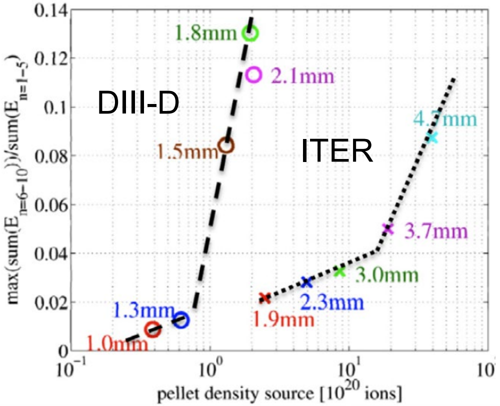
ELM control modelling

- ❑ **ELM control modelling includes processes leading to ELM control (MHD) but also impact on plasma scenarios**

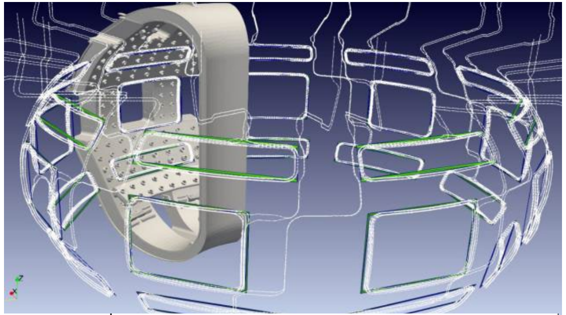


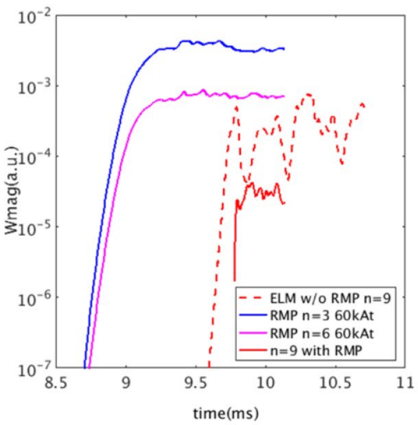
Pellet injection

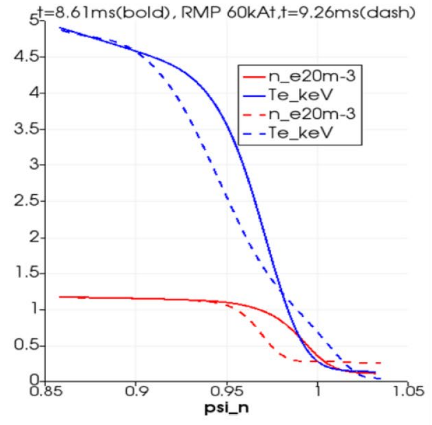
JOREK – Futatani NF 2014

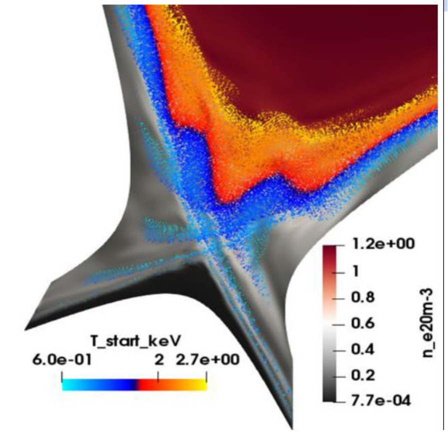


JOREK-Becoulet IAEA 2021





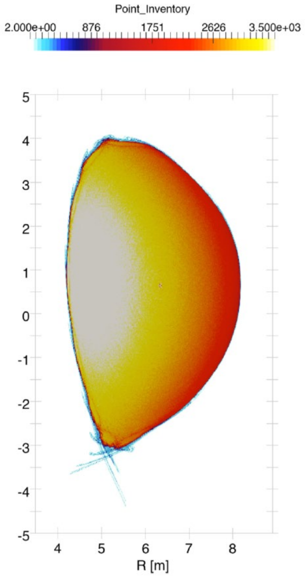


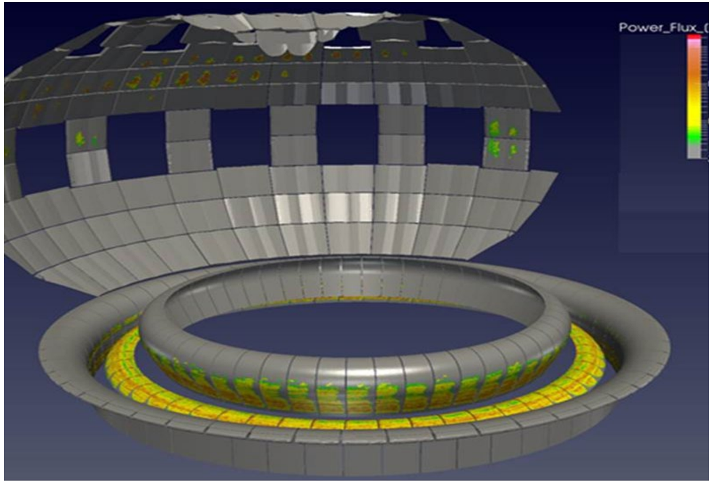


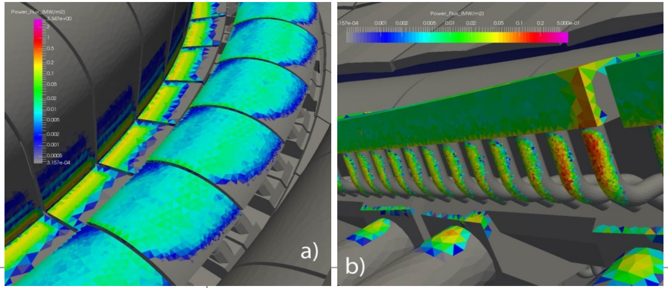
3-D fields for ELM control and fast particle losses

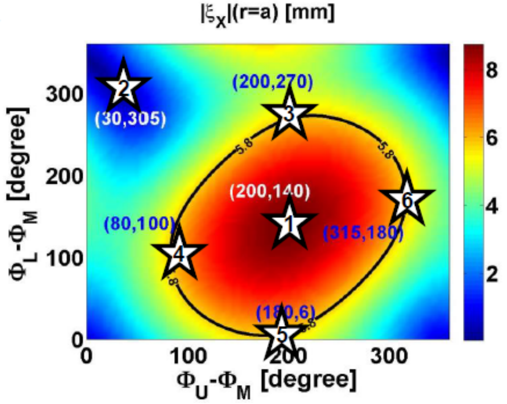
- 3-D fields for ELM control increase fast particle NBI loses due to large edge losses → edge magnetic configuration → optimization is required for integration with scenario

ITER-LOCUST
Akers & Ward









ITER-ASCOT
L. Sanchis
sub. NF 2020

#Case	Max losses (%)
1	13.3
2	0.03
3	8.1
4	8.4
5	9.2
6	12.6

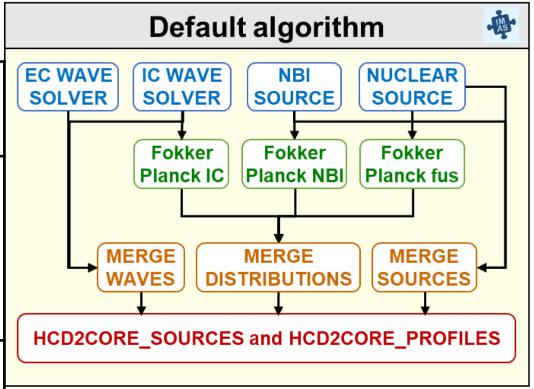
HPC support to integrated modelling for IRP - I

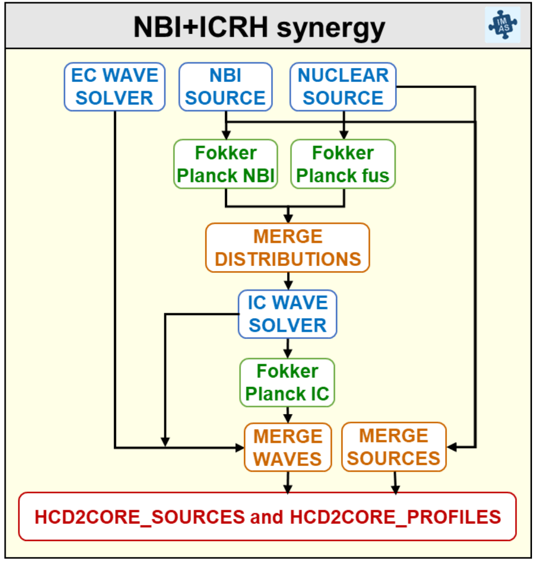
- ❑ Higher fidelity workflows can run parallel modules to speed up computations

M. Schneider APS 2020

	ECRH	ICRH	NBI	Nuclear reactions
Wave or source	GENRAY GRAY TORBEAM	CYRANO LION PION TOMCAT	BBNBI NEMO	AFSI SPOT (α)
Fokker - Planck	∅	FOPLA PION ASCOT SPOT	FOPLA ASCOT SPOT RISK	ASCOT SPOT

The H&CD workflow





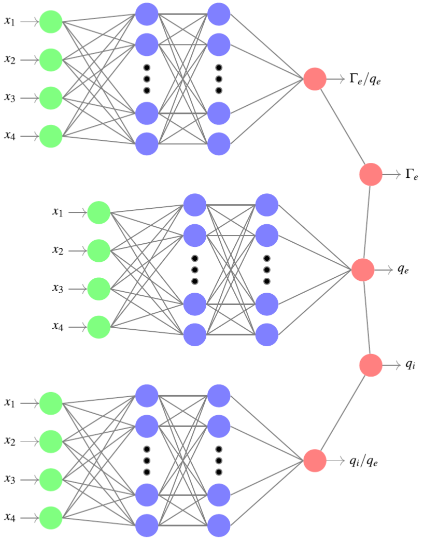
The flexible/composable workflow approach allows for various algorithms implementations.

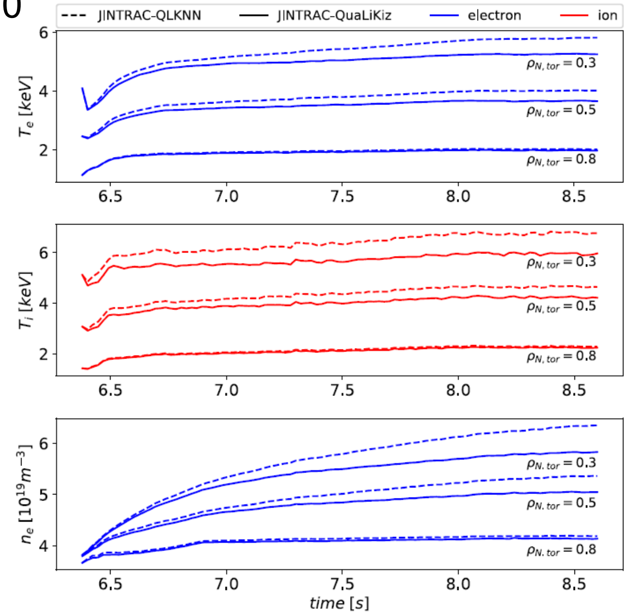
HPC support to integrated modelling for IRP

- ☐ Higher fidelity models can be represented by neural networks and used in integrated modelling without penalty of speed → better description of plasma behaviour in ITER scenarios (scenario design and control)

- ➢ Training database must cover wide range of parameters → HPC support
- ➢ Successfully developed for transport modelling, pedestal modelling , NBI heating source, …
- ➢ Of significant potential for ITER (edge plasmas, diagnostic analysis, …)

K.L. van den Plassche Pop 2020





Conclusions

- ❑ ITER construction is progressing well despite challenges of present pandemic → thanks to strong commitment from ITER Organization and ITER Members

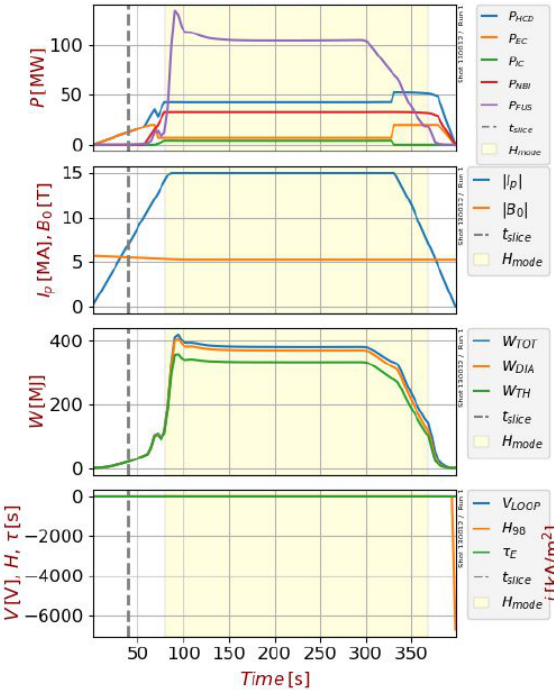
- ❑ ITER Research Plan requires modelling support to:
  - ➢ Develop and refine ITER scenarios
  - ➢ Prepare workflows for analysis of experimental data
  - ➢ Assess specific aspects of ITER scenarios and their optimization

- ❑ HPC should support this effort both by sophisticated modelling of specific processes (MHD, fast particles, PWI, etc.) but also by supporting higher fidelity integrated modelling simulations

Back-up slides

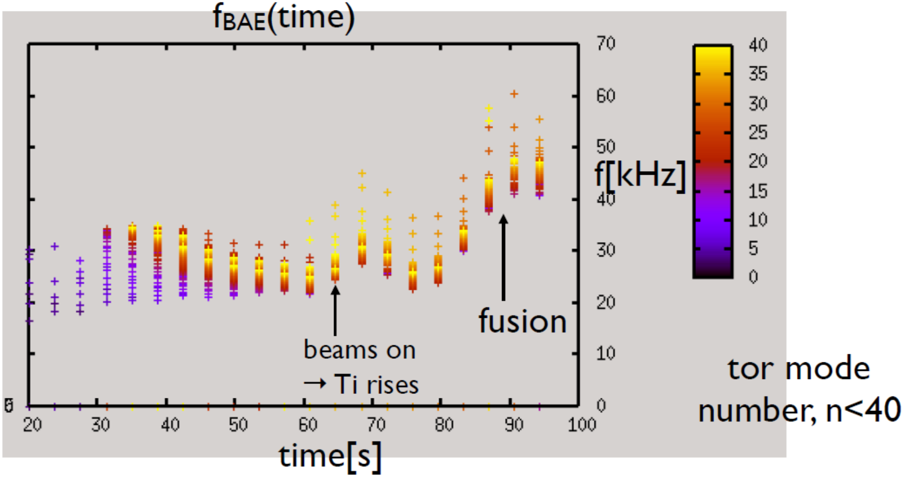
Redistribution of fast ions by instabilities

- ❑ LIGKA/HAGIS Python workflow to assess fast particle stability in ITER scenarios



Ph. Lauber
S. Pinches
IAEA 2020

Frequencies of predicted Beta-induced Alfvén Eigenmodes (fast particle instabilities) during ITER pulse



Transport of fast ions by instabilities changes evolution of plasma profiles → work underway to incorporate these effects in plasma scenario simulations (ITPA/ISFN)

IMAS Data Model (3.30.0)

amns_data
barometry
bolometer
bremsstrahlung_visible
calorimetry
camera_ir
camera_visible
charge_exchange
coils_non_axisymmetric
controllers
core_instant_changes
core_profiles
core_sources
core_transport
cyrostat
dataset_description
dataset_fair

disruption
distribution_sources
distributions
ec_launchers
ece
edge_profiles
edge_sources
edge_transport
em_coupling
equilibrium
gas_injection
gyrokinetics
hard_x_rays
ic_antennas
interferometer
iron_core

langmuir_probes
lh_antennas
magnetics
mhd
mhd_linear
mse
nbi
neutron_diagnostic
ntms
numerics
pellets
pf_active
pf_passive
polarimeter
pulse_schedule
radiation

reflectometer_profile
sawteeth
sdn
soft_x_rays
spectrometer_mass
spectrometer_uv
spectrometer_visible
spectrometer_x_ray_crystal
summary
temporary
thomson_scattering
tf
transport_solver_numerics
turbulence
wall
waves

Extension of Data Dictionary mainly through application to new Use Cases and user feedback. For more details, see links from https://imas.iter.org.

3-D fields for ELM control and power fluxes

- Radiative divertor operation with 3-D resonant fields required at high $P_{aux}+P_{\alpha}$ and I_p in ITER
- q_{div} modification by 3-D fields and radiative divertor exhaust → understanding of connection between field and fluxes required

EMC3-Eirene- H. Frerichs PRL 2020