EUROfusion

Tokamak Exploitation General Planning Meeting

JT-60SA Machine capabilities and enhancements

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ISTITUTO PER LA SCIENZA E TECNOLOGIA DEI PLASMI
Consiglio Nazionale delle Ricerche

JT-60SA Advanced Superconducting Tokamak
BA-Satellite Tokamak Program

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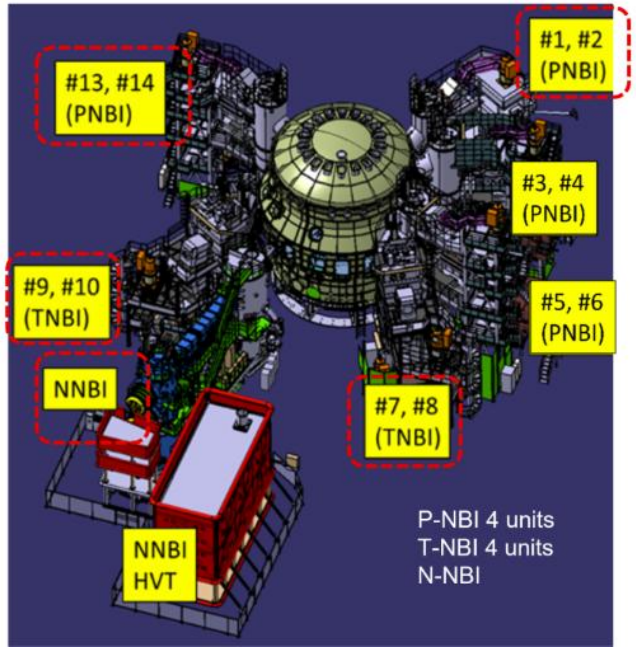
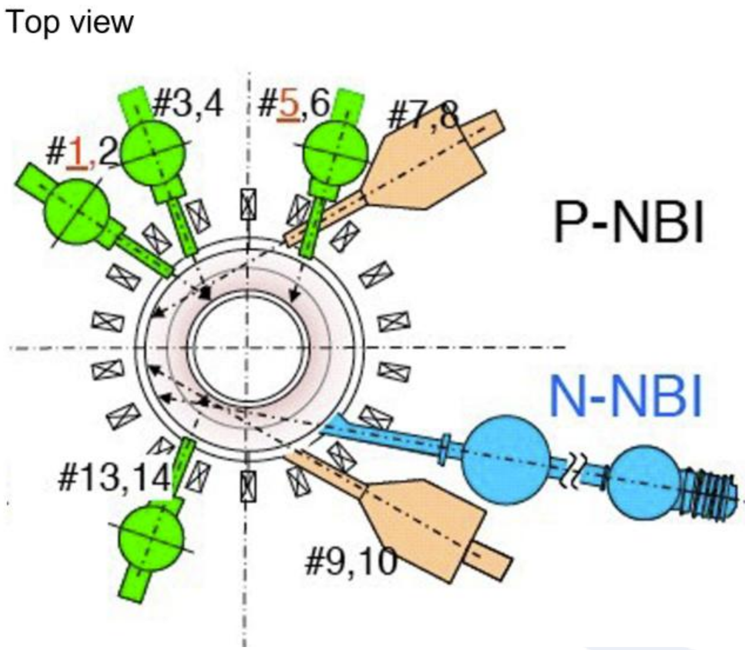
Enhancements in ME1

- Input power upgrade:
  - EC: 1.5 MW → 3 MW (steerable 82, 110, 138 GHz)
  - NB: 0 MW → 16 MW(H) / 23.5 MW(D): 10 MW of 500 keV negative-ion NBI
- Lower divertor (C inertially cooled)
- Several plasma control coils
  - Error Field Correction coil (EFCC),
  - Resistive Wall Mode coil (RWMC),
  - Fast Plasma Position Control Coils (FPPCC)
- ~15 new or upgraded diagnostics
- 2 Massive gas injection for disruption mitigation
- Stabilizing plate : CuCrZr heat sink + Carbon tiles

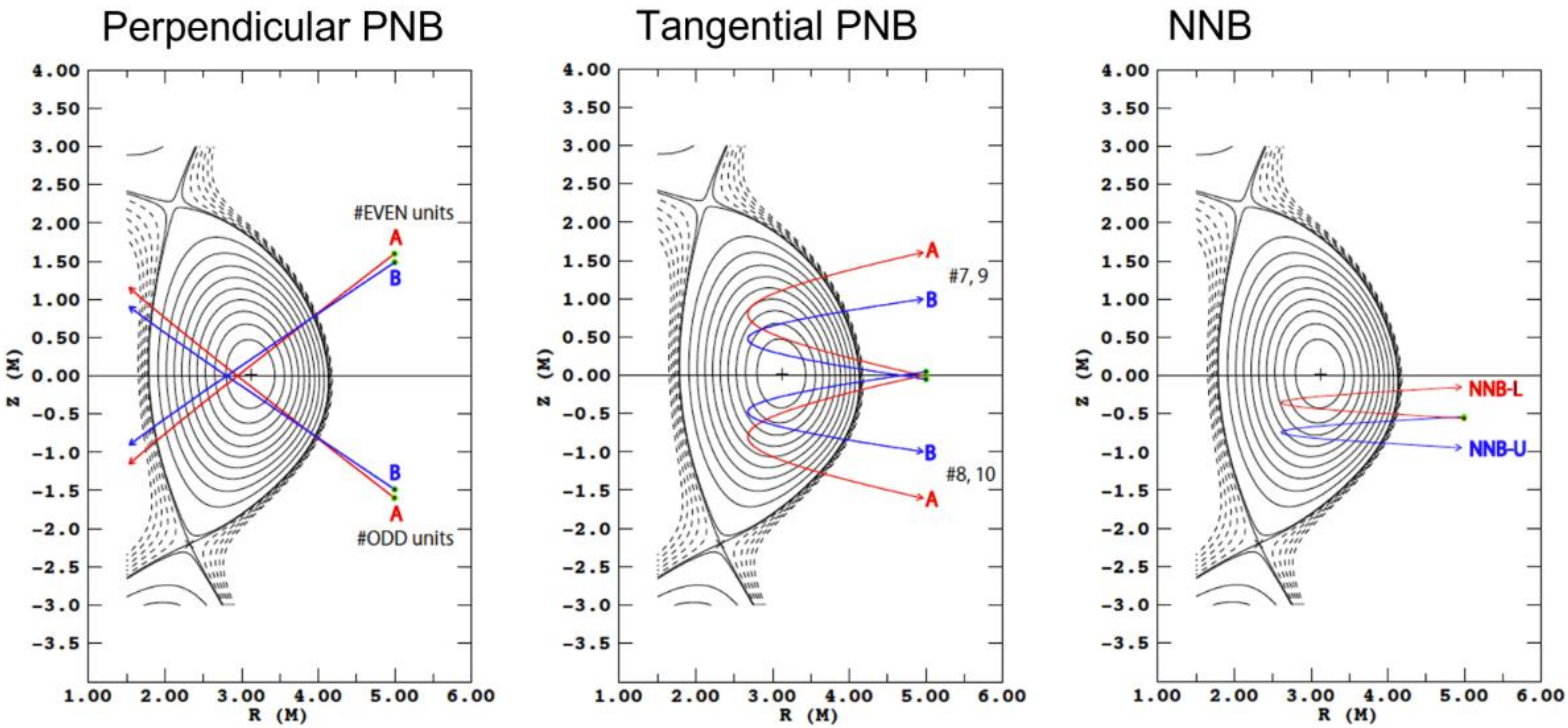
NBI system

- In the Initial Research phase, the NBI system consists of 8 positive-ion-based NBI (P-NBI) units
  - 2 co-current tangential beam units,
  - 2 ctr-current tangential beam units
  - 4 perpendicular beam units.
- #1,2,13,14: perpendicular, #7,8: counter-Ip, #9,10: co-Ip
- one negative-ion-based NBI (N-NBI) unit.





Beams trajectory

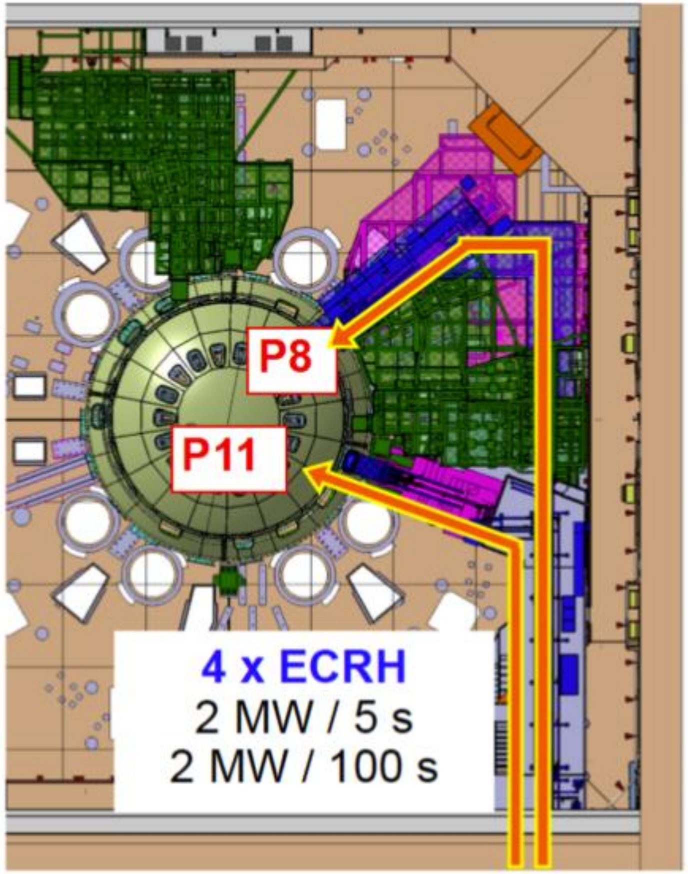


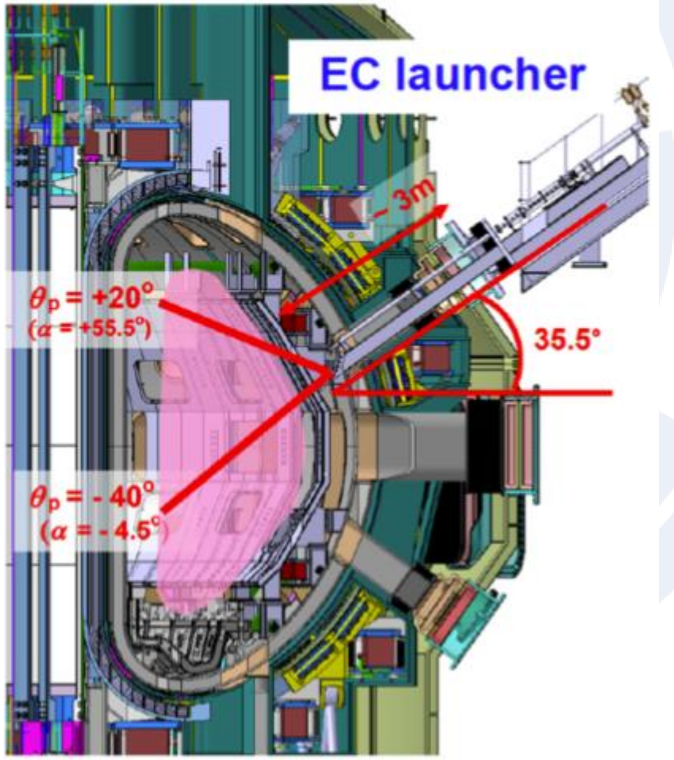
Electron Cyclotron Resonance Heating (ECRH)

Available for OP2

- 2 gyrotrons operating at 110 GHz for up to 5 s
- 2 multifrequency gyrotrons able to operate at 110 GHz/138 GHz for up to 100 s

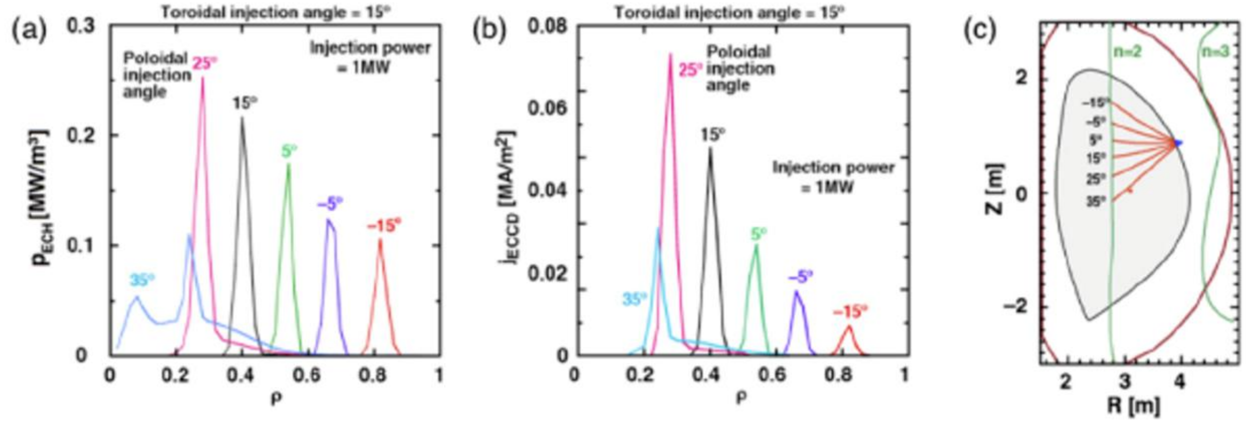
		Unit1	Unit2	Unit3	Unit4
Gyrotron	Frequency	82/110/138 GHz			110 GHz
	Power	1 MW @ gyrotron window			
	Pulse width	110/138 GHz: 100 s 82 GHz: 1 s		5 s	
	Modulation	Up to 5 kHz		Up to 5 kHz / <1 s	
TL	Waveguide	Φ60.3 mm Corrugated waveguide			
	Efficiency	>85%		>80%	
		※ including ~5% loss in Matching Optics Unit			
Launcher	Port location	P-11 UO		P-8 UO	
	Launcher	Two directional front steer 30 deg. (toroidal) & 60 deg. (poloidal)			
	Tokamak injection power	>0.8 MW/beam		>0.75 MW/beam	
		※ Total power by 4 units >3 MW			



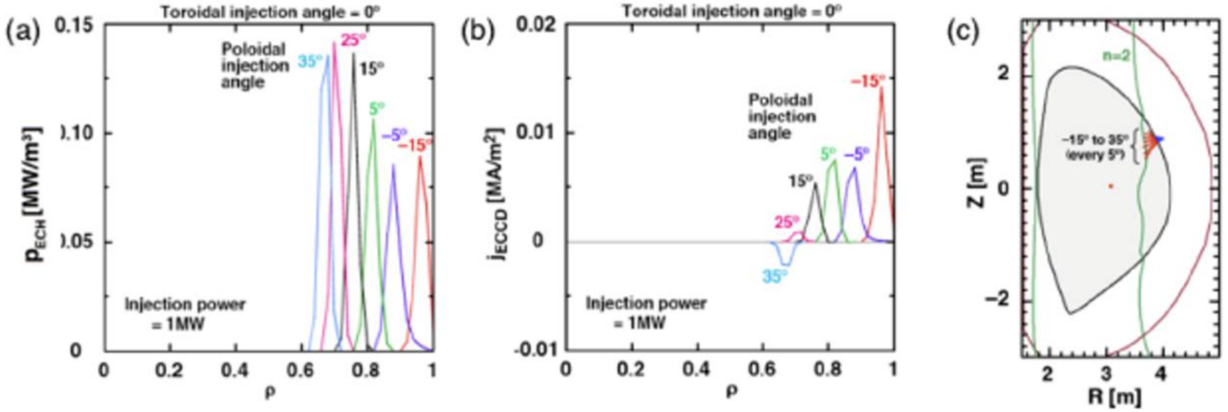


ECRH power deposition

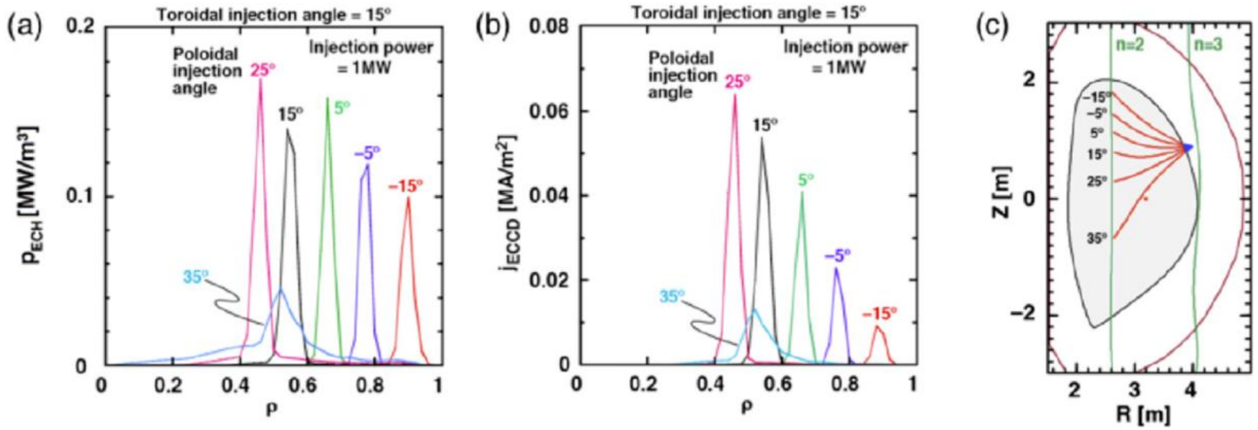
138 GHz, 2.25 T in Scenario 2



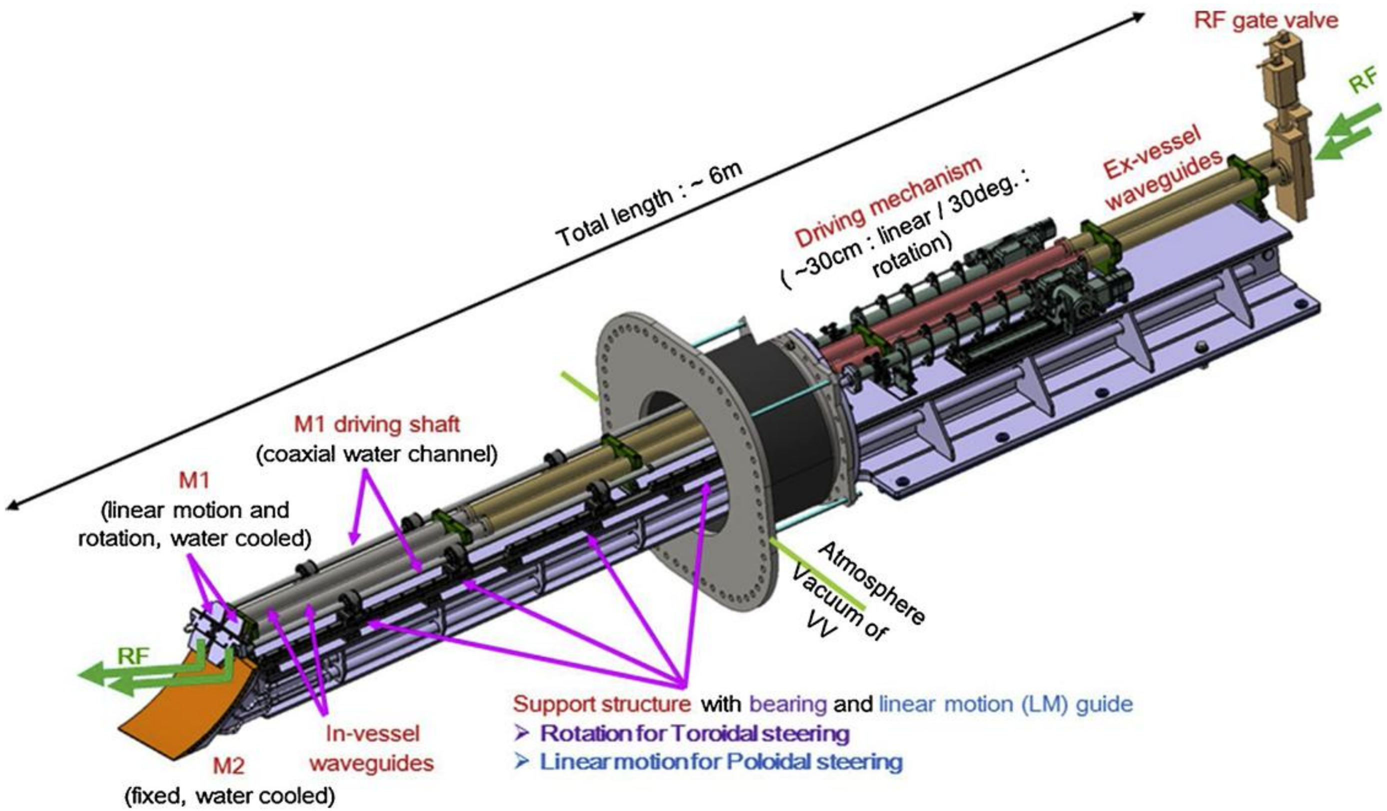
110 GHz, 2.25 T in Scenario 2



110 GHz, 1.7 T in Scenario 5



ECH/ECCD steering capabilities and driven current



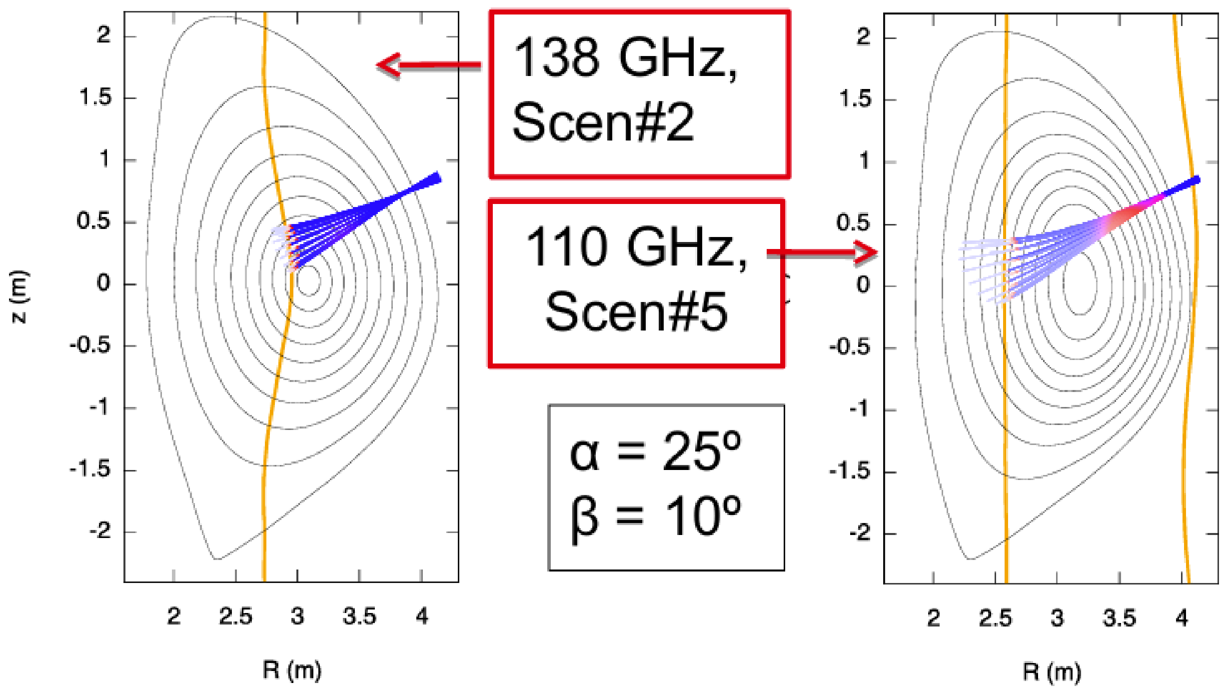
Design parameters of the launcher.

Parameters	Values	
Power	˜ 0.8 MW	(per line)
Pulse length	100 s	
Port allocation	P1UO, P4UO, P8UO, P11UO	
Port size	Width:	480 mm
	Height:	480 mm
	Length:	˜ 3 m
Aperture	Width:	706 mm
	Height:	659 mm
Port angle		35.5°
Beam angle	Pol. (θ_p):	−40° ˜ +20°
	Tor. (θ_t):	−5° ˜ +25°
Life time	Pol.	10^5 cycles
(full stroke)	Tor.	10^4 cycles
Beam width	at θ_p ˜ +5°:	< 100 mm

Scenario	B_0 (T)	I_p (MA)	n_{e0} (m^{-3})	T_{e0} (keV)	$\rho_{q=1}$	$\rho_{q=3/2}$	$\rho_{q=2}$
#2 (full-Ip, inductive)	2.25	5.5	$0.78\ 10^{20}$	12.7	0.55	0.70	0.79
#5 (full non-induct.CD)	1.72	2.3	$0.68\ 10^{20}$	5.9	-	-	0.57

Kobayashi+, https://doi.org/10.1016/j.fusengdes.2019.03.008

ECRF performance analysis



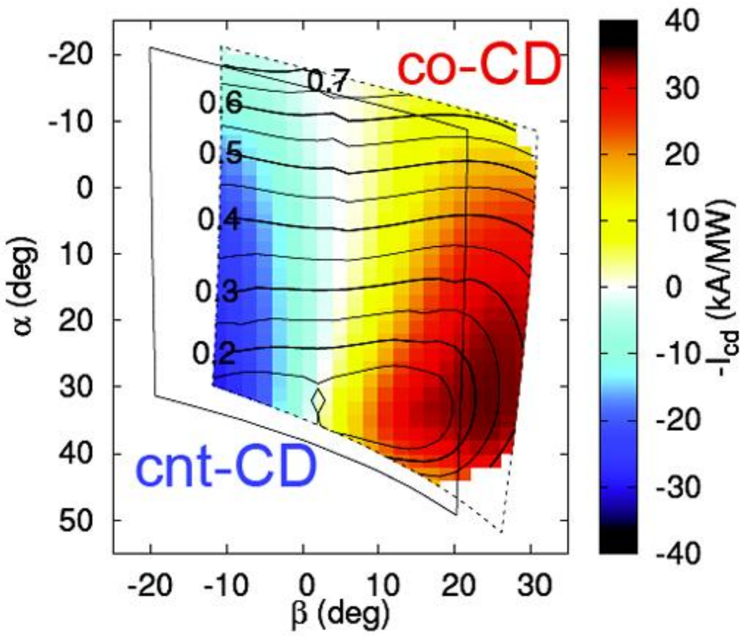
n=2 resonance → X-mode injection

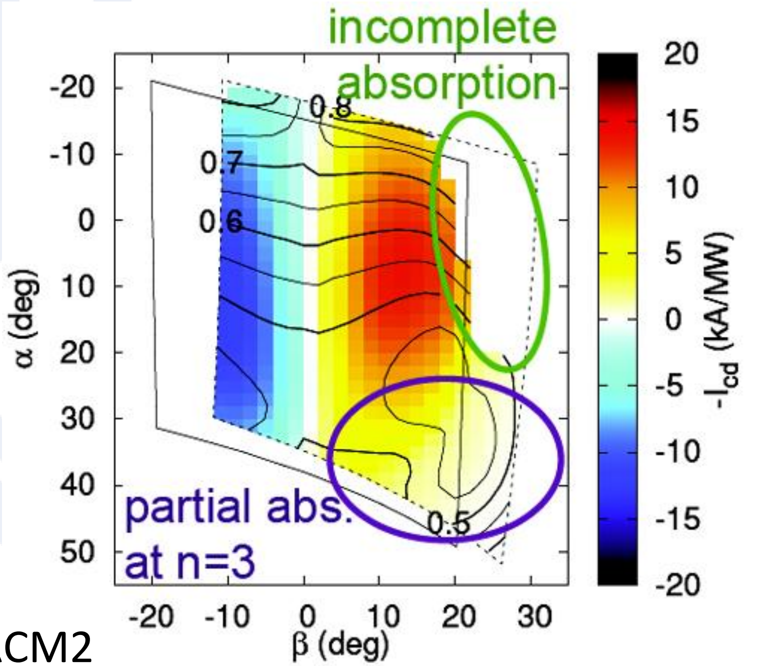
Scen#2 → f = 138 GHz

- n=2 resonance close to magnetic axis
- Current drive possible for 0.15 ≤ ρ ≤ 0.7
- Max driven current Icd for toroidal injection angles β ≥ 20º

Scen#5 → f = 110 GHz

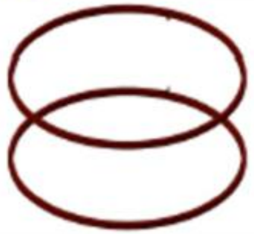
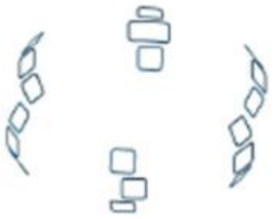
- n=2 resonance on the HFS, n=3 at the LFS plasma edge
- Current drive possible for 0.45 ≤ ρ ≤ 0.8
- When aiming at the plasma centre, n=3 resonance strongly limits CD efficiency (only 40% of the injected power available at n=2 in extreme cases)
- Max Icd at 12º ≤ β ≤ 14º, max Jϕ at β ≈ 10º, incomplete absorption at β > 20º

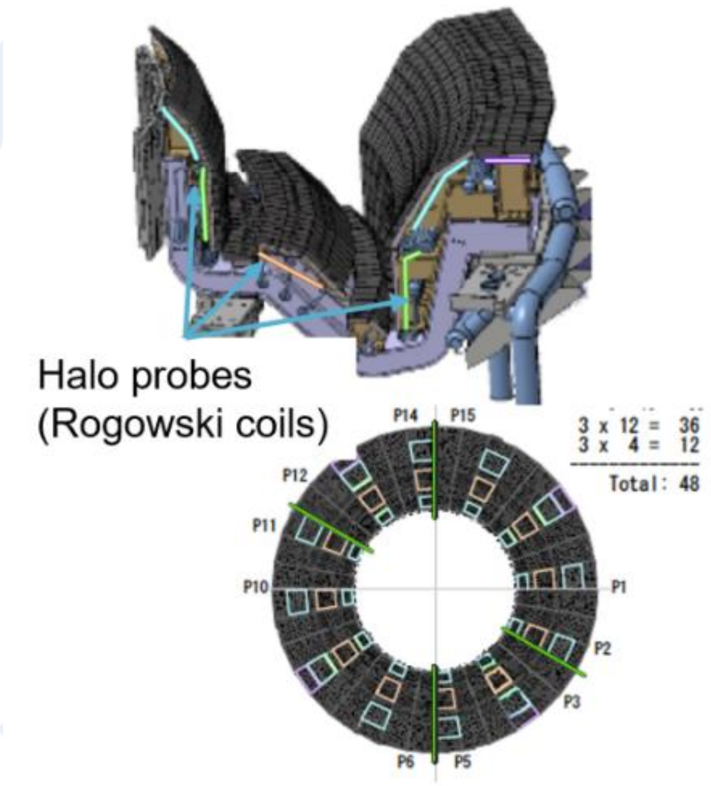




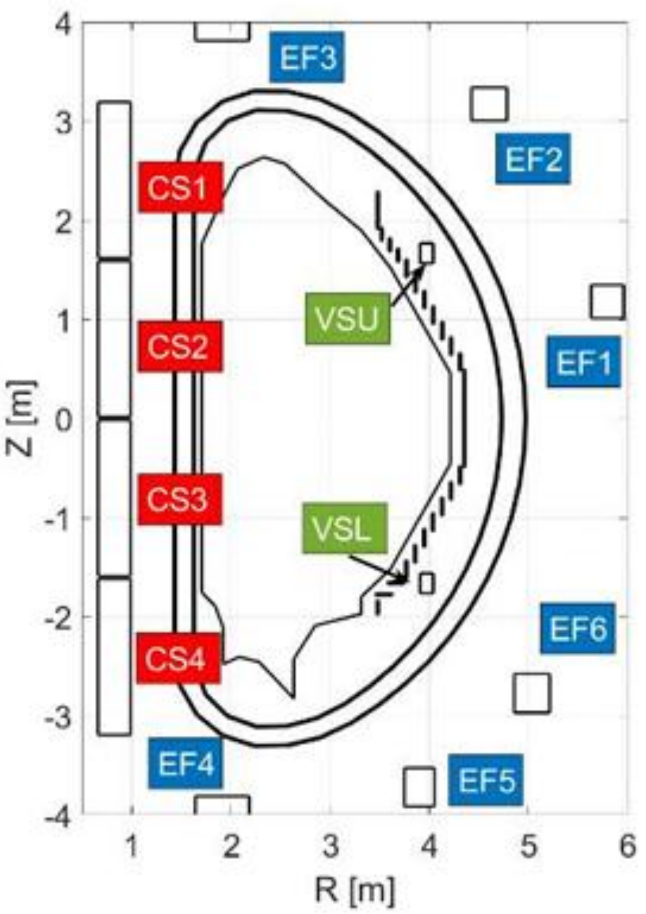
Figini et al. RCM2

In-vessel coils

Name	Purpose	Specification	Figure
FPPC Fast Plasma Position control Coil	fast position (vertical & horizontal) control	Number: 2 (Upper & Lower) Max current:120 kAT Location: Behind SPs	
EFCC Error Field Correction Coil	error fields (n≠ 0) correction and resonant magnetic field perturbation	Number: 18 (Tor 6 x Pol 3) Max current: 45 kAT Location: Behind SPs	
RWMC Resistive Wall Mode control Coil	RWM feedback control	Number: 18 (Tor 6 x Pol 3) Max current: 2.2 kAT Location: In front of SPs	
SP Stabilizing Plate	passive stabilization of VDE and RWM	Wall time constant: ~40ms	



Plasma position shaping and control coils



Parameters for EF Coils (SC NbTi strand)

	EF1	EF2	EF3	EF4	EF5	EF6
Winding Radius(@RT, m)	5.819	4.621	1.919	1.919	3.914	5.054
Winding Width (m)	0.343	0.370	0.556	0.556	0.315	0.370
Winding Height(m)	0.347	0.347	0.441	0.625	0.403	0.403
Max Coil total current (MA)	2.84	3.08	4.94	7.06	3.04	3.60
Conductor Current (kA)	20	20	20	20	20	20
Max conductor current (kA)	20	20	20	20	20	20
Peak Field (T)	4.8	4.8	6.2	6.2	4.8	4.8
Operating Temp. (K)	4.8	4.8	5.0	5.0	4.8	4.8
Number of turns	142	154	247	353	152	180
SP/DP†	SP	SP	DP	DP	DP	SP
Conductor length (m)	439	378	434	434	541	413
Ground/Terminal voltage in Norm Operation (kV)	10/10	10/10	10/10	10/10	10/10	10/10
Ground/Terminal voltage in testing (kV)	21/21	21/21	21/21	21/21	21/21	21/21
Max Joint Resistance	5 nΩ					

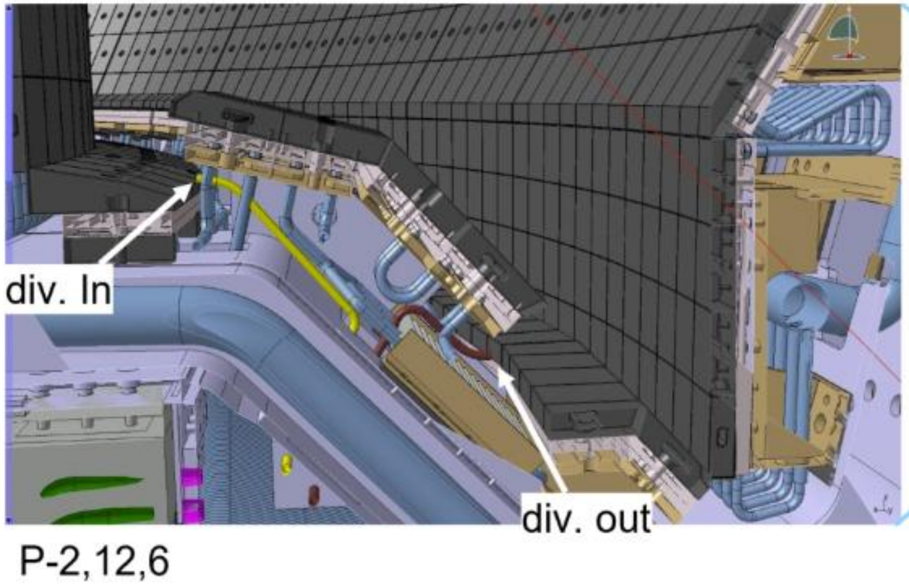
†SP : Single pancake, DP : Double pancake

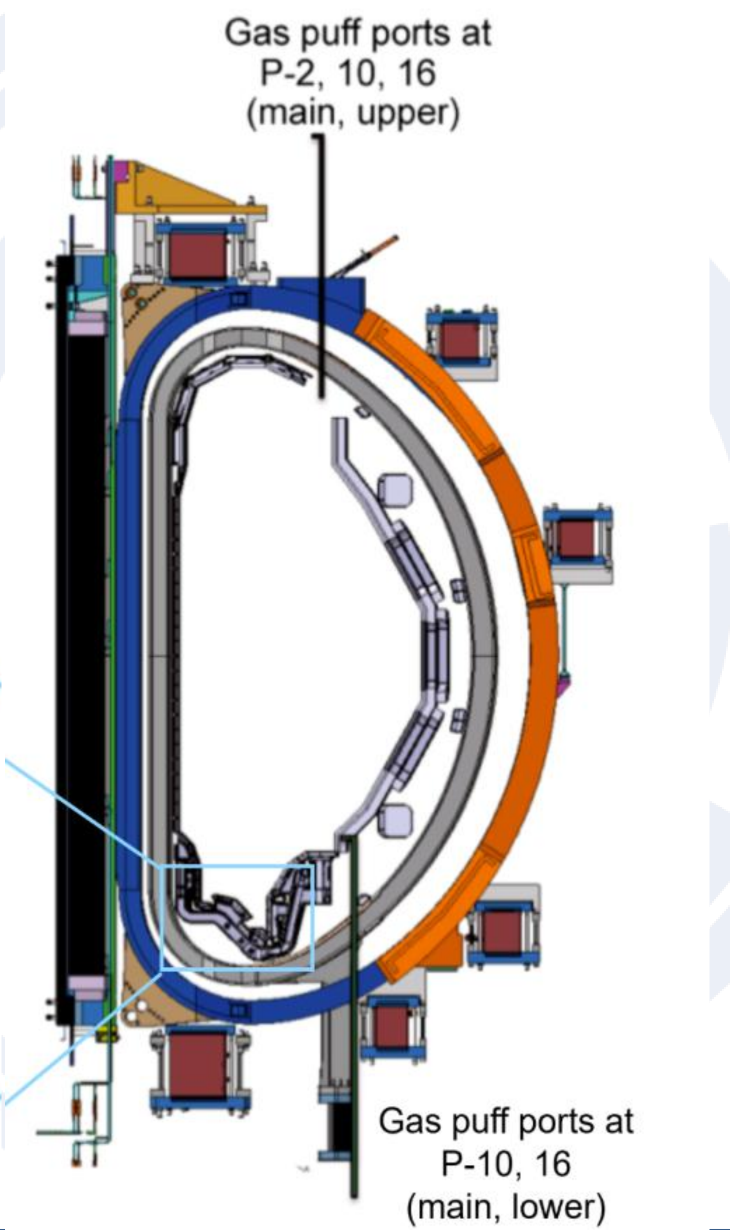
Fast plasma position control coil (FPPC)

- two circular normal-conducting coils (upper and lower).
- independent control of vertical and horizontal field.
- Conductor current 5.0 kA, 25s /2.5 kA 100 s
- Number of turns per coil 23

Fueling (Gas puffing)

- Main gas:
  - H_2: 0.1-100 Pam^3/s per valve
  - D_2: 0.1-70 Pam^3/s per valve
- Extrinsic impurities: He, N_2, Ne, Ar, Kr, Xe
- Pellet: not available in OP2





Target scenarios

- CS/EF will be able to be operated at higher currents and voltages than OP1
- But still, there will be some limitations compared with its original rated values
- In addition, CS might be limited to +/- 15 kA in the beginning of OP2

Coil	Absolute Max Voltage to GND (for coil insulation)	Operating Voltage (Booster PS / SNU)		Max Current		QPC	Varistor Max Clamping Voltage = 1.2 x Peak operating voltage (*2)
		Nominal (excl. ripples)	Peak (incl. ripples) = Nominal + 0.5 kV	Base PS + SNU (min R1 = 0.25 Ohm)	Base PS		
CS	**4 kV** (case 1) **(*1)**	2.8 kV	3.3 kV	+11/-20 kA	+/-20 kA	2.53 kV (CS1/4)	<4 kV
	3 kV (case 2) **(*1)**	2.0 kV	2.5 kV	+8/-20 kA		2.71 kV (CS2/3)	(<3 kV) **(*3)**
EF3/4	**5 kV**	3.5 kV	4.0 kV	+14/-20 kA		3.8 kV	<5 kV
EF1/2/5/6					+10/-20 kA		

(*1) Depending on coil reinforcement **=>** Necessary to prepare the varistors for both cases
(*2) Referring to EF6 test result (max 6.6 kV at 5.0 kV operation) for 2S2P configuration of Metrosil varistors
(*3) Minimum value not to clamp CS2/3 QPC voltage (2.71 kV)

T. Wakatsuki

Original target scenarios will be accessible even with OP1 levels of CS flux consumption

Accessible I_P levels

$\Delta I_{CS}/\Delta I_P$ [kA/MA]	Nominal (+/- 20 kA)	Alternative (+8/-20 kA)	Backup (+11/-20 kA)	Reduced (+/- 15 kA)
OP1 EC: 7.9	5.0 MA	3.5 MA	3.9 MA	3.8 MA
OP1 OH: 9.0	4.4 MA	3.1 MA	3.4 MA	3.3 MA

Main target scenarios, and additional backup scenarios being considered

		Ip/Bt (q95)	β_N/β_P
Original	OP2 Baseline	4.6 MA/2.28 T (q_{95} ~ 3)	~2/<1
	OP2 Hybrid	2.7 MA/1.70 T (q_{95} ~ 4)	~ 2-3/~1
	OP2 ITB	1.7-2.0 MA/1.70 T (q_{95} > 6)	> 3.5/>>1
Backup	Low I_P high B_T	3.5 MA/2.28 T (q_{95} ~ 4)	TBC
	Low B_T Baseline	3.5 MA/1.70 T (q_{95} ~ 3)	TBC

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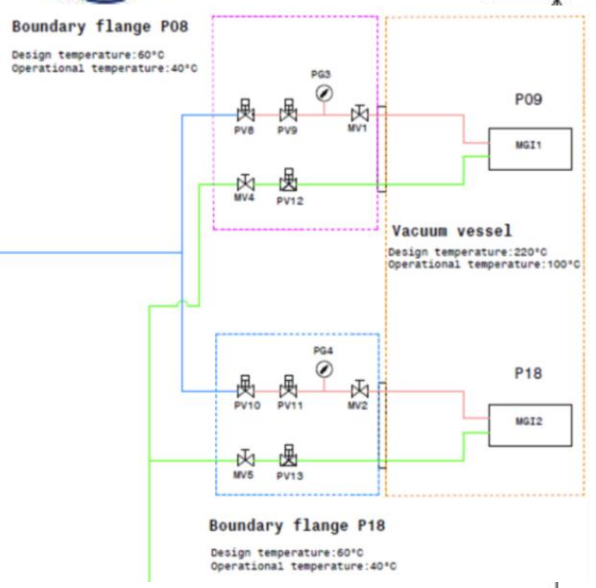
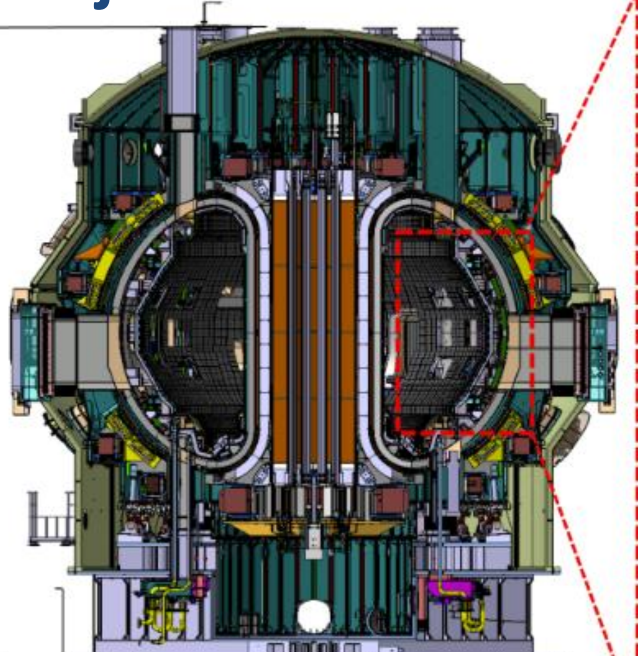
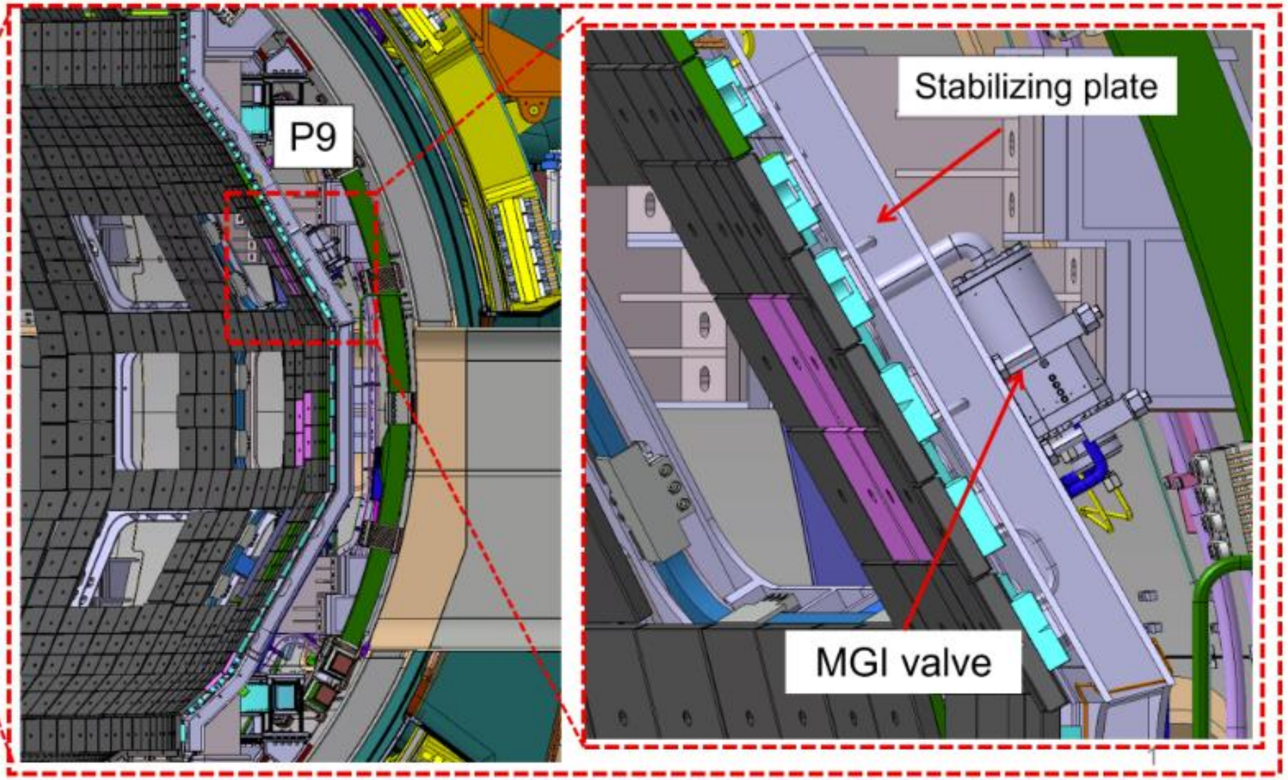
Massive Gas Injection



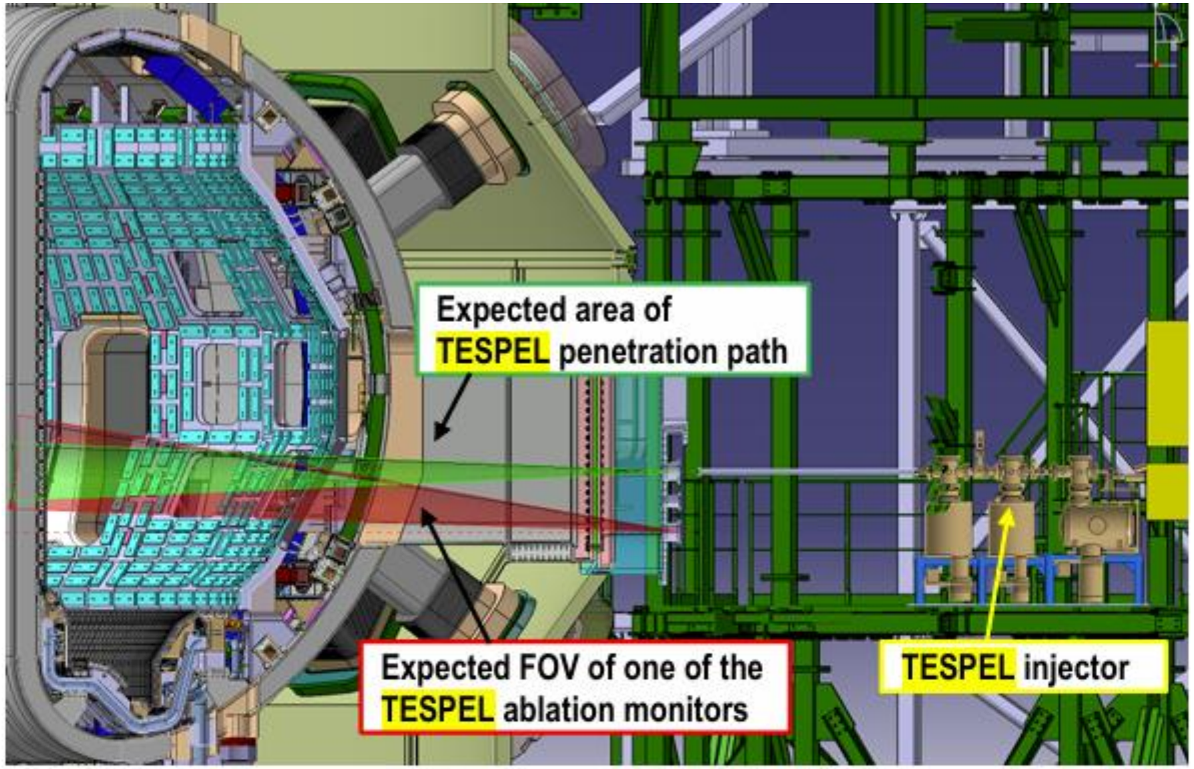




Injection gas volume per valve	815 cm³
Nominal operating pressure in injection volume	7.2 MPa (absolute)
Maximum gas amount per valve	5868 Pa*m³
Maximal number of injected atoms/molecules per valve opening	1.42 x10^{24}
Opening time of valves	< 2 ms
Nozzle diameter	28 mm
Stroke of valve plate	6.7 mm
Leak rate of metal seal to VV	< 10^{-8} Pa*m³/s
Leak rate of valve body to VV	< 10^{-8} Pa*m³/s
Leak rate of nitrogen supply and mitigation gas supply lines inside VV and port	< 10^{-8} Pa*m³/s
Nominal pressure in air closure volume	2.0 MPa (absolute)
Maximum operating pressure in closure volume	8.0 MPa (absolute)
Maximal operating temperature	120 °C
Baking temperature	200 °C

- 2 valves, in P9 and P18, 400-6000 Pam³/each (including in-vessel pipe)
- Gas Species: H_2, D_2, He, Ar, Ne and their mixtures

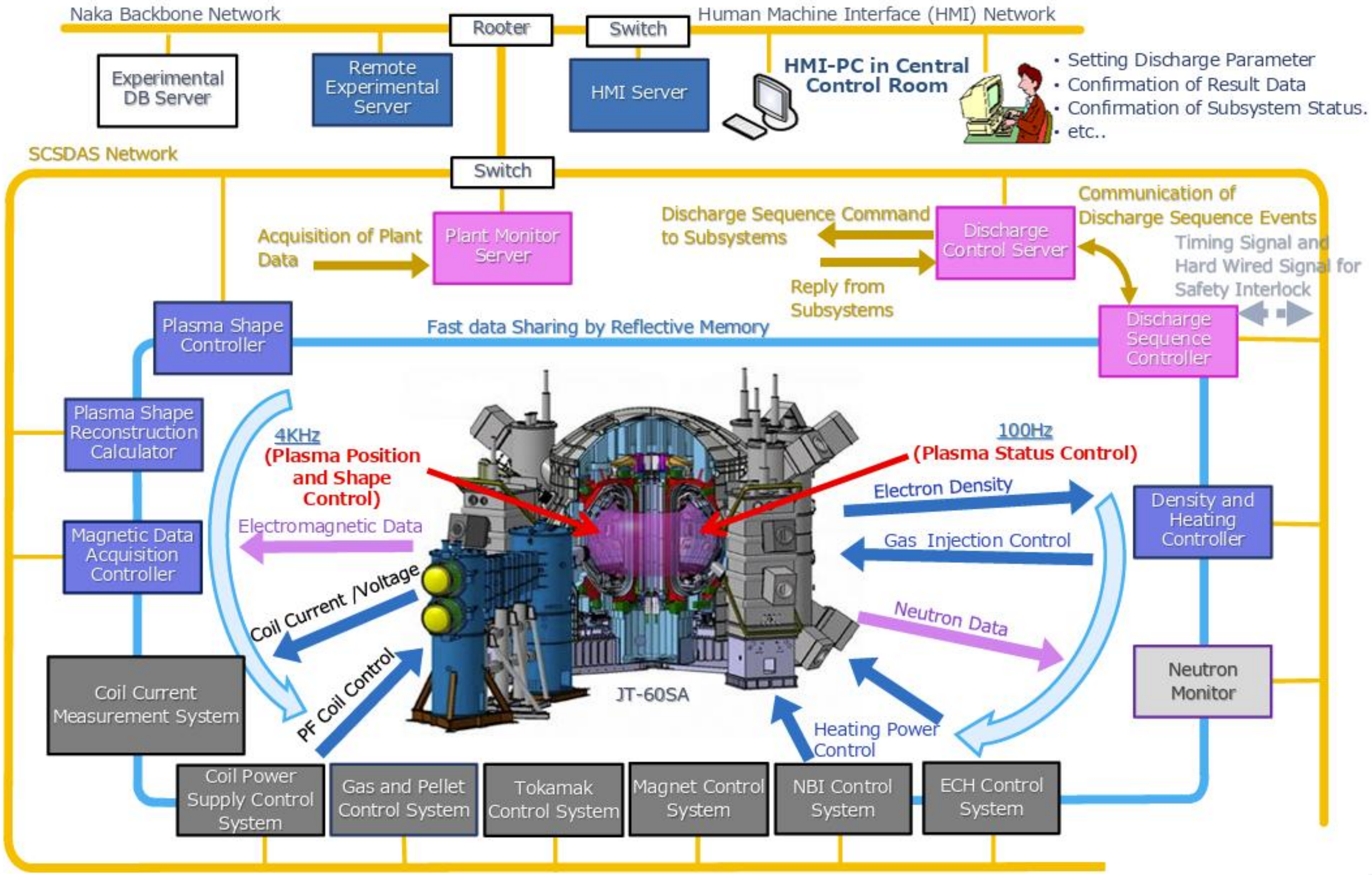
TESPEL (Tracer-Encapsulated Solid Pellet)



TESPEL injector at P9 horizontal port

- polystyrene polymer (C_8H_8 or D_8H_8) as an outer shell ~ 1.2 mm outer diameter and
- impurity tracer particles as a core (typical amount $3x10^{18}$ particles)
- E.g. for W~$2.3x10^{16}m^{-3}$ ~ 0.028%
- Speed about 600 m/s

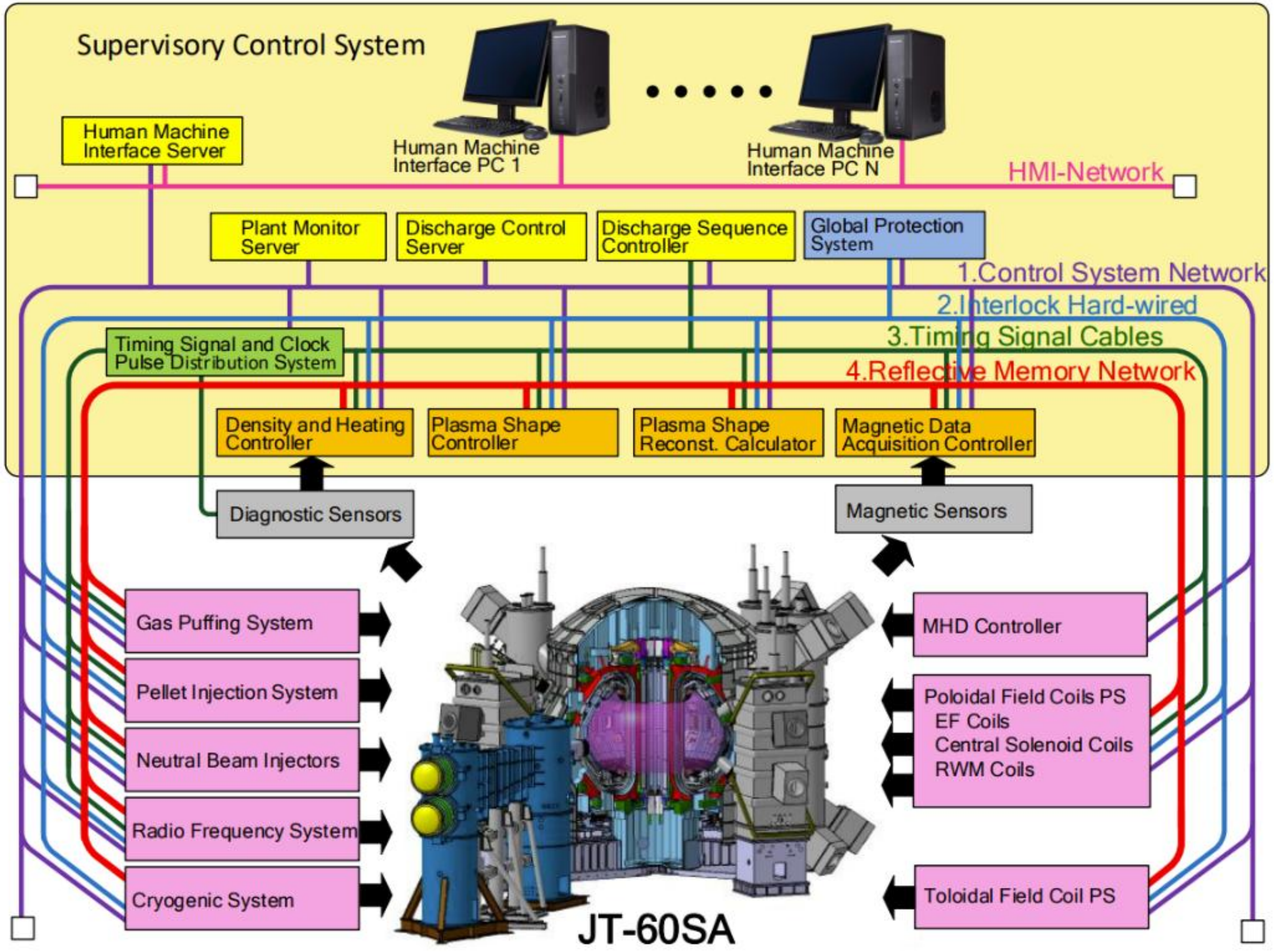
Supervisory Control System and Data Acquisition System (SCSDAS)



SCSDAS scopes

- plant monitoring and machine state management;
- discharge sequence management;
- real-time plasma control;
- device protection and human safety;
- discharge result data storage, archive, and database management;
- remote experimentation

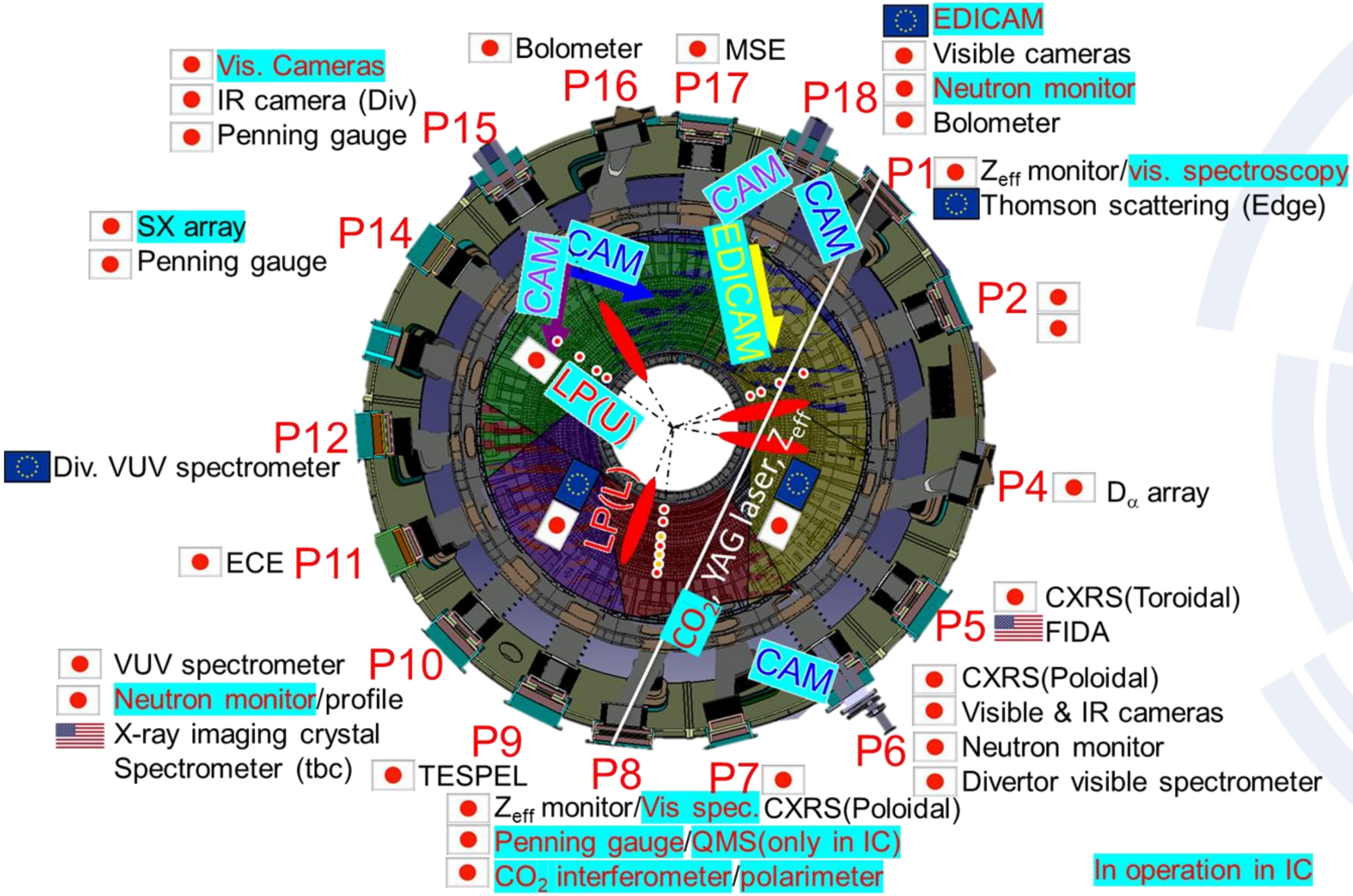
Supervisory Control System and Data Acquisition System (SCSDAS)



SCSDAS communication channels

- Ethernet for transferring operation commands for small amounts of data and discharge result data for large amounts of data, mainly during the discharge preparation period and discharge completion period;
- a reflective memory (RM) network connected by optical cables for rapidly sharing small amounts of data during the plasma discharge period;
- dedicated optical cables and metal wires for transmitting timing signals and clock pulse signals during the plasma operation state;
- dedicated hardwired cables that send interlock signals to drive the relay logic circuits for the Global Protection System

Diagnostics in OP2



- Visible TV camera,
- Infrared TV camera,
- EDICAM,
- Neutron monitor,
- Neutron profile monitor,
- Thomson scattering (Te, ne), core+edge
- ECE (Te),
- CXRS (Ti, Vt, Vp, nc),
- MSE (jr),
- XICS (Te, Ti, Vt),
- Visible spectrometer (Zeff),
- VUV spectrometers (core + edge)
- Da/Ha intensity,
- TESPEL
- Bolometer,
- CO2 interferometer/polarimeter,
- Soft X-ray array
- Divertor probes and thermocouples,
- Neutral pressure,
- Magnetic sensors,
- FIDA

https://qstgojp.sharepoint.com/teams/RMSDiagnostics/SitePages/Home.aspx

Real Time Diagnostics (OP2, tbc)

- Tg CO_2 laser interferometer
- Neutron flux
- Horizontal bolometer
- Magnetics

- Reflective Memory signals map: https://qstgojp.sharepoint.com/teams/SCSDAS/Shared%20Documents/General/JT60SA_RM-MM-map_241218.xlsx?web=1

Training and Synthetic Diagnostics and others

- Training opportunities
  - Pulse design simulator: training material being prepared, aiming to an user course in before mid 2026
    - (https://wiki.euro-fusion.org/wiki/WPSA_CM:_Discharge_simulator) – **to be tested in the new gateway**
  - High Energy Particles workflow (training course (July 2023) can be repeated with updated workflow versions early next year (https://indico.euro-fusion.org/event/2729/)
  - MHD stability workflow (ready: test cases in the repository git@gitlab.eufus.psnc.pl:stability/eqstabil.git)
  - Various example of data access and control room analysis tools developed by users available in a git repository https://git.jt60sa.org/jt60sa/ (see Iafrati's presentation at A&M 1 on the JT-60SA RMS)

  Some example and information attached to this presentation

- Synthetic diagnostics finalized or being completed
  - Edge Thomson Scattering
  - Div. VUV
  - FILD
  - TPCI
  - ECE and ECRH power deposition tools with user interface (in development)

- Remote access re-established in September through IFERC network after 8 month interruption
- not full access granted however
  - Raw data generally not accessible
  - Control PCs of diagnostics not accessible (maintenance of EU developed systems)
- solutions being explored

Sources of information

- Research Management Site (JT-60SA sharepoint): https://qstgojp.sharepoint.com/teams/ETCM/SitePages/Home.aspx
- JT-60SA Research Plan 4.0 https://www.jt60sa.org/wp/wp-content/uploads/2021/02/JT-60SA_Res_Plan-5.pdf
- Plant Integration Document (PID) https://users.jt60sa.org/?uid=22DPA6
- Supervisory Control System and Data Acquisition System https://qstgojp.sharepoint.com/teams/SCSDAS/SitePages/Home.aspx
- EU-led diagnostics projects under development: C. Sozzi et al, IAEA-FEC 2025 (and references)
- https://jt-60saresearchmanagementsite.azurewebsites.net/JT60SAPinboardConference/

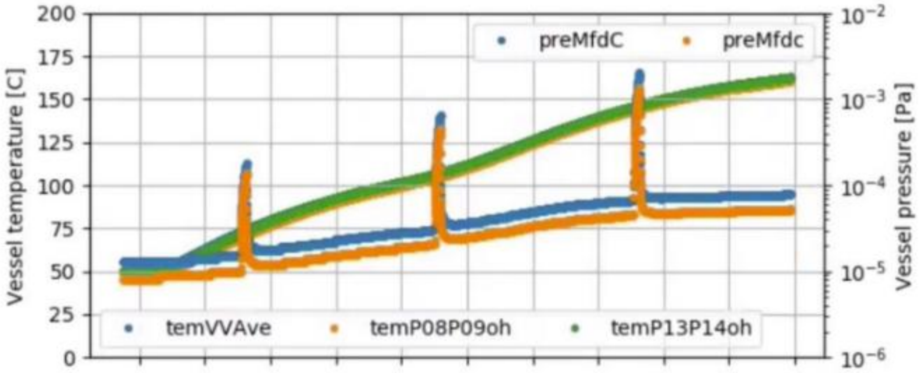
Additional material

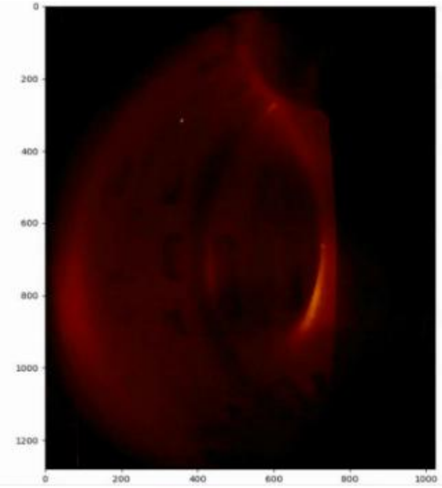
Users developed tools

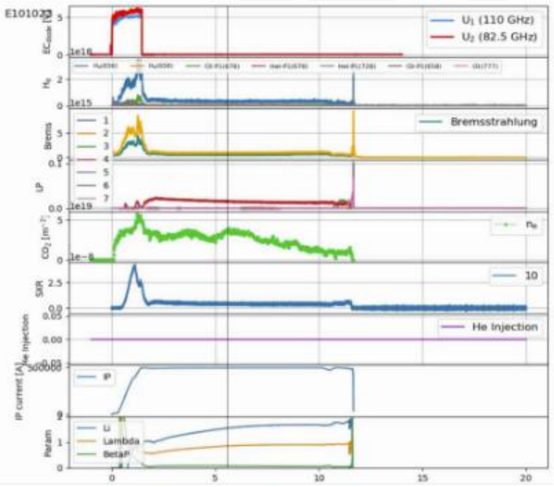
Control room tools developed by users under a conda environment

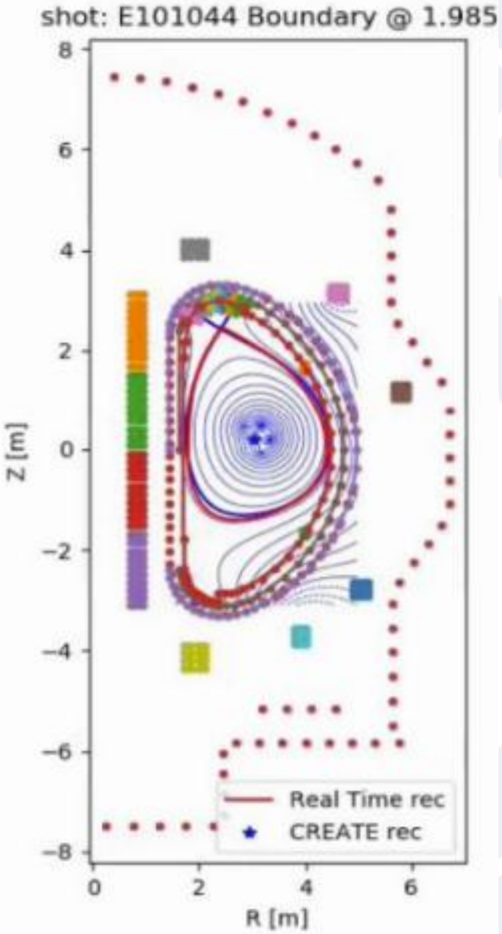
- Conditiong and RGAs monitoring (Gallo)
- Visible cameras and EDICAM Visualization tool (Iafrati et al)
- Plot_geom() (Moreau) and CREATE equilibrium reconstruction (Fiorenza, De Tomasi, Frattolillo)
- SOFT-X visualization tool (Giovannozzi)
- …

Available in a git repository https://git.jt60sa.org/jt60sa/







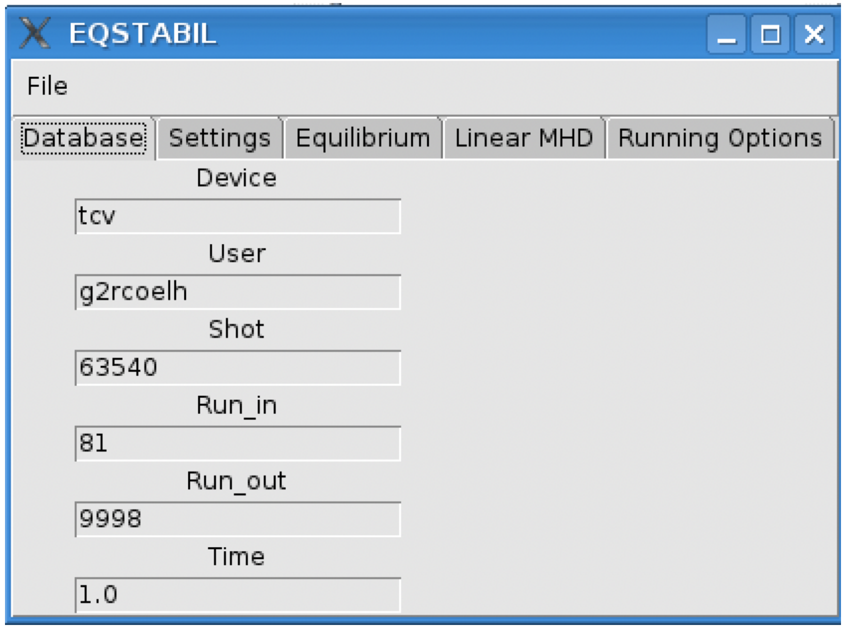


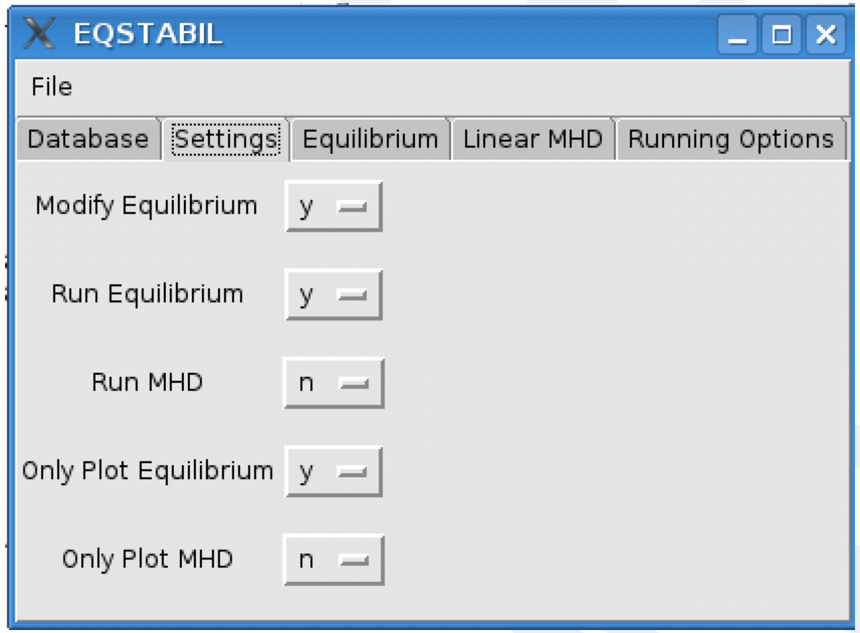
MHD chain - Python based workflow

- **Ideal/resistive MHD workflow for linear stability analysis**, fully compliant to IMAS using iWrap python actors
- Includes HELENA, CHEASE, ILSA (MISHKA-1) and MARS physics codes. Easily extendable to other codes e.g. MARS-X "*family*"
- Fully *multi-device* compatible and *multi-actor* friendly.
- Configuration and physics code parameters fully encapsulated in a ***single JSON file*** (modular and self-contained)
- GUI based but can also be executed on the command line
  - *Driver python script for single time calculation (skips GUI, IDS write to database is optional – useful to integrate in other workflows*)
  - *Driver python script for time series analysis*
- Integration in ***HFPS*** (TSVV11). Also incorporated in ***ETSpy***.
- Extensive set of :
  - Examples for several devices and/or use cases e.g. core/pedestal stability, single/multi toroidal mode number scans, equilibrium scalings.
  - Self-guided training with description of each exemple.

MHD chain Python based workflow

- Already applied to ramp-up stages of 4.6MA scenario taken from ET ORD Sharepoint site
  - *Only H-plasmas are covered.*
  - *MHD stability is tested primarily for n=1,2 modes.*
  - *Plasma resistivity assumed uniform ($S \sim 10^7$) for simplicity.*
  - *EQSTABIL workflow used throughout (GUI or time dependent driver code)*



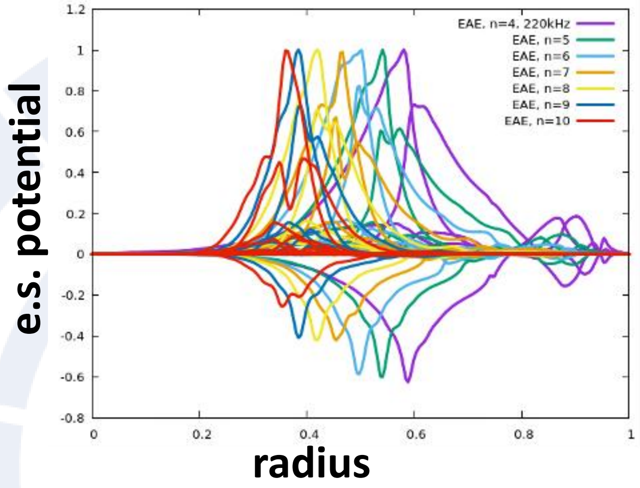


MHD chain : test cases in the repository :
git@gitlab.eufus.psnc.pl:stability/eqstabil.git

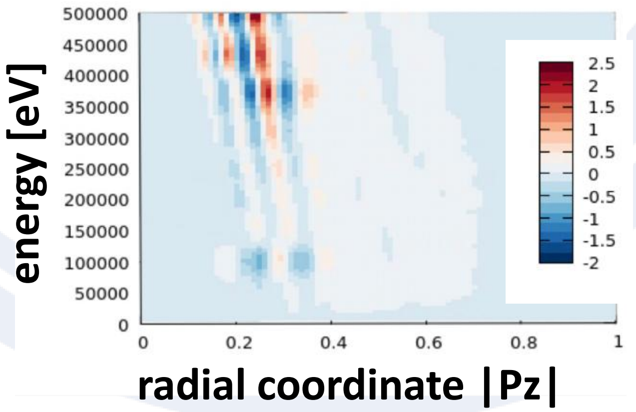
EP-Stability Workflow

- new versions of EP-Stability Workflow available on ITER SDCC and new Gateway (thx T. Hayward-Schneider & V.-A. Popa)
- docker image in preparation (thx to B. Pogodziński, ACH Poznan)
- open source in preparation
- soon: use ATEP and/or EPCOM transformed NBI data (CoM IDSs)
- training course (July 2023) can be repeated with updated workflow versions early next year (https://indico.euro-fusion.org/event/2729/)
- Pending reference JT-60SA cases in IMAS format - the training course should be built on updated JT-60SA equilibria

JT-60SA: EAEs



phase space zonal structure



The Plasma Discharge Simulator

Objectives Tool for scientists & operators to develop their experimental/operation scenario before proposing or implementing an experiment on the machine (developed in a pragmatic way with modelers and operation specialists)

- ✓ Capable of simulating a full discharge **from the start of ramp-up to end of ramp-down**, including X-point formation, with magnetic control, heating, kinetic control, etc …
- ✓ Can evaluate machine operational constraints fulfillment (current limits, controller, etc…)
- ✓ Light tool: « reasonable » CPU time.
- ✓ Friendly interface

What the PDS does not do

- ➢ The simulator is not aimed at describing transport (like with JINTRAC, ASTRA, CRONOS, etc). It uses a light formulation for « reproducing » plasma confinement (METIS).
- ➢ It is **not a high fidelity model for plasma discharges** (e.g. it does not contain disruption models or sophisticated edge or fast particle models …).

The Pulse Design Simulator (PDS) for JT-60SA

- ✓ A complete workflow to design and simulate plasma discharges was built and tested in the last years
- ➢ integration of different components: models, controllers, design procedures, graphical interfaces, …
- ✓ The output has been validated using different codes
- ✓ The controllers used in the simulator have been designed in an ad-hoc way, reproducing the control logics adopted in JT-60SA, but controllers developed for the actual JT-60SA operation and tested in OP1* could be used
- ➢ At this stage tuning the controllers parameters still requires the assistance of a control engineer specialist.
- ➢ The CPU time has not yet been fully optimized but this is future work with the expert users
- ✓ The simulator is available and runs on the EUROfusion Gateway and a user manual has been produced (https://wiki.euro-fusion.org/wiki/WPSA_CM:_Discharge_simulator)*.
- ✓ **The simulator and controllers are ready for use by dedicated experts**
- ➢ Future work will be devoted to include other simulation models and to make it effective in view of JT-60SA operation

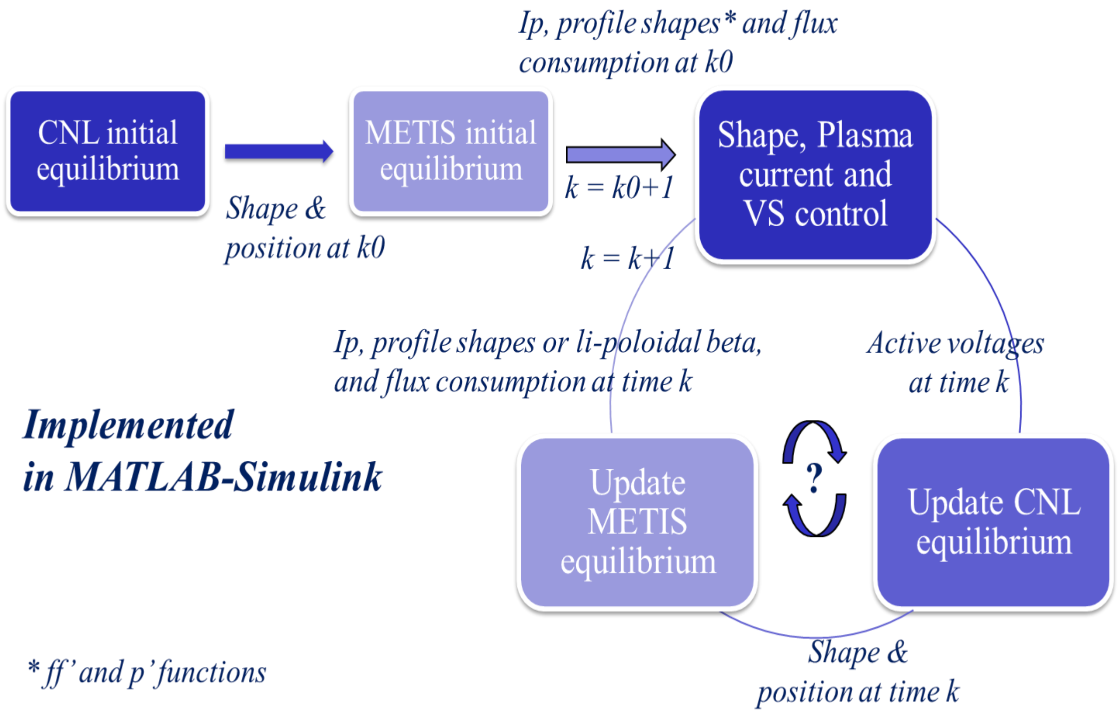
* *to be tested on the new gateway*

E Joffrin et al. IAEA 2025

*[T. Wakatsuki et al 2024 Nucl. Fusion 64 10400]

PDS structure

CREATE/NL-METIS coupling implementation scheme



Implemented in MATLAB-Simulink

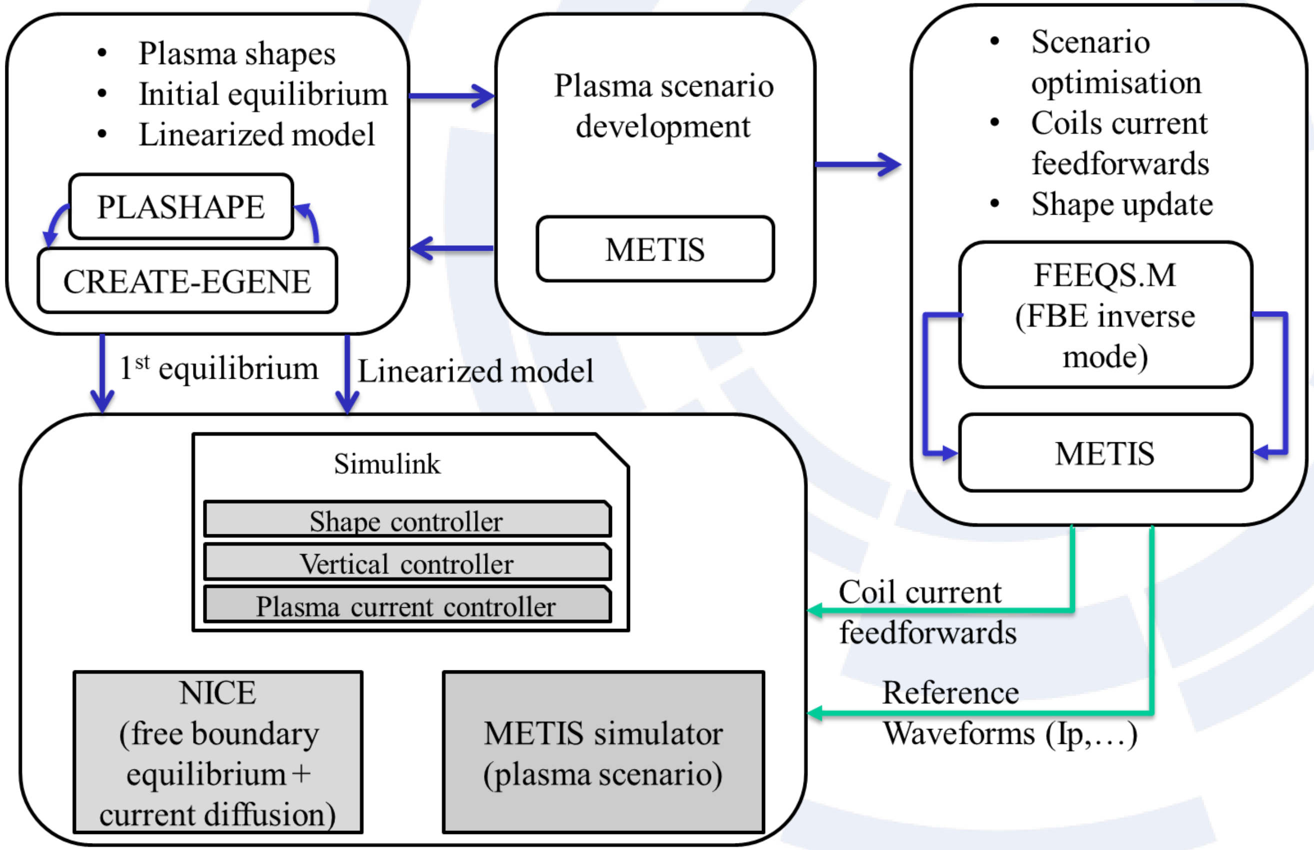
** ff' and p' functions*

[METIS]: J.F. Artaud et al 2018 Nucl. Fusion 58 105001.
[CREATE NL]: G. De Tommasi et al., 2024 Nucl. Fusion 64 076005
[NICE]: B Faugeras et al, Fusion engineering and design, Volume 160, November 2020, 112020

Courtesy M Mattei (CREATE) JF Artaud (CEA)

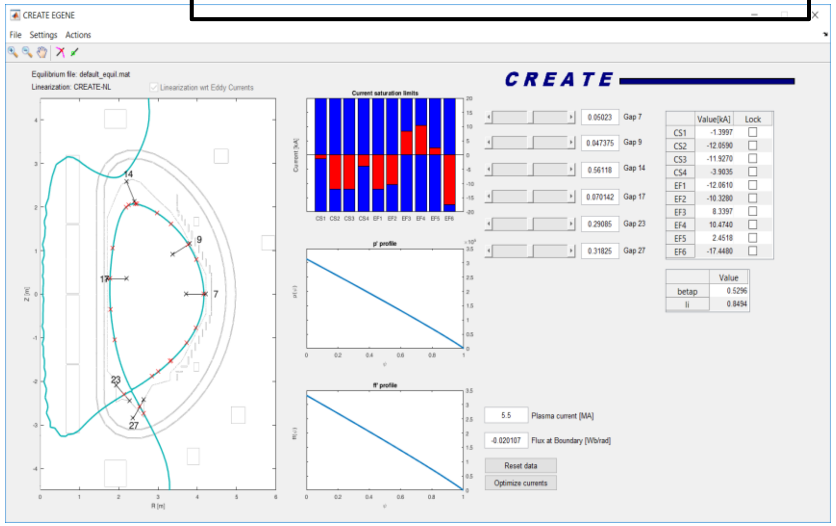
The simulator is coupling three main components:

1. The plasma kinetic simulation from METIS
2. A free boundary equilibrium (FBE) code CREATE_NL or NICE (used in “direct mode”)
3. The Simulink© controllers.



PDS components

CREATE EGENE

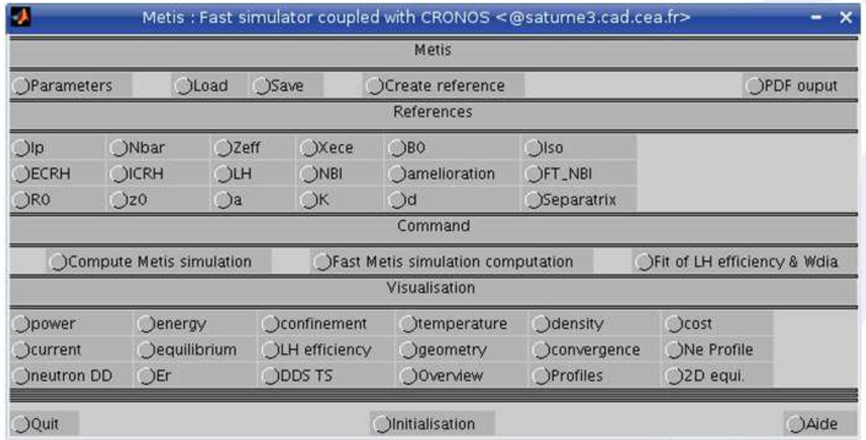


CREATE-EGENE is a graphical user interface (GUI) developed for the CREATE-L/NL codes

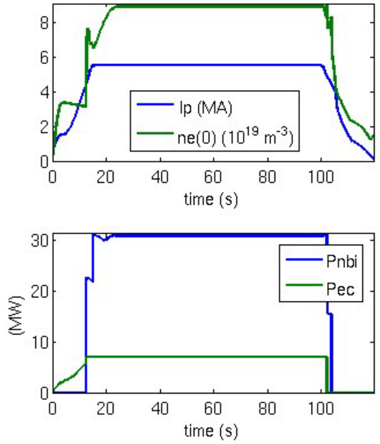
- Visualize the poloidal flux map
- Compare different plasma equilibria
- Optimize currents to obtain the desired shape

Developed for JT-60SA and ITER

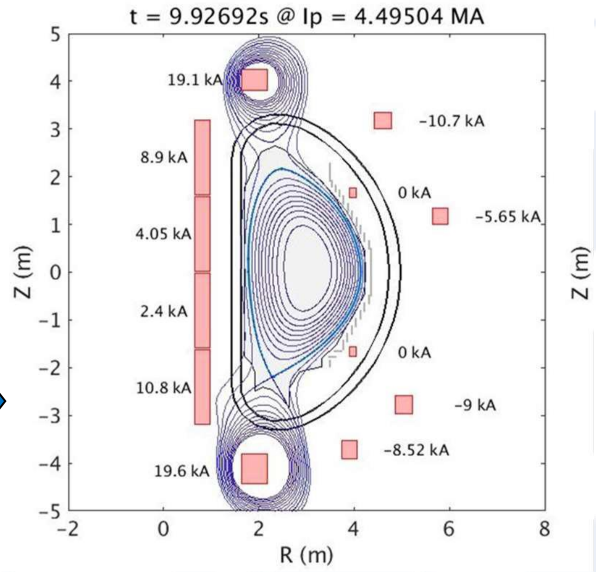
METIS - GUI



METIS is a fast integrated tokamak modelling tool for scenario design



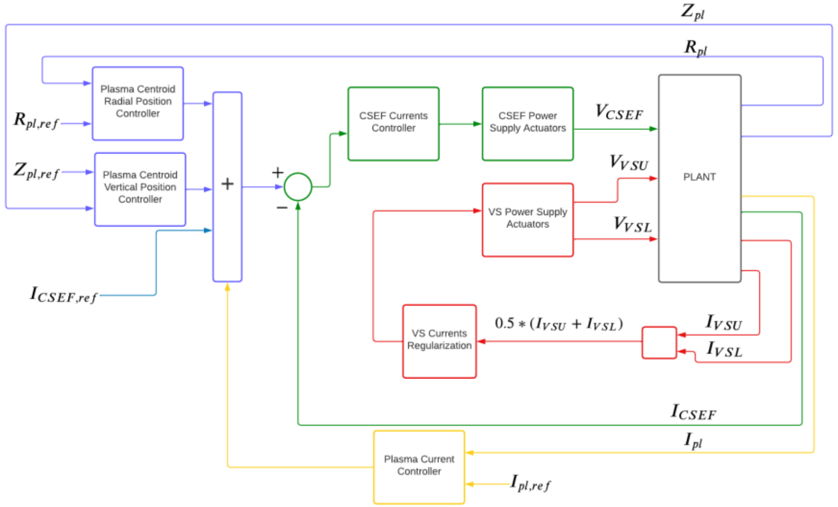
FEEQS



FEEQS is a quasi-static free-boundary equilibrium code that computes the coil currents from P', FF', Ip from METIS and outputs forces, voltage current in passive structures, LCFS shape

Courtesy M Mattei (CREATE) JF Artaud (CEA)

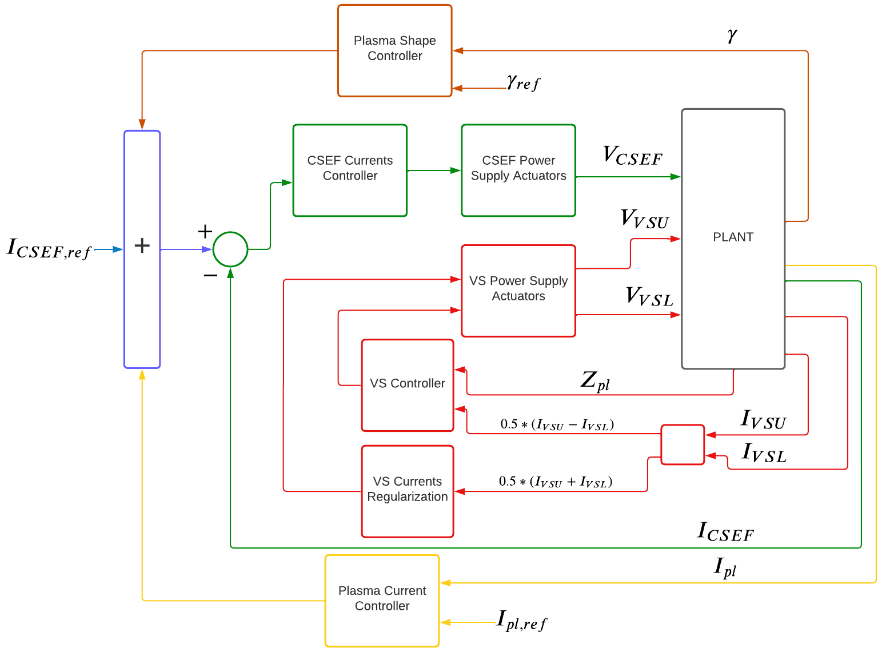
Magnetic Control Scheme - Implemented with NICE-METIS



Early ramp-up phase

It is considered from 0.5s to 2.5s
the active controllers are:

- the plasma current controller,
- the plasma radial and vertical position controller
- the VS currents regularization.



X-Point Formation

From 2.5s to 6.5s / 126s to 130s. Active controllers:

- the VS controller to cope with the plasma instability
- the iso-flux shape controller.
- The plasma current controller and VS currents regularization are active

Diverted Plasma

From 6.5s to 126s

- gap plasma shape controller (gap or isoflux),
- The plasma current controller
- VS controllers and VS currents regularization

NAME	CONTROLLER TYPE	DESIGN METHODOLOGY
VS	PD – SISO	Optimization based design on a 05 s finite time horizon
PFC	P – MIMO	Linear Quadratic Integral Optimal
SC	PI – MIMO	XSC-like approach (based on gaps or Isoflux)
PCC	PI - SISO	Trasformer current pattern approach

G. De Tommasi et al., Control of elongated plasmas in superconductive tokamaks in the absence of in-vessel coils, Nuclear Fusion, Vol. 64, n. 7, p.076005, 2024

L.E. di Grazia et al., A simulation tool to design and test control laws for JT60-SA scenarios, Fusion Engineering and Design, Vol. 192, p. 113631, 2023

D. Corona et al., Plasma shape control assessment for JT-60SA using the CREATE tools, Fusion Engineering and Design, Vol. 146, pp. 1773-1777, 2019

EU enhancement plans (for OP3, OP4)

- JT-60SA tokamak through Machine Enhancements 1 for the whole year
- (Remote) data access unavailable until September 2025
- JT-60SA data server and analysis cluster transferred to IFERC network as one of the actions taken after the OP1 experience

Scope=>

OP1: first plasma

EC assisted breakdown at low $E_{//}$
Plasma control with SC coils
Disruption characterization

OP2: high Ip operation

Extension of the operation domain (high Ip, H mode, Beta, collisionality, …)
Disruptions and Runaway control, Error field
Heat transport L mode with dominant Electron heating
Shine through, Fast ion losses, LH transition, ELMs,
SOL scaling at high IP, Divertor characterization

OP3: H mode development

ITER relevant H-mode and high beta scenarios
High Beta non-inductive steady-state scenarios
NTM, RWM, ST control
Heat transport L mode with dominant Electron heating
Fast ions and turbulence, Alpha particles in D-3He plasma
ELMs regimes, W screening, Seeding