MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

ITER Plan for Gradual Performance Increase Including Transients

W. Treutterer, Max-Planck Institute for Plasma Physics

with special thanks to R. Pitts and A. Loarte, ITER Organization

Views and opinions expressed are those of the author only and do not necessarily reflect those of the ITER Organization.

EUROfusion

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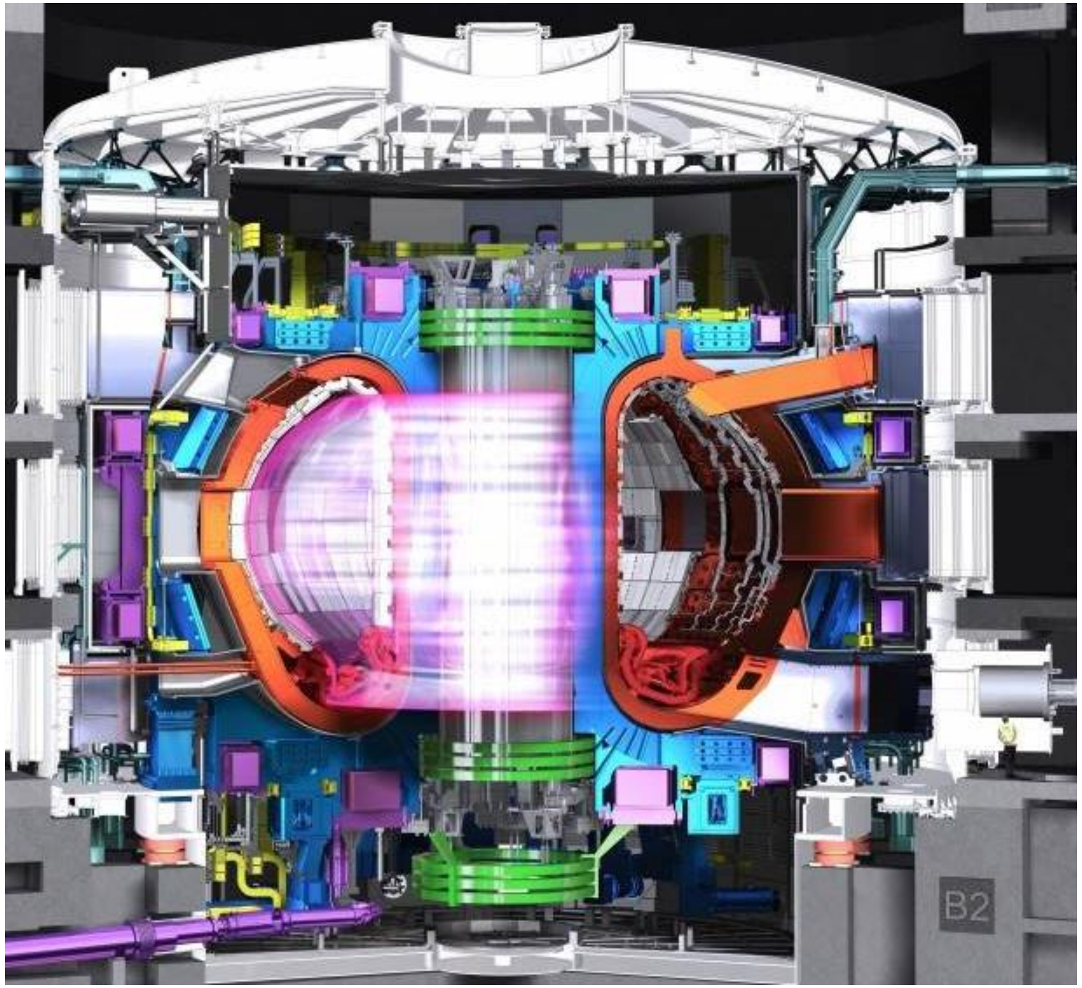
ITER Mission Goals

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
  $P_\alpha / P_{aux\text{-}heat} \geq 2$
- **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
  → $P_\alpha / P_{aux\text{-}heat} \sim 1$



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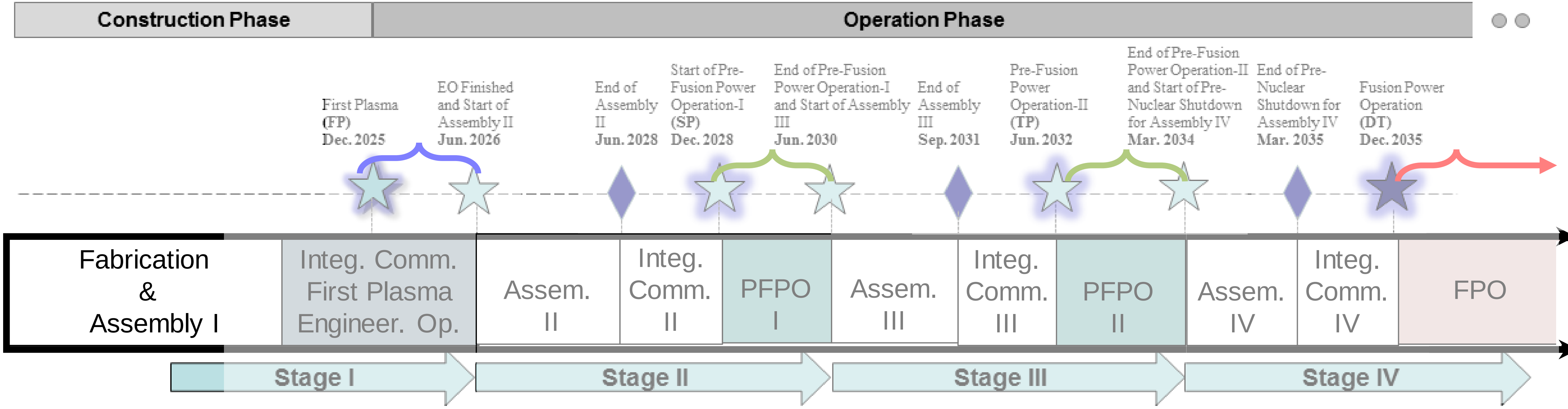
ITER Research Plan (IRP)

R&D Strategy to achieve project's goals with distinct phases :

- **Integrated Commissioning, First Plasma, Engineering Operation**
- **Pre-Fusion Plasma Operation phases (H/He)**
- **Fusion Power Operation (D and DT) → Achievement of high Q goals**



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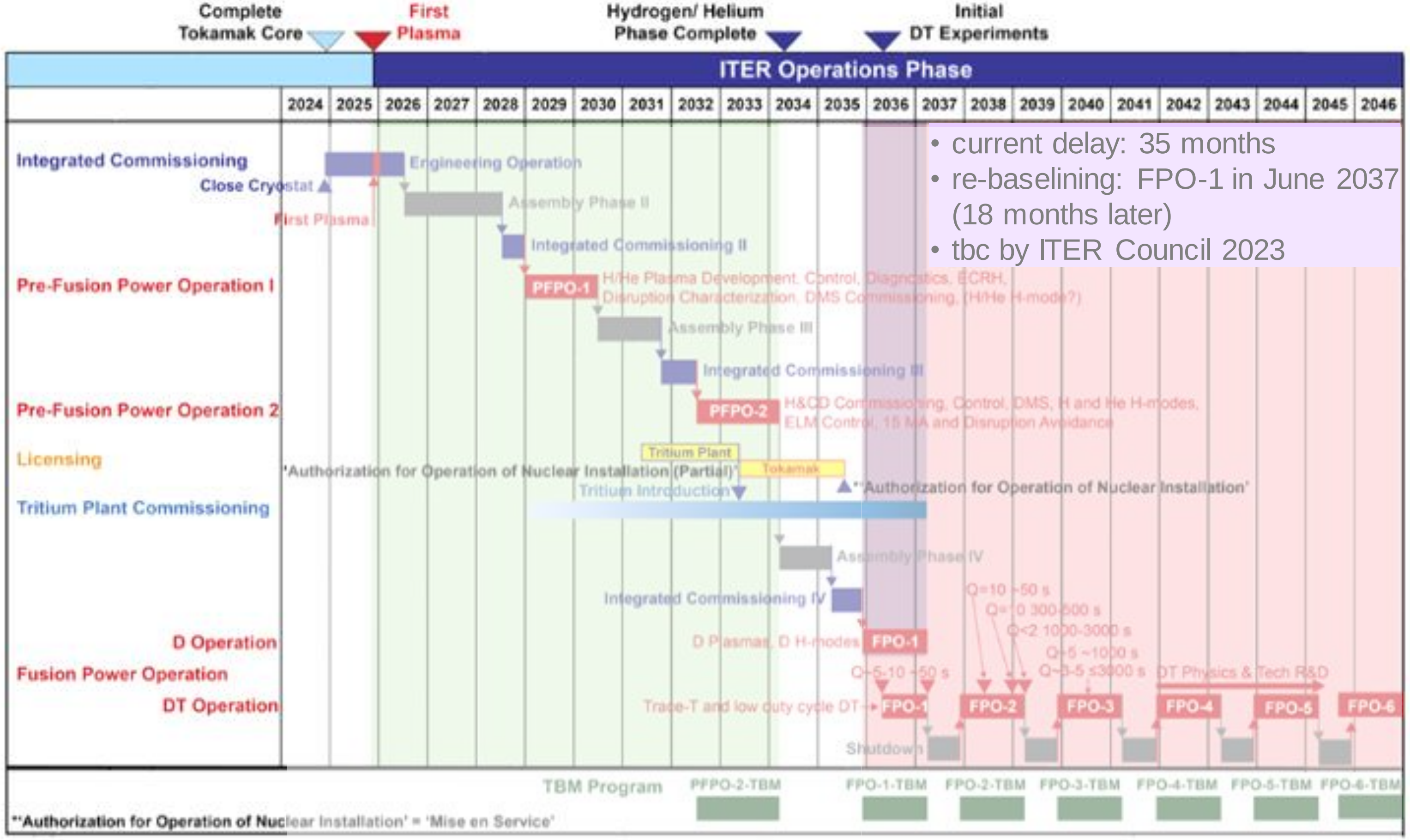
ITER Research Plan (IRP)

IRP describes the strategy for R&D to achieve project goals starting from First Plasma :

Q = 10 (300-500 s), Q = 5 (1000 s) & Q = 5 (steady-state)

Proposed R&D is supported by available systems in each phase



- current delay: 35 months
- re-baselining: FPO-1 in June 2037 (18 months later)
- tbc by ITER Council 2023

https://www.iter.org/technical-reports

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Staged approach and H&CD systems

	1st Plasma	PFPO-1	PFPO-2	FPO	HCD Upgrade
EC	5.8MW, 170GHz, UL	20MW + 10MW[1]	→	→	20MW + 20MW[2]
IC			20MW	→	20MW + 20MW[2]
NB			33MW, H-beam	33MW, D-beam	33MW + 16.5MW[2], D-beam
Key Kinetic Scenarios	First plasma	5MA/1.8T H-mode	7.5MA/2.65T H-mode, 15MA/5.3T L-mode	15MA/5.3T DT H-mode ("ITER baseline")	Hybrid and Steady-State

[1] To be confirmed
[2] HCD upgrade options

Kim, IIS2022

Integrated Commissioning

Integrated Commissioning

- **Commissioning of combined use 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**

- **Repeated before every operation phase**
  - Newly available plant systems
  - Novel functionalities
  - Integration with other (existing) components

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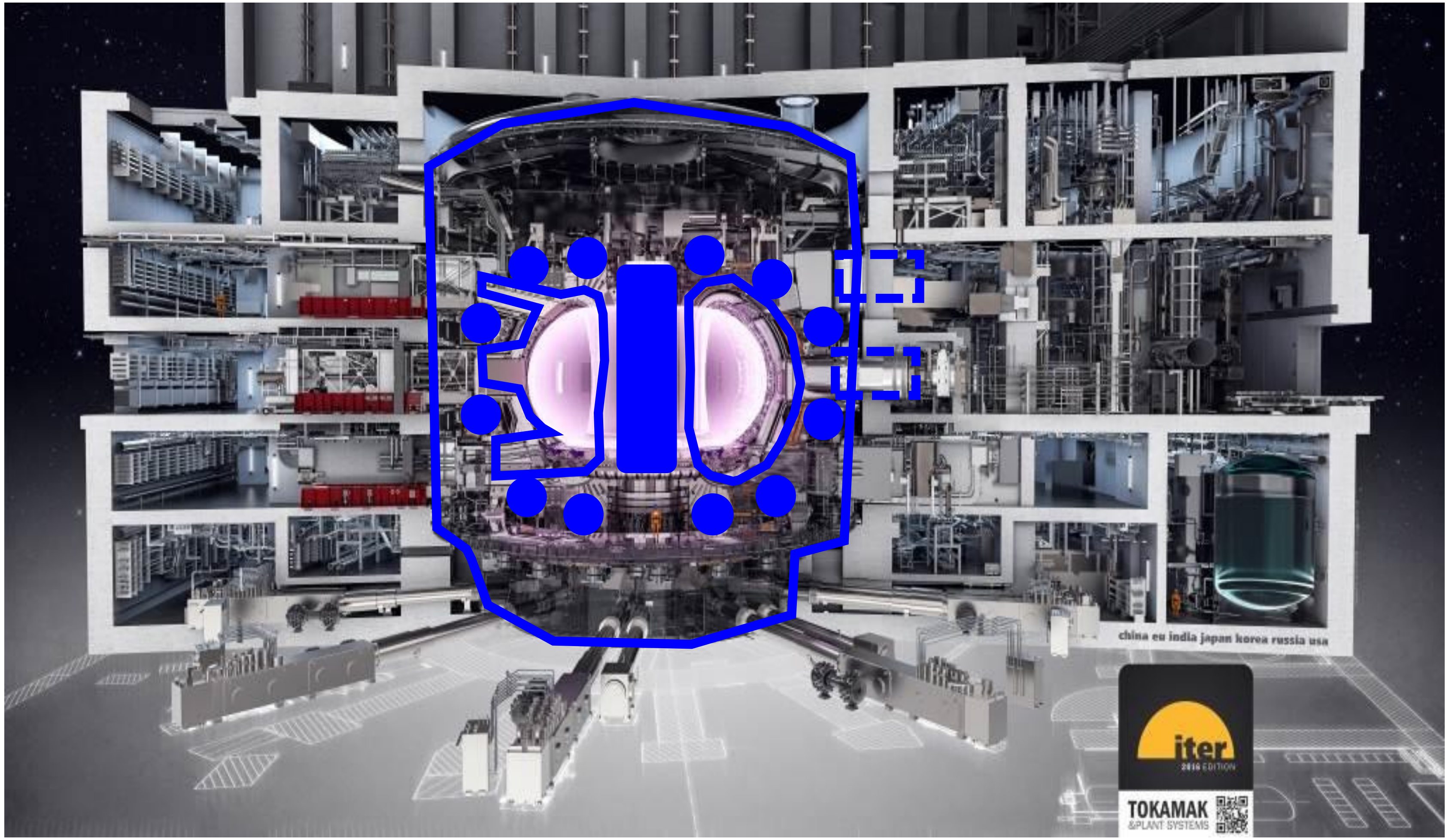
First Plasma (FP) and Engineering Operation (EO)



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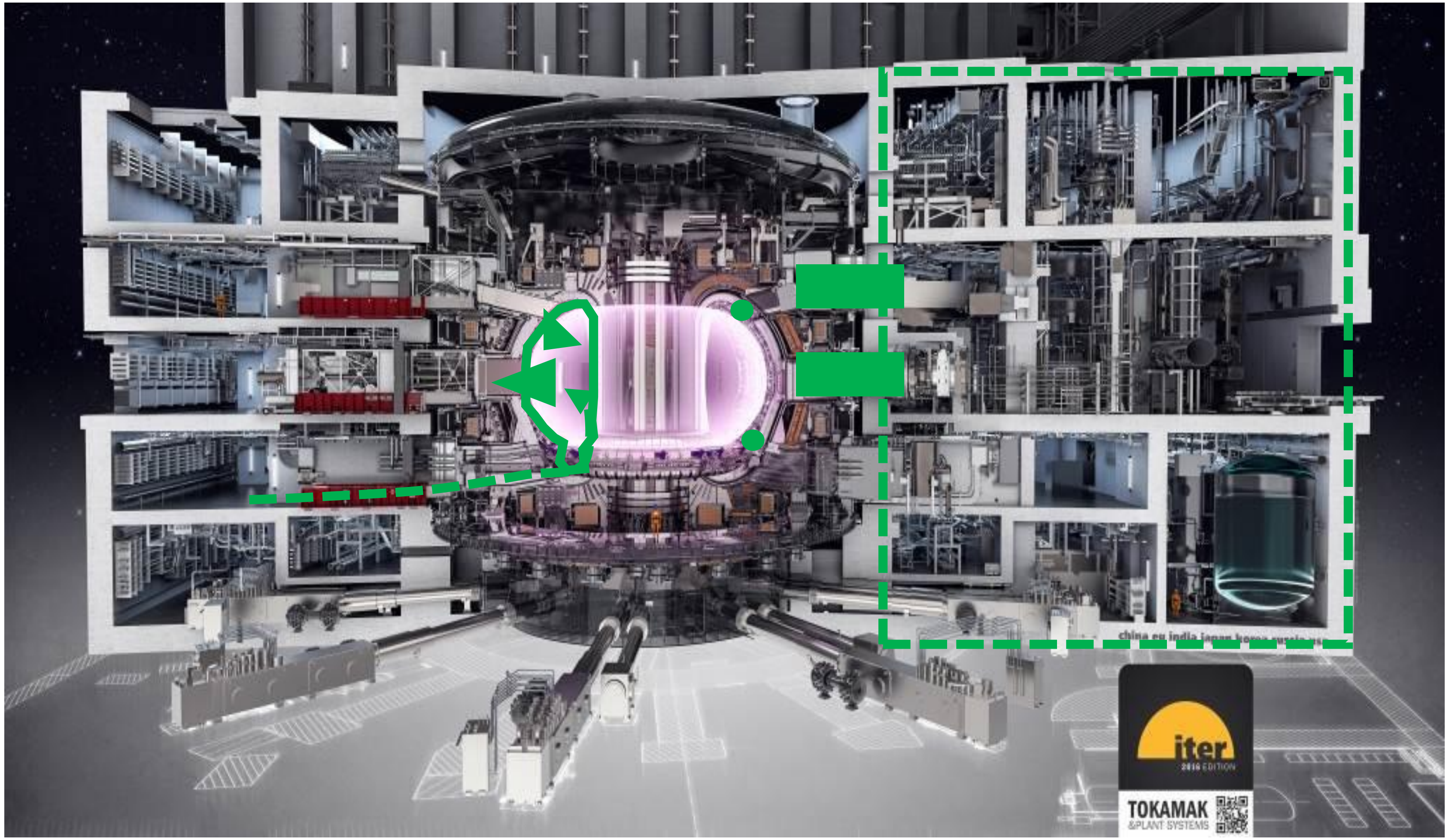
First Plasma

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

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)

Pre-Fusion Plasma Operation-1 (PFPO-1)



- Plasma Facing Components
- Vertical Stability control coils
- Pellet fueling system (partial)
- ECH full system (20 MW)
- Disruption Mitigation System
- Improved diagnostic system fueling, etc.

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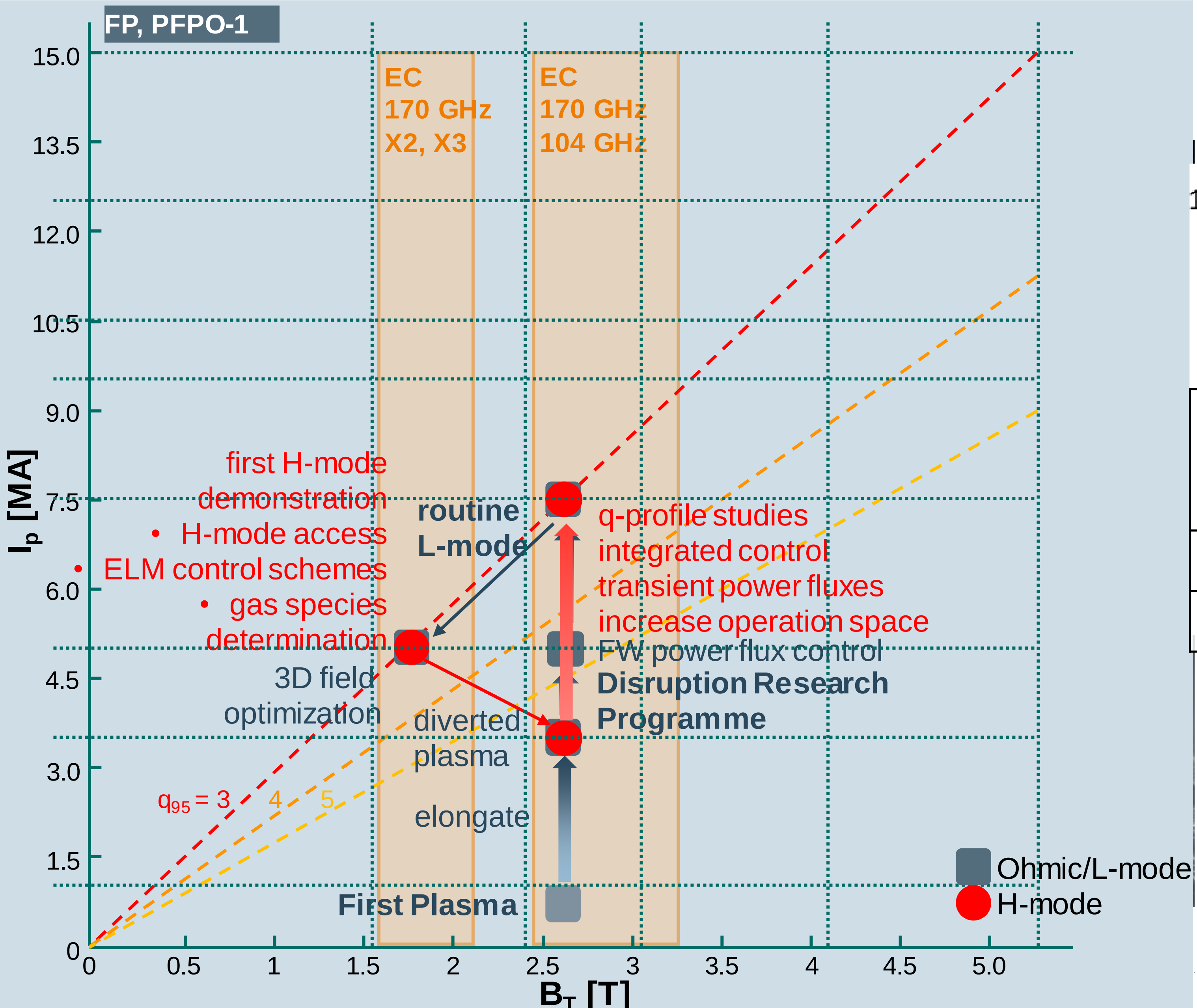
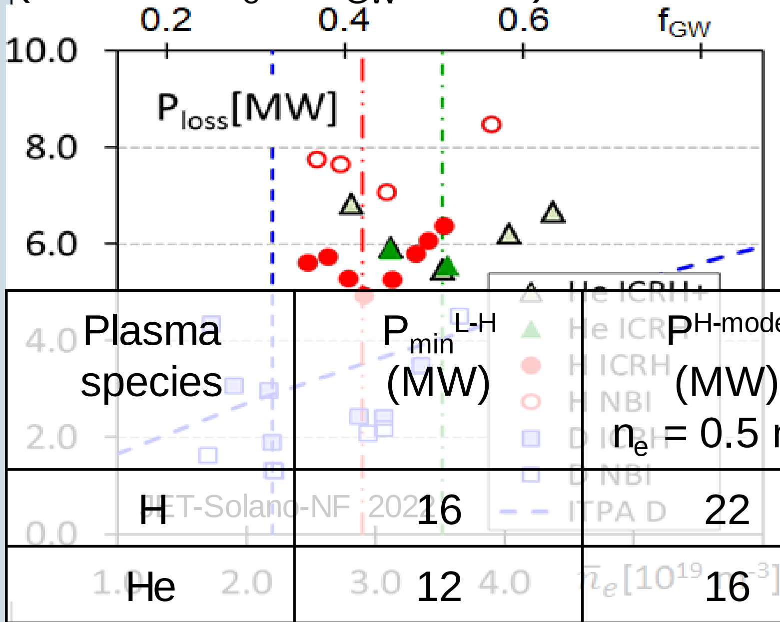
Pre-Fusion Plasma Operation-1 (PFPO-1)



R&D for H-mode access in PFPO-1

5 MA/1.8T H-mode

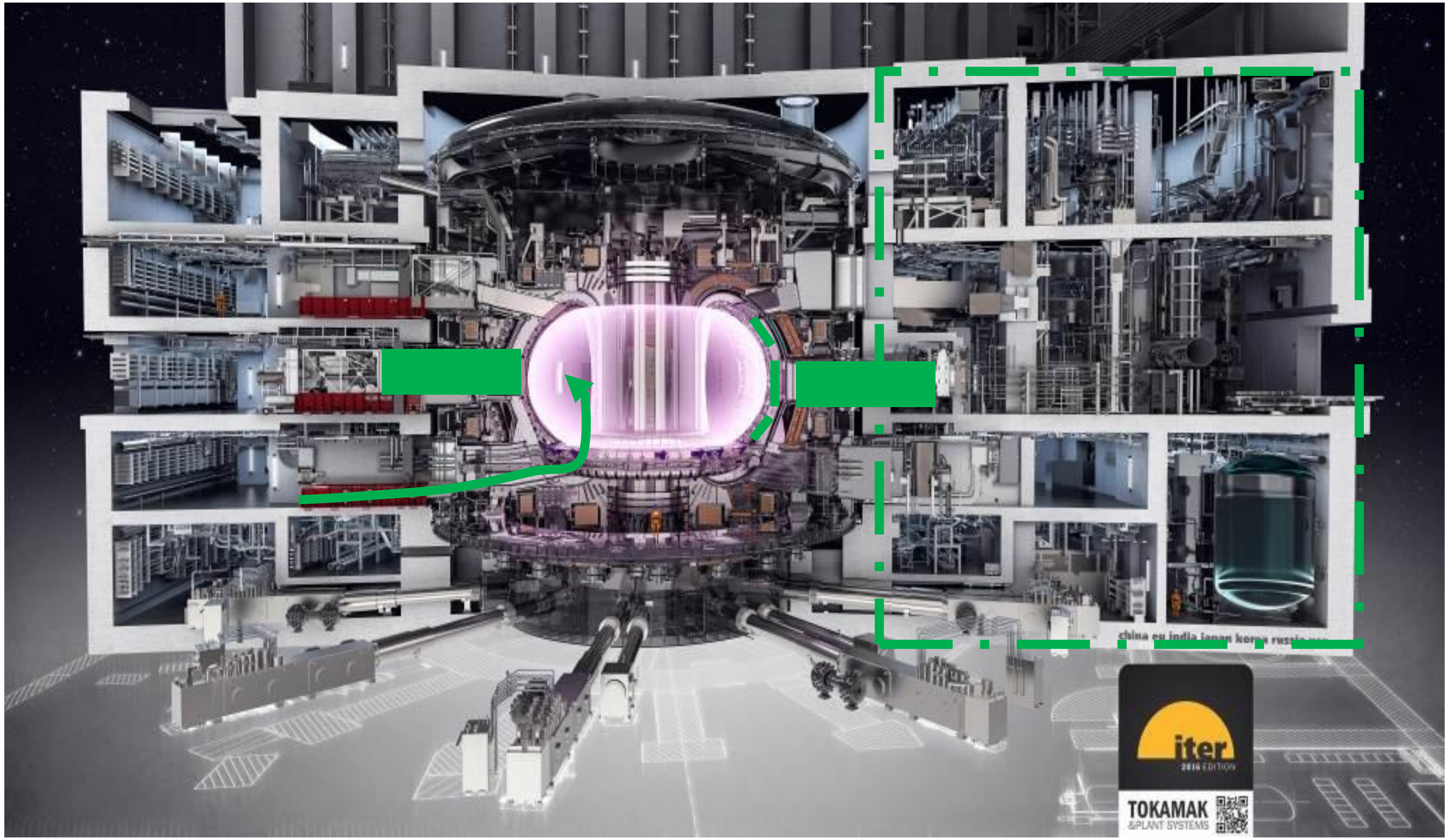
($0.36 \leq \langle n_e \rangle / n_{GW} \leq 0.5$)



Plasma species	$P_{min}^{L\text{-}H}$ (MW)	$P^{H\text{-mode}}$ (MW) $n_e = 0.5\ n_{GW}$
H	16	22
He	12	16

- 20 MW for He plasmas and 30 MW for H plasmas
  → Is this the correct physics picture ?
- Baseline Staged Approach
  → 20 MW ECH
  (10 MW ECH (170 GHz) upgrade ?)

Pre-Fusion Plasma Operation-2 (PFPO-2)



- ELM control coils
- ICH (20 MW)
- NBI (33 MW)
- Pellet fueling system (full)
- Almost complete set of diagnostics
- Test Blanket Modules (Electromagnetic)

(ECH: 20 MW)

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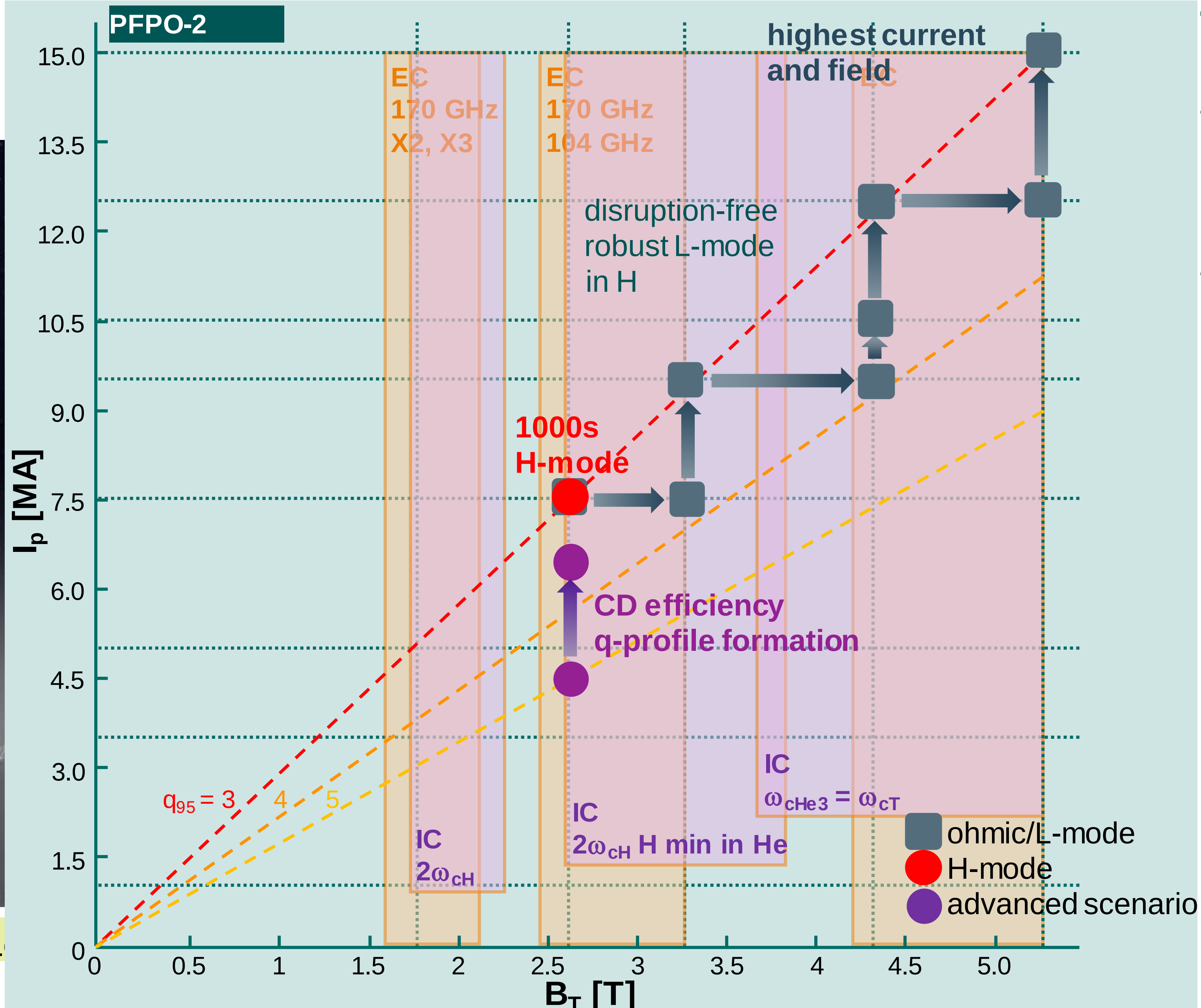
Pre-Fusion Plasma Operation-2 (PFPO-2)

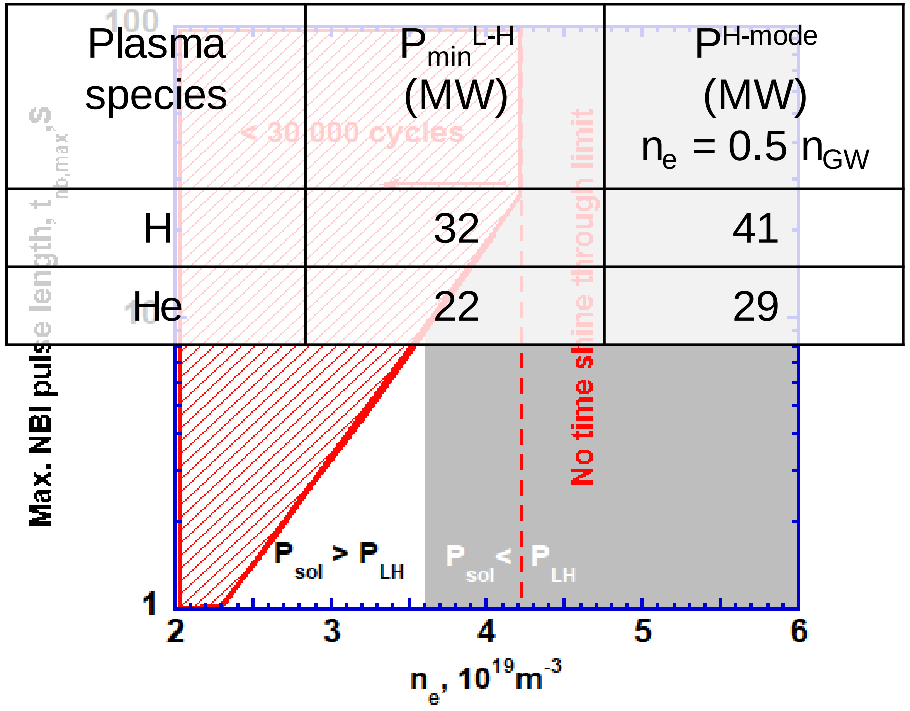


7.5 MA/2.65T H-mode scenarios in PFPO-2 (H, He, H + 10%He)

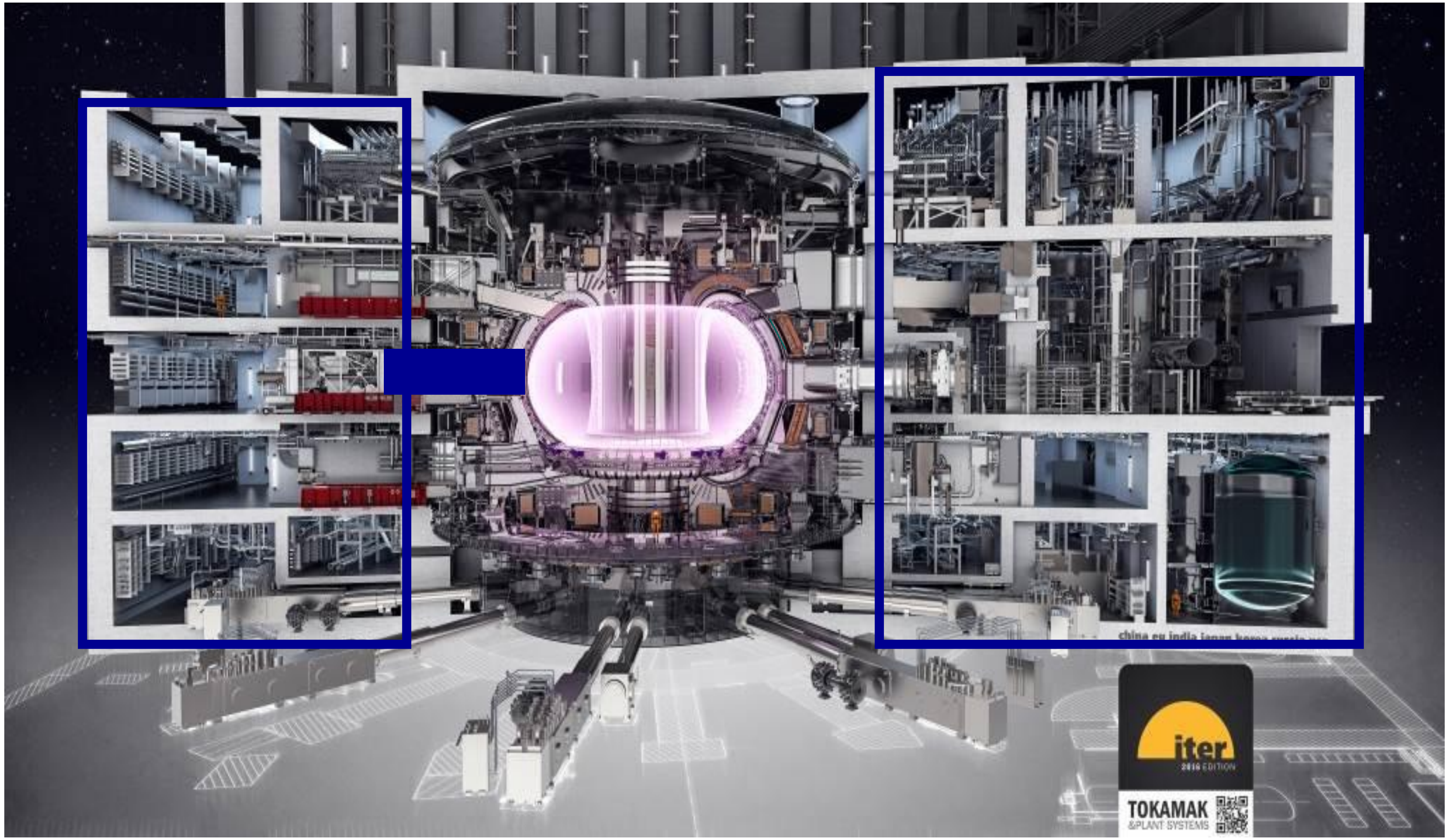
- H H-modes (33 MW NBI + 20 MW ECH) : $P_{aux}/P_{LH} \sim 1$
  → very restricted operation : poor ICH SPA scheme & large NBI shine-through
- He H-modes are robust : $P_{aux}/P_{LH} \leq 2.5$
  → uncertainties regarding extrapolation to DT (fueling, PWI, pedestal, ELM control, …)

B/Ip=2.65/7.5 T/MA in hydrogen with 2% Be + 0.5% Ne, P_{aux}=53 MW

Plasma species	$P_{min}^{L\text{-}H}$ (MW)	$P^{H\text{-}mode}$ (MW) $n_e = 0.5\ n_{GW}$
H	32	41
He	22	29



Fusion Plasma Operation



- Complete set of diagnostics (fusion products : α + 14 MeV n)
- Test Blanket Modules (Nuclear)
- Tritium Plant

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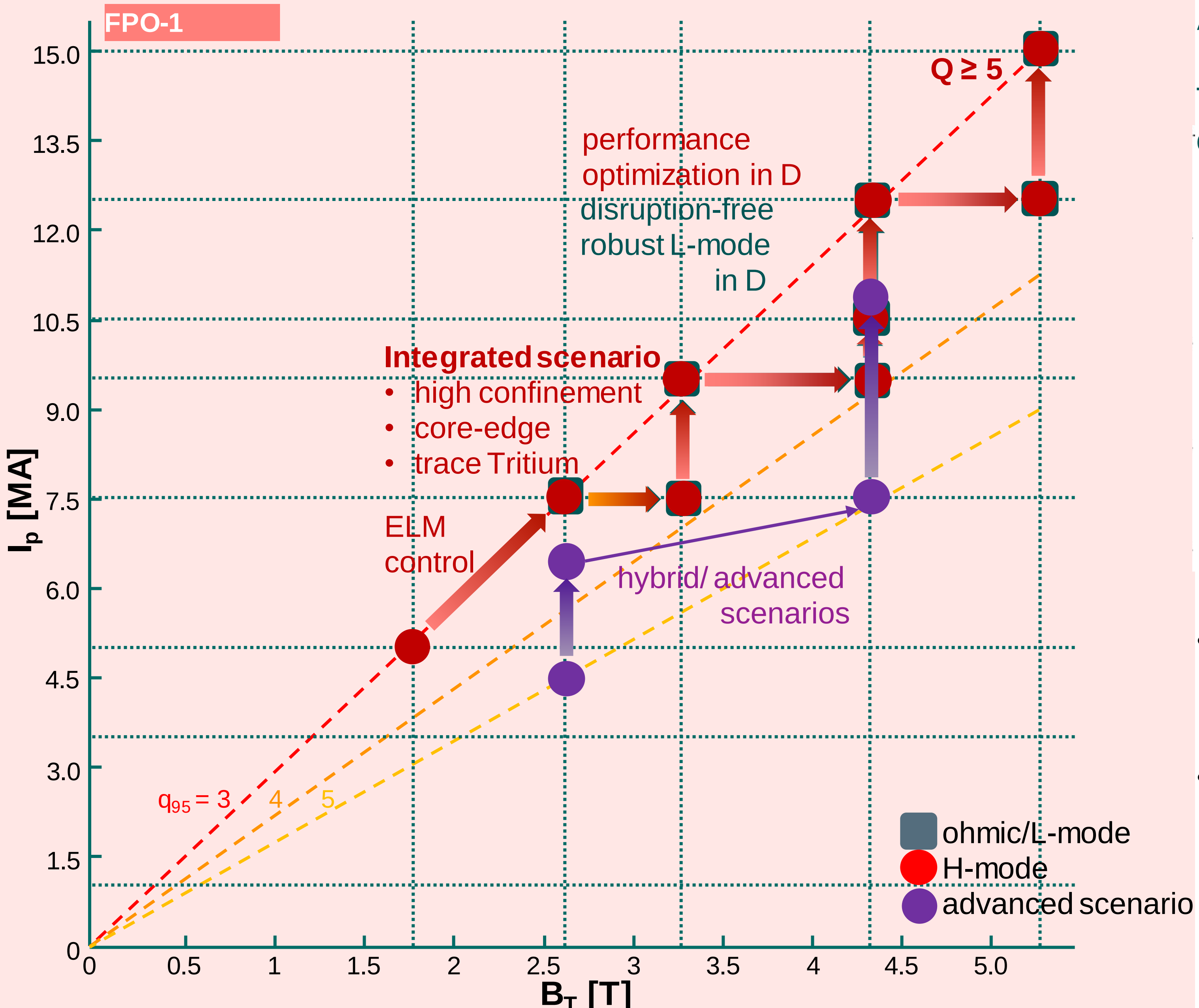
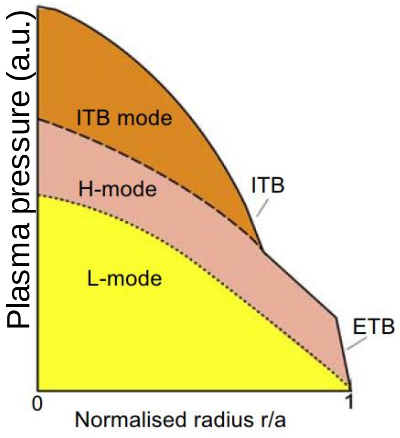
Fusion Plasma Operation

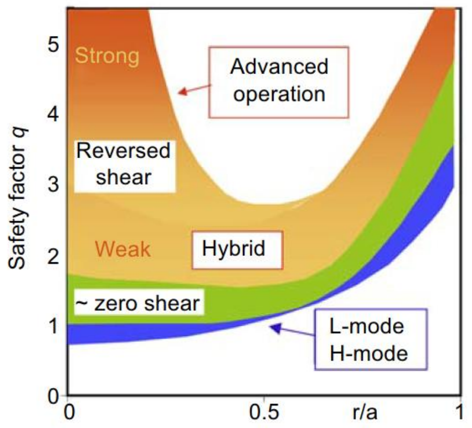


A. L

Advanced Scenarios

Tokamak scenarios are characterized by a combination of pressure and current profile

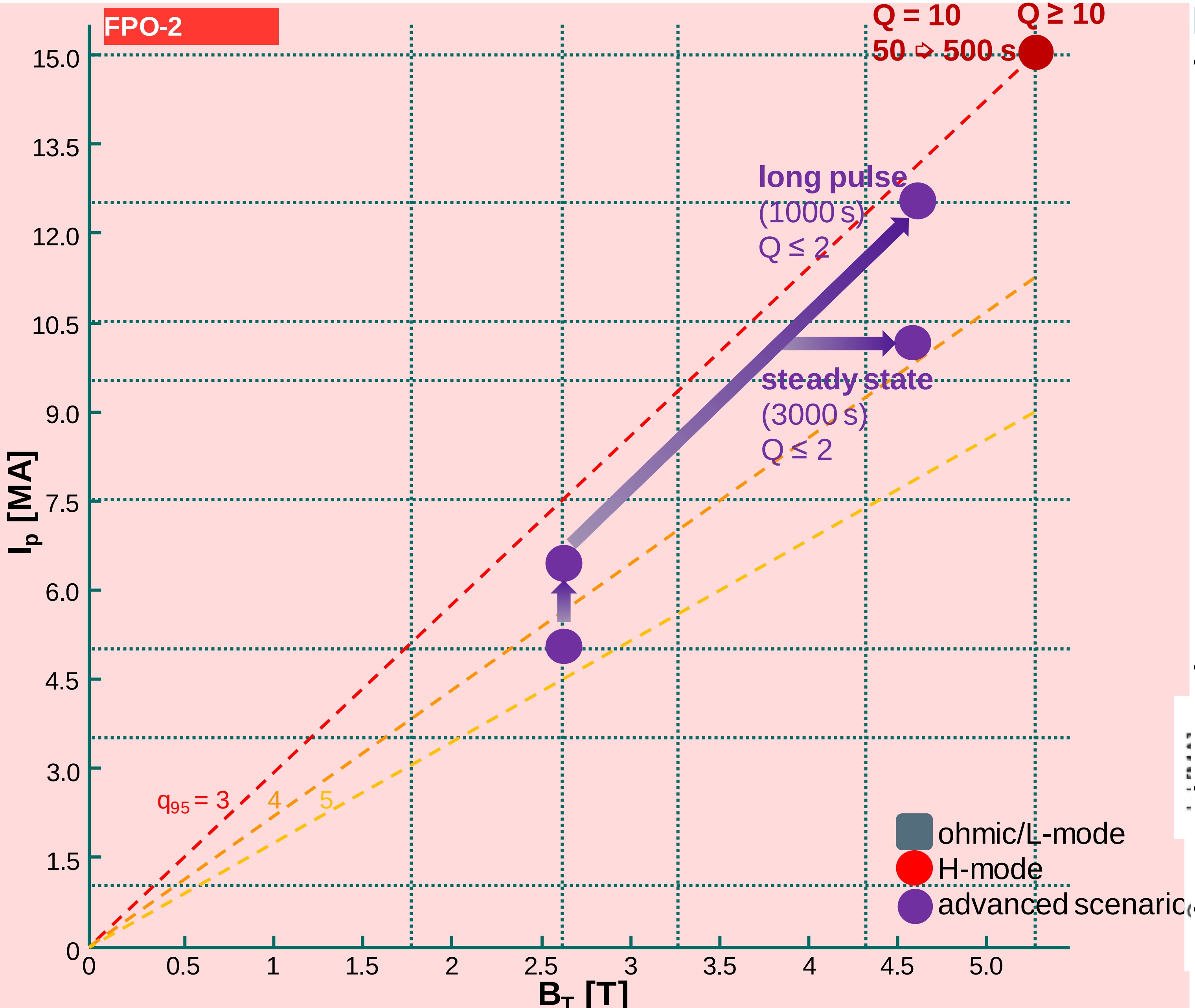




- Accessing and maintaining scenarios can be challenging due to the nonlinear plasma physics
- Control strategies have to be developed to robustly operate the desired scenario

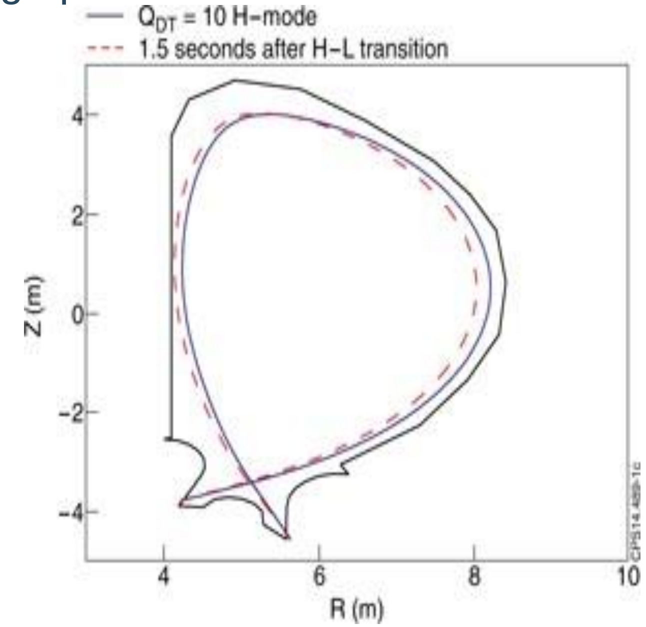
Zohm, IIS 2022

Fusion Plasma Operation



Exit from high Q conditions

- Main issue:avoid fast H-L transitions
  → radial plasma movement difficult to control and large power fluxes to divertor



- Adjust P_{aux}, fueling and Ne seeding
  - to lengthen W_{plasma} decrease phase and
  - avoid too high q_{div} or too deep detachment
- W accumulation can take place in exit due to density/temperature profile evolution if pellet fuelling is quickly switched-off
- P_{rad} remains moderate due to high T_{core}

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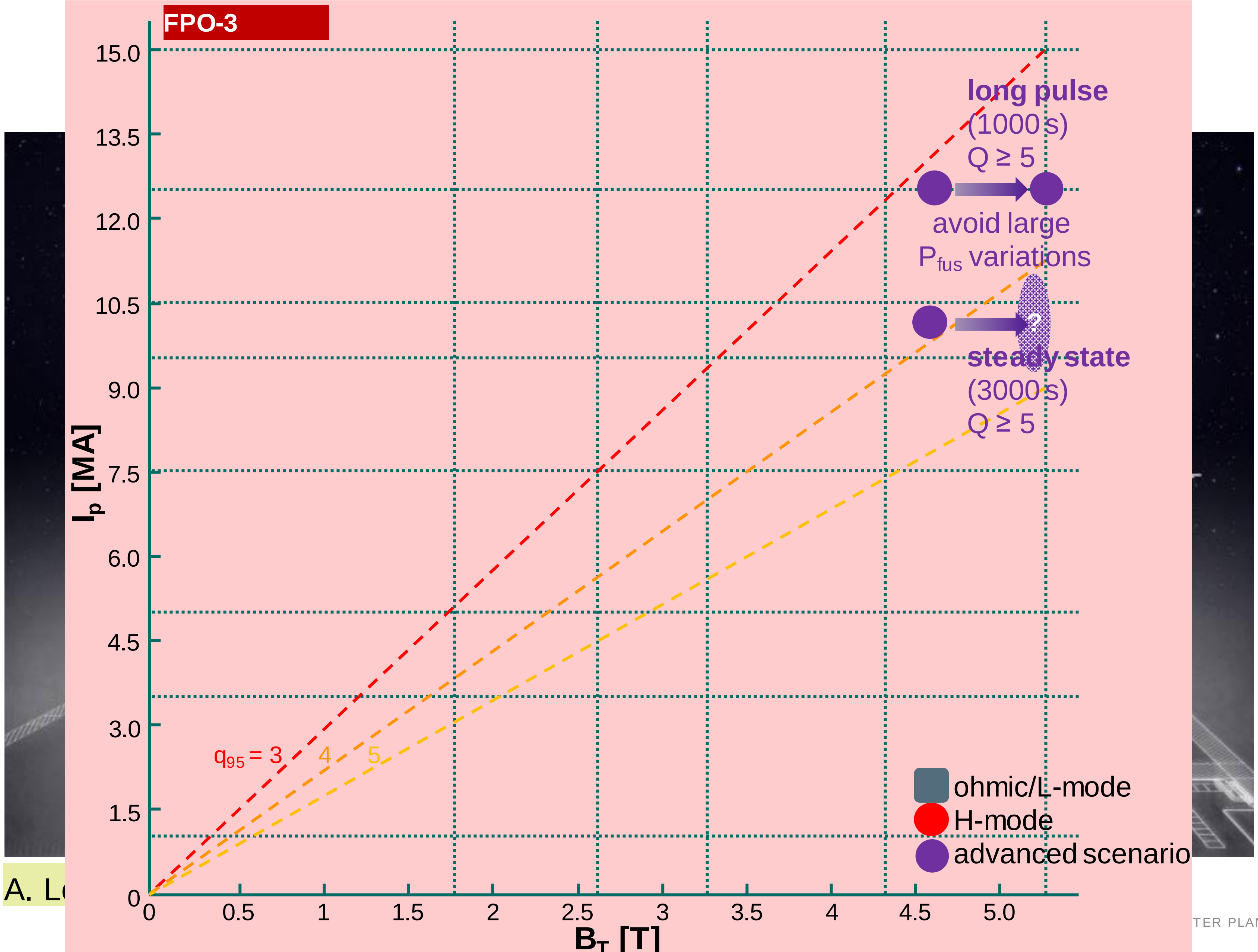
Fusion Plasma Operation-3 (FPO-3)



A. L

- **Complete set of diagnostics (fusion products : α + 14 MeV n)**
- **Test Blanket Modules (Nuclear)**
- **Tritium Plant**

Accompanying R&D Programme


ITER TECHNICAL REPORT

iter

china eu india japan korea russia usa

REPORT NO.
ITR-20-008

TITLE
Required R&D in Existing Fusion Facilities to Support the ITER Research Plan

AUTHOR/AUTHORS
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DATE
22 September 2020

ITR-20-008

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B1: Disruption characterization, prediction and avoidance

B2: Stationary H-mode plasmas, ELMs, ELM control and impact on H-mode and power fluxes

B3: Characterization and control of stationary power fluxes

B4: Plasma-material/component interactions and consequences for ITER operation

B5: Start-up, Ohmic, L-mode scenario development

B6: Conditioning, fuel inventory control

B7: Basic scenario control and commissioning of control systems

B8: Transient phases of scenarios and control

B9: Complex scenario control during stationary phases

B10: Validation of scenario modelling and analysis tools

B11: Heating and Current Drive and fast particle physics

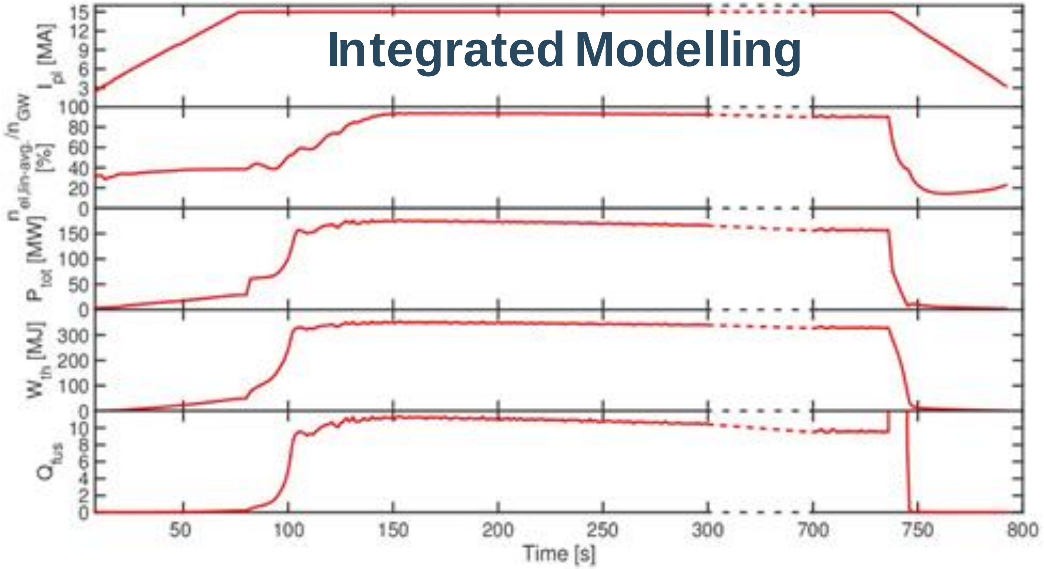
B12: Specific issues for long pulse/enhanced confinement scenarios

Modelling R&D

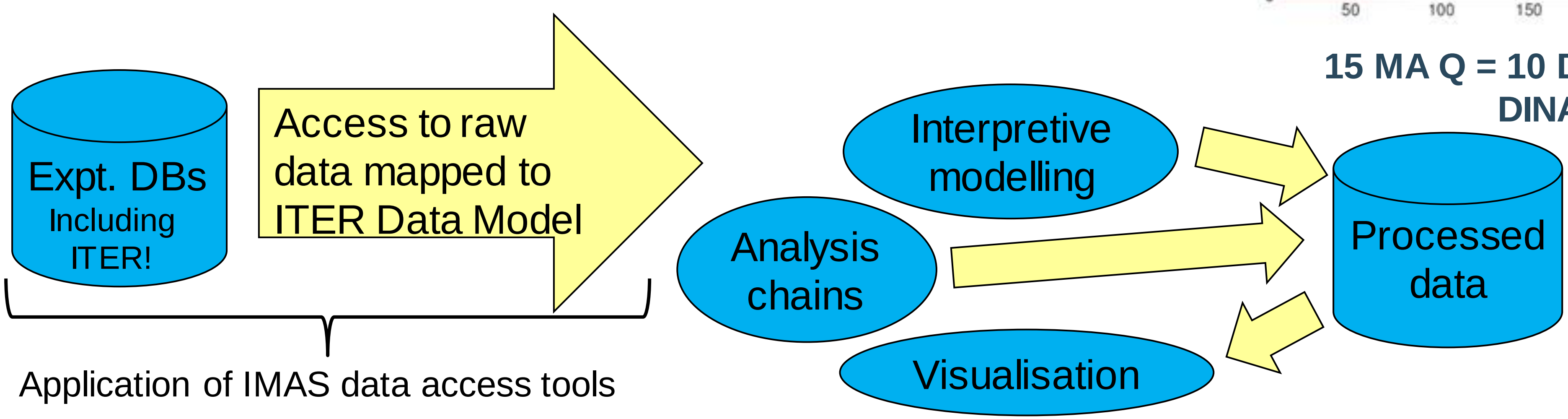
Integrated Modelling and Analysis Suite (IMAS) created to support ITER exploitation:

- **Integrated scenario simulations**
- **Experimental analysis workflows**

IMAS database of ITER simulations representing all phases of IRP (> 120 cases)



15 MA Q = 10 DT ITER baseline scenario with DINA-JINTRAC workflow



S. Pinches

Adopting IMAS → development and validation of ITER modelling/analysis tools

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List of ITER PFPO phase scenarios

DINA

Pulse	Run	Database	Reference	Ip[MA]	B0[T]	Fuelling	Confinement	Workflow
105001	4	ITER	15MA H-DINA2017-01	-14.97	-5.3	H	Ohmic	DINA
105002	4	ITER	15MA H-DINA2018-04	-14.97	-5.3	H	Ohmic	DINA
105003	4	ITER	10MA H-DINA2018-03	-10.08	-5.3	H	Ohmic	DINA
105004	4	ITER	7.5MA H-DINA2016-01	-7.52	-2.65	H	L-mode	DINA
105005	4	ITER	7.5MA H-DINA2016-02	-7.52	-2.65	H	L-mode	DINA
105006	5							
105007	10							
105008	6							
105009	6							
105010	6							
105011	10							
105012	5							
105013	1							
105014	1							
105015	1							
105016	1							
105017	1							
105018	1							
105019	1							
105020	1							
105021	1							
105022	1							
105023	1							
105024	1							
105025	1							
105026	1							
114100	51							
114101	41							
115001	4							
115002	4							

JINTRAC

Pulse	Run	Database	Reference	Ip[MA]	B0[T]	Fuelling	Confinement	Workflow
104001	1	ITER	Elina IAEA-FEC 2016 TH/P2-23 Figure1 15MA 5.16T pe	-15.0	-5.16	H	L-mode	JINTRAC mkimas
104001	2	ITER	Elina IAEA-FEC 2016 TH/P2-23 Figure1 15MA 5.30T pe	-15.0	-5.3	H	L-mode	JINTRAC mkimas
104102	12	ITER	Elina IAEA-FEC2021 figure1, Vasilli Hyd. 5MA 1.8T	-5.0	-1.8	H	L-mode	JINTRAC mkimas + spider-inverse
104102	22	ITER	Elina IAEA-FEC2021 figure1, Vasilli Hyd. 5MA 1.8T	-5.0	-1.8	H	L-H	JINTRAC mkimas + spider-inverse
104102	32	ITER	Elina IAEA-FEC2021 figure1, Vasilli Hyd. 5MA 1.8T	-5.0	-1.8	H	L-H	JINTRAC mkimas + spider-inverse
104102	42	ITER	Elina IAEA-FEC2021 figure1, Vasilli Hyd. 5MA 1.8T	-5.0	-1.8	H	H-mode	JINTRAC mkimas + spider-inverse
104103	12	ITER	Elina IAEA-FEC2021 figure4, Luca Hyd. Ne rich 7.5M	-7.5	-2.58	H	L-mode	JINTRAC mkimas + spider-inverse
104103	22	ITER	Elina IAEA-FEC2021 figure4, Luca Hyd. Ne rich 7.5M	-7.5	-2.58	H	L-H transition	JINTRAC mkimas + spider-inverse
104103	32	ITER	Elina					
104103	42	ITER	Elina					
104104	12	ITER	Elina					
104104	22	ITER	Elina					
104104	32	ITER	Elina					
104105	12	ITER	Elina					
114102	12	ITER	Elina					
114102	22	ITER	Elina					
114102	32	ITER	Elina					
114103	12	ITER	Elina					
114103	22	ITER	Elina					
114103	32	ITER	Elina					
114103	42	ITER	Elina					

CORSICA

Pulse	Run	Database	Reference	Ip[MA]	B0[T]	Fuelling	Confinement	Workflow
100501	3	ITER	Nonactive-H, 7.5MA 2.65T L-H-L, 46.8MW Paux	-7.5	-2.65	H	L-H-L	CORSICA
100502	3	ITER	Nonactive-H, 7.5MA 2.65T L-H dithering, 39.2MW Pau	-7.5	-2.65	H	L-H dithering	CORSICA
100503	3	ITER	Nonactive-H, 7.5MA 2.65T L-mode, 46.8MW Paux	-7.5	-2.65	H	L	CORSICA
100504	3	ITER	Nonactive-H, 9.6MA 3.25T L-mode, 42.8MW Paux	-9.6	-3.25	H	L	CORSICA
100505	3	ITER	Nonactive-H, 12.7MA 4.70T L-mode, 46.8MW Paux	-12.7	-4.7	H	L	CORSICA
100506	3	ITER	Nonactive-H, 15MA 5.3T L-mode, 46.8MW Paux	-15.0	-5.3	H	L	CORSICA
100507	3	ITER	Nonactive-H, 5MA 1.8T L-H-L, 30MW Paux	-5.0	-1.77	H	L-H-L	CORSICA
110501	3	ITER	Nonactive-He, 7.5MA 2.65T L-H-L, 43.0MW Paux	-7.5	-2.65	He4	L-H-L	CORSICA
110502	3	ITER	Nonactive-He, 9.6MA 3.25T L-H-L, 49.2MW Paux	-9.6	-3.25	He4	L-H-L	CORSICA
110503	3	ITER	Nonactive-He, 11.3MA 4.00T L-H dithering, 56.8MW P	-11.3	-4.0	He4	L-H dithering	CORSICA
110504	3	ITER	Nonactive-He, 12.7MA 4.70T L-H dithering, 53.0MW P	-12.7	-4.7	He4	L-H dithering	CORSICA
110505	3	ITER	Nonactive-He, 12.7MA 4.70T L-H dithering, 63.0MW P	-12.7	-4.7	He4	L-H dithering	CORSICA
110506	3	ITER	Nonactive-He, 15MA 5.3T L-mode, 53.0MW Paux	-15.0	-5.3	He4	L	CORSICA
110507	3	ITER	Nonactive-He, 15MA 5.3T L-H dithering, 63.0MW Paux	-15.0	-5.3	He4	L-H dithering	CORSICA
110508	3	ITER	Nonactive-He, 7.5MA 2.65T L-mode, 28.3MW Paux	-7.5	-2.65	He4	L	CORSICA
110509	3	ITER	Nonactive-He, 7.5MA 2.65T L-H-L, 43.0MW Paux	-7.5	-2.65	He4	L-H-L	CORSICA

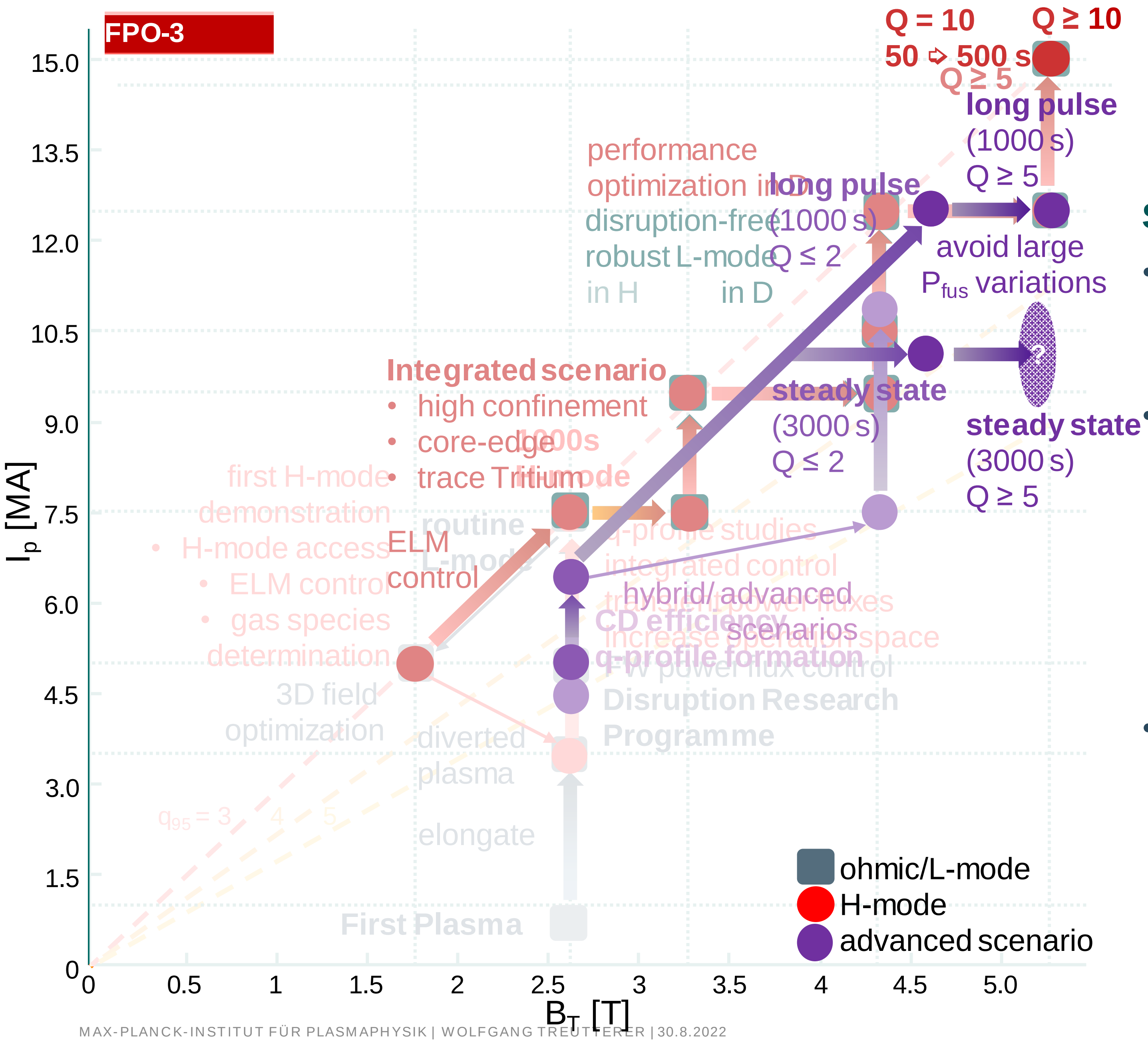
Also METIS, ASTRA, etc.

Kim, IIS2022

Staged Scenario and Control Development

	1st Plasma	PFPO-1	PFPO-2	FPO-1	FPO-2	FPO-3
Disruption mitigation	preliminary limiters,	th./mech load, Disr. res. prg., baseline DMS	DMS optim. for high current and field (H/He)	DMS optim. (D) for burning plasma and H&CD scenarios	operation near stability boundaries	
Disruption avoidance	RE detection and avoidance	vertical stab., disruption-free scenarios	disr.-free op. at high currents and fields	burning H-mode, MHD control in advanced scenarios	robust integrated long-pulse $Q \geq 10$ scenario	
Power flux		power flux char., FW head load prot	power flux control in L-mode	power flux control in H-mode, ELM control	power flux control in $Q = 10$ plasma	robust power flux control in long-pulse scenarios
MHD stability			self-similar scenarios, fast particle effects	NTM and core MHD control, MHD in advanced scenarios	MHD stability on long timescales	MHD effect minimization on P_{fus}
Current profile			current drive efficiency, q-profile formation	advanced/hybrid scenario studies	long pulse/ steady state scenarios $Q \leq 2$	long pulse/ steady state scenarios $Q \geq 5$
Burning plasma				burn condition access/exit	burn control	stable, long-pulse P_{fus} generation

Conclusion



Staged, iterative approach driven by

- **Component availability/upgrade** (heating, diagnostic, control system, TBM, license)
- **Risk mitigation**
  - Re-evaluation and adaptation of existing systems and models
  - Stored energy ~ protection system maturity
  - Alternative paths
- **Ongoing research**
  - Advancement of scenarios, monitoring and control
  - Including stationary and transient phases
  - Accompanying R&D programme

The End

Thank you for your interest!

7.5 MA/2.65T H-mode scenarios in PFPO-2 (H, He, H + 10%He)

- H H-modes (33 MW NBI + 20 MW ECH) : P_{aux}/P_{LH} ~ 1
  → very restricted operation : poor ICH SPA scheme & large NB
- He H-modes are robust : P_{aux}/P_{LH} ≤ 2.5
  → uncertainties regarding extrapolation to DT (fueling, PWI, pedestal, ELM control, …)

I_p = 7.5MA, B_t = 2.65 T

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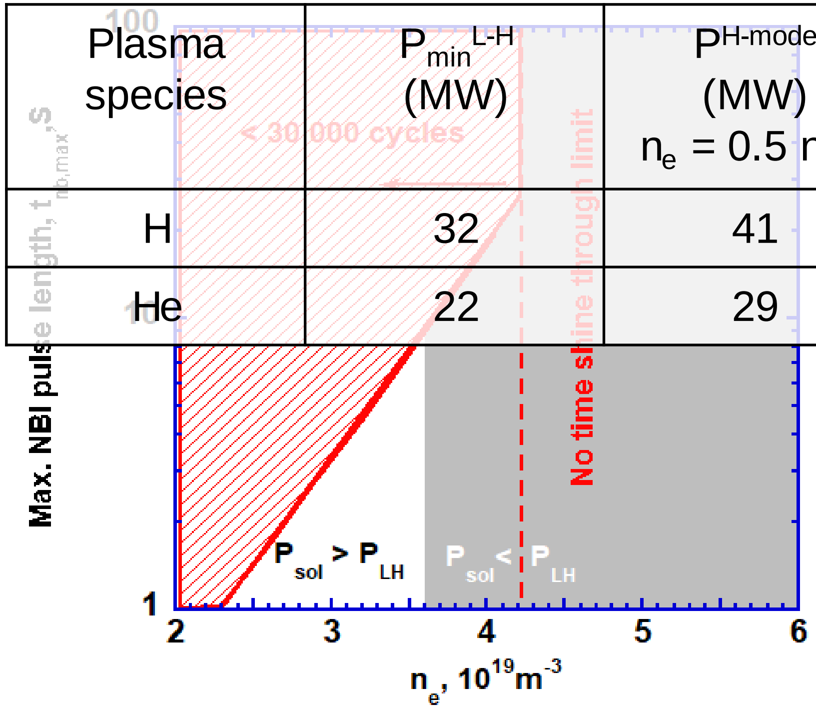

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