energie atomique • energies alternatives

ICOPS 2011 SOFE

Chicago, Illinois
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Tore Supra Status and Future Plans

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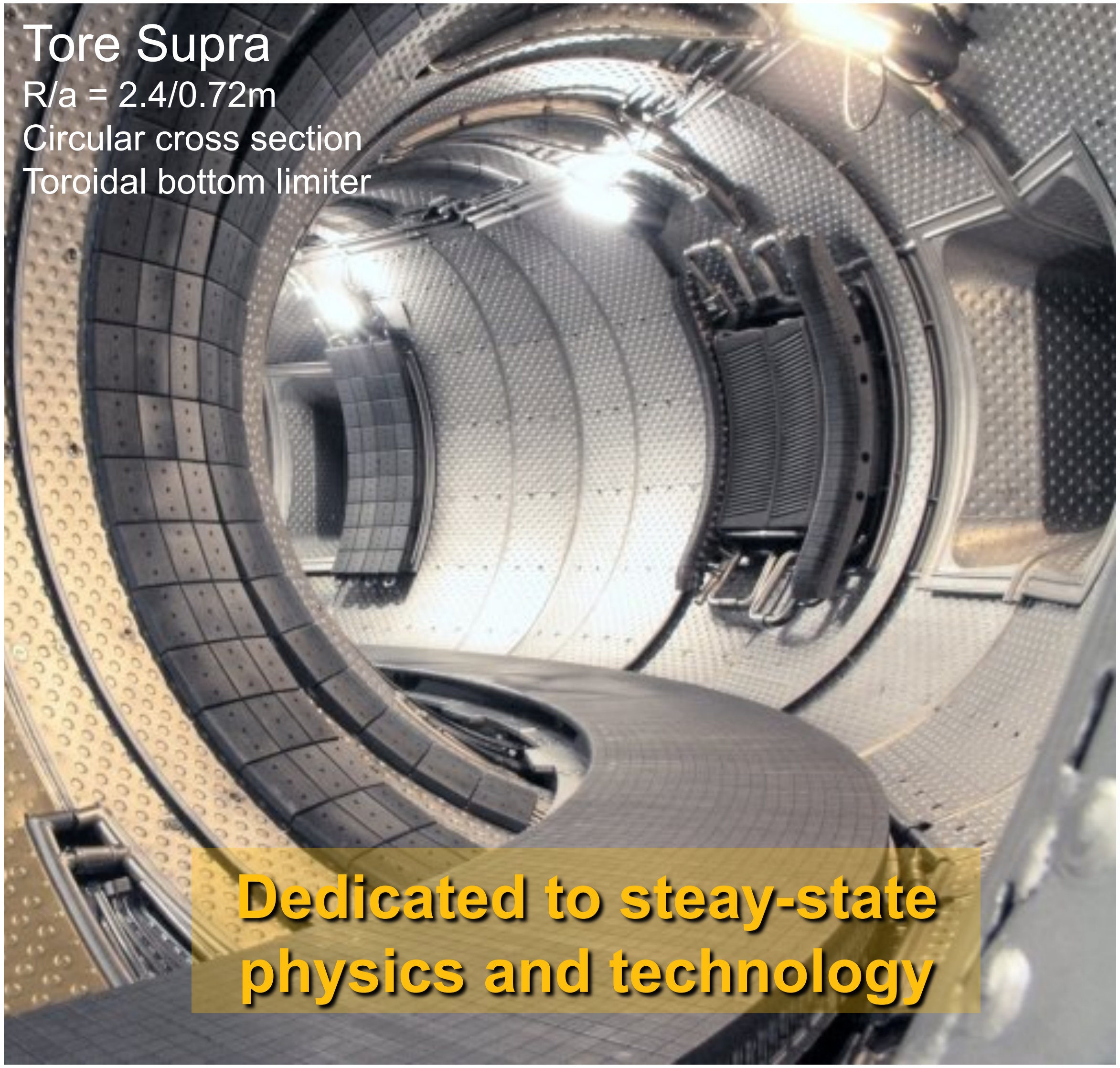
IRFM
TORE SUPRA

A tokamak fully equipped for Long Pulse Operation



- **Superconducting toroidal magnetic field: up to 4T**
- **High heat flux carbon plasma facing components: 10MW/m^2**
- **Actively cooled first wall (SS panels): up to 10MW extracted in steady-state**
- **Strong H&CD capability: 15MW of RF power**
- **Fully non inductive operation: 1GJ with ~400s steady state plasmas**
- **ITER relevant particle fluence within reduced time of operation**

Outline

- **Tore Supra Status**
  - New LHCD system for CW operation
  - ITER startup experiments
  - Disruption and runaway studies
  - Development of a generic multipurpose flight simulator
- **Tore Supra looking WEST for the second ITER divertor**
  - Motivations for the evolution of Tore Supra
  - Implementing a W Divertor into Tore Supra
  - Project schedule
- **Summary**

New LHCD system for CW operation

- Complete renewal of the power transmitter, including **16 new klystrons** TH2103C (Thalès Electron Devices)

L Delpech et al, RF conf. 2011

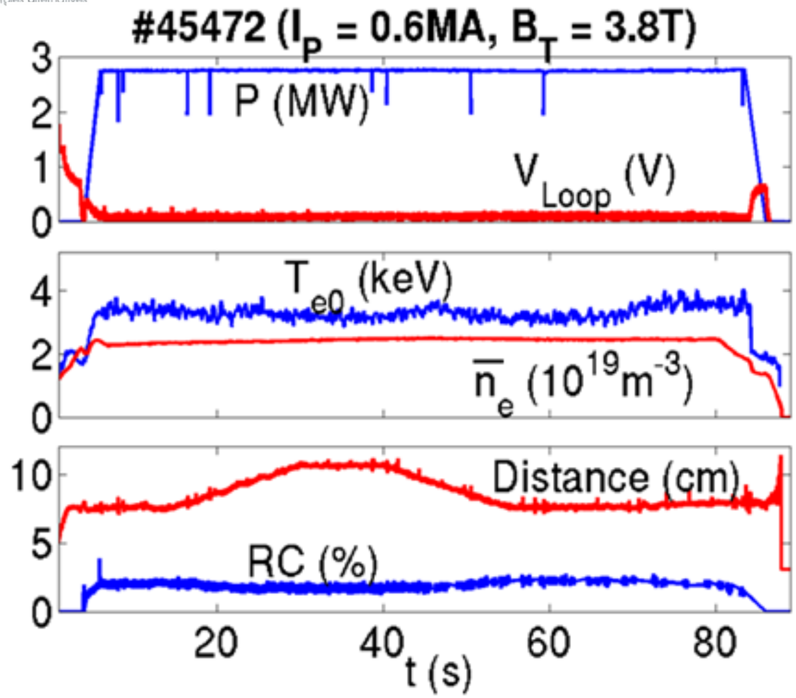
- ITER-relevant **PAM antenna** (Passive-Active Multijunction)
  - > The PAM is foreseen for ITER LHCD launcher

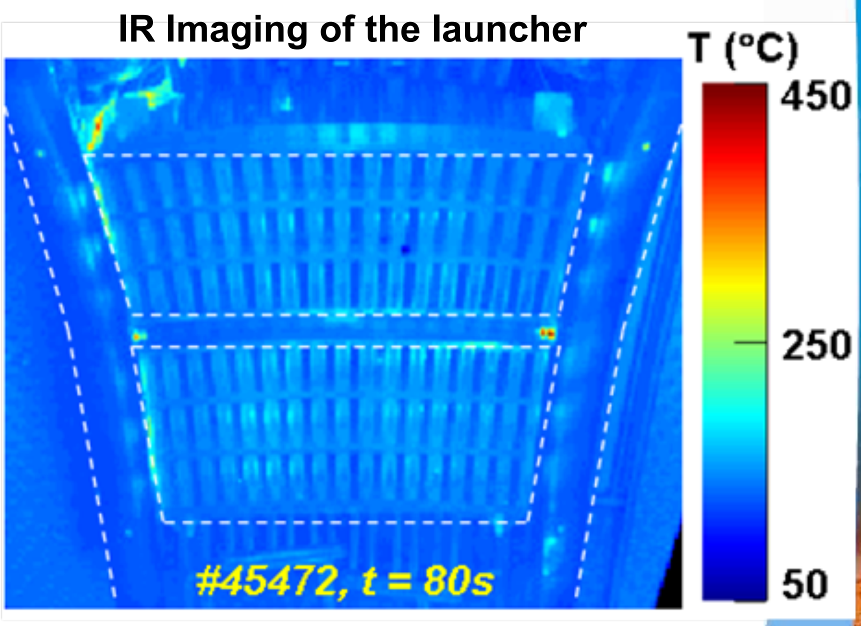
D Guilhem et al, FED 2011

- Extend domain of long pulse operation for Tore Supra: **higher density and plasma current**

ITER power relevant density achieved over long pulses

- **2.75MW (**25MW/m^2) coupled with PAM **for 78 seconds**



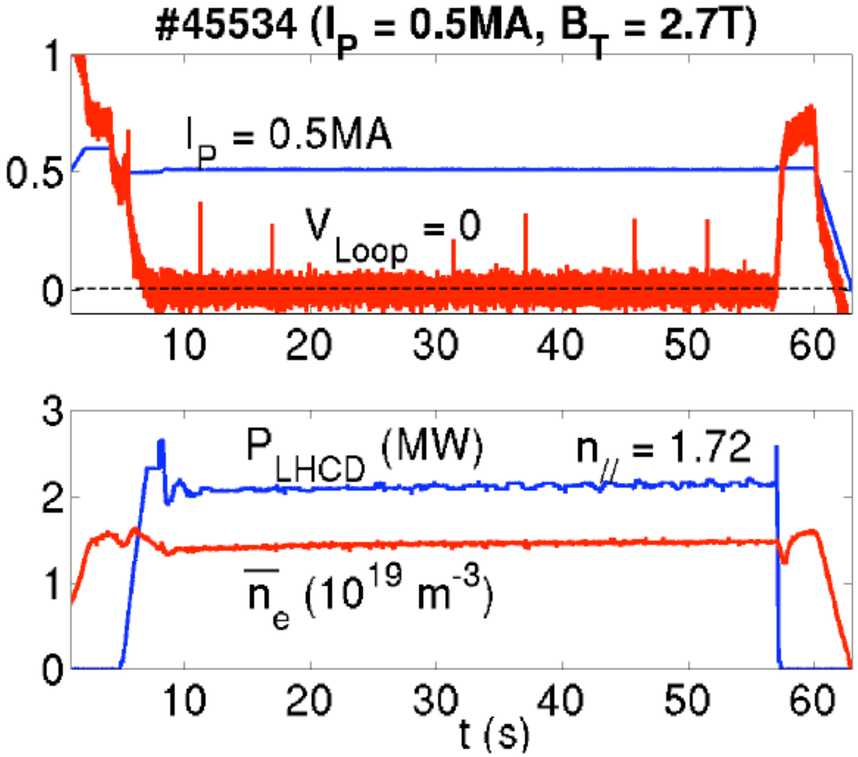


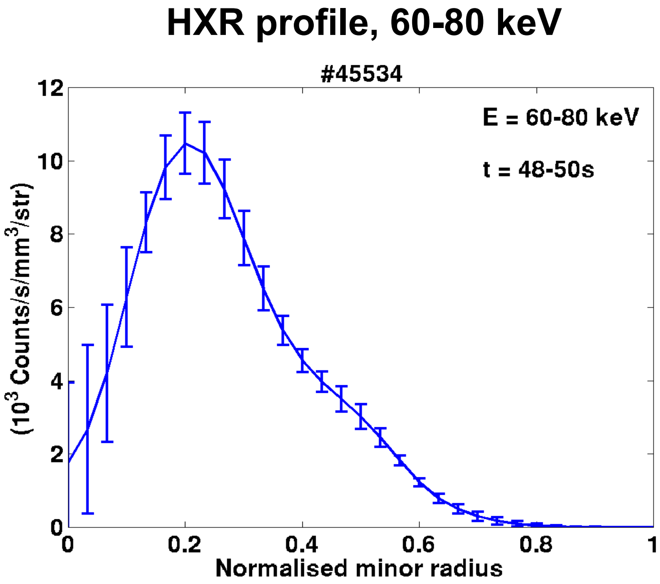
- **Low RC** at large plasma-launcher gap (n_e at launcher > n_{co})
- **Efficient cooling**: waveguides and side protections remain below 270°C
- High RF power density **25MW/m^2 scales to 33MW/m^2 for ITER 5GHz**

A Ekedahl et al, RF conf. 2011

Fully non inductive plasmas with the PAM launcher

- **Zero loop voltage** maintained **over 50s** with 2.2MW LHCD



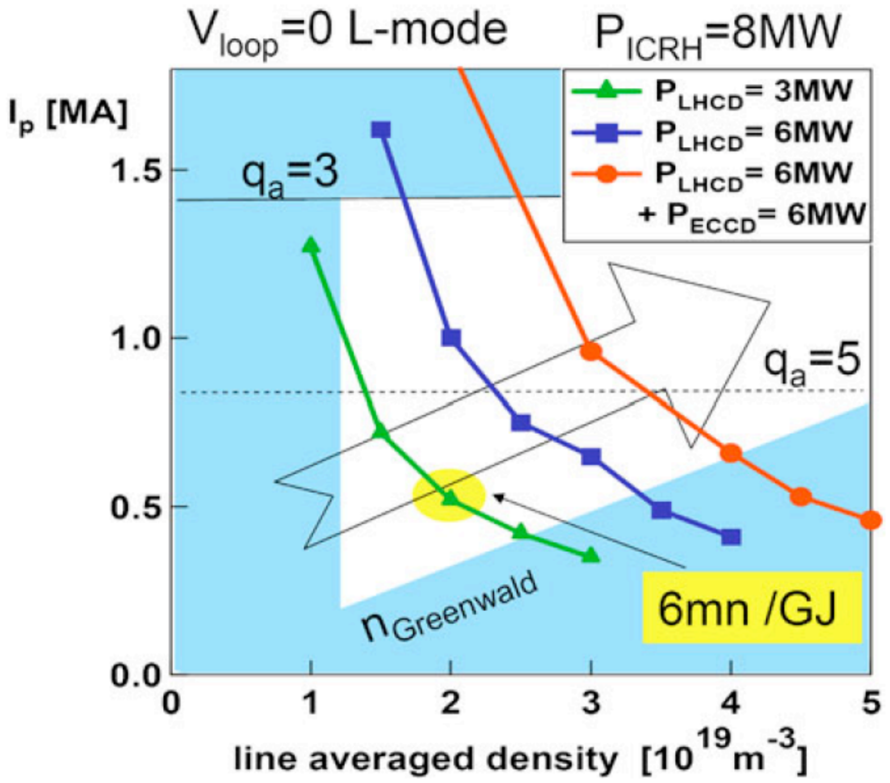


A Ekedahl et al, Nucl. Fusion **50** (2010)

- Double feedback control loops to maintain I_p constant and V_{loop}=0
- **CD efficiency: η_{LHCD} ~ 0.75x10^{19}A/W/m^2** (bootstrap current fraction ~10%)
- Similar to Full Active Multijunction antennas (cf GJ-discharges)

Extended domain of steady-state operation

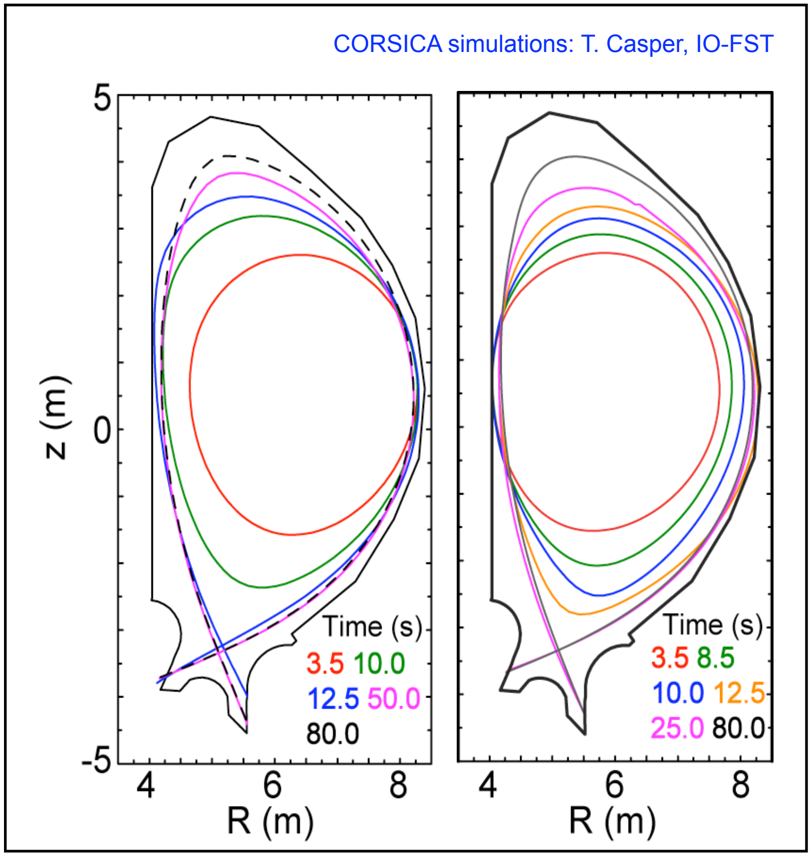
- Using both LHCD antennas together: **4.5MW/150s** readily obtained (650MJ injected energy)
- Opens new operation space (n_e, I_p) for **long pulse operation**



- **High energy with LHCD**
  - 5MW LHCD 400s
- **High energy with ICRH**
  - 4MW LHCD + 3MW ICRH 200s
- **High power discharges**
  - 6MW LHCD + 9MW ICRH 30s

ITER start-up experiments

- **The ITER blanket/first wall** will now be used **as a start-up and ramp-down limiter**
  - > Two original dedicated outboard start-up limiters eliminated, change accepted into the ITER Baseline during Configuration Control Board 047 on 10/05/2010

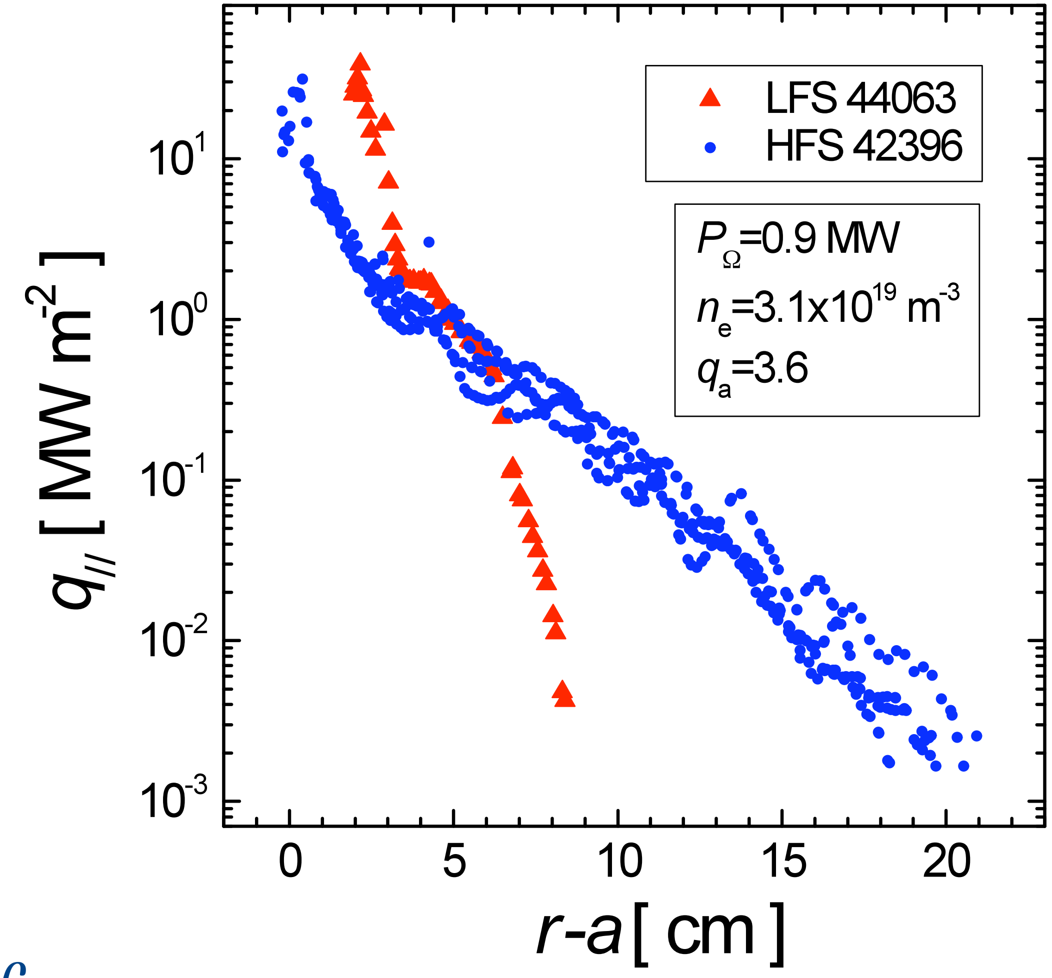

CORSICA simulations: T. Casper, IO-FST

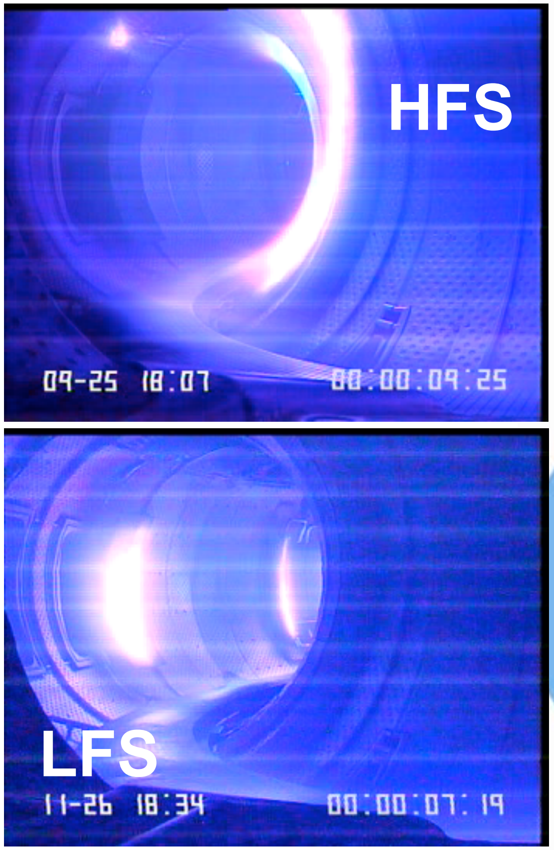
Tore Supra configuration well adapted to start-up studies

- **Six mobile outboard limiters:**
  - > 1 semi-inertially cooled limiter (CFC tiles bolted on Cu cooling channels)
  - > 5 RF antennas with actively cooled side protection tiles (CFC tiles brazed to Cu-Cr-Zr cooling channels → 20MW/m^2)
- **Six fixed inboard limiters:**
  - > CFC tiles bolted on Cu cooling channels

HFS contact results in broader λ_q and lower $q_{//}$

- **For identical core plasmas**, the probe can penetrate a few cm inside the LCFS for HFS contact, but cannot even reach it for LFS contact!

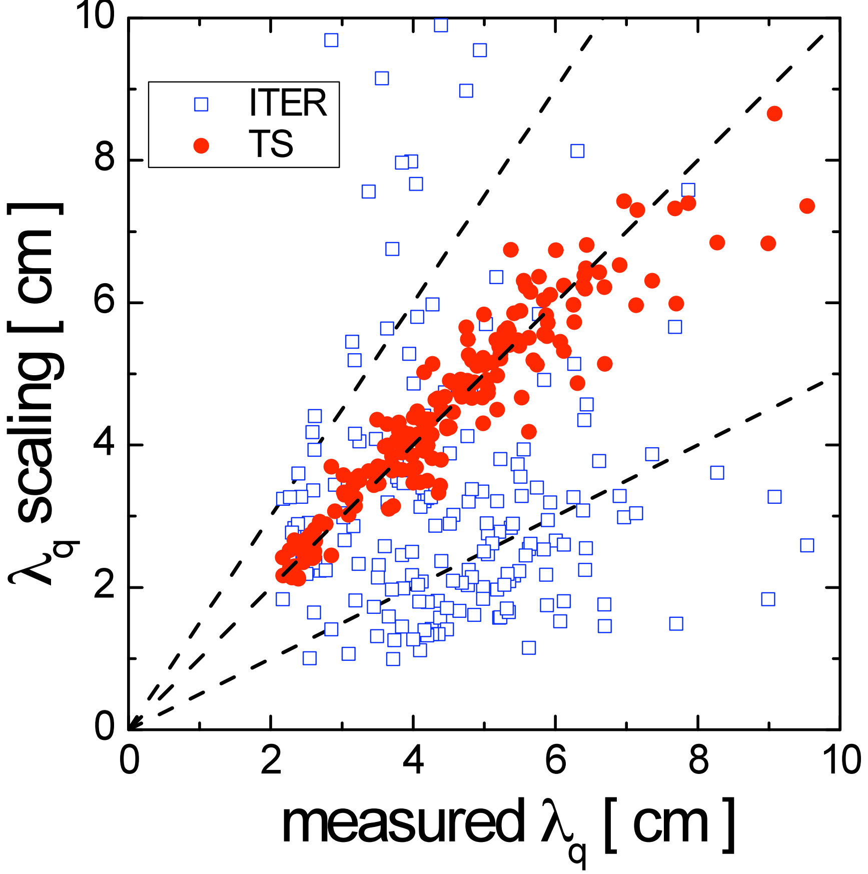




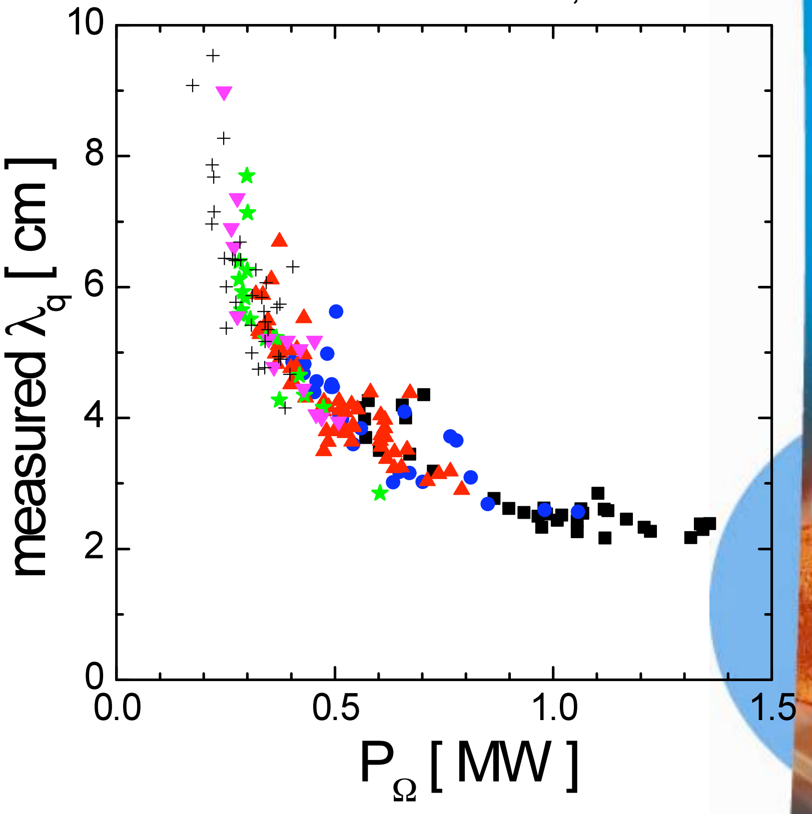
J. Gunn et al, ITPA 2011

Large scatter on ITER scaling law prediction

- Tore Supra measurements are **not well correlated with ITER scaling law**, but they do follow a clear empirical **dependency with ohmic power**



J. Gunn et al, ITPA 2011

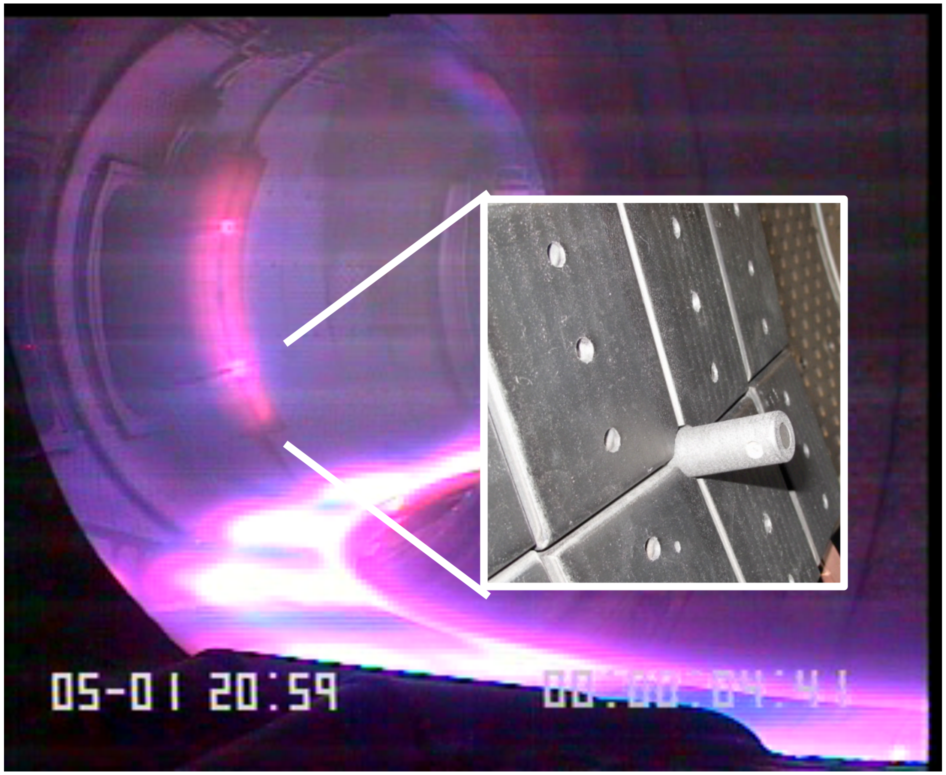


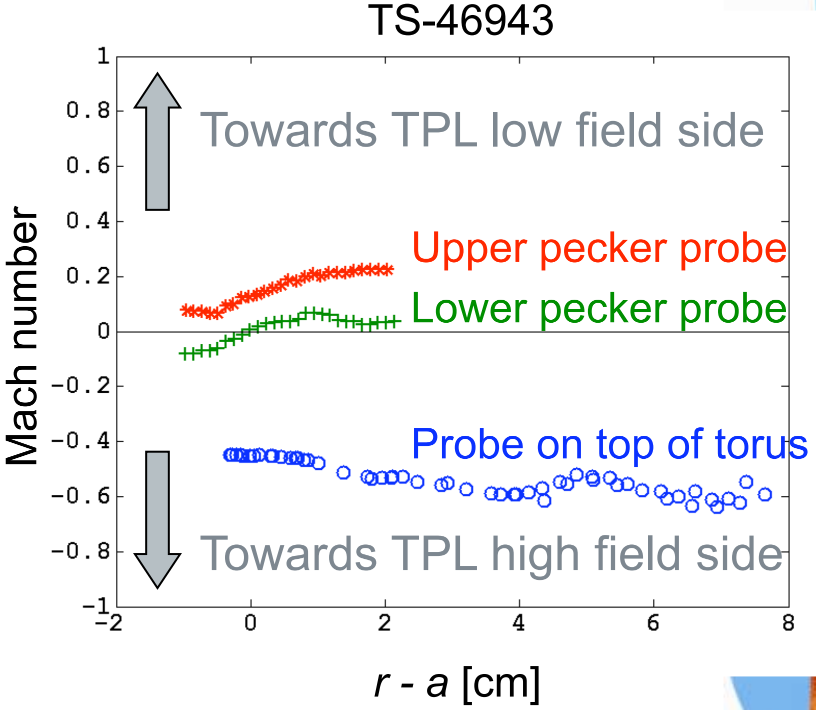
ITER : $\lambda_q = \left(1 \pm \frac{1}{3}\right) 3.6\times10^{-4} R^2 P_{SOL}^{-0.8} q_a^{0.5} n_e^{0.9} Z_{eff}^{0.6}$

TS : $\lambda_q = \left(1 \pm \frac{1}{10}\right) 0.025\, P_{\Omega}^{-0.7}$

New reciprocating probes installed in 2011

- Two magnetically driven reciprocating probes were installed on the **modular outboard limiter** during the winter 2011 shutdown



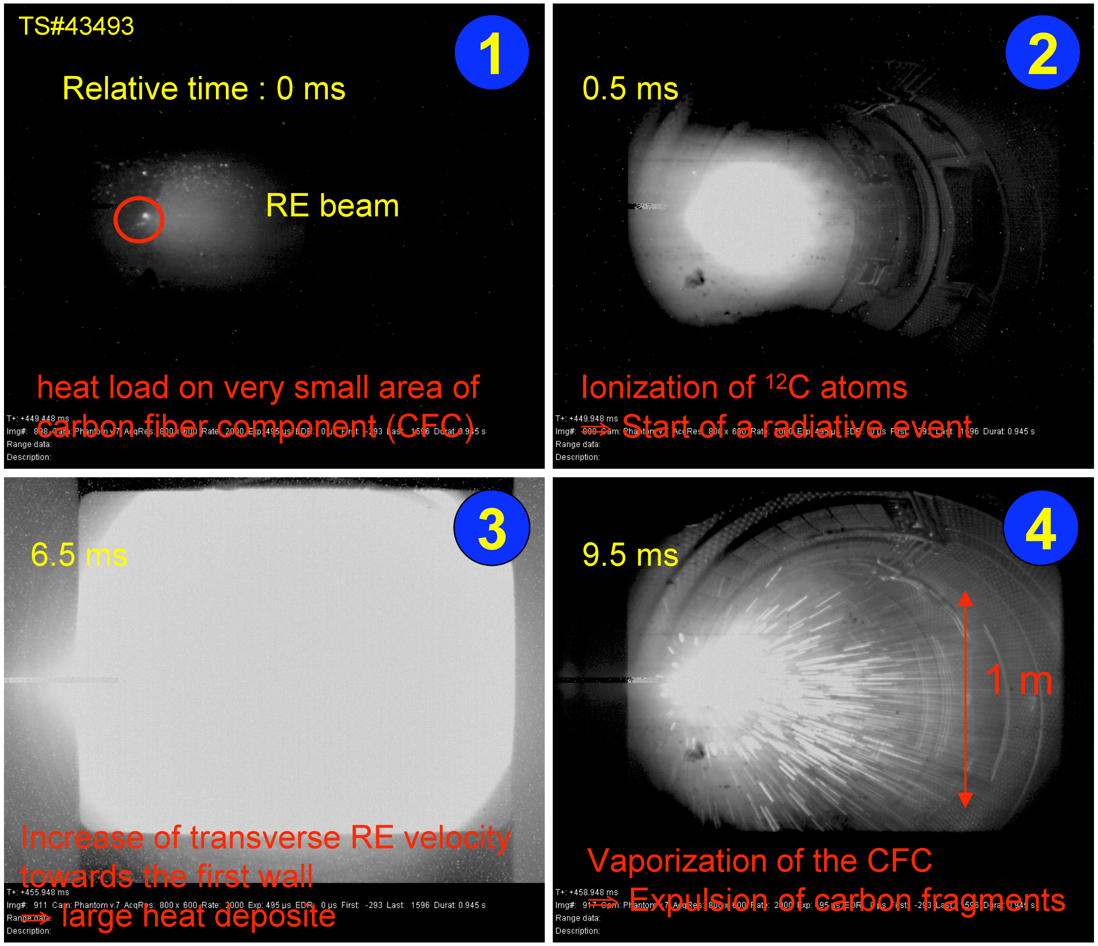


> Real time feedback control of the probe position has been successfully implemented (probe velocity controlled by coil current with 1 ms time resolution, position measured with respect to real LCFS position)

Disruptions and runaway studies

- On Tore Supra, **long lasting RE plateau (multi seconds!!!)** can develops following disruptions

60kA runaway electron beam striking CFC wall in Tore Supra



heat load on very small area of carbon fiber component (CFC)

Ionization of ^{12}C atoms
⇒ Start of a radiative event

Increase of transverse RE velocity towards the first wall
⇒ large heat deposite

Vaporization of the CFC
⇒ Expulsion of carbon fragments

> RE well confined

> Accelerated during current quench (CQ) up to relativistic energy (10-20MeV)

> Very small pitch angle

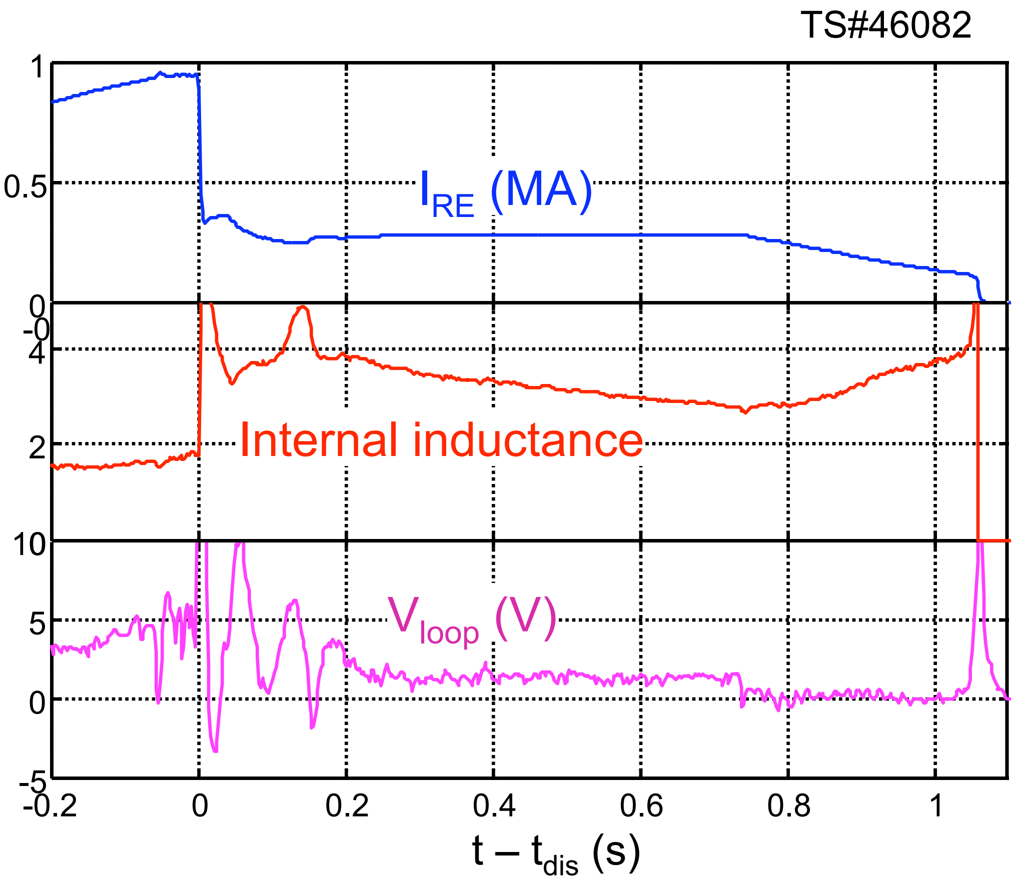
> RE loss on a small wall area

> huge energy density deposits (10MJ/m^2 ~ 1GW/m^2) and deep penetration inside the PFCs (few cm)

Control of the RE plateau regime

- Current carried by **relativistic electrons in the core of a cold plasma**

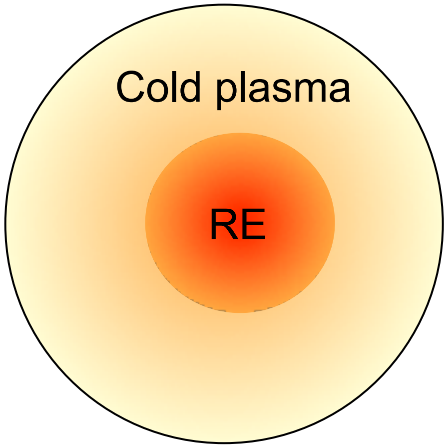
RE plateau with position & current control



> High resistivity (twice ohmic values)

> Large internal inductance (twice pre disruption values)
→ very peaked current profile

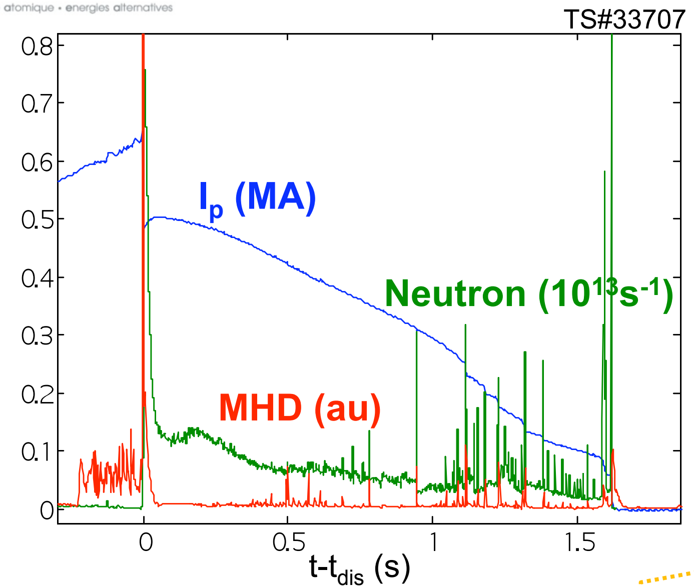
> Slow decrease of li on flattop
→ flattening of the current profile (collisions effect?)

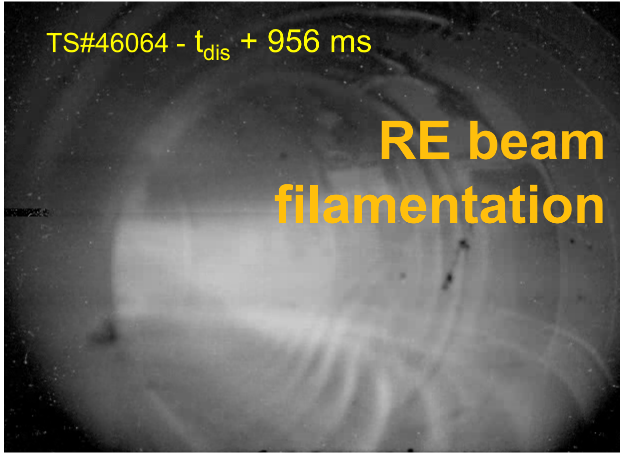


F Saint-Laurent et al, EPS 2011

Two types of events observed during RE plateau

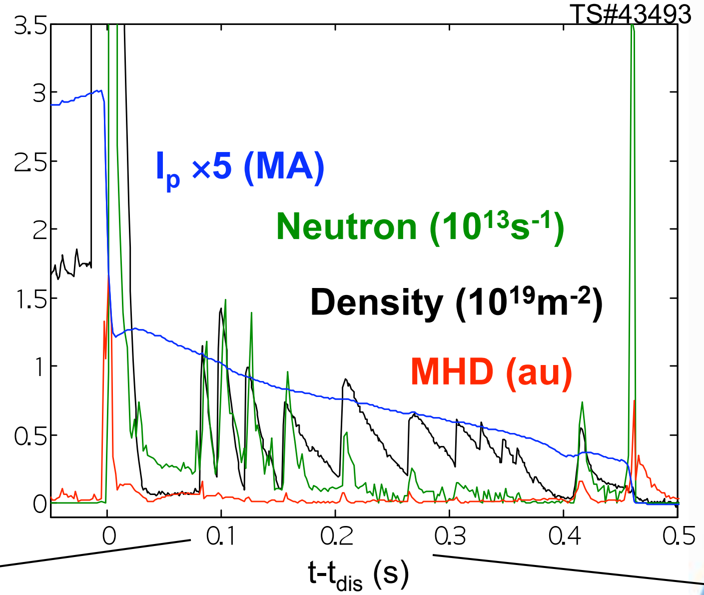
- **Direct losses** onto the wall associated with current drops

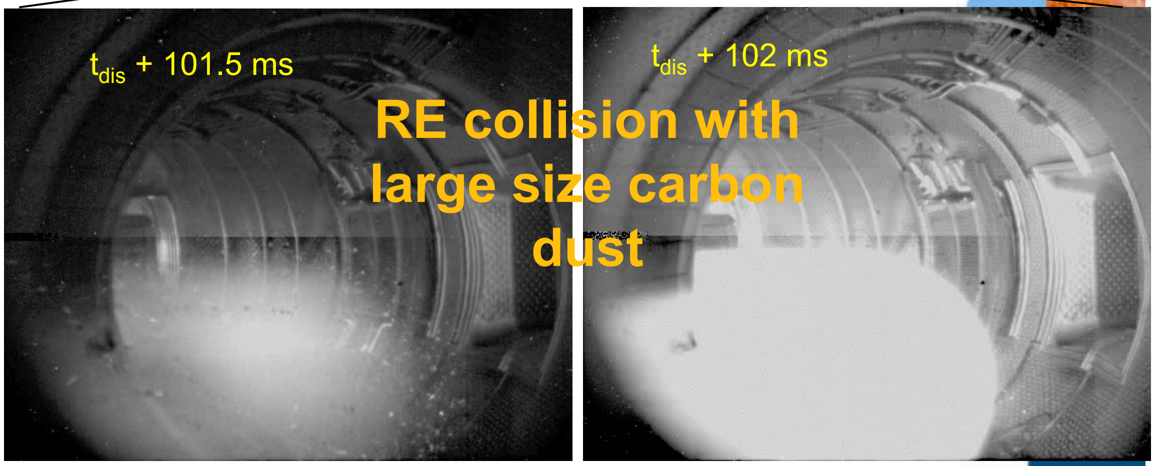




RE beam filamentation

- **Radiative events** ➔ key for RE heat load mitigation?





RE collision with large size carbon dust

New ultra fast gas injector installed in 2011

- **Rupture disk** based high pressure injector

> No delay between trigger and HT pulse
> HT pulse delivered in less than 300µs
> Gas delivered in less than 500µs
> Filling pressure 100-130bars

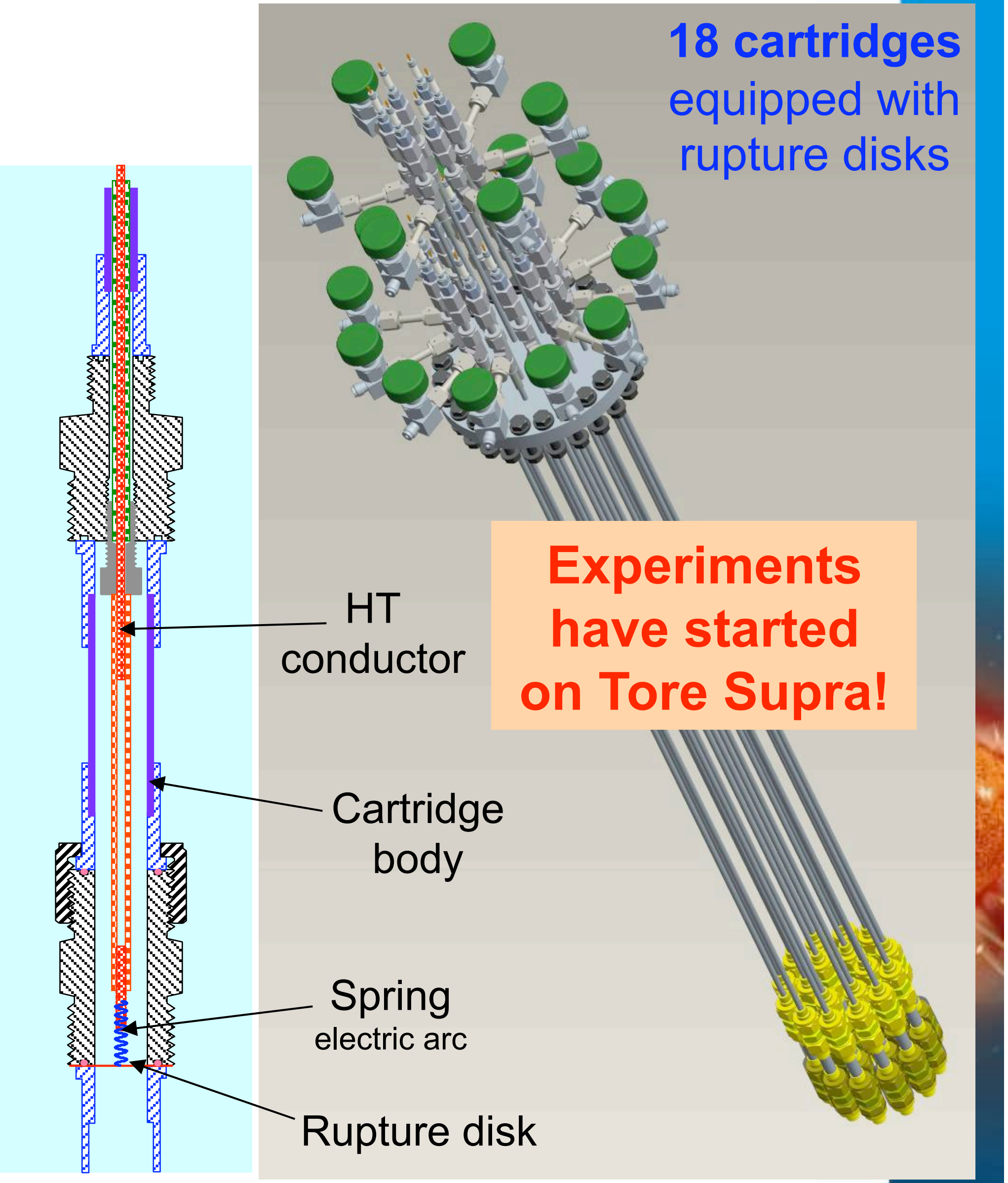
- Injections feasible **during the current quench**

- Expected effect: **spread RE onto the first wall** hindering beam formation

> Gas jet penetration up to q=2
> Destabilization of MHD equilibrium
> Ergodisation of field lines

Under ITER contract

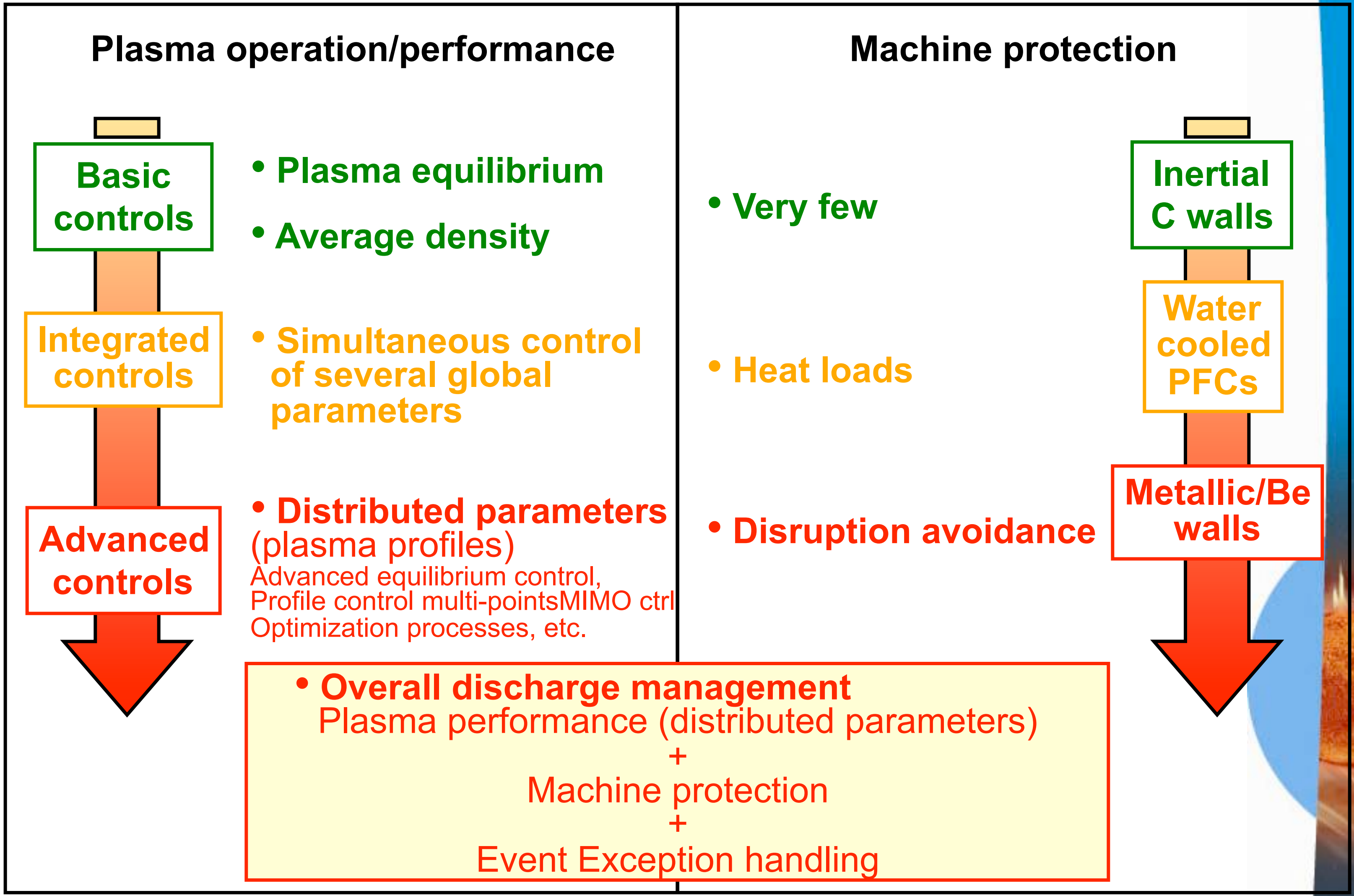
S. Putvinski et al, IAEA 2010



18 cartridges equipped with rupture disks

Experiments have started on Tore Supra!

A generic flight simulator for long pulse operation



Plasma operation/performance

Basic controls

- **Plasma equilibrium**
- **Average density**

Integrated controls

- **Simultaneous control of several global parameters**

Advanced controls

- **Distributed parameters** (plasma profiles)
  Advanced equilibrium control,
  Profile control multi-pointsMIMO ctrl
  Optimization processes, etc.

Machine protection

Inertial C walls

- **Very few**

Water cooled PFCs

- **Heat loads**

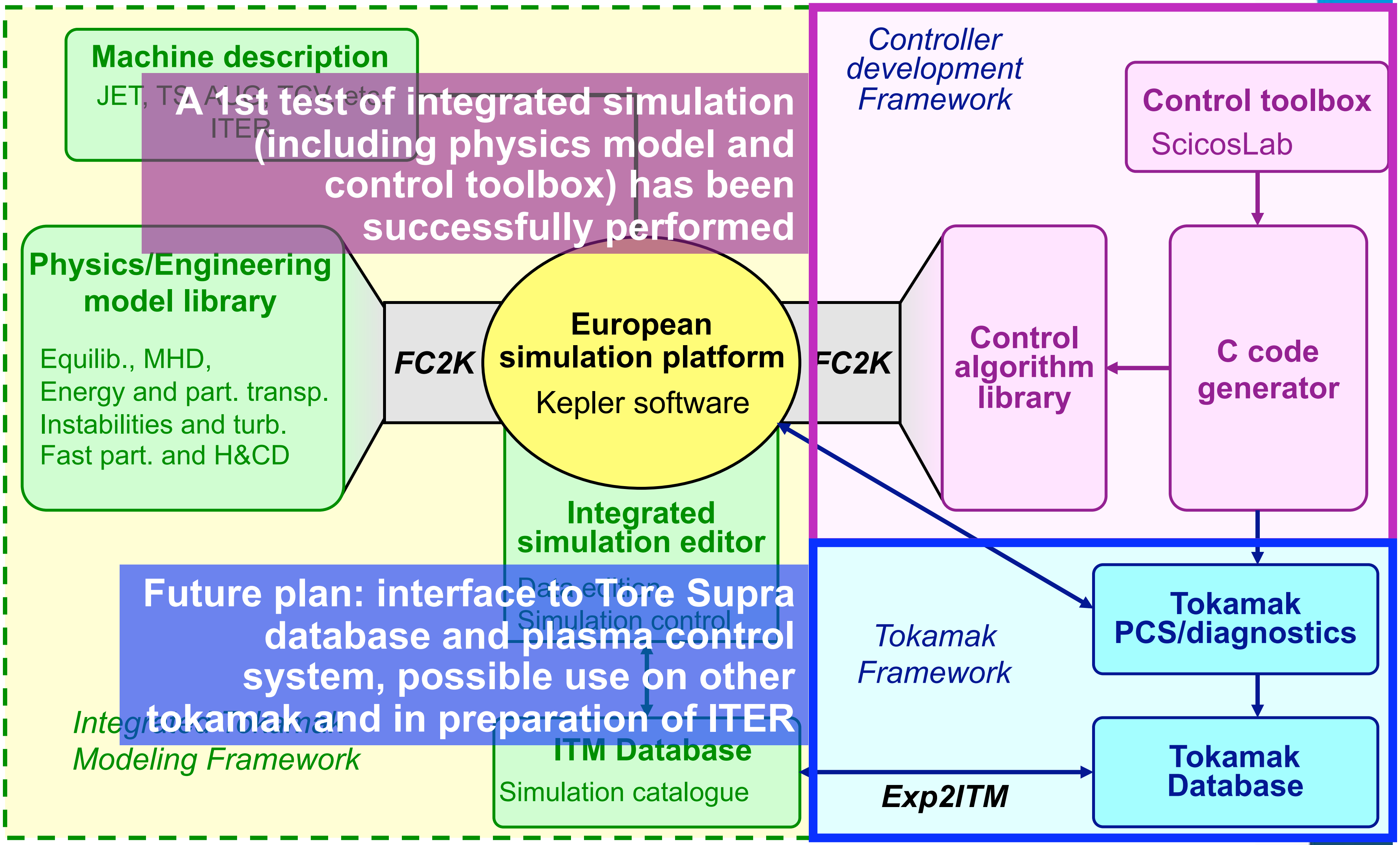
Metallic/Be walls

- **Disruption avoidance**

- **Overall discharge management**
  Plasma performance (distributed parameters)
  +
  Machine protection
  +
  Event Exception handling

Empirical methods not applicable for new tokamak challenges ➔
Tool needed to optimize tokamak operation

Interfacing with the European simulation platform



A 1st test of integrated simulation (including physics model and control toolbox) has been successfully performed

Future plan: interface to Tore Supra database and plasma control system, possible use on other tokamak and in preparation of ITER

P Moreau et al, SOFT 2010

Outline

- **Tore Supra Status**
  - > Installation of an ITER relevant LH antenna
  - > Experimental results with the new LH antenna
  - > ITER startup experiments
  - > Disruption and runaway studies
  - > Development of a generic multipurpose flight simulator
- **Tore Supra looking WEST for the second ITER divertor**
  - > Motivations for the evolution of Tore Supra
  - > Implementing a W Divertor into Tore Supra
  - > Project schedule
- **Summary**

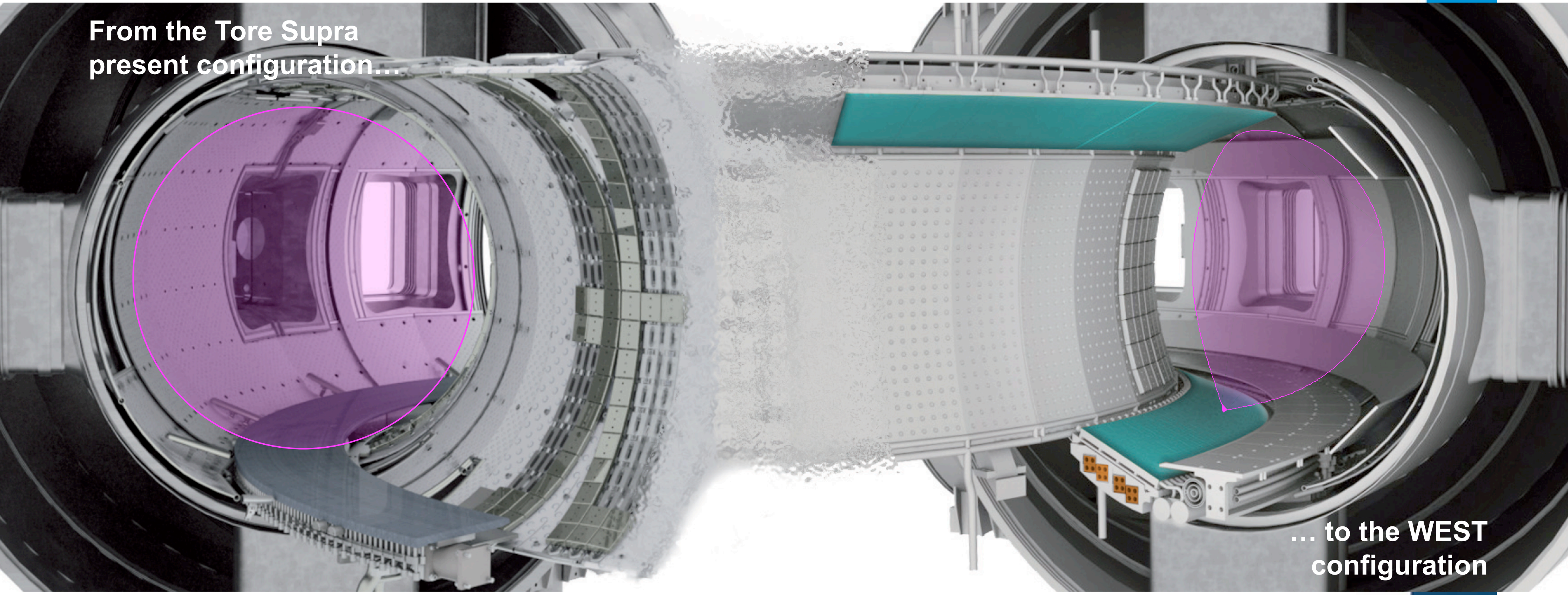
Motivations for the evolution of Tore Supra

- Following ITER recent decision to go to **full tungsten divertor** for its nuclear phase, it is proposed to use Tore Supra facility to **test ITER divertor technology in tokamak environment** in order to **reduce the risks for ITER**

Carbon	Tungsten	Challenges for tungsten components
Heat resistant, **sublimates**	Heat resistant, **melts**	Component integrity Impact on subsequent ITER operation
Full **technology industrial development** for 20 years	Recent technology development, **never tested in fusion devices**	Delay for ITER construction
Used in **most devices** (1980-2010) Basis for **ITER Physics and operation**	**Experience restricted** to ASDEX upgrade (progessive use from 1996 to now)	New physics and operation basis to consolidate
A **few %** plasma pollution acceptable	Plasma pollution acceptable **$<<10^{-4}$**	Plasma contamination impact on ITER fusion performance

Turning Tore Supra into a divertor configuration

- The WEST project: **W E**nvironment in **S**teady State **T**okamak
- The transformation from the present circular limiter geometry to the required X-point configuration will be achieved by installing a set of water cooled **copper poloidal coils inside the lower and upper parts of the vacuum vessel**

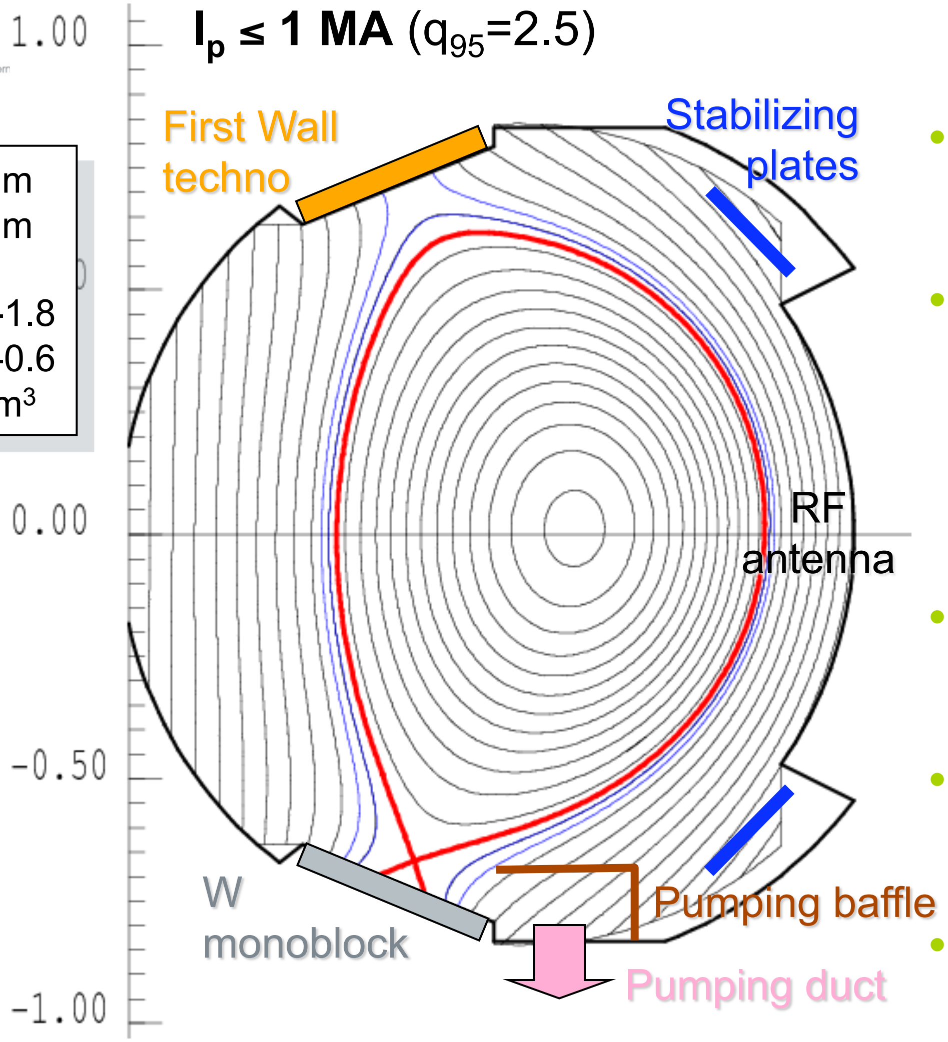


A new steady state divertor tokamak

$B_T = 3.7$ T

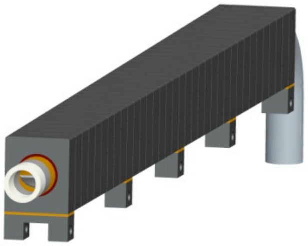
$I_p \leq 1$ MA (q_{95}=2.5)

R: 2.5 m
a: 0.5 m
A: 5-6
κ: 1.3-1.8
δ: 0.5-0.6
V_p: 15 m³



J Bucalossi et al, FED 2011

- Lower, upper, double x-point configurations
- Stabilizing plates for vertical control
- **ITER W monoblock at targets**

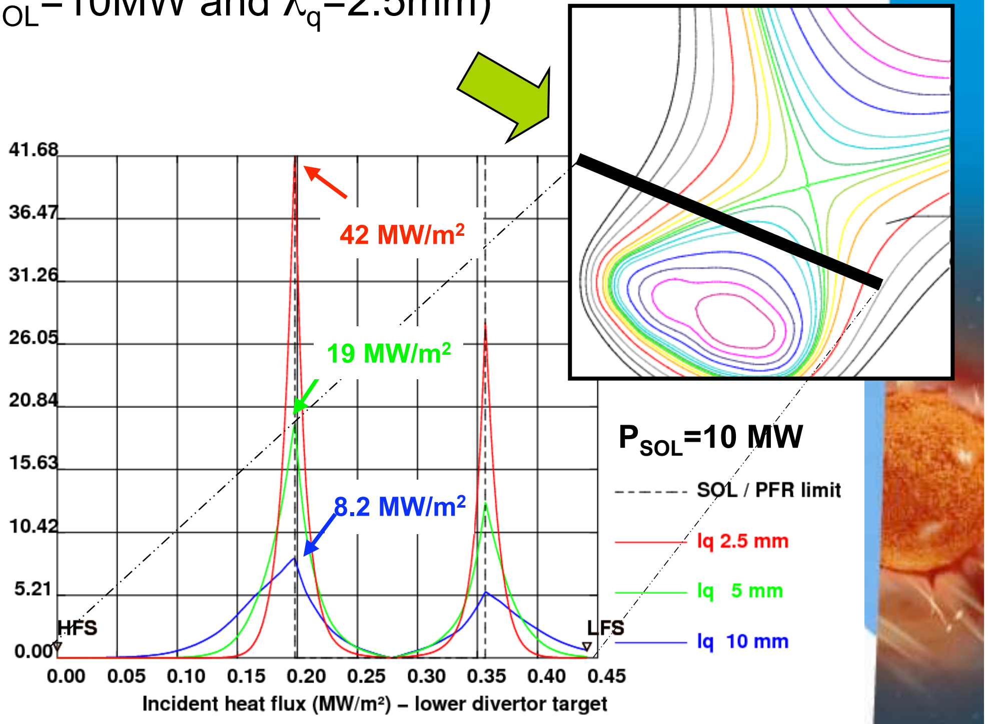


W monoblock design will be closely based on that currently envisaged for ITER

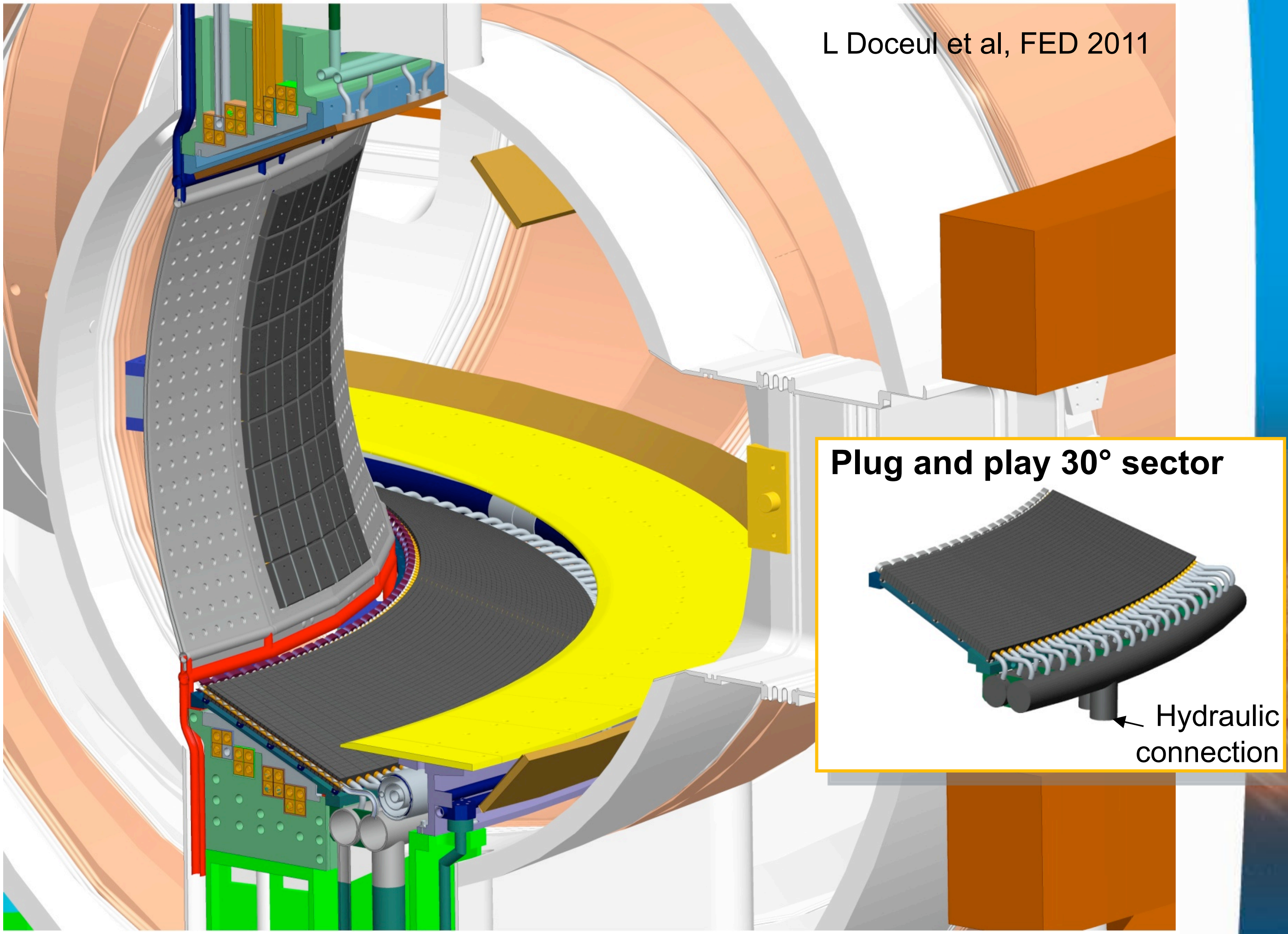
- ITER First Wall (W coated) at upper divertor targets
- Pumping baffle for plasma density control
- Divertor coils reference design for **steady-state operation at Ip ≤ 0.8 MA**

With relevant steady-state heat fluxes

- **LHCD** (10MW) **7MW-1000s** (CIMES project)
- **ICRH** (12MW) **9MW-40s/6MW-60s, ELM compatibility** (3dB couplers), **3MW-1000s**
- **Heat flux controlled by the X-point height** (flux expansion)
  - From **7 to 40 MW/m^2** (for P_{SOL}=10MW and λ_q=2.5mm)
- **W compatibility**
  - Cf. AUG experiments
  - SOLPS/DIVIMP
  - ICRH central heating
- **Type I ELMy H mode**
  - $P_{L-H} \leq 5$ MW
  - $W_{ELM} \leq 50$kJ
- **PFC survey**
  - T_{surf} monitoring (IR)
  - Erosion (W spectroscopy)
  - Visual inspection (AIA robot)



Divertor modular design for easier PFC testing



L Doceul et al, FED 2011

Plug and play 30° sector

WEST plasma scenarios for PFC testing

- The WEST configuration will provide the capability to run **long pulses in the high confinement regime (H mode)** foreseen for ITER, and **test plasma facing components under realistic plasma conditions**

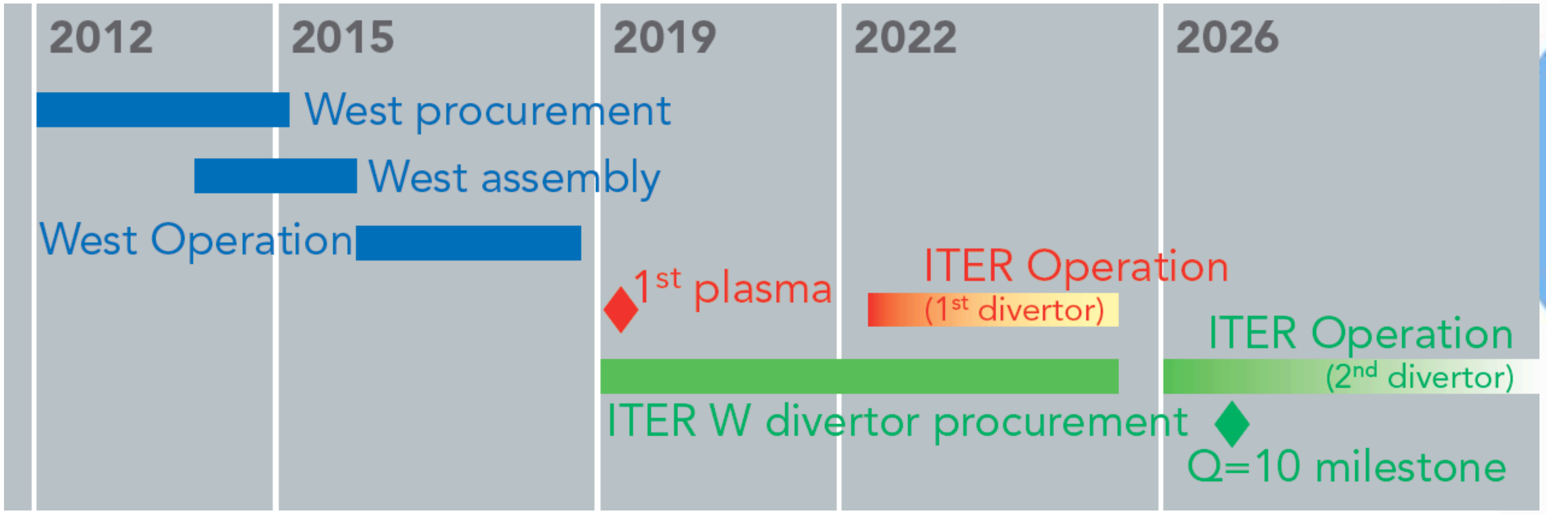
SCENARIO	HIGH POWER	STANDARD	HIGH FLUENCE
Plasma current	**0.8 MA**	**0.6 MA**	**0.5 MA**
Toroidal magnetic field	3.7 T	3.7 T	3.7 T
Plasma density	$9\ 10^{19} m^{-3}$	$6\ 10^{19} m^{-3}$	$4\ 10^{19} m^{-3}$
Total radiofrequency heating power	**15 MW**	**12 MW**	**10 MW**
Lower Hybrid Current Drive	6 MW	6 MW	7 MW
Ion Cyclotron Resonance Heating	9 MW	6 MW	3 MW
Plasma current flat-top duration	**30 s**	**60 s**	**1000 s**
Expected heat load*	**6 MW/m²**	**11 MW/m²**	**15 MW/m²**
Expected ELM energy	51 kJ	32 kJ	26 kJ
Expected ELM frequency	59 Hz	76 Hz	77 Hz
Expected ELM load	40 kJ/m²	52 kJ/m²	74 kJ/m²
Expected operation time to reach one ITER pulse particle fluence	**~6 months**	**~2 months**	**~few days**

*Assuming λ_q = 5 mm

Bringing answer in time for ITER

- The WEST project would **deliver critical information** on:
  *"1) manufacturing failure modes, 2) repairing processes, 3) acceptance criteria, 4) leading edge issues, 5) operation with solidified tungsten melted surfaces, 6) behaviour of cracks under combined thermal and electromagnetic loads, 7) relevant diagnostics for tungsten armoured actively cooled components, etc."**

- Operation of Tore Supra in the WEST configuration can start **about 5 years** after launching the preliminary design activities ~ foreseen minimum time required for the detailed design and **manufacturing of actively cooled W PFC**



*Assessment by an international panel of experts including IO members (December 2011)

Summary

- **Tore Supra is currently addressing some crucial issues for ITER operation:**
    - ITER relevant LHCD antenna concept validated
    - LHCD upgrade will extend domain of steady state operation
    - ITER startup experiments raised issues on heat loads prediction
    - Progress on runaway electrons characterization and control
    - New tools in development to optimize long pulse operation

- **With the WEST project proposal and the implementation of an actively cooled tungsten divertor, Tore Supra will offer the key capability to test ITER HHF PFC technology in real plasma conditions**

- **And thus bring answers in a timely manner for the 2nd divertor foreseen for the nuclear phase of ITER (in complement to JET and ASDEX Upgrade W programmes)**

Preliminary design activities have been launched and ***international partners are invited to participate to the project and scientific exploitation***

ANNEXE

WEST structure and casing

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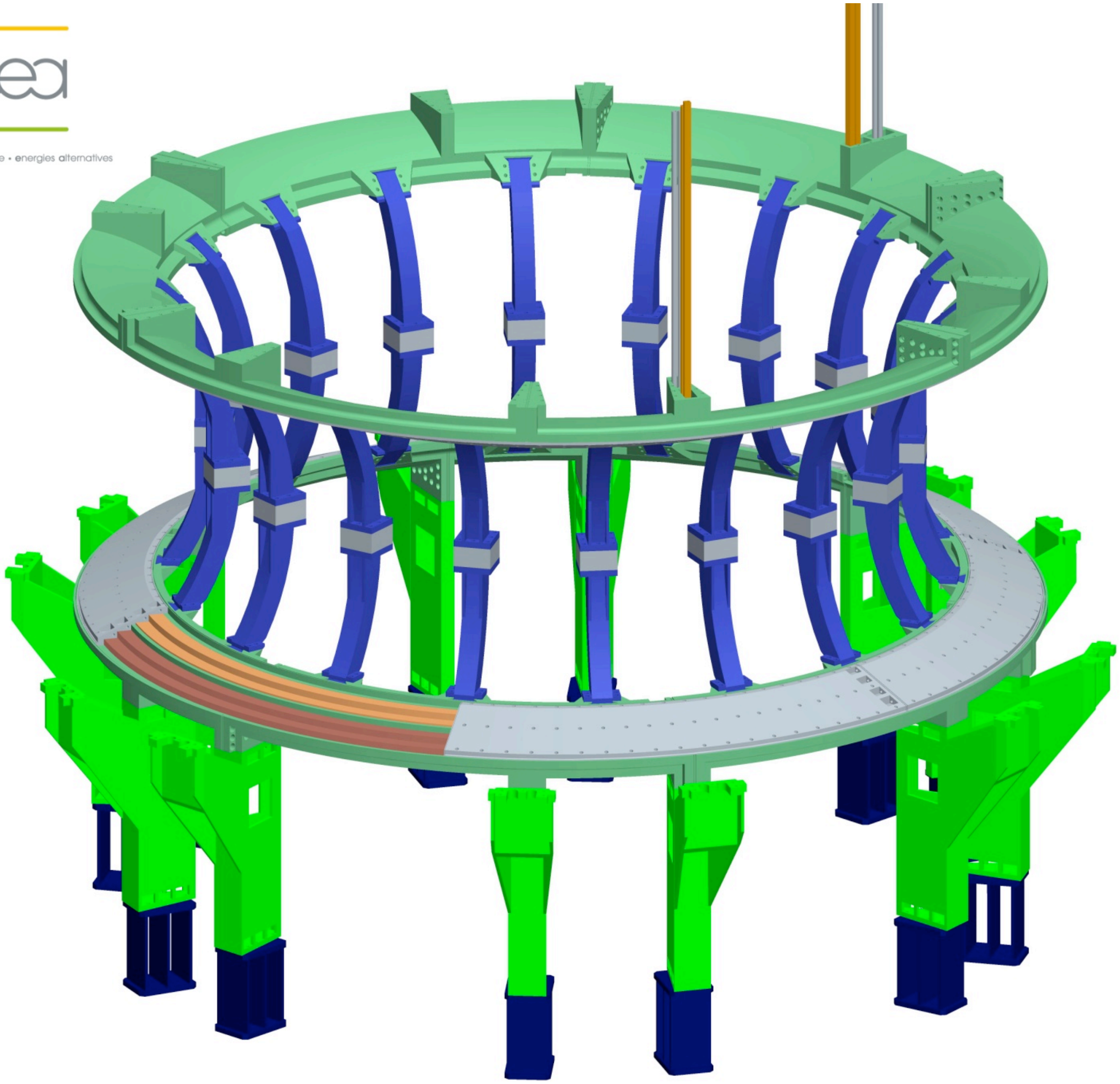

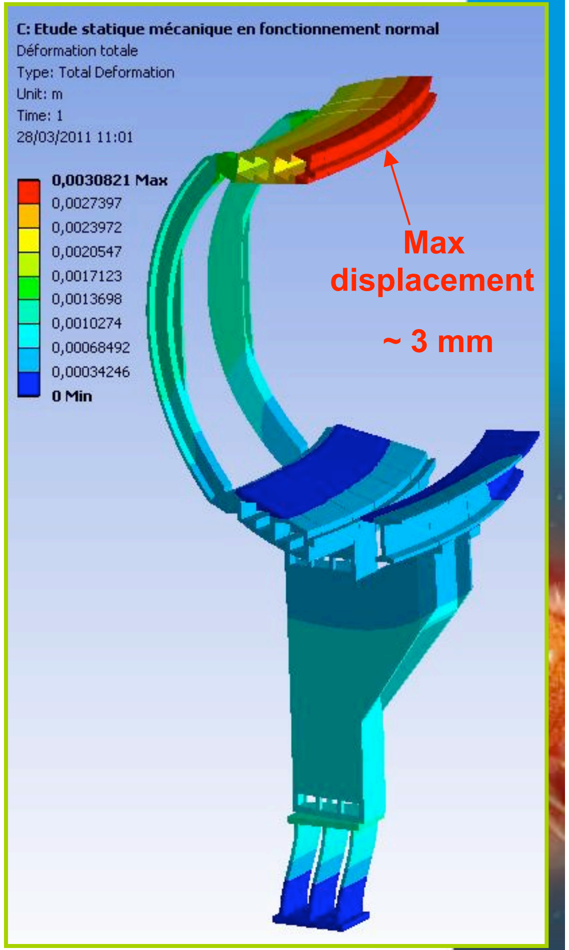

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Type: Total Deformation
Unit: m
Time: 1
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0,0023972
0,0020547
0,0017123
0,0013698
0,0010274
0,00068492
0,00034246
0 Min

Max displacement

~ 3 mm

WEST steady state scenario

- **LHCD @ mid-radius**
- Steady-state wide q-profile reversal
- P_{ICRH} = 9 MW (sensitivity: a minimum of 6 MW is required)
- P_{LH} = 3.7 MW → margin remains on P_{LH}
- 85 % electron heating; $\eta_{LH} = 1.1\ 10^{19}$ A/W/m^2
- **100% non-inductive, 40 % bootstrap** and 60 % LHCD; $\beta_N \sim 1.7$; $\beta_P \sim 3$; $\rho^* = 4.10^{-3}$
- **Very similar q-profile and LH deposition as foreseen for ITER steady-state scenario**

Typical ray trajectory (only 1 ray shown)