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TORE SUPRA : 2011

X LITAUDON on behalf of TORE SUPRA TEAM

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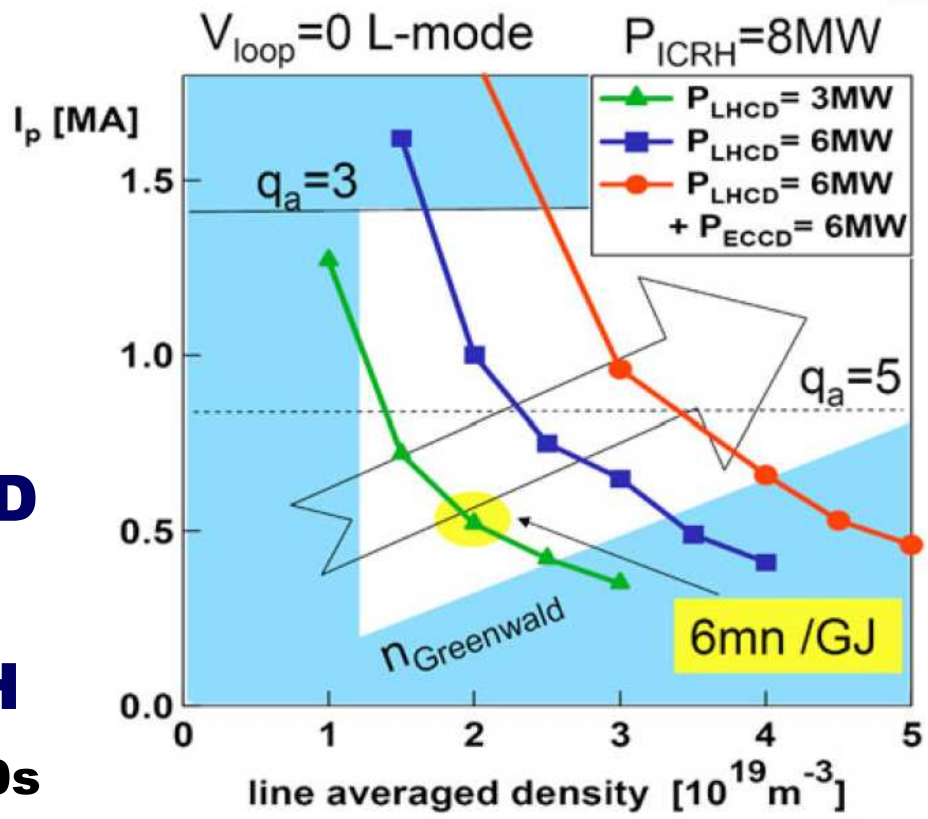
2011 Experimental Campaign

- **21 April up to end July 2011**
- **Overall Coordination**
  - Experiments & physics programme B. Saoutic & Y. Corre
  - Technical coordination M. Houry
- **Three Task forces**
  - Qualification of new CW LHCD system (ITER launcher and transmitter): A. Ekedahl
  - Development of long pulse scenario : R. Dumont
  - ITER operation preparation: S. Bremond

Scenario development: extended domain of steady-state operation

2011 Scenario Development:

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



+ Physics thrusts on MHD, transport, rotation

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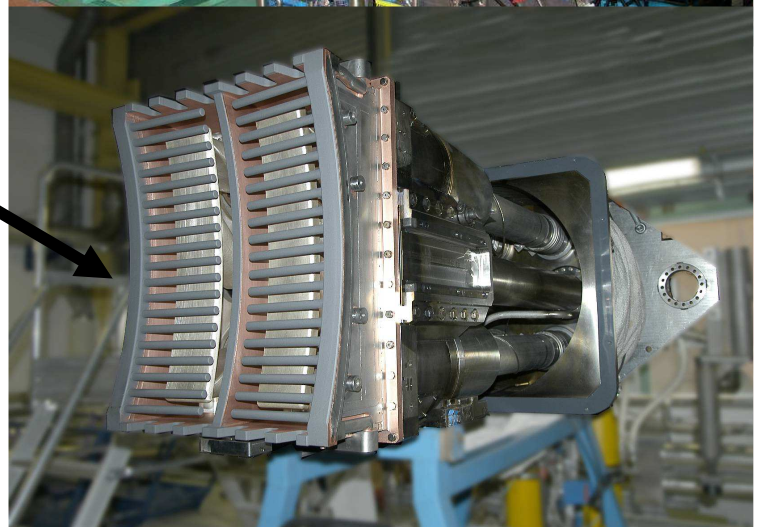
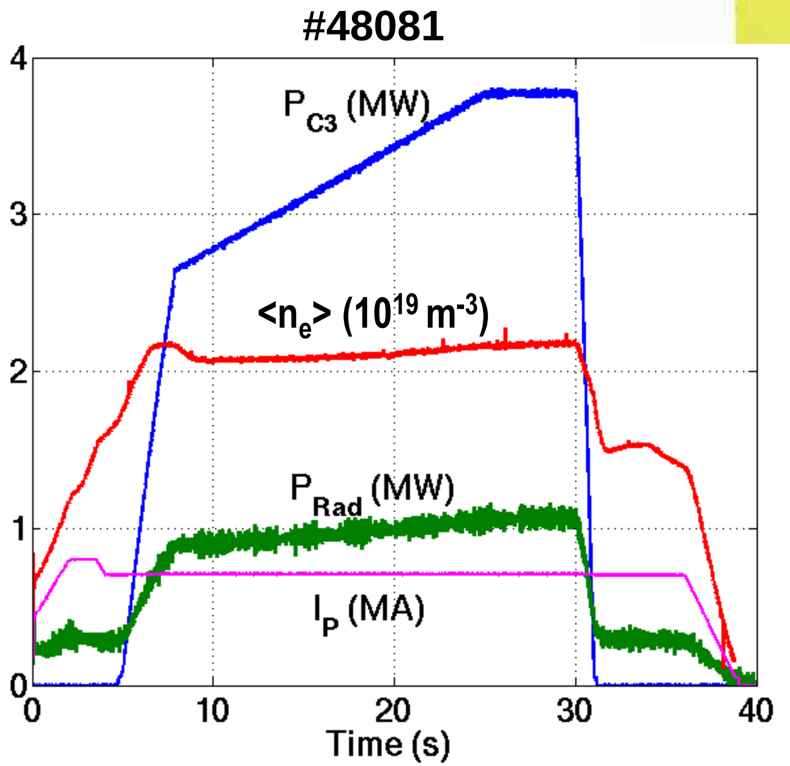
- **LHCD: Recent large upgrade**
  - 2009: Installation of PAM launcher
  - 2010-11: 8 new klystrons on FAM
- **ICRH:**
  - up to 9MW during 30 s (3 antennae)
  - or 3MW long pulse
  - New Faraday screen (one antenna)
- **ECRH:**
  - 700kW during 5s
- **IR monitoring:**
  - for RF operation & to protect fully actively cooled tokamak
- **Upgrade diagnostics**
  - Reflectometry



New CW klystrons validated on plasma operation

Coupled power: 3.8MW (> 4.0MW at klystrons) with Full Active Multi-junction launcher (FAM), fed by a set of eight 700 kW/3.7GHz CW klystrons.

TH2013C: 700kW CW on matched load

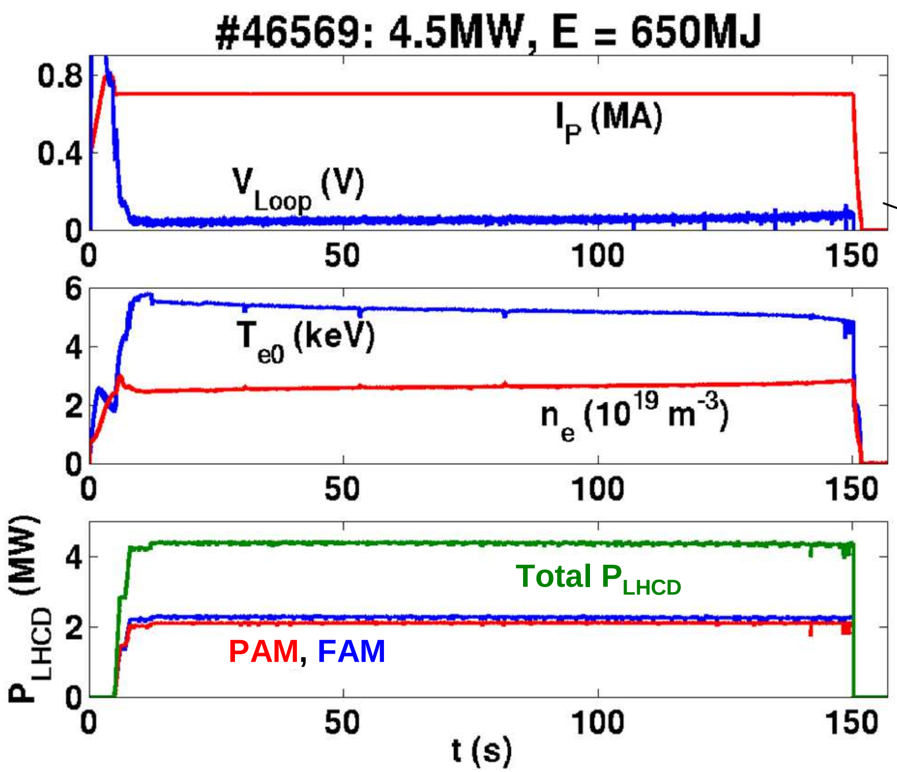


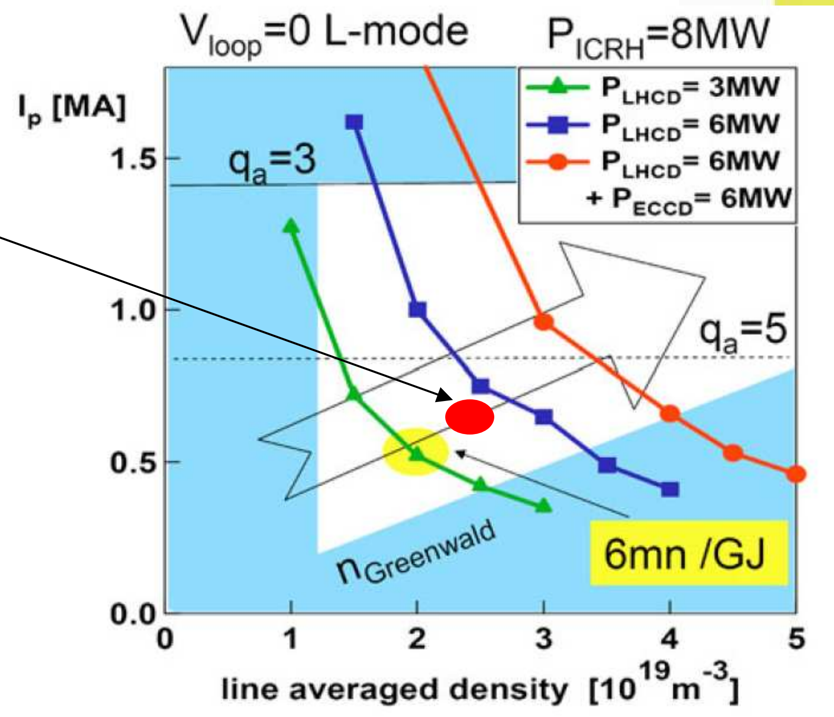
L. Delpech et al., 19th RF Conf., Newport (2011)
G. Berger-by et al., 19th RF Conf., Newport (2011)

Long pulse operation with both LHCD launchers

Both LHCD launchers together ➔ 4.5MW/150s obtained (650MJ injected energy)

Opens new operational space (n_e, I_P) for long pulse operation





Slow increase in density due to non-optimised feedback control

A. Ekedahl et al., 19th RF Conf., Newport (2011)

Control improvements for long pulse operation: transition to feedback controlled loop voltage

Issue: jump in Lower Hybrid power during transition from Ip control to (V_{G0}, P_{LH}) <-> (I_p, V_{loop}) control

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Development : Multi Input Multi Output feedback control

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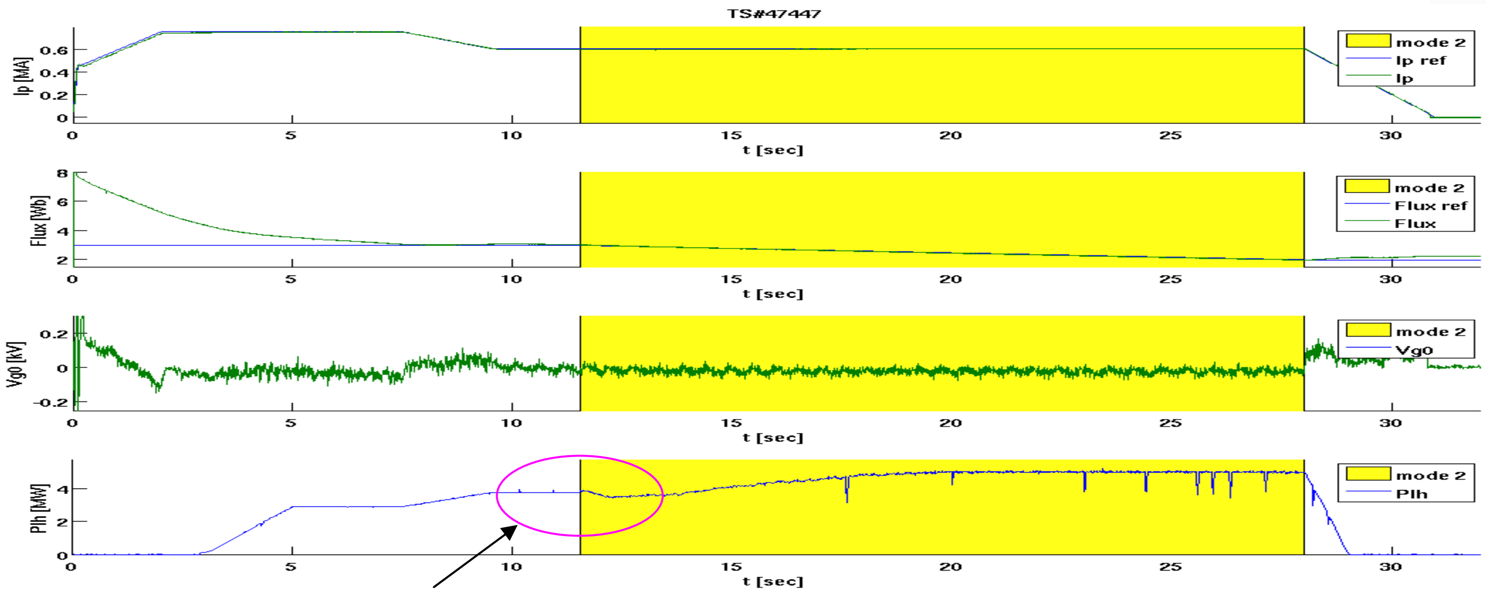
Control oriented model development, feedback control design and test on simplified model and on METIS code, experimental validation

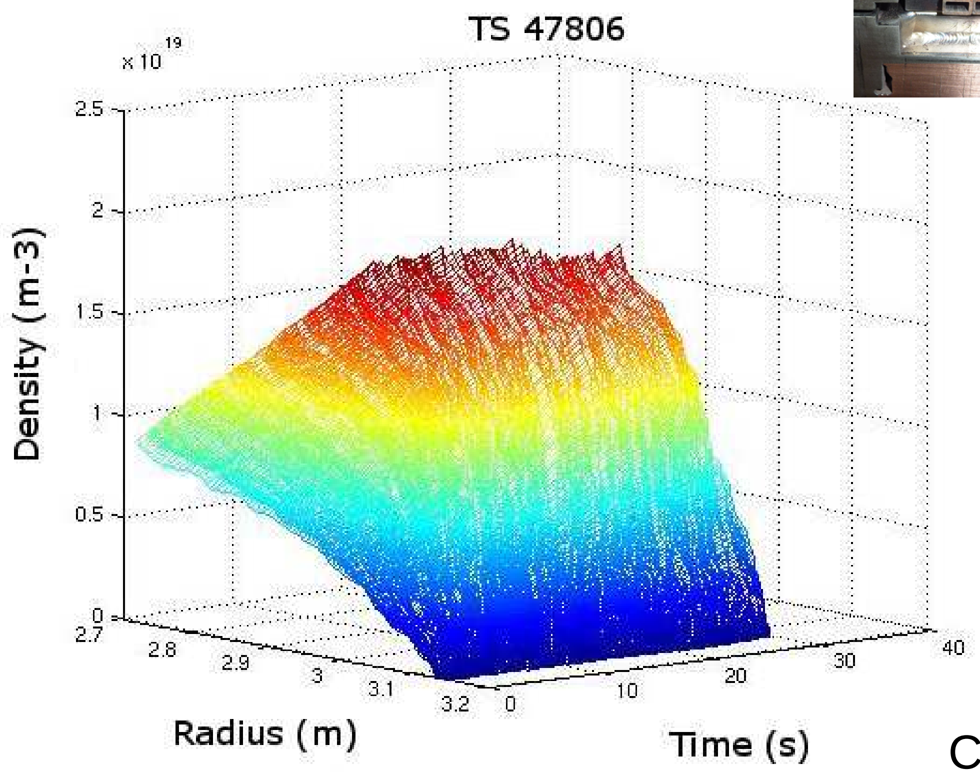


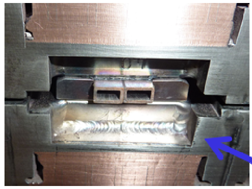
Ph Moreau

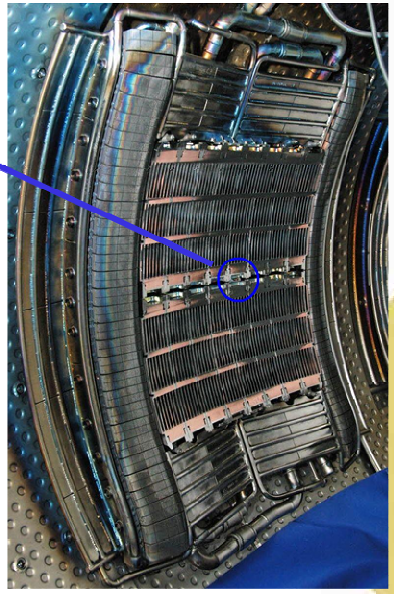
New MIMO control now in routine operation

Measurements of Density Profile in the Scrape-off-Layer with Reflectometer Embedded in the LHCD Full Active Multijunction Antenna

- Crucial to study LH coupling and SOL physics
- Strong increase of density gradient in the SOL during LHCD



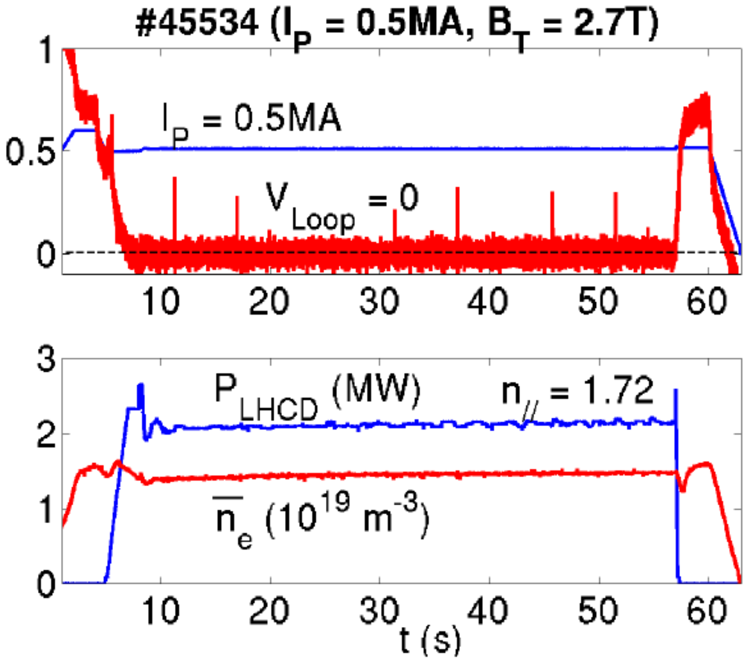


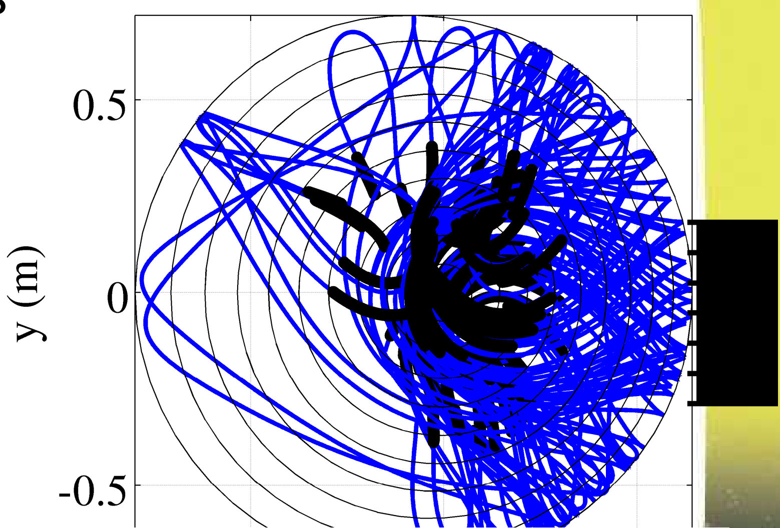


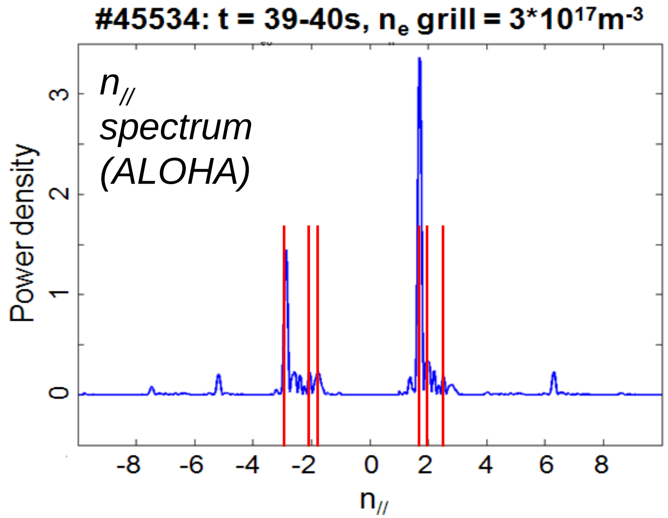
C. Bottereau et al. 2011

Ray-tracing modelling of full current drive discharge

Full CD regime (PAM alone) for 50s



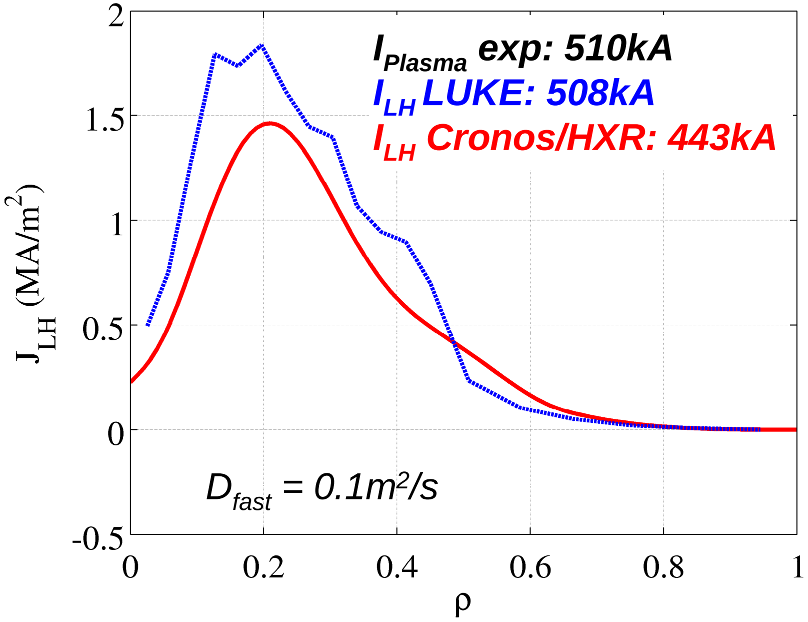




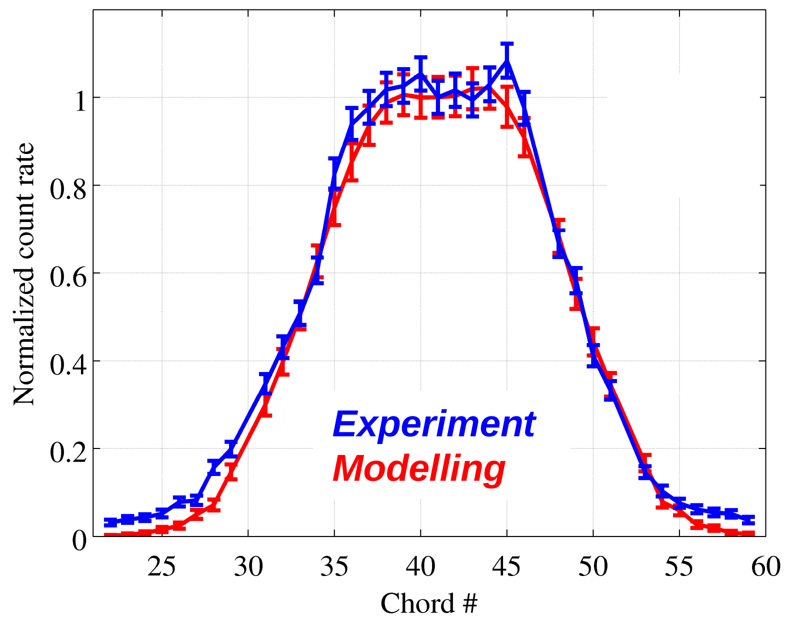
- $n_{//}$ spectrum from ALOHA code (using measured values of power, phase and edge density) Hillairet et al Nucl. Fusion 50 125010
- Ray tracing code, C3PO, using 36 rays (6 $n_{//}$-values x 6 waveguide rows) Y Peysson and J Decker. EPS 2011 & PPCF

Good agreement with modelling, in this example

LH current profile for #45534



Line integrated HXR emission



C3PO/LUKE reproduce well the HXR profile and the driven current.

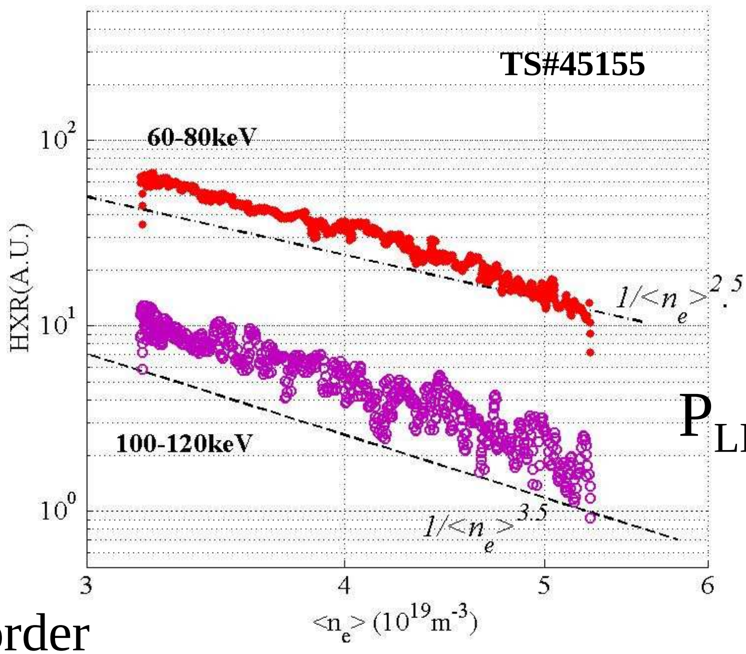
Synthetic diagnostic models well the line integrated HXR emission.

Y Peysson and J Decker, Phys. Plasmas (2008)
J Decker et al., 19th RF Conf., Newport (2011)

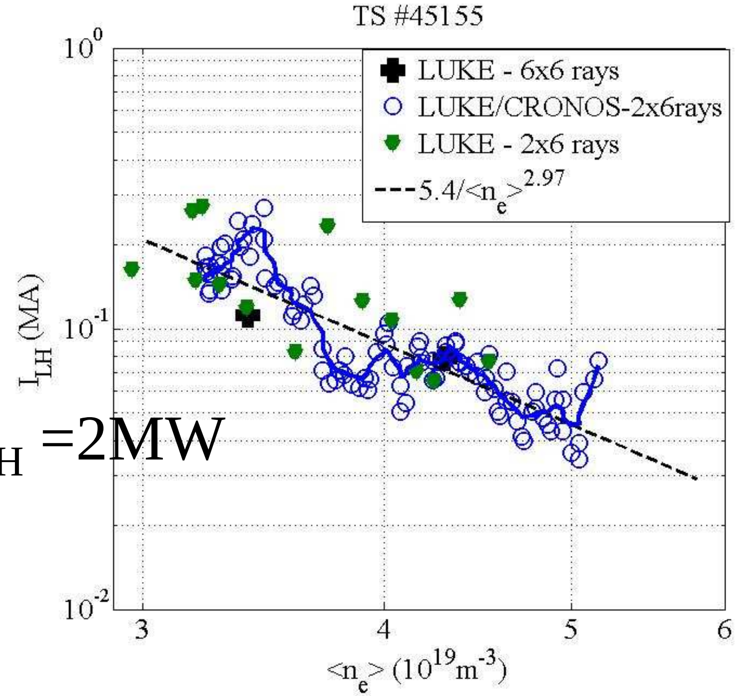
Although good agreement in this example, robustness in LHCD modelling is still required.

Y Peysson et al., 19th RF Conf., Newport (2011)

ITPA-IOS experiment: LHCD modelling vs HXR measurement



P_{LH} =2MW



At first order

$$I_{HXR} \sim n_e n_{fast} Z_{eff}\ f(Z)$$

$$\sim \eta\ Z_{eff} f(Z) \sim T_e\ Z_{eff} f\ (Z) \sim n_e^{-2}$$

$$I_{HXR,\ experimental} \sim \langle n_e \rangle^{-2.5,\ -3.5}$$

$$I_{LH} \sim \eta\ n_e^{-1} \sim T_e n_e^{-1} \sim n_e^{-2}$$

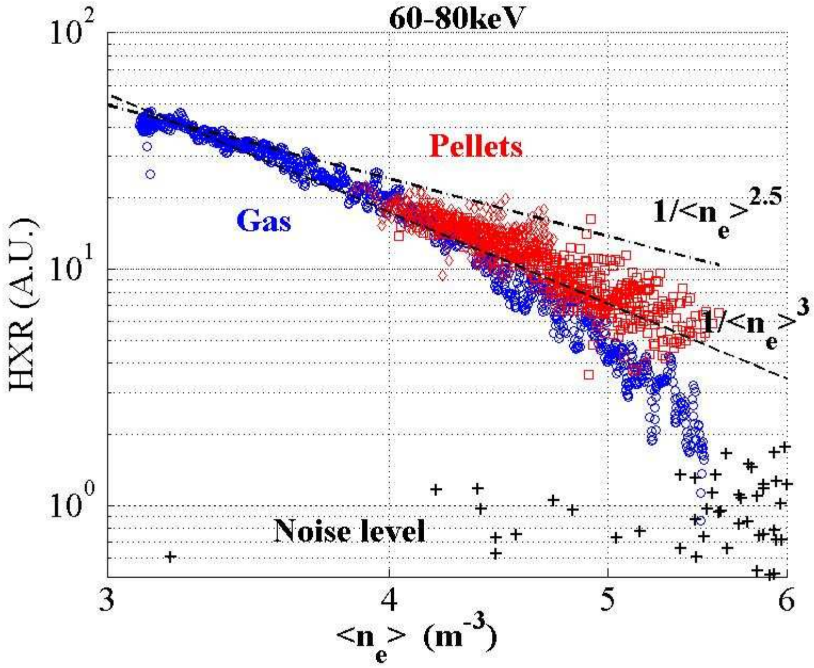
$$I_{LH,\ computed} \sim n_e^{-3}$$

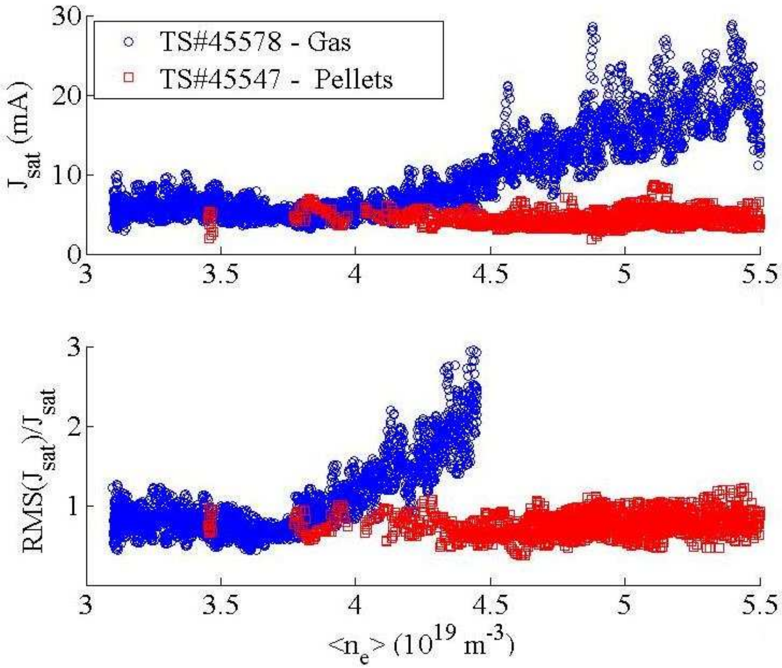
- **Experimental HXR scaling ($n_e^{-2.5,-3.5}$) is consistent with RT/FP computation of I_{LH}**

Goniche et al and Oosako et al RF 2011 conf.

ITPA-IOS experiment, LHCD experiments at High Density :

Gas vs. Pellet Fuelling and role of edge fluctuation





- **HXR emission stronger with pellets when $n_e > 4\times10^{19} m^{-3}$**
- **Faster decay of HXR correlated to strong increase of SOL density fluctuation**

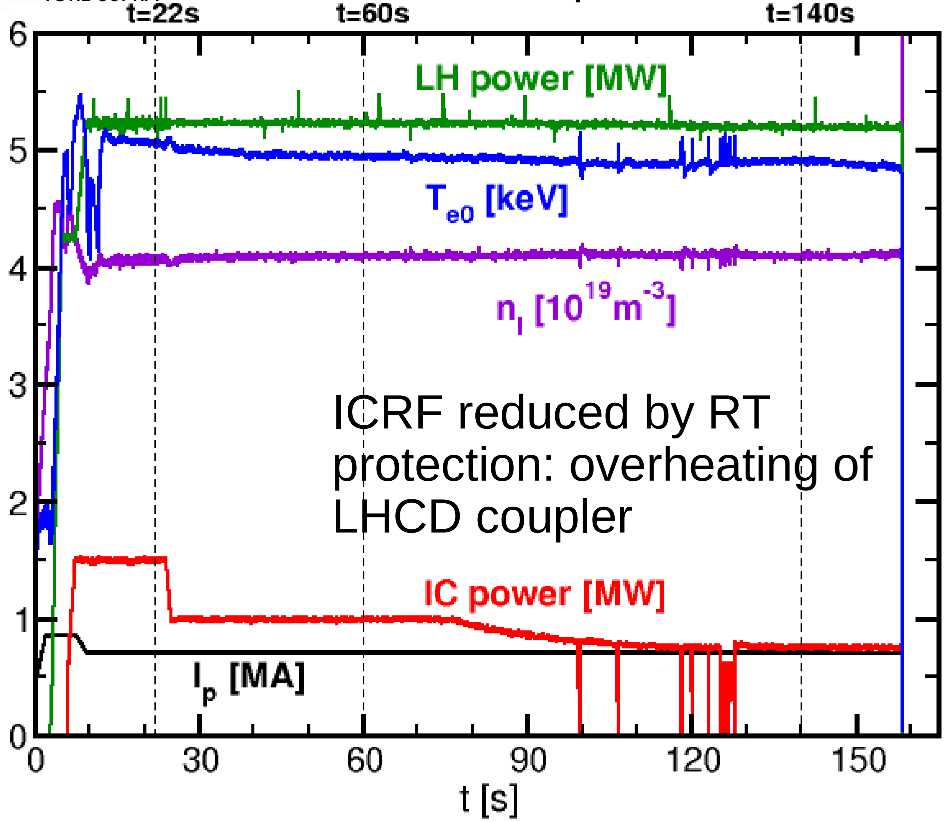
Goniche et al RF & EPS 2011 conf.

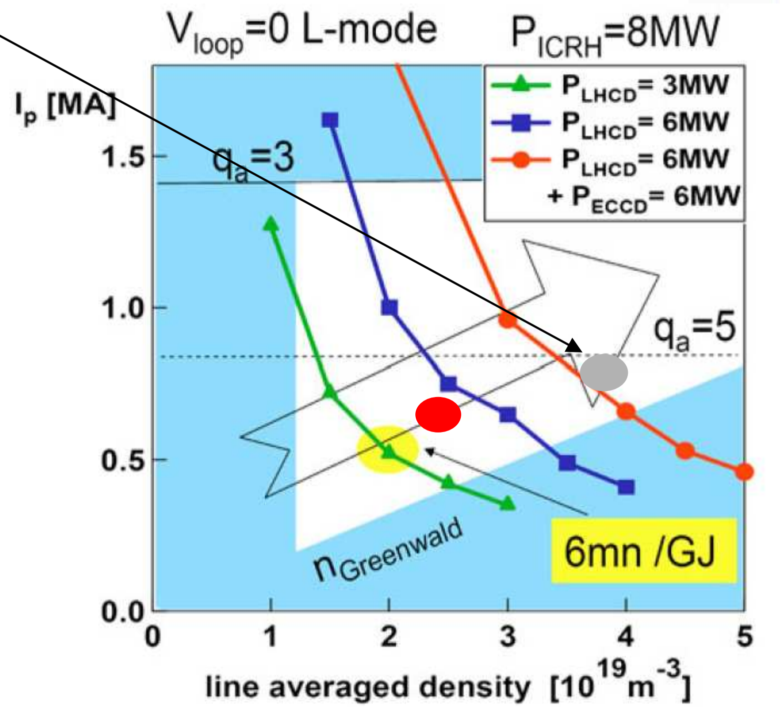
High density long pulse operation with LHCD & ICRH: new GJ discharges in 2011 !!

- ~1GJ (~6.3MW/150s) injected/extracted energy
- Non-inductive fraction ~80% with sustained e-ITB!

B_o~ 3.8T, $n_l = 4.1\times10^{19}m^{-3}$, I_p = 0.7MA
β_p ~0.6, β_N ~ 0.7 P_{LHCD} = 2-6MW P_{ICRH} = 1-3MW

Tore Supra # 47979



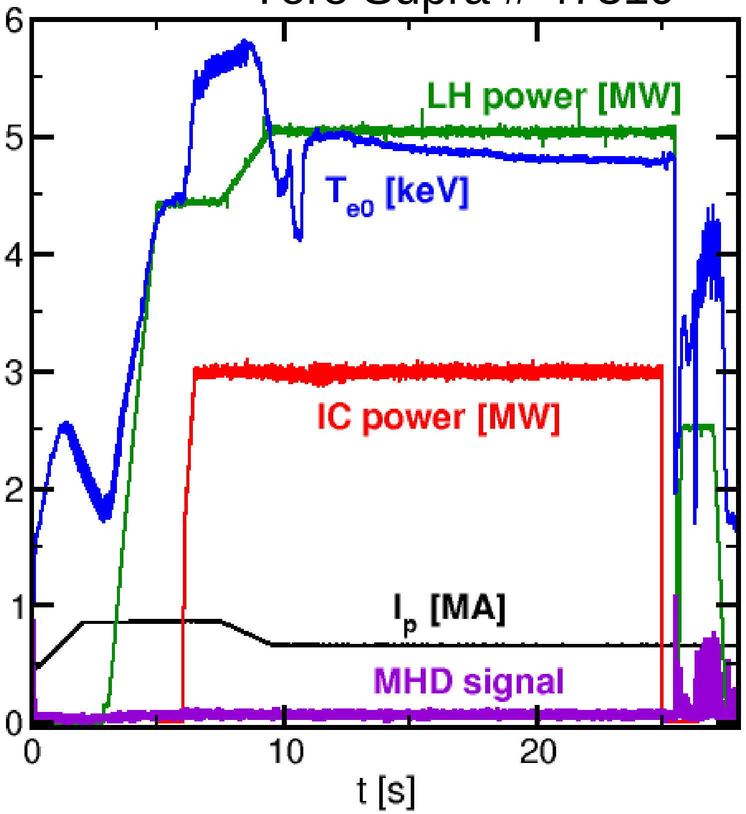


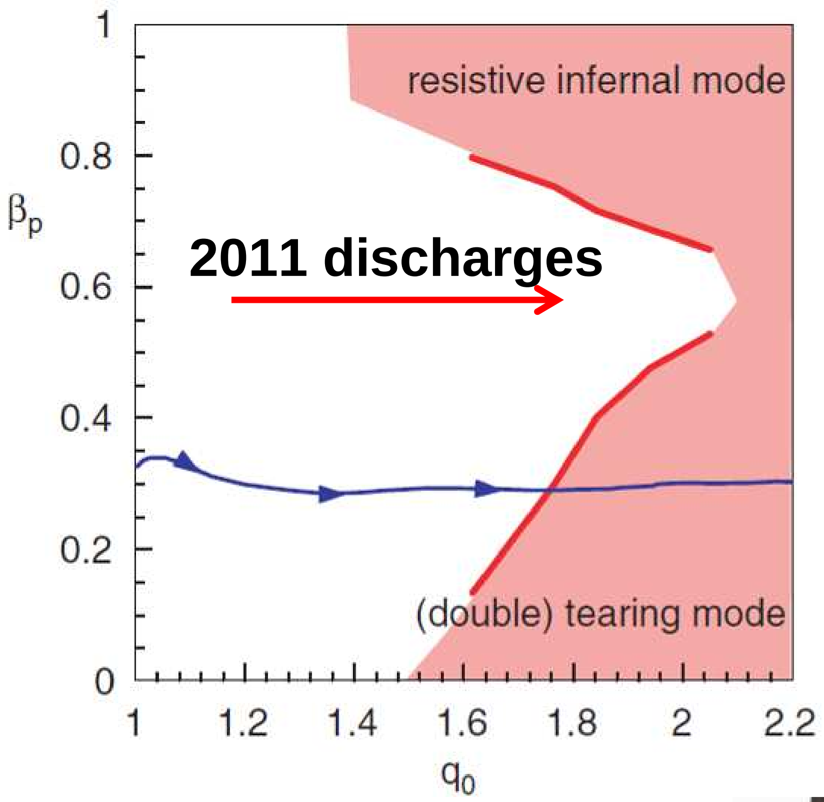
R. Dumont et al

ICRF power stabilizes MHD activity in non-inductive LHCD discharges as expected

MHD activity ~500ms after ICRH swith-off

Tore Supra # 47319



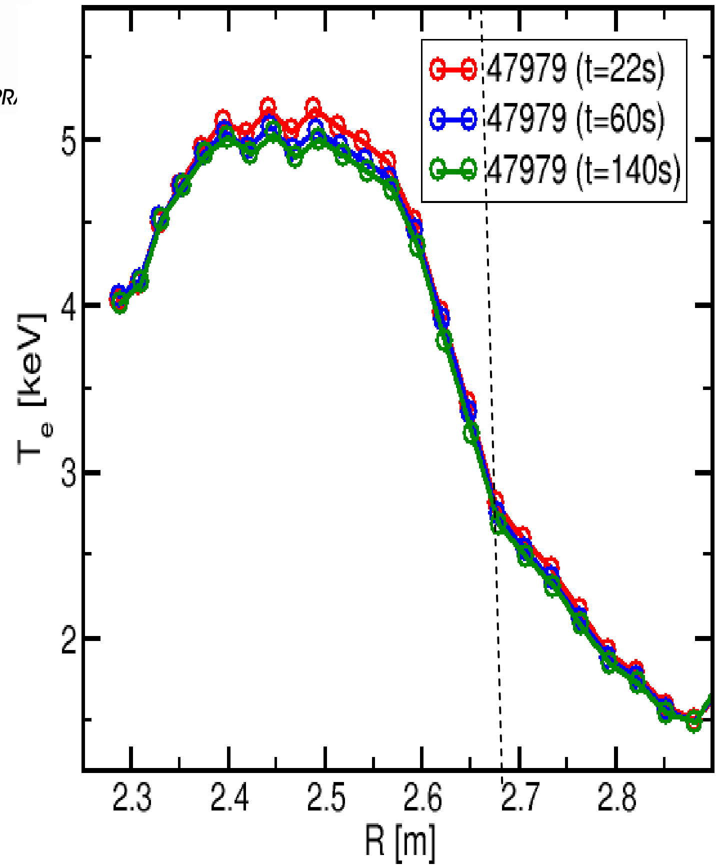


[M. Zabiego et al, PPCF 2001]

R. Dumont et al

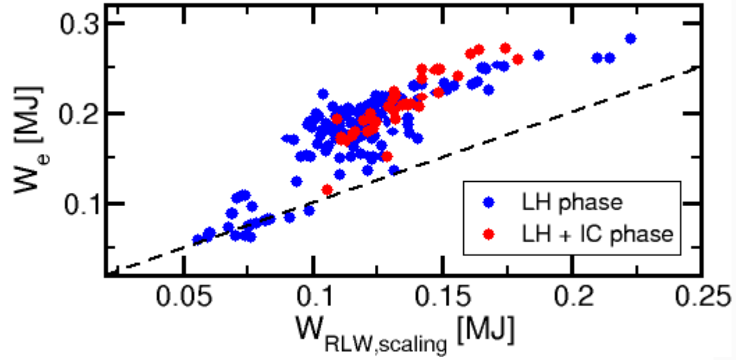
q-profile & improved confinement sustained in the GJ discharges

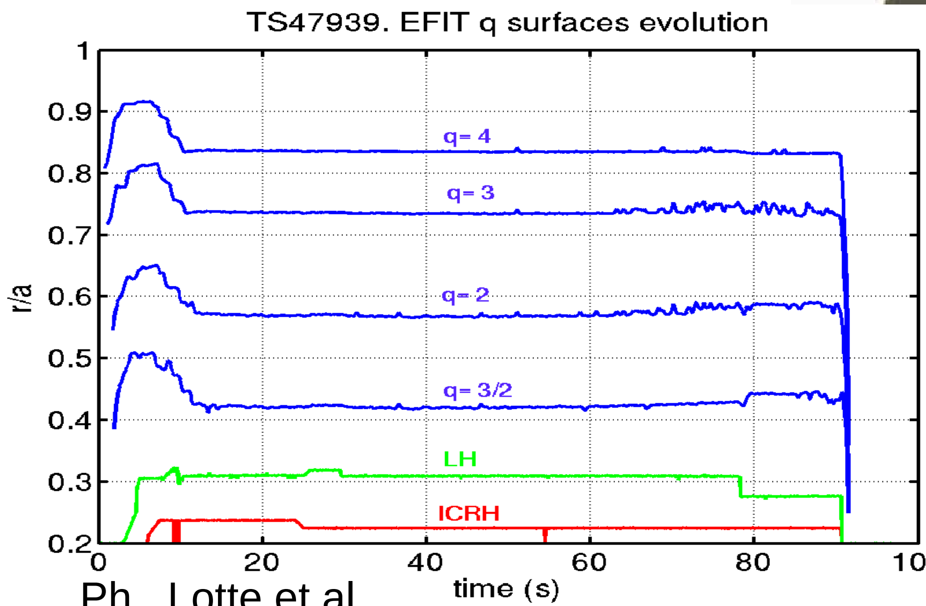
- **electron ITB:**
  - Low magnetic shear in core



R. Dumont et al

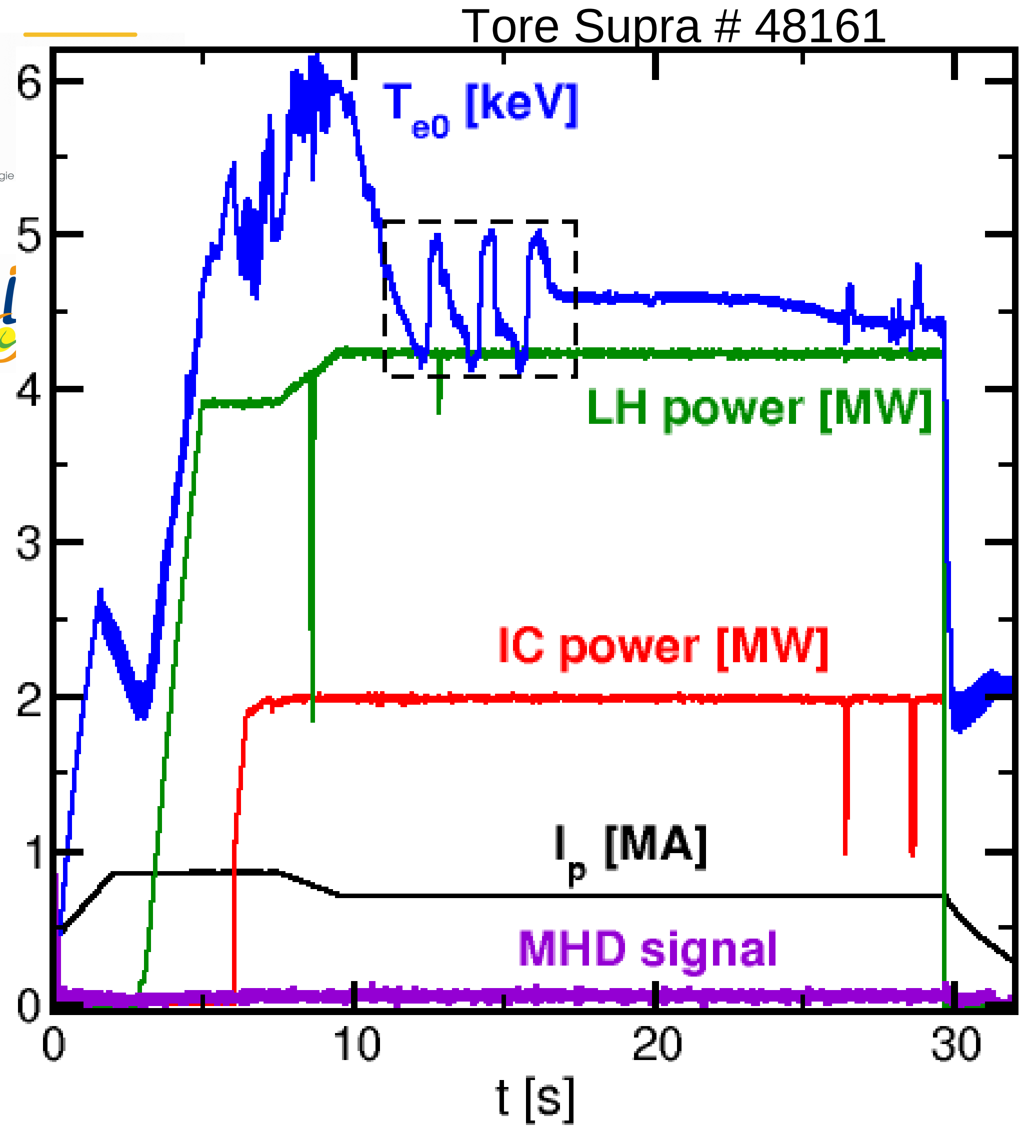
- **Global confinement**
  - High magnetic shear in confinement domain

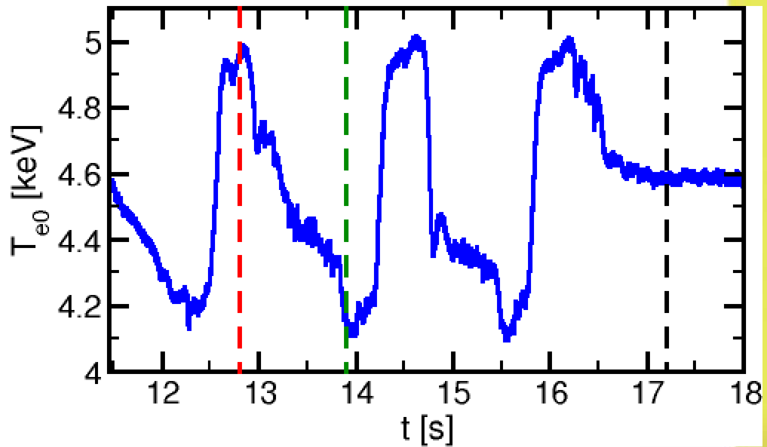


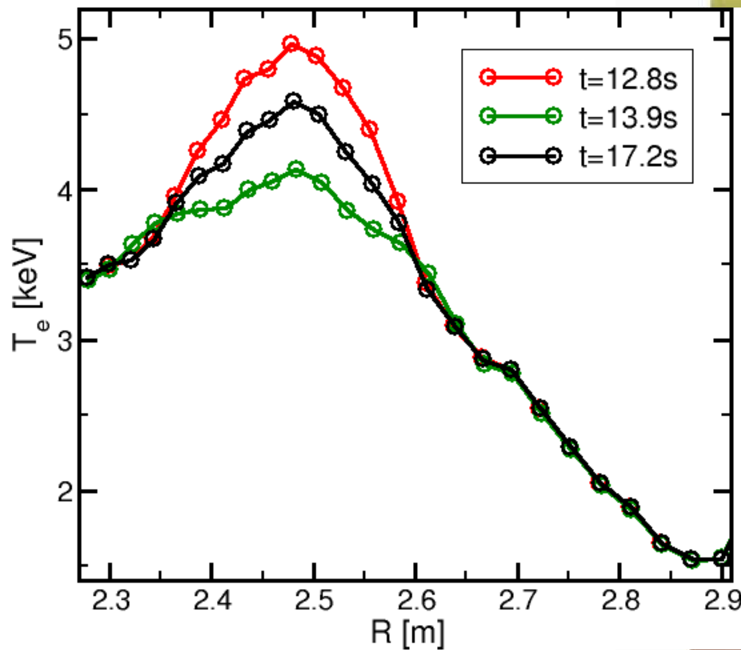


Ph . Lotte et al

Large central temperature variations: coupling q & transport (through bootstrap current ?)





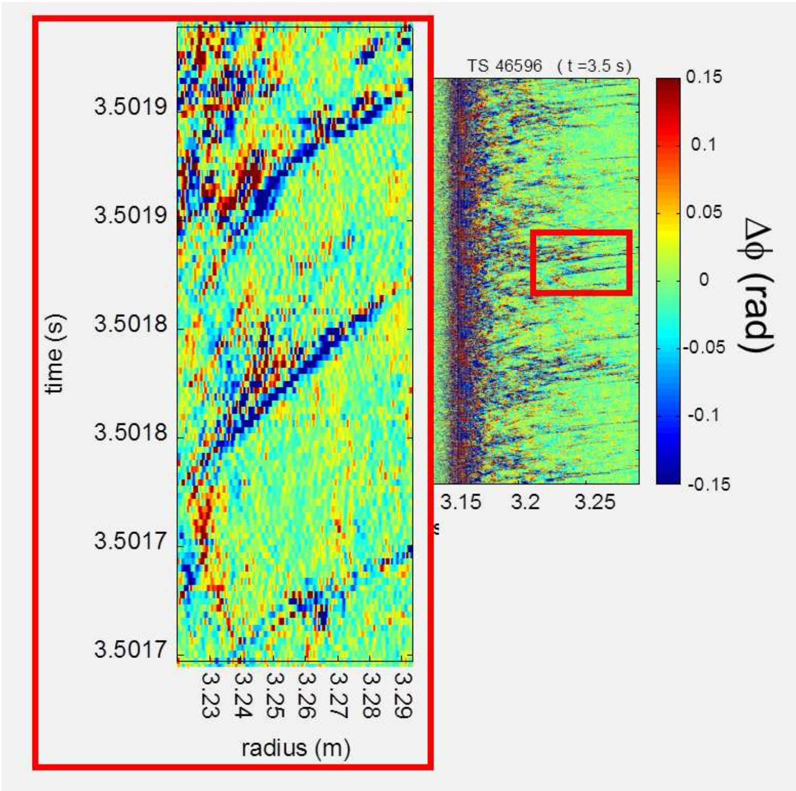


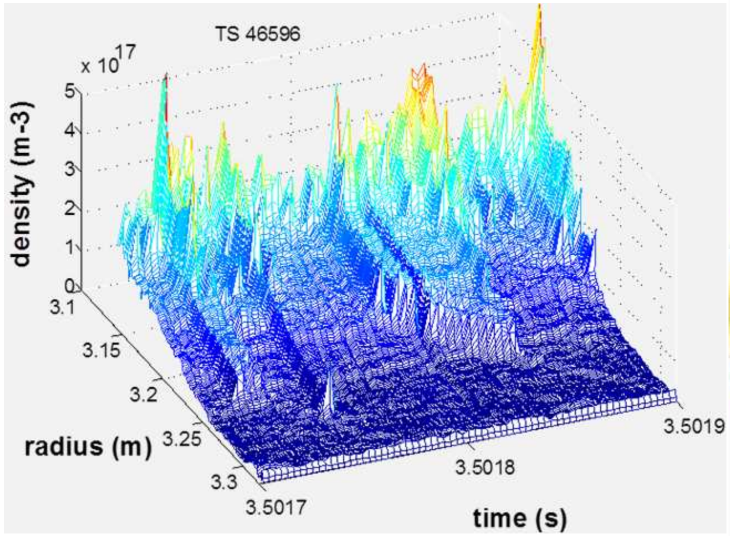
C. Bourdelle 2011, Giruzzi et al PRL 2003, Imbeaux et al PRL 2005 energie atomique • energies alternatives

❑ Strong intermittent behaviour into the SOL

Spatial origin of “Blob-like” structures well identified radially

❑ New plasma physics issues





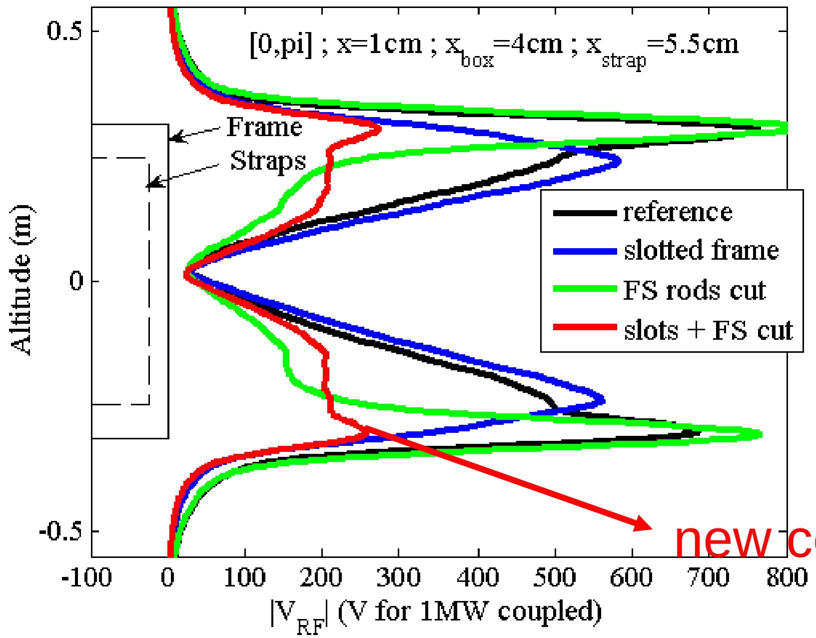
Blob-like structure observed in the SOL of plasmas heated by ICRH

2011: New Faraday Screen for ICRH Antenna

- ❑ Designed to minimize RF sheath potential & mechanical constraint on FS Bars

- ❑ Leak tests validated: jan. 2011
- ❑ RF tests on new test bed facility: 03/11
- ❑ Experiments on Tore Supra: RF sheath physics, power coupling, impurity production, thermal cooling; with participation of ITER-IO & ICRH experts

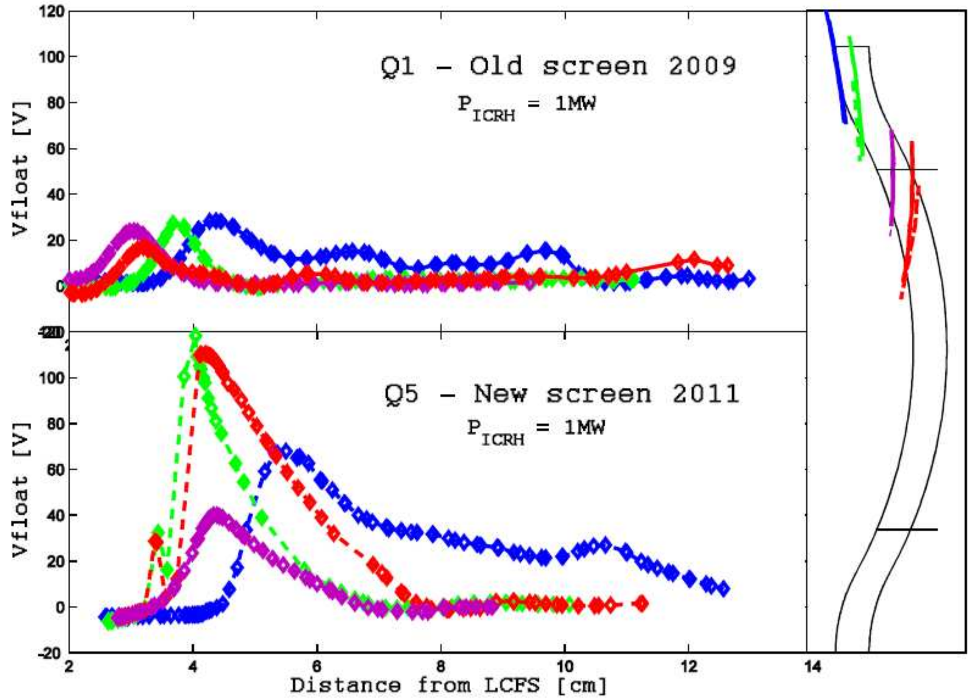
Simulated RF potentials

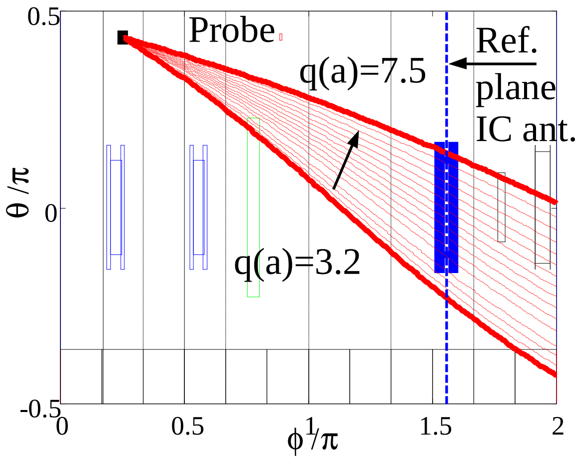


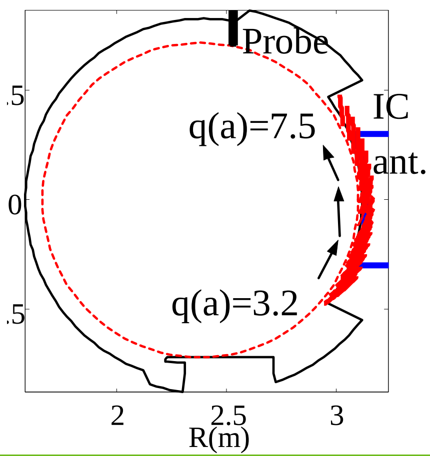
L. Colas K. Vulliez

R&D aspects relevant for ITER

Measurement of the DC floating potential with RF fields (Tunnel probes)

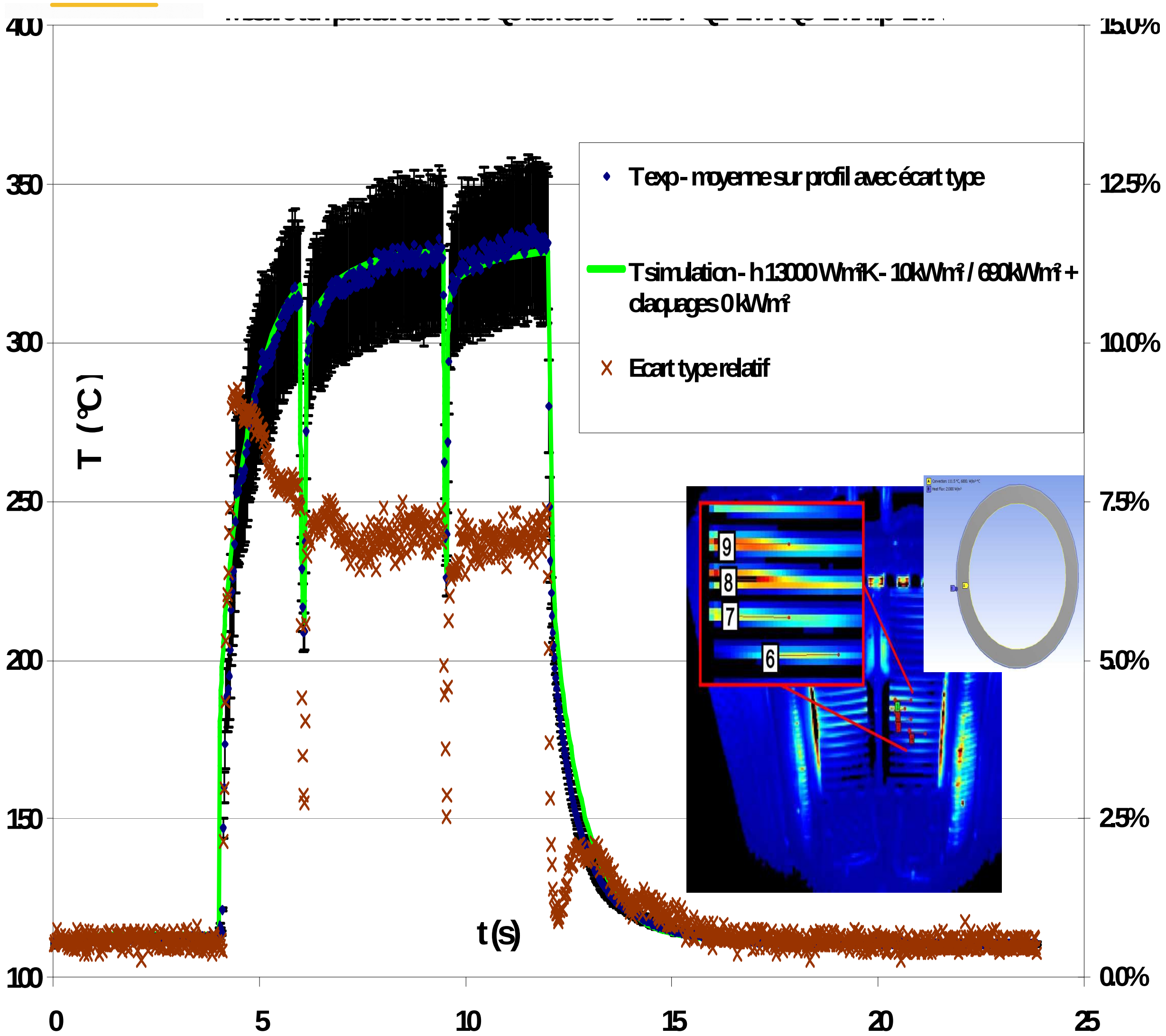






J. Gunn, M. Kubic EPS 2011

Thermo-mechanical calculation and comparison to experiments



M. Firdaouss

- Thermo-mechanical modelling reproduces experiments
- actively cooled Faraday screen: good thermal response
- But the local heat flux is 10 times higher compared to standard FS
  - 375-690 kW/m^2
- **consequences for ITER design**

Other issues related to ITER operation preparation

- **Disruption runaway electrons suppression by high pressure fast gas injection**
- **Event / Exception handling**
- **High density/high radiation Operation**

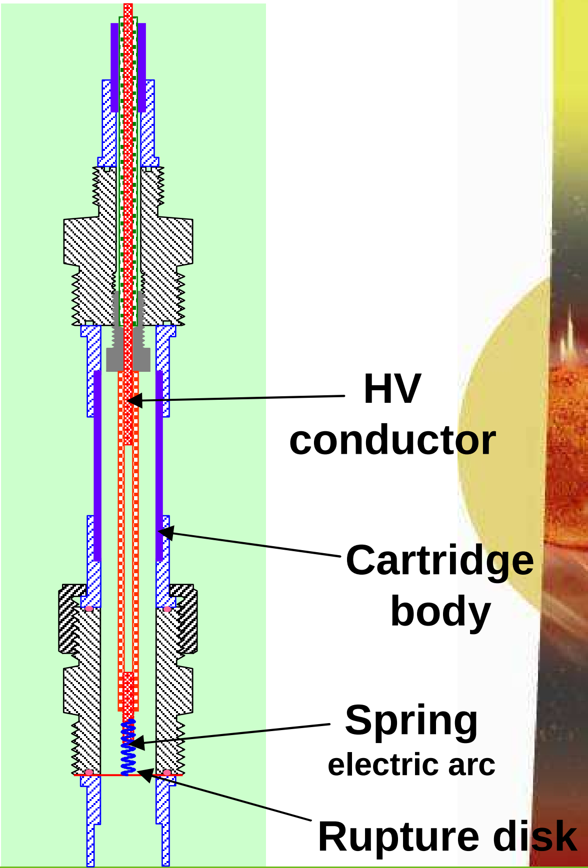
- **EC assisted plasma start-up :** assistance to plasma start-up by 2nd harmonic X-mode ECRH with 20° tangential injection (ITER at half magnetic field)
- **Effect of local gas puffing on IC/ LHCD power coupling**
- **Heat flux pattern on leading edge of misaligned tile**
- **Characterisation of the SOL near limiter plasma tangency point**
- **Wall conditioning by low frequency glow discharges and by Ion Cyclotron**

Runaway electron mitigation by high pressure fast gaz injection

- **Motivation : suppression of runaway electron in ITER by fast injection of dense gas jet in the current quench (alternative to massive material injection)**

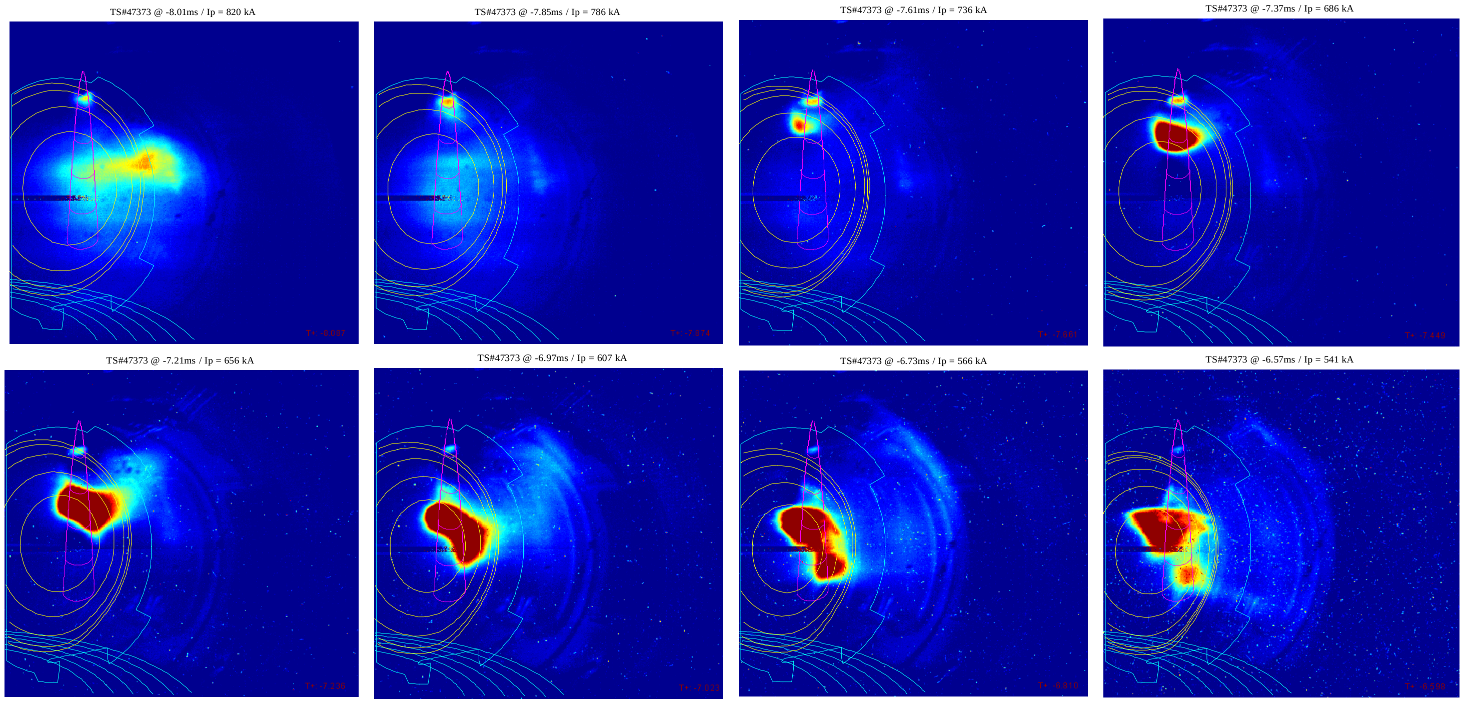
- **FIRE setup (Fast Injection by Rupture disk Explosion) sucessfully developped (ITER contract)**

F. St Laurent



First results: neon gas flow observed by fast camera

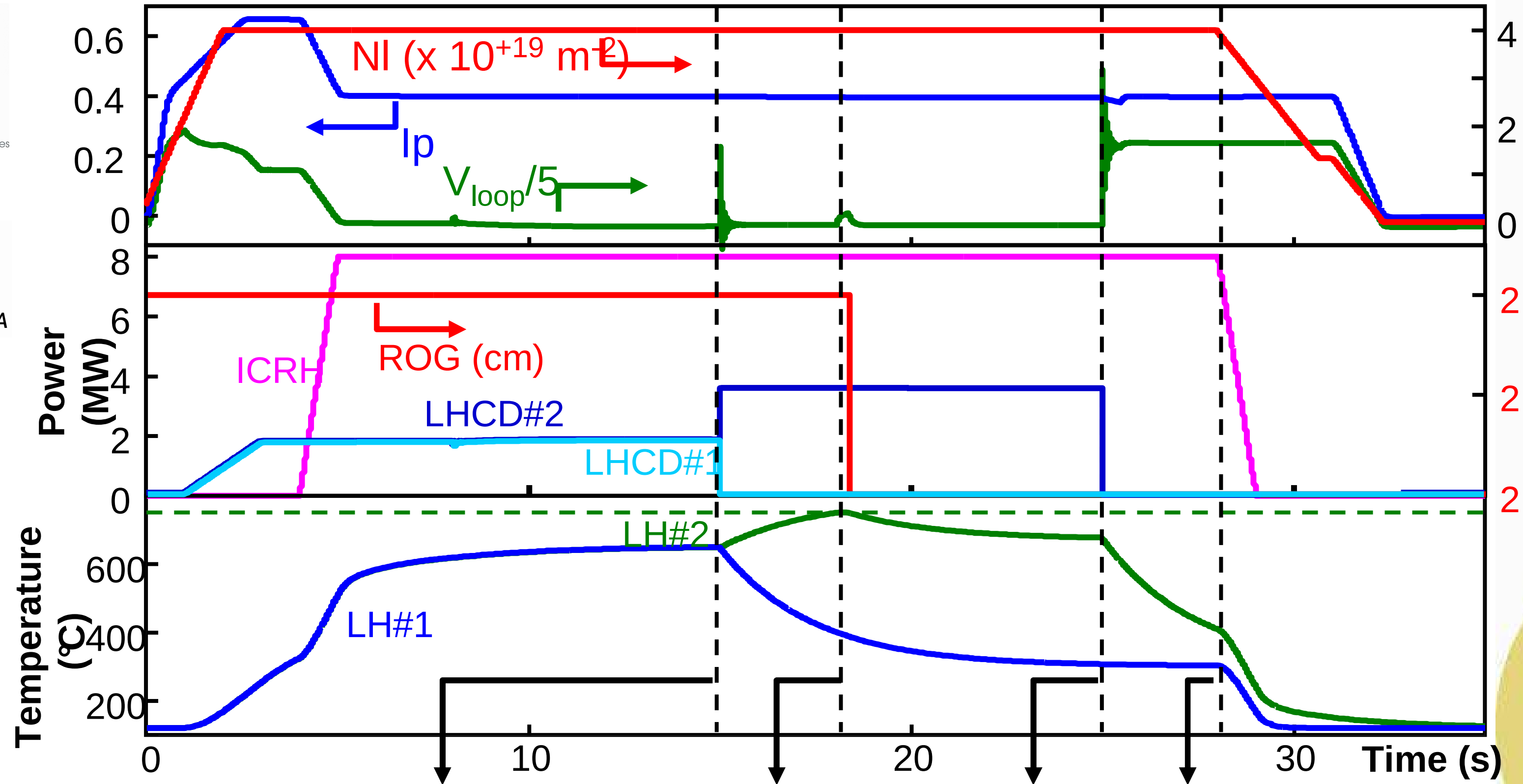
Propagation of the Neon gas injected by Fire from the top of the machine during plasma current quench



Fast visible camera images filtered for Ne I line. Front moves with v ~500 m/s for Ne and 1200 for He (1/2 of gas velocity in vacuum)

F. St Laurent

Modelling of Event / Exception handling



	LH#1 unavailable	LH#2 Temp threshold	LH#2 unavailable	Vloop=0 not recovered
	Missing power redistributed on LH#2 to ensure Vloop=0	ROG is increased, Vloop≠0 during transient (Ip maintained)	Vloop≠0 to maintain Ip	Soft Stop is triggered
Local E/E report	Orange	Red	Red	Red
Global E/E report	Green	Orange	Red	Red

R. Nouailletas

n_e/n_{Gr}=1.4 maintained for several τ_E in RF heated plasmas with 90% radiated power

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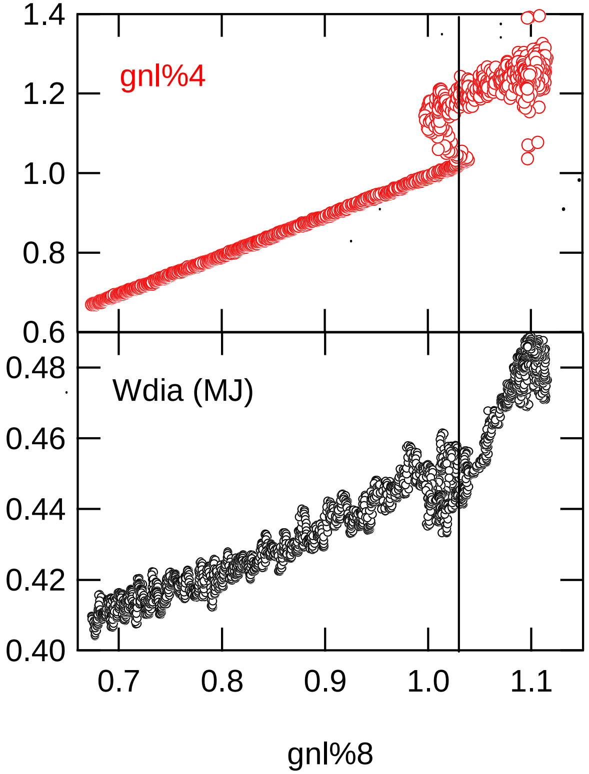
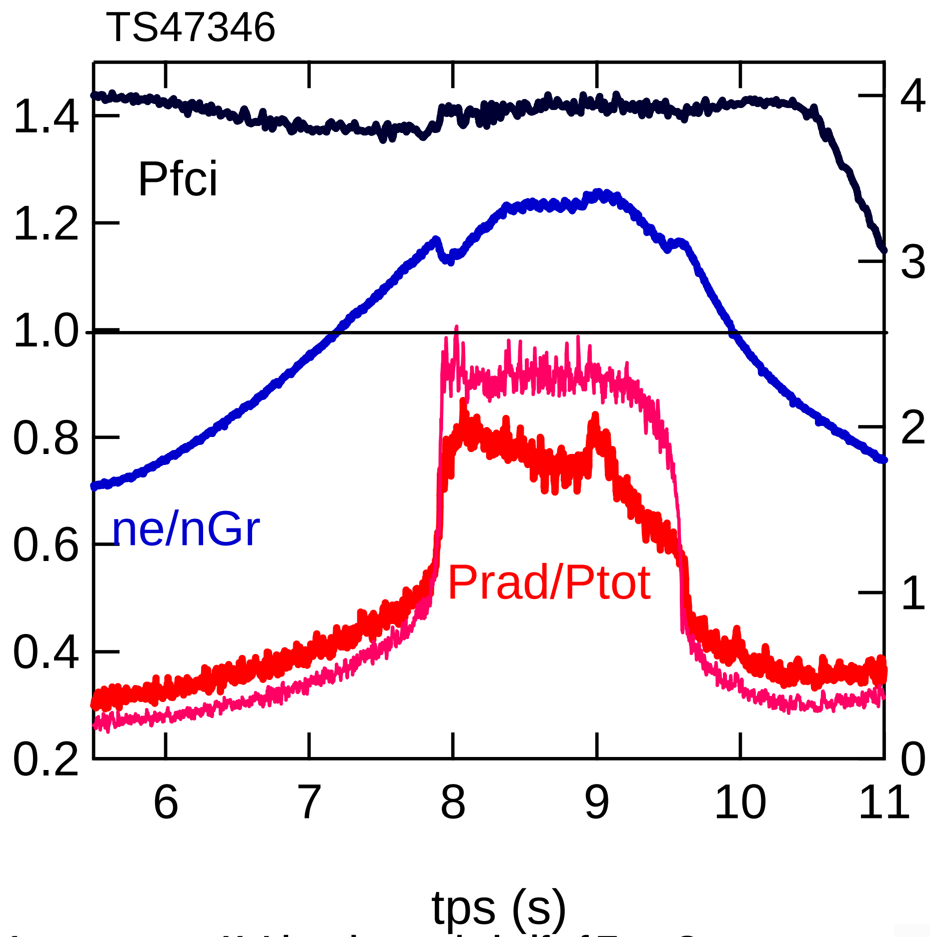
- **Regime similar to 'high recycling' regime in axisymmetrix X-pt divertors**
- **No degradation of global energy confinement**

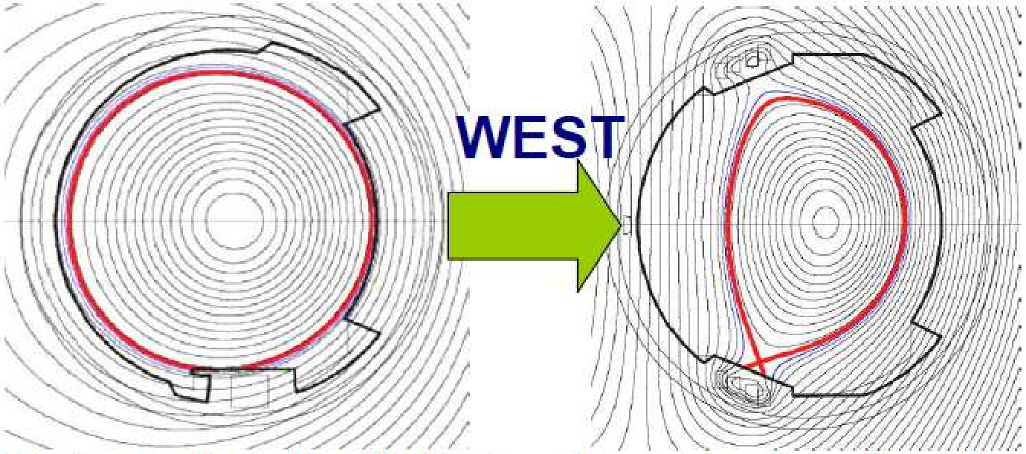




Tore Supra: prepare ITER long pulse operation

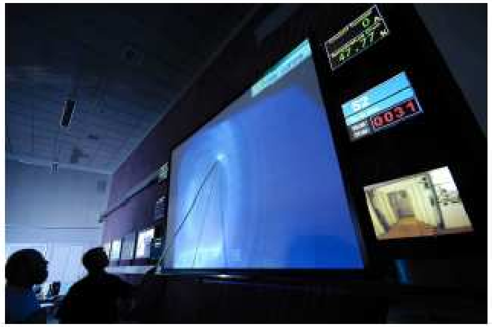
- **Plasma operation restarts in Sept. 2012**
  - Shutdown: modification of HV 400kV network for ITER
- **Full H&CD CW capability & 2012 upgrade**
  - 6-7MW LHCD (CW) + 3MW ICRH on more than ~200s
  - Assess power limit of CW ITER-PAM
  - Antenna & machine protection upgrade
  - Diagnostics upgrade: fast core reflectometry
  - ECRH antenna upgrade (in collaboration with FOM): Mirror mouvement for real time control
- **Master long pulse operation: minimising risks for ITER**
  - **fully non-inductive plasmas at higher I_p and density**
  - Disruption mitigation
  - real time control for machine protection & performance optimisation: IR control of hot spots, ripple fast losses...
  - Physics of evanescent V_{loop} plasma on time scale much longer than current diffusion: MHD, intrinsic rotation, ...

WEST : minimising risks for ITER operation
Use Tore Supra assets to prepare ITER exploitation

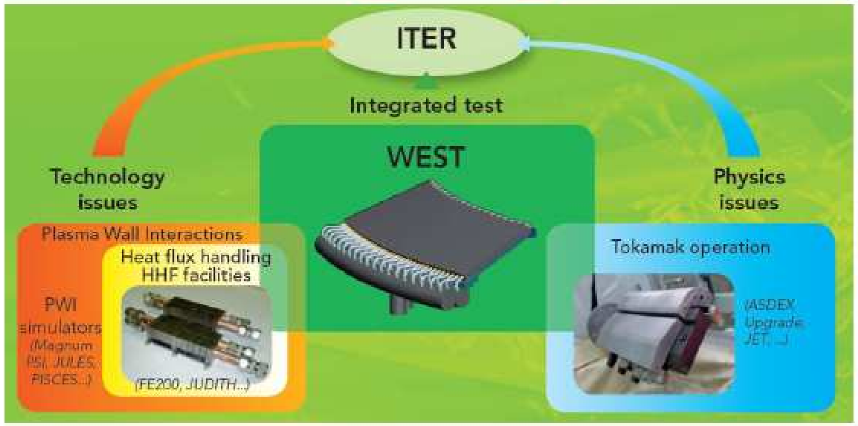


Circular configuration (limiter)   X point configuration (divertor)

Long pulse H mode : ITER reference



WEST : filling the gap towards ITER actively cooled divertor



First integrated test : technology of high heat flux W PFC + tokamak operation

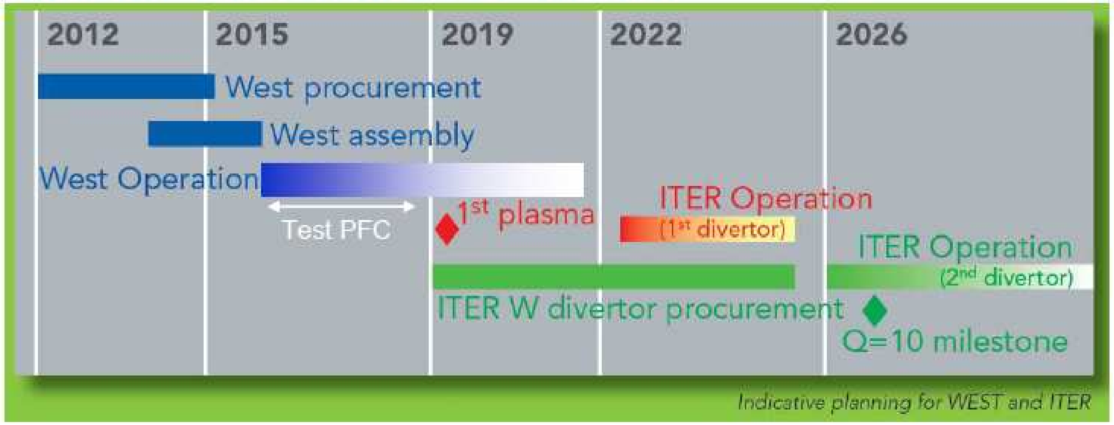
WEST : extending H mode towards steady state and exploring PWI with actively cooled W

- **Standard :**
  long pulse 10 MW/m²
- **High power :**
  high performance
  shorter pulse
- **High fluence :**
  ITER fluence within a few days (6 years for JET !)c

Open for collaboration :
EU + China, US …

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

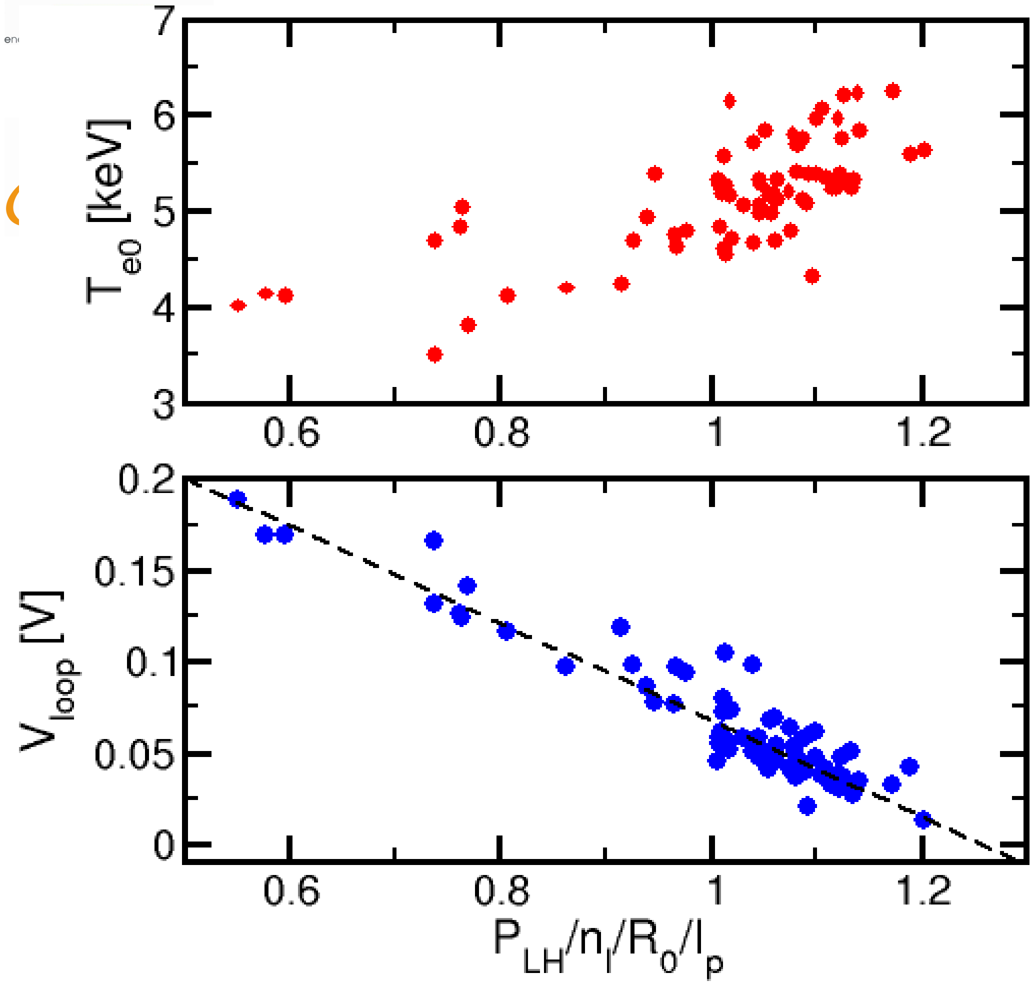
WEST : in time for ITER



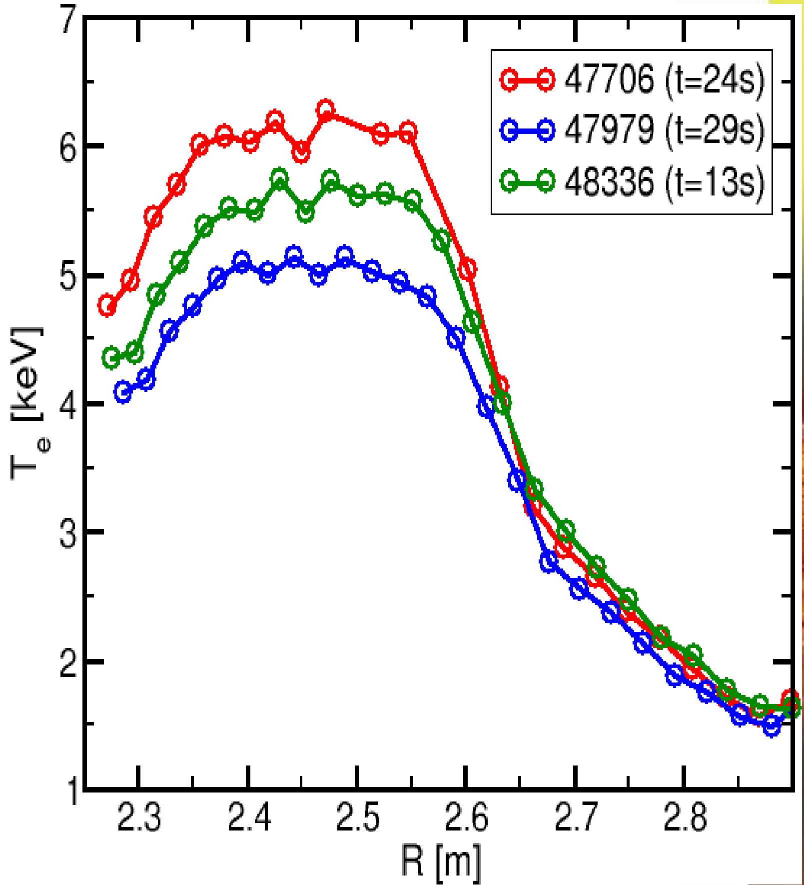
Thanks for your attention !

Stationary electron ITBs in LHCD & ICRH long pulse discharges

2011 discharges



Typical T_e profiles

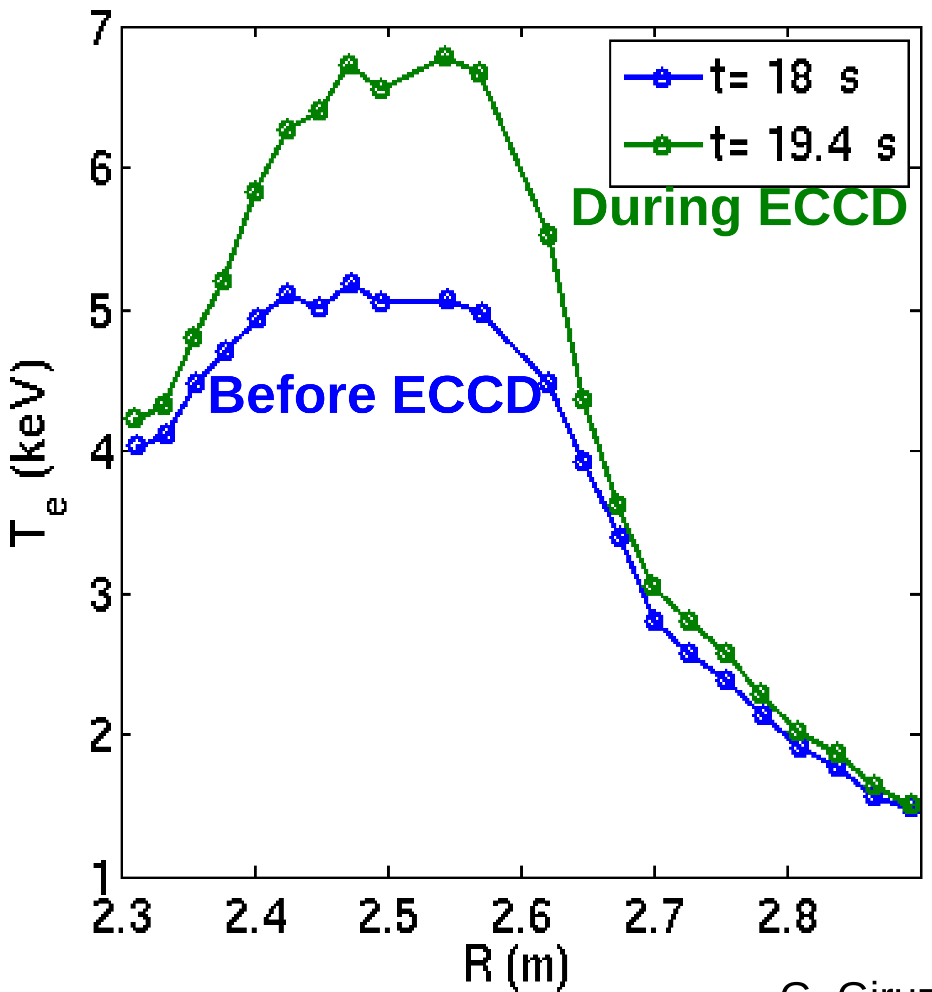


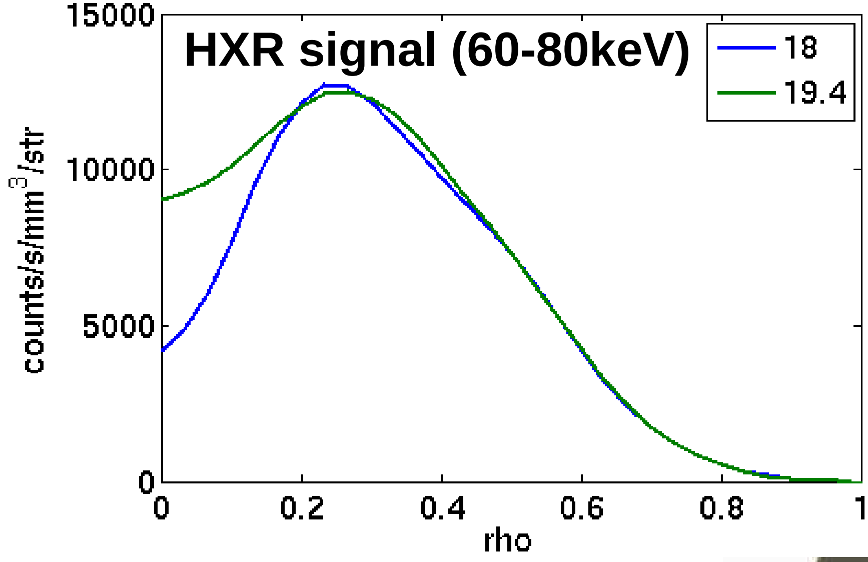
R. Dumont et al

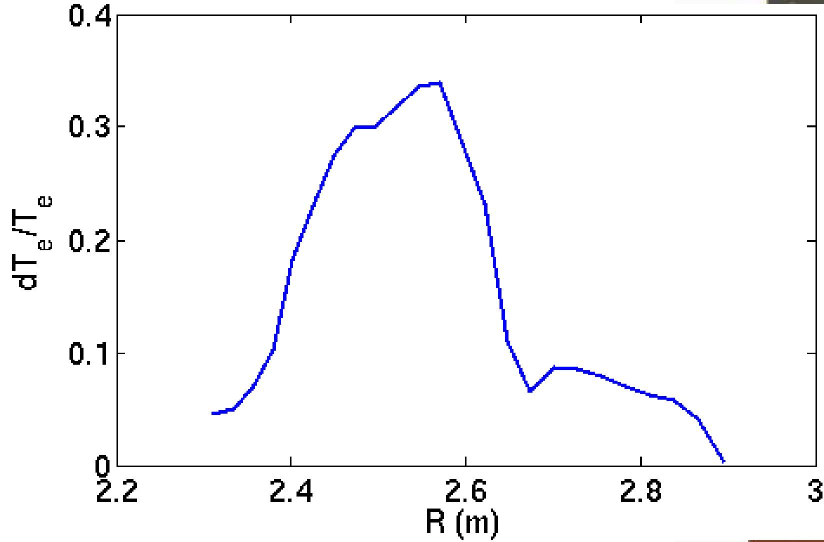
Barrier characterization with ECCD

Tore Supra # 47968

Balanced co/cnt-ECCD (P_{EC} ~ 0.8MW)

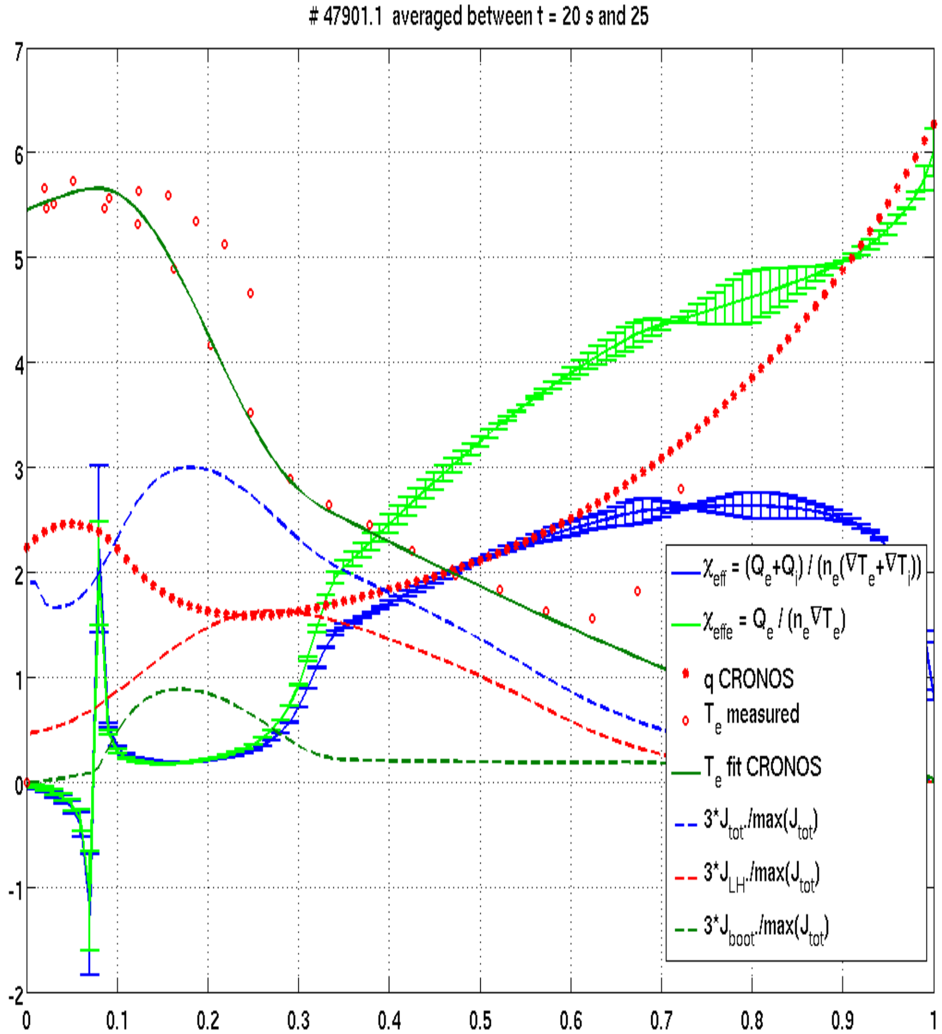






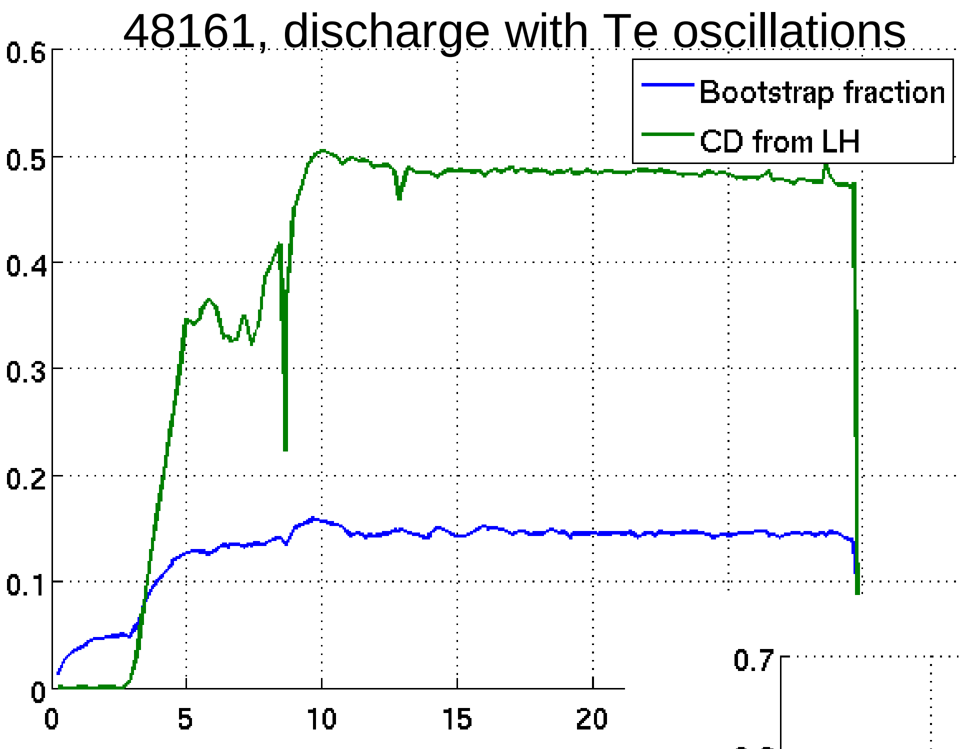
G. Giruzzi et al

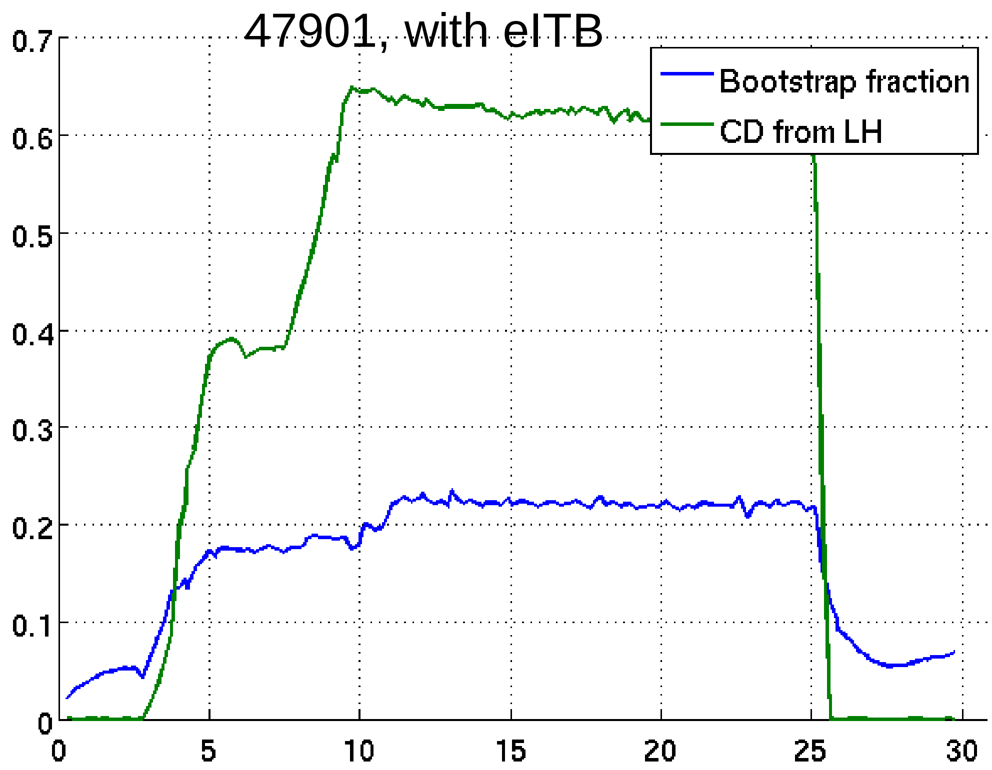
CRONOS interpretative transport analysis: clear e-ITB in the low magnetic shear region



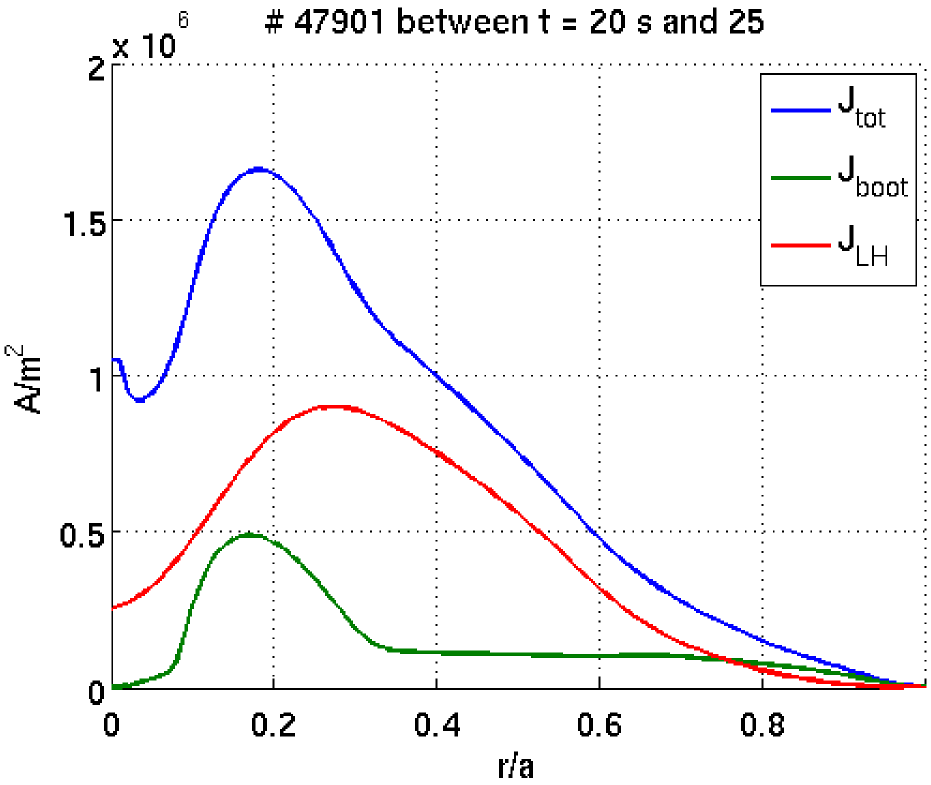
Normalised radius

C. Bourdelle


48161, discharge with Te oscillations
Bootstrap fraction
CD from LH
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20

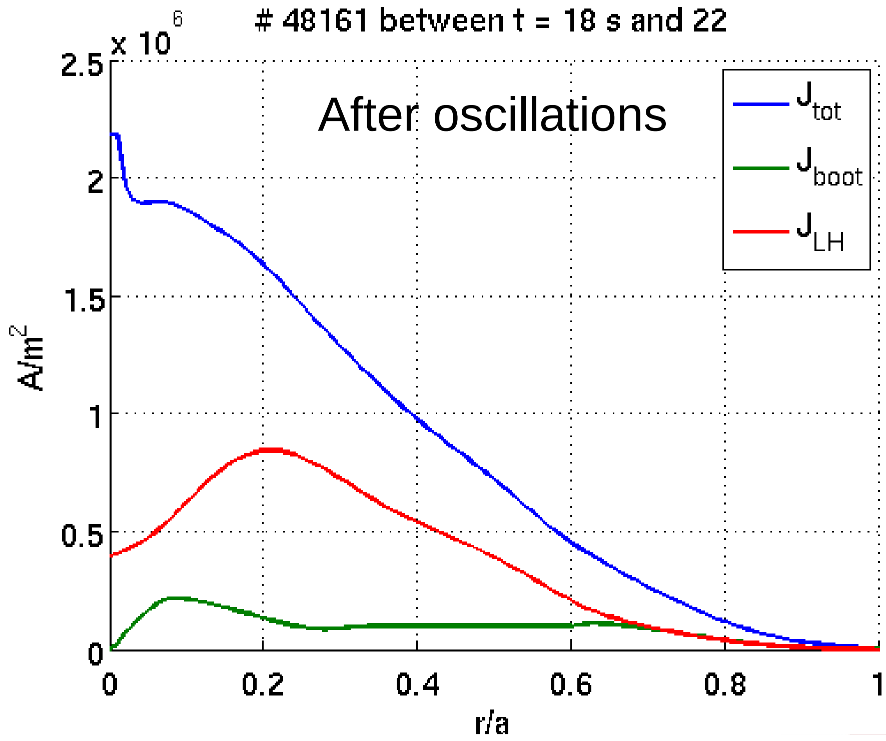

47901, with eITB
Bootstrap fraction
CD from LH
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30

CRONOS



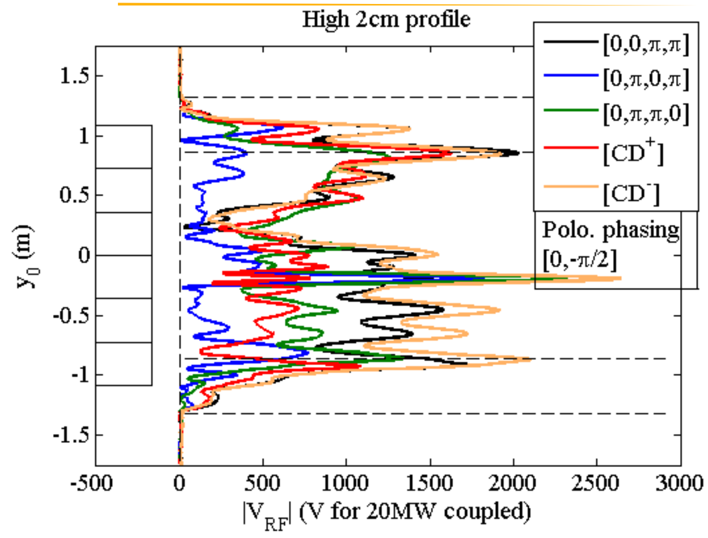
47901 between t = 20 s and 25
x 10^6
A/m^2
r/a
J_tot
J_boot
J_LH

CRONOS



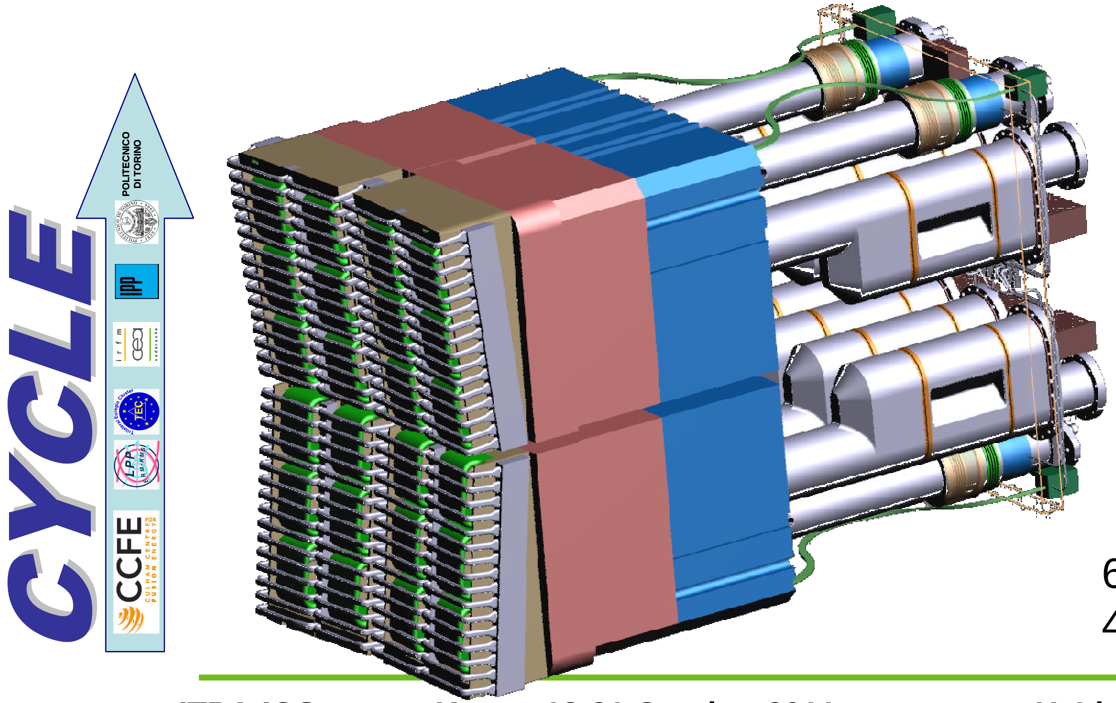
48161 between t = 18 s and 22
x 10^6
After oscillations
A/m^2
r/a
J_tot
J_boot
J_LH

ITER context



- RF sheath modelling with RF fields from TOPICA
  - Non consistent calculation
- Minimisation of RF sheath by minimising the E// (slow wave)

$$\Delta V = \int_{field\ line} E_{//\ RF}\, dl$$



- Design of New Faraday screen on Tore Supra based on the same modelling approach

6 poloidal by 4 toroidal staps ,
40-55MHz, 20MW

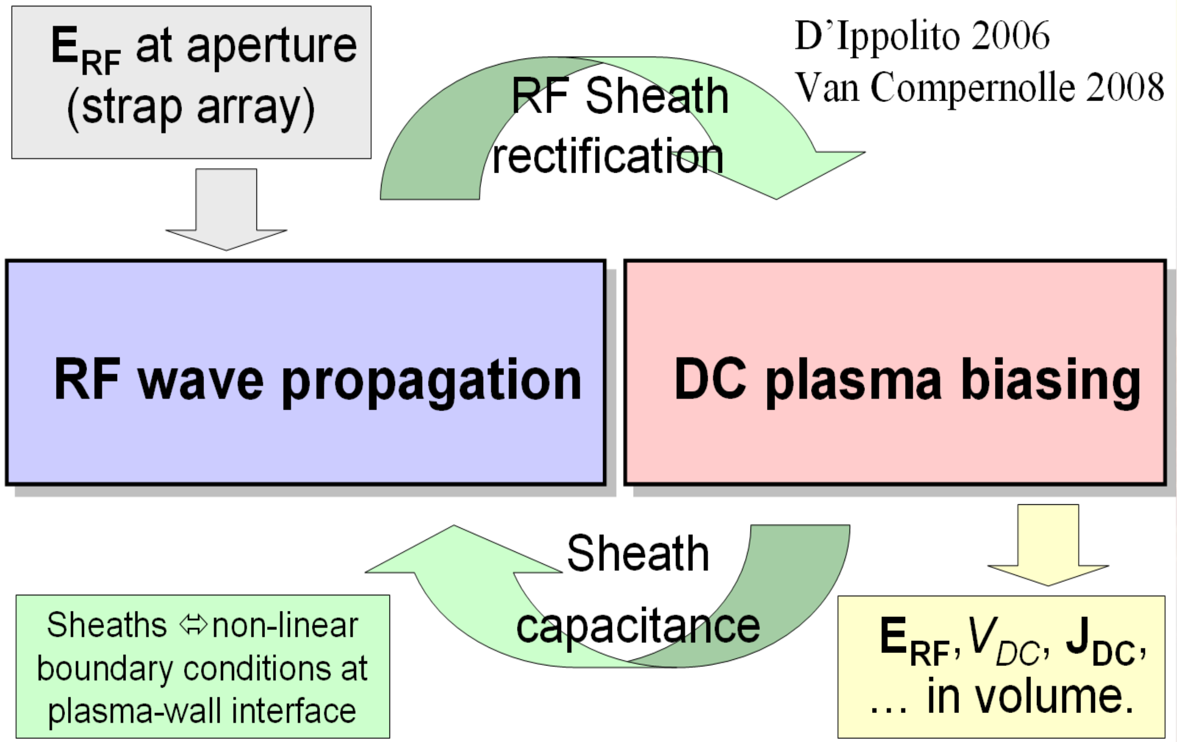
Self-consistent non-linear ICRH wave propagation and RF sheath rectification

- RF **sheath rectification** treated as **Slow Wave propagation self-consistently coupled with DC edge plasma biasing**. Non-linear coupling is ensured *via* **RF and DC sheath boundary conditions**.

SSWICH problem

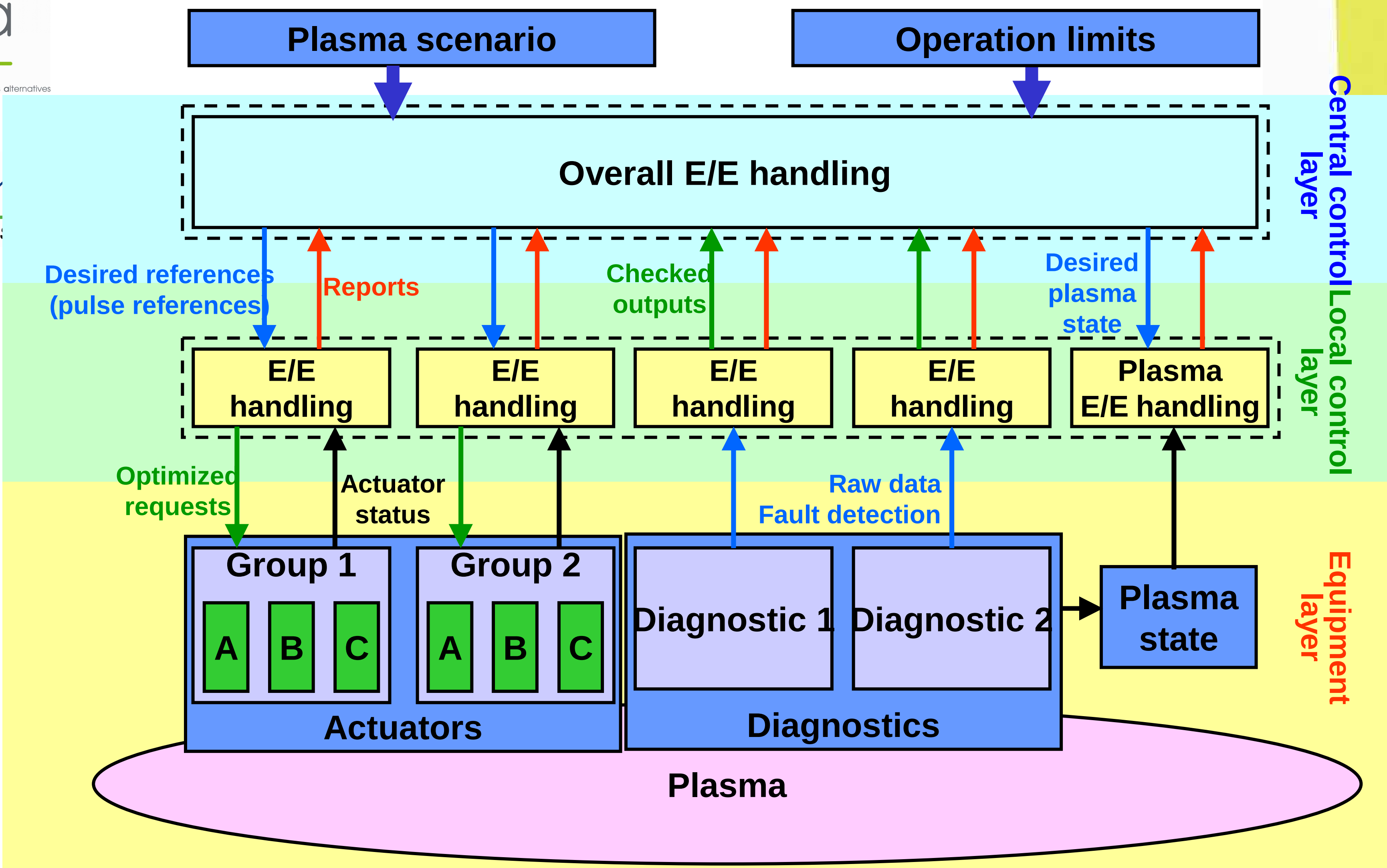
Self-consistent Sheaths & Waves for IC Heating

- **DC current generation:**
  - **the differential biasing of adjacent flux tubes** connected electrically *via* **DC transverse plasma conductivity**
  - **asymmetric RF solicitation** at both ends of the field line

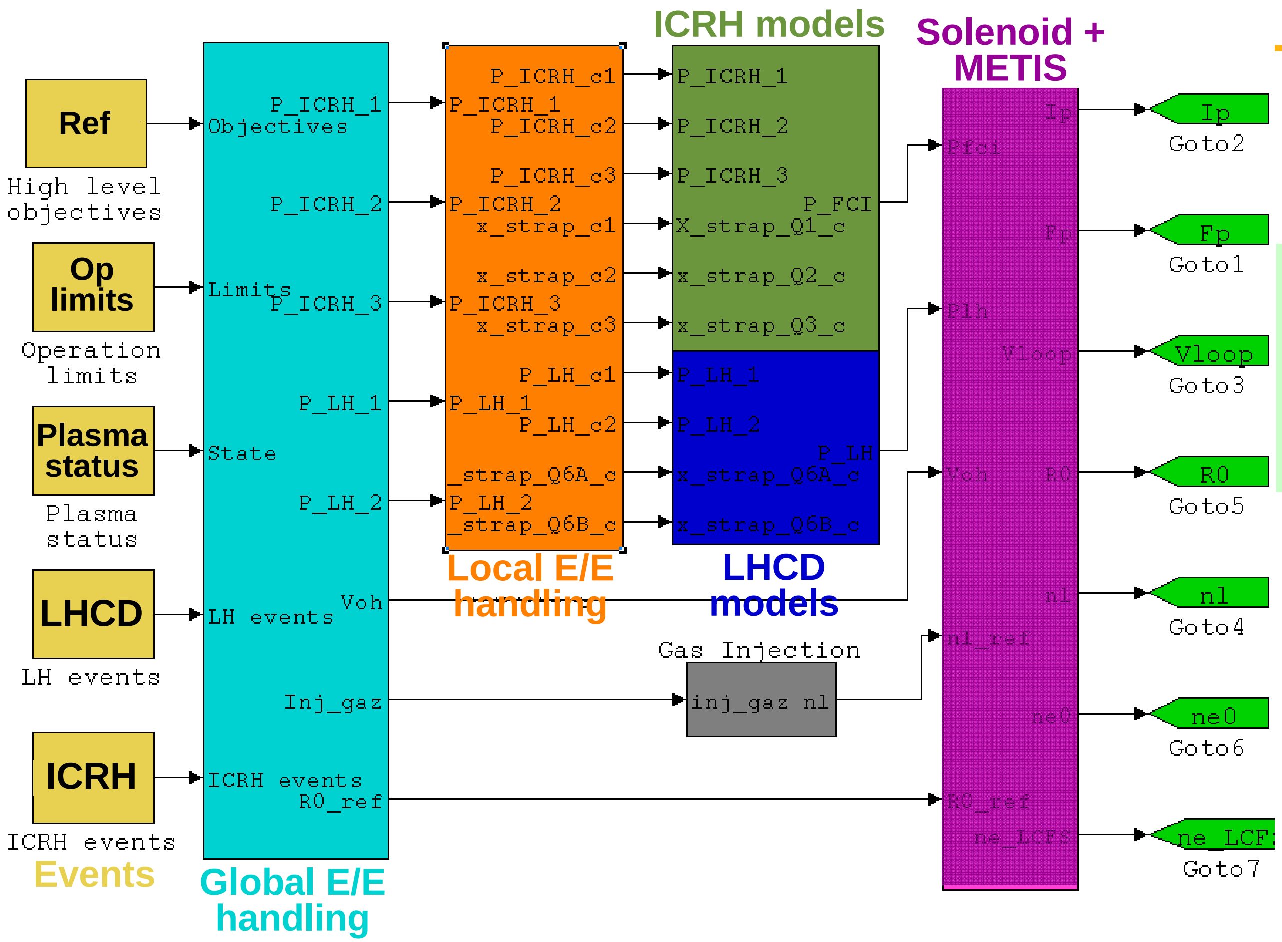


Colas EPS 2010, Jacquot RF conf 2011

Event / Exception handling architecture overview

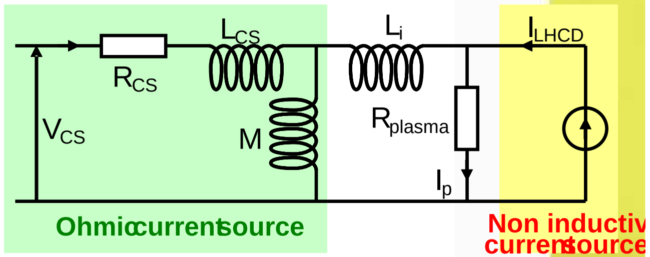


Implementation of an E/E handling system on a tokamak/plasma simulator



Basic plasma models

- **Circuit equation (R, Li, M, constant)**



0-D plasma models replaced by METIS code

- **plasma evolution simulation**
  - → Current diffusion solver
  - → Grad-shafranov equation solver
  - → Scaling law for plasma parameters (inductive/non inductive current, etc.)

- **PFC temperature**

$$\dot{T}_{QiLj} = K_{Qi}\, n_l\, e^{-d_{Qi}/d_0}\, P_{Q_i}^{1/2} + K_{LH}\, P_{LH} + K_{ICRH}\, P_{ICRH} + K_{H_2O}\left(T_{H_2O} - T_{QiLj}\right) + \delta_{QiLj}$$

- **ICRH strap voltage and reflected power**

$$V_{strap} = Z_0 \sqrt{\frac{2P_{Qi}}{R_c L_{strap}}} \qquad R_c = \alpha(t)\, n_l\, e^{-d_{Qi}/dr}$$