Lower Hybrid Current Drive in thermonuclear reactors: ITER and DEMO

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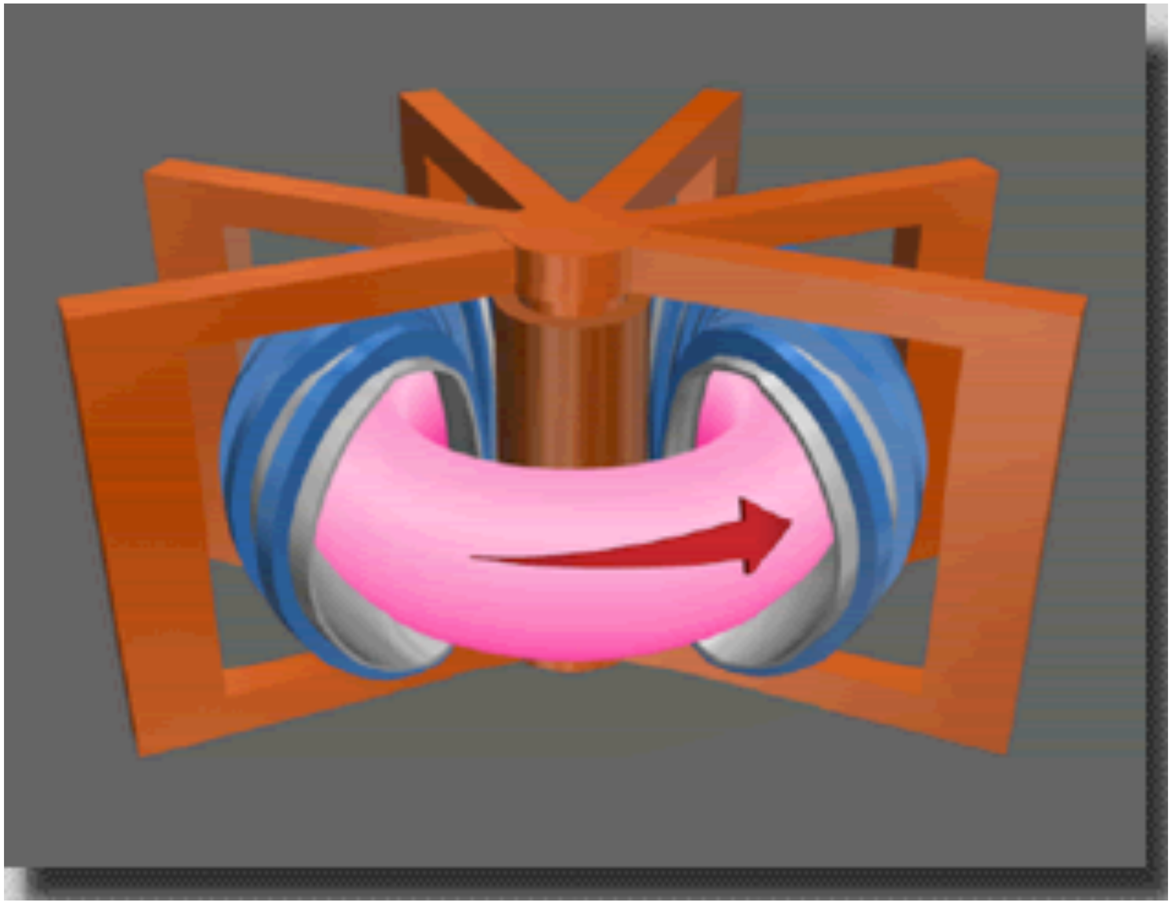
101° CONGRESSO NAZIONALE Societa Italiana di Fisica
Roma September 21–25 , 2015

Outline

- The Tokamak concept
- ITER and DEMO and the need of RF Current-Drive in the Lower Hybrid frequency domain (LHCD).
- Problems connected to the LHCD application in high density, high temperature plasmas.
- Numerical results of the Ray^{star} code in first pass LH absorption: *the role of the wave spectrum and its control in Current Drive*.
- A simple analytical model to explain the numerical result.
- Conclusions

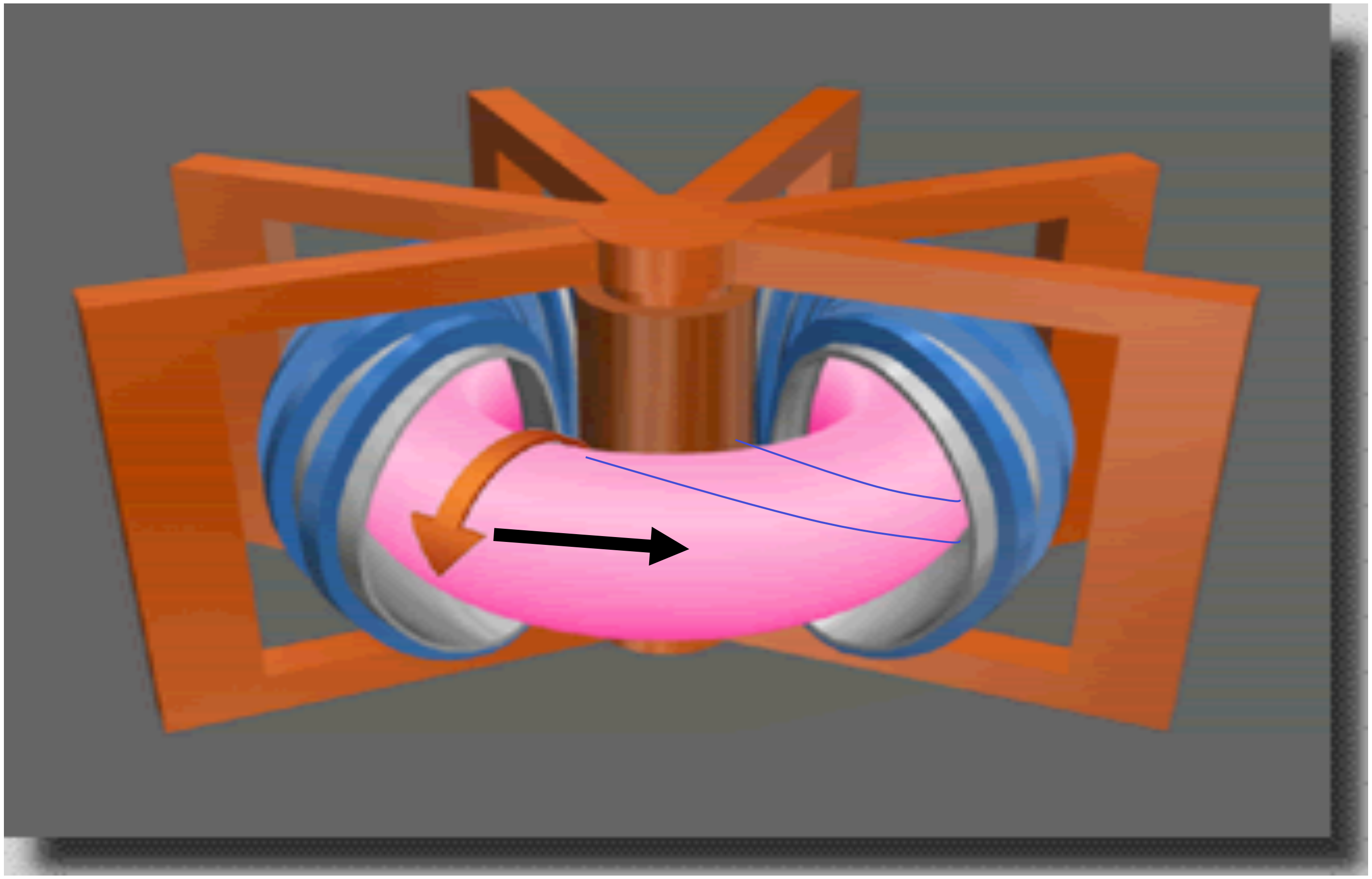
Tokamak concept

toroidalnaya **ka**mera **ma**gnitnaya **k**atushka=toroidal chamber and magnetic coil



The plasma current is induced by the transformer

Tokamak concept

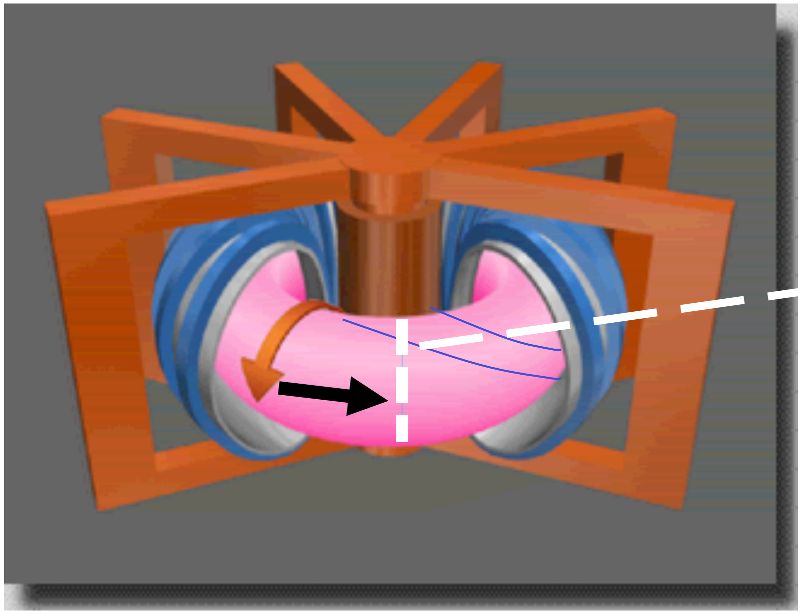


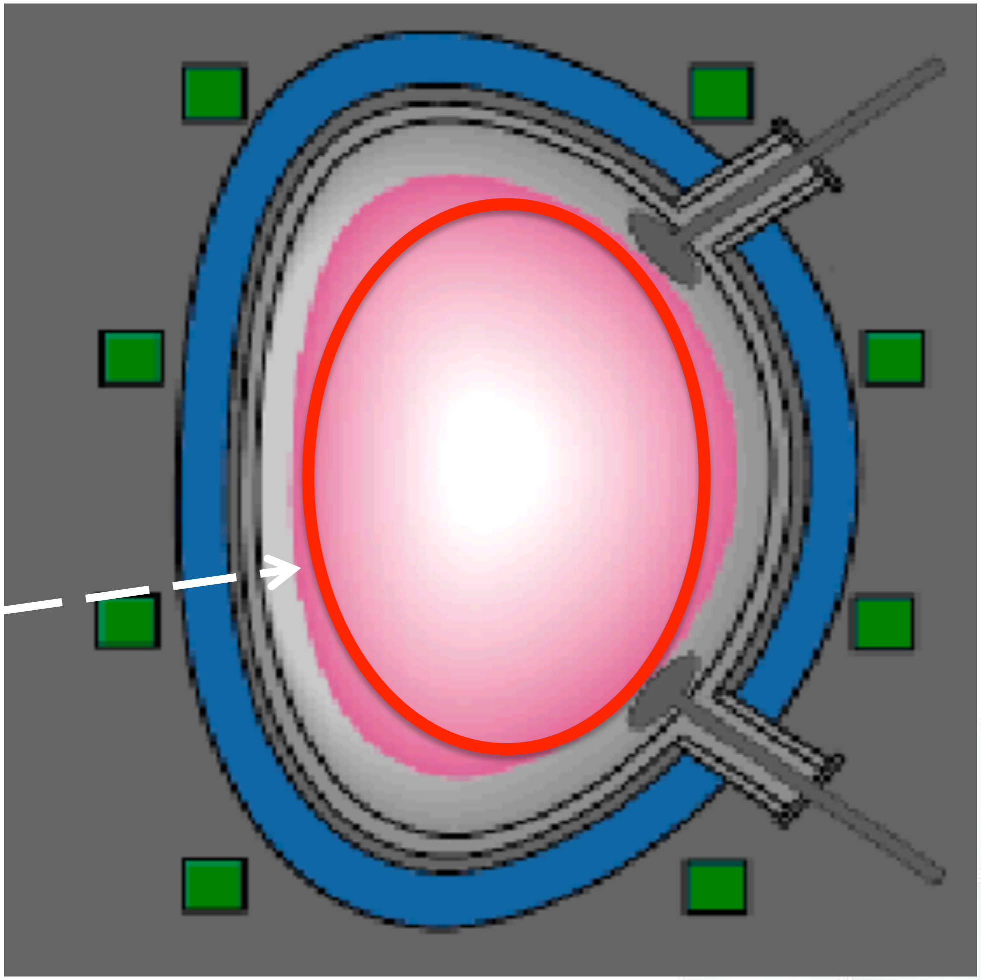
There is also a self-induced current by the bootstrap effect

$$j_{BS} \propto T\nabla n + 0.04\nabla T$$

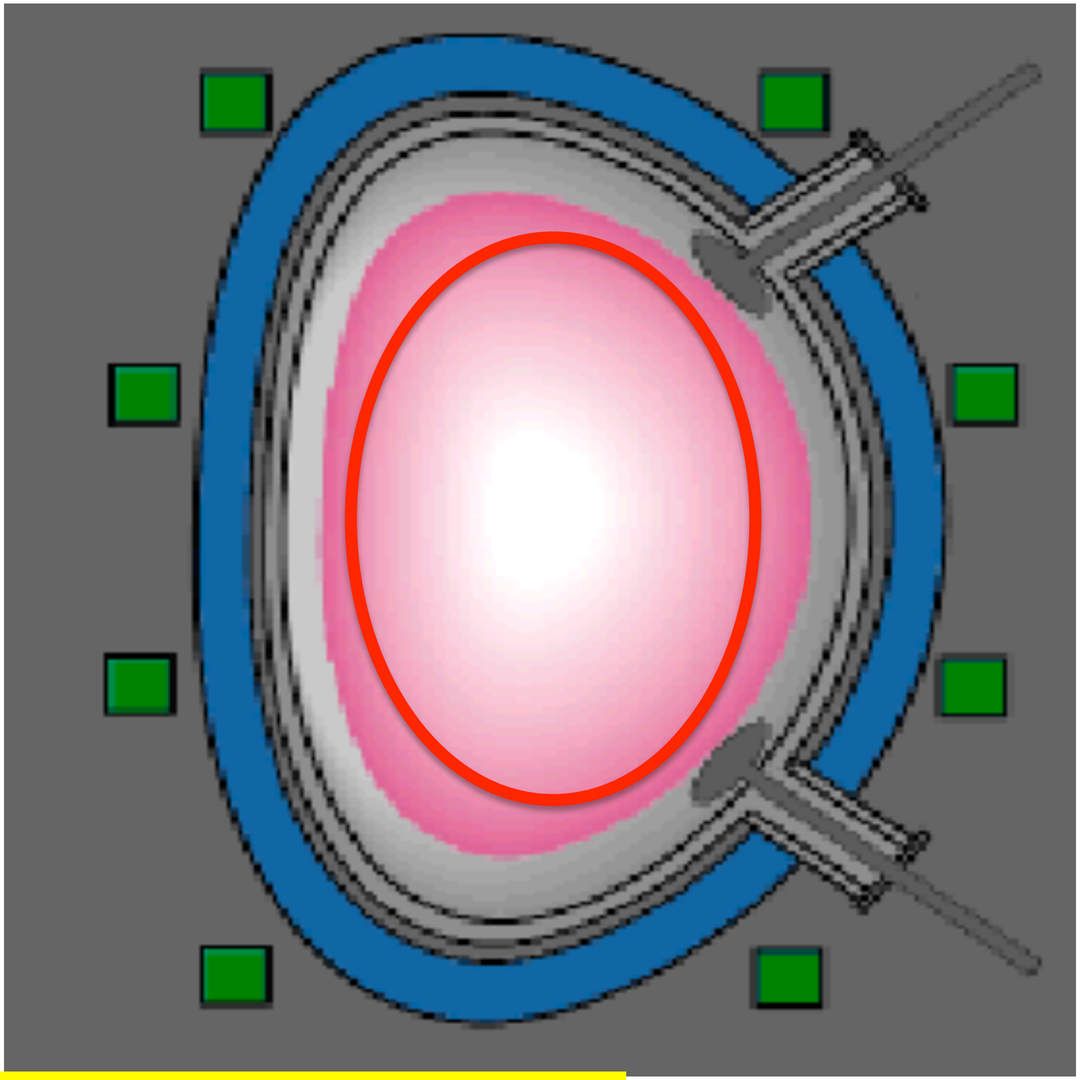
The diffusion of the current in the plasma column

Poloidal Section of the Plasma





The diffusion of the current in the plasma column



Poloidal Section of the Plasma

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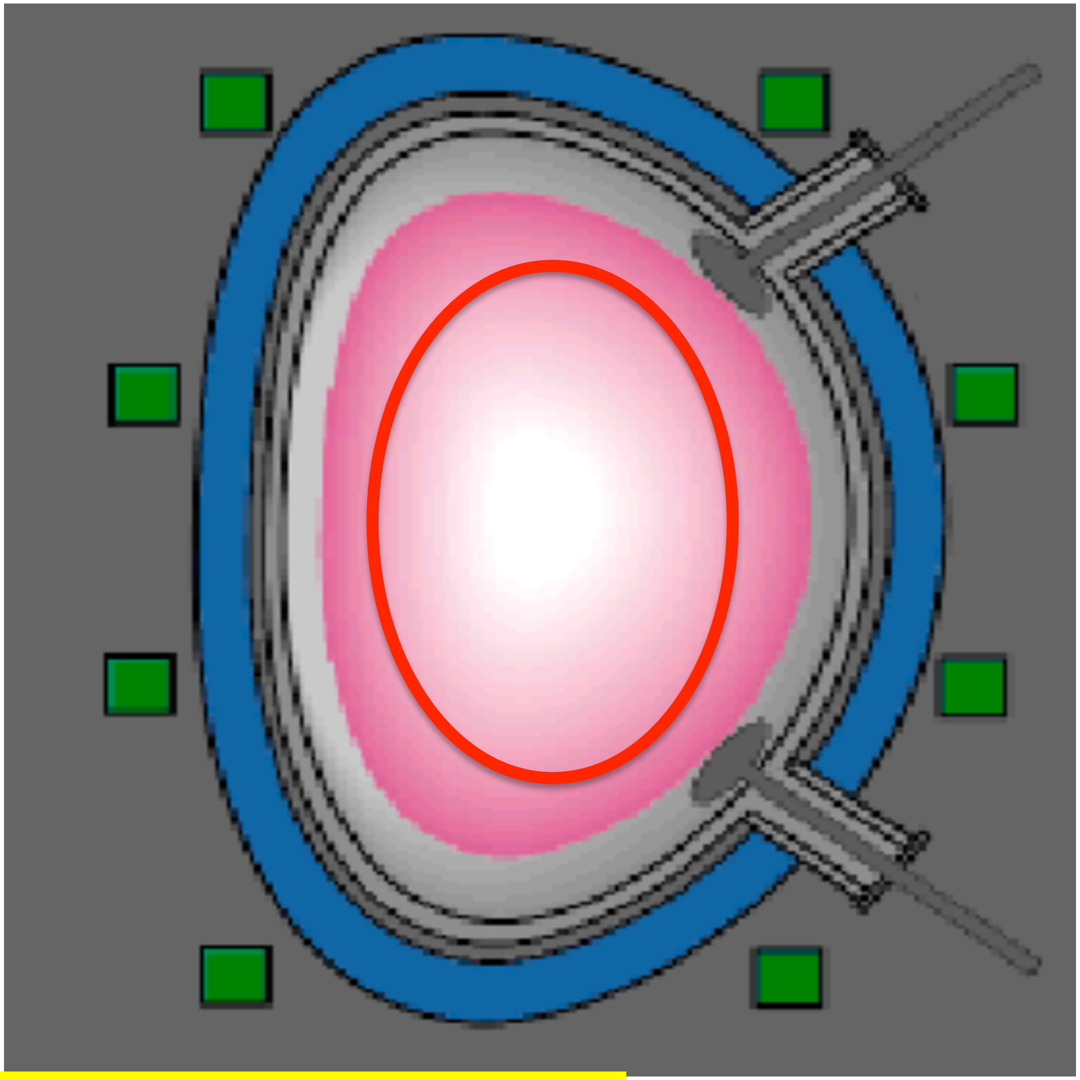

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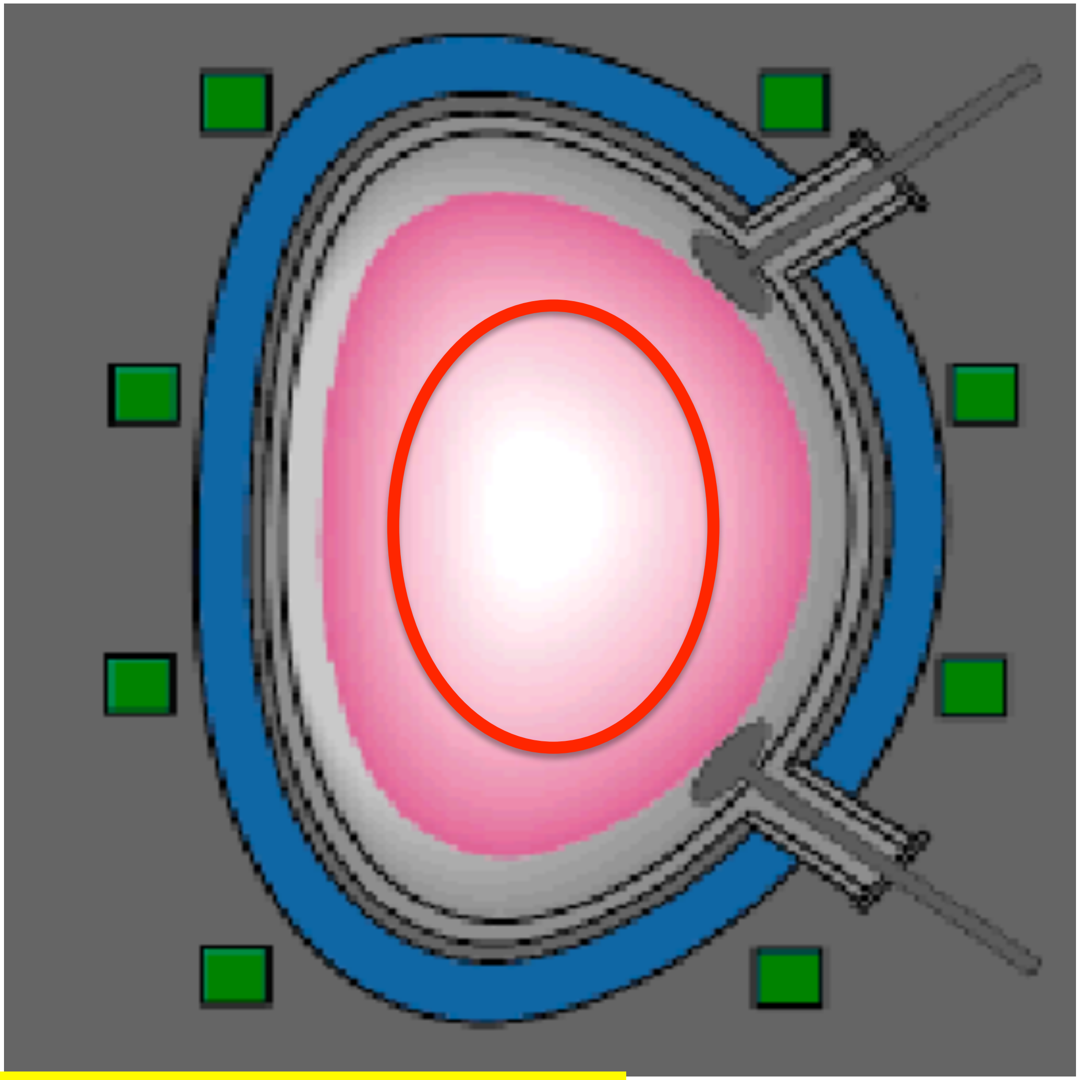

Poloidal Section of the Plasma

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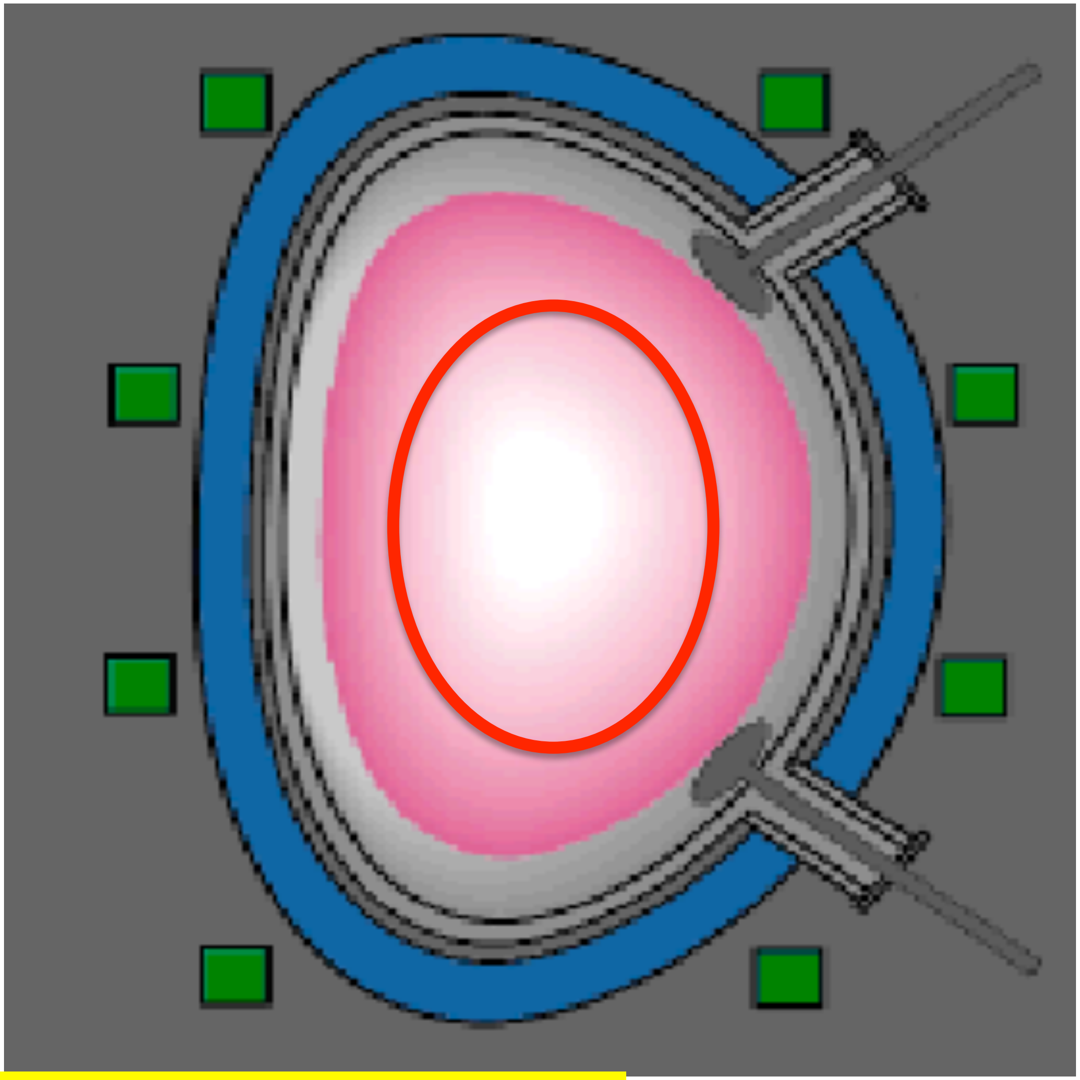
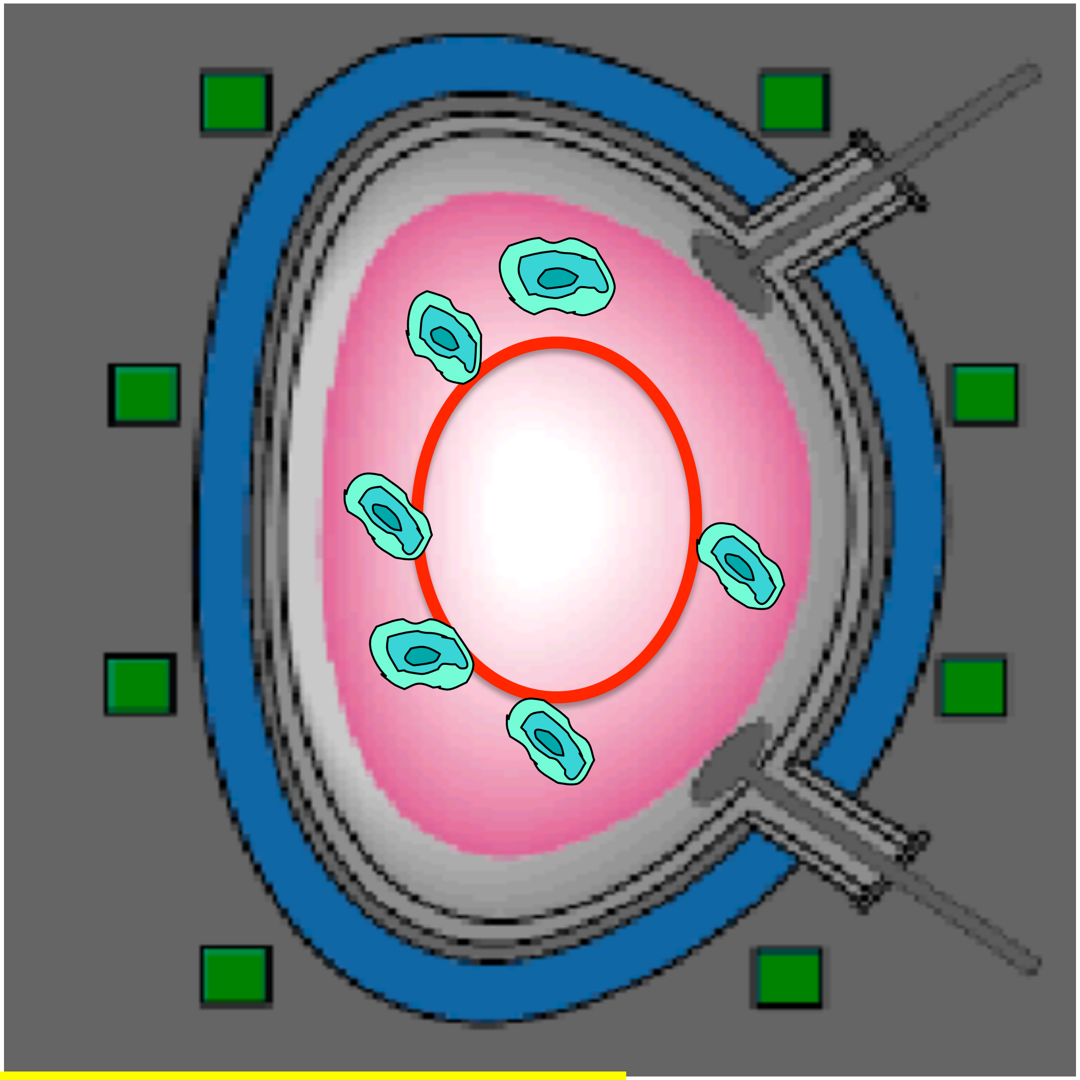


Poloidal Section of the Plasma

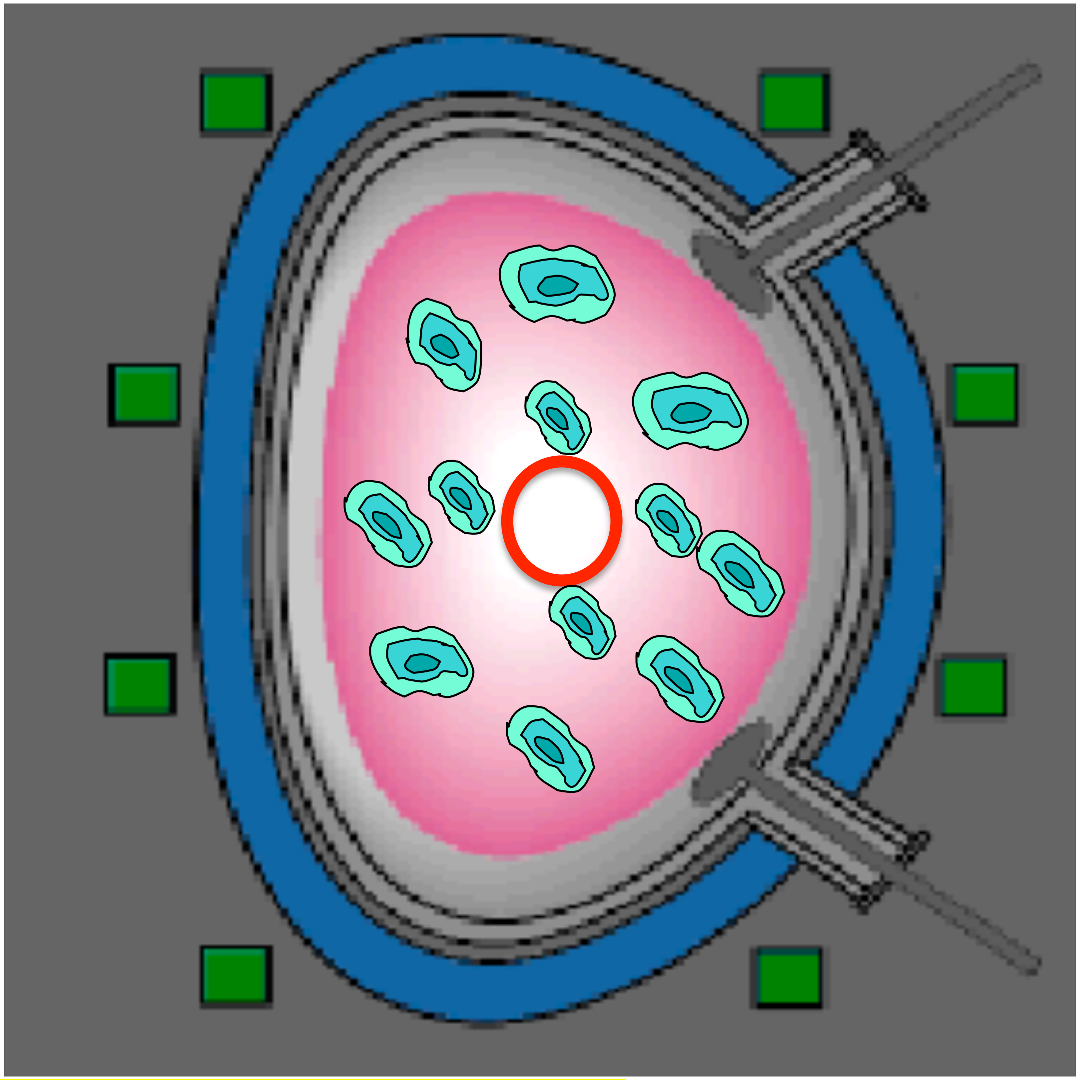
The diffusion of the current in the plasma column



Poloidal Section of the Plasma

The diffusion produces an unstable plasma state

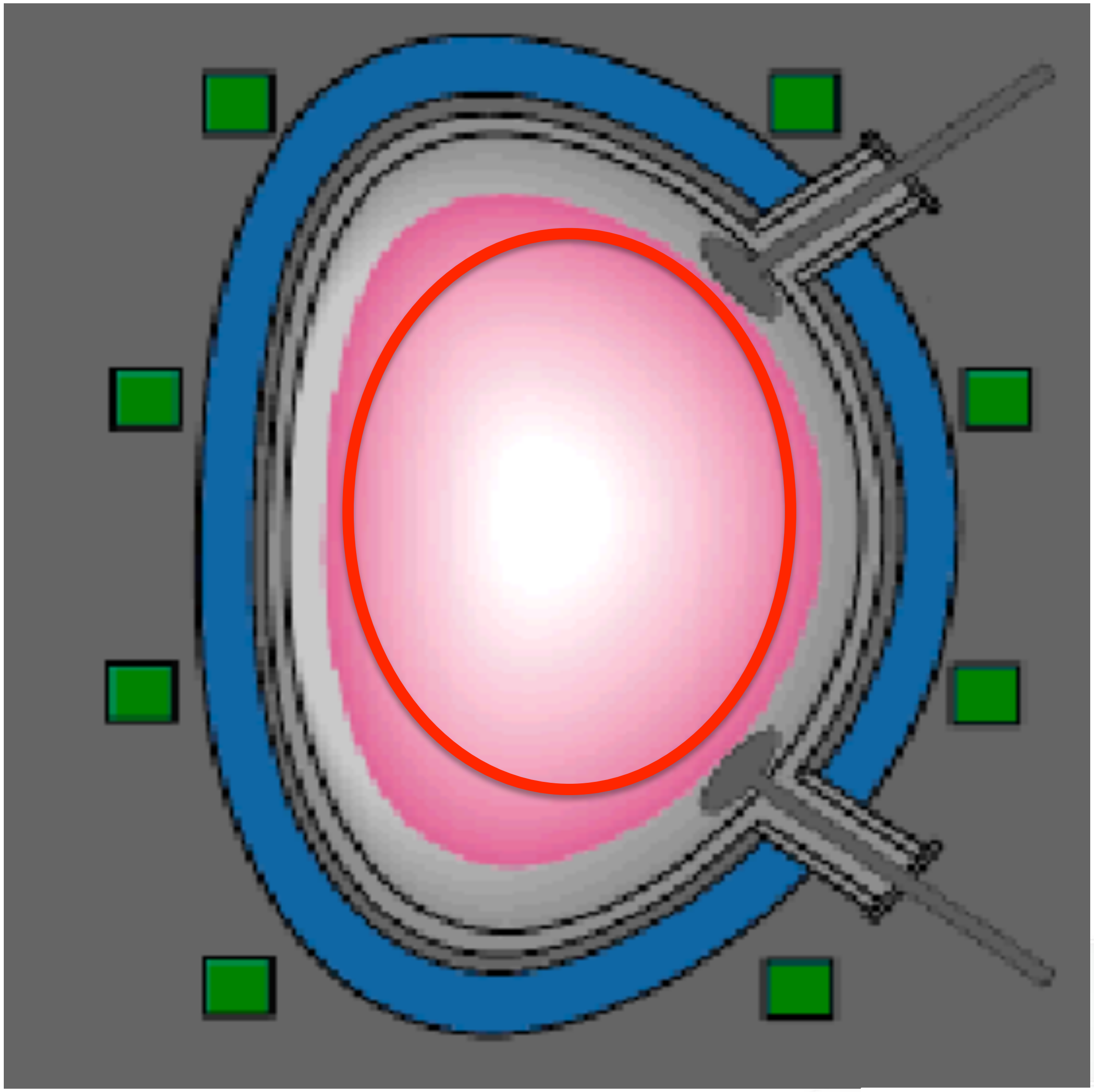
The diffusion of the current in the plasma column



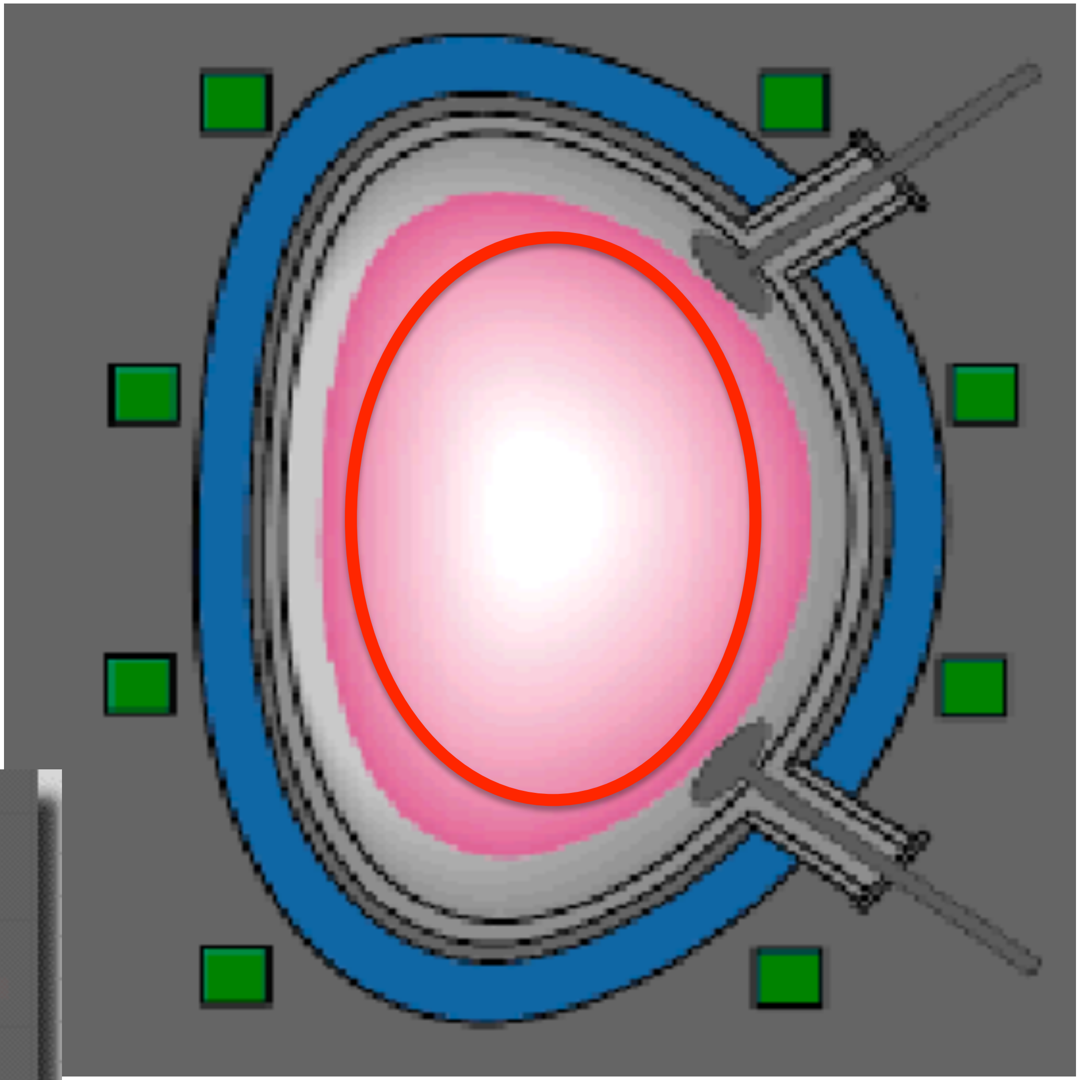
Poloidal Section of the Plasma

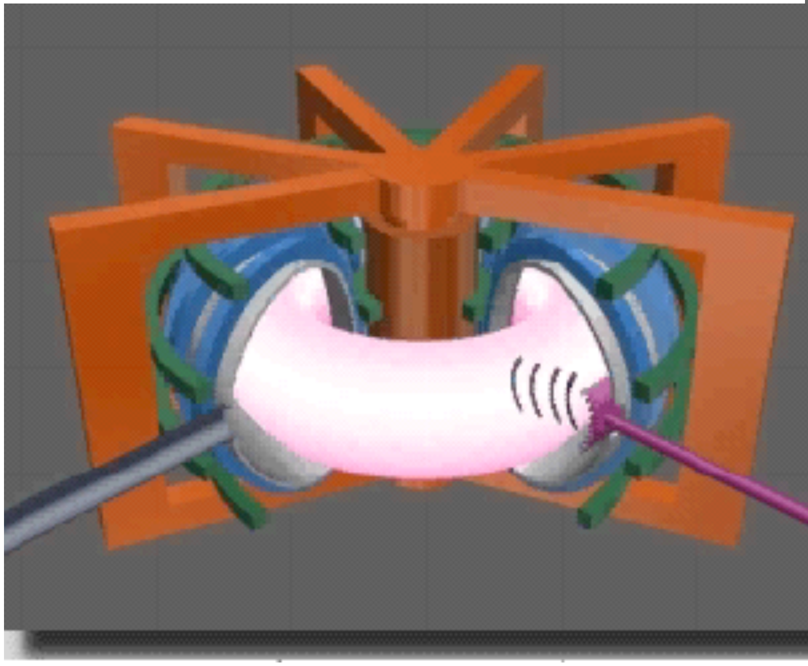
The current diffusion in the plasma column

A fundamental condition for the plasma stability of a reactor is to freeze the current diffusion and sustain the bootstrap current fraction



A fundamental condition for the plasma stability of a reactor is to freeze the current diffusion and sustain the bootstrap current fraction



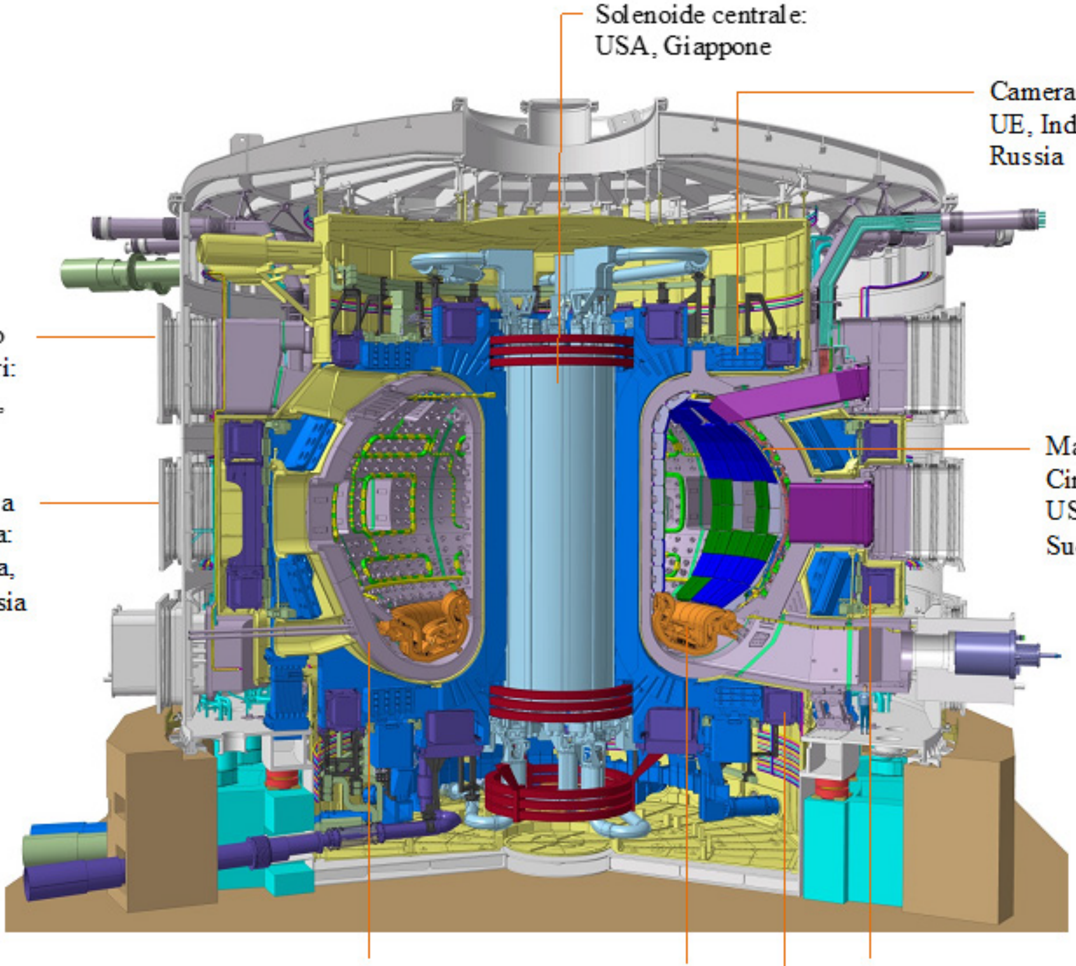


This task could be fulfilled by the RF current drive in LH domain

Scheme of the ITER reactor and of the main components and the indication of the responsible countries

E PLURIBUS UNUM

Diversi paesi membri realizzeranno i componenti di ITER



Solenoide centrale:
USA, Giappone

Camera da vuoto:
UE, India, Sud Corea,
Russia

Riscaldamento
con fasci neutri:
UE, Giappone,
India

Riscaldamento a
radio-frequenza:
UE, USA, India,
Giappone, Russia

Mantello:
Cina, Russia,
USA, Giappone,
Sud Corea, UE

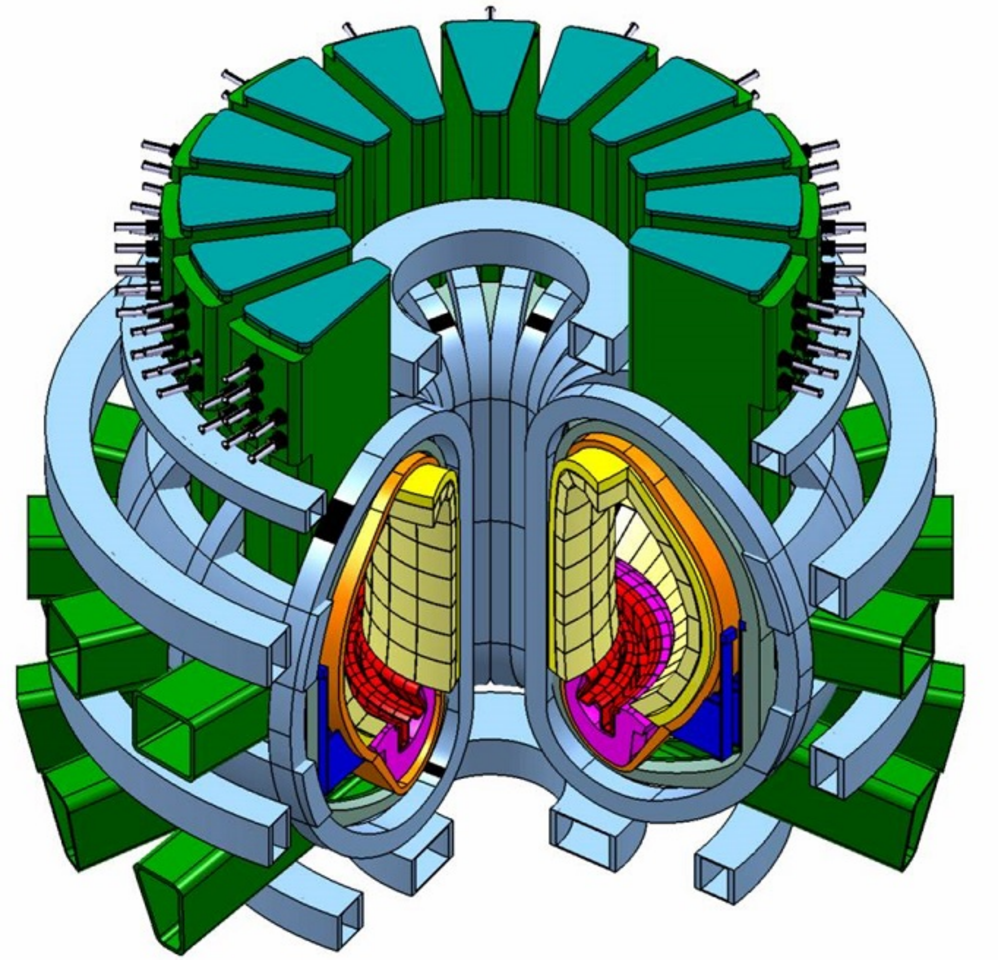
Bobine di campo
toroidale:
Giappone, USA,
UE, Russia, Cina

Divertore:
UE, Giappone,
Russia

Bobine di campo poloidale:
UE, Russia, Cina

ITER parameters
Species=D-T 50%
R=6,7m
a=2m
B=5T
I=9MA
n=10^14cm^-3
T=25keV=250MK

Scheme of EU DEMO DESIGN



DEMO EU parameters
Species=D-T 50%
R=9m
a=2.25m
B=6T
I=22MA
n=10^14cm^-3
T=25-30keV

ITER & DEMO

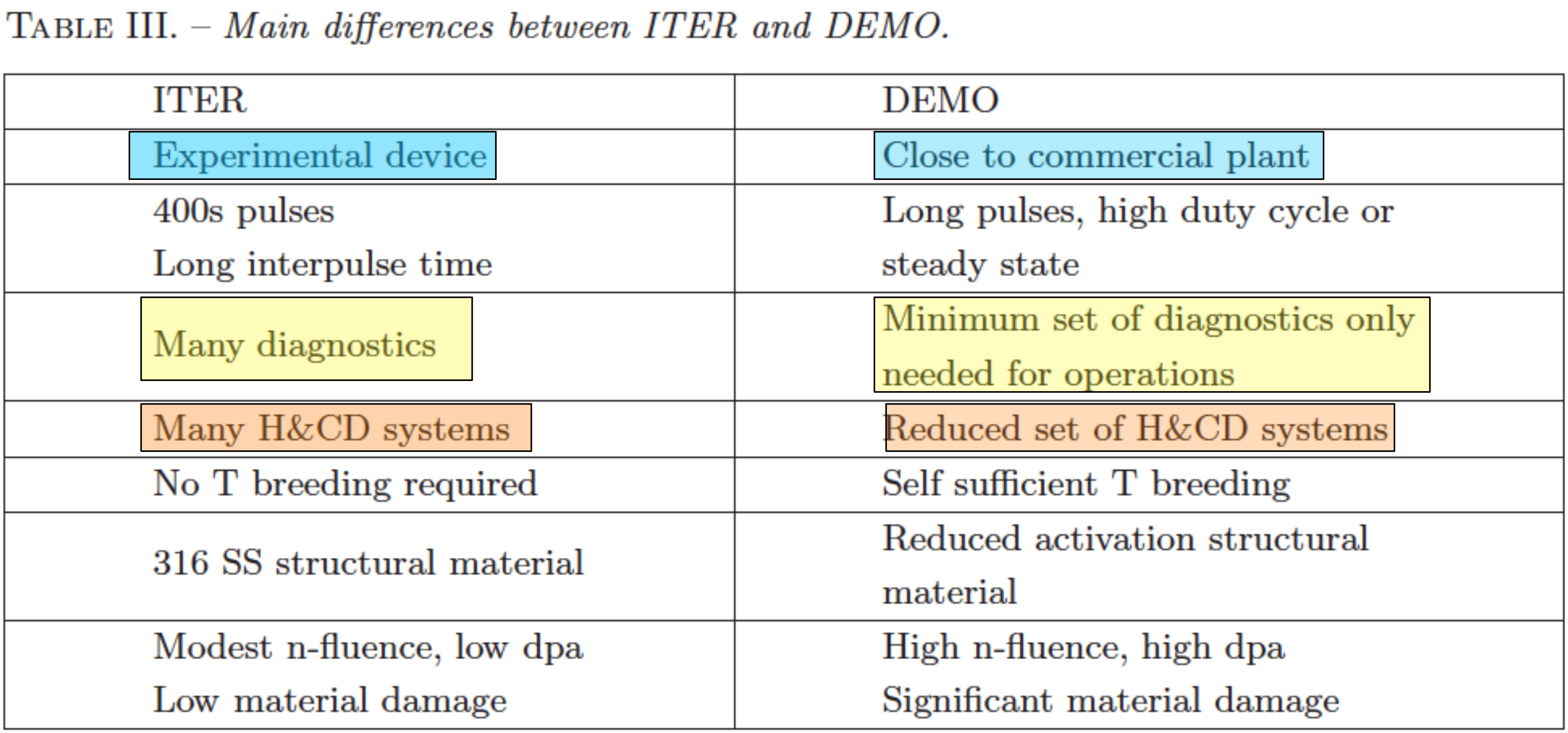


TABLE III. – *Main differences between ITER and DEMO.*

ITER	DEMO
Experimental device	Close to commercial plant
400s pulses Long interpulse time	Long pulses, high duty cycle or steady state
Many diagnostics	Minimum set of diagnostics only needed for operations
Many H&CD systems	Reduced set of H&CD systems
No T breeding required	Self sufficient T breeding
316 SS structural material	Reduced activation structural material
Modest n-fluence, low dpa Low material damage	High n-fluence, high dpa Significant material damage

General considerations

The current profile control is challenging for reactor:

- **Confinement**
  - An efficient tool at large radii is necessary for actively balancing the effect of the j_{BS} (fraction of current due to the density profile) fraction on *the global current* profile

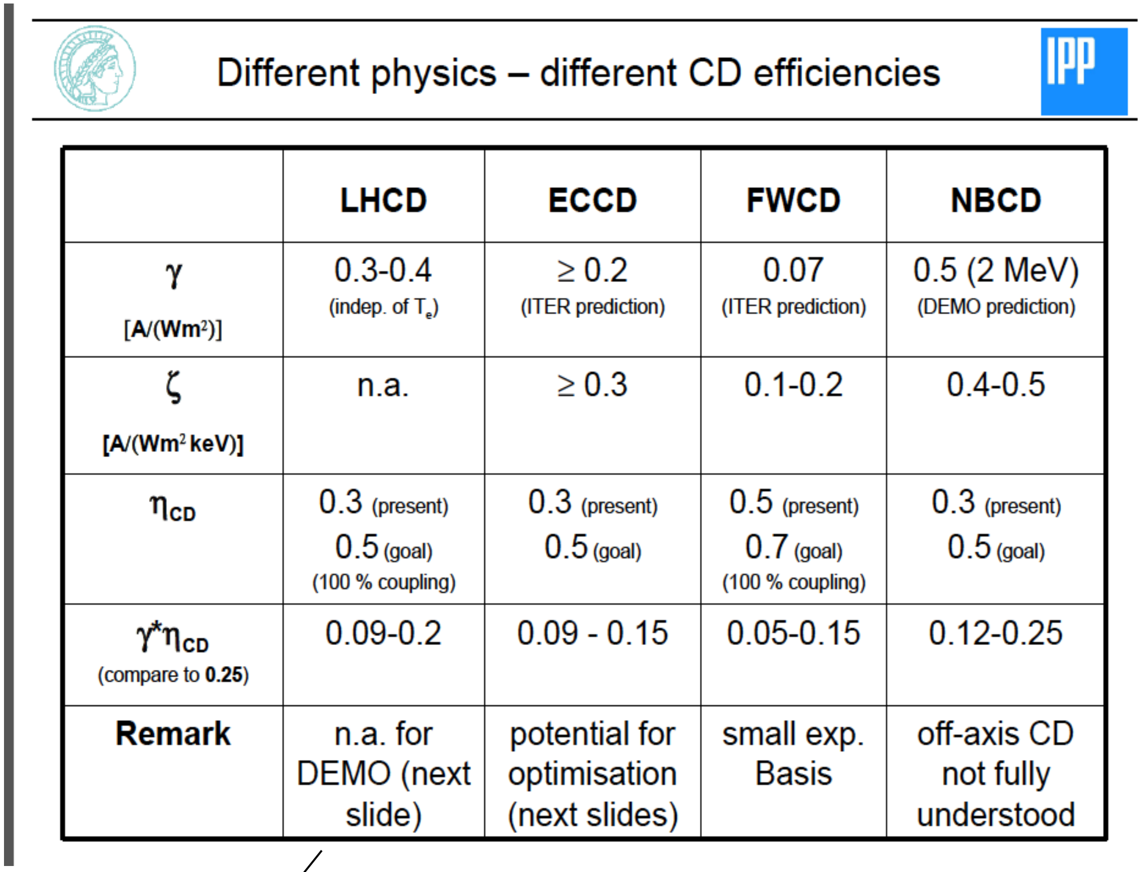
- **Stability**
  - Instabilities occur at plasma periphery (r/a≈0.8–1), and near the pedestal radial layer, where local *j* manipulation can produce successful effects.

See Communication by R. Cesario

Il problema della stabilità del plasma nel reattore a fusione nucleare

Current Drive has been considered for DEMO

H. Zohm et al. IAEA FEC 2012 paper FTP/3-3



Different physics – different CD efficiencies

	LHCD	ECCD	FWCD	NBCD
γ [A/(Wm^2)]	0.3-0.4 (indep. of T_e)	$\geq$ 0.2 (ITER prediction)	0.07 (ITER prediction)	0.5 (2 MeV) (DEMO prediction)
ζ [A/(Wm^2 keV)]	n.a.	$\geq$ 0.3	0.1-0.2	0.4-0.5
η_{CD}	0.3 (present) 0.5 (goal) (100 % coupling)	0.3 (present) 0.5 (goal)	0.5 (present) 0.7 (goal) (100 % coupling)	0.3 (present) 0.5 (goal)
$\gamma^*\eta_{CD}$ (compare to **0.25**)	0.09-0.2	0.09 - 0.15	0.05-0.15	0.12-0.25
Remark	n.a. for DEMO (next slide)	potential for optimisation (next slides)	small exp. Basis	off-axis CD not fully understood

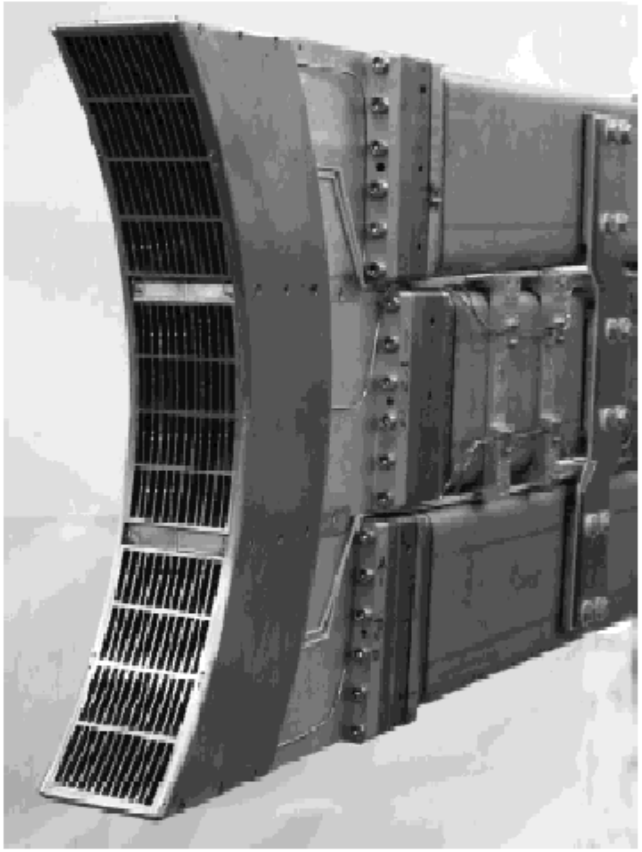
- CD has been considered for DEMO:
  - Three methods are based on RF
    - *LHCD*
    - *ECCD*
    - *FWCD*
  - One method is based on NBI

In the table the various efficiencies are compared.

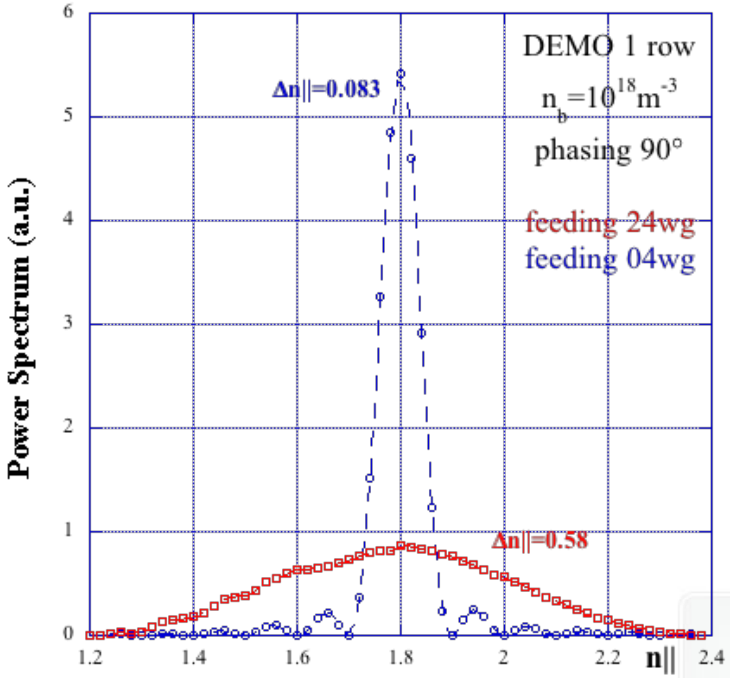
LHCD seems to be not suited for DEMO: absorption too far out in the plasma

Consequently the LH deposition is rather close to the edge and the j control is difficult

Coupling structure for LH waves



The LH waves are injected in a tokamak (and in particular in a tokamak reactor) by this kind of waveguide antenna whose power spectrum depends on the parallel (to the external magnetic field) wave-number.



The power spectrum is characterized by a $n_{||}$ peak and $\Delta n_{\parallel}$ width

General considerations of the physics of absorption

- In a reactor plasma, the window of accessibility of the LH wave is determined by

$$\left(n_{\parallel crit} \approx 1 + \frac{\omega_{pe}}{\Omega_{ce}} \right) < n_{\parallel} < \left(n_{\parallel ELD} \approx \frac{5-7}{\sqrt{T_e}} \right)$$

- *High density on one side and high temperature plasma* on the other hand, in principle, *reduce the window for the wave accessibility*.

General considerations of the physics of absorption

- Quasi-linear effects on the other hands, move (relaxes) the upper limit of the "window"

$$\left(n_{\parallel crit} \approx 1 + \frac{\omega_{pe}}{\Omega_{ce}} \right) < n_{\parallel} < n_{\parallel QL} \approx \left(\frac{6-8}{\sqrt{T_e}} \right)$$

- In this situation the possibility of having an accessible window for the power spectrum becomes realistic.

- In this study we have explored the possibility to exploit such window to drive current in ITER and DEMO *in a plasma zone (outer half radius) useful for controlling the current profile*.

Simulation by the "RAY^{star}" numerical code

The problem of the propagation and absorption of the LH Wave in tokamak reactor has been simulated by the RAY^{star} numerical code. This code is composed by various modules

1) **physics of the edge (LHPI)** (study of the NL plasma-wave interaction (like PDI) to exclude parasitic phenomena)

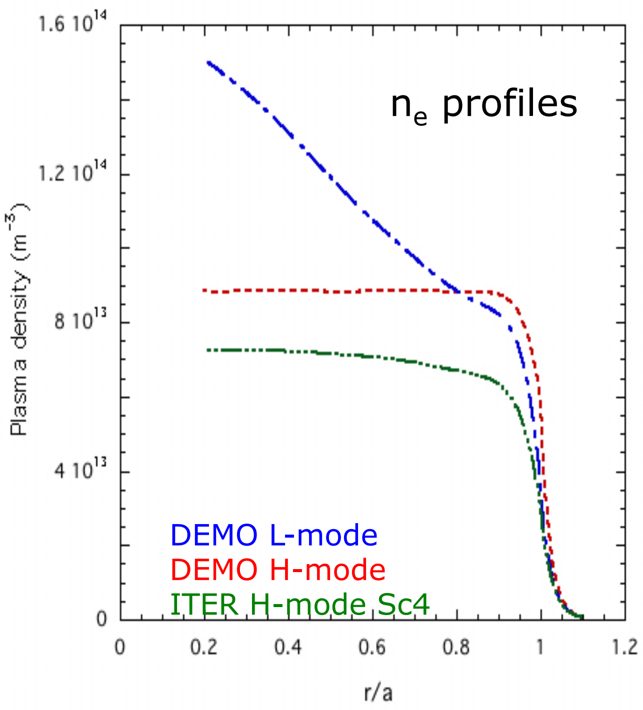
2) **antenna-plasma coupling module (Grill3D)** (study of the linear antenna-plasma coupling and determination of the coupled power spectrum)

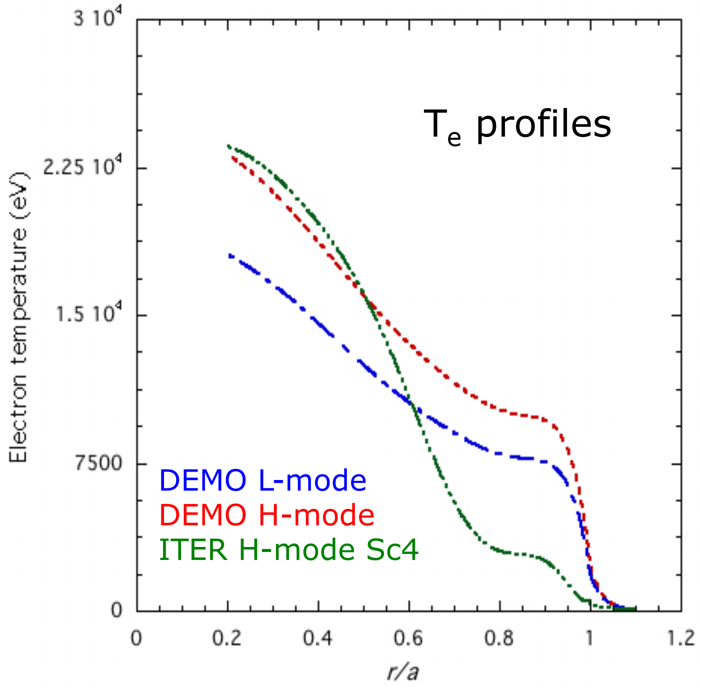
3) **Ray-Tracing in flux function coordinate** (propagation of the em field via WKB analysis (ray trajectories for phase and power))

4) **2-D relativistic Fokker-Planck module with inclusion of trapped electrons** (solution of the FP equation for the electron distribution function in the velocity space, by considering the quasi-linear diffusion due to to the propagating wave)

and it uses the kinetic profiles (density and temperature profiles) as resulting from the ASTRA transport code

The plasma profiles for DEMO and ITER Sc4, as resulting from the transport code ASTRA





Two sets of kinetic profiles, calculated using the transport code ASTRA [1], have been considered for DEMO:

1) The first one assumes a peaked density profile

2) the second set assumes flat density inside the H-mode pedestal as for the ELMy H-mode scenario for ITER.

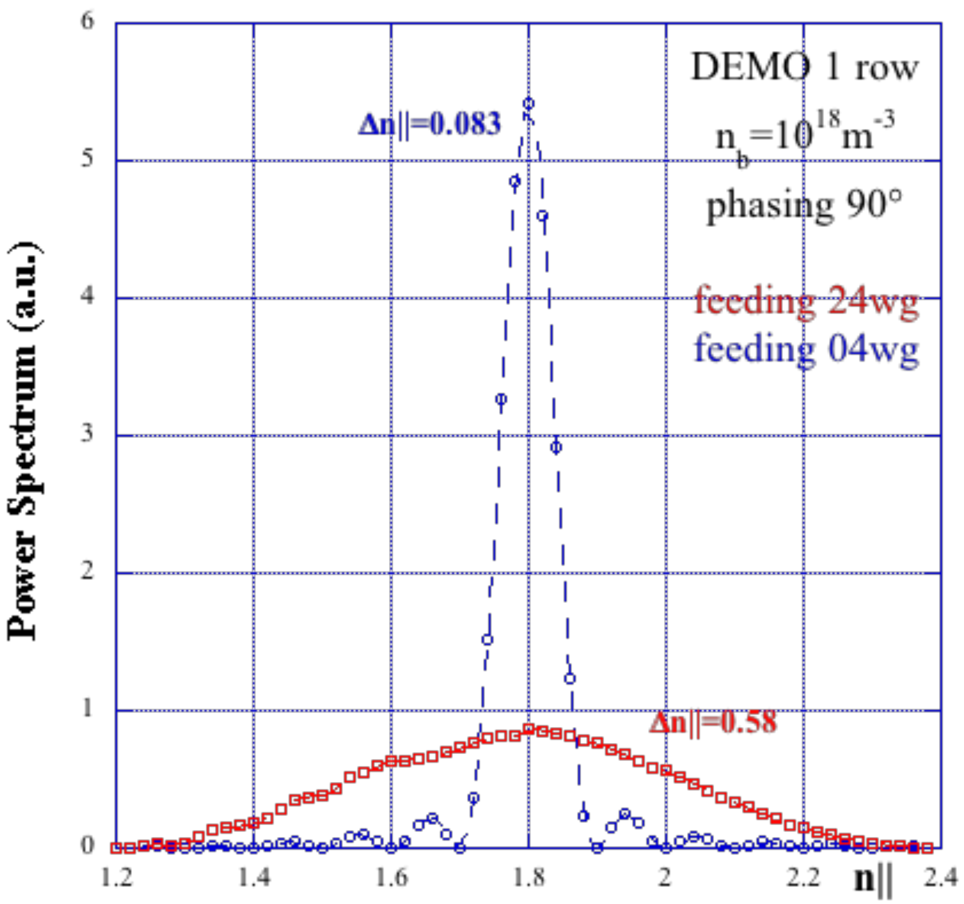
3) for ITER the so-called Sc4 has been considered [2]

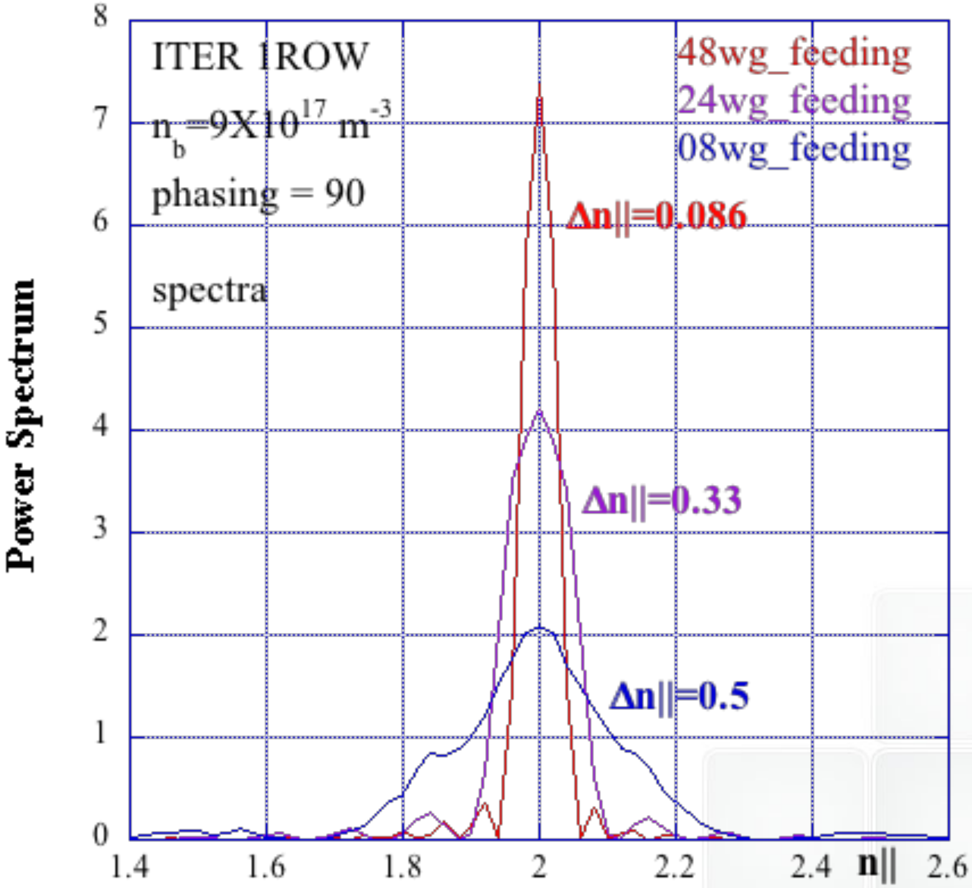
[1] G. Tardini, Private Communications, 2013.
[2] G. T. Hoang et al., Nucl. Fusion **49** 075001 (2009).

The power spectra for DEMO (left) and ITER (right) as results from the ***Grill-3D coupling code***.

These spectra, and those with intermediate widths in between, are obtained by setting suitable phasing and feeding of waveguides.

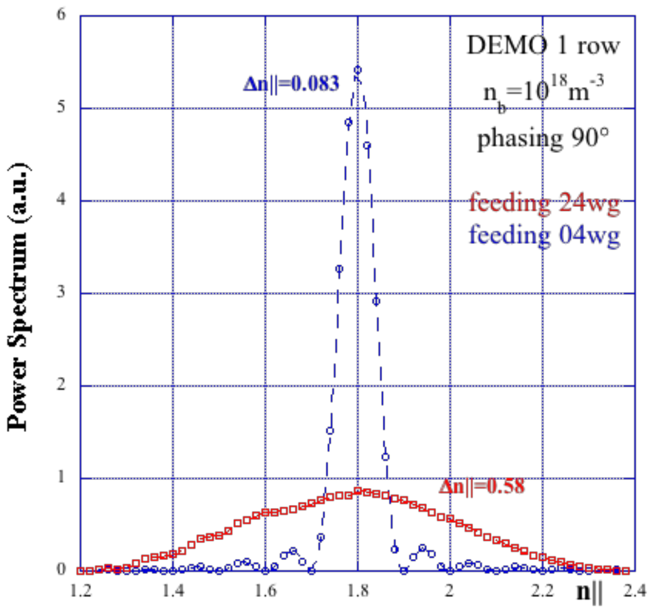
[Ref. M. A. Irzak and O. N. Shcherbinin, "Theory of Waveguide Antennas for Plasma Heating and Current Drive," Nucl. Fusion, 35, 1341 (1995).

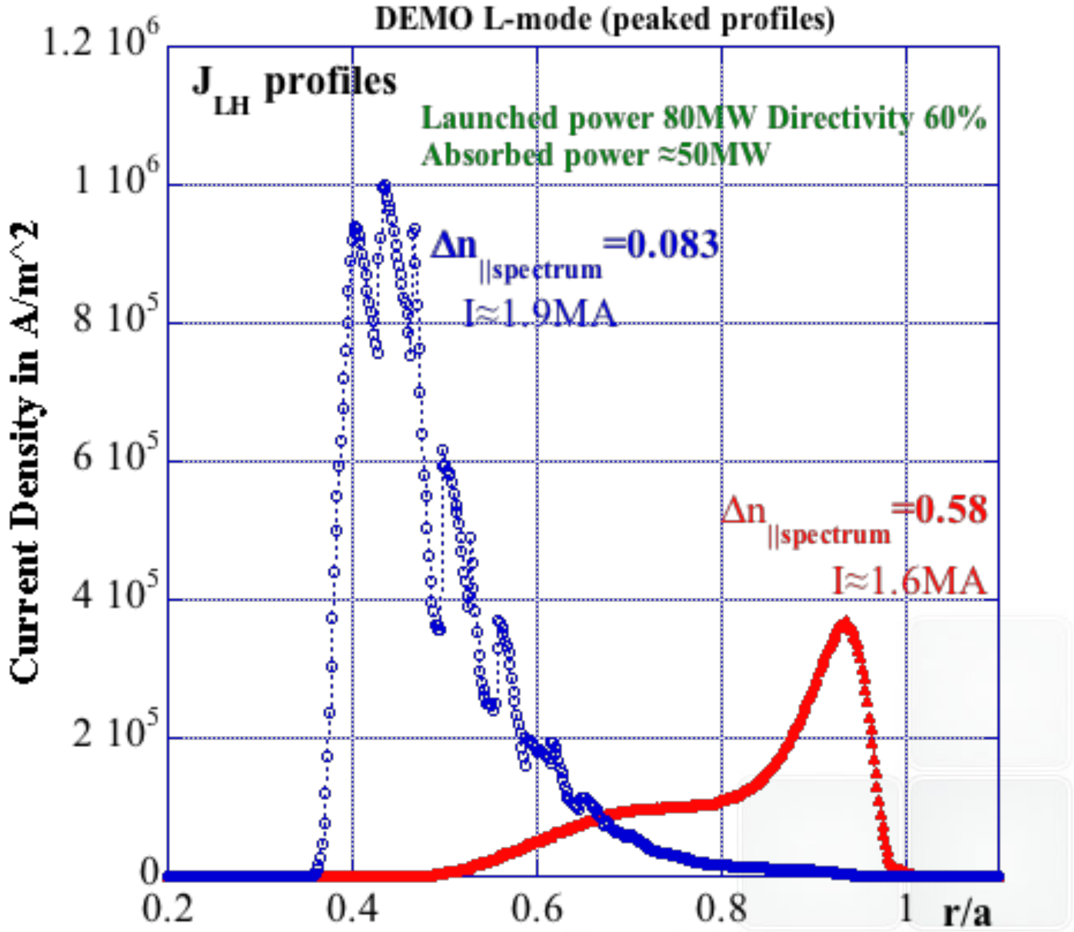




Numerical results: *DEMO L-mode* peaked profiles

1) 80MW launched at f=5GHz
2) 50MW absorbed for CD on the main lobe of the spectrum
3) The remaining power is in electron heating
4) Efficiency for both spectra is around 0.25



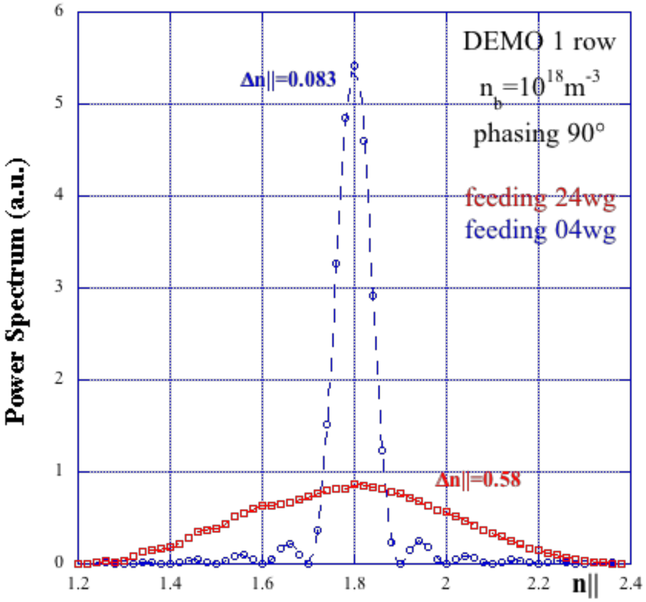


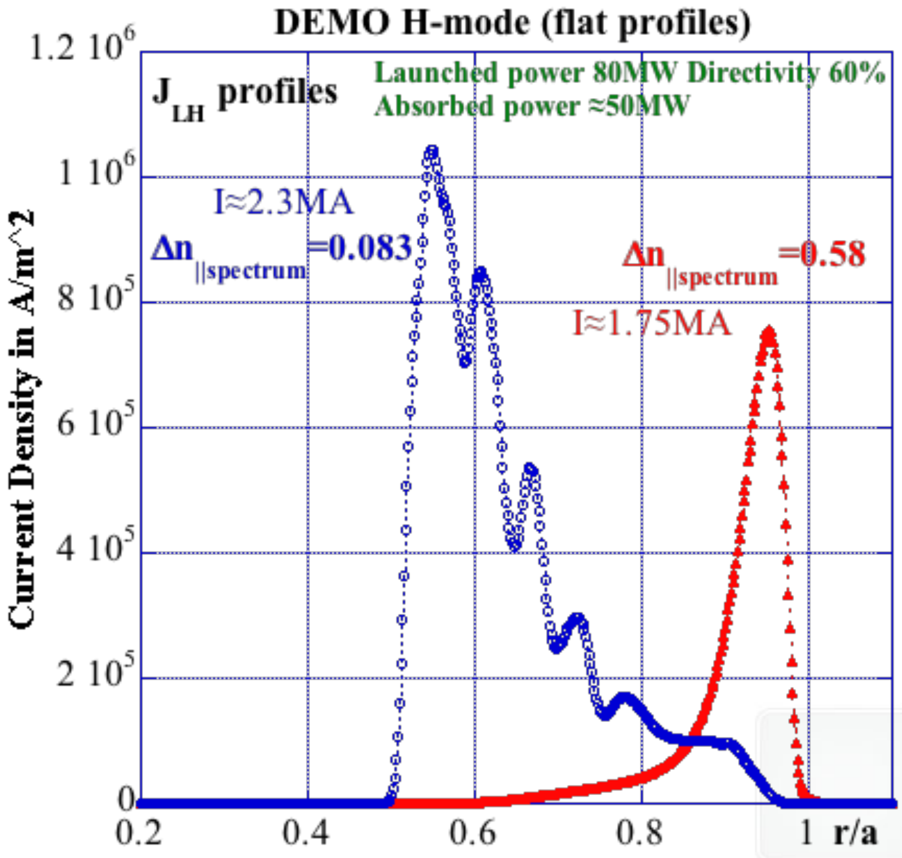
Narrower antenna spectrum enables LHCD in the core of DEMO

Numerical results: *DEMO H-mode* flat profiles

Narrower antenna spectrum enables LHCD in the core of DEMO

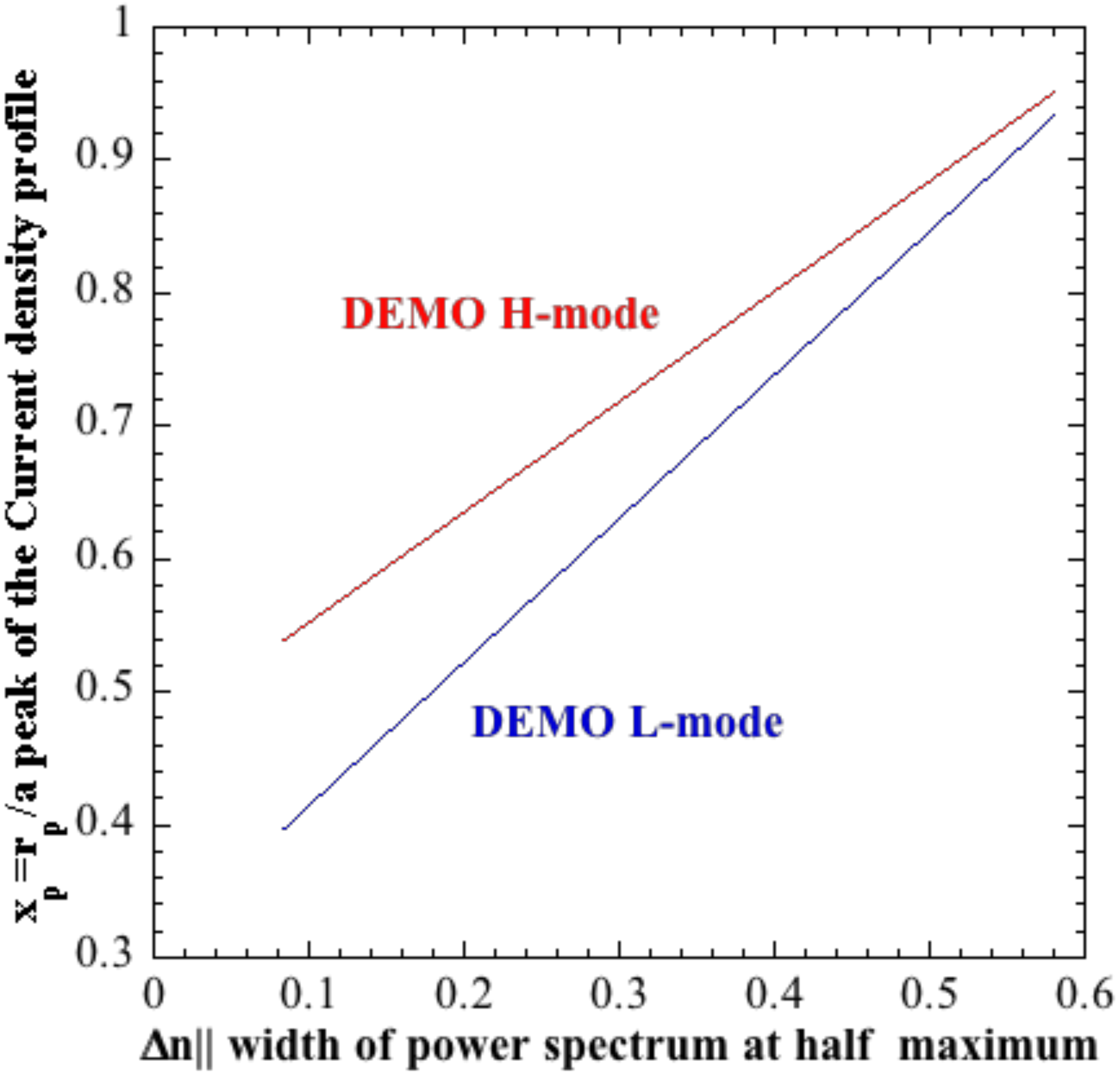
1) 80MW launched at f=5Ghz
2) 50MW absorbed for CD
3) 2.3 MA generated around half-radius in the case of narrow spectrum
4) 1.75 MA generated near the separatrix in the case of large spectrum
5) Efficiency 0.25-0.3





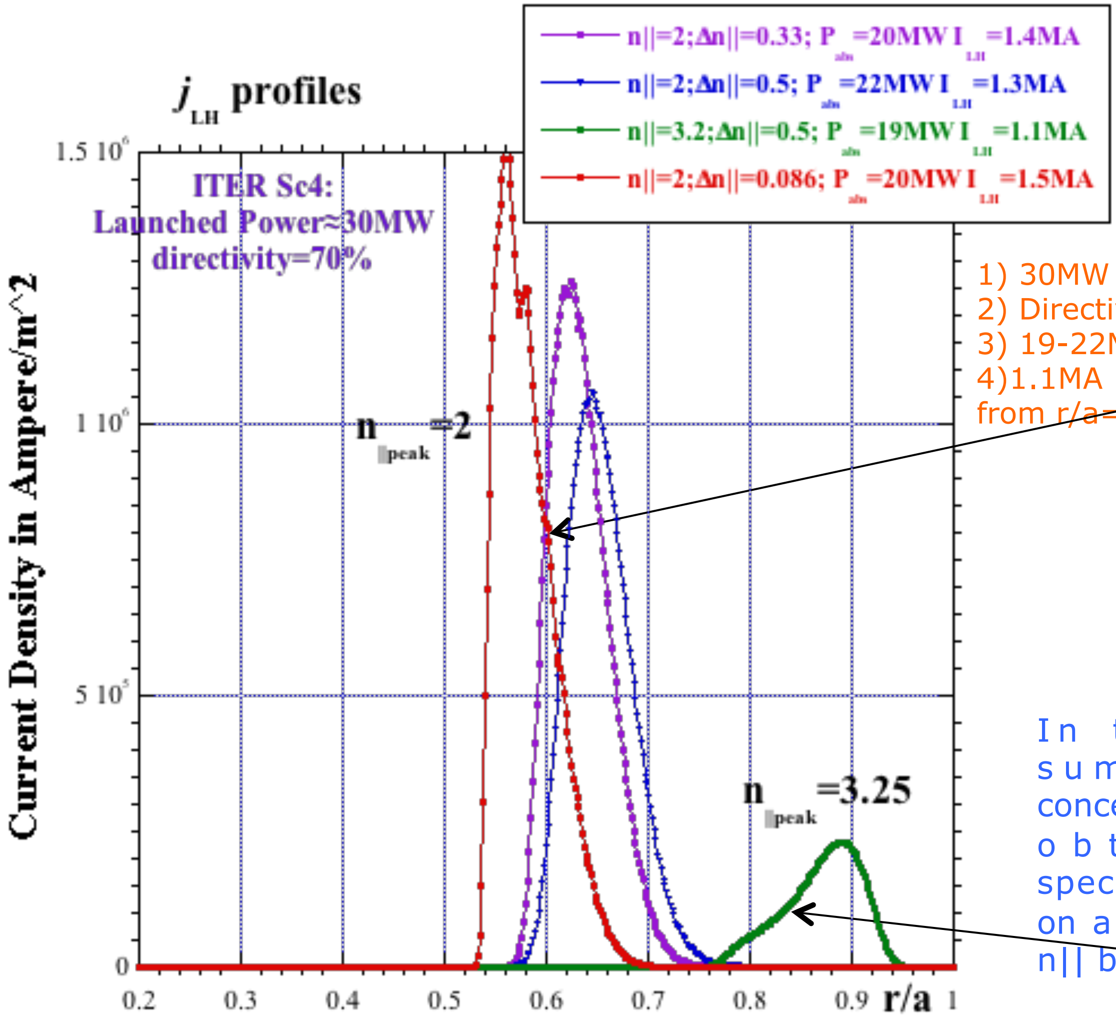
Narrower antenna spectrum enables LHCD in the core of DEMO

Numerical results: DEMO L&H-mode: scan of the deposition layer as function of the spectrum width

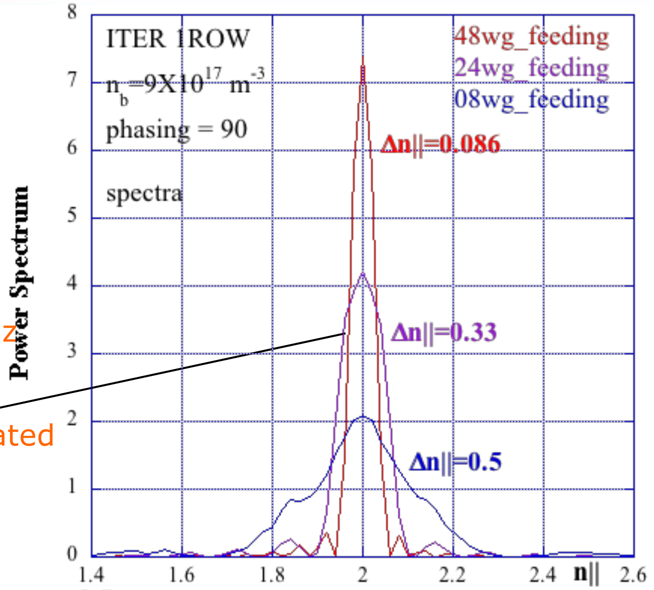


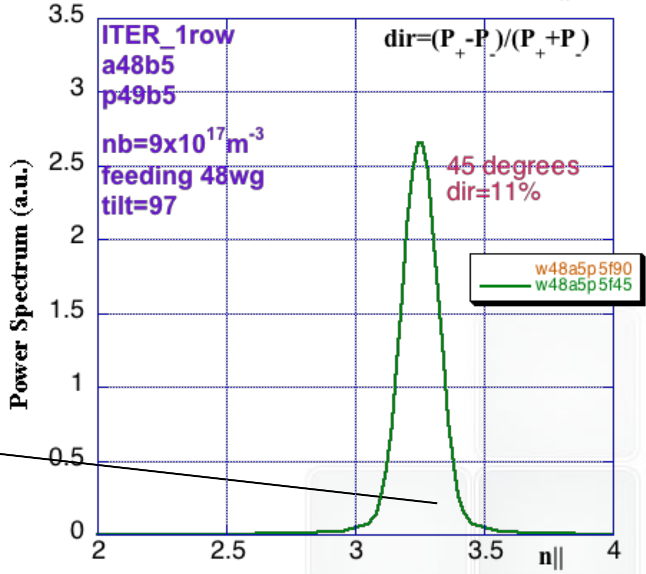
The location of the peak of the LH driven current density profile is plotted against the $n_{||}$-width of the coupled antenna power spectrum.

Numerical results: ITER Sc4 H-mode profiles



1) 30MW launched at f=5GHz
2) Directivity 70%
3) 19-22MW absorbed
4)1.1MA to 1.4MA generated from r/a=0.55 up to 0.9





In this plot is summarized a conceptual study for obtaining a spectrum centered on a higher value of n|| by using Grill3D.

In ITER, in order to control the deposition layer from internal to external zones is necessary, not only to change the width of the spectrum, but also its peak value

Analytical considerations

In order to elucidate the calculation mechanism we will outline an analytical solution of the quasi-linear-ray-tracing system equations based on the 1D Fokker-Planck equation [C. C. F. Karney, N. J. Fisch, Phys. of Fluids **22** 1817 (1979)]

Equation system: Ray-Tracing + Quasi-linear damping

$$\frac{d\vec{\rho}}{dt} = \frac{\partial \varepsilon}{\partial \vec{k}}$$

$$\frac{d\vec{k}}{dt} = \frac{\partial \varepsilon}{\partial \vec{r}}$$

ε **is the Hamiltonian dispersion relation**

$$\frac{dP}{dt} = -2\Gamma_{QL}\left(\omega, k_\perp, k_\parallel, x, \theta, P\right) P$$

$$\frac{\partial f_e}{\partial t} = \frac{\partial}{\partial v_\parallel}\left(D_{RF}\frac{\partial f_e}{\partial v_\parallel}\right) + \left(\frac{\partial f_e}{\partial t}\right)_{coll}$$

The link with the quasi-linear theory is in the power damping rate equation where it is necessary to construct the quasi-linear damping rate Γ_{QL}

Analytical considerations

The quasi-linear damping is

$$\Gamma_{QL} = -\frac{1}{2}\sqrt{\frac{\pi}{2}}\frac{\omega_{pe}^2}{\left(k_\perp^2 + k_\parallel^2\right)u_{the}^2}\left.\frac{\partial f_e(u)}{\partial u}\right|_{u=\frac{\omega}{k_\parallel u_{the}}} =$$

$$= \sqrt{\frac{\pi}{2}}\frac{\omega_{pe}^2}{\left(k_\perp^2 + k_\parallel^2\right)u_{the}^2}\left(\frac{\omega}{k_\parallel u_{the}}\right)\left(\frac{0.5\left(2+Z_i\right)}{0.5\left(2+Z_i\right)+\left(\omega/\left(k_\parallel u_{the}\right)\right)^3 D\left(\omega/\left(k_\parallel u_{the}\right)\right)}\right)\exp\left\{-0.5\left(2+Z_i\right)\int_u \frac{u}{\left(0.5\left(2+Z_i\right)+u^3 D(u)\right)}du\Bigg|_{u=\frac{\omega}{k_\parallel u_{the}}}\right\}$$

$f_e(u)$ comes from the solution of 1D Fokker-Planck equation
[C.F. Karney and N. Fisch, Phys. of Fluids **22** 1817 (1979)]

$$D(x,u) = -\frac{8\pi^2}{\omega^2}\left(\frac{e^2}{m_e^2}\right)\left(\frac{1}{u_{the}^2\nu_{ee}}\right)\frac{c}{u_{the}|u|}\frac{k_\parallel^2}{k_\perp^2\left(k_\parallel, x\right)}\left(\frac{1}{\partial_{k_\perp}\varepsilon}\right)\frac{P_{density-cgs}\Sigma_{antenna}}{\Sigma_x}\hat{P}\left(\vec{x}, k_\parallel\right)\Big|_{k_\parallel=\frac{\omega}{u_{the}u}}$$

For comparison the linear damping is

$$\Gamma_{Lin} = \sqrt{\frac{\pi}{2}}\frac{\omega_{pe}^2}{\left(k_\perp^2 + k_\parallel^2\right)u_{the}^2}\frac{\omega}{k_\parallel u_{the}}\exp\left\{-\frac{1}{2}\left(\frac{\omega}{k_\parallel u_{the}}\right)^2\right\}$$

Analytical considerations

By comparing Γ_{QL} and Γ_{Lin} results that Γ_{QL} appears much weaker with respect to the linear damping this means that the quasi-linear layer is much internal then the linear one

$$\frac{\Gamma_{QL}}{\Gamma_{Lin}} \approx \frac{(1-\rho)_{LIN}}{(1-\rho)_{QL}} = \frac{\Delta\rho_{LIN}}{\Delta\rho_{QL}} \approx \frac{\exp\left(\frac{\alpha}{D}\frac{\Delta u}{u_1 u_2}\right)}{1+u_1^3 D \big/ \alpha} << 1$$

when $D(u)u_1u_2 >> \Delta u$ and $D >> \frac{\alpha}{u_1^3}$

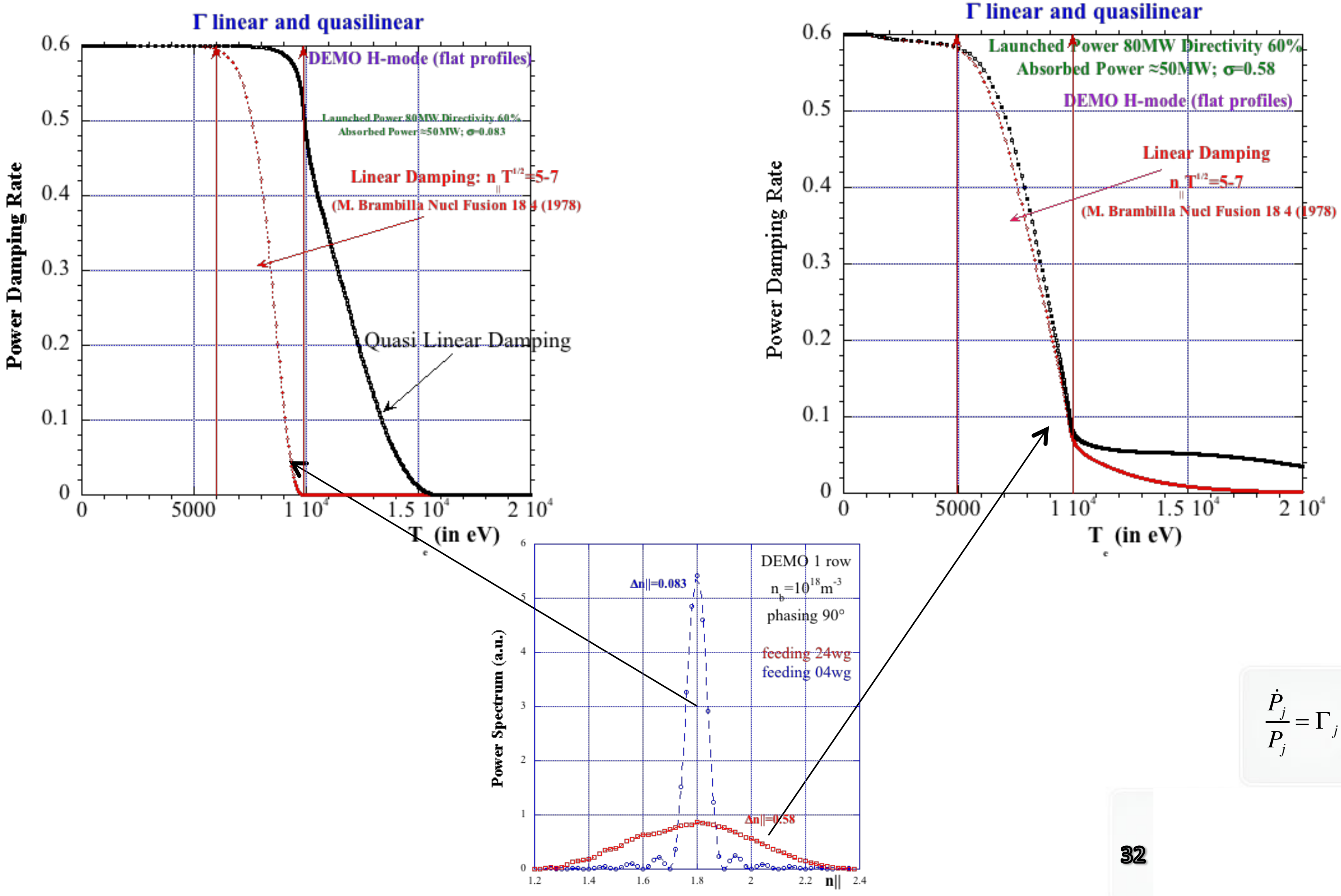
in the opposite limit or when $\frac{D(u)u_1u_2}{\Delta u} = O(1)$ this condition is no more fulfilled and the quasi-linear damping does not differ so much from the linear.

$$\frac{\Gamma_{QL}}{\Gamma_{Lin}} = O(1)$$

Note that $\rho = 1$ is the plasma edge and $\rho = 0$ is the plasma center

Quasi-Linear Damping rate vs the local temperature and the effect of the width of the Power spectrum

It is worth to compare now the quasi-linear damping rate with the linear one (when the distribution function is simply a "Maxwellian" without distortion due to the wave plasma interaction. This is an example of *DEMO H-mode flat profiles*.

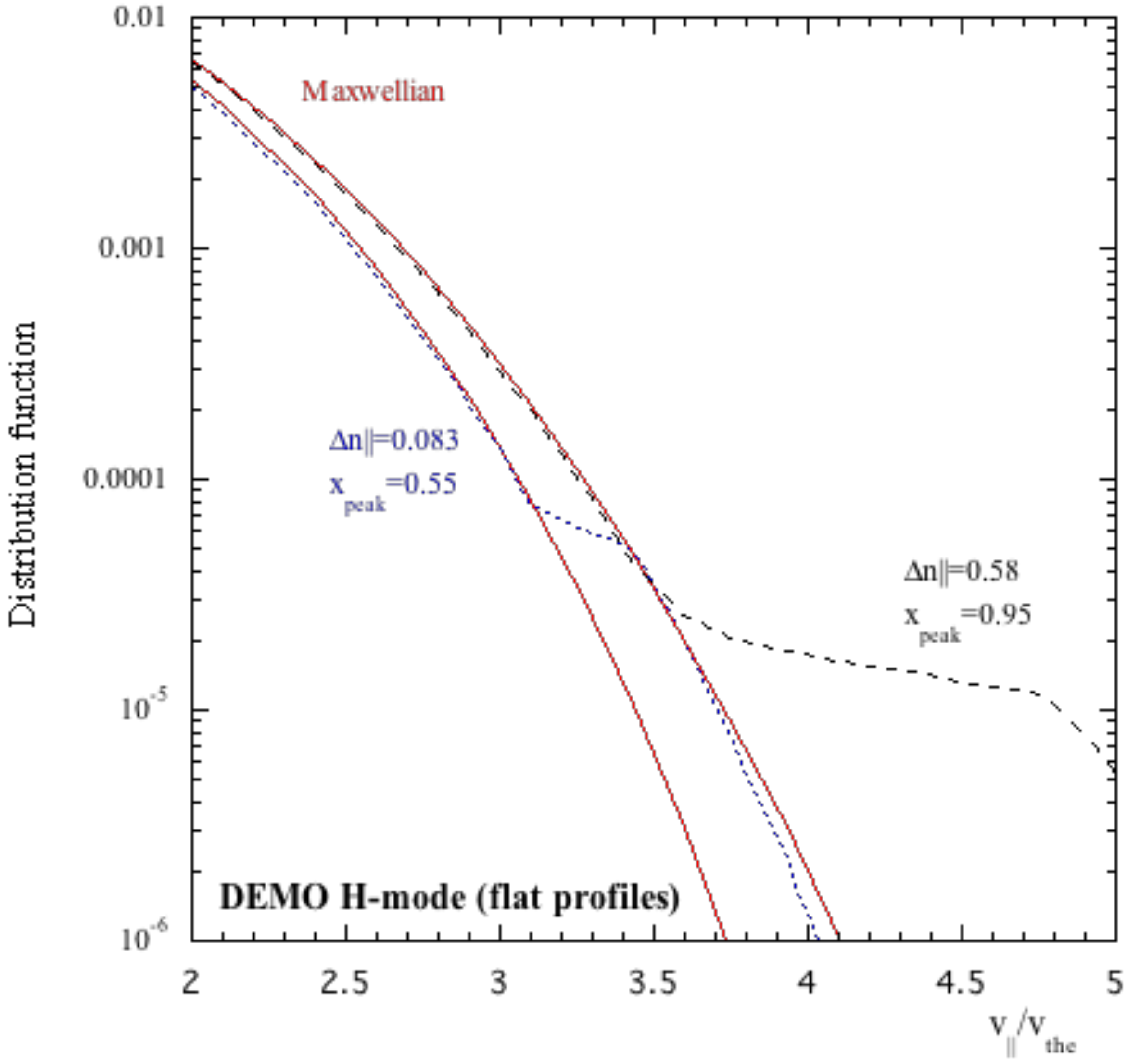


$$\frac{\dot{P}_j}{P_j} = \Gamma_j \Rightarrow P = \sum_j P_j$$

Conclusions

- A self-consistent modeling of the LH wave for DEMO & ITER has shown, by properly considering QL effect of a strong LH power coupled to high density and temperature plasma:
    - that is possible to control the CD layer in DEMO in the outer half radius of the plasma by opportunely changing the width of the power spectrum, keeping fixed the peak value.
    - that is possible in ITER to do the same by acting on the width of the spectrum and on the peak value.
- The active control is operated by the antenna design, involving a suitable *power spectrum and wavenumber control*.
- The full numerical approach, including 2D ray-tracing, 2D Fokker-Planck, 3D antenna-plasma coupling, PDI threshold calculation, has been supported by analytical considerations.

Addenda: Distribution function



Addenda: Alpha Particles Physics with LH

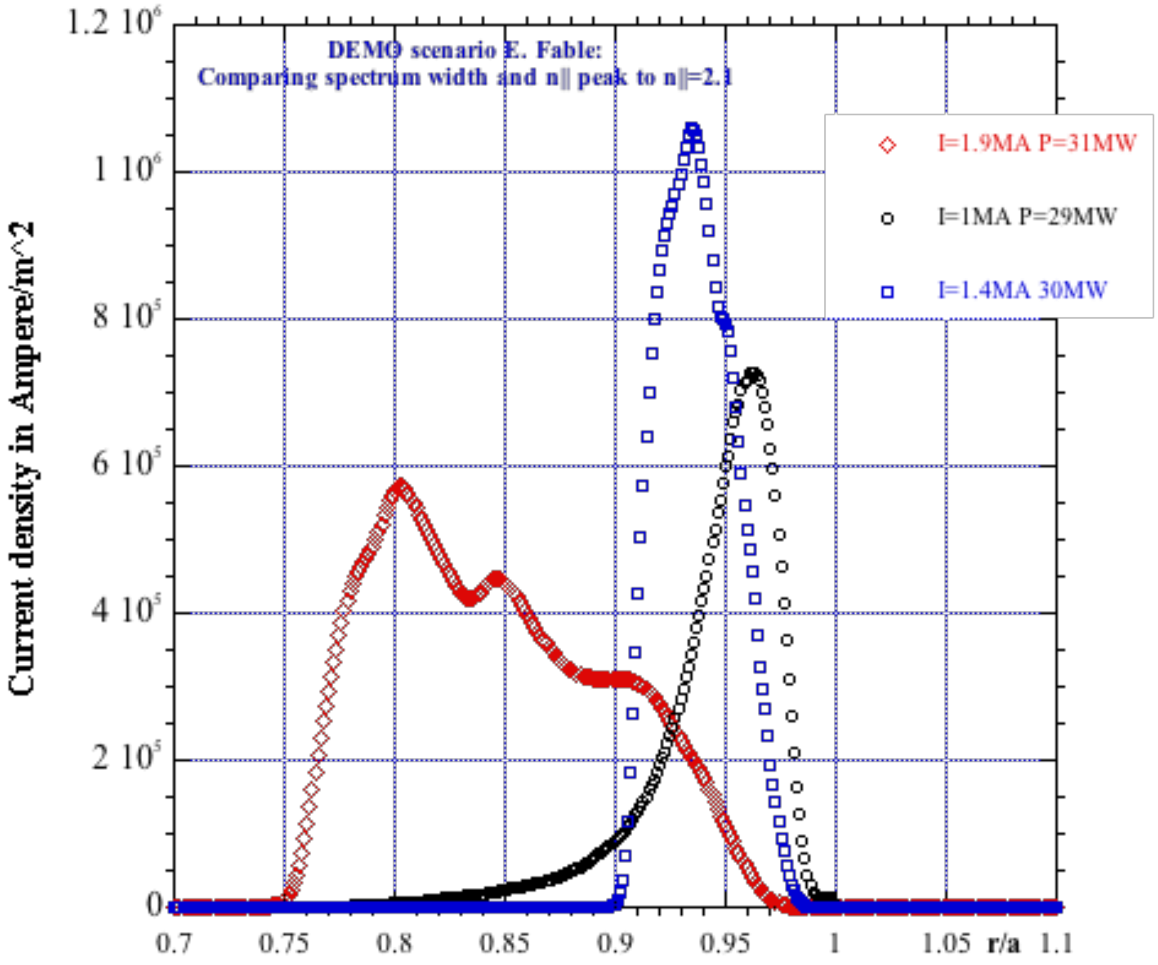
Indications regarding the proper frequency for current drive operation in a reactor have been obtained by performing 1-D simulations for a number of plasma parameters. When these parameters are the standard ones, a frequency of 5 GHz is sufficiently high to guarantee that no wave absorption by alpha particles will occur.

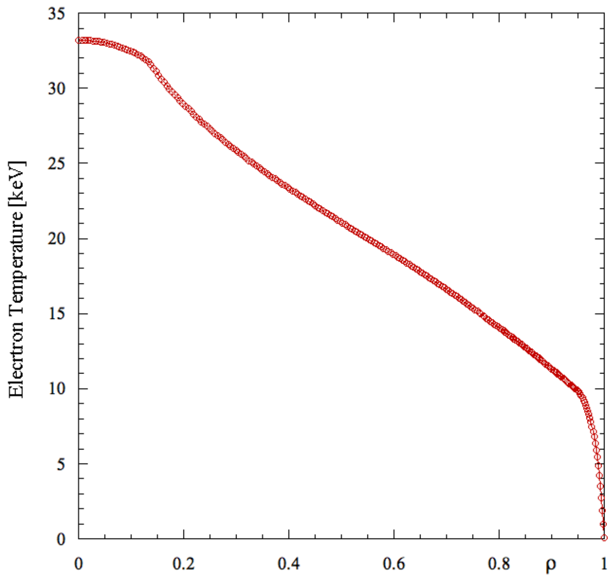
P. Bonoli, M. Porkolab, Nucl. Fusion 27 13441 (1987)
E Barbato, F. Santini, Nucl Fusion 31 683 (1991)
N. Fisch, JM Rax, Nucl. Fusion 32 549 (1992)
M. Schneider, L.-G. Eriksson, F. Imbeaux, J-F. Artaud, Nucl. Fusion 49 125005 (2009)

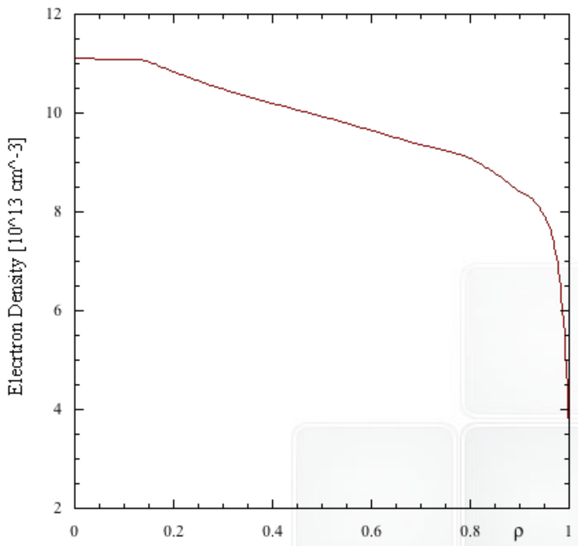
In particular

for f=5GHz and $n_{||}=2$ and r/a=0.5 $P_{alpha}=0$
for f=5GHz and $n_{||}=2.5$ and r/a=0.5 $P_{alpha}=0.45\ W/cm^3$
for r/a=0.6-0.7 it is possible to assume zero for both $n_{||}$

Addenda: New Scenario with a faster temperature increase

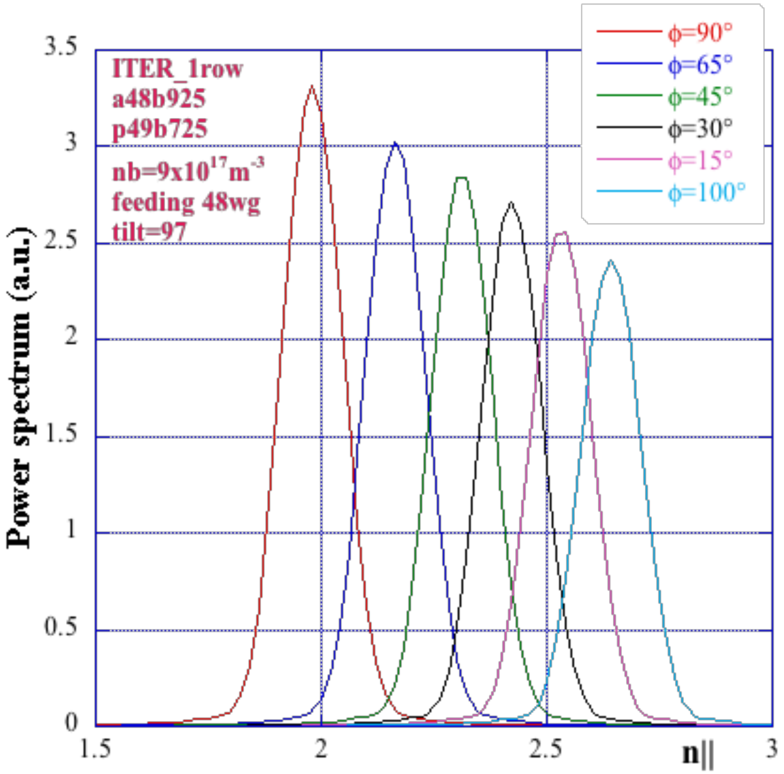


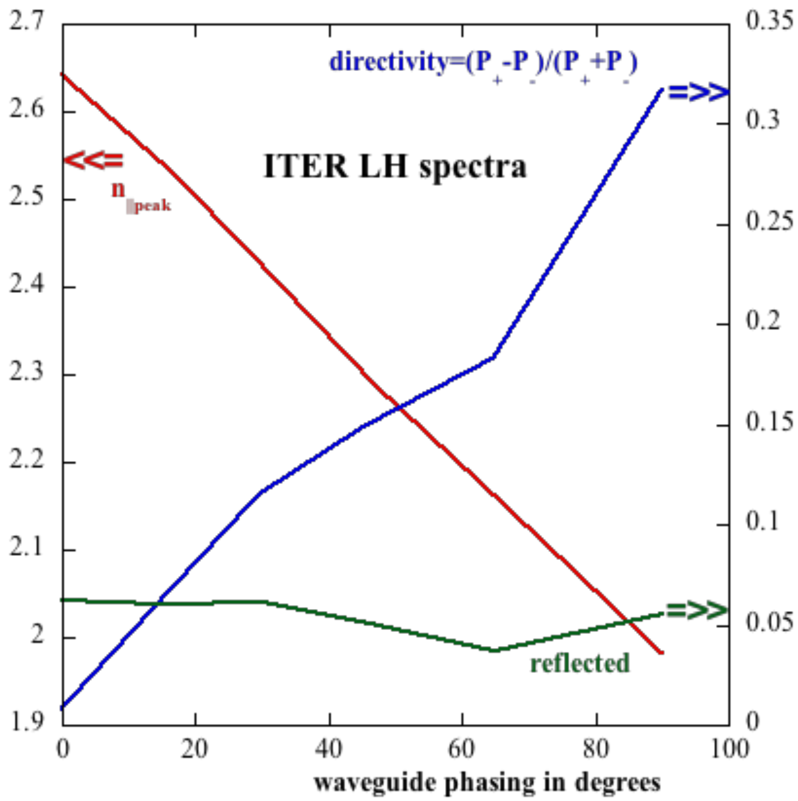




Scenario from TGLF (turbulence) calculations aimed at assessing the pedestal top suitable for 2GW fusion power (transport from ITG/TEM) (E. Fable private comm.)

Addenda: Study of the ITER LH antenna spectra:
1) n|| peak
2) n|| width





Addenda: Study of the ITER LH antenna spectra:
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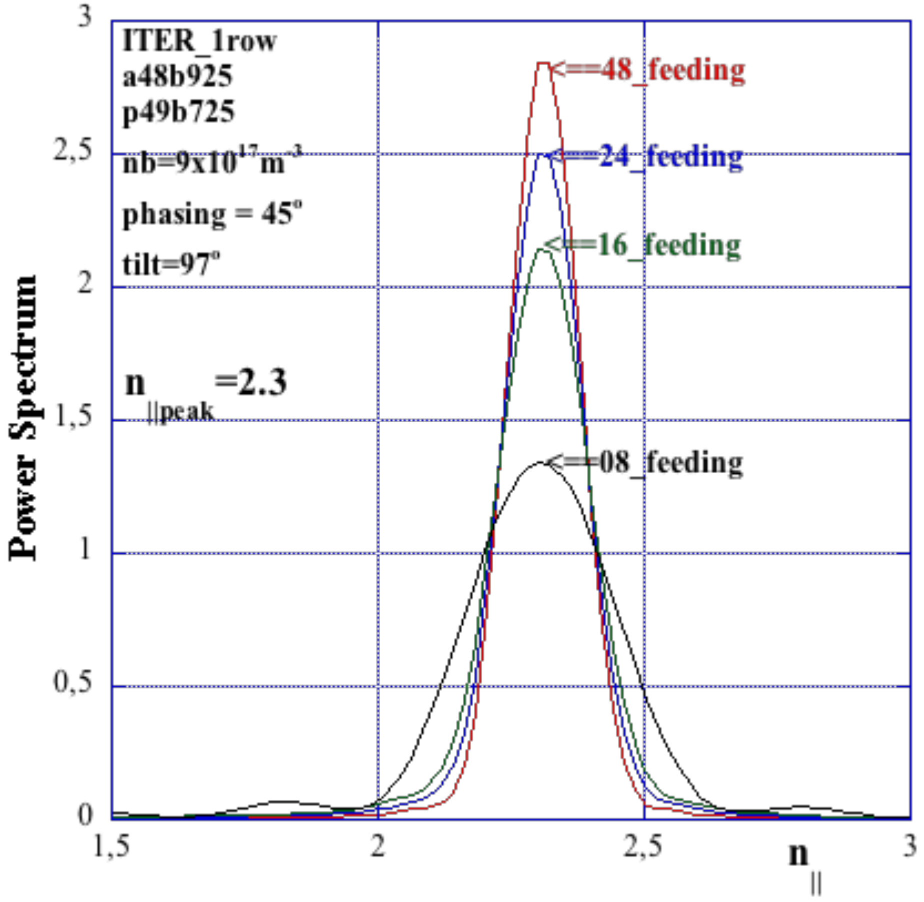
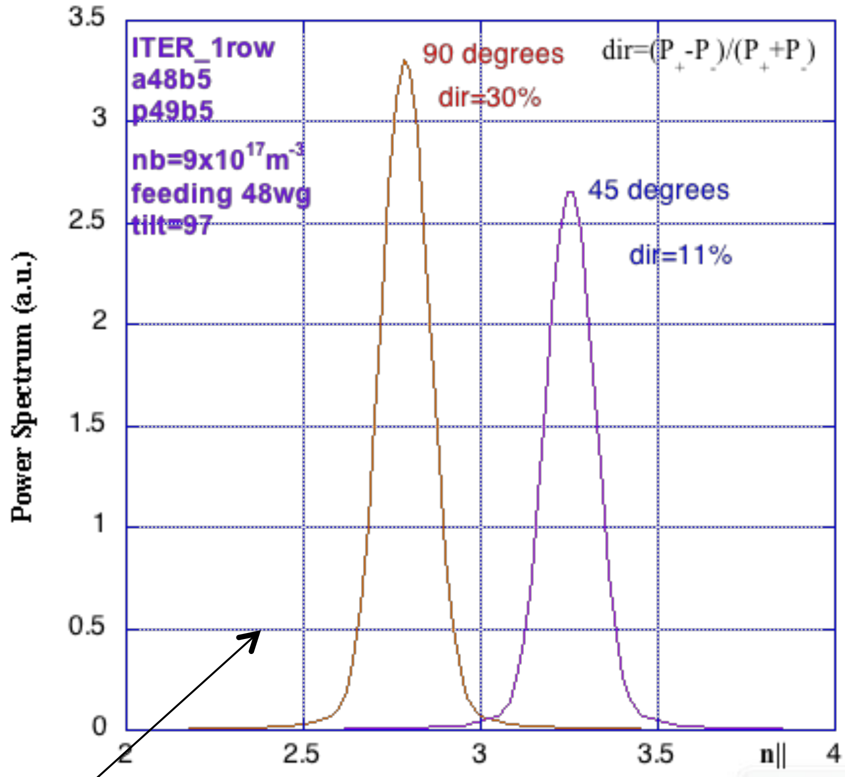
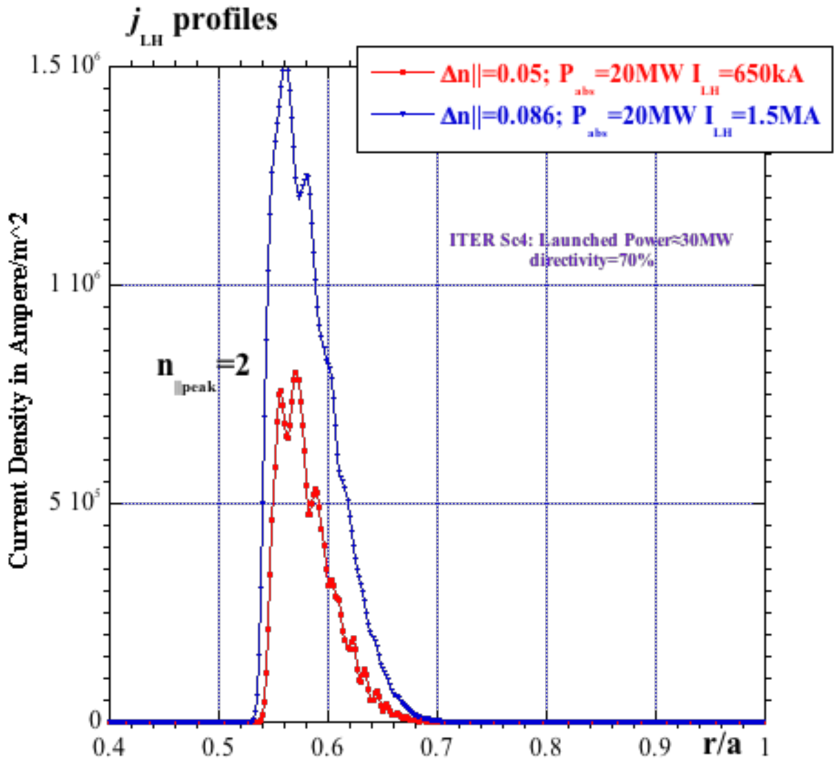




Some conceptual studies with the Grill-3d code to push the n|| peak to higher values

Numerical results: ITER Sc4 H-mode profiles

A very interesting feature in ITER is found when changing the width of the spectrum from $\Delta n_{\parallel} = 0.05$ up to $\Delta n_{\parallel} = 0.086$ at the same level of power



A drop in the current drive and in efficiency is observed when the width of the spectrum falls at $\Delta n_{\parallel} = 0.05$. This can be explained by the fact that we are on the limit where the too narrow spectrum start loosing absorption because of the flatness of the distribution function in the small velocity interval.