Sistemi di potenza a radiofrequenza in plasmi per la fusione termonucleare controllata

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URSI, Taormina 22.6.2011

EU fusion research institutions

ITALY:
ENEA Frascati
RFX Padova
IFP-CNR Milano

EFDA: *European Fusion Development Agreement.*

Agreement between European fusion research institutions and the European Commission to strengthen their coordination and collaboration, and participate in collective activities

www.efda.org

Outline

- Brief introduction to magnetic approach to fusion
- Radiofrequency as a “tool” for
  - plasma heating
  - plasma diagnostics
- Basic physics processes
- RF applications : present experiments
- RF applications : ITER

Fusion in laboratory

- Most favorable fusion reaction: *“Deuterium + Tritium”*

$$\mathbf{D + T \rightarrow {}^4He\ (3.52\ MeV) + n\ (14.1\ MeV)}$$

fusion energy in a D+T plasma at T >10–20 keV

- The reaction is self-sustaining ($P_\alpha = P_{loss}$) :

$$n\ T\ \tau_E > 4\times10^{21}\ \mathrm{m^{-3}\ keV\ s^{-1}}$$

with n and T plasma density and temperature, τ_E energy confinement time

- Main issues to achieve thermonuclear controlled fusion:
  - **particle confinement**
  - **plasma heating**
  - **energy confinement**

Plasma confinement

Magnetic plasma confinement

Plasma composed of electrons&ions

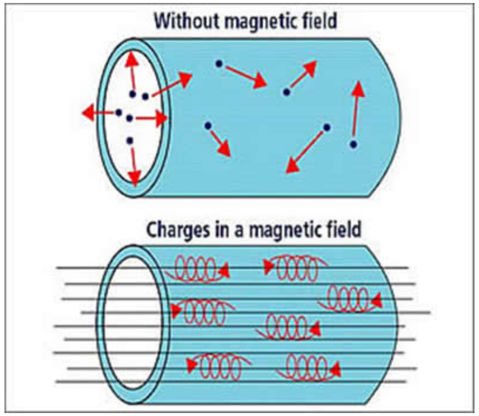
Powerful magnetic fields can be used to isolate the plasma from the walls of the containment vessel

This enables the plasma to be heated to temperatures in excess of 100 million Kelvin

In a magnetic field the charged plasma particles are forced to spiral along the magnetic field lines

no B

with B



Larmor radius

$$r_L = \frac{\overline{v}_\perp}{\Omega} \propto \frac{(m\,T)^{1/2}}{B}$$

^2H, $T_{i,e}$ = 10 keV, B = 5 T

ions:	r_{Li} = 0.14 cm
electrons:	$r_{Le} = 5\times10^{-3}$ cm

The “Tokamak”

Tokamak *(1958 Artsimovich,URSS)*:
toroidal plasma configuration

Basic components of the Tokamak’s magnetic :

• toroidal magnetic field, maintained by poloidal coils surrounding the vacuum vessel *(B ~ 1/R)*

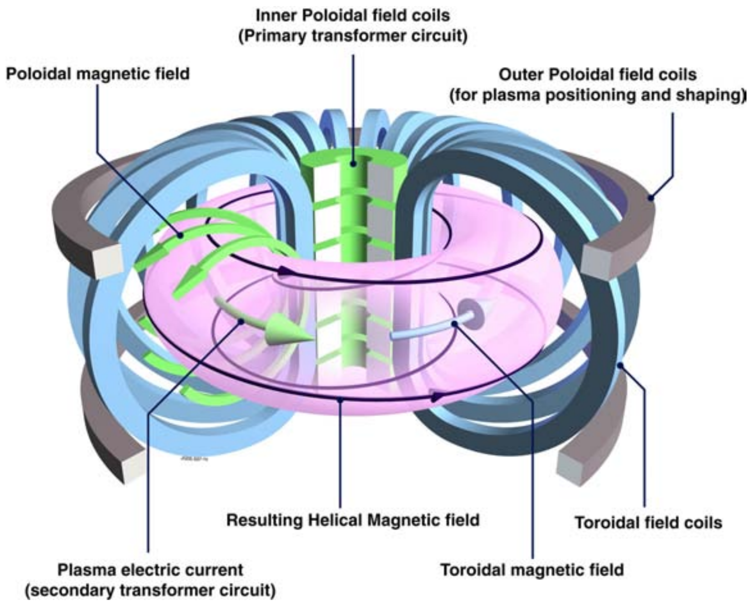
• poloidal magnetic field, induced both by the plasma current and by coils

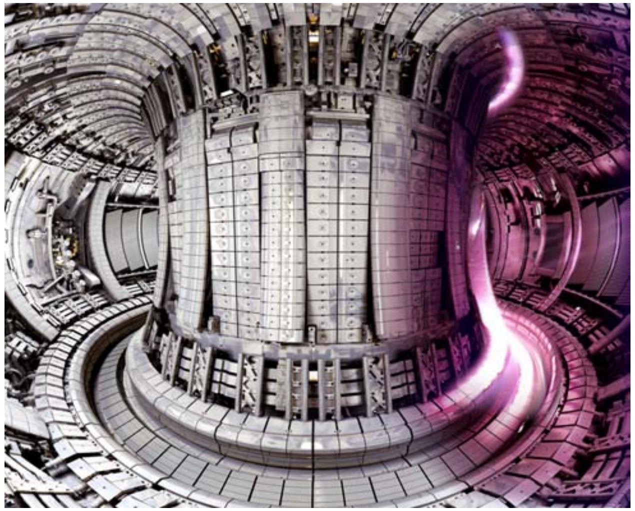
Main plasma current induced in the plasma by the action of a large transformer, with the plasma acting as the transformer secondary circuit.

JET : largest present tokamak (EFDA) (R=3 m, B≤3 T I≤4 MA)

ITER (R=6.2 m, 5.3 T 10-15 MA)
the largest tokamak under construction in France, *international project*

Goal: to achieve $Q = P_{fusion}/P_{ext} \geq 10$





JET

Heating the plasma

To heat the plasma and sustain the current in a magnetized plasma, one can

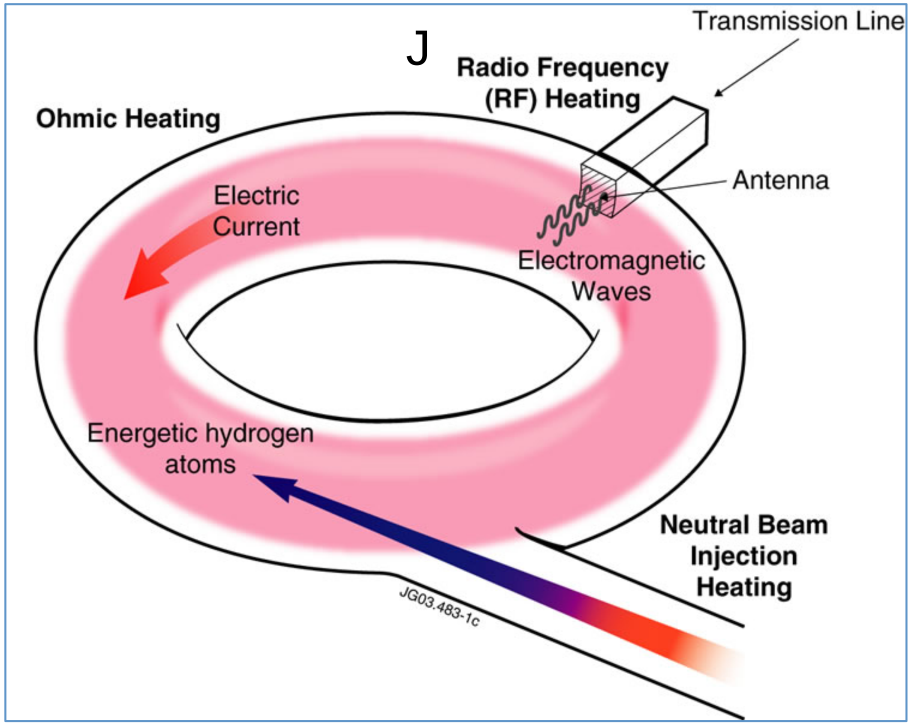
-**induce an electric current**
JET ~ 5 MA, (500 kA – 15 MA),
Ohmic Heating:

$$P_{OH} = \eta J^2, \ \eta \sim T_e^{-3/2}$$

-**inject beams** of high energy of neutral deuterium/tritium
~100 keV - 1 MeV
JET ~ 20 MW NBI power

-**inject electromagnetic waves at high power**

P ≤ 20 MW, f = 25 MHz - 170 GHz
wave-particle resonant interaction



Heating methods

Method	Principle	Heated species
Ohmic Heating	Dissipative heating of current	Electrons
(P-N) Neutral Beam Injection	Injecting neutral atoms at high energy across/along magnetic field lines	Electrons, ions
Electromagnetic Waves	Exciting plasma waves that are damped in plasma • **ion cyclotron waves** • **lower hybrid waves** • **electron cyclotron waves**	 **Electrons, ions** **Electrons** **Electrons**
α-Particles	**Slowing down**	**Electrons (ions)**

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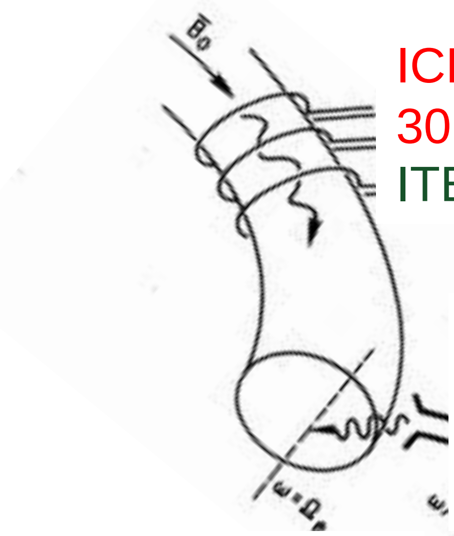
Heating methods: Pros & Cons

- *Neutral Beams* will be needed to heat main ITER plasma, difficult and costly to steer off axis

- ***Ion Cyclotron Waves*** also needed for main heating.
Antennas close to plasma !?!

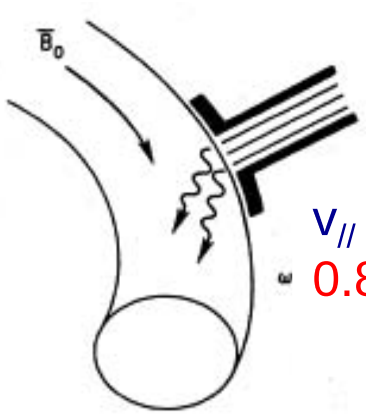
- ***Electron Cyclotron Waves***, needed for heating, optimum for MHD control.
Easily injected.



ICRH Strap antennae
30MHz ≤ f ≤ 120MHz
ITER ➔ 55 MHz

ECRH Mirrors
28GHz ≤ f ≤ 140GHz
ITER ➔ 170GHz

$\omega = \Omega_{ce}$



LH Grill

$v_{//} = \omega/k_{//} > v_{TH}$
0.8GHz ≤ f ≤ 8GHz
ITER ➔ 5GHz

- ***Lower Hybrid Waves,*** best CD efficiency but not very localised, in ITER only very off-axis CD.
Launcher array near plasma !?!

Wave - plasma interaction

- Wave-plasma interaction: ***resonant process*** *Landau/Cyclotron damping*

- Wave-particle resonance condition in a magnetized plasma:

$$\omega = n\,\Omega_{e,i} + k_{||} v_{||} \quad n = 0, \pm 1, \pm 2, .., \ \Omega_{e,i} = eB/\gamma m_{e,i} \quad e, i = \text{el., ioni}$$

wave freq. & cycl. harm. Doppler effect (|| wrt magnetic firld)

$\gamma = 1/(1-v^2/c^2)^{1/2}$ relativistic factor

  - ions / electrons resonance

    $\omega \approx n\Omega_i$ or $\omega \approx n\Omega_e$

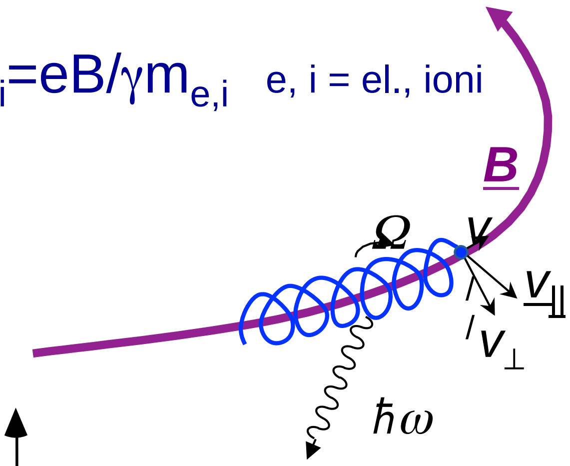
  - spatially localized (~*electrons*)

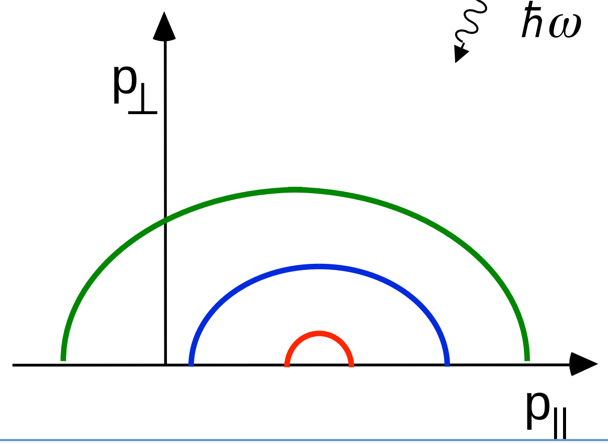
    where $\omega \approx n\Omega_e(\underline{x})$

  - localized in velocity space

    resonance condition Electron Cyclotron waves:

    ellipse in momentum space ($p_{//}$, $p_{\perp}$)





Basic physics process

Wave-particle interaction : energy & momentum exchange

➔ absorption / emission and current drive (|| B)

- electron (charge e and mass m) changes its velocity $\mathrm{v}_{\|} \rightarrow \mathrm{v}_{\|} + \delta\mathrm{v}_{\|}$
- electrons increase their
  - momentum (in || direction): $m\delta\mathrm{v}_{\|}$
  - energy $\delta\varepsilon = m\mathrm{v}_{\|}\delta\mathrm{v}_{\|}$
- variation of current density $\delta j_{\|} = e\delta\mathrm{v}_{\|}$

- Current dissipation via collisions in time interval 1/ν

  ν(v) Coulomb collision frequency
- Power needed to sustain the current $\delta P = \nu\delta\varepsilon = m\mathrm{v}_{\|}\nu\delta\mathrm{v}_{\|}$

- Current drive efficiency

$$\boxed{\frac{\delta j_{\|}}{\delta P} = \frac{e_0}{m\mathrm{v}_{\|}\nu(\mathrm{v})}}$$

Theoretical approaches

Maxwell equations + plasma dynamics equations *(fluids/kinetic)*

- High level of complexity in a non uniform magnetized plasma
- Various theoretical approaches depending on frequency and species *(electrons & ions quite different Larmor radii and resonances)*
  - Full-wave / Monte Carlo ($f \sim f_{ci}$)
  - Beam / ray-tracing ($f >> f_{ci}$ & $f \sim f_{ce}$)
- Different theoretical approaches depending on the power density
  - Linear → dispersion relation
  - Quasi-linear → kinetic equation (Fokker-Planck) for the distribution function
- Large variety of codes being developed by the scientific community
  European project on code integration in the framework of the EFDA Task Force on *Integrated Tokamak Modelling*

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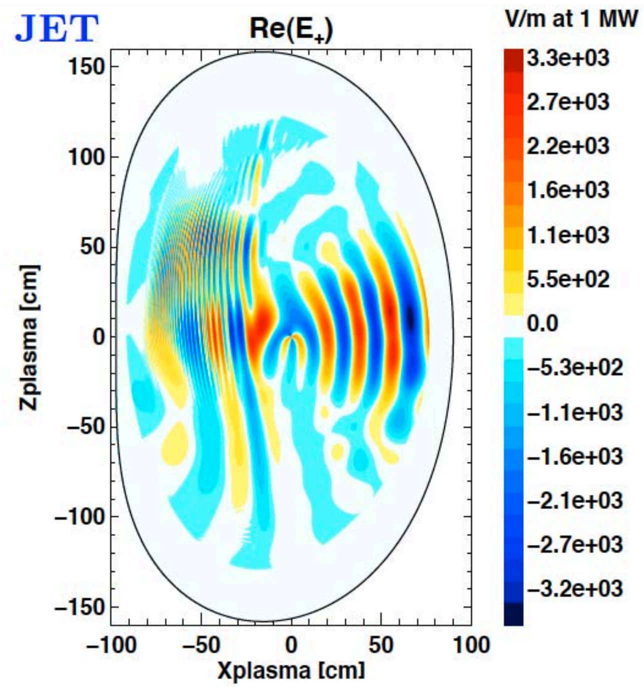
RF simulations for JET

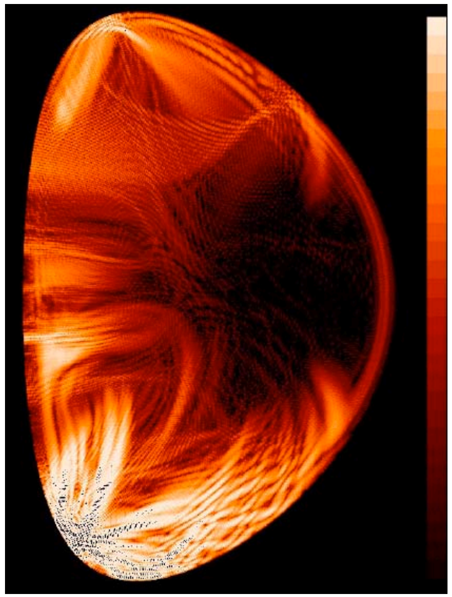
f = 42 MHz



Ion Cyclotron Waves

courtesy R Bilato, MPI- IPP

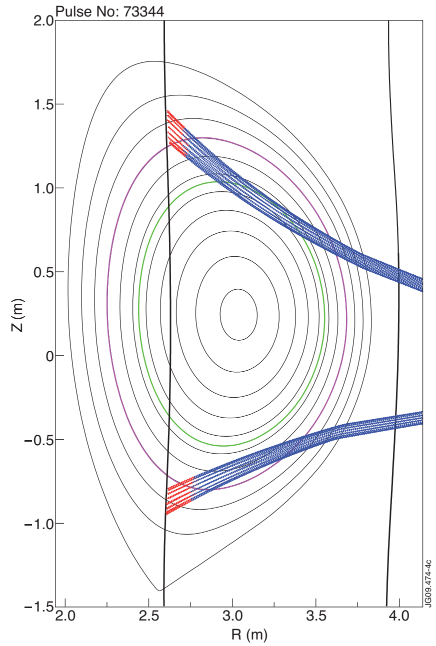
f = 3.7GHz



Lower Hybrid Waves

courtesy R Bilato, MPI- IPP

f = 170 GHz



Electron Cyclotron Waves

D. Farina, IFP-CNR, 2010 proposal

Research in the RF field @ IFP-CNR

IFP-CNR: long tradition in the field of microwaves at the Electron Cyclotron frequency (**EC**) 28-170 GHz.

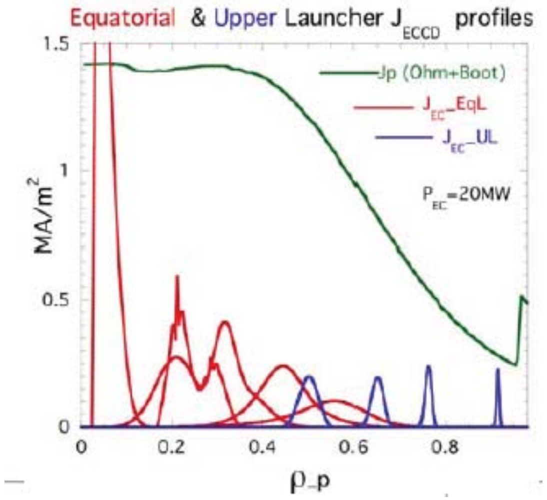
Main research topics in the RF field:

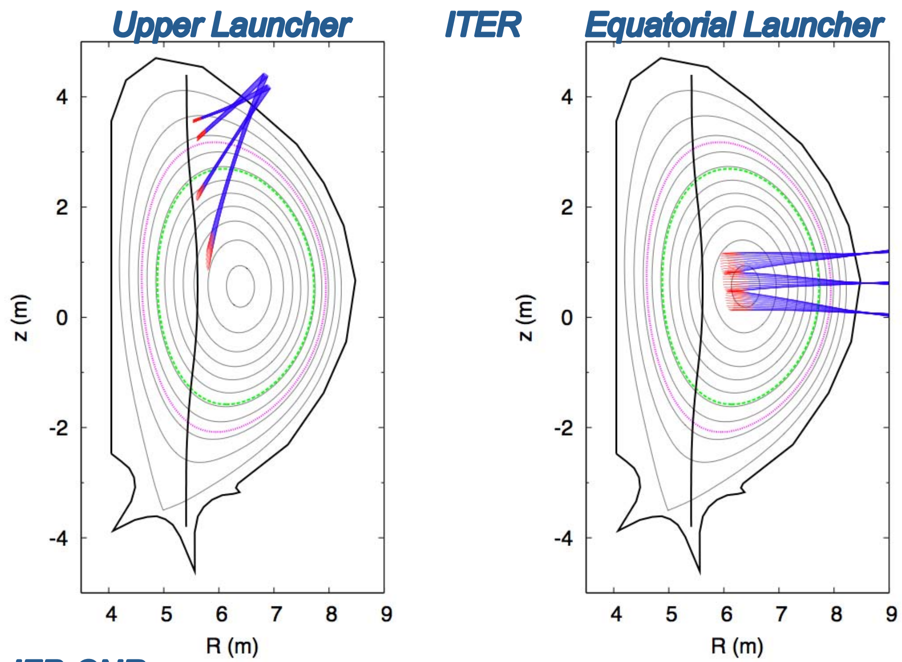
- Theory and models of wave plasma interaction
- EC experiments in tokamak plasmas, THOR, FTU, ASDEX,TCV
- RF diagnostics : ECE (cyclotron emission), reflectometry, CTS
- Design and handling of ECRH system, THOR, FTU
- Design of optical and quasi-optical systems
- Design of active and passive components at high frequency
- Antenna tests for *Planck Satellite*
- Participation to European Grants F4E for
  - *Design of European gyrotron @170 GHz*
  - *Physics &Design of ITER Upper Launcher (2M€ in 2y to European Consortium)*

ECRH&CD simulations

Beam tracing codes developed to perform predictive/interpretative simulations of *propagation, power deposition, and current drive* induced by Electron Cyclotron waves

- Gaussian beams propagation in quasi-optical approximation
  (ITER: wavelength ~2 mm<< waist~2 cm << plasma dimension ~2m)
- absorption: relativistic dispersion, *high Temperature ~20-30 keV*
- current drive: current response function





GRAY code IFP-CNR

mm wave diagnostics

T_e measurements via ECE

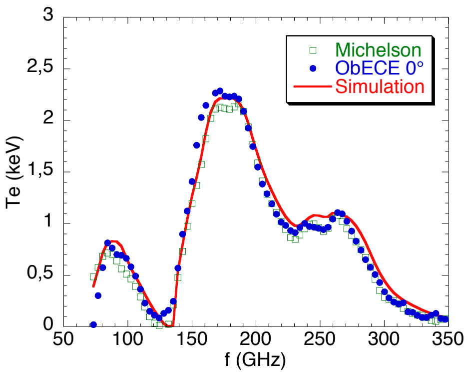
In a plasma at thermal equilibrium:
Kirchhoff Law

$$T_{rad} \equiv \frac{8\pi^3 c^2}{\omega^2} \frac{1}{n_r^2} \frac{j}{\alpha} = T_e$$

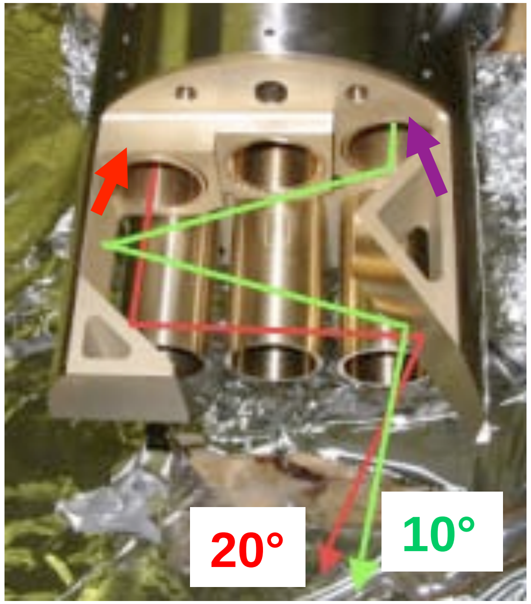
Intensity of emitted radiation in a optically thick plasma:

$$I_\omega \approx \frac{\omega^2}{8\pi^3 c^2} T_e\left(R_{res}(\omega)\right)$$

various frequencies -> different R :
➔ **electron Temperature profile**



Oblique ECE at JET



- Martin-Puplett interferometer
- 3 lines of sight (0º, ~10º, ~20º)
  2 linear polarizations for each oblique line of sight
- Freq. range: 75-800 GHz
  Δf = 7.5 GHz
  Δt = 7.5 ms

EC waves applications and advantages

Main advantages

- **Wave propagates in vacuum** (no antennas close to plasma, high frequency - high specific power ~ 10^9 W/m^2, Mirrors, RT)
- **Electron heating** (strong absorption, no ion/α damping)
- **Localised in space** (beam steering, frequency tuning, limited B range)

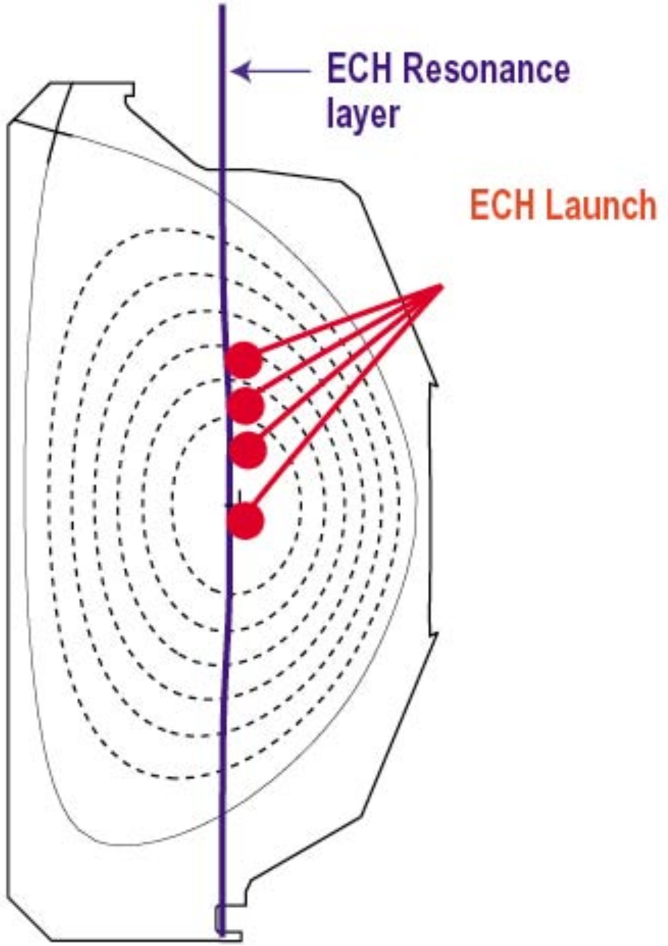
Main applications

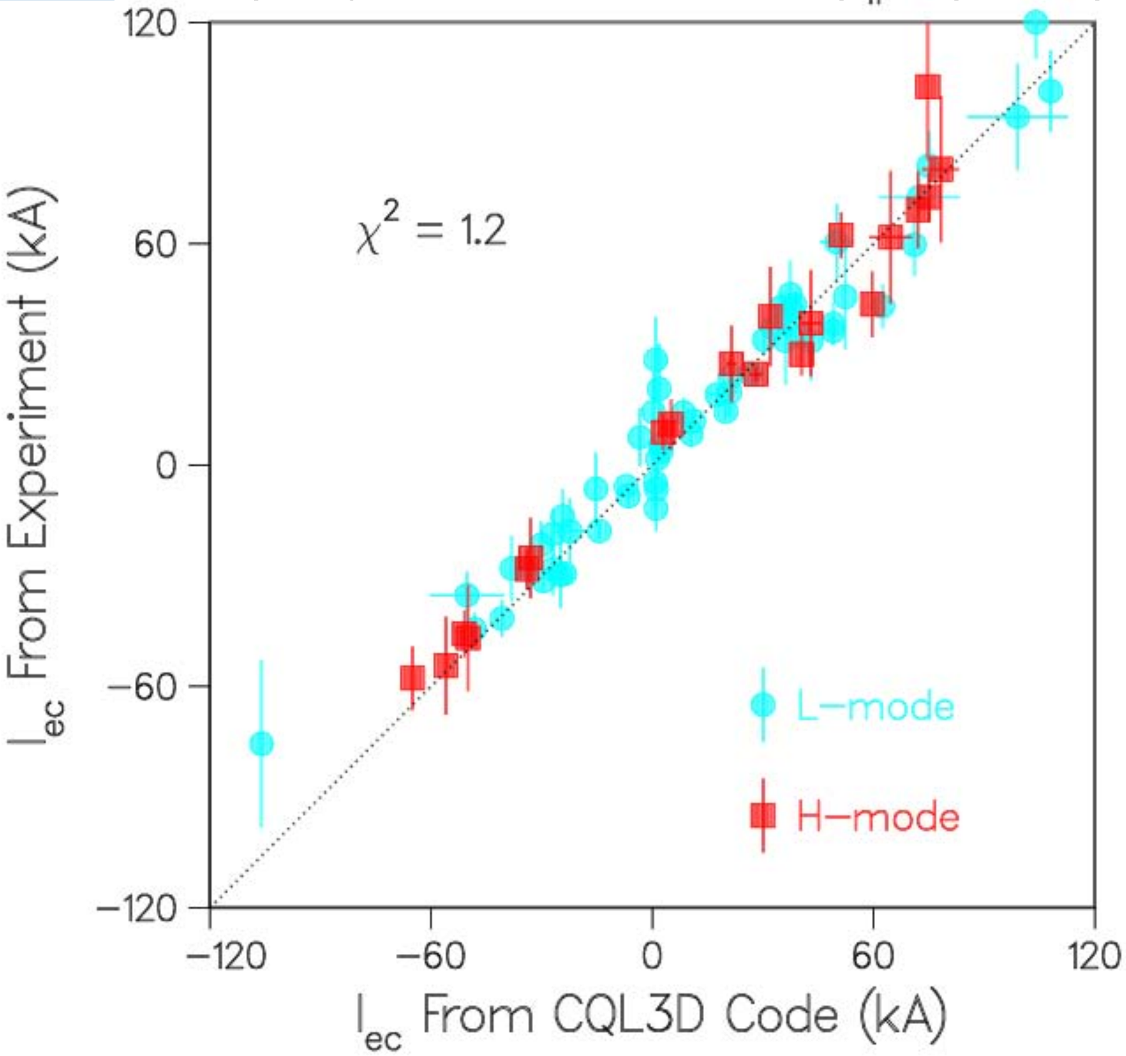
- Highly localized non-inductive Current Drive
- MHD Stabilisation and control
- Plasma disruptions Mitigation / Avoidance
- Modulation for transport studies
- Ionisation and plasma start-up

ECCD in DIII-D (GA San Diego)

Measured ECCD agrees with theory

(Petty et al., Nucl. Fus. 42 (2002) 1366)



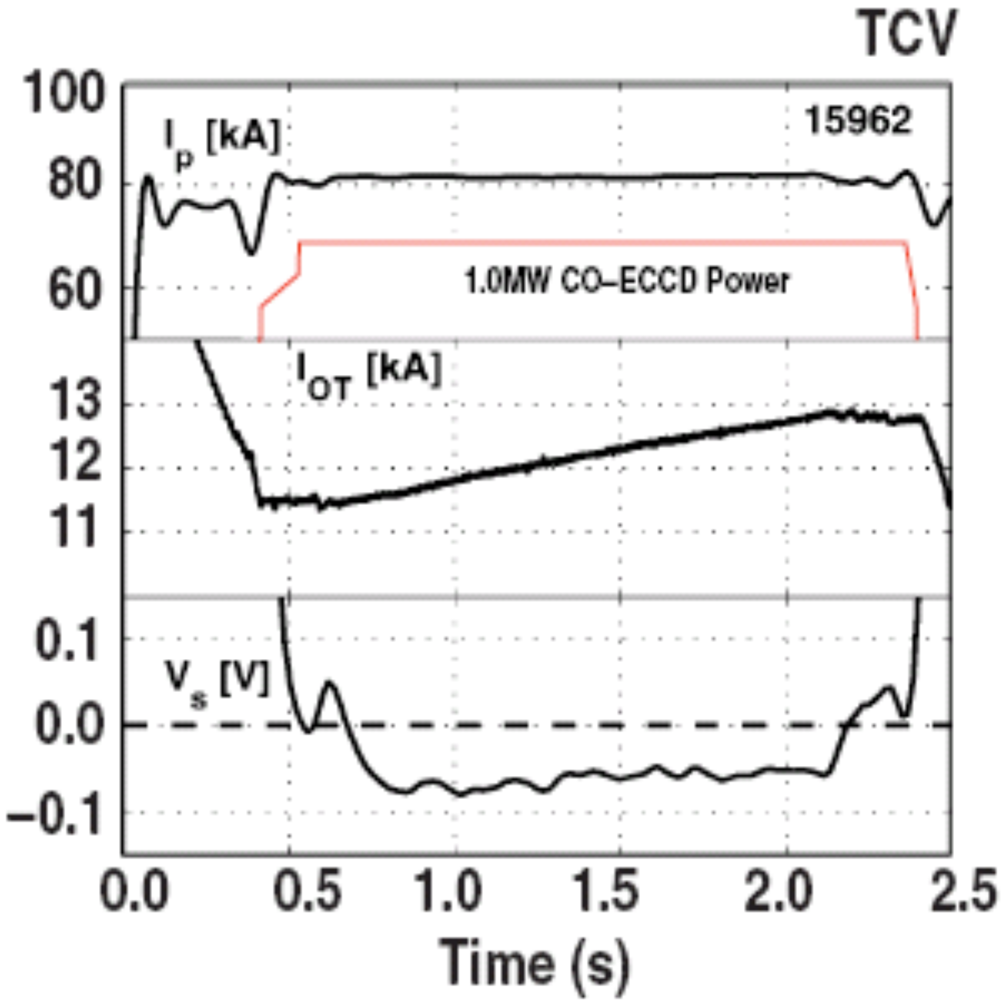


Full non-inductive CD in TCV (CRPP Lausanne)

Plasma current sustained
for 10 current diffusion times

Transformer re-charging ⇒

High power density results in
reduced current drive efficiency
due to radial transport of fast
electrons

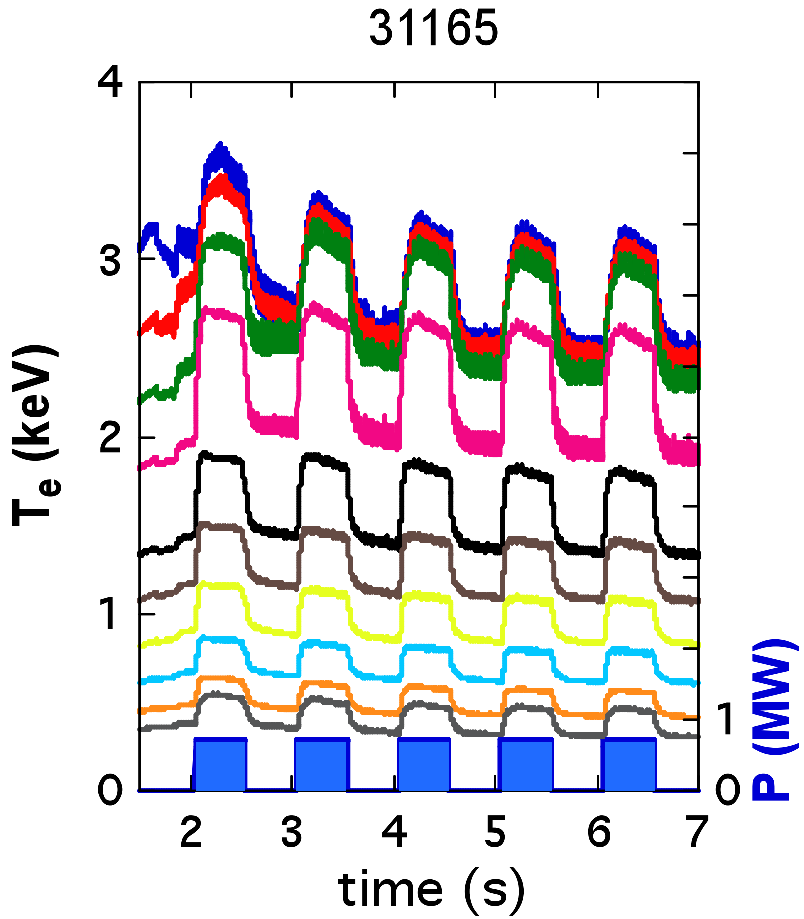


EC modulation in Tore Supra (Cadarache)

Modulation of EC power allows

• to determine the localization of the power deposition

• to perform heat transport studies in the tokamak plasma (determination of thermal conductivity χ)



Electron temperature evolution as given by ECE signal at different frequencies / radial location in the plasma

Control of MHD instabilities

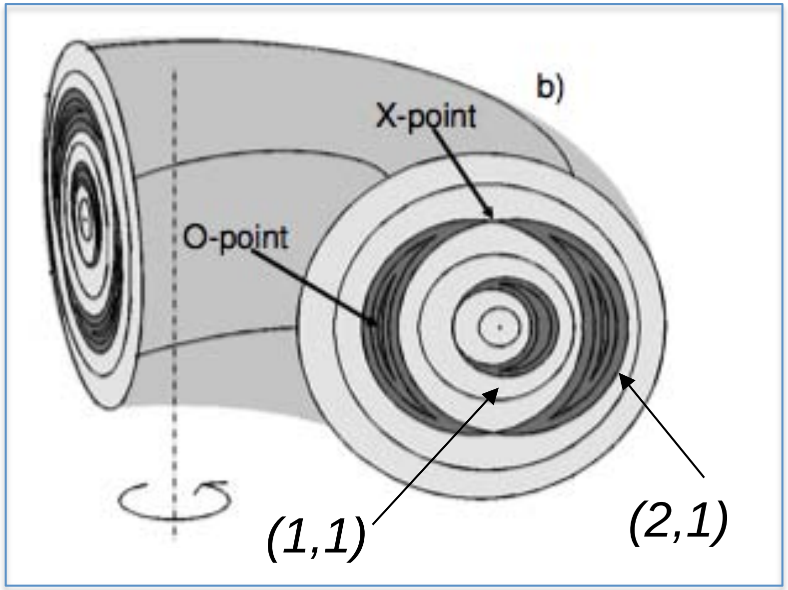
Real time control of plasma stability and performance is one of the major challenges in present experiments and in a large scale tokamak like ITER.

Magnetohydrodynamics (MHD) instabilities can produce deformations of the equilibrium magnetic configuration, reducing the energy confinement and increasing the risk of plasma disruptions.

Control requires proper actuators.

Radio Frequency power injection has been proved to be an efficient tool to control MHD instabilities.

EC waves are the best candidate



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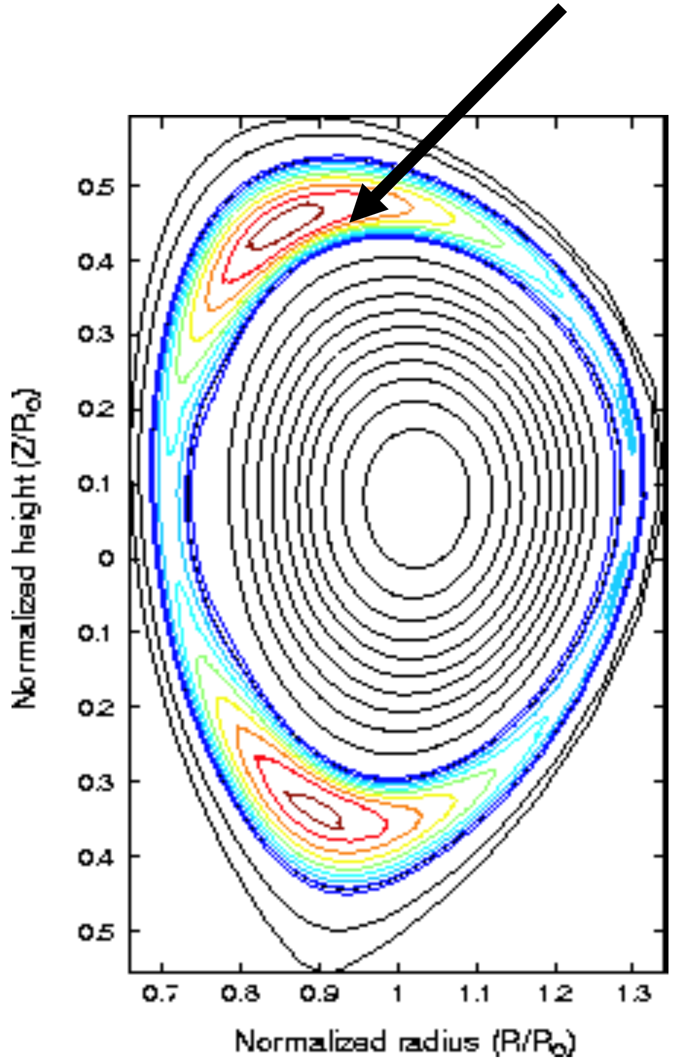
EC waves & control of instabilities

Electron Cyclotron interaction with a large temperature plasma is highly localized both in space and energy

ECRH ideal MHD control actuator

Control via ECRH may be pursued by

- choosing frequency / B field
- steering the beams in the plasma
- varying the injected power
- power modulation



Simulation of an m = 2, n = 1 neoclassical island in an ignited ITER plasma.

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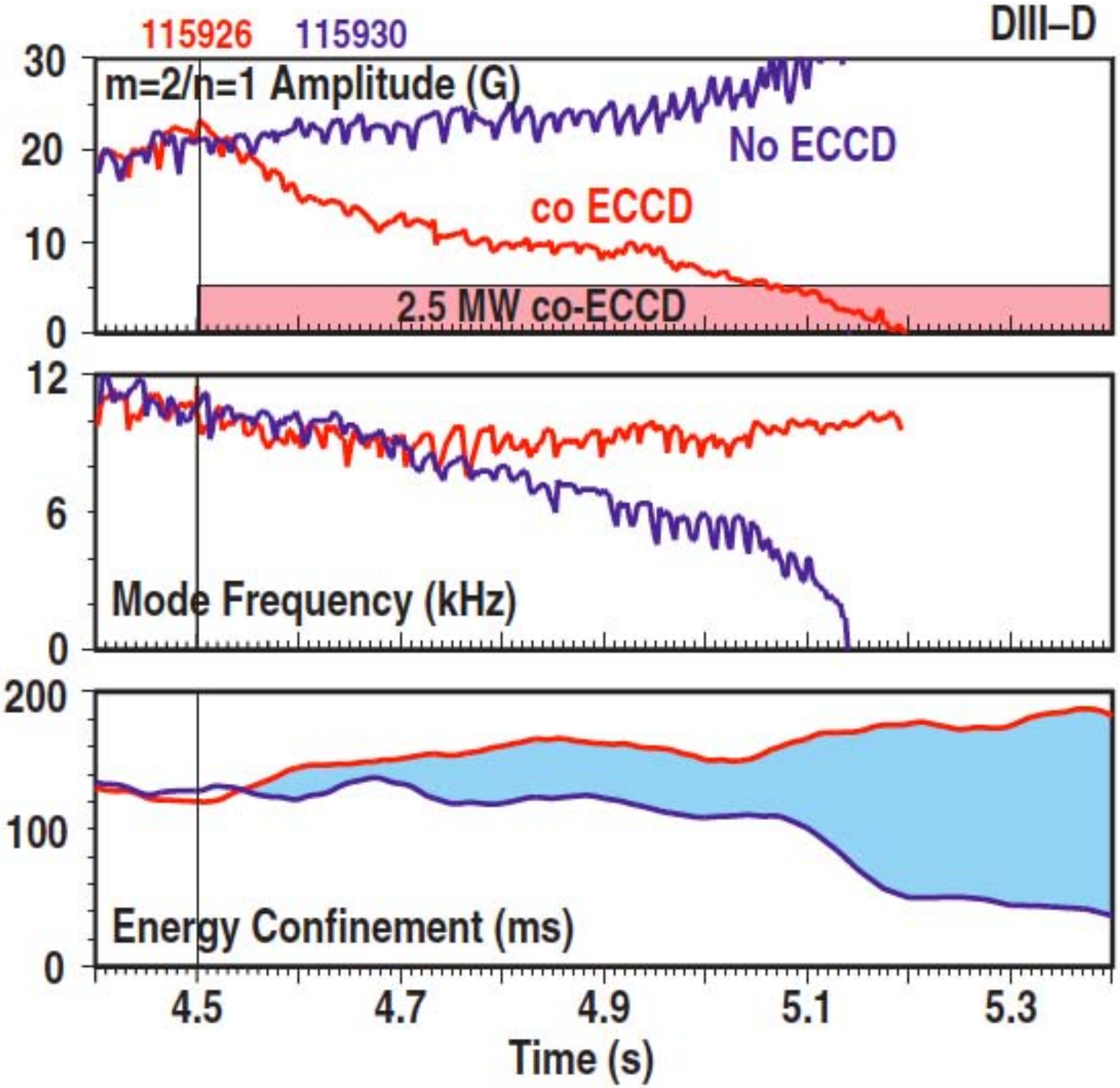
MHD modes stabilization in DIII-D



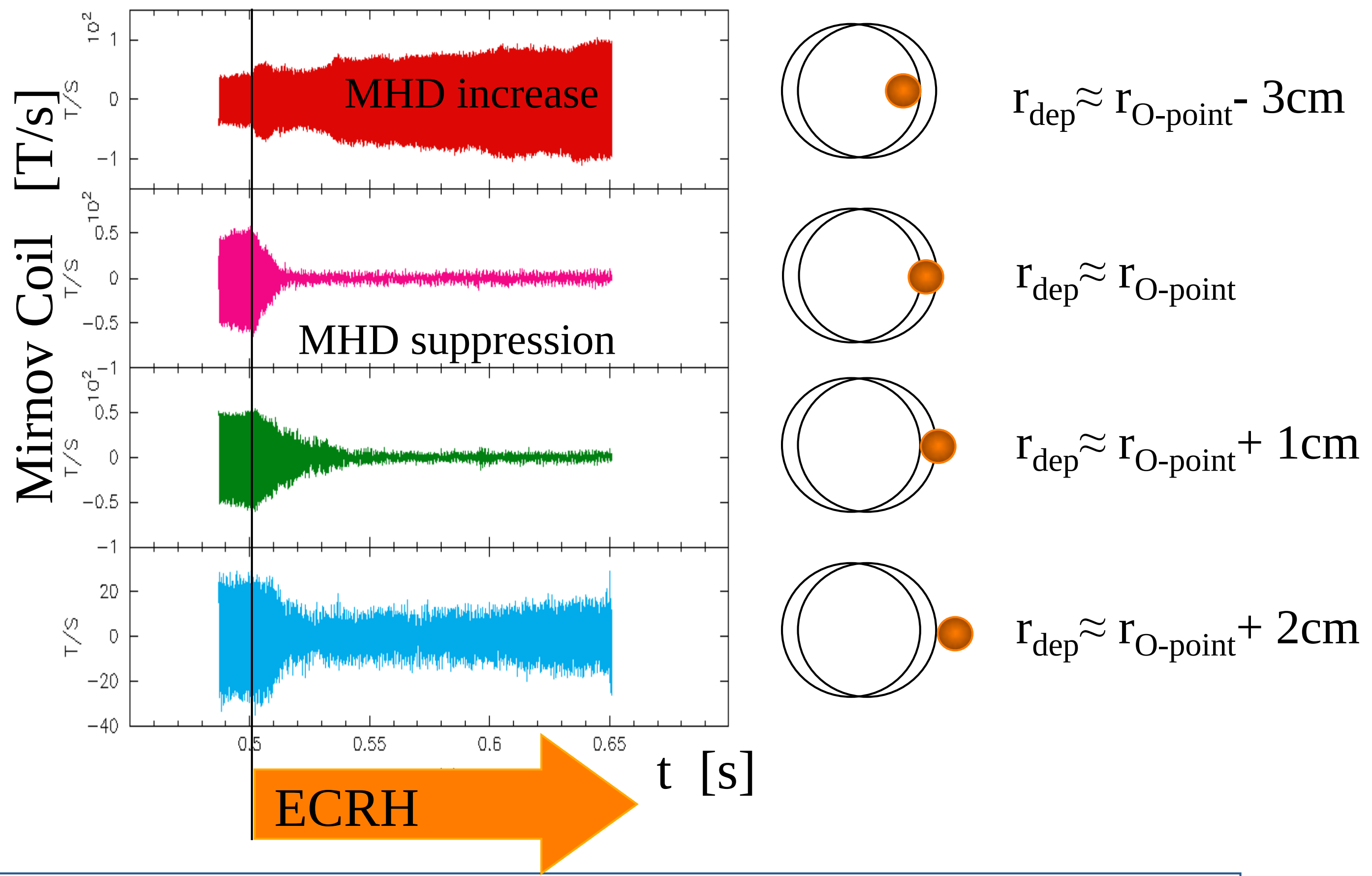
- m=2/n=1 neoclassical tearing mode suppressed by co-ECCD
- 2/1 NTM suppression avoids loss of rotation and mode locking
- Mode suppression leads to improvement in confinement rather than large loss and likely disruption

R. Prater, Review talk APS 2003

MHD modes suppression in FTU

S.Cirant et al. IAEA Sorrento 2000

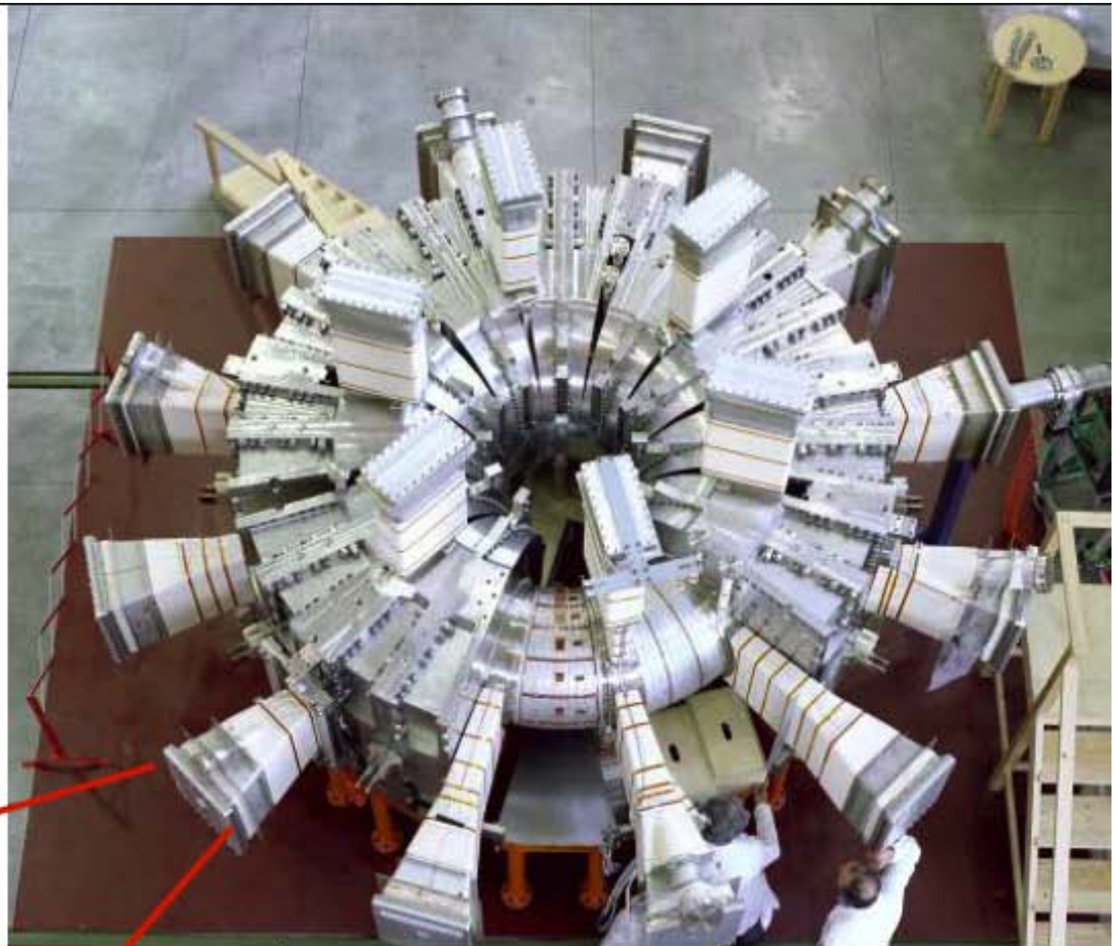
MHD instabilities are monitored by external magnetic signals with Mirnov coil



The islands can be reduced in width or completely suppressed by a current driven (also resistively) by absorption of electron cyclotron waves (EC) accurately located within the island.

Il Tokamak di Frascati

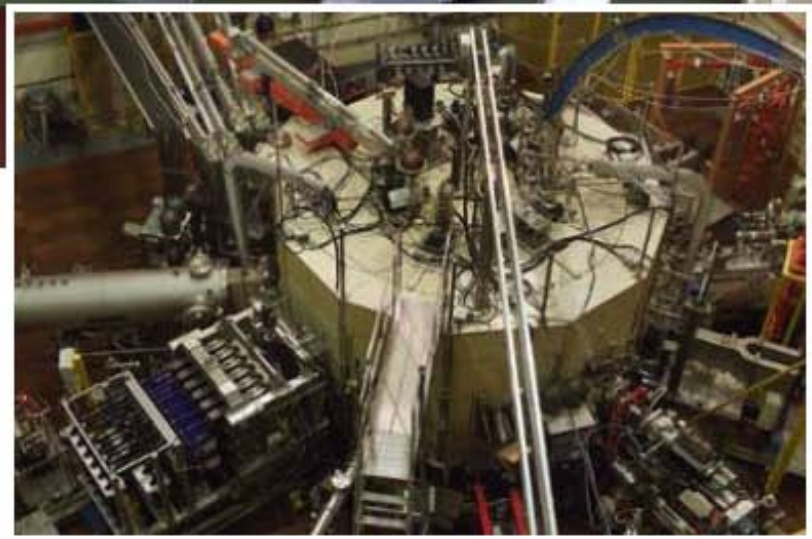
Frascati Tokamak Upgrade (FTU)



R_0= 93.5 cm, a= 33 cm,
B = 8 T, I = 1.6 MA,

$n \leq 10^{21}\ m^{-3}$, $T \leq 15$ keV

Il plasma di FTU osservato da una finestra orizzontale



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Heating system in FTU

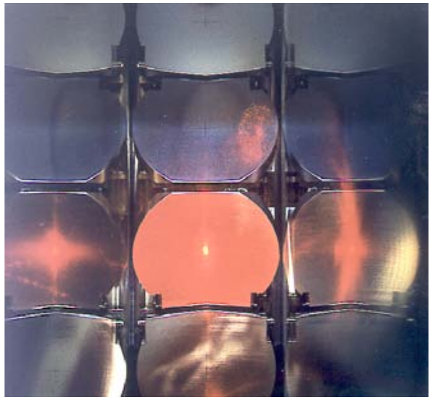
Additional Heating RF systems

- **Electron Cyclotron Waves:** 140GHz / 1.6MW / 0.5s
- **Lower Hybrid Waves:** 8GHZ / 3MW / 1s
- **Ion Bernstein Waves:** 433MHz / 0.6MW / 0.5s

- **EC Antenna:** quasi optical Gaussian beams directed to plasma
- **Sources**: 4 Gyrotrons 140 GHz / 500 kW / 0.5 s
  modulation up to 10 kHz

- **Feedback control** in time for gyrotron switch-on/off

- **Four independent launching mirrors**
  + 2 lateral mirrors for toroidal injection
  beam radius in plasma = 25 mm

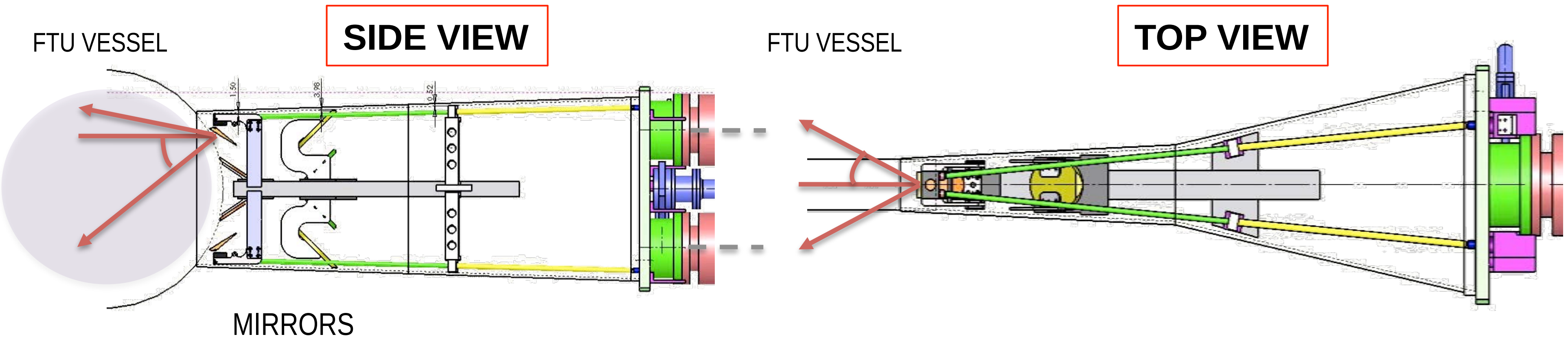


The new fast ECRH launcher in FTU

A new ECH launcher at 140 GHz has been designed by IFP and installed in FTU *(beginning 2011)*

Main physics objectives and steps forwards

- MHD stabilization in real time → *fast and wide mirror steering* ***Δθ = 1° in 10 ms***
- Current profile shaping via localized ECCD → *accurate scan of injection angles*
- Overdense plasma heating via wave mode conversion → *large toroidal injection angle*
- Collective Thomson Scattering Diagnostics *(ITER-like)*



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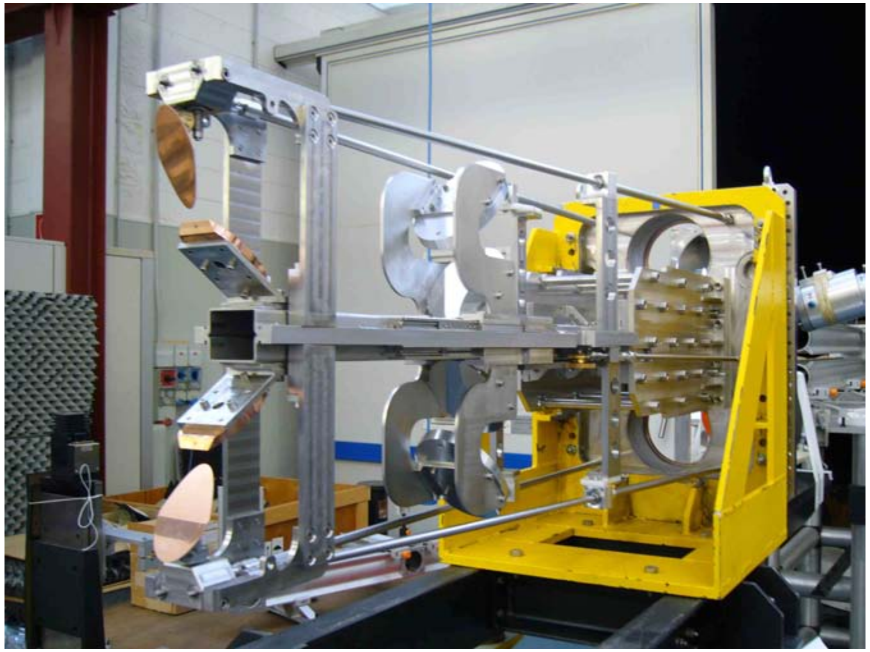
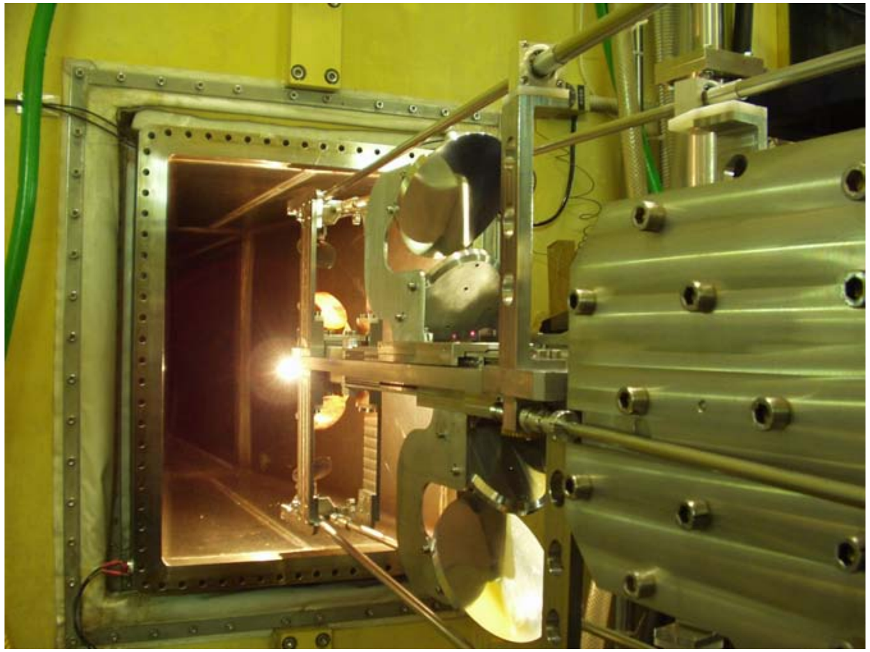
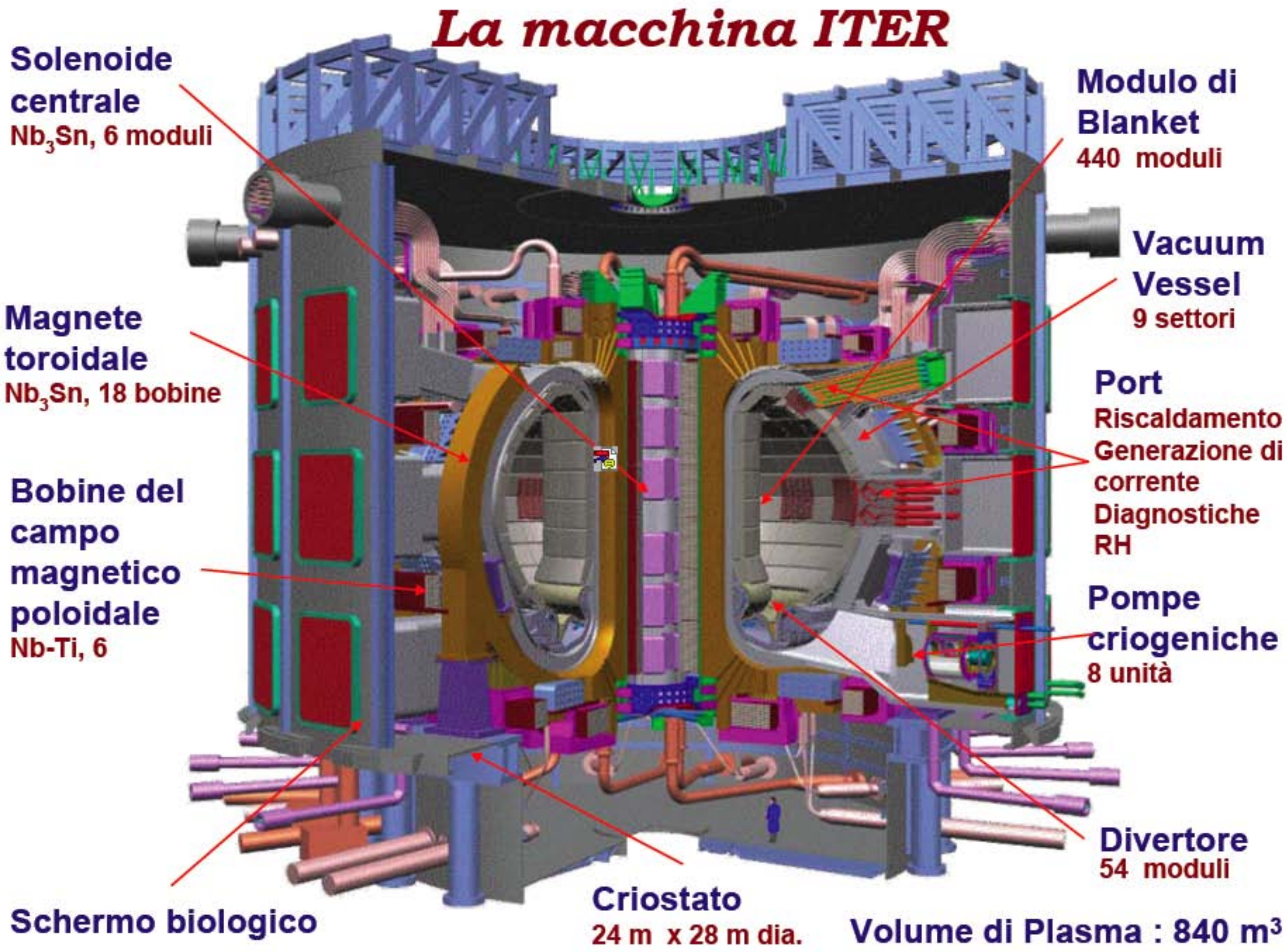
The new fast ECRH launcher in FTU (2)





February 2011

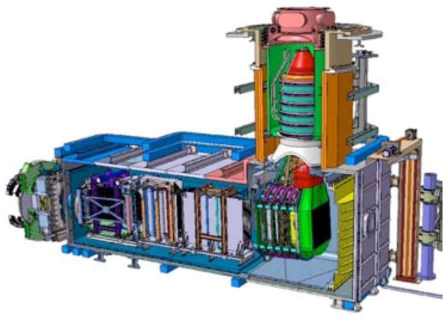
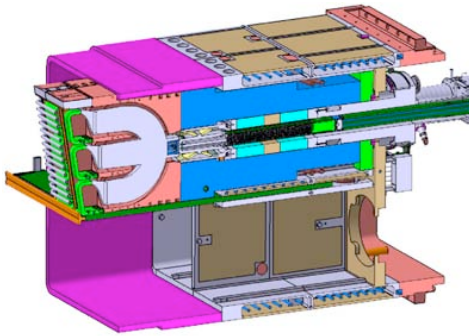
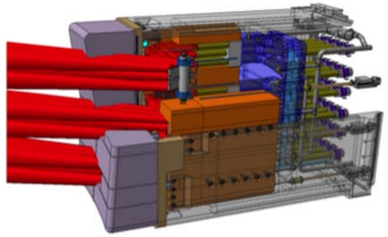
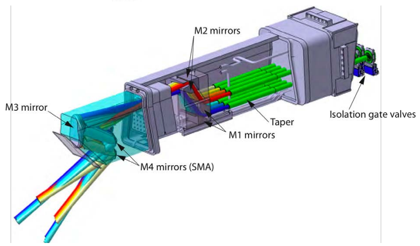
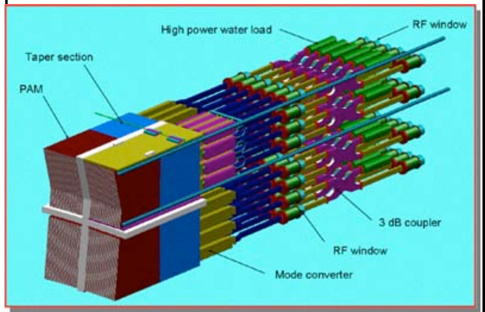
The ITER machine



Massa: 23.350 ton

ITER H&CD Systems

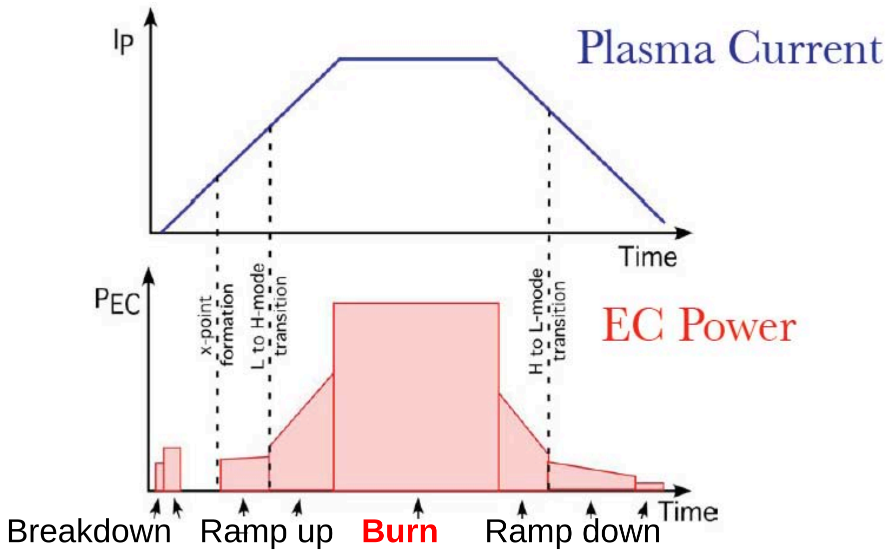
All four heating systems envisioned for ITER in preparation for DEMO

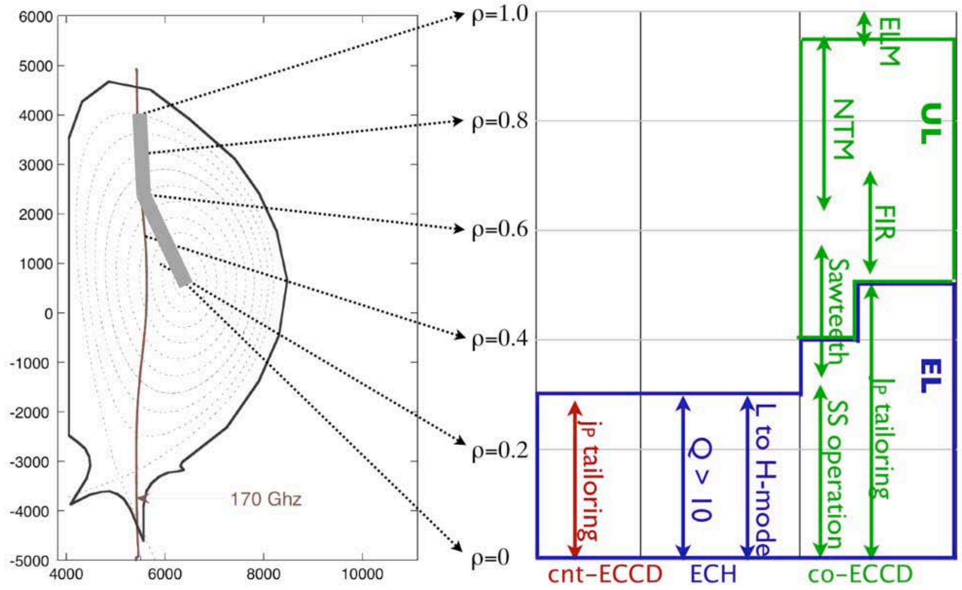
NB	IC	EC	LH
		 	
33MW +17MW	20MW +20MW	20MW +20MW	0MW +40MW
Plasma Rotation for stabilizing RWM	Bulk ion heating	Localized H&CD for MHD control	off-axis Bulk current drive

ECRH&CD in ITER

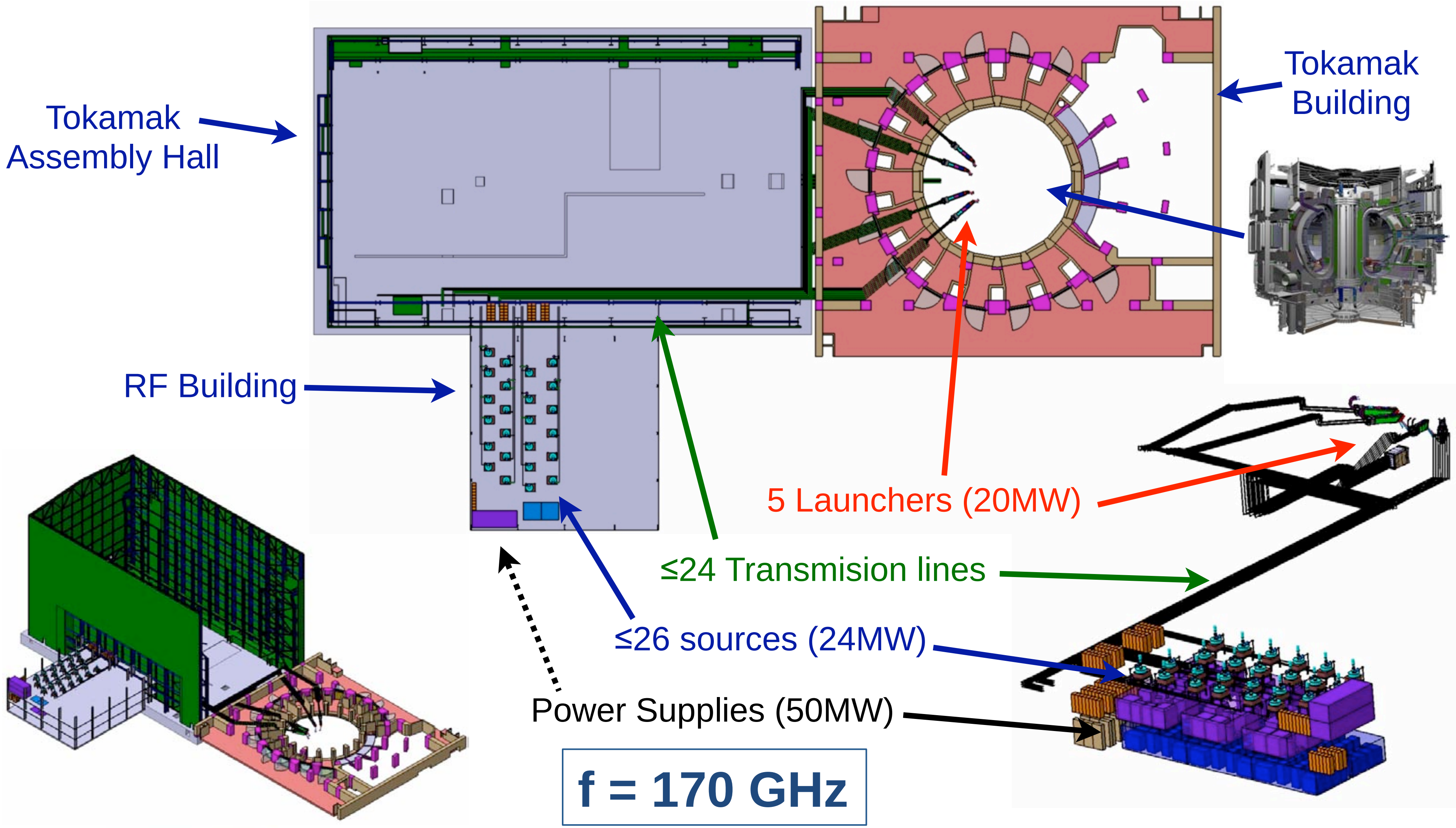
The ECRH system for ITER has been designed to operate at various stages of the plasma discharge to a perform different physics tasks:

- plasma breakdown
- core plasma heating
- current profile tailoring
- NTM stabilization
- NTM prevention (sawtooth stab.)
- impurity control





The ITER EC System

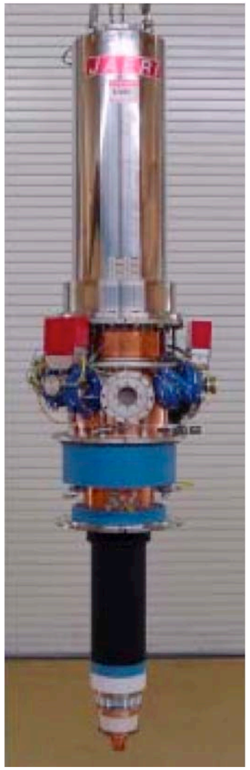


RF Sources

Gyrotrons are rated for:

- Yesterday 800sec, today 3'000sec
- ≥0.96MW after MOU with ≥95% HE_{11} mode purity
- LHe free cryomagnets
- >50% efficiency (P_{out}/P_{in})

JA



1MW
800s

RF

1MW (0.8)
200s (800s)

EU

1.4MW (2.2)
15ms (≤10ms)

IN

TBD

f = 170 GHz

Challenges:

- Mass production
- High Reliability (no arcs)
- Higher Power (≥1.2MW)
- Long life (≥5 years)
- High mode purity (≥98%)
- Higher Electrical efficiency
- Partial Power modulation 5kHz

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EC Launchers in ITER

Two type of launchers:

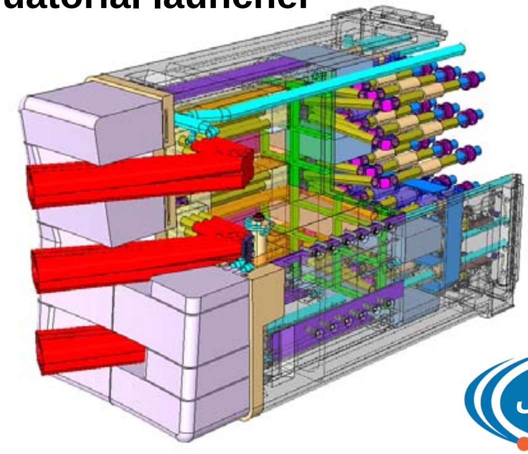
• **Equatorial launcher** (Japan)
for central heating and current drive, *1 port, 24 entries*

•**Upper launcher** (Europe)
for control, *4 ports, 8 entries each*

Main Functionalities

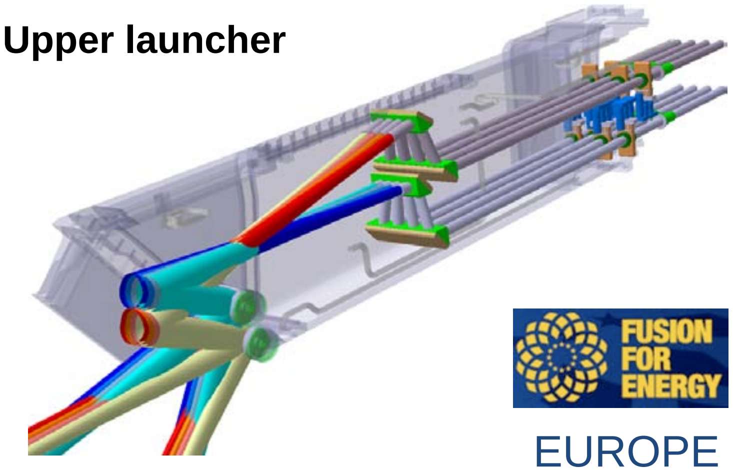
- Assist plasma breakdown and current ramp-up
- Auxiliary heating to access H mode
- Steady state on-axis & off-axis current drive
- Control MHD instabilities by localized CD

Equatorial launcher



JAEA
JAPAN

Upper launcher



FUSION FOR ENERGY
EUROPE

ITER site - March 2010

Future position of the tokamak

Future position of the EC system

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ITER site - 2011

The 500 seat amphitheatre of the future ITER Headquarters building takes shape. May

eams destined for the Poloidal Field Coil Winding Facility's 25 ton travelling crane.

April 2011 - Looking west over the ITER site. Excavation works for the future Tokamak Complex are visible, as well as the first storey of the ITER Headquarters Building in the background. Photo: Altivue

The Poloidal Field Coil Winding Facility is the first building to go up on the ITER platform. 257 m long, 49 m wide and 17 m high, construction will be completed in November 2011. Photo: Spie Batignolles/Altivue

210,000 cubic metres of rock were removed during construction of the Tokamak Complex Seismic Isolation Pit. The Seismic Pit—17 m deep, 120 m long and 90 m—will house the anti-seismic foundations of the future Tokamak Complex. Tower cranes have been positioned at the four corners of the Pit to prepare for the next stage of works: concrete pouring. Photo: ITER Organization (April 2011)