RF heating and diagnostic systems in magnetic confinement plasma devices for fusion power

Lorenzo Figini

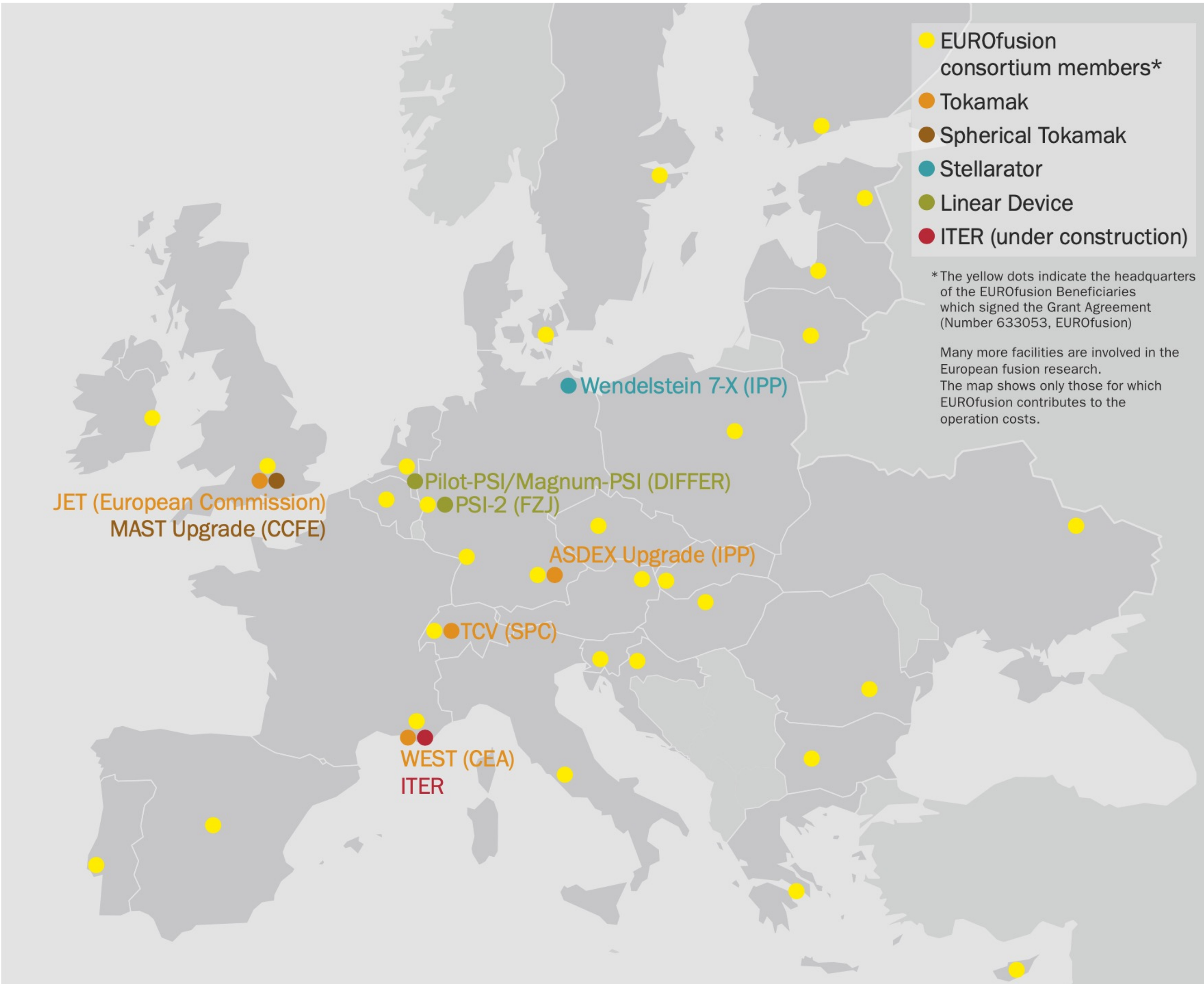
Istituto per la Scienza e Tecnologia dei Plasmi – CNR, Milano, Italy

URSI Commission H: waves in plasma

Outline

- Introduction to Magnetic Confinement Fusion
- Physics of Radio-Frequency waves for
  - Plasma Heating and Current Drive (H&CD)
  - Plasma diagnostics
- Electron Cyclotron (EC) waves in past and present experiments
- Challenges for future devices

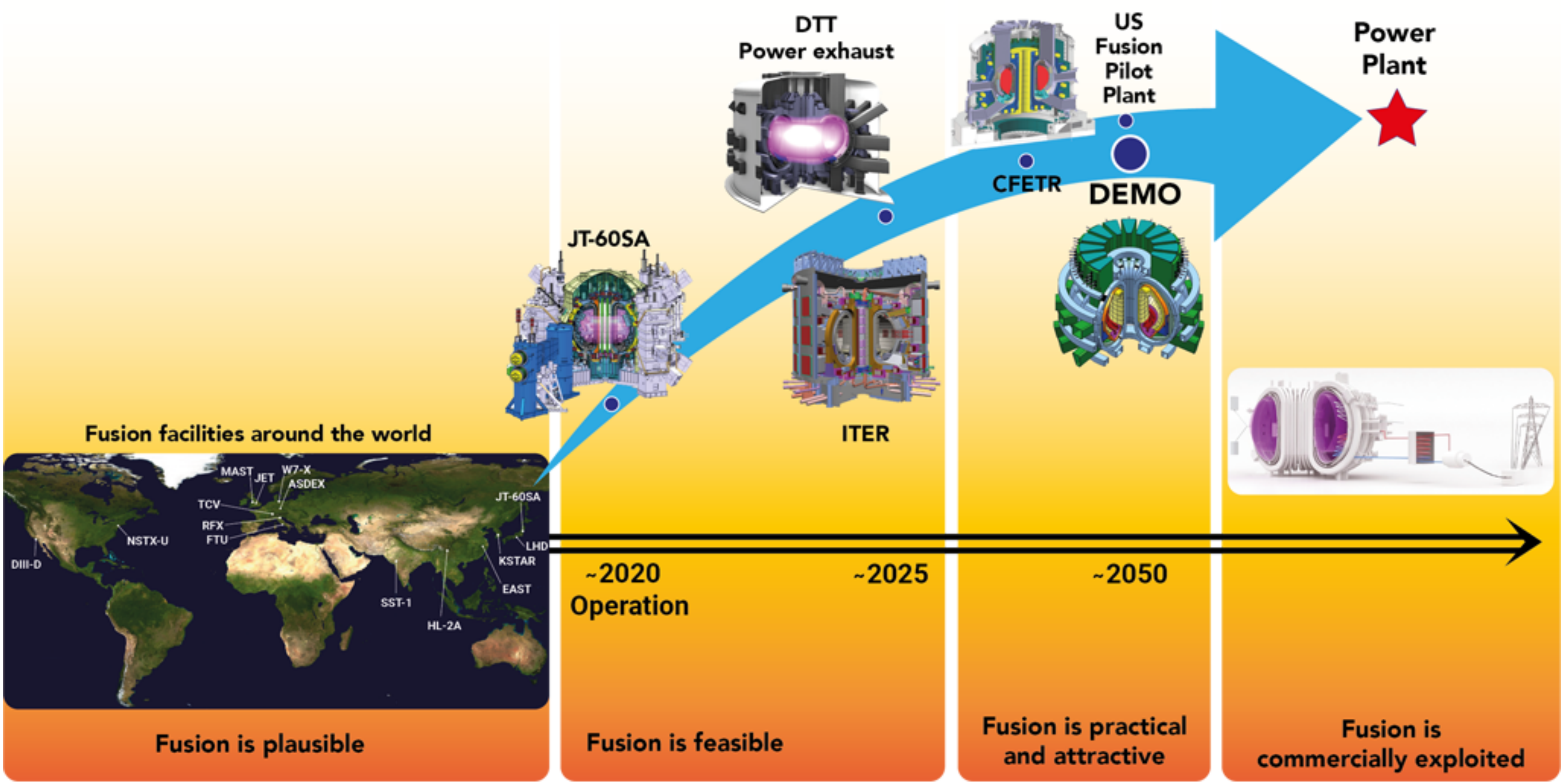
European effort towards fusion energy



EUROfusion is the European consortium for the development of fusion energy.

It supports and funds fusion research activities on behalf of the European Commission’s Euratom programme.

Roadmap towards a fusion power plant



Source: www.dtt-project.it

Fusion in a laboratory

- Most favourable fusion reaction in a lab

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

  relevant reaction rate at T > 10÷20 keV

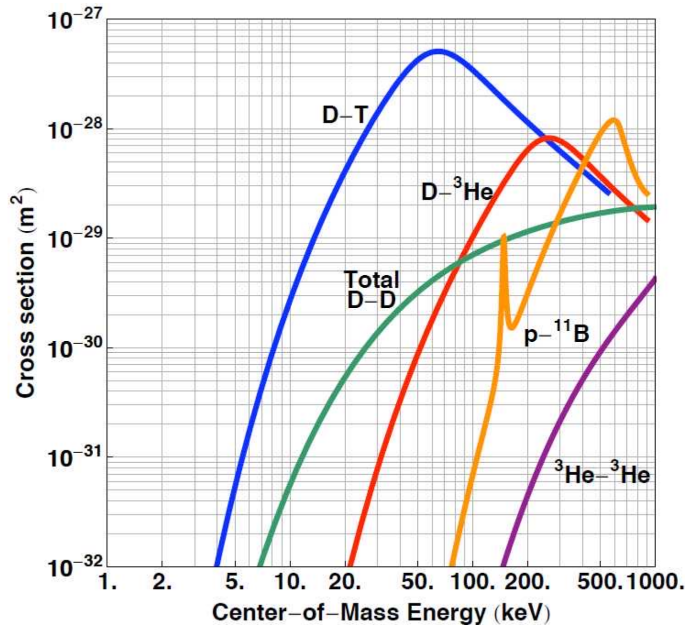
- The reaction is self-sustaining ($P_\alpha = P_{loss}$) if

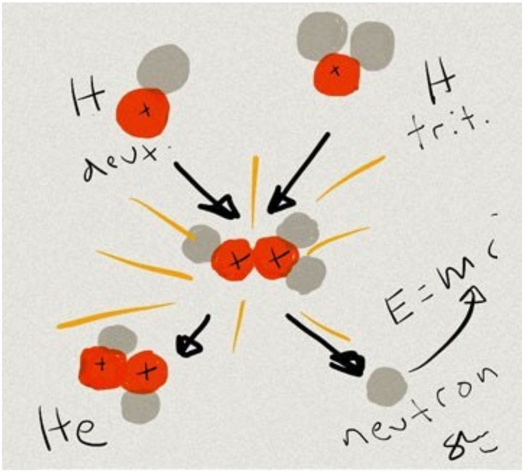
  $n\, T\, \tau_E > 4\ 10^{21}\ m^{-3}\ keV\ s^{-1}$

  n, T plasma density and temperature

  τ_E energy confinement time

- Thermonuclear controlled fusion requires
  1. particle confinement (***n***)
  2. plasma heating (***T***)
  3. energy confinement (τ_E)





Credit: ITER, www.iter.org

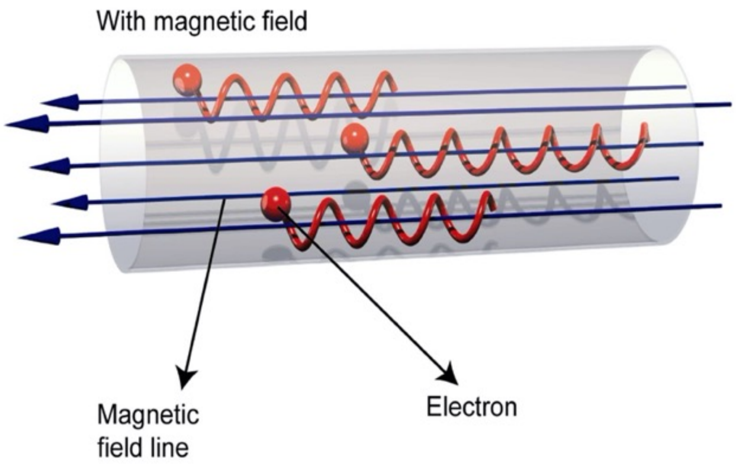
Magnetic confinement

- A strong magnetic field forces the charged plasma particles (electrons & ions) to spiral along the magnetic field lines

Larmor radius

$$r_L = \frac{v_\perp}{\Omega} \propto \frac{\sqrt{mT}}{B}$$

T = 10 keV, B = 5 T, ^{2}H
ions: $r_{Li} \approx$ 1.5 mm
electrons: $r_{Le} \approx$ 50 μm



Credit: ITER
www.iter.org

- The plasma can thus be isolated from the walls of the containment vessel

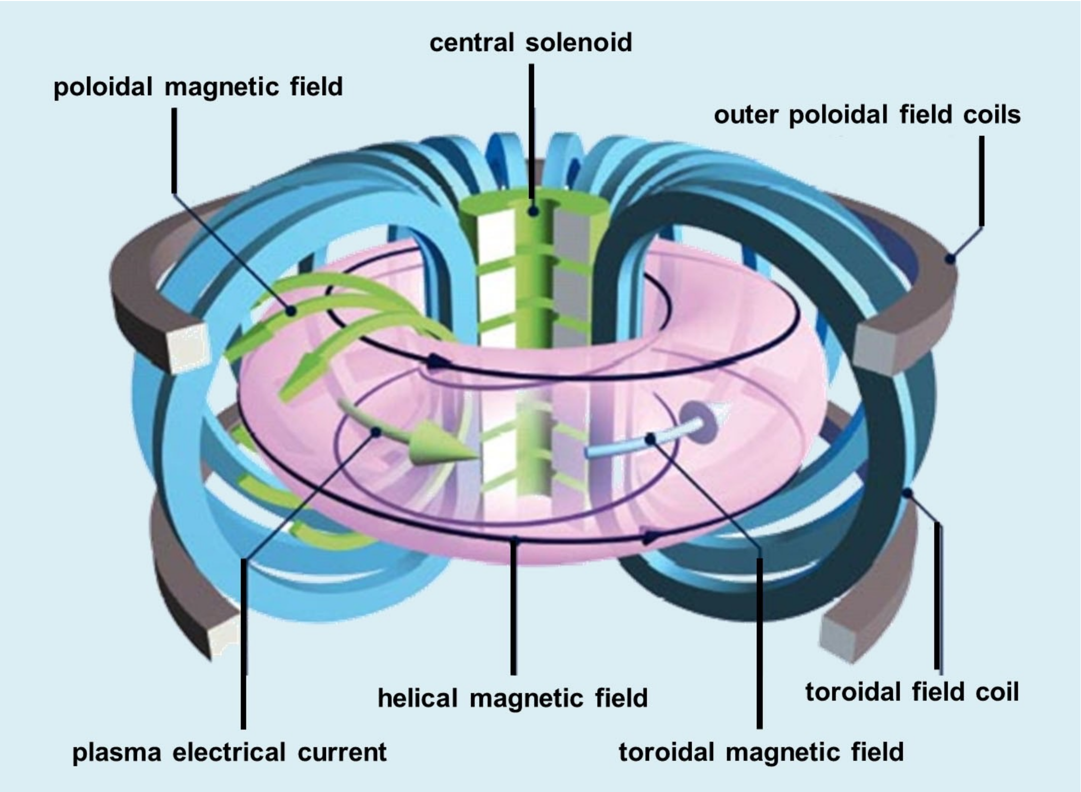
- This enables to heat the plasma to T > 10 keV (~100 million K)

The Tokamak

тороидальная **ка**мера с **ма**гнитными **ка**тушками

TOroidal **CHA**mber with **MA**gnetic **C**oils (1958 Artsimovich, URSS)

- **Poloidal coils** generate a **toroidal magnetic field** B ≈ 1/R
- A **central solenoid** is used as the primary circuit of a **transformer**, with the plasma acting as the secondary circuit
- The **plasma current** and external **toroidal coils** generate a **poloidal magnetic field**



Credit: EUROfusion, www.euro-fusion.org

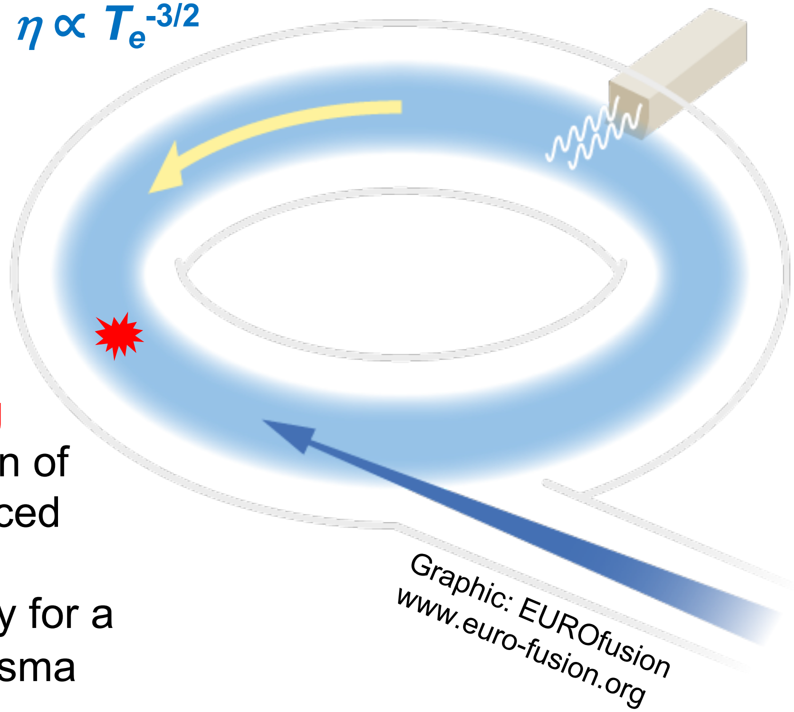
- **Helically twisted** field lines form nested flux surfaces

Plasma heating

Ohmic heating
- Produced by the plasma current
- Efficiency drops at high temperature

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

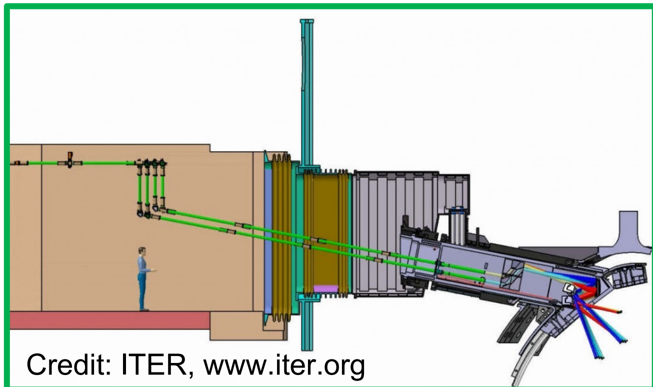
Wave heating
- Injection of high frequency waves **30 MHz – 170 GHz**
- Wave–particle resonant interaction



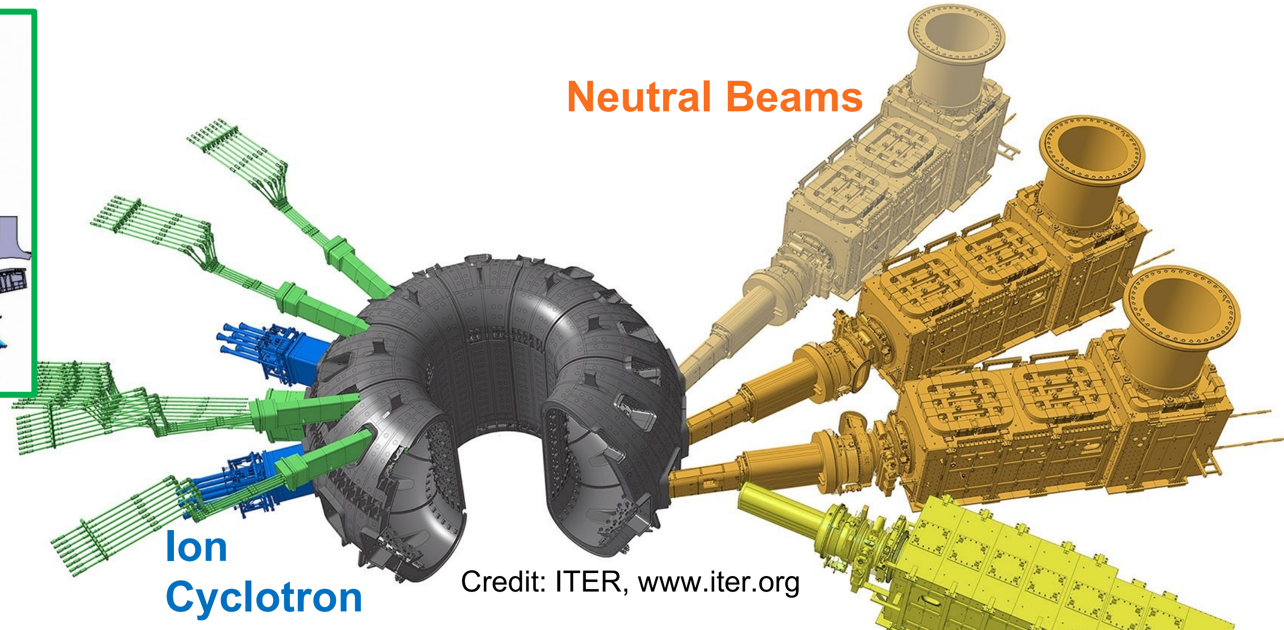
Alpha heating
- Slowing down of fusion-produced α-particles
- Relevant only for a "burning" plasma

Neutral beam injection
- Injection of fast particles **~100 keV – 1 MeV**
- Collisions with plasma particles transfers energy to plasma

Heating methods compared



Electron Cyclotron



		+	–	Key params in ITER
Neutral Beams		Good efficiency, can also be used to enforce plasma rotation	Bulky, difficult to steer	870 keV 33(50) MW
Waves	Ion Cyclotron	Helps heating ions	Antenna (loop arrays) must be close to the plasma	40-55 MHz 20 MW
	Lower Hybrid	Best current drive efficiency	Not well localized, antenna (wg array) close to the plasma, only off-axis at high T_e	5 GHz 0(20) MW
	Electron Cyclotron	Easily injected, localized, antenna easy to steer (mirrors)		170 GHz 20(40) MW

Wave-plasma interaction

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

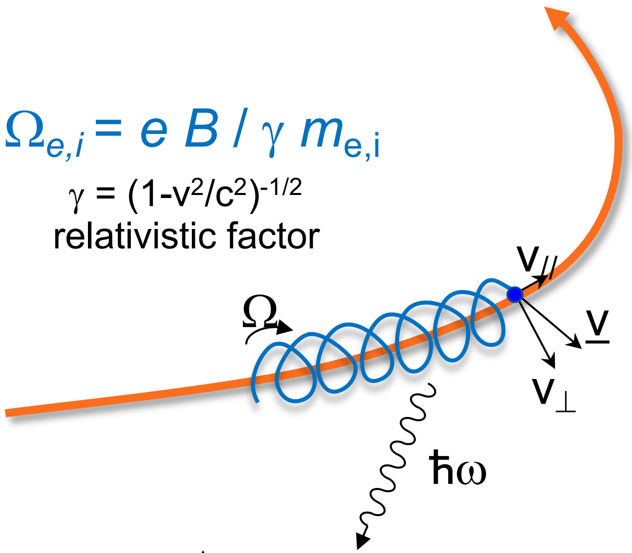
- Resonance condition in a magnetized plasma

$$\omega = n\,\Omega_{e,i} + k_{||}\,v_{||}, \qquad n = 0, \pm 1, \pm 2, \ldots, \qquad \Omega_{e,i} = e\,B / \gamma\, m_{e,i}$$

wave freq. — cyclotron harm. — Doppler shift

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

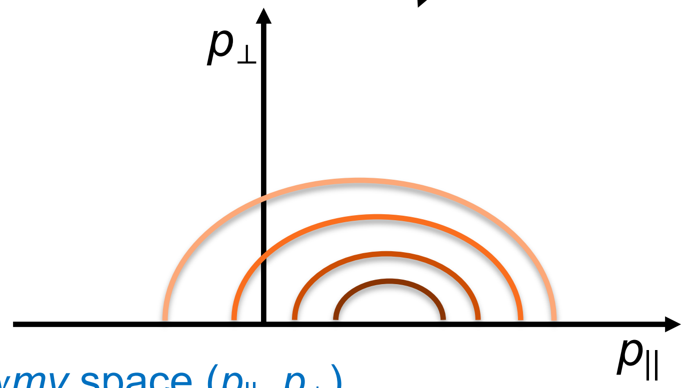
e,i = electrons,ions — || = along the magnetic field



- Electron/Ion Cyclotron (EC/IC) resonance

$$\omega \approx n\,\Omega_{e,i}$$

- EC resonance in Tokamaks ($B \sim 1/R$)
  - Localized in space, where $\omega \approx n\,\Omega_e(R)$
  - Localized in velocity space
    resonance condition is an ellipse in momentum $p=\gamma m v$ space ($p_{||}$, $p_\perp$)



Energy & momentum exchange

- Wave-particle interaction
  → wave **absorption/emission** with energy and momentum exchange

Current Drive (CD):

- Electron changes its || velocity — $v_{||} \rightarrow v_{||} + \delta v_{||}$
  - change in || momentum — $m\,\delta v_{||}$
  - change in energy — $\delta\varepsilon = m\,v_{||}\,\delta v_{||}$
- Variation of current density — $\delta j_{||} = e\,\delta v_{||}$

- Current dissipation via collisions — $\nu(v)$: Coulomb collision frequency

- Power needed to sustain the current — $\delta P = \nu\,\delta\varepsilon = \nu\,m\,v_{||}\,\delta v_{||}$

- Current drive efficiency:

$$\frac{\delta j_{||}}{\delta P} = \frac{e}{m v_{||} \nu(v)}$$

EC Emission as diagnostic tool

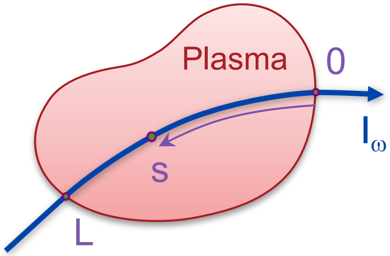
- In a plasma at thermal equilibrium

Kirchhoff law

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

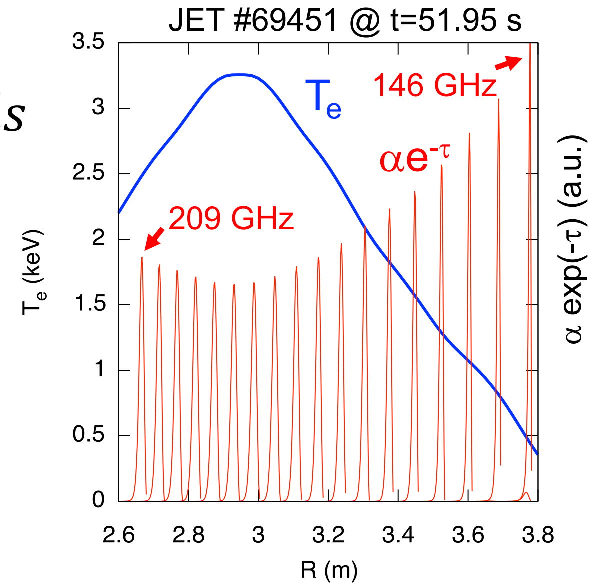
ω : wave frequency
j, α : emission, absorption coefficients
n_r : ray refraction index

- Intensity of emitted radiation



$$I_\omega = \frac{8\pi^3 c^2}{\omega^2}\int_0^L T_{rad,\omega}(s) e^{-\tau(s)}\alpha_\omega(s) ds$$

$\tau(s) = \int_0^s \alpha_\omega(s')ds'$: optical thickness



- Optically thick plasma regime ($\tau \gg 1$)

$$\boxed{I_\omega \approx \frac{8\pi^3 c^2}{\omega^2} T_e(R = R_{res,\omega})}$$

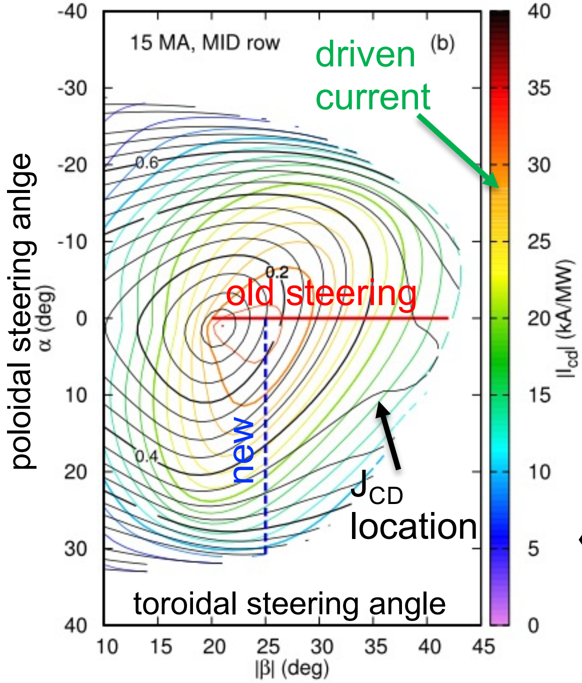
- Each ω "sees" a different R → **T_e profile reconstruction**

EC Heating&CD / Emission modelling

Beam-/ray-tracing is the most suitable approach to compute EC beam propagation given the typical ordering

$$\lambda \ll w \ll L$$

wavelength (~mm) | beam size (~cm) | plasma size (~m)

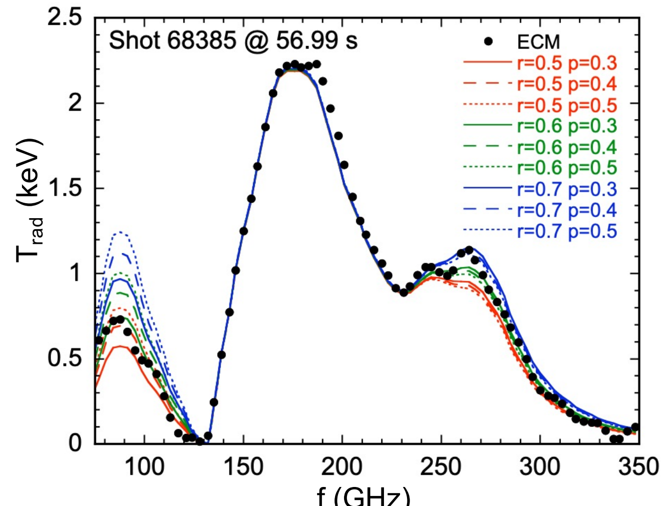


H&CD: GRAY (Farina D. 2008 Fusion Sci. Technol.)

- Gaussian beam propagation in quasi-optical approximation
- Absorption: linear response, fully relativistic dispersion
- Current drive: current response function accounting for momentum conservation (Marushchenko et al 2009 Nucl. Fusion)

ITER EC launcher steering optimization

JET broadband ECE spectra analysis



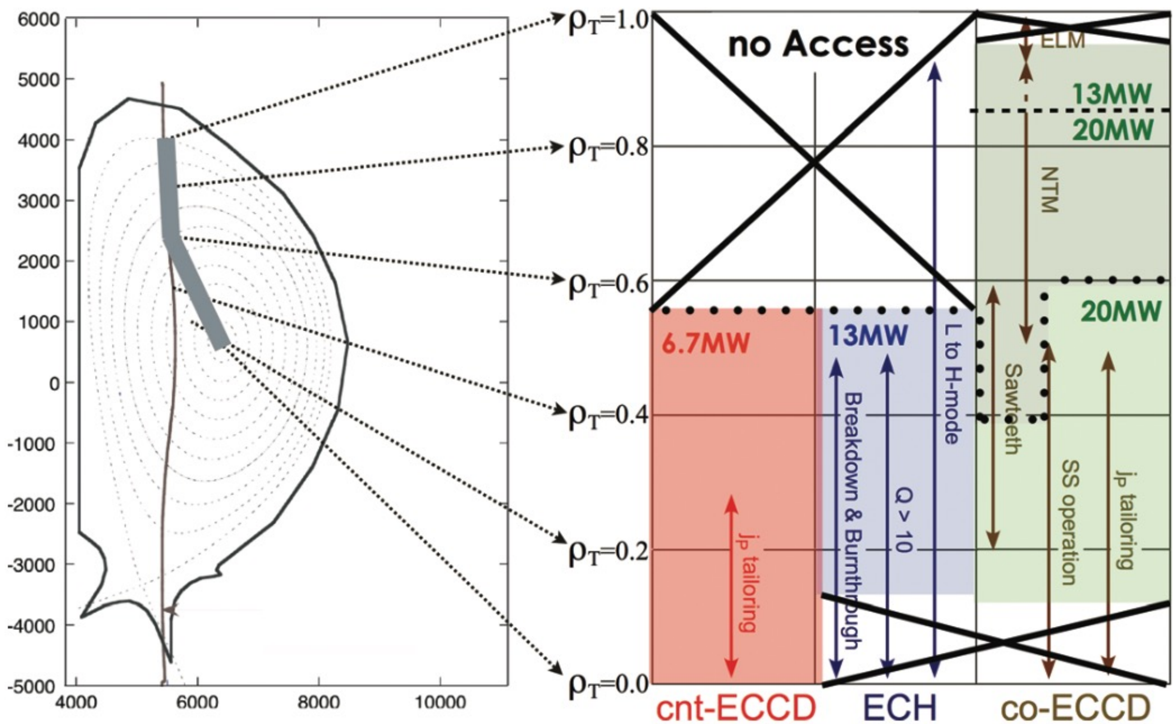
ECE: SPECE (Farina D. et al 2008 AIP Conf. Proc. 988)

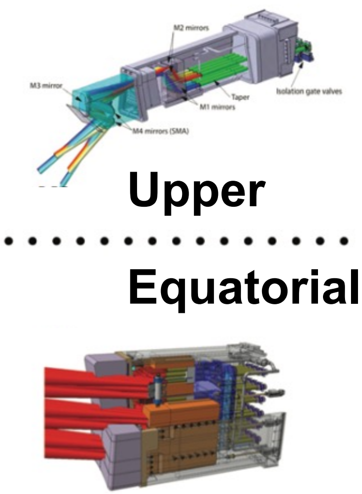
- Emission: fully relativistic dispersion for Maxwellian and multi-Maxwellian electron distributions
- Multi-pass model for optically thin regimes

EC H&CD applications

- Current profile tailoring
- MHD Stabilisation and control
- Ionisation and plasma start-up
- Disruptions mitigation/avoidance
- Impurities control
- Heat transport studies, ...

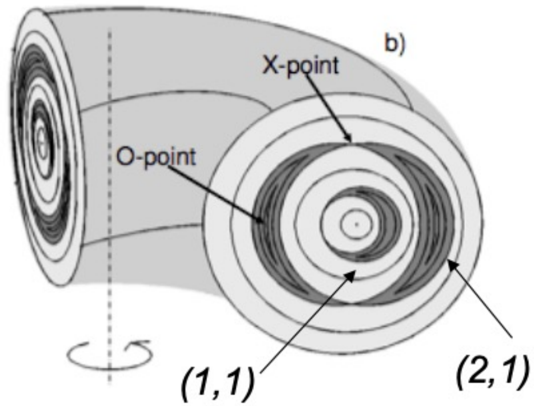
ITER EC launchers targeted applications





Henderson M et al 2015
Phys. Plasmas

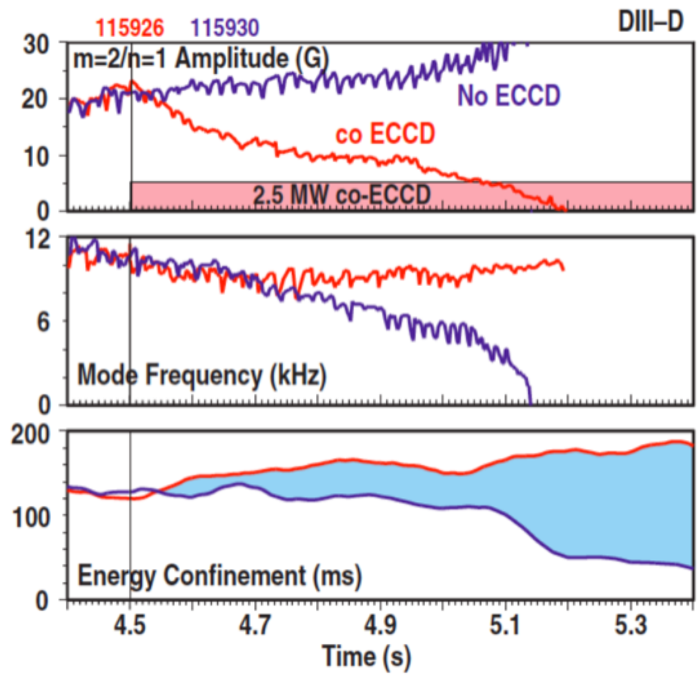
MHD control with ECCD



- Magnetohydroynamic (MHD) instabilities deform the equilibrium magnetic configuration
- Energy confinement is reduced, increasing the risk of disruptions

EC waves are ideal as **MHD control actuator**

- interaction is highly localized
- the EC beam can be easily steered
- power modulation is possible



m=2/n=1 neo-tearing mode (NTM) suppressed by ECCD

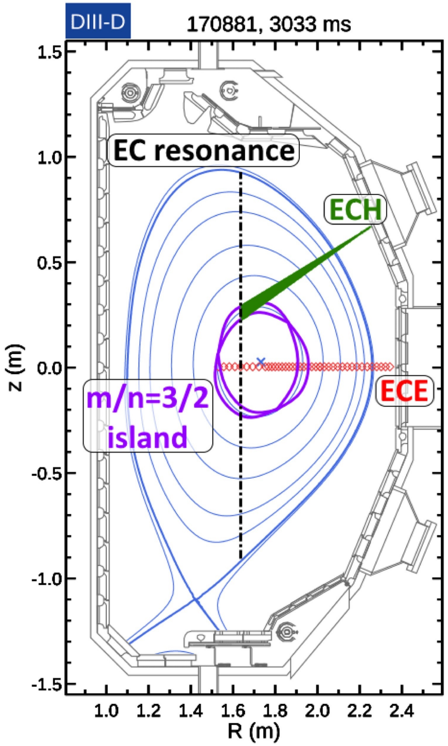
NTM suppression avoids loss of rotation and locking

Improvement in confinement rather than large loss likely leading to disruption

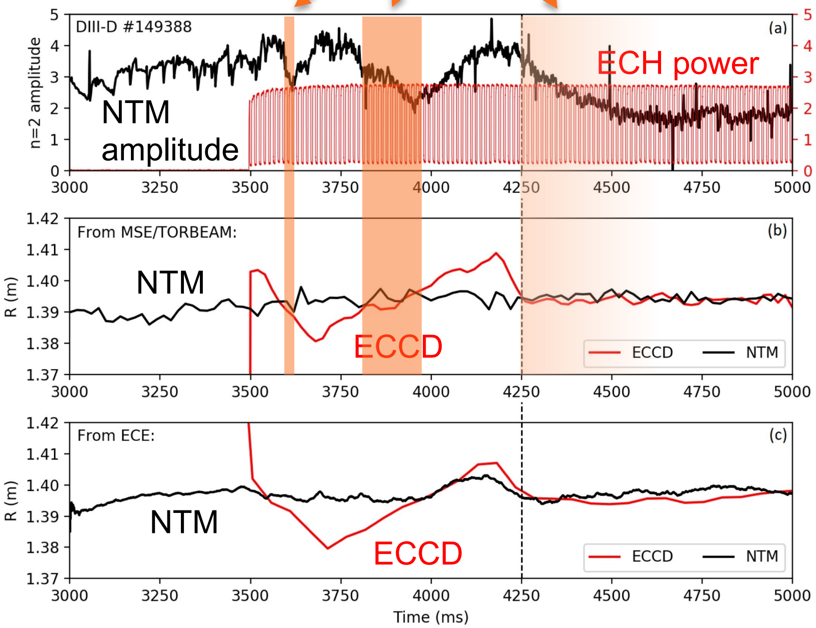
R. Prater, review talk APS 2003

ECE for NTM and ECH tracking (DIII-D)

- "Traditional" approach to NTM tracking requires:
  magnetic measurements + equilibrium reconstruction + ray-tracing algorithm
- Temperature perturbations induced by **NTM** and **ECH modulation** allow localization of both with **ECE** alone



stabilization occurs only for **tight** alignment of NTM and ECCD locations



magnetics + beam-tracing

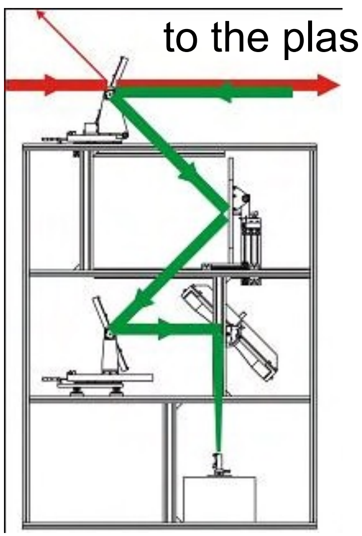
ECE only

A.O. Nelson et al 2019 Fusion Eng. Des.

NTM tracking with in-line ECE (TEXTOR)

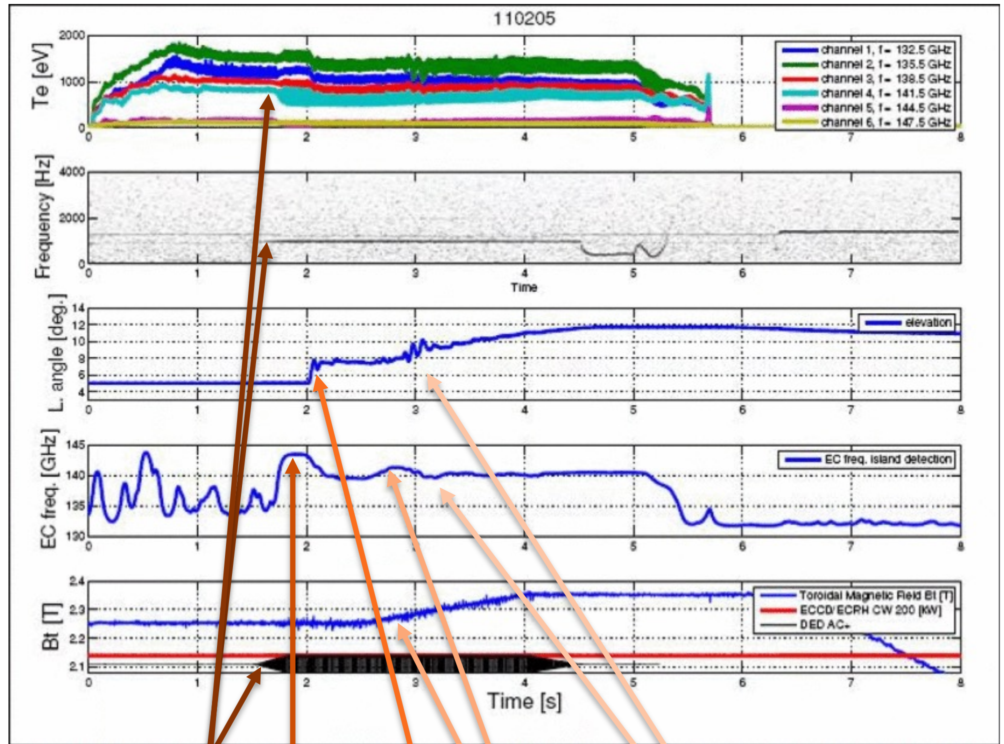
- Beamline shared between ECE and ECH: same localization at equal frequency
- Dielectric plates + notch filter to attenuate possible ECH beam reflections

ECH



ECE detector

M.R. de Baar et al 2011 IEEE Int'l Conf. on Control Applications (CCA) Denver



NTM onset

ECE detects offset

ECH aligns to NTM

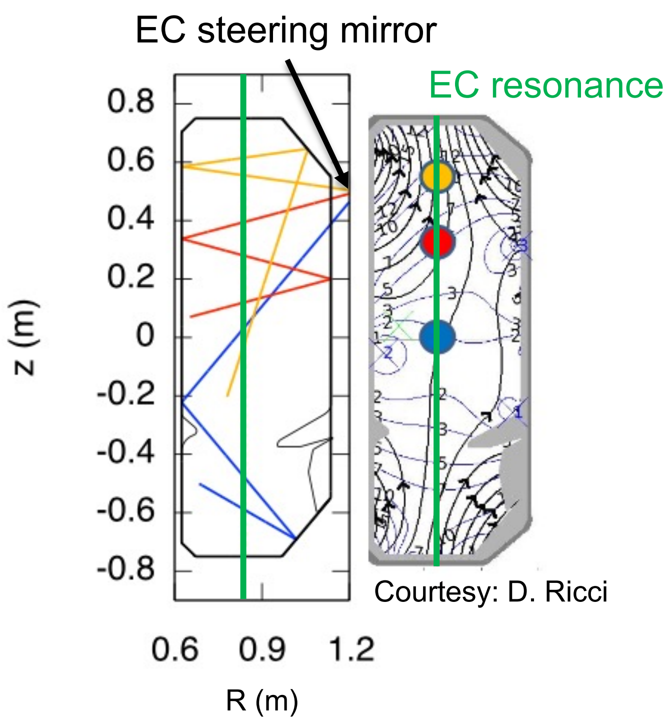
B change forces misalignment

ECH uses ECE information stay aligned

EC-assisted plasma start-up (TCV)

- Energy gained by electrons via collisionless heating is sufficient to pre-ionize the gas
- EC wave absorption help compensating radiative losses during the burn-through phase

→ A smaller loop voltage can be used for plasma initiation

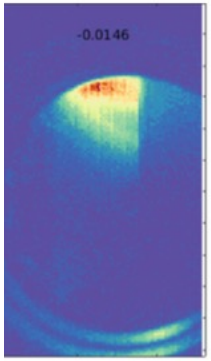


Courtesy: D. Ricci

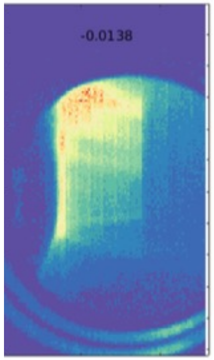
Poloidal angle scan:
-8º, +15º, +50º

First pass at EC resonance:
z = 0.55m, 0.39m, 0.03m

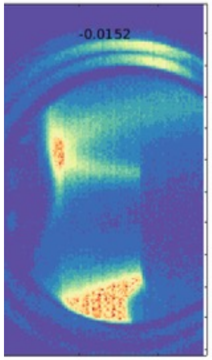
Plasma starts at different z positions, depending on the launching angle



-8º

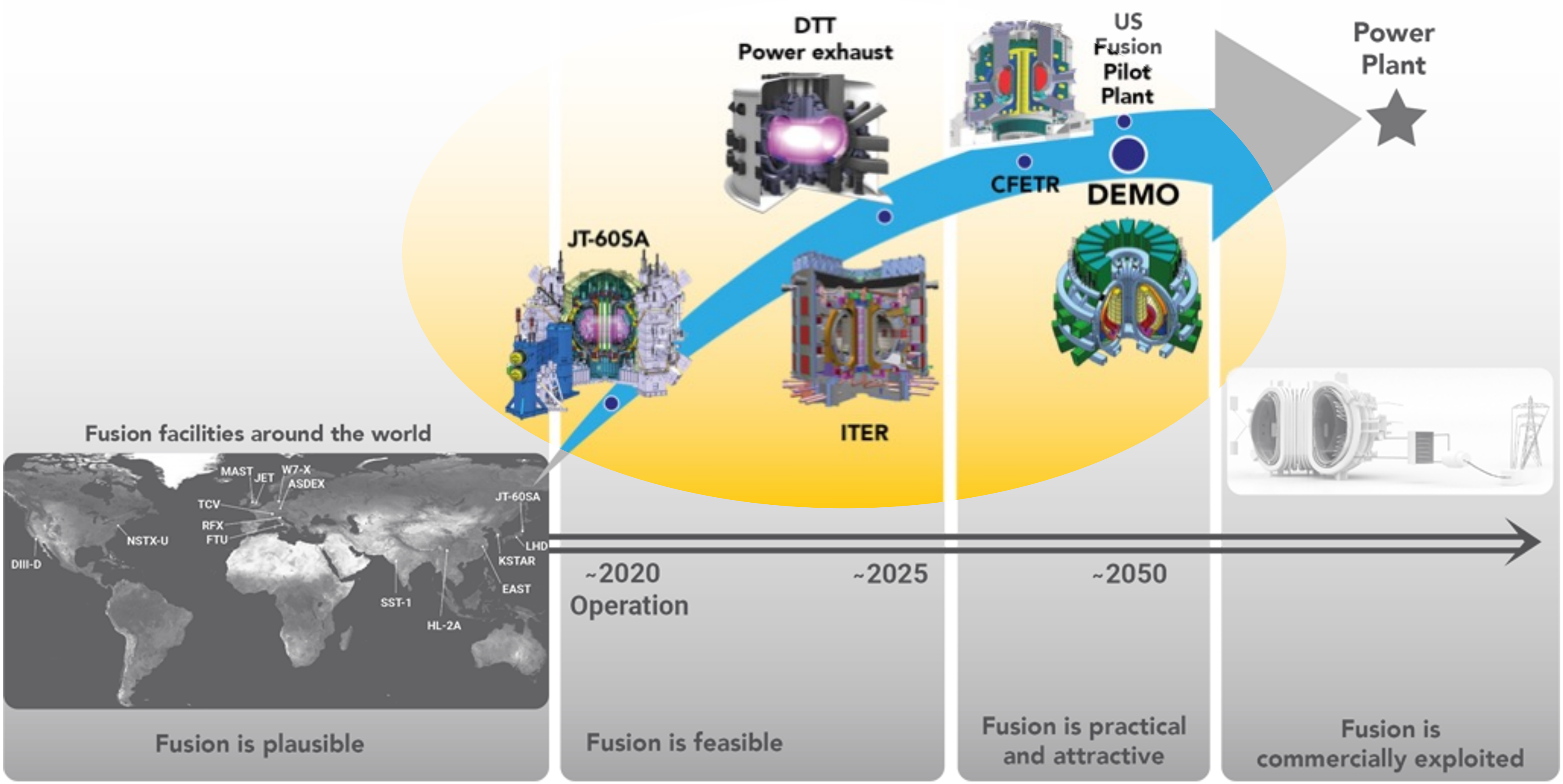


+15º



+50º

Future devices



Source: www.dtt-project.it

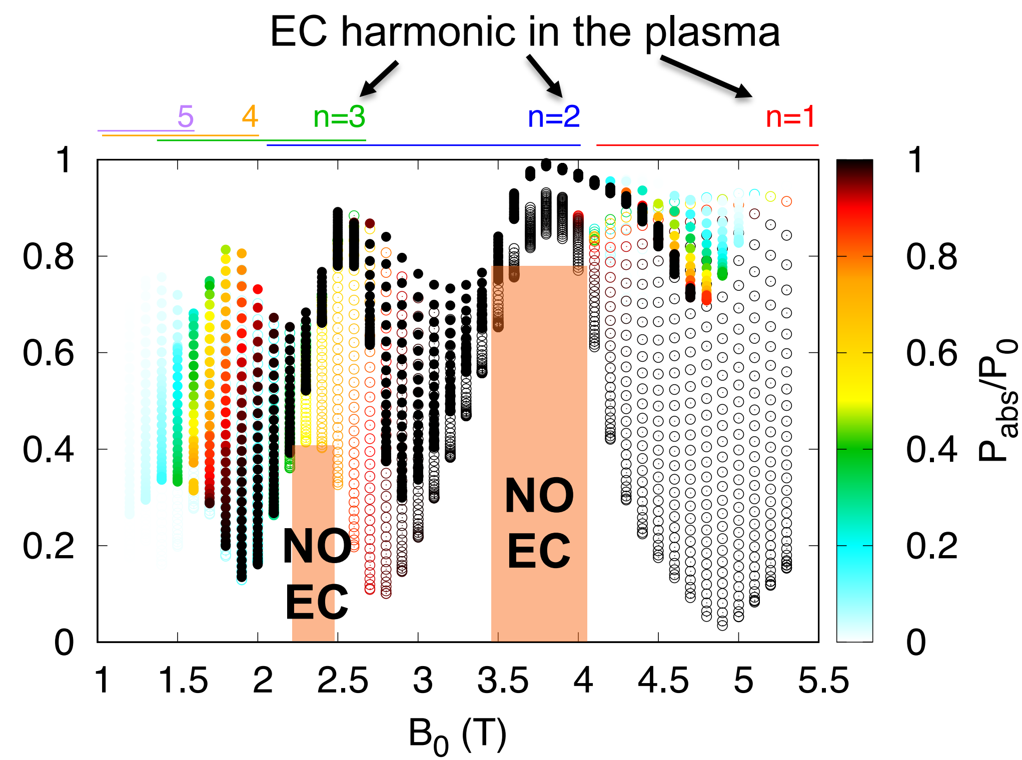
Non-nominal magnetic field

- Efficiency of an EC system strongly depends on the magnetic field
- **ITER** EC frequency (170 GHz), and launching geometry optimized, for the full-performance scenario at B_0 = 5.3 T

Current ITER Research plan

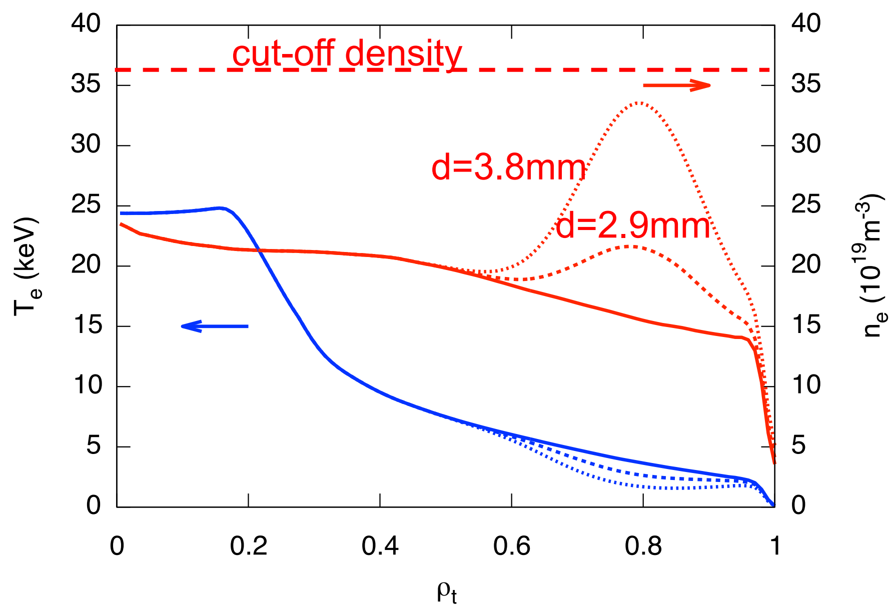
- 1^{st} plasma: B_0 = 2.65 T
- 1^{st} H-mode plasma: B_0 = 1.8 T
- Gradual increase to full-field

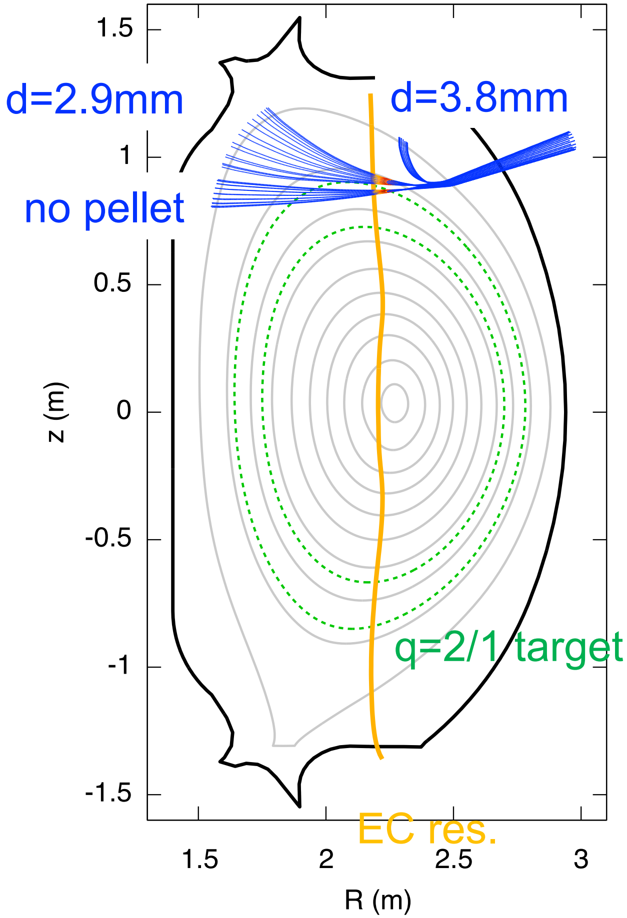
Need to assess B_0 ranges where the EC system can operate



Inter-operation with other systems

- DTT reference scenario during pellet injection (two possible pellet diameters *d*)
- Refraction must be compensated acting on beam steering to keep ECCD on target





B_0 = 6 T @ R_0 = 2.19 m
f_{EC} = 170 GHz

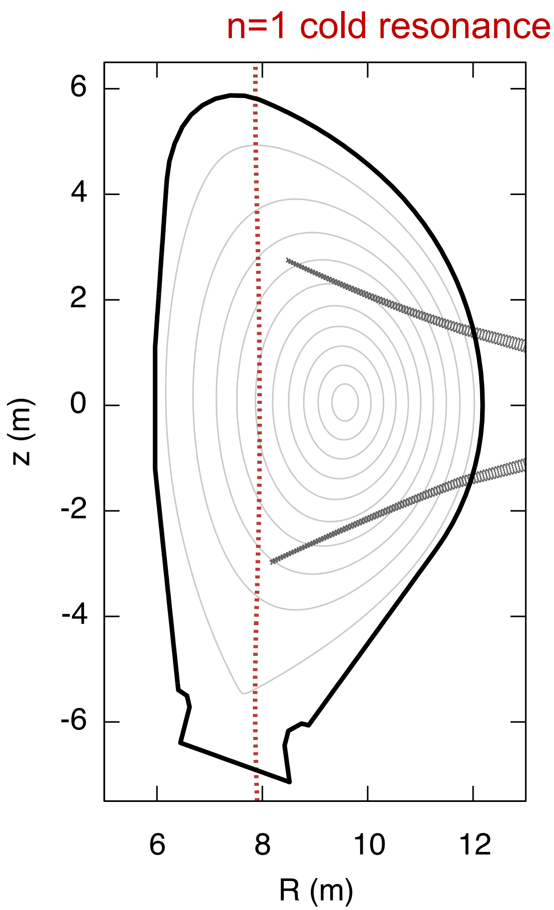
Harmonics overlap at high Te

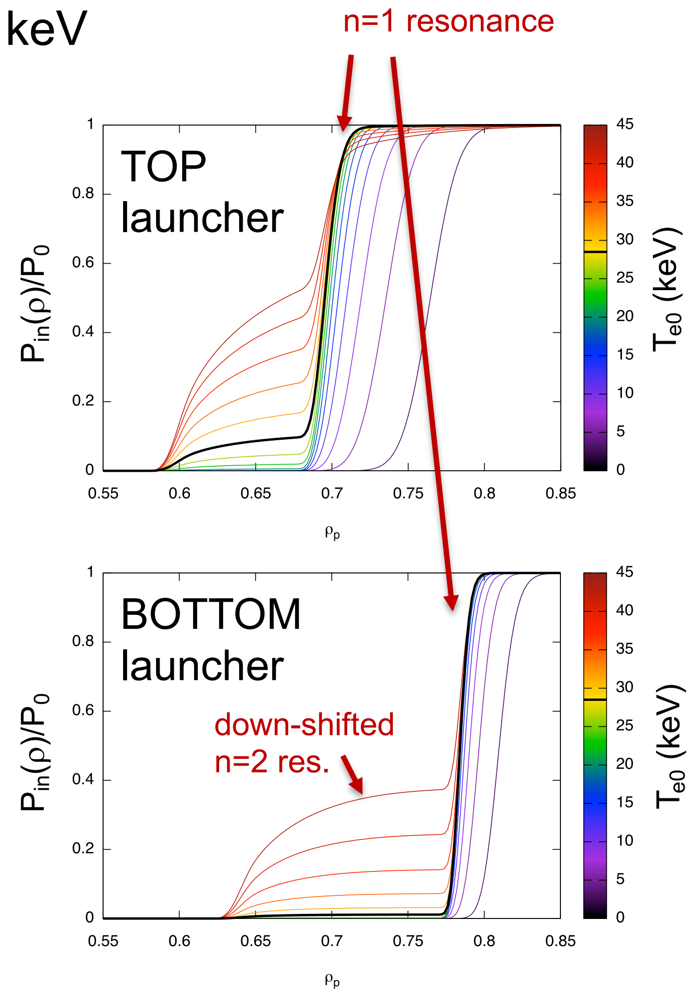
DEMO: the core electron temperature will be T_e>25 keV

- The EC system will nominally work at the n=1 resonance
- "cold" (γ=1) resonances
  - n=1 at R≈8 m
  - n=2 at R≈16 m
- Fast electrons in the core resonate at n=2 with large relativistic down-shift (γ ≈ 2)

$$\omega \approx n\,\Omega_e = n\,eB/\gamma m_e$$

- T_{e0}=40 keV: Up to ≈50% of the injected power is absorbed **before** the n=1 resonance is reached

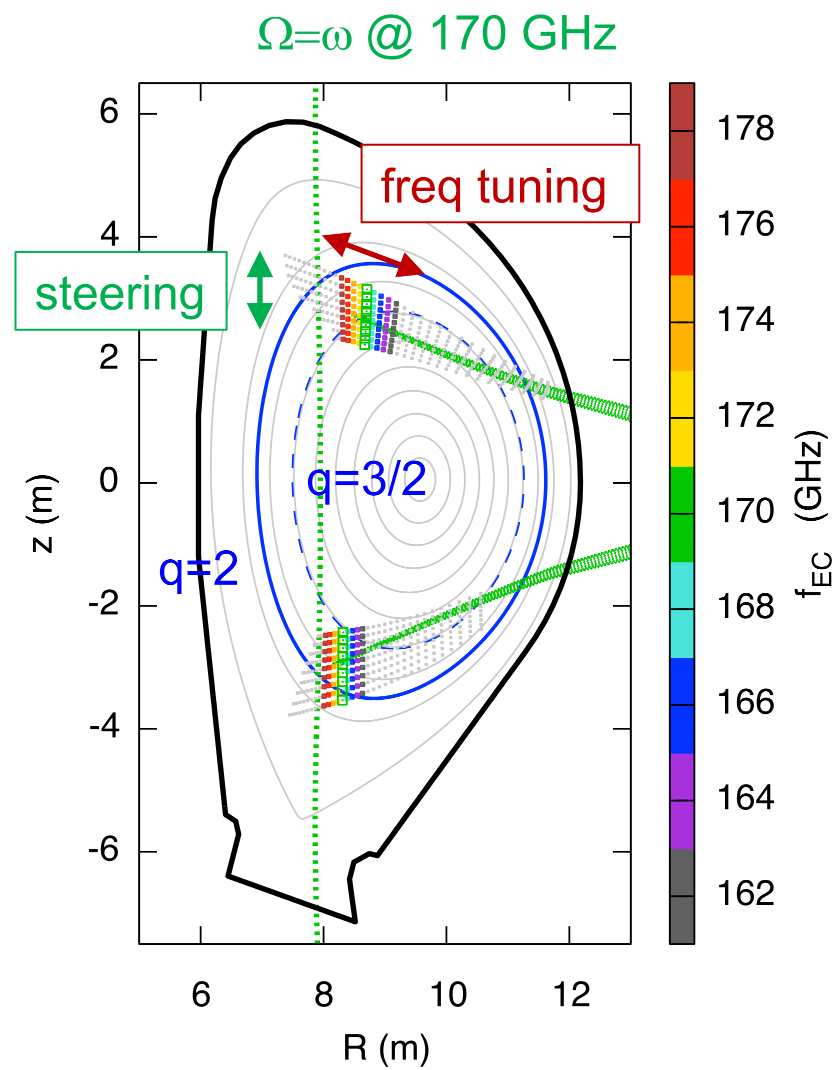




If localized absorption is demanded, the beam path should avoid crossing the core

Frequency tuning

- In the DEMO reactor any opening in the blanked must be minimized to reduce neutron damage
- Plasma facing steering mirrors are not an option
- Limited EC beam steering:
  $|\Delta\alpha| \leq 4^{o}$ from nominal line of sight in present design
- Frequency tuneable sources can help re-gaining the lost flexibility
  $f = (170 \pm 10)$ GHz, Δf = 2-3 GHz
- Frequency tuning not as fast as beam steering, but progress is expected



Summary

- RF waves are routinely and robustly used to heat, diagnose, and drive current into magnetically confined plasmas
- Future fusion-relevant machines will heavily rely on waves at the Electron Cyclotron frequency for a wide range of applications thanks to their flexibility and robustness in harsh environments
- Accurate modelling tools exist to predict ECH&CD performance, helping to evaluate and tackle the challenges in the design of next generation devices

THANK YOU!

Night shot of ITER site, 10 november 2020. Photo: ITER organization/EJF Riche