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Istituto per la Scienza
e Tecnologia dei Plasmi

Plasma-wave interaction in present-day magnetic fusion research

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Acknowledges to ISTP colleagues

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Waves & Plasmas

- Waves in plasmas is a very wide topic in plasma physics
- Depending on the plasma parameters and the wave frequency and power a large variety of physical phenomena can occur
- This talk is focused on the role played in fusion research by specific rf waves injected in magnetically confined plasmas in present-day and future experiments

Waves and fusion research

- Injection of electromagnetic waves can assist the plasma discharge in its various stages for plasma start-up and burn-through, core heating, control of MHD instabilities, etc.
- Linear and nonlinear processes take place on various time scales and lengths, and advanced theory and modelling are required to investigate wave propagation and absorption.
- ISTP-CNR in Milano has a long standing expertise in the field of Electron Cyclotron (EC) waves, spanning from theory, modelling, experiments, system design and technology.
- EC waves in magnetized plasmas are e.m. waves at frequency ω close to the cyclotron frequency Ω or its harmonics $\omega = n\,\Omega$

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EC Waves

- In magnetic confinement fusion research, the magnetic field is in the range 1 T - 6 T and EC frequency is in the range 28 – 170 GHz (i.e. λ = 2 mm – 1 cm in vacuum)

- EC waves interact with the electrons in a plasma via a resonant process
  - Energy is then transferred from electrons to ions via collision: **Electron Cyclotron Resonant Heating – ECRH**
  - In addition, EC waves can drive localized currents in the plasma via momentum transfer and collisional processes **Electron Cyclotron Current Drive – ECCD**

- EC interaction is highly localized in space close to the cyclotron resonance or its harmonics, for relatively large density and temperature
- EC waves can propagate in vacuum thus avoiding coupling issues at the vacuum–plasma boundaries encountered by lower frequency waves

ECRH systems

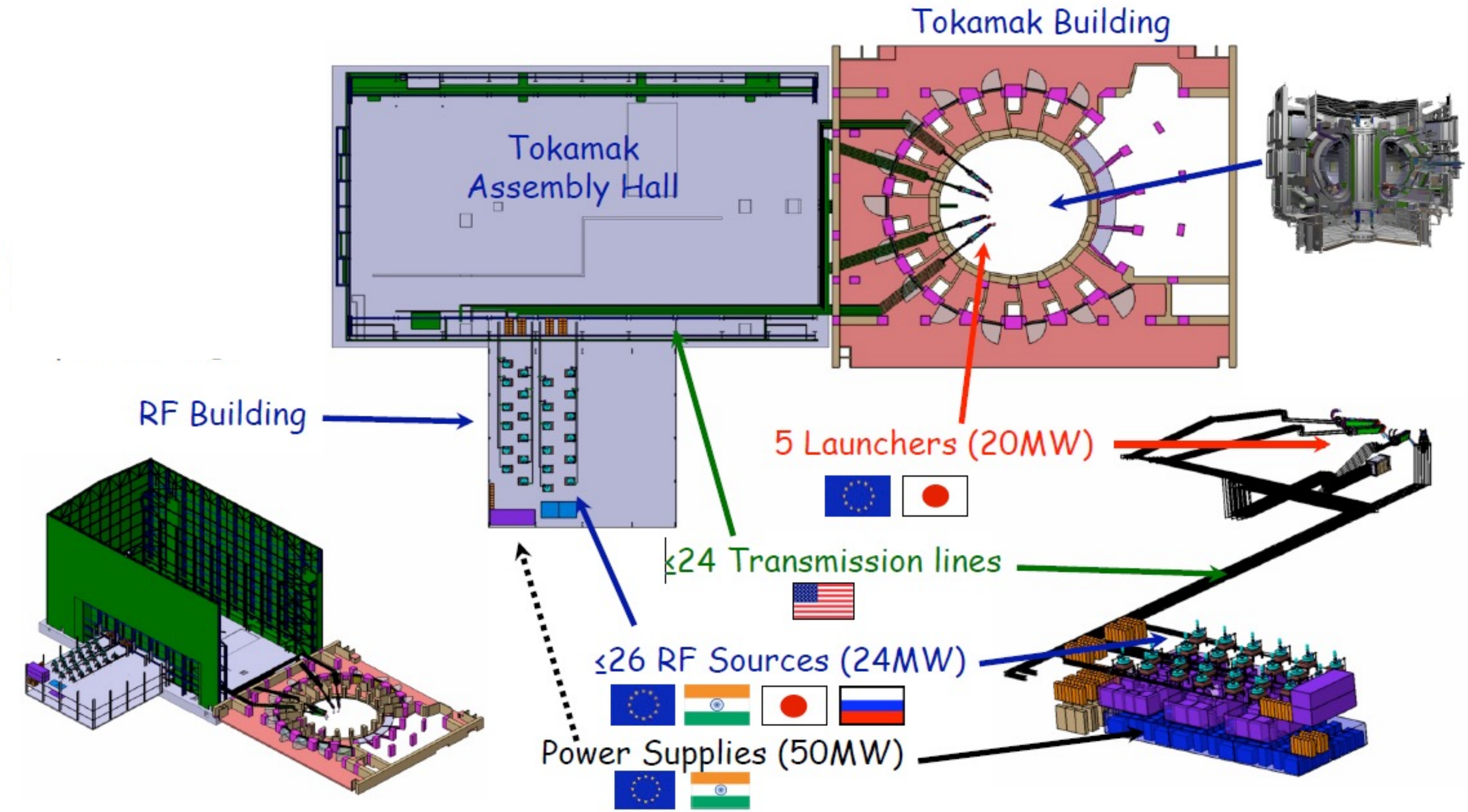
- Most of the present day fusion devices are or will be equipped with an EC system, both in Europe and worldwide

- In ITER it is foreseen to inject into the plasma up to 20 MW of EC power either via an Equatorial Launcher or four Upper Launchers via 24 gyrotron, 170 GHz, 1 MW each.

- The EC system will be the only heating system in ITER first plasma foreseen in 2025-2026.

- In DTT, the tokamak device that will be built in Frascati, it is foreseen to have a major ECRH system, 170 GHz – 24 MW, with possible future update to 33 MW power

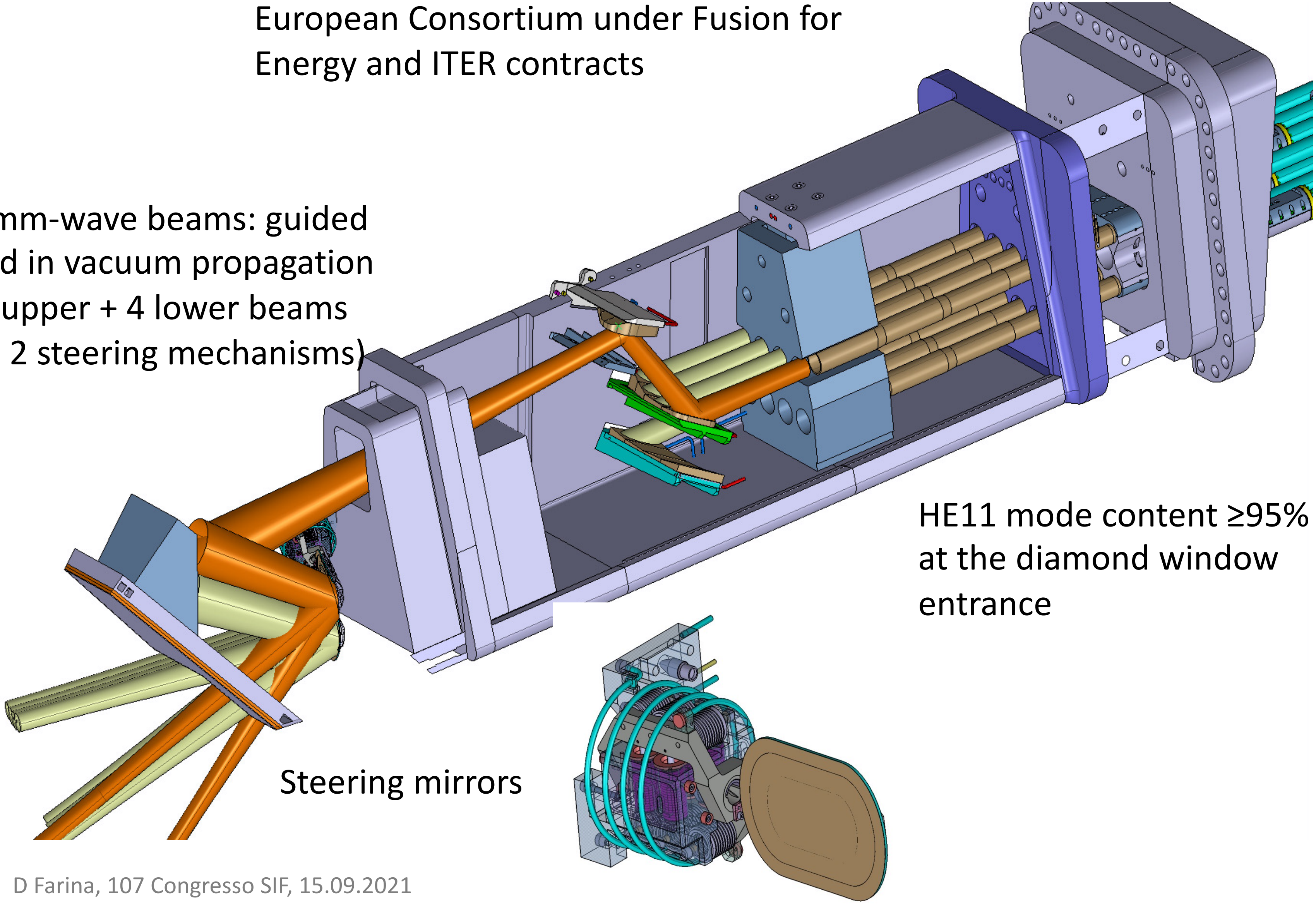
ITER EC system layout



ITER EC Upper Launcher

Upper Launcher design developed by a European Consortium under Fusion for Energy and ITER contracts

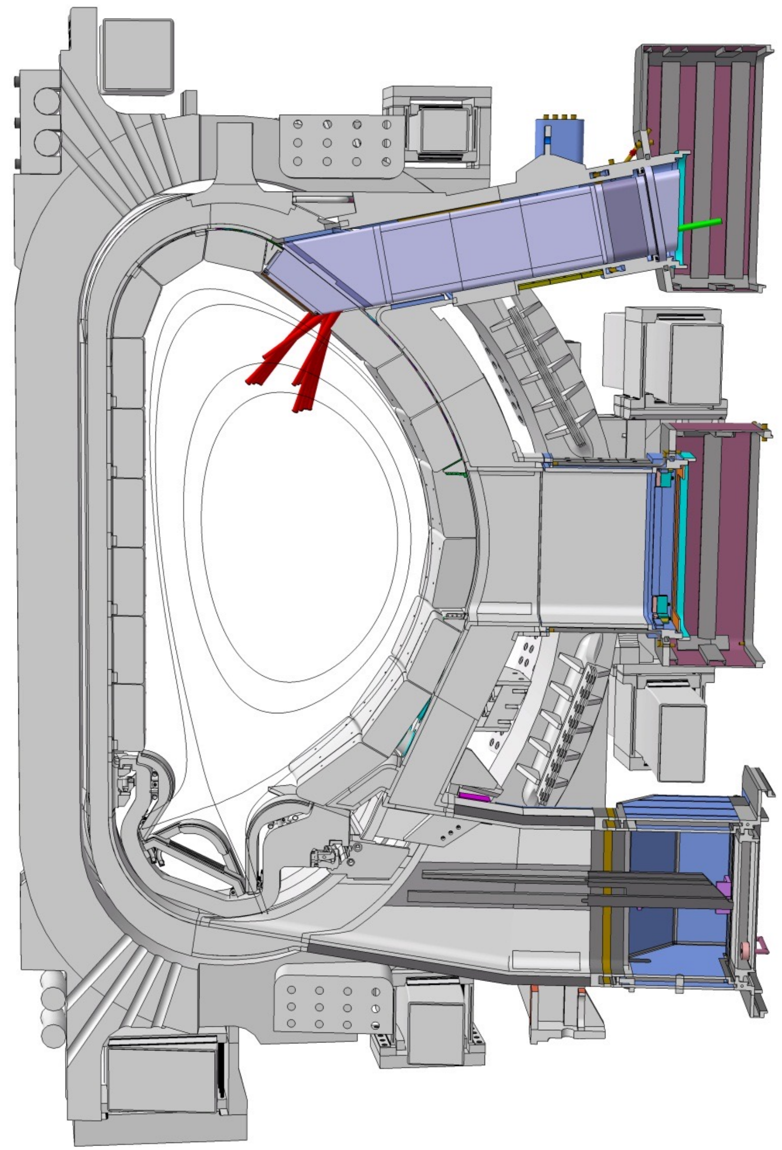
8 mm-wave beams: guided and in vacuum propagation (4 upper + 4 lower beams on 2 steering mechanisms)



HE11 mode content ≥95% at the diamond window entrance

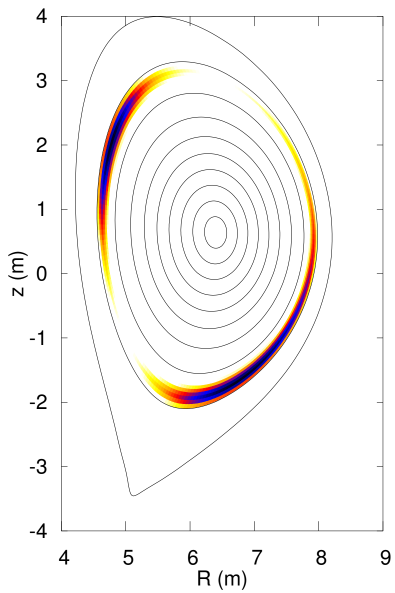
Steering mirrors

ITER EC Upper Launcher



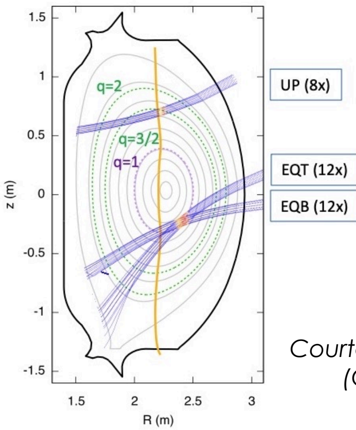
Main Function of the EC Upper Launcher

- Localized current drive for MHD stabilization
- it requires directivity & focusing of the injected EC beams



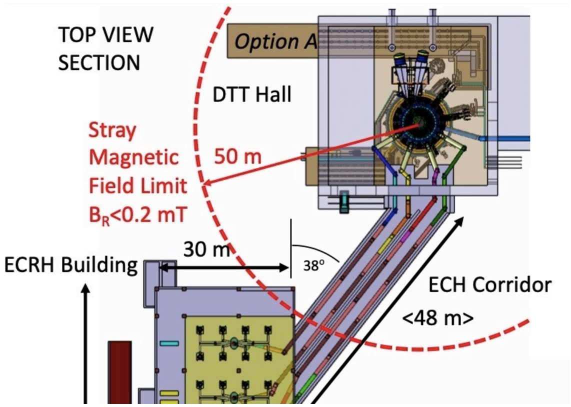
ECRH System

- **Core Heating & Current Drive**: good plasma-wave coupling
- Help in **sustaining plasma current**
- Relevant for actuator management due to its localised deposition for **MHD control** (NTM, ST and ELMs)
- Main limitation: high electron density, scenarios with $n_0/n_{cut\ off} = 0.78$



Courtesy of L.Figini (CNR, Milano)

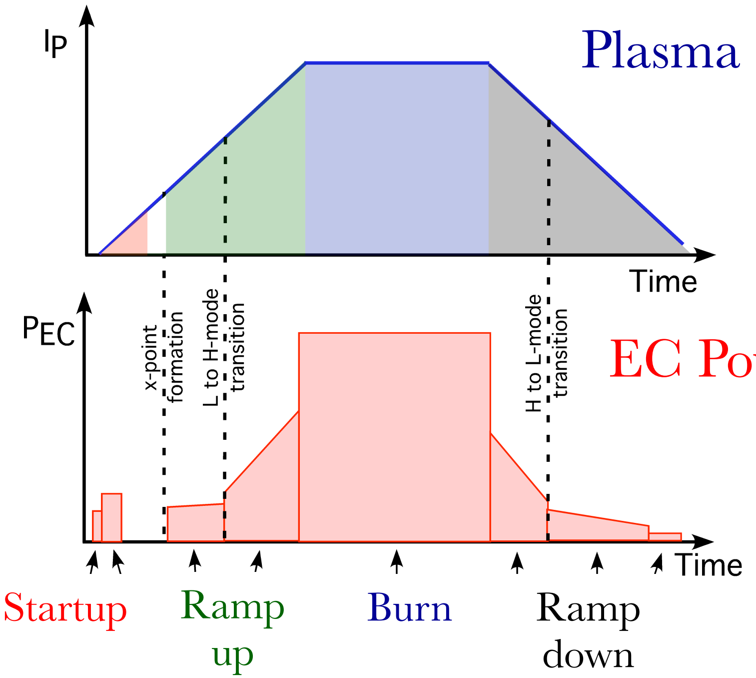
- Power to plasma: up to ~30 MW (ITER: 24 MW)
- Gyrotron source: 170 GHz (resonating at 6T), 1MW/1.2MW each (similar to ITER)
- The architecture is based on **4 clusters** each composed by:
  - **8 gyrotrons**
  - **1 Evacuated multi-beam Quasi-Optical transmission line** delivering the 8 microwave beams from gyrotrons to one tokamak sector
  - **8 independent launching mirrors** in two different sector ports



Courtesy of G.Granucci, S.Garavaglia (CNR-Milano)

ECH&CD functionalities

How has ECH&CD been used on previous devices?



Start-up

- Break down
- Burn through

Ramp-up

- Current ramp up assist
- Elongation assist
- L to H-mode transition
- Central heating
- Profile tailoring

Burn

- Central heating
- Impurity control
- Disruption mitigation
- MHD control
- Profile Tailoring
- ELM control

Ramp-down

- Current ramp down assist
- H to L-mode transition
- Profile tailoring

ECRH&CD activities @ ISTP-CNR

- design of the ECRH system (modelling and R&D)
  - mmw optical design: ITER UL, JT60-SA (JP), DTT, DEMO
  - stray radiation and spillover studies
  - beam dump design

- Plasma physics analysis (modelling&experiments)
  - Gaussian beam propagation and absorption in tokamak plasmas
  - Plasma performance characterization and scenario develpment
  - Neoclassical tearing mode stabilization via localized ECCD
  - Plasma EC assisted startup:
    - Plasma preionization via EC power
    - Plasma burnthrough

- Competencies required:
  - engineer & plasma physicists
  - experimentalists & theoreticians / modellers

Plasma startup

- Plasma initiation is a complex and dynamic process, that involves the transitions from gas breakdown to magnetically confined plasmas, including the interaction of neutrals and impurities with ionized plasmas, plasma-wave and plasma-surface interactions that are not always well understood, and usually not well diagnosed either

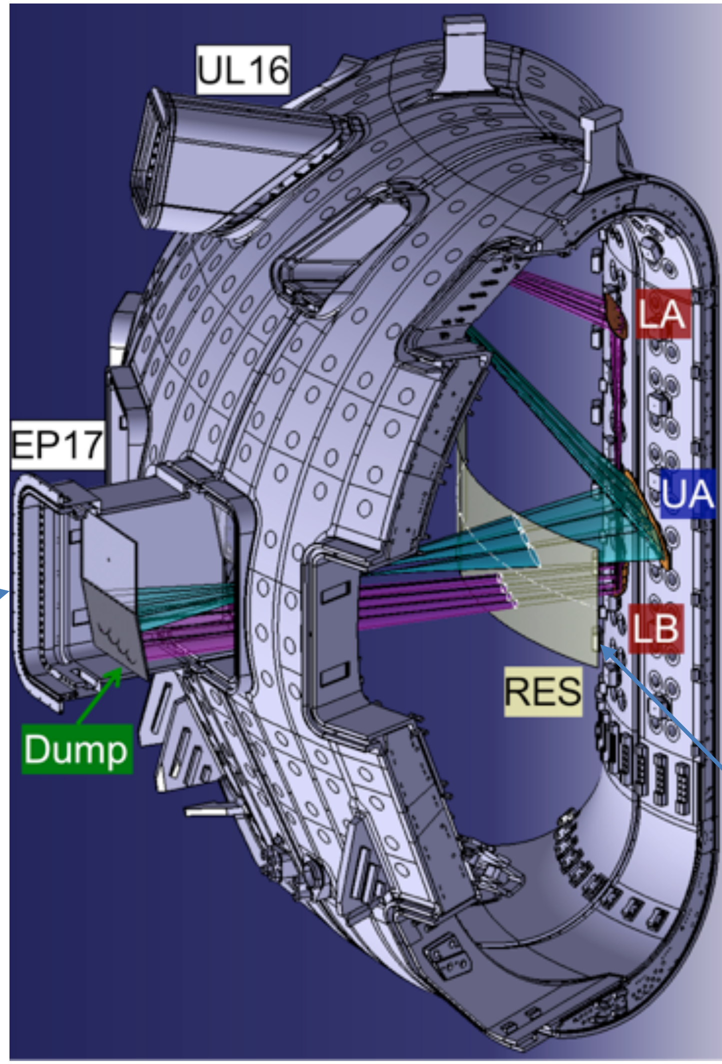
- Injection of rf waves may contribute to a successful startup

EC-assisted breakdown in ITER day 1

EC waves
Upper Launcher

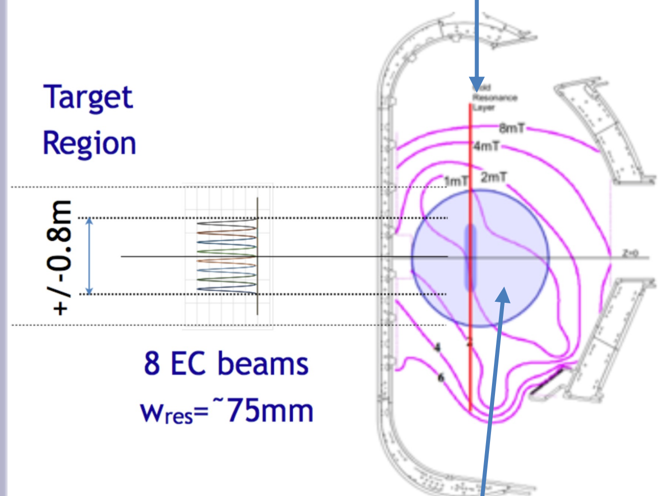
170 GHz
7 rf beams
1 MW each

Beam dump
Equatorial Port



Target Region

EC resonance



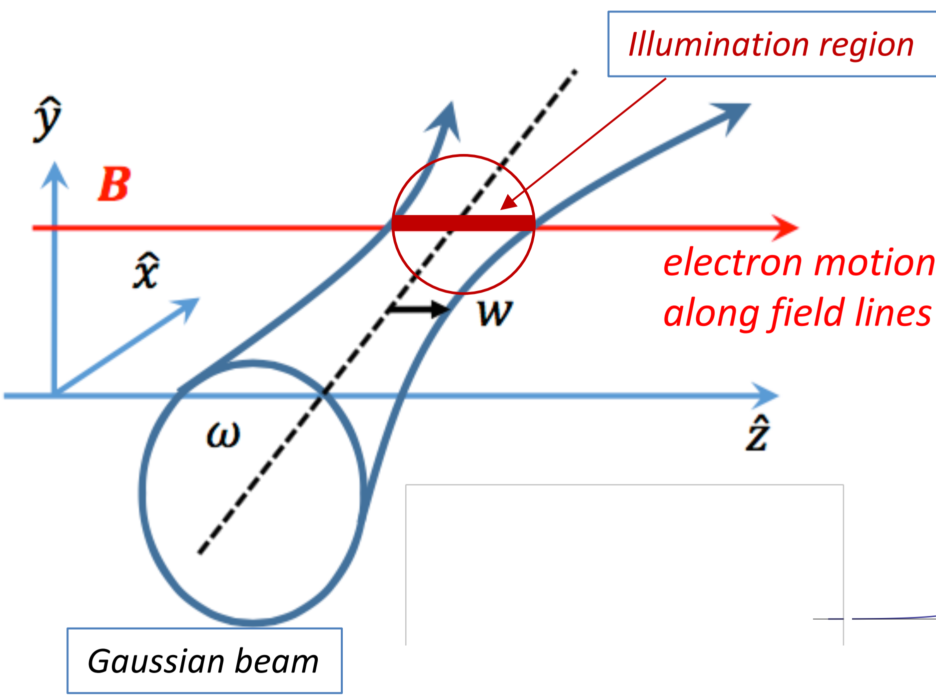
8 EC beams
w_{res}=~75mm

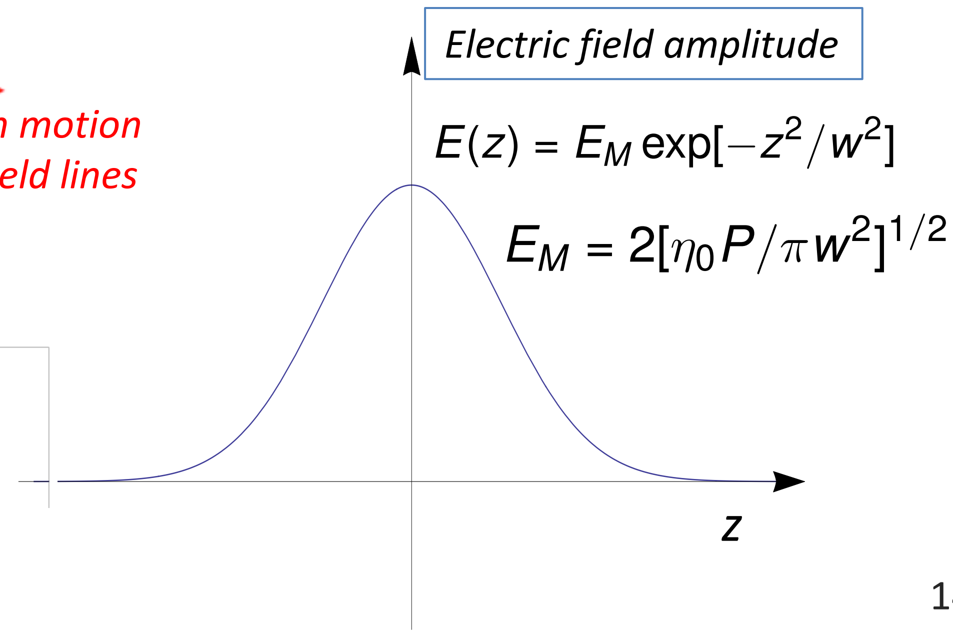
Null region

resonance

EC-plasma collisionless interaction

- Seed electrons at room temperature assumed to be uniformly distributed in the vessel volume.
- Electron motion: single particle in free space in a static magnetic field B_0 under the action of a localized e.m. EC beam with Gaussian amplitude *E(z)*





Theoretical model

Nonlinear theory applies either to extremely high power sources or quite low energy particles as in thevery early stage of a discharge (*D Farina, NF 2018)*

Assumptions

- EC Gaussian beam, *single source* (gyrotron)
- room temperature electrons, T_e= 30 meV
- EC interaction time shorter than collision time

Goal

- To compute the energy gained by an electron after beam crossing
- To characterize the final energy vs frequency, power, beam spot size, harmonic number, polarization

Equations of motion

$$\frac{d\mathbf{x}}{dt} = \mathbf{v}\,, \qquad \frac{d\mathbf{p}}{dt} = -e\mathbf{E}(\mathbf{x},t) - e\mathbf{v}\times[\mathbf{B}_0 + \mathbf{B}(\mathbf{x},t)]\,,$$

$$\mathbf{p} = m\gamma\mathbf{v}, \qquad \gamma = (1 + p^2/m^2c^2)^{1/2}$$

- Electric field with generic polarization (XM & OM)

$$\mathbf{E}(\mathbf{x},t) = E(z)[e_x \sin\chi\,\hat{\mathbf{x}} - e_y \cos\chi\,\hat{\mathbf{y}} + e_z \sin\chi\,\hat{\mathbf{z}}],$$

$$\chi = k_\perp x + k_\parallel z - \omega t$$

$$E(z) = E_M \exp[-z^2/w^2]$$

- Initial conditions for numerical integration: thermal electrons outside the beam region

- ITER parameters:

B_0 = 2.65 / 5.3 T, T_e=30 meV

f = 170 GHz, P_{EC} = 1 MW, w = 10 cm

Nonlinear adiabatic regime

$$\tau_{tr} << \tau_{flight} << \tau_{coll}$$

nonlinear trapping time << flight time << collision time

- τ_{tr} scales with the wave electric field , $\tau_{tr} \propto E_m^{a} \propto (P/w^2)^{a/2}$
  with exponent *a* depending on harmonic number

- τ_{tr} shorter than time scale of *E* field amplitude variation ~ $\tau_{flight} = 2\, w / v_{th}$

- For *P*=1 MW, local beam spot radius *w*=10 cm, T_e=30 meV:

trapping time	$\tau_{tr} \approx$ 2x10^{-8} s
flight time	$\tau_{flight} \approx$ ~ 3x10^{-6} s
collision time elastic+inel. / ionization	$\tau_{coll} \approx$ 5x10^{-4} s - 3x10^{-3} s

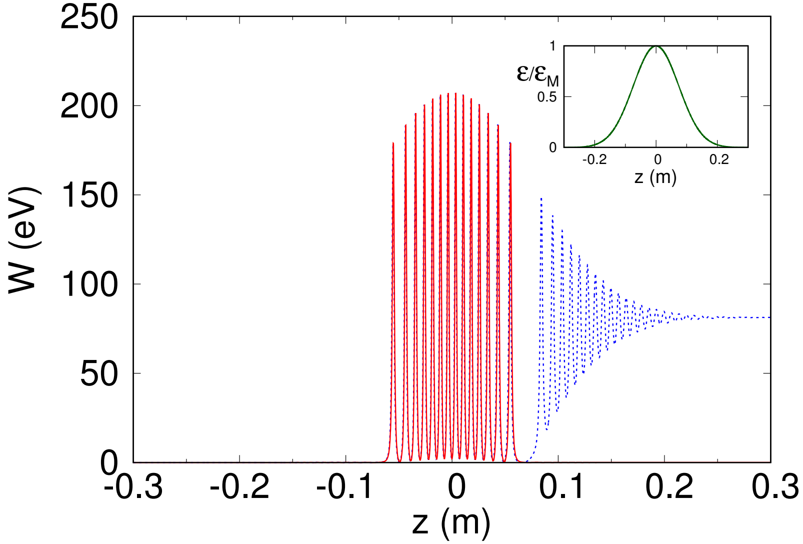
Trapped motion example

kinetic energy W vs z

$2\Omega/\omega = 1$, $N_{//}=0.3$

Electrons crossing the EC beam

- are trapped in the wave field for increasing e.m. amplitude E (z<0)
- experience large energy variations (<200 eV for XM2, much larger for XM1)
- are untrapped when the e.m. amplitude decreases (z>0)
- exit the beam region with two values of final energies:
  - the initial energy, $W \cong 30$ meV
  - a quite large energy $W \cong 80$ eV



$$W = mc^2(\gamma - 1) \approx mv^2/2$$

Blue and red lines:
same initial conditions but different phase θ

Nonlinear motion examples

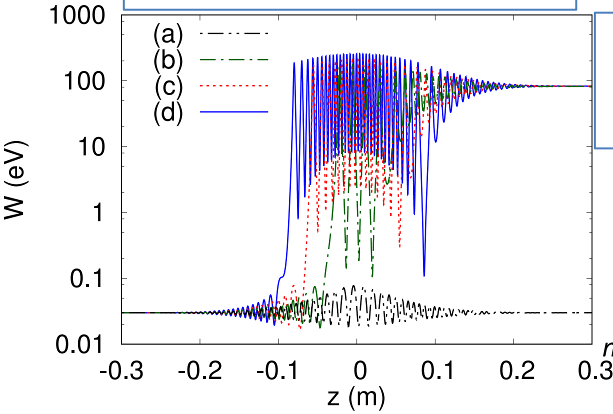
Energy gain occurs **only** if electrons are non linearly trapped in the wave field

Trapping occurs if the **maximum electric field amplitude exceeds a threshold value**

Final energy **is independent of beam power and width**

Energy **increases with the frequency mismatch** from the resonance up to a critical value beyond which is zero.

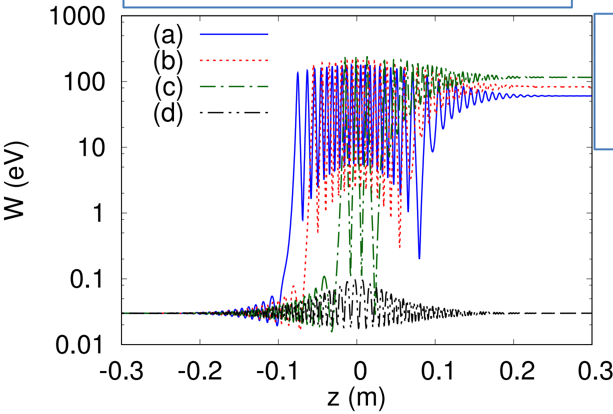
P = 0.3, 0.5, 1, 2 MW



kinetic energy vs *z* for various input EC power

no trapping @ P= 300 kW

$1-\omega/2\,\Omega$ = -2 10^{-5}, 0, 3 10^{-5}, 5 10^{-5}



kinetic energy vs *z* for various frequency shift

no trapping @ $1-\omega/2\,\Omega$ = -2 10^{-5}

In a Tokamak $1-\omega/n\Omega \approx 1-R/R_{EC}$

EC interaction is efficient in a localized radial region $R \approx R_{EC}$

Theoretical framework

- Hamiltonian formulation provides rigorous analytical results
- 2 degrees of freedom time independent Hamiltonian valid for $\omega \sim n\Omega$

$$H(z, \theta, \bar{P}_z, I) = \gamma - (\omega/n\Omega) I = const$$

$$H = H_0(\bar{P}_z, I) + \epsilon(z) H_1(\theta, I, \bar{P}_z) \qquad \epsilon(z) = eE(z)/m\omega$$

I canonical action, $\bar{P}_z$ canonical parallel momentum $\quad P_z = \bar{P}_z + N_{\parallel} \nu_n I$

outside EC region I perpendicular energy, $I = p_{\perp}^2/2, P_z = p_{\parallel}$

- Constancy of the Hamiltonian : at any time $\quad \delta\gamma = (\omega/n\Omega)\delta I$

  parallel dynamics plays a minor role

  fast/slow variables

- When EC resonance condition is met, two different energy values for same constant of motion, transition between two energy states possible

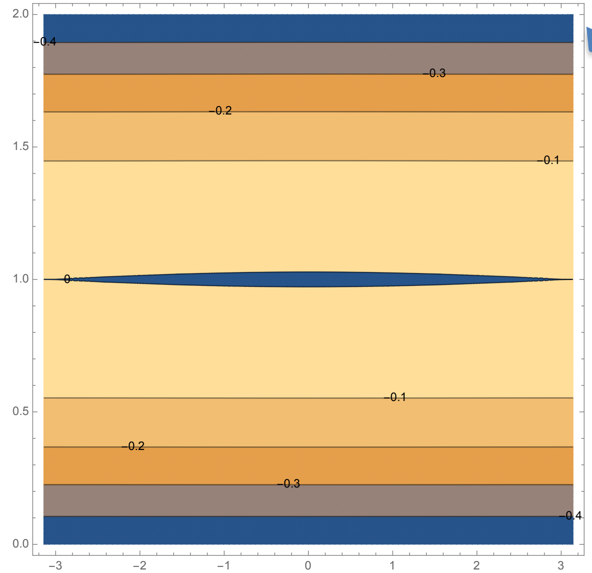
Energy gain

- Energy variation : $\Delta\gamma = n\omega/\Omega\, \Delta I$
  $\Delta\gamma$ is proportional to ΔI (i.e., to Δ perpendicular energy): either zero or finite

- Nonlinear energy gain can occur either in case of a large *E* or of very low energy particles as in the *pre-ionization phase*

Before trapping

After trapping

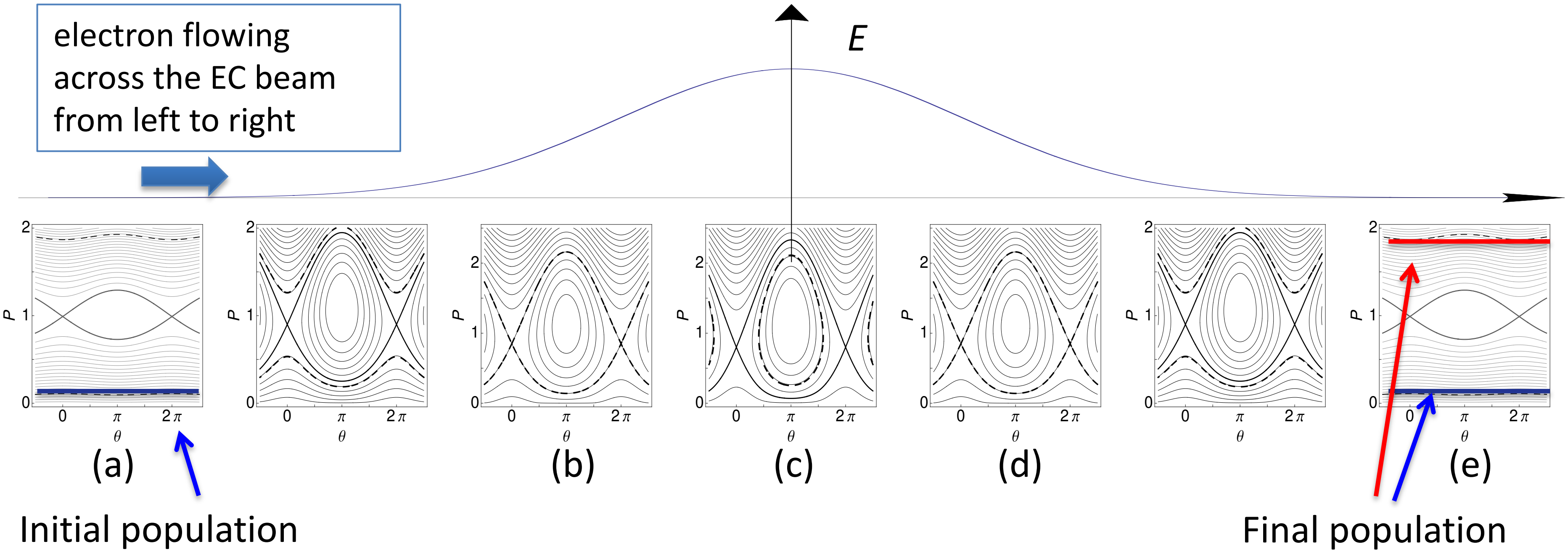


Final distribution

Initial distribution

Nonlinear absorption mechanism

electron flowing across the EC beam from left to right



Phase space (θ, I) snapshots

a) almost zero E field, low energy electrons
b) increasing E, electrons trapped in the wave field
c) maximum E, large energy excursion
d) decreasing E, electrons detrapped
e) two possible energy values, low and high

trapping/untrapping allows electrons to jump to a higher energy level

Nonlinear energy variation

- Motion characterized by an adiabatic invariant which breaks at trapping/detrapping

$$J(z, \bar{P}_z) \equiv n/2\pi \oint I \, d\theta$$

- Breaking of the invariant via trapping/untrapping
  - allows the connection of different phase space regions
  - provides the mechanism for net energy variation to occur

- Motion Equations

$$H(\theta, z, I, \bar{P}_z) = constant$$
$$J(z, \bar{P}_z) = constant$$

- Energy variation equal to the jump of adiabatic integral at the separatrix
- In the low energy limit simple analytical expression can be derived successfully

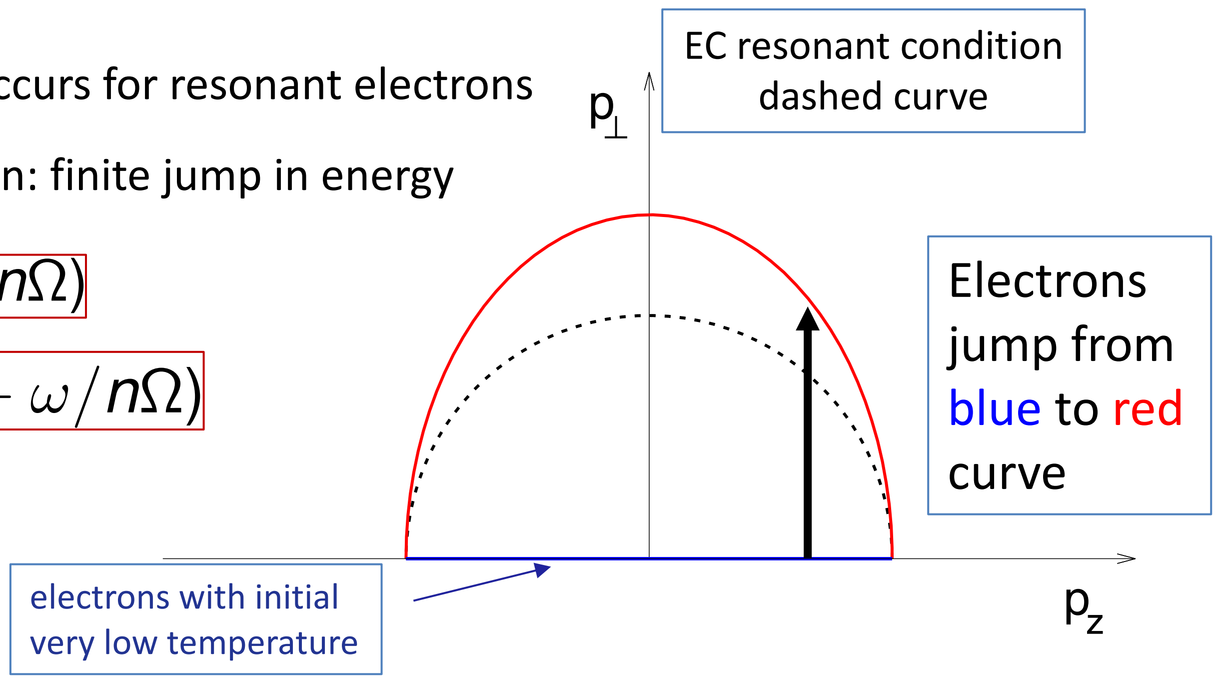
Nonlinear energy gain

- Energy variation proportional to the distance in momentum space from the resonance action value,
  <u>the lower the initial energy the higher the gain</u>
- Final energy is independent of the e.m. amplitude E_M for given $\omega/n\Omega$
- In momentum space:
  - Linear Interaction occurs for resonant electrons
  - Nonlinear interaction: finite jump in energy

$$\Delta\gamma \approx 2(1 - \omega/n\Omega)$$

$$W_f = 2mc^2(1 - \omega/n\Omega)$$

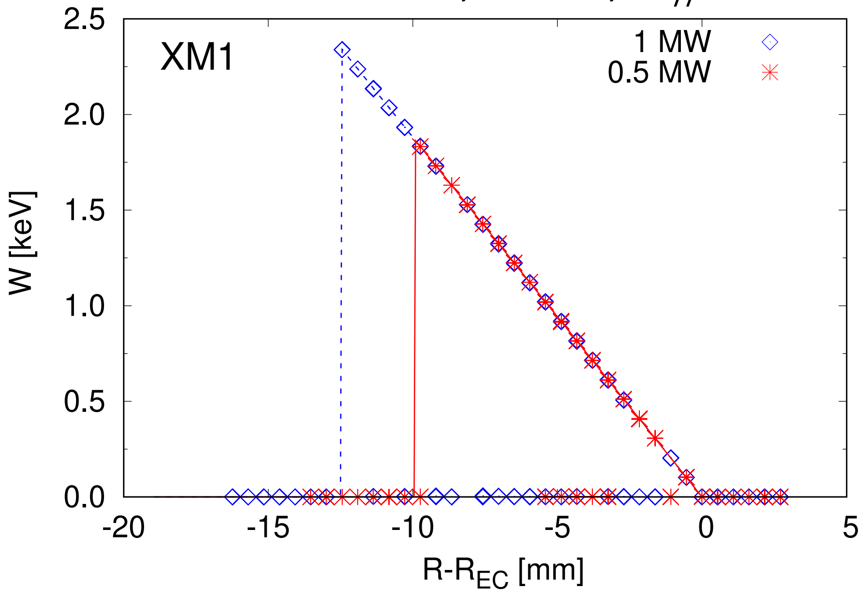
Perpendicular propagation



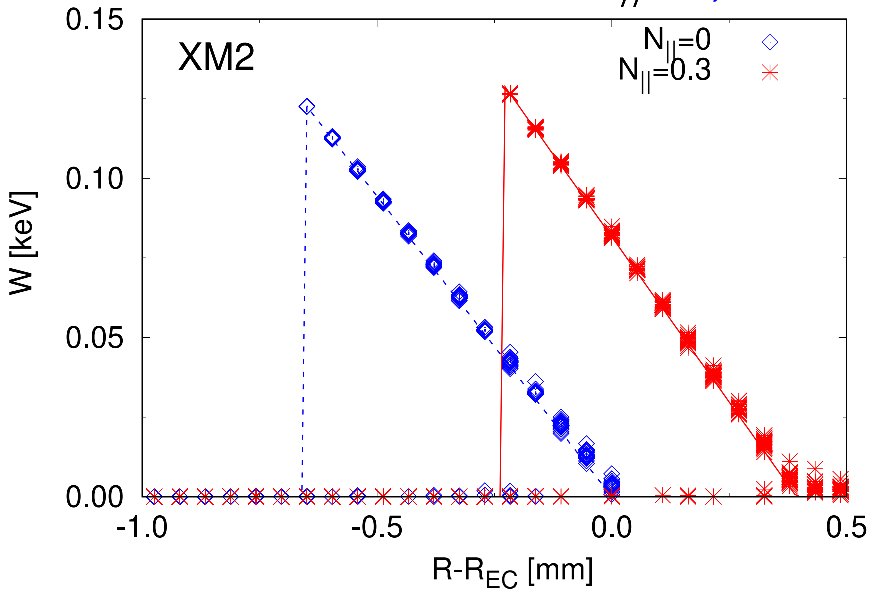
Energy radial profiles

Excellent agreement between
numerical simulations (points) and analytical theory (line)
no free parameters

XM1 P = 0.5, 1 MW, $N_{//}$=0



XM2 P = 1 MW $N_{//}$ = 0, 0.3



- Energy W increases linearly with R_{EC}-R up to a threshold value
- Maximum energy @ threshold is related to separatrix crossing

$W_{XM1} \gg W_{XM2}$ & $\Delta R_{XM1} \gg \Delta R_{XM2}$

Maximum energy –1st & 2nd harmonic

Analytical estimates for Maximum energy and radial absorption width

XM perpendicular propagation

- Maximum energy

$$W_{max,n=1} \cong 15.6 \frac{P^{1/3}}{[fw(1-N_{\|}^2)]^{2/3}}$$

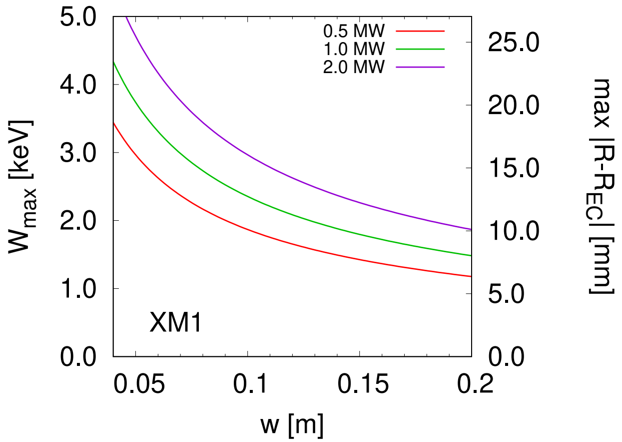
$$W_{max,n=2} \cong 2.1 \frac{P^{1/2}}{fw(1-N_{\|}^2)^{1/2}}$$

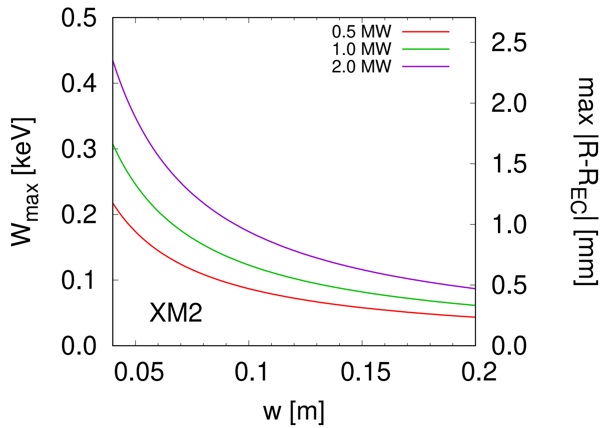
Nonlinear dependence

W [keV], *P* [MW], *f* [GHz], *w* [m]

- radial profile width

$$1 - R/R_{EC} = 1/2\, W_{max}/mc^2$$





Relevance of the energy spectrum

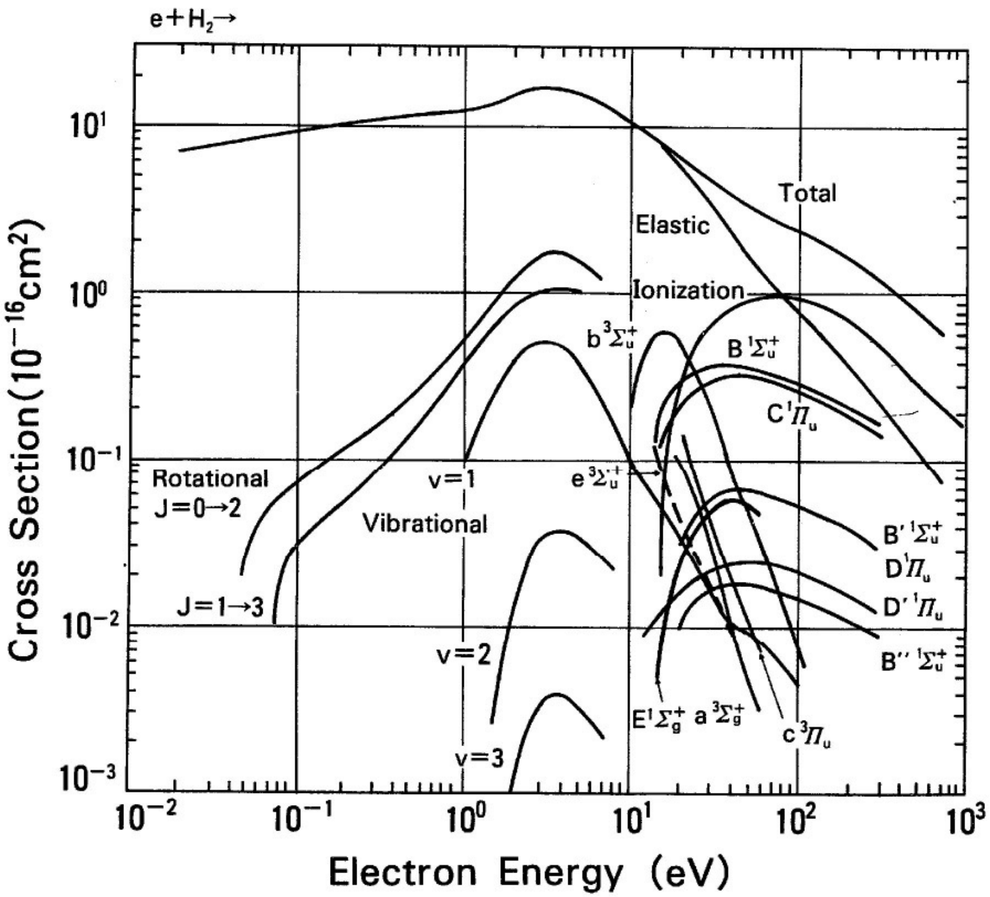


FIG. 2. Comparison of cross sections for various collision processes in neutral H_2. Also for comparison, cross sections of ionization of atomic hydrogen are shown. These data are taken at room temperatures.

J. Phys. Chem. Ref. Data, Vol. 19, No. 3, 1990

Energies within 30-300 eV are fine

Optimum 50-100 eV

J Stober

EC @ third harmonic

- Maximum energy depends on electron temperature and maximum field amplitude

- Present days parameters: to exceed ionization energy (~15 eV)
  $P^{1/2}/w$ should be ≈ 25 times larger

- Theoretical analysis predicts that EC breakdown is not achievable @ n=3

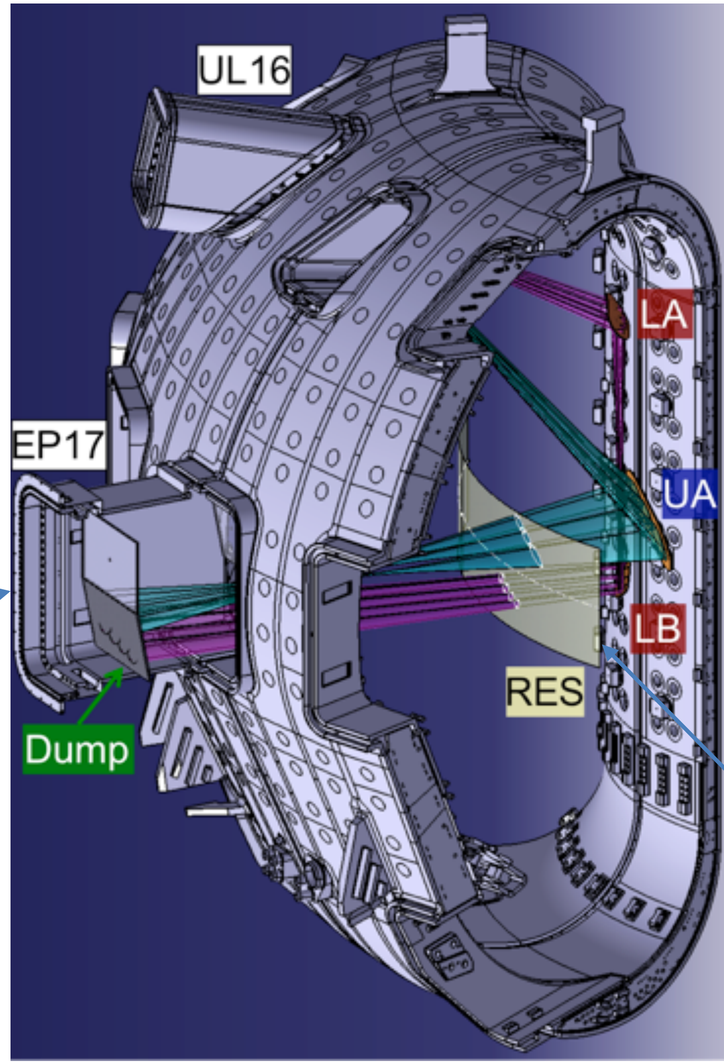
- So far no experimental evidence of successful EC assisted breakdown at 3rd harmonic

EC-assisted breakdown in ITER day 1

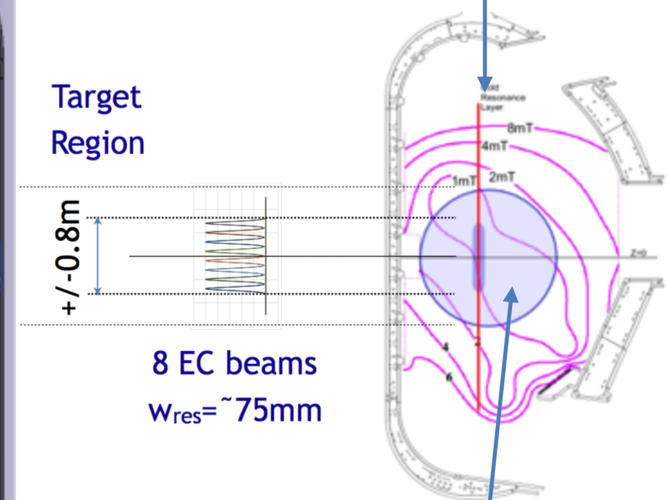
EC waves
Upper Launcher

170 GHz
7 rf beams
1 MW each

Beam dump
Equatorial Port



EC resonance



Null region

resonance

Conclusions

- The developed theory has allowed to derive analytical estimates of the nonlinear wave-particle interaction in the preionization phase

- In present day tokamaks electrons at room temperature can easily gain energies via nonlinear EC interaction
  - up to a few keV @ 1st harmonic
  - of the order of 100 eV @ 2nd harmonic
  - not efficient for higher harmonics

- Heated electrons are excellent drivers of impact ionisation and plasma breakdown

- These estimates contribute to the design of the EC breakdown systems. Experiments are ongoing in various tokamaks to validate the startup phase models and assumptions