Consiglio Nazionale delle Ricerche

Joint European Doctorate in Fusion Science and Engineering

Physics of RF Heating and Current Drive

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Summary

FIRST PART

- Introduction on RF wave in Plasmas
- Basic theory of wave-plasma interaction
  - Unmagnetized Plasma
  - Wave Damping

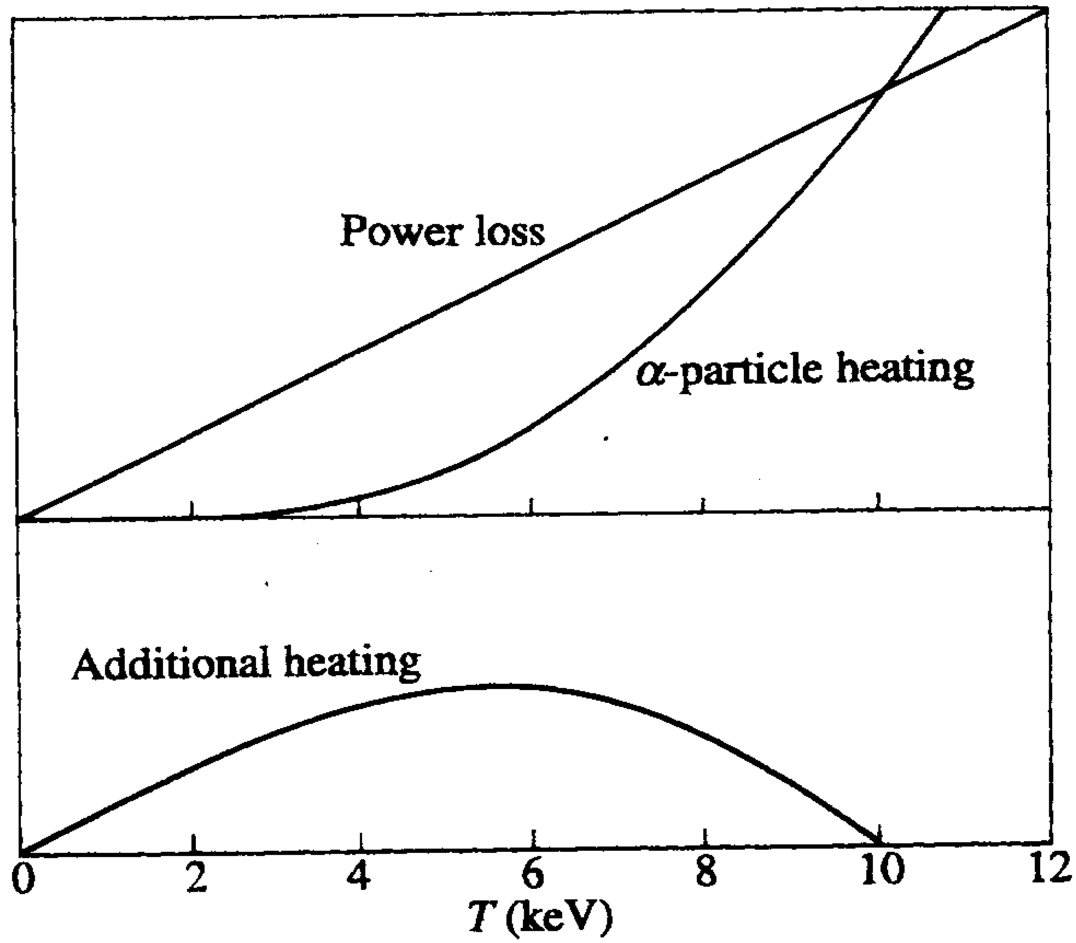
SECOND PART

- Electron Cyclotron Heating in Fusion Plasmas
  - ECCD mechanism
  - Wave Polarization relevance
  - Propagation and absorption in tokamak
- Application of ECH waves:
- EC assisted start-up
- MHD Control

Auxiliary Heating: why?

1.5 Ignition

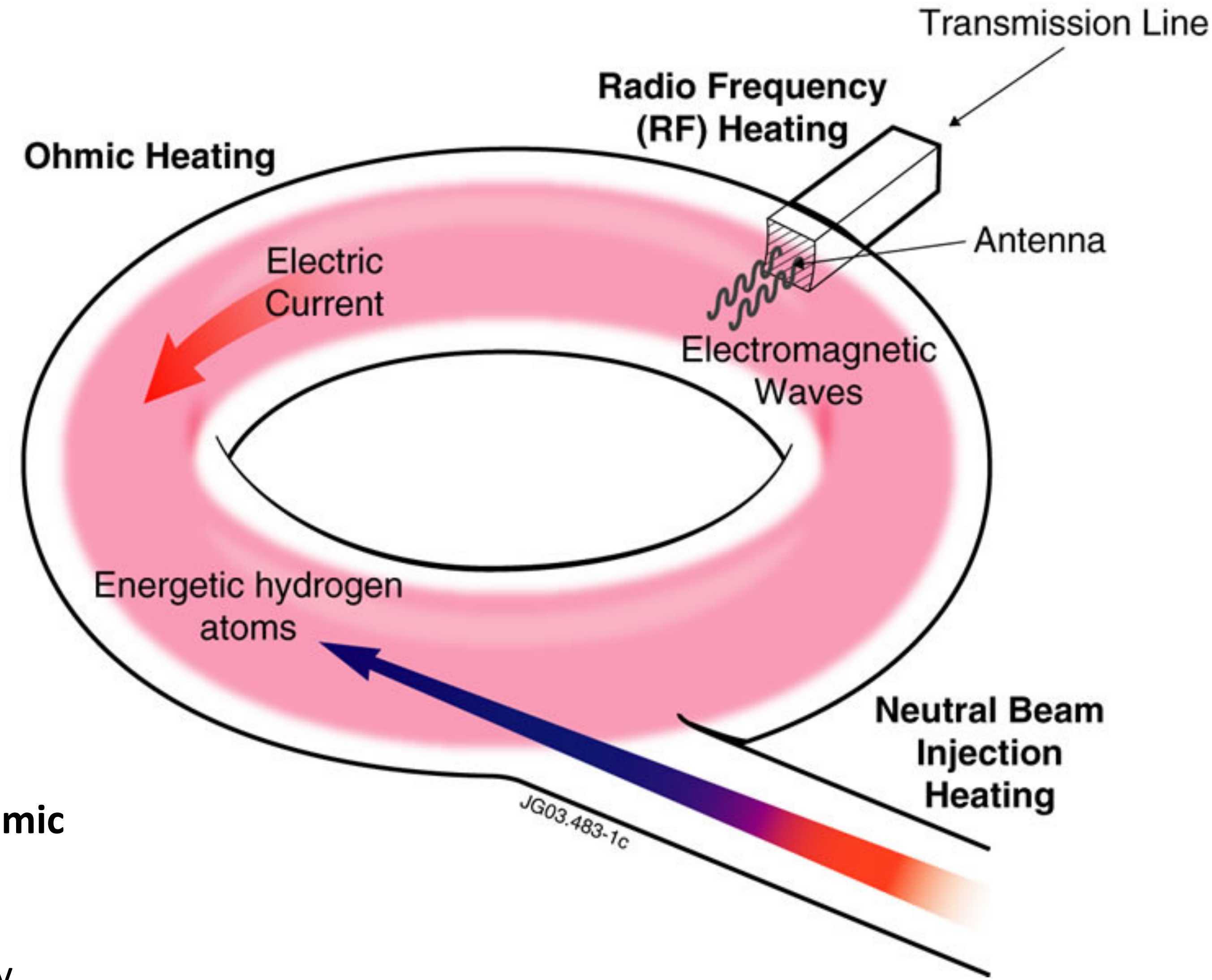
J.Wesson – Tokamaks – 1st Edition – 1987



Additional or Fundamental ?

Without external plasma heating temperature for Nuclear Fusion cannot be reached in any magnetic confinement device.

How to heat Plasma



Internal heating : **Ohmic**

External heatings:
NBI by Kinetic Energy
ICH, **ECH**, LH, IBW…. by E.M. wave

RF Heating Systems

Main RF Heating waves exploited in Nuclear Fusion devices to heat plasma:

ECW: Electro Cyclotron Waves. Heat Electrons in millimetre wave range (2.45 GHz - 170 GHz)

LH: Lower Hybrid. Heat electrons in centimeter wave range

ICW: Ion Cyclotron Wave. Heat ions in RF wave range (MHz)

IBW: Ion Bernstain wave: Heat Ions in RF wave Range (MHz)

E.M. waves transfers energy to charged particle in plasma in correspondence of resonances, a combination of local conditions between magnetic field, particles energy/temperature and wave frequency.

Heating System in main Experiments

Device	NBI	ECRH	ICRH	LH
JET	*32 MW*		*10 MW*	*7.2 MW*
AUG	20 MW	6 MW	6 MW	
FTU		*1.4 MW*	*0.5 MW of IBW*	*2.4 MW*
D-IIID	20 MW	4 MW	1 MW Helicon FW	
WEST		2 MW	9 MW	7MW
TCV	1MW	5 MW		
JT60-SA	34 MW	7MW		
W7-X	19 MW	10 MW	1.5 MW	
EAST	8 MW	4 MW	12 MW	10 MW
KSTAR	8 MW	0.5 MW	6 MW	

Heating System in Future Tokamaks

ITER :

- **NNBI =32 MW**
- **ECRH = 24 MW +24 MW + ?**
- **ICRH= 10 MW**

DTT :

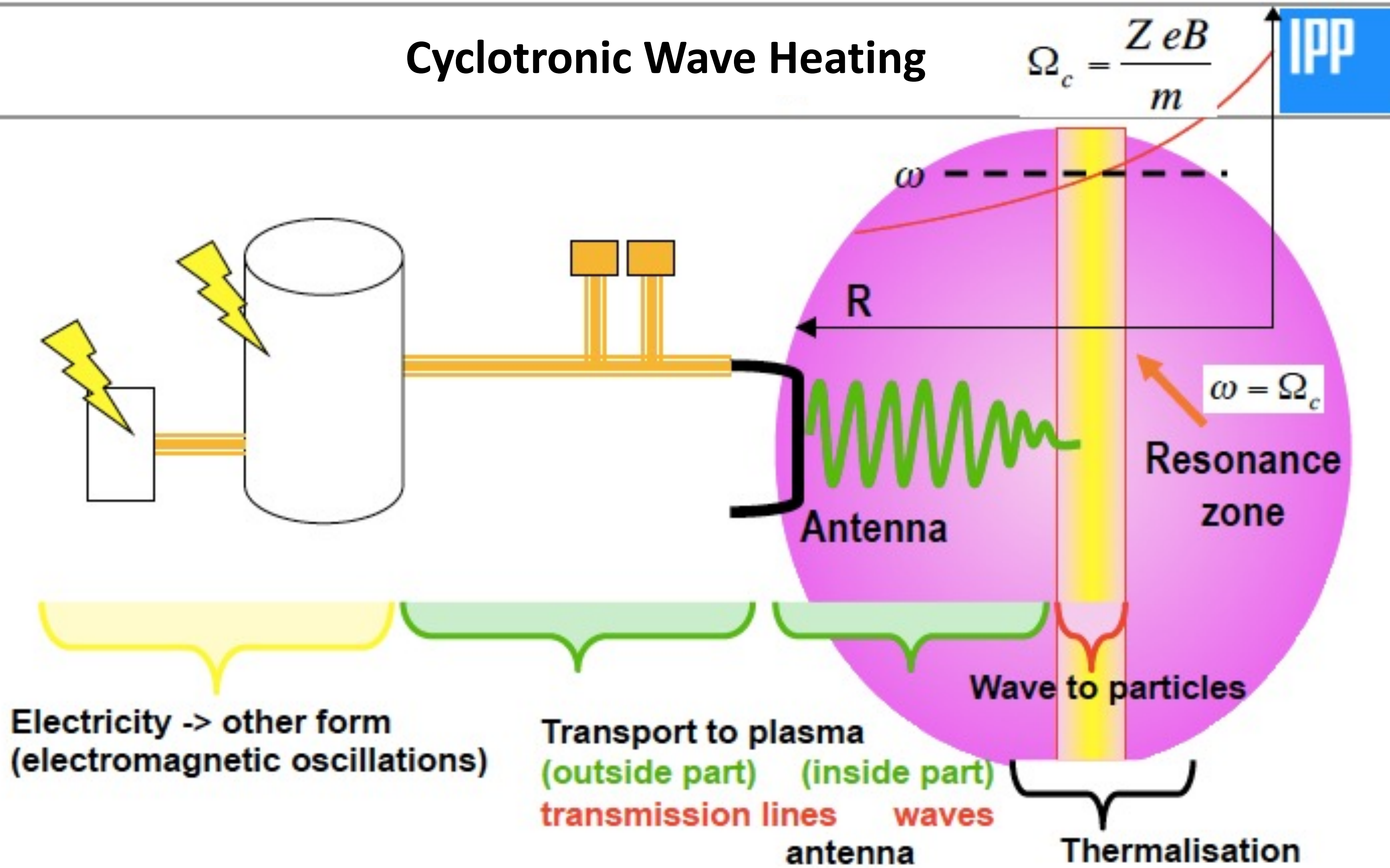
- **NNBI = 10 MW**
- **ECRH = 32 MW**
- **ICRH= 8 MW**

SPARC: ICRH for 48 MW

DEMO project is studying an option fully relying on ECRH

RF heating system will play major role in future tokamaks and in perspective for the Reactor

Cyclotronic Wave Heating



Typical Functions of RF Systems

Tasks	ECRH	ICRH	LH
Break down & Plasma start up	X	X	
Plasma Current Ramp up	X	X	X
H-mode access	X	X	X
Electron Heating	X	X	X
Direct Ion Heating		X	
Not Inductive Current drive	X		X
MHD Control	X	X	
Fast Particle Generation		X	
Profiles Control	X	X	X
Impurity Accumulation Avoidance	X	X	
Transport Studies	X		
Diagnostics (heat pulse)	X		
Wall Cleaning	X	X	

Energy transfer from e.m. waves to plasma

When e.m. waves crosses plasma its **Electric field** accelerates charged particles that transfer this energy by collision to plasma

Collisional absorption scales with $\mathbf{T_e^{-3/2}}$ and is ineffective (as ohmic ones) to heat a hot plasma (as required to reach the fusion conditions)

Waves can transfer energy to plasma also trough **resonant mechanism** that are **collisionless** and can produce strong direct heating

In a multispecies magnetized plasma there are several of resonances.

The variety of waves existing in a magnetized plasma allows different RF heating schemes, generally at different frequencies.

An RF Heating system based on e.m. waves is composed by 3 main elements:

- **Power generator**
- **Low loss transmission lines**
- **Antenna**

Antenna launches (couples) waves in the plasma

➡ waves propagate up to absorption layer and transfer energy (heat or momentum) to plasma

➡ The location of the absorption layer should be controlled

The study of the **waves propagation** is at the basis of the selection of the proper RF heating systems (i.e. of the frequency and of the antenna)

E.M. wave propagation in plasma is (can be) quite complex to be treated formally and is outside the scope of this lecture.

Some simplifications are considered to approach the problem of a realistic tokamak plasma.

The most common and valid approach is the:

cold magnetized plasma model

The model is enough accurate to describe wave propagation in plasma, ***except in regions close to resonance and cut-off***

Plasma Models

Close to these special regions the thermal corrections become important because the wave phase velocity is comparable to the thermal one and the perpendicular wave length (wrt the external magnetic field) is similar to the Larmor radius.

To study energy absorption it is necessary the ***warm model***

Cold model -> fluid equations, no temperature effect
Warm Model -> finite Larmor radius plays a role

- **Coupling** cold plasma
- **Propagation** cold plasma (warm plasma)
- **Absorption** warm plasma

The mathematical approach is the following:

Maxwell equations + Generalize Ohm's law *applied to*

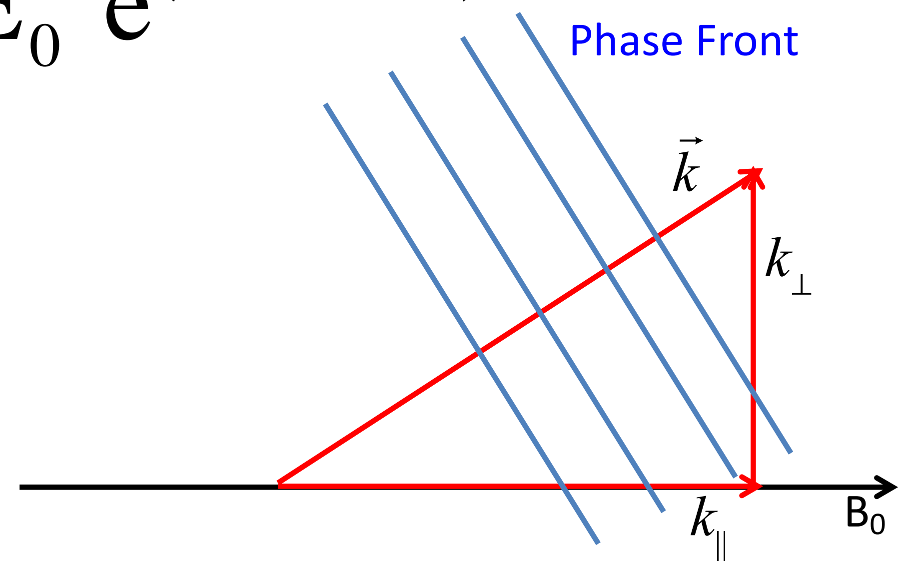
Plane waves: $$\tilde{E}(r,t) = \tilde{E}_0 \; e^{(-i\omega t + \bar{k} \cdot \bar{r})}$$

where

k= wave vector = **2π/λ**

ω = angular frequency = **2π f**

Other useful quantities:



v_{ph} = phase velocity = **ω/k**

v_g = group velocity = d**ω**/dk

N=v_{ph}/c = refractive index **= k/ωc**

$\vec{k}$	Response of Plasma
ω	Fixed by Generator

Electromagnetic Waves in Plasma

Maxwell equations

$$\left\{\begin{aligned}
\vec{\nabla}\cdot\vec{B} &= 0\\
\vec{\nabla}\cdot\vec{E} &= 4\pi\rho\\
\vec{\nabla}\times\vec{B} &= \frac{4\pi}{c}\vec{j}+\frac{1}{c}\frac{\partial\vec{E}}{\partial t}\\
\vec{\nabla}\times\vec{E} &= -\frac{1}{c}\frac{\partial\vec{B}}{\partial t}
\end{aligned}\right.$$

+

Generalized Ohm's Law

$$\vec{j} = j(\vec{E},\vec{B}) \Rightarrow \vec{j} = \underline{\underline{\sigma}}(\omega,k)\cdot\vec{E}_{\omega,k}$$

Dielectric Tensor

+

Plane waves:

$$\tilde{E} = E_0\cos(\vec{k}\cdot\vec{r}-\omega t+\phi) = E_0 e^{i(\vec{k}\cdot\vec{r}-\omega t+\phi)} \Rightarrow \frac{\partial}{\partial t}\rightarrow -i\omega \qquad \vec{\nabla}\rightarrow i\vec{k}$$

$$\nabla \times (\vec{\nabla} \times \vec{E}) = -\frac{1}{c}\frac{\partial(\nabla \times \vec{B})}{\partial t}$$

$$\vec{\nabla} \cdot \vec{E} = 4\pi\rho$$

$$\vec{\nabla} \times \vec{B} = \frac{4\pi}{c}\vec{j} + \frac{1}{c}\frac{\partial \vec{E}}{\partial t}$$

$$4\pi\nabla\rho - \nabla^2\vec{E} = -\frac{1}{c}\frac{\partial}{\partial t}\left(\frac{4\pi}{c}\vec{j} + \frac{1}{c}\frac{\partial \vec{E}}{\partial t}\right) \quad + \quad \vec{j} = \underline{\underline{\sigma}}(\omega,k)\cdot\vec{E}_{\omega,k}$$

Wave Equation

$$\underline{k} \times (\underline{k} \times \underline{E}_{\omega,\underline{k}}) + \frac{\omega^2}{c^2}\underline{\underline{K}} \cdot \underline{\underline{E}}_{\omega,\underline{k}} = 0$$

$$\underline{\underline{K}} = \underline{\underline{1}} + \frac{\underline{\underline{\sigma}}}{i\omega\varepsilon_0}$$

Dielectric Tensor

Wave Equation is **exact**, no approximations have been introduced

$$\underline{k} \times (\underline{k} \times \underline{E}_{\omega,\underline{k}}) + \frac{\omega^2}{c^2} \underline{\underline{K}} \cdot \underline{\underline{E}}_{\omega,\underline{k}} = 0$$

Admit solution only if

defining

N= refractive index

$$\underline{N} = \frac{c}{\underline{v}_{ph}} = \frac{c\underline{k}}{\omega}$$

$$\det[\underline{N} \times (\underline{N} \times \underline{\underline{1}}) + \underline{\underline{K}}(\omega, \underline{N})] = 0$$

Dispersion Relation

$$\underline{\underline{K}} = \underline{\underline{1}} + \frac{\underline{\underline{\sigma}}}{i\omega\varepsilon_0}$$

Plasma

Simpler Case: Cold Un-magnetized Plasma

Maxwell Equations

Motion Equation

$$n_\alpha m_\alpha \frac{\partial \overline{u}_\alpha}{\partial t} + n_\alpha m_\alpha (\overline{u}_\alpha \cdot \overline{\nabla})\overline{u}_\alpha = n_\alpha q_\alpha (\overline{E} + \frac{\overline{u}_\alpha}{c} \times \overline{B})$$

Continuity Equation

$$\frac{\partial n_\alpha}{\partial t} + \overline{\nabla} \cdot (n_\alpha \overline{u}_\alpha) = 0$$

Perturbing Technique

$$f = f_0 + f_1$$

Plasma Model

$$u_0 = E_0 = B_0 = 0$$

$n_0 \neq 0$ density

Dielectric Tensor

Cold un-magnetized plasma

$$\cancel{n_\alpha} m_\alpha \frac{\partial \bar{u}_\alpha}{\partial t} + \cancel{n_\alpha m_\alpha (\bar{u}_\alpha \cdot \bar{\nabla})\bar{u}_\alpha} = \cancel{n_\alpha} q_\alpha (\bar{E} + \cancel{\frac{\bar{u}_\alpha}{c} \times \bar{B}})$$

$$u = u_0 + u_1 = u_1$$

$$E = E_0 + E_1 = E_1$$

$$B = B_0 + B_1 = B_1$$

$$-i\omega m_\alpha \bar{u}_{\alpha 1} = q_\alpha \overline{E_1} \qquad \bar{u}_{\alpha 1} = \frac{i}{\omega} \frac{q_\alpha}{m_\alpha} \overline{E_1}$$

Add the current

$$\bar{j} = \sum q_\alpha n_\alpha \bar{u}_\alpha \Rightarrow \bar{j} = \underbrace{\left(\frac{i}{\omega} \sum \frac{q_\alpha^2 n_\alpha}{m_\alpha}\right)}\bar{E}_1 = \sigma \bar{E}_1$$

From motion equation: Ohm's Law

$$\bar{j} = \sum_{\alpha} q_{\alpha} n_{0\alpha} \bar{u}_{1\alpha} = \frac{i}{\omega}\left(\sum_{\alpha} \frac{n_{0\alpha} q_{\alpha}^{2}}{m_{\alpha}}\right)\bar{E}_{1}$$

Electrical conductivity

- Scalar coefficient
- Independent from k

The dielectric tensor*:

$$K = 1 - \frac{4\pi\sigma(\omega,k)}{i\omega} = 1 - \frac{1}{\omega^{2}} \sum_{\alpha} \frac{4\pi n_{0\alpha} q_{\alpha}^{2}}{m_{\alpha}} = 1 - \frac{\omega_{p}^{2}}{\omega^{2}}$$

* Pay attention to different system (SI)

Where $\omega_p^2 = \sum_\alpha \frac{4\pi n_{0\alpha} q_\alpha^2}{m_\alpha}$ Is the Plasma Frequency, summarized over all the α species

And the Wave Equations is:

$$\left[\frac{k^2c^2}{\omega^2}\left(\frac{\underline{kk}}{k^2} - \underline{I}\right) + K\,\underline{I}\right] : \underline{E} = 0$$

Dielectric tensor

That written in matrix

$$\begin{pmatrix} K-\dfrac{k^2c^2}{\omega^2} & 0 & 0 \\ 0 & K-\dfrac{k^2c^2}{\omega^2} & 0 \\ 0 & 0 & K \end{pmatrix}\begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix}=\begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$$

Admits solution only if Det=0 that leads to:

$$K\left(K-\frac{k^2c^2}{\omega^2}\right)=0$$

That has 2 solutions:

- **K=0**
- **K= k^2c^2/ω^2**

From

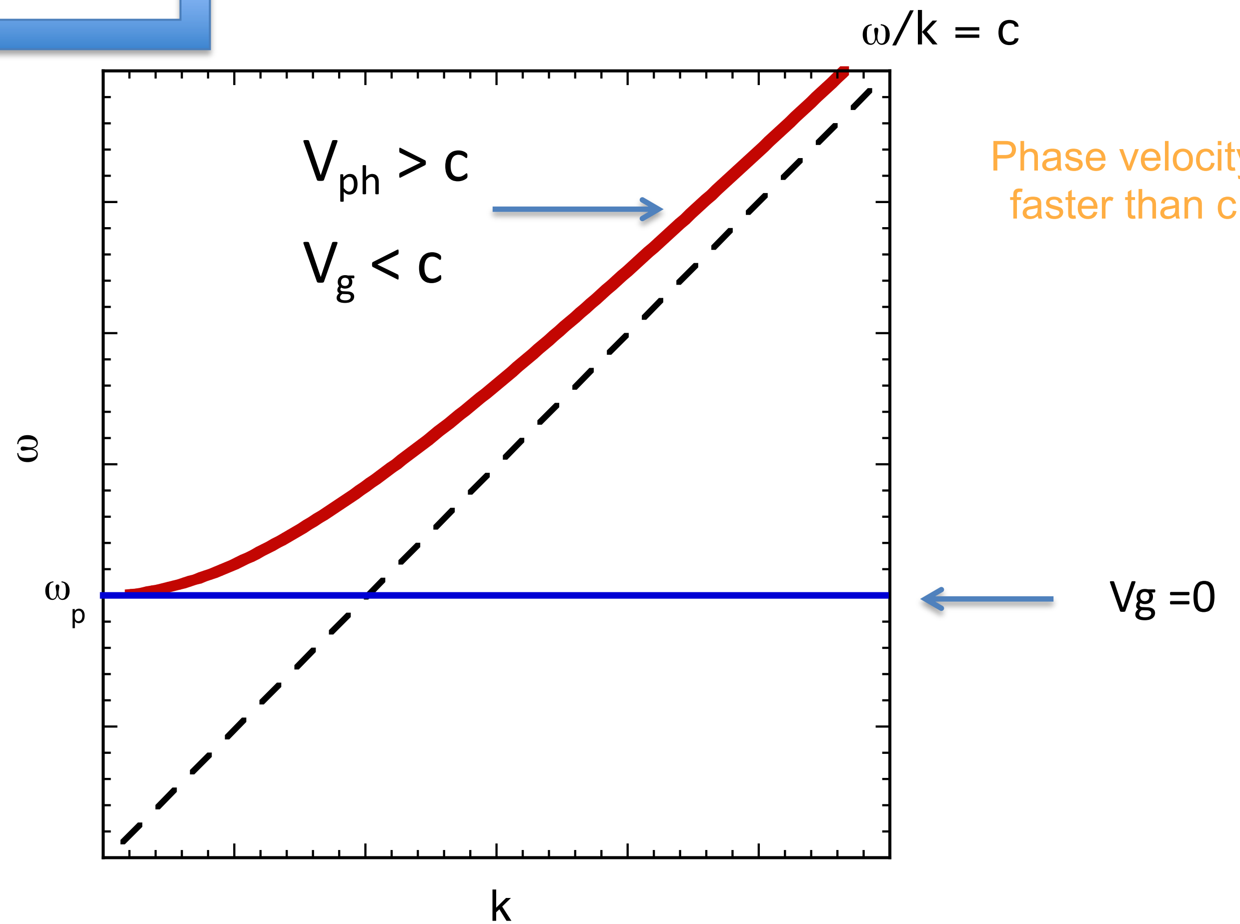
$K=0$ → $$\boxed{\omega^2 = \omega_p^2}$$ Longitudinal $\boxed{k \parallel E}$

$K = k^2c^2/\omega^2$ → $$\boxed{\omega^2 = \omega_p^2 + k^2c^2}$$ Transverse $\boxed{k \perp E}$

$$K = 1 - \frac{\omega_p^2}{\omega^2}$$

$$\boxed{v_{ph} = \frac{\omega}{k}}$$

$$\boxed{v_g = \frac{d\omega}{dk}}$$

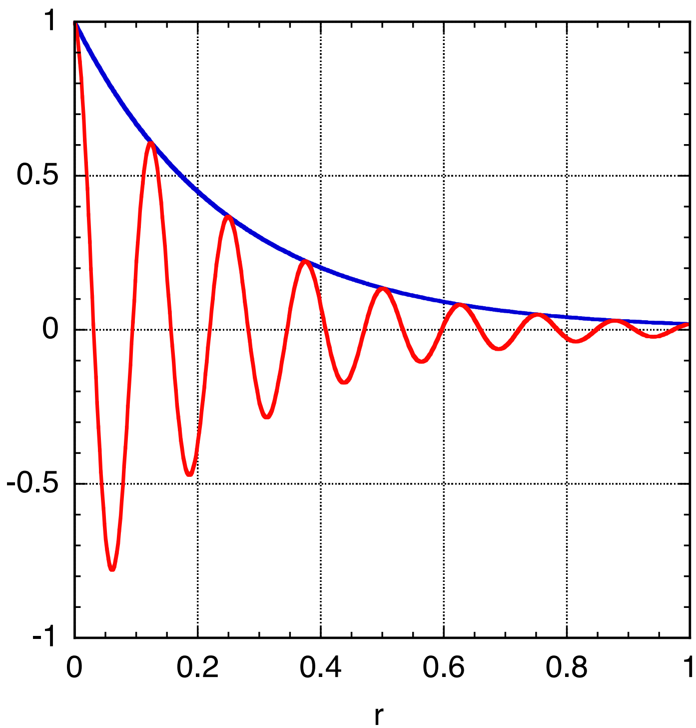


For a transverse wave, extracting k :

cutoff

$$\boxed{k = \sqrt{(\omega^2 - \omega_p^2)/c^2}}$$

The wave can propagate only for $\boxed{\omega > \omega_p}$



if $\boxed{\omega < \omega_p}$

$$\boxed{k = i\left|k\right|}$$

$$\tilde{E} = E_0 e^{-kr} \cdot e^{-i(\omega t + \phi)})$$

Wave Damping

Collisionless dissipation of an electromagnetic waves for

- Ion cyclotron
- Electron cyclotron
- Lower hybrid

is governed by the following relationship:

$$\omega - k_{//} v_{//j} - n\left|\omega_{cj}\right| = 0$$

Landau Damping

***n*= 0** correspond to **Landau damping**:

➡ $E_{//}$ accelerates particle in // direction

It is relevant for **Lower Hybrid** and for fast wave in **Ion cyclotron** range of frequency

Basically Landau damping occurs when electron velocity is equal to the phase velocity of the waves

As phase velocity ranges from thermal to light speed the wave can resonate with thermal and suprathermal electrons

Absorption: Collisionless Damping

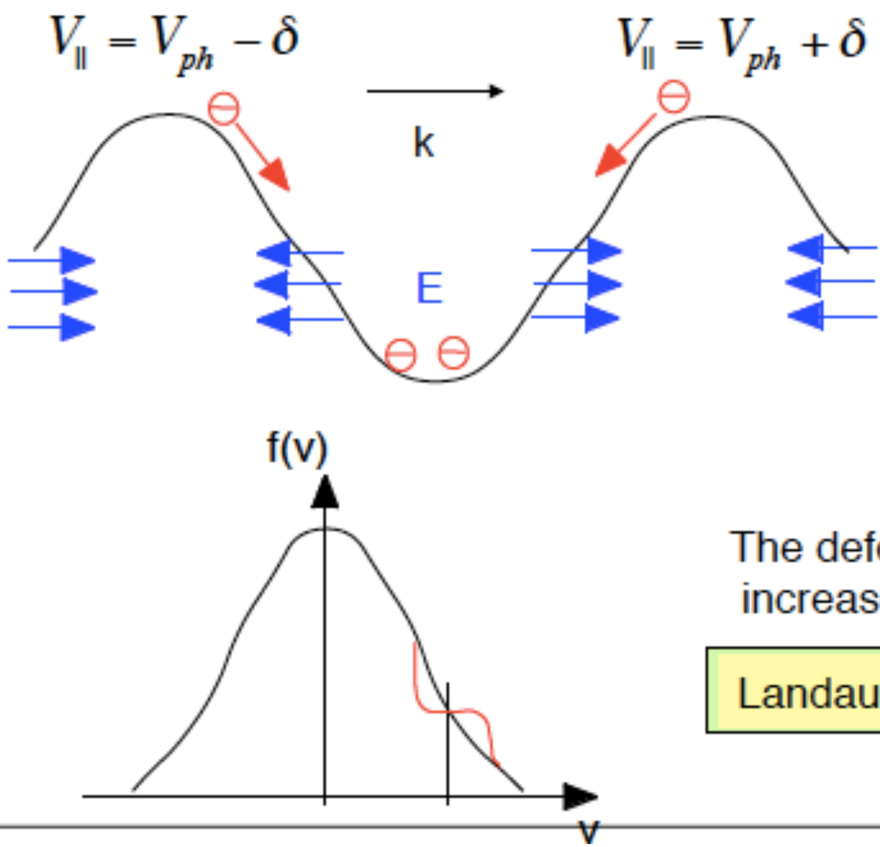
Energy transfer only if $\boxed{\omega - n\omega_c = k_{\|} v_{\|}}$ $\qquad n = 0$

Resonance condition:

$$\boxed{\omega - k_{\|} v_{\|} = 0}$$

Condition for damping

$$\frac{\partial f(v)}{\partial v} < 0$$



The deformation of the distribution function increases the energy of the electron system.

Landau damping: Increase of parallel momentum

Cyclotron Resonance

***n*≠ 0** correspond to **cyclotron resonance**

Particles gain energy in perpendicular direction

Only momentum (?)

The condition of resonance can be written

$$v_{//j} = \frac{\omega}{k_{//}} - \frac{n\left|\omega_{cj}\right|}{k_{//}} \qquad 3$$

It is valid for particles with velocity smaller than the wave phase velocity (*n*>0)

***n*=1** correspond to fundamental resonance:

valid for

Electron cyclotron

Ion cyclotron minority heating

***n*=2** correspond to 2nd harmonic resonance:

valid for

Electron cyclotron

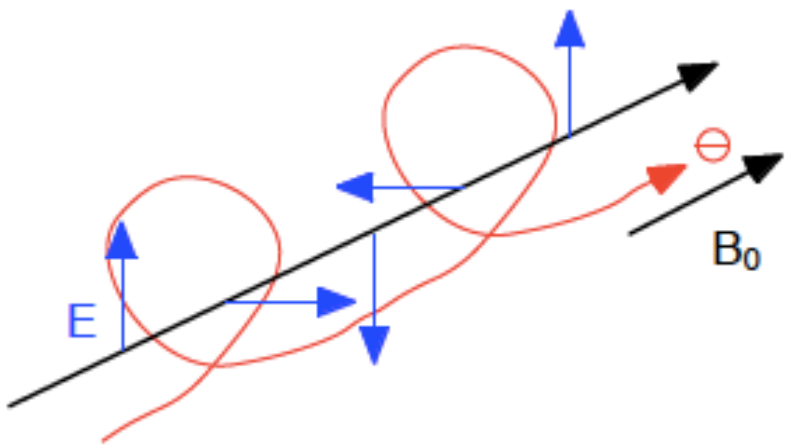
Ion cyclotron

Absorption: Cyclotron Damping

Energy transfer only if $\boxed{\omega - n\omega_c = k_{\parallel} v_{\parallel}}$ $n = 1$

Resonance condition:

$$\boxed{\omega - k_{\parallel} v_{\parallel} = \omega_c}$$



Cyclotron Damping: increase of perpendicular momentum

Wave-plasma absorption

Absorption depends on the temperature: higher absorbs better

3

ICRH: can use both cyclotron or Landau damping, used to heat ions and generate fast particle and current

Fast particle from landau

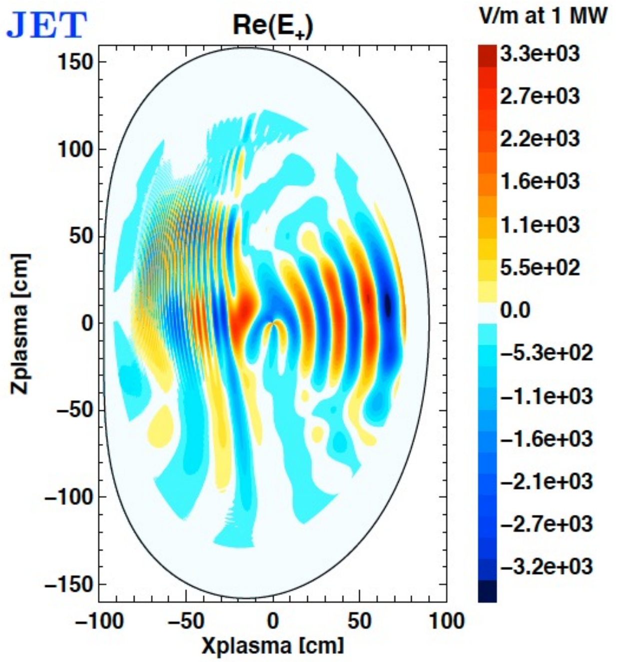
LHCD: only Landau damping, to generate non inductive current

Works better at high temps

ECRH: only cyclotron damping, to heat electrons and generate non inductive current

RF simulations for JET

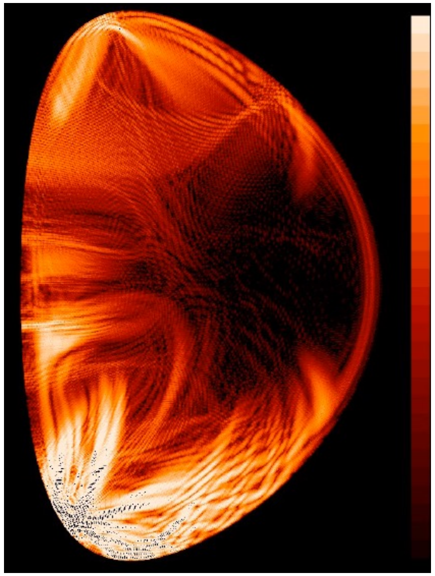
f = 42 MHz



Ion Cyclotron Waves

courtesy R Bilato, MPI- IPP

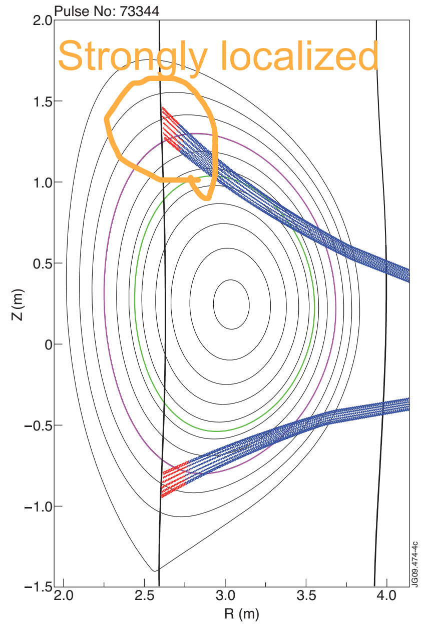
f = 3.7GHz



Lower Hybrid Waves

courtesy R Bilato, MPI- IPP

f = 170 GHz



Electron Cyclotron Waves

D. Farina, IFP-CNR, 2010 proposal

Physics of RF Heating and Current Drive

Part II: Applications of EC waves

Outline II

SECOND PART

- Electron Cyclotron Heating in Fusion Plasmas
  - ECCD mechanism
  - Wave Polarization relevance
  - Propagation and absorption in tokamak
- Application of ECH waves:
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ECRH & ECCD in Fusion Plasmas

ECRH: **E**lectron **C**yclotron **R**esonant **H**eating

ECCD: **E**lectron **C**yclotron **C**urrent **D**rive

The only Heating System able to deposit power or current in highly localized and controllable way

Basic Physic Mechanism

The e.m. wave gives energy to particles rotating at the same frequency around the (toroidal) field B_T.

Resonant with the mode in the plasma

The simplest and quick formula for a specie *x* is:

Harmonic

$$\boxed{\omega_0 = n\Omega_{cx} = n\frac{eB}{m_x c}}$$

* *Maxwellian distribution & perpendicular injection*

For electrons:

$$f_0(GHz) = 28(GHz)\cdot B_T(T)\cdot n$$

For ions:

$$f_0(MHz) = 15.2(MHz)\cdot B_T(T)\cdot\frac{Z}{A}\cdot n$$

Propagation, cut-off & resonances

For ECRH/ECCD application we are considering transversal e.m. waves propagating in vacuum and in the plasma without evanescent region.

Ecrh can go through plasma and be absorbed only
in the region of interest

The waves met cut-off and/or resonances depending by: **wave polarization** & **harmonic**, **plasma density**, **magnetic field** and **θ**.

Resonances and Cut-off

Propagation limits are defined by the two limits in the diffraction index

N=0 → k=0 → *no wave propagation:* **Cut-off**

At cutoff there is reflection

N=∞ → k= ∞ → *wave absorption:* **Resonance**

Cut-off → N=0 $\varepsilon_R \varepsilon_L \varepsilon_3 = 0$

$$\boxed{\omega = \omega_p}$$

Density cutoff (more stuff, watch video)

Right and Left

$$\boxed{\omega = \omega_{R/L} \cong \frac{1}{2}\left(\pm |\Omega_e| + \sqrt{\Omega_e^2 + 4\omega_p^2}\right)}$$

5

Resonance → N= ∞

$$N^2 = \frac{\varepsilon_L \varepsilon_R}{\varepsilon_1}$$

$$\boxed{\omega_{LH}^2 \approx \Omega_e \Omega_i \frac{1 + \dfrac{\Omega_i^2}{\omega_{pi}^2}}{1 + \dfrac{\Omega_e^2}{\omega_{pe}^2}}}$$

Lower Hybrid

$$\boxed{\omega = \Omega_{ce}}$$

Electron Cyclotron

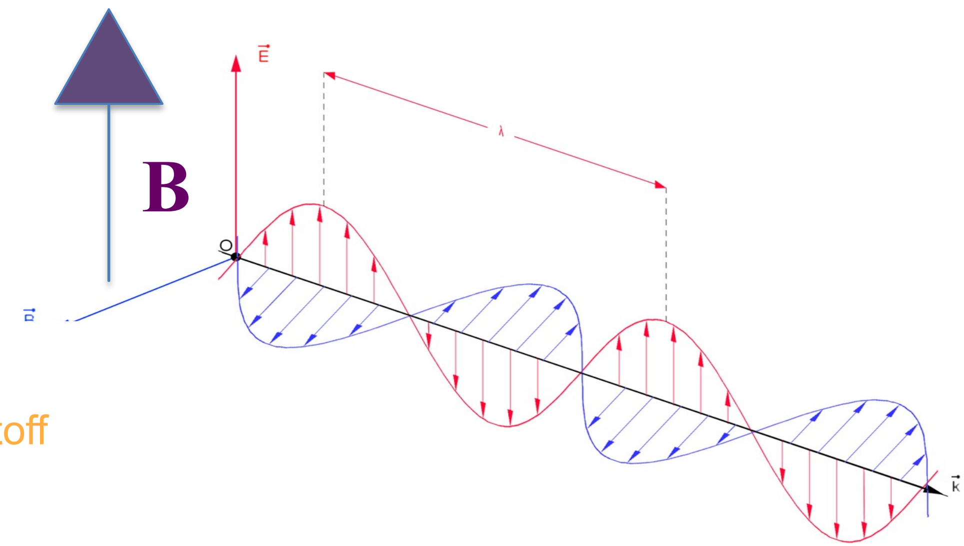
$$\boxed{\omega_{UH}^2 = \Omega_e^2 + \omega_{pe}^2}$$

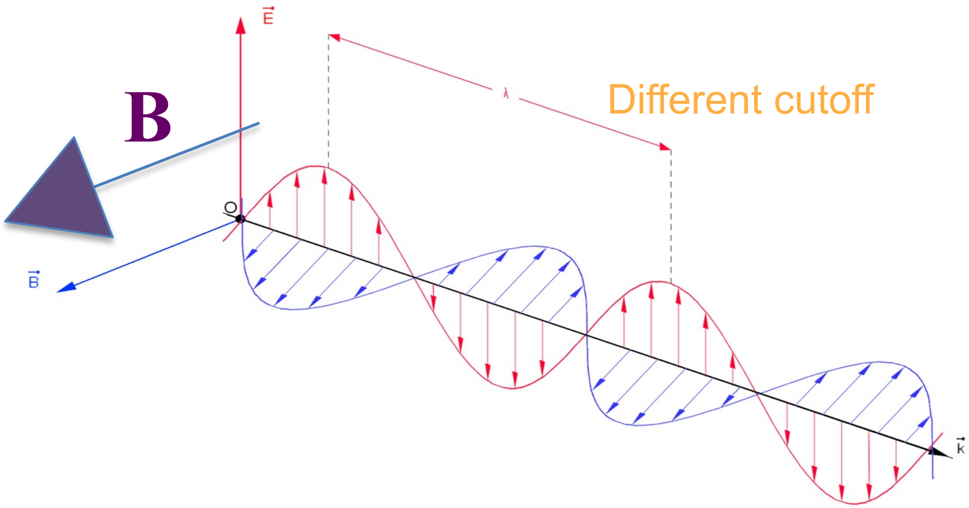
Upper Hybrid

Wave polarization

The polarizzation of e.m. wave in magnetised plasma is defined as the direction of the Wave Electric Field respect to external Magnetic Field direction:

O-Mode *(ordinary) when Electric field is parallel to B_0*





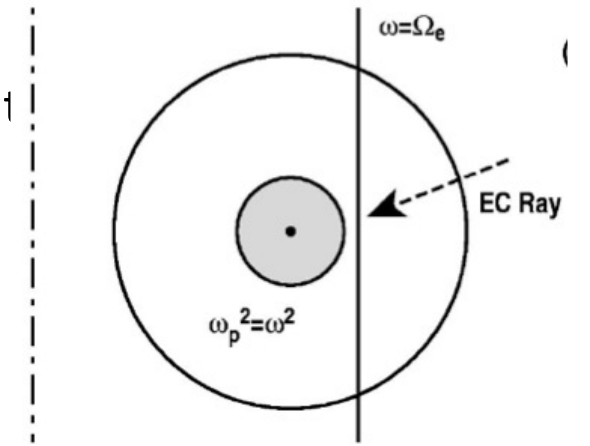
X-Mode *(extraordinary) when Electric field is perpendicular to B_0*

- ***The modes exist only in plasma***
- ***Propagation depends on plasma parameter and $N_{//}$***
- ***The propagating wave is a mixture of the two (elliptic polarization)***

Cut-off & polarization

An e.m. wave propagating in plasma can meet **resonances** and **cut-off** :
At a cut-off surface the waves is reflected backword.

Cut-off (and some resonance) can depend on the polarizat



Density Cut-off $\boxed{\omega = \omega_p}$

Ordinary Mode

$$n_e < n_c = \frac{m_e \omega_o^2}{4\pi e^2} = \frac{B^2{}_T(T)}{10.3} l^2 [10^{20} m^{-3}]$$

Extraordinary Mode

$$n_e < l(l-1) n_c \qquad l > 1$$

$f = 140$ GHz
$O1_{FTU}$ $n_c = 2.4\ 10^{20}\ m^{-3}$
$X2_{AUG}$ $n_c = 1.21\ 10^{20}\ m^{-3}$
$X3_{TCV}$ $n_c = 1.61\ 10^{20}\ m^{-3}$

XM propagation & Cut-off

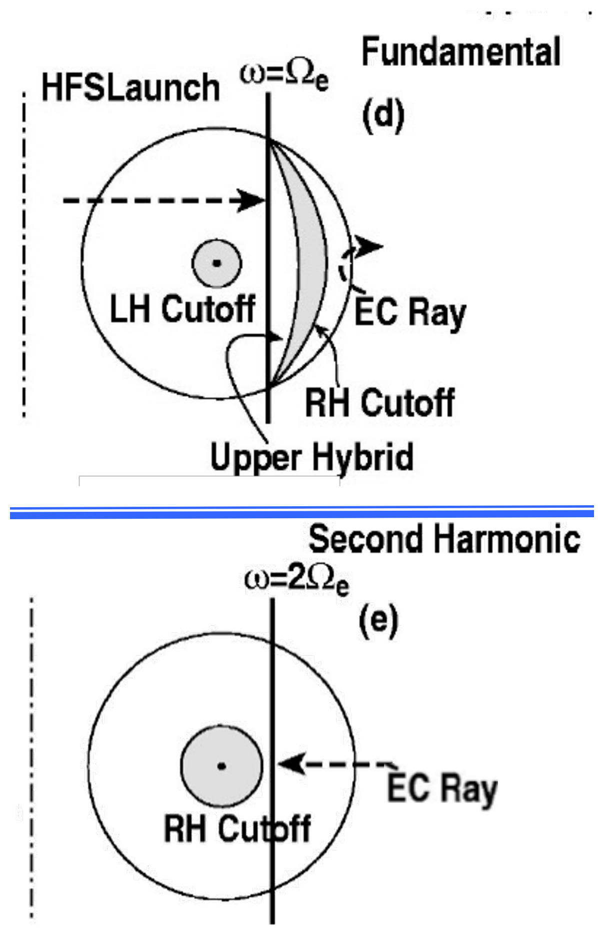
1st Harmonic XM has 2 additional cut-off, the right and left hand cut-off.

$$\omega = \omega_{R/L} \cong \frac{1}{2}(\pm|\Omega_e| + \sqrt{\Omega_e^2 + 4\omega_p^2})$$

The RH cut-off shield the Upper Hybrid and the cyclotron resonance for a wave coming from LFS.

For this reason the XM can be used only with second harmonic.

The LH cut-off is equivalent to a density cut-off.



Cyclotron Waves Absorption

$$P_{abs} = P_0(1 - e^{-\tau}) \qquad \text{where} \qquad \tau = \int \alpha \cdot dl$$

α = *local* absorption coefficient in m^{-1}

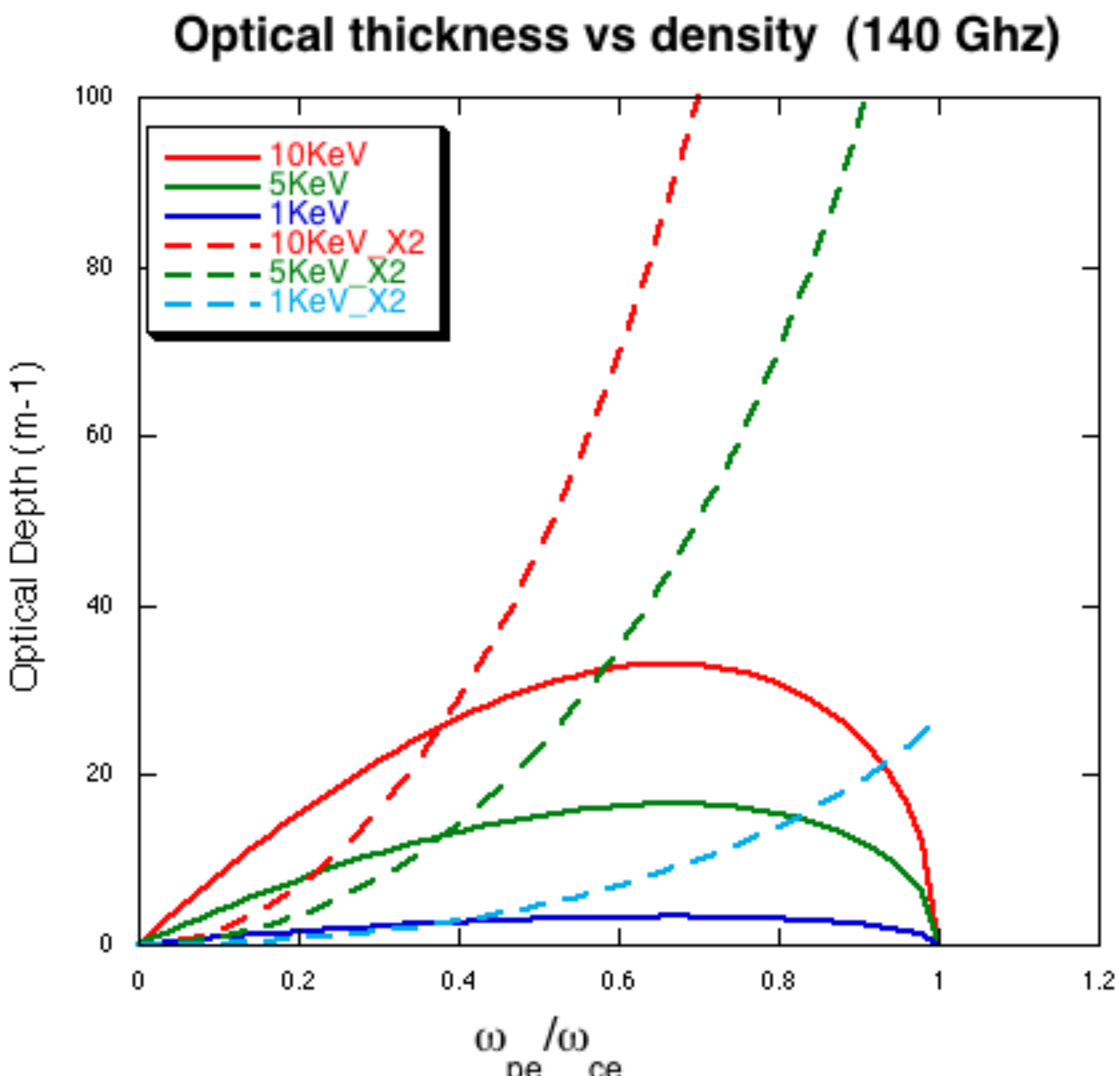
Optical thickness τ changes with polarization, $N_{//}$ and harmonic number. In case of fundamental OM with $N_{//}$=0:

$$\tau_{OM1} = \pi^2 \frac{\omega_{pe}^2}{\omega_{ce}^2}\left(1 - \frac{\omega_{pe}^2}{\omega_{ce}^2}\right)^{1/2} \frac{v_{Te}^2}{c^2}\frac{R}{\lambda}$$

Absorption depends on Te and n_e

$$\tau_{OX2} = 2\pi^2 \frac{\omega_{pe}^2}{\omega_{ce}^2} \frac{\left(6 - \frac{\omega_{pe}^2}{\omega_{ce}^2}\right)^2}{\left(6 - 2\frac{\omega_{pe}^2}{\omega_{ce}^2}\right)^2} \frac{v_{Te}^2}{c^2}\frac{R}{\lambda}$$

Optical thickness



$f_o = 140$ GHz
$N_{//} = 0$

with $\tau > 3 : P_{abs} \sim 95\%$

Absorption depends on Te and ne

XM2 is stronger absorbed approaching cut-off

Fundamental Resonance

A more complete resonance condition is:

$$\frac{1}{\gamma} \cdot n\Omega_{ce} = \omega_o - \vec{k} \cdot \vec{\upsilon} = \omega_o - k\upsilon_{\parallel} \cos\theta$$

Relativistic Gamma

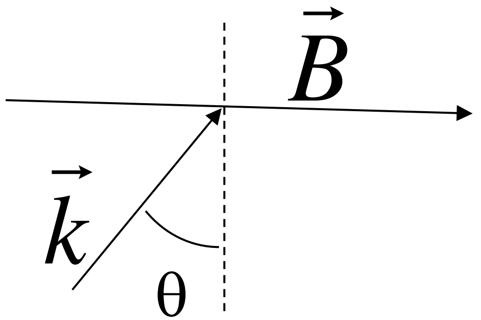
$$\gamma = \frac{1}{\sqrt{1 - \frac{\upsilon_{\parallel}^2}{c^2}}}$$

Electron velocity

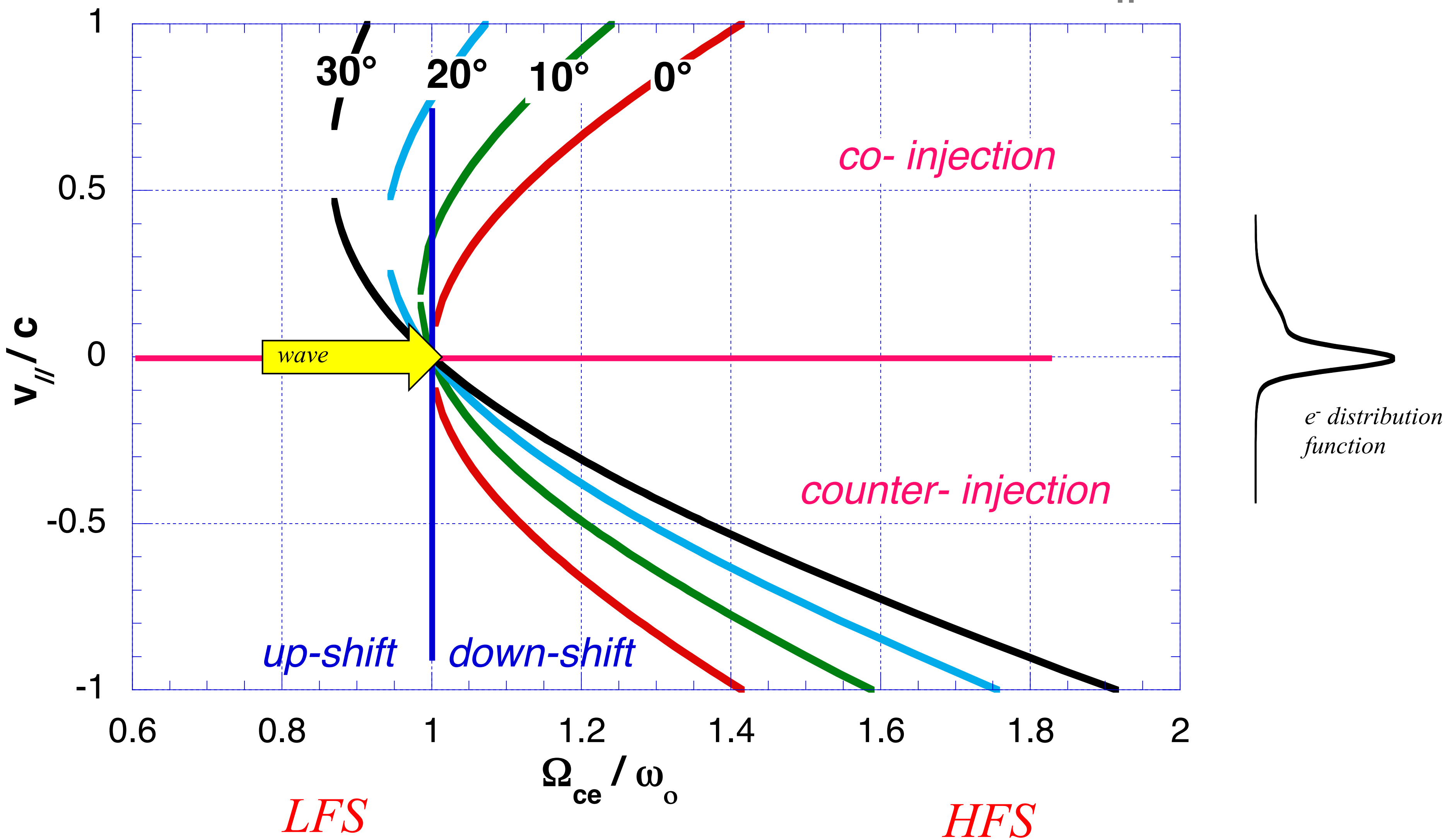
$$\upsilon_{\perp} << \upsilon_{\parallel}$$

Angle between wave propagation and the perpendicular to the magnetic field

$$\boxed{\frac{\Omega_{ec}}{\omega_o} = \frac{c/\upsilon_{\parallel}}{\sqrt{c/\upsilon_{\parallel}{}^2 - 1}} \left(1 - \frac{N_{\parallel}^{EC}}{c/\upsilon_{\parallel}}\right)}$$



The Graphic Solution of Resonance Equation at different $N_{||}$



ECCD: the basic mechanism

EC waves gives only **perpendicular energy** to electrons: no net longitudinal momentum transfer

The EC wave can produce non inductive current drive exploiting two different and opposite effects:

- **Fisch&Boozer effects** (effect on collisionality)
- **Ohkawa effects** (trapped particles balance)

ECCD **efficiency** is **low**, but the high **localization** can be exploited for **current profile control** aiming to **MHD stability** or q profile shaping.

Fisch & Boozer effects

Co-injection*:* power absorption on co-current electrons

$\perp$ Energy increase

Collisionality reduction

Not-symmetric losses (co electrons lost less than cnt electrons)

Net co-current *generation*

ECCD: Okhawa effect

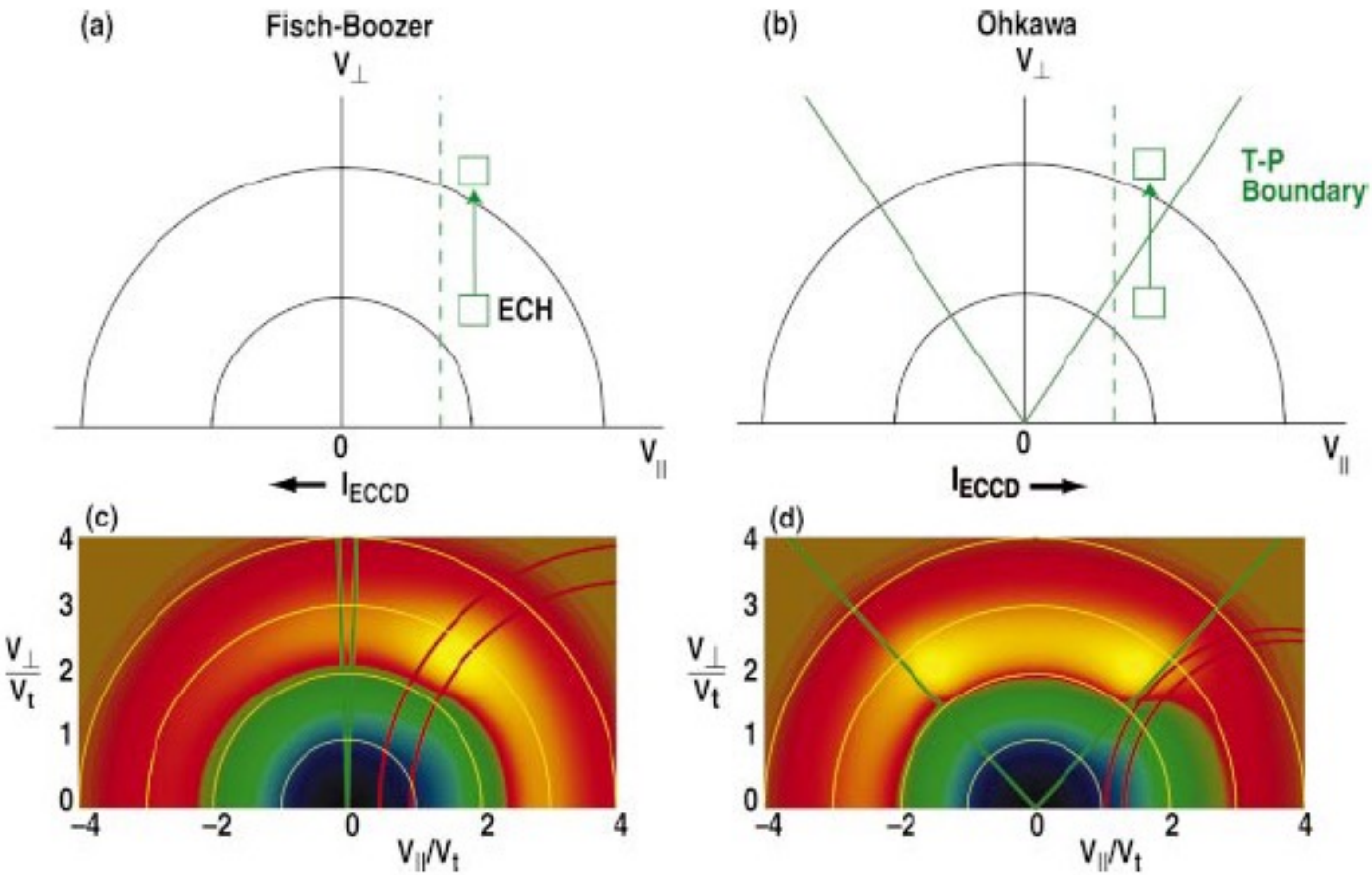
In toroidal geometry the presence of trapped particle is at the basis of Ohkawa ECCD effect.

Electrons, gaining $E_{\perp}$ **from EC wave,** can enter in the **trapped cone**, and stops to drive current (due to the bouncing of such particle in the trapped *banana*).

This create an **asymmetry** for the particles going in the opposite direction than does not absorb EC wave and continue to circulate.

This asymmetry produce a net current drive term in the **opposite** direction with respect to the resonant electrons absorbing the wave.

From CQL3D- Fokker-Planck



EC Power Deposition

EC wave is usually fully absorbed at 1st pass (if T_e >2 KeV and $n_e \sim 0.1\ n_{cutoff}$)

The deposited power is strongly localized, depending on the beam intersection with the resonant layer

The profile of power deposition is calculated (in all experiments) using Ray Tracing and/or Beam Tracing codes well consolidates and benchmarked. Result depends on accuracy of equilibrium, T_e and n_e profiles, being known the mirrors steering.
Main Codes used: TORBEAM, ECGWB, GRAY, TORAY-GA, BANDIT-3D (*beam tracing*, ray-tracing)

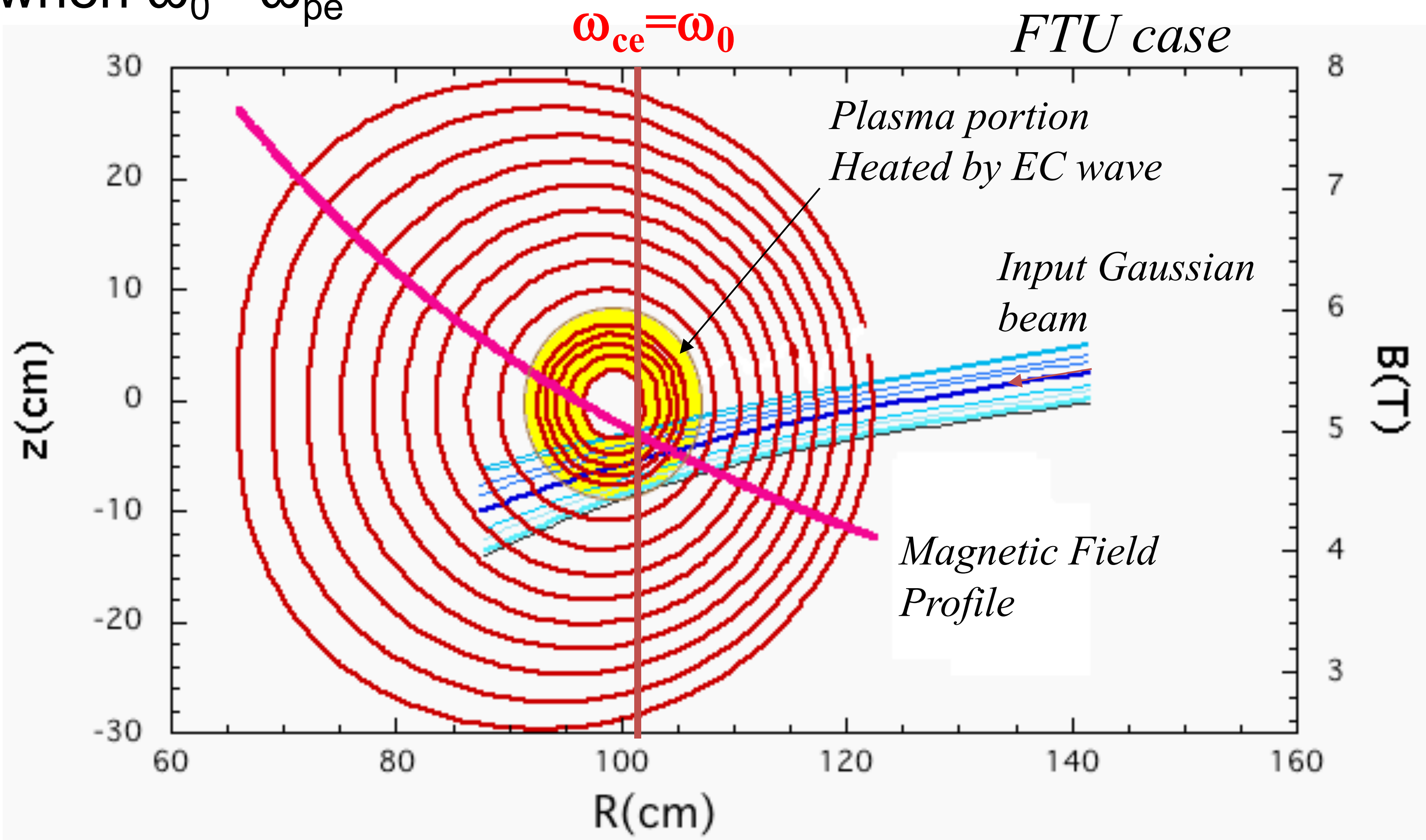
ECCD Efficiency

The amount of CD driven by EC wave is a function of :

Local Temperature
Local Zeff
Wave frequency
Local plasma density
Injection angle
Geometrical Effects

Beam Propagation

The beam suffers of plasma refraction (when it crosses high density regions) up to a full bending (reflection) when $\omega_0 = \omega_{pe}$



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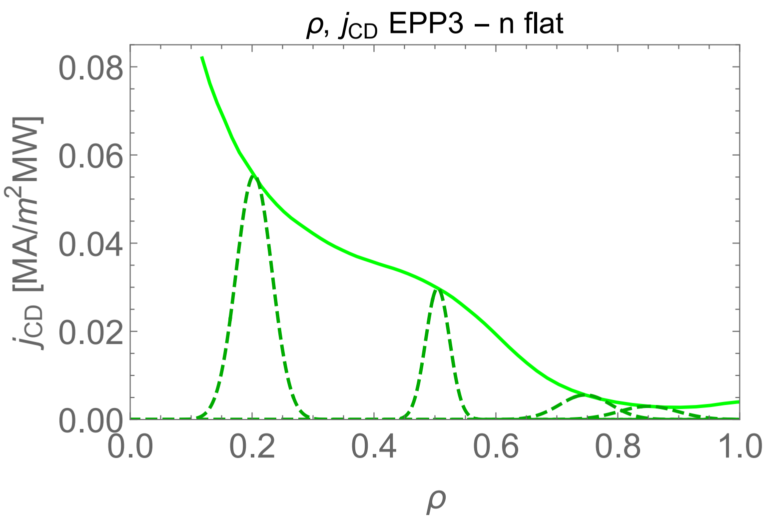
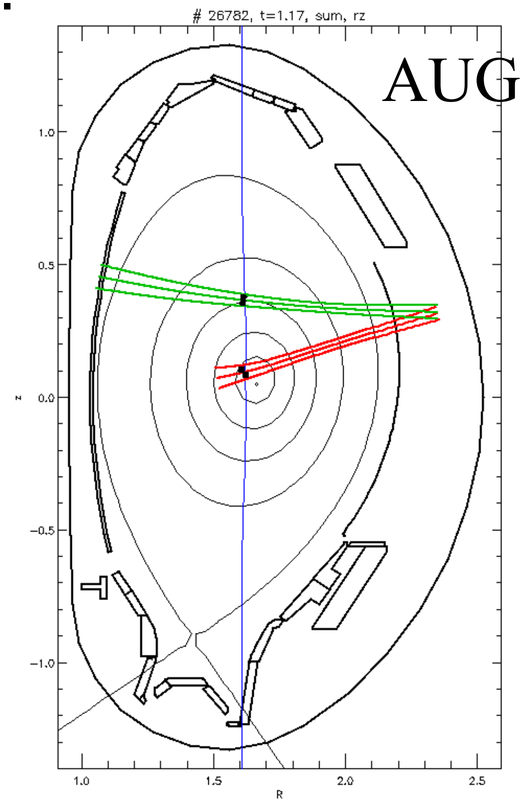
Main Codes used:
TORBEAM, GRAY
TORAY-GA, BANDIT-3D

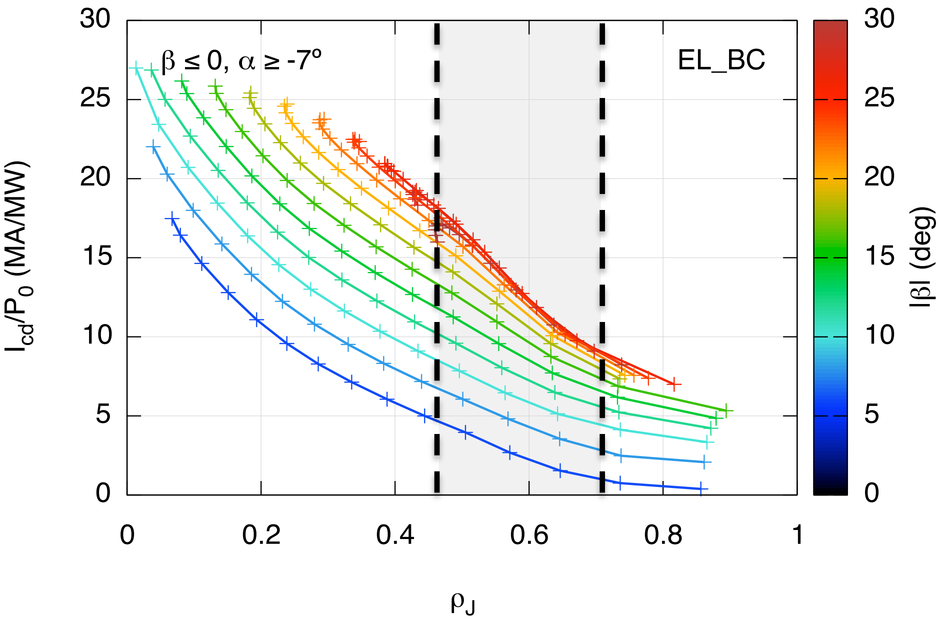




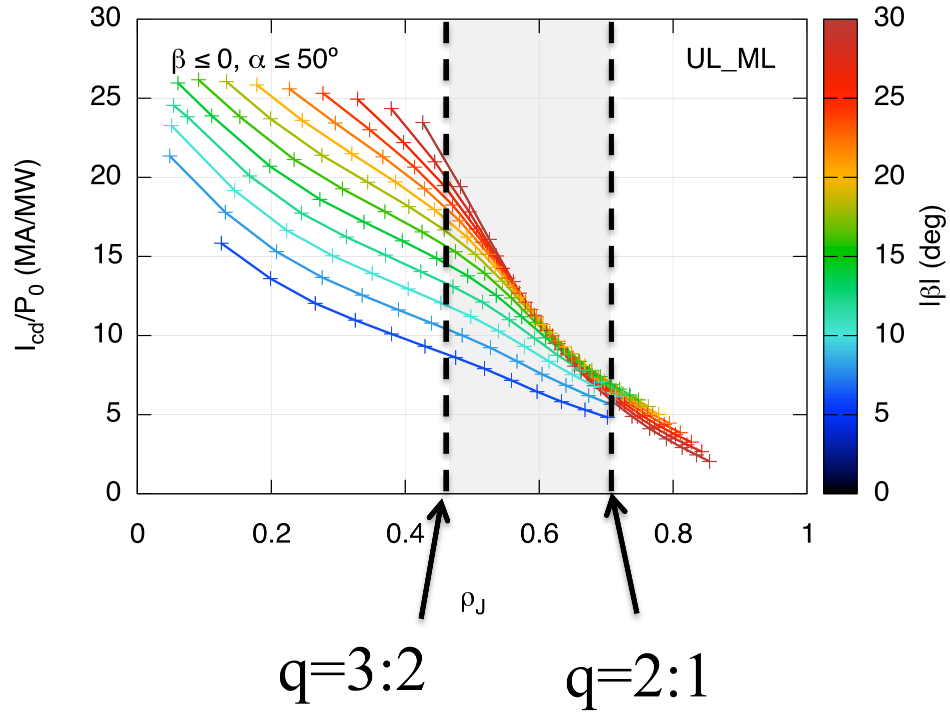
Current drive I_{CD}/P_0 (ρ)

DTT case

Equatorial Launcher



Upper Launcher



Current drive efficiency depends on two parameters:

Local electron temperature

Toroidal angle (beta)

Application of EC power in experiments for Plasma operation and RT control

Introduction

Which are the characteristics of EC wave that make it a suitable tool for plasma control to be used in closed loops?

Easily predictable power deposition localization

➔ geometrical ray tracing and beam tracing

Highly localized power deposition (strong local effect)

➔ the EC wave can be launched as TEM00:
Gaussian beam with $w_o \geq 2\lambda/\pi$ (100 GHz: $w_o > 1.9$ mm!)

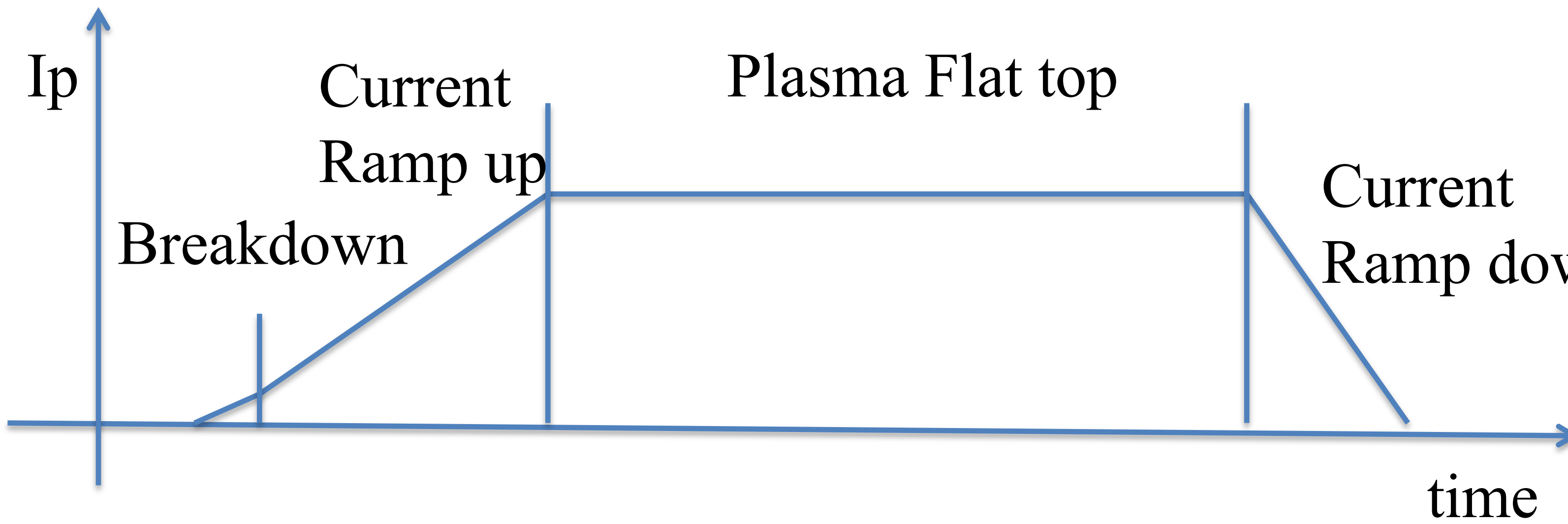
Easy control of deposition localization (radius)

➔ use of steerable mirrors due to the possibility od Q.O. approach

Fast switch on/off time

power rise time limited by HVPS capability (~100μs). Modulation up to 10KHz demonstrated (5 KHz required for ITER)

EC wave in Plasma Operation



Breakdown: **pre-ionization, burn-through**

Ramp up: lower internal inductance, save transformer flux for longer pulses

Flat top: profiles control, **MHD Control** (NTM and ST), Impurity accumulation, localized CD

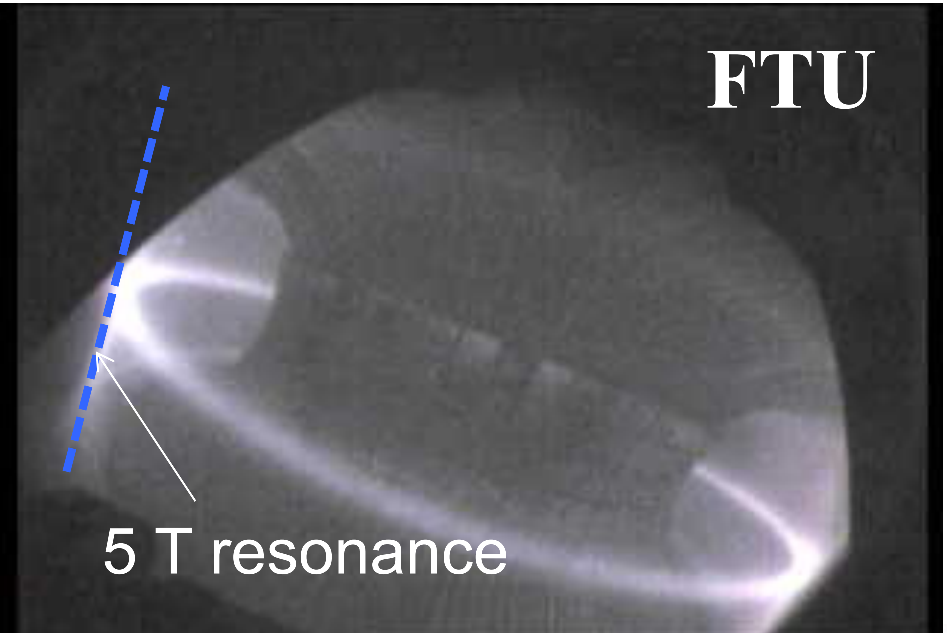
Ramp-down: avoid temperature collapse, **disruption avoidance**/control

EC Assisted Break down

EC wave in presence of resonant magnetic field is able to accelerate electron up to ionization energy, starting the avalanche and sustaining a low temperature (20 eV) and low density (10^{18} m^{-3}) plasma.

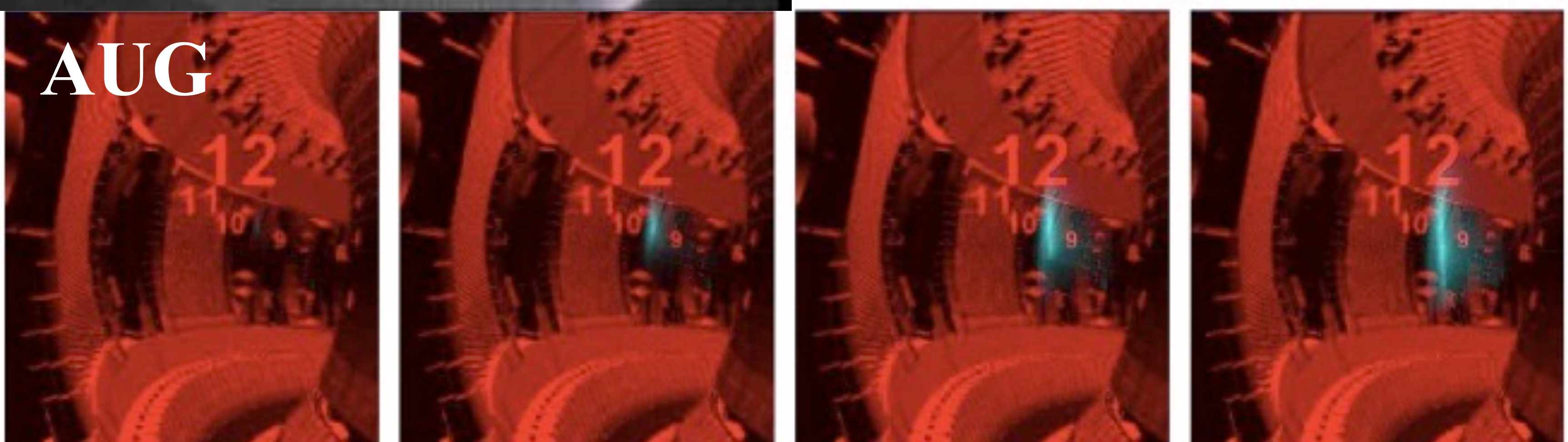
This technique is used in stellarator to sustain plasma and in tokamak to initiate plasma and (applying electric field) ramp-up current.

EC Pre-ionization localization



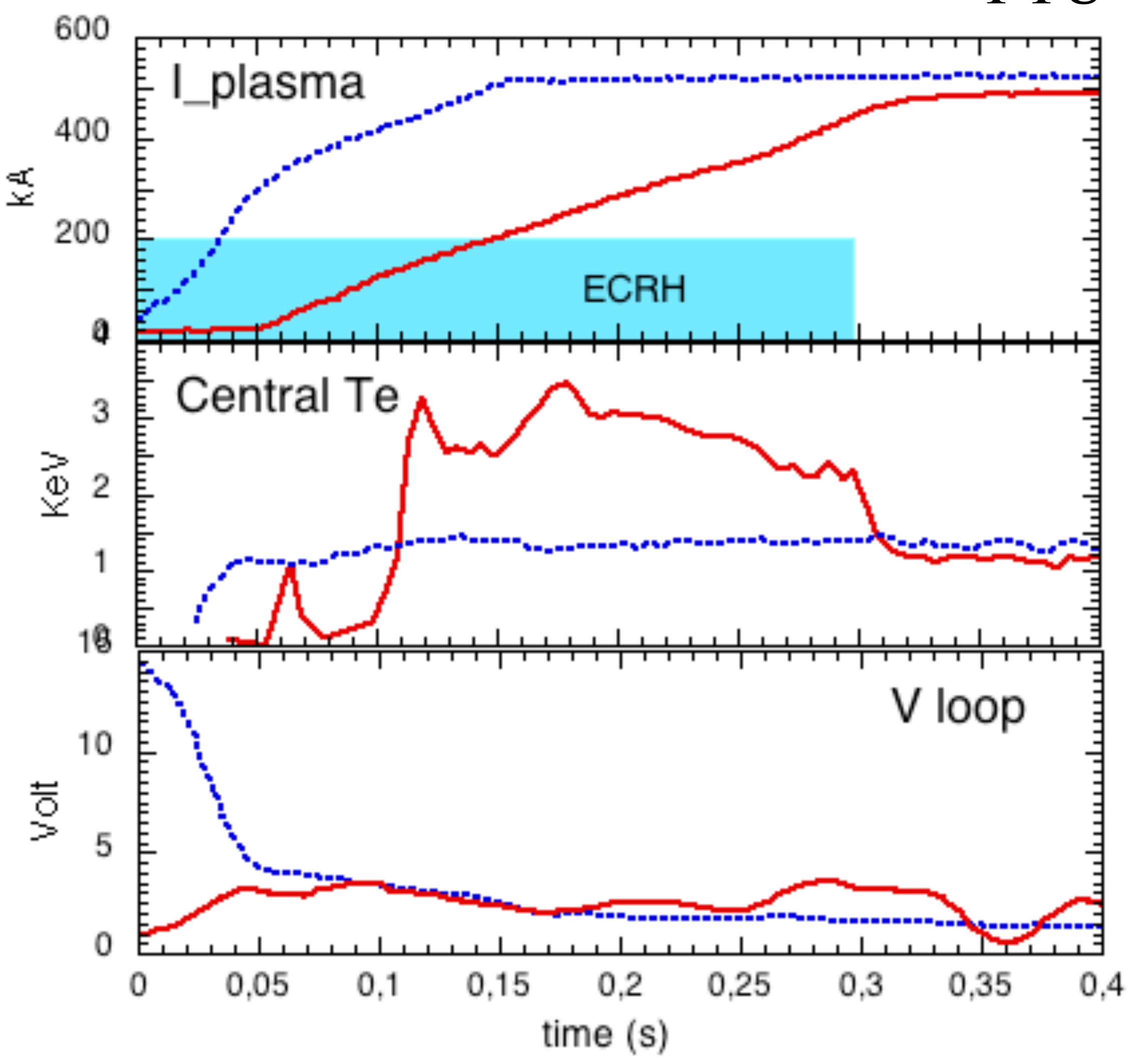
The plasma is ionized where the RF beam crosses the resonance cylinder.

The plasma drift in vertical and outer direction, until the current starts the confinement



EC Assisted Break-down vs ohmic

FTU



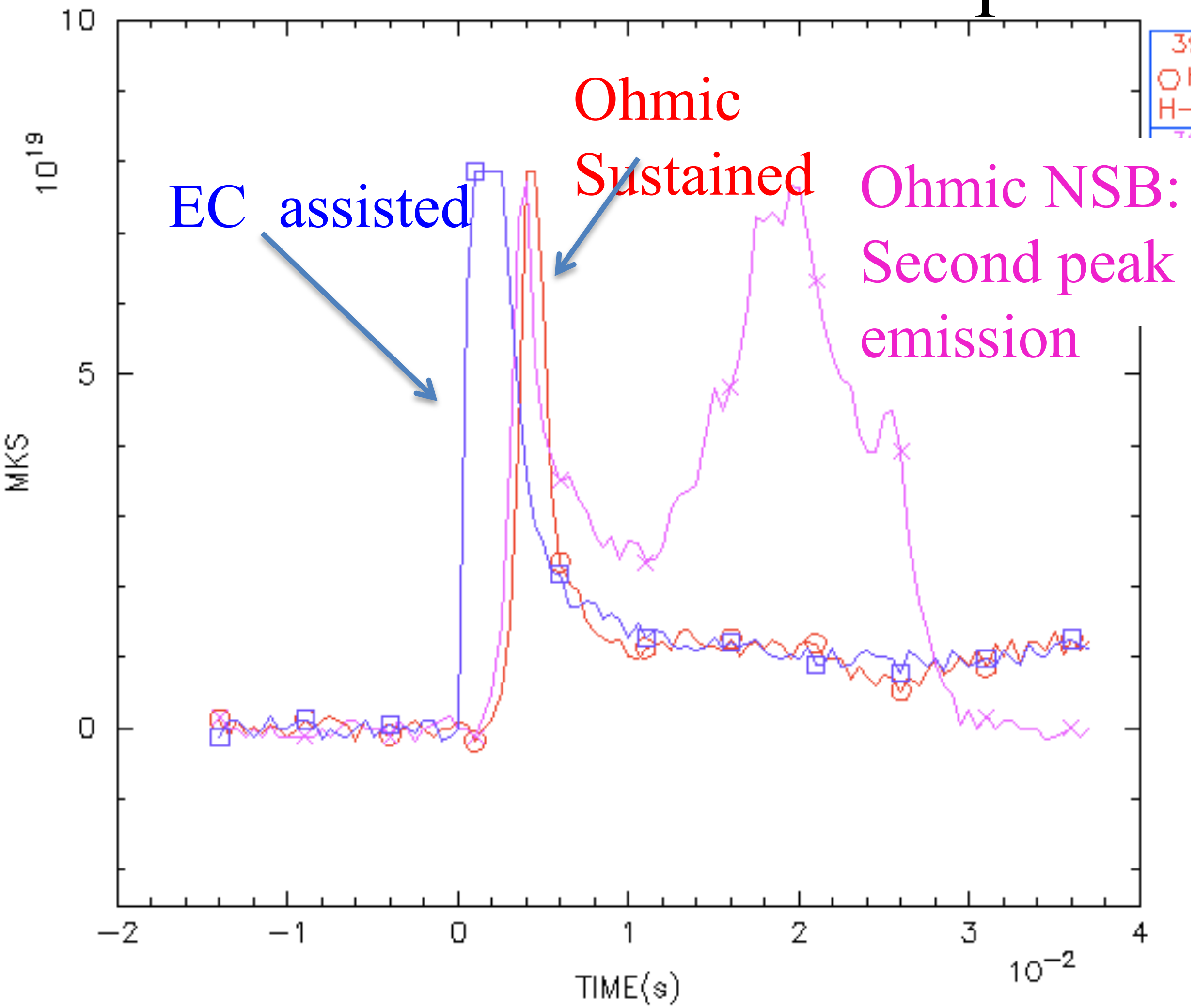
EC power is applied at t=0s and maintained for all the current ramp

With ECH assistance it is possible to start-up tokamak current at low V_{loop}

High Temperature after initial phase at low absorption

Burn- through overcoming

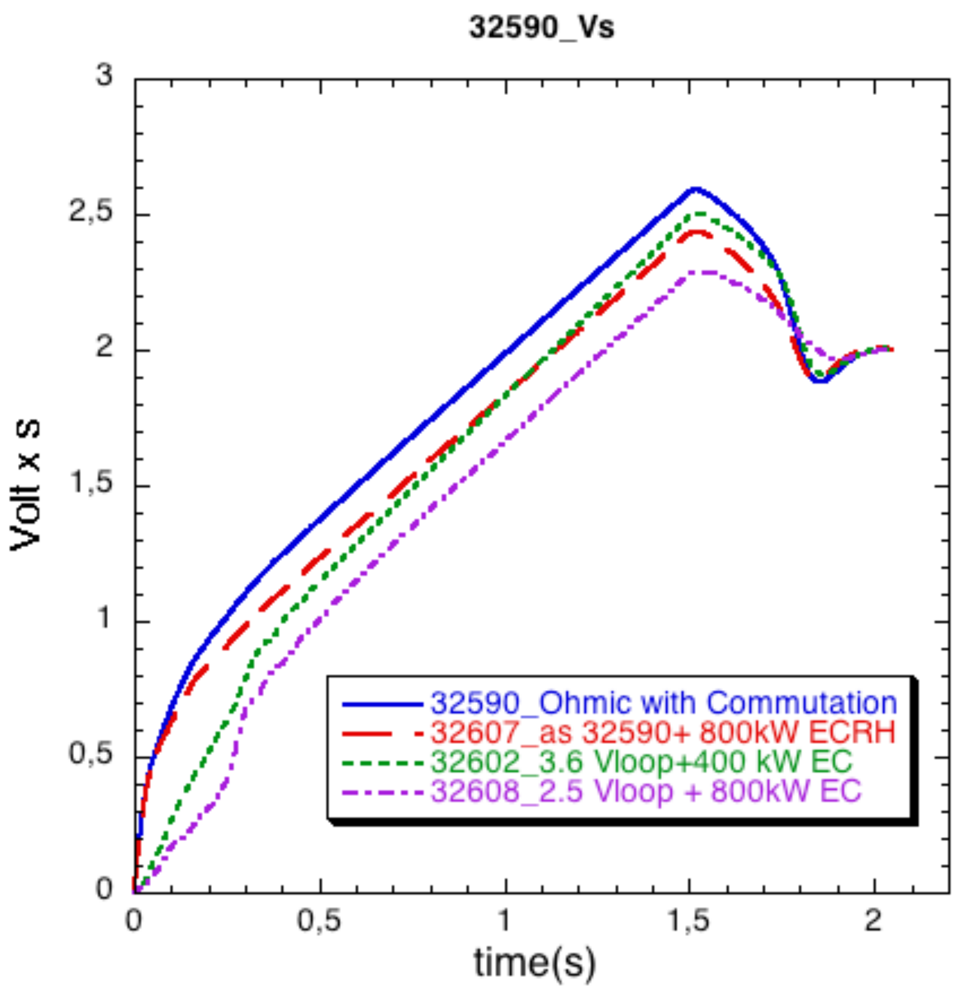
D-alfa emission at start-up



In case of low V_{loop} (or high impurity content) the hydrogen plasma cannot overcome the condition of H-alfa peak (at 20-100eV).

EC power gives energy to compensate radiation losses in the low temperature plasma, allowing to increase of temperature (>200eV) necessary to ramp-up the plasma current

Transformer flux saving

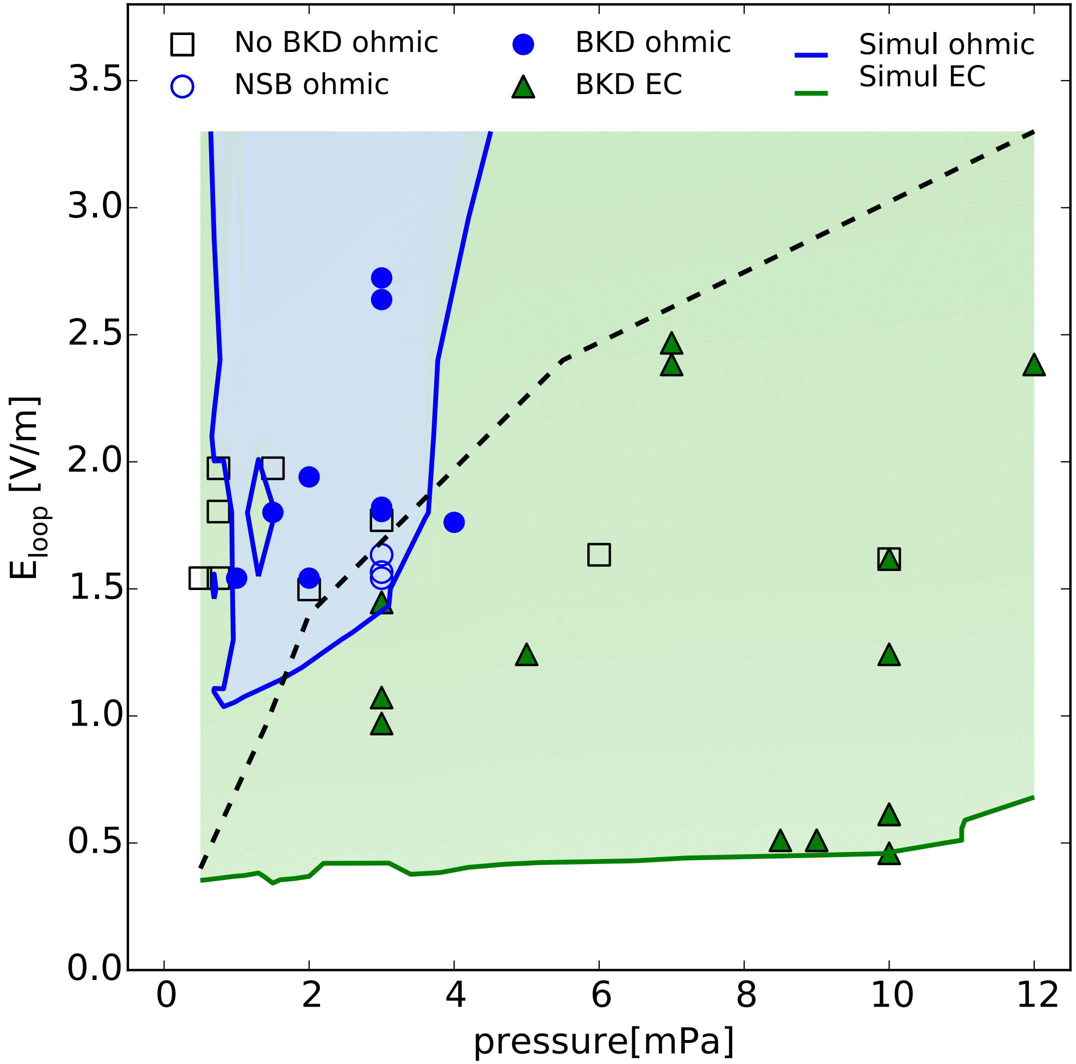


Application of EC power to start-up plasma current leads to flux saving for two main reasons:

1- Breakdown at low Vloop (a fast drop of I_{trafo} is not required)

2- Higher temperature during current ramp reduce plasma resistivity

Breakdown Operational Window



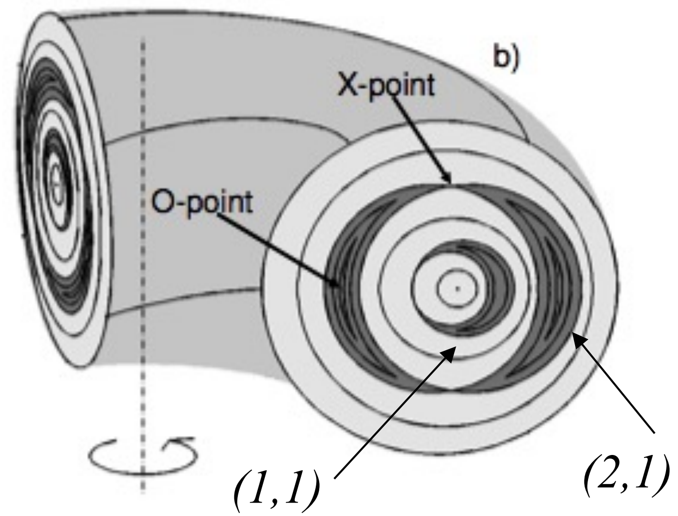
Use of EC power in the start up phase allows wider operational window in term of Electric field and Pressure

Here the FTU results together with simulation from BKD0 code.

MHD Control by EC wave

In a large scale machine (like reactor) the authomatic **control** for plasma stability and performance is one of the main challenge.

Instabilities of Magnetic Hydrodynamic type (MHD) can produce a deformation in the magnetic configuration reducing energy confinement and increasing the risk of plasma disruption.



The control requires correct physic models and proper actuator. One of tool to perform plasma control is the Radio Frequency used as auxiliary heating as Electron Cyclotron Resonance Heating (ECRH).

Rutherford equation expression

Island width evolution

$$g_1 \frac{\tau_R}{r_s^2}\frac{dW}{dt} = \pm\Delta_0' + a_1\Delta_{BS}' - a_4\,\Delta_{cd}'$$

$$\Delta_0'(W) = \Delta' - \alpha W = \lim_{\varepsilon\to 0}\frac{1}{\psi}\left[\left(\frac{d\psi}{dr}\right)_{r_s+\varepsilon} - \left(\frac{d\psi}{dr}\right)_{r_s-\varepsilon}\right] - \alpha W$$

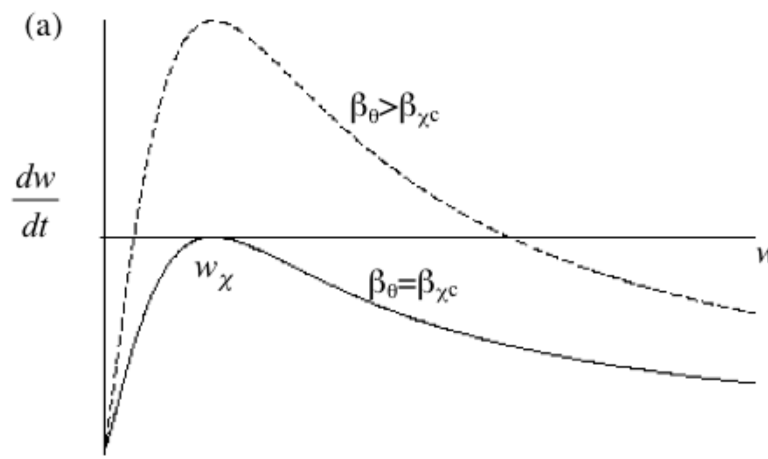
stabiliz./destab. depending on the $\nabla_r J_{//}$

$$\Delta_{bs}' \propto \beta_p \frac{q}{q'}\frac{p'}{p}\frac{W}{W^2+W_s^2}$$

significant for large plasma pressure

$$\Delta_{cd}' \propto \frac{I_{CD}}{I_p}\eta(W/\delta_{CD})\frac{1}{W^2}$$

stabiliz./destab. depending on island radial centering

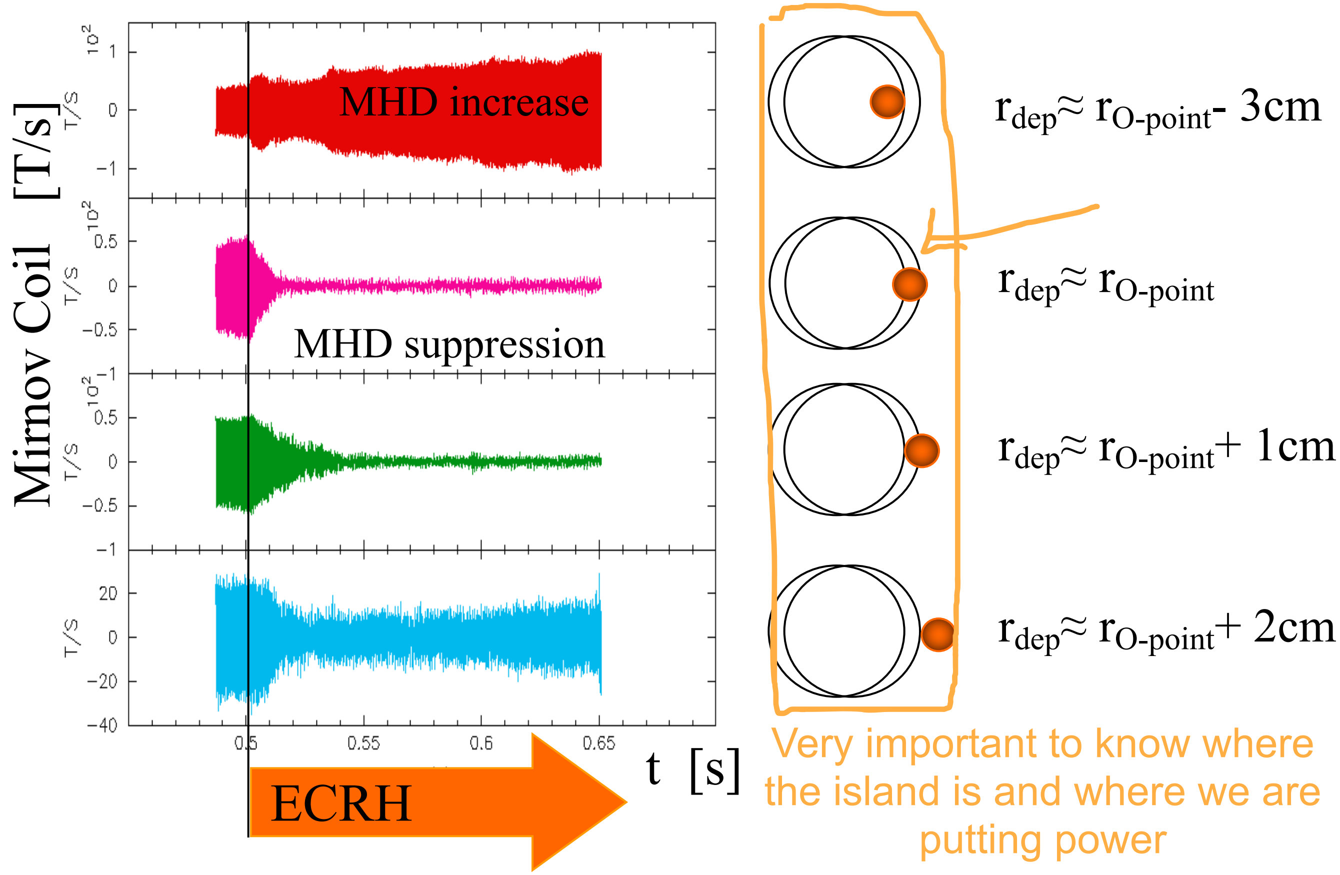


MHD Suppression by ECRH on FTU

First Demonstrative Experiment

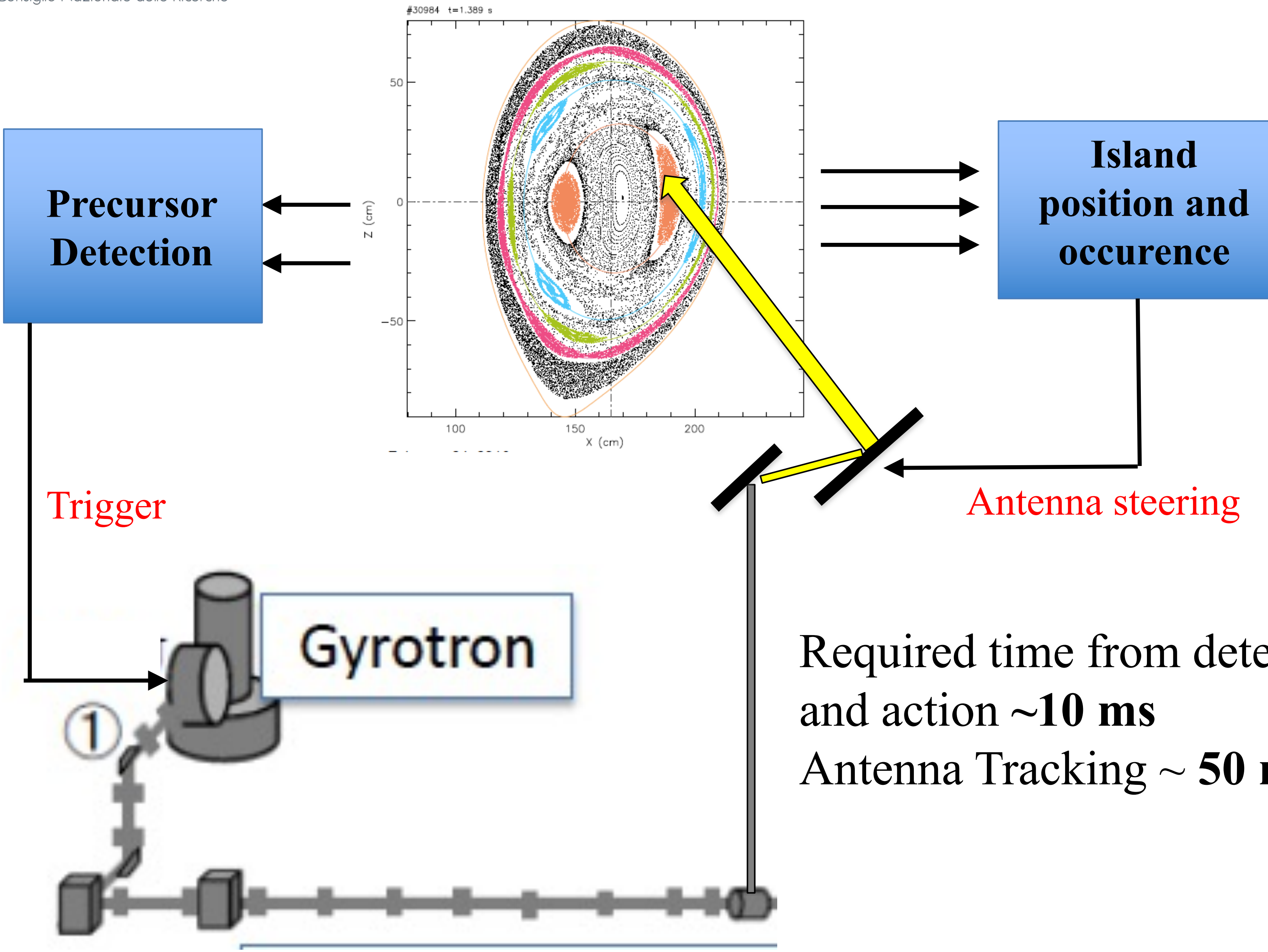
S.Cirant et al. IAEA Sorrento 2000

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.

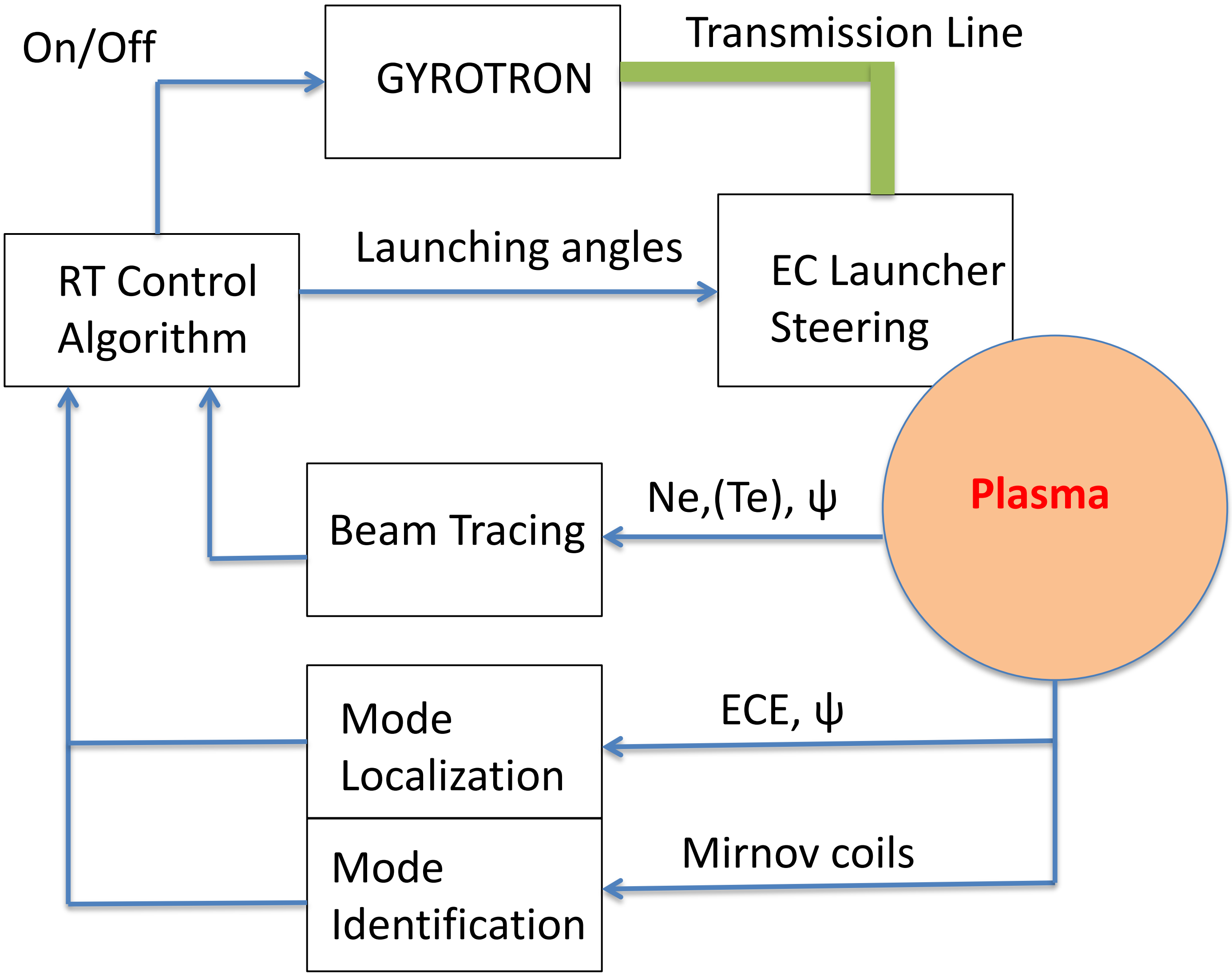
Loop di Control Loop for RT MHD stab.



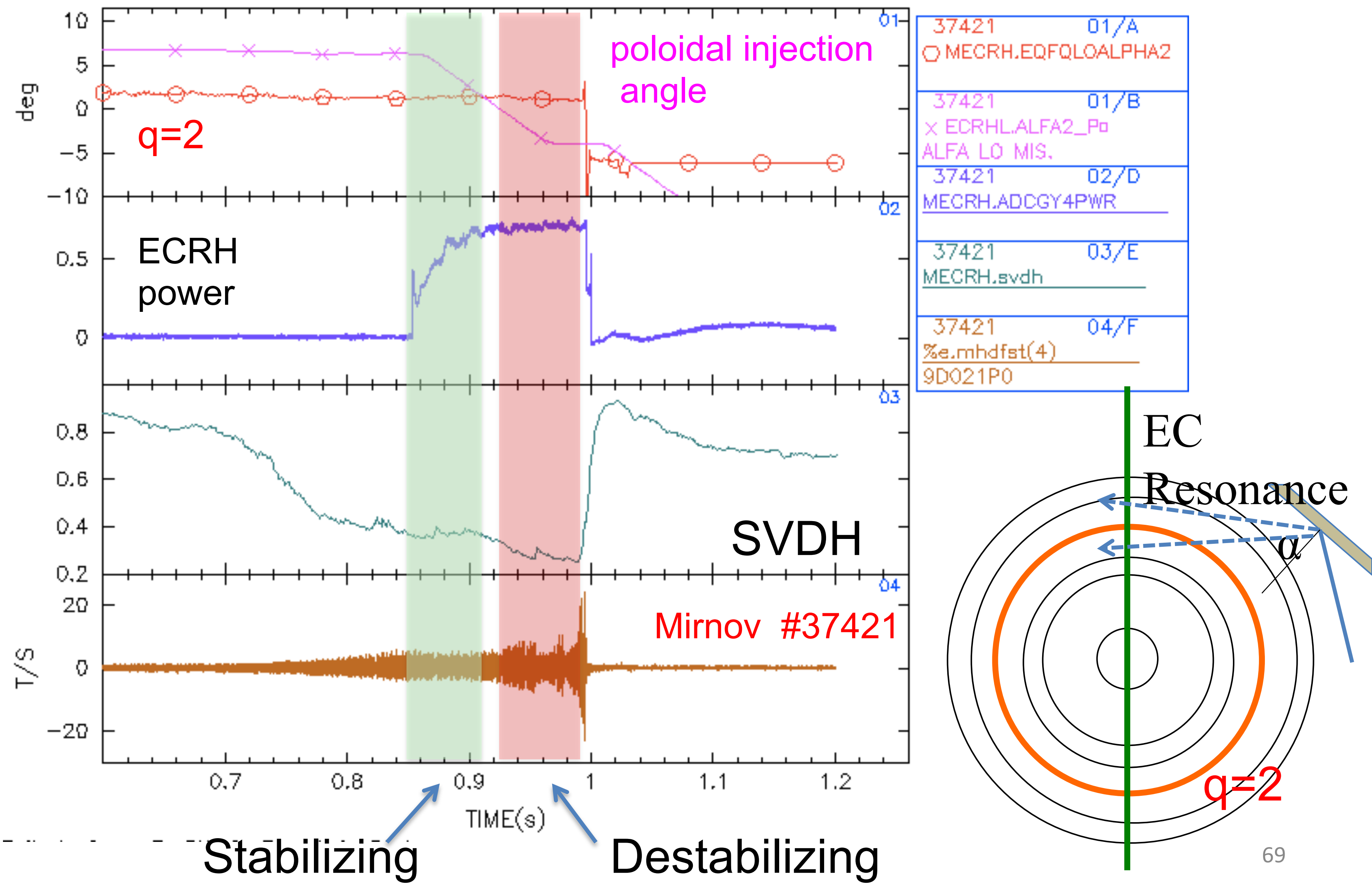
Required time from detection and action **~10 ms**

Antenna Tracking ~ **50 ms**

The ideal MHD control Loop



Stabilization/destabilization depends on the ECRH absorption radius

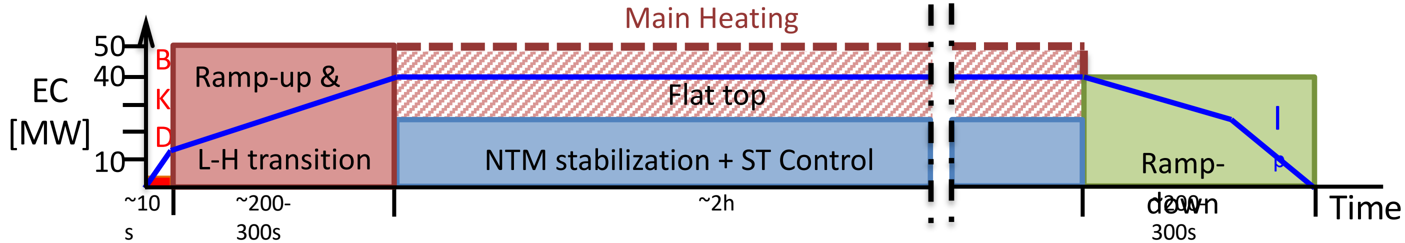


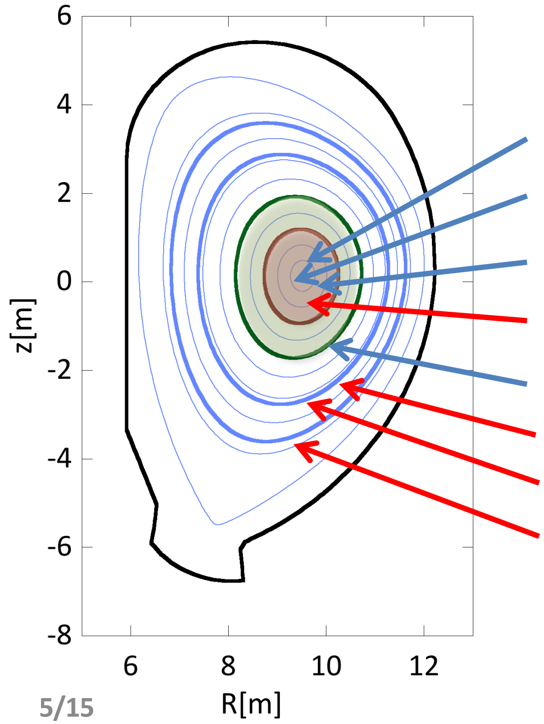
Basic for a Design of an ECRH System

Outline

- Main Physic requirement for ECRH system
- ECRH System General Overview
- RF Power Source
- Gyrotron Power Supply
- Transmission Line
- Polarizer
- Coupling EC power to plasma: Launcher
- Control System

EC System Physical Requirements

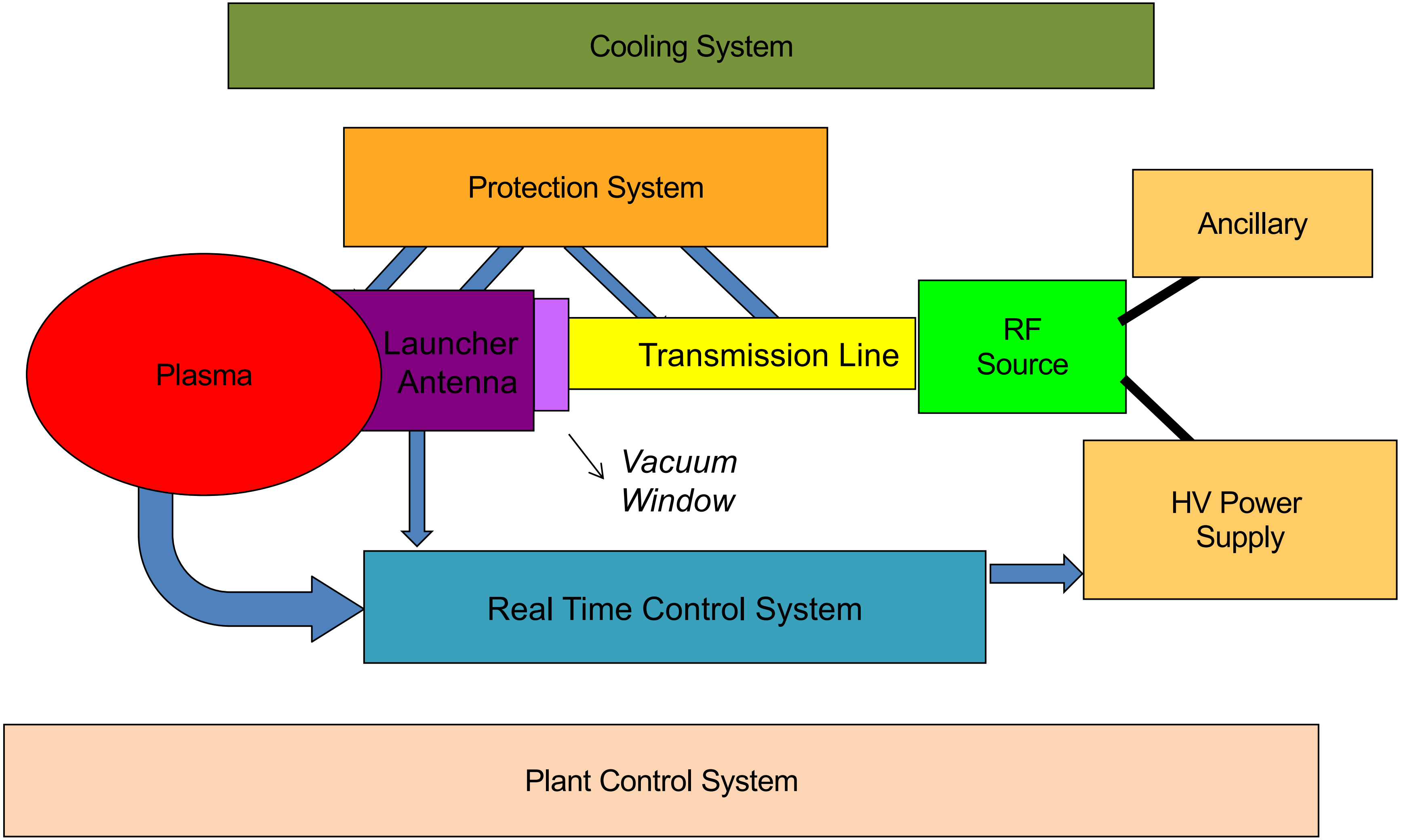




Task	*Power*	*r/a*	*Mode*
Breakdown and start-up	6-10	~central	H/CD
L-H transition in Ip ramp	50 – (80)	central	H/CD
Main Heating	Up to 50	central	H
Sawtooth control	tbd	< 0.3	CD
Ip Ramp down	40	>0.3	H
Disruption control (under study)	tbd	0.7	CD
NTM control (3,2)	>15	0.7	CD
NTM control (2,1)	>15	0.865	CD

5/15

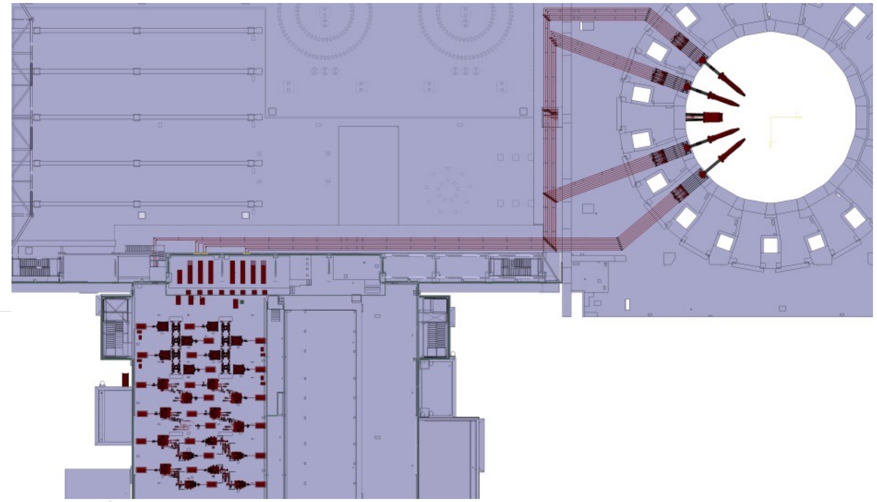
ECRH system in blocks

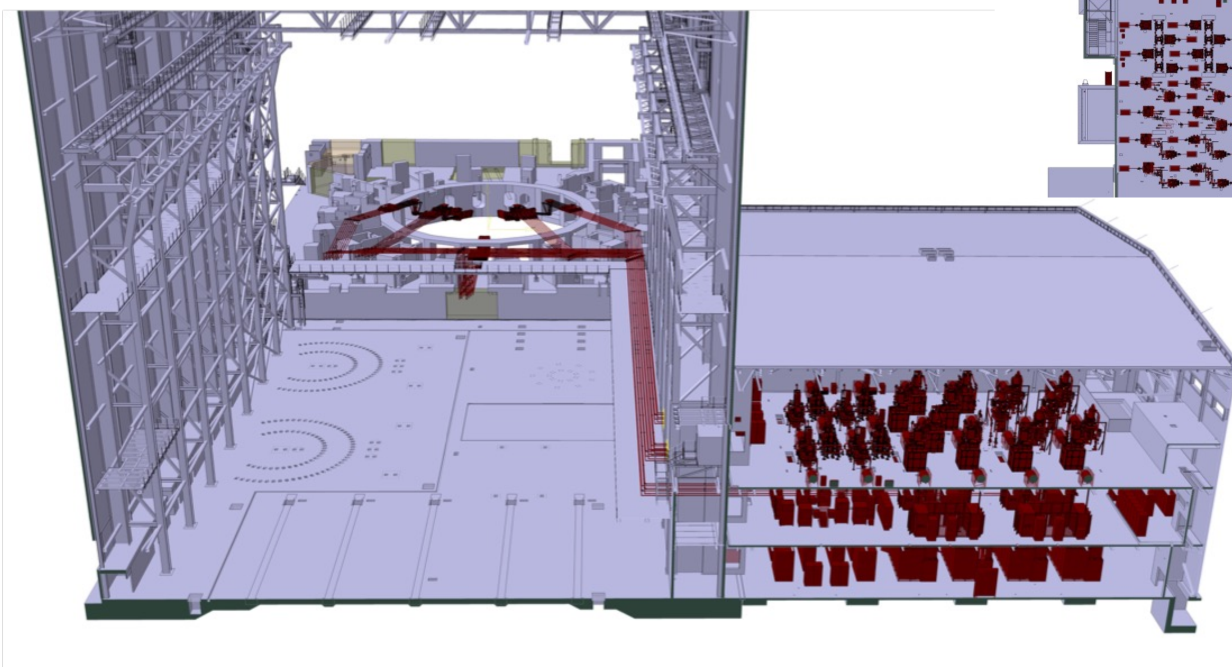


Consiglio Nazionale delle Ricerche

ITER EC System

- ✓ EC system will inject 24 beams of 0.83 MW (20 MW total)
- ✓ Corresponding to **24 MW installed**

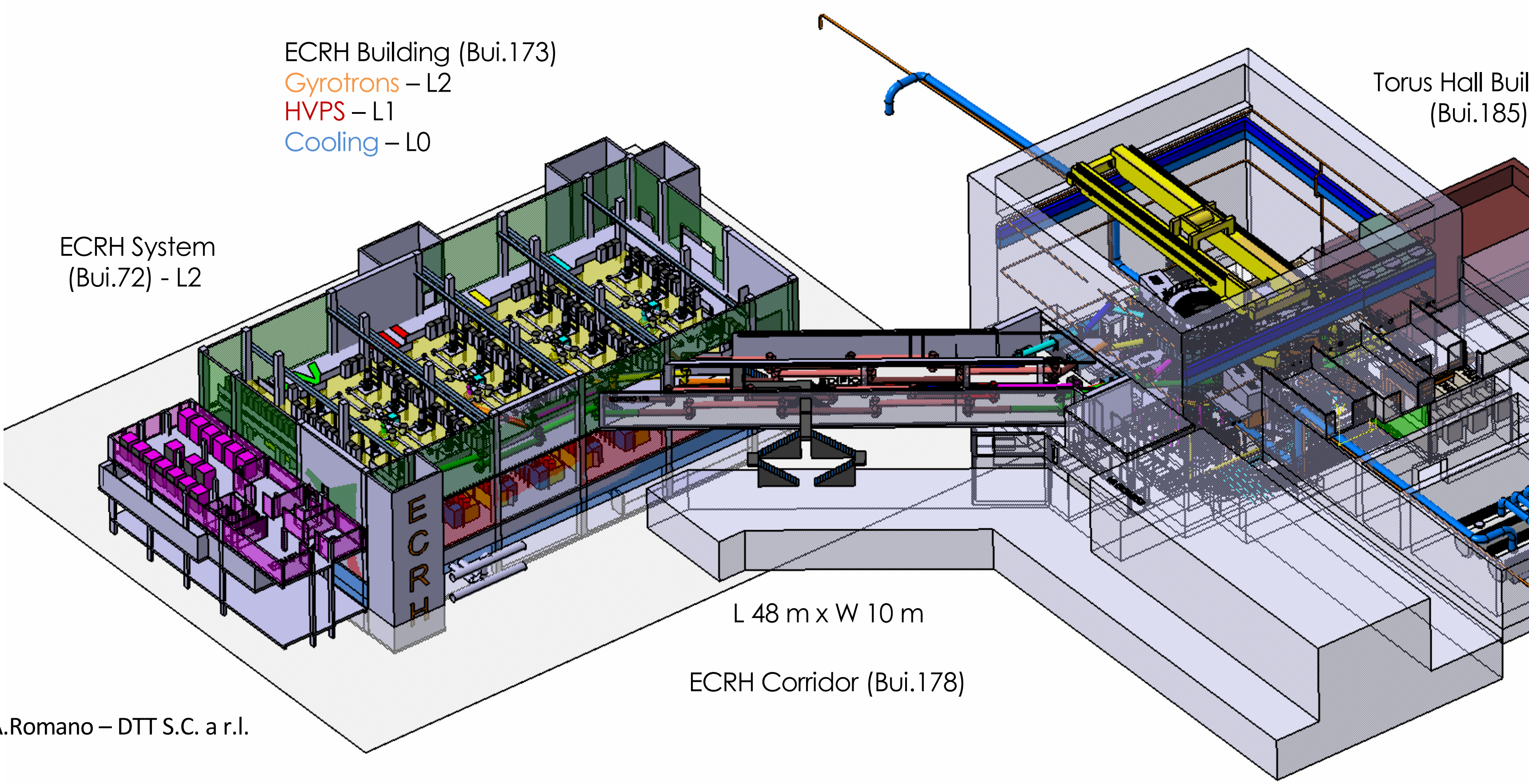




12 HVPS sets
24 Auxiliaries set
24 Gyrotrons
24 Transmission Line
4 Upper Launcher
1 Equatorial Launcher
1 Control system

Courtesy from F.Gandini – EC-20 - 2018

DTT– ECH System: General Layout



A.Romano – DTT S.C. a r.l.

RF
Source

The Microwave Source requirements

- *High Frequency (up to 170GHz)*
- *High Power (1 MW class)*
- *Pulse length: ~1000 s -> cw*
- *Gaussian output: 98%*
- *Reliability: > 94%*

RF Generators for ECRH

- Klystron (for high frequency power decreases)
- Magnetron (i.e. 2.45 GHz : microwave oven)
- BWO (few watts, only for signal measurements)
- **Gyrotron : cw, up to 240GHz, 1-2 MW**
- FEM (Free Electron Maser): high frequency, only prototype study
- CARM: high frequency, high power: under consideration at Enea Lab

In a Gyrotron an electron beam (emitted by a hot cathode) is accelerated in strong magnetic field crossing a cavity shaped for a specific mode. The electrons emit power at frequency:

Effective frequency

$$\omega_c = n\frac{\Omega_{c0}}{\gamma}$$

Relativistic term

$$\gamma = \left[1-\left(\frac{v}{c}\right)^2\right]^{1/2} = 1+\frac{eV_0}{m_o c^2} = 1+\frac{V(kV)}{511}$$

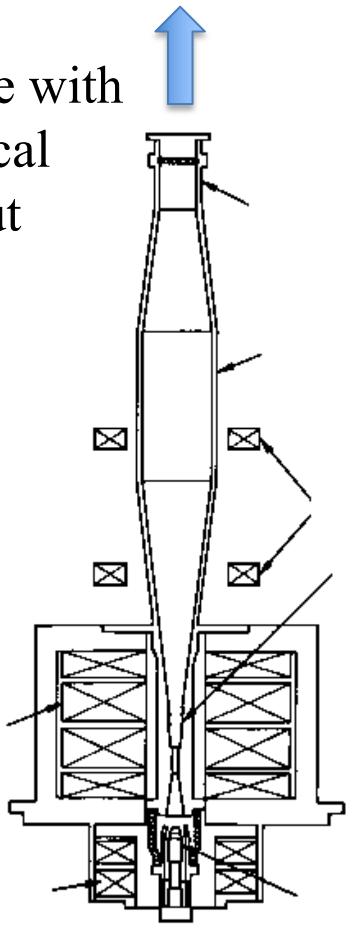
<u>*Gyrotron is an oscillating tube: not an amplifier*</u>

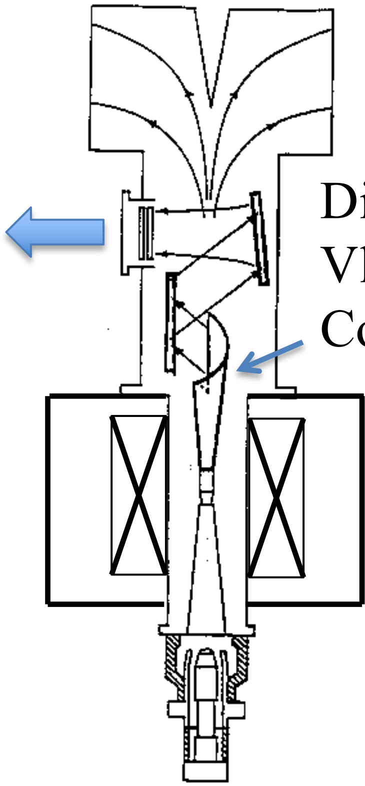
Main Gyrotron Types

Diode, Triode or SPD (Depressed Collector efficiency ~50%)

Vertical output or transversal gaussian output

Diode with Vertical output



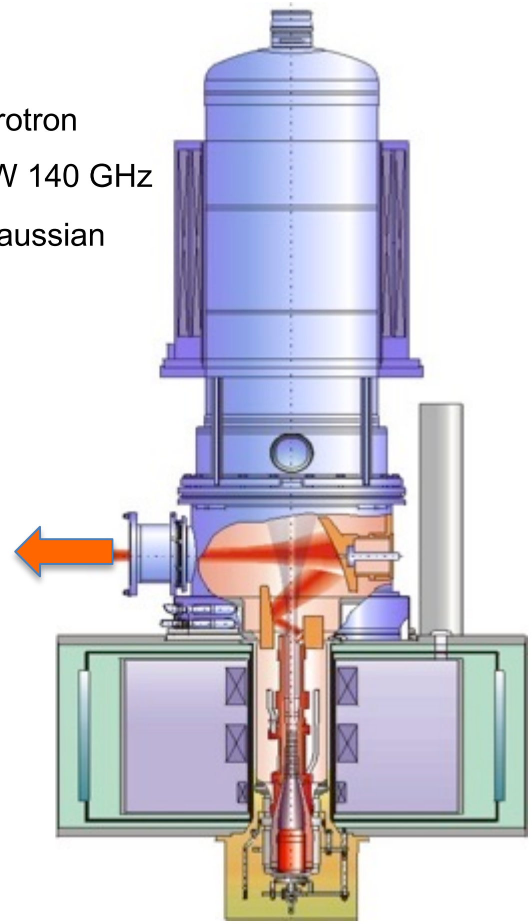


Diode with Vlasov Converter

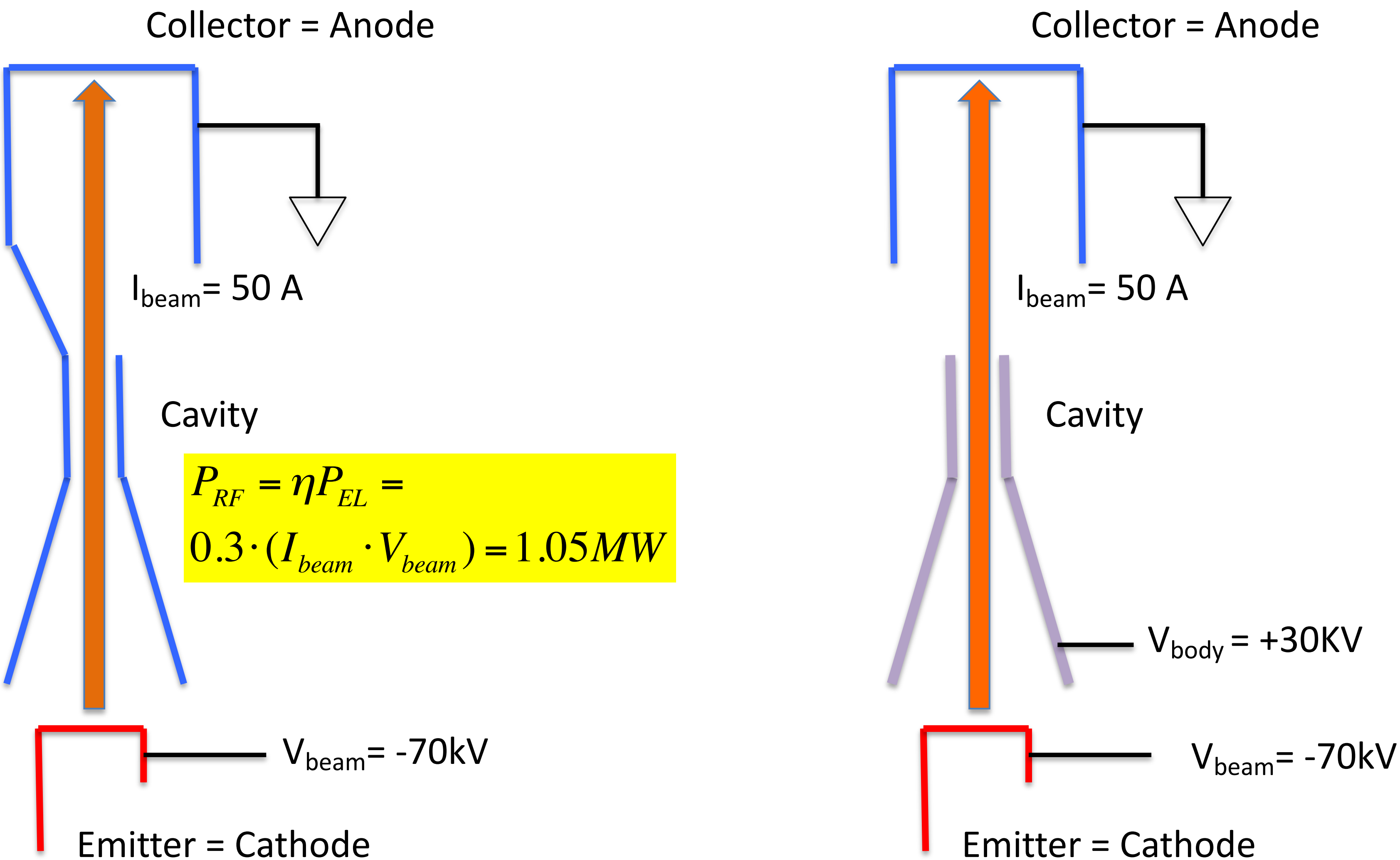
W7-X gyrotron

1 MW CW 140 GHz

Radial Gaussian Output



The Depressed Collector Concept



$$P_{RF} = \eta P_{EL} = 0.3 \cdot (I_{beam} \cdot V_{beam}) = 1.05MW$$

$$P_{RF} = \eta P_{EL} = 0.3 \cdot (I_{beam} \cdot V_{Cath-Body}) = 1.50MW$$

$$\eta = \frac{P_{RF}}{P_{EL}} = \frac{1.5MW}{3.5MW} \sim 42\%$$

The Gyrotron RF output

The gyrotron RF output is not a pure gaussian beam. 10-15% of **spurious modes** are usually present. **Future goal < 2 - 5%**

The out put beam is modified by the use of two shaped mirrors (elliptic or phase corrected): Matching Optics Unit (**MOU**)

The output **polarization** is **linear and horizontal** (with respect to the tube vertical axis) in the last generation tube (with Vlasov Converter)

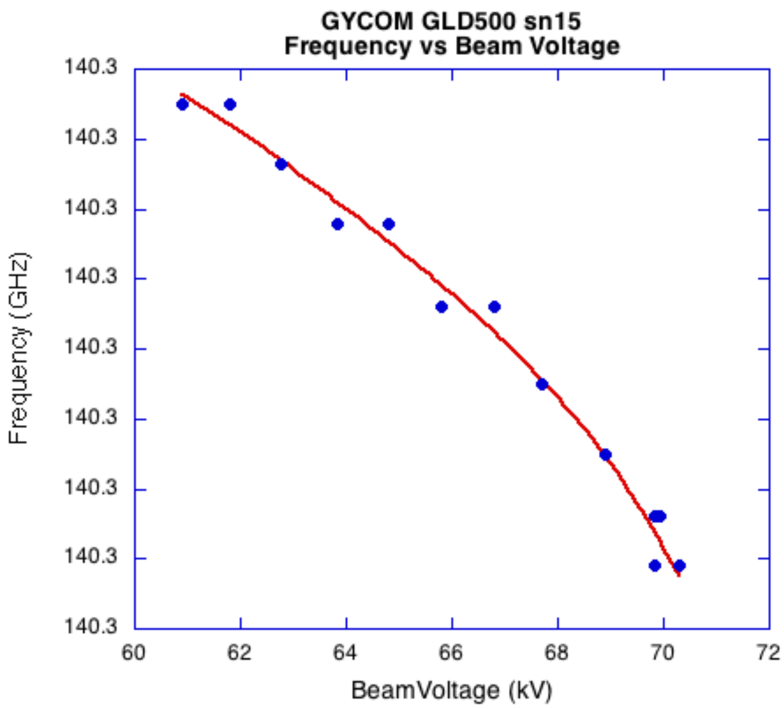
The beam must be matched with the Transmission Line minimizing the **conversion losses**.

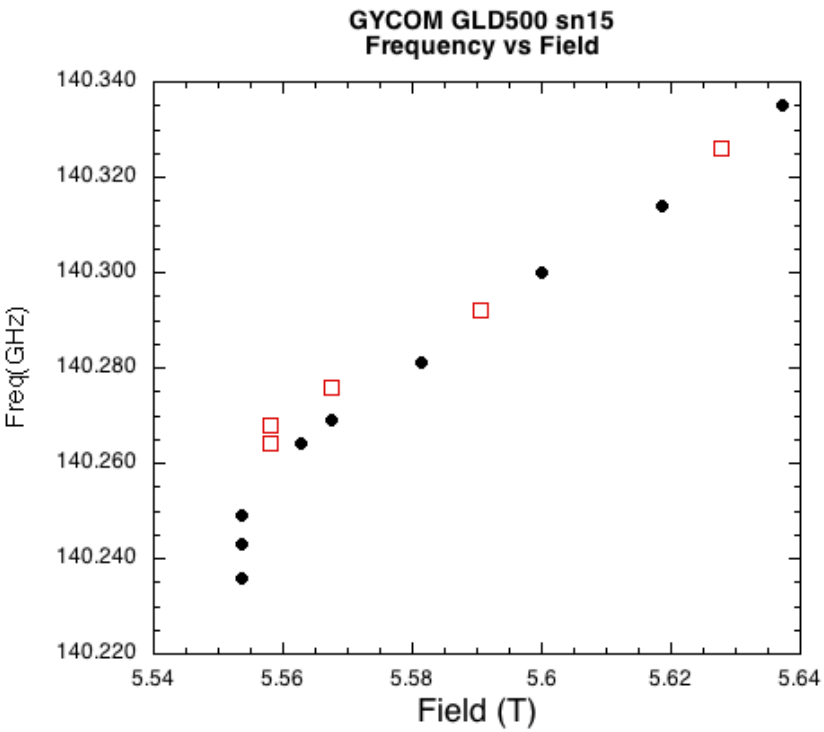
The lost power MUST be absorbed in some way *therefore* ***MUST be minimized***

Frequency dependences in Gyrotron

$$\omega_c = n\frac{\Omega_{c0}}{\gamma} \qquad \gamma = \left[1-\left(\frac{v}{c}\right)^2\right]^{1/2} = 1+\frac{eV_0}{m_o c^2} = 1+\frac{V(kV)}{511}$$

Frequency depends on magnetic field and accelerating voltage (beam voltage)





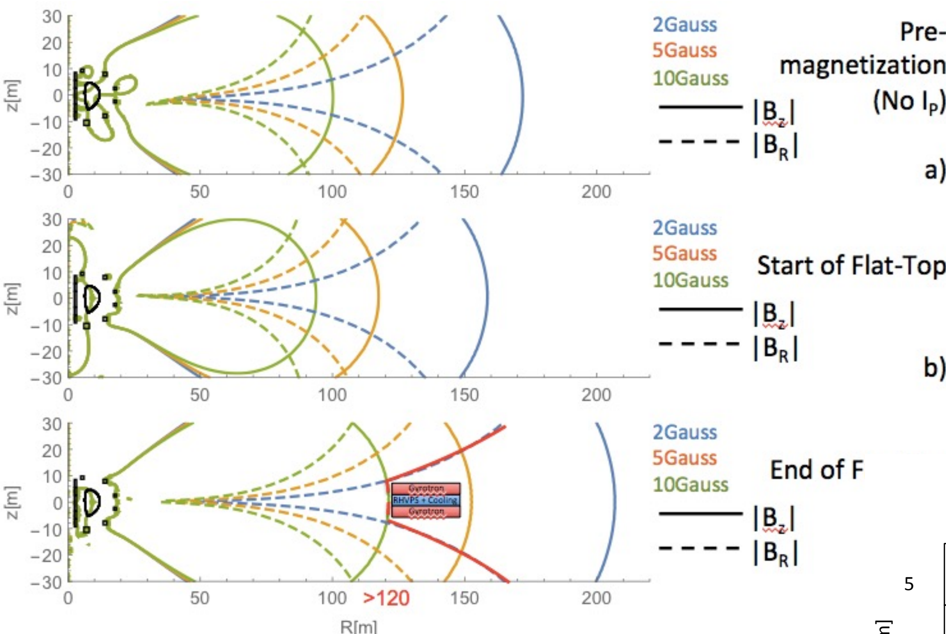
Dependency on magnetic field is <u>linear</u> but too slow (high impedance) to be used

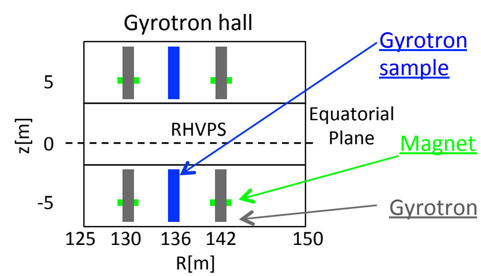
Gyrotron and stray magnetic field

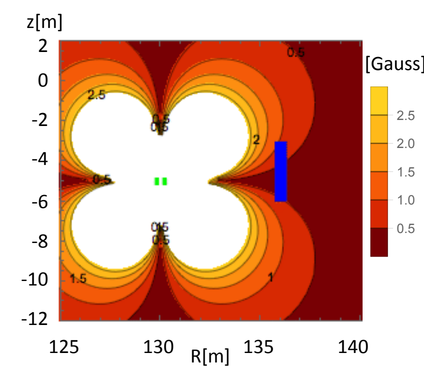
Gyrotron can be damaged by a stray magnetic field at level of collector.

The MW level gyrotrons require:

2 G for radial component
10 G for vertical component

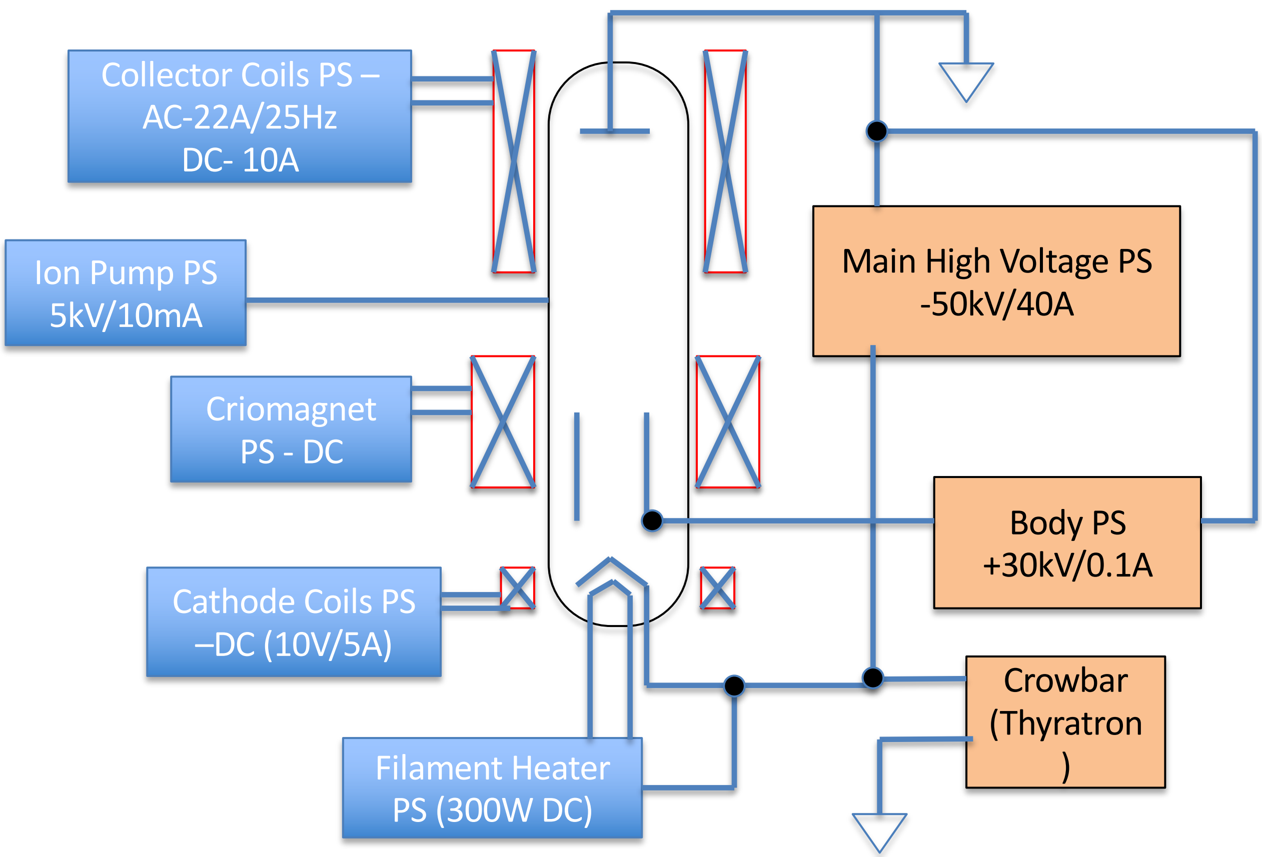






The stray field is generate by:
Plasma Current + Poloidal coils + Central Solenoid
neighbour gyrotrons

Gyrotron Auxiliaries



Characteristic of HVPS for Gyrotron

High stability: ±0.2%

Fast voltage ramp: ~ 1 ms

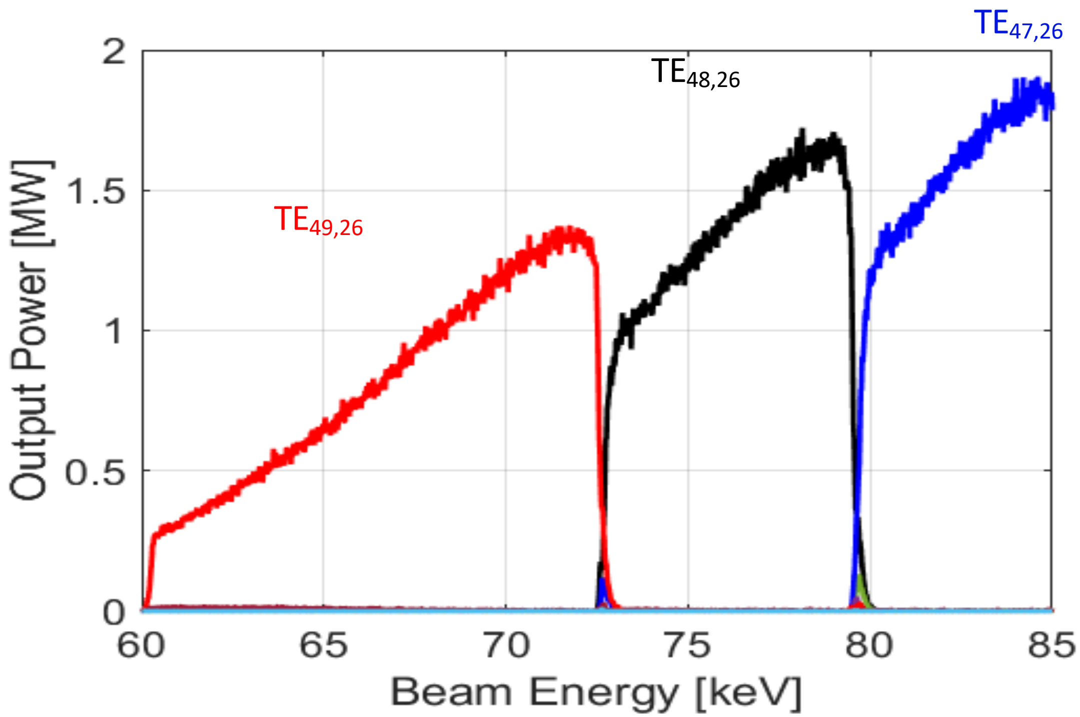
Fast protection time: 5-10 μs (max energy in the fault = 10J)

Up to 5 KHz full modulation (for MHD control)

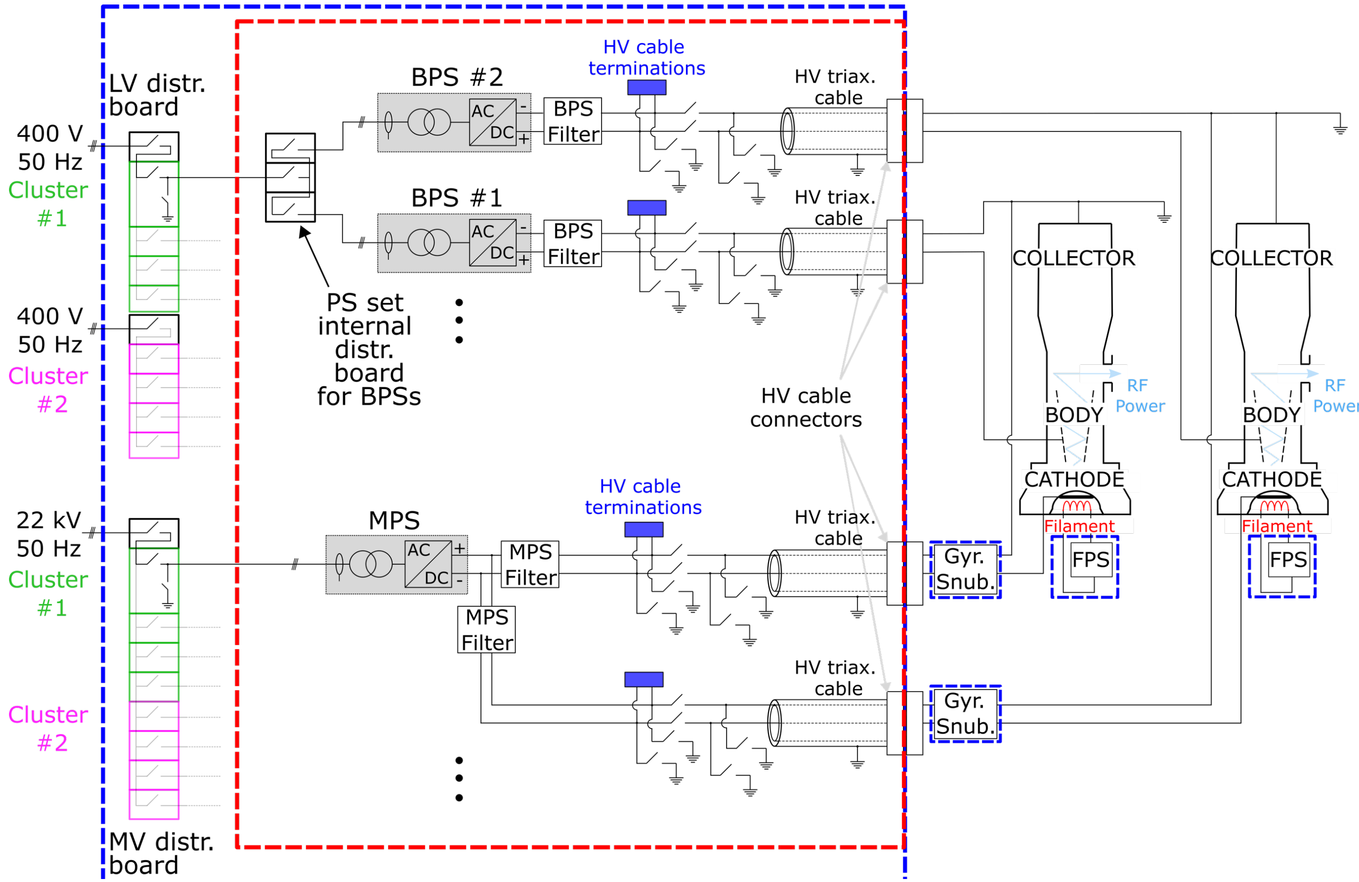
Short distance between PS and gyrotron (low parasitic capacity)

Stabilization using Body PS in feedback on the whole accelerating voltage (Vc+Vb).

Fast Rise time avoid competitive mode oscillation



The HV Power Supplies for CPD Gyrotron



Several IGBT Modules
Digitally controlled
Feed by a multi-secondary transformer

Objective of a Transmission System

To transmit the power with the lower losses

To assure safe and stable operation for the source

To measure the delivered power

To control polarization

To match the delivered power with the plasma

To guarantee a friendly and effective control by operator

Main Transmission Lines Type

Wave guide: metallic structure (cylindrical or rectangular) capable to transmit power at long distance with reduced attenuation

Mirrors: the microwave wavelengths allow a quasi-optical approach. The RF field can be treated as an electromagnetic wave. A set of focussing mirrors can be used to transmit power.

Overview of High Power Transmission Line

Closed system: over-moded waveguide

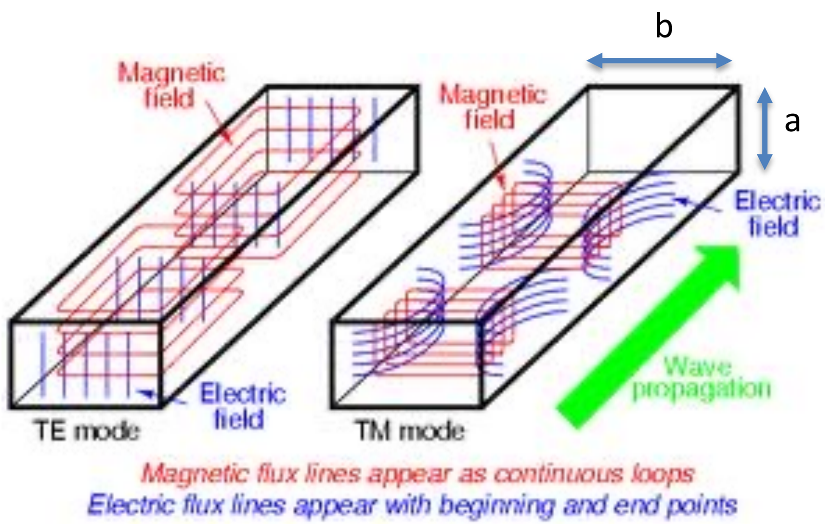
ITER (evacuated)
AUG (in air)
TCV (evacuated)
FTU (in air)
WEST (evacuated)
DIII-D (evacuated)

Open system: quasi-optical approach using reflecting mirror:

W7-X (in air)
DTT (evacuated)
DEMO (evacuated)

Wave Guide concept

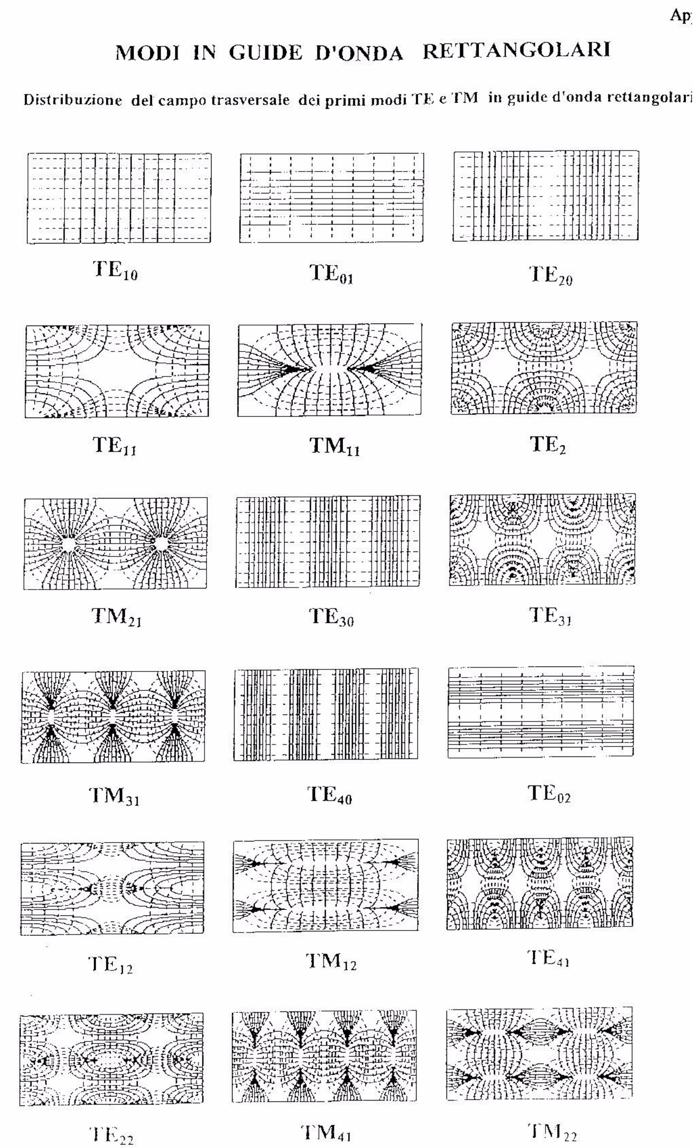
Propagation of e.m filed is sustained by induced current in the metallic wall of the waveguide.



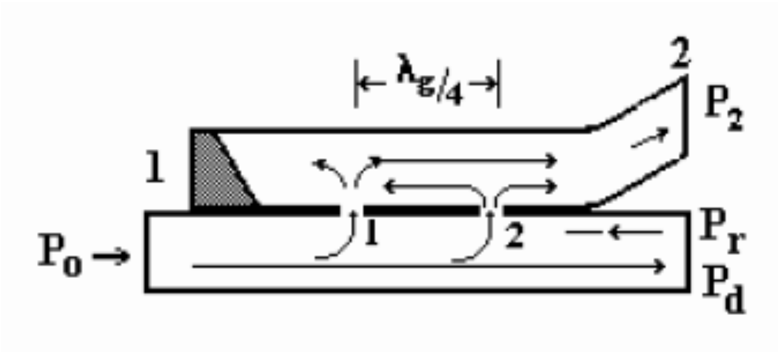
The propagating mode is based on the solution of the telegraphist equation, which is a combination of Bessel functions.

$$\lambda_c = \frac{2}{\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}}$$

For a given dimension (a,b) a cut-off lambda is defined: only waves with lower lambda can propagate or being excited



Directional Coupler



This is used to pick-up part of the wave travelling in a wave guide.

It is used to measure forward (and reflected) power

The power is transmitted across a series of holes at a distance of $\lambda_g/4$.

The power depends on the holes dimension, the coupled wave maintain the propagation direction.

It can be used ONLY in a mono-modal waveguide.

The circular over-mode WG

Transmission of high power requires enough power handling.

In **dry air** the break down electric field is **15 kV/cm**, from the mode choice and the power delivered is possible to fix the minimum i.d. of the waveguide:

$$P = E_{max}^2 1.99 \cdot 10^{-3} a^2 \frac{\lambda}{\lambda_g}$$

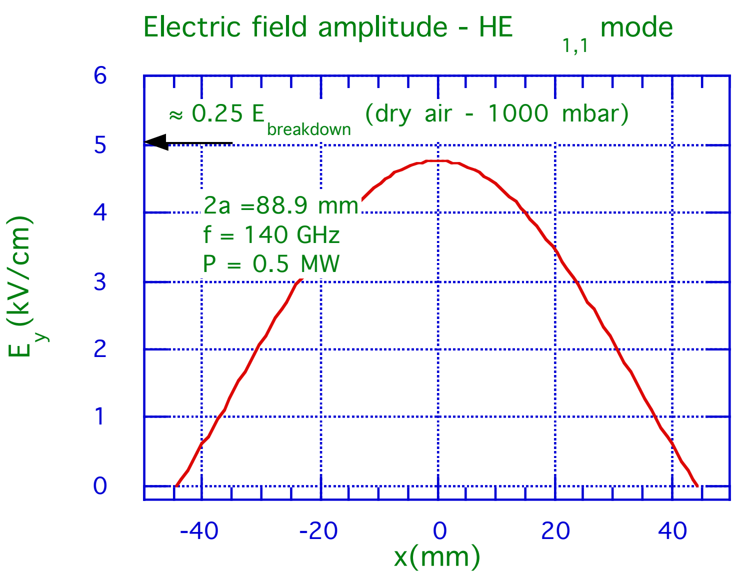
TE1,1 in circular wg

For P = 1MW

E_{max} = 7 kV/cm (in case of reflection at mitre bend)

which requires a diameter of ~ 10 cm

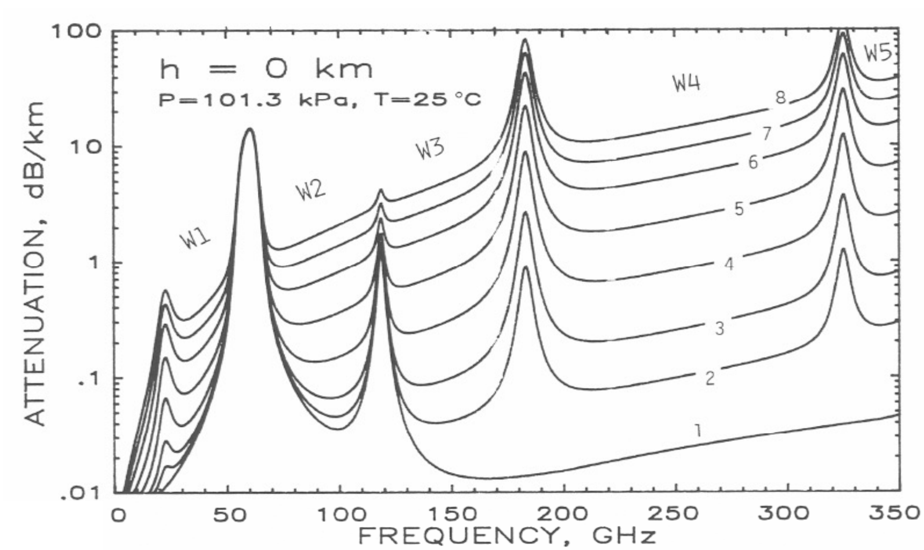
HE1,1 in corrugated over-mode wg



Transmission in air problems

1- Breakdown: transmission of high power wave is limited by air break down that gives a limit to the electric field

2- Losses: the air can absorb high frequencies (losses) depending on humidity, as a consequence it is necessary to cool down the heated.



Propagation in Vacuum reduces the risk of arc (only on metallic surfaces) and eliminates the air losses.

To keep under vacuum a transmission line required a specific design and additional cost.

Under vacuum lines exhibits less problem with the RF leakage

Corrugated waveguide

Consiglio Nazionale delle Ricerche

A small corrugation on the wall of the wg produces a non zero impedance along wg axis (z), in this way a so called **hybrid modes** can propagate (combination of TE_{0N} and TM_{0N}).

When the wg i.d. 2a >> λ > p (period of corrugation) the wg wall begin to look like a surface with an anisotropic reactance:

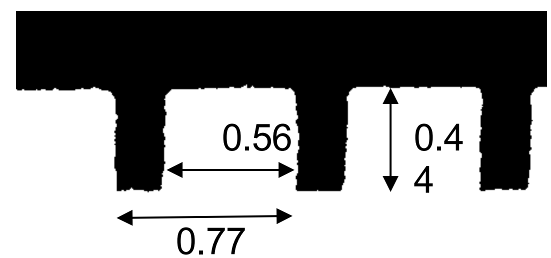
$$Z_\phi = \left.\frac{E_\phi}{H_z}\right|_a = 0$$

$$Z_z = -\left.\frac{E_z}{H_\phi}\right|_a \cong jZZ_0$$

$$Z = \frac{w}{p}\tan(kd)$$

$$Z_0 = \sqrt{\mu_0/\varepsilon_0}$$

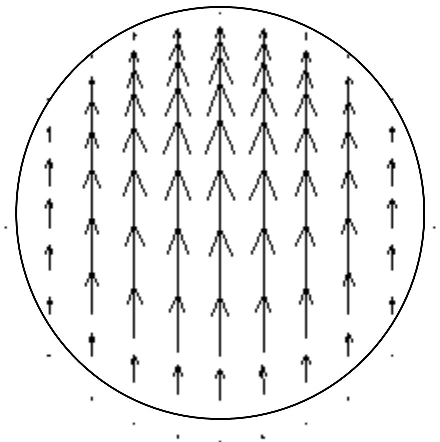
Internal diameter 88.9 mm



Detail of the wg wall section for ECRH-FTU TL system at 140 GHz

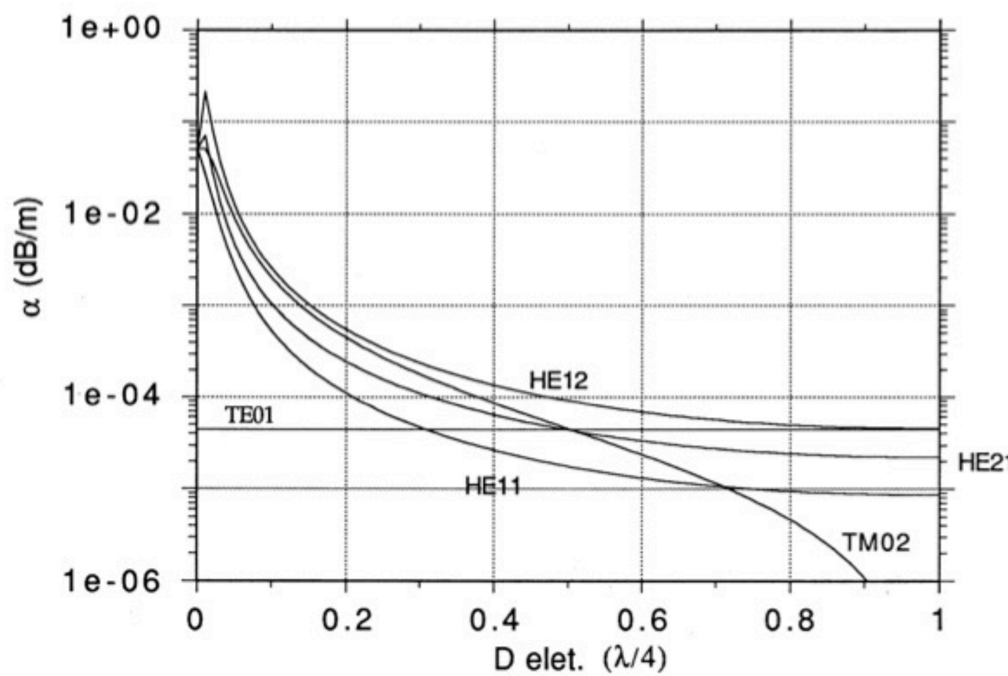
Attenuation of Hybrid Mode

The different attenuation can be exploited as modal filtering



HE11

Attenuation vs corrugation depth

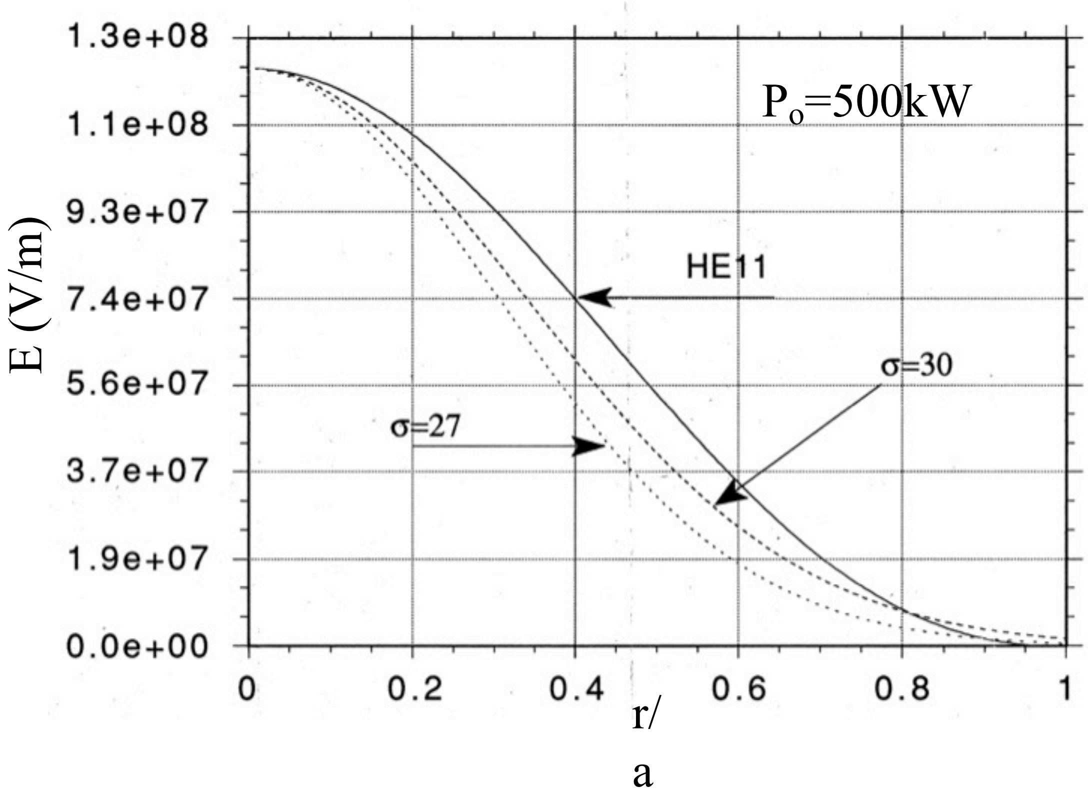


HE11 is the basic mode chosen in fusion application:
It has a **low attenuation** , it is **linearly polarized** and propagate in free space as a **gaussian** mode (TEM00)

The electric field is close to zero at the wall, with consequent low ohmic attenuation

Hybrid Mode Field Profile vs Gaussian mode

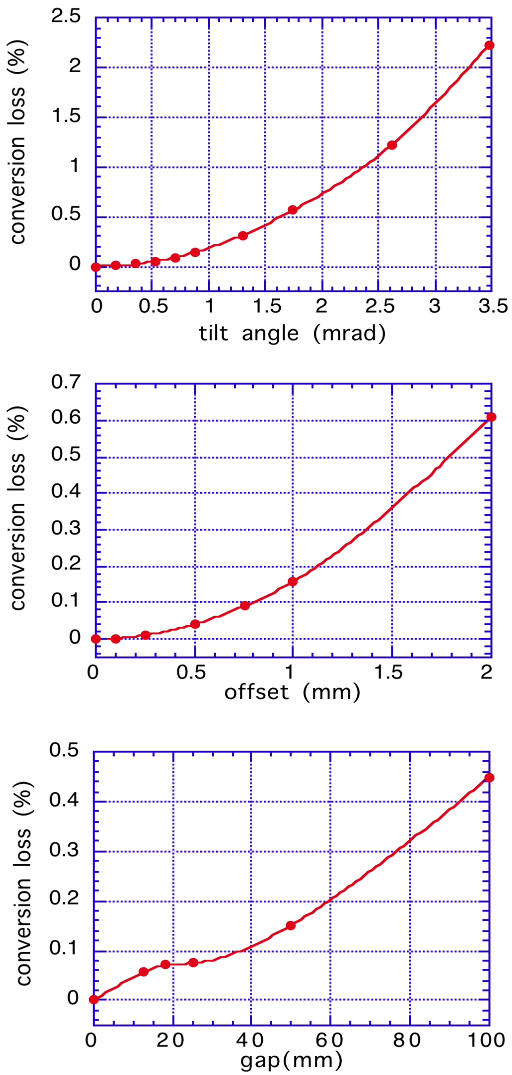
Comparison with Gaussian Distribution (TEM00) with different waist (σ in mm for a = 44.45 mm)



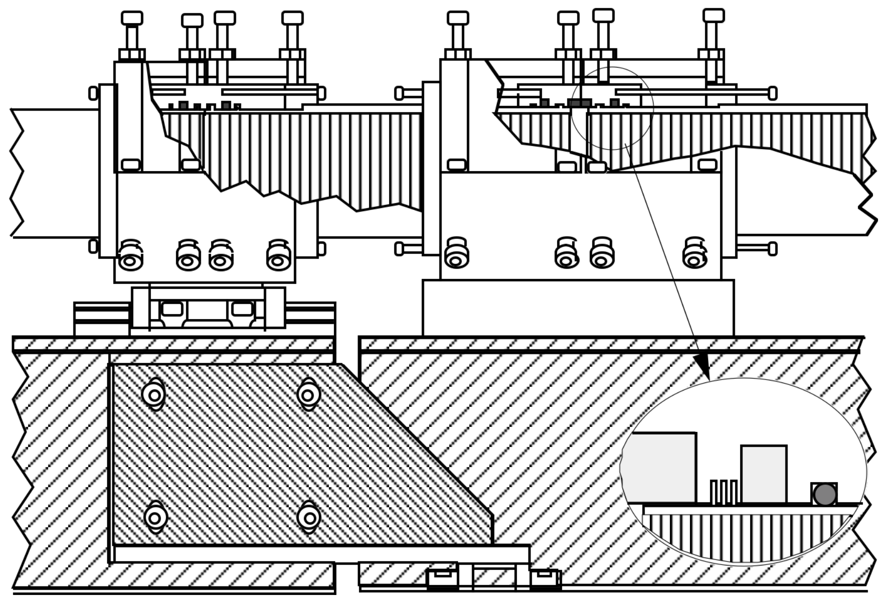
In the conversion from TEM00 to HE11 and vice versa the 2.5% of power is lost

Alignment Issues

Conversion Losses due to alignment errors



Errors (tilt and/or offset) produce conversion to high order modes.
These modes are absorbed by wg requiring a larger cooling or a local increase of electric field (arc risk) .



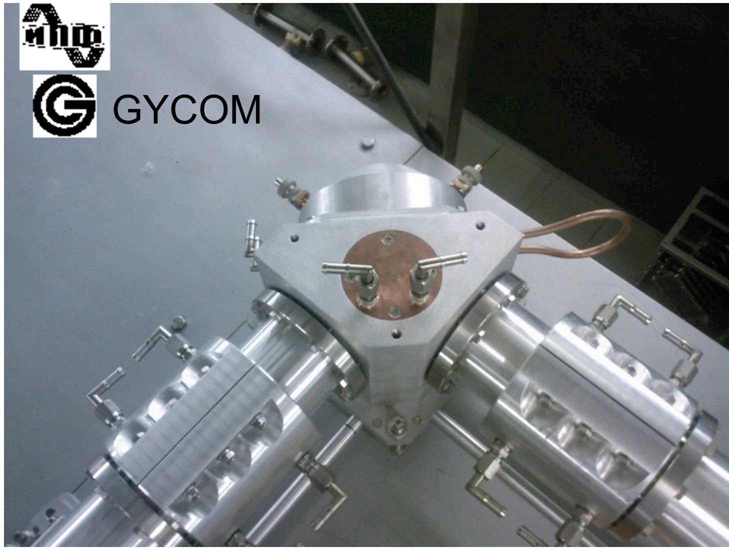
Expansion Joint for FTU ECH system

Mitre bend as directional coupler

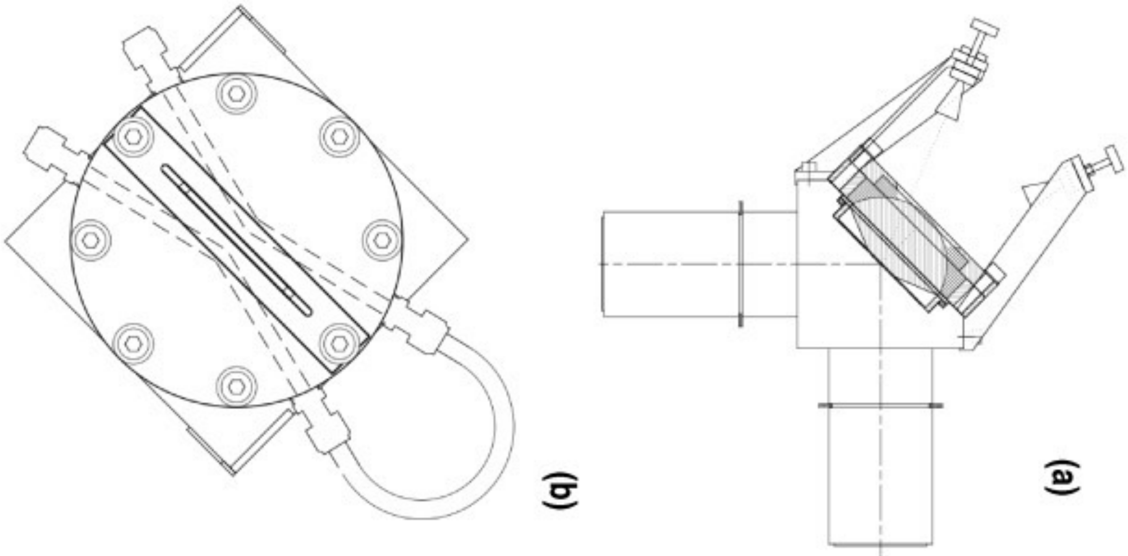
Consiglio Nazionale delle Ricerche

In a over modal corrugated wg the change in direction can be done by reflection on flat mirror of the wave propagating after a open-ended wg.

The losses depends on the length of the gap and on the frequency (+ ohmic one on the mirror)

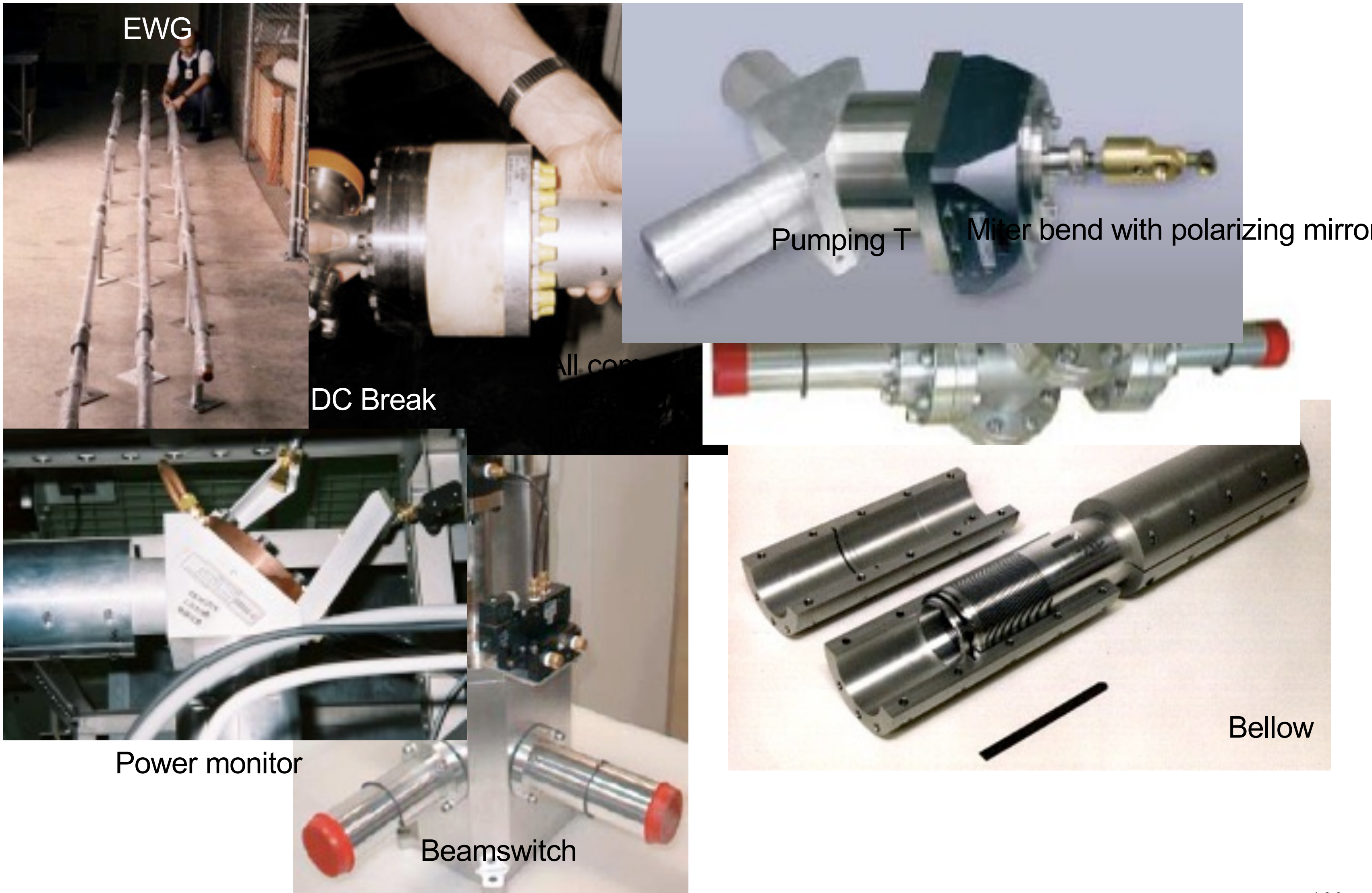


GYCOM 170 GHz mitre bend and clamps for wg cooling



All the component of a cw transmission line must be cooled

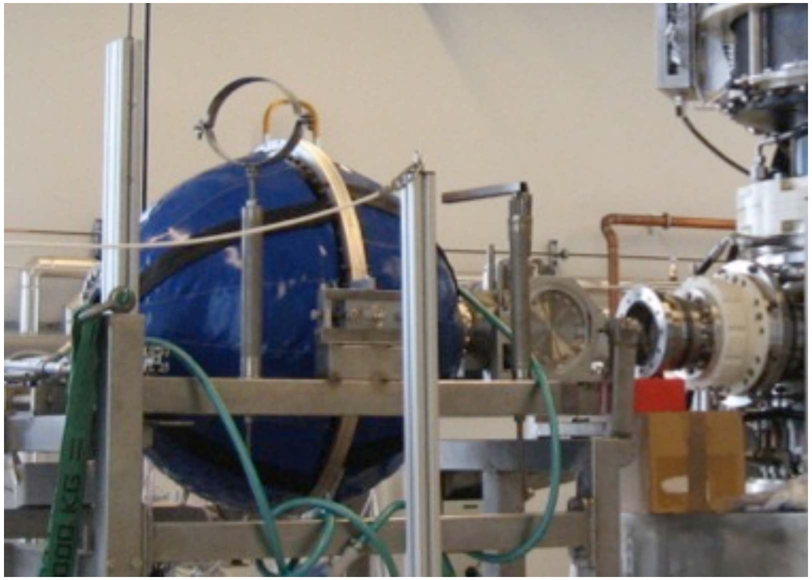
WG evacuated components (GA)



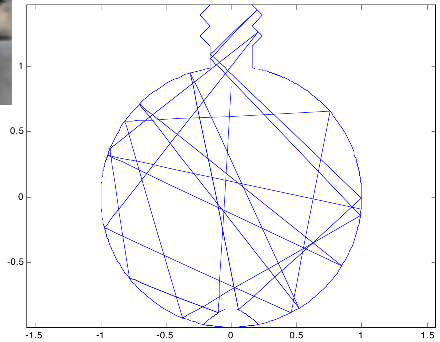
RF loads

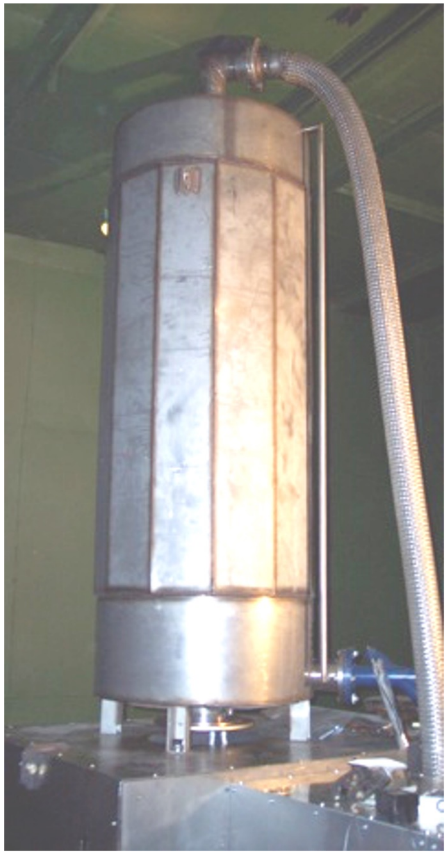
The Gyrotron power must be directed on a **dummy load** during commissioning test or **conditioning**.

The load must have a low reflection (<4%) and the possibility to measure (bolometer) the absorbed power.



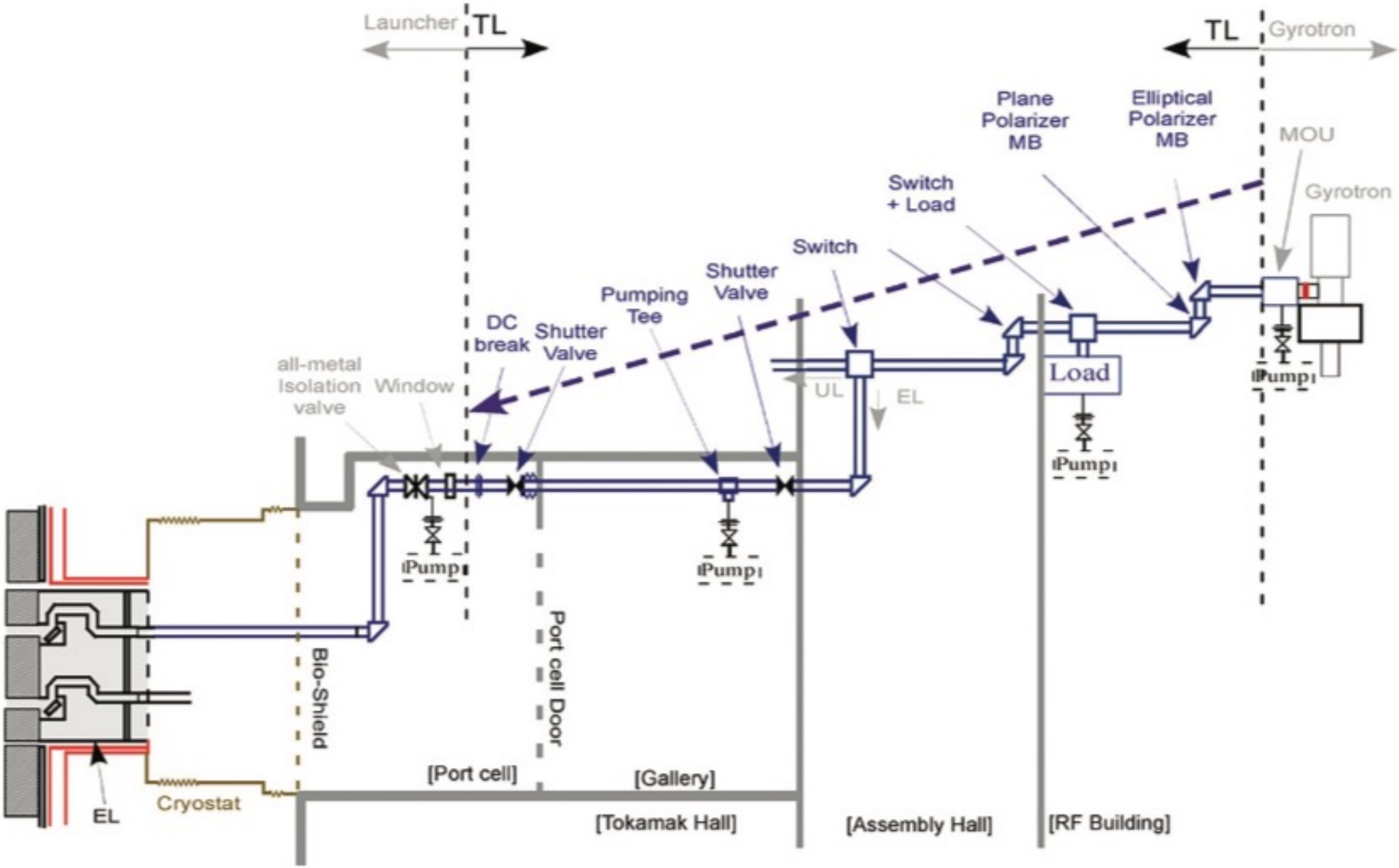
The sphere for FTU and 2MW EU project.





Gycom 2006 version load. 1MW cw in air

ITER TL - ECWG



Launcher
TL
TL
Gyrotron
Plane Polarizer MB
Elliptical Polarizer MB
MOU
Gyrotron
Switch + Load
Switch
Shutter Valve
Pumping Tee
DC break
Shutter Valve
all-metal Isolation valve
Window
UL
EL
Load
Pump
Pump
Pump
Pump
Bio-Shield
Port cell Door
[Port cell]
[Gallery]
EL
Cryostat
[Tokamak Hall]
[Assembly Hall]
[RF Building]

The Quasi Optical Approach

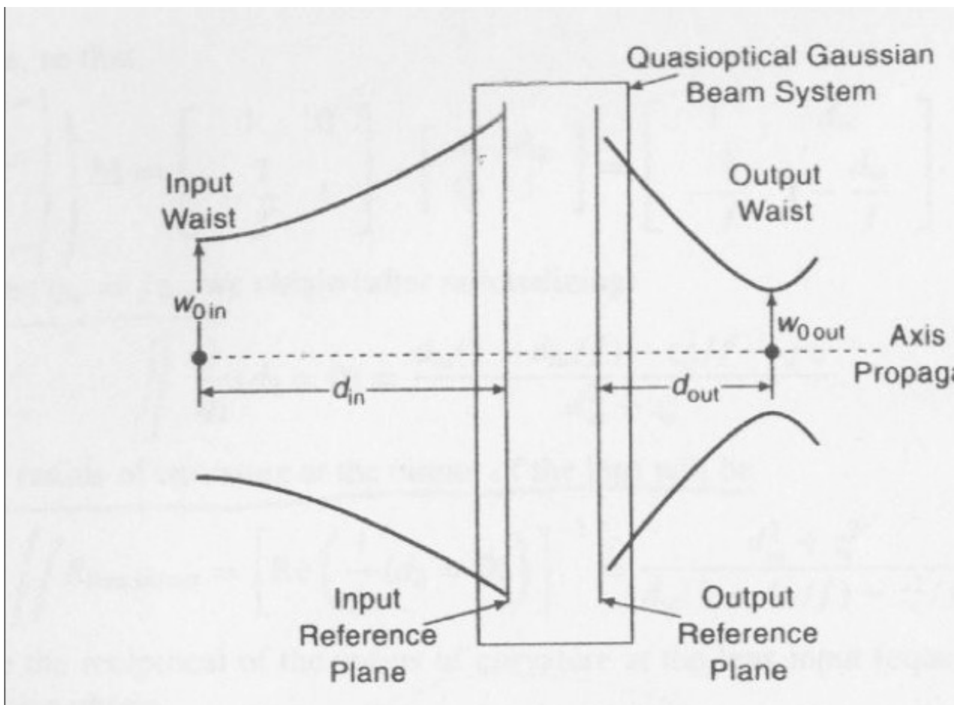
Considering wavelength (mm) the microwave beam can be approached using the optics propagation equations.

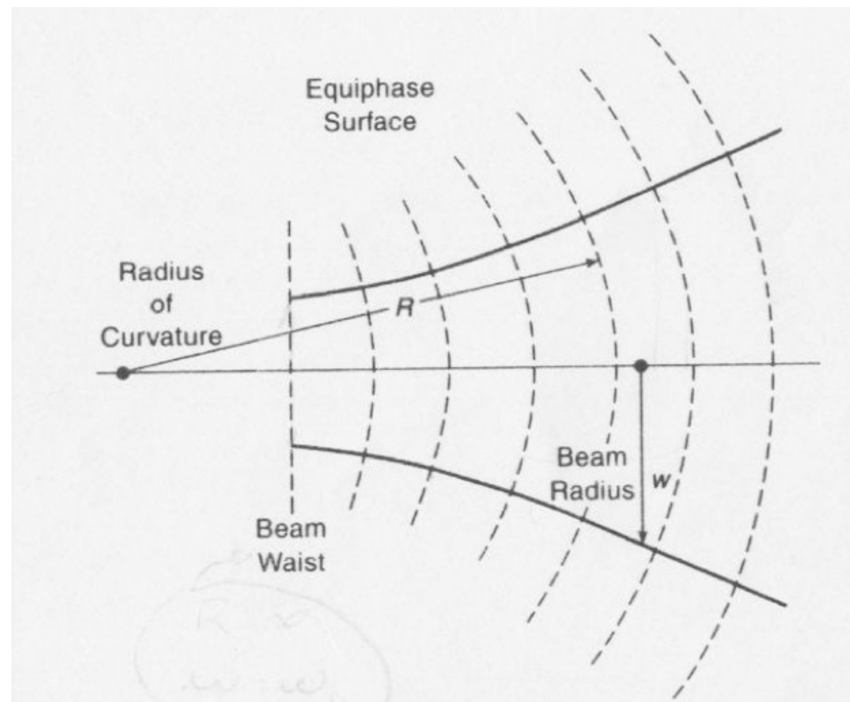
Beam diameter

$$w(z) = w_0\left[1+\left(\frac{\lambda z}{\pi w_0^2}\right)\right]^{1/2}$$

Curvature of phase front

$$R(z) = z\left[1+\left(\frac{\pi w_0^2}{\lambda z}\right)\right]$$





W7-X Q.O. Transmission Line

The power is reflected by large mirrors from the gyrotron output (MOU) to the vessel window.

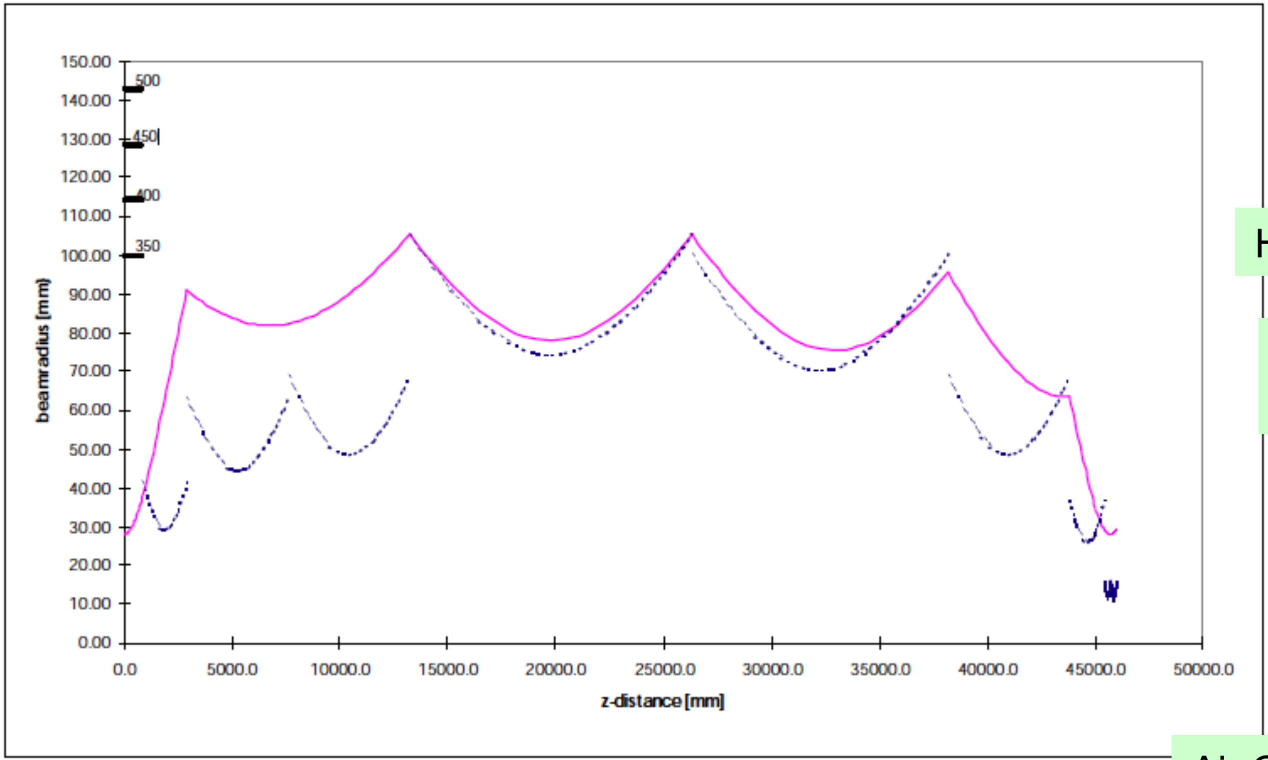
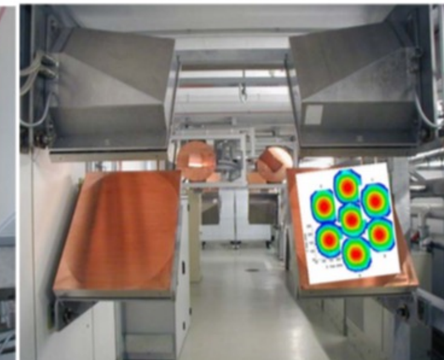


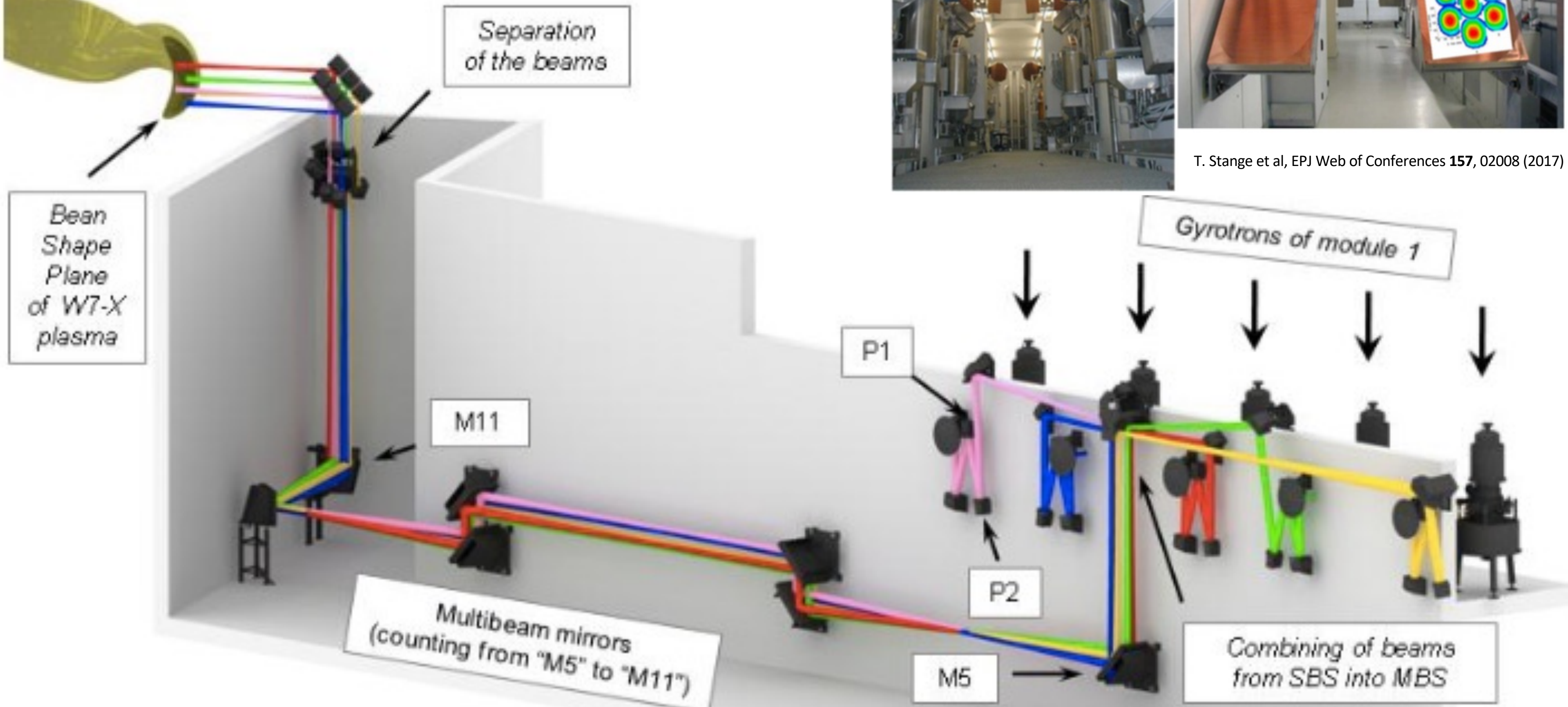
figure 5. Beam radius (1/e E-field radius) along the Q.O. section of the line

- Mirrors dimension ~ 4 w
- High frequency-> less divergence
- Only Ohmic losses (~0.25% per reflection)
- Multi beam capability
- Low mode conversion
- Air Conditioning (to dry and to cool)

W7-X Transmission Line



T. Stange et al, EPJ Web of Conferences **157**, 02008 (2017)



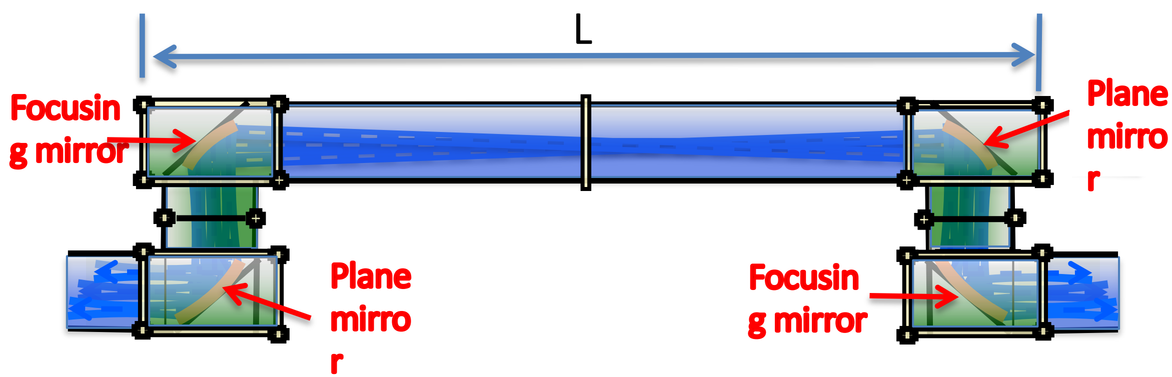
Evacuated Multibeam TL

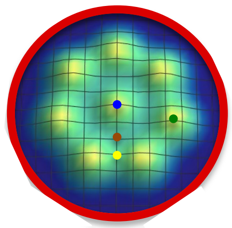
Concept for Multibeam Evacuated QO Transmission Line

Main DEMO TL requirements:

- **Efficiency target: 90%**
- **Power handling: >1MW CW per line**
- **Multi-frequency (or broadband)**
- **Tritium compatible**
- **Large number of beams to be transmitted**

The most promising and simple TL considered is a Quasi Optical Multi Beam Evacuated TL

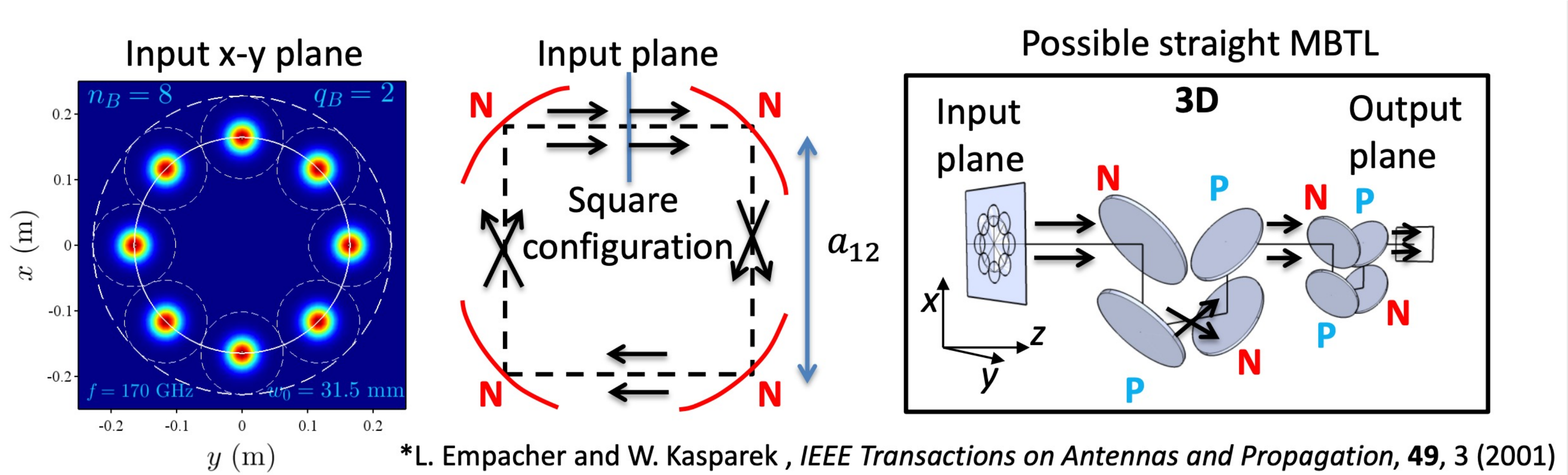




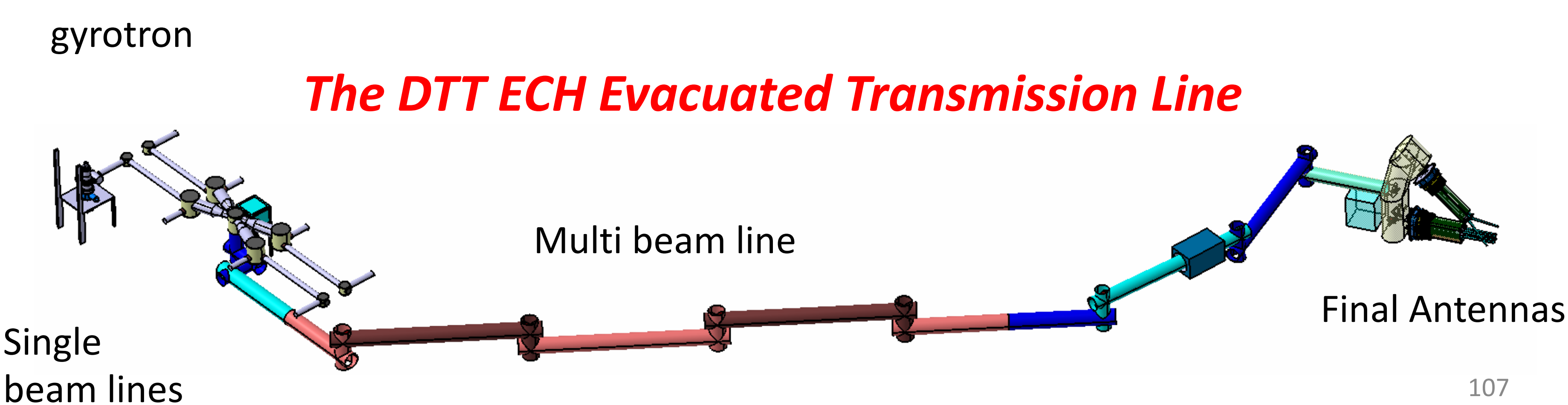
8 beams for each TL with a distance between Focussing units at *L*= 8-10 m ➔ mirror dimension: 0.6 – 0.8 m

The confocal concept for QO TL

The arrangement with 4 non-plana mirrors allows to produce at the output the same image at the input, this is valid also in case of including 4 planar mirrors.



*L. Empacher and W. Kasparek , *IEEE Transactions on Antennas and Propagation*, **49**, 3 (2001)

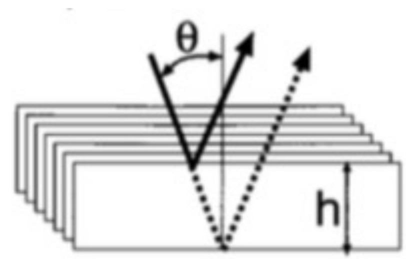


Polarization Control

The linear polarization from the gyrotron must be rotated in order to launch the proper direction with respect the B_T pitch angle. **It is necessary for ECCD.**

Oblique injection requires further rotation in order to compensate the XM or OM components originated by inappropriate angle.

The polarizer are based on corrugated mirrors.



Polarizer Concept

The component $E_{//}$ (with respect to corrugation) is reflected at the bottom

The component $E_{\perp}$ is reflected at the top

A phase shift of $2h/\lambda$ of $E_{//}$ respect to the $E_{\perp}$ (reflected at the top).

This produces a rotation of the electric field.

Using a $\lambda/4$ corrugation depth only linear rotation can be obtained, with $\lambda/8$ one a circular component is introduced to obtain elliptical polarization to be used in case of oblique injection.

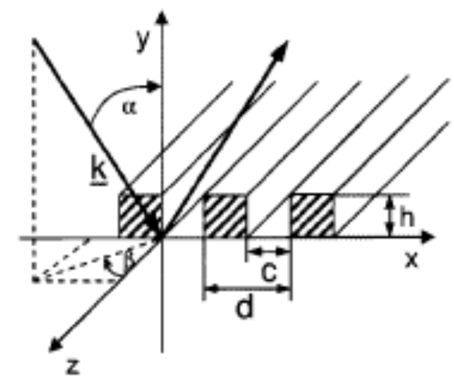
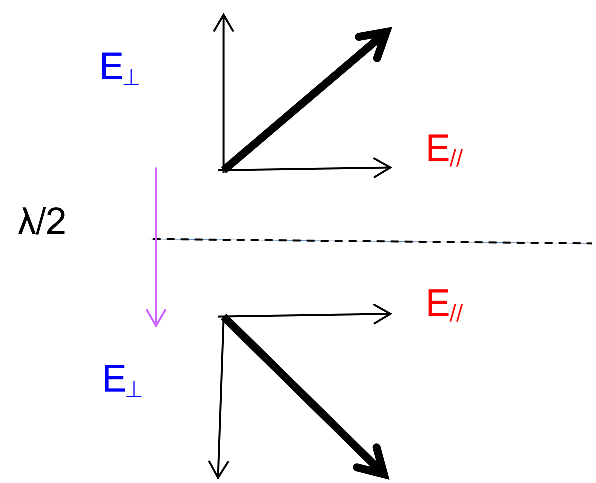
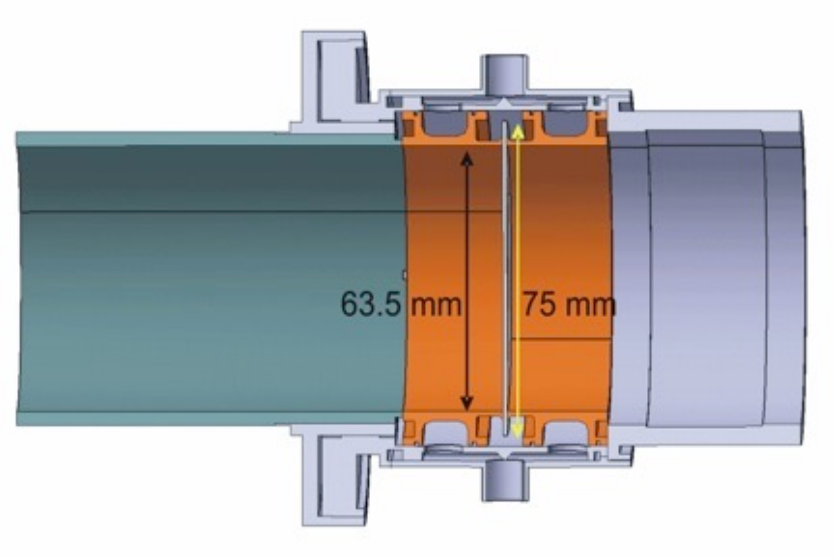


Fig.1 Polarizer corrugation.



The ITER Diamond window



Diamond disk Diameter: 75 mm
Thickness: 1.11 mm

Loss measurements at 170 GHz:

tg δ_{eff}= 0.9 x 10^{-5} (central area)

T. A. Scherer et all 5th IAEA TM
18-20/Feb. 2009 Gandhinagar, India

Launcher

The simpler launcher

At the end of the transmission line the power must be coupled to the plasma. The TL must be connected to an **ANTENNA**. In the EC wave case the antenna becames a **LAUNCHER**, being the frequency so high that the wave can be thought as propagating light beam.

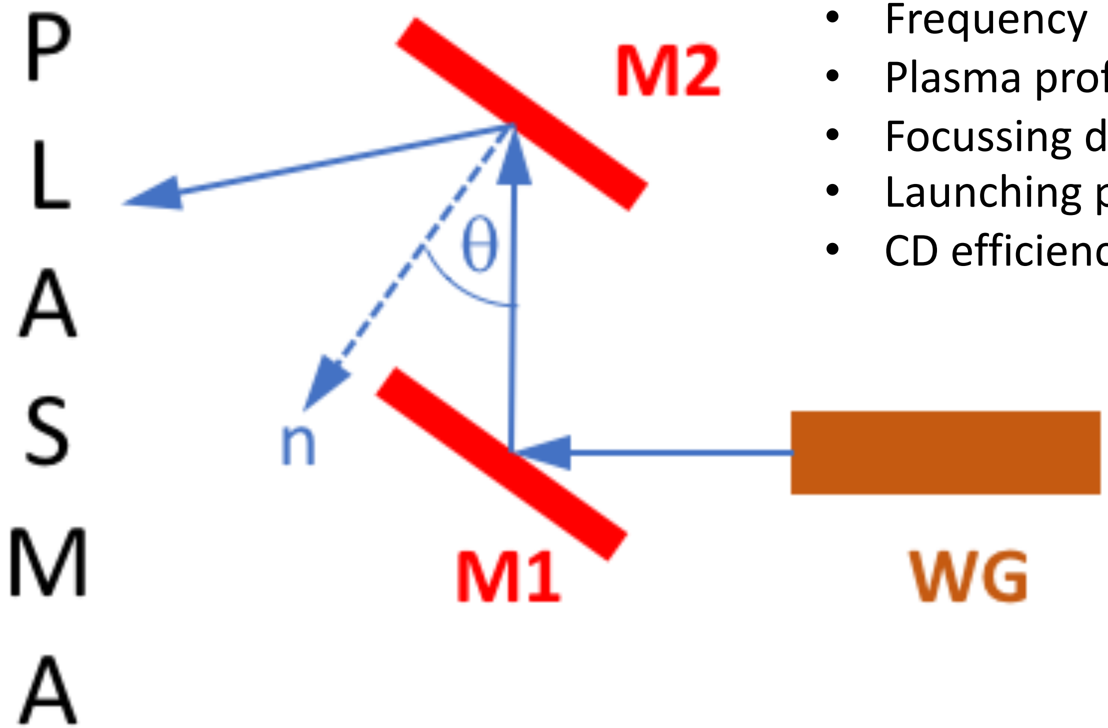
A truncated waveguide propagating the delivered mode (TE0,1 or HE1,1) was the main launching antenna used in the pioneering experiments.

The divergence of the beam can be reduced increasing the wg diameter and the frequency.

This simple launcher is enough for **heating** experiments but not usable for ECCD and MHD control.

The front steering concept

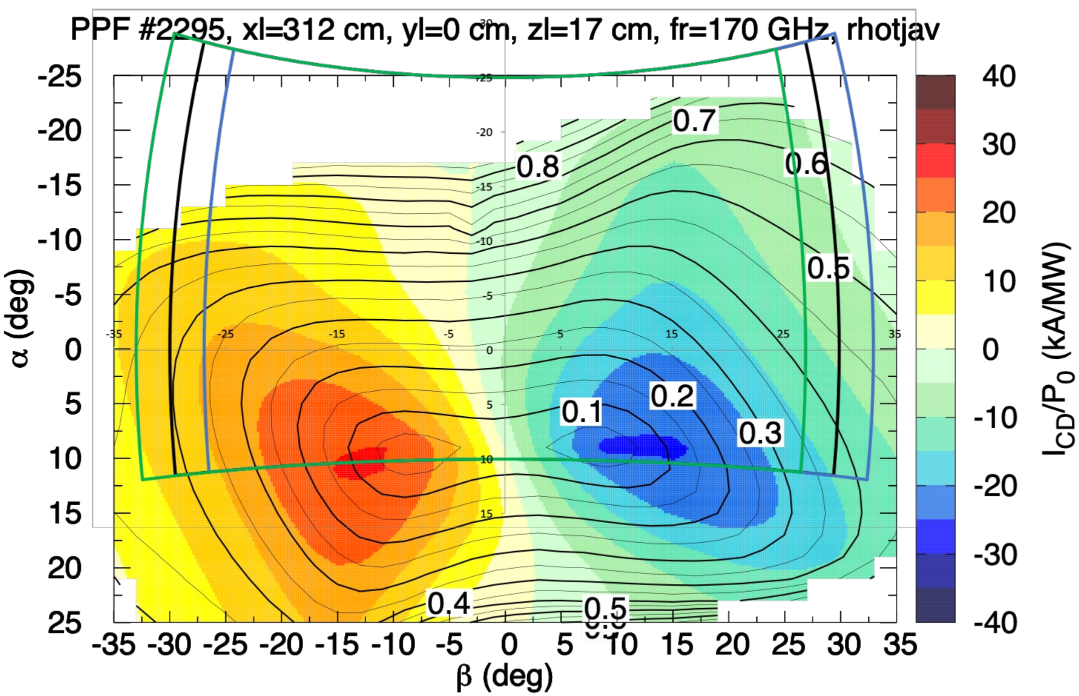
The most popular launcher is a Open Ended Wave Guide, at which is added a mirror to focus and steer the EC beam in plasma



The optics characteristics depend on:

- Frequency
- Plasma profiles
- Focussing distance (q surfaces position)
- Launching points
- CD efficiency required

Steering requirements



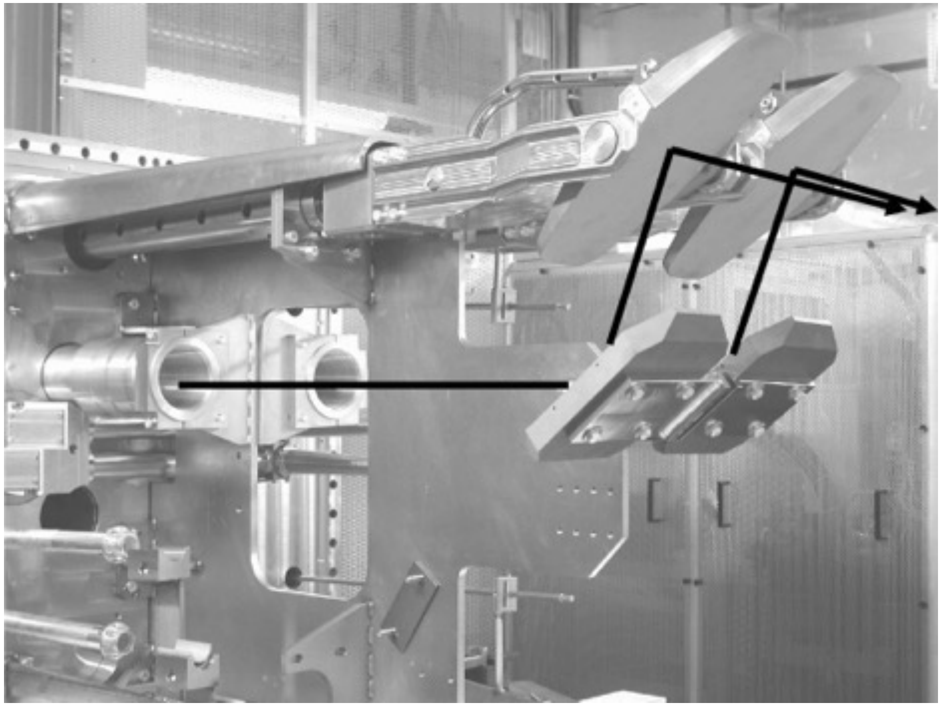
Present steering range for top modules of port 3

To fix the requirements for the steering ranges of the movable mirror a beam tracing map is usually generated.

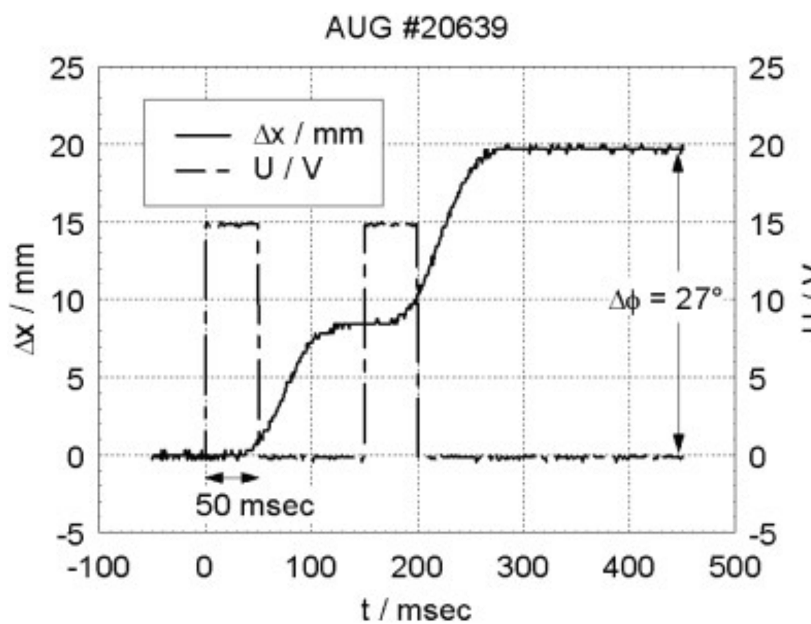
The CD efficiency is calculated as a function of launching angles, and the best range is defined starting form the requirements of the EC system.

GRAY code applied to DTT

Front Steering AUG launcher

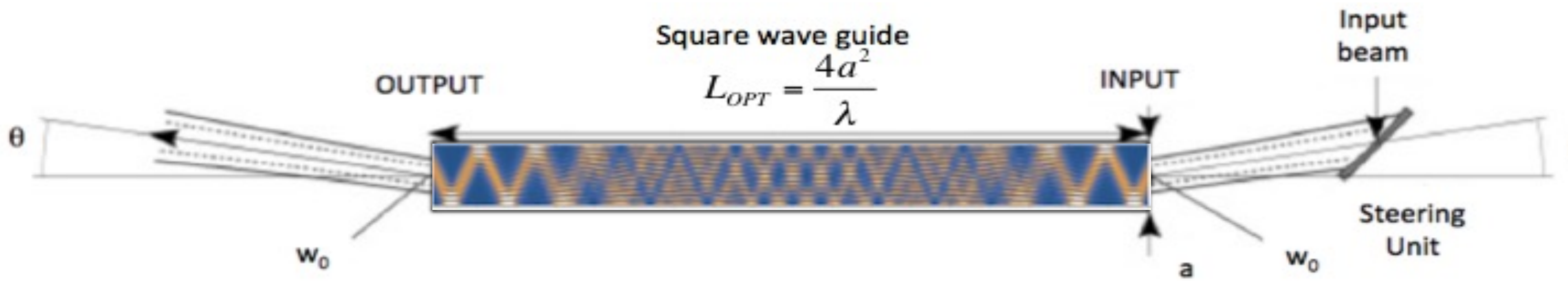


Movable mirrors in front of the plasma to steer the beam in the desired point

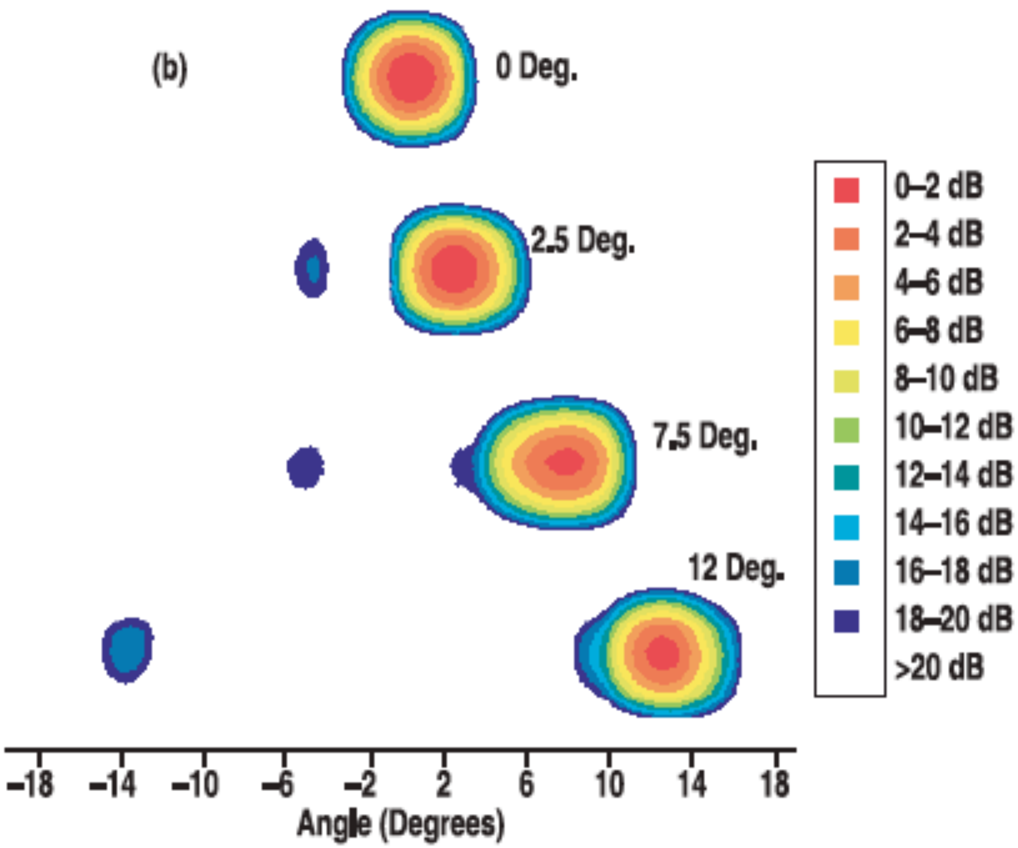


Real time mirrors steering (settling time ~ 100 ms)

The remote steering concept



In a corrugated square waveguide the beam propagates decomposed in different modes that recombine after an integer number of coherent distances

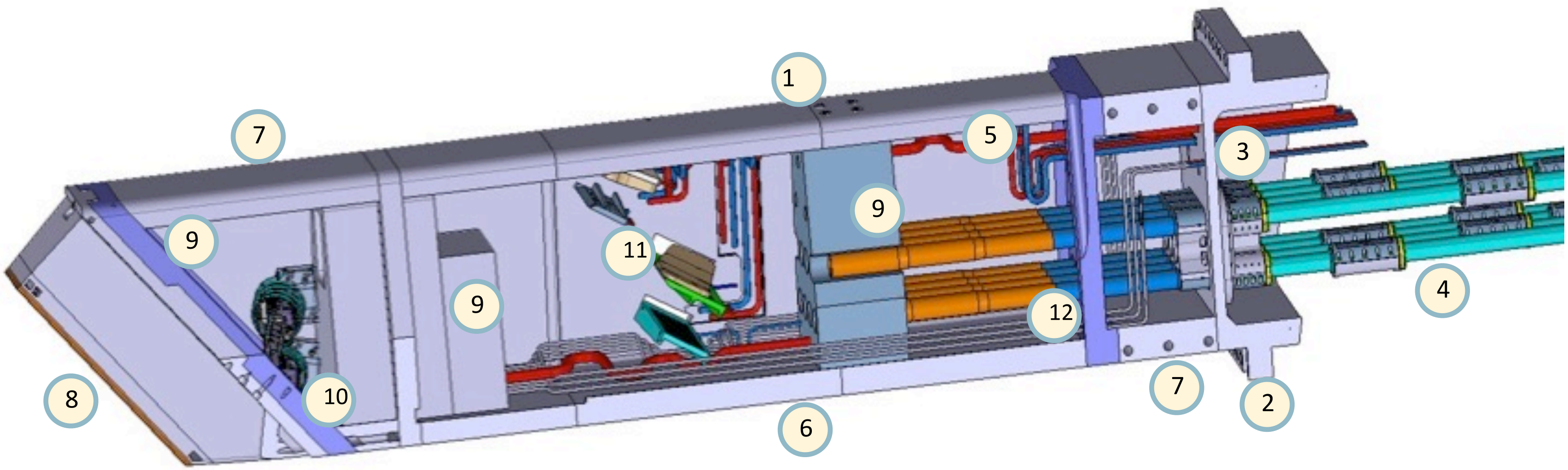


Experimental Output pattern
Good but not enough oblique angle

ITER EC Upper Launcher

Primary Role

- Stabilize MHD activity (Sawtooth and NTM), requiring narrow peaked deposition profile (Deposition width ~4cm)



- Overall port plug length ≈ 6m
- Rear flange width ≈ 1.3m
- Wall thickness mid section = 90mm
- Total weight ≈ 18t (no water)
- Internal layout designed to allow guided and free propagation of 8 mm-wave beams

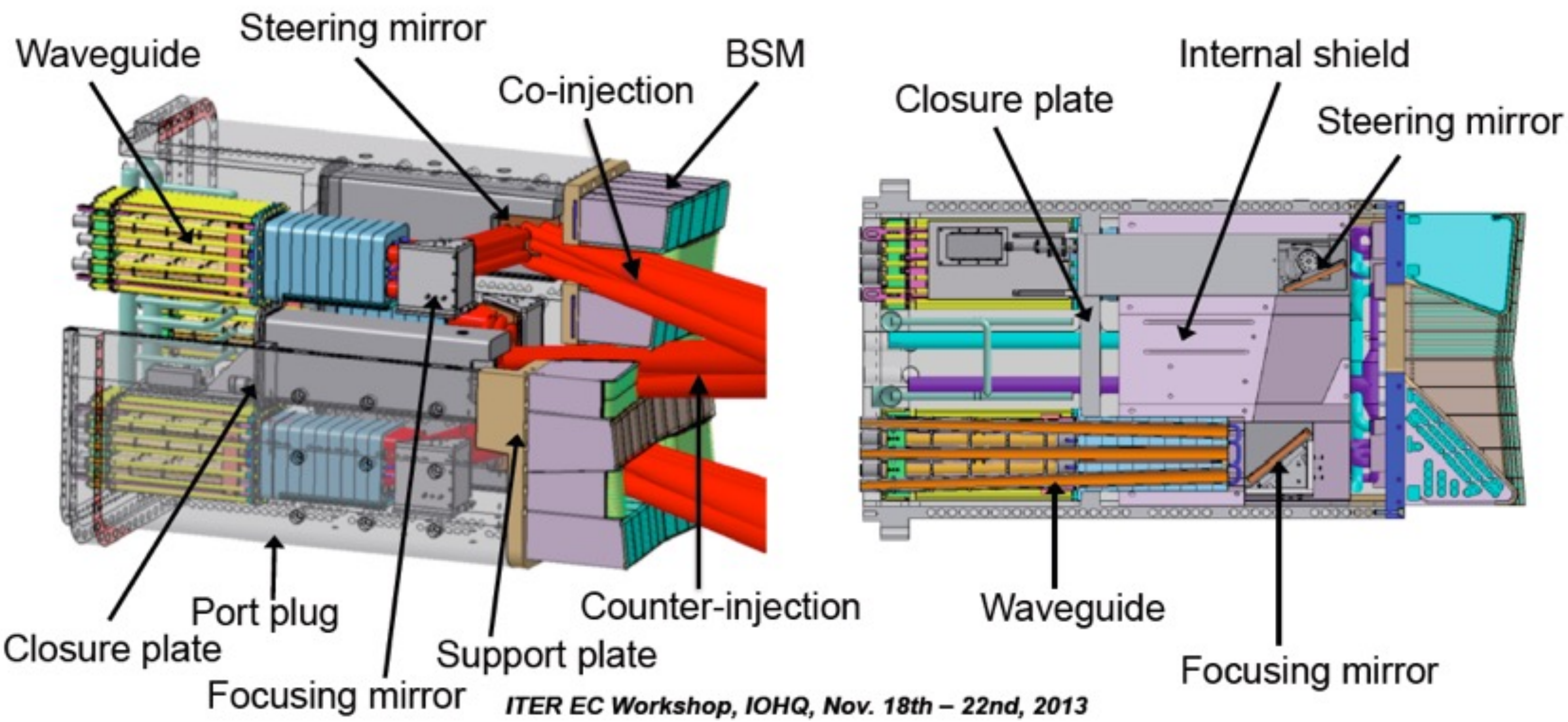
UL components:

1. *Port plug body*
2. *Rear flange*
3. *Closure plate and feedthroughs*
4. *Ex-vessel waveguide assembly*
5. *Services (cooling, gas, etc.)*
6. *Single wall structure*
7. *Double wall structure*
8. *BSM and first wall*
9. *Neutron shield*
10. *Steering mechanisms*
11. *Fixed mirrors*
12. *In-vessel waveguides*

ITER EC Equatorial Launcher

Primary Role

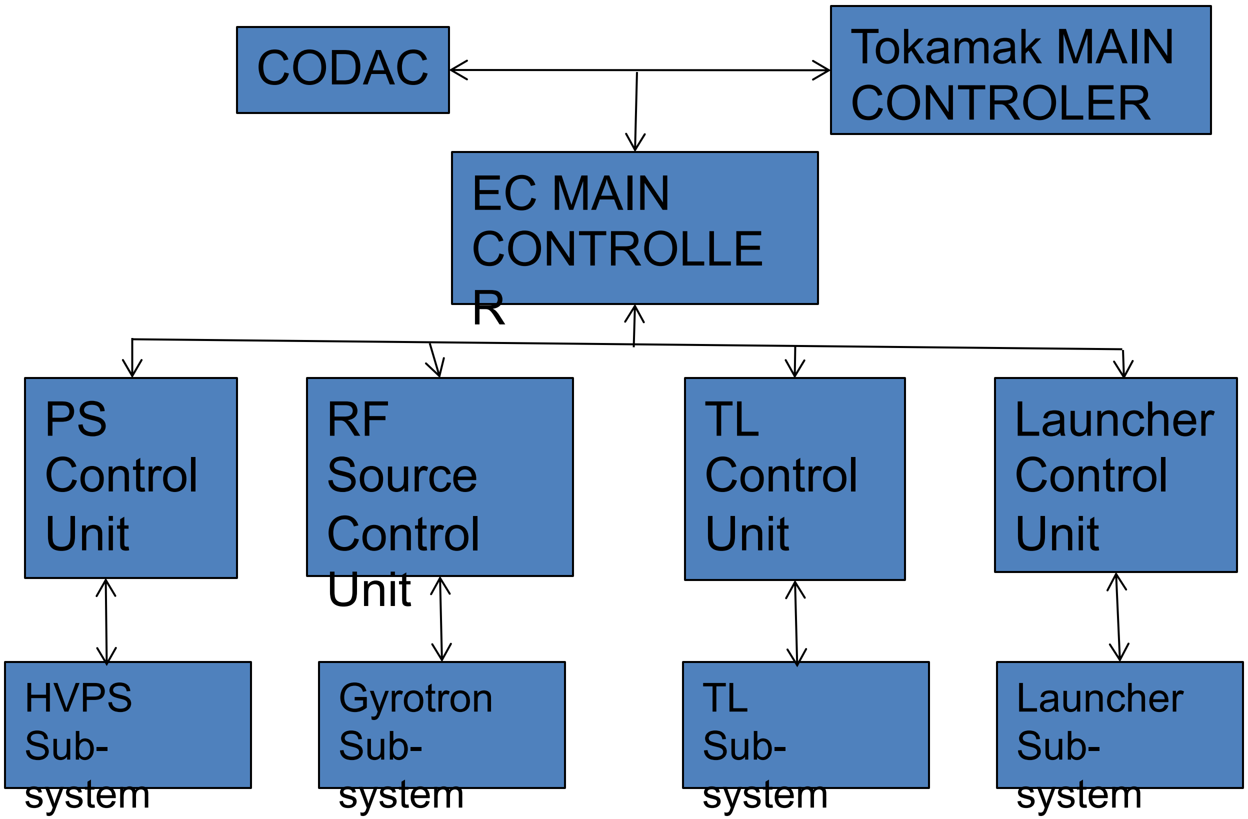
- Central Heating and current drive
- Impurity control
- Breakdown and Burn through
- Current profile tailoring



Note that beams now steer in poloidal direction

Control System

The control system



The EC control system

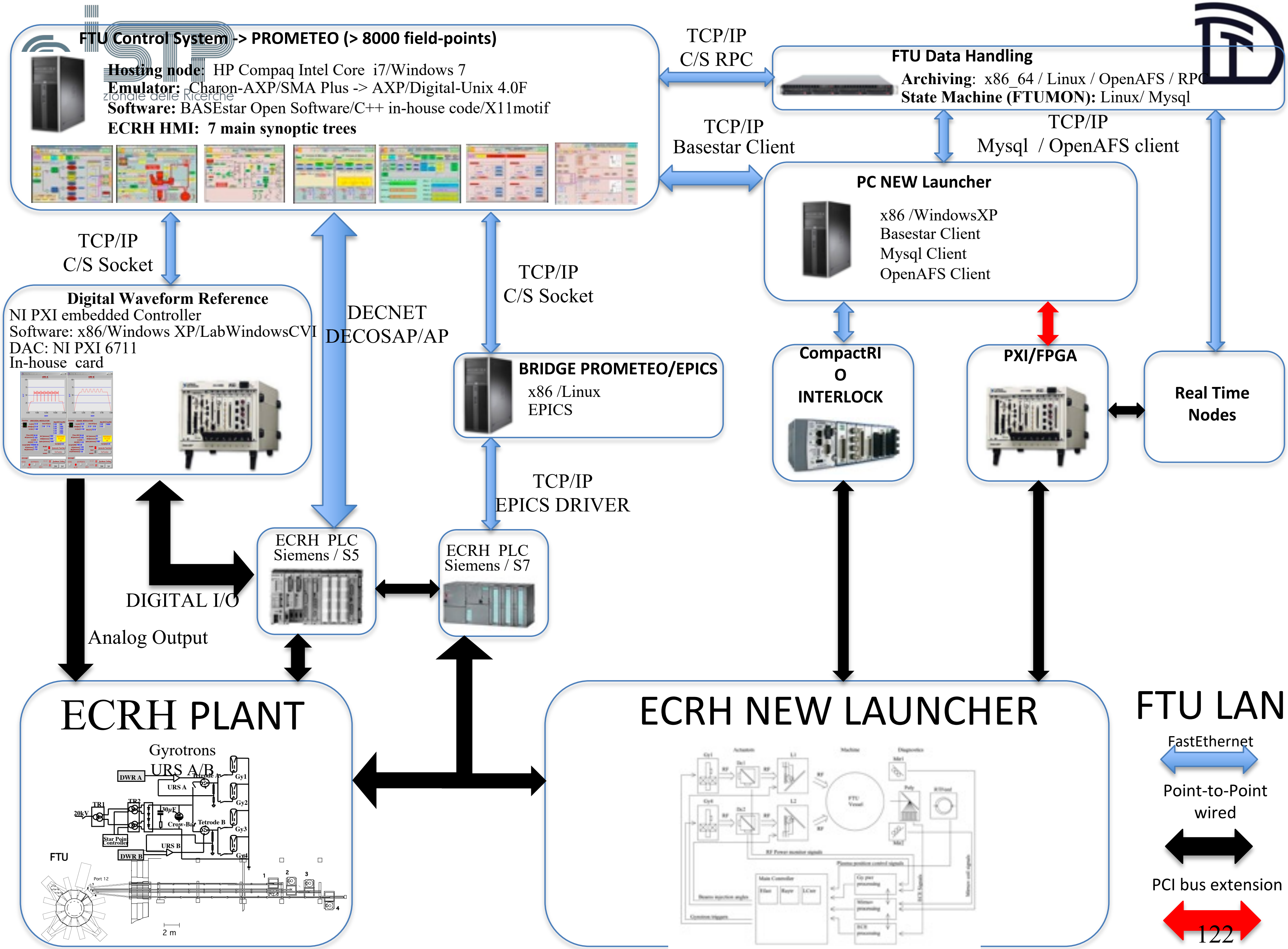
Four different levels of control system:

Fast control: t<1ms
- Fast Sequence Control
- Protection system
- Real Time Control

Local plant control: t ~ 100ms
- PLC

Field to field connections:
- for higher level of safety: t ~ 10ms

Main controller for human interface t ~ 1s
- mimic, sequence control:


FTU Control System -> PROMETEO (> 8000 field-points)
Hosting node: HP Compaq Intel Core i7/Windows 7
Emulator: Charon-AXP/SMA Plus -> AXP/Digital-Unix 4.0F
Software: BASEstar Open Software/C++ in-house code/X11motif
ECRH HMI: 7 main synoptic trees
TCP/IP
C/S RPC
FTU Data Handling
Archiving: x86_64 / Linux / OpenAFS / RPC
State Machine (FTUMON): Linux/ Mysql
TCP/IP
Basestar Client
TCP/IP
Mysql / OpenAFS client
PC NEW Launcher
x86 /WindowsXP
Basestar Client
Mysql Client
OpenAFS Client
TCP/IP
C/S Socket
Digital Waveform Reference
NI PXI embedded Controller
Software: x86/Windows XP/LabWindowsCVI
DAC: NI PXI 6711
In-house card
DECNET
DECOSAP/AP
TCP/IP
C/S Socket
BRIDGE PROMETEO/EPICS
x86 /Linux
EPICS
CompactRI
O
INTERLOCK
PXI/FPGA
Real Time
Nodes
TCP/IP
EPICS DRIVER
ECRH PLC
Siemens / S5
ECRH PLC
Siemens / S7
DIGITAL I/O
Analog Output
ECRH PLANT
Gyrotrons
URS A/B
DWR A
URS A
Tetrode A
Gy1
Gy2
20kV
TR1
TR2
30μF
Crow-Bar
Tetrode B
Gy3
Star Point
Controller
URS B
DWR B
Gy4
FTU
2 m
ECRH NEW LAUNCHER
FTU LAN
FastEthernet
Point-to-Point
wired
PCI bus extension

Final Remarks

EC Systems is nowadays the most promising Heating System for future reactor:

- No component close to plasma
- Remote power generation
- Simple transmission of the power
- Interaction plasma-wave well known
- Modular approach