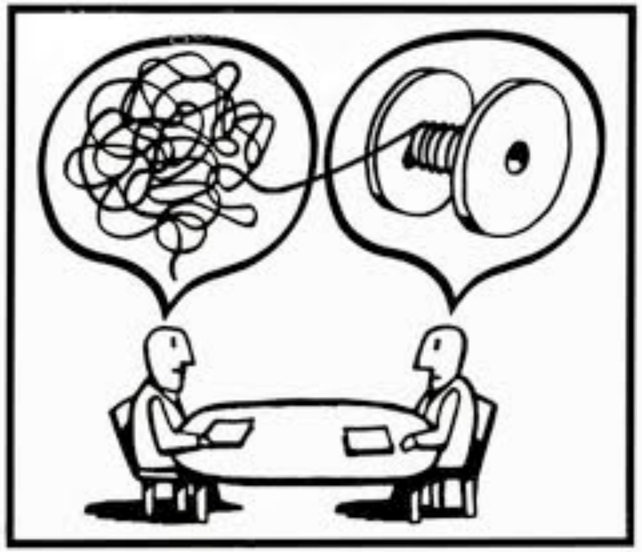
The Physics and Technology of RF Heating and Current Drive in Fusion Plasmas

J.-M. Noterdaeme

with input from

many colleagues



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Why?

Why do we use those heating and current drive methods we use?

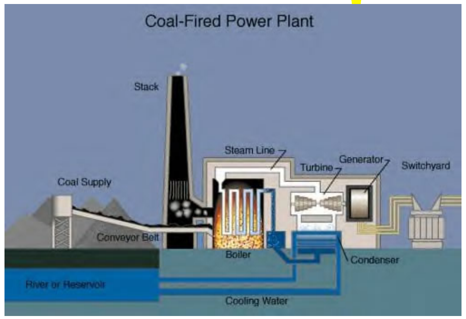
Because only for those are we able to:

1. **Generate the power: transformation**
2. **Transport it to the plasma**
3. **Transport it inside of the plasma**
4. **Have it absorbed inside of the plasma: transformation**

Requirements, an example

Transformation | **Transportation** | **Transformation**

Outside → **Inside**



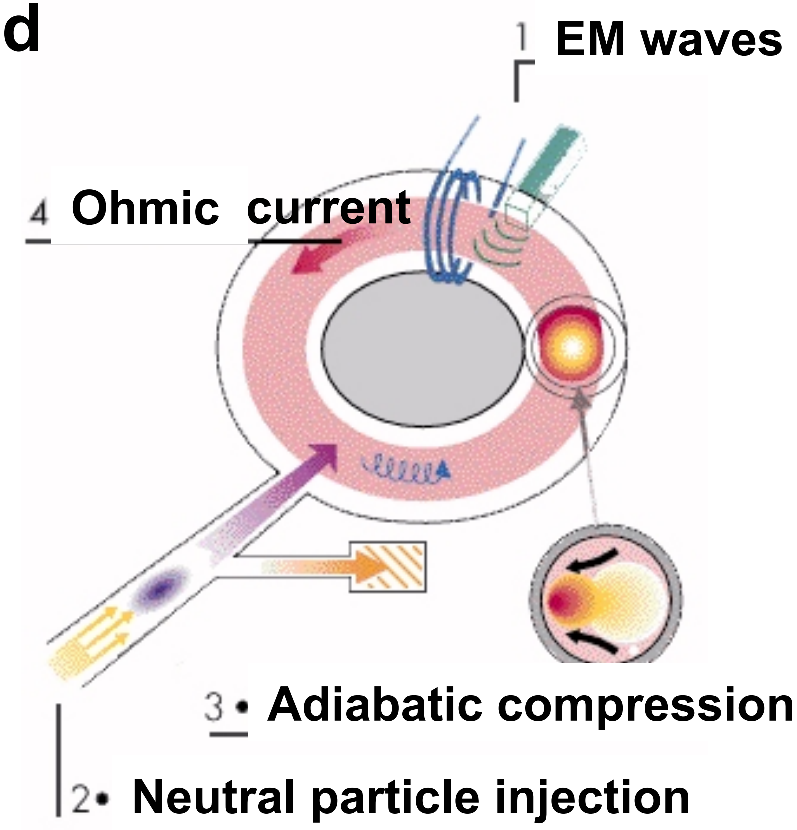
Possible Heating methods

depend on the confinement method

- Ohmic current
- Compression
- Neutral beam injection
- EM Wave (EC, LH, IC, …)

- Laser beam
- Charged particle beam
- Kinetic energy
- Magnetic energy

- Self-heating (alpha particles)



Particles
Electromagnetic

Other uses of the "heating" methods

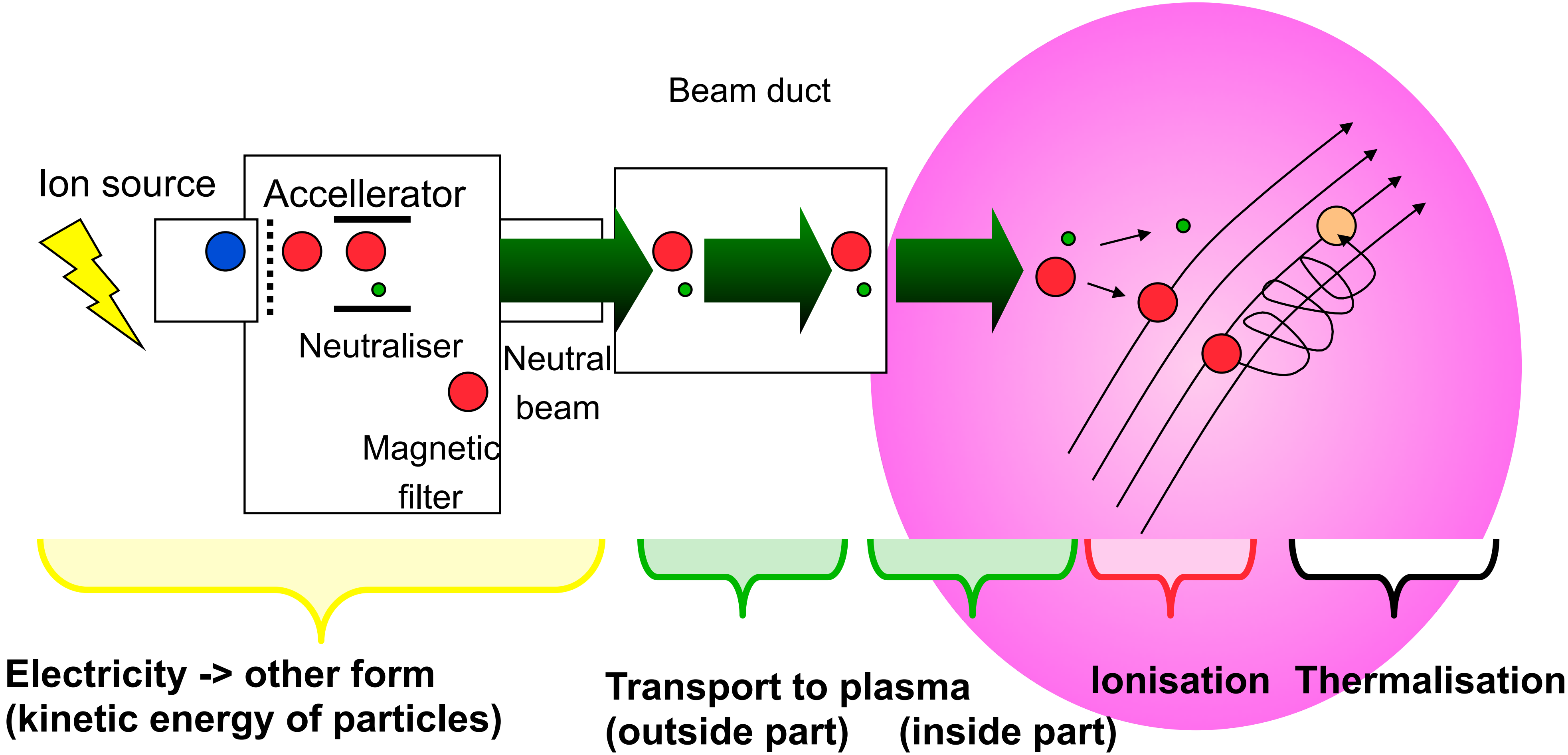
- "Heating" methods, but not just for heating

  and current drive
  - Bulk current
  - Localised current

- Depending on the method, also used for

  - Control
  - Fuelling
  - Inducing Rotation
  - Transport of fast particles
  - Diagnostics

Neutral Beam Injection: principle

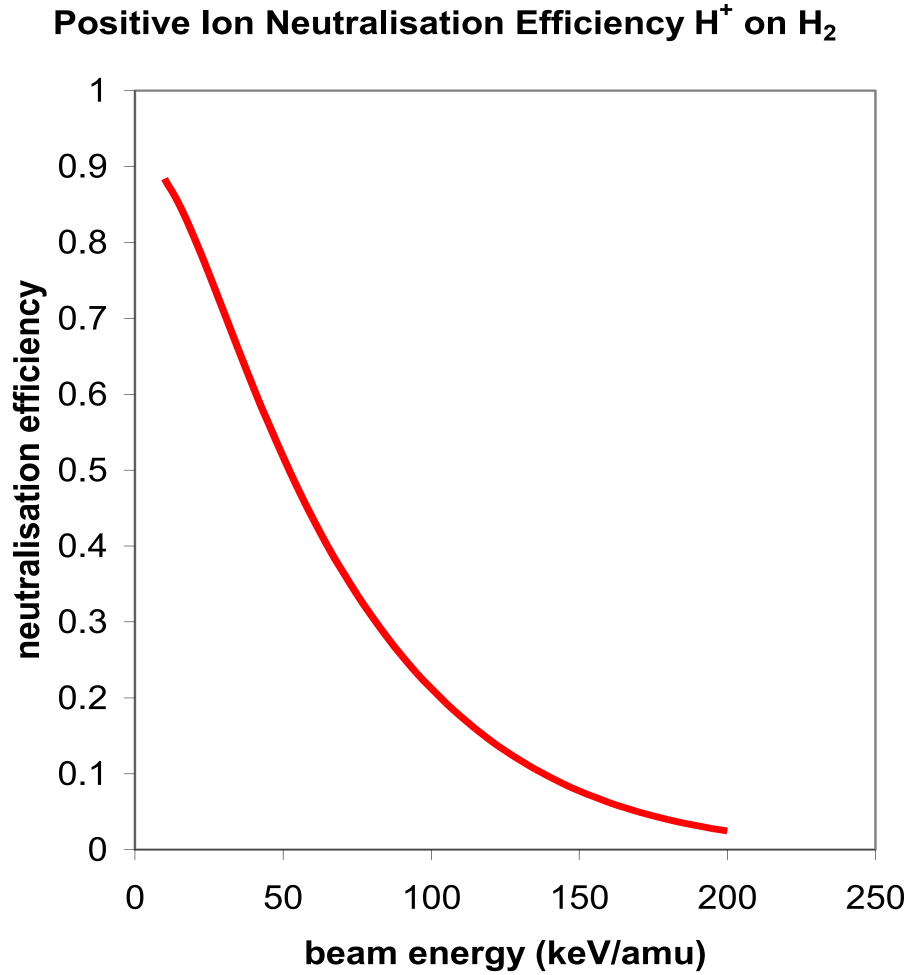


Problem: transport in the plasma

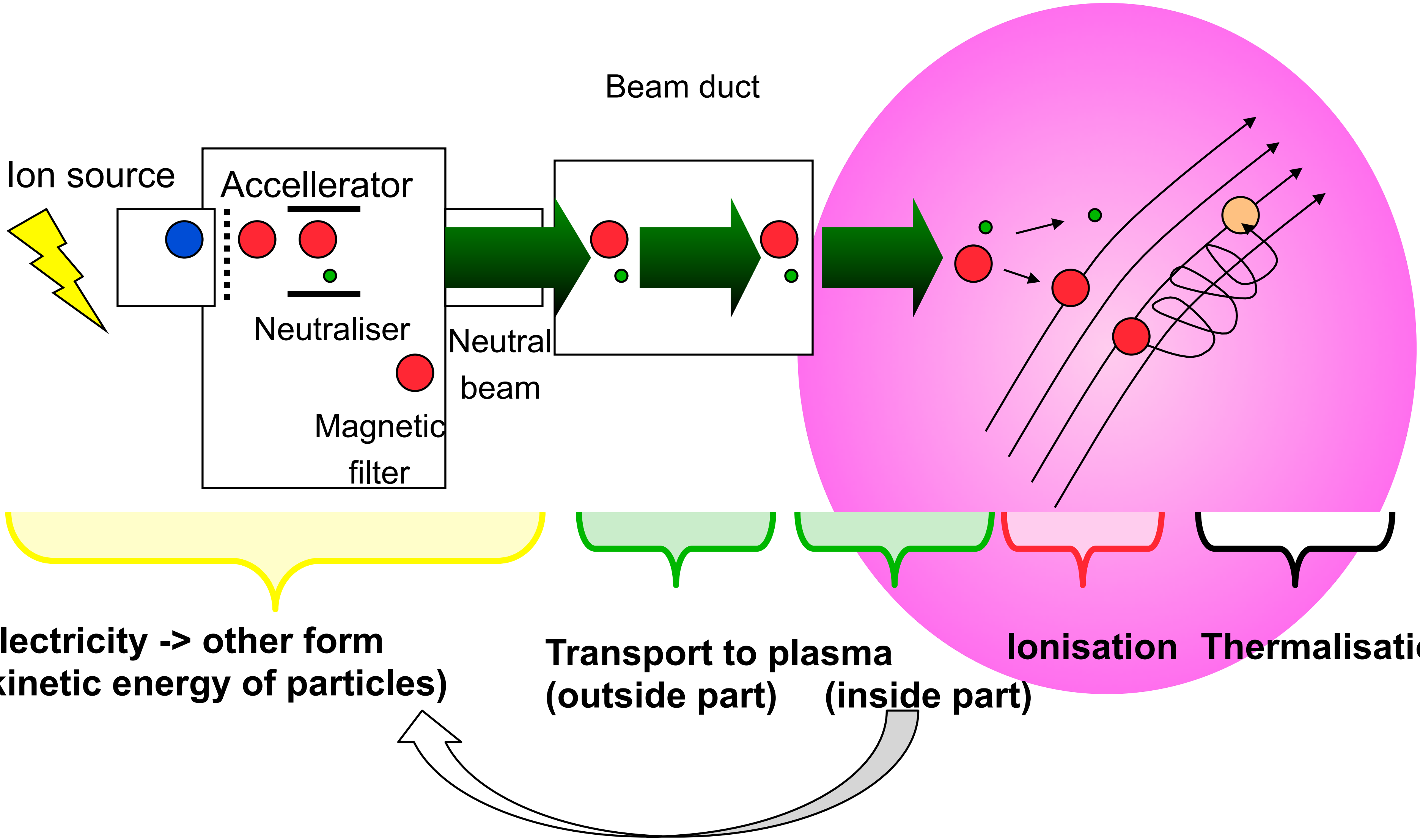
- **Neutrals get easily ionized**

Therefore large machines need high beam velocities thus high beam energies

- **Energetic positive ions are difficult to neutralise**



Neutral Beam Injection: principle



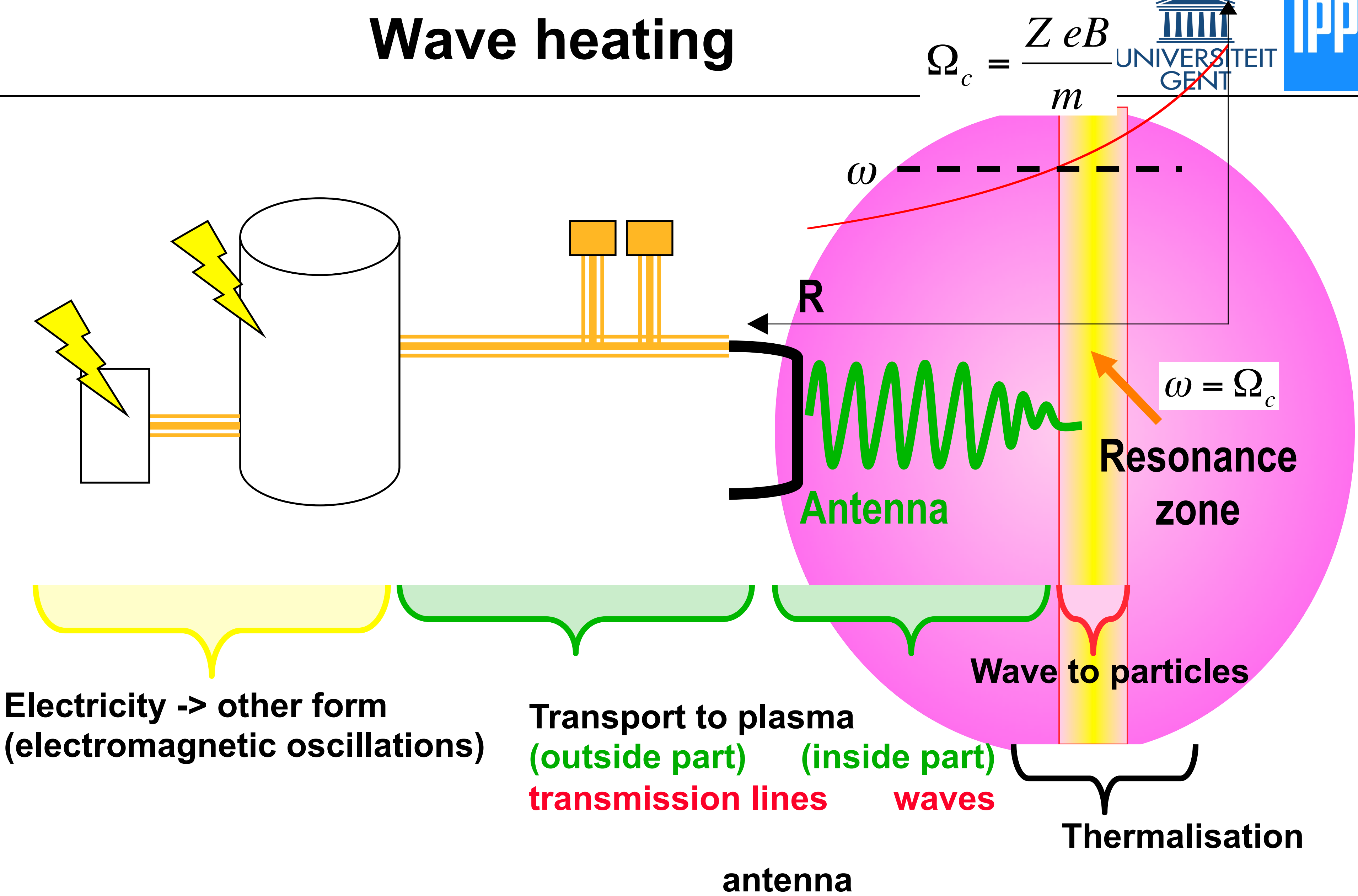
Electricity -> other form (kinetic energy of particles)

Transport to plasma (outside part) (inside part)

Ionisation

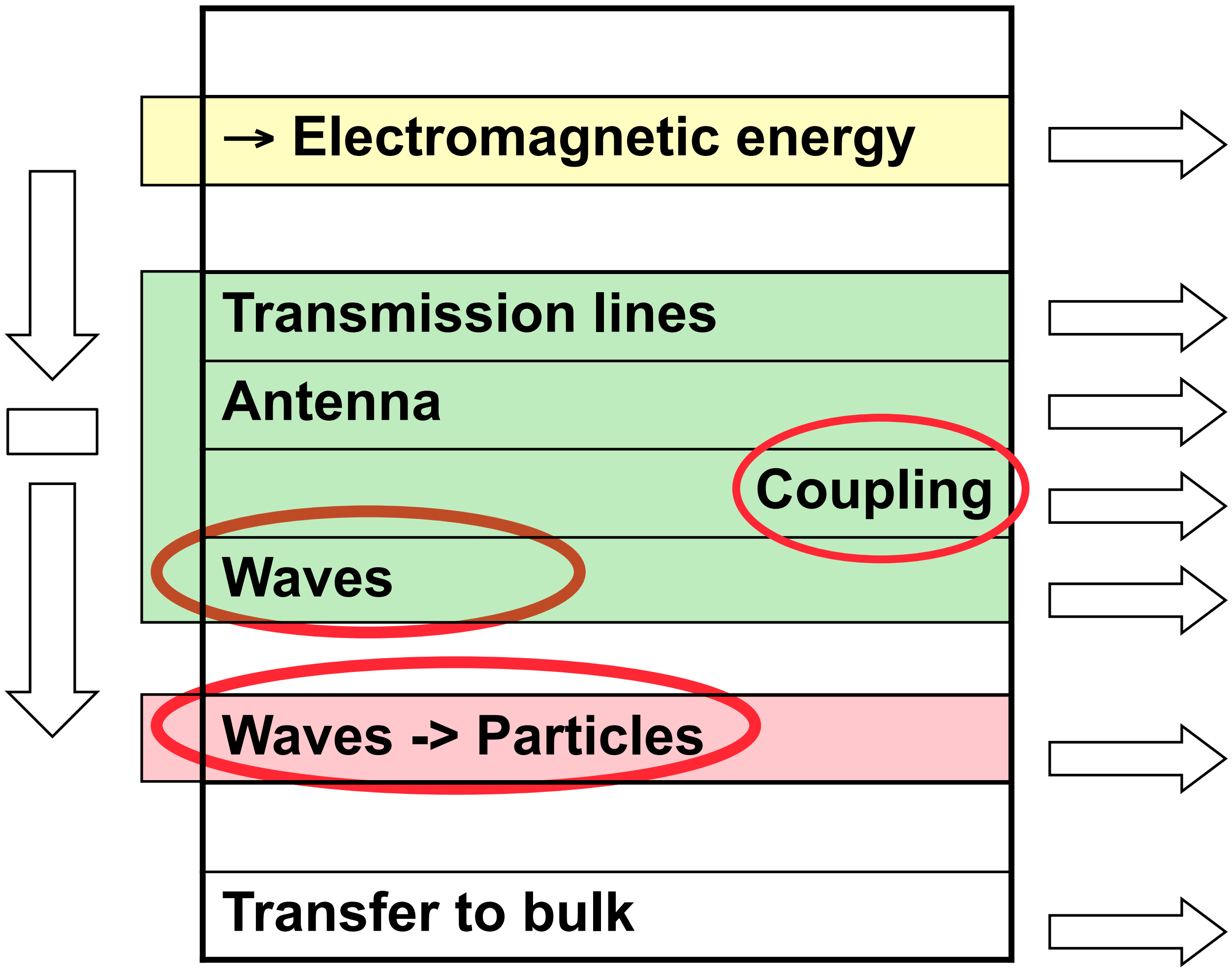
Thermalisation

Wave heating



Wave heating: very tight combination of physics and technology

Wave propagation and absorption sets the frequency range that can be used.



	Physics	Technology
→ Electromagnetic energy		✔
Transmission lines		✔
Antenna	✔	✔
Coupling	✔	✔
Waves	✔	
Waves -> Particles	✔	
Transfer to bulk	✔	

Wave Equation

Maxwell‘s Equations

$\nabla \times$

$$\nabla \times \underline{E} = -\frac{\partial \underline{B}}{\partial t}$$

$$\nabla \times \underline{B} = \mu_0 \varepsilon_0 \frac{\partial \underline{E}}{\partial t} + \mu_0 \underline{j}$$

$$\nabla \cdot \underline{E} = \rho / \varepsilon_0$$

$$\nabla \cdot \underline{B} = 0$$

generalized Ohm‘s law

$$\underline{j} = \underline{j}(\underline{E}, \underline{B})$$

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

$\underline{\underline{\sigma}}$ **: conductivity tensor**

Dispersion relation

- set of ***homogenous***, linear equations for E_x, E_y, and E_z,
- has non trivial (different from 0) solutions

  provided the determinant vanishes
- det = 0 is known as the dispersion relation
- Existence of waves

  that transport energy from edge to inside the plasma

Dispersion relation, cold plasma case

$$\det\left[\underline{N}\times\left(\underline{N}\times\underline{1}\right)+\underline{\underline{K}}(\omega,\underline{N})\right]=0 \qquad N=\frac{c}{\mathrm{v}_{ph}}=\frac{c\cdot k}{\omega}$$

$$A\cdot N^4+B\cdot N^2+C=0$$

with

$$A=S\cdot\sin^2\Theta+P\cdot\cos^2\Theta$$

$$B=R\cdot L\cdot\sin^2\Theta+P\cdot S\cdot(1+\cos^2\Theta)$$

$$C=P\cdot R\cdot L$$

$$S=\frac{1}{2}(R+L)\quad;\quad D=\frac{1}{2}(R-L)$$

$$R=1-\frac{(\omega_{pe}/\omega)^2}{1-\omega_{ce}/\omega}-\sum_i\frac{(\omega_{pi}/\omega)^2}{1+\omega_{ci}/\omega}$$

$$L=1-\frac{(\omega_{pe}/\omega)^2}{1+\omega_{ce}/\omega}-\sum_i\frac{(\omega_{pi}/\omega)^2}{1-\omega_{ci}/\omega}$$

$$P=1-\left(\frac{\omega_{pe}}{\omega}\right)^2-\sum_i\left(\frac{\omega_{pi}}{\omega}\right)^2$$

2 solutions for N^2

form of solution depends on S, P, R, L, Θ

$$tg^2\Theta=-\frac{(N^2-R)\cdot(N^2-L)\cdot P}{(S\cdot N^2-R\cdot L)\cdot(N^2-P)}$$

Θ angle between <u>k</u> and <u>B</u>

Characteristic frequencies

Plasmafrequencies

$$\omega_{pe}^2 = \frac{e^2 n_e}{\varepsilon_0 m_e}$$

$$\omega_{pi}^2 = \frac{(Z_i e)^2 n_i}{\varepsilon_0 m_i}$$

$$R = 1 - \frac{(\omega_{pe}/\omega)^2}{1 - \omega_{ce}/\omega} - \sum_i \frac{(\omega_{pi}/\omega)^2}{1 + \omega_{ci}/\omega}$$

$$L = 1 - \frac{(\omega_{pe}/\omega)^2}{1 + \omega_{ce}/\omega} - \sum_i \frac{(\omega_{pi}/\omega)^2}{1 - \omega_{ci}/\omega}$$

$$P = 1 - \left(\frac{\omega_{pe}}{\omega}\right)^2 - \sum_i \left(\frac{\omega_{pi}}{\omega}\right)^2$$

Cyclotron frequencies

$$\omega_{ce} = \frac{eB}{m_e}$$

$$\omega_{ci} = \frac{Z_i eB}{m_i}$$

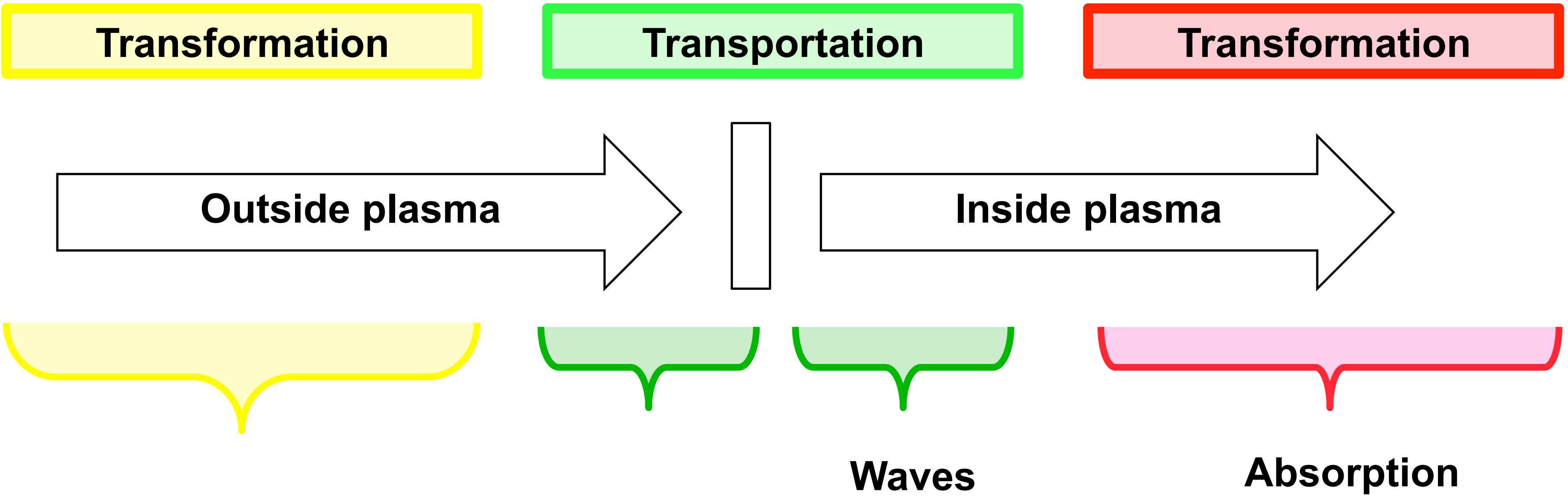
Upper Hybrid frequency

$$\omega_{uh}^2 = \omega_{pe}^2 + \omega_{ce}^2$$

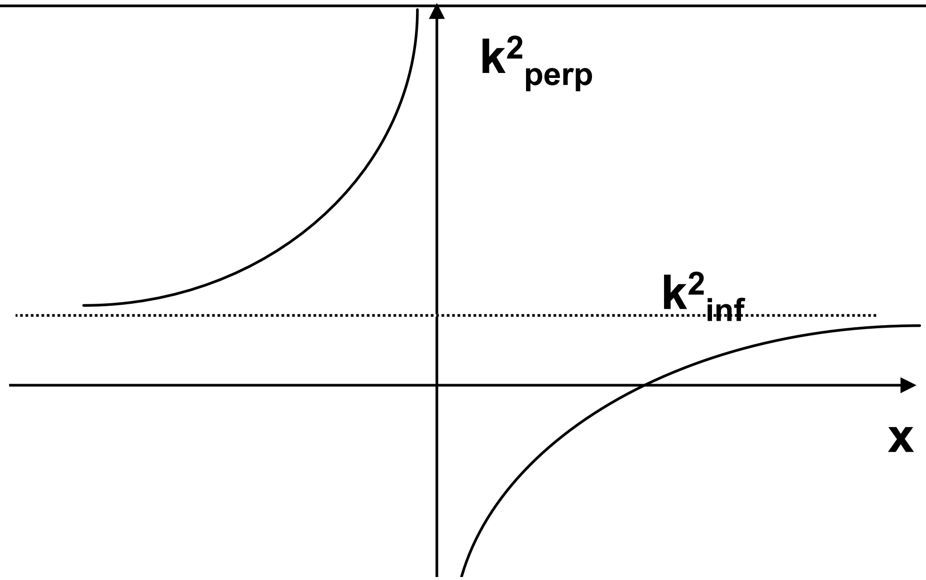
Lower Hybrid frequency

$$\omega_{lh}^2 = \left[\frac{1}{\omega_{pi}^2 + \omega_{ci}^2} + \frac{1}{\omega_{ci}\omega_{ce}}\right]^{-1}$$

Requirements

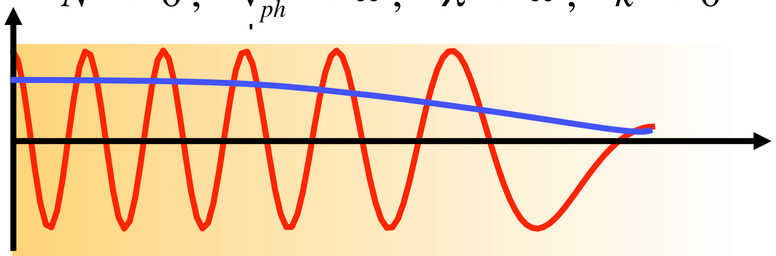


- 2 solutions for $(k/k_0)^2$, function of Θ
  - if > 0 -> propagating
  - if < 0 -> non-propagating

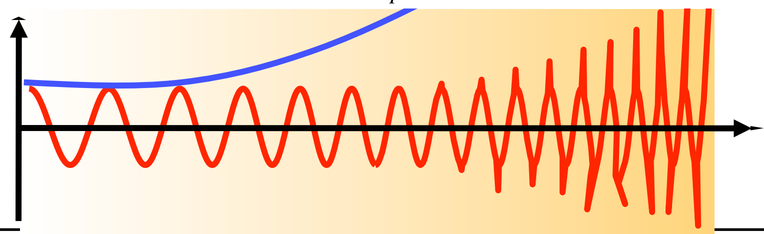


- $(k/k_0)^2$ can change sign
  - by going through 0 -> cut-off
    - reflection
    - evanescent wave
  - by going through infinity -> resonance
    - absorption
    - reflection and transmission

Cut-off $N \to 0\,;\quad v_{ph} \to \infty\,;\quad \lambda \to \infty\,;\quad k \to 0$



Resonance $N \to \infty\,;\quad v_{ph} \to 0\,;\quad \lambda \to 0\,;\quad k \to \infty$



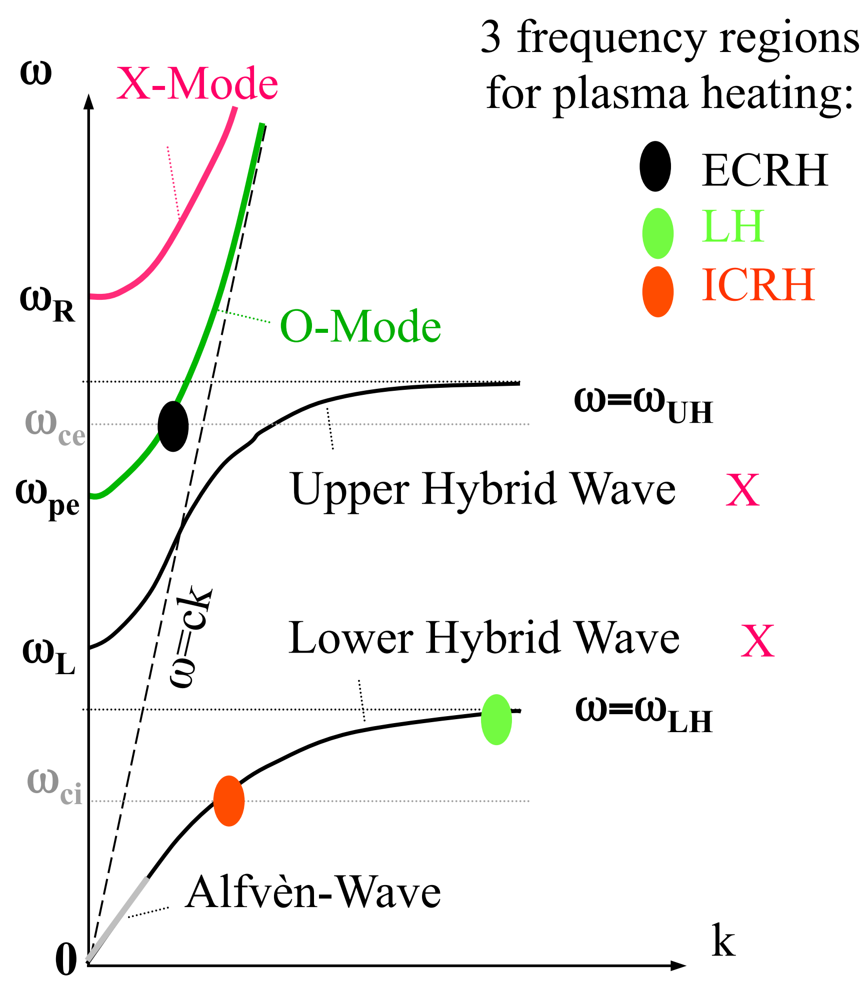
Wave propagation and absorption

$$tg^2\Theta = -\frac{(N^2 - R)\cdot(N^2 - L)\cdot P}{(S\cdot N^2 - R\cdot L)\cdot(N^2 - P)}$$

$$k \perp B \rightarrow \Theta = \pi/2$$

$$N^2 = P \rightarrow \text{O-mode}$$

$$N^2 = \frac{RL}{S} \rightarrow \text{X-mode}$$

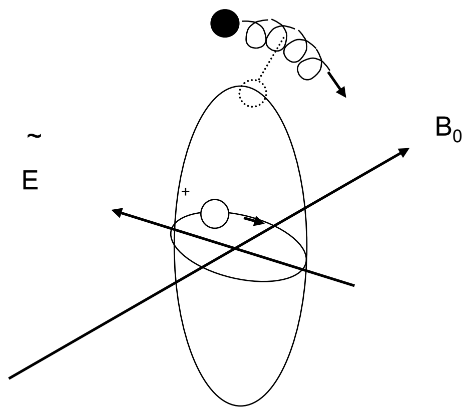


Wave propagation and absorption

- **ECRH**
  - **electron cyclotron resonance heating**
- **LH**
  - **lower hybrid frequency** $\omega_{ci} << \omega << \omega_{ce}$

ion unmagnetized, oscillate with E_1

electrons oscillate with E_1 x B_0 drift



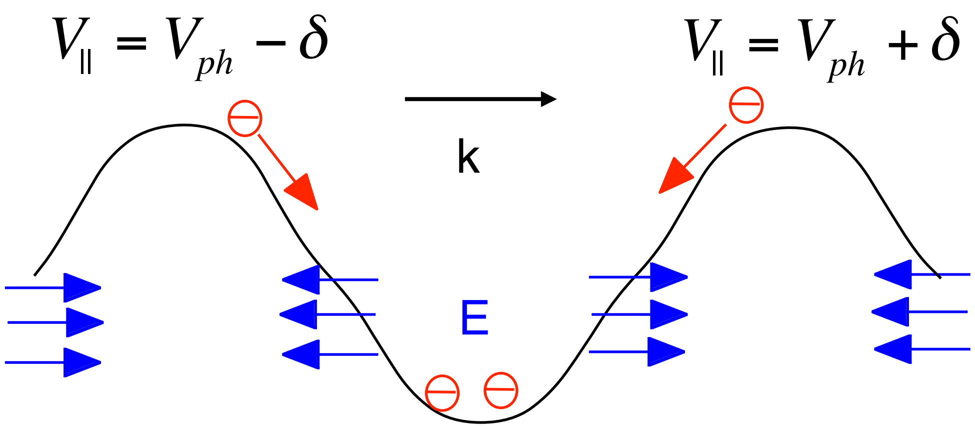
- **ICRF**
  - **Ion cyclotron range of frequencies**

Transport from outside plasma to inside: wave propagation
(wave cut-off and resonance)

Transfer of energy from wave to particles: particle resonance condition
(wave-particle interaction)

Absorption: Collisionless Damping

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

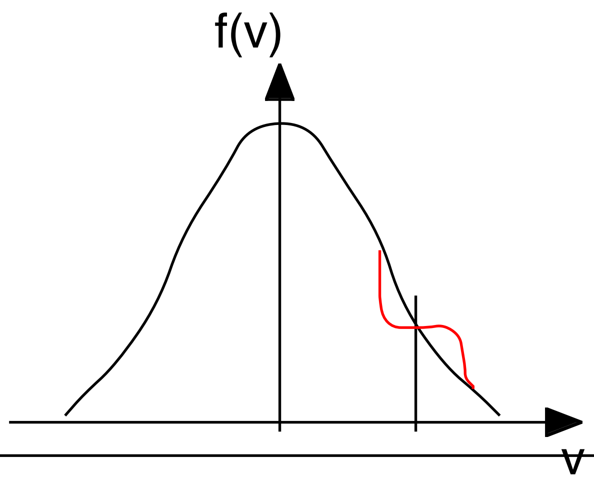


Resonance condition:

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

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

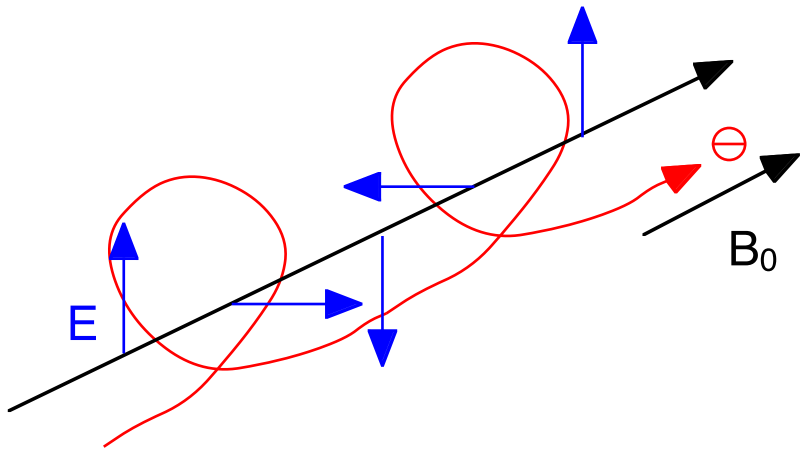
Cyclotron Damping (Doppler shifted)

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

$$n = 1$$

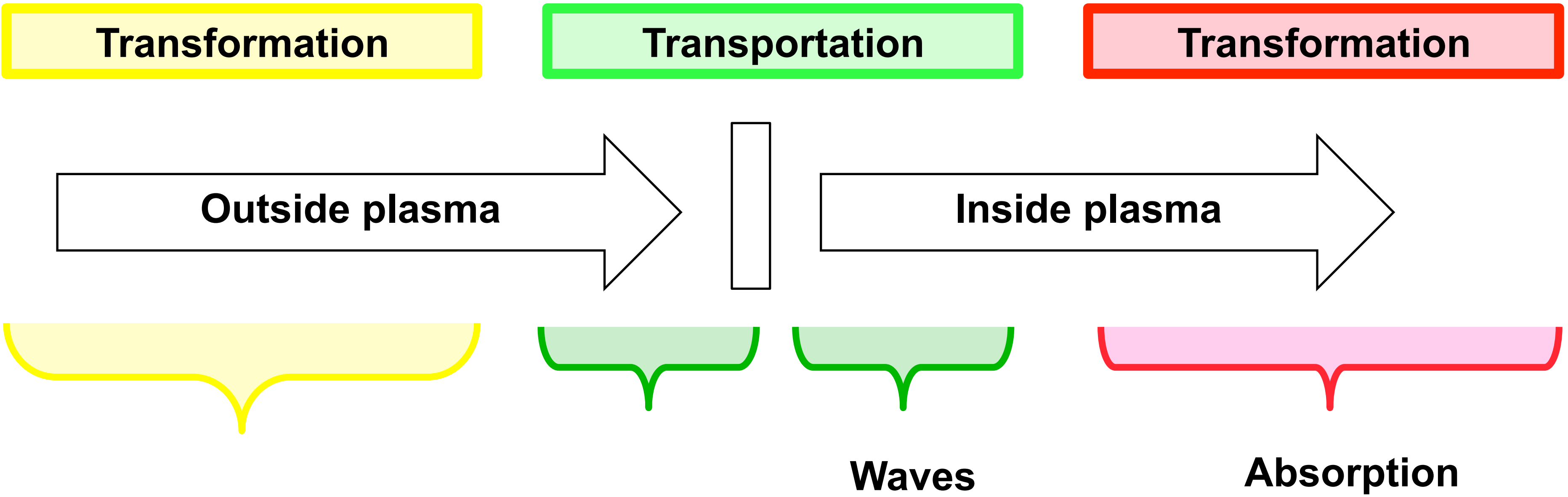
Resonance condition:

$$\omega - k_{\|}v_{\|} = \omega_c$$

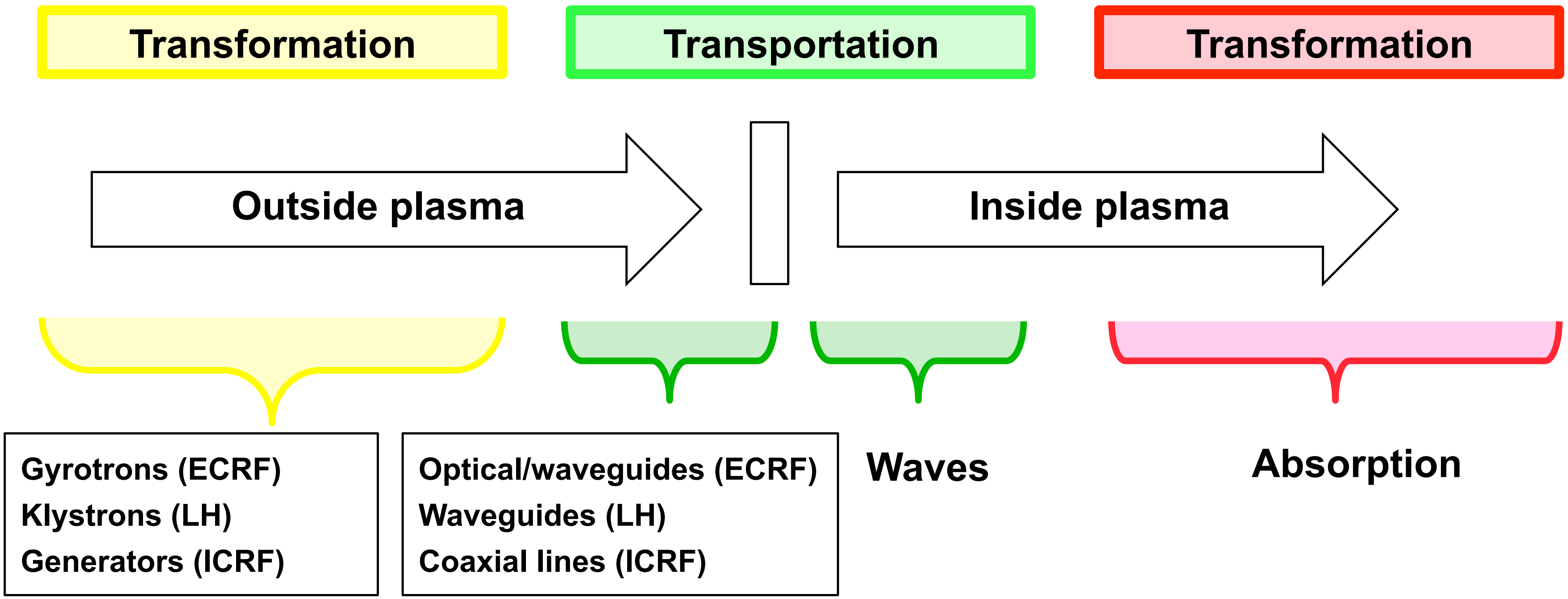


Cyclotron Damping: increase of perpendicular momentum

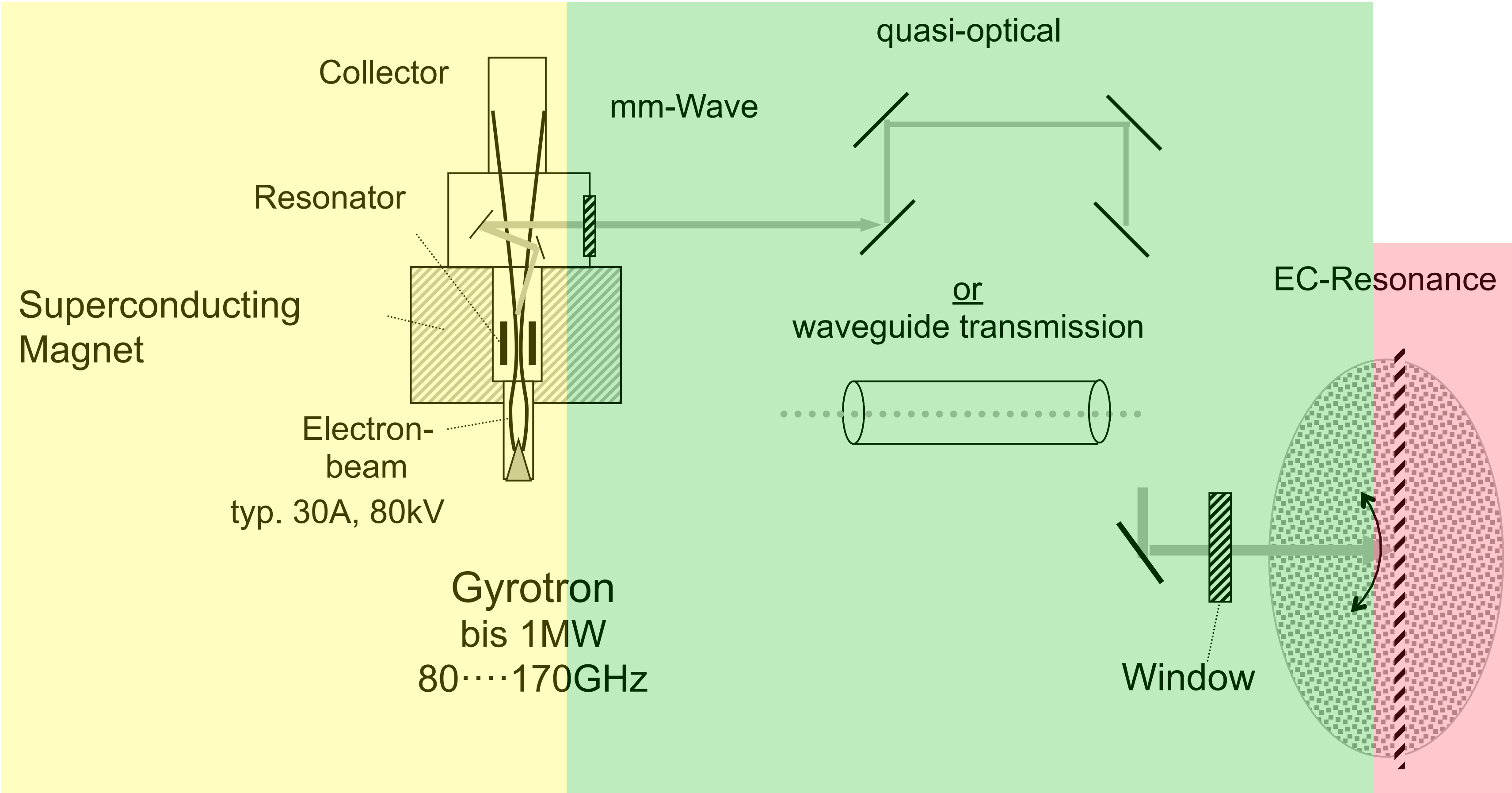
Requirements



Requirements

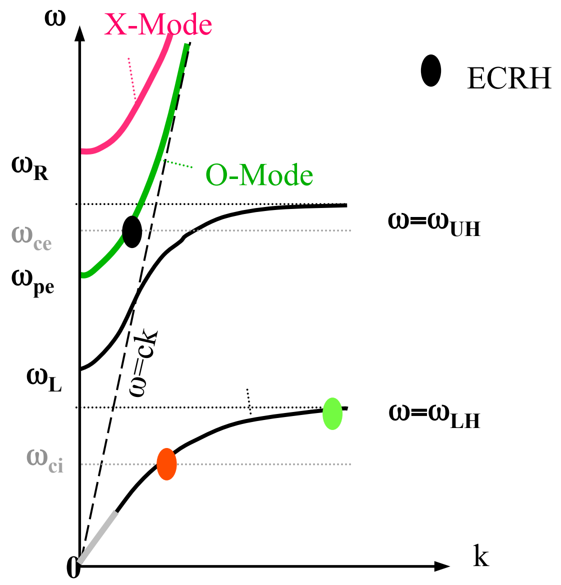


ECRH System



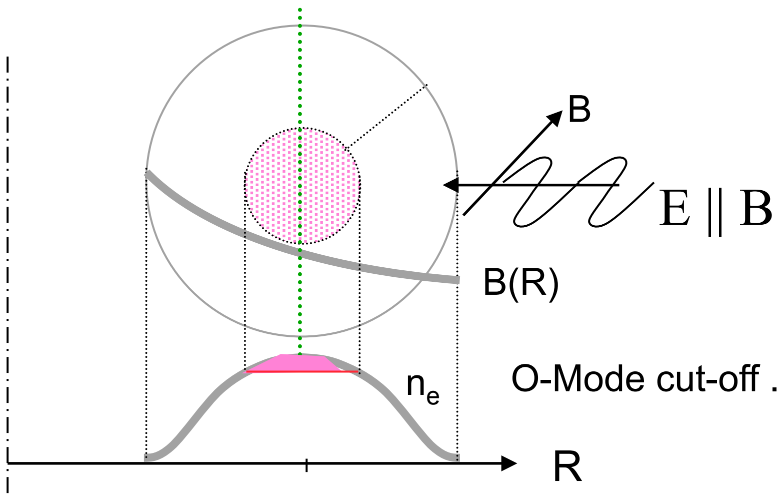
Collector
mm-Wave
quasi-optical
Resonator
Superconducting
Magnet
or
waveguide transmission
EC-Resonance
Electron-
beam
typ. 30A, 80kV
Gyrotron
bis 1MW
80····170GHz
Window

ECR



O-Mode

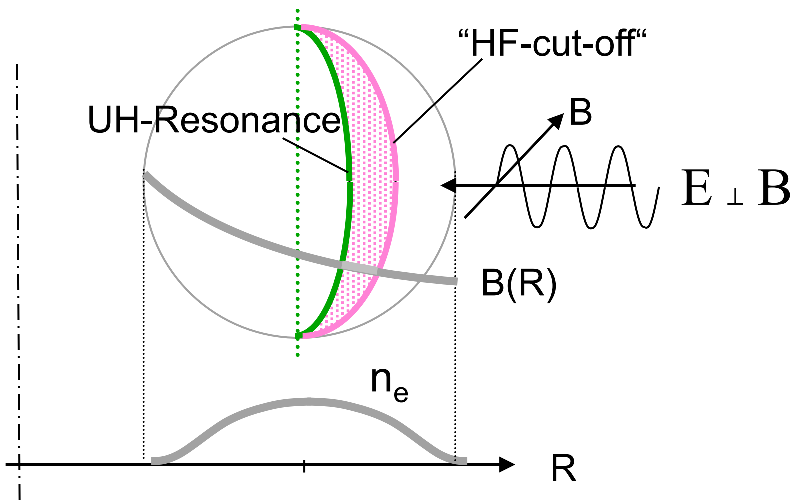
EC-"Resonance"



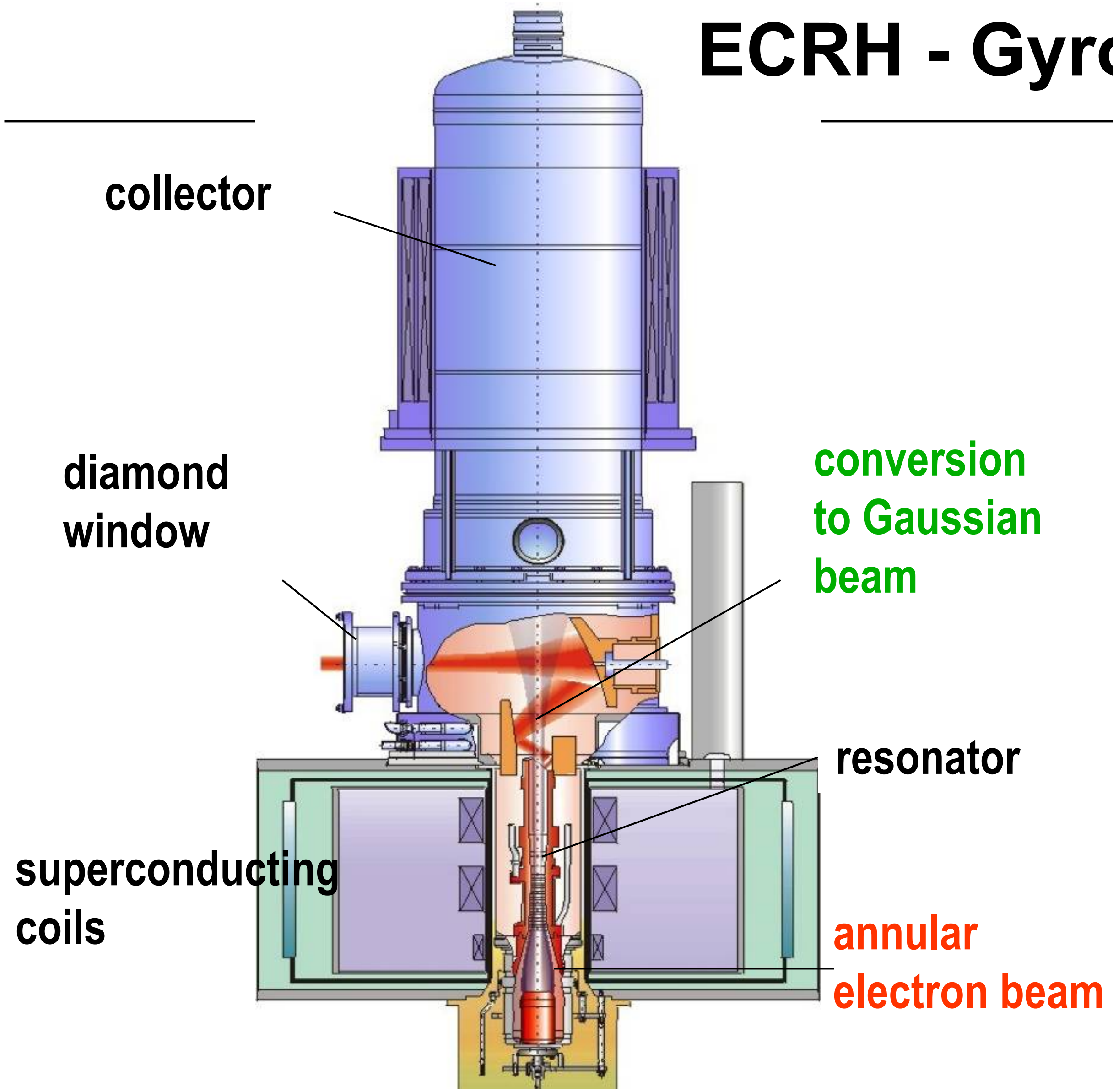
O-Mode cut-off ..if $n_e > n_{crit}$

X_1-Mode

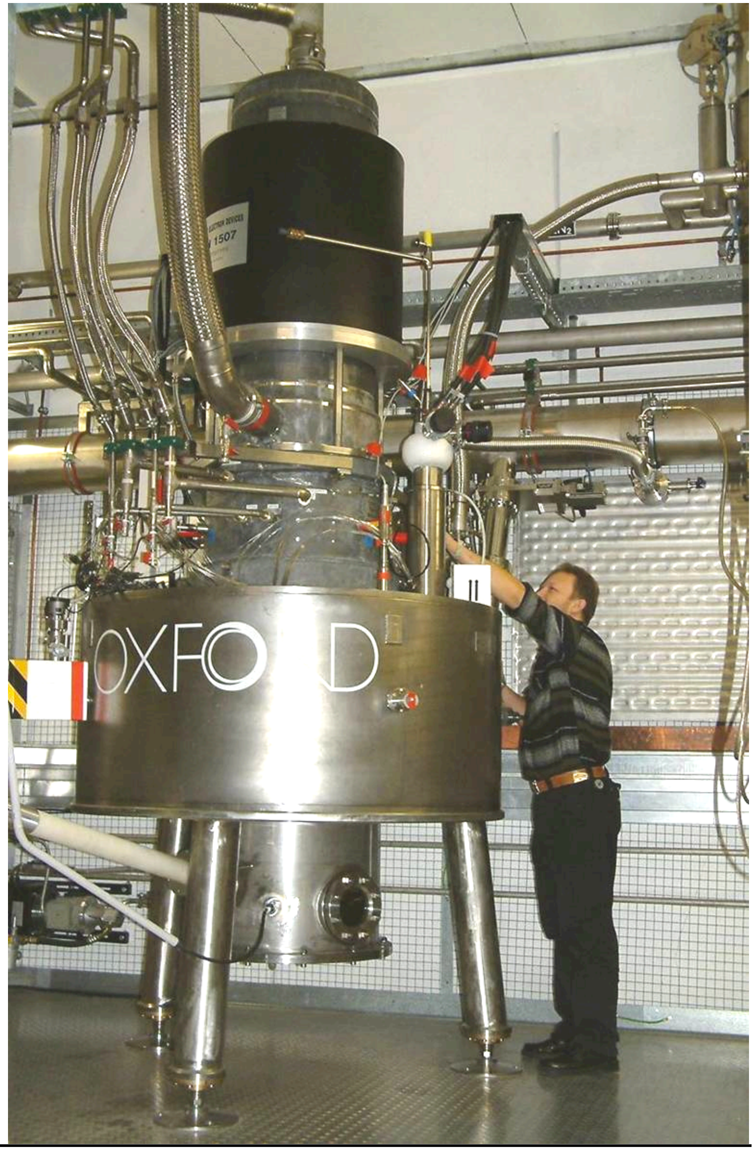
EC-"Resonance"



ECRH - Gyrotrons

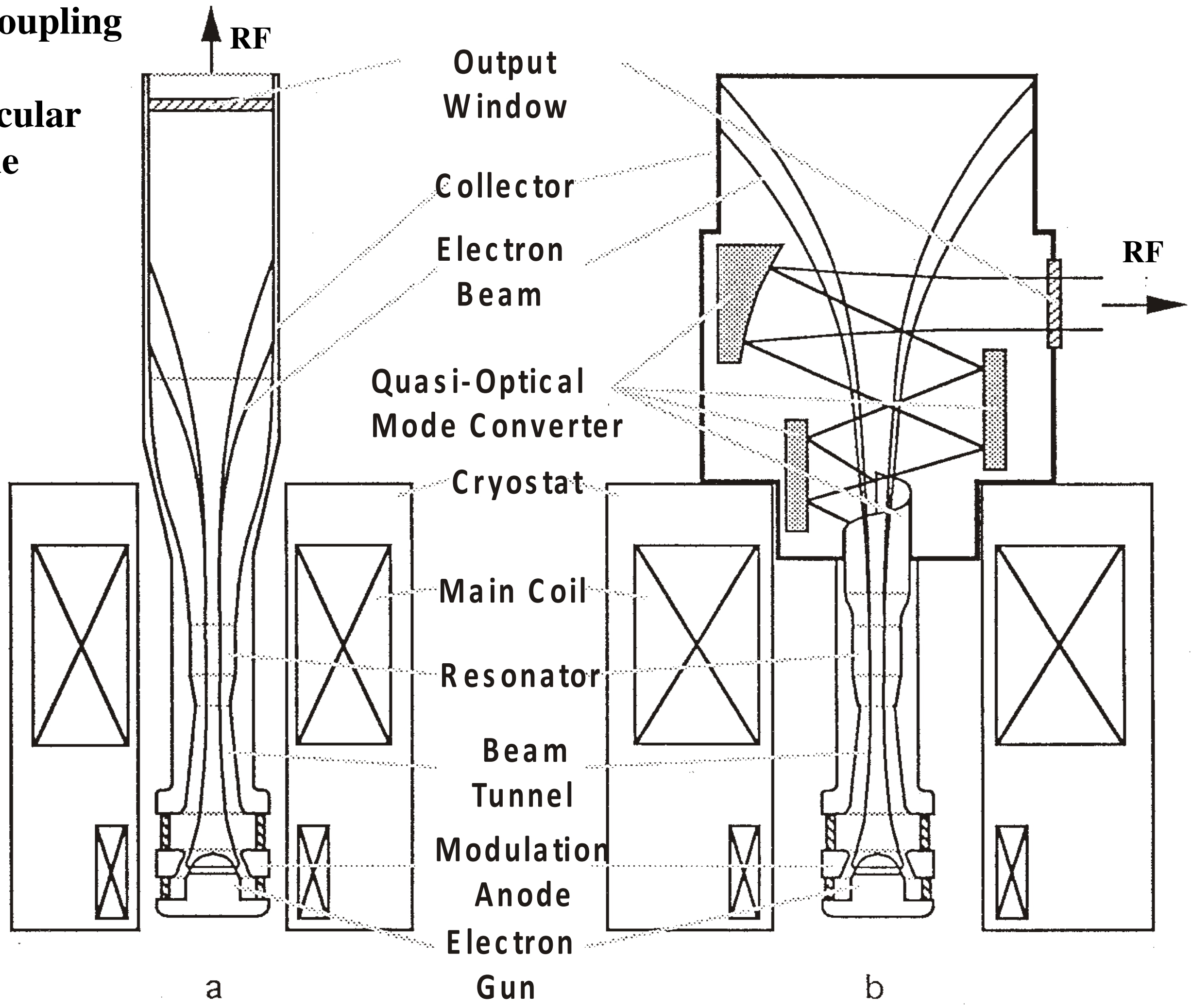


Presently: development of 1 MW cw gyrotrons



Quasi-Optical Output Couplers for High-Power Gyrotrons (1975 Russia)

Axial Output Coupling through Oversized Circular Waveguide e.g. TE_{03}

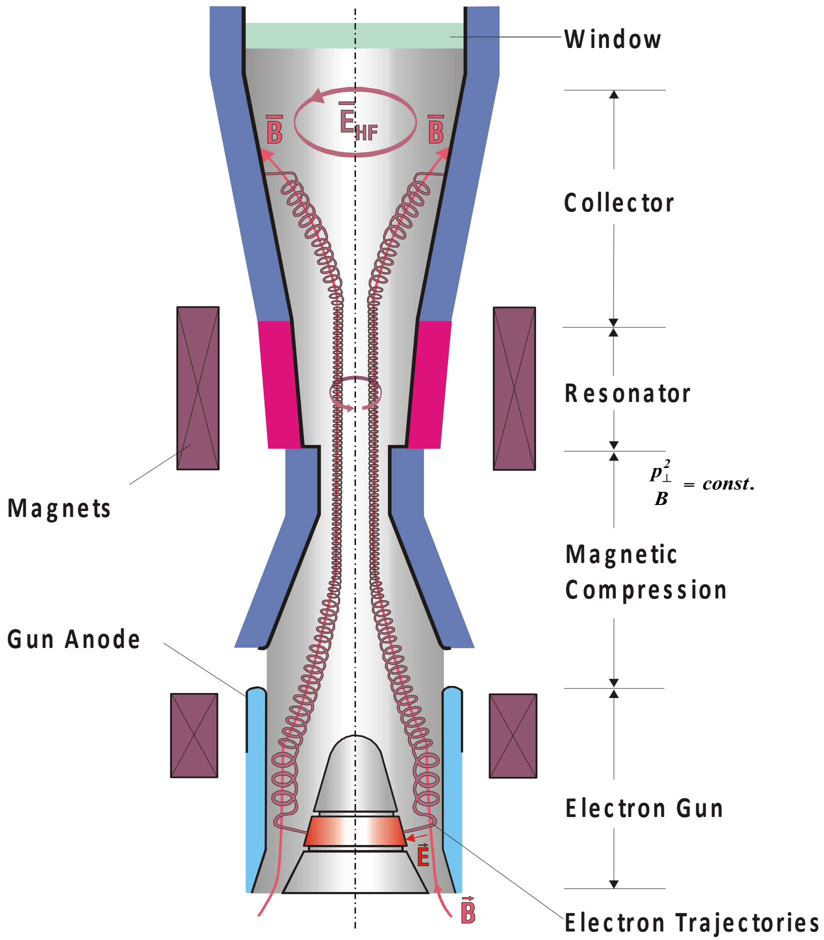


Radial Output Coupling through Optical Elements TEM_{00} (Gaussian Beam)

Advantages :

- **Isolator for Reflections**
- **Optimum Mode for Transmission**
- **Free Choice of Collector Design**

Further developments



Separate window and collector

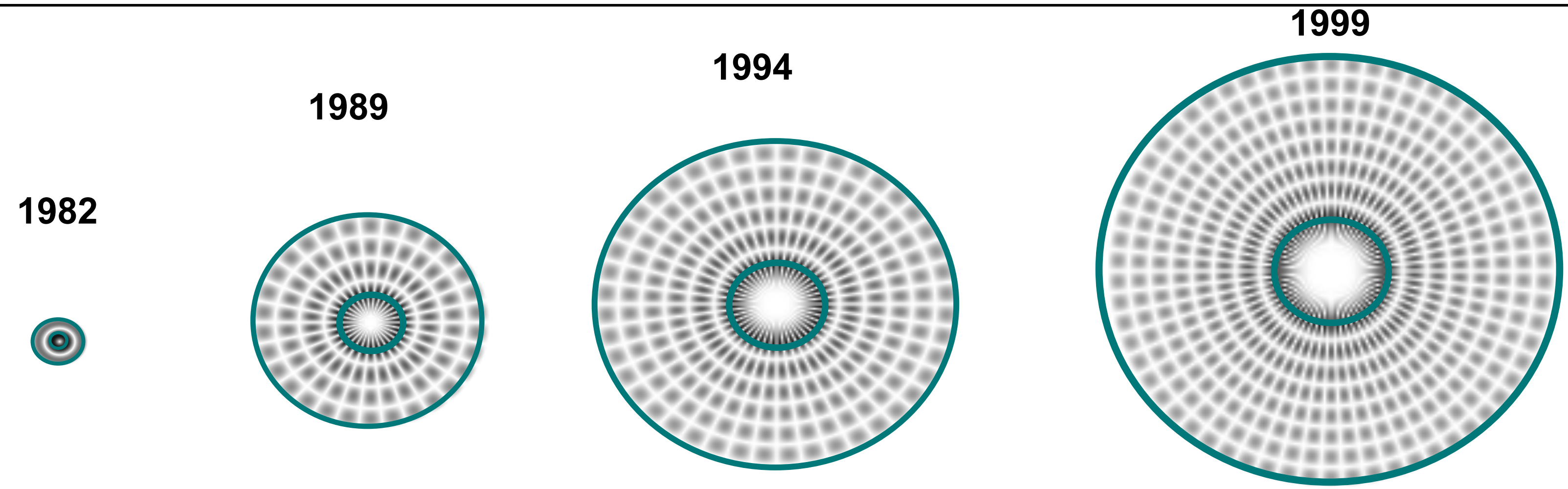
Diamond window

Biased collector

Multimode cavity

Coaxial cavity

High-Order Volume-Mode Operation in Gyrotron

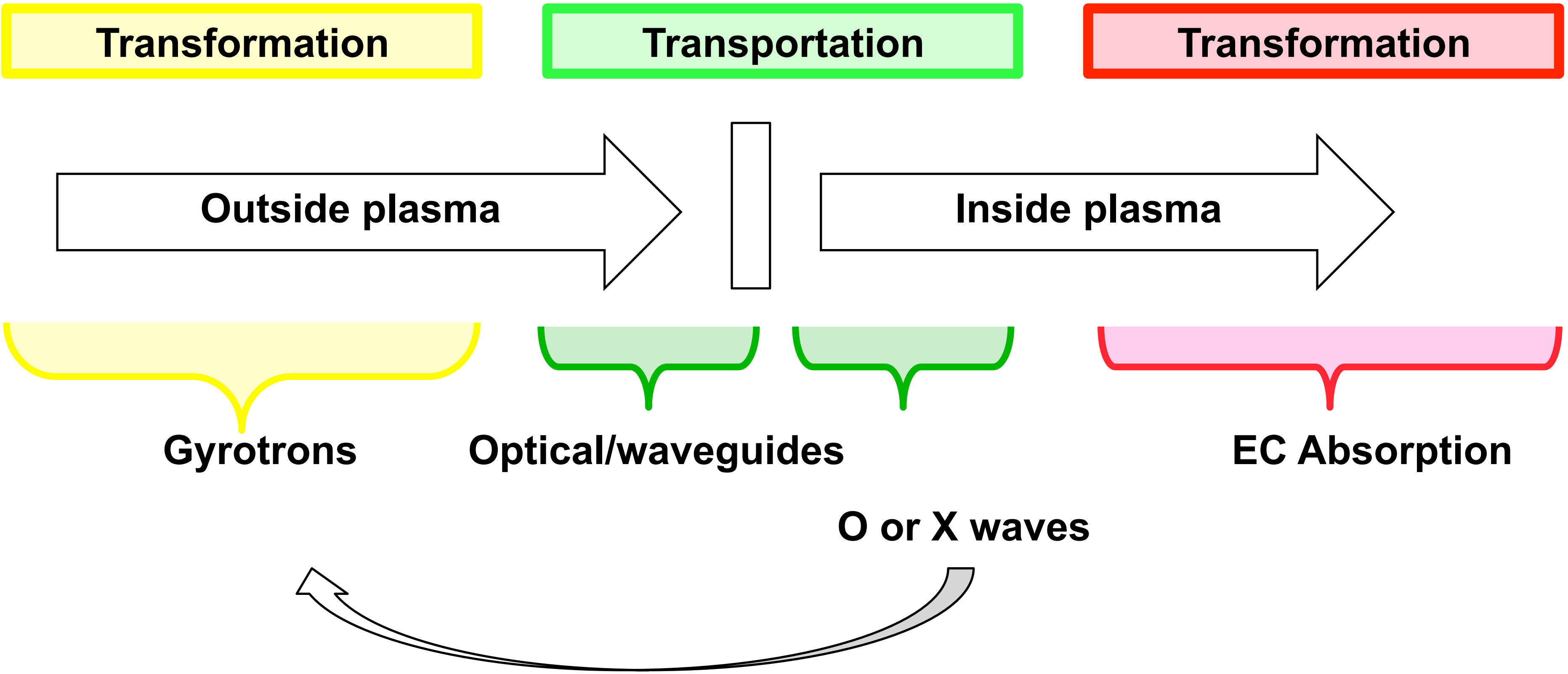


$TE_{0.2}$	$TE_{15.4}$	$TE_{22.6}$	$TE_{28.8}$, $TE_{31.8}$, $TE_{25.10}$
$\varnothing \approx 2\ \lambda$	$\varnothing \approx 10\ \lambda$	$\varnothing \approx 15\ \lambda$	$\varnothing \approx 20\ \lambda$

- electron beam on the first maximum (on the modal caustic)
  $\Rightarrow$ reduced mode competition
- smooth diameter transitions
  $\Rightarrow$ high mode purity (99%)
- dispersion strengthened copper (Al_2O_3)
  $\Rightarrow$ improved thermo-mechanical features

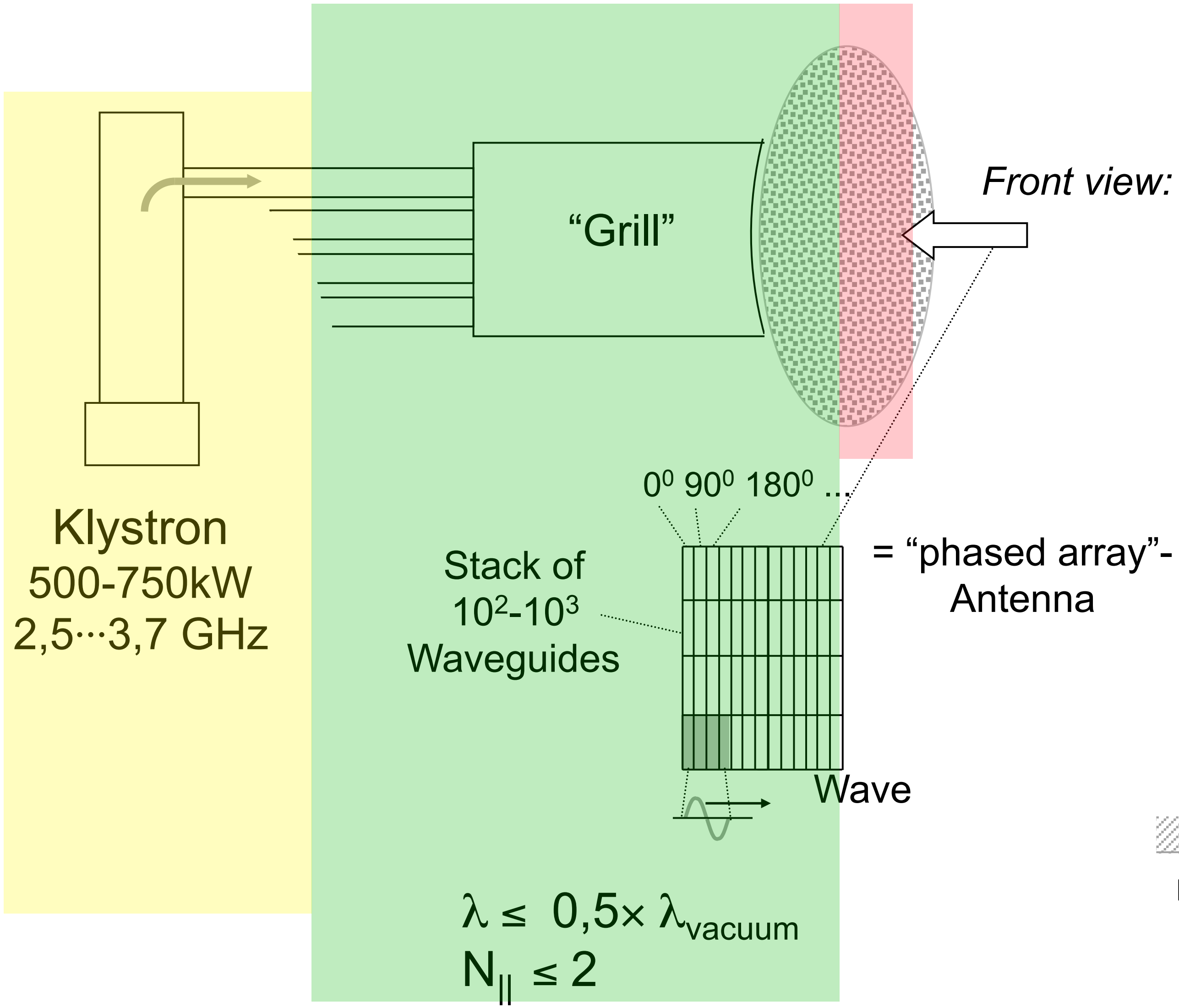
$TE_{28.8}$:	EU	140 GHz (W-7X)
$TE_{31.8}$:	JA	170 GHz (ITER)
$TE_{25.10}$:	RF	170 GHz (ITER)

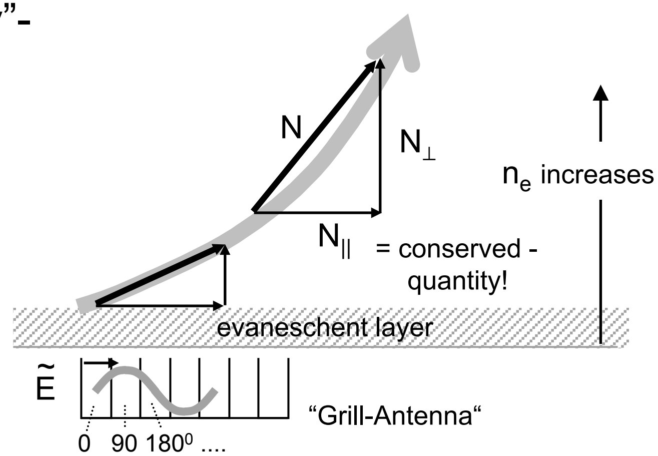
ECRH



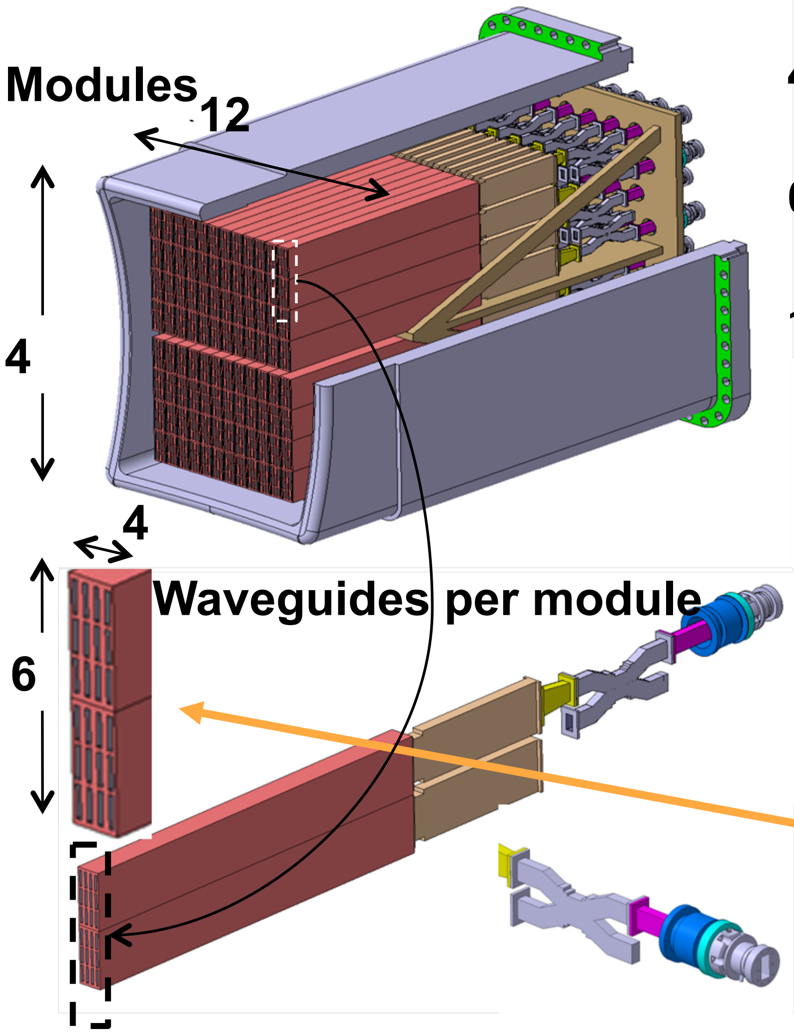
Transformation
Transportation
Transformation
Outside plasma
Inside plasma
Gyrotrons
Optical/waveguides
EC Absorption
O or X waves

Lower Hybrid system





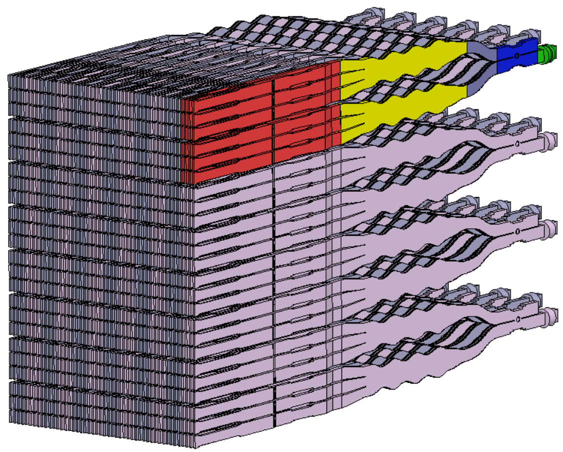
Passive Active Multi-junction Launcher Concept
(PAM)

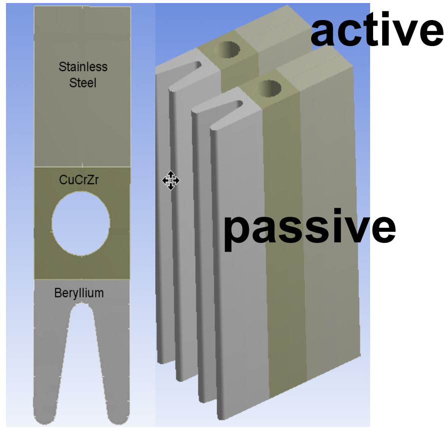


48 modules of

6 (poloidal direction) x 4 (toroidal direction) active WG

1152 active waveguides (WG)





One module:

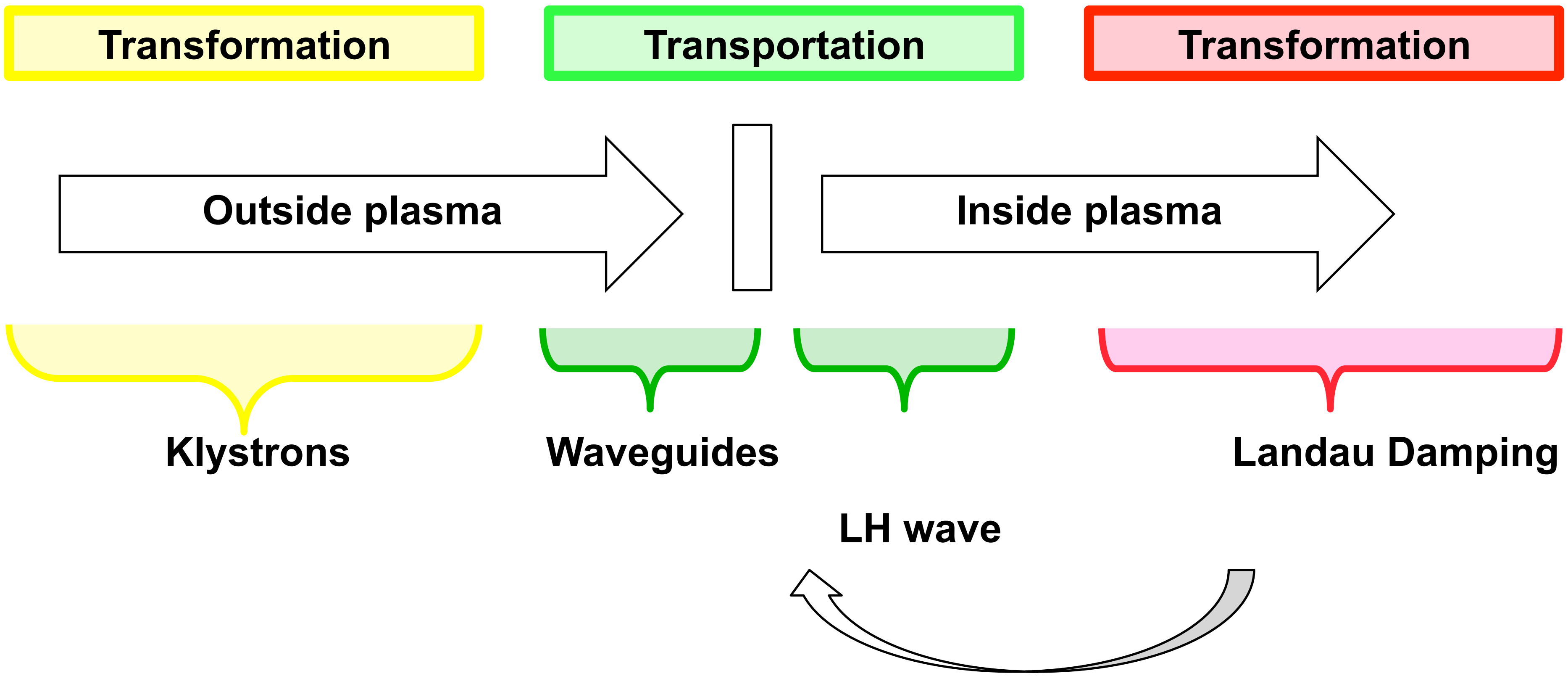
6 rows of multi-junction (6 x 4 active WGs)

2 mode converters,

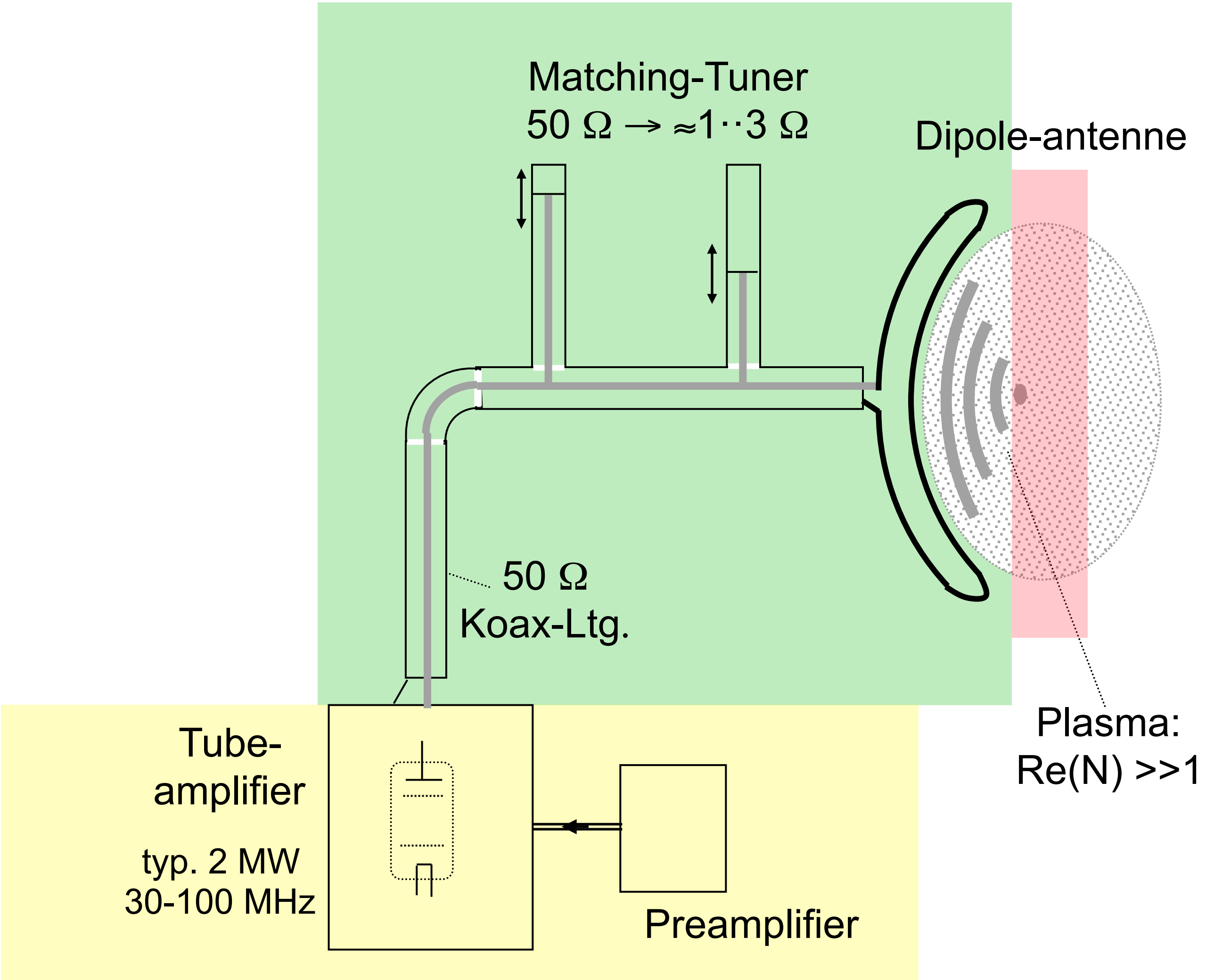
2 tapers, 1 splitter,

1 transmission line, 1 bellow, 1 window

LH

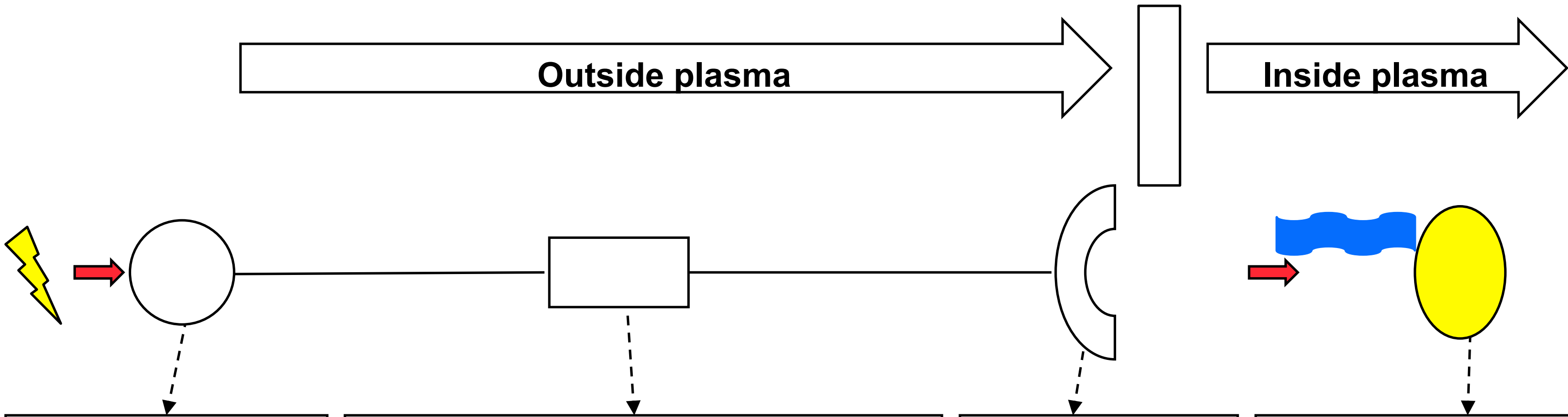

Transformation
Transportation
Transformation
Outside plasma
Inside plasma
Klystrons
Waveguides
Landau Damping
LH wave

Ion cyclotron system

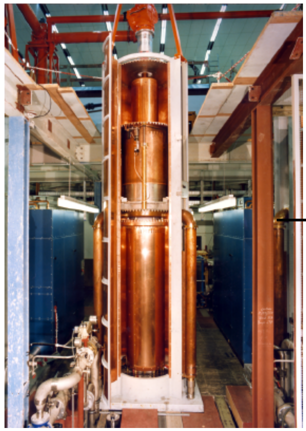


The ASDEX Upgrade ICRF system

Transformation	Transportation	Transformation



Generators

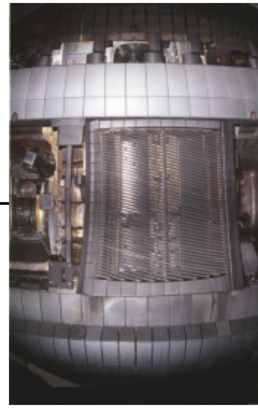


Lines and matching

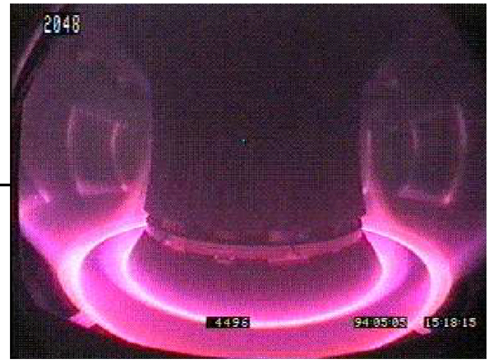
3 dB-couplers

tuners

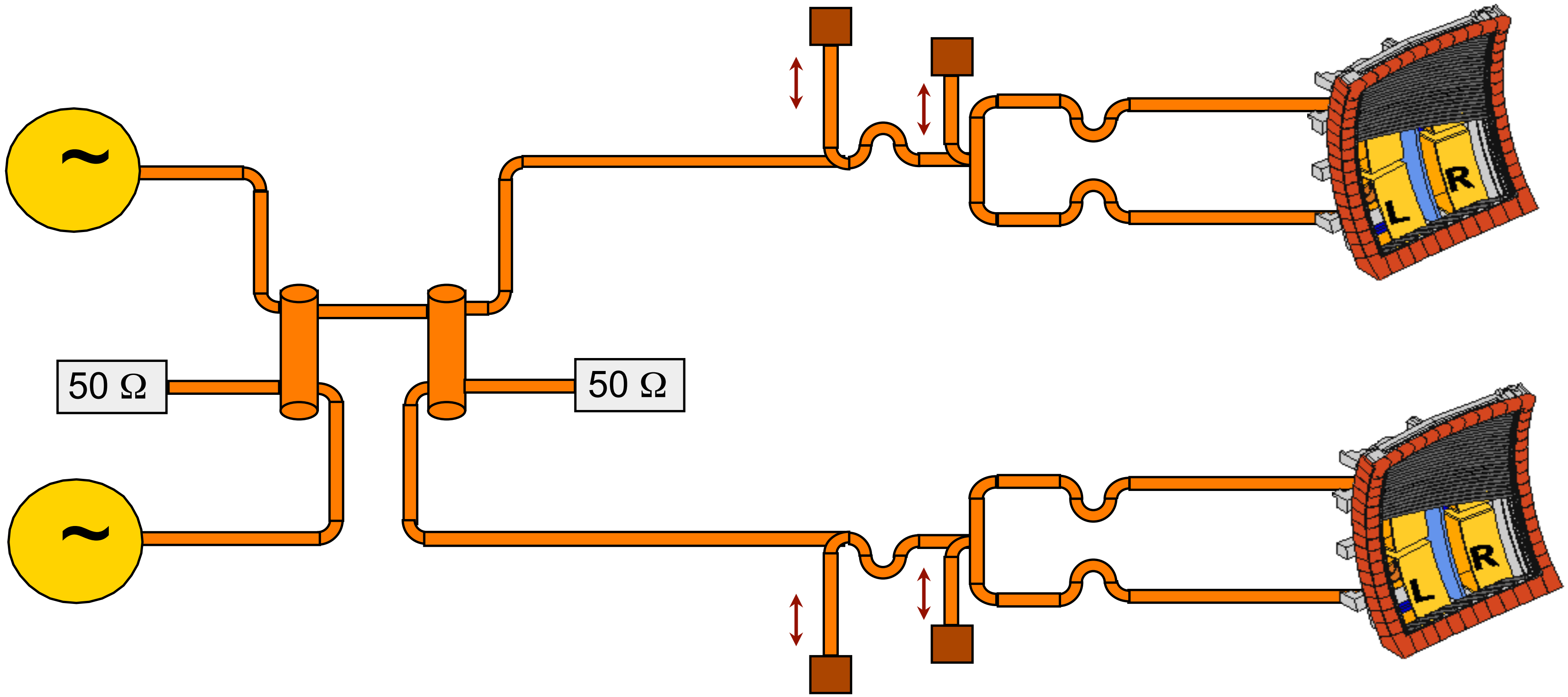
Antenna

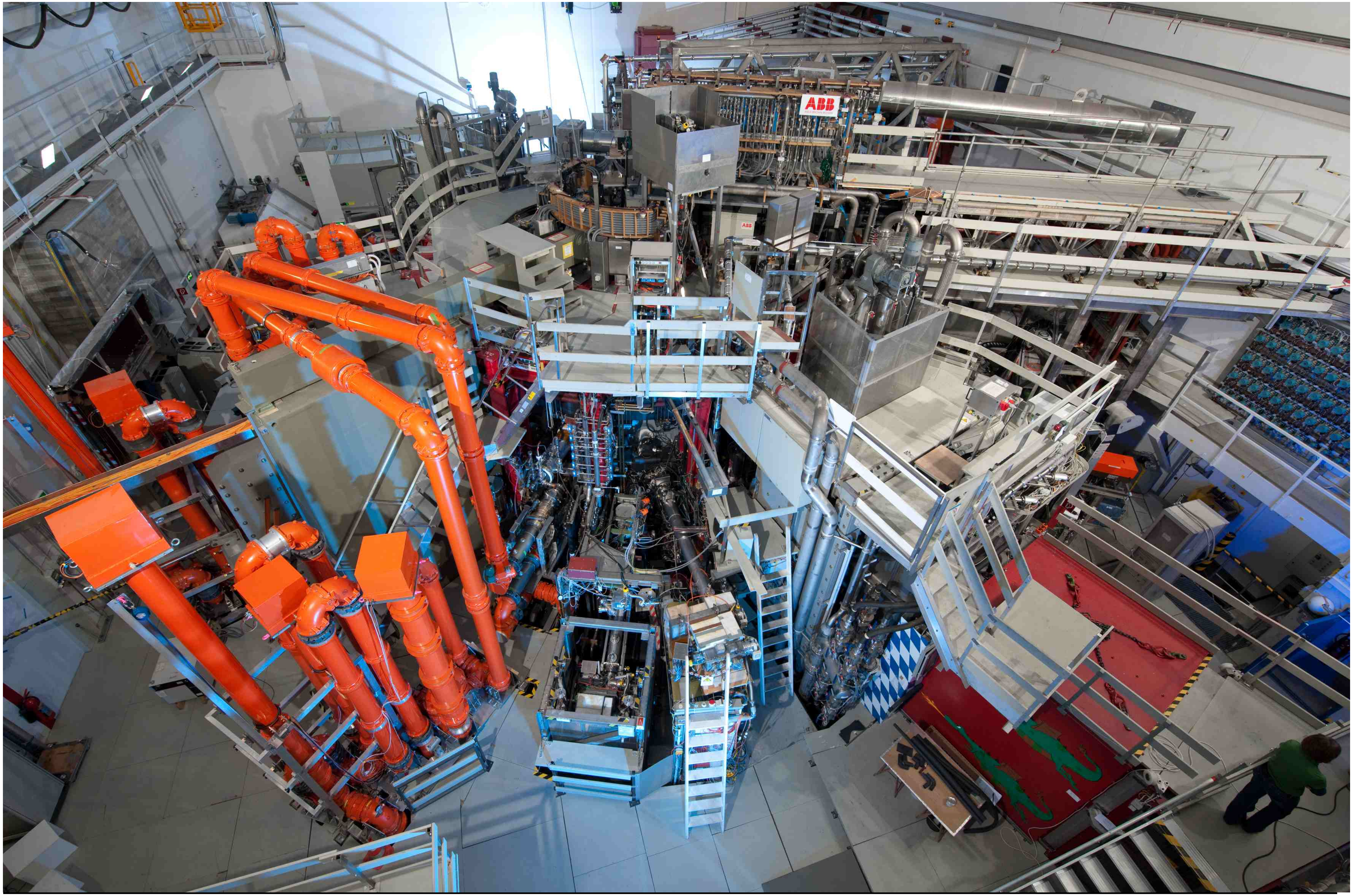


Plasma



Transmission lines
3 dB couplers and dummy loads





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Waveguides would be too large

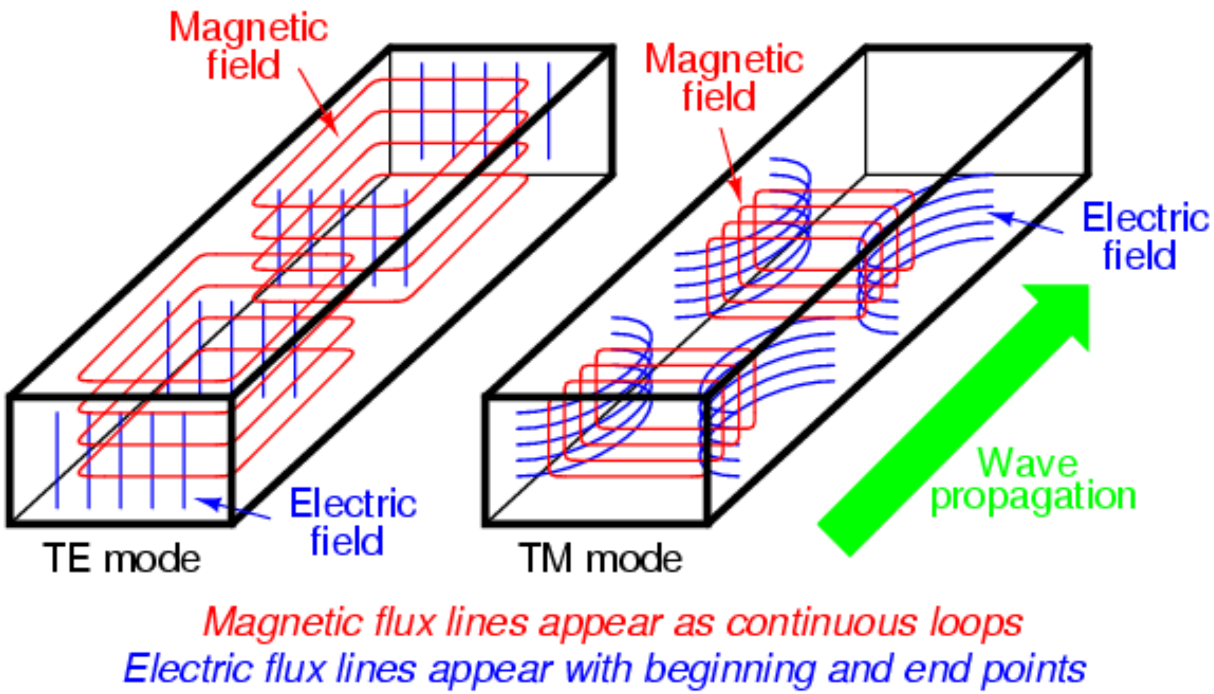
- **Transfer to plasma, outside of the machine**
  - **free space propagation: space >> wavelength = 10m at 30 MHz**
  - **waveguide propagation: lower frequency cut-off of waveguide: dimensions > wavelength/2 = 5m at 30 MHz**

TE01

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

TM11

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



Transmission lines
3 dB couplers and dummy loads

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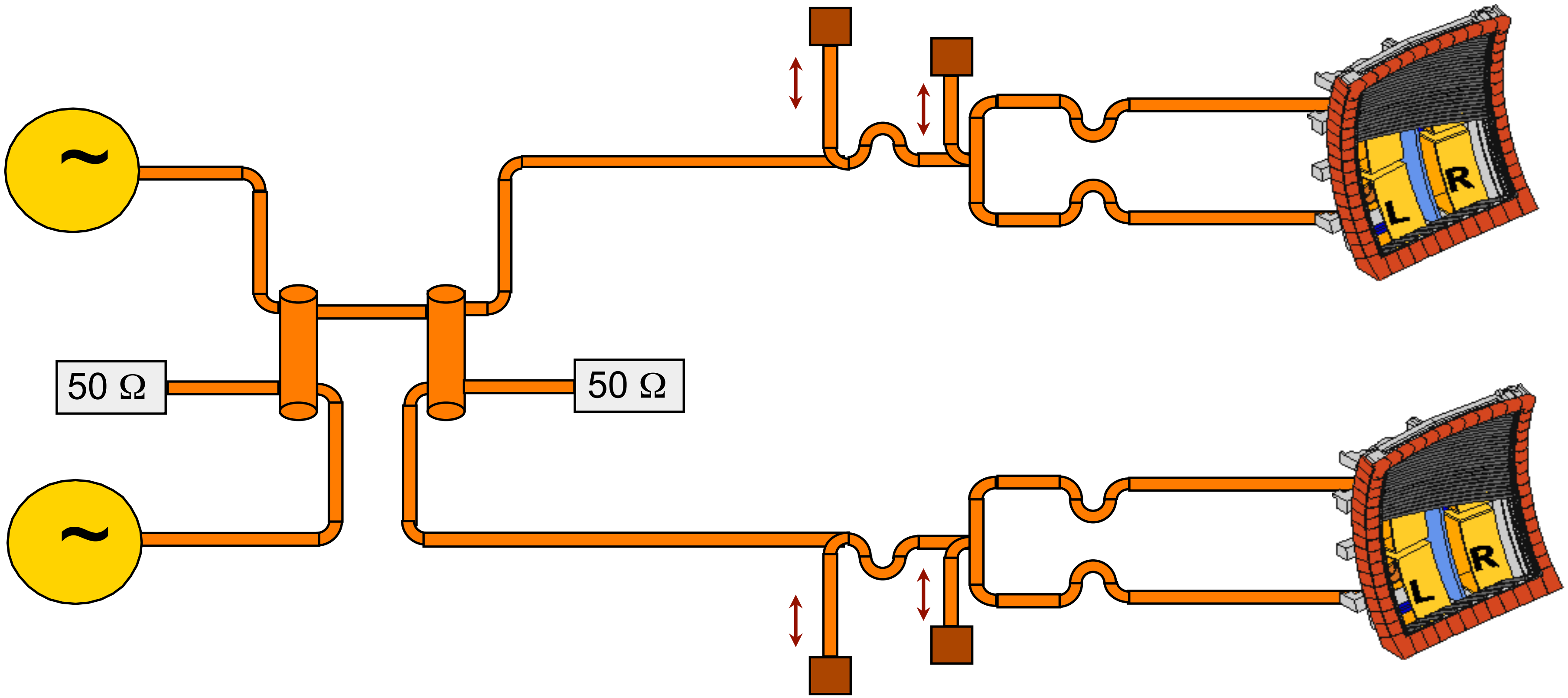
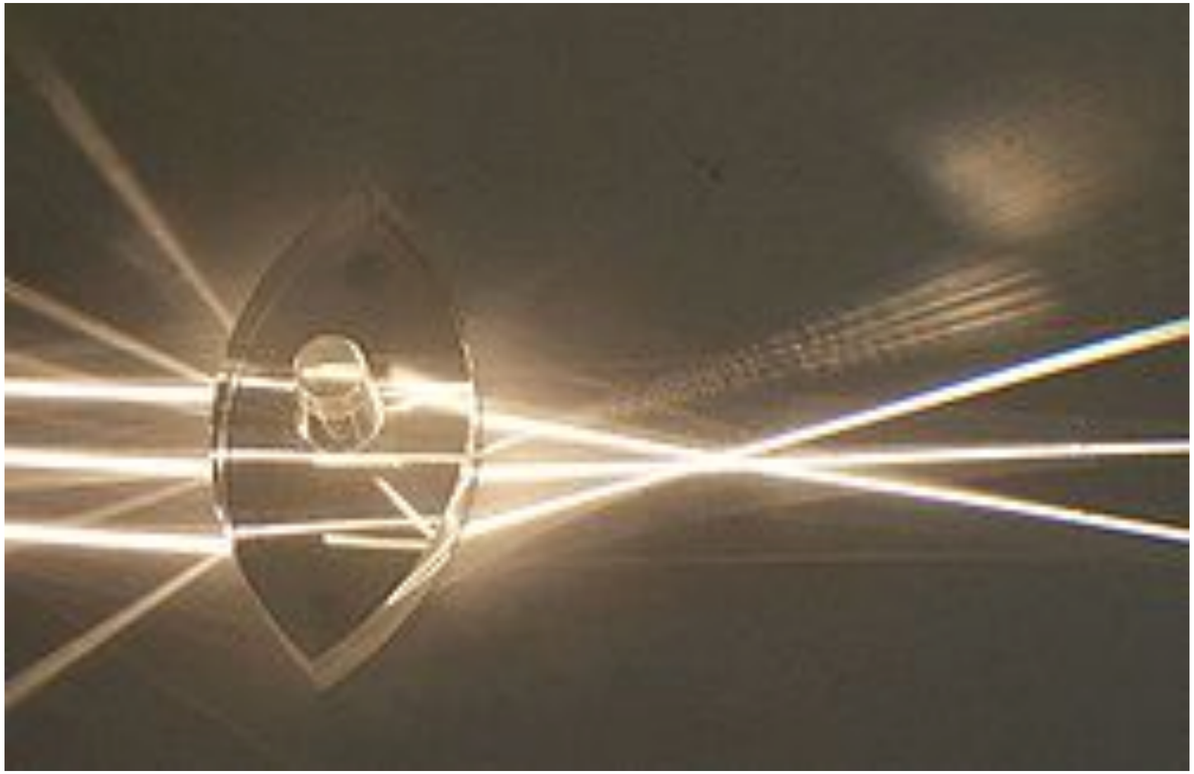
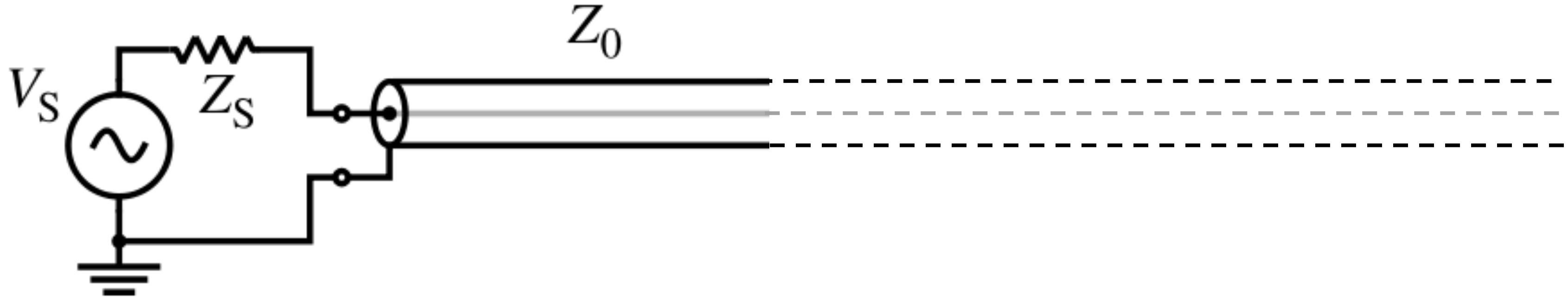
IPP



Backward waves are reflected waves generated at changes in the properties of propagating medium



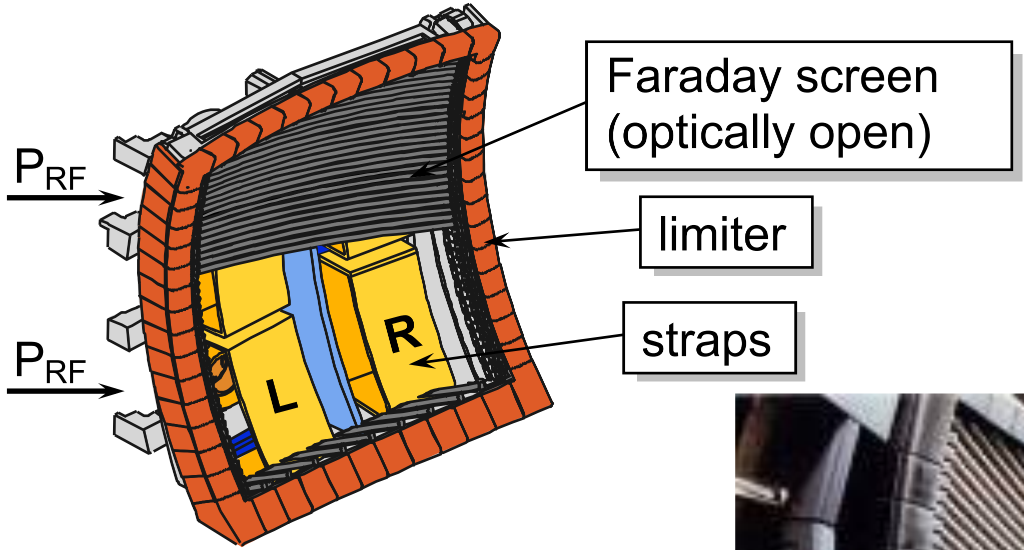
What are the properties of a transmission line?



- **infinitely long, no changes of properties - no reflection**

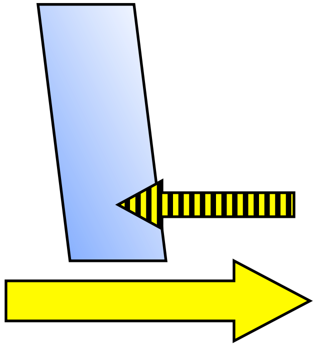
- **can we put at the end of a finite length of TL an impedance**
  such that there are no reflections,
  in other words, that it looks like an infinitely long TL?

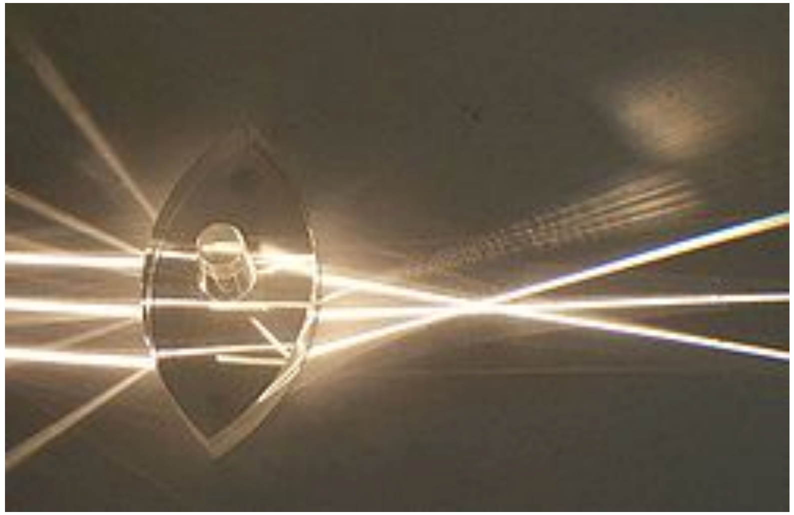
Antenna impedance ≠ Z_0



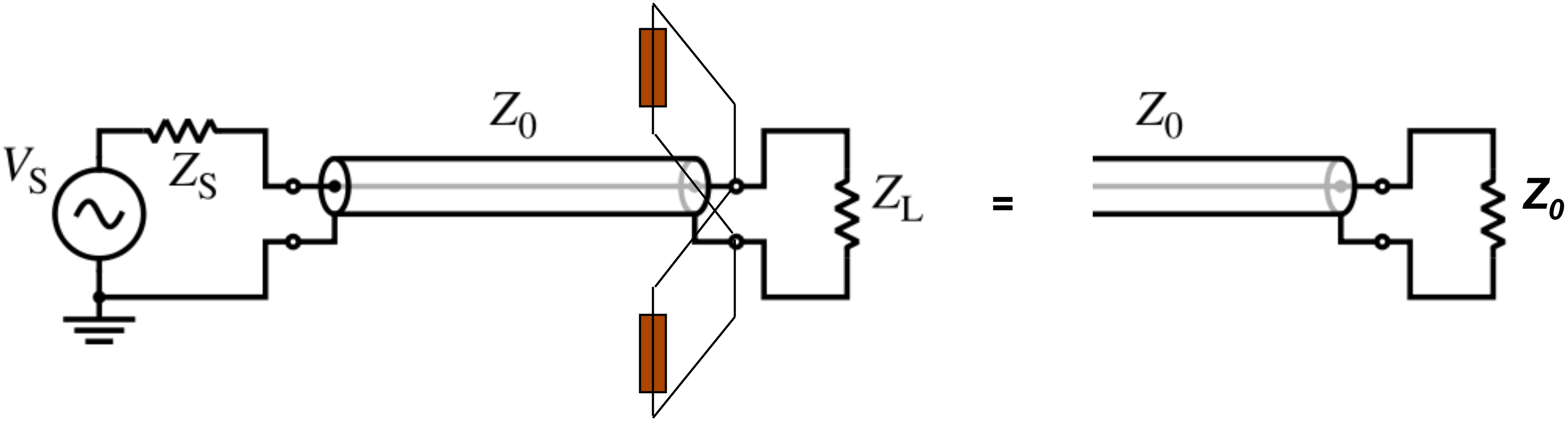
Matching network: two ways to look at it

1) reflect reflections





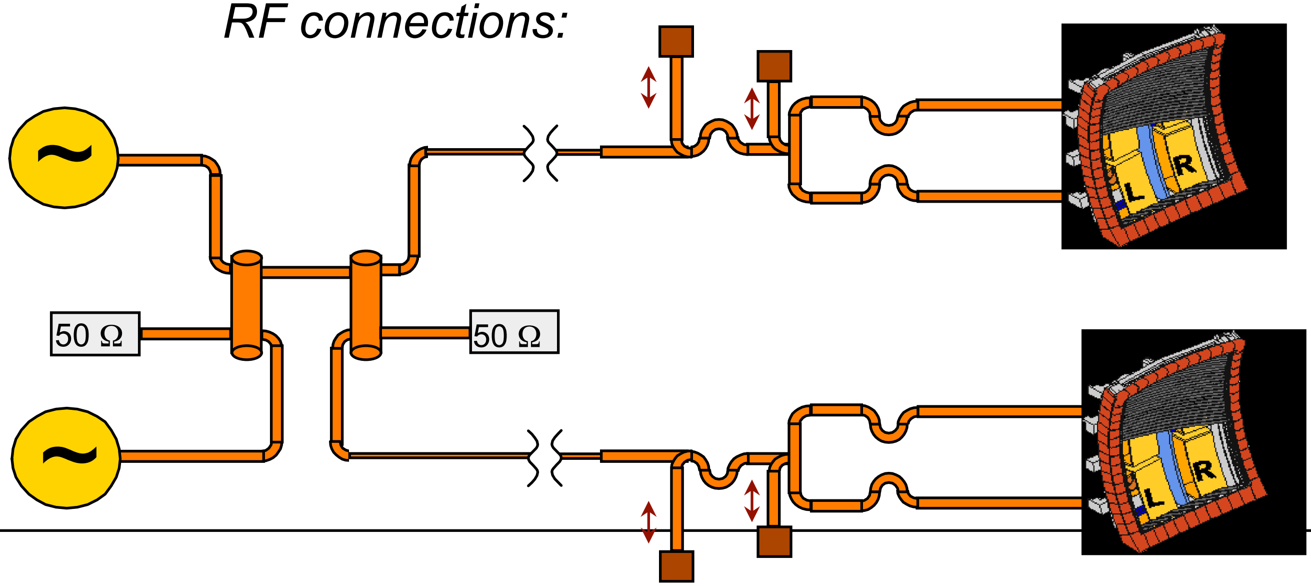
2) add impedances to match

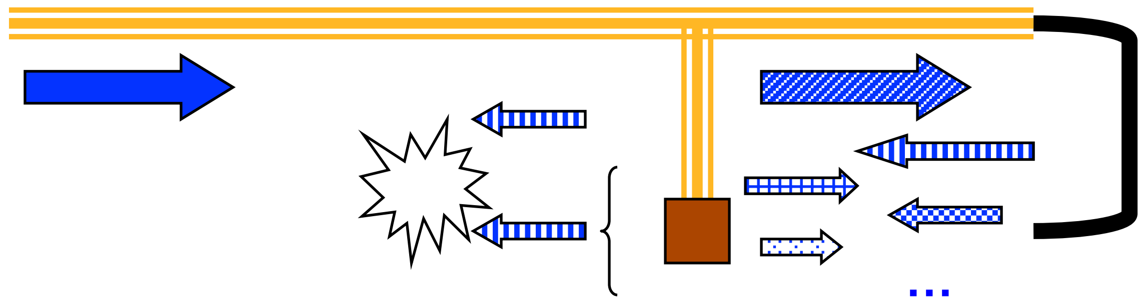


Matching network: reflect reflections

Matching network

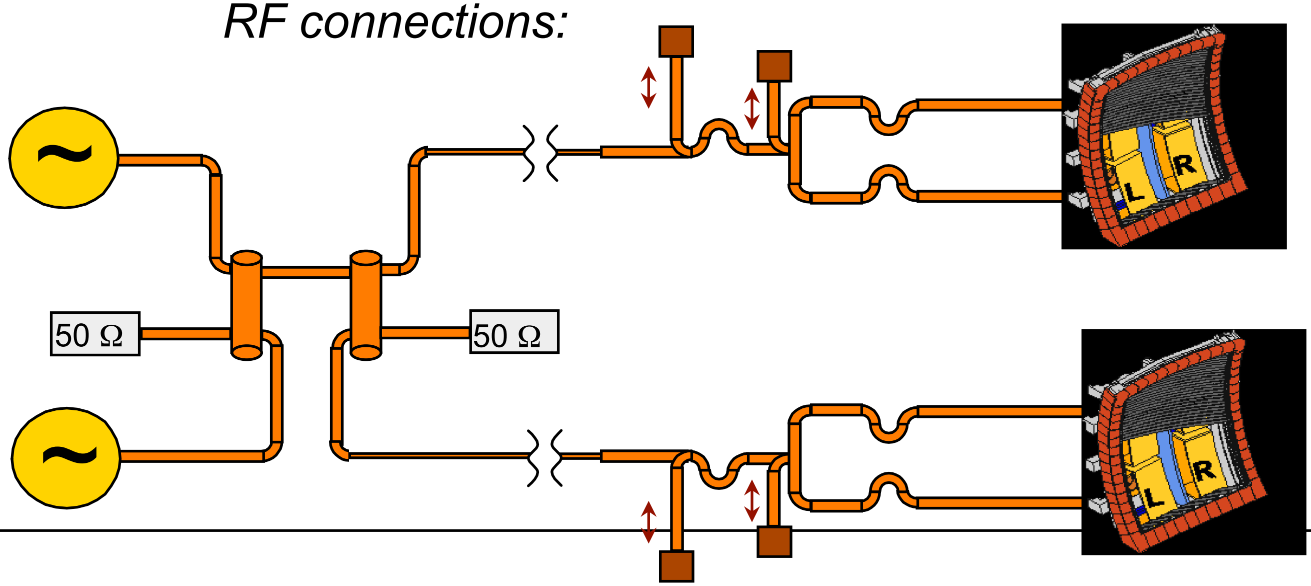
RF connections:



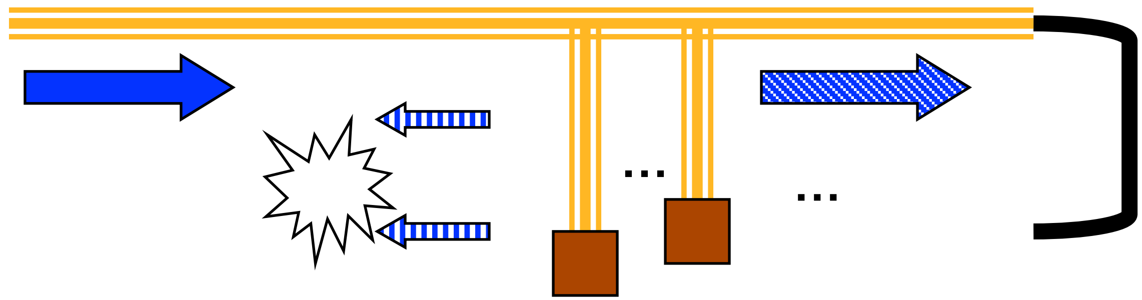


Matching network

RF connections:

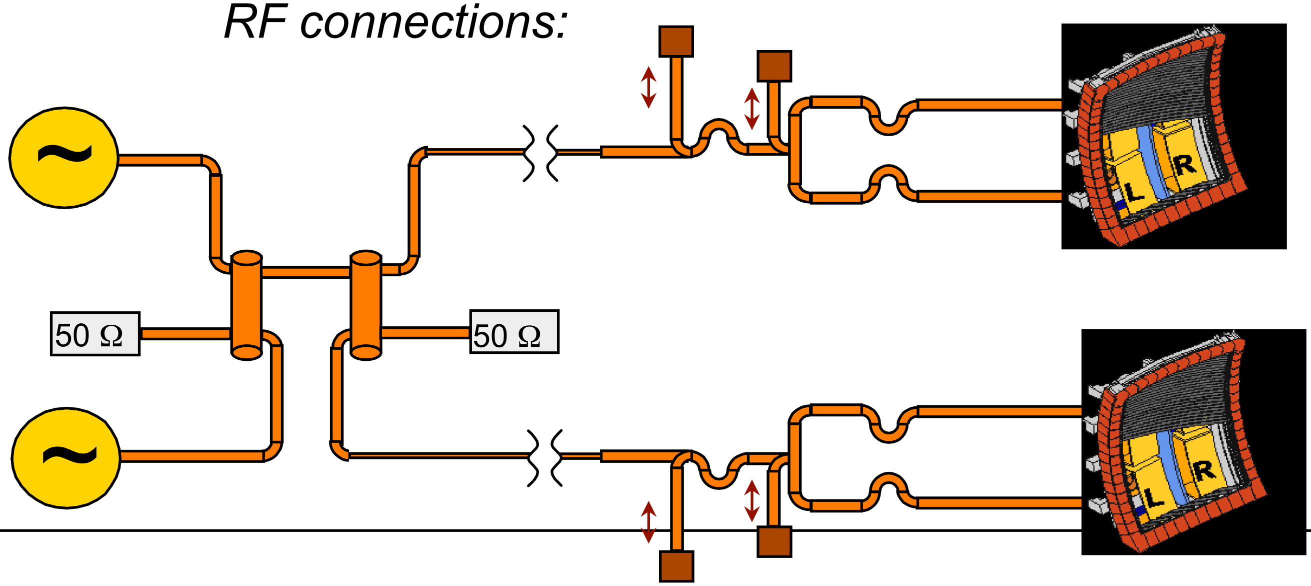


Real and imaginary part

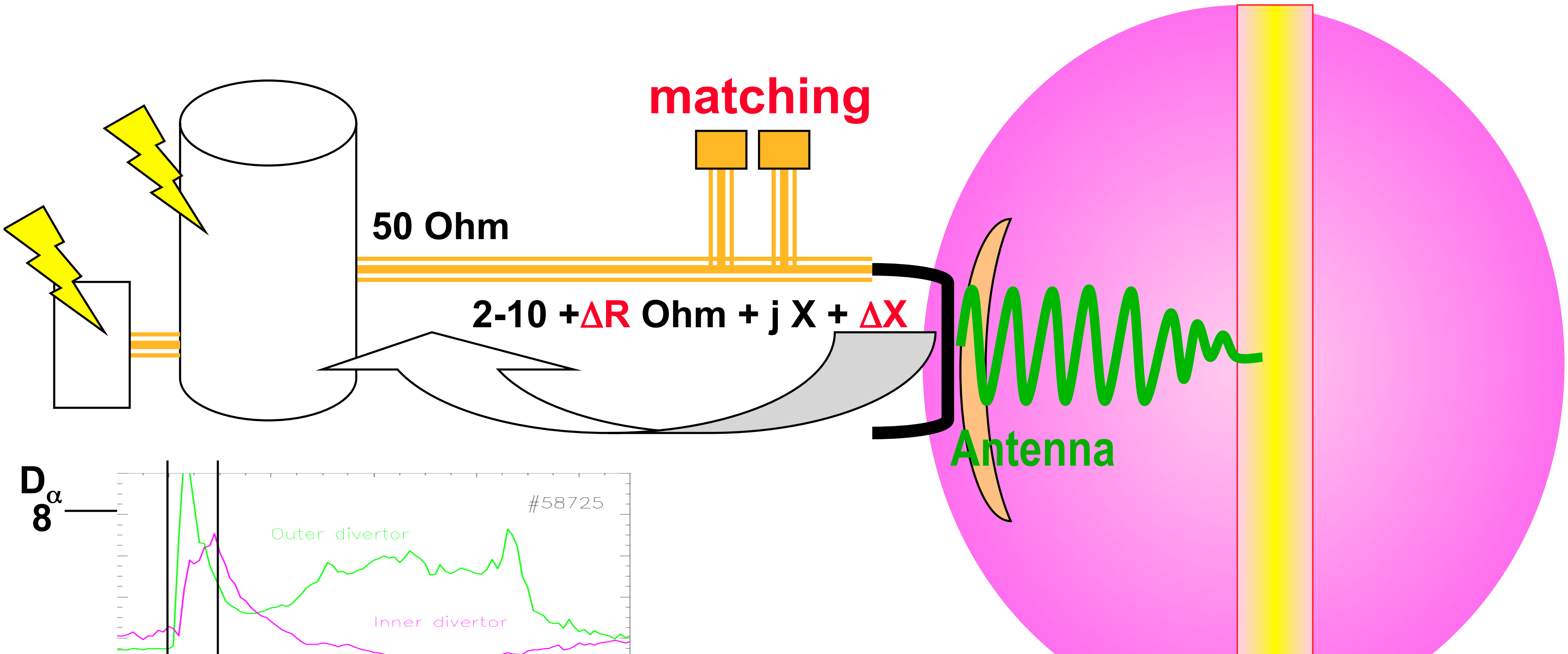


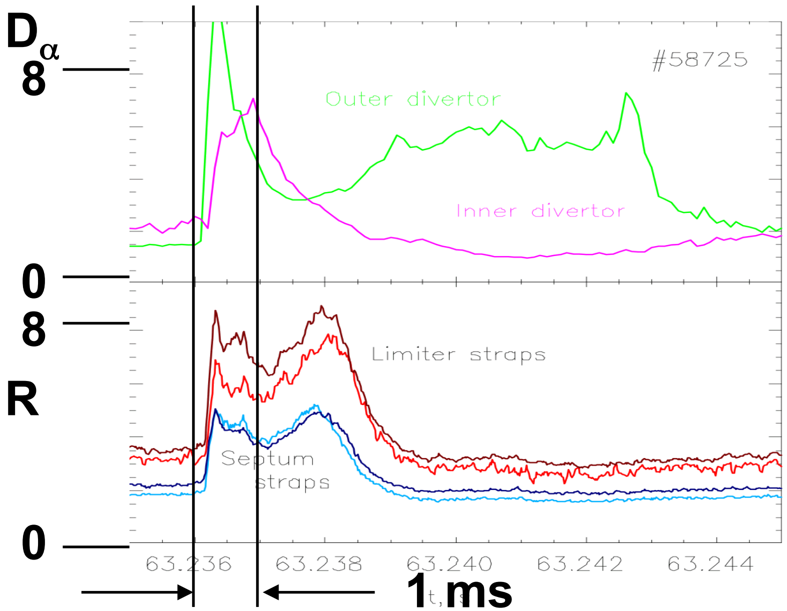
Matching network

RF connections:



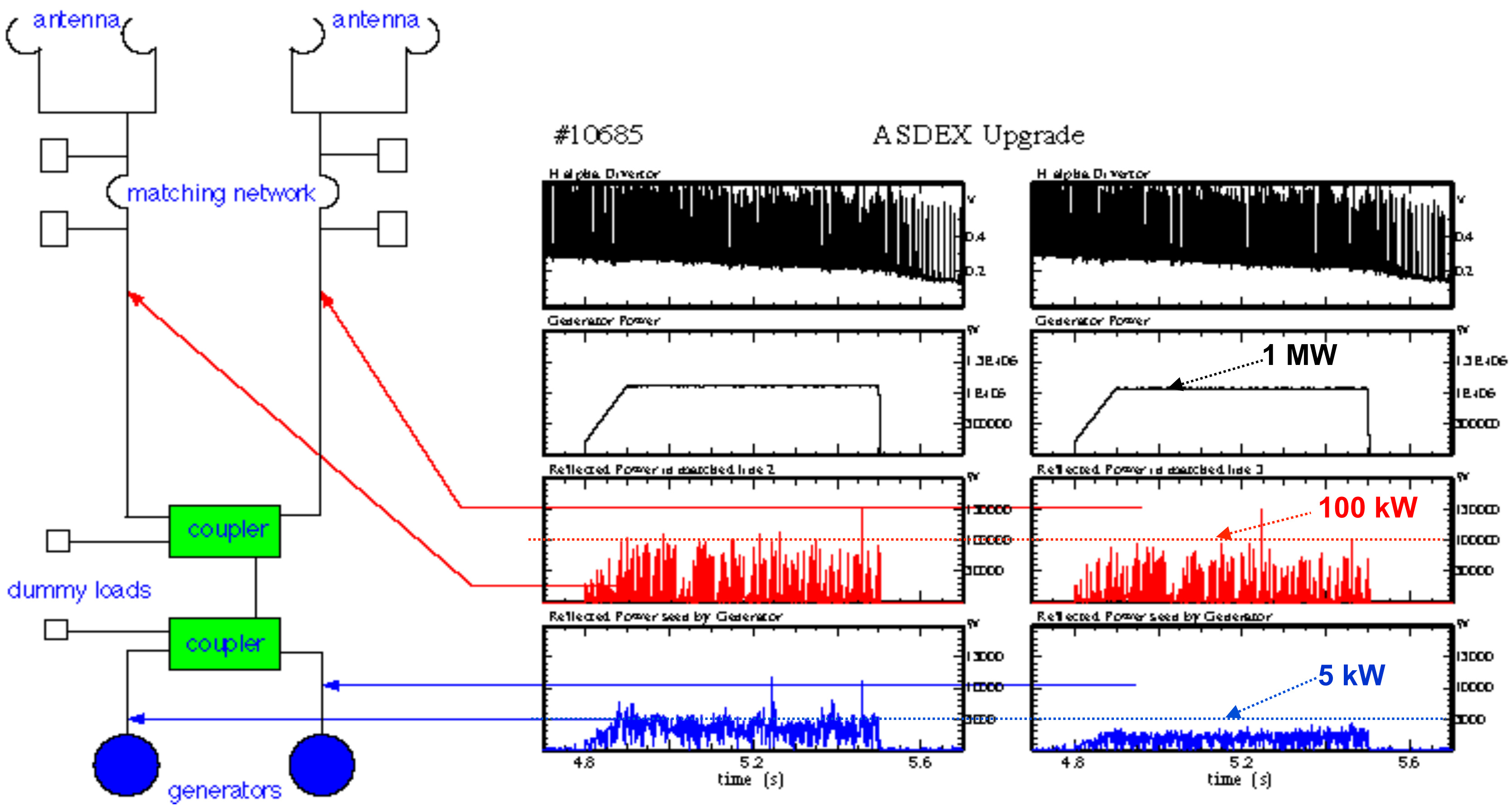
Dynamic matching or load isolation necessary





- **timescales of variations**
  - **particle/energy confinement time** **ms to s**
  - **MHD events** **100μs**

3 dB couplers for ELM resilience



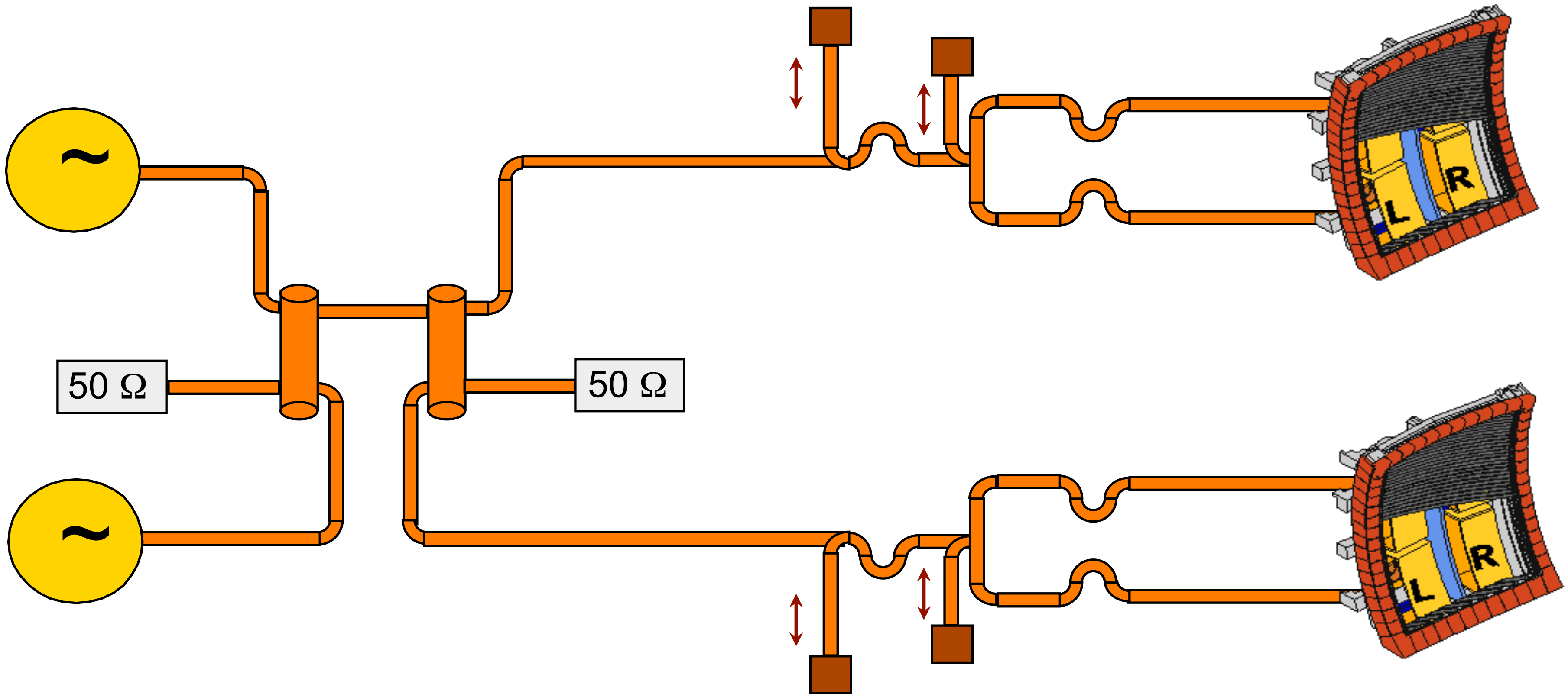
H_α

Power to antenna

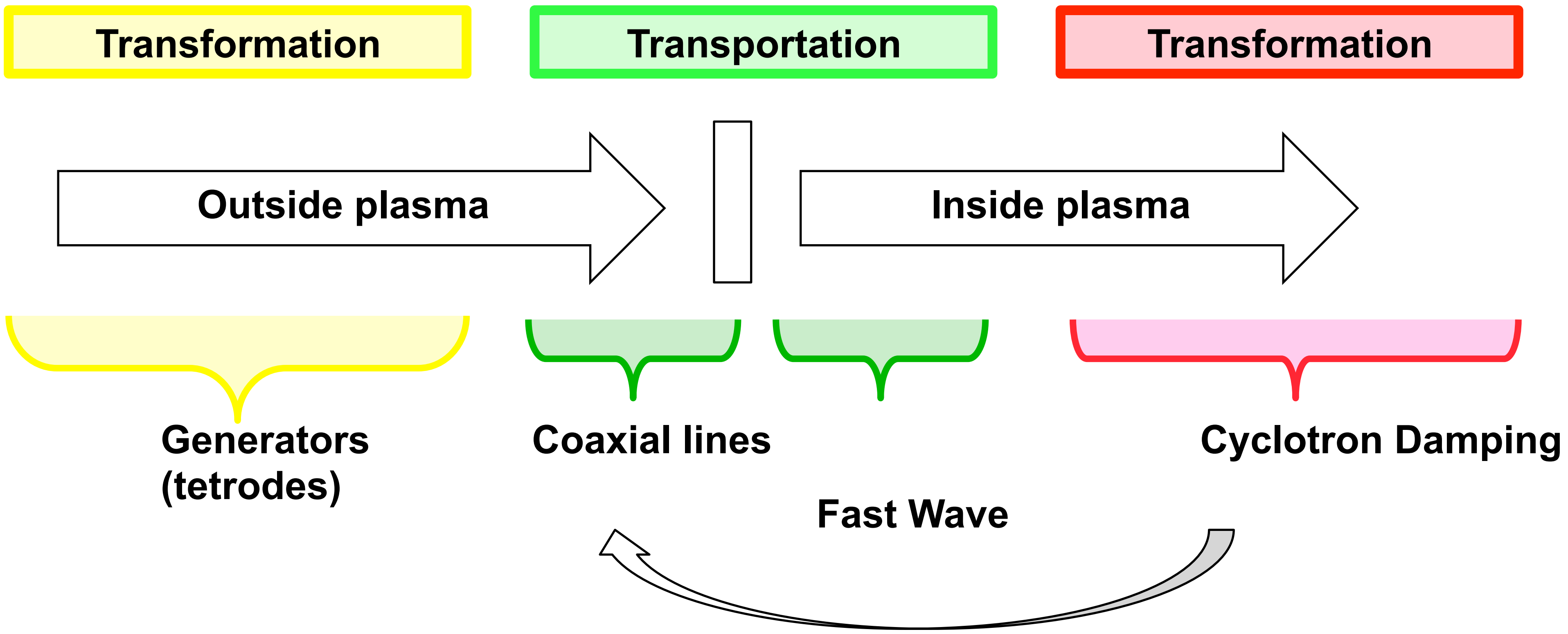
Reflected power

Reflected power at generator

Transmission lines
3 dB couplers and dummy loads



ICRF


Transformation
Transportation
Transformation
Outside plasma
Inside plasma
Generators
(tetrodes)
Coaxial lines
Cyclotron Damping
Fast Wave

Summary EM heating methods

- for power to be absorbed into the plasma it must first get there
- wave propagation: range of frequencies
  - Electron cyclotron
  - Lower Hybrid
  - Ion cyclotron
- absorption in plasma: wave - particle interaction
  - cyclotron damping, also at harmonics
  - Landau damping
- very large number of possibilities, not just heating
  - current drive
  - control of instabilities
  - …

Summary EM heating methods

- one must also be able to generate and transport the power

- Non trivial, examples

  - Negative ions
  - Gyrotron: high frequency, small dimensions
  - LH antenna: PAM
  - ICRF: generators and transmission lines

Remember: 4 steps

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Transformation | **Transportation** | **Transformation**

Outside plasma → | ← Inside plasma →

Electricity -> other form

- fast particles
- electromagnetic oscillations

Transport

(outside part)

- Duct
- optical, waveguides, coaxial and antenna

(inside part)

- Beam
- waves

To plasma particles

- Ionisation
- wave/particle