Plasma Heating

Dirk Hartmann

IPP Summer School 2016

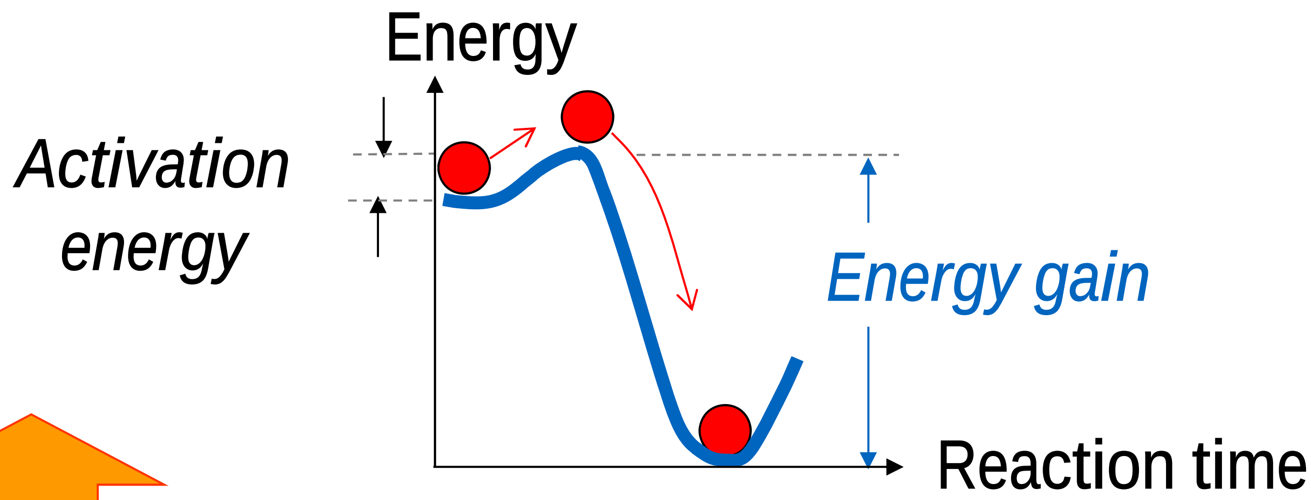
Analogy: coal oven - fusion oven

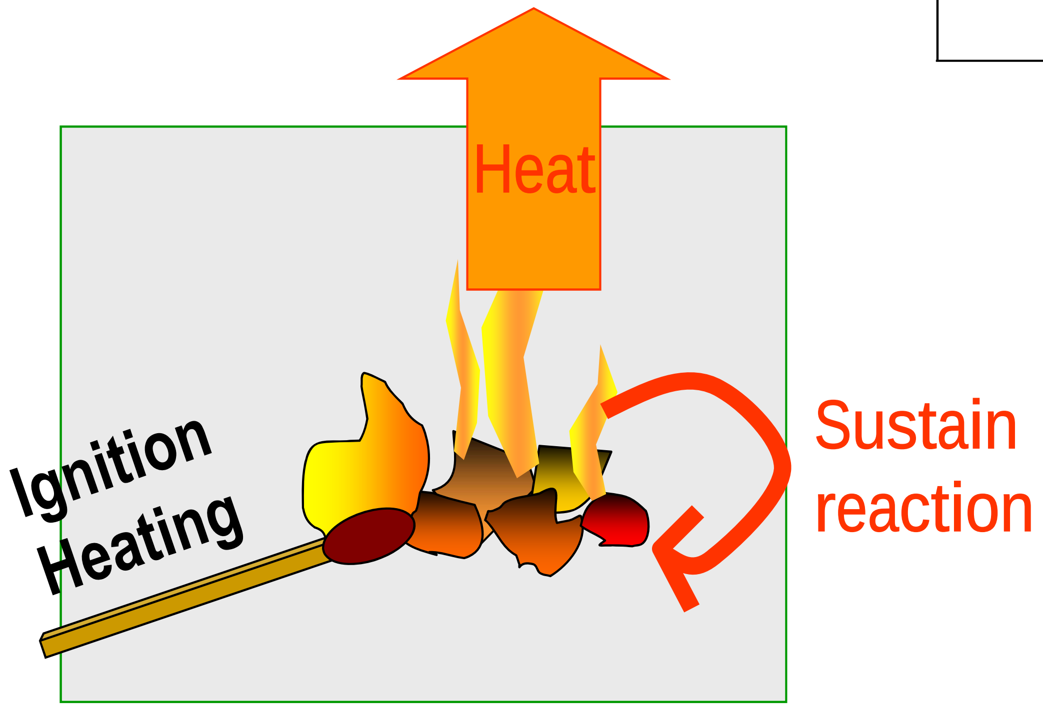
Coal oven

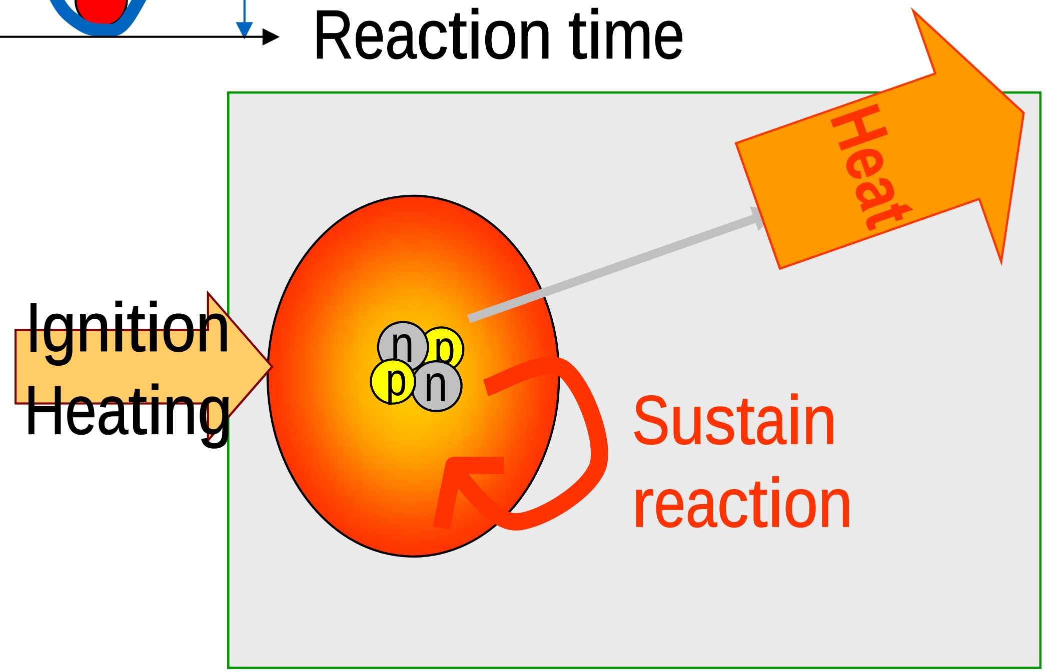
$C + O_2 \rightarrow \boxed{CO_2} + \text{Heat}$

Fusion oven

$D + T \rightarrow \boxed{He^4} + n + \text{Heat}$

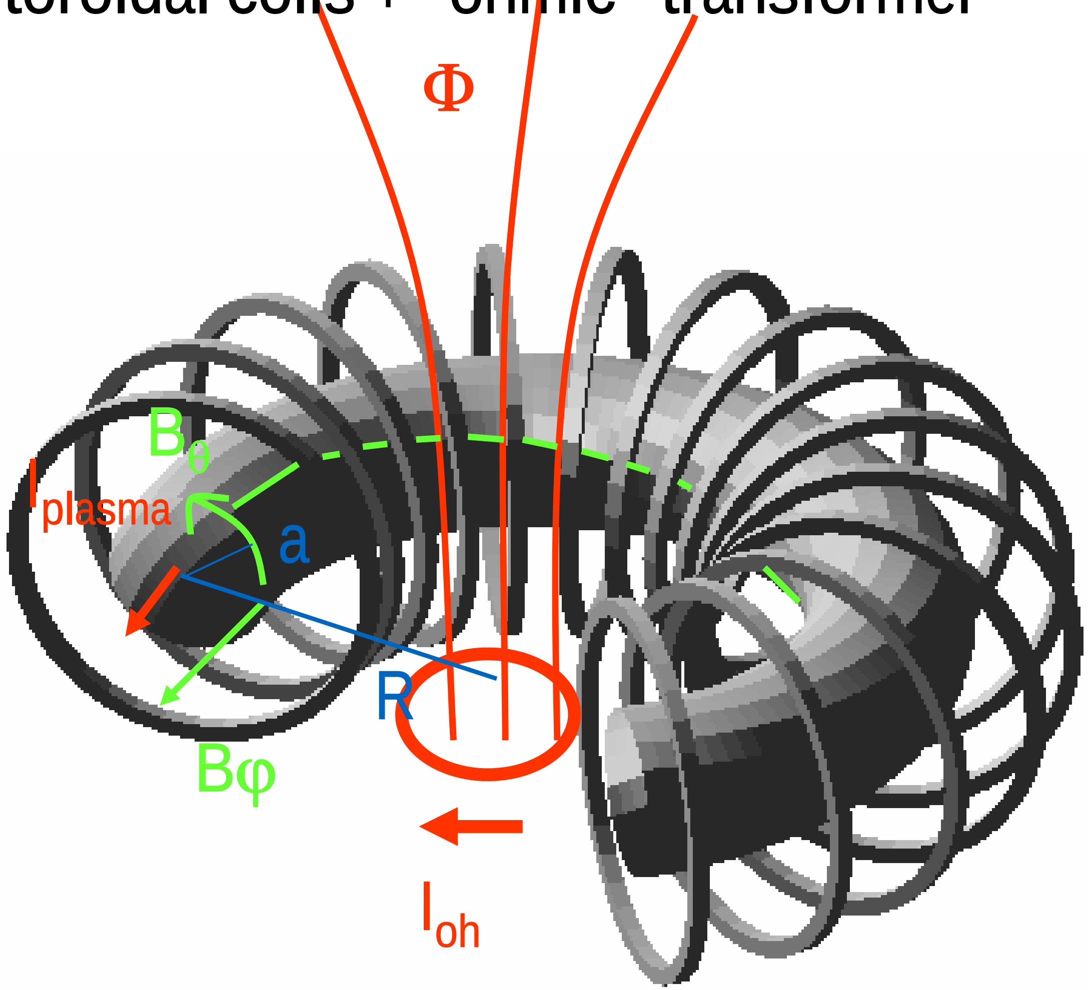






Tokamak

toroidal coils + “ohmic” transformer



Plasma resisitivity: $\eta \propto T_e^{-3/2}$

Dissipated power density: $p = \eta \cdot j^2$

Plasma stability requires:

$$q_{r=a} = \frac{a \cdot B_\varphi}{R \cdot B_\theta} \geq 2$$

Therefore: $j \leq \frac{B_\varphi}{\mu_0 \cdot R}$

Plasma current necessary for confinement sufficient for heating?

Even in tokamak maximum current limited.

Ohmic Heating

Dominant loss mechanism: bremsstrahlung loss power p_b.

$$p_b = 3.2 \cdot 10^{-37} \cdot Z^2 \cdot n_e^2 \cdot \sqrt{T_e} \qquad [\mathrm{Wm}^{-3}, \mathrm{m}^{-3}, \mathrm{keV}]$$

Ohmic heating power: $p_{oh} = \eta \cdot j^2$

$$T_e = \frac{2 \cdot 10^{20}}{n_e} \cdot \frac{1}{Z} \cdot \frac{B_\varphi}{R} \qquad [\mathrm{keV}, \mathrm{m}^{-3}, \mathrm{T}, \mathrm{m}]$$

Ohmic heating alone: T_e only a few keV

$\rightarrow$ need additional heating power!

The need for plasma heating

In fusion reactor:	provide initial heating for ignition	50-100 MW
	influence plasma properties	20 MW
In experiments:	sustain plasmas at relevant T	<40 MW
	simulate α-particle heating	
	study plasma transport properties	

Neutral Beam Injection	heating of plasma ions
Ion Cyclotron Resonance Heating	heating of ions and electrons
Lower Hybrid Heating	heating of electrons, current
Electron Cyclotron Resonance Heating	heating of electrons
α-particle Heating	mainly electrons

α-Particle Heating

D-T fusion reaction: $$D + T \rightarrow \underbrace{n\,(14.1\,\mathrm{MeV})}_{\text{leaves plasma}} + \underbrace{He^4\,(3.5\,\mathrm{MeV})}_{\substack{\text{heats plasma}\\ \text{if sufficiently long}\\ \text{confined}}}$$

Heating power density: $= 0.2 \cdot n_D \cdot n_T \cdot \langle \sigma v \rangle \cdot E$

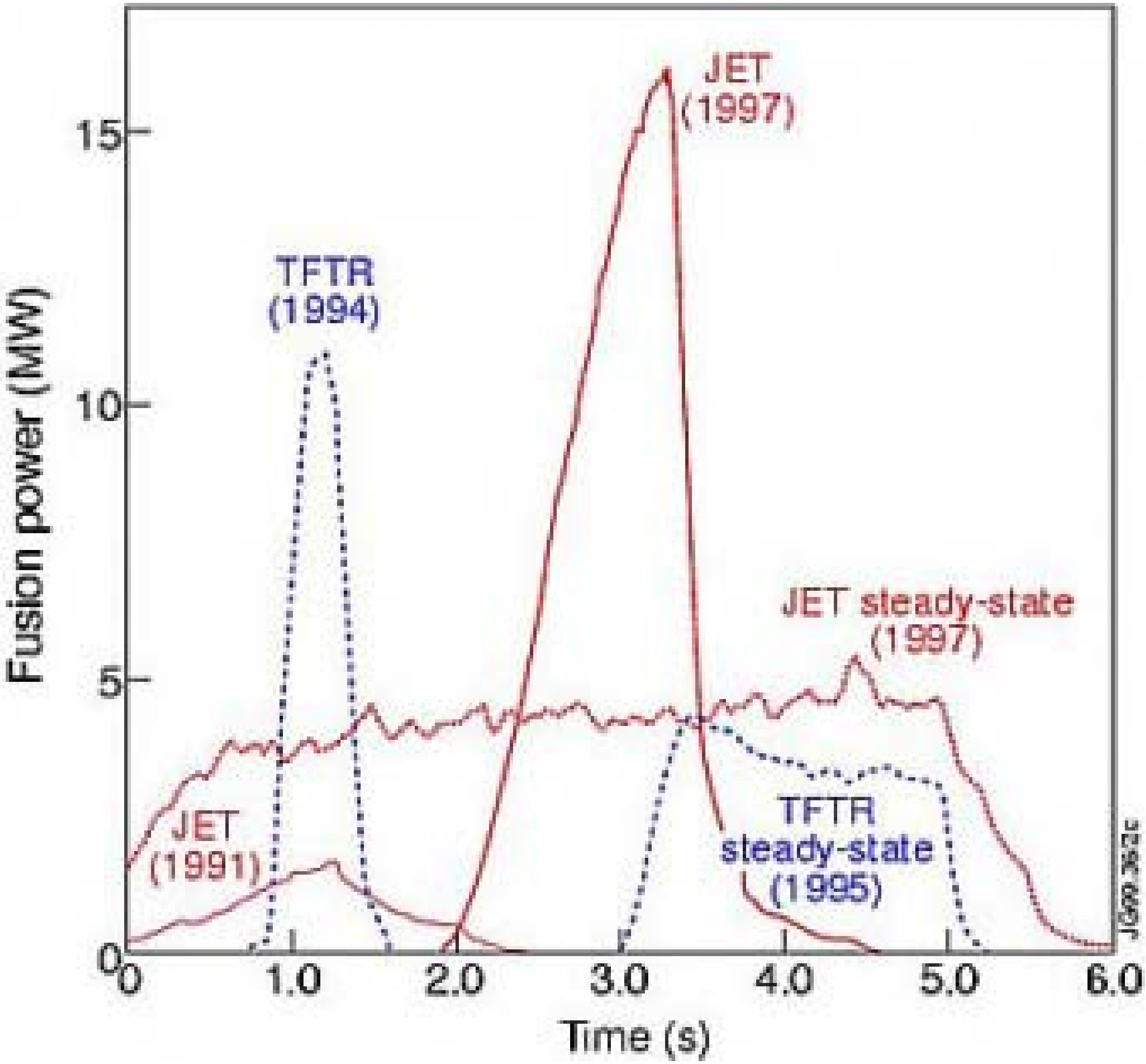
$$\langle \sigma v \rangle \propto T_i$$

$\Rightarrow$ peaked heating profile

α-particles need to be well confined through
large plasma currents in tokamaks
optimized stellarator fields

Loss mechanisms: field ripples
MHD events

D, T experiments only done on JET and TFTR



Overview

Waves	dispersion relation cold plasma warm plasma
Plasma heating	NBI heating EM wave heating current drive

Plasma Waves

Motivation to study plasma waves

diagnostic	density
	electron (and ion) temperature
	small scale structures
	magnetic field
heating	electron heating
	ion heating
confinement	macroscopic current drive

Plane waves

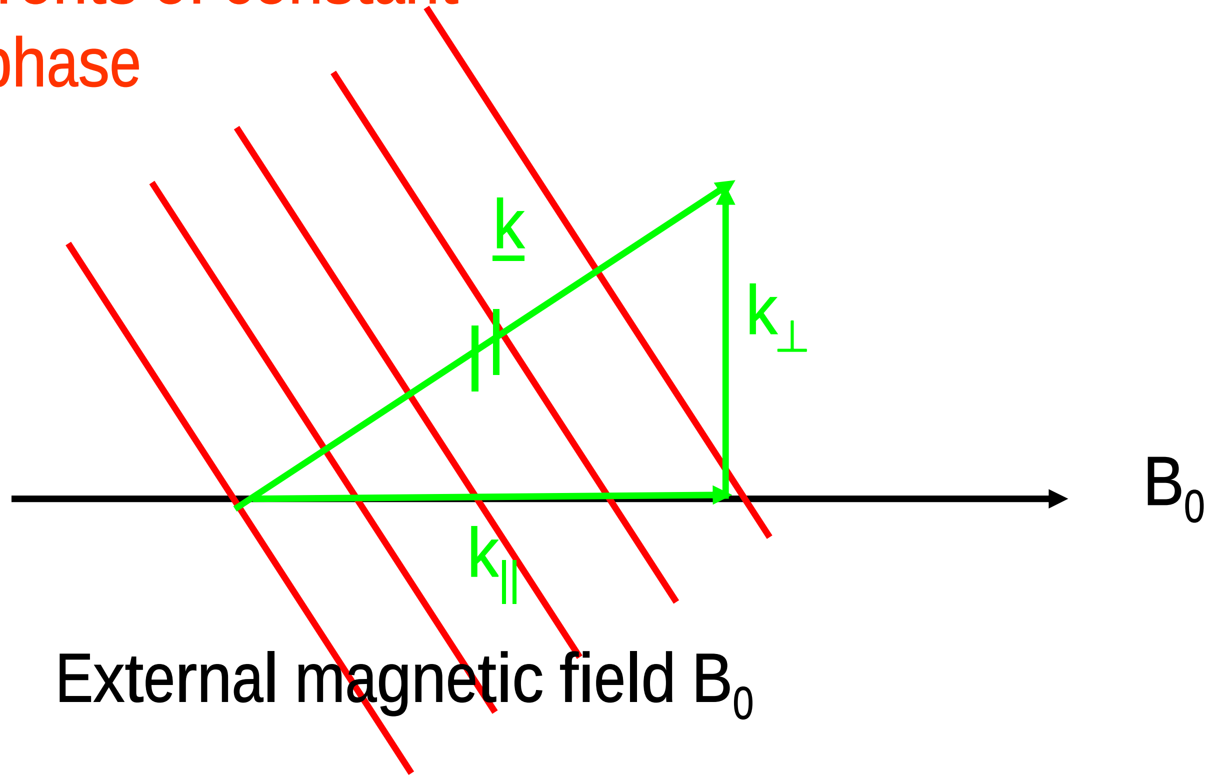
$$\tilde{E}(\underline{r},t) = \sum_{\omega,\underline{k}} \tilde{E}_{\omega,\underline{k}}\, e^{i\underline{k}\underline{r} - i\omega t}$$

$\underline{k}$: wave vector

ω : angular frequency

Plane waves

fronts of constant phase



External magnetic field B_0

$$v_{ph} = \frac{\omega}{k} \text{ : phase velocity}$$

$$N = \frac{c}{v_{ph}} = \frac{c \cdot \omega}{k} \text{ : refractive index}$$

ω fixed by „generator“
k response of plasma

goal: derive k=k(ω)

equivalent to: solve dispersion relation D(ω,k)=0

Wave Equation

Plane waves

Maxwell's Equations

$$\nabla \times \underline{E} = \frac{\partial \underline{B}}{\partial t} \qquad i\underline{k} \times \underline{E} = -i\omega \underline{B}$$

$$\nabla \times \underline{H} = \varepsilon_0 \frac{\partial \underline{E}}{\partial t} + \underline{j} \qquad i\underline{k} \times \underline{H} = -i\omega\varepsilon_0 \underline{E} + \underline{j}$$

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

$$\nabla \cdot \underline{B} = 0 \qquad i\underline{k} \cdot \underline{B} = 0$$

generalized Ohm's law $\underline{j} = \underline{j}(\underline{E}, \underline{B})$ $\qquad \underline{j}_{\omega,\underline{k}} = \underline{\underline{\sigma}}(\omega, \underline{k}) \cdot \underline{E}_{\omega,\underline{k}}$

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

$$\underline{k} \times \left(\underline{k} \times \underline{E}_{\omega,\underline{k}}\right) + \frac{\omega^2}{c^2} \underline{\underline{K}} \cdot \underline{E}_{\omega,\underline{k}} = 0 \qquad \underline{\underline{K}} = \underline{\underline{1}} + \frac{\underline{\underline{\sigma}}}{i\omega\varepsilon_0}$$

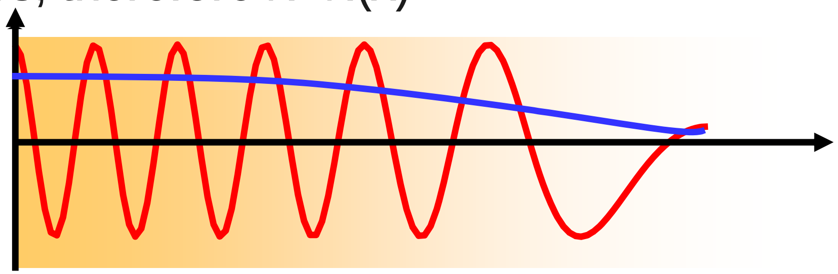
$\underline{\underline{K}}$: dielectric tensor

Disperison relation $\quad \det\left[\underline{N} \times \left(\underline{N} \times \underline{\underline{1}}\right) + \underline{\underline{K}}(\omega, \underline{N})\right] = 0$

resonances and cutoffs

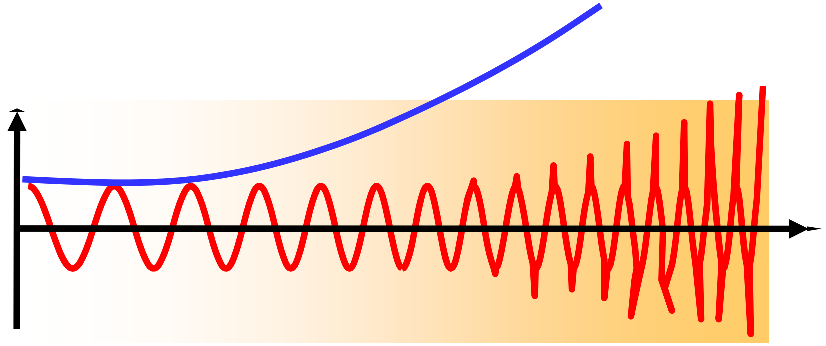
N depends on plasma parameters, therefore N=N(x)

1. $N \rightarrow 0$ „cutoff“



reflexion
tunnelling
v_{ph}>c!

2. $N \rightarrow \infty$ „resonance“



v_{gr} -> 0
wave „gets stuck“
wave energy
dissipation

Ohm's law

Goal: determine j=j(E)

Small perturbation

$$\underline{v} = \cancelto{0}{\underline{v}_0} + \underline{v}_1$$
$$\underline{E} = \cancelto{0}{\underline{E}_0} + \underline{E}_1$$
$$\underline{B} = \underline{B}_0 + \underline{B}_1$$

Lorenz force

cold plasma

$$\frac{d\underline{v}}{dt} = \frac{q_s}{m_s} \cdot (\underline{E} + \underline{v} \times \underline{B})$$

$$-i\omega \underline{v}_1 = \frac{q_s}{m_s} \cdot \left(\underline{E}_1 + \underline{v}_1 \times \underline{B}_0\right)$$

$$\left|\frac{k_\perp v_{th}}{\Omega_s}\right|^2 << 1 \qquad \left|\frac{\omega - n\Omega_s}{k_{||} v_{th}}\right|^2 >> 1$$

$$\underline{j}_1 = \sum_s q_s n_s \underline{v}_{1,s}$$

Vlasov equation

warm plasma

$$\partial_t f + \underline{v} \partial_x f + \frac{q_s}{m_s} \left(E + v \times B\right) = 0$$

$$f_1 = \ldots$$

$$\underline{j}_1 = \sum_s q_s \int \underline{v} \cdot f_1(v) d^3 v$$

Further: Relativistic plasmas, nonlinear waves, …

cold plasma, no magnetic field

Ions immobile, i.e. frequencies too high:

$$\underline{j} = -en\underline{v}$$

$$-i\omega\underline{v} = \frac{-e\cdot\underline{E}}{m_e}$$

$$\underline{j} = \frac{-i\cdot e^2 n_e}{m_e\omega}$$

Plasma frequency: $\omega_{p,e}^2 = \frac{e^2 n_e}{\varepsilon_0 m_e}$

$$K = 1 + \frac{\sigma}{i\omega\varepsilon_0} = 1 - \frac{\omega_p^2}{\omega^2}$$

$$(\underline{k}\cdot\underline{E})\underline{k} - k^2\underline{E} + \frac{\omega^2}{c^2}\left(1 - \frac{\omega_p^2}{\omega^2}\right)\underline{E} = 0$$

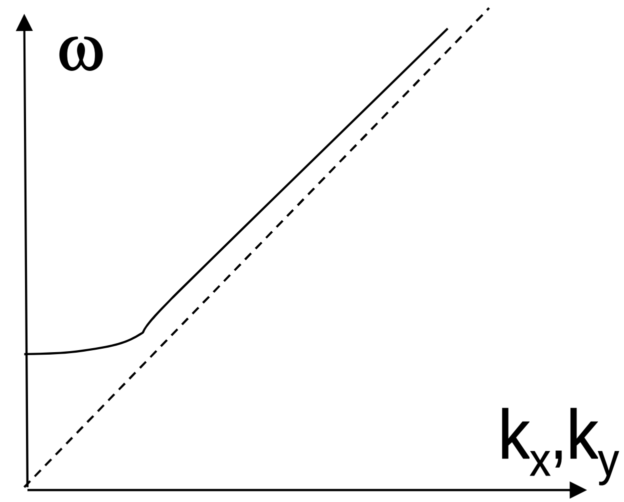
$\underline{k} \,||\, \underline{E}$: Langmuir waves $\omega = \omega_p$ No energy propagation!

$\underline{k} \perp \underline{E}$: EM waves

$$N^2 = \frac{c^2 k^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2}$$

2 solutions $E_x \neq 0$

$E_y \neq 0$



Cold plasma with magnetic field

Rectangular coordinate system, external magnetic field B_0 along z-axis

$$\underline{\underline{K}} = \begin{pmatrix} K_{xx} & K_{xy} & 0 \\ K_{yx} & K_{yy} & 0 \\ 0 & 0 & K_{zz} \end{pmatrix}$$

$$K_{xx} = K_{yy} = 1 - \sum_s \frac{\omega_{ps}^2}{\omega^2 - \omega_{cs}^2}$$

$$K_{zz} = 1 - \sum_s \frac{\omega_{ps}^2}{\omega^2}$$

$$K_{xy} = -K_{yx} = i \sum_s \frac{\omega_{cs}}{\omega} \cdot \frac{\omega_{ps}^2}{\omega^2 - \omega_{ps}^2}$$

Signed Gyration frequency: $\omega_{cs} = \frac{q_s B_0}{m_s}$

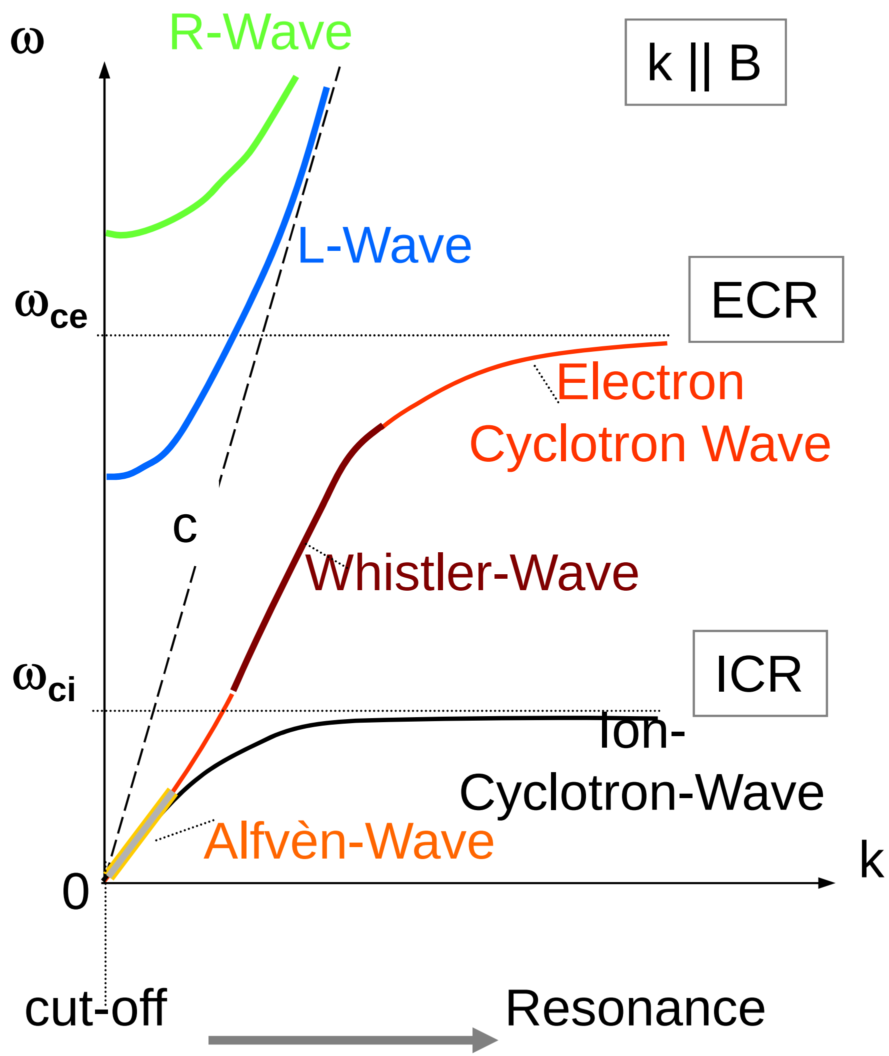
$$\begin{pmatrix} K_{xx} - N_z^2 & K_{xy} & N_x N_z \\ K_{yx} & K_{yy} - N_x^2 - N_z^2 & 0 \\ N_x N_z & 0 & K_{zz} - N_x^2 \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} = 0$$

Dispersion relation: det (...)=0 !

Cold plasma: parallel propagation

$N_x=0$

$$\left\| \begin{pmatrix} K_{xx}-N_z^2 & K_{xy} & 0 \\ K_{yx} & K_{yy}-N_z^2 & 0 \\ 0 & 0 & K_{zz} \end{pmatrix} \right\| = 0$$



2 solutions:

$$N_{z1,2}^2 = K_{xx} \pm iK_{xy}$$

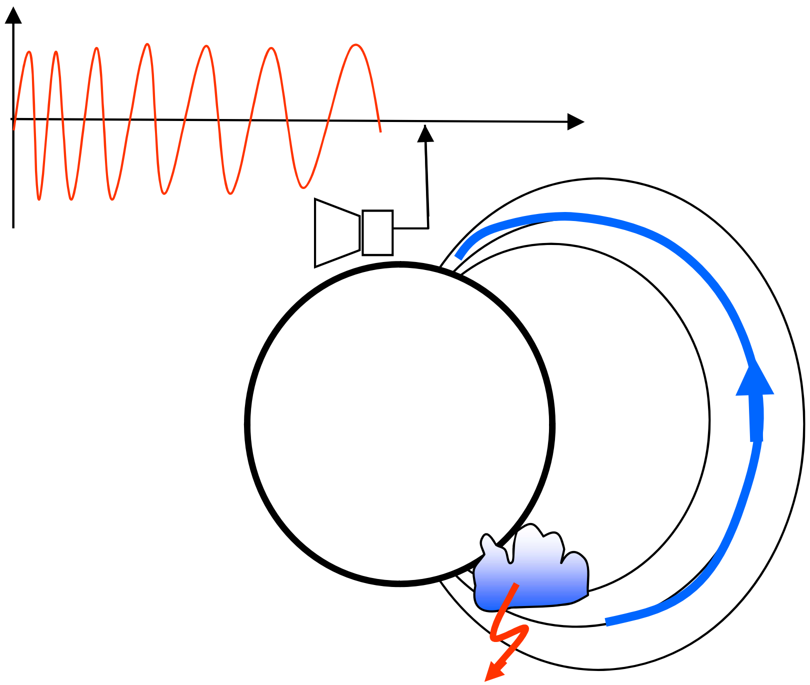
Polarization: $$\frac{E_x}{E_y} = \pm i$$

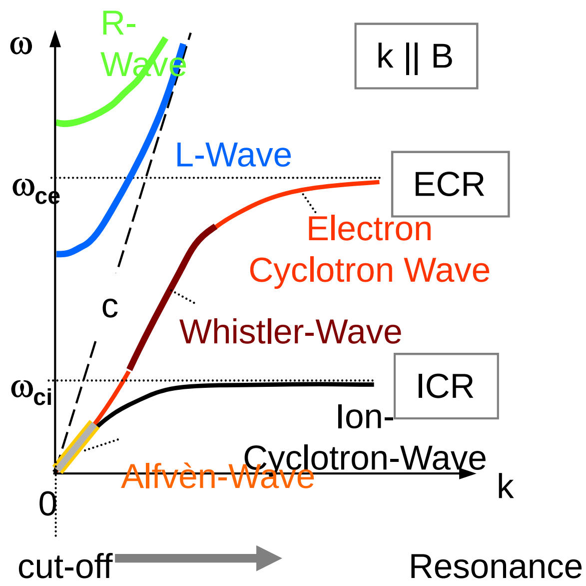
Whistler Waves

Discovered during WW I:

chriping sound

electromagnetic disturbances in the audio frequencies



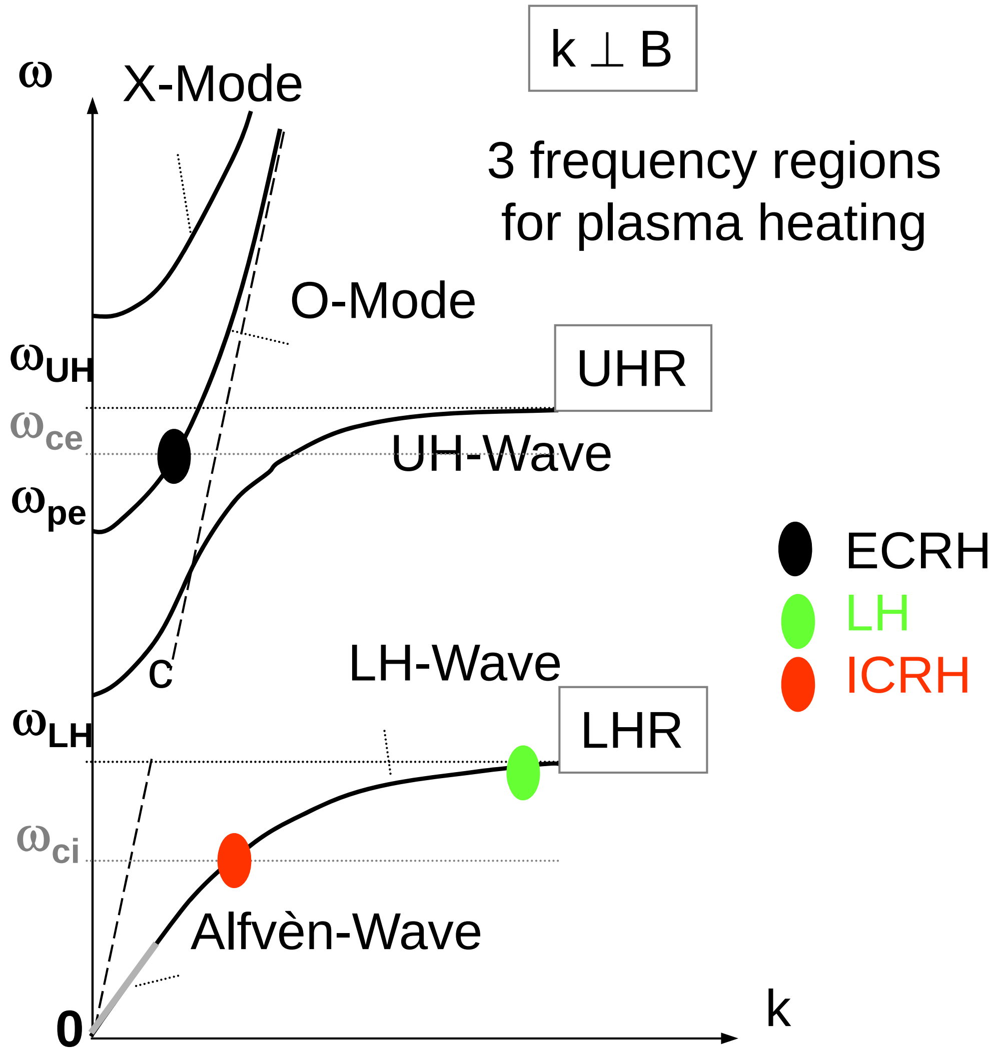


Group velocity $\quad v_{gr} = \dfrac{d\omega}{dk} \propto \sqrt{\omega}$

Cold plasma - perpendicular propagation

$N_z=0$

$$\left\| \begin{pmatrix} K_{xx} & K_{xy} & 0 \\ K_{yx} & K_{yy}-N_x^2 & 0 \\ 0 & 0 & K_{zz}-N_x^2 \end{pmatrix} \right\| = 0$$



2 solutions:

$E \parallel B_0$: Ordinary wave $N_{x1}^2 = 1 - \frac{\omega_p^2}{\omega^2}$

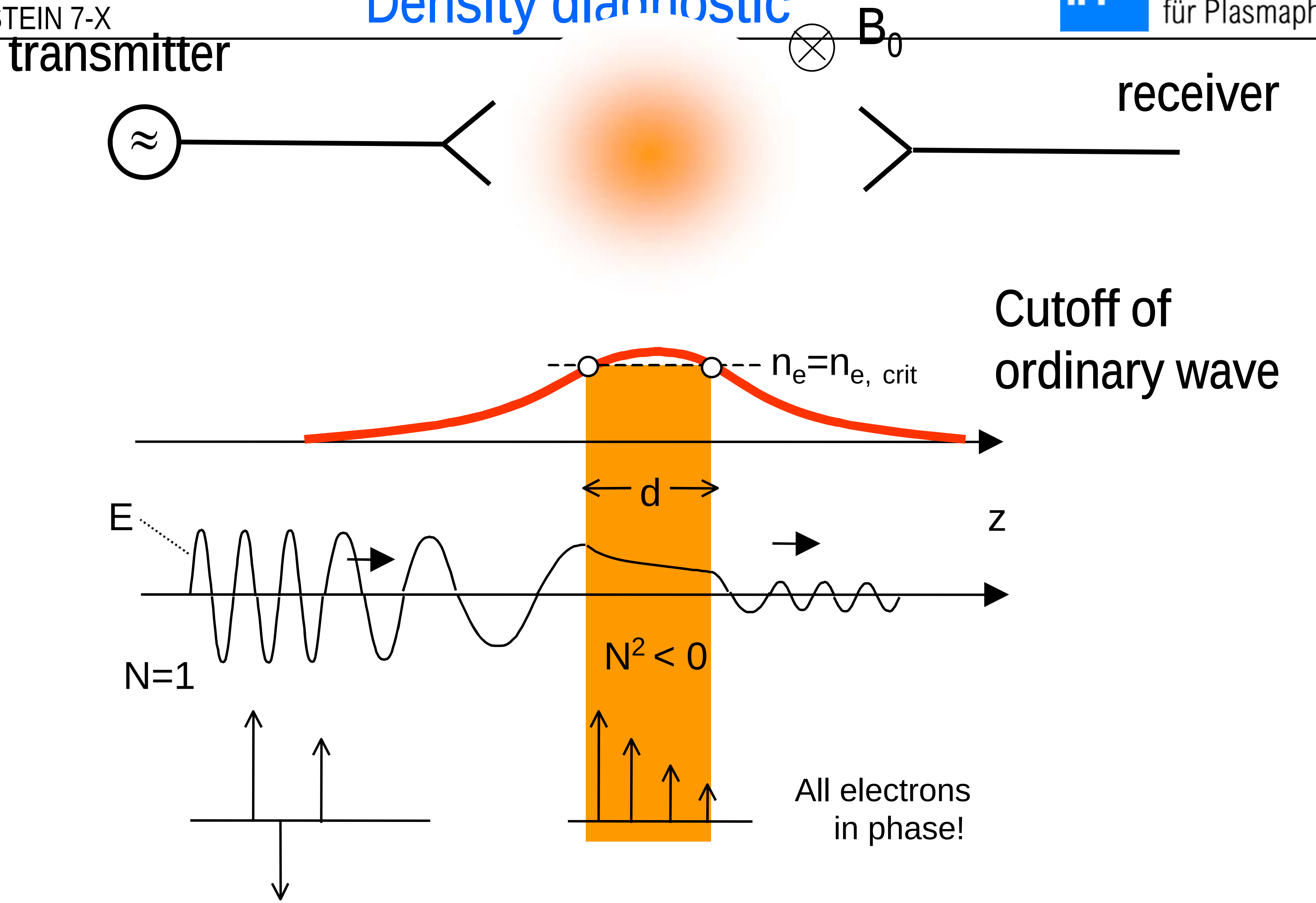
$E \perp B_0$: Extraordinary wave

$$N_{x2}^2 = \frac{\left(\omega^2-\omega_{c01}^2\right)\left(-\omega_{c02}^2\right)}{\left(\omega^2-\omega_{lh}^2\right)\left(\omega^2-\omega_{uh}^2\right)}$$

ω_{lh} : Lower hybrid frequency

ω_{uh} : Upper hybrid frequency

Density diagnostic



Warm plasma

Cold plasma theory breaks down where

$$\left|\frac{k_\perp v_{th}}{\omega_c}\right|^2 \geq 1$$ Average gyro radius ≈ Perpendicular wavelength

or $$\left|\frac{\omega - n\omega_c}{k_{||} v_{th}}\right|^2 \leq 1$$ Wave-particle resonance

Linearized Vlasov equation:

$$\partial_t f_1 + \underline{v} \cdot \partial_x f_1 + \frac{q}{m}[\underline{v} \times \underline{B}_0]\partial_v f_1 = -\frac{q}{m}(\underline{E}_1 + \underline{v} \times \underline{B}_0)\partial_v f_0$$

-> Complicated form of K_{ij}

Now: „new“ set of waves: electrostatic waves for $k_z=0$

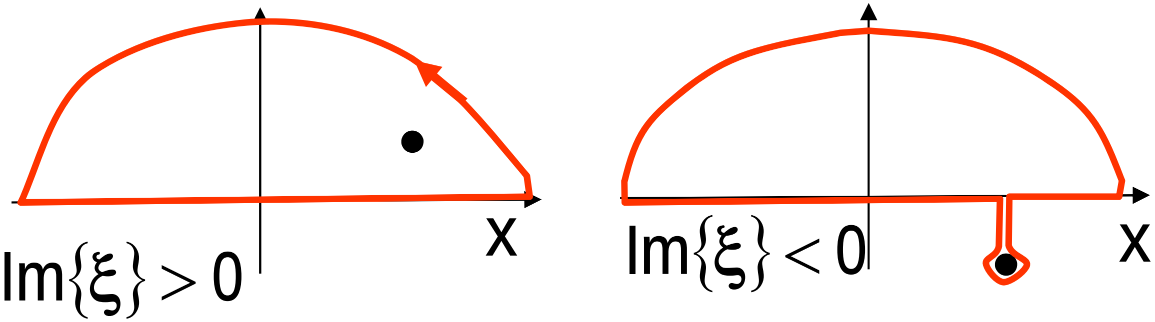
Plasma dispersion relation

For Maxwellian plasma $f_0(v) \propto e^{-v^2/v_{th}^2}$

$$Z(\xi) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{+\infty} \frac{e^{-x^2}}{x - \xi} dx$$

$$\xi_n = \frac{\omega - n\omega_c}{\sqrt{2} k_{||} v_{th}}$$

Integration path



Values of Z are complex

Thus disperison relation has complex solutions.

Waves are damped near regions where $\xi_n \approx 0$ Landau Damping

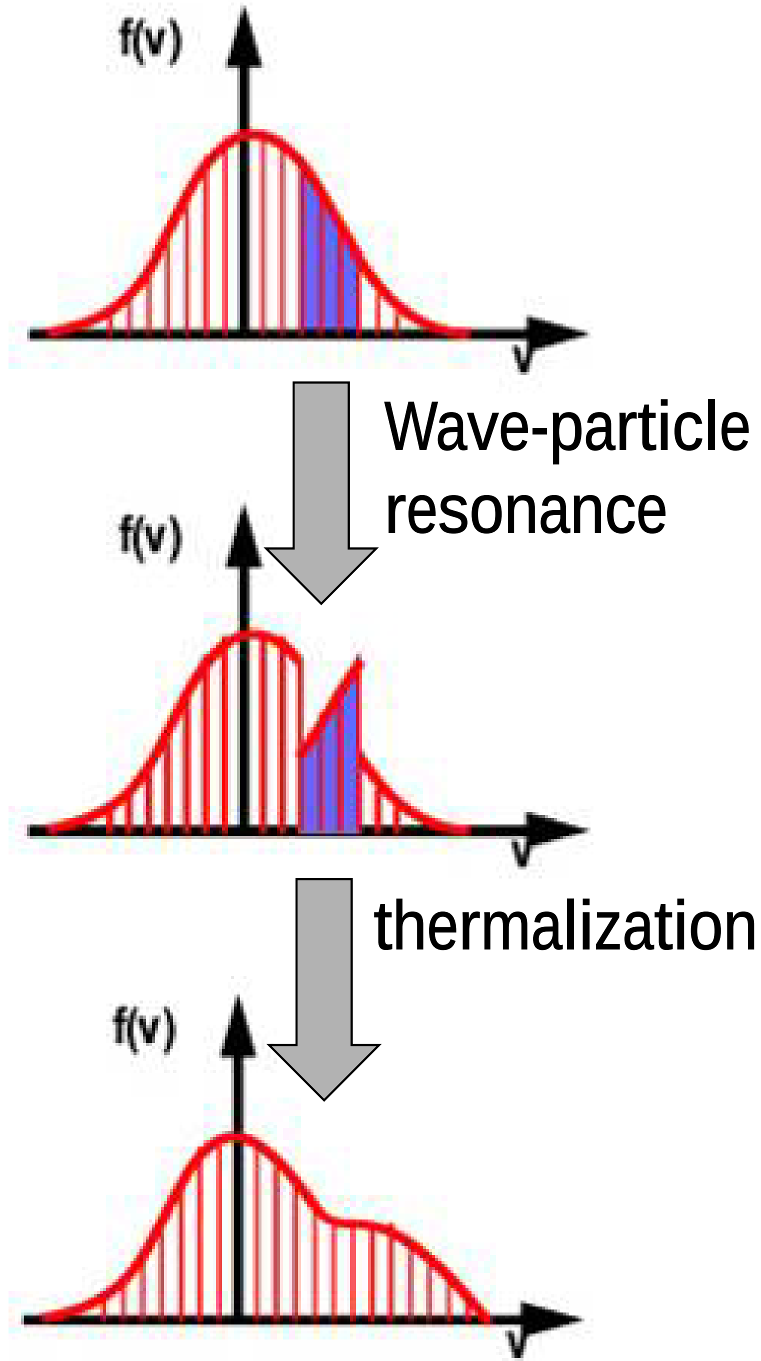
„collisional damping“

Wave damping mechanisms

ν: collision frequency

$\omega << \nu$: low temperature plasmas
collisional damping
all particles involved

$\omega >> \nu$: high temperature plasmas (fusion)
„collisionless“ damping
only some particles (ions, electrons) involved



Collisionless Wave Damping Mechanisms

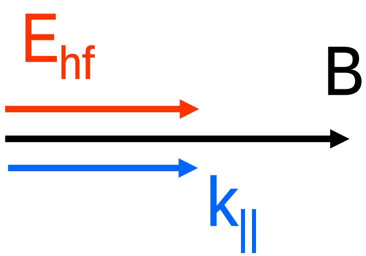
Damping on ions: electric EM wave field E_{hf}

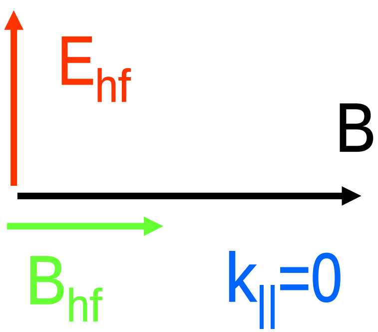
Damping on electrons: electric EM wave field E_{hf}

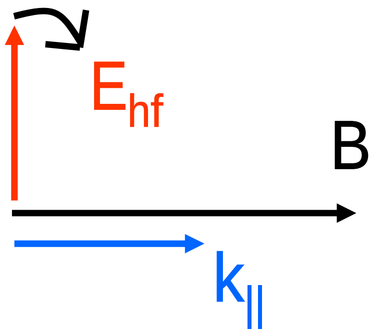
magnetic EM wave field B_{hf}

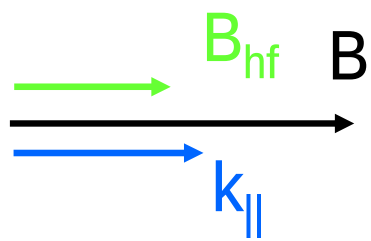
Damping efficient only at finite temperature.

Landau damping	Landau damping	Landau cyclotron damping	Transit time magnetic pumping







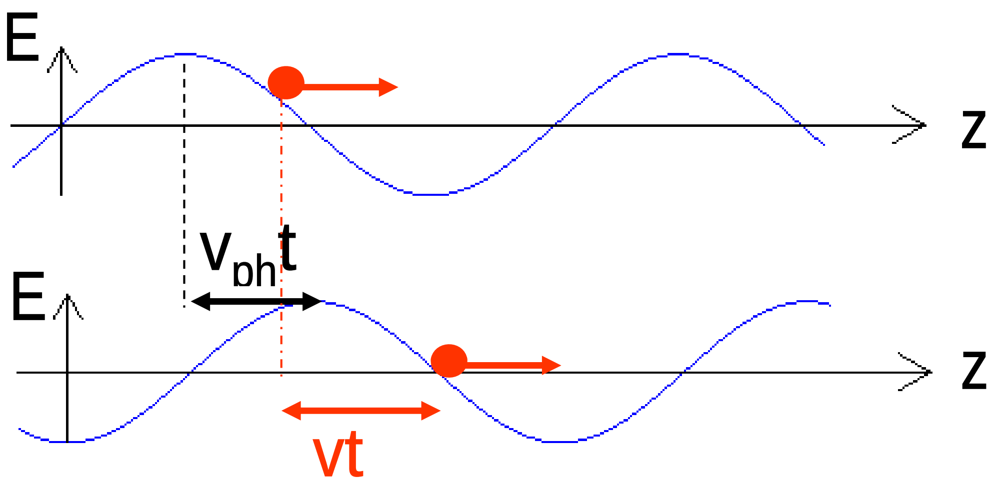


Landau Damping

(Electrostatic) waves, k || E

At t=0

At t=T/4



Strong wave-particle interaction if: $v_{ph}t = vt$

$$\Leftrightarrow \omega/k = v \Leftrightarrow \omega = vk$$

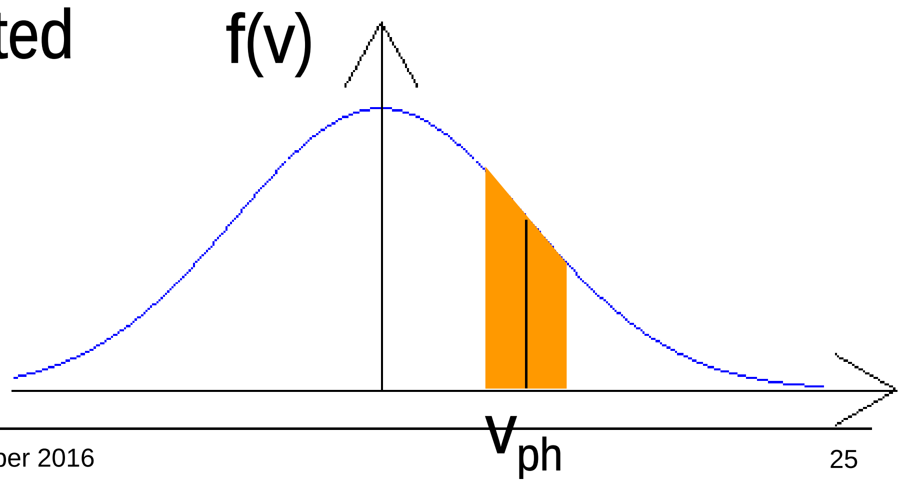
Group of resonant particles: $\left| v - \frac{\omega}{k} \right| \leq \frac{\lambda}{\tau_{coll}}$

On average: slower particles are accelerated
faster particles are decelerated

$$\left.\frac{\partial f}{\partial v}\right|_{v_{ph}} < 0$$

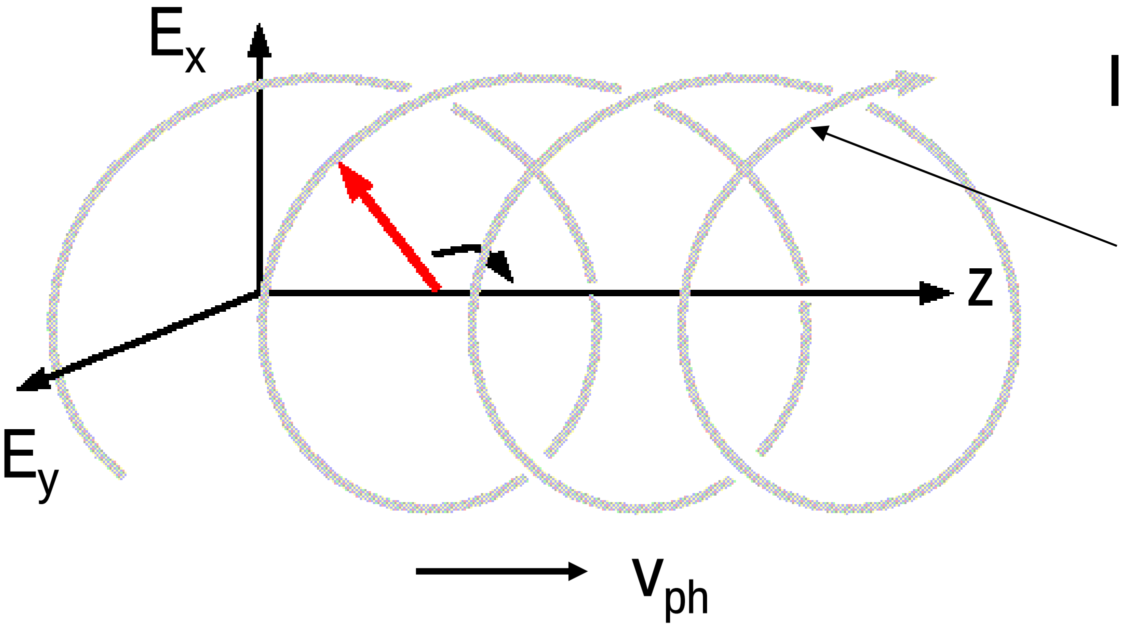
Net loss of wave energy

No collisions necessary!



Landau Cyclotron Damping

Electromagnetic wave $E \perp k$



left-handed polarized wave

tip of electric field vector

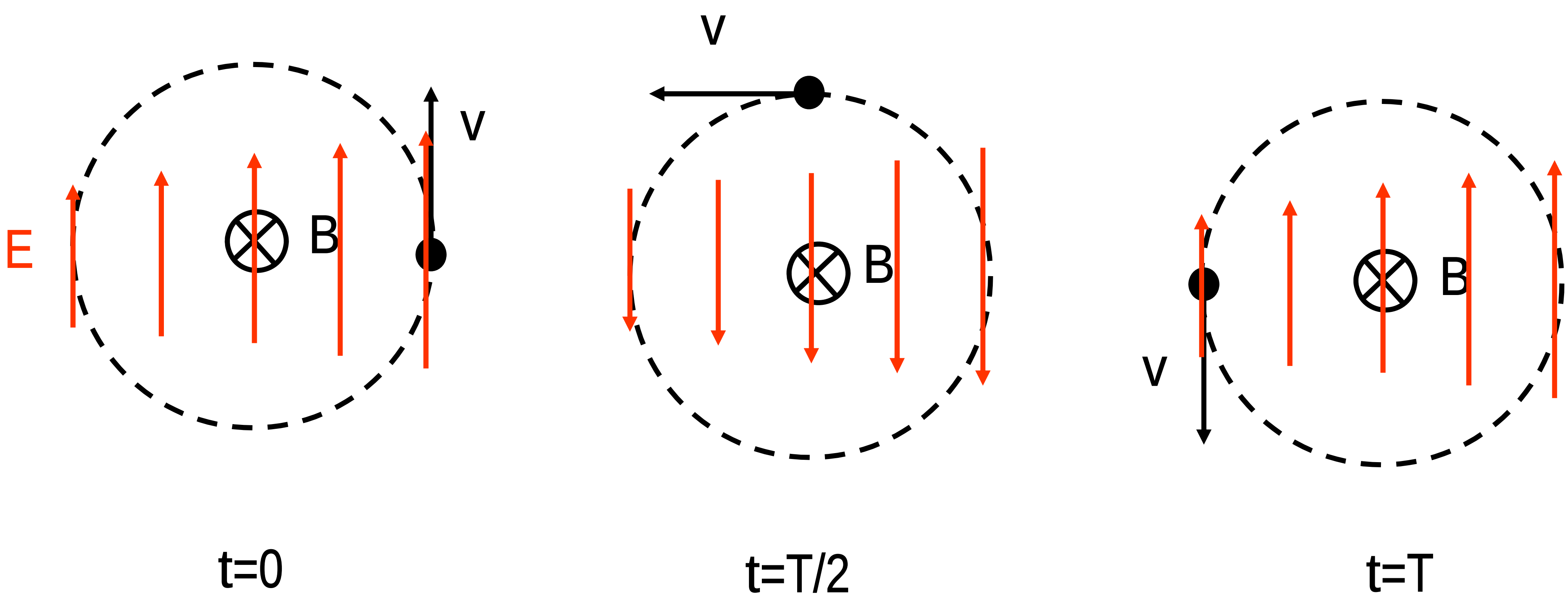
Strong wave-particle interaction if: $\omega - k_{||} \cdot v_{||} \approx l \cdot \Omega_s$ where $l = 1, 2, (3,...)$

Strength of the damping: polarization of the wave

slope of the velocity distrbution $\left.\frac{\partial f}{\partial v}\right|_{\omega/k_{||}}$

Model for second harmonic absorption

gradient of electric field $\frac{\partial^{(l)} E}{\partial r^{(l)}} \neq 0$



$\omega = 2 \cdot \Omega_s$

Summary Waves

Maxwells Equations + linearized equation of motion

Disperison relation k=k(ω)

resonances $k \rightarrow \infty$

cutoff $k \rightarrow 0$

Wave length larger than particle gyro radius

and

no wave particle resonance ($v_{ph}=v_{particle}$)

yes

no

Cold plasma theory

EM waves

Warm plasma theory

EM and electrostatic waves

Collisionless damping
(Landau damping)

Please, stay tuned.

Plasma Heating

Neutral Beam Heating - Principle

Injection of a beam of neutral fuel atoms (H, D, T) at high energies (E_b > 50 keV)

↓

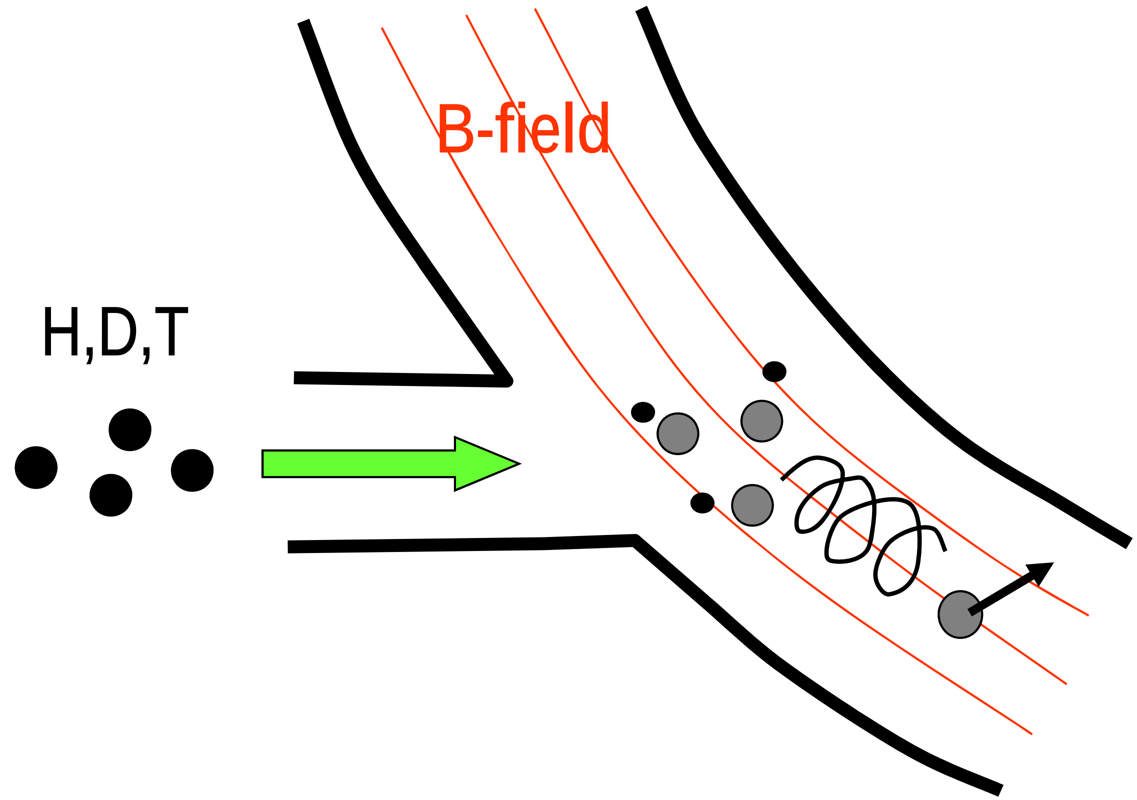
Ionization in the plasma

↓

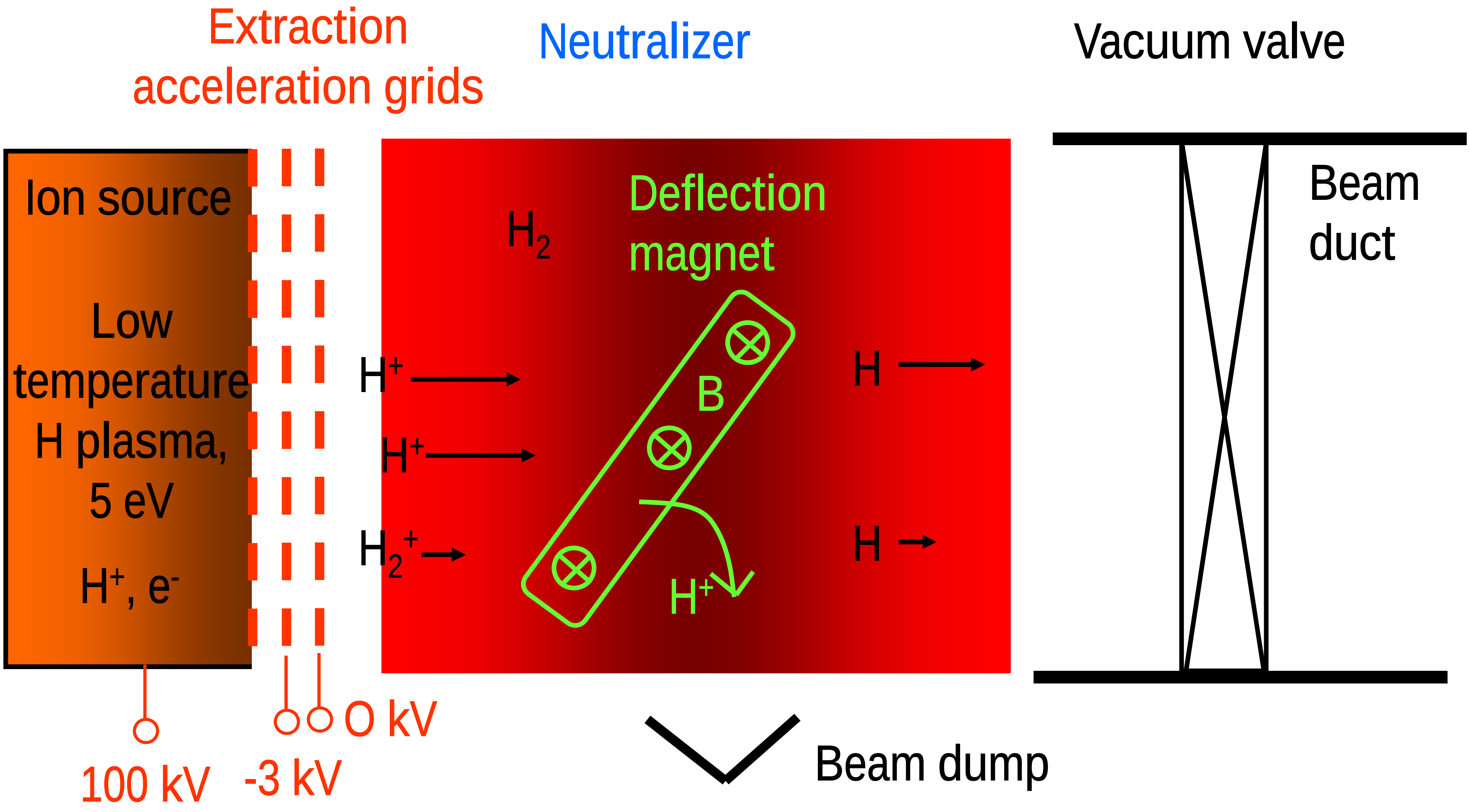
Beam particles confined

↓

Collisional slowing down

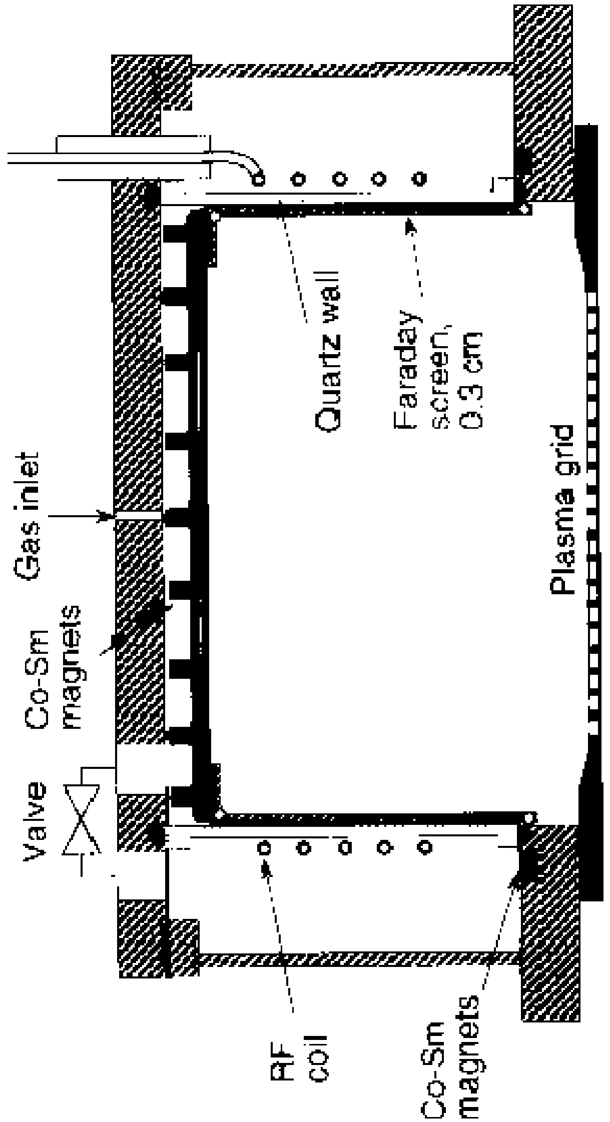


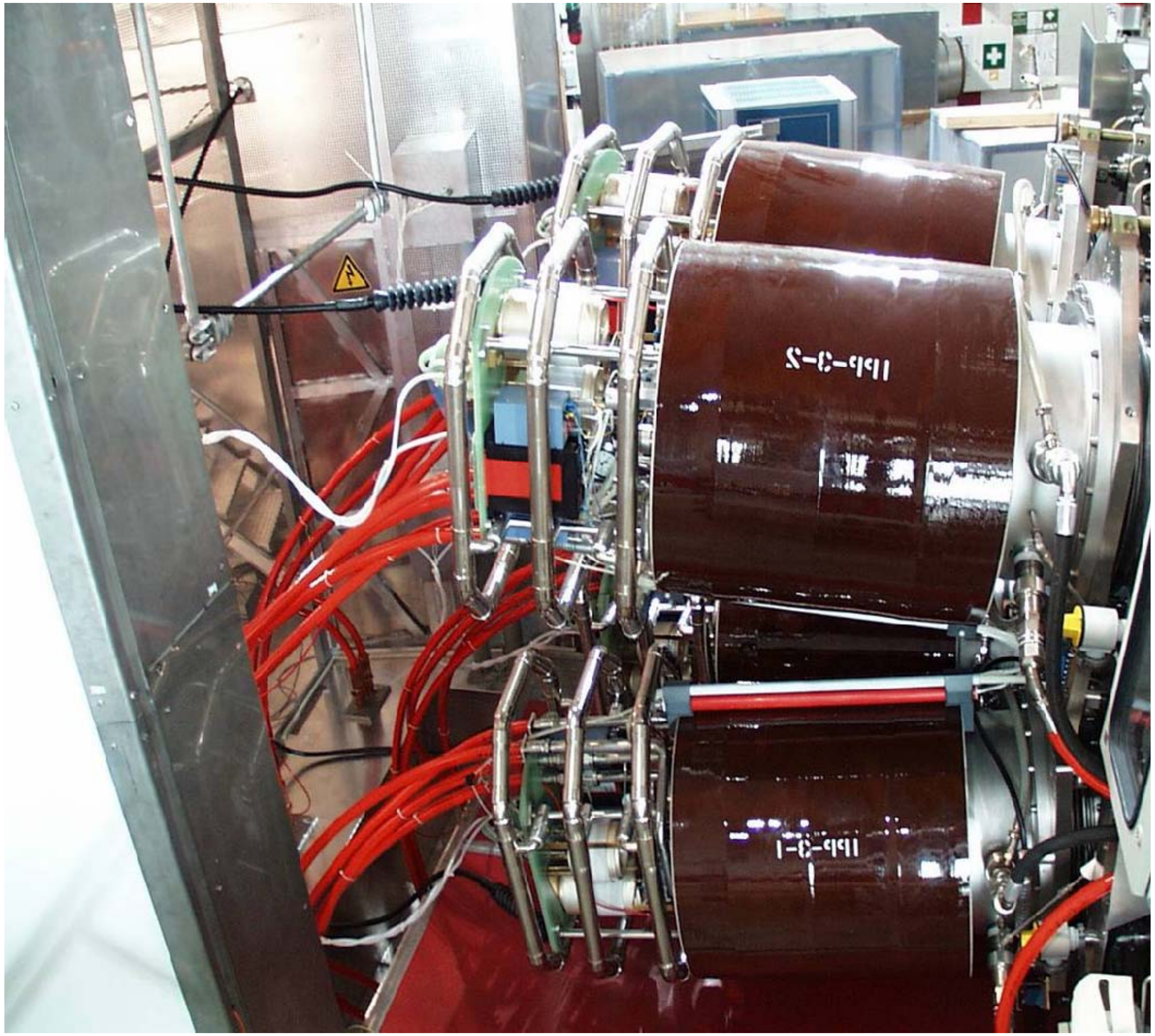
Generation of a Neutral Fuel Beam



Example W7-AS: V=50 kV, I=25 A   power deposited in plasma: 0.4 MW

NBI - Ion source





Based on balancing:

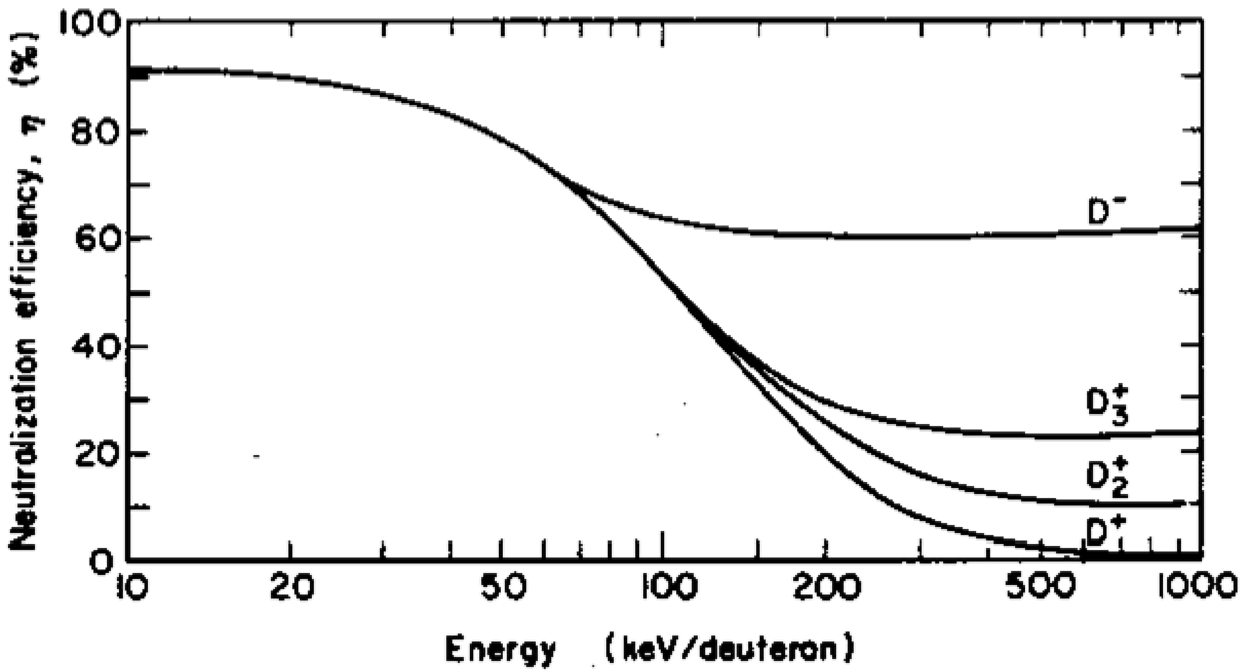
Charge exchange:

$$\underbrace{D^+}_{\text{fast}} + \underbrace{D_2}_{\text{gas}} \rightarrow \underbrace{D}_{\text{fast}} + \underbrace{D_2^+}_{\text{slow}}$$

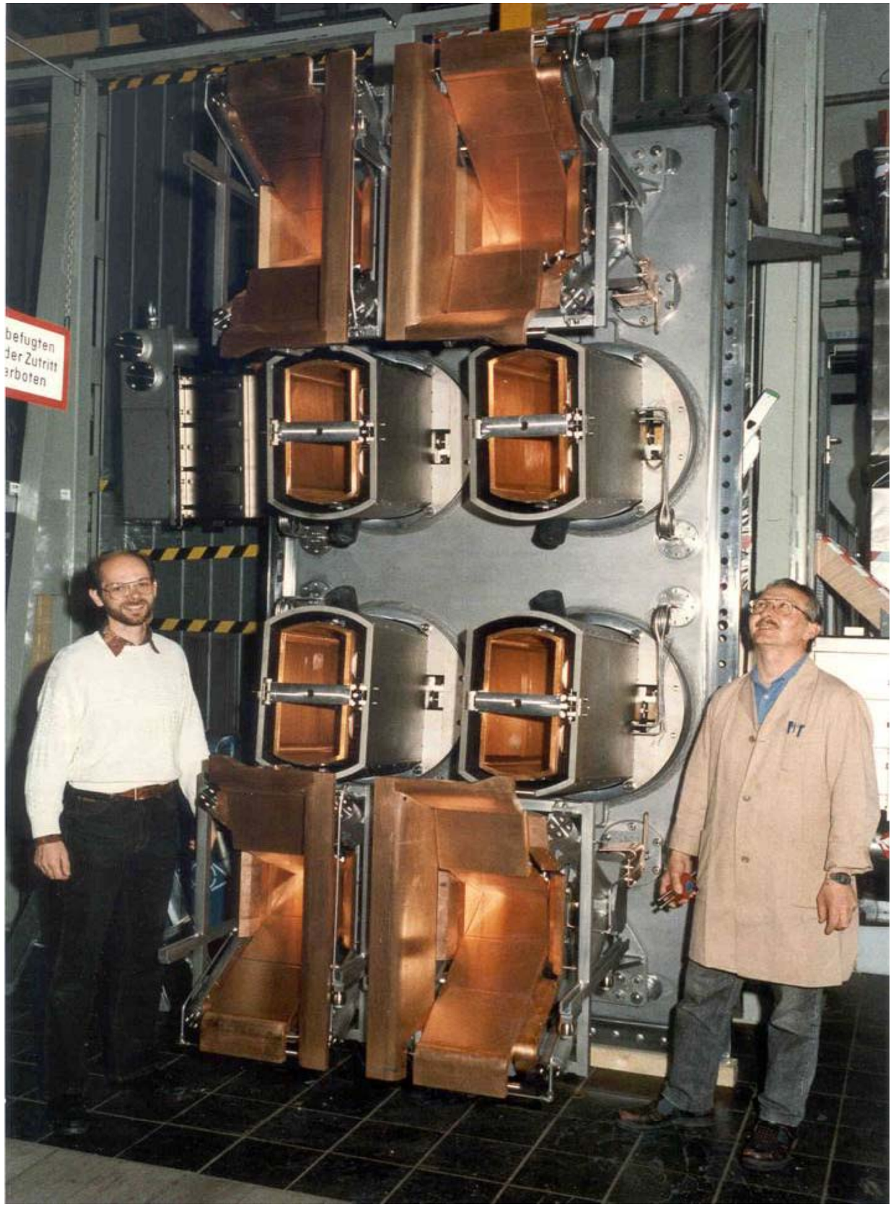
Re-ionization:

$$\underbrace{D}_{\text{fast}} + \underbrace{D_2}_{\text{gas}} \rightarrow \underbrace{D^+}_{\text{fast}} + \underbrace{D_2}_{\text{gas}} + e^-$$

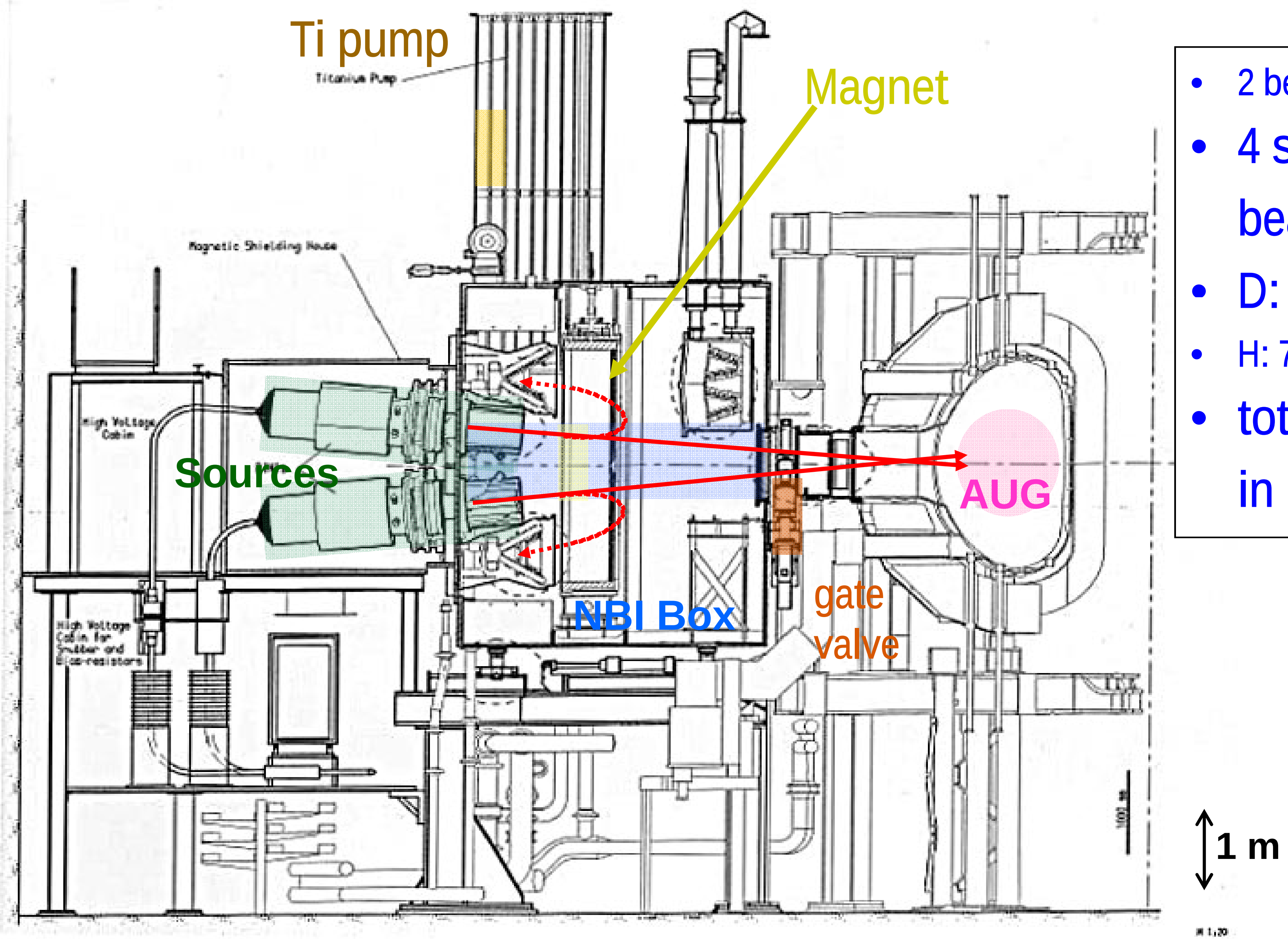
Efficiency:



NBI injector of ASDEX Upgrade



NBI on ASDEX Upgrade



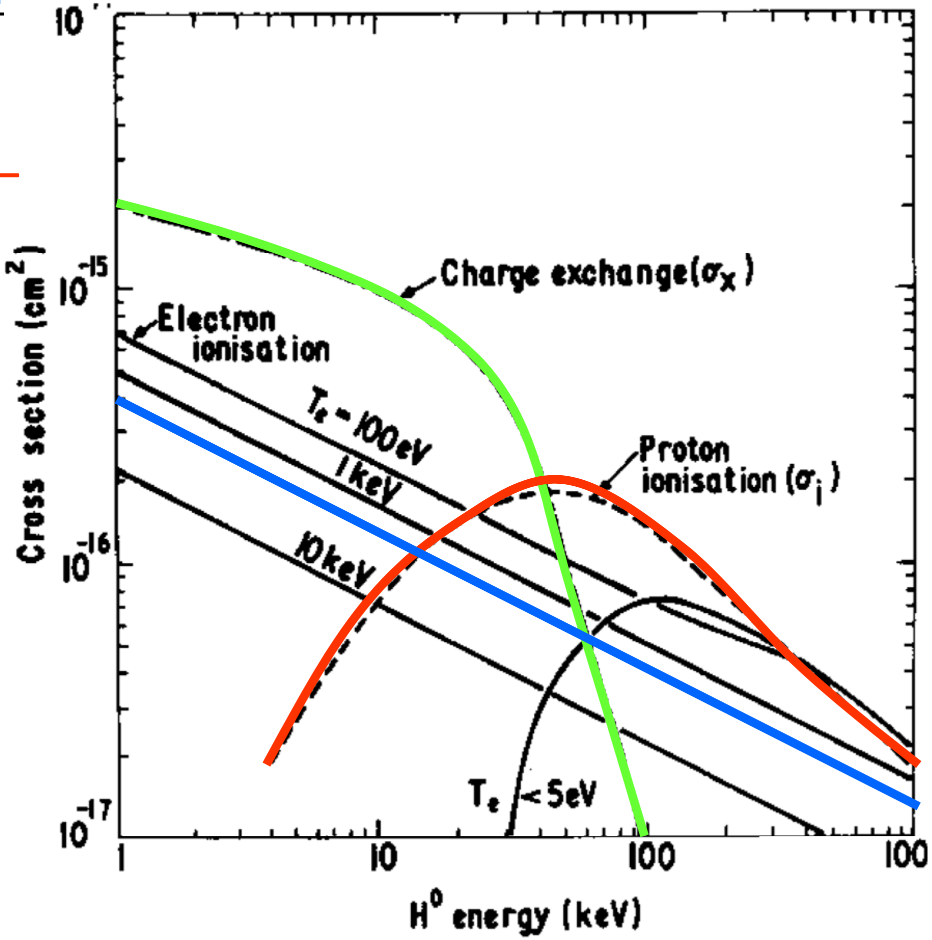
- 2 beamlines
- 4 sources per beamline
- D: 93/60 keV
- H: 72/55 keV
- total NB power in D: 20 MW

NBI - Ionization in the plasma

Charge exchange: $H_{fast} + H^+ \rightarrow H^+_{fast} + H$

Ion collision: $H_{fast} + H \rightarrow H^+_{fast} + H + e^-$

Electron collision: $H_{fast} + e^- \rightarrow H^+_{fast} + 2e^-$



Example:

beam intensity: $I(x) = I_0 \cdot \exp\{-x/\lambda\}$

E_{b0}= 70 keV

$\sigma_{tot} = 5 \cdot 10^{-20} m^2$

$n = 5 \cdot 10^{20} m^{-3}$

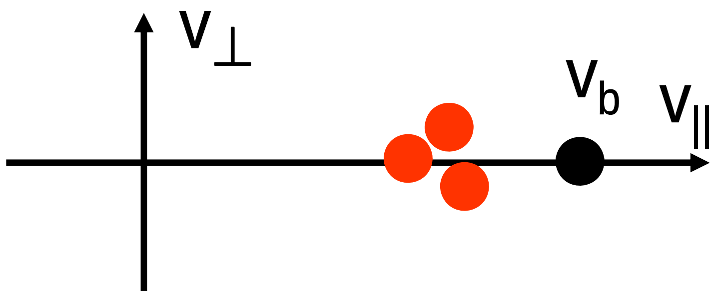
$$\lambda = \frac{1}{n\sigma_{tot}} \approx 0.4m$$

In large reactor plasmas: beam cannot reach core!

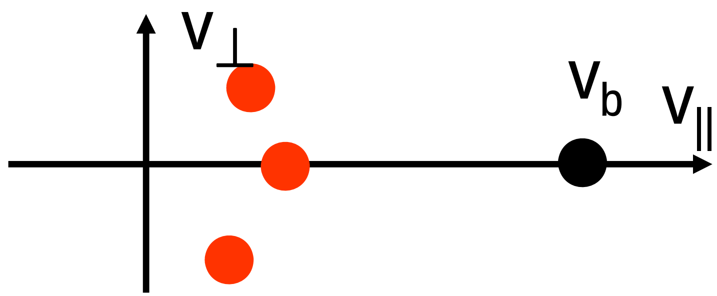
NBI - Slowing down

E_c: critical energy: $$E_c = 14.8 \cdot \frac{A_b}{A_i^{2/3}} \cdot T_e \,[\mathrm{keV}]$$

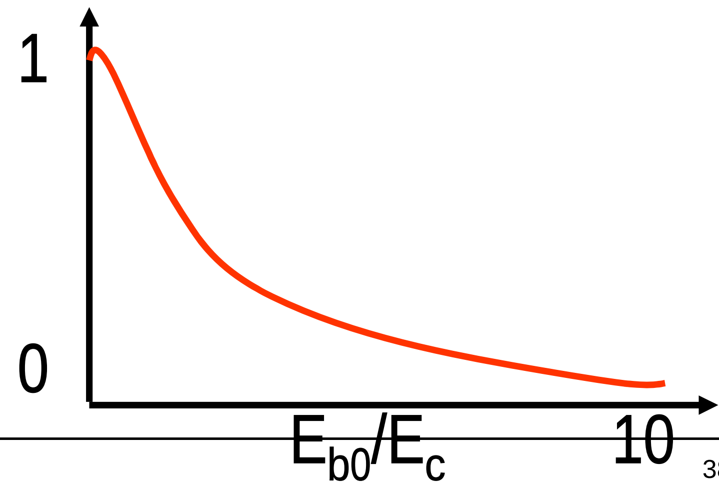
1. $E_b > E_c$: Slowing down on electrons
no scatter



2. $E_b < E_c$: Slowing down on ions
scattering of beams



Fraction of initial beam energy going to ions.

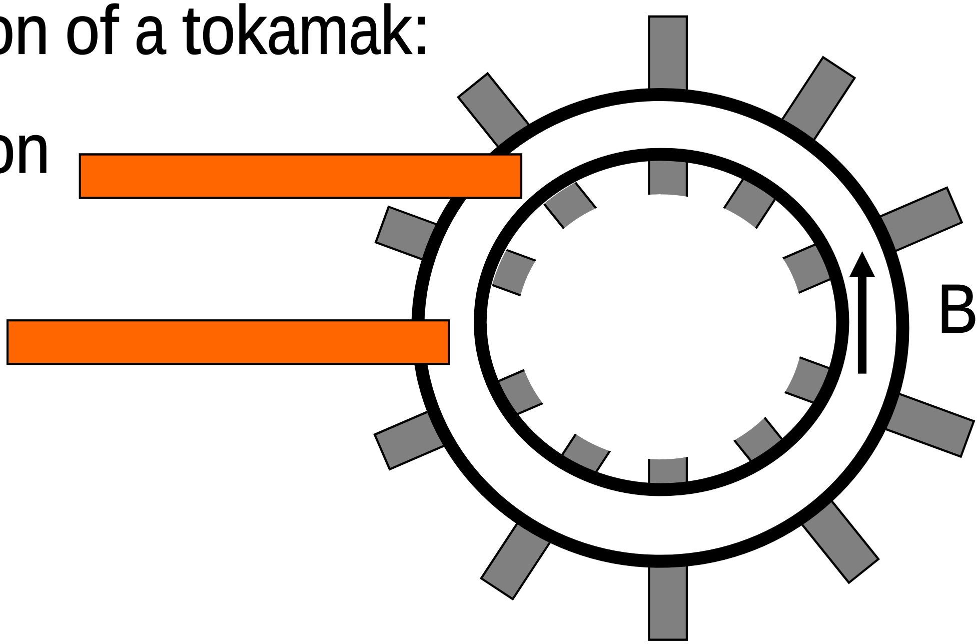


NBI - Injection Angle

Horizontal cross-section of a tokamak:

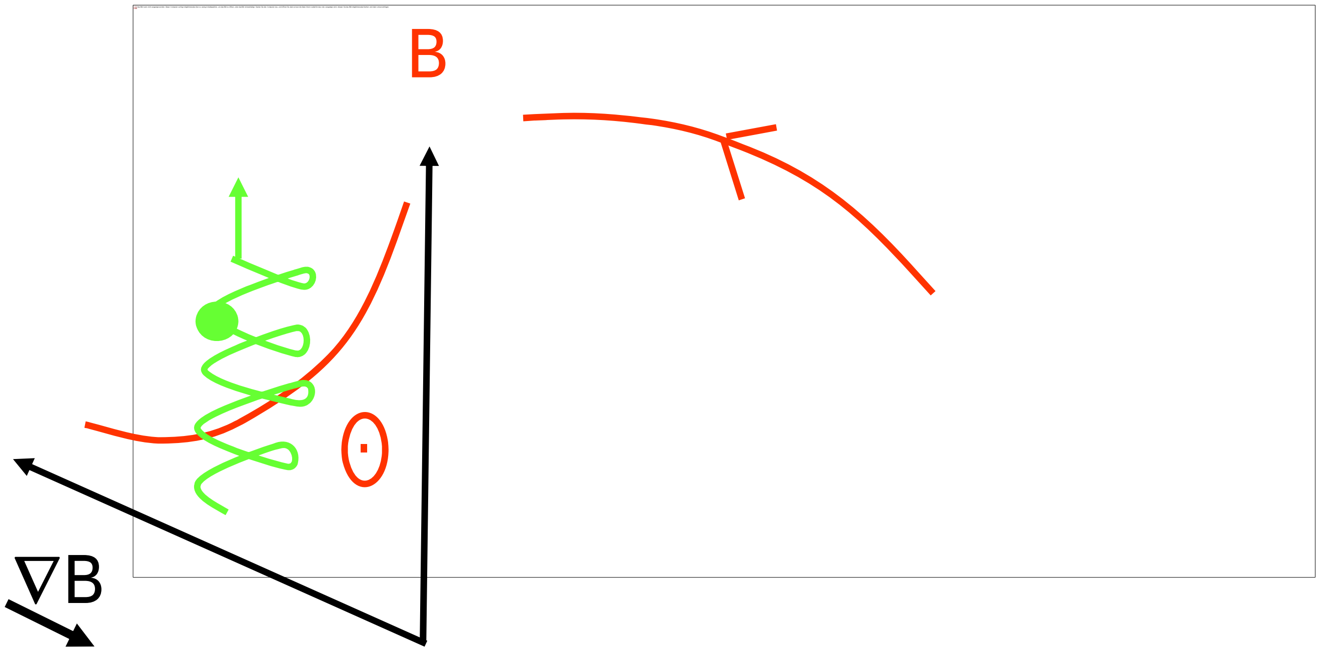
Tangential injection
(counter)

Radial injection

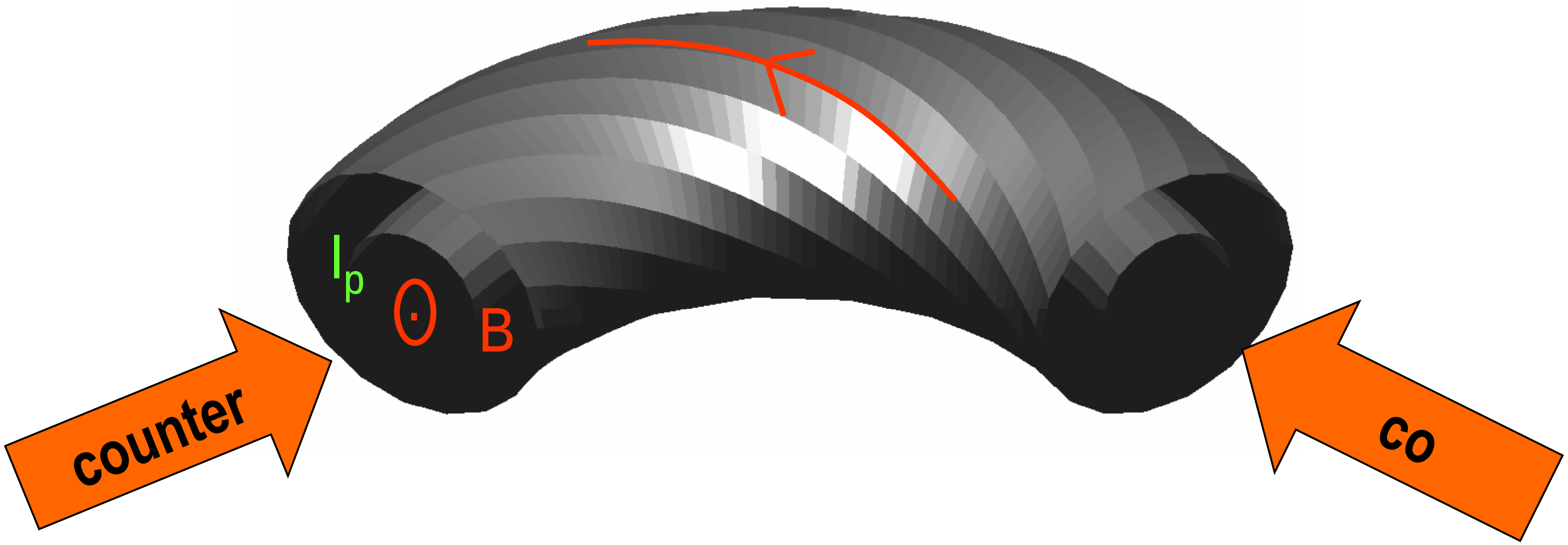


Radial injection:

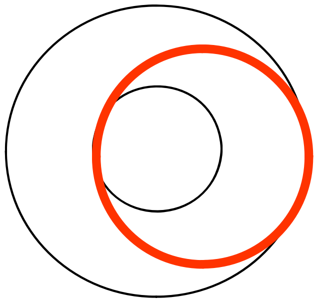
- •Standard ports
- •shine-through
- •particle loss



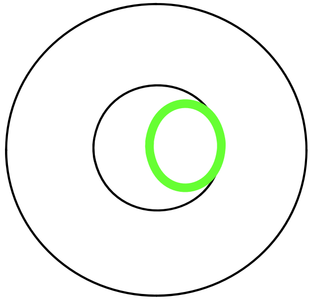
NBI - Injection Angle



Worse heating efficiency



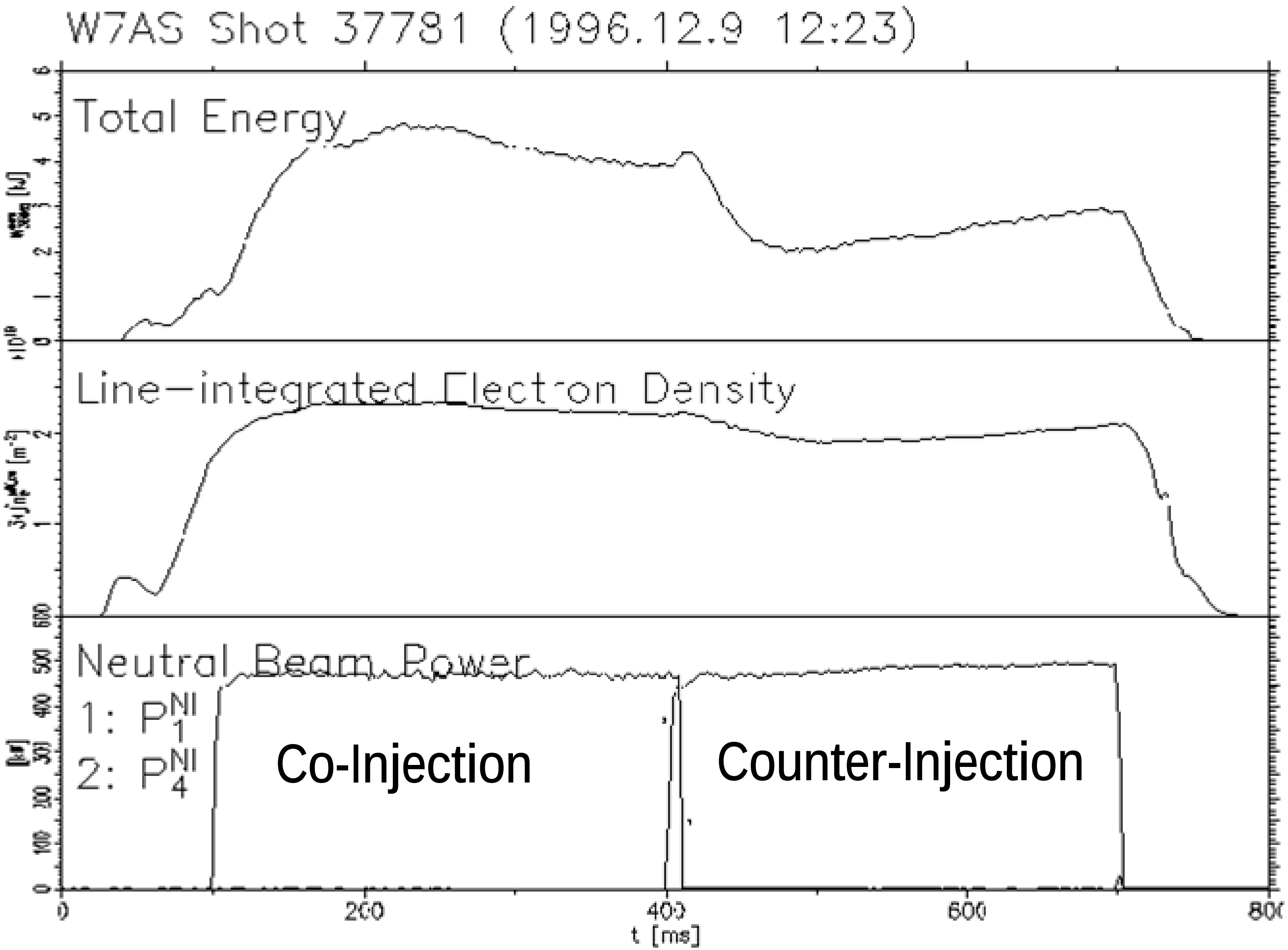
Projected particle drifts



Better heating efficiency

At low magnetic fields heating efficiency depends on NBI direction.

NBI - Example from W7-AS



EM wave heating - principle

Excitation of plasma wave (frequency ω)
near plasma edge

$\Downarrow$

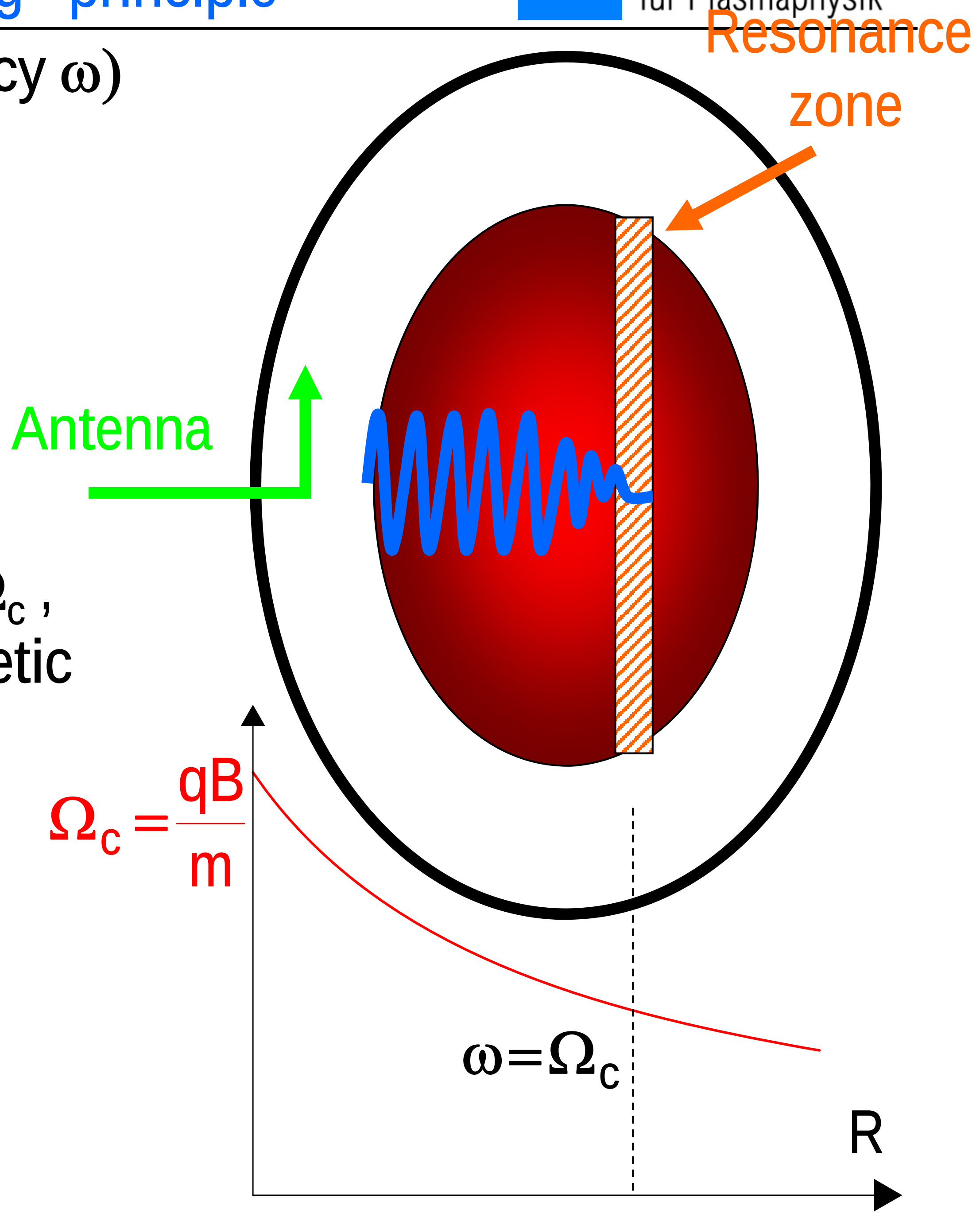
wave transports power into plasma
center

$\Downarrow$

absorption near resonance, e.g. $\omega \approx \Omega_c$,
i.e. conversion of wave energy into kinetic
energy of resonant particles

$\Downarrow$

Resonant particles thermalize.



Frequencies with good absorption

Landau Cyclotron Resonance

generally $k_{||} \cdot v_{th}^{i} / \Omega_s << 1$

Then good absorption where $\omega \approx l \cdot \Omega_s$

Electrons:	28 GHz / B[T]	Electron Cyclotron Resonance Heating	ECRH
Hydrogen:	15 MHz / B [T]	Ion Cyclotron Resonance Heating	ICRH

Landau Resonance

$\omega / k_{||} \approx v_{th}^{e}$ $\quad 1.3\mathrm{GHz} \cdot \sqrt{T_e[\mathrm{keV}]} / \lambda_{||}[\mathrm{cm}]$

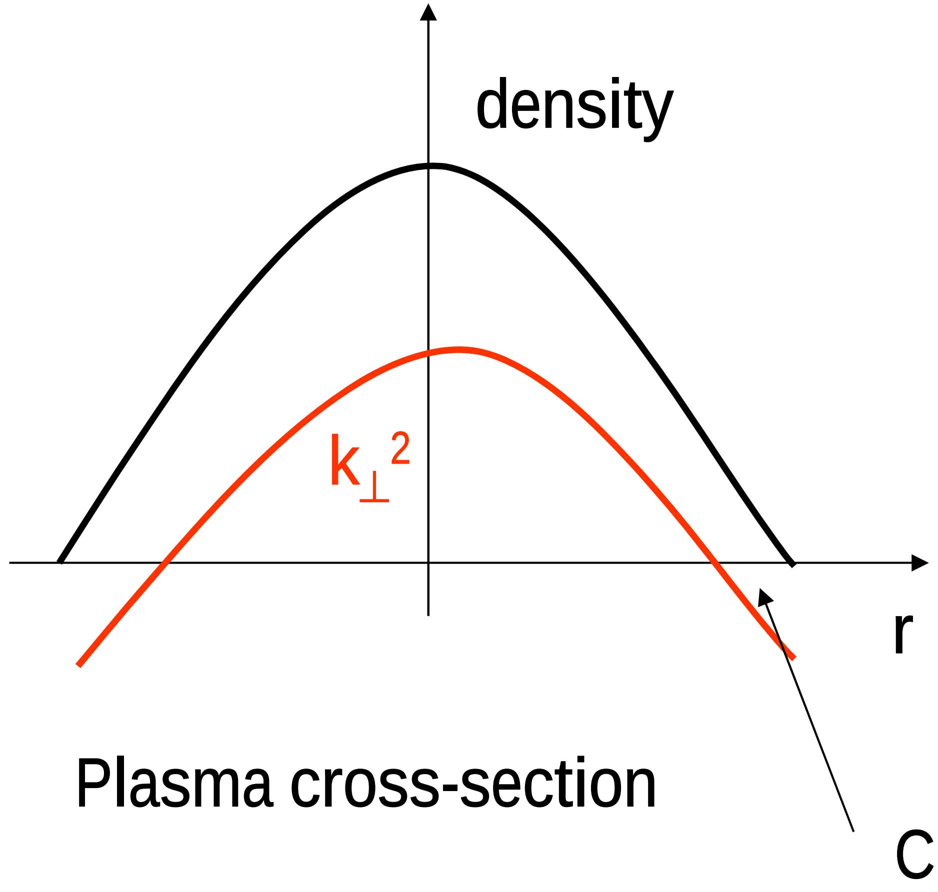
Lower Hybrid Heating LH

Landau Resonance and Magn. Pumping also contribute to ICRH

Dispersion relation has two solutions:

fast wave $E \perp B_0$ lower density limit approx. 2 x $10^{19} m^{-3}$
slow wave $E \parallel B_0$ upper density limit approx. 1 x $10^{19} m^{-3}$

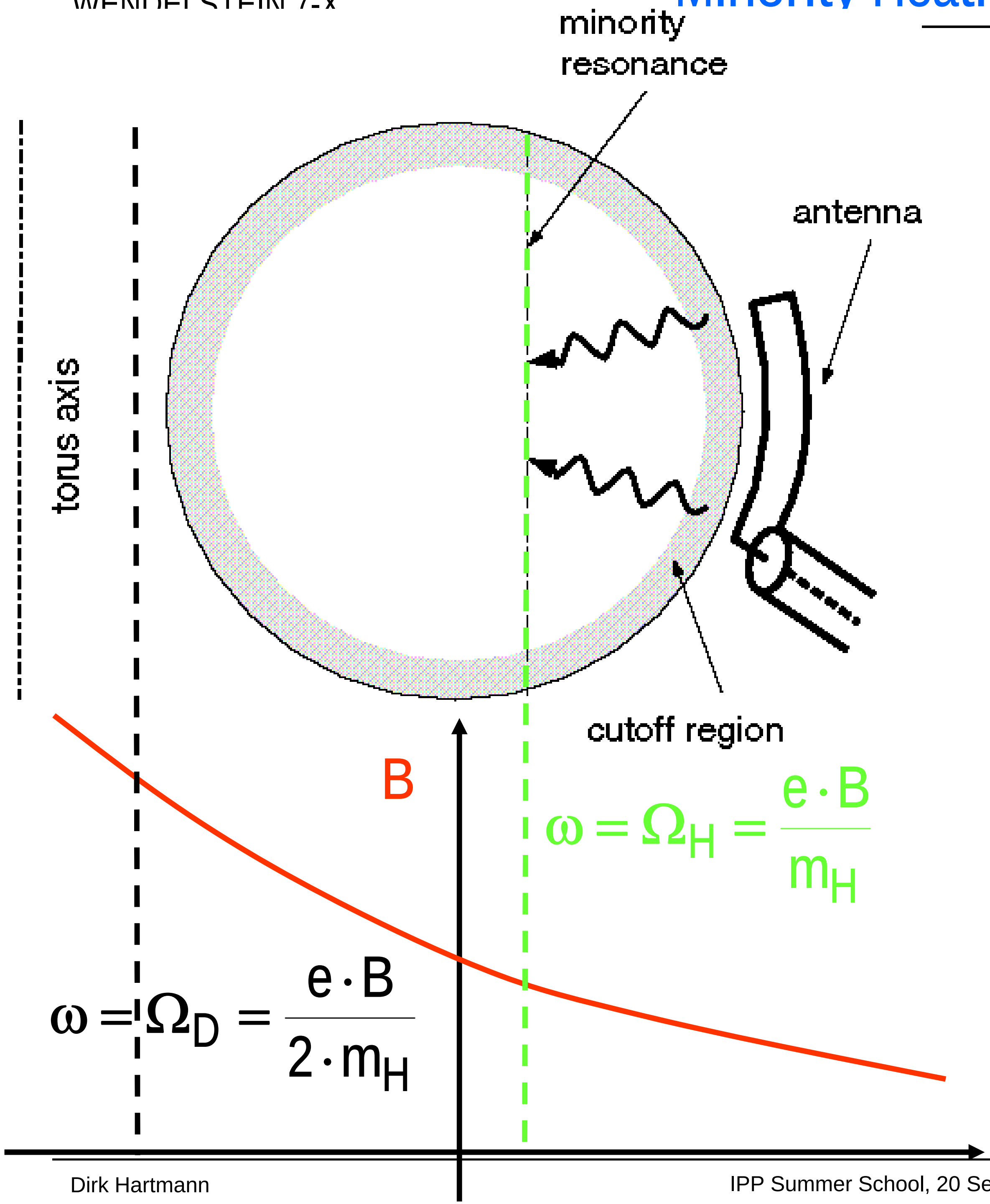
$$\lambda_{\|} \approx 50 - 100\,\boldsymbol{cm}, \lambda_{\perp} \leq 10\boldsymbol{cm}$$



Excite fast wave at plasma edge, needs to tunnel cutoff region.

Problem:
near $\omega=\Omega_i$ wave is right-handed polarized, but ions need left-handed polarization!

Minority Heating



Plasma with mixture of H and D
with $n_H \ll n_D$

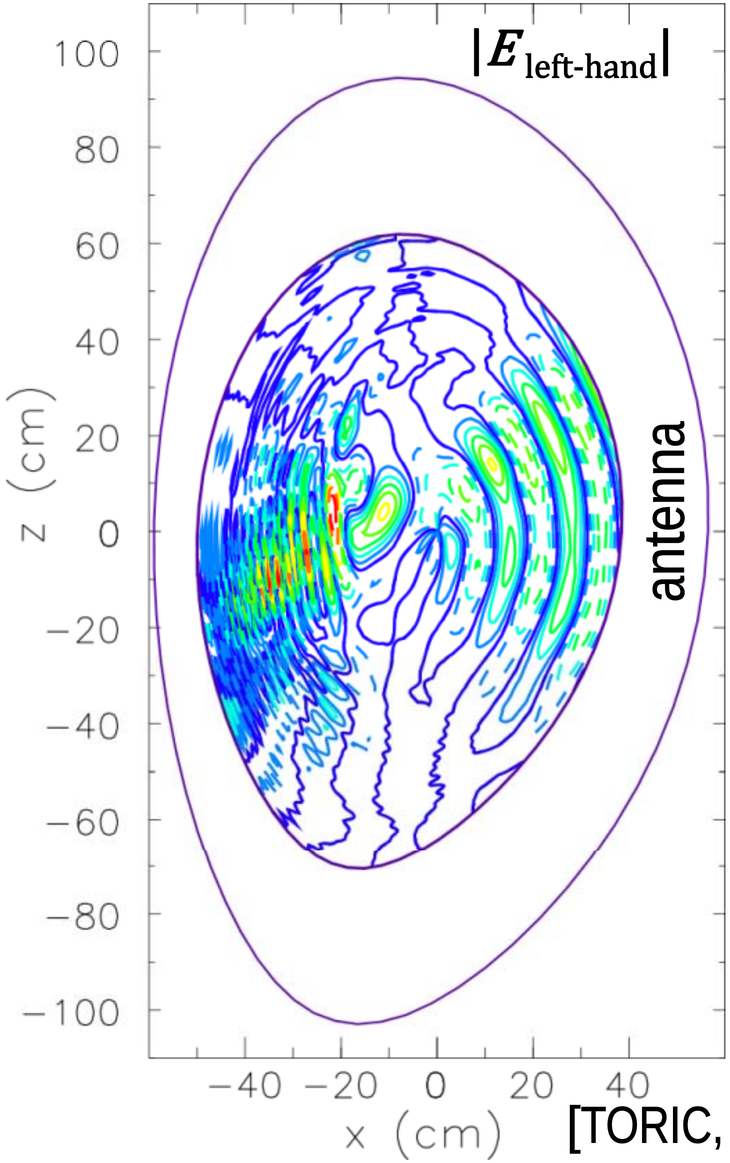
$n_D \rightarrow$ polarization
propagation
$n_H \rightarrow$ absorption

Production of tail in H velocity distribution function.

Good single pass absorption.

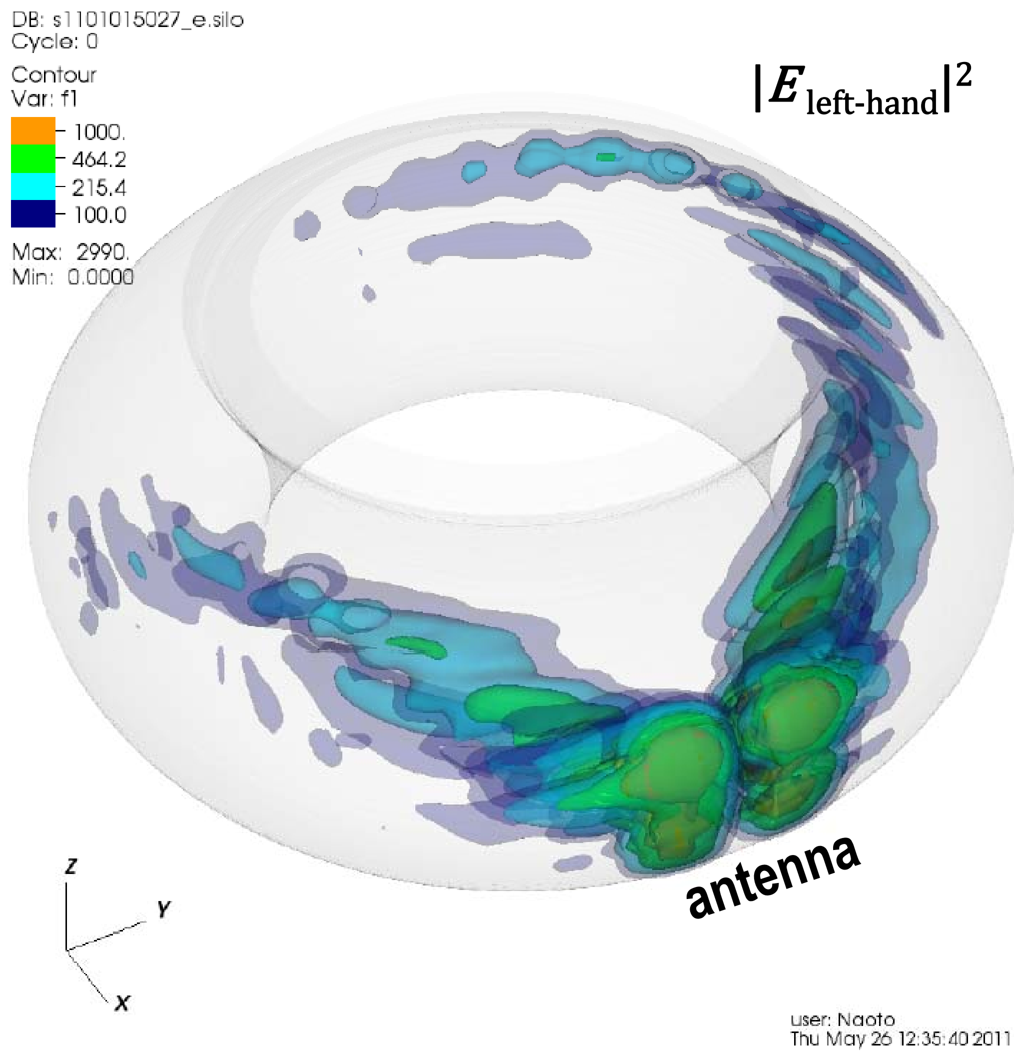
ICRH Wave Propagation (H-minority)

ASDEX Upgrade:



[TORIC, M. Brambilla]

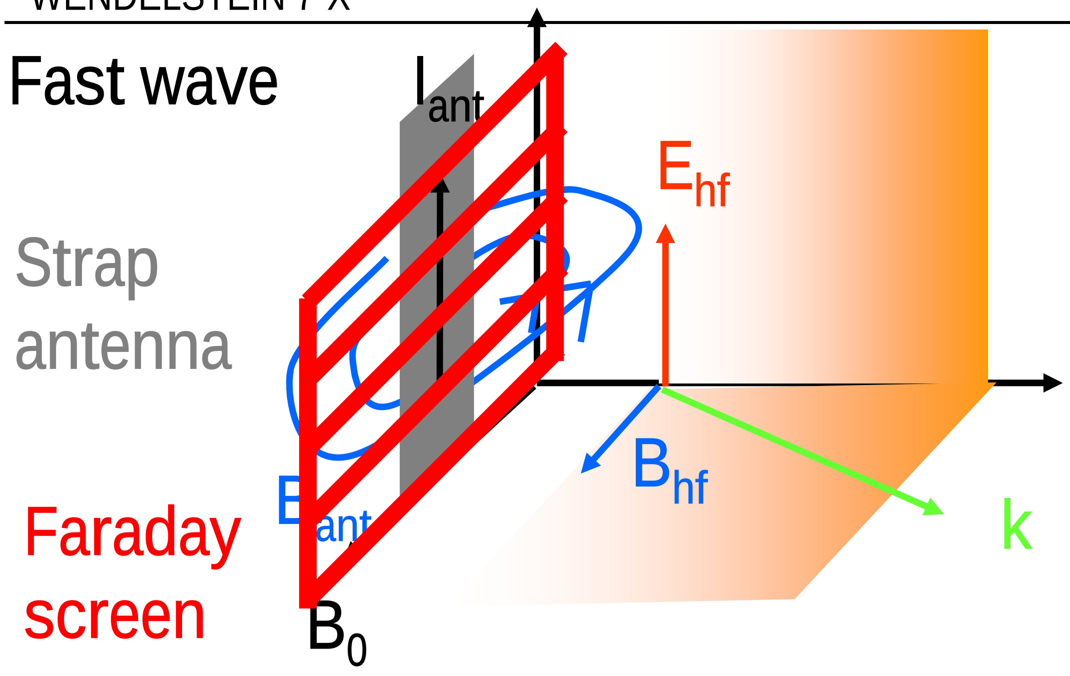
Alcator C-Mod:



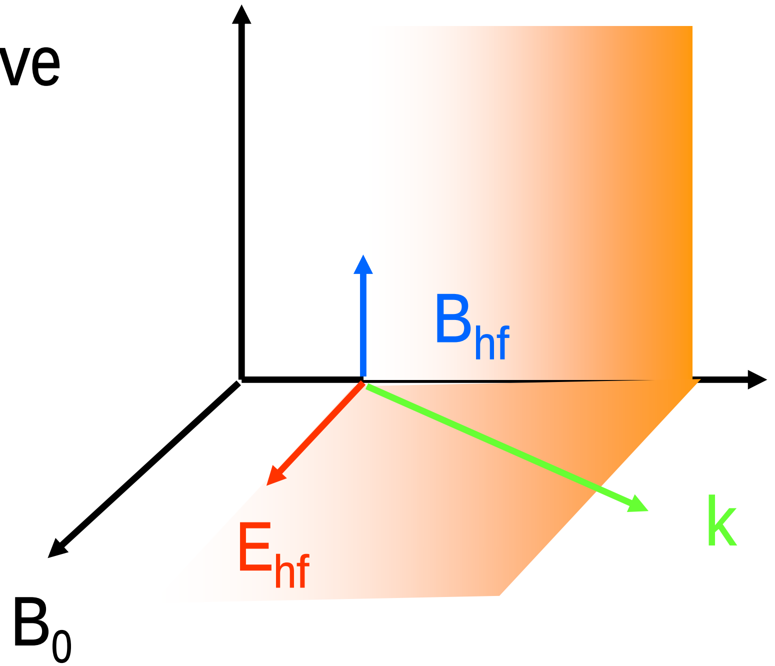
[AORSA/CQL3D, E. F. Jaeger, calculations by N. Tsujii]

ICRH - Wave excitation

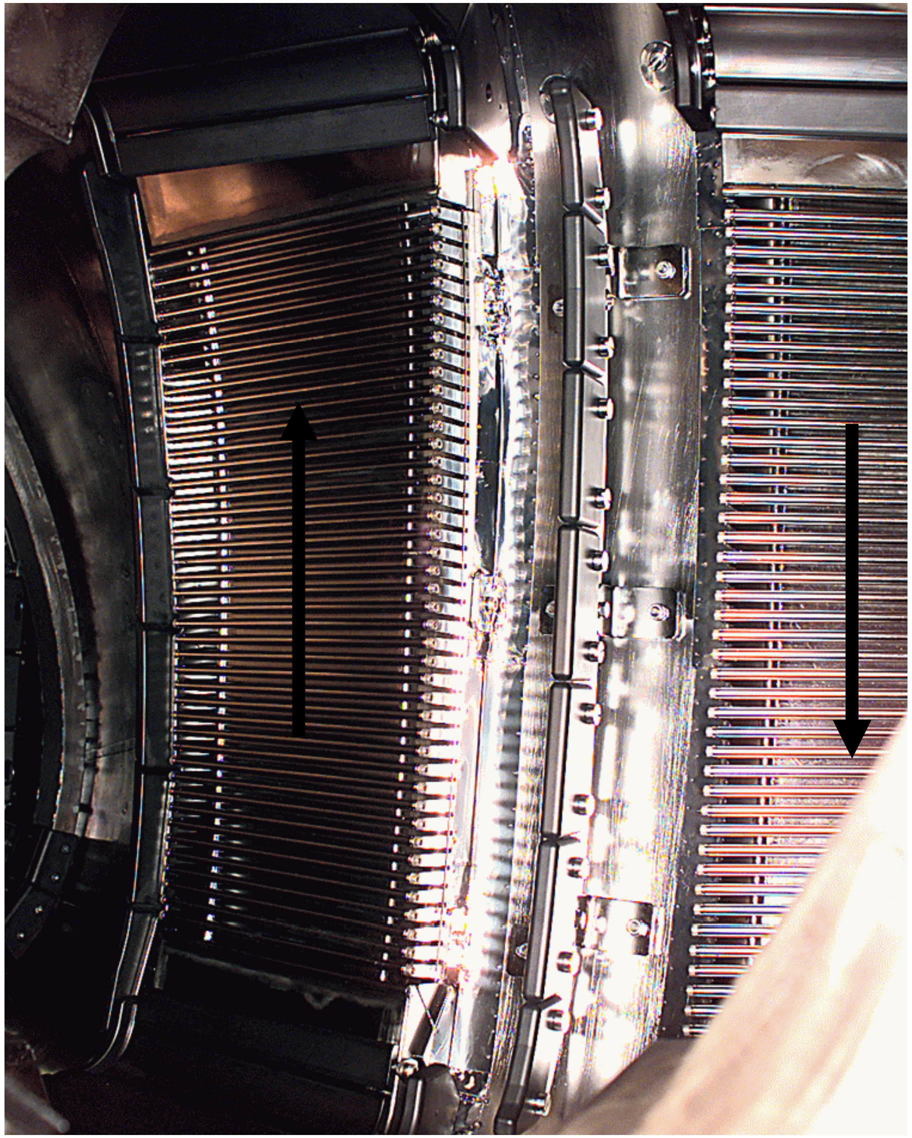
Fast wave



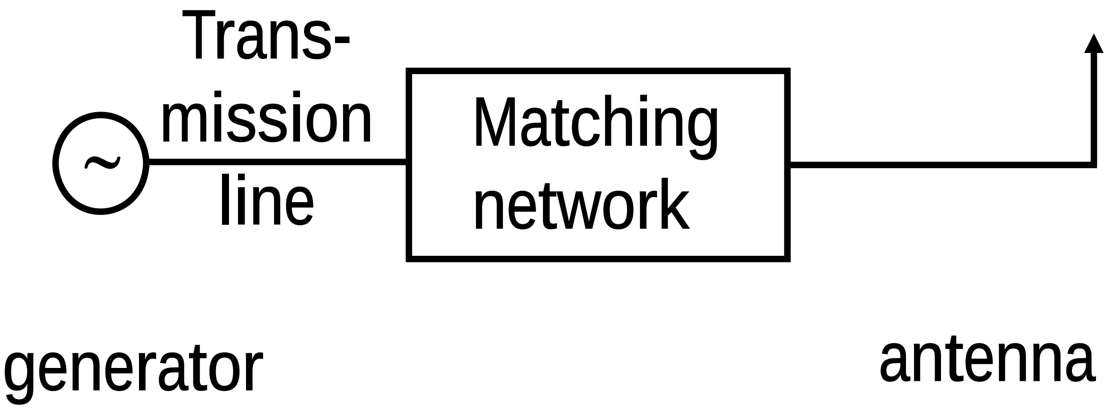
Slow wave

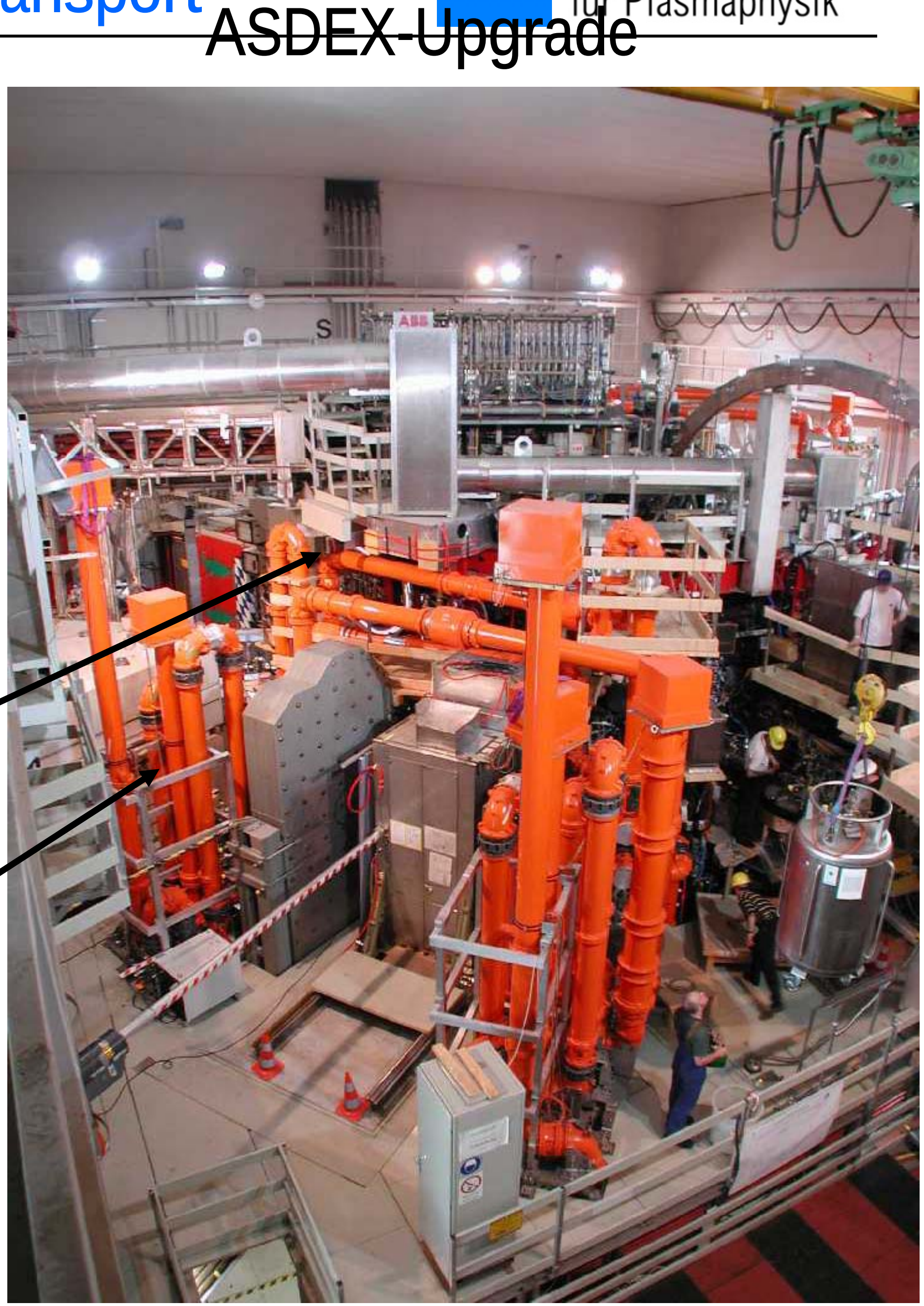


W7-AS Antenna



ICRH - Wave Power Transport





50Ω Coaxial transmission lines

20cm ∅, low loss

Matching network

antenna resistance ≠ 50Ω

dependent on plasma

ICRF Technology - Generator

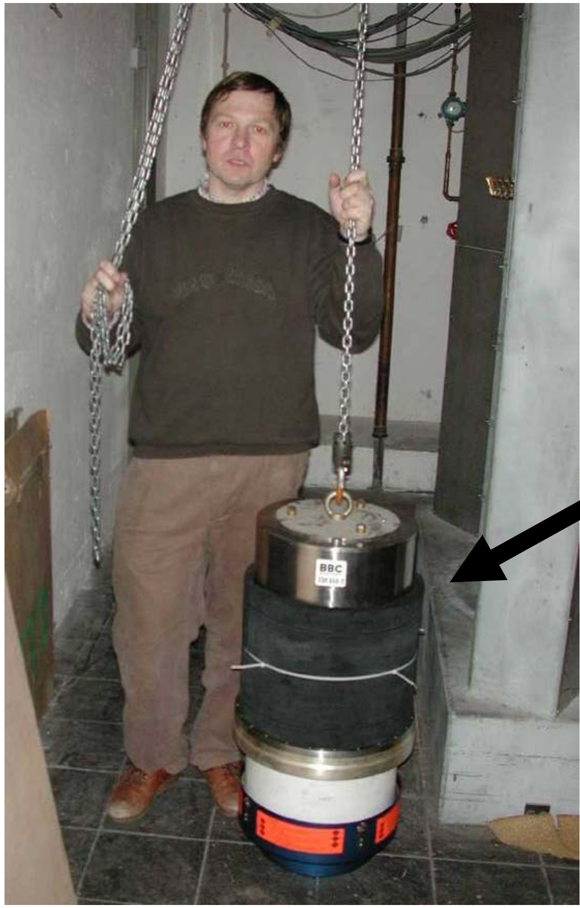
4 amplifier chain

final stage:
tetrode with
2MW / 10 sec

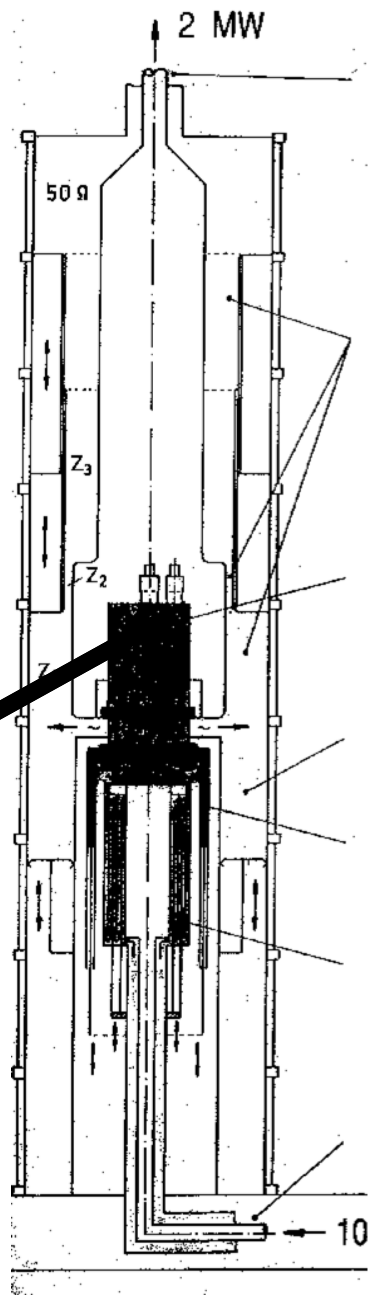
tunable between
30 and 110 MHz

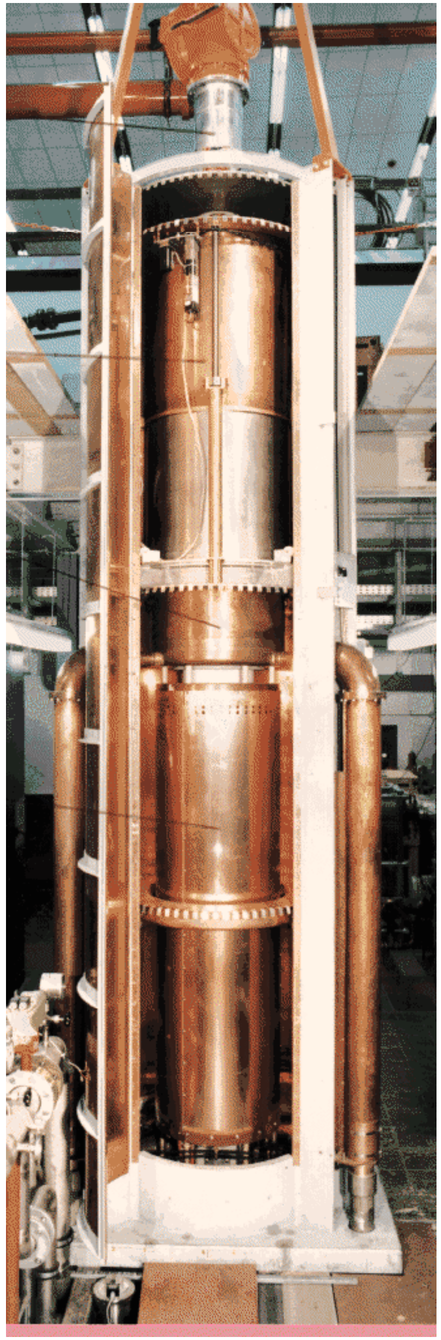
efficiency 60%

end stage



tetrode

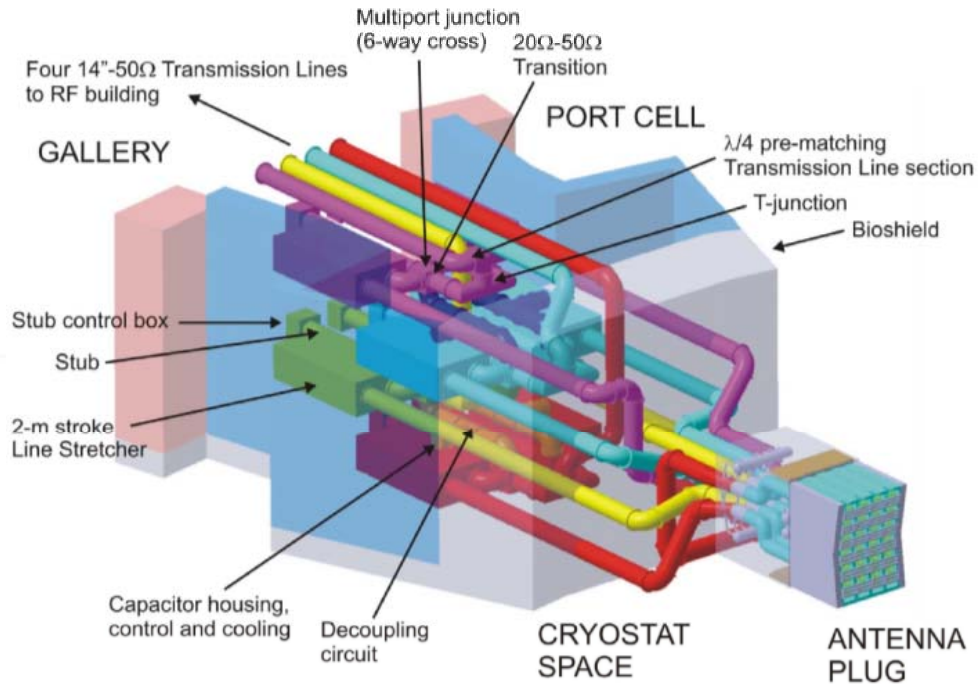




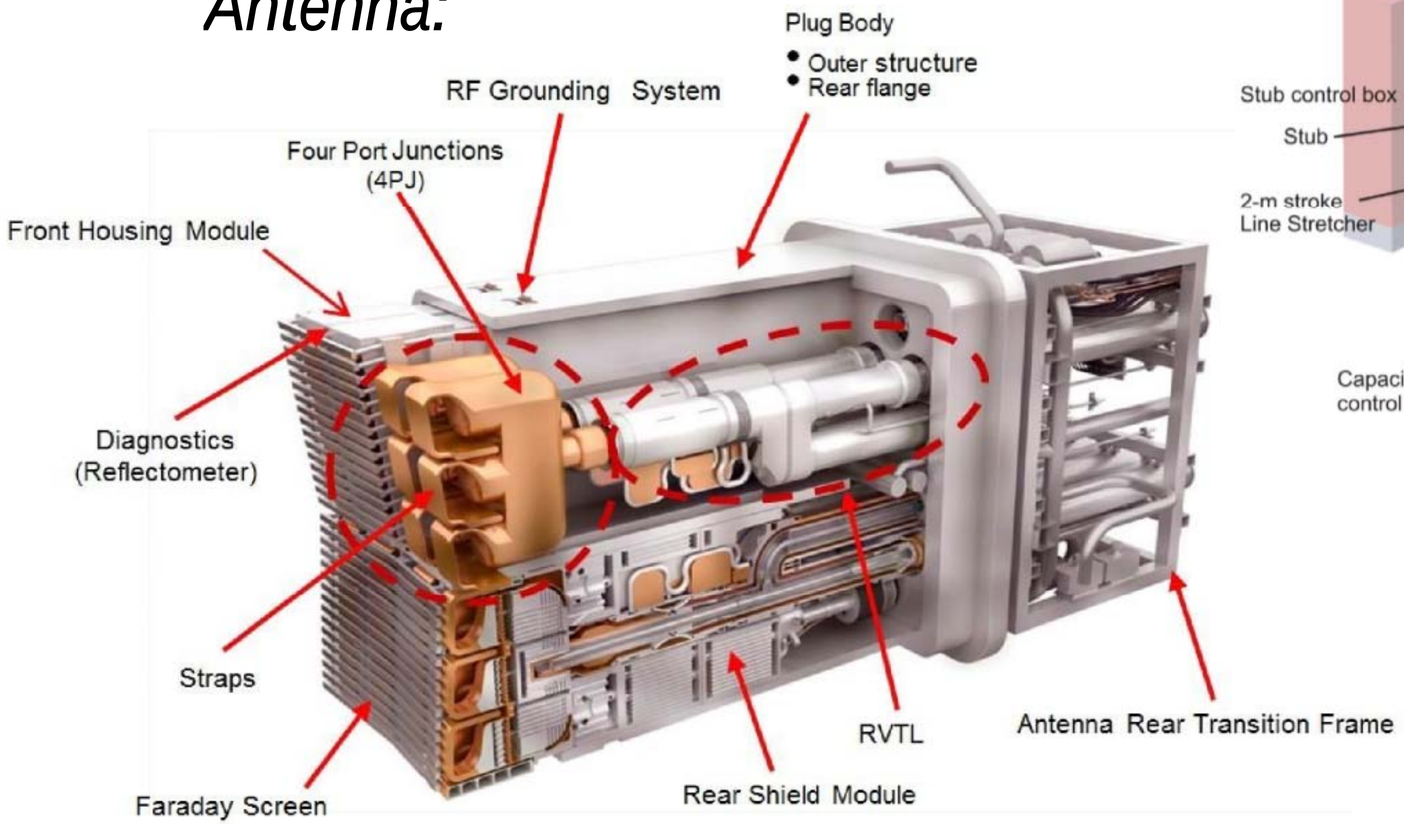
ICRH antenna for ITER

2 ICRH antennas are in the planning,
20 MW each, 40-55 MHz

Matching system:



Antenna:



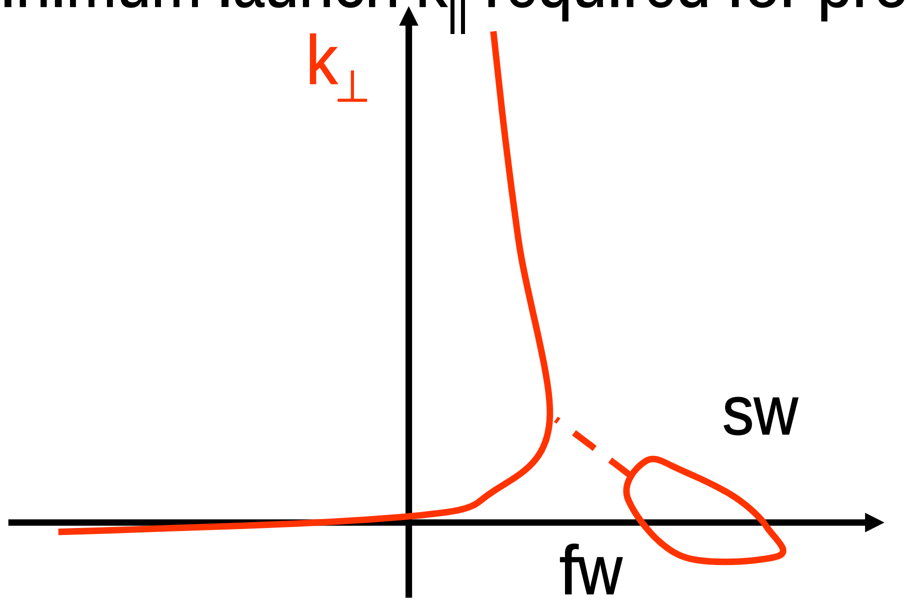
24 current-phased straps,
complicated matching
due to cross-coupling

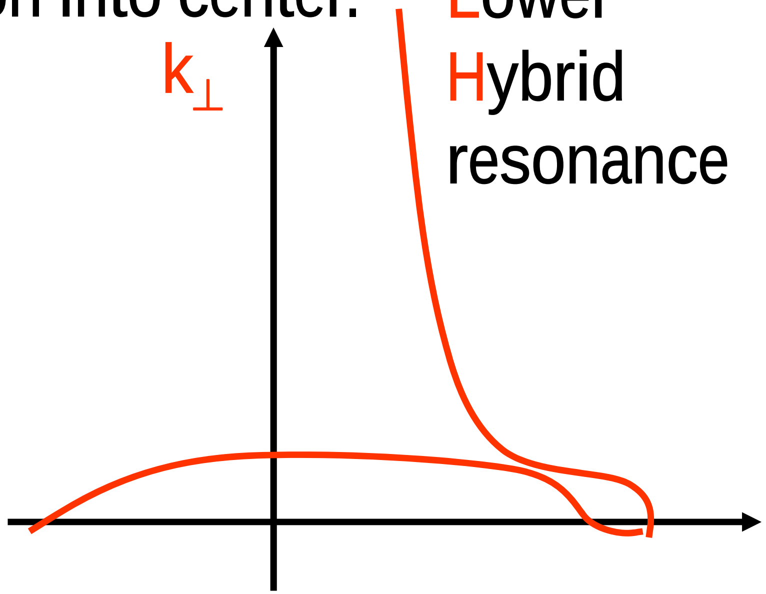
Lower Hybrid Heating

2 solutions of dispersion relation: slow wave (exhibits lower hybrid res.)
fast wave

$\Omega_i << \omega_{LH} << \Omega_e$ $\lambda_{||} \approx 2-10\text{cm}, \lambda_\perp \leq 1\text{cm}$

minimum density required for propagation into plasma (10^{17}m^{-3})
minimum launch $k_{||}$ required for propagation into center.

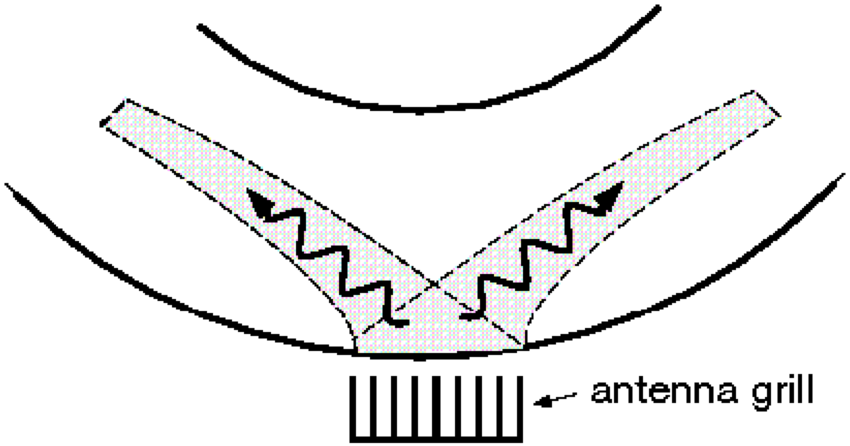


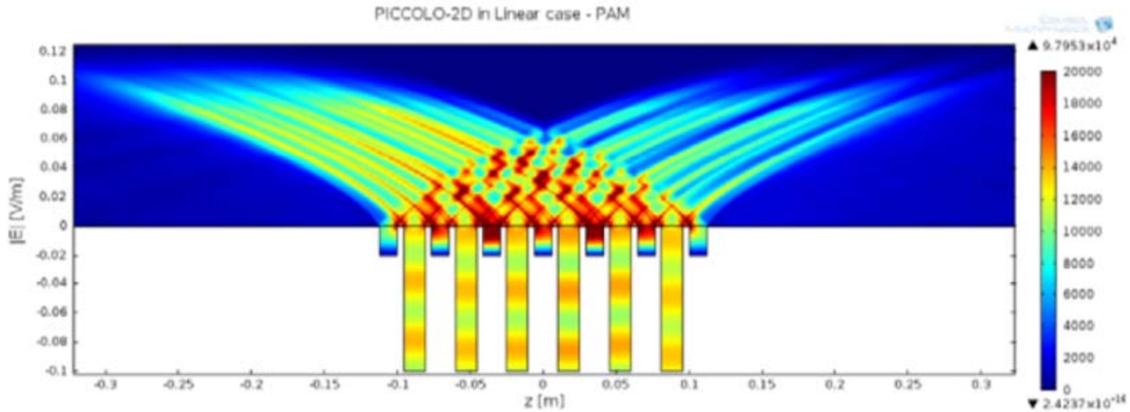


$k_{||}$ too low, power stays near plasma edge

$k_{||}$ sufficiently high, slow wave travels into plasma, absorption at LH or before

LH - Wave Propagation





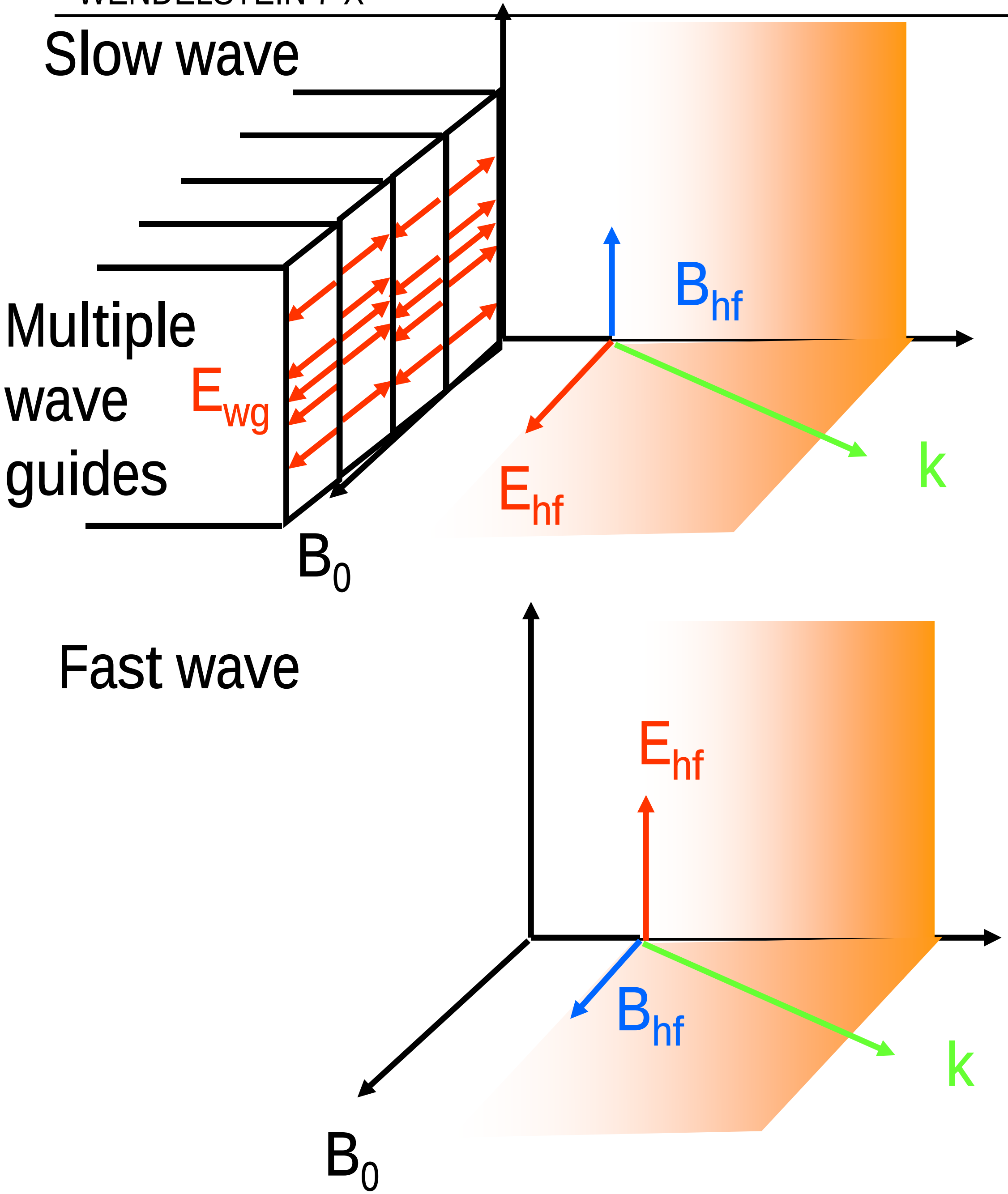
Coupling code PICCOLO-2D [M. Preynas et al.]

For $k_{||} > k_{\text{crit}}$ v_{gr}, v_{ph} independent of $k_{||}$.
$\Rightarrow$ all launched power flows into same direction.

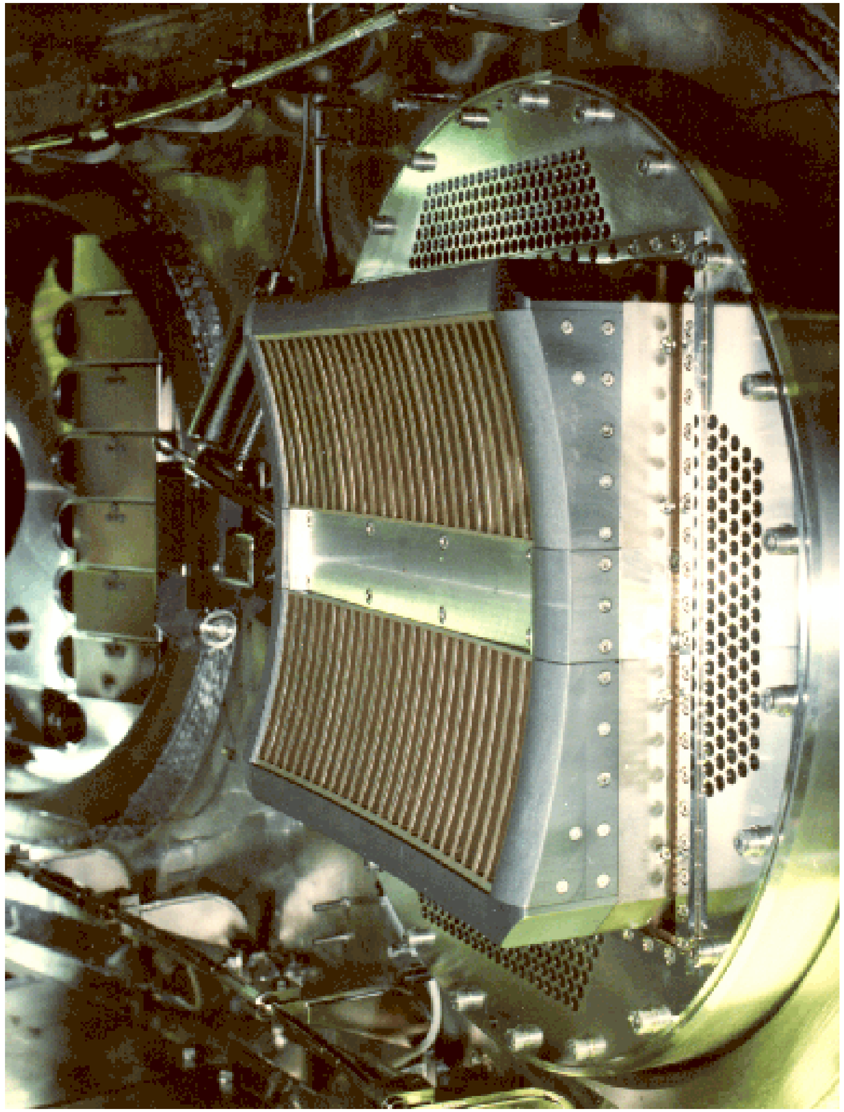
Typically power is absorbed off-axis before reaching LH resonance

Depends on n_e and B

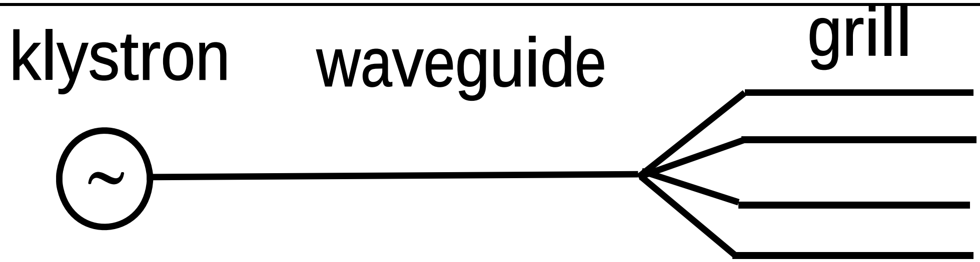
LH - Wave Excitation

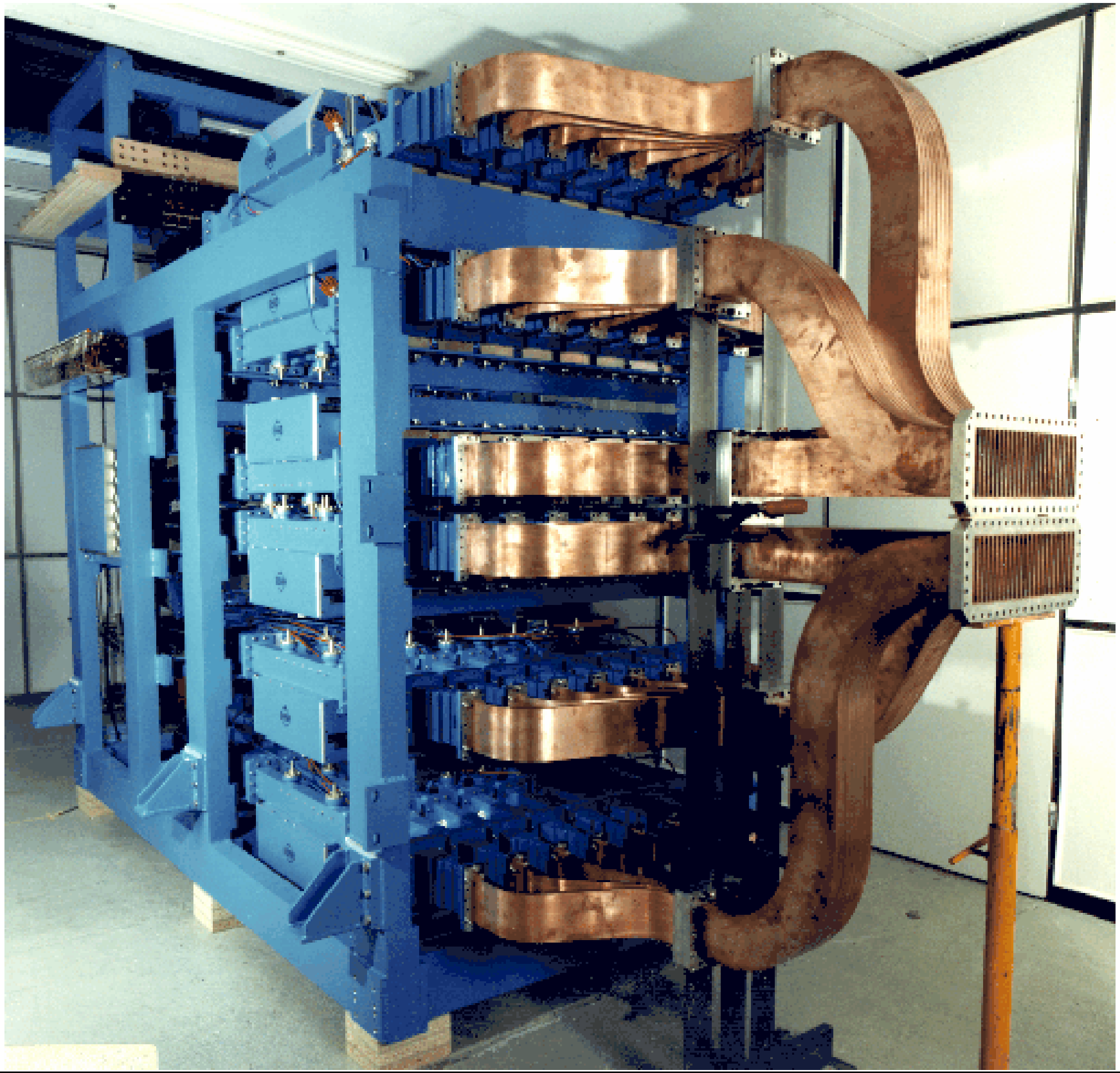


ASDEX

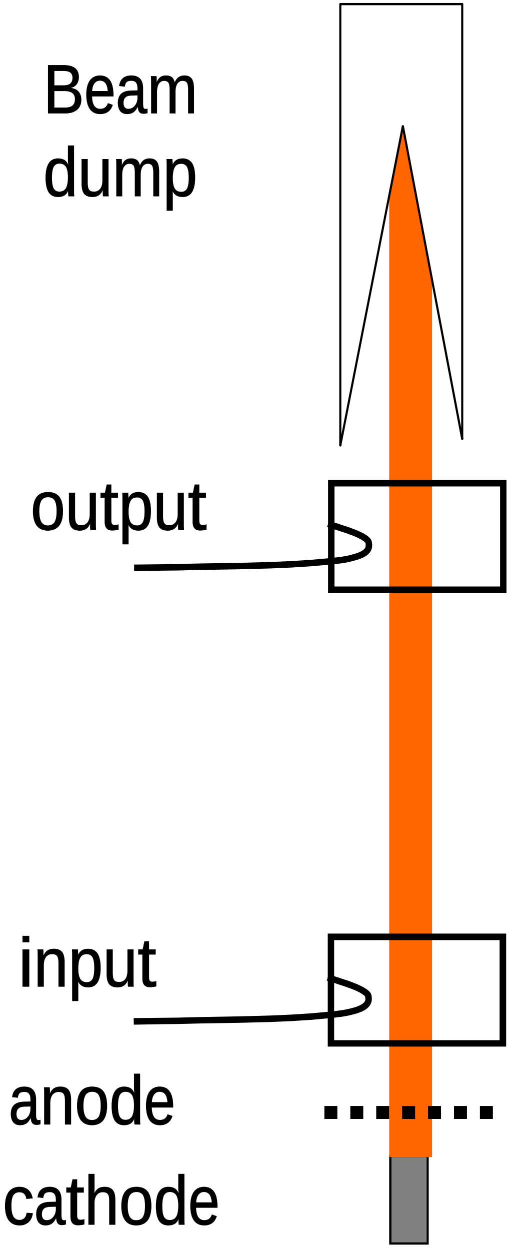


Wave power transport

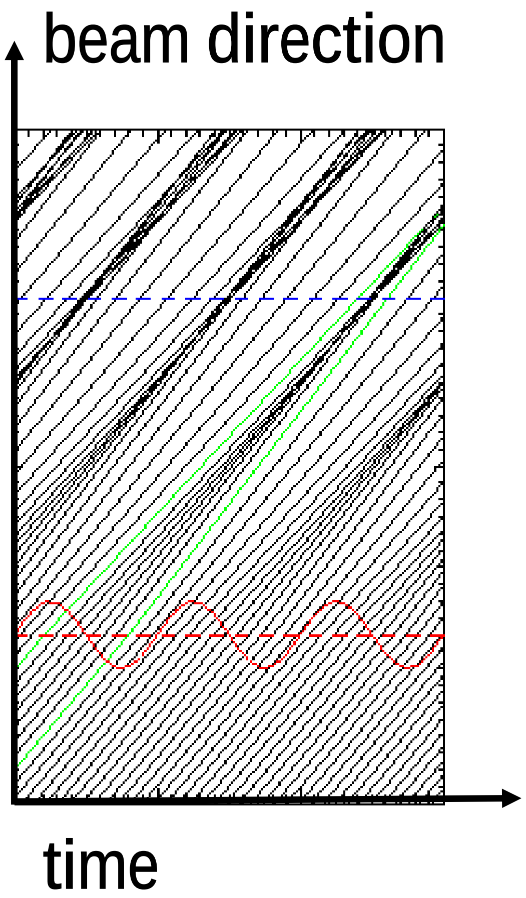




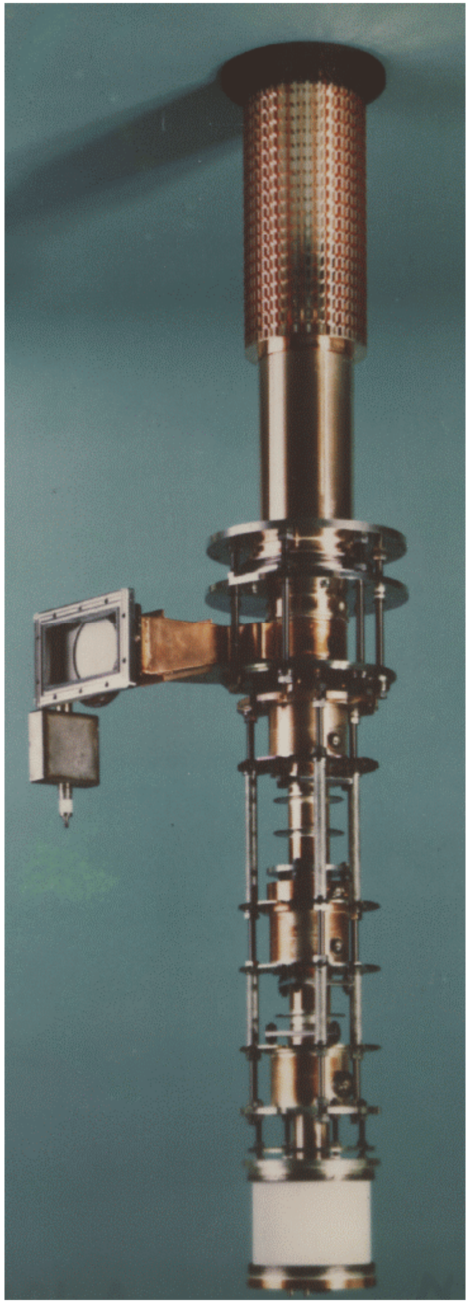
Klystron



3.7 GHz
500 kW, 3 sec



ASDEX



Electron Cyclotron Resonance Heating

Dispersion relation :two solutions for perpendicular propagation:

ordinary (O)-mode $E \parallel B_0$

extraordinary (X)-mode $E \perp B_0$

$$\lambda \approx 2\boldsymbol{mm}$$

No low density cut-off, but high density cutoff.

Ions can be assumed stationary, but relativistic electron mass has to be included.

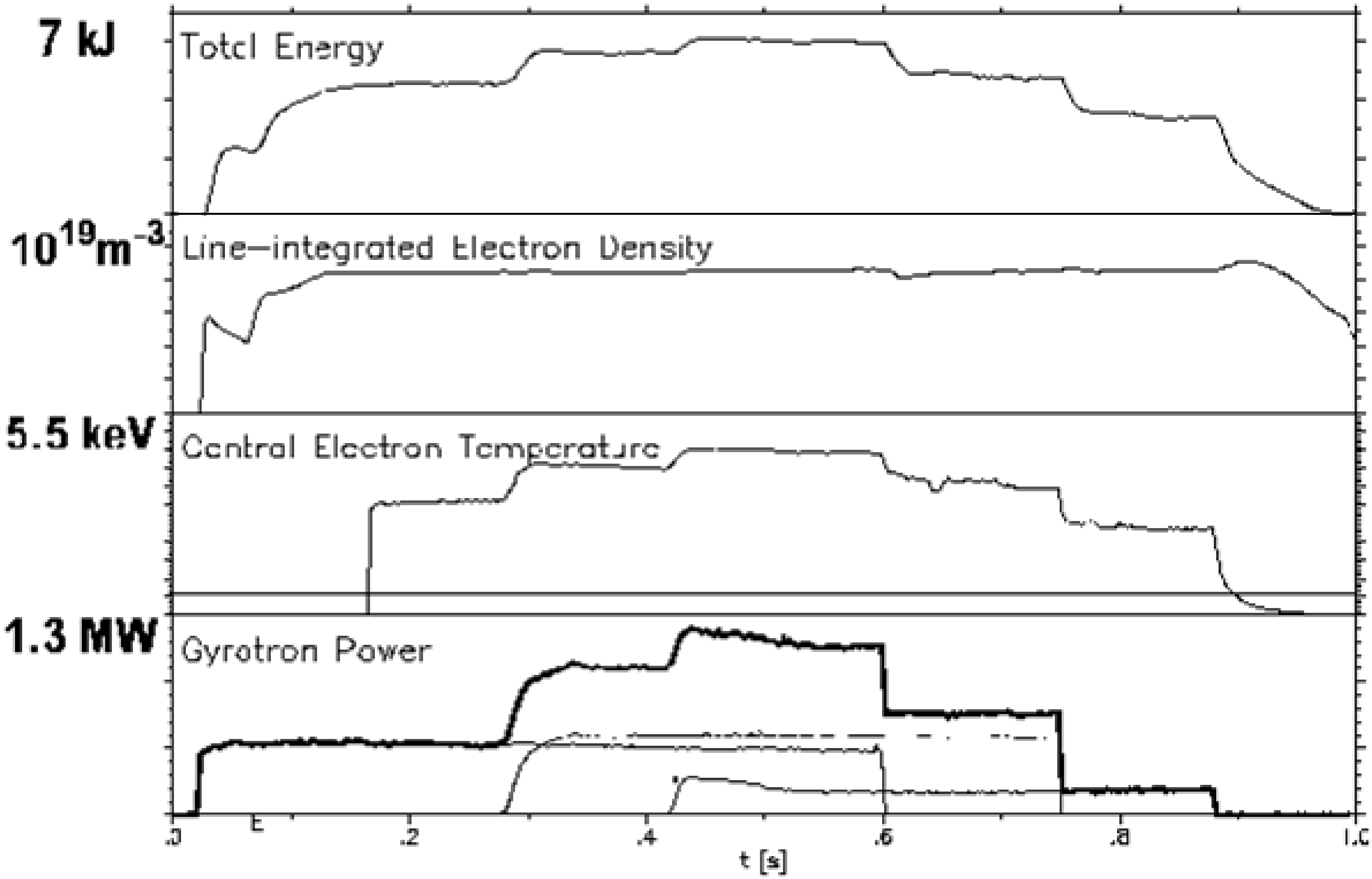
Various absorption mechanisms:

X2 heating

O2 heating

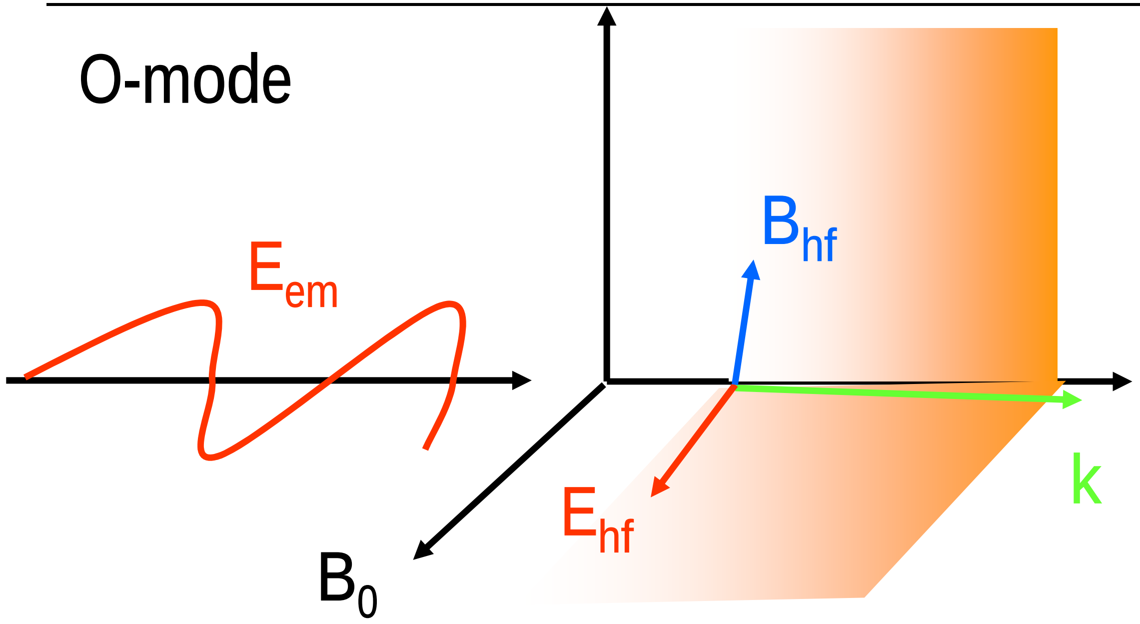
OXB heating…

Example: ECRH X2 heating on W7-AS



ECRH - Wave excitation

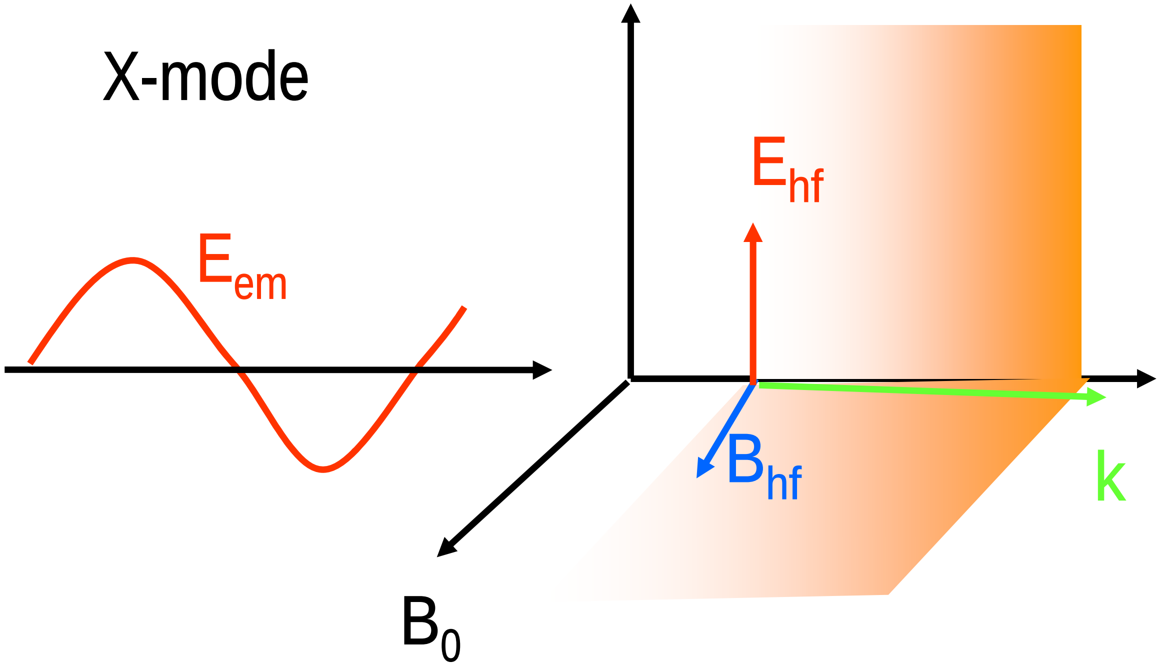
O-mode



$$f^2 = f_{pe}^2 + \frac{c^2}{\lambda_\perp^2}$$

Smooth connection
to vacuum EM waves.

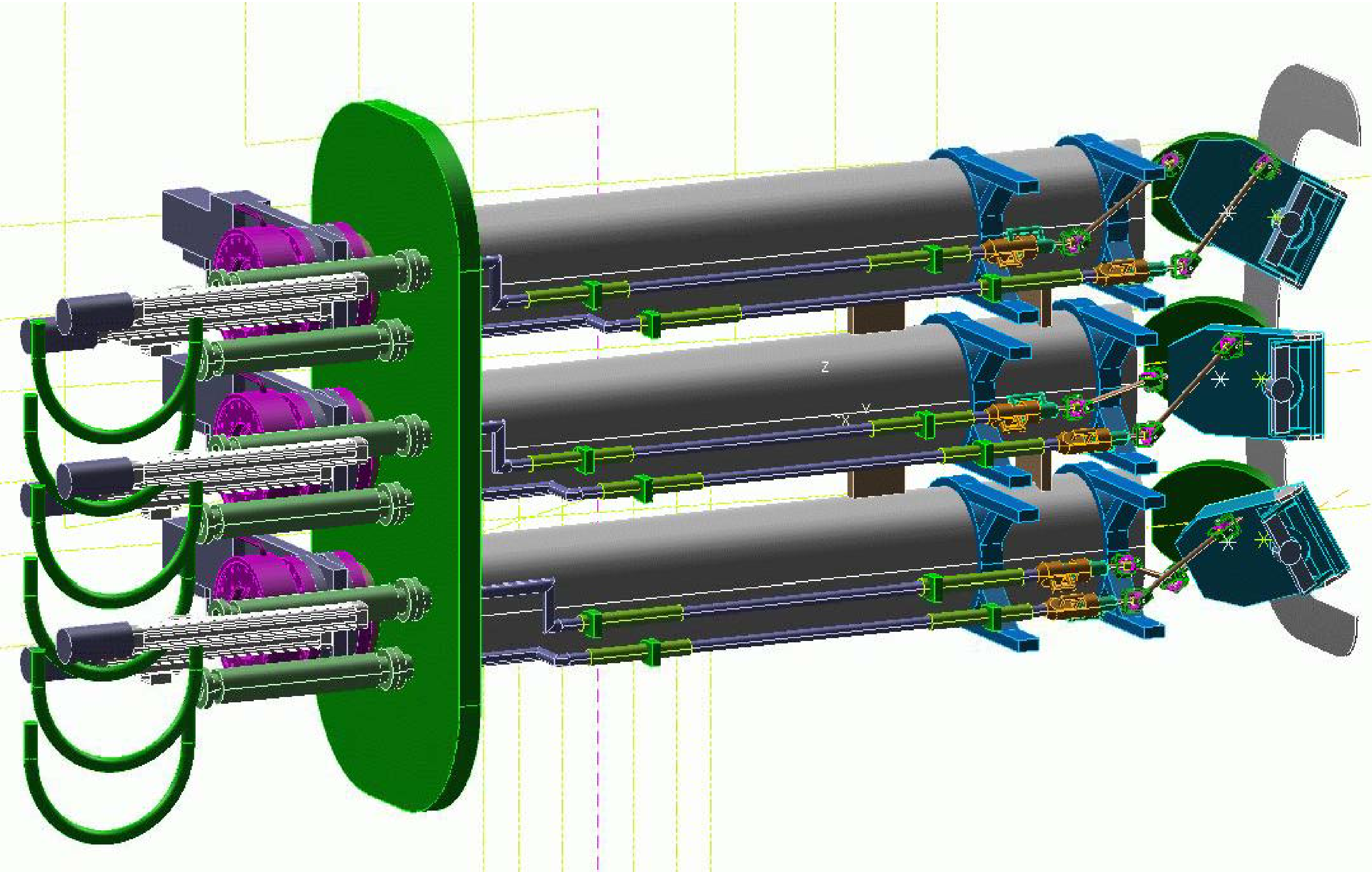
X-mode



Waves are launched with
movable mirrors

Polarization adjustable

Steering mirror launching system of W7-X



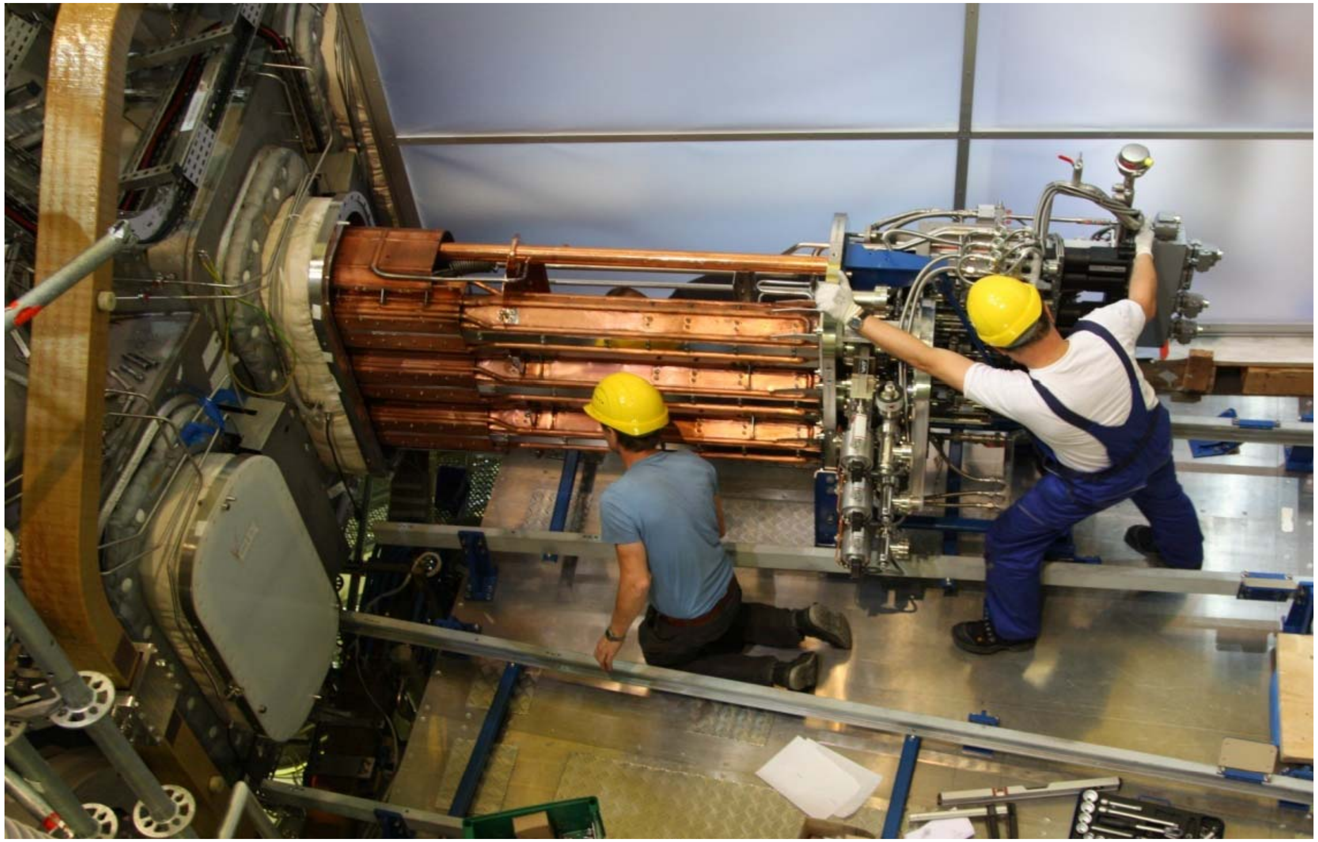
ECRH launcher

7 gyrotrons installed

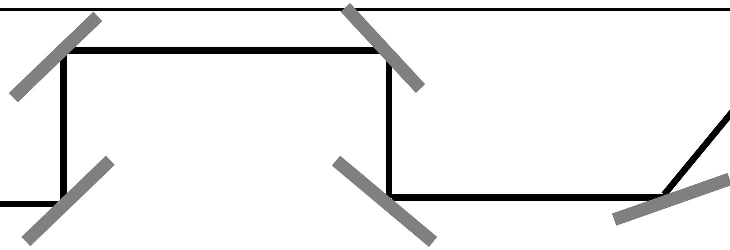
4 optical launches with steerable mirrors installed

Optical transmission installed and adjusted

7 gryotrons with a total power of about 5 MW ready for operation

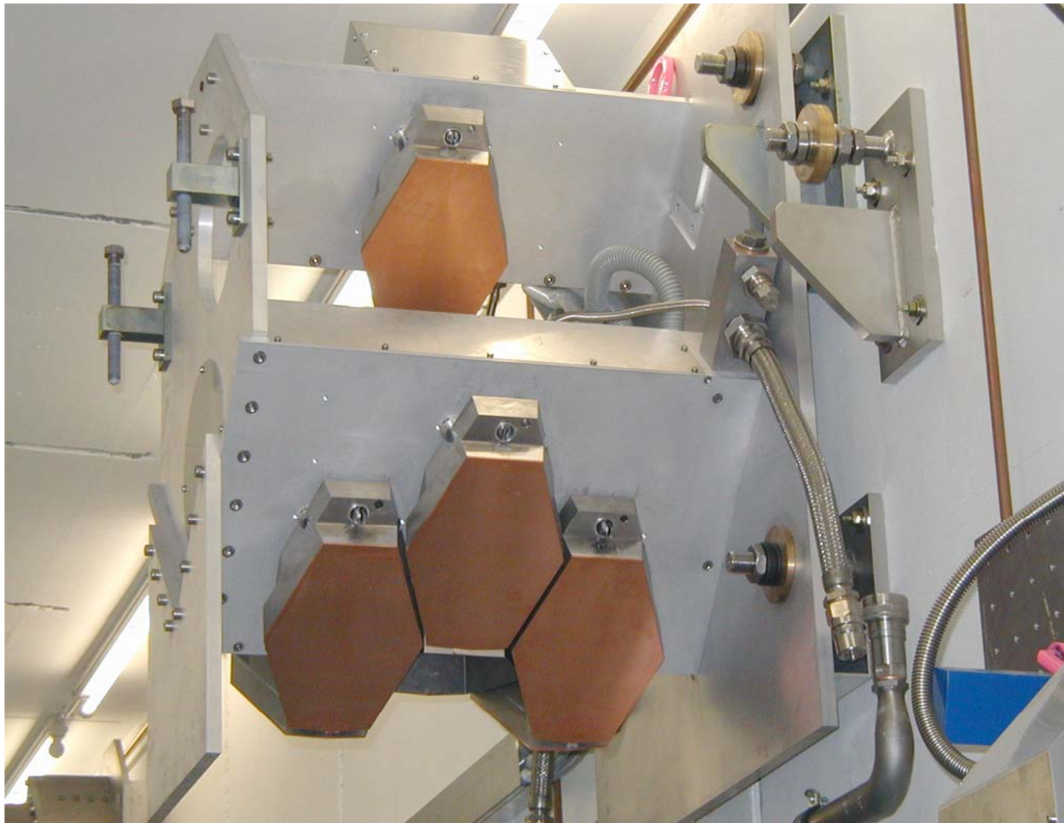


ECRH - Wave Excitation and Transport



mirrors,
can change
polarization

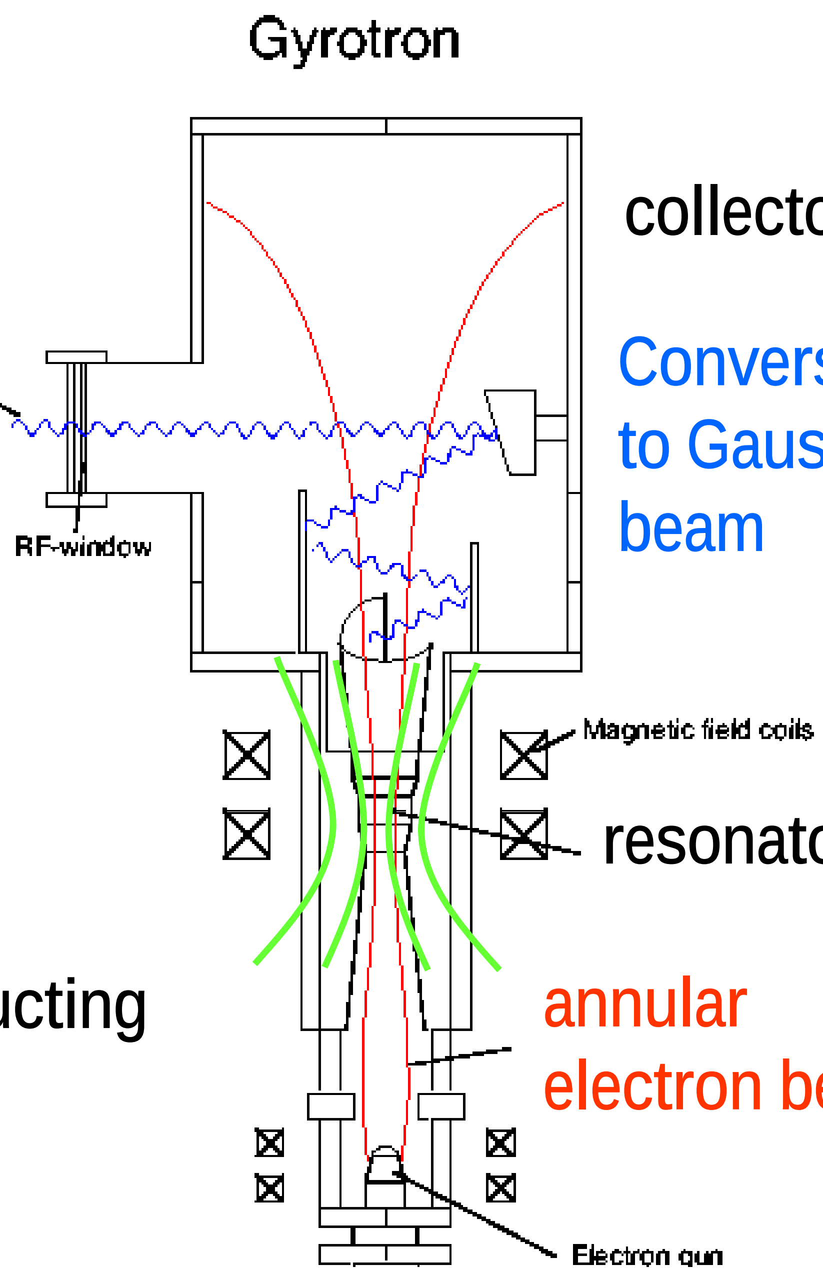
movable
mirror



ECRH - Gyrotrons

Oscillator

Window
Al_2O_3
or C



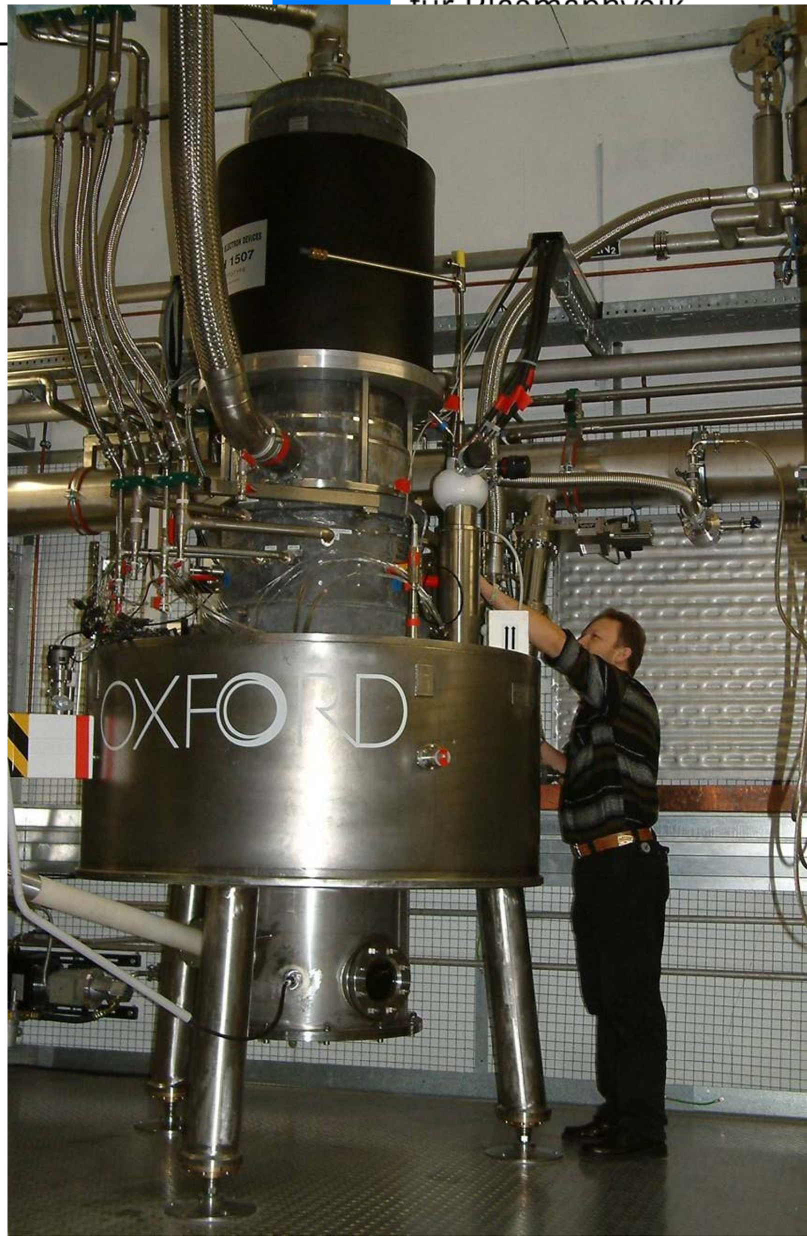
collector

Conversion to Gaussian beam

resonator

annular electron beam

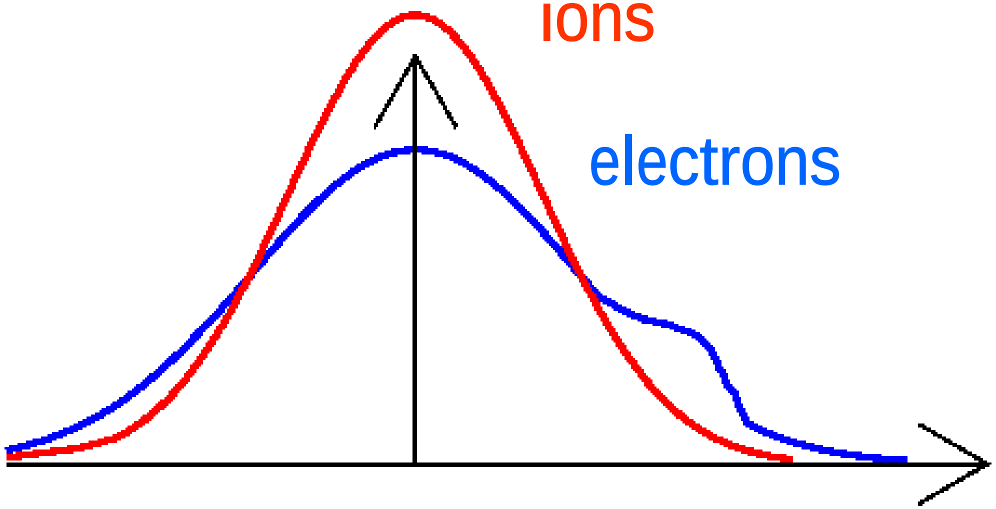
B field superconducting coils



Presently development of 1 MW cw gyrotrons

Non-inductive current drive

Asymmetric velocity distribution can be a side effect of plasma heating.



$$j = \sum_s q_s n_s \int v_{\parallel} f(v_{\parallel}) dv$$

Needed for :

Steady-state tokamak
current profile control in tokamaks
bootstrap current compensation in stellarators

Efficiency: Theory:

$$\eta_{th} = \frac{j}{p} = \frac{e \cdot n_{e\parallel} \cdot v_{\parallel}}{\left(n_{e\parallel} \cdot m_e v_{\parallel}^2 / 2\right) \cdot \nu_{coll}} \propto \frac{1}{v_{\parallel} \cdot \nu_{coll}}$$

Experiment:

$$\eta_{ex} = \frac{n_e \left[10^{20} m^{-3}\right] \cdot R[m] \cdot I[A]}{P[W]} \propto \eta_{th}$$

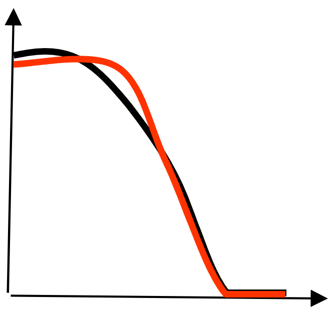
Parallel momentum injection: required total electron momentum $2 \cdot 10^{-4} \mathrm{kg} \cdot \mathrm{m}/\mathrm{s}$

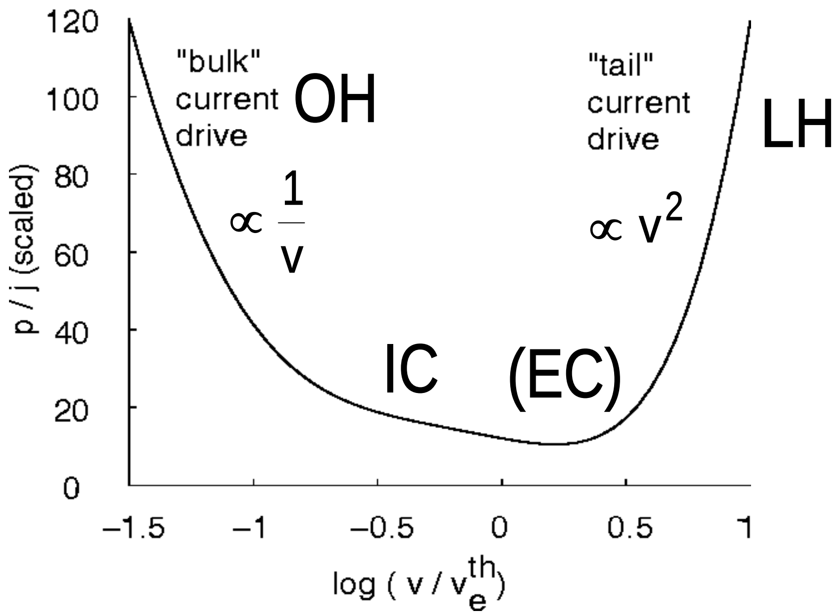
$v_{||} = \omega / k_{||} << v_e^{th}$

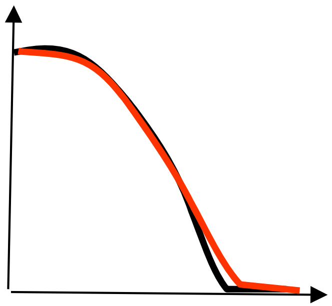
+ change of electron momentum / wave energy
+ many electrons
- large fraction of trapped electrons
- $\nu_{coll} \propto T_e^{-3/2}$

$v_{||} = \omega / k_{||} >> v_e^{th}$

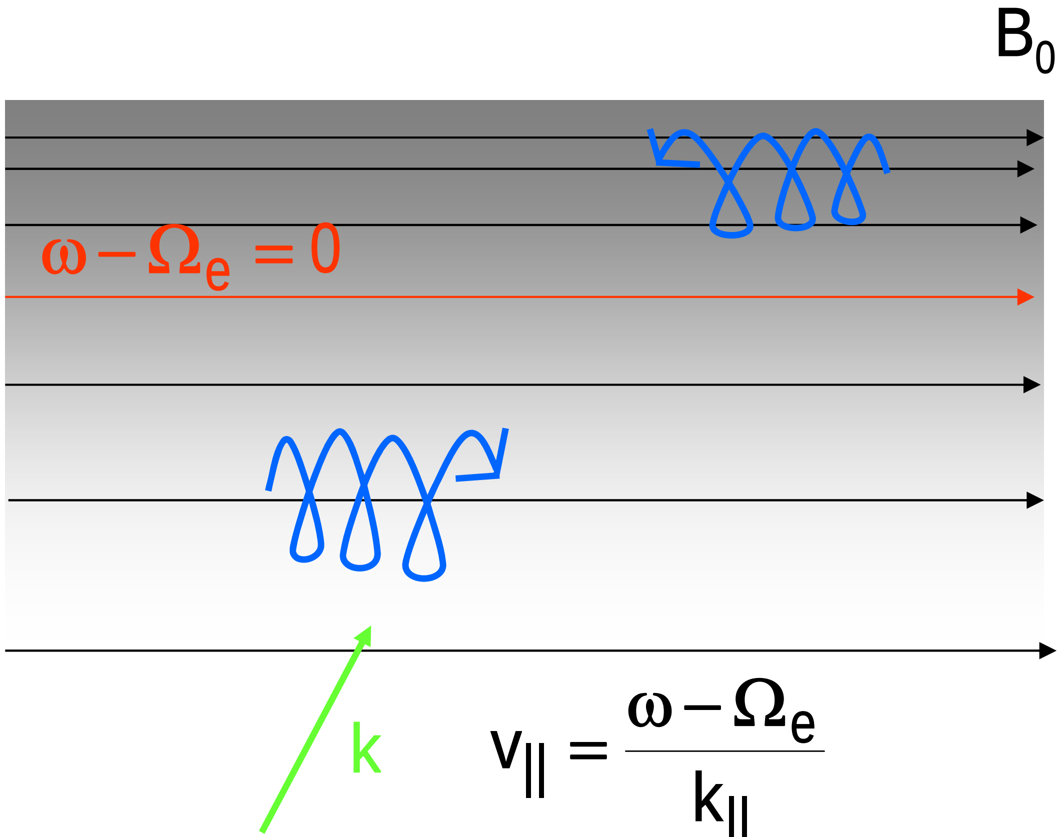
+ $\nu_{coll} \propto v_{||}^{-3}$
- small change of electron momentum



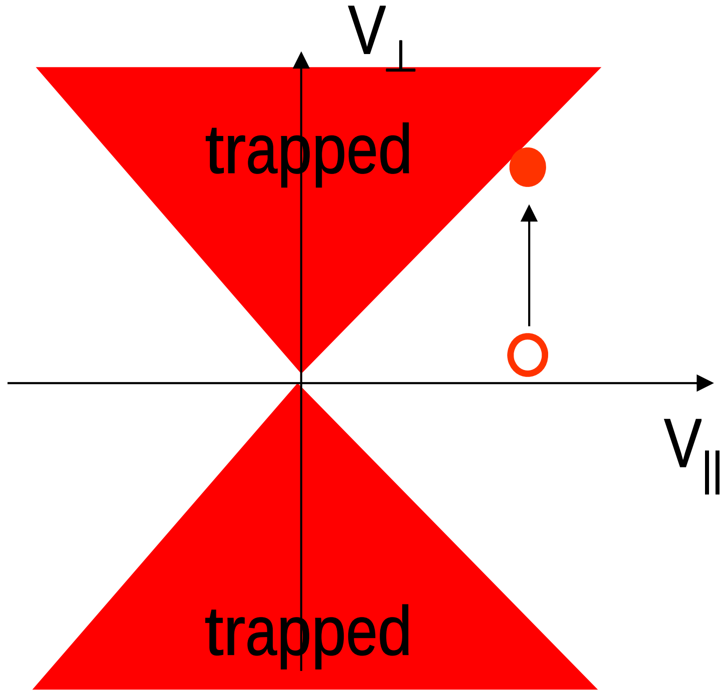




Asymmetric collision frequencies



$$v_{||} = \frac{\omega - \Omega_e}{k_{||}}$$

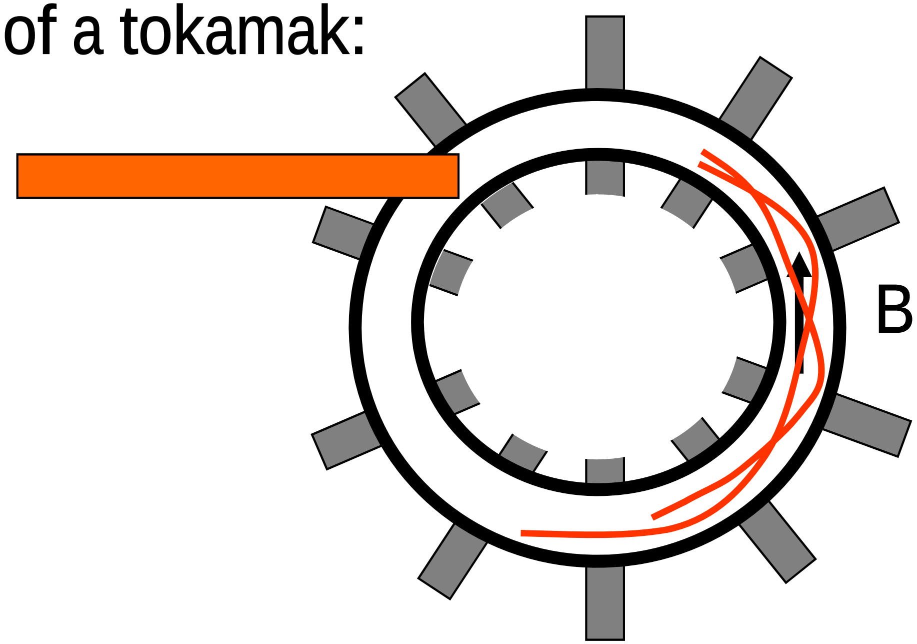


Current drive simply by changing the launch angle.
Faster electrons collide less often.
Trapped electrons reduce efficiency.

Current Drive with Neutral Beam

Horizontal cross-section of a tokamak:

Tangential injection
(counter)



Circulating ions carry current
partially compensated by:

concurrent electron drift
trapping
dependence on collision frequency

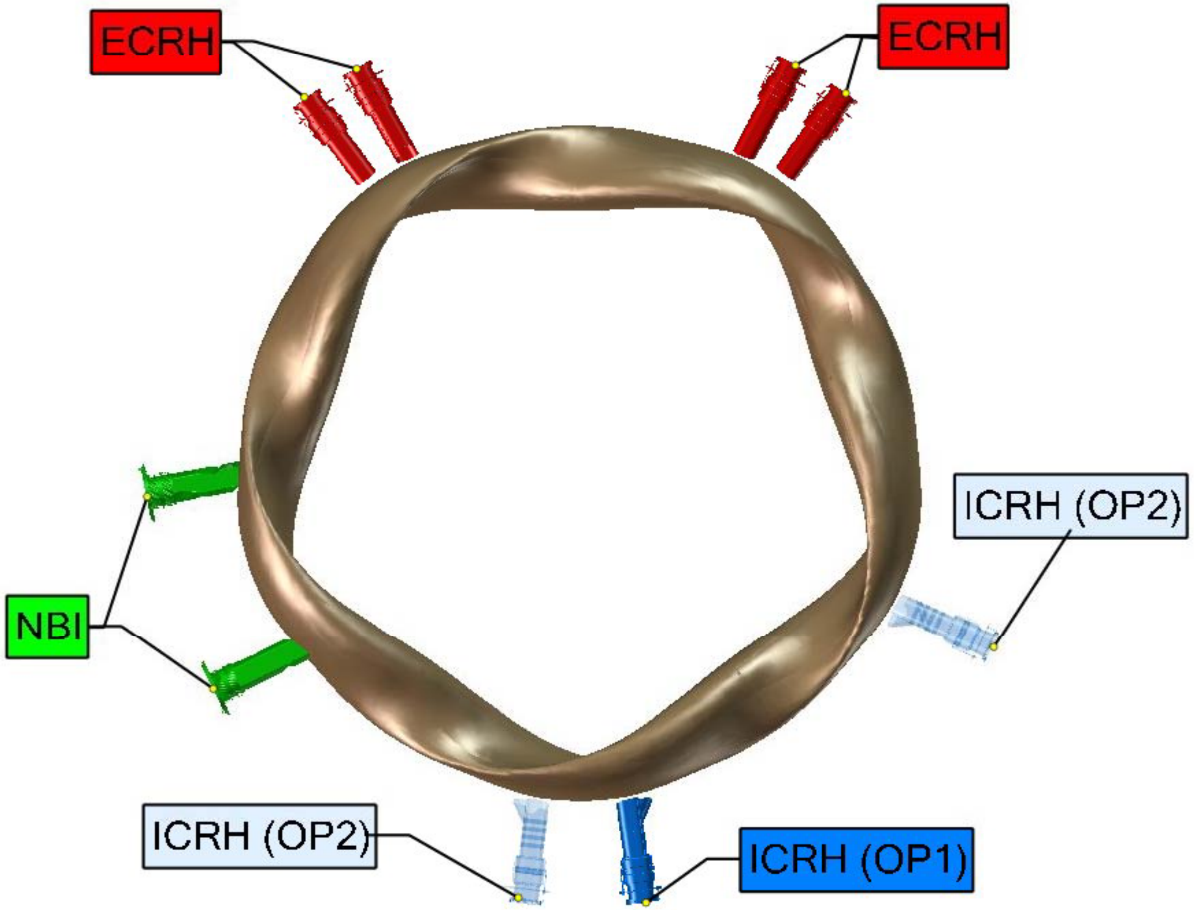
Best efficiency if $E_{NBI} \approx 40 \cdot T_e[\mathrm{keV}] \cdot A_{inj}$

Negative NBI necessary

Current drive efficiencies

	Efficiency
LHCD	0.35 – 0.4
ICCD	0.1 x T_e [10 keV]
ECCD	<0.1 x T_e [10 keV]
NICD	.2 x T_e [10 keV]

Heating systems for OP2



ECRH:
10 x 1 MW cw 140 GHz Gyrotr

NBI
2 x 4 x 2.5 MW 90 kV D Injecti

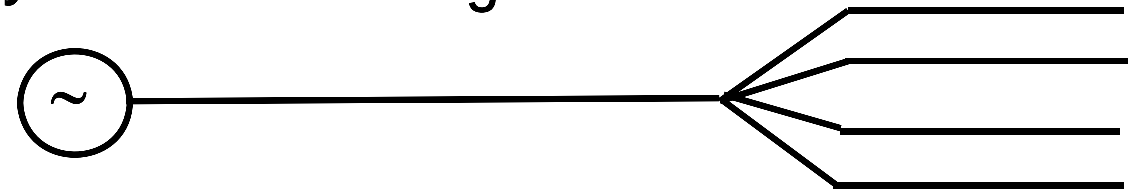
ICRH
2 x 2 MW 10 sec 25-38 MHZ

Summary Heating

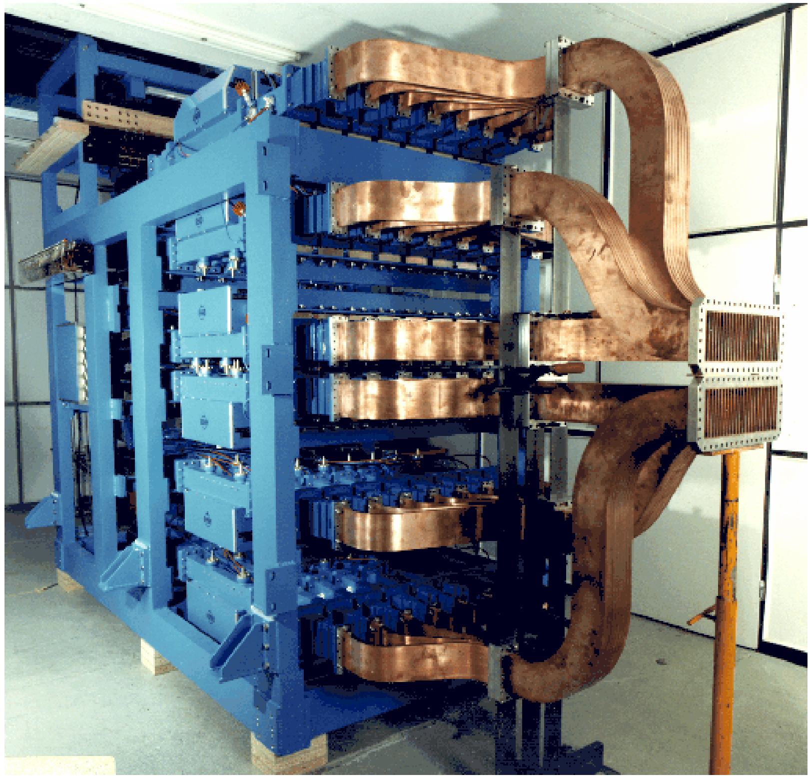
Heating scheme	advantages	disadvantages
Ohmic	efficient	Cannot reach ignition Not in stellarators
NBI	reliable	close to torus negative ions necessary
LH	Efficient current drive	Antenna close to plasma Off-axis
ECRH	Reliable flexible	Electron heating (density limit)
ICRH	Ion-heating Central heating	Antenna close to plasma Antenna coupling

LH technology: Wave generation and transport

klystron waveguide grill



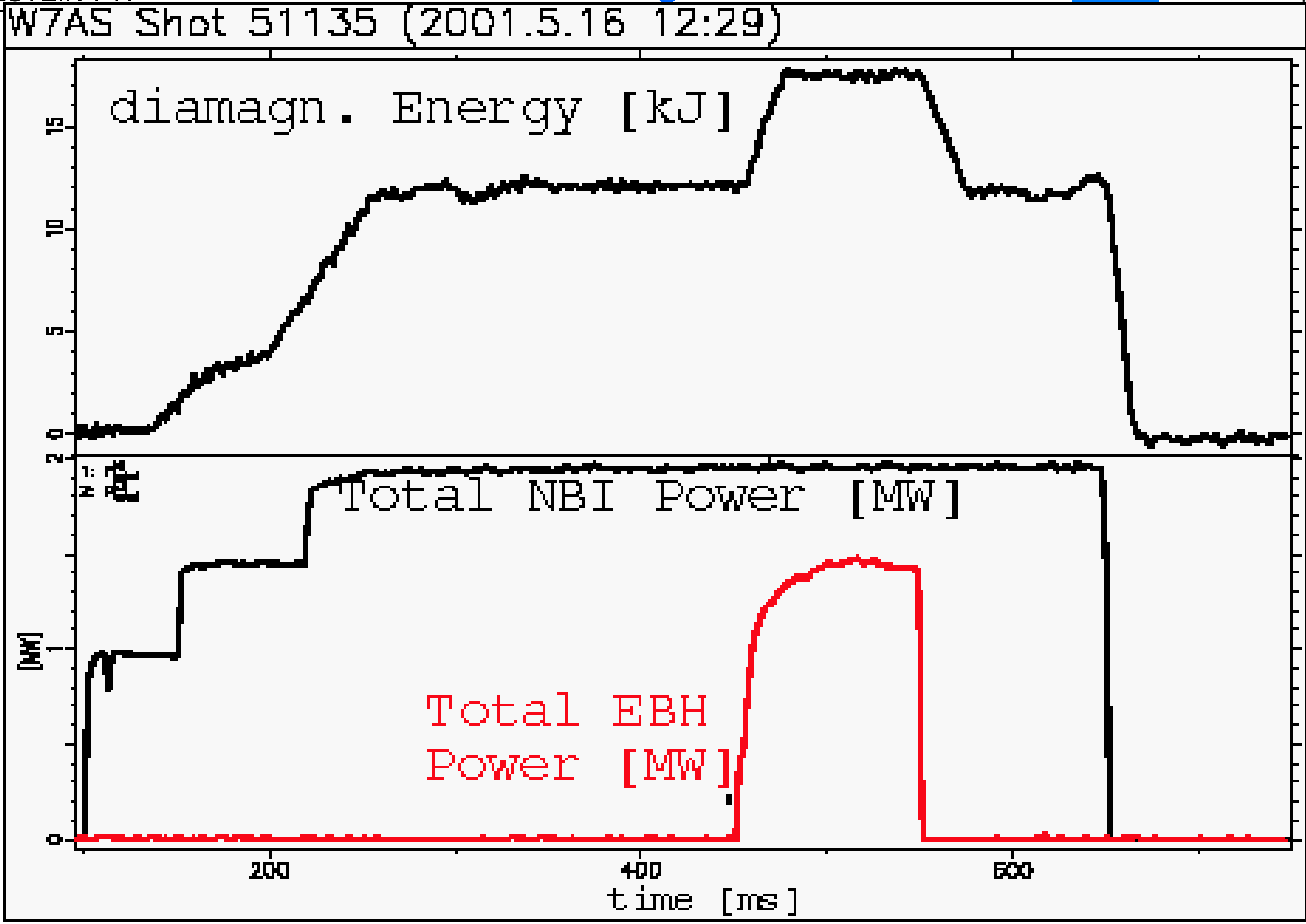
[thalesgroup.com]



ASDEX

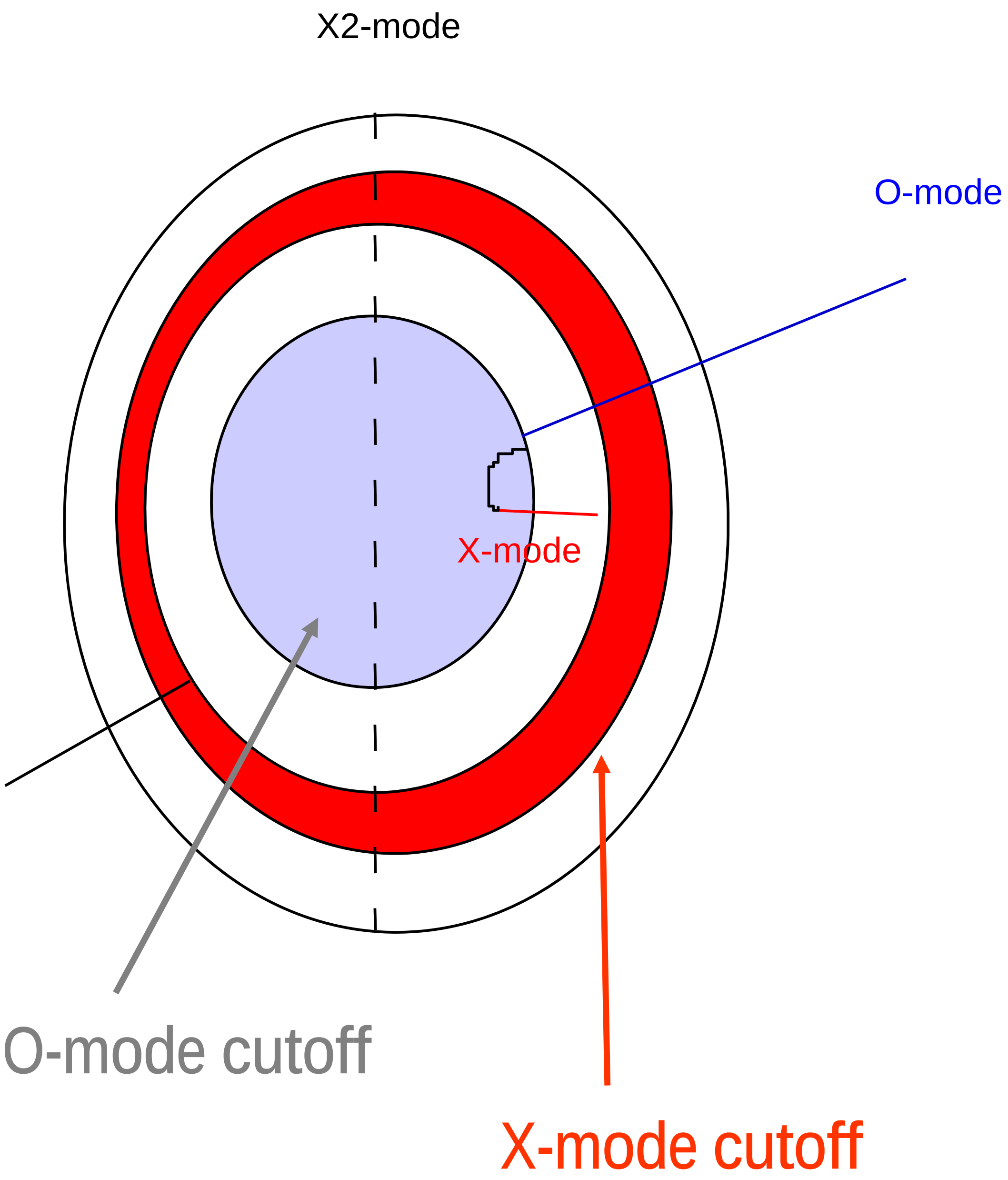
Tore Supra

OXB-mode Heating on W7-AS



ECRH - OXB heating

H. Laqua



Mode conversion process under certain launch angles and for minimum density.

O mode converts into X mode at X-mode cutoff.
X-mode converts into electrostatic electron (Bernstein) wave.
Bernstein wave absorbed by electron Landau damping.

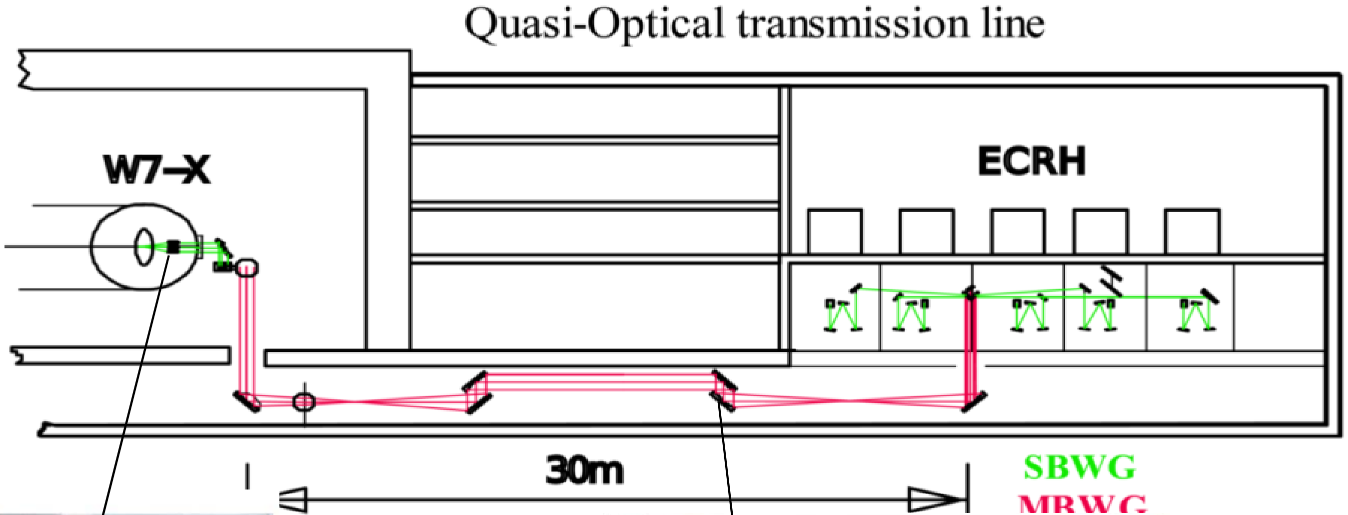
No upper density limit.

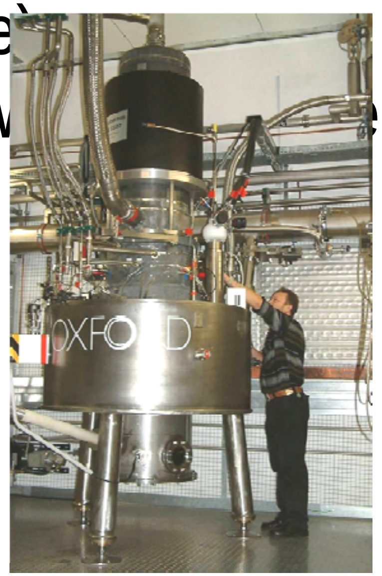
ECRH system

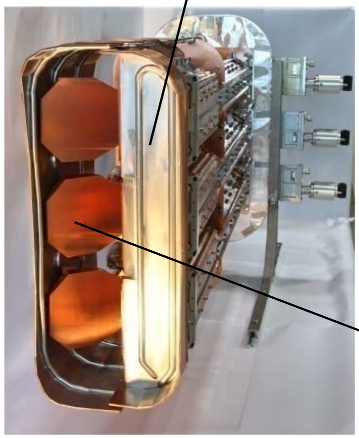
10×1MW 140GHz (10×0.5 MW 106 GHz) for 30min (final state

10 transmission lines (+spare space for 2 beams) with 2 MW

Transmission efficiency of 95% at 1MW cw

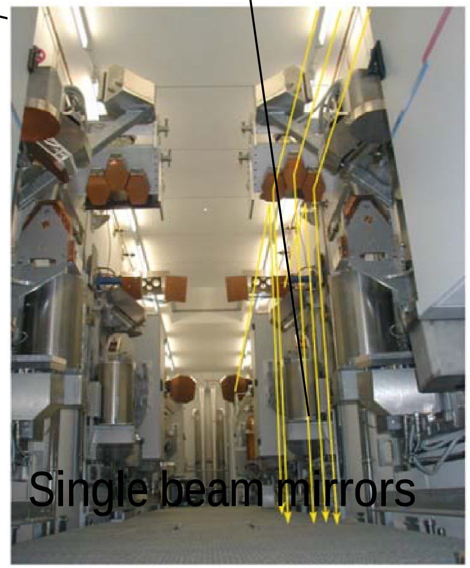






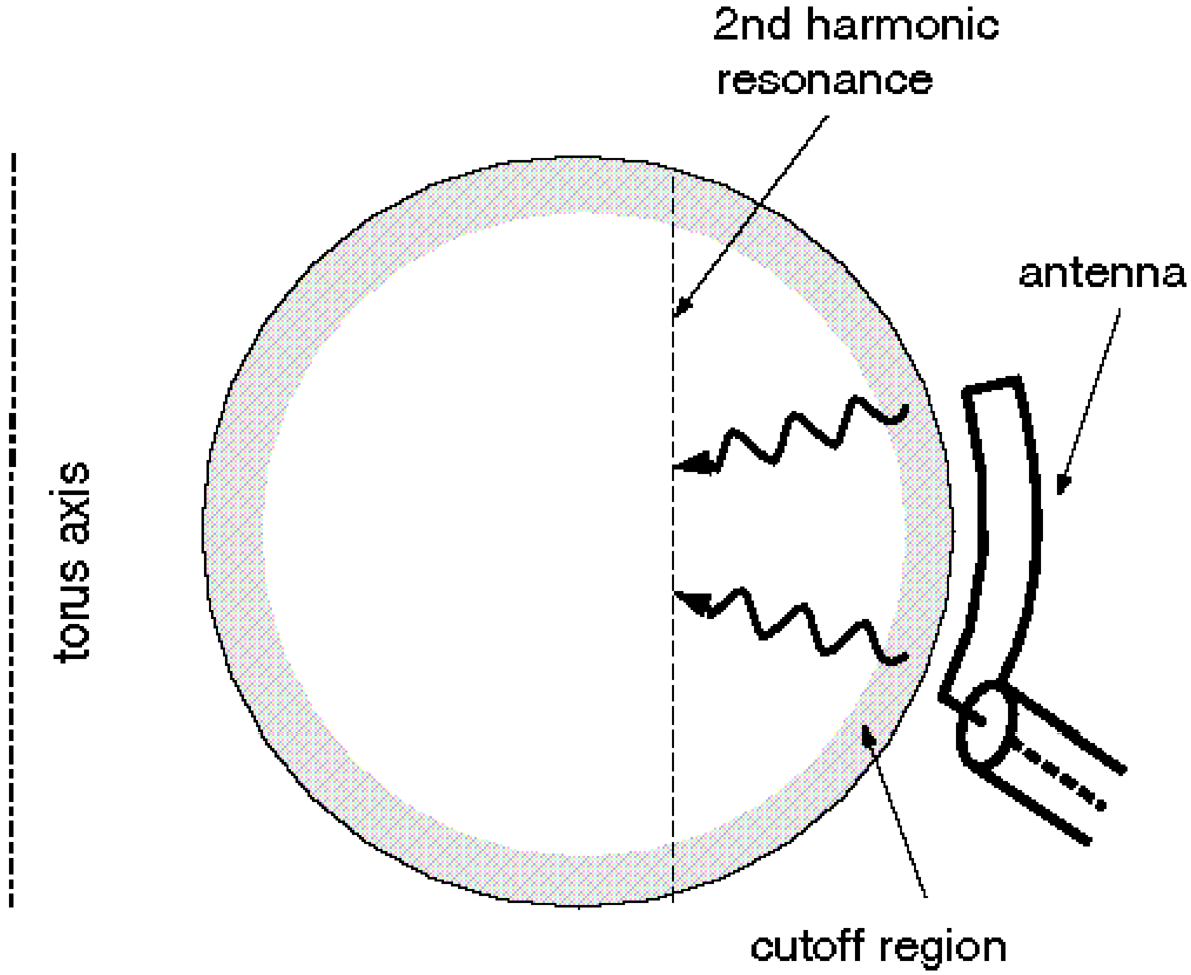
Front steering mirrors

Multi-beam mirrors



Single beam mirrors

ICRH - Second Harmonic Heating



Single species plasma

in large plasmas focussing of wave power

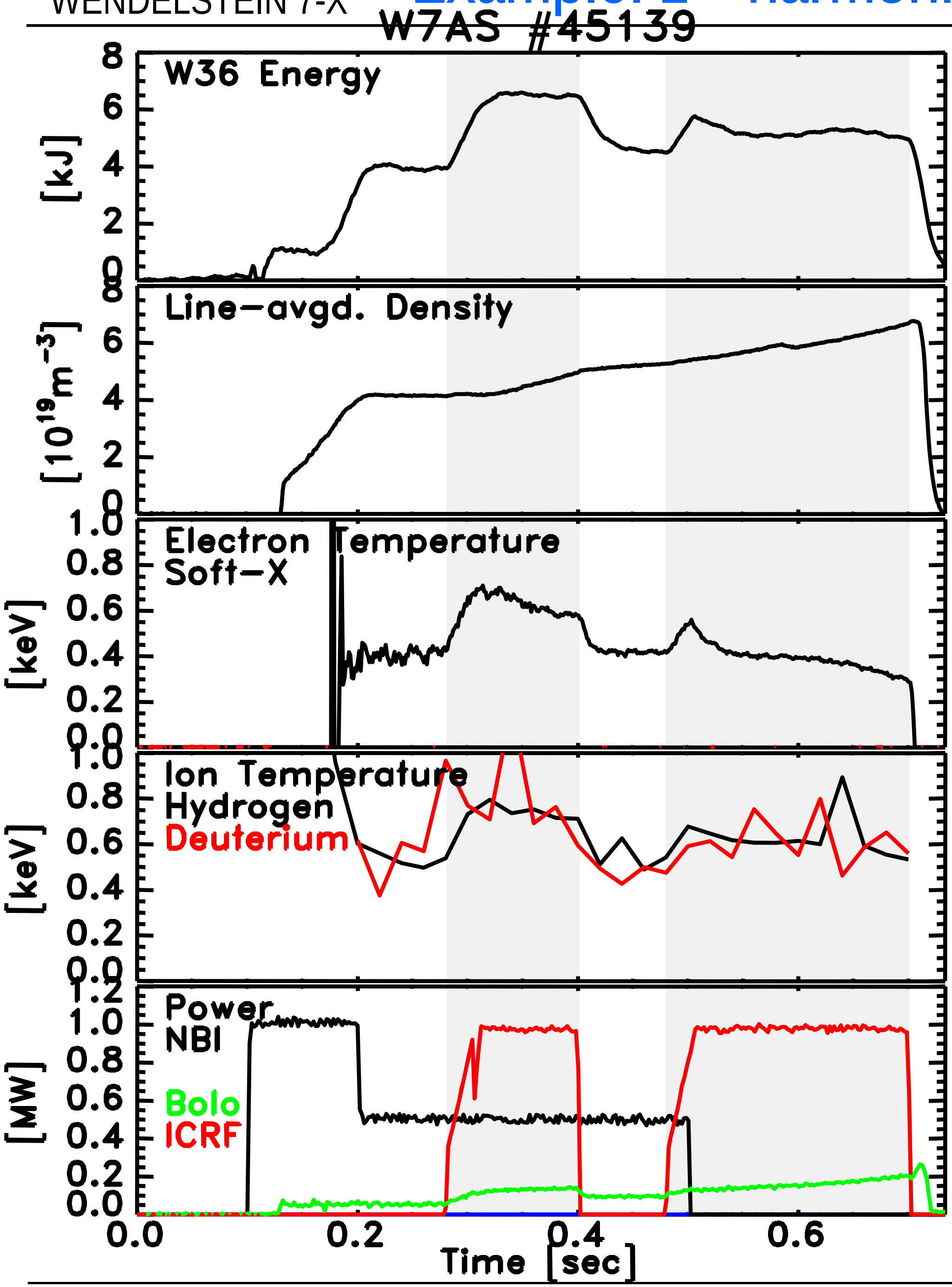
absorption dependent on n $(\rho_i k_\perp)^2$

high density needed

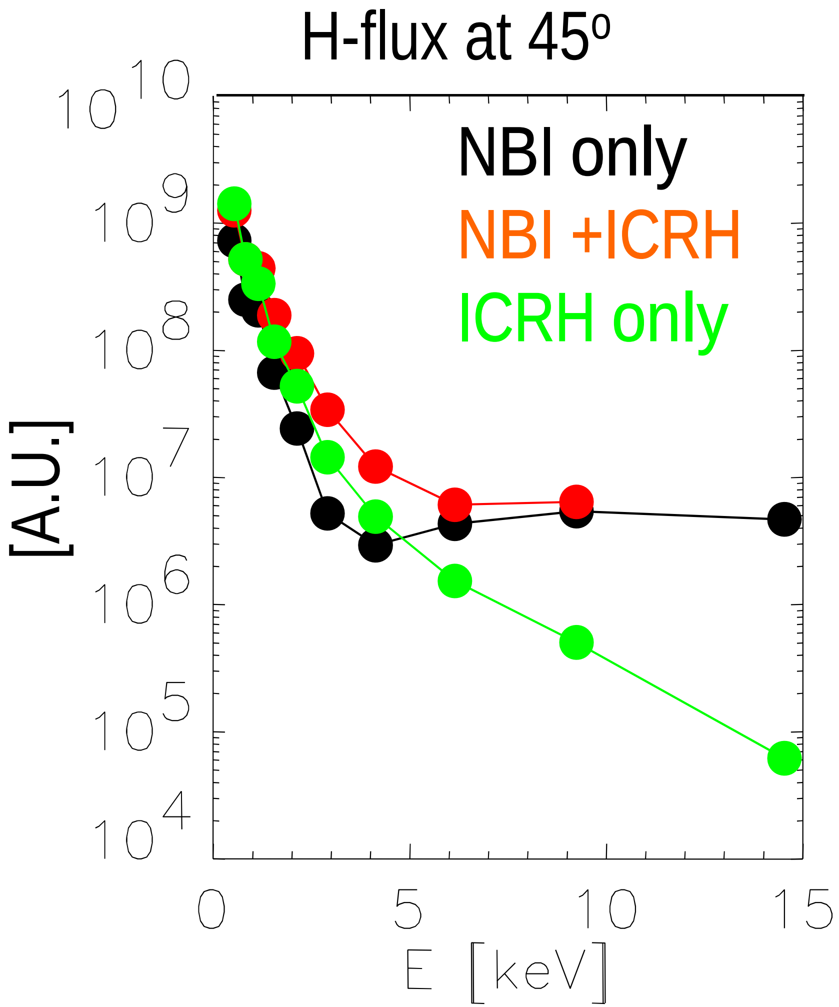
high ion temperature needed

development of tail in velocity distribution function

Example: 2nd harmonic hydrogen heating



B=1.25T



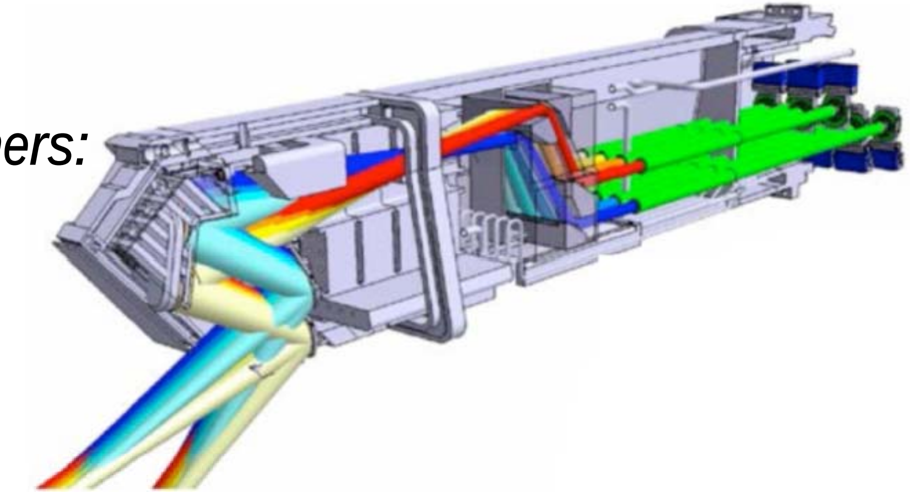
ECRH for ITER

24 gyrotrons, 56 outputs, total 20 MW @ 170 GHz to plasma

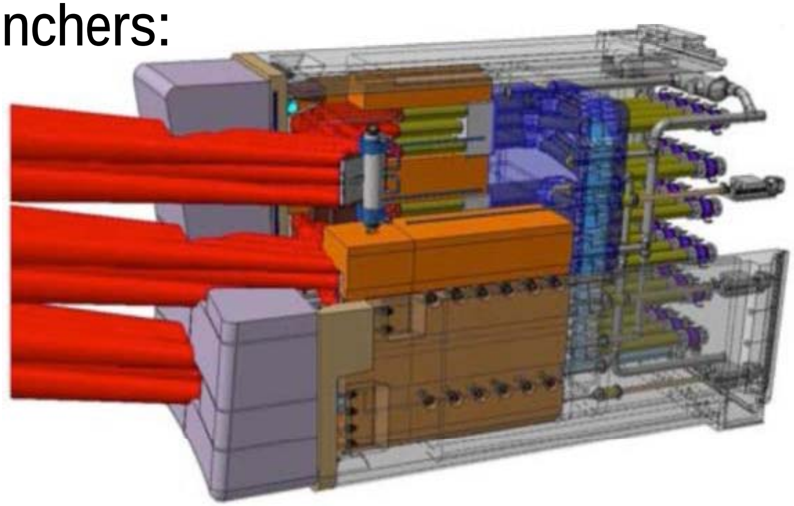
One of gyrotron prototypes:

[iter.org]

Upper Launchers:



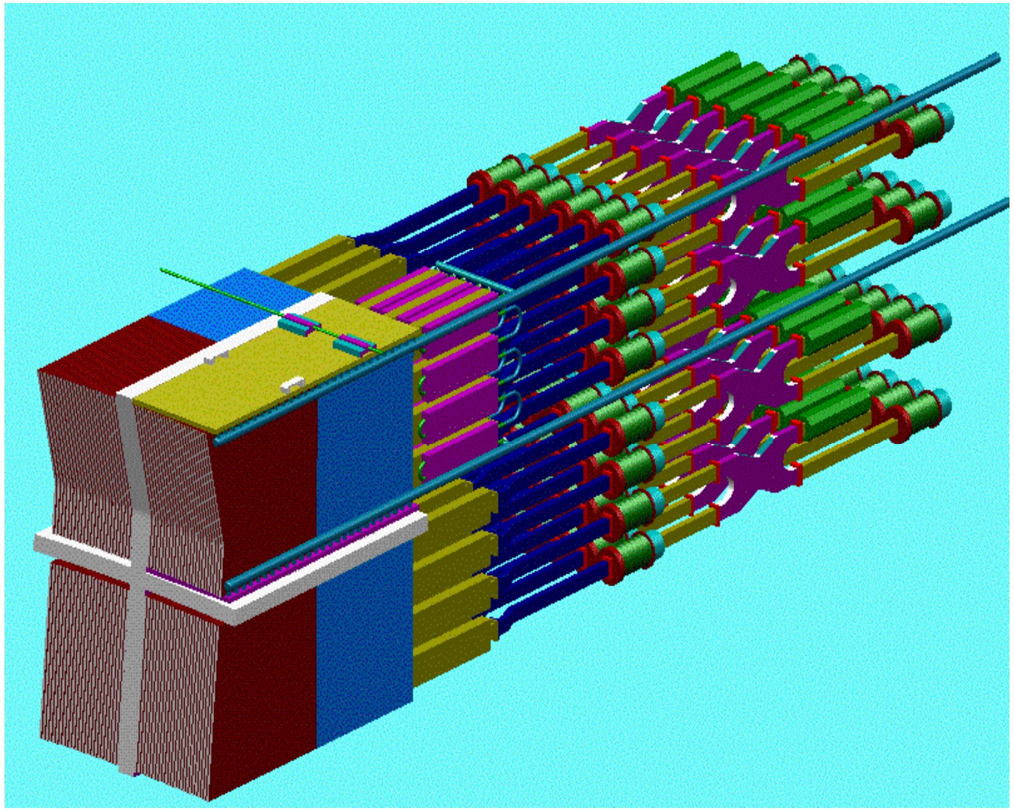
Equatorial Launchers:

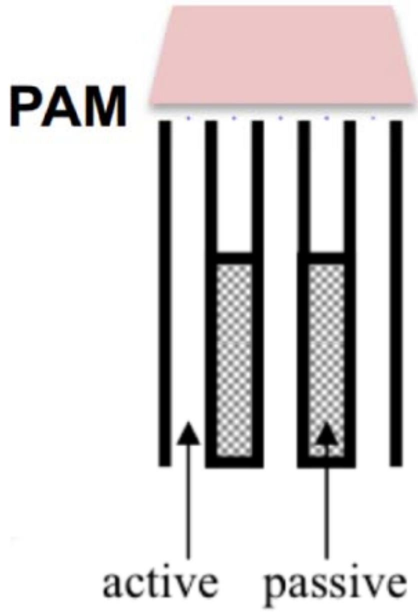


Possible LH launcher for ITER

No LH is planned for initial phase of ITER,
later upgrade under discussion with 20 MW @ 5GHz

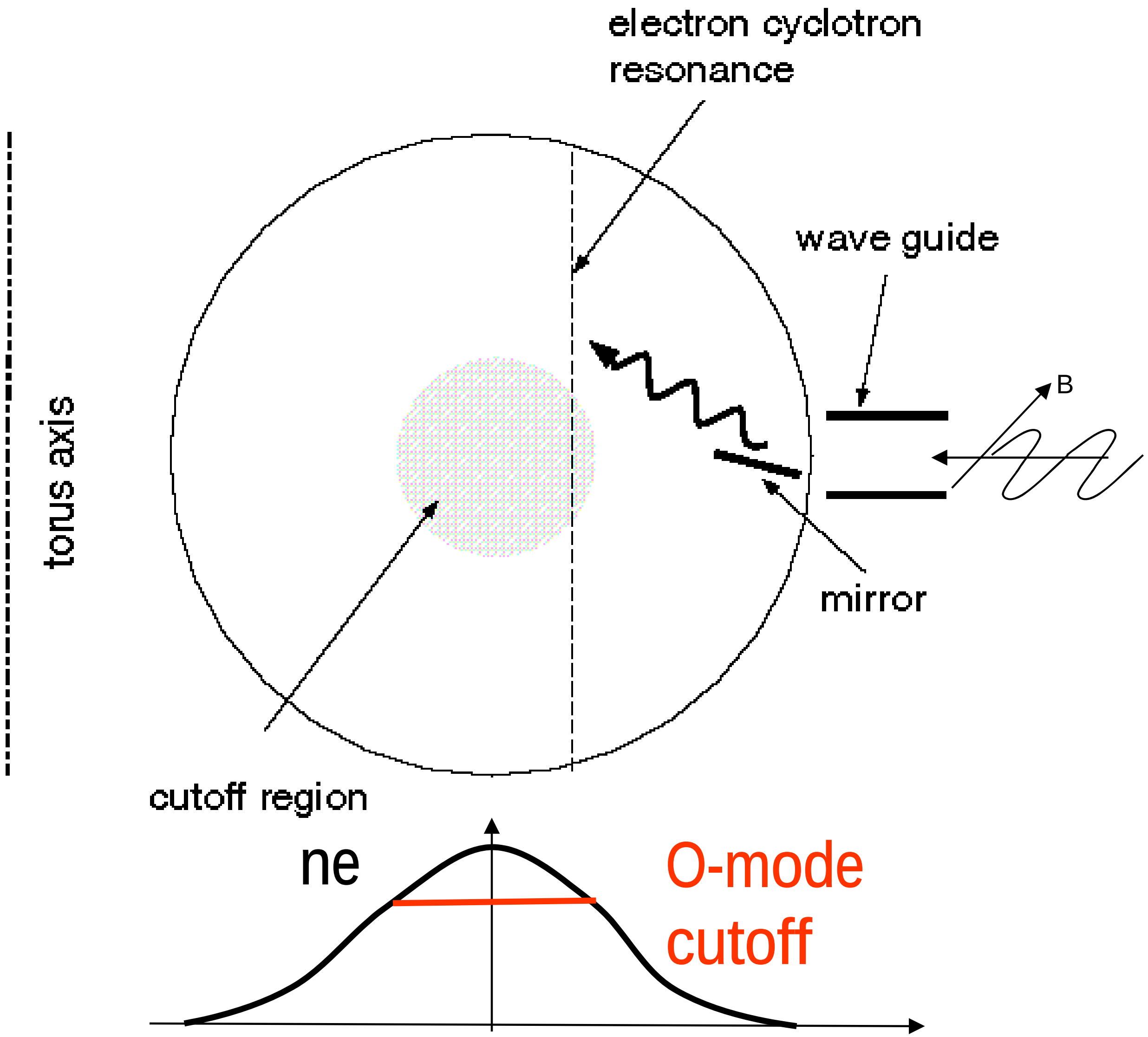
Possible passive-active multijunction (PAM) antenna:





LH system: efficient for current drive

Reflection at cut-off region

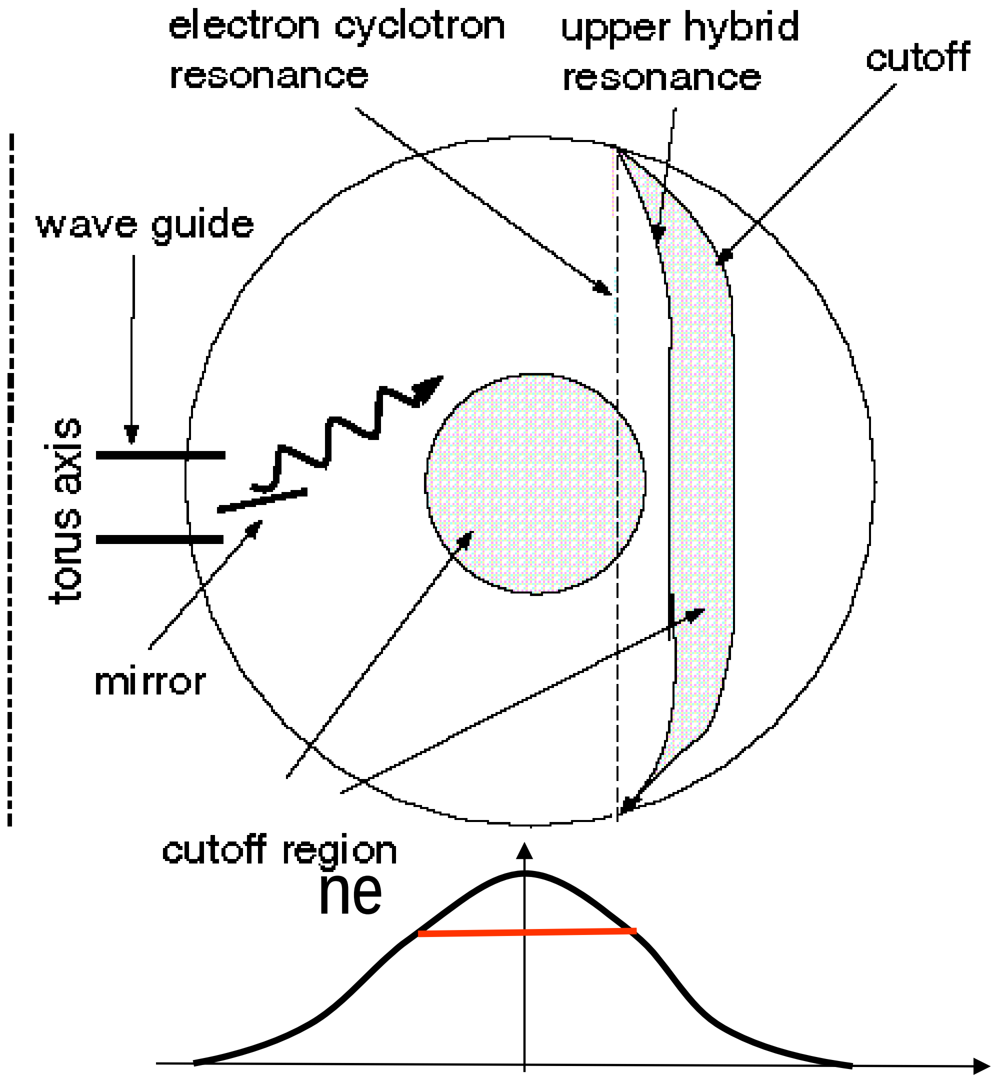


Dispersion

$$\omega^2 = k^2 c^2 + \omega_p^2$$

Density gradient leads to diffraction away from plasma center.

ECRH - X1 mode heating



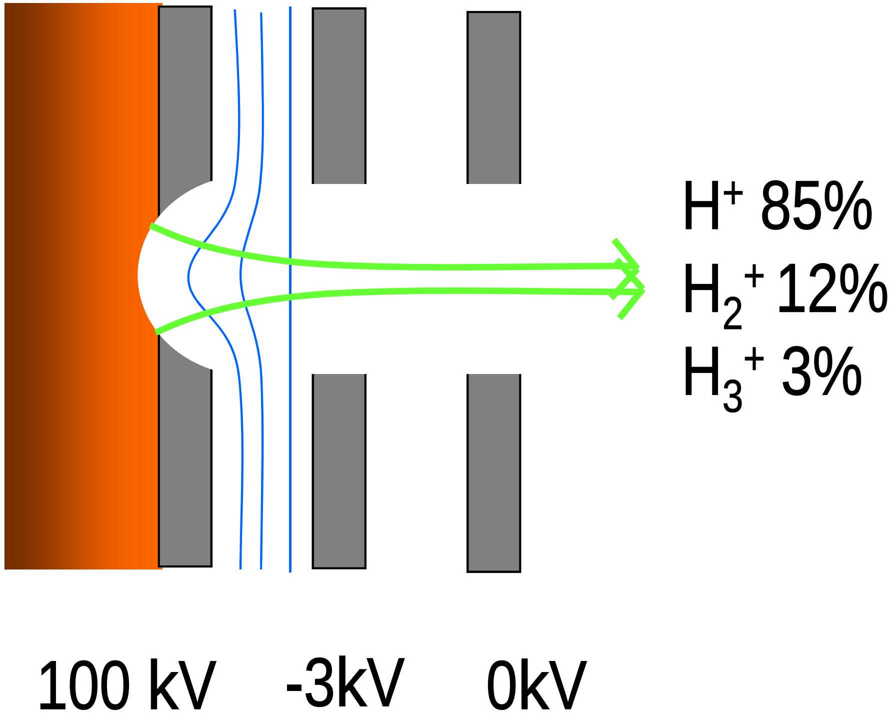
Resonance inaccessible from low field side because no propagation between cutoff and upper hybrid resonance.

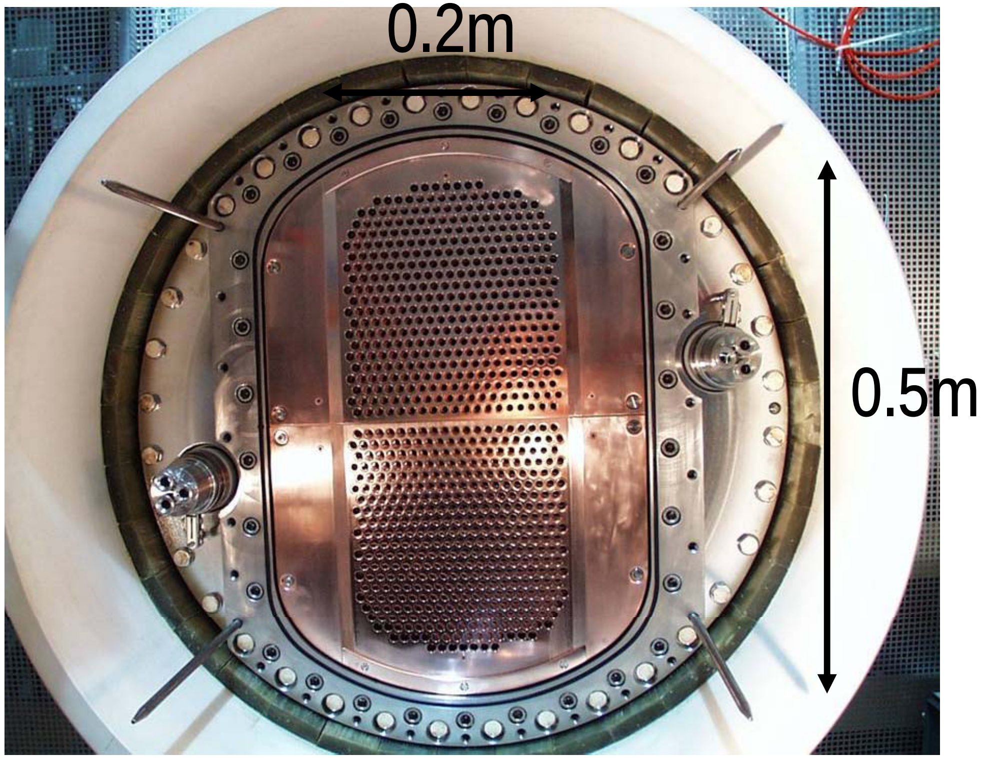
X2 accessible from LFS
i.e. second harmonic heating

NBI - Extraction and steering

3-lens system

potential lines





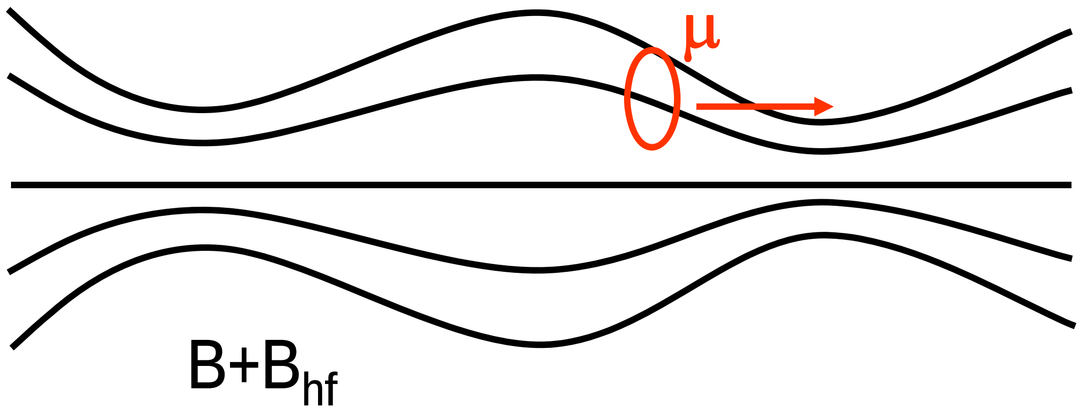
Typically 800 extraction holes per source.

Grid system ASDEX Upgrade.

Transit Time Magnetic Pumping

Magnetic moment approximately conserved:

$$\frac{d}{dt}\mu \approx 0 \quad \text{if} \quad \left(\frac{dB}{dt} \Big/ B \right) \Big/ \Omega << 1$$



Force on magnetic moment: $F = -\mu \nabla B$

Similar to Landau damping with substitution: $\mu \to q$

$\nabla B \to E$