ICRH
Overview and latest developments

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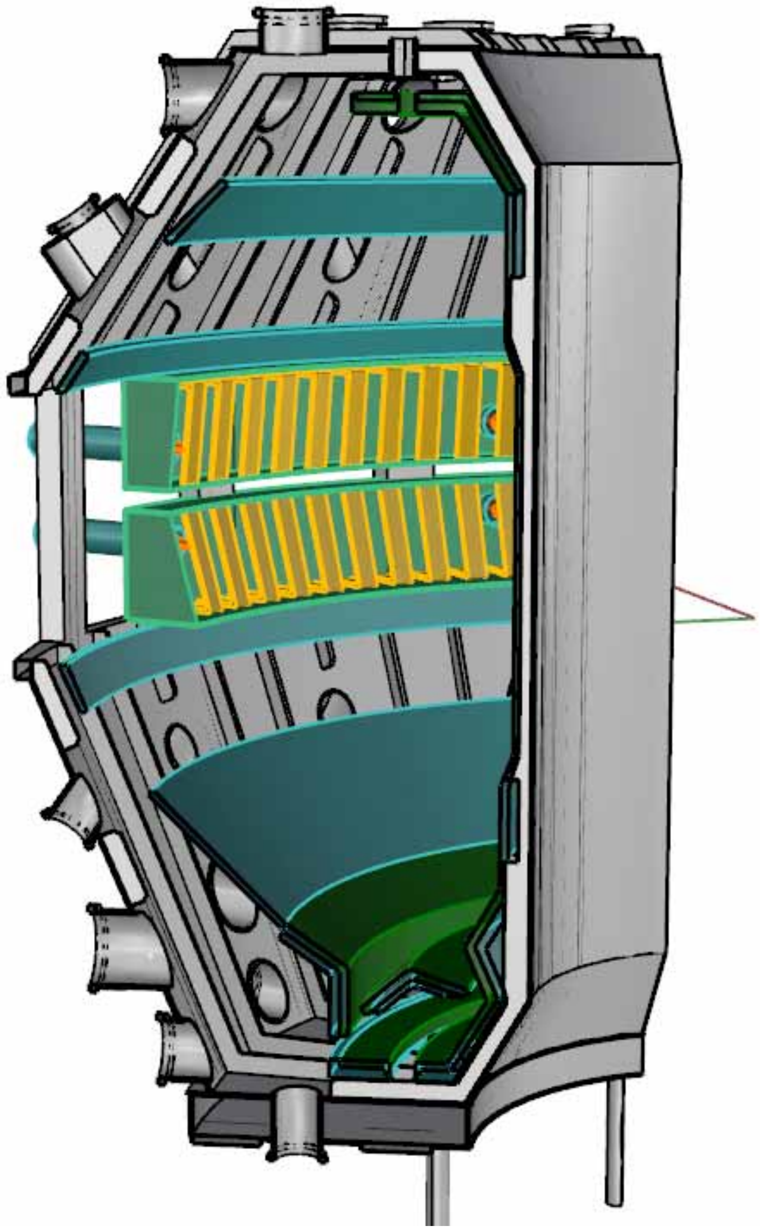

Content

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  - Coupling, Antenna Spectrum
- Heating and current drive using ICRH:
  - Single ion plasmas: fundamental and harmonic heating
  - Two ion plasmas: minority heating and mode conversion
  - Multi ion plasmas: new three ion heating scenario
- Antenna developments in the last 10 years and prospects for T-15MD
  - ITER antenna
  - Proposed Travelling Wave Antenna (TWA) for T-15MD and DEMO
- Early ICRH experiments on the Brussels tokamak ERASMUS
  - Basis for ICRH developments on MEPhISTO
- Conclusions

Introduction

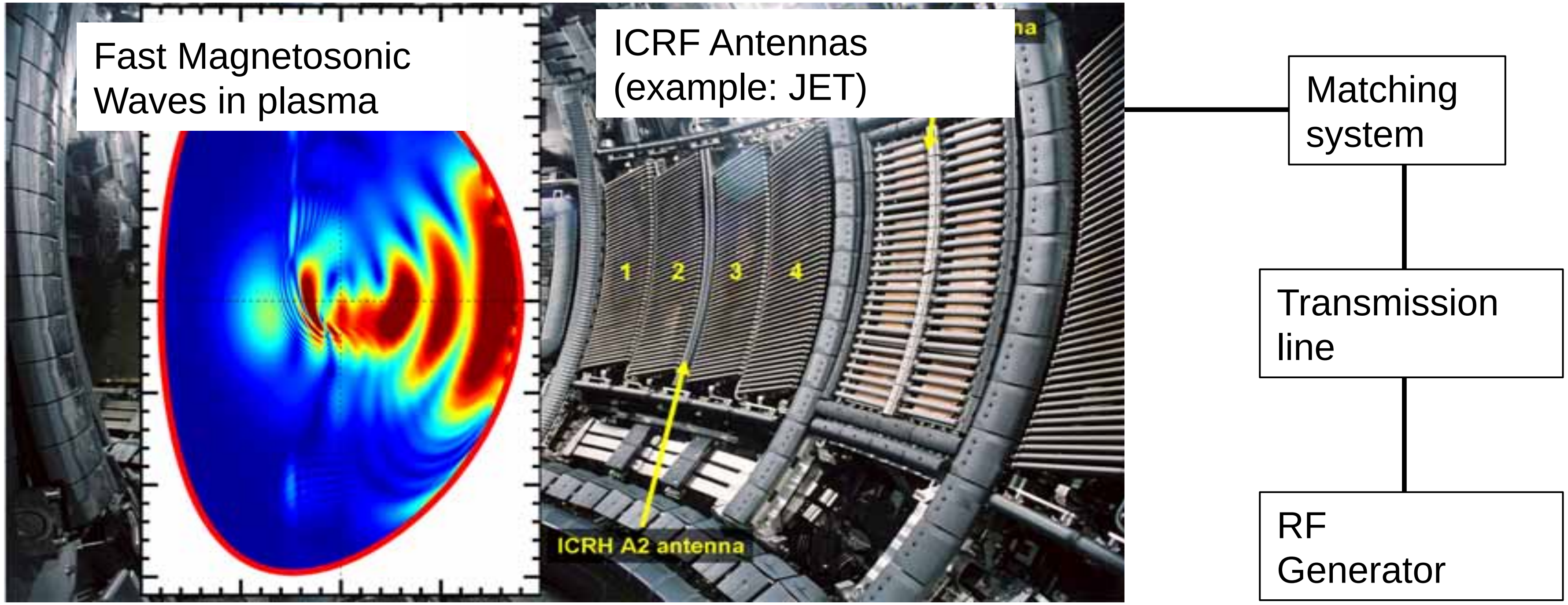
ICRH for the future fusion reactor

- **General**
  - **No density limit to couple power** to high density plasmas
    (… in contrast to ECRH…)
  - **Direct ion heating** possible in D-T plasmas (e.g. 3-ion scenarios)
  - **Impurity control by heating the centre**
  - Technology available for **continuous operation** (short wave broadcasting equipment : напр. в прошлом Голос России)
  - **High efficiency** for RF wave generation and modest price / MW
- **Flexible Heating System**
  - Wide range in possible frequencies
  - Heating / current drive ($k_{//}$ spectrum)
  - Various heating schemes
    - Minority heating
    - 2nd harmonic heating / higher harmonic heating
    - 3-ion scheme
    - Synergy with NBI
    - etc..

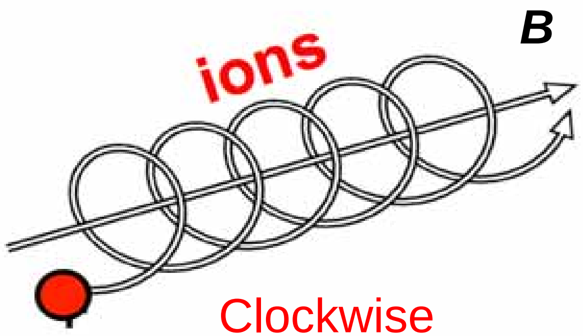
Heating of plasmas with ICRH

- Well established technology for generation of high power RF waves

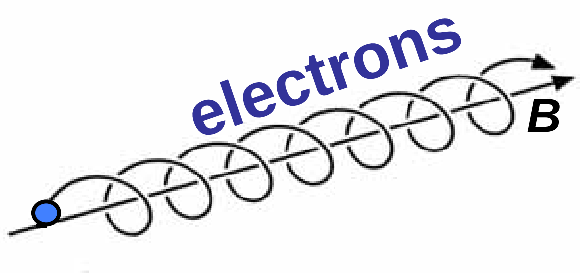
- Principle layout of ICRF system:



Basic properties



Clockwise
Rotation
(15MHz / T for proton)

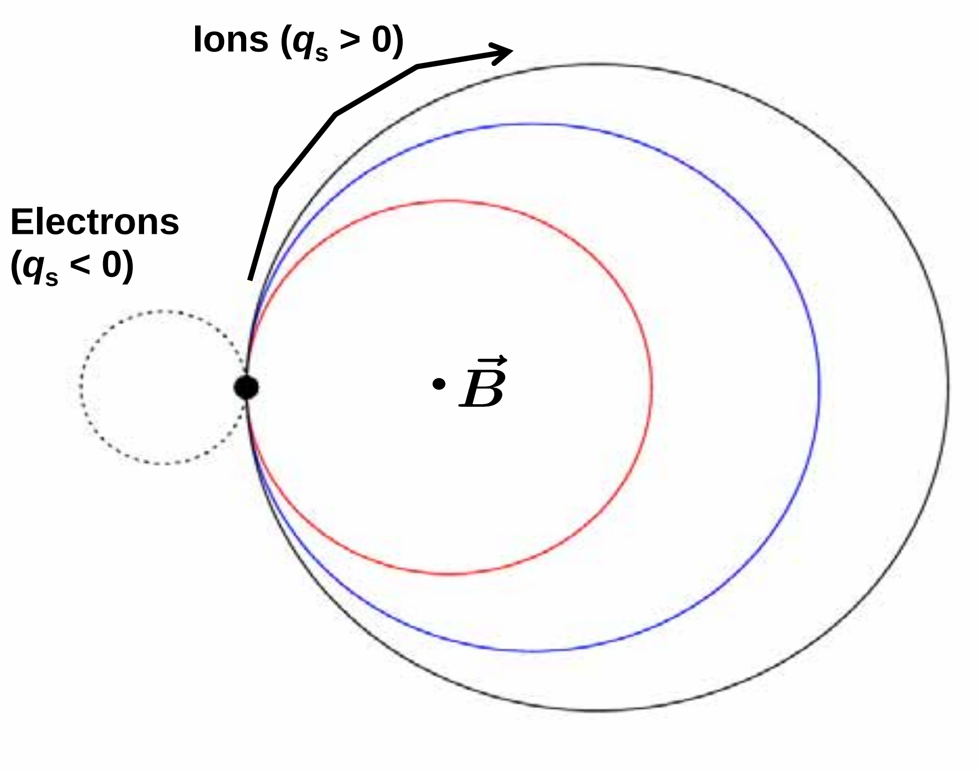


Counter-clockwise
Rotation
(28GHz / T for electron)

Cyclotron frequency:

$$f_{c,i} = \frac{Z_i}{A_i} \frac{|q_e| B}{2\pi m_p}$$

Cyclotron frequency and RF heating



- Hydrogen ions ($A = 1$, $Z = 1$)
- Deuterium ions ($A = 2$, $Z = 1$)
- Tritium ions ($A = 3$, $Z = 1$)

Cyclotron frequency

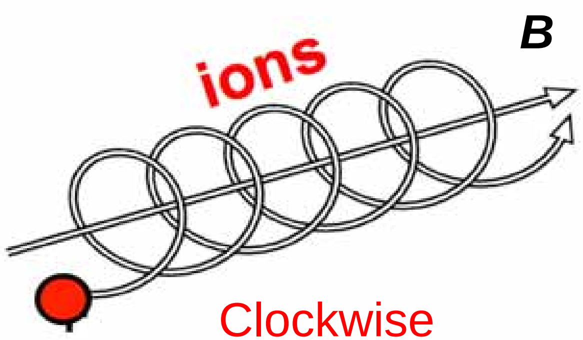
$$\omega_{cs} = (q_s/m_s)\,B$$

- Depends on a particle's charge-to-mass ratio
- Rotation direction is different for ions and electrons

Cyclotron wave-particle interaction

$$\omega = n\omega_{cs} + k_\parallel v_\parallel \quad (n = 1, 2, 3, \ldots)$$

Basic properties



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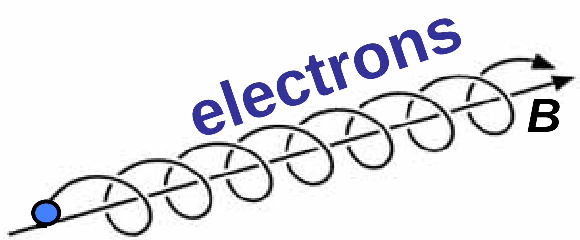

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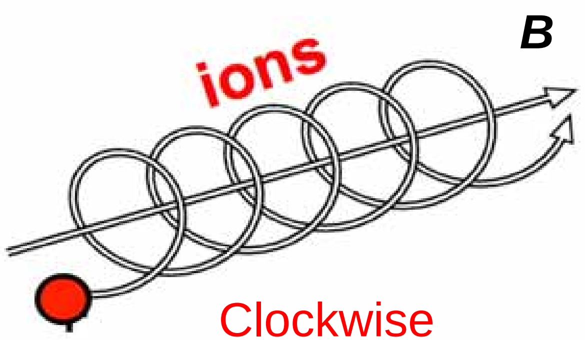
Cyclotron frequency:

$$f_{c,i} = \frac{Z_i}{A_i} \frac{|q_e| B}{2\pi m_p}$$

Illustration of the range of frequencies

Particle In T-15MD	Z_i/A_i	Fundamental Cyclotron (2T) frequency $f_{c,i}$	2nd Harmonic frequency at 2T
H	1/1	30 MHz	60 MHz
D $^4He^{++}$	1/2	15 MHz	30 MHz
$^3He^{++}$	2/3	20 MHz	40 MHz
T	1/3	10 MHz	20 MHz
electron		56 **GHz**	112 **GHz**

Basic properties



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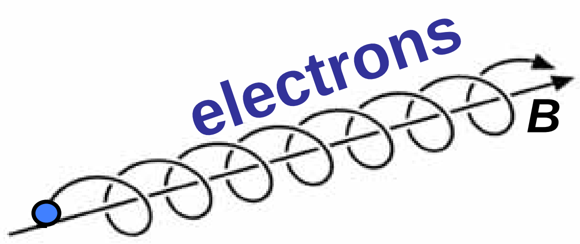

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Intuitive idea behind Ion Cyclotron Resonance Heating (ICRH):

- Inject RF waves at the cyclotron frequency of the particles
- Power from the RF waves should be transferred through resonant wave-particle interactions

Practical realization

Flexible method : by selecting externally ω

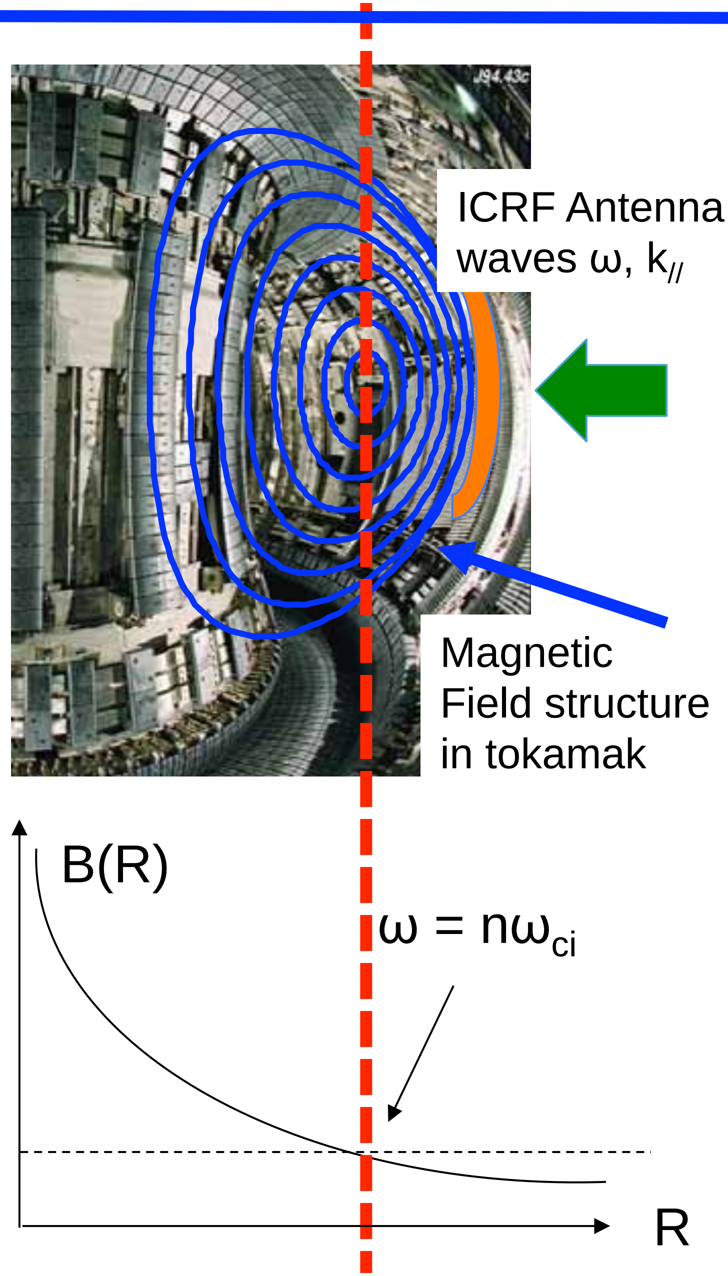
- heat ions with specific Z/A (in contrast to ECRH)

$$\omega_{ci} = \frac{Z_i}{A_i} \frac{|q_e| B}{m_p}$$

- heat at different plasma locations

$$\omega_{ci} \propto B(R)$$

Resonance condition: $\omega = n\omega_{ci}$, n = 1,2,3,..



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- heat at different plasma locations

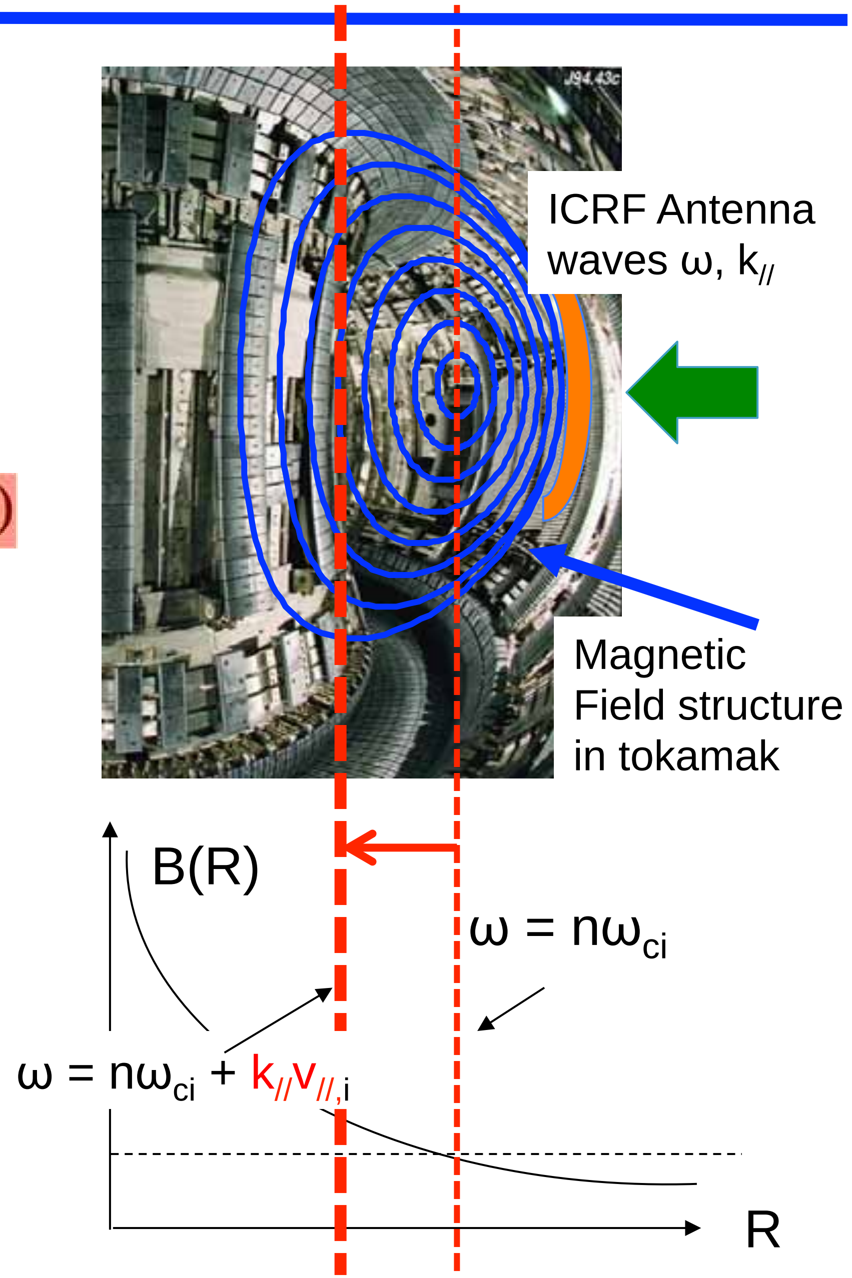
$$\omega_{ci} \propto \boxed{B(R)}$$

Doppler Effect due to speed of particle

Resonance condition: $\omega = n\omega_{ci} + k_{//}v_{//,i}$, n = 1,2,3,..

- $k_{//}$ wave number parallel to B (determined by antenna geometry and phasing)

- $v_{//,i}$ ion velocity parallel to B



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Resonant particle property

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Antenna spectrum

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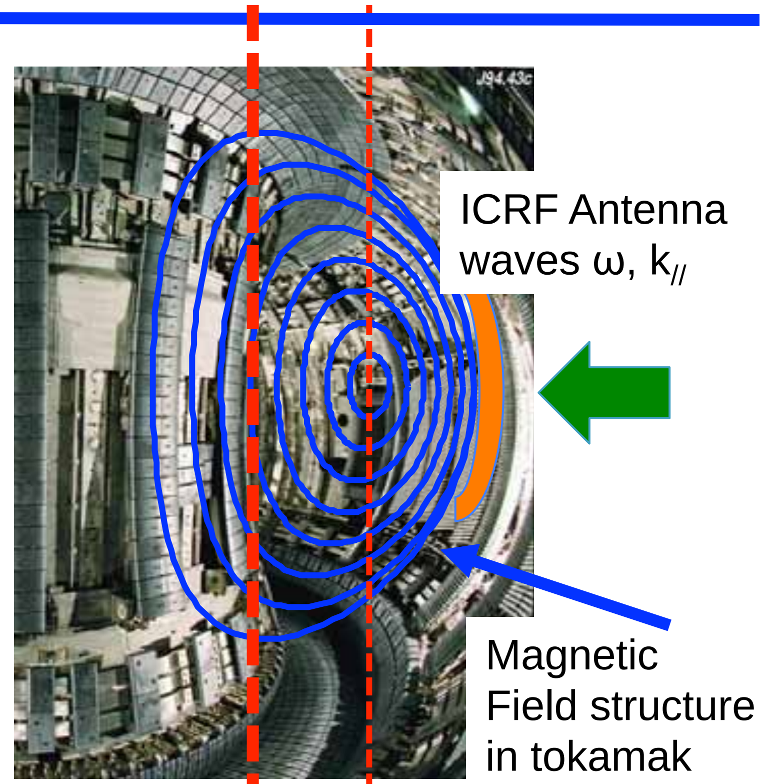

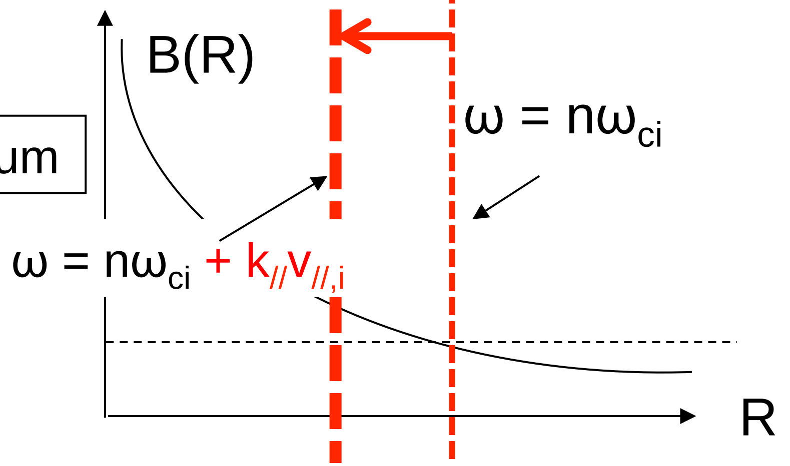

Good absorption:
need (i) resonance condition + (ii) large RF electric field E_+

Flexible method : by selecting externally ω

- heat ions with specific Z/A (in contrast to ECRH) $\omega_{ci} = \frac{Z_i}{A_i}\frac{|q_e|B}{m_p}$

- heat at different plasma locations $\omega_{ci} \propto B(R)$

Resonant particle property

Resonance condition: $\omega = n\omega_{ci} + k_{//}v_{//,i}$, n = 1,2,3,..

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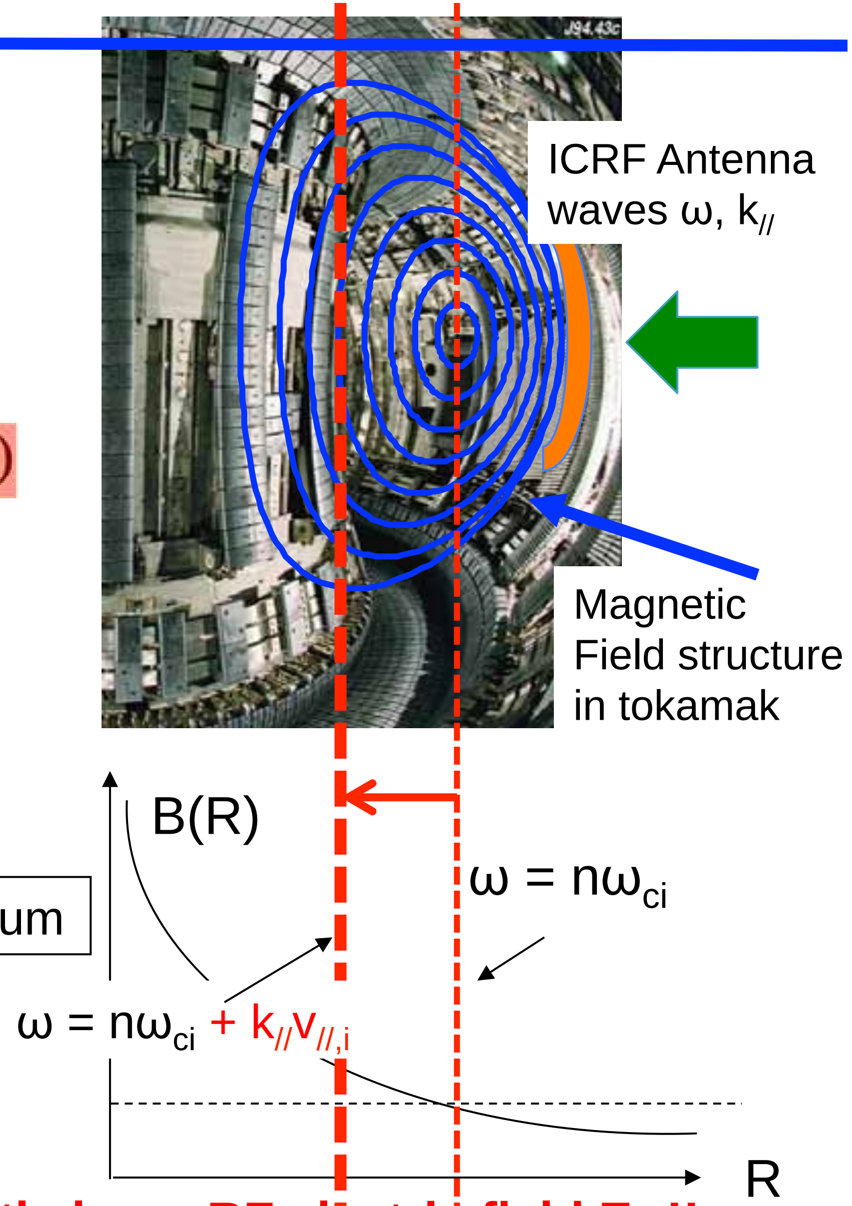
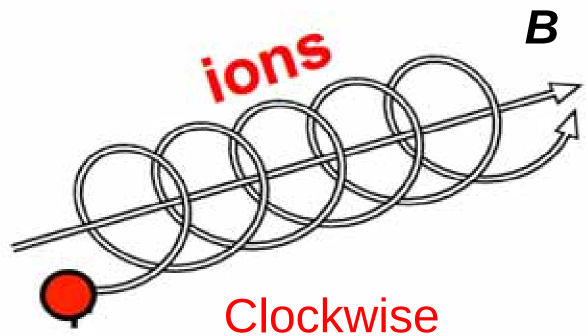


For power absorption, need in addition a sufficiently large RF electric field E_+ !!

Heating and fast particle generation with ICRH in toroidal systems

Basic properties



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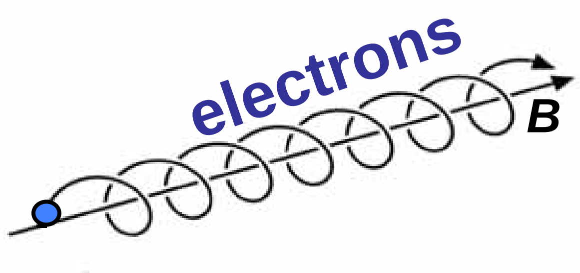

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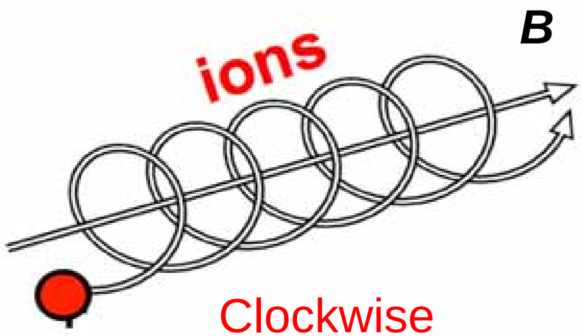

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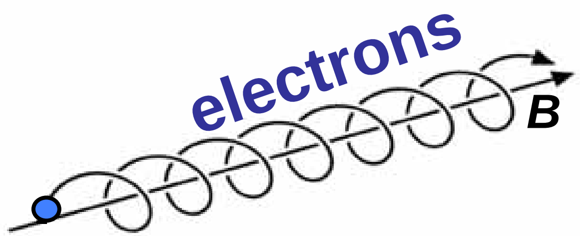

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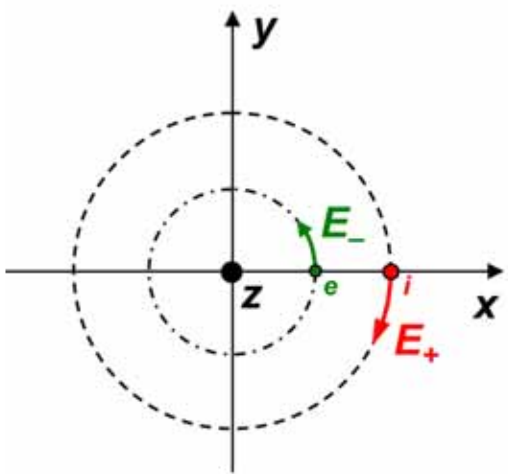
E_+ and E_- components of RF electric field



E_+ ➛ ion rotation direction

E_- ➛ electron rotation direction

ICRF heating in single and two ion plasmas

Correct polarization determines wave absorption

$$\omega = N\omega_{ci}: \qquad P_{\mathrm{abs,i}} \propto \left| E_+ J_{N-1}(k_\perp \rho_\mathrm{L}) + E_- J_{N+1}(k_\perp \rho_\mathrm{L}) \right|^2$$

cold plasma, N=1: $\quad k_\perp \rho_\mathrm{L} \ll 1: \quad J_0 \approx 1, \; J_N \propto (k_\perp \rho_L)^N \ll 1 \quad \rightarrow P_{abs,i} \propto \left|E_+\right|^2$

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From Maxwell equations:
Electric field polarization at resonance position depends on plasma composition

$$\left|\frac{E_+}{E_-}\right| = \left|\frac{\omega - \omega_{ci}}{\omega + \omega_{ci}}\right|$$

ω = frequency applied at the antenna

ICRF heating in single and two ion plasmas

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1. Single ion plasma i heating
   does not work at $\omega = \omega_{ci}$

$$\left|\frac{E_+}{E_-}\right| \simeq \left|\frac{\omega_{ci} - \omega_{ci}}{\omega_{ci} + \omega_{ci}}\right| \simeq 0$$

2. Need two ions in plasma
   e.g. minority heating (H)-D;
   minority at a few %: $\omega = \omega_{cH}$

$$\left|\frac{E_+}{E_-}\right| \simeq \left|\frac{\omega_{cH} - \omega_{cD}}{\omega_{cH} + \omega_{cD}}\right| = \left|\frac{2\omega_{cD} - \omega_{cD}}{2\omega_{cD} + \omega_{cD}}\right| = \frac{1}{3}$$

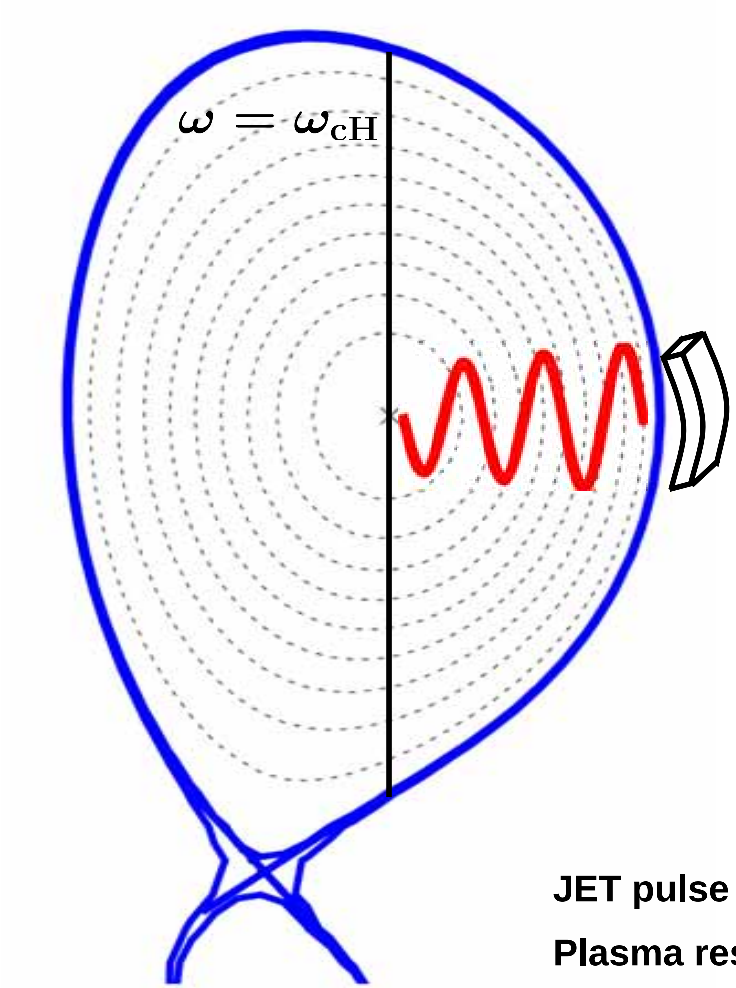
3. Harmonic heating $\omega = N\omega_{ci}$
   (FLR effect, needs β_i)

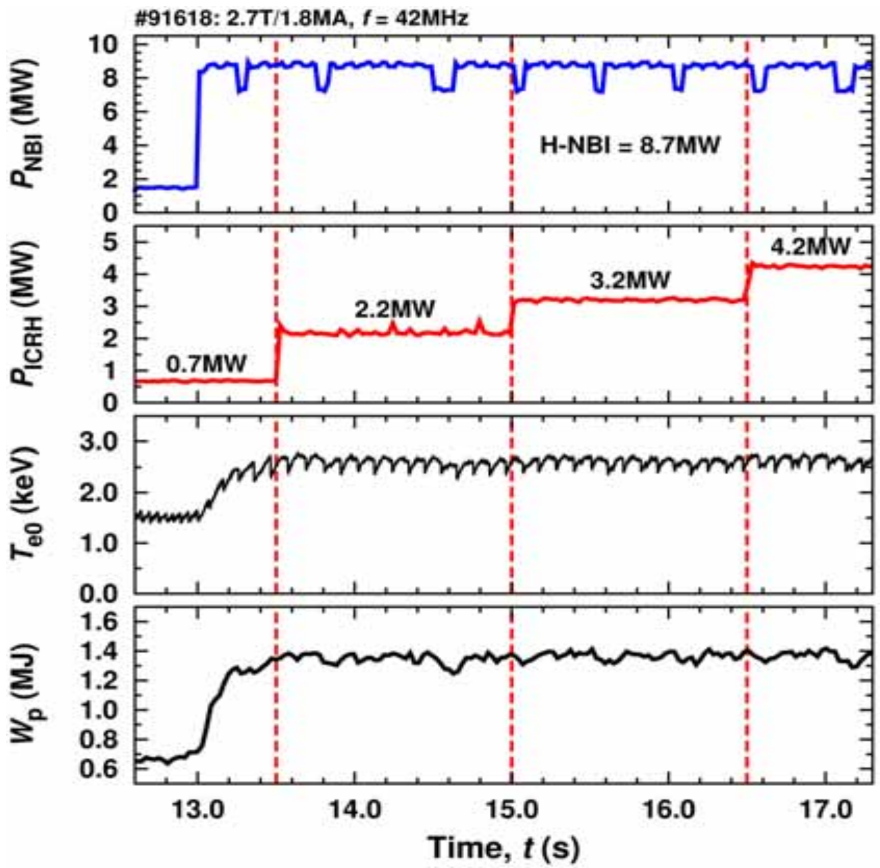
$$\left|\frac{E_+}{E_-}\right| \simeq \left|\frac{N\omega_{ci} - \omega_{ci}}{N\omega_{ci} + \omega_{ci}}\right| = \frac{N-1}{N+1}$$

Ion cyclotron heating of single-ion species plasmas <u>does not work</u>

Example :

Hydrogen plasmas ($n_H/n_e \approx 100\%$)





JET pulse #91618, ICRH power: 0.7MW → 2.2MW → 3.2MW → 4.2MW

Plasma response: $\Delta T_e \approx 0$, $\Delta W_p \approx 0$

$E_+ \sim 0$, thus as $P_{abs,I} \sim |E_+|^2 \sim 0$, i.e. heating effects are possible !

Fundamental ICRF heating of single ion plasmas DOES NOT WORK

Slowing down and energy transfer to the background plasma

Energy W_{fast} of fast particle beam is transferred to ions and electrons

$$\frac{dW_{fast}}{dt} = -2\frac{W_{fast}}{\tau_{slowing\_down}}\left[1 + \left(\frac{W_{crit}}{W_{fast}}\right)^{\frac{3}{2}}\right]$$

electrons

ions

$$W_{crit} = 14.8\, A_{fast} T_e \left(\sum_i \frac{X_i Z_i^2}{A_i}\right)^{2/3}$$

W_{crit} = energy for which 50% goes to electrons and 50% to the ions

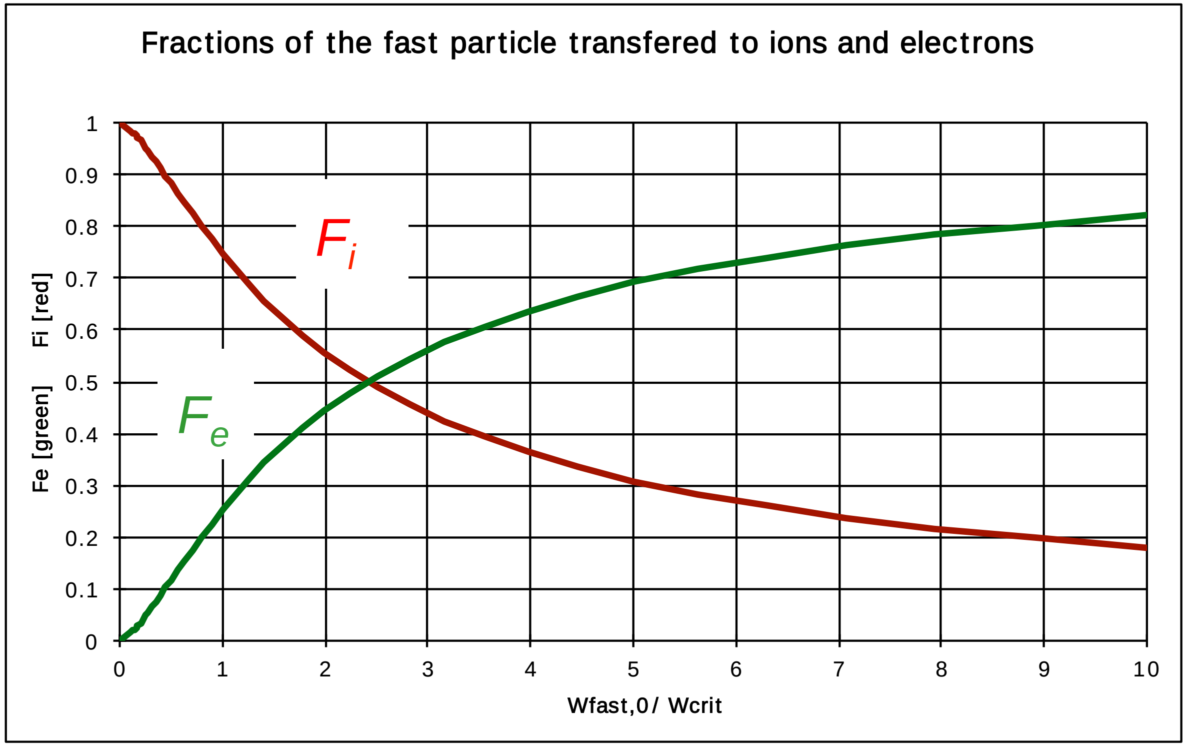
$$W_{fast} \propto e^{-t/(\tau_s/2)}; \quad \tau_s[ms] = 12\frac{T_e^{3/2}[keV]}{n_e[10^{20}m^{-3}]}\frac{A_{fast}}{Z_{fast}^2}$$

Slowing down time

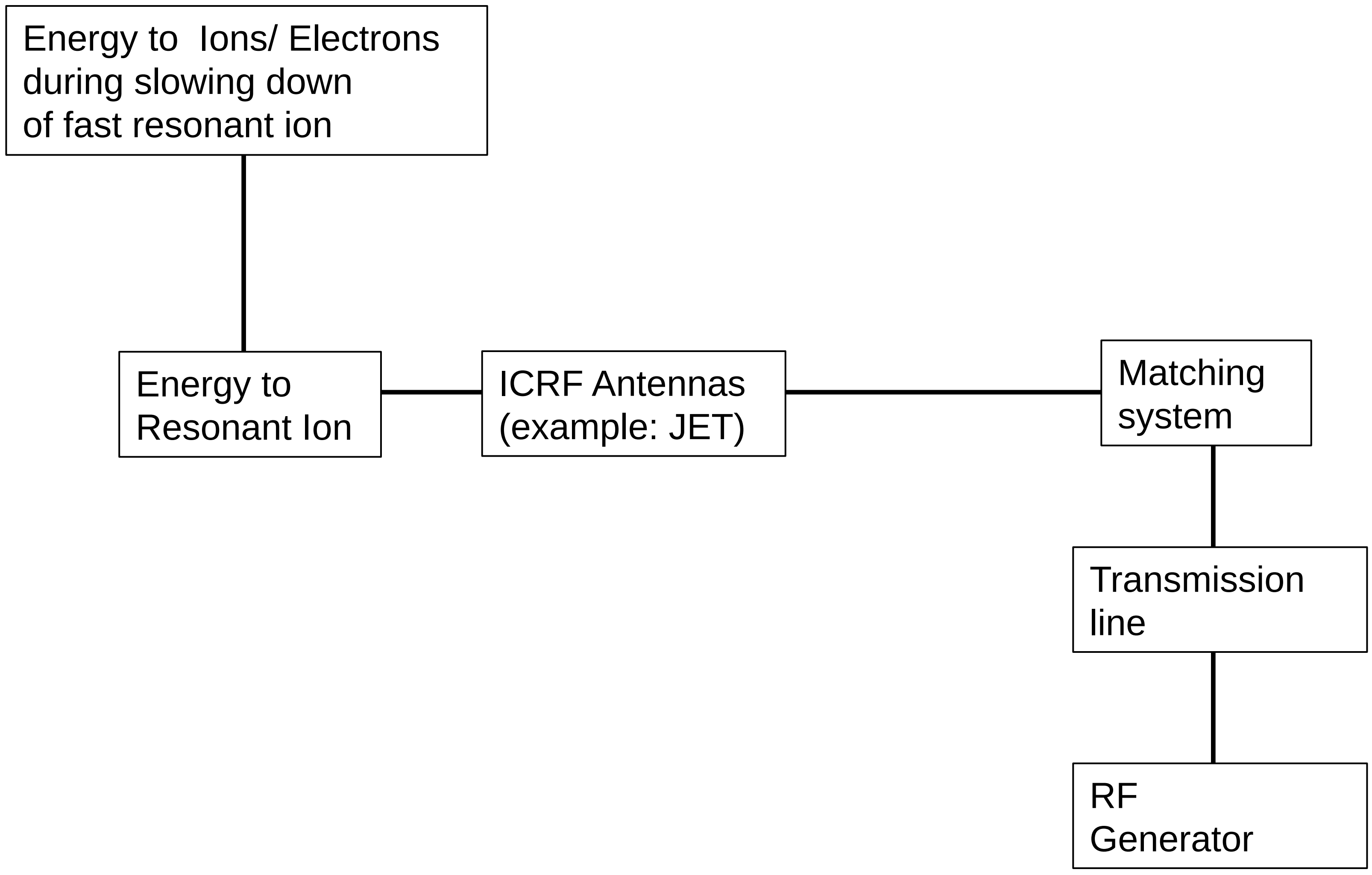
Power transfer to ions and electrons

$$\frac{dW_{fast}}{dt} = -2\frac{W_{fast}}{\tau_{slowing\_down}}\left[1+\left(\frac{W_{crit}}{W_{fast}}\right)^{\frac{3}{2}}\right]$$

Power to ions: $P_i = \frac{2}{\tau_s} W_{fast}\left(\frac{W_{crit}}{W_{fast}}\right)^{3/2}$ Energy to ions: $W_i = \int_0^\infty W_{fast}\left(\frac{W_{crit}}{W_{fast}}\right)^{3/2}(-\frac{2}{\tau_s}dt)$



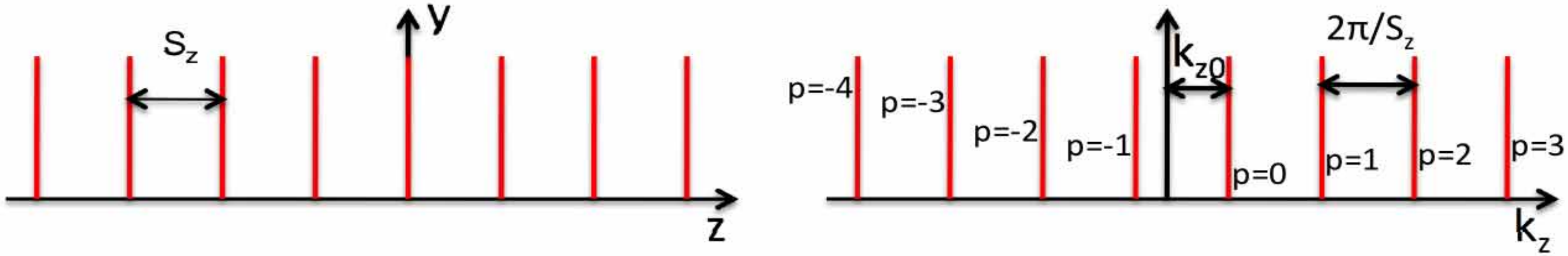
Power transfer to ions and electrons



Antenna power spectrum

Antenna current spectrum and $k_{//}$

1. For infinite number of thin straps with inter-strap phase difference $\Delta\Phi$:



All straps same $|I_A|$

$$J_{y,\infty}(z)= \Sigma_n|I_A| \exp(in\Delta\Phi)\ \delta(z-nS_z) \quad \text{with } -\infty<n<\infty$$

$$\mathbf{J_{y,\infty}(k_z)=(2\pi|I_A|/S_z)\ \Sigma_p\ \delta(k_z-k_{z0}+p2\pi/S_z) \quad with\ -\infty<p<\infty}$$

$$\mathbf{k_{z,max} = k_{z0} + p2\pi/S_z \ with \ \ k_{z0}=\Delta\Phi/S_z}$$

2. For finite number of thin straps n_{str}, modulated by $\sin(\xi_p)/\xi$:

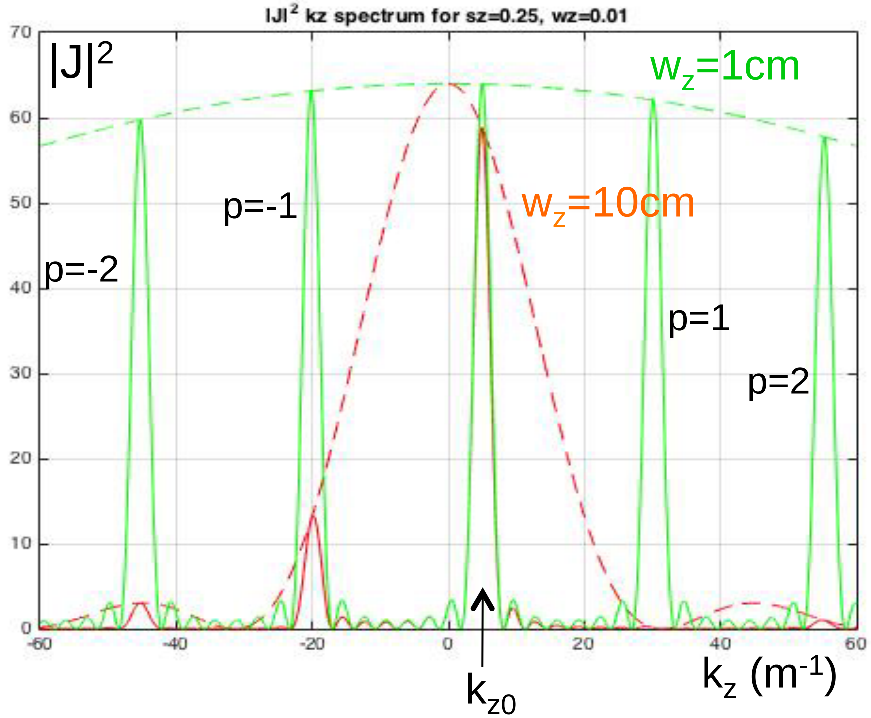
$$J_{y,nstr}(k_z)=n_{str}\ |I_A|\ \Sigma_p\ \varepsilon_p \sin(\xi_p)/\xi_p \quad \text{with } \ \xi_p = 0.5\ n_{str}\ S_z \{k_z - k_{z0}+p2\pi/S_z\}$$

and $\varepsilon_p=1$ for n_{str} odd or $\varepsilon_p=(-1)^p$ for n_{str} even.

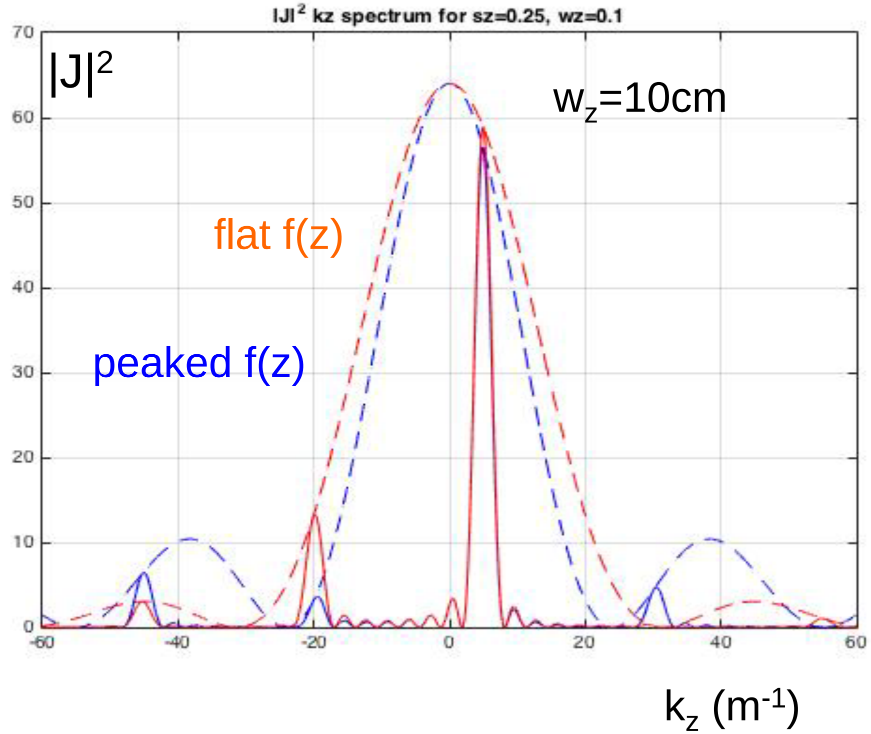
for each p term: $\mathbf{\int |J_{nstr}(k_z)|^2\, dk_z = 2\pi n_{str}|I_A|^2/S_z}$
and therefore
$\mathbf{P_{rad} \propto n_{str}/S_z}$ **with** $\mathbf{P_{rad}(k_z)_{max}}$ **for** $\mathbf{k_{z,max} = k_{z0} + p2\pi/S_z}$

3. For finite number of straps n_{str} of width $2w_z$ assuming on it
(i) flat current distribution $f(z)=I_A/(2wz)$ or
(ii) peaked current distribution at their edges $f(z)=I_A/\{\pi(1-(z/w_z)^2)\}$

Influence of w_z with flat f(z)



Comparison flat and peaked f(z)

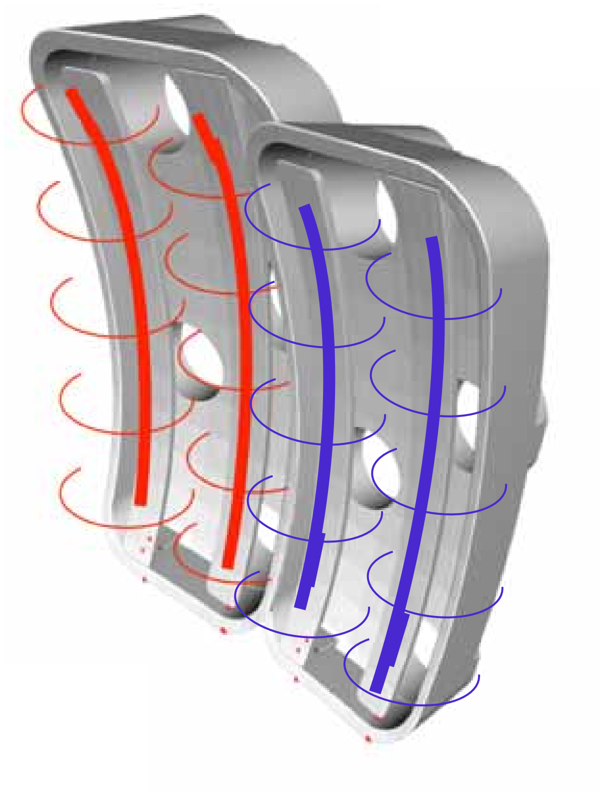


Only p=0, +1 and -1 terms of practical importance in spectrum

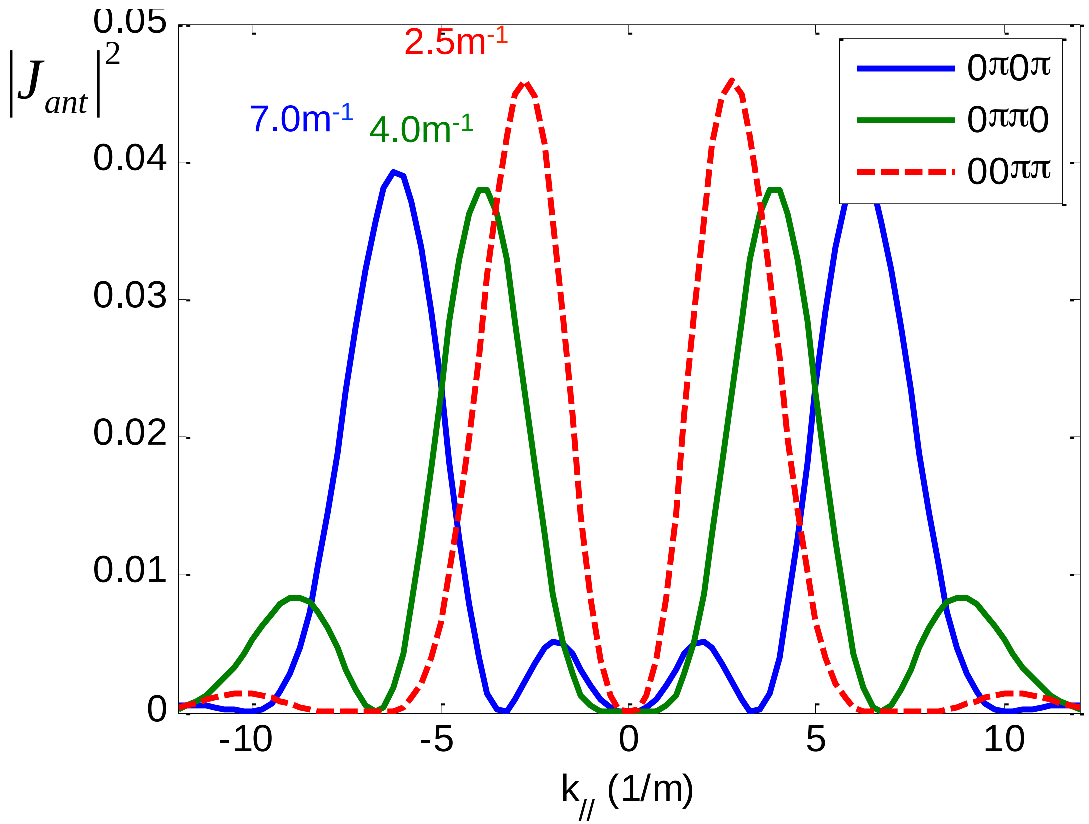
$$k_{z,max} = k_{z0} + p2\pi/S_z$$

Example: $k_{//}$ spectrum of JET 4 strap ICRH antennas

JET 4 strap antenna

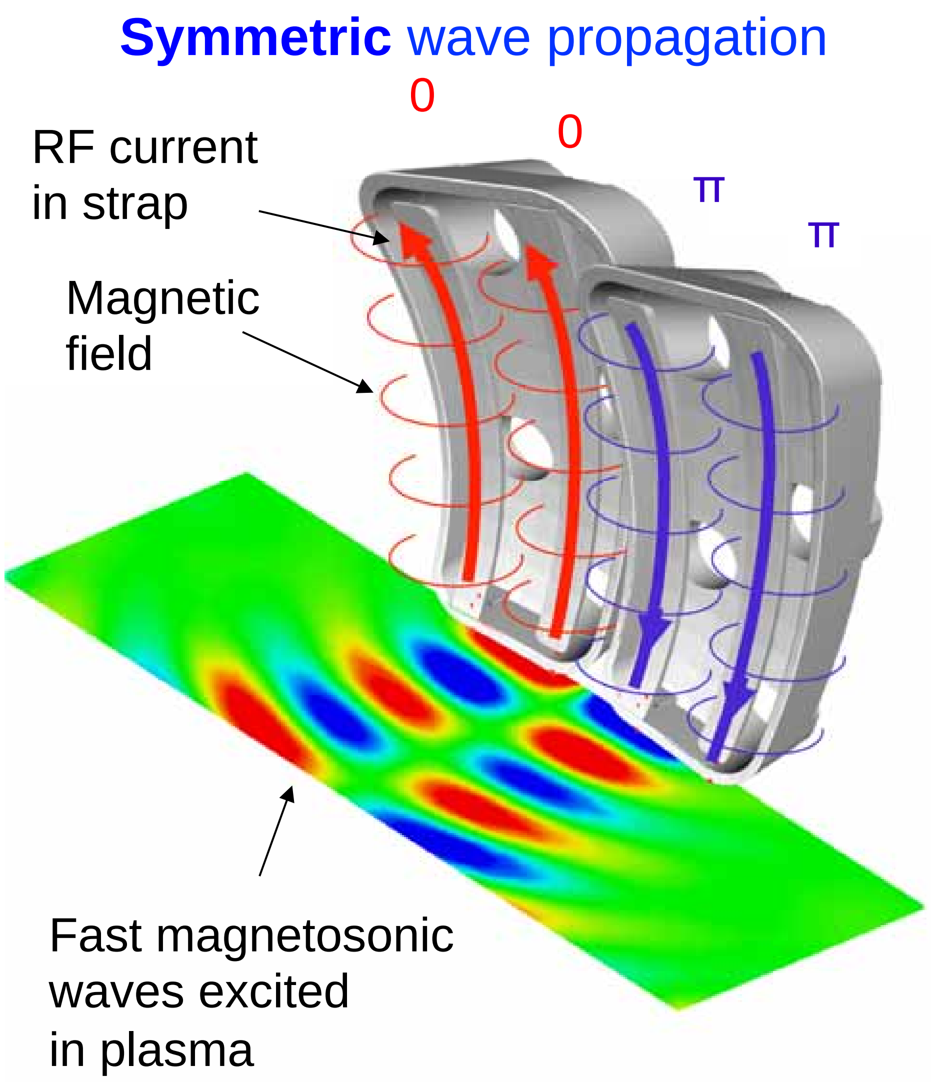


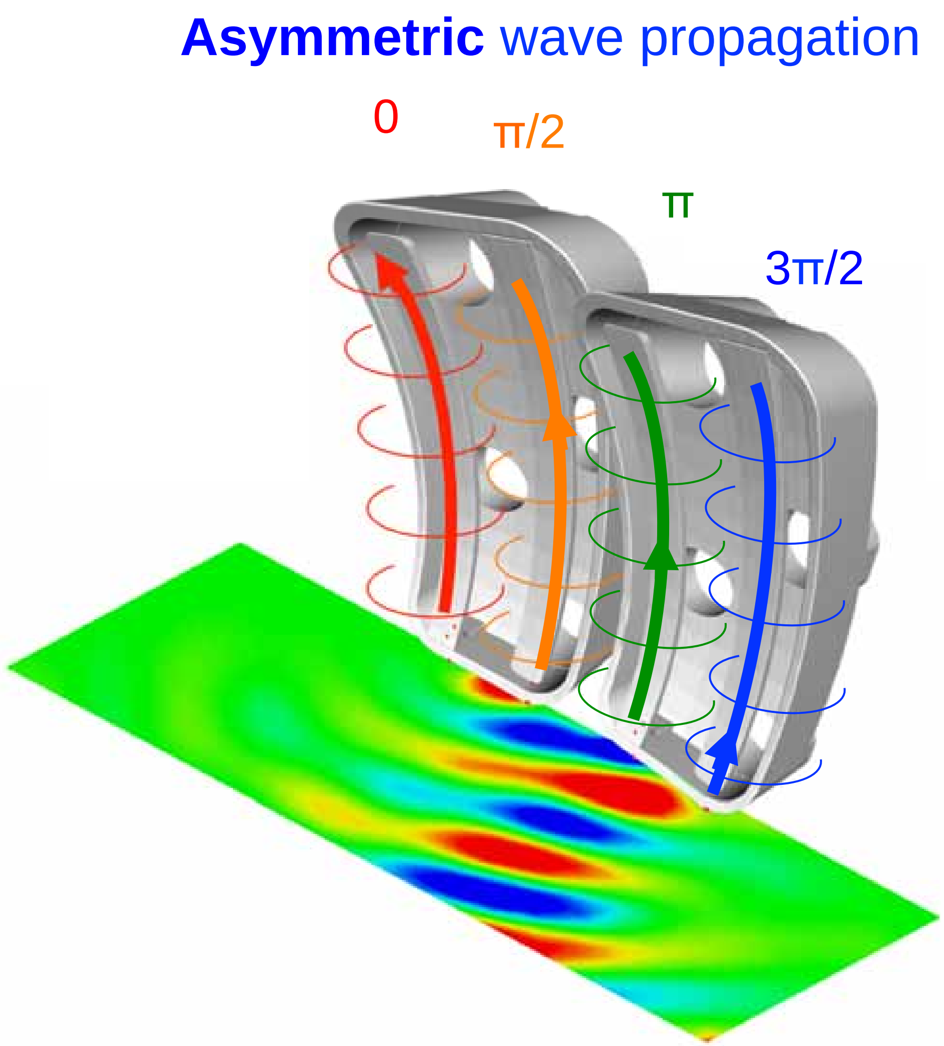
$k_{//}$ spectrum for JET antenna



Exciting the Fast Magnetosonic Wave

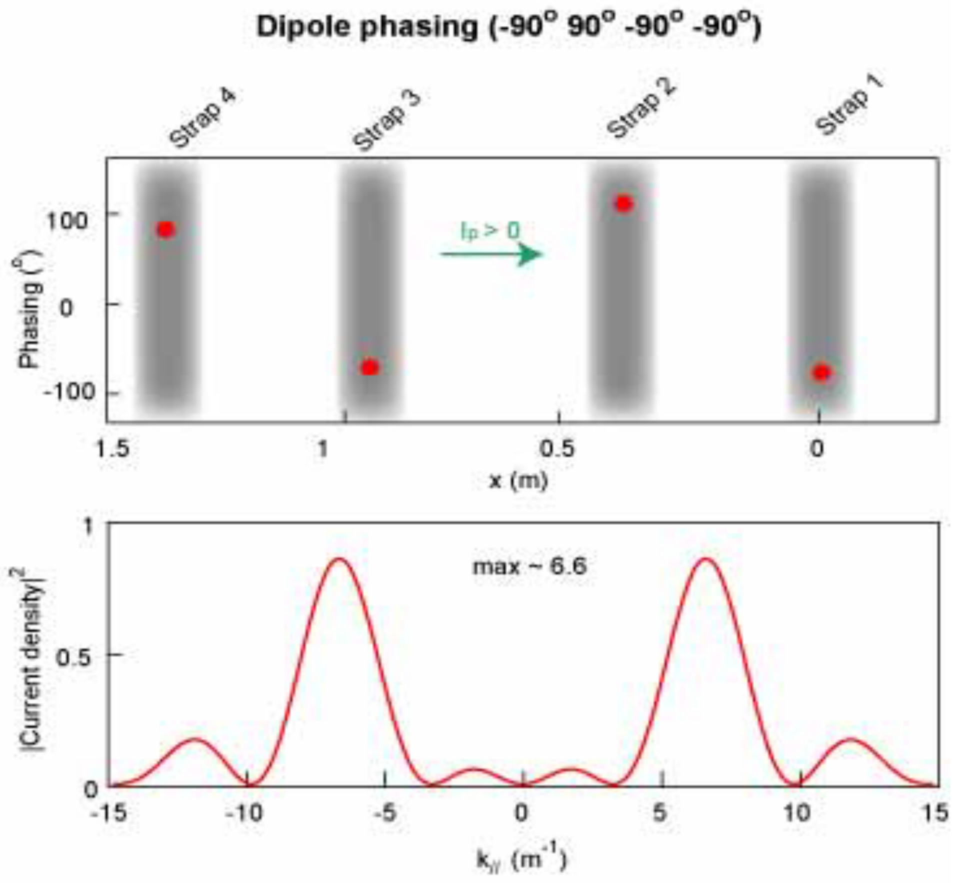
Strap current phasing determines dominant $k_{//}$ and wave directivity





(Toroidal) phasing generally used with the A2 antennas

- Different phasing to currents in antenna straps currents ➔ Possible to change spectrum of the ICRF wave launched
- Commonly used phasings are:
  - Dipole, Monopole, +90o , -90o but other phasings might by used (prepared)



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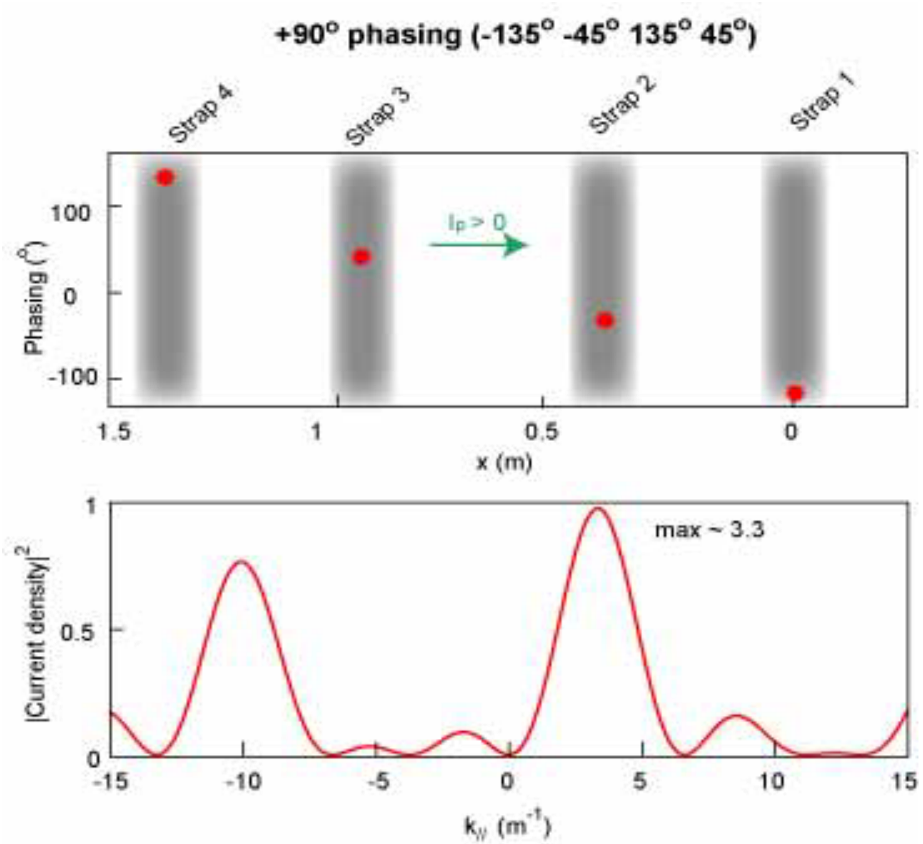

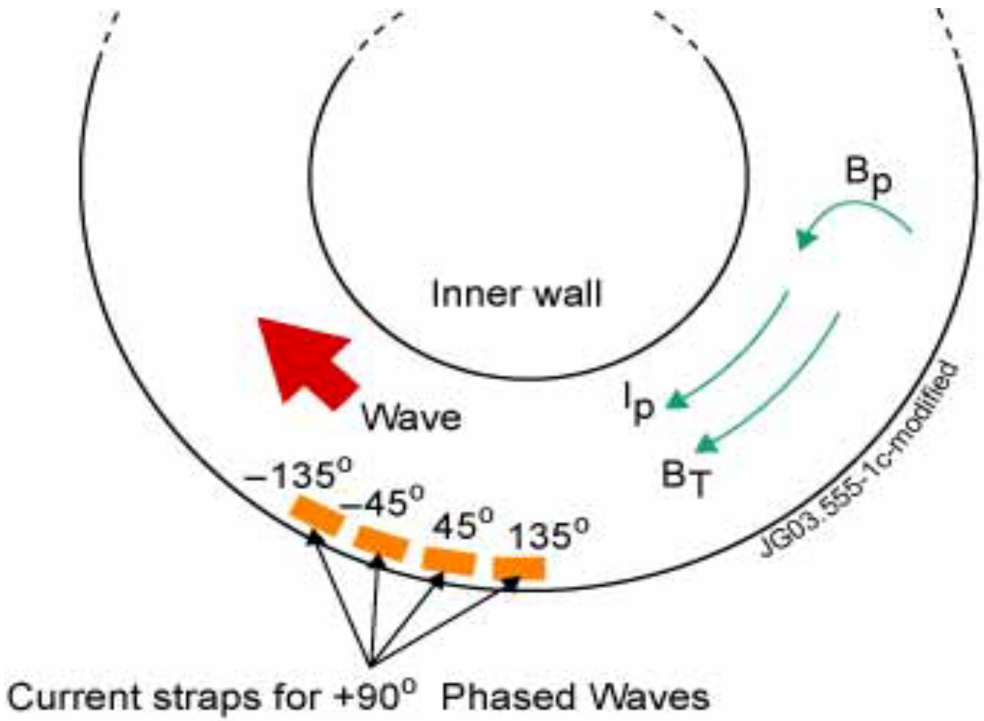

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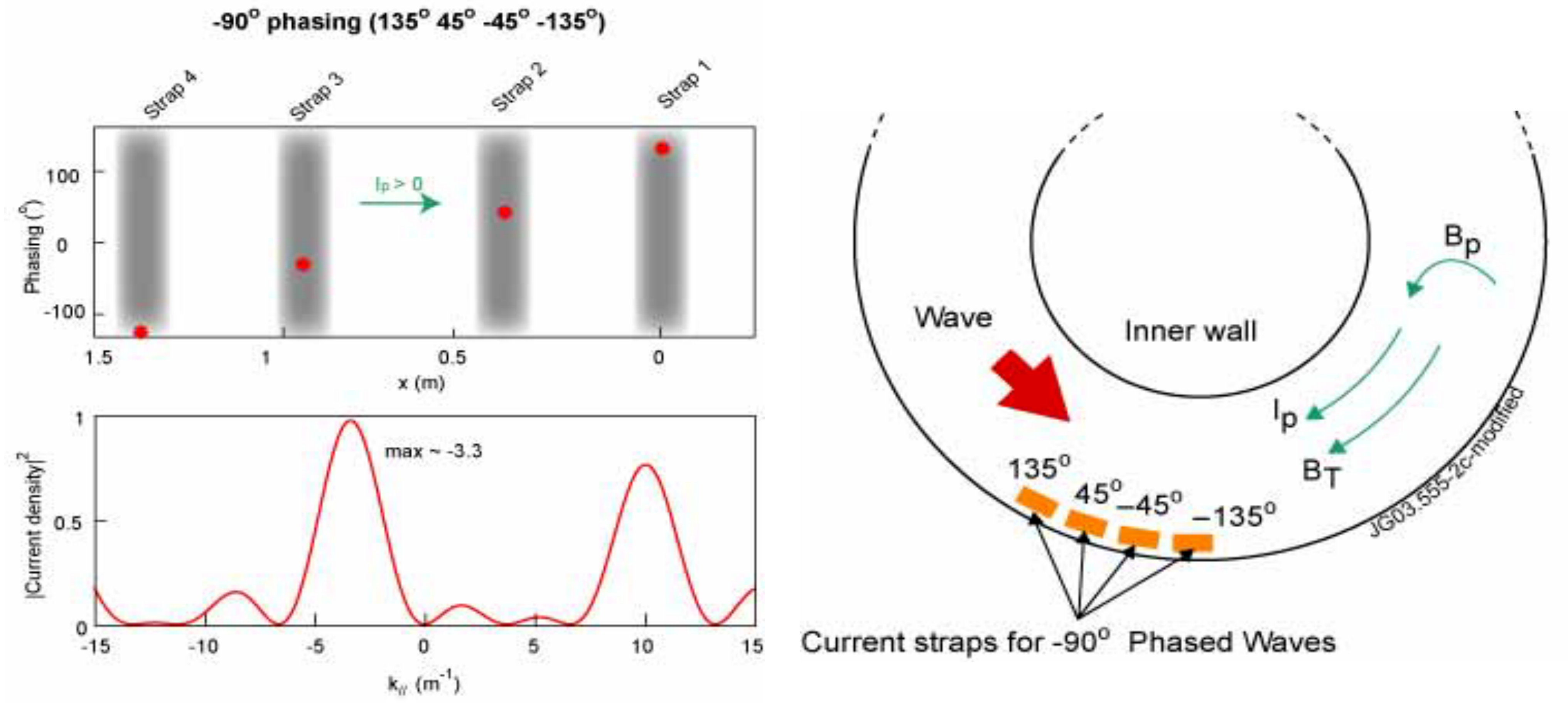
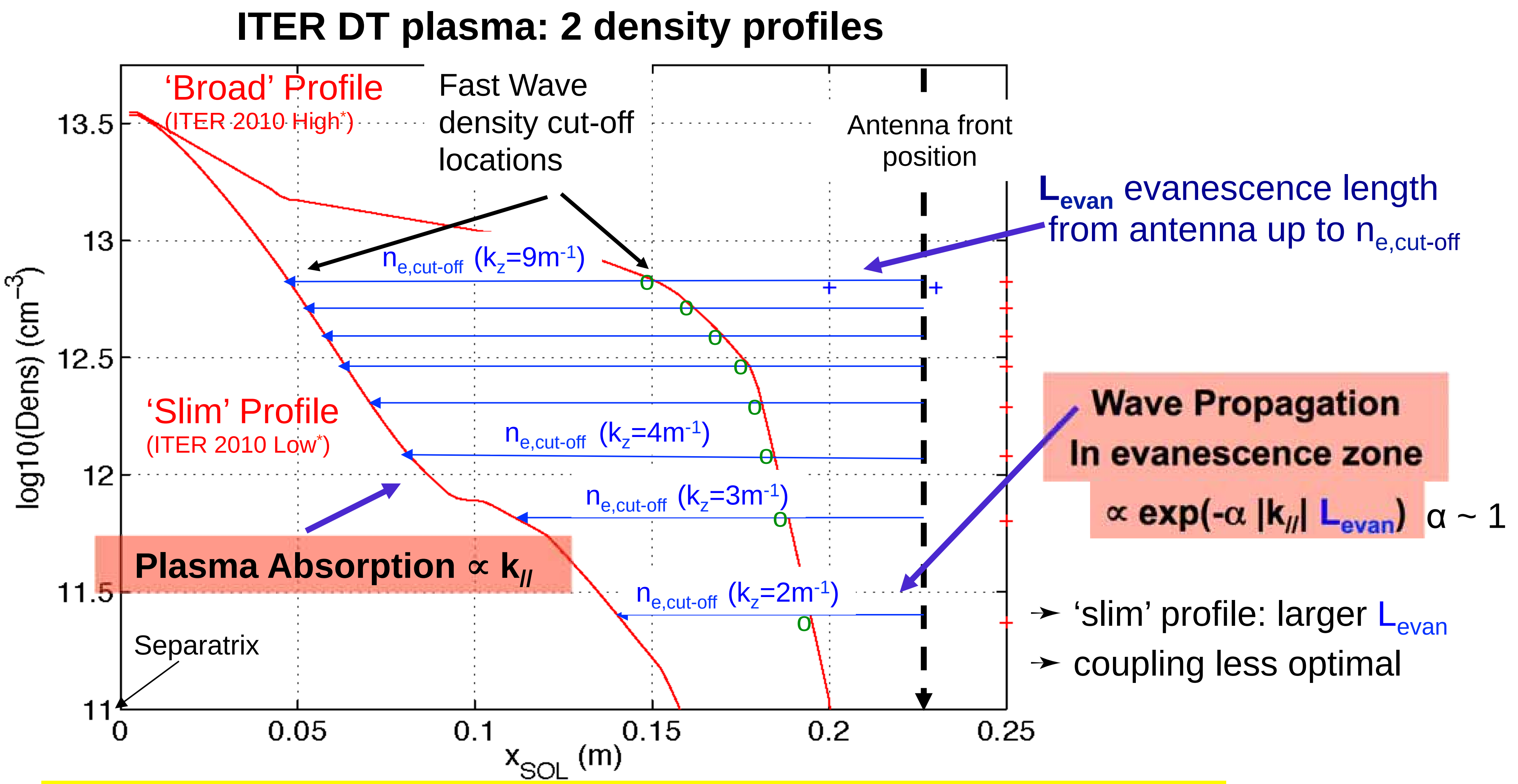


Coupling depends on edge density profile



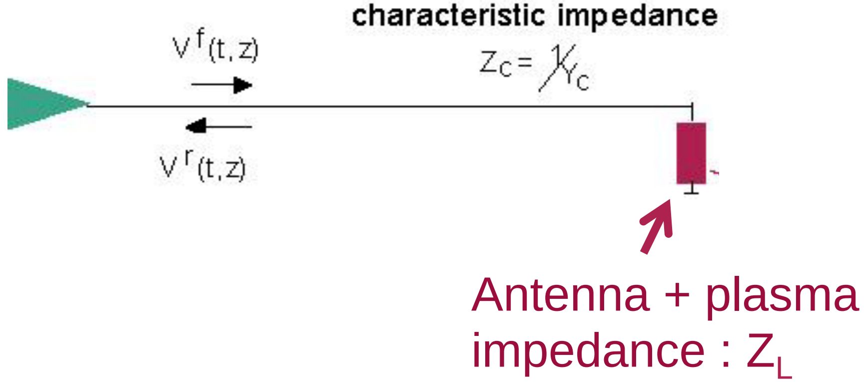
Gas puffing in front of antenna helps to improve RF coupling

Matching RF Generator impedance to the variable plasma loading

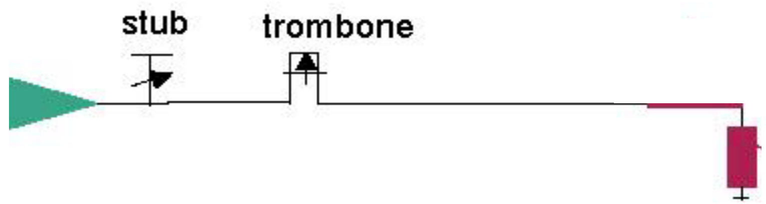
Antenna Coupling to plasma and link with wave reflection

Transmission line impedance Z_c, terminated by load impedance Z_L:

- If $Z_L = Z_C$:
  - All power coming from generator transmitted to load = No power reflected
- If $Z_L \neq Z_C$:
  - Not all power transmitted = Some power reflected



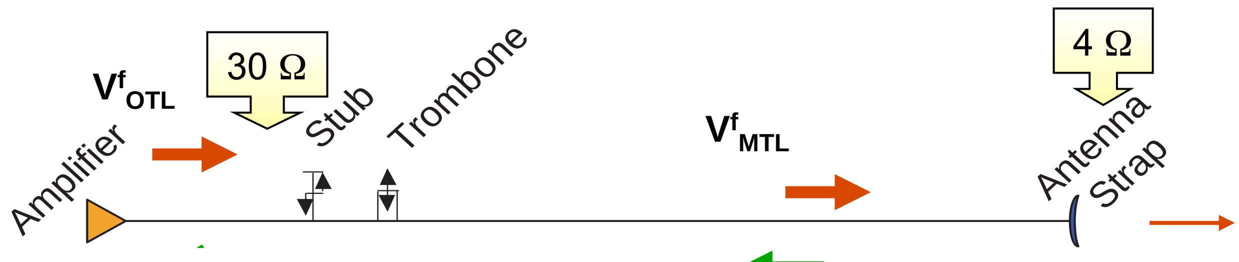
JET A2 antenna + transmission line:



Coupling: what is happening during fast variations of plasma density profile

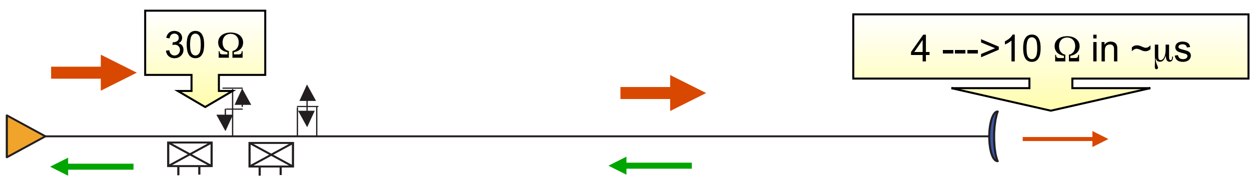
"Matching" principle

- ✓ A2 antenna JET automatic matching system using mechanical adaptation systems modified in real time to cancel reflected power



During fast changes (~ 100μs) of the density profile:

- ✓ Change in coupling in the 100 μs range
- ✓ Mechanical adapting systems **too slow** ⇒ high reflected power ⇒ generator is stopped temporarily



Examples of ICRF heating

Tribute to ICRF pioneer V. L. Vdovin (1937 - 2015)

One of the first observations of H minority heating in TM-1-ВЧ (1976)

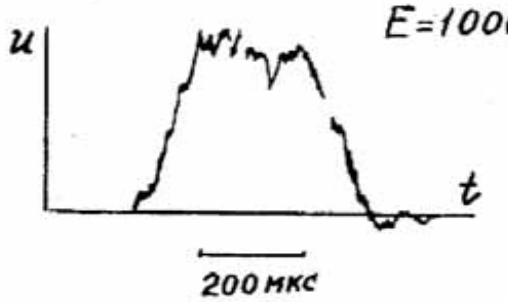
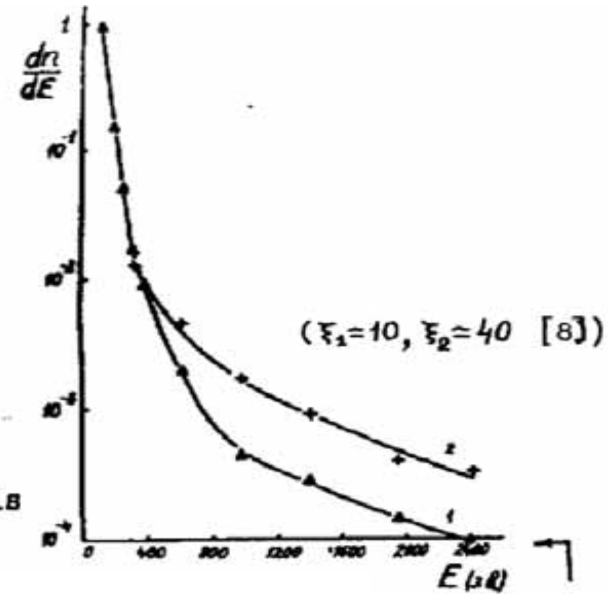


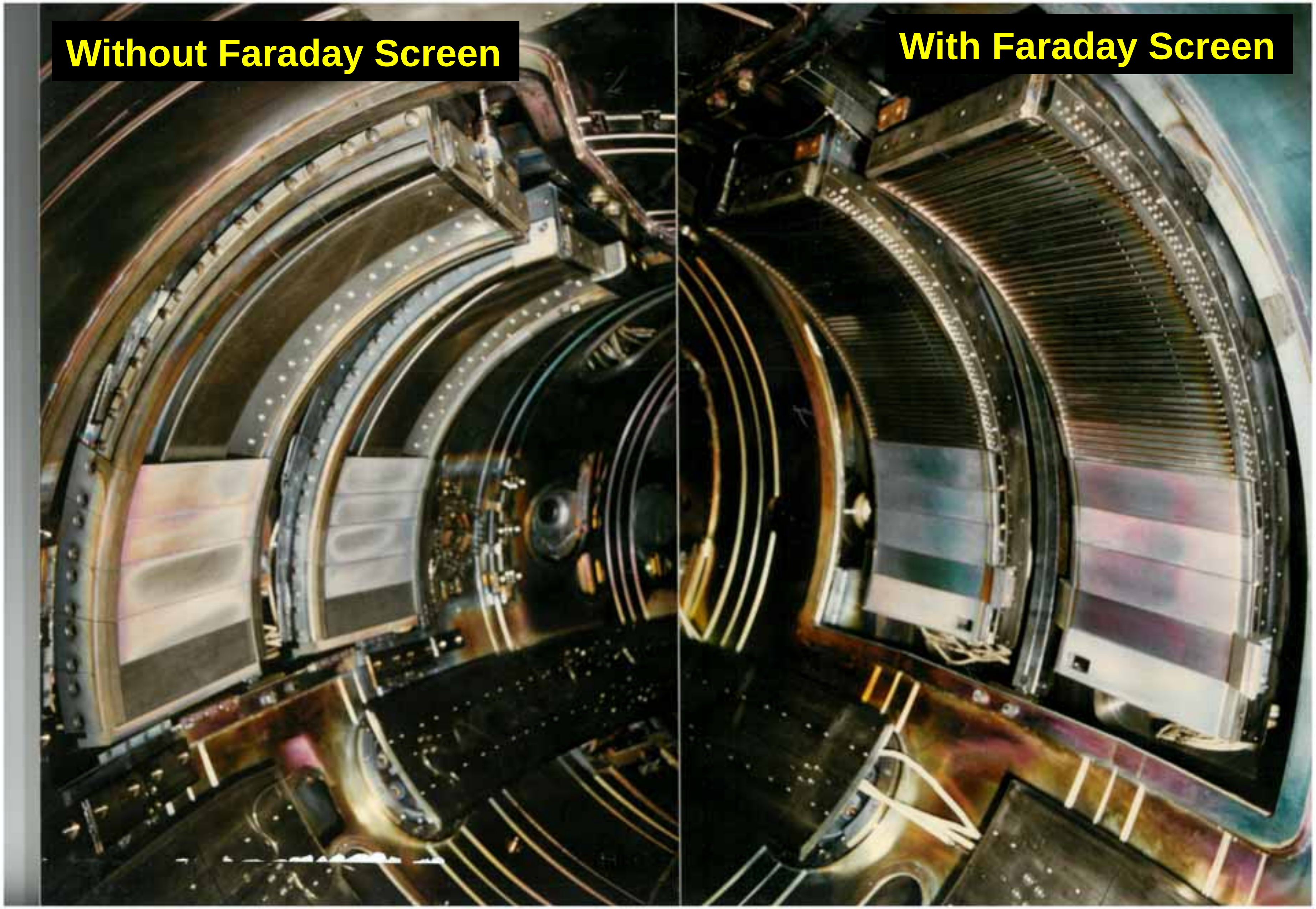
Fig.13.Signal from charge exchange neutral detector at u =1KeV.

Fig.14.Build of a high energy "tail" in the proton (1%) energy distribution in deuterium (99%) for two levels of HF excitation at $\omega = \omega^{H}_{Bi}$.

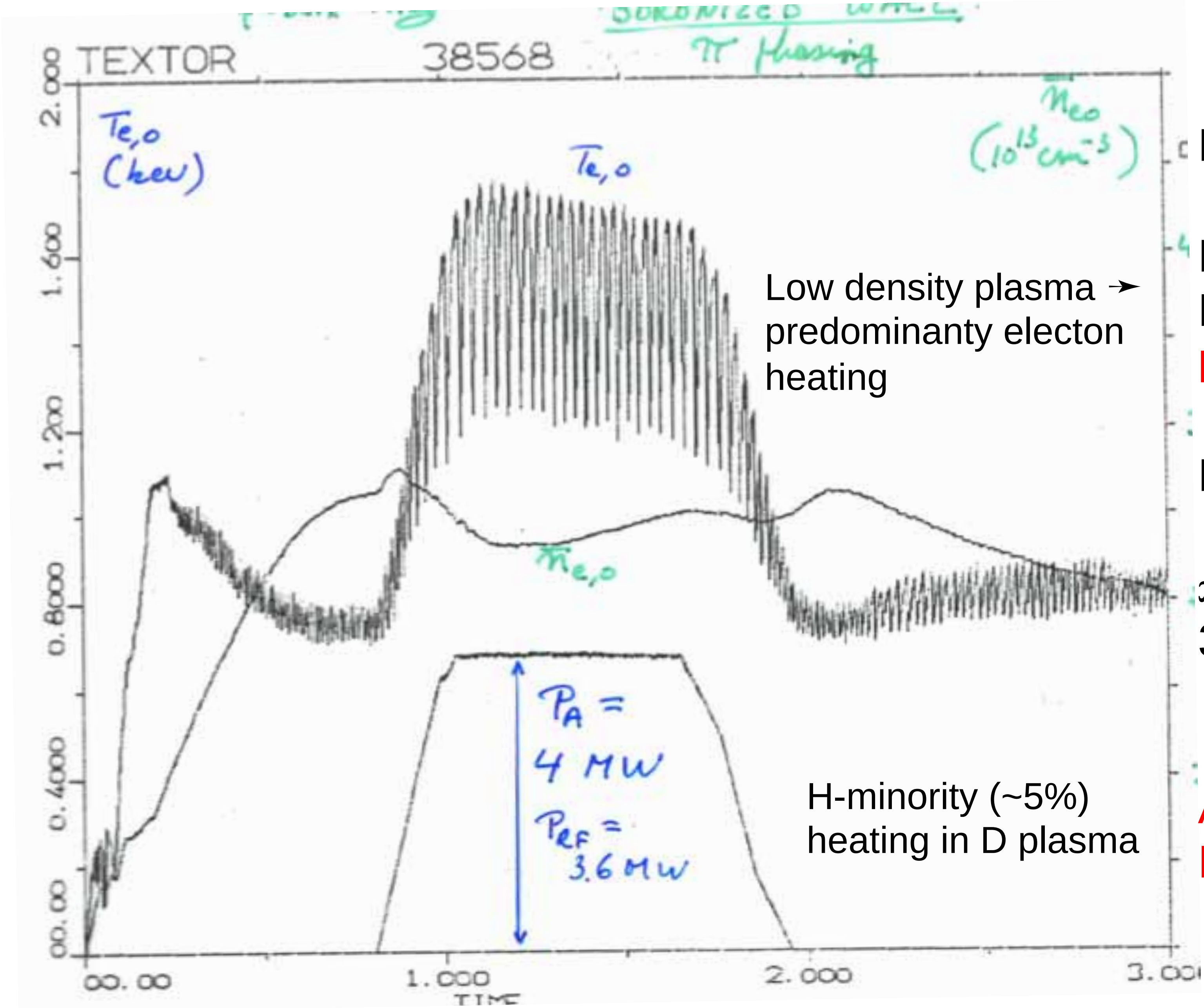


V. L. Vdovin et al, in Proceedings 3rd International Meeting on Heating in Toroidal Plasmas, Grenoble (CEA, Grenoble, Vol. 2, pp 349 (1976).

TEXTOR Antennes



Highly efficient ICRH system on TEXTOR



L-Mode plasma

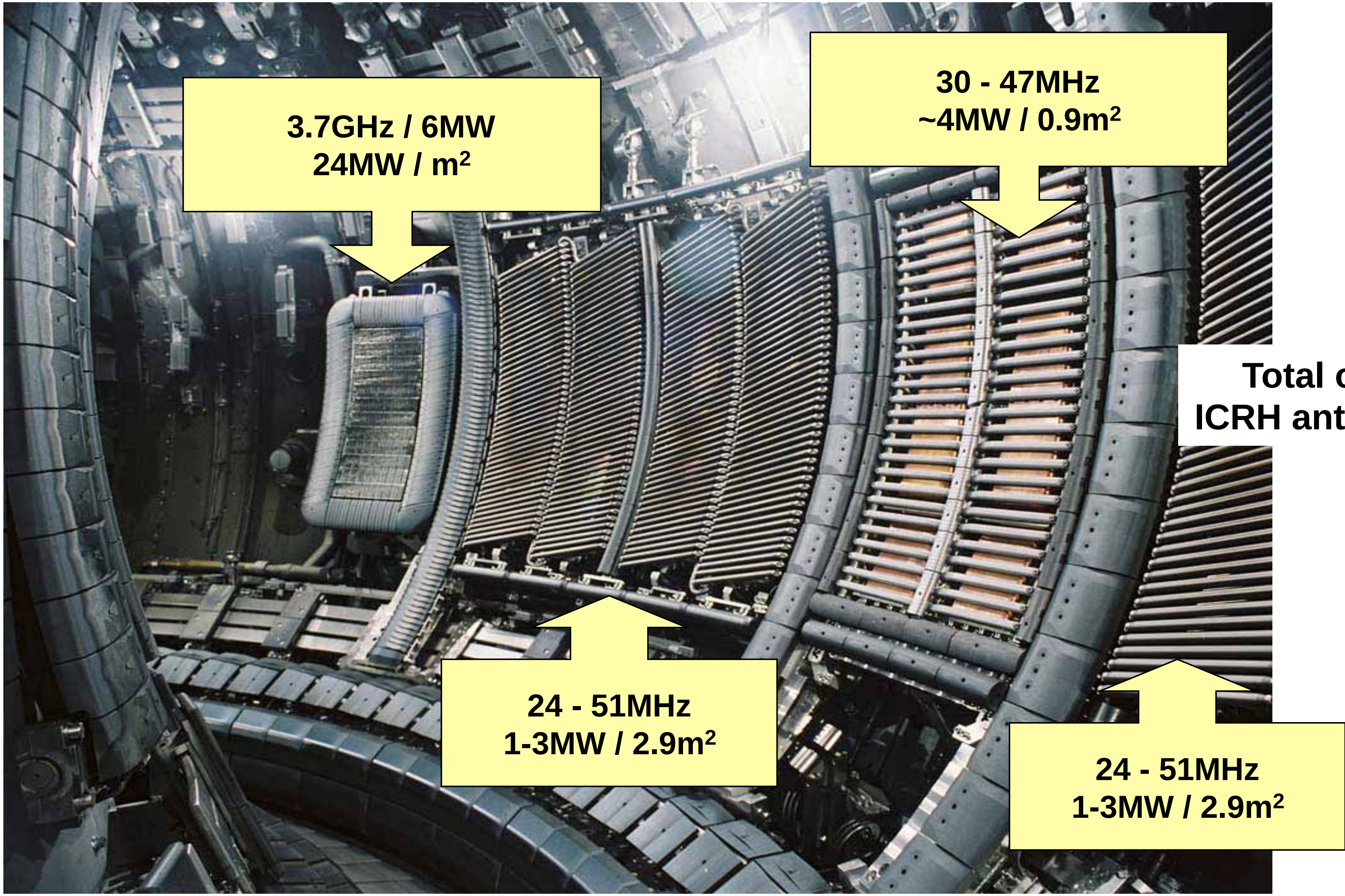
$P_{generator}$ = 4MW
$P_{deposited}$ = 3.6MW
Efficiency 90%

Doubling of $T_e(0)$

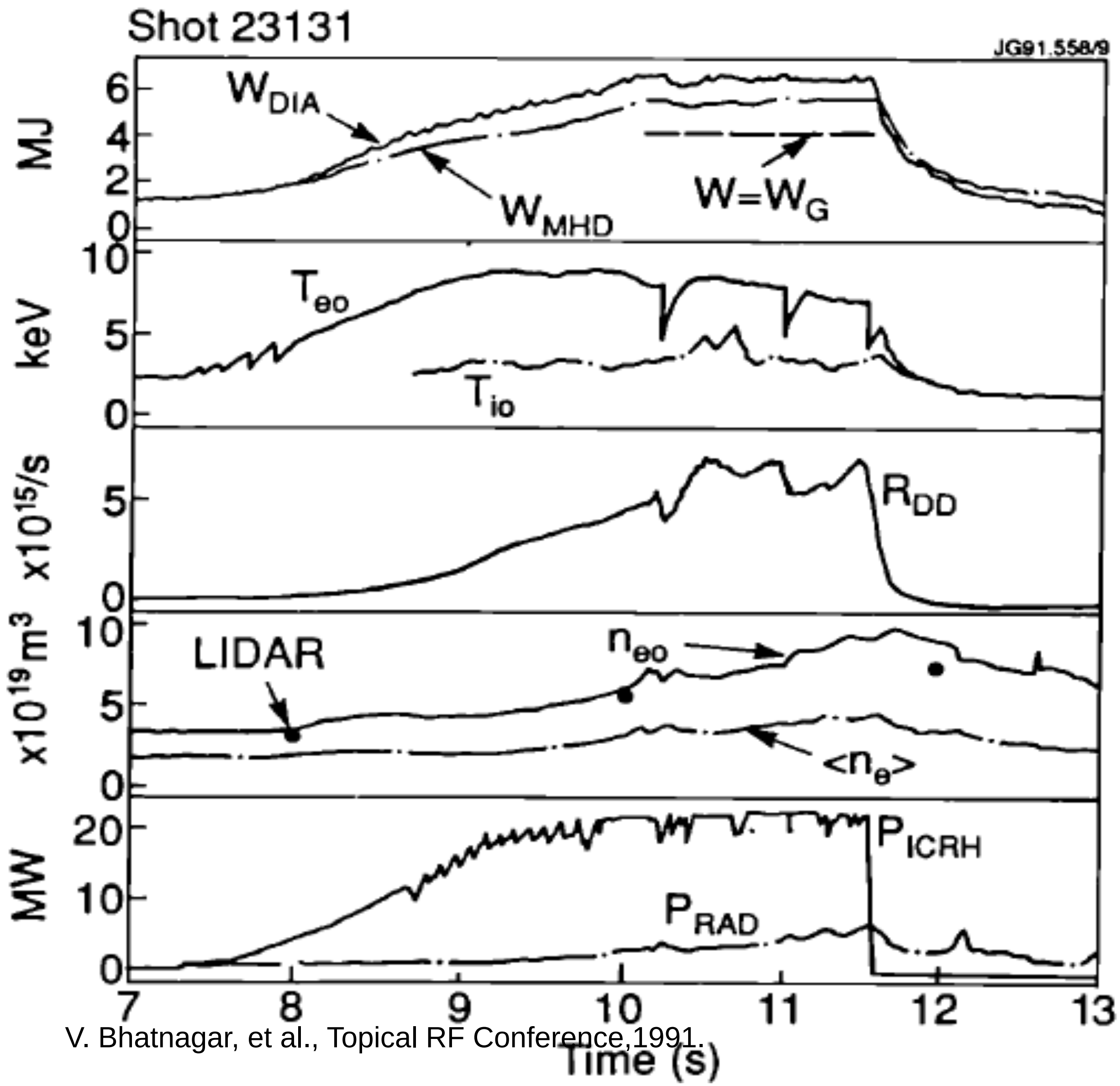
π-phasing
32.5MHz

Also in JET (1991)
L-Mode : 22MW

ICRH (and Lower Hybrid) antennas in JET



22MW Hydrogen minority heating in D, JET (1991)



V. Bhatnagar, et al., Topical RF Conference,1991.

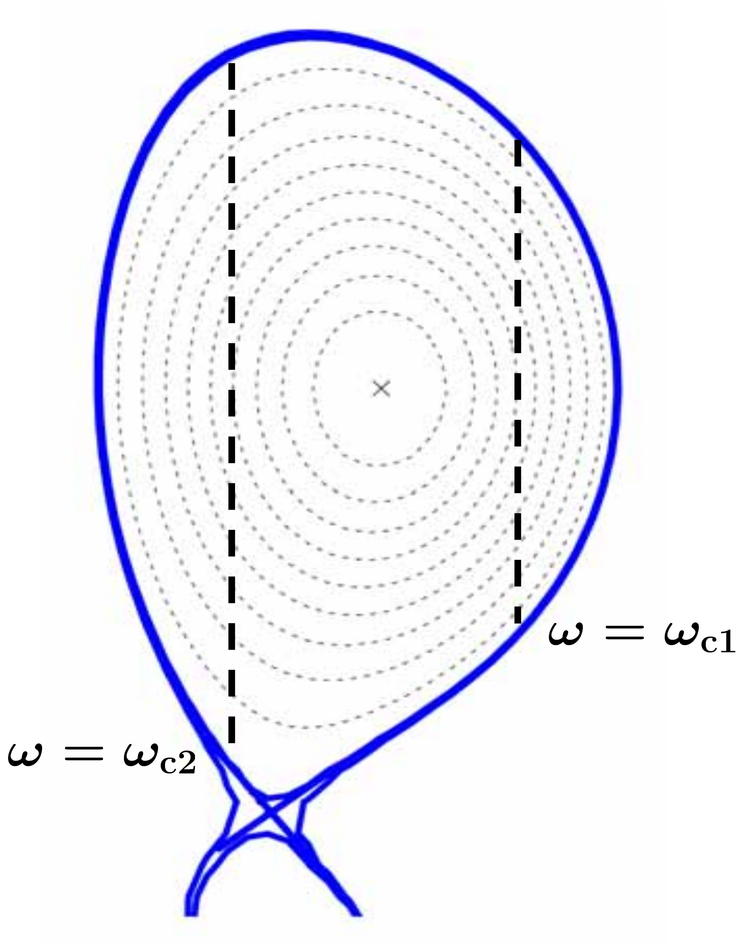
Low density plasma ➛ predominant electron heating

ICRH: 22MW

$\omega=2\omega_{CD}=\omega_{CH}$

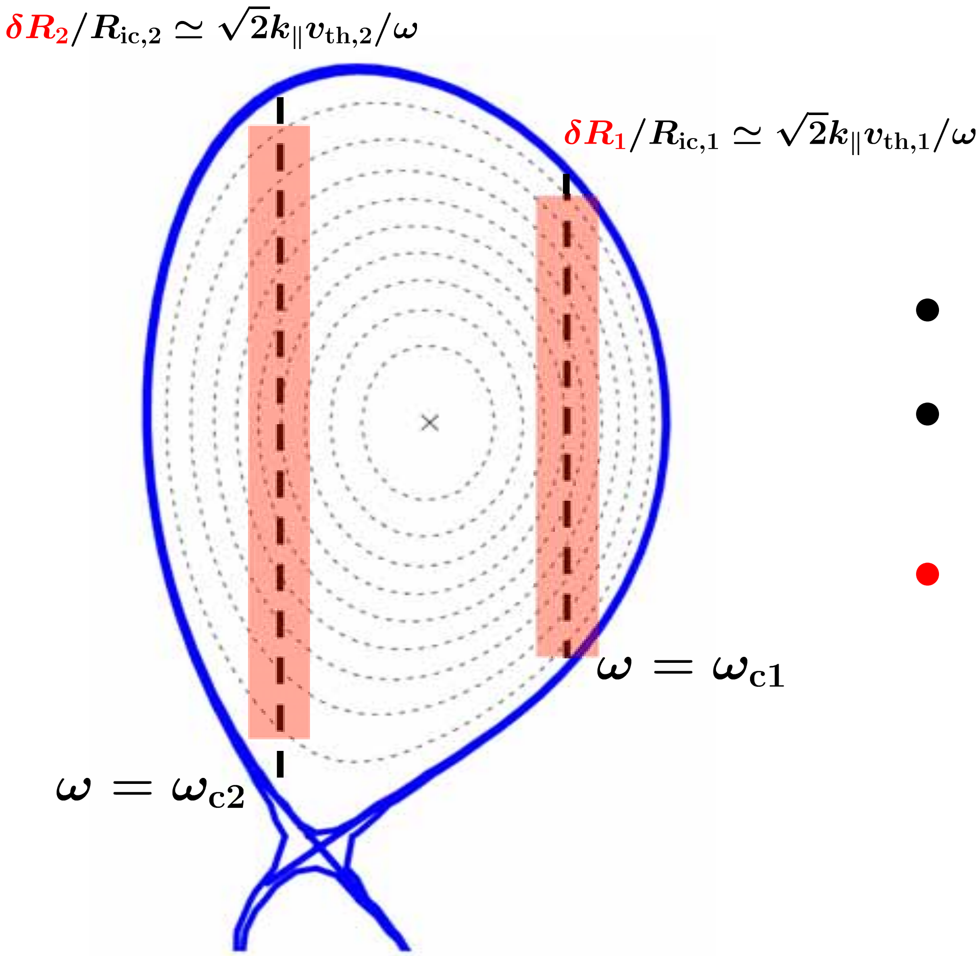
ICRF heating schemes

Heating scenarios in two-ion plasmas



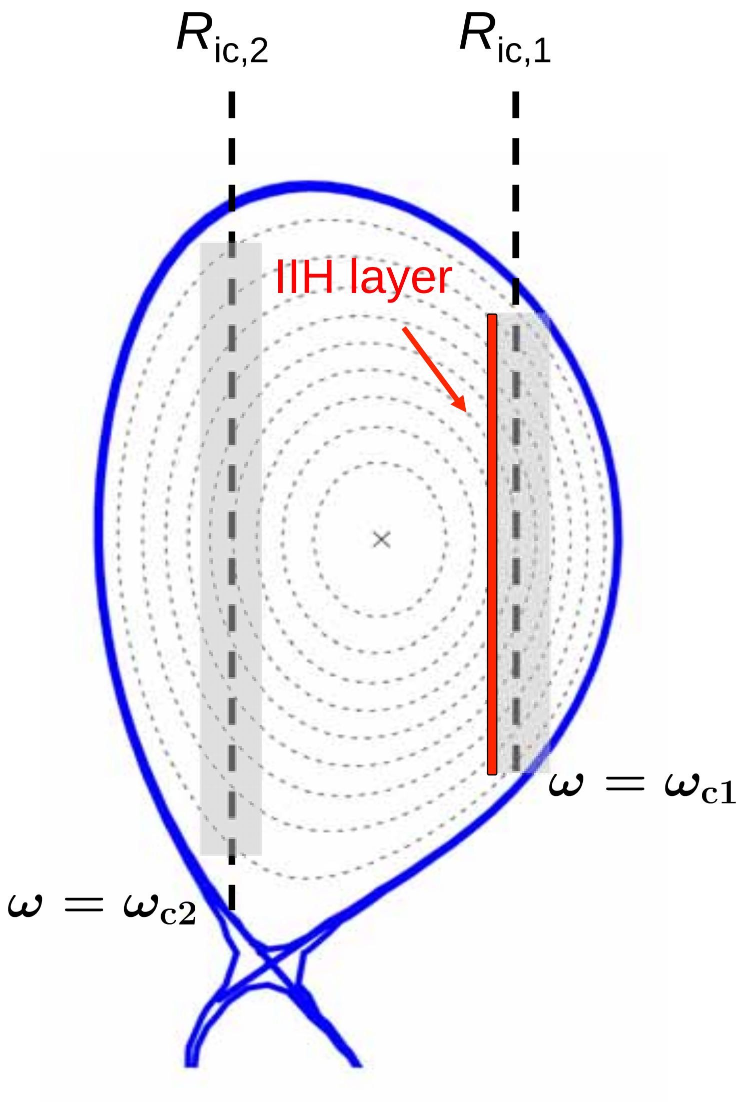
- **Two ion species $(Z/A)_1$ and $(Z/A)_2$**
- **Two ion cyclotron layers:**
  $\omega \approx \omega_{c1}$ **and** $\omega \approx \omega_{c2}$

Heating scenarios in two-ion plasmas



- **Two ion species $(Z/A)_1$ and $(Z/A)_2$**
- **Two ion cyclotron (IC) layers:**
  $\omega \approx \omega_{\mathrm{c1}}$ **and** $\omega \approx \omega_{\mathrm{c2}}$
- **Every IC layer has a natural width $\delta R_{1,2}$**

Heating scenarios in two-ion plasmas

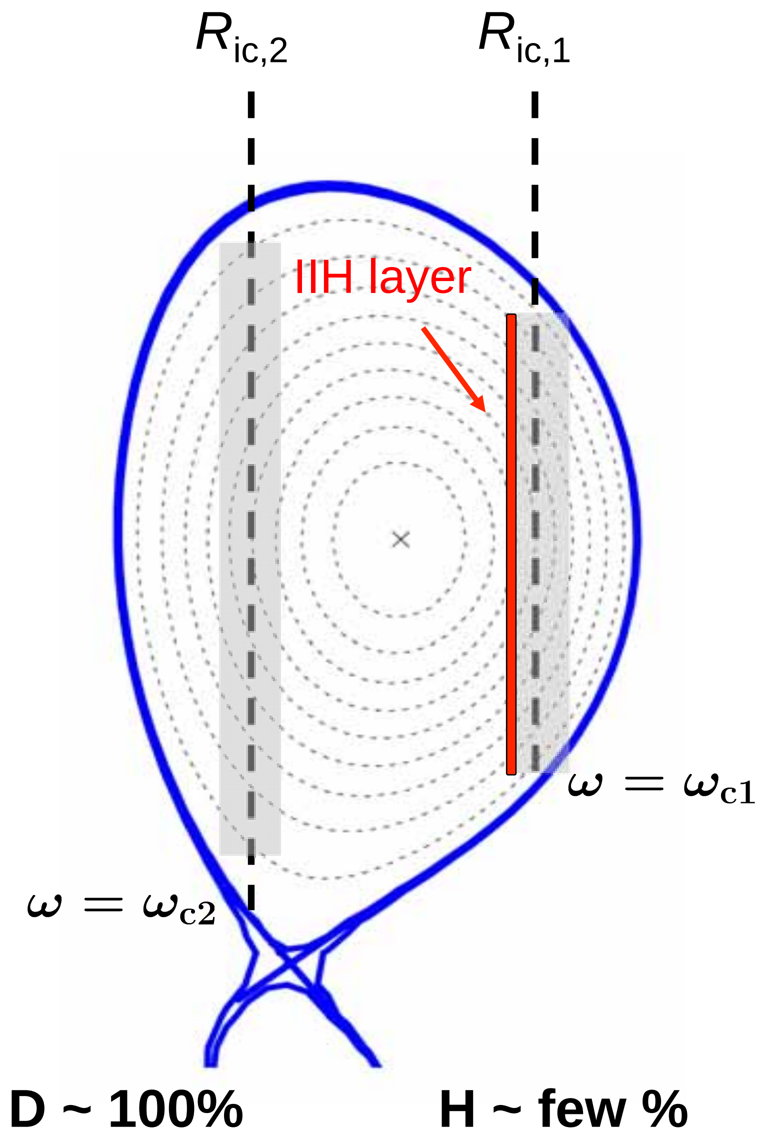


- ✓ **N=1: Ion absorption due to E_+**

$$P_{abs} \propto |E_+ J_0(k_\perp \rho_L) + \cancel{E_- J_2(k_\perp \rho_L)}|^2 \approx |E_+|^2$$

- ✓ **Ion-ion hybrid (IIH) layer, with large E_+: in between $R_{ic,2}$ and $R_{ic,1}$**

Minority heating in two-ion plasmas



- ✓ **N=1: Ion absorption due to *E*$_+$**

$$P_{abs} \propto |E_+ J_0(k_\perp \rho_L) + \cancel{E_- J_2(k_\perp \rho_L)}|^2 \approx |E_+|^2$$

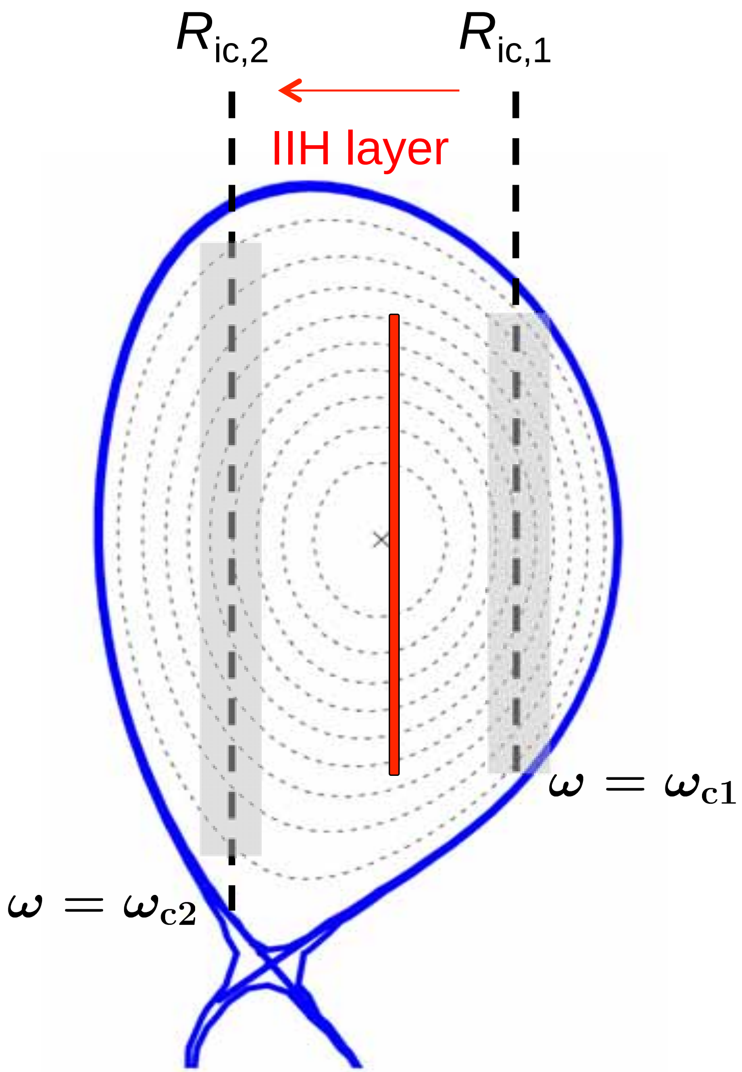
- ✓ **Ion-ion hybrid (IIH) layer, with large *E*$_+$: in between *R*$_{ic,2}$ and *R*$_{ic,1}$**

- ✓ **At low minority concentration IIH layer close to minority resonance layer**

- ✓ **Minority ions get efficiently heated**

$\boxed{\text{Minority heating}}$

Electron heating and mode conversion in two-ion plasmas



D ~ 70% **H ~ 30 %**

- ✓ **N=1: Ion absorption due to E_+**

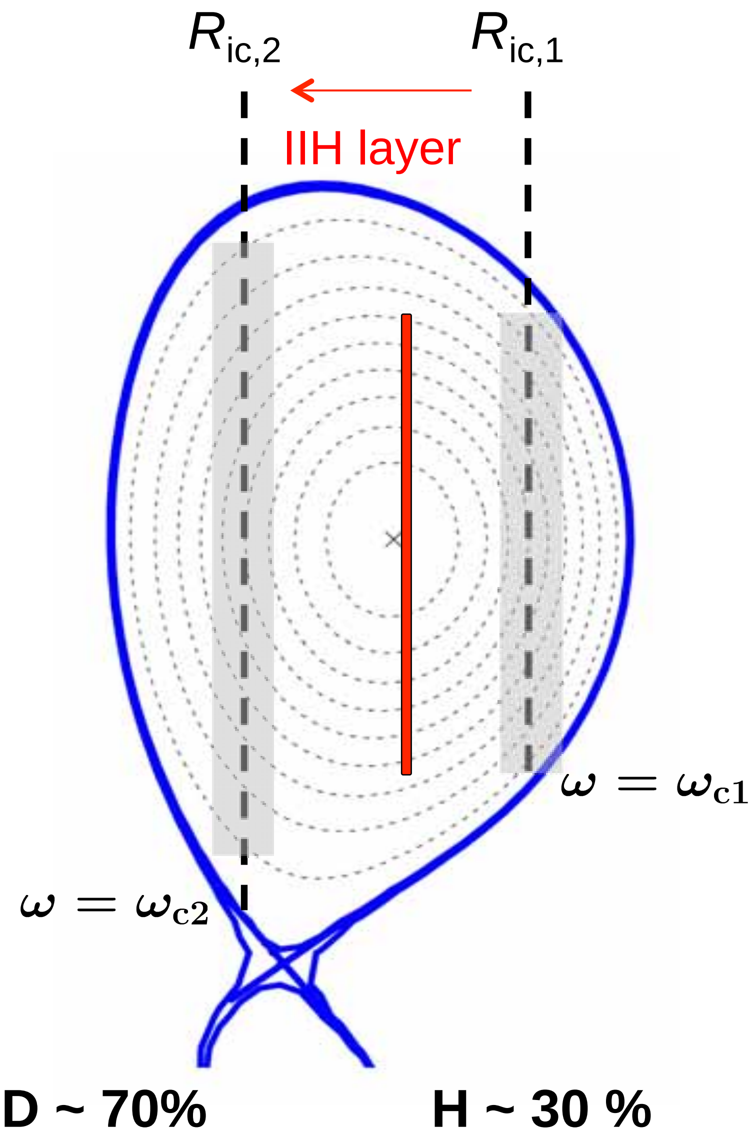
  $$P_{\mathrm{abs}} \propto |E_+ J_0(k_\perp \rho_L) + \cancel{E_- J_2(k_\perp \rho_L)}|^2 \approx |E_+|^2$$

- ✓ **Ion-ion hybrid (IIH) layer, with large E_+: in between $R_{\mathrm{ic},2}$ and $R_{\mathrm{ic},1}$**

- ✓ **At higher minority concentration IIH layer far away from minority resonance**

Electron heating
(by Mode Conversion)

How to heat ions instead of electrons ?



- ✓ **N=1: Ion absorption due to E_+**

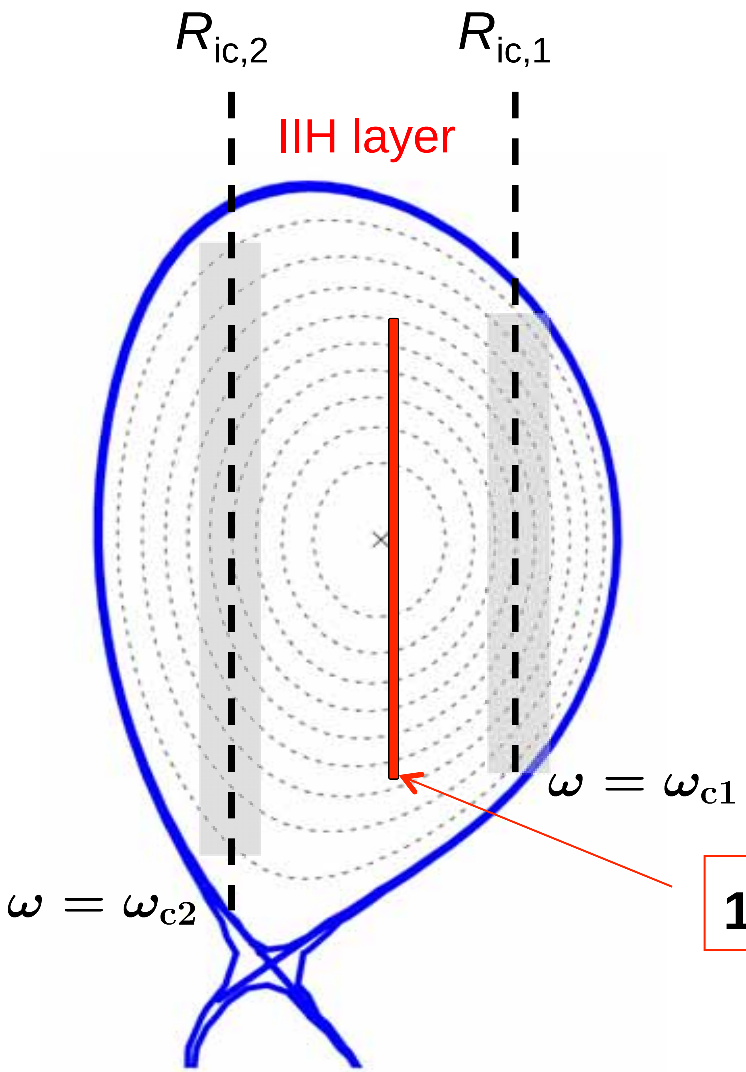
$$P_{\rm abs} \propto |E_+ J_0(k_\perp \rho_L) + \cancel{E_- J_2(k_\perp \rho_L)}|^2 \approx |E_+|^2$$

- ✓ **Ion-ion hybrid (IIH) layer, with large E_+: in between $R_{ic,2}$ and $R_{ic,1}$**

- ✓ **At higher minority concentration IIH layer far away from minority resonance**

How to heat ions?

Use a third ion with different Z/A as resonant absorber



1. Use a third ion with $(Z/A)_2 < (Z/A)_3 < (Z/A)_1$

D ~30%	^{3}He ~1%	H ~70%
Z/A=1/2	Z/A = 2/3	Z/A =1

Nature Physics 13, 973-978 (October 2017)
"Three-ion" scenario

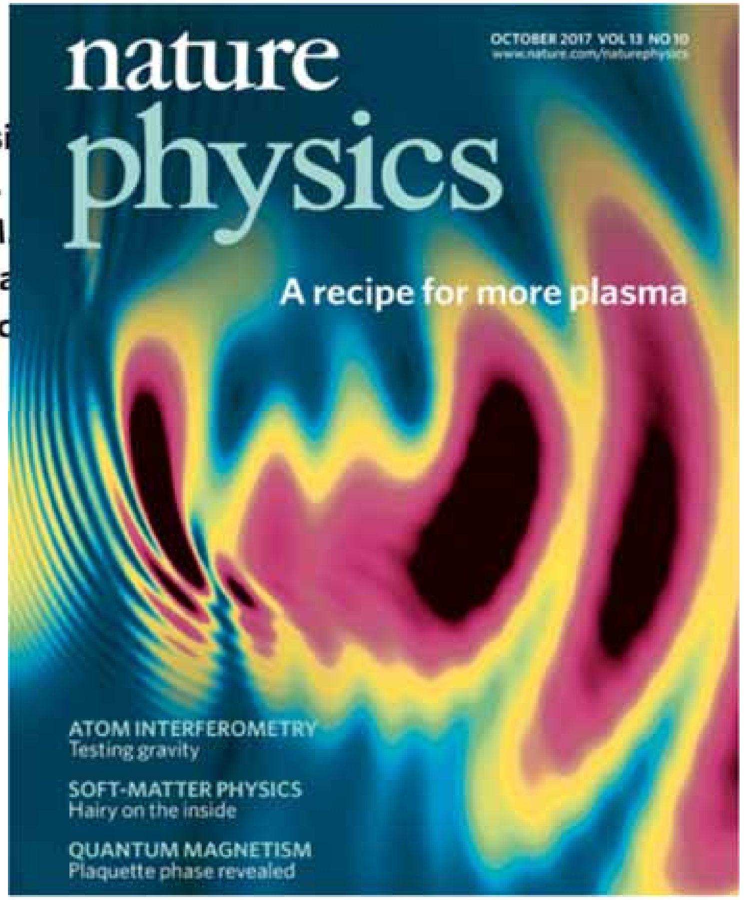
nature physics

ARTICLES

PUBLISHED ONLINE: 19 JUNE 2017 | DOI: 10.1038/NPHYS4167

Efficient generation of energetic ions in multi-ion plasmas by radio-frequency heating

Ye. O. Kazakov[1*], J. Ongena[1], J. C. Wright[2], S. J. Wukitch[2], E. Lerche[1,3], M. J. Mantsi
D. Van Eester[1], T. Craciunescu[6], V. G. Kiptily[3], Y. Lin[2], M. Nocente[7,8], F. Nabais[9], M.
Y. Baranov[3], J. Bielecki[10], R. Bilato[11], V. Bobkov[11], K. Crombé[1,12], A. Czarnecka[13], J. M
R. Felton[3], M. Fitzgerald[3], D. Gallart[4], L. Giacomelli[8], T. Golfinopoulos[2], A. E. Hubba
T. Johnson[15], M. Lennholm[16,17], T. Loarer[18], M. Porkolab[2], S. E. Sharapov[3], D. Valcarc
M. Van Schoor[1], H. Weisen[14], JET Contributors[†] and the Alcator C-Mod Team[†]

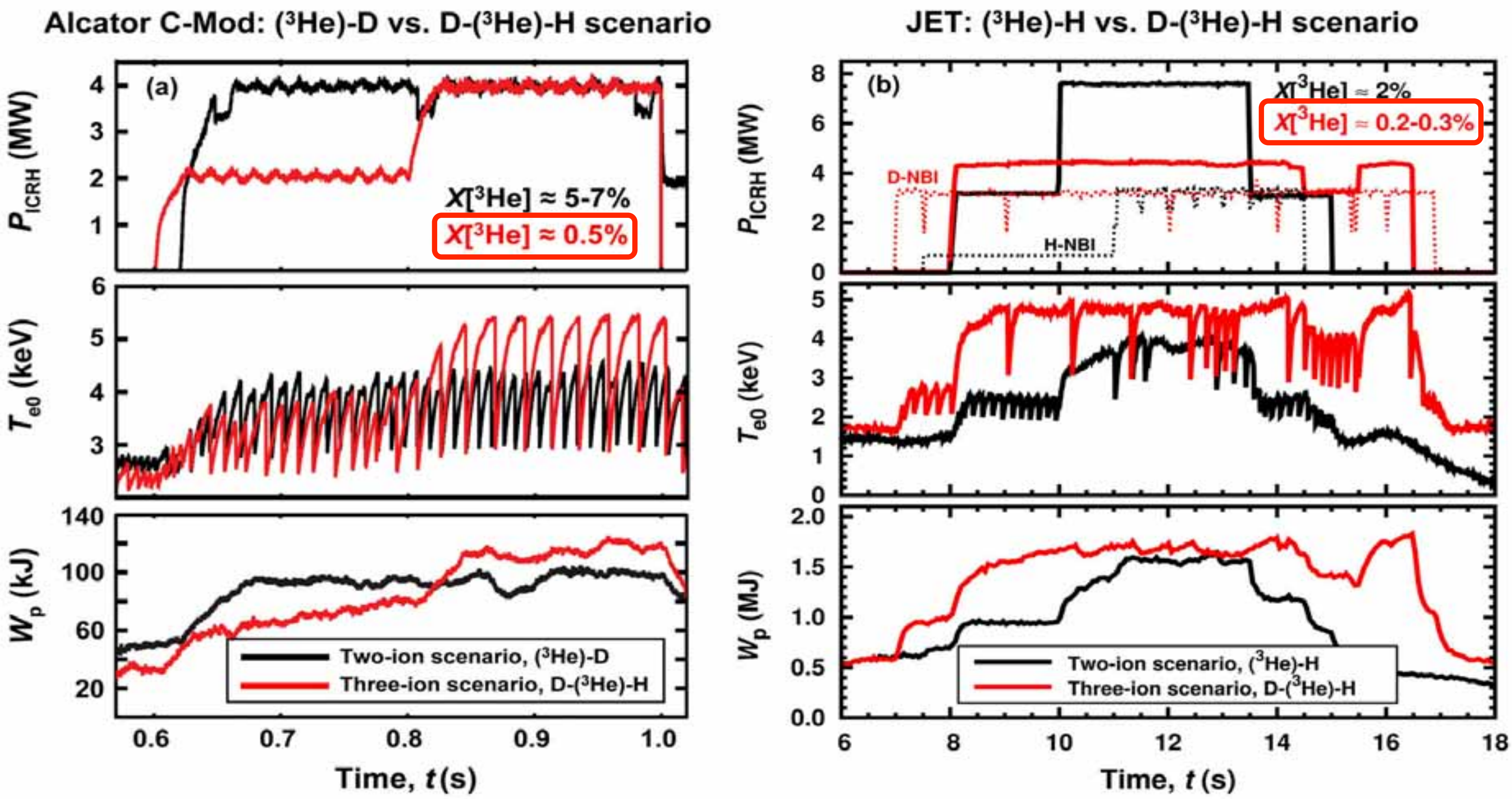


D-(^{3}He)-H scheme in JET and Alcator-C Mod

and

Explanation for ^{3}He rich solar flares

Three-ion ICRH scenario: effective plasma heating demonstrated on Alcator C-Mod and JET

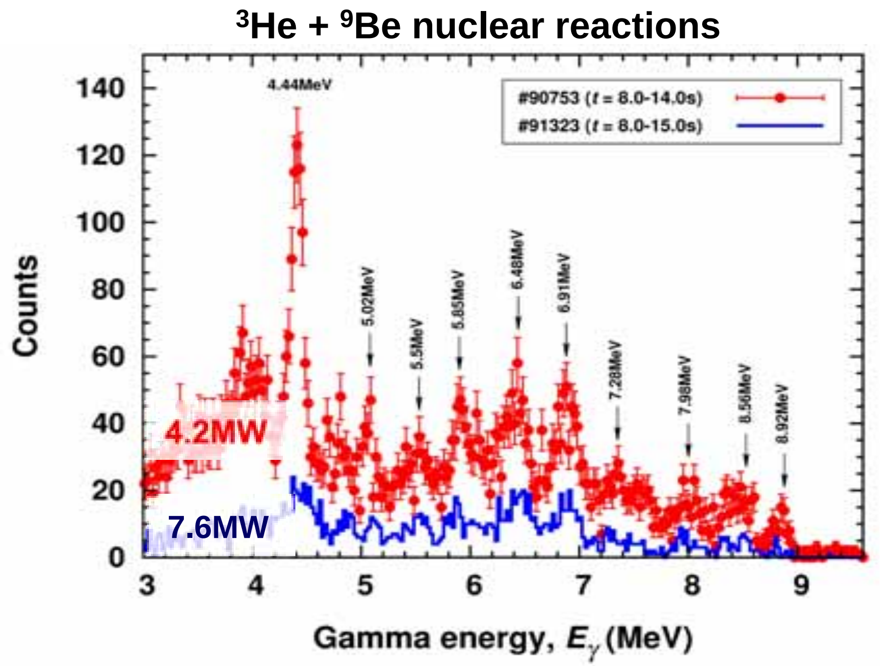


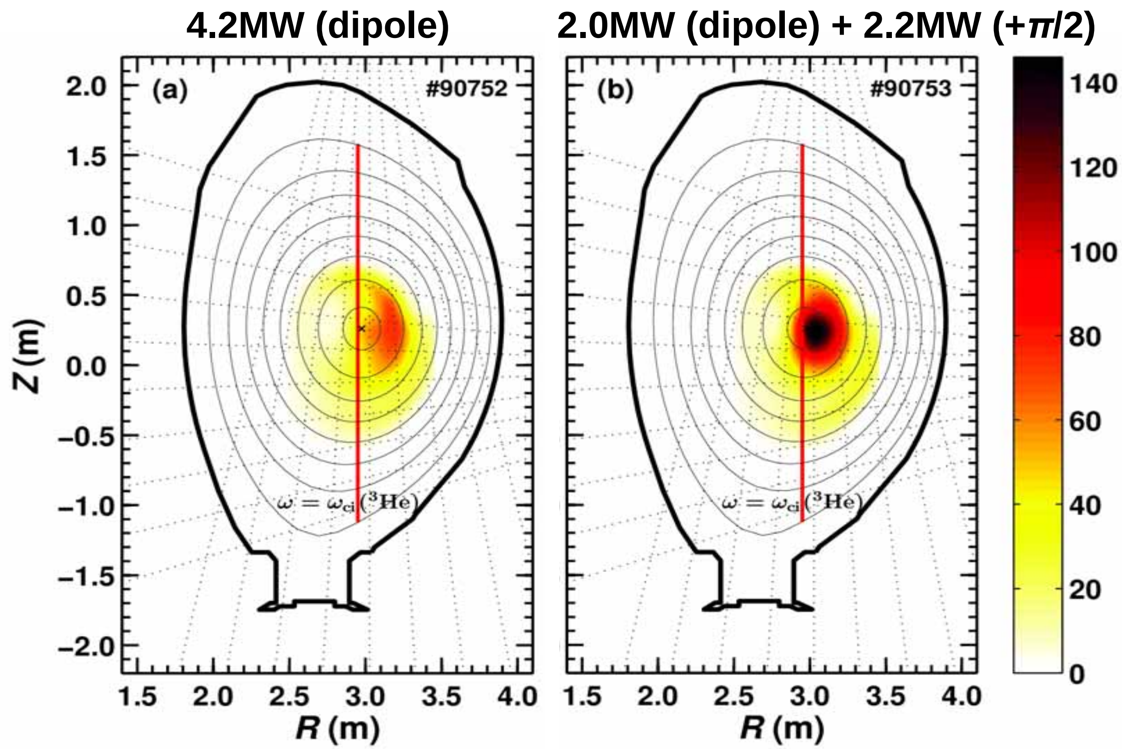
Alcator C-Mod: $n_{e0} \approx 2.8\text{x}10^{20}$ m^{-3}

Three-ion ICRH scenario: effective fast-ion generation demonstrated on Alcator C-Mod and JET

Generation of MeV-range ^{3}He ions confirmed by γ-ray spectroscopy

Reconstructed γ-ray emission: benefit of using $+\pi/2$ ICRH phasing

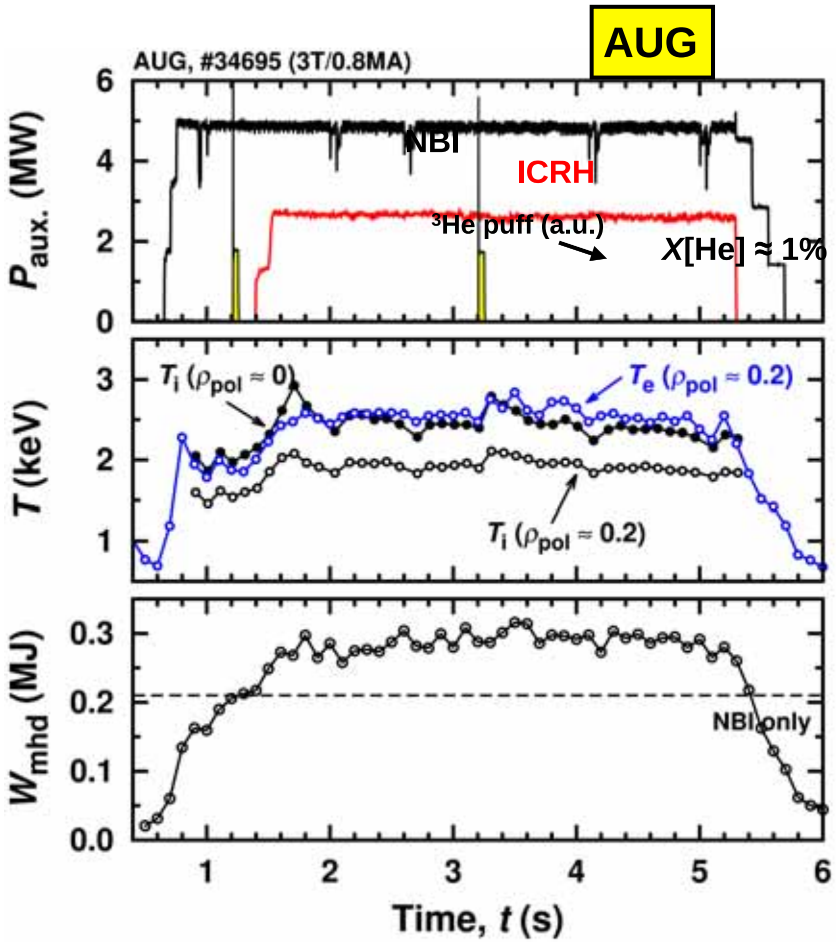




$+\pi/2$ phasing, lower $|k_{||}|$: better RF coupling $\rightarrow$ will be available on W7-X (!)

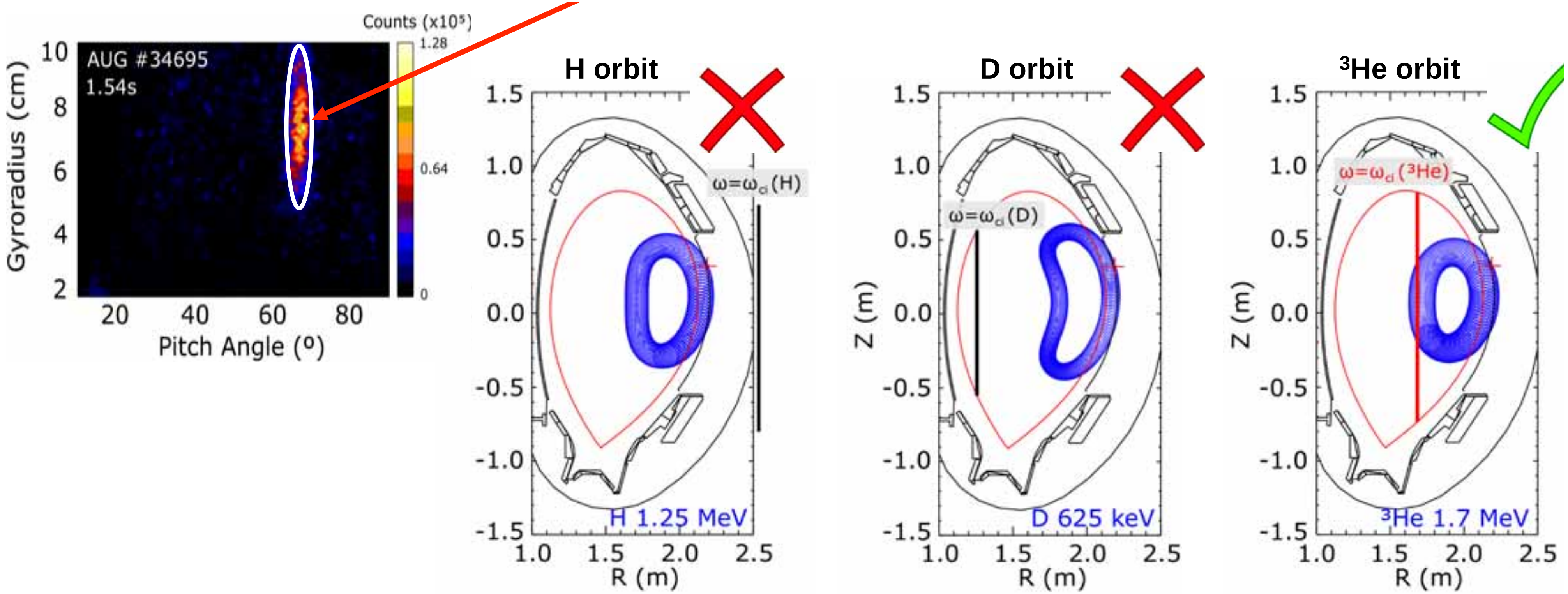
Additional advantage: lower ΔV_{abs} & RF-induced pinch effect – see J. Faustin's talk

3-ion heating scheme demonstrated also on ASDEX Upgrade



3-ion heating scheme demonstrated also on ASDEX Upgrade

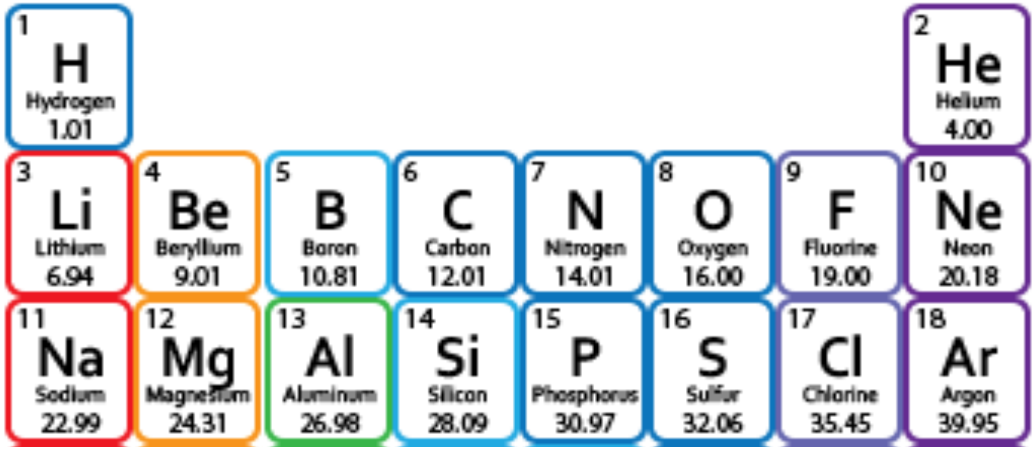
H-D-^{3}He plasma: reconstructed orbits for H, D and ^{3}He ions



- **Backward-orbit tracing of escaping ions measured by Fast Ion Loss Detector: energetic species is ^{3}He**
- $\rho_L \approx$ **6-9cm** $\rightarrow$ $E(^3\mathrm{He}) \approx$ **1.2-2.8MeV**

Various 3-ion ICRH schemes are possible

Make a selection of elements (and their isotopes) out of the table of Mendeleev and list them as a function of Z/A



Ion species	T	Impurities: ^{9}Be, ^{40}Ar, ^{7}Li, ^{22}Ne, …	D, ^{4}He, ^{12}C, ^{16}O, …	^{3}He	H
$(Z/A)_i$	1/3	~0.43-0.45	1/2	2/3	1

Various 3-ion ICRH schemes are possible

Ion species	T	Impurities: ^{9}Be, ^{40}Ar, ^{7}Li, ^{22}Ne, ...	D, ^{4}He, ^{12}C, ^{16}O, ...	^{3}He	H
$(Z/A)_i$	1/3	~0.43-0.45	1/2	2/3	1

Scenarios for the D-T phase of ITER

- **T-(^{9}Be)-D scheme: using ^{9}Be impurities as an ICRH minority for heating D-T plasmas**

Various 3-ion ICRH schemes are possible

Ion species	T	Impurities: ^{9}Be, ^{40}Ar, ^{7}Li, ^{22}Ne, …	D, ^{4}He, ^{12}C, ^{16}O, …	^{3}He	H
$(Z/A)_i$	1/3	~0.43-0.45	1/2	2/3	1

Scenarios for non-active plasmas in ITER

- **^{4}He-(^{3}He)-H scheme: especially off-axis ^{3}He heating in H-^{4}He plasmas for H-mode studies at $B_0 \approx$ 3-3.3T**

Various 3-ion ICRH schemes are possible

Ion species	T	Impurities: ^{9}Be, ^{40}Ar, ^{7}Li, ^{22}Ne, ...	D, ^{4}He, ^{12}C, ^{16}O, ...	^{3}He	H
$(Z/A)_i$	1/3	~0.43-0.45	1/2	2/3	1

Scenarios for non-active plasmas in ITER

- **^{9}Be/Ar-(^{4}He)-H scheme:**
  using impurities (^{9}Be and Ar) to heat ^{4}He ions!

Two ways to fulfill the resonance condition

Magnetosonic wave
frequency

$$\omega = \omega_{ci} + k_{//} v_{//}$$

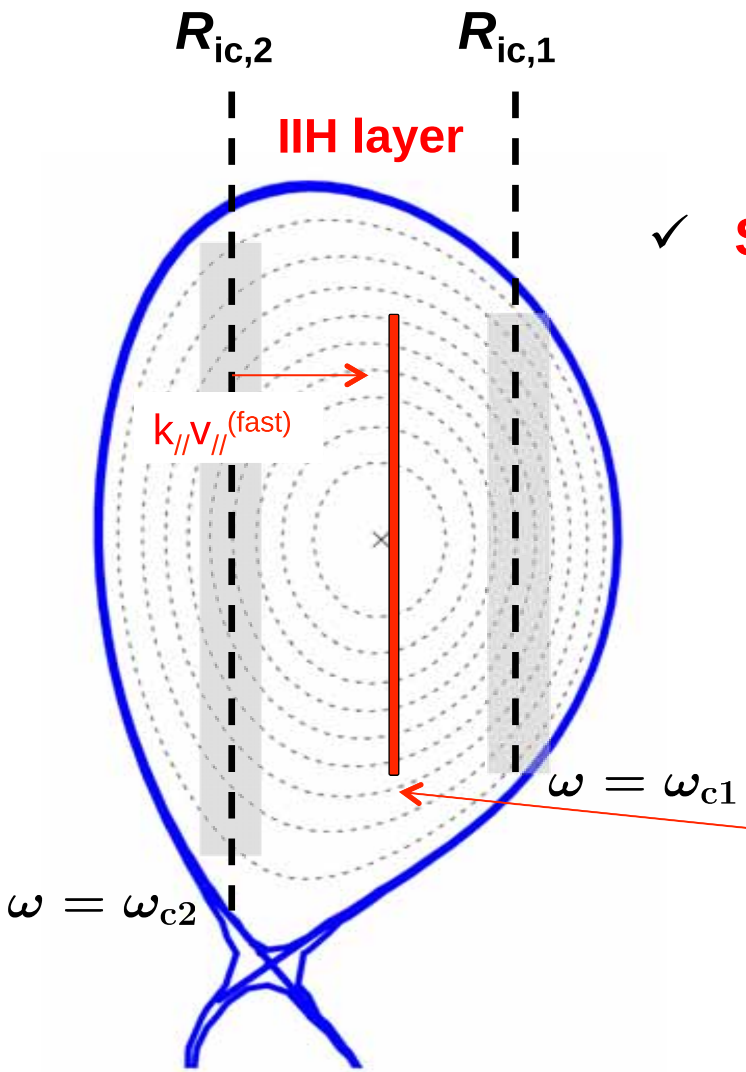
1. Ions with different Z/A
than the main plasma ions

$$\omega_{c,i} = \frac{Z_i}{A_i} \frac{|q_e| B}{m_p}$$

2. Fast particles
with large Doppler shift

Can be majority particles

Use fast ions as resonant absorber



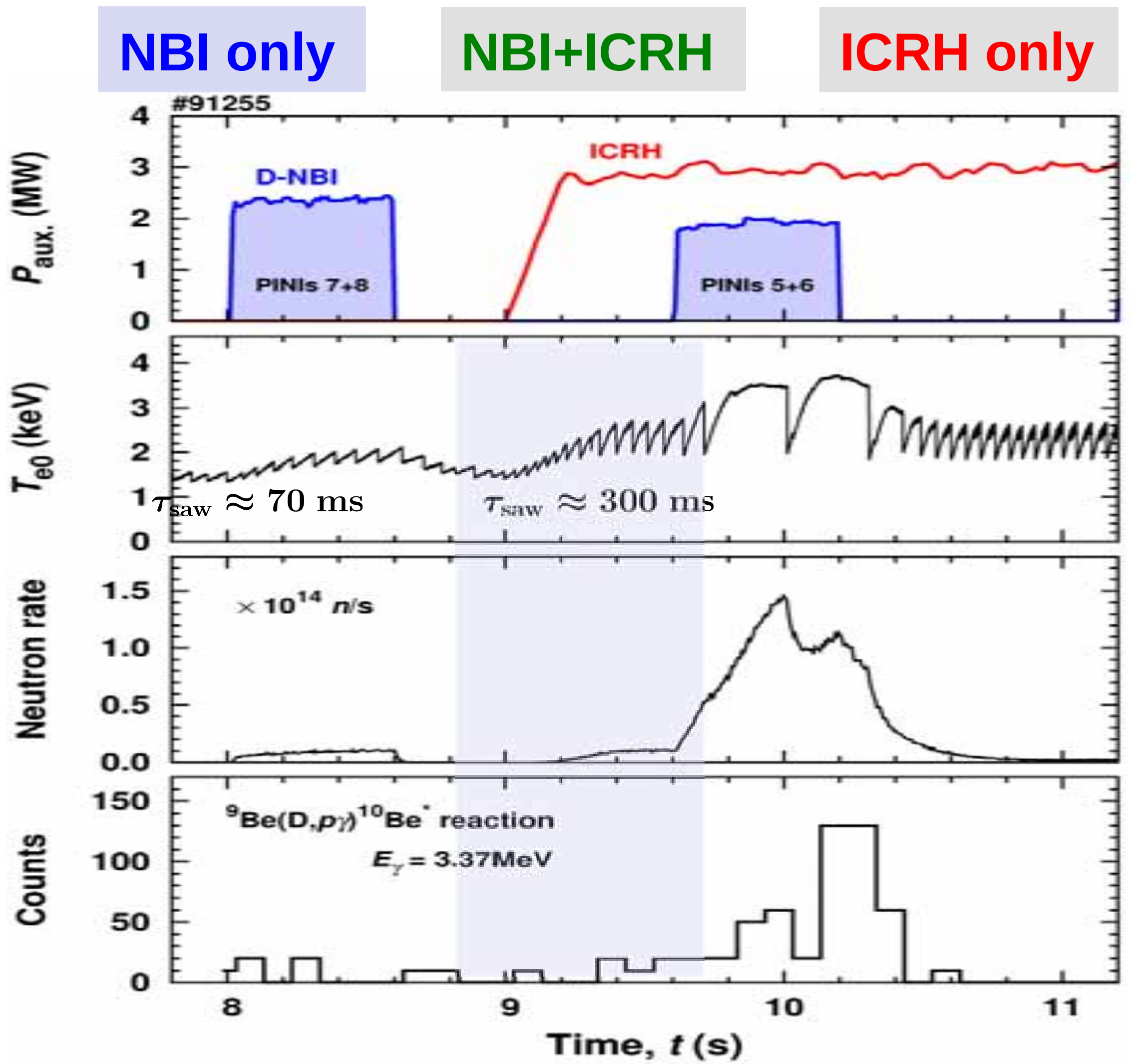
✓ **Still very strong E_+ in the vicinity of the IIH layer**

2. Use fast ions with large Doppler shift

$$\omega = \omega_{c2} + k_{\parallel} v_{\parallel}^{(\mathrm{fast})} \simeq \omega_{\mathrm{MC}}$$

D ~ 15% D_{fast} ~ few% H ~85 %

Clear synergetic heating ICRH+NBI seen on JET



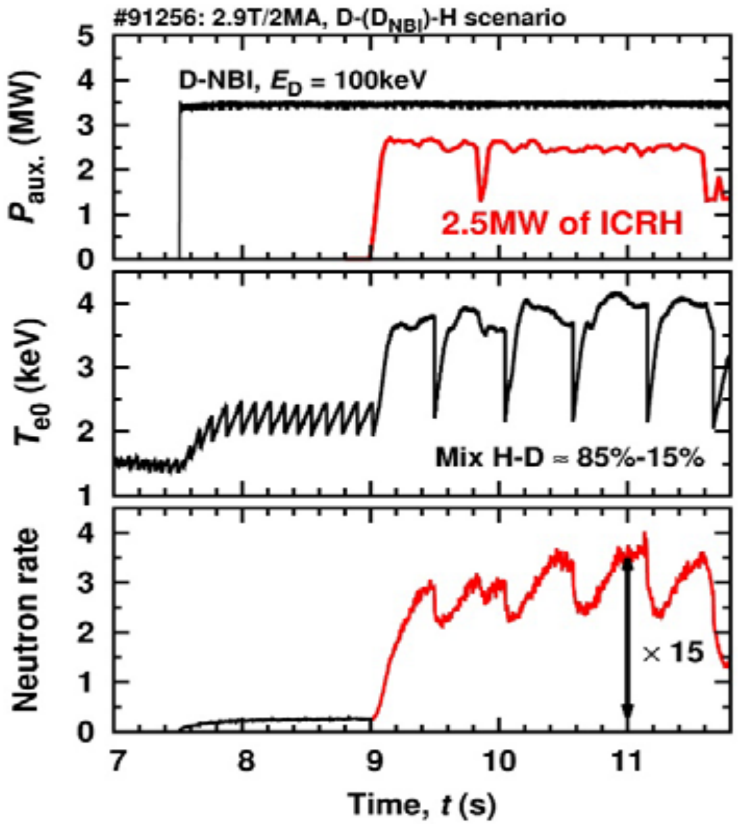
Electron heating
by Mode Conversion

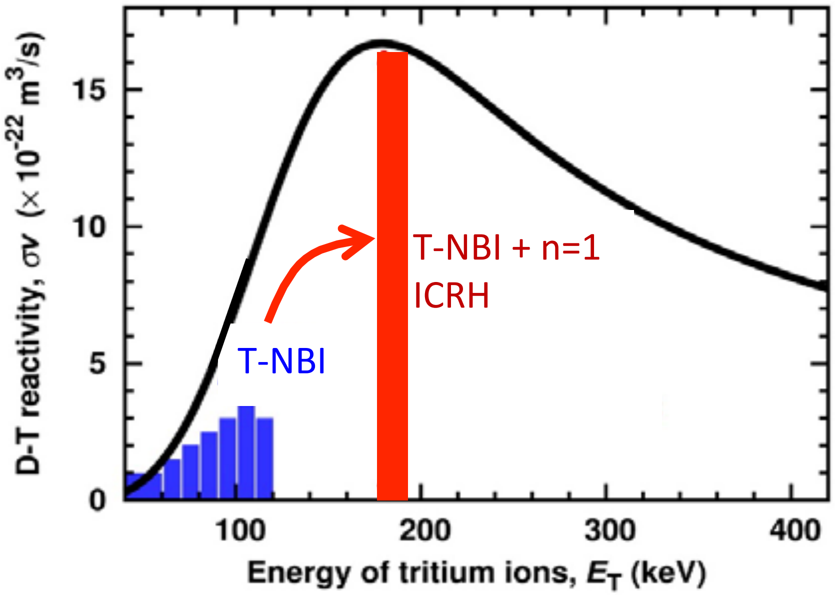
$H/(H+D)_{edge} \sim 0.90$

J.Ongena, Y.Kazakov et al., "Synergetic heating of D-NBI ions in the vicinity of the mode conversion layer in H-D plasmas in JET with the ITER like wall", 22nd Topical Conference on Radio-Frequency Power in Plasmas
EPJ Web of Conferences 157, 02006 (2017)

D-T campaign in JET: T-(T_{NBI})-D scenario to increase Q

Efficient acceleration of NBI ions to higher energies with n = 1 ICRH using 3-ion scenario





- H-D plasmas: x15 increase in neutron rate due to accelerating D-NBI ions to $E_D \approx$ 1-2MeV,
- confirmed with TOFOR, γ-ray measurements and ICRH modeling

D-T plasmas: optimize Q and fusion power using NBI+ICRH synergies:
$E_{T\text{-}NBI}$ = 118keV, →
$\langle E_T \rangle \approx$ 200keV (off-axis n = 1 ICRH)

Clear synergetic heating ICRH+NBI seen on JET

Possibilities for 3-ion scenarios in ITER using D-NBI or H-NBI

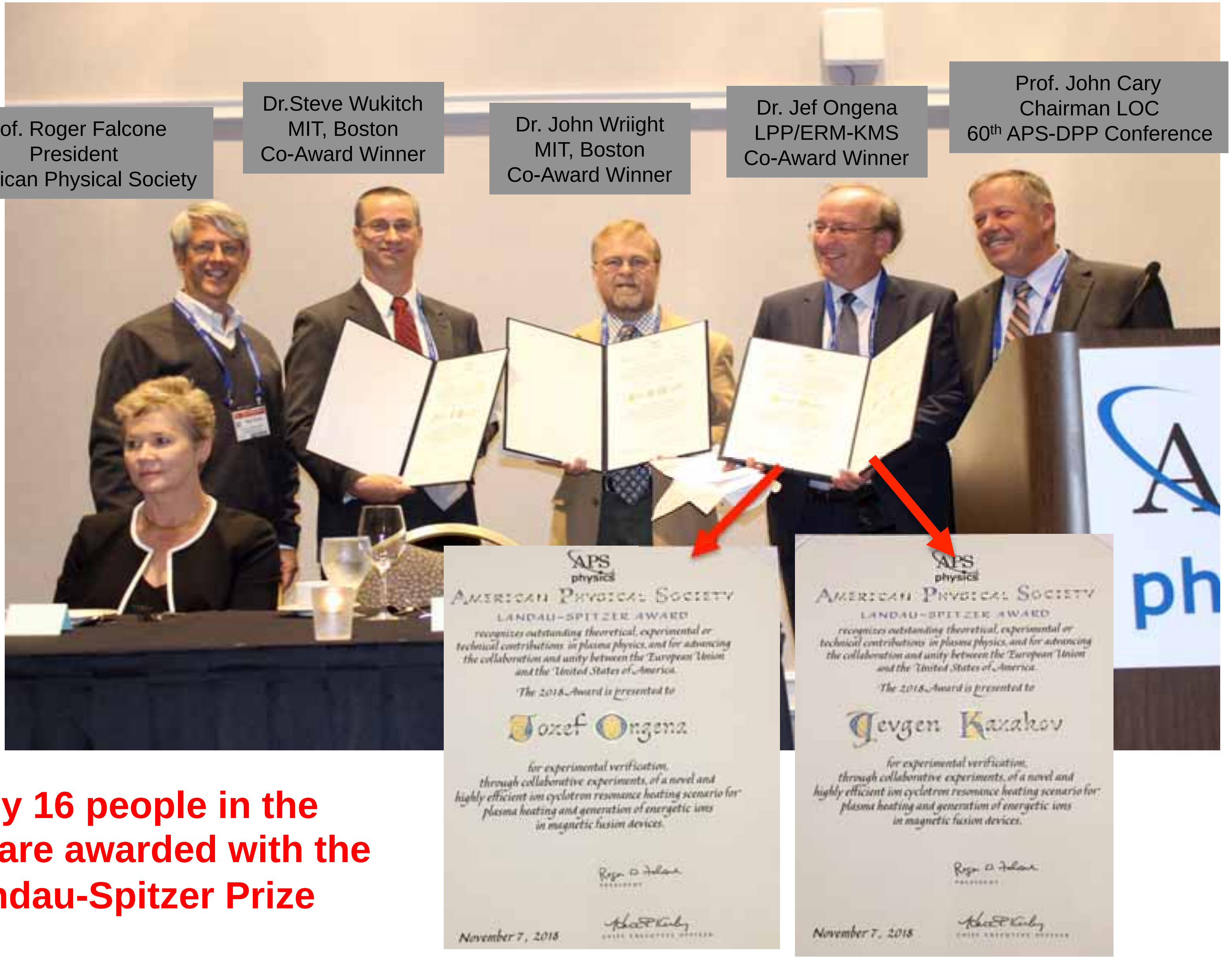
→ T-(D_{NBI})-D scheme for D-T plasmas

→ ^{4}He-(H_{NBI})-H scheme for non-active ^{4}He-H plasmas

A lot of possibilities exist for 3-ion scenarios

	Resonant ions	Main plasma ions	Scenario	Short scenario description
Option 1: using fast NBI ions	H^0 NBI	^{4}He-H D-H T-H	^{4}He-(H_{NBI})-H D-(H_{NBI})-H T-(H_{NBI})-H	Heating and fast-ion studies in non-active plasmas Heating and fast-ion studies in D-H plasmas Heating and fast-ion studies in T-H plasmas
	D^0 NBI	H-D D-^{3}He T-D	D-(D_{NBI})-H D-(D_{NBI})-^{3}He T-(D_{NBI})-D	*Heating and fast-ion studies: demonstrated on JET* Source of isotropic fusion alphas in D-^{3}He plasmas Maximize Q and P_{fus} in JET
	T^0 NBI	D-T T-^{4}He H-T	T-(T_{NBI})-D T-(T_{NBI})-^{4}He T-(T_{NBI})-H	Maximize Q and P_{fus} in JET Mimick T-NBI acceleration in non-active JET plasmas Heating and fast-ion studies in H-T plasmas
Option 2: using thermal ions with an intermediate $(Z/A)_I$	^{3}He	H-D H-^{4}He H-T	D-(^{3}He)-H ^{4}He-(^{3}He)-H T-(^{3}He)-H	*Heating and fast-ion studies: JET, Alcator C-Mod, AUG* Heating and fast-ion studies in non-active plasmas Heating and fast-ion studies in H-T plasmas
	^{9}Be	D-T	T-(^{9}Be)-D	Bulk ion heating in D-T plasmas on JET and ITER
	^{4}He	H-^{9}Be/Ar H-T	^{9}Be/Ar-(^{4}He)-H T-(^{4}He)-H	Non-active scenario for ITER and JET Fast ^{4}He studies in H-T plasmas

International recognition for the work on “3-ion ICRH scenarios”
Landau-Spitzer Award Ceremony 9 November 2018, Portland, Oregon



APS physics

American Physical Society

Landau-Spitzer Award

recognizes outstanding theoretical, experimental or technical contributions in plasma physics, and for advancing the collaboration and unity between the European Union and the United States of America.

The 2018 Award is presented to

Jozef Ongena

for experimental verification, through collaborative experiments, of a novel and highly efficient ion cyclotron resonance heating scenario for plasma heating and generation of energetic ions in magnetic fusion devices.

President

November 7, 2018

Chief Executive Officer

APS physics

American Physical Society

Landau-Spitzer Award

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The 2018 Award is presented to

Yevgen Kazakov

for experimental verification, through collaborative experiments, of a novel and highly efficient ion cyclotron resonance heating scenario for plasma heating and generation of energetic ions in magnetic fusion devices.

President

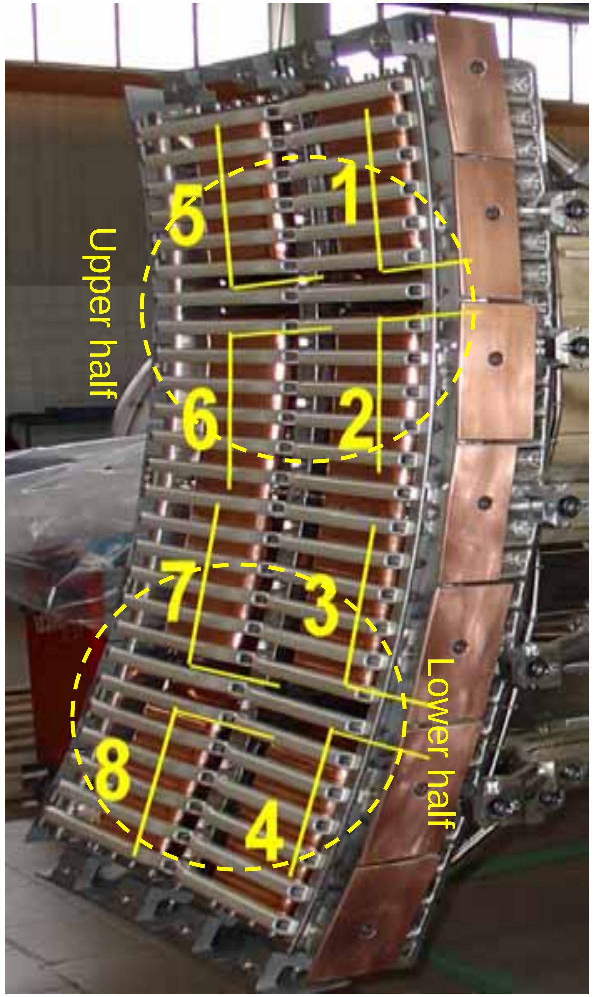
November 7, 2018

Chief Executive Officer

Only 16 people in the world are awarded with the Landau-Spitzer Prize

Recent developments in ICRH Antenna technology

Technology development : JET ITER like antenna



High Power Density ICRF Antenna with load resilience

- 29-51 MHz
- Insensitive to changes in plasma edge
- Designed for power densities up to 8MW/m^2

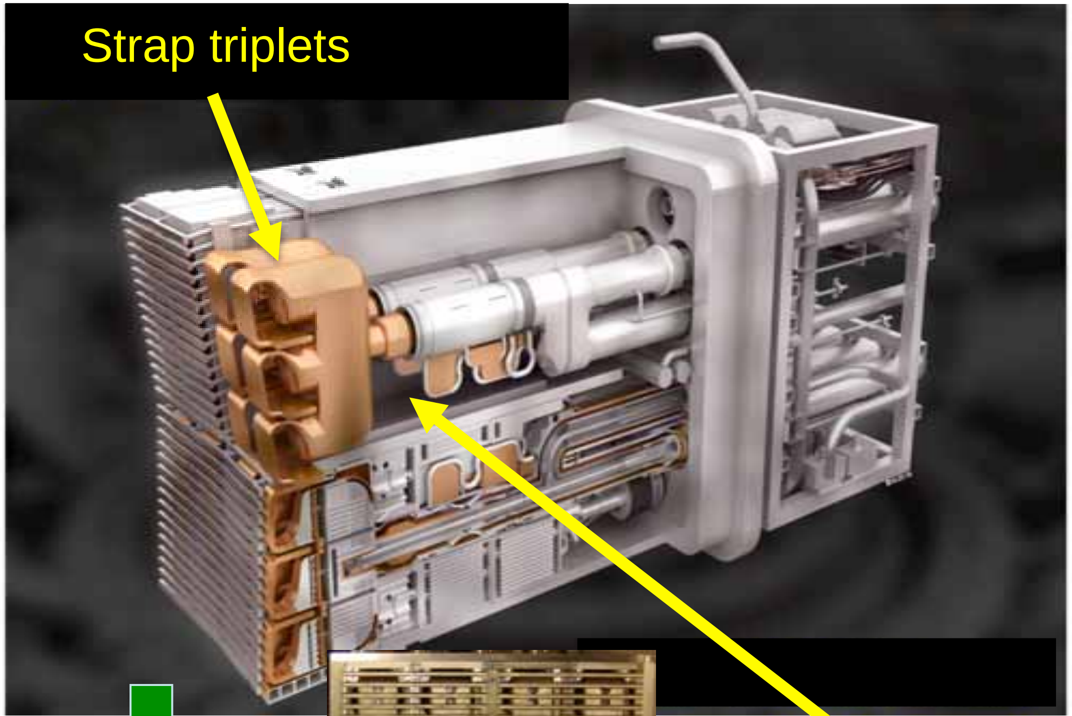
Demonstrated

- Continuous operation independent of large changes in edge density
- Easy frequency (re)-tuning with new algorithms
- High power density
  - up to 6.2MW m^{-2} achieved **(Sun: 60MW/m^2)**
- Operation at high voltages
  - up to 42kV achieved

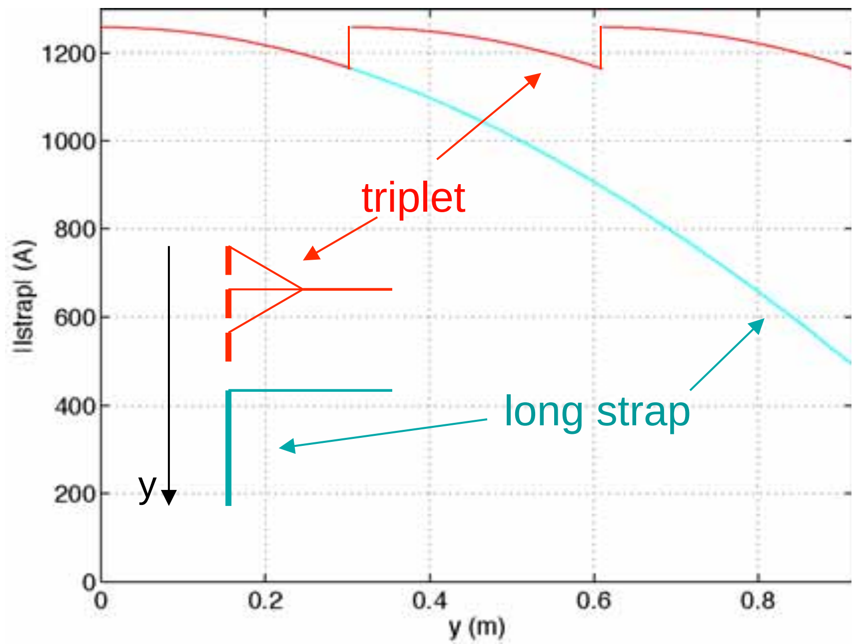
F.Durodié et al., "Physics and engineering results obtained with the ion cyclotron range of frequencies ITER-like antenna on JET", Plasma Phys. Contr. Fusion, 54, 074012 (2012)

ITER ICRF Antenna:
Compact high power density antenna with short straps

40-55 MHz, 20 MW, 10MW/m^2 (Sun: 60MW/m^2)

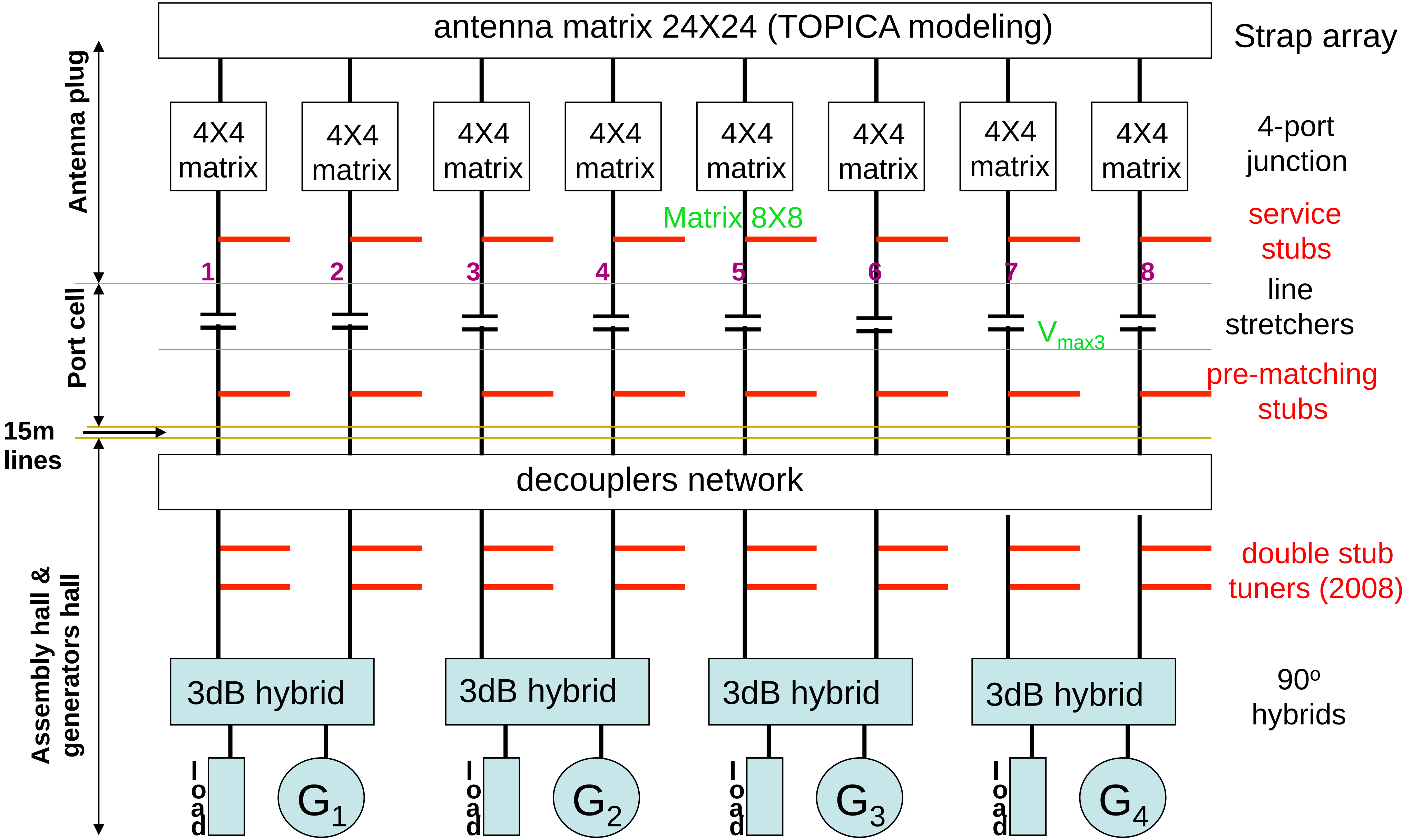


Short straps:
Much more current in front of the plasma



8 strap triplets fed in parallel by 4-port junction

Layout of the decoupling-matching system of ITER



ICRH for the European DEMO

- DEMO will need more ICRF power than ITER (70MW?)
- Depending on the number and size of ports:

  even higher power densities (> 10MW/m^2) expected
- Coupling could be more difficult (larger evanescent layer?)

  ➢ Higher voltages needed than in ITER, arcing problems ?

Proposed solution, avoiding these problems

Distributed Antenna =
Large strap array(s) in the first wall of DEMO

- Increased coupling
- Reduced power density per strap
- Reduced operating voltage

Why Travelling Wave Antenna (TWA) for fusion reactor?

Radiated Power of ICRH antenna in general:

$$P_{rad} = 0.5\, n_{str} G_{str} |V_{str}|^2$$

number of straps

strap voltage

G_{str} Strap surface conductance
(depends on density profile and strap phasing)

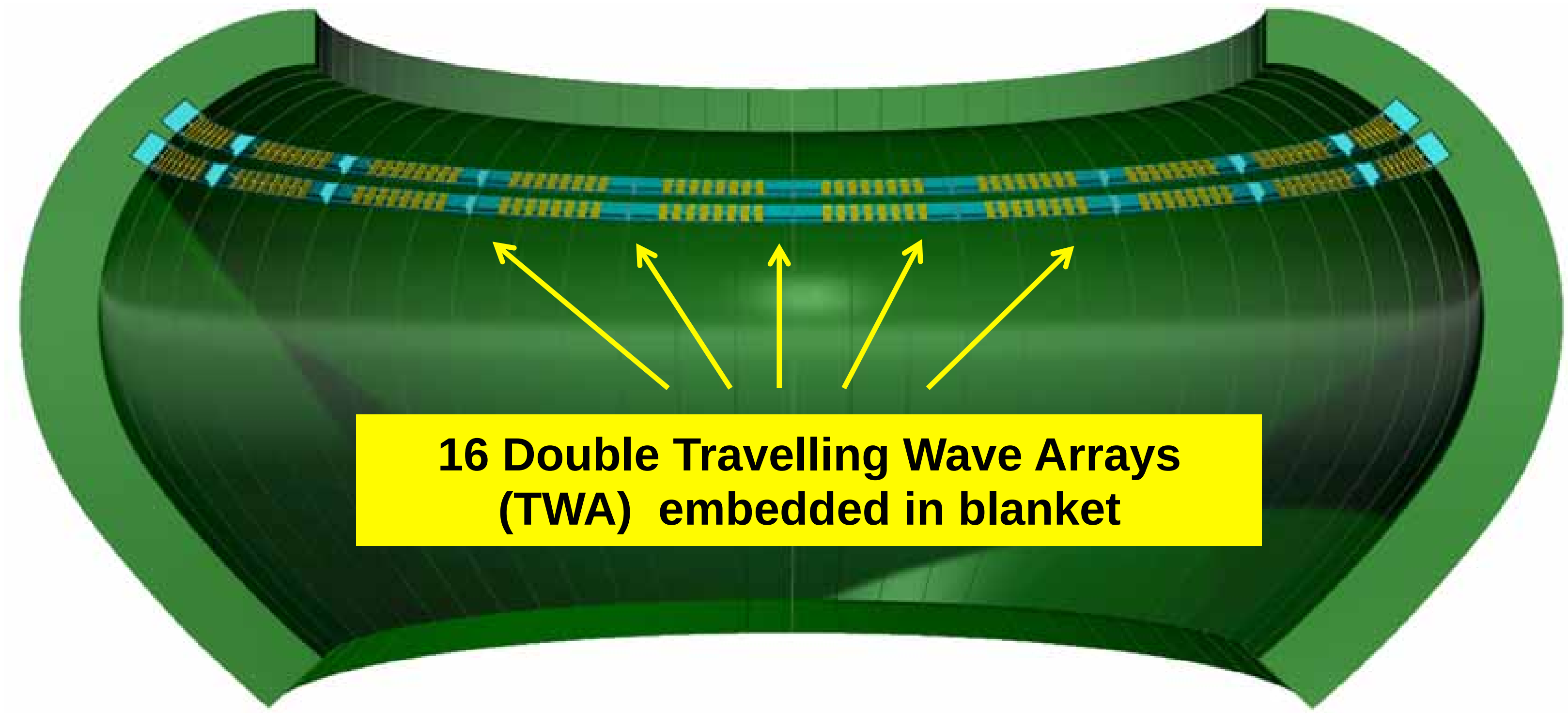
Travelling Wave Antenna – Main Idea
Strap Voltage↓ and Number of Straps↑ for given P_{rad}

Increased reliability

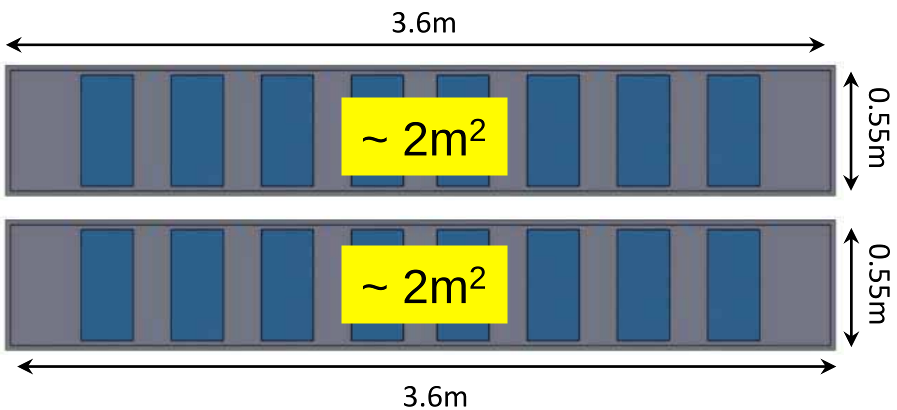
- Larger radiating surface
- Lower power density
- Lower operating voltage
- Increased reliability with sections: one defect, others continue

And: More RF power in plasma for same voltage at antenna
(see also next slides)

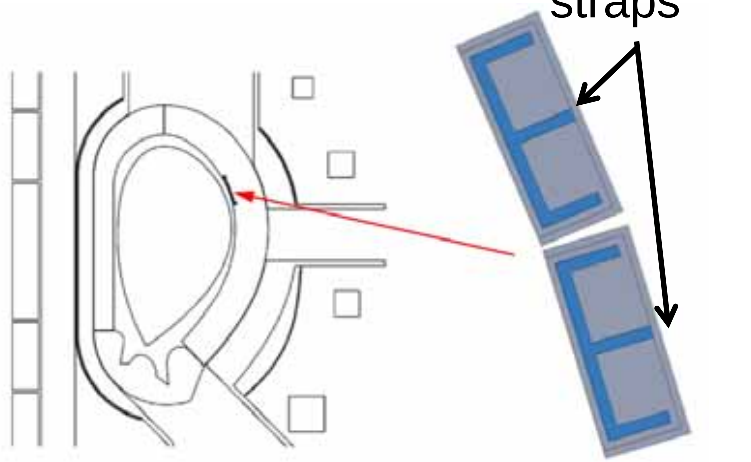
TWA Antenna: proposed ICRH design for EU-DEMO



Details of one section consisting of two superposed TWAs



Approx. 4m^2



Different feeding options considered for EU-DEMO

2 rings of 16 strap sections with each 8 straps
Total 256 straps

3 Possible options to feed all straps:

a) **16 Double TWAs fed by resonant rings**
b) **Feeding each strap individually**
c) **Distributed feeding of the ring**

Best solution: a) feeding by resonant rings

- Lowest VSWR=1 in lines
- Smallest feeder diameters
  (no standing waves)
- Feeders total cross sectional area: 0.5 m^2

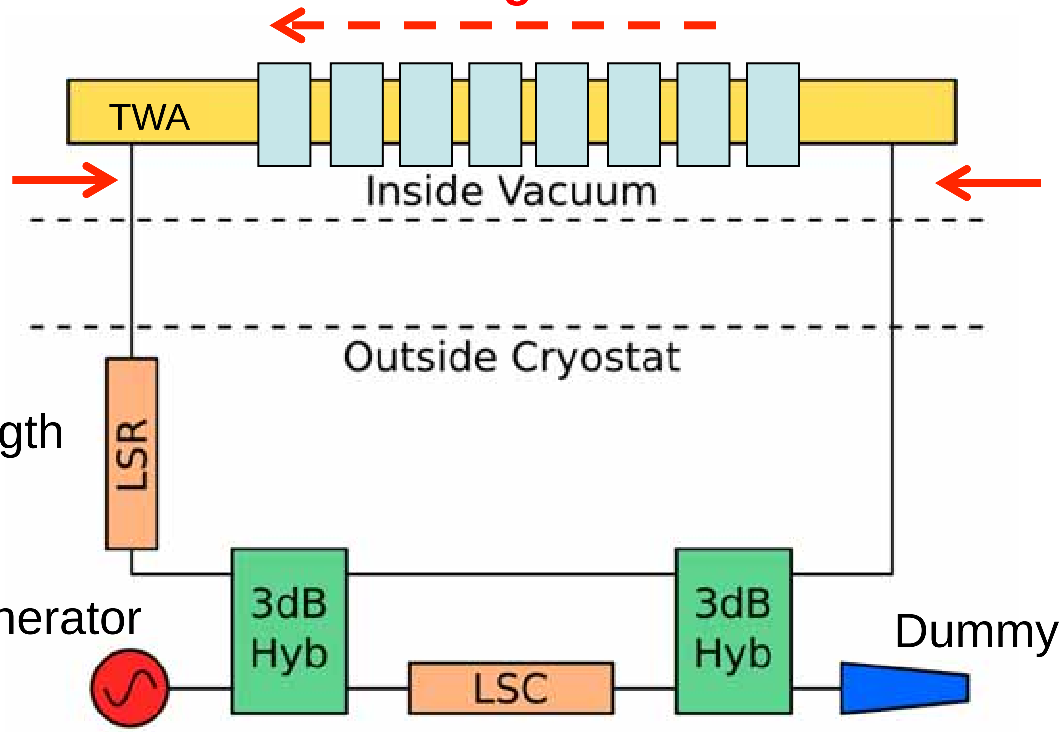
Resonant ring to feed of each TWA section

Only 2 feeding lines for large number of straps

Travelling Wave

Power Output line

Power Input line



Line Stretcher 1
Adjust equivalent length of ring to multiple of RF wavelength

Generator

Dummy load

Line Stretcher 2
Adjust to minimize losses in Dummy Load

Advantages:

- Simple to use: **adjustment by 2 line-stretchers only** (outside machine!)
- TWA section terminated on its characteristic impedance (➛ VSWR=1!)
- No complex matching/decoupling network needed
- Allows recirculation of non-radiated power.

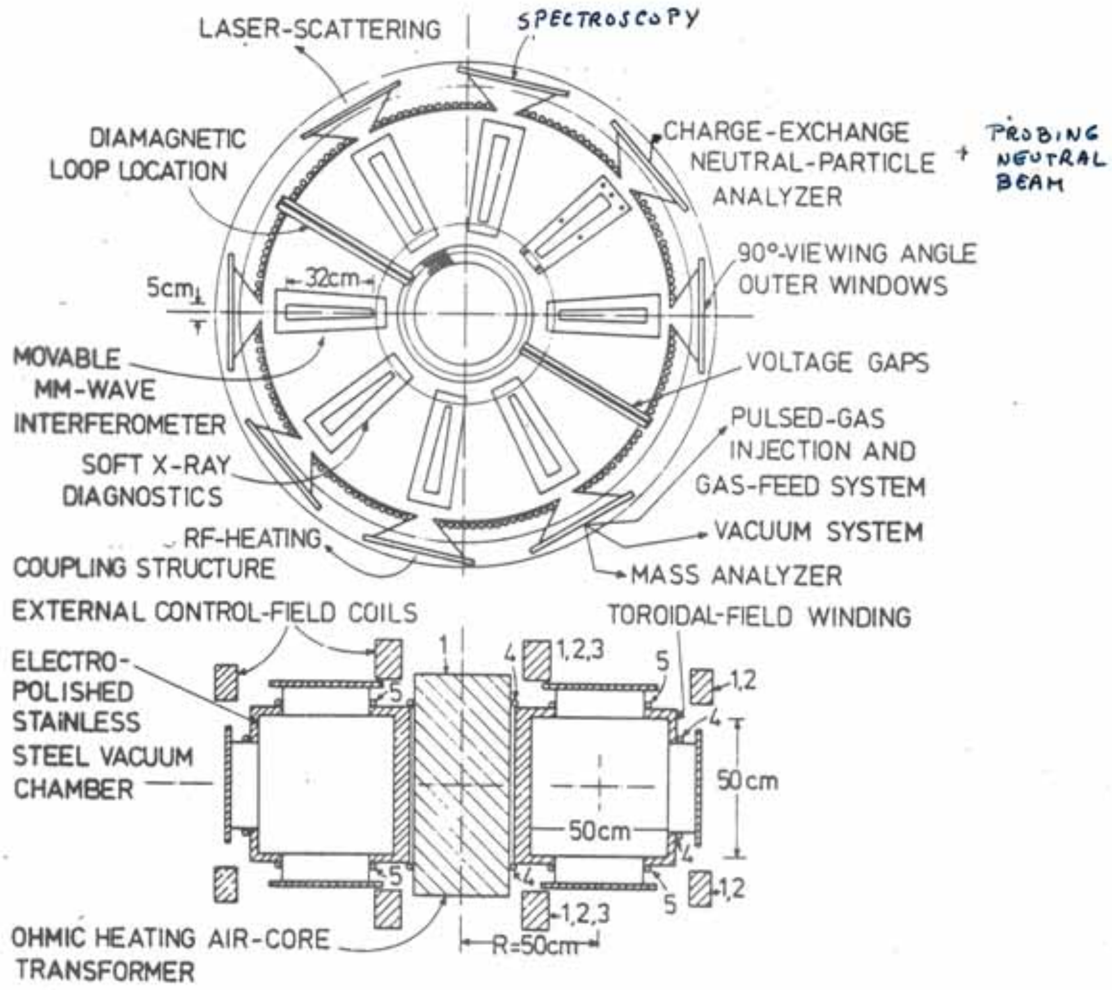
Advantages of the proposed TWA system

- Low power density at the antenna structure
- Highly selective $k_{//}$ (to optimize coupling / absorption)
  ➢ ideal for current drive studies
- Load resilience: no trouble with ELMs, pellets, MHD,..
- No need for matching network/decouplers (≠ ITER)
- Increased reliability by working in sections
- Flexibility for poloidal positioning: not blocking ports

Proof-of-principle needed: T-15MD is ideal testbed

Early ICRH experiments on the ERASMUS tokamak in Brussels and ICRH on TEXTOR

ERASMUS tokamak in Brussels (1976-1983)



a = 0.25m

R= 0.50m

I_p = 50 kA

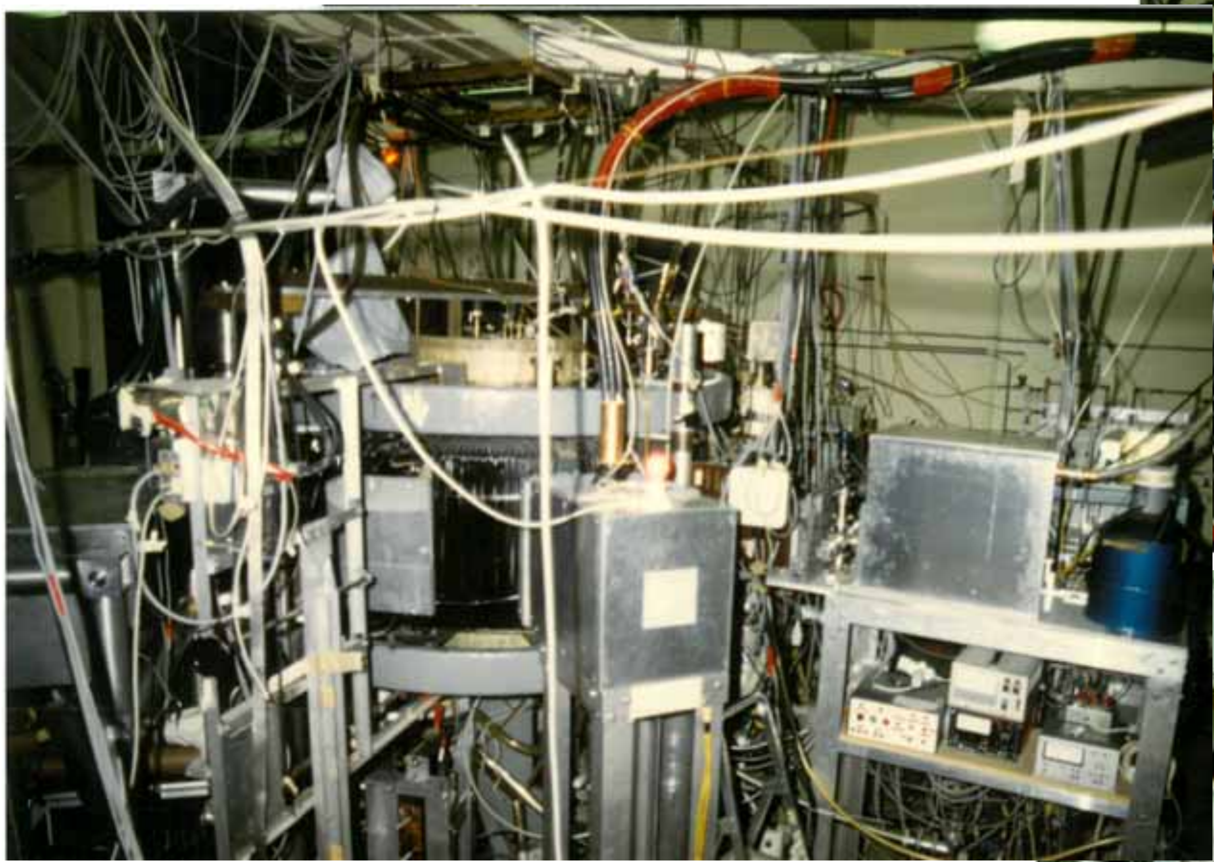
B_t = 0.4T

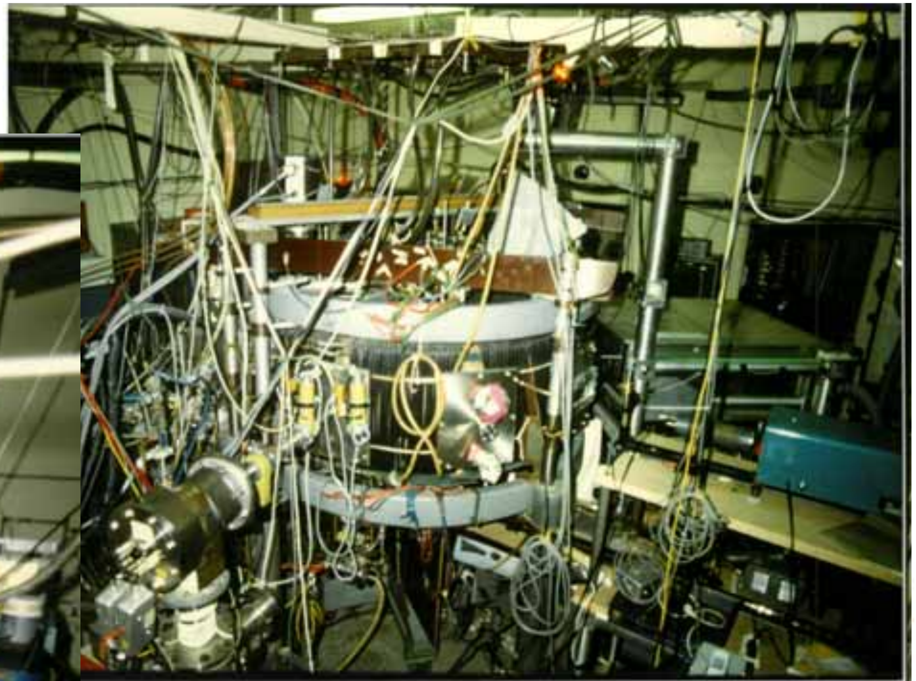
Volume = 0.785m^3

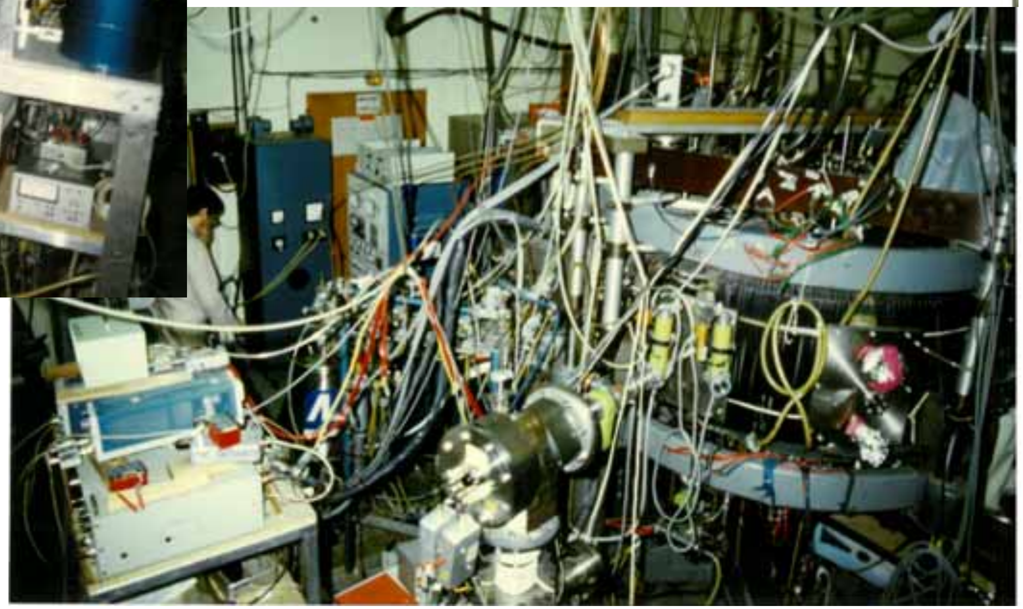
RF Power density:

~ max 650kW/m^3

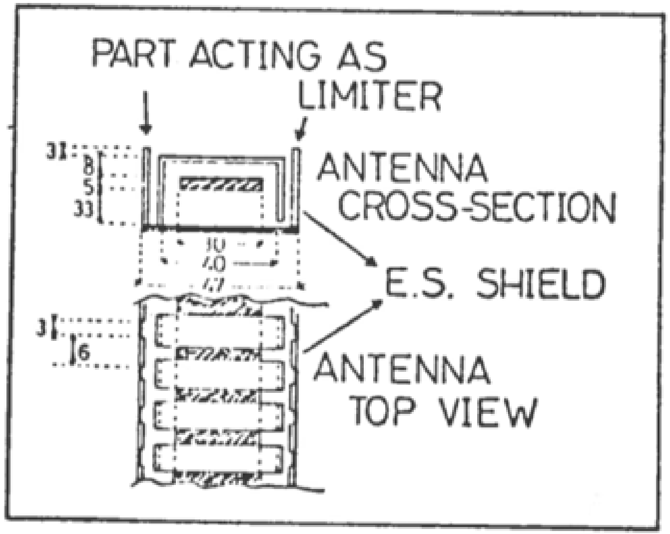
ERASMUS tokamak in Brussels (1976-1983)



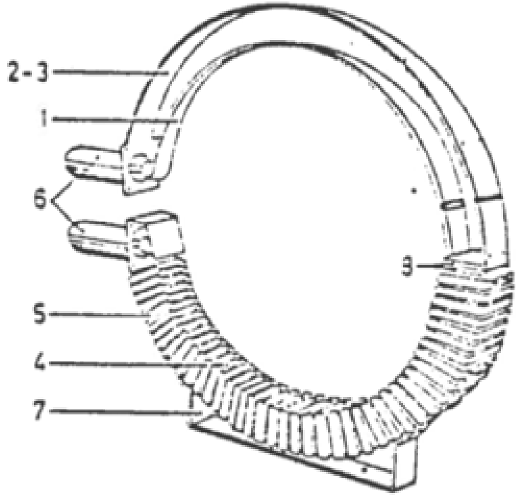




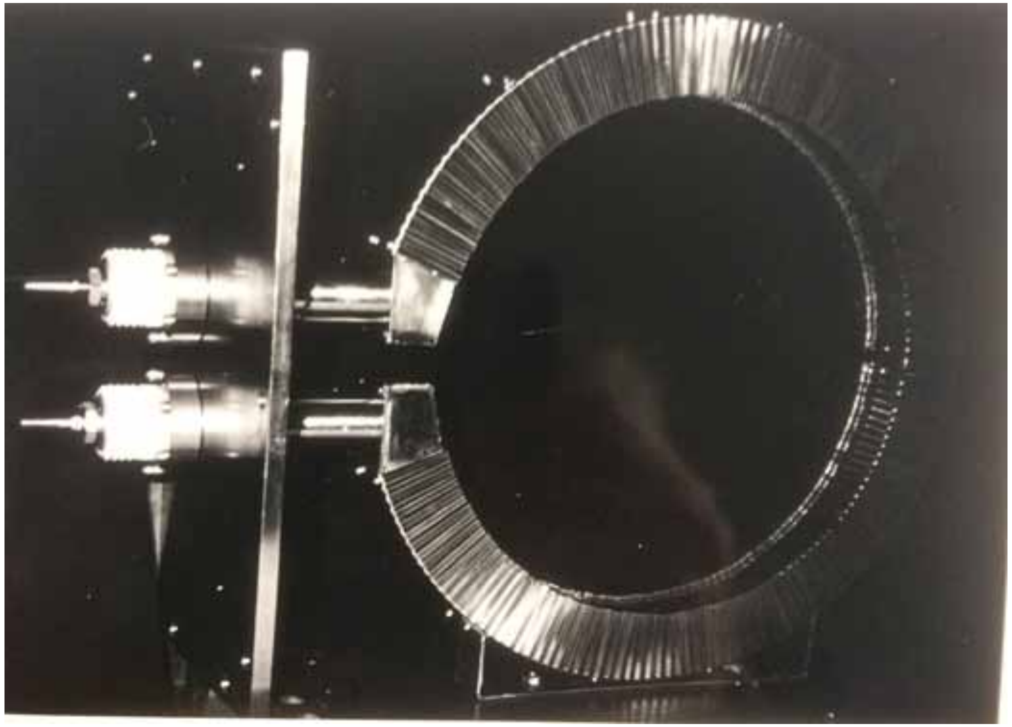
ERASMUS ICRH Antenna



Antenna dimensions in mm

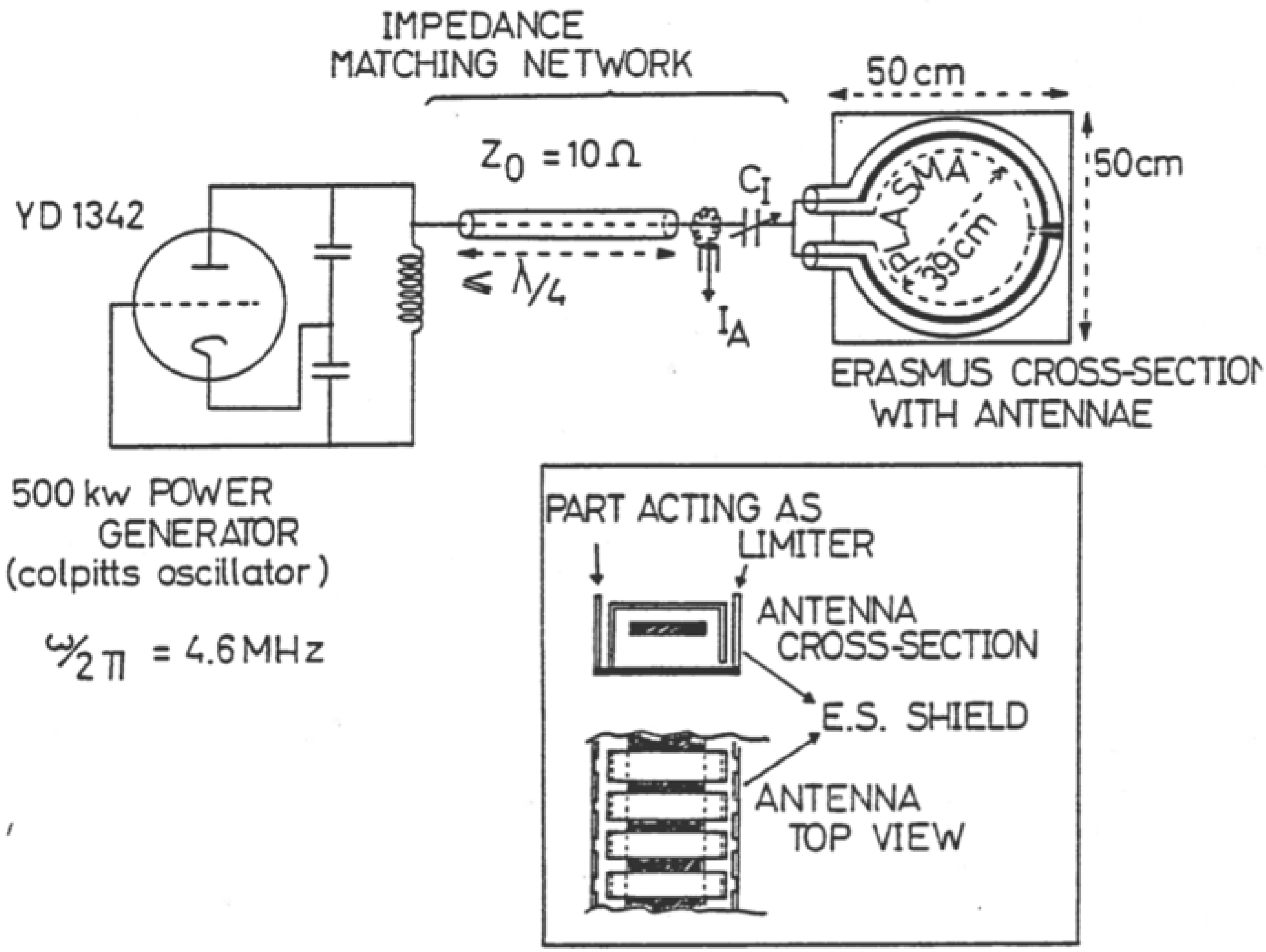


ERASMUS Antenna schematic



1 Central Conductor
2 Return conductor
3 & 7 Steel mechanical structure
4 & 5 Element of the Faraday Screen
6 Coaxial Feeders
8 Short circuits

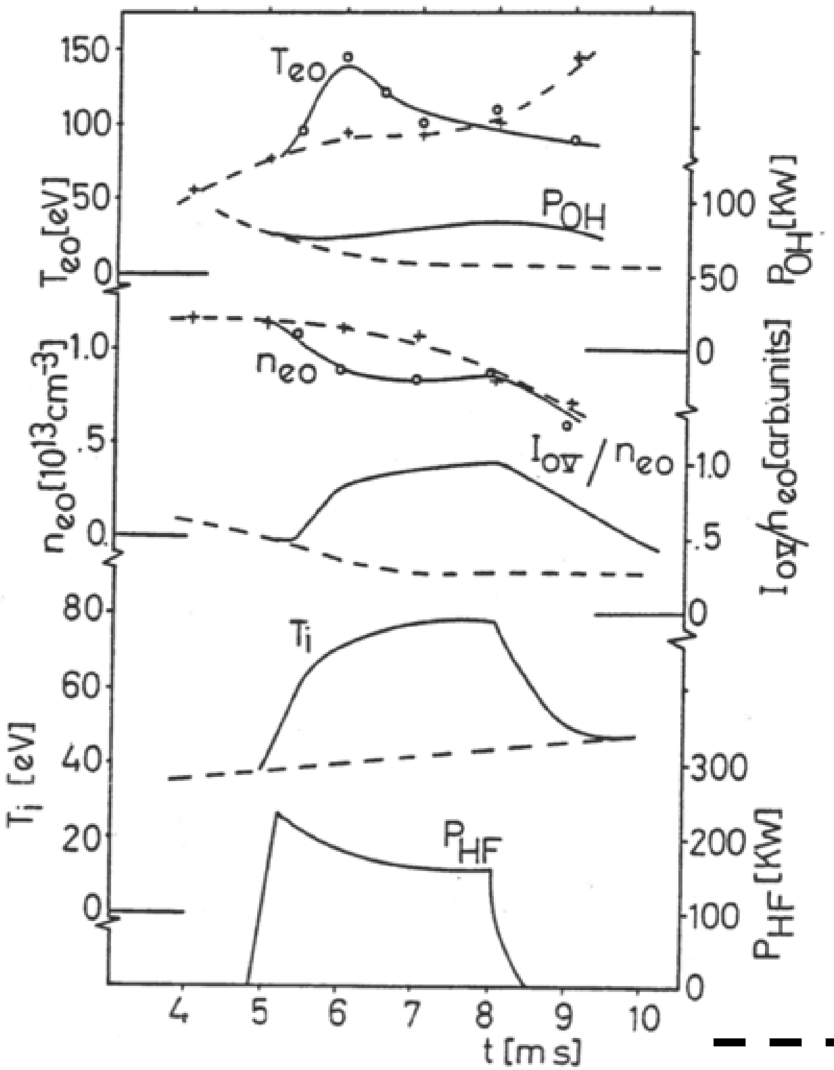
ERASMUS ICRH System Schematic



Up to 200 kW of RF Power coupled to the plasma; $P_{RF}/P_{ohmic} \sim 4$

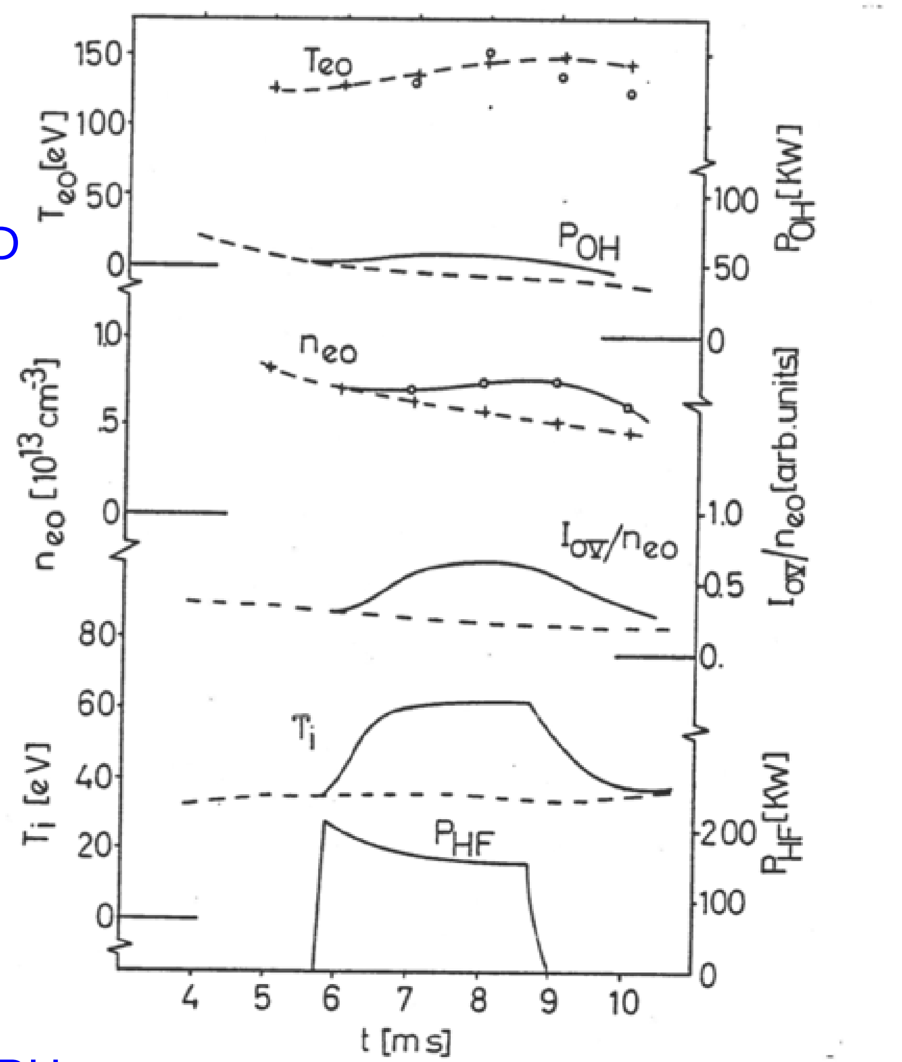
ERASMUS ICRH Typical Results

Non-gettered discharge



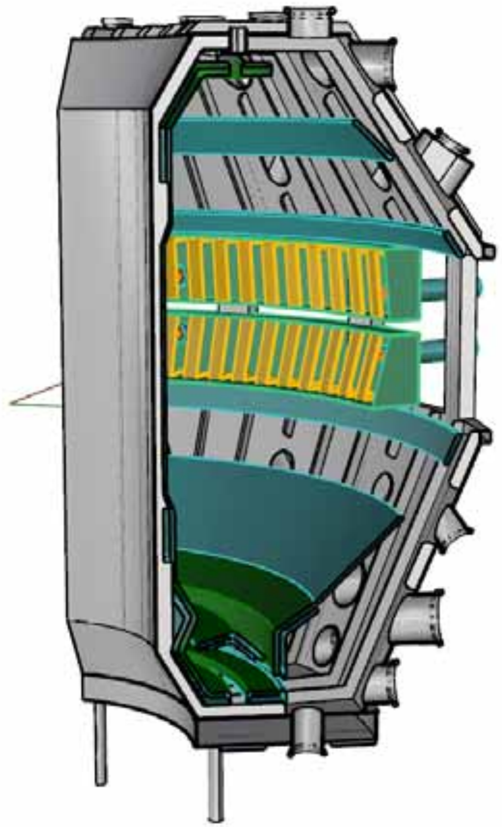
I_p = 25 kA
B_t = 0.36 T
f = 4.6MHz
P_{RF}= 170kW
25%H, 75%D

Gettered discharge



Without
With
ICRH

Collaboration on MEPhISTO and T15-MD



ERASMUS ICRH Typical Results

ERASMUS as a prototype for MEPhISTO

All documentation is available

Presented at the 11 th SOFT sym

A HALF MEGAWATT RF SYSTEM FOR ION-CYCLOTRON HEATING OF THE ERASMUS TOKAMAK

A.M. MESSIAEN[*], G. BOSIA[++], V.P. BHATNAGAR, R.R. WEYNANTS[+++]

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Association "Euratom-Etat belge" - Associatie "Euratom-Belgische Staat"
Ecole Royale Militaire - B 1040 Brussels - Koninklijke Militaire School

ABSTRACT

We discuss the design and oper:
system for ion-cyclotron resonance heating
experiments. It consists of a power Colpitt
a pulsed power output that exceeds half a m
strip line antenna system and a matching ne
successfully operated for ICRH studies on t
easily upgraded to an economic MJ-Unit.

INTERNATIONAL ATOMIC ENERGY AGENCY 134

8th INTERNATIONAL CONFERENCE ON PLASMA PHYSI
AND CONTROLLED NUCLEAR FUSION RESEARCH

Brussels, 1–10 July 1980

IAEA-CN-3:

ION CYCLOTRON RESONANCE HEATING IN THE
ERASMUS TOKAMAK AT POWER LEVELS EXCEEDING THAT OF
OHMIC HEATING.

V.P. Bhatnagar, G. Bosia, E. Desoppere, P. D'Hondt,
R. Koch, A.M. Messiaen, J.M. Noterdaeme, D. Pearson,
G. Poulaert, R.M. Prates-Drozak, G. Telesca,
P.E. Vandenplas, G. Van Oost, G. Van Wassenhove,
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Militaire - 1040 Brussels - Koninklijke Militaire School

BASIC CONSIDERATIONS IN THE ION-CYCLOTR(
RESONANCE HEATING OF THE
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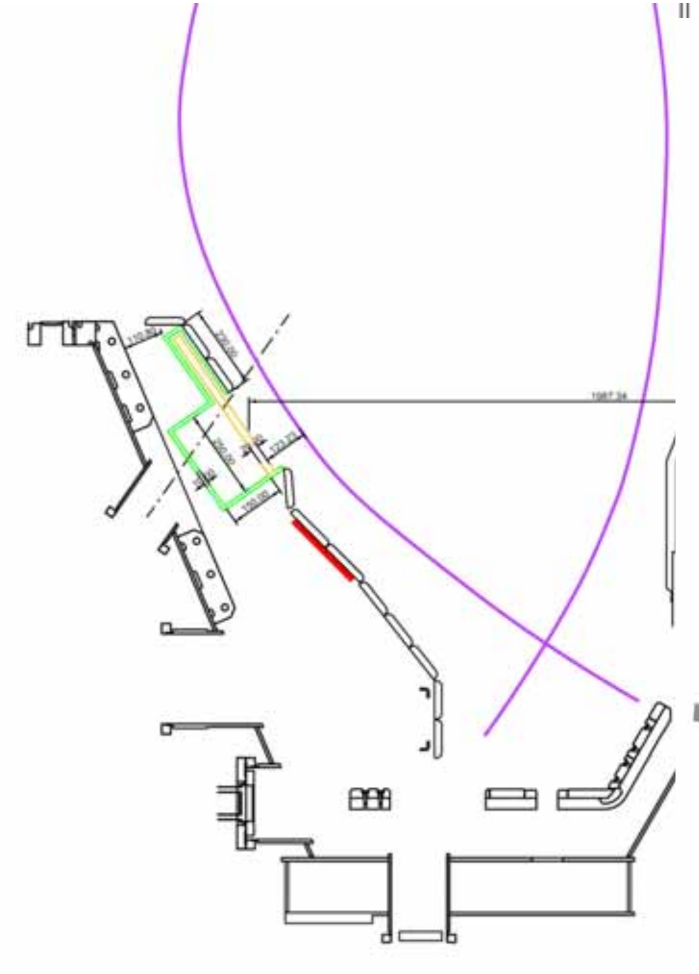
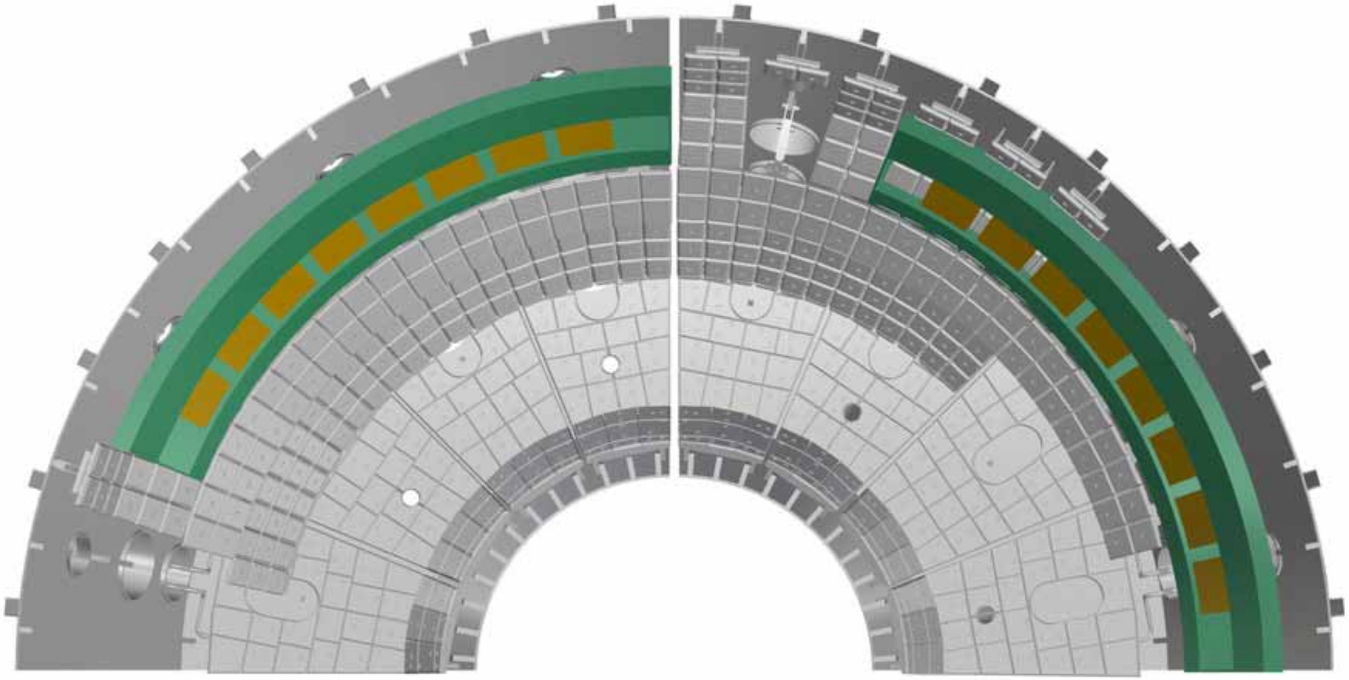
Laboratory Report No. 64
June 1977

Proposal for TWA in T15-МД: inside view





Proposal for MEPhISTO

-- Use the system on ERASMUS as an example for MEPhISTO

-- Technical detailed plans are available

-- Could provide ~ 500 kW power, freq ~ 5 MHz
NOTE: Heating power density is much higher than in DEMO

-- Allows to study minority heating, 2nd harmonic heating,
3 ion heating scheme

-- Important contribution to steady-state operation

-- Opens new physics studies: fast particle and Alfven Eigenmodes

-- Important step to build the ICRH team for T-15MD