EUROfusion

Fast-ion generation with ICRF at Wendelstein 7-X in high-density regimes

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[3] V. Borsuk, O. Neubauer, G. Offermans; [4] R. Dumont

LPP ERM - KMS

IPP Max-Planck-Institut für Plasmaphysik

JÜLICH FORSCHUNGSZENTRUM

cea CADARACHE

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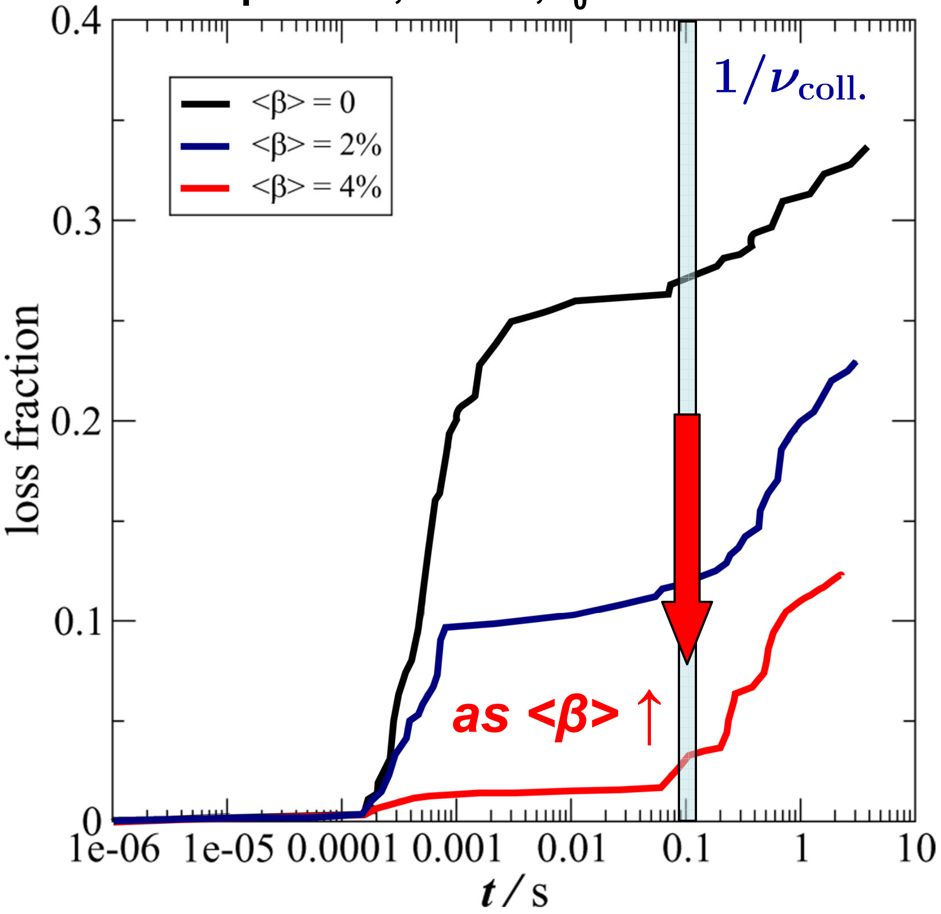
Experimental aim: prove good fast-ion confinement



M. Drevlak, NF2014:
protons, 60keV, r_0/a = 0.06

- Stellarator-reactor must be designed to provide confinement of fusion-born α's

– provide sufficient self-heating of the plasma
– avoid damage to device components

- $\rho_L/a \propto \dfrac{(mE)^{1/2}}{ZBa} = \text{const}$

HELIAS: α-particles (3.5 MeV)
W7-X: protons (60 keV), ^{3}He (80 keV)

- Fast ion sources for W7-X:

– NBI (55 keV) (see e.g. D. Gradic, NF2015)
– ICRH

The main goal of ICRH in W7-X: source of fast ions (~ 50–100 keV),
at very high plasma density $n_{e0} \approx 2\times10^{20}$ m^{-3}
(* also good in view of impurity control, HDH-mode)

Outline

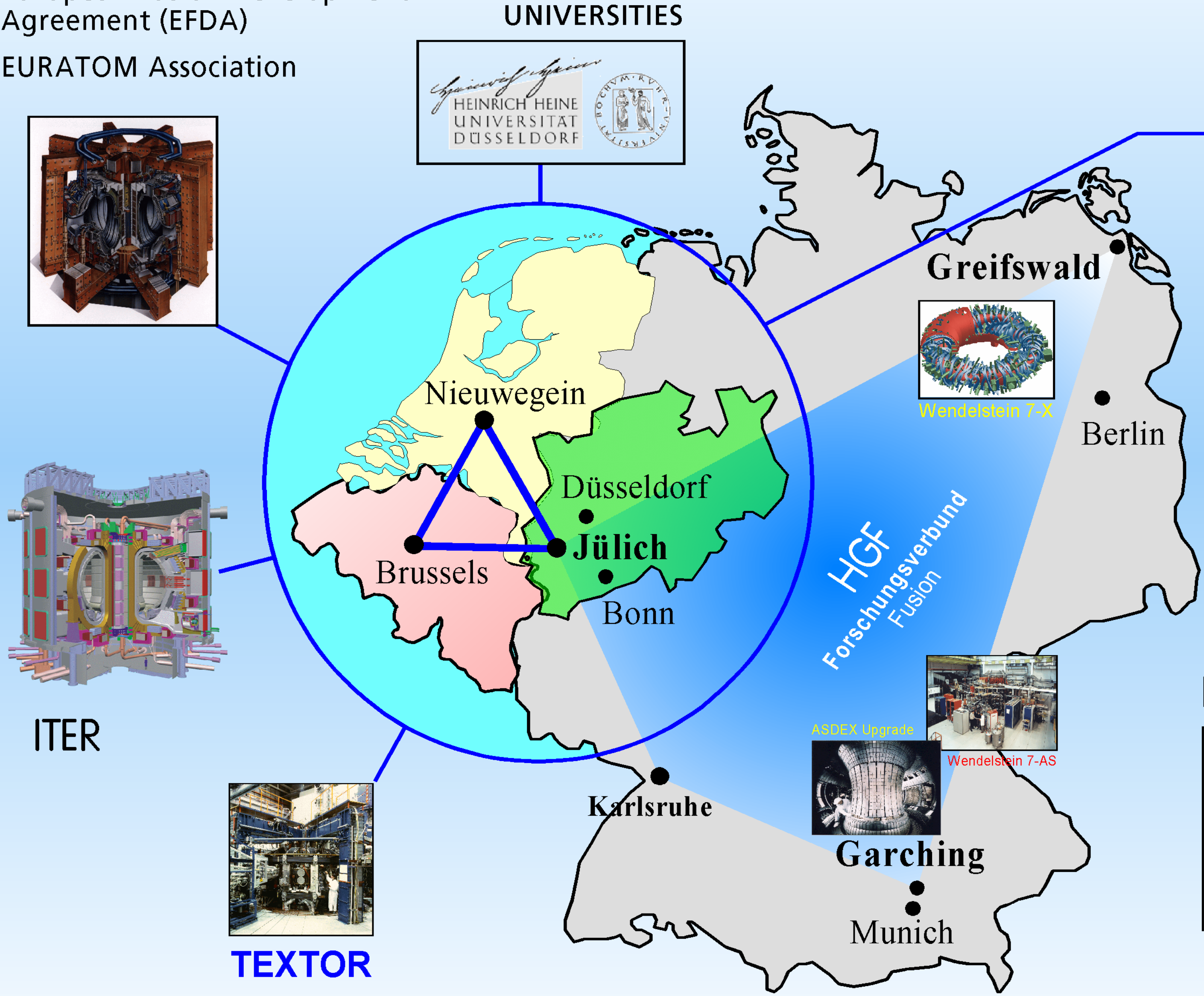
- **Short overview of the ICRF system design**
- **ICRH scenarios for W7-X**
- **Three-ion (^{3}He)-D-H ICRF heating:**
  fast-ion generation at the largest plasma densities on W7-X
- **Summary and conclusions**

Collaboration between Trilateral Euregio Cluster (TEC) and Max-Planck Institut Greifswald

JET: Joint European Torus

European Fusion Development Agreement (EFDA)

EURATOM Association



Trilateral Euregio Cluster

Research Centre Jülich
Institute for Plasmaphysics

Ecole Royale Militaire /
Koninklijke Militaire School
Brüssel / Belgien

DIFFER - Dutch Institute for
Fundamental Energy Research
The Netherlands

IEA Implementing Agreement

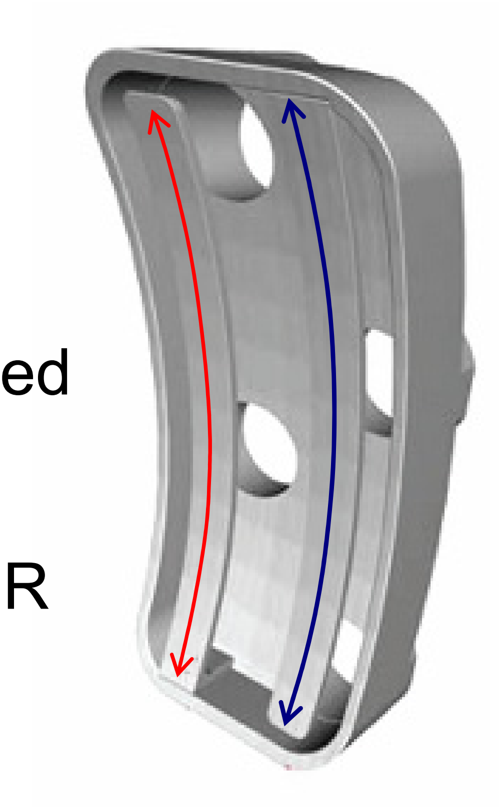
- Japan
- Kanada
- USA
- Research Centre Jülich

The dedicated ICRH antenna for W7-X

- TEC is designing a dedicated ICRH antenna for fast-ion generation in W7-X

- A two-strap antenna will be installed

  → different toroidal antenna phasings can be used e.g. (0;*π/2*), (0;*π*), (0;0), (0;*π/4*)



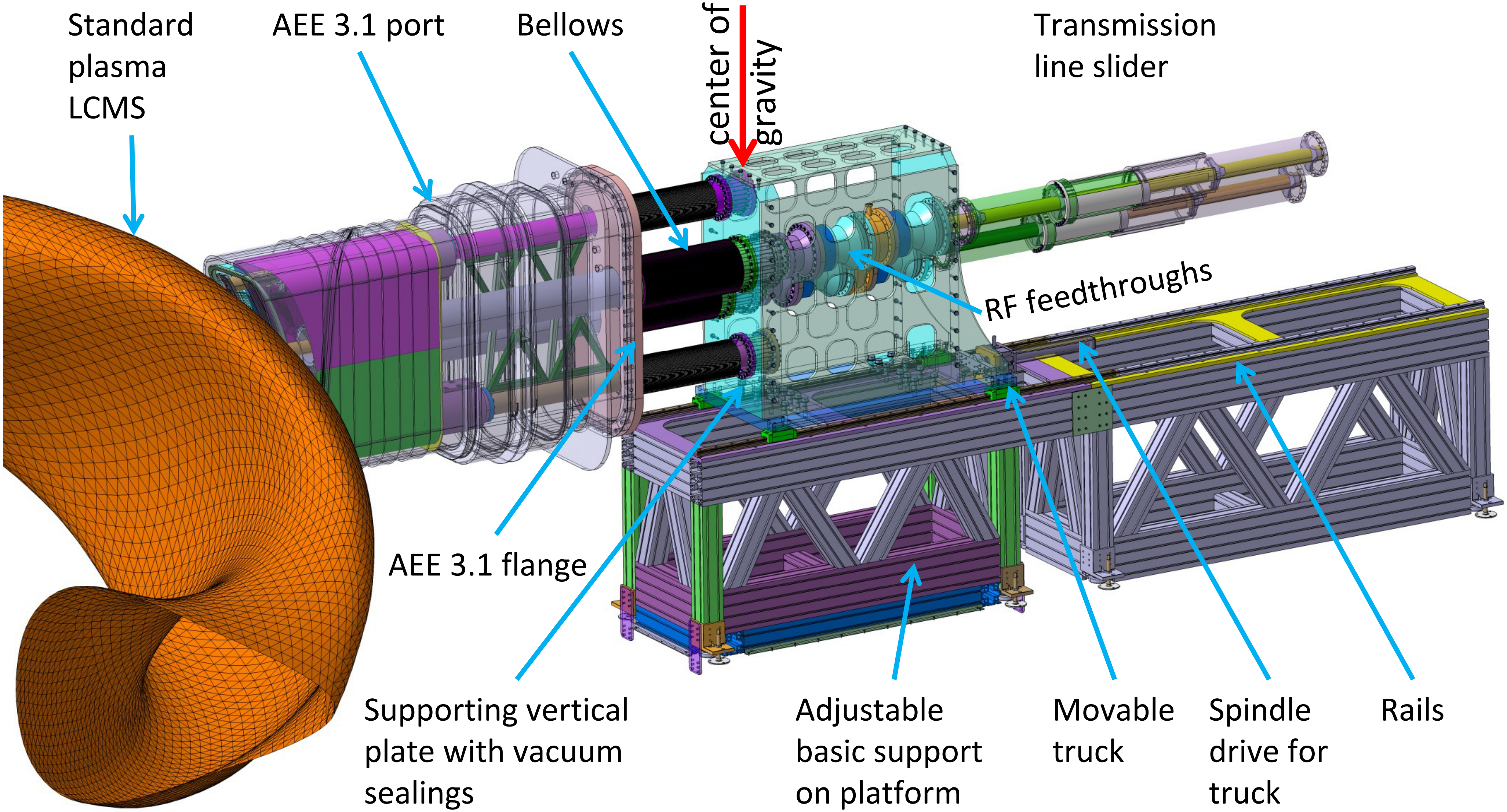
- Using the RF equipment and hardware of TEXTOR (frequency range, *f* = 25–38MHz)

- ICRH coupled power: 1–2 MW for 10s

  (with current assumptions for positioning of launcher and density profile in front of the antenna)

- More details: J. Ongena et al., *Phys. Plasmas* 21, 061514 (2014)

Design overview of the ICRF antenna



Standard plasma LCMS

AEE 3.1 port

Bellows

center of gravity

Transmission line slider

RF feedthroughs

AEE 3.1 flange

Supporting vertical plate with vacuum sealings

Adjustable basic support on platform

Movable truck

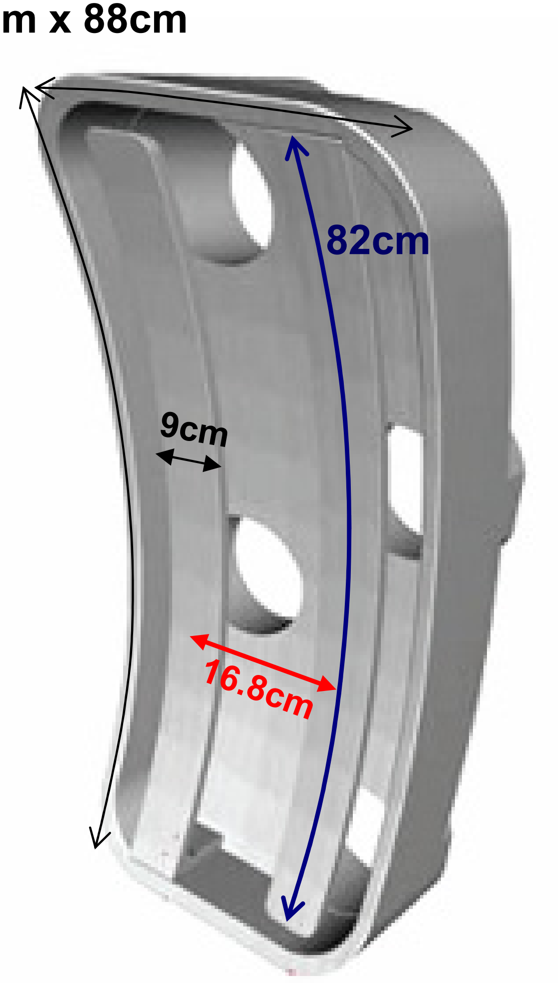
Spindle drive for truck

Rails

J. Ongena et al., *Phys. Plasmas* 21, 061514 (2014)

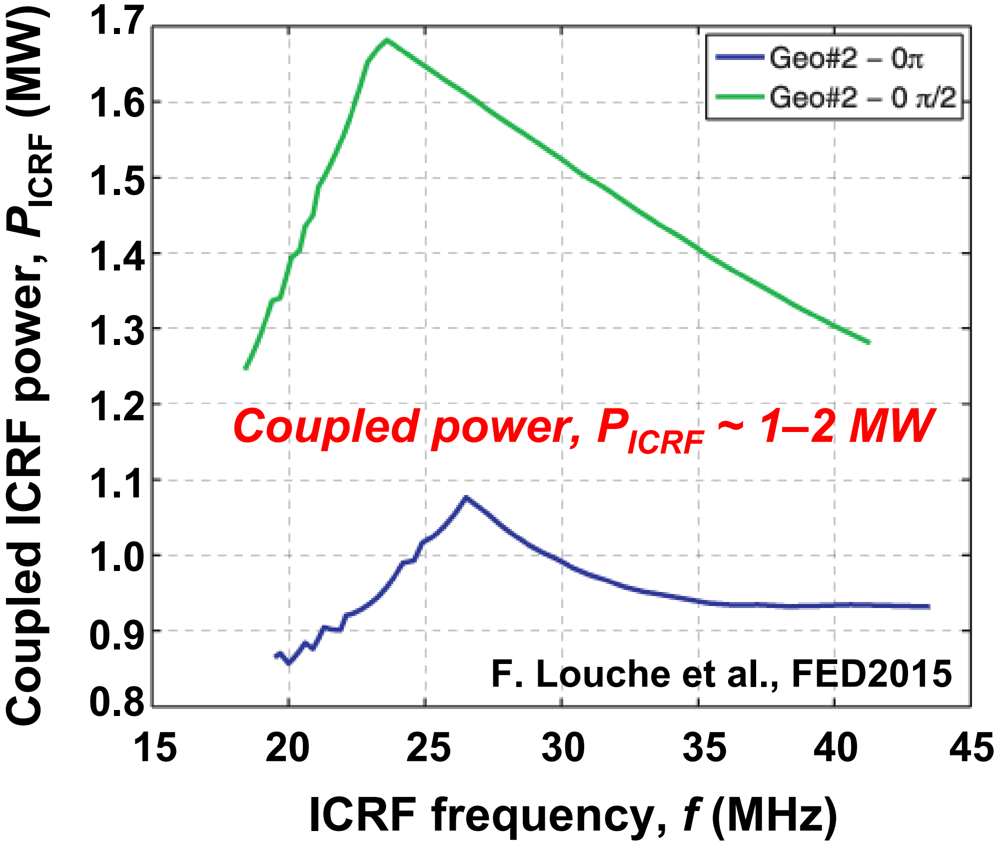
Optimization of ICRF antenna design

Antenna box:
34cm x 88cm



Antenna surface (3D) is designed to mimic LCFS for the standard configuration of W7-X

- **Antenna geometry has been maximized to maximize coupled power (see F. Louche FED2015, e.g. increasing the strap width, 6.8cm → 9cm)**



Coupled power, P_{ICRF} ~ 1–2 MW

- **Short overview of the ICRF system design**
- **ICRH scenarios for W7-X**
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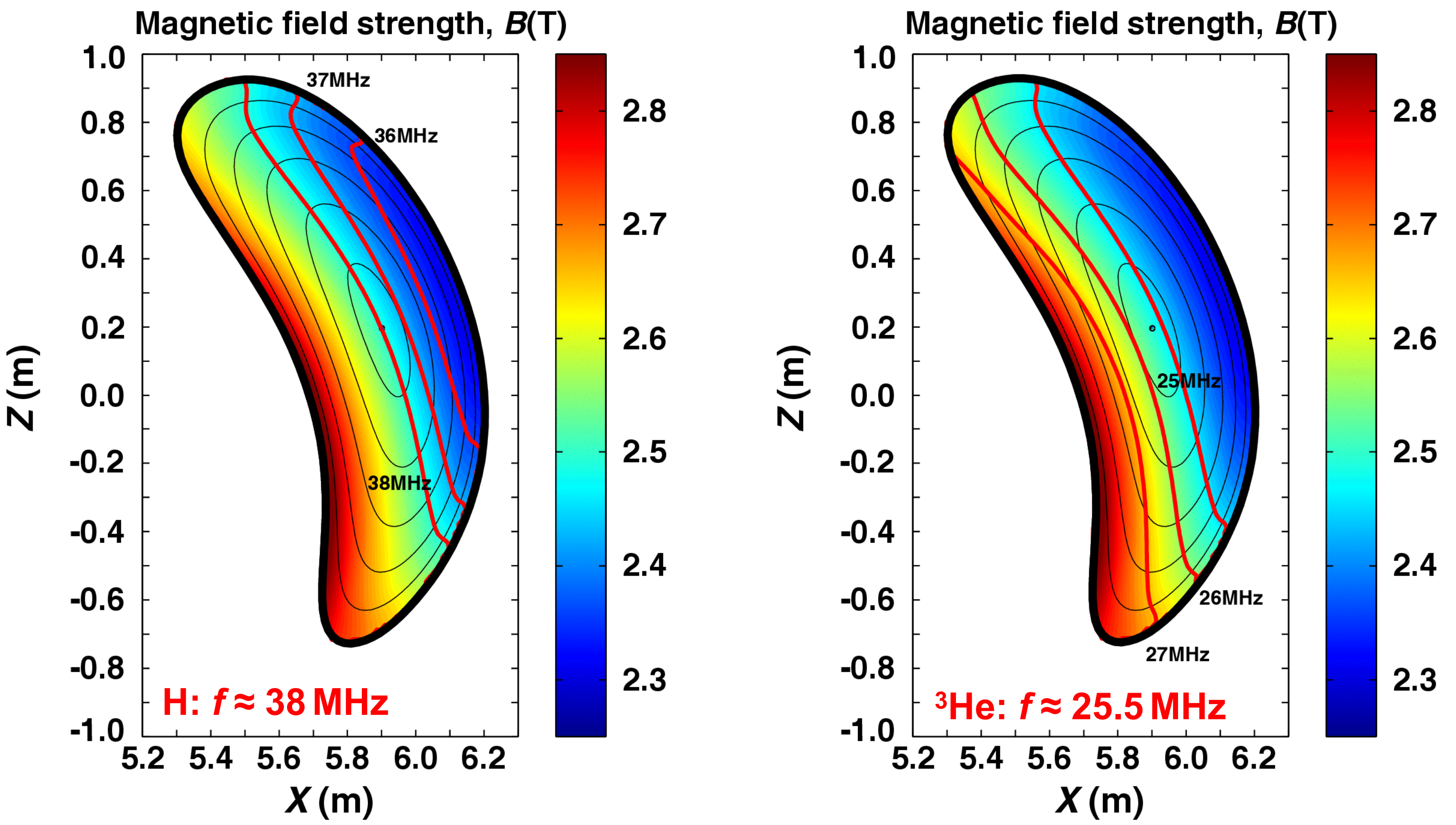
ICRF minority heating: H and ^{3}He resonant ions

$B_0 \approx 2.5$T (ECRH 140GHz), TEXTOR RF generators: f = 25–38 MHz

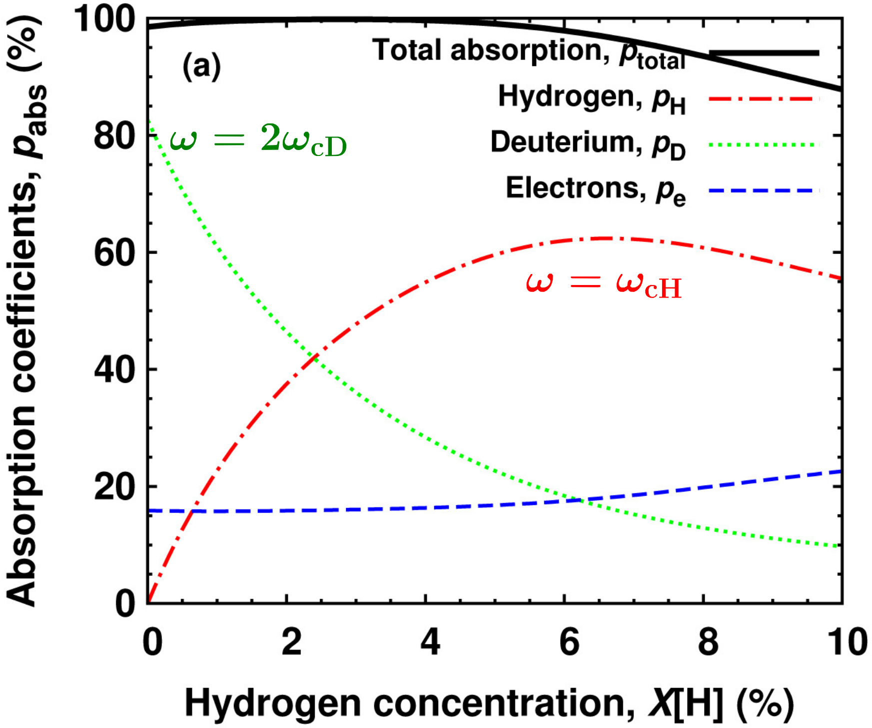


- **ICRF minority heating ($\omega = \omega_{ci}$): a) H ions at $f \approx 38$ MHz, b) ^{3}He ions at $f \approx 25$ MHz**
- **ICRF second harmonic ($\omega = 2\omega_{ci}$): D and ^{4}He ions at $f \approx 38$ MHz ($\omega_{cH} = 2\omega_{cD}$)**

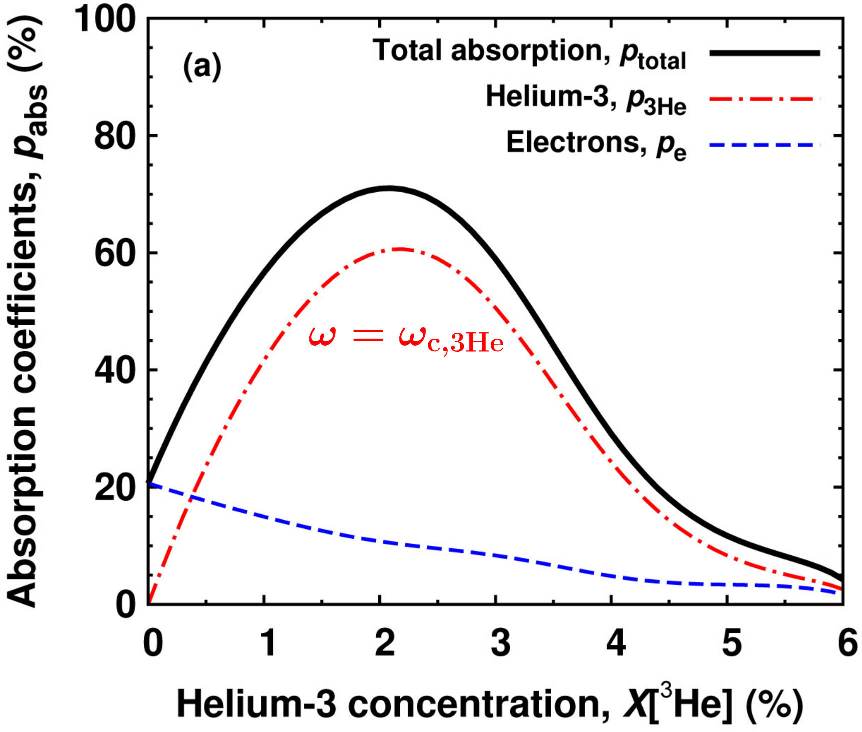
ICRF scenarios: (H)D and (^{3}He)H heating

Single-pass absorption from 1D-TOMCAT code, $n_{e0} = 2\times10^{20}$ m^{-3}

(H) in D at 38 MHz



(^{3}He) in H at 25 MHz

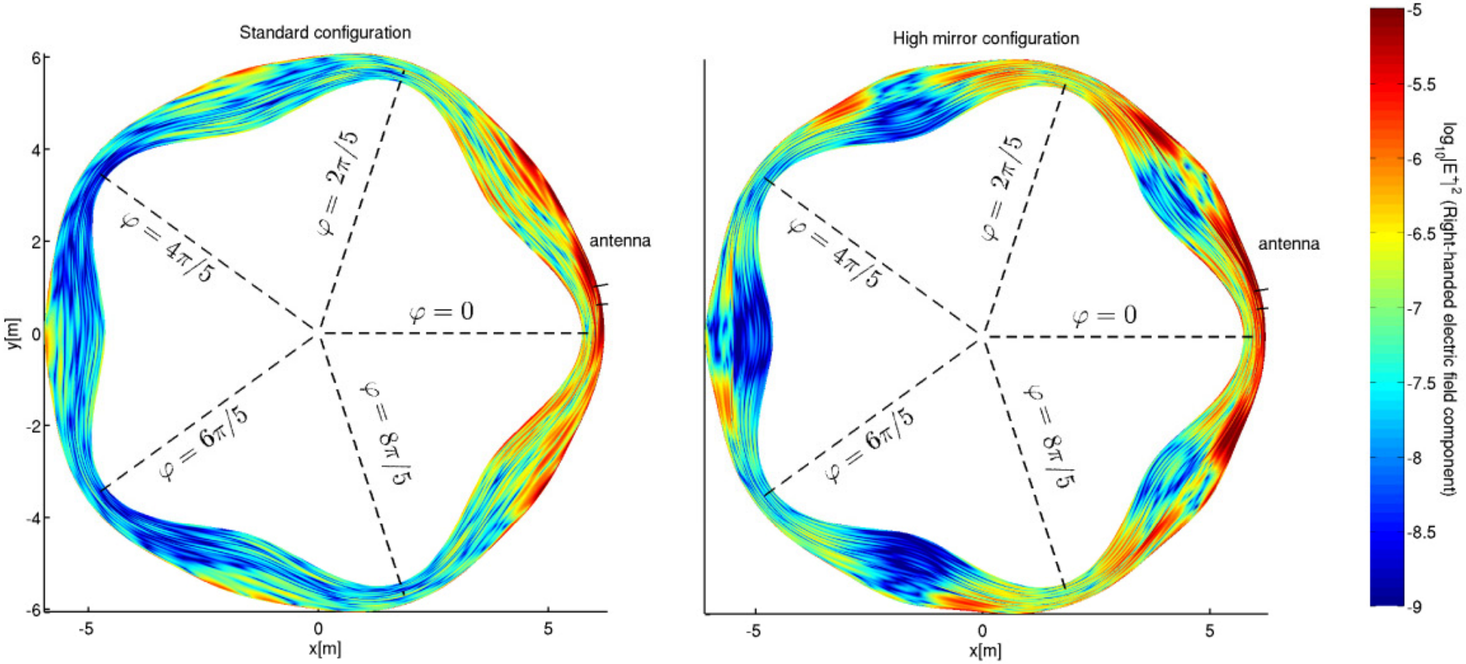


A concentration of minority ions (H or ^{3}He) of a few percent is required

Ye.O. Kazakov et al., *AIP Conf. Proc. 1580, 342-345 (2014)*

Hydrogen minority heating in W7-X (SCENIC, EPFL)

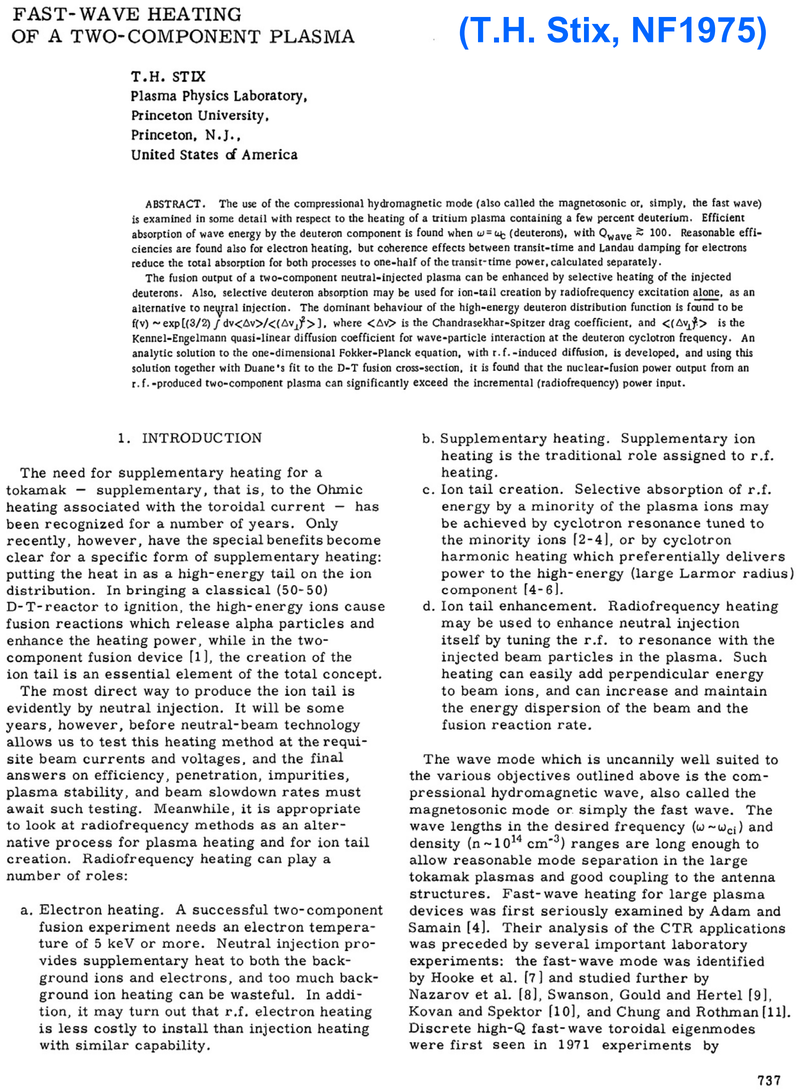
1% of H, n_{e0} = 8x10^{19} m^{-3}, T_0 = 3 keV, P_{ICRH} = 1.5 MW



- **The five-fold periodicity is broken due to the antenna localisation**
- Equilibrium geometry imposes 3D dependency on the resonant layers, i.e. where the wave transfers energy to the particles.
- Wave damping appears in the toroidal direction and is more important for the standard configuration, for which no resonance-free region exists.

J. Faustin et al., "Applications of the SCENIC code package to minority ICRH in Wendelstein 7-X plasmas", WPS2 Kick-off meeting, 20 May 2015

Theory of fast-ion generation with minority ICRF



(T.H. Stix, NF1975)

FAST-WAVE HEATING OF A TWO-COMPONENT PLASMA

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ABSTRACT. The use of the compressional hydromagnetic mode (also called the magnetosonic or, simply, the fast wave) is examined in some detail with respect to the heating of a tritium plasma containing a few percent deuterium. Efficient absorption of wave energy by the deuteron component is found when $\omega = \omega_c$ (deuterons), with $Q_{wave} \gtrsim 100$. Reasonable efficiencies are found also for electron heating, but coherence effects between transit-time and Landau damping for electrons reduce the total absorption for both processes to one-half of the transit-time power, calculated separately.

The fusion output of a two-component neutral-injected plasma can be enhanced by selective heating of the injected deuterons. Also, selective deuteron absorption may be used for ion-tail creation by radiofrequency excitation alone, as an alternative to neutral injection. The dominant behaviour of the high-energy deuteron distribution function is found to be $f(v) \sim \exp[(3/2) \int^v dv \langle \Delta v \rangle / \langle (\Delta v_\perp)^2 \rangle]$, where $\langle \Delta v \rangle$ is the Chandrasekhar-Spitzer drag coefficient, and $\langle (\Delta v_\perp)^2 \rangle$ is the Kennel-Engelmann quasi-linear diffusion coefficient for wave-particle interaction at the deuteron cyclotron frequency. An analytic solution to the one-dimensional Fokker-Planck equation, with r.f.-induced diffusion, is developed, and using this solution together with Duane's fit to the D-T fusion cross-section, it is found that the nuclear-fusion power output from an r.f.-produced two-component plasma can significantly exceed the incremental (radiofrequency) power input.

1. INTRODUCTION

The need for supplementary heating for a tokamak — supplementary, that is, to the Ohmic heating associated with the toroidal current — has been recognized for a number of years. Only recently, however, have the special benefits become clear for a specific form of supplementary heating: putting the heat in as a high-energy tail on the ion distribution. In bringing a classical (50-50) D-T-reactor to ignition, the high-energy ions cause fusion reactions which release alpha particles and enhance the heating power, while in the two-component fusion device [1], the creation of the ion tail is an essential element of the total concept.

The most direct way to produce the ion tail is evidently by neutral injection. It will be some years, however, before neutral-beam technology allows us to test this heating method at the requisite beam currents and voltages, and the final answers on efficiency, penetration, impurities, plasma stability, and beam slowdown rates must await such testing. Meanwhile, it is appropriate to look at radiofrequency methods as an alternative process for plasma heating and for ion tail creation. Radiofrequency heating can play a number of roles:

a. Electron heating. A successful two-component fusion experiment needs an electron temperature of 5 keV or more. Neutral injection provides supplementary heat to both the background ions and electrons, and too much background ion heating can be wasteful. In addition, it may turn out that r.f. electron heating is less costly to install than injection heating with similar capability.

b. Supplementary heating. Supplementary ion heating is the traditional role assigned to r.f. heating.

c. Ion tail creation. Selective absorption of r.f. energy by a minority of the plasma ions may be achieved by cyclotron resonance tuned to the minority ions [2-4], or by cyclotron harmonic heating which preferentially delivers power to the high-energy (large Larmor radius) component [4-6].

d. Ion tail enhancement. Radiofrequency heating may be used to enhance neutral injection itself by tuning the r.f. to resonance with the injected beam particles in the plasma. Such heating can easily add perpendicular energy to beam ions, and can increase and maintain the energy dispersion of the beam and the fusion reaction rate.

The wave mode which is uncannily well suited to the various objectives outlined above is the compressional hydromagnetic wave, also called the magnetosonic mode or simply the fast wave. The wave lengths in the desired frequency ($\omega \sim \omega_{ci}$) and density ($n \sim 10^{14}$ cm^{-3}) ranges are long enough to allow reasonable mode separation in the large tokamak plasmas and good coupling to the antenna structures. Fast-wave heating for large plasma devices was first seriously examined by Adam and Samain [4]. Their analysis of the CTR applications was preceded by several important laboratory experiments: the fast-wave mode was identified by Hooke et al. [7] and studied further by Nazarov et al. [8], Swanson, Gould and Hertel [9], Kovan and Spektor [10], and Chung and Rothman [11]. Discrete high-Q fast-wave toroidal eigenmodes were first seen in 1971 experiments by

737

Energies of fast ions generated with minority ICRF

$$E_{\rm mino} \simeq T_e\, \xi_{\rm mino}^{\rm (Stix)}\,, \qquad \xi_{\rm mino}^{\rm (Stix)} \approx \frac{0.24\,[T_e({\rm keV})]^{1/2} A_{\rm mino}\,\langle P_{\rm RF}\rangle}{n_{e,20}^2\, Z_{\rm mino}^2\, X_{\rm mino}}$$

Good confinement in W7-X requires:

n_{e0} ~ 2x10^{20} m^{-3}, T_0 ~ 3 keV (<β> ~ 4%)

ICRH goal: $E_{\rm mino}$ ~ 50–100 keV

ICRH acceleration factor: $\xi_{\rm mino}$ ~ 20–30

$$\xi_{\rm mino}^{\rm (Stix)} \gtrsim 20 - 30$$

$$P_{\rm ICRF}({\rm MW}) \gtrsim 2.5 X_{\rm mino}(\%)(Z_{\rm mino}^2/A_{\rm mino})\Delta V({\rm m}^3)$$

$V_{\rm W7\text{-}X}$ = 30 m^3, ΔV ~ 5 m^3, $X_{\rm mino}$ ~ 1% → $P_{\rm RF}$ > 10 MW (!) (for full plasma density)

H minority heating – a good option for operation with reduced n_{e0}

Challenge of ICRF in W7-X: produce 50-100keV ions in very high density plasmas

High-plasma density: improving wave absorption vs. complicating fast-ion generation

$$\xi_{\text{mino}}^{(\text{Stix})} \approx \frac{0.24\,[T_e(\text{keV})]^{1/2} A_{\text{mino}} \langle P_{\text{RF}} \rangle}{n_{e,20}^2\, Z_{\text{mino}}^2\, \boxed{X_{\text{mino}}}} \gtrsim 20 - 30$$

Solution: *Decrease the concentration of resonant ions to compensate for the high density plasma*

But what scenario to use ?????

Challenge of ICRF in W7-X: produce 50-100keV ions in very high density plasmas

Answer: a novel ICRH scenario using three ion species

ICRF heating of ^{3}He ions in 30%D – 70%H or 15% ^{4}He – 70% H plasmas with $X[^3\mathrm{He}] < 1\%$

How does it work?

- **Short overview of the ICRF system design**
- **ICRH scenarios for W7-X**
- **Three-ion (^{3}He)-D-H ICRF heating:**
  fast-ion generation at the largest plasma densities on W7-X
- **Summary and conclusions**

Recall theory: wave dispersion and polarization

- **Fast wave (excited by ICRF antenna) is elliptically polarized**

  ***E_+* / *E_-* : left/right-hand polarized component (ions / electrons)**

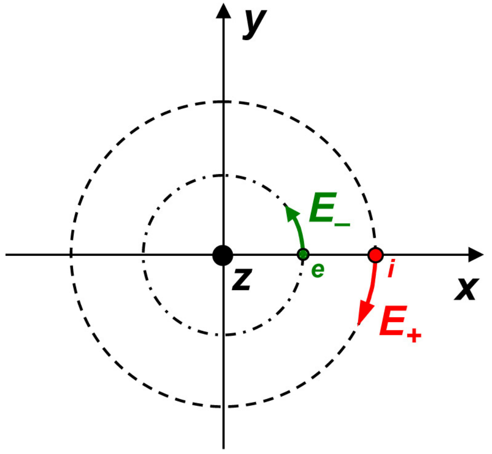
- ***Left-hand polarized component E_+ is responsible for (thermal) ion heating***

$$p_{\mathrm{ion}}^{(N=1)} = A|E_+|^2 + \cancel{B(k_\perp \rho_{\mathrm{L}})^4 |E_-|^2}$$

(see Stix 1975)

- **Plasma (mainly) imposes wave polarization**

$$\left|\frac{E_+}{E_-}\right| \simeq \left|\frac{\epsilon_{\mathrm{R}} - n_\parallel^2}{\epsilon_{\mathrm{L}} - n_\parallel^2}\right|$$



- **Why not single ion species?**

  E_+* (almost) vanishes at the ion cyclotron resonance, *$E_+ \to 0$

Two-ion species plasmas: Minority heating

- **Two ion species:** $\left|\frac{E_+}{E_-}\right|_{\omega=\omega_{c2}} \approx \left|\frac{\mathcal{Z}_2-\mathcal{Z}_1}{\mathcal{Z}_2+\mathcal{Z}_1}\right| \neq 0$ $\qquad \mathcal{Z}_i = (Z/A)_i$

- ***Two-ion minority heating has a limited capability for ion absorption at very low X_{mino} (< 1%)***

D. Start et al., Nucl. Fusion 39 , 321 (1999)

Scenario	Minority ion	E_+ / E_-	Damping
(H)-D	H	≈ 1/3	'Strong'
(D)-T (^{3}He)-H	D ^{3}He	≈ 1/5	'Medium'
(^{3}He)-D	^{3}He	≈ 1/7	'Weak'
(Z)-Y-X	Z	» 1	How? See [1]

Two-ion ICRF minority heating

- **Minority concentrations of ~5% are typically used in present-day experiments**

Three-ion ICRF minority heating

- ***Wave polarization and absorption are fully decoupled***
- ***$X_3 = n_3/n_e$ ~ 0.1–1% (impurity ions)***

[1] Ye.O. Kazakov, D. Van Eester, R. Dumont and J. Ongena, *Nucl. Fusion* 55 (2015) 032001

(Invited talk at the 21st Topical RF Conference, 27-29 April 2015, Lake Arrowhead, USA)

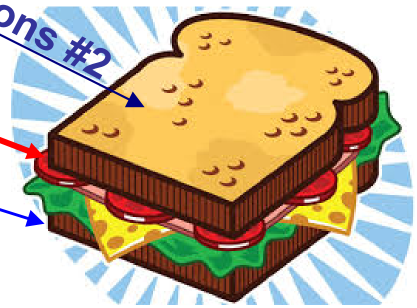
Three-ion ICRF heating: a dedicated tool for fast-ion generation

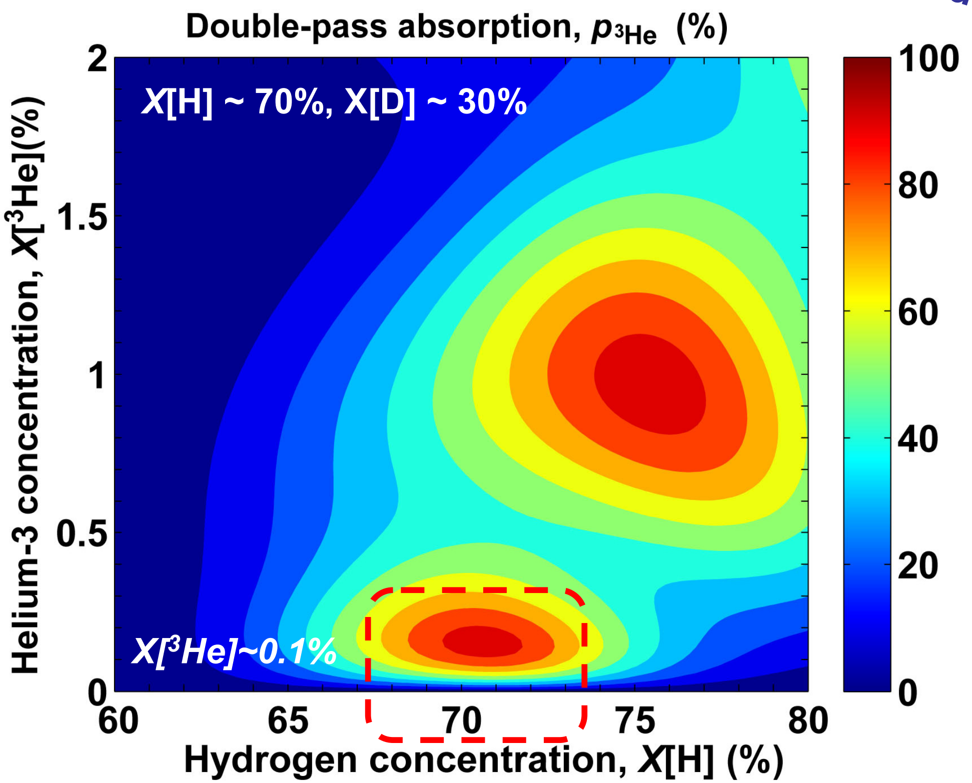
$$\min\{(Z/A)_1, (Z/A)_2\} < (Z/A)_3 < \max\{(Z/A)_1, (Z/A)_2\}$$

bulk ions #1

resonant ions

bulk ions #2





(^{3}He)-D-H or (^{3}He)-^{4}He-H plasmas

Three-ion ICRF heating: *efficient wave absorption at optimized low X_{mino}*

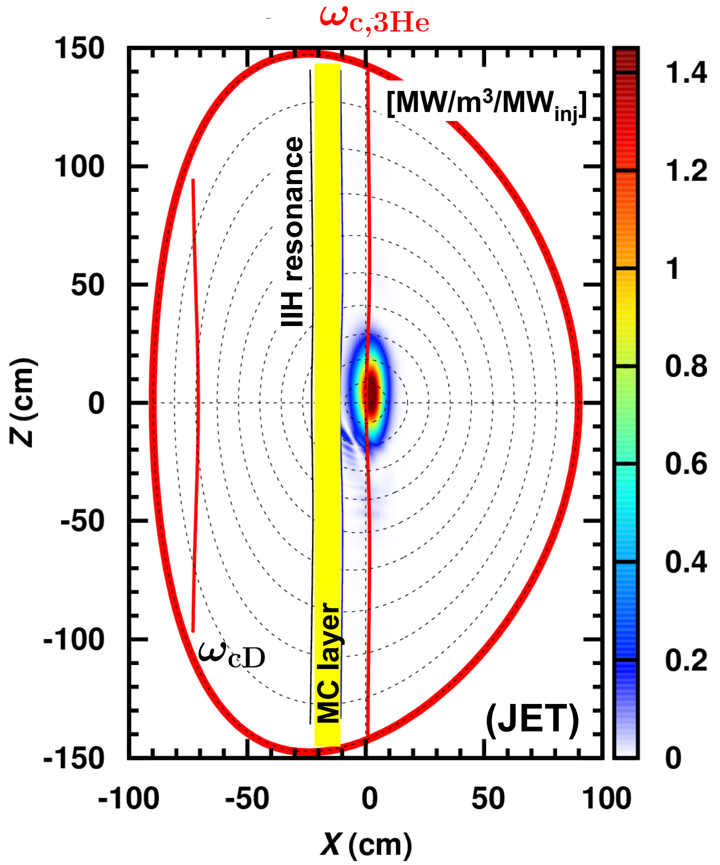
W7-X (baseline conditions): $P_{\mathrm{ICRF}}(\mathrm{MW}) \gtrsim 2.5 X_{\mathrm{mino}}(\%)(Z^2_{\mathrm{mino}}/A_{\mathrm{mino}})\Delta V\,(\mathrm{m}^3)$

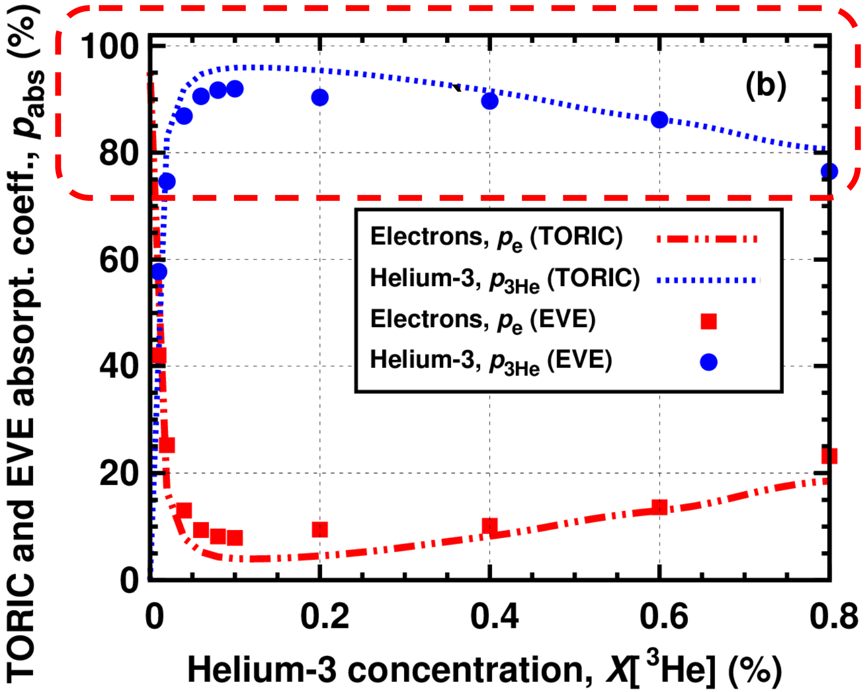
→ ***Reduce the concentration of resonant ions (to X_{mino} ~ 0.1–0.5%)!***

Three-ion ICRF scenarios: fast-ion generation

Power deposition from TORIC, $X[^3He]=0.1\%$, D:H=29:71

Flat p_{abs} dependence in the range $X[^3He]$= 0.05% – 1% (very precise ^3He control not required)





Potential in JET: $X[^3He]$ = 0.2%, E_{3He} ~ 1 MeV/MW$_{inj.}$

Potential in W7-X: $X[^3He]$ ~ 0.1%, E_{3He} ~ 50-100 keV

(dedicated fast-ion source at the largest n_{e0} in W7-X)

Three-ion ICRF heating: $\omega=2\omega_{ci}$ vs. our proposal

- V. Vdovin, T. Watari and A. Fukuyama, “An Option of ICRF Ion Heating Scenario in Large Helical Device”, NIFS-502 (1997)

Three ion species: D (majority, ~90%), H (minority, ~10%) + ^{13}C, ^{21}Ne, ^{7}Li, ^{11}B, ^{40}Ar

Fast Wave (ICRH antenna)	→	IBW (mode conversion)	→	absorption by impurities ($\omega = 2\omega_{c3}$)

Such an impurity RF heating was also observed on TFR, T-10, T11-M, JET, HT-7, …

- LPP-ERM/KMS proposal

Three ion species: H (majority, ~70%), D (minority, ~30%) + ^{3}He

Fast Wave (ICRH antenna)	→	absorption by ^{3}He impurities ($\omega = \omega_{c3}$)

Conclusions

- **ICRH will be used in W7-X as a source of fast ions (E_{fast} ~ 50–100 keV)**
- **A number of ICRF scenarios are available with TEXTOR generators:**
  - ***H minority heating in ^{4}He or D plasmas (good option for reduced n_{e0})***
  - ***Three-ion ^{3}He heating in D-H or ^{4}He-H plasmas (for the largest n_{e0} in W7-X)***
  - ***Second harmonic heating of ^{4}He or D ions in H plasmas (e.g., NBI+ICRH)***
- **Three-ion ICRF: efficient RF power absorption at very small X_{mino} (< 1%):**

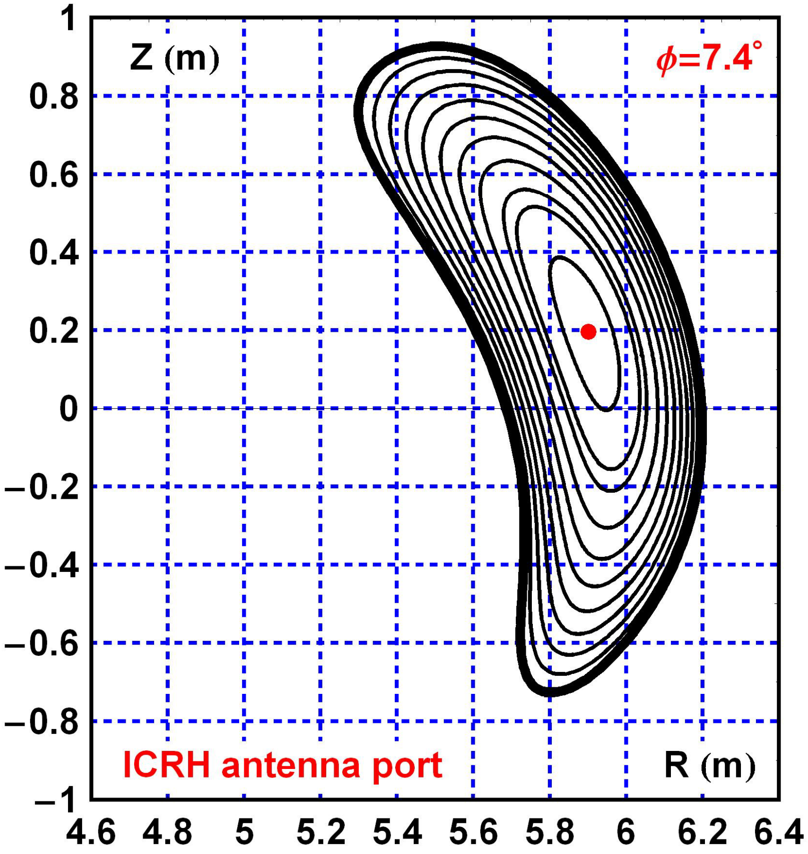
H:D ~ 70:30 or H:^{4}He ~ 70:15 plasmas

Future experiments on three-ion ICRF heating:

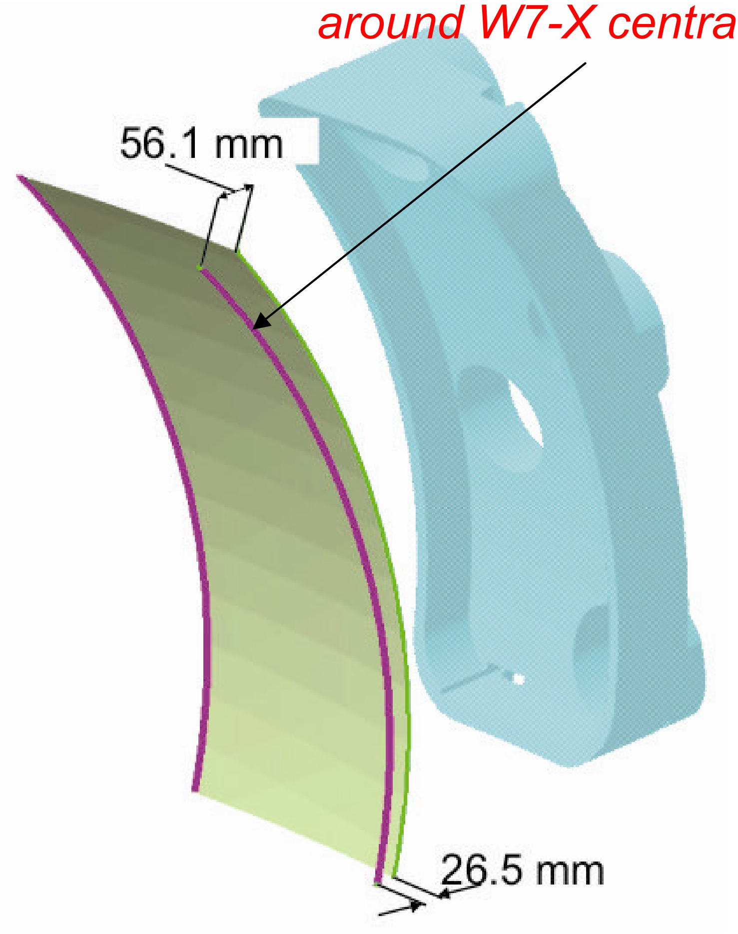
- ► **ASDEX-Upgrade (10 shots, ~ May 2016)**
- ► **JET (selected as a backup experiment for 2015-2016 campaign)**
- ► **Alcator C-Mod (preparatory work with C-Mod Team is ongoing)**
- ► **Any further collaboration is welcome (LHD, EAST, …)**

Backup slides

A real 3D antenna geometry



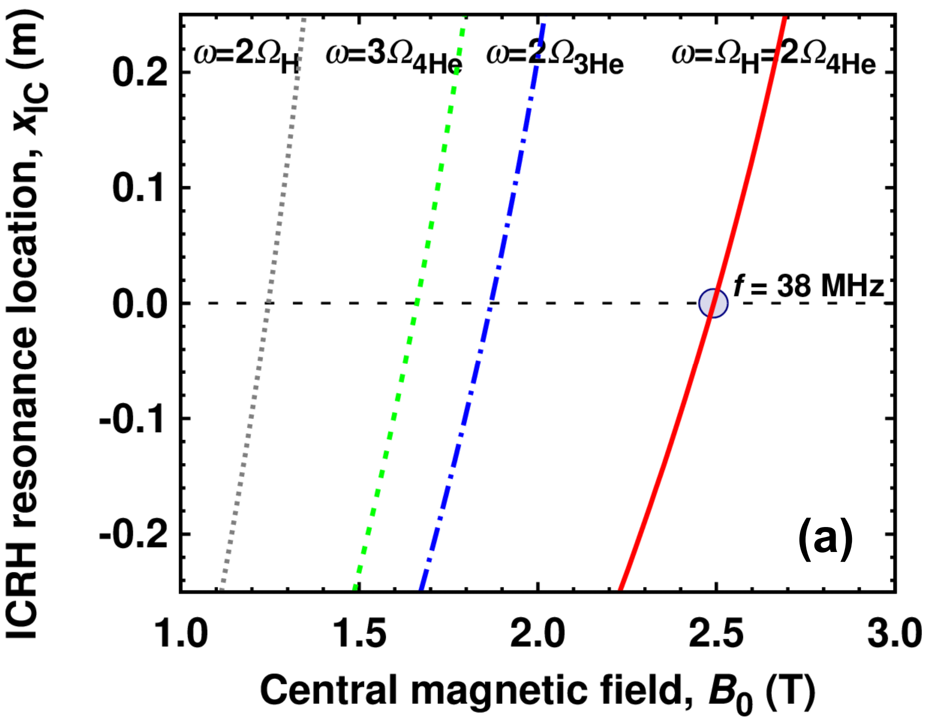
Left edge rotated toroidally around W7-X central vertical axis



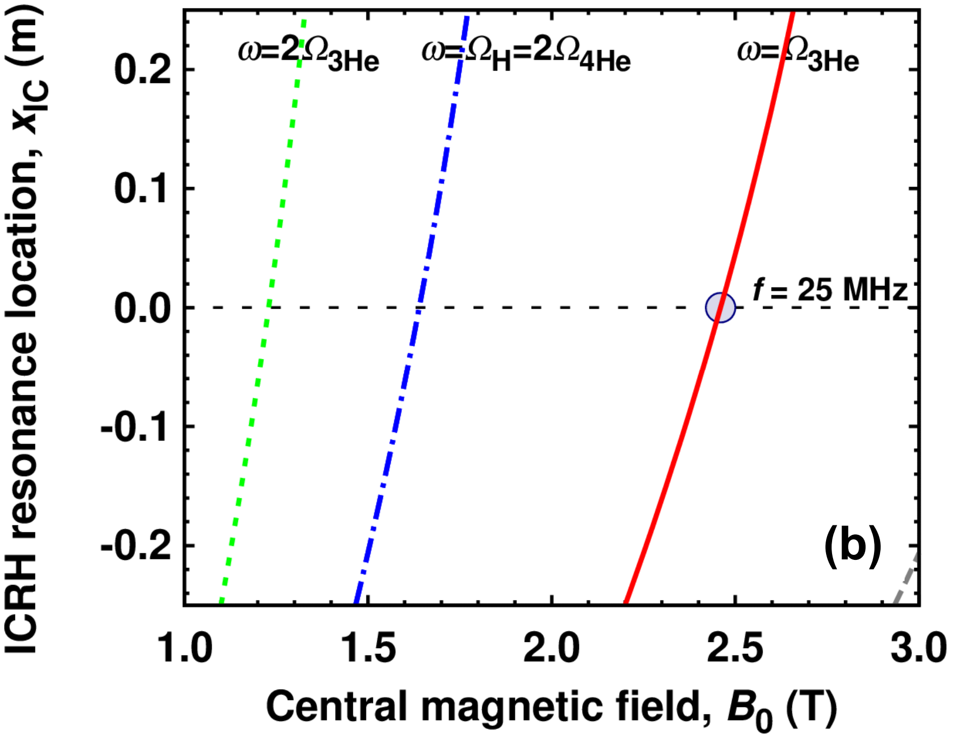
Antenna surface mimicking LCFS for the standard configuration of W7-X

ICRH in Wendelstein 7-X

TEXTOR RF generators: f = 25–38 MHz (B_0 ~ 2.5T, ECRH 140GHz)



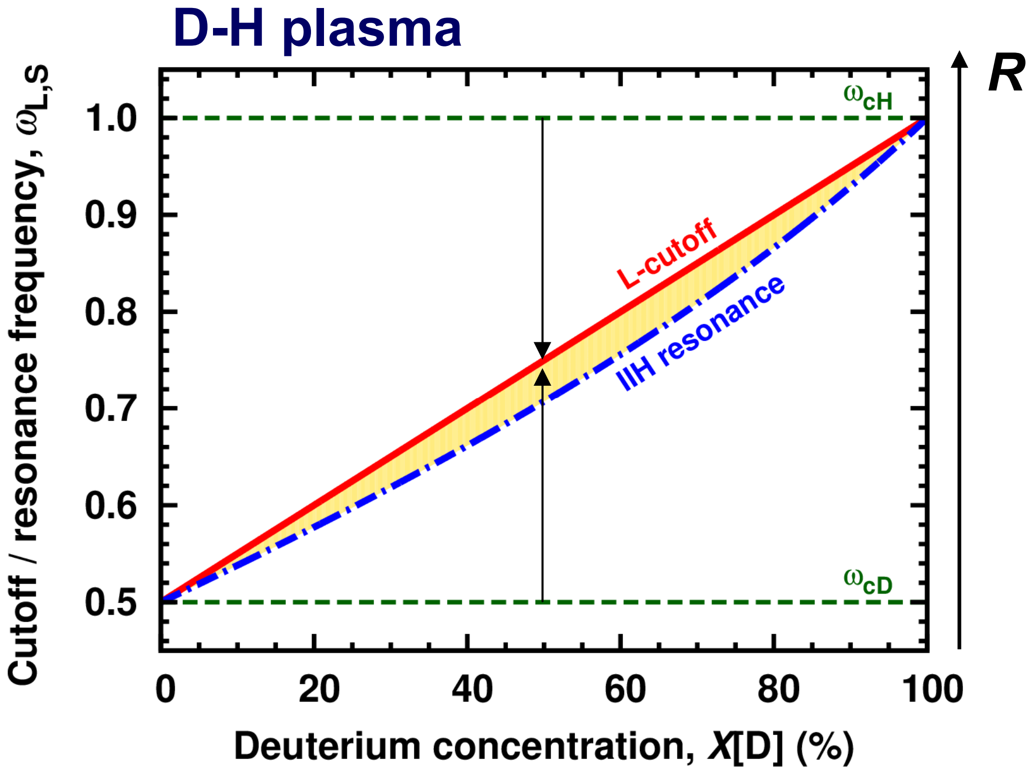
f_{max} = 38 MHz



f_{min} = 25 MHz

- **ICRF minority heating ($\omega=\omega_{ci}$) : a) H ions at $f \approx$ 38 MHz, b) ^{3}He ions at $f \approx$ 25 MHz**
- **ICRF second harmonic ($\omega=2\omega_{ci}$): D and ^{4}He ions at $f \approx$ 38 MHz**

Three-ion species plasmas: (Z)-Y-X scheme



Wave polarization:

$$\left|\frac{E_+}{E_-}\right| \simeq \left|\frac{\epsilon_1 - \epsilon_2 - n_\parallel^2}{\epsilon_1 + \epsilon_2 - n_\parallel^2}\right| = \left|\frac{\epsilon_R - n_\parallel^2}{\epsilon_L - n_\parallel^2}\right|$$

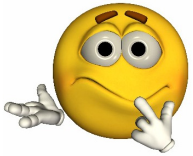
- **IIH resonance** $(\epsilon_1 = n_\parallel^2)$ **:**

  linear polarization $E_+ = E_-$

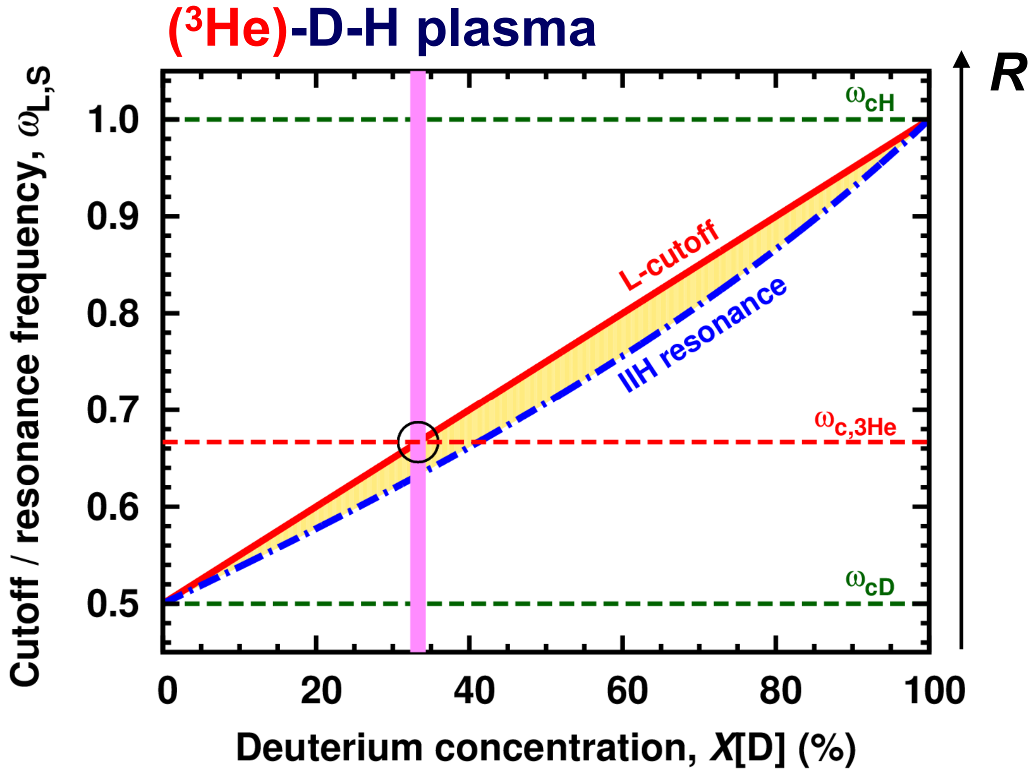
- **L-cutoff** $(\epsilon_L = n_\parallel^2)$ **:**

  E_- vanishes! E_+ carries almost 100% of the FW power

➢ **An enhanced E_+ near the L-cutoff in two-ion species plasmas. None of the minority/majority species is able to profit from that.**



Three-ion species plasmas: (Z)-Y-X scheme


(^{3}He)-D-H plasma

Wave polarization:

$$\left|\frac{E_+}{E_-}\right| \simeq \left|\frac{\epsilon_1-\epsilon_2-n_\parallel^2}{\epsilon_1+\epsilon_2-n_\parallel^2}\right| = \left|\frac{\epsilon_R-n_\parallel^2}{\epsilon_L-n_\parallel^2}\right|$$

- IIH resonance $(\epsilon_1 = n_\parallel^2)$:

  linear polarization $E_+ = E_-$

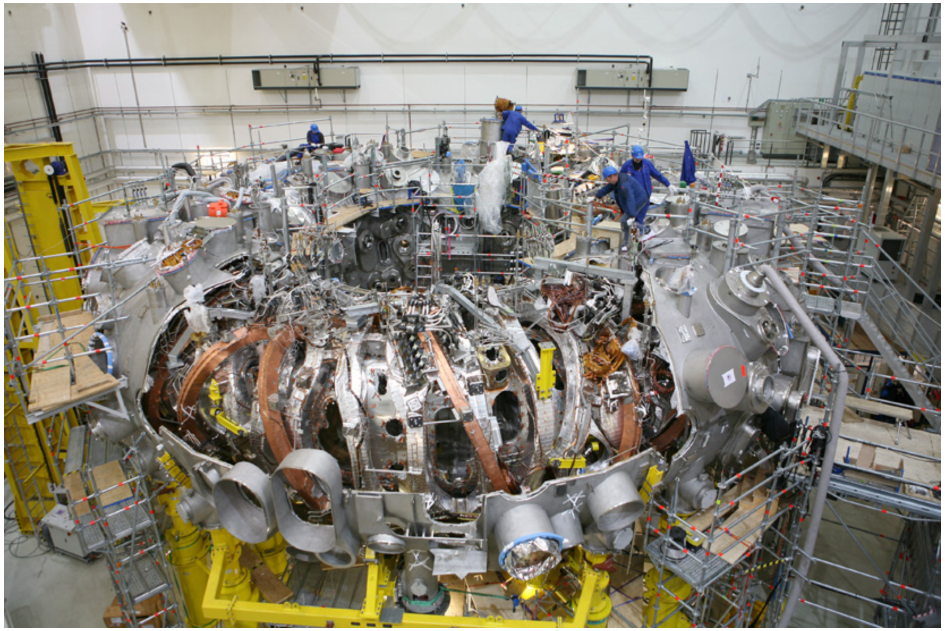
- L-cutoff $(\epsilon_L = n_\parallel^2)$:

  E_- vanishes! E_+ carries almost 100% of the FW power

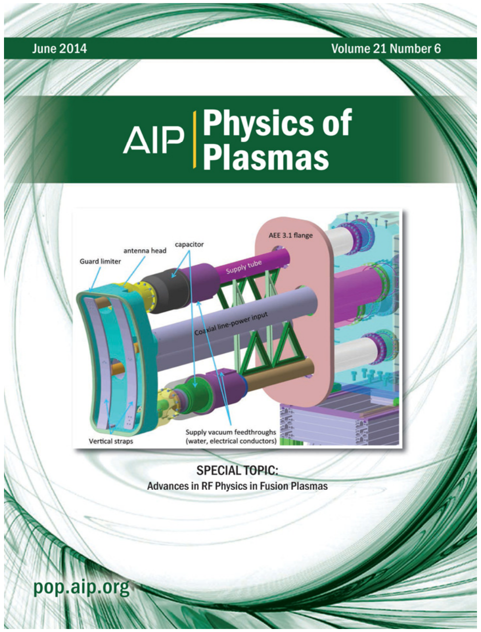
- An enhanced E_+ near the L-cutoff in two-ion species plasmas. None of the minority/majority species is able to profit from that.
- Add the third ion species (^{3}He) at a small concentration to absorb the power.

ICRH in Wendelstein 7-X

Stellarator W7-X (first plasma 2015)



LPP-ERM/KMS: ICRF antenna design



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AIP Physics of Plasmas

SPECIAL TOPIC:
Advances in RF Physics in Fusion Plasmas

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J. Ongena et al., PoP (2014)

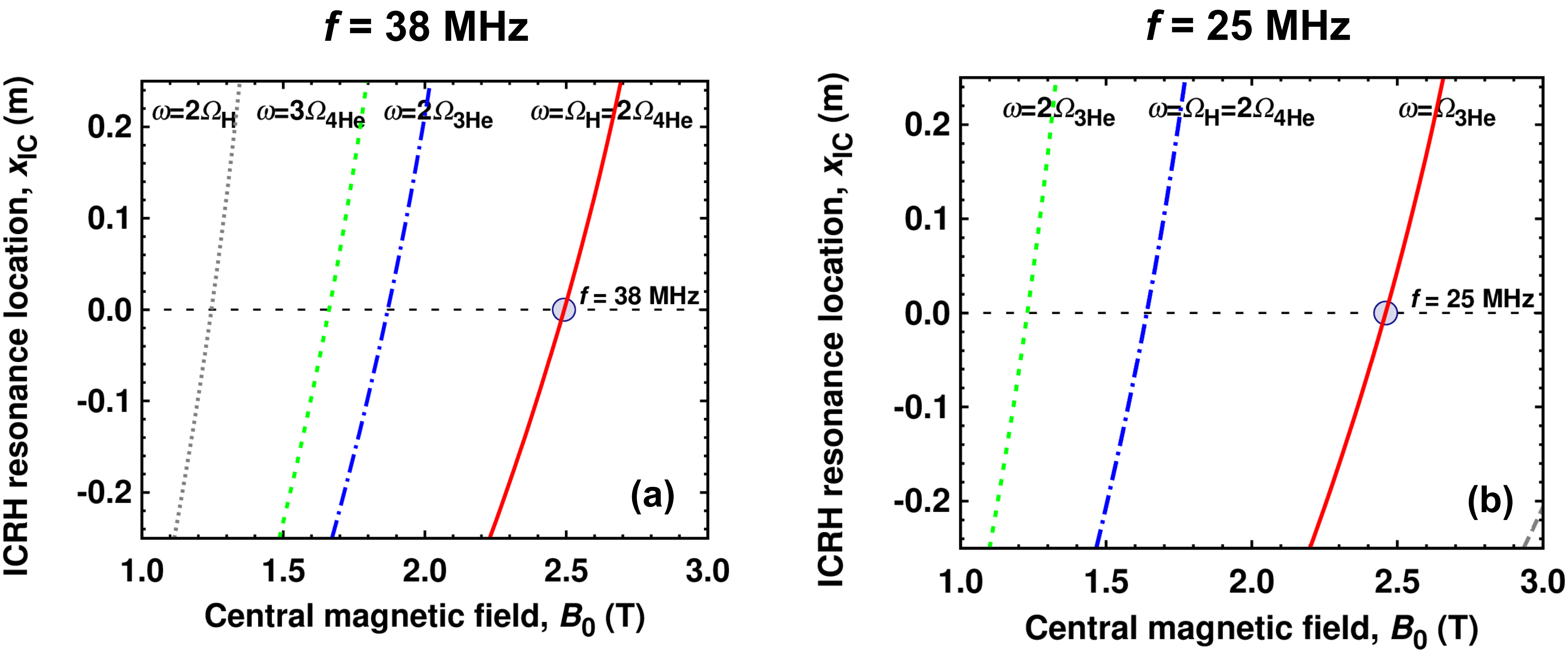
- ► **Main goal of the W7-X: prove fast ions are confined (good core confinement for <*β*> ≈ 4%)**
- ► **Main function of ICRH in W7-X: generate 50–100 keV ions (mimic alphas in HELIAS)**
- ► **Baseline W7-X parameters: very high plasma densities, $n_{e0} \sim 2\text{x}10^{20}$ m^{-3} & $T_0 \sim 3$ keV, $B_0 \sim 2.5$T**

$$\beta(\%) \approx \frac{4n_{e,20}(T^i_{\mathrm{keV}} + T^e_{\mathrm{keV}})}{B(\mathrm{T})^2}$$

$$\beta_0(\%) \approx 7.7\%, \quad \langle\beta\rangle \simeq \beta_0/2 \approx 4\%$$

ICRH in Wendelstein 7-X

TEXTOR RF generators (P_{ICRH} = 1–2 MW): f = 25–38 MHz (B_0 ~ 2.5T)

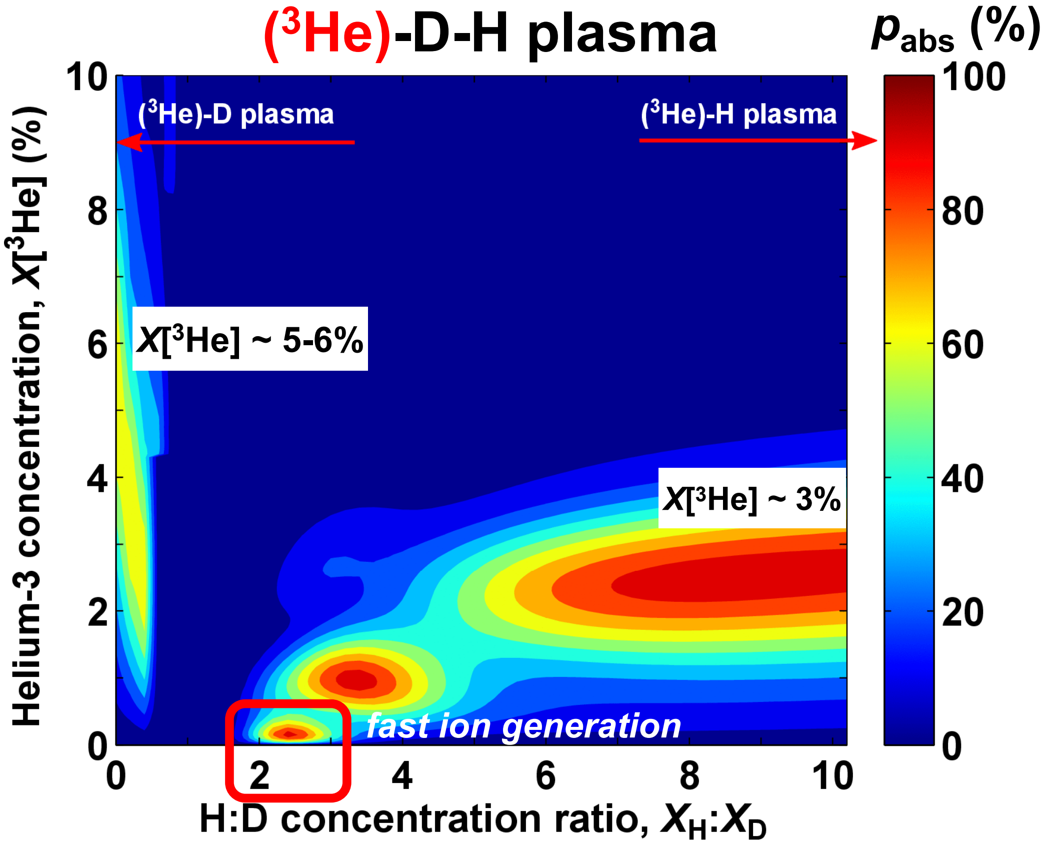


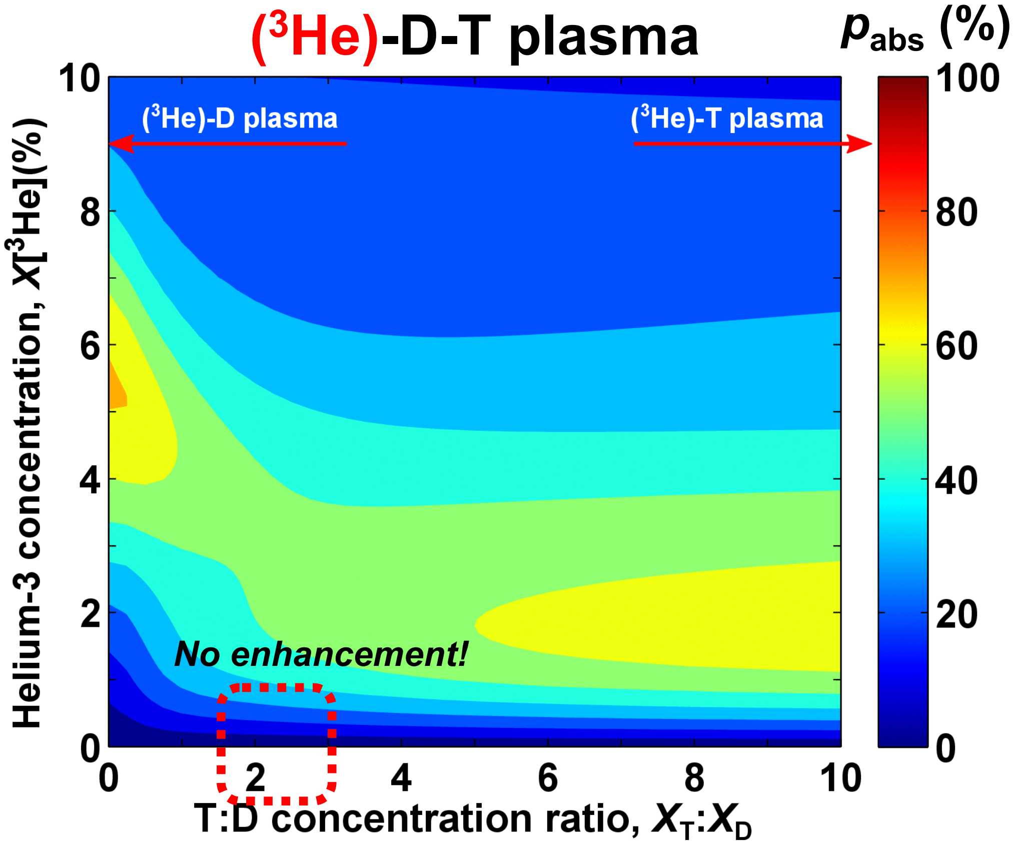
ICRH minority heating: a) H ions at $f \approx 38$ MHz, b) ^{3}He ions at $f \approx 25$ MHz

Three-ion ICRF heating: a dedicated tool for fast-ion generation

W7-X (baseline conditions): $P_{\mathrm{ICRF}}(\mathrm{MW}) \gtrsim 2.5\, X_{\mathrm{mino}}(\%)\,(Z^2_{\mathrm{mino}}/A_{\mathrm{mino}})\,\Delta V\,(\mathrm{m}^3)$

→ *Reduce the concentration of resonant ions (to X_{mino} < 0.1%)!*





Three-ion ICRF heating: ***efficient wave absorption at extremely low X_{mino}***

(presence of three ion species is necessary, but not sufficient!)

Two-ion species plasmas: Minority heating

- **Two ion species:** $\left|\frac{E_+}{E_-}\right|_{\omega=\omega_{c2}} \approx \left|\frac{\mathcal{Z}_2-\mathcal{Z}_1}{\mathcal{Z}_2+\mathcal{Z}_1}\right| \neq 0$ $\mathcal{Z}_i = (Z/A)_i$

  (majority ions → polarization, minority ions → absorption)

- ***Two-ion minority heating has a limited capability for ion absorption at very low X_{mino} (< 1%): fast-wave is mostly right-hand polarized***

D. Start et al., Nucl. Fusion 39 , 321 (1999)

Scenario	Minority ion	E_+ / E_-	Damping
(H)-D	H	≈ 1/3	'Strong'
(D)-T (^{3}He)-H	D ^{3}He	≈ 1/5	'Medium'
(^{3}He)-D	^{3}He	≈ 1/7	'Weak'
(Z)-Y-X	Z	» 1	How? See soon

Two-ion minority heating (N=1)

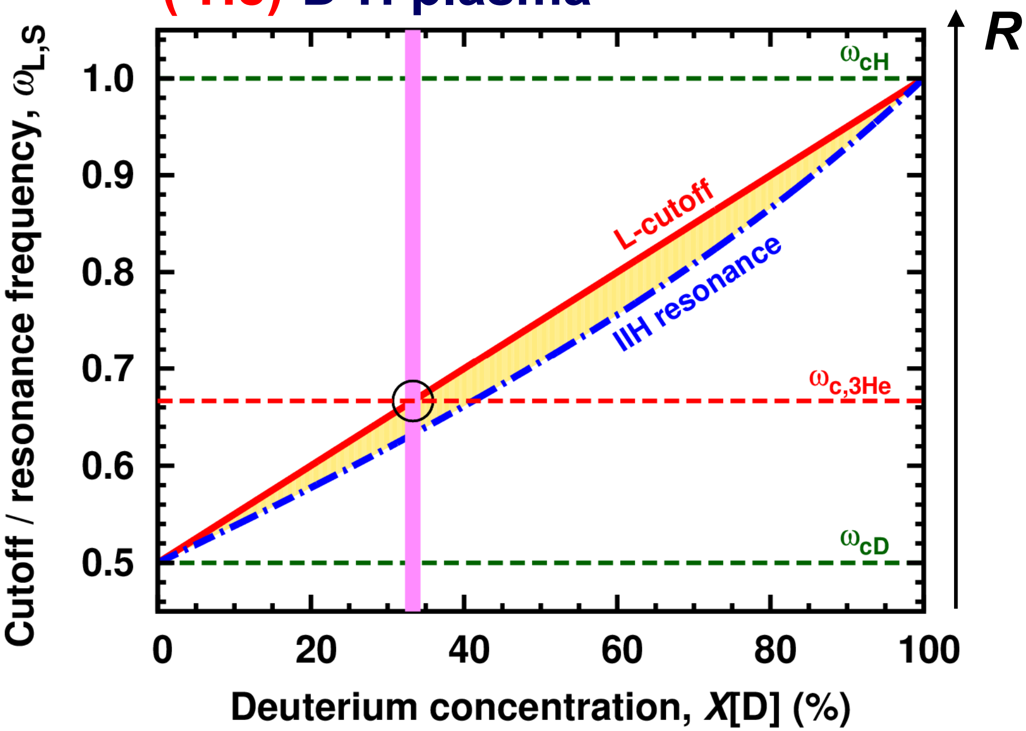
- ■ **Minority concentrations of ~5% are typically used in present-day experiments**

Three-ion ICRF heating (N=1)

- ■ ***$X_3 = n_3/n_e$ < 1% (impurity ions)***
- ■ **Much larger energy per resonant ion**

Three-ion species plasmas: (Z)-Y-X scheme

(^{3}He)-D-H plasma



Wave polarization:

$$\left|\frac{E_+}{E_-}\right| \simeq \left|\frac{\epsilon_1 - \epsilon_2 - n_\parallel^2}{\epsilon_1 + \epsilon_2 - n_\parallel^2}\right| = \left|\frac{\epsilon_R - n_\parallel^2}{\epsilon_L - n_\parallel^2}\right|$$

- **IIH resonance** $(\epsilon_1 = n_\parallel^2)$:

  linear polarization $E_+ = E_-$

- **L-cutoff** $(\epsilon_L = n_\parallel^2)$:

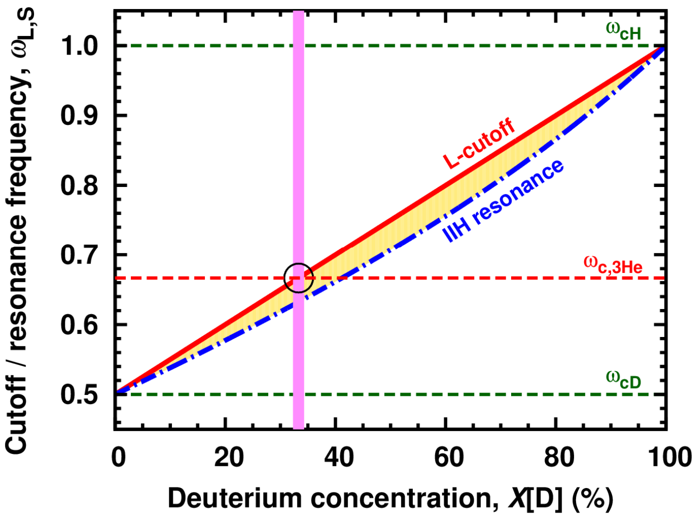
  E_- vanishes! E_+ carries almost 100% of the FW power

- **An enhanced E_+ near the L-cutoff in two-ion species plasmas.** None of the minority/majority species is able to profit from that.
- **Add the third ion species (^{3}He)** at a small concentration to absorb the power.

Optimal plasma composition: X[H]≈70%, X[D]≈30% (X[^{4}He]≈15%) and X[^{3}He]~0.1%

(^{3}He)-D-H scenario: optimal D:H ratio

$$\omega_L \approx \omega_{c2} + (\omega_{c1} - \omega_{c2}) f_2 + \alpha(\omega_{c1} - \omega_{c2})^2 f_2 (1 - f_2)/\omega_{cH} \simeq \omega_{c3}$$

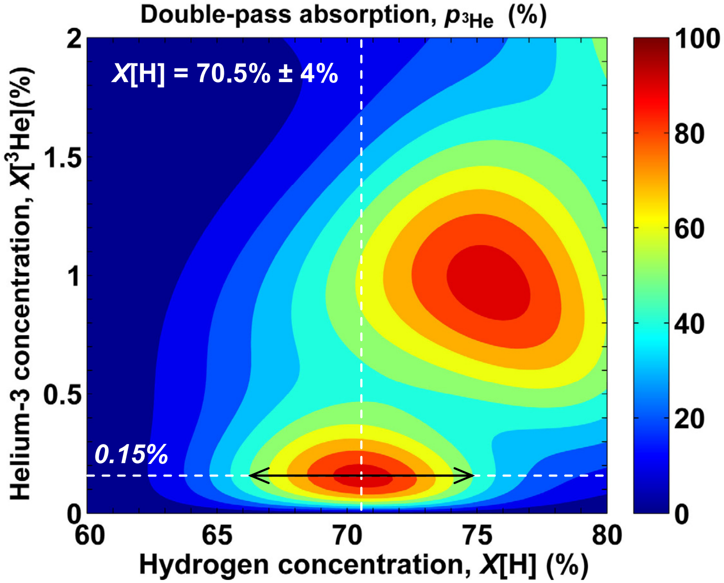


First-order approximation:

$$\hat{X}_2^{(0)} \approx \frac{1}{Z_2}\left(\frac{\mathcal{Z}_3 - \mathcal{Z}_2}{\mathcal{Z}_1 - \mathcal{Z}_2}\right) \qquad \hat{X}_1^{(0)} \approx \frac{1}{Z_1}\left(\frac{\mathcal{Z}_1 - \mathcal{Z}_3}{\mathcal{Z}_1 - \mathcal{Z}_2}\right)$$

‘1’ – hydrogen (1/1); ‘2’ – deuterium (1/2); ‘3’ – helium-3 (2/3)

$\hat{X}[\mathrm{D}] = 33.3\%, \quad \hat{X}[\mathrm{H}] = 66.7\%$ **(H:D ~ 2:1)**



Numerical result (TOMCAT):

$\hat{X}[\mathrm{D}] = 29.2\%, \quad \hat{X}[\mathrm{H}] = 70.5\%$

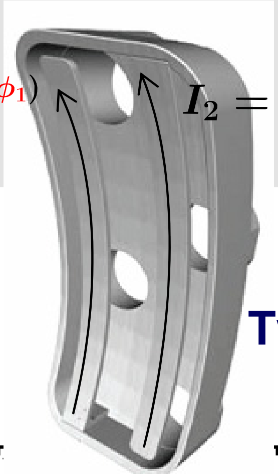
Efficient DPA absorption, p_{3He} > 50% (X[^{3}He]=0.15%) at X[H]=70.5 ± 4%

Ye.O. Kazakov et al., NF 55, 032001 (2015)

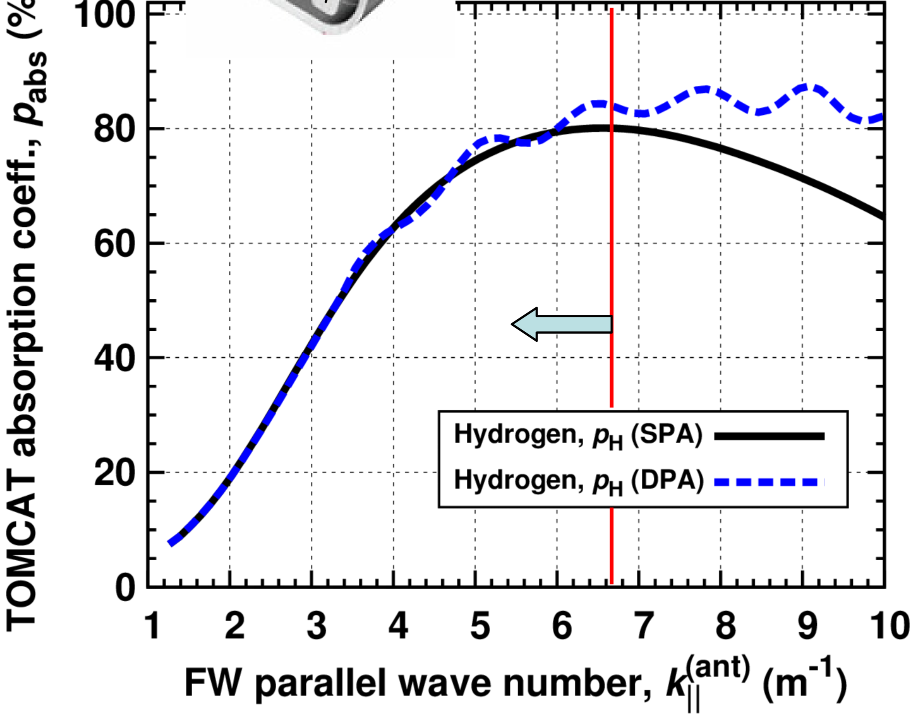
And even more …

$I_1 = I_0 e^{i(\omega t+\phi_1)}$

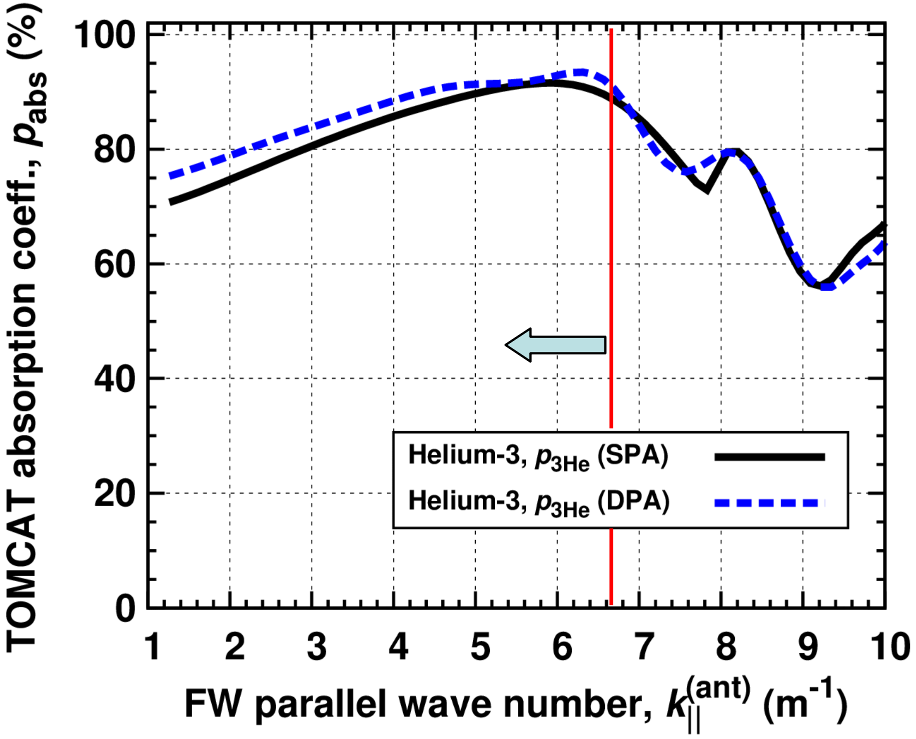
$I_2 = I_0 e^{i(\omega t+\phi_2)}$



Two-ion minority heating,
(H)-D, X[H]=5%



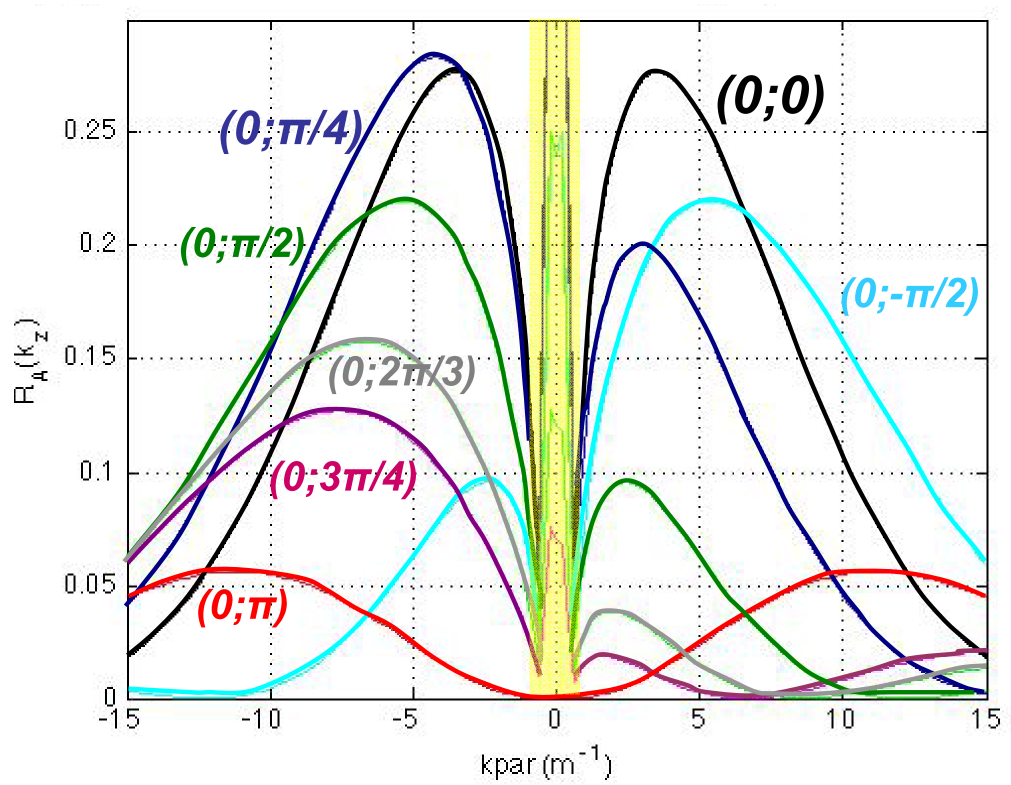
Three-ion (^{3}He)-D-H heating,
$X[^3$He]=0.1%, X[H]=70%

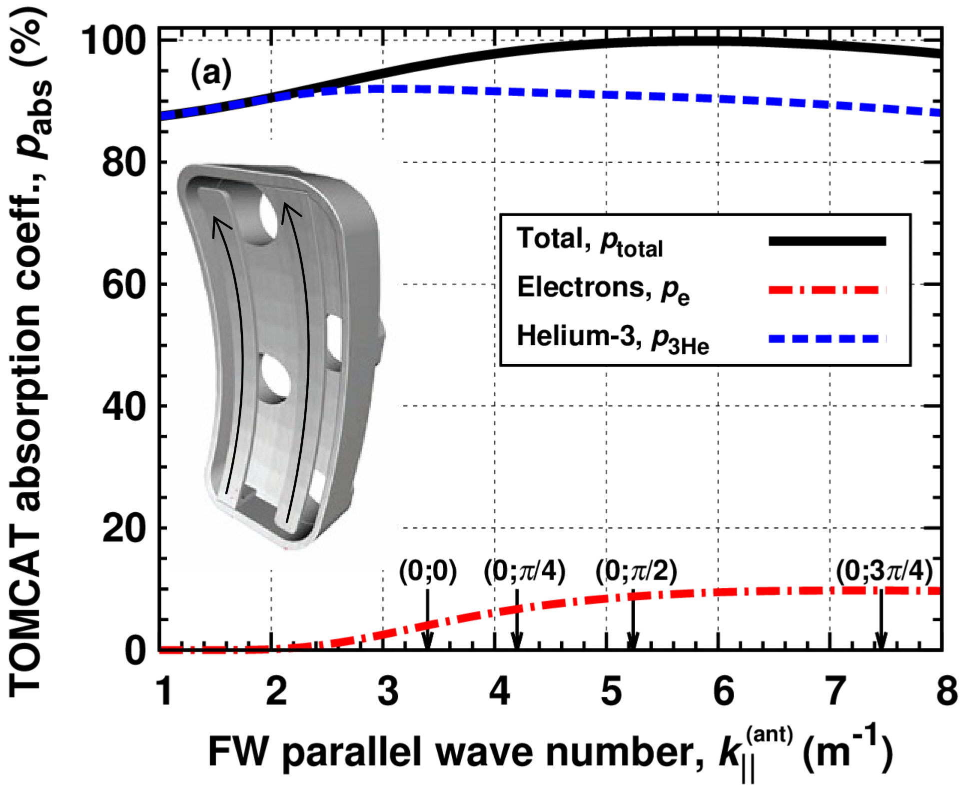


$$\mathcal{P}_{\text{coupling}} \propto e^{-\alpha|k_{\|}|d}$$

Three-ion ICRF scenarios: much better absorption at lower $k_{||}$
(better coupling and good absorption)

Three-ion ICRF scheme in W7-X: p_{abs} vs. $k_{||}$





Phasing	0-0	0-45°	0-90°	0-120°	0-135°	0-180°
$P_{tot,TOPICA}$ (MW)	2.10	1.91	1.35	0.97	0.83	0.62
$P_{tot,ANTITER}$ (MW)	2.03	1.92	1.59	1.28	1.12	0.87

***Strong absorption** even for waves with very low $k_{||}$ → Various phasings with the **improved antenna-plasma coupling** can be tested (e.g., (0;0), (0;π/4))*

As ^{3}He tail develops, the RF power absorption stays strong

Nucl. Fusion **55** (2015) 032001 Letter

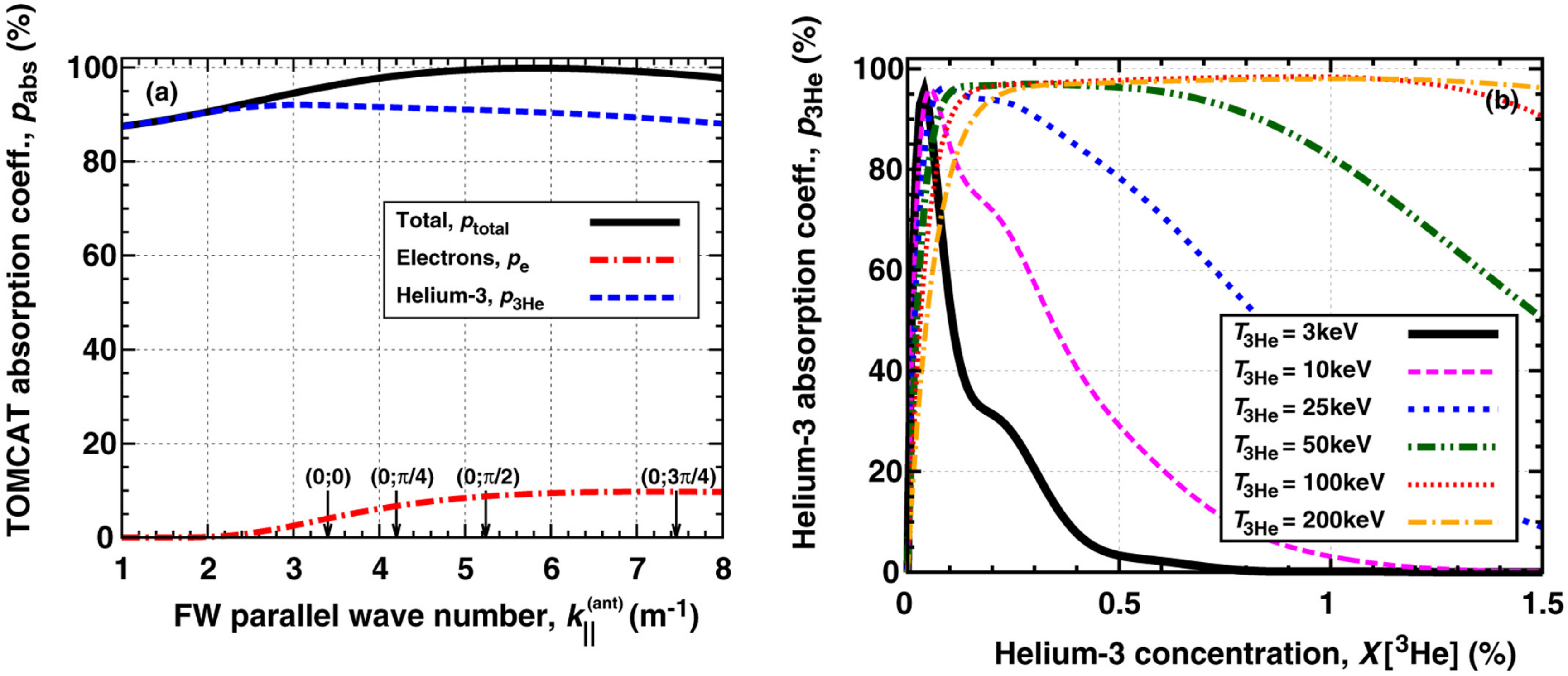


Figure 4. Absorption coefficients for the (^{3}He)–D–H ICRF scenario in W7-X: (*a*) p_{abs} versus the FW parallel wave number $k_{||}$ ($T_0 = 3$ keV, $X[^3\mathrm{He}] = 0.05\%$); (*b*) p_{abs} versus $X[^3\mathrm{He}]$ for various effective ^{3}He temperatures ($k_{||}^{(ant)} = 3.4\ \mathrm{m}^{-1}$—monopole phasing).

Ye.O. Kazakov et al., NF 55, 032001 (2015)

W7-X vs. HELIAS

M. Drevlak, Nucl. Fusion 52, 073002 (2014)

$$\rho_L/a \propto \frac{(mE)^{1/2}}{ZBa} = \text{const}$$

$$E_{\mathrm{W7-X}} = \frac{(Z^2/A)_{\mathrm{W7-X}}}{(Z^2/A)_{\mathrm{HELIAS}}} \left(\frac{a_{\mathrm{W7-X}}}{a_{\mathrm{HELIAS}}}\right)^2 \left(\frac{B_{\mathrm{W7-X}}}{B_{\mathrm{HELIAS}}}\right)^2 E_{\mathrm{HELIAS}}$$

Energy, ^{3}He (keV)	Energy, α (MeV)
0 – 5	0 – 0.2
5 – 20	0.2 – 0.9
20 – 60	0.9 – 2.6
60 – 100	2.6 – 4.3
100 – 140	4.3 – 6.1

- **HELIAS: B_{HELIAS} = 5T, a_{HELIAS} = 3.8$a_{\mathrm{W7\text{-}X}}$, E[^{4}He] = 3.5MeV**

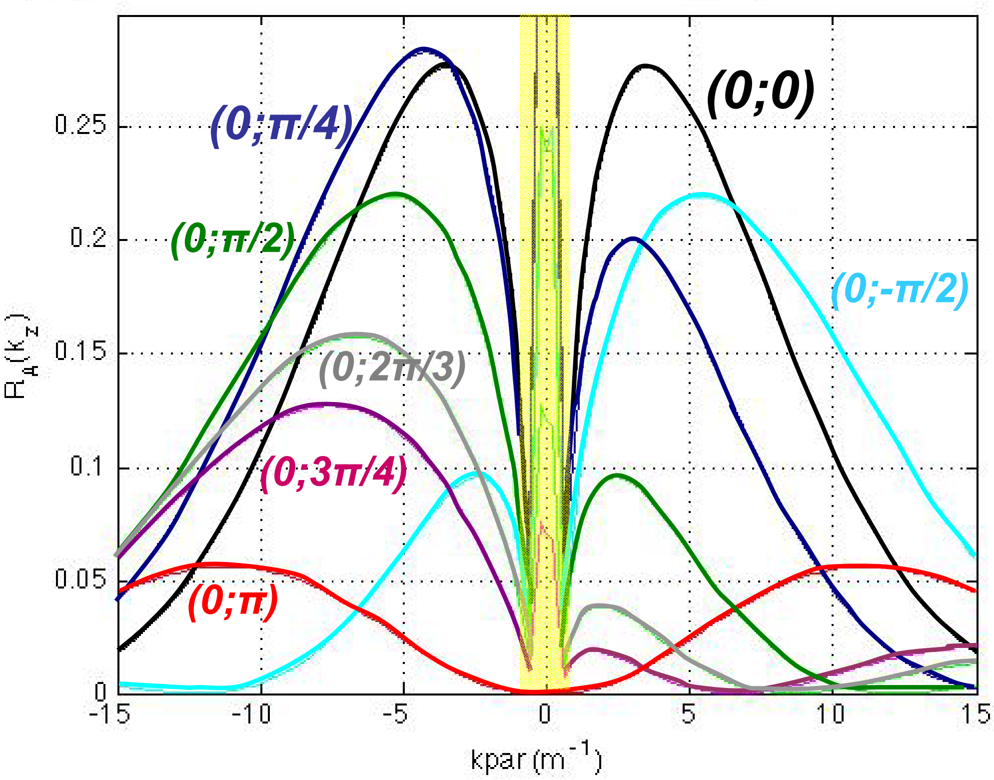
- **W7-X: $B_{\mathrm{W7\text{-}X}}$ = 2.5T**

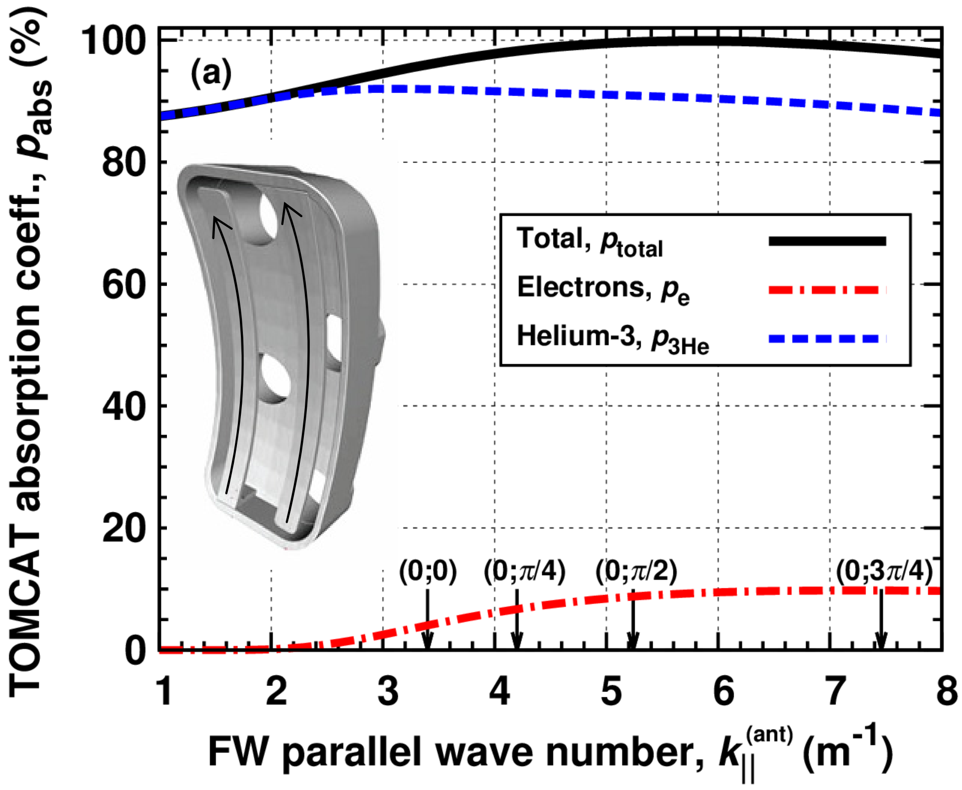
→ **protons, E[p] ≈ 60 keV**

→ **helium-3, E[^{3}He] ≈ 80 keV**

Generation of fast ions with energies of 50-100keV seems to be possible in W7-X operating at the full plasma density, even with 1MW ICRF power coupled.

Three-ion ICRF scheme in W7-X: p_{abs} vs. $k_{||}$





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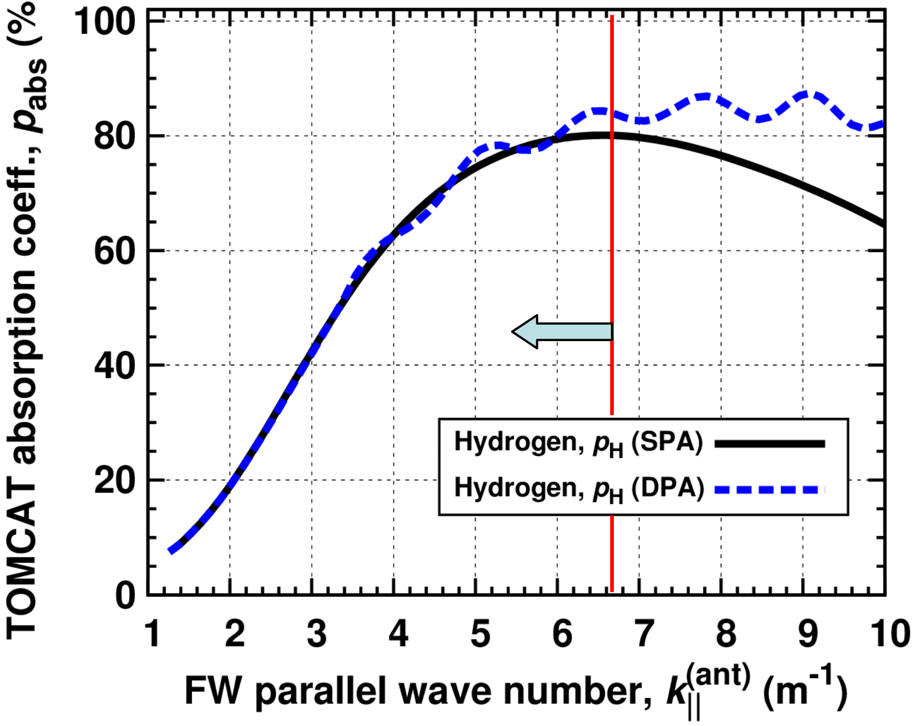
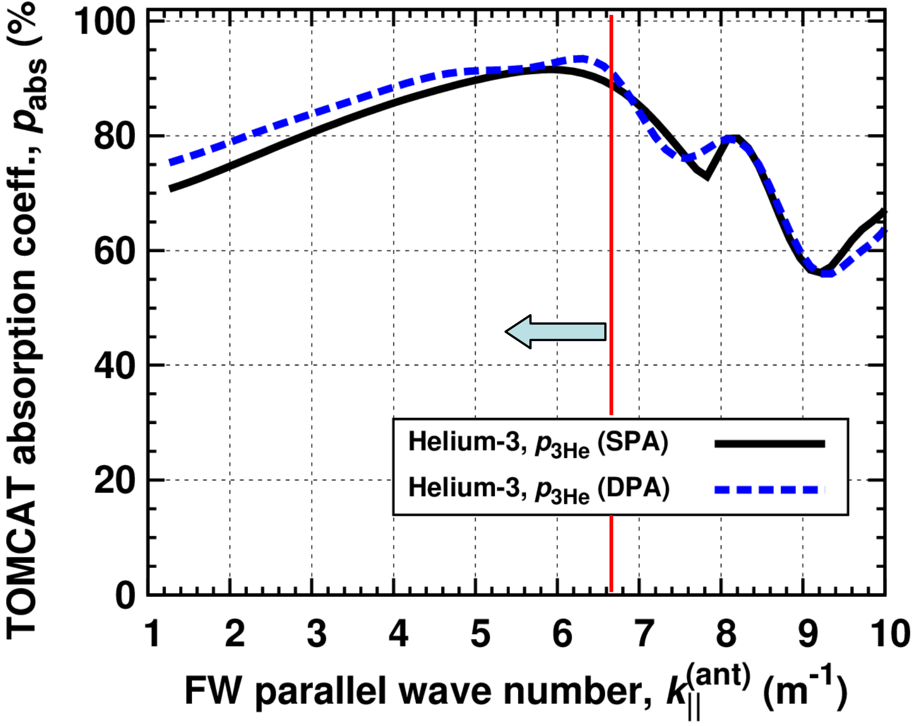


Two-ion minority heating, (H)-D, X[H]=5%

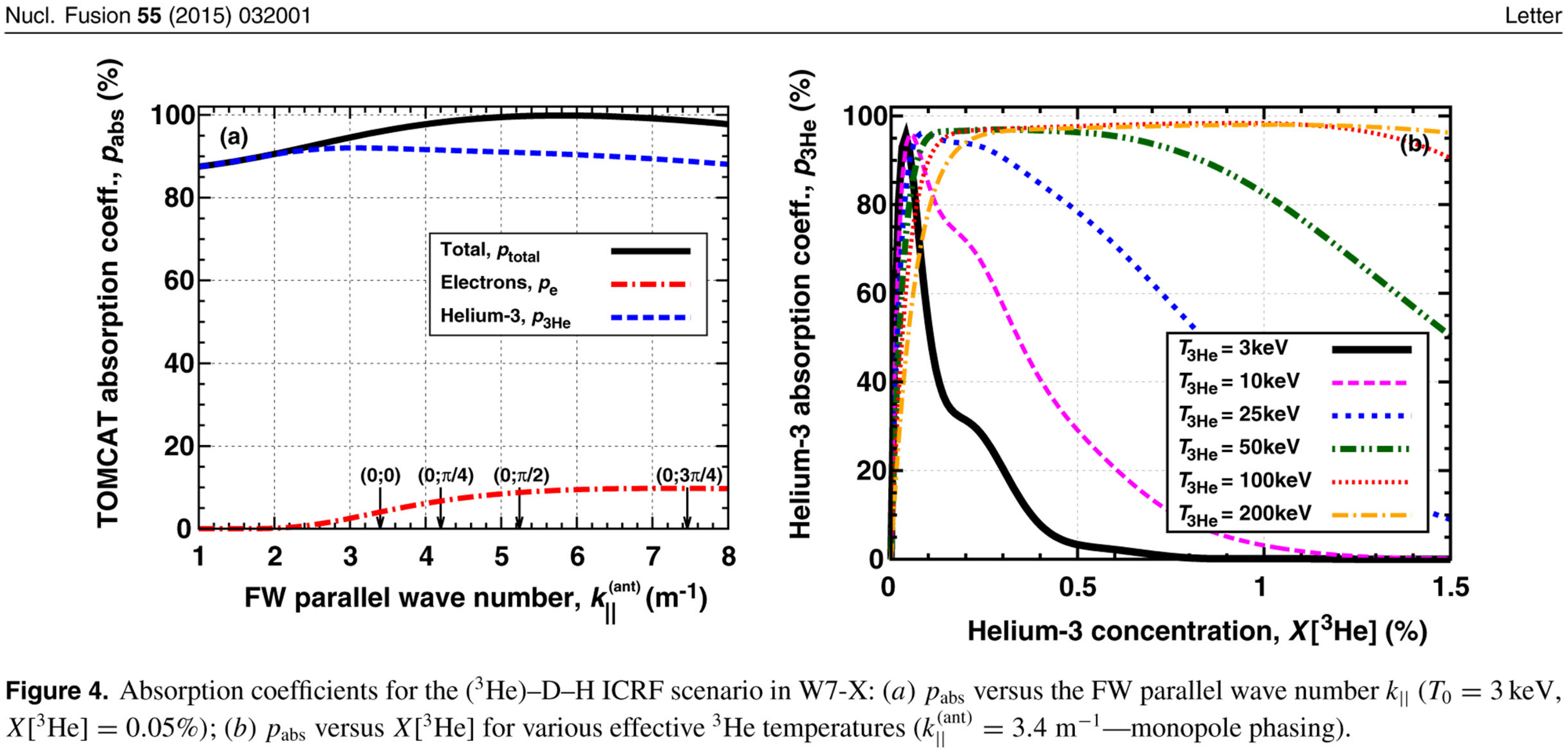


Three-ion (^{3}He)-D-H heating, X[^{3}He]=0.1%, X[H]=70%

$$\mathcal{P}_{\text{coupling}} \propto \mathrm{e}^{-\alpha|k_{\parallel}|d}$$

Three-ion ICRF scenarios: much better absorption at lower $k_{||}$
(better coupling and good absorption)

As ^{3}He tail develops, the RF power absorption stays strong



Nucl. Fusion **55** (2015) 032001 Letter

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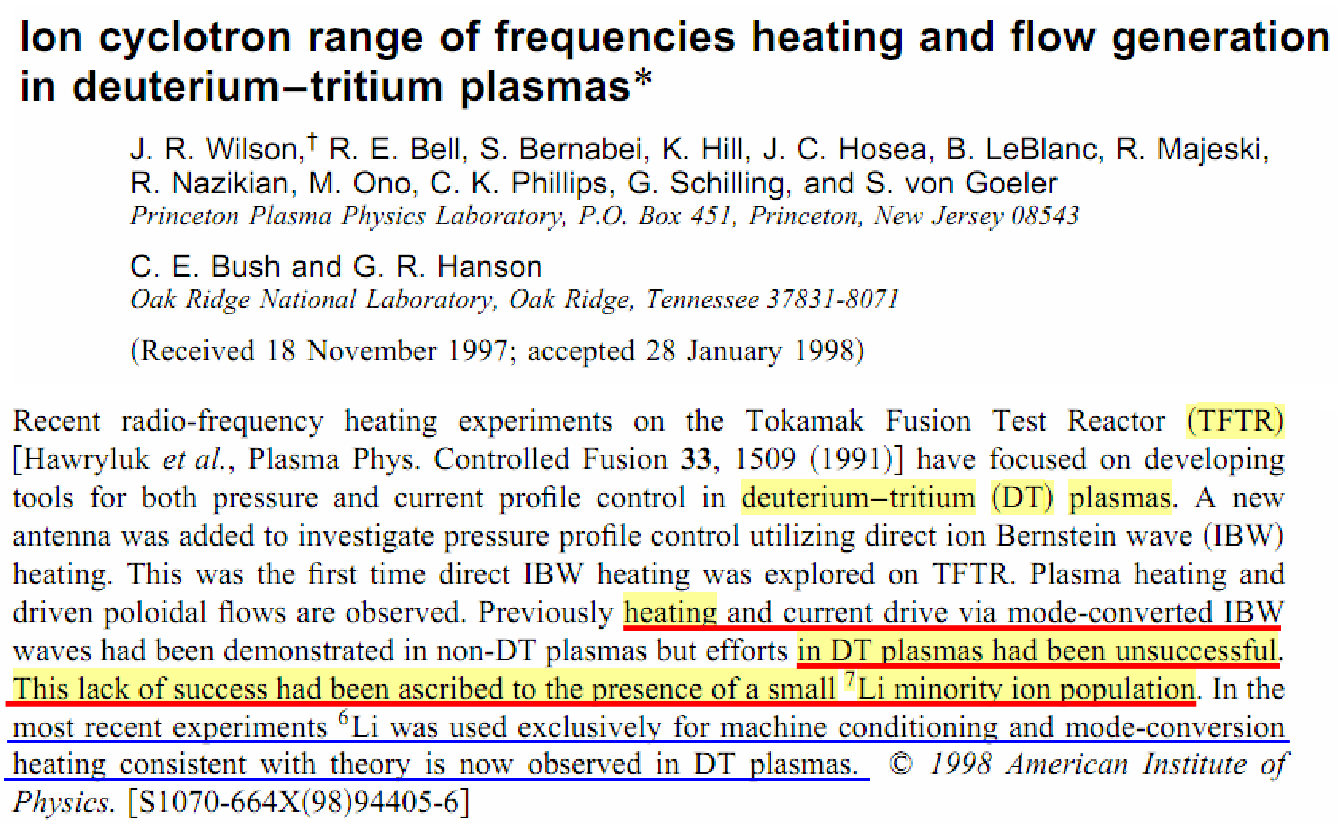
Ye.O. Kazakov et al., NF 55, 032001 (2015)

Experimental evidence of three-ion ICRF scheme: (^{7}Li)-D-T heating in TFTR (1996)

J.R. Wilson et al., Phys. Plasmas 5, 1721-1726 (1998):



Ion cyclotron range of frequencies heating and flow generation in deuterium–tritium plasmas*

J. R. Wilson,† R. E. Bell, S. Bernabei, K. Hill, J. C. Hosea, B. LeBlanc, R. Majeski,
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Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, New Jersey 08543

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Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-8071

(Received 18 November 1997; accepted 28 January 1998)

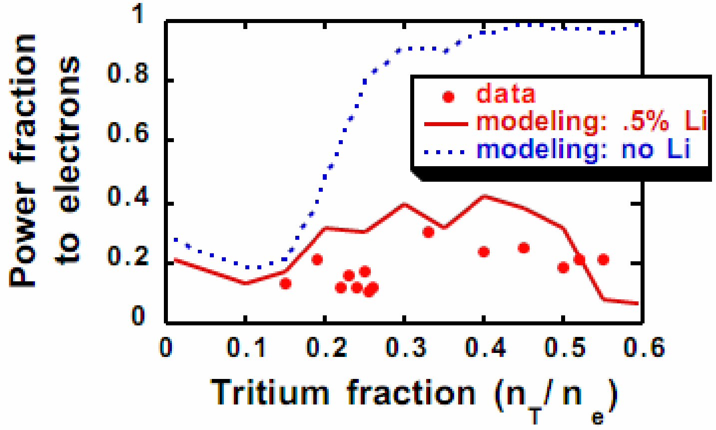
Recent radio-frequency heating experiments on the Tokamak Fusion Test Reactor (TFTR) [Hawryluk *et al.*, Plasma Phys. Controlled Fusion **33**, 1509 (1991)] have focused on developing tools for both pressure and current profile control in deuterium–tritium (DT) plasmas. A new antenna was added to investigate pressure profile control utilizing direct ion Bernstein wave (IBW) heating. This was the first time direct IBW heating was explored on TFTR. Plasma heating and driven poloidal flows are observed. Previously heating and current drive via mode-converted IBW waves had been demonstrated in non-DT plasmas but efforts in DT plasmas had been unsuccessful. This lack of success had been ascribed to the presence of a small ^{7}Li minority ion population. In the most recent experiments ^{6}Li was used exclusively for machine conditioning and mode-conversion heating consistent with theory is now observed in DT plasmas. [S1070-664X(98)94405-6]

$$X[^7\text{Li}] \simeq 0.5\%$$

$$\boxed{\begin{aligned} \text{D} &\rightarrow \mathcal{Z}_1 = 1/2 \\ \text{T} &\rightarrow \mathcal{Z}_2 = 1/3 \\ {}^7\text{Li} &\rightarrow \mathcal{Z}_3 = 3/7 \end{aligned}}$$

$$\text{D} : \text{T} \approx 46\% : 54\%$$

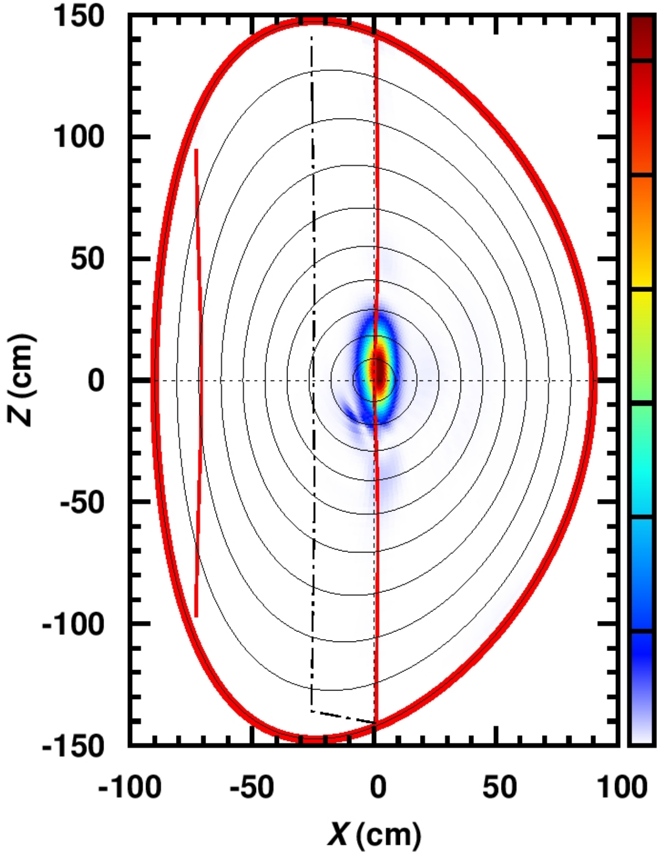
Ion heating dominates!!!



- In TFTR, three-ion ICRF heating was eliminated by using isotopically enriched ^{6}Li pellets for conditioning and standard MC heating was recovered.
- The impact of this 'undesired' impurity absorption can be reverted and such ICRF scenarios have a great potential for fast ion generation and bulk plasma heating

Power absorption: thermal vs. high-energy ^{3}He distrib.

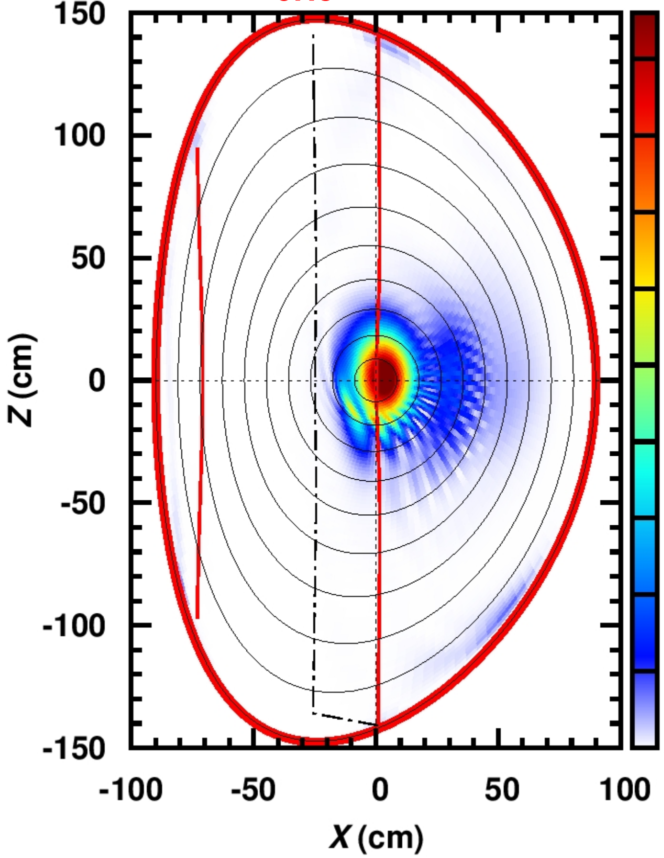
T_{3He} = 4keV



p_{3He} = 96%

$P_{RF,\ 3He}$ = 1.5 MW/m^{3}/MW$_{inj.}$

T_{3He} = 1MeV



p_{3He} = 80%

$P_{RF,\ 3He}$ = 0.5 MW/m^{3}/MW$_{inj.}$

NBI at W7-X:

D. Gradic et al., Nucl. Fusion 55 033002 (2015)
U = 55 kV, $E_0 : E_0/2 : E_0/3 = 51:30:19$