EUROfusion

Recent advances in fast-ion generation and heating multi-ion plasmas with ion cyclotron waves

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JET

LPP ERM - KMS

Alcator C-Mod

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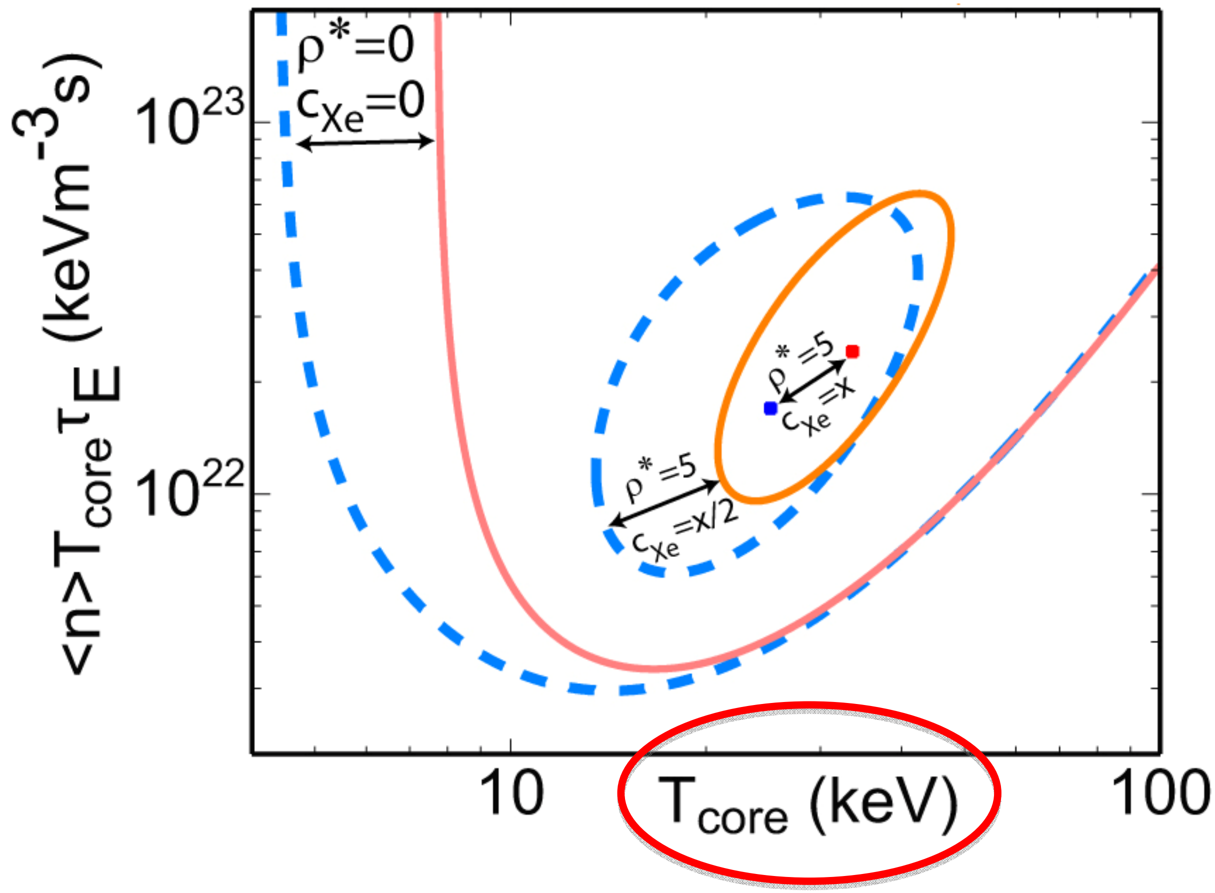
*** See X. Litaudon et al., “Overview of the JET results in support to ITER”, *Nucl. Fusion* 57,102001 (2017)**

Reminder: burn curves for D-T plasmas



T. Pütterich et al., EPS (2015)
T. Pütterich et al., *this conference* (I6)

$$T_{\rm core} \approx 20 - 30\ \mathrm{keV}$$

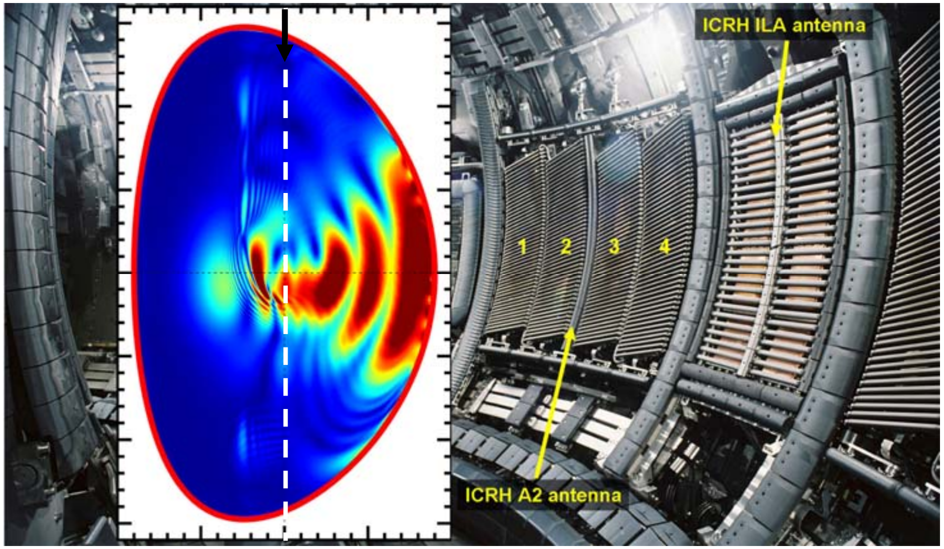
ICRH heating: experimental setup

- **ICRH: heating with waves in the ion cyclotron frequency range,** $\omega_{ci} = (q_i/m_i)B$
- **Intuitive idea: launch RF waves at the ion cyclotron frequency or harmonics**

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

- **Wave-particle resonance condition is satisfied locally since** $B(R) \approx B_0R_0/R$

$\omega = \omega_{ci}$



$\omega = n\omega_{ci}$: vertical line in tokamaks

- **ICRH can also provide electron heating (mode conversion and ELD/TTMP)**

Electron heating in mixture plasmas with ICRH

Wave propagation: cutoffs and resonances

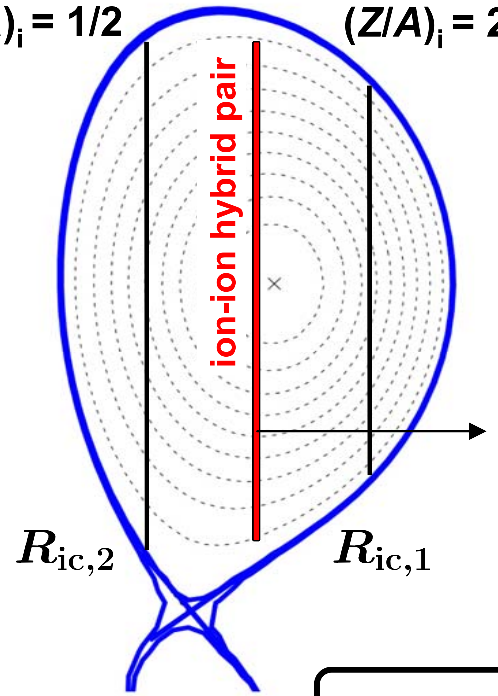
$$n^2_{\perp,\mathrm{FW}}(R) \simeq \frac{(\epsilon_\mathrm{L} - n^2_\parallel)(\epsilon_\mathrm{R} - n^2_\parallel)}{\epsilon_\mathrm{S} - n^2_\parallel}$$

Wave polarization:

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

species no. 2
e.g., D
$(Z/A)_\mathrm{i} = 1/2$

species no. 1
e.g., ^{3}He
$(Z/A)_\mathrm{i} = 2/3$



$$\begin{cases} \epsilon_\mathrm{L} = n^2_\parallel \text{, ion-ion hybrid cutoff (L-cutoff)} \\ \epsilon_\mathrm{S} = n^2_\parallel \text{, ion-ion hybrid resonance} \end{cases}$$

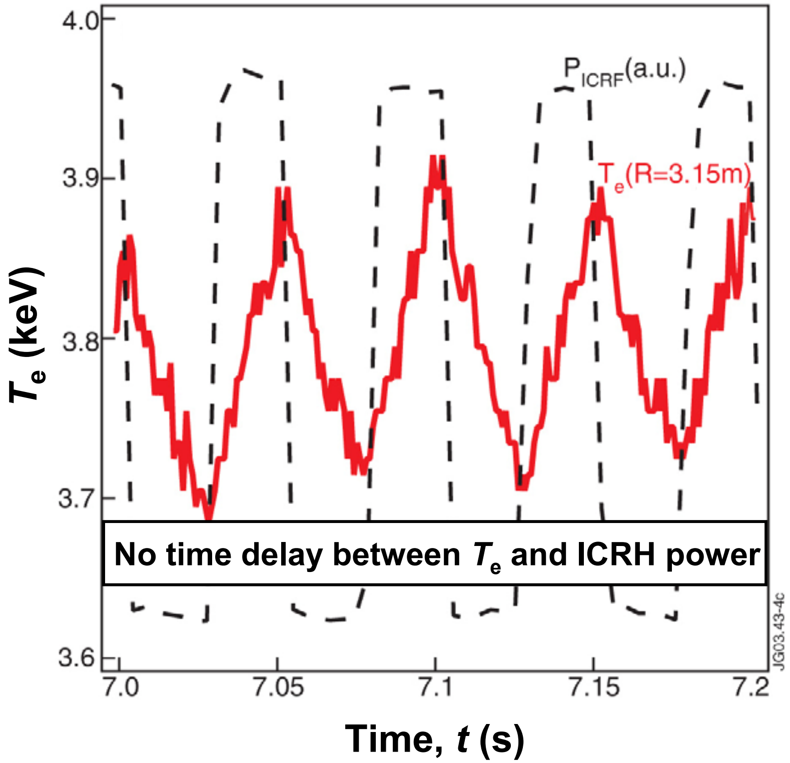
- **Two ion species, $(Z/A)_1$ and $(Z/A)_2$:** **an ion-ion hybrid cutoff-resonance pair** **between $R_\mathrm{ic,1}$ and $R_\mathrm{ic,2}$**
- **Mixture plasmas (large minority concentrations)** **→ direct electron heating with ICRH**

$\epsilon_\mathrm{S}, \epsilon_\mathrm{L}, \epsilon_\mathrm{R}$ are the dielectric tensor components in the notation of Stix

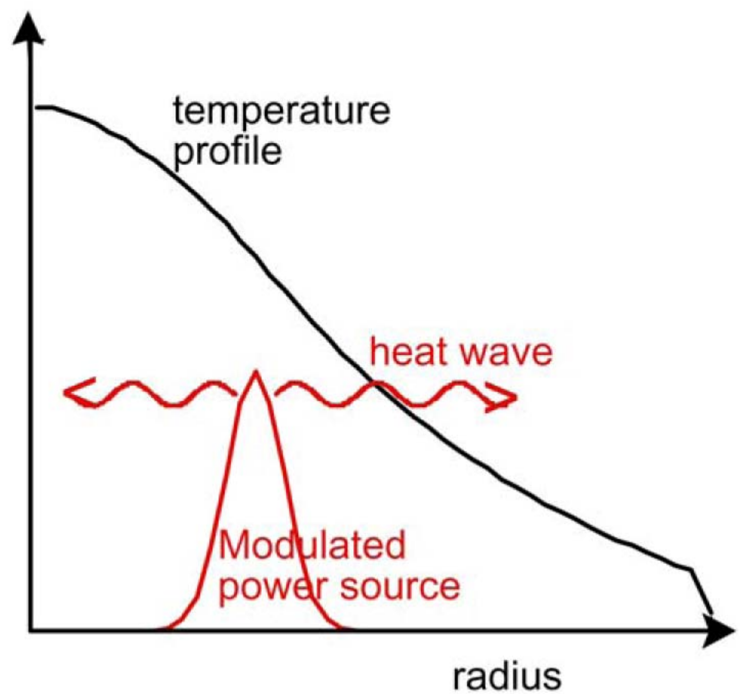
ICRH in mixture plasmas with MC layer: electron heating → ion absorption

Typically used as a localized source of direct electron heating, e.g., for transport studies

D-^{3}He plasma in JET: $X[^3He] \approx 20\%$
M.J. Mantsinen et al., *Nucl. Fusion* (2004)



P. Mantica and F. Ryter (2006)



Wave absorption by ions still possible:

two-ion plasmas → multi-ion plasmas (≥ 3, 'three-ion' species scenarios)

Outline

- ‘Three-ion’ species ICRH scenarios: theoretical concept[1,2,3]
- Recent experiments on Alcator C-Mod and JET

  Scenario 1, D-(^{3}He)-H: minority heating of ^{3}He ions in H-D mixtures[4,5]

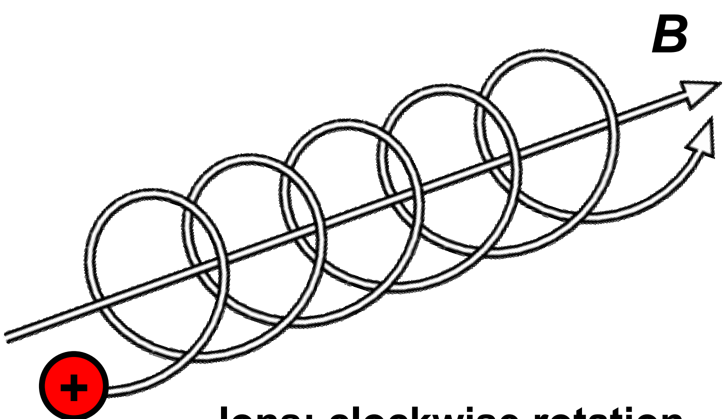
  Scenario 2, D-(D_{NBI})-H: minority heating of D-NBI ions in H-D mixtures[6]
- ^{3}He-rich solar flares and three-ion species experiments[4]
- Applications of new scenarios for JET, W7-X[5] and ITER[2]
- Conclusions

References:

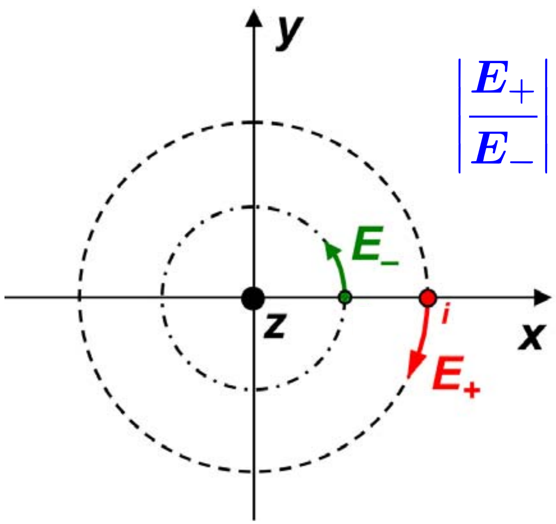
[1] Y. Kazakov, D. Van Eester, R. Dumont and J. Ongena, *Nucl. Fusion* 55, 032001 (2015)
[2] Y. Kazakov, J. Ongena, D. Van Eester, R. Bilato et al., *Phys. Plasmas* 22, 082511 (2015)
[3] D. Van Eester, Y. Kazakov and E. Lerche, *Plasma Phys. Control. Fusion* 59, 085012 (2017)
[4] Y. Kazakov, J. Ongena, J.C. Wright et al., *Nature Physics* 13, 973–978 (2017); http://dx.doi.org/10.1038/nphys4167
[5] J.M. Faustin, J.P. Graves, W.A. Cooper et al., *Plasma Phys. Control. Fusion* 59, 084001 (2017)
[6] J. Ongena, Y. Kazakov et al., “Observations of synergetic acceleration of D-NBI ions in the vicinity of the mode conversion layer in H-D plasmas”, *EPJ Web of Conferences*, accepted for publication

Effect of wave polarization and plasma composition

Ions rotate co-clockwise with an ion cyclotron frequency ω_{ci}



Wave polarization: E_+ and E_- field components



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

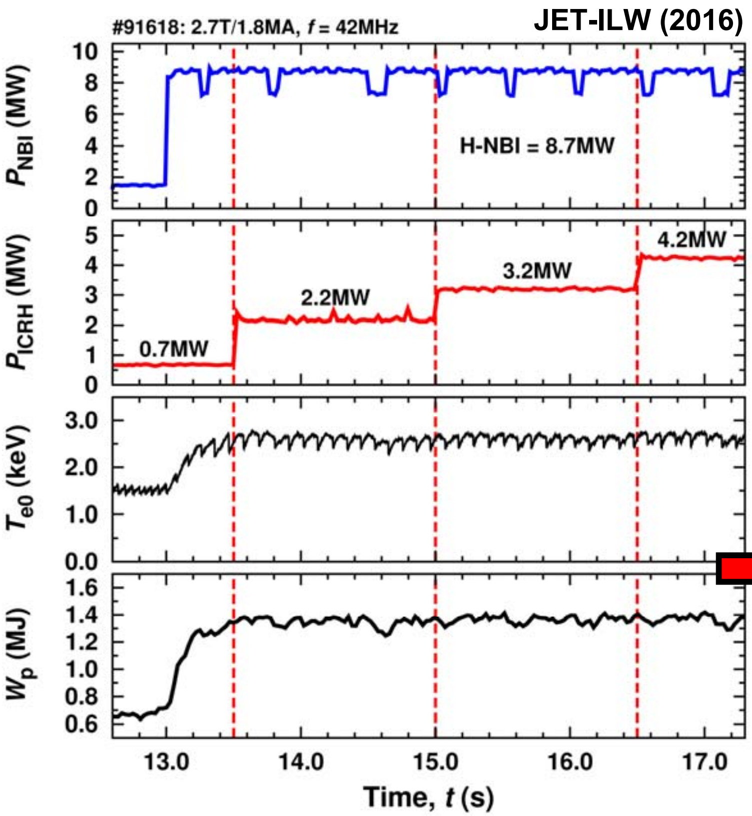
- **Thermal and moderately energetic ions (~ 100 keV): wave absorption is due to the left-hand polarized RF electric field component E_+**

$$\omega \approx \omega_{ci} \quad (n=1): \quad P_{\text{abs}} \propto \left|E_+ J_0(k_\perp \rho_L) + E_- J_2(k_\perp \rho_L)\right|^2 \approx |E_+|^2$$

- **E_+ and E_- vary locally and are mainly determined by plasma composition (number of ion species with different Z/A and their relative concentrations)**

Illustration of the importance of wave polarization

Case 1, single-ion plasmas:
fundamental (n = 1) cyclotron heating of H and H-NBI ions in hydrogen plasmas



Plasma composition: X[H] ≈ 100%

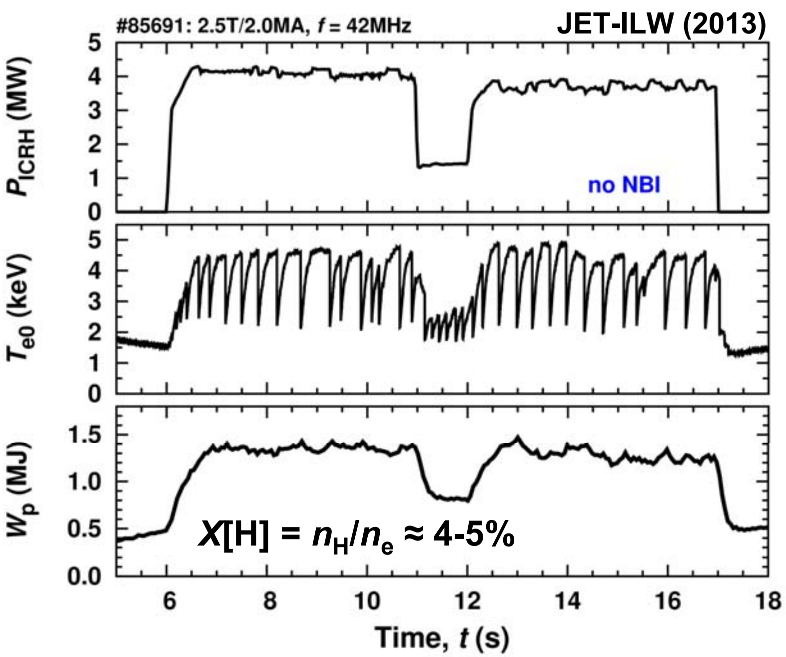
- Wave accessibility to the plasma core
- Presence of resonant ions, $\omega = \omega_{ci} + k_{||}v_{||}$
- Left-hand polarized component, $E_+ = 0$ (single-ion plasmas)

ICRH power: 0.7MW → 2.2MW → 3.2MW → 4.2MW
Plasma response: $\Delta T_e \approx 0$, $\Delta W_p \approx 0$

Outcome: inefficient ICRH heating, $\omega = \omega_{cH} + k_{||}v_{||}$

Illustration of the importance of wave polarization

Case 2, two-ion plasmas:
fundamental (n = 1) cyclotron heating of H (minority) ions in deuterium plasmas



Plasma composition: X[D] ≈ 95%, X[H] ≈ 5%

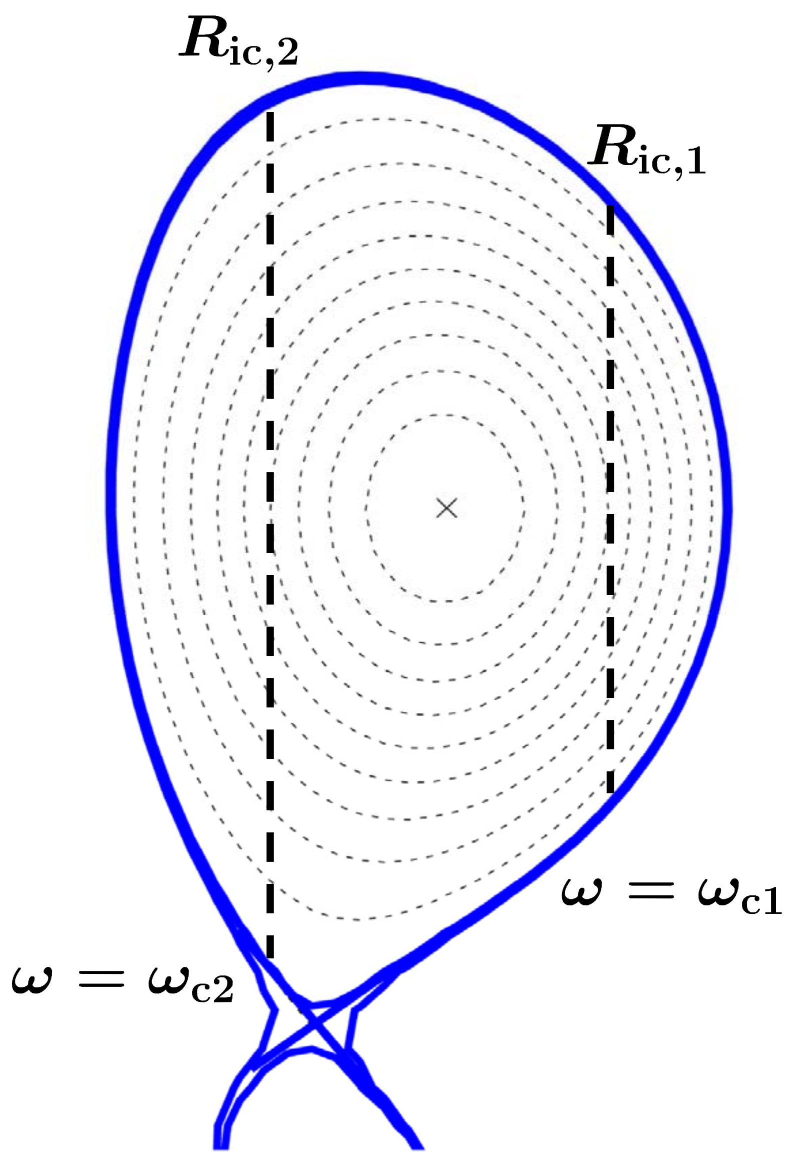
- Wave accessibility to the plasma core
- Presence of resonant ions, $\omega = \omega_{ci} + k_{||}v_{||}$
- Left-hand polarized component, $E_+ \neq 0$ (two-ion plasmas)

Outcome: efficient ICRH heating, $\omega = \omega_{cH} + k_{||}v_{||}$

✓ Minority heating is efficient at $X_{mino} = n_{mino}/n_e \approx$ 2–10%

✓ 'Three-ion' species scenarios extend the operational range for MH

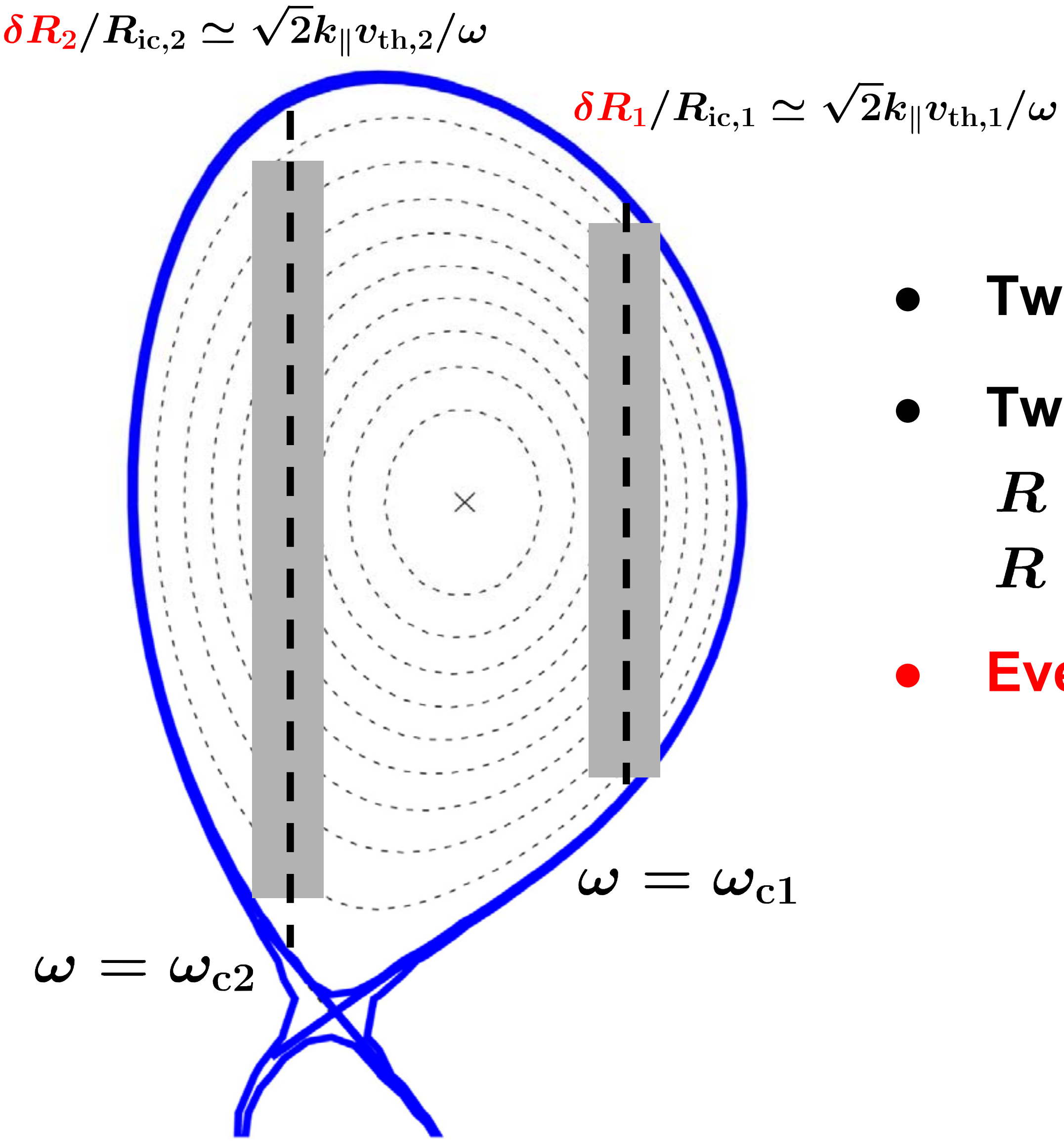
Ion cyclotron heating in two-ion plasmas



- **Two ion species: (Z/A)$_1$ and (Z/A)$_2$**
- **Two ion cyclotron layers:**

$$R = R_{\mathrm{ic},1} \quad (\omega = \omega_{c1})$$
$$R = R_{\mathrm{ic},2} \quad (\omega = \omega_{c2})$$

Ion cyclotron heating in two-ion plasmas

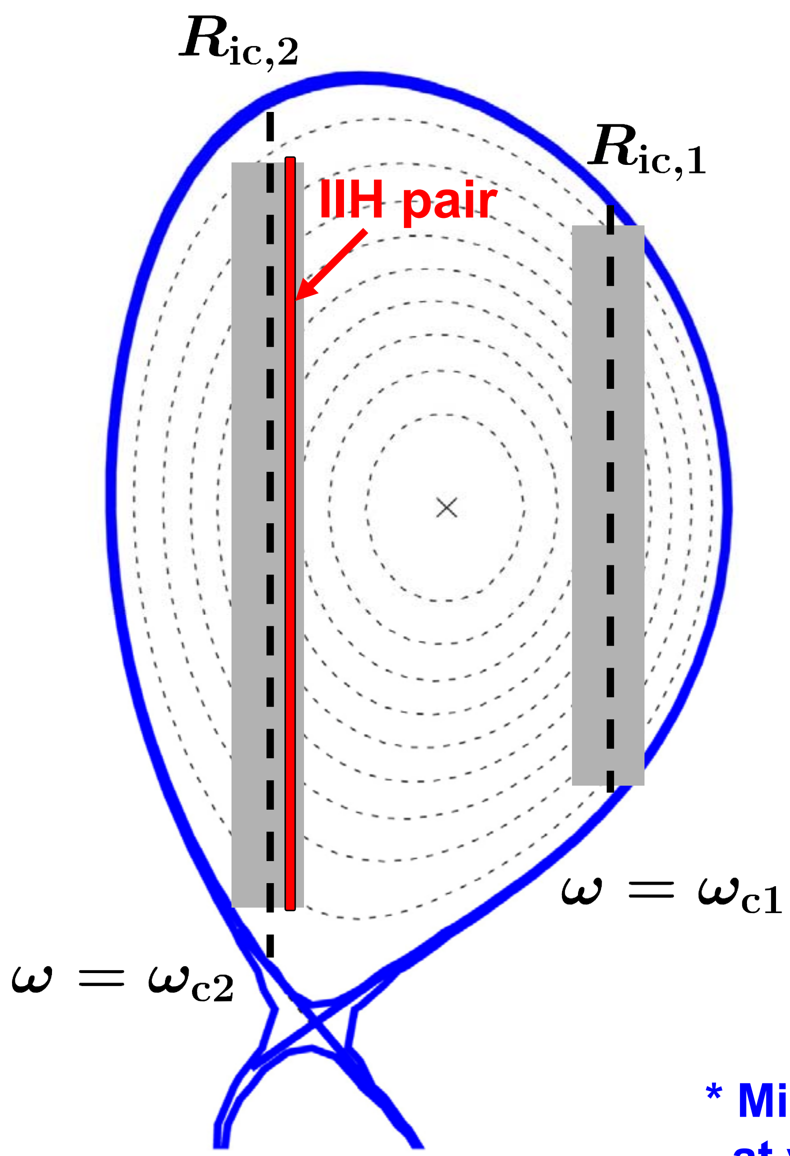


- **Two ion species: (Z/A)$_1$ and (Z/A)$_2$**
- **Two ion cyclotron layers:**

$$R = R_{ic,1} \quad (\omega = \omega_{c1})$$
$$R = R_{ic,2} \quad (\omega = \omega_{c2})$$

- **Every IC layer has a natural width $\delta R_{1,2}$**

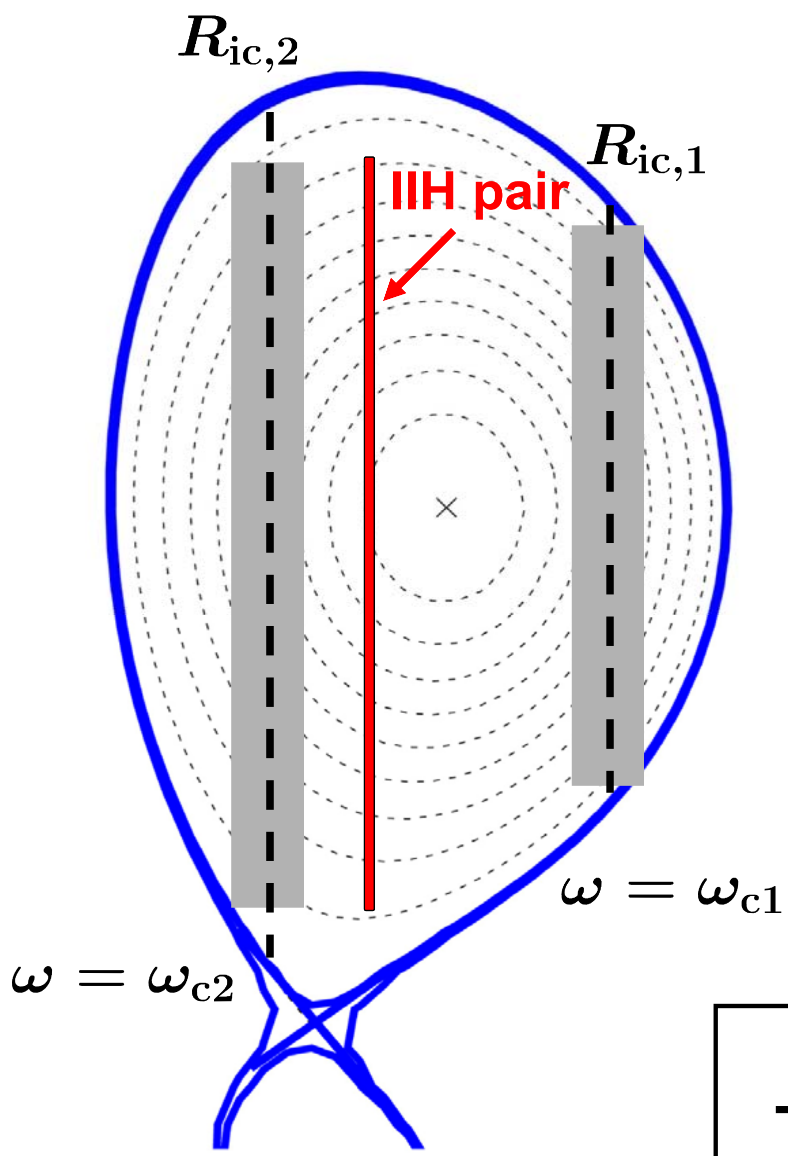
Ion cyclotron heating in two-ion plasmas



- Ion-ion hybrid (IIH) layer, large E_+: located in between $R_{ic,2}$ and $R_{ic,1}$
- IIH layer close to cyclotron resonance if X_2 is a few % $\rightarrow$ minority heating

* Minority absorption in two-ion plasmas is not efficient at very low concentrations (‰): no ion-ion hybrid layer

Electron mode conversion heating in two-ion plasmas



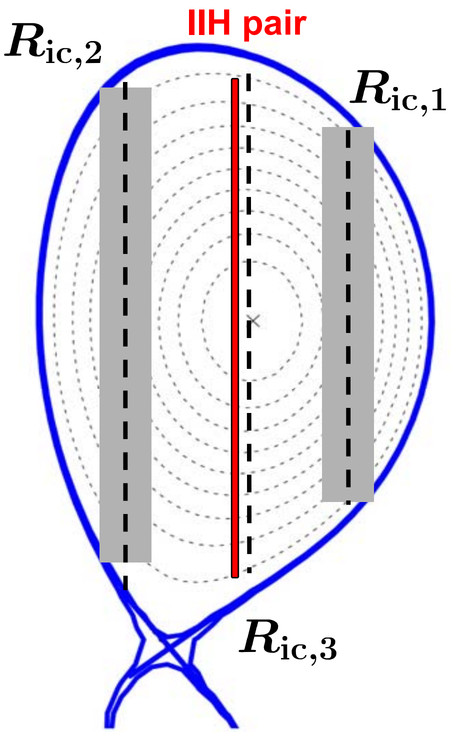
- **At larger X_{mino}, lack of resonant ions capable to absorb RF power**

$$v_{\parallel} = \left| \frac{\omega - \omega_{ci}^{(1,2)}}{k_{\parallel}} \right| \gg v_{\mathrm{th}}^{(1,2)}$$

- **Localized electron heating through mode conversion dominates**
- **Still very strong E_+ in the vicinity of the IIH layer**

Effective ion absorption still possible!
Two-ion plasmas → multi-ion plasmas

Mixture plasmas with MC layer: from electron heating to ion absorption



- **Direct electron heating → ion absorption scenarios:** ***extend plasma composition to include additional ion species***
- **Location of the IIH layer is determined by the concentrations of ion species (X_1, X_2, …)**

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

1) Add third ions with $(Z/A)_i$ different than for the two main ions

$$(Z/A)_2 < (Z/A)_3 < (Z/A)_1$$

2) Add third ions with a large Doppler shift: can have (Z/A) as the majority ions

‘Three-ion’ species ICRH scenarios (option no. 1): optimal plasma composition

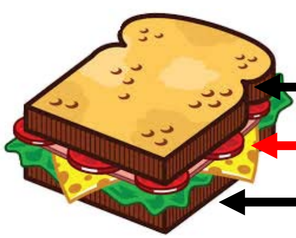
- ✓ **Three-ion species plasmas,** $(Z/A)_2 < (Z/A)_3 < (Z/A)_1$ **(multi-ion plasmas also ok)**
- ✓ **Proper choice of plasma composition:** $X_1 \gtrsim X_1^*, \quad X_2 \lesssim X_2^*$

$$X_1^* \approx \frac{1}{Z_1}\frac{(Z/A)_1 - (Z/A)_3}{(Z/A)_1 - (Z/A)_2} \qquad X_2^* \approx \frac{1}{Z_2}\frac{(Z/A)_3 - (Z/A)_2}{(Z/A)_1 - (Z/A)_2}$$

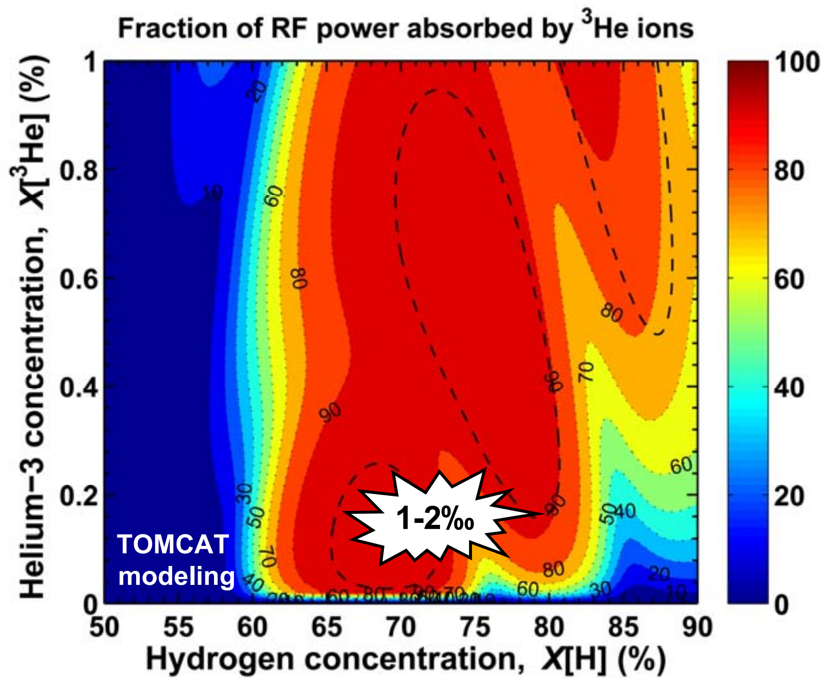
[Y. Kazakov et al., NF (2015)]

- ✓ **Proof-of-principle test:**

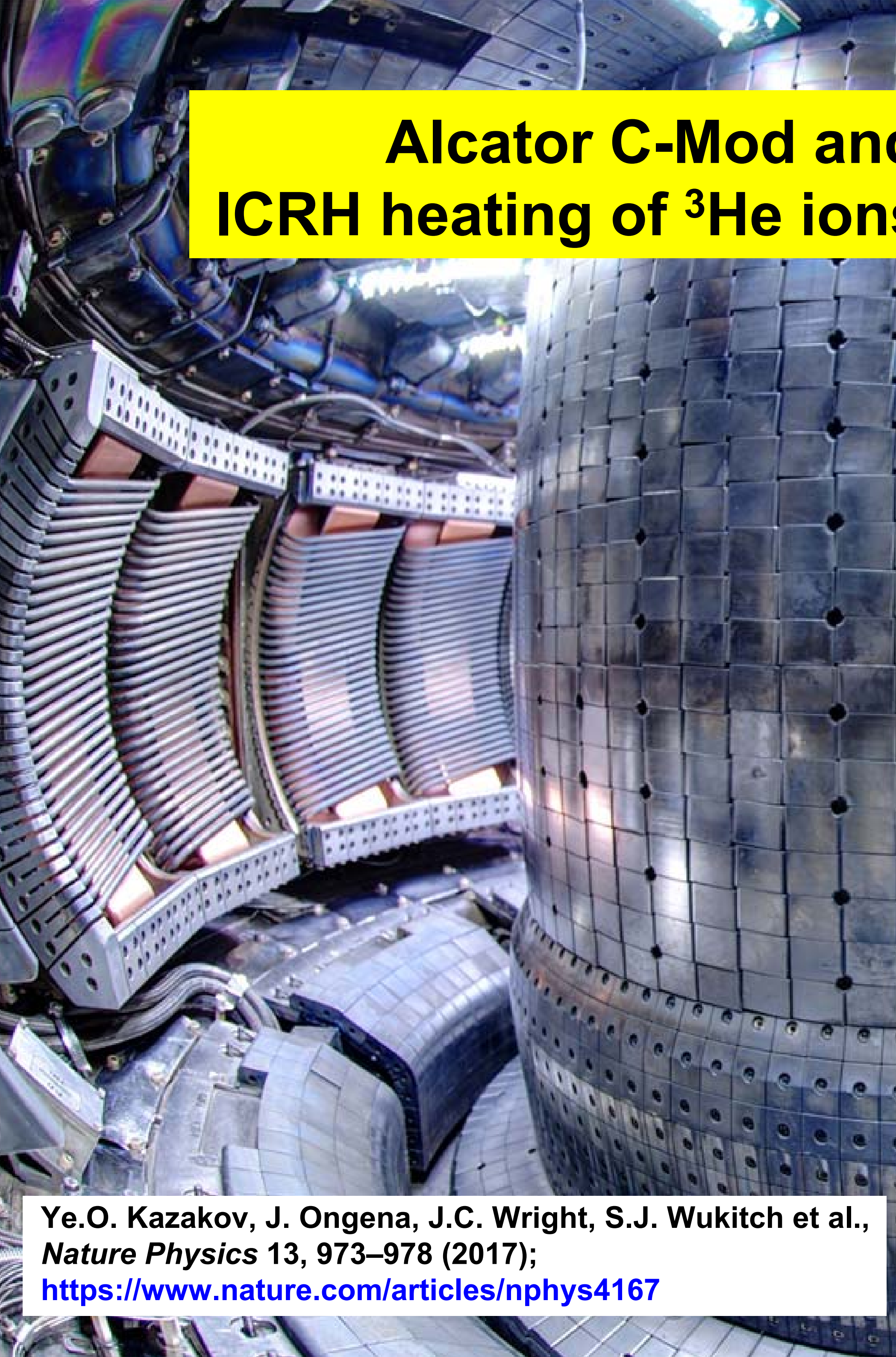
H-D mixture (X[H] ≥ 70%)
Small amount of ^{3}He (≤ 1%, see figure)

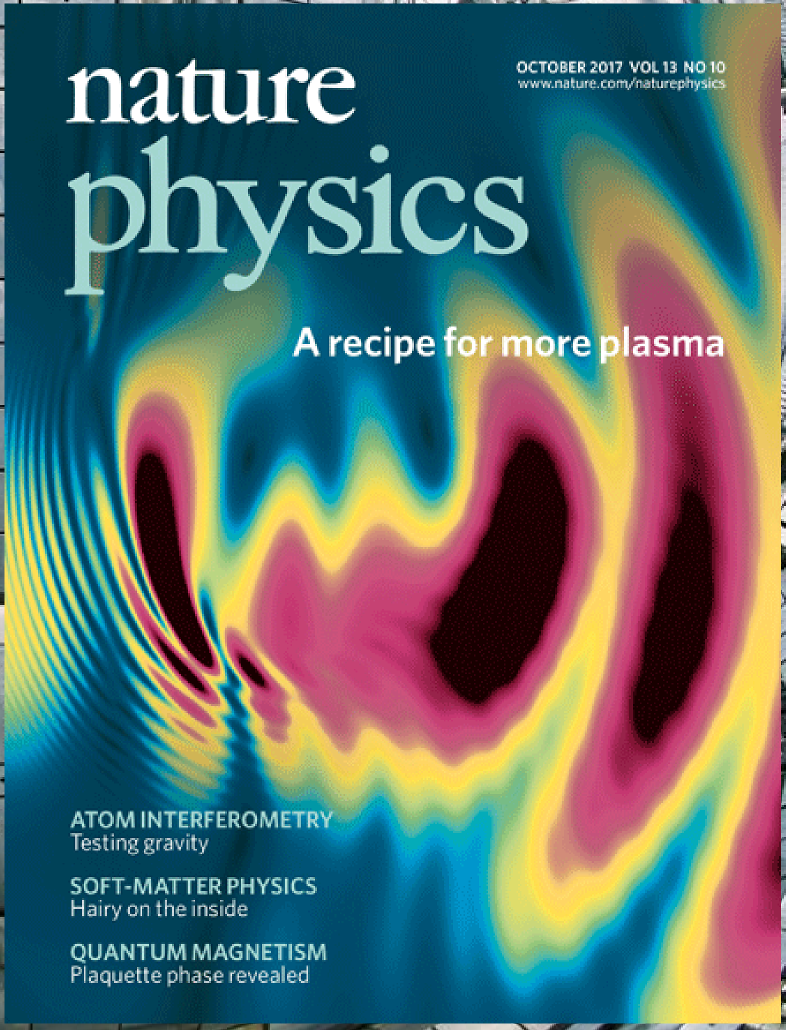


Hydrogen: $(Z/A)_1 = 1/1$
Helium-3 (resonant ions): $(Z/A)_3 = 2/3$
Deuterium: $(Z/A)_2 = 1/2$



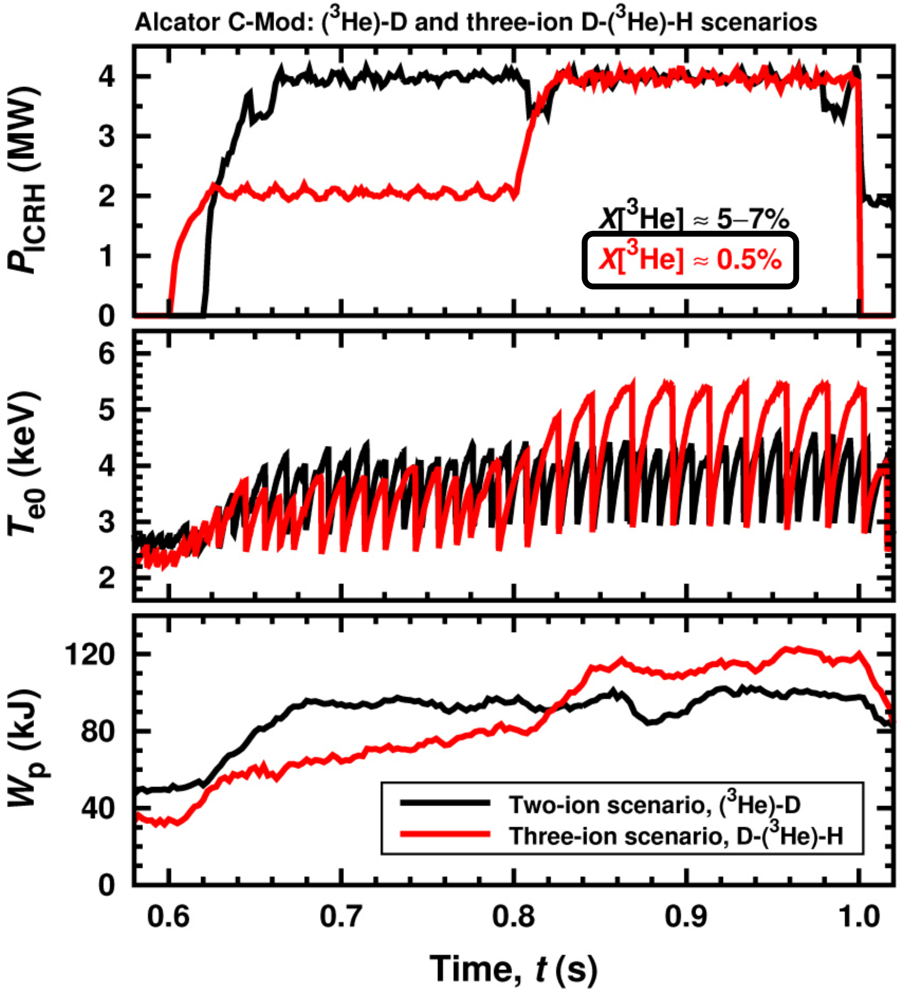
Alcator C-Mod and JET experiments: ICRH heating of ^{3}He ions in H-D mixture plasmas

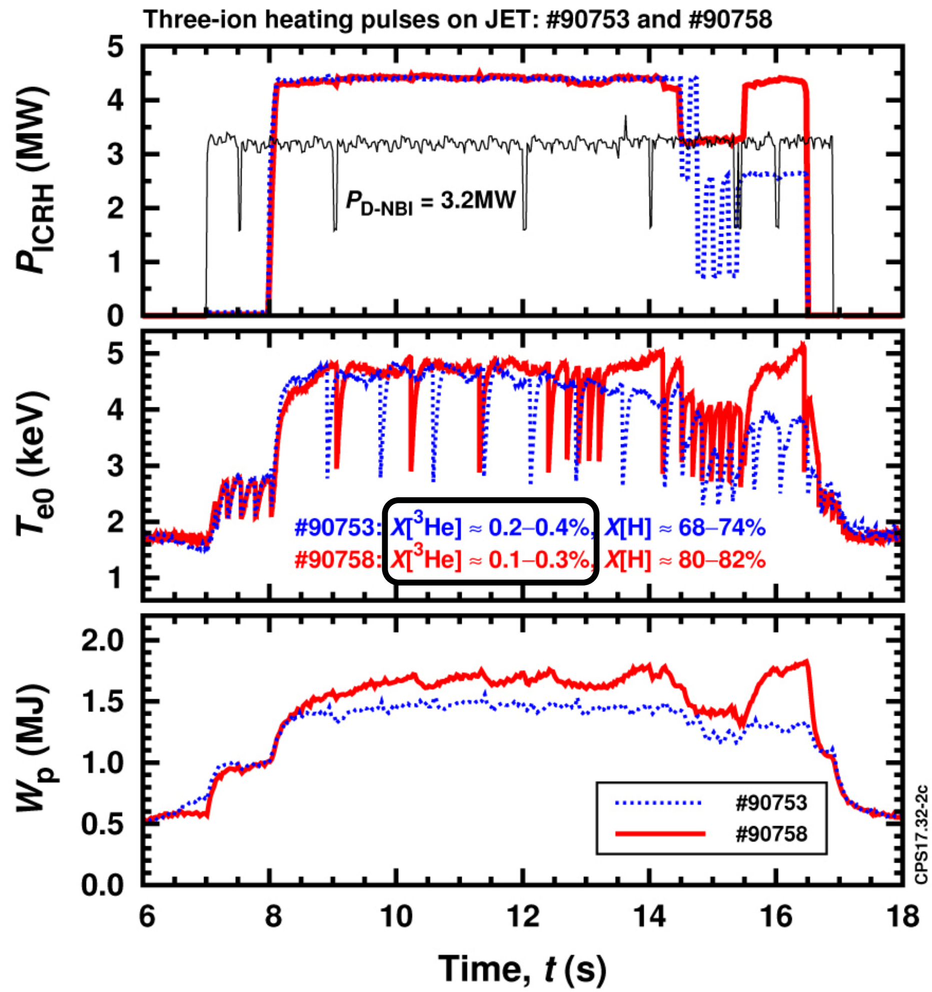




Ye.O. Kazakov, J. Ongena, J.C. Wright, S.J. Wukitch et al., *Nature Physics* 13, 973–978 (2017);
https://www.nature.com/articles/nphys4167

Alcator C-Mod and JET: efficient plasma heating observed





High heating efficiency … while using a factor of 10 less ^{3}He

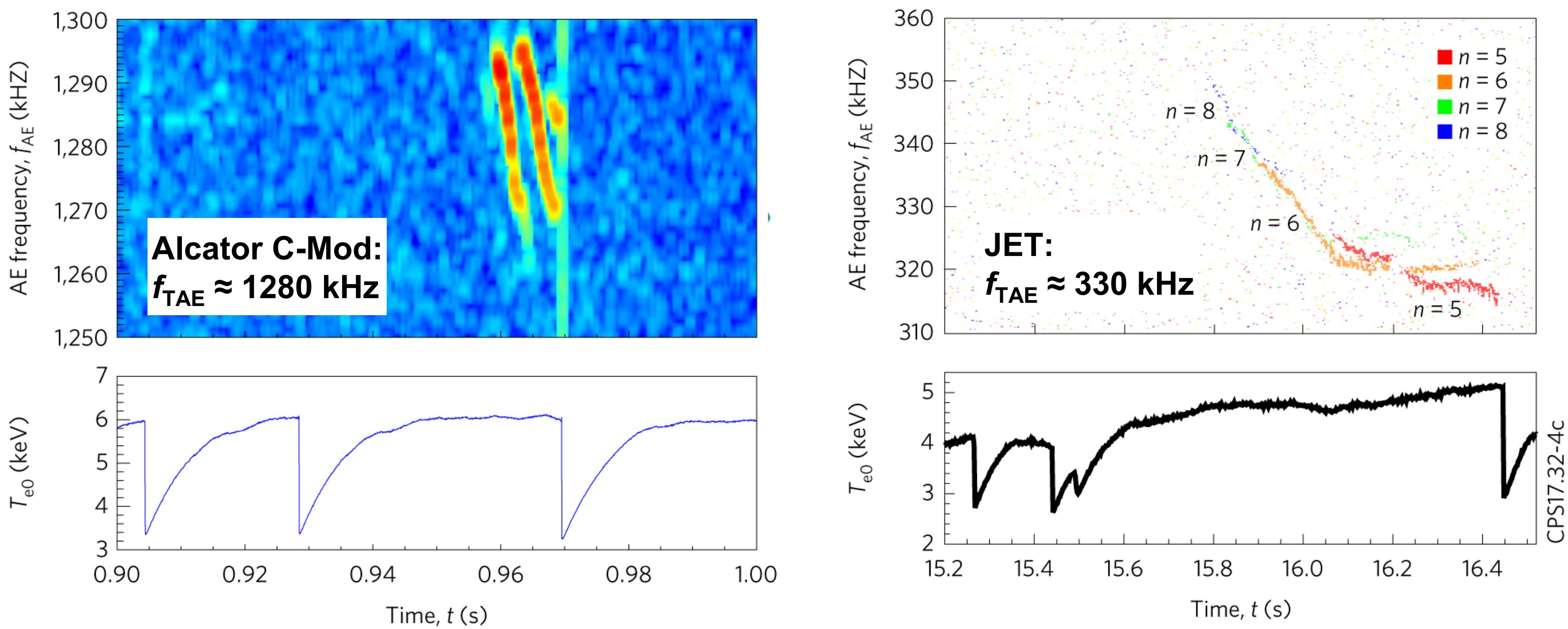
Alcator C-Mod and JET: energetic ions generated

- **Reducing minority concentrations from % to ‰ levels → increasing absorbed ICRH power per resonant ion**

$$E_{\rm mino}^{\rm (Stix)}({\rm keV}) \simeq \frac{0.24\,[T_e({\rm keV})]^{3/2} A_{\rm mino} \langle P_{\rm RF}\rangle_{\rm MW/m^3}}{n_{e,20}^2\, Z_{\rm mino}^2\, X_{\rm mino}}$$

T.H. Stix et al., *Nucl. Fusion*, 1975

- **Efficient tool for generating energetic ions in a plasma**
- **Sawteeth stabilization and core localized TAE modes**

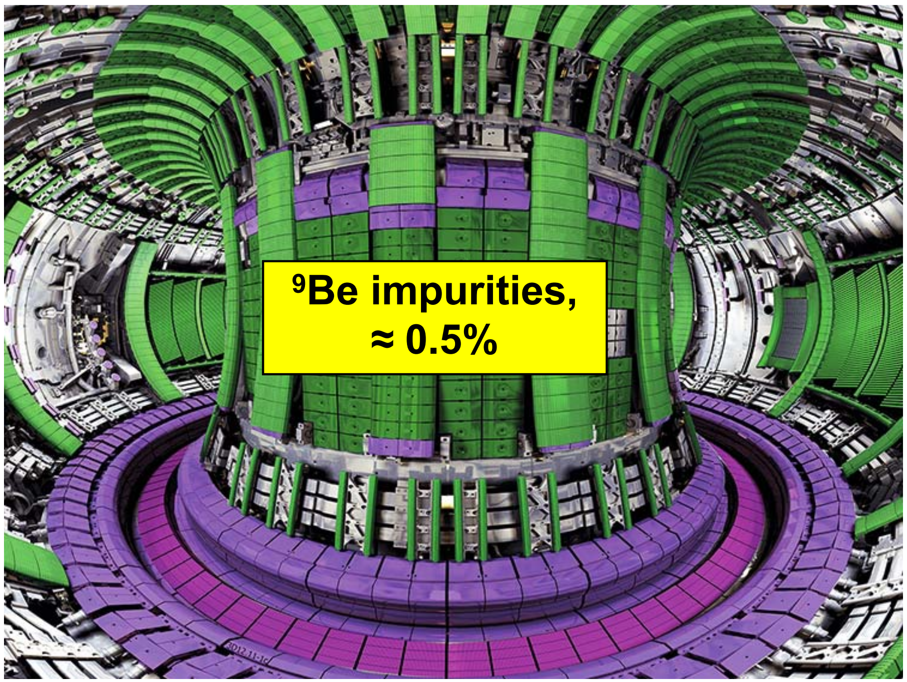


JET: unambiguous detection of MeV-range ^{3}He ions

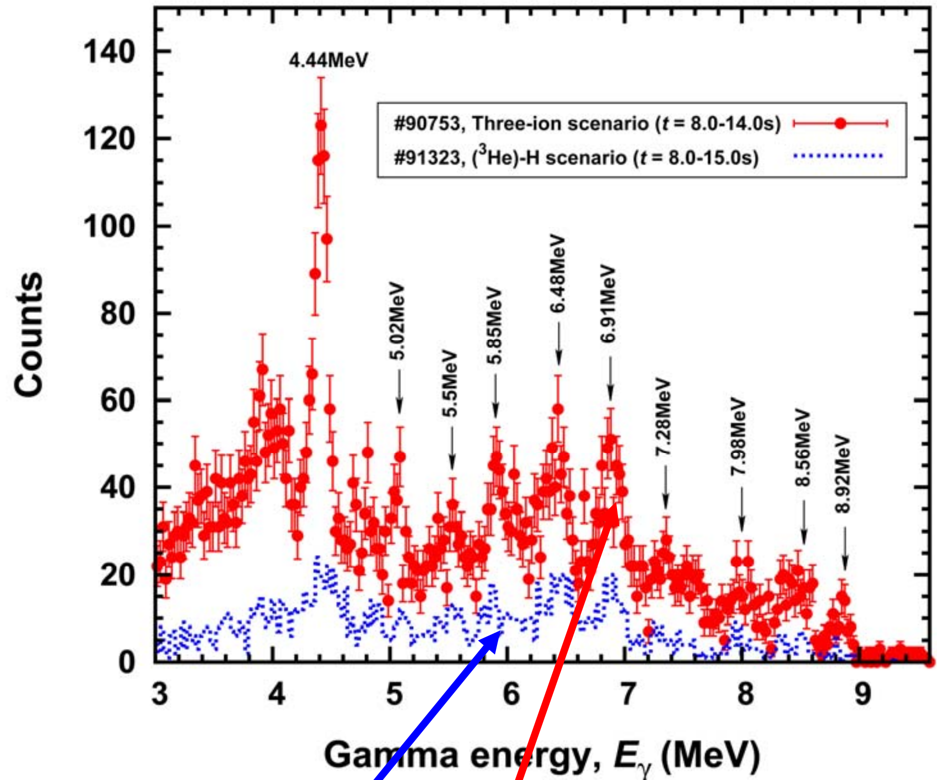
MeV-range ^{3}He ions generated with ICRH → characteristic gamma-ray emission from nuclear reactions between ^{3}He and intrinsic ^{9}Be impurities (~ 0.5%)

^{3}He + ^{9}Be → ^{11}B* + *p*; ^{3}He + ^{9}Be → ^{11}C* + *n*

E_γ = 4.44MeV / 5.02MeV / 5.5MeV / 5.85MeV / 6.48MeV / 6.91MeV / 7.28MeV / 7.98MeV/ …



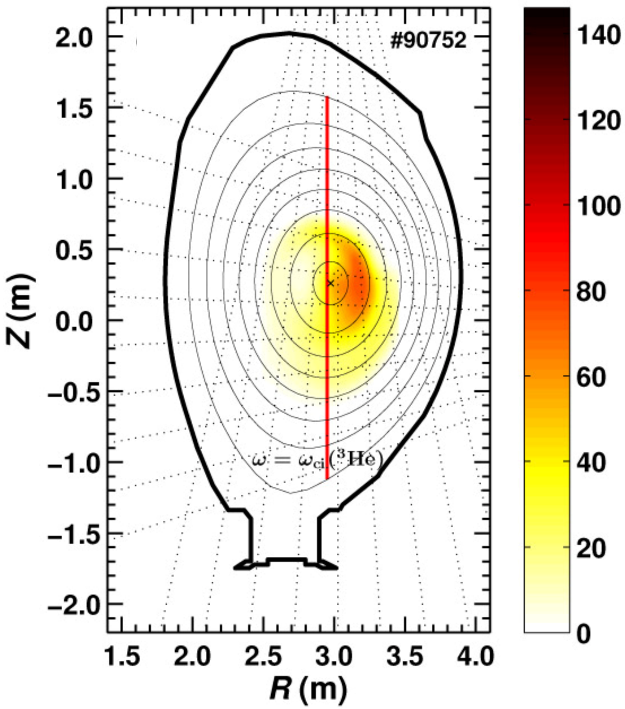
Bulk Be PFCs
Be−coated inconel PFCs
Bulk W
W−coated CFC PFCs



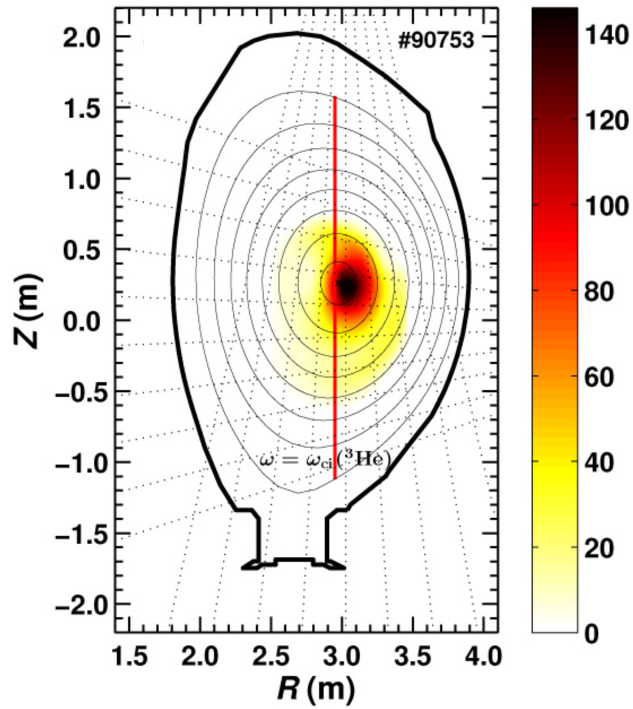
- **(^{3}He)-H scenario (proton plasma): $X[^3\text{He}]$ ≈ 1–2%, P_{ICRH} up to 7.6MW**
- **D-(^{3}He)-H scenario (H-D plasma): $X[^3\text{He}]$ ≈ 0.2–0.4%, P_{ICRH} ≈ 4.4MW**

Reconstructed gamma-ray emission: visualization of fast-ion population

#90752 and #90753: the same ICRH and NBI power, *X*[H] ≈ 70-75% and *X*[^{3}He] ≈ 0.2-0.4%



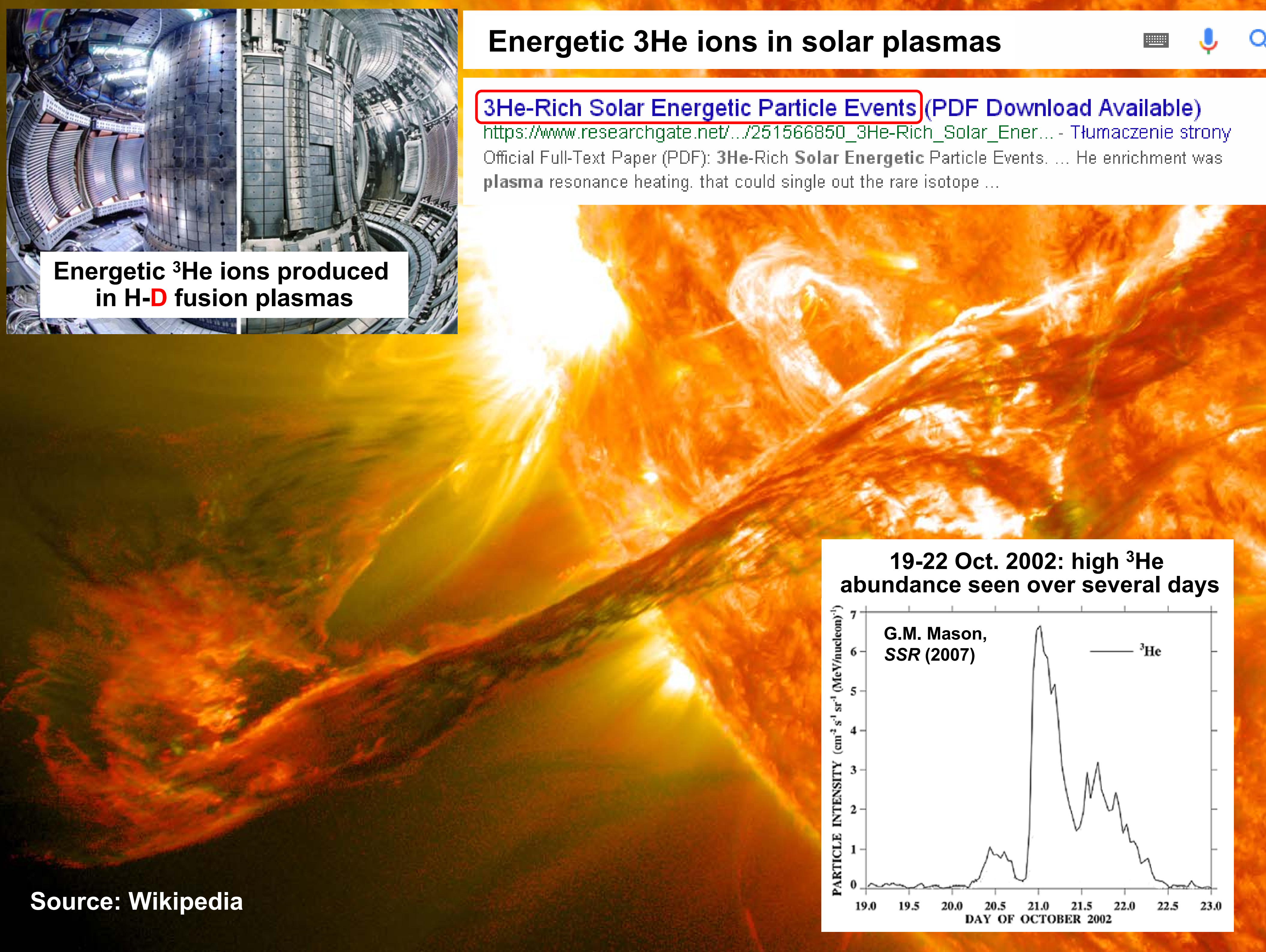
ICRH: dipole phasing (4.3MW)



ICRH: dipole (2.3MW) and +*π*/2 phasing (2.1MW)

- Efficiency of fast-ion generation enhanced by using +*π*/2 phasing of ICRH antennas
- RF-induced pinch effect and lower $|k_{||}|$

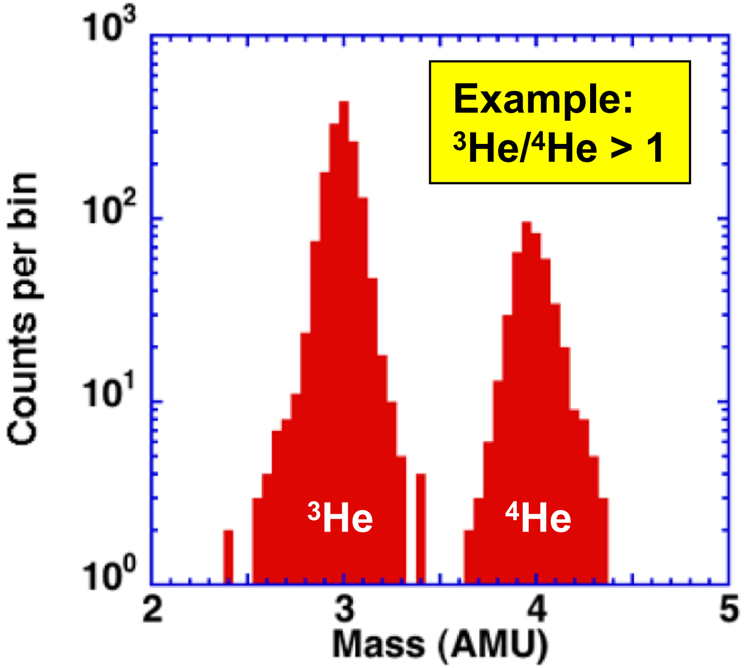
M.J. Mantsinen et al., *PRL* 89, 115004 (2002); J.M. Faustin et al. *PPCF* 59, 084001 (2017)



Energetic 3He ions in solar plasmas
3He-Rich Solar Energetic Particle Events (PDF Download Available)
https://www.researchgate.net/.../251566850_3He-Rich_Solar_Ener... - Tłumaczenie strony
Official Full-Text Paper (PDF): 3He-Rich Solar Energetic Particle Events. ... He enrichment was plasma resonance heating. that could single out the rare isotope ...
Energetic ³He ions produced in H-D fusion plasmas
19-22 Oct. 2002: high ³He abundance seen over several days
G.M. Mason, SSR (2007)
³He
PARTICLE INTENSITY (cm⁻² s⁻¹ sr⁻¹ (MeV/nucleon)⁻¹)
0
1
2
3
4
5
6
7
19.0
19.5
20.0
20.5
21.0
21.5
22.0
22.5
23.0
DAY OF OCTOBER 2002
Source: Wikipedia

^{3}He-rich solar flares

- A class of solar flares with anomalously high $^3He/^4He$ ratio in the MeV-energy range
  D. Reames, *Space Sci. Rev.* 90, 413-491 (1999); G.M. Mason, *Space Sci. Rev.* 130, 231-242 (2007)
- Typical ratio $^3He/^4He \sim 1/2500$ → $^3He/^4He \sim 1$ in ^{3}He-rich solar flares



G.M. Mason, *SSR* (2007)

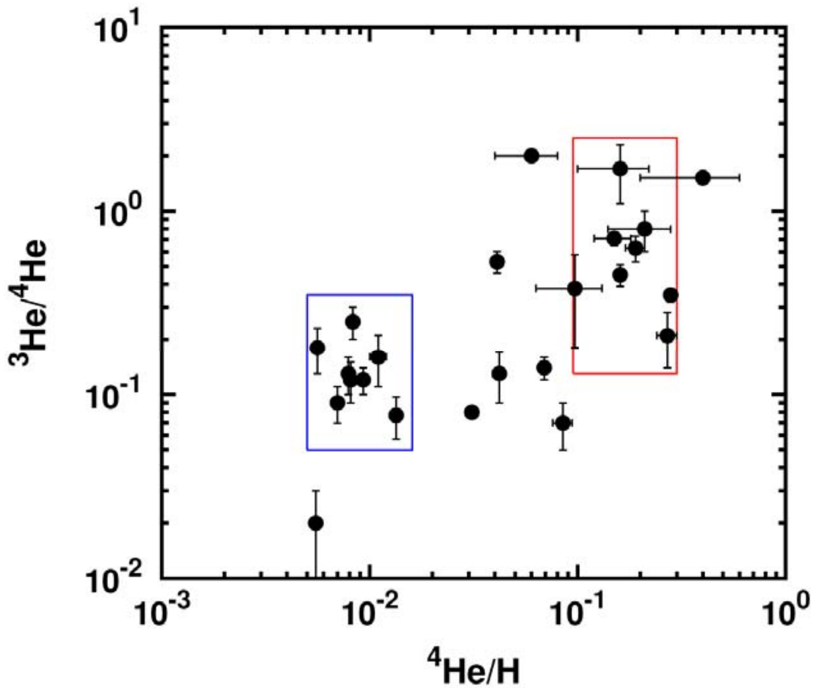
Mechanism for observed ^{3}He enrichment (?)

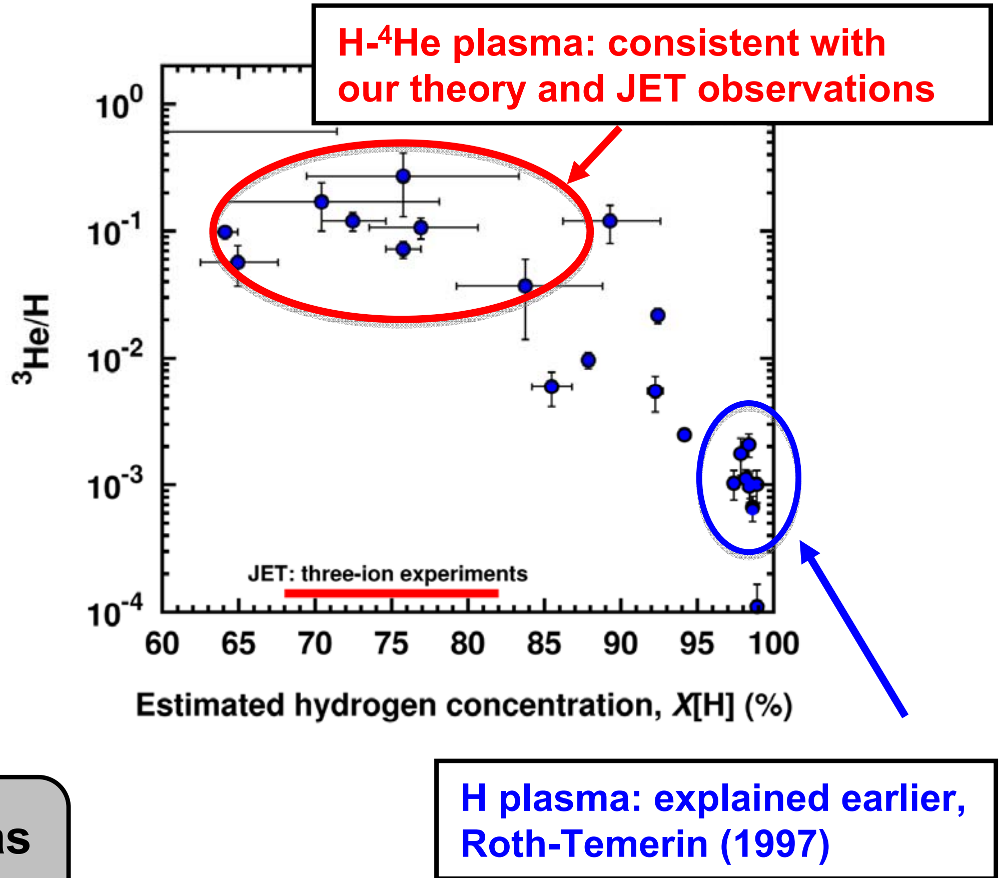
- Production by nuclear reactions ruled out (no increase in D and T)
- Selective interaction of ^{3}He with plasma waves (unique charge-to-mass ratio)
  - → electrostatic waves: H-^{4}He-^{3}He plasma (Fisk, 1978) *second-stage acceleration process required*
  - → electromagnetic waves: H-^{3}He plasma (Roth-Temerin, 1997)
  - → electromagnetic waves: H-^{4}He-^{3}He plasma (Kazakov et al., 2017)

^{3}He-rich solar flares and ^{4}He-(^{3}He)-H three-ion species scenario

Input: experimental data for 24 ^{3}He-rich events (S. Ramadurai et al., 1984)

Output: the largest number of energetic ^{3}He ions observed at X[H] ≈ 70-80%

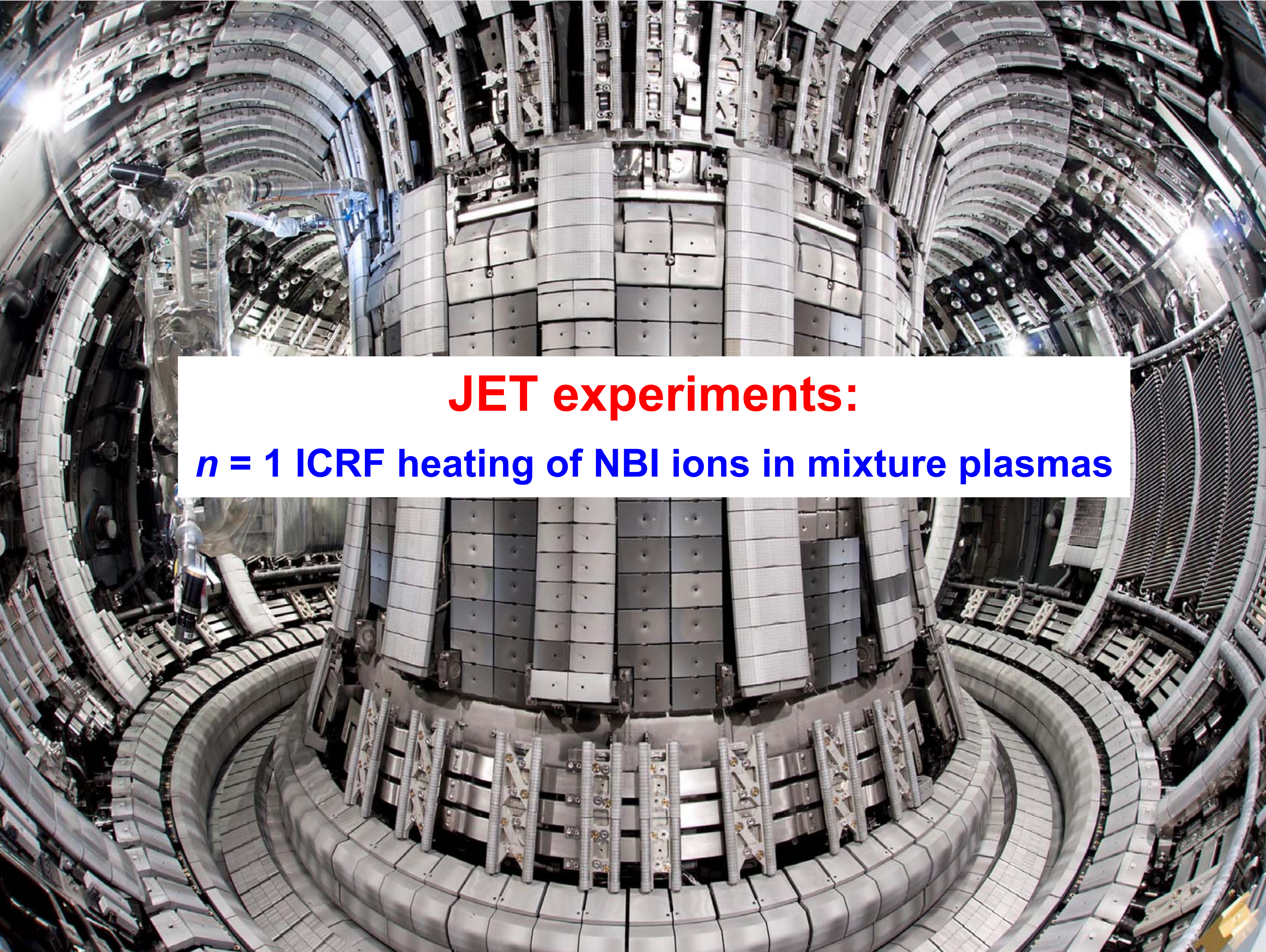




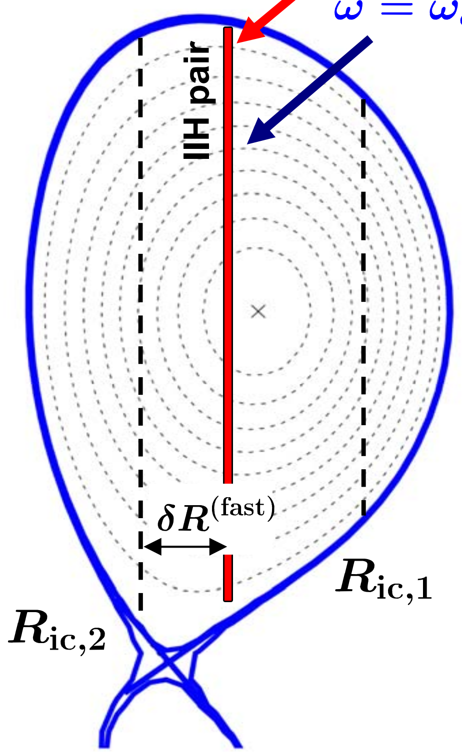
Energetic ^{3}He ions in H-D and H-^{4}He plasmas
$(Z/A)_D = (Z/A)_{4He} = 1/2$

JET experiments:

n = 1 ICRF heating of NBI ions in mixture plasmas



Extension of 'three-ion' species ICRH scenarios: use NBI ions as a resonant absorber in mixture plasmas



$k_\parallel = n_{\text{tor}}/R_{\text{ic},2}$

- **NBI system provides ions resonating in the vicinity of the MC layer, where the E_+ field is strong**

$$R_{\text{MC}} \approx R_{\text{ic},2} \times \left[1 + \left(\frac{(Z/A)_1}{(Z/A)_2} - 1\right) Z_2 X_2\right]$$

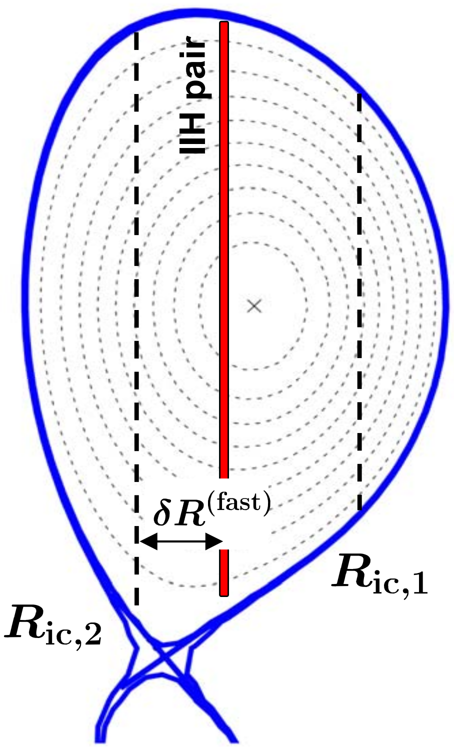
- **NBI: seed of fast ions with a velocity distribution ranging from v_{ti} to $v_{\parallel,\text{max}}$ (large Doppler-shift)**

$$R_{\text{fast}} = R_{\text{ic},2} + \delta R^{(\text{fast})}; \quad \delta R^{(\text{fast})} = n_{\text{tor}} v_\parallel^{(\text{fast})}/\omega$$

- **Resonant wave-particle interaction:**

$$v_\parallel^{(\text{fast})} = \frac{\omega}{k_\parallel} \frac{(Z/A)_1 - (Z/A)_2}{(Z/A)_2} Z_2 X_2 \le v_{\parallel,\text{max}}^{(\text{NBI})}$$

Extension of 'three-ion' species ICRH scenarios: use NBI ions as a resonant absorber in mixture plasmas



- **Fast NBI ions resonating at the MC layer:**

$$v_{\parallel}^{(\mathrm{fast})} = F(X_1, X_2) \leq v_{\parallel,\max}^{(\mathrm{NBI})}$$

Plasma composition

ICRF phasing ($k_{\parallel}$) and freq. (ω)
NBI energy and geometry ($v_{\parallel}$)

$$X_2 \lesssim \frac{1}{Z_2 (Z/A)_1 - (Z/A)_2} \frac{(Z/A)_2}{} \frac{k_{\parallel} v_{\parallel,\max}^{(\mathrm{NBI})}}{\omega}$$

Type of plasma mixture
(H-D, D-T, D-^{3}He, etc.)

Conditions of the JET experiments:

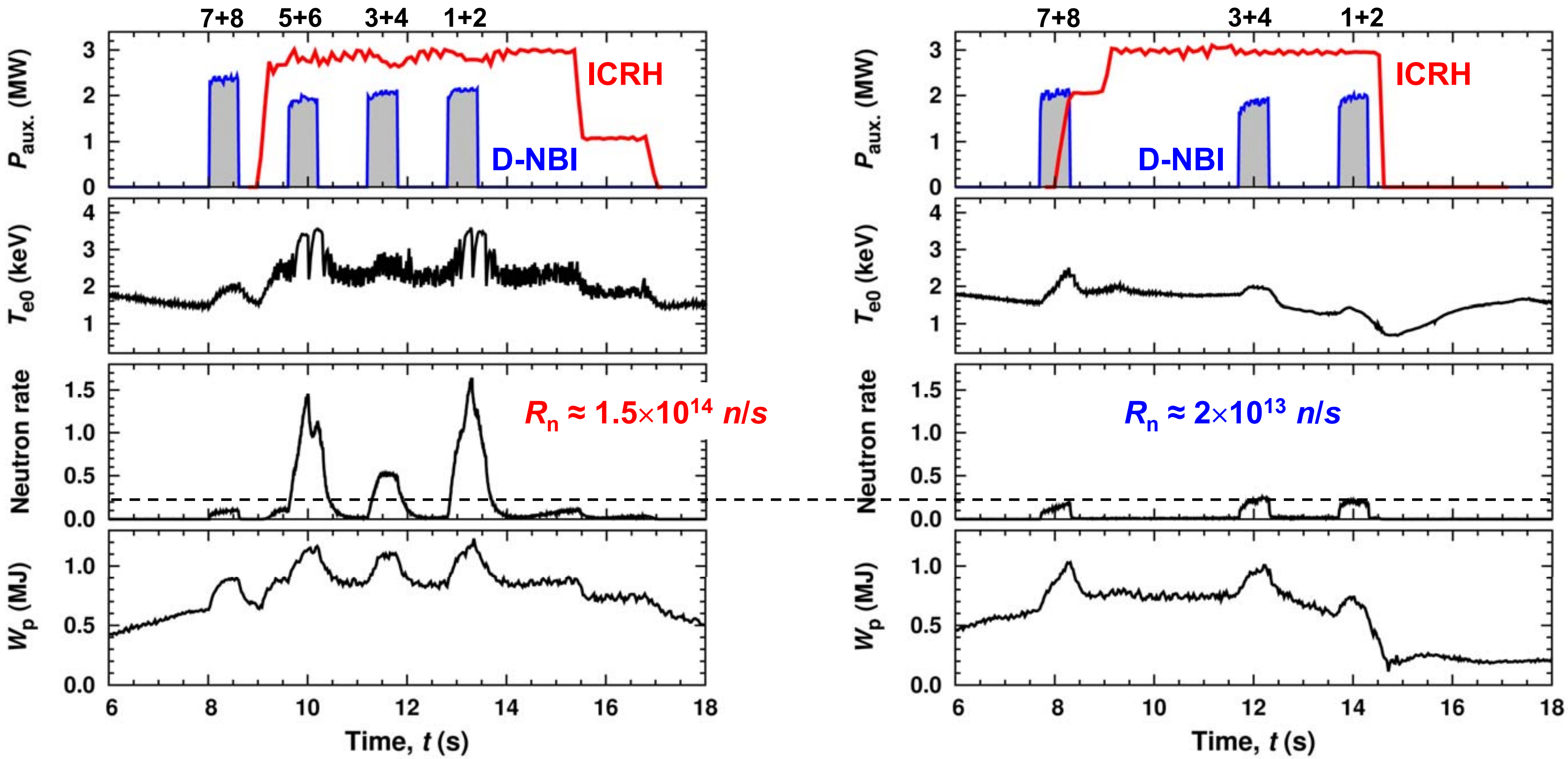
H-D plasma mixture, $E_{\mathrm{D\text{-}NBI}}$ = 100keV, $v_{\parallel}/v$ = 0.62, f = 25MHz, dipole phasing $\rightarrow \quad \delta R^{(\mathrm{fast})} \approx 35 - 40\ \mathrm{cm}$

$$p \approx \delta R^{(\mathrm{fast})} / R_0 \approx 0.11$$

$$X_{\mathrm{D}}^{(\max)} \simeq p/(1-p) \approx 13\%$$

D-(D_{NBI})-H heating scenario: effect of the plasma composition

#91255, *X*[D] ≈ 10-15% | **#91206, *X*[D] ≈ 30%**



$$v_{\parallel}^{(\mathrm{fast})} \le v_{\parallel,\max}^{(\mathrm{NBI})}$$

ICRH + NBI synergy at work

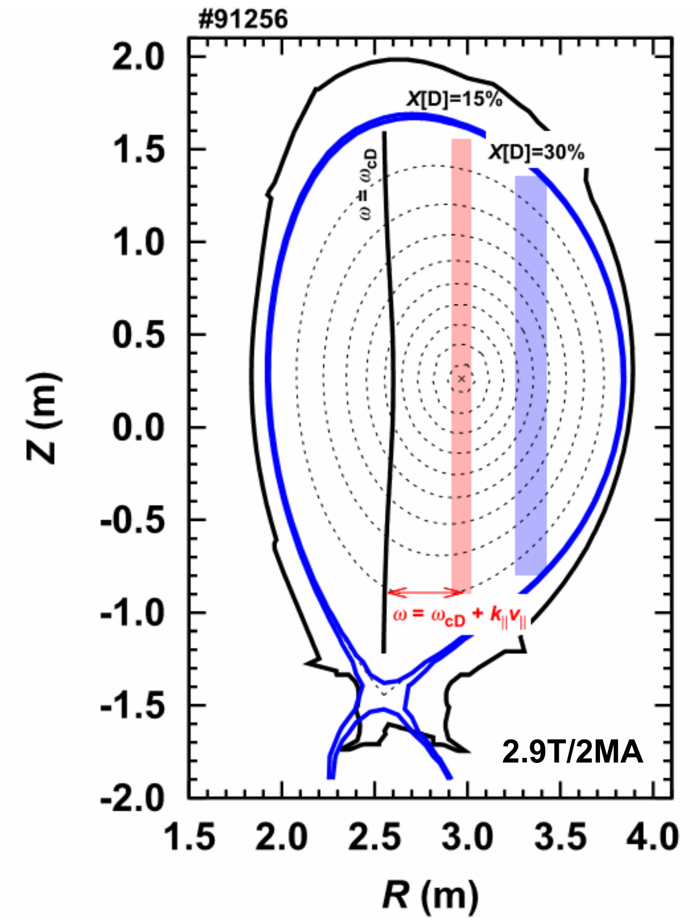
$$v_{\parallel}^{(\mathrm{fast})} > v_{\parallel,\max}^{(\mathrm{NBI})}$$

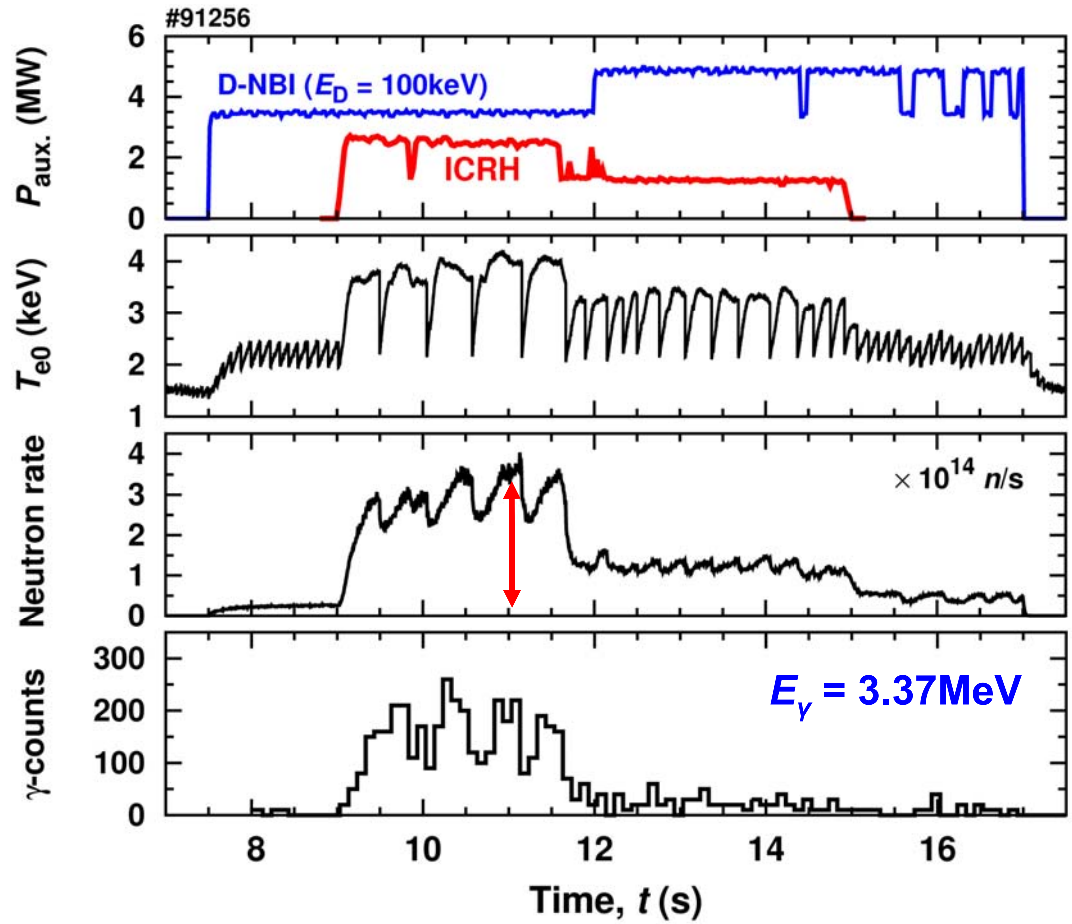
No synergy observed

ICRF heating of D-NBI ions (n = 1) in H-rich plasmas

D-(D_{NBI})-H scenario, H-D plasma with X[H] ≈ 85-90% and X[D] ≈ 10-15%

Acceleration of D-NBI ions to MeV-range energies and increase in neutron rate observed





A ten-fold increase in neutron rate with 2.5MW of ICRH

Presence of energetic D ions and TOFOR observations

D + D → ^{3}He (0.82MeV) + *n* (2.45MeV)

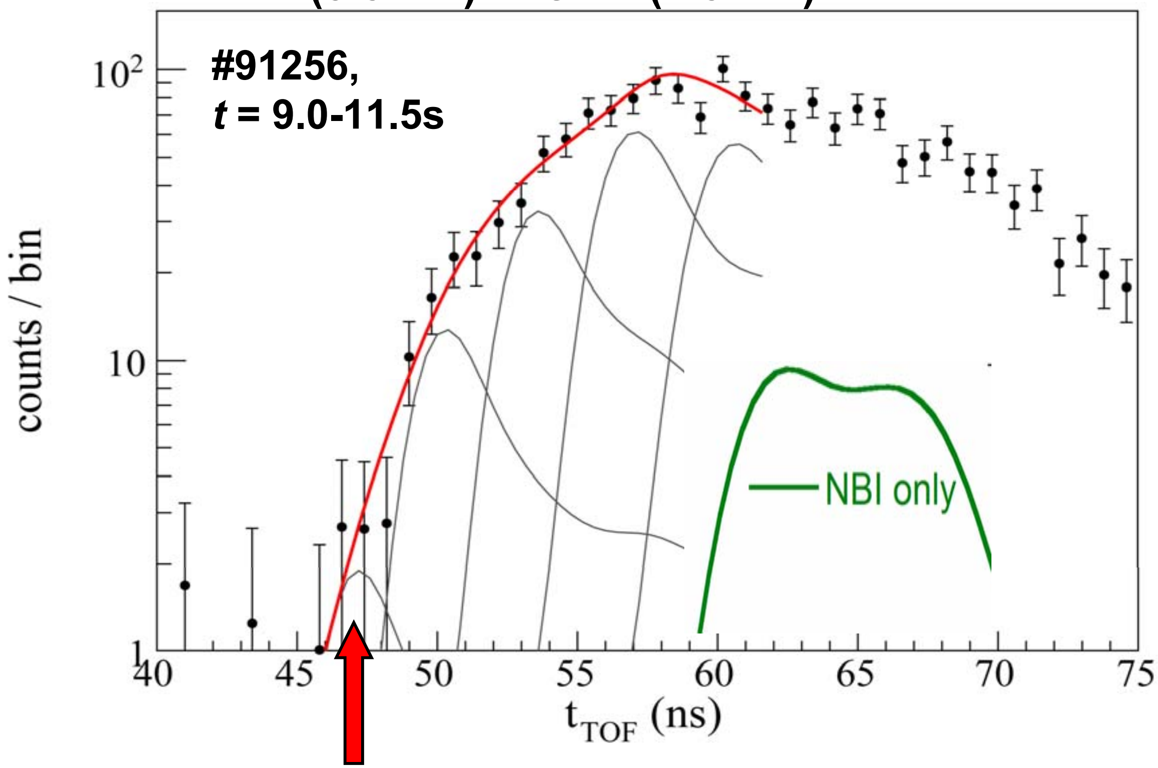
$$E_n \approx 2.9\text{MeV} \times \left[\frac{60}{t_{\text{TOF}}(\text{ns})}\right]^2$$

TOFOR: time-of-flight neutron spectrometer

C. Hellesen et al., *NF* 50, 032001 (2010)

t_{TOF}	65ns	60ns	55ns	50ns
E_n	2.5MeV	2.9MeV	3.5MeV	4.2MeV

D-NBI (3.5MW) + ICRH (2.5MW)



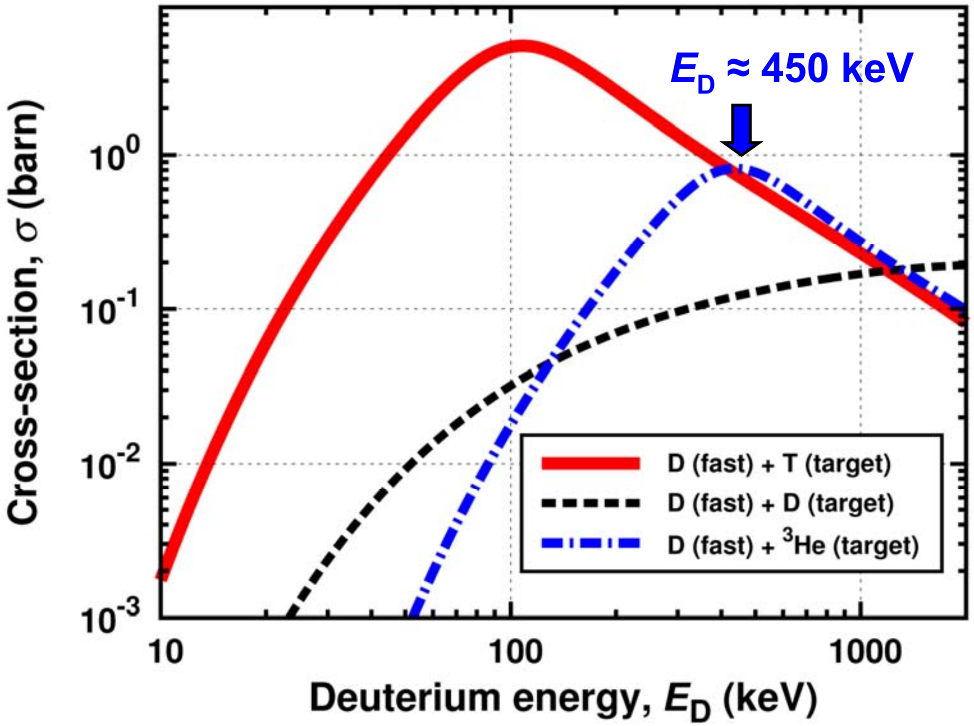
D ions with energies up to ~2MeV

Highlights for future studies

D-T plasma: D + T → ^{4}He (3.5 MeV) + *n* (14.1 MeV)

D-^{3}He plasma: D + ^{3}He → ^{4}He (3.6 MeV) + *p* (14.7 MeV)

D-(D_{NBI})-^{3}He scenario,
X[D] ≈ 50-60%, X[^{3}He] ≈ 20-25%:
source of (nearly) isotropic alpha particles

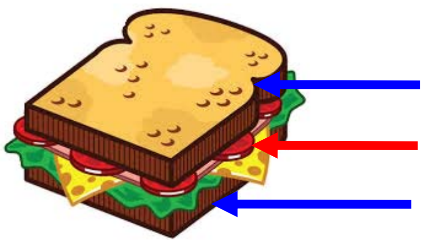


This technique is also applicable for future D-T experiments in JET-ILW

- **T-(T_{NBI})-D scenario: ICRH heating of T-NBI ions in D-rich plasmas**
- **T-(D_{NBI})-D scenario: ICRH heating of D-NBI ions in T-rich plasmas**

[J. Ongena et al., RF Topical Conf. 2017]

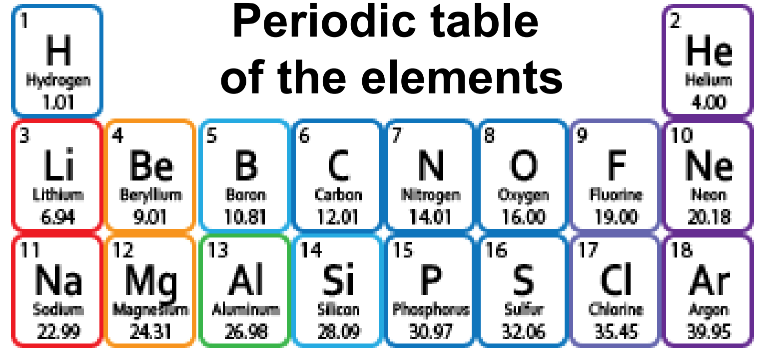
Applications of three-ion species scenarios for JET and ITER



Main ions no. 1

Resonant ions (no. 3)

Main ions no. 2



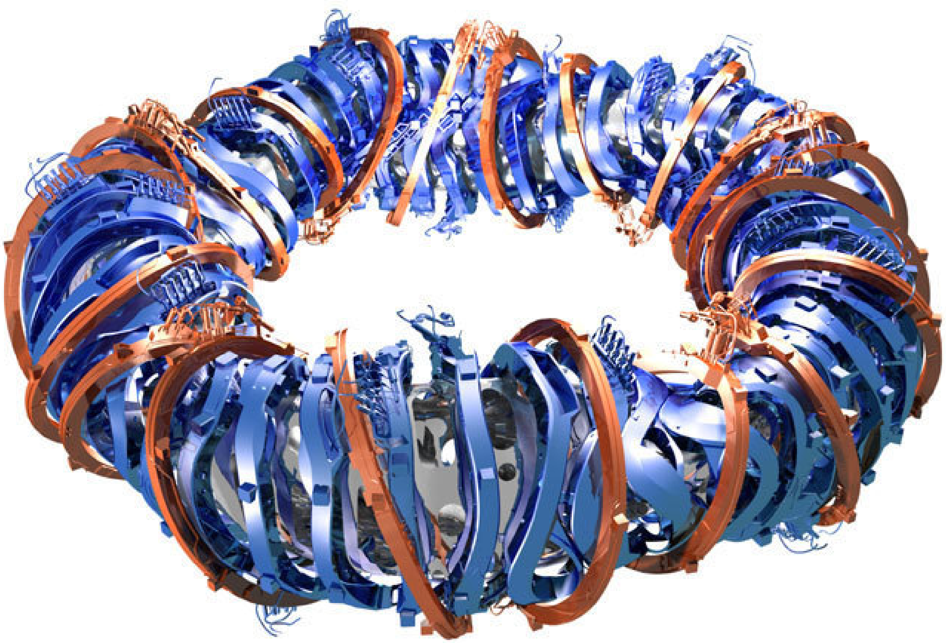
Ion species	T	^{9}Be, ^{40}Ar, ^{22}Ne, ^{7}Li, ^{11}B, …	D, ^{4}He, ^{12}C, ^{16}O, …	^{3}He	H
$(Z/A)_i$	1/3	≈ 0.43-0.45	1/2	2/3	1

Scenario	Resonant ions	ITER phase
^{4}He-(^{3}He)-H	^{3}He	non-active
^{9}Be/^{40}Ar-(^{4}He)-H	^{4}He	non-active
T-(^{9}Be)-D	^{9}Be	active

* Also scenarios with NBI ions as a minority in mixture plasmas

Fast-ion confinement studies in a stellarator Wendelstein 7-X

- Demonstrate good confinement of energetic ions at high plasma beta (n_{e0} > 10^{20} m^{-3})
- Source of fast ions (E_i ≈ 50–100 keV) in the plasma core required (ICRH and NBI)



Recipe for W7-X:

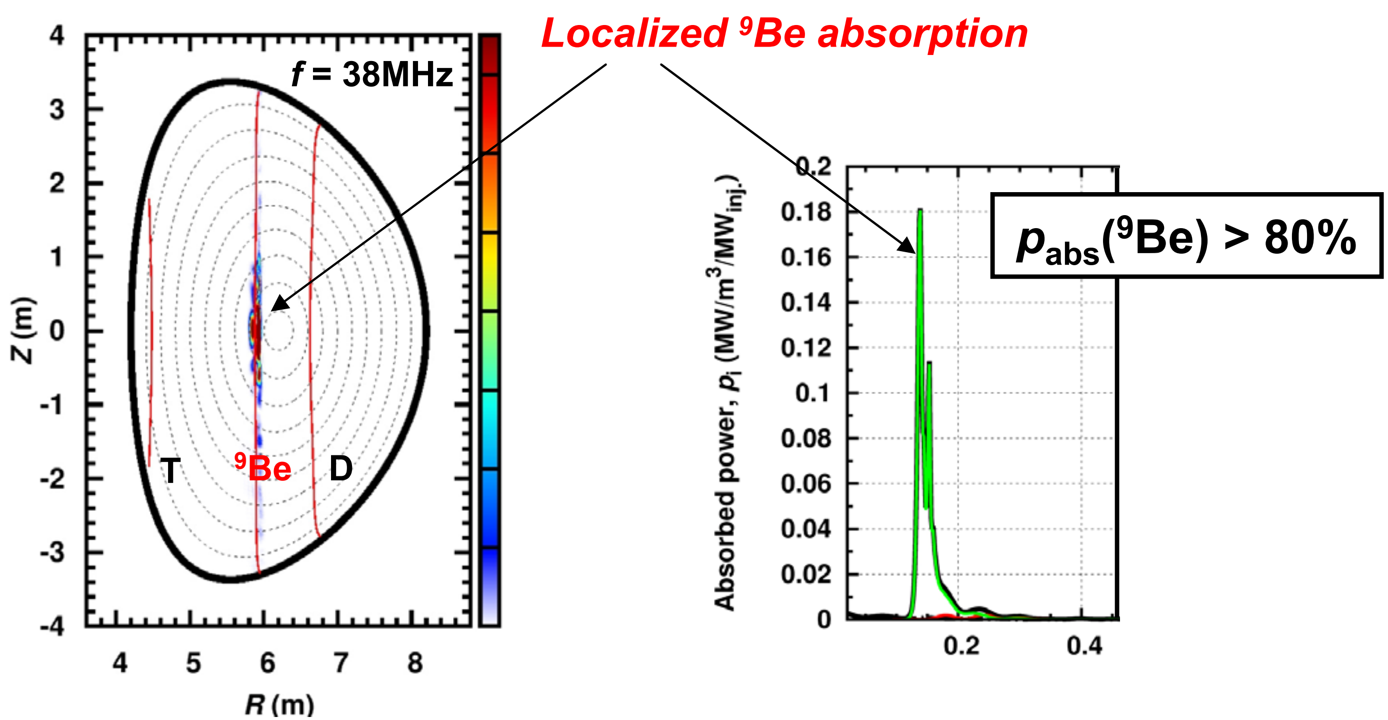
Hydrogen (~70–80%) +
D-like ions (^{12}C, ^{16}O, ^{4}He, D, …) +
^{3}He (~ 0.1-0.2%)

Three-ion species scenario provides a factor of 20 larger number of ions at E_i > 50 keV than MH scenarios

[J.M. Faustin et al., PPCF 59, 084001 (2017); SCENIC modeling]

Use intrinsic ^{9}Be impurities in our favour!

- $(Z/A)_T < (Z/A)_{9Be} < (Z/A)_D$: efficient ICRH absorption by ^{9}Be impurities (~ 0.5-1%)
- ^{9}Be provides dominant heating of bulk D and T ions



[1] Y. Kazakov et al., *Phys. Plasmas* 22 (2015) 082511
[2] J.R. Wilson et al., *Phys. Plasmas* 5 (1998) 1721-1726

Observed in TFTR D-T plasmas: T-(^{7}Li)-D scenario

Conclusions

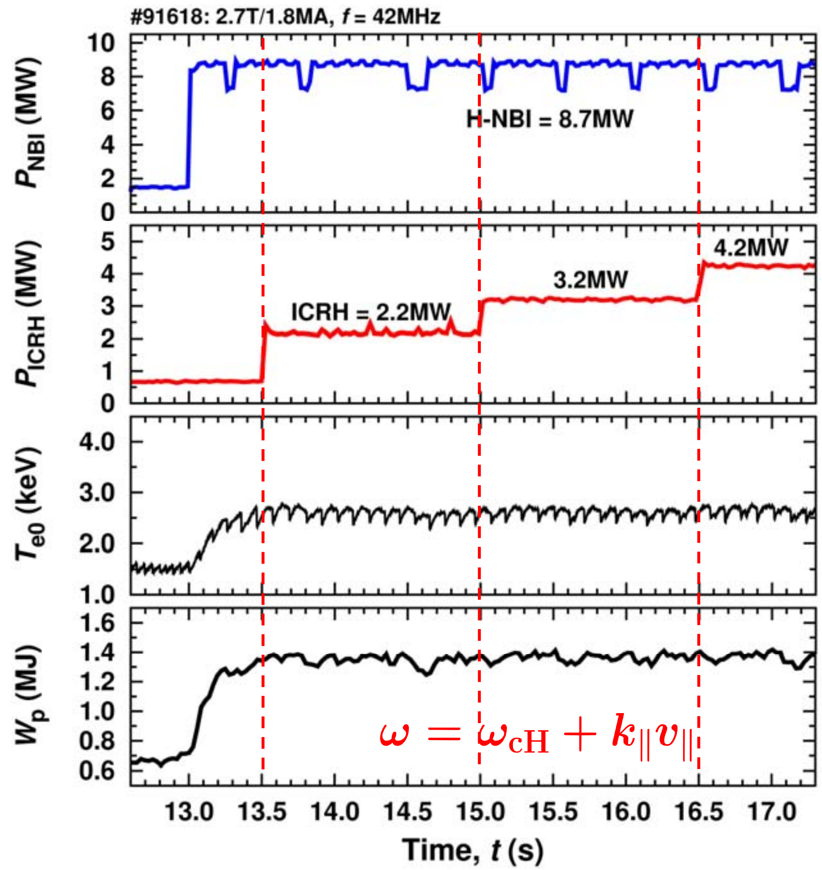
- **Three-ion species scenarios:** a new set of ICRH scenarios for efficient heating of mixture plasmas, $\omega = \omega_{ci} + k_{||}v_{||}$
  → resonant ions satisfy $(Z/A)_2 < (Z/A)_3 < (Z/A)_1$
  → resonant ions have (Z/A) as one of the main ions, but a large Doppler-shift ($v_{||}$)
- **Successfully demonstrated on Alcator C-Mod and JET tokamaks (2016):**
  → H-D plasma mixture (H-D ≈ 75%-25%) + ^{3}He
  → H-D plasma mixture (H-D ≈ 85%-15%) + D-NBI
- **Efficient generation of energetic ^{3}He and D ions confirmed**
  → *sawtooth stabilization, γ-ray emission, excitation of TAE modes, neutrons, …*
- **Various applications for JET, W7-X, ITER, DEMO**
  → *extends the flexibility of ICRH for fusion research studies*
- **Developed technique can also be applied to explain observations of energetic ions in space plasmas, in particular, ^{3}He-rich solar flares**

Thank you for your attention !

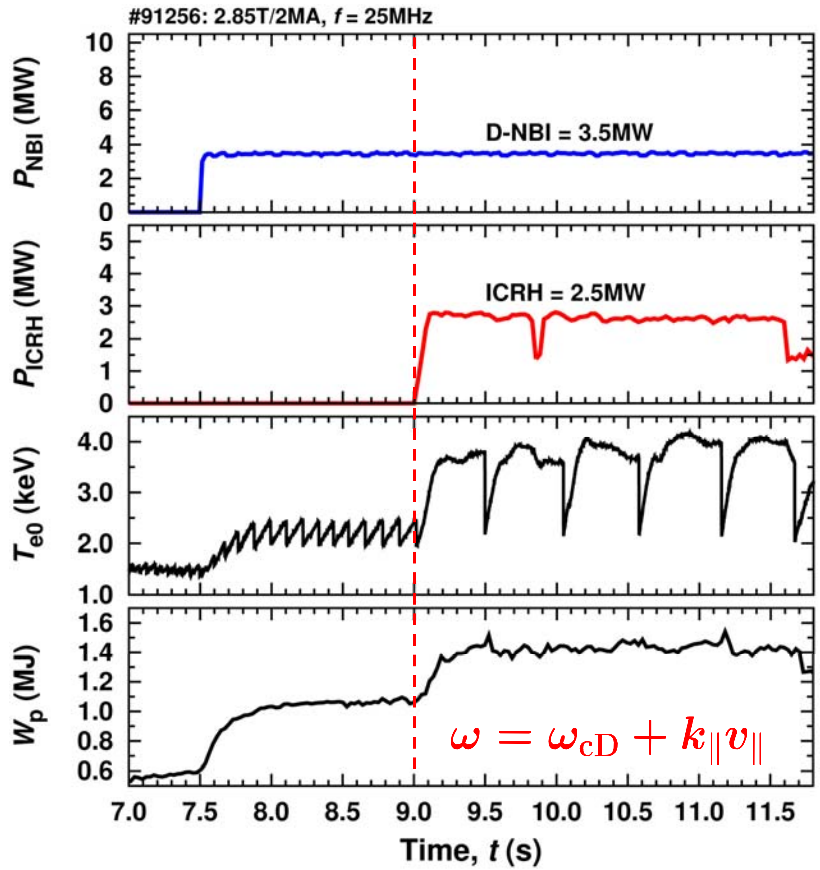
Backup slides

Doppler-shifted cyclotron heating of NBI ions in JET-ILW plasmas

X[H] ≈ 100%



Mixture: X[H] ≈ 85%, X[D] ≈ 15%



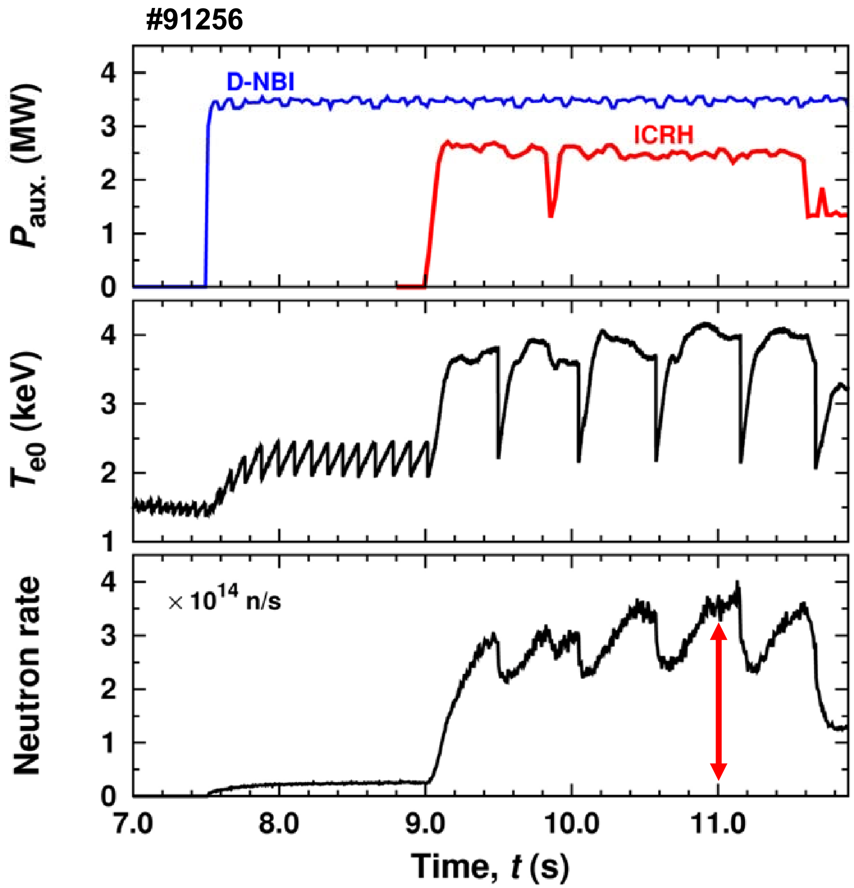
$$P_{\mathrm{abs}} \propto n_{\mathrm{res.ion}} \, |E_+|^2 \exp\left[-\left(\frac{\omega - \omega_{ci}}{\sqrt{2} k_{\parallel} v_{ti}} \right)^2 \right]$$

Case 1: single-ion plasma → E_+ small
→ poor ICRF heating

Case 2: mixture plasma → IIH layer
→ large E_+ → effective ICRF heating

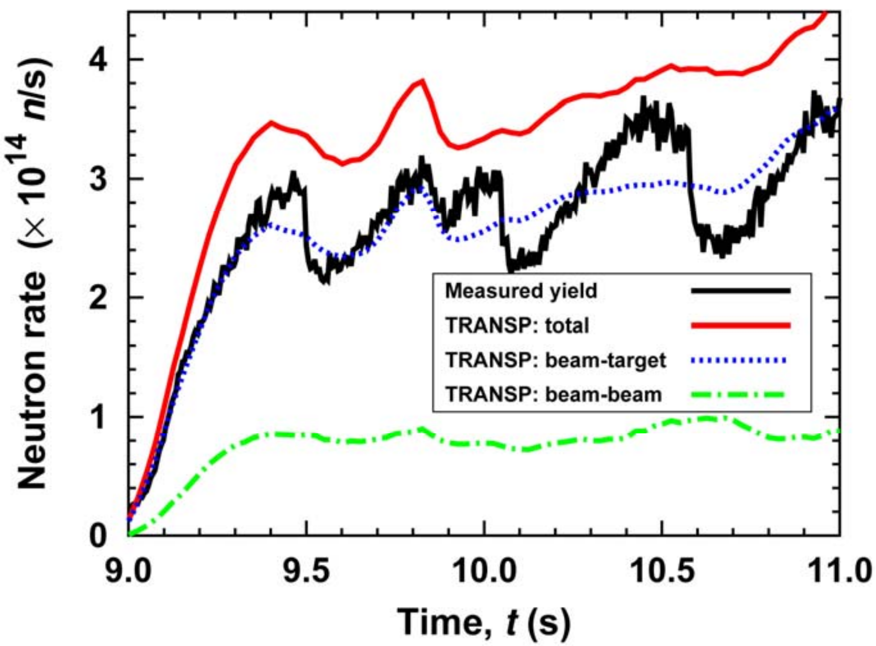
D-(D_{NBI})-H ICRH+NBI heating scenario in JET-ILW: enhanced neutron rate

Temporal evolution of the neutron rate



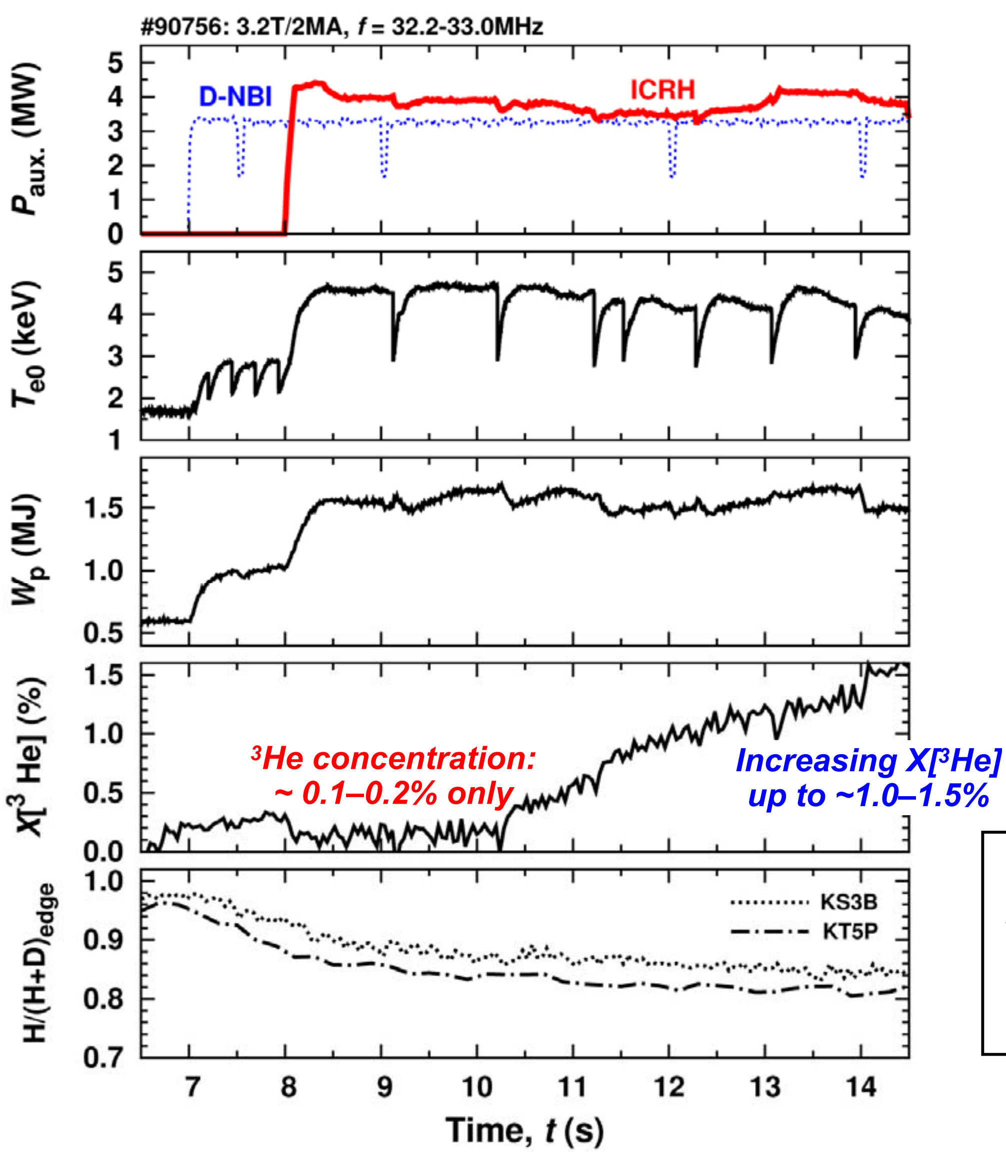
Time-dependent TRANSP modeling

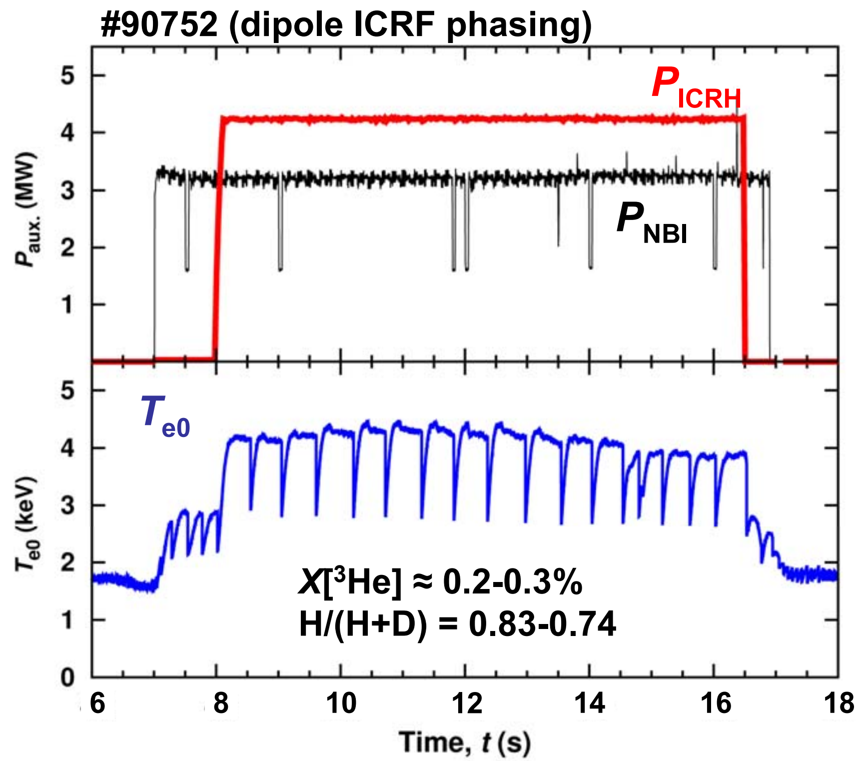
e.g., R. Budny et al., NF (2009)



t = 10.5s: $X[D_{NBI}] \approx 4\%$, $X[H] \approx 85\%$, $H/(H+D)_{edge} \approx 0.89\text{-}0.91$

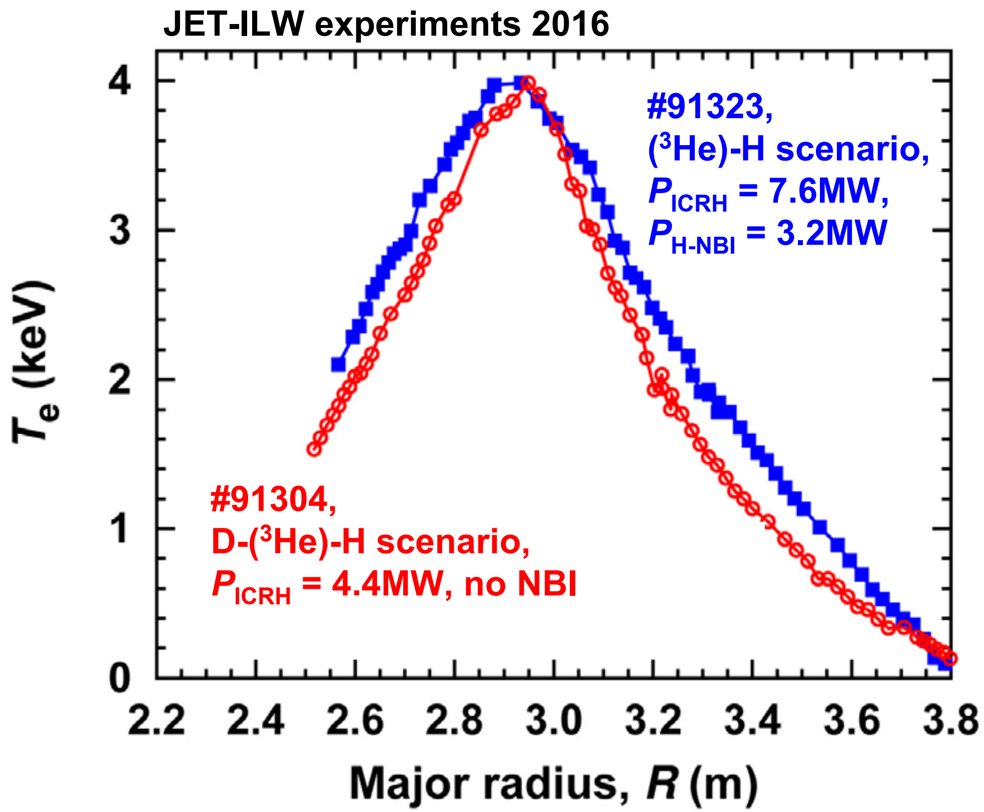
JET: efficient plasma heating observed, both at X[^{3}He] ~ 0.1-0.2% and at ~1%

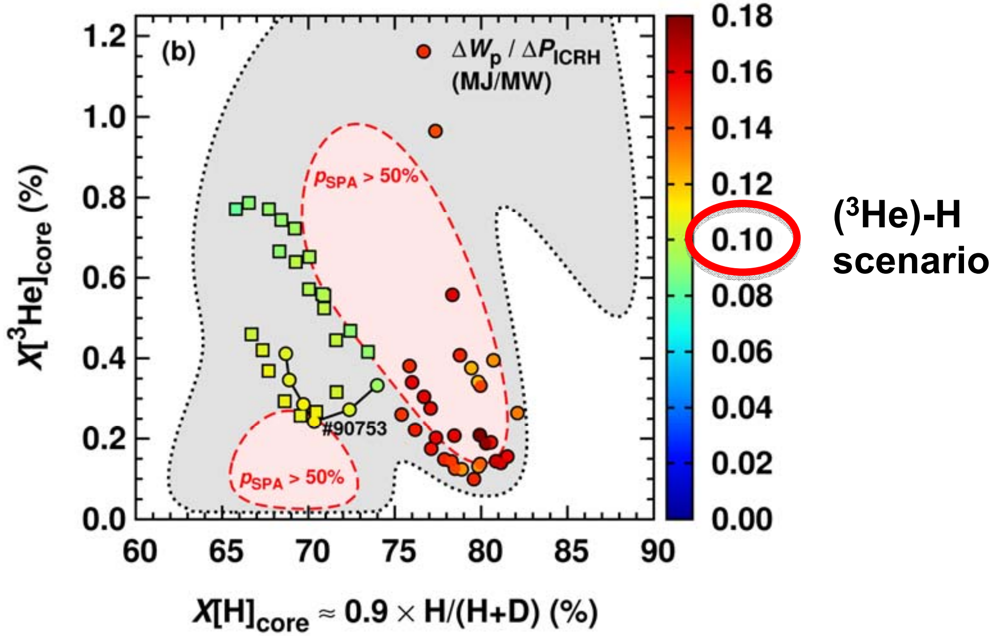




- ^{3}He concentrations as low as 0.1-0.2% were successfully used for plasma heating
- A factor of 20-30 reduction in X[^{3}He]

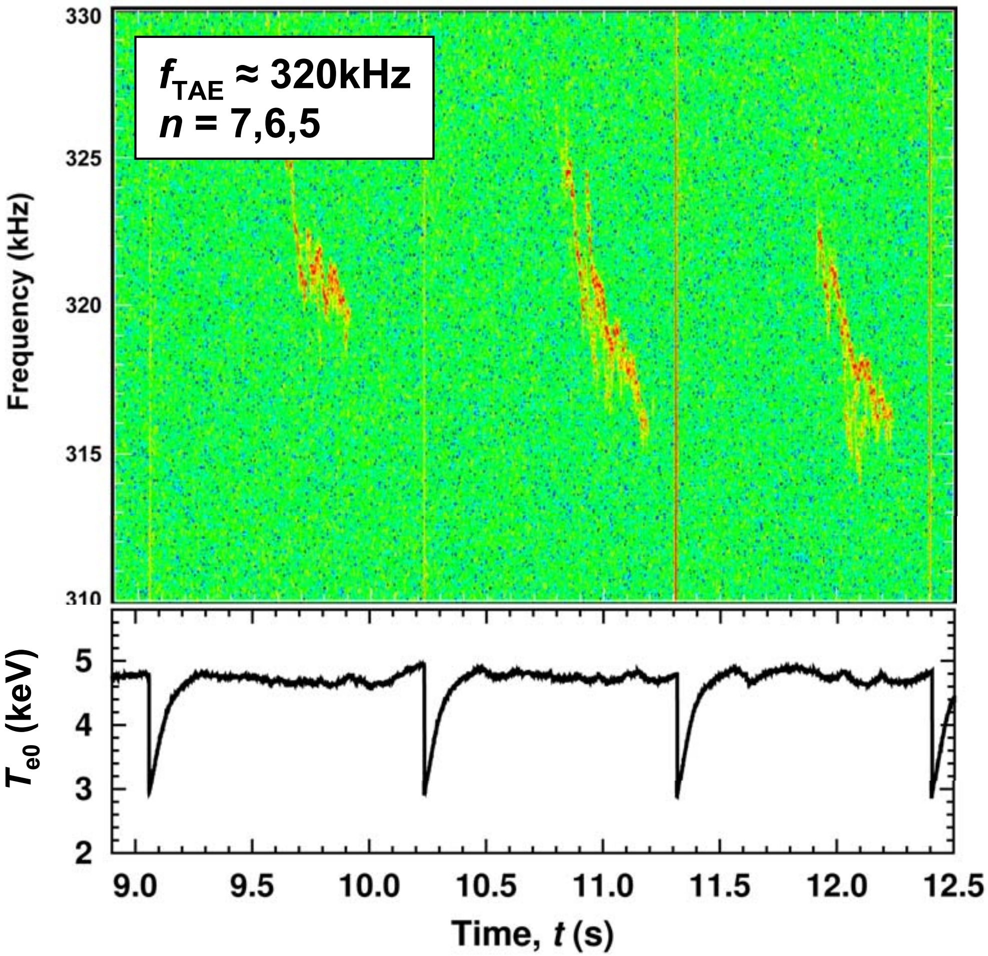
JET: minority heating of ^{3}He ions in H-D mixtures more efficient than in H plasmas



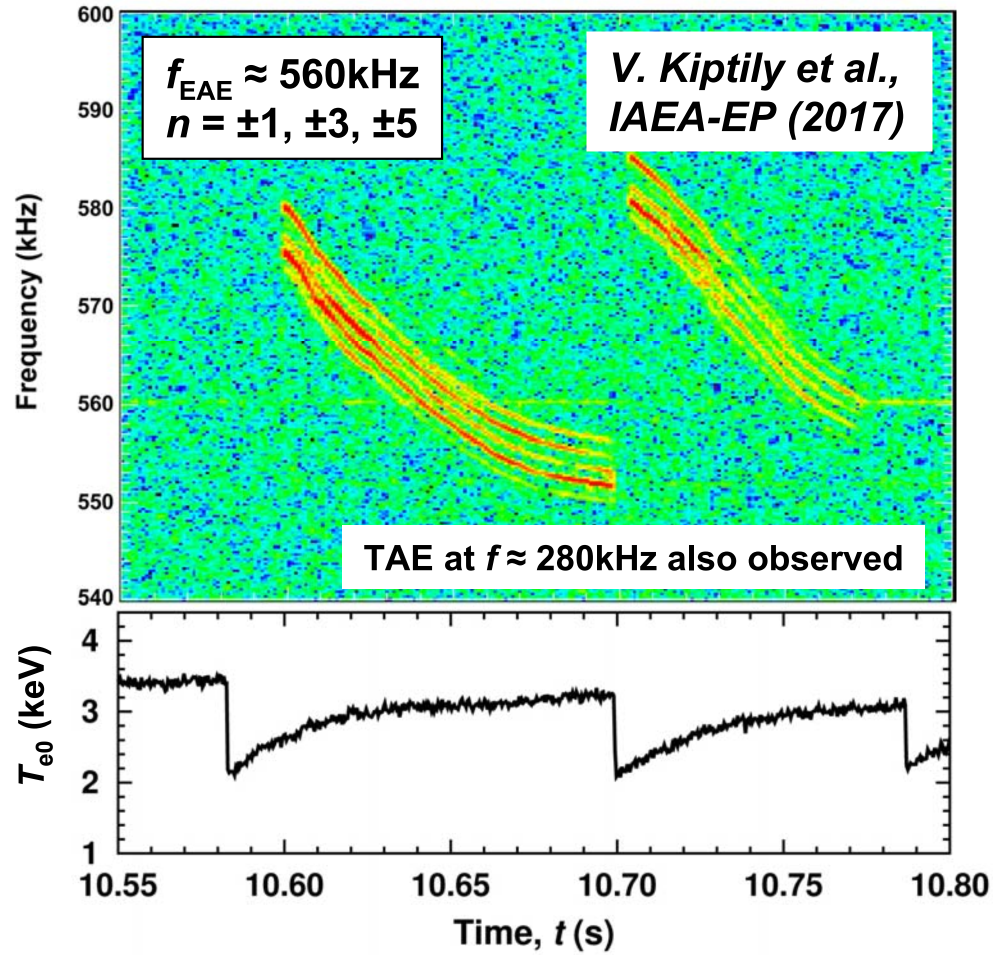


- JET: effective plasma heating as a result of slowing down of energetic ^{3}He ions (good fast-ion confinement)
- JET: ~50% higher performance of ^{3}He minority heating in H-D ≈ 80%-20% mixture if compared to heating H plasmas
- Extension for ITER: use H-^{4}He plasmas (H + 10% of ^{4}He) + a tiny amount of ^{3}He

^{3}He ICRH experiments in H-D plasmas: observation of TAE and EAE modes

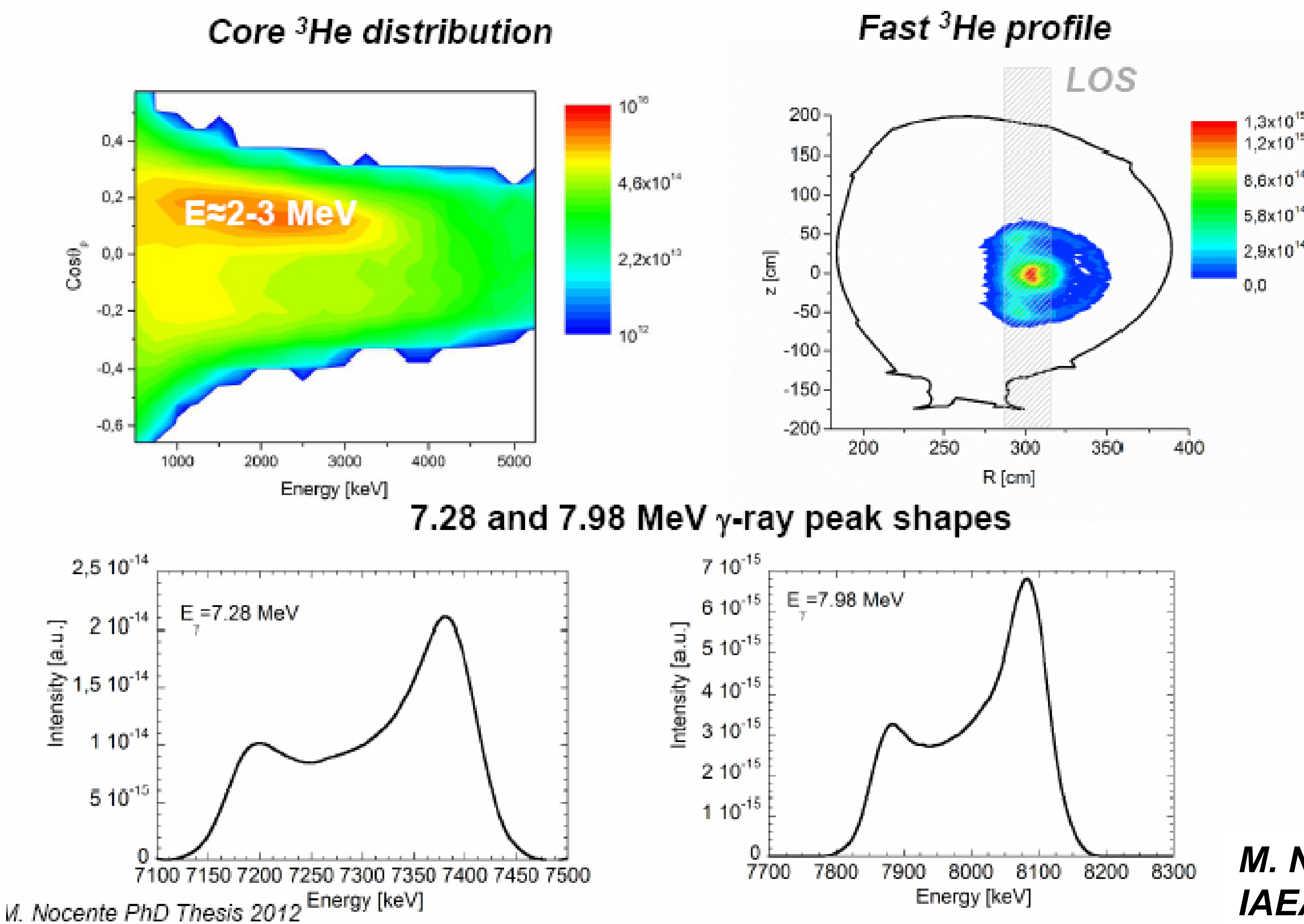


#90758, P_{ICRH} = 4.4MW, $P_{D\text{-}NBI}$ = 3.2MW, TAE modes
X[H] ≈ 80%, X[^{3}He] ≈ 0.1–0.2%



#91304, P_{ICRH} = 4.5MW, no NBI, EAE modes
X[H] ≈ 70-75%, X[^{3}He] ≈ 1%

GENESIS-SCENIC synthetic gamma-ray diagnostics



M. Nocente et al., IAEA-EP (2017)

- **ICRH modeling: SCENIC code (J.M. Faustin, H. Patten et al.)**
- **Gamma modeling: GENESIS code (M. Nocente et al.)**