Efficient generation of energetic D ions with the 3-ion ICRH+NBI synergetic scheme in H-D plasmas on JET-ILW

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on behalf of JET Contributors*

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* *See the author list of E. Joffrin et al., Nucl. Fusion* ***59****, 112021 (2019); https://doi.org/10.1088/1741-4326/ab2276*

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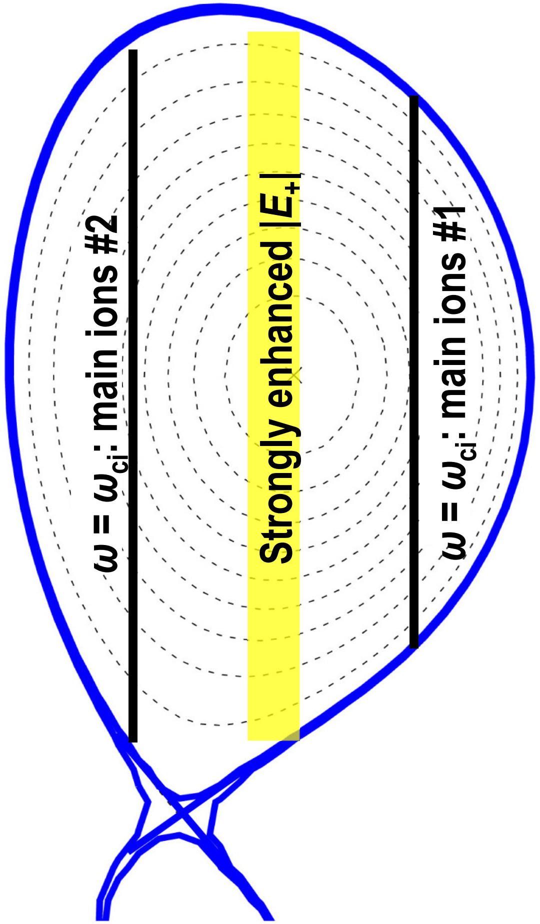
Introduction: '3-ion' ICRF schemes

Target plasma: a mix with two (or more) ion species with different ω_{ci}
→ $|E_+|$ wave field strongly enhanced in the vicinity of mode conversion layer(s)

Strong wave damping can occur in this region by ions that fulfill the resonance condition $\omega \approx \omega_{ci} + k_{||}v_{||}$

Resonant ions: small number of ions, which can be either

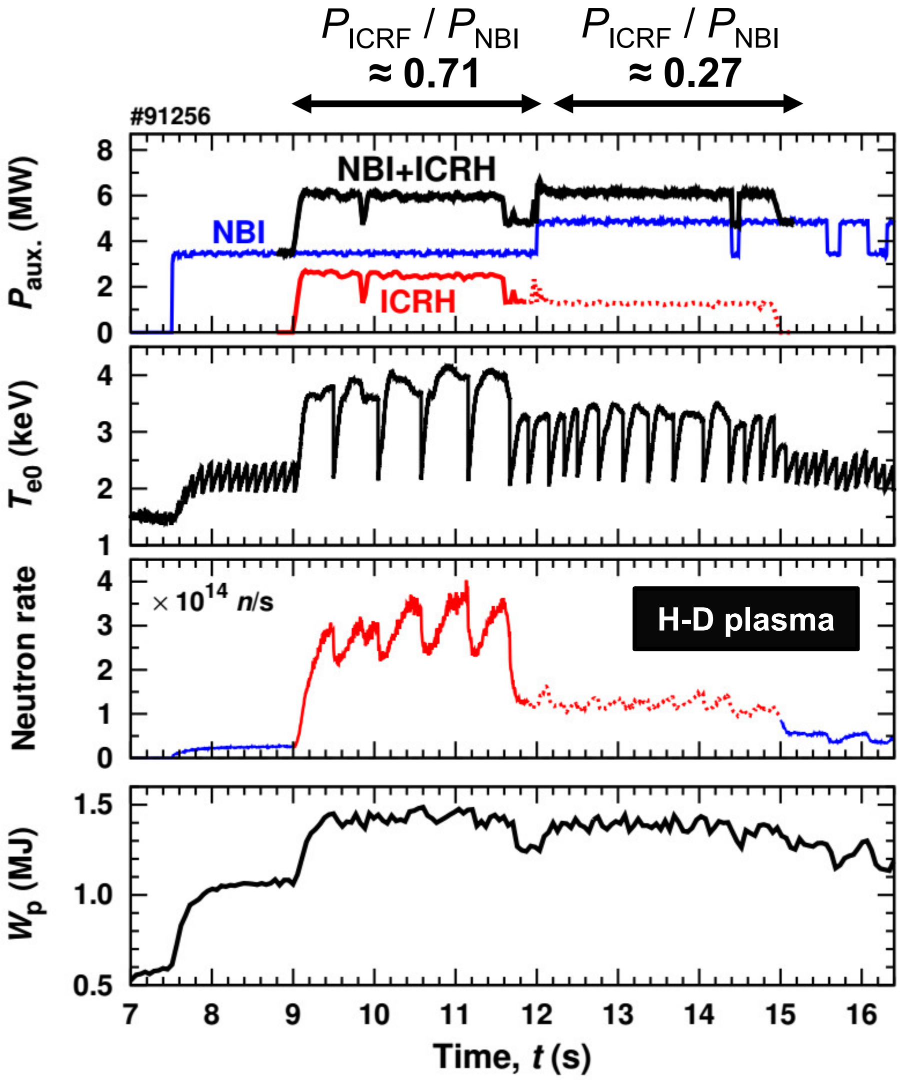
- minority ions with $(Z/A)_2 < (Z/A)_3 < (Z/A)_1$
  → e.g., ^{3}He ions in H-D plasmas: *V. Kiptily, O-19, this conf.*
- minority ions with large $v_{||}$ (NBI ions or fusion products)
  → e.g., D-NBI ions in H-D or D-^{3}He, T-NBI in D-T plasmas: *this talk*



Demonstrated as an efficient plasma heating technique on Alcator C-Mod, AUG and JET

Y. Kazakov et al., Nature Physics (2017)
J. Ongena et al., EPJ Web Conf. (2017)
M. Mantsinen et al., EPS-2019 (2019)

3-ion scheme D-(D_{NBI})-H in JET-ILW: discharge overview



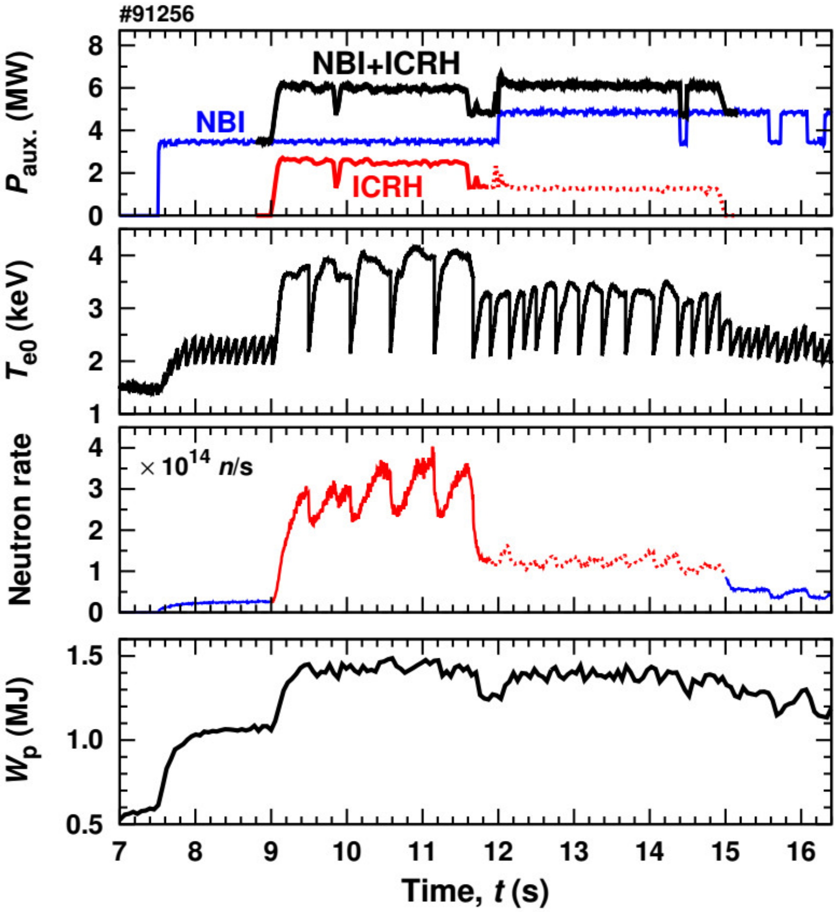
JET pulse #91256, H-D mixed plasma, 2.9T/2MA, L-mode ($R_0 \approx$ 3m, $a \approx$ 1m)
J. Ongena et al., EPJ Web. Conf. (2017)

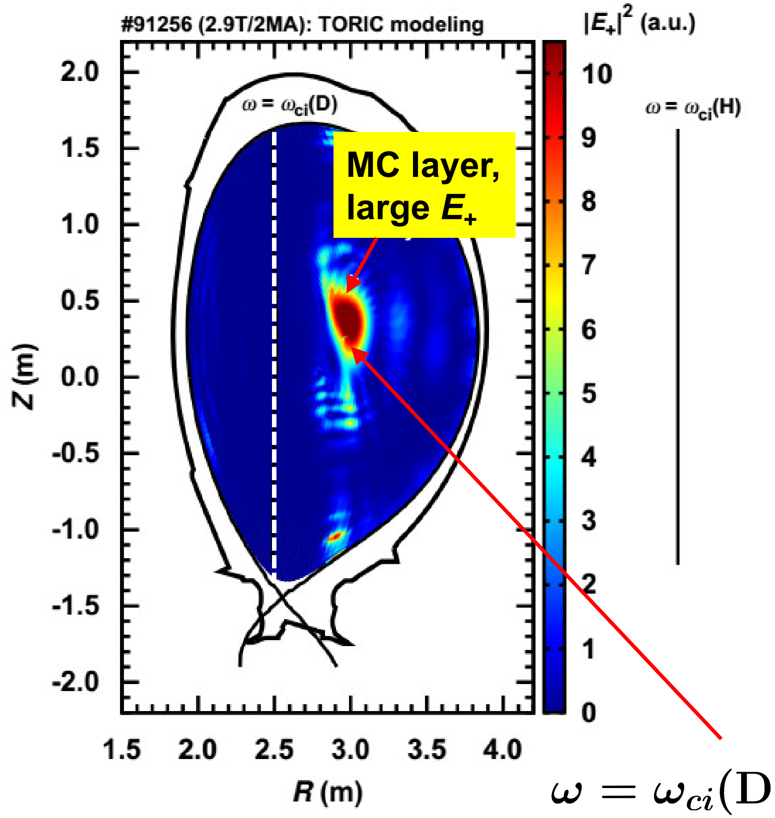
- ICRH: f_{ICRF} = 25MHz (dipole), 1.3-2.5MW
- NBI: E_D = 100keV (tang.), 3.5-4.9MW
- Plasma composition, @11s: $n_H/n_e \approx 86\%$, $n_D/n_e \approx 8\%$, $n_{9Be}/n_e \approx 0.5\%$, $n_{NBI}/n_e \approx$ 3-4% (resonant minority)

Neutron rate, sawtooth period, gamma reactions, MHD activity: strongly enhanced by ICRH, **depending on P_{ICRF} / P_{NBI}**

Optimal values for P_{ICRF} / P_{NBI} are different for D-D, D-^{3}He and D-T fusion
(reflecting the energy dependence of fusion cross-sections)

3-ion ICRH+NBI schemes: superposition of two effects





$$\omega = \omega_{ci}(\mathrm{D}) + k_{\parallel} v_{\parallel}(\mathrm{D})$$

1) **Using mixed plasmas: enhanced RF polarization**

→ Strong E_+ in the vicinity of the MC layer

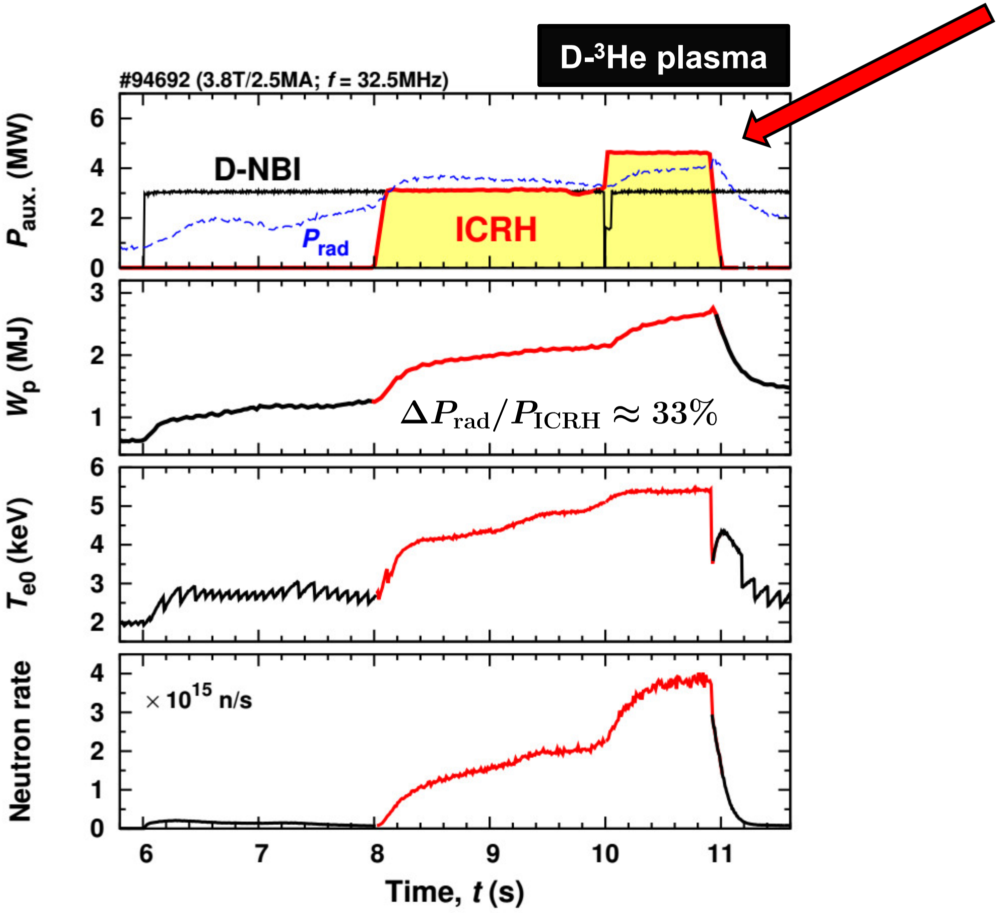
→ Strong spatial localization of RF heating

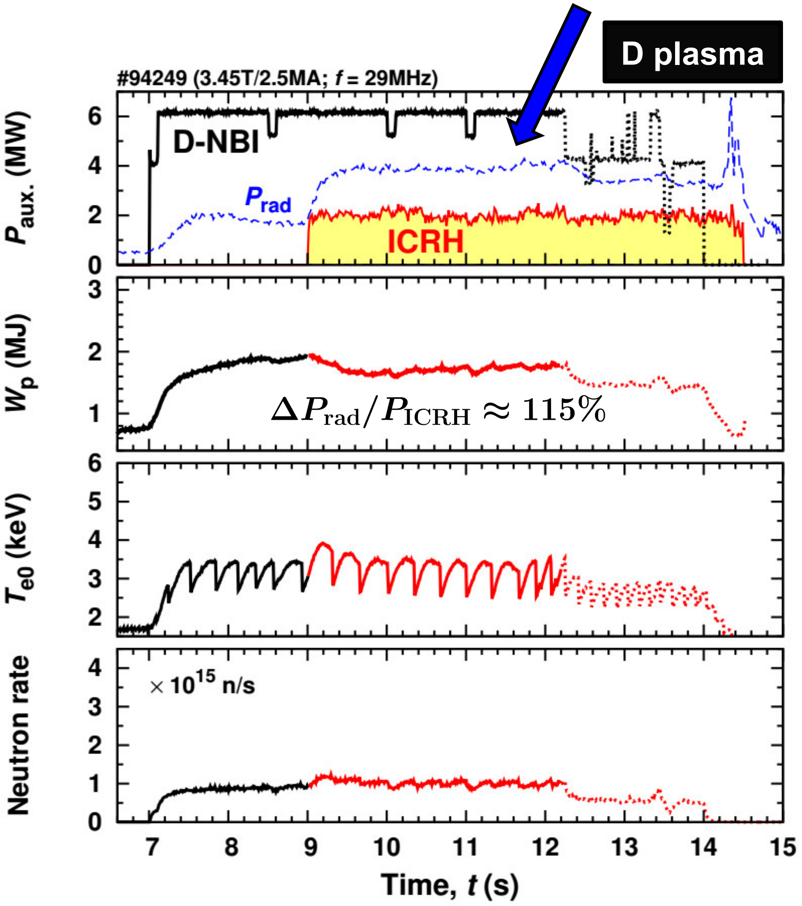
2) **Using beam ions as a 'third' species**

→ Resonate at the MC layer through their Doppler-shifted term

3-ion ICRH+NBI scheme vs. Doppler-shifted ICRH+NBI scheme

	3-ion ICRH+NBI scheme	Doppler-shifted ICRH+NBI scheme
Doppler-shifted beam absorption, $\omega = \omega_{ci} + k_{\|\|}v_{\|\|}$	Yes	Yes
Enhanced $\|E_+\|$ at the MC layer (mixed plasmas)	**Yes**	**No**

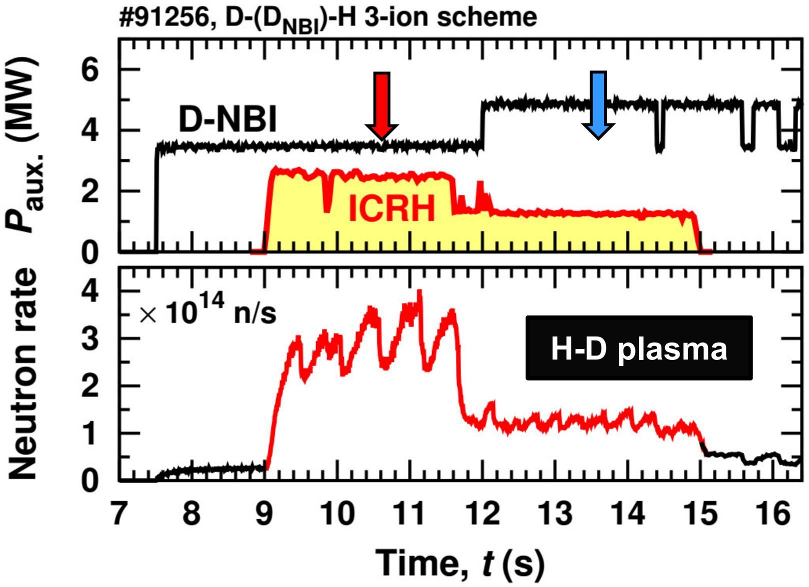




JET-ILW: D-(D_{NBI})-^{3}He 3-ion scheme, very efficient plasma heating

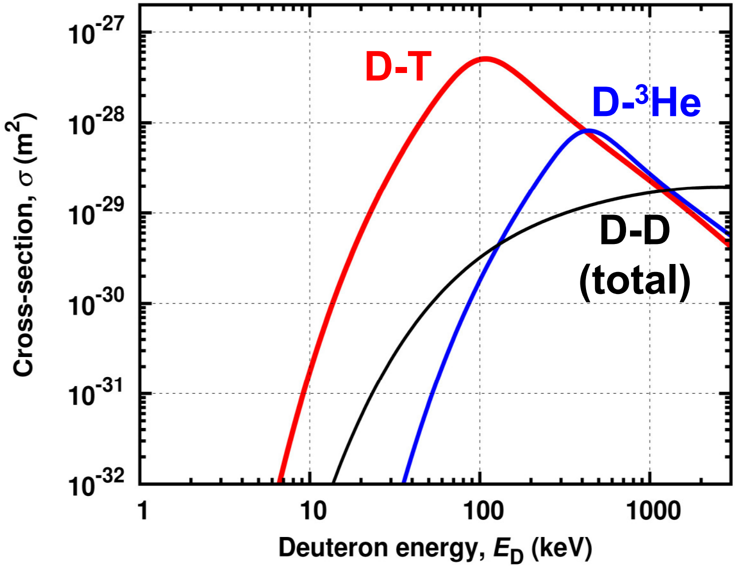
JET-C: A. Krasilnikov et al., *PPCF* (2009)
JET-ILW: strong increase of impurity levels and P_{rad}

Strong increase in neutron rate with 3-ion ICRH+NBI schemes



Neutron rate vs. P_{ICRF} / P_{NBI}

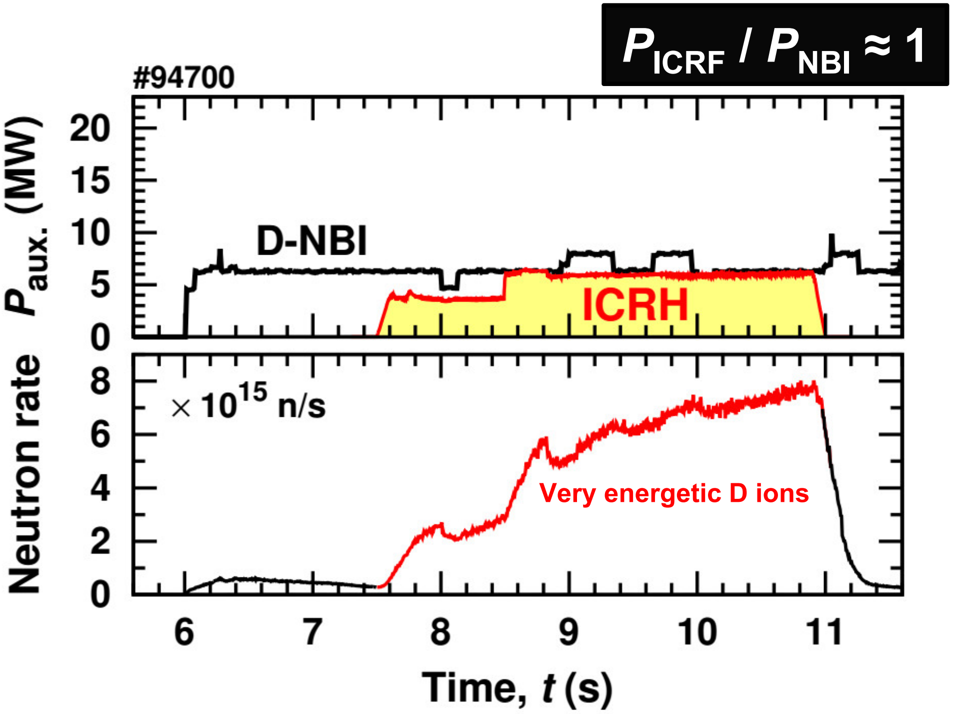
P_{NBI}	P_{ICRF}	P_{ICRF} / P_{NBI}	R_{nt}
3.5MW	–	–	2.4×10^{13} n/s
3.5MW	2.5MW	0.71	**3.5×10^{14} n/s**
4.9MW	1.3MW	0.27	**1.3×10^{14} n/s**



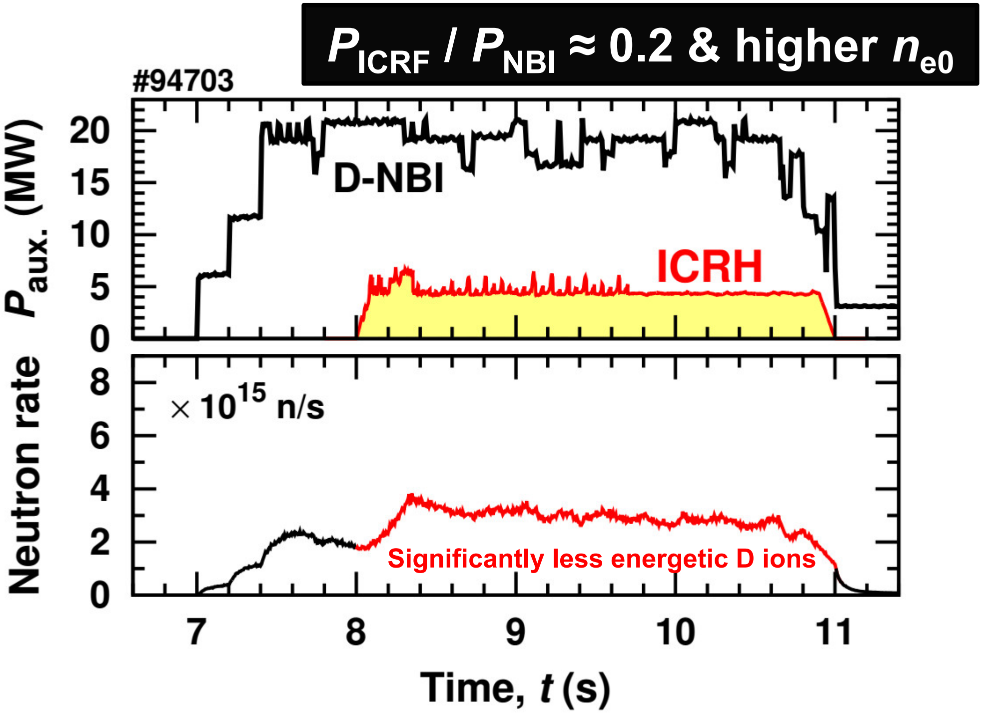
Optimal fast-ion energies are different for D-D, D-^{3}He and D-T fusion

- 3-ion ICRH+NBI schemes: possibility to tailor fast-ion energies
  - → P_{ICRF} / P_{NBI} determines RF power per resonant ion; confirmed by PION modeling [M. Mantsinen et al., EPS-2019]
  - → Additional actuators: n_e, location of RF power deposition, …
- Lower fast-ion energies beneficial for D-T plasmas
  - → Lower P_{ICRF} / P_{NBI}, higher n_{e0}, moving MC layer off-axis, …

Example of controlling fast-ion energies and neutron rate with 3-ion ICRH+NBI schemes



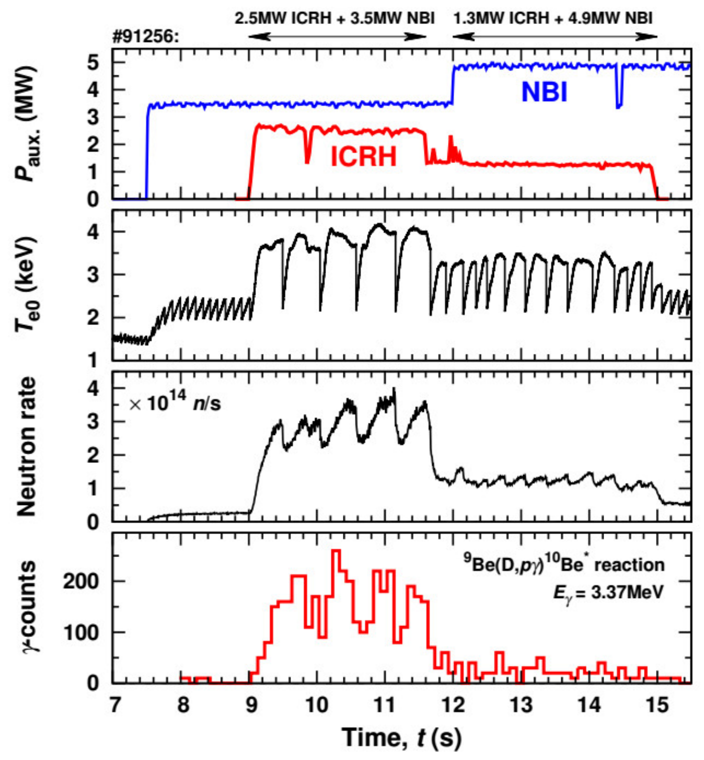
#94700 (left): very energetic D ions (MeV-range)



#94703 (right): significantly less energetic D ions

- Examples from recent 3-ion studies in **D-^{3}He plasmas** at JET, D-(D_{NBI})-^{3}He scheme
- Lower fast-ion energies (~100-200keV) beneficial for D-T plasmas

Summary of fast-ion observations, confirming the presence of energetic D ions



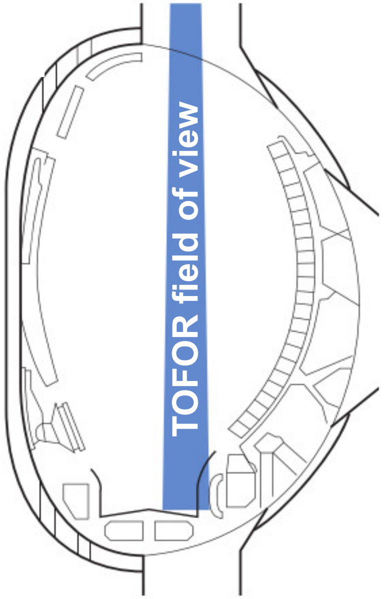
High-energy D ions: TOFOR measurements

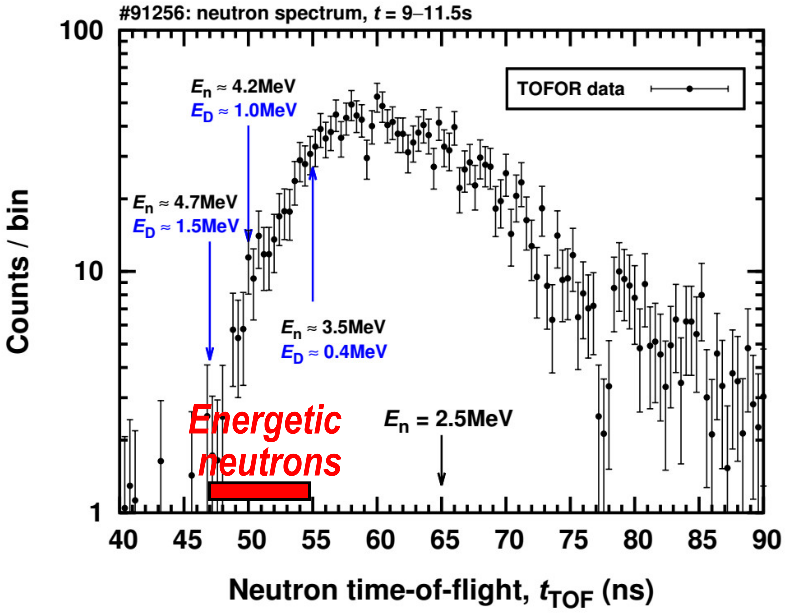
D + D → ^{3}He (0.82MeV) + n (2.45MeV)

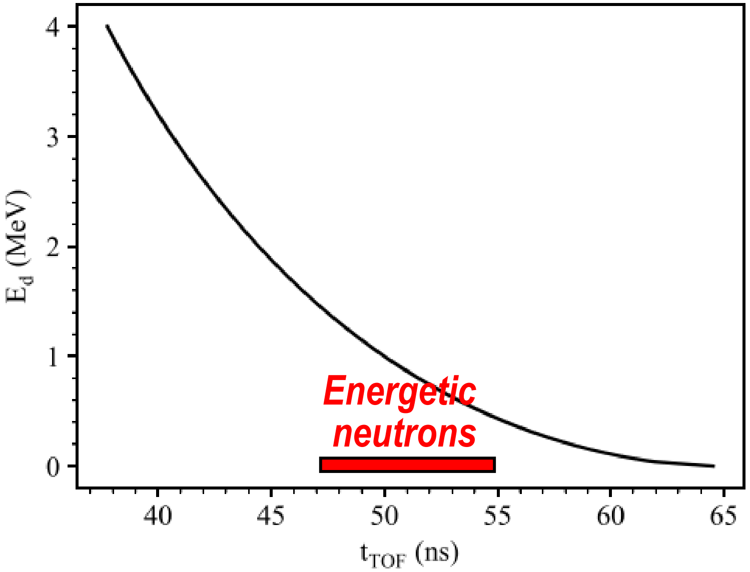
Neutron spectrum in #91256

Minimum E_D required to give rise to a given time-of-flight in TOFOR

[J. Eriksson et al., PPCF (2018)]





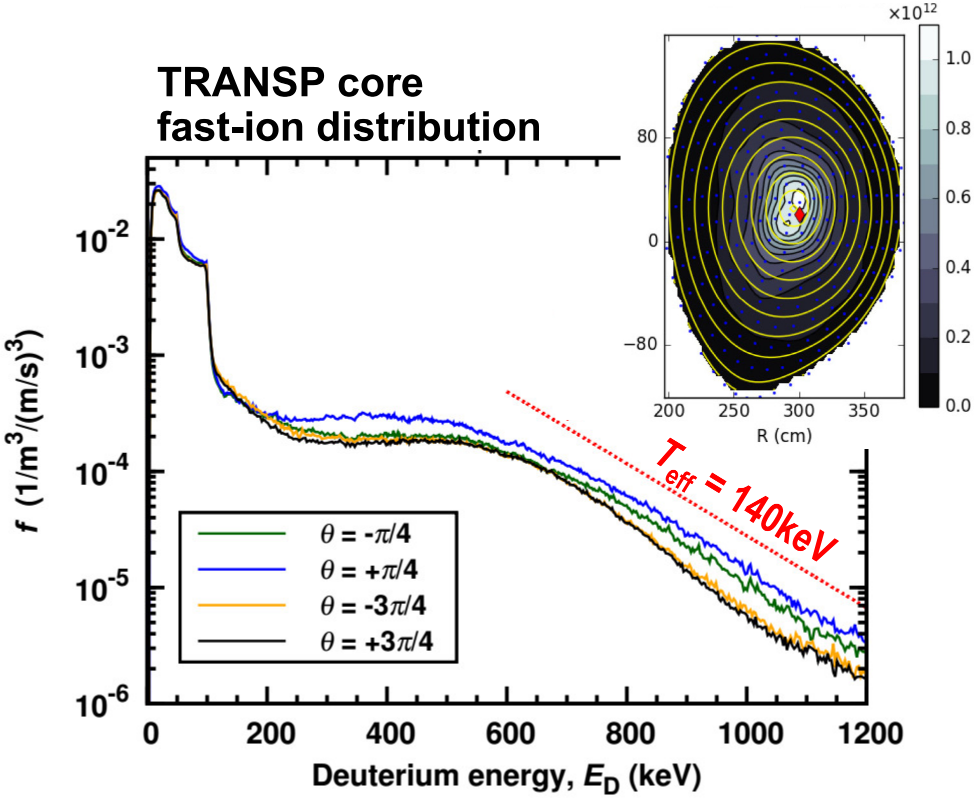


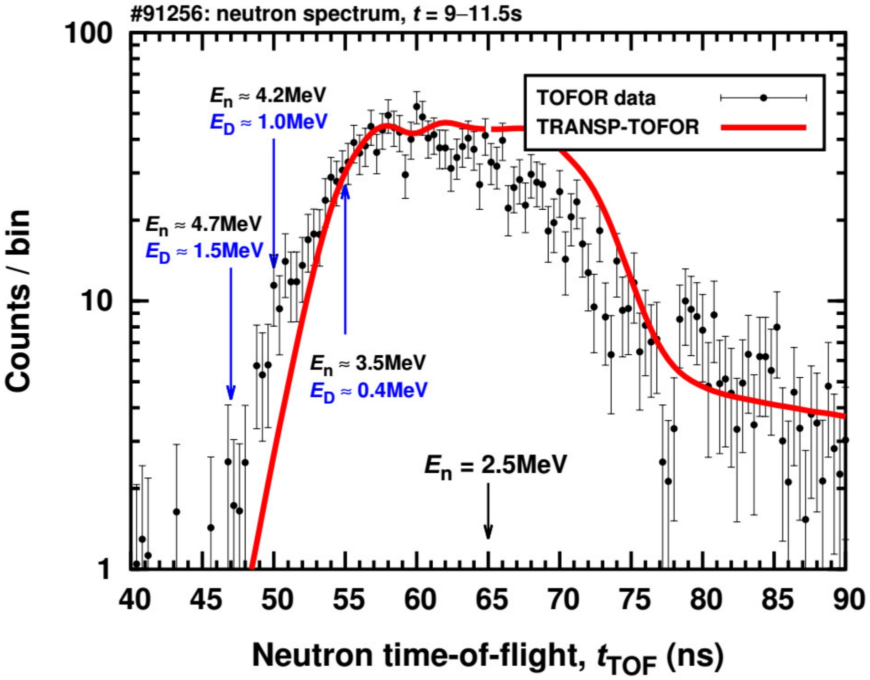
- TOFOR (time-of-flight neutron spectrometer):

  neutrons with t_{TOF} ≈ 47-50ns measured →

  presence of high-energy D ions with energies up to ~1.5MeV

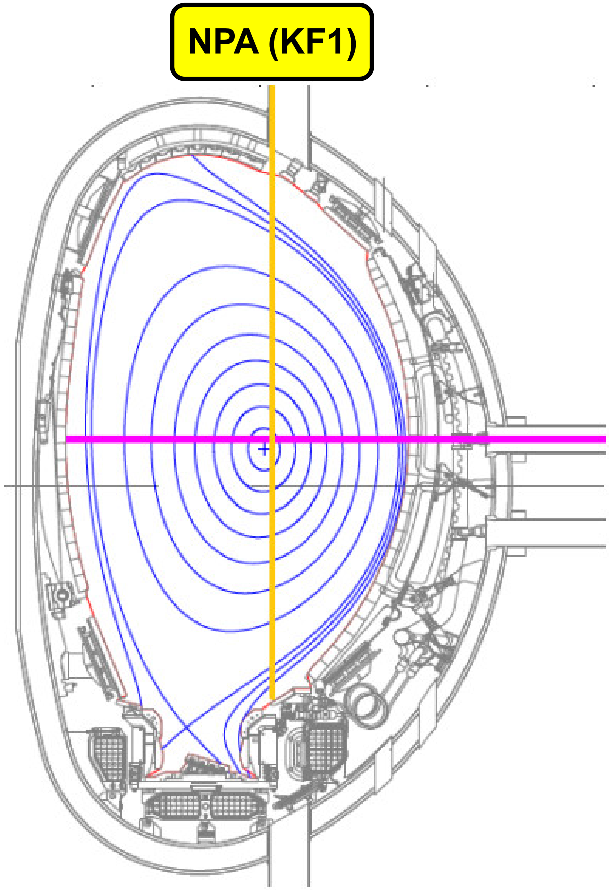
TRANSP fast-ion distribution function and TRANSP-TOFOR comparison

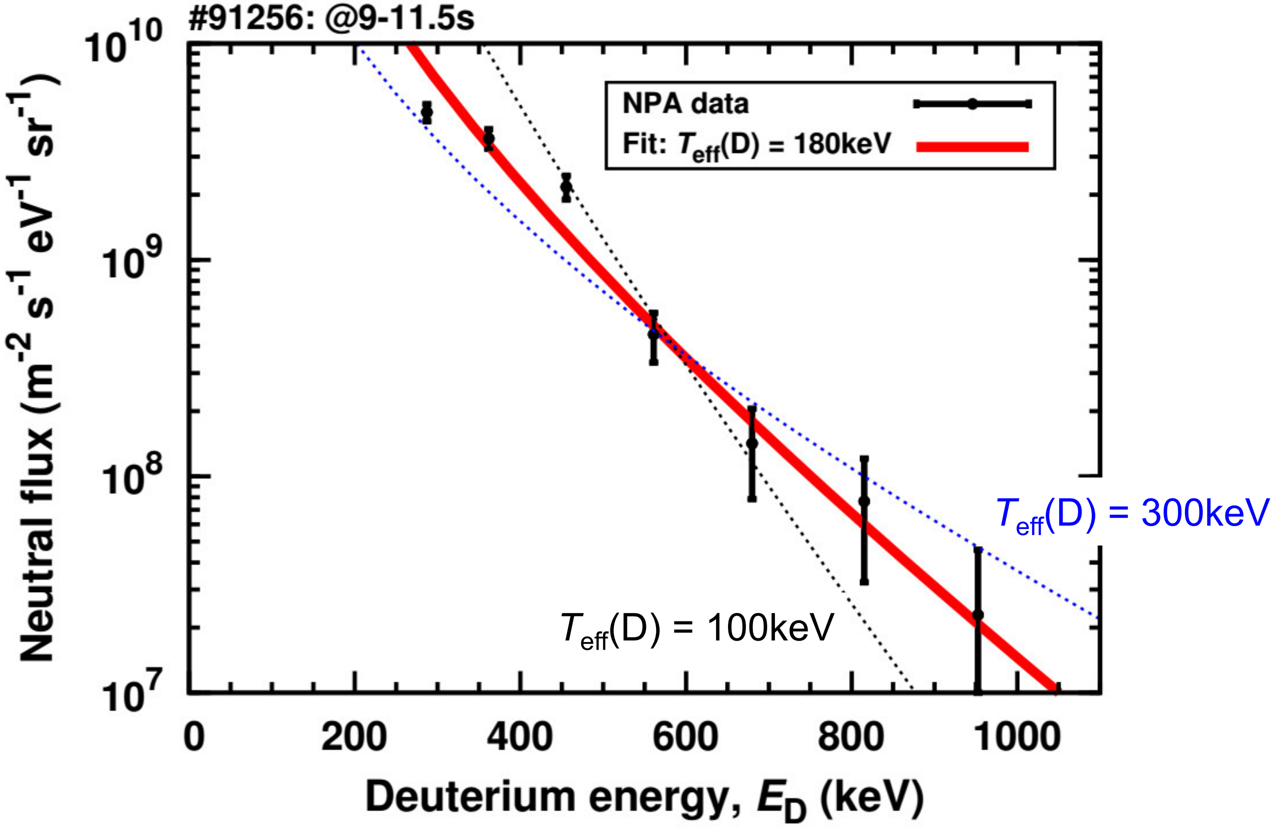




- Left: computed TRANSP velocity distribution function in the core
  [K. Kirov et al., 23rd RF Topical Conference (2019)]
  → acceleration of D ions up to energies ~1.5MeV confirmed
  → high-energy tail, $E_D \geq$ 600keV: **$T_{eff} \approx$ 140keV**
- Right: good agreement between measured TOFOR and TRANSP-TOFOR (forward modeling) neutron spectrum

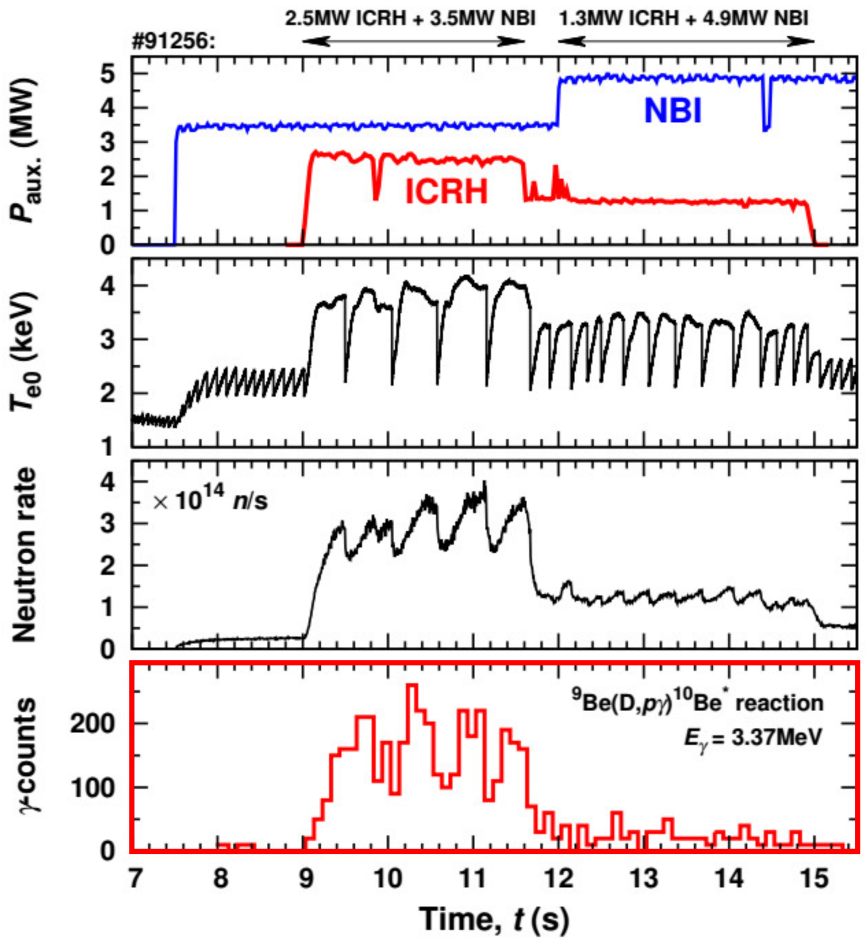
Neutral particle analyzer (NPA) measurements





- NPA measures fast D with energies up to ~1MeV
- NPA tail part (E_D > 0.5MeV) matches a Maxwellian with **T_{eff}(D) = 180keV**
  cf. T_{eff}(TRANSP) = 140keV

High-energy D ions (> 0.5MeV): gamma-ray spectroscopy



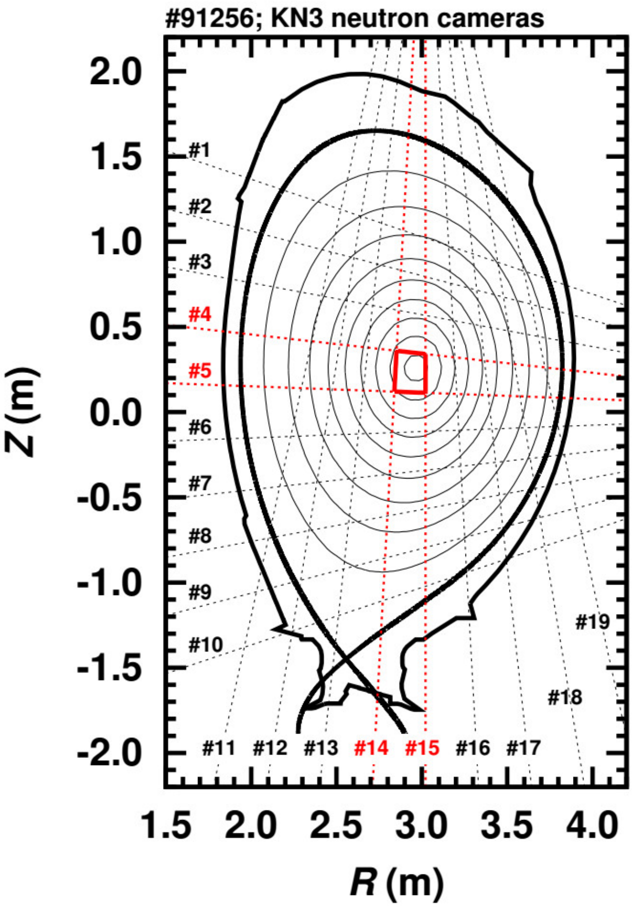
D + ^{9}Be nuclear reactions lead to gamma-ray emission when $E_D > 0.5$MeV

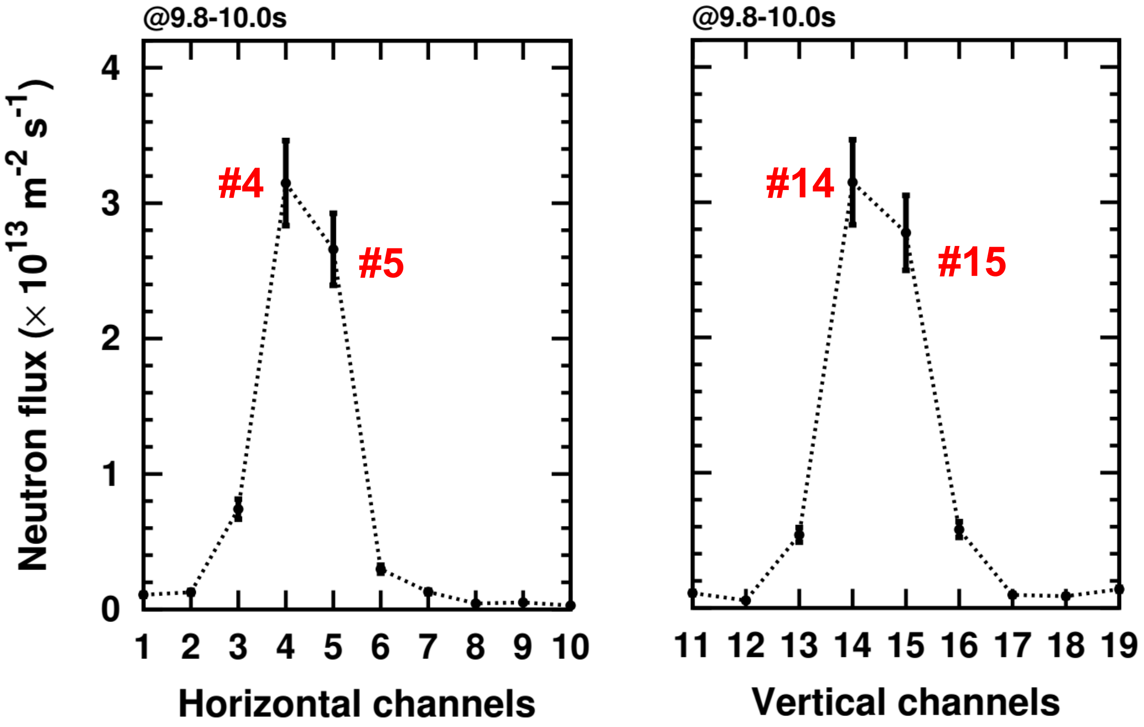
[V. Kiptily et al., PPCF (2006)]

Number of fast D ions with energies > 0.5MeV

- $P_{ICRH} / P_{NBI} = 0.71$ → high γ-count rate
  $P_{ICRH} / P_{NBI} = 0.27$ → low γ-count rate
  NBI-only (E_D = 100keV) → nearly zero γ-count rate
- Possibility to tailor fast-ion energies and optimize fusion rate **with P_{ICRF} / P_{NBI}**

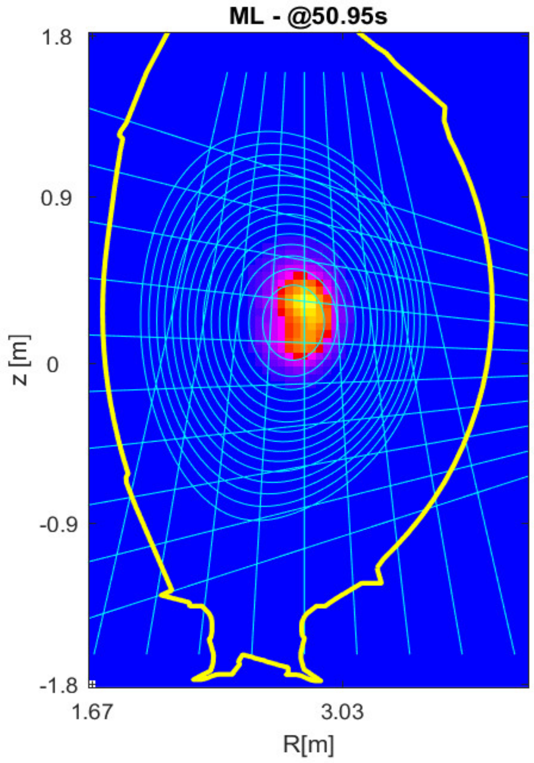
Neutron camera data: core localization of energetic D ions

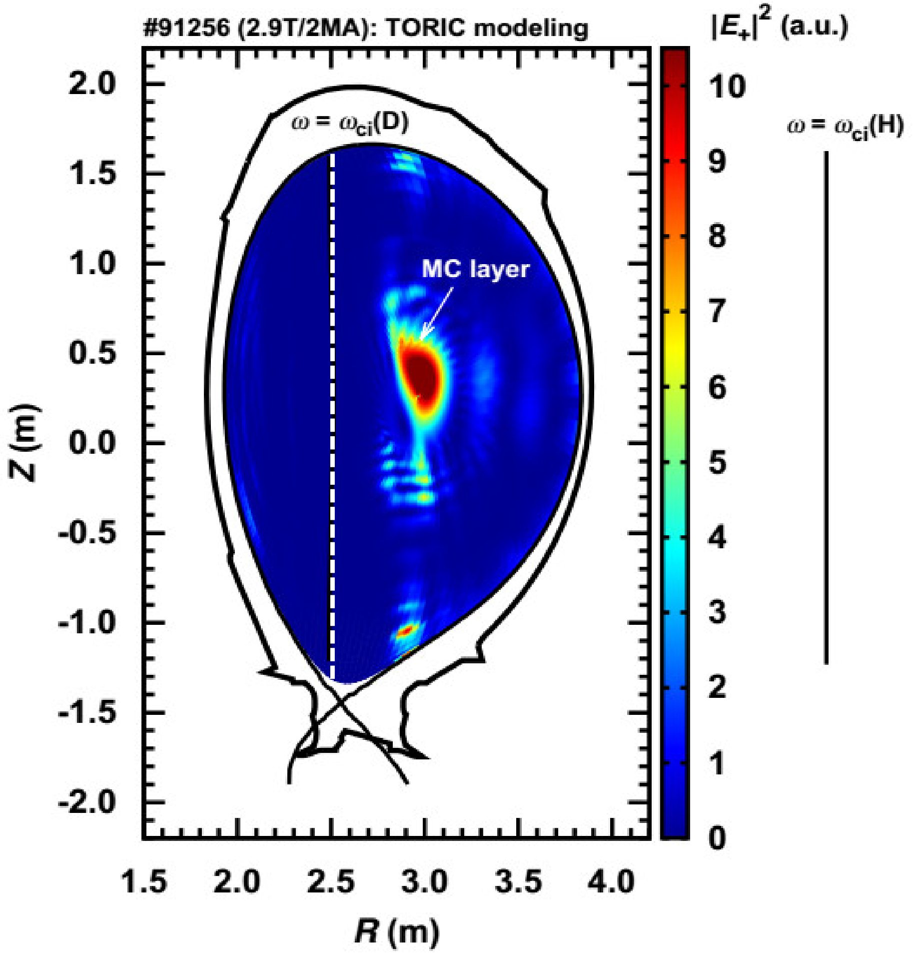




- JET neutron cameras: 19 lines of sight (10 horizontal and 9 vertical)
  → visualize the spatial localization of fast-ion population
- Strong localization of neutron emission in the **plasma core** (channels #4, #5, #14, #15)

Reconstructed neutron emission profile and TORIC-computed location of the MC layer

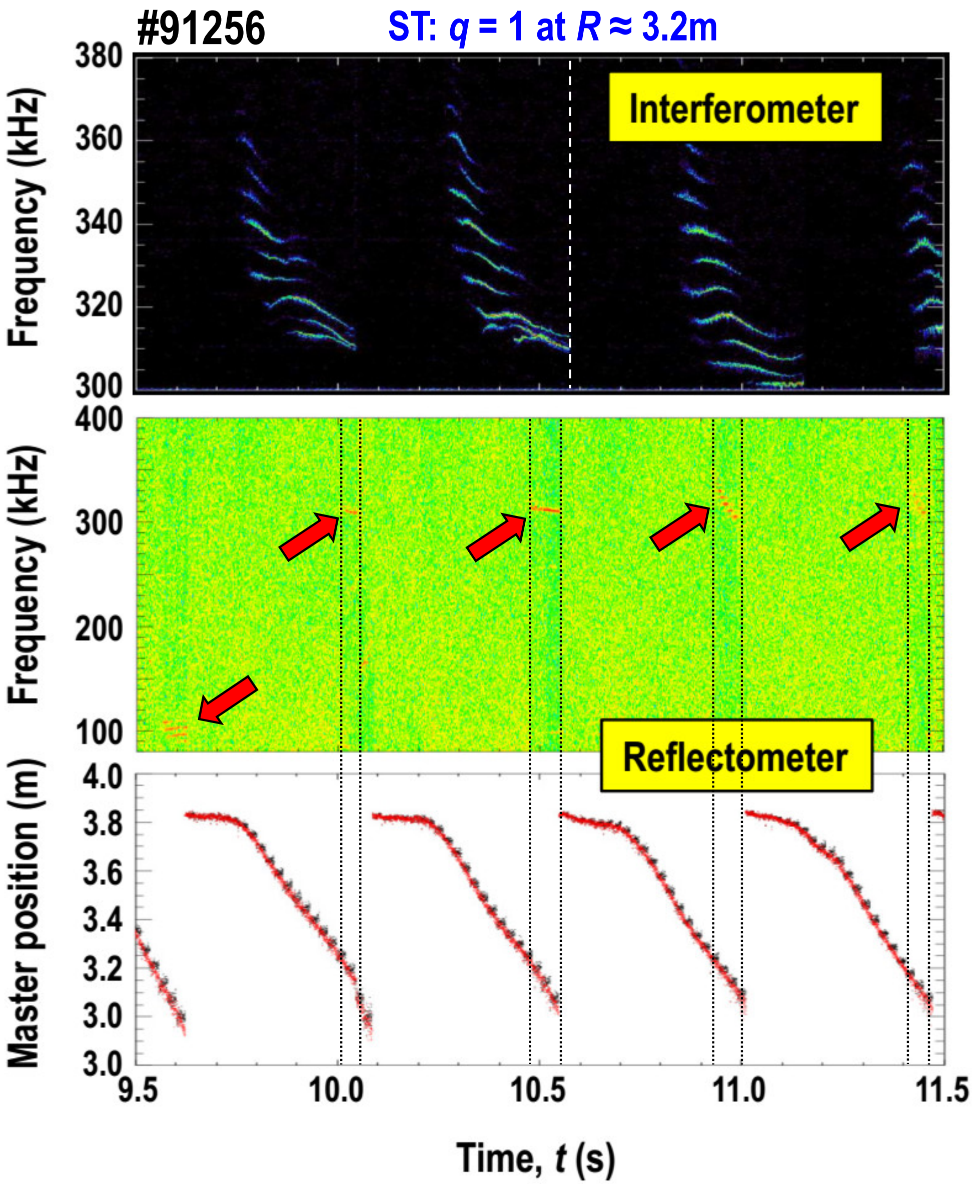


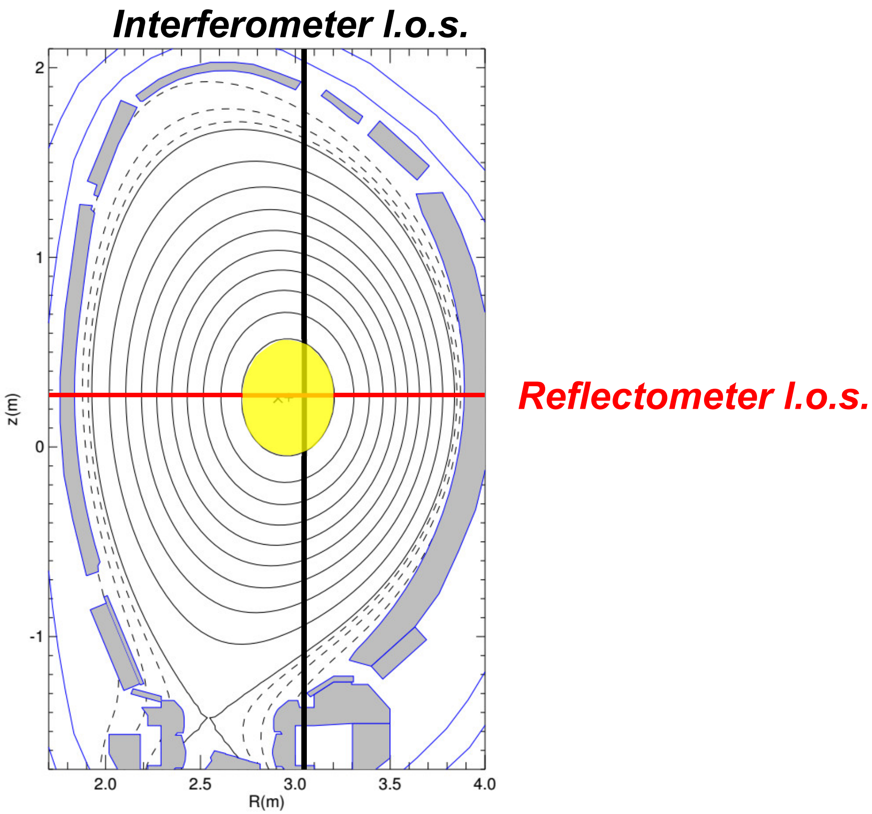


- RF power absorption and fast-ion generation are **strongly localized at the MC layer**
- The high-efficiency of the 3-ion ICRH+NBI schemes is due to the **superposition of two effects**

i) enhanced RF field polarization;
ii) Doppler-shifted absorption for beam ions

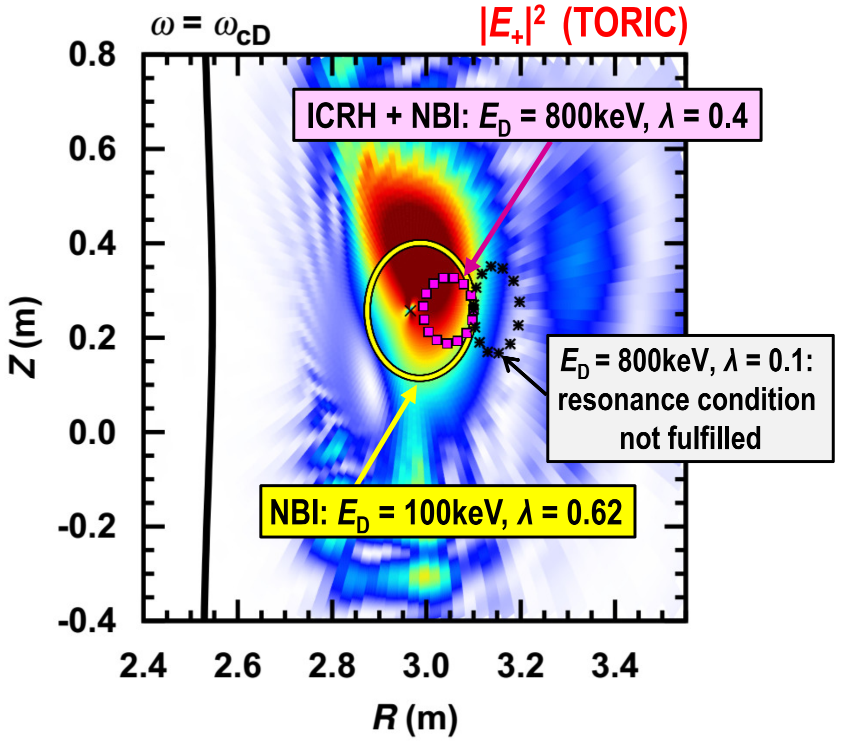
Radial localization of MHD modes

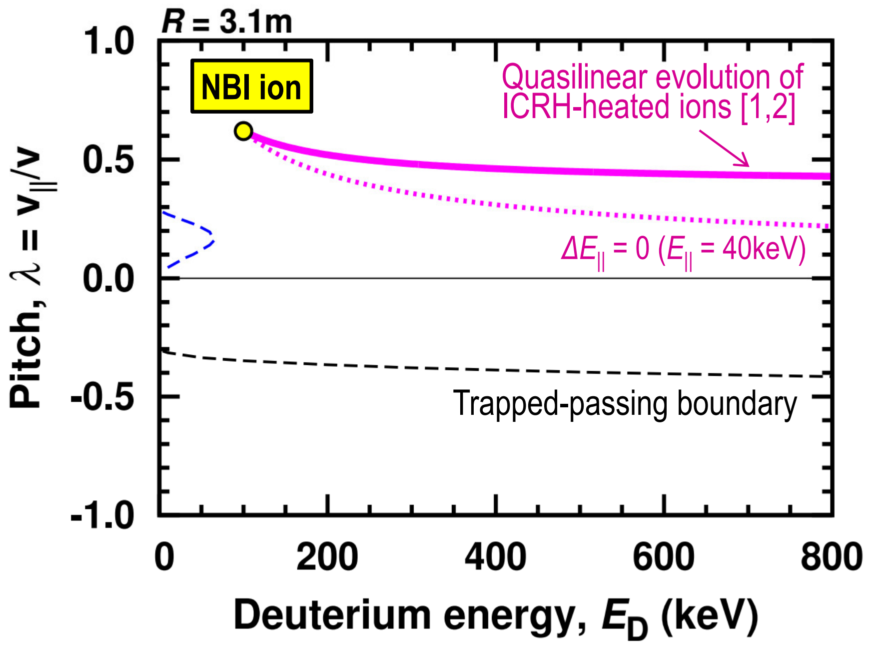




- Core interferometer: AE modes at $f \approx$ 100-150kHz and $f \approx$ 300-360kHz
- Reflectrometer:
  AEs are core-localized, *R* < 3.2m
  (also confirmed by SXR)
- Consistent results between neutron camera data, MHD mode analysis and ICRH modeling

Efficient generation of energetic passing D ions with 3-ion ICRH+NBI scheme





NBI (100keV, λ = 0.62): $E_\perp \approx 60\mathrm{keV}, E_\parallel \approx 40\mathrm{keV}$
ICRH + NBI: $E_\perp \gg E_\parallel;\ \lambda \simeq 0.3-0.4$

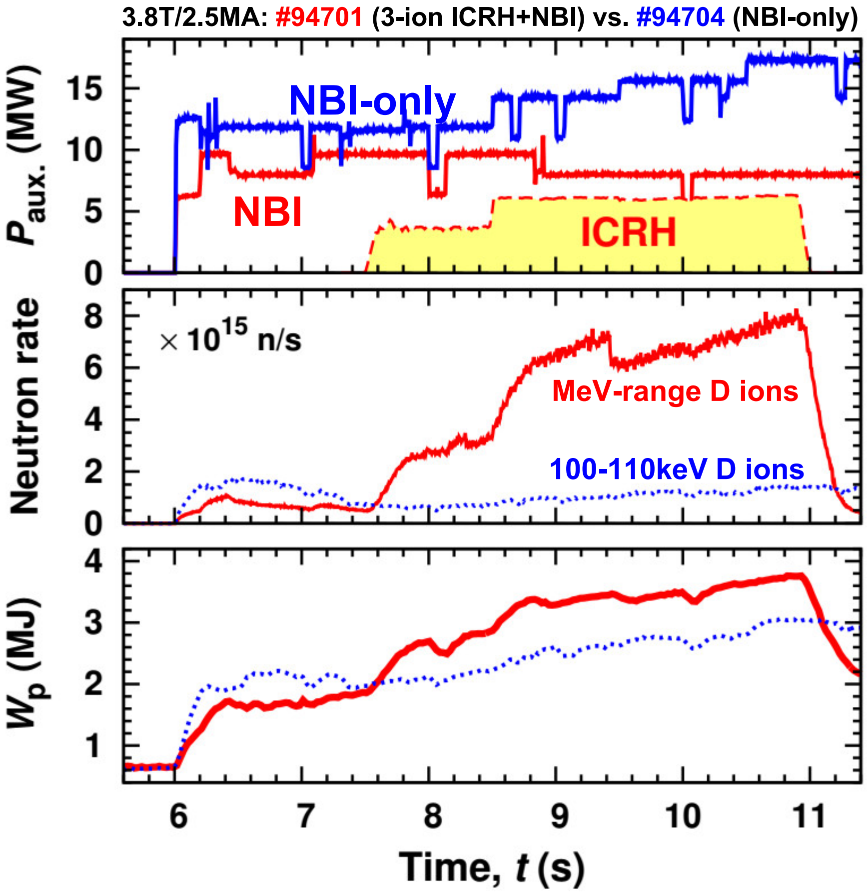
Several contributing effects:

- Resonant NBI ions (passing) start with rather large $E_\parallel \approx$ 40keV
- **MC layer is a combined spatial and velocity space filter for resonant ions**
  - → **resonant ions should pass through the MC layer and fulfill $\omega = \omega_{cD} + k_\parallel v_\parallel$**
  - → **low-λ orbits do not fulfill the resonance condition**
- Very core-localized RF power deposition: non-standard orbit topology
  - → modified trapped/passing boundary and stagnation orbits
- Rather broad $k_\parallel$-spectrum from ICRH and quasi-linear evolution of ICRH-heated ions $(\delta E_\perp; \delta E_\parallel)$

[1] L.-G. Eriksson et al., PoP (1999); [2] T. Hellsten et al., NF (2004)

Outlook for future studies

3-ion schemes on JET: mimicking the conditions of ITER



D-^{3}He plasmas	P_{tot}	R_{nt} (10^{15} n/s)	W_p (MJ)
#94701 (3-ion ICRH)	14.2MW	7.8	**3.7**
#94704 (NBI-only; @8.5-9.5s)	14.3MW	1.0	**2.6**

ITER:

- Dominant electron heating
- Alpha particles can significantly reduce ITG turbulence and heat transport [J. Garcia et al., Phys. Plasmas (2018)]

3-ion ICRH schemes on JET:
plasmas with core electron heating, including a small population of MeV-range ions

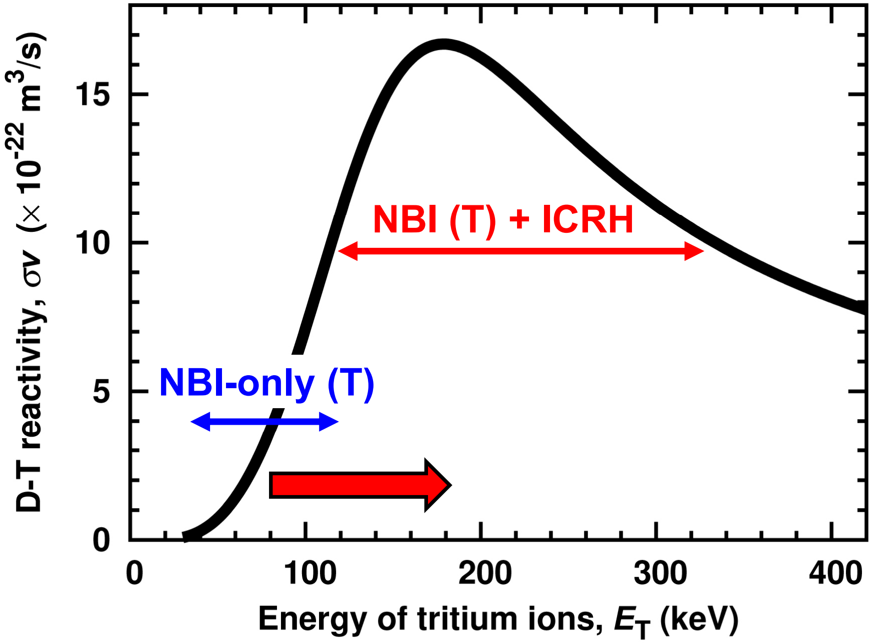
- Mimick the conditions representative for ITER plasmas
- Contribute to the understanding the impact of fast ions on plasma transport, in particular, the impact of alphas in ITER

Relevance of the schemes for JET D-T operation

- **The technique offers a flexibility with electron / bulk ion heating**

- Bulk ion heating schemes
  - → applicable for D-T ≈ 50%-50%
  - → use heavy species (^{9}Be, ^{22}Ne, Ar impurities) and/or off-axis T-NBI heating
  - → Ti-heating with reduced fast-ion generation
  - → contribute to the experiment to demonstrate alpha particle heating in DTE2

- 3-ion scheme with T-NBI as a minority
  - → D-T with $X[\mathrm{D}] \approx 70$-80%
  - → accelerate T-NBI ions to the optimal energies ~150-350keV
  - → fast-ion energy actuators: $P_{\mathrm{ICRF}} / P_{\mathrm{NBI}}$, D:T ratio, n_{e0}, B_0, …



Summary and conclusions

- **3-ion D-(D_{NBI})-H and D-(D_{NBI})-^{3}He schemes on JET**

→ Efficient controlled acceleration of D-NBI ions with **ICRH in mixed plasmas** demonstrated

Actuators: P_{ICRF} / P_{NBI}, n_{e0}, location of the MC layer, …

→ Good example demonstrating the strength and variety of fast-ion diagnostics at JET-ILW:

neutron cameras, TOFOR, NPA, γ-ray spectroscopy, MHD analysis, …

→ Numerical ICRH modeling (PION, TRANSP) is in good agreement with fast-ion measurements (#91256)

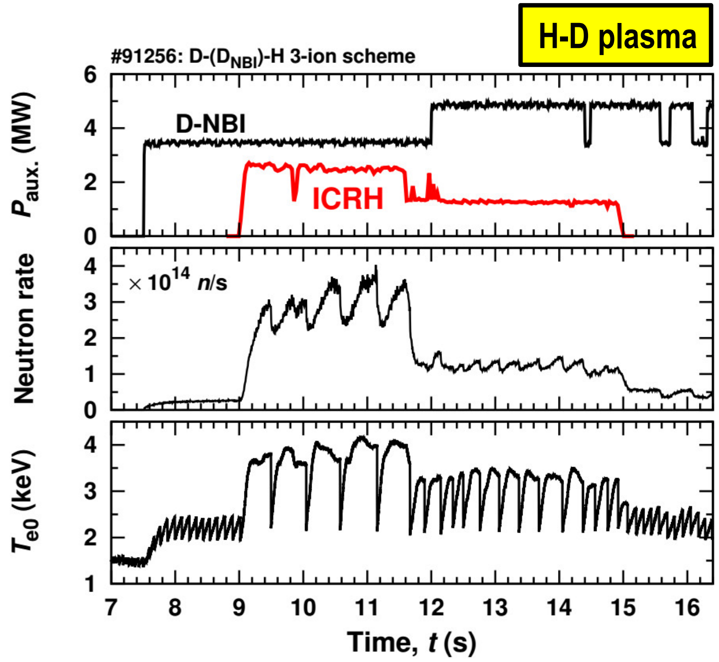
[M. Mantsinen et al., EPS-2019 (2019);
K. Kirov et al., 23rd RF Topical Conf. (2019)]

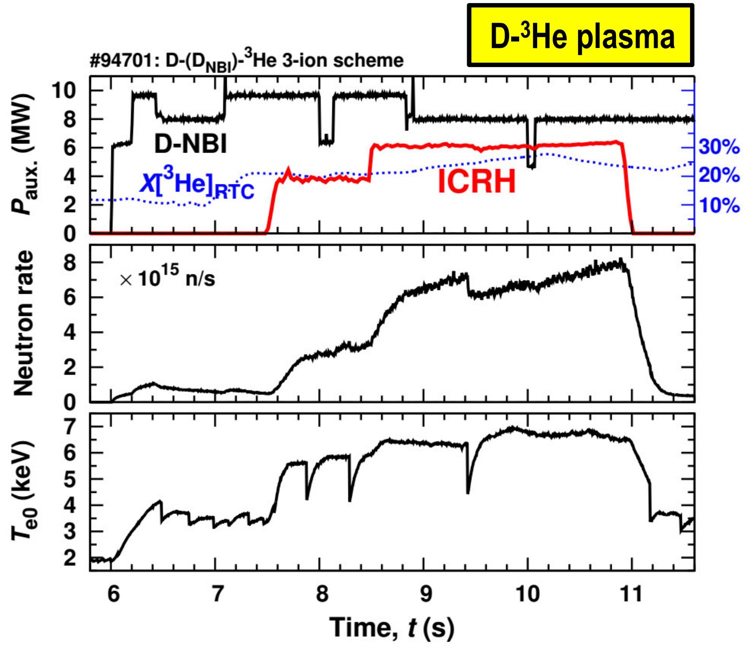
→ This scheme is capable to generate fast passing ions:

beneficial for plasma heating in small tokamaks and stellarators

- **3-ion ICRH schemes are relevant for future JET and ITER operations**

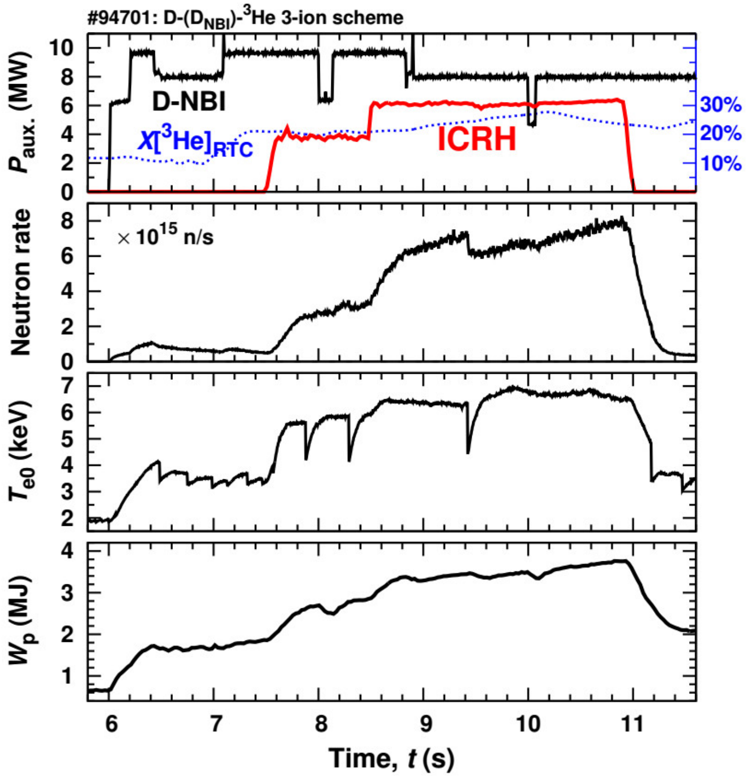
[Y. Kazakov et al., EPS-2018 (2018)]

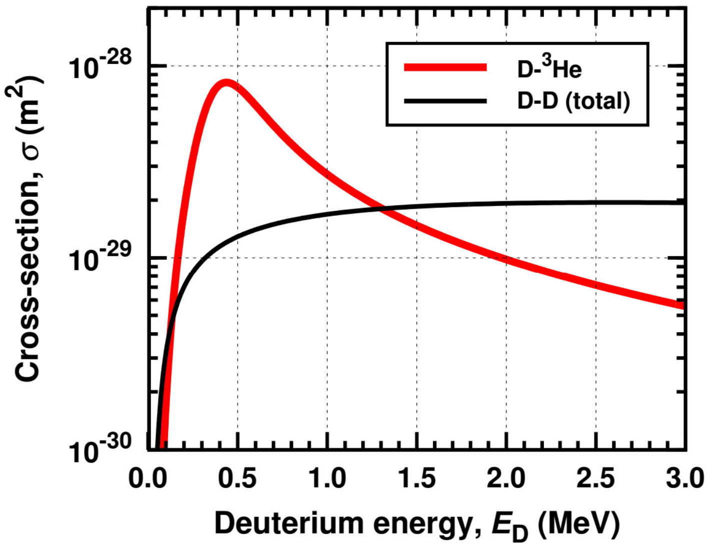




Backup slides

‘3-ion’ ICRF scheme in D-^{3}He mixed plasmas: one-page summary





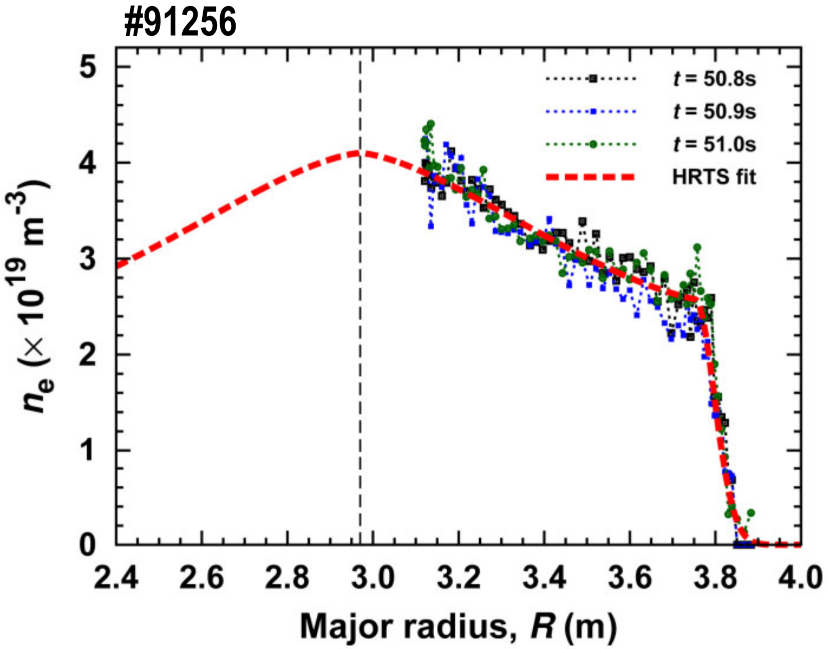
- 3 components for the 3-ion D-(D_{NBI})-^{3}He ICRH scheme
  → thermal D and ^{3}He (~20-25%)
  → fast D-NBI ions as a minority
- Efficient plasma heating and fast-ion generation
- Fast D ions with energies up to ~3MeV generated
- **5 different MeV-range populations in the plasma, including 3.6MeV alpha particles**
  → **H, D, T, ^{3}He and ^{4}He**

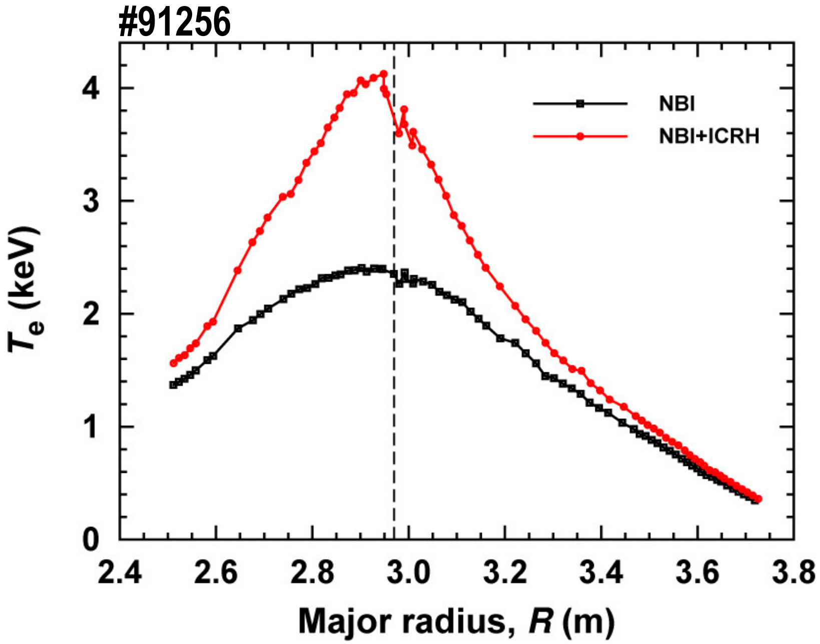
Energetic species	**Energy**	**Fast-ion source**
H	3.02MeV, 14.7MeV	Fusion product (D-D, D-^{3}He)
D	**up to ~3MeV**	**3-ion ICRH+NBI scheme**
T	1.01MeV	Fusion product (D-D)
^{3}He	0.82MeV	Fusion product (D-D)
^{4}He	**3.6MeV**	**Fusion product (D-^{3}He)**

$$D + {}^3He \rightarrow {}^4He\ (3.6MeV) + p\ (14.7MeV)$$

$$D + D \rightarrow \begin{array}{l} T\ (1.01MeV) + p\ (3.02MeV) \\ {}^3He\ (0.82MeV) + n\ (2.45MeV) \end{array}$$

Core ICRF heating: peaked T_e profiles observed



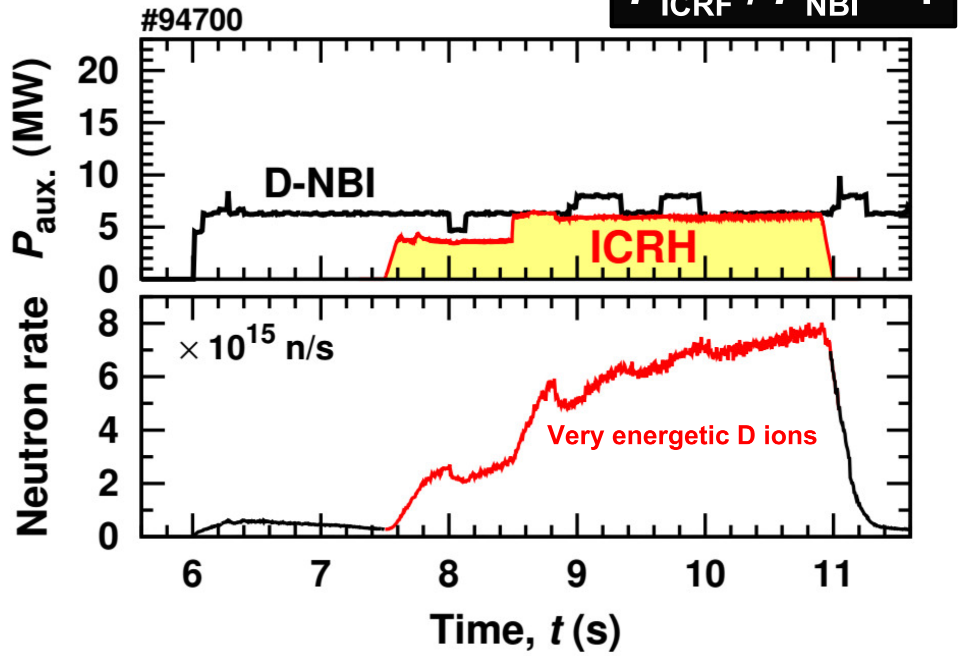


- L-mode plasmas (2.9T/2MA), $n_e(0) \approx 4\times10^{19}$ m^{-3}, H-D ≈ 85%:15%
- **Centrally peaked T_e profiles**

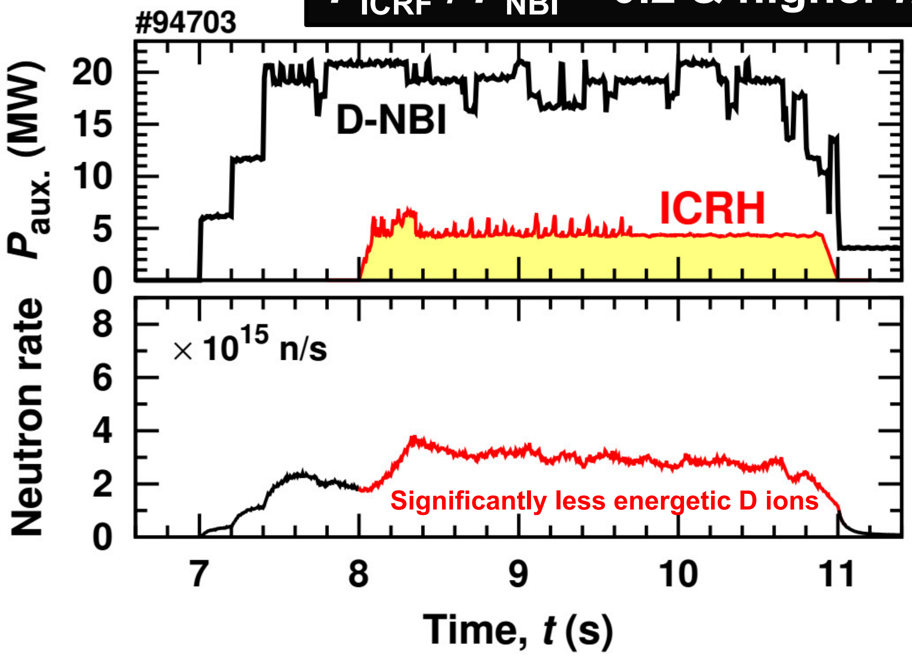
NBI-only: $T_e(0) = 2.4$keV
NBI+ICRH: $T_e(0) = 4.0$keV

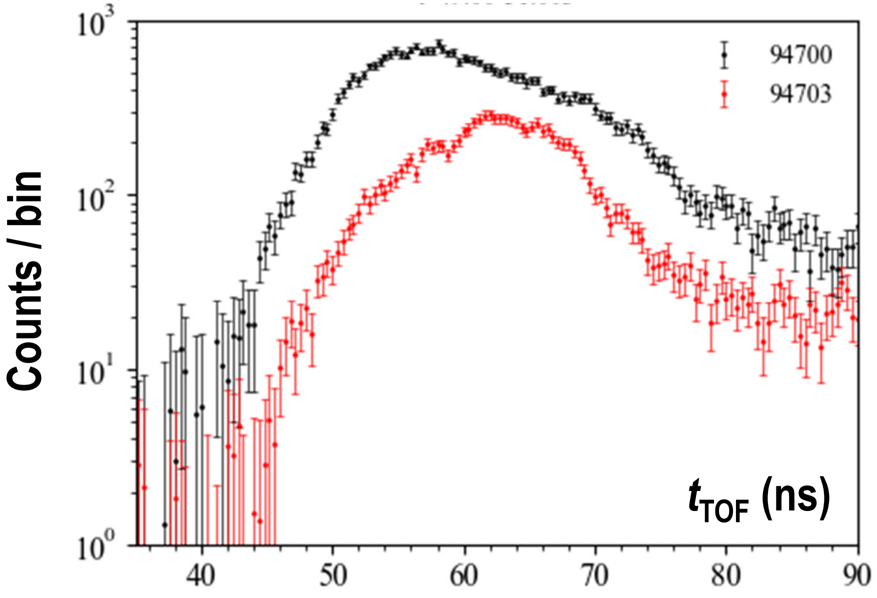
Example of controlling fast-ion energies and neutron rate with 3-ion ICRH+NBI schemes

P_{ICRF} / P_{NBI} ≈ 1



P_{ICRF} / P_{NBI} ≈ 0.2 & higher n_{e0}





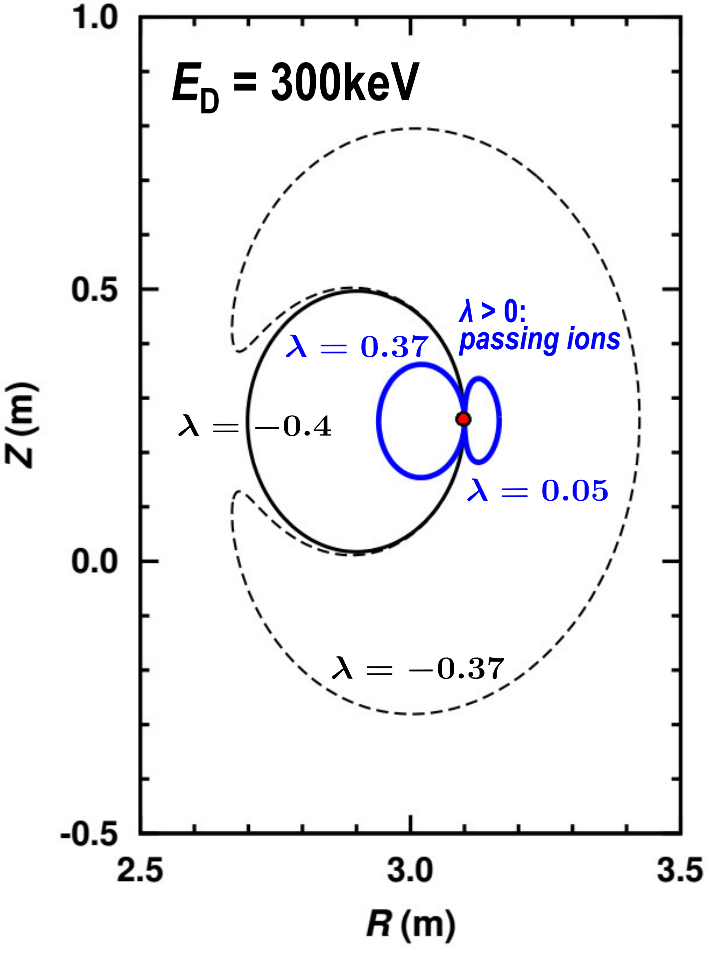
Neutron spectrum from TOFOR (@9-11s):

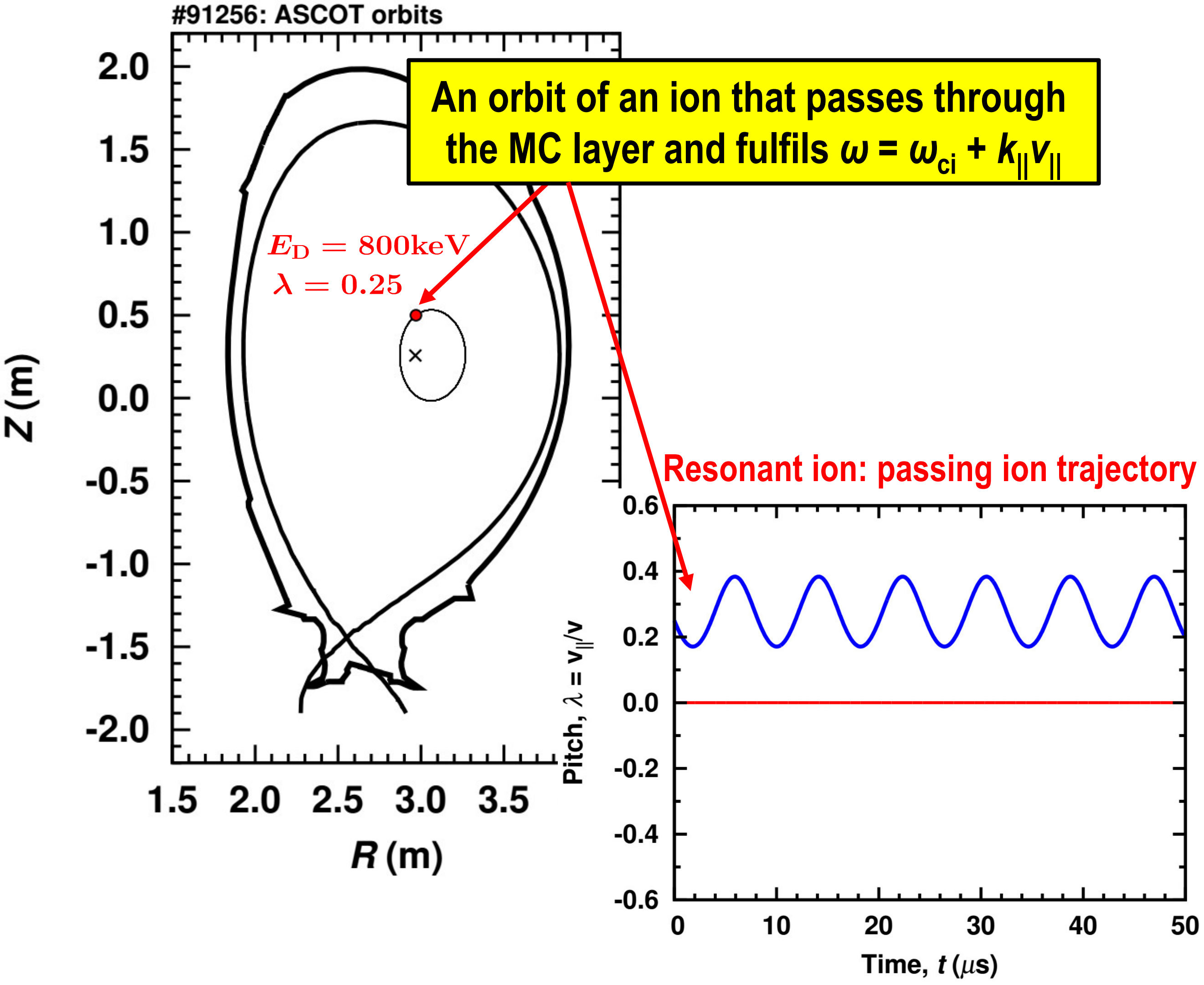
#94700: very high neutron rate and energetic D ions

#94703: reduced fast-D energies *(beneficial for D-T)* due to lower P_{ICRF} / P_{NBI} and higher n_{e0}

ASCOT orbits

Orbits of energetic D ions vs. λ





An orbit of an ion that passes through the MC layer and fulfils $\omega = \omega_{ci} + k_{||}v_{||}$

Resonant ion: passing ion trajectory

λ = 0.13: stagnation orbit

Evolution of $(\delta E_\perp; \delta E_\parallel)$ during ICRH

$\lambda = v_\parallel / v, \quad \mu = m v_\perp^2 / (2B), \quad E = m v^2 / 2$ Normalized magnetic moment: $\Lambda = \mu B_0 / E$

Trajectories in phase space during ICRH (cf., Eq. (8) in [2]): $\delta\Lambda / \delta E = (\Lambda_{\mathrm{res}} - \Lambda) / E$

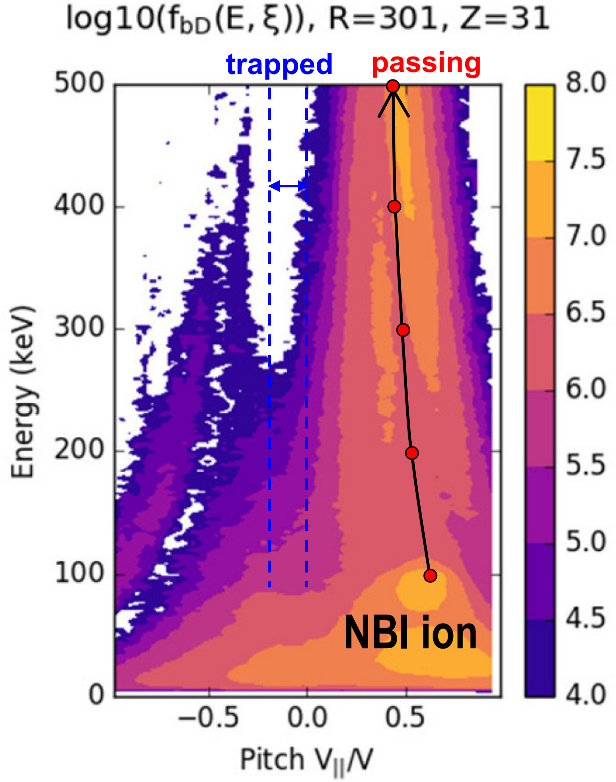
$$\Lambda_{\mathrm{res}} = \frac{n \omega_{ci}(0)}{\omega}$$

Here, $\omega_{ci}(0)$ is the cyclotron frequency at the magnetic axis

Conditions for JET pulse #91256: $E_{\mathrm{NBI}} = 100\mathrm{keV}, \lambda = v_\parallel / v = 0.62$, originally passing NBI ions

$$\Lambda_{\mathrm{res}} = \frac{n \omega_{ci}(0)}{\omega} \simeq \frac{1}{1 + X[\mathrm{D}]} \approx 0.87$$

		$\Lambda \to \Lambda_{\mathrm{res}}$		$\delta E_\perp \gg \delta E_\parallel$	
E	**$\lambda = v_\parallel / v$**	**Λ**	**Λ_{res}**	**$E_\parallel$**	**$E_\perp$**
100keV	0.62	0.63	0.87	40keV	60keV
500keV	0.44	0.82	0.87	100keV	400keV
1MeV	0.41	0.85	0.87	170keV	830keV



log10($f_{bD}(E,\xi)$), R=301, Z=31

[1] L.-G. Eriksson et al., *Phys. Plasmas* 6, 513 (1999)
[2] T. Hellsten, T. Johnson et al., *Nucl. Fusion* 44, 892-908 (2004)
[3] Y. Kolesnichenko et al., *Nucl. Fusion* 57, 066004 (2017)
[4] C. Hellesen, M. Mantsinen et al., *Nucl. Fusion* 57, 056021 (2018)