Recent applications of 3-ion ICRF schemes on ASDEX Upgrade and JET in support of ITER

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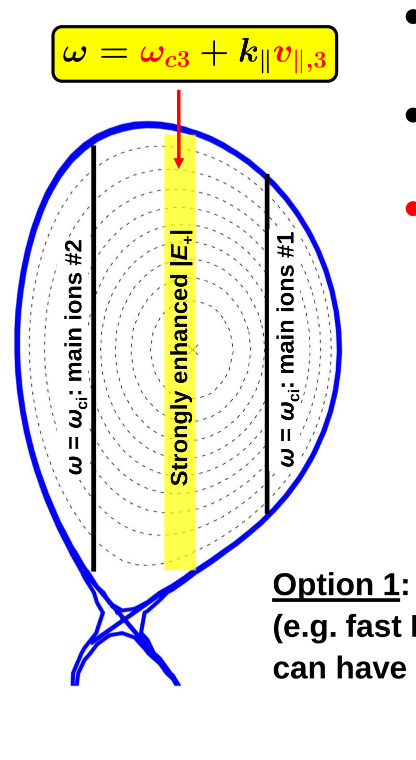
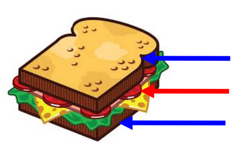
*** See the author list of H. Meyer et al., Nucl. Fusion **59**, 112014 (2019)*
**** See the author list of B. Labit et al, Nucl. Fusion **59**, 086020 (2019)*

1. Introduction: the concept of 'three-ion' ICRF scenarios



- **Mixed plasmas: ion-ion hybrid layer between R_{c1} and R_{c2}, usually applied for electron heating via mode conversion**
- **Locally enhanced E_+ RF electric field → facilitates wave absorption by ions**
- **Three-ion scenarios (n = 1): add a 'third' ion component to absorb ICRF power in mixed plasmas!**



Main ions no. 1
Resonant ions (no. 3)
Main ions no. 2

Range of new applications of ICRF in fusion devices

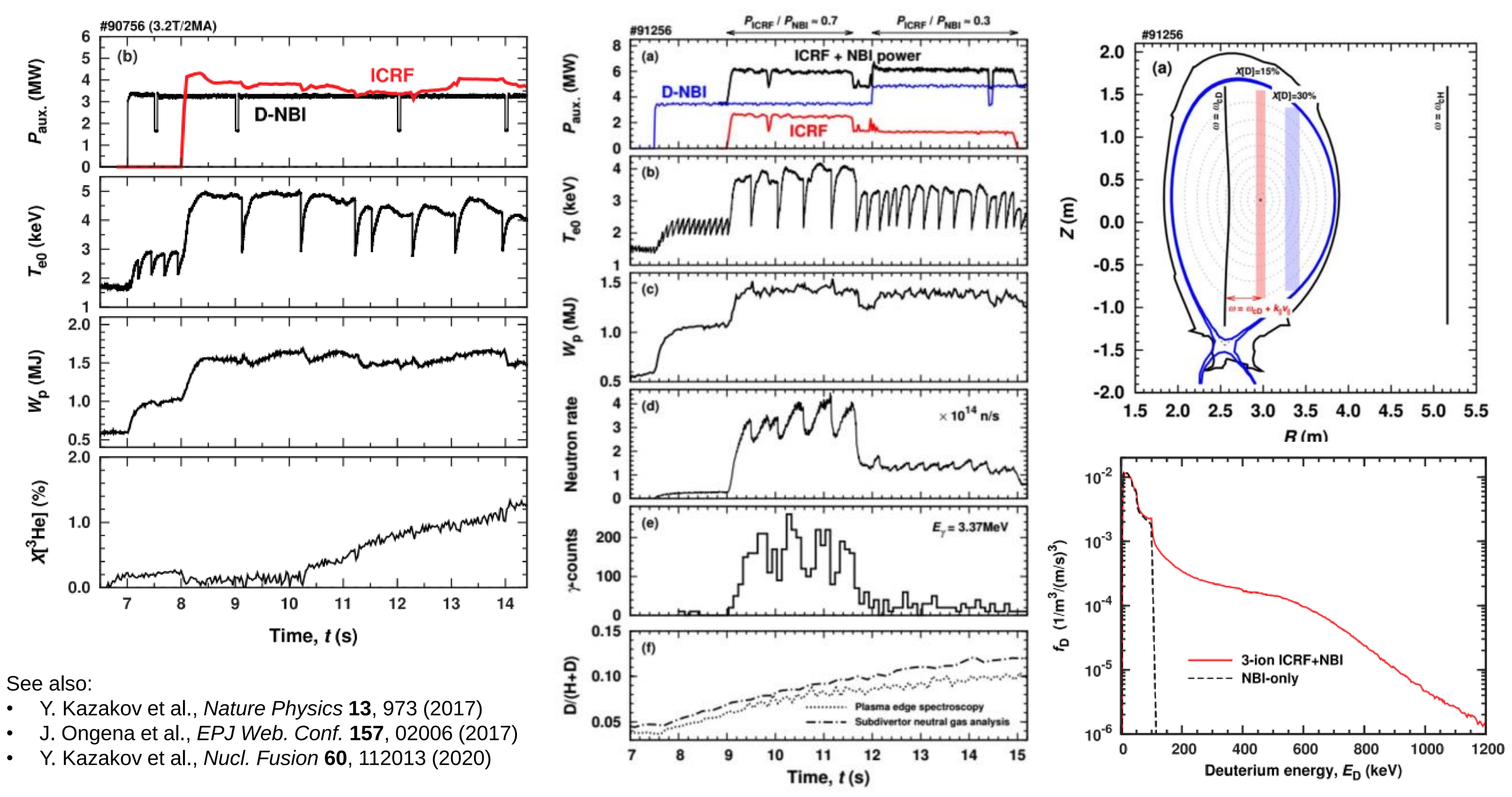
Option 1: add third ions with large $v_{\|}$ (e.g. fast NBI ions or fusion products); can have $(Z/A)_i$ as one of the two main ions

Option 2: add third ions with $(Z/A)_i$ different than for the two main ions $(Z/A)_2 < (Z/A)_3 < (Z/A)_1$

2. Two equivalent choices of resonant absorbers

JET: D-(^{3}He)-H scenario with $n(^3\text{He})/n_e \approx$ 0.1-1.5%

JET: D-(D_{NBI})-H scenario with fast NBI ions as resonant absorbers

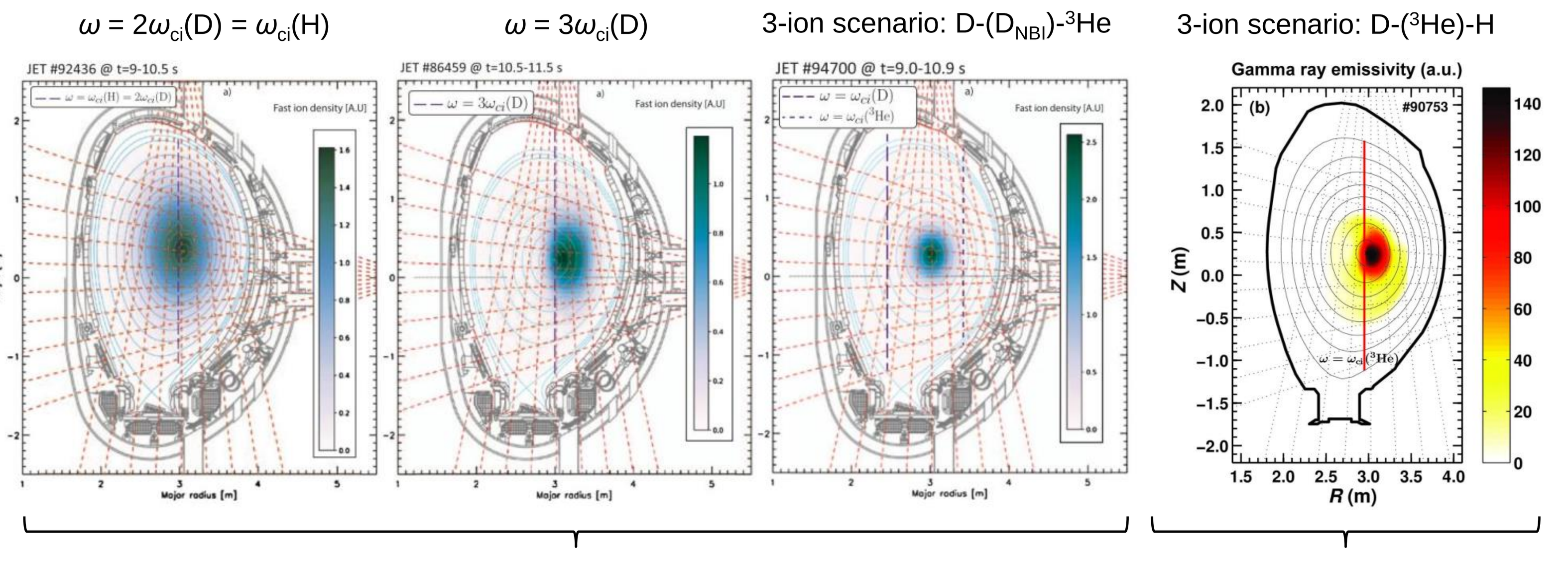


See also:
- Y. Kazakov et al., *Nature Physics* **13**, 973 (2017)
- J. Ongena et al., *EPJ Web. Conf.* **157**, 02006 (2017)
- Y. Kazakov et al., *Nucl. Fusion* **60**, 112013 (2020)

3. JET: generation of passing energetic ions

Strong localization of RF power deposition and fast-ion generation in the plasma core

$\omega = 2\omega_{ci}(\text{D}) = \omega_{ci}(\text{H})$ | $\omega = 3\omega_{ci}(\text{D})$ | 3-ion scenario: D-(D_{NBI})-^{3}He | 3-ion scenario: D-(^{3}He)-H

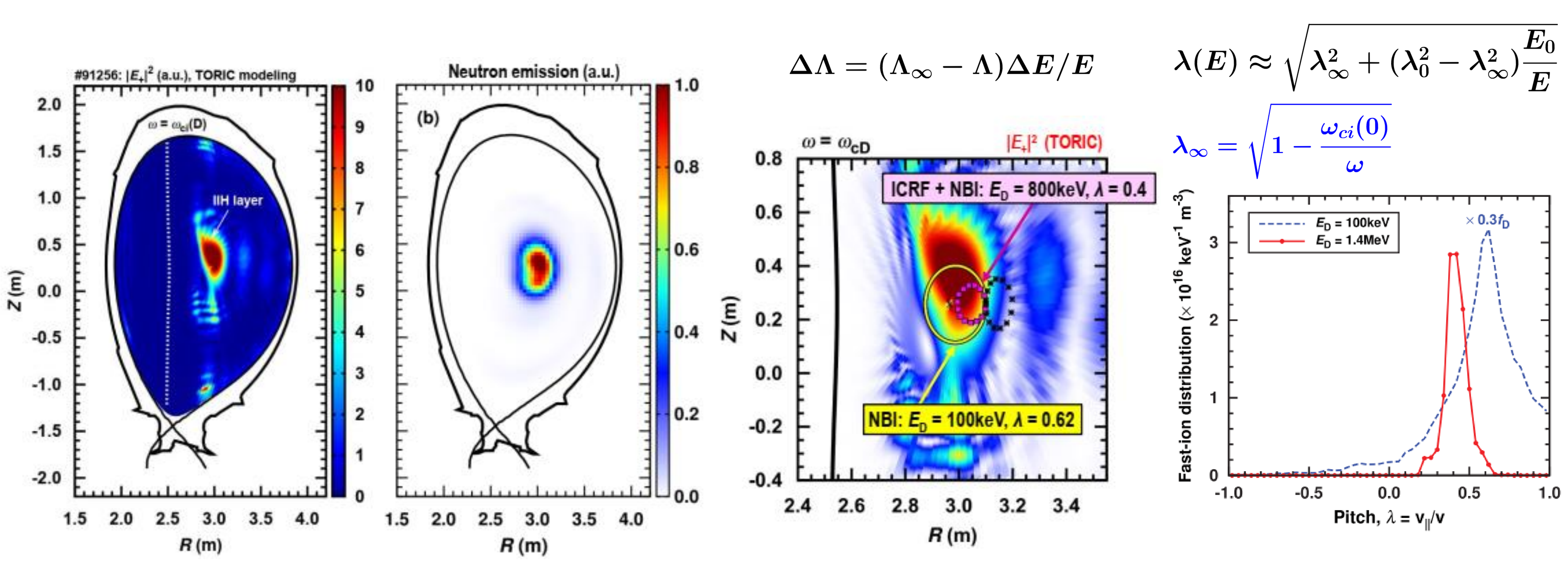


Energetic D ions | **Energetic ^{3}He ions**

More details on neutron measurements:
- Ž. Štancar et al., *this conference (session P2, TH/P2-4)*
- A. Sahlberg et al., *Nucl. Fusion* **61**, 036025 (2021)

Non-standard fast-ion topology in the core and RF quasi-linear diffusion

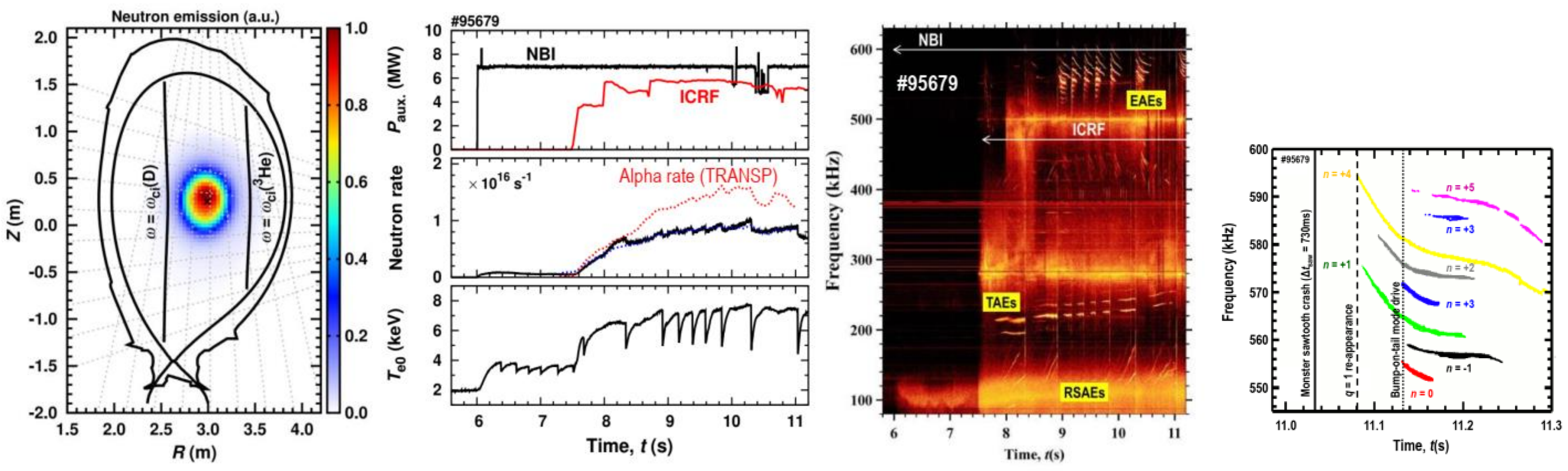
$$\Delta\Lambda = (\Lambda_\infty - \Lambda)\Delta E/E \qquad \lambda(E) \approx \sqrt{\lambda_\infty^2 + (\lambda_0^2 - \lambda_\infty^2)\frac{E_0}{E}} \qquad \lambda_\infty = \sqrt{1 - \frac{\omega_{ci}(0)}{\omega}}$$



Asymmetry in $k_{\|}v_{\|}$ → localized fast-ion current drive

See also:
- M. Nocente et al., *Nucl. Fusion* **60**, 124006 (2020)
- Y. Kazakov et al., *Phys. Plasmas* **28**, 020501 (2021)

4. Fast-ion studies in D-^{3}He plasmas on JET: generation of alpha particles

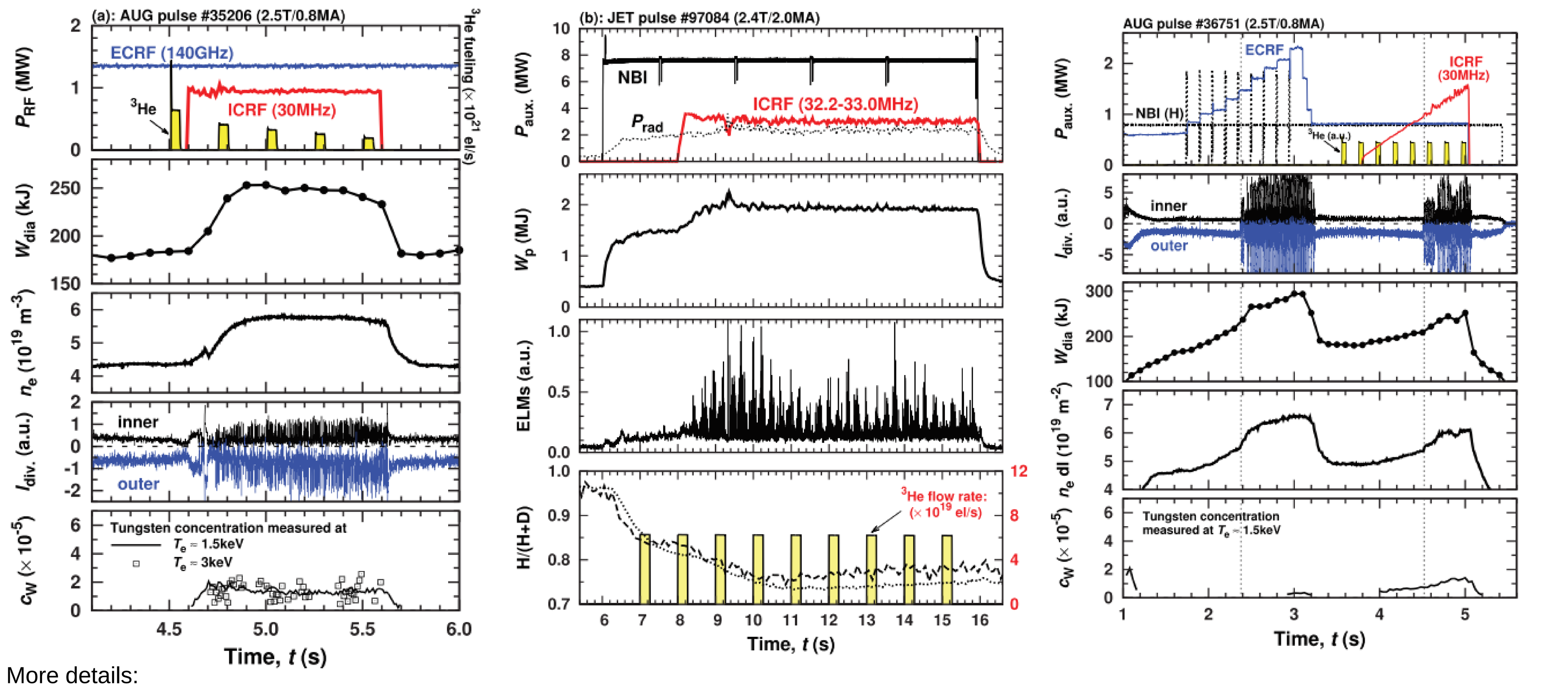


- D-^{3}He plasmas: 3.7T/2.5MA, $n(^3\text{He})/n_e \approx$ 20-25%
- Significant rate of D-^{3}He fusion-born alpha particles, ~2×10^{16} s^{-1}
- Dominant fast-ion electron heating → proxy for alpha heating
- A large variety of Alfvén eigenmodes: TAEs, EAEs, RSAEs
- Complex sawtooth behaviour; correlated with TAE and EAE dynamics

More details:
- M. Nocente et al., *this conference (session P3, #1106)*
- M. Nocente et al., *Nucl. Fusion* **60**, 124006 (2020)
- Y. Kazakov et al., *Phys. Plasmas* **28**, 020501 (2021)
- V. Kiptily et al., *EPS-2021, invited talk*

5. ITER-relevant L-H transition studies on AUG and JET

- Three-ion ICRF scenario has a potential to extend the H-mode operation space in PFPO-2 ITER plasmas, cf. M. Schneider et al., *EPJ Web Conf.* **157**, 03046 (2017); ITER Research Plan (2018)
- ITER: B_0=3.0-3.3T, H + ~10% ^{4}He plasmas, the three-ion ^{4}He-(^{3}He)-H scenario with **off-axis** ^{3}He resonance
- AUG has prototyped the ITER-relevant scenario with NBI, ECRF and ICRF systems for heating H-^{4}He plasmas
- The potential of the scenario was later confirmed on JET

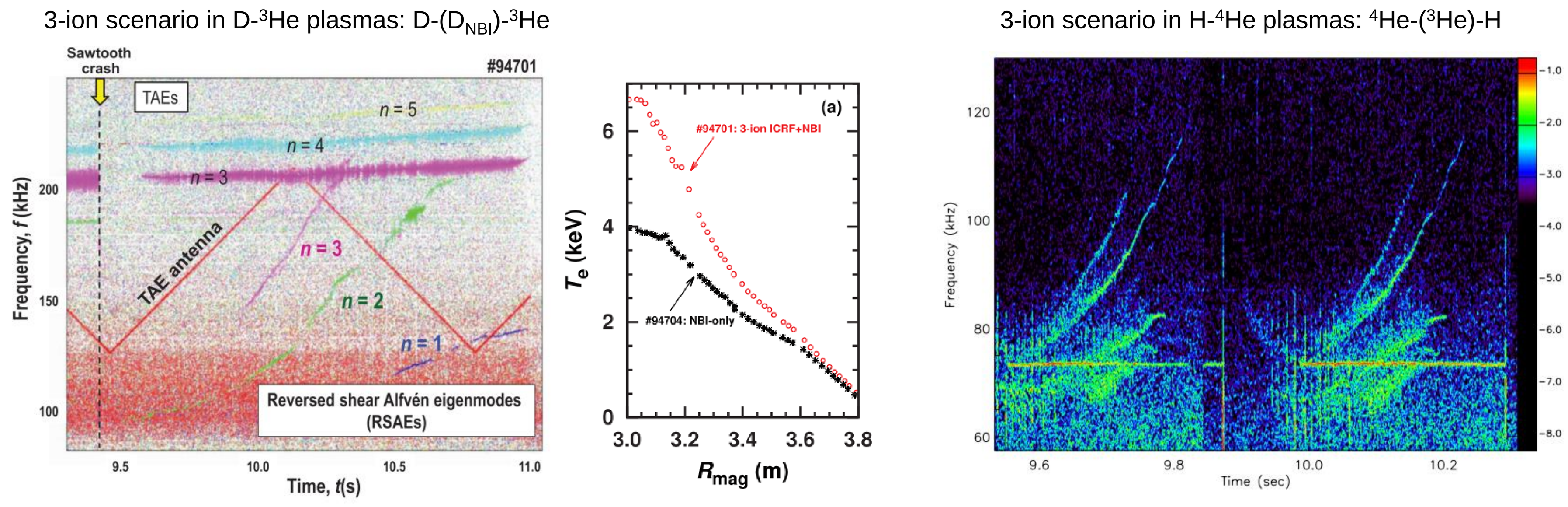


More details:
- Y. Kazakov et al., *Phys. Plasmas* **28**, 020501 (2021)
- Neutron production in ITER PFPO plasmas: A.R. Polevoi et al., *this conference (session P2, TH/P2-8)*

6. A tool to modify the q-profile in the plasma core

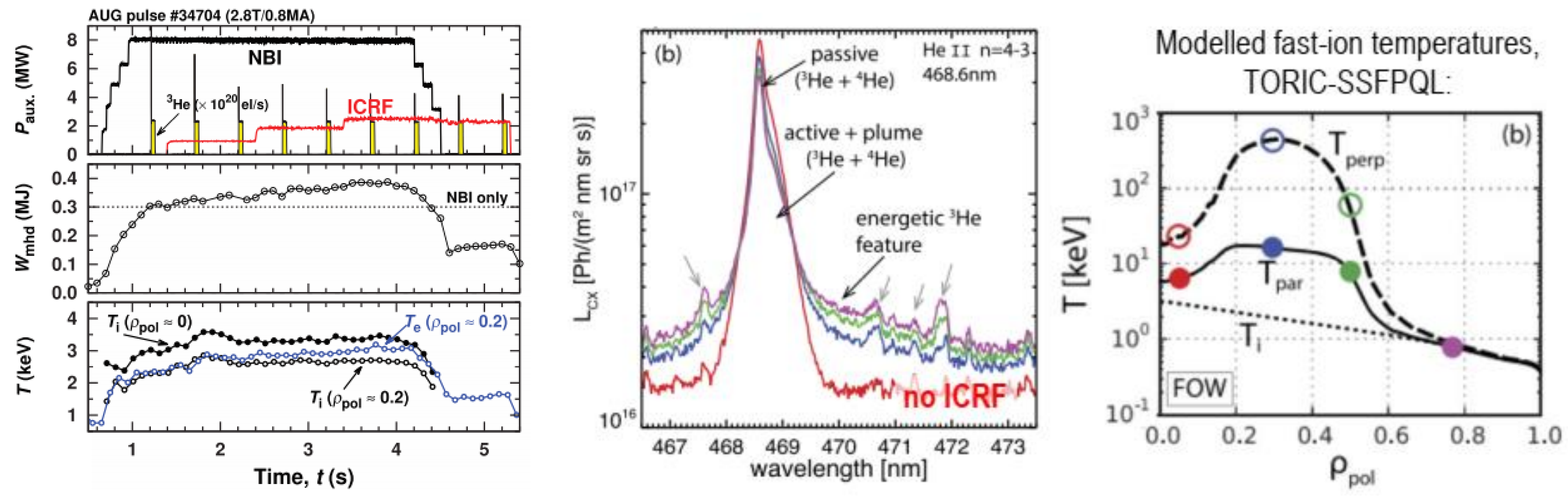
- Reversed-shear Alfvén eigenmodes observed with both types of resonant absorbers
- Reversed q-profiles: an actuator to control plasma dynamics

3-ion scenario in D-^{3}He plasmas: D-(D_{NBI})-^{3}He | 3-ion scenario in H-^{4}He plasmas: ^{4}He-(^{3}He)-H



7. Novel CXRS measurements of energetic He ions on AUG

- Energetic He ions measured with the CXRS system for the first time on AUG
- CXRS measured and forward-modelled (TORIC-SSFPQL) spectra agree well
- More details: A. Kappatou et al., *Nucl. Fusion* **61**, 036017 (2021)



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