Joint W7-X Topical Group “Heating” and “Fast Ions” Meeting

Fast-ion physics phenomena in fusion plasmas heated with the 3-ion ICRF scenario

15 February 2022

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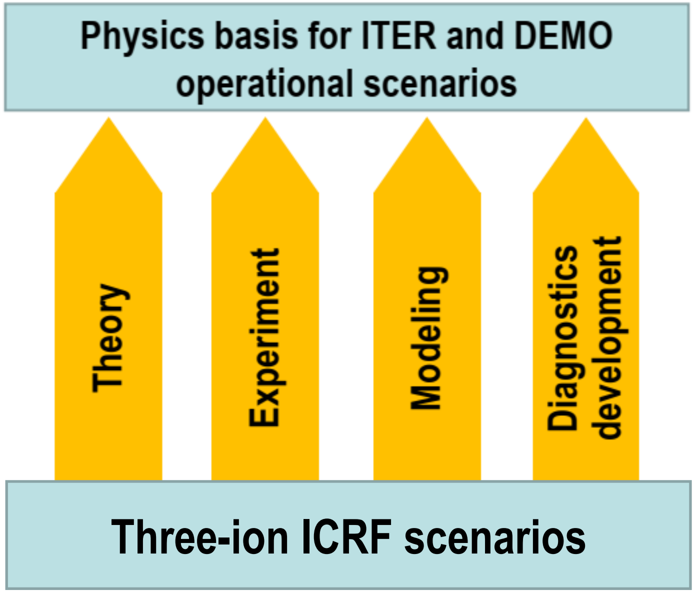
Three-ion ICRF scenarios:
a tool to explore the impact of fast ions on plasma dynamics

☐ JET and AUG experiments with the 3-ion ICRF scheme,
2020-2022 publications by team members:

- Ye.O. Kazakov et al., *Nucl. Fusion* 60, 112013 (2020)
- Ye.O. Kazakov et al., *Phys. Plasmas* 28, 020501 (2021)
- V.G. Kiptily et al., *Nucl. Fusion* 60, 112003 (2020)
- M. Nocente et al., *Nucl. Fusion* 60, 124006 (2020)
- M. Nocente et al., *Plasma Phys. Control. Fusion* 62, 014015 (2020)
- R. Ochoukov et al., *Nucl. Fusion* 60, 126043 (2020)
- A. Kappatou et al., *Nucl. Fusion* 61, 036017 (2021)
- E. Panotin et al., *Rev. Sci. Instrum.* 92, 053529 (2021)
- A. Sahlberg et al., *Nucl. Fusion* 61, 036025 (2021)
- V.G. Kiptily et al., *Nucl. Fusion* 61, 114006 (2021)
- Ž. Štancar et al., *Nucl. Fusion* 61, 126030 (2021)
- A. Teplukhina et al., *Nucl. Fusion* 61, 116056 (2021)
- A. Tinguely et al., *Nucl. Fusion* (2022), accepted
- M. Dreval et al., *Nucl. Fusion* (2022), accepted
- A. Bierwage et al., *Comp. Phys. Comm.* (2022), accepted
- A. Bierwage et al., *Nature Comm.* (2022), submitted
- S. Mazzi et al., *Nature Physics* (2021), submitted



Physics basis for ITER and DEMO operational scenarios

Theory

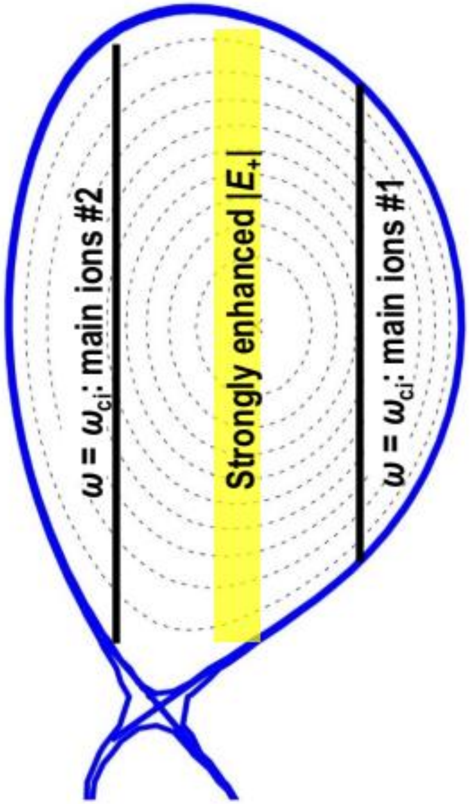
Experiment

Modeling

Diagnostics development

Three-ion ICRF scenarios

Three-ion ICRF scenarios: transforming mode conversion electron heating into a flexible technique for ion cyclotron heating and fast-ion generation



- **Target plasma**: a mixed plasma with two (or more) ion species with different $(Z/A)_i$

  → $|E_+|$ RF electric field strongly enhanced in the vicinity of the ion-ion hybrid (mode conversion) layer(s)

- Strong wave damping can occur in this region by ions that fulfill the resonance condition $\boldsymbol{\omega \approx \omega_{ci} + k_{||}v_{||}}$
- **Two choices for resonant ions**:

  ✓ Option #1: ion population with an ‘intermediate’ charge-to-mass ratio, $(Z/A)_2 < (Z/A)_3 < (Z/A)_1$

  Example: ^{3}He ions in H-D plasmas [1], ^{9}Be impurities in D-T plasmas, …

  ✓ Option #2: ion population with large $v_{||}$ (NBI ions or fusion products)

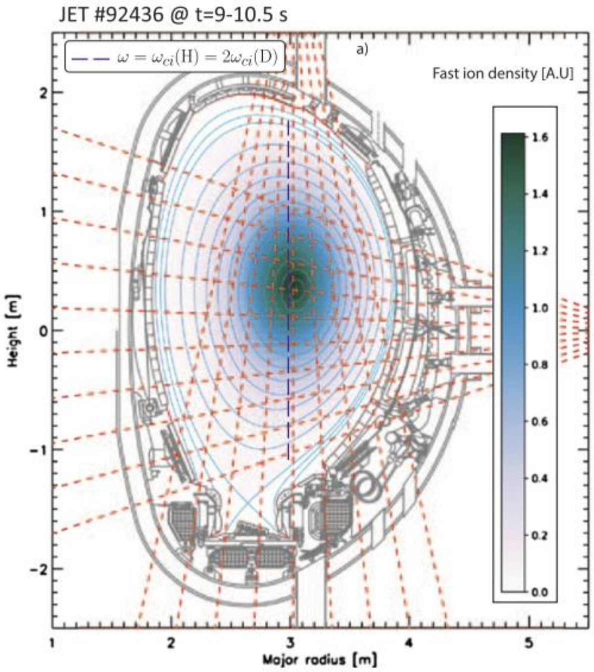
  Example: D-NBI ions in H-D or D-^{3}He plasmas [2,3], …

Demonstrated as an efficient technique on Alcator C-Mod, AUG and JET.
Also observed in past ICRF experiments on JET-C, TFTR and AUG-C.

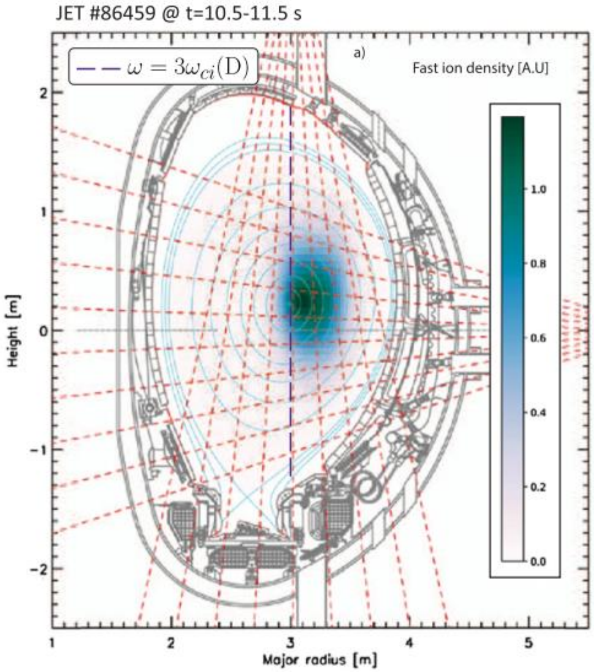
[1] Y. Kazakov, J. Ongena et al., *Nature Physics* 13, 973 (2017)
[2] J. Ongena, Y. Kazakov et al., *EPJ Web Conf.* 157, 02006 (2017)
[3] Y. Kazakov, J. Ongena et al., *Phys. Plasmas* 28, 020501 (2021)

Spatial localization of fast D ions generated with different ICRF scenarios at JET

$\omega = 2\omega_{ci}(D) = \omega_{ci}(H)$



$\omega = 3\omega_{ci}(D)$



3-ion ICRF scenario, D-(D_{NBI})-^{3}He

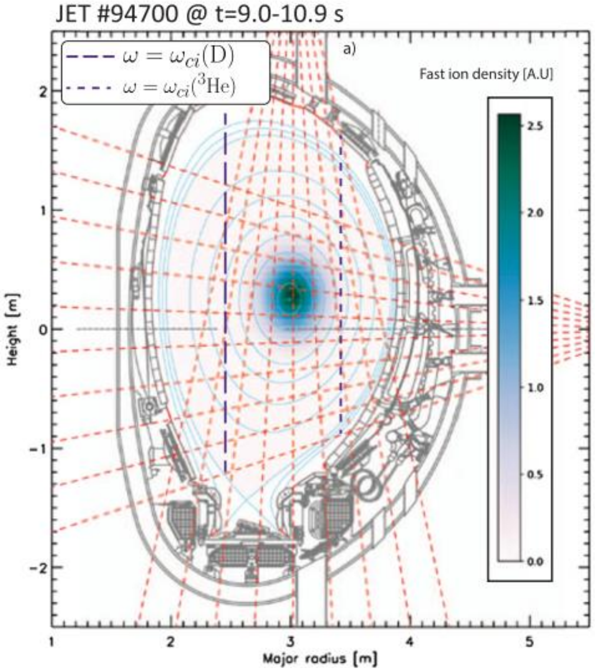


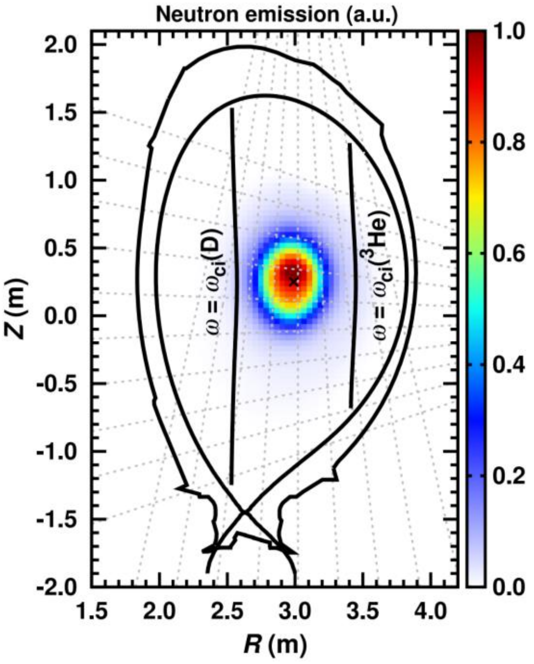
Figure: A. Sahlberg et al., *Nucl. Fusion* (2021)

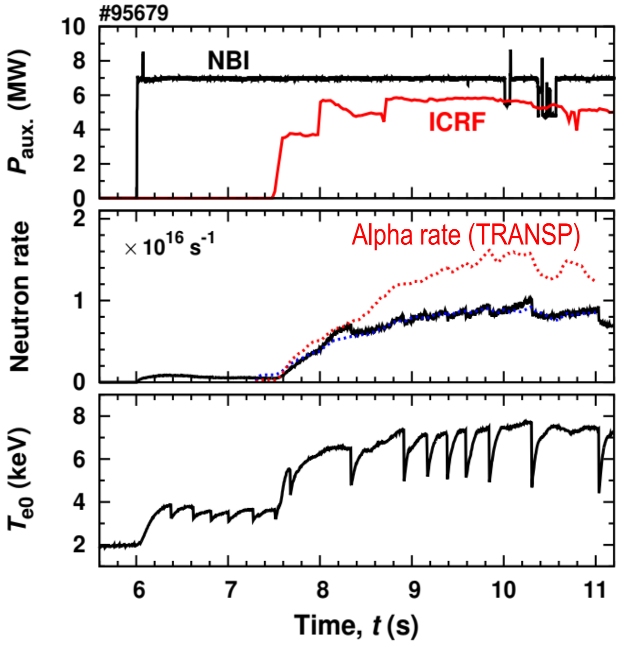
Outline

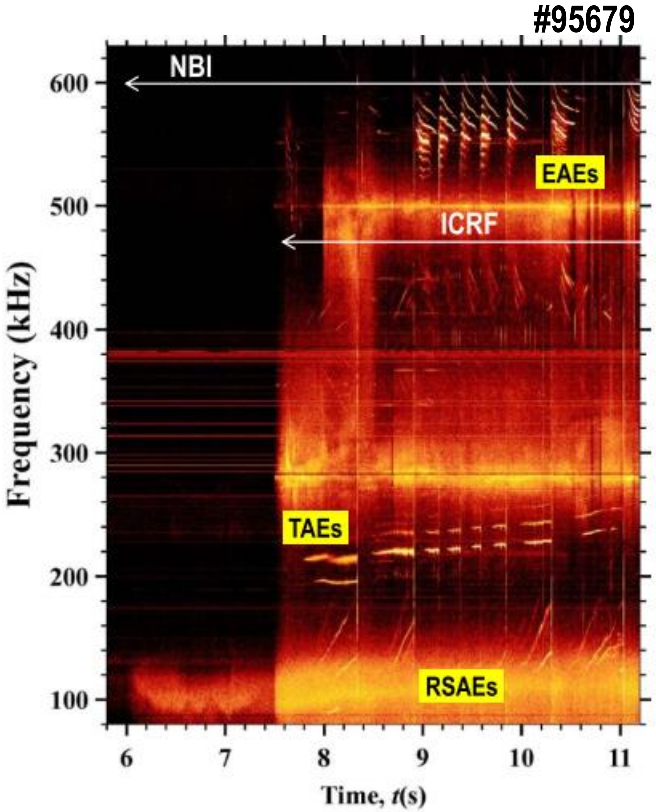
1. Experiments in D-^{3}He plasmas on JET
2. Experiments in H-^{4}He plasmas on JET and AUG
3. LHD experiments with ICRF impurity pump-out (D. Moseev et al.)
4. Summary of proposals

Energetic ions, AEs and plasma confinement

- Three-ion ICRF scenarios at JET: efficient tool to generate high-energy ions (>= 500 keV) and study their impact on the plasma
- A rich variety of fast-ion phenomena, including D-^{3}He fusion-born alpha particles
  D + ^{3}He → ^{4}He (3.6MeV) + *p* (14.7MeV)
- Various types of AEs destabilized: TAEs, EAEs, RSAEs, …



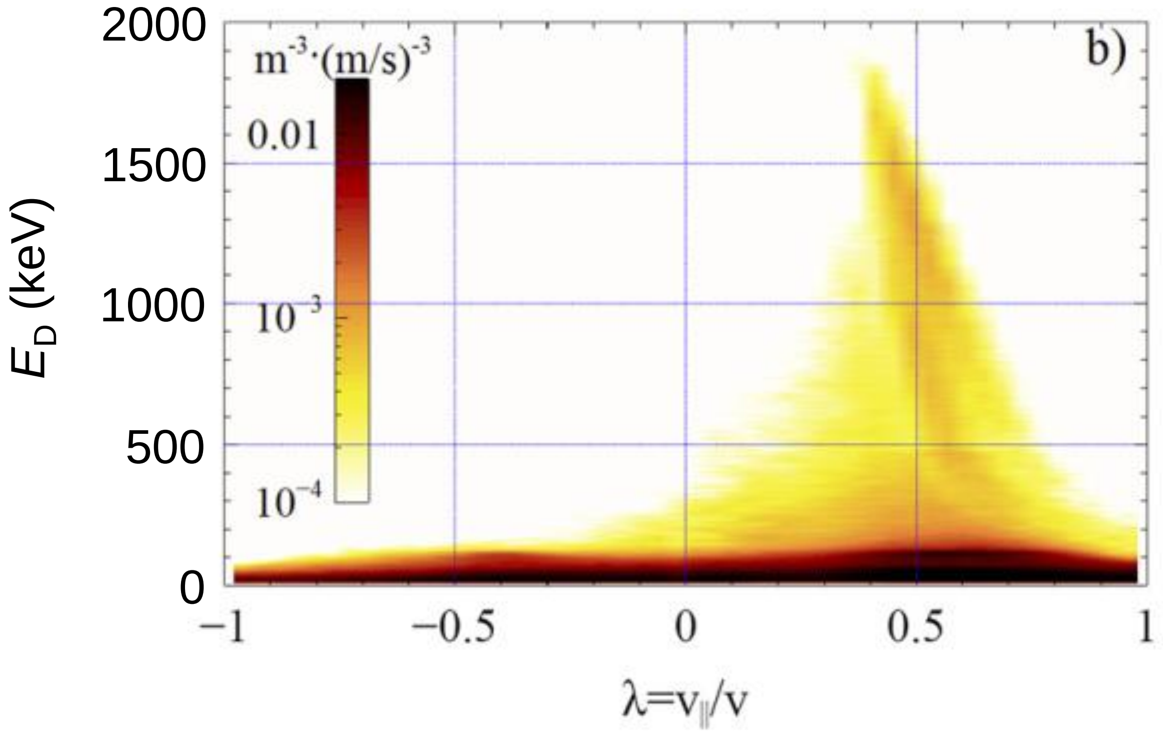




D-^{3}He plasmas with $n(^3\mathrm{He})/n_e \approx$ 20-25% (RTC), 3.7T/2.5MA, $n_{e0} \approx 6\times10^{19}\ \mathrm{m}^{-3}$

More information: M. Nocente et al., *Nucl. Fusion* 60, 124006 (2020)

Three-ion D-(D_{NBI})-^{3}He scenario: typical fast-ion distribution function

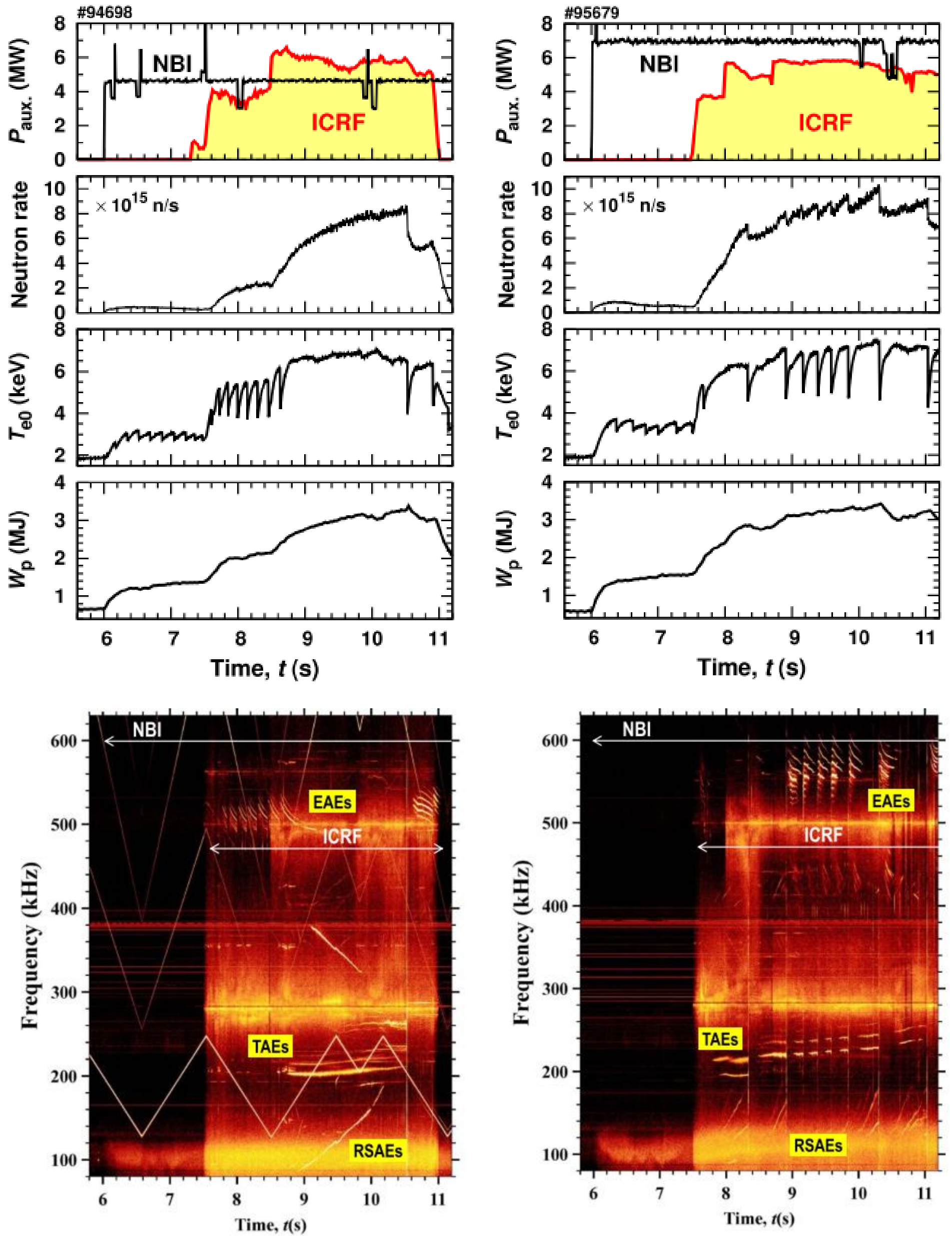


- 3-ion ICRF scenarios: localized RF power deposition and fast-ion generation in the plasma core
- Non-standard fast-ion topology in the core and RF quasi-linear diffusion, $\boldsymbol{\lambda(E) = \sqrt{\lambda_\infty^2 + (\lambda_0^2 - \lambda_\infty^2)\frac{E_0}{E}}}$
  → large populations of passing fast ions generated

$$\boldsymbol{\lambda_\infty = \sqrt{1 - \frac{\omega_{ci}(0)}{\omega}} \approx 0.3 - 0.4}$$

More details: M. Nocente, NF-2020; Y. Kazakov, PoP-2021

Energetic ions, AEs and plasma confinement



- L-mode plasmas with $P_{aux.}$ = 10-15MW: D-D neutron rate ~10^{16} s^{-1} and D-^{3}He alpha rate ~2×10^{16} s^{-1}
- Complex sawtooth dynamics: Δt_{saw} between 0.2s and 3.9s
- A large variety of Alfvénic modes, including RSAEs, TAEs, EAEs and the n = 0 GAE
- Correlation between strong EAEs (localized at q=1) and short-period sawteeth

Figures: M. Nocente et al., *Nucl. Fusion* (2020)

n = -1 EAEs and *n* = 0 modes in D-^{3}He plasmas on JET

Nucl. Fusion **61** (2021) 114006 V.G. Kiptily *et al*

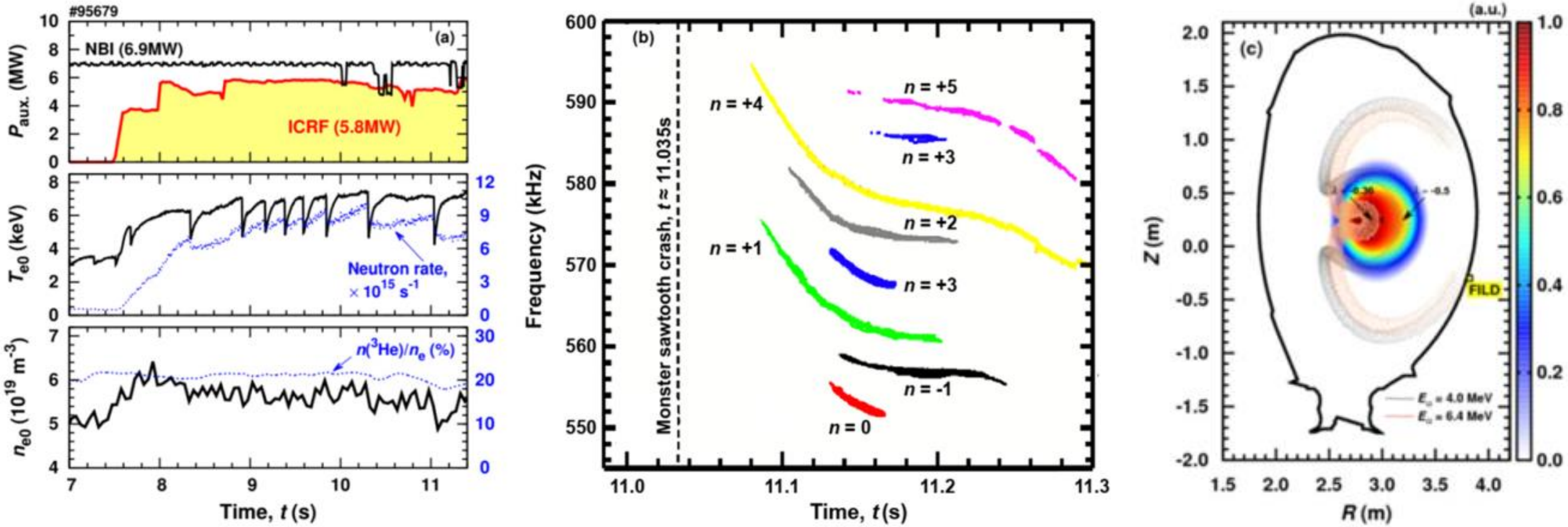
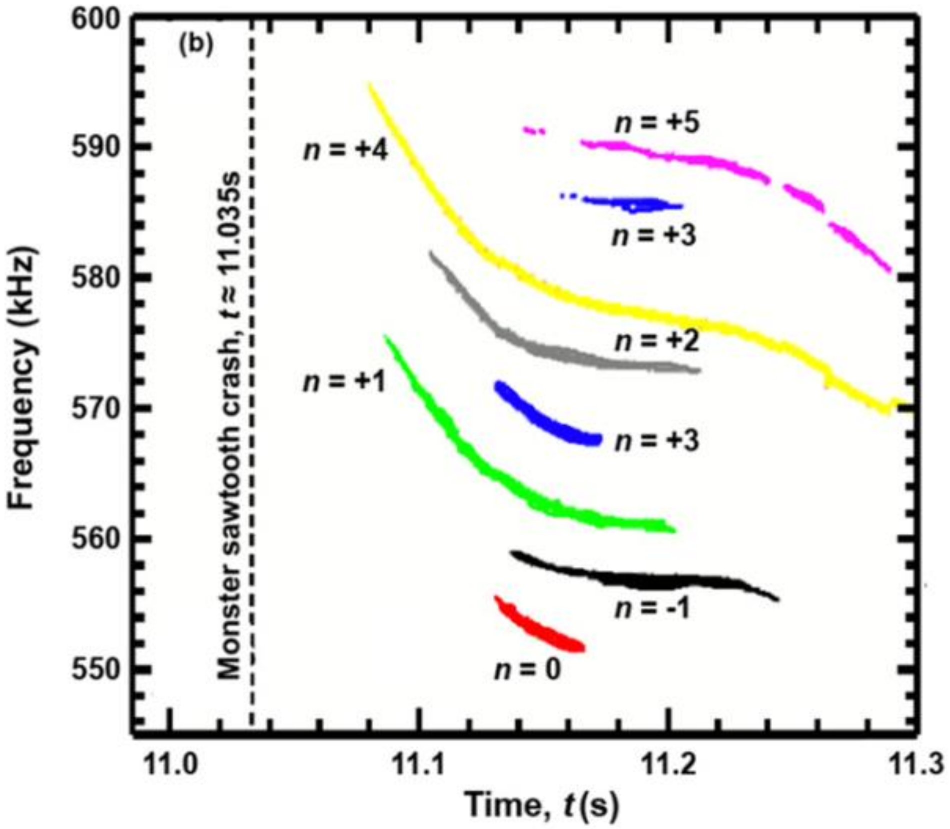


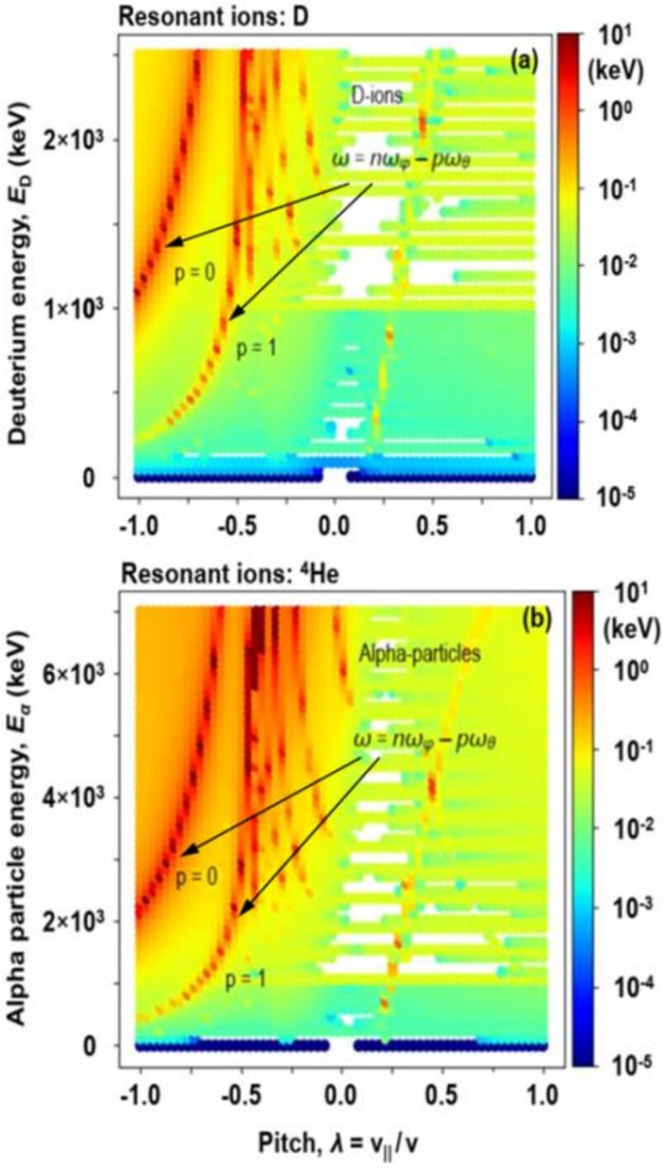
Figure 1. (*a*) Overview of JET pulse #95679 (3.7 T/2.5 MA) in D-^{3}He plasmas with energetic D-ions and fusion-born alpha particles. (*b*) Dynamics of Alfvén activities in the EAE frequency range after the monster sawtooth crash at *t* ≈ 11.035 s.

- Unexpected observation of AEs with *n* < 0 and *n* = 0 in D-^{3}He plasmas with alpha particles
- Evidence for a complex interplay between fast ions, monster sawtooth crashes and AEs
- Unusual conditions and fast-ion distributions after monster sawtooth crashes

More details: V.G. Kiptily et al., *Nucl. Fusion* **61**, 114006 (2021)

Sawtooth-induced AEs with *n* = 0 and *n* < 0





- Evidence for alpha-driven EAEs with *n* < 0
- *n* = 0 and *n* < 0 modes currently not considered for ITER: important for future burning plasmas

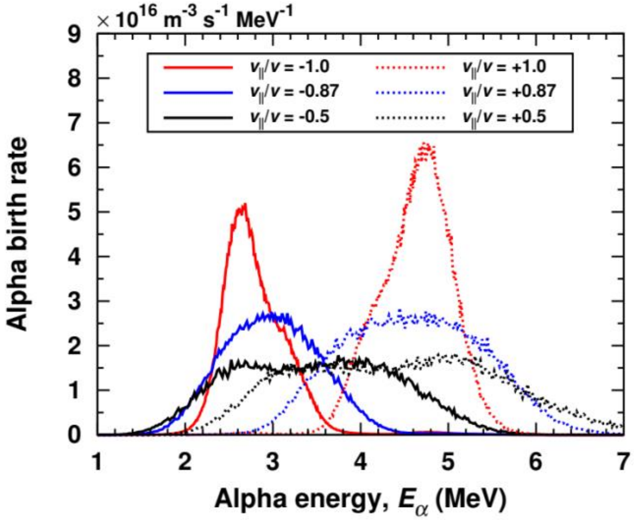
More information:
V. Kiptily et al., *Nucl. Fusion* (2021)

The $n = 0$ mode and sawtooth-sustained bump-on-tail distributions

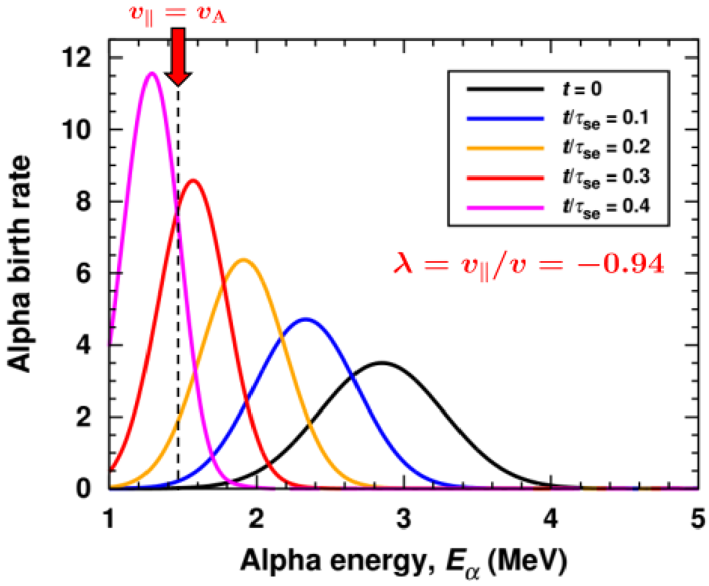
In these experiments **monster sawtooth crashes** leads to

- Redistribution of fast D-ions
  - ✓ Neutron profile changes
- Periodic modulation of the D-^{3}He α-particle source
  - ✓ 17-MeV gamma-rate modulation
- Prompt α-particle losses affect the α-particle source

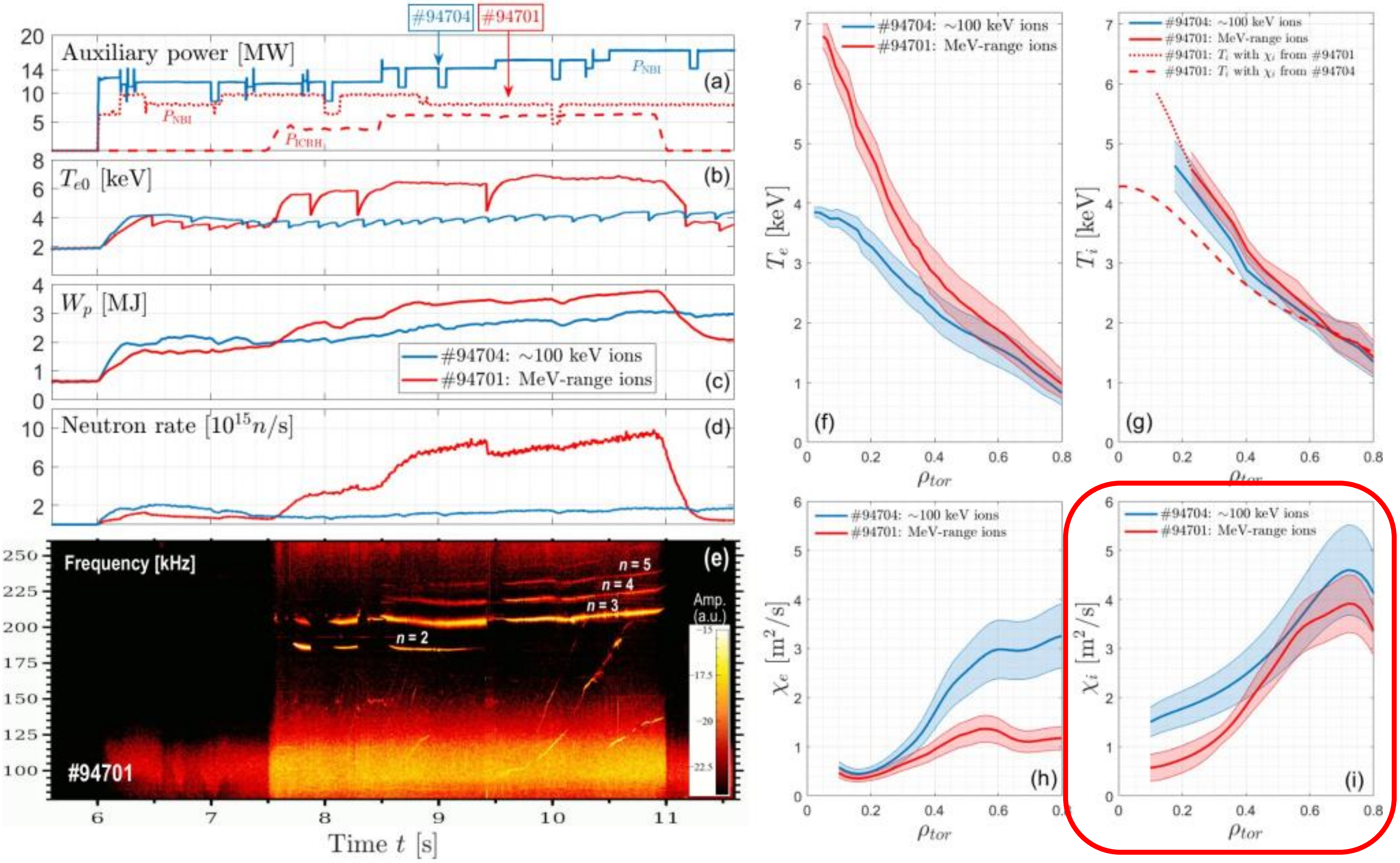
Hence, **the condition $\partial f_\alpha / \partial E > 0$** is achieved for self-sustained excitation of **axisymmetric *n*=0 GAE** [Ross D.W. e
Physics of Fluids **25**, 652 (1982)]



- **$\Delta t_{saw} < \Delta t_{SD}$: alphas do not have sufficient time to establish the slowing-down distribution**
- **NBI modulation experiments for the AE destabilization: successfully designed and demonstrated in DTE2 (S. Sharapov et al.)**
- **Three promising options in W7-X (proposal):**
  i) NBI power modulation
  ii) Interlacing NBI sources
  iii) ECCD
  and their combinations



Improved thermal ion confinement in plasmas with MeV-range ions and destabilized TAEs

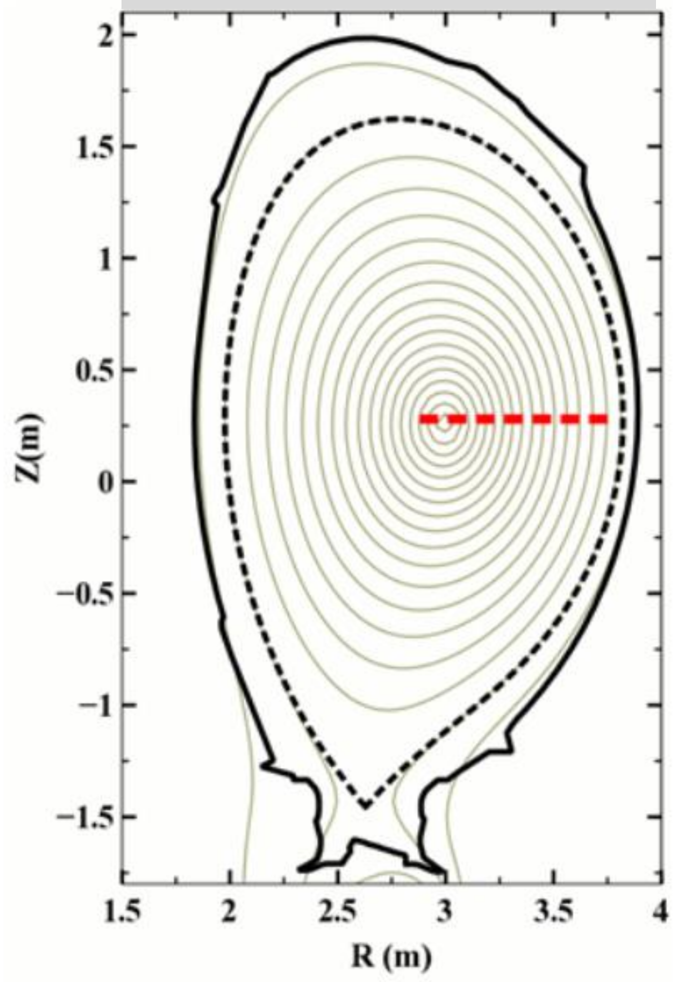


- **ITER-relevant plasmas with strong core electron heating**
- Unexpectedly high T_i in JET plasmas with dominant electron heating

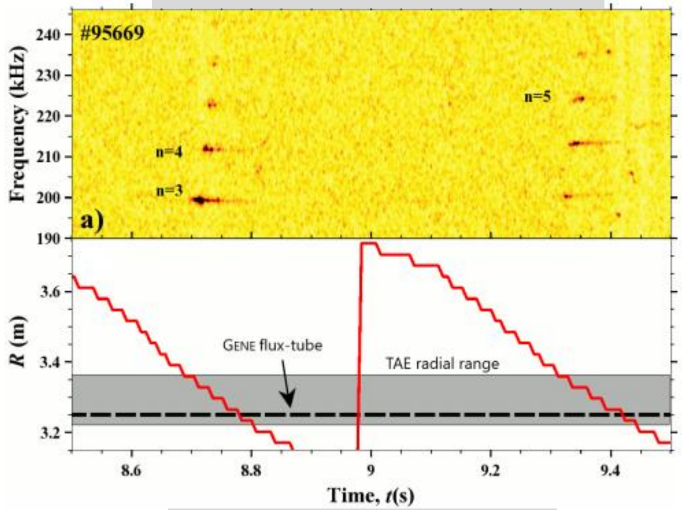
More information:
S. Mazzi et al., *Nature Physics (submitted)*

Advancing fast-ion diagnostics at JET

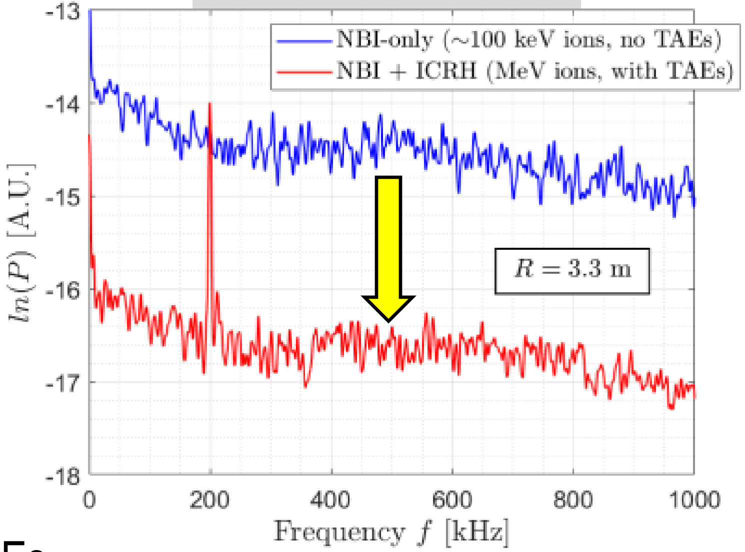
Reflectometer line-of-sight



TAE mode localization



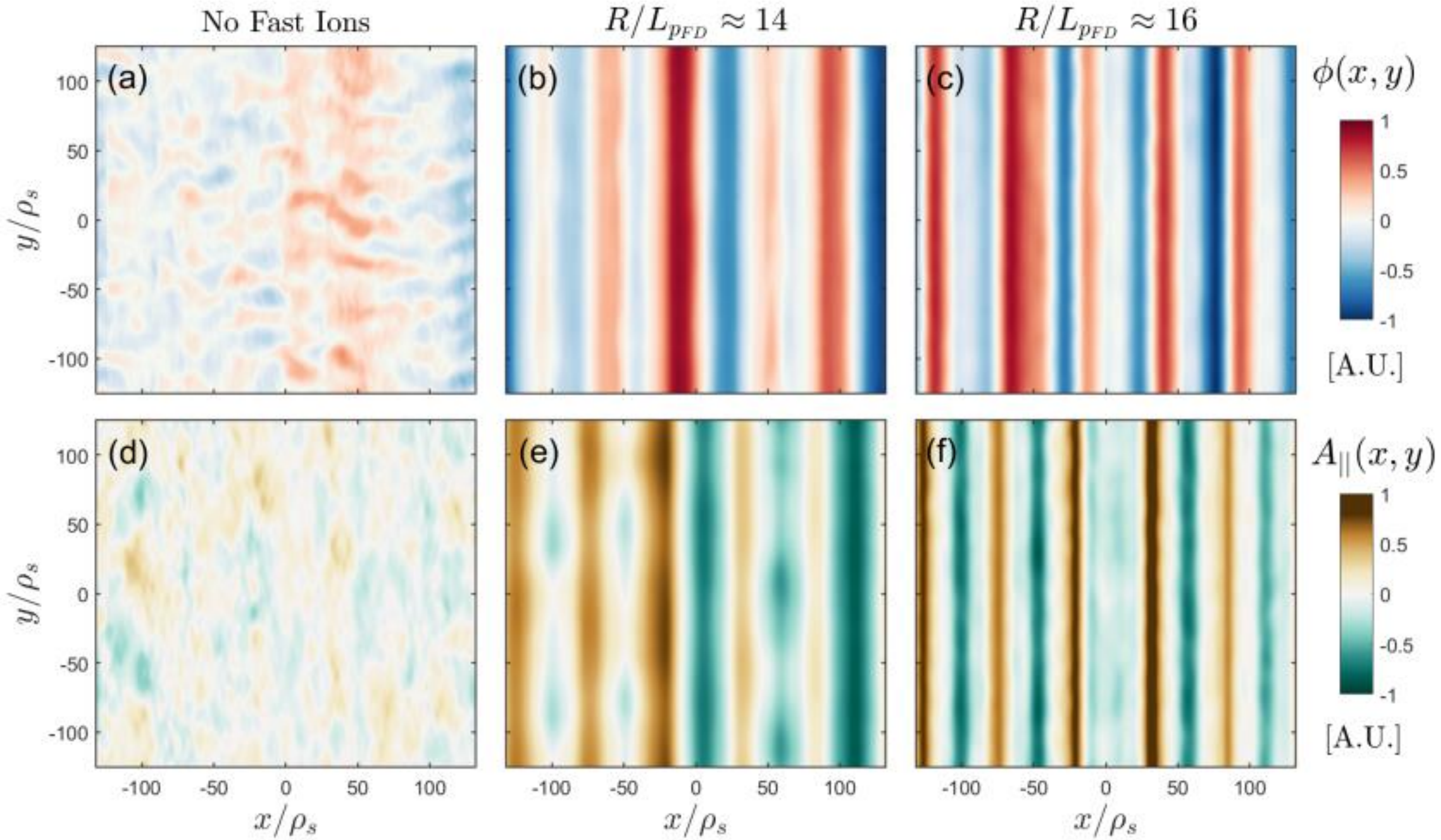
Density fluctuation



Correlation reflectometer analysis:
minimized density fluctuations in the presence of TAEs

ITG suppression in plasmas with MeV-range ions and destabilized TAEs

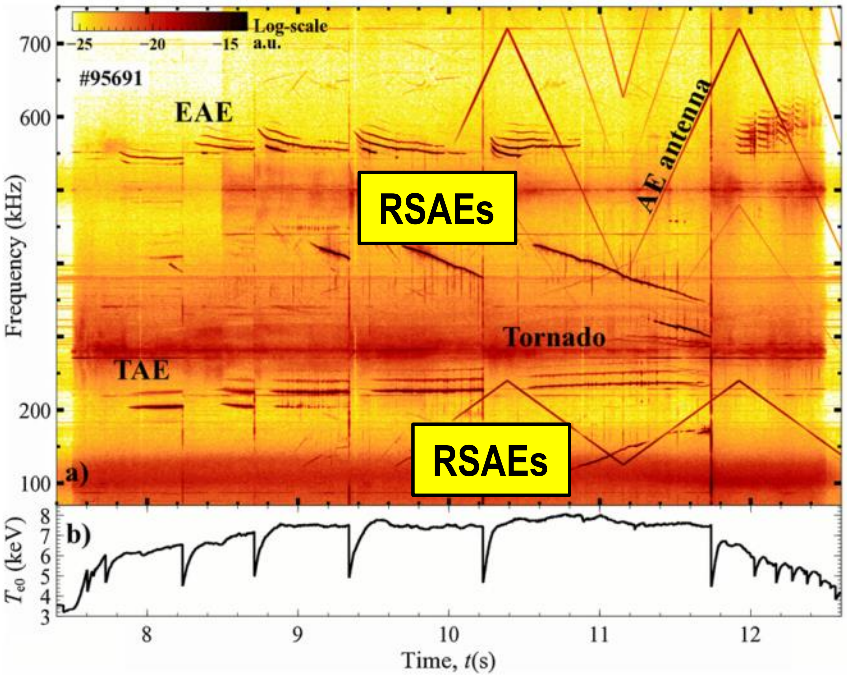
Plasmas with MeV-range ions and fast-ion-driven TAEs



- Unexpectedly high T_i in JET plasmas with dominant electron heating
- Improved thermal ion confinement in the plasma core
- ITG suppression due to the nonlinear generation of zonal structures

More information:
S. Mazzi et al., *Nature Physics (submitted)*

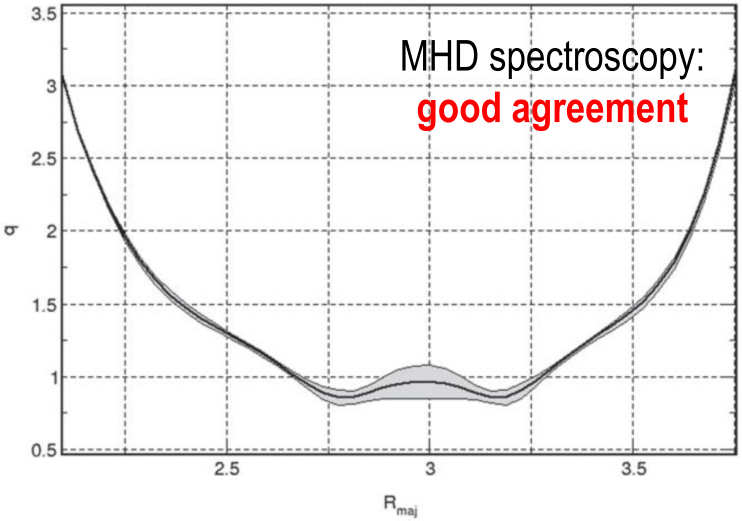
Recent highlights: fast ions as a tool to control the *q*-profile



RSAEs

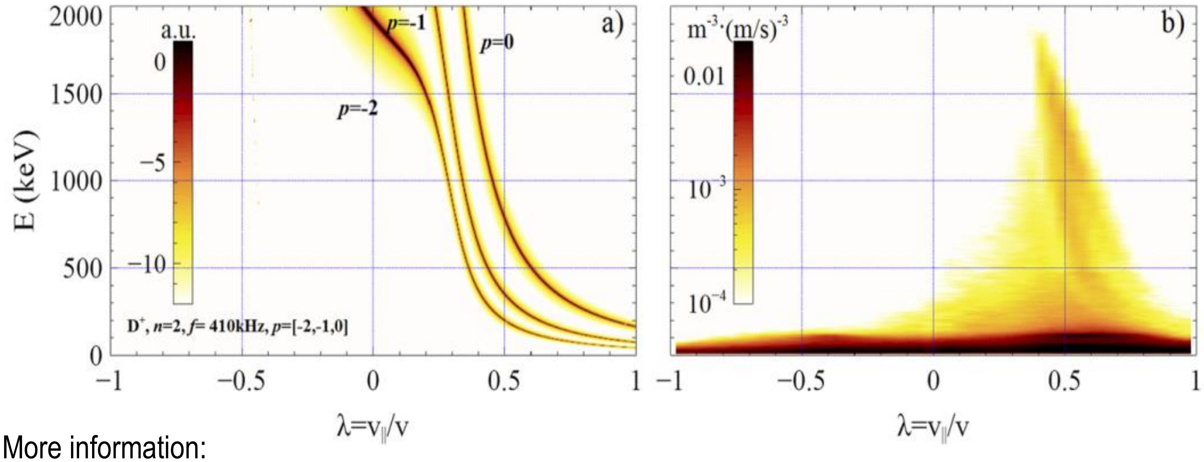
RSAEs

MSE measurements: **inverted** *q*-profile



MHD spectroscopy:
good agreement

Resonance map for the *n* = 2 RSAE, *f* = 410kHz vs. TRANSP fast-ion distribution



- High-frequency RSAEs driven by energetic **passing** ions: **important for ITER**

More information:
M. Dreval, *Nucl. Fusion* (2022), accepted

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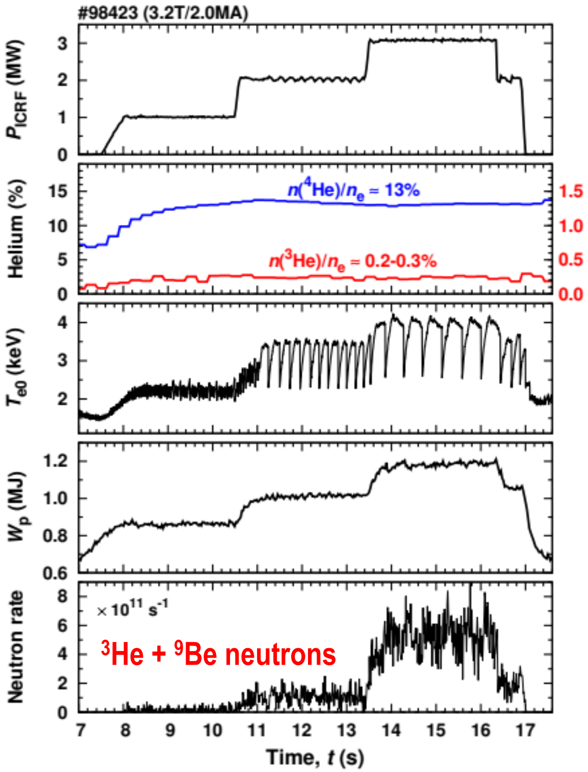
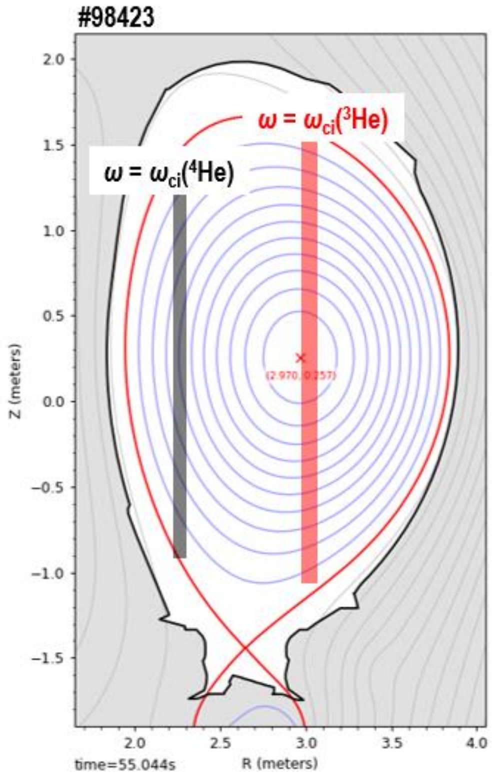
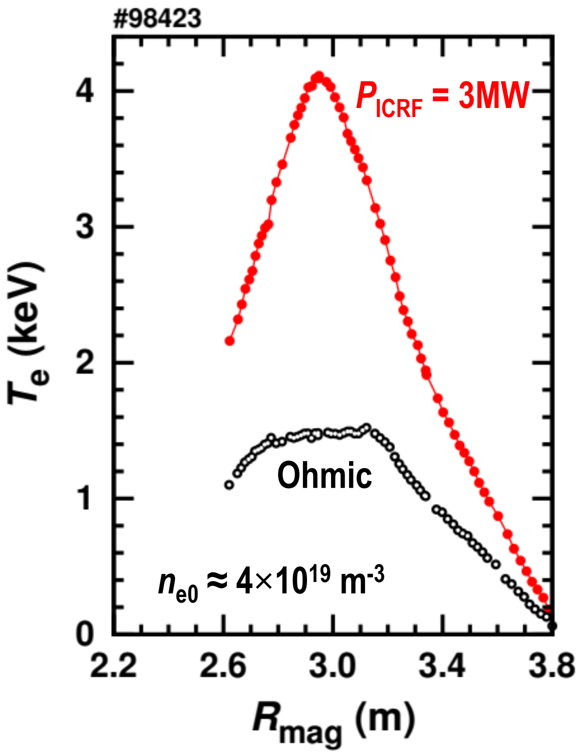
3. LHD experiments with ICRF impurity pump-out (D. Moseev et al.)
4. Summary of proposals

Energetic ^{3}He ions and ^{4}He-(^{3}He)-H scenario: highlights and novelty

- ☐ ITER-relevant non-active plasmas: hydrogen + ~5-15% of ^{4}He
- ☐ Robust scenario: success from the very first pulse (#98423)
- ☐ Efficient plasma heating demonstrated with both on-axis and off-axis ^{3}He resonance





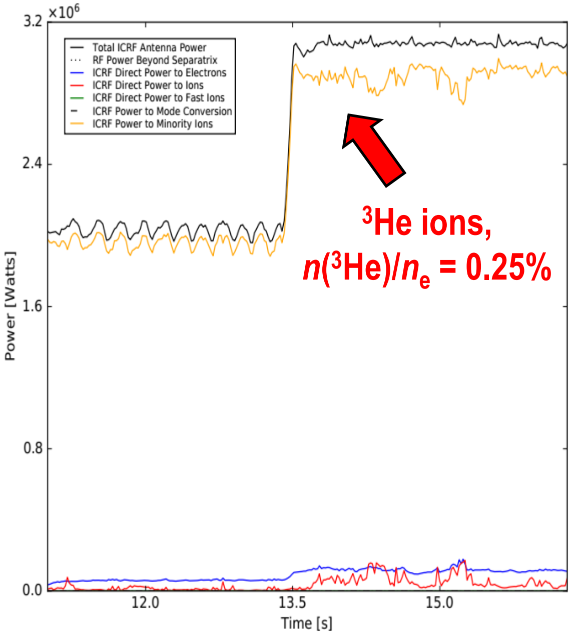


- ☐ Simultaneous measurements of both He isotopes, $n(^4He)/n_e$ and $n(^3He)/n_e$*

** High-resolution sub-divertor gas spectroscopy; optical Penning gauge (ORNL/CEA/UKAEA/JET); more details: E. Delabie et al.*

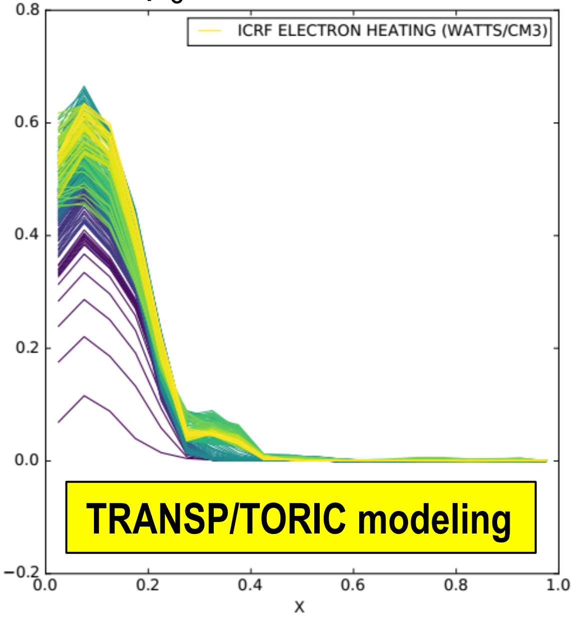
*** He-4 I line: 667.815 nm; He-3 I line: 667.865 nm*

ICRF power deposition and plasma heating profiles



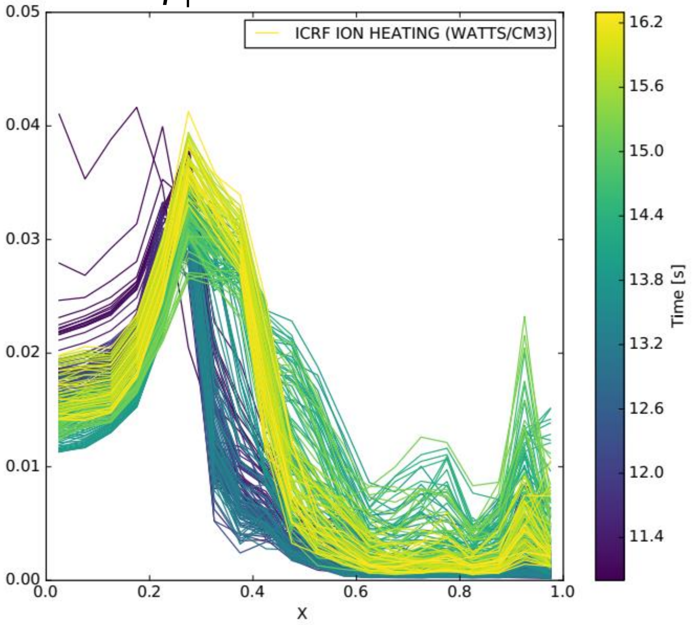
^{3}He ions,
$n(^3\mathrm{He})/n_e$ = 0.25%

p_e ~ 0.6MW/m^3



TRANSP/TORIC modeling

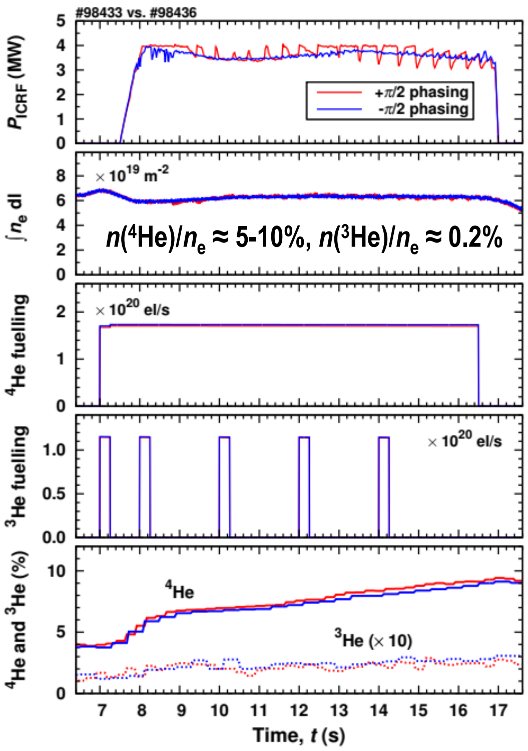
p_i ~ 0.04MW/m^3



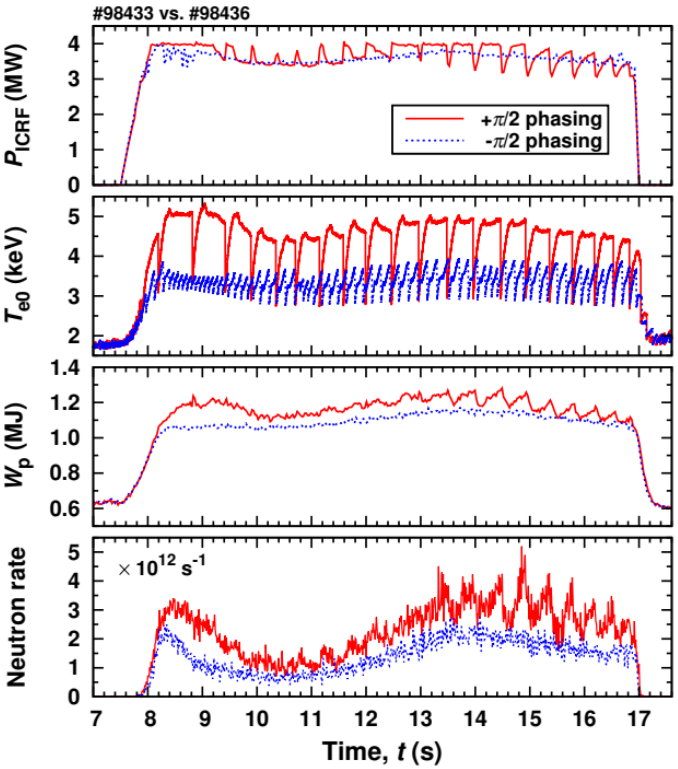
- ☐ ~90% of RF power directly absorbed by ^{3}He ions
- ☐ MeV-range ^{3}He ions → dominant electron heating (collisional)

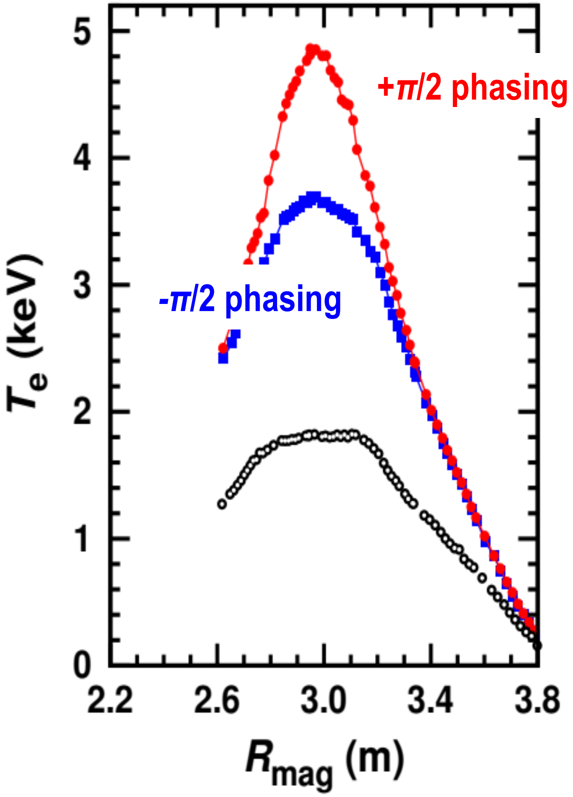
Helium fueling recipe and ICRF antenna phasing comparison

Feedforward ^{4}He and ^{3}He fueling



+pi/2 vs. -pi/2 phasing: plasma response

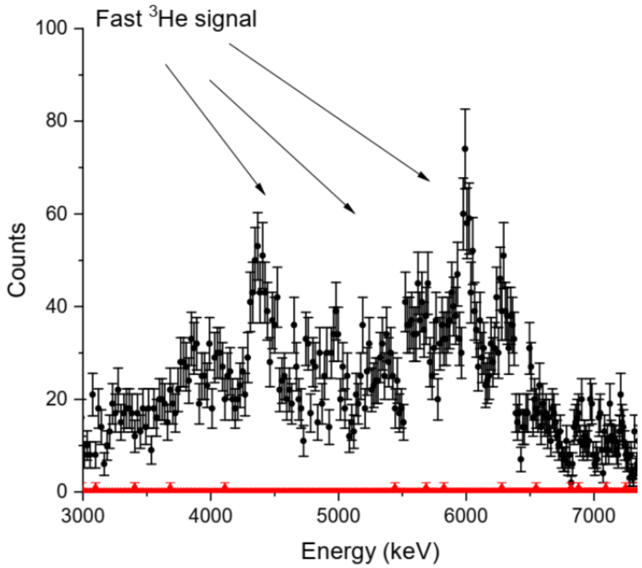


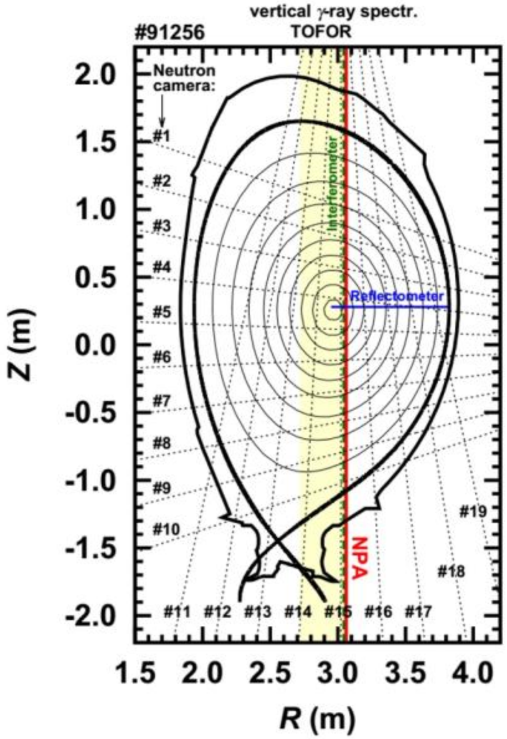


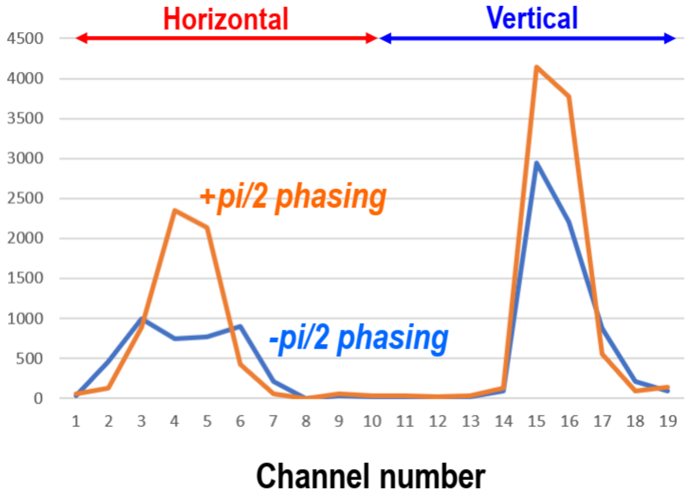
	+pi/2 phasing	-pi/2 phasing
Sawtooth period	470ms	145ms
Neutron rate (max.)	~4×10^{12} s^{-1}	~2×10^{12} s^{-1}
MHD modes	Yes	No

Similar to results in
[L.-G. Eriksson et al., *Phys. Rev. Lett.* **92**, 235004 (2004)]

Energetic ^{3}He ions: gamma-ray measurements

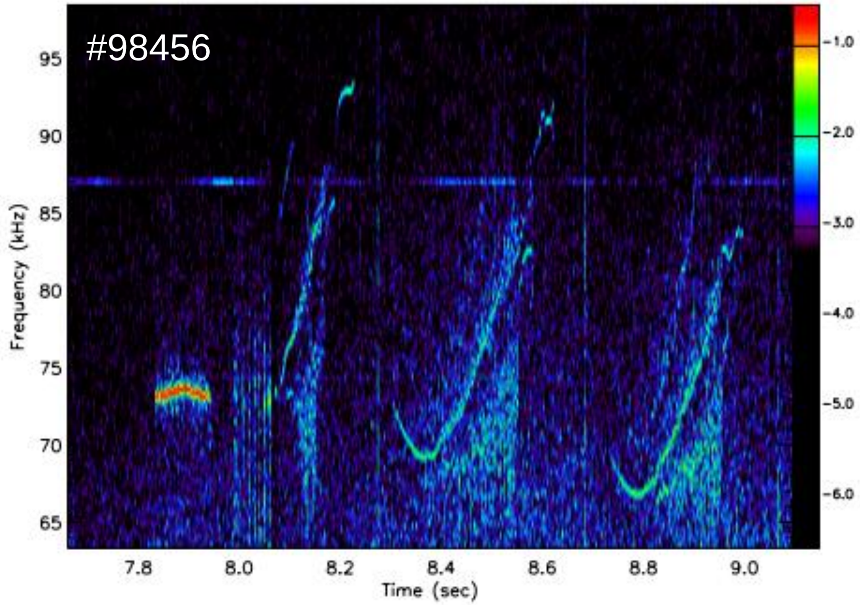


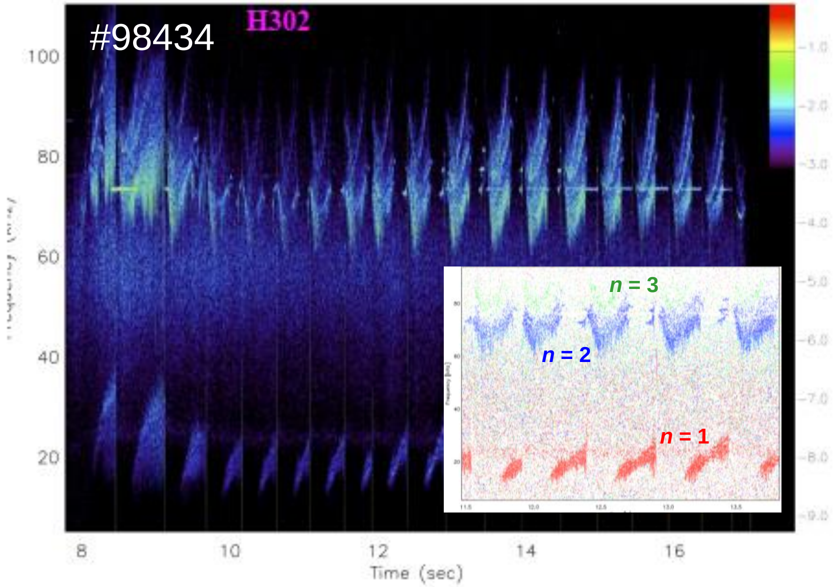




- ❑ $+\pi/2$ phasing: more radially peaked fast-ion distribution
- ❑ Consistent with past ICRF results (fast-ion pinch effect):
  [M.J. Mantsinen et al., *Phys. Rev. Lett.* **89**, 115004 (2002)]

Variety of MHD modes observed





- $f \approx$ 300-320kHz: core-localized TAEs (including $n = 6$; weak in magnetics)

  TAEs seen before:
  Y. Kazakov et al., *Nature Physics* **13**, 973 (2017);
  V.G. Kiptily et al., *Nucl. Fusion* **60**, 112003 (2020)

- $f \approx$ 70-110kHz ($n = 2$, $n = 3$): the onset of Alfvén cascades; sometimes broadband

- $f \approx$ 20-25kHz ($n = 1$): ???

Three-ion ICRF scenarios

↓

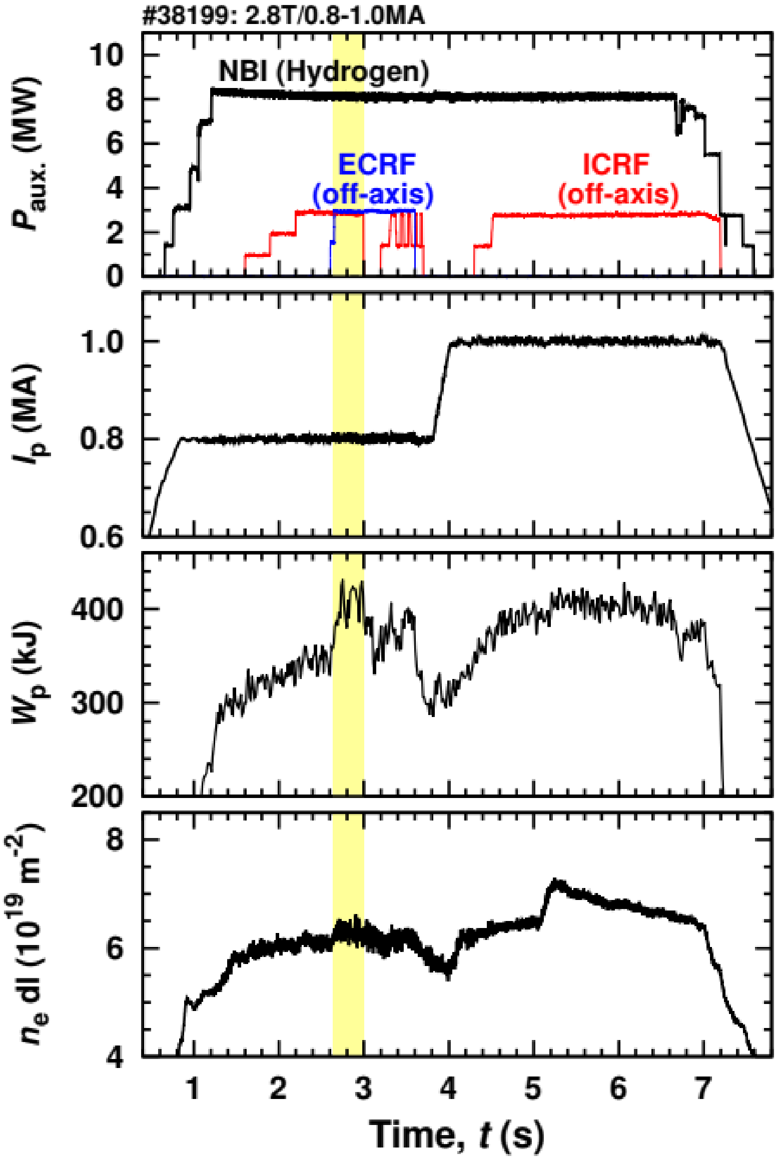
Large populations of passing/potato fast ions
(+ asymmetry in $k_{\parallel}v_{\parallel}$)

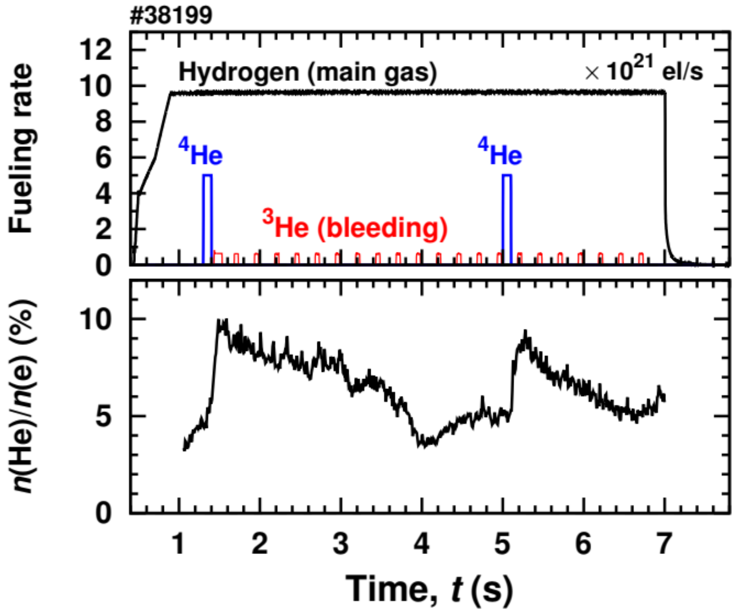
↓

A tool to modify the *q*-profile in the plasma core

More details: Y. Kazakov et al., *Phys. Plasmas* **28**, 020501 (2021)

AUG: 3-ion ICRF studies with ^{3}He in H-^{4}He plasmas





AUG pulse #38199

- Good plasma heating with a combination of NBI, ECRF (off-axis) and ICRF (off-axis); **no W and impurity accumulation**
- Feedforward fueling of three gases: H, ^{4}He and ^{3}He
- ^{4}He concentration, **$n(^4\mathrm{He})/n_e \approx$ 5-10%** (CXRS); $n(^3\mathrm{He})/n_e \approx$ 1% (estimate from H-D exps.)
- He fueling recipe established in the second try
- Further optimization of this ITER-relevant scenario possible

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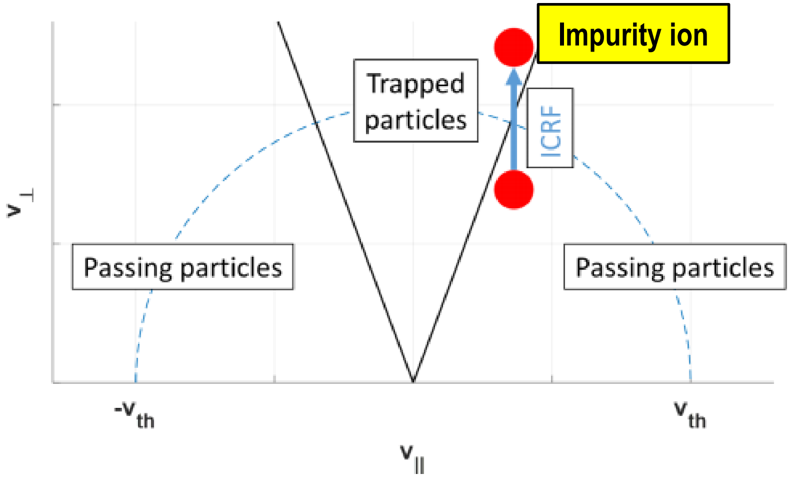
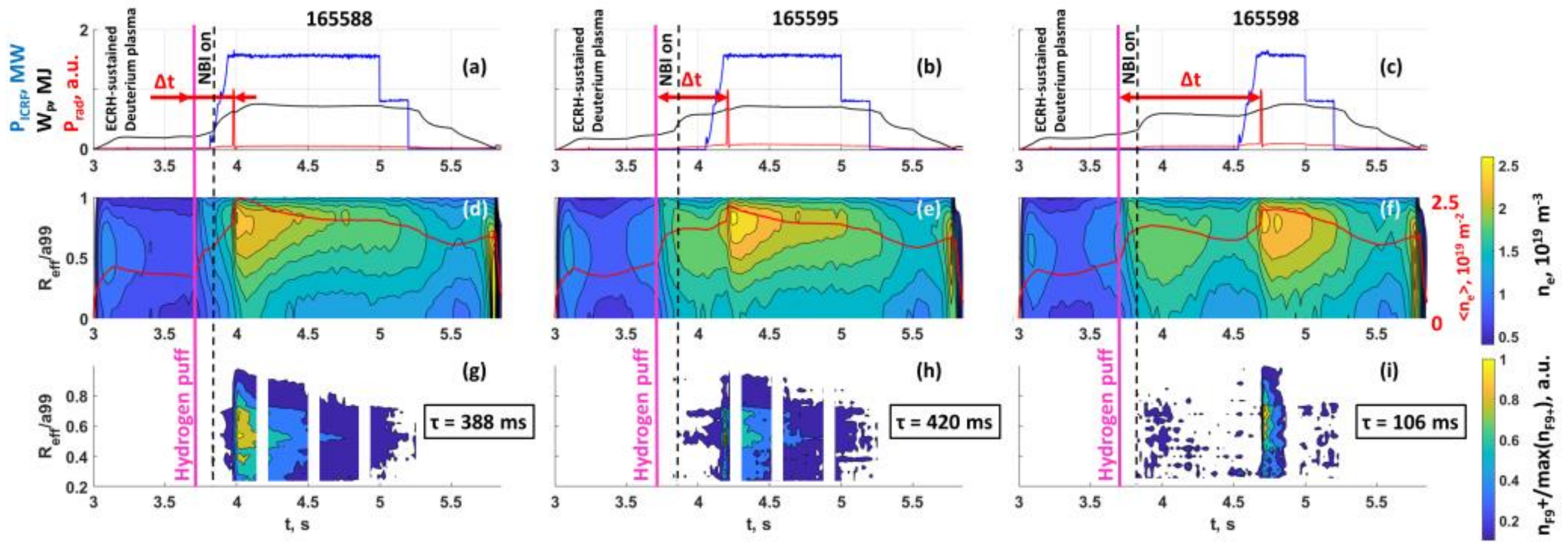
Decoupling impurity from main ion transport in stellarators

Sketch of the proposed impurity exhaust scheme



LHD experiments (D. Moseev et al.)
Target plasma: H-D mix (89% D, 11% H)
Resonant ions: $^{19}F^{9+}$ (Z=9, A=19), ***n* = 2**

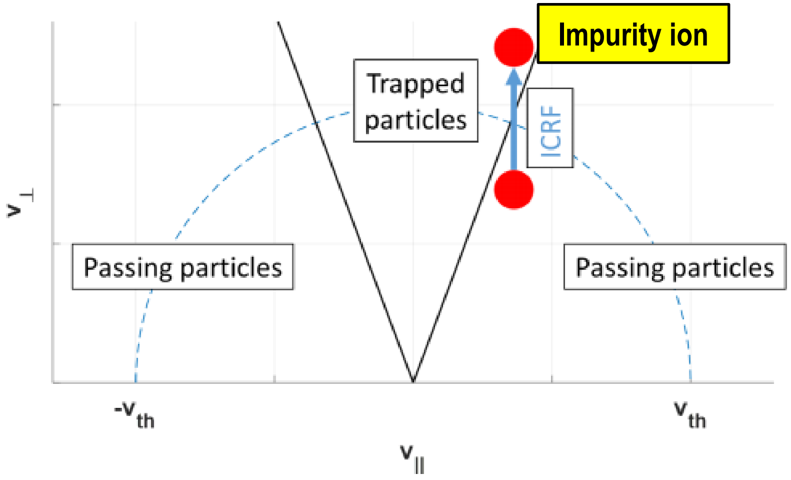
More information: D. Moseev et al., submitted to *Phys. Rev. Lett.*



τ : impurity confinement time
Much shorter in #165598

Decoupling impurity from main ion transport in stellarators

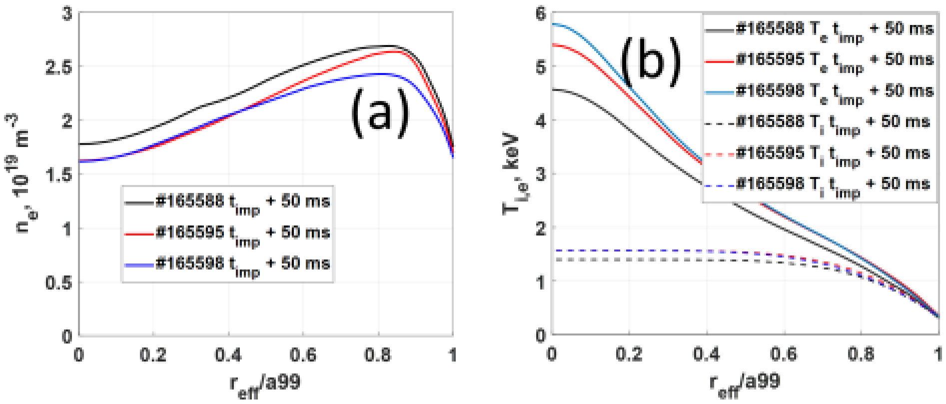
Sketch of the proposed impurity exhaust scheme



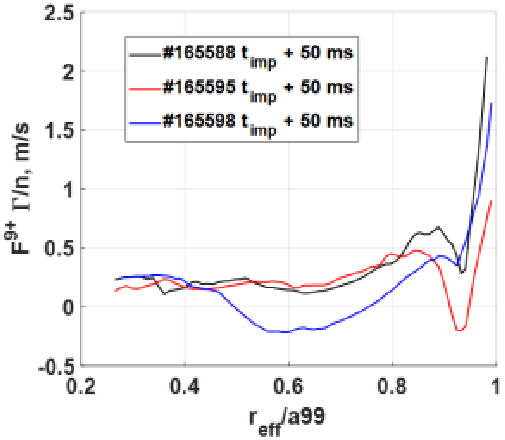
LHD experiments (D. Moseev et al.)
Target plasma: H-D mix (89% D, 11% H)
Resonant ions: $^{19}F^{9+}$ (Z=9, A=19), ***n* = 2**

More information: D. Moseev et al., submitted to *Phys. Rev. Lett.*

Comparable main plasma confinement



Computation predictions: mid-radius impurity accumulation in #165598



1. Experiments in D-^{3}He plasmas on JET
2. Experiments in H-^{4}He plasmas on JET and AUG
3. LHD experiments with ICRF impurity pump-out (D. Moseev et al.)
4. Summary of proposals

Summary of discussed proposals

Proposal	Summary / actuators	Proponents
AE destabilization: NBI modulation	Power modulation; interlacing sources -> non-stationary distribution function	Y. Kazakov, S. Bozhenkov
AE destabilization: NBI + ECCD	ECCD: sawtooth-like crashes	S. Bozhenkov, Y. Kazakov
ICRF with ^{3}He (for OP2.2)	- Scenario development - Phasing comparison - Scenario optimization	Y. Kazakov, J. Ongena
ITG stabilization by ICRF fast ions	- H minority (in He plasmas); scan in H concentration and B_0-scan - ^{3}He (in H plasmas)	Y. Kazakov, J. Ongena
Impurity pump-out with ICRF	TESPEL for impurity injection	D. Moseev
Characterization of T_i stiffness with local ICRF heating	Stationary ICRF; local B_0-scan	S. Bozhenkov, Y. Kazakov, J. Ongena
Heat wave experiments with modulated ICRF	Modulated ICRF	S. Bozhenkov, Y. Kazakov, J. Ongena