Improved understanding of energetic ions impact on plasma confinement from theory and experiments

J. Garcia, Samuele Mazzi, Ye O. Kazakov, J. Ongena, David Zarzoso, M. Dreval, W. H. Lin, M. Nocente, Žiga Stancar, G. Szepesi, et al.

EUROfusion

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JET

DE LA RECHERCHE À L'INDUSTRIE
cea

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Acknowledgements

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Outline

- Energetic ions as a heating mechanism
- Some drawbacks of energetic ions
- Indications of energetic ions impact on the energy confinement
- Towards the study of MeV ions impact on energy confinement
- New results from JET in D-^{3}He plasmas
- Beyond D plasmas: H and He mixtures
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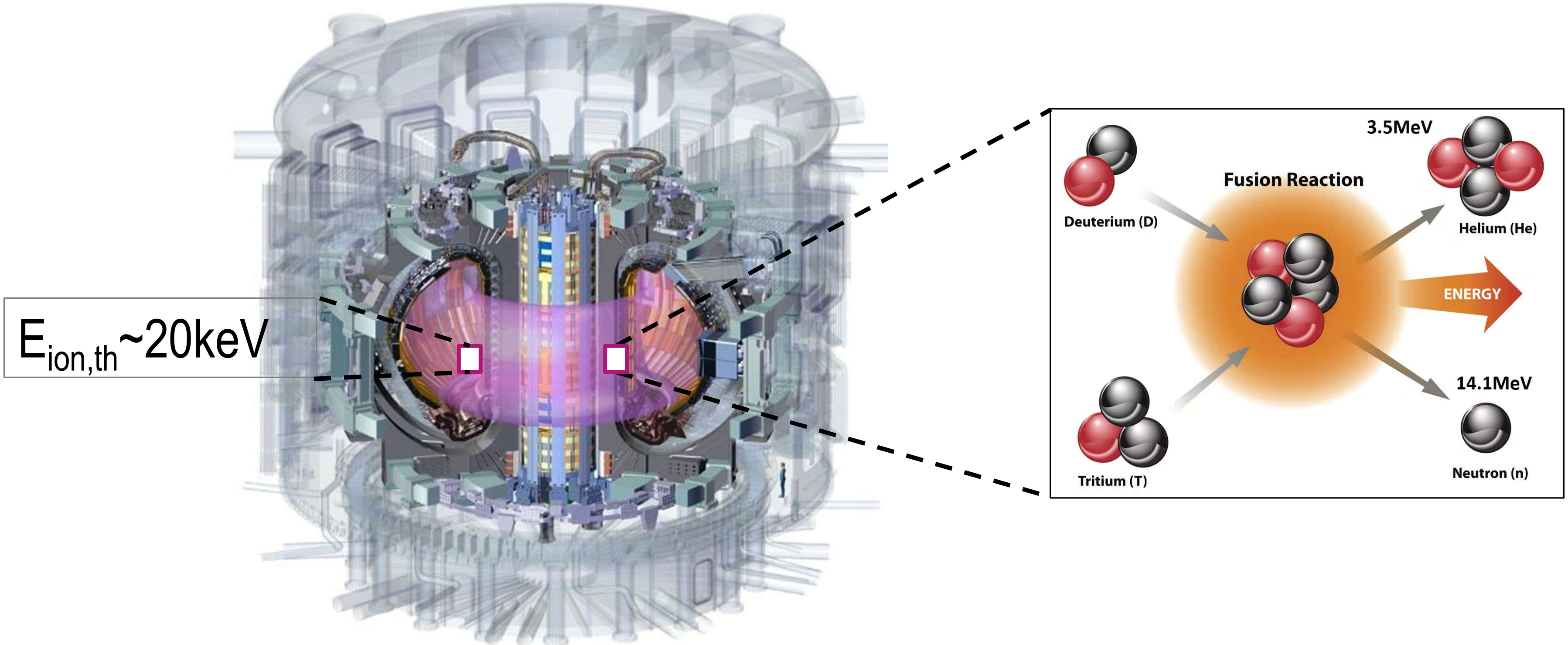
- Conclusions

Magnetically confined fusion energy is in fast evolution

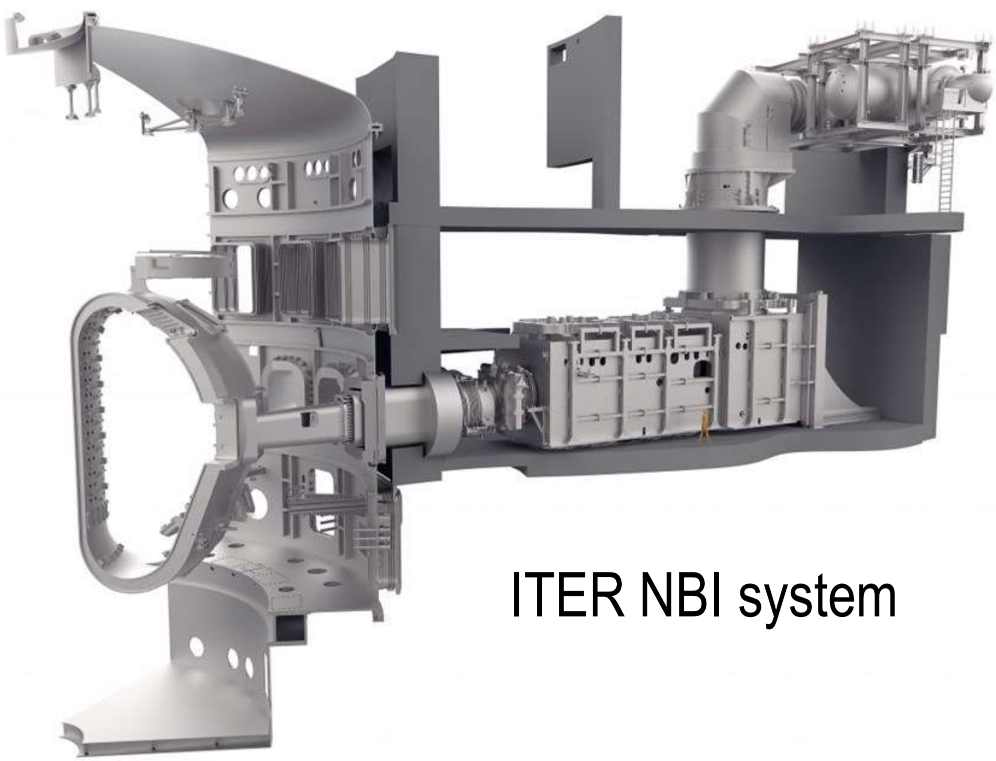
- Several exciting milestones achieved:
  - DT campaign at JET [J. Mailloux this conference I1.104]
  - Construction of JT-60SA [Y. Kamada NF(22)]
  - Record long pulse in EAST
- ITER project getting closer to its completion

3.5MeV alpha particles: key pillar for fusion energy production by plasmas



- Fusion produced 3.5MeV alpha particles→ self heating of plasmas through collisions
- Efficiency as heating method demonstrated by externally produced energetic ions

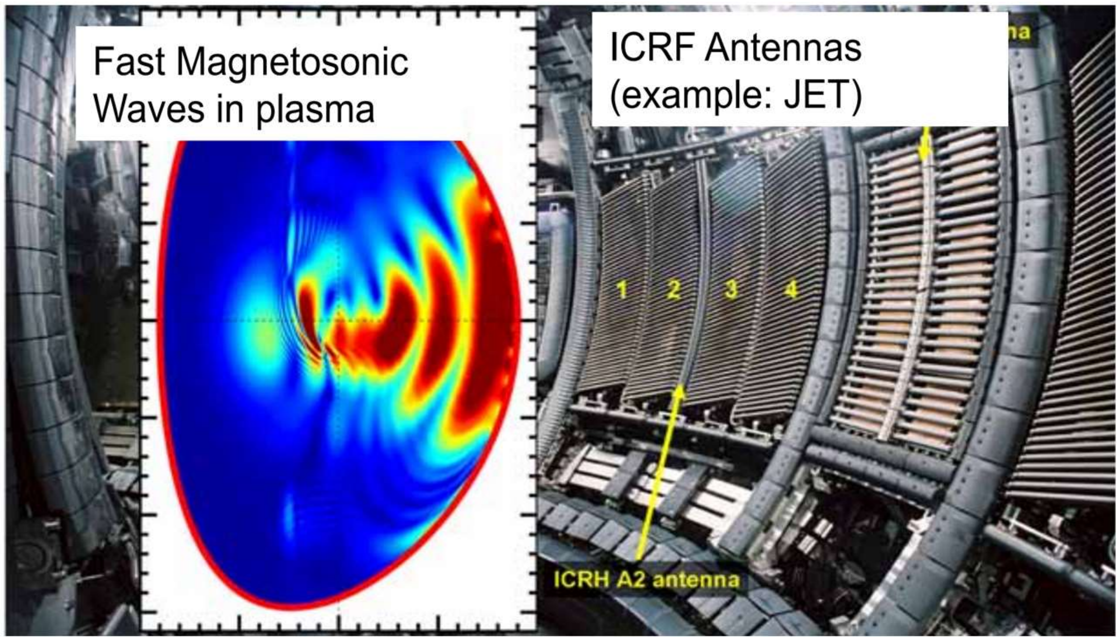
1st method: Neutral Beam Injection (NBI)



ITER NBI system

- Ions are accelerated, neutralized and injected in the plasma
- In present day tokamaks E_{ion}~100keV→ Main heating method
- NBI in ITER will inject E_{ion}=1MeV

2nd method: Ion Cyclotron Resonance Frequency



- ICRF: Externally injecting waves at resonant frequency

$$\omega = n\omega_{ci} + k_{\parallel} v_{\parallel,i}$$

$n\omega_{ci}$: Ion cyclotron frequency

$k_{\parallel} v_{\parallel,i}$: Doppler effect due to particle speed

$$\omega_{ci} = \frac{Z_i |q_e| B}{A_i m_p}$$

- $k_{\parallel}$ wave number parallel to B determined by antenna geometry
- ~MeV ions can be obtained

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- Energetic ions as a heating mechanism
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- Tools for the study of MeV ions impact on energy confinement
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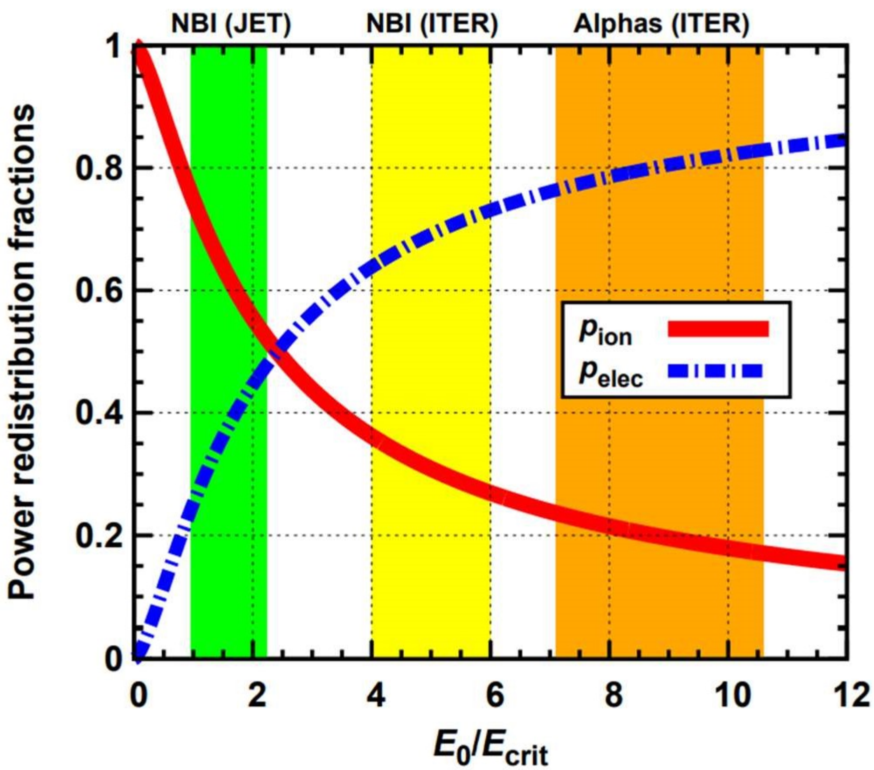
Drawback 1: Alpha energy mostly transferred to electrons



- Redistribution of energy to thermal particles, E_{crit} :
  - $E>E_{crit}$ → Energy transfer mostly to electrons
  - $E<E_{crit}$ → Energy transfer mostly to ions
- Drawback → α particles mostly transfer energy to electrons in ITER!

Drawback 2: Energetic ions can interact with Alfven Waves

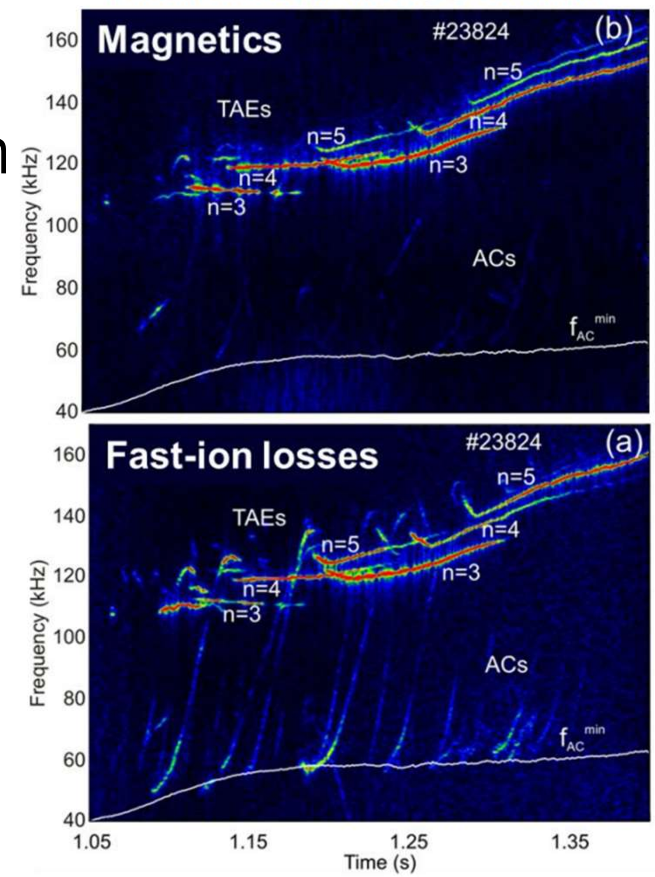
- Energetic ions can interact with electromagnetic perturbations
- Alfven waves are driven unstable with dispersion relation

$$\boldsymbol{\omega} = \boldsymbol{k}_{\parallel}\boldsymbol{v}_{\mathrm{A}}$$

- Slopes of distribution function determines whether plasma particles drive or damp waves

$$\frac{\gamma_{drive}^{EP}}{\omega} \propto \beta_{EP}\left(-\frac{n}{\omega}\frac{E_{EP}}{f}\frac{df}{dP_{\varphi}} + \frac{E_{EP}}{f}\frac{df}{dE}\right)$$

Measured fast-ion losses by Alfvén waves in the AUG tokamak*



[M. Garcia-Munoz PRL (10)]

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- Drawback → Alfven waves responsible for energetic ions transport, losses and confinement degradation

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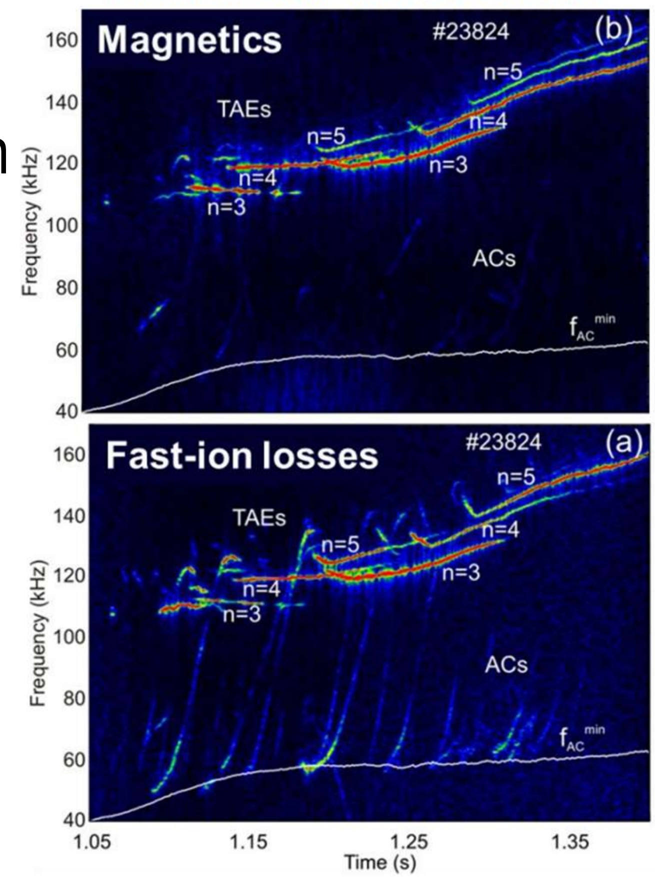

[M. Garcia-Munoz PRL (10)]

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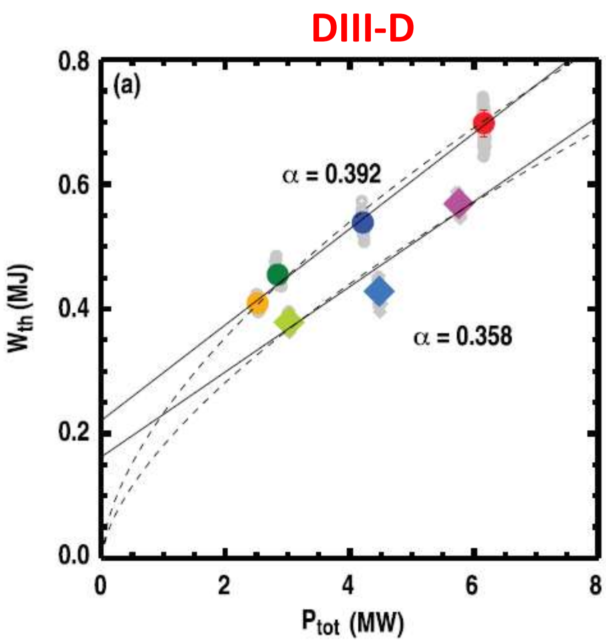
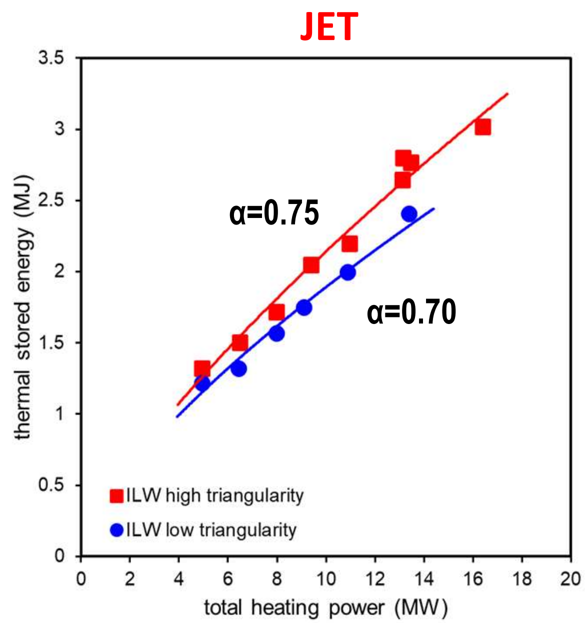
High impact of NBI energetic ions on plasma energy confinement



[T. Luce NF (18)]

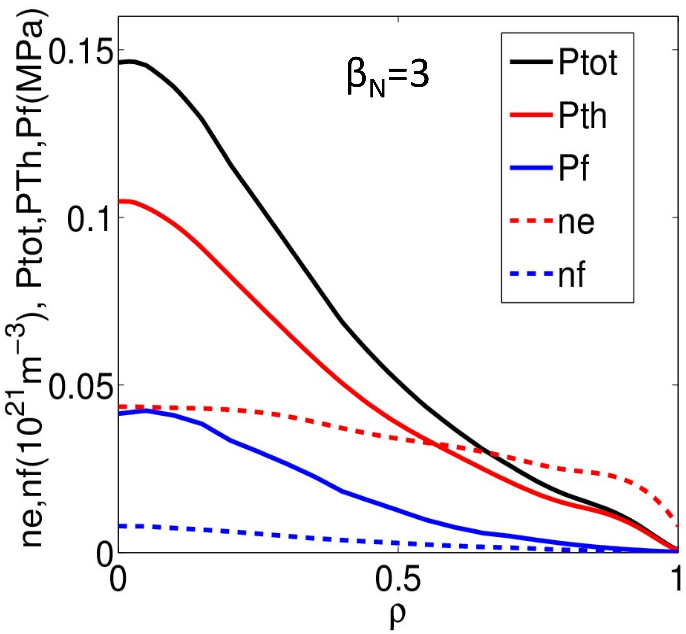


ITER Physics Basis: W_{th}~$P^{\alpha=0.31}$

[C. Challis NF (15)]

- NBI power scans performed in JET and DIII-D
- Thermal energy increases faster than expected
- NBI power induces reduction of energy loses by heat transport?

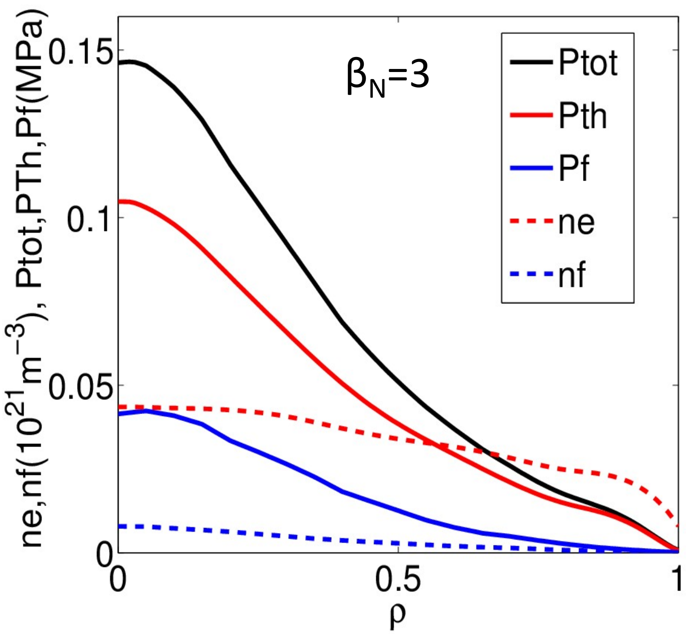
High Impact of NBI energetic ions on plasma energy confinement



[J. Garcia NF 2015]

- High NBI power plasmas at low-medium density characterized by high:
  - Pressure and pressure gradient
  - Beta
  - Energetic ion density fraction
  - Thermal confinement

High Impact of NBI energetic ions on plasma energy confinement



[G. Tardini NF (07)]
[M. Romanelli PPCF (10)]
[D. Testa NF (12)]
[J. Citrin PRL (13)]
[J. Citrin PPCF (14)]
[J. Garcia NF (15)]
[H. Doerk PPCF (16)]
[N. Bonanomi NF (18)]
[J. Garcia POP (18)]
[A. di Siena NF (19)]
[C. Holland NF (21)]
[A. di Siena PRL (21)]
[S. Mazzi Nat. Phys. (22)]

- High NBI power plasmas at low-medium density characterized by high:
  - Pressure and pressure gradient
  - Beta
  - Energetic ion density fraction
  - Thermal confinement
- **<u>Strong experimental and theoretical activity</u>:**
- **Electromagnetic and/or energetic ions effects can strongly reduce heat transport driven by turbulence**

JET cea

Relevance to ITER requires higher energy ions

Case Study	Energetic ion specie	T_i/T_e	n_{FI}/n_e [%]	T_{FI}/T_e
JET High beta– [J. Citrin PPCF(15),J. Garcia NF(2015)]	D	**1.6**	**12**	**7.3**
ITER High beta– [J. Garcia PoP(18)]	^4He	**1**	**0.9**	**41.3**

- Stabilizing energetic ion effect → BUT way less energetic particles than DT fusion born alpha particles [J. Citrin PRL(13), J. Garcia NF(15), N. Bonanomi NF(18), A. Di Siena NF(19)]

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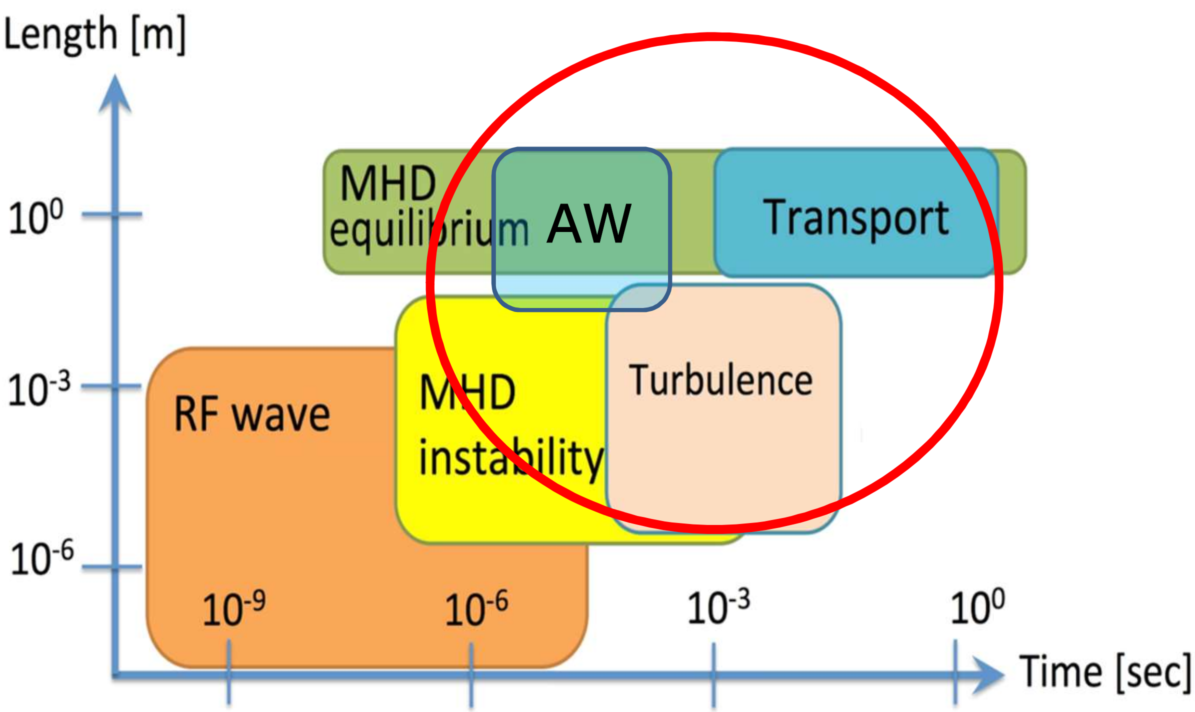
- Stabilizing energetic ion effect → BUT way less energetic particles than DT fusion born alpha particles [J. Citrin PRL(13), J. Garcia NF(15), N. Bonanomi NF(18), A. Di Siena NF(19)]
- Transport/Turbulence reactor relevant studies should include:
    - MeV ions in the energy range of α particles
    - Alfvén waves destabilization as expected in ITER [S. Pinches this conference I3.005]
    - Ti~Te
    - Low rotation

Plasmas: inherent complex multi-scale system



- New results obtained in JET by combining:
  1. **AW destabilized by accelerating ions up to ~E_α**
  2. **Improved multiscale understanding by using HPC**
  3. **Improved diagnostics**

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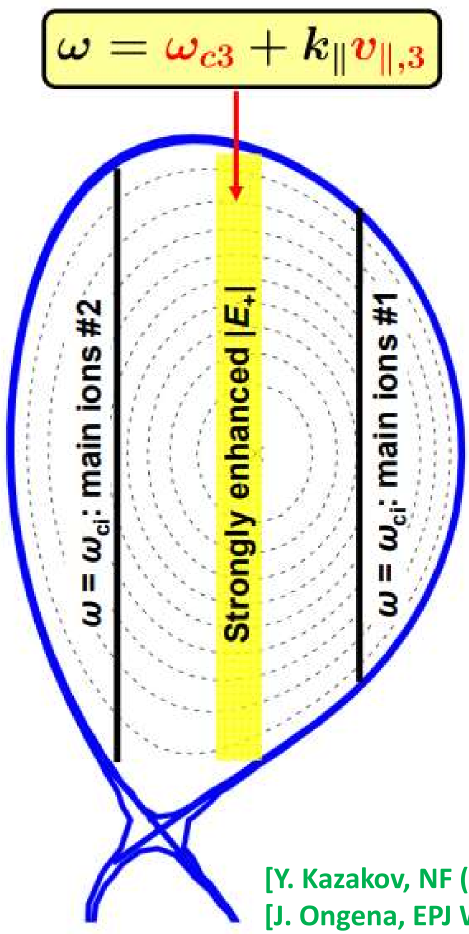
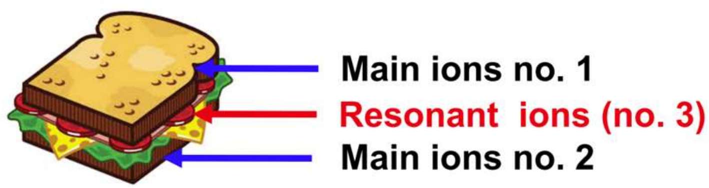
New experiments: novel three-ion ICRF schemes



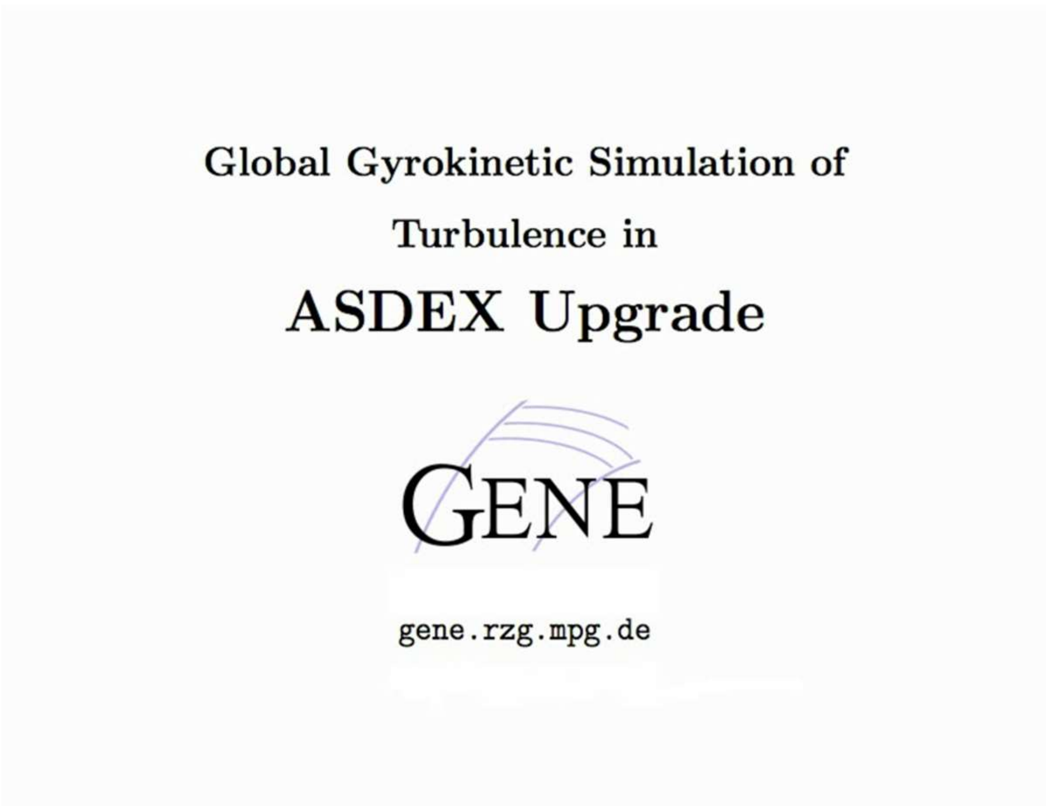
- Three-ion ICRF: efficient heating in mixture plasmas with 'third' ion component to absorb power



- **Efficient way to generate MeV ions!**

[Y. Kazakov, NF (15), POP (15), Nat. Phys. (17)]
[J. Ongena, EPJ Web. Conf. (17)]
[D. Van Eester, PPCF (17)]

Towards multiscale HPC: GENE code



[F. Jenko POP 00]

- GENE code→ Solves gyrokinetic equation [X. Garbet *NF* 10]
- Fluctuations of electrostatic and electromagnetic potentials
- Heat transport radial loses driven by turbulence can be analyzed

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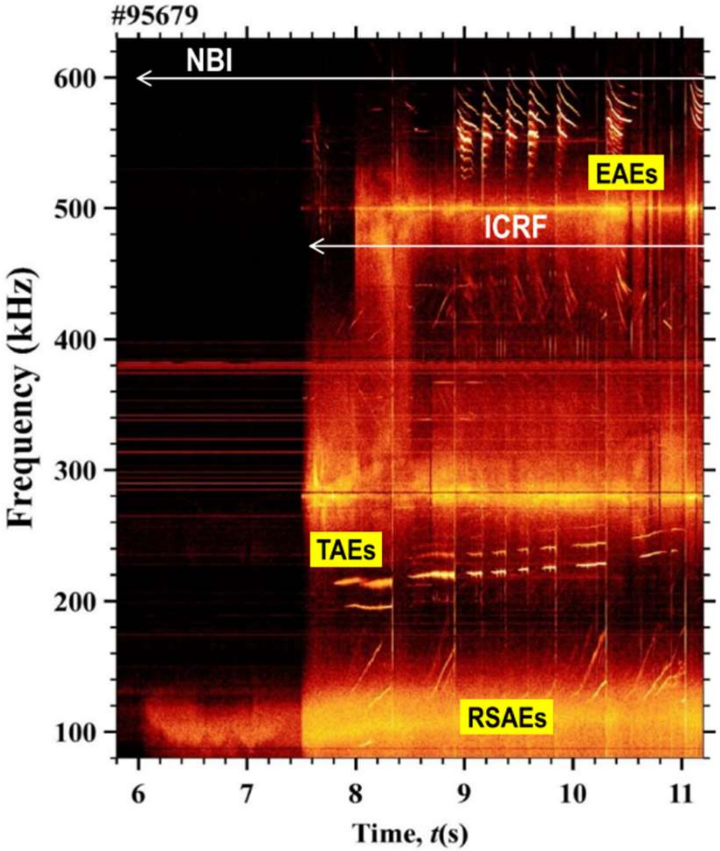
Alfven waves destabilized in JET with ICRF



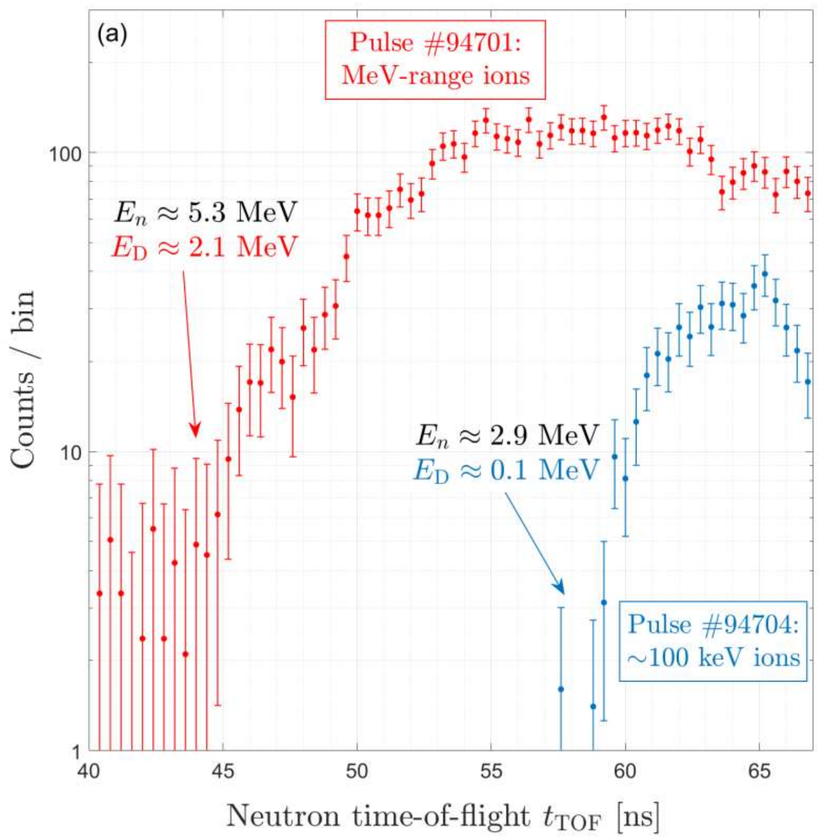
[M. Nocente NF(20)][Y. Kazakov PoP(21)][M. Dreval NF(22)]

D-(D_{nbi})-^{3}He

- New experiments performed at JET in D-(D_{nbi})-^{3}He plasmas
- Heating mechanisms: NBI and ICRF
- Alfven waves in the range of 100-600kHz
- Fluctuations not detected in only NBI phase

MeV ions detected in the presence of ICRF

Time-of-flight neutron spectrometer



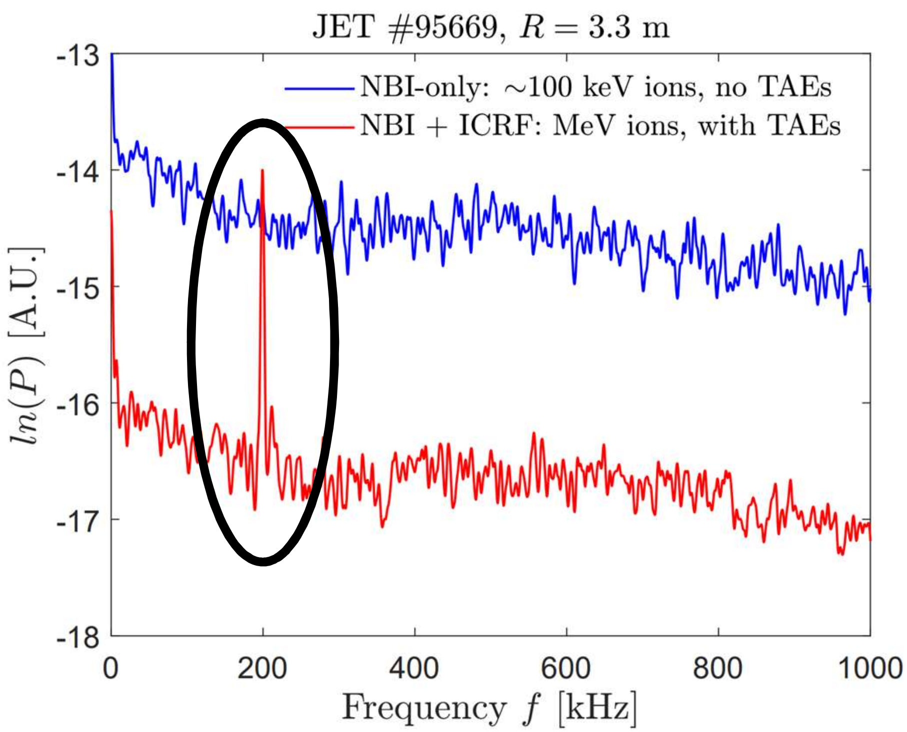
D-(D$_{nbi}$)-^{3}He

- In new D-^{3}He experiments:
  - ICRF energetic ions measured up to 2.1MeV.
  - NBI only energetic ions reach 0.10MeV.
- ~MeV ions are well confined at JET as toroidal current is 2-3MA

[S. Mazzi Nat. Phys. (22)] [S. Mazzi this conference I5.102]

Strong decrease of density fluctuations in the presence of MeV ions

Reflectometry measurements

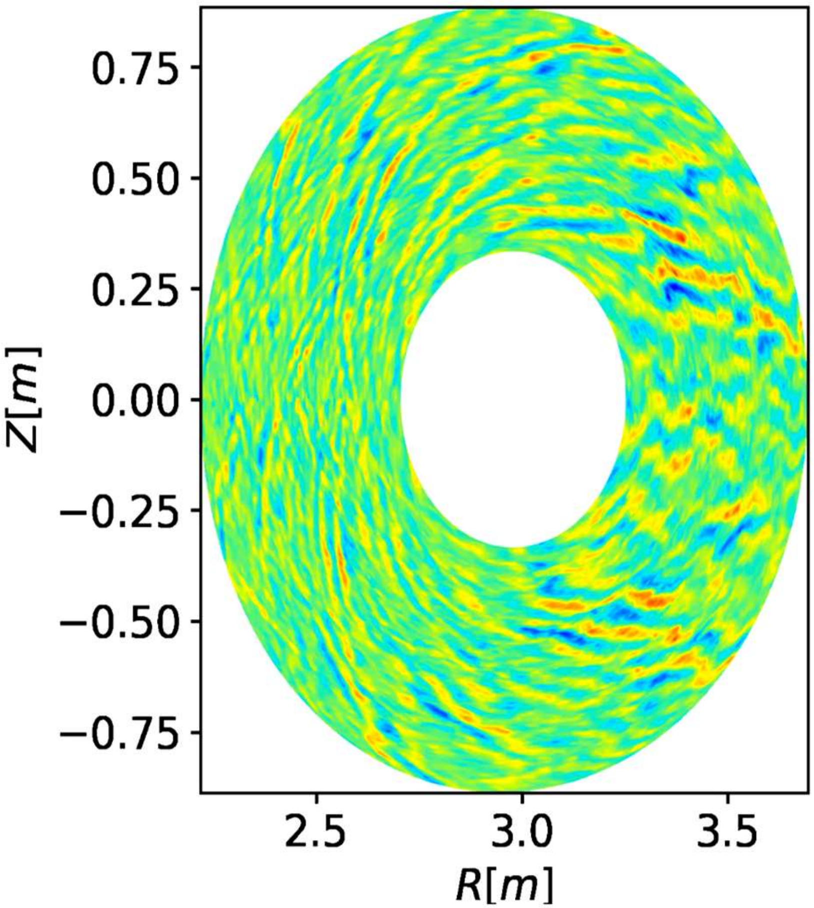


D-(D_{nbi})-^{3}He

- Plasma density fluctuations spectrum→ **turbulence intensity**
- Compared to NBI, fluctuations reduction in the presence of MeV ions
- Unexpectedly, Alfven waves and reduced turbulence coexist

[S. Mazzi Nat. Phys.(22)] [S. Mazzi this conference I5.102]

Multiscale origin of thermal heat transport reduction



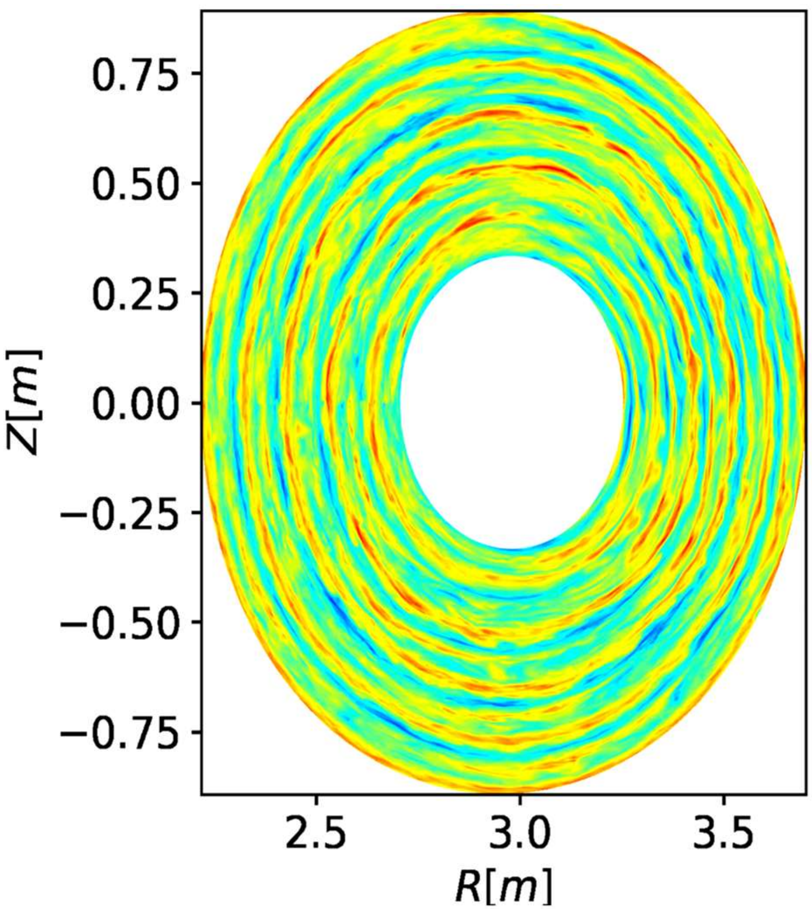
[S. Mazzi Nat. Phys.(22)] [S. Mazzi this conference I5.102]

No energetic ions

D-(D_{nbi})-^{3}He

- Multiscale gyrokinetic simulations performed

Multiscale origin of thermal heat transport reduction



With MeV energetic ions

D-(D_{nbi})-^{3}He

- Multiscale gyrokinetic simulations performed
- MeV ions energy is channelled to zonal flows [P H Diamond PPCF 05]
- Radial energy loses are highly reduced
- Beneficial effects from Alfven waves!

[A. Di Siena NF(19)] [S. Mazzi Nat. Phys.(22)] [S. Mazzi this conference I5.102]

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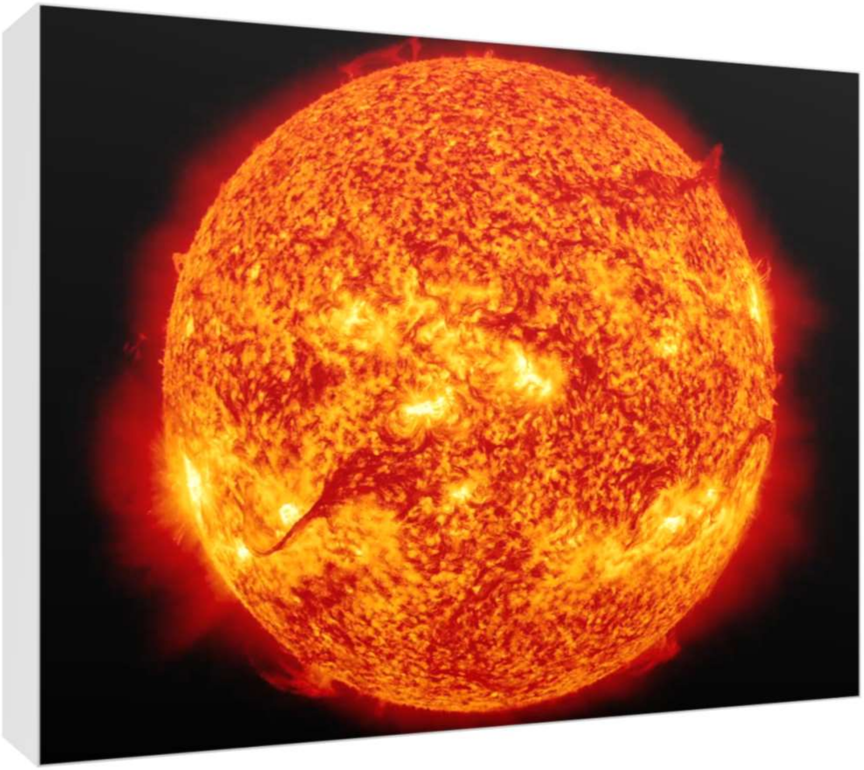
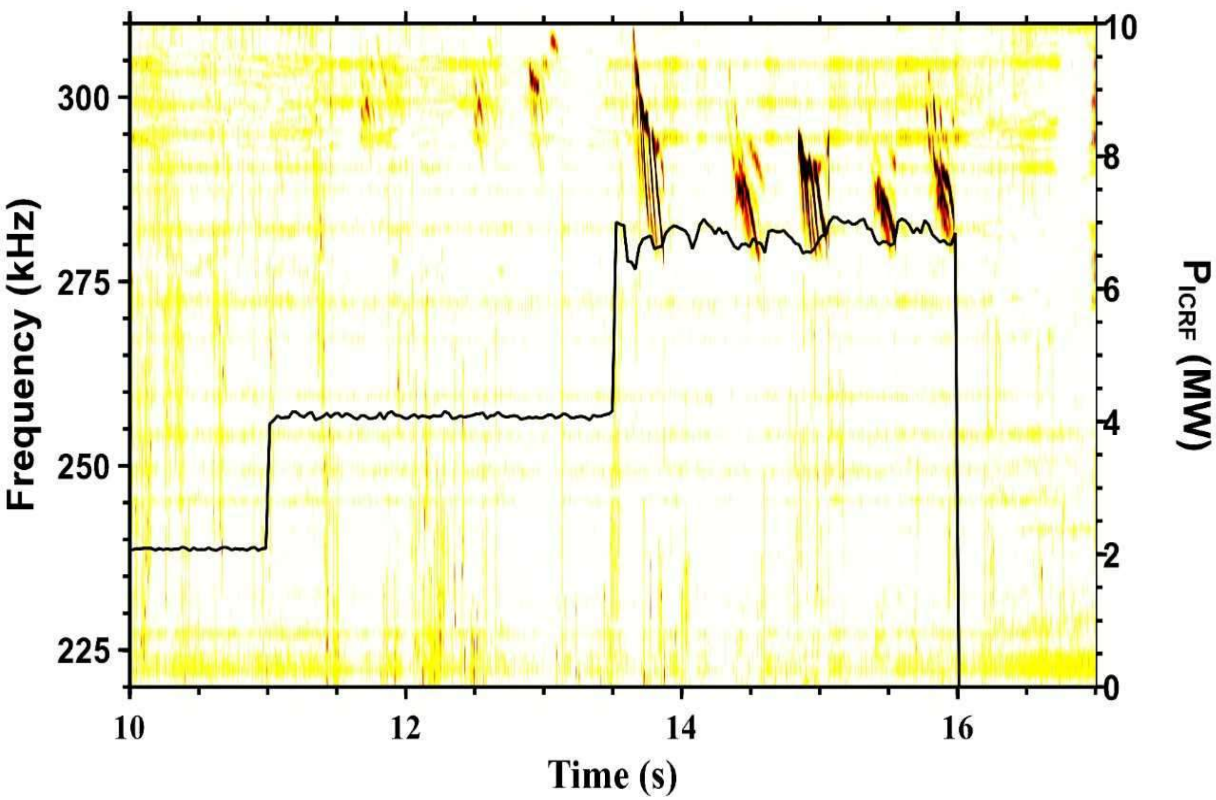
Beyond tokamak plasmas in D: H plasmas



- Similarly to tokamak plasmas, presence in the solar atmosphere of
  - Alfvén waves [S. Tomczyk Science (07)]
  - IC frequency EM waves [Y. Kazakov Nat. Phys. (17)]
  - Turbulence
  - MHD
- Unlike in tokamaks, H and He isotopes are dominant
- <u>Recently, such mixtures have been studied in tokamaks</u>

Alfven waves destabilized in H plasmas

H-(^{3}He)-^{4}He | H-(^{3}He)-D

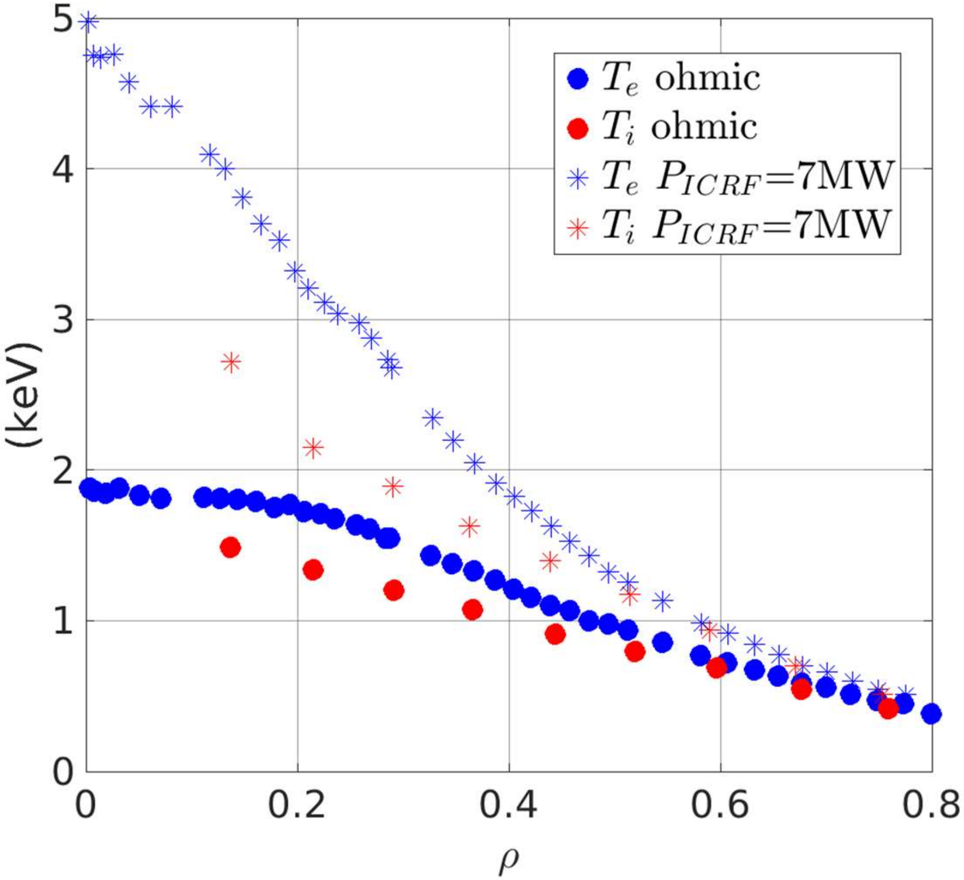


- 3 ions ICRF scheme → ~MeV ions generated
- Alfven waves destabilized
- Complex interplay between MHD and Alfven waves

[Y. Kazakov this conference P2a.118]

JET cea

Ion temperature increases in the presence of electron heating



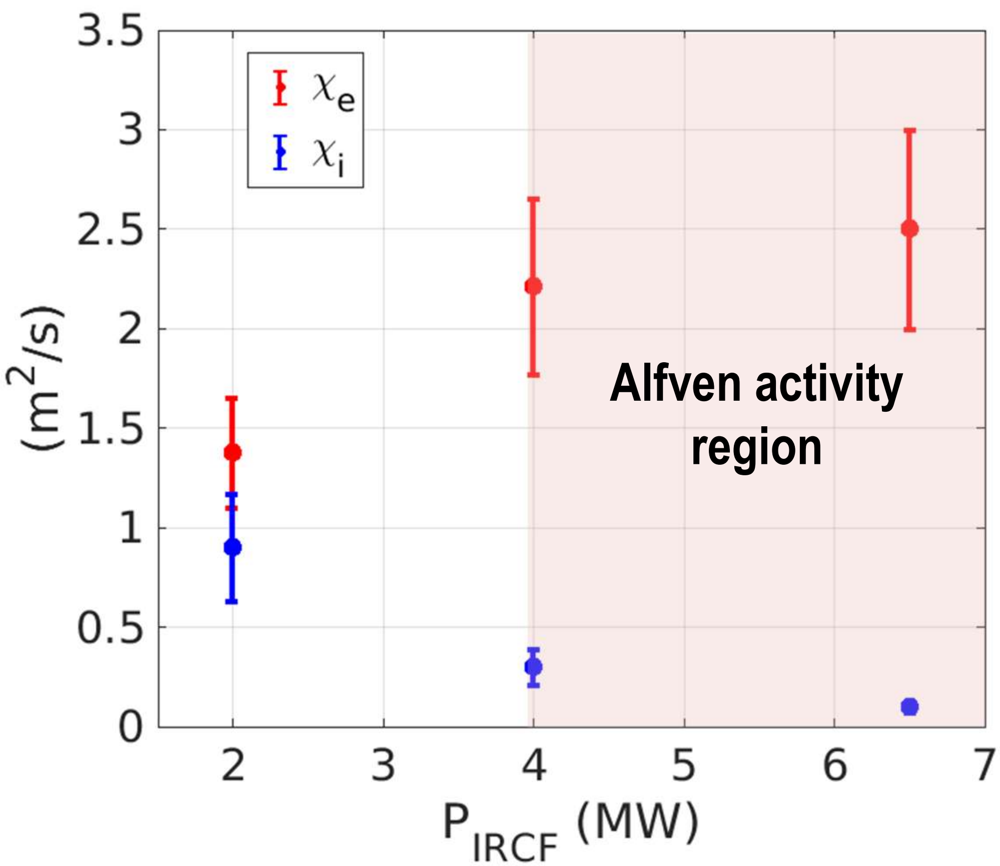
H-(^{3}He)-^{4}He

H-(^{3}He)-D

- 95% of electron heating with ICRF
- Electron temperature increases but…
- …Ti increases along the whole ICRF power scan!

Ion thermal heat transport reduced in the presence of MeV ions

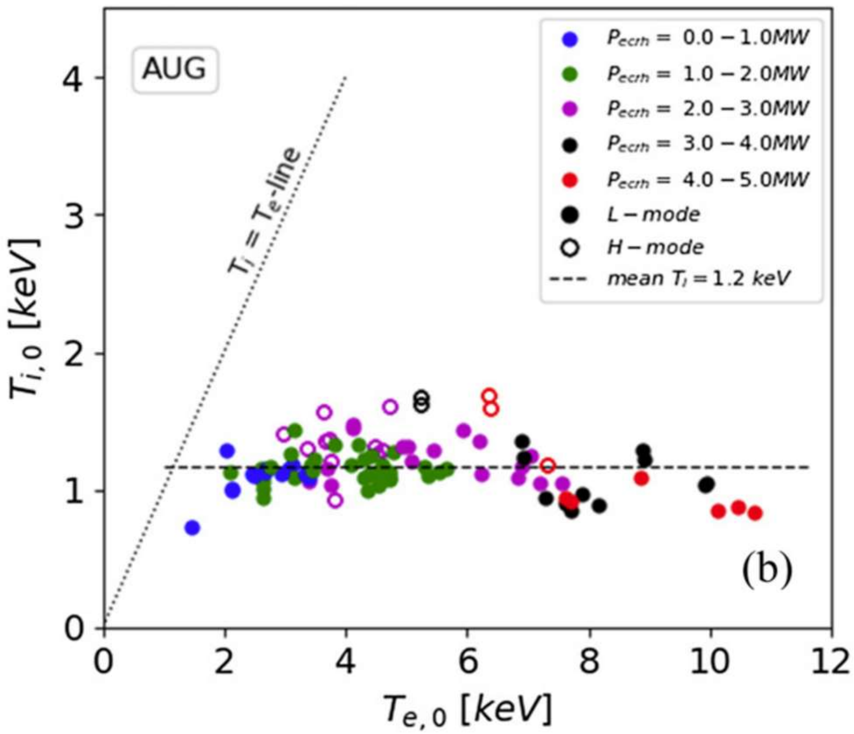
H-(^{3}He)-^{4}He | H-(^{3}He)-D



- Core heat transport characteristics:
  - χ_i decrease with ICRF
  - χ_e increase with ICRF
- Similar results to D-^{3}He plasmas

[S. Mazzi this conference I5.102]

Ion heat transport behavior different in ECRF power scans



[M.N.A. Beurskens NF (22)]

- Results in Asdex-U with Electron cyclotron Resonance Frequency (ECRF)
- Ti,max=1.5keV regardless the ECRF input power
- **Key impact of energetic ions**

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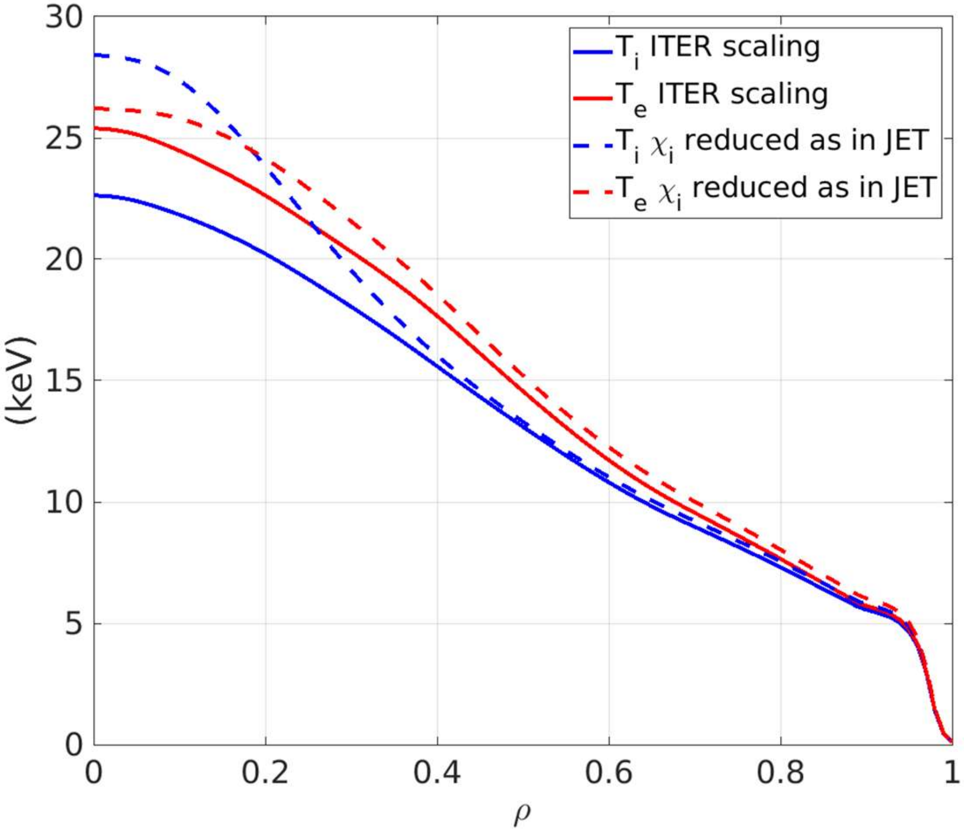
Beneficial impact for ITER



[K Besseghir PPCF (13)]

[J Garcia POP (18)]

- Integrated modelling performed for ITER
- Reduction of thermal ion transport assumed as in JET
- Up to 50MW more of fusion power and Ti>Te!

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Conclusions

- Impact on plasmas of MeV alpha particles is an essential topic
- Concern about negative impact of MeV ions on confinement
- New results with MeV ions and Alfven waves at JET:
  - Ion thermal transport reduction in the presence of Alfven waves
  - Proven in multiple species plasmas including H and He mixtures
  - Multiscale interplay between turbulence and Alfven waves
- New route for improved confinement in ITER in the presence of alpha particles