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

### ► To cite this version:

J. Garcia, Samuele Mazzi, Ye O. Kazakov, J. Ongena, David Zarzoso, et al.. Improved understanding of energetic ions impact on plasma confinement from theory and experiments. 48th EPS conference on plasma physics, EPS, Jun 2022, Videoconference, Netherlands. cea-03766783

**HAL Id: cea-03766783**

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Submitted on 1 Sep 2022

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

**J. Garcia**

*EUROfusion Consortium and CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France.*

**JET**



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



S. Mazzi 1,2,13, Ye. O. Kazakov 3, J. Ongena 3, D. Zarzoso 1, M. Dreval 4,5, W. H. Lin 6, M. Nocente 7,8, Ž. Štancar 9,10, G. Szepesi 10, J. Eriksson 11, J. Ruiz 12, A. Sahlberg 11, S. Benkadda 1 and JET Contributors\*

1 PIIM, UMR 7345, Aix-Marseille University, CNRS, Marseille, France.

2 IRFM, CEA, Saint Paul Lez Durance, France.

3 Laboratory for Plasma Physics, LPP-ERM/KMS, TEC Partner, Brussels, Belgium.

4 Institute of Plasma Physics National Science Center, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine.

5 V.N. Karazin Kharkiv National University, Kharkiv, Ukraine.

6 Southwestern Institute of Physics, Chengdu 610041, China

7 University of Milano-Bicocca, Milan, Italy.

8 Institute for Plasma Science and Technology, CNR, Milan, Italy.

9 Slovenian Fusion Association (SFA), Jožef Stefan Institute, Ljubljana, Slovenia.

10 Culham Science Centre, UK Atomic Energy Authority, Abingdon, UK.

11 Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden

12 Rudolf Peierls Centre for Theoretical Physics, University of Oxford, OX1 3NP, UK

13 Present address: Swiss Plasma Center, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland.

# Outline



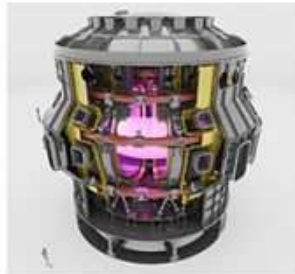
- Energetic ions as a heating mechanism
- Some drawbacks of energetic ions
- Indications of energetic ions impact on the energy confinement
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- Beyond D plasmas: H and He mixtures
- Impact in ITER
- Conclusions

# Magnetically confined fusion energy is in fast evolution



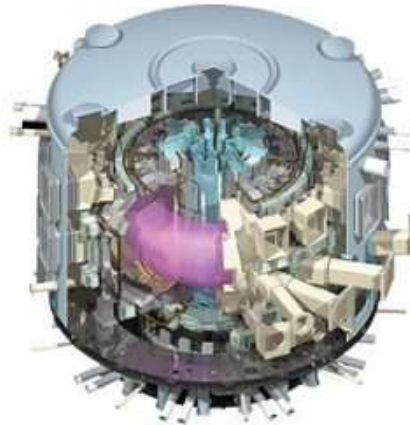
**JET**

80 m<sup>3</sup>



**JT-60SA**

135 m<sup>3</sup>



**ITER**

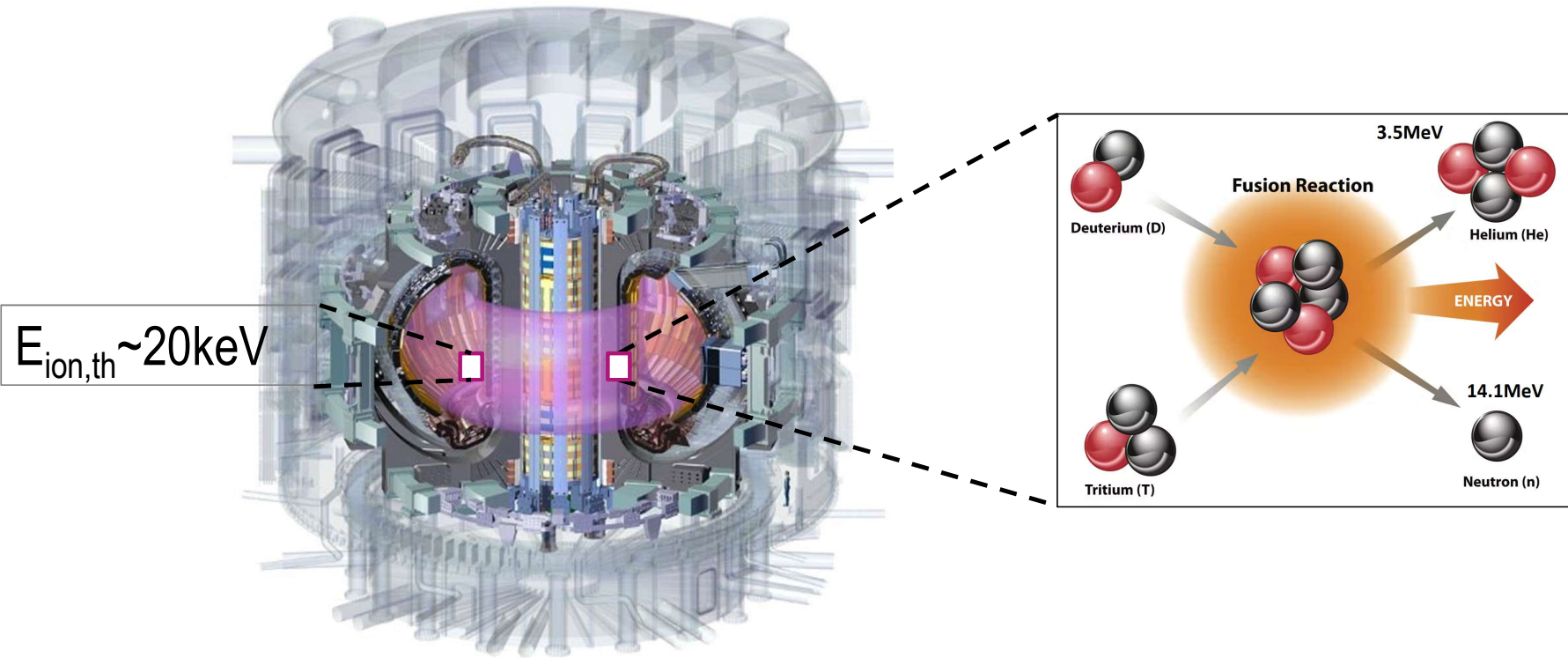
800 m<sup>3</sup>

*(one-third the size of an Olympic swimming pool)*

~ 500 MW<sub>th</sub>

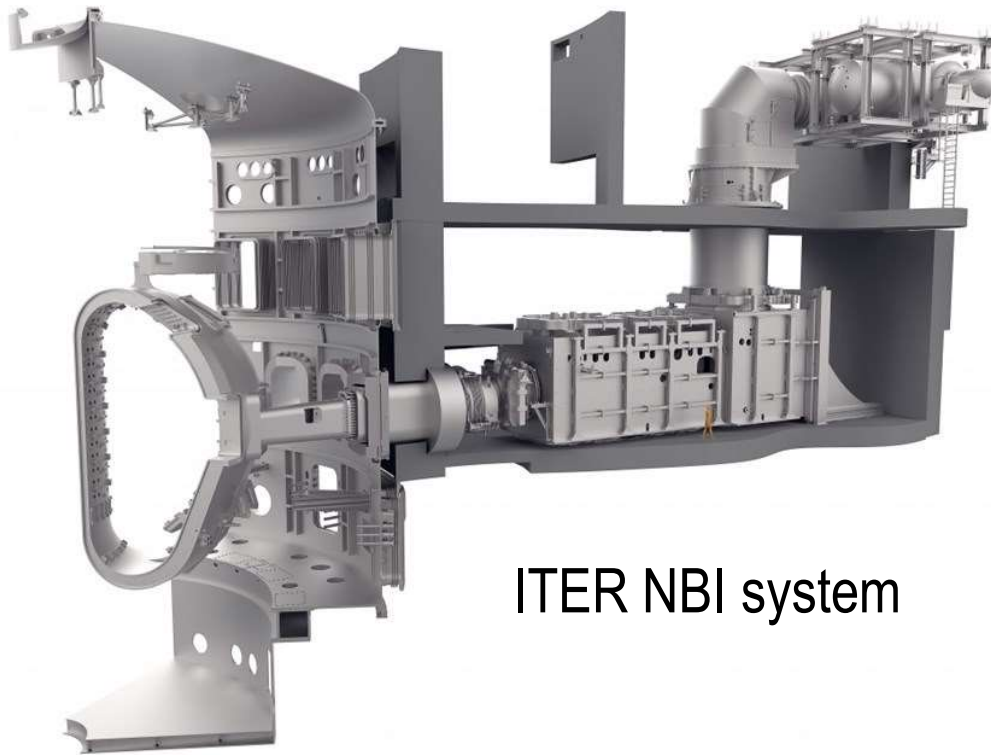
- Several exciting milestones achieved:
  - DT campaign at JET [[J. Mailloux this conference I1.104](#)]
  - Construction of JT-60SA [[Y. Kamada NF\(22\)](#)]
  - Record long pulse in EAST
- ITER project getting closer to its completion

# 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**

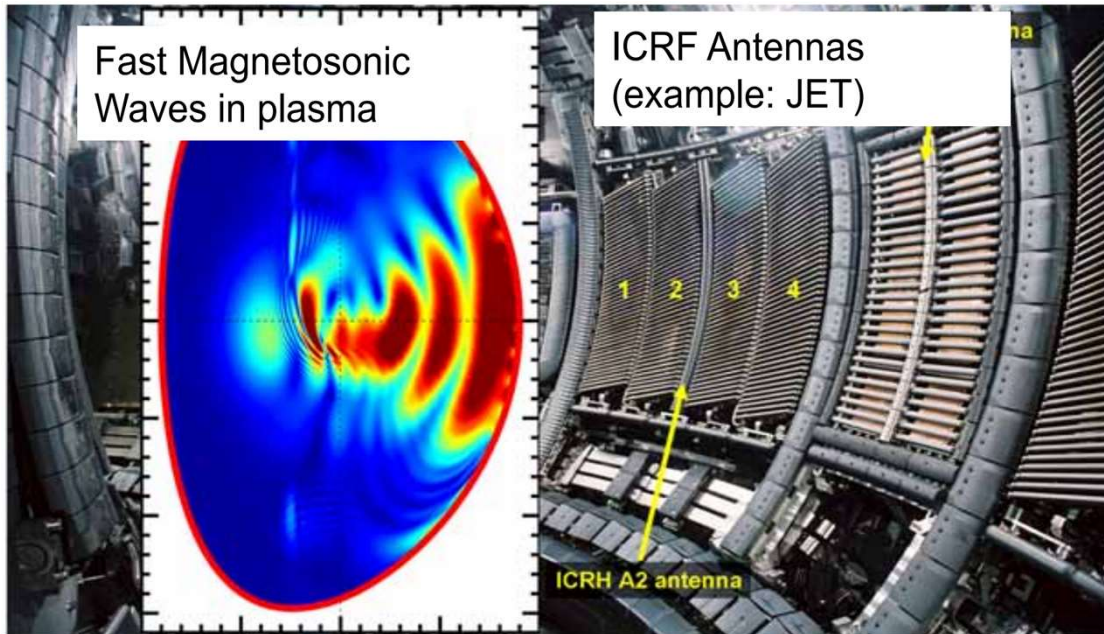
# 1<sup>st</sup> method: Neutral Beam Injection (NBI)



ITER NBI system

- Ions are accelerated, neutralized and injected in the plasma
- In present day tokamaks  $E_{\text{ion}} \sim 100\text{keV} \rightarrow$  Main heating method
- **NBI in ITER will inject  $E_{\text{ion}} = 1\text{MeV}$**

# 2<sup>nd</sup> method: Ion Cyclotron Resonance Frequency



- **ICRF**: Externally injecting waves at resonant frequency

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

Ion cyclotron frequency

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**

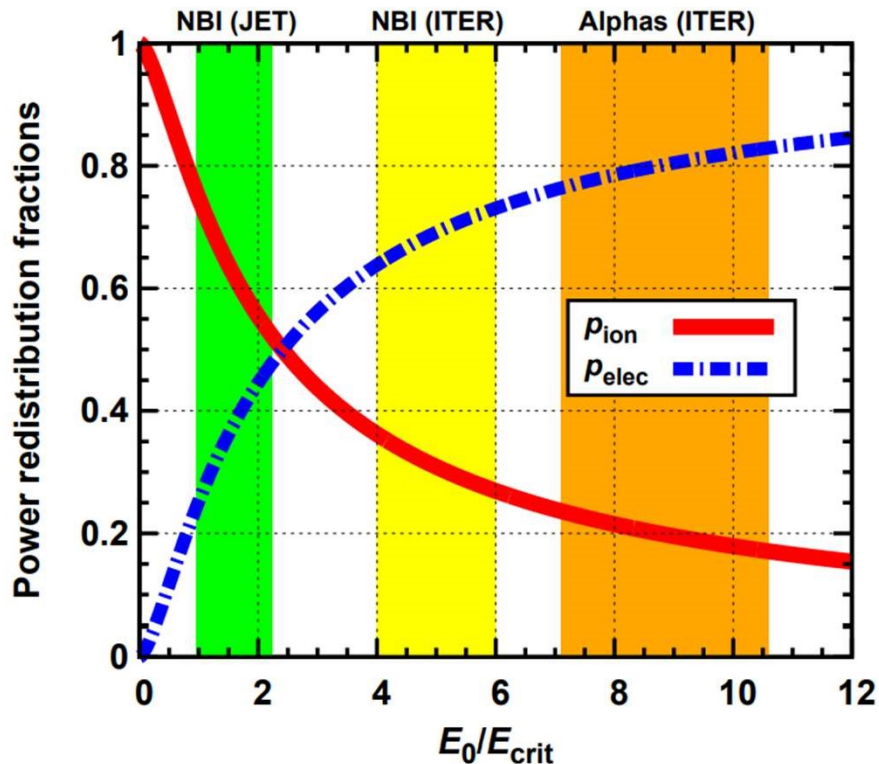


# Outline



- Energetic ions as a heating mechanism
- **Some drawbacks of energetic ions**
- Indications of energetic ions impact on the energy confinement
- Tools for the study of MeV ions impact on energy confinement
- New results from JET in D-<sup>3</sup>He plasmas
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# Drawback 1: Alpha energy mostly transferred to electrons



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

# Drawback 2: Energetic ions can interact with Alfvén Waves

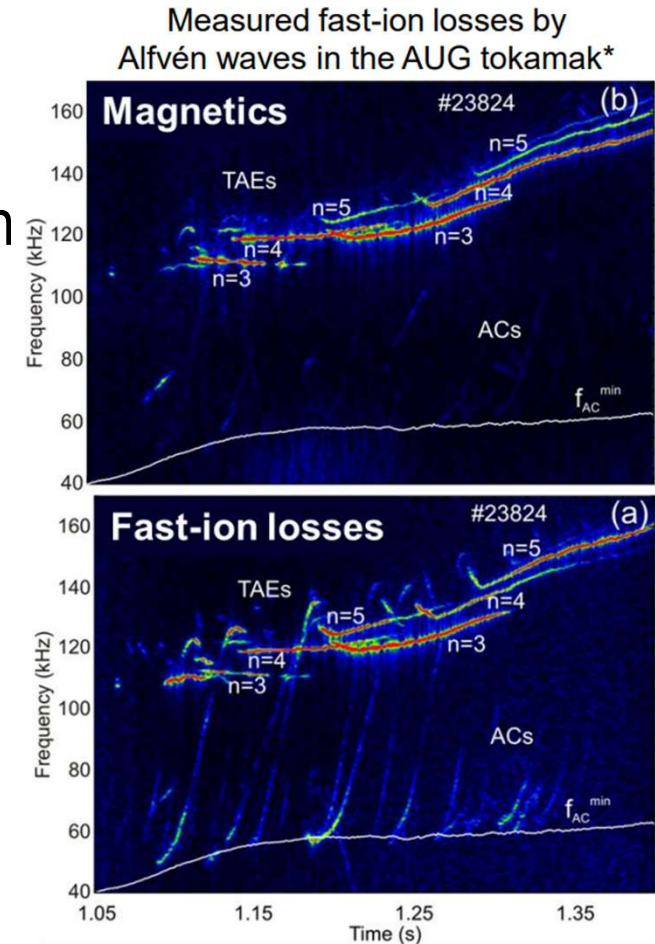


- Energetic ions can interact with electromagnetic perturbations
- Alfvén waves are driven unstable with dispersion relation

$$\omega = k_{\parallel} v_A$$

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

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



[M. Garcia-Munoz PRL (10)]

# Drawback 2: Energetic ions can interact with Alfvén Waves



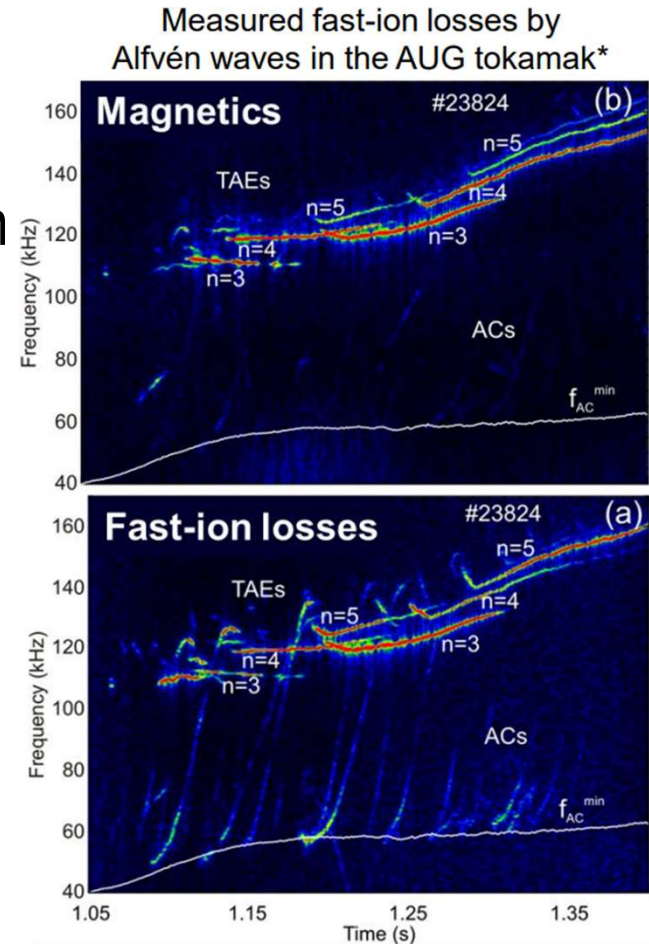
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- Drawback → Alfvén waves responsible for energetic ions transport, losses and confinement degradation



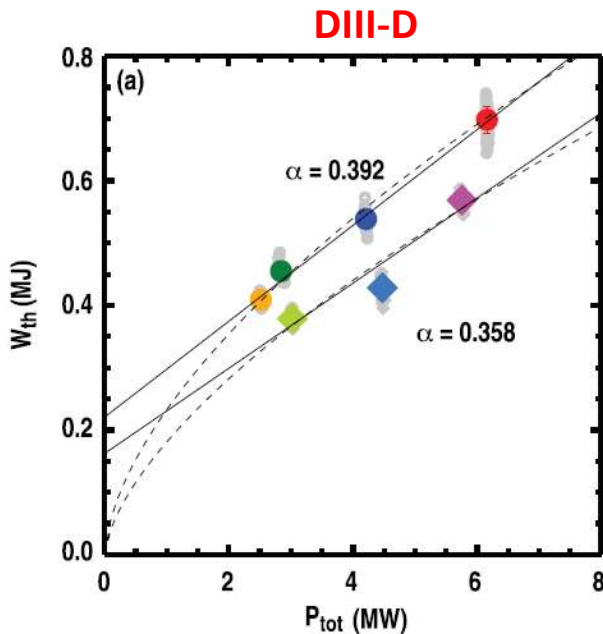
[M. Garcia-Munoz PRL (10)]

# Outline

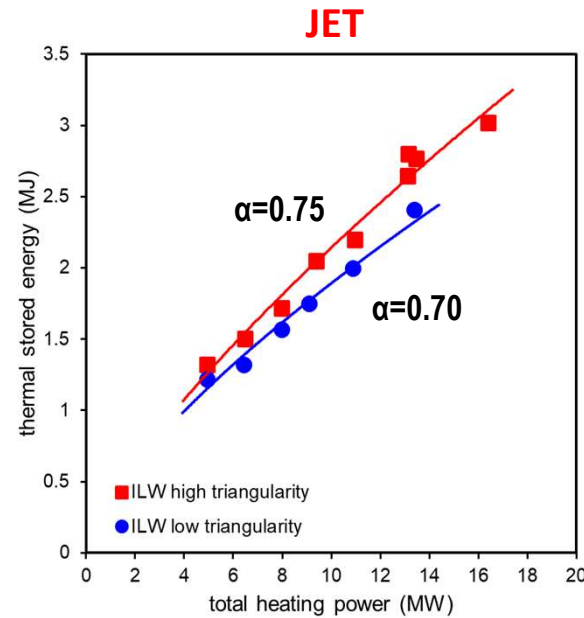


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# High impact of NBI energetic ions on plasma energy confinement



[T. Luce NF (18)]

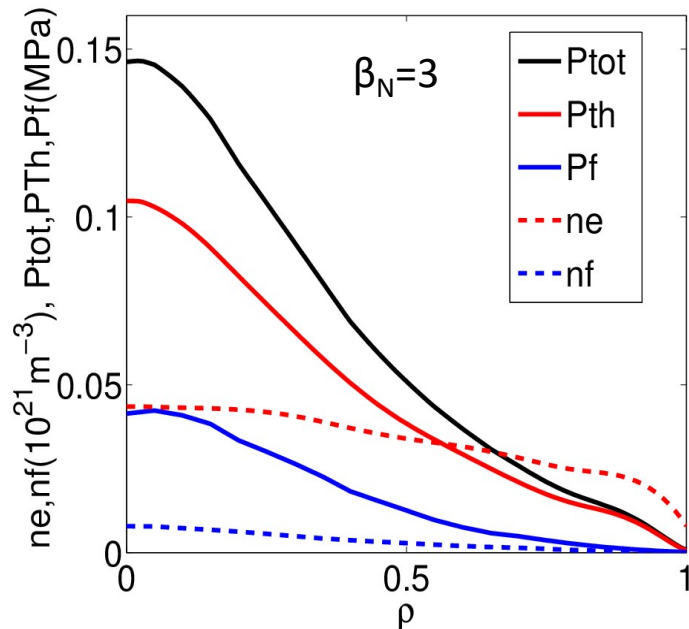


**ITER Physics**  
**Basis:  $W_{th} \sim P^{\alpha=0.31}$**

[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 losses by heat transport?

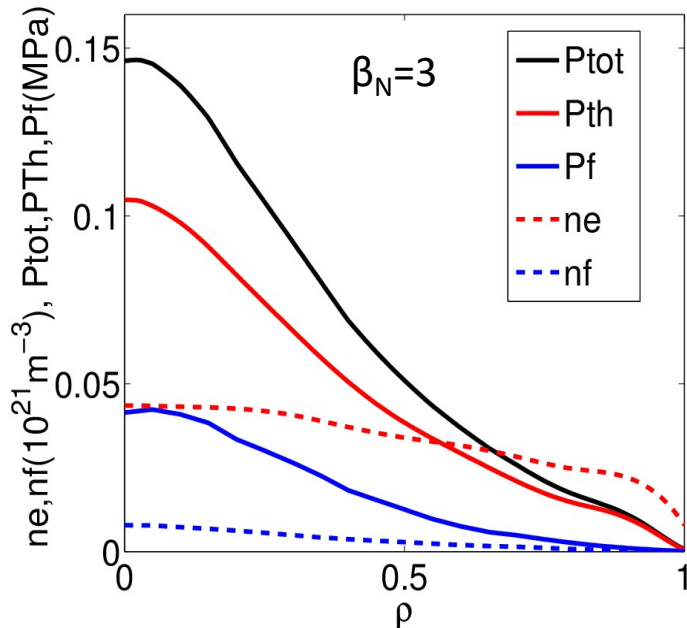
# High Impact of NBI energetic ions on plasma energy confinement



[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



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

[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)]



# 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)]	$^4\text{He}$	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)]

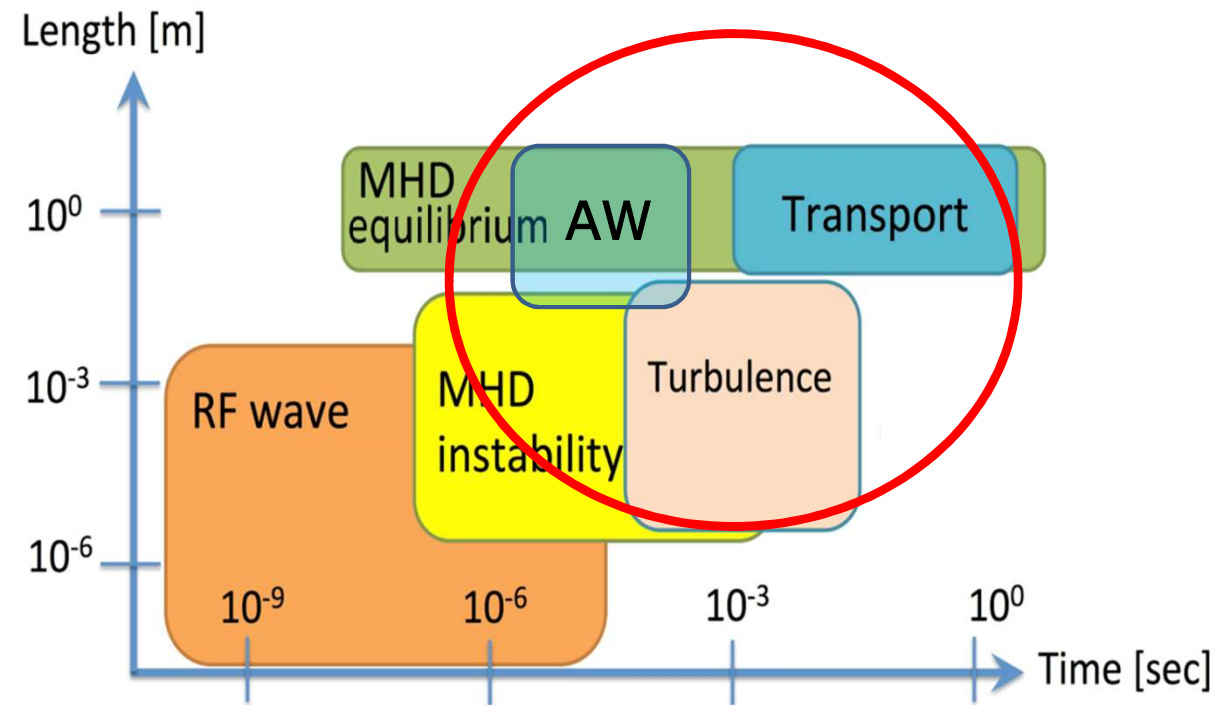
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Case Study	Energetic ion specie	$T_i/T_e$	$n_{FI}/n_e$ [%]	$T_{FI}/T_e$
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- Stabilizing energetic ion effect → **BUT** way less energetic particles than DT fusion born alpha particles [J. Citrin PRL(13), 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  $\alpha$  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  $\sim E_\alpha$**
  2. **Improved multiscale understanding by using HPC**
  3. **Improved diagnostics**

# Outline

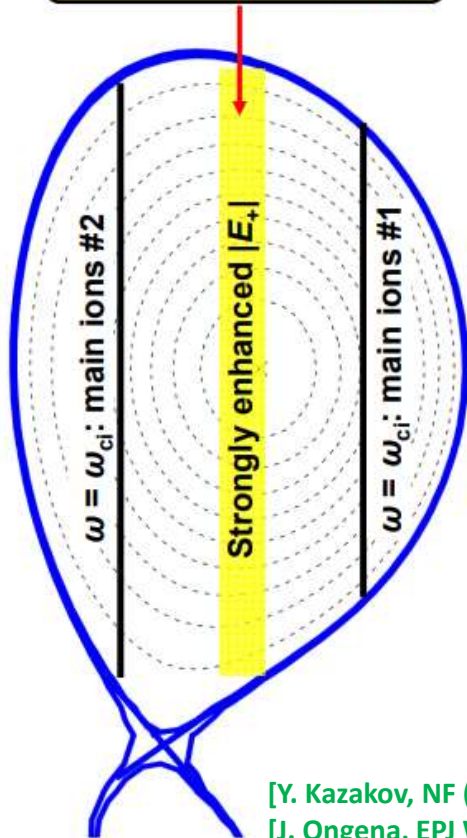


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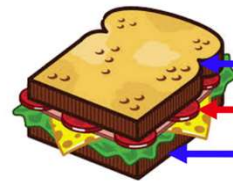
# New experiments: novel three-ion ICRF schemes



$$\omega = \omega_{c3} + k_{\parallel} v_{\parallel,3}$$



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



Main ions no. 1

**Resonant ions (no. 3)**

Main ions no. 2

- 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)]



Global Gyrokinetic Simulation of  
Turbulence in  
ASDEX Upgrade



GENE

gene.rzg.mpg.de

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

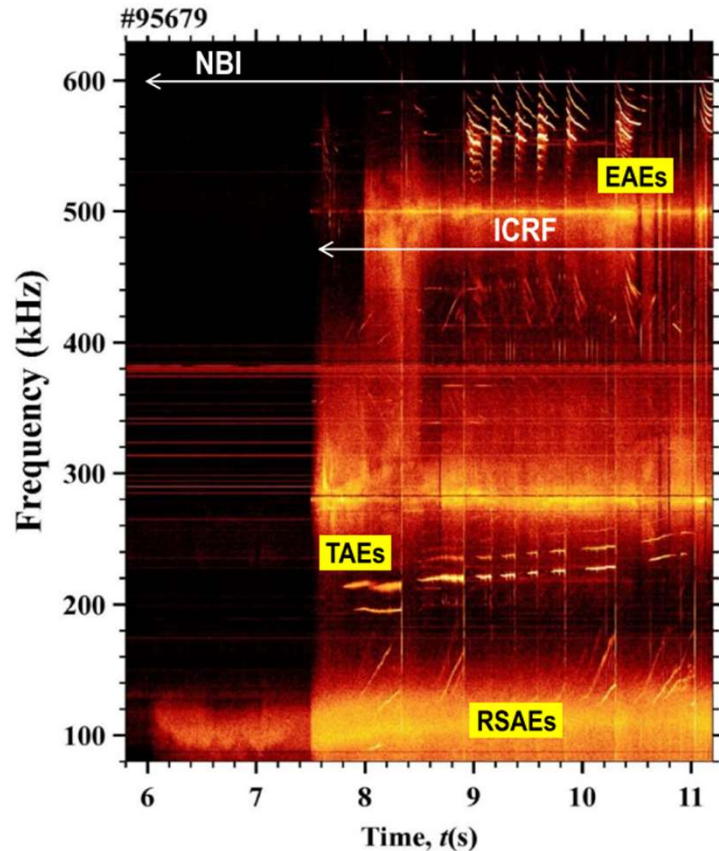
[F. Jenko *POP* 00]

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# Alfven waves destabilized in JET with ICRF



D-(D<sub>nbi</sub>)-<sup>3</sup>He

- New experiments performed at JET in D-(D<sub>nbi</sub>)-<sup>3</sup>He plasmas
- Heating mechanisms: NBI and ICRF
- Alfven waves in the range of 100-600kHz
- Fluctuations not detected in only NBI phase

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

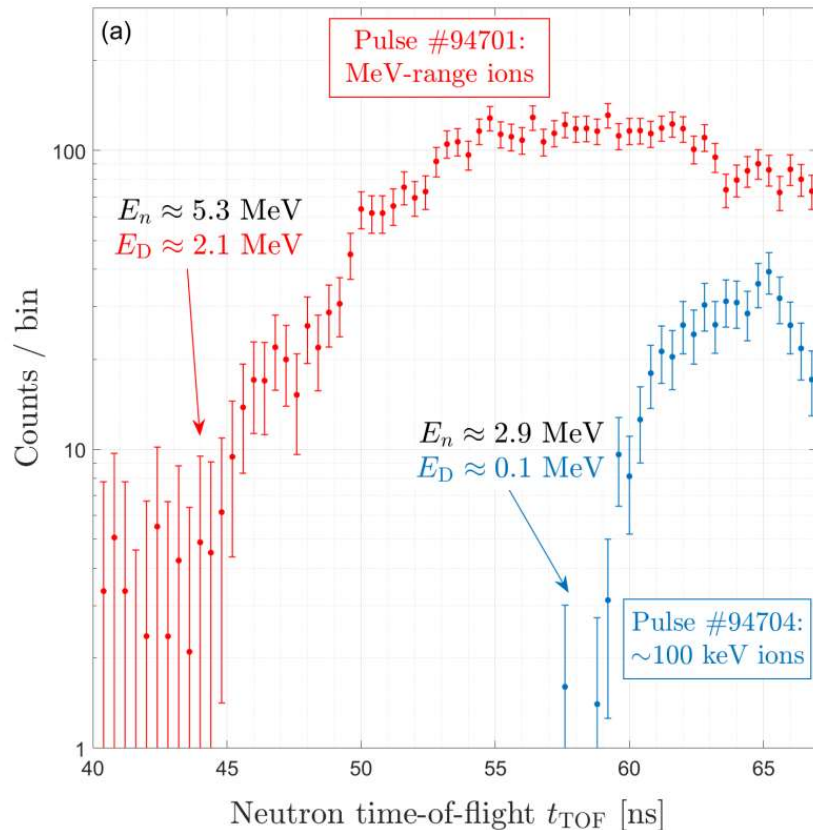


# MeV ions detected in the presence of ICRF



Time-of-flight neutron spectrometer

D-(D<sub>nbi</sub>)-<sup>3</sup>He



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

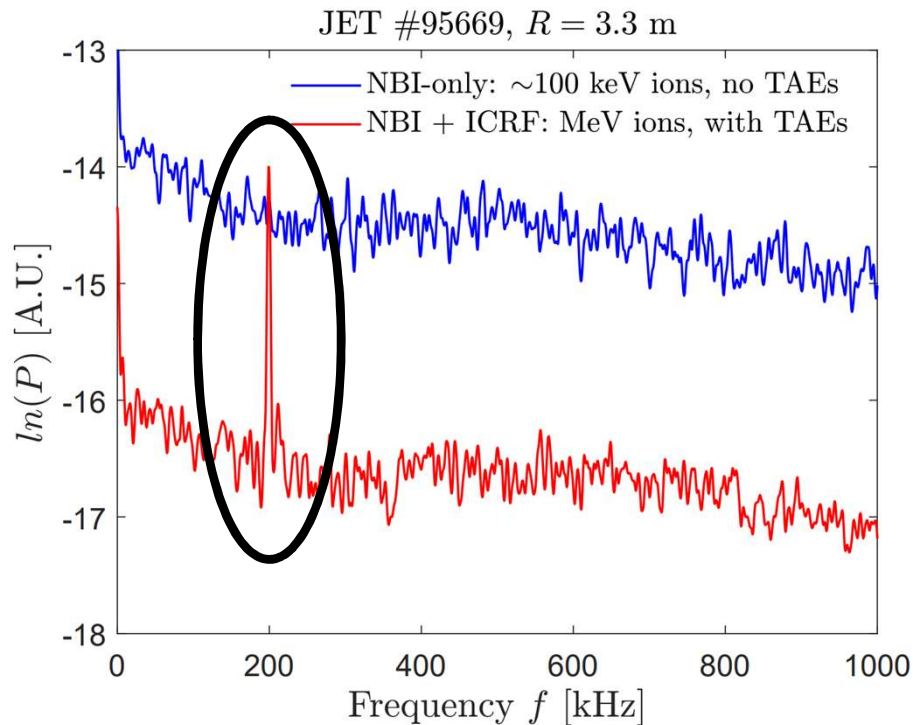
[S. Mazzi Nat. Phys. (22)] [S. Mazzi this conference I5.102]

# Strong decrease of density fluctuations in the presence of MeV ions



Reflectometry measurements

D-(D<sub>nbi</sub>)-<sup>3</sup>He



- Plasma density fluctuations spectrum  $\rightarrow$  turbulence intensity
- Compared to NBI, fluctuations reduction in the presence of MeV ions
- Unexpectedly, Alfvén waves and reduced turbulence coexist

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

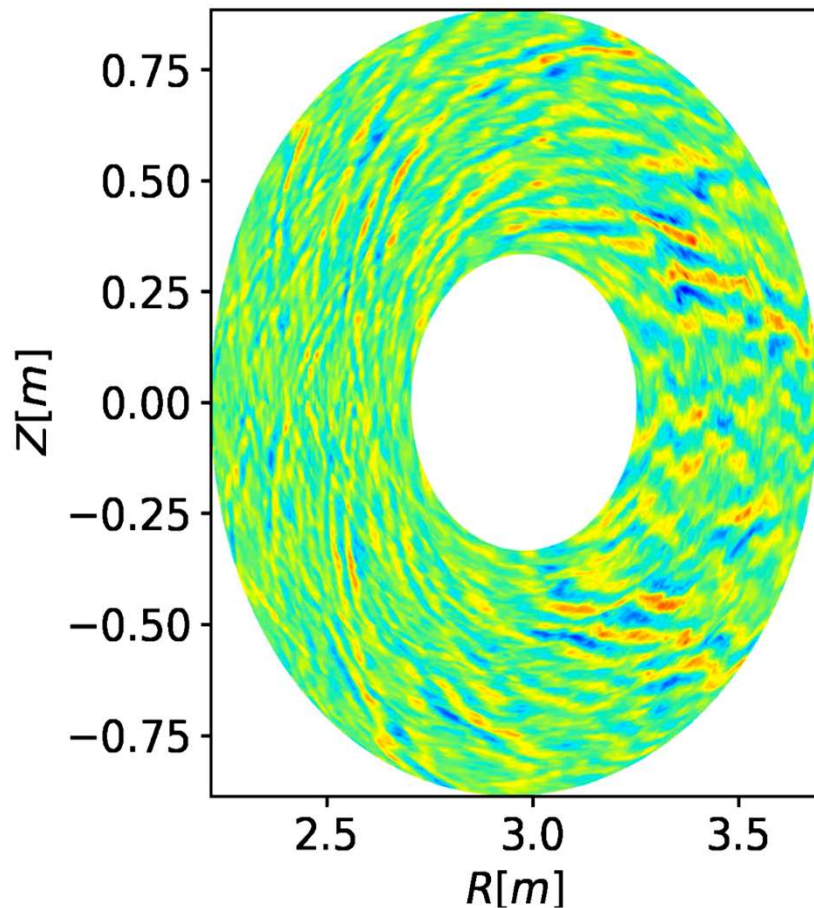
# Multiscale origin of thermal heat transport reduction



D-(D<sub>nbi</sub>)-<sup>3</sup>He

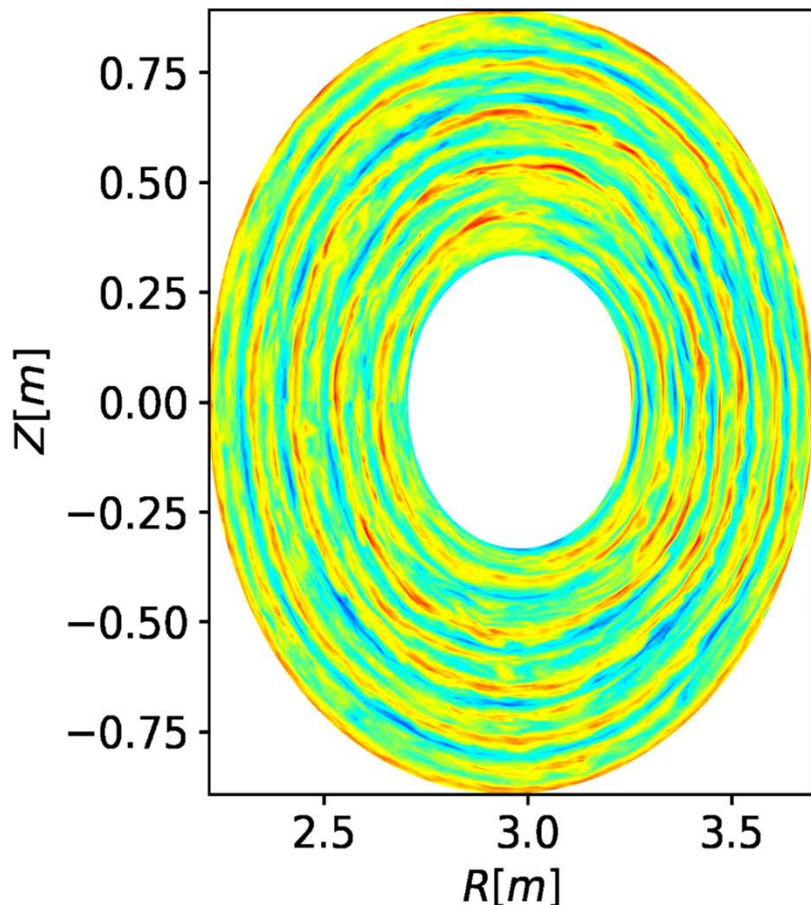
No energetic ions

- Multiscale gyrokinetic simulations performed



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

# Multiscale origin of thermal heat transport reduction



D-(D<sub>nbi</sub>)-<sup>3</sup>He

## With MeV energetic ions

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

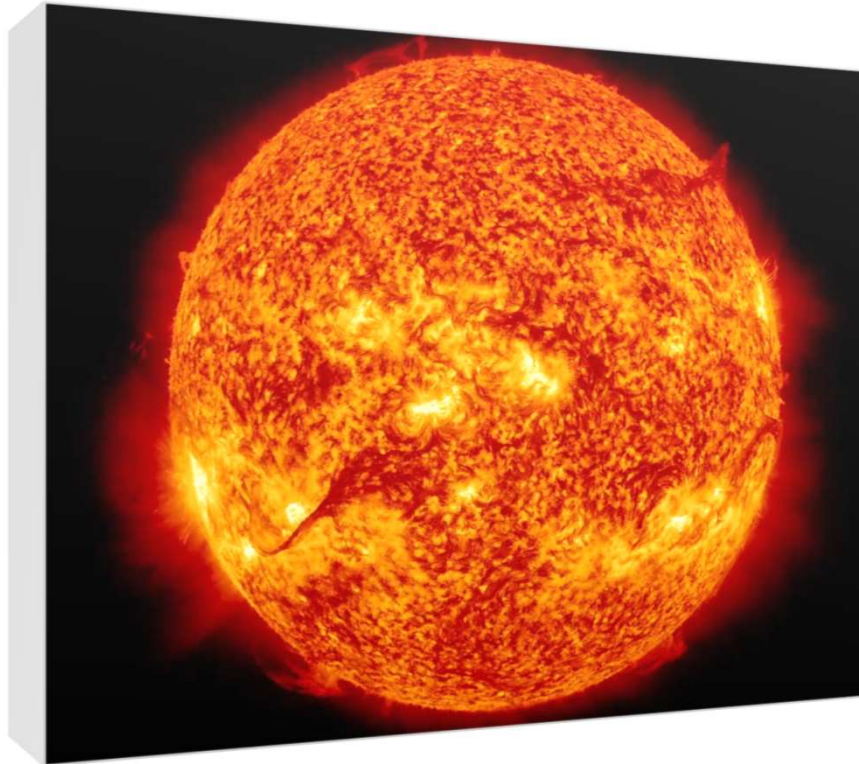
[A. Di Siena NF(19)] [S. Mazzi Nat. Phys.(22)] [S. Mazzi this conference I5.102]

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# Beyond tokamak plasmas in D: H plasmas



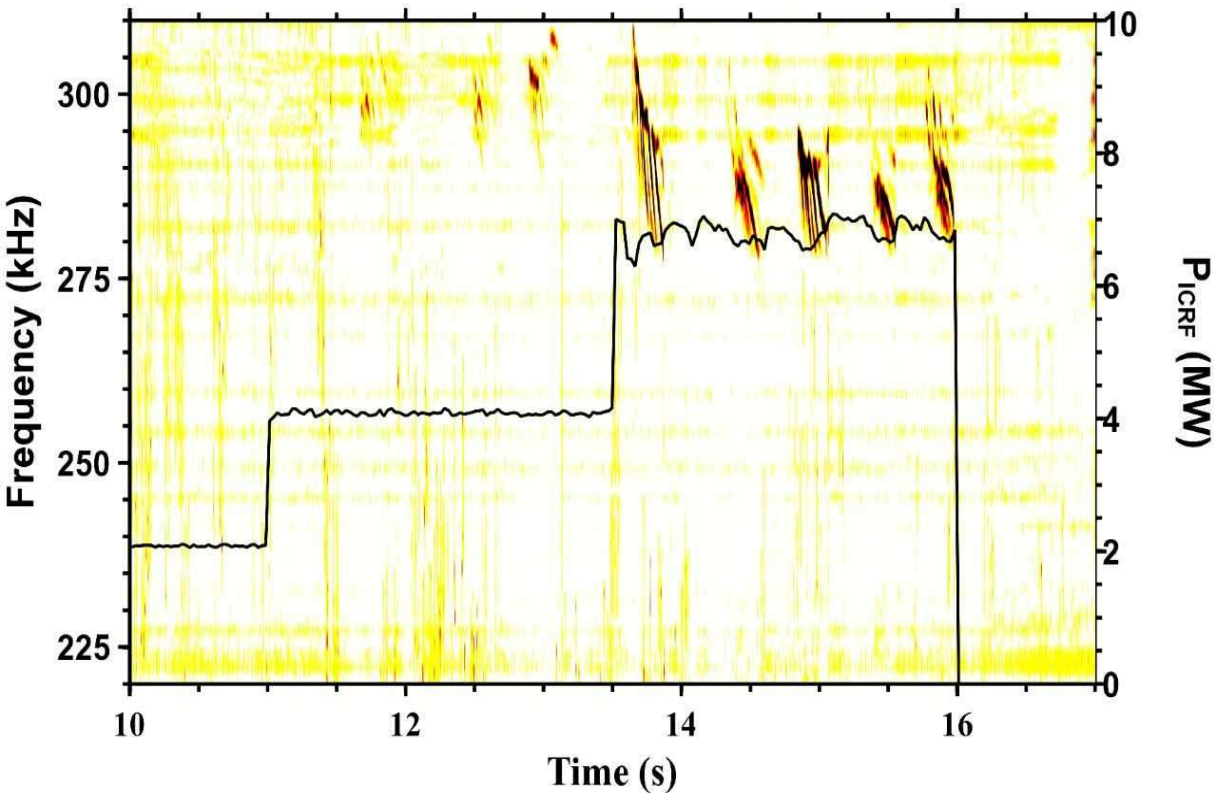
- Similarly to tokamak plasmas, presence in the **solar atmosphere** of
  - Alfvén waves [S. Tomczyk Science (07)]
  - IC frequency EM waves [Y. Kazakov Nat. Phys. (17)]
  - Turbulence
  - MHD
- Unlike in tokamaks, **H and He isotopes are dominant**
- Recently, such mixtures have been studied in tokamaks

# Alfven waves destabilized in H plasmas



H-(<sup>3</sup>He)-<sup>4</sup>He

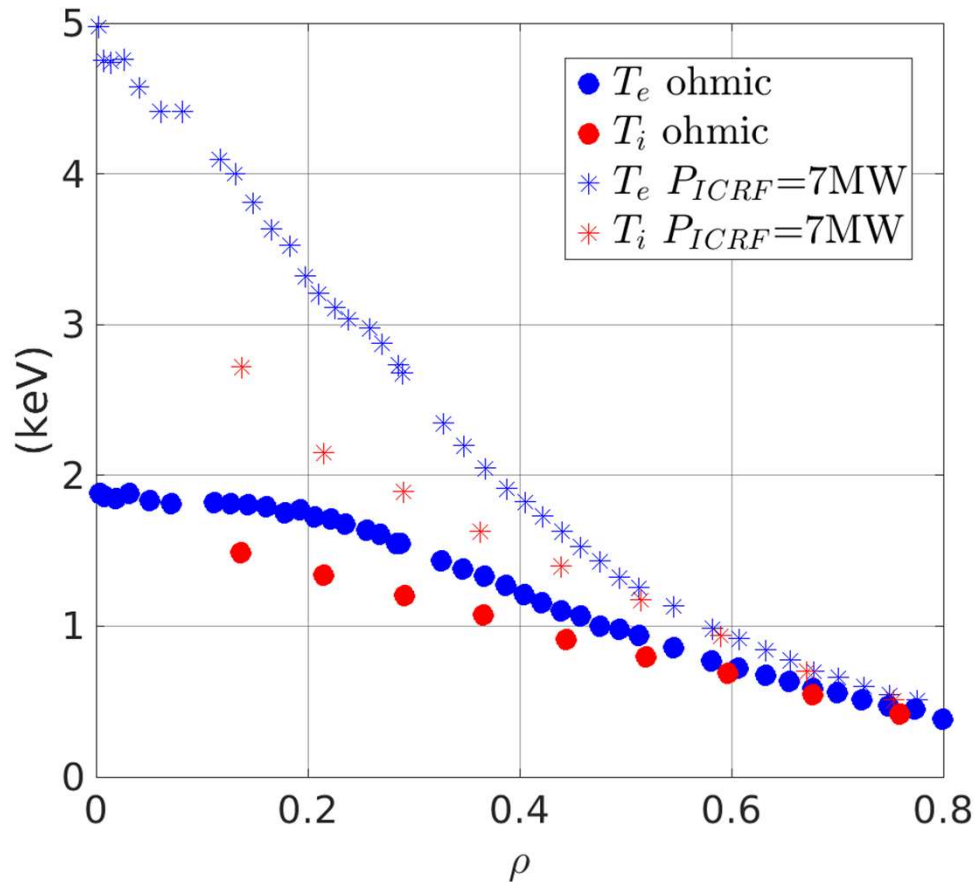
H-(<sup>3</sup>He)-D



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

[Y. Kazakov this conference P2a.118]

# Ion temperature increases in the presence of electron heating



H-(<sup>3</sup>He)-<sup>4</sup>He

H-(<sup>3</sup>He)-D

- 95% of electron heating with ICRF
- Electron temperature increases but...
- ... $T_i$  increases along the whole ICRF power scan!

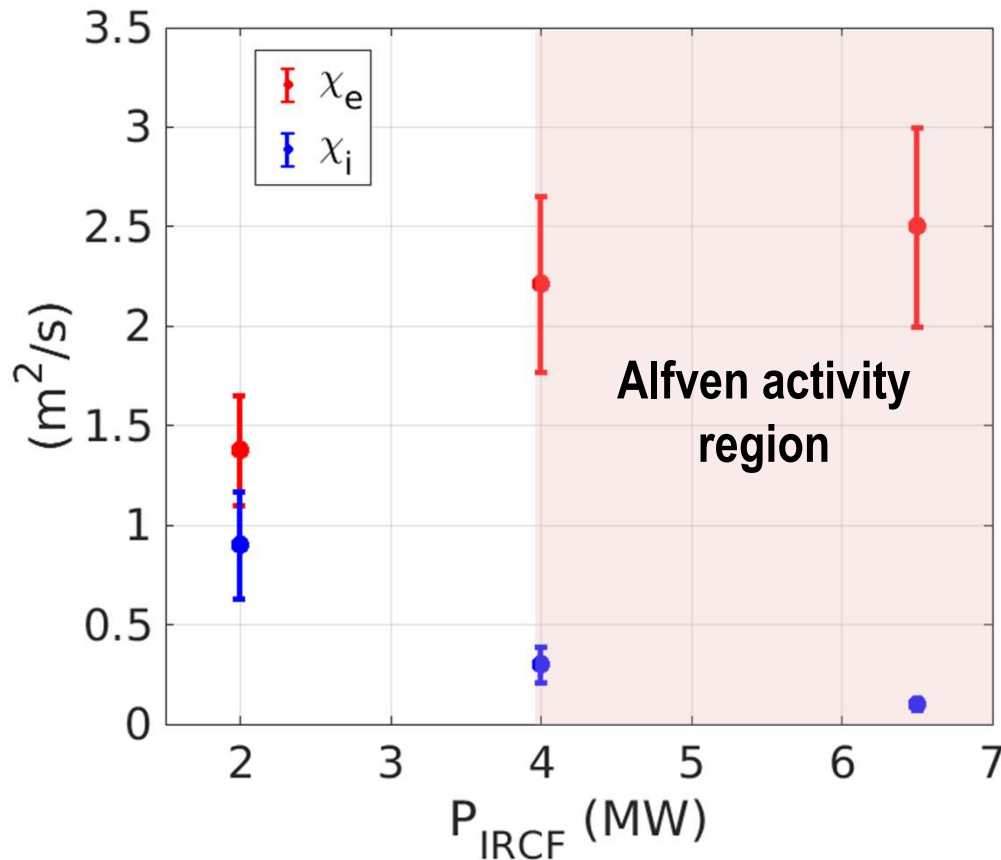


# Ion thermal heat transport reduced in the presence of MeV ions



H-(<sup>3</sup>He)-<sup>4</sup>He

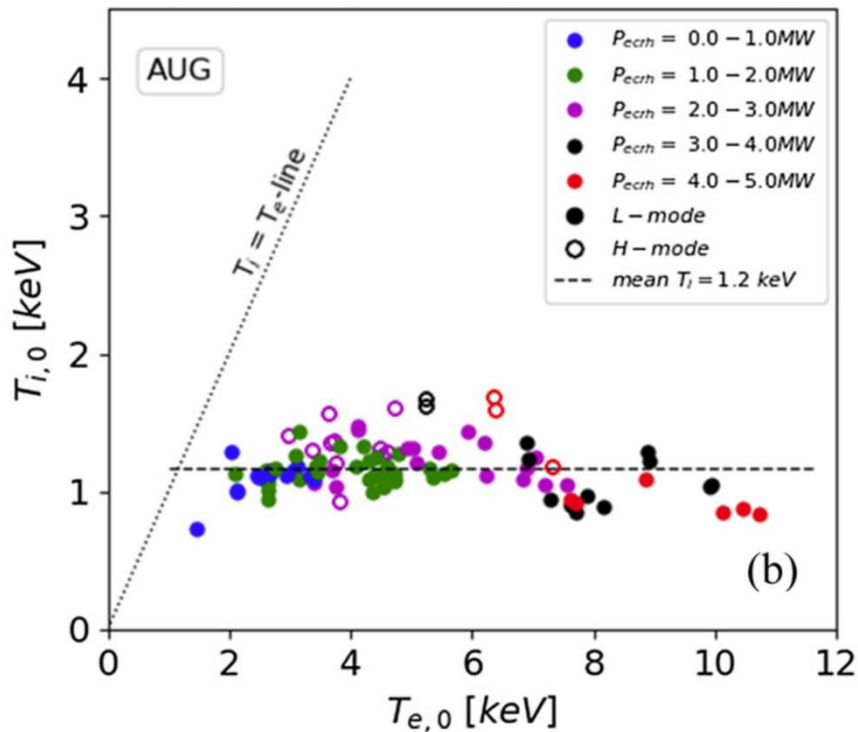
H-(<sup>3</sup>He)-D



- Core heat transport characteristics:
  - $\chi_i$  decrease with ICRF
  - $\chi_e$  increase with ICRF
- Similar results to D-<sup>3</sup>He plasmas

[S. Mazzi this conference I5.102]

# Ion heat transport behavior different in ECRF power scans



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

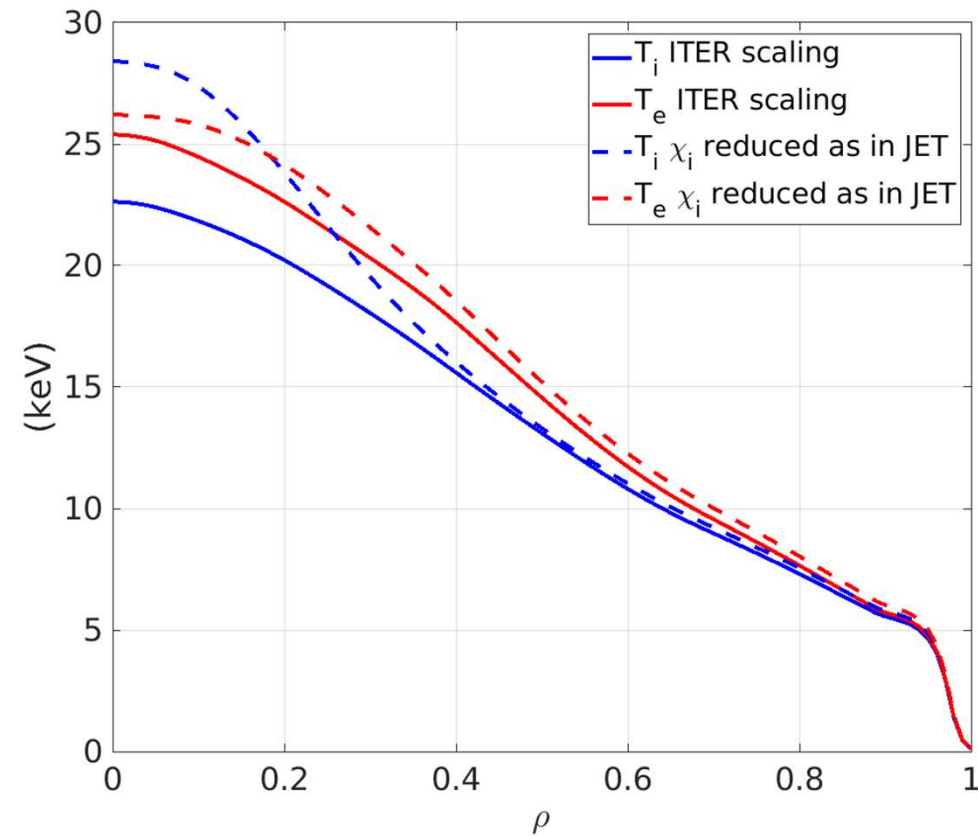
- Results in Asdex-U with Electron cyclotron Resonance Frequency (ECRF)
- $T_{i,max} = 1.5$  keV regardless the ECRF input power
- Key impact of energetic ions

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- **Impact in ITER**
- Conclusions

# 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  $T_i > T_e$ !

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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 Alfvén waves at JET:
  - **Ion thermal transport reduction** in the presence of Alfvén waves
  - Proven in **multiple species plasmas** including H and He mixtures
  - **Multiscale interplay** between turbulence and Alfvén waves
- **New route for improved confinement in ITER** in the presence of alpha particles