Recent advances in ICRF heating of mixture plasmas: survey of JET and AUG experiments and application for JET-DT and ITER

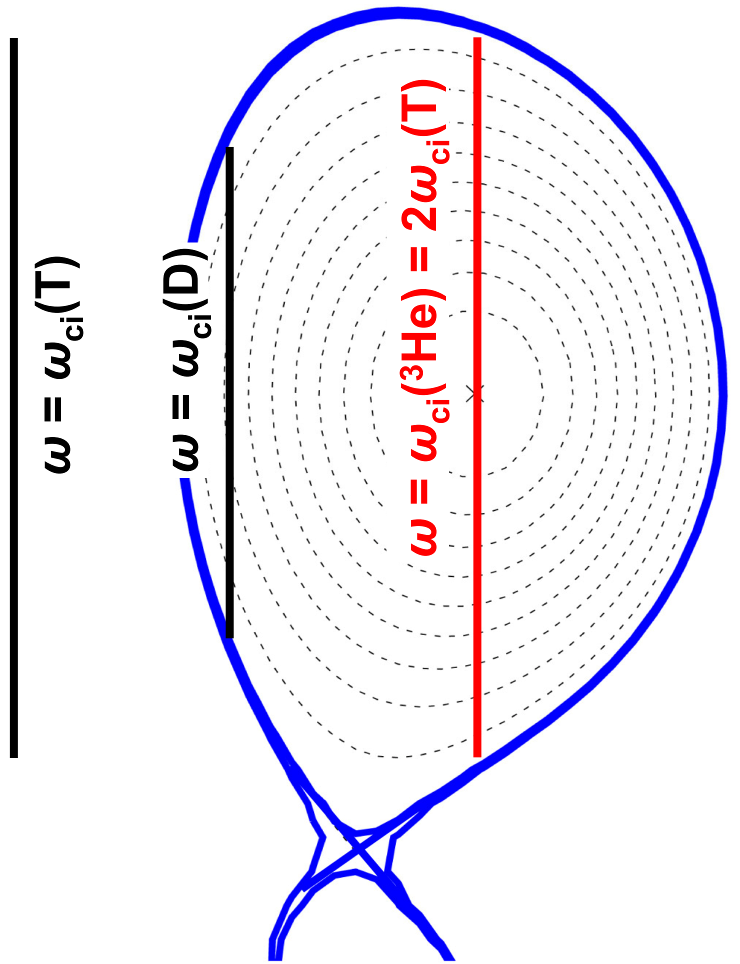
Yevgen Kazakov*
on behalf of JET Contributors, the ASDEX Upgrade Team and the EUROfusion MST1 Team

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

JET overview: E. Joffrin, OV/1-3
AUG overview: H. Meyer, OV/2-1

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Main ICRH scenarios for heating D-T mixture plasmas in ITER



- **ICRH and wave-particle interaction:**

$$\omega = n\omega_{ci} + k_{\|}v_{\|} \quad (n = 1, 2, 3, \ldots)$$

- **Reference ICRH scheme for ITER D-T plasmas:**

**second harmonic ($n = 2$) heating of fuel T ions,
assisted with minority heating ($n = 1$) of ^{3}He ions (~ 2-3%)**

***ITER Physics Expert Group on EP, H&CD, Nucl. Fusion (1999);
R. Dumont and D. Zarzoso, Nucl. Fusion (2013)***

- **Demonstrated in the past D-T experiments on TFTR and JET**

***D. Start, Plasma Phys. Control. Fusion (1998);
J.R. Wilson, Phys. Rev. Lett. (1995)***

D-T fusion plasmas: a multi-ion species environment

Energetic alphas

^{4}He ash

^{3}He minority for ICRH

Fuel D and T ions

Intrinsic impurities:
^{9}Be, W

Extrinsic impurities:
Ar, Ne (^{20}Ne and ^{22}Ne), …

Fast NBI ions:
D-NBI and T-NBI

D-T fusion plasmas: a multi-ion species environment

Energetic alphas

^{4}He ash

^{3}He minority for ICRH

Fuel D and T ions

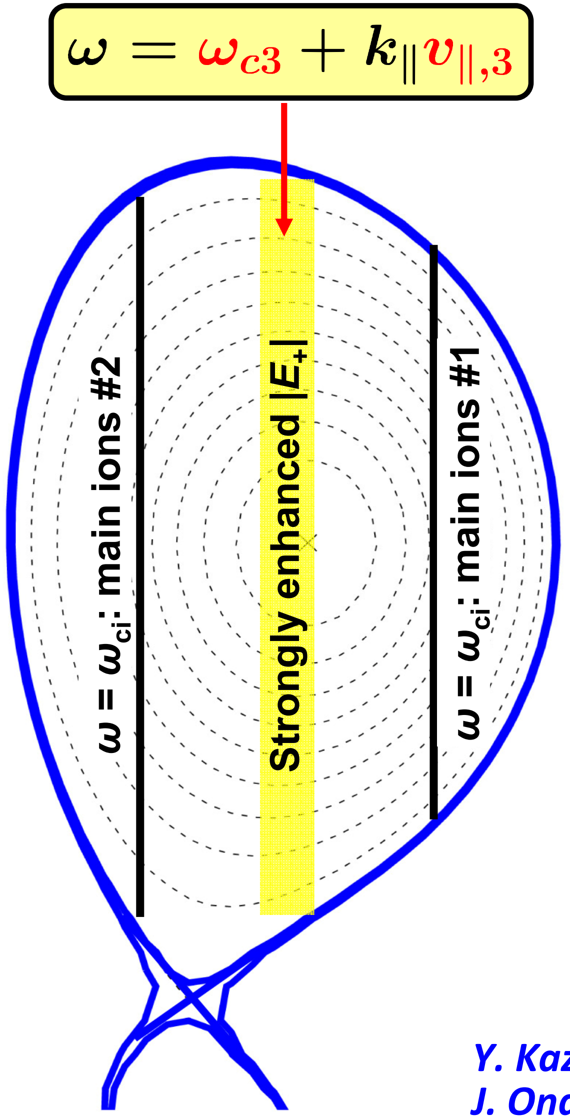
These ions can also effectively absorb ICRH power !

Intrinsic impurities:
^{9}Be, W

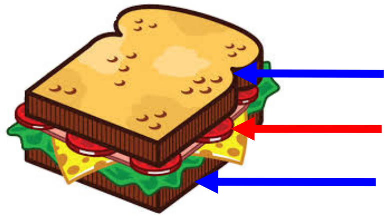
Extrinsic impurities:
Ar, Ne (^{20}Ne and ^{22}Ne), …

Fast NBI ions:
D-NBI and T-NBI

Three-ion ICRH schemes: new efficient scenarios for heating mixture plasmas



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



Option 1: ions with $(Z/A)_i$ as one of the two main ions, but with large $v_{\parallel}$

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

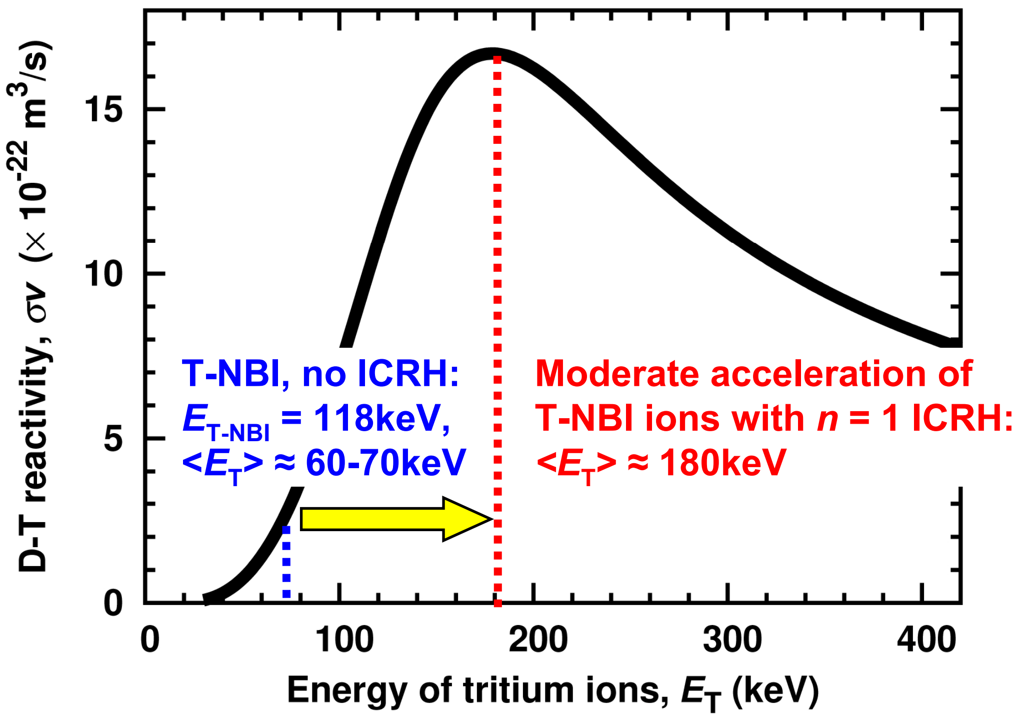
$$(Z/A)_2 < (Z/A)_3 < (Z/A)_1$$

Y. Kazakov, Nucl. Fusion (2015) and Phys. Plasmas (2015);
J. Ongena, EPJ Web. Conf. (2017);
D. Van Eester, Plasma Phys. Control. Fusion (2017)

Application of three-ion schemes for D-T plasmas in JET and ITER

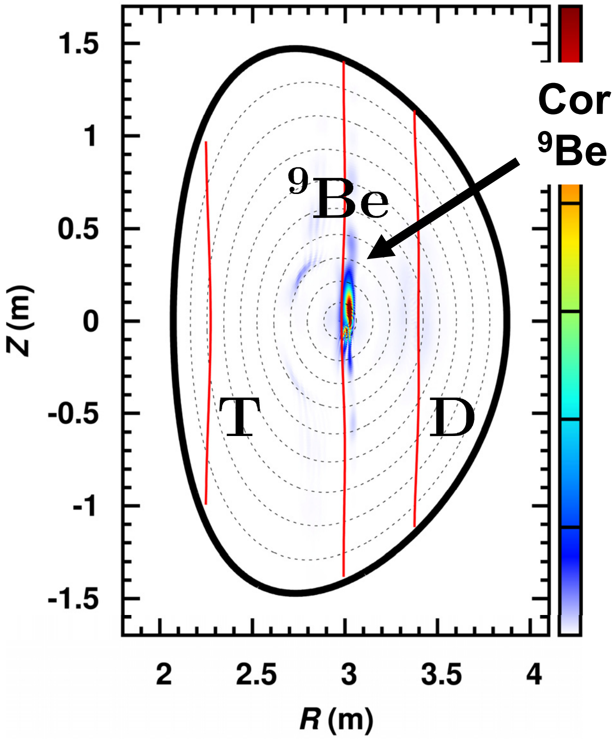
1. Optimize steady-state *Q* and fusion power in JET DTE2

→ accelerate NBI ions with $n = 1$ ICRH to the energies at which D-T reactivity is maximized



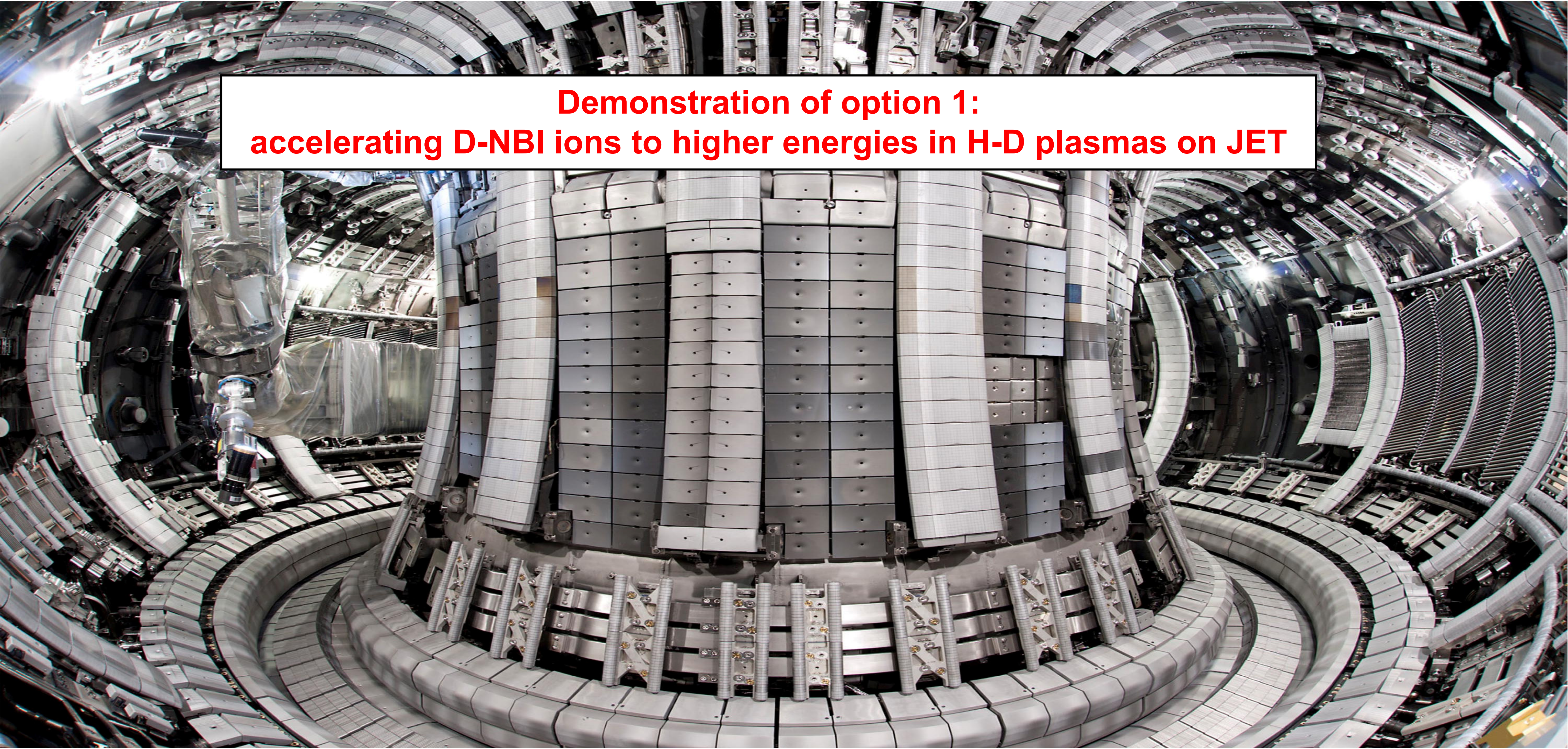
2. Use intrinsic ^{9}Be impurities as ICRH minority: $(Z/A)_T < (Z/A)_{9Be} < (Z/A)_D$

→ strong bulk ion heating *[Y. Kazakov, Phys. Plasmas (2015)]*



Core RF power absorption by ^{9}Be impurities ($X[^9\text{Be}] \sim$ 0.5-1%)

→ also seen in TFTR D-T plasmas with ^{7}Li *[J.R. Wilson, Phys. Plasmas (1997)]*

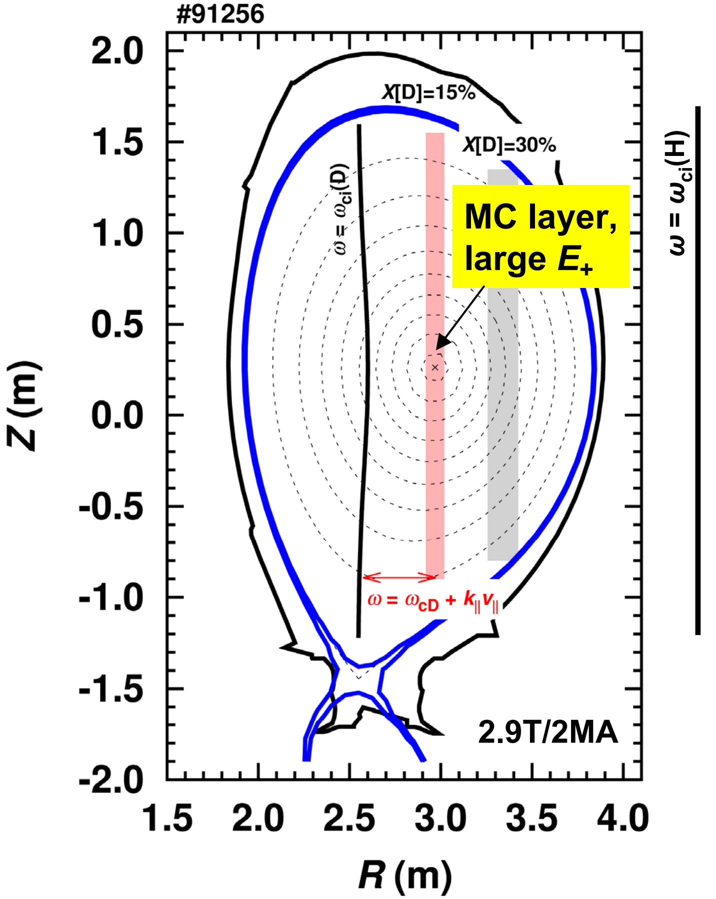


Demonstration of option 1: accelerating D-NBI ions to higher energies in H-D plasmas on JET

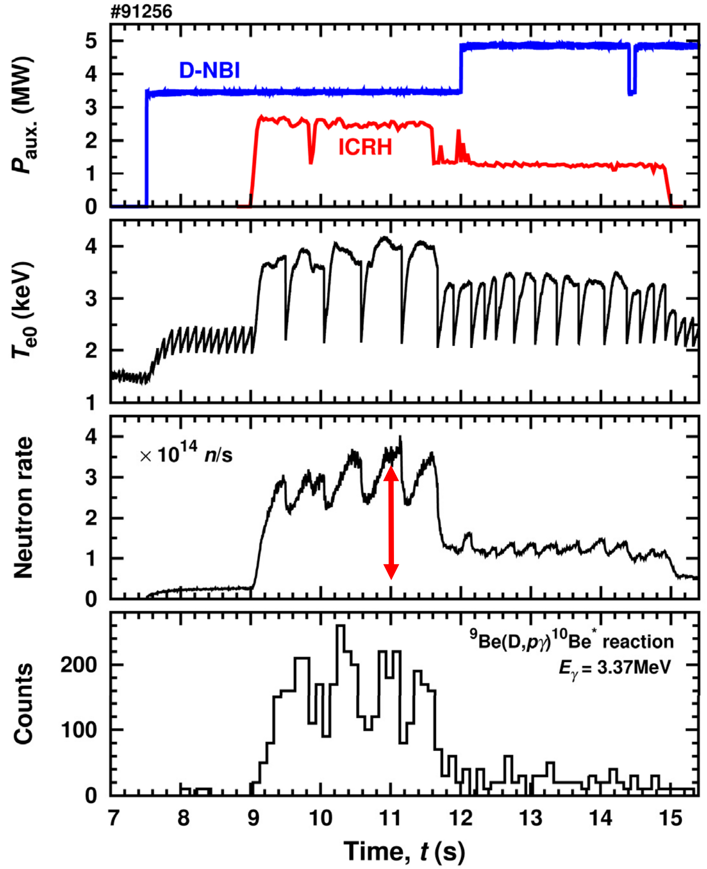
Efficient central plasma heating with D-(D_{NBI})-H three-ion scenario

Acceleration of D-NBI ions (E_{NBI} = 100keV) to MeV-range energies with n = 1 ICRH in H-D mix

[J. Ongena, EPJ Web. Conf. (2017)]



X[H] ≈ 85%, X[D] ≈ 15%



$P_{tot} = P_{NBI} + P_{ICRH} \approx$ 6MW

Increase in $T_e(0)$ and sawtooth stabilization

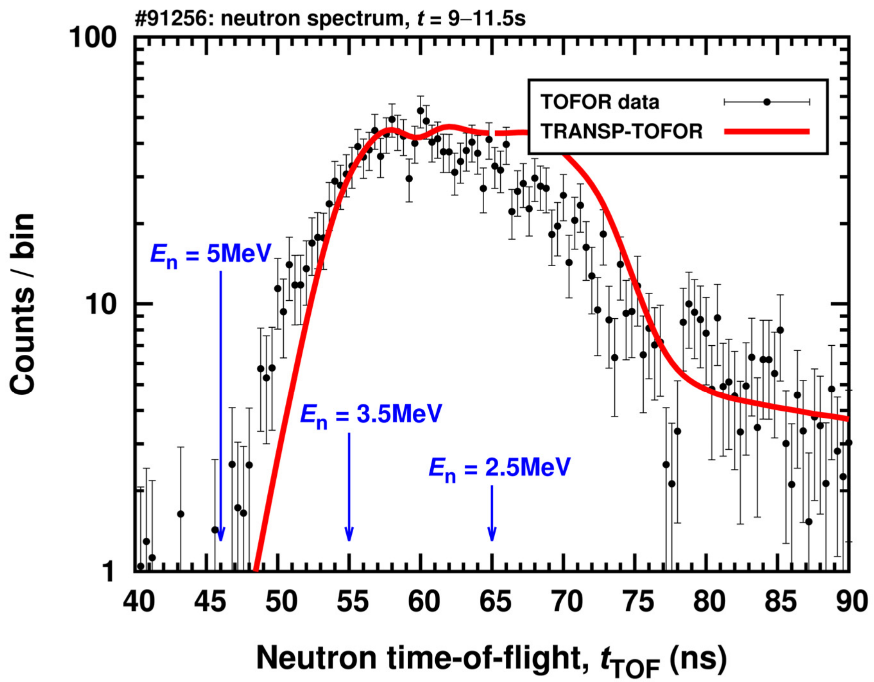
Neutron rate ×15

γ-rays from D + ^{9}Be reactions (E_D > 0.5MeV)

[V. Kiptily, Plasma Phys. Control. Fusion (2006)]

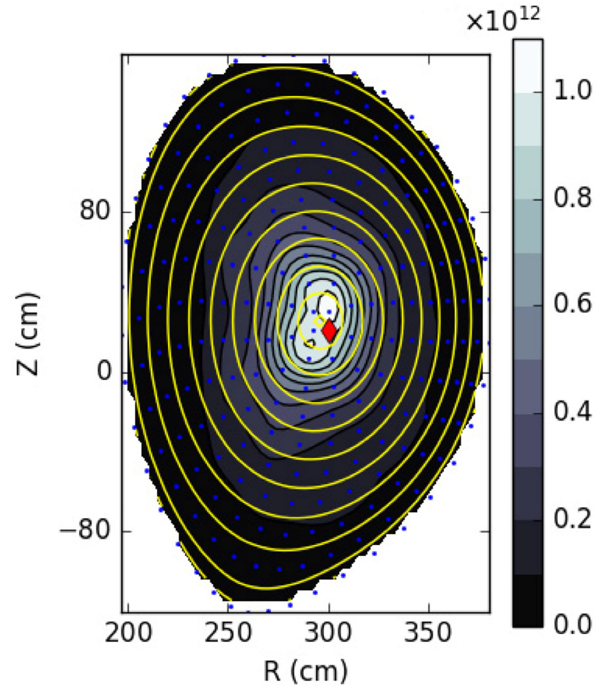
Presence of E_D > 1MeV ions confirmed: TOFOR neutron measurements and TRANSP modeling

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

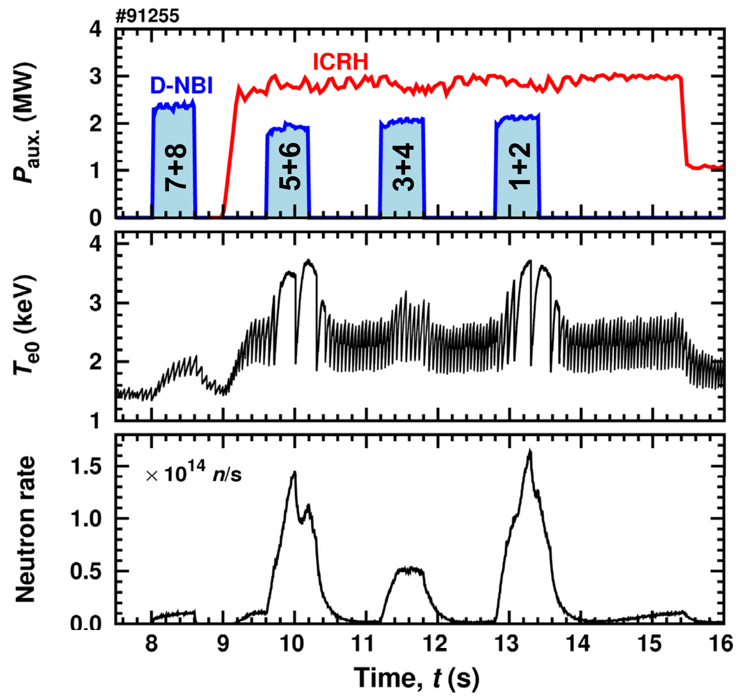


TOFOR diagnostic: C. Hellesen, Nucl. Fus. (2010)
TRANSP analysis: K. Kirov and Y. Baranov (CCFE)

Core-peaked fast-ion density with NBI+ICRH

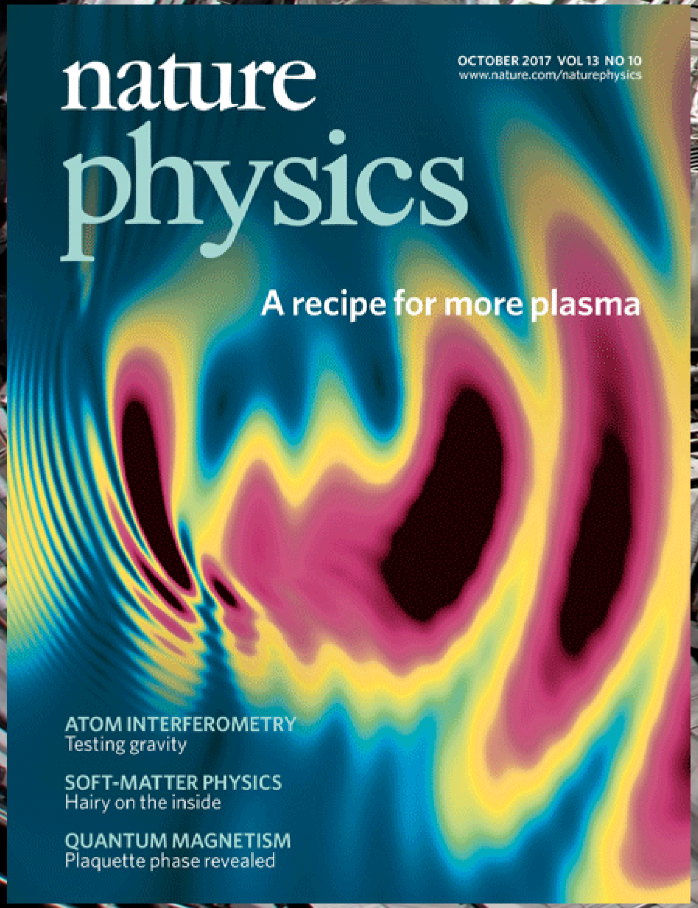


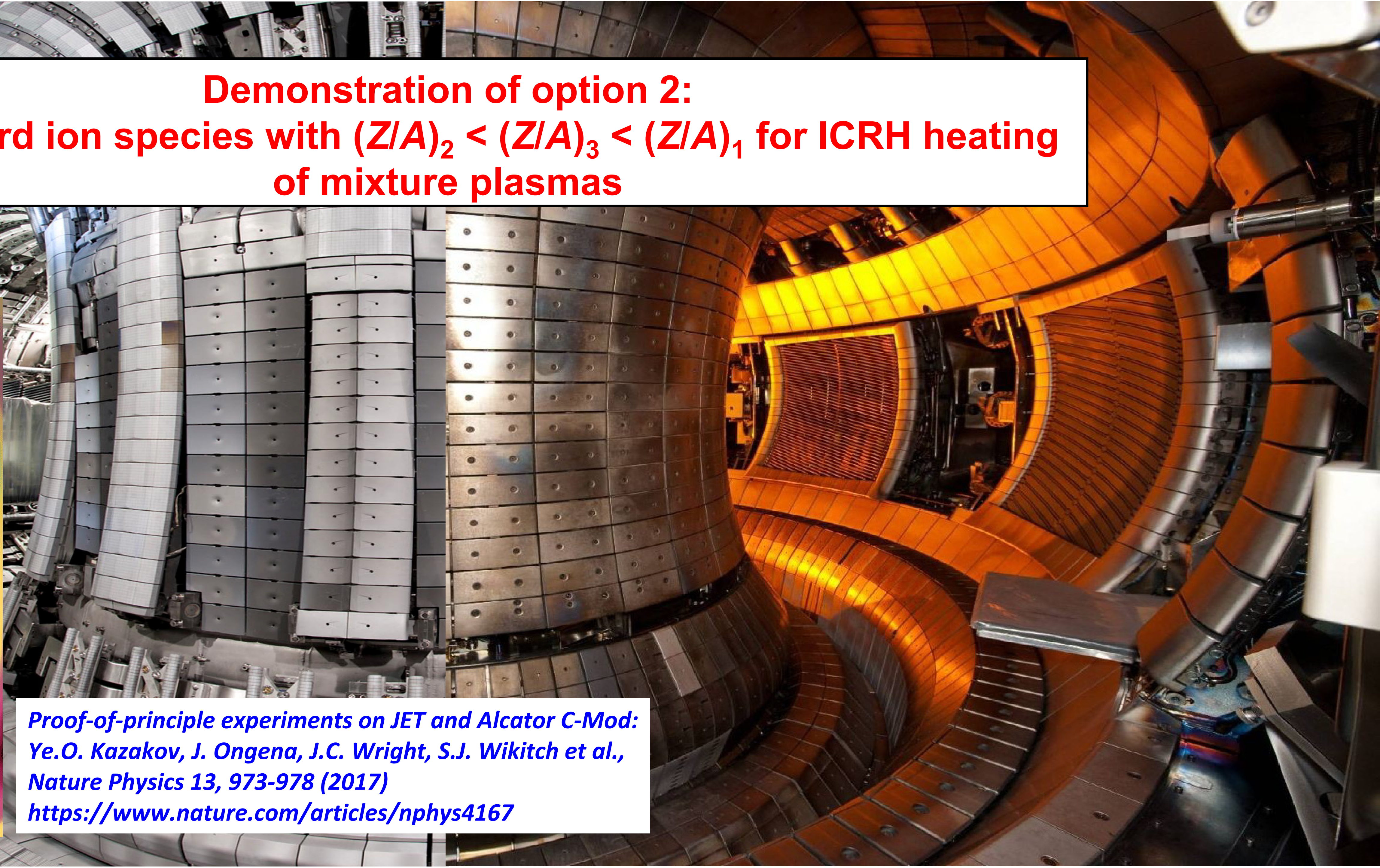
Choice of NBI sources important to optimize ICRH+NBI synergy



- TRANSP: most of energetic ions are passing ions ($v_{||}/v \approx$ 0.3-0.5)
- Actuators to adapt scenario for DT: increasing P_{NBI}, off-axis ICRH deposition and choice of NBI sources

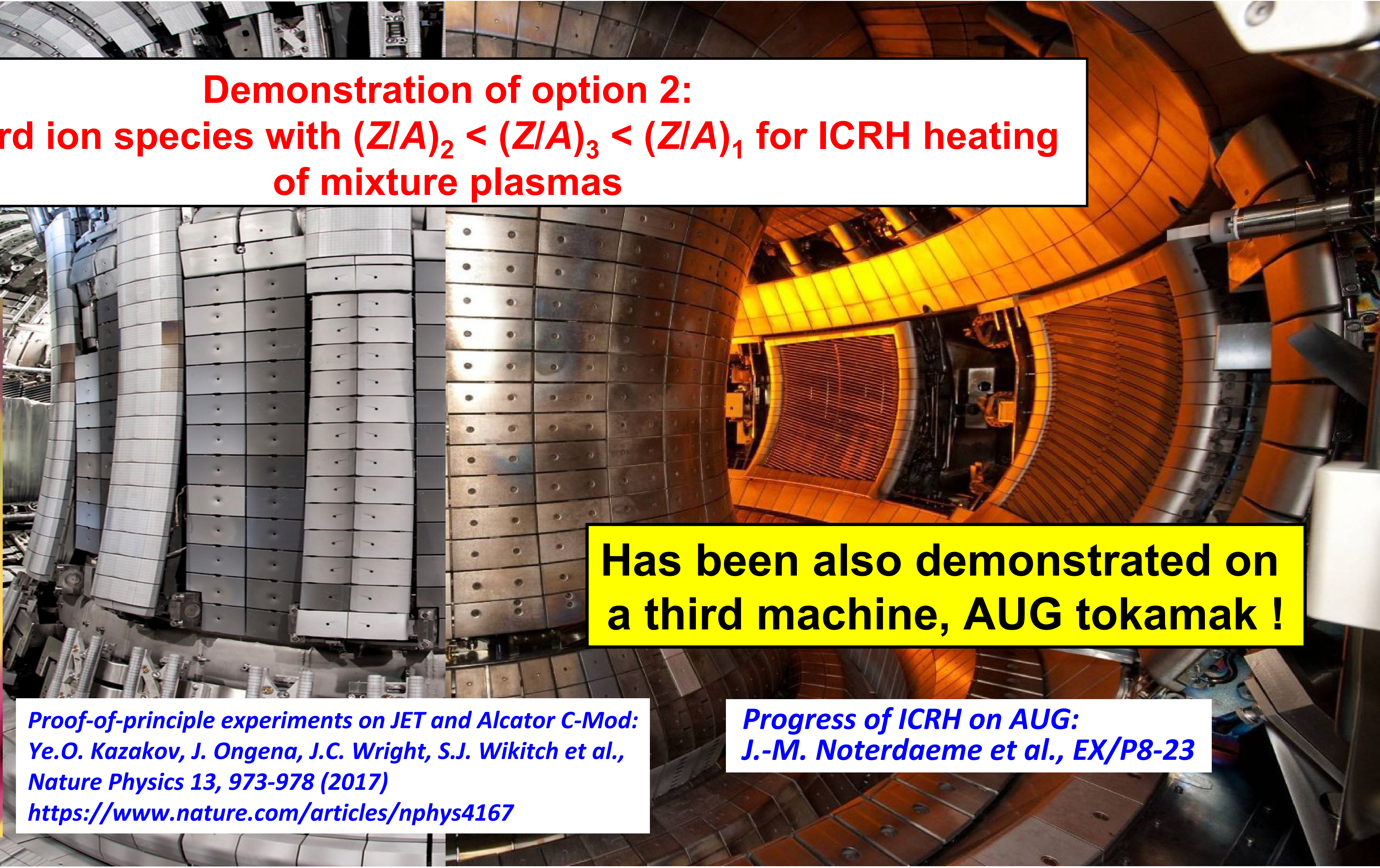
Demonstration of option 2: using third ion species with $(Z/A)_2 < (Z/A)_3 < (Z/A)_1$ for ICRH heating of mixture plasmas

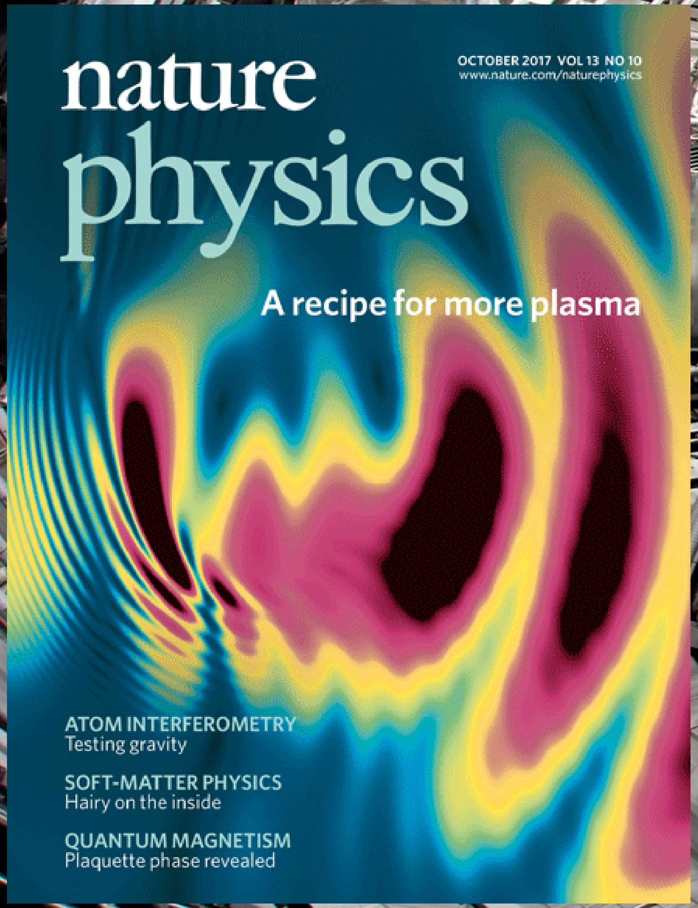




Proof-of-principle experiments on JET and Alcator C-Mod:
Ye.O. Kazakov, J. Ongena, J.C. Wright, S.J. Wikitch et al.,
Nature Physics 13, 973-978 (2017)
https://www.nature.com/articles/nphys4167

Demonstration of option 2:
using third ion species with $(Z/A)_2 < (Z/A)_3 < (Z/A)_1$ for ICRH heating of mixture plasmas





nature physics

OCTOBER 2017 VOL 13 NO 10
www.nature.com/naturephysics

A recipe for more plasma

ATOM INTERFEROMETRY
Testing gravity

SOFT-MATTER PHYSICS
Hairy on the inside

QUANTUM MAGNETISM
Plaquette phase revealed

Has been also demonstrated on a third machine, AUG tokamak !

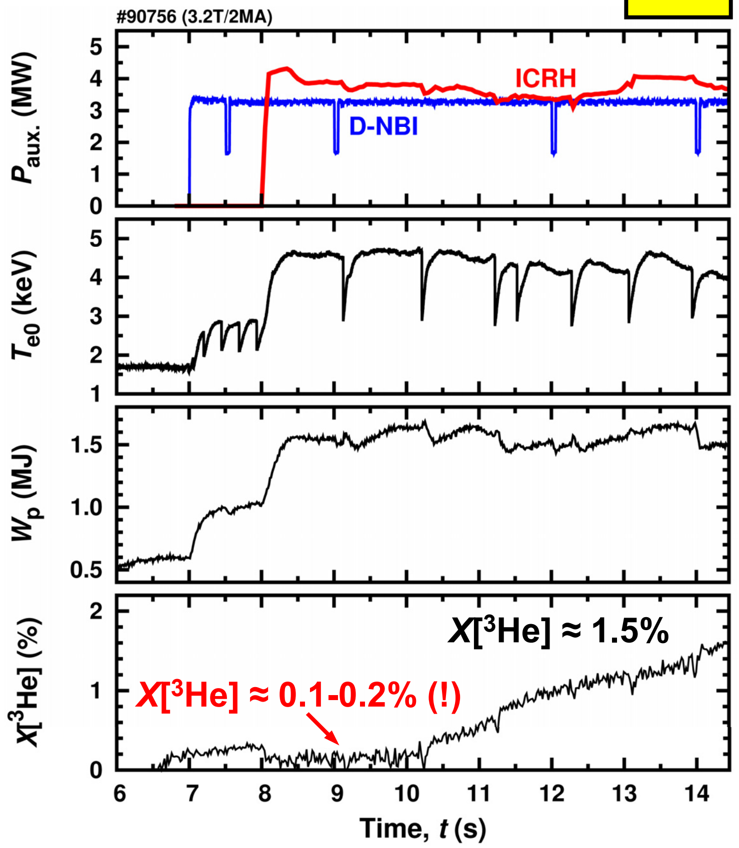
Proof-of-principle experiments on JET and Alcator C-Mod:
Ye.O. Kazakov, J. Ongena, J.C. Wright, S.J. Wikitch et al.,
Nature Physics 13, 973-978 (2017)
https://www.nature.com/articles/nphys4167

Progress of ICRH on AUG:
J.-M. Noterdaeme et al., EX/P8-23

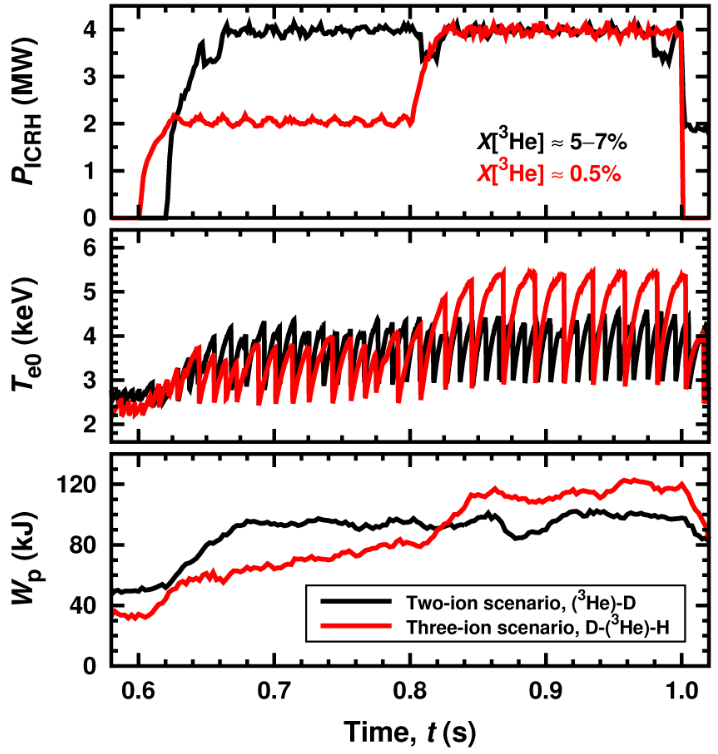
D-(^{3}He)-H ICRH scheme: demonstrated on three tokamaks worldwide

- **Efficient heating of H-D plasmas with ^{3}He demonstrated** on Alcator C-Mod, AUG and JET
- JET: ^{3}He concentrations as low as **~0.1-0.2%** were successfully applied

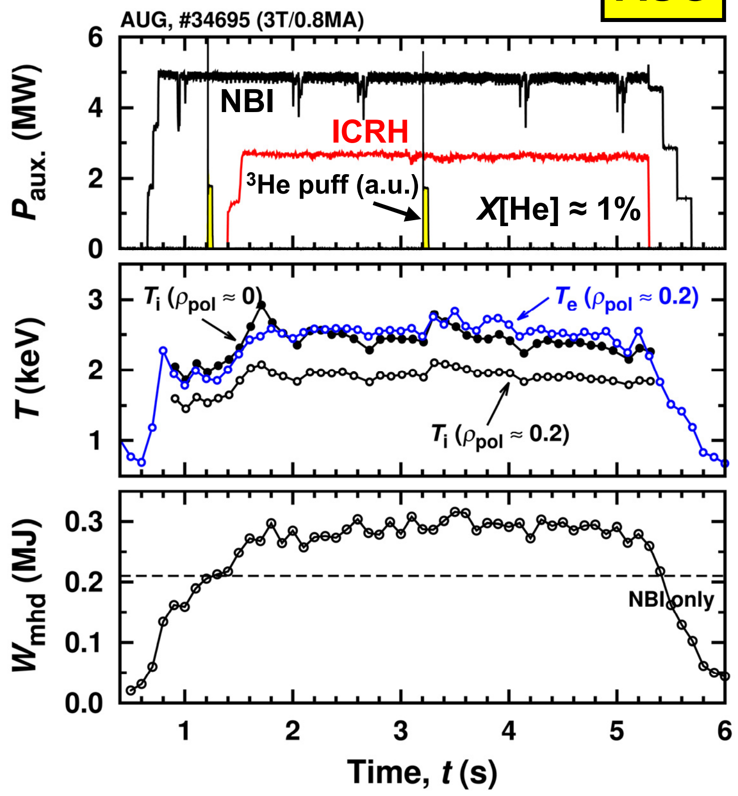
JET



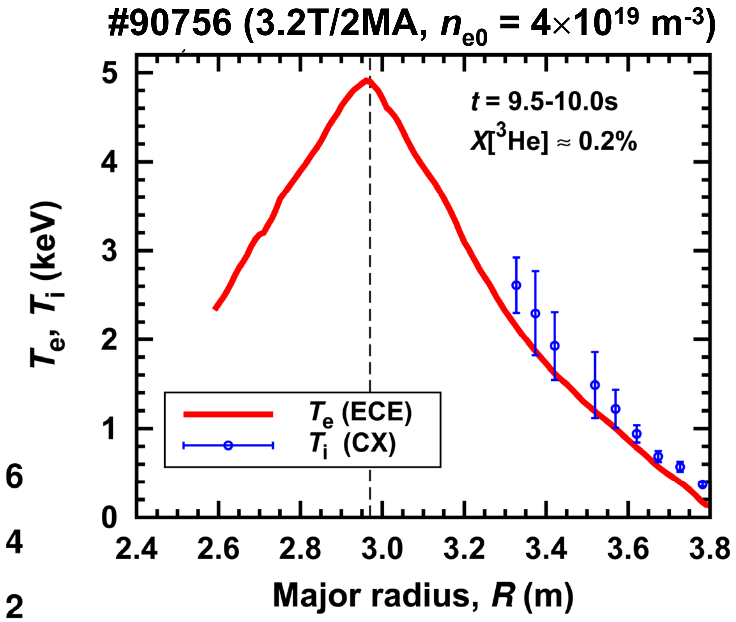
Alcator C-Mod



AUG



D-(^{3}He)-H scheme: efficient technique for heating mixture plasmas



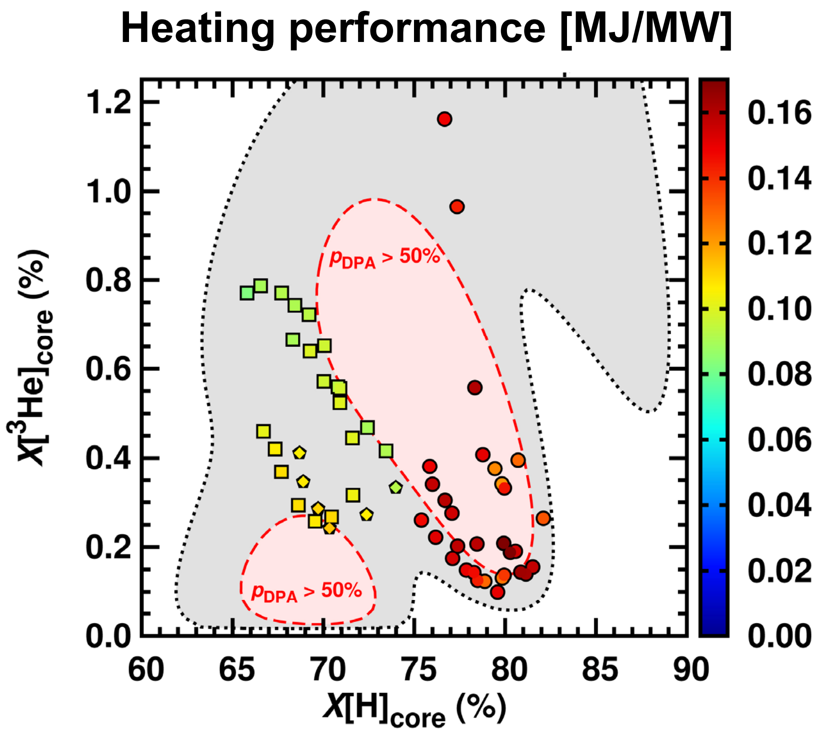
JET observations:

- Efficient plasma heating for 65% ≤ X[H] ≤ 82% and 0.1% ≤ $X[^3He]$ ≤ 1.5%
- Centrally peaked temperature profiles
- Heating performance $\Delta W_p / \Delta P_{ICRH} \approx$ 0.16-0.18MJ/MW
- For similar operational conditions (I_p, B_0, n_{e0}):

  ~10-20% lower than for (H)-D scenario
  ~60-80% higher than for (^{3}He)-H scenario

- Transport effects associated with fast ^{3}He population ?

  ITG stabilization with (^{3}He)-D ICRH on JET and AUG:
  N. Bonanomi, NF (2018); F.N. de Oliveira, EPS-2017 (2017)



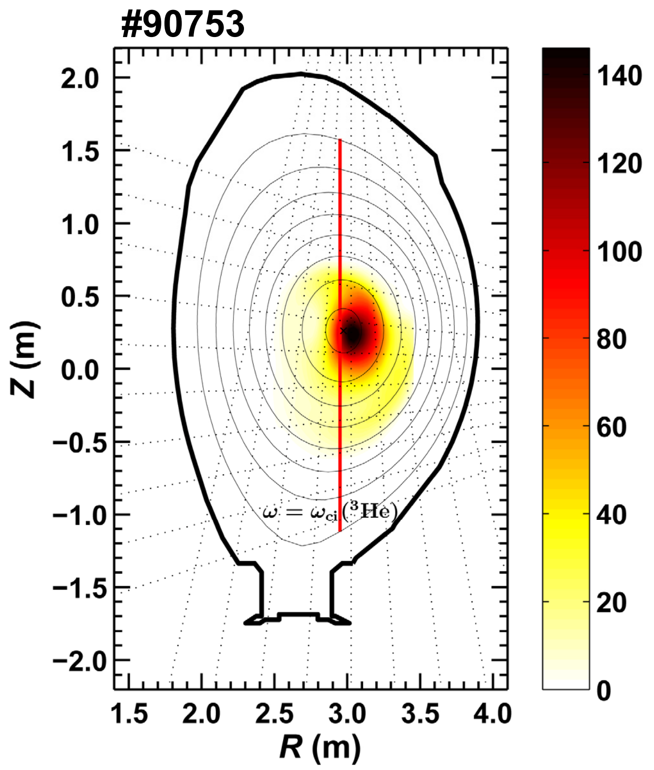
Heating performance:

~0.20MJ/MW for (H)-D scenario: *E. Lerche, AIP Conf. Proc. (2014)*
~0.10MJ/MW for (^{3}He)-H scenario: *D. Van Eester, EPJ Web. Conf. (2017)*

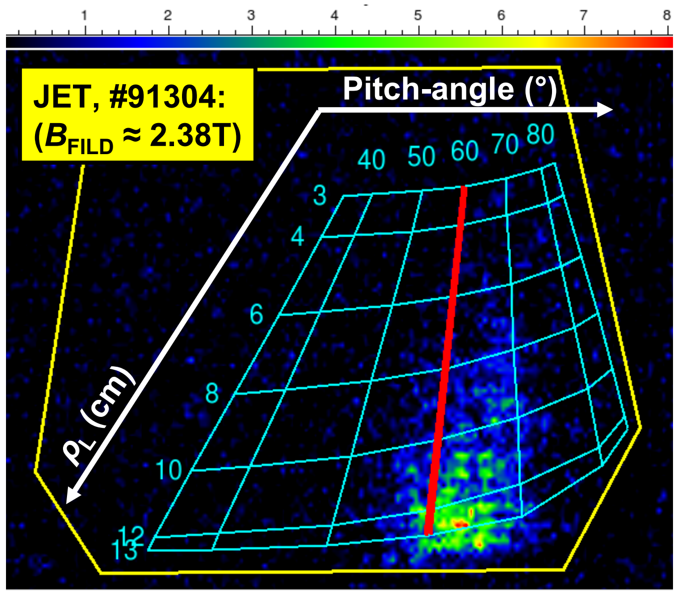
Efficient generation of multi-MeV ^{3}He ions

Confirmed with γ-ray and FILD measurements, excitation of TAE and EAE modes, …

2D γ-ray emission (JET)

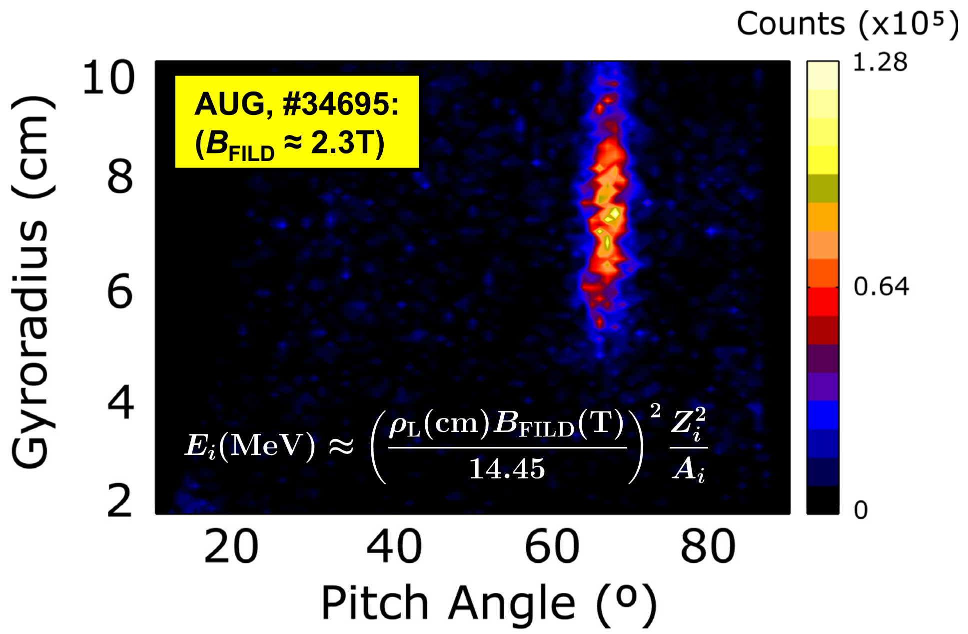


FILD measurements on JET and AUG



Lost fast ions on JET, $\rho_L \approx$ 10-13cm:

$\boxed{E(^3\text{He}) \approx 4\text{-}6\text{MeV}}$



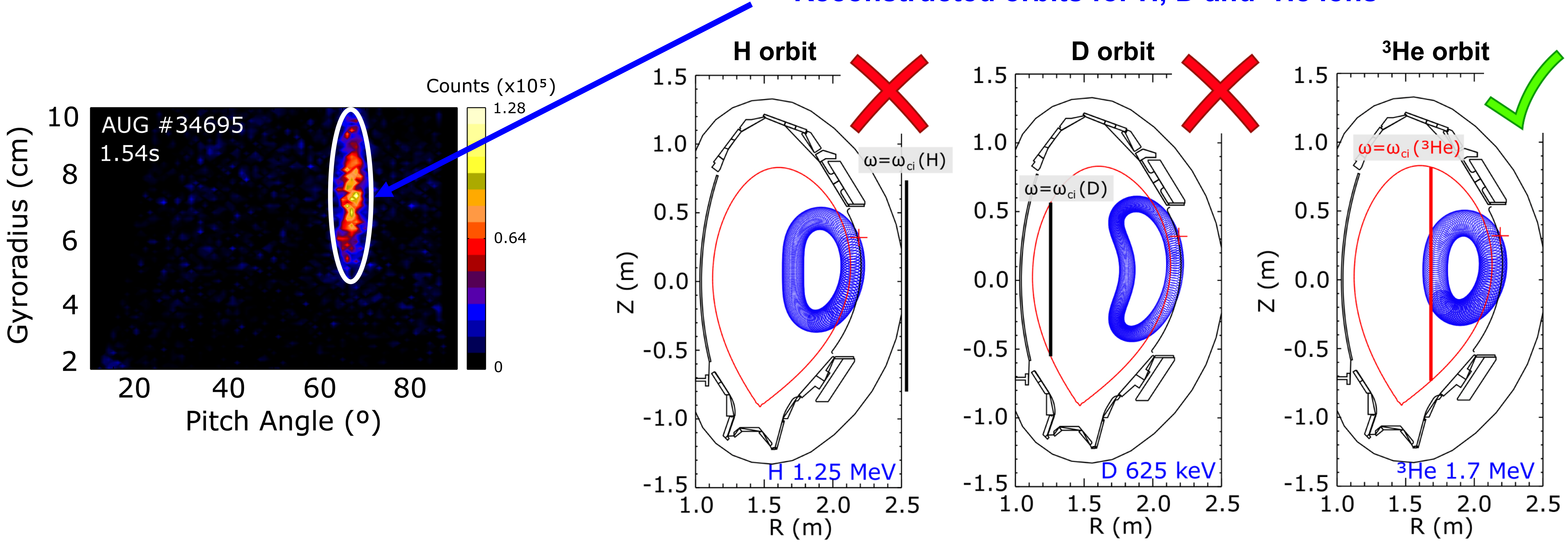
Lost fast ions on AUG, $\rho_L \approx$ 6-9cm:

$\boxed{E(^3\text{He}) \approx 1.2\text{-}2.8\text{MeV}}$

γ-ray spectroscopy: M. Nocente, EPS-2018 (2018)
FILD on JET: V. Kiptily, IAEA-EP Tech. Meeting (2017)
FILD on AUG: J. Galdon-Quiroga, M. Garcia-Munoz et al. (Sevilla Univ.)

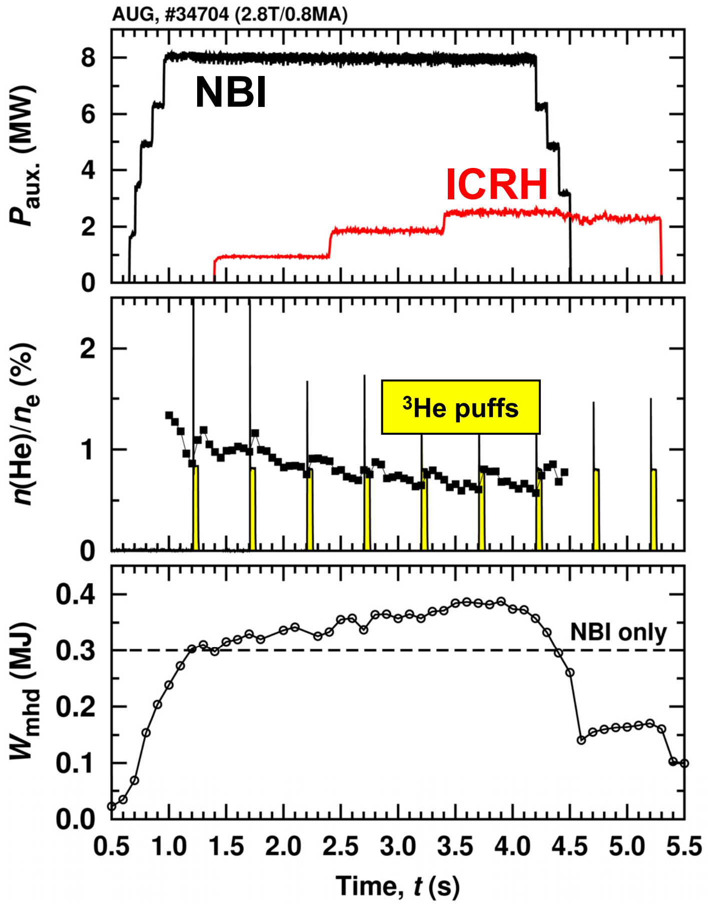
FILD measurements on AUG confirm that ^{3}He is resonant species

Reconstructed orbits for H, D and ^{3}He ions

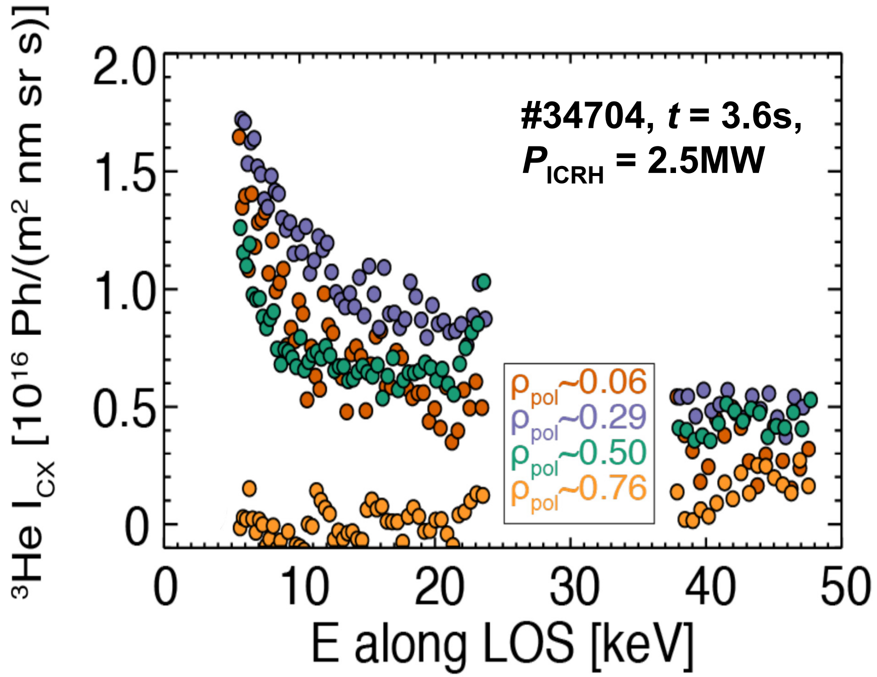


Reducing ^{3}He energies to improve fast-ion confinement in AUG

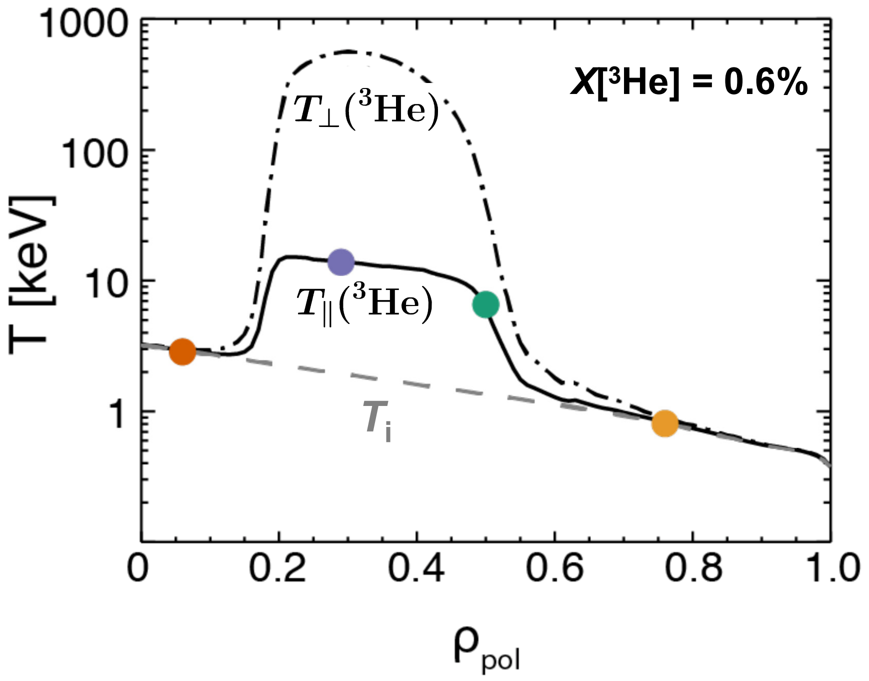
- **#34704: HFS off-axis ^{3}He resonance ($\rho_{pol} \approx 0.3$), efficient plasma heating**
- **CXRS measurements: clear energetic ^{3}He signal identified, correlated with P_{ICRH}**



CX energy spectra



Fast-ion distribution from TORIC-SSFPQL

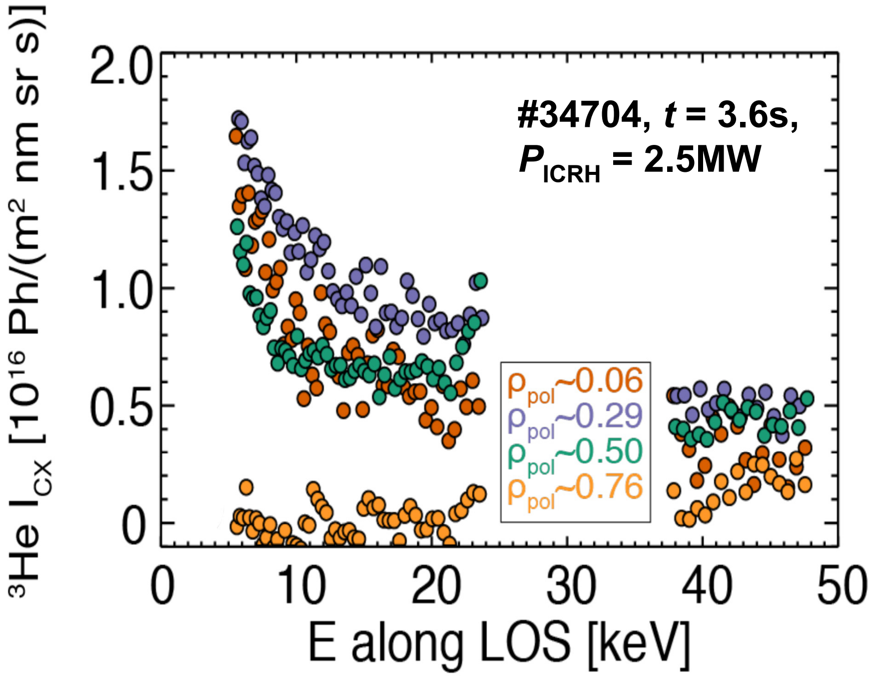


TORIC-SSFPQL: R. Bilato, M. Brambilla et al., Nucl. Fusion (2011)

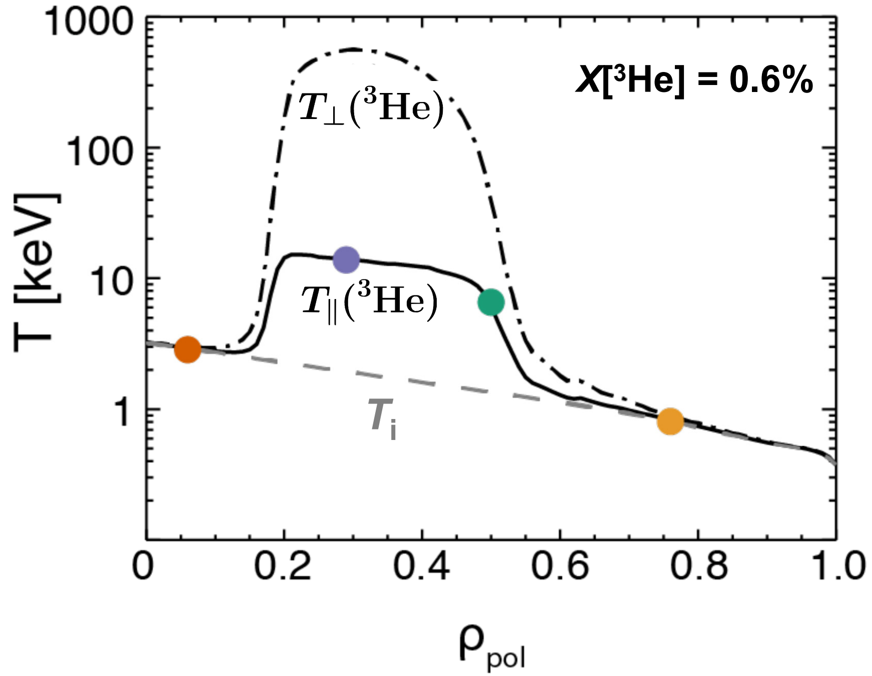
First CXRS measurements of confined energetic He ions in AUG

Measured and modeled CX spectra (using TORIC-SSFPQL) quantitatively agree

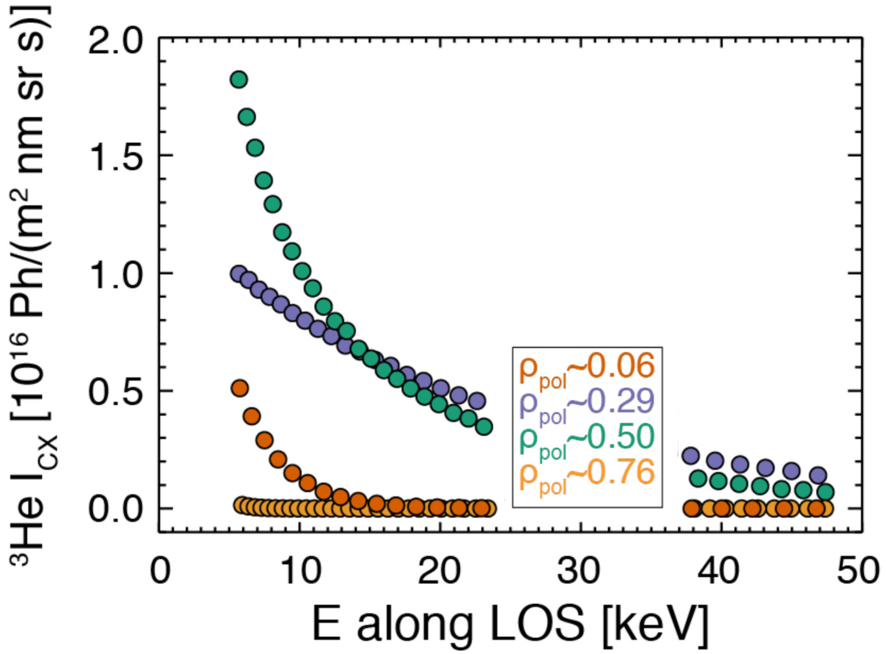
CX energy spectra: measured



Fast-ion distribution from TORIC-SSFPQL



CX energy spectra: predicted



Further details: A. Kappatou et al., EPS-2018, O2.105 (2018)

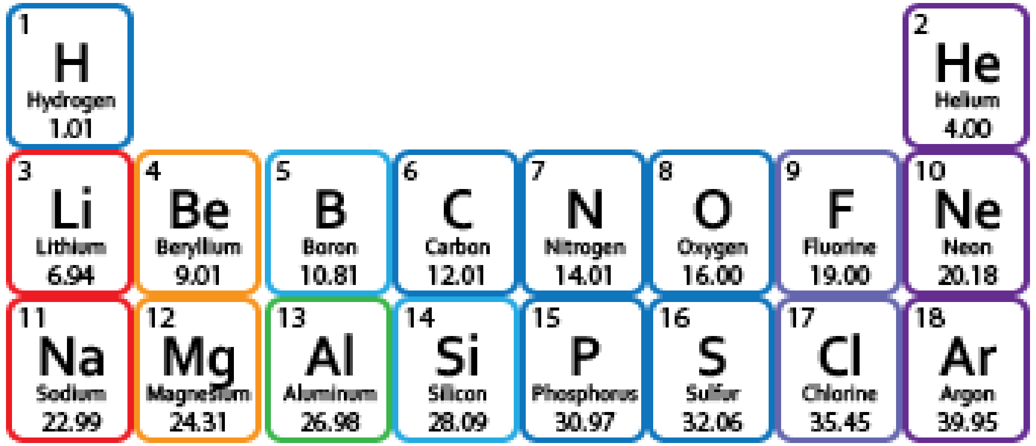
Promising three-ion schemes for ITER

Option 1: using fast NBI ions

→ T-(D_{NBI})-D scheme for D-T plasmas (with D^0 NBI)

→ ^{4}He-(H_{NBI})-H scheme for non-active ^{4}He-H plasmas (with H^0 NBI)

Option 2: using thermal ions with an intermediate $(Z/A)_i$



1 H Hydrogen 1.01							2 He Helium 4.00
3 Li Lithium 6.94	4 Be Beryllium 9.01	5 B Boron 10.81	6 C Carbon 12.01	7 N Nitrogen 14.01	8 O Oxygen 16.00	9 F Fluorine 19.00	10 Ne Neon 20.18
11 Na Sodium 22.99	12 Mg Magnesium 24.31	13 Al Aluminum 26.98	14 Si Silicon 28.09	15 P Phosphorus 30.97	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.95

Ion species	T	Impurities: ^{9}Be, ^{40}Ar, ^{7}Li, ^{22}Ne, …	D, ^{4}He, ^{12}C, ^{16}O, …	^{3}He	H
$(Z/A)_i$	1/3	~0.43-0.45	1/2	2/3	1

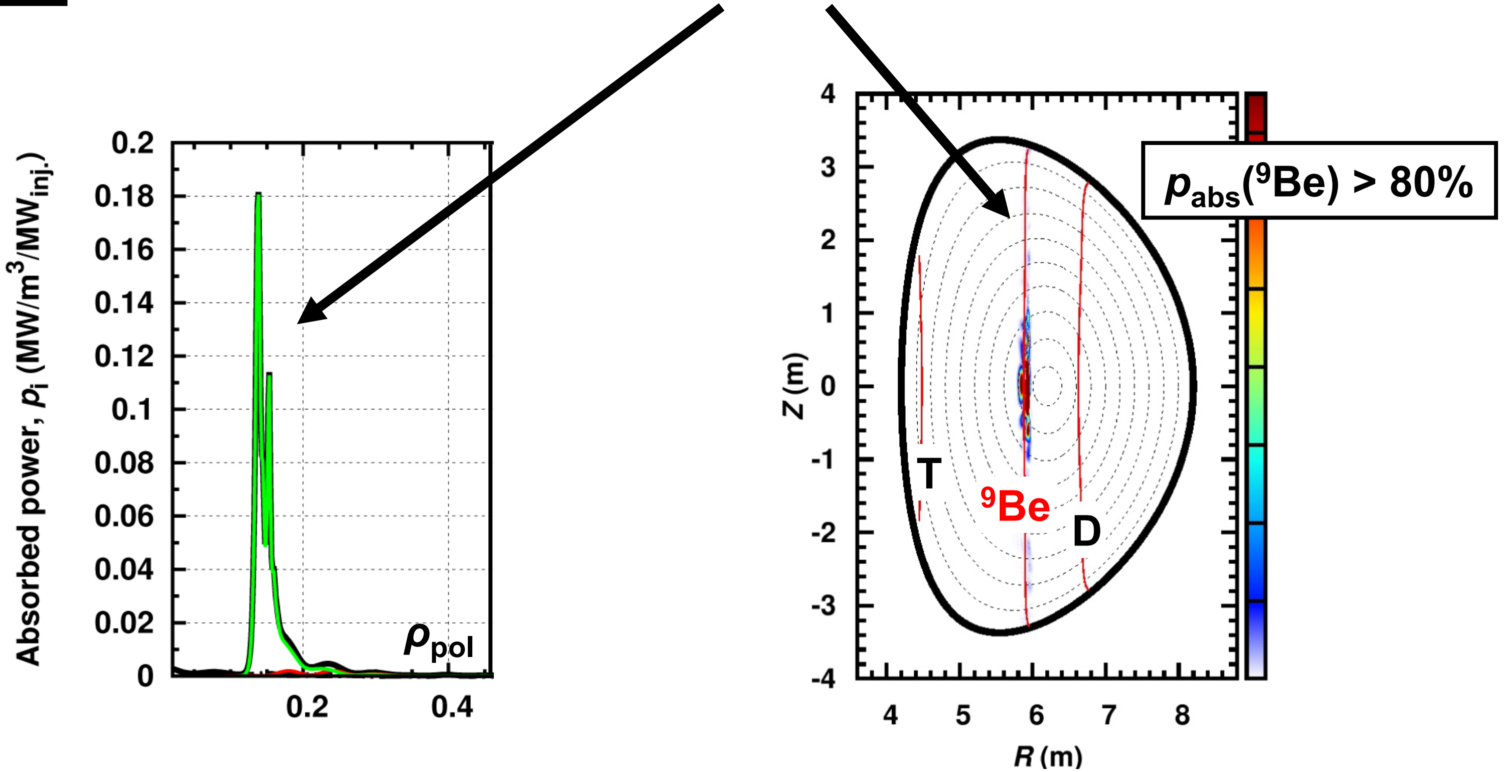
M. Schneider, EPJ Web. Conf. (2017); Y. Kazakov, Phys. Plasmas (2015);
Y. Kazakov, P5.1047, EPS-2018; R. Bilato, P1.1070, EPS-2018

Promising three-ion schemes for ITER

Ion species	T	Impurities: ^{9}Be, ^{40}Ar, ^{7}Li, ^{22}Ne, …	D, ^{4}He, ^{12}C, ^{16}O, …	^{3}He	H
$(Z/A)_i$	1/3	~0.43-0.45	1/2	2/3	1

- **T-(^{9}Be)-D scheme**: using ^{9}Be impurities as an ICRH minority for heating D-T plasmas

Core-localized ^{9}Be absorption
(at f = 38MHz)



M. Schneider, EPJ Web. Conf. (2017); Y. Kazakov, Phys. Plasmas (2015);
Y. Kazakov, P5.1047, EPS-2018; R. Bilato, P1.1070, EPS-2018

Promising three-ion schemes for ITER

Ion species	T	Impurities: ^{9}Be, ^{40}Ar, ^{7}Li, ^{22}Ne, …	D, ^{4}He, ^{12}C, ^{16}O, …	^{3}He	H
$(Z/A)_i$	1/3	~0.43-0.45	1/2	2/3	1

- **Scenarios for non-active plasmas in ITER**

^{4}He-(^{3}He)-H scheme: especially off-axis ^{3}He heating in H-^{4}He plasmas for H-mode studies at $B_0 \approx$ 3-3.3T

→ **reduced L-H threshold (by ~30%) in hydrogen plasmas with 10-15% of ^{4}He observed on JET** ***(J. Hillesheim, EX/4-1)***

→ **possibility already accounted for in** ***ITER Research Plan within the Staged Approach (2018)***

→ **encouraging first results with off-axis ^{3}He ICRH in H-D plasmas on AUG; more studies foreseen**

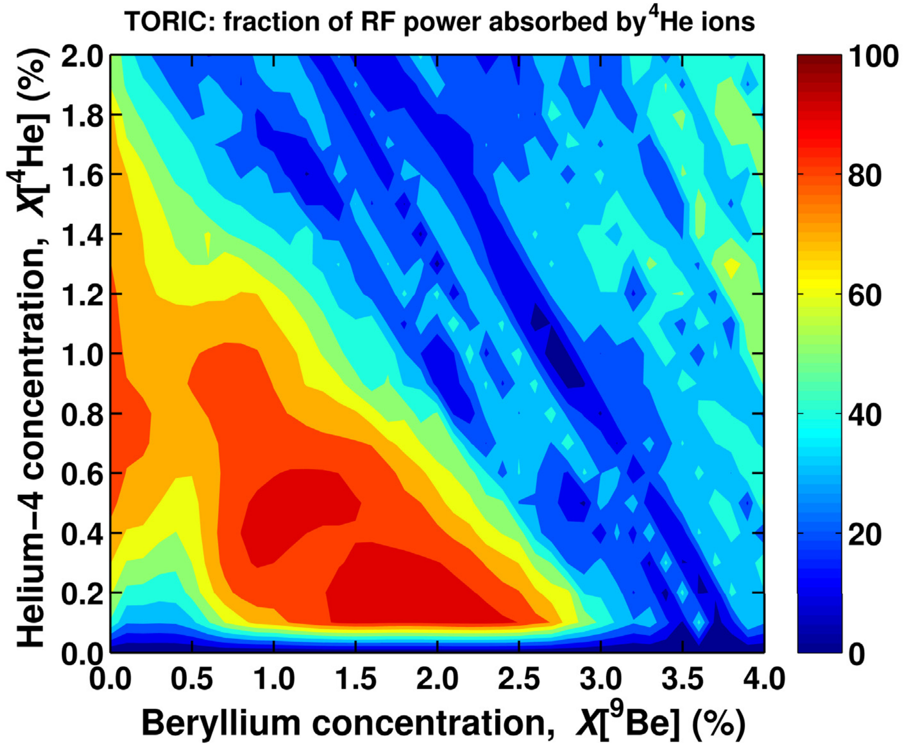
M. Schneider, EPJ Web. Conf. (2017); Y. Kazakov, Phys. Plasmas (2015);
Y. Kazakov, P5.1047, EPS-2018; R. Bilato, P1.1070, EPS-2018

Promising three-ion schemes for ITER

Ion species	T	Impurities: ^{9}Be, ^{40}Ar, ^{7}Li, ^{22}Ne, …	D, ^{4}He ^{12}C, ^{16}O, …	^{3}He	H
$(Z/A)_i$	1/3	~0.43-0.45	1/2	2/3	1

- **Scenarios for non-active plasmas in ITER**

  ^{9}Be/Ar-(^{4}He)-H scheme: ***using impurities (^{9}Be and Ar) to heat ^{4}He ions!***



M. Schneider, EPJ Web. Conf. (2017); Y. Kazakov, Phys. Plasmas (2015);
Y. Kazakov, P5.1047, EPS-2018; R. Bilato, P1.1070, EPS-2018

Summary: three-ion schemes for ITER

Option 1: using fast NBI ions

→ T-(D_{NBI})-D scheme for D-T plasmas (with D^0 NBI)

→ ^{4}He-(H_{NBI})-H scheme for non-active ^{4}He-H plasmas (with H^0 NBI)

Option 2: using thermal ions with an intermediate $(Z/A)_i$

→ T-(^{9}Be)-D scheme for D-T plasmas

→ ^{4}He-(^{3}He)-H scheme for non-active H-^{4}He plasmas

→ ^{9}Be/Ar-(^{4}He)-H scheme for non-active H plasmas with a small amount of ^{9}Be and/or Ar impurities

M. Schneider, EPJ Web. Conf. (2017); Y. Kazakov, Phys. Plasmas (2015);
Y. Kazakov, P5.1047, EPS-2018; R. Bilato, P1.1070, EPS-2018

Contributors

J. Ongena[1], R. Bilato[2], V. Bobkov[2], J.M. Faustin[3], A. Kappatou[2], V.G. Kiptily[4], E. Lerche[1,4], M. Mantsinen[5,6], M. Nocente[7,8], M. Schneider[9], D. Van Eester[1], M. Weiland[2], H. Weisen[10], Y. Baranov[4], J. Galdon-Quiroga[11], M. Garcia-Munoz[11], J. Gonzalez-Martin[11], K. Kirov[4], J. Bielecki[12], S.A. Bozhenkov[3], A. Cardinali[13], C. Castaldo[13], T. Craciunescu[14], K. Crombé[1,15], A. Czarnecka[16], R. Dumont[17], P. Dumortier[1], F. Durodié[1], J. Eriksson[18], R. Felton[4], M. Fitzgerald[4], D. Gallart[5], L. Giacomelli[8], C. Giroud[4], M. Goniche[17], J. Graves[10], C. Hellesen[18], P. Jacquet[4], T. Johnson[19], N. Krawczyk[16], M. Lennholm[20,21], T. Loarer[17], S. Menmuir[4], I. Monakhov[4], F. Nabais[22], M.F.F.Nave[22], J.-M. Noterdaeme[2,15], R. Ochoukov[2], H. Patten[10], M. Porkolab[23], P. Schneider[2], S.E. Sharapov[4], D. Valcarcel[4], M. Van Schoor[1], J.C. Wright[23], S.J. Wukitch[23], JET Contributors*, the ASDEX Upgrade Team†, the EUROfusion MST1 Team

* See the author list of X. Litaudon et al., *Nucl. Fusion* 57, 102001 (2017); † See the author list of H. Meyer et al., *Nucl. Fusion* 57, 102014 (2017)

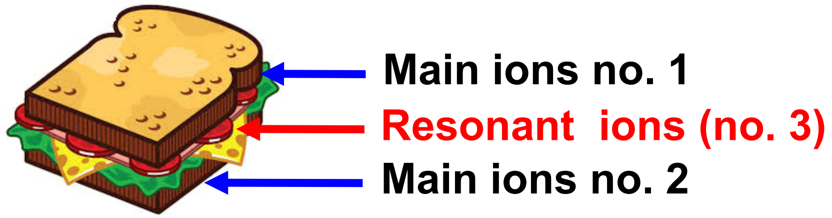
[1] LPP-ERM/KMS, Brussels, TEC Partner, Belgium
[2] Max-Planck-Institut für Plasmaphysik, Garching, Germany
[3] Max-Planck-Institut für Plasmaphysik, Greifswald, Germany
[4] CCFE, Culham Science Centre, Abingdon, UK
[5] Barcelona Supercomputing Center (BSC), Barcelona, Spain
[6] ICREA, Barcelona, Spain
[7] Dipartimento di Fisica, Università di Milano-Bicocca, Milan, Italy
[8] Istituto di Fisica del Plasma, CNR, Milan, Italy
[9] ITER Organization, Route de Vinon-sur-Verdon, France
[10] EPFL, Swiss Plasma Center (SPC), Lausanne, Switzerland
[11] University of Seville, Seville, Spain
[12] Institute of Nuclear Physics, PAS, Krakow, Poland
[13] ENEA Centro Ricerche, Frascati Italy
[14] NILPRP Bucharest, Romania
[15] Dep. Applied Physics, Ghent University, Gent, Belgium
[16] IPPLM, Warsaw, Poland
[17] CEA, IRFM, Saint-Paul-Lez-Durance, France
[18] Dep. Physics and Astronomy, Uppsala University, Sweden
[19] KTH Royal Institute of Technology, Stockholm, Sweden
[20] European Commission, Brussels, Belgium
[21] JET Exploitation Unit, Culham Science Centre, UK
[22] Instituto de Plasmas e Fusão Nuclear, IST, Portugal
[23] MIT-PSFC, Cambridge, USA

Landau-Spitzer Award 2018, EU-US collaboration:

"For experimental verification, through collaborative experiments, of a novel and highly efficient ion cyclotron resonance heating scenario for plasma heating and generation of energetic ions in magnetic fusion devices."

Further details: J. Ongena et al., APS-2018 (09 Nov. 2018; 09:30am)

Summary and conclusions



- **Three-ion ICRH schemes:** a new set of minority scenarios ($n = 1$) for efficient heating of mixture plasmas, $\omega = \omega_{ci} + k_{||}v_{||}$
  → *possibility to tailor achieved fast-ion energies*
- Option 1: use fast NBI ions with large $v_{||}$ to resonate at the IIH layer
  → *moderate acceleration of T-NBI or D-NBI ions with ICRH to maximize the Q-value and P_{fus} in D-T plasmas*
  → *large number of energetic passing ions*
- Option 2: use thermal ions with an intermediate charge-to-mass ratio as resonant species, $(Z/A)_2 < (Z/A)_3 < (Z/A)_1$
  → *heating intrinsic ^{9}Be impurities in D-T plasmas*
  → *ICRH schemes for non-active plasmas in ITER*
- Efficient technique for generating energetic ions needed for fast-ion studies
  → *Application for W7-X: J. Faustin, PPCF 59, 084001 (2017)*

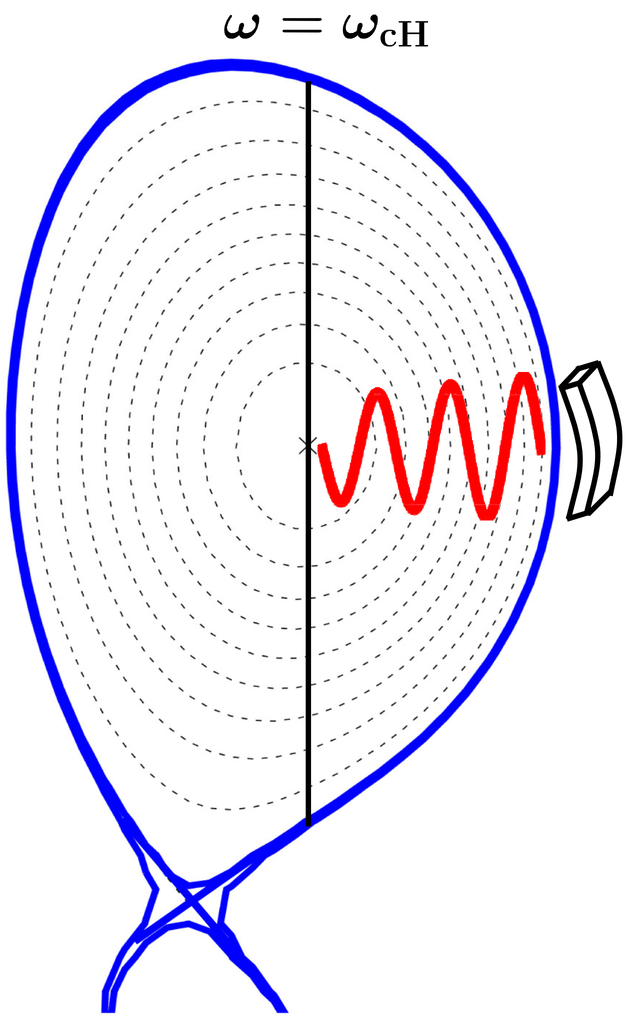
Three-ion schemes extend the flexibility of using ICRH in fusion research

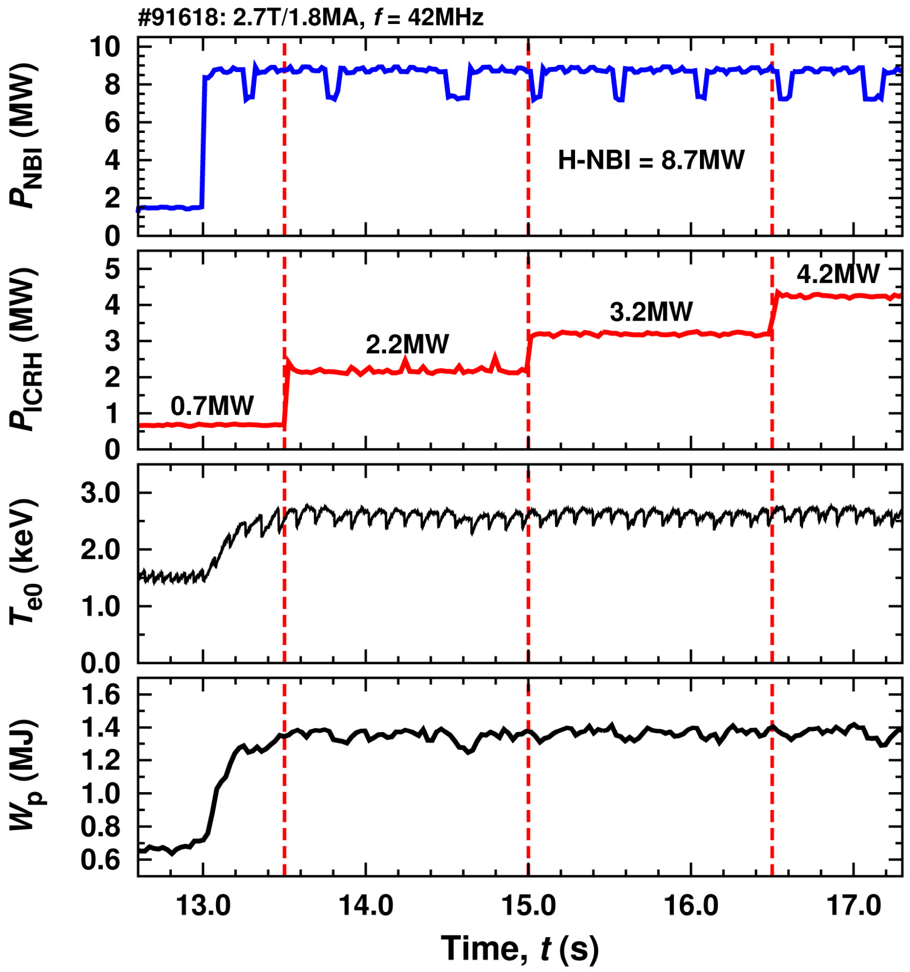
Selection of main three-ion ICRH scenarios

	Resonant ions	Main plasma ions	Scenario	Short scenario description
Option 1: using fast NBI ions	H^0 NBI	^{4}He-H D-H T-H	^{4}He-(H$_{\mathrm{NBI}}$)-H D-(H$_{\mathrm{NBI}}$)-H T-(H$_{\mathrm{NBI}}$)-H	Heating and fast-ion studies in non-active plasmas Heating and fast-ion studies in D-H plasmas Heating and fast-ion studies in T-H plasmas
	D^0 NBI	H-D D-^{3}He T-D	D-(D$_{\mathrm{NBI}}$)-H D-(D$_{\mathrm{NBI}}$)-^{3}He T-(D$_{\mathrm{NBI}}$)-D	*Heating and fast-ion studies: demonstrated on JET* Source of isotropic fusion alphas in D-^{3}He plasmas Maximize Q and P_{fus} in JET
	T^0 NBI	D-T T-^{4}He H-T	T-(T$_{\mathrm{NBI}}$)-D T-(T$_{\mathrm{NBI}}$)-^{4}He T-(T$_{\mathrm{NBI}}$)-H	Maximize Q and P_{fus} in JET Mimick T-NBI acceleration in non-active JET plasmas Heating and fast-ion studies in H-T plasmas
Option 2: using thermal ions with an intermediate $(Z/A)_{\mathrm{I}}$	^{3}He	H-D H-^{4}He H-T	D-(^{3}He)-H ^{4}He-(^{3}He)-H T-(^{3}He)-H	*Heating and fast-ion studies: JET, Alcator C-Mod, AUG* Heating and fast-ion studies in non-active plasmas Heating and fast-ion studies in H-T plasmas
	^{9}Be	D-T	T-(^{9}Be)-D	Bulk ion heating in D-T plasmas on JET and ITER
	^{4}He	H-^{9}Be/Ar H-T	^{9}Be/Ar-(^{4}He)-H T-(^{4}He)-H	Non-active scenario for ITER and JET Fast ^{4}He studies in H-T plasmas

Backup slides

Doppler-shifted H-NBI absorption in H plasmas on JET-ILW





JET-ILW #91618, $P_{\text{H-NBI}}$ = 9MW:

ICRH power: 0.7MW → 2.2MW → 3.2MW → 4.2MW

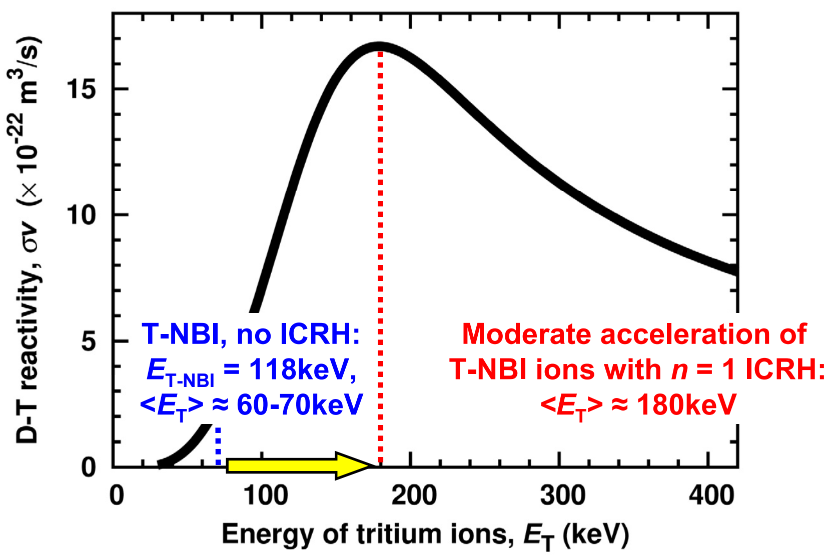
Plasma response: $\Delta T_e \approx 0$, $\Delta W_p \approx 0$

Doppler-shifted D-NBI absorption in D plasmas on JET-C: neutron rate ×1.5

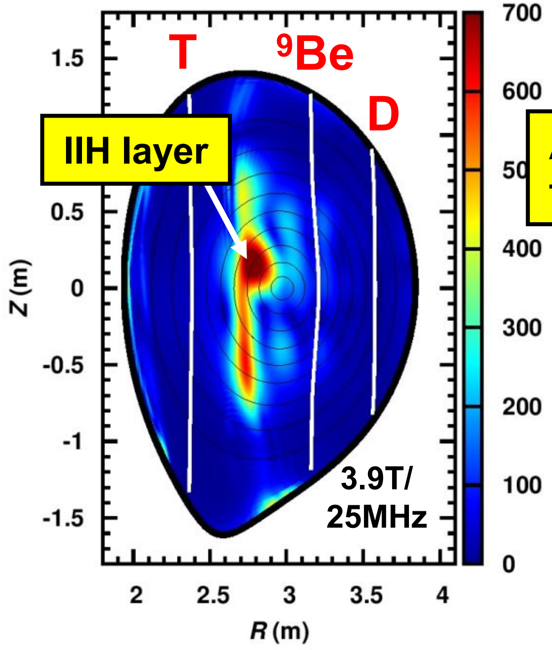
A. Krasilnikov, Plasma Phys. Control. Fusion (2009)

In single-ion plasmas, the left-hand polarized RF electric field component, E_+ nearly vanishes at $\omega \approx \omega_{ci}$

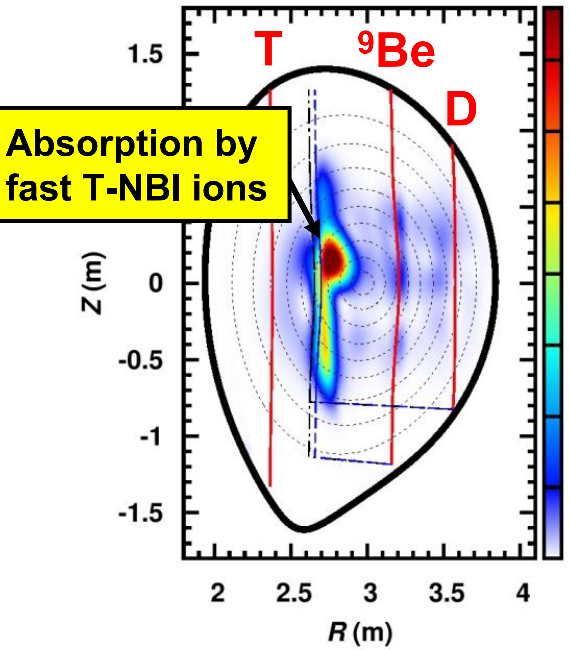
T-(T_{NBI})-D three-ion scenario for DTE2 studies: accelerating T-NBI ions with n = 1 ICRH for maximizing the Q-value and P_{fus}



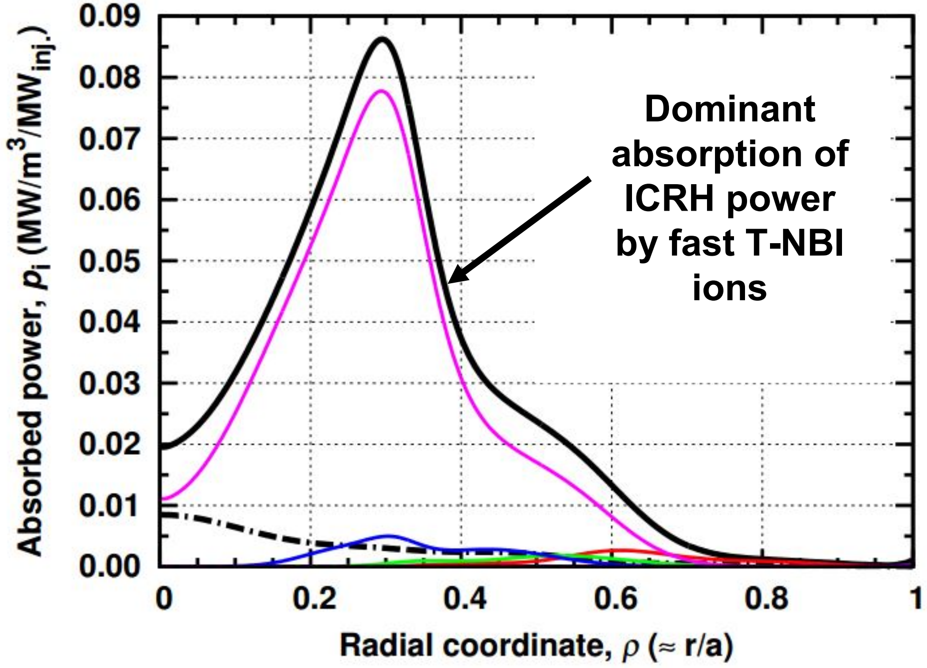
RF electric field $|E_+|$



RF power absorption (2D)

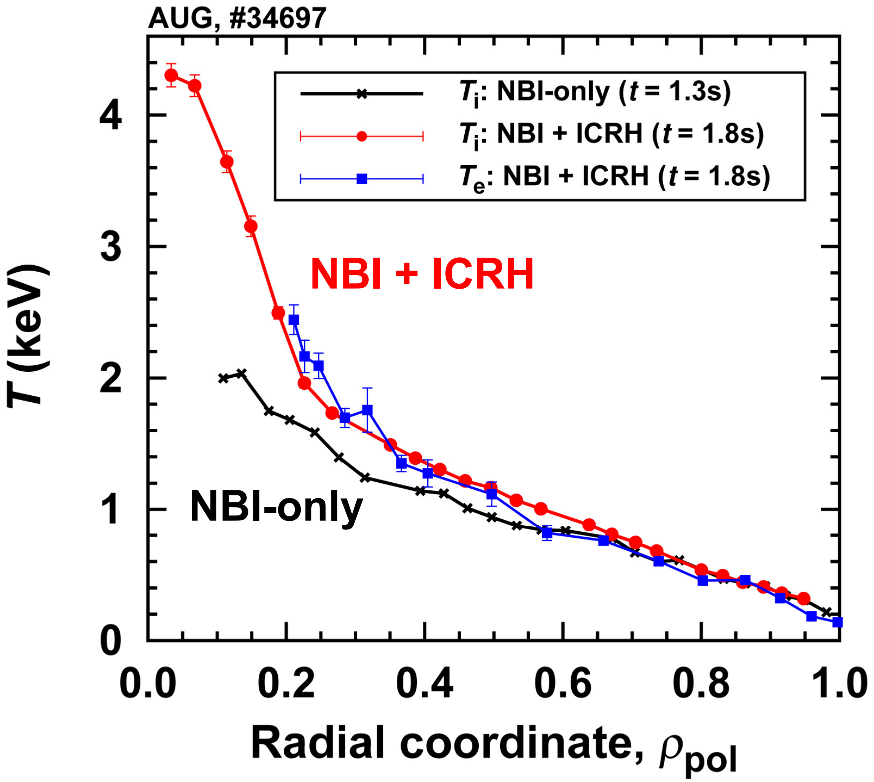


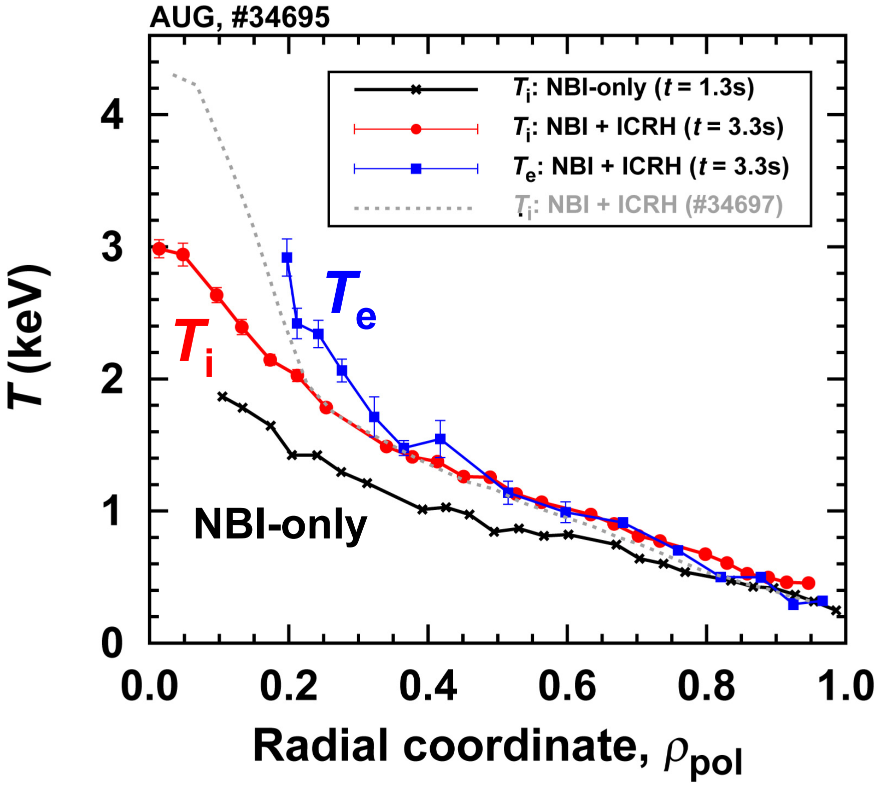
RF power absorption (1D)

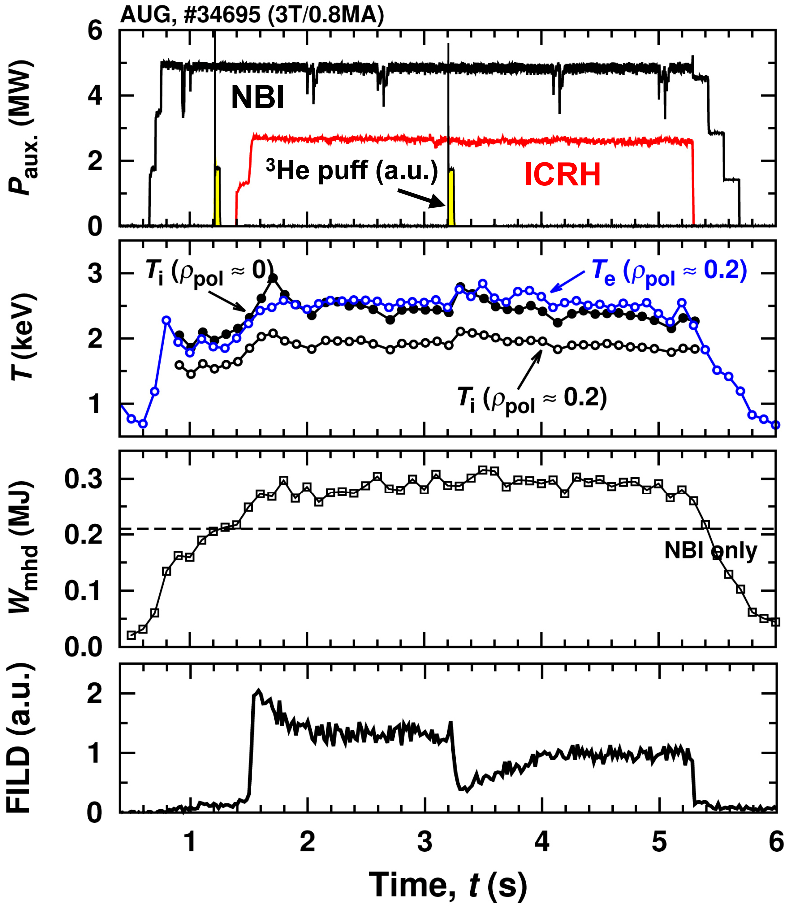


- TORIC modeling: D-T plasma with X[D] = 75%, X[^{9}Be] = 1% and fast T-NBI ions
- Most of ICRH power absorbed by T-NBI ions in the vicinity of the IIH layer

AUG discharges: extra information





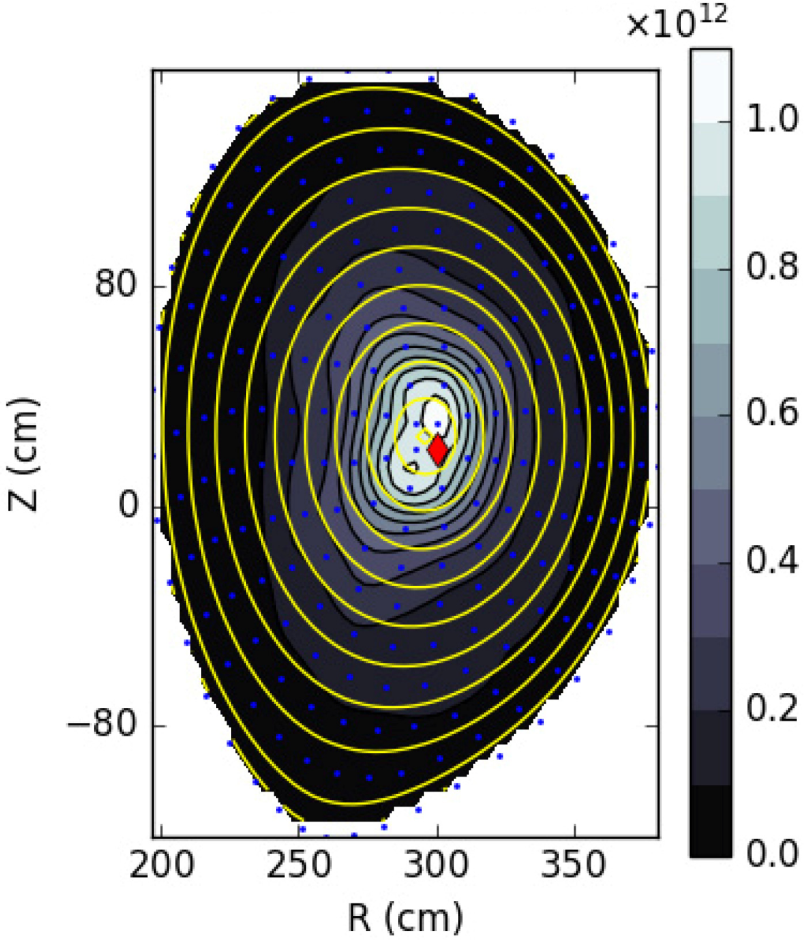


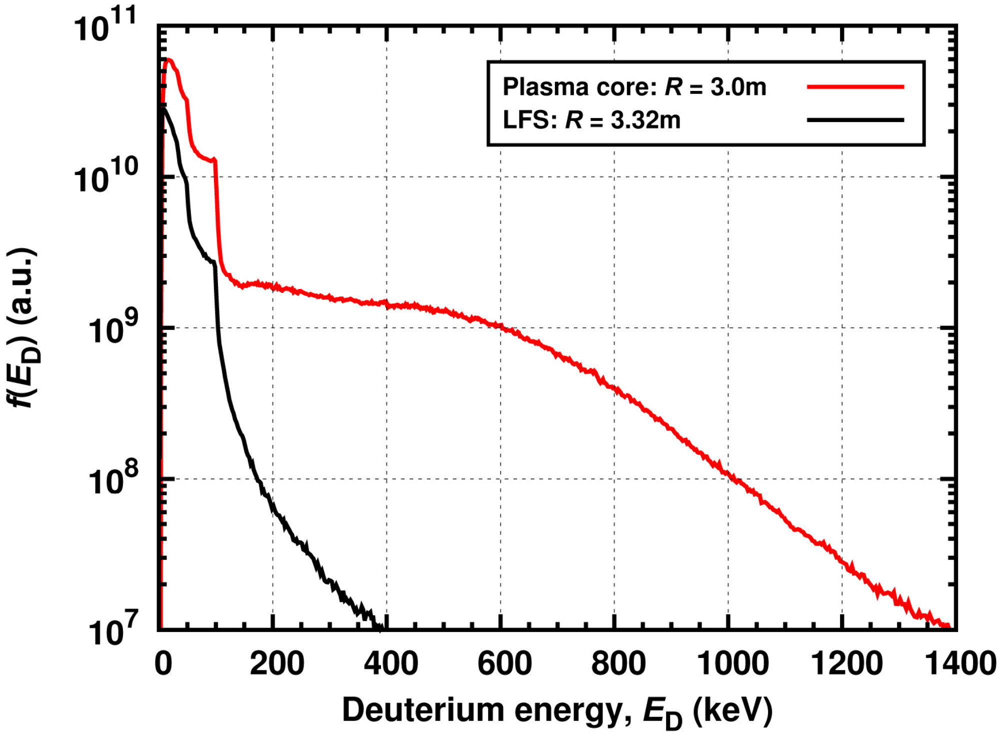
Strongly peaked T_i, T_e and v_{rot} profiles at X[He] ≈ 1.5-2%, similar to observations with (³He)-D scenario,
M.J. Mantsinen, AIP Conf. Proc. 1689, 030005 (2015)

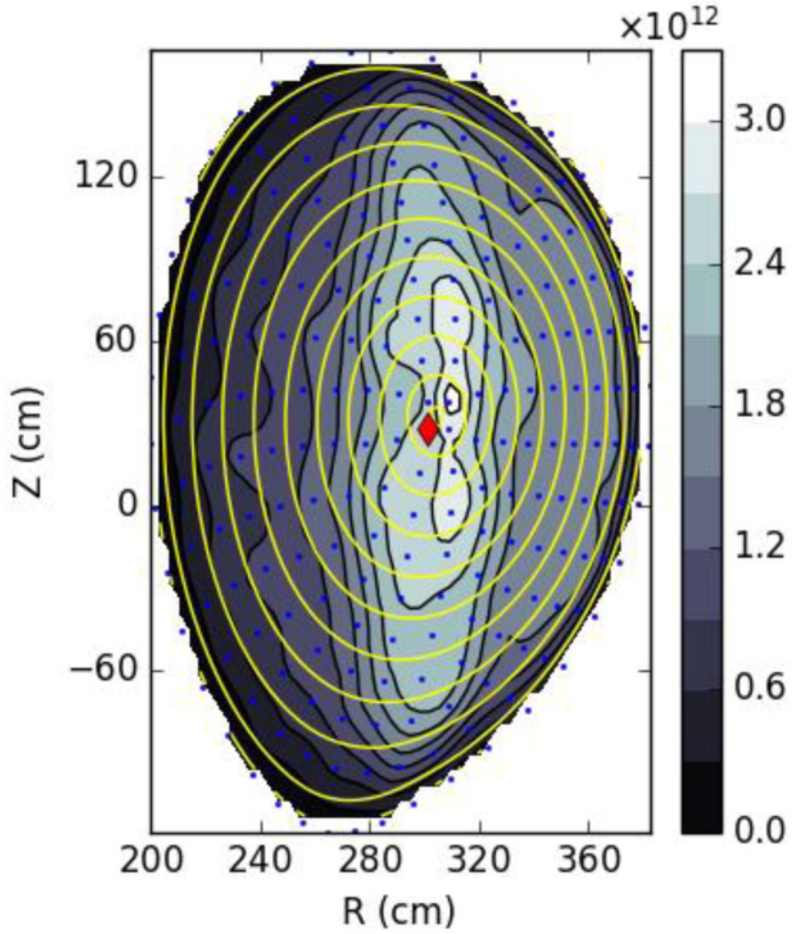
ICRF fast-ion and heating physics or effect caused by changes in the plasma transport ?

- **#34695: on-axis ³He resonance, lower X[He] ≈ 1%**
- **Sawtooth stabilization and reduced fast-ion losses after ³He puff**
- **$T_e(0.2)$ ≈ $T_i(0)$ ≈ 3keV, W_{dia} ≈ 200kJ → 300kJ**

Core-localized fast ions from TRANSP for D-(D_{NBI})-H three-ion scheme on JET







TRANSP modeling of baseline discharge #92436
(K. Kirov, submitted to Plasma Phys. Control. Fusion):

elongated distribution of fast ions along the IC resonance of H ions

TRANSP analysis: K. Kirov and Y. Baranov (CCFE)

core-localized distribution of fast D ions in the vicinity of the ion-ion hybrid layer