

Kiptily V G et al

On confined alpha-particle studies in low-activation plasmas

Acknowledgements

Many thanks to co-authors

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Motivation

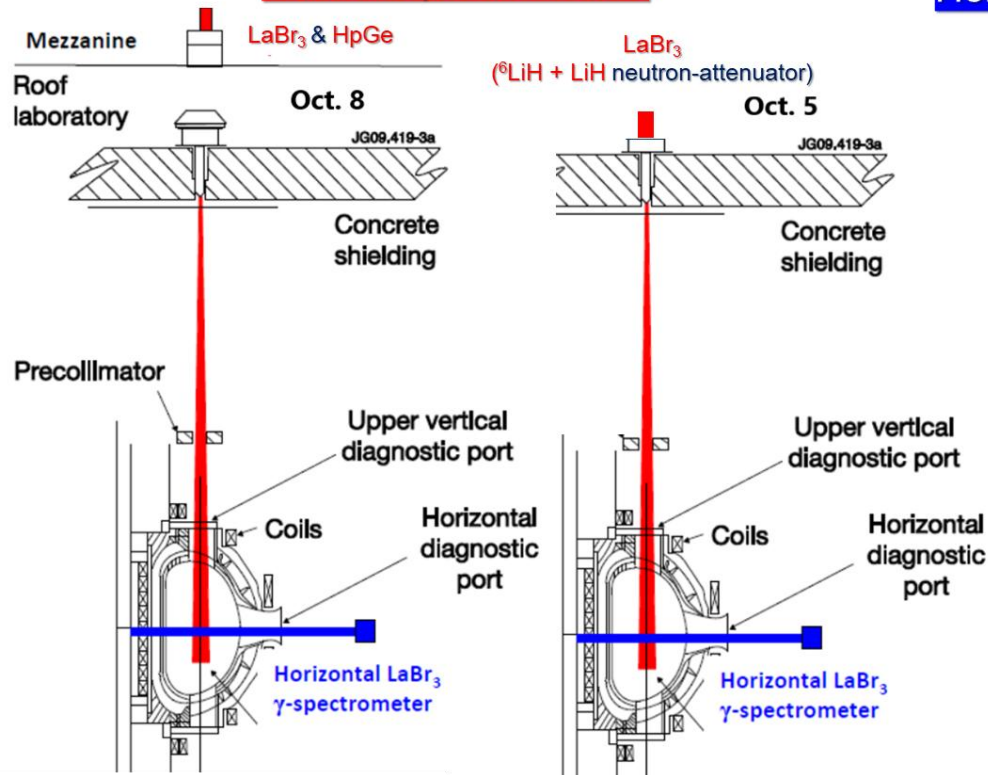
- ❖ The α -particle behaviour study in low-activation plasmas could help to develop optimal plasma conditions in the reactor burning phase.
- ❖ A harsh radiation environment in the D-T plasma phase makes realisation of this task extremely difficult since a restricted set of plasma diagnostics will be available.
- ❖ Experiments with low-activation plasmas could provide insights for the design and modelling of reactor-compatible diagnostic systems, as well as testing them in currently working fusion devices before their use in burning D-T plasma machines.
 - *Tungsten with boronisation* instead of *beryllium* for the vessel's first wall is considered for the future burning plasma machines

α -particle studies in JET low-activation plasma scenarios

- ❖ ^4He -beam ion acceleration with 3rd harmonic ICRF waves
- ❖ Fusion α -particle generation using $D(^3\text{He},p)^4\text{He}$ reaction
 - D -NBI heating of D - ^3He plasmas
 - ICRF heating scenarios:
 - ^3He -minority ICRF heating
 - D -beam ion accelerations with 3rd harmonic waves
 - 3-ion schemes accelerating D -beam ions and ^3He -ions
- ❖ T -NBI blip in deuterium plasmas (TTE): post-blip D - T fusion α -particles
- ❖ T -NBI in tritium plasmas (DTE2): fusion α -particles from $T(t,2n)^4\text{He}$

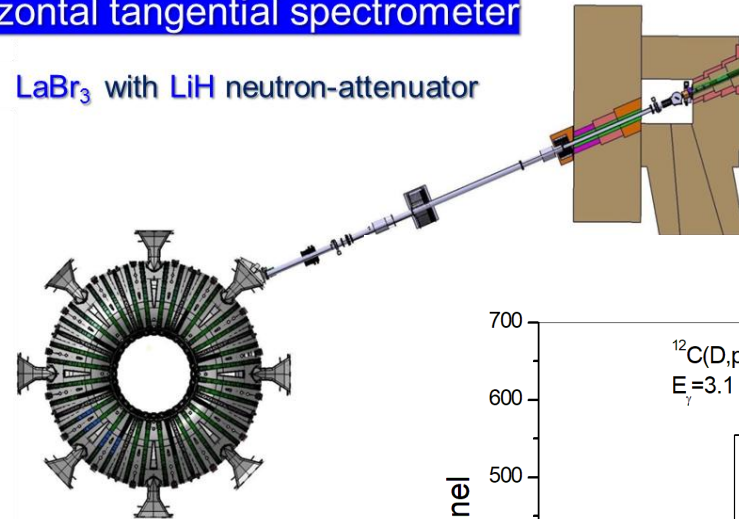
JET confined α -particle studies with γ -rays from ${}^9\text{Be}(\alpha, n\gamma){}^{12}\text{C}$ reaction

Vertical spectrometers



Horizontal tangential spectrometer

LaBr₃ with LiH neutron-attenuator



Kiptily V G et al 2002 NF **42** 999

Kiptily V.G. et al 2004 Phys. Rev. Letters **93** 115001

Kiptily V G, Cecil F E and Medley S S, 2006 PPCF **48** R59

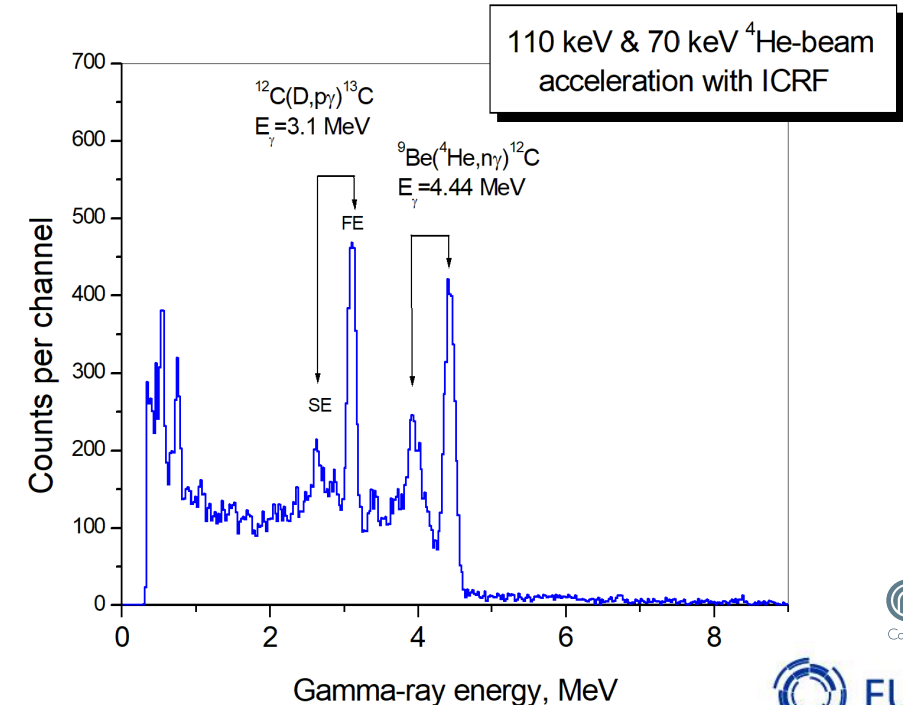
Tardocchi M, Nocente M & Gorini G 2013 PPCF **55** 074014

Nocente N et al 2020 PPCF **62** 014015

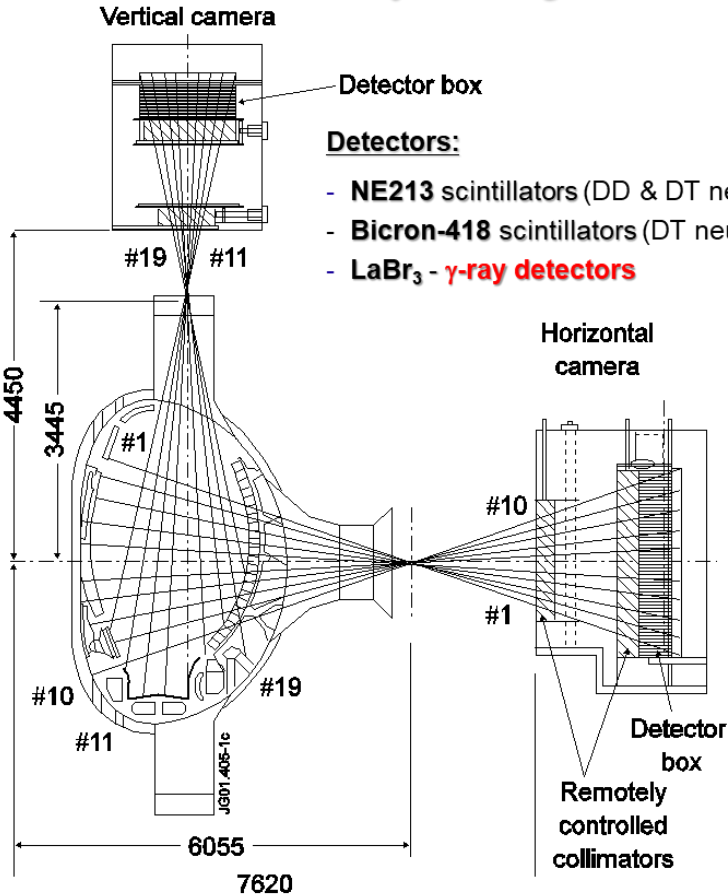
Curia M. et al, 2017 Fus Eng Des **123** 749

Panontin E. et al, 2021 RSI **92** 053529

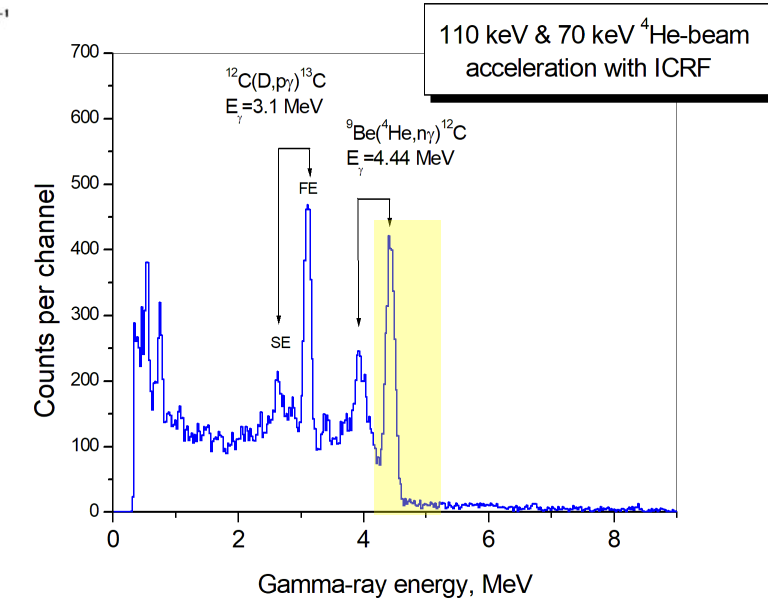
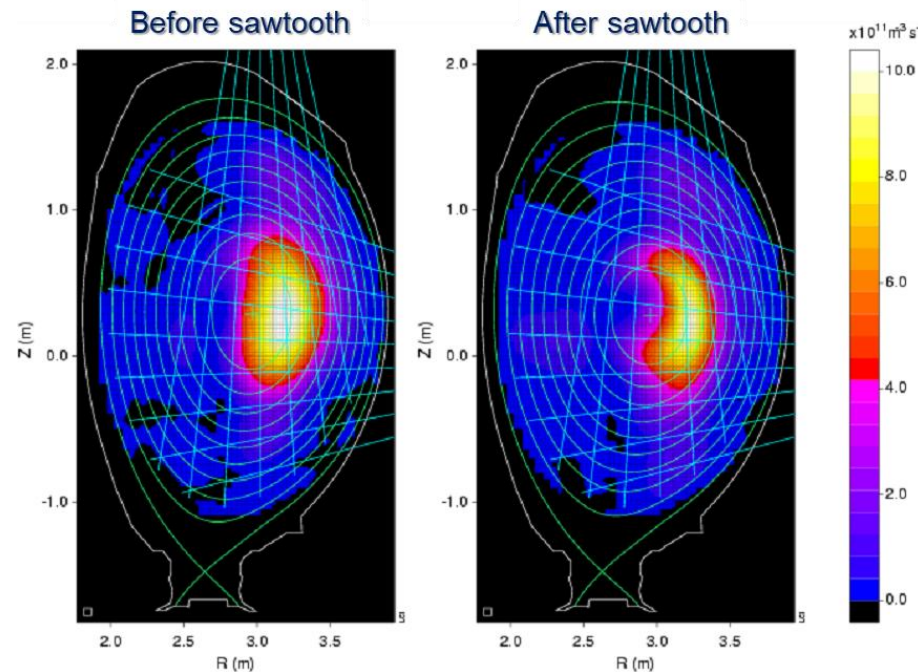
Iliasova et al NIM **A1031** (2022) 166586



JET confined α -particle studies with γ -rays from ${}^9\text{Be}(\alpha, n\gamma){}^{12}\text{C}$ reaction



${}^4\text{He}$ -beam ion acceleration with 3rd harmonic ICRF
 γ -ray image of ${}^4\text{He}$ -ions ($E_\alpha > 1.8$ MeV)



Panontin E. et al, Rev. Sci. Instrum. 92, 053529 (2021)

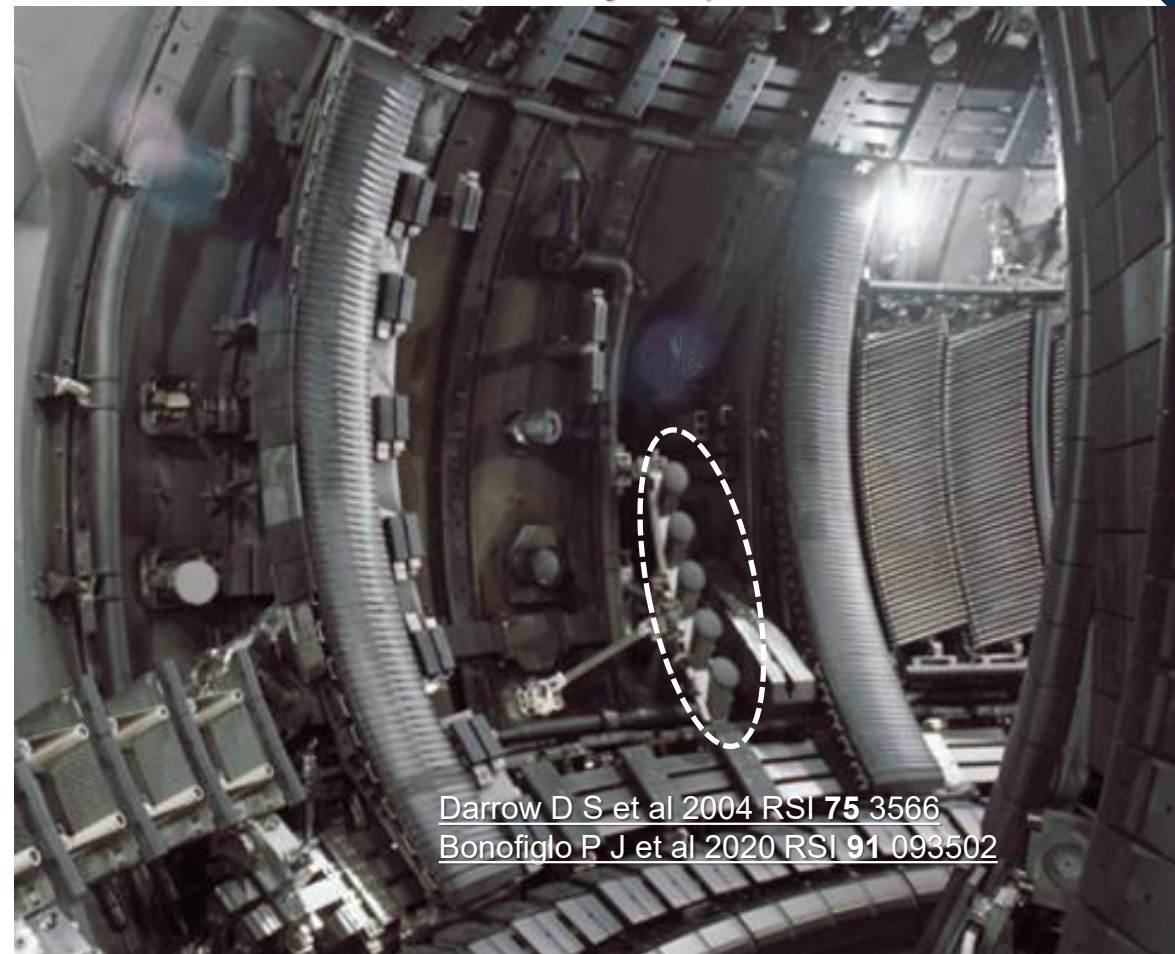
JET α -particle loss measurements

Fast Ion Loss Detector



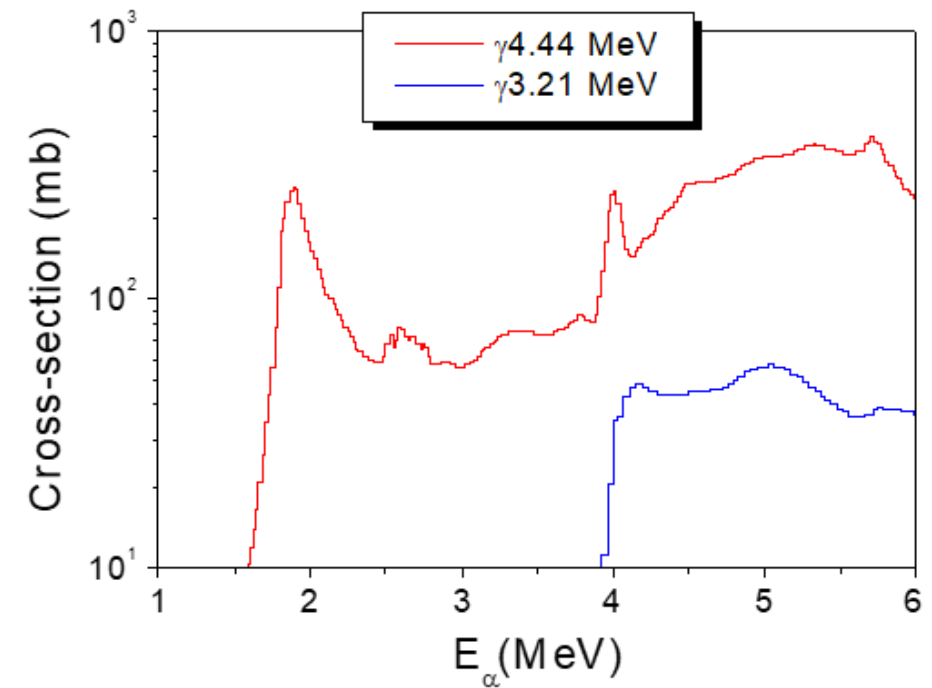
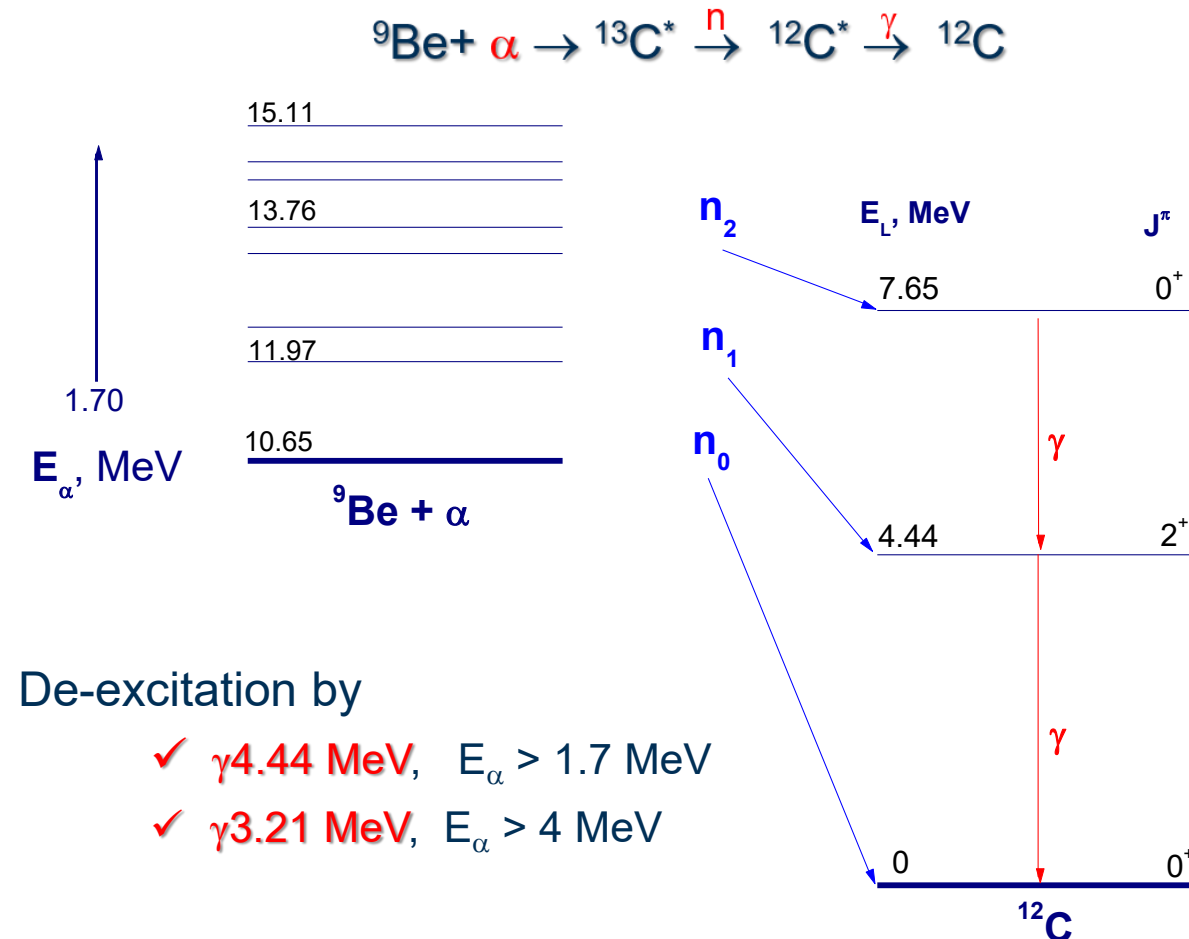
Kiptily V.G. et al Nucl. Fusion **64** (2024) 086059

Faraday Cups



Bonofiglio P.J. et al Nucl. Fusion **64** (2024) 096038

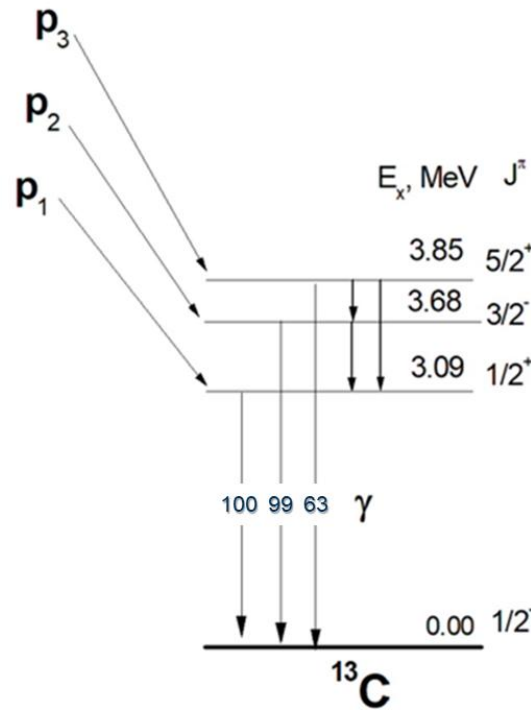
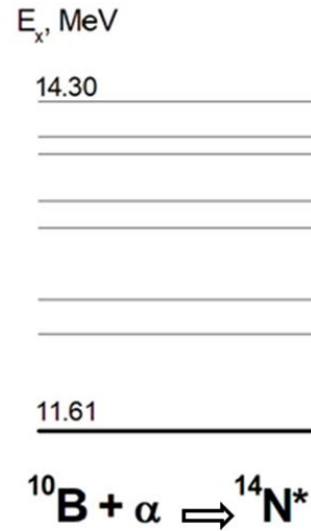
Confined α -particle measurements using ${}^9\text{Be}(\alpha, n\gamma){}^{12}\text{C}$ reaction



[Kiptily V.G., Fusion Technology **18** \(1990\) 583](#)

[Kiptily V.G. et al, Fusion Technology **22** \(1992\) 454](#)

Alternative $^{10}\text{B}(\alpha, p\gamma)^{13}\text{C}$ reaction for α -particle diagnosis in tungsten machines

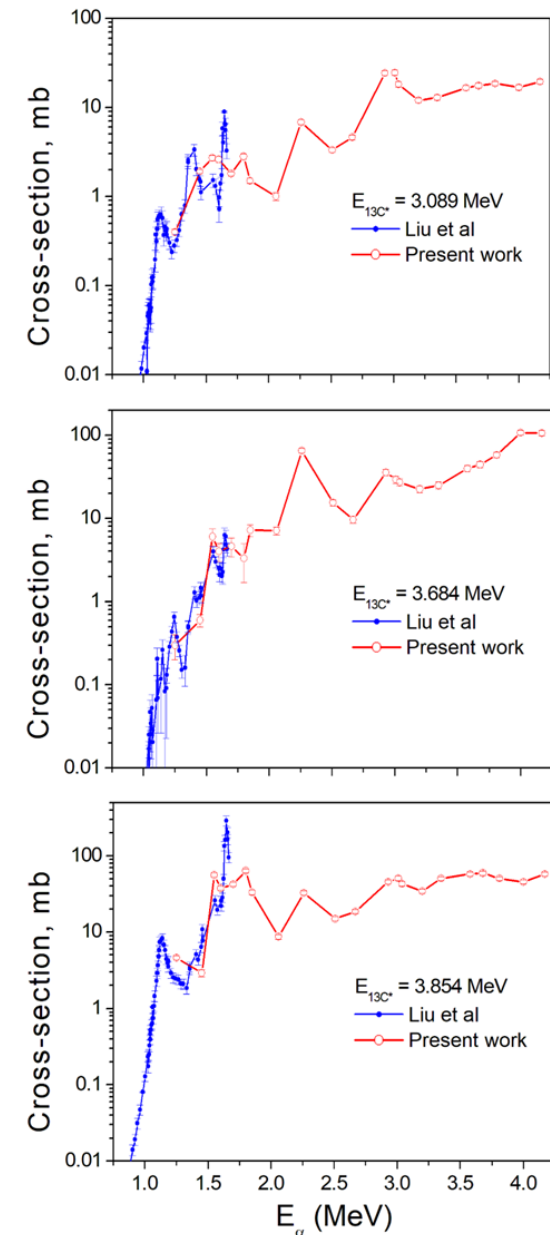


Benefits of using the $^{10}\text{B}(\alpha, p\gamma)^{13}\text{C}$ reaction instead of the $^9\text{Be}(\alpha, n)^{12}\text{C}$:

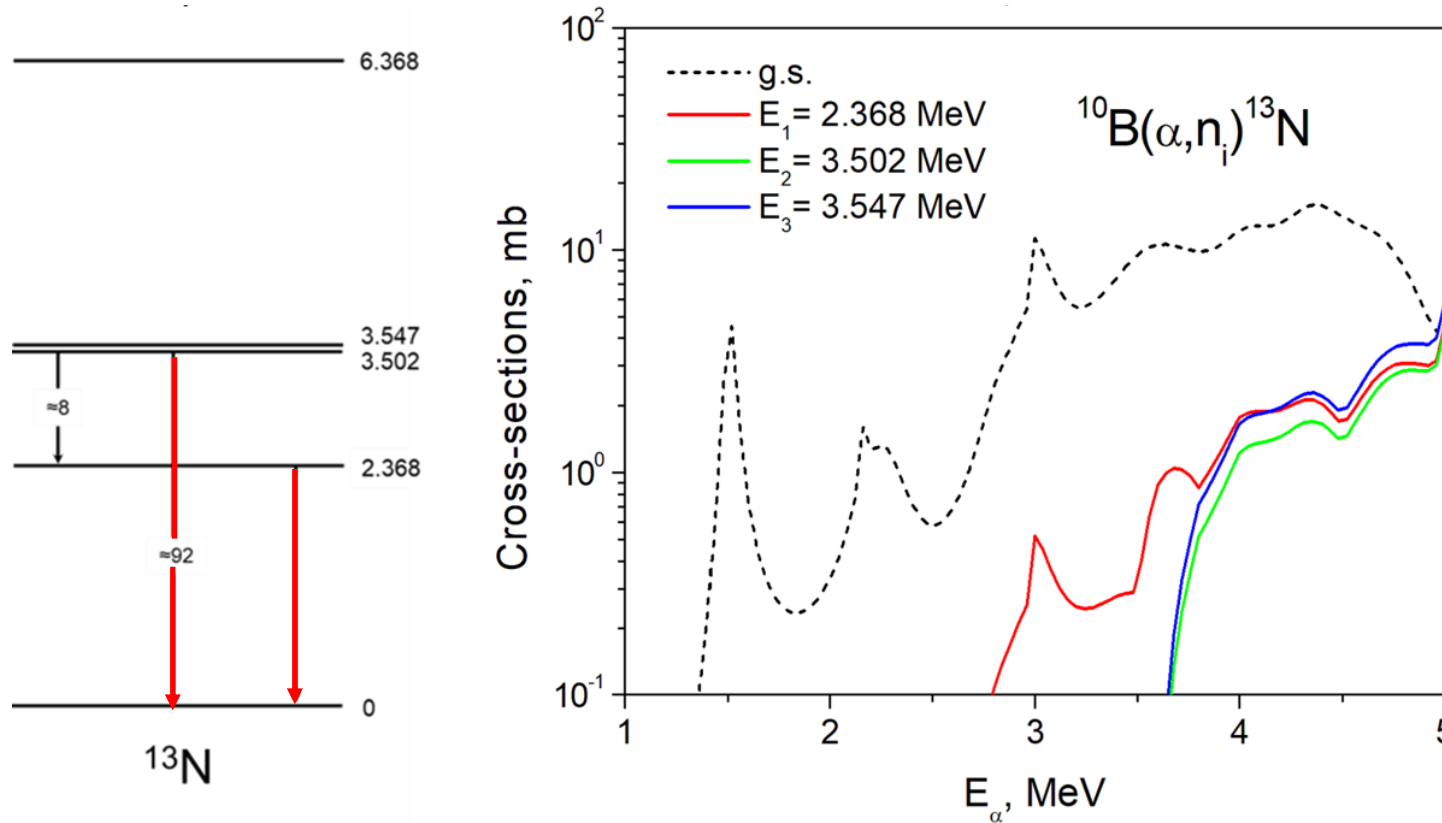
- ✓ energy range $E_\alpha > 1 \text{ MeV}$
- ✓ 3 excited states $\Rightarrow$ 3 γ -rays

Drawback: cross-section is lower

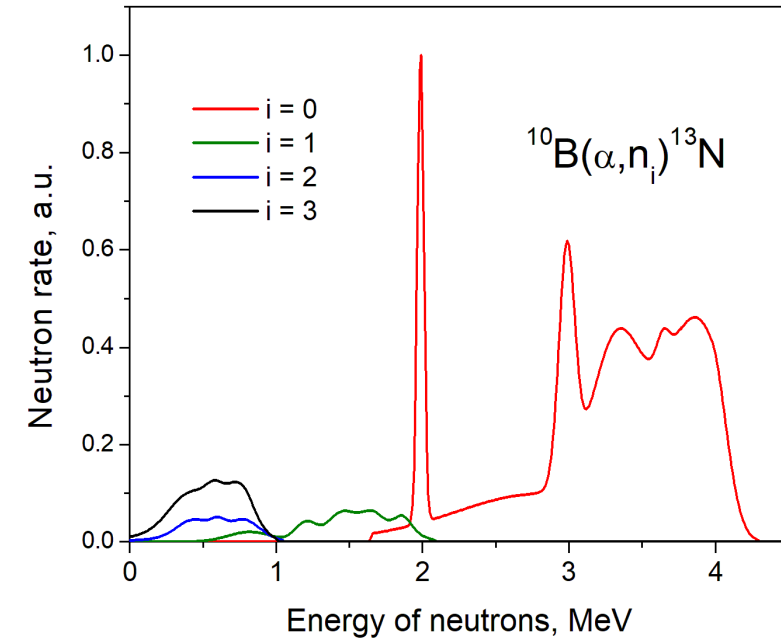
Kiptily V.G. 2025 Fusion Eng. Des. **215** 114959
Nocente M. et al 2026 Nucl. Fusion **66** 096017



α -particle monitoring with $^{10}\text{B}_{20\%}(\alpha, n\gamma)^{13}\text{N}$ reaction



Calculated neutron energy spectra @ $E_\alpha^0 = 4.5$ MeV

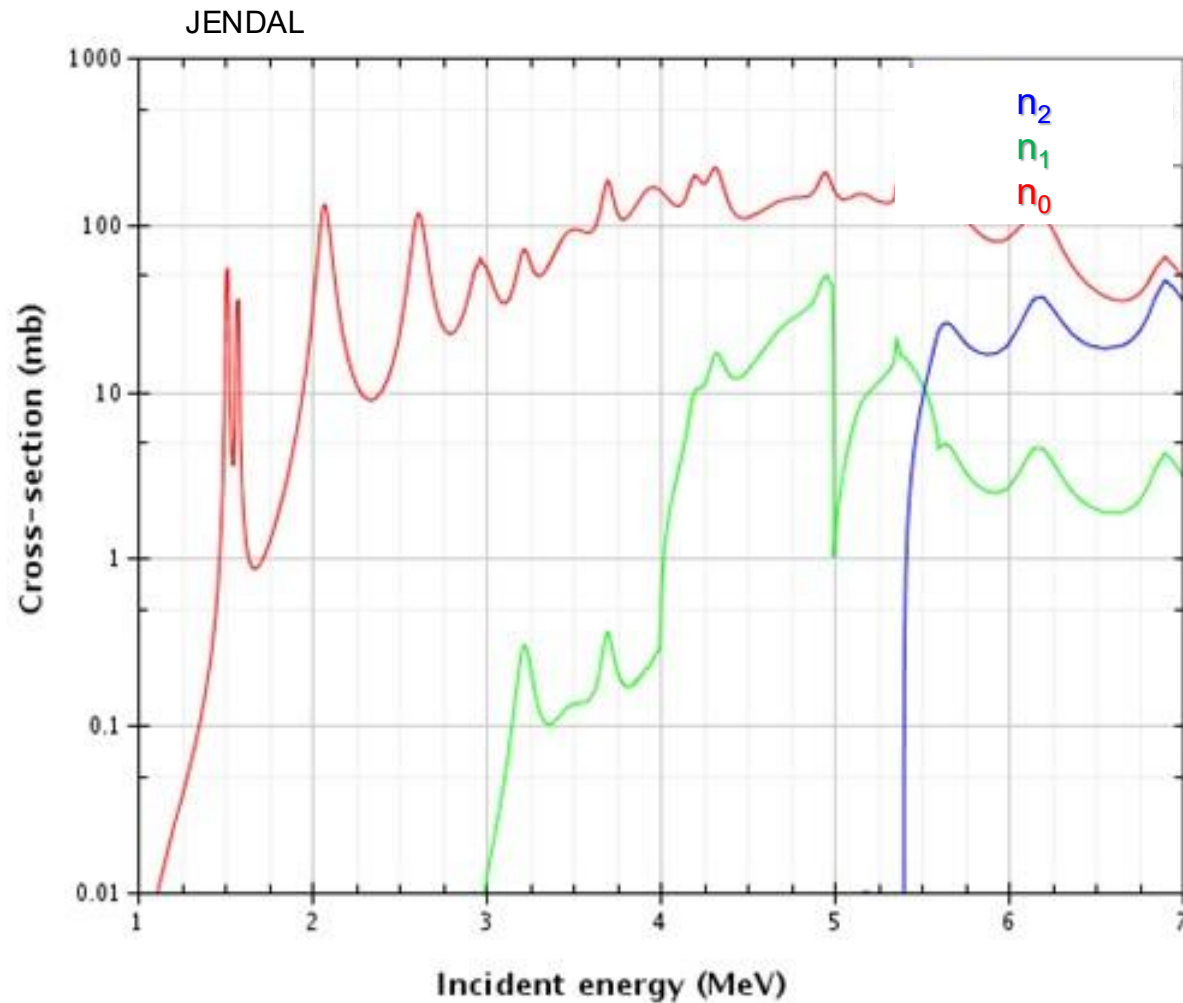


Alphas can be detected with γ -rays and neutrons

- 2.368 MeV at energy $E_\alpha > 1.8$ MeV
- 3.50 MeV at energy $E_\alpha > 3.4$ MeV

Kiptily V.G. et al 2026 Nucl. Fusion **66** 066004

α -particle monitoring with $^{11}\text{B}_{80\%}(\alpha, n\gamma)^{14}\text{N}$ reaction



Alphas can be detected with γ -rays

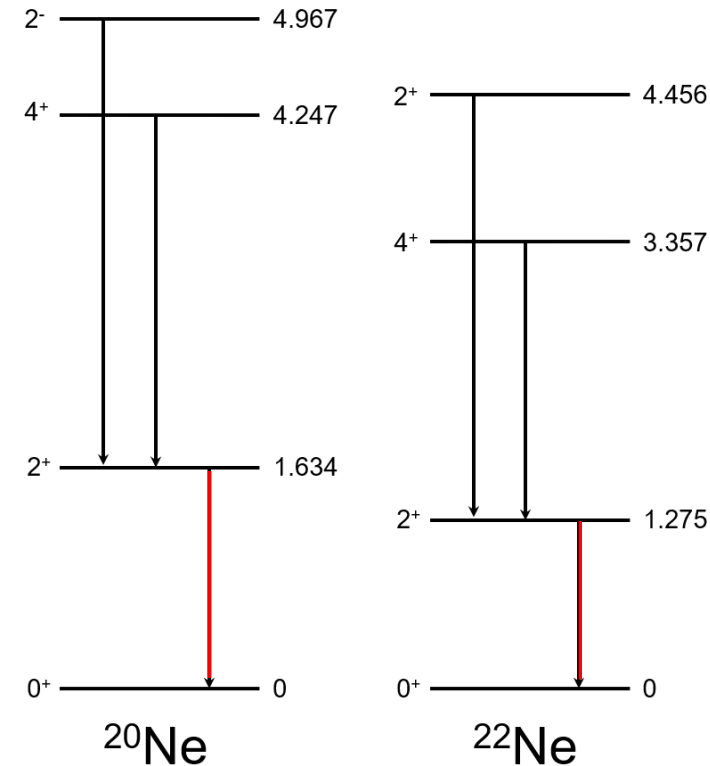
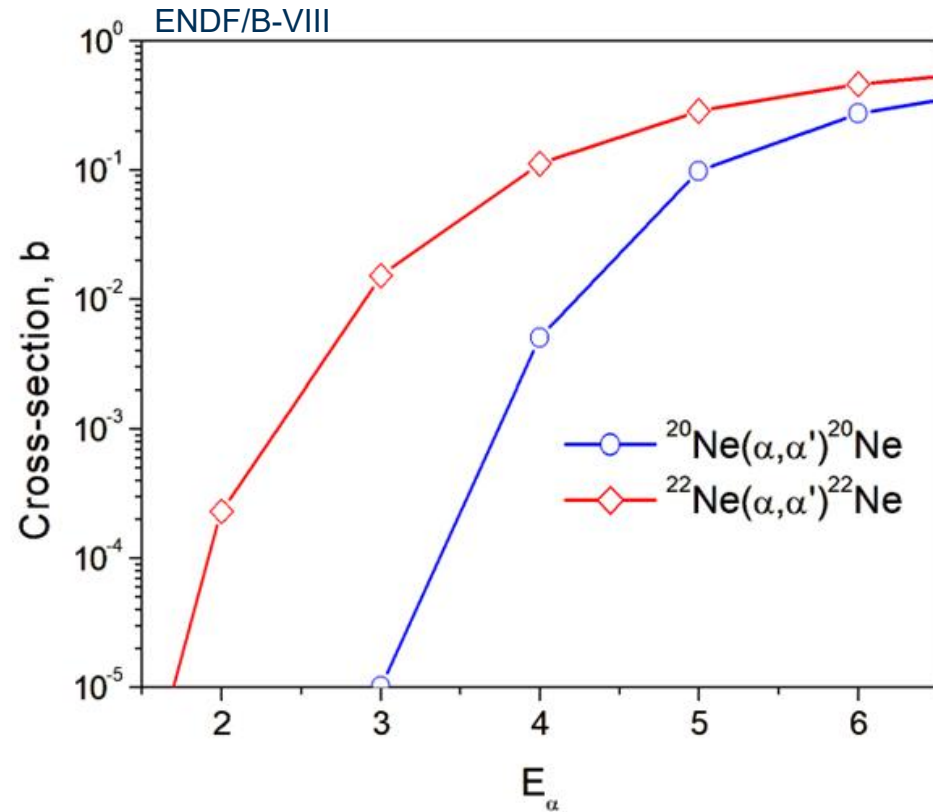
- 2.313 MeV at energy $E_\alpha > 3$ MeV
- 1.635-MeV at energy $E_\alpha > 4.6$ MeV

and neutrons

- e.g. @ $E_\alpha > 3.6$ MeV $\rightarrow E_{n0} > 2.6$ MeV

Kiptily V.G. et al 2026 Nucl. Fusion **66** 066004

Ne as a radiator and target for α -particle diagnostic reactions



Inelastic scattering of energetic alphas on **Ne** can excite the low-lying levels that discharge with **γ -rays** then

Kiptily V.G. et al 2026 Nucl. Fusion **66** 066004

Scenarios for α -particle generation in low-activation plasmas

$D(^3\text{He}, p)^4\text{He}$ ($E_\alpha = 3.6$ MeV) as in JET

- ^3He ICRF heating (several schemes): D-plasma
- D-NBI / ICRF heating: D-plasma with ^3He

$^{11}\text{B}(p, 2\alpha)^4\text{He}$ ($E_\alpha < 6$ MeV)

- H-ICRF heating + boron
- H-NBI heating + boron

D³He α-particle generation: JET benchmark

❖ D-NBI heating

- up to ~15 kW of D³He fusion power at $P_{\text{NBI}} \sim 15$ MW ($n_{3\text{He}}/n_e \approx 30\%$)

Sharapov S.E. et al 2016 Nucl. Fusion **56** 112021

❖ ³He-minority ICRF heating

- up to 140 kW of D³He fusion power ($\sim 4.6 \times 10^{16}$ α-particles per sec) at $P_{\text{ICRH}} = 10$ MW

Jacquinet J. and Sadler G., *Fusion Technology* **21** (1992) 2254 ,

Mantsinen M.J. et al 2002 Phys. Rev. Lett. **88** 115004, Sharapov S.E. et al 2016 Nucl. Fusion **56** 112021

❖ D-beam ion accelerations with 3rd harmonic ICRF

- up to 10 kW of D³He fusion power at $P_{\text{ICRH}} \sim 3$ MW + 4.5 MW of NBI

M.J. Mantsinen et al 2002 PRL. **88** 105002, Kiptily V.G. et al 2002 Nucl. Fusion **42** 999

Sharapov S.E. et al 2016 Nucl. Fusion **56** 112021

❖ 3-ion ICRH scheme, accelerating D- or ³He-ions

- up to 60 kW of D³He fusion power at $P_{\text{ICRH}} = 6$ MW + 7 MW NBI and $n_{3\text{He}}/n_e \approx 22\%$ ($\sim 2 \times 10^{16} \text{ s}^{-1}$ α-particles)

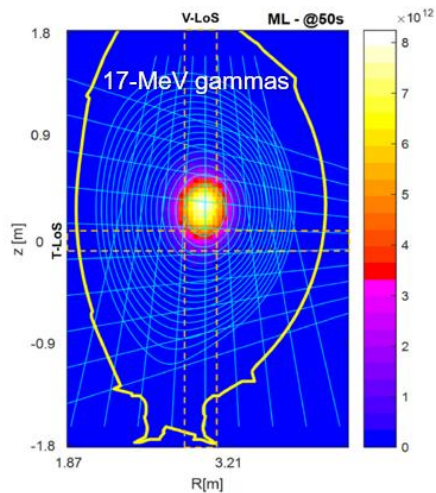
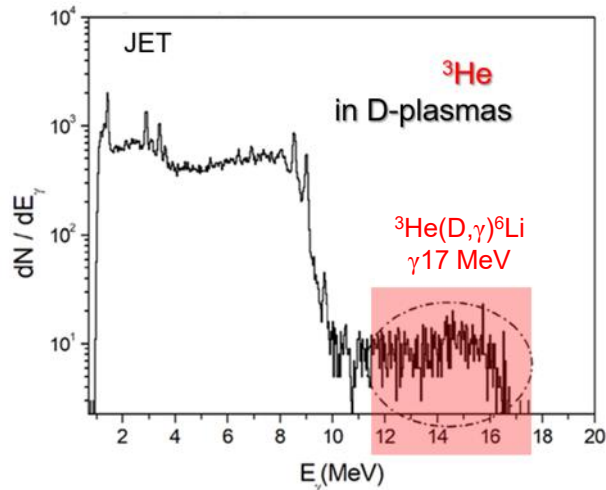
Nocente M et al 2020 Nucl. Fusion **60** 124006,

Kazakov Ye.O. et al Phys. Plasmas **28**, 020501 (2021) ,

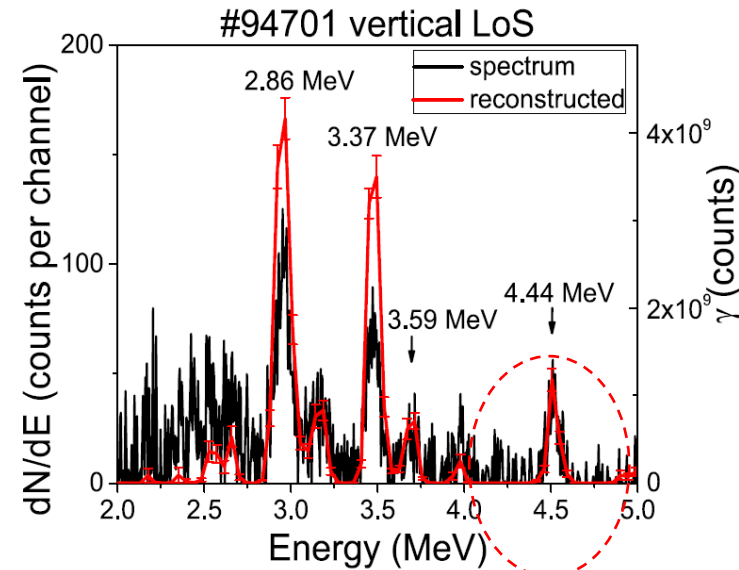
Kiptily V.G. et al Nucl. Fusion **61** (2021) 114006

D³He α-particle studies on JET

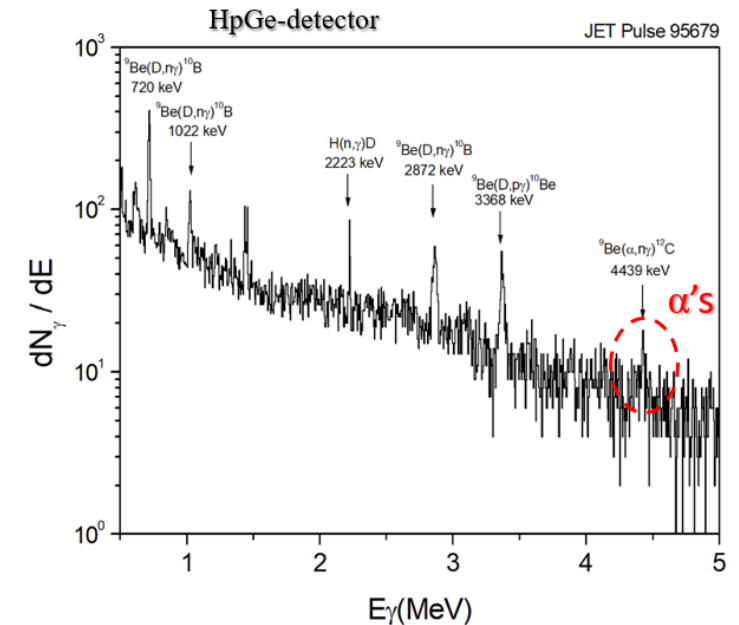
D-ion acceleration with 3-ion ICRH scheme



Measurements of γ -ray from $^9\text{Be}(\text{D},n\gamma)^{10}\text{B}$, $^9\text{Be}(\text{D},p\gamma)^{10}\text{Be}$ & $^9\text{Be}(\alpha,n\gamma)^{12}\text{C}$ reactions



Nocente M et al 2020 Nucl. Fusion **60** 124006
Kiptily V.G. et al 2022 PPCF **64** 064001
Iliasova et al NIM **A1031** (2022) 166586

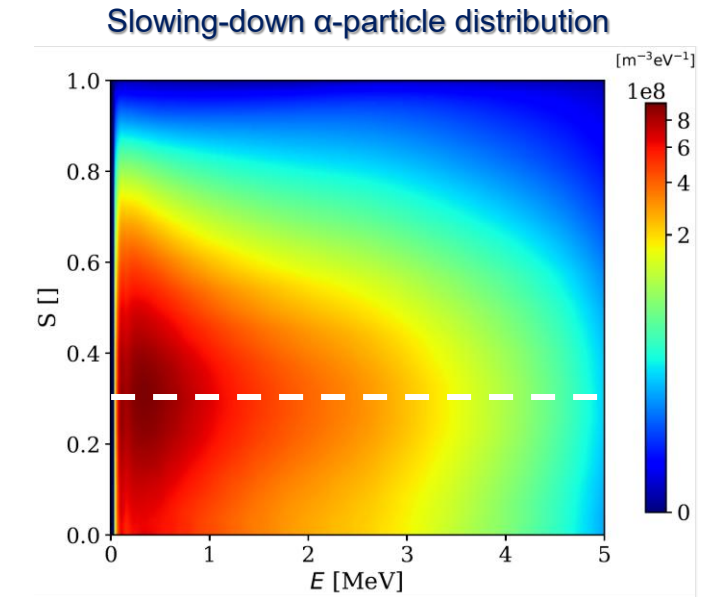
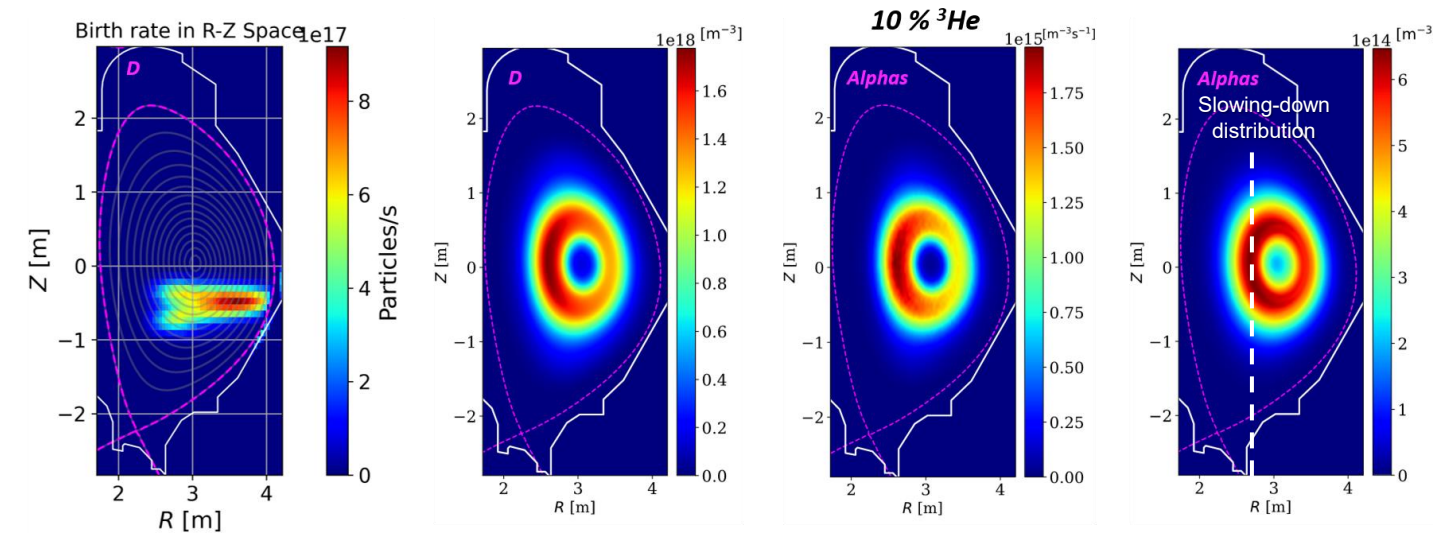


The Doppler broadening of γ -rays measured with HPGe-detector (high energy resolution)

D-NBI in D³He plasma for α-particle studies on JT-60SA

JT-60SA NBI heating system:

- 12 P-NBI, up to 24 MW in total at 85 keV
- 2 N-NBI, 10 MW at up to 500 keV



γ-ray emission rates, $\text{m}^{-3} \text{s}^{-1}$ (preliminary assessments)

E_γ, MeV	$^{10}\text{B}(\alpha, p\gamma)^{13}\text{C}$	$^{10}\text{B}(\alpha, n_1\gamma)^{13}\text{N}$	$^{11}\text{B}(\alpha, n_1\gamma)^{14}\text{N}$
3.09	$8.5 \cdot 10^8$		
3.685	$3 \cdot 10^9$		
3.854	$4 \cdot 10^9$		
2.368		$4.5 \cdot 10^7$	
2.313			$6 \cdot 10^8$

$P_\alpha^{D^3He} \sim 30 - 50 \text{ kW}$ is well-matched with 60-kW D³He-experiment on JET !

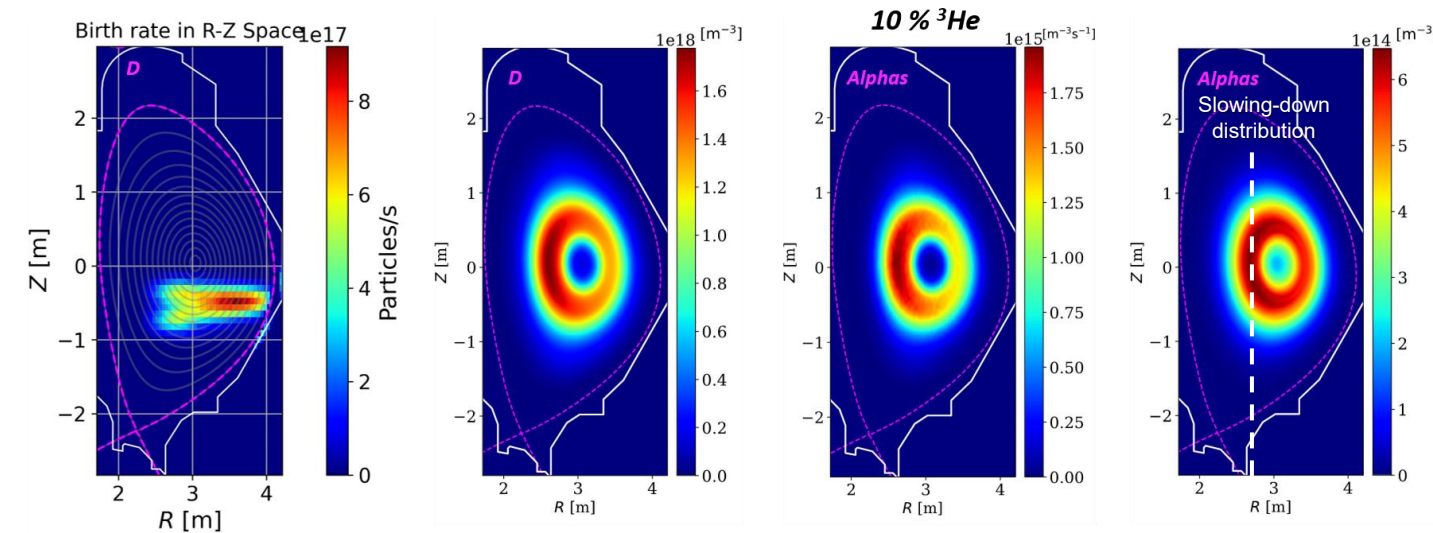
Coelho R. et al Nucl. Fusion **66** (2026) 086029

See presentation and poster of R. Coelho at this Meeting

D-NBI in D³He plasma for α-particle studies on JT-60SA

JT-60SA NBI heating system:

- 12 P-NBI, up to 24 MW in total at 85 keV
- 2 N-NBI, 10 MW at up to 500 keV



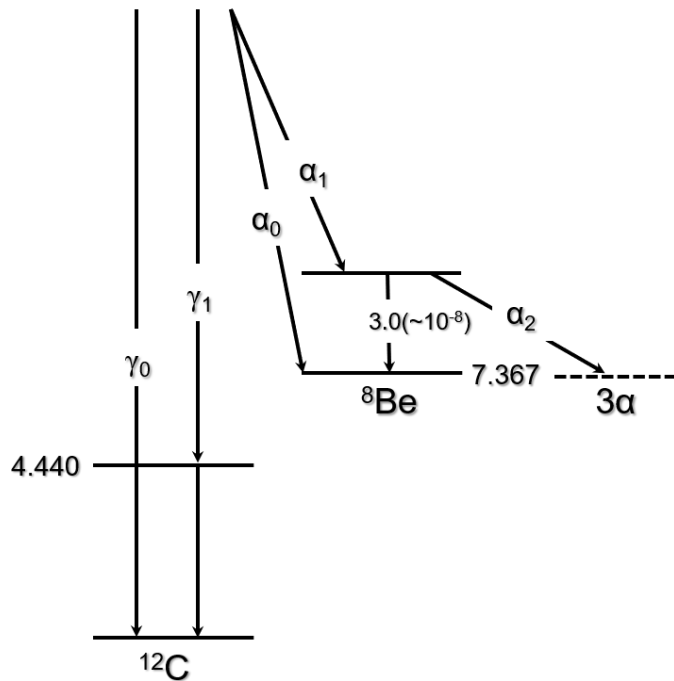
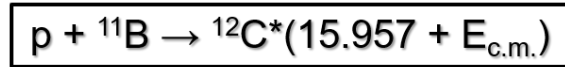
- Thus, α-particle measurements alike JET ones could be feasible on JT-60SA
- Diagnostics designed by JA and EU will be installed in 2027

$P_{\alpha}^{D^3He} \sim 30 - 50 \text{ kW}$ is well-matched with 60-kW D³He-experiment on JET !

Coelho R. et al Nucl. Fusion **66** (2026) 086029

See presentation of R. Coelho at this Meeting

$^{11}\text{B}(p,2\alpha)^4\text{He}$ reaction for α -particle production

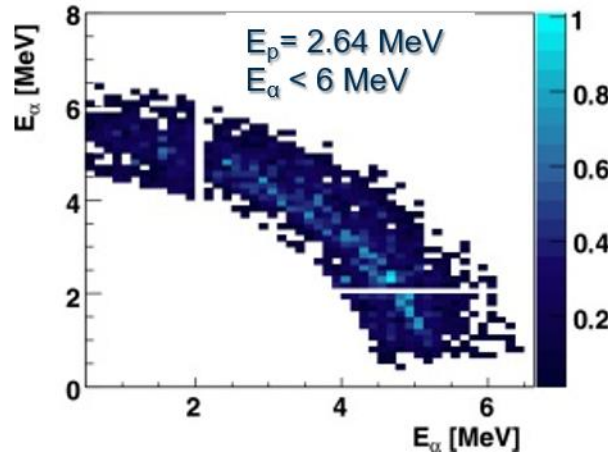
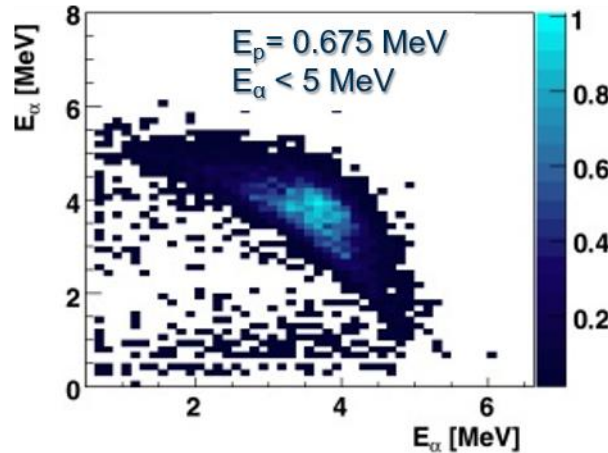


N.B. p - ^{11}B fusion reaction was observed in LHD; α -particles were detected.

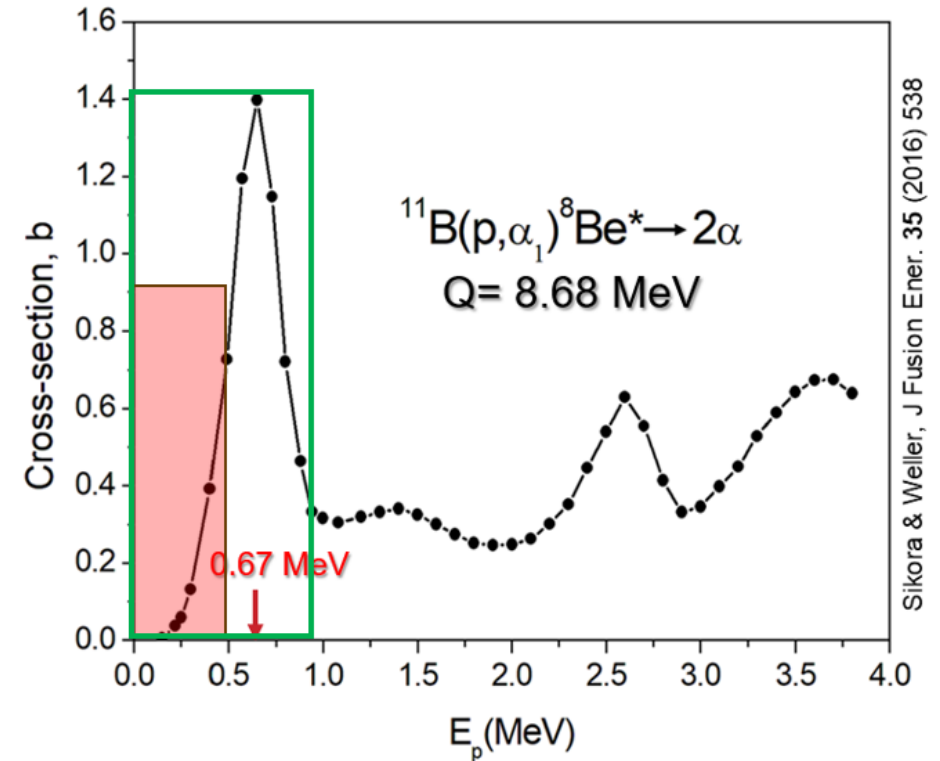
Ogawa K. et al, 2024 Nucl. Fusion **64** 096028

Kamio S. et al, 2026 Nucl. Fusion **66** 036020

Spraker M.C. et al J Fusion Energ. **31** (2012) 357



Normalised α -particle coincidence spectra



JT-60SA: $E_{\text{H-NBI}}(\text{max}) = 500$ keV

ITER: $E_{\text{H-NBI}}(\text{max}) = 870$ keV

H-ion ICRF heating for α -particle generation: JET benchmark

❖ 2nd-harmonic & H-minority ICRF heating in H- & D-plasmas

- α -particles production with ${}^9\text{Be}(p,d)2\alpha$ & ${}^9\text{Be}(p,\alpha){}^6\text{Li}$ reactions
- First α -particle observation in low-activation plasmas

A.V. et al 2018 Nucl. Fusion **58** 026033

Krasilnikov

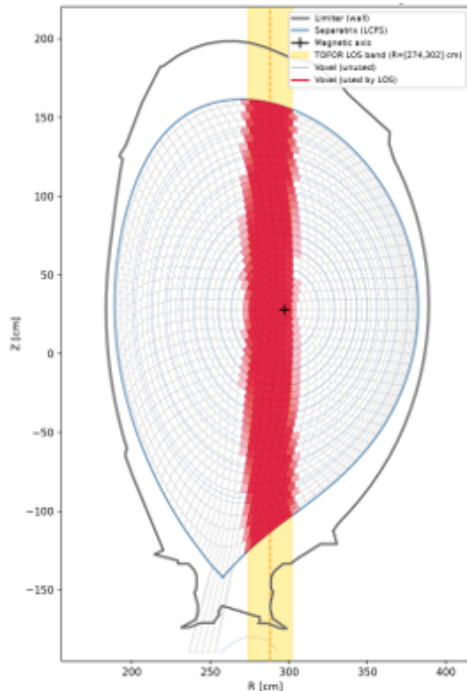
❖ H-minority ICRF heating in He- & D-plasmas

Štancar Ž. et al 2026 Nucl. Fusion **66** 096005

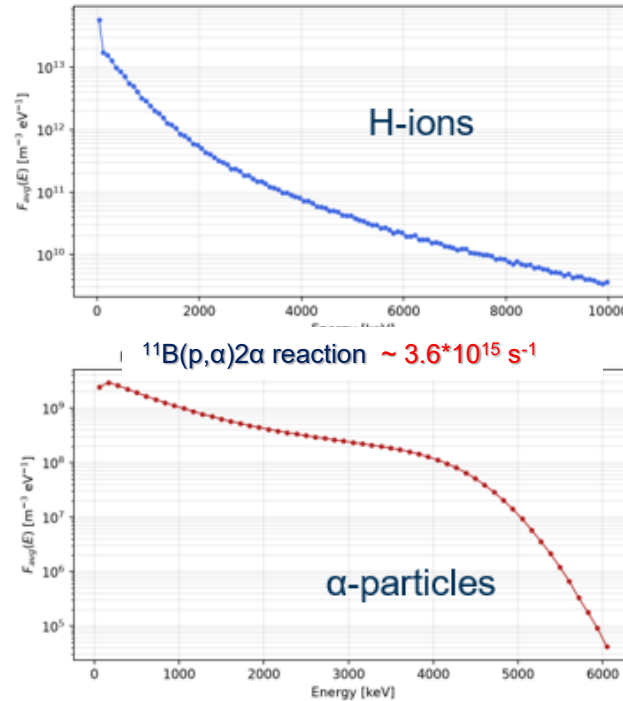
- steady-state L-mode plasma with dominant $p\text{-Be}$ fusion and neutron rate up to $\approx 6 \cdot 10^{13} \text{ s}^{-1}$
- γ -ray emission modelling was validated for both **3.56-MeV** gammas from the ${}^9\text{Be}(p,\alpha){}^6\text{Li}$ reaction and **4.44-MeV** γ -rays due to the secondary ${}^9\text{Be}(\alpha,n\gamma){}^{12}\text{C}$ reaction.
- rates for the ${}^{11}\text{B}(p,\alpha)2\alpha$ reaction ($\sim 3.6 \cdot 10^{15} \text{ s}^{-1}$) and other boron reactions were estimated at JET plasma conditions.
- it could be used as a **benchmark** for feasibility assessments $p\text{-}{}^{11}\text{B}$ α -particle measurements in low-activation plasmas

$^{11}\text{B}+\text{p}$ α -particle generation & studies: JET Pulse No. 101184

LoS of γ -ray & neutron spectrometers



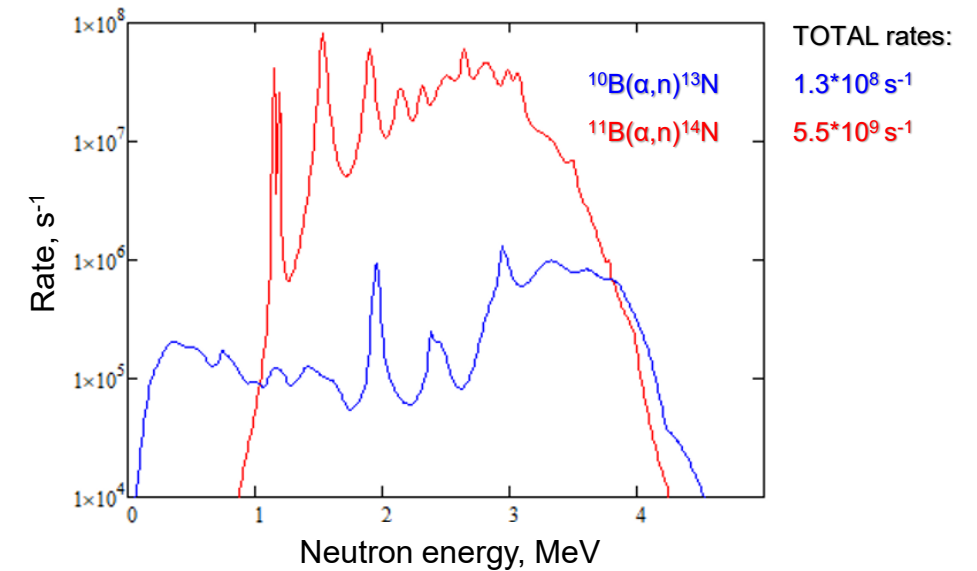
Distribution functions



Štancar Ž. et al 2026 Nucl. Fusion 66 096005

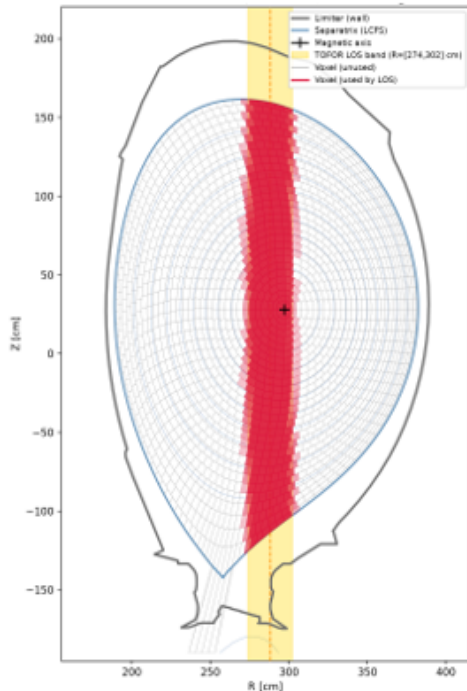
α -particle rate monitoring

Neutron emission rates (preliminary assessments)

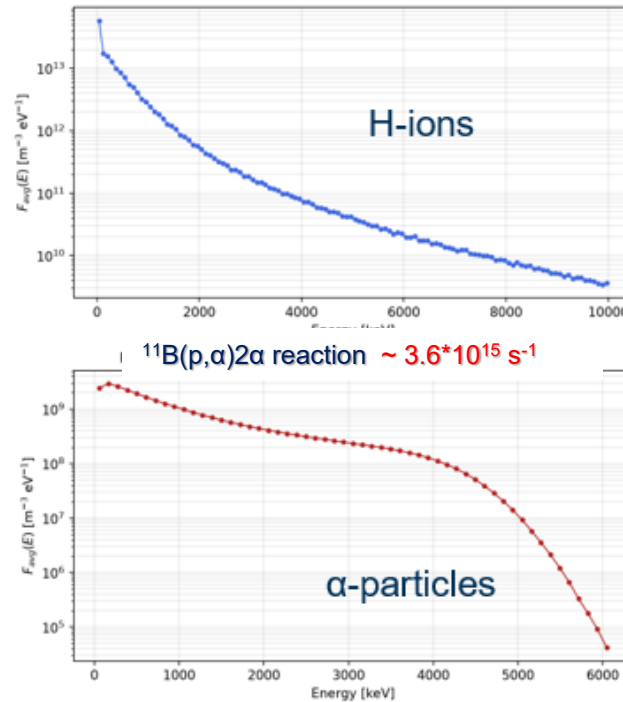


$^{11}\text{B}+\text{p}$ α -particle generation & studies: JET Pulse No. 101184

LoS of γ -ray & neutron spectrometers



Distribution functions



Štancar Ž. et al 2026 Nucl. Fusion **66** 096005

Confined α -particle measurements

γ -ray emission rates, s^{-1} (preliminary assessments)

E_γ , MeV	$^{10}\text{B}(\alpha, p\gamma)^{13}\text{C}$	$^{10}\text{B}(\alpha, n_1\gamma)^{13}\text{N}$	$^{11}\text{B}(\alpha, n_1\gamma)^{14}\text{N}$
3.09	$1.9 \cdot 10^8$		
3.685	$6.6 \cdot 10^8$		
3.854	$8.8 \cdot 10^8$		
2.368		10^7	
2.313			10^8

N.B. JT-60SA with H-NBI & 1% ^{11}B could provide more than $1.7 \cdot 10^{15} \text{ s}^{-1}$

See presentation of Rui Coelho at this Meeting

Summary & conclusions

- ❖ JET experiments have demonstrated feasibility of the energetic α -particle studies in low-activation plasmas
- ❖ Low-activation α -particle studies could be considered for currently working devices (LHD, EXL-50U, AUG, JT-60SA, EAST etc.) as well as for use in the pre-burning phases of forthcoming reactors (SPARC, ITER, BEST etc.)
- ❖ JET studies could be considered as a benchmark for the present and future fusion machines
 - ✓ to produce fast-ions with ICRH or/and NBI heating in D^3He , He -, D - and H -plasmas, using $D(^3He, p)^4He$ & $^{11}B(p, 2\alpha)^4He$ reactions as α -particle generators
- ❖ For measurements of α -particles, $^{10}B(\alpha, p\gamma)^{13}C$ and $^{10,11}B(\alpha, n\gamma)^{13,14}N$ reactions are proposed:
 - ✓ synergy of γ -ray & neutron diagnosis could be an advantage for α -particle experiments