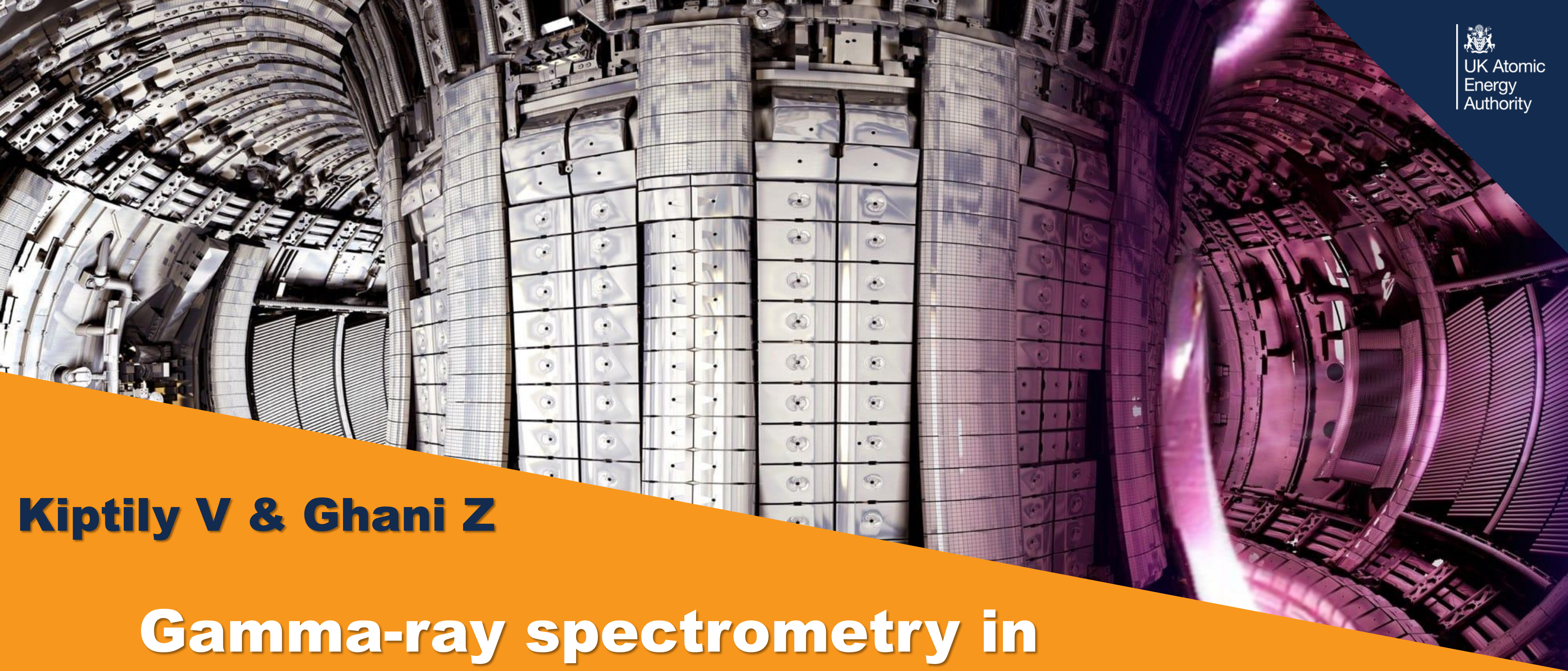

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Kiptily V & Ghani Z

Gamma-ray spectrometry in support of burning plasma scenario developments

18th Technical Meeting on Energetic Particles in Magnetic Confinement Systems, Seville, 17th – 21st March 2025

Contents

- Introduction
  - γ-ray spectrometry on JET
  - fast-ion/α-particle studies on JET
- Gamma-ray diagnostic capabilities in fusion plasma facilities
  - Setup a plasma discharge
  - Commissioning of auxiliary heating systems
  - Plasma scenario developments
  - Alpha-particle studies
- Summary & conclusions

Gamma-ray spectrometers on JET

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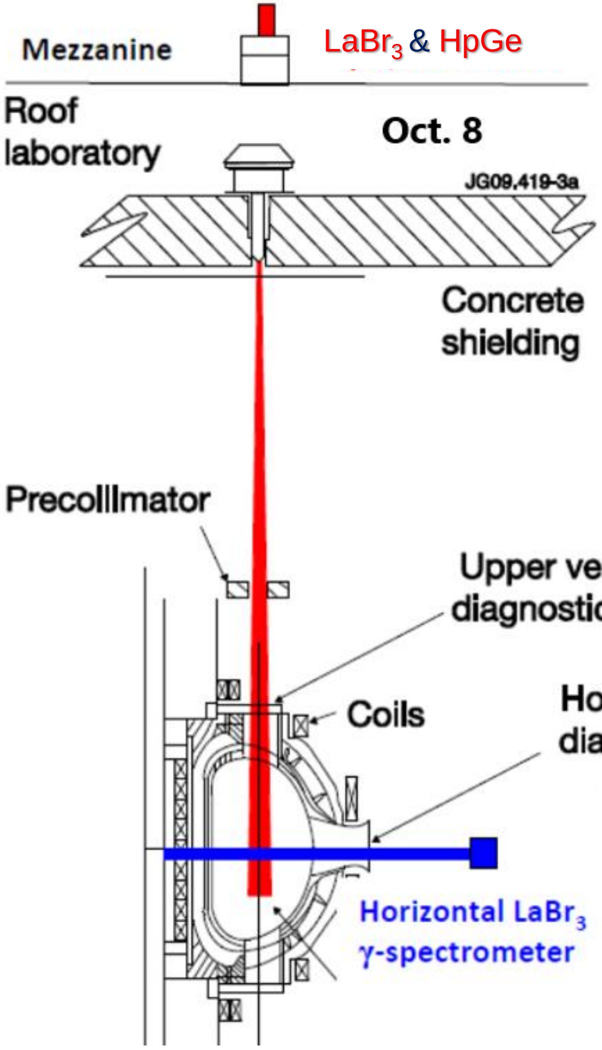
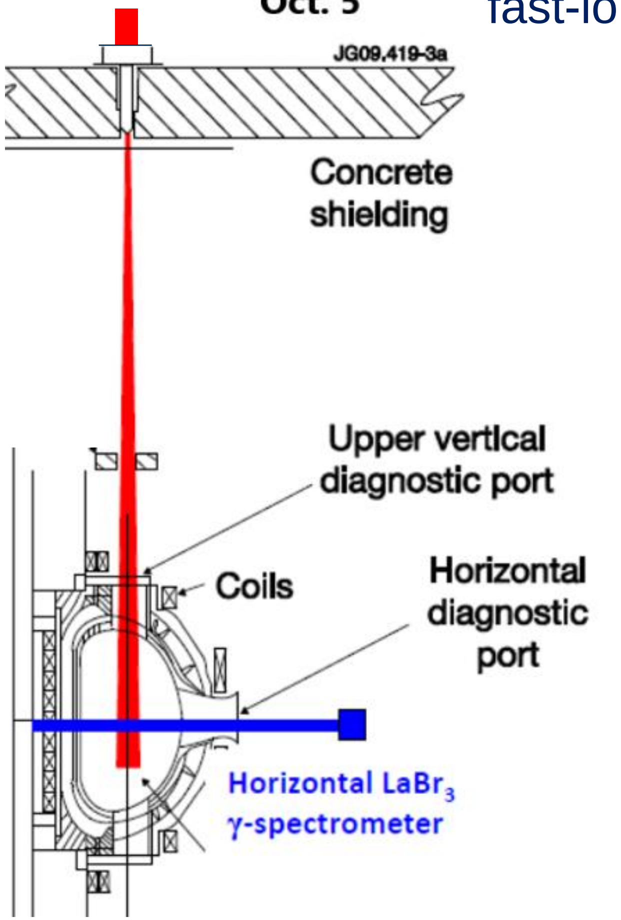
Vertical spectrometers

$LaBr_3$ & HpGe



$LaBr_3$
(^{6}LiH + LiH neutron-attenuator)

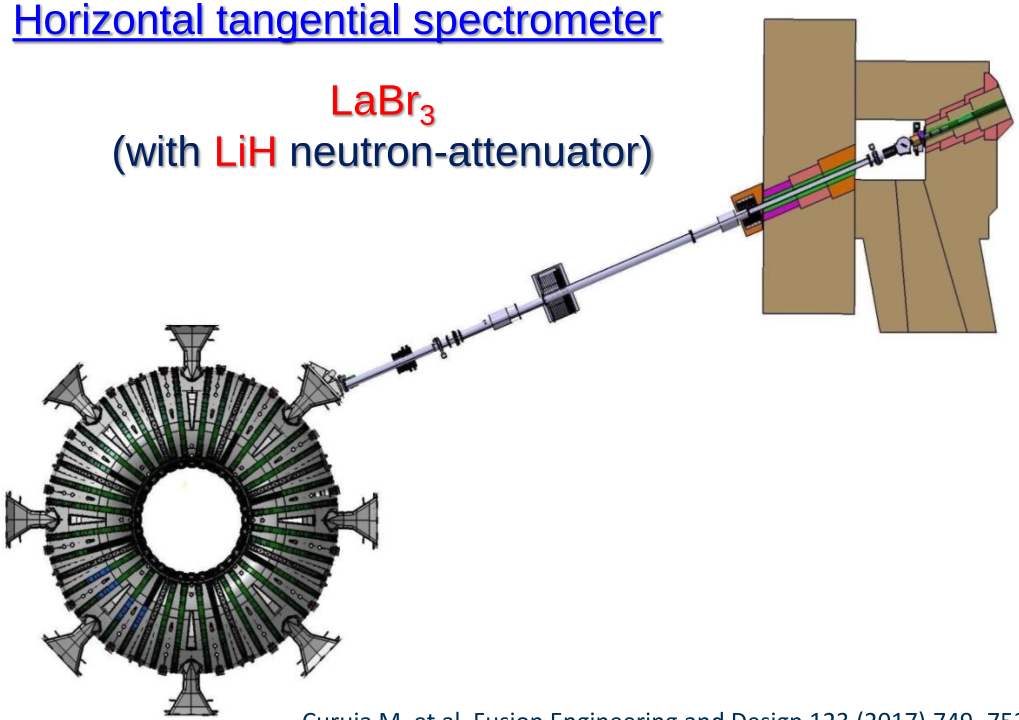


Gamma-ray diagnostics became a routine instrument for fast-ions and fusion-born α-particles studies on JET in XXI century: energy distribution function, imaging of fast-ions and effects of spatial redistribution

Kiptily V G, Cecil F E and Medley S S, 2006 PPCF **48** R59
Nocente N et al 2020 PPCF **62** 014015

Horizontal tangential spectrometer

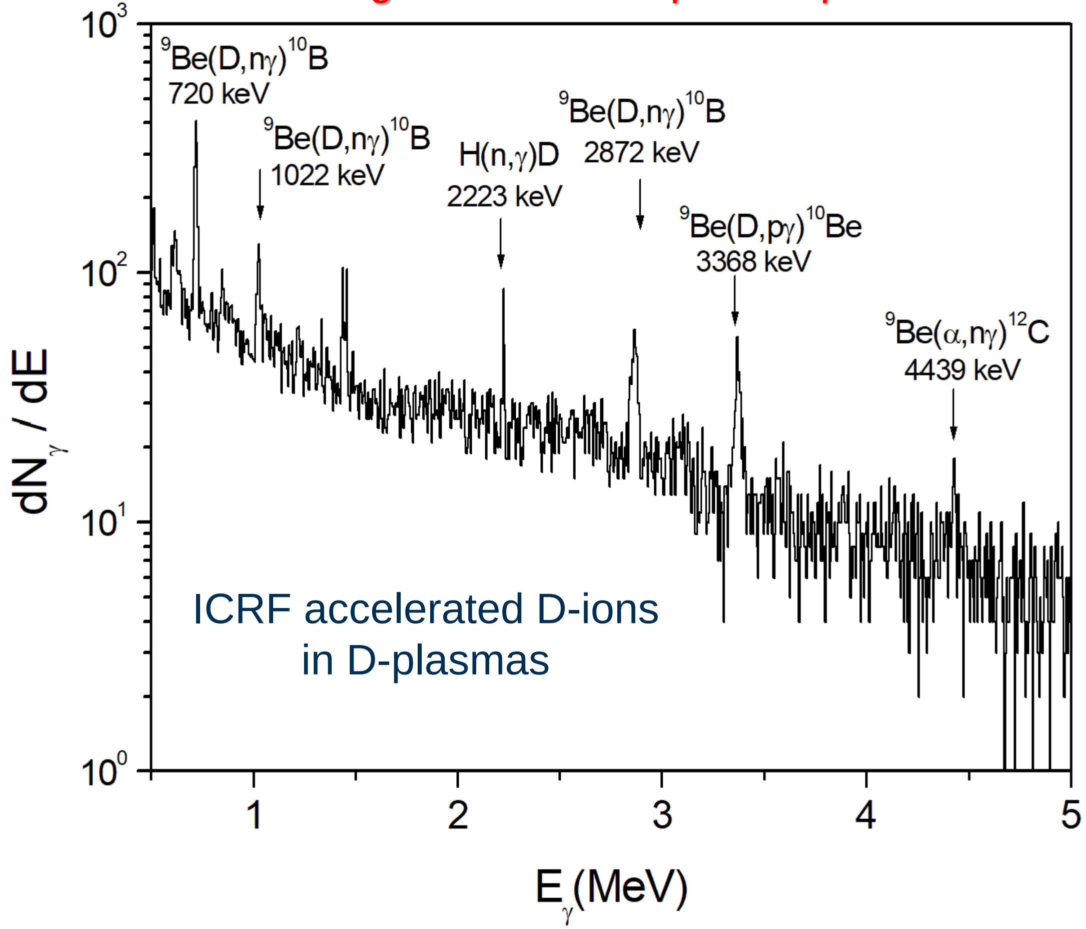
$LaBr_3$
(with LiH neutron-attenuator)



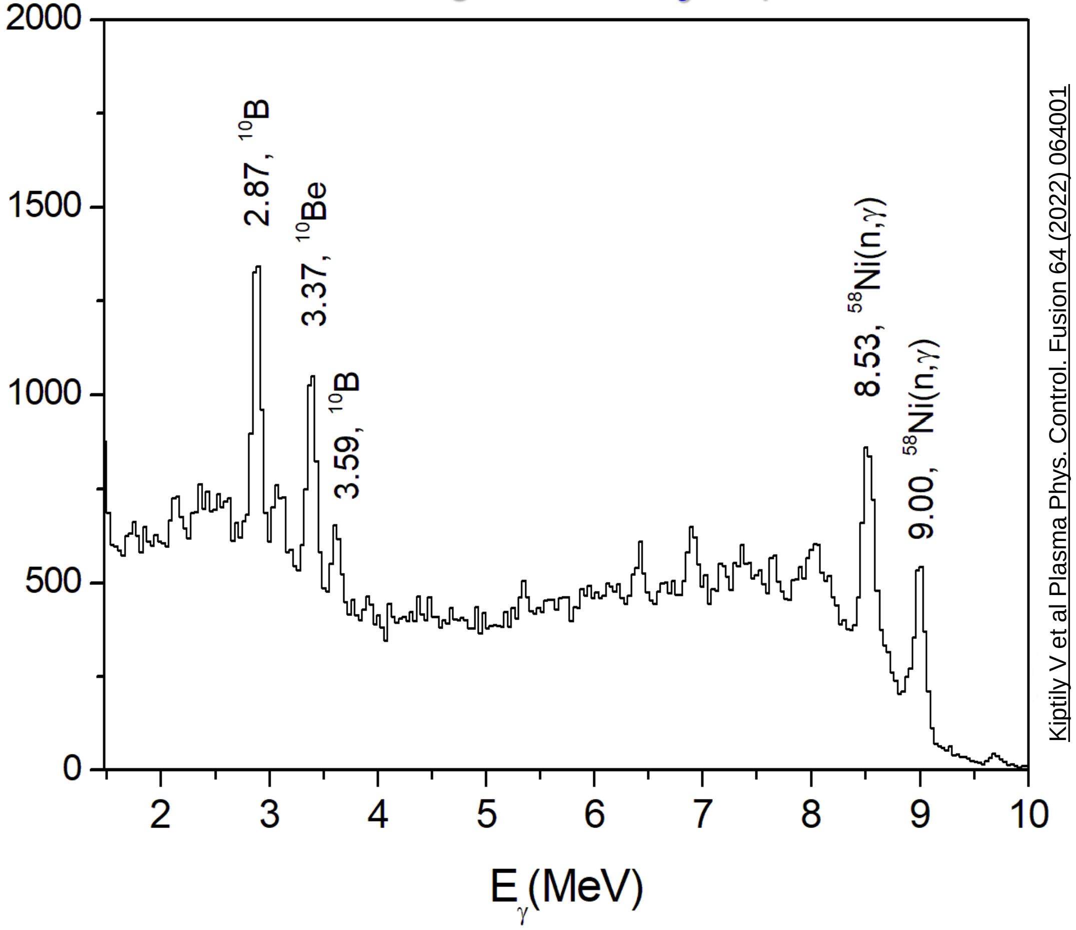
Curuia M. et al, Fusion Engineering and Design 123 (2017) 749–753

Fast-ion studies on JET:
γ-ray spectrometry

Vertical High-resolution HpGe – spectrometer

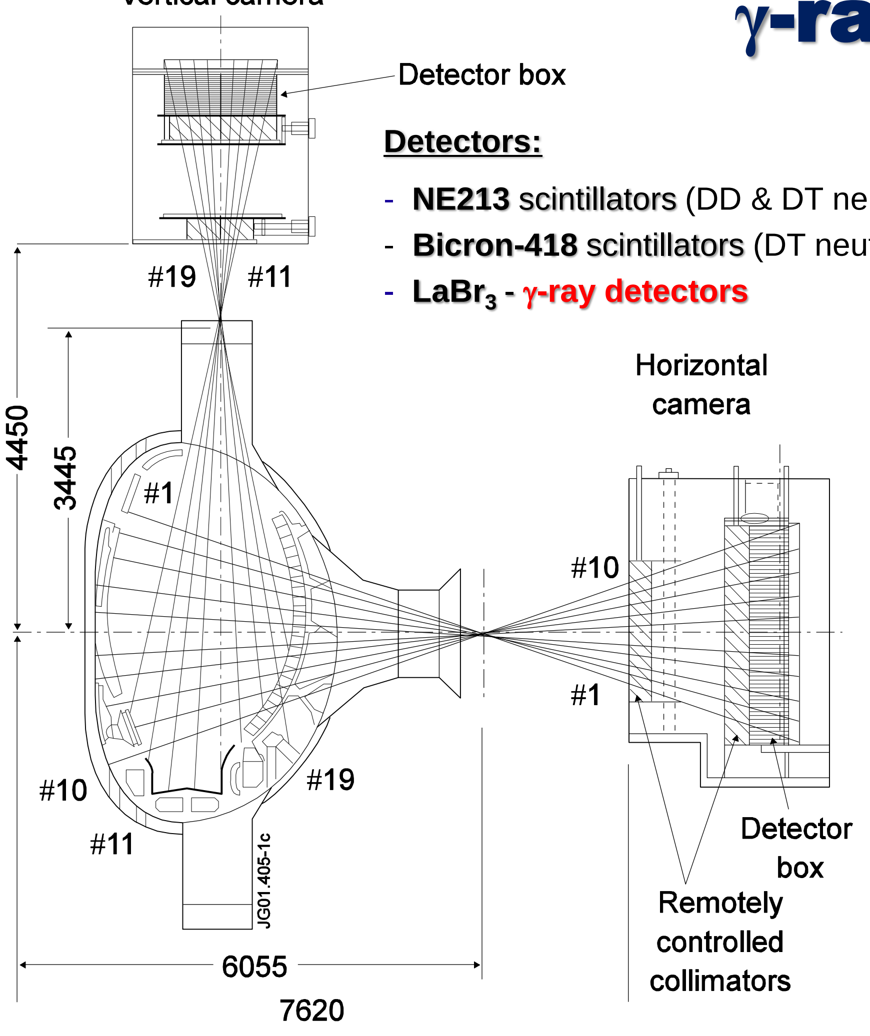


Horizontal tangential $LaBr_3$ – spectrometer



Fast-ion studies on JET:

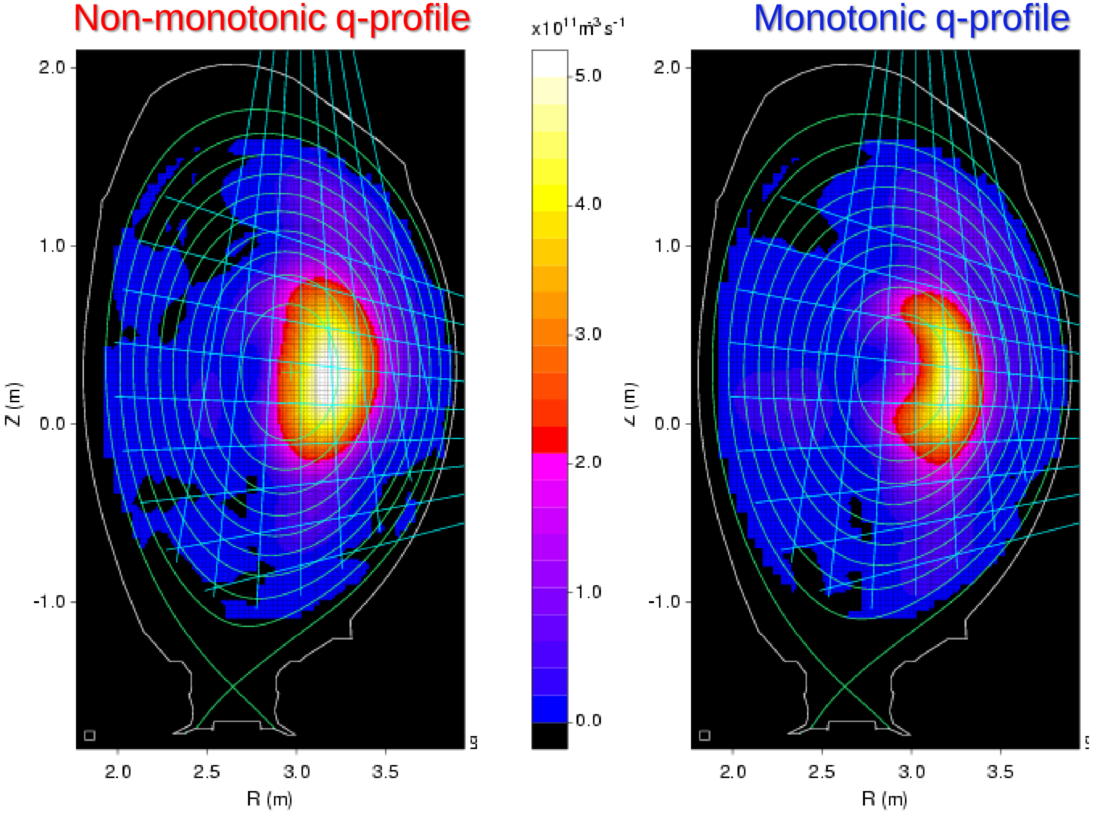
γ-ray tomography



Detectors:

- **NE213** scintillators (DD & DT neutrons)
- **Bicron-418** scintillators (DT neutrons)
- **$LaBr_3$** - **γ-ray detectors**

γ-ray images of ^{4}He-ions with energies E_{4He}>2 MeV



Kiptily V et al 2005 Nucl. Fusion 45 L21

4.44MeV γ-ray emission from the reaction $^9Be(^4He,n\gamma)^{12}C$

Tomographic reconstructions of γ-ray profiles measured in different q-profile phases of the plasma discharge

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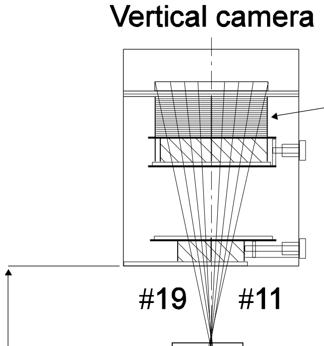
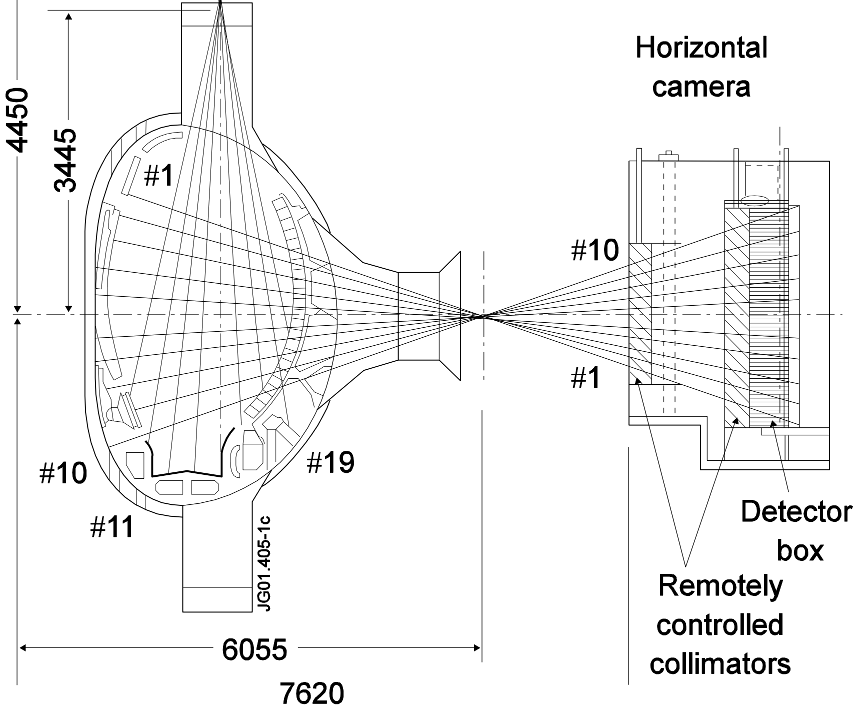
Fast-ion studies on JET:

γ-ray tomography

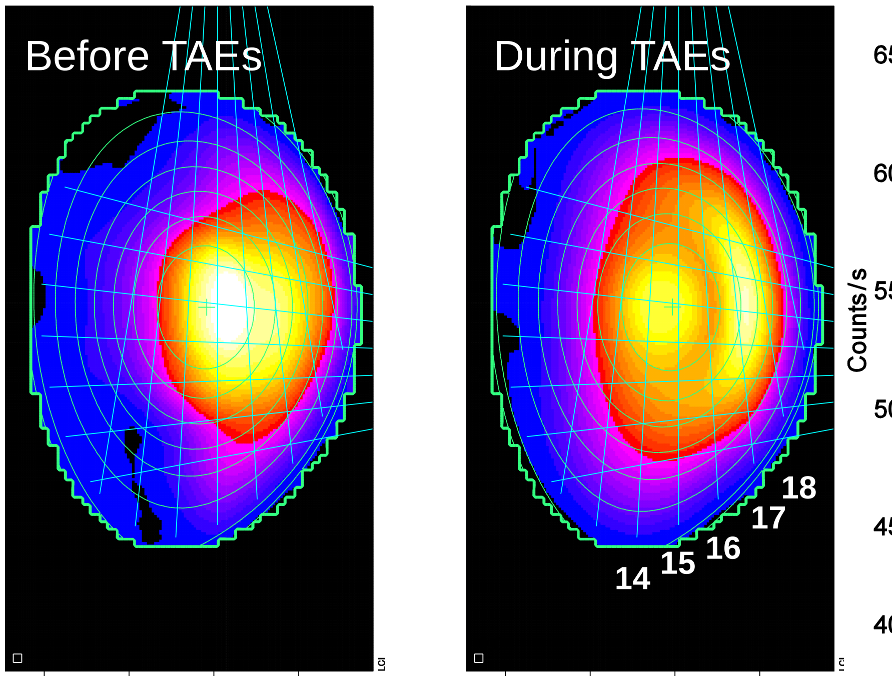


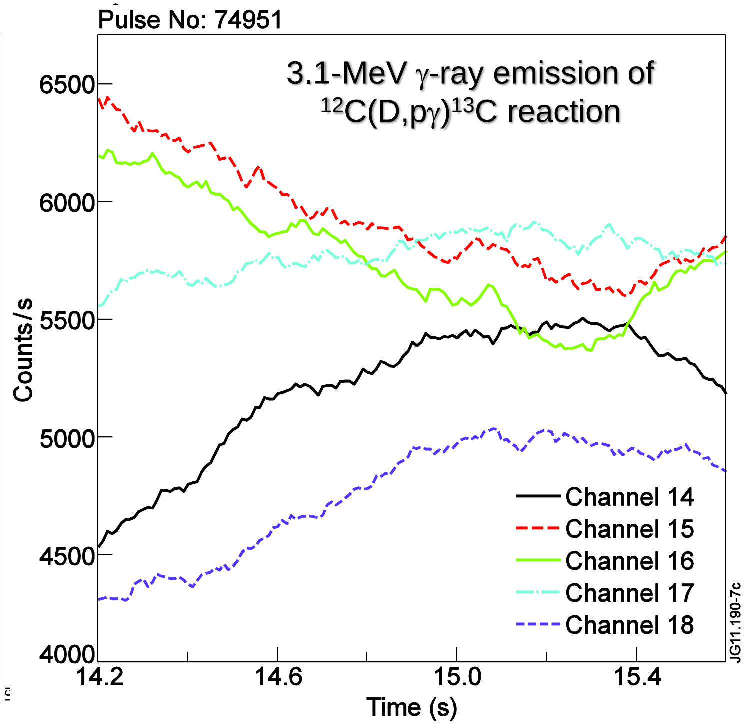
Detectors:

- **NE213** scintillators (DD & DT neutrons)
- **Bicron-418** scintillators (DT neutrons)
- **$LaBr_3$** - **γ-ray detectors**



γ-ray images of D-ions
with energies E_D>0.5 MeV

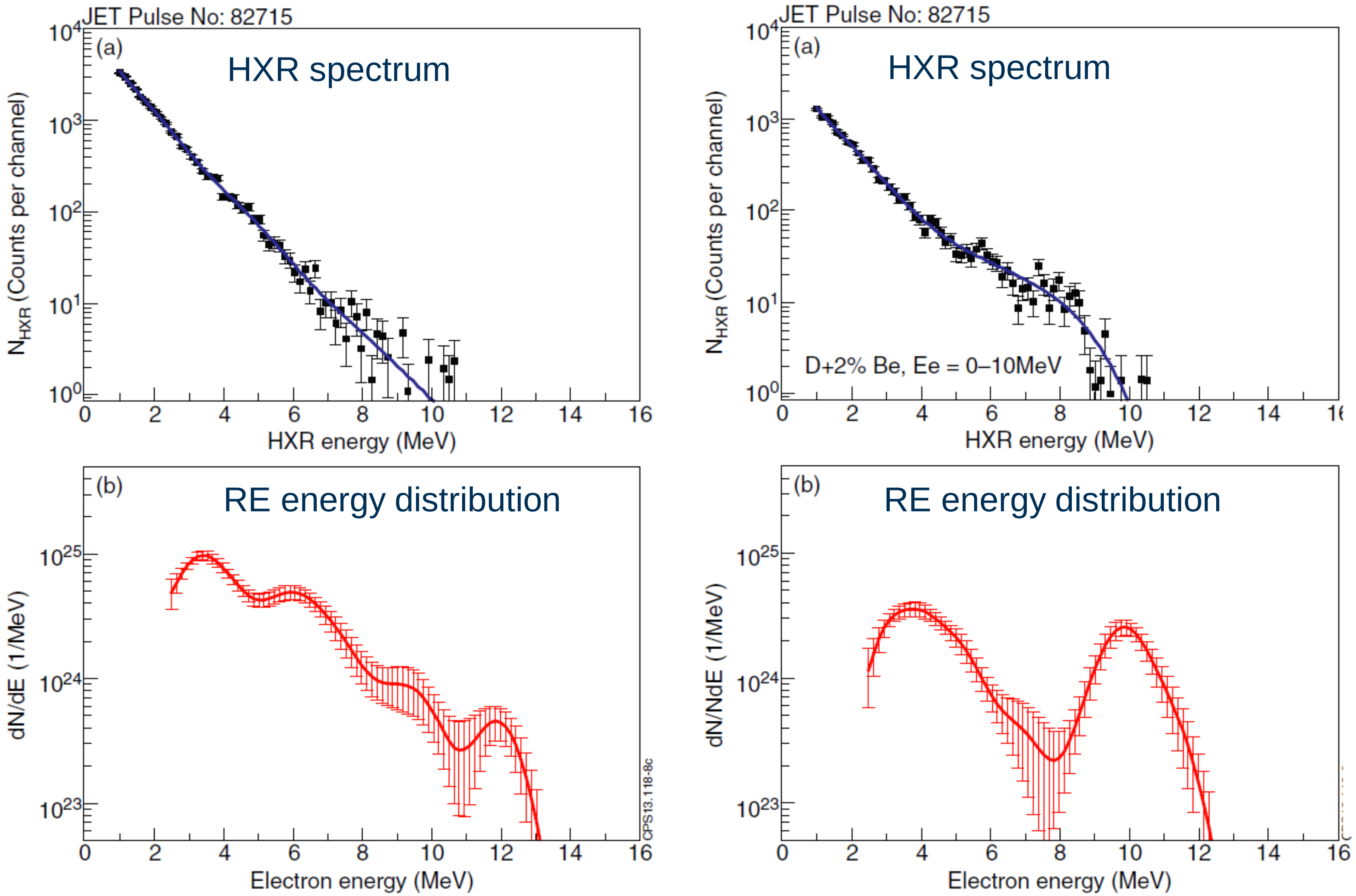




Kiptily V et al 2013 Plasma and Fusion Research: Overview Articles, 8 2502071

Runaway electrons studies on JET:

Start-up & disruption runaways



Shevelev A et al 2013 Nucl. Fusion 53 123004

Gamma-ray diagnostic capabilities in fusion plasma facilities

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- ❑ Setup a plasma discharge
  - ❖ Runaway electrons monitoring
- ❑ Commissioning of auxiliary heating systems
  - ❖ NBI / ICRH characterisation
    - ▪ fast-ions transport
    - ▪ plasma heating performance optimisation
- ❑ Plasma scenario developments (L- , H-modes etc.)
- ❑ Alpha-particle studies

Setup a plasma discharge

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Basic diagnostics of fusion devices:

- neutron monitors (i.e. fission chambers etc.) & fast HXR monitors
- etc.

Beneficial add-on:

- gamma-ray detectors could provide RE distributions

Indeed, in any plasma discharge γ-ray detectors provide :

- ✓ HXR spectrum, if REs are generated during start-up
- ✓ γ-ray spectrum due to fast-ions in the NBI / ICRF heating phase;
- ✓ HXR spectrum is recorded in the case of a disruption

Commissioning of auxiliary heating systems

Characterisation of NBI heating

- H-beam in H-, D-, T- and He-plasmas
- D-beam in H-, D- and T-plasmas

Characterisation of ICRF heating

- ^{3}He-minority in H-, D- & DT-plasmas
- H-minority in D- and DT-plasmas
- 3-ion ICRH schemes

Characterisation of H-NBI heating with γ-ray diagnostics

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H-ions transport in H-, D- & T-plasmas

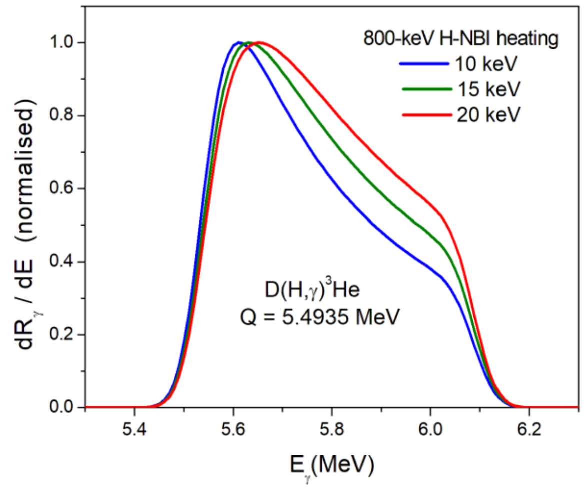
Reaction	Energy of reaction, Q (MeV)	Energy of gammas, E_γ (MeV)	Reaction application comments
$D(H,\gamma)^3He$	5.49	5.5	*D*-plasma, E_{NBI} > 200 keV
$T(H,\gamma)^4He$	19.814	20	*T*-plasma; E_{NBI} > 100 keV
$^7Li(H,\gamma)^8Be$	17.255	17.64, 14.6 & ≈ 3	*Li* dope; E_{res} ≈ 441 keV
$^{11}B(H,\gamma)^{12}C$	15.957	4.44, 11.7 & 16.1	*B* dope; E_{res} ≈ 163 keV
$^{12}C(H,\gamma)^{13}N$	1.9435	2.365	*C* impurity; E_{Res} ≈ 457 keV

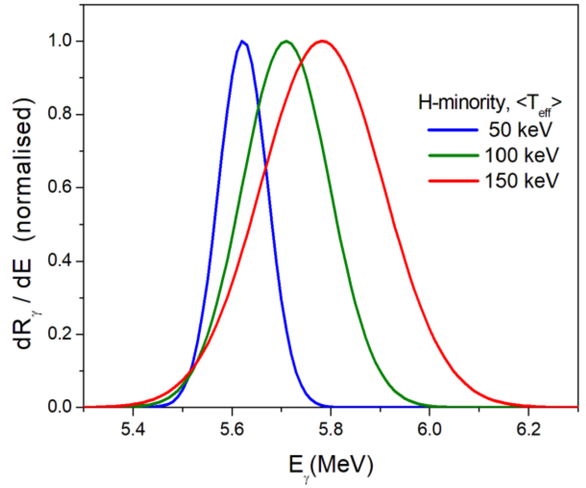
Characterisation of ICRF heating with γ-ray diagnostics

H-minority in D- & T-plasmas

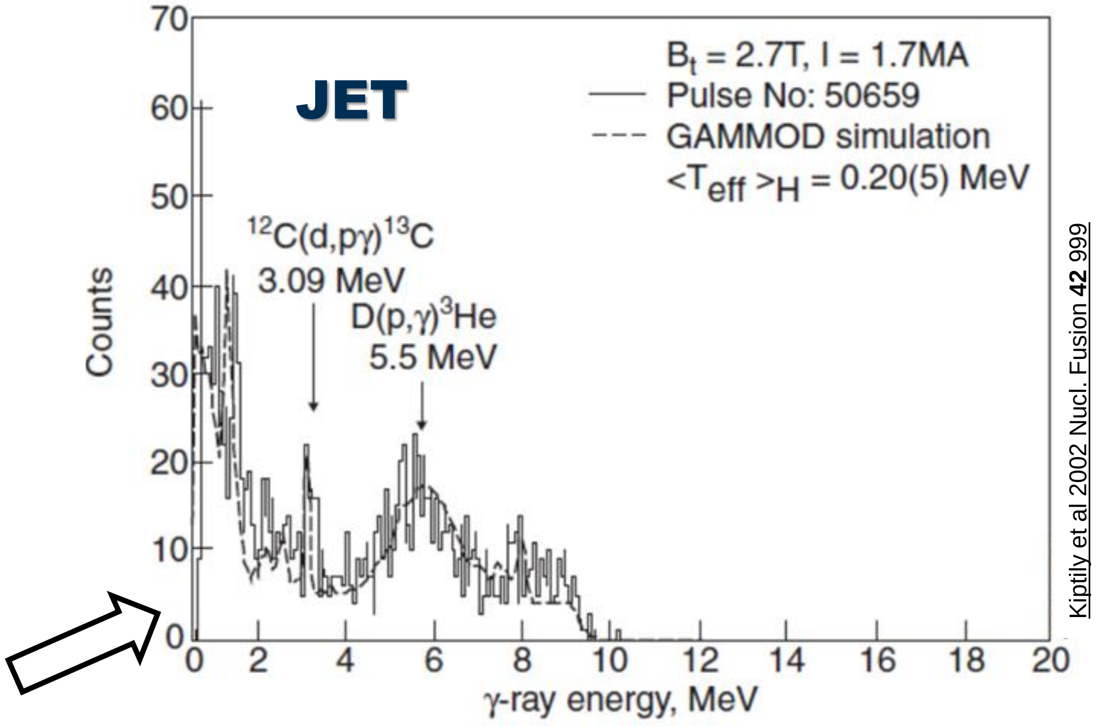
Reaction	Energy of reaction, Q (MeV)	Energy of gammas, E_γ (MeV)	Reaction application comments
$D(H,\gamma)^{3}He$	5.49	5.5	*D*-plasma; effective T_H < 300 keV
$T(H\gamma)^{4}He$	19.814	20	*T*-plasma; Effective T_H > 50 keV
$^{7}Li(H,\gamma)^{8}Be$	17.255	17.64, 14.6 & ≈ 3	*Li* dope; E_{Res} ≈ 441 keV
$^{11}B(H,\gamma)^{12}C$	15.957	4.44, 11.7 & 16.1	*B* dope; E_{Res} ≈ 163 keV
$^{11}B(H,p_1\gamma)^{11}B$	-	2.125	*B* dope; E_H > 2.6 MeV
$^{12}C(H,\gamma)^{13}N$	1.9435	2.365	*C* impurity; E_{Res} ≈ 457 keV

Measurements of energetic H-ions: NBI or ICRF accelerated in D-plasma





D(p,γ)³He, Q=5.49 MeV



Kiptily et al 2002 Nucl. Fusion **42** 999

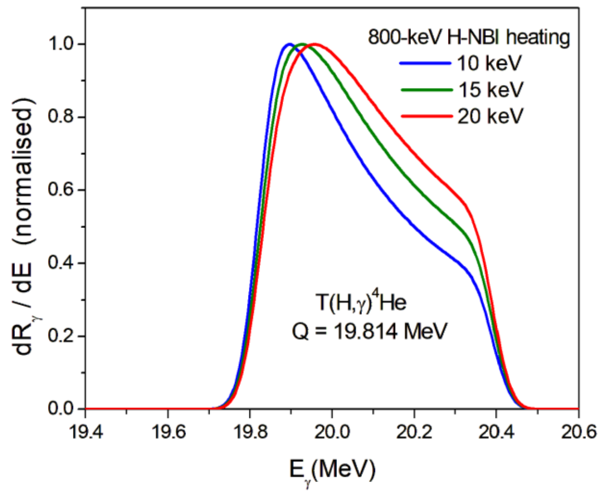
A significant Doppler effect for 5.5-MeV γ-rays is observed due to a high recoil velocity: $v/c \sim 1.5\%$

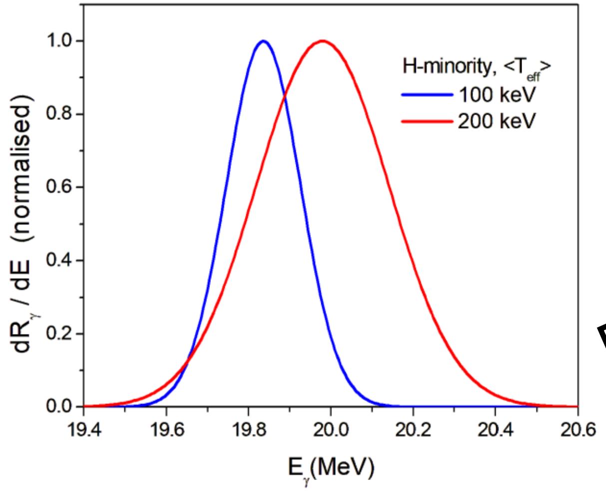
γ-ray spectrum analysis can provide:

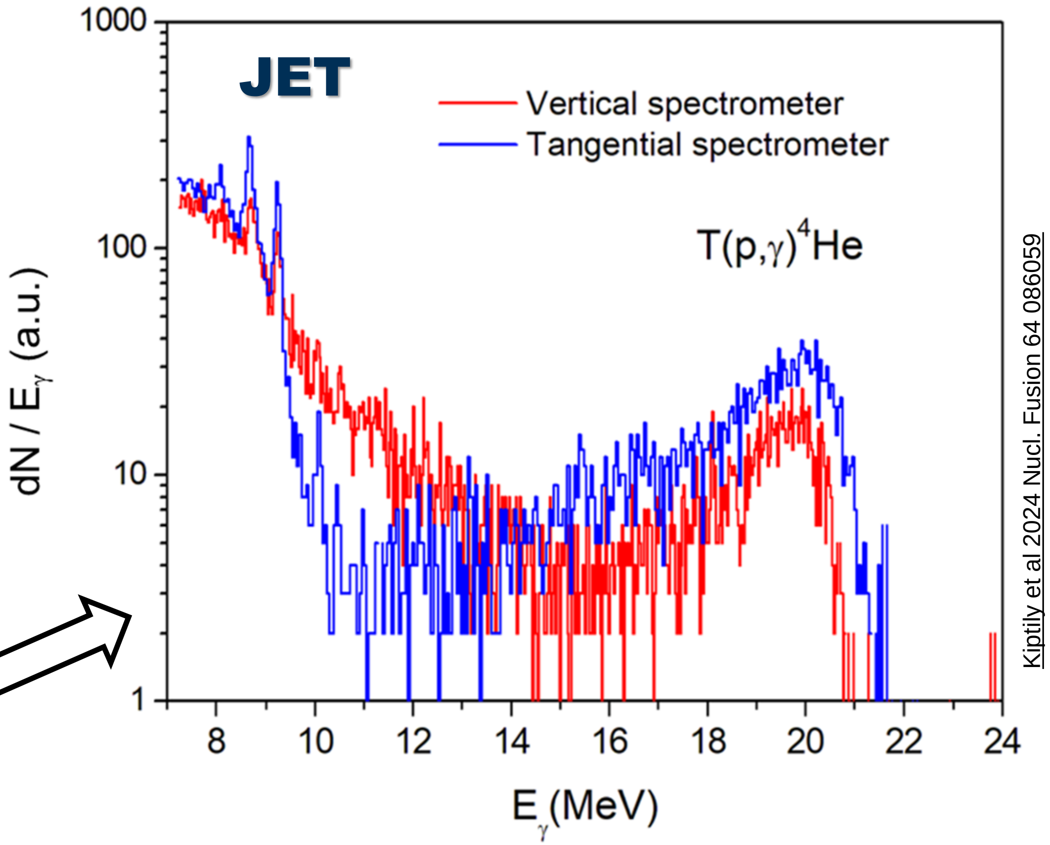
- H-NBI ion-distribution & <Te>
  - Reliable analysis **E_{NBI} > 200 keV**
- $\langle T_H \rangle$ - effective temperature of ICRF accelerated H-minority
  - Reliable $\langle T_H \rangle$ analysis below **300 keV** due to a substantial broadening of the 5.5-MeV γ-peak

Measurements of energetic H-ions: NBI or ICRF accelerated in T-plasma

$T(p,\gamma)^3He$, Q=19.814 MeV







Kiptily et al 2024 Nucl. Fusion 64 086059

Main indicator of H-minority heating in T- & DT-plasmas is 20-MeV γ-rays of $T(p,\gamma)^4He$ reaction

Doppler broadened γ-ray spectrum analysis can provide:

- H-NBI ion-distribution & <Te>
  - Reliable analysis E_{NBI} > **100 keV**
- $\langle T_H \rangle$ - effective temperature of ICRF accelerated H-minority
  - Reliable analysis for T_H > **50 keV**

Boron reactions with H-ions

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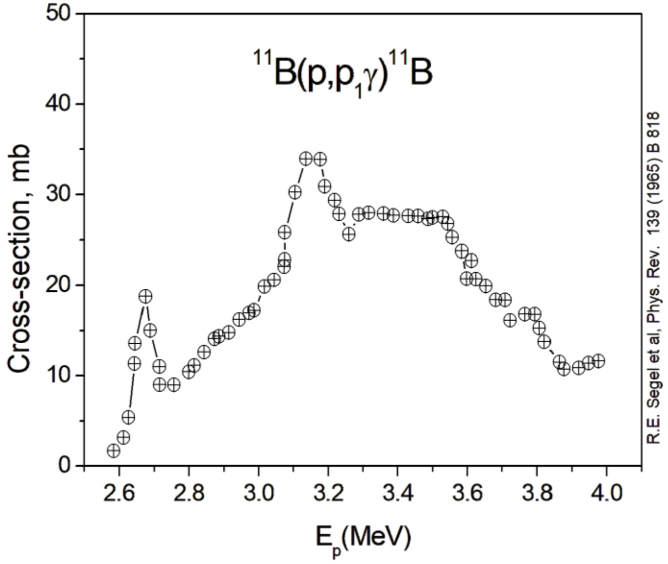
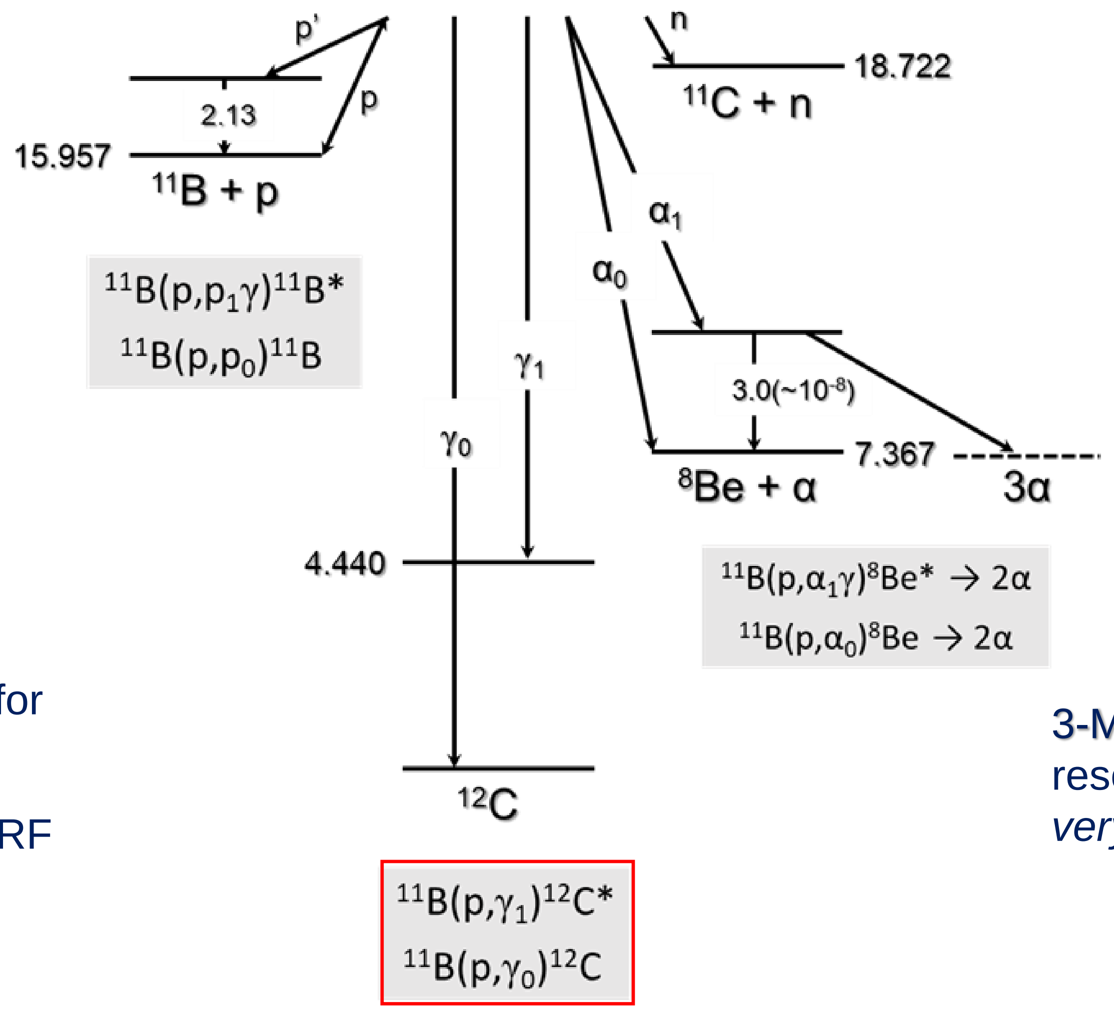
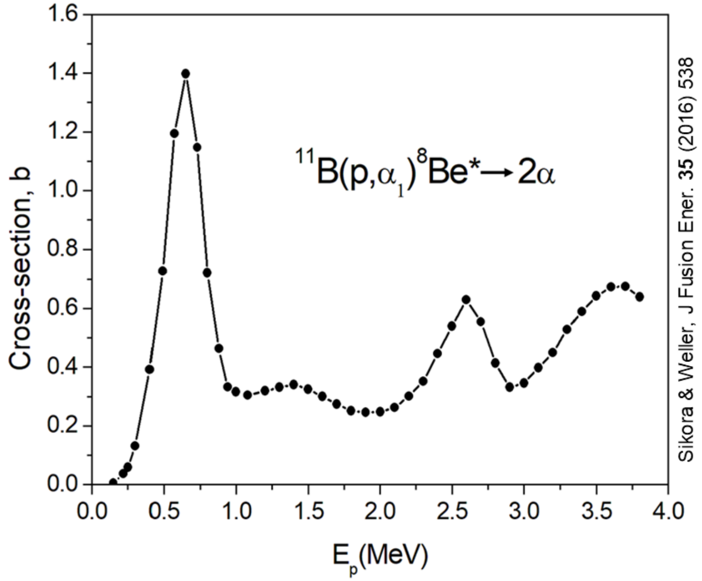
$p + {}^{11}B \rightarrow {}^{12}C^*(15.957 + E_{c.m.})$







$^{11}B(p,p_1\gamma)^{11}B$ reaction can be useful for H-minority heating characterisation:

- 2.13-MeV γ-rays indicate that ICRF H-ion tail is over 2.6 MeV

3-MeV γ-ray yield from the $^{11}B(p,\alpha_1\gamma)^{12}C$ resonant reaction ($E_{Res} \approx 0.65$ MeV) is *very weak:*

$$\frac{^{11}B\,(p,\alpha_1\gamma)^{8}Be \rightarrow 2\alpha}{^{11}B\,(p,\alpha_1)^{8}Be \rightarrow 2\alpha} \sim 10^{-8}$$

Resonant $^{11}B(p,\gamma)$-reaction

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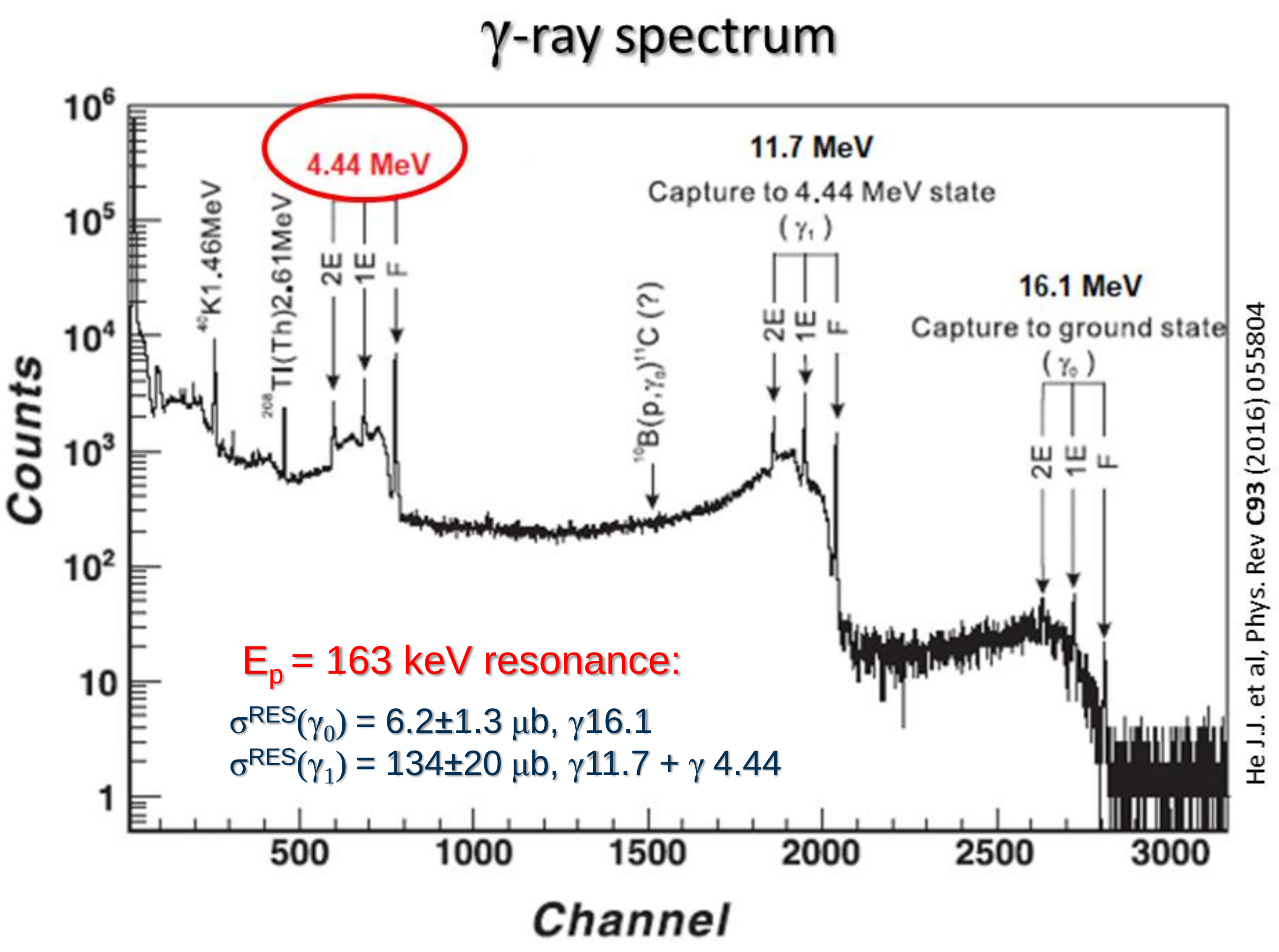
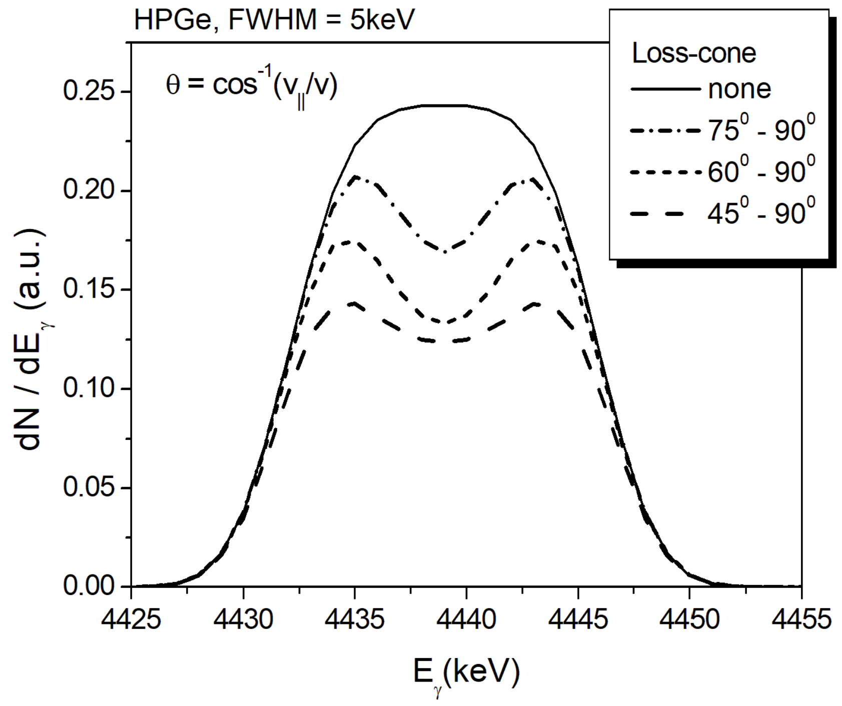


E_p = 163 keV resonance:

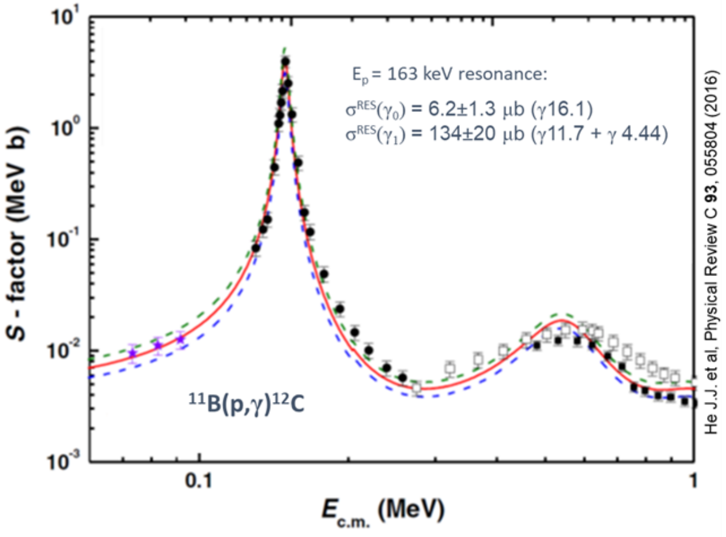
$\sigma^{RES}(\gamma_0)$ = 6.2±1.3 μb, γ16.1

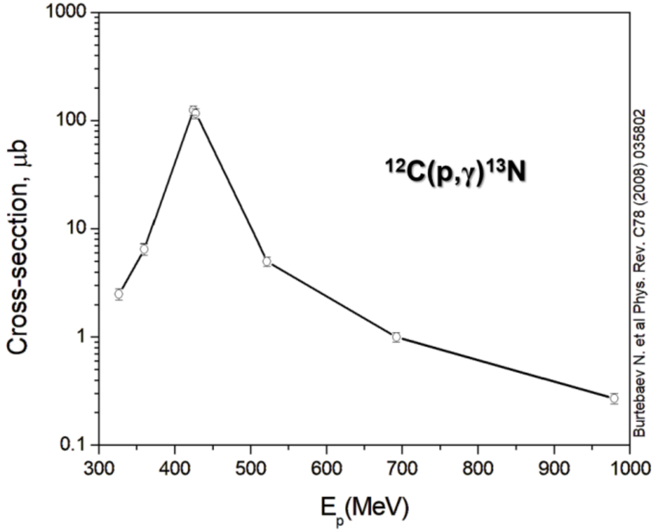
$\sigma^{RES}(\gamma_1)$ = 134±20 μb, γ11.7 + γ 4.44

- $^{11}B(p,\gamma)^{12}C$ reaction gammas can provide information on H-ion heating performance
- Doppler broadening of the recorded 4.44-MeV γ-line in oblique LoS is rather sensitive to H-ion losses



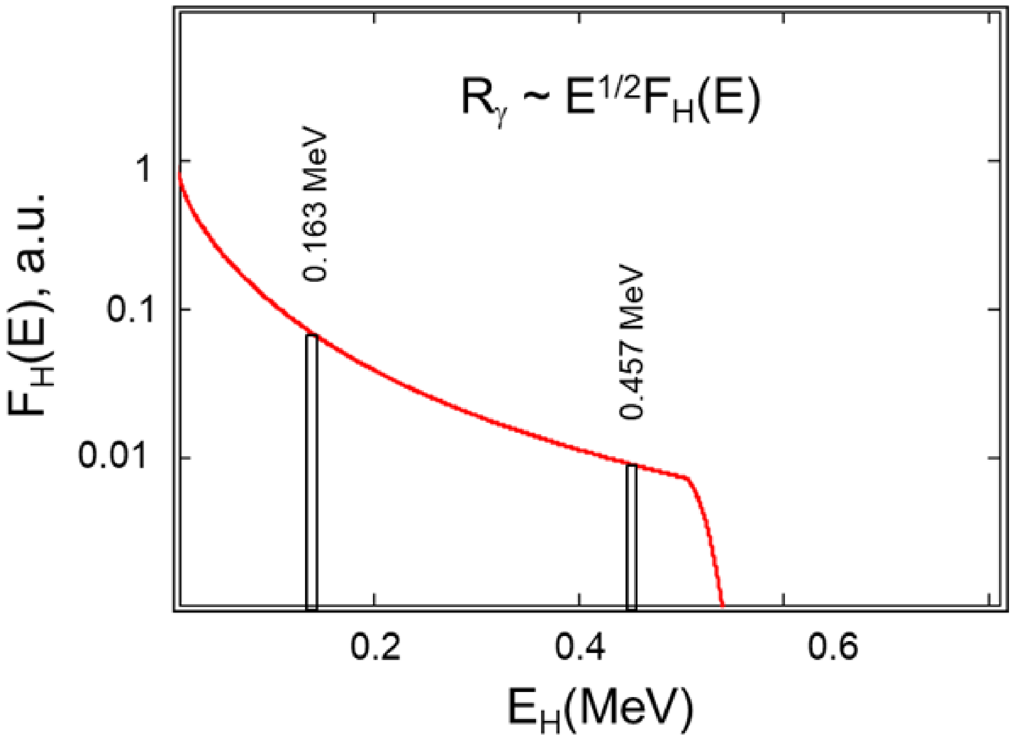
Characterisation H-NBI with $^{11}B(p,\gamma)$ & $^{12}C(p,\gamma)$ reactions





Control H-beam ion transport measuring rate of 4.44-MeV & 2.37-MeV gammas

- 4.44-MeV γ-rays from the $^{11}B(p,\gamma)^{12}C$ resonant reaction at $E_{Res} \approx 0.163$ MeV
- 2.365-MeV γ-rays from the $^{12}C(p,\gamma)^{13}N$ resonant reaction at $E_{Res} \approx 0.457$ MeV



Characterisation of D-NBI heating with γ-ray diagnostics

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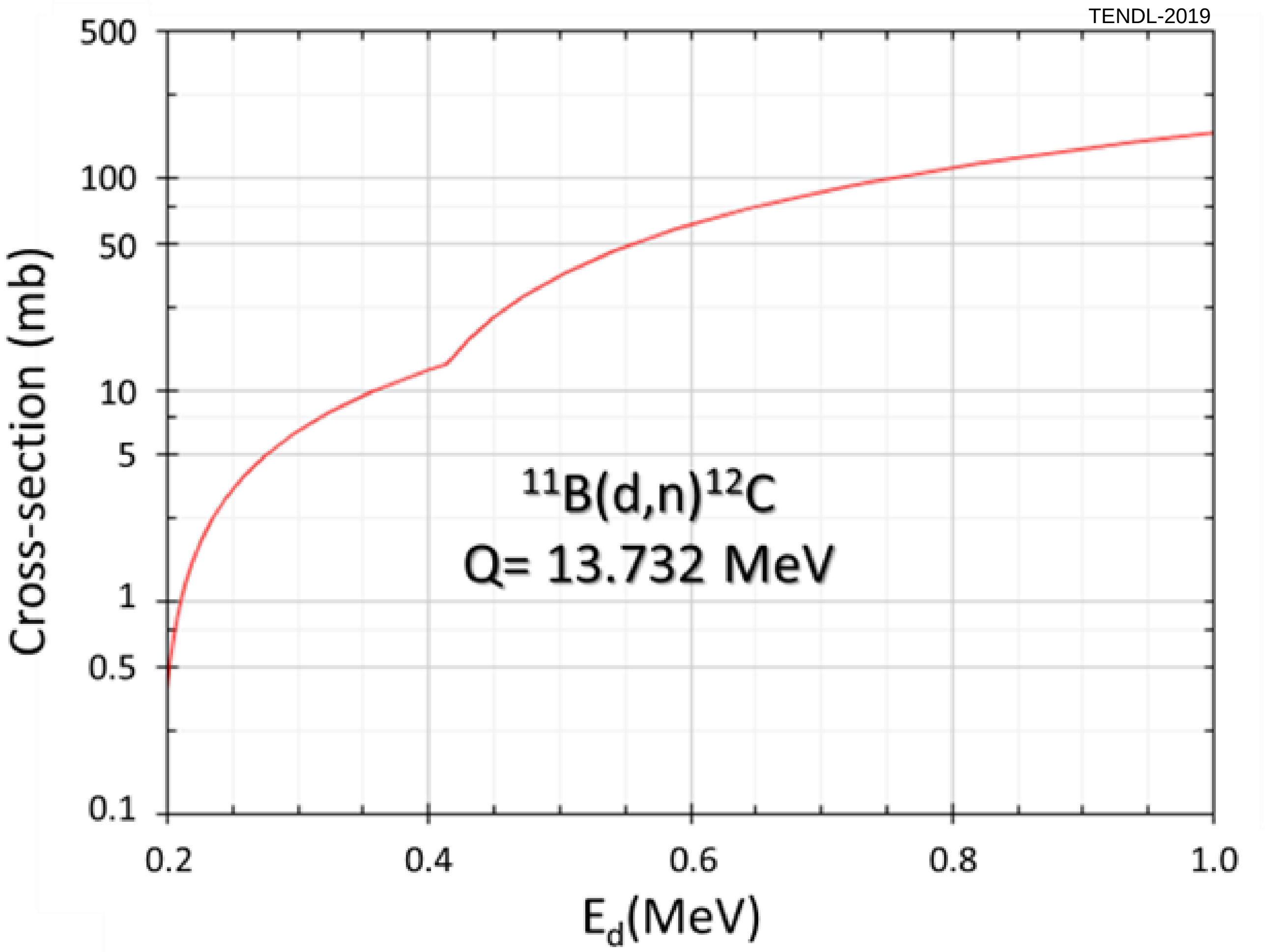
D-ions transport in H-, D-, T-, He- & D^3He-plasmas

Reaction	Energy of reaction, Q (MeV)	Energy of gammas, E_γ (MeV)	Reaction application comments
$H(D,\gamma)^3He$	5.49	5.5	*H*-plasma, E_{NBI} > 400 keV
$D(D,\gamma)^4He$	23.85	E_γ (MeV) = Q + $0.5E_D$	*D*-plasma; σ ~ 0.1 μb @ 1-MeV D-beam
$T(D,\gamma)^5He$	16.79	17 & 15	NBI performance & α-particles generation
$^3He(D,\gamma)^5Li$	16.66	17 & 14	*D^3He* –plasmas; NBI performance & α-particles generation; E_{Res} ≈ 450 keV
$^4He(D,\gamma)^6Li$	1.474	E_γ (MeV) <1.47+ $0.67E_D$	*He*-plasmas
$^6Li(D,n\gamma)^7Be$ $^6Li(D,p\gamma)^7Li$	3.381 5.026	0.429 0.478	*Li* dope, *H*-plasmas
$^{11}B(D,n\gamma)^{12}C$	13.732	4.44, 3.21 & 9.64	*B* dope
$^{12}C(D,p\gamma)^{13}C$	2.722	3.09	*C* impurity; E_D > 0.43 keV

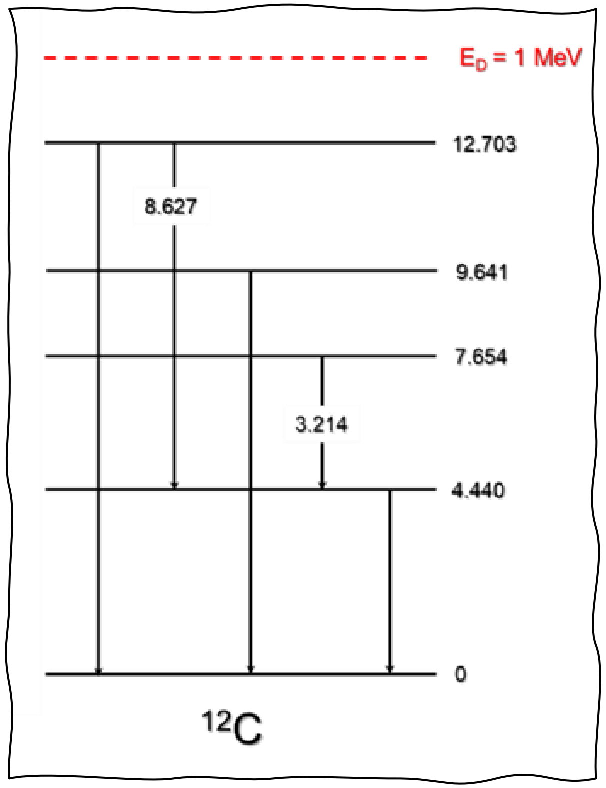
NBI characterisation in plasmas with boron



Amid the possible reactions between D-ions and intrinsic boron,

$^{11}B(d,n\gamma)^{12}C$ reaction

has cross-section, which could provide a necessary γ-ray rate for measurements of D-NBI ions



Gamma-rays:

3.21 MeV
4.44 MeV
8.63 MeV
9.64 MeV
12.70 MeV

Characterisation of ICRF heating with γ-ray diagnostics

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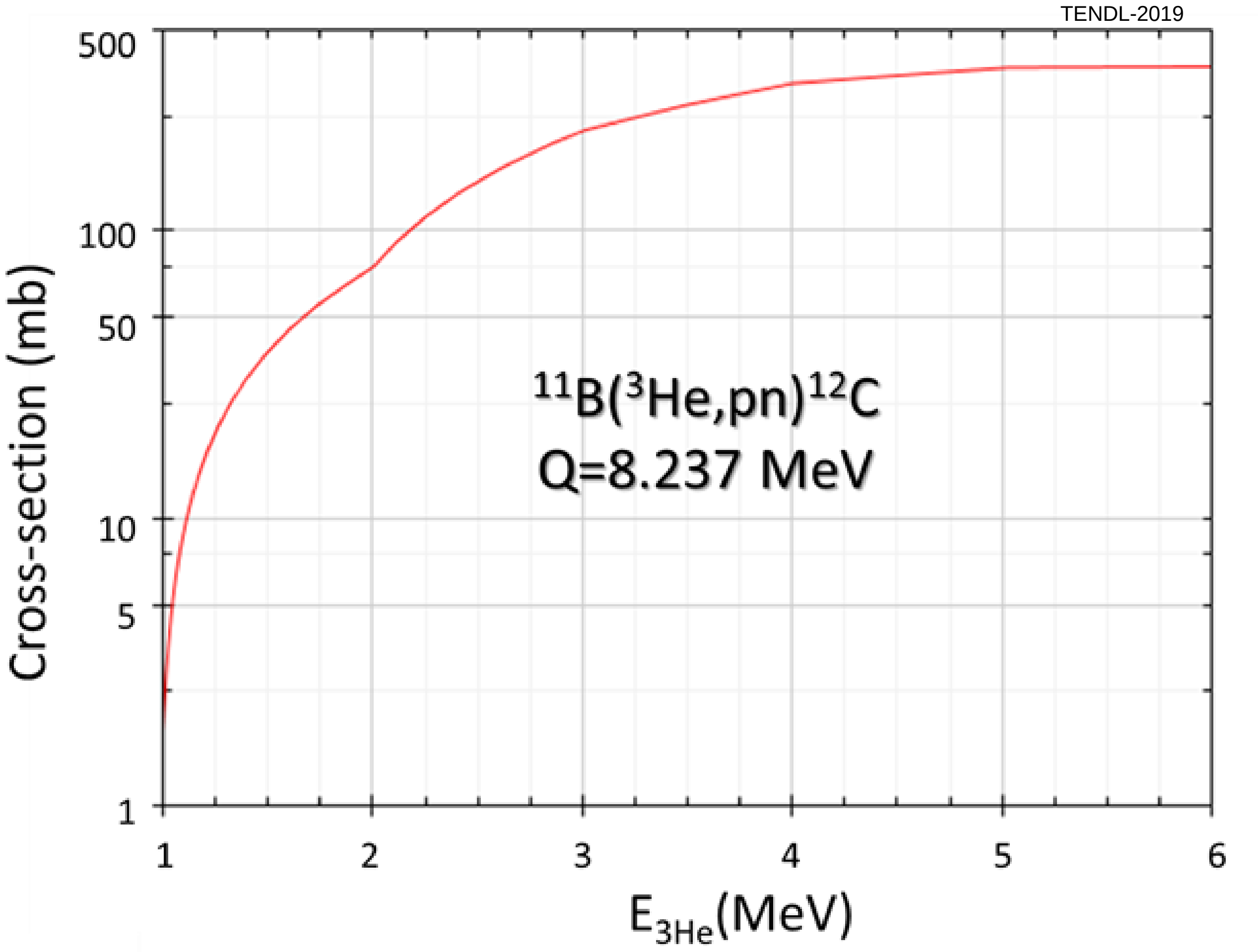
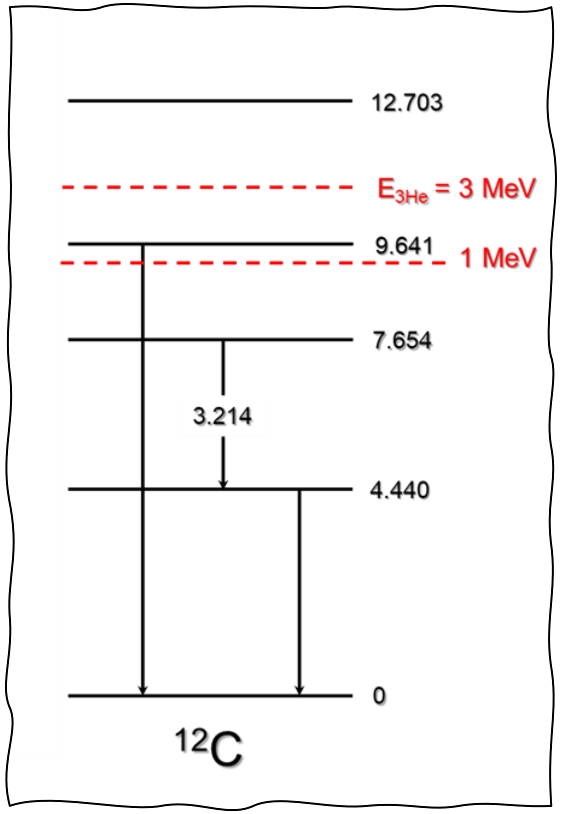
^{3}He-minority in H, D- & T-plasmas

Reaction	Energy of reaction, Q (MeV)	Energy of gammas, E_γ (MeV)	Reaction application comments
$D(^{3}He,\gamma)^{5}Li$	16.66	17 & 15	*D*-plasma; ICRH performance & α-particles generation; $E_{Res} \approx 675$ keV
$^{7}Li(^{3}He,\gamma)^{10}B$	17.788	3.59, 4.77 & $E_\gamma(MeV)=17.788+0.7E_{Res}$	*Li* dope; $E_{Res} \approx 0.92$, 1.44 & 2.16 MeV
$^{11}B(^{3}He,pn\gamma)^{12}C$	8.239	4.44, 3.21 & 9.64	*B* dope
$^{12}C(^{3}He,p\gamma)^{14}N$	4.779	4.914, 2.312 & 1.635	*C* impurity

ICRH(^{3}He) characterisation in H&D-plasmas

^{3}He-ion high-energy tail: E_{3He} > 1 MeV, can be detected with $^{11}B(^3He,pn\gamma)$ reaction





Gamma-rays:

3.21 MeV
4.44 MeV
9.64 MeV

ICRH(^{3}He) characterisation in D-plasmas

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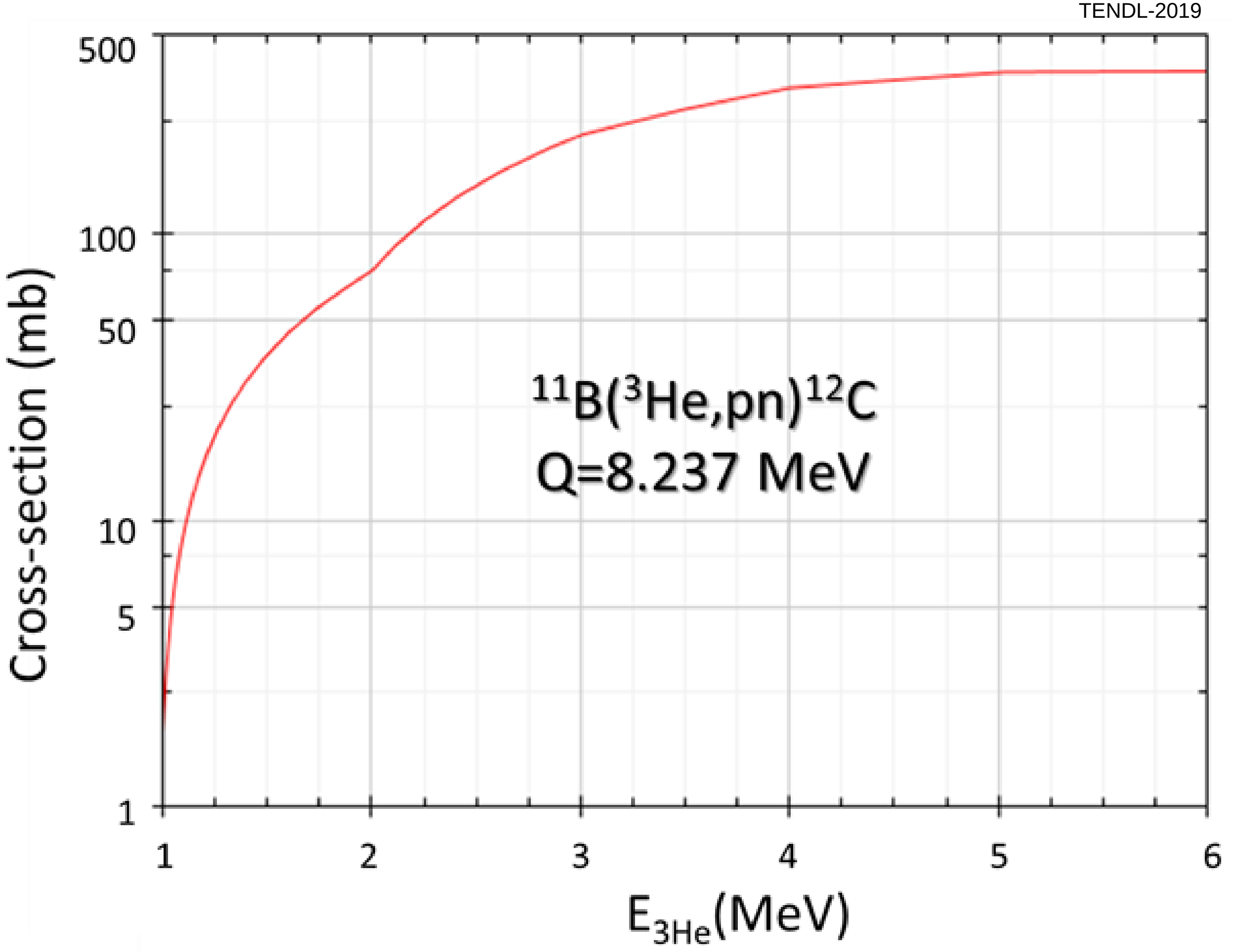
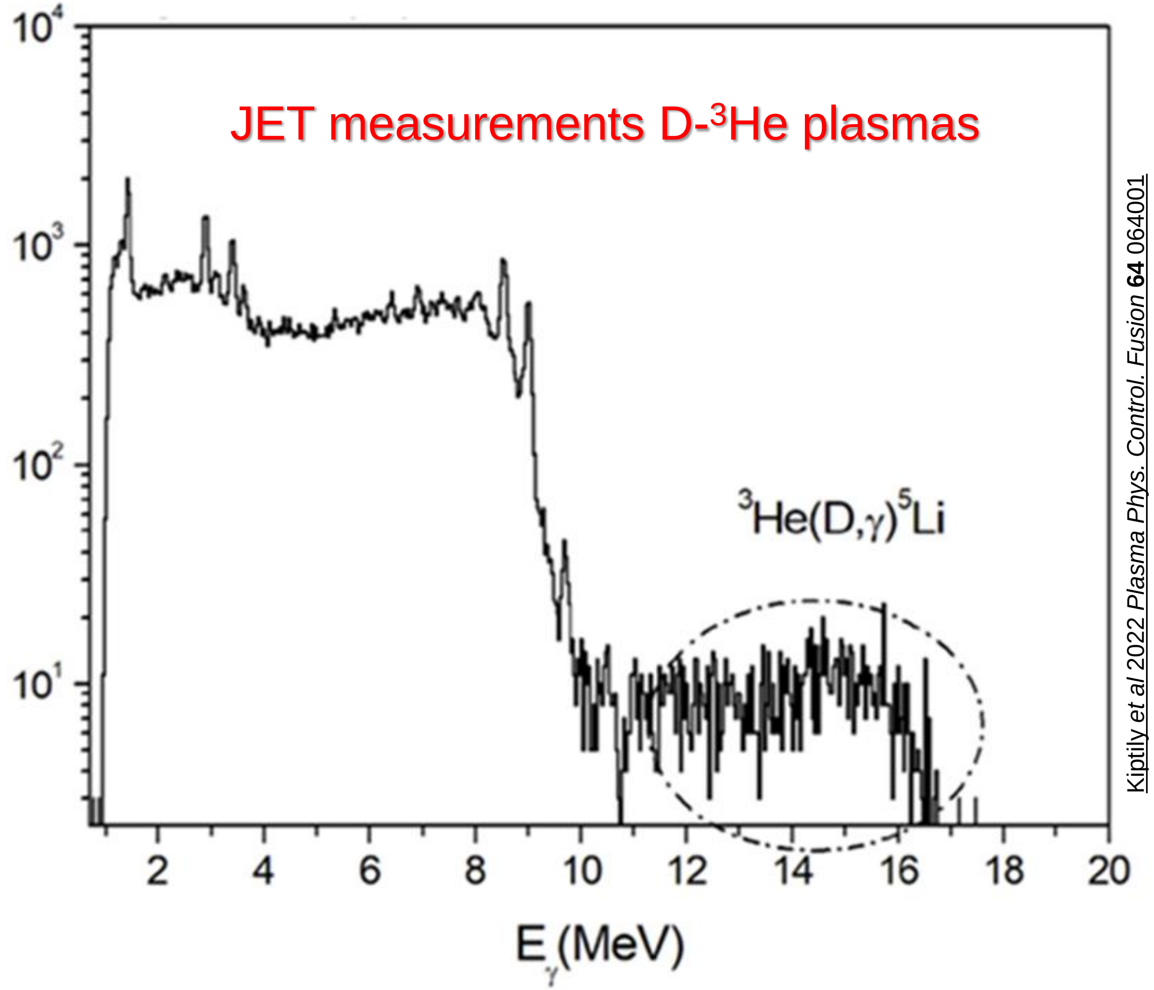
High-energy tail: E_{3He} > 1 MeV



Low-energy tail:

17-MeV γ-ray yield @ E_{Res} ≈0.65 MeV



Kiptily *et al* 2022 *Plasma Phys. Control. Fusion* **64** 064001

Plasma scenario developments with γ-ray diagnostics

Reaction	Energy of reaction, Q (MeV)	Energy of gammas, E_γ (MeV)	Reaction application comments
$D(t,\gamma)^5He$	16.79	17 & 15	*D*-plasma; heating performance by triton burnup monitoring
$^{11}B(t,2n\gamma)^{12}C$	7.475	4.44 & 3.21	*D*-plasma, ***B*** dope; heating performance by triton burnup monitoring
$^{12}C(t,n\gamma)^{14}N$	4.015	2.312 & 1.635	*D*-plasma, ***C*** impurity; heating performance by triton burnup monitoring
$D(T,\gamma)^5He$	16.79	17 & 15	*DT*-plasma: burning plasma performance: α-particle generation rate
$T(p\gamma)^4He$	19.814	20	*DT*-plasma: burning plasma performance; *DD*-protons rate, core temperature & fuel ratio

ICRH characterisation in D-plasmas

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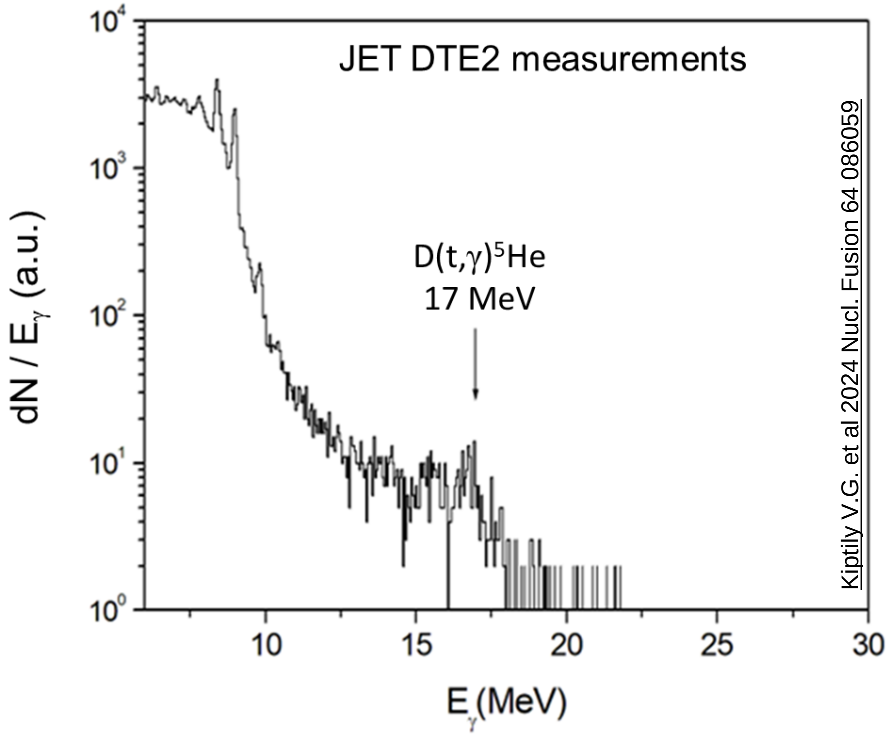
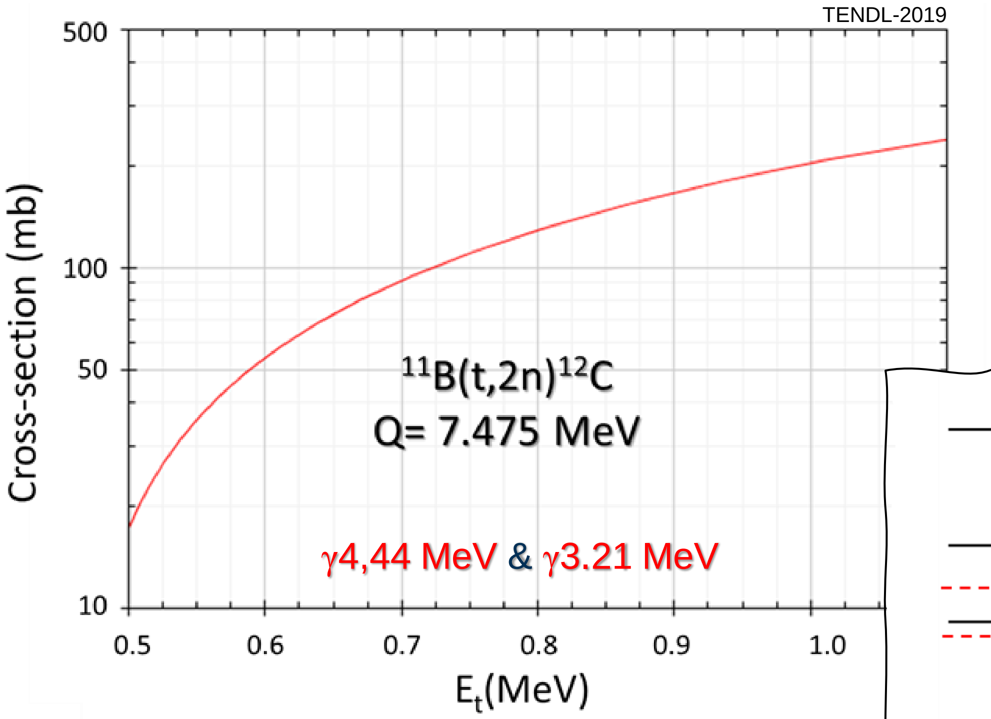
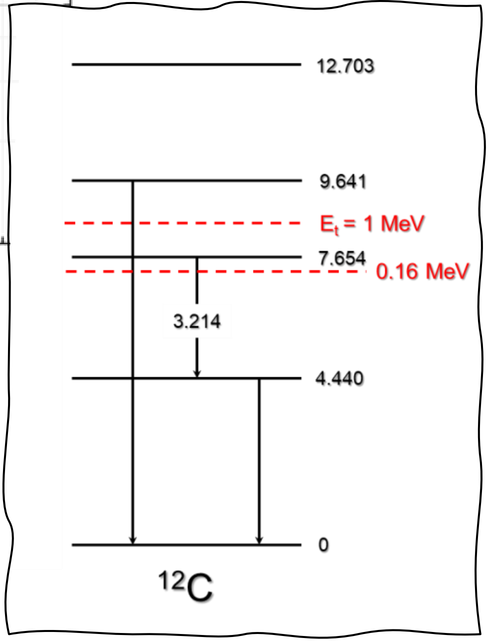
Substantial generation of 1-MeV DD-tritons due to the high-performance ICRF heating



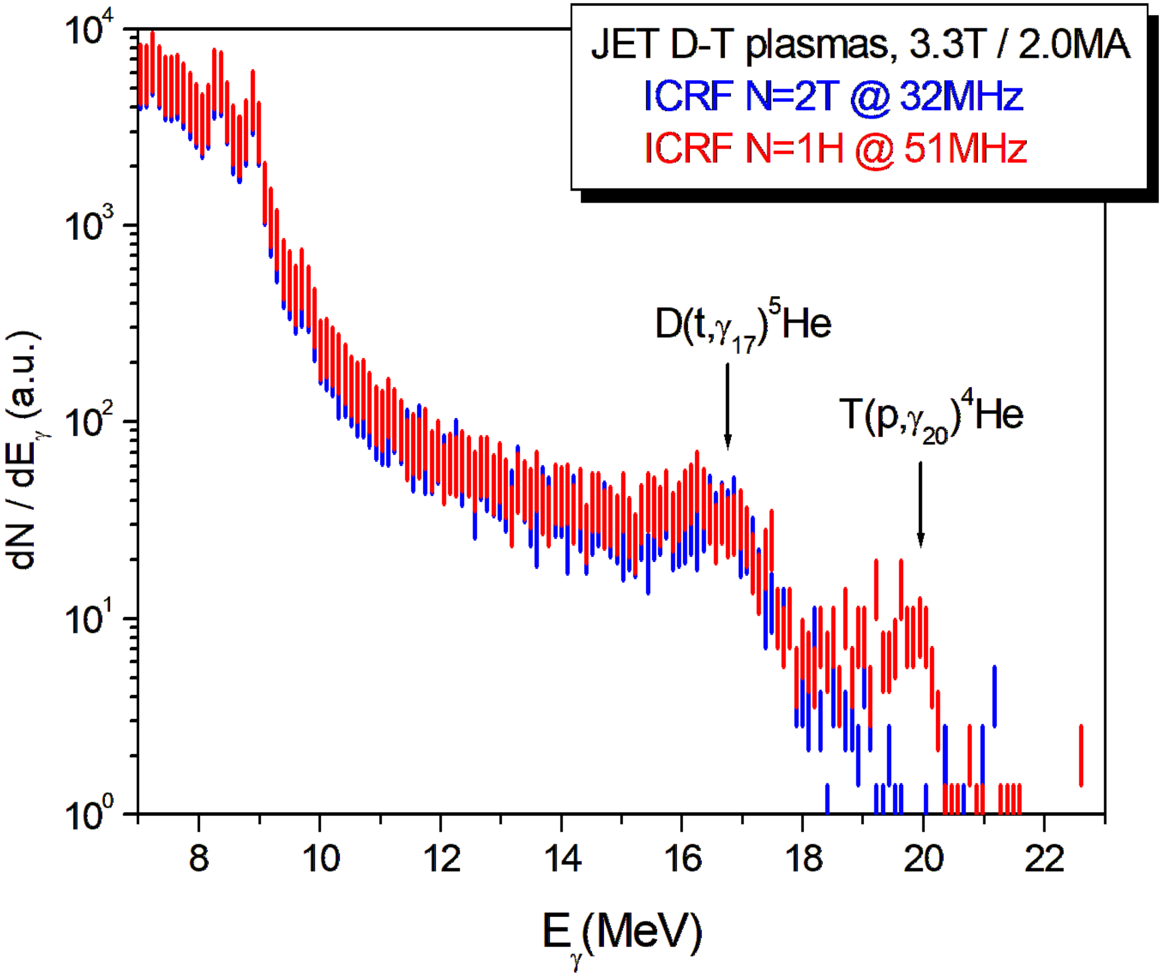




H-minority ICRH performance can be characterised measuring gammas from both $D(t,\gamma)^5He$ and $^{11}B(t,2n\gamma)^{12}C$ reactions:

- γ17-MeV: resonant γ-ray yield @ $E_T \approx 0.16$ MeV
- γ4,44 MeV & γ3.21 MeV: $E_T > 0.25$ MeV

ICRH characterisation in DT-plasmas



Comparison of γ-ray spectra recorded in DTE3 discharges

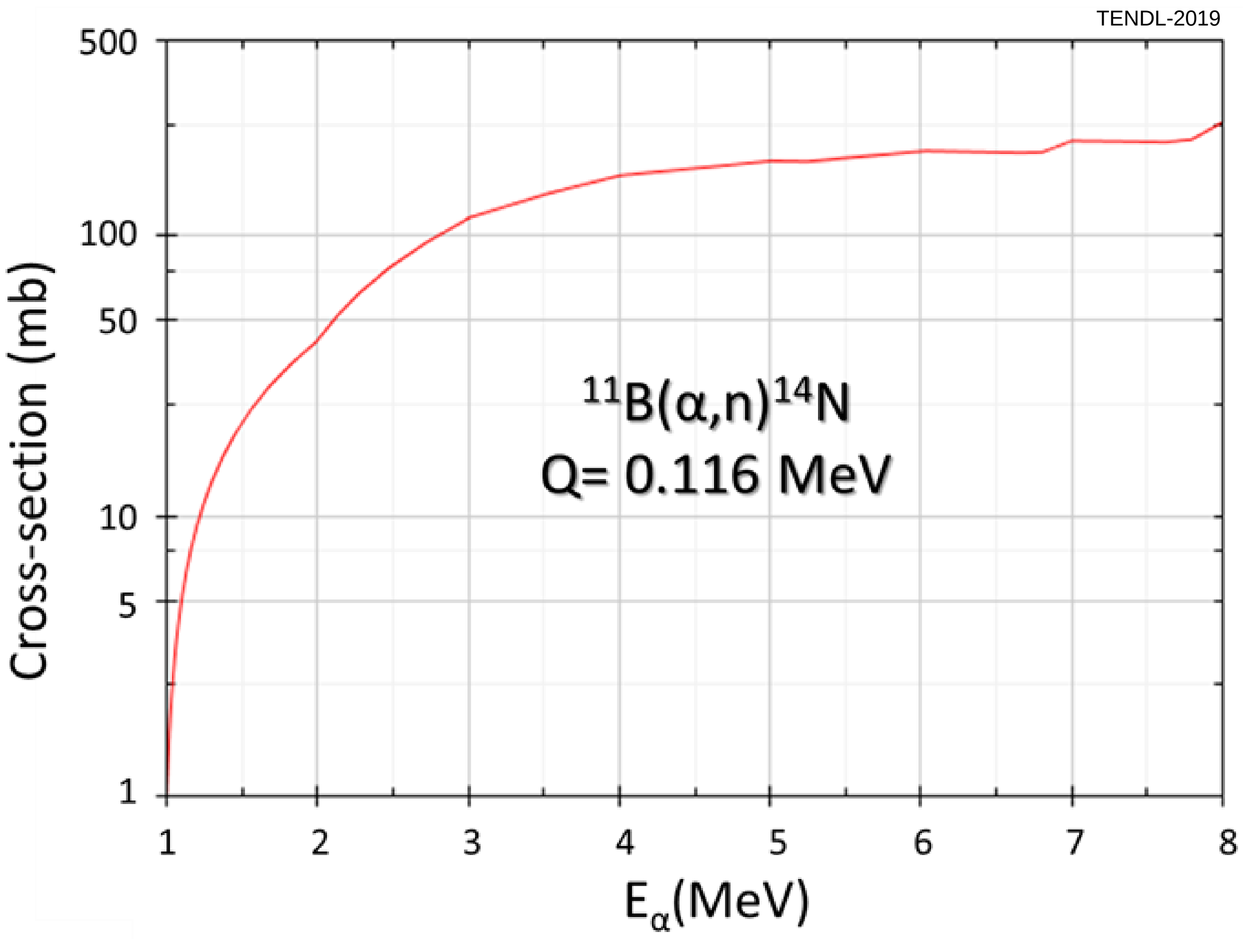
- JET γ-ray measurements show feasibility of the H-minority heating optimisation in D-T plasmas using 17- and 20-MeV γ-rays
- It can be used in ITER DT-phases
- In burning plasmas, $T(p,\gamma)^4He$ & $D(T,\gamma)^5He$ reactions can be used for monitoring both <T_e> & n_D/n_T in the plasma core

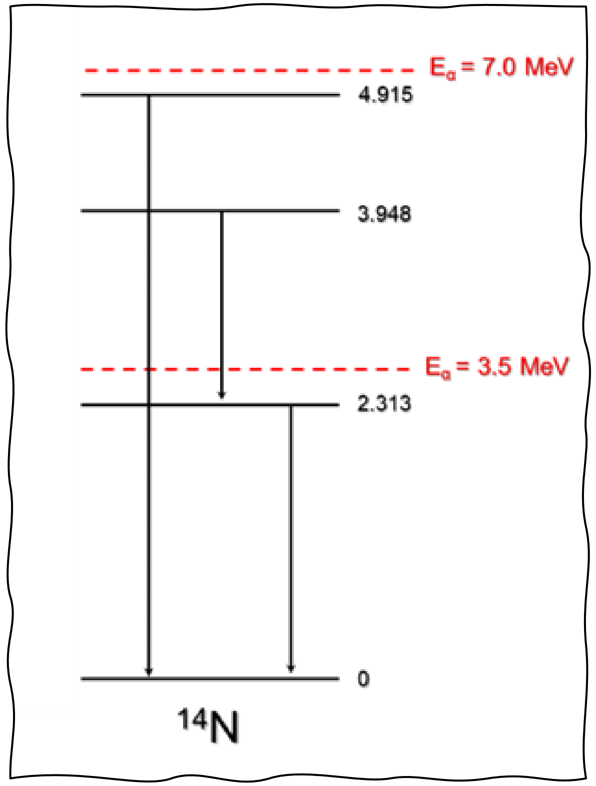
Kiptily V.G. et al 2015 Nucl. Fusion **55** 023008

Alpha-particle study with γ-ray diagnostics

Reaction	Energy of reaction, Q (MeV)	Energy of gammas, E_γ (MeV)	Reaction application comments
$^{7}Li(\alpha,\gamma)^{11}B$	8.66	4.44, 4.74, 4.83, 8.92 & 9.27	*Li* dope; $E_{Res} \approx$ 401, 814 & 958 keV
$^{10}B(\alpha,p\gamma)^{12}C$	4.061	3.09, 3.68 & 3.85	*B* dope; $E_\alpha > 1$ MeV
$^{11}B(\alpha,n\gamma)^{14}N$	0.117	2.313	*B* dope; $E_\alpha > 3$ MeV
$^{22}Ne(\alpha,n\gamma)^{25}Mg$	-0.478	$E_\gamma < 3.4$ MeV	*D^3He* plasmas; *^{22}Ne* seeding

$^{11}B(\alpha,n\gamma)^{14}N$ for α-particle diagnostics





2.313-MeV γ-rays in the energy range of a high background rate

It could be possible to use in D^3He plasmas with boron doping

$^{10}B(\alpha,p\gamma)^{13}C$ for α-particle diagnostics

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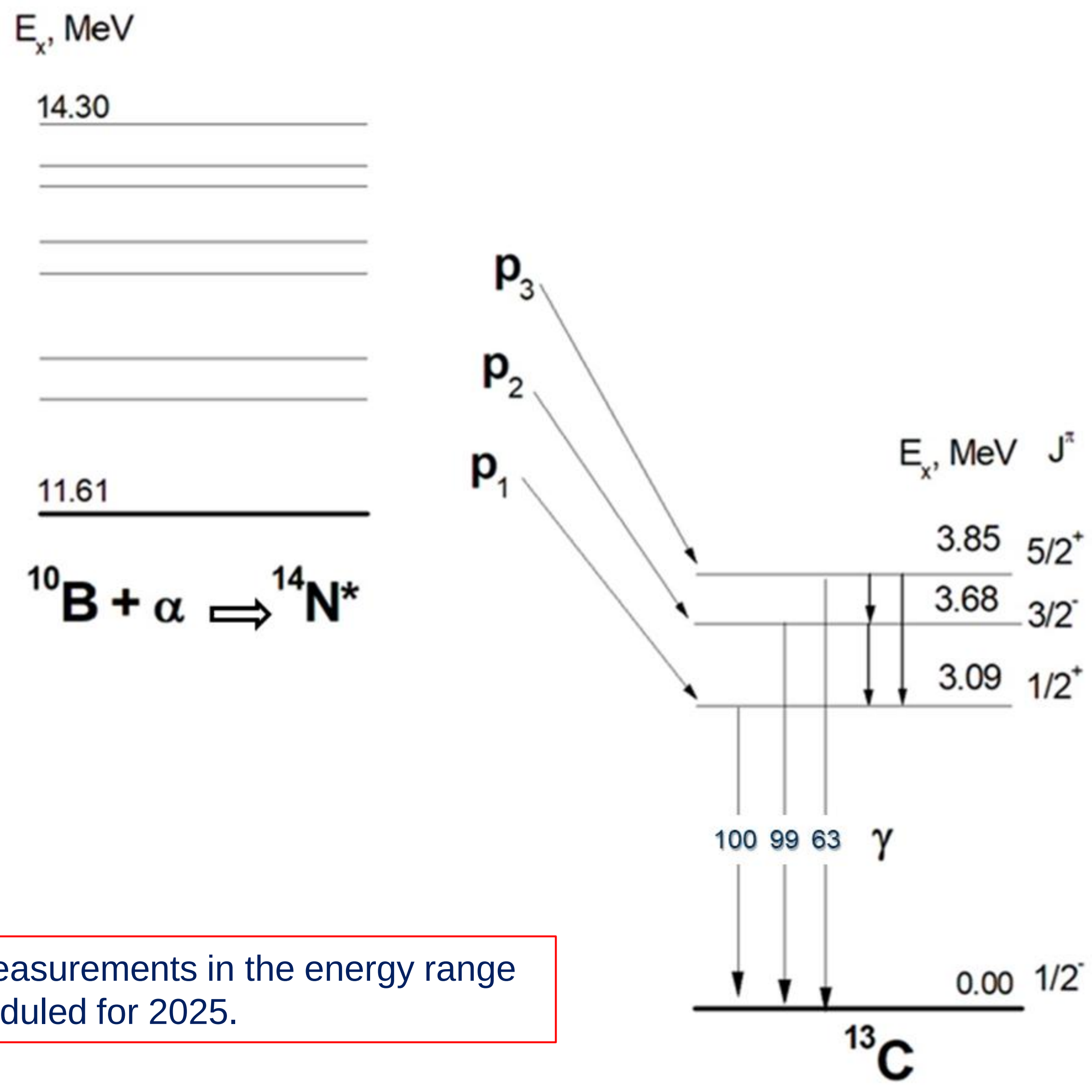

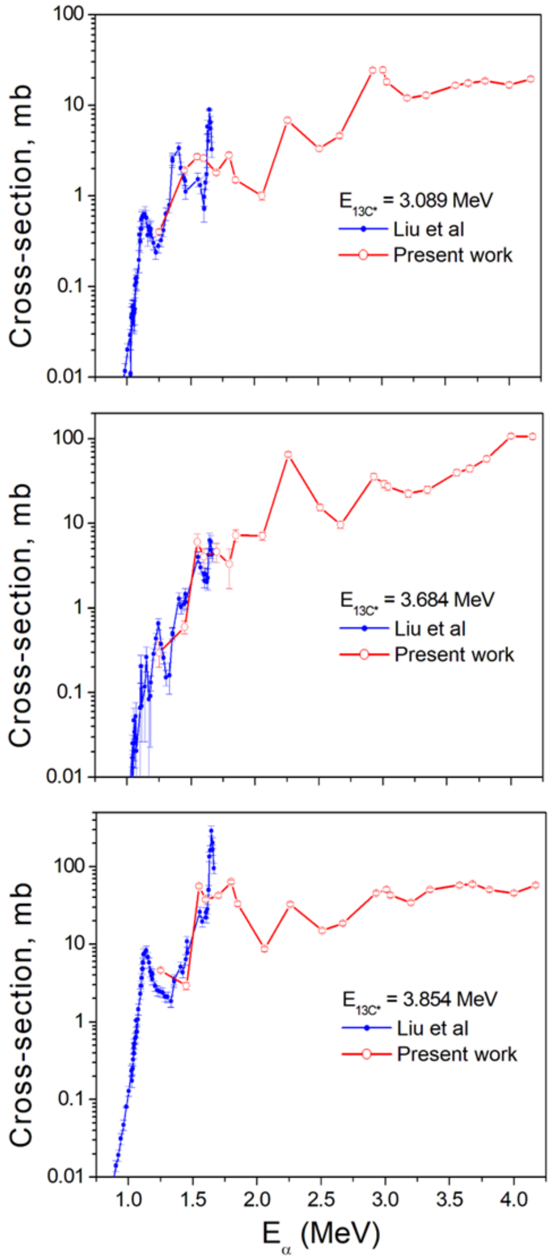

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PS. Cross-section measurements in the energy range E_α > 1 MeV are scheduled for 2025.

$^{22}Ne(\alpha,n\gamma)^{25}Mg$ as α-particle diagnostics

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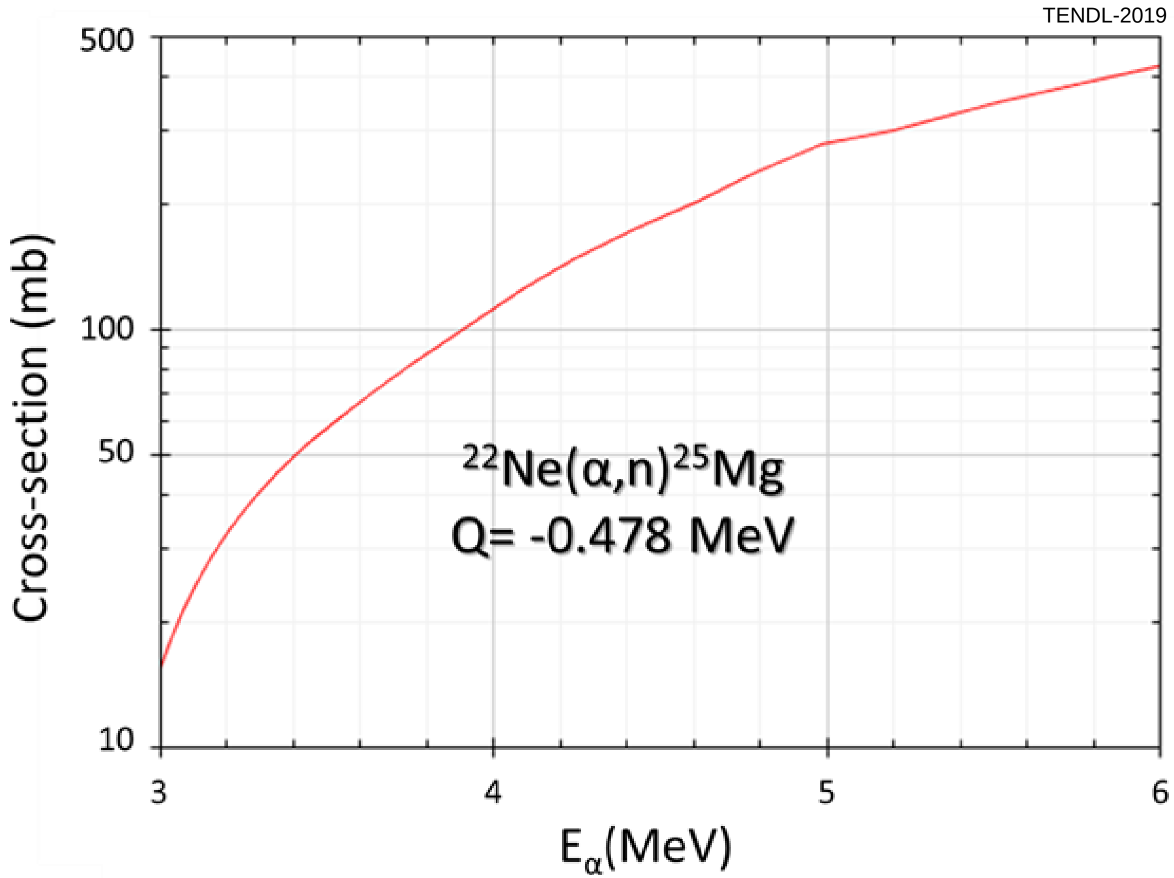

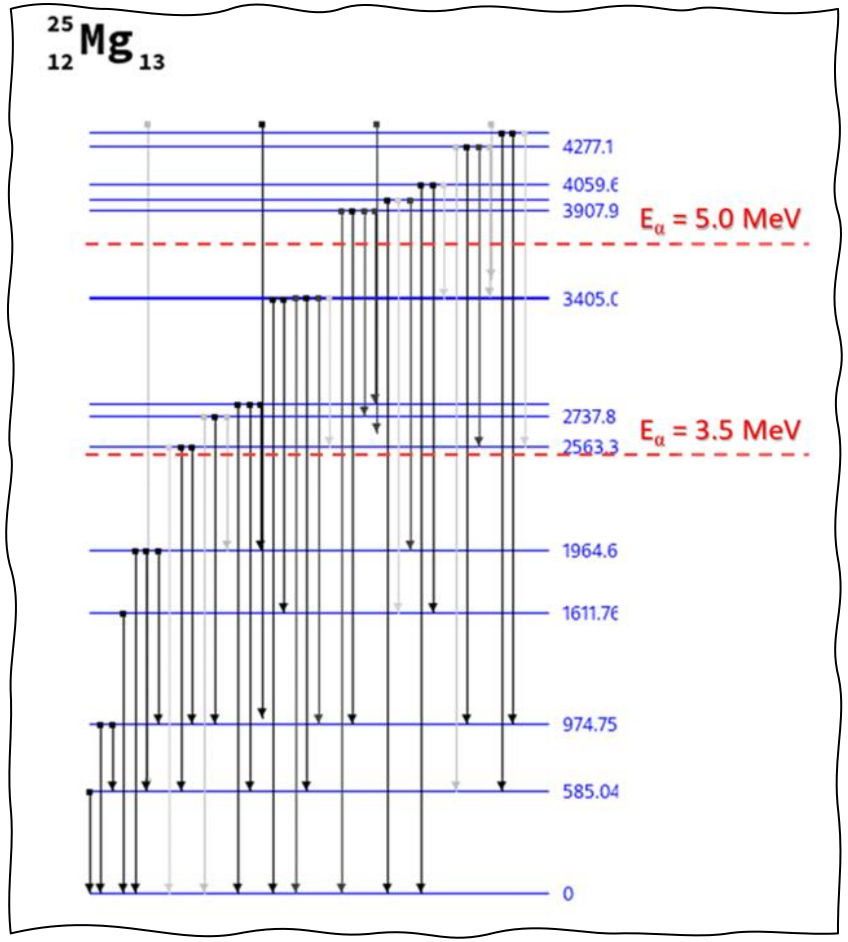

The reaction γ-rays have energies in the range of a high background rate.

It could be possible to use in D^3He plasmas with ^{22}Ne doping (≈9.25%)

Summary & conclusions

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- Gamma-ray diagnostics can be used *in all reactor plasma phases for*
  - Initial setup of plasma discharges (start-up REs, disruptions)
  - ICRH and NBI heating characterisation
  - L- and H-mode scenarios development
  - alpha-particle studies
  - test of the burning plasma diagnostics (<*T*> and fuel-ratio in the plasma core)
- Using both radial and oblique LoS spectrometers is encouraging
- γ-ray techniques proposed for reactors can be tested/used in the pre-burning machines
- Cross-section measurement of the nuclear reactions using *p*-, *d*-, ^{3}He- and ^{4}He-beams is an important further step

Thank you
for your attention