Gamma-ray spectrometry for confined fast ion studies in D^3He plasma experiments on JET

M. Iliasova, A. Shevelev, E. Khilkevich, Ye. Kazakov, V. Kiptily,
M. Nocente, L. Giacomelli, T. Craciunescu, A. Dal Molin, D. Rigamonti,
M. Tardocchi, D. Doinikov, G. Gorini, V. Naidenov, I. Polunovsky
and JET Contributors

The reported study was funded in part by the RFBR, project number 19-31-27001.

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 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Fast D-ions energy distributions

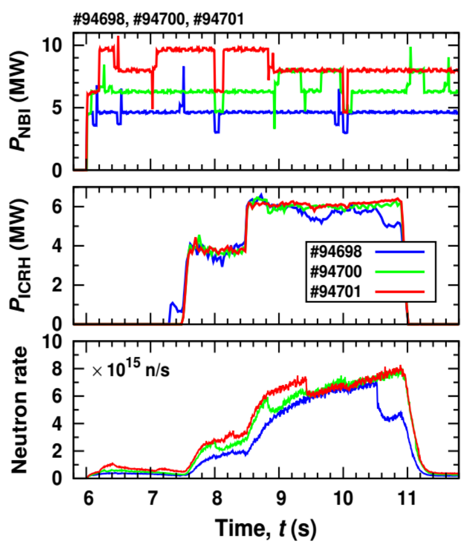
3-ion ICRH scheme in D^{3}He mixed plasmas
D-(D_{NBI})-^{3}He

3 essential components:

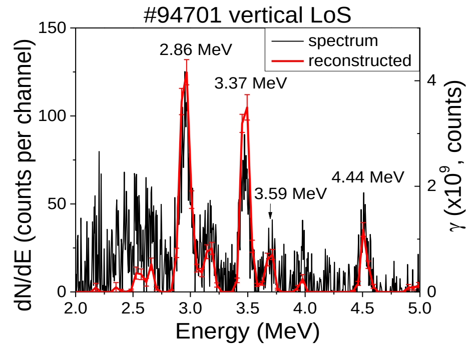
- thermal D
- thermal ^{3}He (~20-25%)
- fast D_{NBI} ions to absorb ICRF power at the MC layer (core)

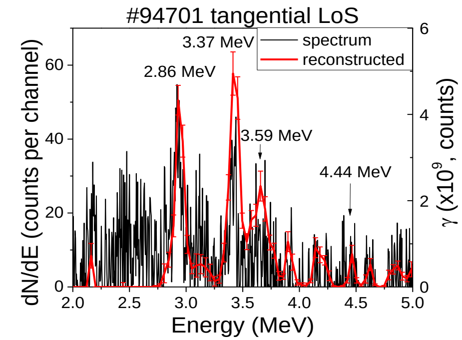
LaBr$_3$(Ce) Ø3"x6" with vertical LoS
LaBr$_3$(Ce) Ø3"x6" with quasi-tangential LoS

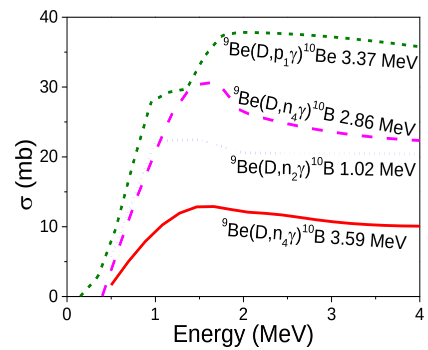
Nocente M. et al, in Proceedings HTPD2020, virtual, 2020, P7E18

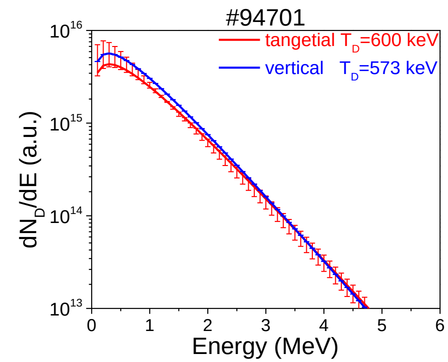


#94698: NBI(3.1MW) + ICRH(6MW), X[^{3}He]~23%
#94700: NBI(8MW) + ICRH(6MW), X[^{3}He]~27%
#94701: NBI(9.8MW) + ICRH(6.2MW), X[^{3}He]~25%









*Vukolov V.A. et al, Phys. of Atomic Nuclei, **58** (1995) 1453*
EXFOR, https://www-nds.iaea.org/exfor

- **^{9}Be(D,nγ)^{10}B** (2.86 MeV, 3.59 MeV)
- **^{9}Be(D, pγ)^{10}Be** (3.37 MeV)
- **^{9}Be(α,nγ)^{12}C** (4.44 MeV) ← **^{3}He(D,p)^{4}He**

$$I_{f,b}^{s} = \int d^3\mathrm{r}\, n_f(\mathbf{r}) n_b(\mathbf{r}) \int d^3v\, \sigma_{f,b}^{s}(|v|) f_f(\mathbf{r},\mathbf{v})$$

*Shevelev A.E. et al, Nucl. Fusion **53** (2013) 123004*

Fast ions distributions: Doppler effect

Vertical HPGe

Tangential $LaBr_3(Ce)$

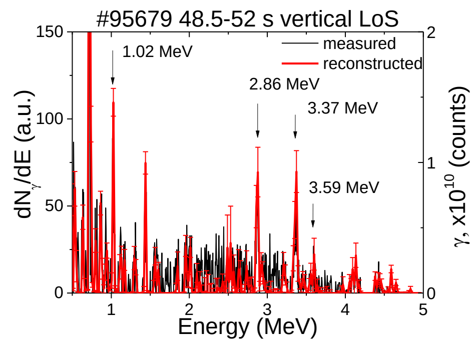
Doppler effect: shift of gamma quantum energy

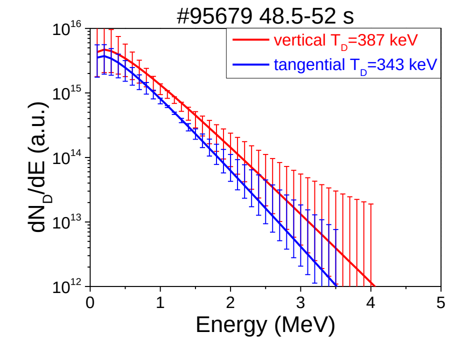
Doppler broadened shape of line:

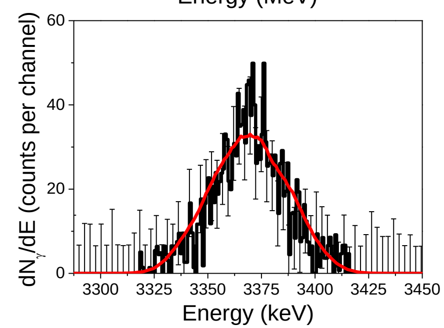
- angular dependence of the probability of emission of a reaction product
- angular dependence of the gamma intensity of radiation
- angular and energy distribution functions of fast ions

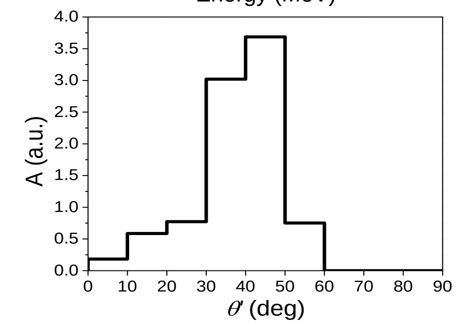
Kiptilyi V. G., et al., Vopr. At. Nauki Tekh., Ser.: Fiz. Yad. Reakt., Spec. Iss., 223

Doppler broadened 3.37 MeV gamma-line ^{9}**Be(D, pγ)**^{10}**Be**





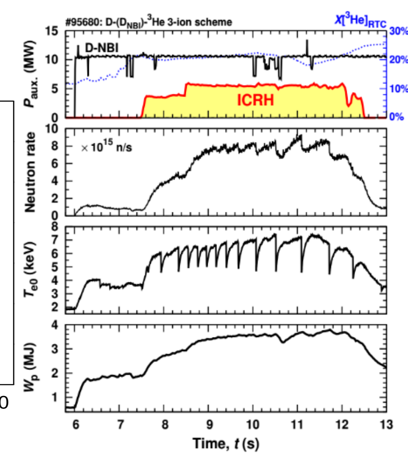


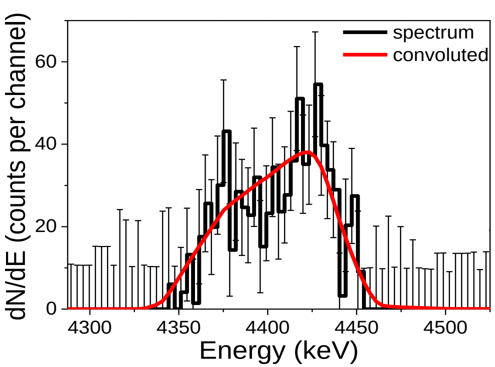


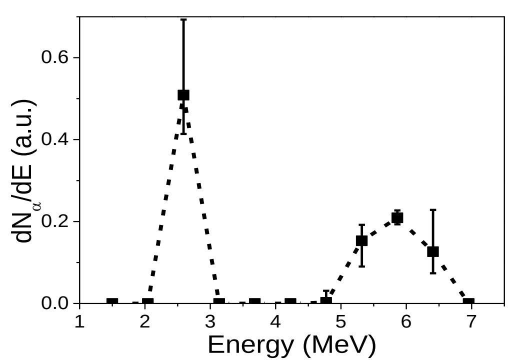
Confined α-particles

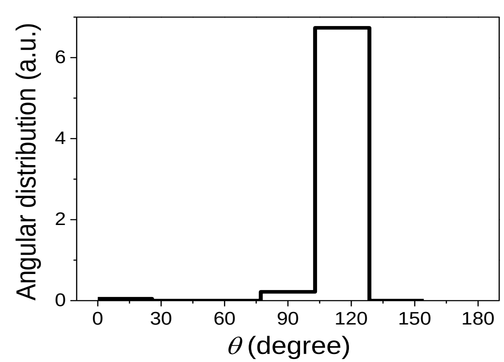
D (fast) + ^{3}He (target) → α + p

$$^{9}Be + \alpha \rightarrow {}^{13}C^{*} \xrightarrow{n} {}^{12}C^{*} \xrightarrow{\gamma} {}^{12}C$$

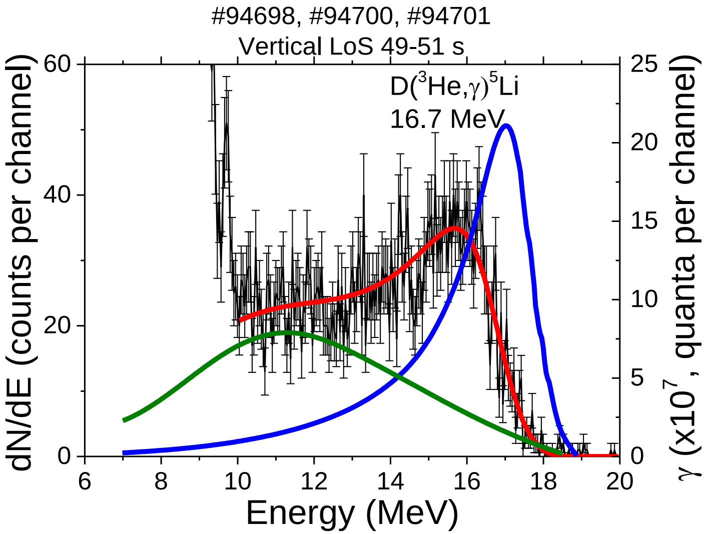








Fusion-born alpha-particle production



Buss W. et al, Nucl. Phys. A112 (1968) 47
Cecil F.E. et al, Phys. Review C 32 (1985) 690

D (fast) + ^{3}He (target) → **^{3}He(D,p)^{4}He**
^{3}He(D,γ)^{5}Li

$$f_\gamma(E) = k_0 f_{\gamma 0}(E) + k_1 f_{\gamma 1}(E)$$

γ_0 and γ_1 states of ^{5}Li are very short-lived, and therefore, the gamma-lines are broad: $\Gamma_{\gamma 0}\approx 1.23$ MeV and $\Gamma_{\gamma 1}\approx 6.6$ MeV

$f_{\gamma 0}(E)$ and $f_{\gamma 1}(E)$ are described by the Breit-Wigner formula

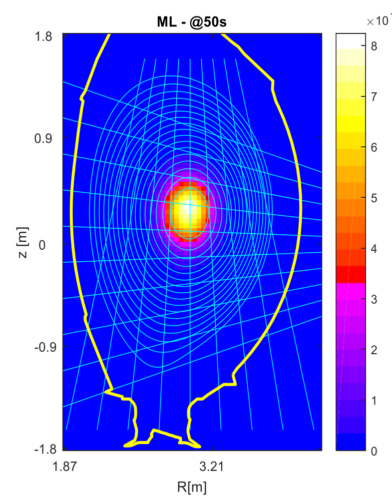
The ^{3}He(D,γ_0)^{5}Li/^{3}He(D,p)^{4}He branch ratio:

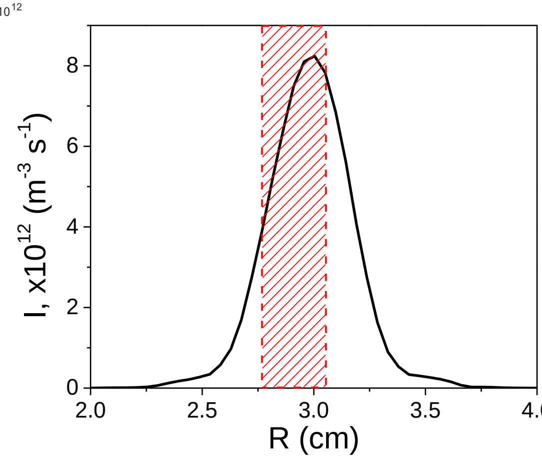
$$\langle B\rangle = \frac{\int f_D(E)\cdot B(E)dE}{\int f_D(E)dE} = 9.073\cdot 10^{-5}$$

D(^{3}He, p)^{4}He reaction rate in the visible plasma volume is **~$3\cdot 10^{13}$ s^{-1}**;

The fraction of the gamma source visible for a vertical spectrometer was estimated as 60.4%.

The averaged alpha-particle production rate was estimated as **$\langle R_\alpha\rangle \approx 7\cdot 10^{15}$ s^{-1}**.





Conclusion

Gamma-ray spectrometry provides:

- 2.86, 3.37 and 3.59 MeV γ-lines of the $^{9}Be + D$ reactions were identified in spectra measured by the $LaBr_3(Ce)$ => indicates presence of the fast D-ions with energy $E_D > 0.5$ MeV. A tail temperature $\langle T_D \rangle$ was estimated as ~600 keV in Maxwellian approximation;
- Fusion α-particles produced in $^{3}He(D,p)^{4}He$ reaction were observed: 4.44 MeV γ-line of $^{9}Be(\alpha,n\gamma)^{12}C$ reaction was identified in the measured spectra => fusion α-particles are confined in the plasma;
- Broadening of the 4.44 MeV γ-line due to Doppler effect was observed in spectra measured by the HPGe. Energy and angular distributions of the confined α-particles were reconstructed;
- γ-radiation from $^{3}He(D,\gamma)^{5}Li$ gammas were detected => fusion α-particles were produced in $^{3}He(D,p)^{4}He$ reaction;
- $^{3}He(D,\gamma)^{5}Li$ and $^{3}He(D,p)^{4}He$ fusion rates were assessed from the intensity of measured γ-radiation. The averaged α-particle production rate is $\langle R_\alpha \rangle \approx 7 \cdot 10^{15}\ s^{-1}$.