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

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ABSTRACT

- Fast D-ions and fusion born α-particles in D-^{3}He plasmas were studied.
- To reconstruct the energy distributions of D-ions, in the experiments with the 3-ion ICRH scheme D–(D$_{NBI}$)–^{3}He, intensities of the γ-lines of the ^{9}Be(D,pγ)^{10}Be and ^{9}Be(D,nγ)^{10}B reactions were used together with excitation functions of these reactions.
- The ^{3}He(D,p)^{4}He reaction rate and α-particle spatial distribution were obtained by measuring 17 MeV γ-rays from the ^{3}He(D,γ)^{5}Li reaction, which is a weak branch of ^{3}He(D,p)^{4}He reaction.
- The energy and pitch-angle distribution of the confined α-particles were reconstructed by means of the Doppler shape analysis of the 4.44-MeV γ-line of the ^{9}Be(α,nγ)^{12}C reaction.

INSTRUMENTATION AND METHODS

INSTRUMENTATION

In the experiments two large volume LaBr$_3$(Ce) Ø3"x6" spectrometers with vertical and quasi-tangential LoS are used. In some discharges the vertical LaBr$_3$(Ce) detector is replaced with a high-resolution HPGe spectrometer for measurements of the Doppler broadening of γ-lines in recorded spectra [2]. The pulse height analysis is conducted in the off-line regime with an application of an advanced method of the amplitude determining. In addition, the γ-ray camera, consisting of 19 compact LaBr$_3$(Ce) Ø25mm×17mm detectors with 10 horizontal and 9 vertical LoS, is used.

RECONSTRUCTION METHODS

To reconstruct the D-ions energy distribution two methods were applied: 1) based on the analysis of intensities of the γ-transitions in nuclear reactions between D and ^{9}Be, which is the major impurity in JET-ILW plasma; 2) based on analysis of the Doppler broadening of γ-lines corresponding to these γ-transitions. The fast D-ions' energy distribution functions were reconstructed with the specially developed γ-ray spectrum analysis code DeGaSum [3]. A spectrum recorded by the detector *S(E)* has the form:

$$S(E)=\int_0^{+\infty} f_\gamma(E')h(E,E')dE' + n(E), \qquad (1)$$

where f_γ is the initial γ-spectrum emitted from plasma, *h* is the detector response function, *n* is Poisson noise, and *E, E'* is the γ-ray energy. To reconstruct $f_\gamma(E)$ by deconvolution method, we used the spectrometer response functions *h(ε)* calculated with the MCNP code.

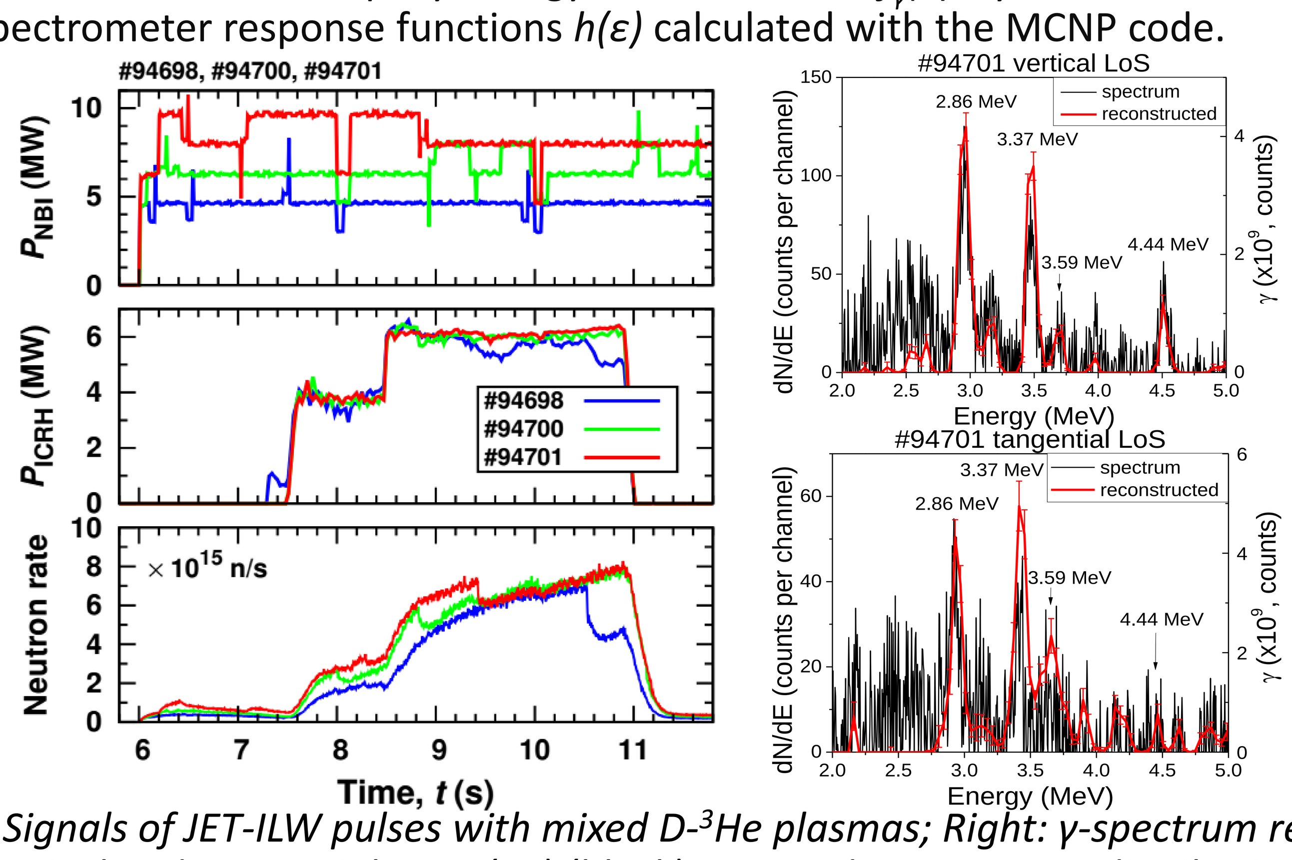

FIG.1. Left: Signals of JET-ILW pulses with mixed D-^{3}He plasmas; Right: γ-spectrum recorded with the vertical and tangential LaBr$_3$(Ce) (black), restored γ-ray energy distribution (red).

The intensity of gamma-ray transition is defined by such physical parameters of plasma as the densities of fast ions and impurity, a partial cross-section of the γ-ray transition, a distribution function of ions. The Doppler effect deforms the shapes of gamma-lines emitted from plasma by excited nuclei. The analysis of the Doppler broadened peak shape adjusts the energy and angular distribution of a given shape to the shape of a line and searches for the energy and angular distribution in an interval form.

OUTCOME: D-ions energy distribution

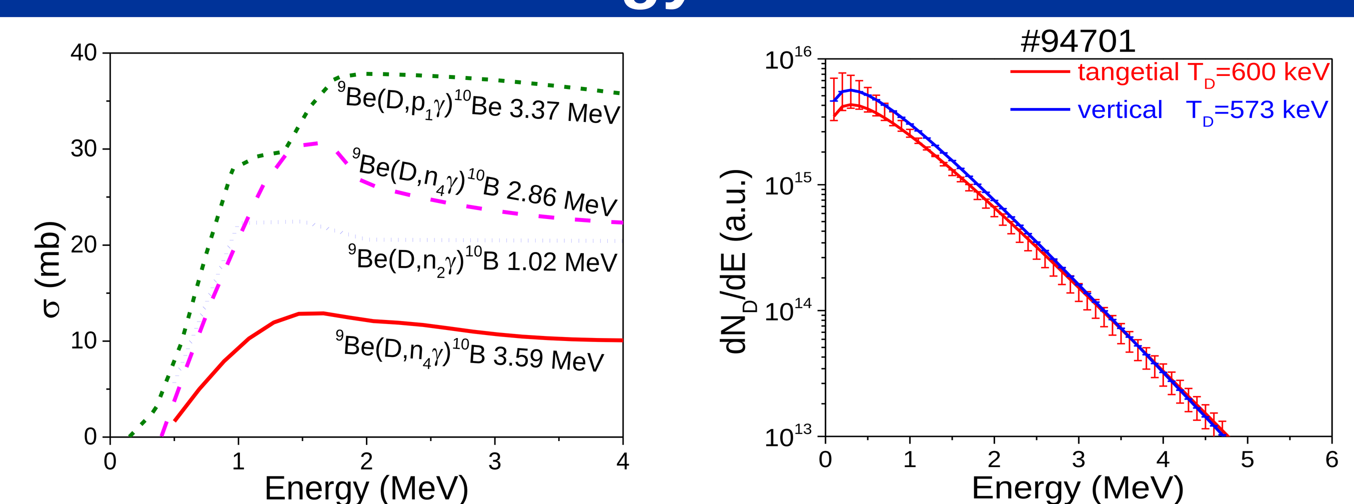

FIG.2. Left: Excitation function of the γ-transition from the ^{9}Be(D,nγ)^{10}B and ^{9}Be(D, pγ)^{10}Be reactions [4]. Right: The reconstructed using 3.37-, 2.86- and 3.59-MeV γ-lines energy distribution of the D-ions for LaBr$_3$(Ce) detectors with tangential and vertical LoS.

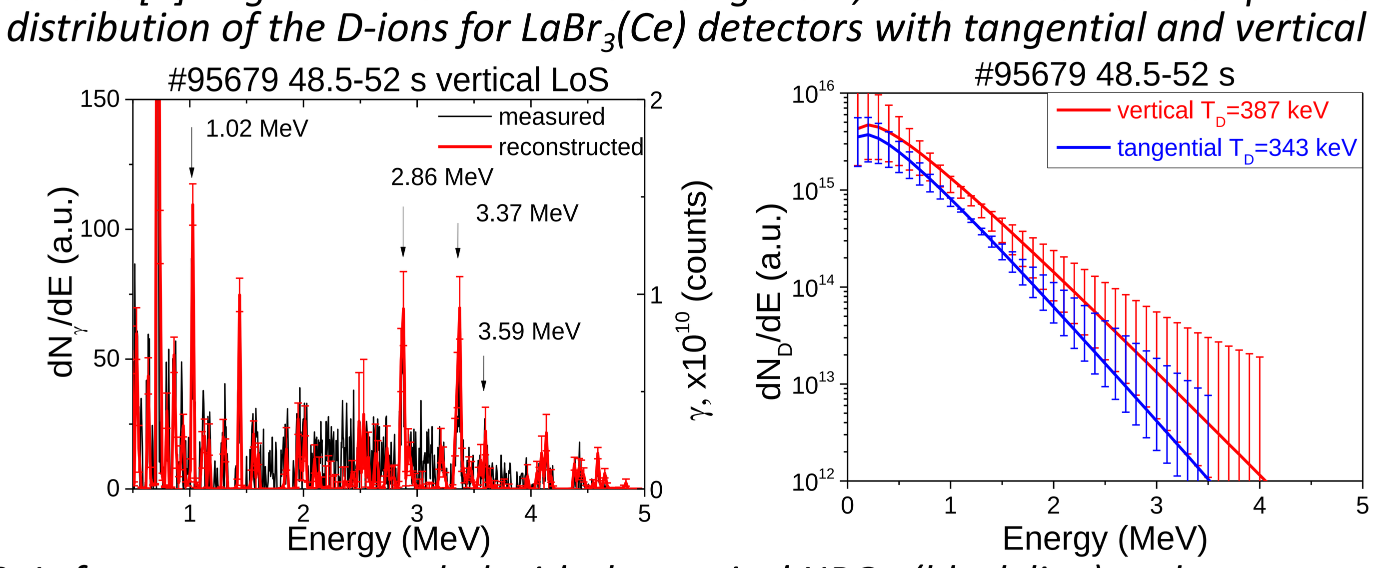

FIG.3. Left: γ-spectrum recorded with the vertical HPGe (black line) and reconstructed γ-ray energy distribution (red line); Right: D-ions energy distribution for tangential LaBr$_3$(Ce) detector and vertical HPGe detector.

BACKGROUND

In the support of ITER, a variety of fast-ion/α-particle diagnostics is under test. Monitoring of fast particles is a top priority for developing effective discharge scenarios with additional (NBI and ICRF) plasma heating. JET is the largest operating fusion machine with powerful additional heating systems, which is equipped with a broad range of fast particle diagnostics essential for ITER. γ-ray spectrometry of the plasma [1] is a tool giving information on the heating efficiency and fast-ion confinement. The source of γ-ray is nuclear reactions between fuel ions as well as due to interaction of confined ions and plasma impurities, i.e. beryllium in JET and ITER. JET is a test bed for fast-ion diagnostics, in particular γ-ray spectrometry.

OUTCOME: Doppler line shape analysis

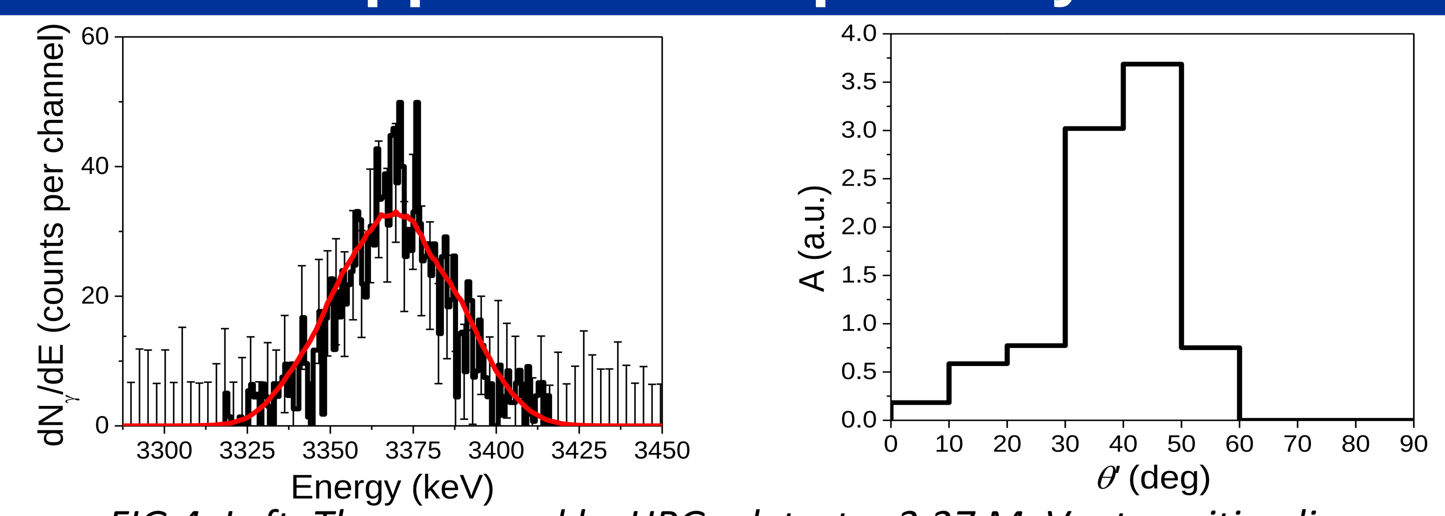

FIG.4. Left: The measured by HPGe detector 3.37 MeV γ-transition line. Right: reconstructed fast D-ions angular distribution relatively to the magnetic axis.

The 3.6-MeV α-particles were generated in the fusion reaction ^{3}He(D,p)^{4}He. Distributions of the confined α-particles can be obtained by analysis of the 4.44-MeV γ-rays from the ^{9}Be(α,nγ)^{12}C.

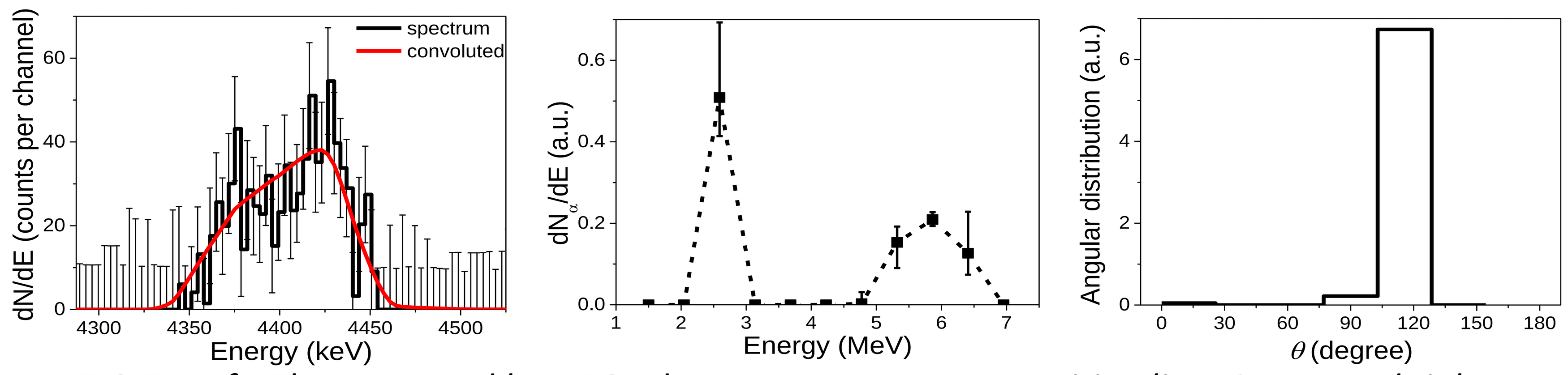

FIG.5. Left: The measured by HPGe detector 4.44 MeV γ-transition line. Center and right: Reconstructed energy and angular distribution of confined α-particles in the apparent plasma.

OUTCOME: Fusion-born α-particle production

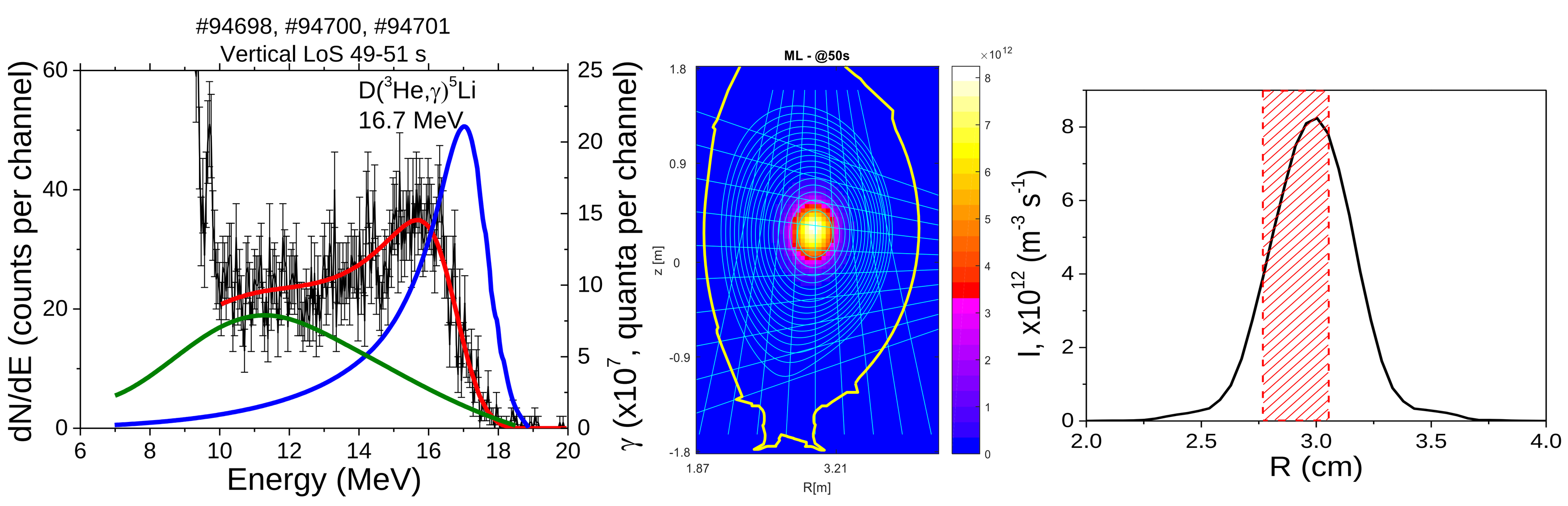

FIG.6. Left: The measured spectrum of γ-radiation in the energy range from 10 to 20 MeV. Center: 2D tomographic reconstruction of γ-emission profiles obtained with γ-cameras. Right: Radial distribution of a γ-source in the equatorial plane of JET. The red shaded area shows the part of the distribution visible for the vertical spectrometer.

The source of the fusion-born α-particles could be obtained by measuring 16.7 MeV γ-rays from ^{3}He(D,γ)^{5}Li reaction, the weak branch of the fusion reaction ^{3}He+D. Ground and 1st excited states of ^{5}Li are very short-lived, the γ-lines are broad – $\Gamma_{\gamma 0}$≈1.23 MeV and $\Gamma_{\gamma 1}$≈6.6 MeV. Then the γ-spectrum is described by convolution of a superposition of two γ-distributions: $f_\gamma(E)=k_0 f_{\gamma 0}(E)+k_1 f_{\gamma 1}(E)$. Energy distributions of γ-quanta $f_{\gamma 0}(E)$ and $f_{\gamma 1}(E)$ can be described by the Breit-Wigner formula [5]. Energy distribution of γ can be reconstructed by fitting the weight coefficients k_0 and k_1. The ^{3}He(D,γ$_0$)^{5}Li/^{3}He(D,p)^{4}He branch ratio averaged over the D-ions distribution ⟨B⟩ ≈ 9.1·10^{-5} [6]. D(^{3}He, p)^{4}He reaction rate in the visible plasma volume is ~3·10^{13} s^{-1}. The fraction of the γ-source visible for a vertical spectrometer was estimated as 60.4%. The averaged α-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 measured spectra. A tail temperature $\langle T_D \rangle$ was estimated as ~600 keV in Maxwellian approximation;
- γ-radiation from ^{3}He(D, γ)^{5}Li were detected. Fusion α-particles were produced in ^{3}He(D,p)^{4}He;
- ^{3}He(D, γ)^{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};
- Fusion α-particles from ^{3}He(D,p)^{4}He reaction were observed: 4.44 MeV γ-line of ^{9}Be(α,nγ)^{12}C 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.

[1] Kiptily V.G., Cecil F.E. and Medley S.S., Plasma Phys. Control. Fusion 48 (2006) R59–R82
[2] Nocente M., (23rd High Temp. Plasma Diagnostic Conf. – HTPD2020, virtual, 2020), P7E18
[3] Shevelev A.E. et al, Nucl. Fusion 53 (2013) 123004
[4] Experimental Nuclear Reaction Data (EXFOR), https://www-nds.iaea.org/exfor/
[5] Buss W., Del Biancco W., Waffler H., Ziegler B., Nucl. Phys. A112 (1968)
[6] Cecil F.E. et al, Phys. Review C 32 (1985) 690

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