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Evaluating a Contribution of the Knock-on Deuterons to the Neutron Yield in the Experiments with Weakly Collisional Plasma Jets (Part 2)

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1. Introduction

In Part 1 of this note (Ref. 1) we considered the kinematics of large-angle scattering (LAS) of the deuterons on the counter-streaming carbon ions, with both flows having the same velocity V. Due to a large mass ratio m_C/m_D, the backscattered deuterons have high velocity of up to (24/7)V. This significantly increases the cross-section for the neutron production in the collisions between the back-scattered and incoming deuterons and may provide significant contribution to the total neutron yield, despite the smallness of a large-angle Coulomb cross-section. This effect becomes particularly important when only one of the colliding streams is made of CD, whereas the other stream is made of CH, as this is done in the Discovery Science collisionless shock experiments [2]. In Part 1 we have evaluated the neutron yield produced by this mechanism and have found that its relative role increases for higher plasma densities and lower velocities.

In this note we discuss signatures of this effect which can be used to identify it experimentally and also discuss in some more detail its spatio-temporal characteristics. It goes without saying that a complete quantitative assessment should be based on numerical simulations accounting for the large-angle scattering.

2. Velocity asymmetry

Here we focus on the discussion of a CD-CH situation, where there are no beam-beam neutron produced. In the case where the LAS effect is strong, the neutrons would be produced in collisions between the incoming deuterons (velocity V) and the backscattered ones (velocity (17/7)V, oppositely directed). The center-of-mass (COM) for the DD collisions will then be moving with the velocity of (5/7)V toward the incoming deuterons. This would produce a strong asymmetry between the arrival times on two detectors aligned with the flow axis and situated on the opposite sides. What would be interesting here is not an average width on these time-of-flight signals, but rather an asymmetry in the earliest parts of the signals. Characteristically, the earliest arrivals should be on the CD side (i.e., on the side of the CD target) and correspond to the direction of the backscattered deuterons.

This is an extreme case, where the exponential dependence of the reactivity “selects” the head-on collisions with the highest relative velocity. For more modest scenarios, the other collision angles would also contribute, and the effect will become less dramatic. Still, the center-of-mass velocities of the DD couples would be significantly higher than in the beam-beam case, and the arrival time of the earliest part of the signals would be significantly different from the case of beam-beam neutrons generated in the symmetric case (CD vs CD), not necessarily with a significant forward-backward anisotropy present. The earlier arrival will be seen on the detectors situated in the equatorial plane as well.

Note that the higher COM velocity in the DD collisions would lead also to a larger energy spread of the protons produced in the other branch of the DD reactions and detected by the proton images technique. For the COM velocity u the proton energy on the film used for their detection will be varying in the range

$$W_p\left(1 \pm 2\frac{u}{\mathrm{v}_p}\right), \qquad (1)$$

where W_p=3.02 MeV and v_p=19.1 Mm/s are the proton energy and proton velocity for the case where the COM is at rest. So, we see that the *full width* of energy spread of the protons is

$$\Delta W_P = 4W_p\frac{u}{\mathrm{v}_p} \qquad (2)$$

or, numerically,

$$\Delta W_P(MeV) = 0.63u(Mm/s)\ . \qquad (3)$$

So, for the modest value of u=0.5 Mm/s, the full width of the proton energy spectrum would be 0.31 MeV.

3. Preliminary analysis of the spatio-temporal characteristics of the neutron pulse.

We now briefly discuss the spatial distribution of the neutron yield and the pulse duration for the CD/CH case. We will use the simplest model where each of the two colliding plasmas has the same velocity V and the duration τ. This means that an axial length of each of the two plasma bunches is L=Vτ. The plasma will be assumed to be uniform; the effects of the finite radial extent will be ignored in this rough assessment. The process of the overlap of the two flows is illustrated by Fig. 1. The time is counted from the moment when the two plasma bunches have just touched each other at the symmetry plane z=0.

The direction of the backscattered deuterons is shown in red arrows. In the case where there is a large contribution of the backscattered deuterons propagating along the CH stream, the neutron generation (integrated over time) will be asymmetric with respect to the mid-plane: it will be shifted in the direction of the CD stream.

The temporal evolution of the overlap area is shown in Fig. 2 which depicts a z-t diagram. The tilted lines depict the motion of the ends of the two counter-propagating bunches. A yellow area shows the zone where the streams overlap. The knock-on deuterons with a large velocity propagate upward in a near-vertical direction and interact with the incoming deuterons, producing neutrons, with an imbalance in favour of the zone z>0.

If a broader range of the scattering angles contributes to the neutron generation, as is the case for higher-velocity streams, the asymmetry would be reduced.

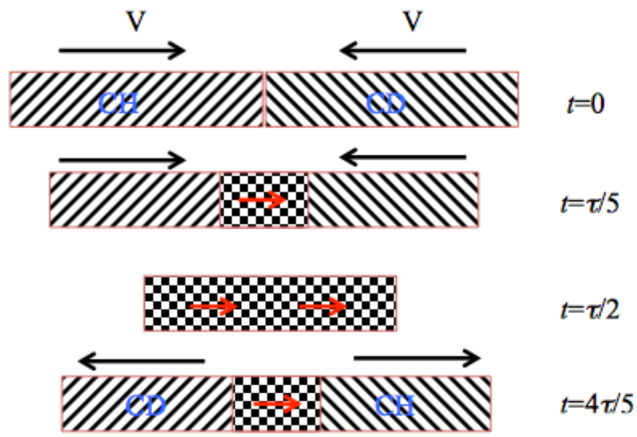

Fig. 1 The overlap of the two streams. The CH stream comes from the left and is hatched; the CD stream comes from the right and is hatched orthogonally to the first one. The overlap zone is cross-hatched. Four instants are shown: t=0 when two bunches just touch each other; t=τ/5, when the streams partially overlap; t=τ/2 where they are fully overlapped; t=4τ/5, when the two bunches are near the final separation. The fast deuterons born near this point produce only a small amount of neutrons, as the deuterium-containing "target" plasma has already moved to the left from the overlap zone.

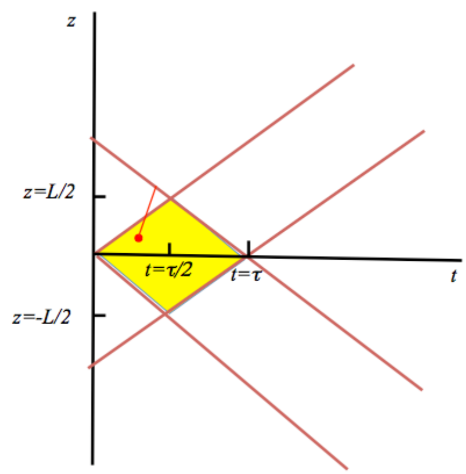

Fig. 2 Characterization of the overlap region in *z-t* plane. At any instant of time the length of the overlap region is determined by the length of the vertical line within the yellow zone. The back-scattered deuteron born at some *z* and *t* (red dot) moves upward along the red line (shown is the case where its axial velocity is 2V); it can produce netrons until it intersects the right boundary of the CD bunch.

4. Summary

The interaction of two CD (CH) plasma streams in the regime transitional between collisional and collisionless interpenetration is a complex multifaceted phenomenon. Some of the insights into the dynamics of the interaction can come from the analysis of the neutron emission from the CD stream with CH stream. In this case, the neutrons can be produced by three processes: 1) collective (collisionless) deuteron scattering leading to the thermalization of the CD stream and generation of the neutrons by the collectively heated deuterium; 2) collisional, small angle scattering also leading to the thermalization of deuterons with a neutron generation by the collisionally heated deuterium; 3) formation of the energetic knock-on deuterons by small-impact-parameter Coulomb collisions and neutron generation via collisions between energetic knock-on deuterons and incoming CD flow. The relative role of these processes depends on the parameters of the streams, with the first one favouring higher velocities and smaller densities; the second favouring higher densities and velocities, and the third favouring lower velocities and the intermediate densities.

The diagnostic tools that can help in the identifying the relative importance of these processes can be based on the time-of –flight neutron detectors and proton imaging. With the first technique, special attention should be paid not to the average parameters (like the so-called "Brysk temperature") but to the temporal evolution of the very early and very late parts of the signals, as well to comparison of these features for the diametrically-opposite detectors. With regard to the second (proton) technique, an attention should be paid to the degree of the axial asymmetry of the proton images.

References

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