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USING CO-MOVING COLLISIONS IN A GEAR-CHANGING SYSTEM TO MEASURE FUSION CROSS SECTIONS*

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Abstract

In this work we look at a possible use for a system that collides beams moving in the same direction using a gear-changing synchronization method as a means of measuring low energy phenomena, such as fusion cross sections. Depending on the energies used this process will allow for interactions for any desired charge state of the target nuclei. Earlier concepts for low energy interactions to study focused on beams crossing at an angle to give the low energy interactions, as well as general investigations of comoving collisions. This proposal would use gear-changing, a method involving two different harmonic numbers of bunches in each collider ring, to have the same types of collisions, with a luminosity equal that of a head-on machine. In this work we detail the design considerations for such a machine, leveraging experimental experience with a co-moving, gear-changing system.

INTRODUCTION

This work will leverage research done on Gear-changing done using the low energy ion machine DESIREE (Double ElectroStatic Ion Ring ExpEriment) at Stockholm University [1-3]. This machine generally performs zero energy mergers of low energy ion beams to study neutralization reactions like those found in the interstellar medium. We were able to use it to demonstrate gear-changing, which is a collider synchronization system where each ring has a different harmonic number. In this case we've shown a 4 on 3 gear changing system where the 3 bunch system moves at 4/3 the velocity of the slow bunches. These collisions occur in a moving reference frame which opens up new possibilities for research.

Having the bunches collide in a moving reference frame leads to a large reduction in the center of mass energy when compared to a head on or fixed target collision. This provides an opportunity to perform low center of mass energy collisions, while preserving the control benefits of higher energy ion beams. An excellent use for these types of collisions would be studying nuclear fusion interactions [4].

The center of mass kinetic energy ranges involved in most fusion reactions are of the order of 100s of keV. One advantage that a comoving system would have is that it could study these interactions at different ionization states, which are generally not attainable using fixed target facilities. Such a system, if properly designed, can also perform research on the effects of spin polarization on these interactions. Finally, with the right reactants this could be used to create a "neutron accelerator" which could be used to create a high energy neutron beam.

In this work we will review some of the initial design considerations for such a machine, and apply them to two possible experimental machine designs. While gear-changing was the basis for this research there are situations where coasting beam systems might be more useful.

CENTER OF MASS ENERGY

The center of mass energy is actually easy to calculate, we can use the total center of mass energy from [5] with θ=π to calculate it, and simply subtract out the rest masses. The equation is:

$$E_{cm} = \sqrt{2E_1E_2 + ((m_1c^2)^2 + (m_2c^2)^2) + 2 * P_1P_2Cos(\theta)}$$

We can then determine the required energies for a given center of mass energy, and starting kinetic energy of one of the atoms. The plot would look like Fig. 1. For a given atom type there is an answer where the other beam is either faster or slower than the first beam. While they don't scale linearly, they do scale with the mass ratio of the two ion species. If we are looking at a system where gear-changing is necessary then we will also have to look at the relative velocities, an example of such is shown in Fig. 2.

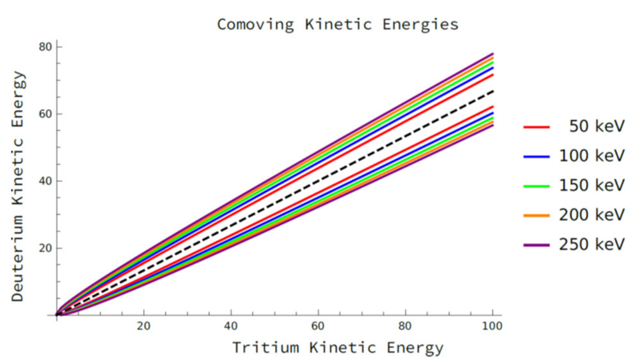

Figure 1: The kinetic energies of the Tritium and Deuterium beams for a variety of center of mass kinetic energies. Two possible energies for each center of mass energy will be given, one where the deuteron is faster, one where it's slower. The dashed line is the mass ratio.

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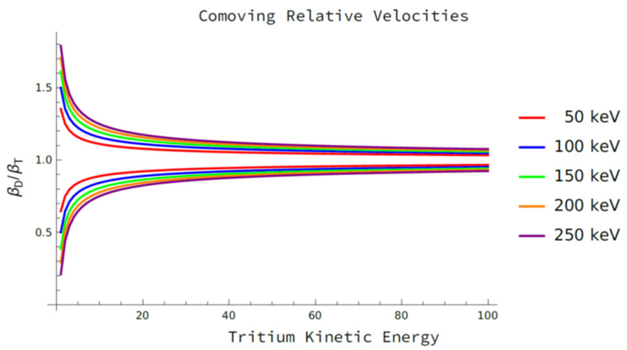

Figure 2: The relative velocity of the deuterium compared to the tritium for a variety of tritium energies and center of mass energies

LUMINOSITY

Interestingly, the luminosity of a comoving system is the same as the luminosity of a head on system so long as the bunches pass completely through each other [6]. We will therefore use the normal luminosity equations for a bunched beam,

$$\mathcal{L} = \frac{N_1 N_2}{2\pi\sigma_x\sigma_y} f$$

and for coasting beam [7],

$$\mathcal{L} = \frac{N_1 N_2 v_1}{2 C_1 C_2}\left(1 - \frac{v_1}{v_2}\right)\sqrt{\frac{p}{p(\mathcal{E}_1^2 + \mathcal{E}_2^2) + \mathcal{E}_1\mathcal{E}_2(1+p^2)}}$$

where $p=\beta_1^*/\beta_2^*$, ε_1 and ε_2 are the emittances, and C_1 and C_2 are the ring circumferences. N_1 and N_2 are the number of ions, and f is the collision frequency.

DAUGHTER PARTICLE DISTRIBUTIONS

The results of these fusion reactions are varied, and will strongly determine the energy range used, as well as the design of the detector(s). Fusion reactions result in daughter atoms, along with other atoms, particles, gamma rays, and occasionally activated nuclei which decay later. For atoms and particles which have mass, the lab frame velocities, energies, and angular spreads can be calculated.

This would include the cutoff where all of the daughter particles are moving along with the colliding beams. This can be important for detector design, especially for reactions that result in neutrons. A look at the relativistic addition of velocities tells us that this cutoff occurs where the center of mass velocity of the system equals the velocity in the center of mass frame of the most energetic daughter particle.

As an example, if we look at D-T fusion with a center of mass kinetic energy of 65 keV, the daughter particles are a helium atom at 3.5 MeV, and a neutron at 14.1 MeV with a velocity of 0.171c. If we take the center of mass velocity in the lab frame as the sum of momenta divided by the total mass, we can calculate the center of mass velocity for a given energy pairing. If we look at Fig. 3, we see that for this system the cutoff for all of the neutrons moving forward is a tritium energy of 39 MeV for the fast deuteron beam, and 43 MeV for the slow deuteron beam.

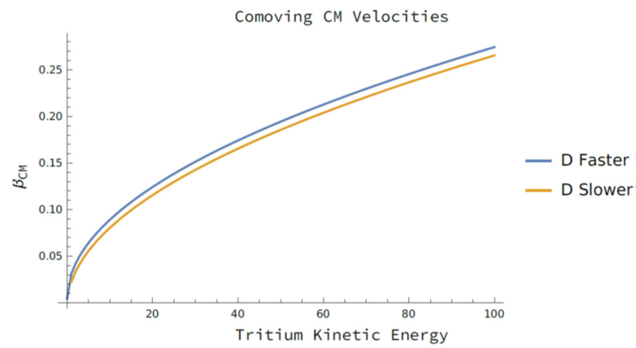

Figure 3: This is the center of mass velocity for the D-T system at 65 keV center of mass energy, which has the highest cross section

Since we are relativistically adding the velocities of the daughter particles to the center of mass velocity, we can effectively boost the energy of the daughter particles in the lab frame. Assuming that the daughter particles will move in all directions with equal probability, then the daughter particles will take on a wide distribution with a boosted top energy. This would allow us to create a high energy neutron beam, The energy could be partially tuned based on collimation, but care should be taken since every high energy neutron pulse from those neutrons that were going forward in the lab frame will have a lower energy pulse from those that were moving backwards in the lab frame. The energy distribution for a D-T reaction at a variety of Tritium energies is shown in Fig. 4.

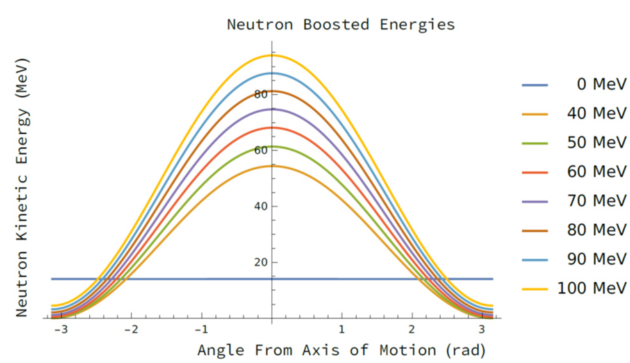

Figure 4: The neutron energy as a function of angle from the direction of motion for a variety of tritium energies, using the system where the deuterons are faster.

For reactions that create gamma rays, the moving collision would lead to red and blue shifting depending on the angle from the line of motion.

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EXAMPLE FACILITY: LOW ENERGY MEASUREMENTS WITH DIFFERENT CHARGE STATES

One of the advantages of a comoving collider system is that the charge state of the target ions can be directly controlled in a way that cannot be done with fixed target measurements. As an example, we want to look at a machine that would be low enough energy that a small lab or university could perform these measurements. Given that we want a variety of charge states, and would prefer no neutron radiation, the obvious candidate would be proton boron fusion.

Proton boron fusion has its peak cross section at 600 keV, which is approximately 1 barn (10^{-28} m^2) [8]. These energies are trivial for a collider system, and the main limitation on this type of machine is luminosity. The daughter particles for this interaction are three alpha particles with 8.7 MeV of energy between them.

The actual performance of this type of machine will be heavily dependant on the ion source. We assume an ECR of 30 kV with a gun current of 200 μA for a given ion state [9]. If we then accelerate the beam to a reasonable boron kinetic energy of 300 keV, we would have the protons with a kinetic energy of 689 keV. At these low energies the velocities of the two beams are different by a factor of 5, so instead of gear changing we would assume coasting beam collisions. We estimate the per ring number of ions of the coasting beam as 2×10^9 ions. Assuming equal β*s and an emittance of 0.5π mm-mrad normalized emittance, then we would expect a luminosity of 1.39×10^{26} m^{-2} for equal 8m circumference rings.

This luminosity would give a reaction every 71 seconds. If we are able to increase the number of ions to 9×10^9 in each beam, and decrease the emittance to 0.2π mm-mrad, then we would see a reaction every 1.4 seconds. This would be within the realm of experiments like those at DESIREE [10], and would gain statistics by running for a very long time. Since the products are alpha particles, and since we aren't boosting the frame significantly, a detector would likely consist of surrounding the interaction region with scintillators.

The key driver of an experiment like this would be the source being used, the better the current and lower the emittance, the better.

EXAMPLE FACILITY: HIGH ENERGY NEUTRON FACILITY

This next design will have a much larger facility that is designed to fuse D and T both to create high energy neutrons, and as a method of testing the effect of ion polarization on these interactions. If we choose 60 MeV tritium, then we will have 44.29 MeV deuterium for a center of mass kinetic energy of 65 keV. If we assume that each bunch will have 1×10^9 ions per bunch, and that the spot size at the interaction region is 2.5mm, then we would expect for a machine that is 60m in circumference a luminosity per bunch of 1.29×10^{28} m^{-2}. Assuming the bunches are 30cm long and fill the ring, this would give 646 fusion interactions per second. A 25% increase in the bunch population, or a commensurate decrease in the spot sizes at the interaction region would bring the reaction rate to 1000 fusion reactions per second.

A device like this would also be able to study the possible effects of ion spin polarization on the directionality of these reactions [11]. In order to preserve the spin polarization, a figure eight type of geometry could be used [12]. The velocity ratio would work especially well in our system for 63 on 62 bunch gear changing.

OTHER TYPES OF MACHINES

The number of possible machines is quite varied, depending on the fusion interactions in question, and the types of detectors being used. The energies accessible in these systems would be very useful for CNO types of interactions, though the cross sections are much lower than D-T or p-B. Since these interactions create gamma rays there would be radiological implications. Some interactions, such as p-C create a gamma ray, and a nucleus that will later decay. A machine that has its energy high enough that all daughter particles move in the same direction could separate out the activated nuclei, trap them, and use their decays to detect the fusion interactions.

ANALYSIS, DISCUSSION, AND FUTURE WORK

As has been shown, from an accelerator standpoint, fusion is not an energy issue, it's a luminosity issue. Thus any machine would be limited mainly by the characteristics of its source. There would also be limitations due to space charge and beam-beam interactions. For this reason, a comoving collision-based system would have many of the advantages of higher energy systems in terms of beam control, while still having the type of low energy interactions needed for fusion research.

We have outlined two machines at either end of the size/energy axis in this paper, but there are a large number of possibilities based on the exact ions being fused. This type of machine could be used as an experimental station at a facility such as FRIB to help study fusion interactions in more exotic ions. Such a general machine would likely need a lot of design work done for the detector, but could provide valuable insight into fusion interactions.

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