Nuclear Fusion of Protons with Ions of Boron *

Alessandro G. Ruggiero

Brookhaven National Laboratory
Upton, Long Island, New York 11973, USA

Summary

This paper describes a method of extracting energy from the fusion events occurring between the collision of a beam of protons with a beam of ions of Boron 11. The two beams are circulating in separated and intersecting storage rings where they collide head-on in a common long-straight section. Requirements on the beam parameters in the collider are presented. Limitations due to space-charge forces are discussed; it is found necessary to provide beam-charge neutralization with electrons. The paper discusses also the effects of Coulomb scattering between particles of the same beam and in the opposing beams. Methods are proposed for the controlling of the electromagnetic interaction.

1. Introduction

One of the most interesting fusion reaction [1] is a proton colliding with an ion of Boron 11 with three α particles as the final product. A proton beam energy of 675 keV is required [2]. A total energy $W = 8.7$ MeV is released under the form of kinetic energy given to the α particles. The fusion process exhibits a large cross-section $\sigma = 0.9$ barn. A method which makes use of two beams, colliding periodically with each other, has been proposed earlier [3,4]. The method is reviewed briefly in Section 2 where also the beam requirements are specified. A small size device delivering a 1 MW power has been taken as an example.

Space charge is a serious limitation on the performance of the collider and a method has been suggested to raise the limit by compensating the beam electric charge with electrons from the vacuum gas ionization; this is discussed in Section 3. Other limitations are due to the Coulomb scattering among the particles of the same beam (Section 4) and between those of the countermoving beams (Section 5).

The beam behavior, because of the large intensity, is dominated by the effects of Coulomb scattering. Particles would be lost as soon they enter the respective storage rings and do not have the time to interact in useful nuclear fusion events. We propose, in Section 6 and 7, methods to overcome these limitations; they are based on the control of the smallest scattering angle and on the use of Crystalline Beams.

2. The Collider

The collider is made of two intersecting storage rings of the same size and magnet configuration [3,4]. They are placed side-by-side and share a common long straight section. The proton beam is generated by a hydrogen-ion source followed by an RFQ device. The beam of ions of Boron, completely stripped, is generated by a battery of ECR sources followed by a common RFQ device. The two beams are circulating in the same direction and collide head-on in the common long-straight...
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where the reactor vessel is also located. They are assumed to have the same particle intensity and dimensions.

Each storage ring has a circumference of \(2\pi R = 3.3\) m and is made of a sequence of 16 FODO cells, each having a phase advance of 90°. Quadrupoles and dipoles are made of permanent magnets. Quadrupoles are 2 cm long. There are 16 dipoles, each 8 cm long, placed in the arcs. The long straights are made of 4 cells each, without bending magnets, and are dispersionless. The average value of the amplitude lattice function is \(\beta_L = 20\) cm.

The energies of the two beams are \(T_p = 56\) keV for the protons, and \(T_B = 619\) keV for the ions of Boron, which yield the same velocity \(\beta = 0.011\). The number of fusion events per unit of time is

\[
\frac{dn}{dt} = \sigma(\eta^2N^2 / S) f_{\text{enc}} = \sigma L
\]

where \(N\) is the total number of particles per beam, \(\eta = 0.25\) is the fraction of \(N\) involved in the collision, \(S\) is the average beam cross-section, \(f_{\text{enc}}\) is the frequency of beam encounter which is equal to the \(1/\pi\) times the revolution frequency, that is \(f_{\text{enc}} = 4\) MHz, and \(L\) is the luminosity of the collision. Denoting with \(W\) the energy released by one fusion event, the instantaneous power produced is

\[
P = W \left(\frac{dn}{dt}\right)
\]

We shall set as a goal \(P = 1\) MW. We can calculate the luminosity required, neglecting the power consumed for the formation of both beams and for the operation of the collider system,

\[
L = \frac{P}{(\sigma W)} = 0.8 \times 10^{42}\text{ cm}^{-2}\text{ s}^{-1}
\]

which corresponds to \(dn/dt = 0.7 \times 10^{18}\) fusion events per second. There is at the same time a depletion of both beams which will occur at the same rate. Beam currents required at injection are around 115 mA. Protons can be produced with a single source. The production of ions of Boron requires source improvement; eventually several ECR sources may be used in parallel.

Assuming that both beams have an emittance \(\varepsilon = 0.1\) \(\pi\) mm mrad, the average beam cross-section \(S = \varepsilon \beta_L = 6.3 \times 10^{-4}\) cm². The design luminosity can then be obtained with \(N = 4.5 \times 10^{16}\) particles per beam. Each particle will spend on average \(N/(dn/dt) = 65\) ms circulating in the storage ring, that is 65 thousand revolutions.

3. Space Charge Limitations

The space charge causes a tune-depression of the storage ring given by

\[
\Delta v = N \frac{r_p Q^2}{(2 \beta^2 \gamma^3 B A \varepsilon)}
\]

where \(r_p = 1.535 \times 10^{-18}\) m is the proton classical radius, \(Q\) the charge state and \(A\) the mass number of the ion specie, \(B\) the bunching factor which we take here to be unit, and \(\gamma \sim 1\). An acceptable limit for \(\Delta v\) is a unit. To keep the beam within the space charge limit, we derive \(\varepsilon > 100-200\) \(\pi\) m rad, that is nine orders of magnitude larger than required.
It is possible to compensate space-charge effects with neutralization of the beam electric charge by trapping electrons produced by ionization of the atoms of the residual gas in the collider vacuum chamber. It has been experimentally demonstrated [5] at INP (Novosibirsk, Russia) that it is possible to store with this method a current nine times larger than the value otherwise set by the space-charge limit. A factor of a thousand is also believed possible.

A vacuum pressure of $1 \times 10^{-7}$ torr yields an electron production [3,4] by gas ionization at the rate of $1 \times 10^{17}$ per second. It takes few seconds to achieve complete space-charge neutralization.

The energy loss that a proton or a ion suffer by the ionization or excitation of the atoms and molecules in the vacuum residual gas is estimated around $10$ keV during the period of time they spend in the collider. On the other hand, scattering of the primary particles with the electrons from ionization causes some concern. Because of their larger mass, protons and ions do not suffer appreciable consequences; but electrons are immediately knocked out of the beam with one single Coulomb scattering. The cross-section for an electron to be scattered by an angle $\theta_b > 0.71$ mrad, corresponding to the beam average divergence, is $3 \times 10^{-10}$ cm$^2$, considerably larger than the ionization cross-section of $3 \times 10^{-18}$ cm$^2$.

4. Intrabeam Scattering

Because of the large density, particles in the same beam will scatter with each other by Coulomb repulsion. This effect will cause a considerable increase of the beam dimensions and particle losses as well.

We have estimated the rates of diffusion using available computer programs. For a small energy spread ($< 10^4$) there is damping of the transverse dimensions and an increase of the energy spread. For larger initial energy spreads ($> 10^3$), the beam emittance grows and the momentum spread is damped. There is an intermediate range where growth occurs in all dimensions. For large energy spreads, the relative growth rate of the betatron emittance can be as large as $10^{11}$ s$^{-1}$. This effect can be reduced considerably with a careful choice of ring lattice and beam parameters.

Large-angle Coulomb scattering causes a particle to be lost in one single event. The number of particles lost can be estimated using the following formula

$$\frac{dN}{dt} = 4\pi c N Q^4 r_p F(\theta_b) I$$

where $\rho = 2.2 \times 10^{17}$ cm$^{-3}$ is the beam particle average density,

$$F(\theta_b) = \frac{1}{\sin^2 (\theta_b/2)} - 1$$

and $I$ is an integral which depends on the velocity distribution. For the case of intrabeam scattering, $I = 4 \pi^2 / \beta^3 \theta_b^2$. The equivalent cross-section for the loss of particles is $1 \times 10^{-8}$ cm$^2$, which is considerably larger than the fusion cross-section. Thus particles are immediately lost as they enter the storage rings, before they have a chance to fuse with the others.
5. Beam-Beam Scattering

The beam-beam electromagnetic interaction causes a betatron-tune depression which adds to that due to the individual beam space-charge forces. This effect is not very significant for the beam of ions of Boron, but in the case of protons there is a beam-beam contribution about equal to that of the single-beam space-charge forces. The beam charge compensation by the electrons produced by ionization will also help to compensate for the beam-beam interaction.

Also in the interaction region, Coulomb scattering is the most disruptive effect; it causes again beam emittance growth and particle loss. The magnitude of the effects are though lesser than those caused by intrabeam scattering. The rate of particle loss can again estimated with Eq. (5) where now \( I = \frac{2 \pi^2}{\beta^2} \). The equivalent cross-section is \( 6 \times 10^{-16} \text{ cm}^2 \), still larger than the fusion cross-section by several orders of magnitude. The emittance growth due to the beam-beam interaction is now \( 10^{-8} \text{ rad} \), few orders of magnitude smaller than the contribution from the intrabeam interaction.

6. Small-Angle Scattering

We have seen that the beam performance is entirely dominated by Coulomb scattering. This may preclude the possibility of producing nuclear fusion between the two beams. In fact particles would be scattered and lost before they had a chance to fuse with each other. Beam intensity is indeed considerably larger than usual, and Coulomb scattering effects are correspondingly enhanced. Nonetheless, the results of our calculations have been obtained with equations, like Eq. (5), which really apply to diluted beams. In reality, particles could be electromagnetically screened from each other above some distance. At this regard we remind the relation between scattering angle \( \theta \) and impact parameter \( b \)

\[
2 \tan \left( \frac{\theta}{2} \right) = \frac{2 Q^2 r_p}{\lambda_D^2 b} \tag{7}
\]

The largest impact parameter is the Debye length given by

\[
\lambda_D^2 = \frac{A (\beta c \theta_b)^2}{(4 \pi \rho c^2 Q^2 r_p)} \tag{8}
\]

If we set \( b < \lambda_D \) then the scattering angle has to be consequently larger than the value calculated with Eq. (7). With our parameters we estimate \( b_{\text{max}} = 3 \times 10^{-7} \text{ cm} \) and \( \theta_{\text{min}} = 2 \times 10^{-5} \text{ rad} \), so that the results of our calculations remain valid.

Despite the large value of \( N \) and \( \rho \), we are still dealing with a diluted beam.

It is conceivable to manipulate the beam parameters to reach a situation where the Debye length is so small that the resulting minimum scattering angle approaches \( \pi \). In this situation, particles would be completely screened from each other and the electromagnetic interaction effectively turned off. If this condition applies to a single beam, it will apply even more to the beam-beam interaction. In particular, there would not be any longer need for space-charge neutralization with electrons. We judge this interesting approach worth of consideration. As an example, we estimate that complete screening can be reached by lowering the beam
emittance down to $10^{-6} \, \pi \, \text{mm mrad}$, leaving all the other parameters unchanged.

7. Crystalline Beams

There is recently considerable interest [4, 6-7] to demonstrated experimentally an ordered state of matter which is made of a low-energy beam of ions circulating in a storage ring where particles occupy rigid positions with respect to each other; essentially equally spaced. The state of the beam is also referred to as being very cold, since particles are allowed only a small amount of kinetic energy which will consent small oscillations. Very powerful and effective cooling techniques are required for reaching the lowest state. It is conceivable that the two colliding beams can be made as Crystalline Beams. This configuration would eliminate electromagnetic interaction. Moreover there would not be any more need to trap electrons for the neutralization of beam space-charge. It remains, nevertheless, the important issue of determining the stability of two Crystalline Beams colliding periodically with each other.

8. Conclusions

We have outlined a method to produce nuclear fusion by the periodic collision of two beams, of protons and ions of Boron 11. We have assessed beam and collider parameters for the production of 1 MW of useful power. We have found that the electromagnetic interaction by Coulomb scattering between particles causes large disruptive effects. Methods based on the control of the smallest scattering angle and on the use of Crystalline Beams are proposed for turning off the particle-particle electromagnetic interaction, and to restore the chance of the particles to fuse with each other.

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10. References

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