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Nuclear Fusion of Protons with Boron

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Nuclear Fusion of Protons with Boron*

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Introduction

One of the most interesting fusion reaction[1] is a proton colliding with an ion of Boron 11. The ion has mass number A=11 and atomic number Z=5. During the reaction the proton fuses with the ion, where it is trapped by the nuclear potential barrier. For a very brief period of time, an ion of Carbon 12 is formed, with mass number A=12 and atomic number Z=6. The new ion is at an extremely excited state at formation and it immediately decays in three α particles.

In order for this reaction to occur, assuming the ion of Boron at rest, the proton needs a sufficiently large energy. There is a broad resonance[2] centered around 675 keV with a width of about ±75 keV; this is followed by others in the few MeV range and preceded by one at 160 keV. The resonance at 675 keV is of particular interest: it exhibits a large cross-section of 0.9 barn. All the others either require a considerably larger proton energy or have lower fusion cross-sections. The low energy combined with the large fusion cross-section makes the reaction a good choice as a method for obtaining fusion nuclear power. Indeed the process is exothermic; once the lowest bound state made of the three α particles is reached, a total energy of 8.7 MeV is released under the form of kinetic energy given to the α particles. The expectation value of the energy each particle takes is just one third of the total, that is 2.9 MeV; but the range of the energy distribution is wide with the upper limit given by one α particle absorbing all of the total energy and the other two produced at rest.

Since it is relatively easy to control the energy of the proton with today's accelerator technology, the fusion reaction here proposed can be easily ignited with no other possible channels of interaction involved. In particular no neutrons or gamma rays are produced, a fact which also makes the process valuable for industrial applications. Another interesting feature is the large state of electric charge (Z=6) of the final products which suggests methods employing electricity for the immediate conversion of the nuclear energy to electric power.

Two methods are investigated in this paper to convert the released fusion energy directly in electric power. The first is very simply the use of a beam of protons traversing a fixed target of Boron. Unfortunately this method cannot be made to work, but its investigation naturally yields to the second method which makes use of two beams, one of protons and one of ions of Boron, colliding with each other. This second method is feasible but it requires a significant amount of research and development in accelerator technology.

*Work performed under the auspices of the U.S. Department of Energy.

An example of Reactor with a Fixed Target

A very simple example of how to capture the energy released by the fusion reaction and how to convert it immediately in electric power is shown in Figure 1. An intense proton beam, of well defined energy (675 keV), with a sufficiently narrow energy and angular spread, impinges on a solid target at rest, made of pure Boron 11, at normal room and temperature conditions. The proton beam can be obtained with several RFQ devices all merging with each other to produce a large output current. Boron exists naturally as a compound of two isotopes: B^{10} at 20% and B^{11} at 80%. High purity Boron may be prepared chemically always as crystallized solid, but also in the form of filaments of small diameter. The melting point is around 2300 ^{o}C and the density at room temperature is 2.535 g/cm^3. The cost may reach the one-hundred dollars per pound.

If one assumes that every proton will fuse with an ion of Boron 11 in the target, for every proton of 675 keV, three α particles for a total energy of 8.7 MeV are produced. The ratio of the two energies is significantly large. For the amount of power spent to produce the proton beam at the required energy, it is possible to recover a power 13 times larger. Moreover the three α particles leaving the target are positively charged since they have been stripped of the orbiting electrons in the process. The target is placed at ground potential and the ions, which are produced moving essentially in every direction, are decelerated by the electric field between the target and an electrode surrounding the target. The electrode is maintained at the positive potential of about 2.9 MVolt. The deceleration of the ions toward the electrode will induce an equivalent electric current flowing along the load R shown in Figure 1 between the electrode and ground. With a 100% conversion efficiency, obtained assuming that every proton will fuse and that all α particles are produced with the energy of 2.9 MeV, the output power so derived is

$$P = 3 \text{ x } (2.9 \text{ MVolt}) \text{ x } I_p = (8.7 \text{ MWatt}) \text{ x } I_p$$

where I_p is the average proton beam current in ampere. Thus, for instance, a one ampere proton beam can generate an electric power of 8.7 MWatt.

Nevertheless the conversion efficiency cannot possibly be 100%. For instance, to generate a proton beam with an average current of one ampere it takes at least 0.675 MWatt for the proton beam itself and, in addition, some power dissipated directly in the source and accelerating device. The extra power required to maintain the process can be as much as the beam power. But even in this case the conversion is highly efficient.

To complicate the situation, the energy distribution of the α particles is very broad. It is possible to harness the electric power from ions with different energies by resorting to a multi-electrode structure as the one shown in Figure 2. Several spherical electrodes are surrounding each other and placed at different positive electric potentials increasing in magnitude toward the outside, so that the one outermost is at the maximum value of 8.7 MVolt. The voltage drop from one electrode to the next can be set at a sufficiently low value by increasing correspondingly the number of electrodes.

More serious effects to the lowering of the conversion efficiency are the facts that not every proton in the target will fuse with an ion of Boron 11 and not every ion resulting from the fusion will emerge from the target itself. Let ζ_p and ζ_B be the fraction respectively of protons and Boron ions yielding to useful fusion events. The following gives the power P_{excess} that can be obtained in excess from the process

$$P_{excess} = (8.7 MWatt)\ \zeta_p\ \zeta_B I_p - (0.675\ MWatt)\ I_p - P_{acc}$$

where P_{acc} is the power spend for the operation of the device itself and the second term is the power proper of the proton beam. In this equation I_p is the average proton current again expressed in ampere. The principle of operation of the simple reactor proposed here is advantageous only when P_{excess} is positive. A break-even situation is reached when $P_{excess} = 0$. Unfortunately it is practically impossible to reach the break-even point for this reactor model. Even ignoring the operating power P_{acc}, the break-even situation would correspond to

$$\zeta_p\ \zeta_B = (0.675\ MWatt) / (8.7\ MWatt) = 1/13$$

In reality the fraction of protons and ions fusing and emerging from the target is considerably lower than this by several orders of magnitude. The number of fusion events occurring by a proton traversing a target having thickness τ is

$$n_{events} = \sigma\ \rho\ \tau$$

where $\sigma = 0.9 \times 10^{-24}\ cm^{-2}$ is the fusion cross-section and $\rho = 2.535\ g/cm^3$ the target density. To get $n_{events} = 1$ one derives $\tau = 8$ cm. This is a long distance for the proton to survive. The stopping power for a proton of sub-MeV energy is around 300 MeV/(g/cm^2) and four times this for the α particles in the few MeV range. The proton will lose all its energy after travelling only 10 microns in the target! This yields $\zeta_p = 10^{-4}$. Thus essentially all protons cannot travel sufficiently long enough to produce a fusion event. The same applies also to the α particles which are the result of the very rare fusion events, though, since they are produced moving in every direction, their chances of leaving the target can be increased by making the target as a filament with a small diameter.

The energy loss that the proton suffers when it is traversing the target is caused entirely by the ionization and the excitation of atoms. There are too many electrons on the way before the proton can collide with the nucleus of an atom of Boron. It is thus necessary to find another environment where the protons can collide directly with ions of Boron 11 already completely stripped of their electrons. This suggest a model of reactor where a beam of protons is this time colliding with a beam of B^{11} completely stripped.

The model of colliding beams was already proposed in the past[3]. We shall look at it again with a more specialized application to the proton-Boron fusion reaction.

An example of Reactor based on the method of Colliding Beams

This is shown schematically in Figure 3. The proton beam is generated with hydrogen ion sources attached to a battery of RFQ devices running simultaneously and in parallel. Each RFQ device can generate an average current of a fraction of one ampere at relatively high frequency, from few tens to few hundred of MHz. This technology[4] is sufficiently advanced these days and it can be proposed with good confidence. It is not clear whether it is necessary to rely on negative hydrogen ions sources; positive ions, that is atomic hydrogen stripped of the electron, may also be adequate; this would eliminate the inconvenience of the stripping target in the subsequent circular device. The proton beam is injected in a cooling and storage ring which is also one of the two rings that make the collider proper. Cooling is needed to reduce or to maintain the beam transverse dimensions (betatron emittance) to sufficiently small values to enhance the collision events in the collider. Considering the small velocity of the beam, electron cooling is the most effective for the purpose. The cooling ought to be very powerful so that the beam spends only a small fraction of the time being cooled and it can be effectively involved in the fusion process.

The beam of ions B^{11} is also prepared already completely stripped from a similar battery of RFQ's each fed by ECR sources[5] which are at the moment the most suitable to generate completely stripped ions. Hopefully, the ECR sources will be capable to deliver an amount of beam intensity matching the one of the proton beam. Also the ion beam will be injected in its own cooling and storage ring which is placed sidewise next to the proton ring. There is thus a continuous streaming of beams at both sides from the sources to the RFQ's, to the storage rings and to the collision region. The two beams are circulating in the same direction in the respective storage rings and collide head-on in the common straight section of the collider, opposite to the insertions where injection occurs and other devices for beam manipulation, cooling and control are located. The collider is thus essentially made of two separated rings placed side by side with one long straight section in common. In this location the two beams will collide and protons and ions will fuse. The RFQ's devices on both sides are operating at the same frequency. During collision the two beams have essentially the same bunching structure, transverse dimensions and intensity.

The long straight section where the two beams collide is surrounded by the reactor vessel itself. This is shown more in details in Figure 4. Since the vacuum chamber and the rest of the collider rings are at ground potential, the interaction region is surrounded by a layer of electrodes placed at positive potentials of magnitude increasing toward the exterior to simulate the same configuration shown in Figure 2.

Beam Requirements.

The advantage of the method of colliding completely stripped beams is that the particles are immediately exposed to each other without having to encounter electrons attached to them along their trajectories. On the other hand, the ion beam is in a more diluted density form when compared to the density one can obtain in a solid fixed target; this will lower correspondingly the chances for collision and fusion, except that with a collider ring the unaffected beam can be used over and over again since it moves periodically on a closed path.

Unless the two rings of the collider have different dimensions, it is important that two beams are moving with the same velocity. At the same time, the energies of the two beams are to be as low as possible. Let T_p and T_B be the kinetic energies respectively of protons and Boron ions. We require $T_p + T_B = 675$ keV. The solution which yields to equal velocity is $T_p = 56$ keV and $T_B = 619$ keV corresponding to the velocity $\beta = 0.011$. With such low energies, both beams can already be delivered from the ion sources with only a modest post acceleration step. The RFQ's may not be required! A summary of beam parameters is given in Table 1.

Let N be the number of particles in each beam that at any one time travel in the interaction region, that is the long straight section which constitutes the nuclear reactor. N is also a measure of the total number of particles circulating in a ring, within a factor of two or three, provided that the straight sections are long enough compared to the circumference of the ring. Any of these particles may collide with another moving in the opposite direction and fuse. Let also S be the common cross-section of the two beams where they collide. The frequency of particle encounter f_{enc} is the revolution frequency. The number of fusion events per unit of time in this configuration is then given by

$$dn/dt = \sigma (N^2 / S) f_{enc}$$
$$= \sigma L$$

where $\sigma = 0.9 \times 10^{-24}$ cm^{-2} is again the fusion cross-section and L is called the *luminosity* of the collision. If each fusion event releases an amount of energy W then the instantaneous power produced is

$$P_g = W (dn/dt)$$

At the same time there is a depletion of both beams which will occur at the rate

$$dN/dt = -dn/dt$$

The ion sources have then to replenish the beams also at these rates. One can estimate the amount of power, respectively P_p and P_B, which will be required just for the beam production

$$P_p = T_p (dn/dt) \quad \text{and} \quad P_B = T_B (dn/dt)$$

To this, one should then add the power P_{acc} that is dissipated for the operation of the entire complex. The equation for the power P_{excess} produced in excess is

$$P_{excess} = P_g - P_p - P_B - P_{acc}$$
$$= (W - T_p - T_B)\,(dn/dt) - P_{acc}$$

All the quantities appearing in this equation are defined positive. It is immediately seen that in order for the process to be power productive, P_{excess} has to be positive, which requires that the following condition is satisfied

$$T_p + T_B < W$$

The energy released by one fusion event is larger than the sum of the kinetic energies of the particles entering the reaction. In our case W = 8.7 MeV and $T_p + T_B$ = 675 keV.

It is very important to minimize the losses and the inefficient use of power for the operation of the facility. In practice P_{acc} can never vanish and, in order for the process to be productive, one requires that the luminosity of the collision is large enough, that is

$$\sigma L > P_{acc} / (W - T_p - T_B)$$

Neglecting the amounts of beam power, a break-even situation is obtained when the power delivered equals the power just needed for the operation of the system. This corresponds to the following condition

$$L = P_{acc} / (\sigma W)$$

It is not clear what value one should take for the operation power P_{acc}. Accelerator technology has improved considerably during the last decade. Accelerator designers and builders are more conscious of the energy problems and optimize their design and operation with very high efficiency. For instance, as a rule of thumb, the power required to operate an accelerator system for large intensities is about equal to the power provided to the beam. More generally, one can measure the operation power in units of the combined beam power, by introducing an efficiency factor $\eta > 0$

$$P_{excess} = P_g - (1 + \eta)(P_p + P_B)$$

It is seen immediately that a break-even point is reached for $\eta = 12$. In the following we shall neglect the power delivered to the beam and the required operation power. We shall assume that the derived nuclear power from the collisions of the two beams is entirely available as excess power. We shall set as a goal the production of P_{excess} = 1 MWatt, so that the required luminosity of the collision is

$$L = P_{excess} / (\sigma W)$$
$$\sim 10^{42}\ cm^{-2}\ s^{-1}$$

This is an exceedingly high luminosity, larger by several orders of magnitude when compared to the figures commonly used in large-energy particle colliders. The rate of fusion events is

$$dn/dt \sim 10^{18} \text{ events per second}$$

This is also equal to the rate of depletion of the beams and to the rate particles are produced at their sources and are entering the system. Beam currents at injection are not excessive since they are about 100 mA-particle for both types of beam. Protons can certainly be produced with a single source; the production of ions of boron require improvement of the sources available with today's technology. Eventually several ECR sources can be used in parallel to each other.

If the circumference of the collider is 3.3 meter, the frequency of encounter f_{enc} is 1 MHz. Assuming a beam cross-section at collision $S = 10^{-4}\ cm^2$, then each beam is made of 10^{16} particles circulating at any time in order to get the required luminosity $L = 10^{42}\ cm^{-2}s^{-1}$. This means that each particle will spend in average 10 msec in the collider, that is will survive in average 10 thousand revolutions. A summary of these parameters is also given in Table 2.

Space Charge Limitations

Given the large number of particles circulating in the collider rings, there is a very serious limitation to the smallest transverse emittance that can be obtained; this is caused by the space-charge limit.[6] It is customary to measure this limit in terms of the maximum value $\Delta\upsilon$ that can be allowed of the betatron tune depression caused by the space-charge forces,

$$\Delta\upsilon = N\, r_p\, Q^2 / (2\, \beta^2\, \gamma^3\, B\, A\, \varepsilon)$$

where $r_p = 1.535 \times 10^{-18}$ m is the classical radius of a proton, N the total number of particles, Q the charge state and A the mass number of the particle specie, B the bunching factor defined as the ratio of average beam current to the peak current and which we take here to be unit, and ε is the full betatron emittance. A reasonable limit on the value of $\Delta\upsilon$ is about unit. Because of the larger charge state, the beam of Boron ions would suffer a larger tune-depression by about a factor of two with all the other beam parameters, except mass number, the same. To keep the beam stable against space-charge limit the betatron emittance cannot be less than $\varepsilon = 50\ \pi$ m rad!

It is very difficult to achieve the required beam spot size of 0.1 mm at the interaction region with such large beam emittance. An ordinarily conceived method is the focussing of the particle motion with quadrupole magnets placed on both sides. One measures the beam envelop with an amplitude lattice function β^* from which one derives the beam radius a according to the formula $a^2 = \varepsilon\beta^*/\pi$. Typically in a storage ring a small value of β^* is few centimeters. In turn this requires a beam emittance $\varepsilon = 10^{-6}\ \pi$ m rad, eight orders of magnitude smaller than the space-charge limit! This figure is also about what one can expect for the beam emittance from the source and therefore at injection into the storage rings.

There is a method to compensate space charge effects in particle accelerators that has often been proposed in the past but in reality rarely employed (probably because either the opportunity or the need rarely presented themselves). Unfortunately this will re-introduce the presence of electrons that we found necessary to remove in the fixed-target model, but in a lesser amount and free. The compensation is done with neutralization of the beam electric charge[7] by trapping electrons within the beam electrostatic transverse potential generated by the space-charge itself. The electrons can be produced by ionization of the atoms of the residual gas in the vacuum chamber of the storage rings. During the same time, the positive ions produced from the ionization process are immediately removed from the same potential barrier.

Beam Space-Charge Neutralization

Let P_{mmHg} be the vacuum in the storage rings expressed in mmHg. We shall assume a vacuum essentially composed of nitrogen (N_2) molecules. At room temperature, the number of molecules per unit of volume is given by

$$n_{mol} = (3 \times 10^{16}/\mathrm{cm}^3)\ P_{mmHg}$$

which corresponds to the following density

$$\rho = (1.4 \times 10^{-6}\ \mathrm{g/cm}^3)\ P_{mmHg}.$$

The stopping power for protons in nitrogen is 750 MeV/(g/cm^2) at the energy of 50 keV, and it is also about the same for the Boron ions. A vacuum pressure of 1×10^{-8} mmHg will then corresponds to an energy loss of less than 1 keV for a particle spending the average 10 milliseconds in the storage ring. This vacuum pressure is thus adequate and it is assumed in the following.

The ionization rate can be estimated with the following equation

$$dn_i/dt = \beta c\ \sigma_\iota\ n_{mol}\ N$$

where $\sigma_i = 2.5 \times 10^{-18}$ cm^2 is the ionization cross-section. We shall assume that essentially a single electron is produced per ionization event. With the vacuum pressure of

10^{-8} mmHg, the number of electrons produced is 10^{15} per second. It takes about ten seconds to produce a number of electrons equal to number of particles to achieve complete space-charge neutralization. As the electrons are being produced and accumulate within the beam dimensions, the potential barrier decreases continuously until vanishes. Beyond that point the electrons produced in excess will leave the beam and the neutralization should persist for a long period of time. It seems then that this method for curing of the space-charge effects is feasible. Of course the control of the method sounds very delicate and requires a closer and deeper examination than done here. For instance, a point of concern is the initial potential barrier for 10^{16} Boron ions not yet neutralized; this is

$$U = NQ\,e/\,(2\pi R)$$

$$\sim 20 \text{ MVolt!}$$

To avoid such large potential, there should be an initial period of time where the beam is slowly established toward full intensity and density in combination of electron cooling and ionization. It is important that the ionization method for space-charge neutralization is also used in a programmed mode during cooling to avoid that the space-charge limit is encountered during cooling itself.

It is also important to estimate the rate and the consequences of the interaction between the trapped electrons and either the protons or the Boron ions. The interaction is essentially Coulomb scattering with a cross-section one or two orders of magnitude smaller than that between the two primary beams. The effect on the protons and the ions may cause ultimately an increase of the beam dimensions. Most important, though, it may cause a removal of the electron itself which in turn may restore some space-charge effects. All these processes can be controlled to some degree by adjusting the pressure of the residual gas.

Electron Cooling

The most important requirement in order for cooling to be effective is to provide velocity matching between the ion beam and the electrons. Since $\beta = 0.011$ this corresponds to an electron kinetic energy of only 30 eV! Whether a beam with such low energy is feasible over an extended length depends on other parameters like intensity and transverse dimensions which in turn depend on the required cooling rate. Given the very low energy of the beam to be cooled, we expect modest requirements on the electron beam.[8]

Cooling should proceed to maintain the beam at the space charge limit with a circulating number of particles equal to 10^{16} and an emittance of 1π mm mrad, which is also the emittance at injection as provided by the sources. From the equation of the space-charge tune-depression we derive for the cooling rate

$$\lambda = (1/\varepsilon)(d\varepsilon/dt) = (1/N)(dN/dt)$$

which gives $\lambda = 100\ s^{-1}$ for $N= 10^{16}$ and $dN/dt = 10^{18}\ s^{-1}$. The formula for the cooling rate is

$$\lambda = (4\pi Q^2 r_e r_p L \mu J/e) / (A \beta^4 \gamma^5 \theta^3)$$

where $r_e = 2.818 \times 10^{-15}$ m is the electron classical radius, μ the ratio of the length of the electron beam to the circumference, J the electron beam density, L ~ 1 the Coulomb log, and θ the angular divergence of the electron beam which we can assume to be larger than the angular divergence of the electron beam $\theta^2 = \varepsilon/\pi\beta^*$. With our parameters $\theta = 10$ mrad. If we take $\mu = 1\%$, which corresponds to a length of about three centimeters, the electron beam density for the cooling of the protons is

$$J = 40\ mA/cm^2$$

With a radius of 2 millimeter, the electron current is then a modest 5 mA. For the ions of Boron, a smaller density by a factor of two is needed. This is a very small current; there are about 10^8 electrons in the length of 3 cm, considerably less than the number of ions in the primary beam. This is a point of concern, of course, since it may violate one fundamental condition for electron cooling: there should be more electrons than ions to be cooled! A summary of the electron cooling parameters is given in Table 4.

Configuration of a Storage Ring

The magnetic rigidity of the protons at 56 keV is 0.355 kGauss-meter and the one of the Boron ions at 619 keV is 0.757 kGauss-meter. As shown in Figure 5, a storage ring is made of two 180^o bending magnets with a bending radius of 20 cm. In the proton storage ring the field is 1.8 kGauss, and in the one for the beam of Boron ions the it is 3.8 kGauss. The long straight sections are one meter long, so that the circumference of each ring is 3.3 meter. Focusing is provided with permanent quadrupole magnets spaced 10 cm from each other with alternating gradient sign, like in conventional FODO cells. If one desires a phase advance of 90^o per cell, which is usually considered optimum for focussing, the quadrupole gradient is 5 kG/cm for the case of protons and 11 kG/cm for the case of the ions, assuming a length of one centimeter. A summary of the lattice parameters of the storage rings is given in Table 3 which should be taken just as an example. The value of the amplitude lattice function β oscillates between a maximum of 34 cm and a minimum of 6 cm. The quadrupoles can be made with a bore diameter of 2 cm and they can be located also inside the two dipole magnets to provide for focussing in those regions. For this purpose, the dipole magnets can be build with a gap of 10 cm, large enough to accommodate the permanent magnets. In principle, extra focussing can be obtained also by introducing a gradient in the dipole magnets with a properly designed profile of the inner iron walls, and/or by modifying the entrance end exit angles. Of course a point of concern is the activation and overheating of the material of all magnets caused by the direct exposure to the α particles produced in the nuclear fusion reaction.

One long straight section is shared by both beams for the fusion reaction and houses the reactor vessel. Injection occurs upstream of the opposite straight section, with the electron beam for cooling placed downstream. Vacuum pumps and beam diagnostic can also be located in this long straight section.

It is estimated that the total power needed for the operation of the entire device is around few tens of kilowatt. The power delivered to the proton beam is a modest 5.6 kW; significantly larger is the power to the ion beam: around 300 kW. It is possible to reduce this figure with a configuration where the two beams have unequal velocity and intensity.

Conclusions

We have examined two methods for the exploitation of the nuclear fusion reaction between protons and Boron 11. We have seen that the fixed-target method is really impractical, and that the colliding-beam method shows some interesting possibilities. The second method requires a considerable amount of research and development of the accelerator technology especially in the following four areas: (1) development of the present state of art of proton and completely stripped ion sources; (2) better understanding of the space charge effects and their control with beam neutralization; (3) performance analysis of the electron cooling and the realization of a stable electron beam at very low energy; and finally (4) a more involved design of the nuclear reactor vessel and study of the conversion to electric power.

Our proposal based on the method of colliding beams has two major points which makes it unusual and quite different from the ordinarily conceived colliders, especially those employed in nuclear and high energy physics: namely, the very low energy of the beams involved in the collision and the very large luminosity required. Nevertheless, experts of accelerator technology have often witnessed in the last two decades surprising advances and progress in the field, also beyond expectations. Thus, it is our judgement that, since there is so much to gain from the control of the nuclear fusion reaction and since our proposal shows a reasonable chance of being feasible, more effort should be devoted to the study and design of it.

Acknowledgment

The author of this report wishes to thank Dr. Antonio Dainelli of the Laboratori Nazionali di Legnaro (INFN), Padua, Italy, for having shown to him the article by Lidsky[1] which explains the merits of the proton-Boron fusion reaction. Doctor Dainelli has also pointed out to the author the possibility to convert nuclear fusion power directly into electric power and the method of the fixed target discussed in this report with more details.

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TABLE 1. Beam Parameters

	Protons	B^{11} Ions	
Charge State, Z or Q	1	5	
Mass Number, A	1	11	
Rest Energy	0.93826	10.145	GeV
Kinetic Energy	56	619	keV
β	0.011	0.011	
Magnetic Rigidity	0.355	0.757	kG-m

TABLE 2. Colliding Beam Scenario

Revolution Frequency	1 MHz
Number of Particles per Beam	10^{16}
Circulating Current	100 mA-particle
Cross Section	0.01 mm^2
Luminosity	10^{42} cm^{-2} s^{-1}
Rate of Fusion Events	10^{18} s^{-1}
Power Generated	1 MWatt
Power in the Proton Beam	5.6 kWatt
Power in the Ion Beam	310 kWatt
Power to operate Device	50 kWatt

TABLE 3. Configuration of a Storage Ring

	Protons		B^{11} Ions
Circumference		3.3 m	
Bending Field	1.8 kG		3.8 kG
Bending Radius		20 cm	
Number of FODO cells		16	
Phase Advance per cell		90^0	
Quadrupole Gradient	5 kG/cm		11 kG/cm
Number of Quadrupoles		32	
Number of Superperiods		2	
Length of Straight Section		1 m	

TABLE 4. Electron Cooling

Cooling Rate	100 s^{-1}
Kinetic Energy	30 eV
β	0.011
Electron Current	5 mA
Beam Radius	2 mm
Beam Length	3 cm
Electron Density	40 mA/cm^2
Coulomb Log	1
Electron Temperature	0.3 eV

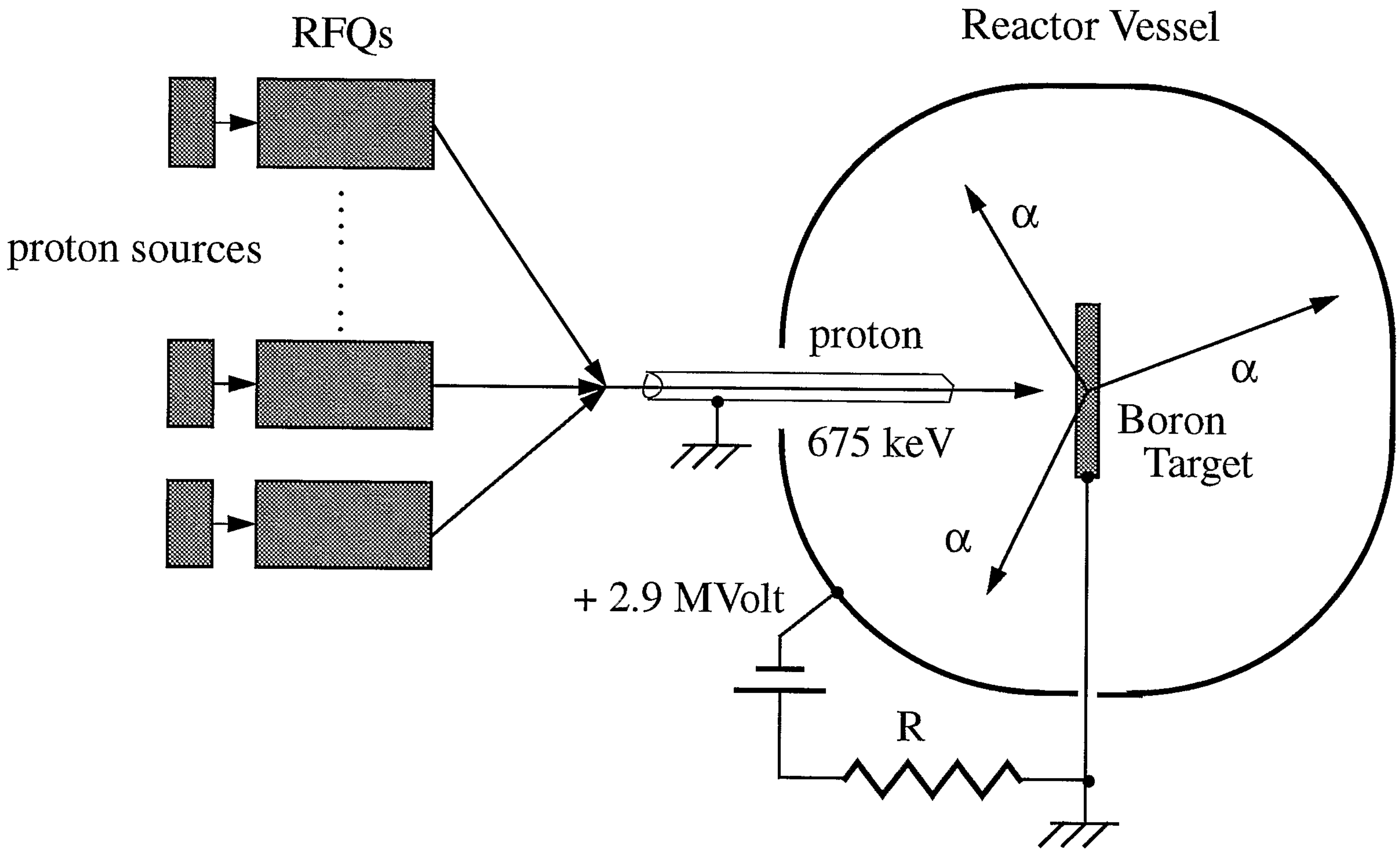

Figure 1. Nuclear Reactor with Fixed Target

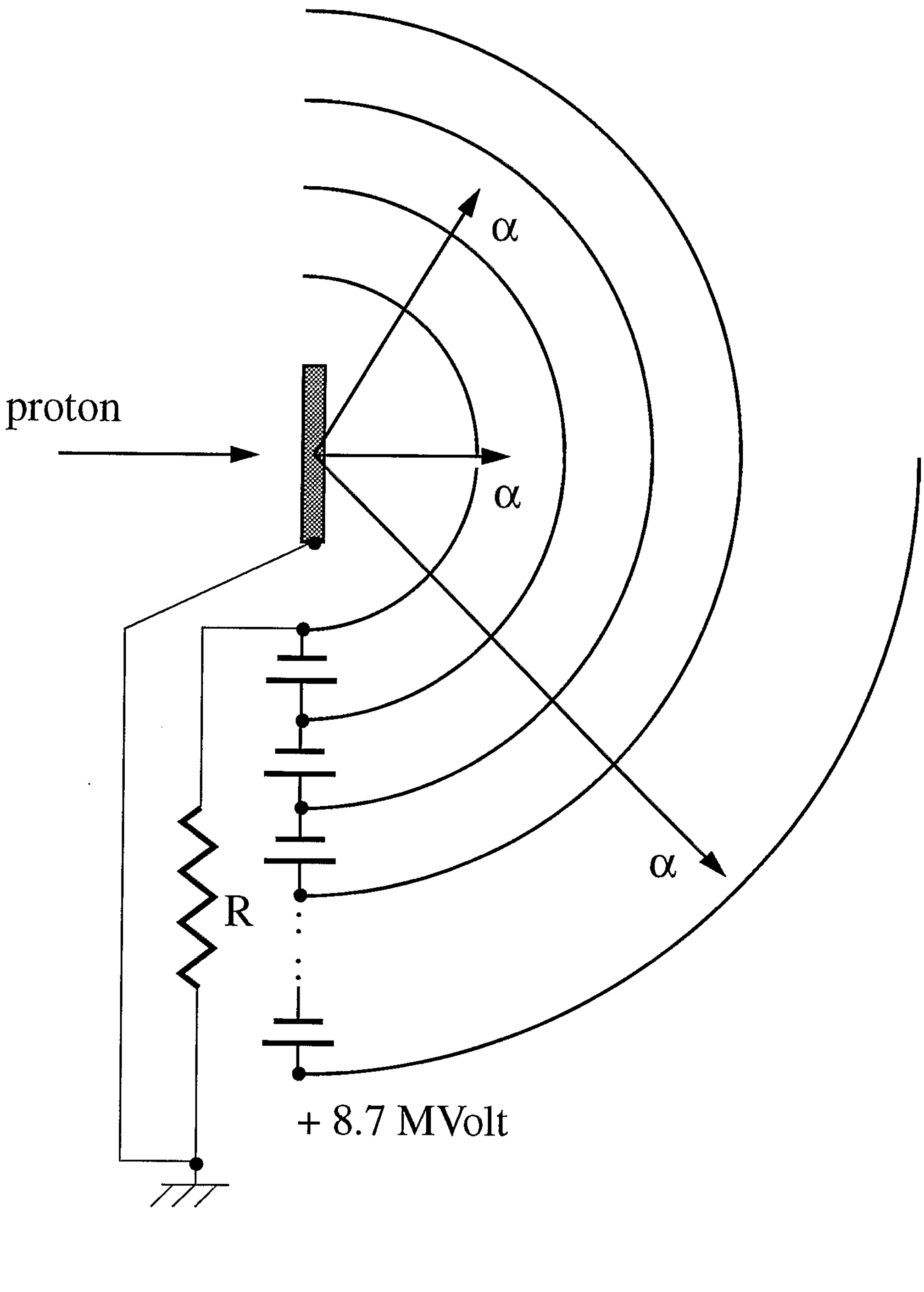

Figure 2. Multiple-Electrode Reactor Vessel

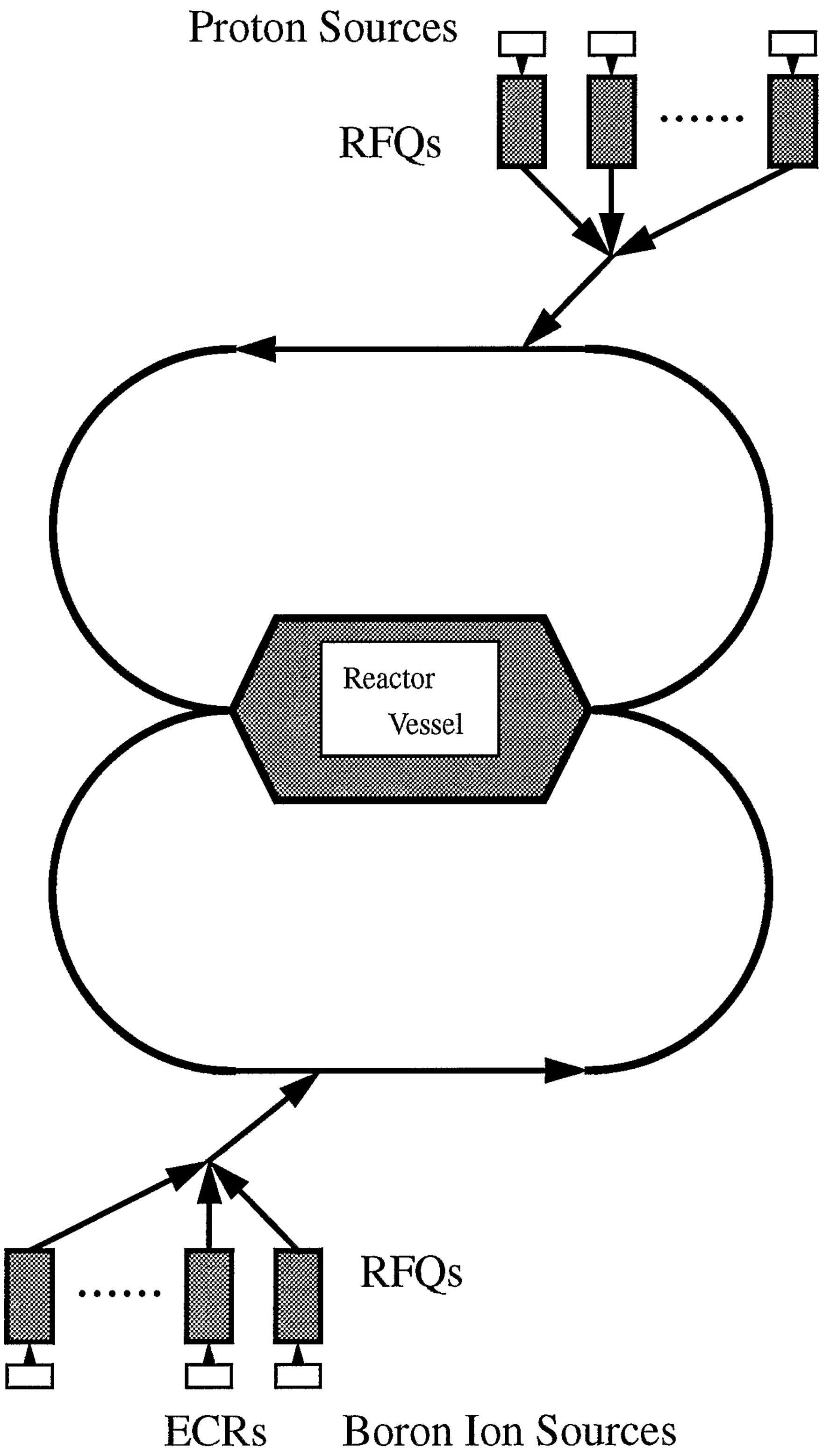

Figure 3. Nuclear Reactor with Colliding Beams

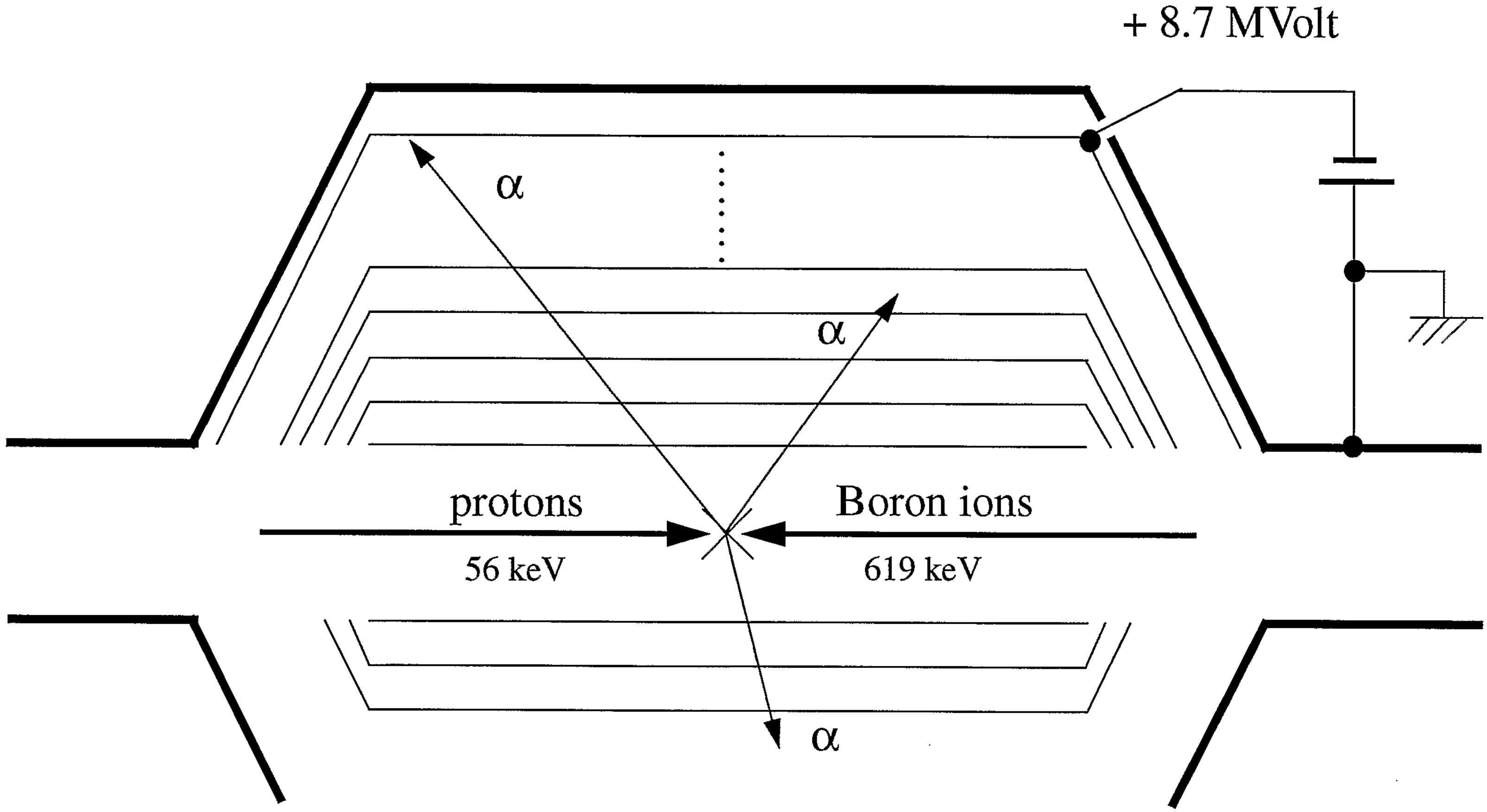

Figure 4. Nuclear Reactor Vessel for Colliding Beams

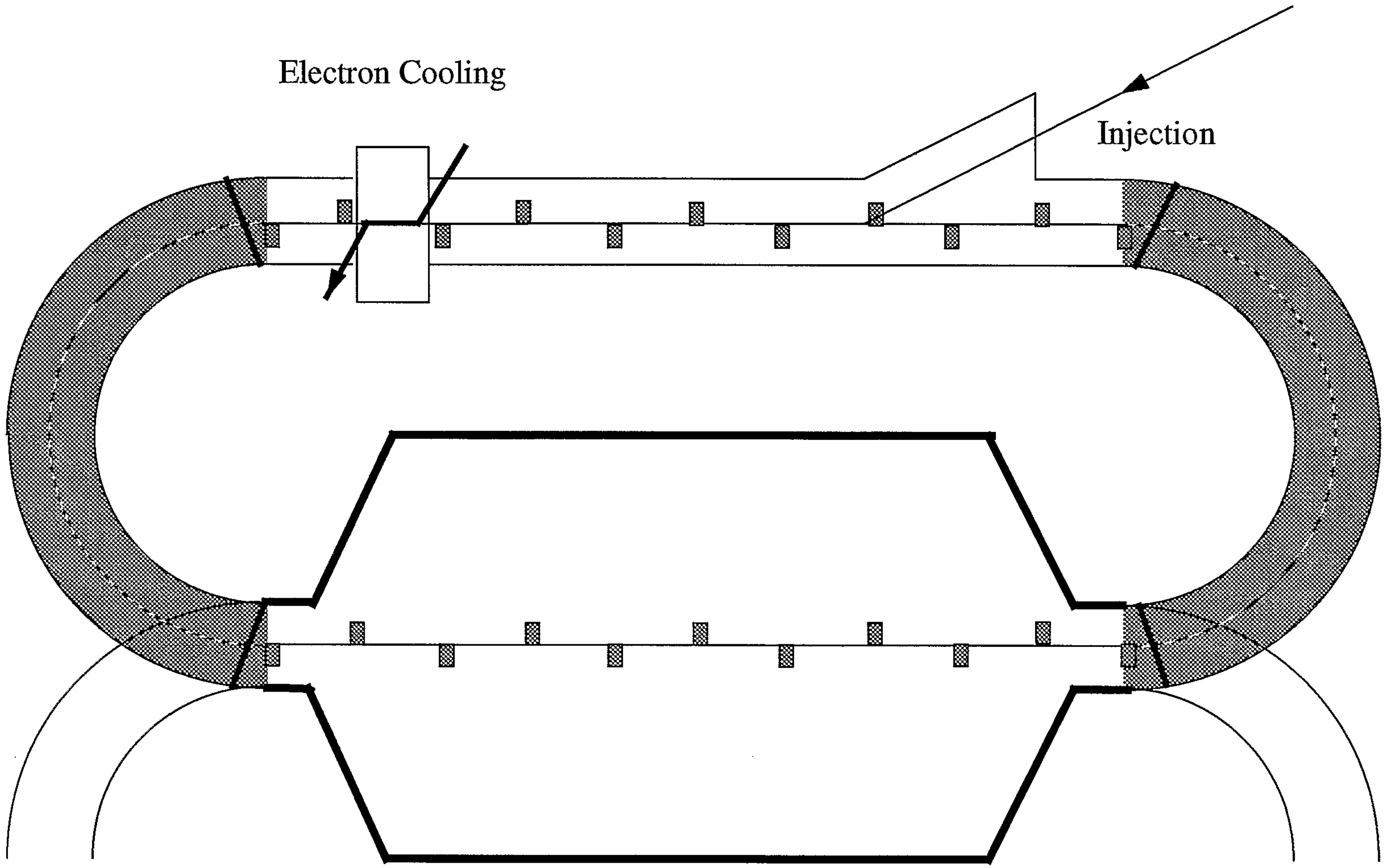

Figure 5. Configuration of a Storage Ring