Concept of a Nuclear Plant based on the Fusion Reaction of Protons with Ions of Boron

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September 10, 1994

Department of Advanced Technology

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Summary *

This report describes a method of extracting energy from fusion events occurring during the collision between a beam of protons, having an energy of 0.37 MeV, and a beam of ions of boron-11, having an energy of 0.31 MeV. The two beams circulate in opposite directions in a common storage ring, with a diameter of about 2.5 m, where they continuously collide head-on along the common circumference. The storage ring is a Circular Radio Frequency Quadrupole made of four parallel copper rods among which a transverse electromagnetic mode is excited. Continuous current flowing along the outer rods provides a magnetic field that bends both beams on the common circular orbit.

Beam Crystallization is proposed as the method of increasing ion-beam densities and, thus, the rate of fusion events exceeding the space-charge and interparticle Coulomb interaction limits. Beam Crystallization is obtained with Laser Cooling that requires the presence of orbiting electrons around the ions. The CRFQ storage ring design is optimized for the realization of Crystalline Beams.

This report reviews expected performance at different beam-intensity levels and dimensions with nuclear power in the range of milliwatts to megawatts. A scenario for the exploration and demonstration in stages is also presented and discussed. The required experimental program is modest in cost and size with respect to other proposed methods to generate nuclear fusion power.

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Introduction

The absence of an electric charge in a neutron makes it capable of interacting with very heavy nuclei and to cause their fission into two or more medium-size fragments with release of energy which can be converted to thermal and mechanical power. Nevertheless, the presence of the neutron itself, in the nuclear fission process and of the fragments being produced, which often have toxic properties, does not make this method of energy always appealing and useful.

On the other hand, the presence of the Coulomb barrier between colliding light ions has been the major impediment for the practical application of nuclear fusion. In the past, several methods have been proposed and studied to generate and to control power from nuclear fusion. These methods, which are based either on magnetic or inertial confinement, require full-size and costly prototypes for demonstration. Even the simplest reaction considered, i.e., the fusion of deuterium with tritium, does not completely remove the presence of neutrons, and the inefficient and elaborate conversion to thermal and mechanical form of energy.

It has been suggested [1] that the fusion reaction between protons and ions of boron-11 is most desirable because of the complete absence of dangerous by-products; for instance, there are no neutron or gamma radiations involved. Moreover, it is possible to harness electric power directly from the reaction process because of the very large charge state of the final product: three α particles. Unfortunately, this reaction exhibits a higher Coulomb barrier which requires larger energies of the colliding elements. It was, therefore, speculated that [2] that the proton-boron reaction could be treated more easily with accelerator technology.

A colliding beam scenario [2], based on the reaction between protons and ions of boron, has recently been proposed and investigated, but found to be seriously limited by space-charge forces and the Coulomb interaction among ions; i.e., the same forces which introduce the Coulomb barrier as the impediment to the two nuclei to fuse together. There is, thus, the need to explore ways to overcome space-charge and Coulomb interaction effects if one desires to develop an energy plant based on nuclear fusion.

Proceeding from a different line of research, recently [3] there has been considerable interest in experimentally demonstrating an ordered state of matter which is made of a low-energy ion beam circulating in a storage ring where particles occupy rigid positions with respect to each other, essentially equally spaced. Particles are allowed only a small amount of kinetic energy variation from each other to mantain the amplitude of the oscillation smaller than the ion separation. Powerful cooling techniques are required to reach the ground state. It has also been determined recently [4] that Crystalline Beams can be obtained in properly designed storage rings having a high degree of periodicity, smoothness, and compactness of focussing.

It is proposed in this report that two ion beams colliding in the storage ring can be cooled at high rates and manipulated to form Crystalline Beams. This configuration would allow us to obtain denser beams by balancing the electromagnetic interaction with the ions' uniform spacing. The method of cooling being examined is Laser Cooling which has been shown [5] to be very effective. It requires that the ions be partially stripped so that the atoms may be excited and de-excited. Protons are replaced by negative ions of hydrogen and the boron beam is made of partially stripped ions with two remaining orbiting electrons.

The storage ring, where both beams circulate in opposite directions, has a circumference of 8 meters; the proton beam has an energy of 0.368 MeV and the boron beam 0.307 MeV. The simultaneous bending and focussing of both beams, which have the same magnetic rigidity, is obtained by placing four circular electrodes (rods) parallel to each other at the distance of two millimeters. The device is similar to a conventional radio frequency quadrupole which is bent and closed on itself. This device provides the most compact focussing with a shorter focussing periodicity compared to storage rings which make use of magnets.

The merits and deficiencies of the two methods of nuclear energy, fission and fusion reactions, are discussed in details in sections 1 and 2. The merits of the fusion reaction between protons and ions of Boron are reviewed in section 3. We describe the storage ring in section 4. The α particles, produced during the fusion process, are decelerated in a Reactor Vessel, described in section 5, made of a series of concentric toroidal electrodes which collect particles and directly convert nuclear energy to electric energy. Properties and requirements for reaching the ground state of Crystalline Beams and the method of Laser Cooling are exposed in sections 6 and 7 respectively. Sections 8 and 9 are a discussion on the performance that can be expected with different beam configurations. The encouraging result is that one is able to demonstrate the case of energy break-even at a level of few kilowatts of nuclear power. A modest-size power plant of ten kilowatt, the need of a typical household in the US, is also described. Section 10 summarizes issues, methods and goals which should be pursued and studied.

1. The Nuclear Fission Process

In a typical nuclear-fission process a thermal neutron is absorbed by a heavy nucleus, like uranium-235 or plutonium-239, causing its splitting in two fragments of about equal size and the releasing of few more neutrons. The reaction is exothermic, i.e., it releases energy under form of kinetic energy of the fragments. This is possible because the original nucleus is kept together with an average binding energy which is lower than the binding energy of the nucleons in the fragments. The kinetic energy of the fragments is converted to heat and to the mechanical motion of a steam turbine. With the use of a moderator, the neutrons generated in the reaction are slowed down sufficiently to interact again with the heavy nuclei and to repeat the process which is known as a *chain reaction*. By acting on the moderator it is possible to control, to activate and to stop the entire process.

The nuclear-fission process has been successfully exploited worldwide, for the last half century, in nuclear plants. The main reason for the relative success is that the primary element, the neutron, interacts only through the strong interaction. Since it does not carry an electric charge, its motion is not affected by the Coulomb barrier of the heavy nuclei. The target nuclei are very close to their stability limit so that very little energy of the neutrons is required to trigger the splitting, whereas, the amount of energy released is of the order of a fraction of MeV, which is the amount of the excess average of the nucleon-binding energy. The energy gain, i.e., the ratio of the released energy-to-the energy of neutron, is very high.

Unfortunately, there are some side effects that do not make the method of nuclear fission quite so appealing to the public exploitation: (i) The fragments have a variety of composition, many of which are capable of dangerous chemistry and need, therefore, to be disposed very carefully. (ii) The neutrons, by lacking electric charge, if not controlled, can also interact easily with the environment inducing dangerous side effects. (iii) The only method to recover nuclear energy from fission is by conversion to heating and then to mechanical motion of turbines by steam. This conversion is not very efficient and a large fraction of the original power is lost in the process. (iv) The availability of fissionable material like uranium-235 is limited around the world. The material, because of its radioactive nature, requires careful handling. It is for these reasons that, during the past half a century, scientists have searched other methods of producing nuclear energy.

2. The Nuclear Fusion Process

The other method of producing nuclear energy is the fusion of two very light ions. This process does not need neutrons, and it is made possible by the fact that the average binding-energy among the nucleons in the final product is higher than in the initial ions. An example, which involves the lightest ions, is the fusion of deuterium and tritium. The ions have to collide at a sufficiently large energy in order to fuse, and the energy gain, the ratio of released energy-to-initial ion energy, is relatively lower when compared to the fission process. In the cited example, the energy gain is about sixty, since 17.6 MeV is the energy released and the colliding energy for fusing has a threshold value of about 300 keV. The cross-section, i.e., the probability of nuclear fusion, is also relatively lower when compared to the fission events.

Nevertheless, the most crucial difference is that the two interacting elements of the fusion event carry an electric charge and that, in order to fuse, they have to penetrate the respective Coulomb barriers. Consequently this requires larger colliding energies and yields a lower cross-section.

Nuclear fusion has now been studied for about half a century, with considerable amount of human and financial effort; yet, practical solutions have not been demonstrated [1]. The major impediment is indeed the presence of the Coulomb barrier, which had no equivalent in the exploitation of nuclear fission. The impediment can be understood by recognizing that electromagnetic interactions are at a longer range and require a large initial energy to bring the two ions closer to the point where the nuclear fusion forces are more effective. Several methods have been proposed and investigated. In some the initial energy is obtained by heating up a plasma made of the ions involved (magnetic confinement), in others the initial energy is obtained by imploding a mixture of the elements with the pressure on an external shell generated by incoming intense ion beams (inertial confinement). Both methods have been found to be very expensive and require prototypes of full size for demonstration.

Historically, to somewhat circumvent the Coulomb barrier problem, the lightest ions, deuterium and tritium, have been taken as interacting elements in a nuclear fusion plant. Unfortunately, neutrons are found again within the final products, the presence of which offsets some of the benefits of the fusion reaction. Moreover, the nuclear energy released, which has the form of kinetic energy of the final elements, has also to be thermically converted accompanied by a loss due to the lower conversion efficiency, as in the case of the nuclear fission. Though there are obvious benefits in a nuclear plant based on nuclear fusion, because of the abundance of the primary elements and the lack of the medium size fragments of toxic nature, we are still far away from a fully controlled and energy effective demonstration. There is obviously need of studying different approaches.

3. The Fusion of Protons with Ions of Boron

It has been suggested [1] that a more advantageous method for obtaining and controlling nuclear power is the fusion between protons and ions of Boron-11 according to the reaction:

$$p + {}^{11}B \text{ --> } {}^{12}C \text{ --> } 3\,\alpha$$

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, ions need a sufficiently large energy [6]. There is a broad resonance centered around the center-of-mass energy of 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 $\sigma_F = 0.9$ 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. Once the lowest bound state made of the three α particles is reached, a total energy W = 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 protons and of the ions of Boron 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 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.

Boron exists naturally as a compound of two isotopes: boron-10 at 20% and boron-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 °C with a room temperature density of 2.535 g/cm^3. The cost may reach the one-hundred dollars per pound.

The major drawbacks of this reaction are the relatively higher initial-energy required, the relatively lower cross-section and the higher charge state of the elements involved. The larger initial energy does not allow easily the use of methods based on the magnetic or inertial confinement. A preliminary examination of the method of colliding beams on the other end was found to be quite interesting and promising [2]. The energy of the beams is large enough for the application of the accelerator technology.

The large charge state of the initial elements of course increases the effect of the Coulomb barrier, only partially offset by the larger particle energies. Since the charge state of the nucleus of Boron is 5, the height of the Coulomb barrier is also five times larger than in the case of deuterium colliding with tritium, which may explain the need of commensurably higher initial energy. In the colliding beam and accelerator technology, the effect of the Coulomb interaction among ions is also referred to as Space-Charge which is a very serious limitation to the collider performance, as shown earlier [2]. These limitations are aggravated by the relatively lower cross section of the fusion event which requires larger colliding beam intensities.

The method of colliding beams has been proposed earlier [7,8], but always in connection with the deuterium-tritium fusion reaction. It was always found, indeed, that space-charge limitations were too severe. Thus, in order to exploit the colliding beam method, it is important to find ways to cope with the effects of space charge. A method has recently been suggested [2] which is based on the formation of Crystalline Beams [9,10] of partially stripped ions with Laser Cooling. We shall propose and describe in the foregoing a method of colliding beams based indeed on these techniques. When these technologies are combined, it is our conclusion that experiments of very modest cost and size may demonstrate very well the attainment of fusion power.

4. The Circular RF Quadrupole Storage Ring

Our method is based on two low-energy beams of ions, completely debunched, circulating in opposite directions in a circular storage ring. In order to allow for Laser Cooling and the Crystallization of both beams, the ions carry a number of orbiting electrons. The ions of Boron are partially stripped to the charge state of Q = 3, whereas instead of protons we actually take negative ions of hydrogen with charge state Q = -1. Both of these ions can be relatively easily produced at low energy in the abundance required. The charge state of the ions of Boron is optimal for generation in the ECR devices [11]; the extraction energy of the third innermost orbit electron is 38 eV against 260 eV for the fourth inner one. Ordinary RFQ devices [12] can be used to accelerate negative ions to the desired energy, but care has to be taken not to bend or deflect excessively the ions since the binding energy of the outermost electron is only 3.4 eV compared to 13.5 eV for the electron on the ground orbit.

Because the two beams have opposite charge sign they can circulate in opposite direction in the same magnetic bending field. In order for them to circulate and collide along the entire length of the same orbit, their energy is adjusted to yield the same magnetic rigidity. At the same time the sum of their energies is 675 keV, as required by the optimal fusion process. The main parameters of the storage ring and of the beams are given in Tables 1 and 2. The ion lifetime is determined as the inverse of the ratio of the rate of fusion events to the total number of circulating particles. The outline of the facility is shown in Figure 1. The storage ring is made of four circular copper rods with the cross-section shaped as shown in Figure 2. Except for the size, which has a much larger diameter of 2.55 m, the storage ring is similar to the ion trap which was used recently [13] for the experimentation and demonstration of Crystalline Beams. Transverse focussing is provided by applying an rf field between the four rods paired as shown in Figure 2. The original ion trap had an internal diameter of 5 mm, a larger diameter of 11.5 cm and a field frequency of 6.56 MHz. In our case, the internal diameter is 2 mm and the field frequency is 500 MHz.

The device is very similar to a four-rod RFQ with constant aperture since the longitudinal field for acceleration is not needed; the excitation is a TEM mode which provides the field for the transverse focussing of the particle motion. The frequency and the dimension are similar to those already demonstrated in more conventional RFQ devices [12]. The peak voltage is 42 kV with a maximum surface field of 40 MV/m, that is about 2 kirkpatrick units. The major difference is that the total length of 8 m is bent completely on itself to form a perfect circular storage ring. The four rods are shaped to generate the optimum quadrupole field with a narrow angular aperture to allow, as much as possible, the flow of the α-radiation emerging in every direction from the beams continuously colliding along the entire circumference of the storage ring.

To maintain both beams circulating on the same orbit in opposite direction, a bending magnetic field is generated by letting a constant continuous current of 30 A flowing in the two copper rods on the side, as shown in Figure 2. This generates a field of 700 gauss on the central orbit. Since ions will spend only a brief period of time before they are exhausted by fusing with each other, spatial quality of both focussing and bending fields is not essential, but precision, accuracy and reproducibility are important. The manufacturing of the ensemble of the four rods is also delicate but it has been proven feasible in other more conventional RFQ devices [12]. We shall not discuss here methods for powering the circular RFQ storage ring, as we shall not describe how the two beams can be injected into and aborted from the storage ring. These issues of course require eventually a closer engineering examination, but we do not believe they are difficult to be solved.

The main focussing parameters are given in Table 3 for both beams. The focussing period is the product $\beta\lambda_{rf}$ where $\lambda_{rf} = 60$ cm is the rf wavelength. It can be seen that, because of the low velocity of the particles, the focussing period is considerably shorter than that can be obtained with quadrupole magnets. A short focussing periodicity is needed for the reaching of compact Crystalline Beams. The periodicity, which is the number N_p of focussing periods per revolution, is also very high. The RFQ focussing parameter B relates to the peak rf voltage V_0 to the rf wavelength λ_{rf} and to the pole-tip radius a according to the formula

$$B = QeV_0 \lambda_{rf}^2 / mc^2 a^2 \qquad (1)$$

where m is the mass of the ion at rest. This parameter determines the phase advance of the oscillations per period and the amplitude-function β_L to which we can relate the beam transverse size. The number $\nu_{v,h}$ of oscillations per revolution is the same in both transverse directions of motion. A requirement for Crystalline Beams is that $\nu_{v,h} < N_p$, as it is in our case. The values shown in the Table 3 are typical of those that have been demonstrated in conventional RFQs.

5. The Reactor Vessel

There is a very wide energy spectrum of the radiated α particles. The average energy is 2.3 MeV, but the spectrum has a maximum of 8.7 MeV, in which case two particles will be produced at rest. The collector system should be capable to collect as many particles as possible over the whole energy spectrum and the solid angle around the beam axis. For this purpose [2], the collector may be made of a series of concentric toroidal electrodes placed around the axis of the RFQ storage ring structure, as shown in Figure 3. The electrodes are set at a constant positive potentials increasing in magnitude toward the outer edge; they are made of metallic filaments to form meshes transparent to the α particles which penetrate at larger energies. To increase the efficiency of collection, a finer structure, with many layers as possible, is preferable. The outer electrode is set at the maximum voltage value of 8.7 MV. The electrodes are all terminated at one side by the load through which the electric power is generated. Since the rods of the RFQ have an oscillating potential of 42 kV, in proximity of ground potential, only a very small fraction of α particles will be lost by scattering against them.

The actual engineering of the reactor vessel and of the collecting electrodes clearly requires a more involved design beyond what it has been described here. The electrostatic voltages are very high and there is concern with spontaneous sparking if the structure is built too compact. At this time it seems to be preferable to maintain the storage ring RFQ structure in proximity of ground potential and keep the outer electrodes at increasing positive potentials; but this constitutes a subtle engineering issue which should be examined more carefully. We shall not deal with this problem any longer here.

6. Crystalline Beams

A Crystalline Beam [9,10] is a state of matter which can be obtained from diluted ion beams in low-energy storage rings with the application of a very fast cooling technique, namely Laser Cooling. If enough energy is internally subtracted at sufficiently large rate, the ions will take a rigid configuration where they are essentially equally spaced from each other, as shown in Figure 4. Crystalline Beams have also been experimentally observed [13], essentially at rest in ion traps, and experiments are being planned for their observation at quasi-relativistic velocities [14].

The interest for experimentally demonstrating and controlling a Crystalline Beam is mainly due to the quest for a beam of ions where particles are essentially screened from the mutual electromagnetic interaction, thus virtually removing the limitations due to space-charge forces and intrabeam scattering. It is only under these conditions that higher beam densities may be obtained. Applications would be various, mostly in the field of particle accelerator technology, for instance in colliders where high luminosity performance is required, as it is in our case.

Evidence of beam Crystallization can be found with computer simulation using the Molecular Dynamics method [15]. An analytical approach was also recently developed [16] which can be used for an estimate of possible Crystalline Beam structures in a given storage ring.

In its ground state, a Crystalline Beam is made of a number n_s of *strings* placed parallel to each other symmetrically around the beam axis. Apart from a possible string located at the origin of the beam semi-axis, because of the left-right and up-down symmetry the number of strings is a binary number, that is

$$n_s = 2^p \tag{2}$$

where p is called the *order of bifurcation*. Particles are equally spaced on each string and the spacing λ_s is the same to all strings. There is a range of spacing $\lambda_1 > \lambda_s > \lambda_2$ in which a particular structure can exist. Typically $\lambda_1 \sim 2\,\lambda_2$ where λ_2 denotes the stability limit

$$\lambda_2 \sim \lambda_c\, c_i \tag{3}$$

with

$$\lambda_c = (\,Q^2\, r_0\, g_0\, R^2 / A\, \beta^2 \gamma^5\,)^{1/3} \tag{4}$$

the critical spacing, where $r_0 = 1.535 \times 10^{-18}$ m is the classical radius of a proton, A the mass number of the ions, R the major radius of the storage ring and $g_0 \sim 1.2$. The dependence on the tuning mode of the storage ring is given by the tuning coefficients c_i with i = v, h, s, c. The stability is lost when a major half-integral resonance is encountered. We have, assuming $\nu_{v,h} < N_p$,

$$c_{v,h} = (2 / \nu_{v,h}{}^2)^{1/3} \tag{5}$$

$$c_s = (4 / N_p)^{2/3} \tag{6}$$

$$c_c = (1 / q \nu_h)^{2/3} \tag{7}$$

where q is the smallest positive value of

$$q = 1 \pm (2 - m_+ N_p / \nu_h)^{1/2} \tag{8}$$

and m_+ is an integer.

The summary of our estimate for the Circular RFQ storage ring is given in Table 4. Crystal spacing at the limit of stability is expected around 1 μm. The stability limit is reached by approaching either the radial or vertical half-integral stopband to the lowest order, that is $\nu_{v,h} = 0$; in fact the tuning coefficient $c_{v,h}$ is the largest. At the limit of stability, the transverse separation between strings is also of the same magnitude of λ_2.

In absence of cooling, there is a very serious limitation to the smallest transverse emittance that can be obtained. This is caused by the space-charge limit. It is customary to measure this limit in terms of the maximum value of depression $\Delta\upsilon$ of the number of oscillation per revolution [17],

$$\Delta\upsilon = N r_0 Q^2 / (2 \beta^2 \gamma^3 A \varepsilon) \tag{9}$$

where N is the total number of particles and ε is the full betatron emittance. The commonly accepted limit is $\Delta\upsilon \sim 0.5$ which can be used to estimate the beam emittance in the diluted state as a function of the beam intensity N. The results are also shown in Table 4 and apply to the beam intensity $N = N_s$ of a single string. The corresponding transverse beam size is obtained as $(\varepsilon\beta_L)^{1/2}$.

7. Laser Cooling

This cooling technique [5] has been used recently for the formation and the observation of Crystalline Beams in ion traps [13]. It has also been demonstrated in low-energy ion storage rings (TSR and ASTRID) [18,19]. It has been proposed as the most fundamental cooling method for the experimentation with Crystalline Beams in these and similar storage rings [14].

The principle of Laser Cooling applies only to ions with orbiting electrons. The laser, which is directed either along or against the motion of the ions, has a frequency adjusted in proximity of the transition frequency of the outermost electron. Depending on its direction, the laser provides or subtracts also an impulse of longitudinal momentum. Subsequently, the ion will decay to its normal state radiating a photon of the same excitation frequency, randomly in any direction. This process, when accompanied by either an external restoring force or by one more laser travelling along the opposite direction, will cause momentum cooling, that is a reduction of the longitudinal momentum spread of the ions.

To allow for Laser Cooling, we have assumed partially stripped ions of ^{11}B with a charge state of $Q = +3$ and negative hydrogen ions with charge state $Q = -1$. The transition frequencies for the excitation of the outermost electron are given in Table 5. The decay rate Γ of the excited state is about the same for both cases. Let I_L denote the Laser intensity and define the optical saturation parameter $S = I_L / I_s$ where

$$I_s = \hbar \omega^3 \Gamma / 4 \pi c^2 \tag{10}$$

is the saturation intensity of the transition being considered with the angular excitation frequency ω. The longitudinal cooling rate for ions of mass number A is given by [20]

$$\lambda_{\parallel} = (8.10 \times 10^{5}\ s^{-1})\ \ \eta_{L}(\hbar\omega)^{2} S\ / A(1+S)^{3/2} \tag{11}$$

where $\hbar\omega$ is to be given in eV, and η_L is the fraction of the storage ring circumference shared with the laser. There is a limit to the amount of cooling that can be obtained due to the Doppler limit. In terms of the longitudinal ion beam temperature the limit is given by [20]

$$k\,T_{\parallel} = (2.20 \times 10^{-16}\,eV)\ \Gamma\ (1 + S)^{1/2} \tag{12}$$

where k is the Boltzmann's constant and Γ is to be expressed in s^{-1} units.

Values of cooling rate, of final beam temperature and of longitudinal momentum spread are shown in Table 5. It is seen that indeed Laser Cooling is characterized by large rate and small beam size at equilibrium. It takes only a small fraction of the time the ion circulates in average in the storage ring to reach the equilibrium value. The requirements on the laser power and spot size are modest and easy to match. The location of the laser beams relative to the ion beams is shown in Figure 1. Two countermoving laser beams per ion beam are assumed. The one moving along the beam direction of motion accelerates and the other decelerates. Their combined action creates a reference stable velocity value toward which the velocity of all ions are moved. Single pass is sufficient, and η_L is estimated to be at least 0.1%.

Laser cooling works only along the longitudinal direction of the beam motion. Some effects on the transverse motion nonetheless have also been observed. This *indirect cooling* is caused by the ion-to-ion Coulomb interaction [21]. As the longitudinal momentum is subtracted by cooling, it is also restored by Coulomb scattering among the ions that has an equalizer effect by transferring transverse momentum to the longitudinal direction. Eventually an equilibrium is reached where all three components of motion share the same limiting temperature. These issues deserve a deeper investigation. It is to be determined how the beam dynamics evolves and what is the influence on the choice of the storage ring lattice, on the rate of cooling and on the location of the transition energy value with respect to the beam energy. If the equi-repartition of temperature is indeed a valid assumption, it is possible to estimate the equilibrium beam transverse dimension σ as the product of the equilibrium momentum spread with the amplitude β_L of the lattice function. This, as also shown in Table 5, has a typical value of few tens of A^0.

8. Collider Performance

There are several advantages in using colliding Crystalline Beams. First, it is possible to obtain more compact beams. Second, most importantly, the particles in each beam occupy well-defined and rigid positions. The uncertainty σ on the transverse location of each string is considerably smaller than the longitudinal spacing λ_2. By carefully aligning the two beams to pair countermoving strings in the collision, it is possible to increase the luminosity by a considerable factor. Indeed the luminosity in this case is proportional to the number of strings in each beam

$$L = n_s\,L_s \tag{13}$$

where

$$L_s = N_s\,(\text{proton})\ N_s\,(\text{Boron})\ f_{enc} / 4\,\pi\,\sigma_{eff}^{2} \tag{14}$$

is the contribution to the luminosity from each pair of countermoving strings; f_{enc} is the frequency of encounter, the larger of the two beams revolution frequency, σ_{eff} is an effective cross-section which is the quadratic combination of the two strings transverse dimensions averaged around the ring, and N_s (proton/Boron) is the number of circulating ions per string.

The estimate of the collider performance, assuming a single string per beam, is summarized in Table 6. The rate of fusion events is

$$d\, n_F / dt \;=\; \sigma_F\, L_s \tag{15}$$

which equals the depletion rate of the ions. The ions which are lost are then to be replaced continuously by the sources. We can calculate the required source current from

$$i_S \;=\; e\, d\, n_F / dt \tag{16}$$

Finally the released fusion power is

$$P_F \;=\; W\; d\, n_F / dt \tag{17}$$

Even with a single string, the amount of fusion power is about a quarter of milliwatt which should be easy to measure. Moreover the required source current is very modest.

The performance improves considerably with more complex Crystalline Beam structures, made of a large number of strings. A comparison can be made by inspecting values in Table 7. All the quantities scale linearly with the number of strings, except the *warm* and *cold* beam dimensions, which scale with the square root of n_s. The warm beam size shown is the maximum value around the storage ring; it has been calculated in absence of cooling and it corresponds to the space-charge limit. The cold beam size is approximately given by $\lambda_2\, n_s^{1/2}$.

The case of a single string has a very modest performance and can be easily demonstrated. It could represent the first goal of an experimental program. Raising the order of bifurcation to 10 will also raise the fusion power to a fraction of watt. There are no limitations foreseen also for this case. The experimental goal would be to determine that indeed colliding Crystalline Beams with complex structure are feasible. To note that the size of the beam in the dilute state (warm) is just about the separation of the circular RFQ rods. A more interesting case is represented by the third column, with p = 20. The fusion power is now a fraction of kilowatt, a considerable amount. The required source current is 26 μA-particle, which is within the present technical capability. The transverse dimensions of the Crystalline Beams are now comparable to the separation of the rods, and the dilute beam dimensions are considerably larger. This case may represent a phase of experimentation where one learns how to efficiently inject into the storage ring a beam of an intensity well above the space-charge limit. The last column, corresponding to p = 30, is clearly a case well beyond the capability of the collider described in this report. The beam dimensions are too excessive and one requires a considerable improvement of the ions sources. It is an interesting case to study, to determine alternative ways and improvements of the present scheme to achieve a larger performance. As a conclusion, it seems that a limit is to be expected somewhere in excess of p = 20, but less than p = 30, with a fusion power released of about few kilowatts, which is an amount sufficient for the needs of an average household in the US.

9. Energy Balance and Net Gain

Considerations can be made concerning the energy balance of the entire process. For an efficient production, the total power P_c, actually converted electrically, should exceed the power P_d dissipated for the operation of the entire device. When the two amounts equal each other, we have reached the break-even point. The following is a reasonable budget of the power that is dissipated:

-- Negative Ion Source and linear RFQ	1 kW
-- Boron Ion Source (ECR) and RFQ	1 kW
-- Circular RFQ Storage Ring, Lasers, Vacuum, miscellaneous...	1 kW
-- Beam Power	P_B

which gives $P_d = 3\text{ kW} + P_B$. On the other end $P_c = \eta\, q\, P_B$, where η is the overall conversion efficiency to electric power in the Reactor Vessel, and $q = 12.9$ is the ratio of fusion power to beam power. Break-even is reached, assuming 80% efficiency, at $P_B = 322$ W, i.e., the total fusion power released $qP_B = 4.15$ kW. We can extrapolate from the first three columns of Table 6 the requirements for the break-even mode and for a nuclear plant delivering a net power of 10 kW. These are shown in the last two columns at the right of Table 6. They correspond to a bifurcation order respectively $p = 24$ and 26. Both of these cases are limited by the estimated size of the Crystalline Beam. An experiment may determine the actual dimension and reveal ways to reduce it.

10. Research and Development

There are two categories of problems that ought to be investigated. The first category deals with hardware problems, of mechanical and electric nature. The second category is made of issues of conceptual nature that need to be demonstrated. In the first category, there are issues which are to be studied very closely but can all be solved in principle, with the possible exception of the design of the Reactor Vessel which has some delicate features.

- Design and Development of the Circular Radio Frequency Quadrupole. One should estimate the mechanical tolerances, the tooling required and the implications for construction. It should be understood how to assemble the entire device mechanically and how to provide the electric connections. It is an engineering type of work which we do not expect to give insurmountable complications.

- Design and Development of the Ion Sources. The negative ion source can be located on a electrostatic platform at around 50 kV and injected in a modest linear RFQ for the acceleration to 0.37 MeV. An ECR is the source proper of the ions of Boron, which have a larger charge state. Thus, the ECR may be located on a 20 kV platform and injected in a linear RFQ with a total voltage of only 100 kV. The mode of operation for both sources is continuous with 100% duty cycle. The beam emittance has to be small enough compared to the acceptance of storage ring (30 - 90 π mm mrad), and the beam current has to be in the range up to few particle-mA. All these parameters are within the limits of the present technology. The most challenging part is the design of an overall source which does not dissipate too much power. As we have seen in the previous section, a total power dissipation not exceeding 1 kilowatt for each source is desirable. This will need some development design and research.

- Beam Injection and Abort. They should not cause disruption to the behavior of the circulating beam by avoiding introducing too drastic discontinuities to the layout of the CRFQ storage ring. The sources may be connected directly to the injection locations with a linear extension of the RFQ itself. To provide a smooth matching the external and circular RFQ will have the same frequency and dimensions as illustrated in Figure 1. The entire system will then take the look of a solidly connected device.

- Vacuum System. Though the ions spend only a brief period of time circulating in the storage ring before they are lost by nuclear fusion, their velocity is relatively too small and there are certain consequences from their interacting with the residual gas in their environment. Vacuum is therefore a concern and very likely one needs a low pressure, around 10^{-10} torr or lower, to avoid losses, mostly due to electron capture and stripping.

- The Laser System. There should not be major concern here, except making sure that the system takes only a little power to operate. There are a total of four laser beams, and one has to configure their layout paths without them interfering. It is also important to assess availability of wavelengths and tuning.

- Diagnostic. It is important to determine the need for beam observation and manipulation. Considering the small dimensions involved, it is important to economize space and, again, power dissipation. One should also investigate the requirement of control with a computer on line.

- Power Supply. Several components need to be powered to work: both ion sources and the CRFQ. In particular it is crucial to determine how the Circular RFQ can be driven in the required TEM mode without interfering with the beam motion and the collection of the α particles.

- Development of the Reactor Vessel. This is the most problematic technical issue which needs very careful examination and innovative ideas, specially because of the large voltages involved. Moreover, it is important to determine ways for the most efficient assembling of the entire device to minimize interference between electric and mechanical parts, and to allow easy access to the components, operation and maintenance.

There are four topics of research in the second category of problems which deal with demonstration of concepts: (i) Laser Cooling demonstration of cooling rates and final beam temperatures, (ii) Evaluation of space-charge limitations for dilute beams at injection. Since there are two beams circulating at the same time with opposite charge-sign, there is an extra contribution to the amount of space-charge affecting the negative ions; space-charge on the ions of Boron is essentially unchanged. (iii) Beam Crystallization. Issues concerning this topic are as follows. The longitudinal spacing and the separation among strings can be determined exactly only experimentally. Here we have used estimates. Crucial to the entire process is the understanding of the relation between cooling and the particle-particle interaction, and determining how the beam relaxes internally in all three directions of motion, from the initial dilute and space-charge dominated state toward the final one when ions, by ordering themselves, would effectively screen each other. Finally, (iv) Collision between two beams. What happens when two Crystalline Beams collide with each other? Is it possible to create at the same time two of such beams countermoving? Also, ions carry orbiting electrons, required for Laser Cooling; when they collide, would their presence interfere with the ultimate event of nuclear fusion?

11. Conclusions

The project we have described is of a dimension that can fit within an area of no more than ten square meter, it can be handled by a staff of very few people and has the merit of low cost. These are reasons to proceed with a program of research and development. The scope and goals are well defined and limited in size. It will be easy to demonstrate all the principles and the techniques involved, whether they will work or not. This project stands clear for its simplicity with respect to other methods of nuclear fusion energy, based on magnetic and inertial confinement, which have been investigated until now for about half a century, with large human and financial efforts. Of course, the other major difference is the goal of the amount of nuclear power: few kilowatts against the several hundred MW. Sometime the key to success is to start modest.

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Table 1: Circular RFQ Storage Ring

Circumference, $2\pi R$	8.0606	m
RFQ Pole Tip Radius, a	1	mm
rf Frequency	500	MHz
rf Peak Voltage, V_0	42	MV
estimated Surface Field	40	MV/m
Bending Field	0.6837	kG
dc Current	30	Amp

Table 2: Colliding Beam Parameters

	Proton	Boron
Charge State, Q	-1	$+3$
Mass Number, A	1	11
Rest Energy, GeV	0.93826	10.145
Kinetic Energy, MeV	0.36835	0.30665
β	0.028013	0.007775
Revolution Frequency, MHz	1.042	0.289
Magnetic Rigidity, kG-m	0.8770	0.8770
Ion Lifetime, ms	69.6	31.6

Table 3: RFQ Focussing Parameters

	Proton	Boron
Focussing Period, mm	16.80	4.66
Number of Periods, N_p	480	1729
RFQ Focussing Parameter, B	16.1	4.5
Phase Adv. per Period / 2π	0.2882	0.0800
No. of Oscillations / turn, $\nu_{v,h}$	138.33	138.28
β_L-function (max), mm	30.23	11.65

Table 4: Crystalline Beam Parameters

	Proton	Boron	
Critical Spacing, λ_c	15.7	34.5	μm
Tuning Coefficients: $c_{v,h}$	0.047	0.047	
c_s	0.041	0.018	
c_c	0.021	0.021	
Crystal Spacing, λ_2	0.74	1.62	μm
No. of Ions per String, N_s	1.09×10^7	4.96×10^6	
Warm Beam Emittance (*)	0.0213	0.103	π mm mrad
Warm Beam max. radius (*)	0.0254	0.0347	mm

(*) For the intensity of a single string, at the space-charge tune shift of 0.5

Table 5: Laser Cooling

	Proton	Boron	
Excitation Wavelength	6562.8	2823.4	A°
Decay Rate, Γ	4.41×10^7	4.55×10^7	s^{-1}
Optical Saturation Parameter, S	0.1	0.4	
Saturation Intensity, I_s	9.7	126.0	mW/cm^2
Laser Intensity, I_L	1.0	50.4	mW/cm^2
Cooling Rate, $\lambda_{\|\|}$	251	343	s^{-1}
Cooling Time	4.0	2.9	ms
Equivalent No. of Revolutions	4157	843	
Equilibrium Long. Temperature	10.2	11.8	neV
Equilibrium $\Delta p/p$	0.17	0.20	10^{-6}
Equilibrium Transverse Size, σ	50.3	22.9	A°

Table 6: Performance for a Single String Mode

Luminosity	1.74×10^{32}	$cm^{-2}\ s^{-1}$
Rate of Fusion Events	1.57×10^8	s^{-1}
Fusion Power released	0.218	mW
Source Current	25.1	particle-pA

Table 7: Summary of the Collider Performance

Order of Bifurcation, p	0	10	20	30	24 (*)	26 (**)
Number of Strings, n_s	1	1024	1024^2	1024^3	1024^2 x 16	1024^2 x 64
Total no. of ions: Proton	1.09×10^7	1.12×10^{10}	1.14×10^{13}	1.17×10^{16}	1.82×10^{14}	7.28×10^{14}
Boron	4.96×10^6	5.08×10^9	5.20×10^{12}	5.33×10^{15}	8.32×10^{13}	3.33×10^{14}
Warm Beam radius: Proton (mm)	0.0254	0.813	26.0	832.	104.	208.
Boron (mm)	0.0347	1.109	35.5	1135.	142.	284.
Cold Beam radius: Proton (mm)	0.00073	0.0237	0.756	24.2	3.024	6.05
Boron (mm)	0.00162	0.0520	1.664	53.2	6.656	13.31
Luminosity, cm^{-2} s^{-1}	1.74×10^{32}	1.78×10^{35}	1.82×10^{38}	1.87×10^{41}	2.91×10^{39}	1.16×10^{40}
Rate of Fusion Events, s^{-1}	1.57×10^8	1.61×10^{11}	1.65×10^{14}	1.69×10^{17}	2.64×10^{15}	1.06×10^{16}
Fusion Power, P_F	0.218 mW	0.224 W	0.229 kW	0.234 MW	3.664 kW	14.7 kW
Source Current, i_S	25.1 pA	25.7 nA	26.3 μA	27.0 mA	0.421mA	1.68 mA

(*) Break-even Plant

(**) 10 kW Plant

(**) 10 kW Plant

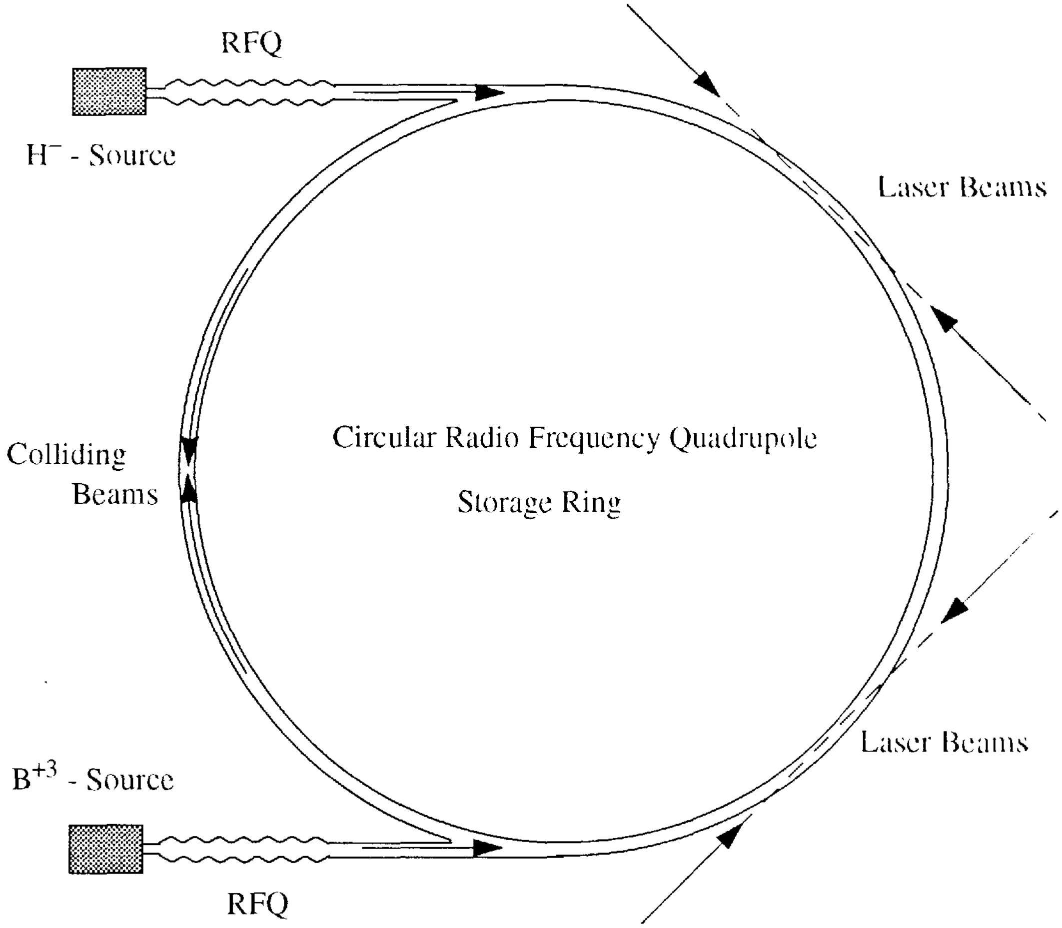

Figure 1. Schematic Layout of the Nuclear Plant based on the Fusion Reaction between Protons and Ions of Boron. (Not in scale).

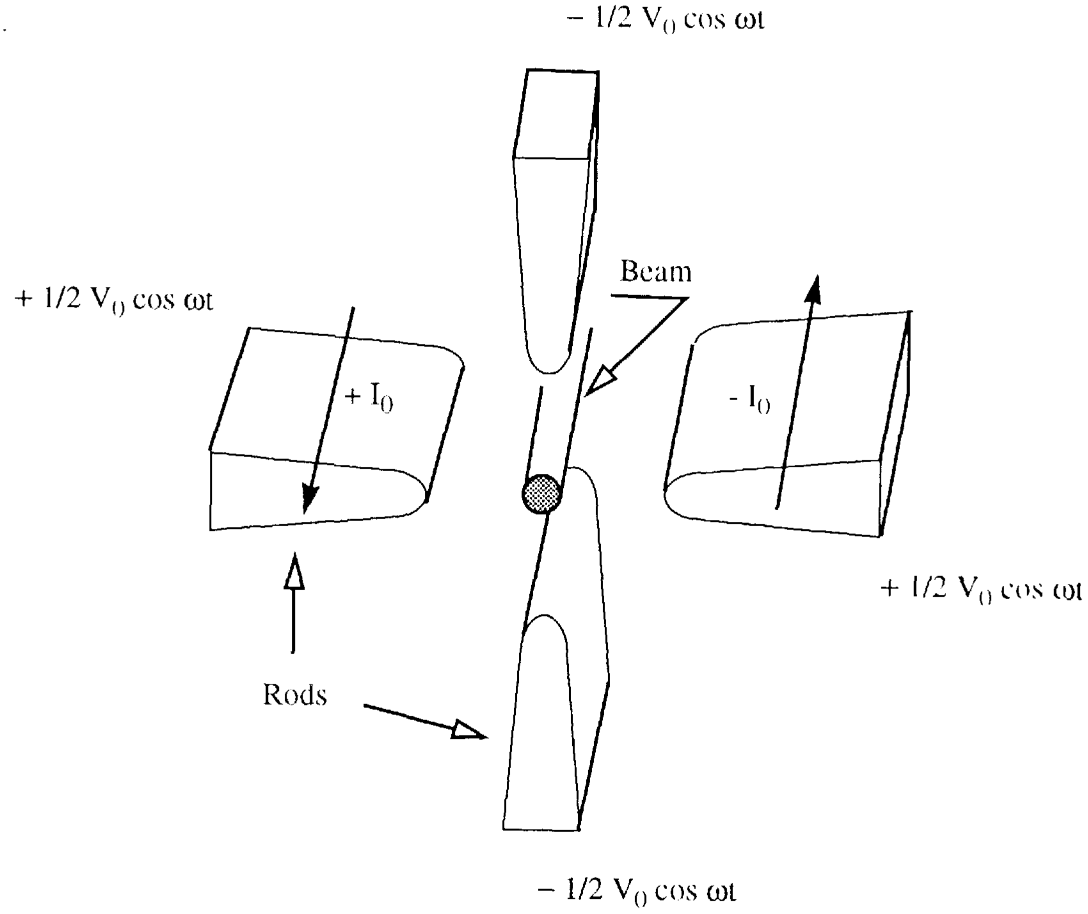

Figure 2. Cross-section View of the Circular Radio Frequency Quadrupole (CRFQ). A Transverse Electro-Magnetic mode (TEM) is excited between the four electrodes (Rods). Quadrupole focussing field is obtained with the alternating rf excitation as shown. Dc current I_0 flows along the outer rods generating a magnetic field to bend the beam circulating in the region inside.

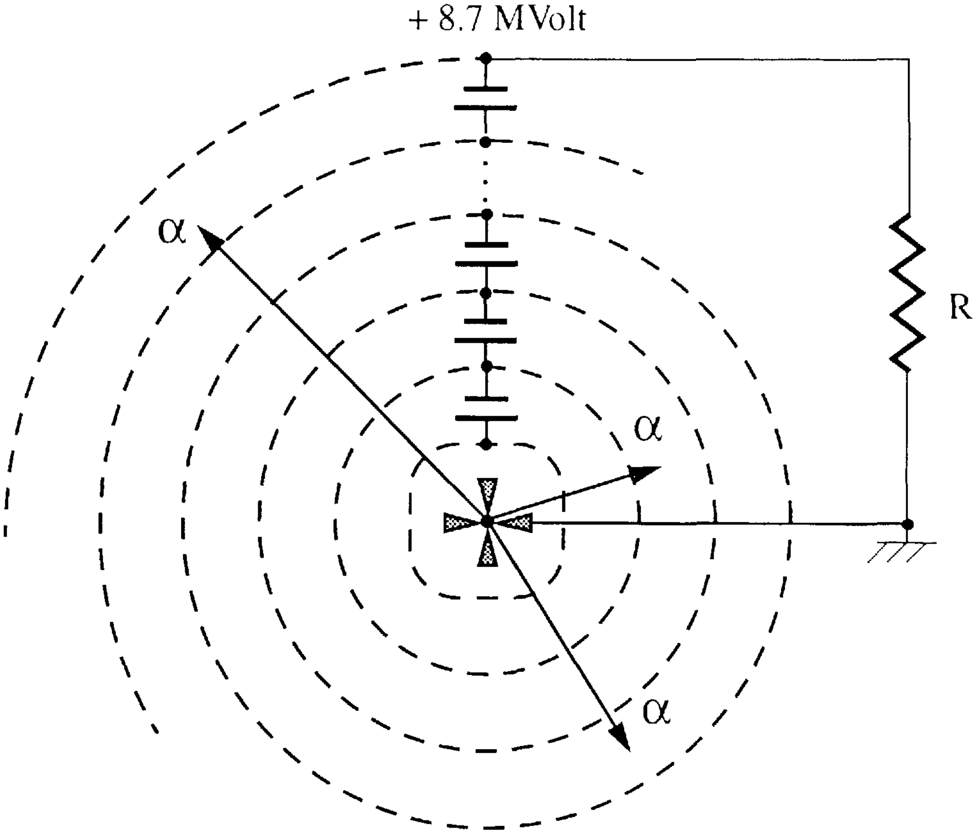

Figure 3. View of the <u>Reactor Vessel</u> surrounding the CRFQ and the Colliding Beams. The dashed circles are toroidal electrodes made of metallic wires set at increasing constant positive potentials to decelerate the α particles and convert their kinetic energy to electric energy.

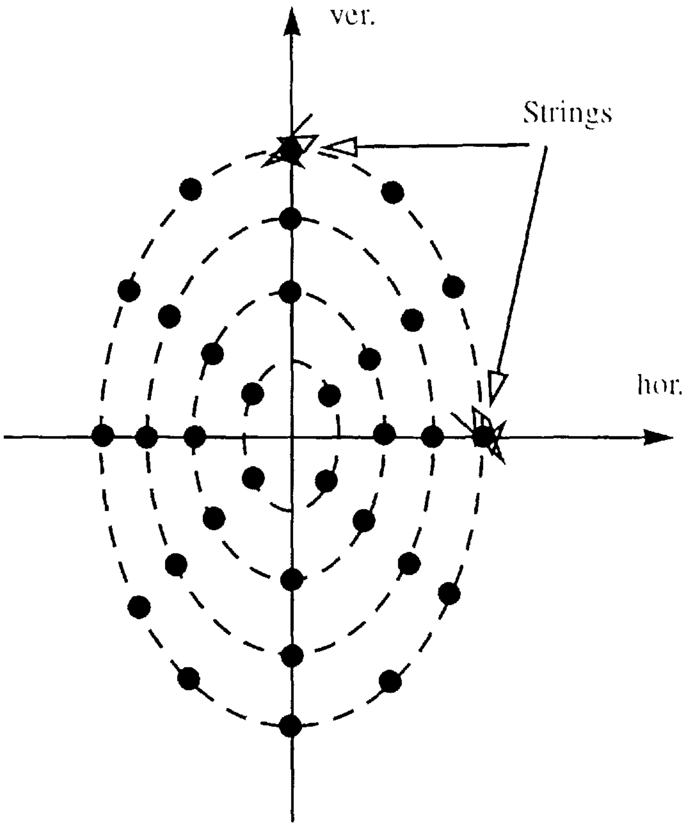

Figure 4. A Crystalline Beam made of $n_s = 32$ ($= 2^5$) Strings. Ions are equally spaced. The amplitude of motion is smaller than the ion spacing.