DESIGN STUDY OF AN ACCELERATOR FOR HEAVY ION FUSION

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ABSTRACT

Design of a demonstration accelerator for heavy ion fusion based on a synchrotron system is briefly described. The proposed complex system of injector linac, rapid cycling synchrotron and five accumulation rings can produce a peak current 1.6 kA, peak power 32 TW and total energy 0.3 MJ. Investigations of the intrabeam scattering give a lifetime of the beam longer than the fusion cycle time of 1 sec.

1. INTRODUCTION

In recent years interest in high energy heavy ions has been growing in various fields of science and applications. In Japan an accelerator complex responding to these demands has been proposed at INS, University of Tokyo; this is called the NUMATRON[1, 2)] and it should provide heavy ions up to uranium in an energy range of 0.1 ~ 1.3 GeV per nucleon. The main feature of the accelerator is to provide a high intensity heavy ion beam by the use of two synchrotrons and an injection method which combines the techniques of multiturn injection and RF stacking.

Here we will present the design of the demonstration synchrotron-based accelerator complex for fusion power generation: it is not directly aimed at producing practical fusion power plant, but is a first step to show the feasibility of heavy ion fusion.

General requirements for the accelerator are given in Table 1.

Table 1 General Requirements for the Demonstration Accelerator

Total energy	0.3 MJ
Peak Power	32 TW
Beam pulse width	10 ns
Number of particles	1×10^{14}
Peak Current	1.6 kA
Energy deposition	6.8 MJ/g
Repetition rate	1 Hz

2. OUTLINE OF THE ACCELERATOR

The accelerator consists of two ion sources followed by 1 MV Cockcroft-Walton generators, Wideröe linacs, Alvarez linacs, rapid cycling synchrotron and five accumulation/compression rings, from which 20 beam bunches are extracted simultaneously and are carried to a reactor chamber located at the center of the accumulators. Total beam intensity is 1×10^{14} within a time of 10 ns, which corresponds to 32 TW total peak power, 300 kJ total energy and 1.6 kA peak current. Throughout the design of the accelerator, xenon ions have been assumed because their intensity and characteristics at the ion source stage are well understood at present.

3. INJECTOR LINAC

From the point of view of acceleration efficiency, high charge state of the ion is preferable. However, since the available intensity of high charge state ions is low, in the present paper a Xe^{2+} beam is assumed at the ion source stage.

The Xe^{2+} beam is accelerated by the 1 MV Cockcroft-Walton and is injected into the first π-3π mode Wideröe linac. The expected intensity from this injector system is 5 particle mA[3)], and two such systems are funneled to obtain an intensity of 10 particle mA. Kinetic energy and velocity at the input of the first Wideröe linac are $T_i = 15.15$ keV and $\beta_i = 0.57\%$, respectively, and the structure of the Wideröe linac is almost the same as the one designed for the NUMATRON project. After acceleration to 400 keV per nucleon by the two π-3π mode Wideröe linacs, the xenon beam is stripped by a gas stripper to the equilibrium charge state of q = 4. The fraction in the equilibrium charge state at this stripping energy is estimated to be 0.2$^{1)}$. The resulting 2 particle mA beam is accelerated to 20 MeV per nucleon by the π-3π and π-π mode Wideröe linacs and the Alvarez linac. The total length of linacs is about 250 m.

If the intensity of Xe^{4+} at the ion source stage were sufficiently high, say 2 particle mA, the injector system would be much simpler.

4. RAPID CYCLING SYNCHROTRON

Basic requirements for the synchrotron are as follows:

1. Xe^{4+} beam is injected at the energy of 20 MeV/u and should be accelerated up to around 150 MeV/u.

2. The output intensity of the synchrotron should amount to 1×10^{14} particles per second.

Linac beam is injected into the synchrotron by the multiturn injection method, 10 turns horizontally by 5 turns vertically. Assuming the dilution factor to be 2, the emittances after the multiturn injection are $100\pi \times 10^{-6}$ m rad in horizontal phase space and $50\pi \times 10^{-6}$ m rad in the vertical one.

The space charge limit in the ring is simply given by

$$N = \frac{2\pi\Delta\nu}{Br_p} \left(\frac{A}{q^2}\right) \varepsilon\beta^2\gamma^3 \quad , \qquad (1)$$

where B is a bunching factor, r_p is the classical proton radius 1.533×10^{-18} m and ε is an emittance. If we take the bunching factor as 10, the space charge limit at injection energy is calculated to be 2×10^{12} particles/pulse. In order to attain the intensity required by the fusion program, say 1×10^{14} particles/s, the synchrotron should be a rapid cycling one with a repetition rate of 50 Hz.

The required peak current from the Alvarez linac is given by

$$I_{peak} = \frac{N \times e}{50 \times \tau_{rev}} = 0.89 \text{ mA}, \qquad (2)$$

which is obtained easily by the present technique of heavy ion linacs.

From considerations of magnetic rigidity and attainable maximum field in normal bending magnets, the parameters given in Table 2 are suitable for the present design.

The RF voltage required for the acceleration of the beam is given by

$$V \sin\phi_s = 2\pi\rho R\dot{B} \ . \qquad (3)$$

In the present design, the maximum $\dot{B}$ is 186 Webers/m^2·sec and the stable phase angle is 30°, so that V is 5.4 MV/turn. This enormous RF voltage is supplied by 50 cavities, each of which has 2 accelerating gaps with a gap voltage of 54 kV. The revolution frequency of the beam changes from 139.2 kHz at injection to 346.5 kHz at ejection, so that the RF frequency ratio is the moderate value 2.5.

The vacuum pressure required to assure 80 percent survival rate of the accelerated beam is 6.2×10^{-9} torr, taking the charge exchange cross section due to collisions of the Xe beam with N_2 gas to be 2.7×10^{-16} cm^2 at 150 MeV/u and 1.7×10^{-15} cm^2 at 20 MeV/u.$^{4)}$ Using a bellows type vacuum chamber of 0.12 mm thick stainless steel, and a dry pumping system, this vacuum pressure is easily obtained without eddy current effects on the beam.

We will consider the transverse coherent resistive wall instability, TCI, which is most severe for the acceleration of high intensity heavy ion beams. The TCI limit is given by$^{5)}$

Table 2 Synchrotron Parameters

Design kinetic energy	
at injection	20 MeV/u
at ejection	150 MeV/u
Intensity (Space charge limit)	2×10^{12} ions/pulse
Repetition Rate	50 Hz
Radius of curvature	33 m
Average radius	70 m
Circumference	439.8 m
Focusing structure	$F\bar{O}D\bar{O}$
Number of betatron oscillations per turn	~ 6.25
Transition kinetic energy	5.8 GeV
Number of cells	64
Length of the unit cell	6.87 m
Length of the bending magnet	3.24 m
Magnetic field strength of the bending magnet	
at injection	5.93 kG
at ejection	18.32 kG
Maximum time derivative of the magnetic field	1863 kG/s
Momentum compaction factor	2.56×10^{-2}
Momentum spread of the beam	
at injection	5×10^{-4}
at ejection	1.25×10^{-4}
Revolution frequency	
at injection	139.2 kHz
at ejection	346.5 kHz
Required energy gain per turn	2.7 MV
Harmonic number	10
RF frequency	
at injection	2.78 MHz
at ejection	6.93 MHz
Number of accelerating stations	50
Number of RF cavities per station	2
Total number of accelerating gaps	100
Vacuum pressure	6×10^{-9} Torr

$$N \leqslant \frac{2A}{q^2} \frac{F_\gamma}{\left|\frac{Z_T}{Z_0}\right| r_p} \nu \, |(n-\nu)\hat{\eta} + \xi| \, \frac{\Delta p}{p} \qquad (4)$$

where Z_T is the transverse impedance of the ring and Z_0 is the vacuum impedance $120\pi\Omega$, $\hat{\eta} = 1/\gamma_t^2 - 1/\gamma^2$, and ξ is a chromaticity The momentum spread of the injected beam is assumed to be 5×10^{-4}. When we introduce a chromaticity of around $\xi = \left(\frac{\partial\nu}{\partial(\Delta p/p)}\right) = -6$, the intensity limit is 5.6×10^{10} particles, which is much smaller than the space charge limit. However, the growth time of this instability is about 10 ms even when 2×10^{12} particles are injected into the synchrotron. This growth time just equals the acceleration time, and so the TCI will be well corrected by suitable sextupole and octupole magnets.

Due to adiabatic damping during acceleration, the momentum spread and emittances at the final energy are 1.25×10^{-4}, $35\pi \times 10^{-6}$ m•rad (horizontal) and $18\pi \times 10^{-6}$ m•rad (vertical), respectively.

Most parameters of the synchrotron are given in Table 2.

5. ACCUMULATION AND COMPRESSION RINGS

Ten pulses of the synchrotron beam are stacked in each accumulation ring, whose diameter is twice as large as that of the injector synchrotron. Two pulses are injected in separate longitudinal spaces, and RF stacking is repeated five times. The space charge limit of each ring is calculated to be 6×10^{13} particles, assuming that bunching factor during a stacking process is 1.0 in the ring, and the emittance is $17.7\pi \times 10^{-6}$ m•rad. This limit is large enough compared with 10 pulses from the synchrotron, 2×10^{13} particles.

The RF stacking process in the accumulation ring is similar to that which is used for the ISR at CERN[6] and for TARN at INS.[7, 8] The outline of the RF stacking process is as follows.

The beam from the synchrotron bucket is transferred into the accumulation ring bucket with synchronization of the RF systems. After capture of the beam, the RF frequency is varied for changing the equilibrium orbit. The rate of momentum change for the synchronous particle is given by:

$$\frac{dp/dt}{p} = \frac{1}{E_s \beta^2} f_{rev} \, \varepsilon \, eV \sin\phi_s \quad , \qquad (5)$$

where E_s is total energy per nucleon. Assuming the momentum difference between the injection orbit the top of the stacked orbit to be 2 , and the RF stacking time to be 5 ms, the required RF voltage is 400 kV. During this process the RF frequency must be changed at the rate:

$$\frac{df}{dt} = \frac{\varepsilon \, eV \cos\phi_s \, . \, h \, . \, f_s^2 \, . \, \kappa}{E_s} \quad , \qquad (6)$$

where f_s is a revolution frequency and   is η/β^2. Substituting numerical parameters, we obtain the sweep range of RF frequency as 52.5 kHz.

In the final bunch compression process, the required RF voltage is [9)]:

$$eV = 2\pi\gamma A m_p c^2 \left[\frac{3Nqh \, r_p g}{A\gamma^3 R\Delta\phi_o \, \Delta\phi_{MIN}(\Delta\phi_o + \Delta\phi_{MIN})} + \frac{h \cdot \eta\beta^2}{q\Delta\phi^2_{MIN}} \left(\frac{\Delta p}{p}\right)^2 \right] \quad , \qquad (7)$$

where $\Delta\phi_{min}$ is given by the relation

$$\Delta\phi_{MIN} = \frac{h\beta c}{2R} \Delta t \quad .$$

For the purpose of reducing the RF voltage, the harmonic number of the accumulation ring is determined at 20. Substituting $\Delta t = 10$ ns, $\frac{\Delta p}{p} = 2.5 \times 10^{-3}$, $N = 2 \times 10^{13}$, $\Delta\phi_o = 2\pi$, we obtain V = 28.6 MV/turn, which will be supplied by 60 RF cavities with 240 accelerating gaps. Each gap produces a potential difference of 120 kV which is within present RF technique. The compression time is estimated to be 5.8 µs which corresponds to 2.9 revolutions in the ring.

In order to afford spaces for cavities and equipment for the extraction channels, the cell number of the magnetic focusing structure is chosen to be 128 and each cell has a long straight section.

The vacuum pressure required to assure 80 percent survival rate is 1.5×10^{-10} torr. On the other hand, the lifetime due to intrabeam scattering of the Xe^{4+} beam at the 2×10^{13} intensity is 1.52 sec in the designed accelerator.[10)]

In Table 3, major parameters of the accumulation ring are given.

Table 3 Accumulation/Compression Ring Parameters

Kinetic energy of Xenon ion	150 MeV/u
Intensity	2×10^{13} ions/pulse
Repetition rate	1 Hz
Magnetic Field Bending Magnet	18.32 kG
Radius of Curvature	$\rho = 33$ m
Average radius	R = 140 m
Circumference	C = 879.65 m
Number of cells	128
Focusing structure	$F\bar{O}D\bar{O}$
Revolution frequency	173.25 kHz
Transition kinetic energy	9.61 GeV
Number of betatron oscillations per revolution	~ 10.25
Required energy gain per turn	28.6 MV/turn
Momentum compaction factor	9.52×10^{-3}
Momentum spread of the stacked beam	6.52×10^{-4}
Harmonic number	h = 20
R.F. frequency	3.465 MHz
Number of R.F. cavities	60
Total number of gaps	240
Final bunch length	20 ns
Bunching time	5.8 µs = 2.9 revolutions
Vacuum pressure	1.5×10^{-10} Torr
Number of extraction channels	20
Momentum Spread after compression (full width)	1.33%
Emittance after compression	
(Horizontal)	$35\pi \times 10^{-6}$ m rad
(Vertical)	$18\pi \times 10^{-6}$ m rad

The intensity limit due to the transverse coherent resistive wall instability is 5 x 10^{11} particle if we introduce a chromaticity of -6. The e-folding growth time of the instability for the intensity of 2 x 10^{13} is 1 ms, a factor 3 less than the accumulation time. From the point of view of TCI, the momentum spread of the stacked beam should be large to give larger tune spread for Landau damping. As is clear from equation (7), large momentum spread requires enormous RF voltage which is far beyond present RF techniques, so that other methods to cause Landau damping, for example creating an amplitude dependent tune shift by octupole magnets, will be useful.

6. CONCLUSION

The goal of our design for a heavy ion fusion accelerator is achieved by a massive system which consists of 5 acccumulation rings, each with 20 beam lines, and a rapid cycling synchrotron. For further progress of the design, detailed investigation of the techniques for surmounting the transverse resistive wall instability is necessary.

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