IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

SYSTEM DESIGN OF HEAVY ION FUSION EXPERIMENT

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Summary

A brief description is given on the design of a high energy accelerator system for an intense heavy ion beam as an igniter of the inertial fusion. The compromise between the requirements for the final beam and the cost is the problem of principal concern. The flexibility and the reliability of the design, including the use of the system with the multiple purposes in the wide range of science other than the nuclear fusion, are also considered.

Introduction

Recently the idea of heavy ion fusion with the conventional high energy accelerators such as the linacs, synchrotrons, storage rings and the related technologies has been recognized to be promissing.[1] With intense heavy ion beam as the energy source, the design problem of the inertial fusion reactor will be well separated into two parts; the target and the accelerator systems. The structure of the D-T micro pellet has been usually studied to laminate multi-layers in a very sophisticated manner, aiming at the large energy gain in a fashion similar to the case in the laser-fusion program. Apart from the details, most calculations are consistent in giving the following requirements for the energy deposition in the target: 1-10 MJ per pellet of 1-10 mm radius transferred in 10-30 ns. It is far beyond the ordinary out put power of any existing high energy accelerator. Then a first step to be reached is the beam of much less energy, in the use of just showing the feasibility of the heavy ion fusion scenario. Here presented is one example of the arrangement of the accelerating systems, which can presumably produce and carry the necessary energy for the demonstration experiment (∿100 kJ) with a moderate cost, within the present technological capability.

Design Principles

(1) The total energy of the beam ∿100 kJ: It was concluded that this amount of the beam energy will be minimum for testing the heavy ion inertial fusion program with a pellet of reasonable size.[1]

(2) Compromise between the beam requirement and the cost: All designs presented so far assumed enormously huge systems including a storage ring of kilometers radius, tens of synchrotrons with the final energy of several tens of GeV or a linac extending over ten kilometers. These figures are at least one order larger than any machine in operation. Certainly it is crucial how much the cost can be reduced, keeping the reliability at a moderate level.

(3) Multiple purposes in various fields: For the system with the minimum cost, the budget still should be quite large and might range in some thousands million dollars. To avoid the risk that the investiment finally does not pay, the system should be designed, taking into consideration the multiple purposes in other fields of science, for example high energy nuclear physics, biochemistry and medical uses. The need for a multi-purposes heavy ion accelerator has been growing rapidly in these years.[2]

(4) Construction stage by stage: Needless to say, the design should be made to facilitate the continuation to the future plan. It is very desirable that the system presented here can be used as an injector to the next larger step.

Accelerator System

A schematic diagram of the whole system is shown in Fig. 1 with the main parameters of the respective stages. The line up of the accelerating sections is rather conservative. It consists of the plural ion sources followed by 1 MV Cockcroft, 2 sections of Wideröe Linac, 1 Alvarez Linac, 2 boosters and one main synchrotron which delivers about 4×10^{13} particles of 20 GeV into a storage ring placed inside the synchrotron ring, where 4 bunches are rapidly formed with the peak current ∿1 kA. 4 extraction lines can carry the beam of 10 TW total power and 100 kJ total energy to the reactor chamber located in the center of the accelerator rings. Throughout the description presented here, a hypothetical ion of $A \simeq 200$ and $q = 4$ is assumed for brevity. Detailed parameters of the respective stage are listed in Table I ∿ III. The figures for the target are shown in Table IV. Principal points in the scheme are as follows:

a) Linac System: To increase the beam intensity, keeping the emittance at the output of the ion source the moderate value, the "Funnel" loading of succeeding linacs is adopted. The ratio of $\beta\gamma$ of βout and βin in a linac is taken to be 2.52 so as to reduce the phase width of a bunch by a factor of 2. Auxilliary stripping cells and deflection magnets are inserted between the linac and enable the beam to be used in some low energy experiments with different mass number and charge states. The normalized emittance of the beam is required to be smaller than 5×10^{-6} m.rad, which is not in any way severe in the ordinary operation. Total lengths of the accelerator and of the linac tank system are estimated to be about 300 m and 320 m respectively. The transit time from the outlet of the Cockcroft to the injection port of the booster is about 20 μs. Considering that the four turn injection into the boosters takes 62 μs, the linac might be pulse-operated with the repetition rate 2 Hz and with the duration of, say, 1 msec. The small duty cycle can reduce the cost of RF power supply. The beam intensity limitation by the space charge effect is crucial only in the first stage of the accelerator, with the "Funnel" loading, however, it could be managed.

b) Booster-Synchrotron: The number of the accelerated particles N is limited principally by the tune shift of the betatron frequency due to the transverse space charge effect.[1] Keeping the bunching factor B (the ratio of the peak and the average currents) constant, N is determined by the value of $\beta\gamma$ at the injection, to be 0.19×10^{14} for the parameters shown in Table II with B = 2. The number of the particle, N does not depend on the length of the circumference $2\pi R$ of the ring and then can be increased, using multiple boosters. 2 boosters with a half radius of that of main ring accelerates 0.38×10^{14} particles up to 7.5 GeV, when the allowable N is nearly doubled. The beams are injected into main ring in a similar way with "Funnel" loading and the total energy of the circulating beam is increased by a factor two with the average and the peak currents unchanged. The harmonic number h of the accelerating RF frequency should be now also doubled.

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0018-9499/79/0600-3109$00.75 © 1979 IEEE

To keep the bunching factor as low as possible with the reasonable value of RF voltage, the rate of the change of the magnetic field is assumed to be low. The boosters and the synchrotron are operated with 2 Hz.

The harmonic number of RF is taken rather low, 24 in booster and 48 in synchrotron. Because of low repetition, $\alpha/\Gamma^{1/2}$ can be large, where α is the factor between moving and stationary bucket area of RF field and $\Gamma = \sin \phi_s$ (ϕ_s is the stable phase[1]), leading to small ϕ_s. Through the acceleration cycle in the booster, ϕ_s is kept about 18°. The beam area in the RF bucket is decreasing adiabatically with the energy increase of the particles and the resulting bunching will be unfacourable in view of the space charge limit. Voltage programming of RF power[3] and/or the dilution of the beam into the whole area of RF bucket by perturbing the RF fields with frequencies of the order of the RF oscillation[4] could be useful techniques to avoid the unnecessary bunching and to reduce the RF powers. The final required RF voltage per turn is less than 1 MV in both of booster and synchrotron. This easy acceleration scheme suggests that a higher repetition cycle will be more desirable as the future plan.

c) Accumulator Ring and Final Transport: At the end of the acceleration period in the synchrotron, the beam is transferred to the storage ring, which is placed inside the synchrotron ring. The magnetic field is assumed to be 1.2 T, 20% higher than that of synchrotron. The beam is debunched by turning off the RF and compressed again into 4 bunches rapidly. The final compression is supposed to be very rapid so that the limit of the tune shift could be exceeded without causing a great loss of the beam, as usual. The beam length is now shortened to 10 ns and the final bunching factor will be about 65. This bunching should be obtained with the RF system and an auxiliary bunching may be possible in the final transport lines, if necessary. The beam is extracted through 4 ports into the transport channels which consist of series of Q-magnets and lead the power of 120 TW to the target in the reaction chamber. The peak current in each channel is estimated to be 0.61 kA and the power of 18.8 TW can be carried per channel, according to Maschke's formula[5] and the design parameters used here. The reactor chamber is assumed to have a radius of about 10 m. The details of its structure are beyond the scope of this paper and are to be discussed separately. Inside the storage ring, a sufficient space may be supplied for the reactor, the target modeling and handling systems and other related facilities. An example of the general layout of the whole assembly is shown in Fig. 2.

Uses for Multiple Purposes

The accelerator system stated here is designed as a joint program of a laboratory which is mostly fusion-oriented and an organization for the study of nuclear research. The latter will be open to the co-operative use of any facility belonging to the institute by any academic scientist working in Japan. There should be numerous applications of heavy ion beams in both of basic and applied researches. Nuclear physics, astrophysics, radiation biology and radiation therapy are the examples of them. With a small modification of the accelerator assembly and adding some supplemental systems such as charge exchange chambers to get the ions of various charge state, the machine designed for the inertial fusion will be well consistent for the simultaneous uses of many kinds of objects. The cite will include the space for laboratories of plasma and nuclear physics.

Future Plan

Two ways of successive programs are being considered. One is the remodeling of the synchrotron and the accumulator ring with use of superconductive technology. If the magnetic field can be increased up to about 3 T, the final energies of the particles are close to 140 GeV, which result in the total energy of 900 kJ and the power of 85 TW, without significant change of other sections of the accelerator.

The other is the injection of the heavy ion beam from the accumulator into an induction linac. The beams of 20 GeV and several tens of amperes are enough for the effective operation of the induction linac, allowing the use of the large accelerating gradient, say 2 MV/m (8 MeV/m for Z = 4). Operation of the synchrotron with a high repetition and stacking of the beam into the accumulator may reduce the necessary length of the induction linac to a few kilometers. Many problems certainly remain unsolved. Here is presented a very simple sketch of our tentative plan and considerable further studies are required even for getting a rough concept of the possible scheme of the inertial fusion by conventional accelerators.

References

1. Proceedings of heavy ion fusion workshop held at Brookhaven National Laboratory, BNL 50769, 1977.
2. For example, see the review paper by H. A. Grunder: Annual Rev. of Nuclear Science 27 353, 1977.
3. K. Huke and G. Iwata: Japan Journ. of Applied Phys. 2 394, 1963.
4. S. Kawasaki: Japan Journ. of Applied Phys. 4 677, 1965.
5. Proceedings to the ERDA Summer Study of Heavy Ions for Inertial Fusion, LBL 5543, 1976.

Table I LINAC PARAMETERS

A = 200 q = 4 1MV Cockcroft Injector

	Wideröe I	Wideröe II	Alvarez
Unit Number	4	2	1
Length (m)	14	30	200
Frequency (MHz)	18	36	72
β in	0.0066	0.0166	0.0419
β out	0.0166	0.0419	0.1445
T in (MeV)	4	26	162
T out (MeV)	26	162	2000
Average Current (mA)	30	60	120
Focusing	FODO	FODO	FFDD
Aperture (cm)	2.5	1.8	0.7
Gap Number	50	100	400
Tank Type	π - 3π	π - 3π	2π
Average Acc. Field (MV/m)	0.39	1.13	1.53

Funnel loading for current amplification

Table II BOOSTER AND SYNCHROTRON PARAMETERS

	Booster	Main Ring	(S.C)
Number	2	1	
Particle Number limited by space charge with bunching factor = 2	0.190×10^{14}/ring at 2 GeV	0.380×10^{14}/ring at 7.5 GeV	
T in (GeV)	2	7.5	
T out (GeV)	7.5	20	(140)
β in	0.145	0.276	
β out	0.276	0.430	(0.821)
RF harmonic number	24	48	
RF frequency (MHz)	3.13 — 5.98	5.98 — 9.33	
Magnet			
Max. Field (T)	1.2	1.0	(3)
Curvature (m)	37.0	73.8	
Lattice unit	FFDD	FFDD	
Revolution frequency (kHz)	130 — 249	124 — 193	(371)
Average circulating current (A)			
input	0.40	0.76	
output	0.76	1.18	
Normalized transverse emittance (m.rad)	20×10^{-6}	20×10^{-6}	

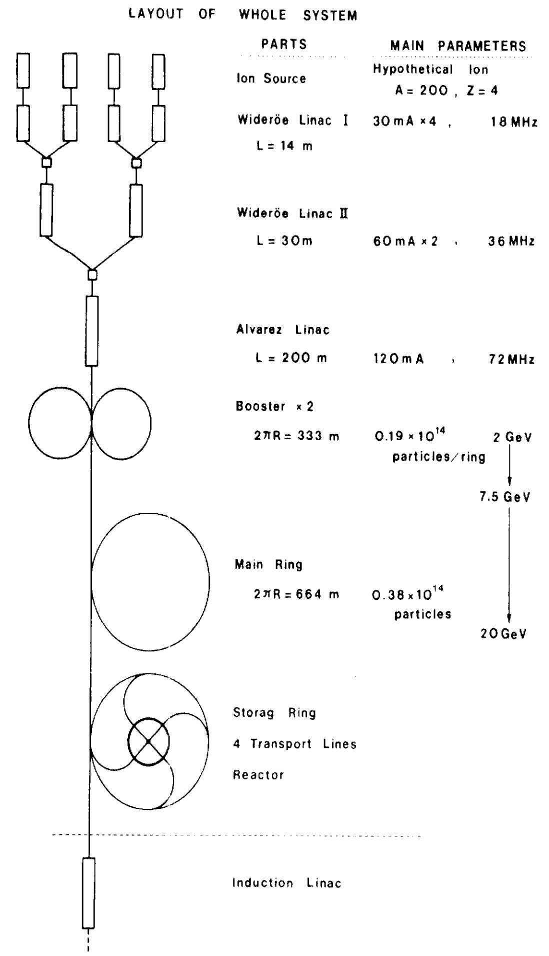

Fig. 1. Schematic diagram of the whole system

Table III ACCUMULATOR AND FINAL TRANSPORT

Accumulator	
Magnet	
Max. Field (DC)	1.2 T
Curvature	60.5 m
Lattice Unit	FODO
Revolution Freq.	232 Kc
Average Current	14.2 A
Bunching	48 → 4
Transport	
Number	4
Type	Q (FODO)
Length	60 m/line
Max. Field	1.5 T

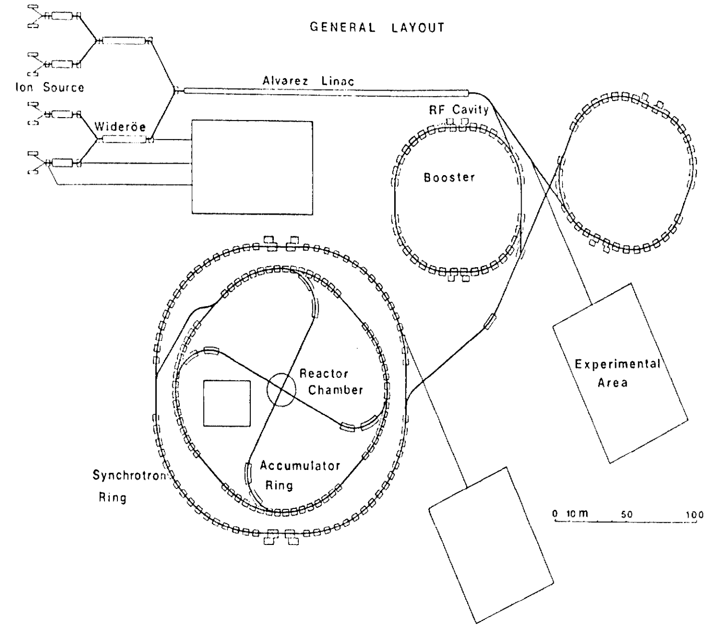

Fig. 2. General layout of the whole assembly