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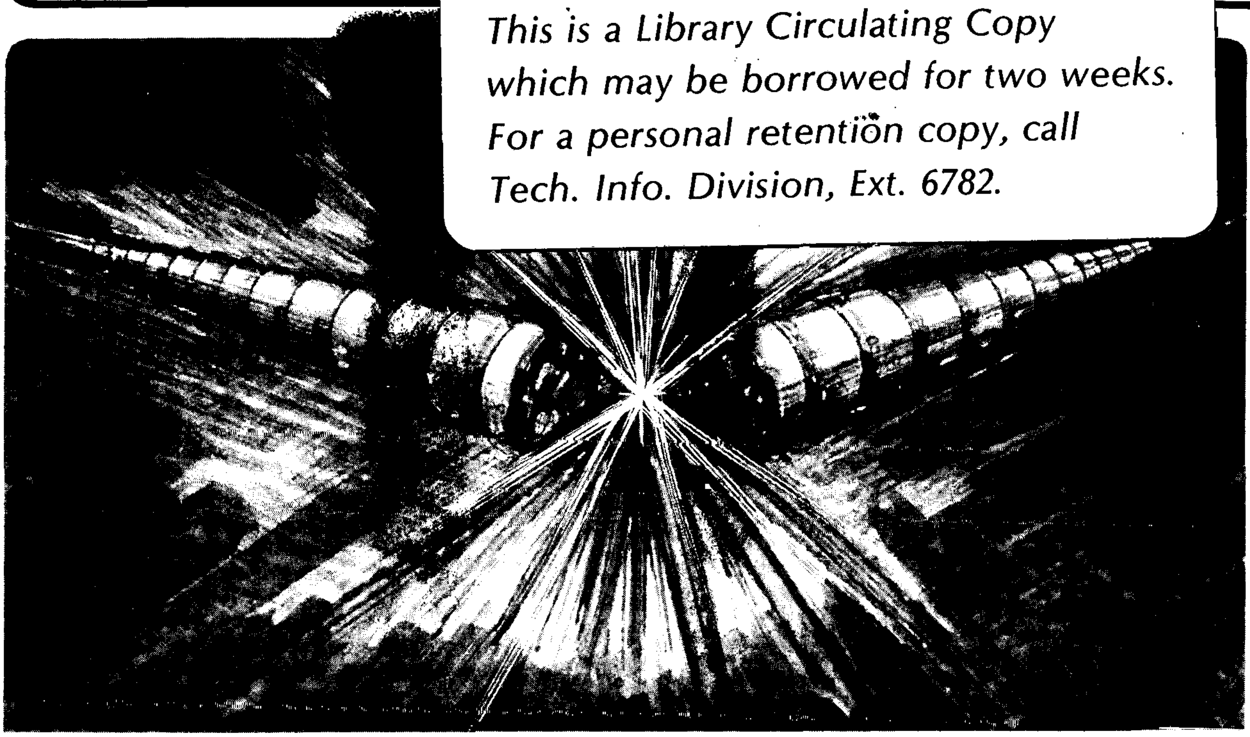

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DISCLAIMER

AN ISOCHRONOUS STACKING RING APPROACH TO THE HTE*

LBL-15208

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Introduction

The problem of finding a suitable apparatus for demonstrating heavy ion fusion is a difficult one to approach in moderate steps. An accelerator which can achieve break-even is probably too expensive as a first step in the present climate of trimmed budgets. As suggested by Mark et. al.[1] a meaningful test of many of the concepts could be achieved with a device capable of heating a disk of material to plasma temperatures in the neighborhood of 100 eV (10^6 degrees K). Such apparatus would be useful for testing beam transport, focusing and targeting concepts, as well as target behavior in the plasma regime. Ideally, the technology used in this "high temperature experiment" (HTE) could also be extended to construct a prototype fusion facility.

Target heating for the HTE requires a short beam burst on the order of tens of nanoseconds with a total beam energy of a kilojoule or more. The rf linac falls far short of this capability. A number of studies have considered the use of storage rings for accumulating beam current. The present paper looks at an alternative means, using a rf linac followed by an isochronous stacking ring (ISR), producing rapidly the high multiplication of beam current required. This method avoids the necessity for beam manipulations such as beam splitting, rf bunching in a storage ring, etc. Because of the fast transit time in the ISR, storage ring instabilities are not a problem.

Beam Stacking with an Isochronous Ring

In an isochronous ring, the effective magnetic radius R will be proportional to momentum, and from this we deduce that the radial separation of adjacent orbits is given by (non-relativistically)

$$\Delta R = \frac{2qV\bar{R}}{T_n A} \qquad (1)$$

where V is the accelerating voltage per turn, q is the charge state, A is the mass number, and T_n is energy per nucleon. For injection into the inner radius of the ring, ΔR must be made large enough so that turn separation will be sufficient for beam to clear the septum. At larger radii V can be decreased, even reduced to zero at extraction radius, causing a large number of turns to occupy a small radial extent.

The use of this property of turn-compression, to stack a large current of protons in an isochronous ring at extraction radius, has been studied by Joho[2]. By assuming conservation of longitudinal phase space, he finds that N_m, the maximum number of turns which can be stacked is related to the energy spread ΔT_o of the extracted beam by the formula

$$N_m = \frac{\Delta\Psi_o}{\Delta\Psi_i} \quad \frac{\Delta T_o}{E_{g,i}} \quad , \qquad (2)$$

where $\Delta\Psi$, $\Delta\Psi_o$ are the phase spreads at injection and extraction, respectively, and $E_{g,i}$ is the energy gain per turn at injection. From Eq. 2 we see that to achieve a large number of stacked turns both the phase spread at injection and the energy gain per turn at injection should be as small as possible. The energy spread at extraction should be as large as is consistent with transport to the target.

The maximum current which can be stacked near the outer radius will be limited by the incoherent betatron tune shift. The space charge forces act to shift ν_r, ν_z downward. Thus locating ν_r and ν_z well above integral stopbands is an important consideration in order to maximize allowable current. In order to lower the required energy gain per turn at injection, ν_r is set to 1.25. Then by injecting on a displaced orbit, a coherent betatron oscillation can be produced which will aid the beam in clearing the septum, so the energy gain per turn at injection can be made on-third as large as would otherwise be necessary.

A computer program has been written to track particles through an ISR, in a simulation of the stacking process. Space charge effects have not as yet been included in these calculations. Fig. 1 shows the accelerating voltage used for the particular case which will be illustrated in this paper. Fig. 2 shows the particle energy, the rms energy spread and phase spread of the last 100 turns, as a function of the turn number. This demonstrates the compression, which is optimum at 320 turns in this case, as well as the corresponding phase growth. Particles would be extracted where ΔT_{rms} is a minimum, but the calculation has been extended further, showing an increase in both ΔT_{rms} and $\Delta\Psi_{rms}$. The reason for this behavior becomes clearer in Fig. 3, where the ΔT, ΔΨ phase space boundary of a group of particles is plotted at injection, at minimum ΔT_{rms}, and at a later time. It is evident that as the phase space is compressed in energy, the corresponding extension in phase results in particles with a phase shift obtaining less energy, thus distorting the phase space.

Use of an ISR for the HTE

In Fig. 4 is shown the elements of the proposed HTE using an isochronous ring. The apparatus consists of an ion source, a rf linac, a stacking ring and a number of beam lines to transfer beam bunches to the target. By operating the ring on a suitable harmonic, the beam bunch structure is retained, with bunch separations such that fast kicker magnets can be used for extraction and switching in the external beam lines. After extraction, a separate beam line is used for each bunch. Bunch length, which has been established by the choice of rf frequency, is made to be consistent with the pulse length needed for the test.

The beam bunches are formed at the entrance to the linac by a low beta structure, operated a low rf frequency, on the order of 5-10 MHz. As the ions proceed through the linac, the rf frequency is progressivly raised, so that at the exit the frequency is on the order of 50-100 MHz. In the

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present example, the beam energy on target required is about 5 MeV/A, of this the linac will provide 4.55 MeV/A, the isochronous ring the remainder.

Although in the present paper no attempt has been made to estimate costs, we can recognize here a few of the considerations that must be taken into account in optimizing this system.

- In order to reduce the number of beam lines to the target, the circumference of the ISR should be made as small as possible. Thus we consider superconducting magnets as being most desirable.
- To obtain the maximum stacked current it is necessary to use $q=1$, with A as large as economy permits, because the ring space charge limit is proportional to A/q^2.
- Choosing a low injection energy in the ring will lower the linac cost, but there is practical limit imposed by the width of the field in the ring dipoles. As the field width is increased, the magnet cost will go up. Thus the ring injection energy will probably be determined by minimizing the overall cost of linac + ring.

Target Requirements

We must know the requirements for the HTE target conditions to be achieved in order to design a suitable accelerator. The most important considerations are - the target temperature T reached for a given irradiance S (in Watts/cm^2) as a function of time, the requirements for beam transport, and for focusing on the target.

The maximum divergence and momentum spread are set by the permissible aberrations in the final transport elements. This problem has been discussed in several papers[3]. For this study we will use for maximum divergence, ± 30 mrad, with momentum spread ± 0.25 percent.

As the temperature of a material is raised, energy is deposited in internal degrees of freedom, until such time as electron bonds are broken and the material begins to disassociate. Using as a model a disk of low-density material imbedded in the surface of high-density material, this behavior has been studied with the aid of computer simulations[1,4]. An empirical formula which represents these results to a good approximation is [5]

$$t/\tau = \int_0^x \frac{x^{1/2}}{1-x^4}\,dx \qquad (3)$$

where $x = T/T_f$, with T_f defined by $S = \sigma T_f^4$ and

$$\tau = \frac{3C_1R}{2\sigma T_f^{5/2}} \qquad (4)$$

The "heat coefficient" $C_1 = 1.02\ 10^4$ J/(gm-eV$^{3/2}$), the ion range R is assumed to be 10 mg/cm^2, and σ is the Stefan-Boltzmann constant, 1.03 10^5 W/(cm^2-eV^4). Eq. 3 is plotted in Fig, 5. We note that as T approaches the asymptotic limit T_f the material starts to disassociate. To determine a useful pulse length we will take $t = \tau$, where $T = 0.95\ T_f$, and presumably the blowing-up process has just started. A longer pulse than τ would waste particles because the last arrivals would not contribute to raising the temperature, while for a shorter pulse than τ, T would fall short of $0.95\ T_f$.

Ring and Target Parameters

There is no unique choice of parameters to reach a given target temperature. The higher the mass number A, the easier it will be to reach a given temperature, but increasing A increases the cost of linac, ring, and transport lines. In the limits of the present paper we cannot treat this subject more fully, instead will use a set of parameters chosen to demonstrate the possibility of using an isochronous ring to achieve a temperature high enough to be useful for the HTE. Ring and target parameters based upon this choice are given in Table I. The stacking behavior has been illustrated in Figs. 1-3.

Table I. HTE Parameters Using $A=165$, $q=1^+$

Ion Source	Current	7	mA
	Emittance (norm.)	0.3π	mm-mrad
Linac	Low β rf freq.	5	MHz
	Final rf freq.	50	MHz
	" energy	4.55	MeV/A
	" emittance (norm.)	$1.0\ \pi$	mm-mrad
	Momentum spread	$\pm 0.25 \cdot 10^{-4}$	
Ring	Energy at extraction	5.0	MeV/A
	RF frequency	10.0	MHz
	No. of beam bunches	19	
	Ions per bunch	$9 \cdot 10^{11}$	
	Dipole magnet field	6	Tesla
	Accelerating field at injection	0.74	MV/turn
	Betatron frequencies ν_r, ν_z	1.25, 0.9	
	No. of stacked turns	100	
	Transit time in ring	1.6	msec
Target	Spot radius	1.0	mm
	Total no. of particles	$1.7 \cdot 10^{13}$	
	Ion range	10	mg/cm^2
	Pulse length	50	nsec
	Irradiation	$1.5 \cdot 10^{12}$	W/cm^2
	Total energy	2.2	kJ
	Disk temperature	59	eV

Conculsions

There is a strong possibility that isochronous stacking rings will be a useful tool for producing the intense bursts of heavy ions needed for the HTE. Also, it appears that this technology can be extrapolated for use in a heavy ion fusion driver. Additional work needs to be done on the effects of the stacking process on phase space dilution, particularly the effect of space charge. The design of suitable large-aperature superconducting magnets also needs to be studied.

Acknowledgements

We are indebted to D. Judd and L. Smith for valuable suggestions on the dynamics of isochronous rings. S. Boyle has been very helpful with computer software.

References

1. J. Mark, Proc. of the Symposium on Accelerator Aspects of Heavy Ion Fusion, Darmstadt, 1982 (GSI-82-8), pp. 454-513.
2. W. Joho, SIN unpublished report, April 1982, and Particle Accelerators 6, pp. 41-52 (1974).
3. Proceeding of Darmstadt Symposium (see ref. 1, pp. 362-402). See also report of earlier HIF workshops.
4. R. Bangerter, private communication.
5. E. Lee, private communication.

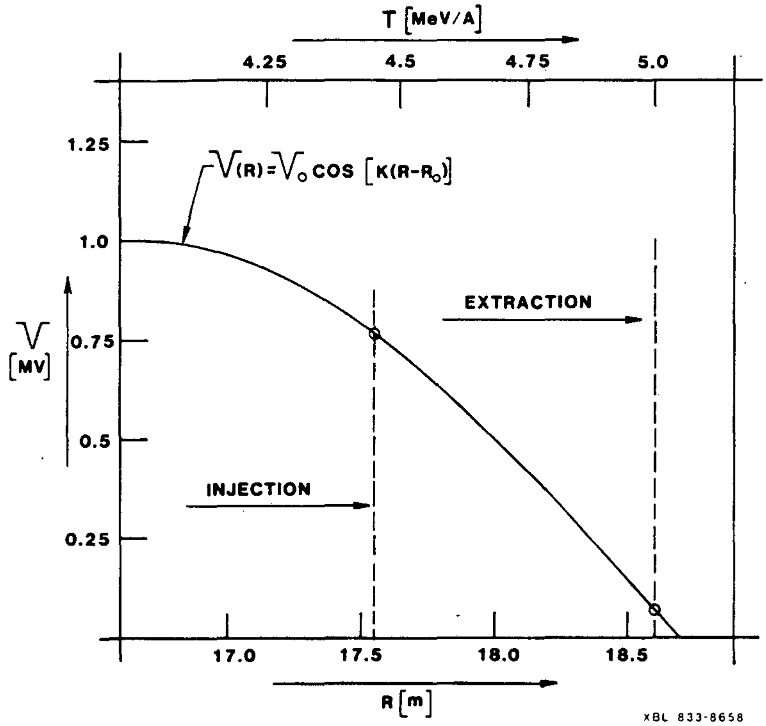

Fig. 1 - RF accelerating voltage as a function of radius, for the ISR calculations of this paper.

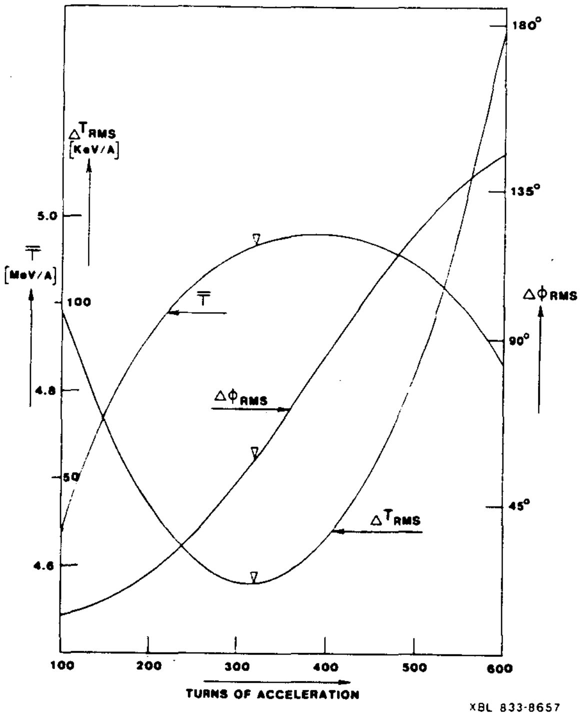

Fig. 2 - For a group of particles comprising 100 consecutive turns, the average energy $\bar{T}$, rms energy spread Δ_{rms}, and rms phase spread $\Delta\Psi_{rms}$ are plotted, as a function of total accelerated turns. The triangles indicate the optimum point for extraction, after 320 turns.

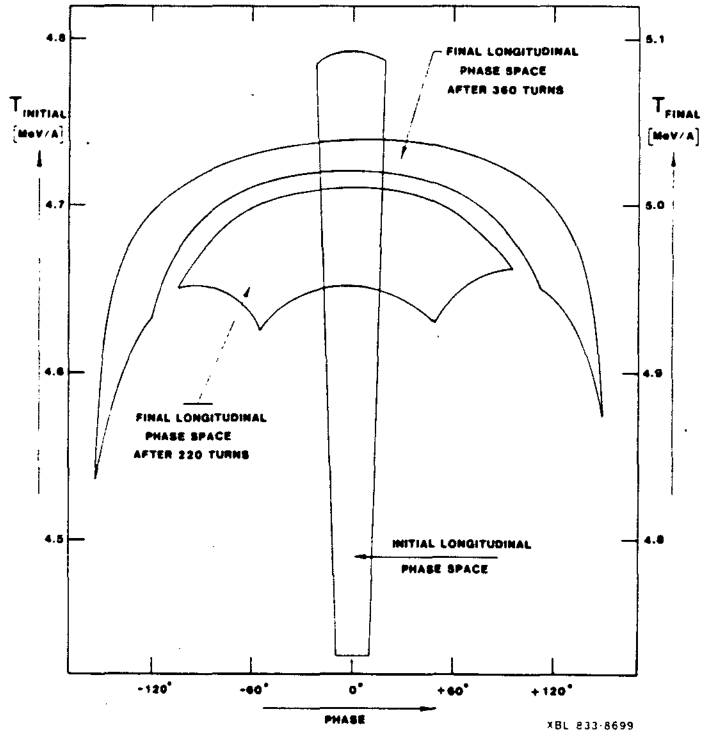

Fig. 3 - Distributions of 100 turns in ΔT, $\Delta\Psi$ phase space following turns 1, 220 and 360, showing the increasing distortion due to phase spreading.

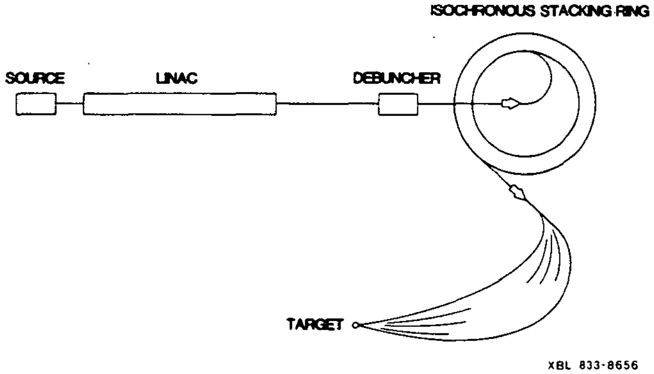

Fig. 4 - Schematic of a possible use of an isochronous stacking ring for the HTE.

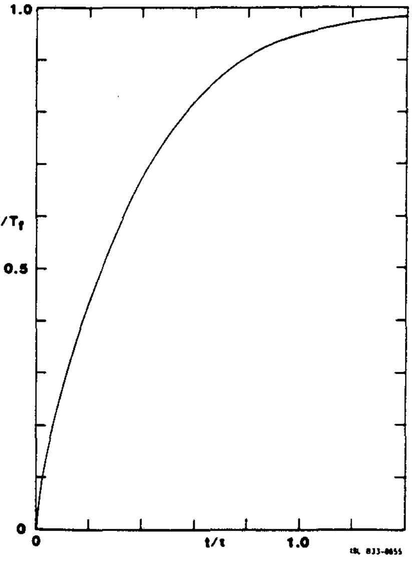

Fig. 5 - Heating of a disk target by an ion beam. T_f is the asymptotic limit, where radiation and plasma losses equal heat input. The characteristic time τ is defined in the text.

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