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Introduction

We present results of exploratory and preliminary studies of a next generation of heavy ion accelerators. This is not intended to be a definitive report, but only a brief summary of some of the most important considerations. Exact specifications must ultimately be derived from the physics to be investigated at such a facility, a topic extensively discussed in other contributions to this conference. For the present purpose we take as given that the following conditions should be met.

1) The availability of ion beams with masses up to Uranium (A=238).
2) Low energy capability overlapping with the presently available energy range (i.e. Bevalac energies).
3) The provision of CM-energies approximately one order of magnitude beyond Bevalac energies, i.e. $\sim$ 20 GeV/amu.

With these as premises let us now look for optimum hardware to do the job. First, we will be able to take as given that we can build linacs of high intensity. Second, we must expect to use superconducting magnets in any large facility, in order to avoid an unacceptable power bill. Third, it is clear that to reach the CM energies required, with reasonable-size machines, that we must use colliding beams, while retaining a conventional fixed target capability to meet experimental needs at the low energy end.

Assuming tentatively, and somewhat arbitrarily, a maximum synchrotron rigidity of $\sim$ 80 T_m (corresponding to $\gamma \sim 10$ for $Z = 80$, $A = 200$) a scheme as illustrated in Fig. 1 has been worked out. The reasoning underlying this approach, and estimates of expected performance will be given in the following sections. In Table I are shown the expected linac performance and the basic ring parameters.

II. The 2-Ring Concept

Optimum utilization of a given machine $B\rho$ with respect to final energy requires fully stripped ions, but stripping implies a considerable loss of beam intensity unless it is carried out at an energy where essentially all ions are completely stripped. For obvious reasons, i.e. non-existence of an appropriate facility at this time, this energy is not known experimentally for high mass ions, but theoretical considerations and the extrapolation of existing data point toward several hundered MeV/amu to maybe $\sim$ 1 GeV/amu for Uranium. An injector linac of this energy is economically unfeasible. A 1 GeV/amu booster synchrotron injector with $q/A \simeq 0.2$ on the other hand, requires a $B\rho$ of $\sim$ 1/3 that of the main machine in our example. From here it is only a small step to consider two equal rings which opens up both various interesting modes of fixed target operation, as well as the extension to a colliding beam facility. The central task then is to establish that a balanced solution is possible. By this we mean that a good match be achieved between linac brightness and the ring acceptance requirements as dictated by tune shift considerations. This seems to be possible, as outlined in the section on performance estimates. Before entering this topic however, we will describe the various modes of operation.

III. Modes of Operation

It is common to all opertional modes that the linac beam will not be stripped at injection. For the heavier ions stripping would imply a beam loss of $\sim$ one order of magnitude and furthermore, aggravate synchrotron space charge problems. (The tune shift is proportional to q^2/A). The number of injected turns is about 100, and stacking in both vertical and horizontal betatron planes is desirable.

a) Low energy mode. In this mode beam is accelerated in the first ring, then transferred to the second ring which serves as stretcher ring to provide a slowly extracted beam of essentially 100% duty cycle. This mode is illustrated in Fig. 2. Energies as low as a few tens of MeV/amu would be practical.

b) High energy mode. In this mode the beam is extracted from ring 1, stripped and transferred to ring 2 where acceleration to the final desired energy occurs. This mode is illustrated in Fig. 3. Average beam intensities for fixed target modes are shown in Fig. 4. These values are realistic, assuming a rate of field rise of 1 to 2 Ts^{-1}, achievable with an ESCAR type magnet. High energy average intensities as shown are based on accelerating one pulse only from ring 1 to its maximum energy (Fig. 3). Accelerating more than one pulse and to a lower energy in ring 1, so as to reach space charge limit again in ring 2, will increase average intensity, admittedly with a loss in duty factor.

c) Storage ring operation. About 100 to 200 pulses from ring 1, depending on the assumed linac intensity, momentum spread and choice of apertures, are stacked in momentum space in ring 2 at $\gamma \sim 5$. Acceptable beam loss and background during colliding beam experiments will certainly require fully stripped ions. A conservative approach, in view of our limited knowledge about charge changing cross sections at high energies, dictates that the stacking process too be carried out with fully stripped ions. At this energy no loss in beam brightness of the individual pulses from ring 1 results but the space charge limit in ring 2 is depressed by about a factor of 4, because of the increase in charge state after stripping. After completion of the stack the field in ring 1 is reversed, the beam in ring 2 bunched on the second harmonic and one bunch is transferred to ring 1. Acceleration/deceleration then creates the desired condition: Counter-rotating beams at specified energies, $2 \lesssim \gamma \lesssim 10$.

The storage ring mode and bunching process are schematically depicted in Figs. 5 and 6, respectively. The procedure as described refers to beams of equal masses. It should be pointed out however, that there exists a capability of operating with unequal mass beams. This rests on the fact that particles of different charge to mass ratios, Z/A, if stacked on the same orbit will have different γ, hence different momentum per nucleon, and therefore different revolution frequencies. No difficulties are expected in stacking these beams on top of each other, Fig. 7 showing schematically the result of such a stack in $(\Delta p, \Delta s)$-space. RF-separation will require bunching with h = 1 using two RF-systems with $\Delta f/f = \gamma^{-2}\ \Delta(Z/A)/(Z/A)$. The reasonable assumption is made that this procedure will work if the RF-buckets at the required bunching factor are separated in Δp by the order of one to two bucket heights. Computer simulations leading from the fully debunched beams to bunches sufficiently short are shown in Figs. 8 and 9. They will precess with respect to each other. When maximum separation occurs (Fig. 10), a fast kicker magnet transfers one of them to the other ring. The difference $\Delta(Z/A)$ determines the allowable stack momentum spread $\Delta p/p$.

IV. Lattice Design

It would be premature at this stage to work out very detailed lattices. In order to provide a basis for the performance estimates which will conclude this report, however, some initial concepts had to be established. As long as the contemplated energy is of the order of 10 to 12 GeV/amu it seemed advantageous to operate with a rather high ν, which results in a high acceptance for a given magnet aperture, and helps to achieve a low dispersion, and raises γ_{tr} above the range of operating energies. This latter point will also be seen helpful in the context of current limitations due to intra-beam scattering. Relatively low β interaction regions are envisaged and a variable interaction angle is desirable in order to maximize luminosity at all operating energies. Since relatively small crossing angles are attempted, dispersion suppression at the crossing points is assumed. A conceptual layout of an interaction region and the corresponding beta functions are shown in Figs. 11 and 12. The large β_y of Fig. 12 is not acceptable for operations with large beam emittances (injection at 10 MeV/u, etc.), consequently a tunable insertion must be designed. Considerable work and also interaction with the experimental user will be required to perfect the design of these crucial areas and ensure high luminosity and a flexible experimental environment.

V. Performance Estimates and Limitations

A preliminary analysis of expected performance indicates that the proposed scheme merits further, in-depth study which can serve as a starting point for the design of an accelerator complex for relativistic heavy ion research.

We base our discussion on the following simple formula for the luminosity $\mathcal{L}$ and the beam-beam tune shift $\Delta\nu^{bb}$:

$$\mathcal{L} \propto \frac{I^2}{\alpha}, \quad \Delta\nu^{bb} \propto \frac{I}{\alpha} \quad \text{and therefore } \mathcal{L} \propto I \, \Delta\nu^{bb}$$

which hold for interaction angles α sufficiently large compared to the beam divergence $\Delta x'$ at the interaction point, and equal currents I in both rings. Assuming the canonical value $\Delta\nu^{bb} = 5.10^{-3}$, we therefore arrive at the maximum expected luminosity (and the corresponding interaction angle) once we have established an upper limit for the current I.

The following current-limiting considerations were taken into account (see also Table II):

a) Incoherent space-charge tune shift $\delta\nu$. We assume $\delta\nu \lesssim 0.05$ during colliding beam operation, $\delta\nu \lesssim 0.25$ during the bunching and reinjection process. With a circular vacuum chamber and magnet yokes, only the direct term is important at the energies under consideration, yielding:

$$I_{sp.ch.} \lesssim \frac{A}{q^2} \quad \frac{\delta\nu}{R} \quad \beta^3 \gamma^3 \quad f(a, \bar{\beta}, \varepsilon_z) \quad B$$

where R is the average radius, a the horizontal beam half-width, $\bar{\beta}$ the average β-function, ε_z the vertical emittance, and B the RF-bunching factor. In Fig. 13 this current is plotted versus γ for $\delta\nu = 0.05$, $B = 1$ and beam sizes compatible with our preliminary lattice design and a clear aperture of $\sim$ 125 mm diameter.

b) Longitudinal instability. A limiting current is devised from the Schnell-Keil criterion

$$I_{max} \simeq \left(\frac{n}{Z_{11}} \right)^{-1} \quad \frac{M_o c^2}{e} \quad \frac{A}{q^2} \quad \beta^2 \ \gamma \ |\eta| \left(\frac{\Delta p}{p} \right)^2$$

where $\eta = \gamma^{-2} - \gamma_{tr}^{-2}$. Our treatment is to some degree arbitrary since $\frac{\Delta p}{p}$, or I, of each injected pulse can be manipulated to a certain extent. Fig. 13 shows two extreme cases for the maximum current, once applying the criterion to the full stack, which then constitutes an absolute upper limit. The lower curve assumes each pulse to be limited to the same value as the first stacked pulse.

c) Intra-beam Scattering. The theory developed by Piwinsky was applied to determine limitations due to intra-beam scattering. Relaxation times which depend very steeply on γ and the initial phase-space volume were not investigated in detail since we propose to operate below transition where the theory predicts that the six-dimensional phase-space volume occupied by the beam remains bounded and the scattering process results simply in an equilibration between the different phase planes characterized by:

$$\varepsilon_z = \varepsilon_x,\ \frac{\Delta p}{p} \simeq \left(\frac{\varepsilon_x}{\bar{\beta}_x}\right)^{1/2} \quad \eta^{-1/2}$$

Assuming a maximum tolerable emittance ε and a given $\frac{\Delta p}{p}$ for each pulse this translates into a maximum number of stacked pulses. The corresponding current limit is again plotted in Fig. 13.

d) Pressure Bump Phenomenon. This constitutes potentially the most dangerous limitation, especially if we keep in mind that the ionization cross sections for heavy ions will be approximately Z^2 times those applicable in the case of protons. In any system with lumped pumps, typically "conductance limited" in accelerator installations, there exists a critical current I_{crit} which cannot be exceeded without pressure blowup if the net desorption coefficient η is positive. The only safe way to guarantee adequate luminosity in a heavy ion storage ring using lumped pumps is to achieve $\eta < 0$, i.e. create by judicious choice of wall material and treatment a situation where beam pumping results. This phenomenon has been demonstrated, and the required precautions and techniques have been developed at the ISR.

A more speculative alternative, in need of theoretical and most importantly experimental investigation, is the use of distributed pumps. The most attractive form would be the use of a cold bore with its added advantage of reduced magnetic volume and savings on isulation.

Presently we conclude that it will be possible to achieve vacuum conditions which will not impose current limitations more severe than those previously outlined.

The luminosity as a function of γ corresponding to the limiting currents outlined above is shown in Fig. 14. The interaction angle α is assumed to vary with γ, as shown in Fig. 15, so as to maximize the luminosity subject to the condition $\Delta\nu_{bb} \lesssim 5.10^{-3}$.

A few comments may be in order with respect to these estimates. First, the luminosities for the very low energy end, where $\alpha < 10$ mrad, may be slight overestimates since the simple formulae for luminosities and beam-beam tune shifts are inaccurate. Second, a more careful calculation of the effects of intra-beam scattering, taking the variations of the β-functions into account, may be indicated.

VI. Facility Cost

An approximate cost figure for the facility can be estimated by applying gross unit cost figures (cost per meter of ring, tunnel, etc.) taken from costs of similar facilities now being built, such as PEP and ISABELLE. Cost information is also available for ESCAR superconducting magnets. Table III shows the result of such a simple exercise, in which the facility is broken into four major components - injector, beam transfer lines, rings, and conventional facilities.

VII. Conclusion

Our preliminary investigations lead to the conclusion that useful luminosities are feasible in a colliding beam facility for relavistic heavy ions. It is furthermore seen that such an accelerator complex may be laid out in such a fashion as to provide extracted beams for fixed target operation, therefore allowing experimentation in an energy region overlapping with that presently available. These dual goals seem achievable without undue complications, or penalties with respect to cost and/or performance. Further work aiming at a refined understanding of critical areas and firmer, complete sets of parameters is in progress.

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TABLE I

Linac Performance and Tentative Basic Ring Parameters

A. Linac

Energy	$T_{max} = 10$ [MeV/amu]
Charge to mass ratio	$q/A = 0.2$
Output current	$I \geq \frac{4000}{Z}$ [particle μA]
Emittance	$E_x = E_z \simeq \pi\text{-}10^{-5}$ [m], unnormalized
Momentum Spread	$\frac{\Delta p}{p} \leq 5.10^{-3}$, FWHM (without debunching)

B. Ring Parameters

Average Radius	$\bar{R} \simeq 75$m
Dipole Field	$B_{max} \sim 5$T
Aperture	$\sim$ 125mm, circular bore
Energies	T_{max} $(q/A = 0.2) = 3.8$ GeV/amu $(\gamma \simeq 5)$
	T_{max} $(Z/A = 0.4) = 8.5$ GeV/amu $(\gamma \simeq 10)$
	T_{max} $(Z/A = 0.5) = 10.8$ GeV/amu $(\gamma \simeq 12.5)$
Lattice	FODO (regular cells)
Transition energy	$\gamma_{tr} \sim 16$
β-functions	$\beta_{max,x} \simeq \beta_{max,Z} \simeq 7.5$m (regular cells)
	$0.5\text{m} \lesssim \beta_Z \leq 1\text{m}$ (interaction regions)
Number of interaction regions	3 to 4 (for experimental use)
Interaction angle	$5\text{mrad} \lesssim \alpha \lesssim 20$ mrad

TABLE II

Summary of Performance Limiting Assumptions

1) Tune Shifts

   $\delta\nu$ (injection at 10 MeV/amu) $\lesssim 0.25$

   $\delta\nu$ (stacking/colliding beam operation) $\lesssim 0.05$

   $\delta\nu$ (bunching/reinjection) $\lesssim 0.25$

   Only direct space charge terms are considered, since the image term contribution to the incoherent tune shift is still insignificant at this energies for a circular bore.

   $\Delta\nu$ beam-beam $\leq 5\cdot 10^{-3}$

2) Instabilities

   Longitudinal impedance $\left|\frac{Z_{11}}{n}\right| \leq 20\ \Omega$

   Transverse impedance $|Z_t|<|Z_{11}|$ assumed

   Clearing electrodes to prevent ion-electron instabilities.

3) Intra-Beam Scattering

   Equilibration in six-dimensional phase space assumed; limited currents calculated based on Piwinsky's theory.

4) Vacuum and Pressure Bump Phenomenon

   Base pressure $P < 10^{-11}$ Torr

   Wall treatment to achieve negative net desorption coefficient, i.e. "beam pumping" throughout whole machine required.

   The exploration of distributed pumping (cold bore?) is suggested.

TABLE III

Facility Cost
(Excluding Experimental Equipment)

Cost Elements

1.	Conventional Facilities:	C(con)	=	Const + \$10K/m
2.	Accelerator/Storage Ring:	C(acc)	=	\$35K/m/ring
3.	Beam Transfers :	C(tran)	=	\$12K/m
4.	Injector :	C(inj)	=	\$200K/m

$$C_{Total} = C(con) + NC(acc) + C(tran) + C(inj)$$

For $\bar{R} = 75M, N = 2$

$C_{Total} \sim \$50M$

(Not including the injector)

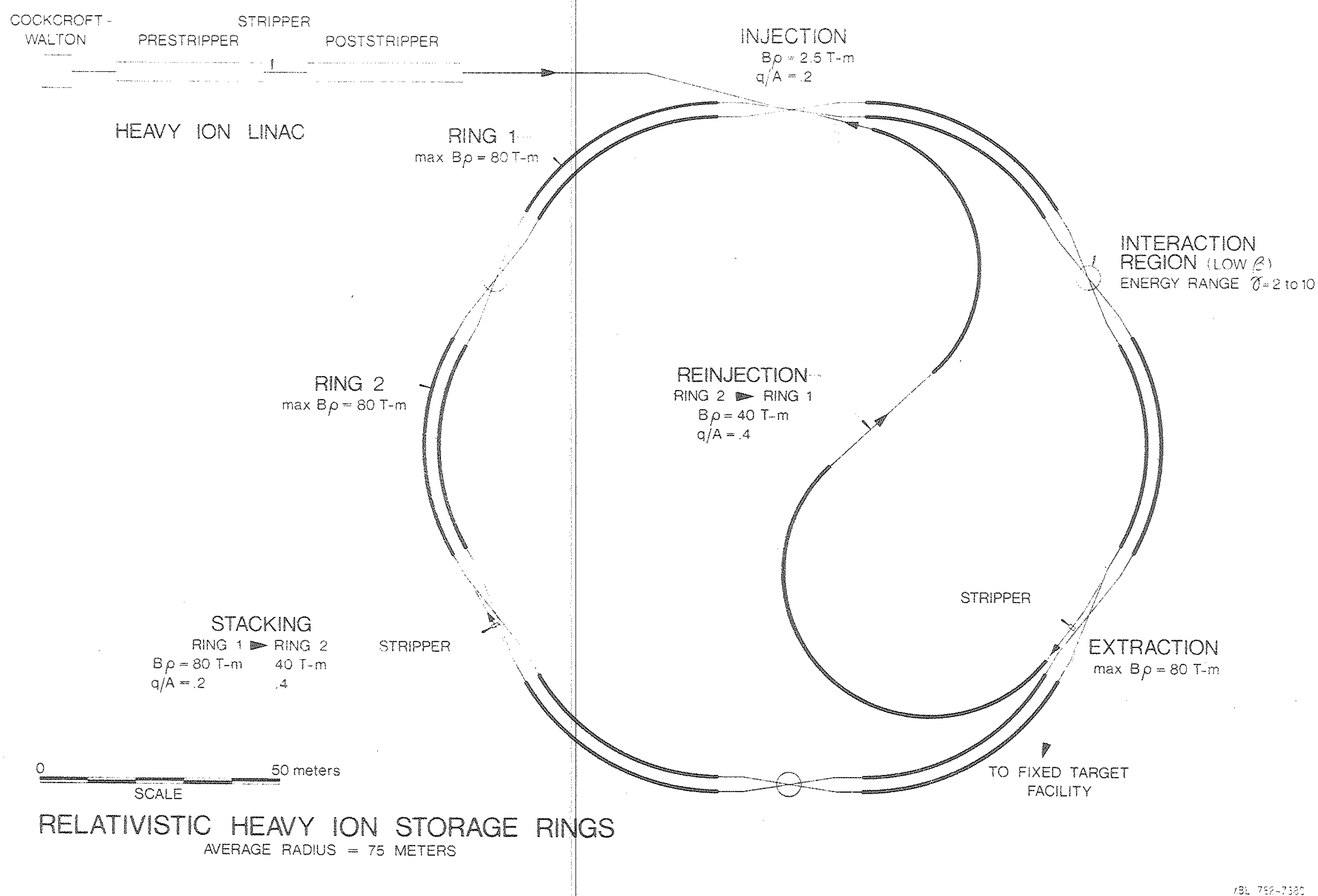
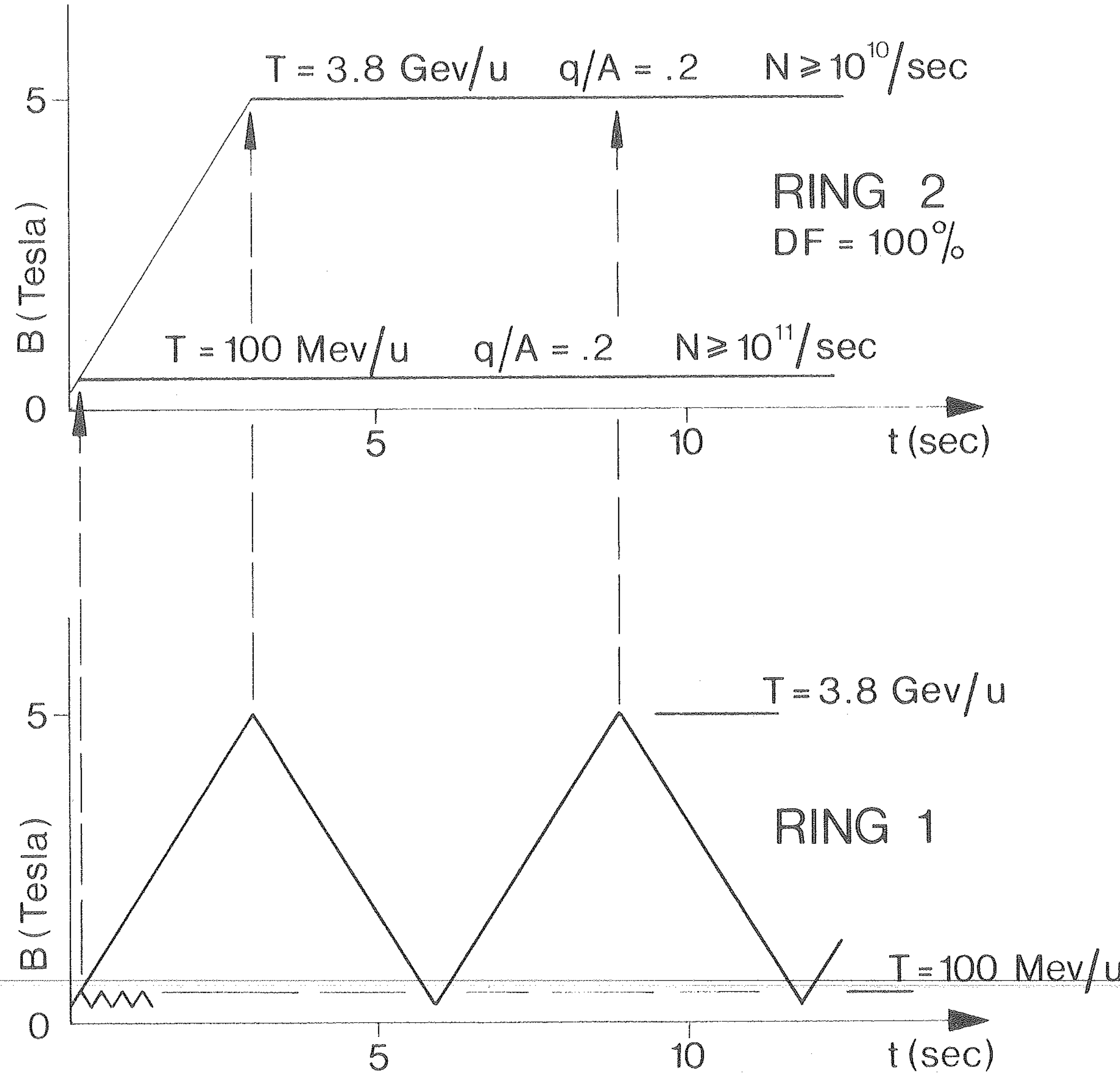

COCKCROFT - WALTON
PRESTRIPPER
STRIPPER
POSTSTRIPPER
HEAVY ION LINAC
INJECTION
Bρ = 2.5 T-m
q/A = .2
RING 1
max Bρ = 80 T-m
INTERACTION REGION (LOW β)
ENERGY RANGE γ = 2 to 10
RING 2
max Bρ = 80 T-m
REINJECTION
RING 2 ► RING 1
Bρ = 40 T-m
q/A = .4
STRIPPER
STACKING
RING 1 ► RING 2
Bρ = 80 T-m 40 T-m
q/A = .2 .4
STRIPPER
EXTRACTION
max Bρ = 80 T-m
TO FIXED TARGET FACILITY
0
50 meters
SCALE
RELATIVISTIC HEAVY ION STORAGE RINGS
AVERAGE RADIUS = 75 METERS
XBL 752-7380

FIG. 1



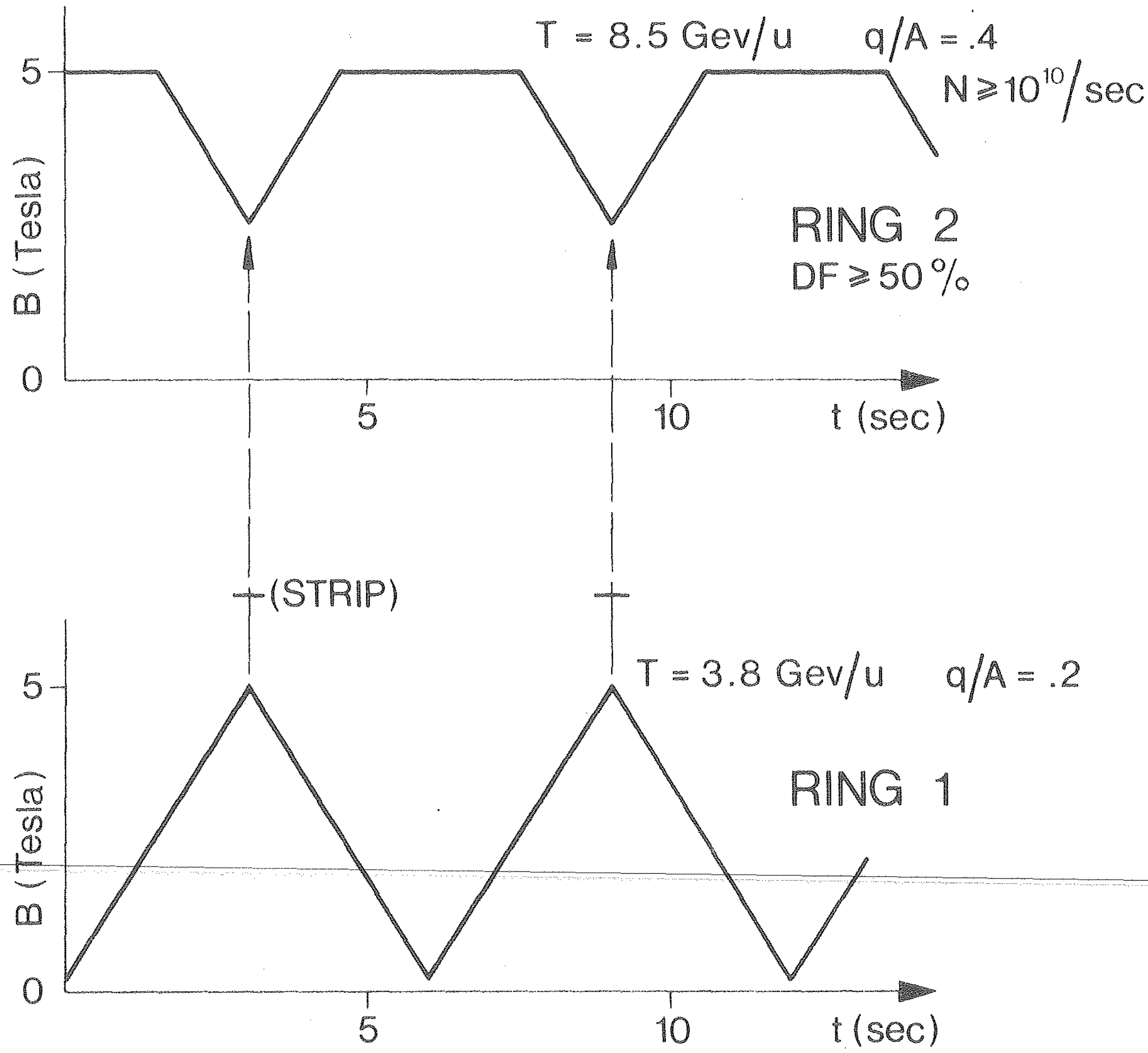
FIXED TARGET ACCELERATOR OPERATION

ENERGY 0.1* to 3.8 Gev/u

* Operation at reduced intensity to .03 Gev/u

XBL 783-7480

FIG. 2



FIXED TARGET ACCELERATOR OPERATION

ENERGY 3.8 to 8.5 Gev/u

XBL 783-7479

FIG. 3

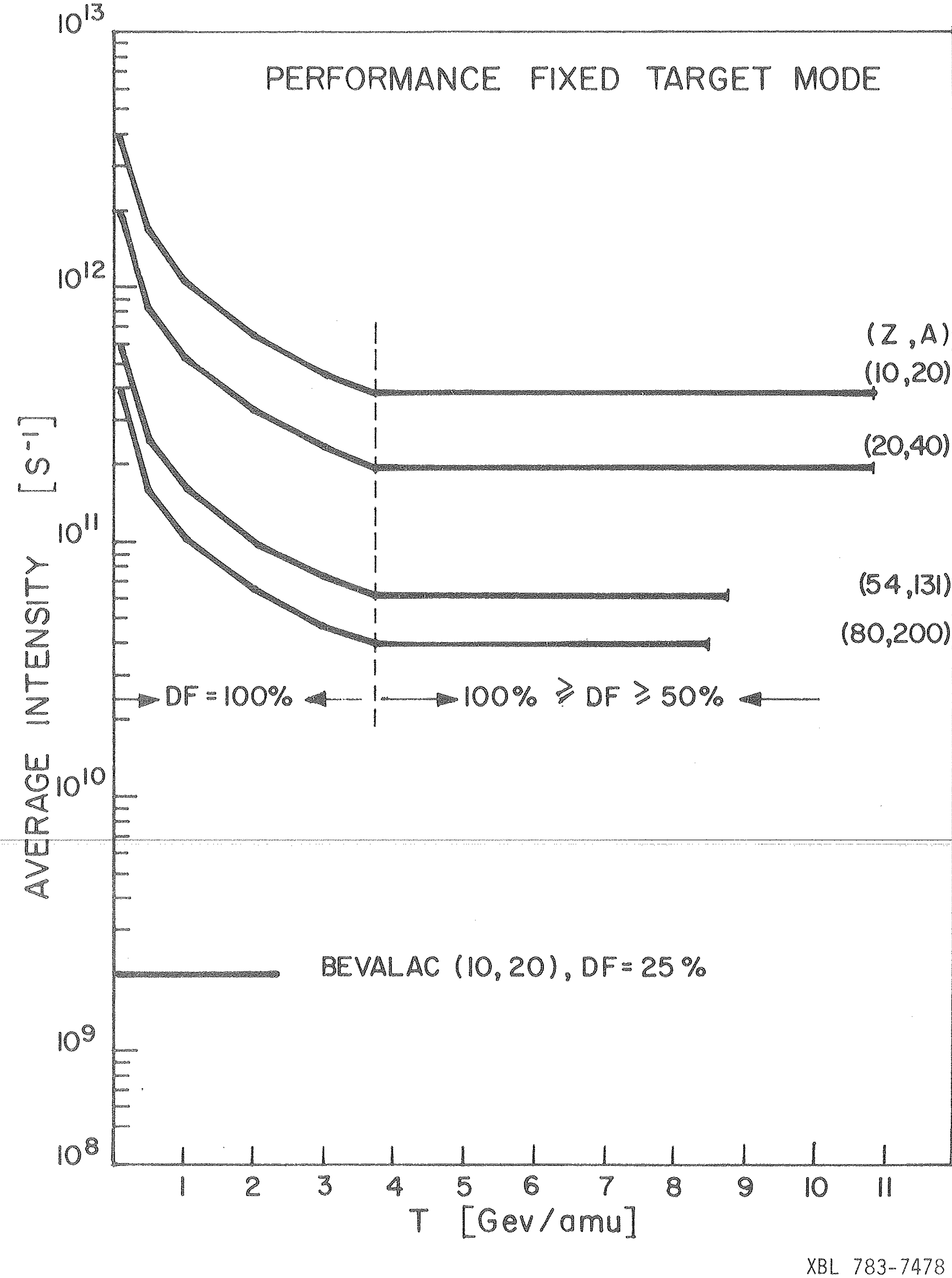
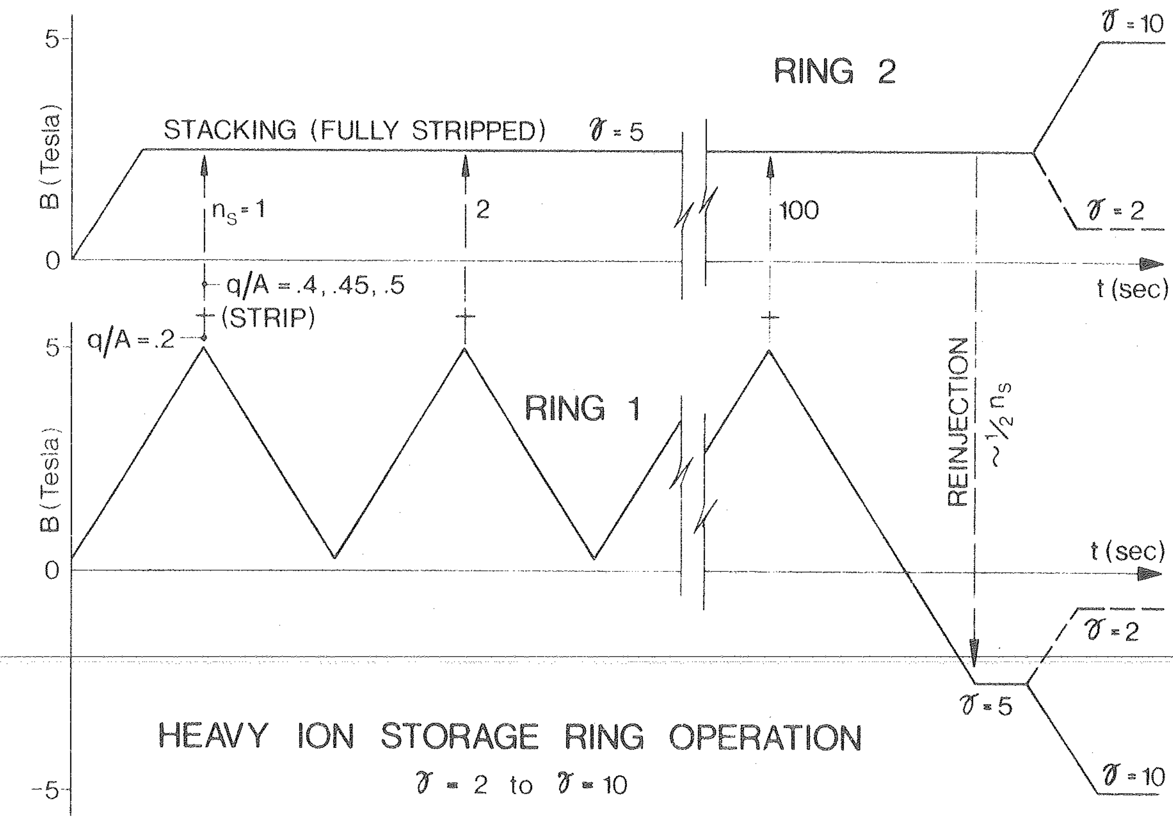
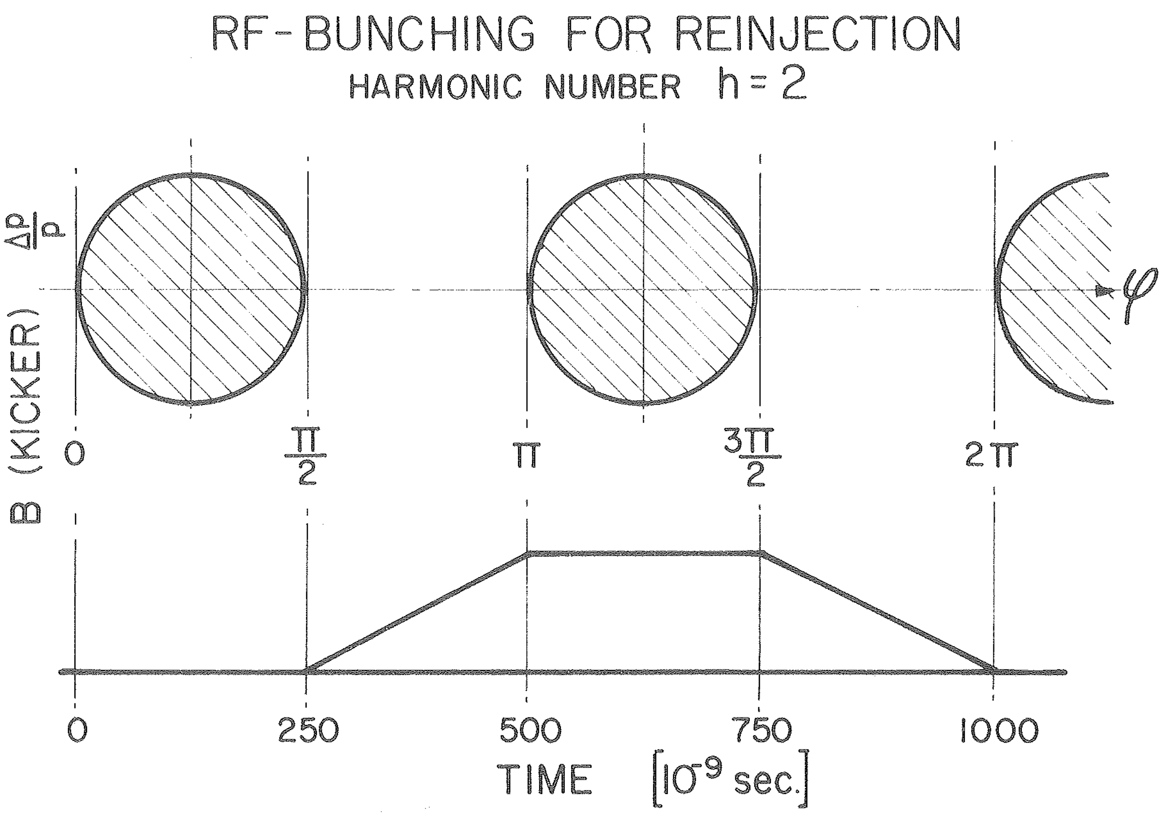

PERFORMANCE FIXED TARGET MODE
AVERAGE INTENSITY [S-1]
(Z ,A)
(10,20)
(20,40)
(54,131)
(80,200)
DF = 100%
100% ≥ DF ≥ 50%
BEVALAC (10, 20), DF = 25 %
T [Gev/amu]
XBL 783-7478

FIG. 4



XBL 783-7475

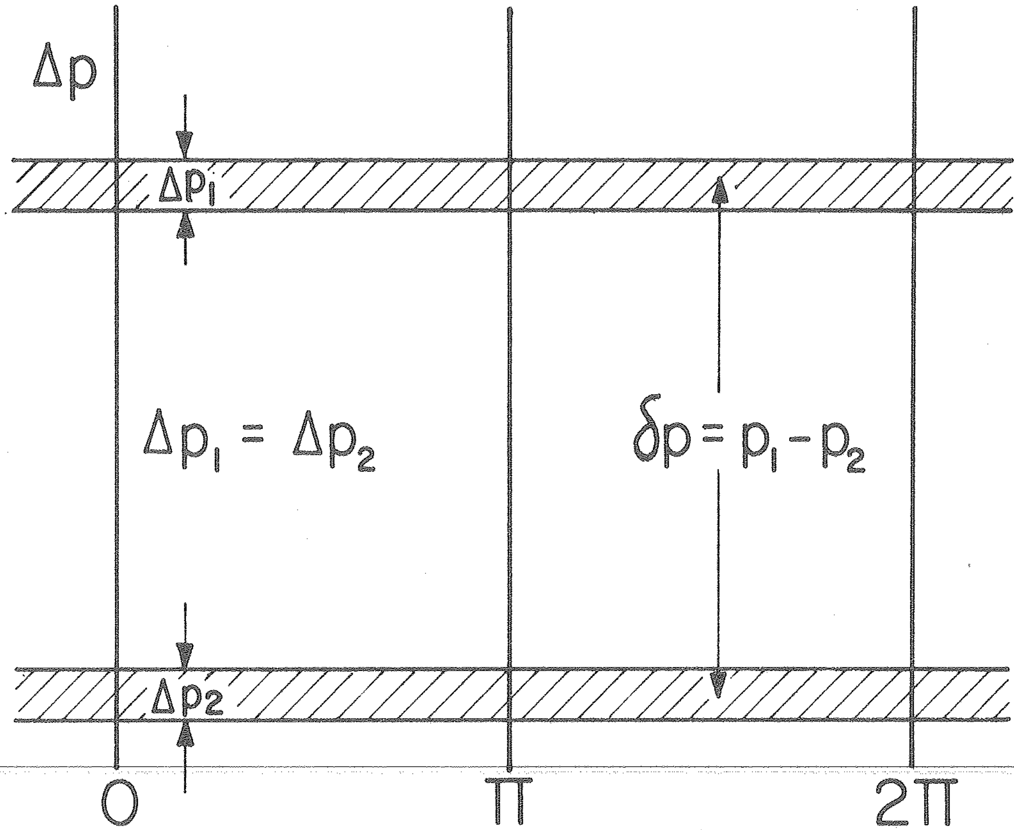
FIG. 5



XBL 783-7471

FIG. 6

STACKING OF PARTICLES WITH DIFFERENT (Z/A)



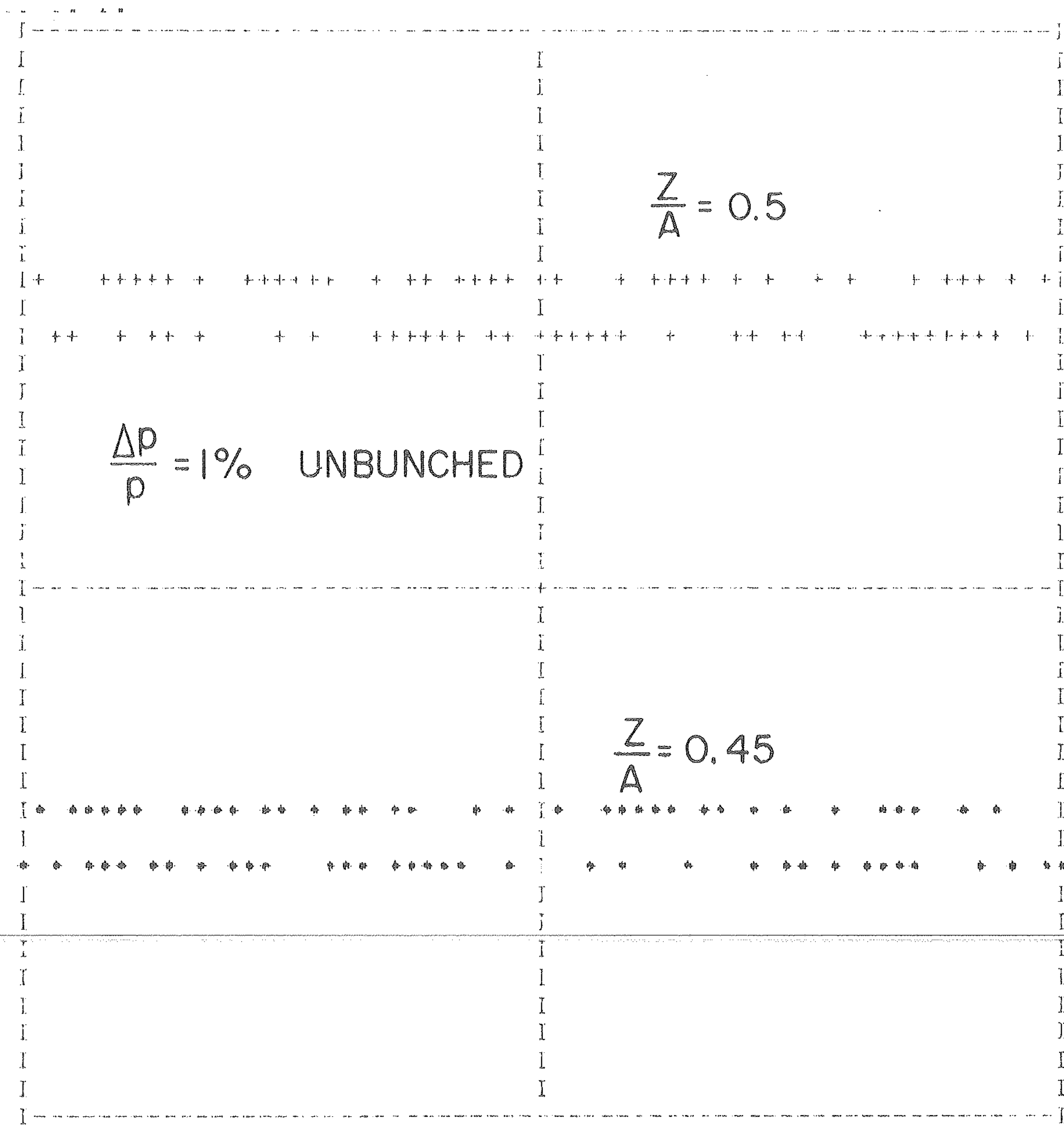
$$BR\big|_1 \equiv BR\big|_2$$

$$p_1 = \left[\frac{Z_1}{A_1}\frac{A_2}{Z_2}\right] p_2$$

FOR PRACTICAL PURPOSES $\frac{p_1}{p_2} - 1 \geq \pm .1$

XBL 783-7470

FIG. 7



XBL 783-7468

FIG. 8

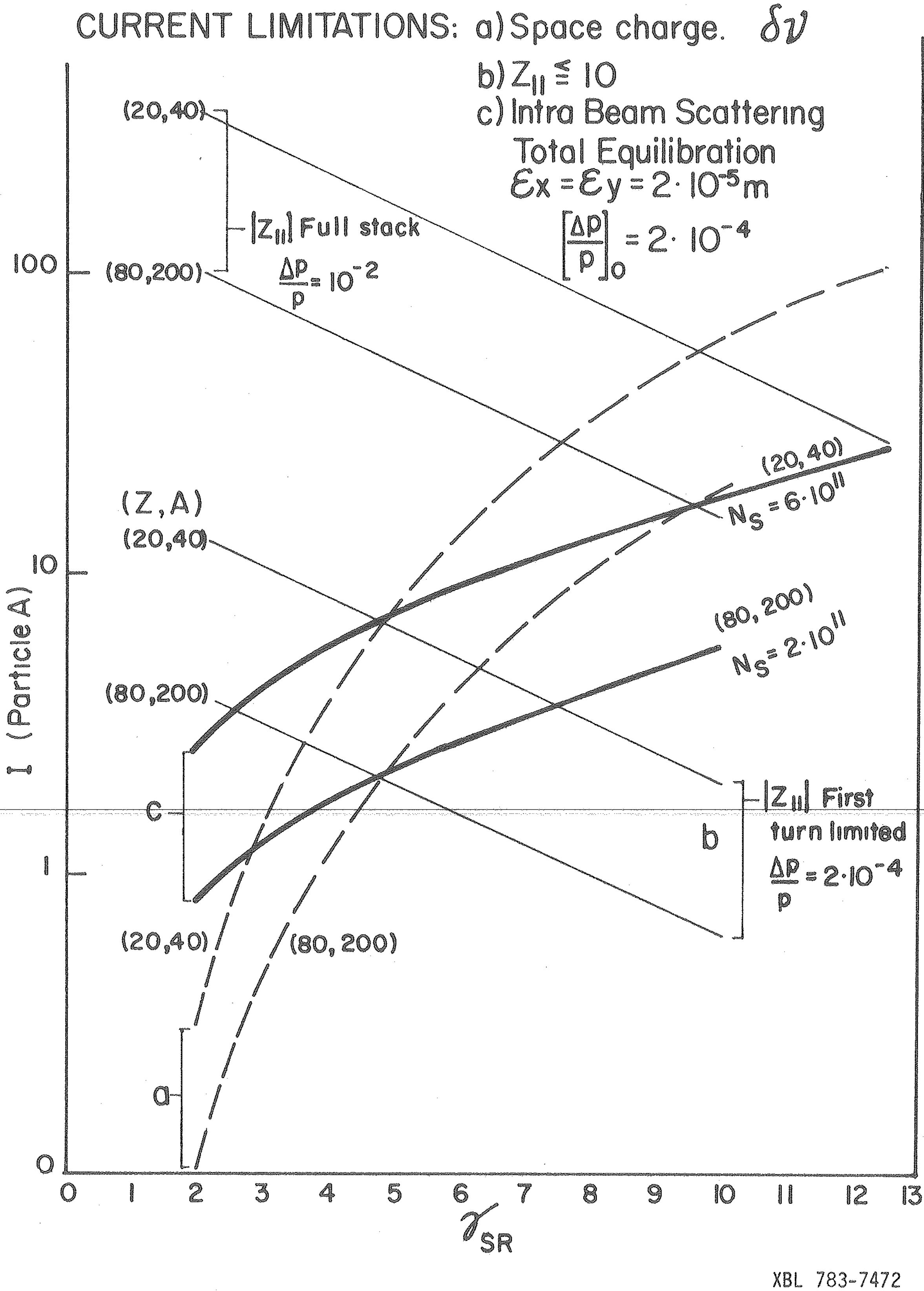

CURRENT LIMITATIONS: a) Space charge. δν
b) Z∥ ≦ 10
c) Intra Beam Scattering
Total Equilibration
Ɛx = Ɛy = 2·10⁻⁵m
[Δp/p]₀ = 2·10⁻⁴
(20,40)
|Z∥| Full stack
Δp/p = 10⁻²
(80,200)
(20,40)
Ns = 6·10¹¹
(Z, A)
(20,40)
(80,200)
Ns = 2·10¹¹
(80,200)
|Z∥| First turn limited
Δp/p = 2·10⁻⁴
c
b
a
(20,40)
(80,200)
I (Particle A)
100
10
1
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13
γSR
XBL 783-7472

FIG. 13

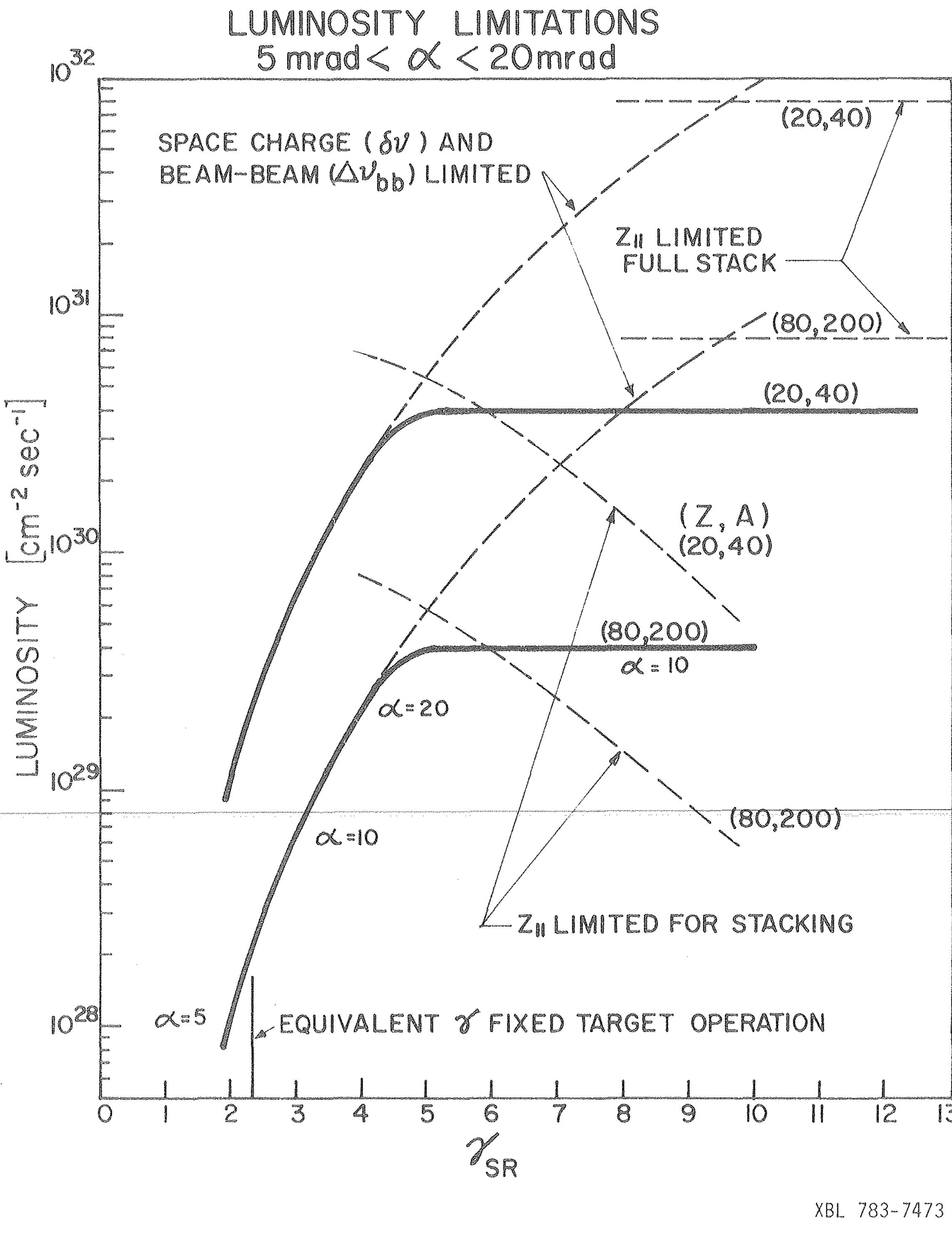

LUMINOSITY LIMITATIONS
5 mrad< α < 20mrad
SPACE CHARGE (δν) AND
BEAM-BEAM (Δν_bb) LIMITED
Z‖ LIMITED
FULL STACK
(20,40)
(80,200)
(20,40)
(Z, A)
(20,40)
(80,200)
α = 10
α=20
α=10
α=5
(80,200)
Z‖ LIMITED FOR STACKING
EQUIVALENT γ FIXED TARGET OPERATION
LUMINOSITY [cm⁻² sec⁻¹]
γ_SR
XBL 783-7473

FIG. 14

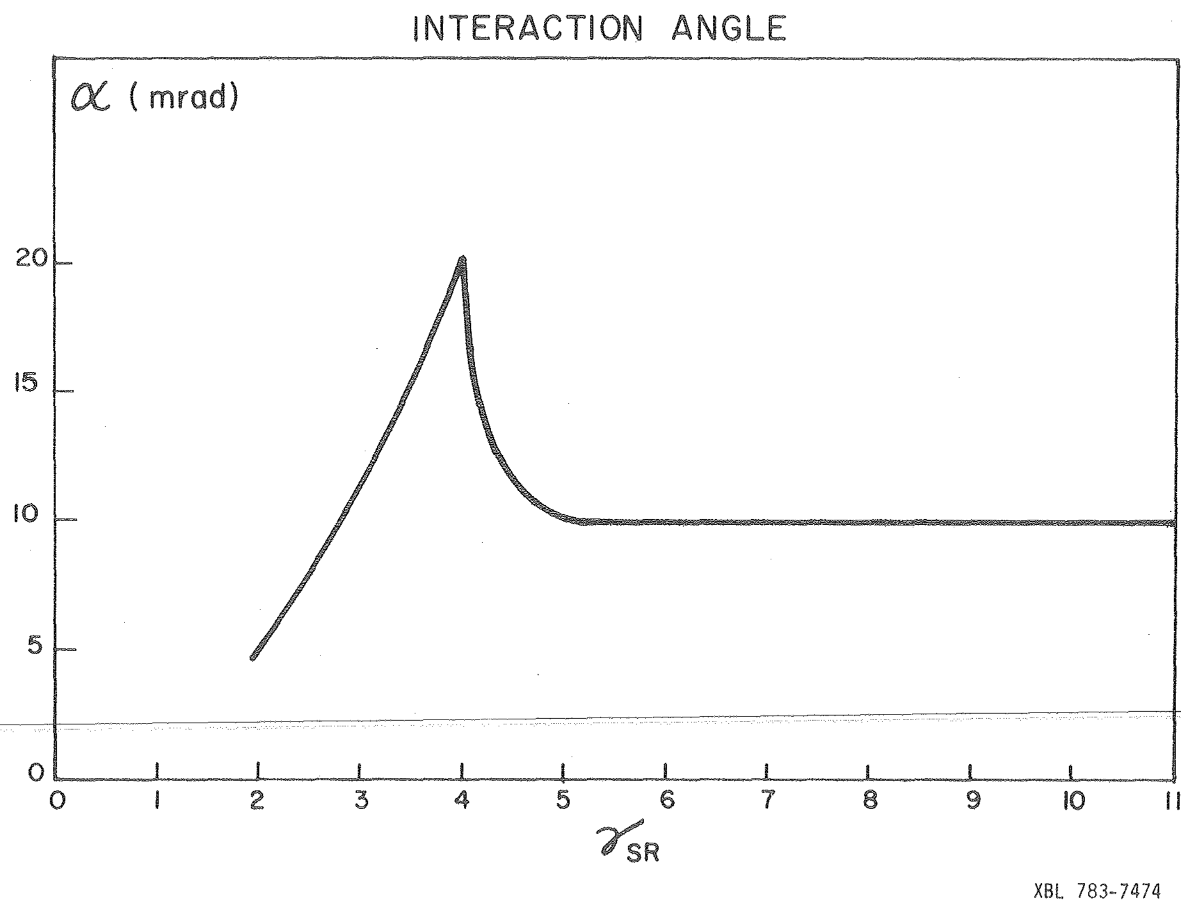

INTERACTION ANGLE
α (mrad)
20
15
10
5
0
0
1
2
3
4
5
6
7
8
9
10
11
γSR
XBL 783-7474

FIG. 15

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
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