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PROPECTS FOR HIGH ENERGY HEAVY ION ACCELERATORS*

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Introduction

The acceleration of heavy ions to relativistic energies ($T \geq 1$ GeV/amu) at the beam intensities required for fundamental research falls clearly in the domain of synchrotons. Up to date, such beams have been obtained from machines originally designed as proton accelerators by means of modified RF-programs, improved vacuum and, most importantly, altered or entirely new injector systems. Similarly, for the future, we do not foresee substantial changes in synchrotron design itself, but rather the judicious application and development of presently known principles and technologies and a choice of parameters optimized with respect to the peculiarities of heavy ions.

The low charge to mass ratio, q/A, of very heavy ions demands that superconducting magnets be considered in the interest of the highest energies for a given machine size. Injector brightness will continue to be of highest importance, and although space charge effects such as tune shifts will be increased by a factor q^2/A compared with protons, advances in linac current and brightness, rather than substantially higher energies are required to best utilize intensity wise a given synchrotron acceptance. However, high yields of fully stripped, very heavy ions demand energies of a few hundred MeV/amu, thus indicating the need for a booster synchrotron, although for entirely different reasons than in proton facilities. Finally, should we consider colliding beams, the high charge of heavy ions will impose severe current limitations and put high demands on system design with regard to such quantities as e.g., wall impedances or the ion induced gas desorption rate, and advanced concepts such as low β insertions with suppressed dispersion and very small crossing angles will be essential to the achievement of useful luminosities.

Present Status

Fig. 1 summarizes beam performance obtained or projected for the near future at presently operating facilities of which all except the CERN PS are or will be supporting a research program devoted predominantly or to a substantial degree to heavy ion research. Deuterons and α-particles of ~ 15 GeV/amu were obtained at the CPS, utilizing the 2 $\beta\lambda$-mode in the injector linac and a harmonic jump with intermediate flattop and adiabatic de/rebunching in the synchrotron[1]. Deuterons were stacked in the ISR to a luminosity in excess of 10^{30} cm^{-2}s^{-1}. Fully stripped ions from an EBIS-source and acceleration in the 2 $\beta\lambda$-mode characterize the injector systems at both the synchrophasotron and Saturne II[2]. Light ion beam intensities comparable to those of Saturne are obtained at the Bevalac by accelerating partially stripped ions (e.g. C^{+4}) from a PIG-source in the old 20 MeV proton linac, while for higher intensities and masses the Superhilac[3] serves as injector. These systems are limited by injector performance and synchrotron vacuum. The sharp drop, e.g. in intensity between A = 40 and A = 56 observed at the Bevalac is predominantly due to the present vacuum of $2 \cdot 10^{-7}$ Torr. The presently ongoing Bevalac improvement program therefore includes first a new injector for the Superhilac, a Wideröe accepting a minimum q/A of 0.02 to provide intense high mass beams[4] and second, an improvement in synchrotron vacuum to 10^{-10} Torr[5] to assure survival of these beams in the Bevatron.

Future Facilities

Beam Requirements - Ideally we would base the design of new facilities on relatively firm specifications of basic parameters such as ion masses, beam intensity and energy, derived from experimental needs. The study of relativistic heavy ion collisions, although becoming respectable and recognized as a frontier in physics, is still a very young branch of science and although symposia and workshops (GSI, 1978, LBL 1979) will undoubtedly help to clarify design goals, it is unavoidable that at present our design efforts are based to a somewhat larger extent on speculative ideas than is the case e.g., for present major proton projects where a few big, simple issues can be pinpointed.

The trends are clear however, intense beams of the heaviest ions are required and smooth energy variability from ~ 100 MeV/amu up in the 10 to 20 GeV/amu range are desired. The need for ultra high energies is more speculative but the study of the implications of colliding beams seems indicated, if only in the interest of the longest useful life time of a major new facility.

Concepts for New Facilities

Approximate performance expectations of concepts developed in Japan, the USSR, Germany and the U.S. are summarized in Fig. 2. None of them represents a completely funded construction project but test facilities for the Numatron have been built, the Soviet proposals are expected to become reality within the next 5 years and funding for the GSI machine seems virtually assured. A formal proposal for the latter is just being worked out at present but the project has the advantage of an existing powerful heavy ion linac, and a substantial amount of R&D in the area of magnets, RF and vacuum systems conducted in the context of an earlier more modest proposal known as SIS[6]. At LBL, where the Bevalac improvement program represents the present main commitment in the heavy ion field, preliminary studies have been conducted at a modest effort level exploring the feasibility and implications of a combined accelerator/storage ring facility[7,8]. Specialized heavy ion linacs are proposed throughout, linacs with low β front ends suitable for weakly charged ions, an interdigital H-mode structure in the Russian concepts, Wideröes in all others. At LBL and to some extend at GSI the linac itself is viewed as one of the main target areas for intensity improvement but other concepts are found. The Numatron[9] proposes an accummulator ring combining multiturn injection in betatron phase space with stacking in momentum space while stripping injection is an integral part of the Soviet concept and has, in modified form, been

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considered at GSI as well[10]. The Numatron approach will increase intensity from the synchrotron, although at the expense of increased longitudinal emittance, requiring substantial RF-voltage and precluding later stacking such as would be required in a colliding beam facility. Stripping injection at low energies (~10 MeV/amu) promises true brightness increase, somewhat analogous to stripping H^--injection known from proton synchrotrons [11], but only if all charge states occurring with significant probability after passage of the beam through a stripper are accepted. This requires a lattice with large momentum acceptance, strong sextupole correction to deal with chromaticity and zero dispersion at the stripper location to avoid the excitation of large betatron oscillations. Furthermore problems associated with energy loss and multiple scattering have to be overcome but the Soviet originators of the concept are confident that beam cannot only be accumulated in this fashion but actually accelerated, stripping to increasingly higher mean charge states until at energies between 200 and 300 MeV/amu transfer to the synchrophasotron, or in a more distant future, the Nuklotron would occur[12].

None of these concepts proposes a rapid cycling main ring, conventional magnets will be used in the Numatron and the GSI machine, while superconducing magnets are foreseen for the Nuklotron and were assumed in our studies at LBL.

The LBL-Study as a Design Example

The LBL - study results will be used in the following to convey an idea of the looks of a potential major heavy ion facility and to illustrate some elementary design considerations.

Facility Layout and Operational Modes - Fig. 3 shows two rings with superconducting magnets injected by a heavy ion linac. Indicated is a $B\rho$ of 80 Tm but presently we foresee 175 Tm, 5 T peak field and 1 T average field. Injection will occur without stripping at the linac exit in ring 1 while extraction is accomplished from ring 2. A number of transfer points between the two rings are indicated. With this arrangement 3 distinct modes of operation become immediately evident.

For energies not exceeding those achievable with partially stripped ions (9.6 GeV/amu for q/A = 0.2, $B\rho$ = 175 Tm) ring 2 is not required for acceleration. The field in ring 1 can follow a simple triangular pulse shape with single turn ejection-injection transfer to ring 2 which serves then as stretcher ring. Slow resonant extraction from ring 2 will then provide 100% duty cycle beam on target.

For higher energies stripping is required. Beam is accelerated in ring 1 to an energy sufficiently high to allow essentially lossless stripping in the fully ionized state. At this energy ejection, stripping and injection in ring 2 will occur where acceleration to the desired final energy, followed by slow extraction completes the cycle. Average flux on target may be increased by accommodating several pulses in ring 2, either stacking in longitudinal phase space or, if the required stripper thickness allows, by stripping injection.

Finally a colliding beam mode can be envisaged. To this end partially stripped ions are again accelerated in ring 1 (to full field), ejected, stripped and stacked in ring 2. Upon completion of the stacking operation the field in ring 1 is reversed, the beam in ring 2 is bunched on a low, even harmonic and half the bunches are transferred to ring 1 by means of the S-shaped reinjection loop. Acceleration or deceleration to the desired operating energy followed by debunching then produces the desired final configuration: counter-rotating coasting colliding beams.

Rationale For This Approach

The basic consideration underlying this solution are outlined in the following and this concept will be seen to follow naturally from simple considerations even if at the outset we concentrate only on optimizing fixed target performance.

Superconducting Magnets - High field magnets are essential with the low value of Z/A of very heavy ions, especially if compounded by the inherently low packing factor of a colliding beam facility. They seem desirable however for an exclusive fixed target synchrotron as well. Undoubtedly R&D will be required but it is encouraging to note that recently at LBL[13] an ESCAR type magnet with improved coil compression and helium circulation reached 4 T in continuously pulsed operation at 1 Ts^{-1} and 3.77 T at 1.9 Ts^{-1}. The total power loss was 20 W for the 1 m long magnet at 1 Ts^{-1} and improvements to reach 10 W only seem relatively straightforward. This translates into just over 1 MW input power to the cryogenic plant for one of our 175 Tm rings, quite favorable compared with ~ 20 MW power dissipation for conventional magnets assuming a gap of 70 mm and a current density of 1000A/cm^2. Net savings will be less than the factor of 20 implied but the potential for substantial economies cannot be denied.

Injector Considerations - Optimum utilization of synchrotron acceptance is achieved when we reach the space charge limit at injection, as given by the Laslett tune shift equation. From this, assuming a certain dilution $D_\perp = D_x \cdot D_z$ of transverse phase space density, a minimum linac brightness is calculated. In practice we want also to impose a limit on the number of injected turns which implies a condition on linac current. Fig. 4 summarizes for an ion with A = 200, q/A = .2, .3,.4 the required values, $B_L R$ and $I_L B_L R^2$, where B_L, I_L are linac brightness and current, R the synchrotron radius. Clearly higher energies are required to reach the same space charge limited synchrotron current for higher values of q/A (provided they were available at all). More importantly we see that with the assumed values ($\varepsilon_{z,s} = \varepsilon_{x,s} = 2\cdot10^{-4}$m, R = 175m $D_\perp$ = 10) present linac performance indicates a severe brightness rather than space charge limitation and that even with values of 50 particle μA in $\pi\cdot10^{-5}$ m, an ambitious but realistic long term goal for injector linacs, injection energies not much higher than ~ 10 MeV/amu are adequate.

It seems likely that q/A = 0.2 is the maximum we might expect from a bright, high current linac for very heavy ions without resorting to stripping at the linac exit. Consequently, the maximum energy obtainable with a given $B\rho$ is substantially reduced compared to that for fully stripped ions. This is indicated in Fig. 5, where we however see that stripping at the linac exit with 10 MeV/amu $\leq$ T $\leq$ 20 MeV/amu will allow energies of between 80% to 90% of the maximum possible value. This is of course associated with a loss in intensity of about one order of magnitude. Experimental data on stripping of very heavy ions at energies of hundreds of MeV/amu are not available, or possible to obtain, today and we have to rely on semi-quantitative theoretical considerations[14], which indicate that 10% to 20% yields of fully stripped very heavy ions should be expected for 200 MeV/amu $\leq T \leq$ 300 MeV/amu. A cautious guess is that ~1 GeV/amu is required to achieve essentially lossless stripping of very heavy ions in the completely ionized state. This requires a substantial booster. Only for main ring rigidities of 1500 Tm, i.e. approaching the size of the FNAL main ring is it possible to achieve a value of $B\rho_{booster}/B\rho_{main\ ring}$ comparable to that for typical proton facilities. In the presently more relevant range, 100 Tm $\leq B\rho_{MR} \lesssim$ 200 Tm, the booster will have a rigidity of $0.16\ B\rho_{MR} \lesssim B\rho_B \lesssim 0.35\ B\rho_{BR}$.

We see that the combination of an intense linac, 10 MeV/amu $\leq T \leq$ 20 MeV/amu with a single, large ring will provide a quite powerful combination and a satisfactory first step towards a high performance fixed target facility. The ultimate in performance requires a booster of substantial size however, and from here it is only a small logical step to drop entirely the distinction between booster and main ring and think in terms of two identical rings. This in turn challenges us to explore the feasibility of colliding heavy ion beams.

Colliding Beam Performance

The design of a storage ring will be substantially more demanding than that of a straight forward synchrotron. Low β-insertions, possibly tuneable "in-flight" to avoid excessive quadrupole apertures at low energies, will be required and γ_t will either have to be changeable by $\sim \pm 1$ or moved above the operating range. Experimental insertions will require zero dispersion while others (for stacking) need non-zero dispersion. This should indicate a few complications just with regard to lattice design. It is mandatory that we explore carefully expected performance for the colliding beam mode. First, tolerable current levels will be established, then from this the corresponding luminosity.

Incoherent Tune Shifts - For a nearly round, nearly centered beam in a circular enclosure of diameter much larger than the beam the incoherent tune shift is dominated by the direct terms even at energies of 10 to 20 GeV/amu, and the limiting current (in particle amp) is given by the usual expression:

$$I = \frac{ec}{R} \cdot \frac{A}{q^2} \cdot \frac{\Delta\nu}{r_p} \cdot B_f \cdot \beta^2 \left(\frac{1}{\gamma^2} - n_e\right)^{-1} \cdot \varepsilon_N \qquad (1)$$

For coasting beams (B_f = 1), $\Delta\nu$ = 0.05, A = 200, q = 80 and a normalized emittance $\varepsilon_N = 3 \cdot 10^{-5}$ m, I > 0.5 particle A results for $\gamma \geq 7$ (Fig. 6). The neutralization will be kept low by clearing electrodes, a maximum value from considerations of the ion-electron instability has not yet been determined.

Longitudinal Stability

From the well known stability criterion[15)]

$$\frac{|Z_{||}|}{n} \leq F \cdot \frac{A}{q^2} \cdot \frac{\beta^2 \gamma E_0}{e} \cdot \frac{|\eta|}{I} \cdot \left(\frac{\Delta p}{p}\right)^2 \qquad (2)$$

the most stringent limitation is obtained if it is applied to a single, debunched pulse from the synchrotron. Assuming $2 \cdot 10^{11}$ particles (q/A = 80/200) a minimum tolerable $\frac{\Delta p}{p}$ is computed from which in turn, for a given stack momentum width a maximum number of stacked pulses and therefore a limit on obtainable circulating current is obtained. (Fig. 7).

Intra-Beam Scattering - This was explored using lattice functions from preliminary designs and the theory developed by A. Piwinsky[16,17)]. Growth and decay times of emittances are given by:

$$\tau_z^{-1} = A\ f(a,b,c)$$

$$\tau_x^{-1} = A\ \ f(a/b,\ 1/b,\ c/b) + (1-T) f(b/a, 1/a, c/a) \qquad (3)$$

$$\tau_p^{-1} = 2A\ T\ f\ (b/a,\ 1/a,\ c/a)$$

We refer to the literature [17)] for the meaning of these quantities, suffice if to say that f(1,1,c) = 0, from which for $\bar{\beta}_x = \bar{\beta}_z$ an equilibrium condition with:

$$\varepsilon_{z,N} = \varepsilon_{x,N} = \varepsilon_N\ ; \delta_T^2 = \frac{\pi\varepsilon_N}{\bar{\beta}_x} \cdot \frac{1}{\gamma} \cdot \frac{1}{\eta} \qquad (4)$$

is predicted, realizable obviously only below transition (η > o). From δ_T, the total stack momentum width from (4), again a maximum number of stacked pulses and a current limitation is obtained which, below transition, for our parameters is very close to the limits imposed by the $\Delta\nu$ = 0.05 requirement (Fig. 8). Above transition no such equilibrium exists, for $\varepsilon_N = 3 \cdot 10^{-5}$m, $\delta_T = 2 \cdot 10^{-2}$, time constants $-\tau_z \sim \tau_x \sim \tau_p \sim 10^5$s follow for 0.2 particle A circulating current. These values might be just slow enough for colliding beam operation. Furthermore a low noise (certainly possible with q = 80, N ~ $5 \cdot 10^{12}$) stochastic cooling system with a bandwith of 2-3 GHz should be able to provide cooling times of a few 10^4s, capable of counteracting beam blow-up by intra-beam scattering.

Pressure Bump - Wall surfaces have been prepared to show a negative net ion induced desorption coefficient η [18)] in which case beam pumping rather than a beam induced pressure rise occurs and no limiting current exists. Assuming $\eta \sim 3$, closely spaced pumps, compatible with the short magnets envisaged for this lattice, $\sigma_{80,200}(CO) = 80^2\, \sigma_{1,1}(CO)$ a limiting current of 0.34 pA is obtained with a bore radius of 8 cm. Clearly the possibility of using a cold bore must also be explored and for purposes of estimating luminosity we assume I = 0.2 particle A for A = 200. A summary of these current limitations is given in Fig. 9.

Luminosity Estimates

Luminosity was estimated on the basis of 0.2 pA coasting beams for the heaviest ions. For head-on collisions (ψ = 0) the luminosity is:

$$L \approx \frac{2\ I^2}{e^2 c \pi} \cdot \frac{d}{\varepsilon \beta_I} \qquad (5)$$

valid for $\beta_{x,I} = \beta_{z,I} = \beta_I$ and d $\leq 2\ \beta_I$. For a given current and emittance then the only free parameter is β_I because d is constrained by the requirement that the beam-beam tune shift must not exceed a certain limit. From:

$$\Delta\nu^{bb} \simeq 8k^{bb} \cdot \frac{q^2}{A} \cdot \frac{I\,d}{p\,\varepsilon}\,;\; k^{bb} \simeq 2.386 \cdot 10^{-9}\left[A^{-1}\cdot \mathrm{GeV/c/amu}\right] \quad (6)$$

we obtain $d \simeq 1.25$m independent of momentum p for $\varepsilon_N = \varepsilon\beta\gamma = 3\cdot 10^{-5}$ m and $\Delta_\nu^{bb} = 0.005$. With β_I as low as 0.5 m both luminosity and tune shift equations as given are still quite accurate and for $\beta_I = 1$m, $L > 10^{29}$ cm^{-2}s^{-1} seems achievable for the heaviest ion beams.

Such a short interaction length requires a bending magnet arrangement somewhat restricting free space immediately around the interaction point and $\psi \neq 0$ might be more desirable[8)].

We have in this case:

$$L \simeq \frac{2\, I^2}{e^2 c \sqrt{\pi}\, \varepsilon^{1/2} \beta_{z,I}^{1/2}} \cdot \frac{1}{\psi} \quad (7)$$

$$\Delta\nu^{bb} \simeq 8\sqrt{2\pi}\; k^{bb} \cdot \frac{q^2}{A} \cdot \frac{1}{p} \cdot \frac{I\, \beta_{z,I}^{1/2}}{\psi\, \varepsilon^{1/2}}$$

For given I and ε, ψ and $\beta_{z,I}$ must now be adjusted to maximize L subject to $\Delta_\nu \leq 0.005$. Again the validity of the simple tuneshift expression is restricted, breaking down for extremely small β_I and ψ[19,20)]. At $\beta_{z,I} = 1$m and the values of ψ resulting from $\Delta_\nu^{bb} = 0.005$, 2.5 mrad (at 20 GeV/amu) $\leq \psi \leq$ 6mrad (at 4 GeV/amu) it is however still quite accurate. The resulting luminosity is shown in Fig.10.

Conclusion

The first major new relativistic heavy ion facility may not look like what is described here but may well be a straightforward synchrotron with conventional magnets, approximately of the size of the CPS or AGS. We believe however to have demonstrated, at least in principle, the feasibility of a far advanced approach, posing many challenging design problems which should however not deter us if this should be the research tool needed for the exploration of relativistic heavy ion collision in the future.

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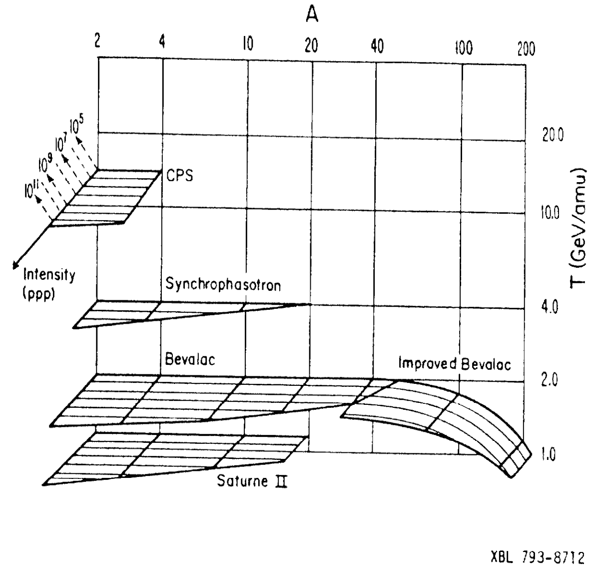

Fig. 1 Present Facilities, Beam Performance as obtained or predicted for near future

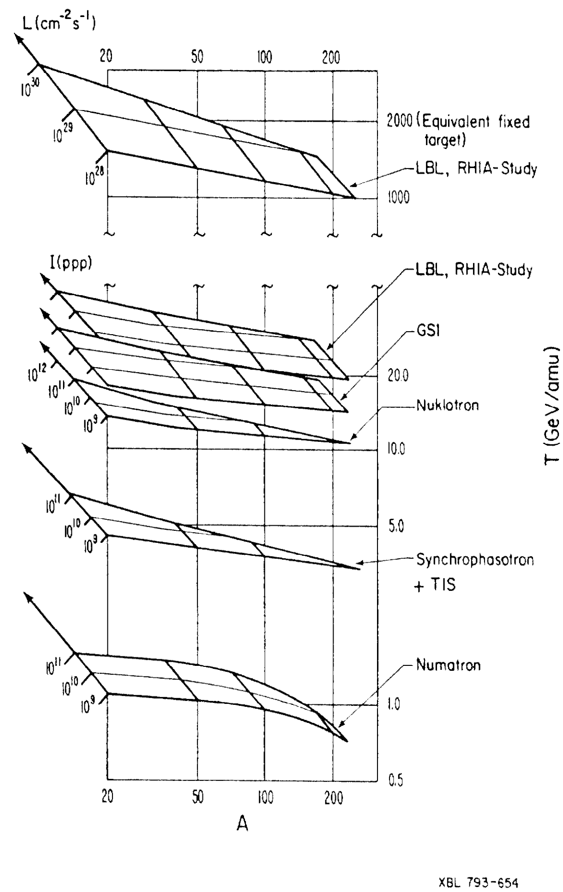

Fig. 2 Approximate performance goals of presently investigated concepts of new facilities

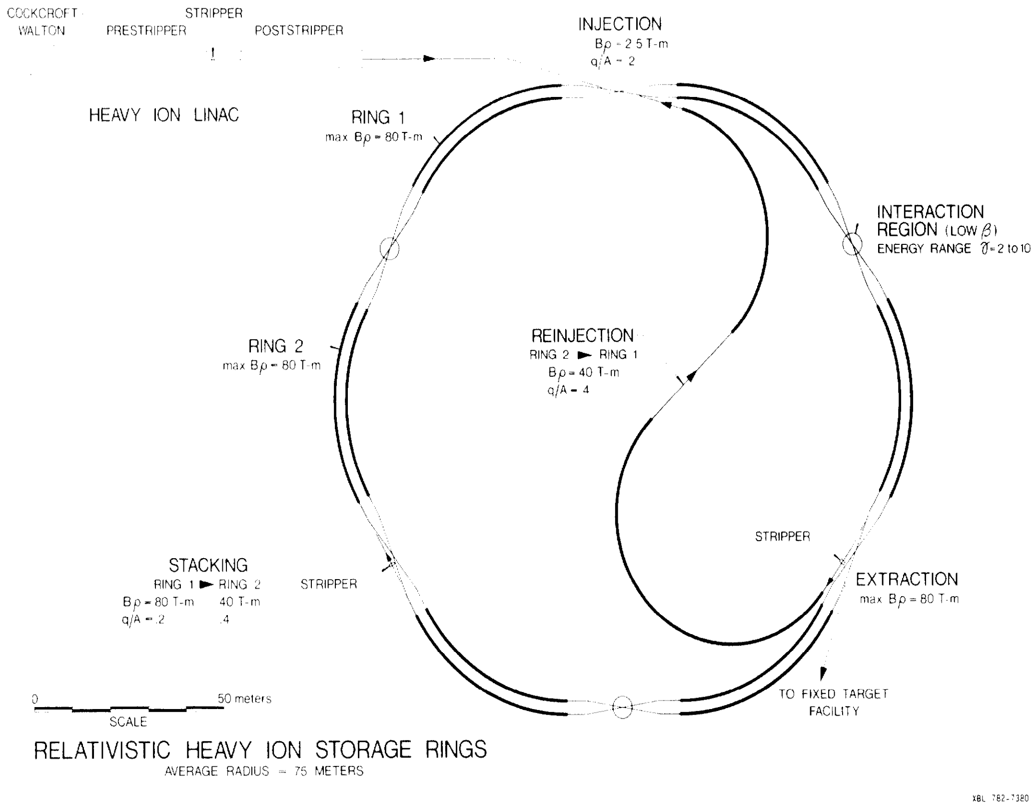

Fig. 3 Accelerator/Storage ring concept from preliminary LBL-studies. Bρ assumed in this paper is 175 Tm, B_{max} = 5T, $\bar{B}$ = 1T

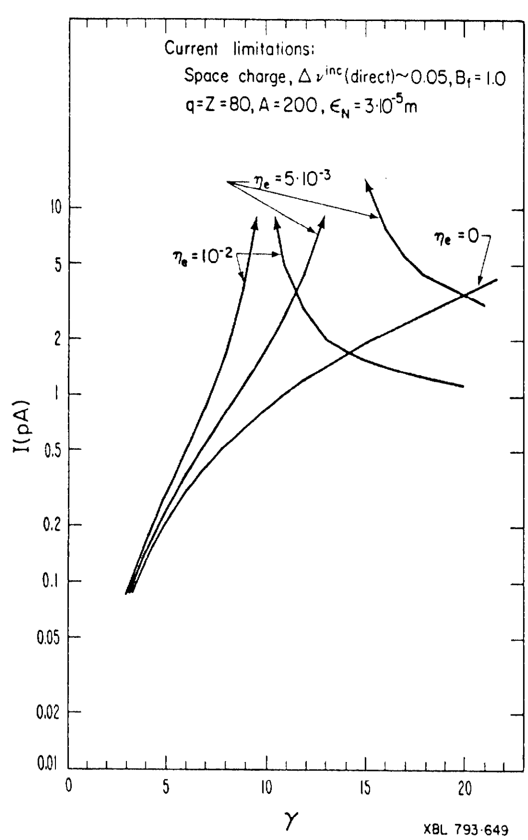

Fig. 6 Space charge limited currents for parameters indicated in figure.

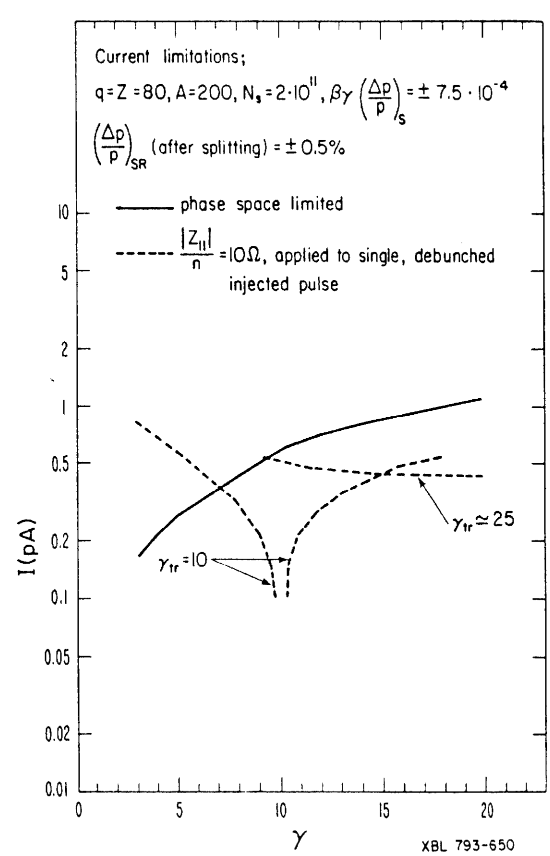

Fig. 7 Current limitations from longitudinal stability considerations (dashed lines), from linac momentum spread (solid lines).

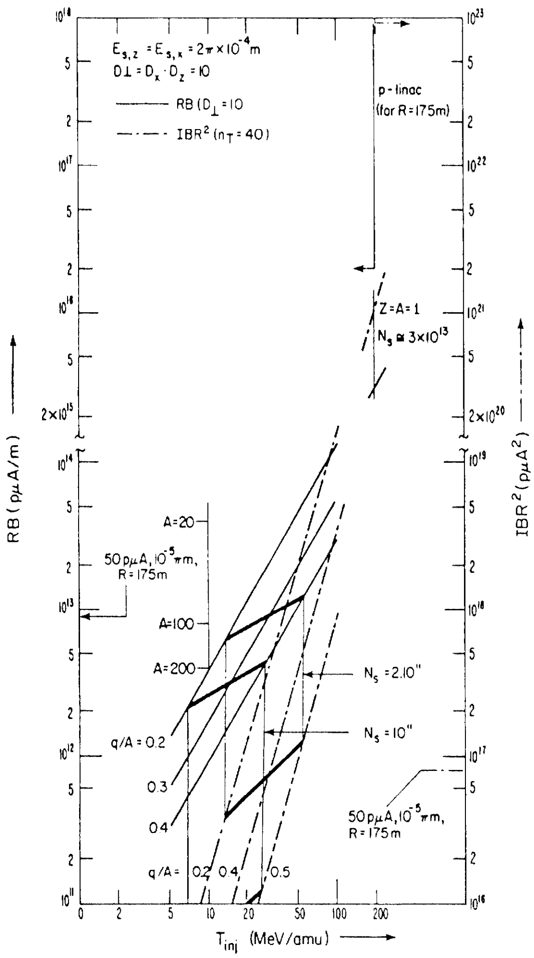

Fig. 4 Linac brightness B (solid lines), current-brightness product IB dashed lines), multiplied by R, R^2 respectively, as required to reach space charge limit N_s in synchrotron for A = 200. Assumed is total transverse dilution $D_\perp = D_x \cdot D_z = 10$, number of injected turns = 40, horizontal and vertical acceptance = 2π 10^{-4} m. Heavy solid lines correspond to $N_s = 2 \cdot 10^{11}$ and 10^{11} respectively.

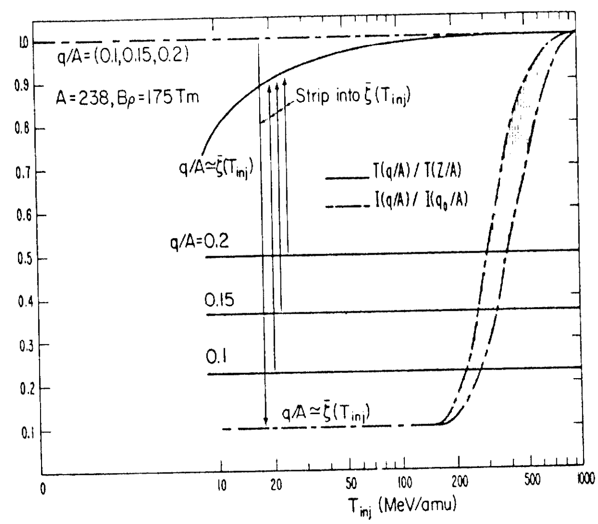

Fig. 5 Solid lines indicate kinetic energy obtainable with given q/A, with and without stripping at linac exit normalized to T(Z/A). Dashed lines indicate corresponding intensity, normalized to intensity obtained without stripping.

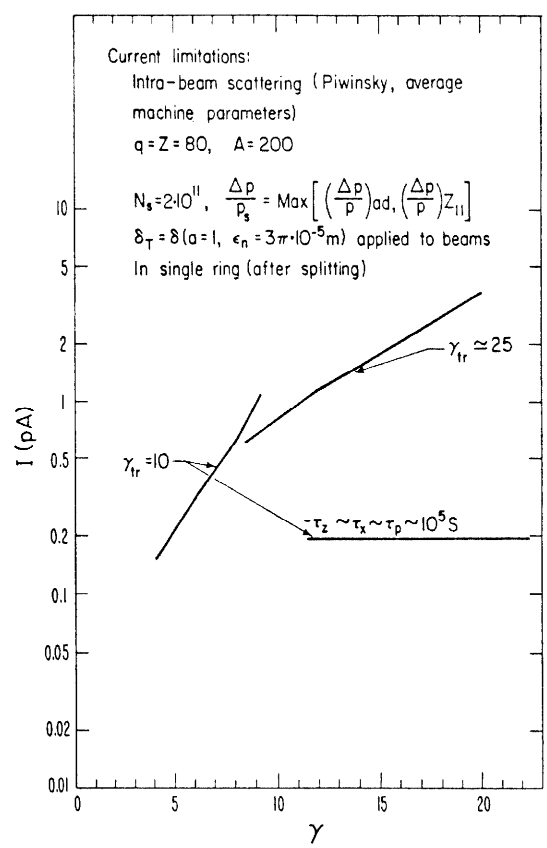

Fig. 8 Current limitations from intra-beam scattering.

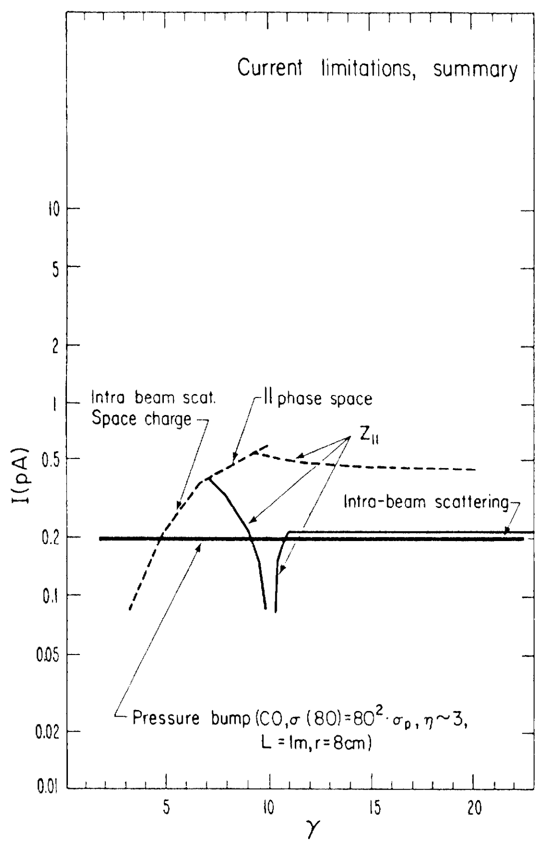

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Fig. 9 Summary of currents limitations, including estimate of limitation imposed by pressure-bump phenomenon.

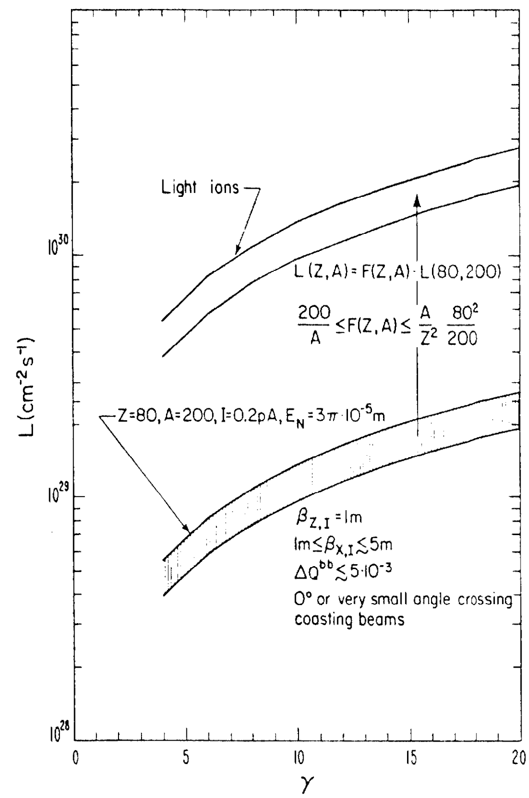

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Fig. 10 Luminosity estimates for parameters indicated in figure