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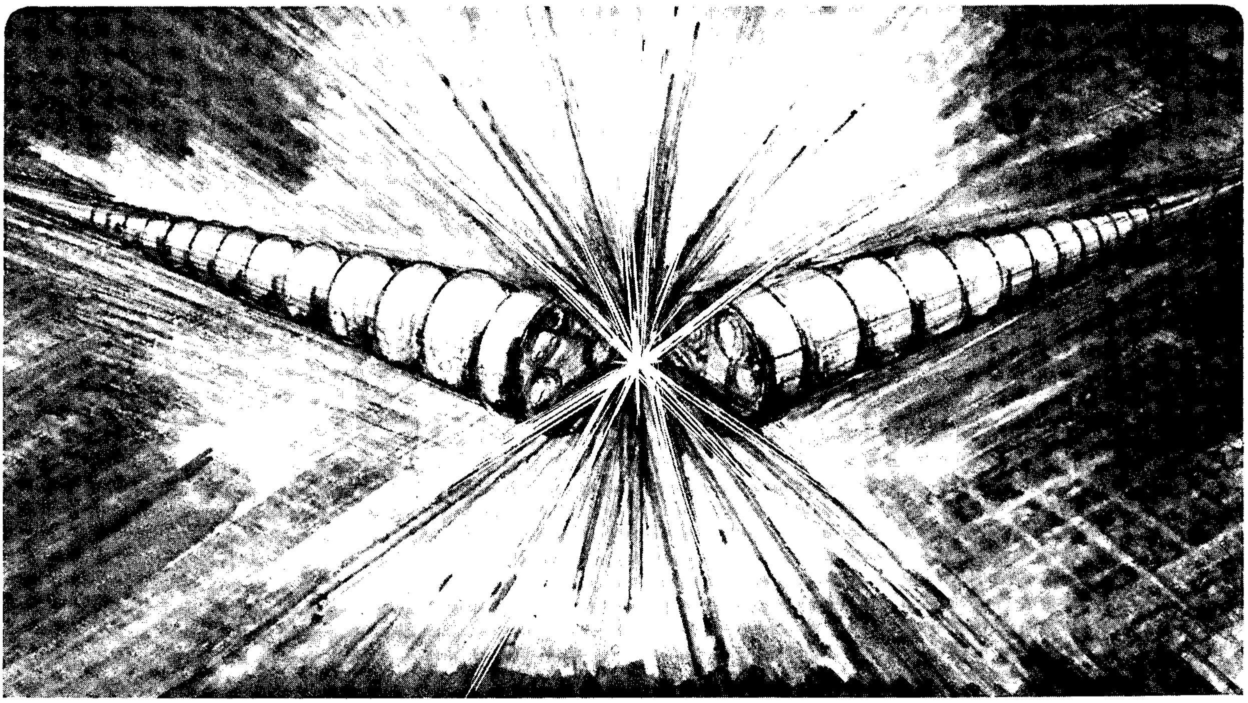
May 1983



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Heavy Ion Fusion With RF Linac and Cyclotron Technology*

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INTRODUCTION

Inertial fusion with heavy ions is now recognized as an approach that will probably work to produce useable power, but which will take a large commitment of money and resources before this can be demonstrated. As happens when any new large enterprise is undertaken which utilizes known technology, but in an unfamiliar way, a great deal of R and D needs to be done in order to improve accelerator technology in those areas where inertial fusion will place the greatest demands. Ion energies are modest compared with some existing machines (~50 MeV/amu), but the ion currents (~10^{15} particles in 10^{-9} sec) are far in excess of what is now routine. But this is largely because physics experiments have not demanded such performance - there seems to be no fundamental bar to achieving this goal.

The two approaches to heavy ion fusion which appear at present to offer the most promise are the use of an induction linac, to produce in one pulse the required particle flux, and the use of a conventional rf linac feeding a storage ring or rings, which accumulate the desired beam intensity before it is directed to the target.

In this second approach, the storage ring design has presented a serious difficulty, because of instabilities which limit maximum current. Also, stored beams debunch, so that rebunching is necessary before delivering beam to the target. This paper will look at the performance of a another possibility for accumulating beam - an isochronous ring - because it can also be used to accumulate a large current, but with this type of ring stacking and extraction occur before instabilities have time to build up. Another feature is that bunch structure is preserved during stacking, and thus rebunching can be avoided.

We will look at the use of an isochronous ring for a demonstration "high temperature experiment" which has been proposed as a means for developing and proving the accelerator technology,[1] but with a more modest investment than required for the fusion driver, then examine the possible extrapolation of this concept to a demonstration driver. We have reported in an earlier paper some of the basic ideas underlying the scenario presented here.[2]

USE OF AN ISOCHRONOUS RING FOR BEAM STACKING

The radial separation of adjacent orbits in an isochronous ring is given (non-relativistically) by

$$\Delta\bar{R} = \frac{qV\bar{R}}{2T_n A} \tag{1}$$

Where $\bar{R}$ is the effective magnetic radius, V the accelerating voltage per turn, T_n the energy per nucleon of a particle of mass number A and charge q. At injection, $\Delta\bar{R}$ must be large enough for the beam to clear the septum, which will determine the minimum value required for V at the inner radius. At larger radii V can be decreased, even reduced to zero at extraction radius, with the result that a large number of turns will occupy a small radial extent.

Starting with a beam bunch of small azimuthal extent, as turns are compressed in this fashion, the phase spread of the bunches will grow. From Maxwell's equations, we can see that this is because the radial electric gradient gives rise to a vertical B field and a radial electrical field component, or both. Both of these compoents cause a radial momentum change Δp_r for particles crossing the accelerating cavity with non-zero rf phase. For a ring with a single cavity and homogeneous B-field the rf phase slip per turn is, to first order approximation,

$$\Delta\phi_t = h\ \Delta p_r\ / p_s \tag{2}$$

where h is the harmonic number, Δp_r the radial momentum kick and p_s the tangental momentum component.

Ions with phase greater than +90 degrees or less than -90 degrees are decelerated. Thus in trying to achieve maximum radial compression, the bunch width at extraction will be about 180 degrees of rf phase. The maximum number of turns which can be compressed can be estimated by assuming that longitudinal phase space is conserved.[3] Let $E_{g,i}$ be the energy gain per turn and $\Delta\phi_i$ the phase spread at injection, and ΔT_o the energy spread and $\Delta\phi_o$ the phase spread of the extracted beam. Then if the extracted beam contains N_m turns, we can write

$$N_m \leq \frac{\Delta\phi_o}{\Delta\phi_i}\ \frac{\Delta T_o}{E_{g,i}} \tag{3}$$

since the phase area at extraction will be no smaller than the phase area at injection. From this relation 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 posssible. The energy spread at extraction should be as large as can be tolerated by transport and targeting requirements.

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 both ν_r, ν_z downward. Thus locating ν_r and ν_z as far as possible above integral stop bands is an important consideration in order to maximize allowable current. In order to lower the 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 to clear the septum, so that the energy gain per turn at injection can be made one-third as large as would otherwise be necessary.

STACKING-COMPUTATIONAL RESULTS

A computer program has been written to track particles through an isochronous ring. An initial distribution in ΔT, $\Delta\phi$ space is followed for several hundred turns, and particle positions at each turn are saved. A group of turns can then be examined as a bunch, to see the resulting ΔT, $\Delta\phi$ spread. Fig. 1 shows the results of one such calculation. A group of 100 turns is examined at injection, after 440 turns, and after 600 turns. The compression in ΔT space, and the extension in $\Delta\phi$ space are evident. It is also evident, that while phase area is conserved, the phase area of the stacked beam becomes progressively more curved. This happens because as particles with non-zero phase slip in phase, they obtain less energy gain than particles with a smaller absolute value of phase angle, due to the cos ωt falloff of the rf accelerating voltage. Fig. 2 shows curves plotted from the same data, showing rms energy and phase of the last 100 turns, as a function of turn number. The average energy $<T_n>$ reaches a maximum at 4.99 MeV/A, then starts decreasing, at the point where some particles have slipped more than 90 degrees in phase and now decelerated. The energy spread goes through a minimum at about 600 turns. The subsequent increase in ΔT_{rms} is a consequence of azimuthal spreading of phase space leading to decelerated particles, and to the progressive curving of phase space illustrated in Fig. 1. As a function of radius, the rf voltage is given by

$$V = V_0 \cos \left[\frac{\pi}{2} \cdot \frac{r - r_i}{r_f - r_i}\right] \cos \omega t \tag{4}$$

where r_i is the radius corresponding to injection energy, and r_f is chosen to be slightly greater than extraction radius. In Fig. 2 the peak gap voltage is plotted, as a function of turn number. Note that the damping of energy spread closely follows the decrease in accelerating voltage.

In order to see if greater compression could be gained by flat-topping the rf, another set of computations was made, in which the only change was to assume that the rf was a perfect square wave, with amplitude

$$V = V_0 \cos \left(\frac{\pi}{2} \cdot \frac{r-r_i}{r_f-r_i}\right) G(\phi) \tag{5}$$

Where $G(\phi) = 1$ for $-\pi/2 < \phi \pmod{2\pi} \leq \pi/2$

and $G(\phi) = -1$ for $\pi/2 < \phi \pmod{2\pi} \leq 3\pi/2$

The results are shown in Figs. 3, 4. The curvature of phase space due to cos ωt does not occur, so a greater compression is reached. The minimum ΔT_{rms} is 8 keV/A, compared to 14 keV/A for the CW wave rf. But the corresponding phase spread for the square wave is much wider - 64 degrees rms compared to 40 degrees rms for the CW case. Clearly there is some advantage to be gained from flattopping, which would have to be weighed against the additional expense in a particular case.

SPACE CHARGE EFFECT ON LONGITUDINAL PHASE SPACE

The stacking in momentum space by means of the radial turn compression in an isochronous ring is achieved at the expense of a corresponding increase of the bunch length. The presence of space charge forces could result in an even faster growth of the bunch length. This growth can be prevented, however, by installation of a bunching cavity operating at the proper voltage to just compensate for the space charge forces. In order to estimate the required voltage, we make the assumption of a gaussian line charge distribution along s:

$$\lambda(s) = \frac{N}{\sigma_\phi \sqrt{2\pi}} \quad \exp\left(- \frac{s^2}{2\sigma_\phi{}^2} \right) \tag{6}$$

where N is the total number of particles per bunch and $\sigma\phi$ is the standard deviation. The longitudinal space charge force at s will be

$$F_s = - \frac{g}{\varphi^2} q^2 e^2 \frac{d\lambda}{ds} \tag{7}$$

where g is a geometry factor chosen to be equal to 2. The result of evaluating this formula is given in Fig. 5. The solid lines represent the change of the dispersion $\Delta p/p$ per unit length due to the longitudinal space charge forces with $\sigma_\phi = 20$ degrees and 30 degrees, respectively, which are shown by dashed curves. Finally the counteracting effect on $\Delta p/p$ by a one MV rf buncher operating on the same harmonic as the accelerating rf system is also shown. Obviously such a buncher has sufficient strength to overcome the debunching effect of the longitudinal space charge forces.

REQUIREMENTS FOR A HIGH TEMPERATURE EXPERIMENT

A proposal has been made by Mark et al[1] for an experiment which should be a means for testing accelerator concepts, as well as provide means for studying the interaction of ions with high temperature plasmas. An ion beam is used to heat a disk of low density material imbedded in a block of high density material. The latter provides confinement for the low density material in order to enhance the heating. Plasma temperatures to be attained are in the neighborhood of 50 - 100 eV (corresponding to 0.5 - $1.0*10^6$ degrees K). Since the heating is done on a surface, with the beam impinging normally, the beam transport is simplified. Also, the beam energy can be lower - 5 MeV/amu as opposed to 50 MeV/amu required for a driver, where the beam must compress a spherical pellet.

In using target requirements to decide upon accelerator parameters, the important consideration is - the target temperature T reached with a given irradiance S (in Watts/cm^2) as a function of time. Heating will deposit energy in internal degrees of freedom until such time as electron bonds are broken and the material begins to disassociate. This behavior has been studied with the aid of computer simulations.[1,4] An empirical formula which represents the results to a good approximation is[5]

$$t/\tau = \int_0^x \frac{x^{1/2}\,dx}{1 - x^4} \tag{8}$$

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

$$\tau = \frac{3C_1 R}{2\sigma T_f{}^{5/2}} \tag{9}$$

R is the ion range, the "heat coefficient" $C_1 = 1.02 * 10^4$ J/(gm-$eV^{3/2}$), the Stefan-Boltzmann constant $\sigma = 1.03 * 10^5$ W/(cm^2-eV^4). Eq. 8 is plotted in Fig. 6, using R = 10 mg/cm^2. Evidently as the temperature approaches T_f as an asymptotic limit, the materials begins to disassociate. To determine a useful pulse length we will take $t = \tau$, where $T_1 = 0.95\ T_f$, and presumably the blowing-up process has just started. A longer pulse than τ would waste particles because some particles would not contribute to raising the temperature, while for a shorter pulse than τ, the maximum temperature would fall short of 0.95 T.

The total energy deposited by a beam of irradiance S into a disk of radius r in time τ is

$$E_t = \pi r^2 S \tau, \qquad (10)$$

while on the other hand, if the ring stacks N_p particles each of energy T_n per nucleon, the total beam energy per pulse will be

$$E_p = N_p \, T_n \, A. \qquad (11)$$

In order to heat economically, that is, to reach the highest possible temperature with a given number of ions, we should make $E_t = E_p$. With this consideration, combining Eqs. 10 and 11, and substituting σT_f^4 for S gives for the target spot radius

$$r^2 = \frac{N_p \, T_n \, A}{\pi\sigma \, T_f^4 \tau} \qquad (12)$$

This is a useful equation for accelerator design, as it expresses the relation of the most important parameters to the asymptotic temperature T_f. Note however that while N_p and τ have been retained for clarity, they are not independent parameters. τ depends upon T through Eq. 9, and N_p depends upon T_n, A, and τ, as they all will enter in the space charge limit.

Some idea of the dependence of T_f on τ, A and r can be seen in Fig. 7. In this graph, a reference case was taken with A=165, r = 1 mm, τ = 50 nsec, which gives T_f = 62 eV. The center curve shows the variation of r with A, keeping τ (and T_f) constant. The other curves show the effect of shorter and longer pulse lengths. Achieving higher temperatures requires shorter pulses.

If the requirement that $E_t = E_p$, i.e. that particles be used economically is given up, higher temperatures can be reached by making r smaller. The limit will be set by the minimum spot size achievable with a focusing system. Fig. 8 shows an example, in which the assumption is made that r can be made as small as desired, ignoring aberrations. The small circle is the same reference case as in Fig. 7, in which 19 bunches are used in the irradiation. The solid curve shows the temperature achieved by irradiating with one bunch, as the spot size is made smaller and smaller.

CHOICE OF PARAMETERS

When applied to the problem of fusion, heavy ion accelerator technology is pushed to it's limits in several areas. Such areas must be carefully investigated, in some cases by building hardware for testing, before we are on sure ground in setting specifications. In the machines being considered here, there are many tradeoffs, where one set of specifications can be relaxed, by making a complementary set tighter. Achieving an overall minimum cost will of course play a major part in such optimization. Somewhat arbitrarily, a set of parameters has been chosen to facilitate the present discussion. They are given in Table I.

Following are listed some of the major considerations, and how they affect the choice of parameters.

1. Minimize length of linac.

o Injection energy of isochronous ring to be as low as possible. This is limited by the turn compression in the ring, also by the practical width of the guide field magnet aperture.

2. Maximize the stacked current in the isochronous ring.

- The space charge limit is proportional to the allowable tune shift, and to the emittance, bunching factor, and mass number, so these should be made as large as possible. It is inversely proportional to the square of the charge state, so that for maximum stacked current q = 1 is necessary.
- Bunch separation must be great enough to permit operation of fast kicker magnets, without disturbing the bunches.

3. Minimize the number of bunches by minimizing the ring circumference. Thus a high magnetic field for the guide magents is important.

- Coalesce bunches, after extraction, into super-bunches for transport to the target.

4. Minimize aberrations in the transport system.

- Chromatic abberations, if uncompensated, limit the momentum spread which can be transported. This in turn places strong constraints upon the required energy spread from the linac, and the number of turns which can be stacked in the ring. However it has been shown[6] that the use of sextupoles in the final transport can greatly reduce the focusing aberrations at the target due to energy spread.
- For a given target spot size, the maximum allowable divergence in the final focusing will determine the beam emittance. Therefore the aberrations in targeting arising from divergence need to be compensated, in order to maximize the emittance which can be transmitted.

5. Optimum bunch length for target heating

- The bunch length is determined by phase width relative to ring rf, at extraction, plus subsequent lengthening due to space charge, and to energy spread. This spreading can be limited by the use of bunching cavities.

PROPOSED APPARATUS FOR A HIGH TEMPERATURE EXPERIMENT

The components of a possible high temperature experiment are shown schematically in Fig. 9. An intermediate mass ion, A=165, with 59 eV for the plasma temperature is chosen, on which to base a design example. Table I is a list of the major parameters. A 4 MeV/amu rf linac is used to inject beam into the isochronous ring, which increases the energy to 5 MeV/amu in 700 turns before the last 100 turns are extracted with a fast kicker magnet. The entrance section of the linac is operated at a low frequency, 4.2 MHz. This is the desired bunch frequency, to be retained through the linac and isochronous ring. Later linac sections operate on successively higher frequencies, up to 76 MHz. A debuncher between the linac and isochronous ring is used to reduce the energy spread of the linac beam. The ring is operated at 8.4 MHz, which will produce bunch lengths of about 40 nsec. The bunch separation will be about 200 nsec, which is adequate for turning on and off the kicker magnet used for extraction.

A schematic of the isochronous ring is shown in Fig. 10. In addition to accelerating rf, with voltage decreasing with radius, other rf is operated in a bunching mode, to offset space charge forces.

The number of circulating bunches is proportional to the ring circumference, which in turn is determined largely by the magnetic field intensity. It is advantageous to make this as small as possible, so we have chosen a high value of magnetic field - 6 Tesla. The number of circulating beam bunches is 16. If, after extraction, these bunches are all to reach the target simultaneously, a scheme must be devised so that the bunches extracted first can be delayed, permitting later bunches to catch up. One straightforward, but expensive, method would be to divert each bunch into a separate beam line after extraction, and adjust the length of each beam line so that the bunches arrive at the target simultaneously.

An approach will be outlined which requires a much shorter total length of beam transport lines. Another ring, called the staging ring, is interposed between the isochronous ring and the target (see Fig. 9). The staging ring has several purposes. One is to provide a means for further stacking beams in transverse phase space, in order to reduce the number of final beam lines. Secondly, the resulting geometry permits short final delivery beam lines. Finally, the total number of fast kicker magnets required is much reduced. Unlike the isochronous ring, however, there is no great advantage in making the diameter of the staging ring as small as possible. It can be regarded as simply a transport system built in a circle, as it will use the same magnet element designs as the final transport lines.

The operation can be understood by reference to Fig. 11. In this example, 16 bunches are to be extracted from the isochronous ring and delivered to the target. The effective circumference of the staging ring is approximately 3 times the circumference of the isochronous ring. A fast kicker magnet extracts every fifth bunch from the isochronous ring. The bunch is then inflected into the staging ring. When four bunches have been so transferred, the process is halted to permit the bunches to complete one revolution of the staging ring, then the extraction process again sends four bunches timed to arrive exactly in phase with the first four bunches. The process is repeated, until four superbunches are rotating in the staging ring. When these superbunches arrive at the proper azimuth, they are simultaneously extracted, each to a separate beam line, and transported to the target. The amount of time spent in the staging ring is short-about 3 1/2 revolutions.

In placing beam bunches in the staging ring, the techniques of multiturn injection are used. The maximum number of bunches allowed per superbunch will depend upon the emittance allowed in the final beam transport. An injection method should be used that achieves equal emittance in both horizontal and vertical planes, for example, using a corner septum.[7,8] Advantage can also be taken of the fact that in the staging and final transport the identity of the bunches can be retained, i.e. emittance need not be distorted to the point where bunches become "mixed". Thus a crossection of the superbunch in the final focusing elements could appear as shown in Fig. 12. Each bunch has retained it's identity, and it could be possible to introduce separate abberation corrections in each quadrant, if this is needed.

Table I. Parameters for a High Temperature Experiment

Ion Source	Ion mass chamber		165	
	Ion charge		+1	
	Current		10	mA
	Emittance (norm.)		0.3π	mm-mrad
Linac	Low-β rf frequency		4.2	MHz
	Final rf frequency		76	MHz
	Final energy		4.0	MeV/A
	Final Emittance (norm.)		1.0π	mm-mrad
	Final momentum spread (after debunching)		$\pm 3 * 10^{-4}$	
	Total length (est.)		450	m
Isochronous Ring	Energy at extraction		5.0	MeV/A
	Circumference		117.5	m
	Rf frequency		8.4	MHz
	No. of beam bunches		16	
	Ions per bunch		$8 * 10^{11}$	
	Dipole magnetic field		6	T
	Accelerating field at injection		0.75	MeV/turn
	Batatron frequencies	ν_r	1.25	
		ν_z	0.90	
	No. of stacked turns		100	
	Transit time in ring		2.7	msec

	r, z emittance at extraction (norm.)		3.0π mm–mrad
Stacking Ring	Circumference		352.4 m
	No. of superbunches		4
	Ions per superbunch		$3 * 10^{12}$
	Beam rigidity		53.2 T–m
	Emittance (norm.)	$\varepsilon_{x,n}$	27π mm–mrad
		$\varepsilon_{y,n}$	27π mm–mrad
Target	Spot radius		0.85 mm
	Total number of particles		$1.3 * 10^{13}$
	Ion range		10 mg/cm^2
	Pulse length		50 nsec
	Irradiation		$1.5 * 10^{12}$ w/cm^2
	Total energy		1.7 kJ
	Disk temperature		59 eV

EXTRAPOLATION TO A HEAVY ION FUSION DRIVER

Although the logical next step in heavy ion fusion is to build a test set-up on the lines of the one that has been described, this effort will be much more interesting if the same technology proves suitable for a full-scale driver.

For the high temperature experiment, we have shown that an isochronous ring can stack 16*100=1600 bunches of a state-of-the art linac beam (10 mA) and that there is a reasonable way to bring this energy (2.2 kJ) to the target within 50 nsec time slot. For the driver, about three orders of magnitude more energy is required, and it must be delivered in a shorter time, about 10 nsec, in order to reach temperatures on the order of 200 eV.

Ion energies used for the driver will be about 50 MeV/A. Since the ring space charge limit is proportional to energy, a ring will stack ten times as many particles, each with ten times the high temperature experiment energy, giving 100 times as much energy on target, if all other factors remain the same. By using a heavier ion, increasing the filling factor, and by allowing a greater tune shift, a ring can be made to store a greater number of particles, but to achieve the remaining factor of ten it is probable that several rings will be needed.

The linac, when extended from 4 to about 45 MeV/A, and when provided with several low-β sections to funnel beam, so as to fill the buckets that are empty in the 4 MeV/A version, will be capable of delivering enough particles to fill all of the isochronous rings.

Some major problems remain to be solved, however. The 10 nsec pulse length, coupled with the requirement for a high filling factor, lead to a requirement for large-aperture fast kicker magnets with risetimes on the order of 50 nsec. Also, the total number of bunches in the isochronous rings will be large, so that in order to reduce the number of final beam lines, many more bunches will need to be combined into superbunches in the staging ring.

ACKNOWLEDGMENTS

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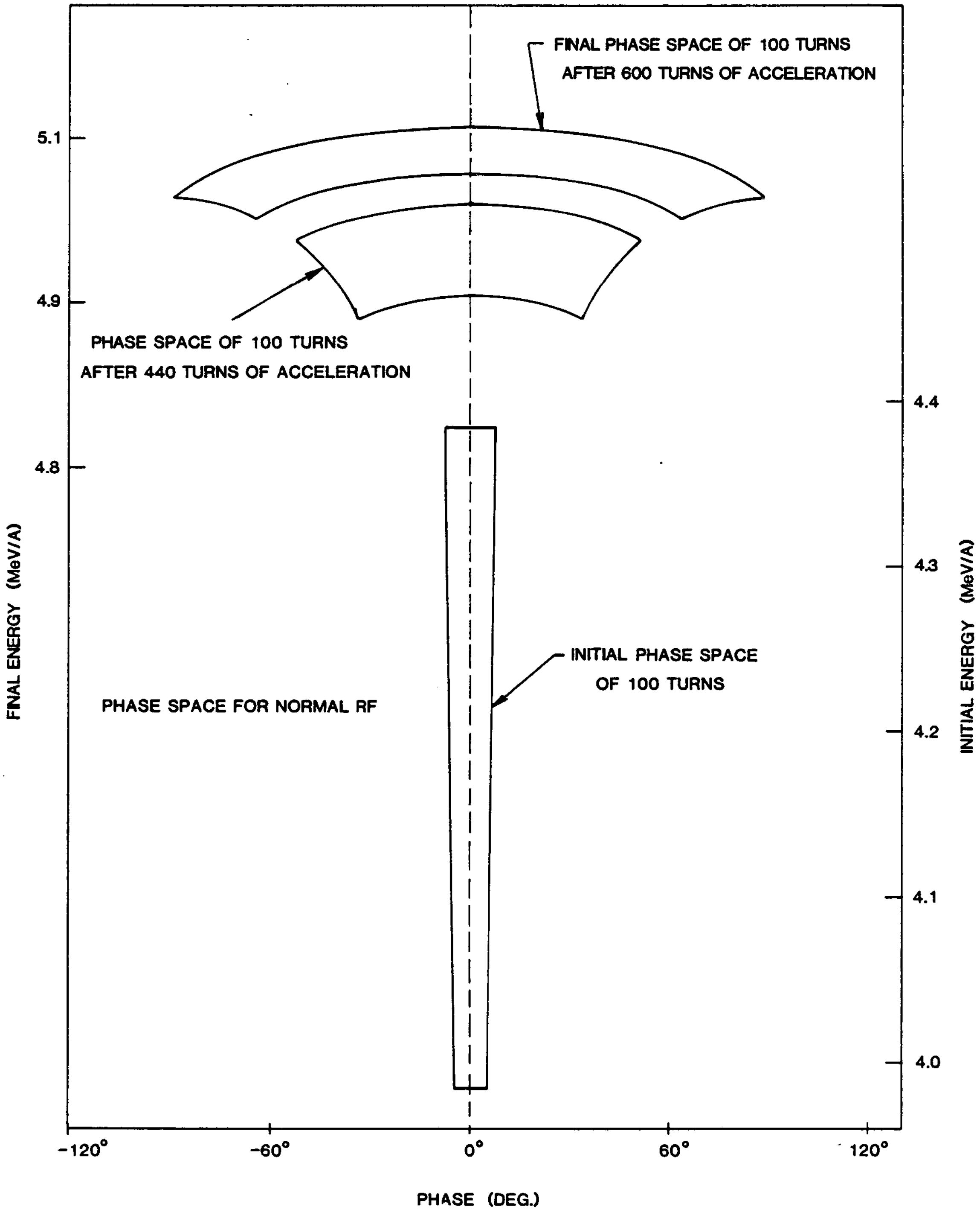

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Fig. 1. Phase space areas corresponding to 100 turns during stacking using CW (normal) rf.

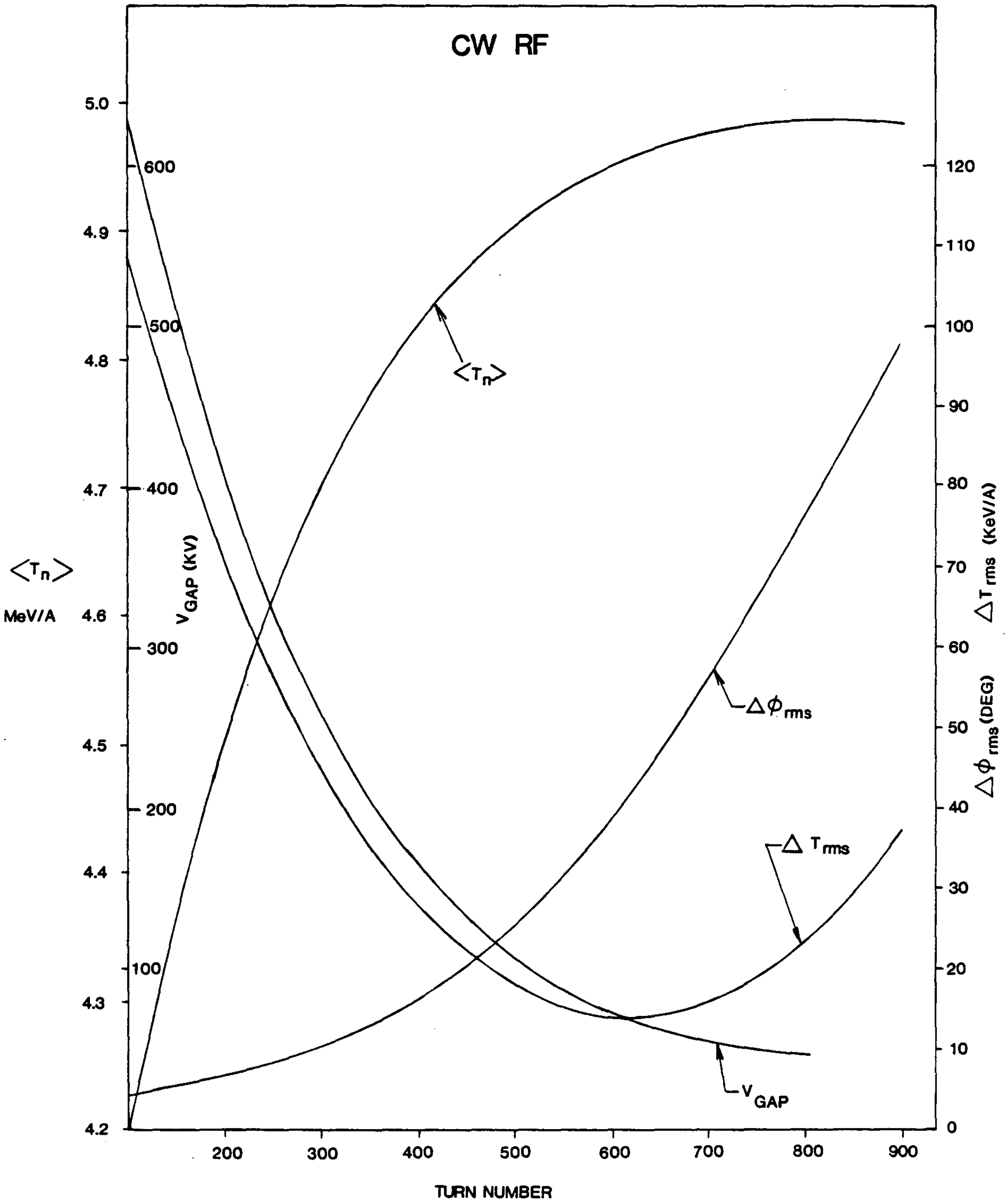

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Fig. 2. Average energy, and rms values of energy and phase spread of 100 turns, during CW rf stacking. Accelerating gap voltage is also shown.

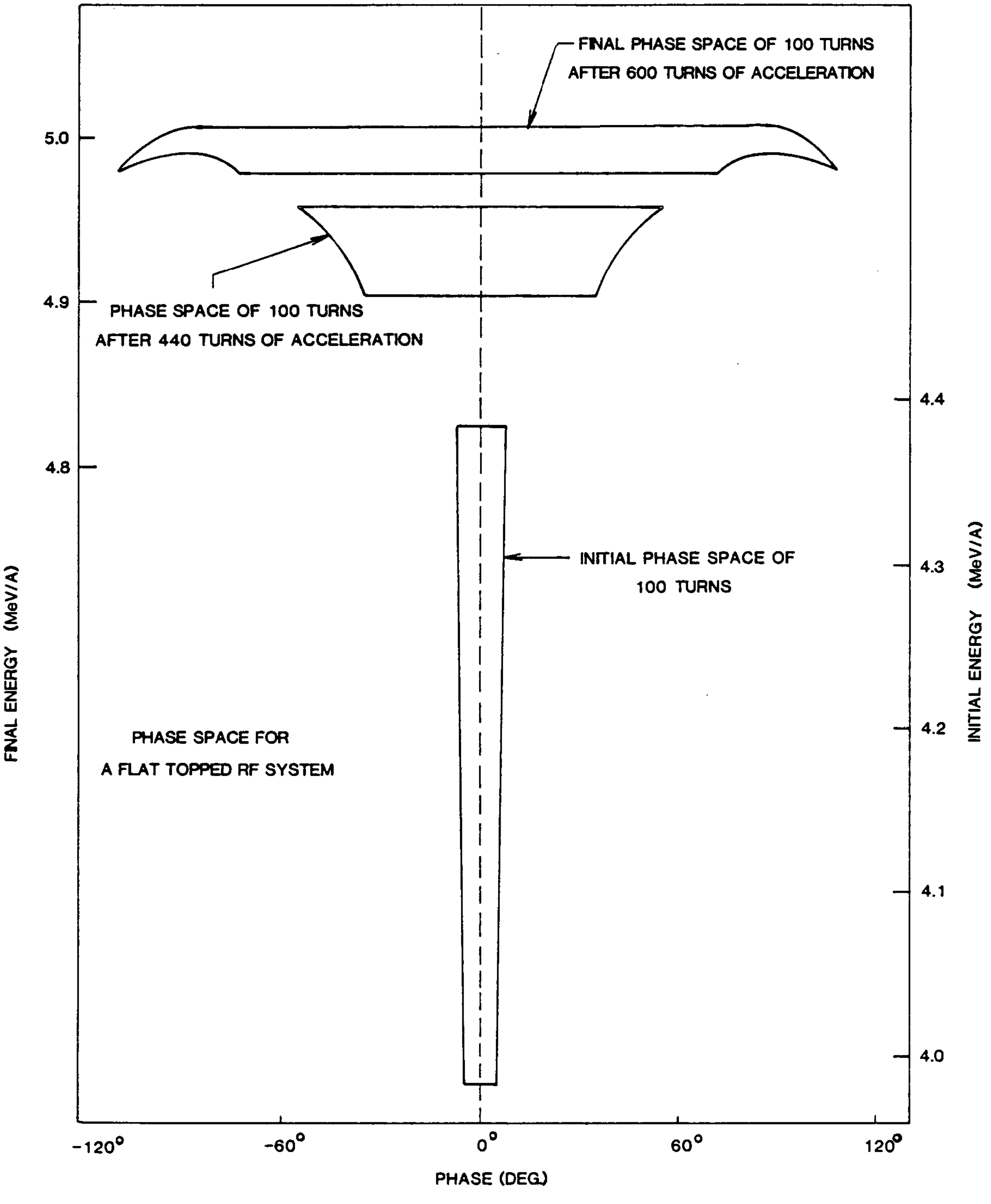

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Fig. 3. Phase space areas corresponding to 100 turns during stacking using flat-topped rf.

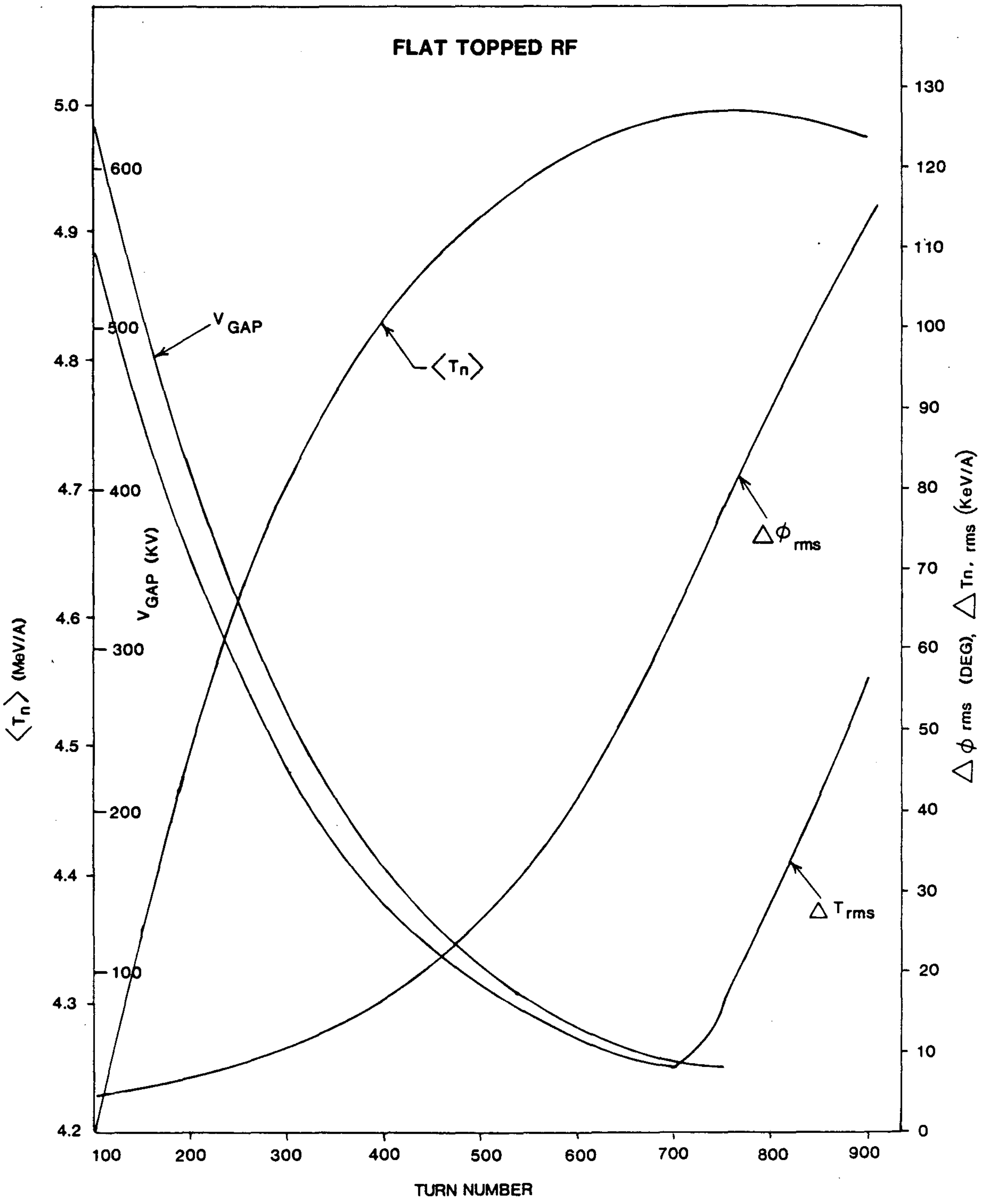

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Fig. 4. Average energy, and rms values of energy and phase spread of 100 turns, during flat-topped rf stacking. Accelerating gap voltage is also shown.

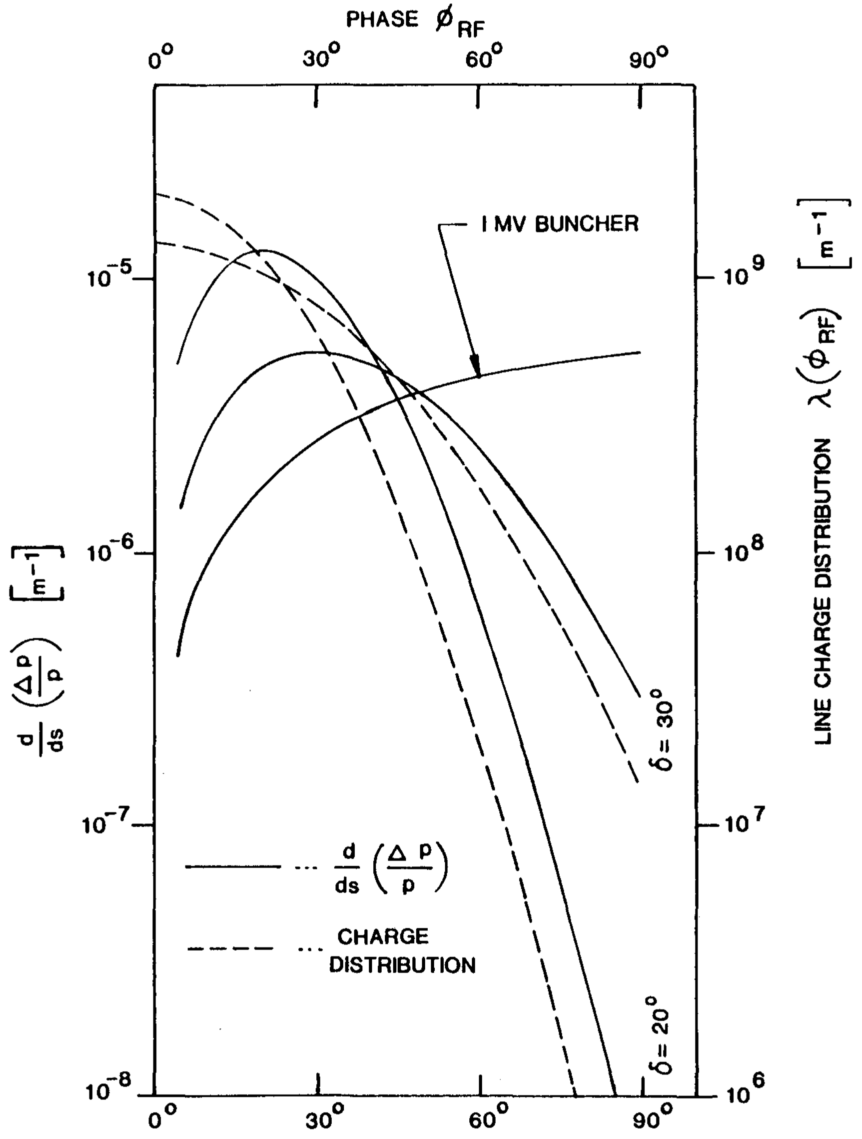

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Fig. 5. Space charge forces on beam bunches. Azimuthal debunching force due to line charge distributions is compared with the bunching force of a 1 MV cavity.

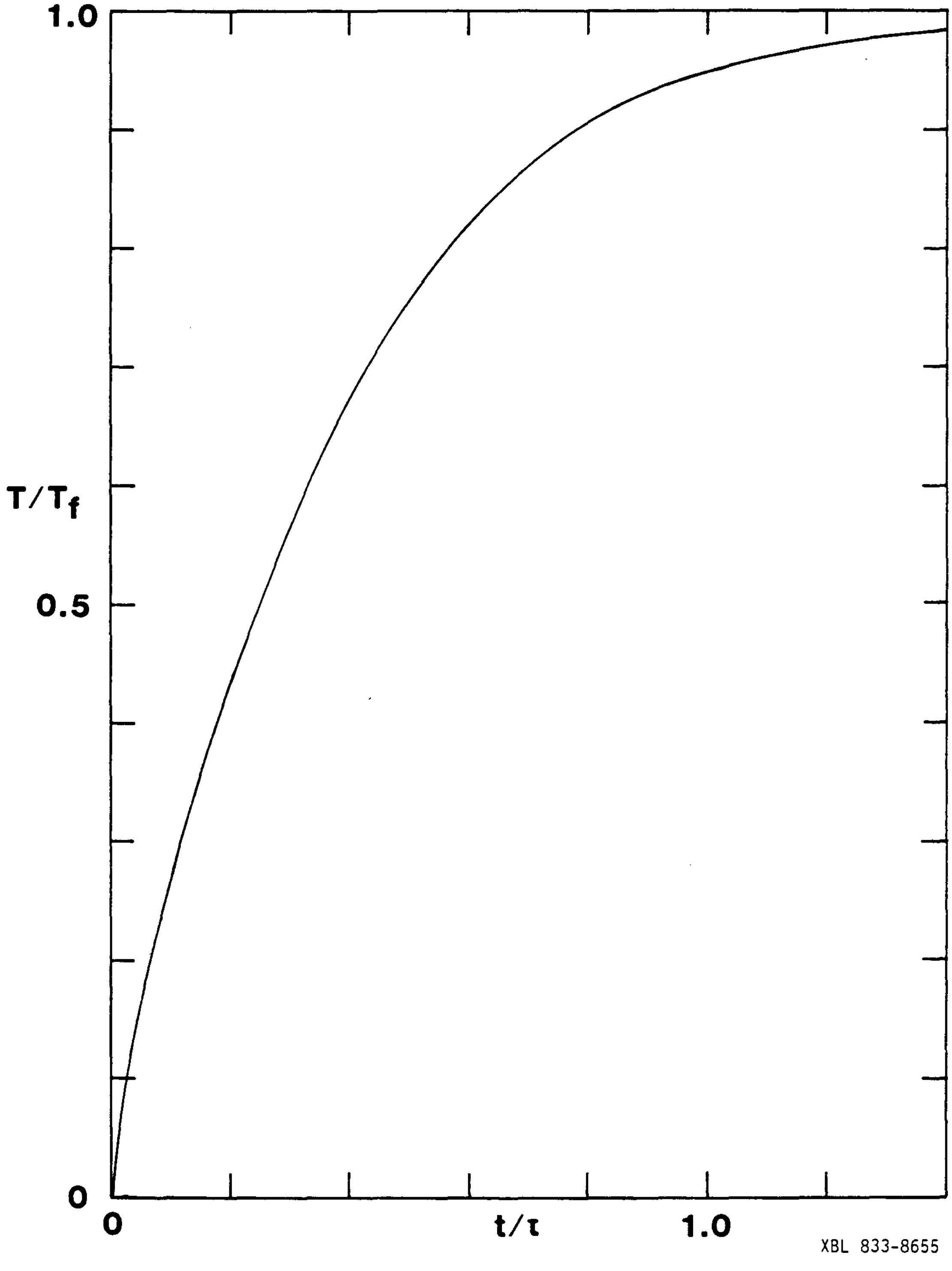

Fig. 6. Heating of a disk target by an ion beam. The asymptotic temperature T_f and the characteristic time τ are defined in the text.

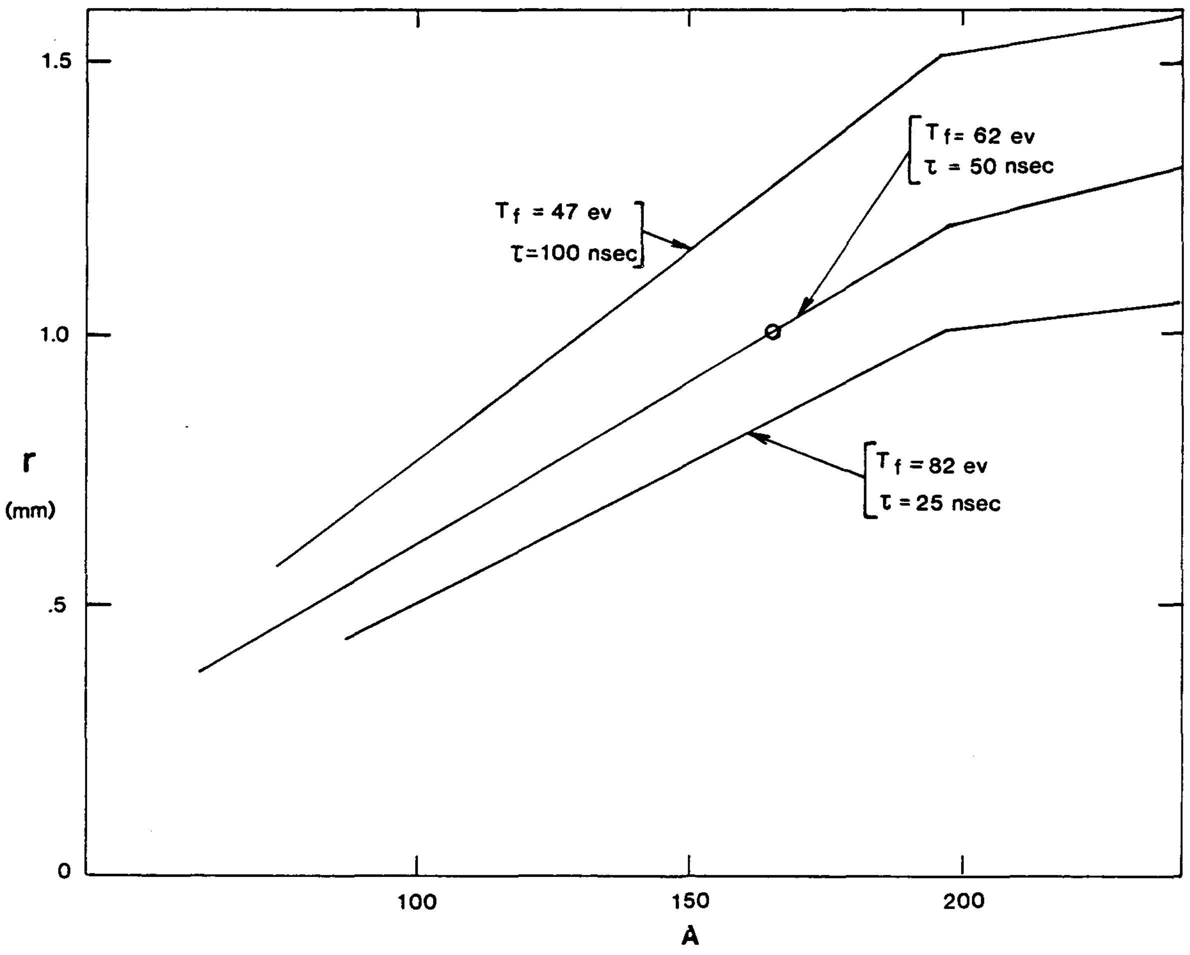

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Fig. 7. Characteristics of disk heating, showing variation of spot radius with mass number A, when other parameters are held constant. The decrease in slope for A > 200 is due to the longer range of 5 MeV/A very heavy ions (such as Uranium).

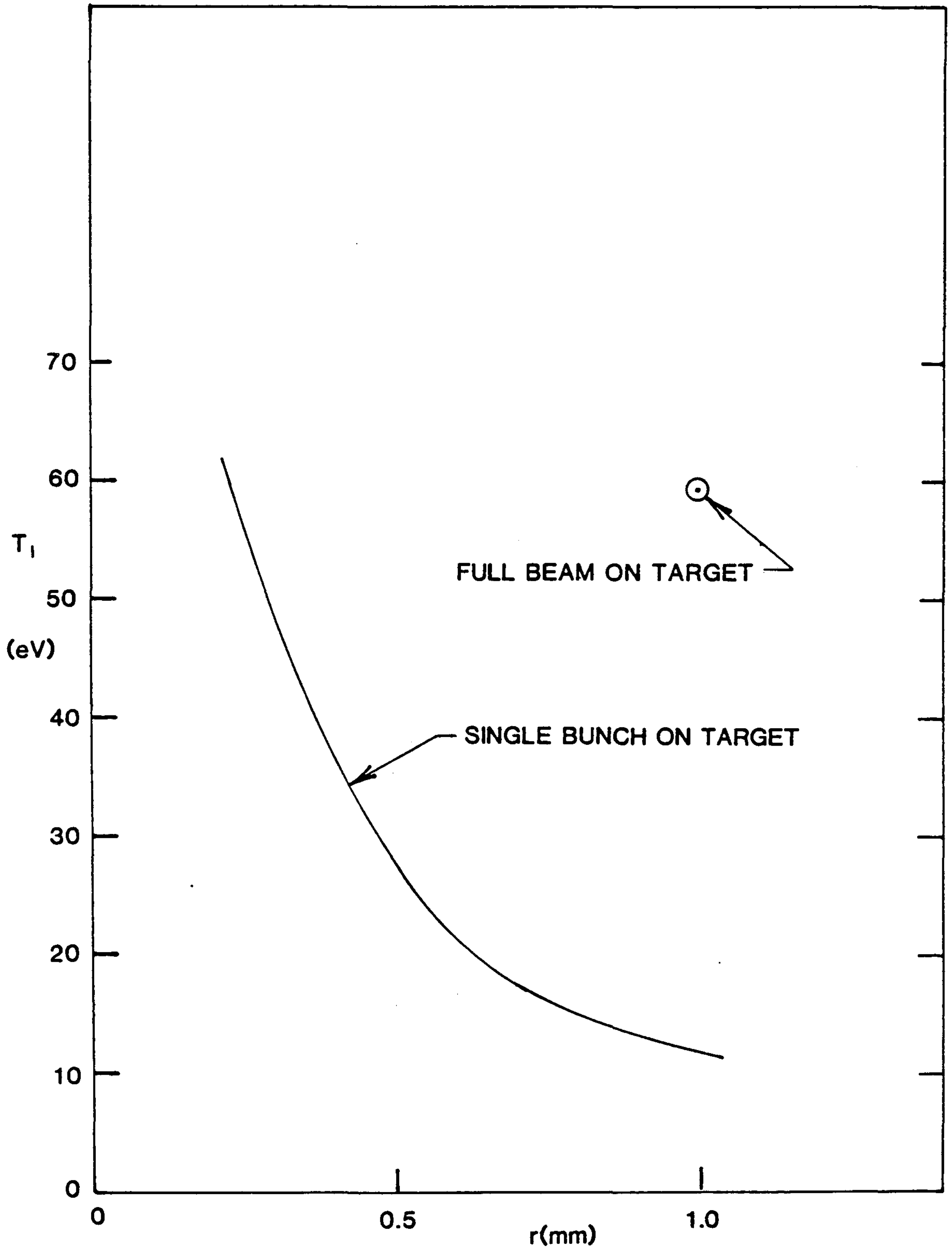

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Fig. 8. Variation of target temperature $T_1 = 0.95\ T_f$ with spot size, when focusing aberrations are neglected. A single bunch is here assumed to be 1/19 of the full beam.

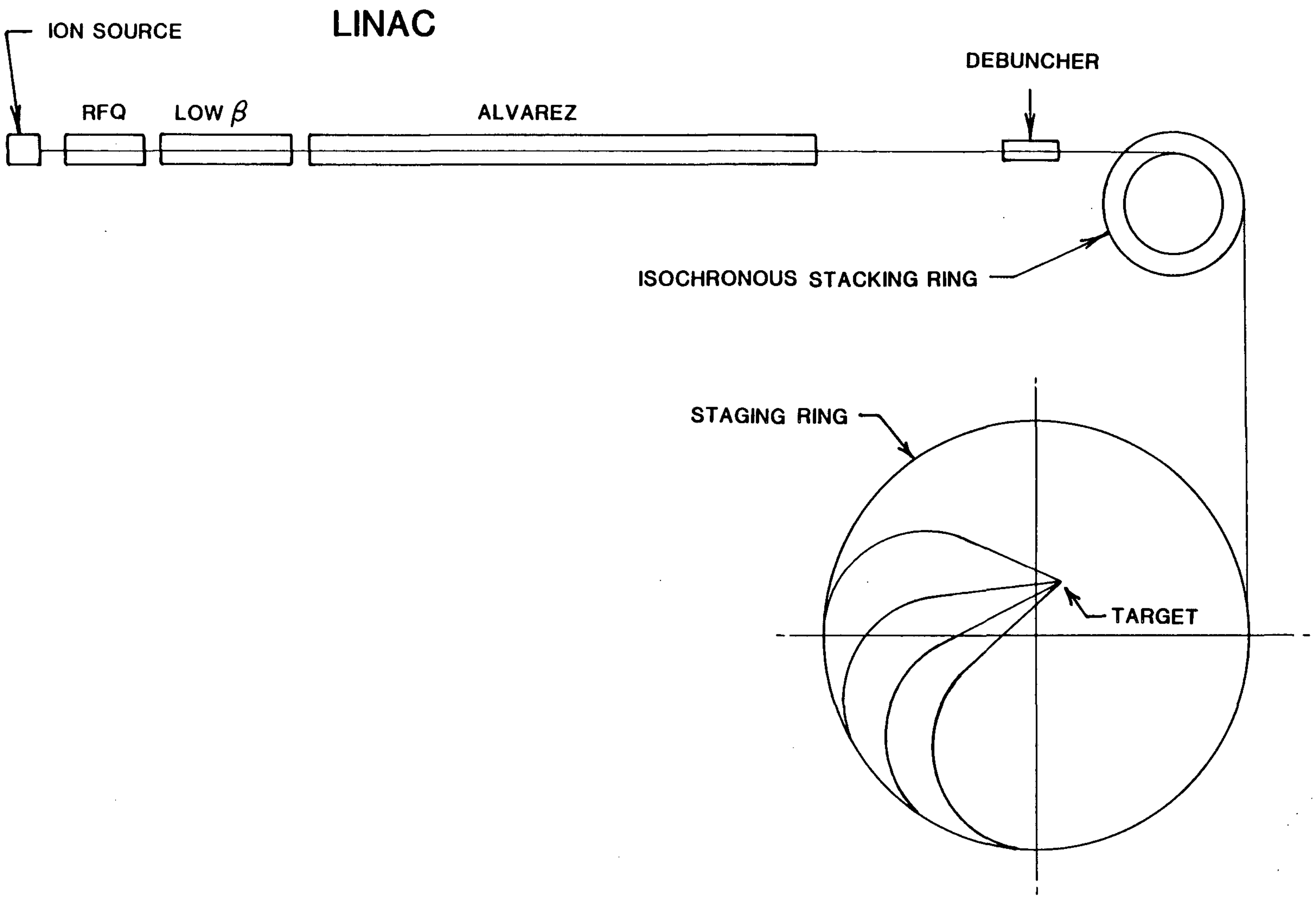

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Fig. 9. Schematic of a possible high temperature experiment, using a rf linac, an isochronous stacking ring, and a staging ring to deliver beam to a disc target.

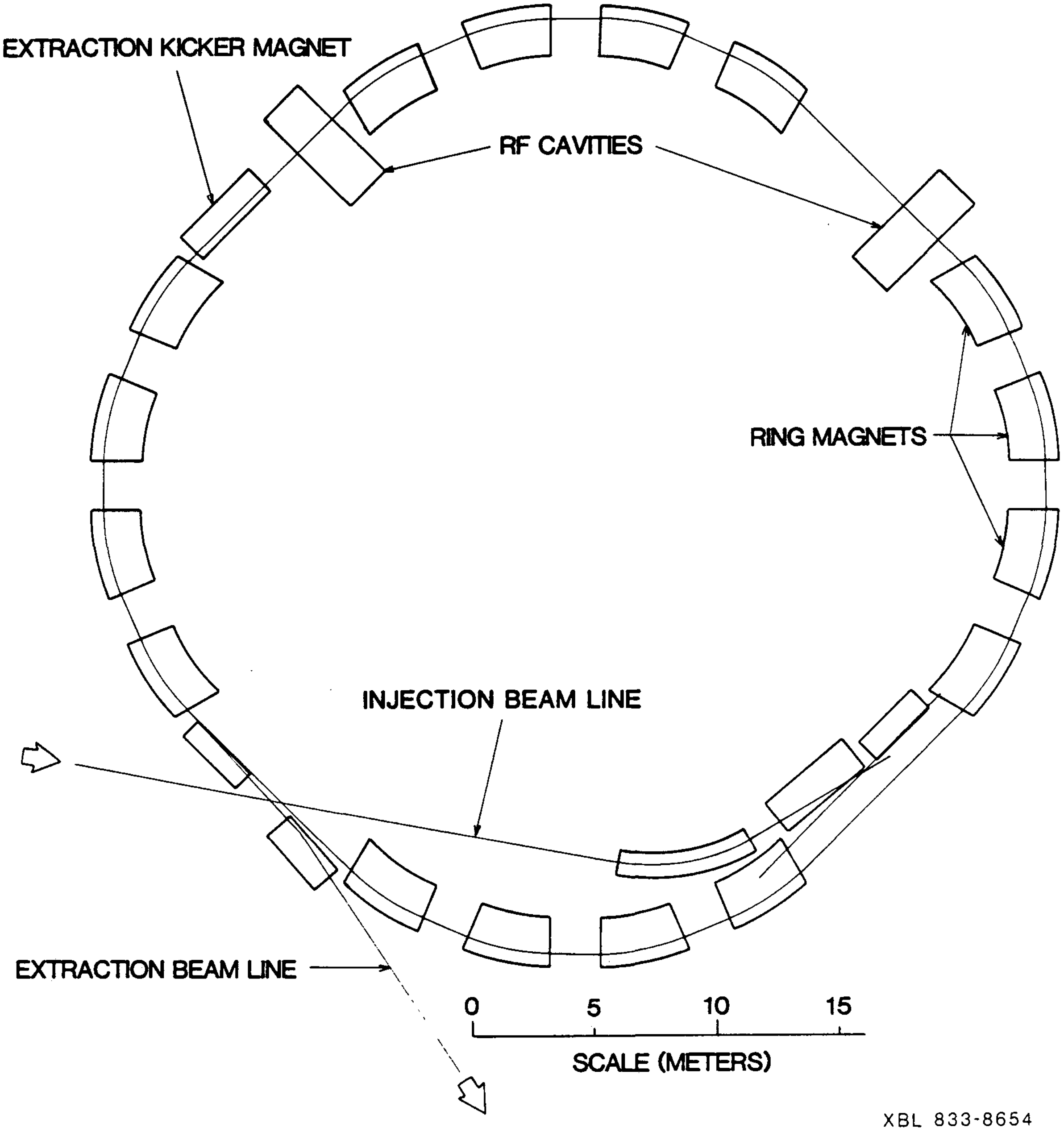
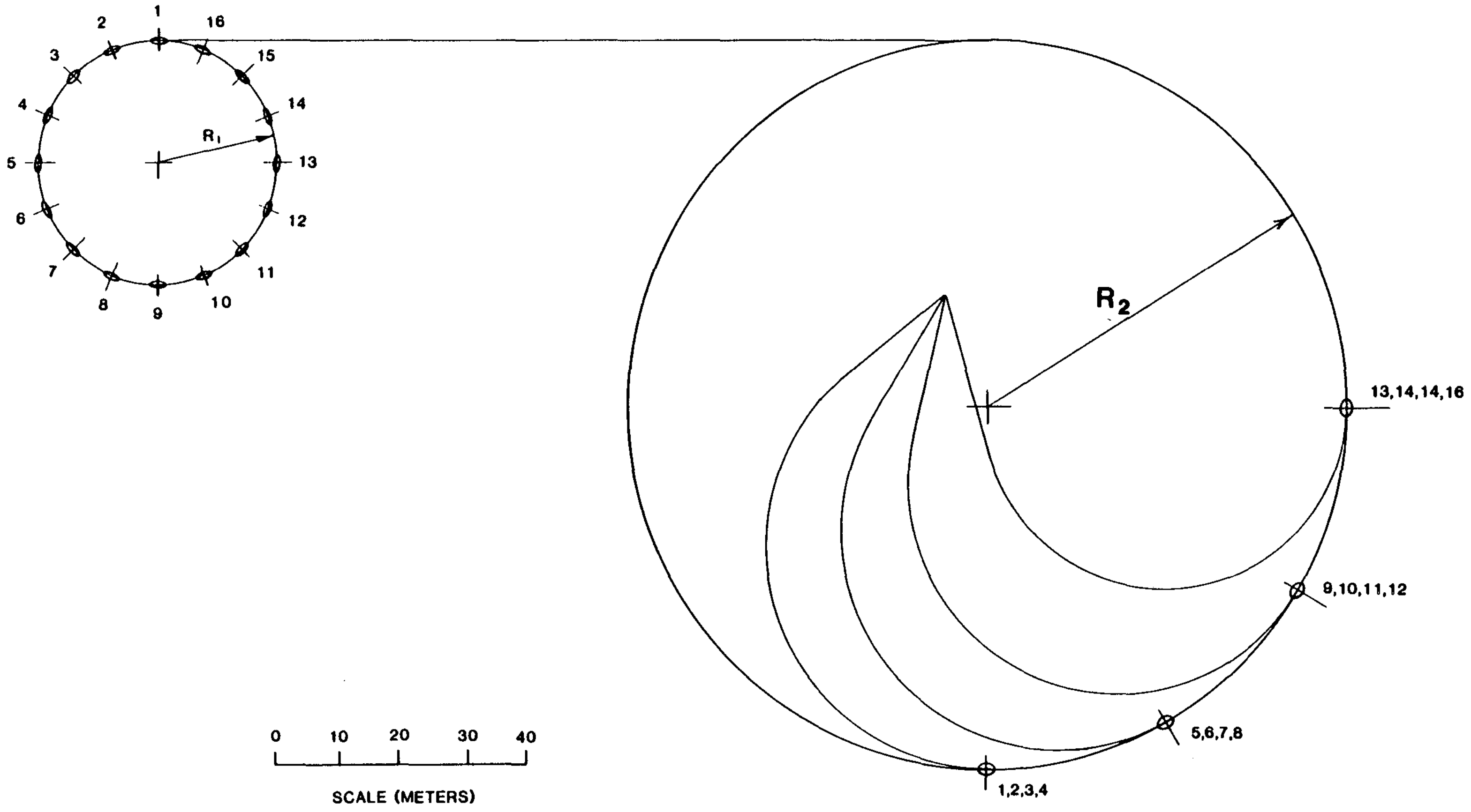


Fig. 10. Schematic of an isochronous stacking ring.



XBL 835-9880

Fig. 11. Schematic showing one method of transferring 16 bunches from the stacking ring, to produce 4 superbunches in the staging ring.

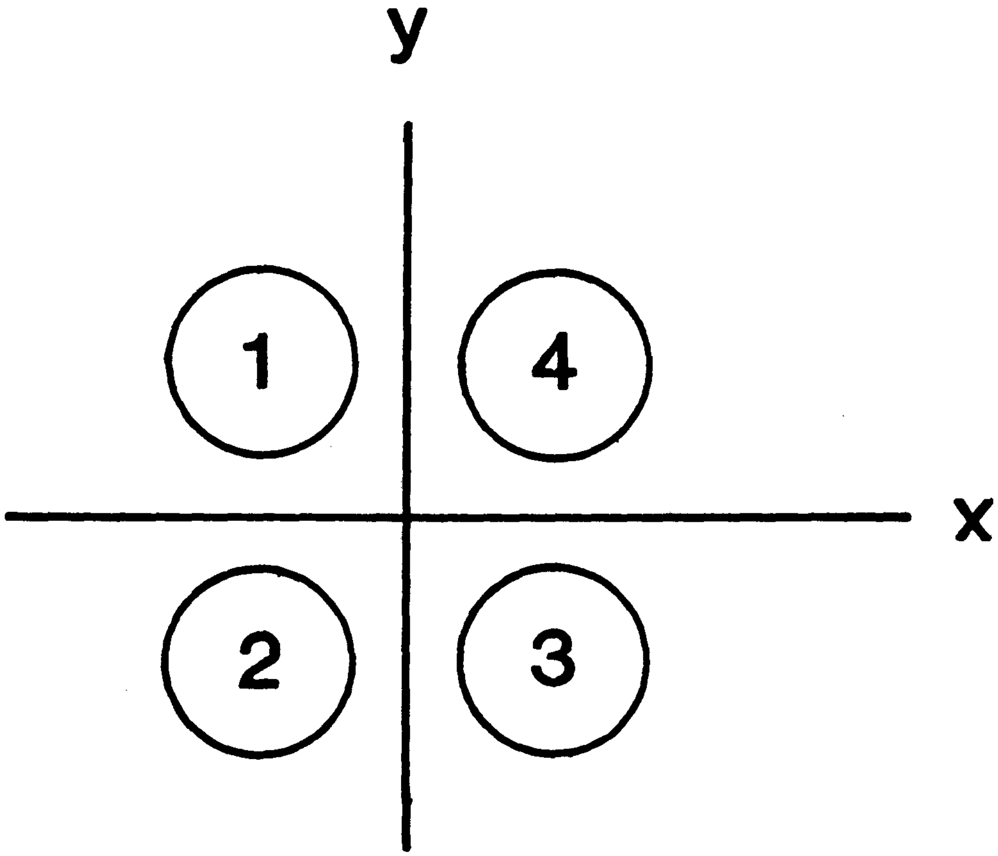


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Fig. 12. A possible final focussing pattern, showing arrangement of 4 bunches in a superbunch.

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