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Principles of non-Liouvillean pulse compression by photoionization for heavy-ion fusion drivers

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Photoionization of single-charged heavy ions has been proposed recently by Rubbia (1989) as a non-Liouvillean injection scheme from the linac into the storage rings of a driver accelerator for inertial confinement fusion. The main idea of this scheme is the accumulation of high currents of heavy ions without the usually inevitable increase of phase space. Here we suggest the use of the photoionization idea in an alternative scheme: if it is applied at the final stage of pulse compression (replacing the conventional bunch compression by an rf voltage, which always increases the momentum spread), there is a significant advantage in the performance of the accelerator. We show, in particular, that this new compression scheme can potentially relax the tough stability limitations, which were identified in the heavy-ion fusion reactor study HIBALL (Badger *et al.* 1984). Moreover, it is promising for achieving higher beam power, which is suitable for indirectly driven fusion targets (10^{16} W/g, in contrast with 10^{14} W/g for the directly driven targets in HIBALL).

The idea of non-Liouvillean bunch compression is to stack a large number of bunches (typically 50–100) in the same phase-space volume during a change of charge state of the ion. A particular feature of this scheme with regard to beam dynamics is its transient nature, since the time required is one revolution per bunch. After the stacking the intense bunch is ejected and directly guided to the target. The present study is a first step in exploring the possibly limiting effect of space charge under the parameter conditions of a full-size driver accelerator. Preliminary results indicate that there is a limit to the effective stacking number (non-Liouvillean "compression factor"), which is, however, not prohibitive. Requirements on the power of the photon beam from a free-electron laser are also discussed. It is seen that resonant cross sections of the order of 10^{-15} cm^2 lead to photon beam powers of a few megawatts.

1. Introduction

It is presently accepted that among the various components of inertial confinement fusion (driver, target, reactor) the feasibility of an appropriate driver is the principal issue (Bangerter 1989). The HIBALL study (Badger *et al.* 1984) was the first systematic investigation of the accelerator driver, target, and reactor chamber for heavy-ion inertial fusion. It showed that the requirements for directly driven inertial fusion targets can, in principle, be met by conventional accelerator technology using an rf linac, several storage rings for accumulating the required total charge, buncher rings for final bunch compression, and a transport system for guiding the beams to the target. In that study it was, however, recognized that there are severe limitations owing to the space charge of the intense beams. The emittance growth associated with space charge at various stages of the acceleration, stacking, storage, and final bunch compression was not well known on account of a lack of experience with intense beams at nonrelativistic energies. The potential of the new GSI

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accelerator facility SIS/ESR—going fully into operation in 1990—in solving most of these problems was discussed previously (Boehne 1984; Hofmann 1984a, 1989). The uncertainty of the HIBALL design would be serious if several large emittance growth factors had to be accepted.

In his recent proposal Rubbia (1989) pointed out that confidence in realizing a heavy-ion fusion driver could be greatly increased by introducing at some stage of the complex acceleration scheme a process that reduces the effectively filled phase-space volume. Since stochastic or electron cooling is not applicable because of the long cooling times involved, Rubbia proposed a non-Liouvillean injection into a storage ring by means of photoionization of singly charged ions. This is related, in principle, to the H^- injection through a foil currently used in many proton synchrotrons for high intensity. Another related suggestion was made by a group at Argonne National Laboratory, who proposed using photodissociation of molecular ions for a non-Liouvillean injection from a synchrotron into a storage ring (Arnold *et al.* 1977). The usefulness of a non-Liouvillean injection into a storage ring is limited, however, by the existence of various instabilities and nonlinear resonances that appear in the storage ring at high intensity. This limits the number of turns in the storage ring that can be packed into the same phase-space volume. We therefore propose an alternative, in which the photoionization non-Liouvillean technique is used not at injection into the storage ring, but during the stage from the storage ring to the final bunch compression ring. This follows essentially an idea described by Hofmann (1989), in which foil stripping was suggested (for lighter ions). By using an appropriately pulsed laser beam, one can produce a short bunch, which after completion of the stacking is directed to the target. The main advantage of this new scheme is that the beam remains in the compression ring for only a relatively small number of revolutions; hence the phase-space density can go beyond the thresholds valid for extended storage time. In the storage rings, on the contrary, the phase-space density is reduced. Thus one can easily achieve stability with respect to the longitudinal microwave mode, which was not the case in the HIBALL scenario.

Moreover, with this non-Liouvillean compression scheme it appears possible to reach considerably higher power-density requirements than those for indirectly driven fusion (Meyer-ter-Vehn 1989), in which conversion of beam energy into soft X rays drives the target implosion. We consider the typical set of parameters for the driver accelerator that are listed in table 1.

The main motivation for indirect drive is an increased confidence in the target physics by avoiding the Rayleigh–Taylor instability of directly driven targets with nonrotationally symmetric beam illumination. It is noted that the specific beam power is more than an order of magnitude higher than in the old HIBALL case (6×10^{14} W/g). This can be achieved only by a reduction of pulse duration and focal spot size, which in turn requires smaller

TABLE 1. Driver accelerator parameters

Ion (typical candidate)	Bi^{+1} stripped to Bi^{+2}
Kinetic energy	10 GeV
Total energy	5 MJ
Number of particles	$N = 3.125 \times 10^{15}$
Final pulse duration	10 ns
Momentum spread at target	$\Delta p/p = 5 \times 10^{-3}$
Emittance at target	16π mm mrad
Specific power (ion range 0.3 g/cm^2)	5×10^{15}–10^{16} W/g

final emittance and momentum spread. On the other hand the complexity of the final beam lines in indirectly driven fusion is reduced, since beams impinge on two beam stoppers placed at opposite sides of the target, rather than illuminating the target from all sides as in directly driven targets. The main issue for the accelerator design is the increased phase-space density, which can be achieved only by a substantial gain due to a non-Liouvillean procedure. We note that the scheme discussed here is also attractive for an accelerator aiming at an ignition or low-gain target physics experiment at small repetition rate, which will be the subject of future studies (see also Arnold & Miler 1989).

2. Desired phase-space "compression factor"

Starting from the HIBALL accelerator as a reference, we estimate the desired "compression factor" in phase-space volume by the following conditions:

1. The enhanced beam power for indirect drive must be delivered.
2. The safety margin for stable operation (in the sense of beam dynamics) must be increased, in particular with respect to the longitudinal microwave instability.

In the absence of detailed information about the physics of indirect drive, we start from a first approximation of parameters, given in table 2, which could result in the required estimated specific power deposition (Meyer-ter-Vehn 1990). The main challenge is the factor of 9 reduction in spot area. This requires an appropriate reduction in the product emittance × (momentum spread), which enters into the following scaling relationship for chromatic aberrations (Hofmann 1983):

$$\epsilon \Delta p/p \propto r_0^2/L, \tag{1}$$

where L is the focal length (i.e., reactor chamber radius).

It is not enough to cut down only the momentum spread, since the final focusing optics also suffers from geometrical aberrations. If we use a simple scaling relationship (Hofmann 1983) for this, according to

$$\epsilon \propto r_0^{5/4}, \tag{2}$$

we find that the old HIBALL values need to be reduced by a typical set of numbers: (1) 4 times smaller ϵ, (2) 2.25 times smaller $\Delta p/p$, and (3) 2 times shorter pulse length. Here we have assumed that the shorter pulse is performed by additional rf compression conserving phase space. Hence, it requires a correspondingly lower initial momentum spread. We thus require a total factor-of-18 reduction in the product $\epsilon \Delta p/p$ in order to meet the new target requirements. In addition, we want to increase the momentum spread in the storage rings from the HIBALL value of 10^{-4} to (3–5) × 10^{-4}. This would have the advantage of a current that is below the threshold for the longitudinal microwave instability. In this case

TABLE 2. Parameter approximations

	Direct drive (HIBALL)	Indirect drive
Beam power	250 TW	500 TW
Absorber mass	400 mg	45 mg
Spot diameter	8 mm	2.7 mm
Final pulse duration	20 ns	10 ns
Specific power	6×10^{14} W/g	10^{16} W/g

the assumption of a stabilizing tail (Hofmann 1984b) in the momentum distribution, as is made for the HIBALL storage rings, becomes unnecessary.

The ideal case would thus be a total non-Liouvillean compression factor ≈ 50–100 in the product $\epsilon\Delta p/p$. This specifies—as a first orientation for the ideal case—that the non-Liouvillean technique should be applied to the stacking of 50–100 beamlets without significant increase of phase space. In this case one could use as an injector the HIBALL linac, but now with the much more comfortable momentum spread of 5×10^{-4} rather than 10^{-4}.

3. Schematics of the compression scheme

In the following we discuss some general features of the proposed non-Liouvillean compression scheme. We assume that the required 3×10^{15} particles are filled into ten storage rings, as in the HIBALL scheme. For Bi^{+1} and an emittance of 16π mm mrad we obtain a Laslett tune shift $\Delta Q = 0.21$ for the coasting beam, which should be tolerable for the assumed maximum storage time during filling of all the rings within 5–10 ms.

The photon beam from a free-electron laser is turned on for an interaction time Δt_i (which is a small fraction of the revolution time), during which the charge state is changed from 1+ to 2+ in a single transit. The simplest scheme (figure 1) uses two strong dipole magnets to separate the orbits. Owing to the double magnetic rigidity, one can introduce, by using superconducting magnets, an angle of the order of 100 mrad between the two beams and thus guide the doubly charged ion into the adjacent compression ring.

This method of using the laser in a combined function as a "razor" to cut off chops of beam of finite duration, and as a tool for non-Liouvillean stacking, is more attractive than a conventional rapid kicking of an rf bunched beam into the laser interaction region. The conventional kicking method has the disadvantage of requiring prebunching in the storage rings, which is associated with the questions of bunched-beam stability and increased ΔQ. The razor method, however, requires a higher laser power to produce a sufficiently steep rise of converted beam intensity.

Starting from a total power of 500 TW delivered by ten beams with a kinetic energy of 10 GeV, we obtain a particle current of 5000 A per beam. We assume that the short final pulse length of 10 ns can be achieved only by applying an appropriate bunching voltage (to be calculated later). The bunching should lead to a compression by a factor of 10 during the final transport from the compression ring to the target. Hence, in the compression ring the finally stacked bunch must have a particle current of 500 A and a duration of 100 ns. This could be a reasonable compromise in the following sense: a much shorter pulse length during stacking would require a correspondingly higher laser power, whereas a longer pulse length would increase the bunching voltage during final bunching and at the same time the final $\Delta p/p$.

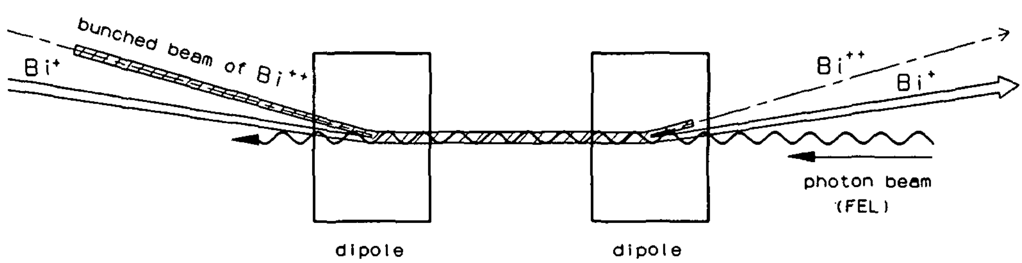


FIGURE 1. Scheme of photoionization non-Liouvillean procedure.

In order to arrive at an estimate of the minimum size of these rings, we consider a simple triplet focusing for the compression ring. We consider a dense arrangement of focusing quadrupoles in order to keep the transverse beam size as small as possible and choose, as the simplest case, a 6.9-m-long unit cell with focusing (F) and defocusing (D) magnets and drift spaces in between (O). The focusing strength is described in terms of the phase advance of the betatron oscillation per cell in the absence of space charge, which we have chosen as $\sigma_x = 88.4°$ and $\sigma_y = 90.0°$. The corresponding quadrupole lengths and gradients are

O	F	O	D	O	F	O	
1.5	0.5	1.0	0.9	1.0	0.5	1.5	m
0	77.5	0	−77.5	0	77.5	0	T/m

We observe that from the point of view of beam dynamics these compression rings are quite different from the usual storage rings owing to the large currents. At a current of 500 A, space charge reduces the betatron phase advance to $\sigma_x = 32.3°$ and $\sigma_y = 32.9°$. We observe that for straight-beam transport systems there is experimental evidence that such a strong space-charge effect is tolerable (Keefe, 1986). For this structure and 500-A current the maximum beam radius occurs in the central magnet in the y direction and has a value of 2.2 cm (for uniform density). This size is equivalent to a value of the "β function" (a normalized size in accelerator terminology) of about 30 m. The magnetic field at the beam edge is 1.7 T, which is probably too high from a practical point of view.

We solved numerically the Kapchinskij–Vladimirskij envelope equations for this simple system and plot the envelopes over 11 triplet cells in figure 2. Using the 3-m-long drift space between the triplets for bending magnets of 2-m length and 8-T field, we obtain a minimum radius of 47 m for the compression ring at a magnetic rigidity of 108 T m. In this case the ring has 43 unit cells and a zero-space-charge tune (i.e., number of betatron periods per revolution) of $Q_x = 10.56$ and $Q_y = 10.75$, where we have neglected any focusing effects from dipoles.

At 500 A and with the same emittance, the betatron tune is only $Q_x = 3.86$ and $Q_y = 3.93$, which indicates the quite serious effect of space charge that is expected under these conditions. The increase of beam envelopes in the center of the 3-m-long drift section due

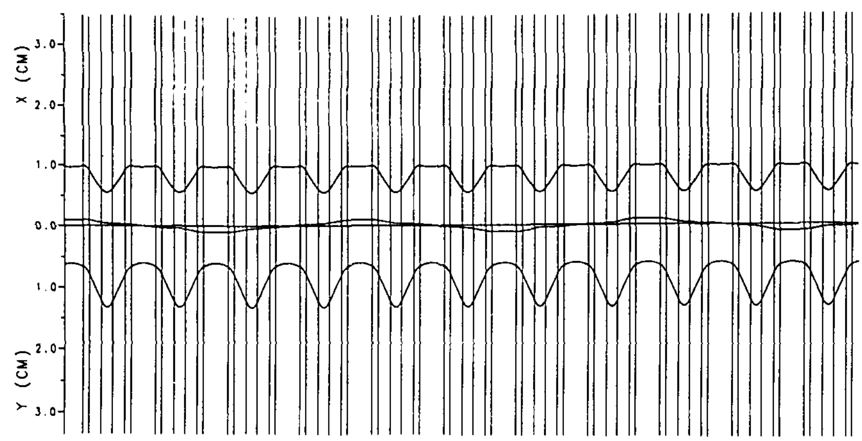


FIGURE 2. Beam envelopes for pure triplet focusing (zero space charge).

to the increase in the current by 10 A every triplet (instead of a full revolution realistically) is practically proportional to the current and leads to a doubling at the maximum particle current of 500 A (see figure 3). We note that this maximum current applies to the bunch center only.

As is expected, the main effect of the increasing current in this ideal regular lattice is the increasing beam envelope. We observe, however, that a convenient lattice design may require some insertions in providing space for the laser interaction region as well as for injection and fast extraction. The interruption of the regular structure can substantially change the smooth behavior of figure 3, owing to resonant effects of the insertions, which is discussed in Section 5.

The storage rings should have a larger radius to cope with the doubled rigidity. For convenience we chose a radius of 111 m, i.e., a revolution time of 7.5 μs. In order to arrive at a pulse length of 100 ns, we thus require a stacking factor of 75. For this radius the coasting-beam current in the storage ring is 6.67 A, which is still below the threshold of the longitudinal microwave instability.

Such a scenario is shown schematically in figure 4. We omit here a discussion of the injector linac and accumulator rings for current multiplication, which would follow very much the concept developed in the HIBALL study. From such accumulator rings the beam is injected into the storage rings, which are filled one after the other, under stable conditions, in 5–10 ms, depending on the linac current. Then the non-Liouvillean transfer into the compression rings occurs. Here we observe that the radius of the compression ring must be adapted to the storage ring radius in the following sense: after one revolution in the compression ring the bunch must not intersect with a gap of the storage ring beam, which requires an appropriate ratio of revolution times. The final beam transport lines (a stack of five beam lines from each side) must accommodate induction linac sections in providing a bunching voltage for a final compression from 100 to 10 ns; this requirement is discussed in the next section.

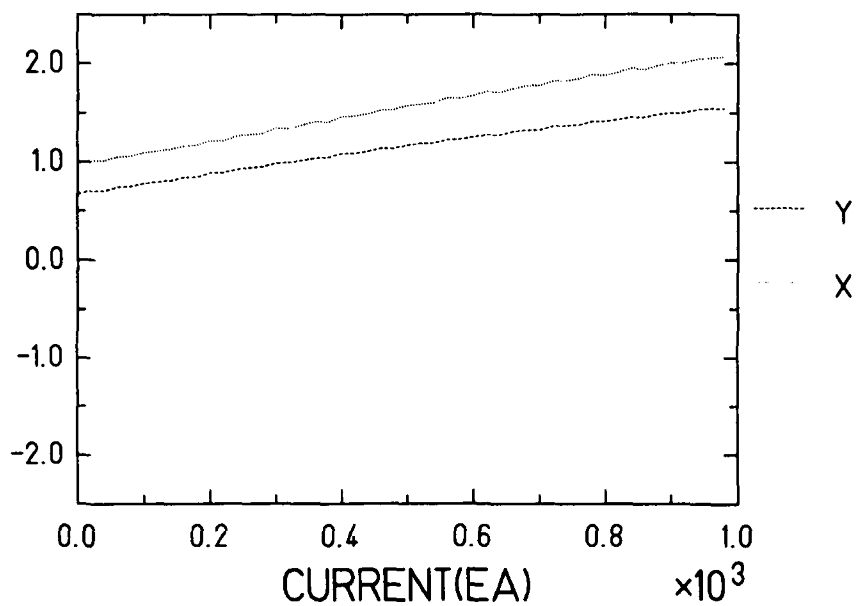


FIGURE 3. Dependence of beam envelopes (cm) on current (eA) for figure 2 lattice.

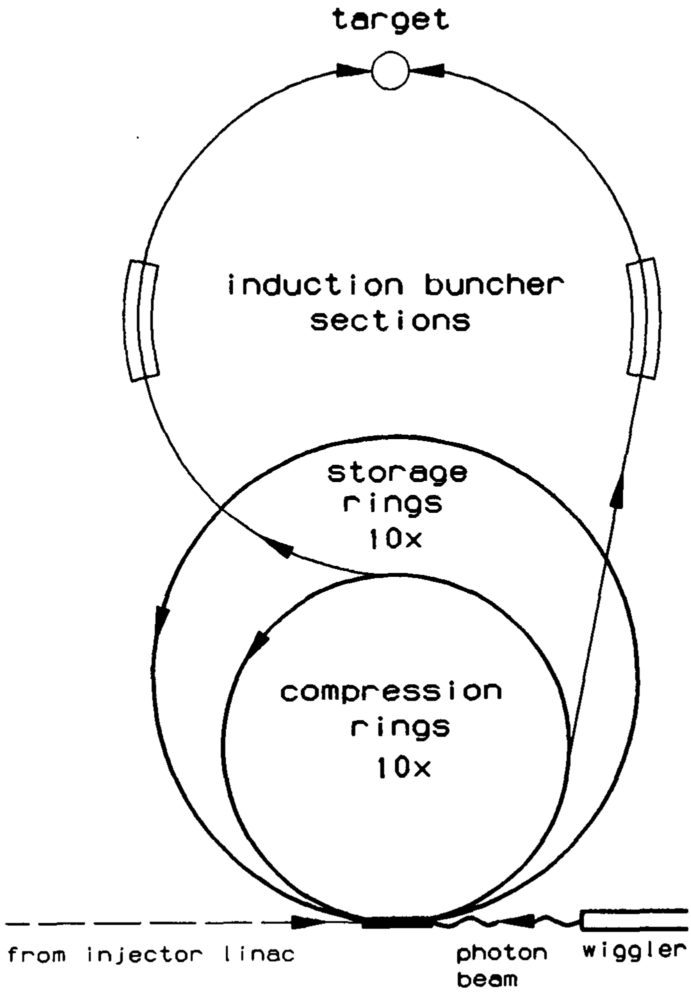


FIGURE 4. Scenario of storage and compression rings with final transport.

4. Longitudinal space-charge force in final transport

In order to define a realistic final bunch length of the very intense stacked beam, we need to consider the longitudinally repulsive effect of space charge, which must be overcome by an appropriate rf voltage in order that the bunches are at their minimum length at the time they hit the target. In HIBALL this voltage is supplied by rf cavities in the final rings.

It is easily seen that in our scheme it is inconvenient to supply this voltage by rf cavities in the compression rings. This would at least require a one-quarter synchrotron period, over which the bunches would not be stable. We thus need to apply the voltage in the transport lines from the rings to the target, and we suggest using a section of the induction cavities.

The required voltage can be calculated easily by means of the longitudinal envelope equation, which we solve backwards from the target. Space-charge repulsion then leads to a coherent initial momentum spread (Smith 1976), which must be provided by the cavities:

$$\left(\frac{\Delta p}{p}\right)^2_{\text{coh}} = \left(\frac{\Delta p}{p}\right)^2_{\text{targ}} + 3\,\frac{r_p g N Z^2/A}{\beta^2\gamma}\,(l_{\text{targ}}^{-1} - l^{-1}), \tag{3}$$

where N is the number of ions per ring; Z is the charge state of an ion of mass A; β, γ are relativistic factors; l is the starting bunch length (m); and l_{targ} is the length at the target (0.45 m for 10 ns). r_p is the classical proton radius ($= 1.53 \times 10^{-18}$ m); and $g = 1 + 2 \ln (R_w/R_b)$ is a geometrical factor (≈ 3) with R_w, R_o the beam pipe and beam radius, respectively.

For $(\Delta p/p)_{targ} \approx \pm 5 \times 10^{-3}$ we obtain $(\Delta p/p)_{coh} \approx \pm 4 \times 10^{-2}$. This requires a voltage ramp of about 800 MV, which can be provided by an induction linac section of typically 400-m length. It should be noted that only two such linac sections are necessary if the induction cavities are built around a stack of five beam lines. The relatively short starting pulse length (100 ns) should keep the cost reasonable.

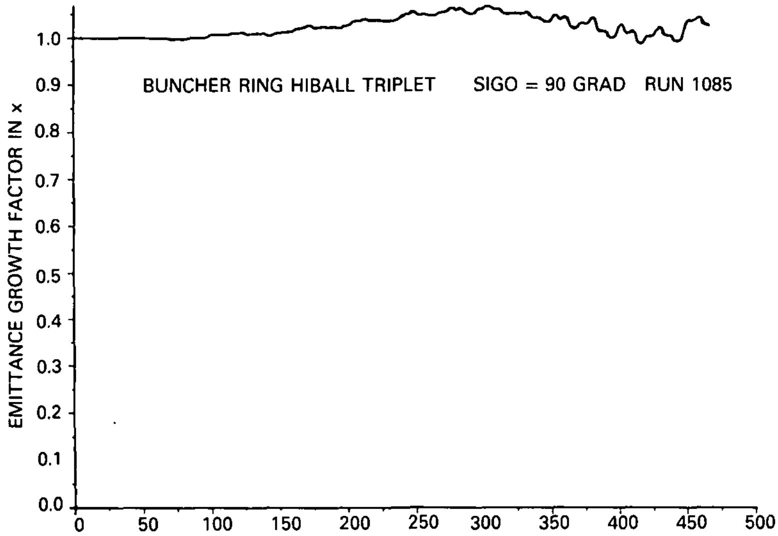
5. High-current beam dynamics in the compression ring

The non-Liouvillean stacking leads to a stepwise increase of beam current in the compression ring to a maximum value of 500 A. If we consider only 75 revolutions (i.e., 240 μs for the minimum radius) for this process, we can assume that there are no problems with single-bunch stability, even though the final current is far above the Keil–Schnell threshold for the longitudinal microwave instability. Also, we expect that there is no serious bunch lengthening due to space charge during the time considered. This requires, however, a more careful study, in particular if the bunch shape is nonparabolic, in which case there may be distorting effects due to nonlinear space-charge forces at the bunch ends.

We tried to gain some insight into the question of emittance growth in the transverse phase planes during current increase. The problem here is that the lattice must accommodate the zero-current bunch ends as well as the high-current bunch center, which is increased by 6.67 A every revolution (in our example). There is only very limited machine experience with bunches of an intensity such that the space-charge-induced betatron tune shift ΔQ exceeds considerably the "conservative" value of 0.25. At the CERN proton synchrotron (PS), emittance growth has been observed for bunches with initial $\Delta Q \approx 1.5$ (Möhl 1990). It is not clear to what extent these observations were specific for the PS focusing structure, and how the stepwise current increase discussed here modifies the effect of resonances induced by space charge. In a numerical simulation the effect of dipole errors during crossing of an integer resonance for the incoherent betatron tune has been found to be small (Hofmann *et al.* 1983), unless the coherent tune also crosses the integer. For the nonrelativistic energies considered here the coherent tune shift depends only on electrostatic images on the beam pipe; hence it can be made small for a sufficiently large pipe. This should not pose a problem for the low-emittance beams considered here.

We made a first attempt at studying the effect of space charge by computer simulation for the simplified model of a coasting beam, increasing the particle current from 0 to 500 A in steps of 10 A. This is equivalent to a 50-fold compression in phase-space density. We used a two-dimensional tracking code with space charge calculated by means of a Poisson solver (Struckmeier 1985). In most cases we used 500 simulation particles and modeled the current increase by increasing the charge per simulation particle appropriately. In all calculations we assumed a straight lattice, ignoring bending magnets.

The results were found to depend on the actual choice of the lattice; in particular, on the length of a superperiod. For a first orientation we studied the simplest case of the pure triplet structure shown in figure 2, in which superperiod is identical with the strong period. In figure 5 we show the change of the rms emittance with time in both transverse planes and note that there is practically no increase. This is in agreement with theoretical calculations (Hofmann *et al.* 1983) and experimental observations in long high-current transport chan-



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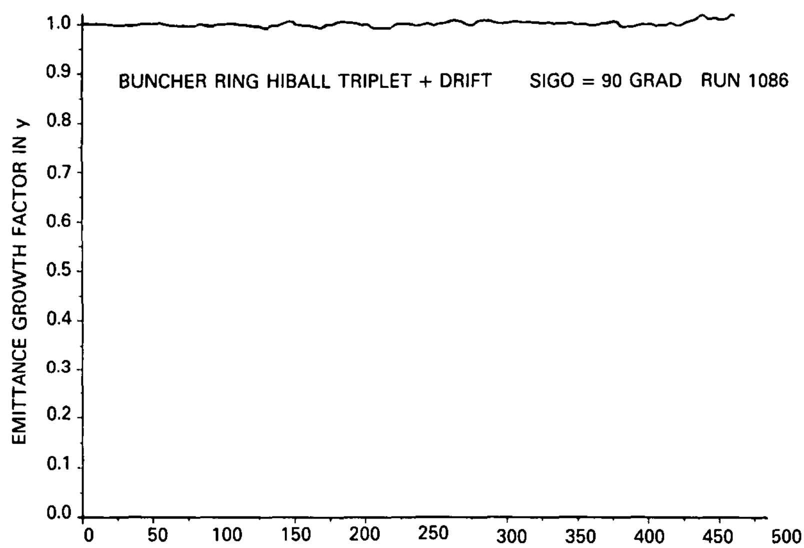

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FIGURE 5. Emittance growth factors for pure triplet focusing and particle current increased stepwise from 0 to 500 A.

nels (Keefe 1986), according to which no significant resonance of multipole oscillations occurs for a system with 90° phase advance per focusing cell.

We have compared these results with cases in which the superperiod consists of M triplets plus an insertion with a more extended drift section of 4.5-m length and four matching quadrupoles on each side. The insertion has a zero-space-charge phase advance of $\sigma_x = 283.7°$ and $\sigma_y = 151.4°$. At least one such insertion on the whole ring may be convenient for accommodating the interaction region with the photon beam (possibly another one for fast extraction). The more appropriate solution of the realistic problem with only one such insertion on the circumference is to transform the beam through $M = 43$ triplets at constant current and then step up the current by 10 A. Since this was beyond the capabilities of our code, we approached the realistic problem by studying "model rings" with one superperiod consisting of $M = 1$, 5, or 9 triplets plus the insertion, where the current is stepped up by simply increasing the charge per simulation particle. The matched-envelope solution for zero space charge is shown in figure 6.

An important parameter in interpreting the numerical results is the zero-space-charge tune per superperiod of these model rings:

No. of triplets M	1	5	9	43
Tune in xy	1.03, 0.67	2.02, 1.67	2.99, 2.67	11.59, 11.17

The results are summarized as follows in terms of rms emittance growth:

1. For the simple pure triplet focusing there is practically no increase of emittance (about 10%) during step up of current.
2. For $M = 1$ (i.e., a current increase after going through one triplet and one insertion) there is a wild envelope instability setting in after about 50 A and leading to a complete disruption of the transverse phase-space distribution.
3. For $M = 5$ there is only 20% of emittance growth (in x) up to 300 A and a somewhat larger growth of about 80% in the range 300–400 A (see figure 7). In the y direction the emittance growth is slightly weaker.
4. For $M = 9$ there is a doubling of emittances until about 300 A, and a further doubling until 500 A (in x and y).

Our conclusion is that the presence of an insertion seems to drive coherent transverse oscillations, which lead to growth of the rms emittance. In the case $M = 1$ this is obviously a quadrupole (i.e., envelope) mode (Hofmann *et al.* 1983), whereas in the $M = 5$ and $M = 9$ examples there is an indication that higher-order multipole oscillations are excited. This is due to the strong space-charge effect, which can be appreciated by noting that the current increase would depress the tune to about one-third of its zero-space-charge value if the emittance were unchanged. It should be noted, however, that, except for the case $M = 1$, the rms emittance growth is initially (up to 300 A) affecting only a relatively small

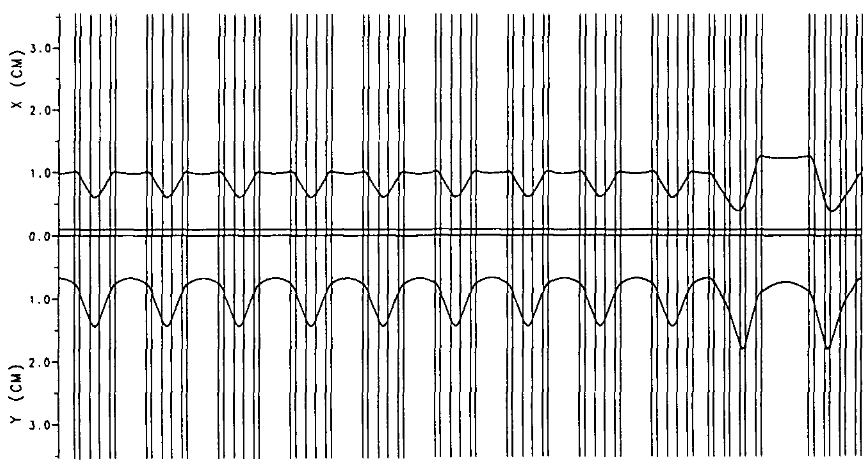
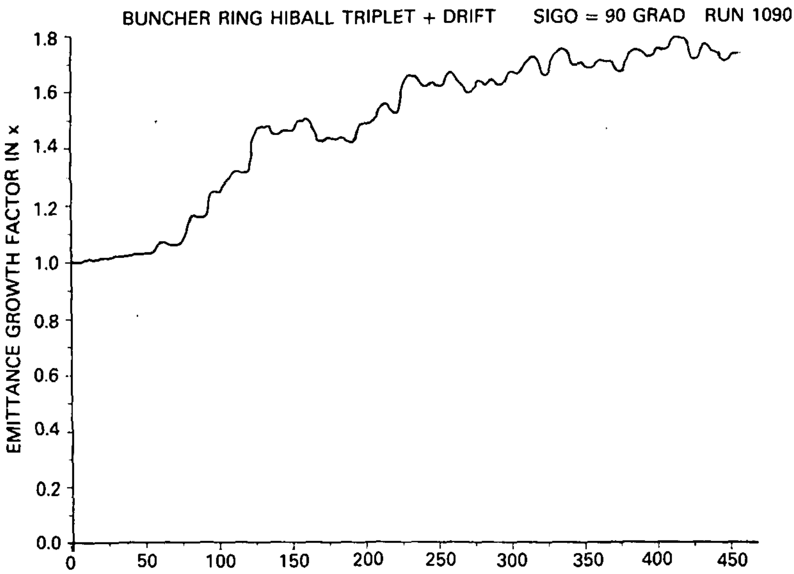


FIGURE 6. Matched envelopes for $M = 9$ superperiod (zero space charge).



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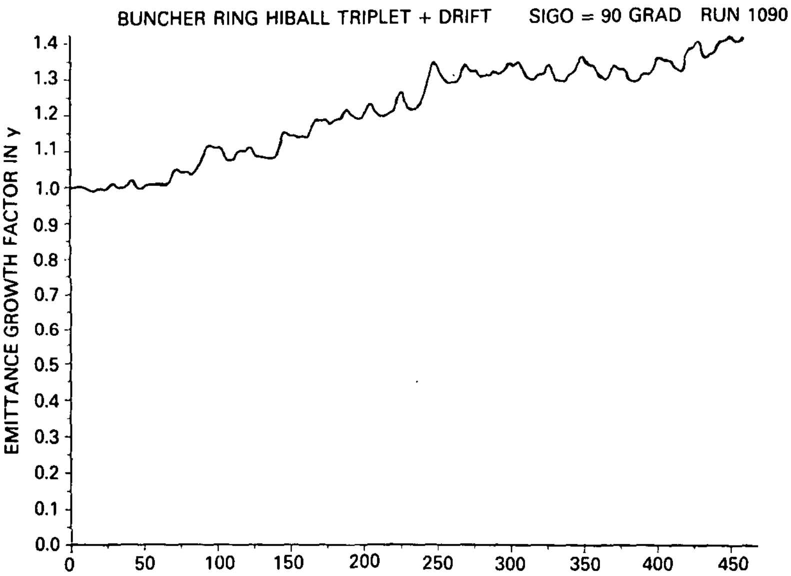

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FIGURE 7. Emittance increase for $M = 5$ superperiod during change of particle current from 270 to 360 A.

fraction of the total intensity, whereas the bulk of the occupied phase space remains at its original volume. Certainly, this subject requires careful consideration for realistic lattices before one can make reliable estimates of the maximum compression factor. In our example much of the emittance growth could be avoided if the total current increase were taken to be only half as much, i.e., depressing the tune to about two-thirds of its zero-space-charge value only. This would reduce the compression factor by a factor of 2 as well.

6. Discussion of FEL beam parameters

We first consider the photoionization process $Bi^{1+} \rightarrow Bi^{2+}$ (see Rubbia 1989) and assume a cross section σ_{ph}, a photon density n_{ph}, and a conversion path length Δl. With $\Delta N = N n_{ph} \sigma_{ph} \Delta l$ we find for 90% conversion that

$$n_{ph}\sigma_{ph}\Delta l \approx 2.3. \tag{4}$$

Since we are interested in pulses of doubly charged ions of 100-ns duration, we can allow for only typically 10 ns of interaction for the stripping process. This is equivalent to traveling over a distance of 93 cm for $\beta = 0.31$. We thus assume an interaction length of only 1 m and obtain

$$n_{ph} \approx 2.3 \times 10^{-2}/\sigma_{ph}\ (\mathrm{cm}^{-3}). \tag{5}$$

The β functions in the drift section of our lattice were typically 10 m in x and 5 m in y; hence for an emittance of 16π mm mrad we obtain a typical beam cross section of $F \approx 3\ \mathrm{cm}^2$. This allows us to calculate the power P of the photon beam for photons with energy E (eV):

$$P = 2.3\ (n_{ph} F\, ce\, E/\Delta l \sigma_{ph})\ (\mathrm{W}) \tag{6}$$

which for our example becomes

$$P \approx 3.3 \times 10^{-10} E/\sigma_{ph}\ (\mathrm{W}). \tag{7}$$

In the moving frame we require a Doppler-shifted photon energy of 20 eV for $Bi^{1+} \rightarrow Bi^{2+}$ and in the laboratory frame we require a Doppler-shifted energy of 14.5 eV. If we assume a cross section of $3 \times 10^{-17}\ \mathrm{cm}^2$, this requires delivery of a laser power of 160 MW during the pulse time of 100 ns.

This laser power might be higher than technically feasible, and therefore we looked at other ions with possibly more favorable cross sections. Measured cross sections exist for Ba^{+} ions (Lyon *et al.* 1986). For energies above the ionization threshold, namely at about 21.2 eV, these cross sections are as large as $2.8 \times 10^{-15}\ \mathrm{cm}^2$. They are sharply peaked and are due to resonant autoionization effects. Simple estimates show that the energy and angular resolution of our beams are roughly compatible with the resonance width, which is about 0.025 eV. For this case there could be a reduction of the required laser beam power by almost two orders of magnitude; hence 2 MW would be sufficient. In the literature we have not found information about cross sections for further ionization due to the repeated traversal of the doubly charged ions through the laser beam. These should be at least 2–3 orders of magnitude lower, which is realistic in view of the large resonant values for the transition 1+ to 2+.

7. Concluding remarks

We estimated that from the point of view of indirectly driven targets and of high confidence into beam stability in the accelerator it would be desirable to apply the non-Liouvillean stacking procedure to typically 50–100 bunches. In this case the current in the storage rings is still low enough to ensure stability with respect to the longitudinal microwave mode. The resulting maximum current of 500 A in the compression rings leads to a significant reduction of betatron tunes due to space charge. The ring lattice must be looked at as a high-current transport system in this case. We found by computer simulation that for a focusing lattice with only triplets the beam quality is practically conserved during the stacking process. This is in agreement with experimental findings for straight-beam long transport systems. The introduction of insertions and thus a superperiod can be a source of emittance growth owing to resonance of (transverse) multipole oscillations with this superperiod. This requires a more careful study of realistic ring lattices, and possibly somewhat lower maximum currents as a means of limiting the emittance growth. Another issue, which has not been addressed here, is the control of the longitudinal space-charge force during the stacking process. We expect a debunching effect, which can be compensated for by the voltage from rf cavities as long as the bunch shape is parabolic; hence the respective space-charge force varies linearly from the bunch center. For a nonparabolic bunch shape the problem is to tailor the rf voltage to the nonlinear space-charge force by means of several rf harmonics.

Regarding the photon beam the main issue is the required light power, which is in the reasonable range of a few megawatts provided that one can benefit from resonant cross sections of the order of 10^{-15} cm^2. The light beam must be pulsed with a duration of 100 ns per revolution period (about 5 μs) and it must be made available for each of the ten compression rings. A crucial issue is the design of an appropriate FEL with photon energy in a sharp resonant band of typically 20 eV at a width of 10^{-3}. As a basis for the design of the FEL, more atomic physics data (for different ions) than are presently available are needed.

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