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RECENT DEVELOPMENT IN INERTIAL FUSION BASED ON RF ACCELERATION

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Abstract

Heavy ions continue to be a challenging driver option for inertial confinement fusion. Completion of the GSI facility in 1990 provides an ideal testing ground for most of the accelerator issues for the rf linac/ storage ring approach to HIF. The status of this work is presented as well as the performance of an advanced driver scheme using non-Liouvillean stacking by photoionization of single charged ions. This scheme is expected to fulfil the increased power requirements of indirectly driven targets.

Introduction

The HIBALL study [1] has been the first overall system study for HIF. It has shown that the requirements for directly driven targets can in principle be met by conventional accelerator technology using an rf linac, several storage rings and buncher rings for final bunch compression. In that study it was, however, recognized that there are severe limitations due to the space charge of the intense beams and the associated emittance growth at various stages of the acceleration, stacking, storage and final bunch compression. The uncertainty of the HIBALL design would be serious, if several large emittance growth factors had to be accepted. It is accepted that the design of a consistent driver scenario has the highest priority among the various issues of inertial fusion (driver, target, reactor) [2]. The new GSI accelerator facility SIS/ESR - going fully into operation in 1990 - is suitable to answer most of these problems [3],[4],[5].

Recently Rubbia [6] has pointed out that the confidence in realizing a heavy ion fusion driver can be greatly increased by introducing a non- Liouvillean stacking from the linac into the accumulator ring. A related suggestion was made earlier by a group at Argonne National Laboratory who proposed to use photodissociation of molecular ions for non- Liouvillean injection from a synchrotron into a storage ring[7]. The most efficient use of the non- Liouvillean technique is, however, not at injection from the linac into the accumulator ring, but from the storage ring to the final bunch compression ring. This follows essentially an idea described in Ref. [5], where foil stripping was suggested for lighter ions. The main advantage of this new scheme is that the beam remains only a relatively small number of revolutions in the compression ring. Thus the phase space density can go far beyond the thresholds valid for usual storage times and power requirements of indirect drive can be fulfilled.

Status of SIS/ESR

The SIS/ESR (see Fig.1) is suitable as a testing ground for HIF machine and beam dynamics studies mainly for the following reasons:
(a) the UNILAC provides ions up to the highest masses.
(b) injection and re-injection from the SIS into the ESR gives a high flexibility in modes of operation.
(c) electron cooling allows to achieve maximum phase space densities for bunched and unbunched beams near the thresholds of instabilities.

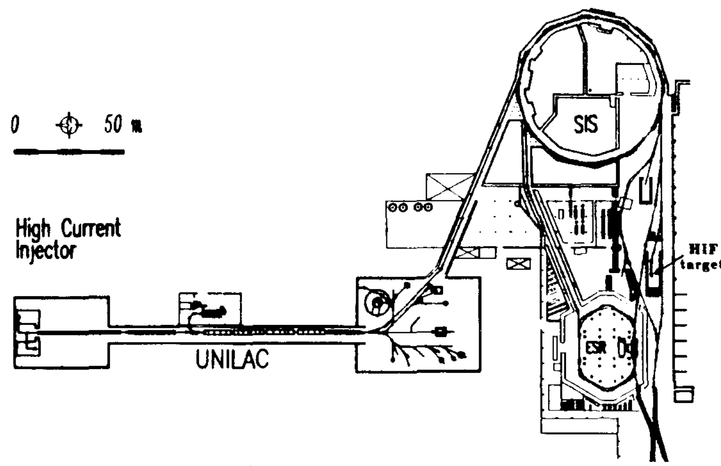

Fig.1. The SIS/ESR accelerator system.

Running-in Experiments

After beginning of operation of the ESR in April 1990 the main effort went into closed orbit, tune and chromaticity measurements and corrections. Electron cooling has been successfully demonstrated for beams of relatively low intensities (typically $< 10^8$ particles) with the Schottky diagnosis system, which indicates a decrease of $\Delta p/p$ from $\pm 2 * 10^{-4}$ to almost $\pm 10^{-5}$. An increase of the intensity by an order of magnitude due to a more efficient transfer of beam from the SIS into the ESR is the goal of the next machine development periods end of 1990. This will bring the cooled beam into the space charge dominated regime with all phenomena of collective behaviour, in particular instabilities and nonlinear space charge forces.

High-Current Injector

A high-current injector into the UNILAC is planned for completion by the end of 1992. It will provide a beam of 1.4 MeV/u of charge state 2+ up to the heaviest ions. A prototype of the first section of the 27 MHz RFQ is presently built in a collaboration with the University of Frankfurt. Together with electron cooling we expect to yield maximum intensities in a single bunch of up to 10^{11} particles and 2.5 kJ energy. In Table I we show the expected performance for a cooled Xe beam with the SIS filled by a high-current injector.

TABLE I
Expected Performance of Target Experiments at SIS/ESR

Ion	Xe^{44+}
N	$1.2 * 10^{11}$
energy MeV/u	1100
Δt nsec	70
total energy J	2500
power density TW/cm^2 (peak)	200
average range g/cm^2	25
specific power TW/g	8

This will permit new experiments on beam plasma interaction, generation of plasmas near solid state density and dense plasma hydrodynamics [8].

Beam Dynamics Investigations

Longitudinal Microwave Instabilities

A heavy ion storage ring must operate at intensities, which are above the conventional Keil-Schnell threshold for the onset of the longitudinal (resistively driven) microwave instability, otherwise it would be impossible to satisfy the requirements on beam phase space density. An important result has been obtained in the Heidelberg TSR electron cooling storage ring. In Fig.2 we show the Schottky noise spectrum of a coasting beam of 2.5 mA of C^{6+} at 11.7 MeV/u before and after cooling [9].

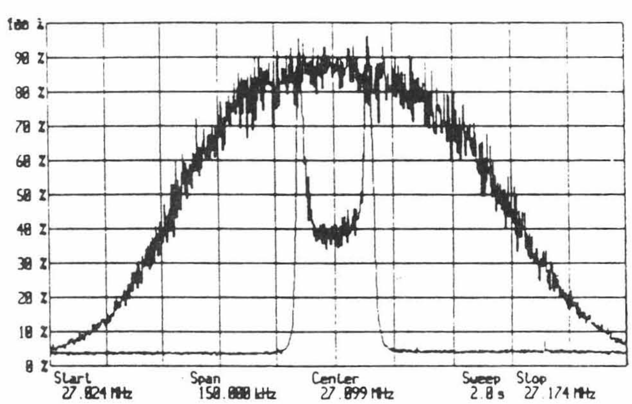

Fig.2. Schottky noise spectrum of uncooled and cooled beam in the TSR.

The uncooled beam noise spectrum reflects the Gaussian momentum distribution. The cooled beam spectrum (still with a Gaussian momentum distribution) shows two strong peaks, which are due to the excitation of collective oscillations. A theoretical evaluation of this noise spectrum has shown that it is equivalent to a current, which is a factor of 5.7 above the Keil-Schnell threshold [10]. The latter is usually defined for an assumed parabolic distribution; the cooling experiment has obviously resulted in a Gaussian distribution, which has extended tails that provide Landau damping and thus permit a higher current than a parabolic distribution.

This is an important basis for the design of the storage rings described below, where we can thus rely on a factor of 6 above the Keil-Schnell threshold. In the near future experiments can be performed in the ESR, which allow to study the resistive instability of bunched beams in the time domain. By stripping of a Ne^{3+} beam to Ne^{10+} we could exceed the threshold by an additional factor of 11 and investigate theoretical predictions on a nonlinearly evolving stabilizing tail [11] for beams far above the Keil-Schnell threshold.

Longitudinal Bunch Compression

In the ESR such experiments can be performed precisely under the conditions of final bunching in HIF, where the crossing of one or two integer resonances due to space charge forces is required. Cooling of a Ne^{3+} beam in an rf bucket of 0.16 kV amplitude to a space charge tune shift of $\Delta Q=0.01$, stripping to 10+ in the re-injection line to the SIS and subsequent rf bunching by rising the amplitude to 16 kV can lead to $\Delta Q \approx 1$. This results in crossing of an integer and two half-integer resonances. Moreover, the effect of nonlinear space charge forces can be studied by measuring the longitudinal beam current profile at different instants of the bunch compression.

Advanced Concept for a Driver with Photoionization

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 considerations:

1. *The higher beam power for indirect drive must be delivered. We are aiming for a power density of 10^{16} W/g.*

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.*

The main change is the smaller spot area by a factor 9. This requires an appropriate reduction in the product emittance times momentum spread, if we use as a first order estimate the following scaling relationship for chromatic aberrations [15]

$$\epsilon \Delta p/p \propto r_0^2/L \qquad (1)$$

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

In addition we want to increase the momentum spread in the storage rings from the HIBALL value of 10^{-4} to $3 * 10^{-4}$ to bring the current in agreement with the above discussed experimental threshold for longitudinal stability. In this case the asumption of a stabilizing tail [11] in the momentum distribution as assumed for the HIBALL storage rings becomes unnecessary.

The reduced spot area and stability of storage rings thus require a reduction in the product $\epsilon\Delta p/p$ by a typical factor 27. This can be achieved, for instance, by a non- Liouvillean "compression-factor" of 16 (i.e. 16-fold stacking) and an increase of the total number of beam lines to the target from 20 to 40. We remark that the beam overlap at the focal spot has a similar effect as the non- Liouvillean stacking in the sense that it helps save phase space volume.

Photoionization 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 10 storage rings similar as in HIBALL. For this purpose one could use as an injector the HIBALL linac, but now with the much more comfortable momentum spread of $3 * 10^{-4}$ rather than 10^{-4}.

For Bi^{+1} and an emittance of 16π mm mrad we obtain a Laslett tune shift in the storage rings of $\Delta Q = 0.21$ for the coasting beam. This should be tolerable for the assumed maximum storage time during filling of all the rings within 5...10 milliseconds.

The next step is the transfer of the coasting beams into the compression rings by photoionization stacking in a common section of the two rings. 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 (Fig.4) is using two strong dipole magnets to separate the orbits. Due to the doubled magnetic rigidity and by using superconducting magnets it is possible to introduce an angle of the order of 100 mrad between the two beams and thus guide the doubly charged ion into the adjacent compression ring.

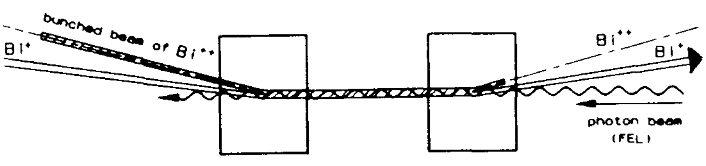

Fig.4. Scheme of photoionization bunch stacking

This method of using the laser in a combined function as "razor" to cut off chops of beam of finite duration, and as a tool for non- Liouvillean stacking allows to work with a coasting beam in the storage rings, rather than a bunched beam. The timing of the photon beam is such that the content of each storage ring is converted into 4 bunches of 100 nsec duration in the compression ring. This process takes 16 revolutions, after which an rf bunching voltage must be applied to compress the bunches from 100 nsec to 10 nsec by a fast bunch rotation. The final part of this rotation occurs within the beam lines to the target. The lattice of the beam lines most be sufficiently dense to transport the maximum current of 2.5 kA. For the above parameters we have calculated that this is consistent with a tune depression from $\sigma_0 = 60^0$ to $\sigma = 4.7^0$ for a pole-tip field of 3 Teslas.

The general scenario is shown in Fig. 5, where a stack of 10 storage and compression rings is required. We assume that the storage rings are filled one after the other by horizontal betatron stacking from the large accumulator ring, into which the linac beam is injected by vertical betatron stacking. A 8x8 stacking is required in order to step up a linac current of 122 mA to the storage ring current of 7.8 A. After transfer into the compression rings the final bunch rotation requires a coherent momentum spread of ±1% to overcome space charge, which can be provided by rf cavities in the compression rings. 20 beam lines should deliver beam on each target absorber disk.

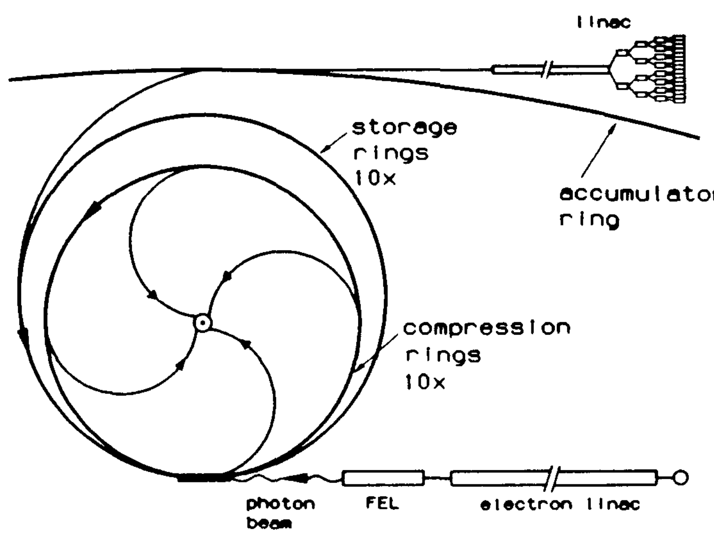

Fig.5. Advanced driver scenario.

High Current Beam Dynamics

Emittance growth in connection with the photon-ion beam interaction region is a crucial issue of the photoionization compression scheme, which leads to a step-wise increase of beam current to a maximum value of 250 A. As we consider only 16 revolutions for this process, we do not expect any 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.

Emittance growth in the transverse phase planes during current increase has to be examined more carefully. The problem here is that the lattice of the compression ring must accommodate the zero-current bunch ends as well as the high-current bunch center, which is increased by 15.8 A every revolution (in our example). The betatron tune in our case is depressed to about half of its initial value due to space charge, hence the beam dynamics of these bunches is more related to a linac than to a storage ring. 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 [16], 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 by taking a sufficiently large beam pipe. We conclude that integer crossing is not a problem and that the lattice behaves more like a linear system. Hence, the remaining problem is to study the beam dynamics in a lattice composed of 16 periodically repeating interaction sections, with transport sections in between that correspond to the length of the ring circumference.

We have studied the effect of space charge by computer simulation of a coasting beam by increasing the current in steps of 8 A every time the beam goes through the interaction region. The code we have used is a two-dimensional tracking code with space charge calculated by means of a Poisson solver. In most cases we have used 500 simulation particles and modeled the current increase by increasing the charge per simulation particle.

For the lattice of the interaction region one can consider either a "mini-beta" waist or a periodic transport section with dense focusing. A small size of the beam in the interaction region is crucial in order to reduce the required laser power. Here we report about results for the mini-beta solution. With the relatively large emittance we have found that a 0.3 cm radius waist can be used effectively over 1 m length. We have defined such a mini-beta system with matching quadrupoles to match to the periodic transport under zero current conditions. The results can be summarized as follows:

(1) With increasing current the waist has moved away from its original position. This mismatch has to be compensated by resetting the matching quadrupoles every time the current is increased.
(2) The stacking of the phase space distribution within the original emittance works in principle, but a small fraction of the particles develop into a ring halo in transverse phase space (see Fig.6)

This preliminary result is encouraging as it shows that with acceptance of a small loss of intensity one can indeed stack in transverse phase space, even under extreme space charge conditions.

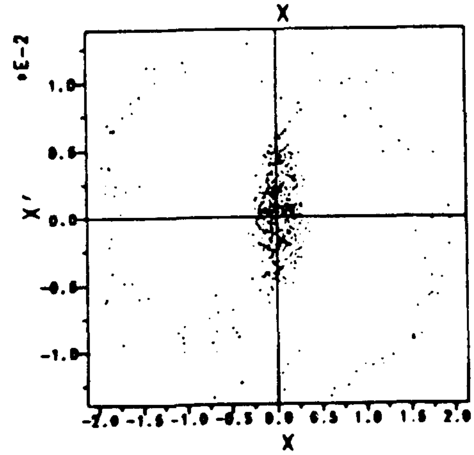

Fig.6. Transverse phase space after stacking.

FEL Requirements

We first consider the process $Bi^{1+} \rightarrow Bi^{2+}$ (see Ref.[6]) and assume a cross section σ_{ph}, a density of photons, n_{ph}, and a conversion path length Δl. With $\Delta N = N n_{ph} \sigma_{ph} \Delta l$ we find for 90% conversion that

$$n_{ph}\sigma_{ph}\Delta l \approx 2.3 \tag{2}$$

Since we are interested in pulses of doubly charged ions of 100 ns duration we can only allow for 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 1 m and obtain for the light beam of photons with energy E (eV) and a beam cross section F:

$$P = 2.3 \frac{FceE}{\Delta l \sigma_{ph}} \quad Watts \tag{3}$$

For our example with F=0.28 cm^2 we find:

$$P \approx 0.3 * 10^{-10} E/\sigma_{ph} \quad Watts \tag{4}$$

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 a Doppler shifted energy of 14.5 eV. If we assume a cross section of $3 * 10^{-17}$ cm^2 this results in a laser power of 16 Megawatts to be delivered in pulses of 100 ns duration.

This might be more than technically feasible, even with advanced FEL schemes. We have therefore looked at other ions with possibly more favourable cross sections. Measured cross sections exist for Ba^+ ions[17]. For energies above the ionization threshold, namely at about 21.2 eV, these cross sections are as large as $2.8 * 10^{-15}$ cm^2. They are sharply peaked due to resonant autoionization effects. Simple estimates show that the energy and angular resolution of our beams is 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 0.2 Megawatt would be sufficient. This is the average laser power, which can be delivered by a train of short pulses. The requirements on electron beam performance for a high-gain FEL at 80 nm wavelength are demanding. Bonifacio [18] has suggested a double undulator, where the first one is resonant at the more comfortable wavelength of 240 nm wavelength and generates a third harmonic bunching of the beam, which is amplified in the second undulator. Thus one obtains several Megawatts of light at 80 nm wavelength, which can be generated periodically by an electron linac.

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