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HEAVY ION FUSION RESEARCH AT GSI

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Heavy ion fusion research at GSI is dedicated to accelerator experiments and theory in the RF-Linac/Storage Ring approach as well as experimental work in ion beam focusing and ion beam plasma interaction. The status of the accelerator based work is summarized in this paper. Important topics along this line have been the studies on the European Ignition Facility, high current development at the SIS and beam target experiments, experimental and theoretical studies on the longitudinal resistive instability, bunched beam experiments using a streak camera as well as theoretical work on resonance crossing.

I. INTRODUCTION

The proposal of a European Study Group on an Ignition Facility [1,2] is based on the large potential of high energy accelerators for energy production [3]. Along with this proposal a parallel development of driver design and beam dynamics experiments and simulation has become a crucial issue. The potential of the SIS/ESR facility at GSI to carry out such "accelerator tests" has improved with progressive operating experience; the machine time available herefore is, however, limited by the increasing demands on beam time in different areas of GSI research.

Important progress has been possible with cooled high (longitudinal) phase space density beams in the ESR. The streak camera technique has been applied for the first time to the environment of an ion storage ring as an important tool of simultaneous time and space resolved diagnostics. This may turn out as useful for future optimization of high intensity bunch formation and resonance crossing. Dedicated experiments on the longitudinal instability driven by the impedance of the RF cavity are a significant step forward in one of the key questions in heavy ion fusion. The comparison with simulation has considerably raised our confidence in the reliability of particle-in-cell (PIC) simulation of such processes and in the predictions of simulation under conditions, which are difficult to study in experiments, like the dependence on initial perturbations.

Experiments with significant longitudinal as well as transverse space charge are planned in the near future in the SIS. Presently such experiments are modelled by computer simulation for the injection process into the SIS [4] and for transverse oscillations and resonance crossing phenomena [5].

II. IGNITION FACILITY STUDIES

In pursuing the goals of the Ignition Facility Proposal we have started to work on a first order design of the storage ring part with estimates of the final transport and compression as well as final focusing requirements. This enables us to define first order estimates of the necessary emittance and momentum spread and thus the minimum number of storage rings.

Generally speaking the requirements of an ignition driver are not too different from those of a reactor driver. The most obvious differences are a much lower repetition rate and smaller stand-off distance final lens to target. The latter assumes that wall and lens protection are substantially relaxed in an experimental facility; hence it seems acceptable to approach the target with the final lens as close as technically feasible and work with a somewhat larger emittance and momentum spread as in a reactor chamber. High repetition rate, on the other hand, is an inherent feature of high energy accelerators in general and related to the relatively low energy concentration if compared with pulsed power technology. Hence there is no obvious reduction of the complexity of the accelerator scheme due to low repetition rate. A main challenge for the design of the ignition facility therefore lies in exploring the upper limits (for final

focusing) of tolerable beam emittance and momentum spread. The use of space charge neutralization in the target chamber will have to be examined in this context.

We estimate that 50π mm mrad (unnormalized) is an upper limit of beam emittance, which requires pulsed lenses due to the serious packing problems if one needs to focus on a converter within a spatial angle not exceeding substantially $\pm 30^\circ$. This large an emittance allows us to use two storage rings only. In Fig. 1 we show one out of two such modules.

FIG. 1. Preliminary design of ignition facility driver for 3 Megajoules of 10 GeV Bi^+ , showing one out of two modules of storage ring & final transport.

From the point of view of RF compression the minimum number of bunches per ring is typically 16; for 8 bunches only the required compression voltage (MV/m) and final momentum spread (doubled!) would be prohibitively large.

An important constraint is the final momentum spread of $\pm 1\%$, which can be reduced only by working with a larger number of bunches. As it is desirable to work with a minimum number of bunches one needs as small a ring radius as possible, hence we have assumed an average dipole field of 4 Tesla. This poses severe constraints on the ring lattice design. For a first orientation we have assumed a super-period of 50 m length consisting of 5 cells with 66.6° phase advance and 2 drifts left empty for kickers or RF cavities. For a ring with 7 such super-periods the resulting tune would be $Q_0 = 6.48$ with only a modest space charge tune depression of 0.2 for the coasting beam current of 40 A; and of 0.5 for the bunched beam current of 100 A assuming a bunching factor $B_f = 0.4$. The effect of resonance crossing will be studied in the near future. It may be desirable to do a further compression by a factor 2 in the ring prior to the final linac compression, which would allow us to double the linac frequency.

An important boundary condition has been the final momentum spread of $\pm 10^{-2}$, which is a consequence of the relatively small number of bunches per ring presently considered, i.e. 16. This makes the final drift distance - after applying the final bunch compression voltage - quite short (≈ 120 m), hence on such a short distance it is only possible to remove the last or last two delay steps, which requires 20 resp. 40 m path difference. We have therefore assumed a bunch compression RF linac at the doubled frequency of 2.9 MHz, which needs to provide the relatively large gradient of 1.5 MV/m over 150 m length. The delays are mainly removed in a stack of 8 (or 4, if two delay steps after linac) delay rings making 8 (or 4) bunches synchronous due to an appropriately larger revolution time in the delay rings as compared with the storage rings. This requires 8 (or 4) parallel beam lines through the buncher linac. The remaining synchronization of 2 (or 4) bunches is performed after the buncher linac. In Fig. 2 we show the two outermost of a total of 16 arcs of the final focusing beam lines [6].

FIG. 2. Schematic layout of final focusing lines to reaction chamber showing 2 out of 16 (stacked) beam lines aiming at one converter.

The problem of injection of the space charge dominated linac beam into the storage ring with a large factor of current multiplication (≈ 100) is presently investigated. First results have been obtained for the longitudinal debunching problem and the adiabatic RF rebunching of the coasting beam on harmonic 16 [4]. The adiabatic rebunching appears to be possible during the period of 2 ms, which is short enough to be tolerable from the point of view of beam loss by intrabeam charge exchange [7]. The more difficult issue of transverse stacking with space charge will receive special attention in the near future.

III. EXPERIMENTS AT THE SIS

One goal of present SIS machine development is to reach the space charge limit for Ne^{10+} ions with 2×10^{11} particles. Presently we inject from the UNILAC 1.3×10^{11} ions, but only 50% are stacked by multiturn injection, with further loss of 30% during RF capture (see Fig. 3).

FIG. 3. Maximum SIS intensities N (ions per pulse) after multiturn injection (N_{inj}) and acceleration to 300 MeV/u for various injection pulse lengths.

A further important step will be made in 1997, when electron cooling and simultaneous multiturn injection into the SIS are expected to allow a significant intensity upgrade for heavier ions; in 1998 a high current injector will be ready for full intensity performance for all ions (see Fig. 4).

FIG. 4. High current upgrade plans for the SIS at GSI including cooling stacking (1997) and high current injector (1998).

This development is a necessary step to achieve the highest beam power deposition for ion beam target experiments. Presently the highest intensities for Ne yield sufficient power deposition to vaporize and form a plasma only for cryogenic rare gas targets, which have binding energies one order of magnitude lower than metals. Such an experiment was carried out with a 300 MeV Ne^{10+} beam of approximately 10^{10} particles depositing 1.1 J with a specific energy deposition of 60 J/g. A gas jet streaming out of the heated deposition volume could be observed. Furthermore some hydrodynamic motion was indicated by the emitted light. In the future it is planned to test hydrodynamical codes with such experiments (see Fig. 5 and also Ref. [8]). The further improvement of the performance of a high-current plasma lens is part of the experimental program. Its short-term goal is an increase of the specific energy deposition on the target with a focal spot of 200 μm , and its long-term goal a demonstration of its relevance to focusing in the experimental chamber of the ignition facility (see Ref. [9]).

FIG. 5. Cryogenic rare gas target heated by 300 MeV/u Ne^{10+} beam depositing 60 J/g. Gated CCD camera pictures showing a gas jet streaming out of the beam produced channel.

IV. LONGITUDINAL INSTABILITY STUDIES

During storage of coasting beams for several milliseconds there is a concern that currents exceeding the "Keil-Schnell circle threshold" by a large factor - here 10-30 times - might be subject to the longitudinal instability. It is well-known that for space charge dominated (inductive) impedance and a small resistive impedance the "circle" criterion is irrelevant as the actual stability boundary in the complex impedance plane depends very sensitively on the actual distribution function [10]. For a Gaussian momentum distribution it is onion-shaped and extends infinitely in the direction of inductive impedance, if no resistive component is present. In this case infinite current or vanishing momentum spread would be tolerable, whereas a small resistive component - relative to the space charge component - would still guarantee stability for large currents. In reality this argument may be questioned for several reasons: (a) is the linearized stability theory valid if finite initial modulations of the injected current are present? (b) the actual

distribution function after injection from a linac need not be Gaussian, but closer to parabolic; (c) what happens to the momentum distribution if the resistive impedance is finite and moves the working point somewhat outside the stability boundary? (for this case computer simulation has predicted the development of a super-Gaussian "stabilizing tail" [11]).

Experiments on the longitudinal instability with only limited relevance to our problem have been carried out in the past. The ISR experiments on the longitudinal instability driven by an RF cavity [12] have been performed at relativistic energies and compared with numerical simulation [13]. As space charge was negligible at those energies their findings are not directly applicable to the situation in heavy ion fusion. Another experiment was done at the appropriate energy of 50 MeV/u: observation of microwave signals during stripping injection into the ISIS synchrotron gave evidence of some growth of an initial (linac) modulation, but no quantitative analysis of the effect was possible [14]. Cooler ring experiments had shown that currents can exceed the "circle criterion" by a factor as large as 10, yet with the friction effect of the electron cooling continuously present [15].

This strongly justified the need for experiments and a comparison with results from computer simulation. We have therefore performed a first dedicated experiment with the following possibilities: (1) a variable (in frequency and strength) resistive impedance large enough to excite the instability, and (2) the option of turning off electron cooling at an appropriate time. We have realized this experiment in the ESR at an energy of 370 MeV/u by detuning of the eigenfrequency of the RF cavity at zero amplitude during beam cooling. At some point the eigenfrequency was rapidly shifted to the revolution frequency, hence the beam experienced its resistive impedance of 1200Ω , while simultaneously the electron cooling was turned off. As a result we were able to observe the longitudinal instability by the signal on the fast longitudinal pick-up, which is proportional to the current modulation. This is shown in Fig. 6 for a Ca^{20+} beam of 5 mA current over 200 ms corresponding to 3×10^5 revolutions.

FIG. 6. Longitudinal resistive instability driven by RF cavity at 370 MeV/u. Shown is the signal on a longitudinal pickup over a total time of 200 ms (20 ms/div).

It is seen that after shifting the RF eigenfrequency to the 2nd harmonic of the revolution frequency (at $T = 0$; a small initial modulation at this time is due to a residual voltage on the gap of some 50 V) there is an initial exponential growth and subsequently nonlinear saturation of the instability. Details of the current modulation recorded over $1\mu\text{s}$,

which is almost two revolution periods, are shown in Fig. 7 at different times during the evolution. It is noted that the originally exponential growth of a sinusoidal perturbation leads to steepening with a sharp gradient in the nonlinear saturation phase (see $T = 70\text{ms}$). A yet not well-understood phenomenon is the growing instability at high frequency ($\approx 90\text{MHz}$) after the fundamental mode instability has gone into saturation. This instability was not observed, if the fundamental mode was stable as was the case with the RF cavity sufficiently detuned.

FIG. 7. Full resolution current signals at different times (ms) of the evolution of the instability.

After calibrating the current level we have found that the self-bunching modulation of the coasting beam current is $\pm 50\%$. This level of nonlinear saturation agrees very well with computer simulation with the r-z particle-in-cell code SCOP-RZ/PATRIC, which takes into account the self-consistent electric field as well as an extra complex coupling

impedance on a given harmonic. For parameters corresponding to the experiments and a purely resistive cavity impedance of $ReZ = 1200\Omega$ simulation results are shown in Fig. 8. The simulation also reproduces the sharp steepening effect at the wave front. Note that the unstable slow wave moves to the left in the beam frame; this picture is time reversed in the lab frame, since the slow wave moves opposite to the beam direction. From the corresponding longitudinal phase space evolution it is seen that the instability develops some kind of bucket ("phase space cavity"), which leads to trapping of part of the distribution and a slowing down, i.e. shift to negative velocities in the beam frame as well as an overall broadening.

FIG. 8. PIC simulation of longitudinal instability: left column showing longitudinal phase space at different times after start; right column corresponding line current profiles (time replaced by distance around circumference).

We have also carried out a number of experiments where the eigenfrequency of the RF cavity was detuned by a few 10's of kHz, which allows to vary the resistive impedance from the maximum value of 1200Ω down to values as small as 100Ω . At the same time the cavity offers an imaginary part of the impedance, which increases or decreases the

space charge impedance depending on the direction of detuning. For small resistive impedance of only a few hundred Ohm we observed no instability at all, which is in full agreement with simulation and also the stability diagram for an assumed Gaussian momentum distribution. We conclude that the broadband impedance alone - estimated to $Z/n \approx 50\Omega$ in the ESR [16] - is hence not exciting any instability. The phase space density in these experiments was such that in the best cases the current exceeded the Keil-Schnell circle threshold by a factor 7. The corresponding Schottky noise spectrum of such a cold beam prior to the instability (i.e. RF cavity frequency far away) is shown in Fig. 9 (top), along with the noise spectrum after the saturation phase of the instability (bottom). We observe that the noise has pronounced coherent features contrary to the usually observed incoherent noise.

FIG. 9. Measured Schottky signal (noise power vs. frequency) recorded at 63.8 MHz prior (top) and after (bottom) instability.

In a different beam time with lower current, but extremely well cooled, we have had a case where the nonlinear wave profiles showed nearly time-symmetric triangular waves rather than the sharp steepening at the wave front

observed previously (see Fig. 10). By means of simulation we were able to recognize that the origin of this was an unintended detuning of the RF cavity frequency such that apparently its imaginary part largely cancels the space charge impedance, which is normally responsible for the real part of the frequency shift, i.e. wave propagation velocity. Thus the resulting instability is dominated by amplitude growth rather than wave propagation, which leads to nearly complete self-bunching and peak currents as high as four times the original coasting beam current.

FIG. 10. Longitudinal instability observation with detuned RF cavity (mainly growing instability) showing full time history over 400 ms (top) and fully resolved (bottom) with observation of triangular waves and nearly complete self-bunching.

Our confidence in using simulation to predict stability properties under the even more difficult conditions of a driver storage ring has considerably increased with these experiments. In the future it is planned to explore systematically the effect of different impedances as may be expected for an ignition storage ring for both coasting and bunched beams.

V. BUNCHED BEAM DIAGNOSTICS

Besides heavy ion fusion there are several other applications of intense charged particle beams, such as spallation neutron sources or radioactive waste transmutation, where knowledge of the space charge distribution in all three dimensions is required in order to determine the ultimate intensity performance and possible sources of phase space

dilution. In view of this fundamental interest in time and space resolved measurements we have applied the streak camera technique frequently used in plasma physics to the environment of an ion storage ring [17]. This has enabled us, in particular, to perform correlated measurements between time and horizontal deviations. The bunches have been cooled by electron cooling to a stationary state on a time scale of seconds. Thereafter they have been extracted in one turn and guided to a plastic scintillator, the light of which was recorded by the streak camera.

The histogram of a streaked image of a C^{6+} cooled bunch with 1.15 mA (distributed over two bunches) is shown in Fig. 11. The CCD screen has a resolution of 512x512 pixels. Cuts through the bunch center indicate Gaussian profiles both in horizontal and longitudinal direction.

FIG. 11. Histogram of streak camera image of electron cooled C^{6+} bunch at 250 MeV/u.

We have evaluated quantitatively the horizontal width by Gaussian fits and plotted the 1σ deviation against time (in pixels), i.e. longitudinal position. This is compared in Fig. 12 with the intensity curve obtained by summing up at each time pixel the intensities of all horizontal channels. In this example and in all other cases evaluated we have found that the beam width is constant over $\pm 2\sigma$ longitudinal deviation within $\pm 5\%$ accuracy. This observation allows us to conclude that we deal with a "cylindrical bunch model" as opposed to "ellipsoidal" or other bunch models. For a bunch that is - in transverse direction - not dominated by space charge, the constant width is equivalent to constant emittance or temperature. This is precisely the property of a Maxwell-Boltzmann distribution (see, for instance, Ref. [18]), which we have thus verified by our measurements:

$$f = c_0 \exp\left(\frac{-H_{\perp}}{k_B T_{\perp}}\right) \exp\left(\frac{-H_{\parallel}}{k_B T_{\parallel}}\right) \quad (1)$$

We have assumed here constant focusing ("smooth approximation") and allowed for different temperatures in the transverse and longitudinal degrees of freedom. In the case of a transversely space charge dominated bunch obeying a Maxwell-Boltzmann distribution the spatial shape is expected to become more ellipsoidal. Verifying this experimentally with the streak camera method is planned for the future, when low kinetic energy necessary for large transverse

space charge effects is feasible in the ESR.

FIG. 12. Intensity (horizontally integrated) vs. time (top) and bunch width vs. time (bottom) for C^{6+} double bunch evaluated from streak camera data.

VI. RESONANCE CROSSING

In the preliminary concept of the ignition facility only a relatively modest space charge induced tune shift of $\Delta Q \approx 1$ is anticipated for the storage rings, if most of the final bunch compression is performed in the buncher linac. This would still require crossing of a half or an integer resonance at relatively low speed of several hundred turns. For considerably faster crossing results obtained in an experiment at the CERN PS have led to the conclusion that $\Delta Q \approx 1$ leads to acceptable emittance growth [19]. It is planned to examine the slow crossing in an experiment at the SIS in the near future. For this purpose we have started a systematic study by means of simulation of the role of space charge - taken into account fully self-consistently - in crossing different kinds of resonances:

- envelope instability (σ_0 exceeding 90° per cell as is the case for the SIS);

- systematic half-integer stopband due to super-periodicity (as in the ESR);
- error resonances due to integer, half-integer and higher order resonances;
- fourth order resonances excited by the space charge nonlinearity itself.

For the first two cases it was confirmed by simulation that even fastest crossing is impossible through such stopbands that are inherent to the lattice structure [5].

VII. OUTLOOK

In the context of the ignition facility study we have started parallel efforts in accelerator design of the storage ring & final transport section as well as in accelerator experiments with emphasis on the main high current issues. These experiments are presently using the electron cooling technique in the ESR, where the experiments on the longitudinal instability can be further pursued only after the shut-down period of the ESR is ended in the first half of 1996. Meanwhile experiments at high current level are in the process of realization for light ions in the SIS (debunching, adiabatic capture, resonance crossing). In this effort computer simulation plays an important role in order to bridge the gap between existing experiments and the conditions of an ignition driver, where all space charge limits have to be pushed to the very extreme. The agreement found in comparing experiment and simulation in the relatively complex situation of the nonlinear behaviour of the longitudinal instability has been encouraging in this regard.

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-
- [1] *Proposal for a European Study Group: Heavy Ion Ignition Facility*, GSI-Report GSI-95-03, Darmstadt (1995)
 - [2] G. Plass, this Conference.
 - [3] R. Bock, Proc. EPS Conference on Large Facilities in Physics, Lausanne, Sept. 12-14, 1994, p. 348 (1995)
 - [4] U. Oeftiger and I. Hofmann, this Conference.
 - [5] R.W. Hasse and I. Hofmann, this Conference.
 - [6] P. Spiller et al., this Conference.
 - [7] D. Budicin et al., *Nuovo Cimento* **106A**, 1621 (1993)
 - [8] M. Dornik et al., this Conference.
 - [9] M. Stetter et al., this Conference.
 - [10] A.G. Ruggiero and V.G. Vaccaro, CERN-Report ISR-TH/68-33, CERN, Geneva (1968)
 - [11] I. Hofmann, *Laser and Part. Beams* **3**, 1 (1985)
 - [12] B. Zotter and P. Bramham, *IEEE Trans. Nucl. Sci.* **NS-20**, 830 (1973)

- [13] E. Keil and E. Messerschmidt, Nucl. Instr. Meth. **128**, 203 (1975)
- [14] R.L. Martin et al., Nucl. Instr. Meth. **A278**, 151 (1989)
- [15] I. Hofmann, Proc. 1991 Part. Accel. Conf., San Francisco, May 6-9, 1991, p. 2492 (1991)
- [16] G. Kalisch, Dissertation, GSI-Report GSI-94-05, Darmstadt (1994)
- [17] I. Hofmann et al., to be published in Phys. Rev. Letters
- [18] M. Reiser and N. Brown, Phys. Rev. Letters **71**, 2911 (1993)
- [19] R. Cappi et al., Proc. EPAC 94, London, June 27 - July 1, 1994, p. 279 (1994)