High Current Beam Physics Group

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In 1998 the High Current Acceleration Group has focused its work on completing the HIDIF (Heavy Ion Driven Inertial Fusion) Report [1], investigations in connection with a future GSI facility, and beam physics studies in circular machines under conditions of high space charge. The efforts in developing our computer simulation capabilities (1D, 2D and 3D codes including all possible cooling and dissipative mechanisms) have resulted in new possibilities to interpret and model high intensity phenomena in existing facilities as well as future scenarios.

1 Studies Related to a Future Facility for Plasma Physics

An important focus in the discussion of a new accelerator facility at GSI has been the advancement of plasma physics target experiments to significantly higher bunch energies (10's of kJ) and target temperatures (30-100 eV). It was found that the optimum performance for plasma physics near and above 100 eV could be achieved with a 100 Tm synchrotron accelerating the U^{4+} beam from the high current injector (Fig. 1).

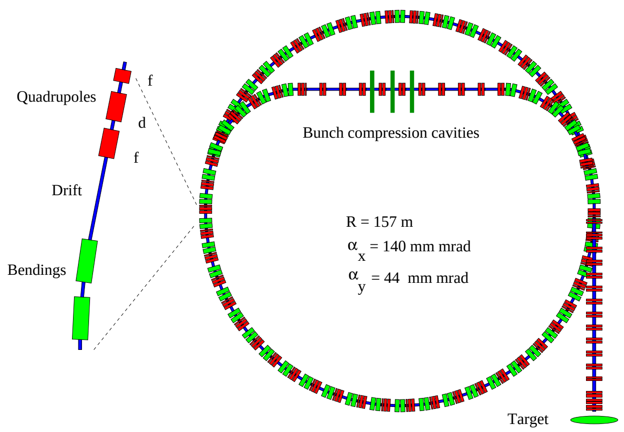

Figure 1: Lattice example of a 100 Tm synchrotron for plasma physics applications to reach 100 eV in solid Au using 10^{13} U^{4+} ions at 127 MeV/u.

After multi-turn injection of 20 turns and acceleration to 127 MeV/u at h=4 the bunches are merged into a single bunch, which is compressed to 30-40 ns bunch length by a fast rotation using 2-3 MV/turn of RF at 145 kHz. The resulting 40 kJ energy in one bunch are focused on a target with 0.8 mm radius, which leads to 100 TW/g specific energy deposition and roughly 100 eV temperature. A major challenge is the computer modeling of bunch compression in such a facility (with the compression cavities assumed in the bypass section) and the issue of emittance growth in the presence of dispersion and space charge. The subject was found to be an issue also for compression in the SIS.

1.1 RF and Induction Compression Schemes

Economic considerations dictate that the axial bunching needed to achieve high intensity on target be carried out in a ring using a fast bunch rotation of the longitudinal phase-space. Studies have shown that both magnetic alloy RF cavities developed for this purpose at GSI and new, high rep-rate induction technology already tested at LLNL are consistent with the likely range of project options. This new induction technology is based on FET electronic modulators, and working designs have been operated at up to 2 MHz pulse repetition frequency with 3 μs to 200 ns micropulses at 22 kV/m.

Various RF bunching prescriptions were explored and it was found that low-order harmonic smoothing provided optimal use of cavity bunching voltage [2]. This simple smoothing (4 harmonic with a 75% ring initial prebunch) is readily realized without dynamic RF harmonic control, minimizes prepulse due to nonlinear phase-space wrapping, and optimizes peak power on target with respect to total RF voltage. It was anticipated that a required bunching could be carried out with less total induction voltage since the high rep-rate modulators allow sufficient pulse flexibility to shorten compression waveforms from lap to lap as the bunch compresses, thereby making more effective use of a given bunching voltage. Comparisons showed that equivalent amounts of bunching to the optimal RF prescription could be achieved with induction technology using a factor of 0.4 times the optimal RF bunching voltage (assuming yet untested bipolar modulators with self-reset cores) to a factor of about unity (existing, conservative unipolar modulators with applied reset). This saving in the assumed bipolar case results from both this more efficient use of bunching voltage and from the self-reset induction core enabling a full ring prebunch which gives a more efficient phase-space rotation. In the conservative, unipolar case, the savings due to waveform flexibility are mitigated due to a factor of 2 cost from the need to independently synthesize each bunching polarity and the need for a lesser prebunch fraction of the ring to allow time between pulses for induction core reset as the bunch circulates from lap to lap.

As a practical matter, induction technology may be cheaper than RF per volt of bunching potential since it eliminates the need for RF tubes, and the high-rep rate electronic modulators allow simple bunching waveform adjustment to vary the pulse profile on target, compensate for errors, etc. It is also anticipated that in fast bunching, significant waveform noise can be tolerated in induction modulators since the bunching occurs only over a quarter synchrotron period of longitudinal particle oscillations. Impedances are expected to be similar for the two technologies. Full engineering evaluations of waveform control and costing will be needed to make a final decision on which technology to employ in future scenarios. Such tests are more critical with the more attractive option of bipolar induction modulators since waveform control while the material is driven through saturation could be an issue. It is hoped that such evaluations will be undertaken in the coming year.

1.2 Dispersion and Space Charge Effects in Rings

Fast bunch rotation schemes call for the compression of an initially prebunched beam in a ring with a momentum spread of $\Delta p/p \sim 10^{-4}$ to a final spread of $\Delta p/p \simeq 10^{-2}$ at the final focus optic. The transverse space-charge strength and incoherent momentum spread at mid-pulse rapidly increase during the final phase of this compression. For the range of rings considered, this compression takes place over 50-150 laps and, in the absence of transverse emittance dilution, results in 1-4 integers of space-charge induced tune shift at peak compression. This combination of strong transverse space-charge strength and large momentum spread in the ring and the extraction line to the target lead to numerous issues in maintaining transverse beam focusability (i.e., limiting emittance growth). These issues are essentially the same whether the compression is implemented by RF or induction technology and are being explored with a hierarchy of two- and three-dimensional electrostatic PIC simulations employing codes developed at GSI and LLNL[3]. These simulations include lattices with varying levels of detail, a proper treatment of dispersion, and self-consistent space-charge fields. The focus has been on identifying and understanding emittance growth processes as opposed to evaluating detailed designs.

A simulation of a characteristic mid-pulse rms emittance evolution is shown in Fig. 2 for a 180° phase-space rotation (over 120 laps) in an 18 Tesla-meter FODO ring with strong space-charge parameters. This simulation was produced by the WARP code developed at LLNL agrees with micro-map and PIC simulations with GSI codes. The in-bend-plane x-emittance undergoes a large increase at peak compression (90°, 60 laps), whereas the out-of-bend y-emittance undergoes a smaller, nonlinear space-charge driven increase. The thickness of the x-emittance trace indicates the amplitude of emittance oscillations at the particle betatron frequency that are induced by the (initially matched) distribution being dispersion mismatched due to the bunch compression. The envelope of oscillations moves up as the compression-pumped momentum spread increases. In the absence of space charge, resonance effects, etc., such emittance growth induced by distribution distortions represents correctable, "reversible" growth. Such a correction can be implemented by extracting the beam at a dispersion function null point or bending the extraction line appropriately to correct the distortion. With space-charge, resonances, etc., a component of this growth is thermalized in the distribution and represents "irreversible" growth. Such irreversible growth must be understood and controlled since it can interfere with the correction of the large, reversible growth component. The increases in emittance at the 180° rotation point provides a measure of the irreversible growth, since the momentum spread is approximately the initial value at this point. Preliminary considerations suggest that the following processes are issues of concern:

- Nonlinear space-charge forces, chromaticity in focusing elements, and possibly additional processes phase-mixing otherwise reversible distribution distortions into irreversible growth.
- Space-charge leading to a broadening and mismatch seeding of envelope instabilities associated with high phase advance parameters sometimes employed for increased dynamic aperture.
- Discrete kicks from bunching cavities/cells when placed at points of nonzero dispersion.

Other issues such as space-charge induced resonance crossings, dispersion induced integer resonance crossings, and transverse/longitudinal coupling seem to be less problematic. Progress has been made, but continued work is necessary to better understand these processes (which are not fully decoupled) and determine reliable design criteria.

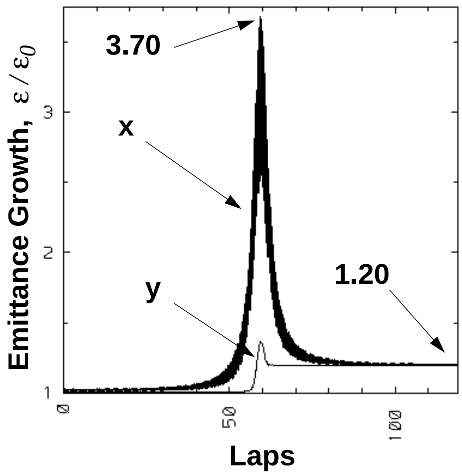

Figure 2: RMS emittance growth verses ring laps of the bunch centroid in a typical bunch compression scenario assuming a 180° rotation.

2 Simulation Code Development

A 'High Current Simulation Code Project' was established to help increasing our understanding of basic space charge and kinetic effects that limit the quality and the intensity of intense ion beams in ring machines. The optimization of the existing GSI heavy ion accelerator facility for high beam intensities and the design of a new high current ring accelerator facility at GSI are potential applications. Likewise the code can be applied to bunch compression experiments in the SIS to model similar manipulations in heavy ion fusion storage rings.

The code self-consistently tracks macro-particles through arbitrary focusing lattices together with the space charge field and the fields induced in the ring environment. In addition it will be possible to include cooling mechanisms and intrabeam scattering (IBS) on a kinetic level. The code is written in a modular fashion. 1D, 2D and 3D simulation geometries can be chosen. The accurate simulation of space charge effects in ring machines is a time and memory consuming task. Therefore a parallel computer (20 processors) was installed at GSI for the realistic modeling of high intensity phenomena in existing facilities as well as future scenarios. The parallel implementation of the code uses direct message passing routines as well as FFT library functions for the parallel Poisson solver.

The comparison of the numerical results with analytic calculations for simplified problems is one of the most time consuming part of our simulation project. For the moment we use the code to study the resistive longitudinal instability, halo generation and emittance growth in mismatched beams and bunch compression.

The simulations of the longitudinal instability focus on the long time behavior observed in the ESR [4]. In Fig. 3 snap shots of the distribution function together with the line density and the velocity distribution are shown. First the slow wave steepens and decays by trapping particles in the self-excited potential. The resulting hole structure has a life time of several 100 ms before it starts to smooth out due to IBS. During this period the 'hole' causes localized line density dilutions. The excited hole structure can be regarded as a collective mode, similar to a traveling BGK-like (Bernstein-Green-Kruskal) wave [5] caused by non-linear Landau damping in ideal plasmas [6]. We find that due to the presence of the resistive impedance a pure stationary BGK solution cannot be reached, even in the absence of IBS. The 'holes' cause local current perturbations that continue interacting with the resistive impedance. Consequently, after the first saturation stage a second hole structure is excited.

For multi-turn injection schemes space charge induced emittance growth and halo generation are potential threats. Therefore we started the systematic investigation of emittance growth and halo generation due to beam mismatch in the SIS. Fig. 4 shows the phase space evolution resulting from our simulation of an initially mismatched beam (Ne^{10+}, 2 mA, 11.4 MeV/u) in the SIS. Space charge causes the filling of the available phase space area within 30 turns.

3 Longitudinal-Transverse Resonance in 3D Halo Formation

We find that in space charge dominated ellipsoidal bunched beams a coherent (2:1, i.e. parametric) resonance condition is responsible for coupling between transverse and longitudinal mismatch eigenmodes and 3D halo formation. The bunches are allowed to be non-equipartitioned, and may deviate noticeably from spheroidal. We can easily explore this coherent resonance behaviour by using the nonlinear envelope equations. For simplicity we assume constant focusing and bunched beams with a rotational axis, which restricts the analysis to the transverse "breathing mode" [7] generalized by the presence of longitudinal motion, as well as a longitudinal mode. The rms envelope equations can be written as

$$\frac{d^2a}{dt^2} + k_{0,x}^2 a - \frac{3Nr_c}{2\beta^2\gamma^3 ac}\left(1 - f/\gamma^2\right) - \frac{\epsilon_x^2}{a^3} = 0 \qquad (1)$$

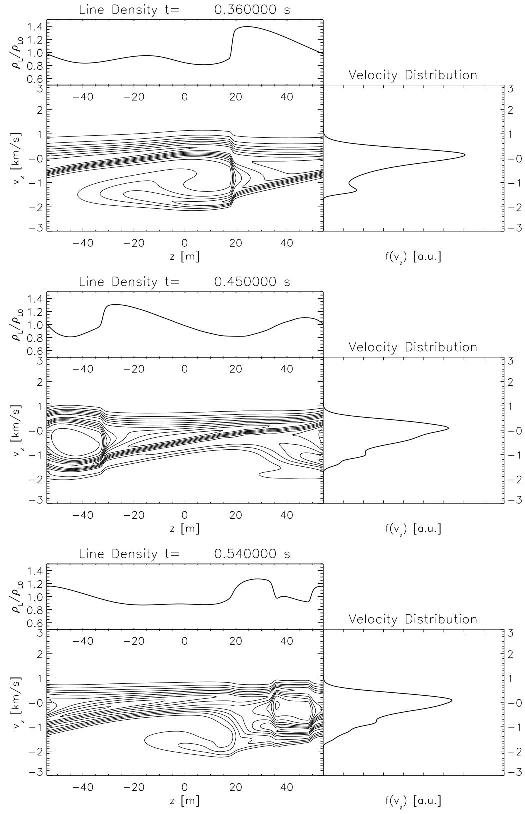

Figure 3: Contour plot of the distribution function together with the corresponding line density and velocity distribution obtained from the simulation. The simulation models the experimental observation in the ESR.

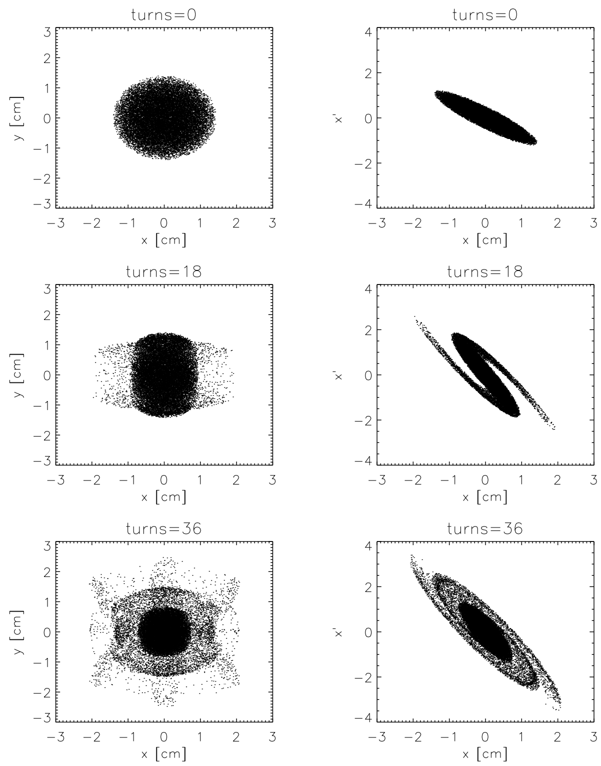

Figure 4: Phase space evolution for an initially RMS mismatched beam in a FODO channel.

$$\frac{d^2c}{dt^2} + k_{0,z}^2 c - \frac{3Nr_c}{\beta^2\gamma^5 a^2} f - \frac{\epsilon_z^2}{c^3} = 0 \qquad (2)$$

The geometry factor f is also dependent of the aspect ratio $p \equiv c/a$ according to

$$f \equiv \frac{p\ \mathrm{arccosh}(p)}{(p^2-1)^{3/2}} - \frac{1}{(p^2-1)} \qquad (3)$$

for $p > 1$, and $p^2 - 1$ replaced by $1 - p^2$ for $p < 1$.

Using these nonlinear equations and for the parameters set to fulfil the 2:1 resonance condition between transverse and longitudinal mismatch eigenfrequencies results are shown in Fig. 5 for an initial mismatch of the transverse envelope by a factor of 1.5. The 2:1 resonance has

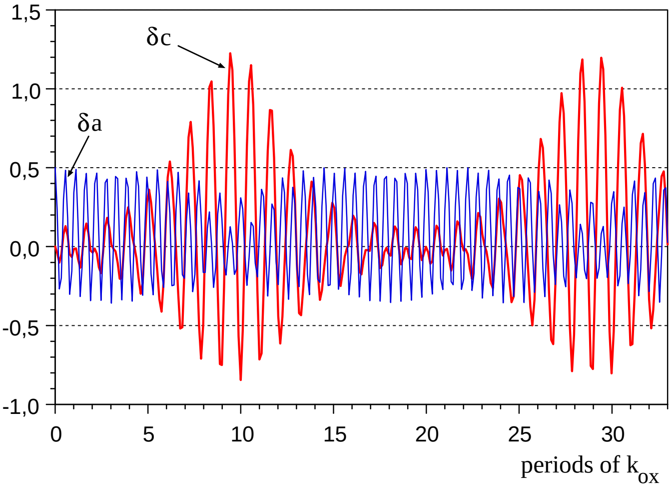

Figure 5: Solutions from the nonlinear envelope equation at parametric coherent resonance with initial transverse mismatch by factor 1.5, driving a longitudinal mismatch.

the effect that a transverse "breathing mode" mismatch δa drives a longitudinal mismatch mode δc. Due to the absence of damping in the envelope equation this repeats itself periodically.

A more complete picture of the resonant nature of this coupling process is shown in Fig. 6 for fixed zero-current tune ratio $k_{0,z}/k_{0,x} = 0.6$, transverse tune depression $k_x/k_{0,x} = 0.7$, initial transverse mismatch factor 1.5, and using the (equilibrium) aspect ratio c/a as free parameter. It is noted that there is a stopband for the coupling process around the linear theory parametric resonance condition $\omega_{lo}/\omega_{tr} = 0.5$. The width of the stopband is about $\pm 10\%$ in this frequency ratio. The maximum longitudinal amplitude is, however, slightly shifted towards smaller frequency ratios. This can be explained as amplitude dependent nonlinear de-tuning effect.

Results from 3D Particle-In-Cell simulations (in a constant focusing channel) using several million simulation particles have shown that for large initial transverse mismatch (30-50%) a longitudinal halo results, which is as pronounced as the accompanying transverse halo [8].

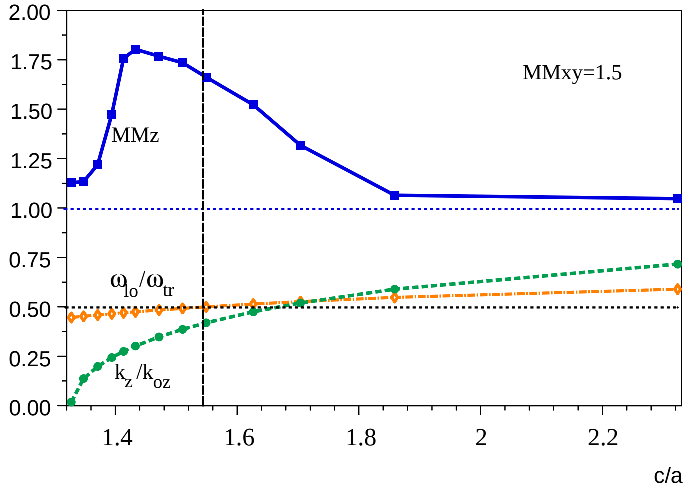

Figure 6: Maximum axial mismatch factors induced by resonant coupling in nonlinear envelope model for fixed $k_{0,z}/k_{0,x} = 0.6$, $k_x/k_{0,x} = 0.7$ and $MM_{xy} = 1.5$ as function of bunch aspect ratio c/a.

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