STUDY OF SELF-BUNCHING EFFECTS FOR HIGH-CURRENT INJECTION INTO SIS

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1 ABSTRACT

Longitudinal time domain signals of a Ne^{10+} beam have been measured at SIS. The signals were obtained with a coasting beam directly after multi-turn injection, and during the adiabatic RF capture. The results show a longitudinal instability at currents a factor 2-3 below the transverse space charge limit. The origin of this instability is the shunt impedance of the two cavities and the longitudinal space charge impedance. Together they exceed the impedance threshold for longitudinal beam stability, since no feedback is applied in SIS. The detected longitudinal instabilities have been simulated using a two dimensional particle-in-cell code. The simulation results are in good agreement with the signals and intensity thresholds observed in the experiments.

On this basis we have used the simulation code to estimate an upper limit for the cavity shunt impedance of a Heavy-Ion Driven Fusion Ignition Facility (HIDIF), where beam currents up to 70A are expected. In this regime the beam-cavity interaction is of great importance for the beam stability. Two injection scenarios have been investigated - an adiabatic RF capture process and the multi-turn injection into a barrier bucket.

2 INTRODUCTION

Beam particles interact via direct space charge fields and through the electromagnetic fields induced in the walls of the vacuum chamber and the environment surrounding the beam. When a small coherent beam disturbance occurs longitudinal and transverse electromagnetic fields are induced, which will perturb the particle trajectory. The fields, and in turn the beam perturbation, can "self-amplify" such that an instability occurs resulting in beam degradation and loss [1,2]. The beam environment may be characterized by a longitudinal and transverse impedance. The longitudinal impedance $Z_{\|}$ is defined as the integral over the longitudinal fields $E_{\|}$ induced by the beam current I_{beam} around the machine. The statistical fluctuations of the circulating particles can be seen by a pick-up as a current density modulation, which may give rise to beam instabilities. Below a certain threshold of intensity the beam is naturally stabilized by the spread in the oscillation frequencies of individual particles - this mechanism is called Landau damping [3].

The impedance of RF cavities is of major importance for the beam stability at frequencies around the first harmonics of the eigenfrequency of these insertions. The following studies consider the effect of the interaction of the circulating beam with the RF cavities in SIS and in a HIDIF ring.

3 OBSERVATION OF LONGITUDINAL INSTABILITIES IN THE SIS

An important parameter for the strength of the beam-cavity interaction is the shunt impedance of the RF cavities, which is in the case of a SIS cavity around 4 kΩ - in the SIS no active feedback system is installed yet. We have studied the interaction of the beam with the SIS RF cavities by recording the longitudinal beam signal in time domain with a sample rate of up to 100 MHz [4].

Due to the finite multi-turn injection interval (given by the chopper window) the machine is filled inhomogenously around the ring. Corresponding to this density modulation we observed a strong signal at the first harmonic in the frequency spectra. In agreement with the momentum spread this modulation vanishes after 3ms.

As in normal operation mode the resonance frequency of the SIS cavity was tuned to the 4th harmonic of the revolution frequency. The density perturbations of the injected beam excite TEM modes in the SIS cavity via the cavity impedance. Fig. 1 shows a waterfall plot of beam signals taken 20ms after multi-turn injection. The bunching process starts at the end of the measurement interval. Similar to signals observed at the ESR [5] the beam-cavity interaction results in a strong density modulation of the beam. Here Landau damping is weak.

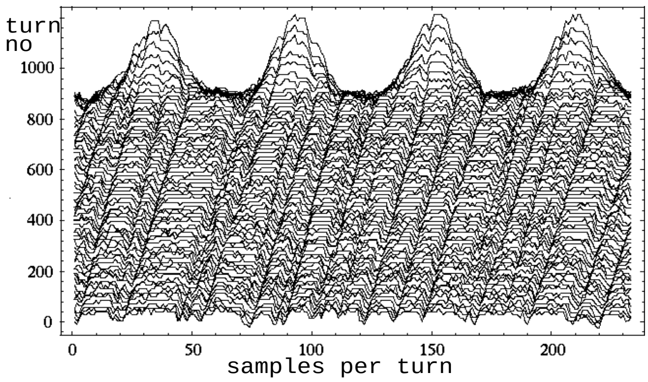

Fig. 1: Longitudinal beam pick-up signal recorded 20ms after multi-turn injection into SIS (I_{beam}≈ 5mA). Each trace corresponds to the longitudinal beam density over one turn.

The measurement has been repeated without starting the bunching process. With beam intensities of about 5mA the signal disappeared after 200ms, whereas measurements with higher beam currents (>10mA) show non-damped self-bunching effects. This intensity threshold has been verified in computer simulations using a two-dimensional particle-in-cell code.

4 PARTICLE TRACKING SIMULATIONS

Particle tracking simulations have been carried out using the particle in cell (PIC) code SCOP-RZ. This program has already successfully been used to simulate the observed self-bunching signals in the ESR [5]. It includes space charge effects as well as the interaction of the beam with an RF cavity via the cavity impedance. The cavity impedance is given by the well-known resonance curve of a narrow band resonator, where the initial resonator impedance is kept constant over the simulated time interval. Due to this assumption the computer code cannot describe the long-term beam behavior after the beam has become unstable (e.g. precise simulation studies of the Robinson effect are not possible yet). Nevertheless it is a powerful tool to derive the thresholds for longitudinal instabilities.

As seen in figure 2 the simulations show increasing density modulations, which are equivalent to those observed in the SIS measurements. The observed dependency of the beam instability on the momentum width was in agreement with the one seen in the measurements.

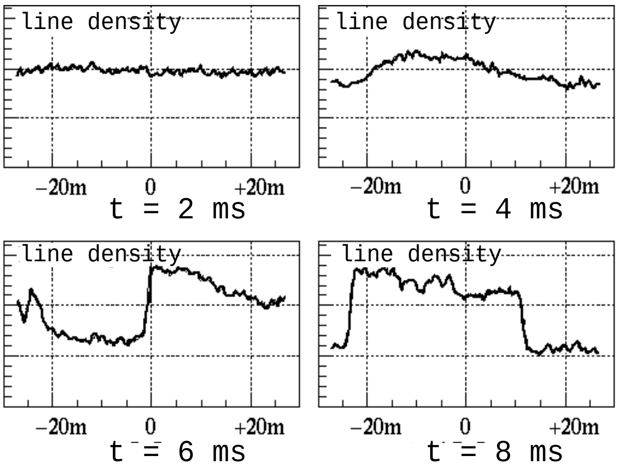

Fig. 2: Computer simulation of a longitudinal beam signal (line charge density over 1/4 of the machine length) with respect to space charge and strong beam -RF cavity interaction.

5 BEAM-CAVITY INTERACTION IN A HIDIF ACCELERATOR

Due to the high intensity beam of a HIDIF it is expected that the strong interaction of the beam with the RF cavities will lead to beam instability at much lower values of the shunt impedance. Therefore it is important to simulate this effect for the circumstances of a HIDIF ring and to determine an upper limit for the total cavity shunt impedance for this accelerator, where no longitudinal instability will occur.

Tracking simulations have been carried out on the basis of two different injection scenarios. In the first we assumed a multi-turn injection into a HIDIF ring, where an adiabatic RF capture process starts several ms after injection.

Figure 3 shows a computer simulation of the development of the longitudinal phase space distribution for an initially coasting beam in a HIDIF. The circulating beam becomes unstable after about two milliseconds. In this case cavity parameters similar to those of the SIS cavities were taken. The time interval from multi-turn injection to completion of the beam capture process would consist of several milliseconds, therefore an instability growth time of some milliseconds is not acceptable. From further simulations a threshold of 800Ω for the total cavity shunt impedance has been concluded as tolerable. Here, Landau damping is sufficiently strong to avoid the growth of longitudinal instabilities due to beam-cavity interactions.

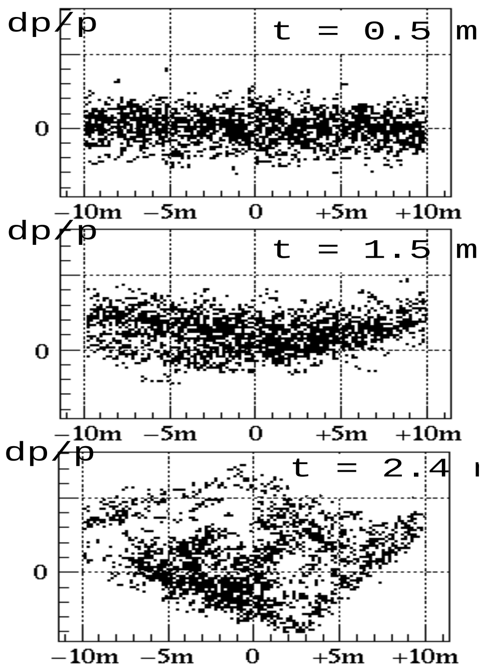

Fig. 3: Computer simulation of the development of the longitudinal phase space (particle momentum vs. longitudinal location) due to beam-cavity interaction with respect to space charge effects in a HIDIF accelerator.

In a second simulation scenario we assumed that the linac beam is already pre-bunched via a flattop chopper window. This beam will be injected into a barrier bucket during 20 turns. The barrier bucket is created by RF cavities tuned to different harmonics of the fundamental RF frequency.

In reality only a small number h_{max} of Fourier harmonics can be realized. The amplitude A_h of the Fourier coefficient at Fourier harmonic *h* of a rectangular bucket with flattop length *a* and bucket length *b* is proportional to:

$$A_h \propto \frac{\sin(h \pi a/b)}{h} \qquad (1)$$

In order to minimize the waviness at the flat bottom of the barrier bucket, one has to choose h_{max} such that A_{hmax} is zero (fig. 4). Simulation results show that the bucket length should be 20% larger than the length of the injected bunches. Otherwise the initial RF potential of the outermost particles of the bunch is too high and they will be lost later. With given ring parameters we found out that 5 Fourier harmonics are reasonable (fig. 5).

Particle tracking simulations have been carried out including the beam-cavity interaction via the shunt impedance (fig. 6). At low harmonic numbers the beam stability is mainly determined by the space charge impedance per harmonic and the RF cavity shunt impedance at the *h*-th Fourier harmonic. Therefor the strongest effect occurs at the highest Fourier harmonic. We observed an upper limit for the shunt impedance at the 5th Fourier harmonic of $R_s \approx 10k\Omega$. Above this threshold longitudinal beam instabilities grow within 1ms, after which the beam will be extracted from the machine.

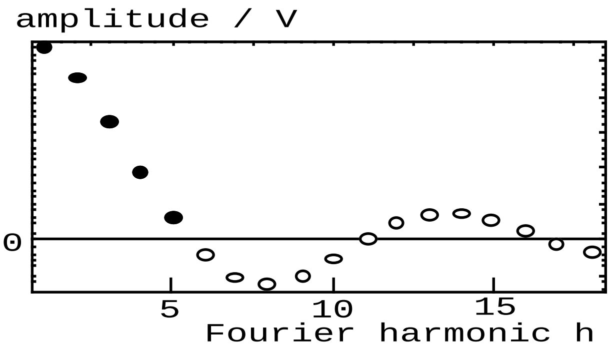

Fig. 4: Fourier coefficients of a rectangular barrier bucket up to the 18th harmonic of the RF fundamental frequency (bunch length = 25m, bucket length = 29m, RF fundamental wave length = 36.65m).

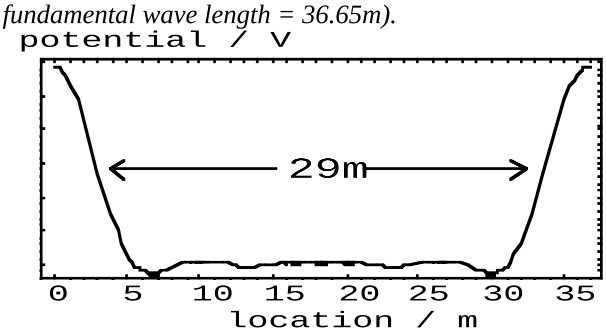

Fig. 5: Potential using 5 Fourier harmonics according to the parameters of fig. 4. Note the small waviness (<5%) at the bottom of the potential.

5 CONCLUSION

Although the beam-cavity interaction in SIS is not responsible for the non understood beam losses with high currents in the SIS, the measurement results and the computer simulations predict that this effect will be of great importance for the beam stability in the case of higher currents of 20-25mA in the machine.

For a HIDIF RF capture scenario a bunching voltage of around 500kV will be needed to capture the space charge dominated beam. Ferrite loaded cavities have to be used in order to operate the RF at frequencies of some MHz. From this one has to expect a total cavity impedance of the order of 1 MΩ. This impedance has to be reduced by a factor of around 1000 according to the simulation results to guarantee beam stability. One may achieve a factor of up to 100 by means of a longitudinal feedback system.

For a barrier bucket injection scenario we observed a similar acceptable total shunt impedance of 2kΩ per Fourier harmonic of the RF fundamental frequency.

We conclude that the strong beam-cavity interaction in a HIDIF forcefully demands for a dramatic reduction of the RF cavity shunt impedance in such a facility. Up to now we have not studied the case in which two or more shunt impedance's - at different Fourier harmonics - do influence the beam stability.

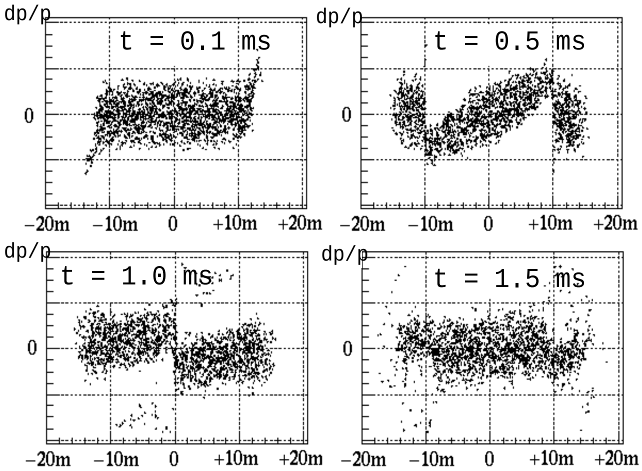

Fig. 6: Computer simulation of the longitudinal phase space distribution (momentum vs. location) after multi-turn injection. A small number of particles are not captured inside the barrier bucket and will be lost later.

6 ACKNOWLEDGMENT

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7 REFERENCES

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