SIMULATIONS OF SPACE CHARGE EFFECTS IN LOW ENERGY ELECTROSTATIC STORAGE RINGS*

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Abstract
Electrostatic storage rings have proven to be invaluable tools for atomic and molecular physics. Due to the mass independence of the electrostatic rigidity, these machines are able to store a wide range of different particles, from light ions to heavy singly charged bio-molecules.
However, earlier measurements showed strong space charge limitations; probably linked to non-linear fields that cannot be completely avoided in such machines. The nature of these effects is not fully understood.
In this contribution, we present first results from simulating an electrostatic storage ring under consideration of non-linear fields as well as space charge effects using the computer code OPERA/SCALA.

INTRODUCTION

Despite their distinct advantages for fundamental research in the low energy regime, only three electrostatic ion storage rings are in operation around the world, all of them having a comparable, compact racetrack-shape layout and working at a fixed energy of 20 keV [1,2] or 30 keV [3] with a continuous beam. A double electrostatic ring, operating in a merged beam configuration and at temperatures below 20 K, is presently being built at the Manne Siegbahn Laboratory in Stockholm [4]. In addition, a fixed energy storage ring for energies up to 50 keV was designed and assembled at the University of Frankfurt [5,6], a cryogenic storage ring (CSR) is being built up at the Max Planck Institute for Nuclear Physics [7], and a fixed energy machine for beam energies of up to 30 keV is presently being constructed at KACST [8]. In addition, an the electrostatic ultra-low energy storage ring (USR) [9], that is being developed by the QUASAR Group, will form a key element of the Facility for Low energy Antiproton and Ion Research (FLAIR).

The understanding of beam stability is of crucial importance for a successful operation of these machines. In order to study space charge effects, as well as the influence of non-linear fields on the beam, the ELISA ring, which has been in operation in Aarhus since the late 90s [1], was chosen. In the initial ring configuration, electrostatic deflectors of spherical shape were used [10] to provide a strong focusing in both, the horizontal and vertical plane. It was found that in this configuration, the beam life time strongly depended on the beam intensities, see Fig.1. Some possible reasons for this current limit were proposed [11] and simulations of several effects which might influence the beam life time, such as parametric resonances due to modulations of the space charge tune shift and coupling between the longitudinal and transverse directions, were carried out [12].

It should be pointed out that the measured beam losses were found at rather low intensities and thus a shift of the betatron tune due to parametric resonances seemed unlikely. Therefore, additional studies were initiated to improve the understanding of the nature of these effects.

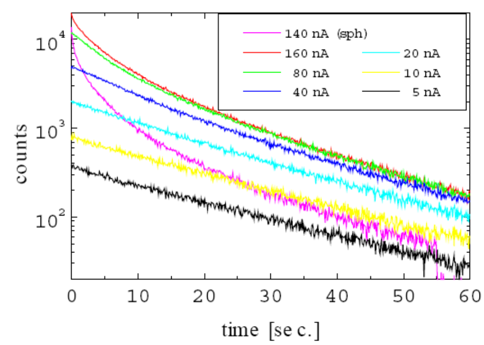

Figure 1: Decay of stored O^- beams at 22 keV [3].

THE OPERA CODE

In order to study the above mentioned effects, it was decided to input the entire ELISA ring into the commercial 3D field simulation code OPERA. This code package includes a number of different modules, amongst which the electrostatic 3D field solver TOSCA3D and SCALA3D. The latter allows for beam tracking under the influence of space charge effects.

The ELISA storage ring consists of two main electrostatic deflectors, that bend the beam by an effective angle of 160°, two pairs of 10° parallel plate deflectors and four pairs of electrostatic quadrupoles, see Fig.2.

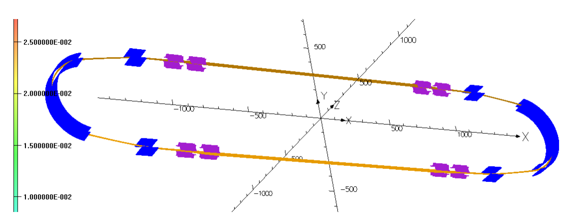

Figure 2: Model of the ELISA ring in OPERA3D. The Dimensions and distances were taken from [12]. All particles were tracked over 700 turns.

In order to benchmark earlier experimental data, both, spherical and cylindrical deflectors, were implemented as main deflectors. The angular extension of the main deflectors was reduced to 154° to include the effects from

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fringe fields and to give an effective deflection angle of 160°. All other geometry parameters can be found in [12].

Each ion optical element, as well as the parts of the ring between bending and focusing elements where fringe fields were present, was split in multiple cells and bodies to provide a correct distribution of the electric field , see Fig.3. By this measure, the total size of the OPERA output file with the full 3D electric field distribution was reduced from 1 GB to around 200 MB. The full ring was modeled making use of its three symmetry planes.

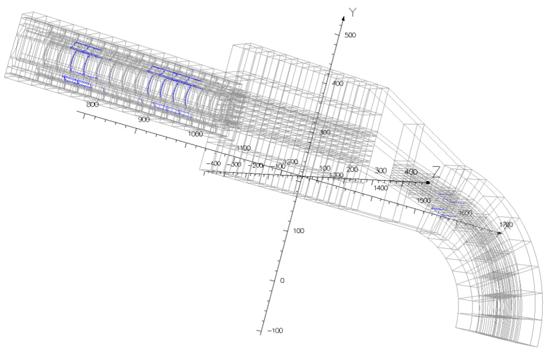

Figure 3: Illustration of how the ring geometry was split in multiple sectors and parts to provide a correct distribution of the electric field. Shown is a region of ELISA with quadrupoles, a 10° parallel plate deflector and part of the 160° bend.

PARTICLE TRACKING

All ELISA machine parameters, such as the betatron tunes, dispersion function, etc. were first verified by implementing the ring lattice in the computer codes TRACE-3D and MAD-X. This was used as a basis to find stable working points for the ring configuration with cylinder, as well as with spherical deflectors. It was confirmed that the horizontal and vertical beta-functions for the configuration with spherical deflectors were between 0.2-0.4 m in the middle of the deflector, independent of the ring tune. When this deflector is replaced by cylindrical electrodes, the horizontal beta-function of the ring is around 0.25 m in the middle of deflector, while the vertical beta-function can be varied between 0.25 - 2.5 m. It should be noted that the higher value of the beta-function is accompanied by a reduction of the vertical betatron tune to $\nu_z < 1$. Earlier measurements showed that regimes with a vertical tune of less than one are unstable [12].

The local tune shifts due to space charge effects are similar for both deflector types. Thus the slope of the beam losses curve versus the beam current should be identical for both deflector types, which contradicts the experimental data shown in Fig.1.

Moreover, it was measured that the beam losses grow with beam intensity, and that losses occur already at absolute currents that are well below the limits for space charge tune shifts. Therefore, additional effects have to have an impact on beam stability.

ORBIT TRACKING

First, a closed orbit was searched for in the OPERA ring model to allow for tracking ions for many turns. For this purpose, a central particle was tracked over 700 turns in the full 3D electric fields. Snap-shots of the orbit coordinates x and p_x, taken in radial phase space after each revolution, resulted in a closed motion with all quadrupoles initially switched off. The particle was then moved off the central orbit and the quadrupoles adjusted to provide both, radial and axial focusing.

The betatron tunes that were estimated from the tracked orbits are $\nu_x \approx 2.56$ and $\nu_z \approx 1.38$ for the ring with cylindrical electrodes. These estimations are in agreement with the results from MAD-X where stable tunes range between $\nu_x \approx 2.4$ and $\nu_x \approx 2.85$ in the radial plane and between $\nu_z \approx 1.84$ and $\nu_z \approx 1.45$ in the vertical plane.

DYNAMIC APERTURE

As a next step, the beam dynamics in radial and axial phase space was studied in more detail to better understand the particle motion in the ring. The resulting dynamic aperture of the ring with cylinder deflectors is shown in Fig.4. In contrast to the middle of the straight section, where the radial width of the stable beam can reach up to 17 mm, the total area of the dynamic aperture is ~100 mm^2. This indicates that the maximum amplitude of stable radial oscillations in the middle of the deflector is only ±4mm. Any particle with radial or vertical oscillations of more than ±4mm inside the deflector will be lost, even though the geometric gap width between the deflector electrodes is almost four times larger. The area of the dynamic aperture at an azimuth angle of 90° is about 16 mm^2, which is 7 times smaller than in the rest of the ring.

Based on these results, one can assume that the dynamic aperture is strongly limited by non-linear electric fields and in particular by a coupling between radial and axial motion.

For the spherical deflectors, the nonlinearities of the electric field are even higher. They are so strong, that the maximum stable amplitude is between 30–50% smaller than for cylindrical electrodes. The non-linear nature of the reduced dynamic aperture is correlated to the fact that the residual potential on the central line between the spherical electrodes is 170 V when the total voltage difference between the electrodes reaches almost 6 kV. In an identical configuration, the remaining potential in the centre of a cylinder deflector is only 40 V, i.e. four times smaller.

It should be noted that equal potentials (±2987.5 V) were applied to both cylindrical electrodes to find the closed equilibrium orbit, while +2812 V was applied to the outer spherical electrode and -3162 V to the inner one.

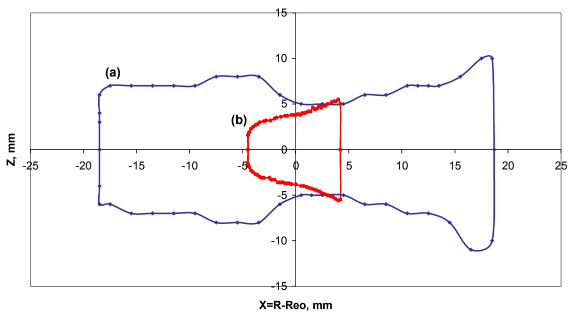

Figure 4: Dynamic aperture of the ring with cylinder deflectors. OPERA-TOSCA simulations: a) Middle of long straight section, azimuth θ=0°, b) middle of 160° bend, azimuth θ=90°.

RING ACCEPTANCE

The ring acceptance in radial and axial phase space was calculated by tracking the beam over many turns. As can be seen in Fig. 5 and 6, nonlinearities became clearly visible in both planes. The amplitude of the radial motion as well as the transverse momentum with respect to the reference orbit was varied over a wide range to find an area of stable orbits, Fig.5. Two different positions in the ring were investigated in detail: The middle of the straight section, i.e. θ=0°, and the middle of the main deflector, where θ=90°. It can be seen that an upright ellipse is formed in the middle of the deflector. Based on these results, the radial acceptance of the ring was estimated as A_x~130÷160 π mm·mrad.

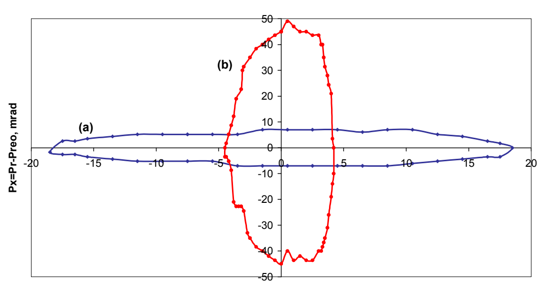

Figure 5: Radial acceptance of the ring with cylinder deflectors. OPERA-TOSCA simulations: a) Middle of long straight section, azimuth θ=0°, b) middle of 160° bend, azimuth θ=90°.

Strong non-linear effects became clearly visible in axial phase space, see Fig.6. The maximum allowable beam size in the vertical direction was reduced from ±8 mm at θ=0° to ±3 mm or even less inside the deflector. The ring acceptance in the vertical plane was estimated as A_x~30π mm·mrad, i.e. five times less than in the radial direction. This results needs to be compared to the fact that the radial gap between the electrodes is rather narrow (±15 mm), while the electrodes extend over ±50 mm in the vertical direction.

Therefore, a strong coupling between the radial and axial phase spaces can be seen as a possible explanation of the beam losses in the ring. For spherical deflectors, the acceptances in both planes are even more limited and thus the effects more pronounced. At the moment, the main force that drives the ions to the periphery of the ring acceptance is still unclear.

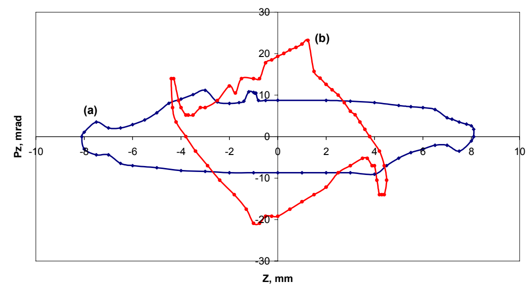

Figure 6: Vertical ring acceptance with cylinder deflectors. OPERA-TOSCA simulations: a) Middle of long straight section, azimuth θ=0°, b) middle of 160° bend, azimuth θ=90°.

SUMMARY

It was shown that non-linearities in the electric field distribution, in combination with an emittance growth in the beam from the ion source with increasing beam currents can be a reason for reduced ring acceptance. These effects were particularly strong with spherical deflectors. As a next step, simulation studies with nonlinear electric field maps will be carried out to analyze the reasons for beam losses in more detail.

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