MODELLING SPACE-CHARGE AND ITS INFLUENCE ON THE MEASUREMENT OF PHASE SPACE IN ALICE BY TOMOGRAPHIC METHODS*

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Abstract

ALICE is an experimental electron accelerator designed to operate over a range of energies up to 35 MeV, and with up to 80 pC bunch charge. A dedicated tomography diagnostic section allows measurement of the transverse phase space with different beam parameters. In the low-energy, high-charge regime, space charge effects must be considered: to quantify these effects, the tracking code GPT has been used to simulate beams in the tomography diagnostic section. The results can be compared with simplified models, and with experimental measurements.

INTRODUCTION

The ALICE accelerator provides the electron beam for the EMMA non-scaling Fixed-Field Alternating Gradient (FFAG) accelerator ring, via an injection line which also incorporates the tomography diagnostic section. This comprises two FODO cells, having fluorescent YAG screens in between and at each end, and is preceded by a four-quadrupole matching section, as shown in Fig. 1. [3]

A previous paper [1] has described experimental work which was designed to use the method of phase-space tomography to investigate the possible effect of space-charge in the EMMA injection line. Although results showed systematic differences in reconstructed phase-space at the selected location, the observations were not conclusively explained by space-charge, and further detailed simulation studies were indicated.

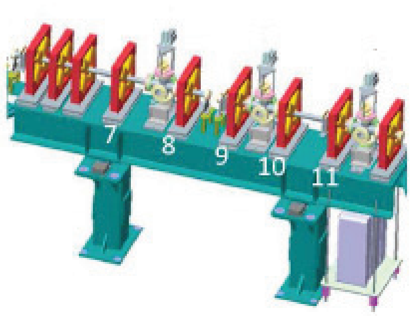

Figure 1: ALICE Tomography Section, indicating quadrupole numbers (7-11).

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BENCHMARKING CODES WITH SPACE-CHARGE

The General Particle Tracer (GPT) is an established tracking code previously used in studies of space-charge in the EMMA injection line [3]. GPT includes standard routines for applying space-charge effects, which have properties applicable to different types of problem and parameter range. However, as internal implementation details are largely unknown, it was considered prudent to perform a benchmarking exercise on the code against the results of algorithms based on established theory. In situations where exact solutions are available, such as uniform cylindrical particle distributions, these allow the analytical calculation of macroscopic quantities, such as RMS beam-size, at different points as the bunch progresses along the beam-line.

Cases were devised to represent the range of typical values for ALICE bunch parameters:

- Cylindrical symmetry
- Uniform & Gaussian transverse distributions
- Radius 0.3 - 1.2 mm
- Length 0.5 - 2.0 mm
- Charge 5 - 80 pC

with initial divergence = 0, i.e. all particles start parallel to the longitudinal (z) axis

Beam in Drift Space

Linear space-charge theory has been applied in the form of the envelope equation [1,2]:

$$\tilde{x}'' + k\tilde{x} - \frac{\varepsilon^2}{\tilde{x}^3} - \frac{K}{4\tilde{x}} = 0 \qquad (1)$$

where x is the beam radius, $k(s)$ is the focussing strength, s is the position along the beam path. K is defined as the *perveance*, given by:

$$K = \frac{I}{I_0}\frac{2}{\beta^3\gamma^3}, \ with \ I_0 = \frac{4\pi\varepsilon_0 m_0 c^3}{q}$$

where I is the beam current, β and γ are the relativistic factors, c the speed of light, q the electronic charge, m_0 the electron rest mass, ε_0 the permittivity of free space.

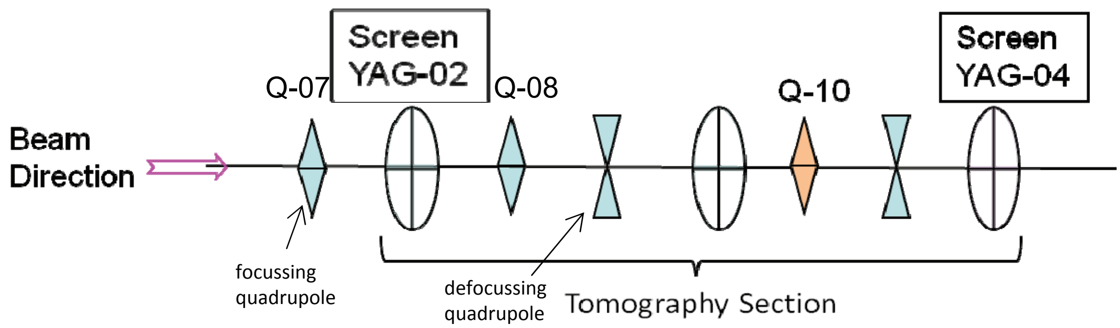

Figure 2: Schematic of ALICE Tomography Line, showing YAG screens and quadrupole magnets.

These differential equations are then solved for z from 0 to 1.5 m, the length of the tomography section. Results as summarised in Fig. 3a confirm the prediction that as particles are closer to each other, on average, space-charge forces are greater. The effect on the RMS radius is increased for shorter, smaller and higher-charge bunches.

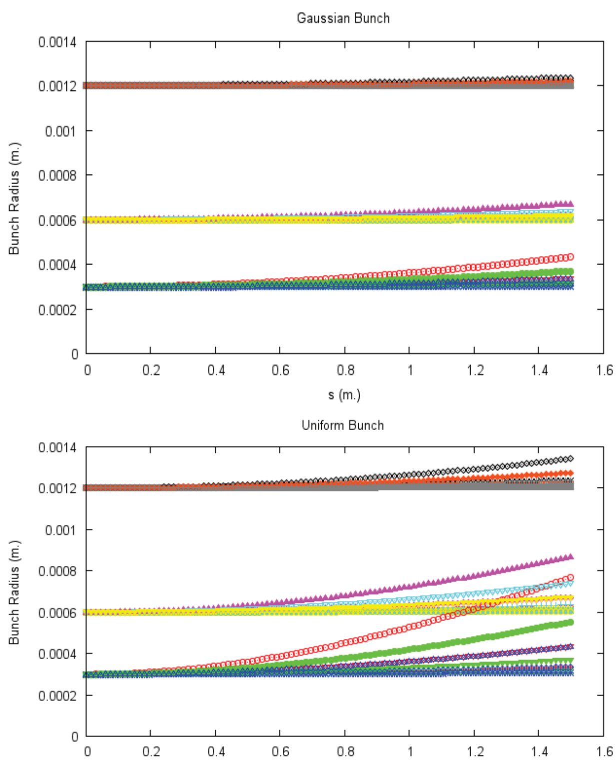

Figure 3a: Analytical Code. Space-charge effect on bunch radius - Gaussian (top) and uniform (bottom).

The GPT space-charge routine, on the other hand, solves Poisson's equation in 3-D for all particles of the bunch, taking proper account of relativity.

In the GPT case, data is collected only at the start and end of the line, i.e. at the z = 0 and z = 1.5m. positions. Nevertheless, comparison of Fig. 3a and 3b, which plot the same parameters grouped in the same way, shows good agreement between analytical and GPT-modelled values over the parameter range considered.

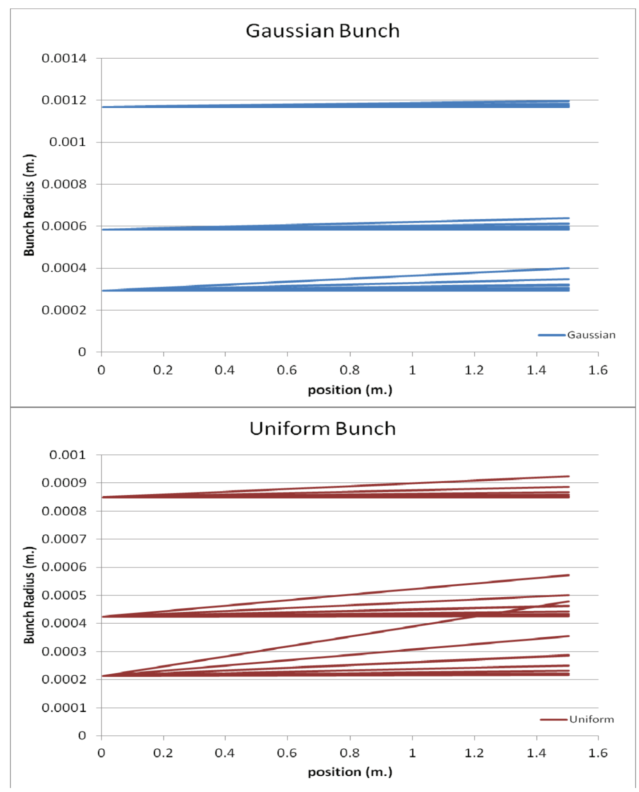

Figure 3b: GPT Code. Space-charge effect on bunch - Gaussian (above) and uniform (below).

SPACE-CHARGE IN THE EMMA INJECTION LINE TOMOGRAPHY SECTION

A detailed model of the ALICE tomography section, with its 3 screens and 4 quadrupoles, as shown in Fig. 2, has been built in GPT. Simulations of a realistic beam have been run using established quadrupole settings, and results analysed in terms of RMS beam-sizes σ_x and σ_y at positions along the beam-line.

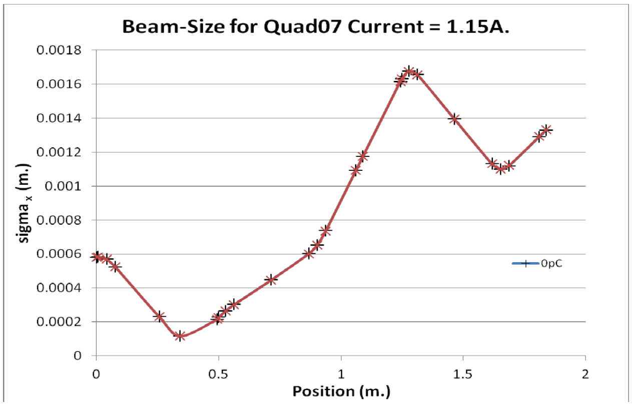

Figure 4: Horizontal RMS beam-size along the tomography beam-line.

In Fig. 4, the evolution of beam-size at positions along the beam-line is plotted, at fixed quadrupole settings.

In addition, plots have been made to show more explicitly how space-charge affects beam-size at a fixed position, as the quadrupole strength is changed. This is demonstrated in Fig. 5 by the differential beam-size change $\Delta\sigma_x/\sigma_x$ between high and low charge.

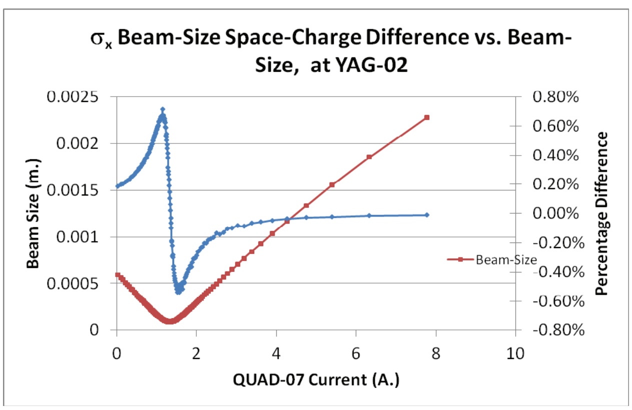

Figure 5: Percentage horizontal change & beam-size at YAG-02, with increasing QUAD-07 current.

MODELLING THE FULL TOMOGRAPHY PROCESS

The detailed GPT model of the ALICE tomography section (Fig. 2) may be used to simulate the complete tomographic data collection and reconstruction process. This allows experimental differences in phase-space reconstructed from quadrupole scan data at QUAD-07 & YAG-02, and QUAD-10 & YAG04, to be investigated. The technique is as follows:

1. Start with reconstructed phase-space at QUAD-07 entrance (based on experimental QUAD-07 and YAG-02 scan data, April 2011, as Fig. 6)
2. In GPT, start a beam with this phase-space and transport to YAG-04
3. In GPT, scan QUAD-10 and collect the simulated YAG-04 screen data
4. Based on this data, reconstruct phase-space at QUAD-07 entrance
5. Repeat GPT runs with (a) space-charge OFF, and (b) space-charge ON
6. Compare simulated phase-space with experimental results.

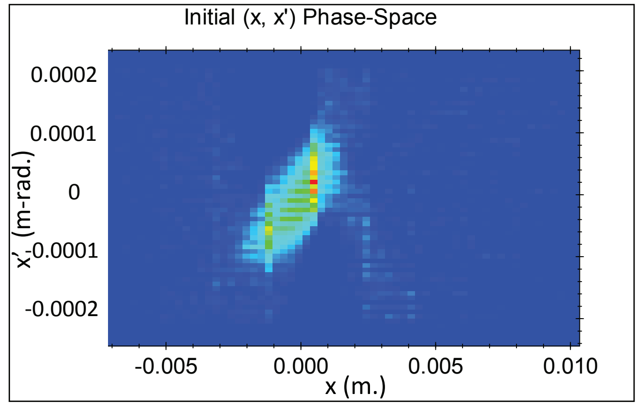

Figure 6: Measured phase-space as GPT input.

This approach allows detailed investigation of calibration errors or misalignments in the beam-line elements between QUAD-07 and QUAD-10. These may account for the clear differences in outline of the phase-space distributions at the QUAD-07 entrance when calculated from QUAD-07 and from QUAD-10 scan data obtained experimentally [1]. As the observed discrepancies are also seen to be strong functions of the bunch charge, this will be a key parameter.

CONCLUSION

Further experimental work is planned, to collect new tomography data and confirm earlier results. It will be extended to a wider energy range and to vertical as well as horizontal phase-space.

Analysis of this new data will be carried out by methods similar to those used previously [4]. Direct comparison of the modelling results presented here with both experimental data sets will allow conclusions to be drawn about the source of the apparent anomalies in [1].

ACKNOWLEDGMENT

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