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IMPROVED SIMULATION FOR CENTRE REGION OF TRIUMF 500 MeV CYCLOTRON WITH SPACE CHARGE*

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Abstract

The TRIUMF 500 MeV cyclotron delivered routinely a total current up to 200 μA protons for 15 years till 2001. Since 2002, developments towards 300 μA total extraction became compelling because of the ISAC expansion. To meet future requirements (for addition of a new beam-line), a total extraction of 310-450 μA shall be anticipated. With such an increase of beam current, the space charge effect becomes a major concern in the centre region, as it limits the maximum amount of beam current achievable out of the machine. Therefore, numerical simulation on particle orbits with the space charge force has been initiated, starting from the injection gap. This study is focused on the beam bunches which are very long compared with transverse size (because TRIUMF extraction is by stripping and separated turns are not required). We validated the simulations performed without and with the space charge force, also utilized a physical initial beam condition and realistic centre region geometry for our modeling. Our goal is to work out the space charge limits and their dependence upon the bunchers, rf voltage, and matching. In this paper we present our recent progress in this study.

INITIAL BEAM

In 1970s, orbit dynamics in TRIUMF centre region was studied in-depth to optimize the design for beam quality and rf phase acceptance [1]. The study was conducted through single particle tracking without taking into account space charge force. Figure 1 illustrates one of the simulation results that we reproduced, showing the 1st two-turn orbits of particles of a 50° phase interval in the centre region 3D electric- and magnetic fields. However, this outcome does not really mean that the machine's rf phase acceptance is 50°, because these particles were simply launched from a zero emittance beam in the transverse planes. We wish to establish a more practical initial beam condition for the simulation. Therefore we reviewed the TRIUMF injection line 3D (6 phase space dimensions) envelope calculation [2]. This calculation is to the first order only, but contains all the relevant physics of that order: the space charge force, axial magnetic field, coupling in all 3 planes through the spiral inflector. The result is given in Table 1 as a 6×6 σ−matrix of beam arriving at the exit of centre region spiral inflector/deflector.

This is a fully correlated beam in 6 dimensions; and the bunch length is much longer than the transverse size. In terms of this σ−matrix, we can randomly create particles

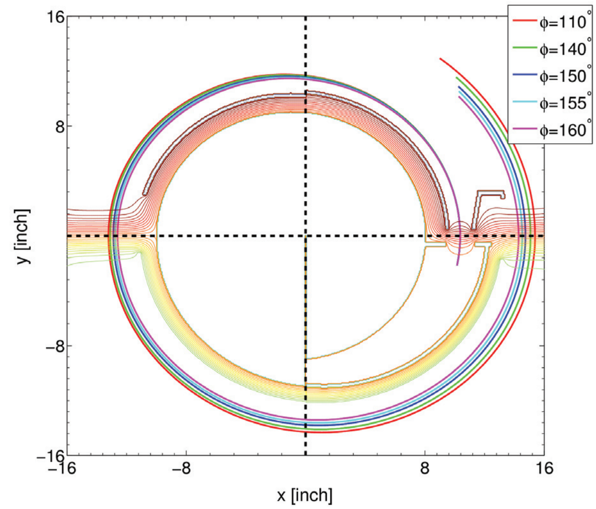

Figure 1: The centre region electric field equipotential lines and the 1st 2-turn orbits of particles of a 50° phase interval.

Table 1: The beam σ−matrix (2rms) obtained from the envelope calculation of injection line.

	Diagonal	Off-Diagonals (Normalized Form)				
x (inch)	0.14					
θ **(mrad)**	5.97	0.81				
y (inch)	0.11	-0.026	-0.01			
ϕ **(mrad)**	6.13	-0.01	0.022	-0.55		
l (inch)	0.81	-0.24	-0.26	-0.65	0.43	
δ **(mrad)**	0.93	-0.32	-0.34	-0.70	0.65	0.96

in the 6D phase spaces, and then transform them from the s-domain to the time-domain as we execute simulation using time as independent variable, given the reference particle's initial coordinate.

BUNCH SNAPSHOT

Without space charge, the resulting snapshot of bunch in the horizontal plane is shown in Fig. 2 for 40 turns, plotted once every 5 (=rf harmonic number) rf periods. It's seen that with the increase of turn number (energy), the bunch stretches and becomes very significantly smeared in the tail compared with the head. This is arisen from the phase dependent radial-longitudinal coupling, where the lagging particles assume a larger gradient in the energy spread as they are farther from the crest of cosine rf wave.

The bunch snapshot in the **(r, z)** plane is shown in Fig. 3 for the 1st 5 turns. The radial sharp edge is attributed to the particles sitting on the crest of rf wave. The particles in the vicinity of the crest undergo weaker vertical electric focusing, that's why they display larger vertical oscillations;

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whereas the particles far from the crest receive less energy gain, thus they fall more inboard radially.

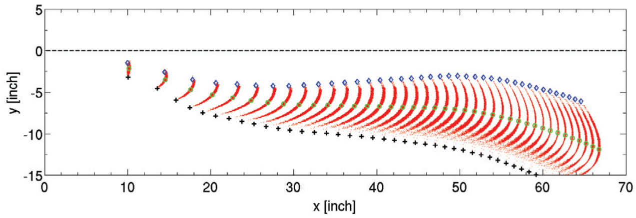

Figure 2: Snapshot of bunch in the **(x, y)** plane (in 1:1 aspect ratio) for 40 turns without space charge, plotted once every 5(=rf harmonic number) rf periods. The blue, green and black points mark the leading, centered and trailing particles.

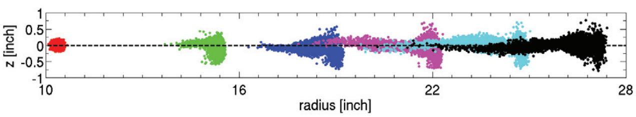

Figure 3: Snapshot of bunch in the **(r, z)** plane (in 1:1 aspect ratio) over the 1st 5 turns, plotted once every 5 rf periods.

With the increase of energy, the particle's radius gain due to energy gain is decreasing, while the bunch's tail is lengthening. Summing up all the radial distributions of particles on every individual turn gives a radial density plot of the low energy (LE) probe scan, as shown in Fig. 4. This picture is agreed with the the result measured with a short bunch [3] under low space charge.

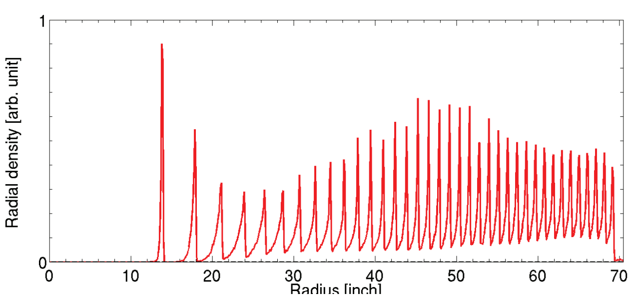

Figure 4: Radial LE probe scan without space charge.

PHASE ACCEPTANCE

In the first a few turns, the vertical focusing that particles undergo is dominated by the electric rather than the magnetic focusing. As a result, the phase acceptance is determined by two factors: the leading particles must undergo enough vertical focusing to survive from machine's vertical apertures, while the trailing particles must receive enough energy gain to clear the centre post. Figure 5 shows the good particles which can survive and get accelerated to high energy, along with the bad particles which get lost either vertically or radially within the first 10 turns. This indicates that the machine's phase acceptance reaches ∼ 60° when the space charge force is null. This agrees well with the result of measurement taken at very low peak current.

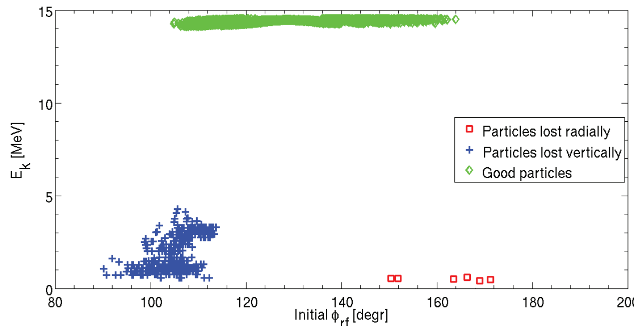

Figure 5: Ending energy vs. the initial rf phase angle for the good particles (Green) and bad particles (Red and Blue). The good particles are meant those survived and accelerated to high energy (here only plotted up to ∼14 MeV), whereas the bad ones get lost either radially or vertically within 10 turns. This indicates that the machine's phase acceptance reaches about 60° when space charge force is null.

SPACE CHARGE EFFECT

PIC Validation

We began with test runs to validate the simulation of Particle-In-Cell (PIC) [4] with space charge force in a cyclotron. This was accomplished by modeling a uniformly-charged sphere's evolution under space charge, in comparison with the result of envelope calculation including linear space charge force [5]. We launched particles from their own equilibrium orbits in the radial plane with azimuthal momenta exactly matched with their starting radial positions, while having the vertical momenta being set to zero.

The first test was using a perfectly isochronous magnetic field of zero flutter. With a bunch charge of 1.1 nC (i. e. 5 mA protons of 600 keV), both the radial and longitudinal envelopes turn out to be oscillating periodically with nearly identical frequency, while the vertical envelope is blown up. The second test simply replaced the isochronous field with a radially-decreasing field so that vertical focusing is exerted. As a consequence, the bunch envelope displays an oscillation in each of 3 dimensions. In both tests, the PIC simulation gives very well agreed result with the envelope calculation. Figure 6 shows the envelope variations over 6 turns.

Vortex Motion

It's well understood that the space charge force is a local effect, depending on the local particle density, not average current. Given the σ-matrix in Table 1, one could find infinite number of distributions for the particles. It's random. However, here we keep the initial distribution the same as in the previous section for a bunch charge of 22 pC (i. e. for a time average current of 500 µA). The beam vortex motion emerges from turn ∼#15 onward (see Fig. 7) and becomes fairly pronounced by turn #25. The vortex motion causes complicated structure to appear in the radial density plot (see Fig. 7). Also, the space charge force causes the rf phase

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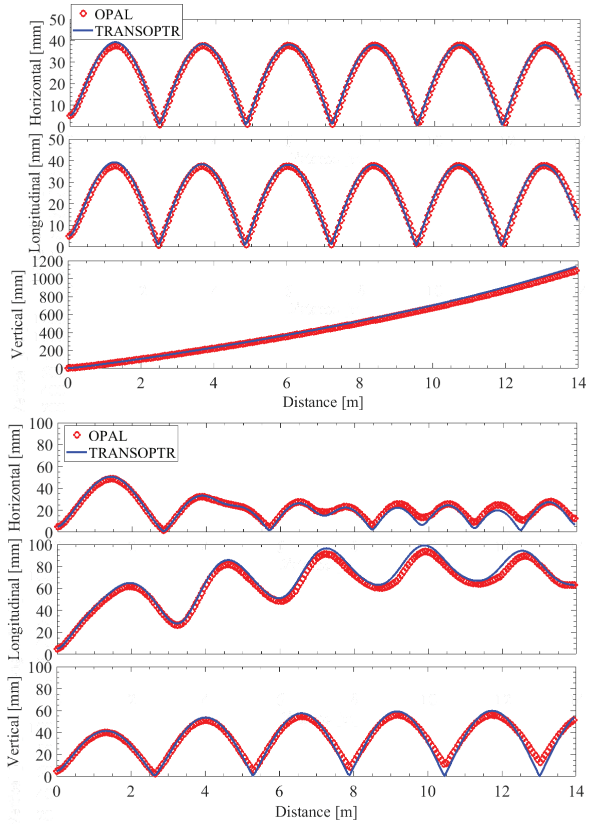

Figure 6: Comparison of beam envelope (hard-edged) of an initially uniformly-charged sphere under the space charge force between the PIC simulation and the statistical calculation, using isochronous field (upper 3) and a radially-decreasing field (lower 3) respectively.

acceptance to reduce to ~ 40° from 60° (compare Fig. 8 and Fig. 5), because it further reduces the focusing force to the head of the bunch which is much more weakly focused than the tail.

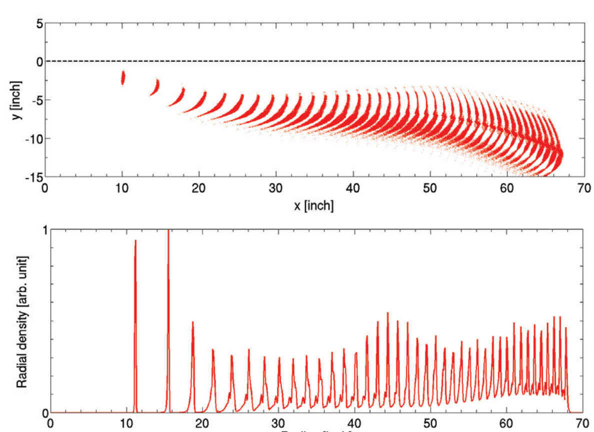

Figure 7: Snapshot of bunch over 40 turns in the $(\mathbf{x}, \mathbf{y})$ plane under space charge of 22 pC per bunch (upper), and the radial LE probe scan (lower).

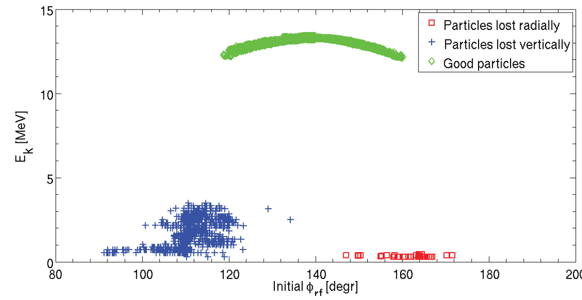

Figure 8: The rf phase acceptance reduced to ~ 40° under the space charge of 22 pC per bunch.

Notch Monitor Observations

We observed bumps and changes on the falling edge of beam pulse from a notch monitor recently installed in the UCN beamline, shown in Fig. 9 as an example. The falling-edge of a beam pulse lasts for a period of tens micro-seconds, which comprises hundreds bunches. From bunchers off to bunchers on, the falling edge shows bumps, which probably implies that many turns overlap of local fine structures in the bunch due to the space charge effect. We'll need further studies to understand this picture better.

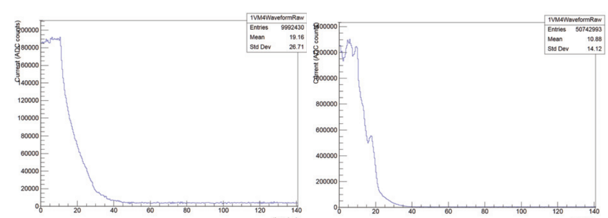

Figure 9: The notch monitor measured falling edge of beam pulse from bunchers off (left) to bunchers on (right).

REFERENCES

[1] G. Dutto, C. Kost, G. H. Mackenzie, M. K. Craddock, "Optimization of the Phase Acceptance of the TRIUMF Cyclotron", in *Proc. Cyclotrons'72*, Vancouver, Canada, 1972, pp. 340–350.

[2] R. Baartman, "Optics design of the ISIS Vertical Section", TRIUMF Design Note, TRI-DN-09-11, September, 2009.

[3] T. Planche, Y.-N. Rao, R. Baartman, "Measurement of Turn Structure in the Central Region of TRIUMF Cyclotron", in *Proc. Cyclotrons'13*, Vancouver, Canada, 2013, pp. 177–179.

[4] Andreas Adelmann *et al.*, "The OPAL Framework (Object Oriented Parallel Accelerator Library) Version 1.4.0 (compiled March 30, 2016) User's Reference Manual", PSI Report, PSI-PR-08-02.

[5] R. Baartman, "TRANSOPTR: changes since 1984", TRIUMF Beam Physics Note, TRI-BN-16-06, May, 2016.

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