Space-charge Simulation of TRIUMF 500 MeV Cyclotron

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On behalf of Yi-Nong Rao, T. Planche, and R. Baartman

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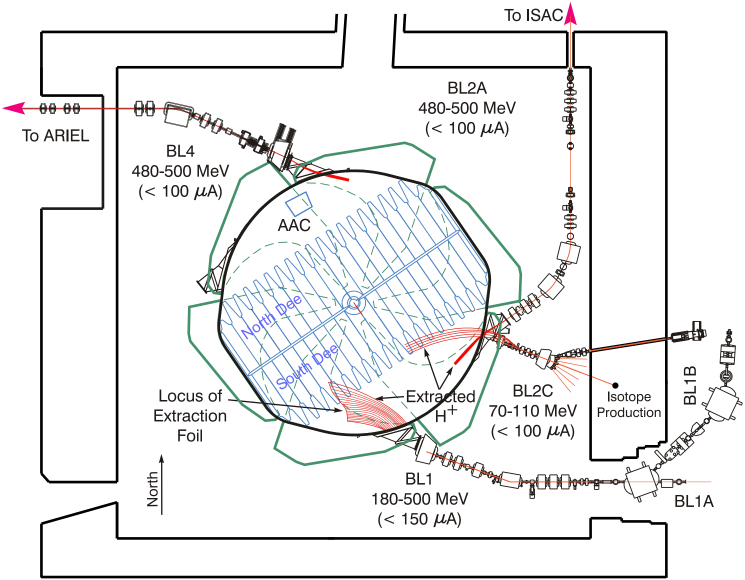
Motivation: reach $> 400\mu A$ routine delivery.



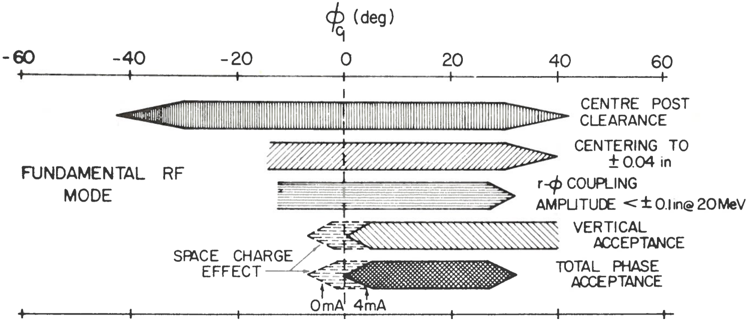
Space Charge Limit

- Horizontal/longitudinal space charge forces: NOT a concern since turn separation is not needed for extraction*.
- But vertical space charge forces limit us:

*TRIUMF cyclotron accelerates H^- ions and uses charge charge-exchange extraction.

Space Charge Limit: Vertical

Space charge $\Longrightarrow$ vertical defocusing $\Longrightarrow$ reduce phase acceptance.



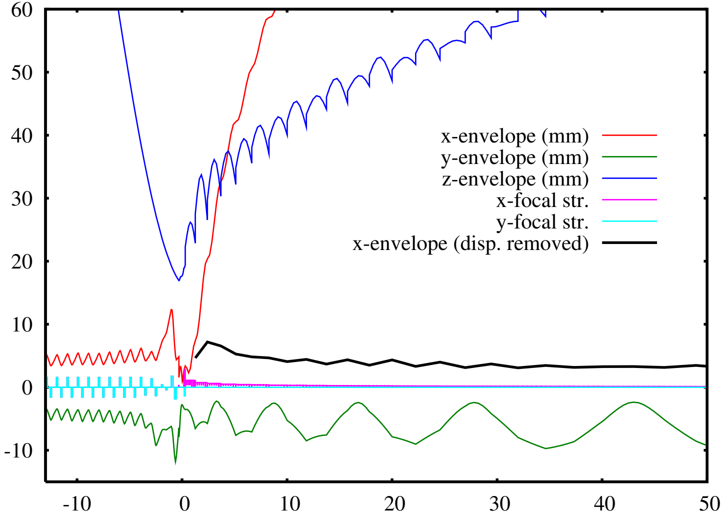
From: J. R. Richardson, Proc. of Cyclotron Conf. **1972**, p. 138.

Outline

1. "Pre-existing" simulation tools (TRANSOPTR & SPUNCH).
2. PIC[†] simulation: challenges specific to H^- cyclotrons.
3. Simulation results.

[†] particle-in-cell

Envelope Matching to Cyclotron with TRANSOPTR:



From: R. Baartman, TRIUMF design note TRI-DN-09-11, 2009.

TRANSOPTR

First order envelope code; includes all relevant physics:

+ 3-D space charge,
+ stray field, spiral inflector, bunching...

...to **first order** only:

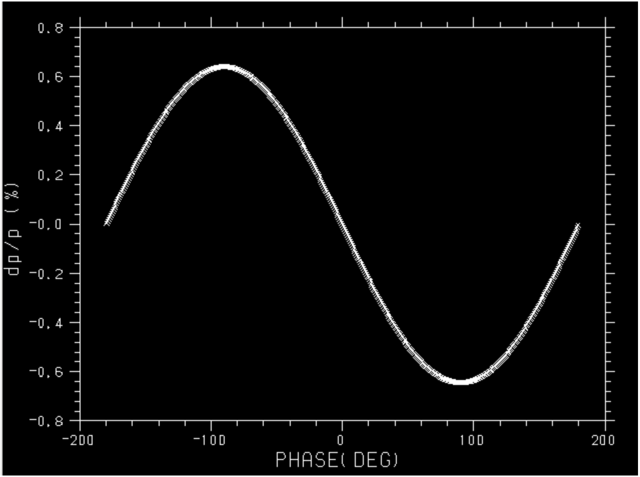
- "sees" no detail beyond second moments;
- does not account for the non-linearity of rf sine wave.

Bunching with SPUNCH

Our two-buncher system:

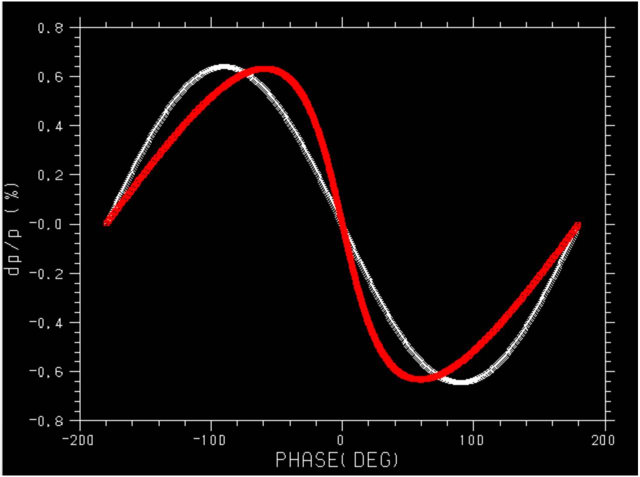
- 1^{st} harmonic ($\sim$23 MHz) buncher 21 m upstream of the inflector,
- 2^{nd} harmonic ($\sim$46 MHz) buncher 16.5 m upstream of the inflector.

Bunching with SPUNCH: with space charge



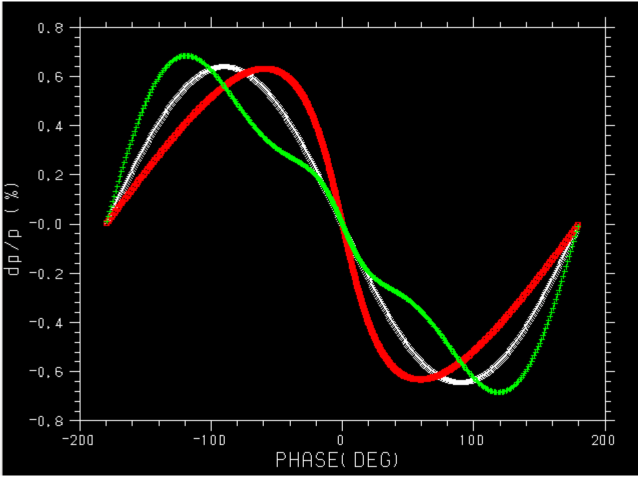
After the 1^{st} buncher.

Bunching with SPUNCH: with space charge



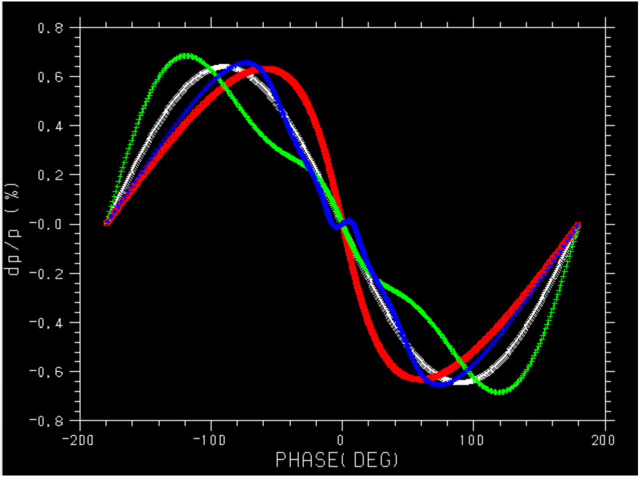
After some drift.

Bunching with SPUNCH: with space charge



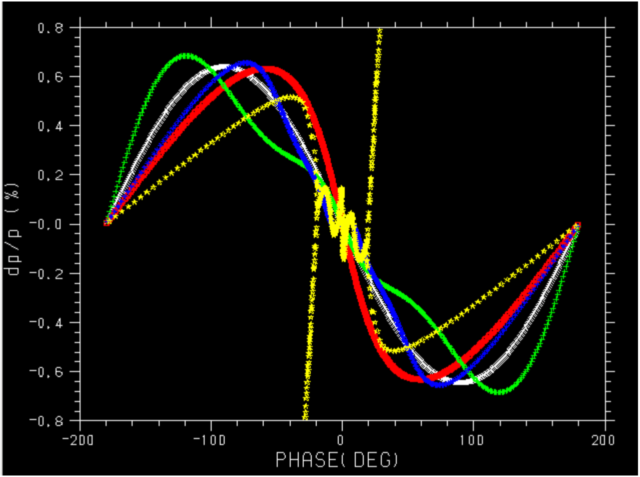
After the 2^{nd} buncher.

Bunching with SPUNCH: with space charge



After some more drift.

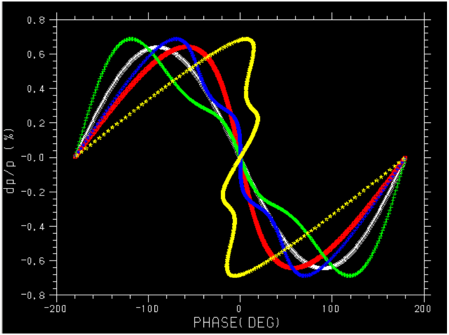
Bunching with SPUNCH: with space charge



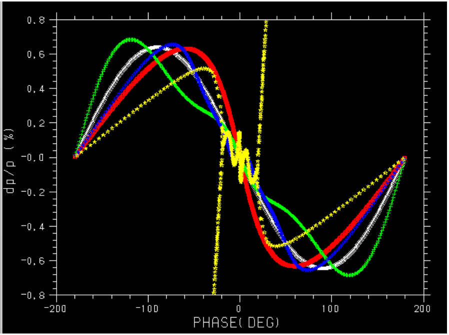
At injection (exit of inflector/deflector).

Bunching with SPUNCH

Bunching without:



And with space charge:



- Space charge reduces energy spread at injection.
- The larger the beam current, the smaller the ideal distance between bunchers and injection.

Challenges of Particle-In-Cell Simulation in H^- Cyclotrons

Large phase acceptance $\sim 60^\circ$:

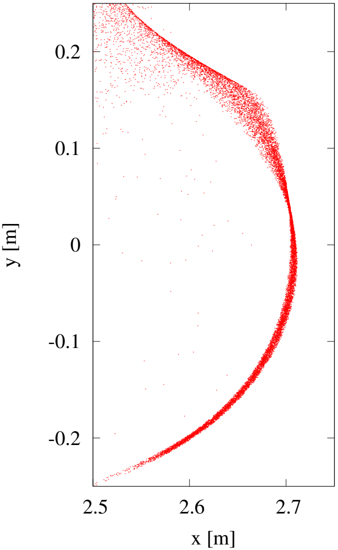
- particles at extreme phases take ~ 150 more turns,
- many turns overlap.

$\Longrightarrow$ "Brute force" PIC simulation would require:

- very large PIC grids,
- simultaneous tracking of many bunches (neighbours).

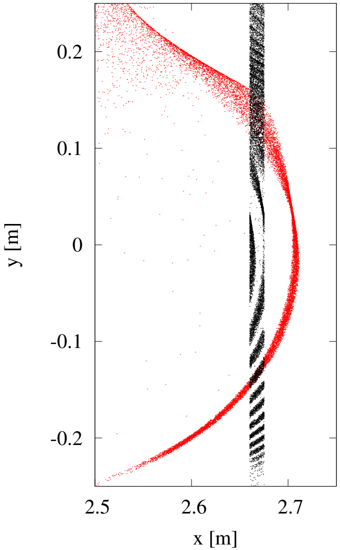
E. Pozdeyev's Trick

Instead we used symmetry. Lets look at turn #100:



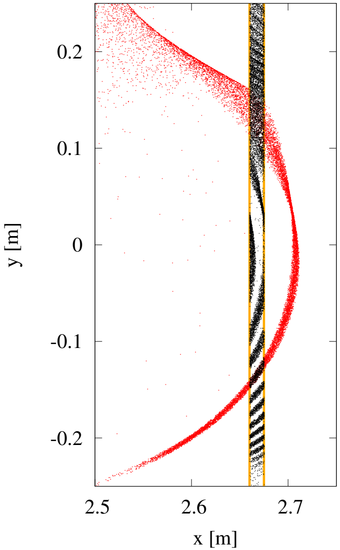
E. Pozdeyev's Trick

Beam is folded onto itself; width = turn separation:



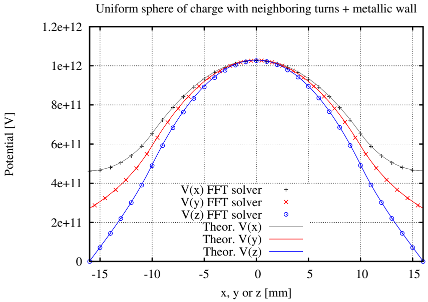
E. Pozdeyev's Trick

Symmetric boundary condition are used by the Poisson solver.

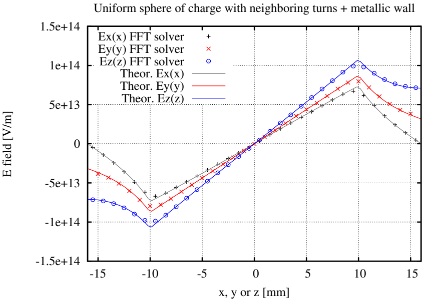


Poisson Solver Test: Uniform Sphere of Charge

Electrostatic potential:

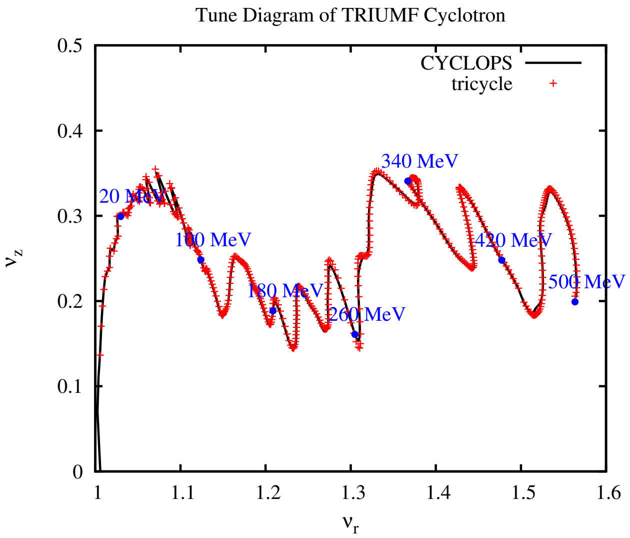


Electric field:



Dots are from our Poisson solver ($32 \times 32 \times 32$ grid, 10^6 particles); solid lines are from theory. Note the three different boundary conditions in x, y, and z: periodic, open, and metallic.

Code testing: vs CYCLOPS



RF acceleration

Acceleration by “thin” rf gaps, focusing included:

$$\begin{aligned} \delta E_k =& q V_{\mathrm{rf}} \sin\phi \\ \delta z' =& K\,\frac{1-a}{2} z \\ \delta r' =& K\,\frac{1+a}{2}(r - r_0) \end{aligned} \tag{1}$$

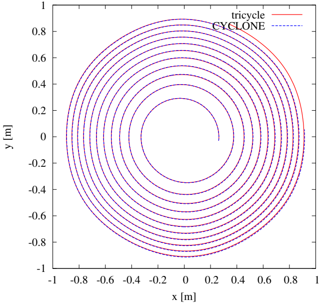
where the focal power K is given by Reiser's formula:

$$K = \frac{V_{\mathrm{rf}}}{V_c}\frac{\pi}{\beta\lambda_{\mathrm{rf}}}\cos(\phi) + \frac{F}{2b\pi}\left(\frac{V_{\mathrm{rf}}}{V_c}\right)^2 \sin^2(\phi) \tag{2}$$

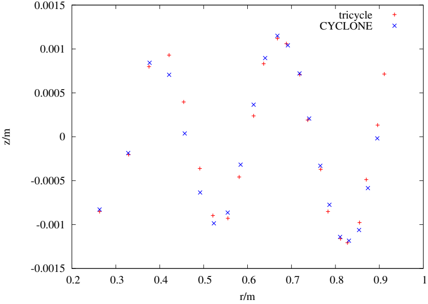
See the proceeding for more details.

Code testing: vs CYCLONE

Accelerated orbit:



and vertical motion:

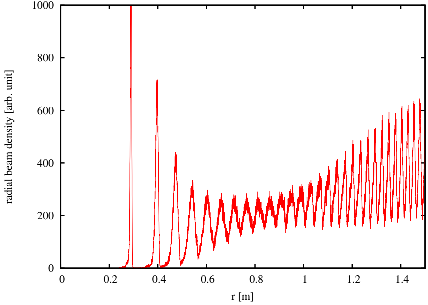


Note: CYCLONE uses a 3-D electric field map instead of rf kicks.

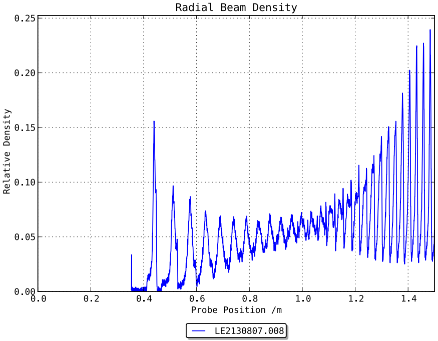
Code testing: vs measurements

No space-charge, bunched beam:

Simulation:



Measurement (pepper-pot in):

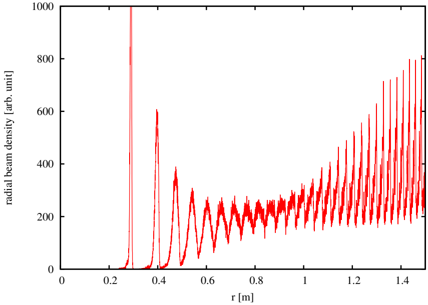


`TRANSOPTR` is used to generate initial particle distribution:
6D Gaussian, **fully correlated**.

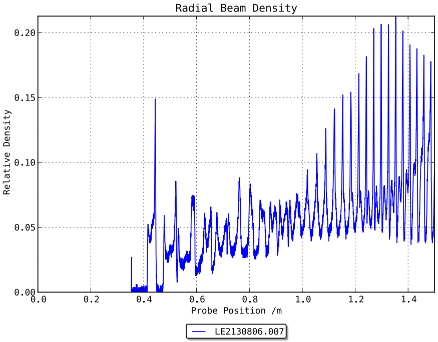
Code testing: vs measurements

With pace charge:

Simulation (500μA injected):



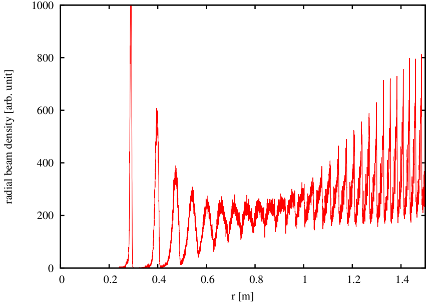
Measurement ($\sim 410\mu$A injected):



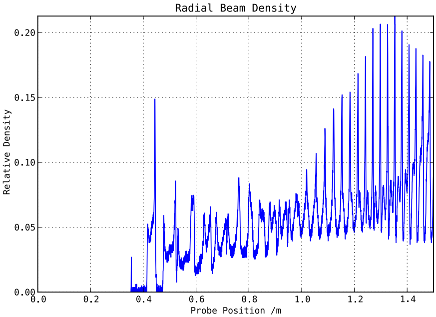
Code testing: vs measurements

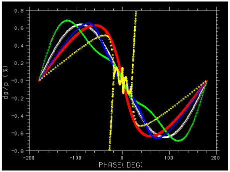
With pace charge:

Simulation (500μA injected):



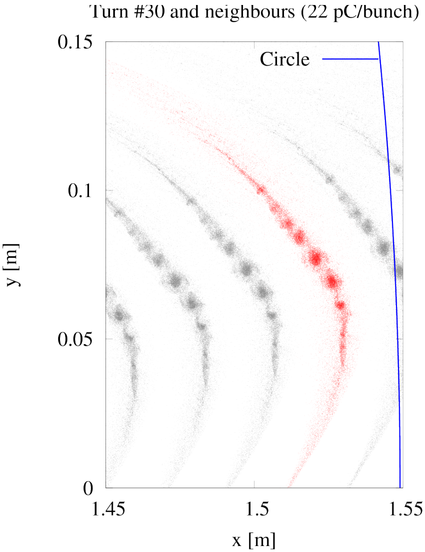
Measurement ($\sim 410\mu$A injected):





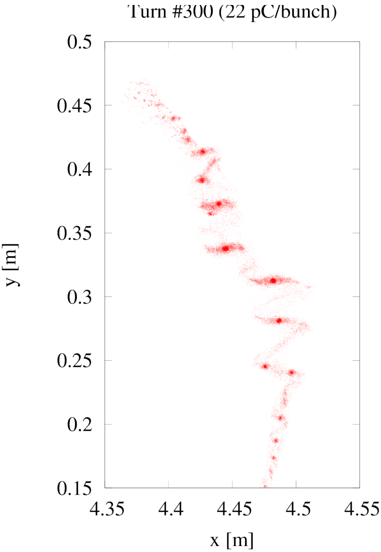
500μA injected Turn #30

Beam breakup (vortex motion):



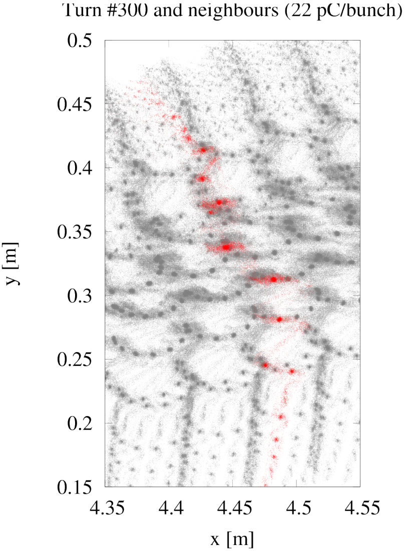
500μA injected Turn #300

Beam breakup (vortex motion):



500μA injected Turn #300

Beam breakup (vortex motion):



Work in progress...

- Working intensively with CIAE to simulate long bunches using `OPAL`.
- Working on starting simulation from the injection line (bunching).

Goals:

- Study longitudinal matching: design 3^{rd} buncher.
- Study transverse matching: re-design inflector, guide operators to tune matching quads, etc.
- Determine accurately the ultimate current limit of our cyclotron.

Thank you!

Thank you for your attention.