High Intensity Beam Dynamics Simulation for the DAEδALUS Cyclotrons

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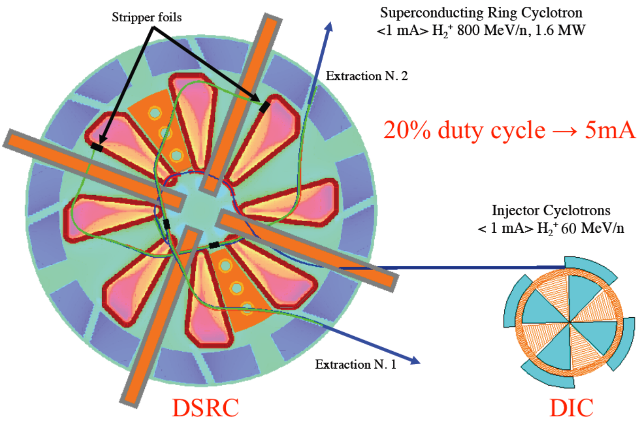
Outline

Outline

DAEδALUS Cyclotrons For CP violation



Generalized perveance:

$$K = \frac{qI}{2\pi\epsilon_0 m\gamma^3\beta^3}$$

1. DIC: K of 5 mA, 35 keV/n H_2^+ equal to 2 mA, 30 keV proton
2. DSRC: K of 5 mA, 800 MeV/n H_2^+ equal to 2.5 mA, 800 MeV proton
3. “Easier” extraction by stripping than proton, higher bonding energy than H^-

OPAL Introduction

OPAL is a tool for charged-particle optics in large accelerator structures and beam lines including 3D space charge. Two of the flavors are:

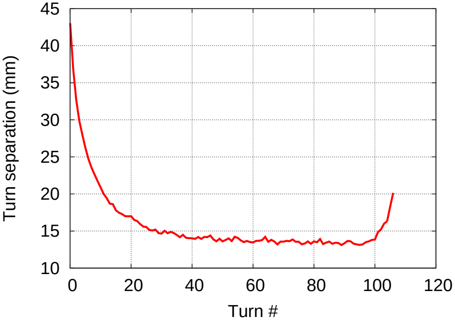
- OPAL-T : RF gun, XFEL, beam line
- OPAL-CYCL : cyclotron, FFAG
  - tracks particles with 3D space charge including neighboring turns
  - Use 4th-order RK and Leap Frog integrator
  - Also can do single particle tracking and betatron tune calculation

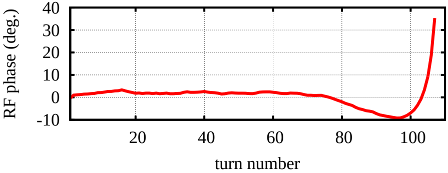
Recent development on OPAL-CYCL

- 4 new elements: stripper, probe(r/phase), collimator(r/z), septum
- Multiple 3D RF field maps handling
- A faster integrator MTS (by M. Toggweiler)
- Bunch compress/decompress effects of RF cavity
- Easer interface between OPAL-T and OPAL-CYCL
- Machine global aperture (r/z)

Outline

Basic Facts of the DIC

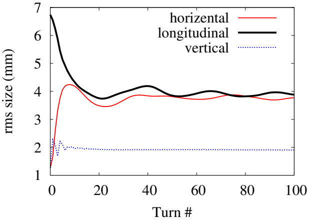


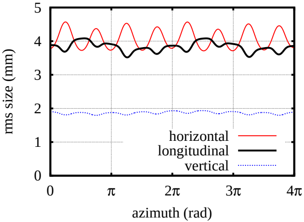


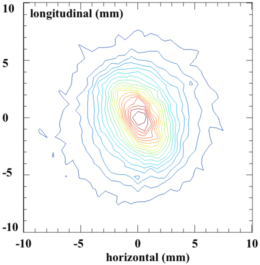
- Compact cyclotron with axial injection @ 70keV/n H_2^+
- Reach 61.7 MeV/n in 107 turns with 4 double-gap cavities
- Maximal average radius 2.1 m (3.7 m for PSI Injector 2)
- Single turn extraction with electrostatic deflector
- ΔR rises to 20 mm at extraction
- Integrated phase slipping less than $< 20^\circ$ during accelaration

Stationary Matched Beam Formation

Tracking initial mismatched coasting beam (1.5MeV, 5mA) in 100 turns







snaphot after per turn

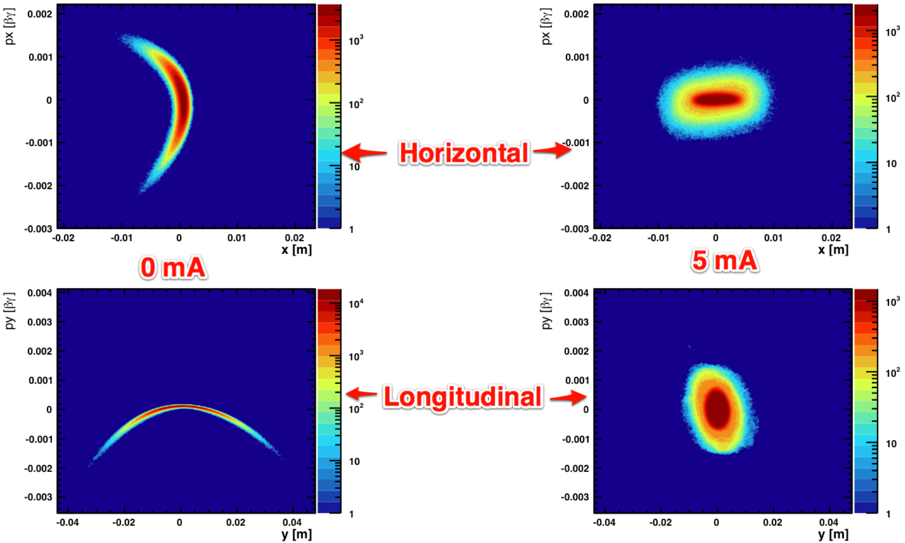
last 2 turns

final distribution at 0°

- r-θ vortex motion causing longitudinal focusing effects
- The compact stationary matched distribution develops formed at low energy
- Flat-top cavity is NOT needed, like PSI Injector 2

Space Charge Effects in Acceleration

Phase space after 100 turns

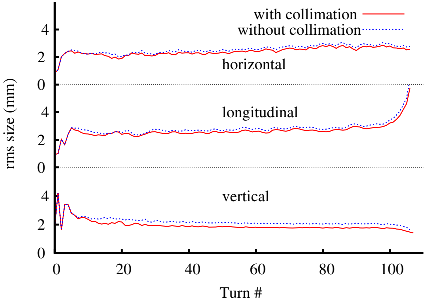


Acceleration Simulation of 5 mA Beam

Acceleration and collimation

OPAL simulation settings

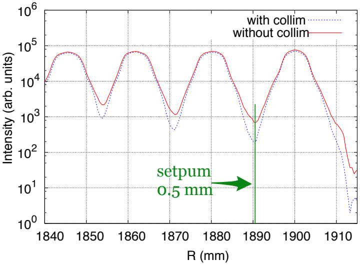
- Start at the exit of central region
- $\epsilon_n(2\sigma)$=0.6 πmm-mrad in the transverse directions
- Assume phase acceptance of 10°
- Initial energy spread of 0.4% (2σ)
- Different collimation schemes are studied, preferred solution is 4 collimators at 1.9 MeV/n, cutting 10% particles
- Gaussian distribution with 10^6 macroparticles
- 64^3 grid for space charge calculation

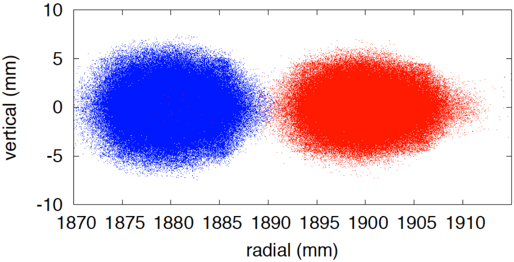


1. Radial size increased slowly
2. Longitudinal size increase slowly
   →phase width compressed
3. Phase shift destroys longitudinal space charge focusing at last turns

Acceleration Simulation of 5 mA beam

Beam Extraction

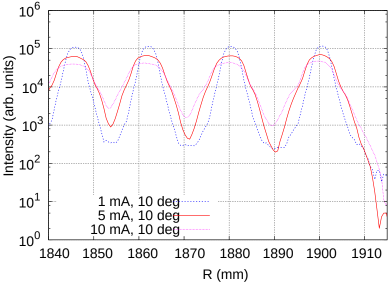


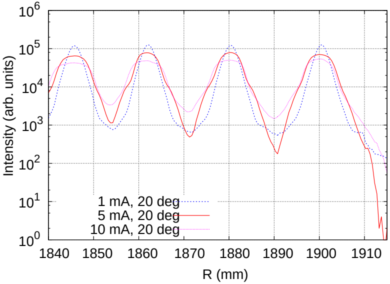


Last 4 turns' radial profile r-z projection of last 2 turns with collim.

rms parameter	r mm	z mm	$\epsilon_{r,n}$ πmm-mr	$\epsilon_{z,n}$ πmm-mr	θ deg	$\Delta E/E$ %
Inj.	0.84	1.85	0.15	0.15	1.67	0.2
Ext. (collim.)	2.55	1.22	0.37	0.35	1.34	0.16
Ext. (no collim.)	2.75	1.46	0.43	0.49	1.50	0.17

Sensitivity of Beam Loss at Septum





Initial phase width	1 mA	5 mA	10 mA
10°	30 W	120 W	1200 W
20°	70 W	110 W	1580 W

Conclusions on DIC Cyclotron

1. DIC is a space charge dominated cyclotron:
   - helps to form a stationary compact beam
   - enlarges the radial beam size, which increase beam loss on septum
2. Phase slipping at extraction enlarges bunch length, but does not affect radial size
3. Magnet design is well improved based on the space charge study
4. Up to 5mA maximal current, the beam loss at extraction is only about 120W, i.e., the extraction efficiency of 99.9% for 20% duty cycle, which is acceptable

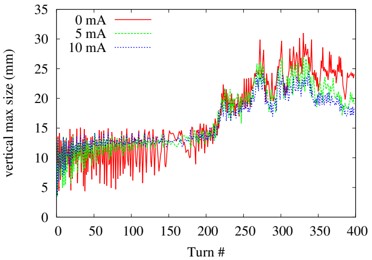
Outline

Introduction

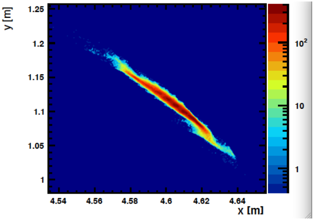
DIC cyclotron study

DSRC cyclotron study

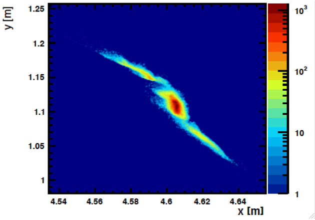
Acceleration Simulation for Different Current



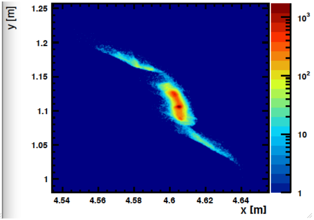
1. Energy reaches 800MeV/n in 400 turns
2. Vertical beam extent < 30 mm (hill gap is 80 mm)
3. Stationary compact shape is not developed, full length ≈ 20 cm !
4. SC force splits beam into 3 sub bunches longitudinally



0 mA



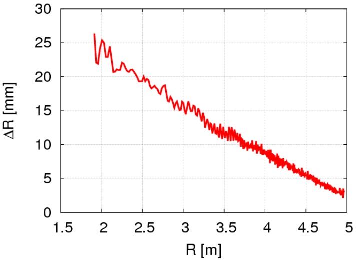
5 mA

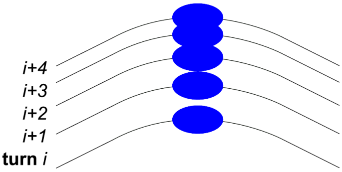


10 mA

Top view of the final turn at extraction

Radially Neighboring Bunch (NB) Effects

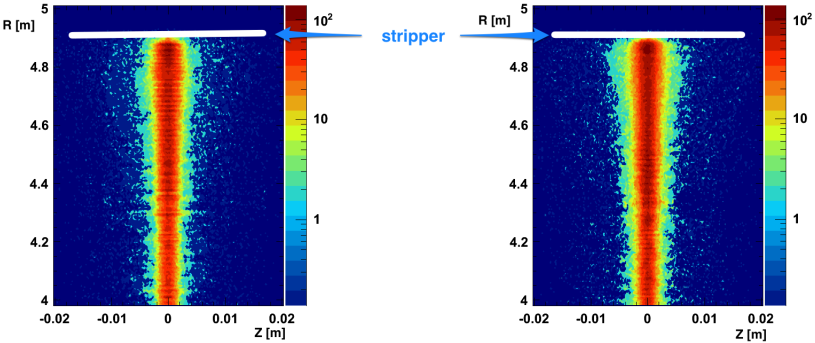




Computation Model and Tool (PhysRevSTAB.13.064201)

1. Use the "Start-to-Stop" numerical model, which is uniquely implemented in OPAL
2. Start with single bunch and automatically transfer to multi-bunch tracking where NB effects become important
3. A small scale simulation: $512 \times 64 \times 16$ grid, 10^3 particle/bunch takes 2 weeks on 64 processors

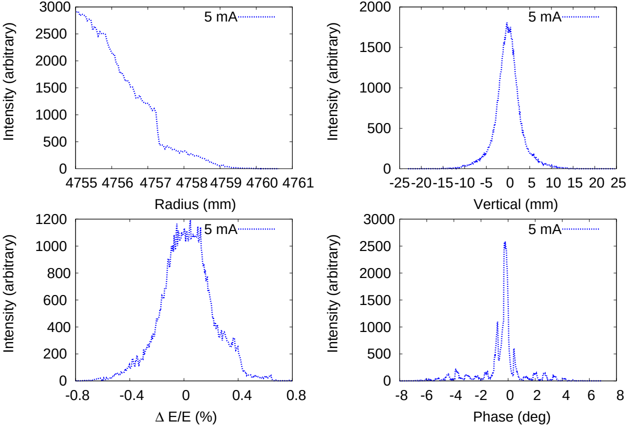
Bunches During Acceleration for 10° initial Phase



0 mA 5mA

- SC and NB introduce vertical beam halo, but the influence is small
- Beam halos extends vertically to ±20 mm, still far away from the magnet sector and vacuum chamber (hill gap is 80 mm)

Particle Distribution on Stripper

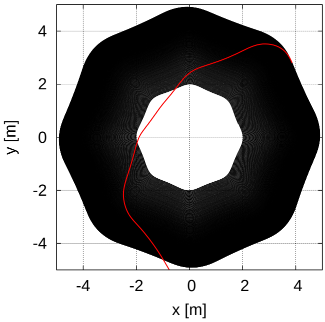


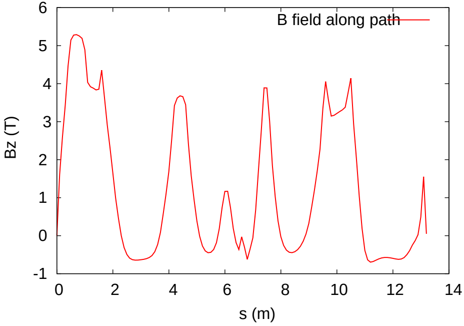
parameter	rms	90%
r (mm)	0.9	3.2
z (mm)	3.3	12.0
$\Delta E/E(\%)$	0.2	0.8
$\Delta\phi(^\circ)$	1.6	2.0
$\epsilon_{r,n}$ (mm-mr)	1.1	
$\epsilon_{z,n}$ (mm-mr)	1.4	

Note: extracted beam is contributed by 15 turns

- This is taken as the initial distribution for extraction simulation in next slides, and input of the temperature calculation by H. Okuno
- 100% extraction efficiency assumed, physics is not included yet

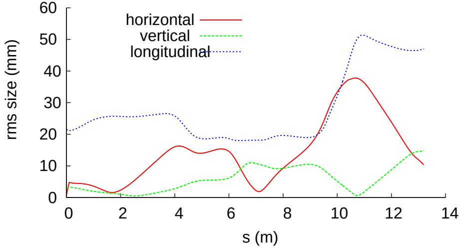
10 mA Proton Beam Extraction





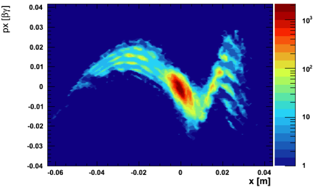
- Protons experiences complicated bending fields including nonlinear fringe fields
- Protons are accelerated and decelerated for 3 times
- Extra dipole field with 1.6 kG/cm is applied at the inner free space to strengthen vertical focusing

10 mA Proton Beam Extraction

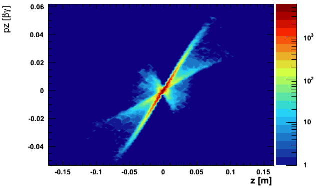


- Vertically well focused with the help of extra dipole field
- Momenta dispersion increase horizontal and longitudinal beam size
- Exotic phase space caused by multi-turn stripping scheme

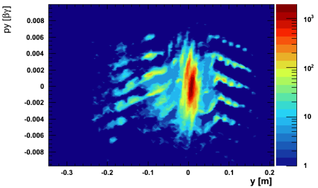
Phase space at the last point:



horizontal



vertical



longitudinal

Conclusions on DSRC

1. Magnet design is optimized based on the space charge study
2. The important beam properties on the stripper are dominated by the initial conditions
3. SC and NB introduce the vertical beam halo, but the influence is small
4. In order to reduce the beam size and energy spread, a smaller initial phase is preferred

Acknowledgment

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