Beam Dynamics Modelling for the IsoDAR Cyclotron

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All LEBT data from D. Winklehner

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Challenges in BD-Modelling for the IsoDAR Cyclotron

- LEBT and Injection (efficiency)
- Controled and uncontrolled losses at $10^{-4} \ldots 10^{-5}$, Inj2 (223 kW) Ring (1.4 MW)
- S2E

Note:

- High intensity cyclotrons are limited by the losses
- High fidelity beam dynamics simulations are needed

The Low Energy Beam Transport System (LEBT)

The LEBT typically serves the following purposes:

- Transport the beam from the ion source to the accelerator
- Preserve beam quality (emittance) from the source
- Separate unwanted ion species (e.g. protons in IsoDAR case).
- Provide space for diagnostics.
- Bunch the beam using (multiharmonic) buncher.

IsoDAR calls for 50 mA of H_2^+ ion beam current in LEBT. For such high current, need to take special care of:

- **Space Charge:** The repulsion of beam ions from each other leading to additional beam spread.
- **Space Charge Compensation:** Beam-Residual gas interaction leads to the production of slow secondary electrons that are trapped by the beam potential well and lower the space charge potential.

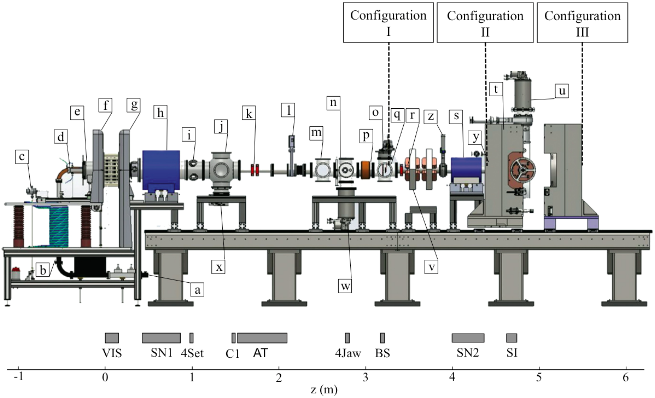
For LEBT design, we need accurate simulations that include 3D Space Charge and Space Charge Compensation.

Simulations of the LEBT (WARP)

Presently, the code WARP [Grote et al.] is used for LEBT simulations.

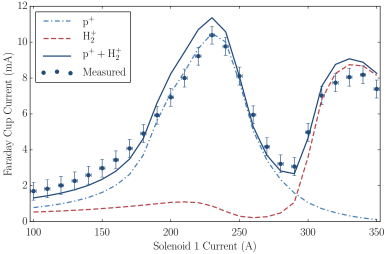
- Particle-In-Cell (PIC) code developed at LBNL/LLNL.
- Includes a multitude of different field-solvers which are discussed in the references. For the LEBT, the XY-slice solver was chosen.
- The XY-slice solver is robust and fast (ideal candidate to map a large parameter space).
- Beam is transported through a series of transversal slices along the z-axis (typically 0.5 mm step size)
- The transversal self fields (Space Charge) are calculated on a 2D grid (typically 512^2) at each time step.
- This is a suitable approach for a DC ion beam in which the longitudinal self fields are largely negligible.
- Space Charge Compensation is calculated each time step using our own subroutine based on a theory by Gabovich/Soloshenko [Gabovich:75, Gabovich:79].

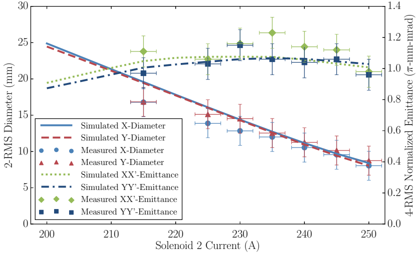
The Best Cyclotron Systems, Inc. (BCS) Teststand



- Ion Source, LEBT, and Injection tests at BCS in Vancouver during summers of 2013 and 2014 (VIS=Ion Source, SI=Spiral Inflector).
- Excellent opportunity to test accuracy of LEBT and SI simulations.

Using the BCS Teststand to Benchmark Simulations





- Left: Faraday Cup current vs. Solenoid 1 current (SN1 in previous schematic) measured 3.2 m after extraction.
- Right: Emittance and Diameter vs. Solenoid 2 current (SN2 in previous schematic) measured 4.8 m after extraction.
- Good agreement of WARP simulations with experiment. Even very detrimental space charge effects of this beam line configuration (hollow beam) were readily reproduced.

OPAL in a Nutshell I

OPAL is an open-source tool for charged-particle optics in large accelerator structures and beam lines including 3D space charge, particle matter interaction and multi-objective optimisation.

- OPAL is built from the ground up as a parallel application exemplifying the fact that HPC (High Performance Computing) is the third leg of science, complementing theory and the experiment
- OPAL runs on your laptop as well as on the largest HPC clusters
- OPAL uses the Mad language with extensions
- OPAL (and all other used frameworks) are written in C++ using OO-techniques, hence OPAL is easy to extend.
- Documentation is taken very seriously at both levels: source code and user manual
- Regression tests running evert day on the head of the repository

OPAL in a Nutshell II

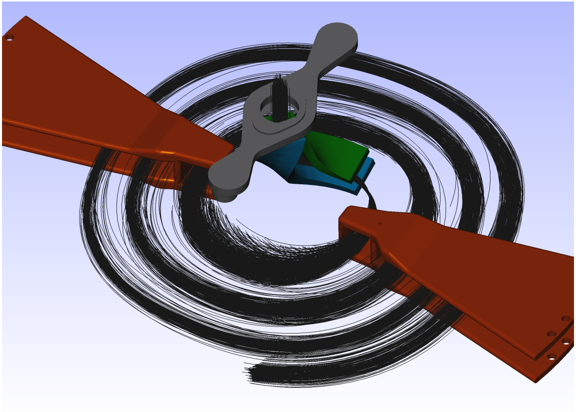
- At the moment we have an international team of 12 developers A. Gsell (PSI), T. Kaman (PSI/ETH), Ch. Kraus (HZB), Y.Ineichen (IBM), S. Russell X. Pang (LANL), Ch. Wang, J. Yang (CIAE), D. Winklehner (MIT/PSI) Ch. Rogers, S. Sheehy (Rutherford) & AA (PSI)
- webpage: `https://amas.psi.ch/OPAL`
- manual: `http://amas.web.psi.ch/docs/opal/opal_user_guide.pdf`
- problems, suggestion etc. mailing: opal AT lists.psi.ch
- Forum: `https://lists.web.psi.ch/mailman/listinfo/opal`

OPAL in a Nutshell III

For this project

- Ongoing effort to incorporate geometry information as boundary conditions for Smoothed Aggregation Algebraic Multi-Grid (SAAMG) fieldsolver
  [A. Adelmann, P. Arbenz, et al., JCP, **229** 12 (2010)]. Very close to being able to do highly realistic spiral inflector simulations for IsoDAR.

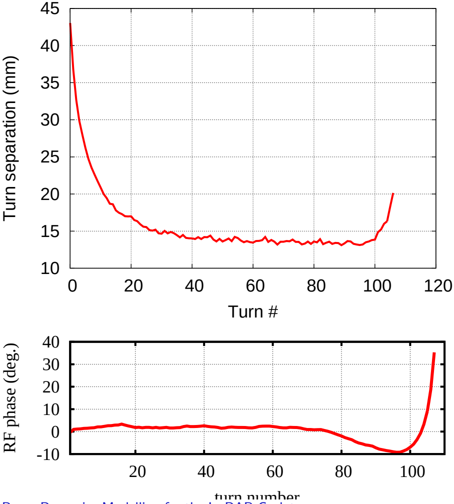
The Spiral Inflector (SI)



- The spiral inflector guides the particles from the axial direction into the mid-plane of the cyclotron (Cyclotron B-field + SI electrostatic field).

Characteristics of the DIC

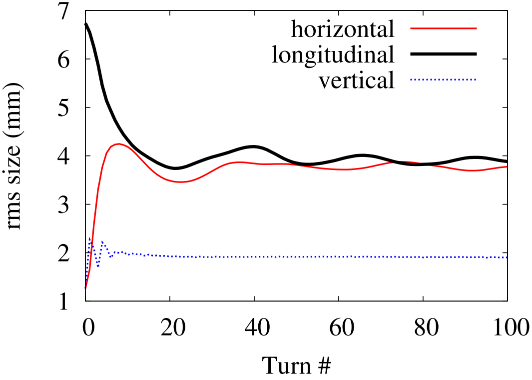
From [J. Yang, A. Adelmann, et al., NIM-A **704**(11) (2013)]



- Compact cyclotron with axial injection @ 70 keV/n H_2^+
- Reaches 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

Matched Stationary Beam

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



- r-θ vortex motion causing longitudinal focusing effects
- The compact stationary matched distribution is formed at low energy

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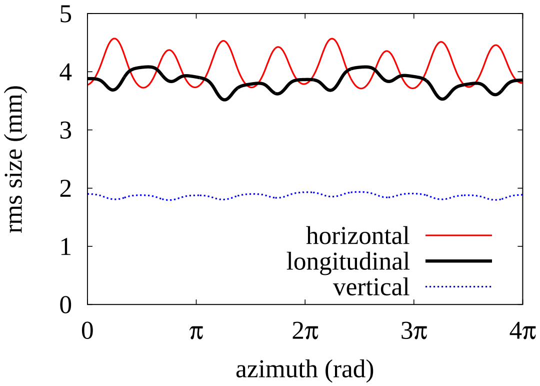

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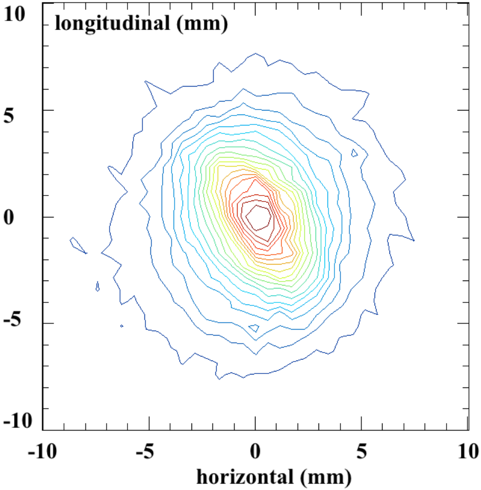
Matched Stationary Beam

Tracking initial mism



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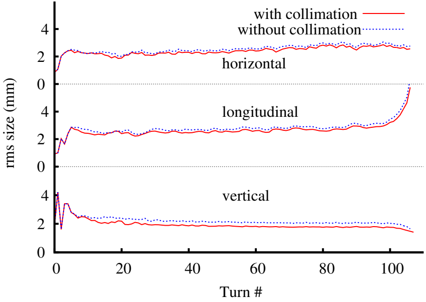
Simulation with 5 mA H_2^+

Acceleration and collimation

OPAL simulation settings

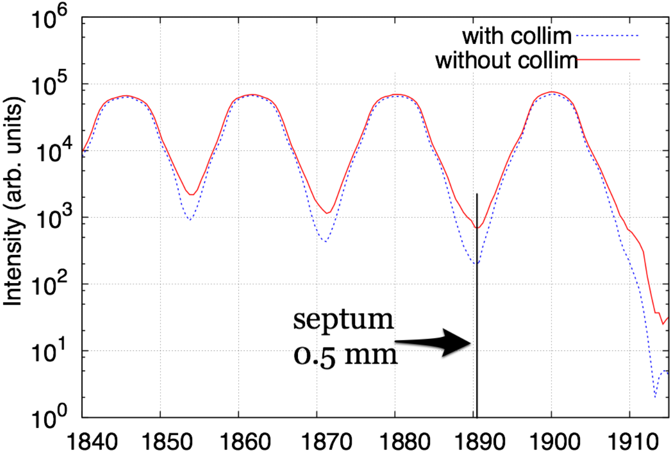
- Start at the exit of central region
- $\varepsilon_n(2\sigma)$=0.6 π mm-mrad in the transverse directions
- Assume phase acceptance of 10°
- Initial energy spread of 0.4% (2σ)
- Different collimation schemes are studied, preferred solution are 4 collimators at 1.9 MeV/n, cutting 10% particles
- Gaussian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



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

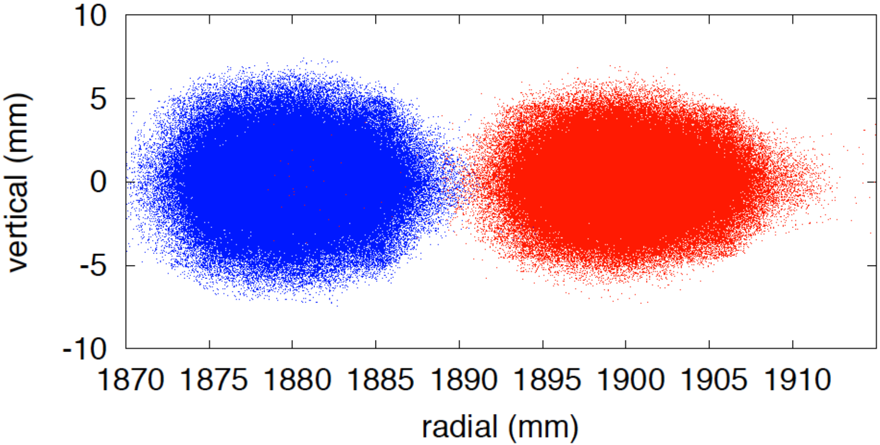
Simulation with 5 mA H_2^+

Beam Extraction



Full S2E Simulation with 5 mA H_2^+

Beam Extraction



Full S2E Simulation with 5 mA H_2^+

Beam Extraction

rms parameter	r	z	$\varepsilon_{r,n}$	$\varepsilon_{z,n}$	θ	$\Delta E/E$
	mm	mm	π mm-mr	π mm-mr	deg	%
Injection	0.84	1.85	0.15	0.15	1.67	0.2
Extraction	2.75	1.46	0.43	0.49	1.50	0.17
Ext. (collim.)	2.55	1.22	0.37	0.35	1.34	0.16

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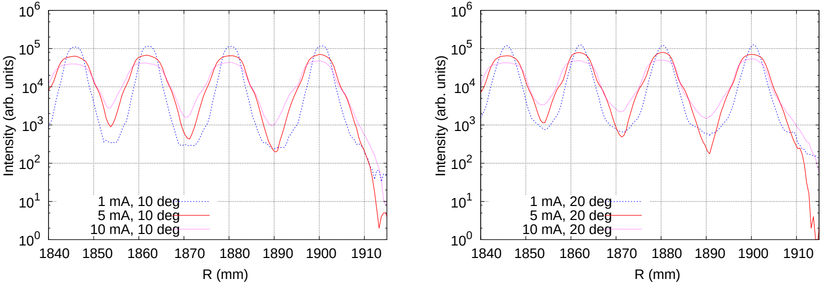
The Sensitivity of Beam Losses at the Septum



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

Conclusions and Future Work I

- We have excellent simulation tools for IsoDAR (WARP & OPAL)
- Benchmarks show, so far, in excellent agreement
  - BEST test
  - PSI cyclotrons [Y. Bi, A. Adelmann, et al., PR-STAB **14**(5) (2011), J. Yang, A. Adelmann, et al., PR-STAB **13**(6) (2010)]
- The simulation models must being improved in order to
  - be able to perform S2E
  - reach the necessary LOD

Next steps at MIT (D. Winklehner et al.):

- With the soon available SAAMG field solver, we will close the gap between LEBT simulations and cyclotron simulations for full start-to-end simulations
- Building a high intensity Multicusp Ion Source optimized for H_2^+ .
- Investigating the option of using an RFQ-based LEBT.

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Conclusions and Future Work II

- We are writing a Conceptual Design Report (CDR) for IsoDAR, to be published in fall.

Next steps at PSI (AA & Post Doc. 20% and 20% t.b.h):

- Improving SAAMG solver in OPAL in order to correctly model the complicated injection region
- Finish automated finding of linear & non-linear matched distribution
- Add new AMR solver to OPAL and benchmark with data from PSI Ring cyclotron
  - Full S2E simulations with high statistics possible
  - Model ready for S2E
- work on reduced order space charge models toward model optimising in commissioning and operation (seek for partial funding of PhD)

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References

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