Challenges in Simulating MW Beams in Cyclotrons

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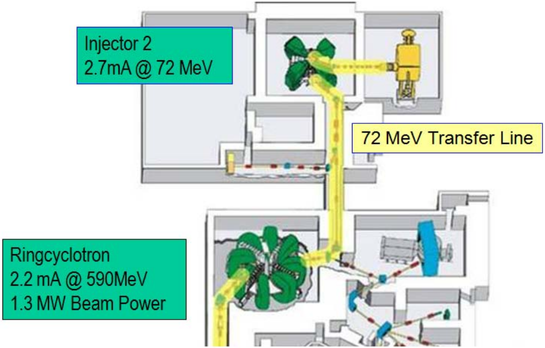
Outline

Motivation: Upgrade Project of the PSI Cyclotron Facility

- The **most powerful machine** of this kind worldwide
- Better **quantitative understanding** of this machine
- Cover: 72 MeV and Ring Cyclotron simulations



Background

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The Simulation Tool OPAL

OPAL (Object Oriented Parallel Accelerator Library) is a tool for charged-particle optics in large accelerator structures and beam lines including 3D space charge

- OPAL-t tracks particles which 3D space charge uses time as the independent variable.
- OPAL-cycl tracks particles which 3D space charge including neighboring turns in cyclotrons with time as the independent variable

At PSI lots of Measurements are available

- 18 profile monitors are available in the 72 MeV transfer line
- 3 time structure probes between Injector 2 and Ring
- Radial probes in the Ring cyclotron

Particle Matter Interaction Model

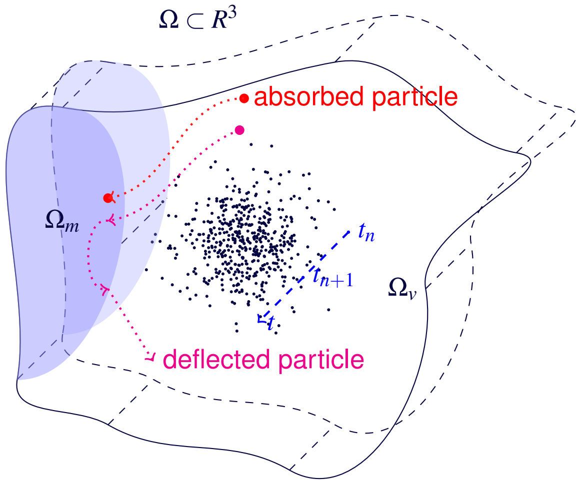
Why implement a particle matter interaction model?

- General-purpose Monte Carlo codes can't track particles in both complex external field and space charge fields

The particle matter interaction model

- Energy loss
- Multiple Coulomb scattering
- Large angle Rutherford scattering

Particle Matter Interaction Model cont.



Particle Matter Interaction Mode cont.

- Energy loss: Bethe-Bloch equation

$$-\frac{dE}{dx} = \frac{Kz^2Z}{A\beta^2}(\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2Tmax}{I^2} - \beta^2)$$

- Energy straggling: Gaussian in form

$$\sigma_0^2 = 4\pi N_A r_e^2 (m_ec^2)^2 \rho \frac{Z}{A} \Delta s$$

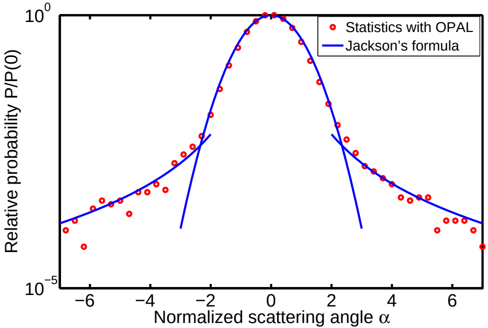
Particle Matter Interaction Model cont.

- Multiple- and single-scattering distributions (Classical Electrodynamics, by J. D. Jackson)

$$\begin{cases} P_M(\alpha)d\alpha = \frac{1}{\sqrt{\pi}} e^{-\alpha^2} d\alpha, \\ P_S(\alpha)d\alpha = \frac{1}{8\ln(204\, Z^{-1/3})} \frac{d\alpha}{\alpha^3} \end{cases}$$

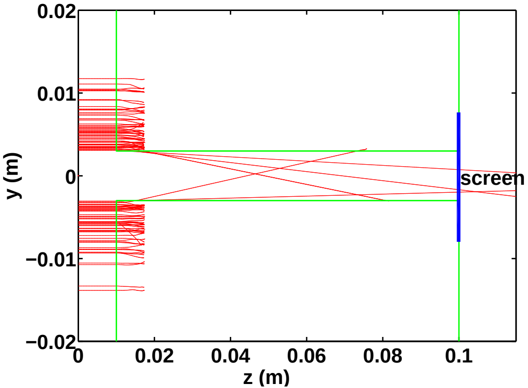
$$\alpha = \frac{\theta}{<\Theta^2>^{1/2}} = \frac{\theta}{\sqrt{2}\theta_0}$$

$$\theta_0 = \frac{13.6MeV}{\beta cp} z\sqrt{\Delta s/X_0}[1+ 0.038\ln(\Delta s/X_0)]$$



Particle Matter Interaction Model cont.

Code Benchmark

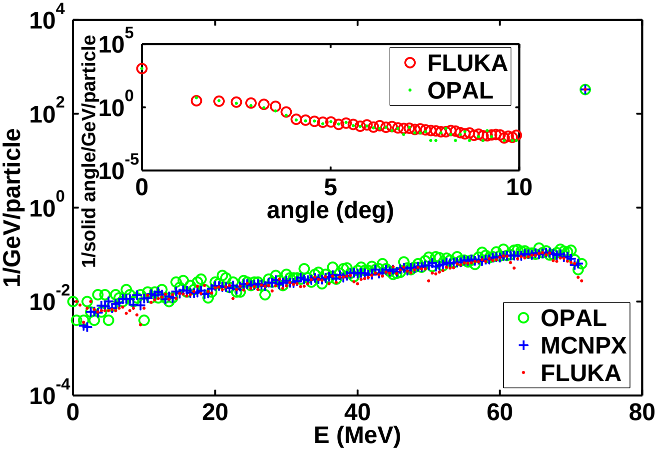


Trajectories of Particles through a Slit

A 72 MeV cold Gaussian proton beam with $\sigma_x = \sigma_y = 5$ mm is send through a copper slit with the half aperture of 3 mm.

Particle Matter Interaction Model cont.

Comparison against two General-Purpose Monte Carlo Codes



Initial Conditions for Ring Cyclotron

72 MeV Transfer line

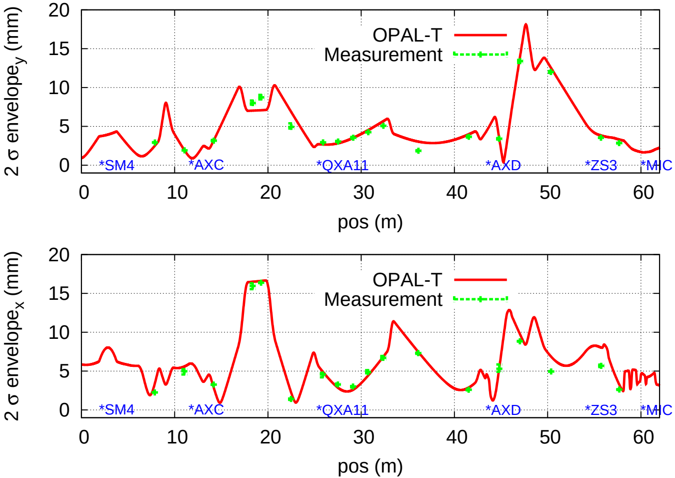
- Add Dispersion to the initial particle distribution, including the correlation coefficient between x,px and t,pt. Specify off-center beams for the initial distribution.
  sigmax= 2.935e-03, sigmapx= 43.6386, corrx=-0.139, offsetx=0.000165, sigmay= 0.471e-03, sigmapy=62.867, corry=0.068, offsety=0.000987, t=0.0062, sigmat= 0.0062, pt=72.4976e6, sigmapt=74.8, corrt=0.0, r61=-0.920, r62=0.0, r51=0.0, r52=0.0;
- Fitting the profile monitor data using transport

Ring cyclotron

- The transverse emittance obtained at the end of the transfer line
- The bunch length measured with the time-structure measurement

Initial Conditions for Ring Cyclotron cont.

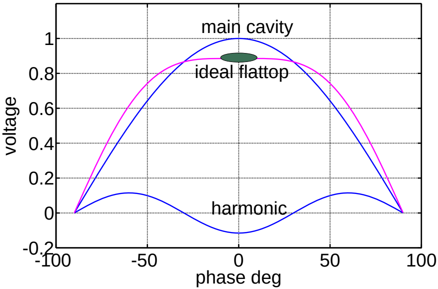
Simulation of the Transfer Line (2 mA)

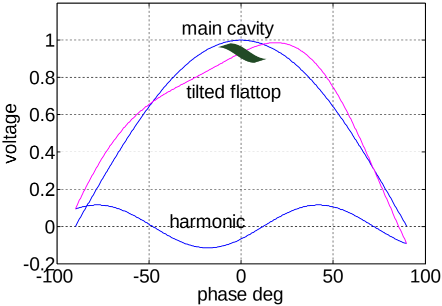


Towards Realistic Ring Simulations

Flattop

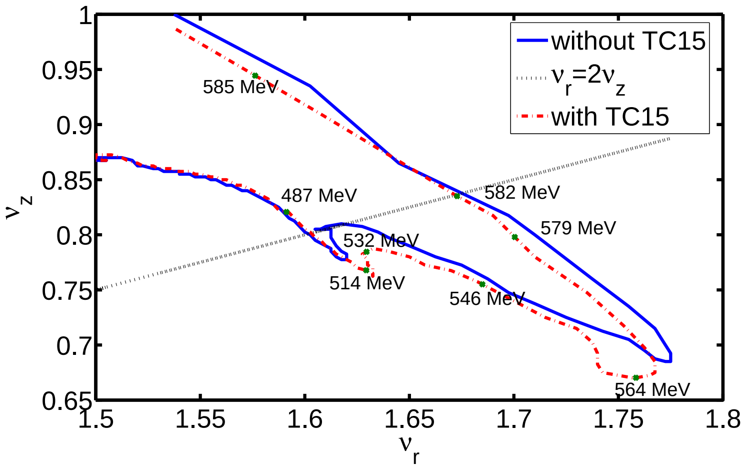
- the energy difference from the main cavity
- the linear part of the space charge force





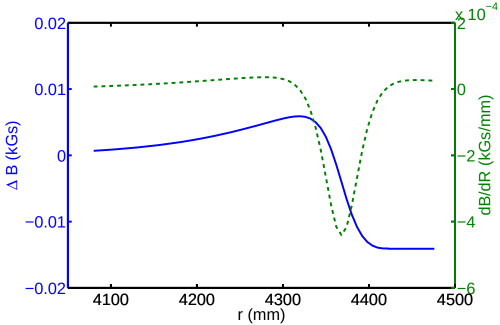
Towards Realistic Ring Simulations cont.

Using Trim Coil TC15 to move away from the coupling resonance



Towards Realistic Ring Simulations cont.

Trim Coil TC15



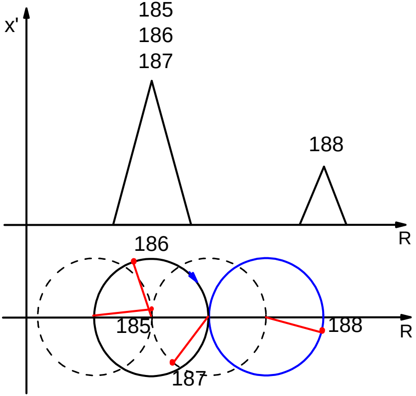
$$\begin{cases} \nu_r^2 = 1 - n \\ \nu_z^2 = n + \underbrace{\frac{N^2}{N^2-1} F(1 + 2\tan^2\delta)}_{\approx const} \end{cases}$$

$$n = -\frac{dB}{dR}\frac{R}{B}$$

$$\begin{cases} \Delta\nu_r \approx \frac{R}{2\nu_r}\frac{d\overline{B}}{\overline{B}dR} \approx 0.014 \\ \Delta\nu_z \approx -\frac{\nu_r}{\nu_z}\Delta\nu_r \approx -0.028 \end{cases}$$

Towards Realistic Ring Simulations cont.

Injection Position and Angle



- Centroid beam:

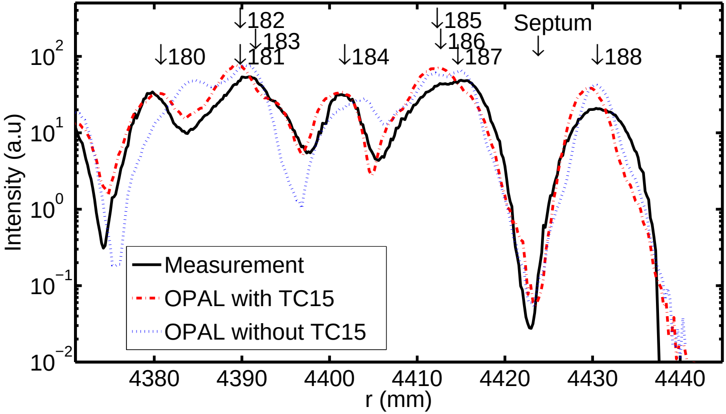
$$\frac{dR}{dn} = \frac{\gamma}{\gamma+1} R \frac{dE/dn}{E} \frac{1}{1+n}$$

- Turn pattern:

$$\nu_r \approx 1.7$$

Towards Realistic Ring Simulations cont.

Compare Radial Beam Profile Simulations with Measurements
Effect of TC15



Towards Realistic Ring Simulations cont.

For fixed energy, the change on radius

$$p = qBR \longrightarrow \frac{\Delta R}{R} = -\frac{\Delta B}{B}$$

eg.

$$\frac{\Delta \tau}{\tau}\Big|_{max} = 2.7e-4$$

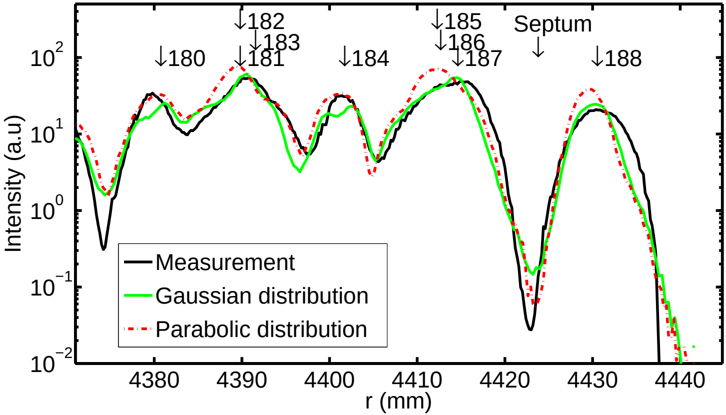
$$\frac{\Delta B}{B} = -\gamma^2 \frac{\Delta \tau}{\tau}$$

$$\Delta R\,\Big|_{max} = 3mm$$

Towards Realistic Ring Simulations cont.

Compare Radial Beam Profile Simulations with Measurements

Impact of the initial distribution



Conclusion

- New features in OPAL
    - The particle matter interaction model: enables the prediction of lost particles including space charge
        - Energy loss
        - Multiple Coulomb scattering
        - Large angle Rutherford scattering
- Transfer Line and Ring simulation:
    - Beam profiles: quantitative agreement with experiments
    - Losses at extraction septum: quantitative agreement with experiments
    - Large scale simulations with 4 orders of magnitude dynamic range
- Work in progress
    - The experimental verification of the particle matter interaction model in the PSI 72 MeV line
    - A better characterization of the initial conditions at the entrance of the Ring Cyclotron - correlation measurements

Acknowledgments

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Thanks for your attention!

Particle Matter Interaction Model cont.