Summary

- Brief introduction to accelerator physics.
- COSY facility overview
  - Beam source
  - JULIC Cyclotron
  - Injection Beam Line
  - Injection
- Optimization
  - IBL optimization
  - Tracking
  - Emittance measurement
- Next steps
Introduction
Introduction

$$\begin{bmatrix} x \\ x' \end{bmatrix}_{s_1} = M(s_1, s_0) \cdot \begin{bmatrix} x \\ x' \end{bmatrix}_{s_0}$$
Introduction

\[
\begin{bmatrix} x \\ x' \end{bmatrix}_{s_1} = M(s_1, s_0) \cdot \begin{bmatrix} x \\ x' \end{bmatrix}_{s_0}
\]

\[
M = M_D \cdot M_{QD} \cdot M_D \cdot M_{QF}
\]
Introduction

\[
\begin{bmatrix}
  X \\
  X'
\end{bmatrix}_{s_1} = M(s_1, s_0) \cdot \begin{bmatrix}
  X \\
  X'
\end{bmatrix}_{s_0}
\]

\[
M = M_D \cdot M_{QD} \cdot M_D \cdot M_{QF}
\]
Introduction

\[
\begin{bmatrix}
X \\
X'
\end{bmatrix}
_{s_1}
= M(s_1, s_0) \cdot 
\begin{bmatrix}
X \\
X'
\end{bmatrix}
_{s_0}
\]

Rms beam size:
\[
\sigma_{rms} = \sqrt{\epsilon \beta}
\]

Geometrical emittance:
\[
\varepsilon = \pi \epsilon
\]

\[M = M_D \cdot M_{QD} \cdot M_D \cdot M_{QF}\]
Facility overview
Facility overview
Facility overview

\[ p = 0.3 - 3.7 \text{ GeV/c} \]
\[ L = 184 \text{ m} \]
Facility overview

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\[ L = 184 \text{ m} \]
Beam source
Beam source
Beam source
Beam source

- 2.0-4.5 KeV/A beams.
- 20ms pulses.
- Polarization up to 80%.
JULIC Cyclotron

Commissioned in nine six eight. Upgraded in nine nine two.

Originally built for light ions up to Ar. Nowadays only used for $H^-$ and $D^-$. seven zero tons of iron.

$f = $ two zero three MHz.

$B_{\text{max}} = $ one three five T.

$9 / 32$
JULIC Cyclotron

JULIC Cyclotron


Originally built for light ions up to Ar.
Nowadays only used for $H^-$ and $D^-$.

- 700 tons of iron.
- $f = 20 - 30 \text{MHz}$.
- $< B >_{\text{max}} = 1.35T$
JULIC Cyclotron

\[ I_{\text{max}} = \frac{\text{n}}{0.01} \text{mA \ at \ extraction.} \]

Provides \( \text{MeV} \) or \( \text{MeV} \) \( H^- \) or \( D^- \) beams with \( \text{ms} \) cycles.
JULIC Cyclotron

![Graph showing beam current vs. cyclotron radius]

- In 2013, the beam current was higher than in 2007.
- Septum transmission was 56%.

Equation: \( I_{\text{max}} = \frac{\text{one.pnum}}{\text{zero.pnum}} \).
JULIC Cyclotron

\[ I_{\text{max}} = \frac{\text{zero.pnum}}{\text{one.pnum}} \text{mA} \text{ at extraction.} \]

Provides \( \frac{\text{four.pnum}}{\text{five.pnum}} \) MeV \( \text{H}^- \) or \( \frac{\text{seven.pnum}}{\text{six.pnum}} \) MeV \( \text{D}^- \) beams with \( \frac{\text{two.pnum}}{\text{zero.pnum}} \) ms cycles.
JULIC Cyclotron

\[ I_{\text{max}} = 0.1 \text{mA at extraction.} \]

Provides 45 MeV \( H^- \) or 76 MeV \( D^- \) beams with 20 ms cycles.
Injection Beam Line (IBL)

Provides the connection between JULIC cyclotron and COSY. It is nine meters long. Composed by four quadrupole magnets, two dipole magnets, and one steerer magnet. Diagnostic tools included along the IBL: eight proton grids and three phase probes. Injection dipole at the end.
Injection Beam Line (IBL)

Provides the connection between JULIC cyclotron and COSY. It is nine meters long. Composed by four quadrupole magnets, two dipole magnets, and one steerer magnet. Diagnostic tools included along the IBL: eight profile grids and three phase probes. Injection dipole at the end.
Injection Beam Line (IBL)

Provides the connection between JULIC cyclotron and COSY.
- It is 94m long.
- 30mm of vertical offset.
- Composed by 42 quadrupole magnets, 12 dipole magnets and 14 steerer magnets.
- Diagnostic tools included along the IBL: 8 profile grids and 3 phase probes.
- Injection dipole at the end.
Injection Dipole
Injection Dipole

- Injection in COSY is performed by stripping injection into a "distorted orbit".
- Injection dipole is responsible to align the beam coming from the cyclotron with the beam cycling in COSY.
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Injection
Distorted orbit

Displacement $x$ can be controlled by the steerer magnets, but not the angle $x'$. 
Injection

Distorted orbit

Displacement $x$ can be controlled by the steerer magnets, but not the angle $x'$. 
Optimization

The goal is to make the injection of particles into COSY as efficient as possible. Steps:
- Develop a model for the IBL.
- Match design specifications.
- Control injection point parameters.
- Match IBL emittance with COSY acceptance.
Optimization

Overview

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Optimization

Overview

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- Develop a model for the IBL.
- Match design specifications.
- Control injection point params.
- Match IBL emittance with COSY acceptance.
Injection optimization

IBL

Not all quadrupoles independent → one.pnum/two.pnum free parameters.
Constraints Optimized according to INTERATOM:
Sections /two.pnum, /four.pnum, /six.pnum: FODO structures
Sections /one.pnum, /three.pnum+/four.pnum+/five.pnum and /seven.pnum achromats.
Section /eight.pnum controls injection.

/one.pnum/five.pnum / /three.pnum/two.pnum
Injection optimization

IBL

Not all quadrupoles independent

→ /one.pnum/two.pnum

free parameters.

Constraints

Optimized according to INTERATOM:
Sections /two.pnum,/four.pnum,/six.pnum: FODO structures
Sections /one.pnum, /three.pnum+/four.pnum+/five.pnum and /seven.pnum achromats.

Section /eight.pnum controls injection.

/one.pnum/five.pnum / /three.pnum/two.pnum
Injection optimization

IBL

Not all quadrupoles independent → 12 free parameters.

Constraints

Optimized according to INTERATOM:

- Sections 2,4,6: FODO structures
- Sections 1, 3+4+5 and 7 achromats.
- Section 8 controls injection.
Injection optimization
IBL
Injection optimization

IBL
Injection optimization

IBL
Injection optimization

Tracking at IBL

Phase-Space X

X [mm]

X' [mrad]

Initial
End
Injection optimization
Tracking at COSY
Injection optimization

Tracking at COSY
Injection optimization

Tracking at COSY

Survival Histogram

Loops in COSY
Injection optimization

Tracking at COSY
Injection optimization

Emittance measurement
Injection optimization
Emittance measurement

\[
M = \frac{\text{one.pnum}}{\sqrt{D}} \cdot \cos(\sqrt{KL}) - \sqrt{K} \sin(\sqrt{KL}) \cos(\sqrt{KL})
\]
Injection optimization

Emittance measurement

\[ M = \begin{bmatrix} 1 & D \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos(\sqrt{KL}) & \frac{1}{\sqrt{K}} \sin(\sqrt{KL}) \\ -\sqrt{K} \sin(\sqrt{KL}) & \cos(\sqrt{KL}) \end{bmatrix} \]
Injection optimization

Emittance measurement

\[ M = \begin{bmatrix} 1 & D \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos(\sqrt{KL}) & \frac{1}{\sqrt{K}} \sin(\sqrt{KL}) \\ -\sqrt{K} \sin(\sqrt{KL}) & \cos(\sqrt{KL}) \end{bmatrix} \]
Injection optimization

Emittance measurement

\[ M = \begin{bmatrix} 1 & D \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \cos(\sqrt{K'L}) & \frac{1}{\sqrt{K'}} \sin(\sqrt{K'L}) \\ -\sqrt{K'} \sin(\sqrt{K'L}) & \cos(\sqrt{K'L}) \end{bmatrix} \]
Injection optimization

Emittance measurement

Plot of beam size squared vs quadrupole strength for Q17, Y axis.
Injection optimization

Emittance measurement

Fit using first order approximation of $M$ matrix.

$\chi^2/ndf = 3.81E-04/3.0 \ m^2$
Injection optimization

Emittance measurement

Fit using second order approximation of M matrix.

\[ \chi^2/\text{ndf} = 1.69 \times 10^{-4} / 3.0 \, m^2 \]
Next steps for optimization

The planned upcoming steps for optimizing the injection are:

- Analyze the injection dipole.
- Try to find steerer magnets which allow for $x$ and $x'$ variation of the injected beam in the stripping foil.
- Connect IBL and COSY in a simulation for a full tracking including the orbit bump at injection.
- Try to match phase space at IBL exit with COSY acceptance.
- Improve the emittance measurement at IBL. Look for other methods.
References

20 years of JULIC operation as COSY’s injector cyclotron
Proceedings of Cyclotrons 2013, Vancouver, BC, Canada.

C. Weidemann (2016)
COSY injection and tuning
Workshop on Beam Dynamics and Control studies at COSY.

Implementation of quadrupole-scan emittance measurement at
Fermilab’s Advanced Supercomputing Test Accelerator (ASTA)
6th International Particle Accelerator Conference.
Spare slides

Phase-Space Y

Initial
End

Y [mm]

Y [mrad]

-10.0
-7.5
-5.0
-2.5
0.0
2.5
5.0
7.5
10.0

-40
-30
-20
-10
0
10
20
30
40
Spare slides
Spare slides
Spare slides

Beam Size X vs Quadrupole Strength

\[ \chi^2/ndf = 2.83 \times 10^{-4}/3.0 \, m^2 \]

Fit
Data

Beam width \( x^2 \) [m^2]
Residuals [m^2]

\( K_{Q17} \) [1/m^2]
Emittance Measurement: Quadrupole Scan Method

\[ M = \begin{pmatrix} 1 & D \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \cos(\sqrt{K}L) & \frac{1}{\sqrt{K}} \sin(\sqrt{K}L) \\ -\sqrt{K} \sin(\sqrt{K}L) & \cos(\sqrt{K}L) \end{pmatrix} \]

\[ \Sigma_{beam}(s) = M \cdot \Sigma_{beam}^0 \cdot M^T \]

where

\[ \Sigma_{11} = \langle x^2 \rangle \]
\[ \Sigma_{12} = \Sigma_{21} = \langle xx' \rangle \]
\[ \Sigma_{22} = \langle x'^2 \rangle \]

Finally:

\[ \Sigma_{11} = \langle x^2 \rangle = M_{11}^2 \Sigma_{11}^0 + 2 M_{11} M_{12} \Sigma_{12}^0 + M_{12}^2 \Sigma_{22}^0 \]

And:

\[ \epsilon = \pi \sqrt{\det(\Sigma_{beam})} = \pi \sqrt{\Sigma_{11}^0 \Sigma_{22}^0 - (\Sigma_{12}^0)^2} \]
First order approximation:

\[
\Sigma_{11} = \langle x^2 \rangle = f(K^2, K) \Rightarrow \quad \text{Parabolic fit with: } g(K) = AK^2 + BK + C
\]

\[
\begin{align*}
\cos(x) &\approx 1 + O(x^2) \\
\sin(x) &\approx x + O(x^3)
\end{align*}
\]

Second order approximation:

\[
\Sigma_{11} = \langle x^2 \rangle = f(K^4, K^3, K^2, K) \Rightarrow \quad \text{Fourth order fit: } g(K) = AK^4 + BK^3 + CK^2 + EK + F
\]

\[
\begin{align*}
\cos(x) &\approx 1 - \frac{x^2}{2} + O(x^4) \\
\sin(x) &\approx x - \frac{x^3}{3!} + O(x^5)
\end{align*}
\]