Optimization of low-energy beam transport

Kernfysisch Versneller Instituut –
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The Netherlands
• Introduction

• KVI- situation *(brief)*
  – Magnet aberrations and 4rms-emittance growth

• Optimization low energy beam line
  – Quick compensation by an additional sextupole effect?
  – General method to calculate the 4rms-emittance growth
    – Sectupoles
    – Solenoid lens
    – Einzel
  – Conclusions.
Introduction

Accelerator Laboratories:

- Ion source
- Transport
- Accelerator
- Transport
- Experiment

Low magnetic rigidity
High magnetic rigidity
Introduction

Accelerator Laboratories:

\[ \varepsilon_{4\text{rms}} = 20-100 \text{ mm.mrad} \]
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Accelerator Laboratories:

Low magnetic rigidity
Ion source  Transport  Accelerator

High magnetic rigidity
Transport  Experiment

$\varepsilon_{4\text{rms}} = 20\text{-}100 \text{ mm.mrad}$
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Accelerator Laboratories:

- \( \varepsilon_{4\text{rms}} = 20-100 \text{ mm.mrad} \)
- Geometrical acceptance = 100-200 mm.mrad

Ion source \quad \text{Transport} \quad \text{Accelerator} \quad \text{Transport} \quad \text{Experiment}
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- $\varepsilon_{4\text{rms}} = 0.004 - 1 \text{ mm.mrad}$
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Loss of beam intensity

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Ion source Transport Accelerator Transport Experiment

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Low magnetic rigidity

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Transport

Accelerator

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Loss of beam intensity

Challenge: avoid emittance blowup due to:
1. lens aberrations
2. absence of space charge compensation
Introduction

Research emittance growth

– Simulations
  • Particle tracking codes, Raytrace, Track, GPT,
    +: any field configuration. Lorentz3D
    -: slow (equation of motion is calculated for every track)
  • Mapping codes: Transport, GIOS, COSY Infinity 9.1
    +: fast (equation of motion is already in the matrix)
    -: fixed elements.

– Measurements
  • Measurement of emittance
    – Slit grid, Allison scanner:
      - measurement in one plane, integrates over other planes
        + proven technology
    – pepper pot emittance meter:
      + measurement in two planes, cross correlations, slices emittances
      - Fixed grid
Emittance

Gaussian distribution

\[ \sigma_{11} = \int\int (x_i - \langle x \rangle)^2 \rho(x, x') dx dx' \]
\[ \sigma_{22} = \int\int (x'_i - \langle x' \rangle)^2 \rho(x, x') dx dx' \]
\[ \sigma_{12} = \int\int (x_i - \langle x \rangle)(x'_i - \langle x' \rangle) \rho(x, x') dx dx' \]

\[ \varepsilon_{xx' - 4\text{rms}} = 4 \cdot \sqrt{\sigma_{11} \sigma_{22} - \sigma_{12}^2} = \frac{A_{86\%}}{\pi} \]

\[ \varepsilon_{xx' - 4\text{rms}, n} = \varepsilon_{xx' - 4\text{rms}} \cdot \beta \cdot \gamma \]
Emittance

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Emittance

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KVI-CART facility layout

- Top view experimental hall
KVI-CART facility layout

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• Top view experimental hall
Measured and simulated

- Simulated phase-space projections of a 25 kV He$^{1+}$ validated by measurements
Measured and simulated

- Simulated phase-space projections of a 25 kV He\textsuperscript{1+} validated by measurements
Measured and simulated

- Simulated phase-space projections of a 25 kV He\(^{1+}\) validated by measurements
• Conclusion:
  – Higher order components \((y|x'y')\), \((x|y'y')\) and \((x|x'x')\) identified
  – Strengths: 5.3, -2.4 and -0.9 respectively.
  – Ion displacement in image plane due to aberrations are 26, 12 and 5 times larger than first order imaging. Image = aberration

25 kV He\(^{1+}\) with phase-space cutoffs
• How to fix the aberrations

• Method to calculate the emittance growth

• Apply this method to:
  – Add sextupoles
    • sextupoles
  – Add field lenses
    • Solenoid
    • Einzel lens
Optimization of low-energy beam transport.

Method to calculate the 4-rms emittance growth

\[ X_0 \]

\[ X_1 = M^{(k)} \cdot X_0 \]

4\text{rms} = 65 \text{ mm.mrad}

Area = 65.\text{p mm.mrad}

No difference with or without ion distribution in extraction aperture
Optimization of low-energy beam transport.

Dipole with an additional two Sextupoles

- Top view analyzing magnet

4RMS emittance 21 H$^{1+}$

as function sextupole excitation

\[
\begin{align*}
(y|x'y') &= 5.3 \quad -2.4 \quad -0.9 \quad \text{aberrations dipole} \\
-5.3 &\quad +2.7 \quad -2.7 \quad \text{compensation sextupoles 0.013T} \\
0 &\quad +0.3 \quad -3.6 \quad \text{dipole corrected with sextupoles}
\end{align*}
\]
Optimization of low-energy beam transport.

- Compensation by sextupoles and small pole face adjustment

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Conclusion:
1. Yes, second order is partially compensated. However large higher order terms.
Optimization of low-energy beam transport.

Dipole with an additional solenoid

- Top view

21 kV H$^{1+}$

Side views

$I = 0 \text{kA}$

$I = 320 \text{kA}$
Optimization of low-energy beam transport.

Dipole with additional einzel-lens

- Top view analyzing magnet

4RMS emittance 21 kV H\(^{1+}\)

as a function of the Einzel lens potential
Optimization of low-energy beam transport.

Detail: In the image plane of the dipole remnant 4-rms emittance generated by the einzel lens.

4-rms emittance growth due to einzel lens, 21 kV H$^{1+}$

4-rms emittance in image plane dipole of a 21 kV H$^{1+}$ beam
Optimization of low-energy beam transport.

Conclusions:

1) Solenoid option is the best option. However 500 kA.Turn is difficult to integrate in existing setup.

2) Einzel lens reduces the emittance growth roughly with factor of 3 in both planes.

3) Diameter of the Einzel lens should be larger than 70 mm diameter.

4) Design strategy for a low energy beam-lines to accept beams with large divergence:
   1) First, reduce the fringe fields as much as possible and included additional correction.
   2) Secondly, calculate which coefficients causes the aberrations and change the phase-space upstream such that the effect of fringe fields on the beam phase-space is minimized.
• Thank you for your attention
• Measurements 25 kV He\textsuperscript{1+} beam
• Measurements 25 kV He$^{1+}$ beam

$x = -11.96$

$x = -10.92$

$x = -9.88$

$x = -8.84$
• Measurements 25 kV He$^{1+}$ beam
• Measurements combined with simulations of a 25 kV He$^{1+}$ beam

![Diagram with measurements]
Simulated influence of limiters on projections

The limitations

Effects on projections

Complete beam
Optimization of low-energy beam transport.

Result in phase-space of the Einzel lens

('Fifth order calculation: Drift (0.3175) - Einzel (0.075) - Drift (0.3175) - Dipole - Drift (0.534) - Image plane', '8.5')
Simulated

- Theoretical model of the setup \( X_1 = M_T \cdot X_0 \)

Transfer matrix: \( M_t \)

\[
\begin{array}{cccccccc}
\text{\( x_1 \)} & \% & \text{\( x'_1 \)} & \% & \text{\( y_1 \)} & \% & \text{\( y'_1 \)} & \% & \text{\( (x,x',y,y',\delta,l)_0 \)} \\
\hline
0.82648 & 24 & 2.26816 & 5.8 & 0 & 0 & 0 & 0 & 100000 \\
1.668E+06 & 0 & 1.20995 & 108 & 0 & 0 & 0 & 0 & 010000 \\
0 & 0 & 0 & 0 & -0.85078 & 9.2 & -1.258137 & 3.8 & 001000 \\
0 & 0 & 0 & 0 & 9.100E-02 & 35 & -1.040819 & 110 & 000100 \\
-1.3220 & 0 & -0.84624 & 0 & 0 & 0 & 0 & 0 & 200000 \\
-2.0211 & -2 & -1.6758 & 0.1 & 0 & 0 & 0 & 0 & 110000 \\
-0.94047 & 33 & -1.1015 & 3.4 & 0 & 0 & 0 & 0 & 020000 \\
0 & 0 & 0 & 0 & 1.96766 & 0 & -3.98394 & 0 & 101000 \\
0 & 0 & 0 & 0 & 3.85987 & 1.5 & -3.84397 & 0.4 & 011000 \\
0 & 0 & 0 & 0 & 5.16242 & 2 & 5.65309 & 0.6 & 100100 \\
0 & 0 & 0 & 0 & 5.34891 & 71 & 3.59906 & 13 & 010100 \\
-3.35827 & 0 & -5.66803 & 0 & 0 & 0 & 0 & 0 & 002000 \\
-3.03125 & 3 & -6.27946 & 0.6 & 0 & 0 & 0 & 0 & 001100 \\
-2.43596 & 86 & -3.12330 & 9.8 & 0 & 0 & 0 & 0 & 000200 \\
\end{array}
\]

\( X_0: \) KV distribution
Simulated

• Theoretical model of the setup

\[ X_1 = M_T \cdot X_0 \]

Transfer matrix: \( M_t \)

\[
\theta_t = (\theta / x)x_0 + (\theta / x')x'_0 + (\theta / y)y_0 + (\theta / y')y'_0 + (\theta / xx)x_0^2 + (\theta / xx')x_0x'_0 + (\theta / x'y)x_0y'_0 + (\theta / x'y')(x'_0y_0 + (\theta / x'y')x'_0y'_0 + (\theta / yy)y_0y'_0 + (\theta / yy')(y'_0y_0 + (\theta / yy')y'_0y'_0)
\]

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• Measured phase-space projections He$^{2+}$ beam

\[ \varepsilon_{xx'-4\text{rms}} = 387 \text{ mm.mrad} \]
\[ \varepsilon_{yy'-4\text{rms}} = 359 \text{ mm.mrad} \]
Measured and simulated

- Measurements combined with simulations of a 25 kV He$^{1+}$ beam
Ion source

AECR (LBNL type)
34 kV Extraction Voltage

Bending radius = 0.4 m
Bending angle = 110 deg

Pepper pot emittance meter
Optimization of low-energy beam transport.

Dipole with an additional two quadrupoles

- Top view analyzing magnet

4RMS emittance 24.5 He$^{1+}$ as function of the quadrupole excitation
• Possible options to fix.

• Minimize the aberration
  – Add sextupoles
    • Pole curvature
    • Add sextupoles