MADX and Aperture Studies for the BI Transfer Line

C. Bracco, E. Benedetto, B. Mikulec, G. Rumolo
Checks for Different Linac4 Transfer Line Optics

C. Bracco

Acknowledgments: A. Lombardi, B. Mikulec, B. Goddard
# Optics at End of BI-TL

## Target

<table>
<thead>
<tr>
<th>Case</th>
<th>$\beta_{T,H}$ (m)</th>
<th>$\alpha_{T,H}$</th>
<th>$\beta_{T,V}$ (m)</th>
<th>$\alpha_{T,V}$</th>
<th>$D_T$ (m)</th>
<th>$D_T'$</th>
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<tbody>
<tr>
<td>All matched</td>
<td>5</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>-1.4</td>
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<tr>
<td>Zero disp.</td>
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<td>0</td>
<td>4</td>
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<tr>
<td>D matched, small $\beta$'s</td>
<td>2.5</td>
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<td>2</td>
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<tr>
<td>Zero dispersion, small $\beta$'s</td>
<td>2.5</td>
<td>0</td>
<td>2</td>
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<td>Zero dispersion, large $\beta$'s</td>
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<td>0</td>
<td>8</td>
<td>0</td>
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</table>

For all optics (ring 3), $D_{TV} = D_{TV}' = 0$

## Optics parameters at PSB injection:

<table>
<thead>
<tr>
<th>Case</th>
<th>$\beta_{T,H}$ (m)</th>
<th>$\alpha_{T,H}$</th>
<th>$\beta_{T,V}$ (m)</th>
<th>$\alpha_{T,V}$ (m)</th>
<th>$D_{TH}$ (m)</th>
<th>$D_{TH}'$</th>
<th>$D_{TV}$ (m)</th>
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</table>

A. Lombardi: [https://edms.cern.ch/document/1391781/0.1](https://edms.cern.ch/document/1391781/0.1)

[https://indico.cern.ch/event/331610/]
What’s next?

• Alessandra and team performed full study with PATH for all the optics ([https://edms.cern.ch/document/1391781/0.1](https://edms.cern.ch/document/1391781/0.1)):
  - Apertures checked (including errors) ➔ no losses
  - Flexible optics
  - All four rings considered? (Worst case for vertical dispersion, Ring 1)

• What is missing? Aperture cross-check?
  1. Use PATH output: Need all optics with H&V Dispersion!
  2. Fully independent check needed?
     • MAD-X (no space charge)
     • PTC + ORBIT (with space charge)
     • Need sequence, strength files, initial conditions for all optic (something already available)

Not ideal for non-experts!

Time and resources!
Goal of the Studies

- MADX version of the BI-TL optics (from BHZ40): all optics and all 4 rings!
  - Check layout (magnets positions)
  - Crosscheck with “PATH” optics
  - Define effect of SC
  - Provide MADX optics for quick checks (aperture, steering, etc.)
Optics “0 Dispersion”

- Lattice manually derived from “Path” output
- “s” coordinates rechecked wrt existing BI-TL

<table>
<thead>
<tr>
<th>Quads strengths</th>
<th>L [m]</th>
<th>B [T/m]</th>
<th>B [T/m]</th>
<th>B [T/m]</th>
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<tbody>
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<td>0.401532</td>
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</table>

Initial conditions (start of BHZ40*, beginning of BI line)

| (X,BGX') 100%-Emittance [m.rad] | 1.62E-05 |
| (X,BGX') 90%-Emittance [m.rad]  | 1.30E-06 |
| (Y,BGY') 100%-Emittance [m.rad] | 3.11E-07 |
| (Y,BGY') 90%-Emittance [m.rad]  | 1.54E-05 |
| (Y,BGY') RMS-Emittance [m.rad]  | 1.45E-06 |
| (PHI,dE) 100%-Emittance [deg.MeV] | 7.58E+01 |
| (PHI,dE) 90%-Emittance [deg.MeV] | 1.09E+00 |
| (PHI,dE) RMS-Emittance [deg.MeV] | 3.13E-01 |
| (X,X') Alpha [1] | 9.89E+01 |
| (X,X') Beta [m/rad] | 9.02E+00 |
| (Y,Y') Alpha [1] | 1.34E+00 |
| (Y,Y') Beta [m/rad] | 4.53E+01 |
| (PHI,dE) Alpha [1] | 1.09E+01 |
| (PHI,dE) Beta [deg/MeV] | 4.09E+03 |
| dx [m] | 0 |
| dxp | 0 |
| dy [m] | 0 |
| dyp | 0 |

*Smallest SC effect

Change sign in MADX (H⁻)
Optics “0 Dispersion”

- Lattice manually derived from “Path” output
- “s” coordinates rechecked wrt existing BI-TL

### Quads strengths

(https://edms.cern.ch/document/1391781/0.1)

<table>
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<th></th>
<th>B [T/m]</th>
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<td>BI-QN60</td>
<td>0.466</td>
<td>2.015537</td>
<td>2.359182</td>
</tr>
</tbody>
</table>

### Initial conditions

(START of BHZ40*, beginning of BI line)

- *(X,BGX') 100%-Emittance [m.rad] = 1.62E-05
- *(X,BGX') 90%-Emittance [m.rad] = 1.30E-06
- *(X,BGX') RMS-Emittance [m.rad] = 3.11E-07
- *(Y,BGY') 100%-Emittance [m.rad] = 1.54E-05
- *(Y,BGY') 90%-Emittance [m.rad] = 1.45E-06
- *(Y,BGY') RMS-Emittance [m.rad] = 3.34E-07
- *(PHI,dE) 100%-Emittance [deg.MeV] = 7.58E+01
- *(PHI,dE) 90%-Emittance [deg.MeV] = 1.09E+00
- *(PHI,dE) RMS-Emittance [deg.MeV] = 3.13E-01
- *(X,X') Alpha [1] = 9.89E+01
- *(X,X') Beta [m/rad] = 9.02E+00
- *(Y,Y') Alpha [1] = 1.34E+00
- *(Y,Y') Beta [m/rad] = 4.53E+01
- *(PHI,dE) Alpha [1] = 1.09E+01
- *(PHI,dE) Beta [deg/MeV] = 4.09E+03
- dx [m] = 0
- dxp = 0
- dy [m] = 0
- dyp = 0

*Smallest SC effect

---

**Change sign in MADX (H-)**
# Main Magnet Positions

Compared magnets position with 2014 Linac2 layout.

<table>
<thead>
<tr>
<th></th>
<th>Actual position [m]</th>
<th>Path position [m]</th>
<th>Difference [m]</th>
</tr>
</thead>
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<td>0.45</td>
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<td>BI3.INJPT</td>
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</tbody>
</table>

Few cm difference in longitudinal position. Final check ➔ input for PATH.
Kept Q30 and Q40 as in table from Alessandra ➔
calculate DVT30 ➔ DIS and DVT40 strengths

kdvt30 := 0.001676;
kbqn1_30 := 0.82535/brho;
kbqn1_40 := -0.914672/brho;
kbqn1_s30 := -0.000857;
kbqn1_s40 := 0.002533;
kdis3 := 0.003710;
kdis4 := 0.003702;
kdis4 := 0.003702;
kvt40 := 0.007412;

Agreement within few % wrt afs DB
### Ring 1 - 2 - 3 - 4

![Graph showing distances and increments along rings with data points and labels for +360 mm @ BVT, +35 mm @ SMV2, -35 mm @ SMV2, -70 mm @ SMV1, -360 mm @ BVT, and -720 mm @ BVT.]
Nominal Betax,y "0 Dispersion"
Ring3

No MADX matching!
MADX-PATH agreement <15%
Difference likely due to SC!
Nominal Betax,y “0 Dispersion”

MADX matching for other rings (using QN50 and QN60)!
MADX-PATH agreement < 20%

<table>
<thead>
<tr>
<th>Path [K1]</th>
<th>MADX [k1]</th>
<th>Max. Diff. [%]</th>
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<td></td>
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<tr>
<td>Ring1</td>
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<td>Ring2</td>
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<td>Ring4</td>
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<tr>
<td>BIQN60</td>
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</table>
Vertical Dispersion
Vertical Dispersion

vertical dispersion [m] in PSB injection area.

Path:

vertical dispersion [m] in PSB injection area.

distance from DVT30 [m]

vertical dispersion [m]

0 5 10 15 20 25 30

0 -0.2 -0.4

0 0.2 0.4 0.6 0.8 1

Ring 4
Ring 3
Ring 2
Ring 1

ring 3
ring 1

s [m]

0 5 10 15 20 25 30 35 40 45 50

-0.6 -0.4 -0.2 0
Optics “Matched 1.4m Dispersion”

- Lattice manually derived from “Path” output
- “s” coordinates rechecked wrt existing BI-TL

<table>
<thead>
<tr>
<th>L [m]</th>
<th>B [T/m]</th>
<th>B [T/m]</th>
<th>B [T/m]</th>
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<tbody>
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</tr>
</tbody>
</table>

Initial conditions (start of BHZ40*, beginning of BI line)

| (X,BGX') 100%-Emittance [m.rad] | 1.62E-05 |
| (X,BGX') 90%-Emittance [m.rad] | 1.30E-06 |
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| (Y,BGY') RMS-Emittance [m.rad] | 3.34E-07 |
| (PHI,dE) 100%-Emittance [deg.MeV] | 7.58E+01 |
| (PHI,dE) 90%-Emittance [deg.MeV] | 1.09E+00 |
| (PHI,dE) RMS-Emittance [deg.MeV] | 3.13E-01 |
| (X,X') Alpha [1] | 9.89E-01 |
| (X,X') Beta [m/rad] | 9.02E+00 |
| (Y,Y') Alpha [1] | 1.34E+00 |
| (Y,Y') Beta [m/rad] | 4.53E+01 |
| (PHI,dE) Alpha [1] | 1.09E+01 |
| (PHI,dE) Beta [deg/MeV] | 4.09E+03 |
| dx [m] | 1.13 |
| dxp | -7.55E-3 |
| dy [m] | 0 |
| dyp | 0 |

Change sign in MADX (H-)

*Smallest SC effect
Nominal Betax, y “1.4 m Dispersion”

MADX matching for Ring 1-2-4
(using QN50 and QN60)!
MADX-PATH agreement < 30%

Max $\Delta \beta = 2$ m
Max $\Delta \alpha = 0.5$ rad

Max $\Delta \beta = 0.6$ m
Max $\Delta \alpha = 0.5$ rad

Max $\Delta D = 0.5$ m

Max $\Delta D = 0.1$ m
## Strengths

<table>
<thead>
<tr>
<th></th>
<th>RING 1</th>
<th>RING 2</th>
<th>RING 3</th>
<th>RING 4</th>
</tr>
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<tr>
<td>kDVT1</td>
<td>0.00174889</td>
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<td>kSMV1</td>
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<tr>
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<td>kQN50</td>
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<td>kQN60</td>
<td>-0.991892</td>
<td>-1.02530</td>
<td>-1.160830793</td>
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</tbody>
</table>
Conclusion I

- A **MADX model** (without space charge) of the BI-TL has been prepared which agrees within **30%** with the PATH model (with space charge).
- Hint that Quads strengths for nominal, small and large beta in wrong order (tbc).
- Small **differences** (~cm) were found in the **longitudinal position of the main magnets** between the PATH model and the sequence in the afs DB (final checks needed).
- Some **geometric matching** of the line was needed to close the **bump** at the DIS for Ring3 and get the expected **offsets** at Ring 1,2 and 4 (magnets strengths change by ~%).
- Some **optics matching** was also needed for Ring 1,2 and 4 (**QN50** and **QN60**, strengths changed by < 15%).
- This model was used for aperture checks!
Beam Envelope & Aperture Checks

$$4 \sigma_{\beta_{x,y}(+20\%)} + D_{x,y} \Delta p/p + \text{Orbit}$$

(nominal $\beta_{x,y}$ normalized r.m.s. $\varepsilon_{x,y} = 0.5 \text{ mm mrad}$)

$Dp/p = 0.0044$ (1.13 MeV longitudinal painting)

Orbit = ±2 mm

Assuming all beam on the same vertical axis!!

In reality @ DIS there is a common chamber + vertical separation.

A maximum vertical offset of ±10 mm can be applied at the end of the line for the large emittance beams (i.e. ISOLDE)
Beam Envelope & Aperture Checks

\[ 4 \sigma_{\beta_{x,y}(+20\%)} + D_{x,y} \cdot \Delta p/p + \text{Orbit} \]
(nominal \( \beta_{x,y} \) normalized r.m.s. \( \varepsilon_{x,y} = 0.5 \text{ mm mrad} \))

\( Dp/p = 0.0044 \) (1.13 MeV longitudinal painting)

Orbit = ±2 mm
Beam Envelope & Aperture Checks

\[ 4 \sigma_{\beta x,y(+20\%)} + D_{x,y} \Delta p/p + \text{Orbit} \]
(nominal \( \beta_{x,y} \), normalized r.m.s. \( \varepsilon_{x,y} = 0.5 \text{ mm mrad} \))
\[ D_{p/p} = 0.0044 \text{ (1.13 MeV longitudinal painting)} \]
\[ \text{Orbit} = \pm 2 \text{ mm} \]

The beam at the end of the BI-TL has a **10 mm horizontal offset** towards the PSB ring in order to be injected exactly on the circulating beam orbit when the chicane (46 mm) and the injection bump (35 mm) are on.
PSB Injection Region

Aperture checks over last 3 m of BI line where inner diameter = 60 mm (@ BHZ162) and 57.1 mm (@ BI.BSW)

BHZ162 (PSB ring)
BHZ162

Injected beam (BI-TL) Circulating beam (PSB)
Beam Envelope & Aperture Checks

28.55 mm radius @ BSW1

Extreme case:
Longitudinal painting
+ 10 mm beam horizontal offset
+ 10 mm beam vertical offset

Beam scraping the chamber!
Beam Envelope & Aperture Checks

28.55 mm radius @ BSW1

**Extreme case:**
- Longitudinal painting
- 10 mm beam horizontal offset
- 10 mm beam vertical offset

Beam scraping the chamber!

Realistic operational scenarios

**LHC beams:**
- No longitudinal painting and maximum \( \frac{Dp}{p} = 0.0031 \) (0.8 MeV)
  \( \Rightarrow \) 10% smaller beam envelope

**Large emittance beams:**
- A 2 mm horizontal offset between injected and circulating beam is allowed \( \Rightarrow \) 8 mm horizontal offset.
- Simulations show that a maximum \textbf{vertical offset} of 8 mm allows reaching reasonably large vertical emittance (6 mm mrad)

Possible to off-centre the vacuum chamber by 1 mm at least in the horizontal plane?
Beam Envelope & Aperture Checks

28.55 mm radius @ BSW1

**Extreme case:**

- Longitudinal painting
- 10 mm beam horizontal offset
- 10 mm beam vertical offset

→ Beam scraping the chamber!

**Operational case:**

- Longitudinal painting
- 8 mm horizontal offset
- 8 mm vertical offset
- 1 mm horizontal offset vacuum chamber

→ > 2 mm margin

Realistic operational scenarios

**LHC beams:**

- No longitudinal painting and maximum $Dp/p = 0.0031$ (0.8 MeV)
→ 10% smaller beam envelope

**Large emittance beams:**

- A 2 mm horizontal offset between injected and circulating beam is allowed → 8 mm horizontal offset.
- Simulations show that a maximum **vertical offset** of 8 mm allows reaching reasonably large vertical emittance (6 mm mrad)

Possible to off-centre the vacuum chamber by 1 mm at least in the horizontal plane?
Beam Envelope & Aperture Checks

Extreme case:
- Longitudinal painting
- 10 mm beam horizontal offset
- 10 mm beam vertical offset
- 0 margin

30 mm radius @ BHZ162

Realistic operational scenarios

LHC beams:
- No longitudinal painting and maximum $Dp/p = 0.0031$ (0.8 MeV)
  - $\Rightarrow$ 10% smaller beam envelope

Large emittance beams:
- A 2 mm horizontal offset between injected and circulating beam is allowed
  - $\Rightarrow$ 8 mm horizontal offset.
- Simulations show that a maximum vertical offset of 8 mm allows reaching reasonably large vertical emittance (6 mm mrad)

Operational case:
- Longitudinal painting
- 8 mm horizontal offset
- 8 mm vertical offset
- 1 mm horizontal offset vacuum chamber
- $\Rightarrow$ 3 mm margin

Possible to off-centre the vacuum chamber by 1 mm at least in the horizontal plane?
Can we off-center the chambers?

- BSW: the chamber can be off-centered by 1 mm by displacing the septum plate and tightening the tolerances (no impact on reliability or performance, only more expensive) → OK!!
Can we off-center the chambers?

BHZ162

• An horizontal alignment (< 1 mm) of the vacuum chambers for the injected beam in the magnet BHZ162 can be done installing a metallic plate on the top of the magnet and using the "fil a plomb"

• An additional coil has to be added to allow operation at 160 MeV. We measured 12 mm for shimming, assuming that we have to count for 9 mm for the additional coil we could still move the chamber further in by 1-2 mm.
Can we off-center the chambers?

- In the present design there is a rectangular block around the chamber (60 mm inner diameter).
Can we off-center the chambers?

- In the present design there is a rectangular block around the chamber (60 mm inner diameter).
Can we off-center the chambers?

- In the present design there is a rectangular block around the chamber (60 mm inner diameter). The option of using the block as vacuum chamber is considered (gain 1.5 mm in radius, also vertically!).
- Other possibilities: different machining of the hole in the block (mechanically difficult and possible deformation of the chamber).
Conclusions II

- **Aperture checks** for the BI-TL were performed for the **nominal matched optics** (nominal beta and matched dispersion), for the 4 PSB rings (new MADX model)

- **Bottlenecks** were identified at the end of the BI-TL (BHZ162 and BSW1)

- Some **margin** can be operationally gained by **reducing the horizontal and vertical offset**.

- The chamber at the BSW can be **off-centered by 1 mm** by displacing the septum plate and tightening the tolerances

- An **alignment system** can be implemented at the BHZ162 magnet to align the vacuum chambers with an **accuracy < 1 mm**. An **aperture gain** between 1 and 3 mm in horizontal plane and ~1 mm in the vertical plane can be envisaged (ECR to be written and approved by all involved experts).

- **Achievable optics flexibility** (maximum allowed beta at injection point) **t.b.d.**