DESY FEL Seminar 2019-02-26

Progress in Optics Setup / Pt.1

Mathias Vogt (MFL) & Johann Zemella (MPY1)

- Reminder: Motivation
- Reminder: Matching/Re-Matching: Methods
- Reminder: Matching/Re-Matching: FLASH-Sections
- Side track: The Asymmetric Super Gaussian
- Typical Injector Matches 2018
- First Injector Matches 2019

DESY Free-Electron Laser in Hamburg
Reminder: Motivation

• **RF–GUN:** space charge dominated regime (lowest $E$)

• **Design Optics:**
  → starts exit of solenoid **1GUN**
  → zero current limit (**no SC**)
  → valid only **un–compressed**

  ⇒ **DBC2:** match beam from RF–GUN into design optics in linac

• Dominant sources of optics perturbation (un–compressed):
  → “**ACC2–Badlands**” ’till FL2020+
  → energy profile (!!!) :
    \[ k_1 := \frac{\partial B_y}{\partial x} / (p e) \]

  ⇒ Necessity of **re–match** → constraints

  • (Finally:
    correct for **SC** in compressed beam!)
Matching / Re–matching of Beamlines: Basic Concepts (1)

Linear optics!

Beam ellipse:
\[ \tilde{z}^T B(s)^{-1} \tilde{z} = \epsilon \]

Map
\[ M_{b \leftarrow a}(k_i, \ldots, k_j) \text{ from } s_a \text{ to } s_b \text{ through quads } Q_i \text{ to } Q_j \text{ w/ strengths } k_i \text{ to } k_j. \]

Outgoing beam measurement section
Reference point
\[ s_0 \]
\[ s_1 \]
\[ \ldots \]
\[ s_n \]
Measurement section
Reference point
\[ \tilde{z}(s_b) = M_{b \leftarrow a}(k_i, \ldots, k_j) \tilde{z}(s_a) \]

Outgoing beam
Incoming beam
Matching section
Reference point
\[ s_0 \]
\[ s_1 \]
\[ \ldots \]
\[ s_n \]
Modified design
Perturbed design
Design
Design
Reference point for initial cond.
Reference point for measurement
Design
Modified design
Perturbed design
Design

\[ B(s) = \begin{pmatrix} \beta(s) & -\alpha(s) \\ -\alpha(s) & \gamma(s) \end{pmatrix} \]

\[ \begin{pmatrix} \beta_b \\ \alpha_b \\ \gamma_b \end{pmatrix} = T_{b \leftarrow a} \begin{pmatrix} \beta_a \\ \alpha_a \\ \gamma_a \end{pmatrix}. \]
Matching / Re–matching of Beamlines: Basic Concepts (2)

- for each transv. plane (X & Y):

1: **measure beamsizes** $\sigma_i$

\[\sigma(s_i) = \sqrt{\beta_i \varepsilon}, \quad i = 2, \ldots, n \geq 4\]

Twiss parameters at reference point $s_1$ as least square solution of:

\[
\begin{pmatrix}
\sigma_2^2 \\
\vdots \\
\sigma_n^2
\end{pmatrix} = 
\begin{pmatrix}
(I_{2 \leftarrow 1})_{1,*} & (I_{2 \leftarrow 1})_{2,*} & \cdots & (I_{2 \leftarrow 1})_{n,*} \\
(I_{n \leftarrow 1})_{1,*} & (I_{n \leftarrow 1})_{2,*} & \cdots & (I_{n \leftarrow 1})_{n,*}
\end{pmatrix}
\begin{pmatrix}
\beta_1 \varepsilon \\
\alpha_1 \varepsilon \\
\gamma_1 \varepsilon
\end{pmatrix}
\]

2: **transport** $\beta_1, \alpha_1, \gamma_1$ backwards

\[
\begin{pmatrix}
\beta_0 \\
\alpha_0 \\
\gamma_0
\end{pmatrix} = I_{0 \leftarrow 1}
\begin{pmatrix}
\beta_1 \\
\alpha_1 \\
\gamma_1
\end{pmatrix}
\]

→ gives “measured” initial cond. $\beta_0, \alpha_0, \gamma_0$

- Remark: $I_{i \leftarrow 1} (i = 2, \ldots, n)$, and $I_{0 \leftarrow 1}$ are assumed close to design!

3: **match** measured $\beta_0, \alpha_0, \gamma_0$

into design $\beta_1, \alpha_1, \gamma_1$

\[
\begin{pmatrix}
\beta_1 \\
\alpha_1 \\
\gamma_1
\end{pmatrix} = I_{1 \leftarrow 0}(k_i, \ldots, k_j)
\begin{pmatrix}
\beta_0 \\
\alpha_0 \\
\gamma_0
\end{pmatrix}
\]

using quads $Q_i$ to $Q_j$

- Remark: $\beta \gamma + \alpha^2 \equiv 1 \Rightarrow$ needs at least 4 quads for both planes (X & Y)
The \((n \geq 3)\)--Screen/Wire Method

- typically \(s_1 \equiv s_2\)
- best: \(n \geq 4\); \((n = 3:\text{ no errorbars})\)
- **screen**: measure \(X\) & \(Y\) simultaneously
- optimum phase advance per screen/wire: \(45^\circ\)
  \((0^\circ, 45^\circ, 90^\circ, 135^\circ\) w/ 4 stat.)
- fit (1:) might yield negative \(\beta_1 \epsilon\)

**What can go wrong?**: (apart from broken equipment...)
- large \(E\)--spread & spurious dispersion
- beam distorted / broken into beamlets
  ← how do \(\sigma\)'s compare for totally different beam shapes?
- **screen**: coherent OTR
  ⇒ go to minimum \(E\)--spread
  \((\text{m.o.l. on-crest})\)
  & “beautify” beam (steering,...)!
- small charge \(\rightarrow\) small signal
The Single–Quad–On–Single–Screen/Wire Method

- max. possible downstream $s_1$ is entrance of scanned quad
- concept: changed focusing shifts beam waist through $s_2$
- (simplified evaluation for 1-quad-on-1-screen → e.g. Minty & Zimmermann)
- for thin-lens quad: $\sigma_2^2(k_1)$ should be a parabola ($\ast$)
- **screen:** measure X & Y simultaneously — iff optics suited for (halfway) symmetric scan: $(k_1 \approx 0 \Rightarrow X \& Y$ beam waists symmetric around $s_2$
- scan in cycle direction!

**What can go wrong?**:
(apart from broken equipment...)
- Same as w/ ($n \geq 3$)–screen/wire method
- parabola ($\ast$) not sufficient → can still yield imaginary $\beta_1$
→ hard to judge quality of scan until finally evaluated
- FLASH:
watch “injector cycle” vs. “linac cycle”
Modified Optics Upstream Screens During Measurement

- while reducing number of quads for actual matching,
- modify optics between $s_1$ (from design) and $s_2$
+ to optimize measurements
- i.e. for symmetric beam waist for single-quad-scan.

- can be applied to all before mentioned techniques
- since optics between $s_1$ and $s_1^{(old)}$ modified from design
  → matching section prolonged further upstream
  → See Johann’s Pt.2!
Matching/Re-Matching in FLASH/1/2 (1)

- **Injector Match:**
  - 4 OTRs in DBC2
  - 5 quads upstream BC2 (try preserving waist in last dipole)
    - *all of them can be used after recent magnet upgrade (TQAS) in triplet!*
    & 5 independently powered quads DBC2 : no longer needed!
  - nice beam required — or no convergence
  - *used* to converge typically after 3-4 iterations
  - *recently* (January 2019) lousy convergence, asymmetric reconstructed initial conditions, asymmetric and too large emittances → ???? ← but SASE works fine...
Matching/Re–Matching in FLASH/1/2 (2)

- **4 Screen at SFUND:**
  - too small beam images at high $E$
  - $\rightarrow$ **Symm. Single Quad Scan** $\rightarrow$ **Pt.2 (JZ)**
  - $\rightarrow$ 6 matching quads in ORS

- **5–6 wires in UNDU:**
  - servers *being* ported to (XFEL) $\mu$TCA standard
  - $\rightarrow$ 6 matching quads in SFELC/SMATCH
  - undulator match might violate LOLA constraints

- **4 screens FL2SEED:**
  - 6 matching quads in FL2EXTR and FL2SEED
  - suffers extremely from spurious dispersion
  & from **too small beam images at high $E$**
  - $\rightarrow$ work in progress

- **Symmetric Single Quad Scan**
Sidetrack: Asymmetric Super Gaussian

- FEL beams: transv. spatial densities often non-Gaussian
- Extension: “asymmetric super Gaussian” → see how well it fits ↓↓!

\[ \rho_{\text{asg}}(q) := \frac{1}{\mathcal{N}(s, \epsilon, r)} \exp\left(-\frac{1}{2}\left|\frac{q-q_0}{s(1 \pm \epsilon)}\right|^r\right) \]

- \( \pm := q \geq q_0 \) ? + : – (in c notation :-)
- \( q := x, y \)
- \( q_0 \in \mathbb{R}, \ s > 0, \ |\epsilon| < 1, \ r > 1 \)
- \( \mathcal{N}(s, \epsilon, r) \) so that \( \int \rho_{\text{asg}}(q) \, dq \equiv 1 \)
  \[ \Rightarrow \sigma_q^2 = \int (q - q_0)^2 \rho_{\text{asg}}(q) \, dq, \]
  etc.
Typical 2018 Injector Match (after 4 iterations)

2018-11-02 : 0.4nC/1.2mm, 308.5A, 52MeV/m, min-$E$-spread in BC2

4DBC2 6DBC2 8DBC2 10DBC2

$\beta_T = 2.46$ m $\beta_M = 2.75 \pm 0.12$ m
$\alpha_T = -1.20$ $\alpha_M = -1.03 \pm 0.05$
$\varepsilon_T = 0.48$ um $\varepsilon_M = 0.48 \pm 0.01$ um

$m_P = 1.05$ $\lambda_P = 1.36$

$\beta_T = 2.66$ m $\beta_M = 2.47 \pm 0.15$ m
$\alpha_T = 1.31$ $\alpha_M = 1.29 \pm 0.08$
$\varepsilon_T = 0.52$ um $\varepsilon_M = 0.52 \pm 0.02$ um

$m_P = 1.01$ $\lambda_P = 1.11$
Typical 2018 Injector Match (after 4 iterations)

FLASH1

\[ \delta E / p_0 = 0. \]

Table name = TWISS

\[ \beta_x, \beta_y \]
Typical 2018 Injector Match (after 6 iterations)

\[
\begin{align*}
4\text{DBC2} & \quad 6\text{DBC2} & \quad 8\text{DBC2} & \quad 10\text{DBC2} \\
\beta_T &= 2.46 \text{ m} & \beta_M &= 2.44 \pm 0.14 \text{ m} \\
\alpha_T &= -1.20 & \alpha_M &= -1.21 \pm 0.07 \\
\epsilon_T &= 0.49 \text{ um} & \epsilon_M &= 0.49 \pm 0.02 \text{ um} \\
m_P &= 1.00 & \lambda_P &= 1.03 \\
\beta_T &= 2.66 \text{ m} & \beta_M &= 2.51 \pm 0.14 \text{ m} \\
\alpha_T &= 1.31 & \alpha_M &= 1.26 \pm 0.06 \\
\epsilon_T &= 0.51 \text{ um} & \epsilon_M &= 0.51 \pm 0.02 \text{ um} \\
m_P &= 1.00 & \lambda_P &= 1.06
\end{align*}
\]
Typical 2018 Injector Match (after 6 iterations)

Table name = TWISS

\( \delta E / p_0 = 0 \).

\( \beta_x, \beta_y \)
Remeasured 2018-11-08-night, (file restored)

same conditions as 2018-11-02

\[ \beta_T = 2.46 \text{ m} \quad \beta_M = 2.22 \pm 0.11 \text{ m} \]
\[ \alpha_T = -1.20 \quad \alpha_M = -1.14 \pm 0.06 \]
\[ \varepsilon_T = 0.48 \text{ um} \quad \varepsilon_M = 0.48 \pm 0.02 \text{ um} \]

\[ m_P = 1.01 \quad \lambda_P = 1.13 \]

\[ \beta_T = 2.66 \text{ m} \quad \beta_M = 2.34 \pm 0.10 \text{ m} \]
\[ \alpha_T = 1.31 \quad \alpha_M = 1.15 \pm 0.05 \]
\[ \varepsilon_T = 0.53 \text{ um} \quad \varepsilon_M = 0.53 \pm 0.02 \text{ um} \]

\[ m_P = 1.01 \quad \lambda_P = 1.14 \]
0.0 5. 10. 15. 20. 25. 30. 35. 40.
\( \delta \) / \( \beta_x \)
\( \beta_y \)

Table name = TWISS

\( \delta / p \cdot c = 0 \)

Unix version 8.51/17 09/11/18 01:52:30

\( s \) (m)
Remeasured after One Single Rematch

4DBC2 6DBC2 8DBC2 10DBC2

\[
\begin{align*}
\beta_T &= 2.46 \text{ m} & \beta_M &= 2.74 \pm 0.13 \text{ m} \\
\alpha_T &= -1.20 & \alpha_M &= -1.44 \pm 0.06 \\
\varepsilon_T &= 0.48 \text{ um} & \varepsilon_M &= 0.48 \pm 0.02 \text{ um} \\
\end{align*}
\]

\[
\begin{align*}
\beta_T &= 2.66 \text{ m} & \beta_M &= 2.73 \pm 0.14 \text{ m} \\
\alpha_T &= 1.31 & \alpha_M &= 1.34 \pm 0.06 \\
\varepsilon_T &= 0.52 \text{ um} & \varepsilon_M &= 0.52 \pm 0.02 \text{ um} \\
\end{align*}
\]

\[
\begin{align*}
m_P &= 1.01 & \lambda_P &= 1.16 \\
\end{align*}
\]

\[
\begin{align*}
m_P &= 1.00 & \lambda_P &= 1.02 \\
\end{align*}
\]

\[
\begin{align*}
\frac{(\alpha_T x + \beta_T x')}{\sqrt{(\varepsilon_T \beta_T)}} \\
\frac{\alpha_T y + \beta_T y'}{\sqrt{(\varepsilon_T \beta_T)}} \\
\end{align*}
\]
First 2019 Injector Match Campaign (Jan 2019)

<table>
<thead>
<tr>
<th>$I_{sol}$ /A</th>
<th>GUN-GRAD.SP ×m/MV</th>
<th>init MiMaAmpl x/y</th>
<th>init emitt x/y /μm</th>
<th>final MiMaAmpl x/y</th>
<th>final emitt x/y /μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>308.0</td>
<td>53.0</td>
<td>6.2/2.8</td>
<td>5.3/5.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>310.0</td>
<td>53.0</td>
<td>7.9/3.0</td>
<td>2.9/3.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>310.0</td>
<td>52.5</td>
<td>7.1/2.9</td>
<td>1.2/1.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>310.0</td>
<td>52.0</td>
<td>1.5/1.9</td>
<td>0.7/0.9</td>
<td>1.12/1.08</td>
<td>0.78/0.93</td>
</tr>
<tr>
<td>314.0</td>
<td>53.0</td>
<td>2.4/1.9</td>
<td>1.0/1.0</td>
<td>1.6/1.1*</td>
<td>0.9/1.0</td>
</tr>
<tr>
<td>315.0</td>
<td>53.0</td>
<td>1.3/2.4</td>
<td>0.8/0.9</td>
<td>1.15/1.05</td>
<td>0.78/0.91</td>
</tr>
</tbody>
</table>

*: had to stop before convergence was reached
L2, 0.4 nC @1.2 mm, 52 MV/m, 309.0 A, orbit optimized:

<table>
<thead>
<tr>
<th>n</th>
<th>plane</th>
<th>emit (um)</th>
<th>MiMaAmp</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>x</td>
<td>0.53871</td>
<td>1.58393</td>
<td>start</td>
</tr>
<tr>
<td>0</td>
<td>y</td>
<td>0.63430</td>
<td>1.29700</td>
<td>start</td>
</tr>
<tr>
<td>1</td>
<td>x</td>
<td>0.53169</td>
<td>1.42207</td>
<td>converging</td>
</tr>
<tr>
<td>1</td>
<td>y</td>
<td>0.62418</td>
<td>1.10099</td>
<td>converging</td>
</tr>
<tr>
<td>2</td>
<td>x</td>
<td>0.54155</td>
<td>1.39209</td>
<td>converging</td>
</tr>
<tr>
<td>2</td>
<td>y</td>
<td>0.64147</td>
<td>1.05138</td>
<td>converging</td>
</tr>
<tr>
<td>3</td>
<td>x</td>
<td>0.50515</td>
<td>1.64444</td>
<td>worse!</td>
</tr>
<tr>
<td>3</td>
<td>y</td>
<td>0.67027</td>
<td>1.11305</td>
<td>slightly worse</td>
</tr>
<tr>
<td>3a</td>
<td>x</td>
<td>0.49267</td>
<td>1.63046</td>
<td>consistent to 3</td>
</tr>
<tr>
<td>3a</td>
<td>y</td>
<td>0.67691</td>
<td>1.17800</td>
<td>consist. 3</td>
</tr>
<tr>
<td>3b</td>
<td>x</td>
<td>0.49118</td>
<td>1.59053</td>
<td>consist. 3/3a</td>
</tr>
<tr>
<td>3b</td>
<td>y</td>
<td>0.63460</td>
<td>1.12547</td>
<td>consistt. 3/3a</td>
</tr>
<tr>
<td>2a</td>
<td>x</td>
<td>0.53879</td>
<td>1.45391</td>
<td>back to 2 / cons. 2</td>
</tr>
<tr>
<td>2a</td>
<td>y</td>
<td>0.64420</td>
<td>1.11709</td>
<td>back to 2 / cons. 2</td>
</tr>
<tr>
<td>3c</td>
<td>x</td>
<td>0.51058</td>
<td>1.68901</td>
<td>unfortunately cons..3/3a/3b</td>
</tr>
<tr>
<td>3c</td>
<td>y</td>
<td>0.66145</td>
<td>1.10411</td>
<td>cons.. 3/3a/3b</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>5</td>
<td>x</td>
<td>0.49273</td>
<td>1.24337</td>
<td>even better</td>
</tr>
<tr>
<td>5</td>
<td>y</td>
<td>0.66844</td>
<td>1.02634</td>
<td>even better</td>
</tr>
<tr>
<td>6</td>
<td>x</td>
<td>0.50653</td>
<td>1.35338</td>
<td>slightly worse</td>
</tr>
<tr>
<td>6</td>
<td>y</td>
<td>0.63467</td>
<td>1.12317</td>
<td>slightly worse</td>
</tr>
<tr>
<td>7</td>
<td>x</td>
<td>0.46405</td>
<td>1.34840</td>
<td>same</td>
</tr>
<tr>
<td>7</td>
<td>y</td>
<td>0.61860</td>
<td>1.00542</td>
<td>xtrmly good</td>
</tr>
<tr>
<td>8</td>
<td>x</td>
<td>0.46915</td>
<td>1.16498</td>
<td>BEST→STOP</td>
</tr>
<tr>
<td>8</td>
<td>y</td>
<td>0.63902</td>
<td>1.03903</td>
<td>GOOD</td>
</tr>
</tbody>
</table>
First 2019 Injector Match Campaign (Jan 2019)

- **L2, BSA: 1.3mm**, gun: 52 MV/m, 0.8deg, $I_{sol} = 310.3A$
  $\rightarrow$ final emit x/y/µm: 0.51/0.86; final MiMaAmpl x/y: 1.47/1.10

- **L2, BSA: 1.2mm**, gun: 52 MV/m, 0.8deg, $I_{sol} = 310.3A$
  $\rightarrow$ final emit x/y/µm: 0.57/0.87; final MiMaAmpl x/y: 1.56/1.02

- **L2, BSA: 1.1mm**, gun: 52 MV/m, 0.8deg, $I_{sol} = 310.3A$
  $\rightarrow$ final emit x/y/µm: 0.61/0.88; final MiMaAmpl x/y: 1.33/1.04

- **L2, BSA: 1.0mm**, gun: 52 MV/m, 0.8deg, $I_{sol} = 310.3A$
  $\rightarrow$ final emit x/y/µm: 0.63/0.83; final MiMaAmpl x/y: 1.39/1.11

Luckily: SASE is was very nice in 2019 !!!

$\Rightarrow$ work in progress!
Thank you for listening to part one!
Next: part two !!!