DESY FEL Seminar 2019-02-26

Progress in Optics Setup / Pt.1

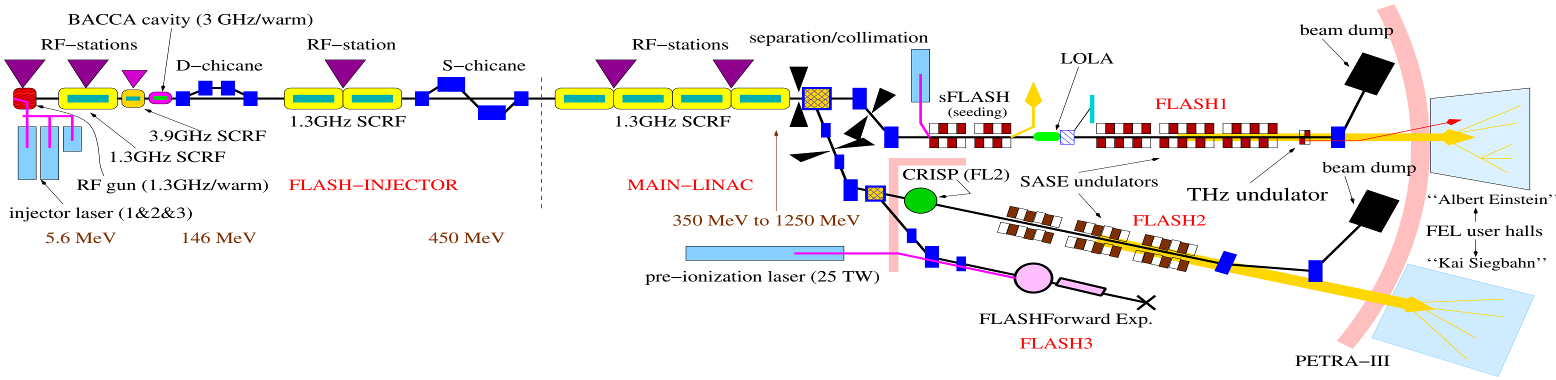
Mathias Vogt (MFL) & Johann Zemella (MPY1)

- 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.

FLASH
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 (!!!) :

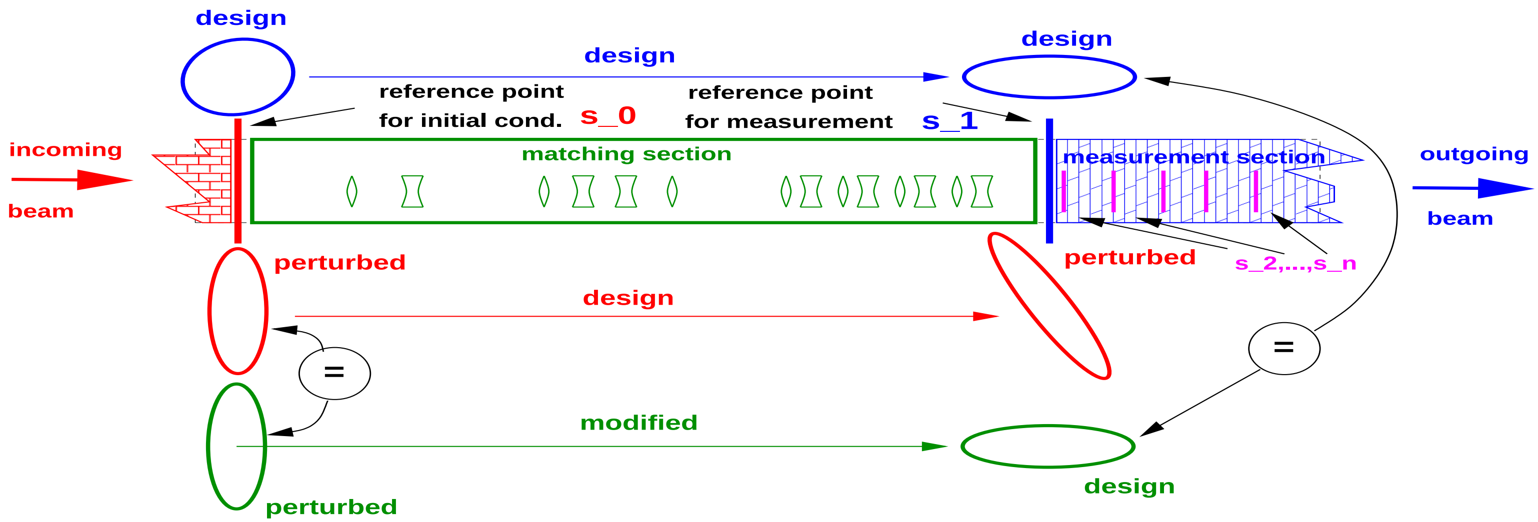
$$k_1 := (\partial B_y/\partial x)/(p\ e)$$

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

- (Finally:

  correct for SC in compressed beam!)

Matching / Re–matching of Beamlines: Basic Concepts (1)



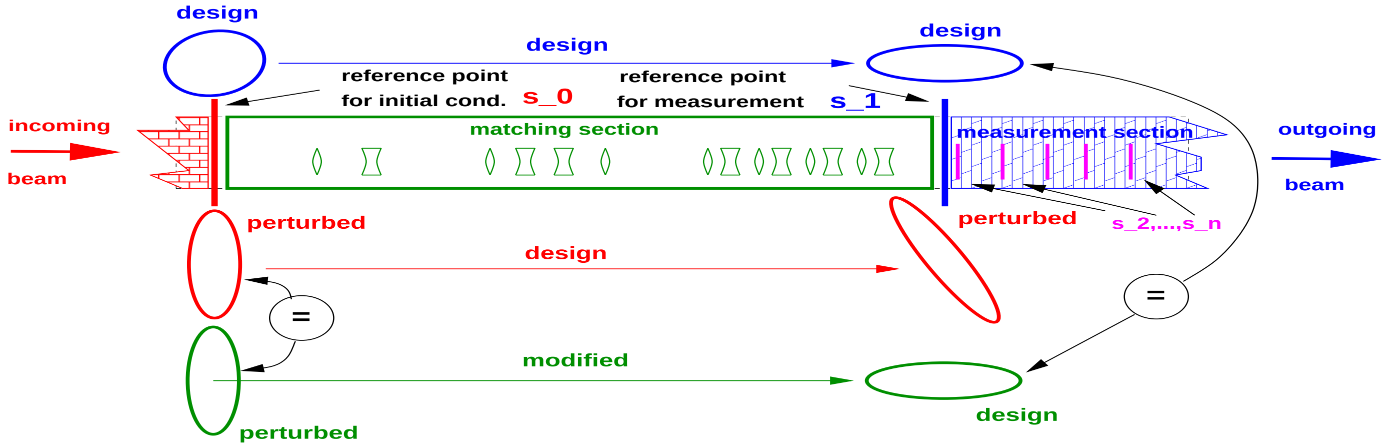
- **linear optics !** $\rightarrow\ \vec{z}(s_b) = \underline{M}_{b\leftarrow a}(k_i,\ldots,k_j)\ \vec{z}(s_a)$
- beam ellipse: $\vec{z}^{\mathrm{T}}\ \underline{B}(s)^{-1}\vec{z} = \epsilon$ $\Rightarrow\ \underline{B}(s_b) = \underline{M}_{b\leftarrow a}\,\underline{B}(s_a)\,\underline{M}_{b\leftarrow a}{}^{\mathrm{T}}.$
- $\underline{B}(s) = \begin{pmatrix} \beta(s) & -\alpha(s) \\ -\alpha(s) & \gamma(s) \end{pmatrix}$

$\leftarrow$ linear in $\underline{B}$, quadratic in $\underline{M}\rightarrow$

$$\begin{pmatrix} \beta_b \\ \alpha_b \\ \gamma_b \end{pmatrix} = \underline{\mathcal{T}}_{b\leftarrow a} \begin{pmatrix} \beta_a \\ \alpha_a \\ \gamma_a \end{pmatrix}.$$

- map $\underline{M}_{b\leftarrow a}(k_i,\ldots,k_j)$ from s_a to s_b through quads Q_i to Q_j w/ strengths k_i to k_j.
- $\underline{\mathcal{T}}_{b\leftarrow a} = \underline{\mathcal{T}}_{b\leftarrow a}(k_i,\ldots,k_j)$

Matching / Re–matching **of Beamlines**: Basic Concepts (2)



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

1: measure beamsizes σ_i

$\sigma(s_i) = \sqrt{\beta_i \epsilon}$, $i = 2, \ldots, n \geq 4$

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

$$\begin{pmatrix} \sigma_2^2 \\ \cdots \\ \sigma_n^2 \end{pmatrix} = \begin{pmatrix} (\mathcal{T}_{2\leftarrow 1})_{1,*} \\ \cdots \\ (\mathcal{T}_{n\leftarrow 1})_{1,*} \end{pmatrix} \begin{pmatrix} \beta_1 \epsilon \\ \alpha_1 \epsilon \\ \gamma_1 \epsilon \end{pmatrix}$$

2: transport β_1, α_1, γ_1 backwards

$$\rightarrow \begin{pmatrix} \beta_0 \\ \alpha_0 \\ \gamma_0 \end{pmatrix} = \mathcal{T}_{0\leftarrow 1} \begin{pmatrix} \beta_1 \\ \alpha_1 \\ \gamma_1 \end{pmatrix}$$

$\rightarrow$ gives "measured" initial cond. β_0, α_0, γ_0

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

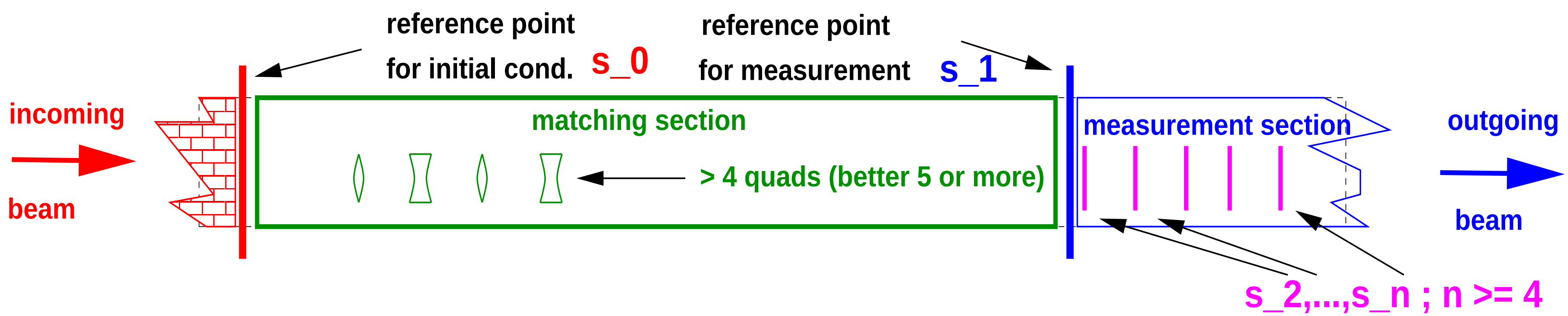
3: match measured β_0, α_0, γ_0 into **design** β_1, α_1, γ_1

$$\begin{pmatrix} \beta_1 \\ \alpha_1 \\ \gamma_1 \end{pmatrix} = \mathcal{T}_{1\leftarrow 0}(k_i, \ldots, k_j) \begin{pmatrix} \beta_0 \\ \alpha_0 \\ \gamma_0 \end{pmatrix}$$

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: $n \geq 4$;($n = 3$: no errorbars)
- *screen:* measure X & Y simultaneously
- optimum phase advance per screen/wire : 45°
  (0°, 45°, 90°, 135° w/ 4 stat.)

\- fit (1:) might yield negative $\beta_1 \epsilon$

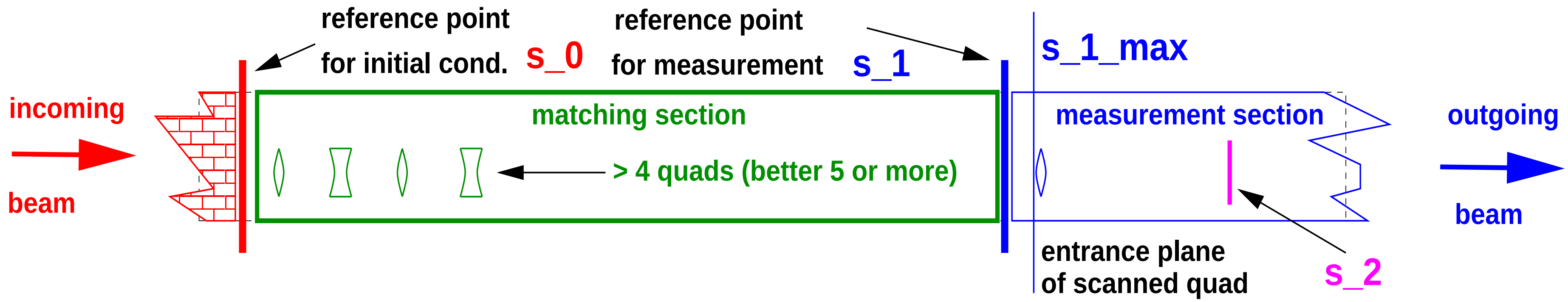
What can go wrong ? :
(apart from broken equipment. . .)

- large E–spread & spurious dispersion
- beam distorted / broken into beamlets
  ←how do σ's compare for totally different beam shapes?
- screen : coherent OTR

⇒ go to minimum E–spread
(m.o.l. on–crest)
& "beautify" beam (steering,. . .)!

- small charge → 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 $(*)$
- *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 ? :

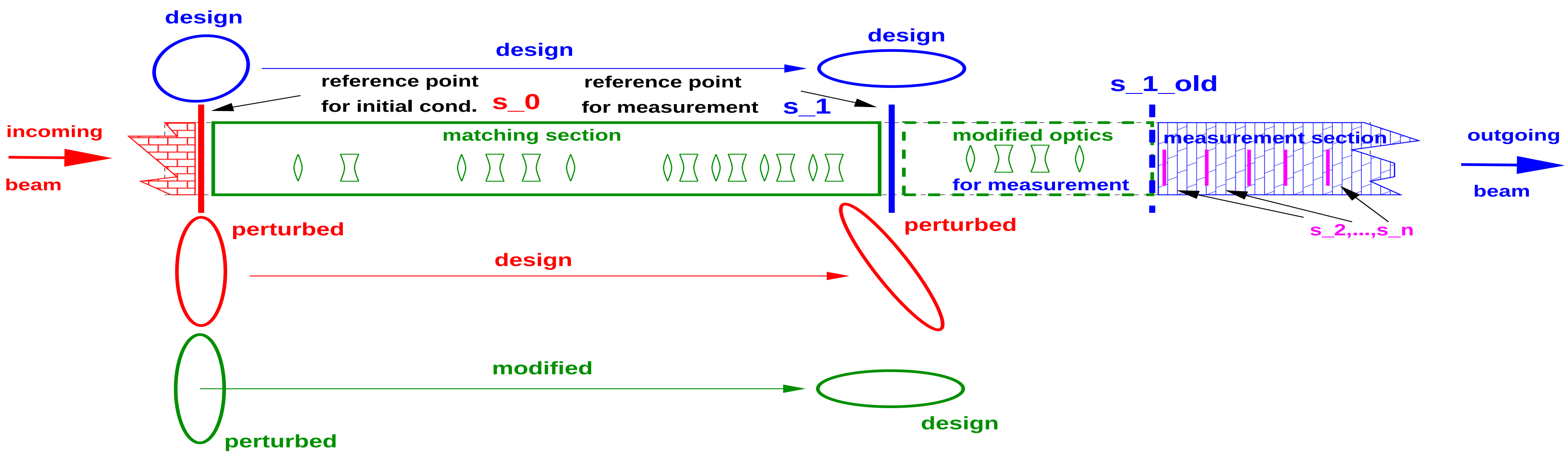
(apart from broken equipment. . .)

- Same as w/ ($n \geq 3$)–screen/wire method
- parabola $(*)$ not sufficient
  → can still yield imaginary β_1

→ hard to judge quality of scan until finally evaluated

- FLASH:
  watch “injector cycle” vs. “linac cycle”

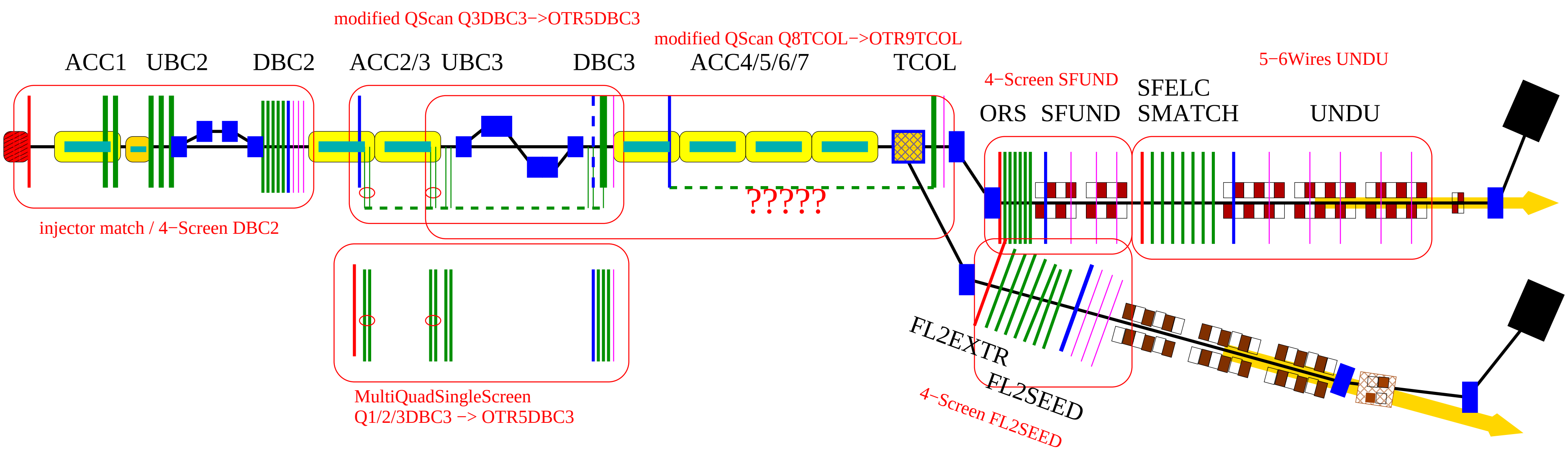
Modified Optics Upstream Screens During Measurement



- 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.

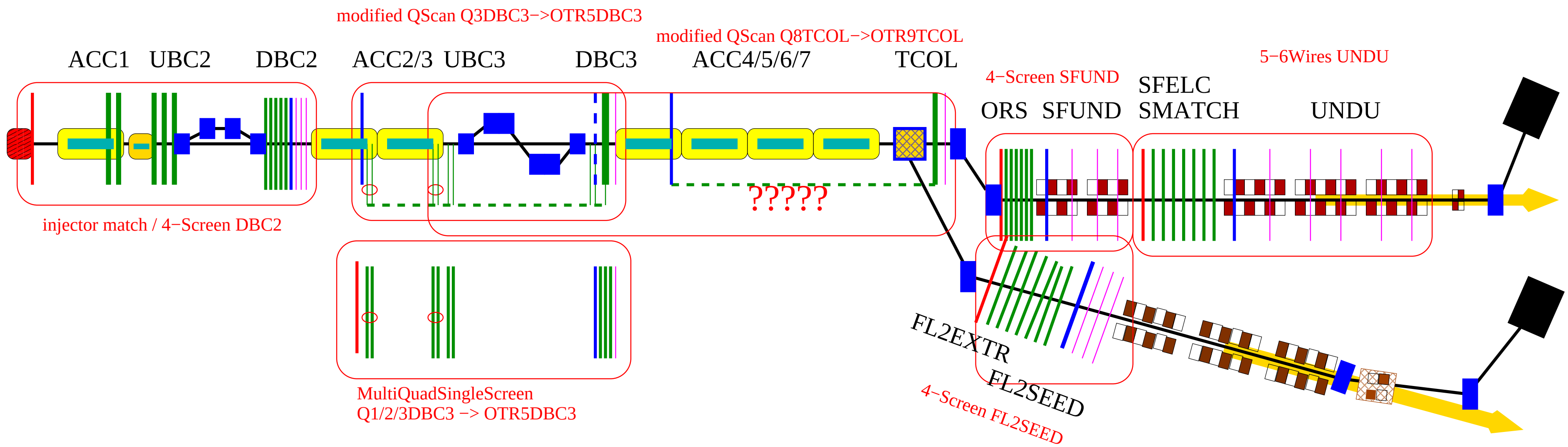
- • can be applied to all before mentioned techniques
- • since optics between s_1 and $s_1^{(\mathrm{old})}$ modified from design
- → matching section prolonged further upstream
- → See Johann's **Pt.2** !

Matching/Re–Matching in FLASH/1/2 (1)



- **Injector Match:**
- 4 OTRs in DBC2
- 5 quads upstream BC2 (try preserving waist in last dipole)
  $\leftarrow$ *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 $\rightarrow$ **???** $\Leftarrow$ 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:**
  $\rightarrow$ servers *being* ported to (XFEL) μTCA 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

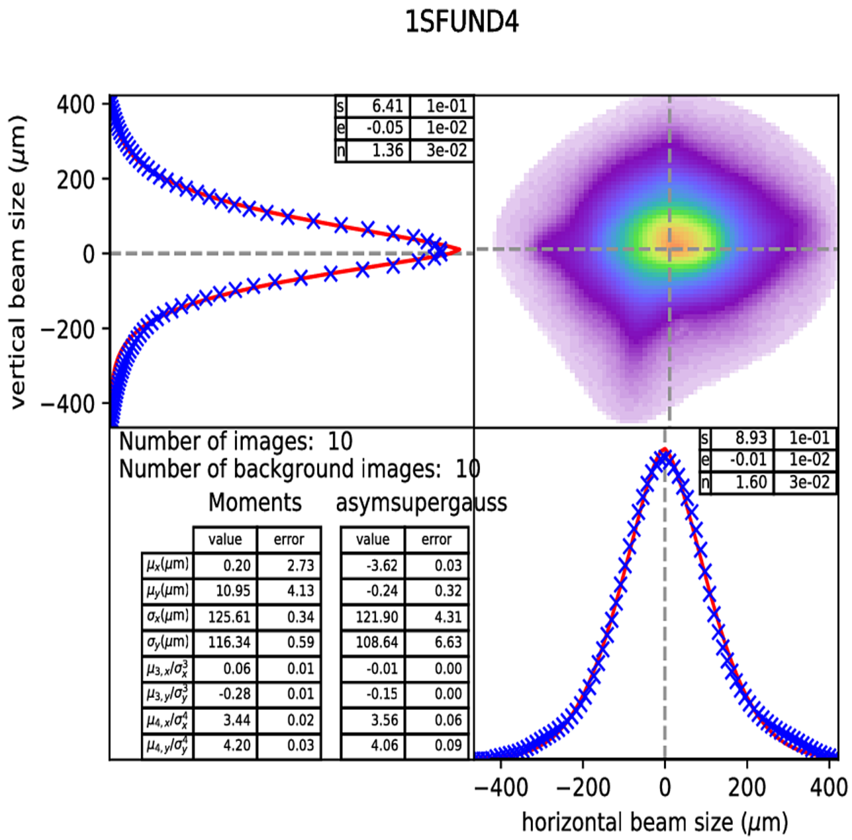
& from **too small beam images at high E**

$\rightarrow$ work in progress

- **Symmetric Single Quad Scan**

Sidetrack: Asymmetric Super Gaussian

- FEL beams: transv. spatial densities often **non-Gaussian**
- Extension: "asymmetric super Gaussian" $\rightarrow$ see how well it fits $\downarrow\downarrow$!



	Moments value	Moments error	asymsupergauss value	asymsupergauss error
$\mu_x(\mu m)$	0.20	2.73	-3.62	0.03
$\mu_y(\mu m)$	10.95	4.13	-0.24	0.32
$\sigma_x(\mu m)$	125.61	0.34	121.90	4.31
$\sigma_y(\mu m)$	116.34	0.59	108.64	6.63
$\mu_{3,x}/\sigma_x^3$	0.06	0.01	-0.01	0.00
$\mu_{3,y}/\sigma_y^3$	-0.28	0.01	-0.15	0.00
$\mu_{4,x}/\sigma_x^4$	3.44	0.02	3.56	0.06
$\mu_{4,y}/\sigma_y^4$	4.20	0.03	4.06	0.09

- Asymmetric Super Gaussian:

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

- $\pm := q \geq q_0 \; ? + \; : \; -$ (in c notation :-)
- $q := x,\, y$
- $q_o \in \mathbb{R}$, $s > 0$, $|\epsilon| < 1$, $r > 1$
- $\mathcal{N}(s,\epsilon,r)$ so that $\int \rho_{\text{asg}}^{[x/y]}(q)\, dq \equiv 1$

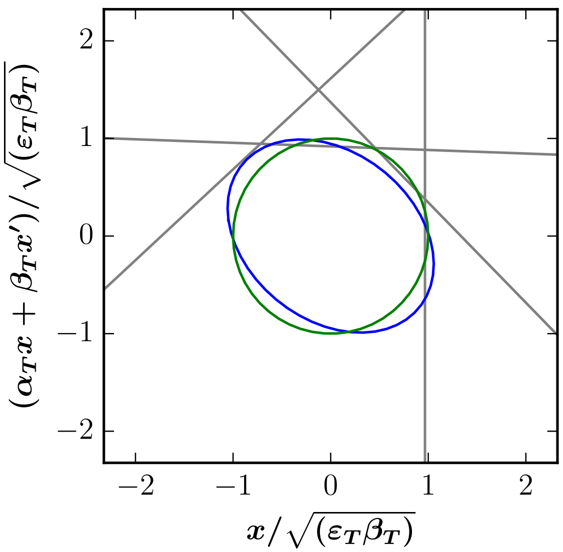
$\Rightarrow$ $\sigma_q^2 = \int (q - q_0)^2 \rho_{\text{asg}}^{[x/y]}(q)\, dq$, etc.

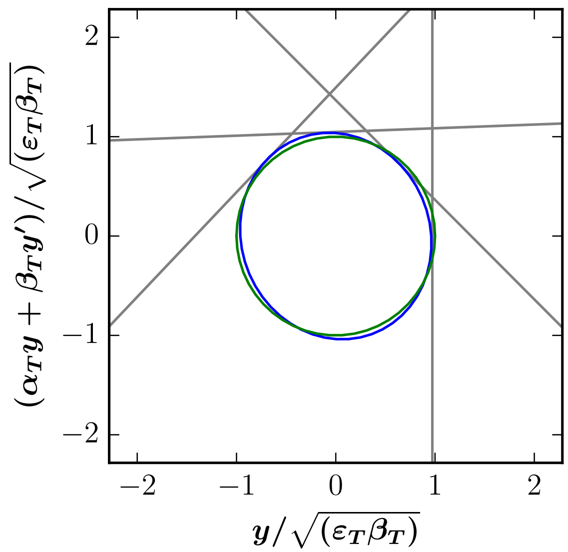
Typical 2018 Injector Match (after 4 iterations)

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

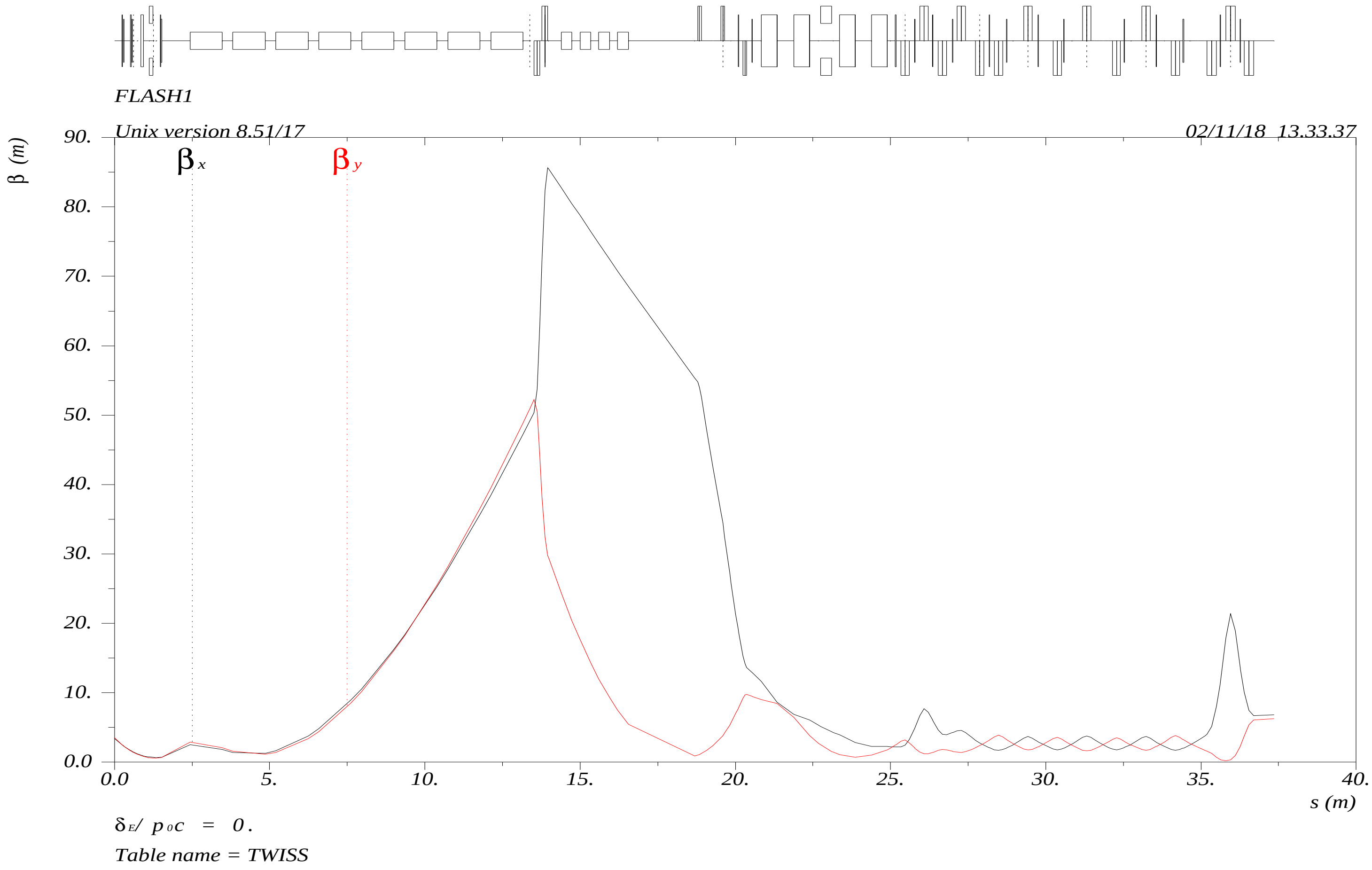
4DBC2 6DBC2 8DBC2 10DBC2

β_T = 2.46 m	β_M = 2.75 +- 0.12 m	β_T = 2.66 m	β_M = 2.47 +- 0.15 m
α_T = -1.20	α_M = -1.03 +- 0.05	α_T = 1.31	α_M = 1.29 +- 0.08
ε_T = 0.48 um	ε_M = 0.48 +- 0.01 um	ε_T = 0.52 um	ε_M = 0.52 +- 0.02 um
m_P = 1.05	λ_P = 1.36	m_P = 1.01	λ_P = 1.11





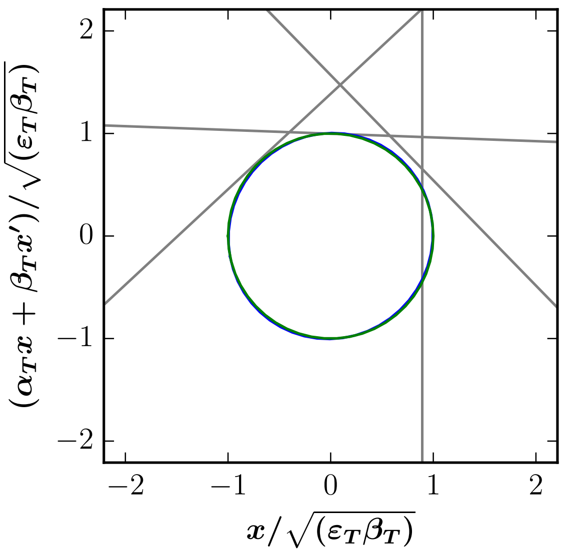
Typical 2018 Injector Match (after 4 iterations)

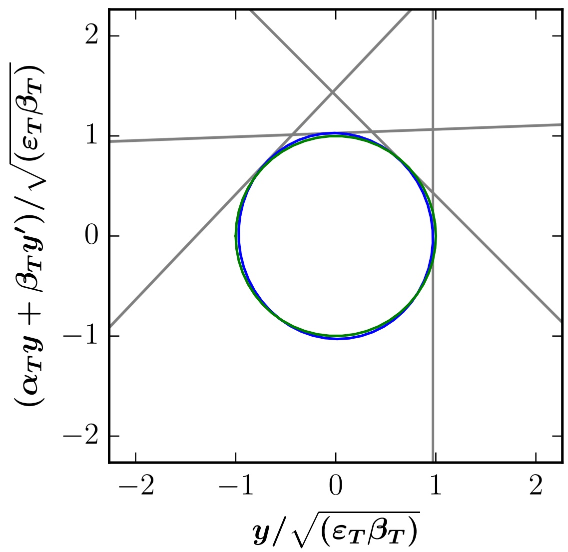


Typical 2018 Injector Match (after 6 iterations)

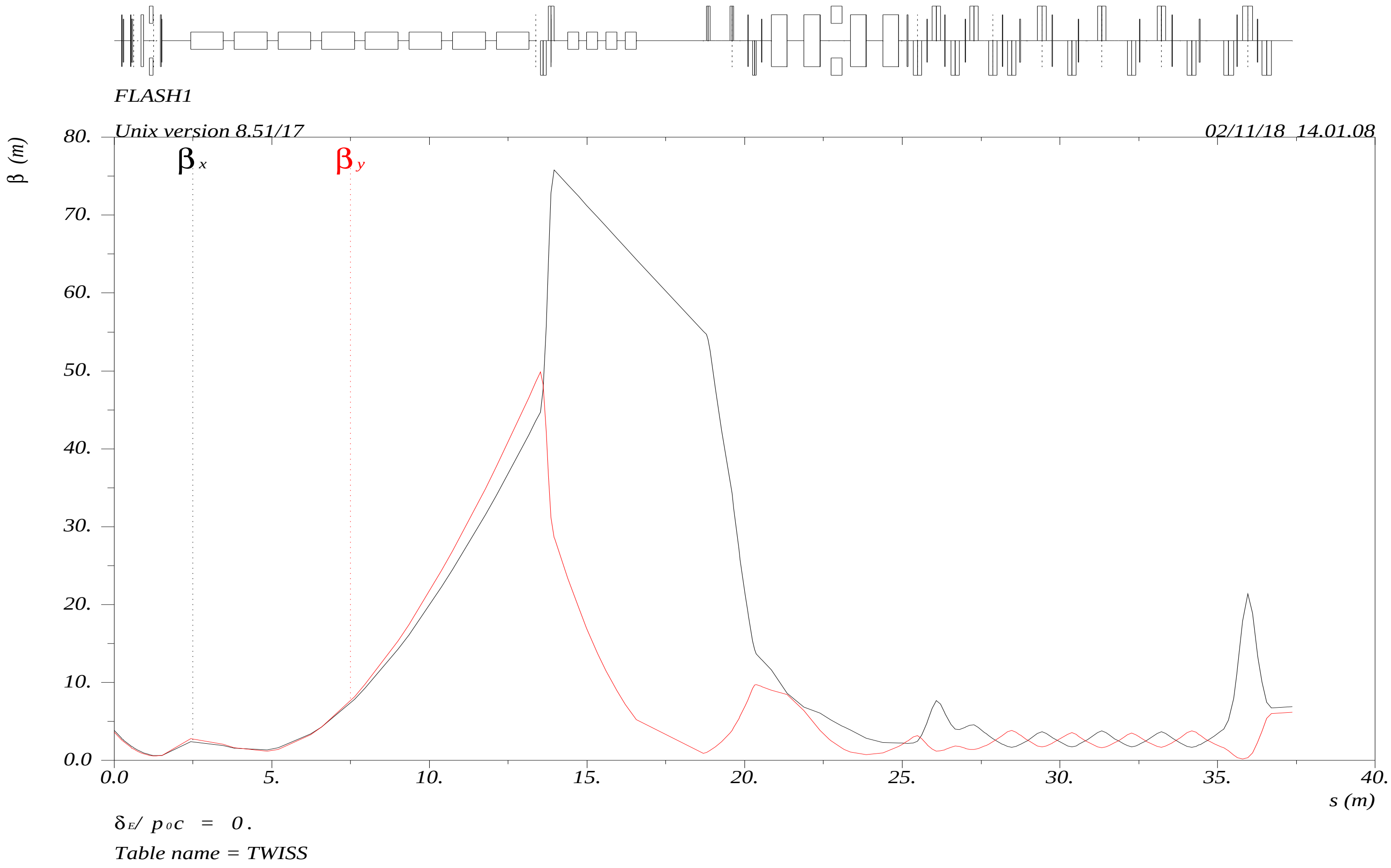
4DBC2 6DBC2 8DBC2 10DBC2

$\beta_T = 2.46$ m	$\beta_M = 2.44$ +- 0.14 m	$\beta_T = 2.66$ m	$\beta_M = 2.51$ +- 0.14 m
$\alpha_T = -1.20$	$\alpha_M = -1.21$ +- 0.07	$\alpha_T = 1.31$	$\alpha_M = 1.26$ +- 0.06
$\varepsilon_T = 0.49$ um	$\varepsilon_M = 0.49$ +- 0.02 um	$\varepsilon_T = 0.51$ um	$\varepsilon_M = 0.51$ +- 0.02 um
$m_P = 1.00$	$\lambda_P = 1.03$	$m_P = 1.00$	$\lambda_P = 1.06$





Typical 2018 Injector Match (after 6 iterations)



Remeasured 2018-11-**08**-night, (file restored)

same conditions as 2018-11-02

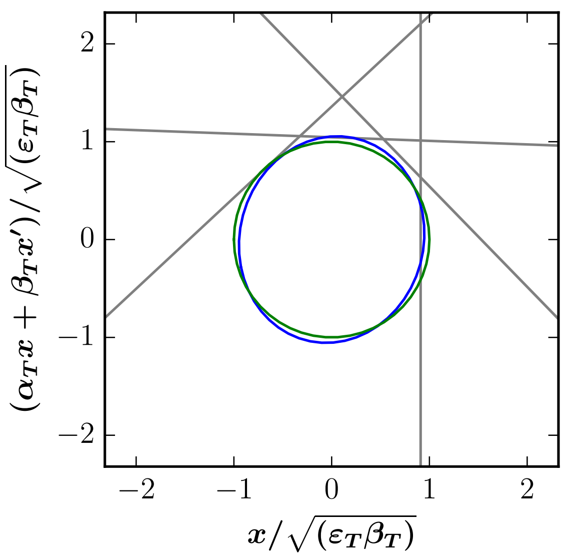
4DBC2 6DBC2 8DBC2 10DBC2

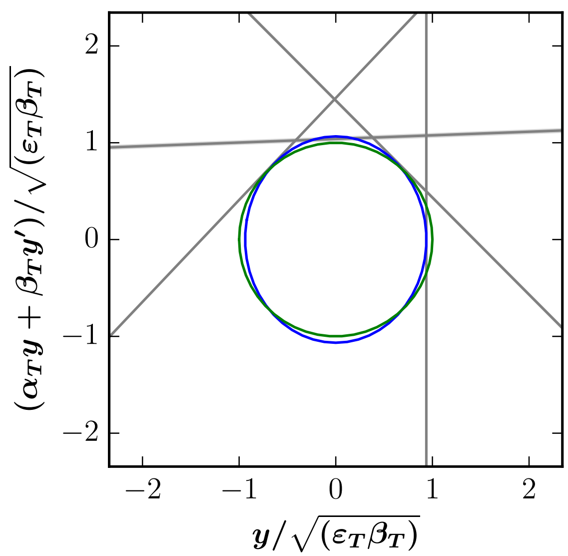
β_T = 2.46 m β_M = 2.22 +- 0.11 m
α_T = -1.20 α_M = -1.14 +- 0.06
ε_T = 0.48 um ε_M = 0.48 +- 0.02 um

m_P = 1.01 λ_P = 1.13

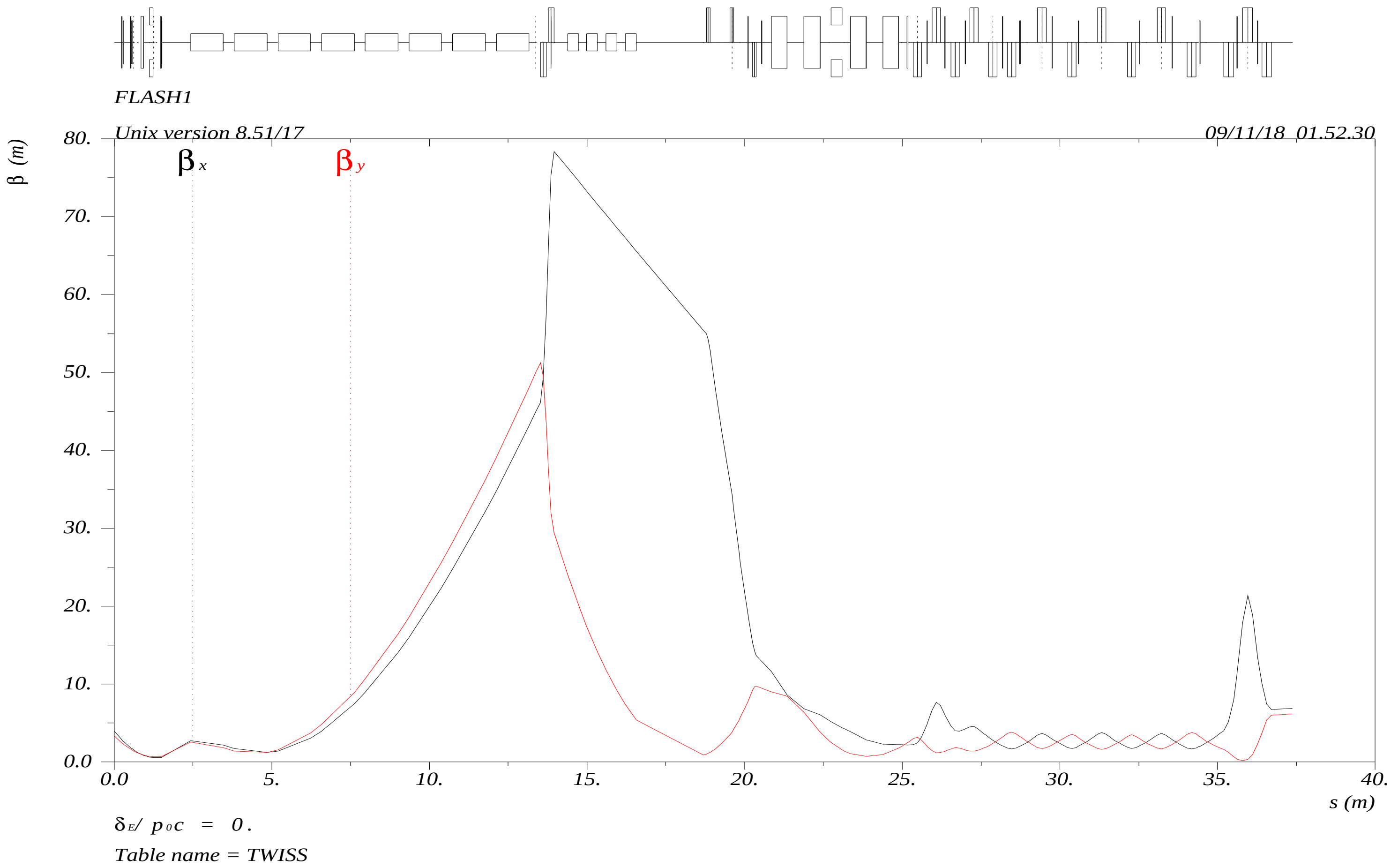
β_T = 2.66 m β_M = 2.34 +- 0.10 m
α_T = 1.31 α_M = 1.15 +- 0.05
ε_T = 0.53 um ε_M = 0.53 +- 0.02 um

m_P = 1.01 λ_P = 1.14





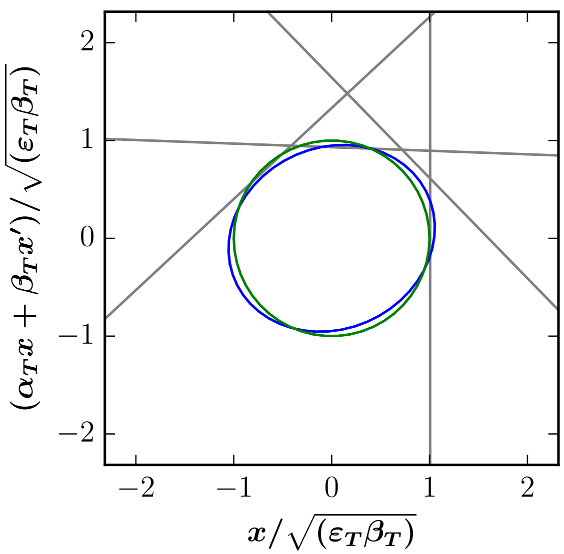
... One Single Rematch

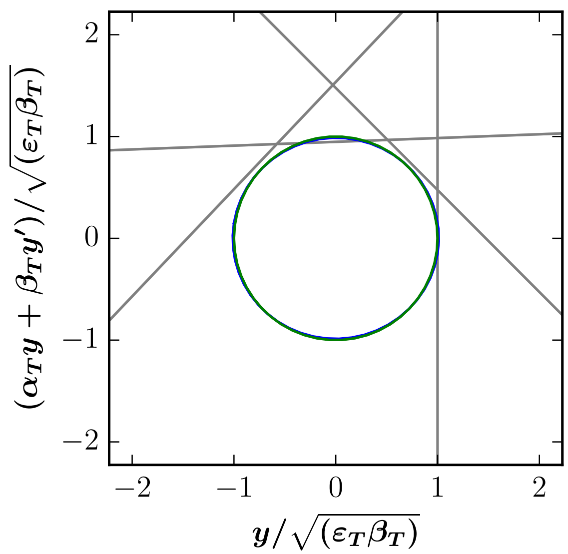


Remeasured after One Single Rematch

4DBC2 6DBC2 8DBC2 10DBC2

β_T = 2.46 m	β_M = 2.74 +- 0.13 m	β_T = 2.66 m	β_M = 2.73 +- 0.14 m
α_T = -1.20	α_M = -1.44 +- 0.06	α_T = 1.31	α_M = 1.34 +- 0.06
ε_T = 0.48 um	ε_M = 0.48 +- 0.02 um	ε_T = 0.52 um	ε_M = 0.52 +- 0.02 um
m_P = 1.01	λ_P = 1.16	m_P = 1.00	λ_P = 1.02





First 2019 Injector Match Campaign (Jan 2019)

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

*: had to stop before convergence was reached

L2, 0.4 nC @1.2 mm, 52 MV/m, 309.0 A, orbit optimized;

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

First 2019 Injector Match Campaign (Jan 2019)

- L2, **BSA: 1.3mm**, gun: 52 MV/m, 0.8deg, I_{sol} =310.3A
  → 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
  → 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
  → 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
  → 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 !!!

⇒ work in progress !

Than you for listening to **part one**!

Next: **part two !!!**