Optimization of the BESSY II optics for the VSR project -

Increase the installation length for the VSR cryomodule in the T2 section of the BESSY II storage ring

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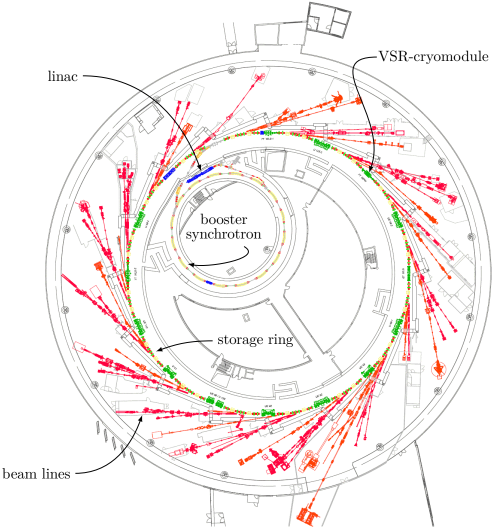
Motivation

BESSY II - A third generation light source



Floor plan of synchrotron light source BESSY II [1].

Parameters of the BESSY II storage ring.

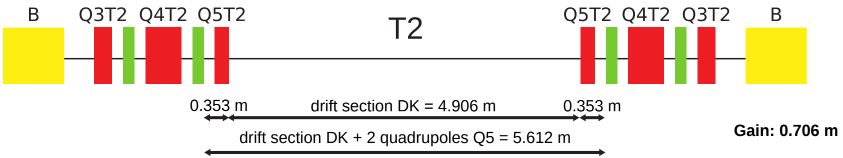
Parameter	**Value**
nominal energy	1.7 GeV
circumference	240 m
RF-frequency	500 MHz
revolution time	800 ns
beam current	300 mA
number of cells	16
number of bending magnets	32
bending radius	4.361 m
beamlines	$\approx$ 50

Bunch length σ_z - BESSY II vs BESSY VSR [2].

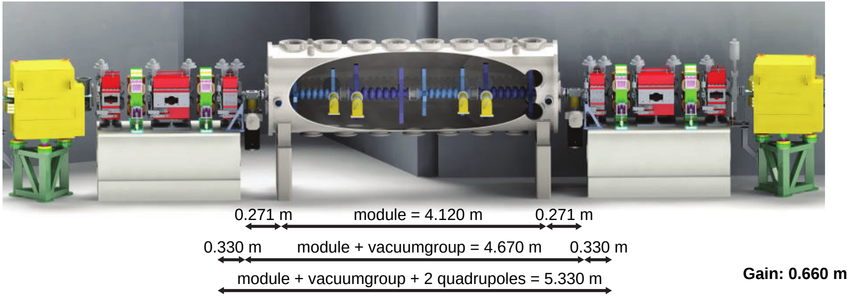
	Bunch length σ_z / ps
BESSY II	15
BESSY II low alpha	3
BESSY VSR short bunch	1.7
BESSY VSR long bunch	15

The VSR-cryomodule in the T2 straight

BII lattice files:



Vacuum / construction department:



The cryomodule and the magnets of the T2 section (dipole-yellow, quadruple-red, sextupole-green).

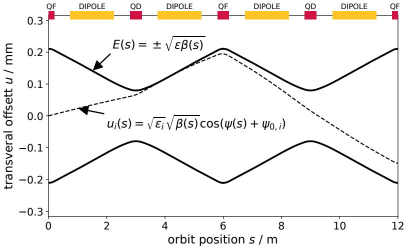
Transverse linear beam dynamics in circular accelerators

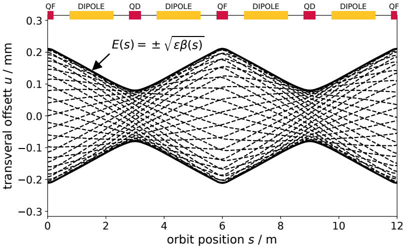
Transverse linear beam dynamics in circular accelerators

The equations of motion for a charged particle in a magnetic field in linear order

$$u''(s) + K(s)u(s) = 0 \quad \overset{\text{Floquet's theorem}}{\Longrightarrow} \quad u(s) = \sqrt{\epsilon}\sqrt{\beta(s)}\cos(\psi(s) + \psi_0) \tag{1}$$

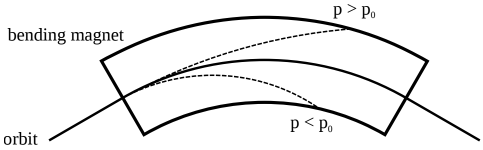
$$\psi(s) = \int_0^s \frac{d\bar{s}}{\beta(\bar{s})} \quad \overset{\text{one revolution}}{\Longrightarrow} \quad Q = \frac{1}{2\pi}\int_s^{s+C} \frac{d\bar{s}}{\beta(\bar{s})} \tag{2}$$





The envelope of a particle beam at the example of a FODO cell. The betatron oscillation for 33 electrons with an emittance of 5 nm rad is shown in the right graphic.

Transverse linear beam dynamics in circular accelerators II



Momentum dispersion in a dipole magnet.

The dispersion function

$$\eta(s) = \frac{\mathrm{d}u(s)}{\mathrm{d}\delta} \tag{3}$$

$$u(s) = u_\beta(s) + u_\delta(s) = u_\beta(s) + \eta(s)\delta \tag{4}$$

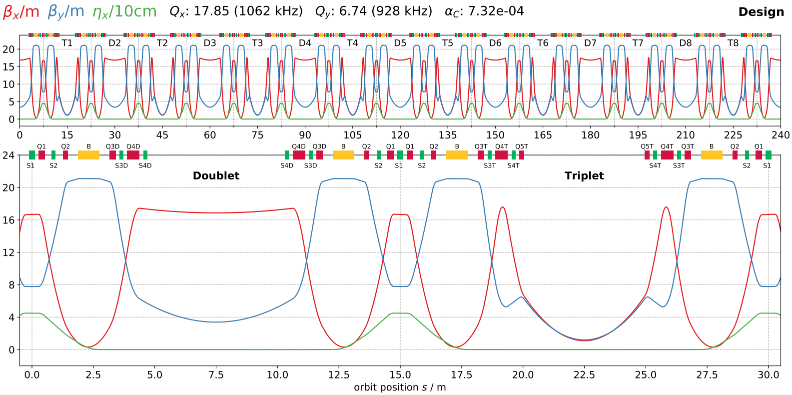
The momentum compaction factor

$$\alpha_c = \frac{\Delta C_\delta / C_\beta}{\delta} \quad \text{with} \quad C = C_\beta + \Delta C_\delta \tag{5}$$

$$\alpha_c = \frac{1}{C_0}\int_0^{C_0} \kappa_{x0}(s)\eta(s)\mathrm{d}s \tag{6}$$

The BESSY II storage ring lattice

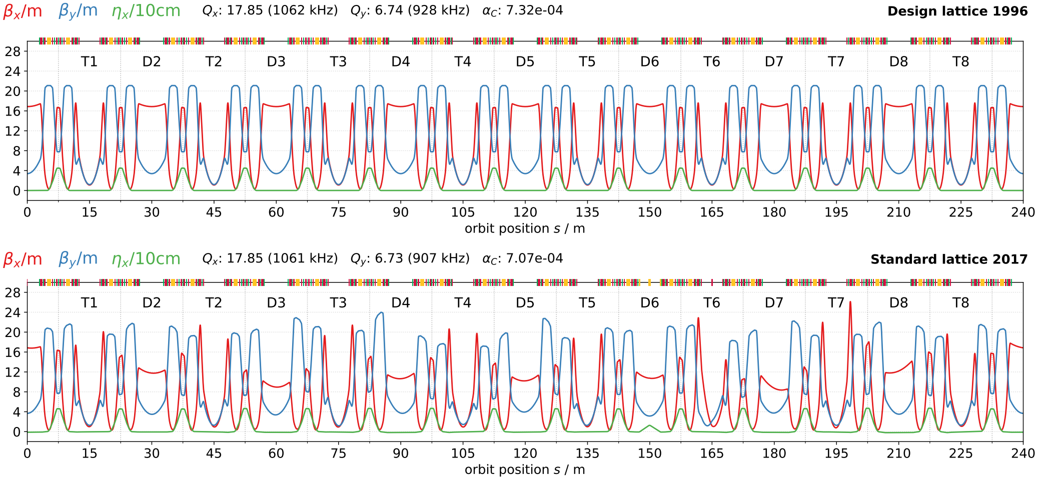
The Design lattice from 1996



Magnet	k / m^{-2}
Q1	+2.45190
Q2	-1.89757
Q3D	-2.02025
Q4D	+1.40816
Q3T	-2.46319
Q4T	+2.62081
Q5T	-2.60000

The design lattice of the BESSY II storage ring.

The design lattice and the current standard lattice



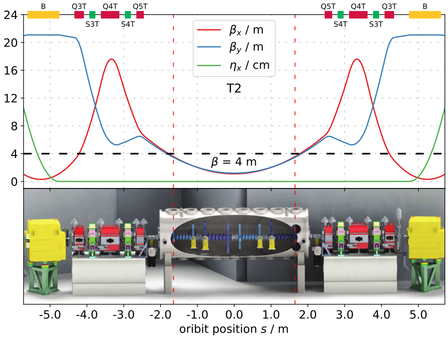
Comparison between the design lattice and the current standard lattice (2017).

Requirements for new optics - Transverse multibunch instabilities

As stated in [1, p. 79] the transverse cavity impedances

$$Z_{\text{th}}^{\perp}(\tau_{\text{d}}^{-1}) = \frac{\tau_{\text{d}}^{-1}}{\beta}\frac{4\pi E/e}{\omega_{\text{rev}} I_{\text{DC}}} \tag{7}$$

scale directly with the value of the beta function and could drive transverse multibunch instabilities. Therefore a beta function below 4 m is required.

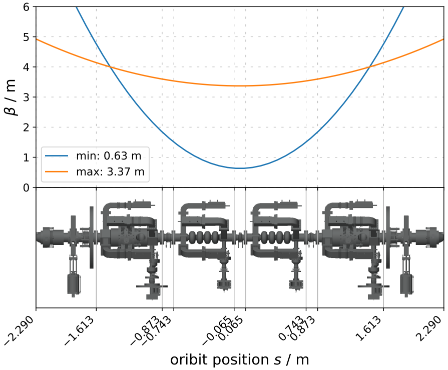


The horizontal and vertical beta functions $\beta_{x,y}$ in the T2 sections (based on [1]).

The beta functions at the cyromodule

The beta function at distance s to a symmetry point can be calculated by:

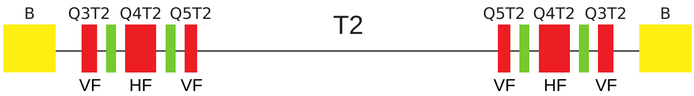
$$\beta(s) = \beta^* + \frac{s^2}{\beta^*} \tag{8}$$



The maximal and average beta function within the cavity in dependence of the minimal beta function β^* (based on [3, 4]).

Simulations of the new optics and verification at the machine

First approach to turn off the Q5T2 magnets



1. Test how much the Q5T2 can be reduced without chancing any other magnet.

$\Rightarrow$ The beam was lost at about 94 % of the initial value.

2. Compensate the vertical focusing Q5T2 by increasing the vertical focusing Q3T2.

$\Rightarrow$ First allowed to reduce the Q5T2 slightly more, but lead then to the loss of the beam.

3. Compensate the vertical focusing Q5T2 by decreasing the horizontal focusing Q4T2.

$\Rightarrow$ Achieved a working machine with switched of Q5T2 and an injection efficiency of about 20 %.

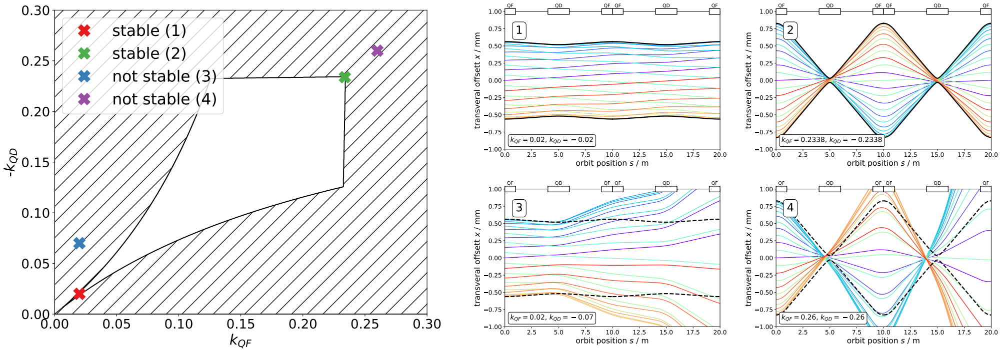
Changes in ampere of the quadrupoles in the T2 section compared to the standard BESSY II values

signal	**saved value** / A	**present value** / A	**factor**
Q3PT2R:set	226.5832	219.7057	1.031
Q4PT2R:set	189.587	246.5637	0.769
Q5PT2R:set	18.25	227.68	0.080
Q5PT2R:stat1	OFF	ON	-

Limits of the lattice stability - FODO cell

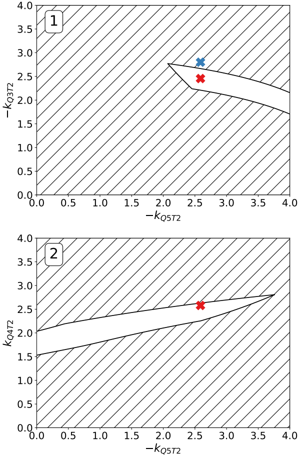
The beta function for a periodic lattice:

$$\beta(s) = \frac{2R_{12}}{\sqrt{2 - R_{11}^2 - 2R_{12}R_{21} - R_{22}^2}} \tag{9}$$

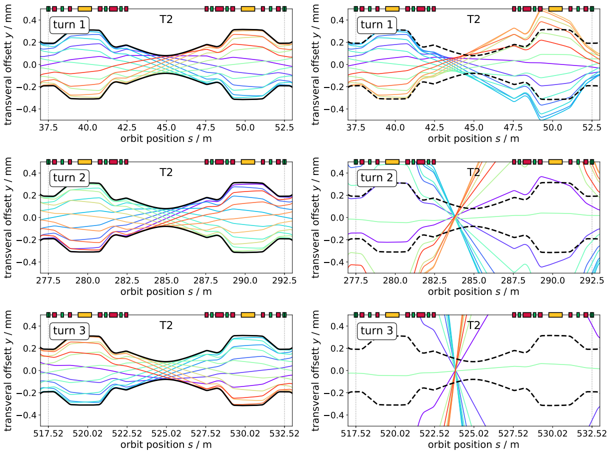


Limits of the FODO lattice stability.

Limits of the lattice stability - BESSY II

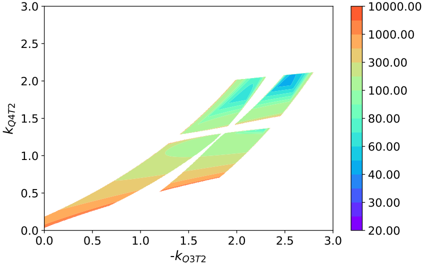


The lattice stability for BESSY II.



Instability of the BESSY II storage ring lattice by the changing of the Q3T2.

Optimization by minimization of a scalar function



Maximum value of the beta function with switched off Q5T2.

Two conditions:

1. The initial values must be in a stable area.
2. Optimization methods which does not need the derivative.

Three repetition of the Nelder-Mead algorithm:

Step 1: Turn off the Q5T2

$$f_1 = 10 \cdot (k_{\mathrm{Q5T2}})^{\frac{1}{4}} + \frac{\beta_{\mathrm{max}}}{\beta_{\mathrm{max,ref}}} + \frac{\overline{\beta}_{\mathrm{x,rel}} + \overline{\beta}_{\mathrm{y,rel}}}{2} \quad \text{with } \overline{\beta}_{\mathrm{u,rel}} = \frac{1}{L}\int_0^L \mathrm{d}s \, \frac{\beta_{\mathrm{u}}}{\beta_{\mathrm{u,ref}}} \tag{10}$$

Step 2: Optimize the beta functions

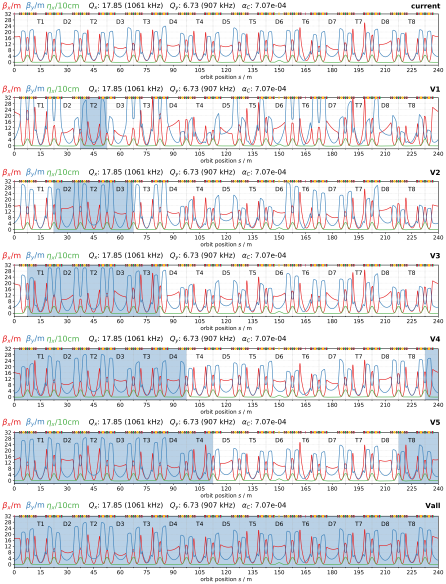
$$f_2 = \frac{\beta_{\mathrm{max}}}{\beta_{\mathrm{max,ref}}} + \frac{\overline{\beta}_{\mathrm{x,rel}} + \overline{\beta}_{\mathrm{y,rel}}}{2} \tag{11}$$

Step 3: Correct the tunes

$$f_3 = \frac{\beta_{\mathrm{max}}}{\beta_{\mathrm{max,ref}}} + \frac{\overline{\beta}_{\mathrm{x,rel}} + \overline{\beta}_{\mathrm{y,rel}}}{2} + 10 \cdot \left(|Q_{\mathrm{x}} - Q_{\mathrm{x,ref}}| + |Q_{\mathrm{y}} - Q_{\mathrm{y,ref}}| \right) \tag{12}$$

Overview of the solutions with existing hardware

Version	Used quadrupoles
V1	T2
V2	D2, T2, D3
V3	T1, D2, T2, D3, T3
V4	D1, T1, D2, T2, D3, T3, D4
V5	T8, D1, T1, D2, T2, D3, T3, D4, T4
Vall	all quadrupoles



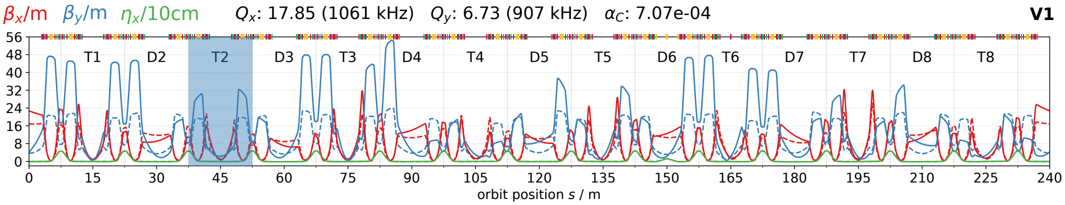
Local solutions: V1

Using only the magnets in the T2 section to compensate the turn off of the Q5T2.

Output of the minimization method for the local compensation V1.

	Magnets	Initial	Final	Difference	Factor	Factor (exp.)
1	Q5PT2R	-2.588	0.000	2.588	-0.000	0.080
2	Q4PT2R	2.579	2.032	-0.547	0.788	0.769
3	Q3PT2R	-2.455	-2.630	-0.174	1.071	1.031

Q_x / kHz	Q_y / kHz	$\beta_{x,max}$ / m	$\beta_{y,max}$ / m	$\overline{\beta}_{x,rel}$ / m	$\overline{\beta}_{y,rel}$ / m
1060.54	907.38	32.34	54.57	1.08	1.43



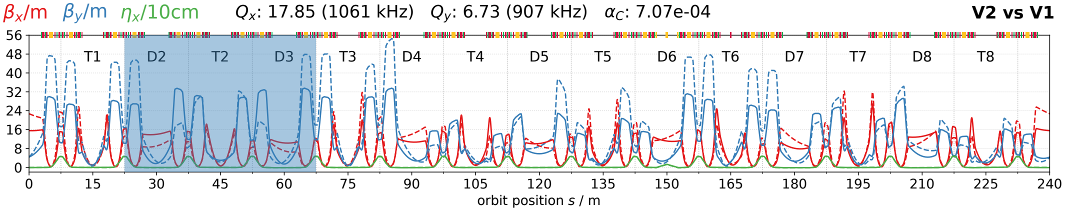
Comparison of the V1 lattice (solid) with the current standard lattice (dashed).

Local solutions: V2

Output of the minimization method for the extended local compensation V2.

Q_x / kHz	Q_y / kHz	$\beta_{x,max}$ / m	$\beta_{y,max}$ / m	$\overline{\beta}_{x,rel}$ / m	$\overline{\beta}_{y,rel}$ / m
1060.54	907.39	26.89	33.58	1.01	1.13

	Magnets	Initial	Final	Difference	Factor
1	Q5PT2R	-2.588	0.000	2.588	-0.000
2	Q3PD2R	-2.125	-2.187	-0.062	1.029
3	Q3PD3R	-2.126	-2.220	-0.094	1.044
4	Q3PT2R	-2.455	-2.449	0.006	0.997
5	Q4PD2R	1.479	1.457	-0.022	0.985
6	Q4PD3R	1.486	1.458	-0.028	0.981
7	Q4PT2R	2.579	2.052	-0.527	0.796



Comparison of the V1 (dashed) and the V2 (solid) lattice.

Test of the V1 and V2 optics in April

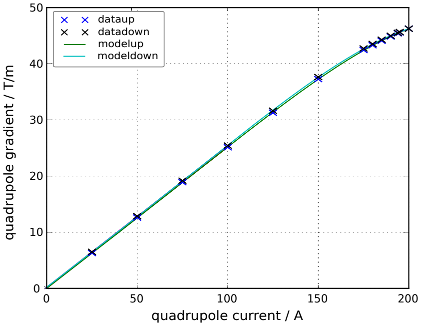
Calculation of the power supply values

If

$$k \propto I, \tag{13}$$

the new power supply can be calculated by the new and old quadrupole strengths as well as by the old power supply values:

$$I_{\text{new}} \approx \frac{k_{\text{new}}}{k_{\text{old}}} I_{\text{old}} \tag{14}$$

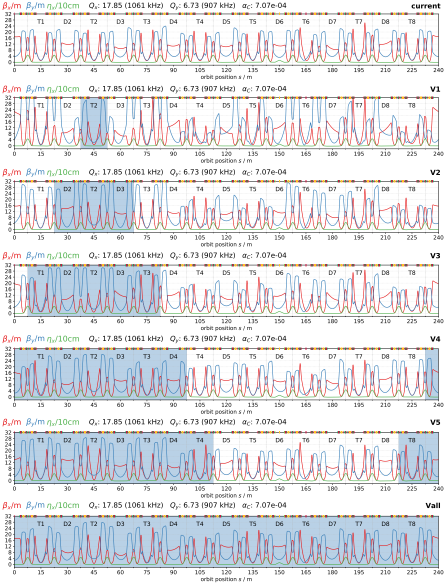


Q4PT transfer line - The quadrupole strengths k vs the power supply value I [5].

- V1: Injection efficiency of about 20 % to 30 %
- V2: Injection efficiency of about 35 %-43 %.
- V2 with optimized sextupoles: Injection efficiency up to 65 % and a lifetime of 4,7 h (high current test).

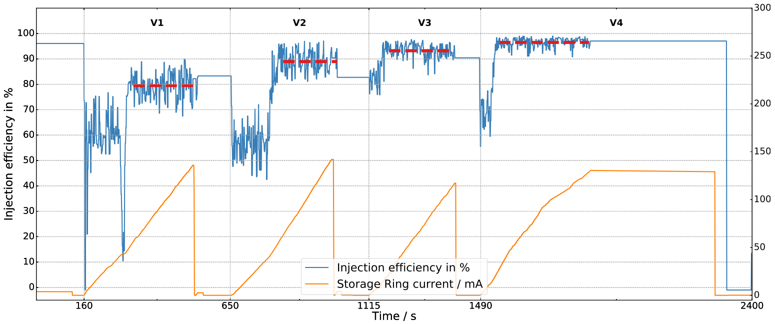
Both optics were measured with LOCO. Both Twiss parameter and quadrupoles strengths were very consistent.

Simulation of all optics V1 - Vall



Version	Q_x / kHz	Q_y / kHz	$\beta_{x,max}$ / m	$\beta_{y,max}$ / m	$\overline{\beta}_{x,rel}$ / m	$\overline{\beta}_{y,rel}$ / m
current	1060.54	907.38	26.14	24.00	1.00	1.00
V1	1060.54	907.38	32.34	54.57	1.08	1.40
V2	1060.54	907.39	26.89	33.58	1.01	1.13
V3	1060.53	907.38	28.74	30.22	1.04	1.08
V4	1060.54	907.38	24.48	28.38	1.00	1.06
V5	1060.54	907.39	25.43	28.65	1.01	1.07
Vall	1060.54	907.38	24.43	27.92	1.00	1.04

V1 - V4 tested at BESSY II

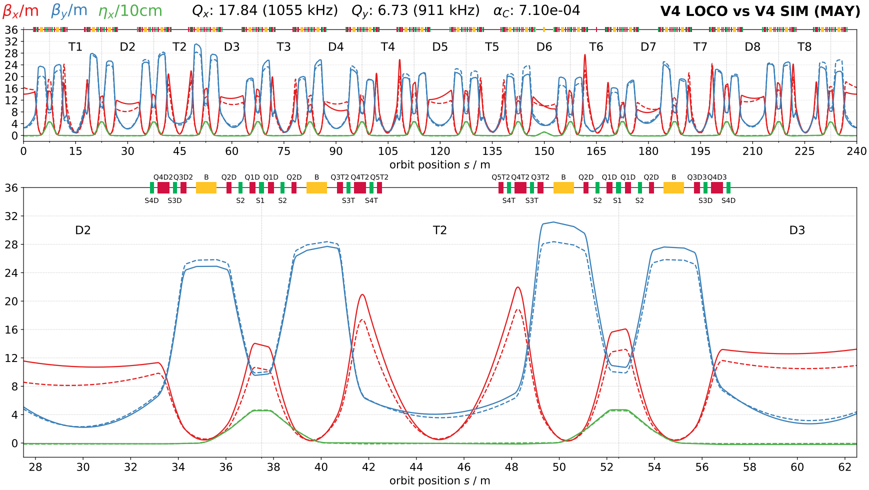


Version	Injection efficiency
V1	79.5 %
V2	89.0 %
V3	93.2 %
V4	96.5 %

Comparison of the mean injection efficiency of the different version for an optimized sextupole setting for the V4 optics. The mean injection efficiency is marked with a red dashed line.

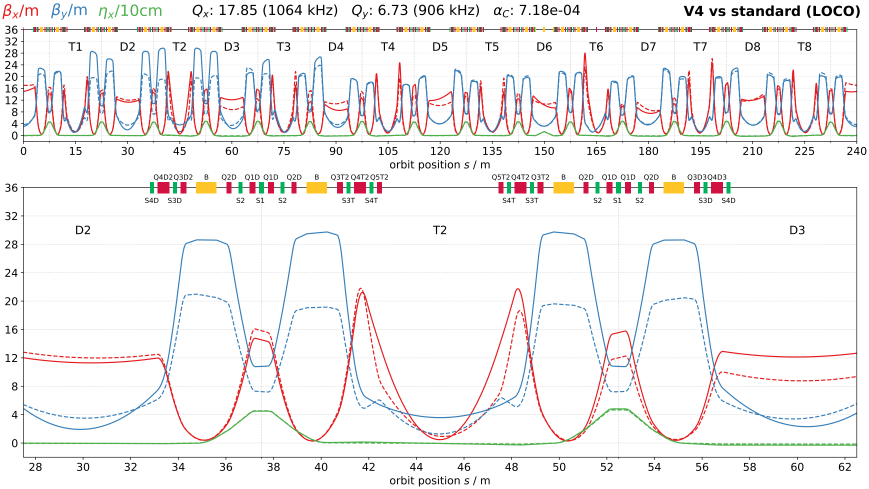
- Phase acceptance was quickly optimized for the V4 optics
- All superconducting IDs were off $\Rightarrow$ Sextupole setting was optimized for SCIDs on

The best solution V4: Simulation vs LOCO measurement



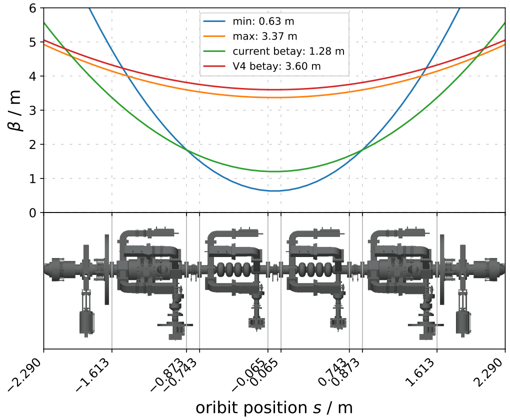
Comparison of V4 LOCO (solid) with V4 SIM (dashed).

The best solution V4 compared to the current standard user optics



The loco measured V4 optics (solid) in comparison to the standard optics (dashed).

V4: The beta function at the cryomodule in the T2 section



The maximal and average beta function within the cavity in dependence of the minimal beta function β^* (based on [3, 4]).

Conclusion and Outlook

Conclusion and Outlook

1. Adaptation of the objective function of the optimization method

   At the moment the main weighting factor is the mean relative residual of the beta function. This means that a change from 4 m to 2 m corresponding to -50 % has the same weight as a change from 20 m to 30 m (+50 %). This has the result that the beta function in some straights is smaller than the reference value and is therefore larger in the subsequent DBA.

2. Possiblity to set the value of the beta function at certain points

   This would allow to adjust the beta functions at the VSR cryomodule to the desired value.

3. Optimization of the non-linear beam dynamics

   The sextupoles can be used to enhance the phase and momentum acceptance.

4. Correct conversion of the quadrupole strengths

   It would be very convenient to have conversion functions for the individual quadrupole families. These should be tested with LOCO to make sure that the simulated optics is transfered correctly to the machine.

5. Test solutions with hardware modification

   This thesis only considered solutions with existing hardware. Splitting up the quadrupole and sextupole families in the T2, D2 and D3 sections would increase the degrees of freedom. It has to be verified by simulations if this approach will lead to a better solution.

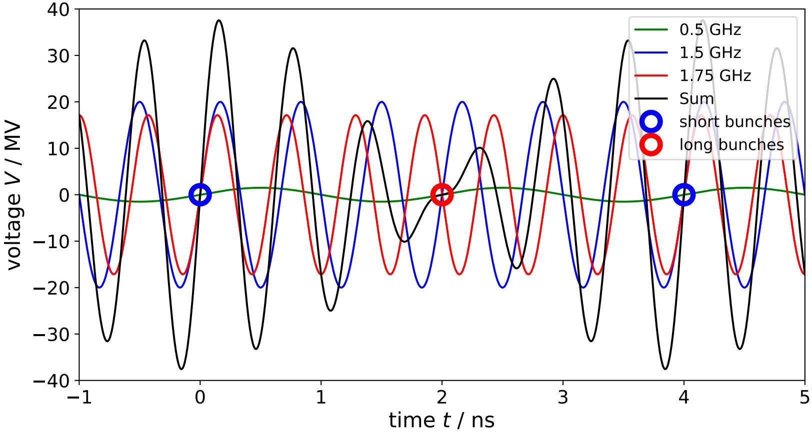
6. A better optimization method

   The used Nelder-Mead method is relatively slow and it has a weakness when considering local minima. Due to the increasing hype on machine learning, many new open source software libraries have been developed, which can be used to solve diverse optimization tasks. Their applicability to lattice optimization problems should be tested.

Questions?

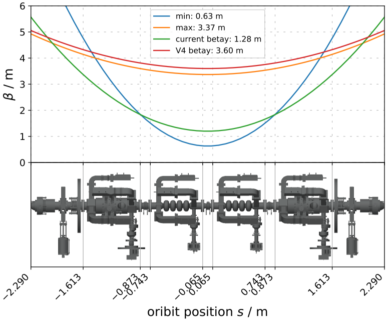
Backups

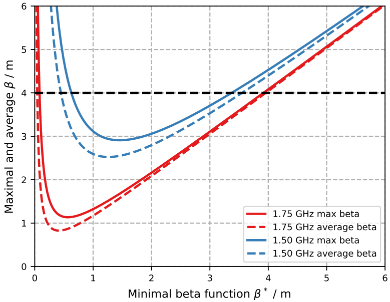
Backup - Superposition of the VSR cavity voltages



Superposition of the cavity voltages for BESSY-VSR (based on [1, 2]). The large gradient at $t = 0$ ns and $t = 4$ ns generates short bunches. The small gradient at $t = 2$ ns leads to long bunches.

Backup - The beta functions at the cyromodule





The maximal and average beta function within the cavity in dependence of the minimal beta function β^* (based on [3, 4]).

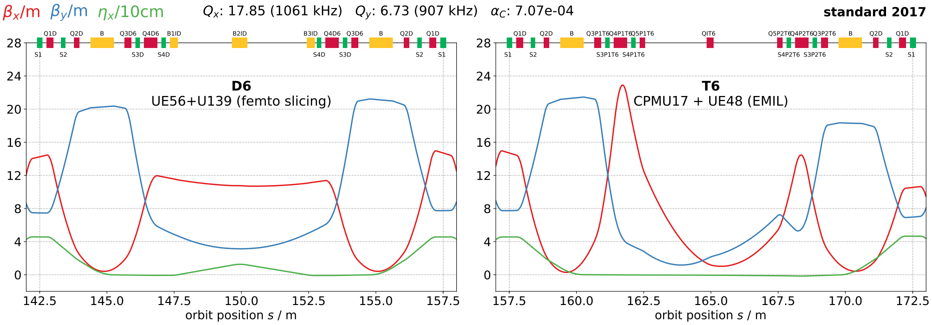
The beta matrix in distance from the symmetry point $s = 0$ is given by

$$\mathbf{B}(s) = \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \beta^* & 0 \\ 0 & 1/\beta^* \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ s & 1 \end{pmatrix} = \begin{pmatrix} \beta^* + \frac{s^2}{\beta^*} & \frac{s}{\beta^*} \\ \frac{s}{\beta^*} & \frac{1}{\beta^*} \end{pmatrix}, \tag{15}$$

The beta function at distance s to a symmetry point can be calculated by:

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*} \tag{16}$$

Backup - Femto slicing und EMIL



The Twiss parameter in the Emil straight and femto slicing straight.

1. Installation of 3 additional dipoles in the D6 straight (femto slicing)
2. Installation of the vertical focusing quadrupole QIT6 (EMIL)

Backup - Optics scans

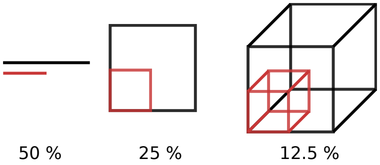
1. Quadrupole scans for many parameters are very time consuming.

   We assume one iteration to calculate the transfer matrices, the Twiss parameter and the tune would take $t_1 = 1\,\mathrm{ms}$. A quadrupole scan in the neighborhood of $l = 1\,\mathrm{m}^{-2}$ with a steps size $\Delta k = 0.01\,\mathrm{m}^{-2}$ for a combination of $M = 6$ magnets would need

   $$t_C = t_1 \cdot \left(\frac{l}{\Delta k}\right)^M = 1\,\mathrm{ms} \cdot \left(\frac{1}{0.01}\right)^6 \approx 32\,\mathrm{a}. \tag{17}$$

2. The ratio of the *solution space* to the *scanned space* strongly depends on the interval of the scan.

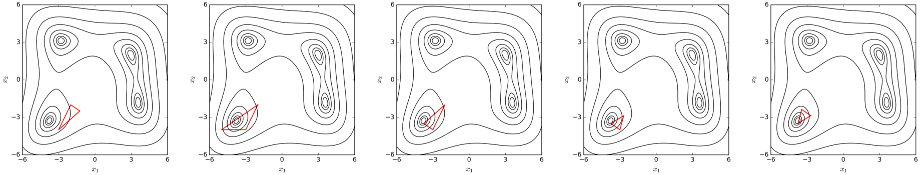
   For higher dimensions it is more difficult to choose good scan intervals. As the solutions space in general is unknown (and not continuous), this means that for higher dimensions more and more of the scanned area will not be a solution.



Backup - Nelder Mead algorithm

- Every set of parameters is assigned to a scalar value by an objective function.
- Two conditons:
  1. The initial values must be in a stable area.
  2. Optimization methods which does not need the derivative.

⇒ After testing several methods the downhill simplex algorithm from Nelder and Mead [6] was chosen.



Source: Wikipedia

Advantages

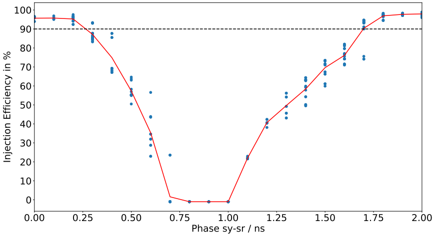
The Nelder-Mead method does not need the derivative and is very reliable.

Disadvantages

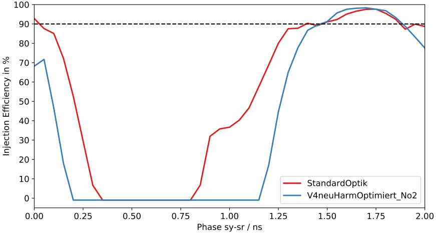
The Nelder Mead algorithm is very slow and can, like many other optimization methods, converge towards a local minimum.

Backup - Phase acceptance scan

For the VSR project it is assumed that 0.8-1.0 ns with 90 % injection efficiency is the needed to inject into the short bucket [7].



Phase acceptance scan with SCIDs off (May 2017):
The region with injection efficiency above 90 % is 0.57 ns for the V4 optics

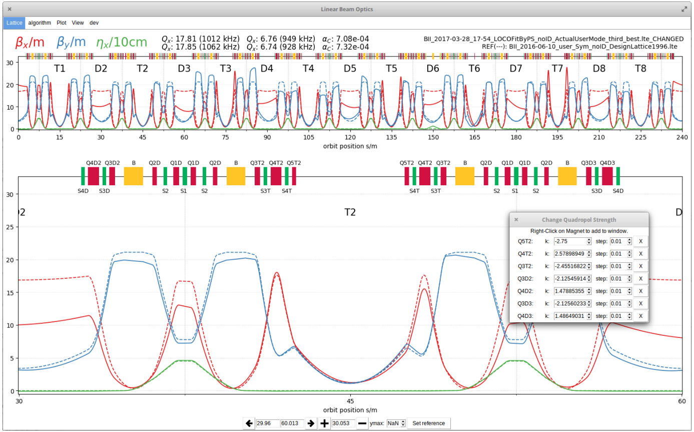


Phase acceptance scan with SCIDs on (September 2017):
The region with injection efficiency above 90 % is 0.65 ns for the current standard user lattice and 0.45 ns for the V4 optics

Backup - LOCO (Linear Optics from Closed Orbits)

1. Measure the LOCO data (BPM response matrix, dispersion function, BPM noise)
2. Build the LOCO input file (choose a accelerator model).
3. Fit the LOCO data to the model.

Backup - The Twiss GUI

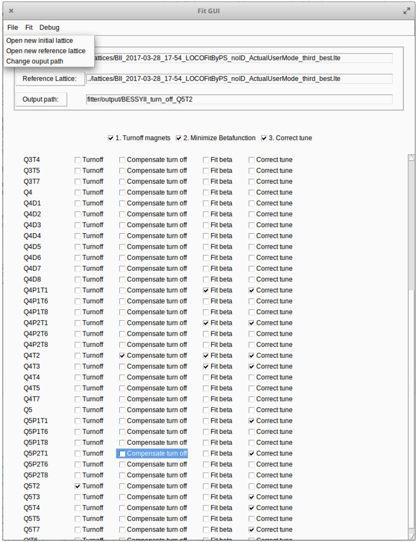


Screenshot of the Twiss GUI

- Build with the python integrated Tkinter module in combination with matplotlib libary [8].
- Change quadrupoles in the style of the control room software.

Backup - Optimizing of the optics

- GUI can be used to choose the sets of parameters.
- The different fits can be configured one by one and are then computed in parallel.
- Afterwards the GUI can be closed without terminating the process.



Screenshot of the Fit GUI

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