Quadrupole Gradient Accuracies in Storage Rings

Motivation 1:

- - - ***"we hope that at the next FCC week the tolerance requirements will be technically more feasible"***

… I think, this person never worked on collider simulations.

- - - ***"in LHC we know the dipole fields with an accuracy of 10^{-6} "***

… if so, we would not need polarisation to determine the beam energy.

… in LHC the eight dipole power converters are locked to each other with 10^{-6} precision.

- - - ***"in LHC we cannot measure the quadrupole gradients better than 10^{-3} "***

No: we can measure better and so we know that due to persistent currents (that depend on many external parameters) the field reproducibility is in the order of some units (= 10^{-4})

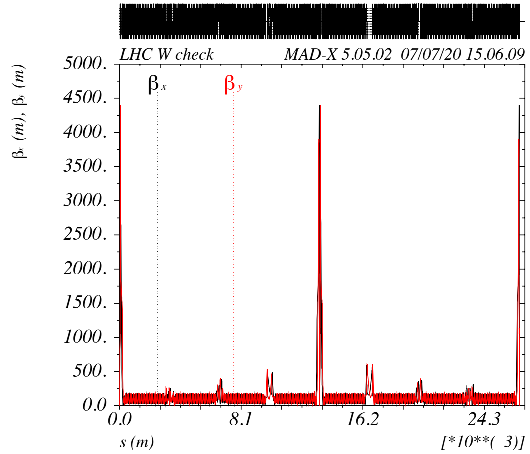
And by the way …. FCC-ee will have normal conducting magnets.

```
! ---------------------------------------------------------------------
! ********Magnet type : MQXC/MQXD (new Inner Triplet Quad)***************
! ---------------------------------------------------------------------
                    bn in collision
b1M_MQXCD_col  :=  0.0000 ;   b1U_MQXCD_col  :=  0.0000 ; b1R_MQXCD_col  :=  0.0000 ;
b2M_MQXCD_col  :=  0.0000 ;   b2U_MQXCD_col  :=  0.0000 ; b2R_MQXCD_col  :=  0.0000 ;
b3M_MQXCD_col  :=  0.0000 ;   b3U_MQXCD_col  :=  0.4600 ; b3R_MQXCD_col  :=  0.8900 ;
b4M_MQXCD_col  :=  0.0000 ;   b4U_MQXCD_col  :=  0.6400 ; b4R_MQXCD_col  :=  0.6400 ;
b5M_MQXCD_col  :=  0.0000 ;   b5U_MQXCD_col  :=  0.4600 ; b5R_MQXCD_col  :=  0.4600 ;
b6M_MQXCD_col  :=  0.0000 ;   b6U_MQXCD_col  :=  1.7700 ; b6R_MQXCD_col  :=  1.2800 ;
b7M_MQXCD_col  :=  0.0000 ;   b7U_MQXCD_col  :=  0.2100 ; b7R_MQXCD_col  :=  0.2100 ;
b8M_MQXCD_col  :=  0.0000 ;   b8U_MQXCD_col  :=  0.1600 ; b8R_MQXCD_col  :=  0.1600 ;
b9M_MQXCD_col  :=  0.0000 ;   b9U_MQXCD_col  :=  0.0800 ; b9R_MQXCD_col  :=  0.0800 ;
b10M_MQXCD_col :=  0.0000 ;   b10U_MQXCD_col :=  0.2000 ; b10R_MQXCD_col :=  0.0600 ;
b11M_MQXCD_col :=  0.0000 ;   b11U_MQXCD_col :=  0.0300 ; b11R_MQXCD_col :=  0.0300 ;
b12M_MQXCD_col :=  0.0000 ;   b12U_MQXCD_col :=  0.0200 ; b12R_MQXCD_col :=  0.0200 ;
b13M_MQXCD_col :=  0.0000 ;   b13U_MQXCD_col :=  0.0200 ; b13R_MQXCD_col :=  0.0100 ;
b14M_MQXCD_col :=  0.0000 ;   b14U_MQXCD_col :=  0.0400 ; b14R_MQXCD_col :=  0.0100 ;
b15M_MQXCD_col :=  0.0000 ;   b15U_MQXCD_col :=  0.0000 ; b15R_MQXCD_col :=  0.0000 ;
```

Motivation 2:

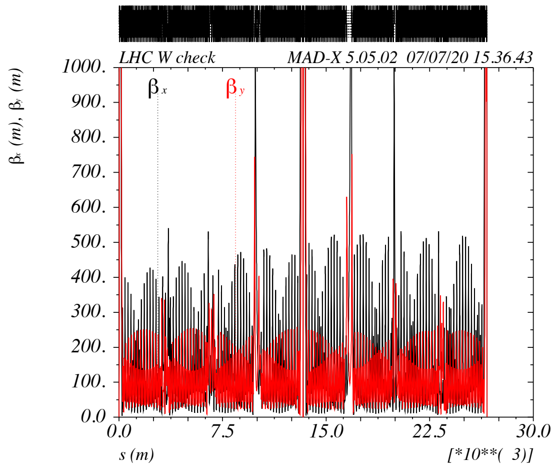
… it is all too easy to spoil a beam optics, on a level where even a most sophisticated correction algorithm cannot do the job.

LHC standard Luminosity Optics:



All Main quads auf 1.5e-3 Gradient Error —>

DKNR:={0, 1.5e-3*tgauss(2.0), 0};



All Main quads auf 2e-3 Gradient Error —>

DKNR:={0, 2e-3*tgauss(2.0), 0};

```
++++++ Error: seterrorflag : Errorcode: 1
Reported from pro_twiss:
++++++ Error: seterrorflag : Description:
TWISS failed
```

Goal of the simulation campaign:

Develop correction tools —> for orbit (x & y)
—> and for the optics (β, D, κ)

to bring the beam optics as close as possible to the ideal (i.e. theoretical) values

to correct the orbits to a level that minimises unwanted influence on the beam dynamics via coupling and synchrotron light.

$$\varepsilon_x = \frac{55}{32\sqrt{3}} \frac{\hbar}{mc} \gamma^2 \frac{\left\langle \frac{1}{R^3} \mathcal{H}(s) \right\rangle}{J_x \left\langle \frac{1}{R^2} \right\rangle}.$$

$$\mathcal{H} = \left(\gamma\ D^2 + 2\ \alpha\ D\ D' + \beta\ D'^2\right)$$

In the case of FCC-ee especially the vertical emittance (i.e. coupling & D_y) have to be controlled.

—> determine the tolerance limits, that still guarantee these goals.

What do the others do ?

Which gradient tolerances do they assume for their beam simulation studies & to run the machine ?
Which tolerances can be achieved nowadays in modern electron storage rings ?

Daniel Schoerling, CERN
Olaf Dunkel, CERN
Bastian Haerer, KIT-FLUTE
Axel Bernhard, KIT-ANKA / FLUTE
Stefan Russenschuck, CERN
Markus Koerfer DESY
Markus Schloesser DESY
Aleksandre Matveenko, BESSY
Joerg Feikes, BESSY
Christian Carli, ELENA, CERN

… and conference & workshop papers from
ALS / APS / Australian Light Source / CLIC / ESRF & EBS / MAX IV /
NSLS II / PETRA 3 / PETRA IV / SLS

FCC-ee Tolerance studies:

Our approach: **determine the tolerance requirments that allow to obtain a sufficient number of successful seeds which lead to the design emittance values**

Tessa's Summary:

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)
Arc quadrupole*	50	50	100	50
Arc sextupoles*	50	50	100	50
Dipoles	100	100	100	500
Girders	70	70	-	500
IR quadrupole	100	100	100	100
IR sextupoles	100	100	100	100
BPM**	40	40	100	-

* misalignments relative to girder placement
** misalignments relative to quadruple placement

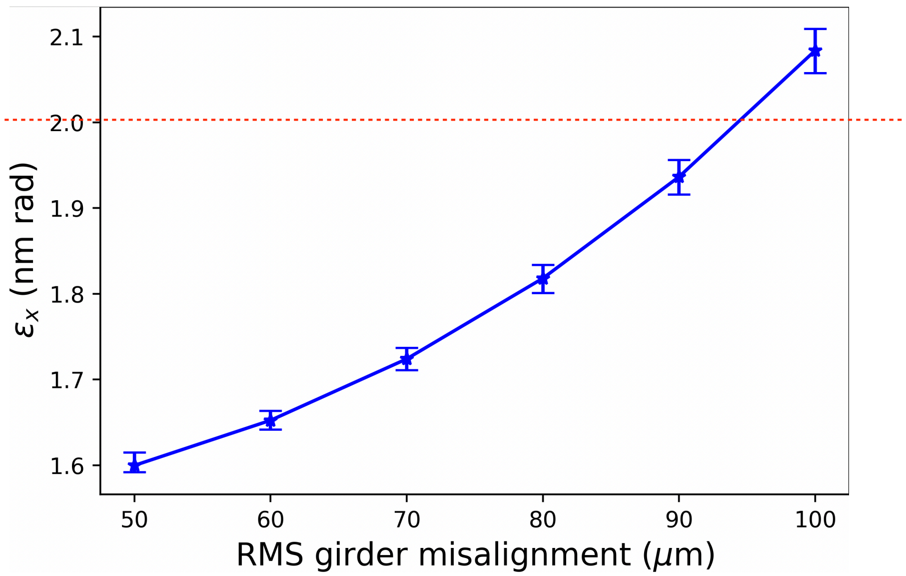
Type	Field Errors
Arc quadrupole	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles	$\Delta k/k = 2 \times 10^{-4}$
Dipoles	$\Delta B/B = 1 \times 10^{-4}$
IR quadrupole	$\Delta k/k = 2 \times 10^{-4}$
IR sextupoles	$\Delta k/k = 2 \times 10^{-4}$

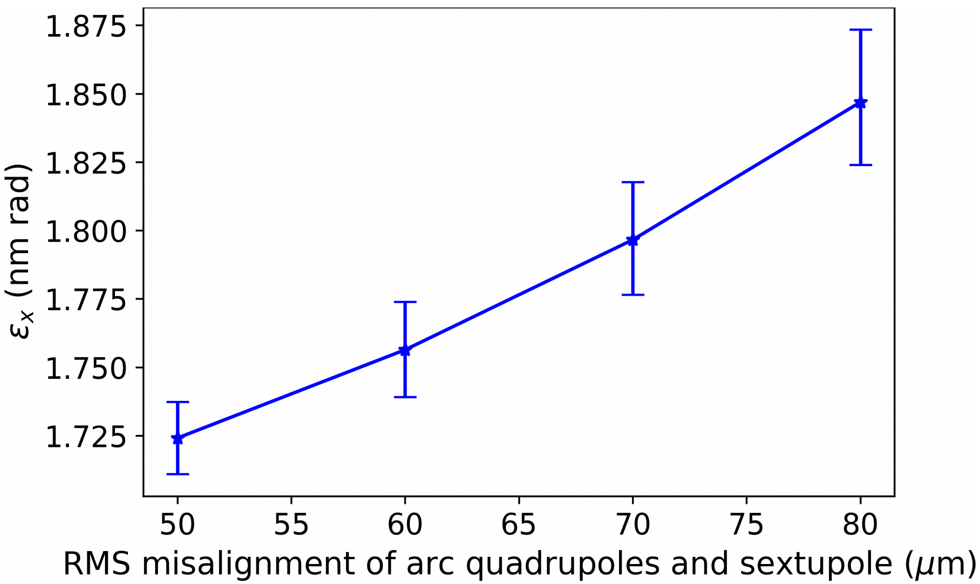
Example: Study of the Girder misalignments::

The girder misalignment has the strongest influence on horizontal emittance of all the parameters listed in Table I.

That is, the tolerance of the girder misalignment has the greatest impact on the achievable horizontal emittance.

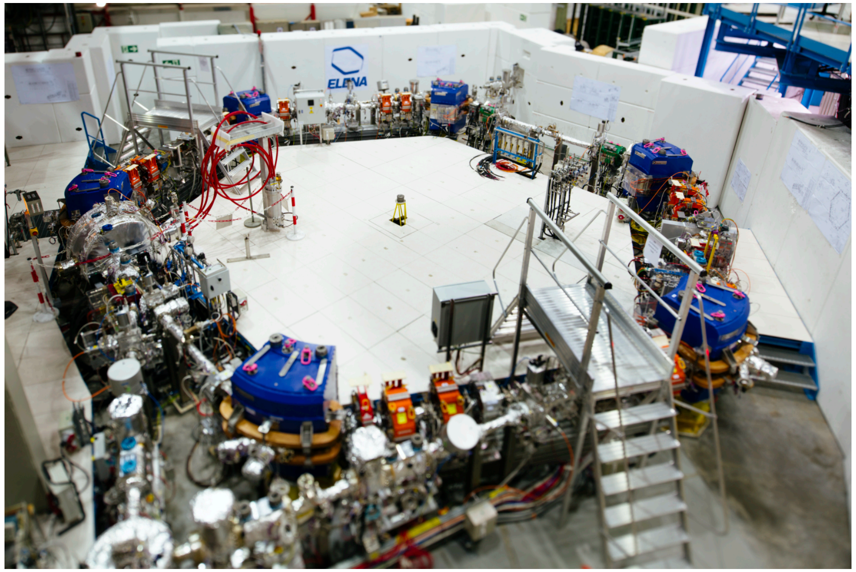
Emittance values after correction for girder and magnet misalignment:





Conclusion: we can correct alignment tolerances, however not with infinite perfection. There weill always be a certain impact left to the achievable emittance values.

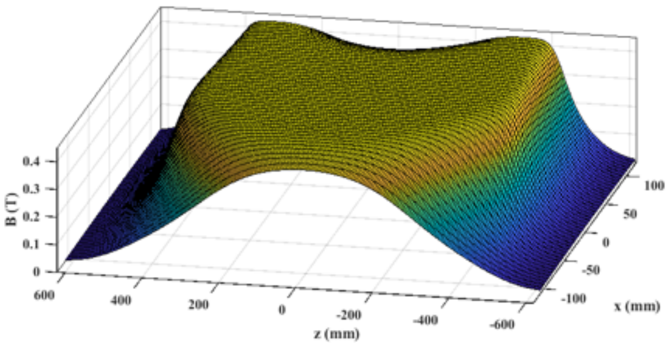
ELENA Dipoles



Magnet measurement using a PCB coil array for measuring curved accelerator dipoles:

The absolute value of the coil equivalent surfaces can be measured in a reference magnet, but the accuracy of such calibration is reduced due to the difficulty to find a reference magnet with an homogeneous field in the 10 ppm order over a large dimension to cover the entire fluxmeter.
The in-situ calibration has shown a maximum difference with respect to the coil on the central trajectory of the MBH-C fluxmeter of 2 × 10-4

Despite of seasonal and daily thermal fluctuations of + 6 °C in the measurement workshop, the calibration results have shown (*longterm*) variations below 0.2×10^{-4}.



ELENA Dipoles

Magnetic length, as measured for the ELENA dipole magnets

Table 6. The magnetic length (L_m) measured on all magnets.

MAGNET	Shim laminations	L_m	ΔL_m
		[mm]	[%]
PXMBHEKCWP-DA000001	0	971.4	0.08
PXMBHEKCWP-DA000002	4+4	971.1	0.05
PXMBHEKCWP-DA000003	4+4	970.7	0.00
PXMBHEKCWP-DA000004	4+4	970.7	0.01
PXMBHEKCWP-DA000005	3+3	970.2	-0.05
PXMBHEKCWP-DA000006	3+3	970.7	0.01
PXMBHEKCWP-DA000007	3+3	970.1	-0.05
PXMBHEKCWP-DA000008	4+4	971.0	0.04
Average (2 to 8)		**970.7**	**0.00**
Max-Min (2 to 8)		**1.0**	**0.10**

typical difference: a few 10^{-4} … 10^{-3}

useful literature:

1. PCB coil array for measuring curved accelerator dipoles: two case studies on the MedAustron accelerator",
2. 20th IMEKO TC4 International Symposium and 18th International Workshop on ADC Modelling and Testing, Benevento, Italy, September 15-17, 2014

Carlo Petrone , CERN, PSB Quadrupoles

*"**There is not a unique answer** because it is a combination of different measurement methods. Nevertheless,* (for the integrated gradient) although challenging)*, it can be better than 10^-3 in some circumstances."*

Aleksandr Matveenko, BESSY

*"A **reproducibility of 10 ^ -3** would be a correct estimate (for quadrupoles, **without too much effort**). The exact number depends on how much you go into saturation, **which cycle you drive and whether you only** operate magnets with one current, or whether you "drive" from time to time.*
By reproducibility I mean field deviation in a magnet from switching on to switching on."

for a steady state machine, which is not ramped, it should be easier.

ALS-U:

Toolkit for simulated commissioning of storage-ring light sources and application to the advanced light source upgrade accumulator

Thorsten Hellert , Philipp Amstutz, Christoph Steier, and Marco Venturini

Lawrence Berkeley National Laboratory

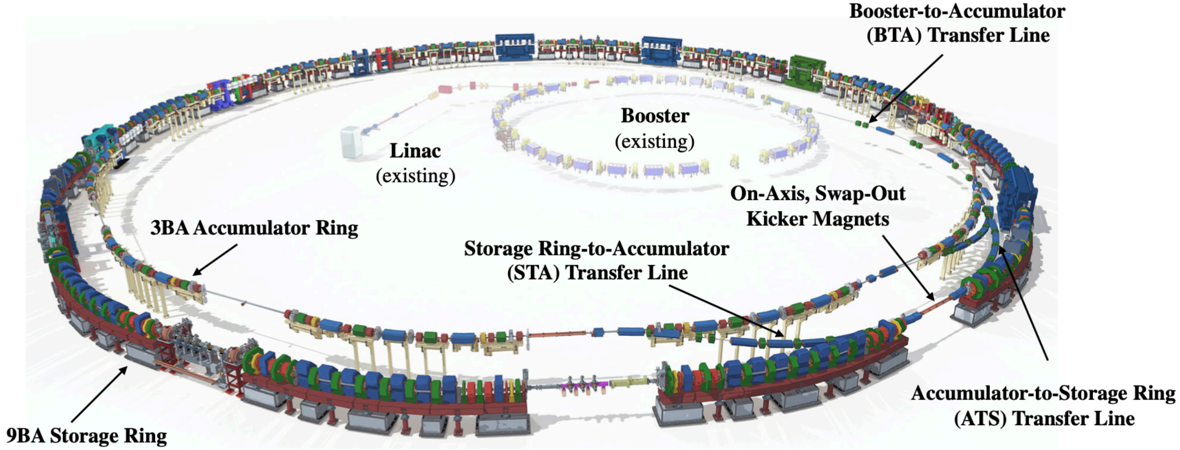


TABLE II. Errors assumed in the commissioning simulations.

Type	Rms	Type	Rms
Section Offset	100 μm	BPM Offset	500 μm
Girder Offset	50 μm	BPM Roll	4 μrad
Magnet Offset	50 μm	BPM Noise (TbT)	10 μm
Magnet Rolls	200 μm	BPM Noise (CO)	1 μm
Girder Rolls	100 μrad	BPM Calibration	5%
CM calibration	5%	rf Voltage	0.5%
Magnet calibration	0.1%	rf Phase	90°
Circumference	0.2 mm	rf Frequency	0.1 kHz

PHYSICAL REVIEW ACCELERATORS AND BEAMS 22, 100702 (2019)

APS-U Commissioning simulations for the Argonne Advanced Photon Source upgrade lattice

TABLE VIII. Brief summary of all correction steps.

Step	Goal	Observables	Actors	Algorithm	Performance
Lattice adjustment before commissioning	Move tunes away from integer resonance and turn off sextupoles	Done offline	Q1-Q2 quad knobs and sextupoles		Design tunes moved to 0.17 and 0.23
Injected beam trajectory correction (without energy)	Reduce injected beam trajectory error in Sector 1	BPM readings in Sector 1	Correctors in BTS and injection kickers	Inverse trajectory response matrix	$x, y = 0.5$ mm rms, $x', y' = 0.1$ mrad
Trajectory threading	Reach half of first turn	BPM readings along the ring	Correctors	Multicorrector threading	
Injection energy correction	Energy correction of injected beam	X bpm readings averaged over half the ring	Booster extraction timing		$\Delta E/E = 10^{-3}$ rms
Trajectory threading	Reach the end of first turn	BPM readings along the ring	Correctors	Multicorrector threading	~1 beam-turns
Equalizing end-of-turn coordinates to injection	To create closed orbit conditions	BPM readings in Sector 1	Correctors in the last sector	Multicorrector threading	~2 beam-turns
Coarse rf setup, repeated after every trajectory correction iteration	Initial setup of rf frequency and phase	X BPM readings averaged over 1 turn	rf settings	Fit of average BPM orbit	
Global trajectory correction	Achieve multiturn transmission	BPM readings on first turn	Correctors	Inverse trajectory response matrix	>10 beam-turns
Betatron tune correction, repeated after every orbit correction iteration	Keep tunes away from integer resonances	Trajectory response to a corrector change	Q1-Q2 quadrupole knobs	Sector-by-sector beam motion analysis using NAFF	0.05 rms tune accuracy
Very coarse orbit correction	Achieve many turns	Turn-by-turn BPM readings	Correctors	Inverse orbit response matrix	>100 beam turns
Sextupole ramp	Reach design sextupole setpoints			Done in 10 steps between orbit correction iterations	
Coarse orbit correction	Achieve thousands of turns	Turn-by-turn BPM readings	Correctors	Inverse orbit response matrix	10 minutes median lifetime
BPM offset measurement	Reduce BPM offset errors to 30 μm			Not simulated, offsets just reduced in simulation	
Orbit correction	Reduce orbit errors as much as possible	Multiturn BPM readings	Correctors	Inverse orbit response matrix	<100 μm rms orbit error, 0.5 hour median lifetime
Coarse lattice correction, repeated every few orbit correction iterations	Lattice correction	Turn-by-turn BPM motion	One quadrupole per sector	Betatron motion amplitude used as proxy for beta functions	~20% rms beta function errors
Beam energy correction	Reduce energy errors introduced by correctors	X BPM average over turn readings	rf frequency		$\Delta E/E = 5 \times 10^{-4}$ rms
Lattice correction	Beta function correction and coupling minimization	Response matrix fit	All quads and skew quads	Orbit response matrix fit	~1% rms beta function errors
Coupling adjustment	Increase emittance ratio to 10%	Beam size monitor	Skew quadrupoles	Excitation of nearby coupling resonance	
Tune adjustment back to design values			Q1-Q2 quad knobs		

PHYSICAL REVIEW ACCELERATORS AND BEAMS

22, 040102 (2019)

gradient errors assumed in simulations:

...ies for various errors used for start-to-end lattice commissioning simulation.

Girder misalignment	100 μm
Elements within girder	30 μm
Dipole fractional strength error	1×10^{-3}
Quadrupole fractional strength error	1×10^{-3}
Dipole tilt	0.4 mrad
Quadrupole tilt	0.4 mrad
Sextupole tilt	0.4 mrad

NSLS II

An estimate of the alignment tolerances for the sextupoles can be made by calculating the reduction of the DA versus random strength error of the lattice quadrupoles (δK1/K1). **This was estimated to be ~5x10-4** for an 80% reduction of the DA [1].

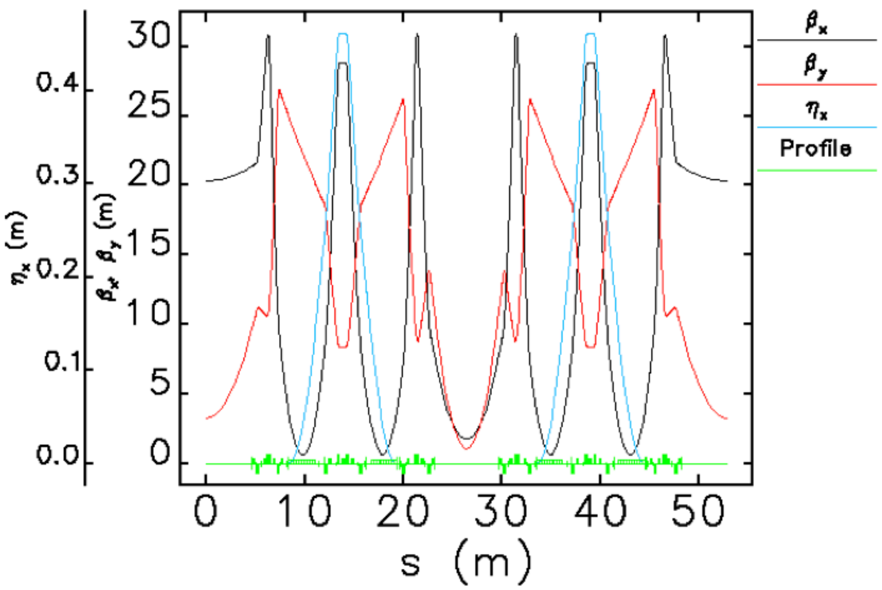


Figure 1: Twiss parameters for one superperiod of the NSLS-II lattice, with 9.3 m and 6.6m (center) ID lengths.

Table II: Alignment Tolerances for NSLS-II

Element	δx, δy [mm]	Roll angle [mrad]
Quadrupoles	0.03, 0.03	0.2
Sextupoles	0.03, 0.03	0.2
Dipoles	0.1, 0.1	0.5
Multipole Girder	0.1, 0.1	0.5
BPM BBA error	0.01, 0.01	0.1

Olaf Dunkel: best regards from a sailing trip on the Atlantik.

Bastian Haerer, FLUTE @ KIT:

The quadrupoles for FLUTE were measured by Danfysik down to 10 ^ -4 (see below).

Danfysik: Webpage for the magnet m,easurement dec90vices on stock:
Model 692
Multipole Magnet Measurement System

DANFYSIK

Specifications

OVERALL	
Relative accuracy of integrated main harmonic	$\pm 3 \cdot 10^{-4}$
Angular phase absolute accuracy	<±0.1 mrad/K
Lateral positioning of magnetic center with respect to rotation axis	±0.03 mm
Positioning accuracy of alignment targets with respect to coil axis	±0.03 mm
Accuracy of ratio between integrated field of a multipole component and the main component at the major coil radius	$\pm 3 \cdot 10^{-4}$ (For R_{coil} >25 mm)

integrated gradient determined on a level of +/- $3*10^{-4}$

Markus Koerfer, Magnet Measurements for PETRA III

*State of the art and achievable routinely without much effort
is $\Delta g/g = 1*10^{-3}$.
Here we talk indeed about the absolute **accuracy of the integrated gradient** along the magnet length.

"*With some effort you can maybe improve the measurement technology to achieve smaller values.*
The length of the laminated iron yokes is typically given by the manufacturing tolerance of 1/10 mm or given a one meter long magnet, 10 ^ -3."

this is not our problem, as we have tapered magnets anyway.

For completnes:
"In PETRA III, the magnets (von Laue Halle) are positioned transversely to each other within 50 µm and the girders to each other (likewise transversely) by 100 micro m."

Markus Koerfer, Magnet Measurements for PETRA IV:

"The requirements for the transverse positioning accuracy of the magnet already lies on the level of the conventional magnet manufacturing tolerances. In my view, this is problematic and will *still be a topic in the project!"*

this is not our problem, as we have tapered magnets anyway.

Tolerances, as assumed for the PETRA IV, in the design report to achieve the required emittances:

	Number of magnets	Δx [mm]	Δy [mm]	Δs [mm]	$\Delta\psi$ [mrad]	Field errors
Dipole	214	0.25	0.25	0.50	0.2	$\Delta B/B = 0.2 \times 10^{-4}$
Quadrupole old octants	281	0.25	0.25	0.5	0.2	$\Delta k/k = 2 \times 10^{-4}$
Quadrupole new octant	98	0.1	0.1	0.5	0.2	$\Delta k/k = 2 \times 10^{-4}$
Sextupole	140	0.25	0.25	0.50	0.2	
Monitors	198	0.2	0.2			

Table 3.2.15: Magnet and monitor alignment errors and magnet field errors.

ESRF UPGRADE PROGRAMME PHASE II (2015 - 2022)

TECHNICAL DESIGN STUDY

“To determine the values of alignment and field integral errors,
a correction sequence is applied, iterating through a closed orbit correction,
a correction of coupling and dispersion, and a correction of the beta- modulation.

The resulting model is evaluated in terms of residual closed orbit, corrector strengths, residual beta-modulation, on- and off-momentum dynamic aperture and emittances

this is exactly our approach ;-)

Error	Tolerance
Quadrupole Δx	50 µm
Quadrupole Δz	50 µm
Quadrupole Δφ	350 µrad
Sextupole Δx	50 µm
Sextupole Δz	75 µm
Dipole Δx	50 µm
Dipole Δz	50 µm
Dipole Δφ	300 µrad
BPM Δx	50 µm
BPM Δz	50 µm
Girder Δx	50 µm
Girder Δz	50 µm
Girder Δφ	200 µrad
Dipole ΔBl/Bl	10^{-3}
Quadrupole ΔGl/Gl	$0.5\ 10^{-3}$
Sextupole ΔHl/Hl	$3.5\ 10^{-3}$

http://www.esrf.eu/Apache_files/Upgrade/ESRF-orange-book.pdf

Table 2.2: Resulting tune shifts observed with Tracy-3 for a 0.05% gradient error in all magnets of a certain quadrupole or dipole (QD) family. The most significant contributions in either plane have been underlined.

Family	$\Delta\nu_x$	$\Delta\nu_y$
QF	<u>0.014</u>	0.014
QFm	0.006	0.006
QFend	0.013	0.010
QDend	0.003	0.012
DIP	0.004	<u>0.030</u>

Analysis of Impact of Gradient Errors on beam dynamics

Dipoles and quadrupoles will be shunted in two stages. A first stage should be performed by the manufacturer as a result of magnetic field measurements. This coarse shunting should assure deviations from design values below 0.2% rms [4].

After the magnets have been installed and machine commissioning has started, LOCO analysis will deliver the necessary results for the second stage of shunting that will be performed on site by the machine group. This shunting should then assure deviations from design approach a level of roughly 0.02% rms [4].

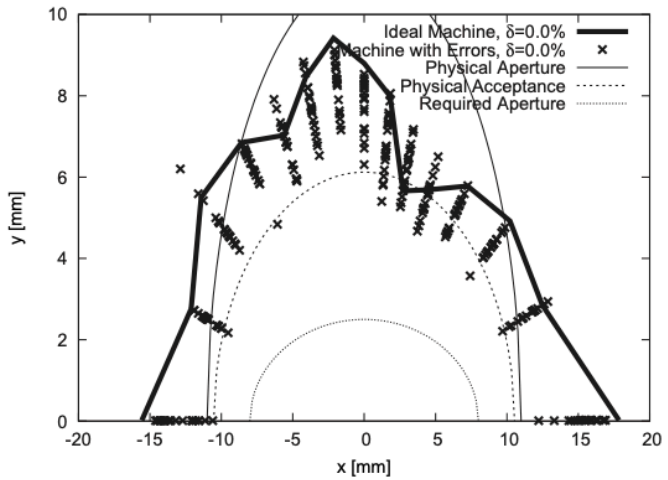


Figure 2.4: Dynamic aperture at the center of the long straight section as calculated by Tracy-3 on and off energy ($\delta = \pm 4.5\%$) for a machine configuration with 4 PMDWs. The solid line shows the dynamic aperture for the ideal machine. The crosses show results for 20 error seeds. For the error seeds a 0.2% rms gradient variation across all dipole, quadrupole, sextupole, and octupole magnets was assumed with a cutoff at 2σ.

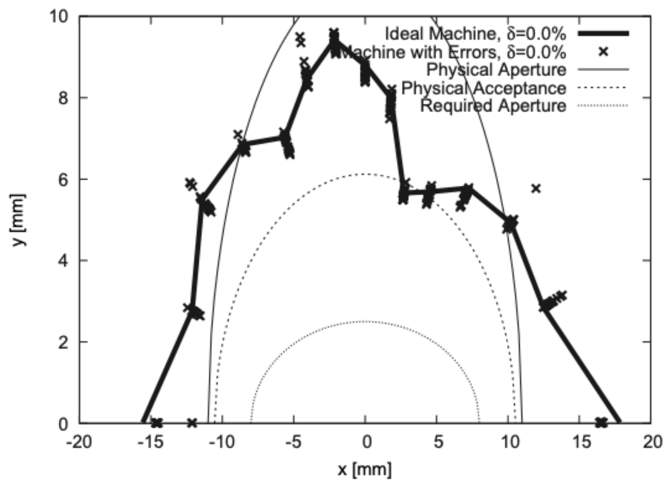


Figure 2.5: Dynamic aperture at the center of the long straight section as calculated by Tracy-3 on and off energy ($\delta = \pm 4.5\%$) for a machine configuration with 4 PMDWs. The solid line shows the dynamic aperture for the ideal machine. The crosses show results for 20 error seeds. For the error seeds a 0.02% rms gradient variation across all dipole, quadrupole, sextupole, and octupole magnets was assumed with a cutoff at 2σ.

And beyond … some useful additional items … PETRA 3:

Temperature
coefficient steel:

$\alpha = 1.18*10^{-5}$ /K , $\alpha L = \frac{dL}{dT}$

TUXRA01 Proceedings of IPAC'10, Kyoto, Japan

Table 2: Orbit Stability Requirements

Stability requirement	**Low β_x cell**	**high β_x cell**
horizontal	3.0 µm	14.0 µm
vertical	0.6 µm	0.6 µm

In order to ensure orbit stability passive and active measures have been taken. In the following some of the passive measures are listed:

- The air temperature in the accelerator tunnel of the new hall has to be stable within 0.1° C and the temperature of the cooling water has be stable within a few tens of a degree.

Daniel Schoerling:

a few additiional aspects

“The colleagues (that mention 1*10^-3 as achievable accuracy for the integrated gradient) certainly are right when it came to the current machines at CERN.
But we can do certainly better with effort …

I think you can measure the integrated gradient pretty well if you calibrate the rotating coil with which you measure,
I think the order of magnitude 10 ^ -5 between the magnets should be relatively easy achievable
(… even more precisely, but then it gets expensive).

Absolute values may be more difficult to achieve with this accuracy. Then you can shim the magnets in length to similar values, i.e. they are all the same length (within a few ~ 10-5).
This applies to the field that was measured and only as long as the current and the temperature of the magnet have not been changed (keyword: hysteresis and expansion).

)…) if you want accuracies in the range of 10-5 -10-4 for all magnets (including each other), I would proceed as follows when building magnets:

-*Purchase of all steel*
- *Mix so that the proportion of steel from different rolls (and depending on the accuracy also the position in the roll) is the same in the different magnets*
- *Measure all magnets individually and trim to length*
-*Gaussian demagnetization cycle of the magnets*
-*Power all magnets exactly according to the same cycle ….*

Furthermore, I would recommend to determine a reference magnet and measure it continuously (keyword: B-train), this will definitely improve the model.
Order of magnitude 10-3 means de-facto 1 mm deviation in length to 1 m, that's ok at a fairly constant temperature; 0.1 mm to 1 m (10-4) is certainly still possible with shimming and the temperature of the machine should be fairly constant (coefficient of expansion iron is at least 10-5 / K at 20 ° C).

Resume

Tolerances in magnet alignment, girder alignment, BPM accuracy
and gradient errors have been studied,

and it can be shown that we can compensate their impact on the beam dynamics.

The resulting emittances (x & y) depend largely on the level of the assumed tolerances.

The misalignment and gradient errors set for the FCC-ee to achieve design parameters are challenging,

However, they are comparable to other state of the art machines (top-light sources).