High
Luminosity
LHC

Update on powering for HL-LHC triplets

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Acknowledgments: R. De Maria, M. Giovannozzi

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Outline

1) Previous studies
2) Proposed powering scheme
3) Comparison with the nominal LHC
4) Alternative powering schemes

Previous studies

Summary of results of previous studies:

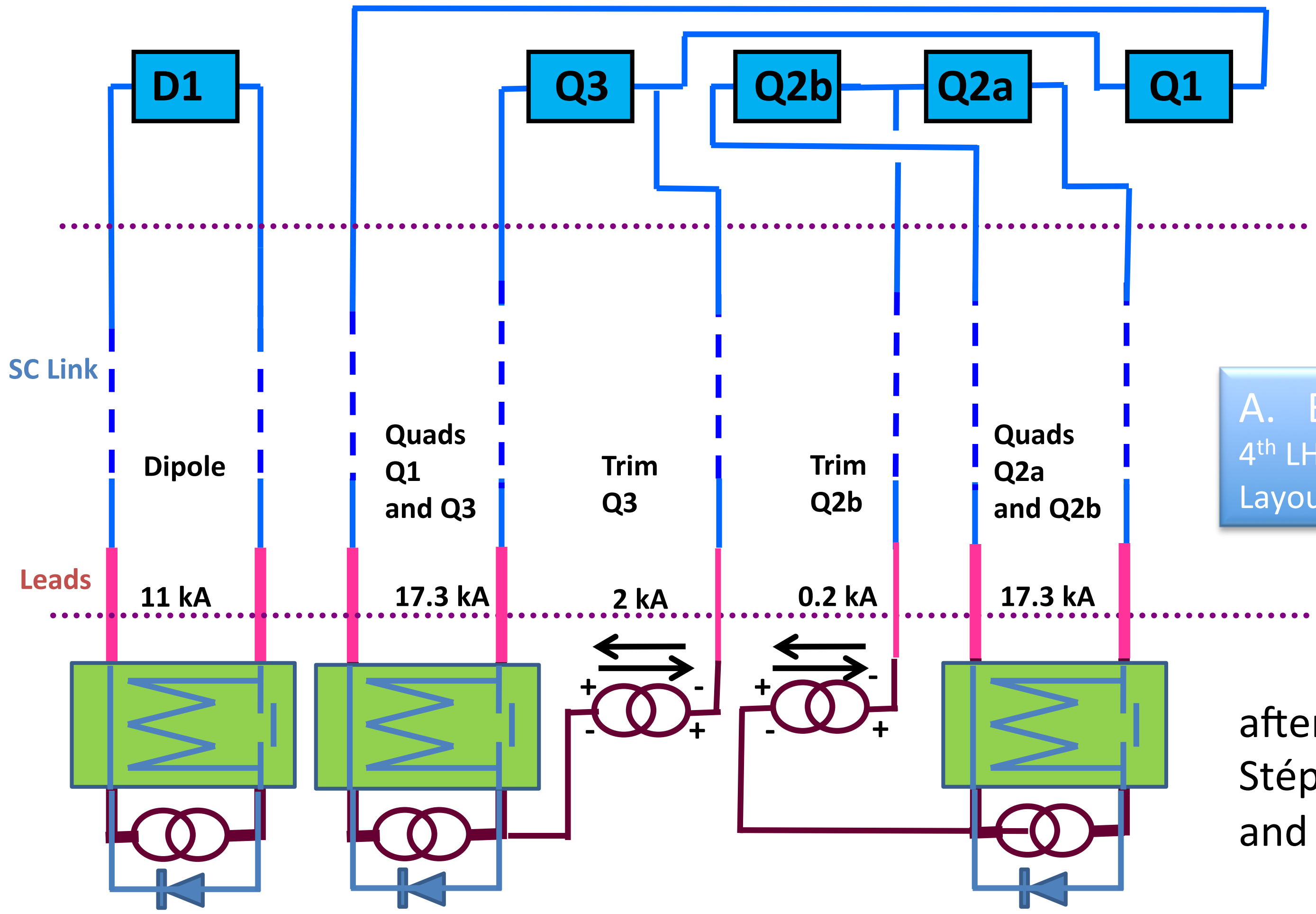
- A ripple on the current/voltage induces a change in tune, beta-beating, orbit, chromaticity ... In general the changes in beta-beating, orbit and chromaticity are negligible, but the induced tune ripple can be non-negligible.
- Experiments at the SPS [1,2] suggest that a tune ripple of 10^{-4} is acceptable while experiences at HERA [3] show that for low frequencies even a tune ripple of 10^{-5} and for high frequencies 10^{-4} can lead to significant particle diffusion.
- Experiment [1,2], theory and tracking studies [4,5] show that several ripple frequencies are much more harmful than a single one.
- Typical ripple frequencies lie between 5-1200 Hz [1,2,3]

[1] X. Altuna et al., CERN SL/91-43 (AP)
[2] W. Fischer, M. Giovannozzi, F. Schmidt, Phys. Rev. E 55, Nr. 3 (1996)
[2] O. S. Brüning, F. Willeke, Phys. Rev. Lett. 76, Nr. 20 (1995)
[3] O. S. Brüning, Part. Acc. 41, pp. 133-151 (1993)
[4] M. Giovannozzi, W. Scandale, E. Todesco, Phys. Rev. E 57, Nr.3 (1998)

⇨ First estimate by calculating the tune ripple induced by a uniformly distributed error on the current, which should stay below 10^{-4}

Proposed powering scheme (1)

Proposed powering scheme HL-LHC (Baseline):



A. Ballarino,
4th LHC Parameter and
Layout Committee

after discussion with
Stéphane, Ezio, Amalia
and Jean-Paul

Proposed powering scheme (2)

Simulation using MAD-X, HLLHCV1.0 optics:

- uniformly distributed (independent) errors on current => gradient error:

```
itok  = kmax/(17.3)
di    = 1e-06
dk1l5    = 2*itok*17.3*di*(ranf()-0.5)
dkt3l5   = 2*itok*2.0*di*(ranf()-0.5);
…
```

kmax=0.599599999902e-02

+/-1 ppm ripple on current

+/-di uniformly distributed error

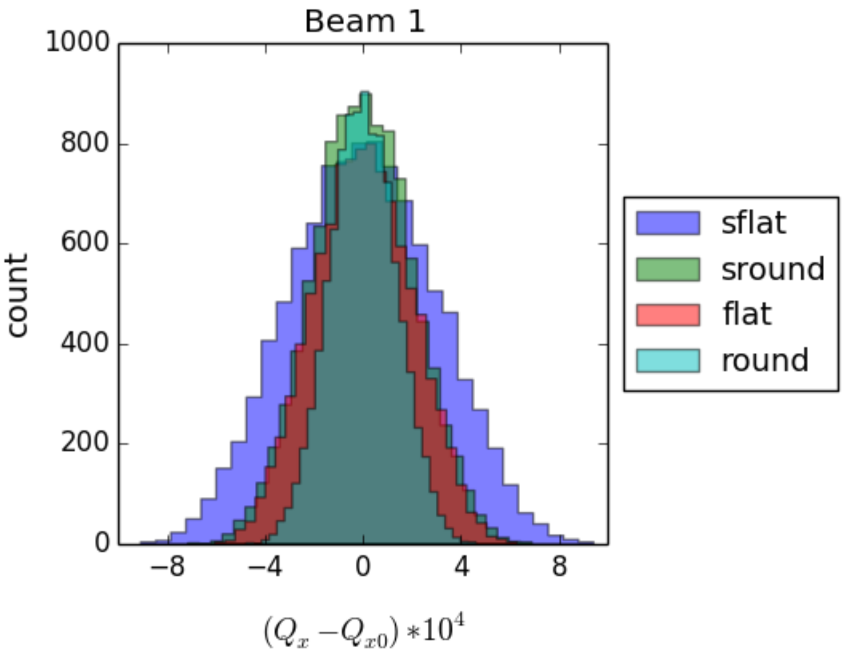
```
kqx1.L5     :=  kqx10.L5     + dk1l5
kqx2a.L5    :=  kqx2a0.L5    + dk2l5 ;
kqx2b.L5    :=  kqx2b0.L5    + dk2l5  + dkt2bl5 ;
kqx3.L5     :=  kqx30.L5     + dk1l5  +  dkt3l5 ;
…
```

powering scheme

- optics: round (β*=15 cm), flat (β*=7.5/30 cm), sround (β*=10 cm), sflat (β*=5.0/20 cm)

Proposed powering scheme (3)

- linear dependence on relative current error (note: $\Delta Q = \frac{1}{4\pi}\oint \beta(s)\Delta k(s)ds$)
- almost no effect from trims for Q3 and Q2b
- dependence on β*: apply +/- 1.0 ppm current ripple



x 1.9
x 1.5
x 1.25
x 1.0

$$\Delta Q = \frac{1}{4\pi}\oint \beta(s)\Delta k(s)ds$$ and

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*} \approx \frac{s^2}{\beta^*}$$ and

$$\Delta Q_{\mathrm{tot}} = \Delta Q_{\mathrm{IR1}} + \Delta Q_{\mathrm{IR5}}$$ and

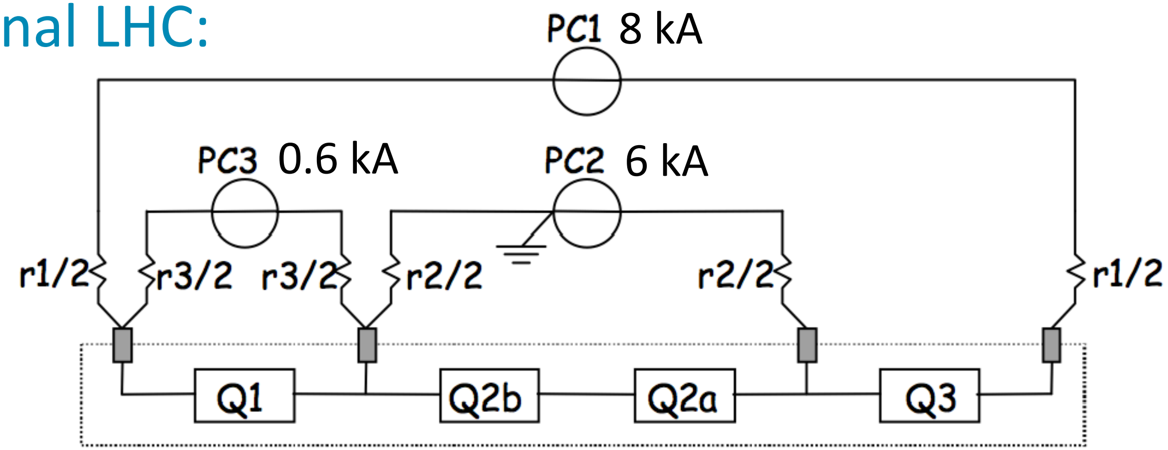
alternate xing + anti-sym. triplet

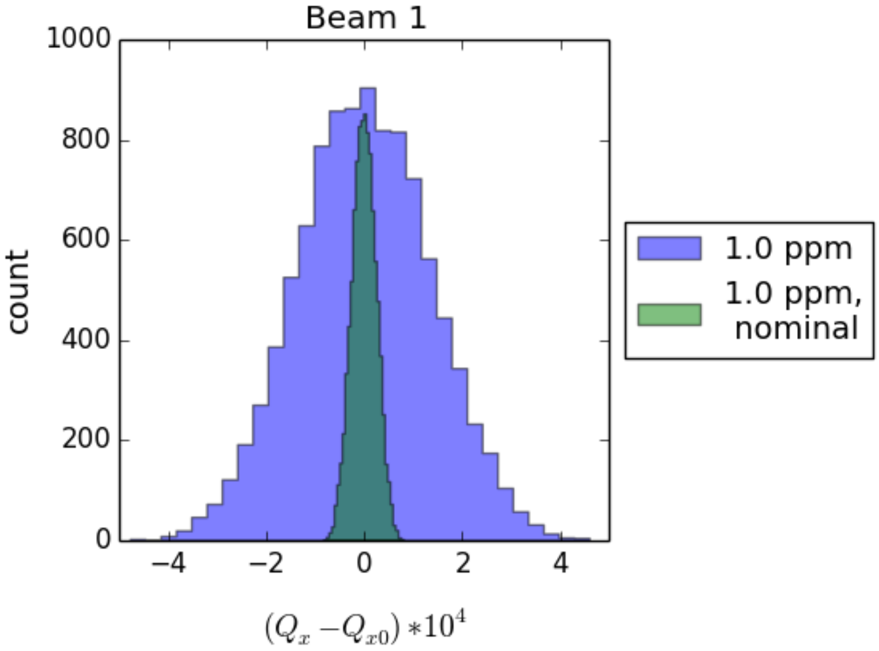
$$\boxed{\Rightarrow \Delta Q_z \sim \left(\frac{1}{\beta^*_{1,z}} + \frac{1}{\beta^*_{2,z}}\right)}$$

similar result for Q_y and beam 2

Comparison LHC and HL-LHC

Powering Scheme nominal LHC:





assuming +/- 1.0 ppm current ripple

⇒ approx. x5 larger tune ripple for HL-LHC (β*=15 cm) than for the nominal LHC (β*=55 cm, V6.5.coll.str)

	rms($(Q_z\text{-}Q_{z0})\text{x}10^4$)
Baseline HL-LHC	1.35
nom. LHC (7 TeV)	0.25

Alternative Powering Schemes (1)

Contributions to tune ripple:

tune shift due to quadrupole error $\Delta Q = \frac{1}{4\pi} \oint \beta(s) \Delta k(s) ds$

assume $\delta k = \Delta k / k = \mathrm{const} \cdot \Delta I / I = \mathrm{const} \cdot \delta I$

thus for a given δI the max. tune shift is then (approx.) given by

$\Delta Q_z = \frac{1}{4\pi} \int \beta_z(s) \cdot \mathrm{const} \cdot \delta I \cdot k(s) ds = \frac{1}{4\pi} \cdot \mathrm{const} \cdot \delta I \cdot I_z$ with $I_z := \int \beta_z(s) k(s) ds$

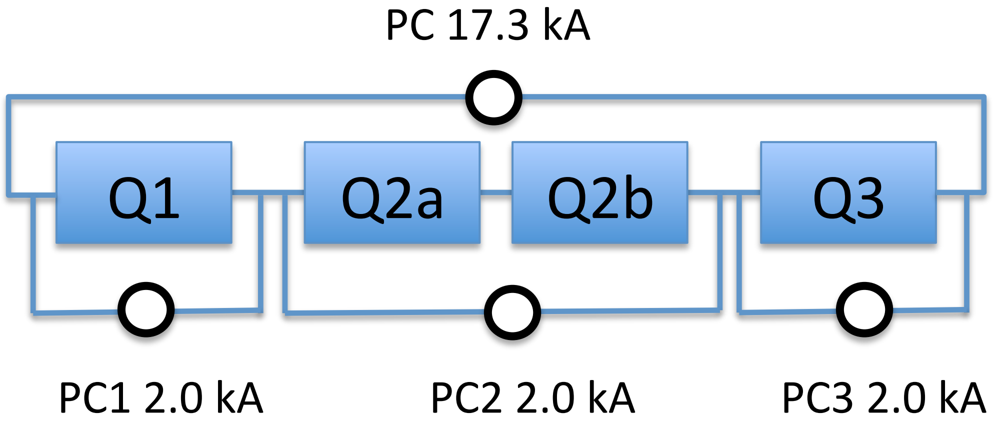
Beam 1	HLLHCV1.0 (β*=0.15 m)	V6.5, V6.5.coll (β*=0.55 m, 7 TeV)	(V6.5, V6.5.coll)*7/4*55/60 (β*=0.6 m, 4 TeV)
Ix1L1	-274.14	-78.21	-125.46
Ix3L1	-452.98	-122.48	-196.48
Ix2aL1	723.22	184.03	295.21
Ix2bL1	792.92	201.09	322.58
Ix1R1	208.04	61.89	99.28
Ix3R1	905.56	201.39	323.06
Ix2aR1	-182.81	-50.37	-80.80
Ix2bR1	-306.29	-74.92	-120.18

High Luminosity LHC

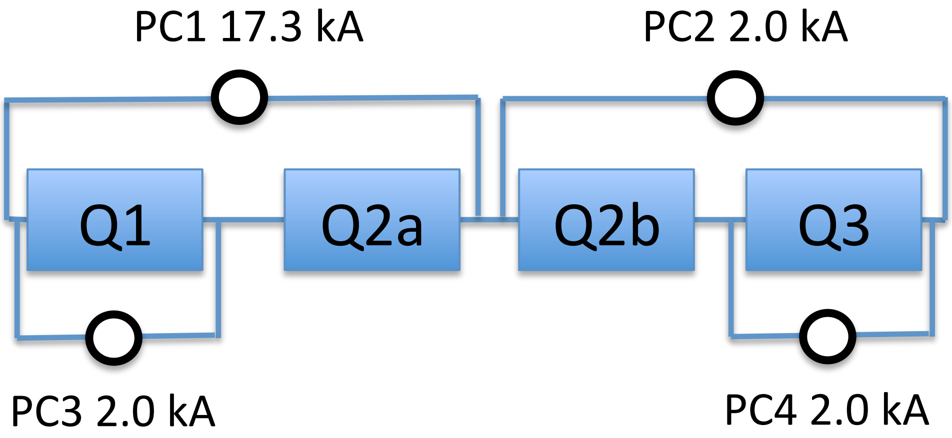
Alternative Powering Schemes (2)

All in series (Q1-Q2-Q3):

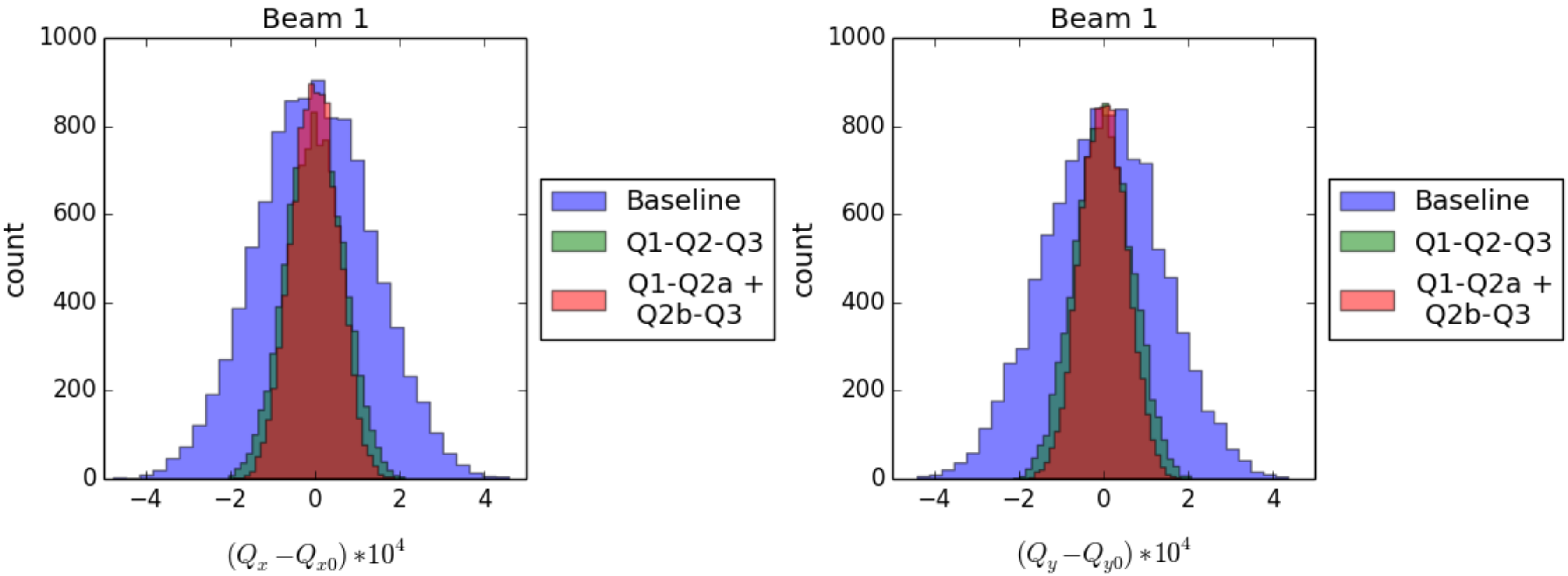
rejected for magnet protection
(see A. Ballarino, 4th PLC)



Partial Compensation (Q1-Q2a and Q2b-Q3):



Alternative Powering Schemes (3)



approx. x2 to x2.5 reduction of tune ripple with alternative powering scheme, but eventually less optics reachability towards high β*

	$\mathrm{rms}((Q_z\text{-}Q_{z0})\mathrm{x}10^4)$
Baseline	1.35
Q1-Q2-Q3	0.67
Q1-Q2a + Q2b+Q3	0.54

Alternative Powering Schemes (4)

	Ix IR1	Iy IR1	Ix IR5	Iy IR5
nominal LHC, 7 TeV, 0.55 m (4 TeV, 0.6 m)				
Beam 1	353.28 (566.72)	353.28 (566.72)	353.28 (566.72)	353.28 (566.72)
Beam 2	353.28 (566.72)	353.28 (566.72)	353.28 (566.72)	353.28 (566.72)
Baseline				
Beam 1	2075.26	2075.26	2093.17	2093.17
Beam 2	2071.11	2071.11	2095.62	2095.62
Q1-Q2-Q3				
Beam 1	1006.25	1006.25	1014.93	1014.93
Beam 2	1004.24	1004.24	1016.12	1016.12
Q1-Q2a and Q2b-Q3				
Beam 1	822.79	822.79	829.89	829.89
Beam 2	821.15	821.15	830.86	830.86

x2.0 reduction

x2.5 reduction

nominal LHC: $I=Sqrt[(I_{Q1L}+I_{Q3L}+8/(6+8)*(I_{Q2aL}+I_{Q2bL}))^2+ (6/(6+8)*(I_{Q2aL}+I_{Q2bL}))^2+$
$[(I_{Q1R}+I_{Q3R}+8/(6+8)*(I_{Q2aR}+I_{Q2bR}))^2+ (6/(6+8)*(I_{Q2aR}+I_{Q2bR}))^2]$

Baseline: $I=Sqrt[(I_{Q1L}+I_{Q3L})^2+(I_{Q2aL}+I_{Q2bL})^2+[(I_{Q1R}+I_{Q3R})^2+(I_{Q2aR}+I_{Q2bR})^2]$

Q1-Q2-Q3: $I=Sqrt[(I_{Q1L}+I_{Q2aL}+I_{Q2bL}+I_{Q3L})^2+(I_{Q1R}+I_{Q2aR}+I_{Q2bR}+I_{Q3R})^2]$

Q1-Q2a and Q2b-Q3: $I=Sqrt[(I_{Q1L}+I_{Q2aL})^2+(I_{Q2bL}+I_{Q3L})^2+[(I_{Q1R}+I_{Q2aR})^2+(I_{Q2bL}+I_{Q3R})^2]$

Conclusions

- uniformly distributed relative current error of +/-1.0 ppm leads to a tune ripple of 4.0-8.0x10^{-4} depending on the optics
- linear scaling with relative error and scaling with beta function according to $(1/\beta_1^*+1/\beta_2^*)$
- x5 larger tune ripple compared to the nominal LHC
- x2 reduction of tune ripple with alternative powering scheme

Open questions and next steps

- Acceptable tune ripple?

  ⇒ DA studies (sixtrack)

- Model of power converter ripple (from PC experts)?
  - Does the current ripple scale with the max. current?
  - Conversion of voltage ripple (measurable) into ripple on norm. quad. strength?
  - Frequency spectrum of ripple?
  - …

  ⇒ update model of power converter ripple in sixtrack

- If tolerances on ripple turn out to be too tight, possible compensation like in HERA?

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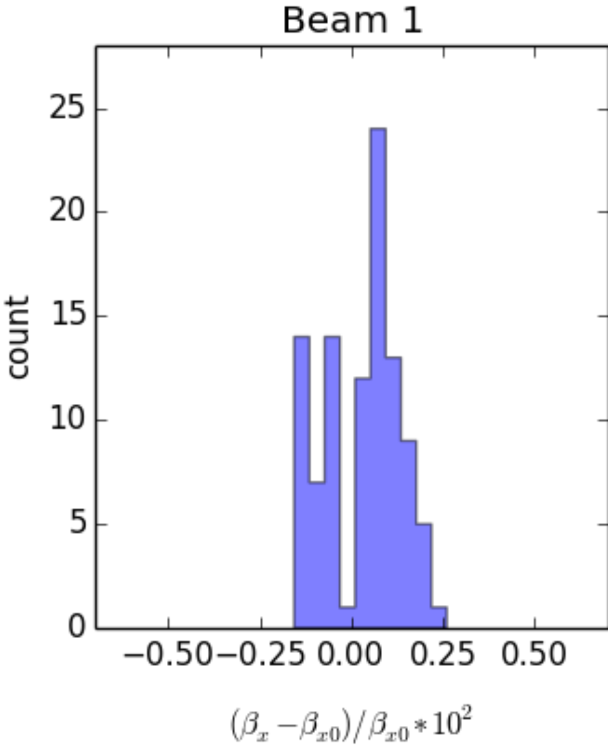
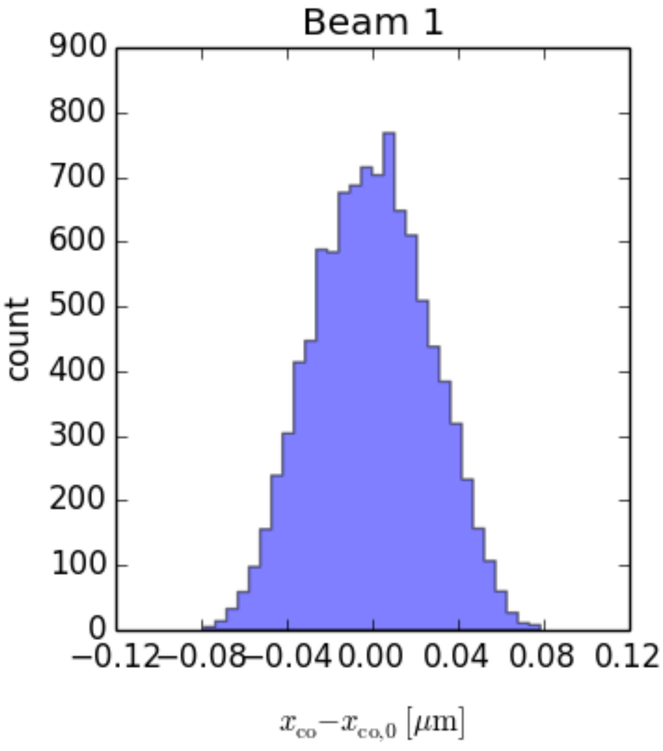
Effect on other optics paramters

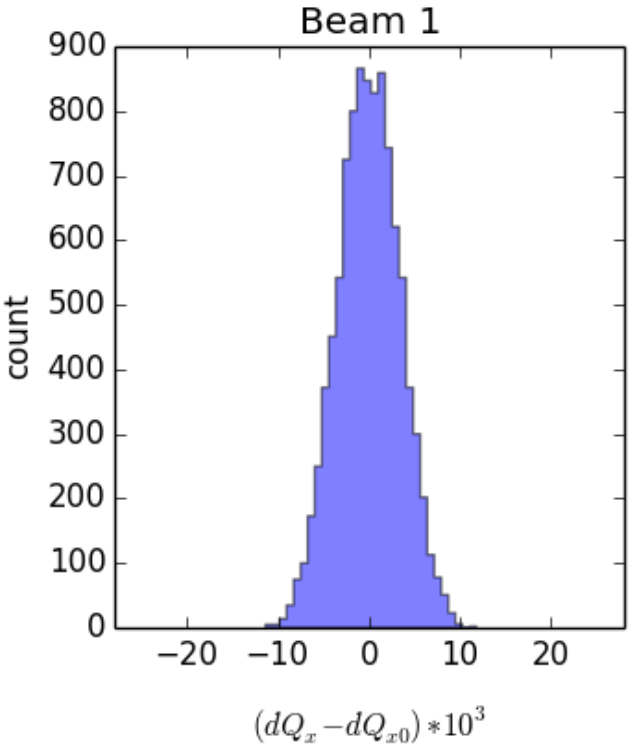
Effect on beta-beating, orbit and chromaticity for round optics (15 cm β*) and +/-1.0 ppm ripple on current :



max. beta-beating (complete ring)



closed orbit IP5, beam 1



chromaticity

Contributions to tune ripple (1)

	HLLHCV1.0 (β*=0.15 m)		V6.5, V6.5.coll (β*=0.55 m)	
Beam 1	x	y	x	y
I1L1	-274.14	208.66	-78.21	61.89
I3L1	-452.98	908.24	-122.48	201.39
I2aL1	723.22	-183.36	184.03	-50.37
I2bL1	792.92	-307.2	201.09	-74.92
I1R1	208.04	-274.95	61.89	-78.21
I3R1	905.56	-454.31	201.39	-122.48
I2aR1	-182.81	725.34	-50.37	184.03
I2bR1	-306.29	795.25	-74.92	201.09
I1L5	-276.51	209.54	-78.21	61.89
I3L5	-456.89	912.05	-122.48	201.39
I2aL5	729.45	-184.13	184.03	-50.37
I2bL5	799.76	-308.49	201.09	-74.92
I1R5	209.84	-276.1	61.89	-78.21
I3R5	913.38	-456.22	201.39	-122.48
I2aR5	-184.39	728.39	-50.37	184.03
I2bR5	-308.94	798.59	-74.92	201.09

	HLLHCV1.0 (β*=0.15 m)		V6.5, V6.5.coll (β*=0.55 m)	
Beam 2	x	y	x	y
I1L1	207.64	-274.53	61.89	-78.21
I3L1	903.78	-453.63	201.39	-122.48
I2aL1	-182.46	724.24	-50.37	184.03
I2bL1	-305.69	794.04	-74.92	201.09
I1R1	-273.59	208.36	-78.21	61.89
I3R1	-452.07	906.88	-122.48	201.39
I2aR1	721.75	-183.09	184.03	-50.37
I2bR1	791.32	-306.74	201.09	-74.92
I1L5	210.1	-275.75	61.89	-78.21
I3L5	914.47	-455.64	201.39	-122.48
I2aL5	-184.62	727.45	-50.37	184.03
I2bL5	-309.31	797.57	-74.92	201.09
I1R5	-276.82	209.28	-78.21	61.89
I3R5	-457.42	910.92	-122.48	201.39
I2aR5	730.29	-183.9	184.03	-50.37
I2bR5	800.68	-308.11	201.09	-74.92