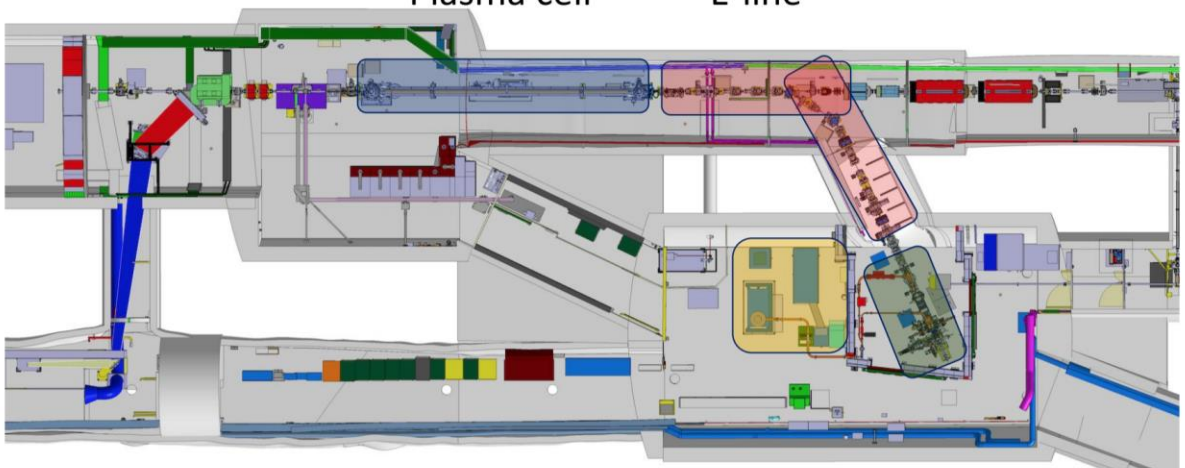
AWAKE Run 2C
Experiment Requirements => HW Specs

F.M. Velotti, R. Ramjiawan

Quick introduction

- For AWAKE Run 2c, the main goal is to achieve high gradient plasma WF acceleration AND preserve the accelerated beam quality
- The plan to achieve that is (very roughly) to add an additional plasma cell (2), upgrade the existing proton line, refactor the existing electron line and to design and build a new high energy electron line
  - => **1 p+ line 400 GeV** from SPS, **1 e- line ~18 MeV** to stabilise accelerating structure, **1 e- line 150 MeV** to produce the witness bunch

Run 1 elements



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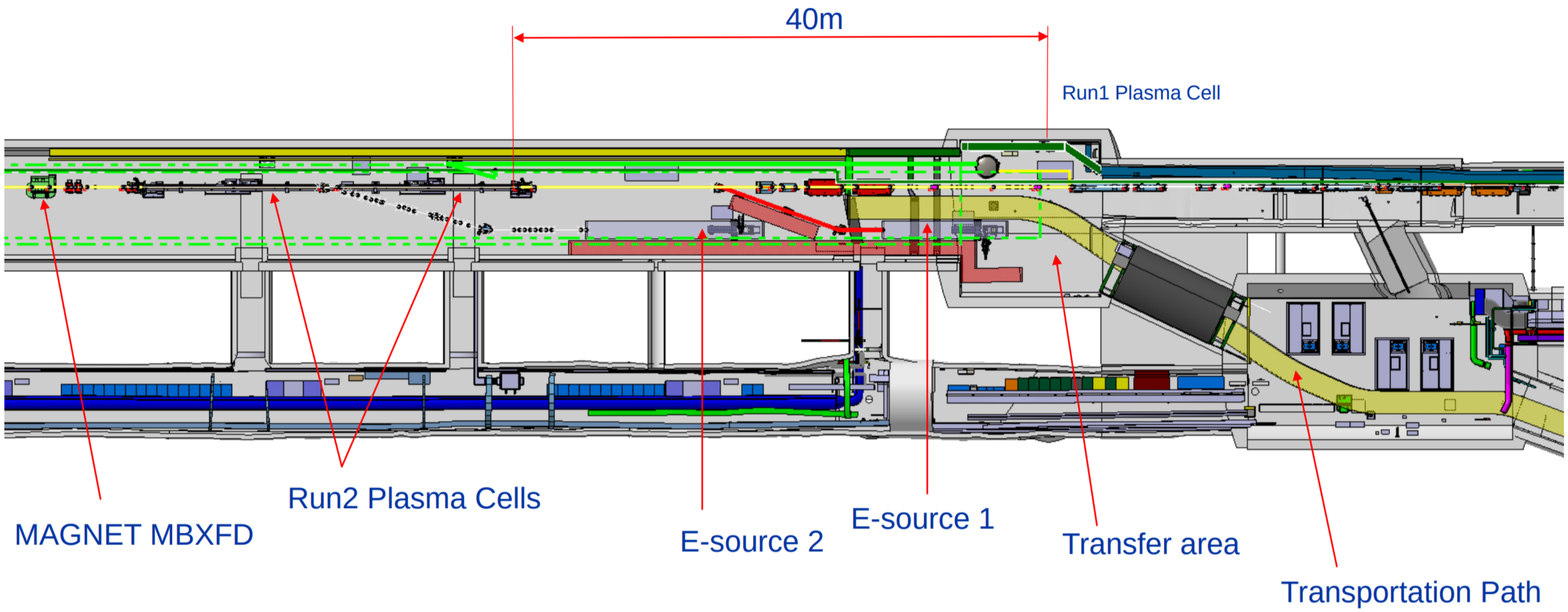

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- All this leads though to very tight specifications for the 150 MeV electron line...

At injection point

Parameter	Nominal value
Dispersion	0
$\sigma_{x,y}$	5.75 µm
Bunch length	200 fs/60 µm
Electron energy	150 MeV
$\epsilon_{x,y}$	<2 mm mrad
Mom. spread	<0.2%
Charge	100 pC

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- All this leads though to very tight specifications for the 150 MeV electron line...
- ...and even more challenging for the proton line
- The main challenge, though, seems to be in the stability - for both beam size (e-) and trajectory (both e- and p+)

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Beamline design

- $\sigma^*[\mu\text{m}] = \sqrt{4.87[\text{mm}] \times \epsilon[\text{nm}]}$ at injection.
- Achromatic and no bunch lengthening.
- Gaussian beam at injection point.
- α = 0 at injection point.
- Spatial constraints from 1 m plasma cell gap.
- Relative alignment between proton and electron beams of <13 um
- Width < 3 m.

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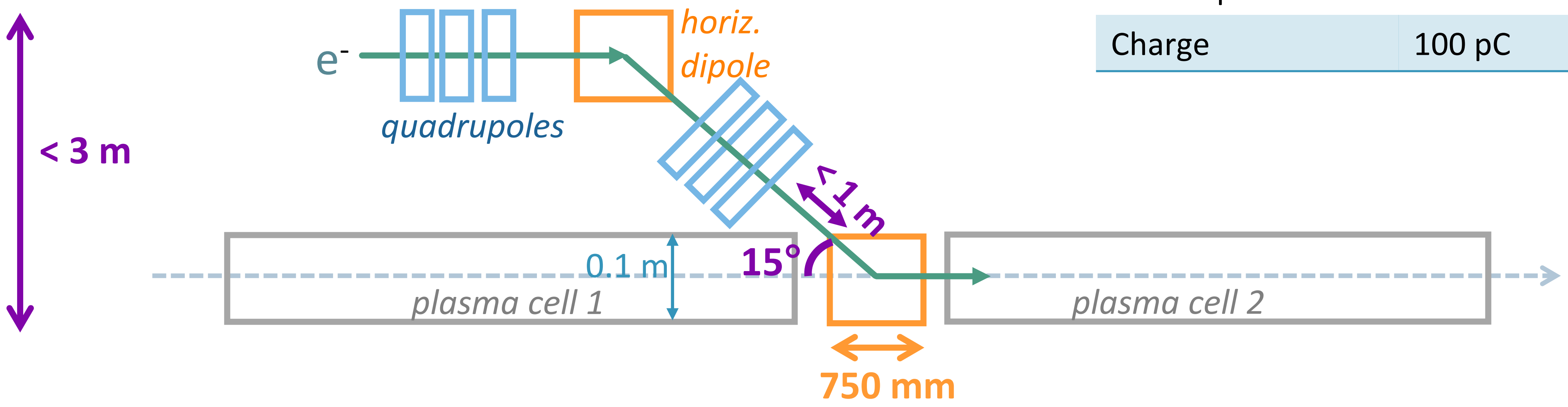

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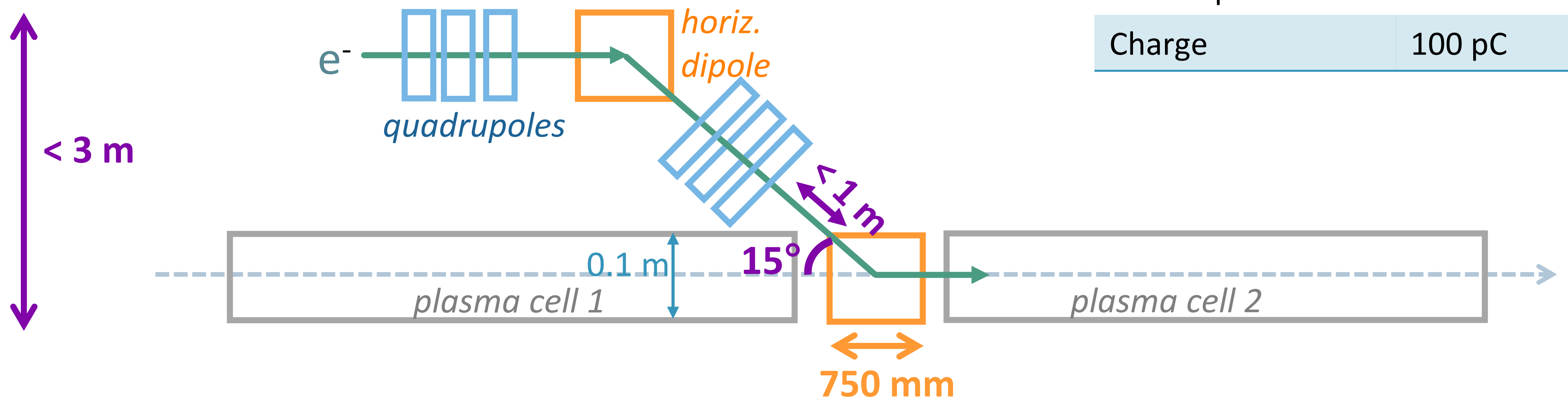

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Required parameters achieved in the <u>ideal</u> case

Still quite far when considering real elements!

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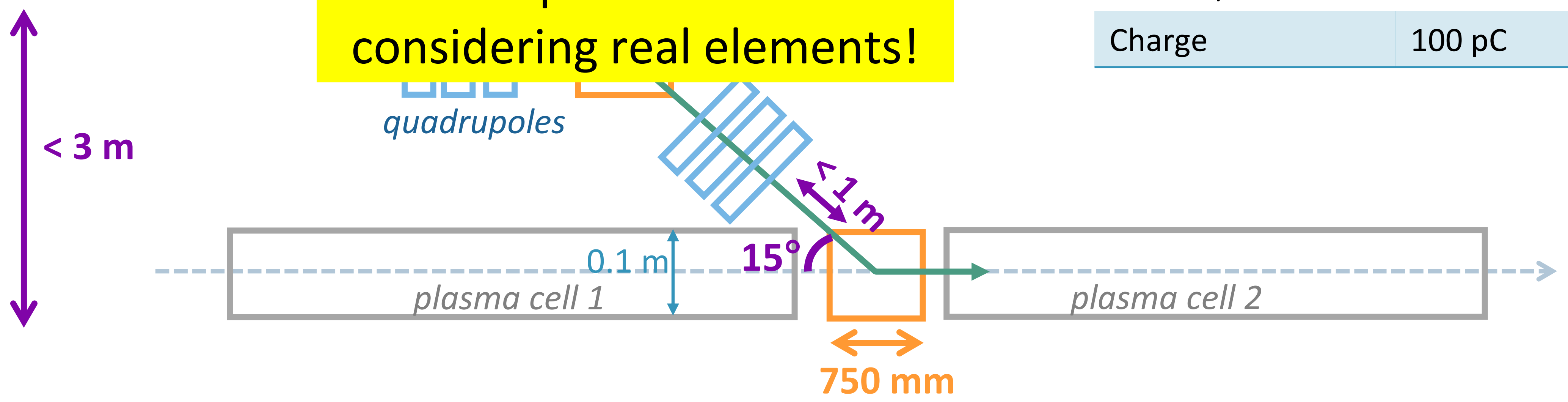


Relative alignment requirements

- Requirement calculated by M. Weidl of relative alignment between p^+ and e^- beams of **$<$ 13 µm at the injection point.**

M. Weidl, *https://edms.cern.ch/document/2427196/0.1*

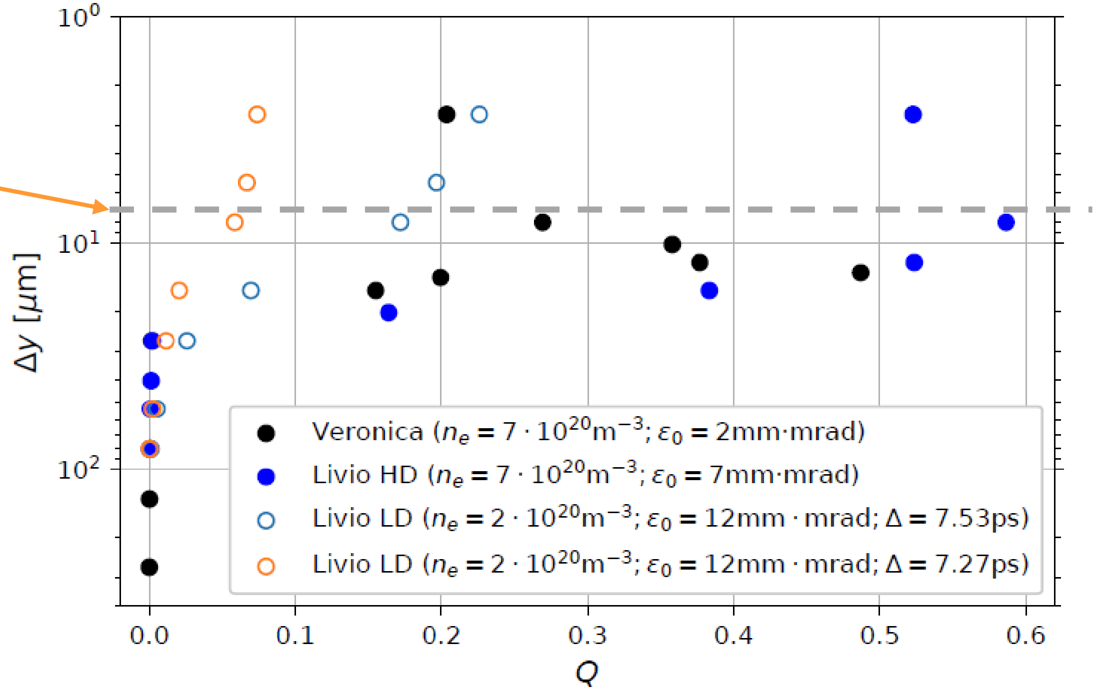
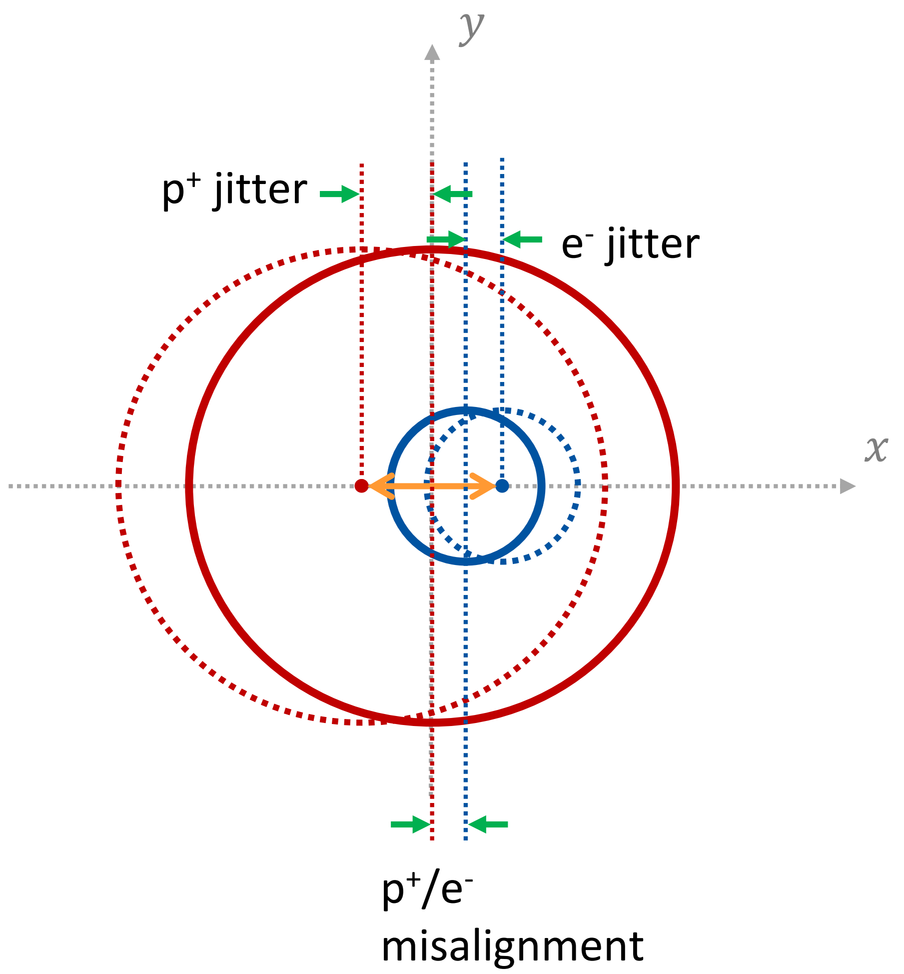


Figure 1: Dependence of the beam goodness metric Q (high is good) on the initial transverse offset Δy for four different beam parameters at the end of the ten-metre accelerating stage (qv3d simulations)

Relative alignment requirements

The 13 μm budget for the relative alignment of the beams must include misalignments and jitters for both beams.



Offset between p^+ and e^- beams including misalignment and jitters of both beams.

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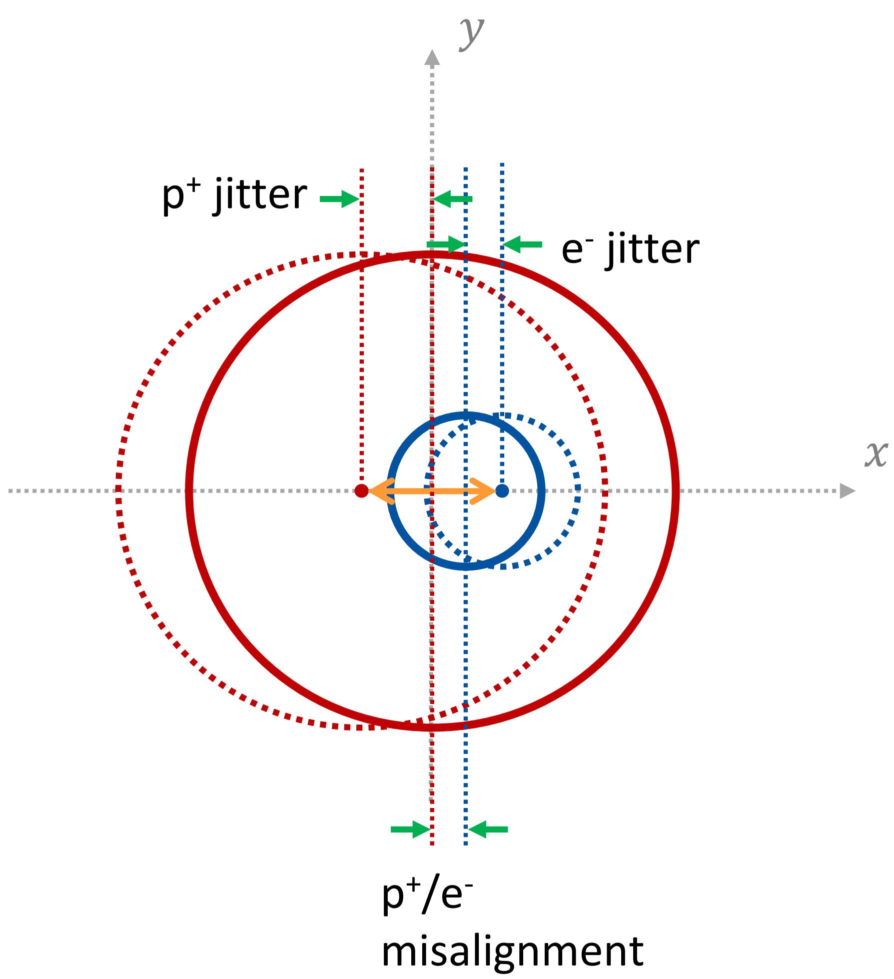
=> this basically means that the rms jitter per beam should be in the order of 2 um!!!



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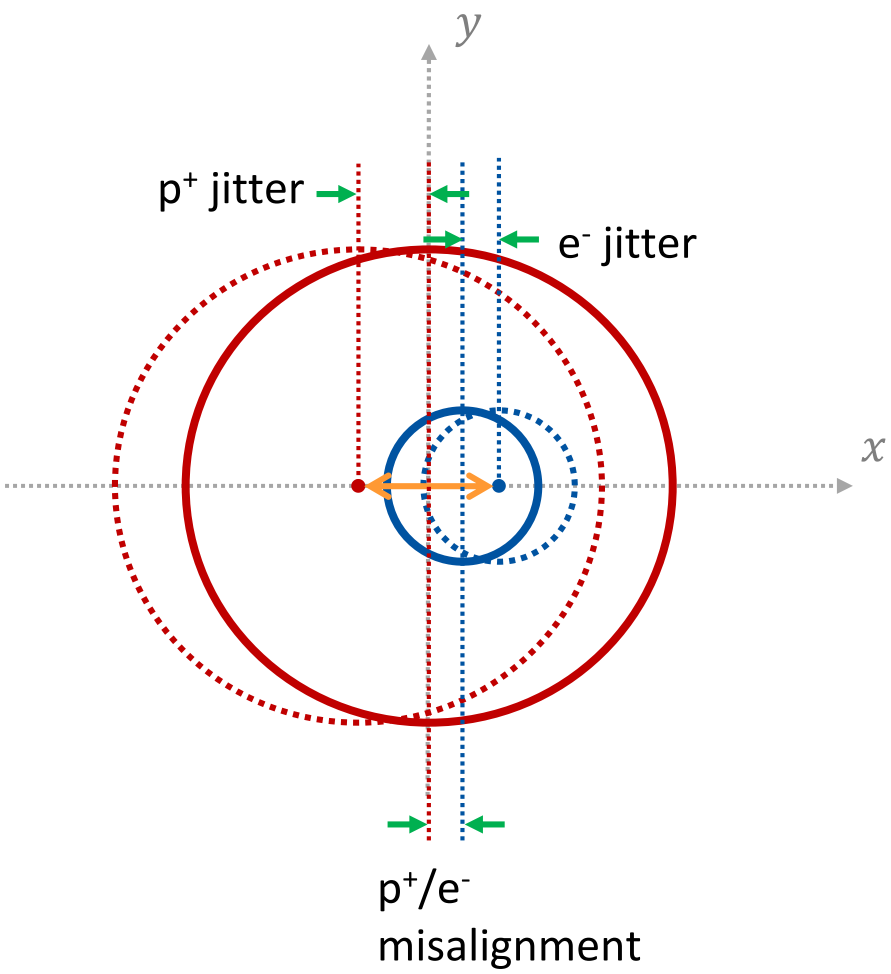
On top we should then add the resolution of the BTV to measure position of both beams!



Offset between p^+ and e^- beams including misalignment and jitters of both beams.

Witness beam size requirements

To preserve emittance of witness beam, the "matched" beam size is given by:

$$\sigma_{x,\mathrm{matched}} = \left(\frac{2c^2 {\epsilon^*_{x,0}}^2}{\gamma \omega_p^2} \right)^{1/4}$$

With AWAKE experimental parameters…

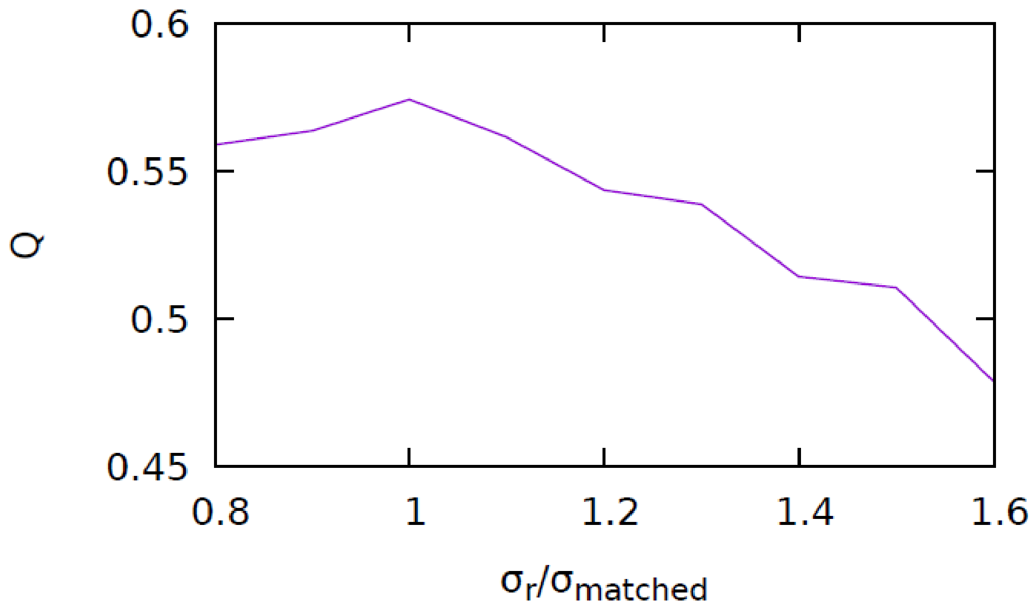
$$\sigma_{\mathrm{matched}} = \sqrt{4.8 \text{ mm} \times \epsilon}$$

With nominal emittance 2 mm mrad…

$$\sigma_{\mathrm{matched}} = 5.75 \text{ µm}$$

From plot (right), should try to keep beam size within **20%** of matched value $< \mathbf{6.9\ \mu m}$.

J. Farmer (Awake Run 2 meeting - August 27, 2020)



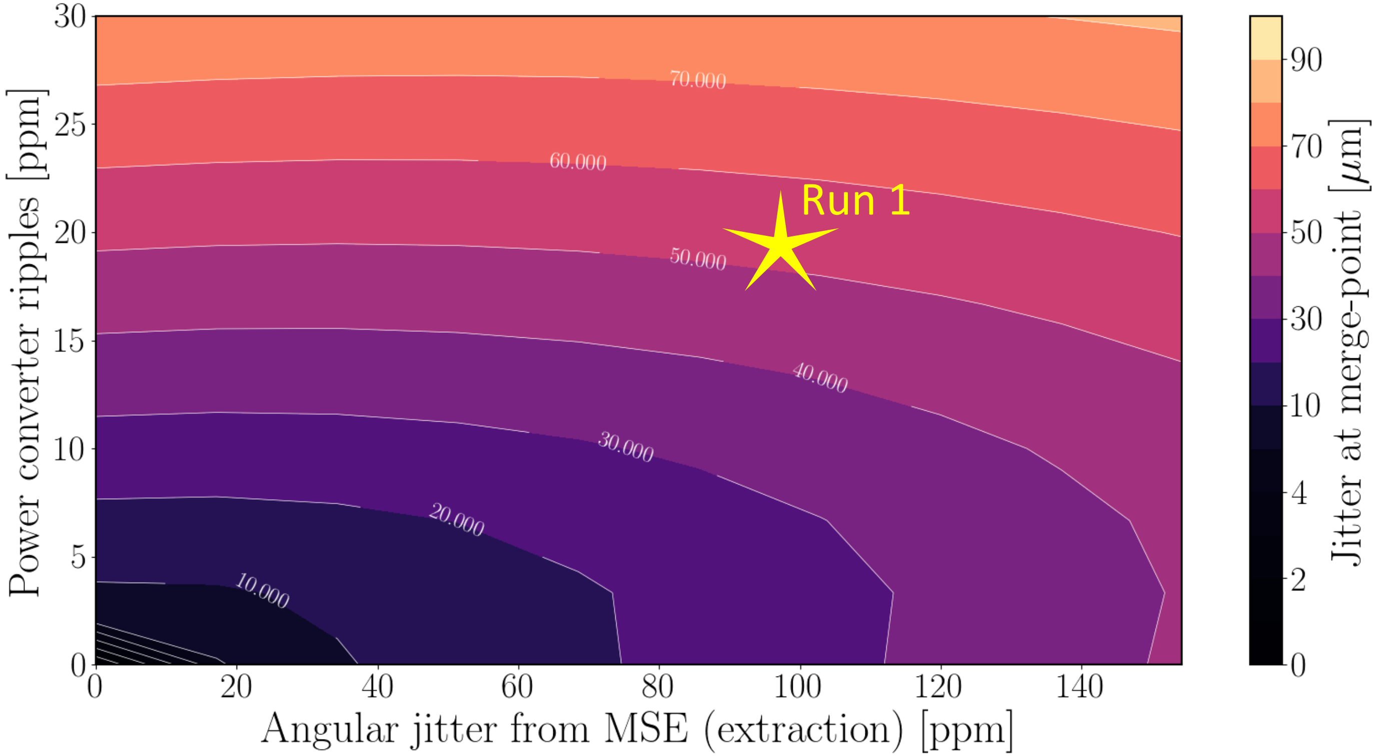
- Q: acceleration quality
- $\frac{\sigma_r}{\sigma_{matched}}$: ratio of beam size to matched beam size

How this translates in HW requirements?

Proton beam: shot to shot jitter

- From data, rms MSE jitter ~100 ppm and average of other converters in TT40/41 ~20 ppm (in agreement with L. Drosdal studies too)

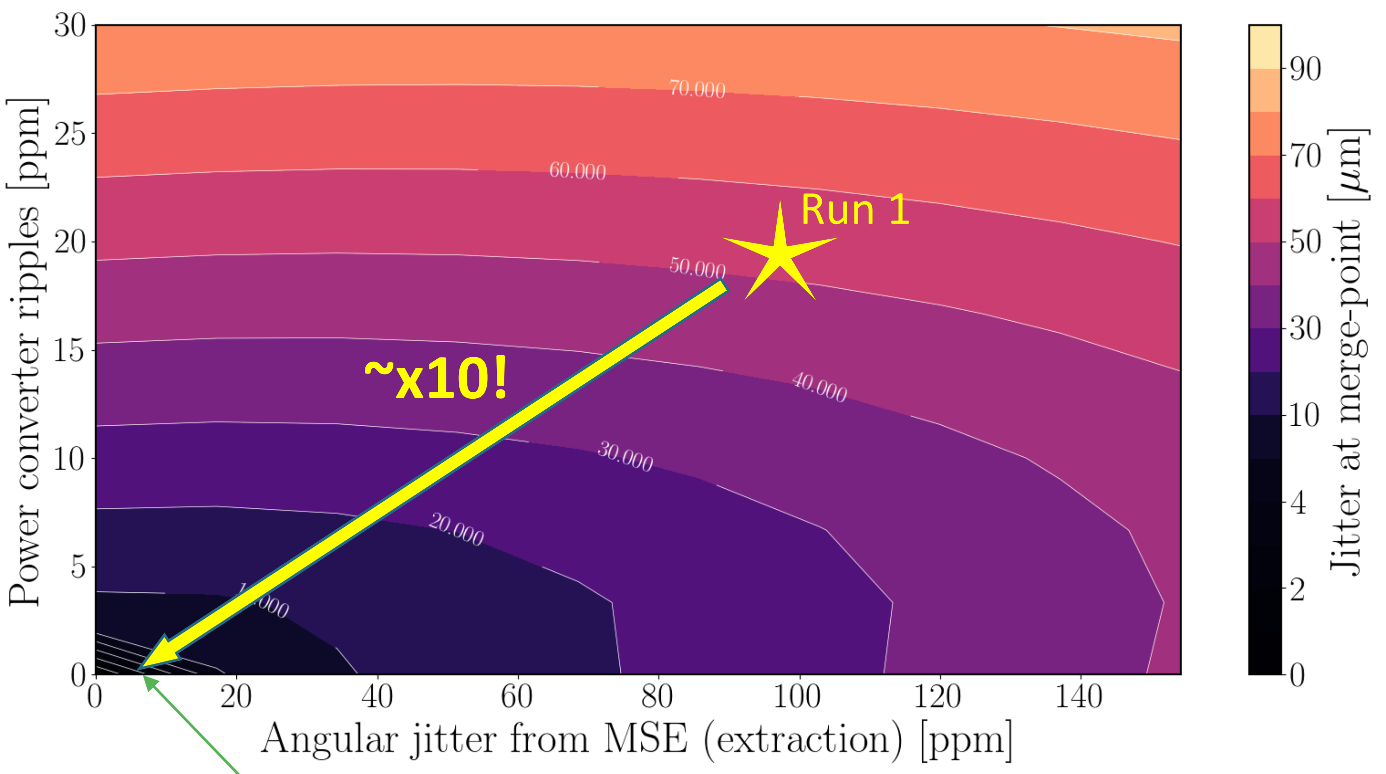
Simulated proton beam position jitter at injection point



Proton beam: shot to shot jitter

- From data, rms MSE jitter ~100 ppm and average of other converters in TT40/41 ~20 ppm (in agreement with L. Drosdal studies too)
- We can look at the **expected (simulations) jitter at the injection point for ripples on all PCs and MSE**
- All values given are r.m.s values.
- **This is an optimistic case**, as it is only considering angular not position jitter.

Simulated proton beam position jitter at injection point

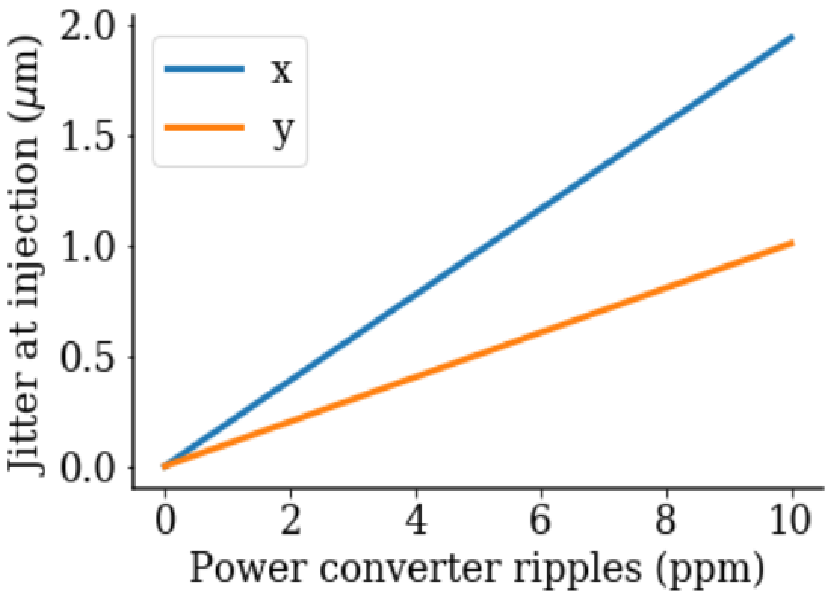


2 μm r.m.s proton jitter

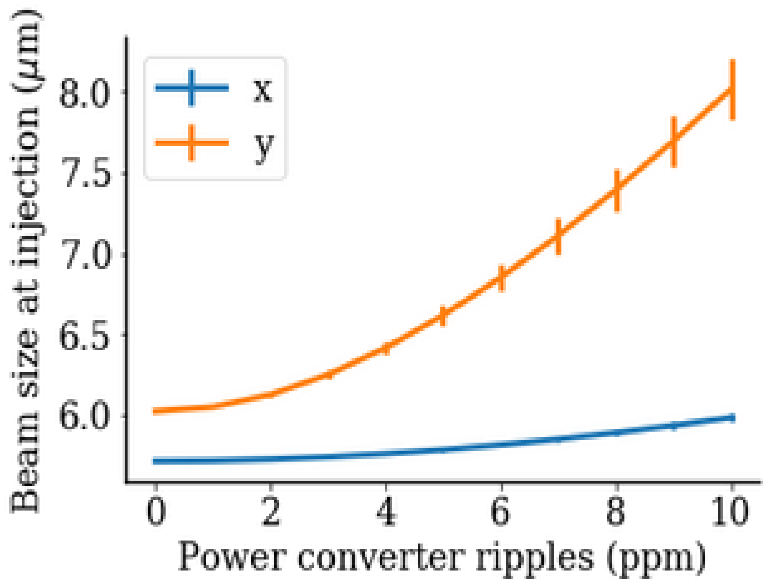
Electron line shot to shot variations

- Study effect of power converter ripples on beam stability and beam size at injection point.
- For jitter study, 10 um r.m.s misalignments of all magnets first.
- 50 seeds at for each misalignment, 10 different seeds of misalignment.

Position shot to shot jitter



Beam size shot to shot jitter



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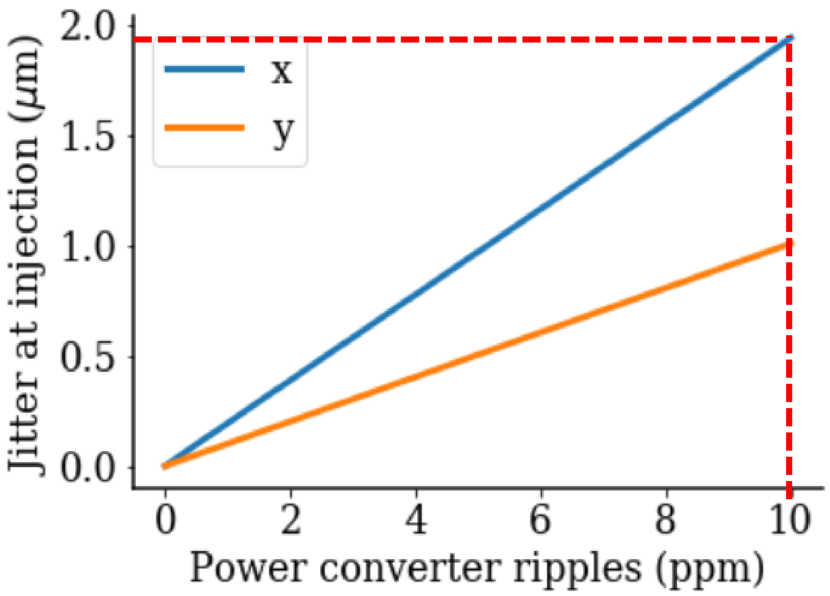

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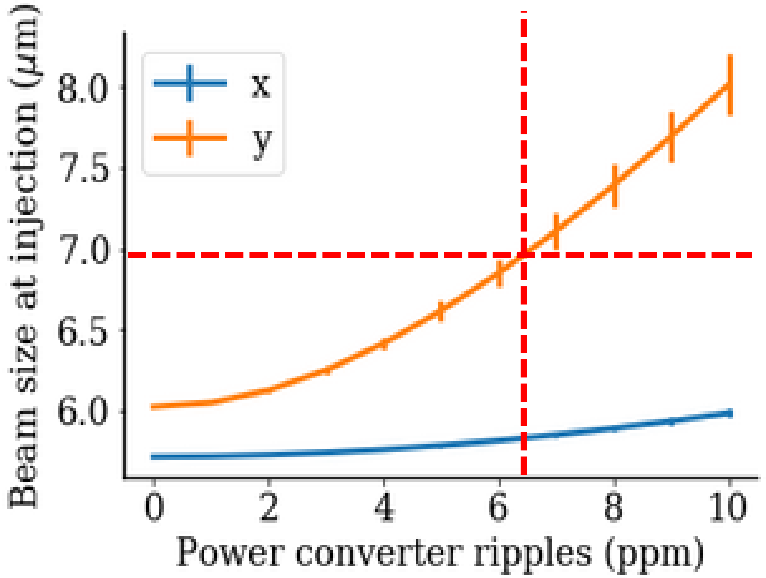
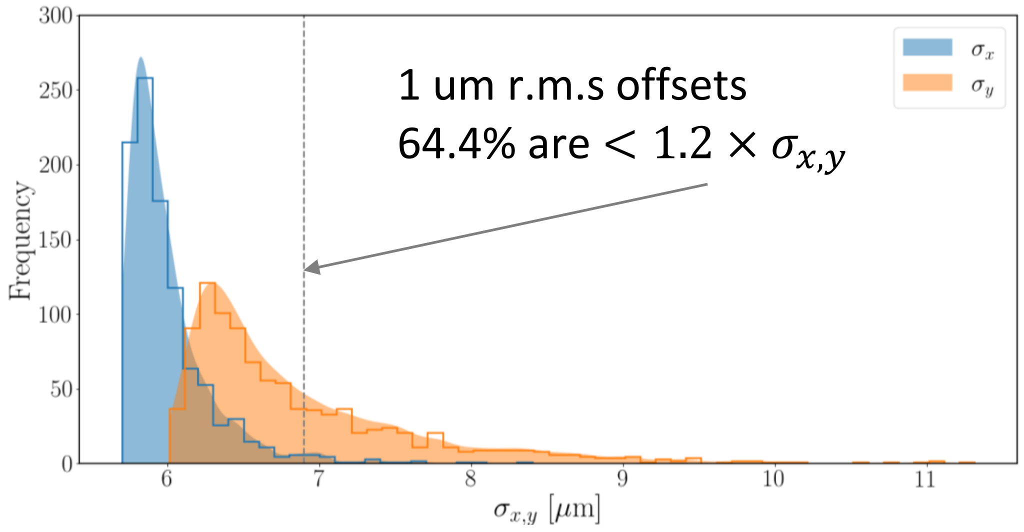
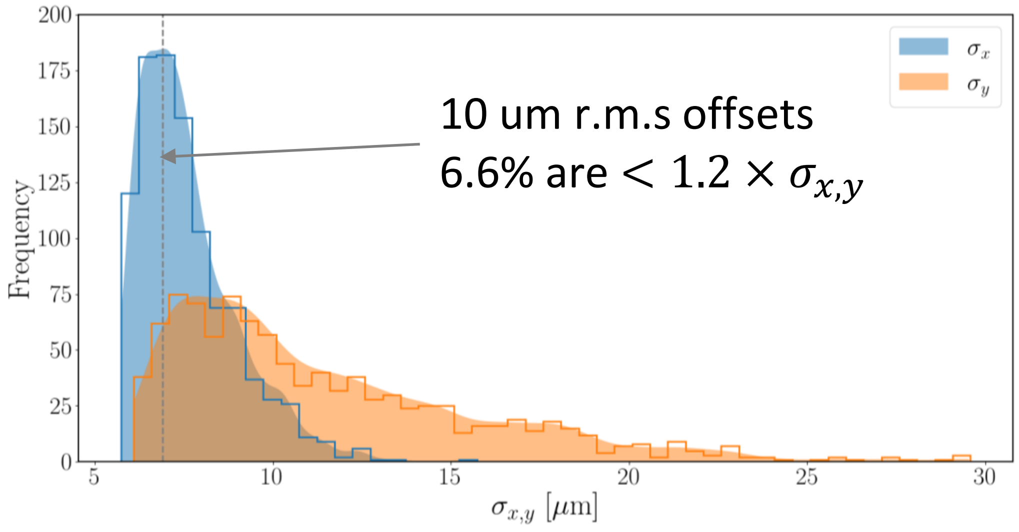


Instrumentation requirements

- The more precisely we can align the quadrupoles, the more shots will satisfy experimental beam size requirements.
- Tried to find alignment methods which use measurements of *relative* offsets at BPMs, to reduce requirements for quad-BPM alignments. Will use **quadrupole movers for alignment** – need to be able to resolve small changes in their position.
- **BPM resolution requirements – better than 1 μm (see plots).**
- **BPM accuracy requirements depend on the BTV accuracy achievable for p^+ and e^- measurements**.First estimation seems to suggest accuracy better than 5 μm for the BPMs in the dogleg needed.



To achieve this level of alignment we would need **200 nm** bpm resolution.



To achieve this level of alignment we would need **1 um** bpm resolution.

Magnet	Label	Int. field strength	4 $\boldsymbol{\sigma_x}$ [mm]	4 $\boldsymbol{\sigma_y}$ [mm]	Length
Dipoles	$d_{1,2}$	-0.144 Tm	1.244	1.202	0.6 m
Quadrupole	q_1	0.198 T	1.130	1.258	0.3 m
Quadrupole	q_2	-0.733 T	0.941	1.881	0.3 m
Quadrupole	q_3	1.078 T	1.508	0.807	0.3 m
Quadrupole	q_4	0.692 T	8.078	14.371	0.3 m
Quadrupole	q_5	-0.666 T	2.713	23.371	0.3 m
Quadrupole	q_6	0.760 T	6.209	2.895	0.3 m
Quadrupole	q_7	-0.666 T	7.646	26.817	0.3 m
Quadrupole	q_8	0.692 T	14.226	12.652	0.3 m
Sextupole	s_1	7.941 T/m	8.372	10.707	0.1 m
Sextupole	s_2	-6.786 T/m	5.636	19.770	0.1 m
Sextupole	s_3	-39.953 T/m	2.628	11.263	0.1 m
Sextupole	s_4	-40.449 T/m	5.623	2.815	0.1 m
Sextupole	s_5	11.340 T/m	1.096	16.878	0.1 m
Sextupole	s_6	-4.534 T/m	12.306	11.012	0.1 m
Octupole	o_1	230.22 T/m^2	4.324	27.279	0.1 m
Octupole	o_2	-637.375 T/m^2	10.983	20.722	0.1 m
Octupole	o_3	1196.745 T/m^2	10.683	9.625	0.1 m

Quad range: 0.1-1.5 T

Sext range: 2-80 T/m

Oct range: 100-2000 T/m^2

Example of possible operational scenario

Run 1000 seeds with random errors with distributions as specified below.

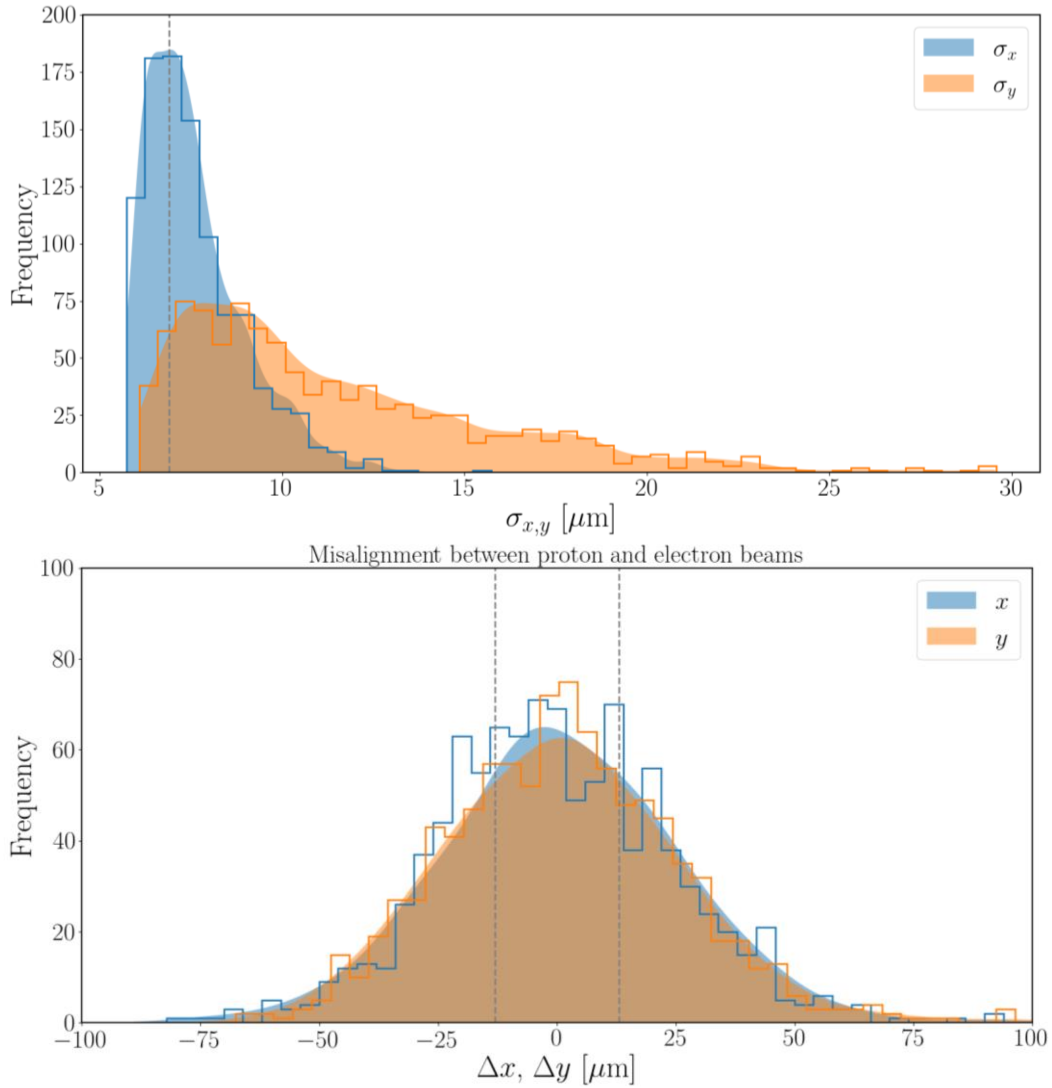
Percentage of seeds which satisfy requirements:

- 6.6% satisfy beam size requirements ($< 1.2 \times \sigma_{\mathrm{matched}}$)
- 16.3% satisfy offset requirements ($< 13\ \mu\mathrm{m}$)
- **0.6% satisfy both => <280 cycles per AWAKE run (2 weeks)**

Gaussian distributions of errors with r.m.s values:

- e-line power converter ripples = 10 ppm (see Appendix)
- Momentum jitter = 1e-3 (see Appendix)
- e-line input position jitter = 10 µm
- **Proton line jitter at injection point = 26 µm**
  - Power converter ripple = 10 ppm
  - Add angular jitter MSE = 50 ppm
- Dipole misalignments =50 µm
- Magnet field error = 10 ppm
- Quad misalignments = 10 µm
- Sextupole misalignments = 10 µm
- Octupole misalignments = 25 µm
- BPM resolution = 1 µm
- **Field homogeneity not included yet.**

More than factor of two smaller than current value.



Summary

- HW requirements for both proton and electron line are very challenging
  - **These are obtained as direct translation of experimental specifications**

- The main challenge for the proton line is the s2s jitter
  - Need, ideally, **a 10 fold improvement in PC ripples of the whole TT40/41 and MSE!**
  - Questions:
    - Is this feasible? How long to study, if needed?
    - How long to study and develop a solution?
    - How much could cost something like that?
    - If not, what could be a more reasonable improvement for the PC stability?
- For the electron line, same story but "limited" by beam size => <7 ppm rms on all new PC
  - Questions: see above...
- Magnets initial specifications given
  - They can be used now to see design and then PC dynamic range to request
- Beam instrumentation requirements will be challenging too - first numbers out:
  - **BPM resolution < 1 μm**
  - BPM accuracy closely linked to BTV position accuracy for p+ and e-

Thanks!

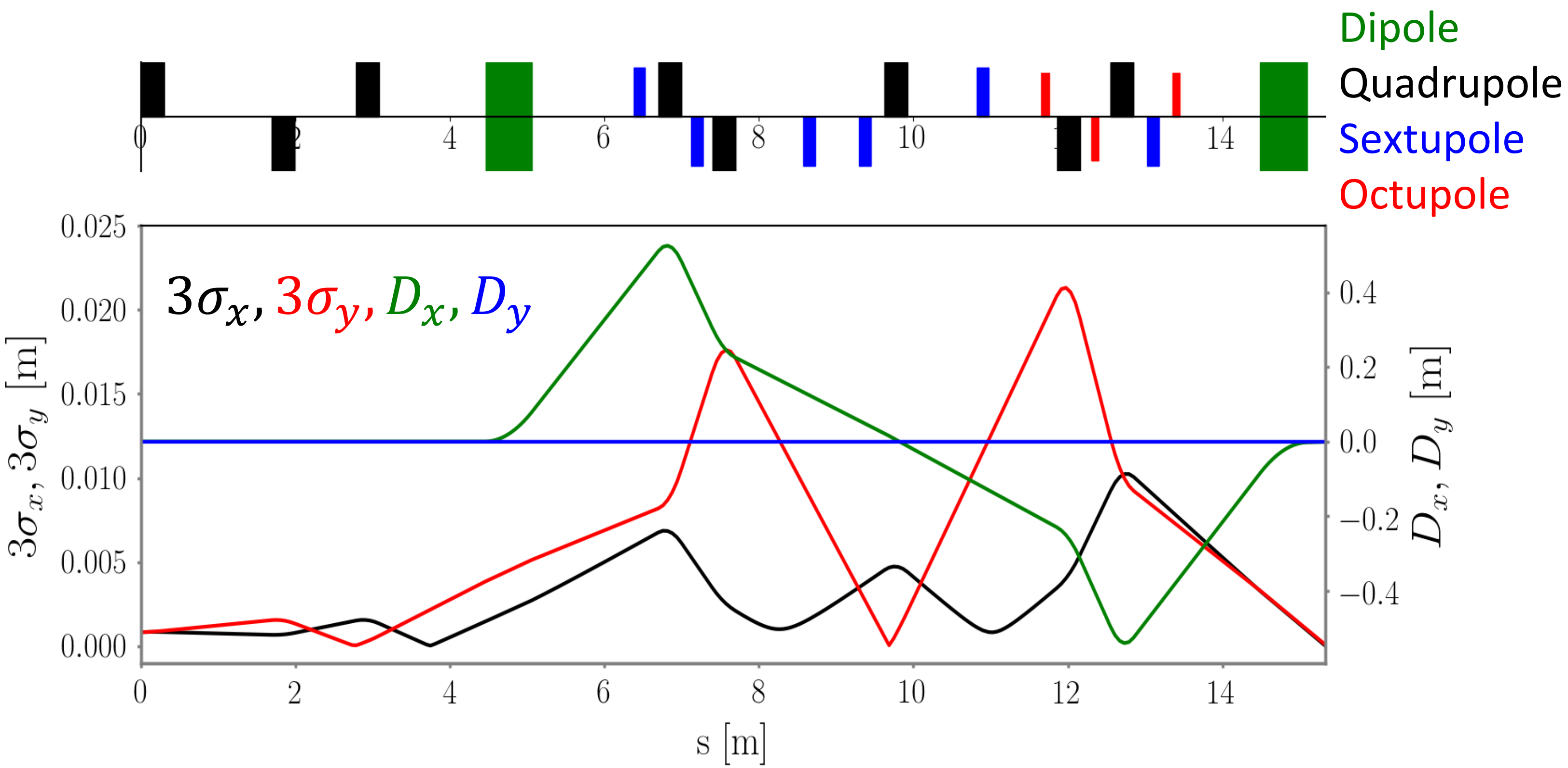
Appendix

Current design

- Design optimised to meet the matching condition at the plasma merge-point, which requires: $\boldsymbol{\sigma = \sqrt{4.87\ \mathrm{mm} \times \epsilon}}$ using statistical emittance at the end of the line:

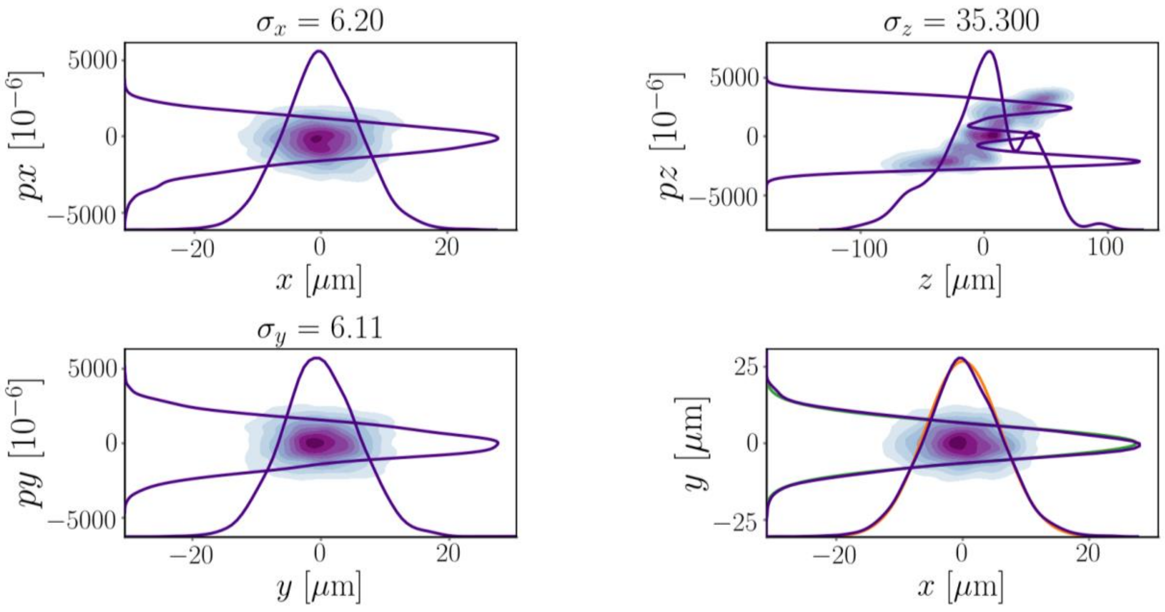
$$\epsilon = \sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle xp_x\rangle^2}$$

- Modelling aperture limits as 2.5 cm.



Beam at plasma merge-point

- The matched beam sizes would be 6.2, 6.1 µm and we can achieve this with Gaussian beams.
- Bunch shortening of almost a factor of two – would need longer input beams.
- Current minimum beam sizes we can get 5.8, 6.0 um (unmatched).



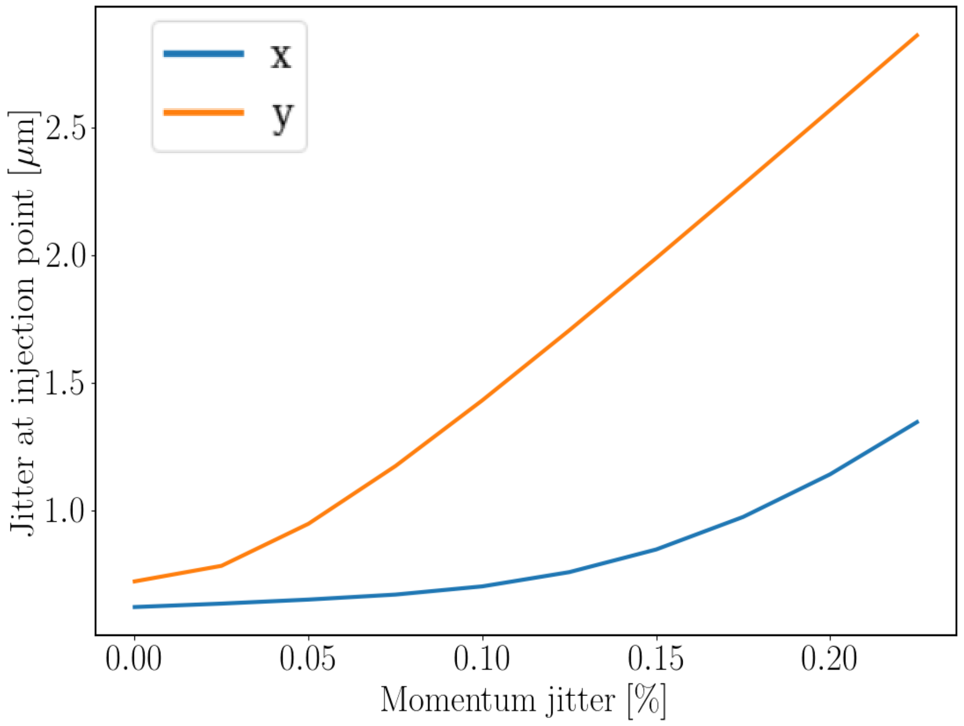
Parameters at merge-point

- $\sigma_x = 6.20\ \mu m$
- $\sigma_y = 6.11\ \mu m$
- $\alpha_x = 0.00$
- $\alpha_y = 0.00$
- $D_x = -0.0003$
- $D_y = 0$

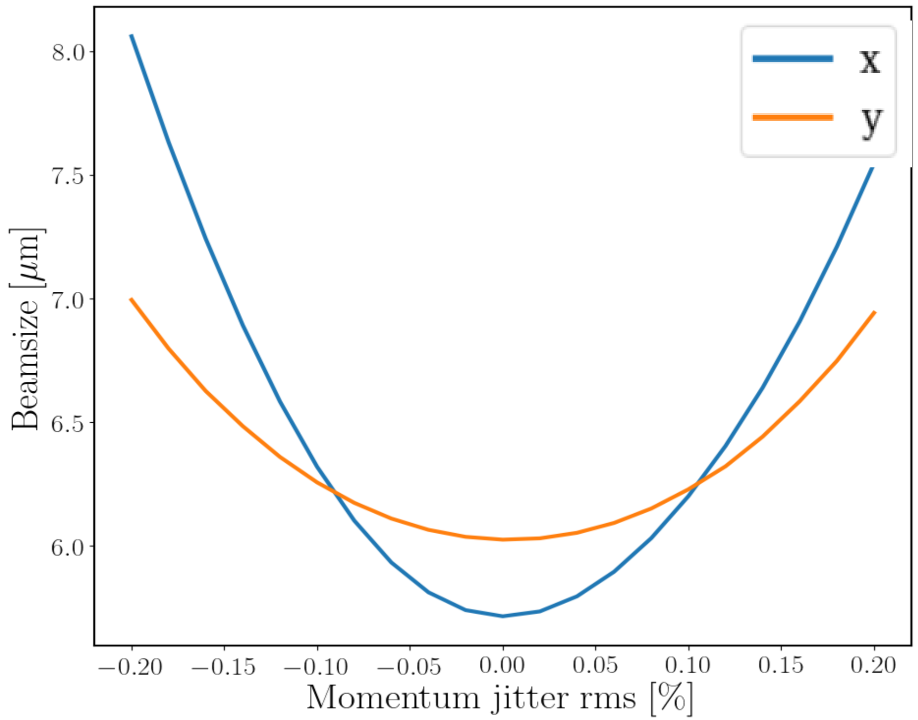
Momentum jitter

- Study effect of momentum jitter on beam stability and beam size at injection point.
- For jitter study, 10 um r.m.s misalignments of all magnets first.
- 50 seeds at for each misalignment, 10 different seeds of misalignment.

Jitter at injection point



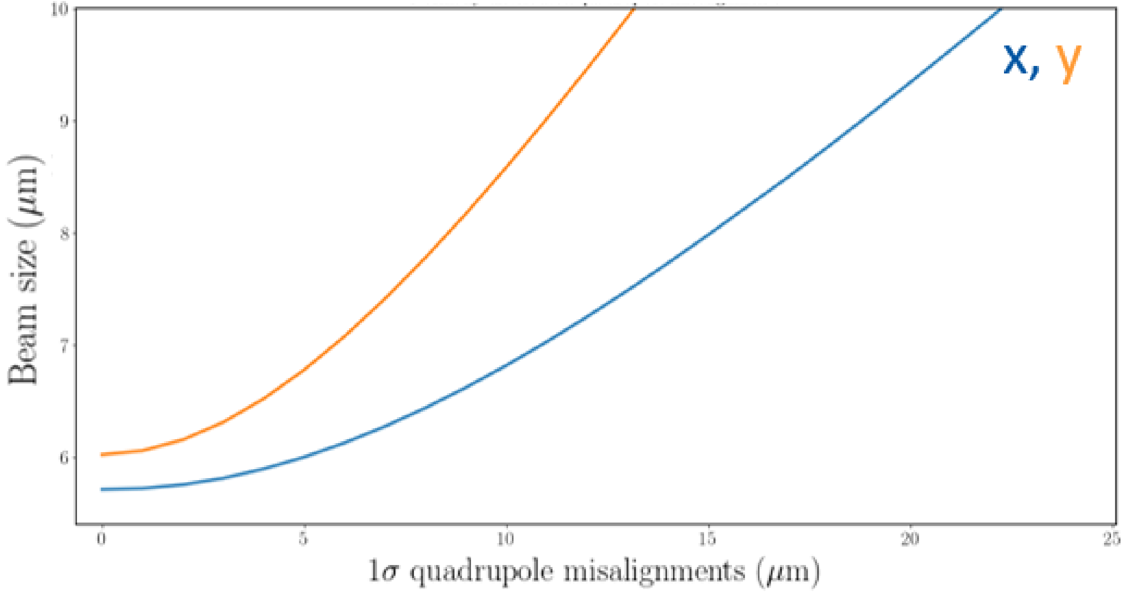
Beam size at injection point



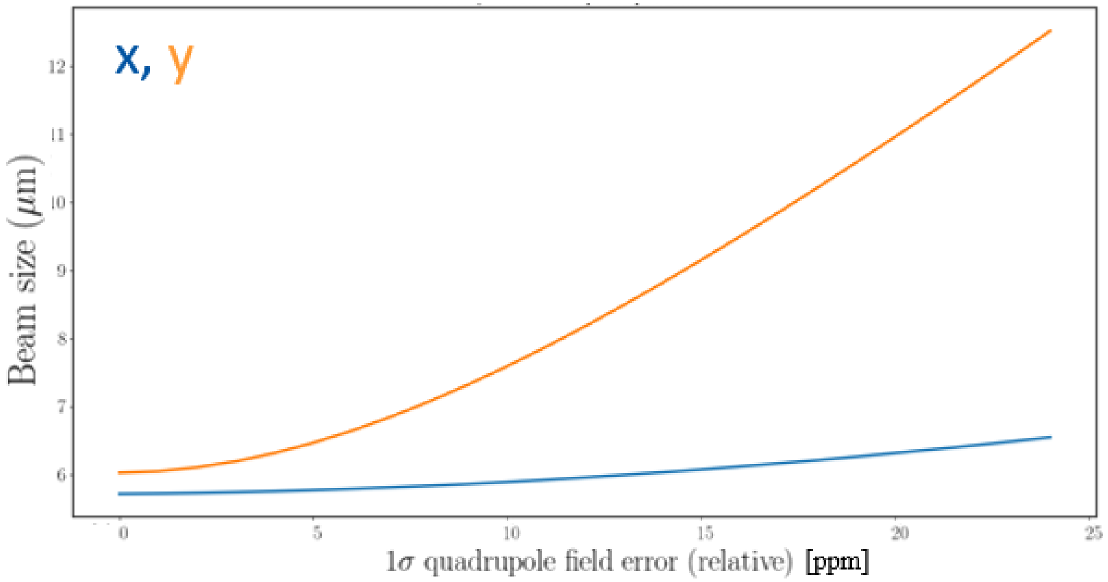
Individual error studies

- We started with studies for each error to see what is the upper limit we could tolerate if that was the **only** error. Clearly, this is then very a optimistic limit!
- This represents the beam-quad alignment we would have to achieve after steering and alignment.

Only quadrupole misalignments

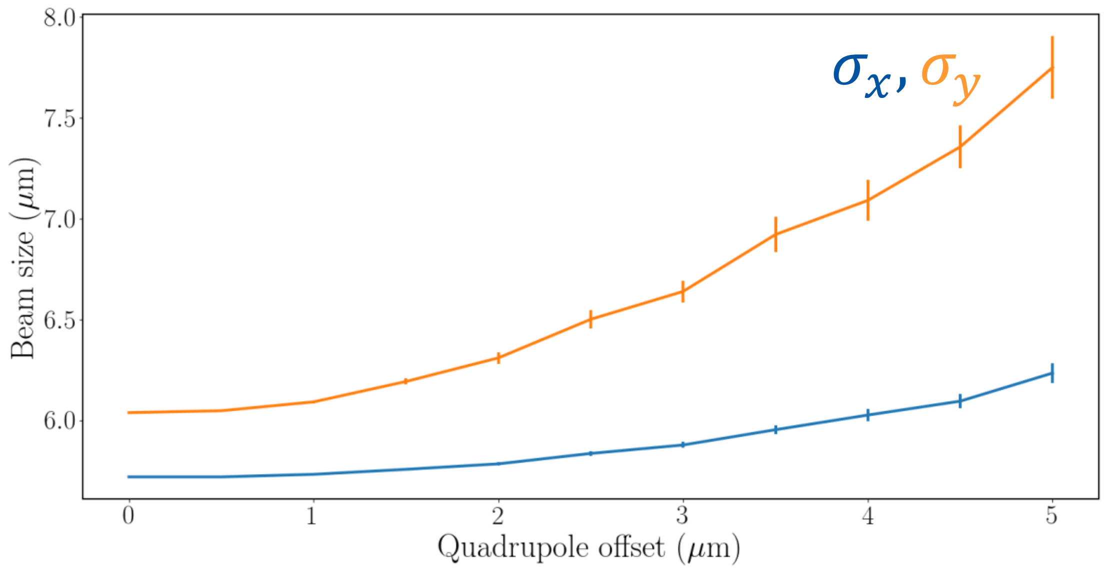


Only quadrupole field errors



Magnet misalignments

- The addition of errors/misalignments makes meeting the beam size requirements even more challenging.
- Preliminary error studies have been performed to determine our tolerances for various errors.
- Alignment needed between beam and quadrupoles of ~ 1 μm (see plot below), for sextupoles of ~ 5 μm and for octupoles of ~ 25 μm.
- These beam-magnet alignment requirements will require the magnets to be on movers, it is not sufficient just to use correctors to steer the beam.



- 100 seeds of quadrupole misalignments - no other errors and no correction.
- This gives us an upper limit for beam-quadrupole misalignments we can have after beam-based alignment and steering.

Best case: factor of 5 on proton jitter at waist

- 3.9% satisfy beam size requirements
- 39.1% satisfy offset requirements
- **1.1% satisfy both**

```
e_power_conv_ripples = 10e-6
mom_jit = 1e-3
input_jit = 10e-6
proton_jit (um) = 10.6
bend_mis =50e-6
field_error = 10e-6
quad_mis = 10e-6
sext_mis=10e-6
oct_mis=25e-6
```