Design of the 150 MeV electron line for AWAKE Run2 experiment

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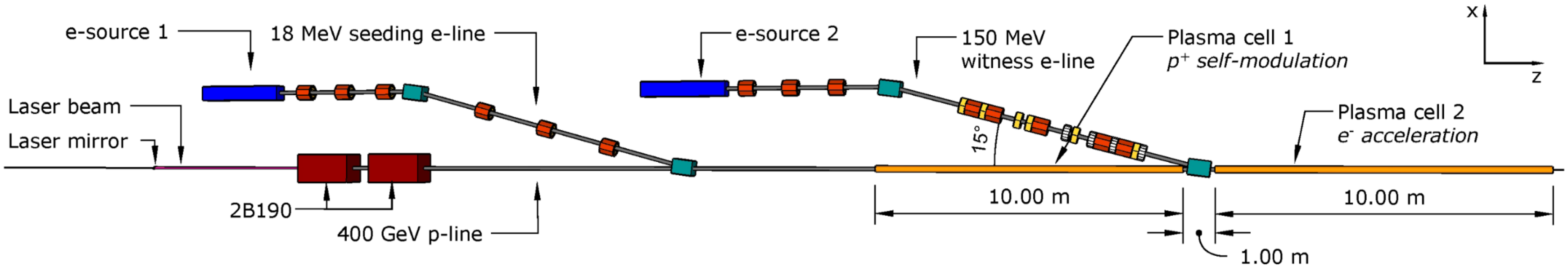
EARLI meeting
21/03/2023

Outline

- **Electron line design**
  - Design strategy
  - Optimization methods
  - Updated design
  - Errors and alignment procedure studies
- **Scattering foils**
  - Tracking
  - Multi-objective optimisation
- **Conclusions and next steps**

AWAKE Run2

- AWAKE Run2 aims to demonstrate the scalability of the experiment for high energy physics studies.
- It the divided in 4 phases (a, b, c, d). We are presently in Run2a.
- For Run2c the experimental setup will be modified, adding a 150 MeV witness electron line to inject electron in a second plasma cell.



Courtesy of R. Ramjiawan

Electron line design

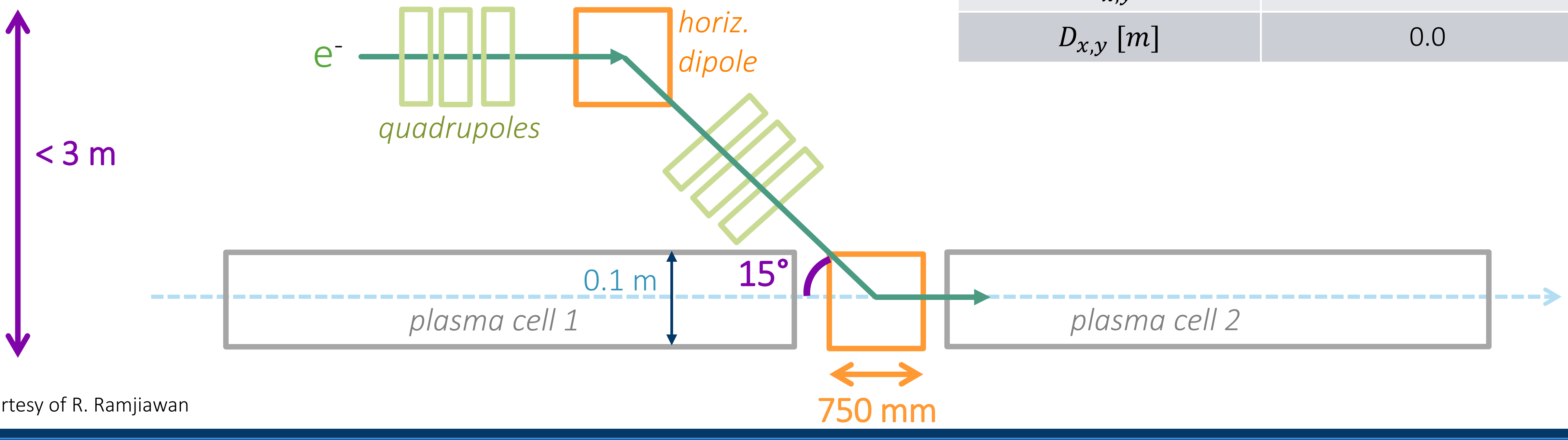
Design constraints

Beam specifications

- At injection require σ^* = 5.75 um .
- Achromatic, with no bunch lengthening.
- Dipole angle 15° so beampipe doesn't hit plasma cell.
- Plasma cell gap < 1 m to reduce proton defocusing.

	Specifications
$\sigma_{x,y}\ [\mu m]$	5.75
$\sigma_z\ [\mu m]$	60 (200fs)
E_k [MeV]	150
$Q\ [pC]$	100-200
$\varepsilon_{x,y,norm}$ [mm mrad]	2
$\alpha_{x,y}$	0
$D_{x,y}\ [m]$	0.0

Footprint constraints



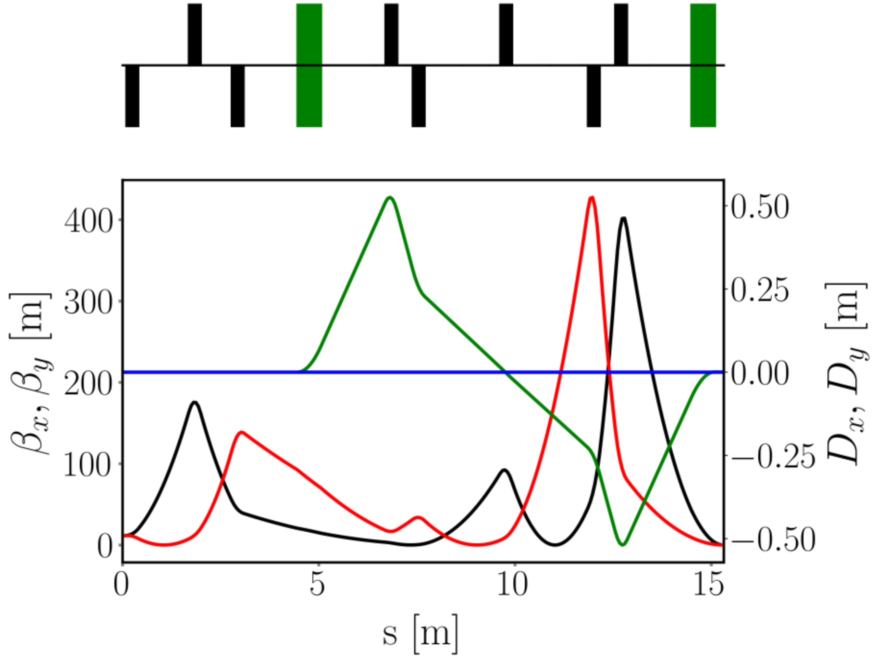
Courtesy of R. Ramjiawan

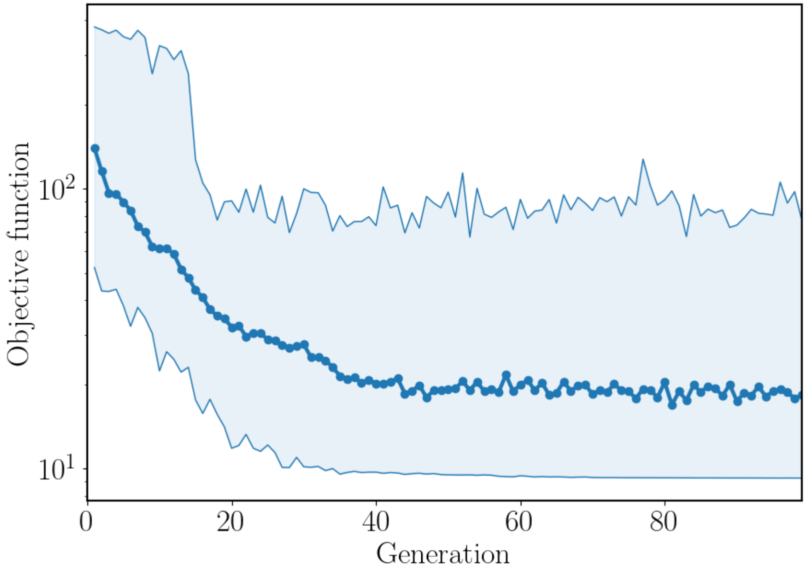
Design methodology

- The first version of the design was finalized by R. Ramjiawan, and the main results are summarized in PRAB paper

Frist step:

- Use genetic algorithms to optimize quadrupoles positions and strengths
- The beam sizes specification were not achieved due to chromatic effects



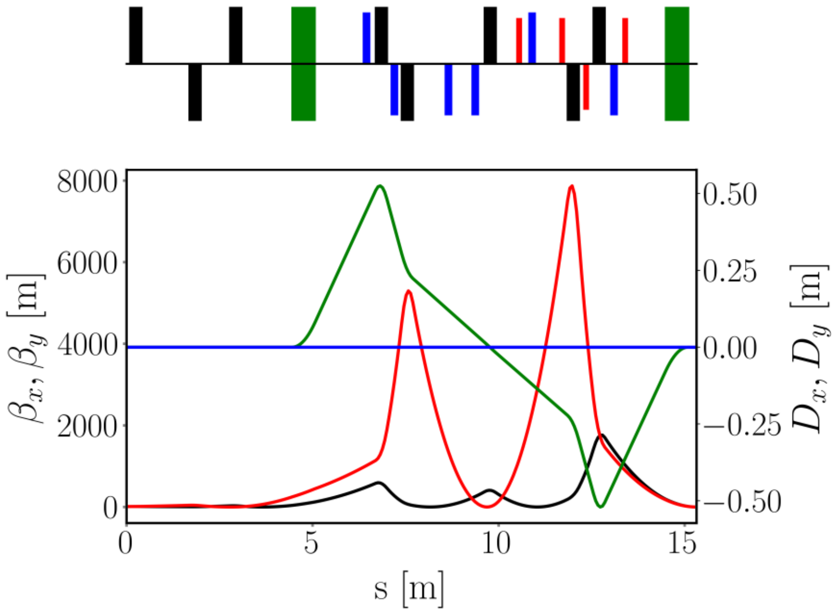


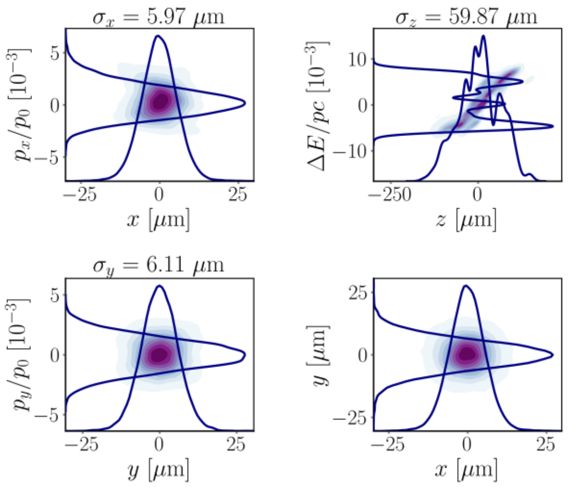
*Ramjiawan, R., et al. "Design and operation of transfer lines for plasma wakefield accelerators using numerical optimizers."

Courtesy of R. Ramjiawan

Design methodology

- In order to compensate for chromatic contributions to beam sizes sextupoles were added
- Octupoles were finally added to mitigate detuning with amplitude effects
- At each stage a combination of different optimization algorithms was used (Powell, Nelder Mead)
- Reached specifications and set baseline design





	Specifications	x-plane	y-plane
$\sigma_{x,y}\ [\mu m]$	5.75	5.97	6.11
$\sigma_z\ [\mu m]$	60	59.87	
$\beta_{x,y}\ [\mu m]$	4.8	4.82	5.41
$\alpha_{x,y}$	0.0	0.0	0.0
$D_{x,y}\ [m]$	0.0	0.0	0.0

*Ramjiawan, R., et al. "Design and operation of transfer lines for plasma wakefield accelerators using numerical optimizers."

Courtesy of R. Ramjiawan

Next step

What's new?

- After iteration with magnets team, the specifications on magnets dimensions were updated (Thanks P. Schwarz)
- BI team provided dimensions for instrumentation (Thanks S. Mazzoni)
- The electron line required some adjustment to account for new dimensions

New magnets and BI dimensions

New mechanical lengths for magnets

	B/M. L old [mm]	B. L new [mm]	M. L new [mm]	Width [mm]
Qaudrupoles	300	300	450	440
Sextupoles	150	200	340	450
Octupoles (1700 T/m^2)	100	200	320	400
Octupoles (1000 T/m^2)	100	200	270	400
Correctors (<0.6 mrad)	-	-	40	-

B L = Magnetic length
M L = Mechanical length

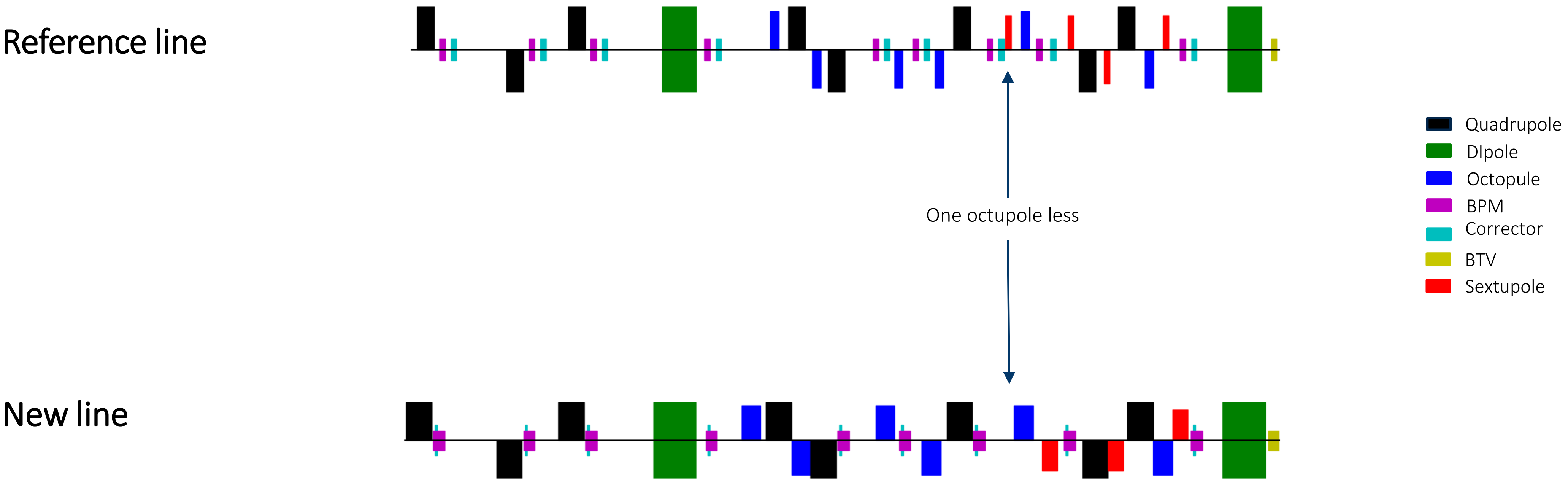
Depends on integrated strength field

New mechanical lengths for BI

	Length old [mm]	Length new [mm]	Width old [mm]	Width new [mm]
BPM	-	207	-	Similar to pipe
BTV	-	207	-	190
Bunch length	-	300	-	-

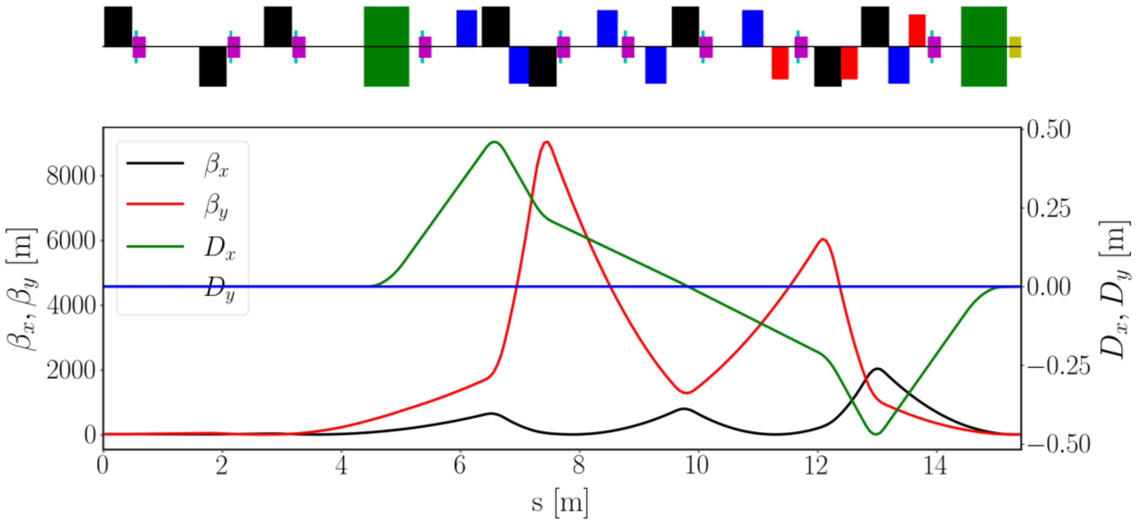
New magnets and BI dimensions

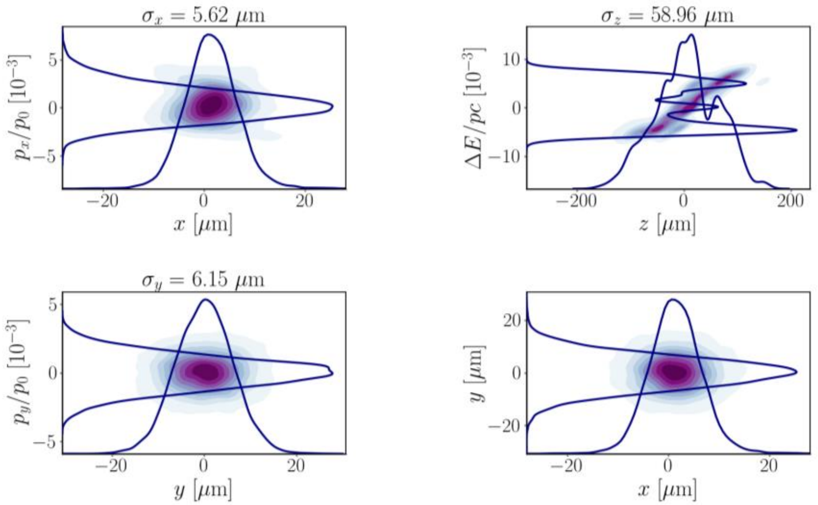
- The mechanical length were included in the simulation model
- The line configuration had to be modified accordingly
- The optics optimization and the tolerance studies were performed again



New optics optimization

- The previous optics parameters were used as starting point for the optimization
- Optimization process was performed using mainly two algorithms (Nelder-Mead and Powell)
- Modified optics tracking results are very close to the specifications





	Specifications	x-plane	y-plane
$\sigma_{x,y}$ $[\mu m]$	5.75	5.62	6.15
σ_z $[\mu m]$	60	58.96	
$\beta_{x,y}$ $[\mu m]$	4.8	2.6	5.1
$\alpha_{x,y}$	0.0	0.0	0.0
$D_{x,y}$ $[m]$	0.0	0.0	0.0

Introducing errors

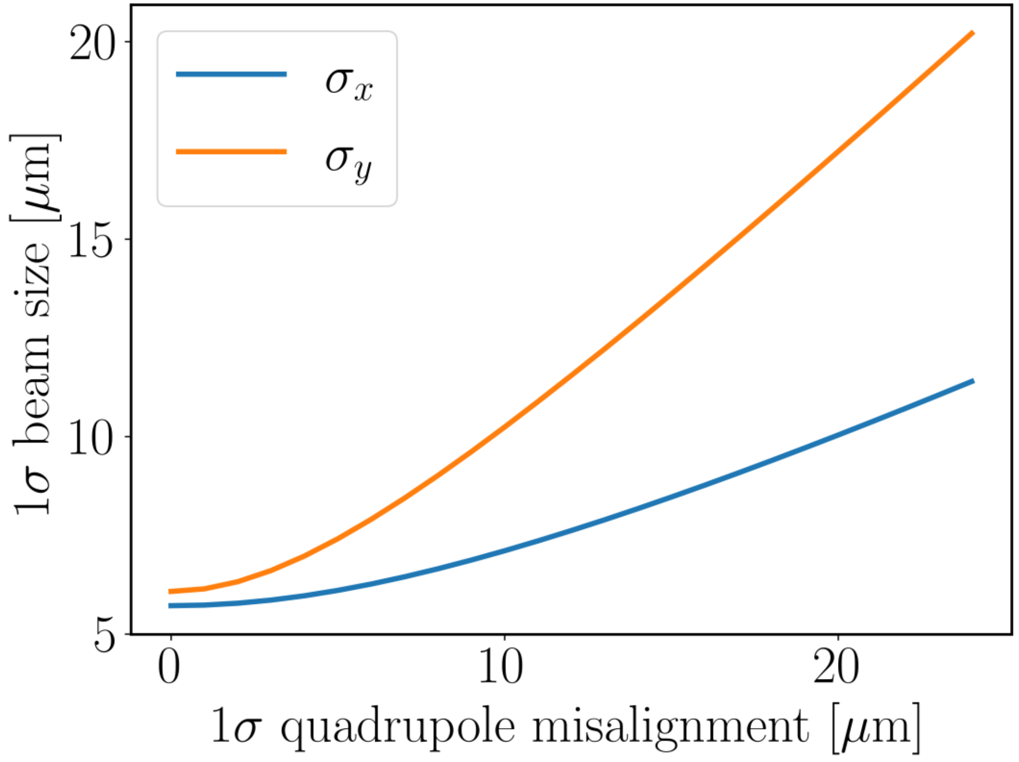
- Effect of single error type on beam size was used to define tolerances (R. Ramjiawan paper)
- Then alignment procedure was optimized to correct for all errors together

Goals

- Beam size within $1.5\boldsymbol{\sigma}^* = 8.6\ \mu m$
- Relative beam offset between e- and p+ beam < $10\ \mu m$

R.M.S of errors used in simulation

- BPM resolution: $10\ \mathrm{\mu m}$
- BTV resolution: $1\ \mathrm{\mu m}$
- Magnet mover error: $1\ \mathrm{\mu m}$
- Corrector error: $1\ \mathrm{\mu rad}$
- Initial magnet offsets: $100\ \mathrm{\mu m\ r.m.s}$
- e-line power converter ripples = $7\ \mathrm{ppm}$
- Momentum jitter = $1\mathrm{e}{-3}$
- e-line input position jitter = $10\ \mathrm{\mu m}$



Alignment procedure

- Quadrupole, sextupoles and octupoles need to be installed on movers to reach beam pointing specifications
- Three techniques used for alignment

① Quadrupole shunting

Centre quadrupoles w.r.t beam orbit.

- Change quad strength Δk and record change in BPM reading Δx_{BPM}
- Calculate quad-beam position shift Δx_{QUAD}
- Move quadrupole of - Δx_{QUAD}

② Dispersion free steering

Minimize parasitic dispersion and orbit

- Change beam energy
- Record the change in position at the BPM
- Use corrector to steer the beam trough the quadrupole

③ Numerical optimization

Use optimization algorithms to align sextupoles and octupoles

- Minimize beam size at injection point
- Use algorithm that requires low number of function evaluations (BOBYQA)

- Alignment procedure consists of a combination of iterations of ①+②+③ (less than 1 hour time)

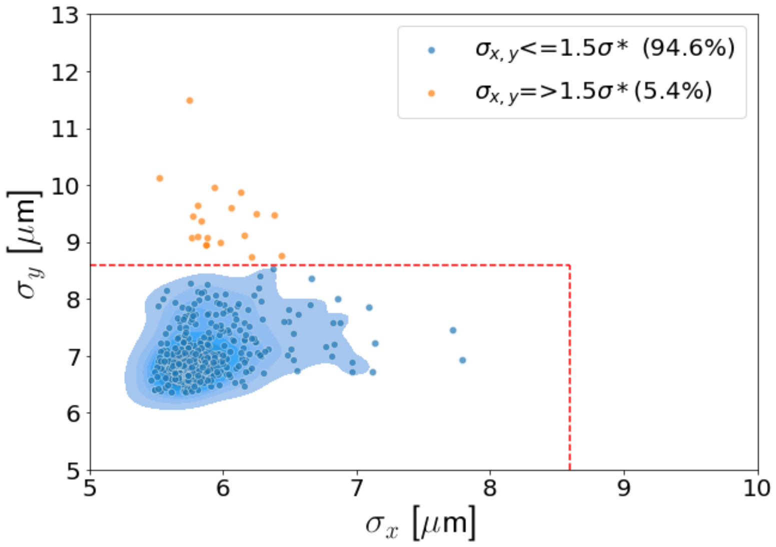
Alignment results

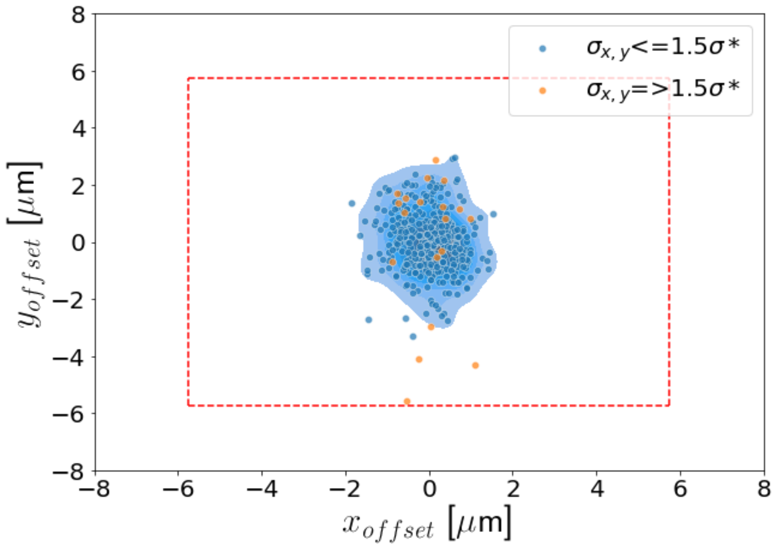
Test the alignment by simulating the alignment procedure for 200 error seeds

- The 93.3% of the cases the beam is within $1.5\boldsymbol{\sigma}^*$
- 100% of the case has a beam offset within $\boldsymbol{\sigma}^*$

When the alignment procedure fails, it has to be performed again

- The result of the alignment is dependent on the initial positions of the magnets
- With different initial conditions the alignment converges

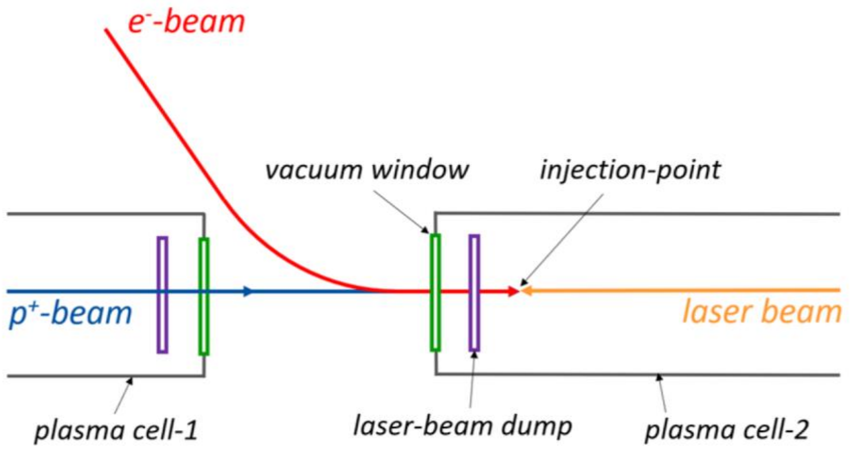




Scattering foils

New optics optimization with foils

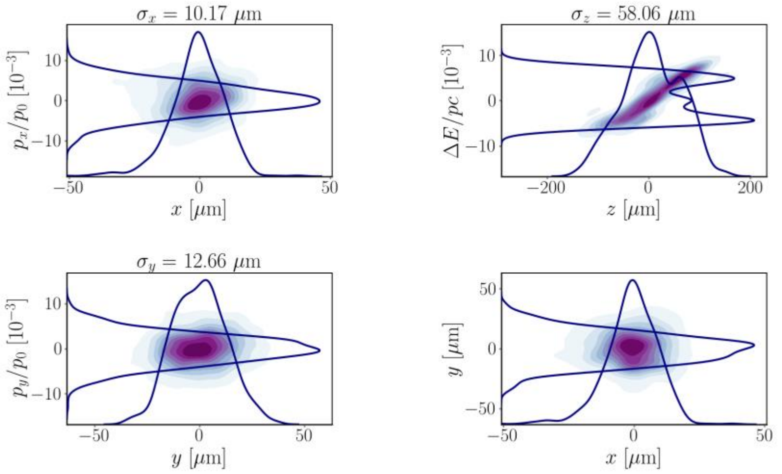
- Two scattering foils (vacuum window and laser beam dump) are needed upstream the injection point.
- The effects of multiple scattering effects caused by the two foils has to be considered.
- Simulations were performed assuming a thickness of 100 um per foil and aluminum as reference material
- The study results will be upgraded as soon as more info about the foils specifications will be available



New optics optimization with foils

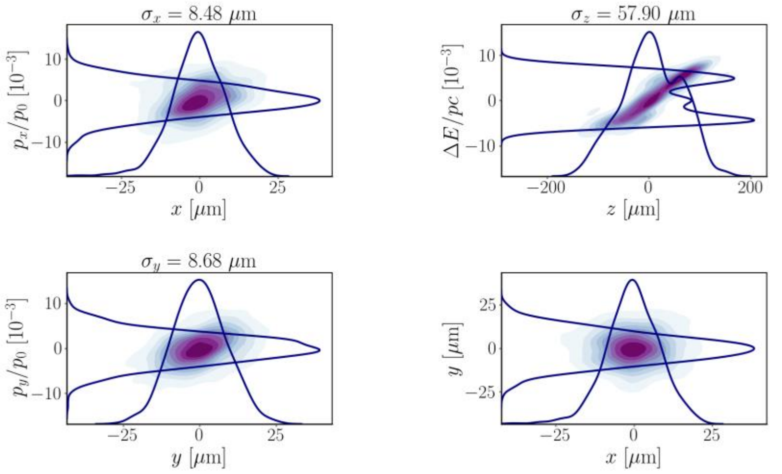
- The study shows that a compromise between beam size and $\alpha_{x,y}$ has to be found
- The optics can be adjusted to privilege either small beam size or $\alpha_{x,y}$
- Multi objective optimization can be used to find a set of optimal solutions.

Case 1: Privilege to $\alpha_{x,y} = 0$



	x	y
$\varepsilon_{RMS,Norm}\ [\mu m]$	11.2	12.6
$\beta\ [mm]$	2.5	2.87
$\alpha\ [mm]$	-0.03	-0.08
D_x	0	0

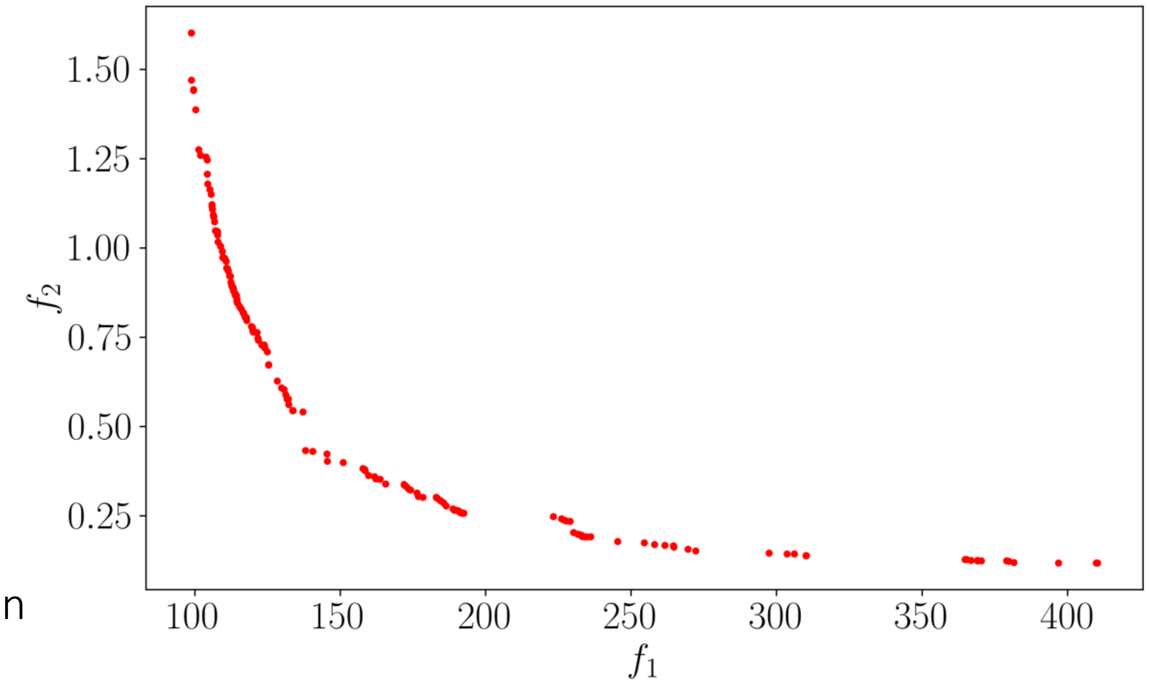
Case 2: Privilege to beam size



	x	y
$\varepsilon_{RMS,Norm}\ [\mu m]$	8.7	7.9
$\beta\ [mm]$	2.2	8.8
$\alpha\ [mm]$	-0.30	-0.43
D_x	0.0	0

Pareto front

- Optimizing for α=0 and minimal emittance separately using multi-objective genetic optimization NSGA-II
- Both objective functions also include the condition of zero dispersion and losses at injection point
- The Pareto front is the set of most efficient solutions and represents the best trade-off between the two objective functions
- The study shows that a compromise has to be found between the two parameters



Summary and next steps

Summary

- The design of the witness 150 MeV e-line was adjusted considering the updated mechanical size of the line elements.
- The alignment procedure was adapted to the updated design and demonstrated to perform within specs.
- The optics can be adjusted to rematch the beam when scattering foils are added to the line. Emittance and beam size are bigger than for nominal case.
- Multi-objective optimization shows that compromise has to be found between $\alpha = 0$ and small emittance.

Next steps

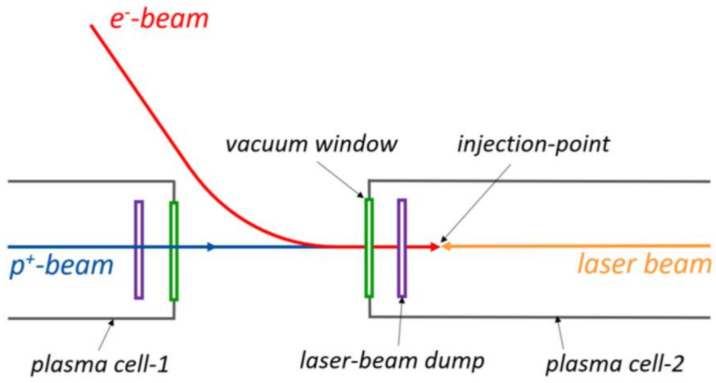
- Implementation of beam characterization methods for operations (emittance reconstruction, energy spread, etc.) in progress.

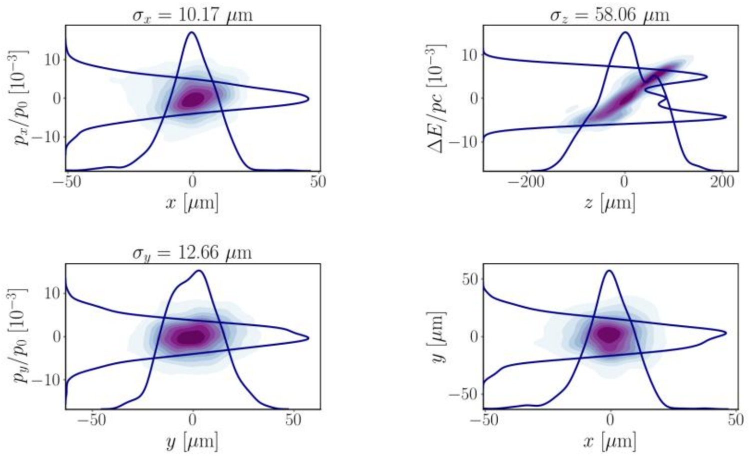
Thank you for your attention!

TT40/TT41 power converters ripples analysis

Adding the scattering foils

- Two scattering foils (vacuum window and laser beam dump) are needed upstream the injection point.
- Simulations were performed assuming a thickness of 100 um per foil and aluminum as reference material
- Due to the scattering foil the focal point is shifted, and the matching had to be adjusted
- The matching conditions can be achieved, but with bigger beam size and emittances





	x	y
$\varepsilon_{RMS,Norm}\ [\mu m]$	11.2	12.6
$\beta\ [mm]$	2.5	2.87
$\alpha\ [mm]$	0.0	0.0
D_x	0.0	0.0

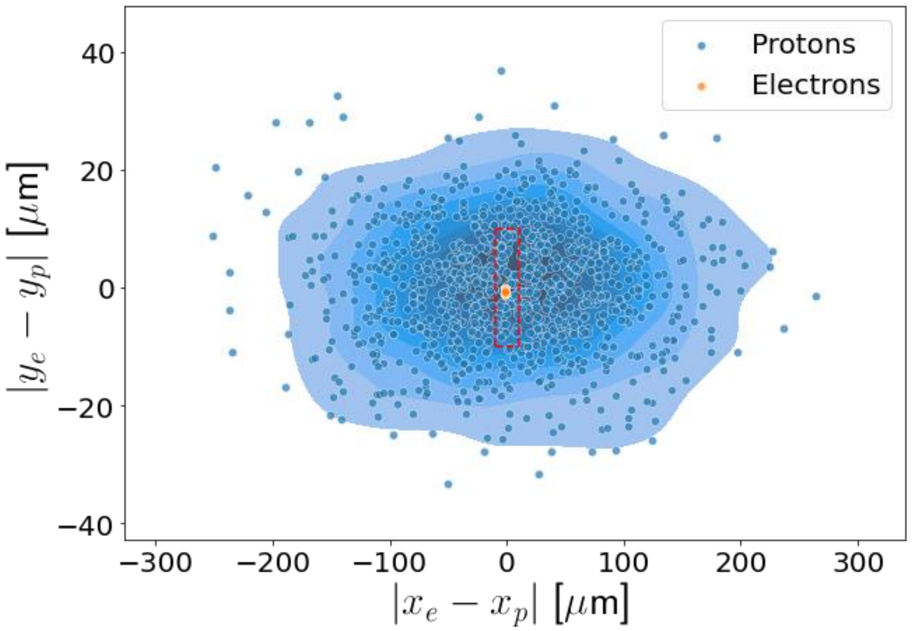
The problem

As shown by Rebecca

- Relative offset between p+ and e- beam driven by p+ beam jitter
- Ripples in power converters current is the main source of p+ beam jitter at injection point

Question:

- Is there any recurrent or predictable component in the ripple that could help in correcting/predicting the beam position offset at injection?

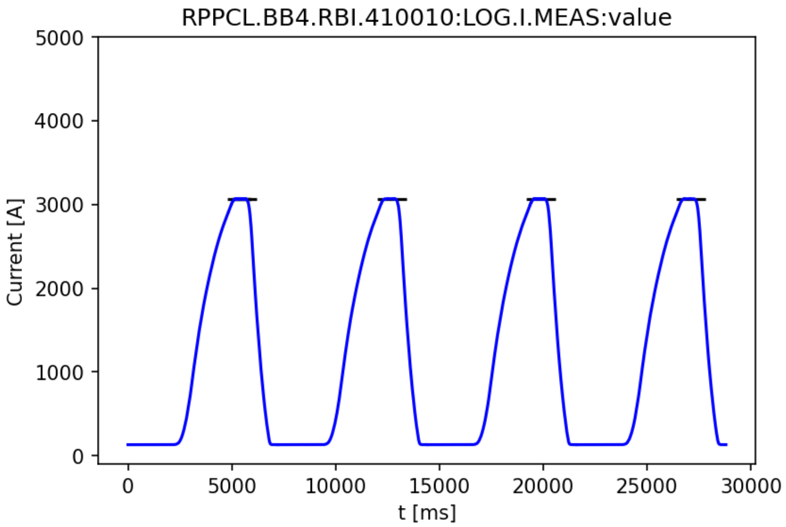


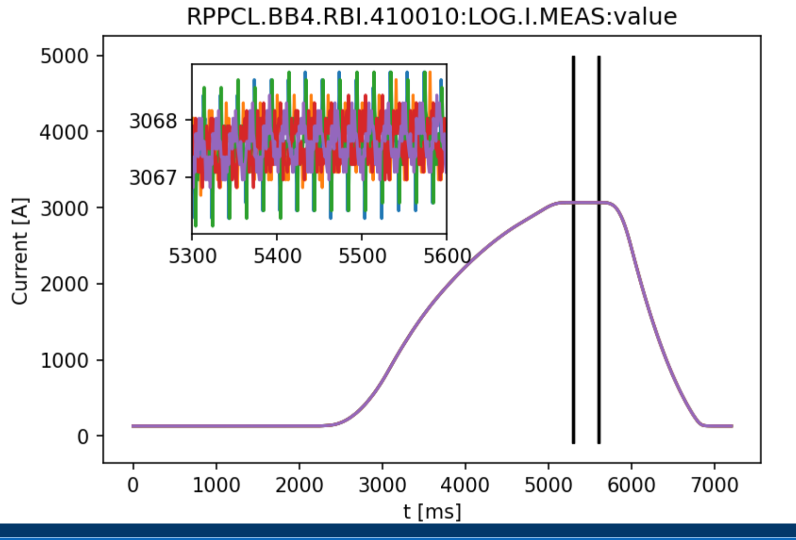
Analysis approach

Two time scales

a. Average current analysis: considers the flat-top average current

b. Ripple analysis: consider the time structure of the ripple within the flat-top





Analysis approach

Two time scales

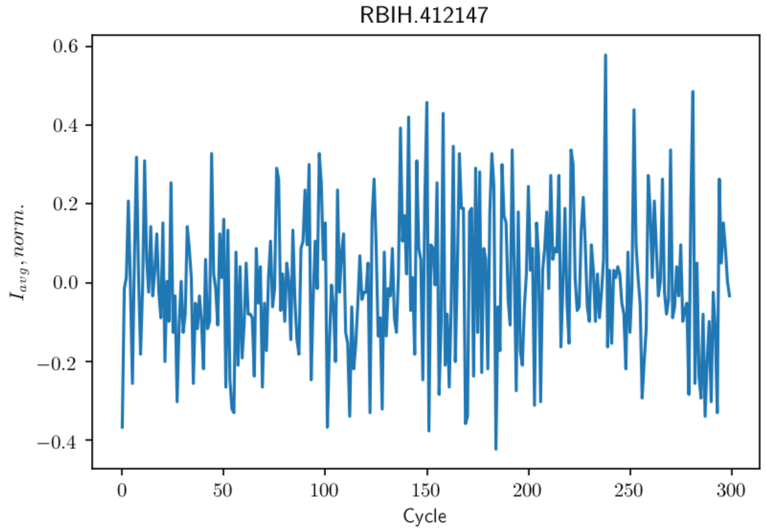
a. Average current analysis: considers the flat-top average current

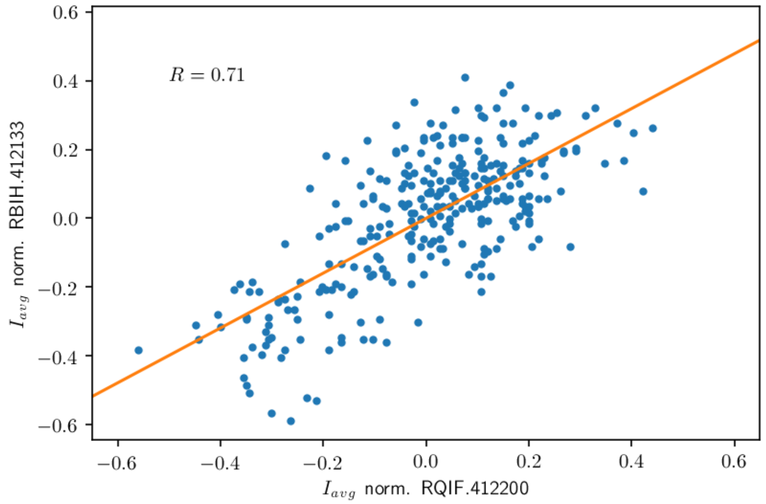
b. Ripple analysis: consider the time structure of the ripple within the flat-top

What are we looking for?

1. Reproducible patterns in time for each power converter (Is there a periodicity? Apply Fourier transform)

2. Similar ripple evolution in time in different power converters (Is there a correlation between the current evolution in the different PC? Calculate correlation)





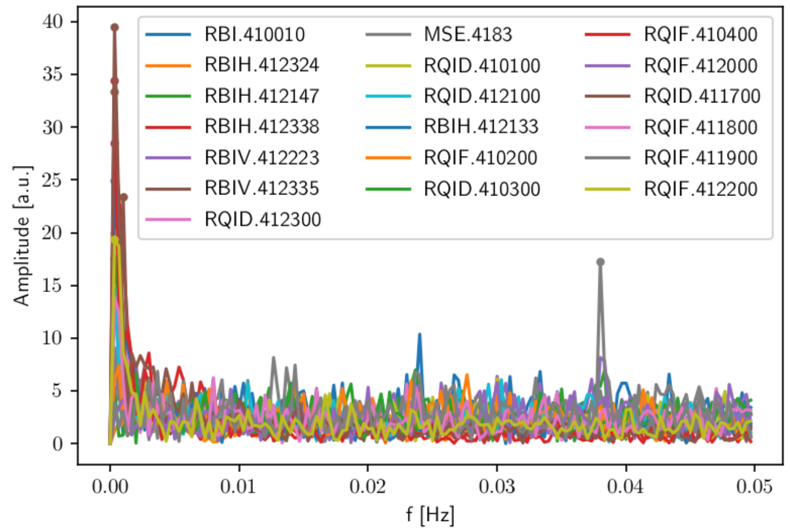
Average current analysis (a.1)

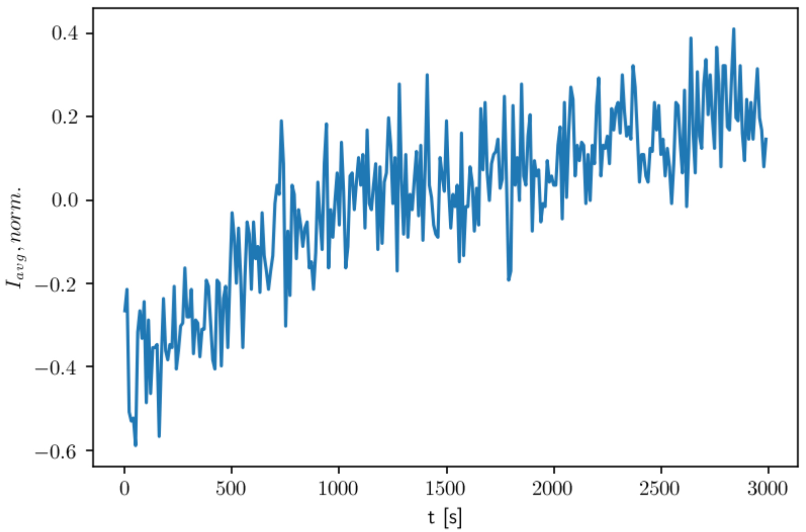
Reproducible patterns in time for each power converter

- Fourier transform of the average current evolution in time
- Absence of clear peaks means no periodic patterns can be recognized

Results

- There is a very low frequency component in some of the PC current…
- It corresponds to a slow drift
- We are looking for shot-to-shot correlation!

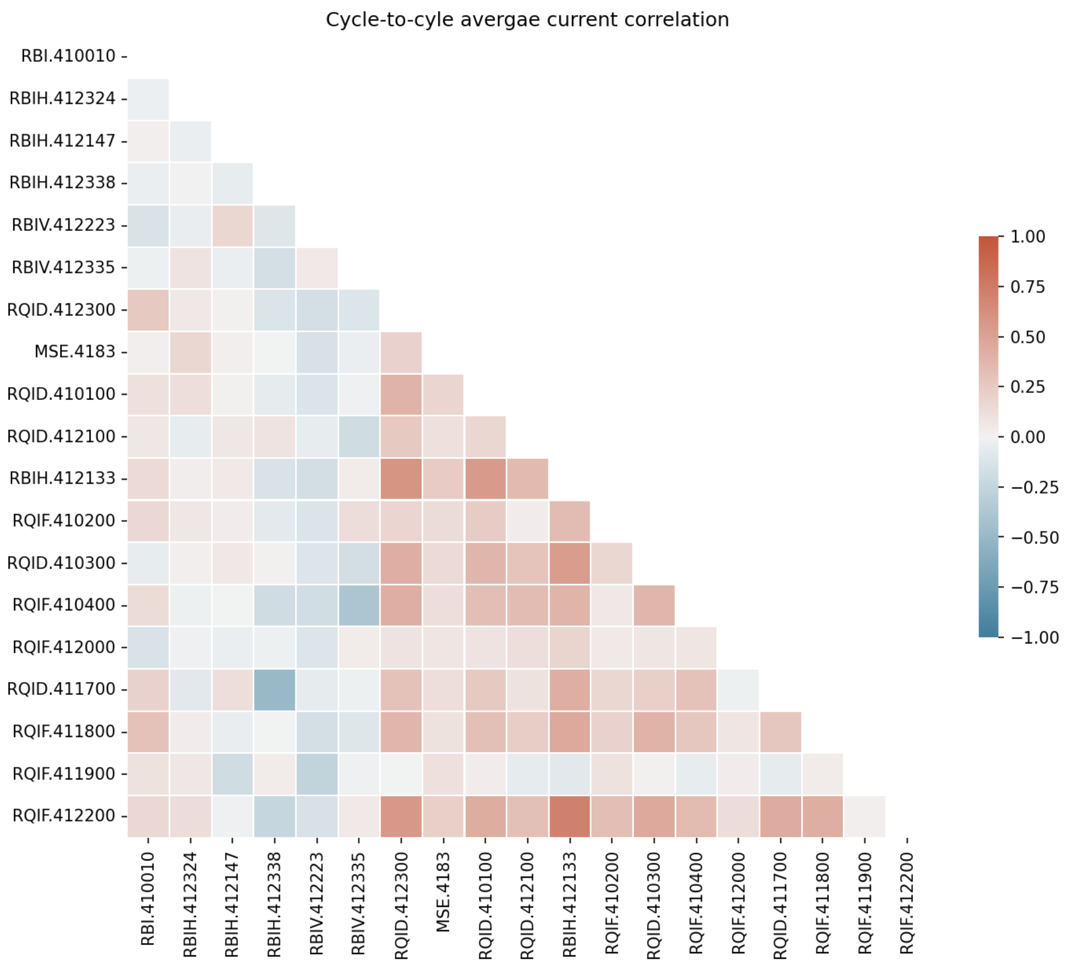




Average current analysis (a.2)

Correlation between average values in different power supplies

- The correlation matrix shows the R value correlating each PC average current with the ones in the other PC
- Max R = 0.7. In general, much lower
- Correlated PC could have same source of noise



Results

- The study shows week correlation between the parameters
- The correlation is given by the low frequency drift, which can be observed in various PC
- We are looking for shot-by-shot correlations

Average current analysis

Conclusions 1

a.1

- No periodic component can be found in the evolution of the flat-top average current.

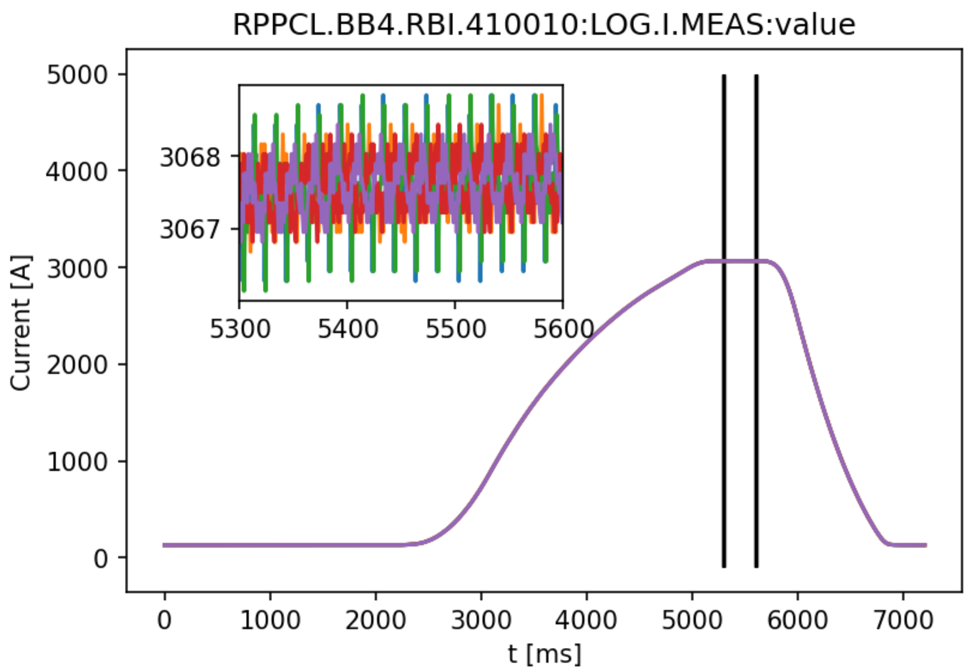
a.2

- A correlation between average current in few power converters can be observed.
- The low frequency drift occurs simultaneously in different PC.
- The information could be useful to find common sources for the drift.

Flat top signal analysis (b.1)

Reproducible patterns in time for each power converter

- Fourier transform of flat-top signal
- Analysis of the main harmonics
- Look for periodic behavior in phase (would make it predictable)



Flat top signal analysis (b.1)

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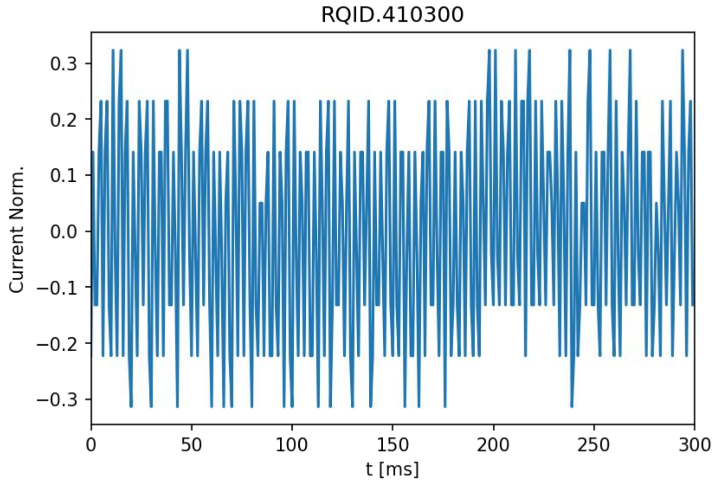
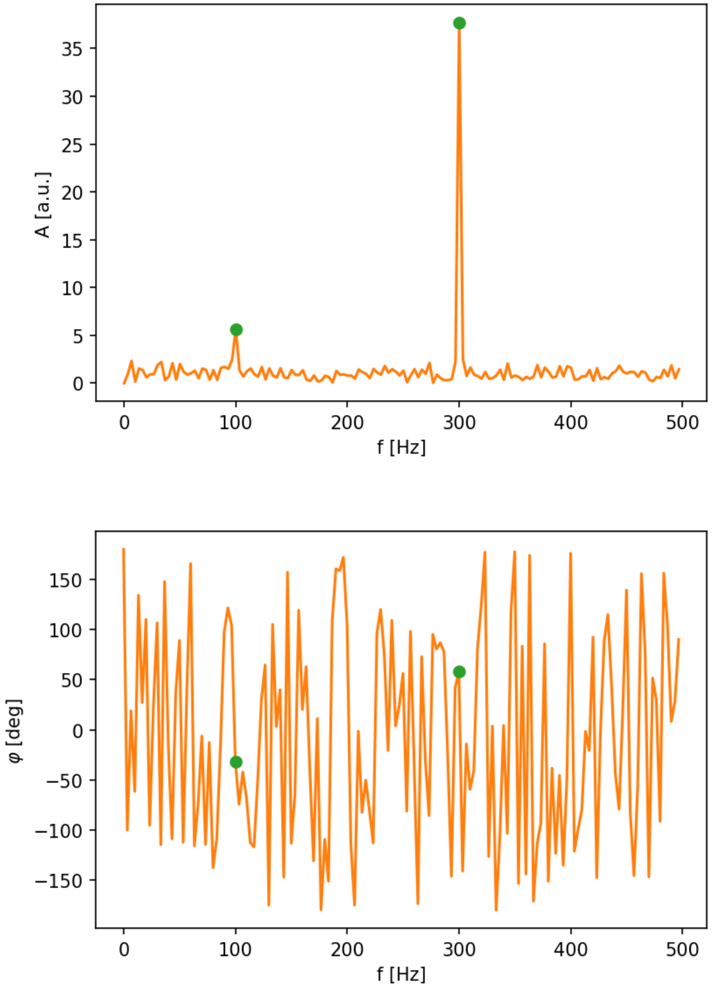


FFT



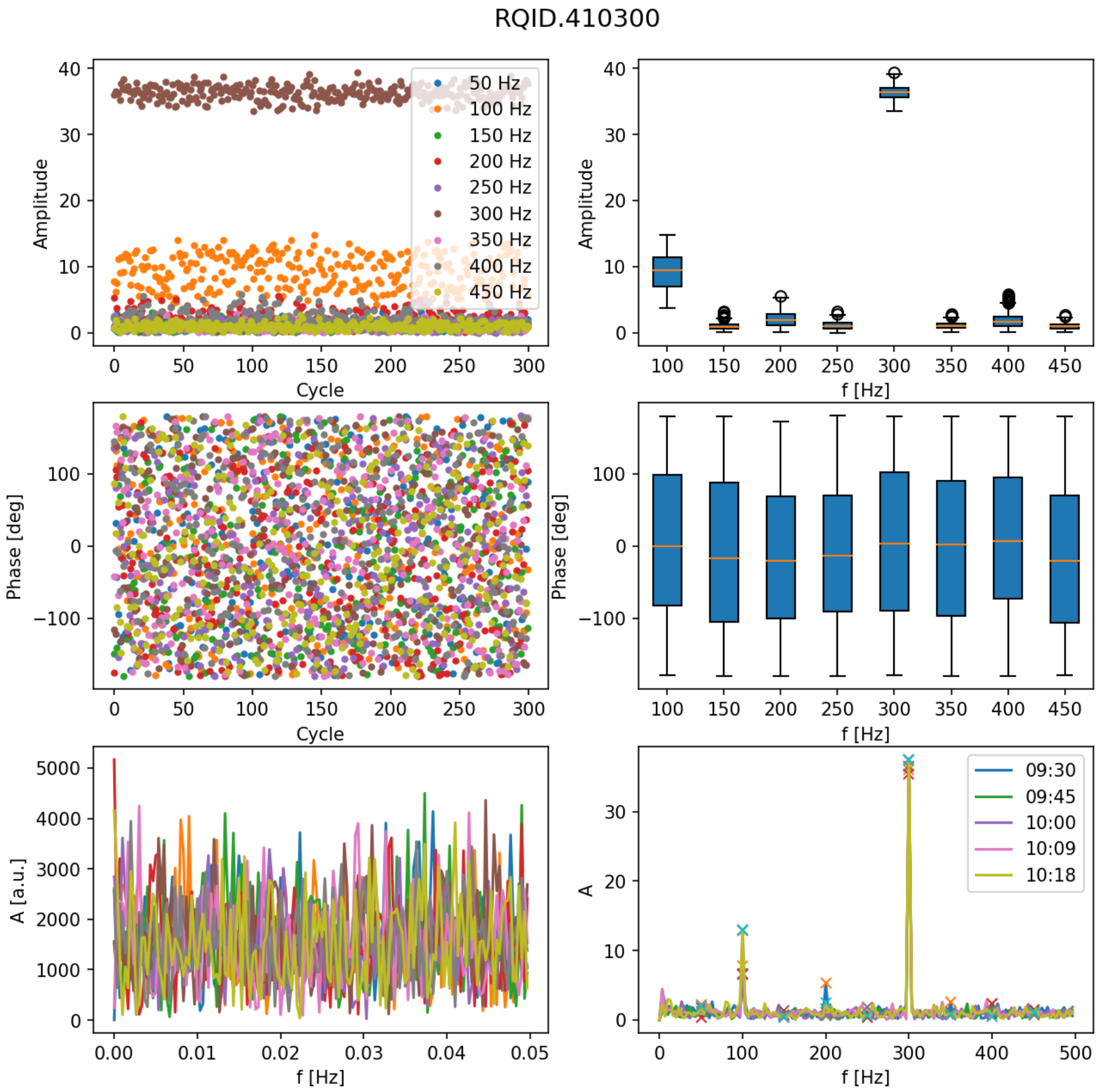
Flat top signal analysis (b.1)

Reproducible patterns in time for each power converter

- Fourier transform of flat-top signal
- Analysis of the main harmonics
- Look for periodic behavior in phase (FFT)

Results

- No periodic time structure found for the phase in any of the Power Converters



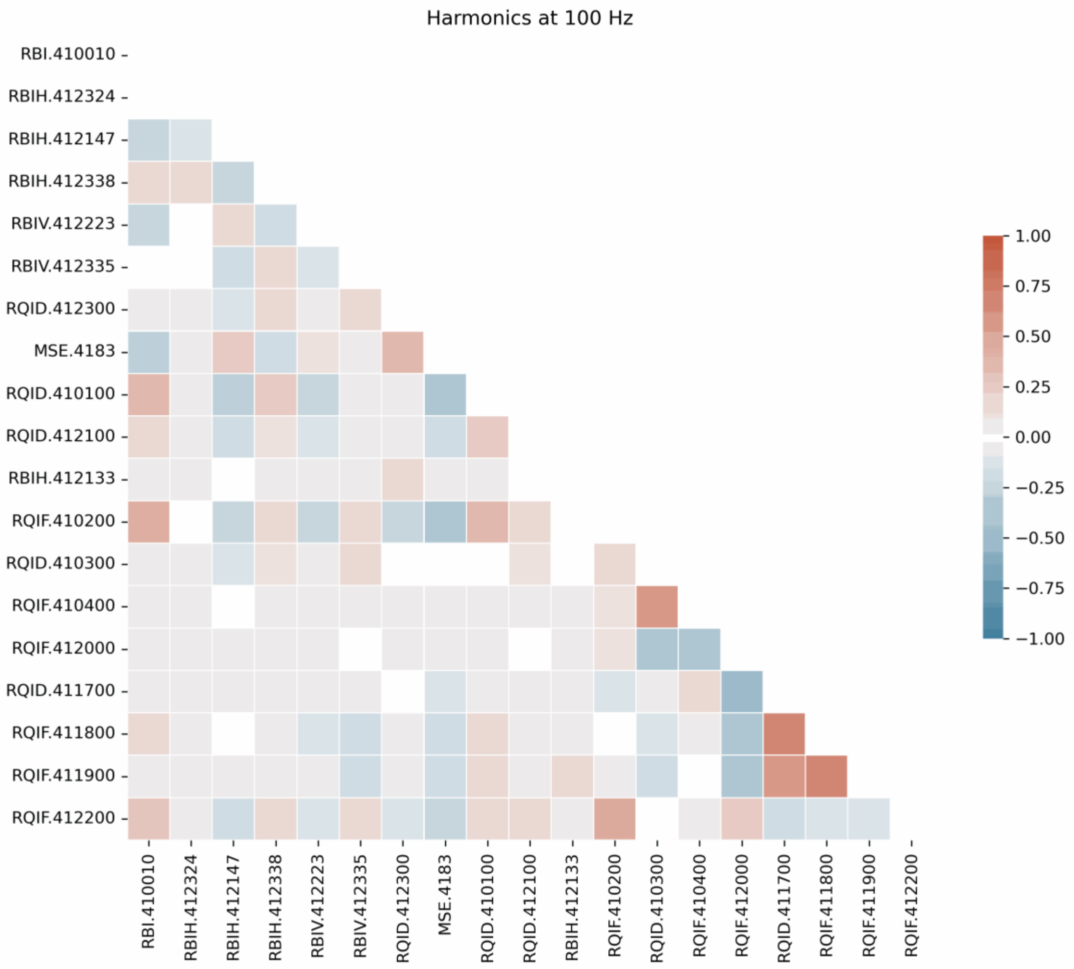
Flat top signal analysis (b.2)

Correlation between FFT harmonics phases in different PC

- Correlate the phase of the different harmonics
- Allows us to understand if there are common causes of noise for the different PC

Results

- Some of the PC show a correlation (especially at 50 Hz and 300 Hz)



Flat top signal analysis

Conclusions 2

b.1

- Fourier analysis allows to identify main harmonics of flat-top current.
- No periodic time structure was found for any of the harmonics phase, meaning that it cannot be predicted

b.2

- A correlation between the phase in different power converters can be observed at some frequncies

Comments and conclusions

Conclusions

- The analysis shows that there is not a periodic or predictable time structure in the evolution of the average current nor in the evolution of the phase of the FFT harmonics
- Therefore, for the moment the implementation of a feed forward system for correction seems hardly feasible.

Comments

- The analysis was performed analyzing the available data (from pyTimber), which are taken at MUGEF, **not on the PC**
- Direct measurements (G. Le Godec) at PC on circuit RPPCL.BB4.RBI.410010 show completely **different harmonics** than the ones available on PyTimber. Discussion and work in progress, thanks Gilles!
- For the average values, studies from Rebecca show very good agreement with measured values. We trust them.
- The beam extracted beam is not extracted always at the same time wrt to the cycle timing! Within a 100 ms range

Open questions

- How does the timing of the data acquisition work? Is it reliable?
- Is the discrepancy between direct measurement and measurement at MUGEF present in other circuits?

Thank you for your attention!

Alignment results

Test the alignment by simulating the alignment procedure for 200 error seeds

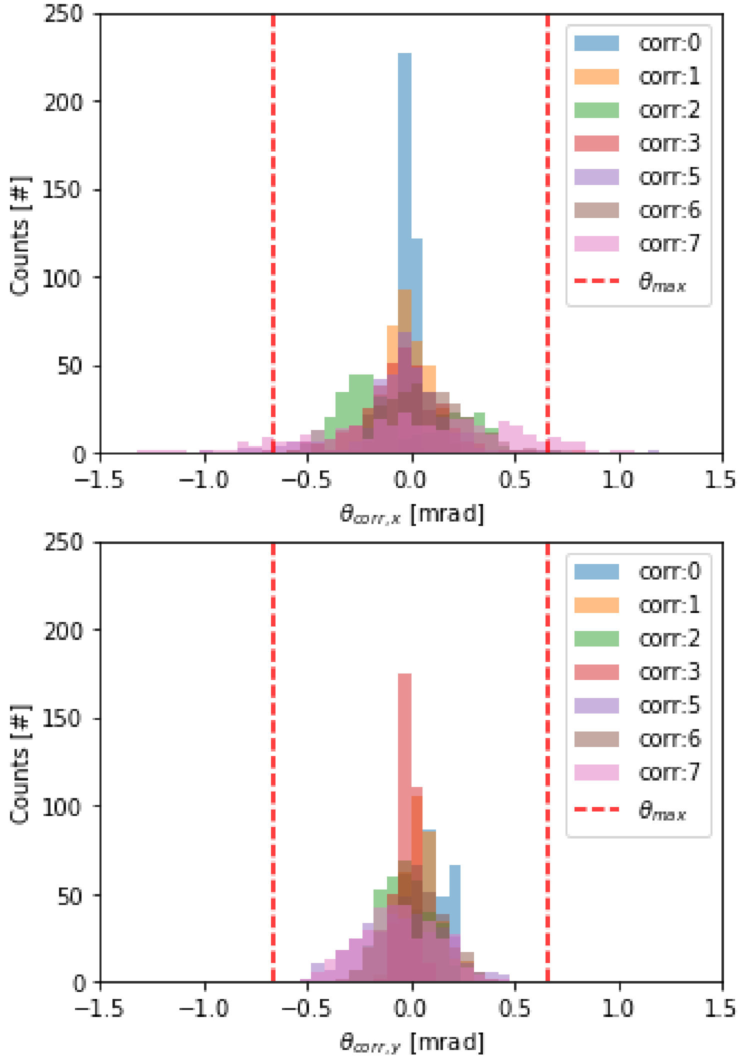
- The 93.3% of the cases the beam is within $1.5\boldsymbol{\sigma}^*$
- 100% of the case has a beam offset within $\boldsymbol{\sigma}^*$

When the alignment procedure fails, it has to be performed again

- The result of the alignment is dependent on the initial positions of the magnets
- With different initial conditions the alignment converges

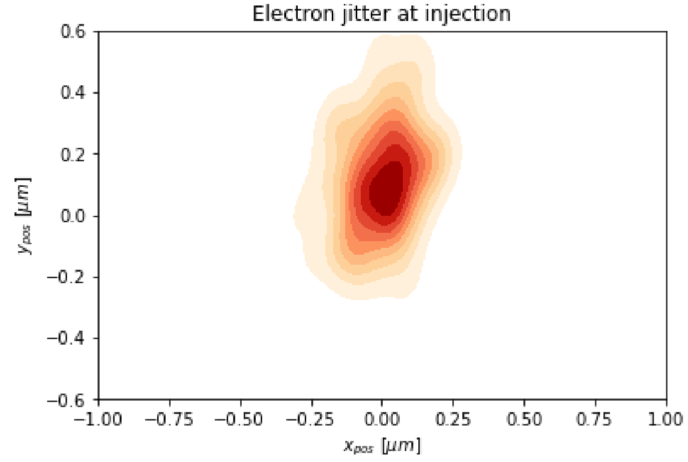
Assessing correctors strengths

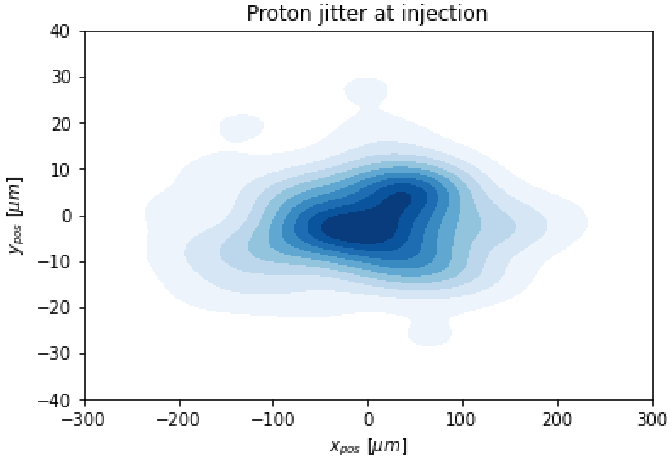
- Can we use same correctors installed on 18 MeV line?
- Mainly limited by corrector 7. Working on new scheme to reduce it.

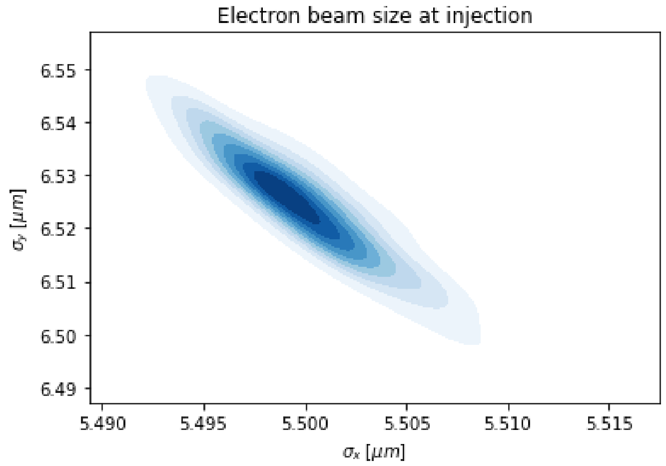


Proton and electron beam jitter at injection

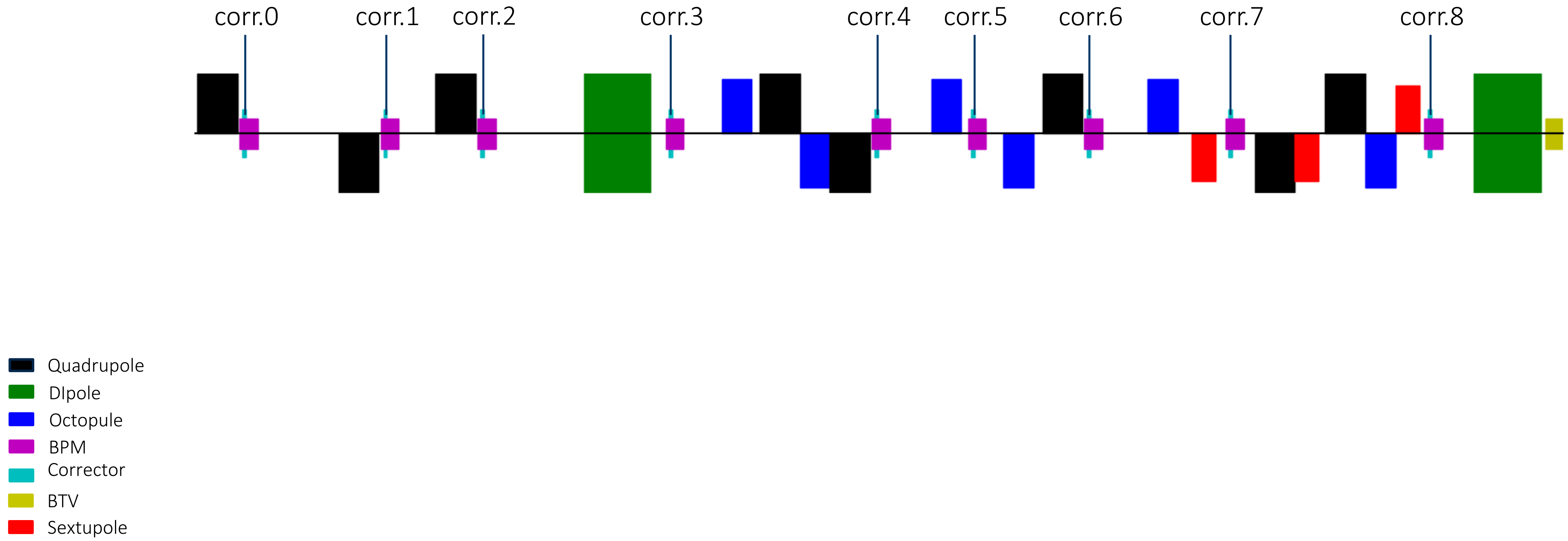
- Evaluate the effect of the beam and power supply jitter on the position and beam size at injection point
  - Select a random set of errors
  - Perform alignment procedure
  - Measure beam position and size at injection point
- Gaol for relative alignment is <=10 um
- The difference between the proton and electron beam position at injection is clearly dominated by proton beam, as shown by Rebecca’s study (work ongoing on proton line power supplies analysis)
- Beam size jitter is very small





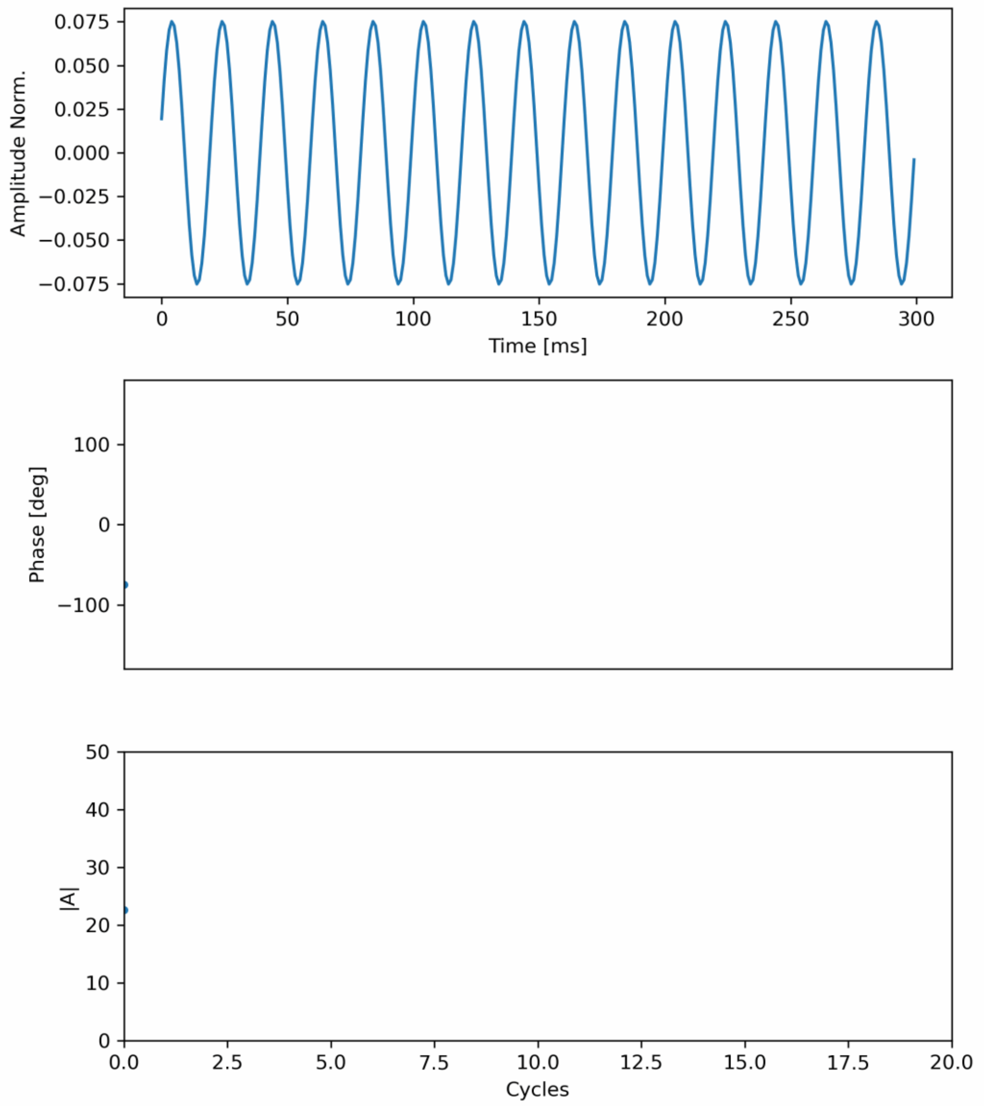


New magnets and BI dimensions



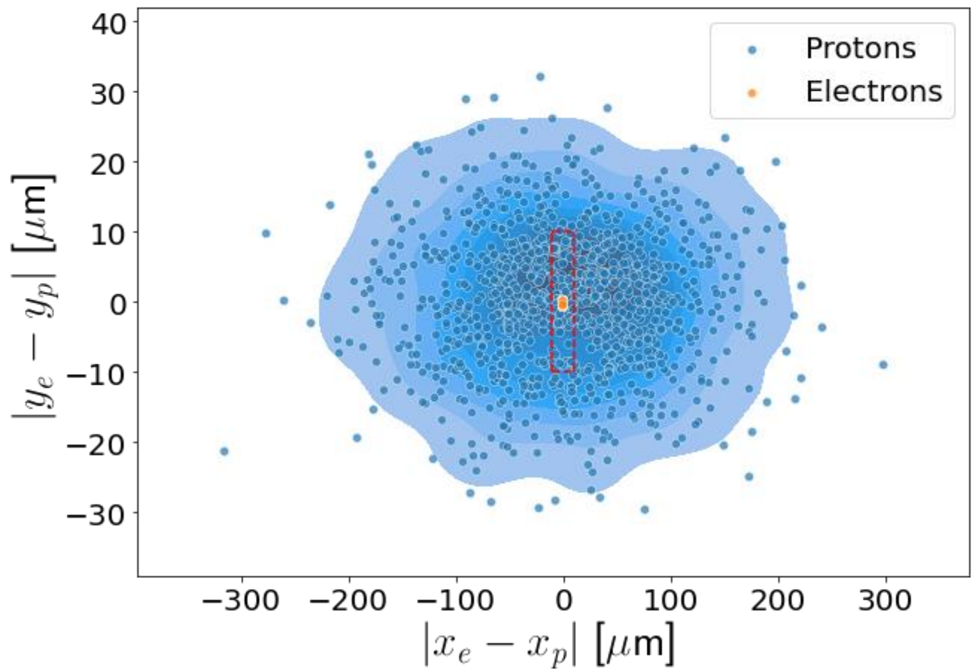
Fourier transform

- In this case 50 Hz components is the more important
- We can select it and check how the current evolves cycle by cycle

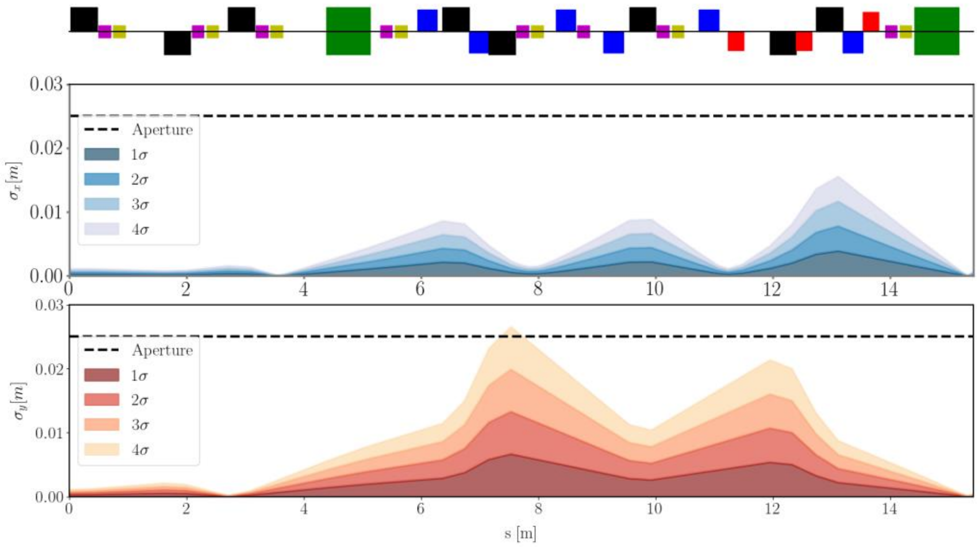


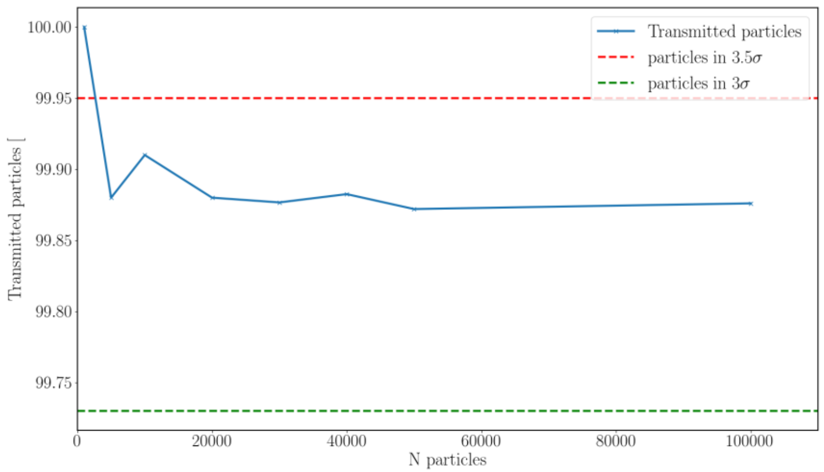
Alignment results

- Study on power converters ripple and beam simulations to quantify the p+ beam jitter at injection point
- Only in the 6% of the cases the alignment between the p+ and e- beam is better than 10 um
- It is completely driven by the proton beam jitter!



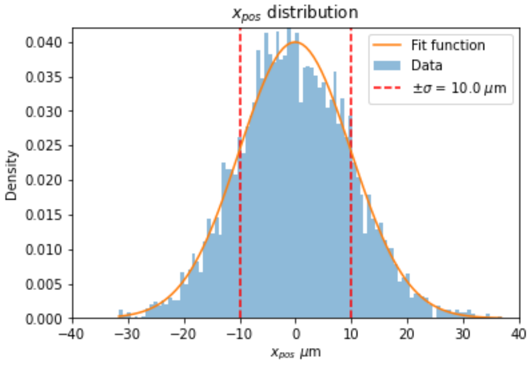
Optimization of the new optics





A practical example

Let’s consider an example with x_{pos} has an RMS jitter of 10 um and the resolution of a BPM in 10 um



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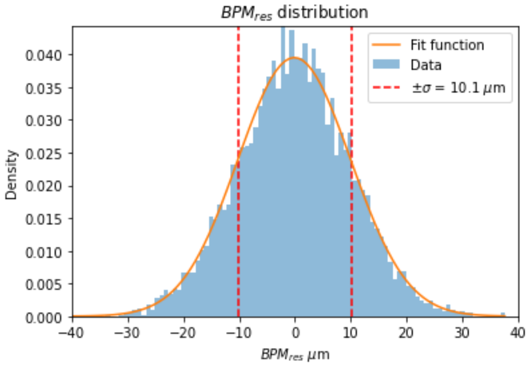

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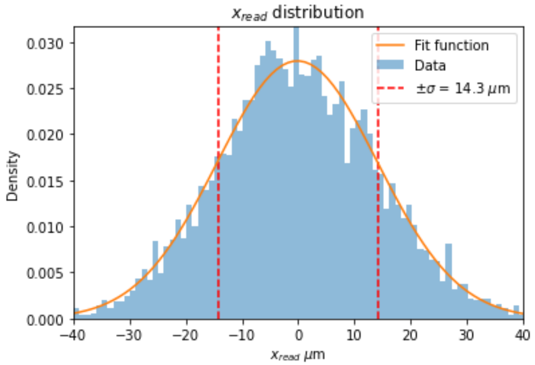
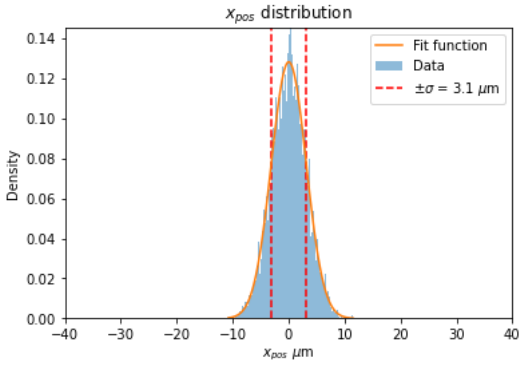


If we consider to average over 10 shots we can therefore reduce the jitter and the resolution, aligning the system more precisely



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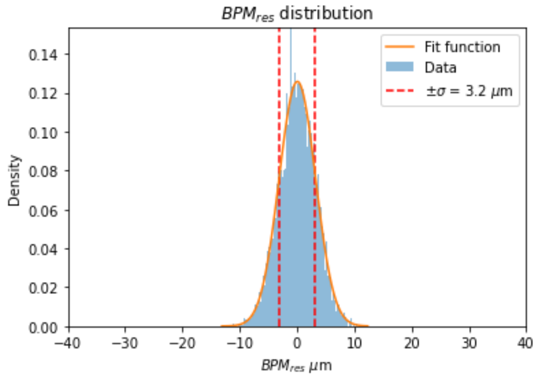

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