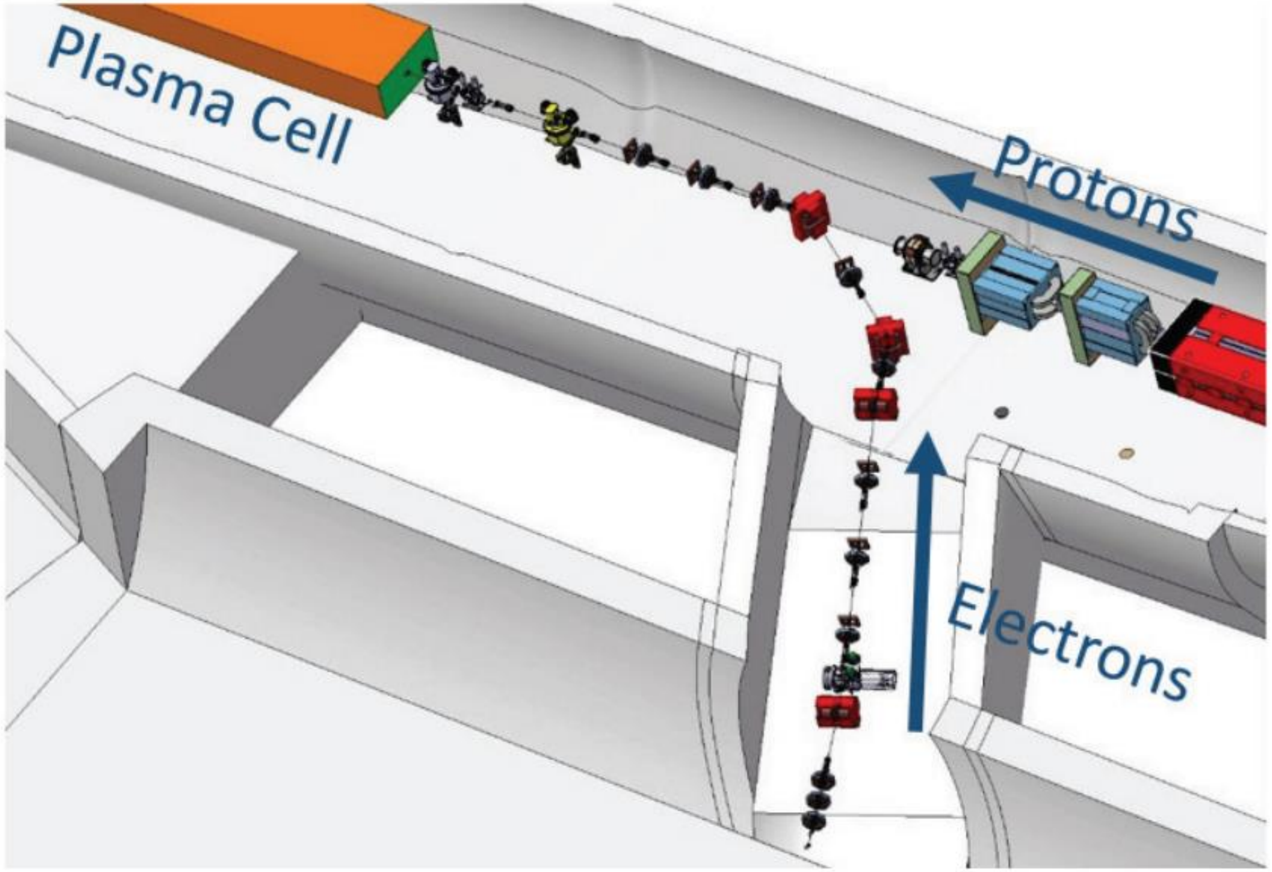
Updates on electron beam lines operations during AWAKE 2022/23 run

V. Bencini, F. Velotti, G. Zevi Della Porta

AWAKE-UK Collaboration Meeting
25/04/2023

Outline

- Main challenges in TT43
- Addressing orthogonal steering issues
  - What is orthogonal steering?
  - Demagnetisation
  - Results
- Phase space tomography
  - Tomography for beam physics
  - Method
  - Results
- Conclusions and next steps



Main challenges

The need of improving the line performance came with the high stability and precision required to perform hosing studies (and in general to improve the operations of the electron line!).

Three key improvement areas were identified:

- Quick optics rematching ➔ Online adjustment of beam parameters at plasma entrance
- Orthogonal steering ➔ Change beam center position and angle at plasma entrance
- Emittance measurement ➔ Precise characterization of input beam distribution

Main challenges

The need of improving the line performance came with the high stability and precision required to perform hosing studies (and in general to improve the operations of the electron line!).

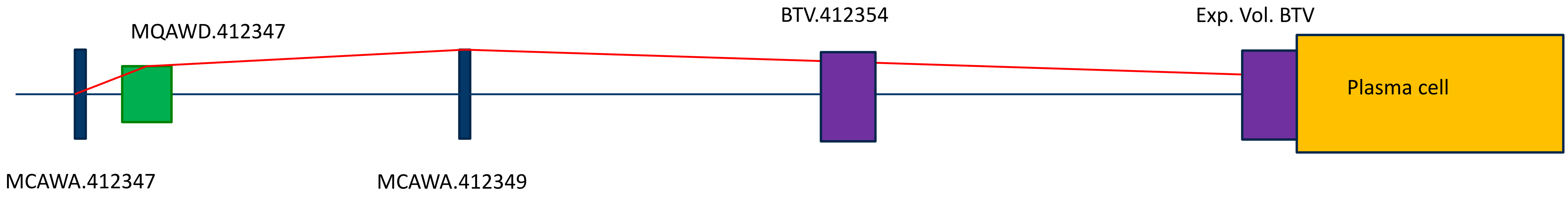
Three key improvement areas were identified:

- Quick optics rematching ➔ Online adjustment of beam parameters at plasma entrance (more details in here)
- Orthogonal steering ➔ Change beam center position and angle at plasma entrance
- Emittance measurement ➔ Precise characterization of input beam distribution

Orthogonal steering

- Use last two correctors to steer the beam at desired angle and position. More details in [ref to my talk]
- Two main issues in achieving the required precision

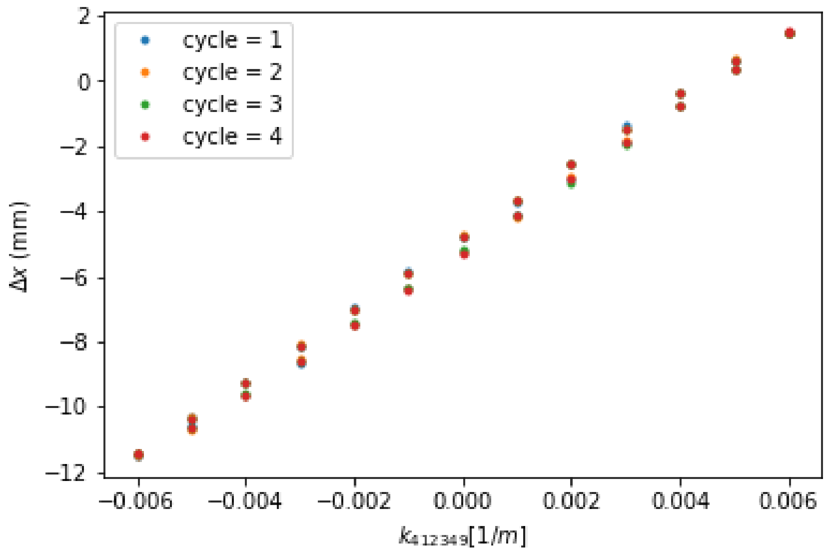
How it was done:



Orthogonal steering

- Use last two correctors to steer the beam at desired angle and position.

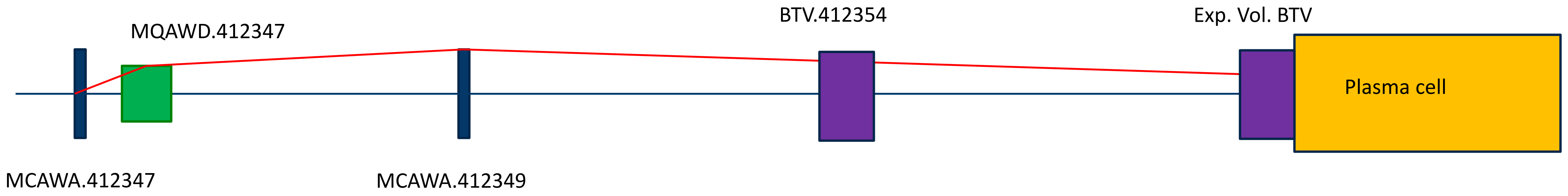
- Two main issues in achieving the required precision
  - ❌ Hysteresis ➔The kick response coefficient change with hysteresis cycle



Orthogonal steering

- Use last two correctors to steer the beam at desired angle and position.
- Two main issues in achieving the required precision:
  - ✗ Hysteresis ➔The kick response coefficient change with hysteresis cycle
  - ✗ Presence of a quadrupole between correctors ➔Additional uncertainty to steering (non linearities, field fluctuations,…)

How it was done:



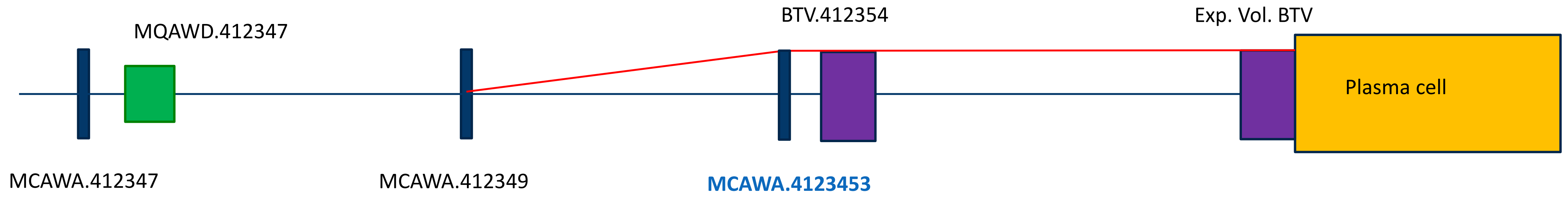
MCAWA.412349

Orthogonal steering

- Use last two correctors to steer the beam at desired angle and position.

- Two main issues in achieving the required precision:
  - ✗ Hysteresis ➔The kick response coefficient change with hysteresis cycle
  - ✗ Presence of a quadrupole between correctors ➔Additional uncertainty to steering (non linearities, field fluctuations,…)

What's new:



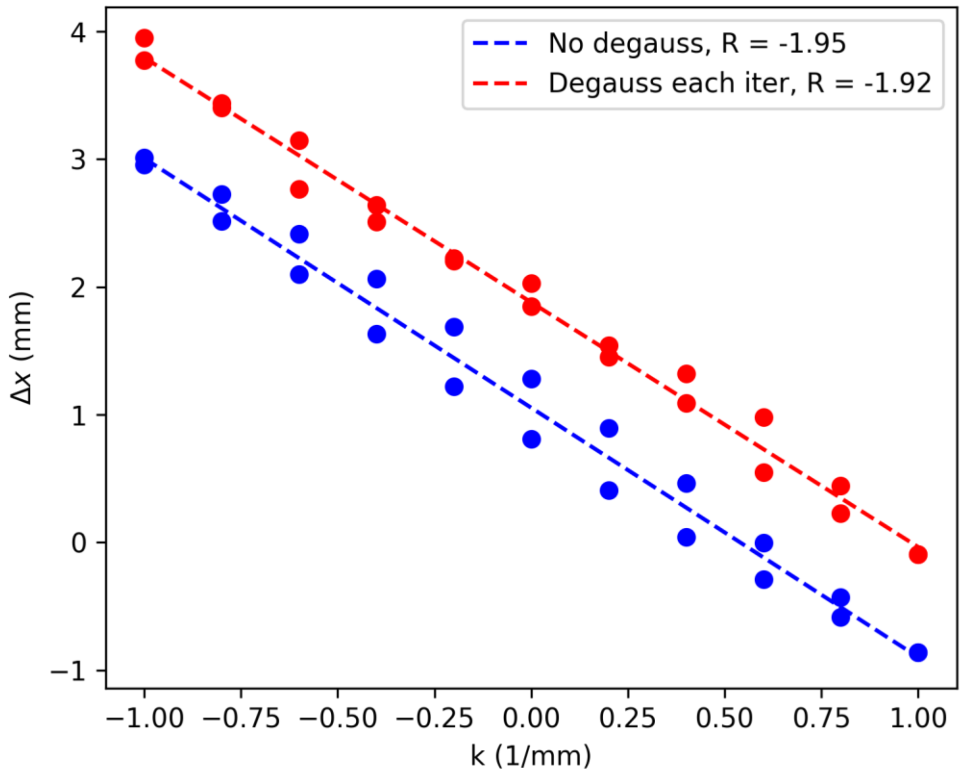
- ✓ New corrector MCAWA.412353 installed.
- ✓ Absence of quadrupole and closer to plasma cell ➔ higher precision

Demagnetisation

- To compensate hysteresis **demagnetisation** can be used
- A **complete** demagnetization cycle consist in:
  - Three cycles between I_{min} (-10 A) and I_{max} (10 A).
  - Follow a dump sinusoidal function toward zero.

- **Advantages:** should provide a response value which is the “real” one (as if no hysteresis existed).

- **Drawbacks:** Unstable, time expensive (minutes per cycle).



Demagnetisation

- To compensate hysteresis **demagnetisation** can be used
- A **complete** demagnetization cycle consist in:
  - Three cycles between I_{min} (-10 A) and I_{max} (10 A).
  - Follow a dump sinusoidal function toward zero.

- **Advantages:** should provide a response value which is the "real" one (as if no hysteresis existed).

- **Drawbacks:** Unstable, time expensive (minutes per cycle).

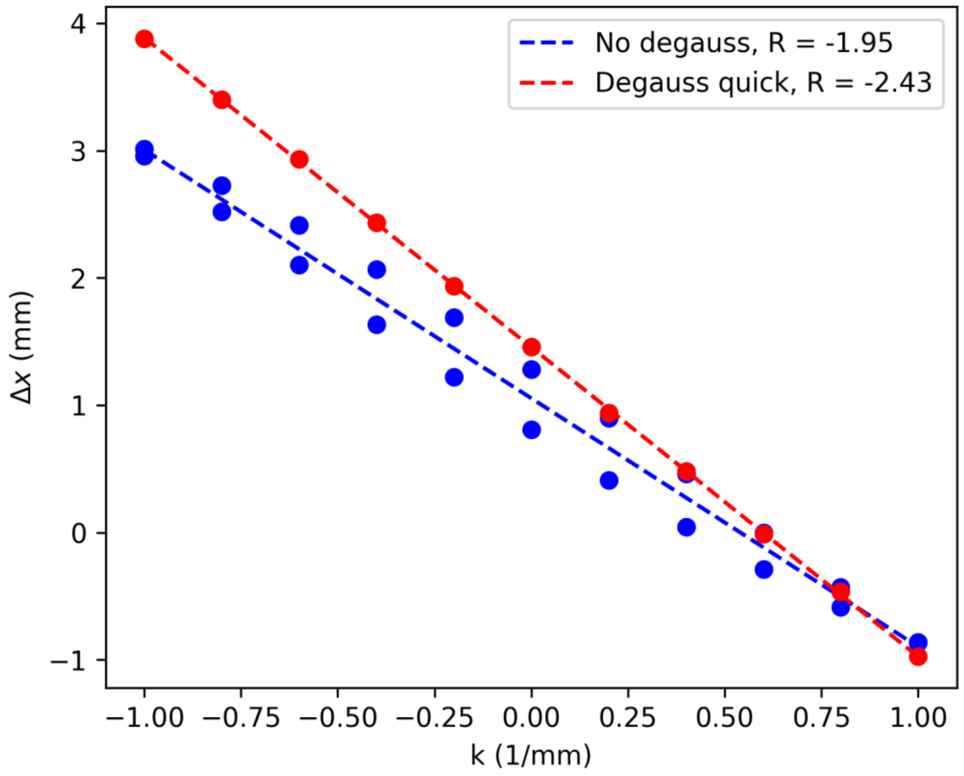
A better solution: Quick demagnetization (thanks magnet experts and Giovanni)

- Only goes from I_{min} to I_{max} and then to the set k.

- **Advantages:** Highly reproducible, small error (<15 µm RMS around the fit line)

- **Drawbacks:** The response coefficients is not the "real" one.

K = -1:0.2:1



Demagnetisation

- To compensate hysteresis **demagnetisation** can be used
- A **complete** demagnetization cycle consist in:
  - Three cycles between I_{min} (-10 A) and I_{max} (10 A).
  - Follow a dump sinusoidal function toward zero.

- **Advantages:** should provide a response value which is the “real” one (as if no hysteresis existed).

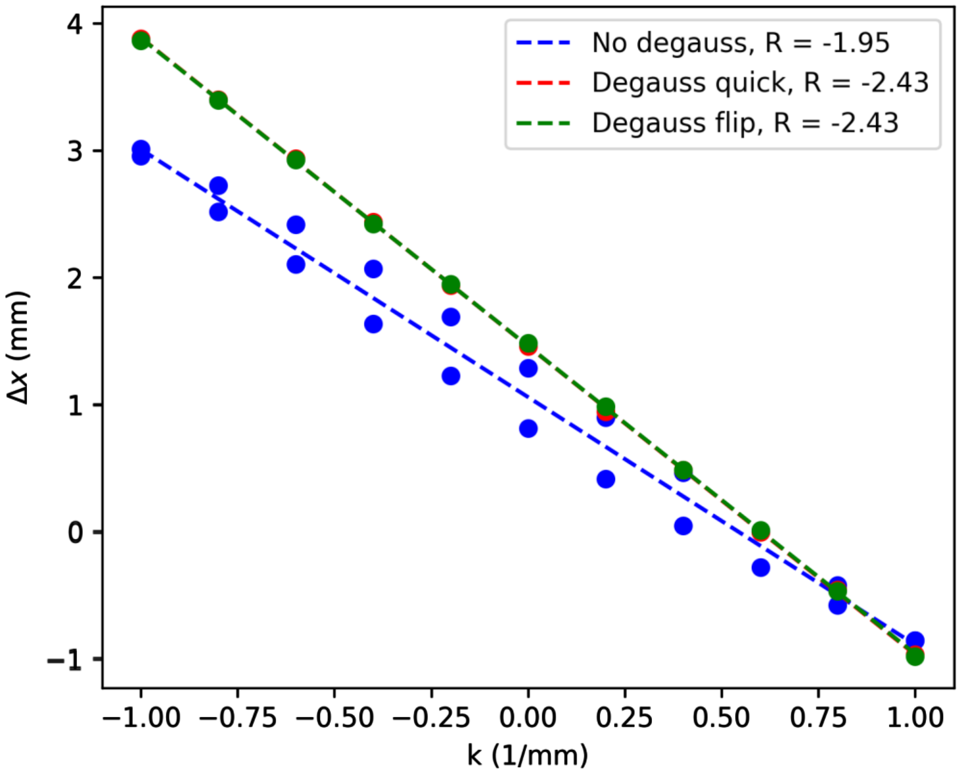
- **Drawbacks:** Unstable, time expensive (minutes per cycle).

A better solution: Quick demagnetization (thanks magnet experts and Giovanni)
- Only goes from I_{min} to I_{max} and then to the set k.

- **Advantages:** Highly reproducible, small error (<15 μm RMS around the fit line)

- **Drawbacks:** The response coefficients is not the “real” one.

K = 1:0.2:-1



Demagnetisation

- To compensate hysteresis **demagnetisation** can be used
- A **complete** demagnetization cycle consist in:
  - Three cycles between I_{min} (-10 A) and I_{max} (10 A).
  - Follow a dump sinusoidal function toward zero.

- **Advantages:** should provide a response value which is the "real" one (as if no hysteresis existed).

- **Drawbacks:** Unstable, time expensive (minutes per cycle).

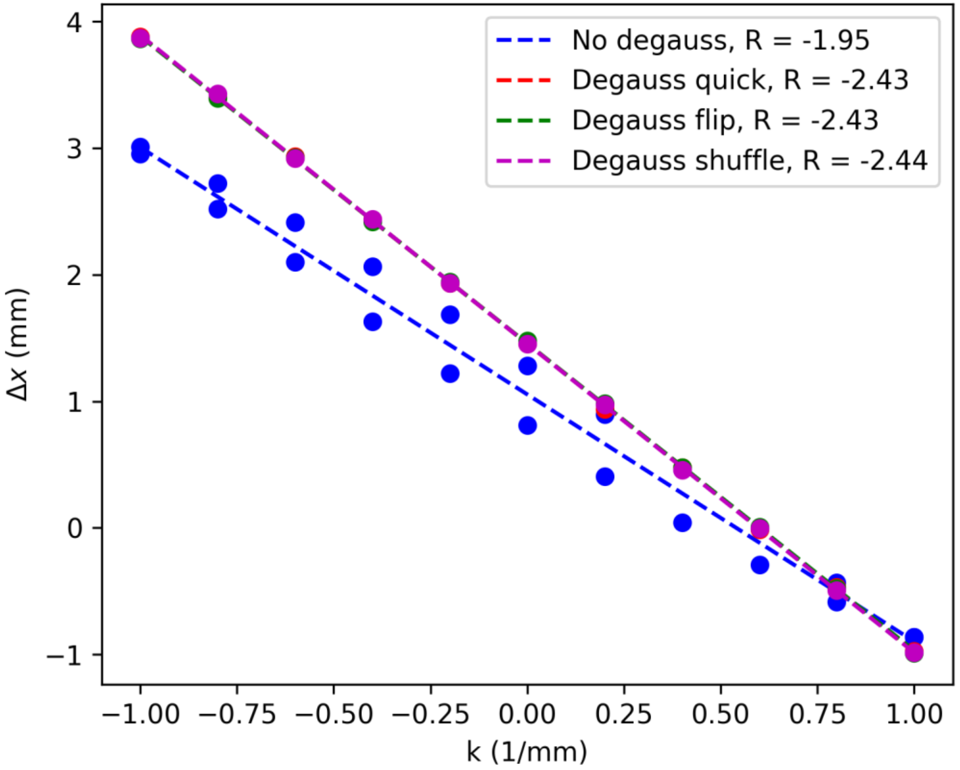
A better solution: Quick demagnetization (thanks magnet experts and Giovanni)

- Only goes from I_{min} to I_{max} and then to the set k.

- **Advantages:** Highly reproducible, small error (<15 µm RMS around the fit line)

- **Drawbacks:** The response coefficients is not the "real" one.

K = [0.0, -1.0, 0.8, 1.0, -0.6, -0.8, 0.6, -0.2, 0.4, -0.4, 0.2]



Demagnetisation

- To compensate hysteresis **demagnetisation** can be used
- A **complete** demagnetization cycle consist in:
  - Three cycles between I_{min} (-10 A) and I_{max} (10 A).
  - Follow a dump sinusoidal function toward zero.

- **Advantages:** should provide a response value which is the "real" one (as if no hysteresis existed).

- **Drawbacks:** Unstable, time expensive (minutes per cycle).

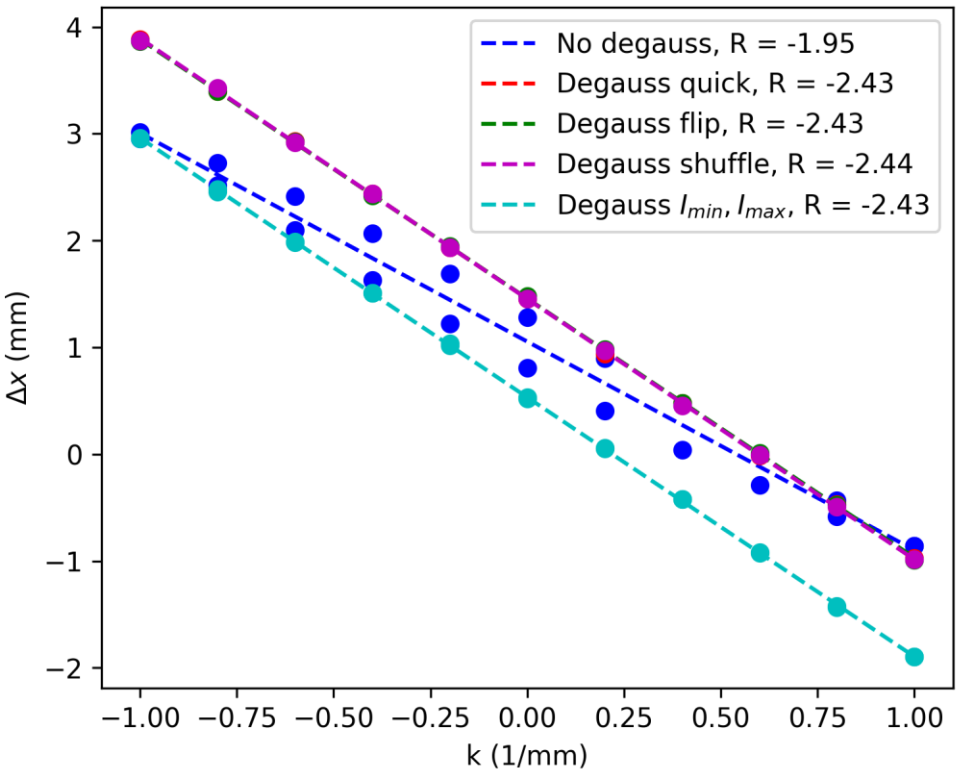
A better solution: Quick demagnetization (thanks magnet experts and Giovanni)

- Only goes from I_{min} to I_{max} and then to the set k.

- **Advantages:** Highly reproducible, small error (<15 µm RMS around the fit line)

- **Drawbacks:** The response coefficients is not the "real" one.

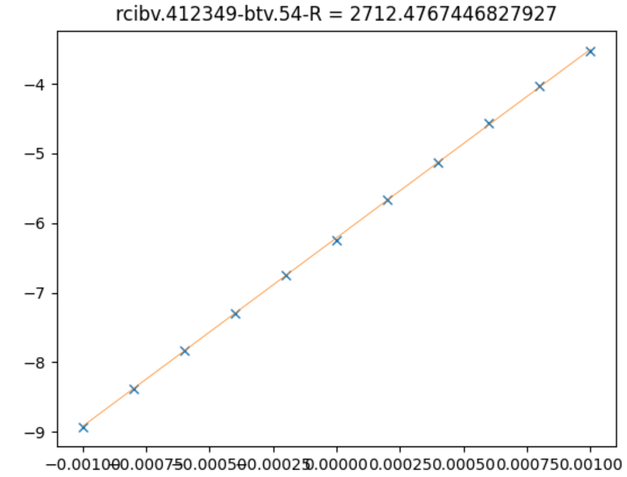
Inverting cycle order from I_{max} to I_{min}

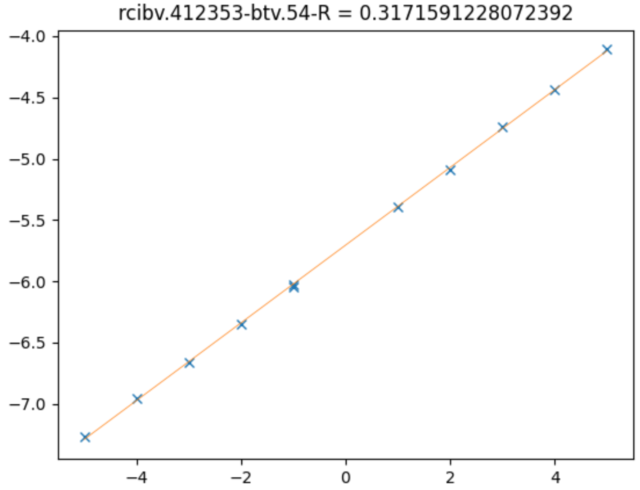


Results

- Tested quick demagnetization for orthogonal steering.

- Preparing for the test
  1. Included quick degauss in orthogonal steering script
  2. Measured response coefficients for both MCAWA.412349 and MCAWA.412353
  3. Plug new coefficients in script





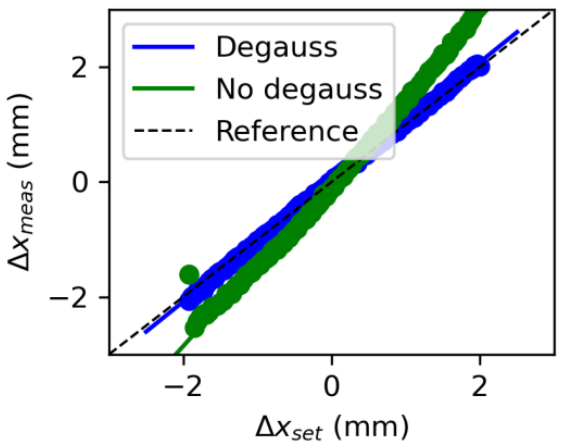
Results

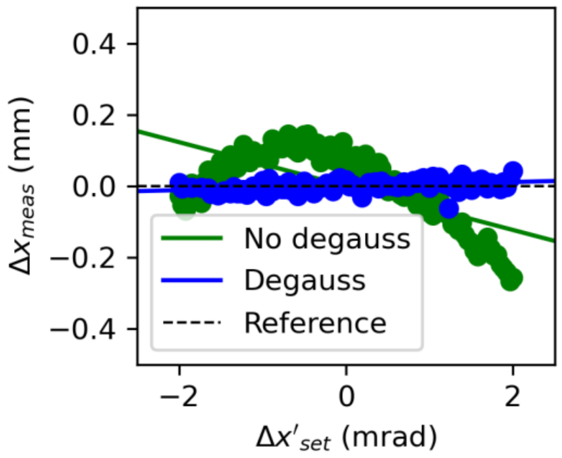
- Tested quick demagnetization for orthogonal steering.

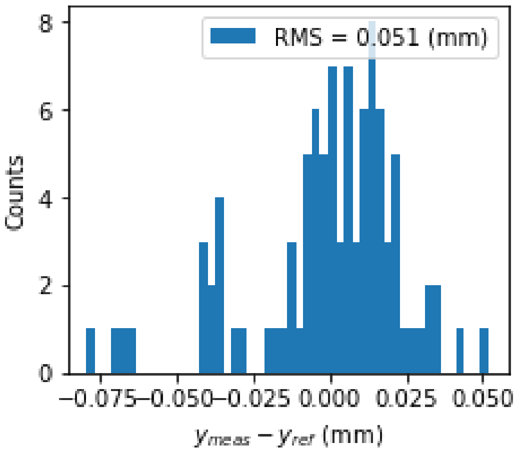
- Preparing for the test
  1. Included quick degauss in orthogonal steering script
  2. Measured response coefficients for both MCAWA.412349 and MCAWA.412353
  3. Plug new coefficients in script

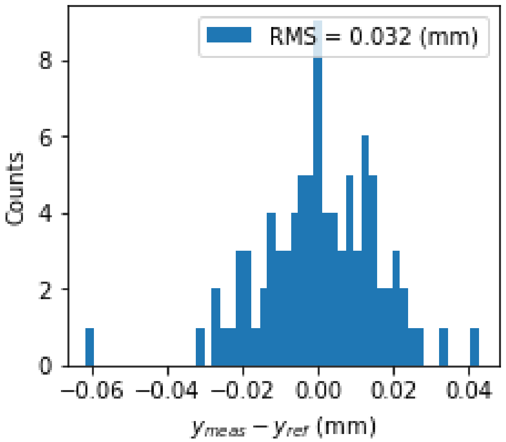
- Performed two scans:
  1. Position with constant angle ($\Delta x' = 0$) at BTV.54
  2. Angle with constant position ($\Delta x = 0$) at BTV.54

- Extremely good accuracy in setting position and angles was observed.
- Errors in the order of magnitude of beam jitter!









Emittance measurement

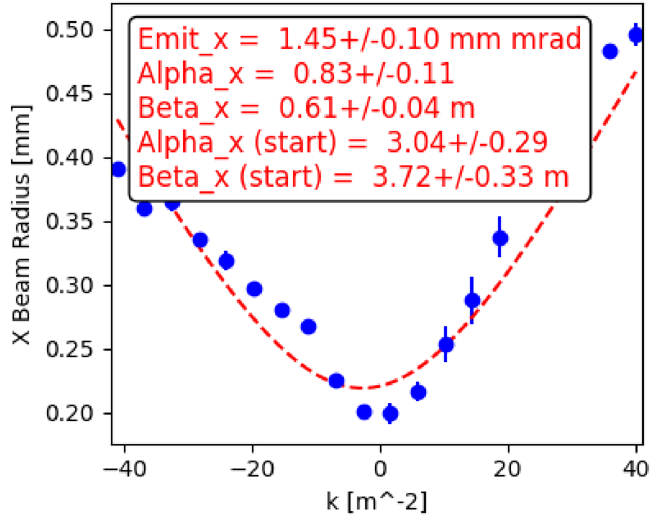
- Emittance measurement is fundamental to obtain good agreement between simulations and measurements

Emittance measurement

- Emittance measurement is fundamental to obtain good agreement between simulations and measurements

How it was done:

- Presently emittance is measured using classical quad scan
  1. Fit gaussian to measured beam profile
  2. Fit proper parabolic function
  3. Extract the Twiss parameters



- Main limitations to accuracy:
  - ❌ Beam is not gaussian!
  - ❌ Parabolic curve does not fit measurements (in x plane at least)

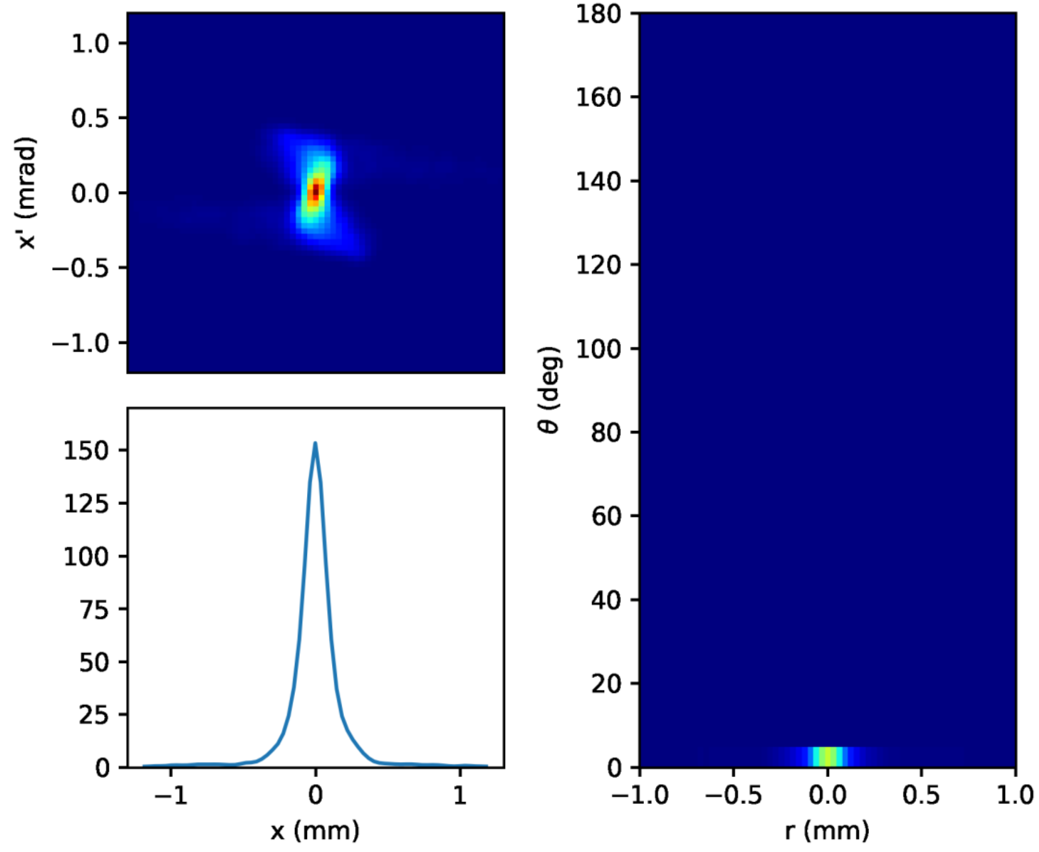
Solution (under development)

- Use phase space tomographic reconstruction.

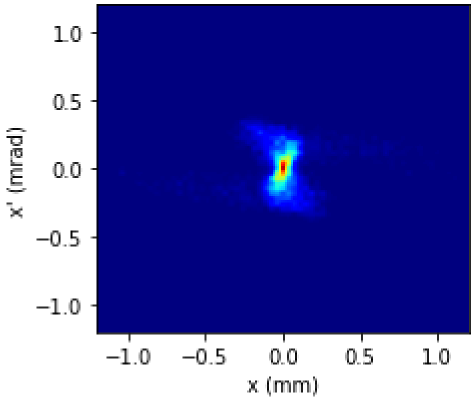
Emittance measurement

- We can use 1D projections taken from different angles around an object to reconstruct the 2D object itself
- The projections are stacked in a 2D image called **sinogram**

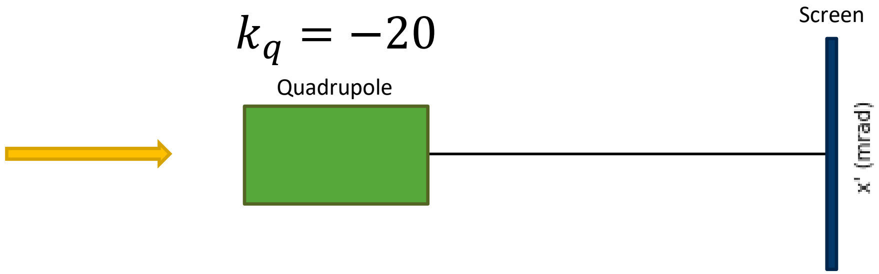
➡ Quadrupole scan is equivalent (with some tricks) to rotation in phase space!

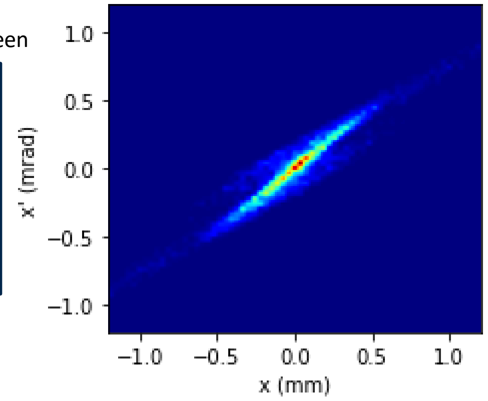


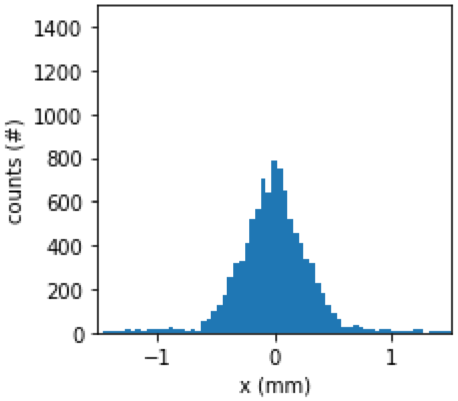
How this applies to beam physics?



$$k_q = -20$$

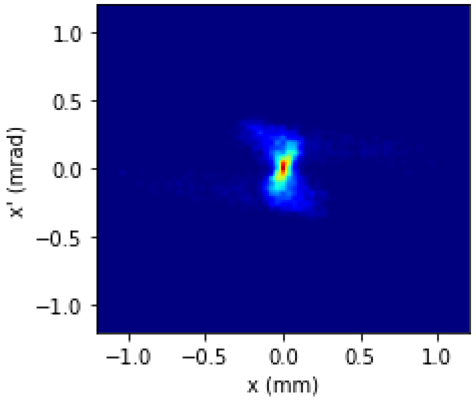




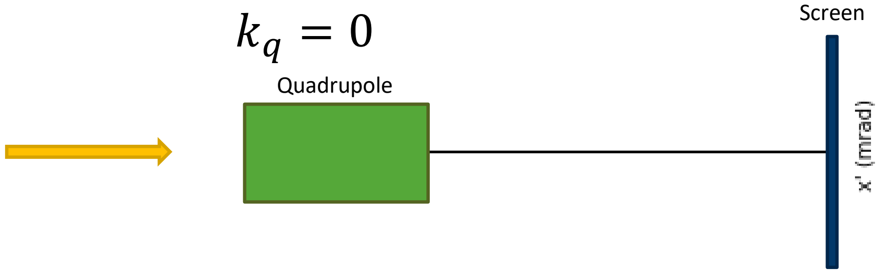


$$\begin{bmatrix} x_s \\ x'_s \end{bmatrix} = \begin{bmatrix} M_{1,1}(k_q) & M_{1,2}(k_q) \\ M_{2,1}(k_q) & M_{2,2}(k_q) \end{bmatrix} \begin{bmatrix} x_0 \\ x'_0 \end{bmatrix}$$

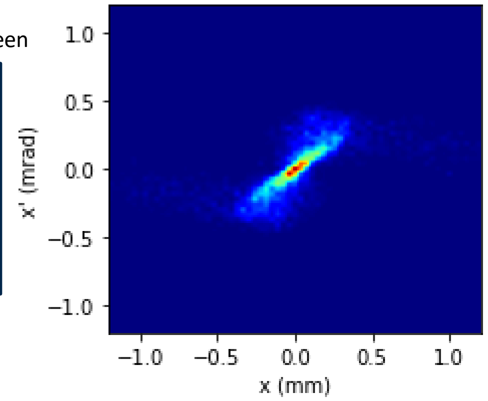
How this applies to beam physics?

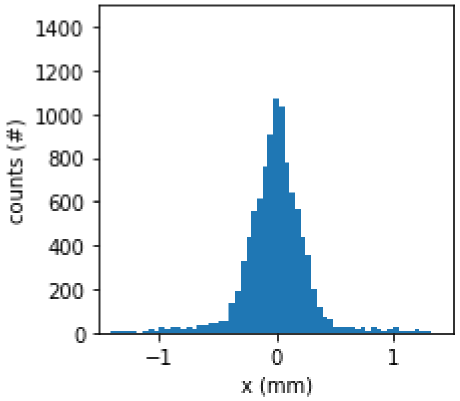


$$k_q = 0$$

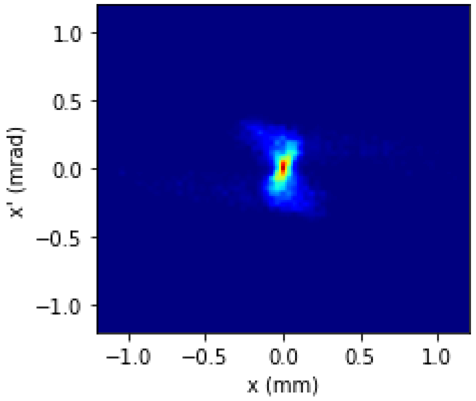


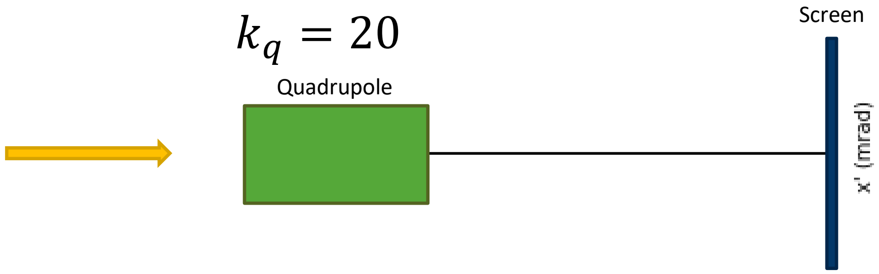
$$\begin{bmatrix} x_s \\ x'_s \end{bmatrix} = \begin{bmatrix} M_{1,1}(k_q) & M_{1,2}(k_q) \\ M_{2,1}(k_q) & M_{2,2}(k_q) \end{bmatrix} \begin{bmatrix} x_0 \\ x'_0 \end{bmatrix}$$



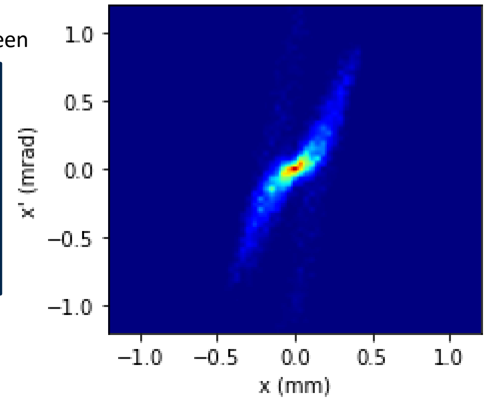


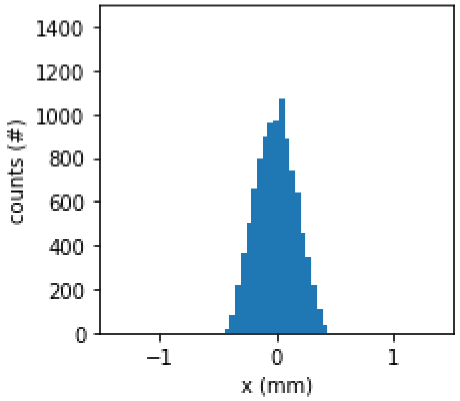
How this applies to beam physics?



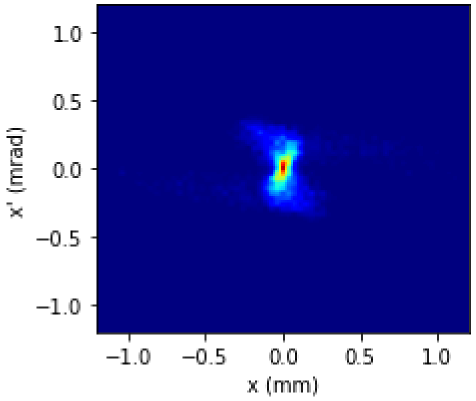


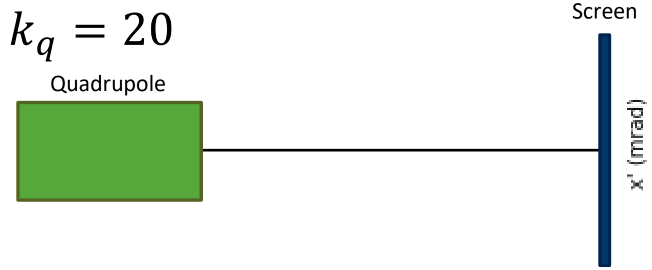
$$\begin{bmatrix} x_s \\ x'_s \end{bmatrix} = \begin{bmatrix} M_{1,1}(k_q) & M_{1,2}(k_q) \\ M_{2,1}(k_q) & M_{2,2}(k_q) \end{bmatrix} \begin{bmatrix} x_0 \\ x'_0 \end{bmatrix}$$

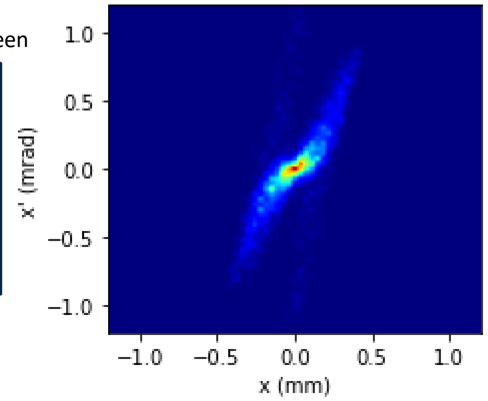


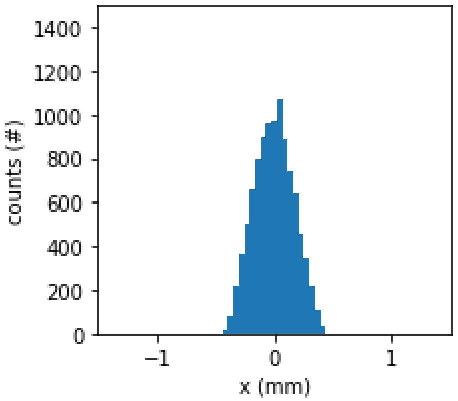


How this applies to beam physics?

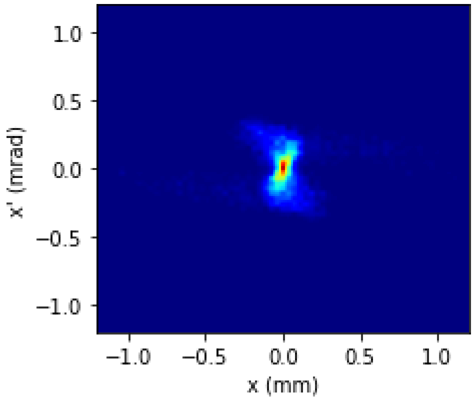








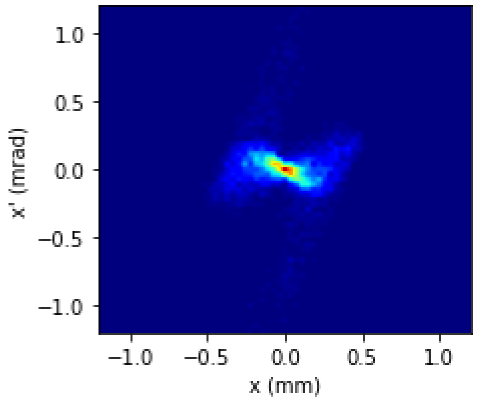
$$\begin{bmatrix} x_s \\ x'_s \end{bmatrix} = \begin{bmatrix} M_{1,1}(k_q) & M_{1,2}(k_q) \\ M_{2,1}(k_q) & M_{2,2}(k_q) \end{bmatrix} \begin{bmatrix} x_0 \\ x'_0 \end{bmatrix}$$

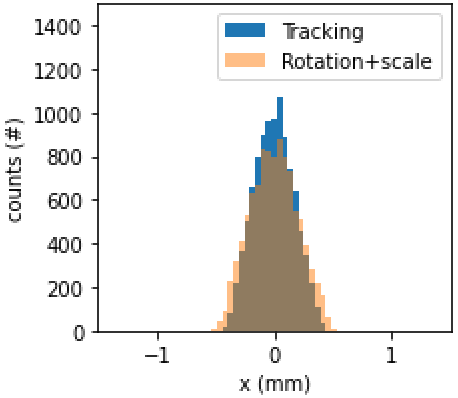


ROTATE

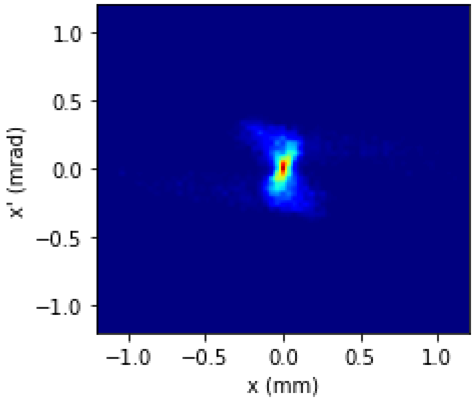
$$\theta = \operatorname{atan}\left(\frac{M_{1,1}(k_q)}{M_{1,2}(k_q)}\right)$$

$$\theta = 101°$$

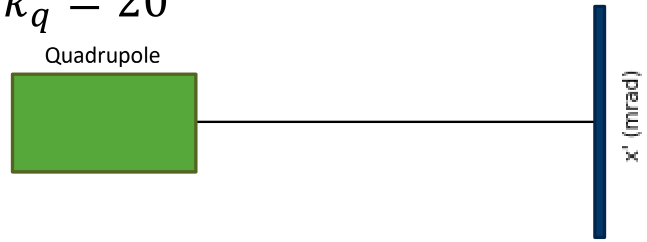


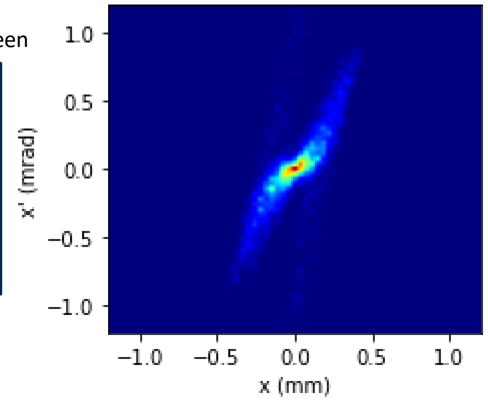


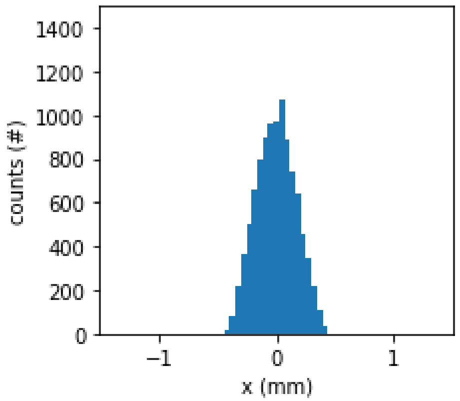
How this applies to beam physics?



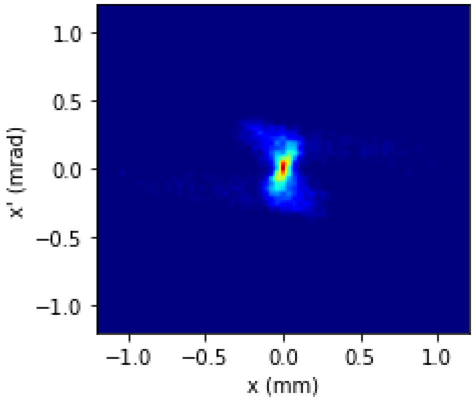
$$k_q = 20$$







$$\begin{bmatrix} x_s \\ x'_s \end{bmatrix} = \begin{bmatrix} M_{1,1}(k_q) & M_{1,2}(k_q) \\ M_{2,1}(k_q) & M_{2,2}(k_q) \end{bmatrix} \begin{bmatrix} x_0 \\ x'_0 \end{bmatrix}$$



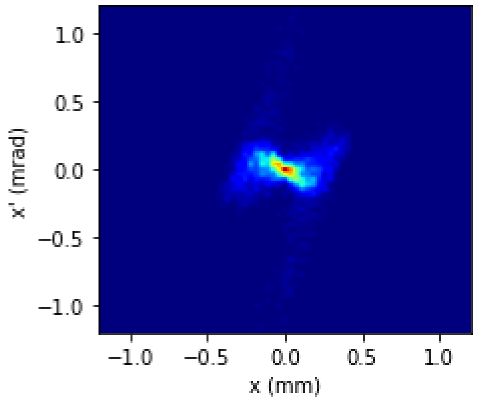
ROTATE

$$\theta = \operatorname{atan}\left(\frac{M_{1,1}(k_q)}{M_{1,2}(k_q)}\right)$$

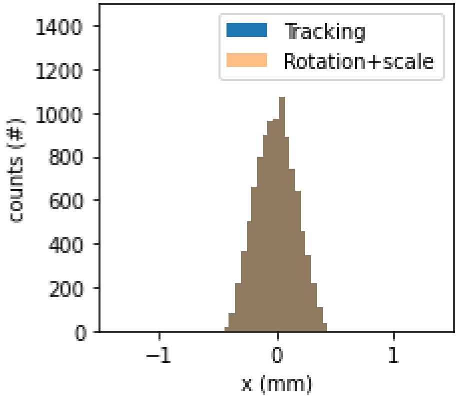
SCALE

$$s = \sqrt{M_{1,1}^2(k_q) + M_{1,2}^2(k_q)}$$

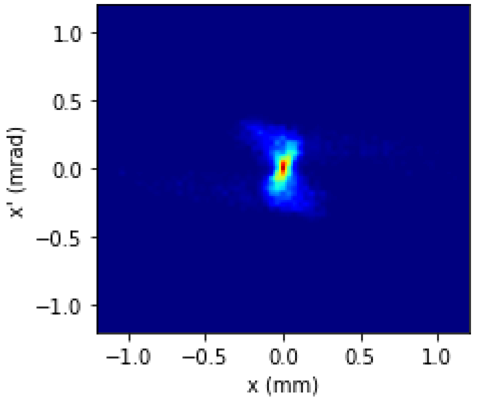
$$\theta = 101°$$



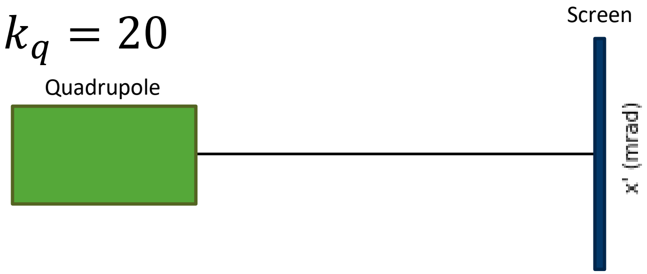
$$s = 0.84$$

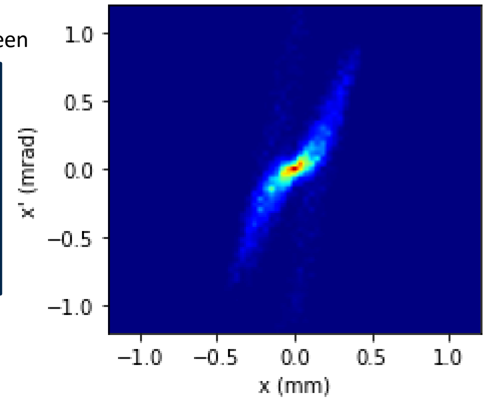


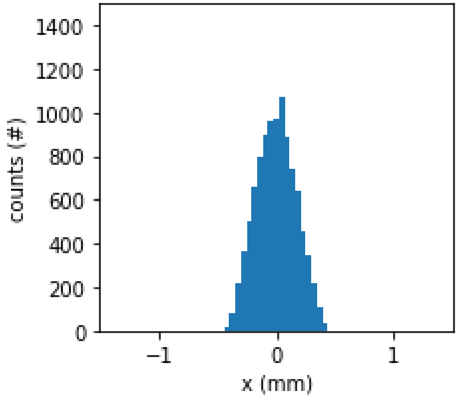
How this applies to beam physics?



$$k_q = 20$$

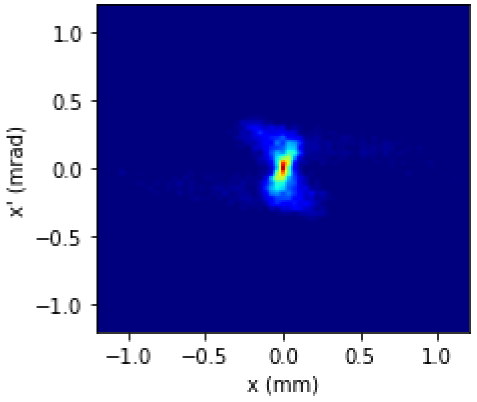






$$\begin{bmatrix} x_s \\ x'_s \end{bmatrix} = \begin{bmatrix} M_{1,1}(k_q) & M_{1,2}(k_q) \\ M_{2,1}(k_q) & M_{2,2}(k_q) \end{bmatrix} \begin{bmatrix} x_0 \\ x'_0 \end{bmatrix}$$

THANKS TO THIS TRANSFORMATION WE TREAT IT AS A TOMOGRAPHY PROBLEM!



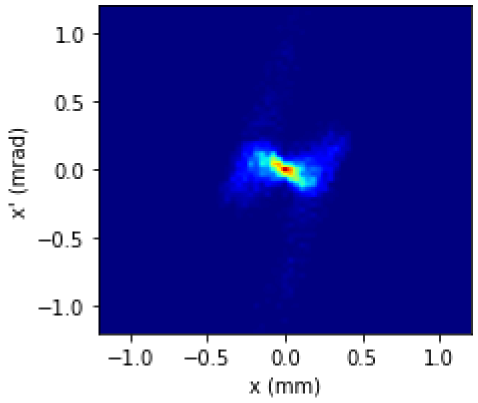
ROTATE

$$\theta = \mathrm{atan}\left(\frac{M_{1,1}(k_q)}{M_{1,2}(k_q)}\right)$$

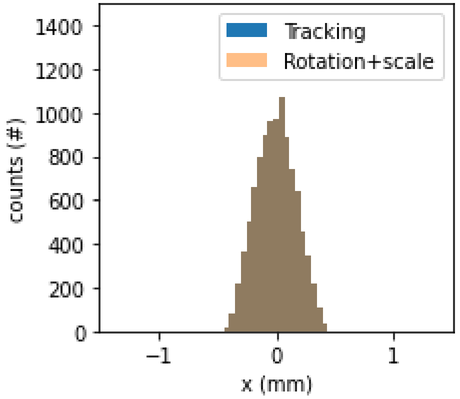
SCALE

$$s = \sqrt{M_{1,1}^2(k_q) + M_{1,2}^2(k_q)}$$

$$\theta = 101°$$



$$s = 0.84$$



Reconstruction method

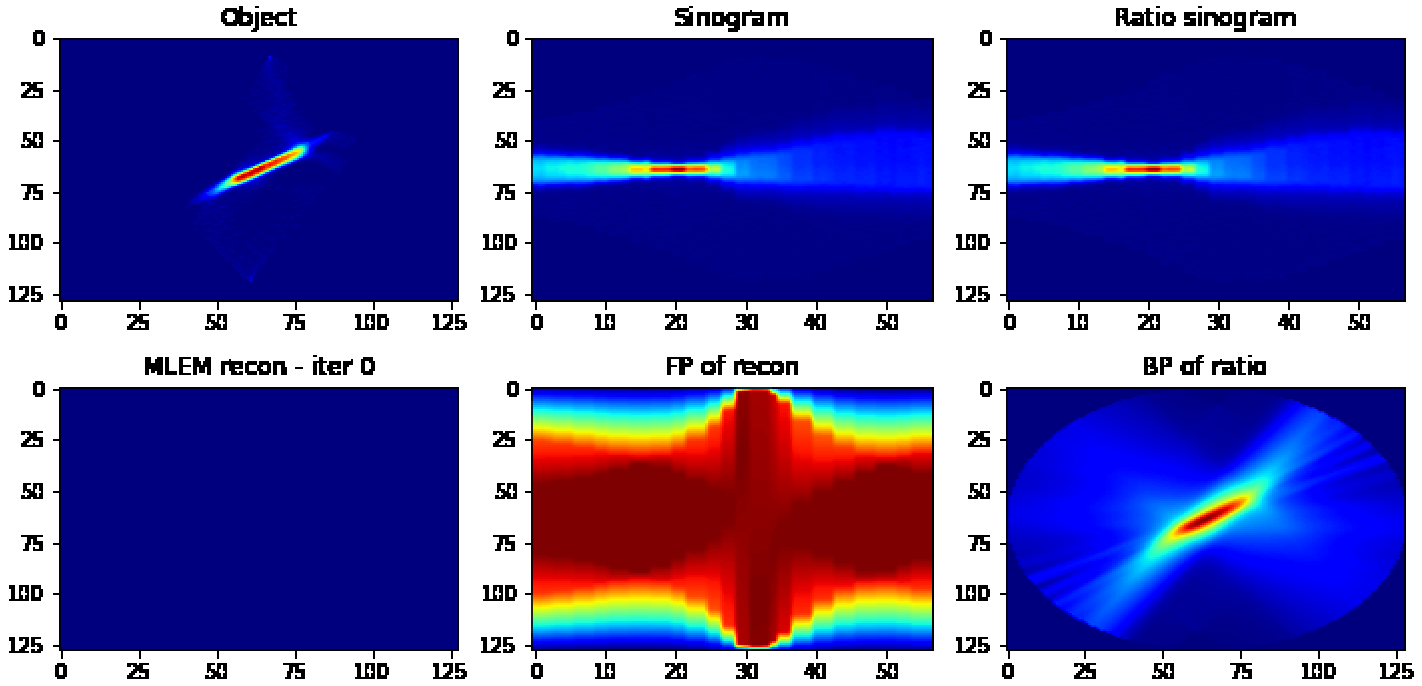
- **Maximum Likelihood Expectation Maximisation** was selected as reconstruction method:

- It is an iterative method that follow the steps:
  1. Assume a prior distribution and forward propagate (FP) getting the corresponding sinogram.
  2. Take the ratio between the original sinogram and the propagated one and back propagate (BP) it.
  3. Multiply the old distribution by the correction matrix
  4. Repeat until the two sinograms are identical

Reconstruction method

- Maximum Likelihood Maximum Estimation was selected as reconstruction method:

- It is an iterative method that follow the steps:
  1. Assume a prior distribution and forward propagate (FP) getting the corresponding sinogram.
  2. Take the ratio between the original sinogram and the propagated one and back propagate (BP) it.
  3. Multiply the old distribution by the correction matrix
  4. Repeat until the two sinograms are identical



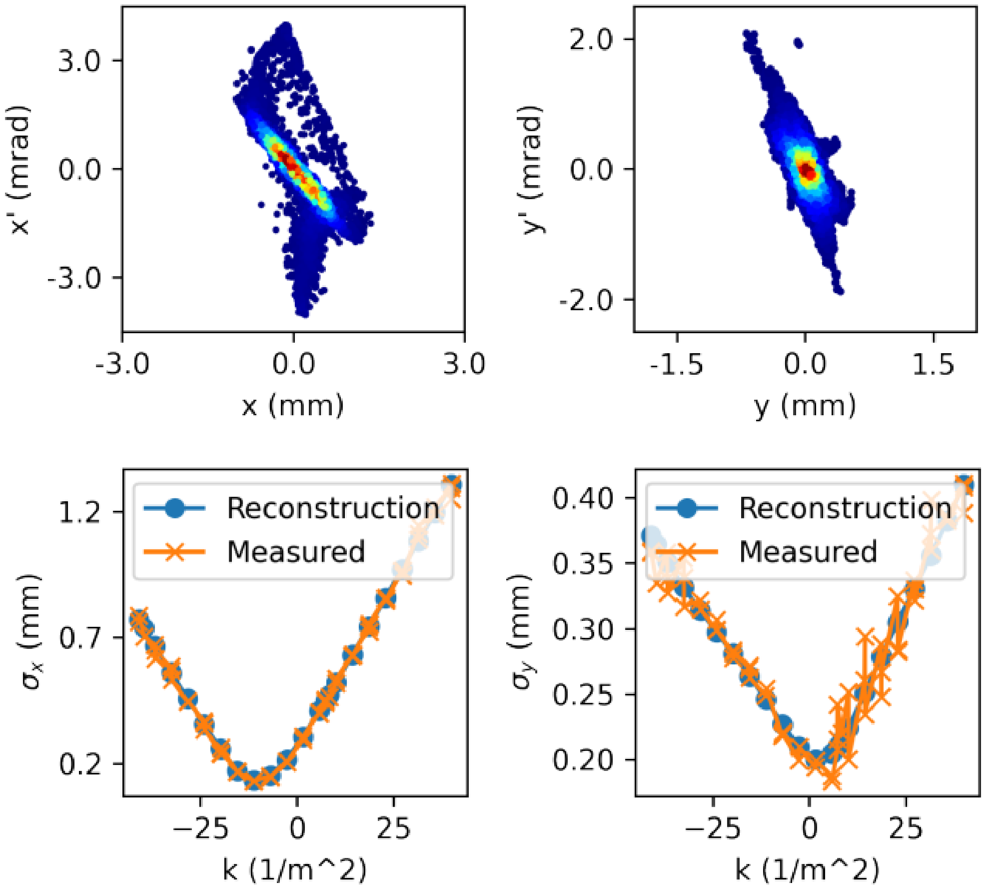
Reconstruction method

Used old measurement for emittance reconstruction

To compare the outputs:

- Track reconstructed beam at same k_quad as the measurements
- Fit a gaussian and take $\sigma_{x,y}$ to both measurements and simulations
- Compare the two curves

Very good agreement between simulations and measurements!



Conclusions and next steps

Conclusions

- Past year was fundamental to gain a better knowledge of the issues of the beam line and develop tools to address them.
- Orthogonal steering can finally be used as operational tool for alignment with high precision.
- Phase space tomography developed in simulations and tested on AWAKE beam.
- The results match very well with expectations. This method could be used for diagnostics at different points along AWAKE!

Run periods

- (laser) Align marker [and IR] on streak camera ✅
- (e) Estimate uncertainty from IN/OUT screen motion ✅
- (e) Commission orthogonal steering with new corrector
- (p) Estimate position uncertainty on YAG vs OTR screen
- (e) Test 4D tomography of beam
- (e) Commission optimizer to match beamline to injector
- (e) Test cycling (vs de-gaussing) for hysteresis ✅

Conclusions and next steps

Conclusions

- Past year was fundamental to gain a better knowledge of the issues of the beam line and develop tools to address them.
- Orthogonal steering can finally be used as operational tool for alignment with high precision.
- Phase space tomography developed in simulations and tested on AWAKE beam.
- The results match very well with expectations. This method could be used for diagnostics at different points along AWAKE!

Run periods

- (laser) Align marker [and IR] on streak camera
- (e) Estimate uncertainty from IN/OUT screen motion
- (e) Commission orthogonal steering with new corrector
- (p) Estimate position uncertainty on YAG vs OTR screen
- (e) Test 4D tomography of beam
- (e) Commission optimizer to match beamline to injector
- (e) Test cycling (vs de-gaussing) for hysteresis

Conclusions and next steps

Conclusions

- Past year was fundamental to gain a better knowledge of the issues of the beam line and develop tools to address them.
- Orthogonal steering can finally be used as operational tool for alignment with high precision.
- Phase space tomography developed in simulations and tested on AWAKE beam.
- The results match very well with expectations. This method could be used for diagnostics at different points along AWAKE!

Next step

- Improve operational tool to perform orthogonal steering (integrate kick response scan feature).
- Deploy operational tool to perform phase space tomography (for the moment is performed offline).
- Use the reconstructed beam distribution in simulations and compare with measurements.

Thank you for your attention!

Main challenges

In 2022/23 the experiment required to produce a new set optics to test new experimental configurations

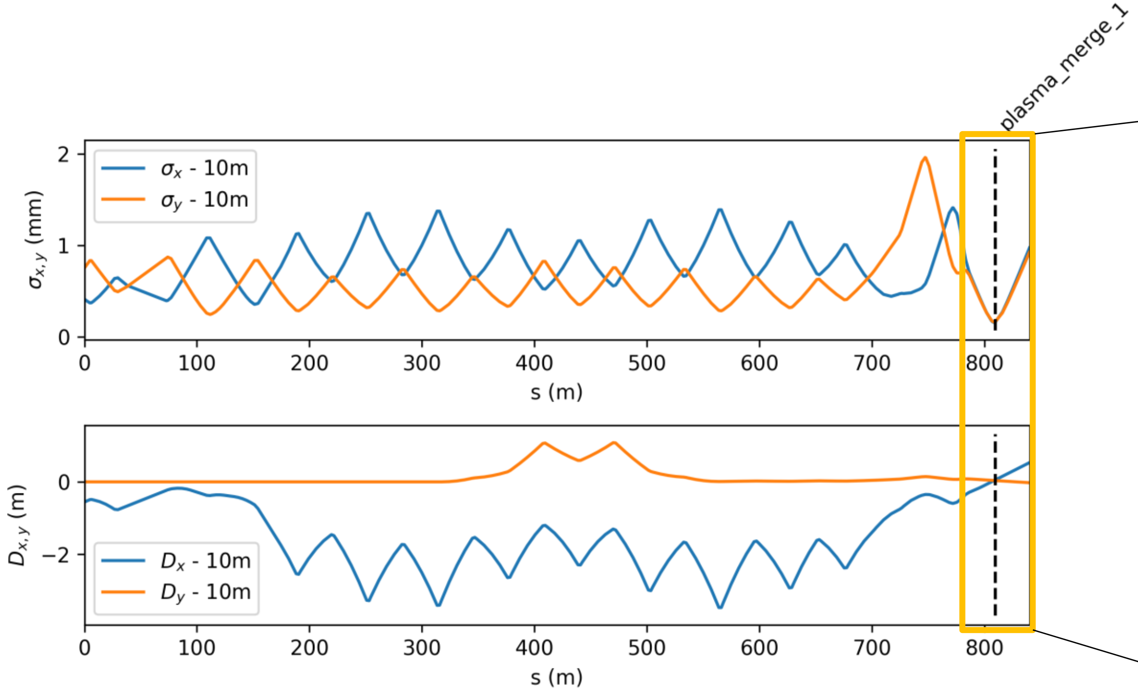
The main challenges were:

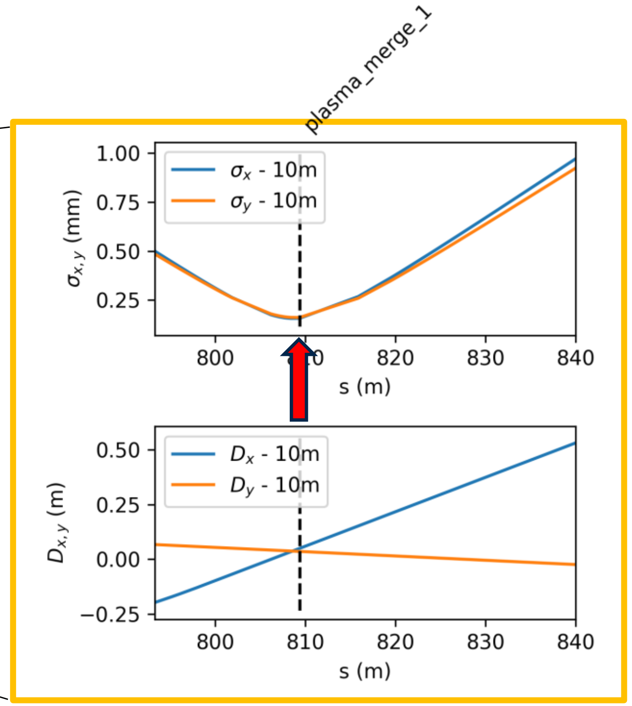
- Generate with simulations new optics with a waist of 500 um at the plasma entrance
- Test and benchmark simulations with measurements
- Produce new optics for Discharge Plasma Source

	QS x	PT x	QS y	PT y
$\alpha_{x,y}$	1.12	1.05	0.31	0.81
$\beta_{x,y}$	0.61	0.54	0.31	0.43
$\varepsilon_{x,y}$	0.209	0.27	0.093	0.055

PT = Phase Tomography
QS = Quad Scan

TT41 optics

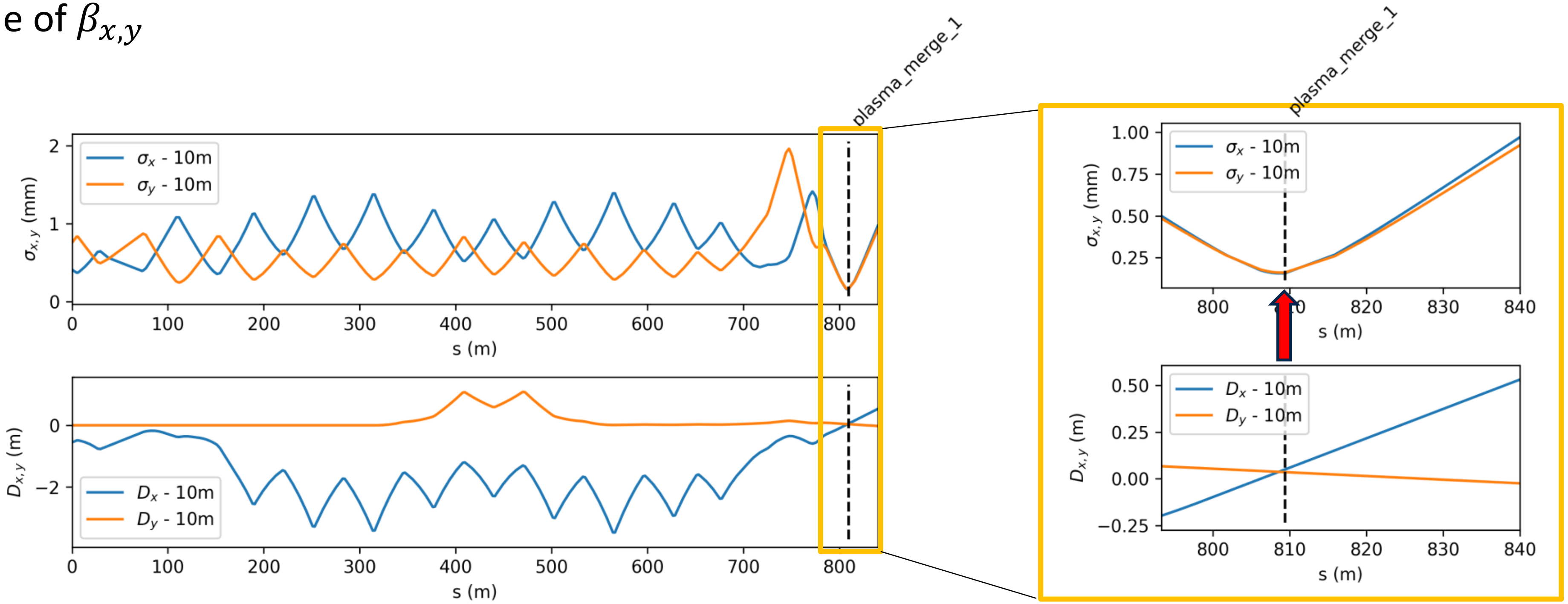

plasma_merge_1
σ_x - 10m
σ_y - 10m
$\sigma_{x,y}$ (mm)
s (m)
D_x - 10m
D_y - 10m
$D_{x,y}$ (m)
s (m)


plasma_merge_1
σ_x - 10m
σ_y - 10m
$\sigma_{x,y}$ (mm)
s (m)
D_x - 10m
D_y - 10m
$D_{x,y}$ (m)
s (m)

TT41 optics

Optimization problem:

Variables: 7 quads strengths
Constraints: given by the quads' current limits (and polarity) and sign
Objective function: include $\alpha_{x,y}$, $D_{x,y}$, $\sigma_{x,y}$, $|\sigma_x - \sigma_y|$, a limit for maximum value of $\beta_{x,y}$



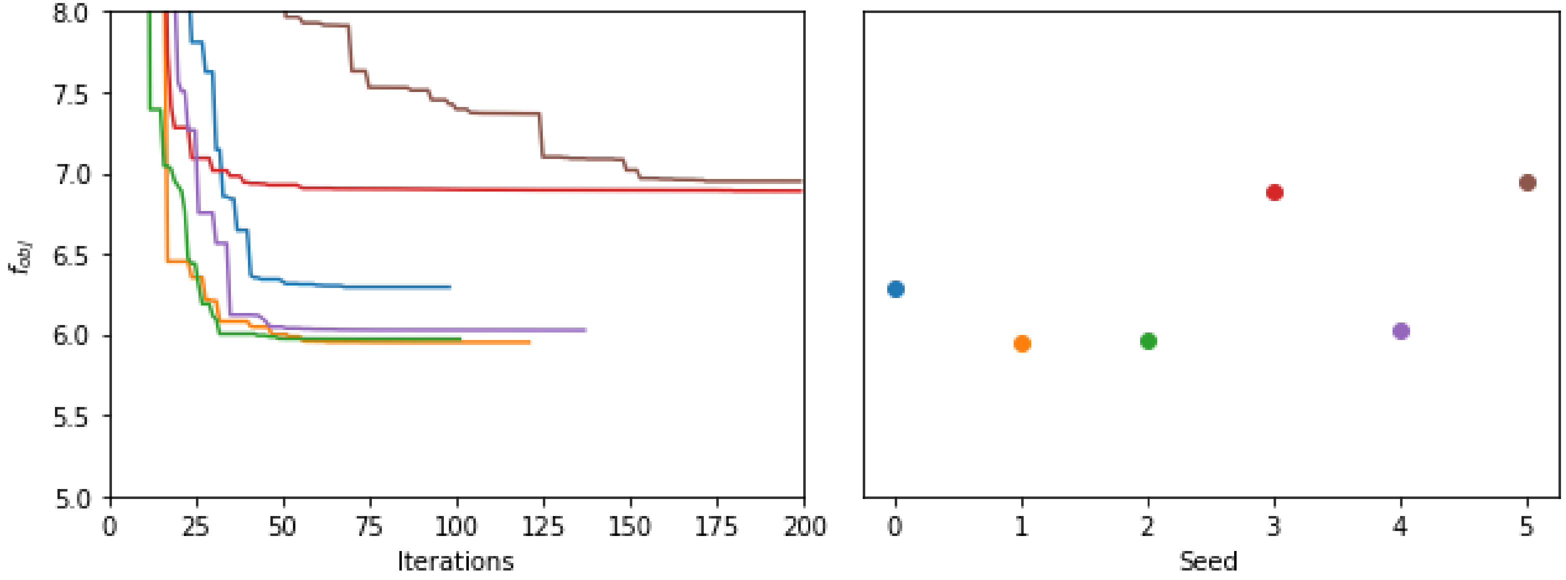
Method

Optimization problem:

Variables: 7 quads strengths
Constraints: given by the quads' current limits (and polarity) and sign
Objective function: include $\alpha_{x,y}$, $D_{x,y}$, $\sigma_{x,y}$, $|\sigma_x$- $\sigma_y|$, a limit for maximum value of $\beta_{x,y}$

Optimization process:

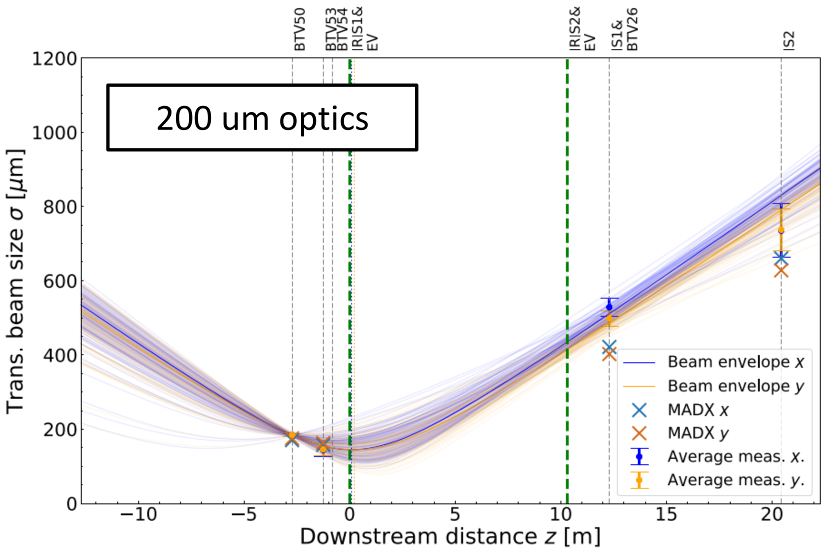
1. Genetic Algorithm: Run genetic algorithm starting with different seeds
2. Run Nelder-Mead optimizer in most promising optics coming from GA

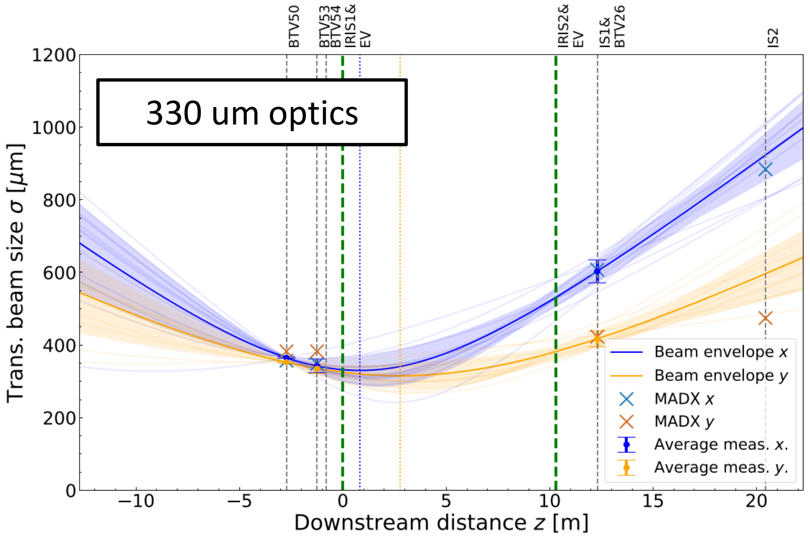


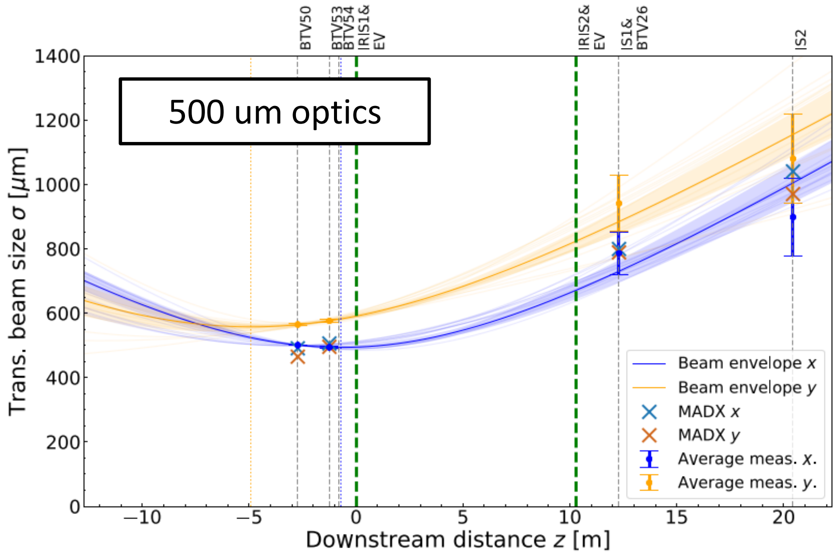
Optics benchmark

- Typical requirements:
  - $\alpha_{x,y} = 0$
  - $D_{x,y} = 0$
  - $\sigma_{x,y} = 200, 500\ \mu m$ (depends on optics)
- The MADx simulated optics was compared with measurements
- Results show very good agreement

➔ We can trust simulations to produce new optics!

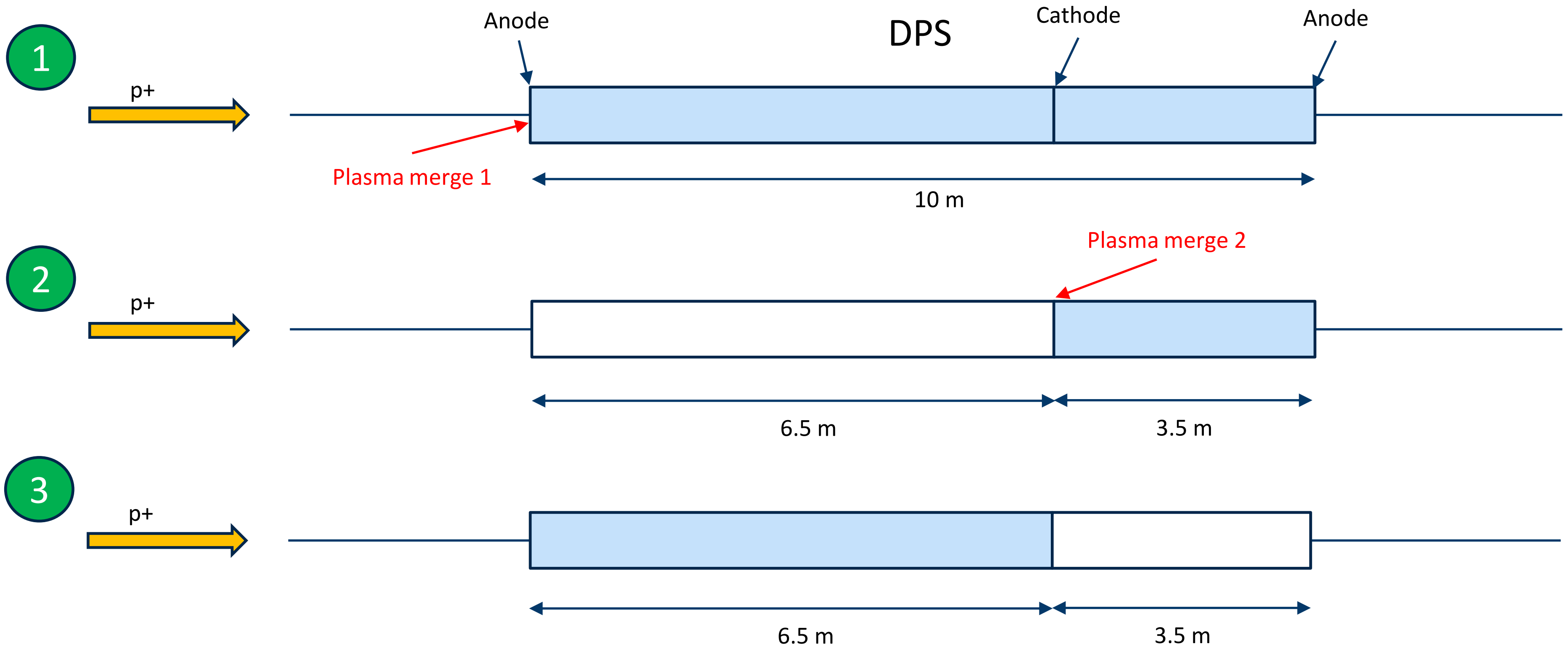






Optics for DPS

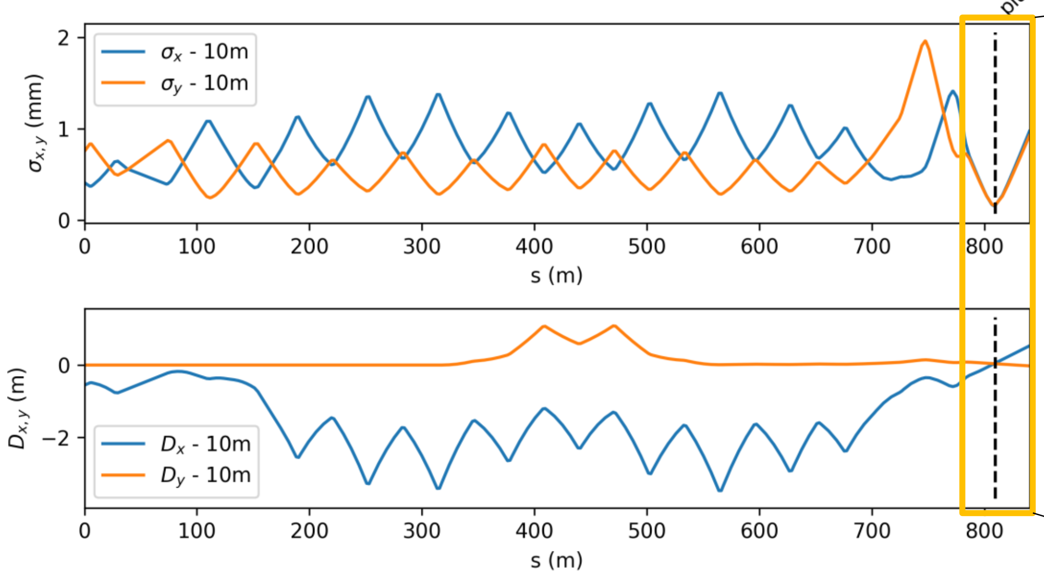
- New Discharge Plasma Source (DPS) can be operated in three different configurations.
- In two of the configurations the entrance of the plasma is at the same longitudinal position.
- In the third configuration, the entrance of the plasma is shifted 6.5 meters downstream.
- To obtain comparable results, the beam parameters had to be the same in all configurations.

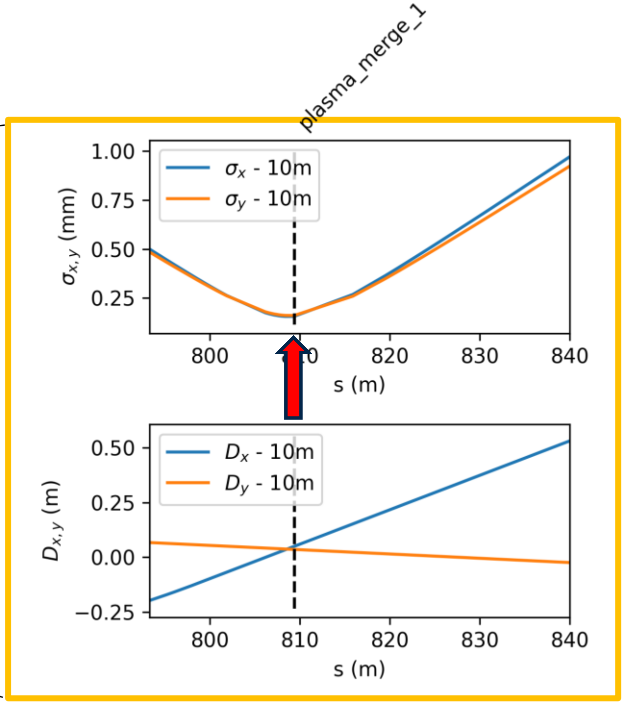


Optics for DPS

- New Discharge Plasma Source (DPS) can be operated in three different configuration.
- In two of the configurations the entrance of the plasma is at the same longitudinal position.
- In the third configuration, the entrance of the plasma is shifted 6.5 meters downstream .
- To obtain comparable results, the beam parameters had to be the same in all configurations.

➡ A new proton beam optics for TT41 line has to be produced.

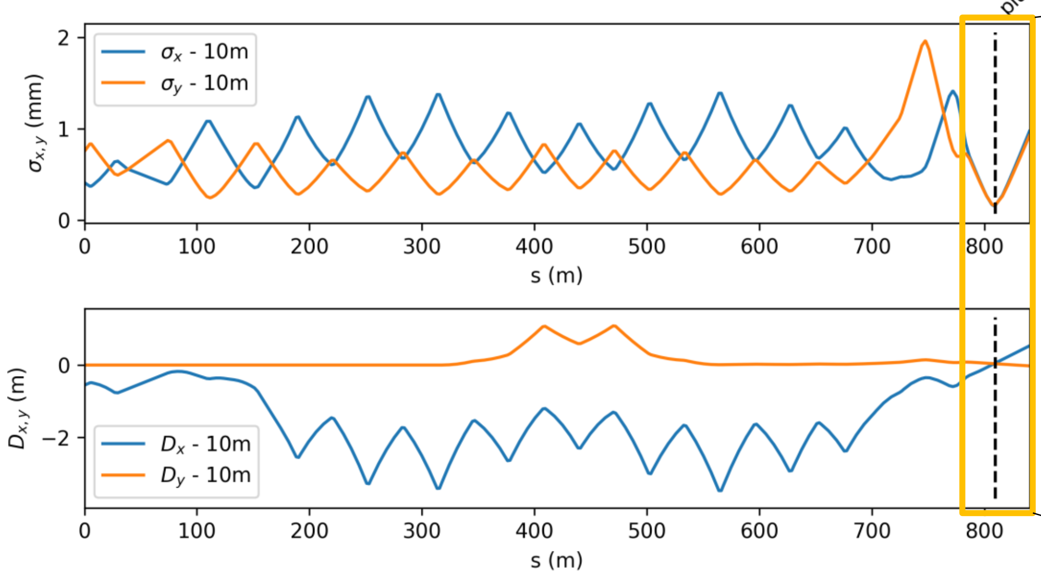


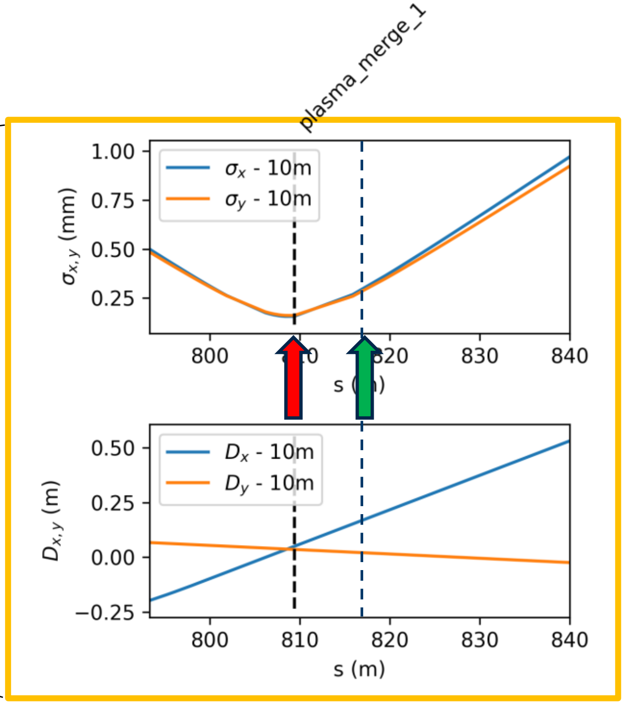


Optics for DPS

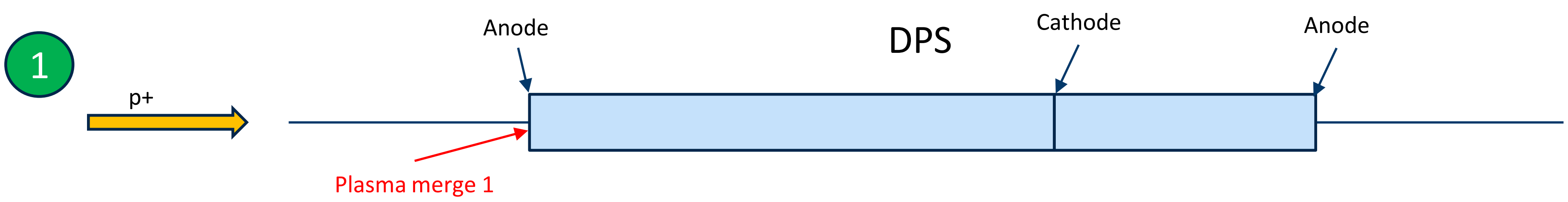
- New Discharge Plasma Source (DPS) can be operated in three different configuration.
- In two of the configurations the entrance of the plasma is at the same longitudinal position.
- In the third configuration, the entrance of the plasma is shifted 6.5 meters downstream .
- To obtain comparable results, the beam parameters had to be the same in all configurations.

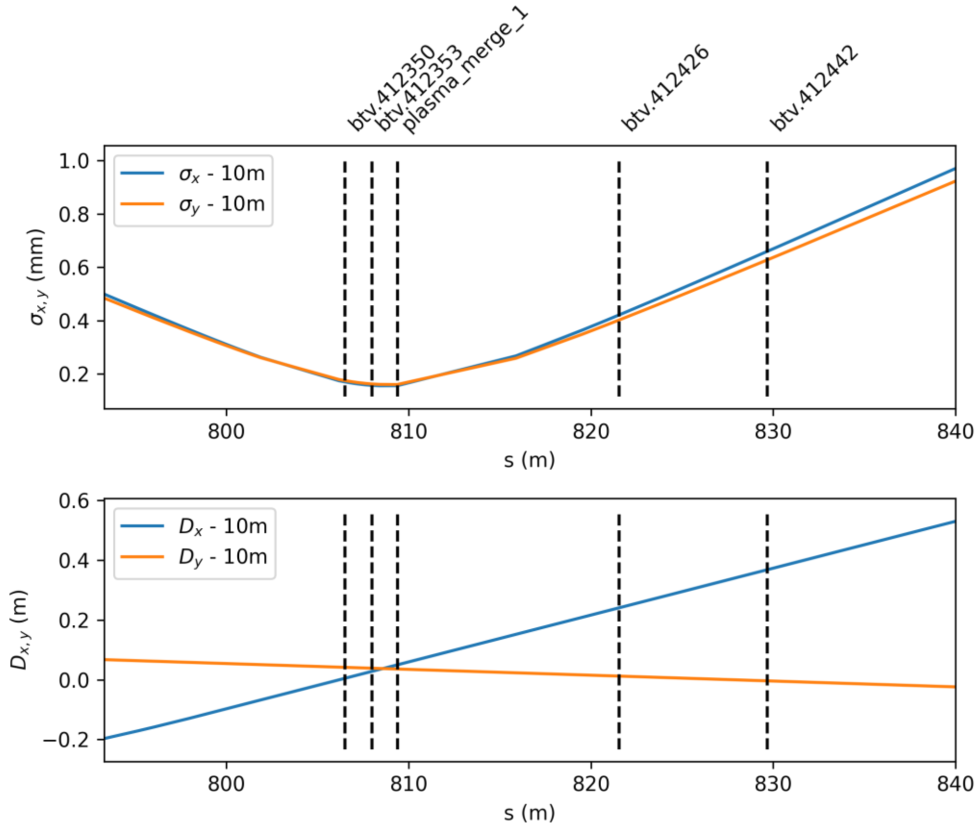
➡ A new proton beam optics for TT41 line has to be produced.





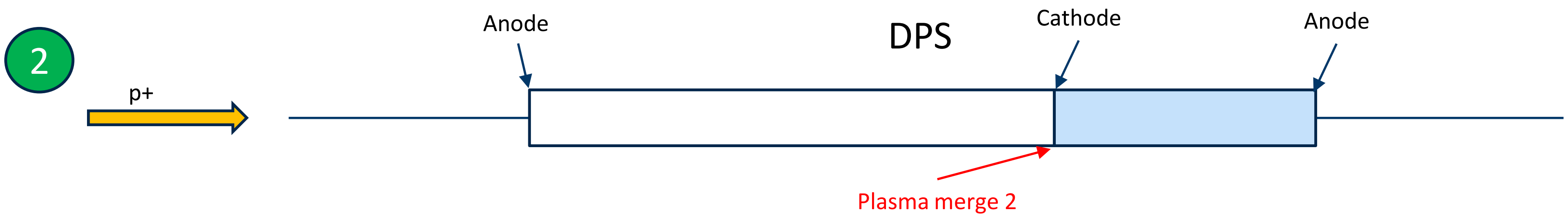
Configuration 1

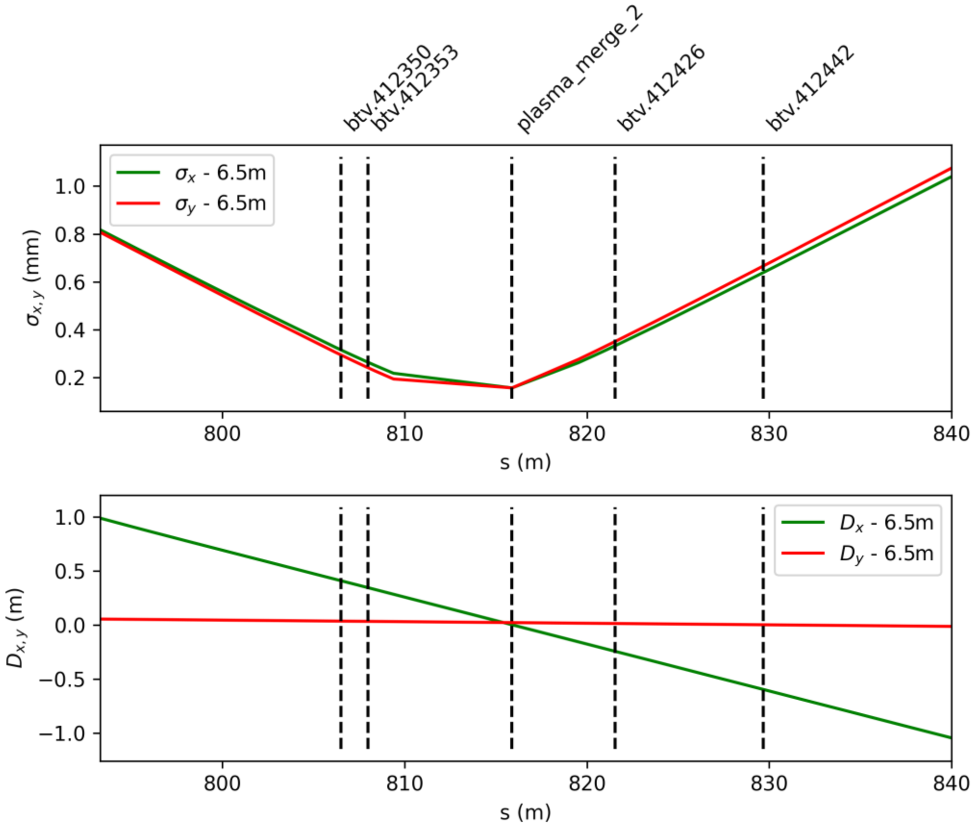




	x-plane	y-plane
$\alpha_{x,y}$	-0.10	-0.09
$D_{x,y}\ (m)$	0.05	0.04
$\sigma_{x,y}\ (\mu m)$	156.76	161.06

Configuration 2





	x-plane	y-plane
$\alpha_{x,y}$	-0.70	-0.90
$D_{x,y}\ (m)$	0.00	0.02
$\sigma_{x,y}\ (\mu m)$	157.17	157.32

Conclusions and next steps – proton line

Conclusions

- Benchmark simulations with measurement allow us to gain confidence when producing new optics.
- Genetic algorithm is a very powerful tool to quickly optimize new optics.
- New shifted optics for DPS was generated. It will be tested during April DPS run.

Next step

- Generate new shifted optics with wider beam size at waist (500 um)

Thank you for your attention!

What’s new

Are we sure that the optimization results corresponds to a waist?

- Simulate optimization prosses
    - Considered random input Twiss parameters
    - Run Py-BOBYQA with same operational parameters
    - Check the waist position and beam size