Toward precise beam injection into the AWAKE experiment

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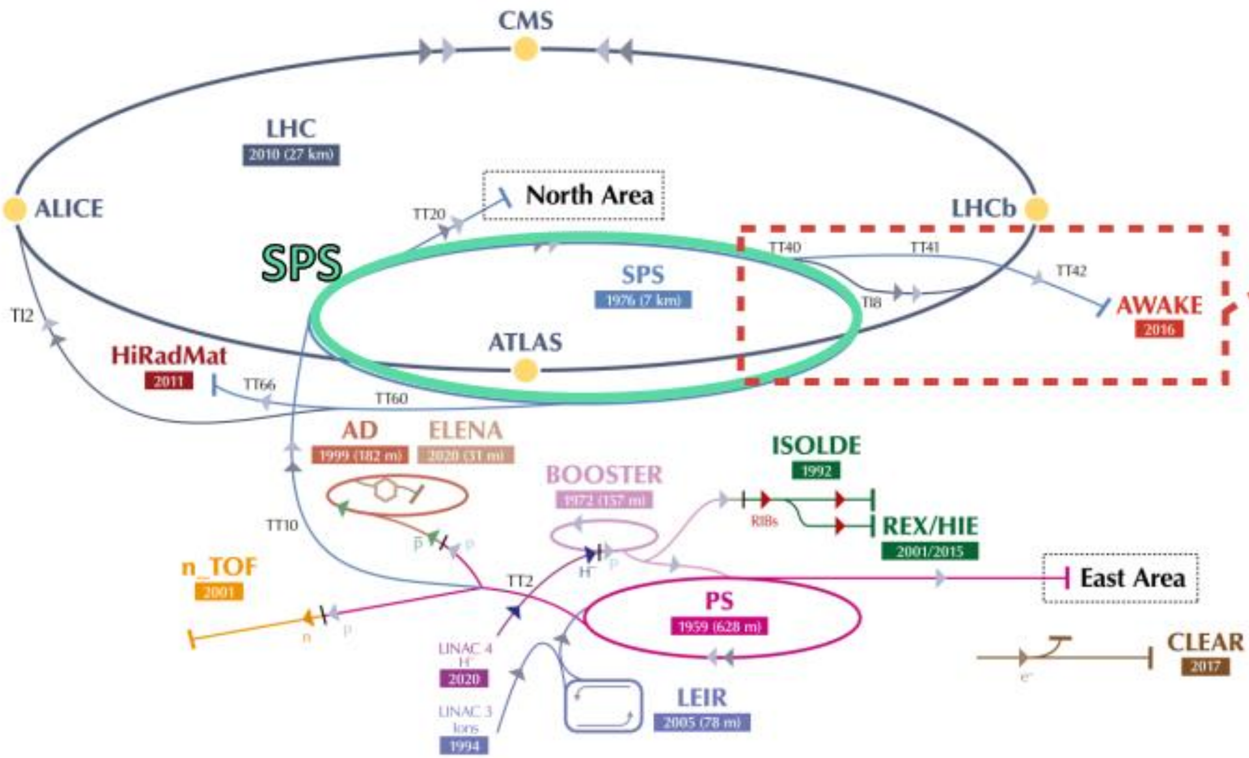
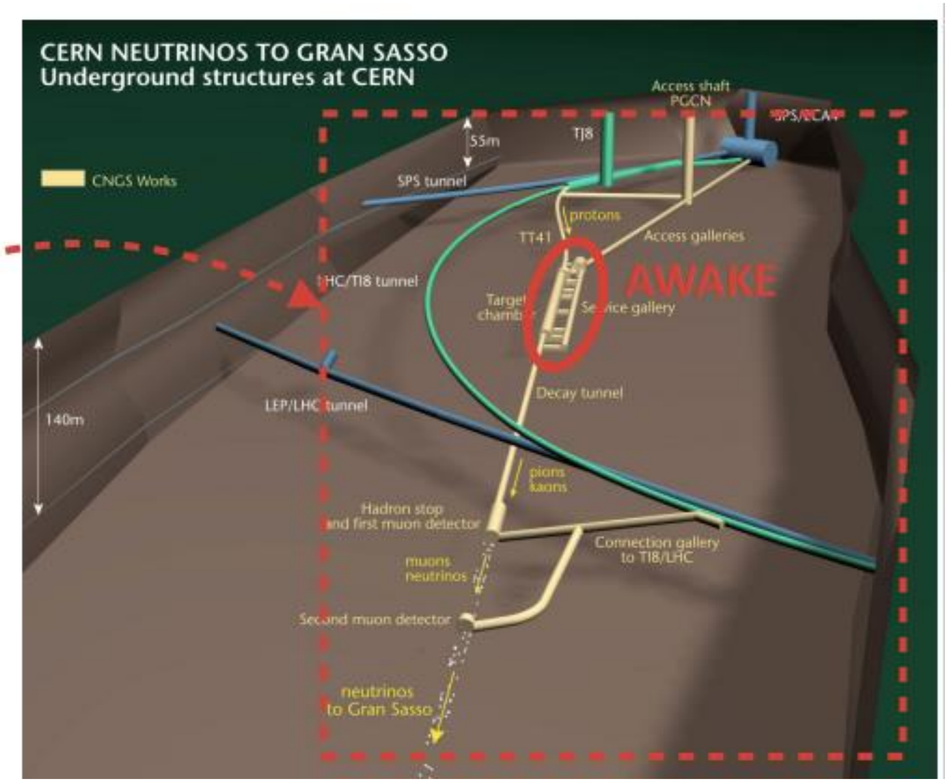
Outline

- Introduction to AWAKE
- Run2b injection challenges
  - Orthogonal steering
  - Phase space tomography
  - Optics validation
- Conclusions

Experimental setup

- AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment
  - Proof of principle R&D experiment to study proton driven acceleration
  - 23 institutes, >100 people. Approved in 2013, electron acceleration in 2018





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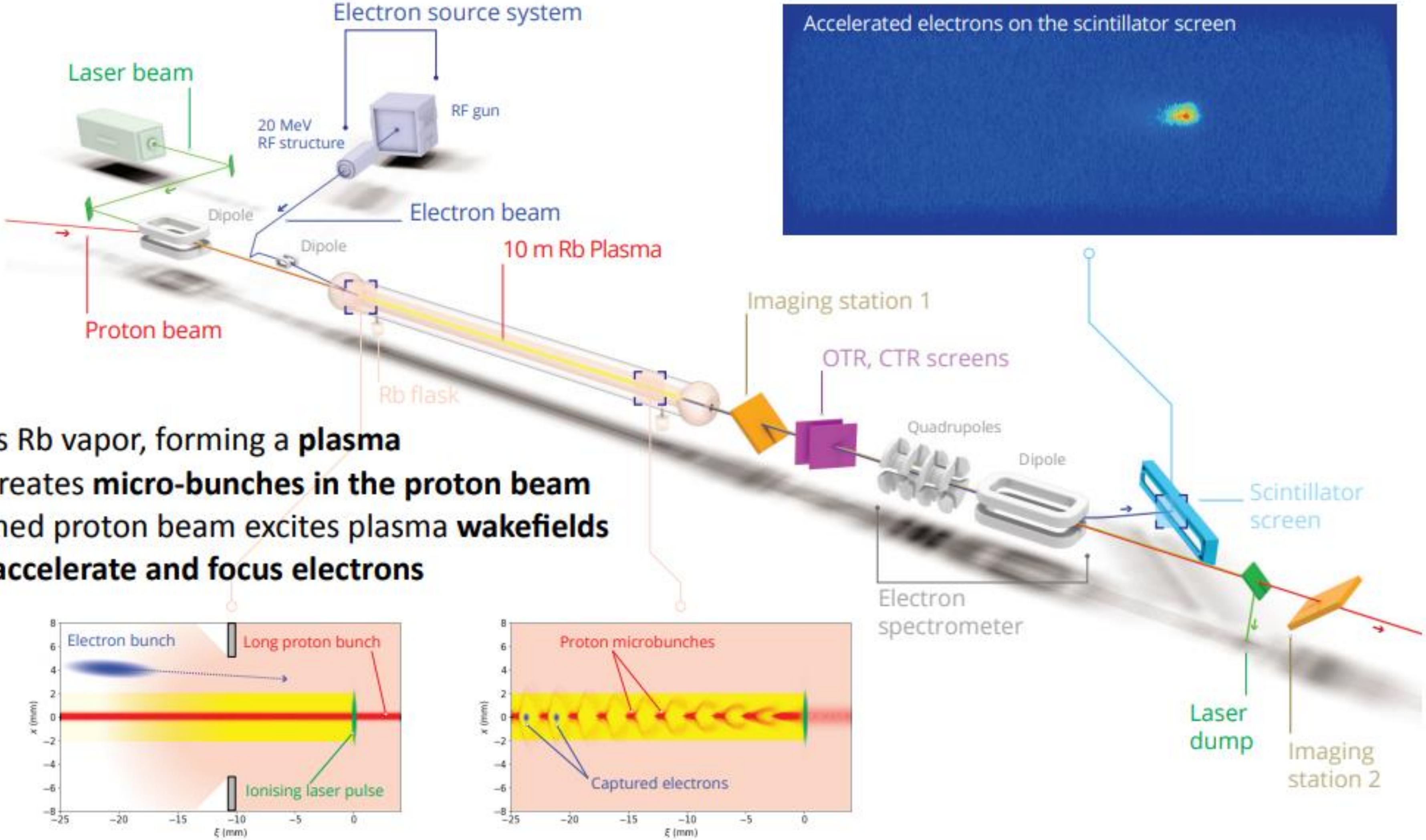
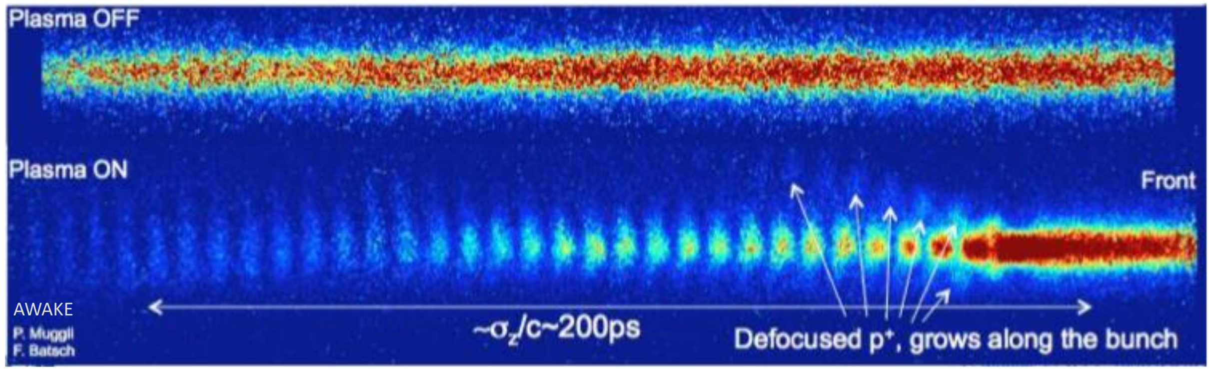


1) **Laser** ionizes Rb vapor, forming a **plasma**
2) Rb plasma creates **micro-bunches in the proton beam**
3) Micro-bunched proton beam excites plasma **wakefields**
4) Wakefields **accelerate and focus electrons**

AWAKE Run1

2016/2017: SELF-MODULATION

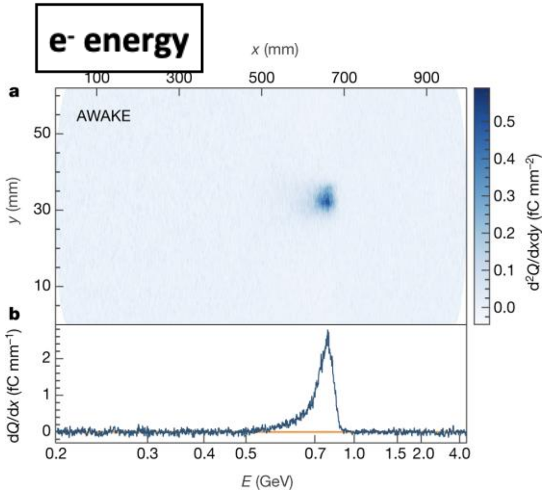
- First seeded self-modulation of a high energy proton bunch in plasma
- Phase-stability and reproducibility are essential for electron acceleration!
- —> Demonstration that SPS proton bunch can be used for acceleration <—

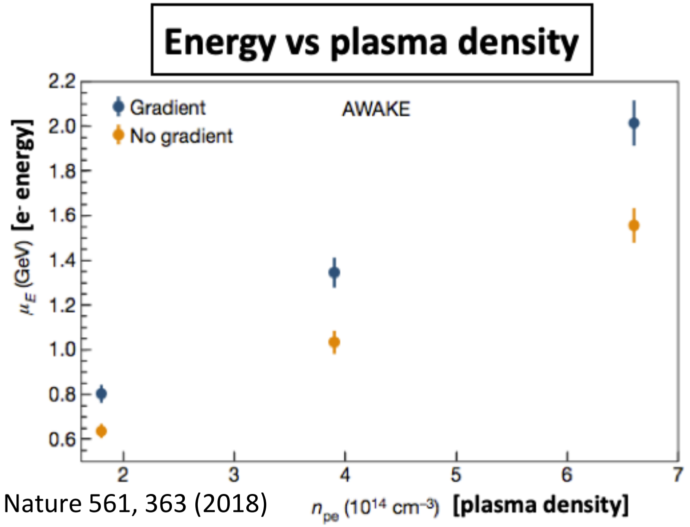


AWAKE Collaboration, PRL 122, 054802 (2019)

2018: ACCELERATION: from 19 MeV to 2GeV

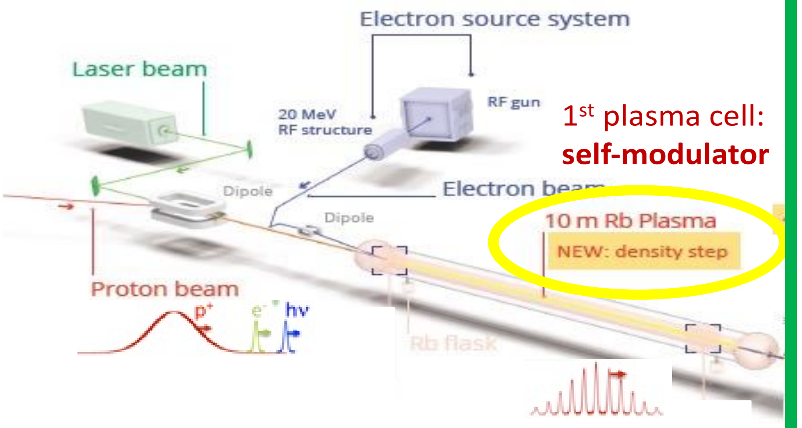
- Inject e- and accelerate to GeV in the wakefield driven by the SPS protons
- Maximum accelerated charge ~100 pC (~20% of injected)





AWAKE Collaboration, Nature 561, 363 (2018)

AWAKE Run2

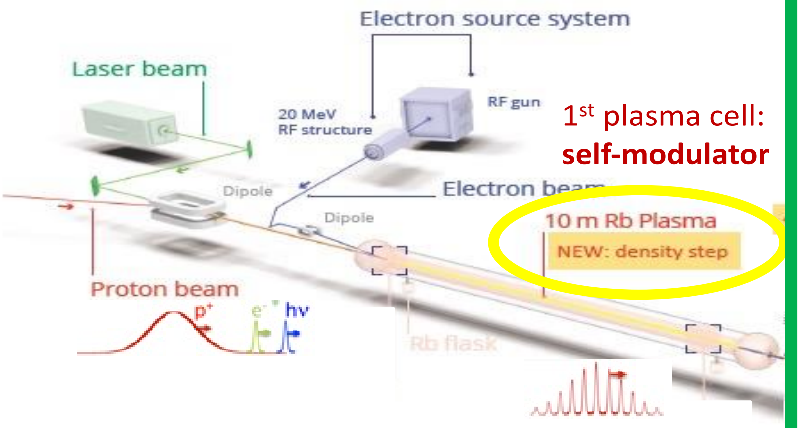


In existing AWAKE facility:

Run 2a: demonstrate electron seeding of self-modulation in first plasma cell

Run 2b: demonstrate the stabilization of the micro-bunches with a density step

AWAKE Run2



1st plasma cell:
self-modulator

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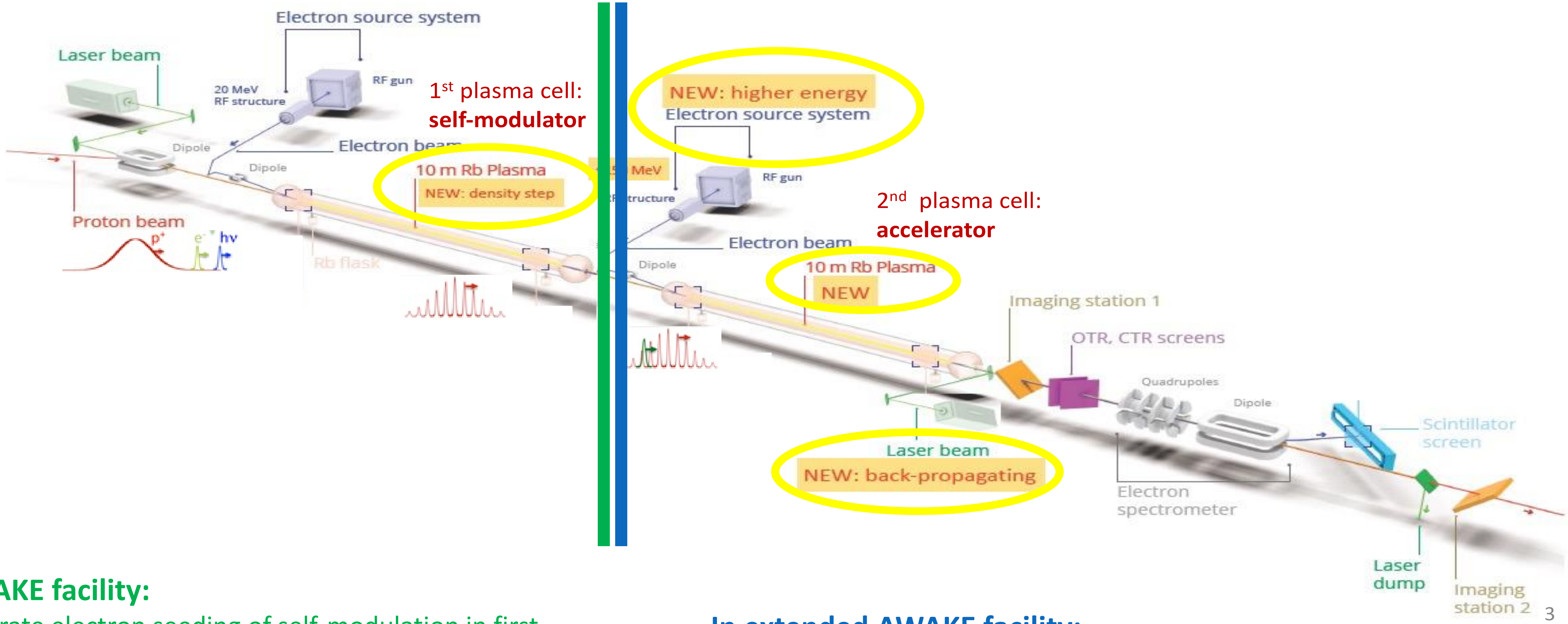


In existing AWAKE facility:

Run 2a: demonstrate electron seeding of self-modulation in first plasma cell

Run 2b: demonstrate the stabilization of the micro-bunches with a density step

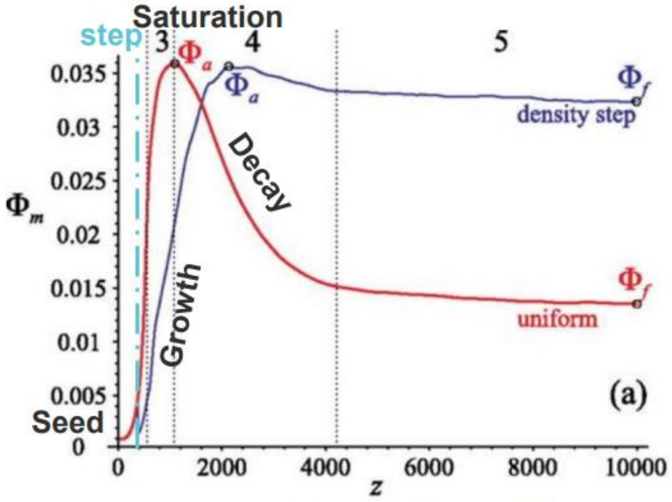
In extended AWAKE facility:

Run 2c: demonstrate electron acceleration and emittance preservation

Run 2d: demonstrate scalable plasma sources

Injection challenges

- The last runs of 2023 were dedicated to the characterization of a new "**density step**" Rb plasma source.
  - Density step should **increase wavefield amplitudes**
  - This can be demonstrated by looking at the electron beam energy after the plasma cell



K. V. Lotov, Physics of Plasmas 22, 103110 (2015)

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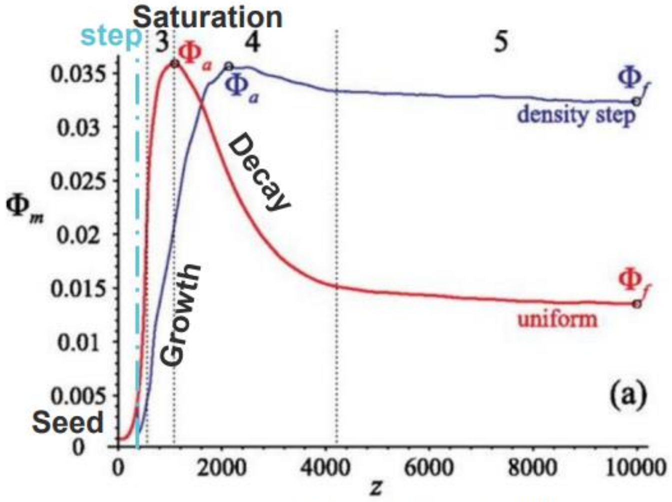

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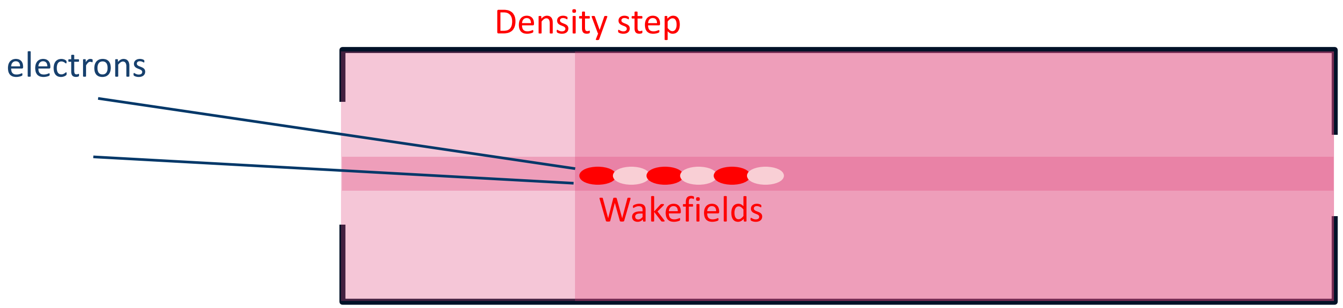

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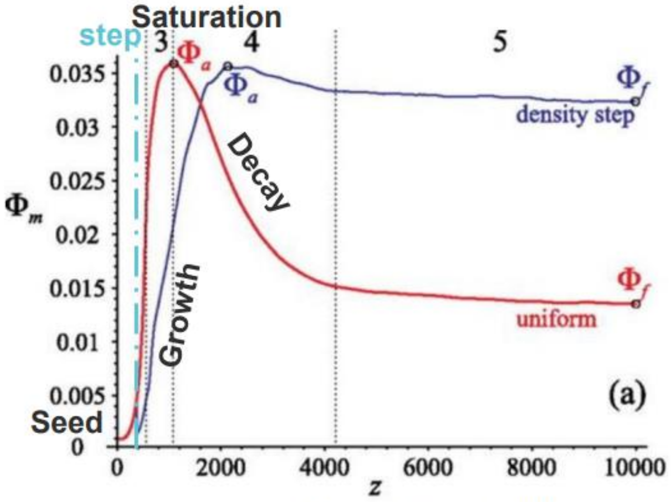
- Need external electron injection downstream of density step
  - Control beam position and angle



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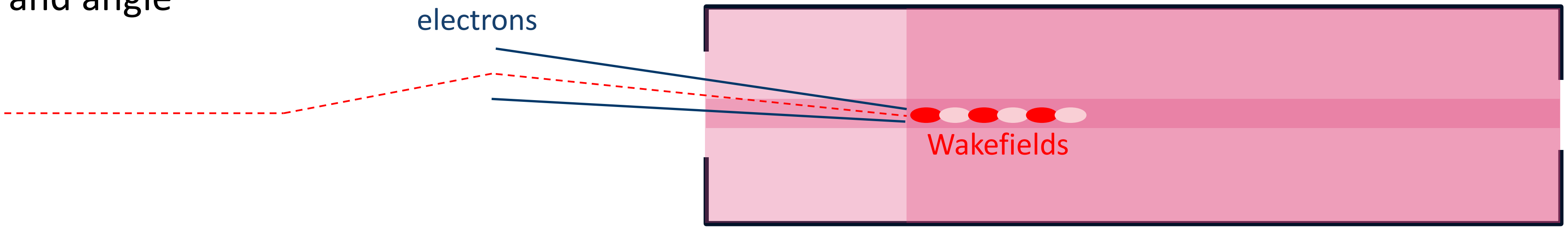

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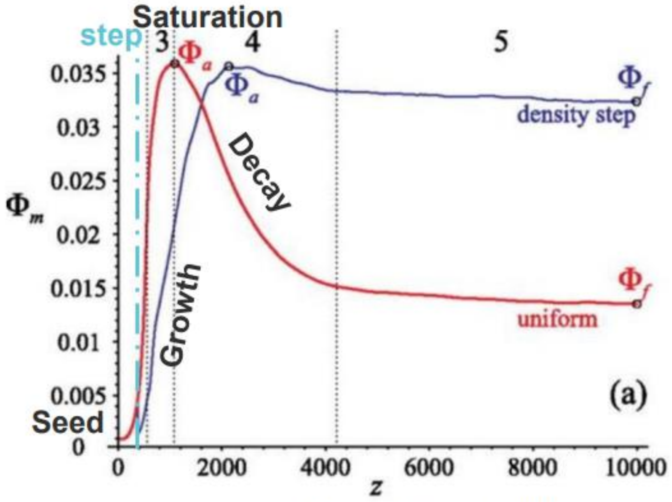

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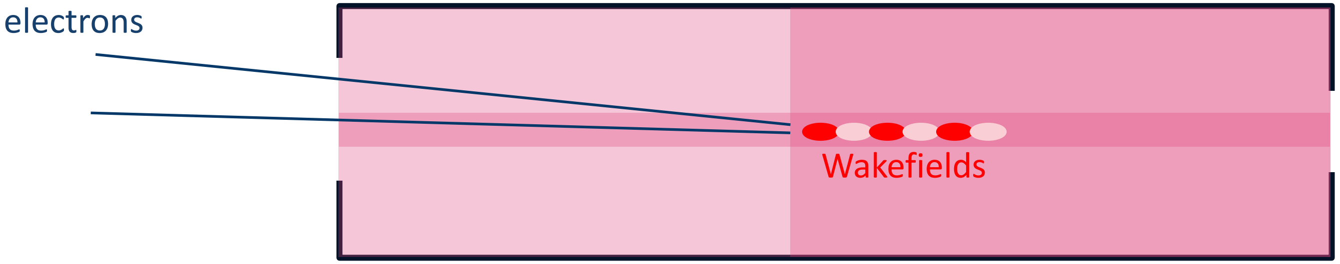

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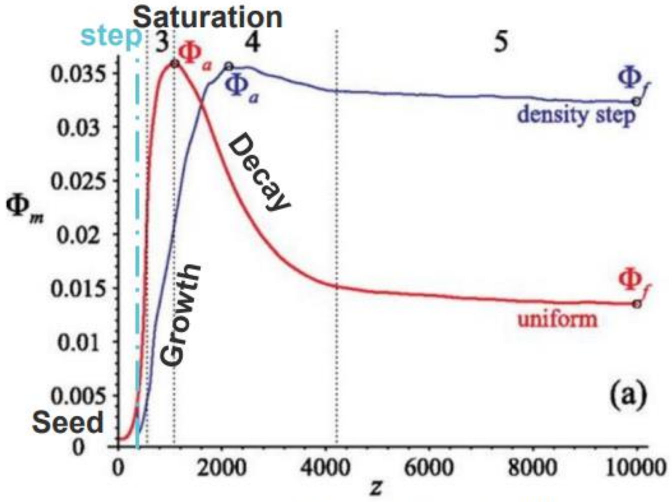

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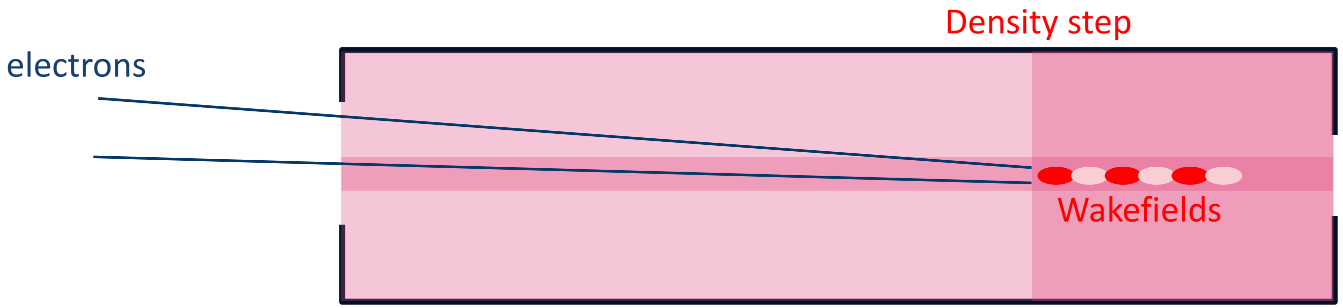

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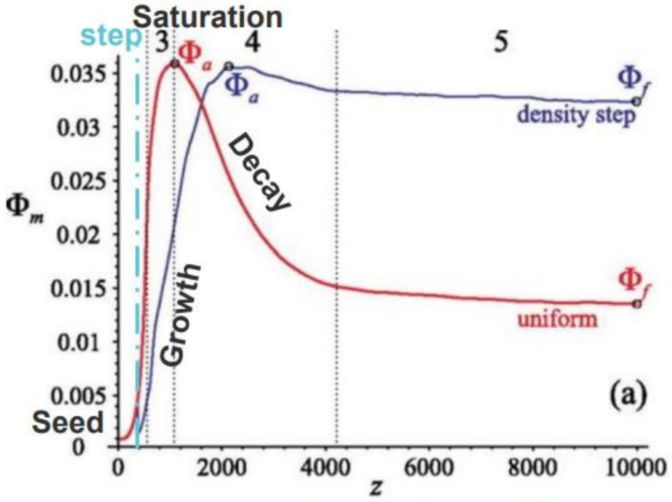

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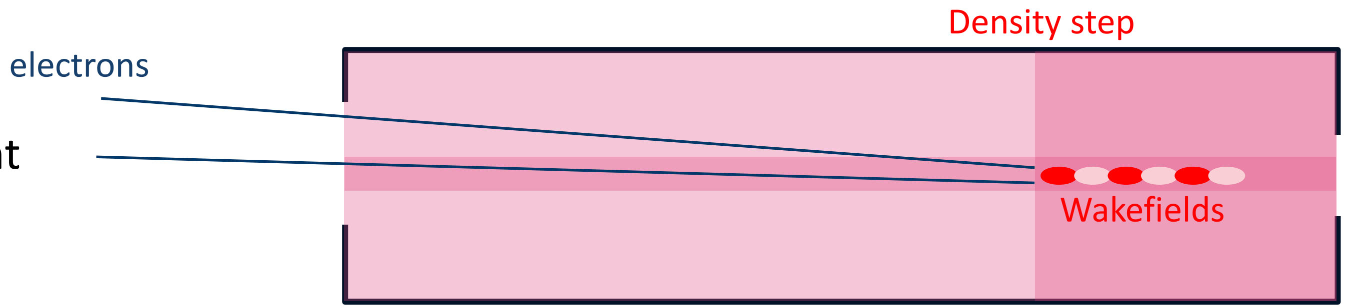

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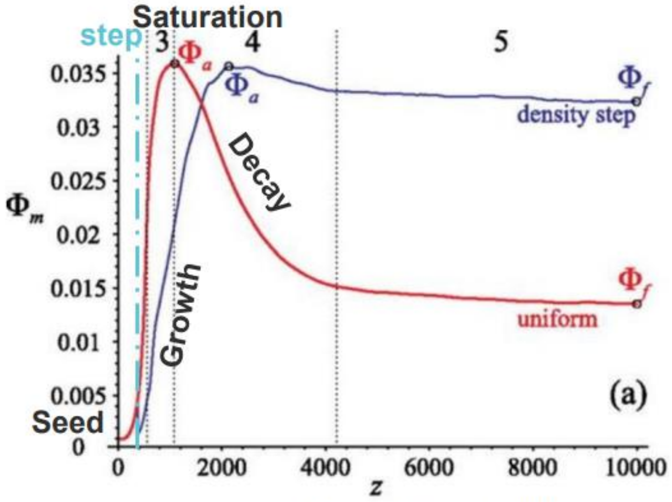

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  - Control beam position and angle → Orthogonal steering
  - Move focal point to injection point → Phase space tomography; Genetic algorithm for optics generation
  - Achieve desired beam parameters at focal point → Phase space tomography; Genetic algorithm for optics generation

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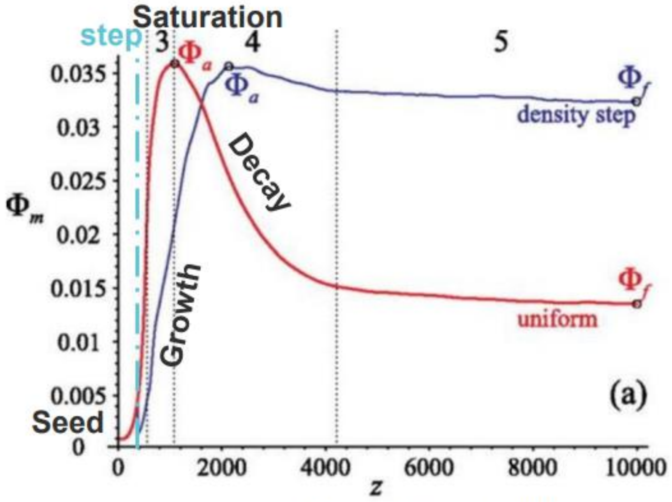

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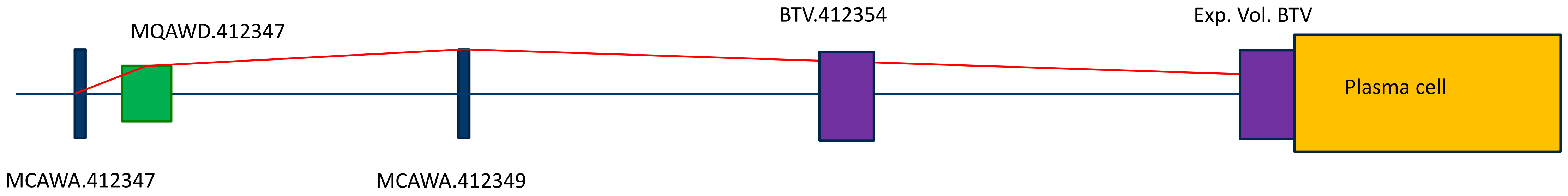
Orthogonal steering

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

- Two main issues in achieving the required precision:
  ❌ Presence of a quadrupole between correctors ➔ (non linearities, field fluctuations, field errors,…)

How it was done:



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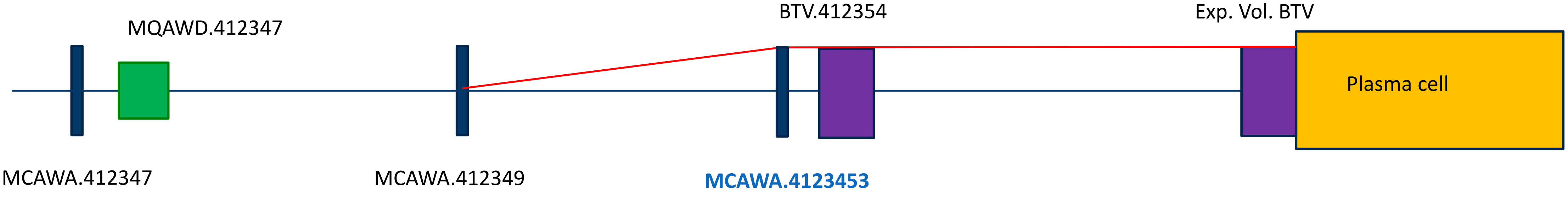
What's new:



✓ New corrector MCAWA.412353 installed.

✓ Absence of quadrupole and closer to plasma cell ➔ higher precision

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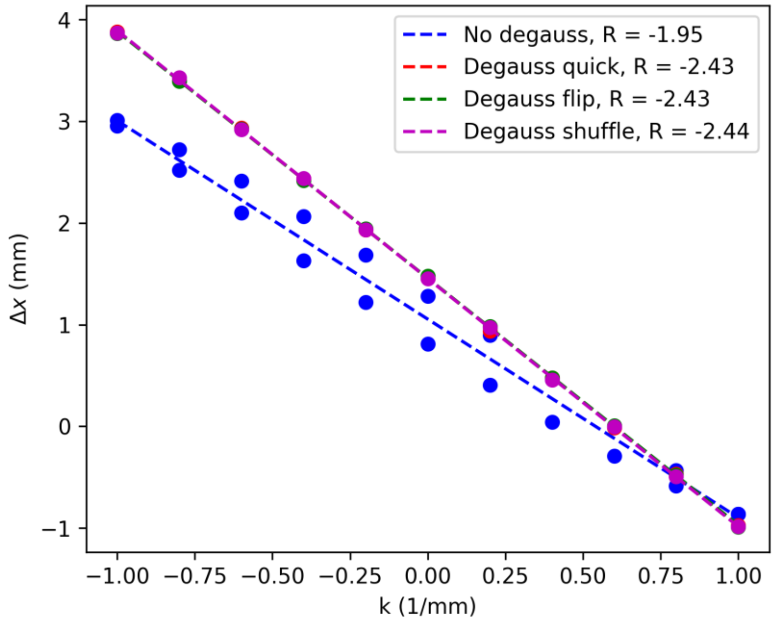
  - ✗ Hysteresis ➔The kick response coefficient change with hysteresis cycle



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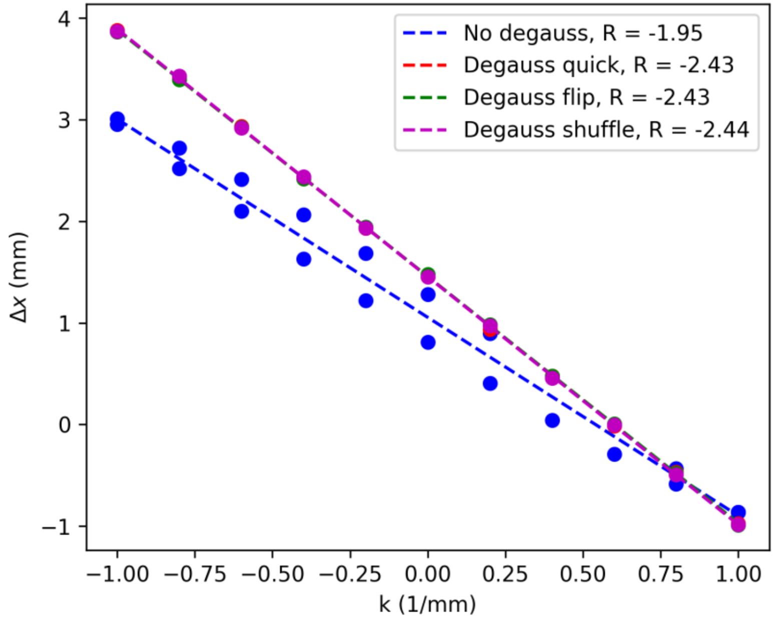
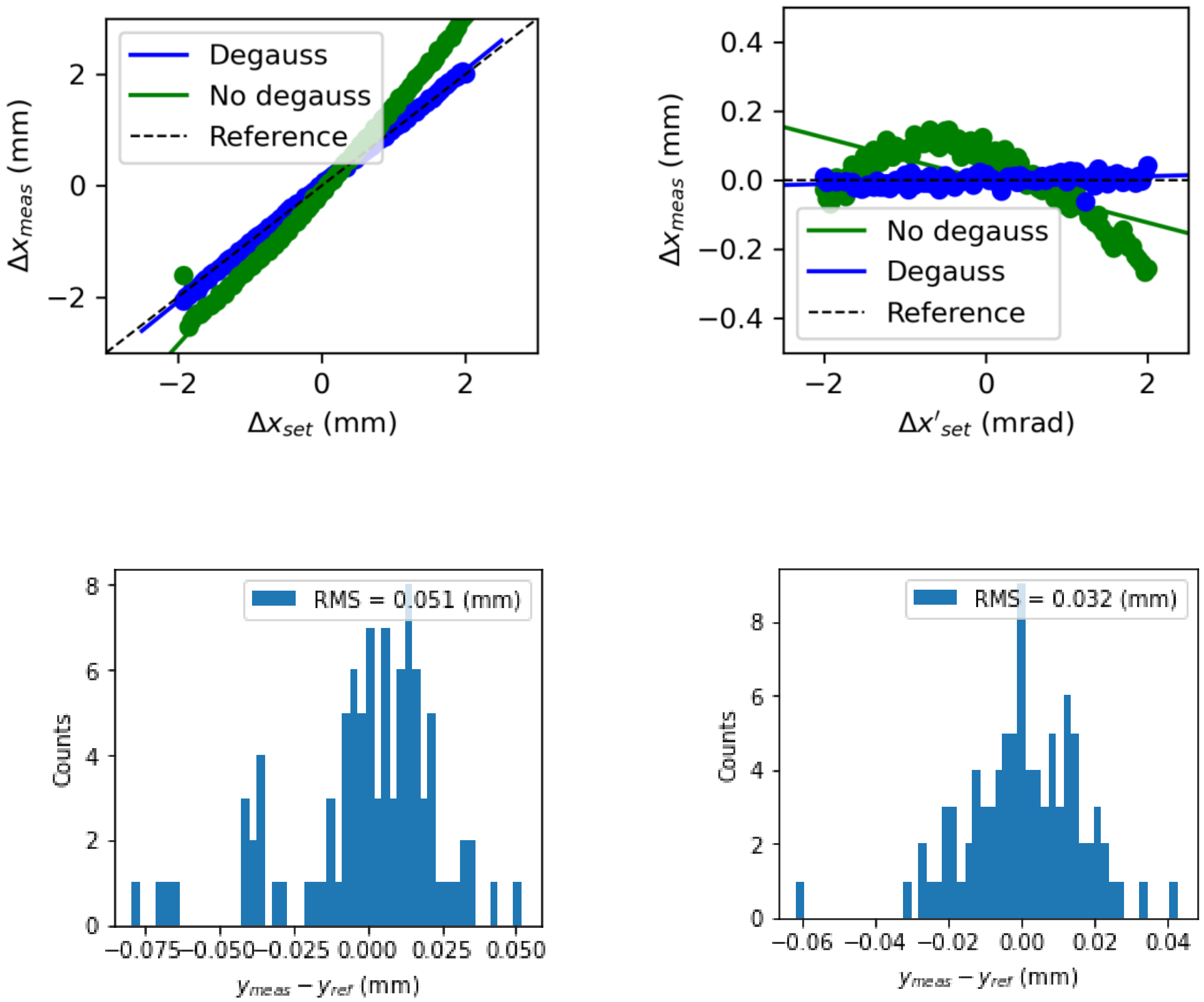


✓ Quick demagentisation (set corrector the min and max current before goal value)

Orthogonal steering

- Method was tested
- Performed two scans:
  1. Position with constant angle ($\Delta x' = 0$) at screen
  2. Angle with constant position ($\Delta x = 0$) at screen
- Extremely good accuracy in setting position and angles was observed.
- Errors in the order of magnitude of beam jitter!



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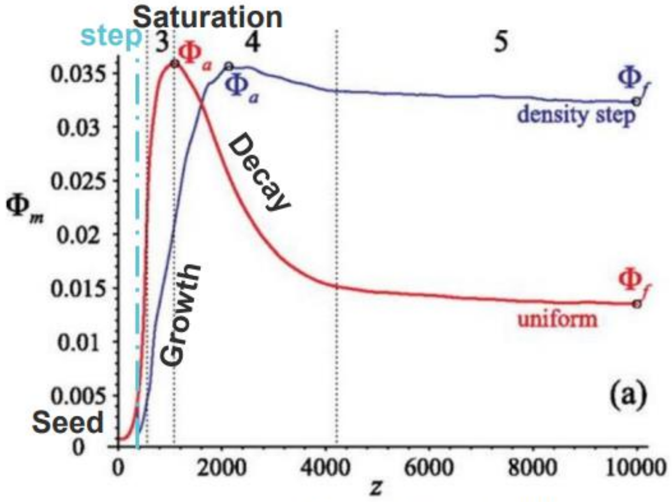

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Orthogonal steering

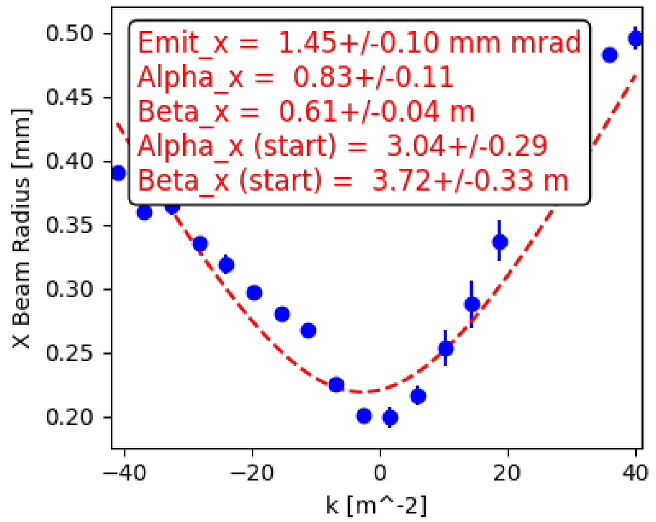
Phase space tomography
Genetic algorithm for optics generation

Phase space tomography

- To correctly generate new optics it is essential to know the beam parameters at the beam line entrance

How it was done:

- Emittance was 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)

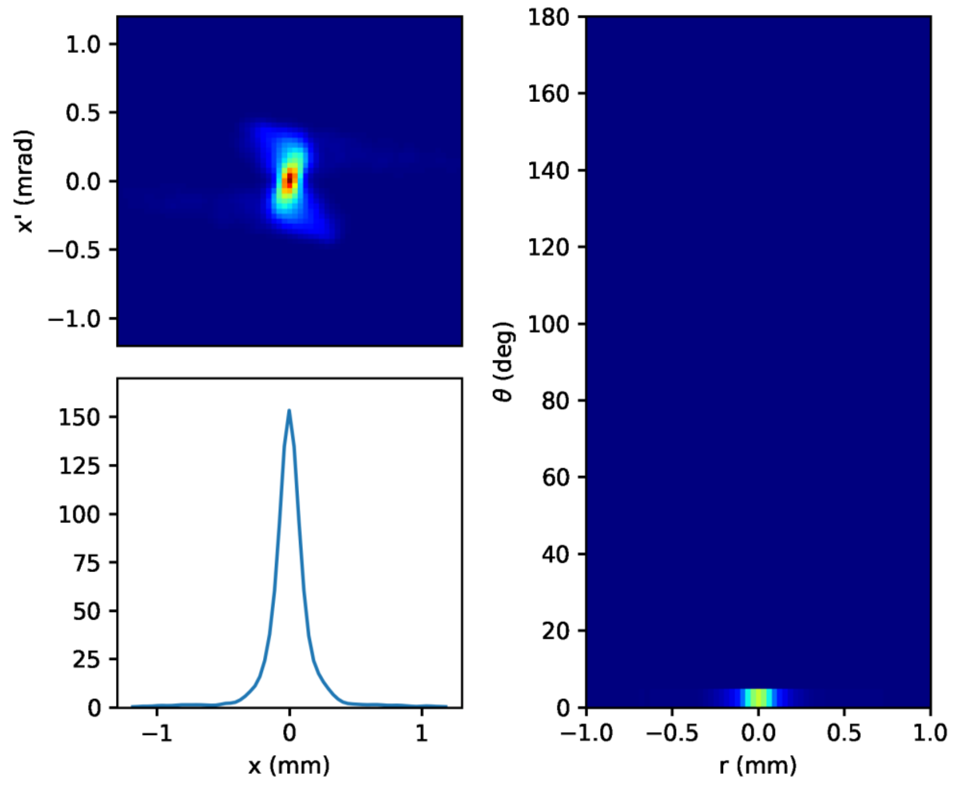
Solution (under development)

- Use phase space tomographic reconstruction.

Phase space tomography

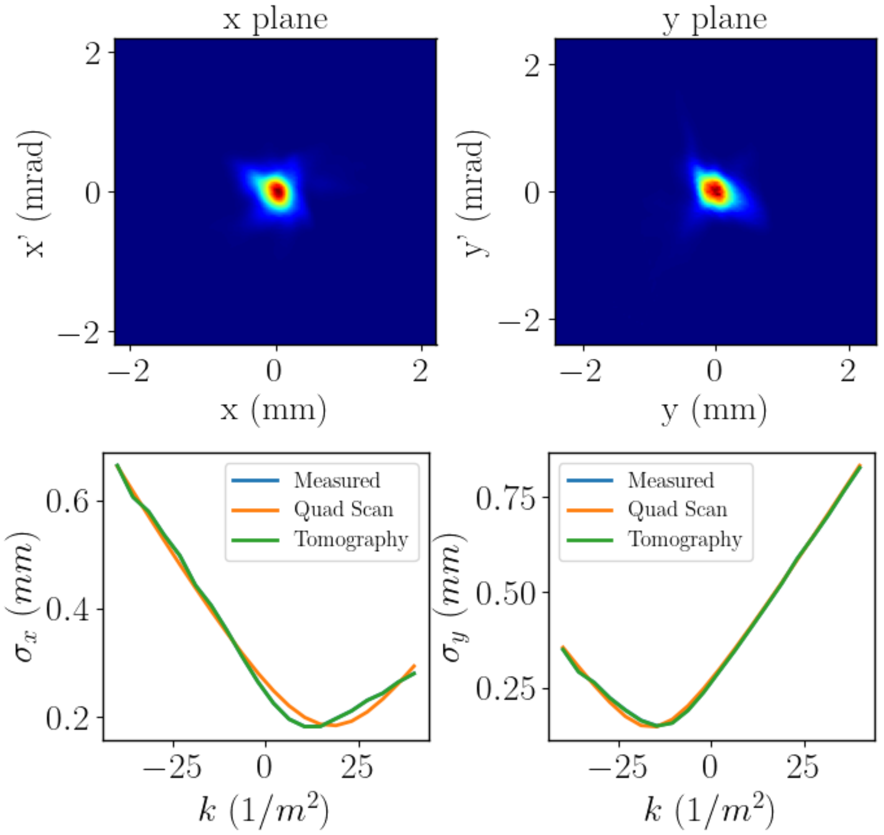
- We can use 1D projections taken from different angles around an object to reconstruct the 2D object itself
- The projections are stacked in a 2D image called **sinogram**

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



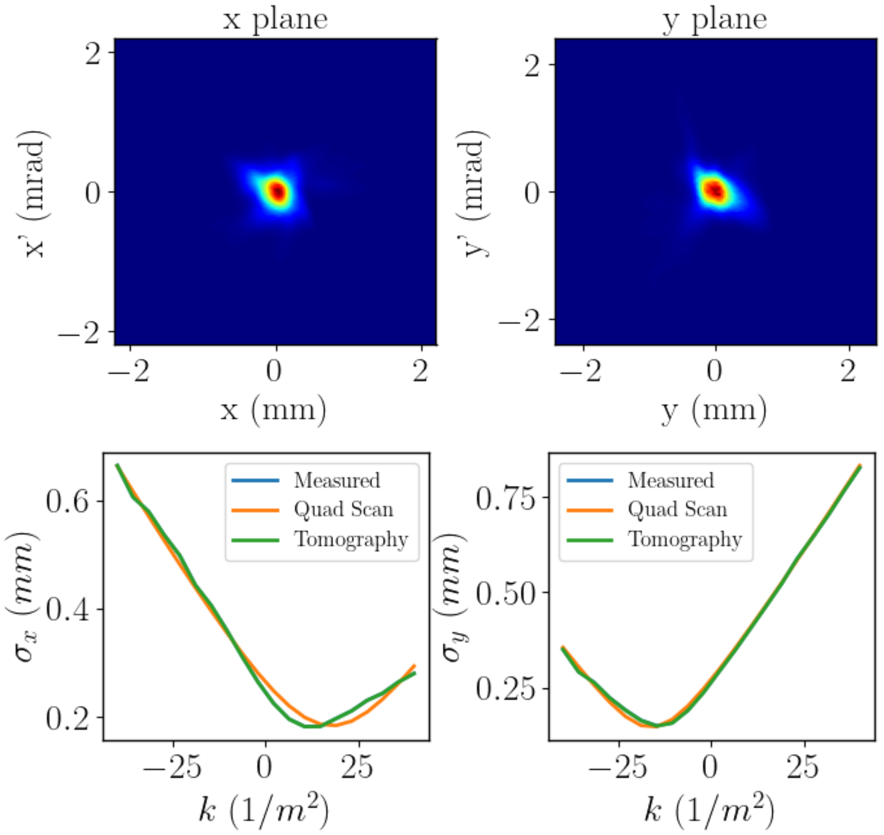
Phase space tomography

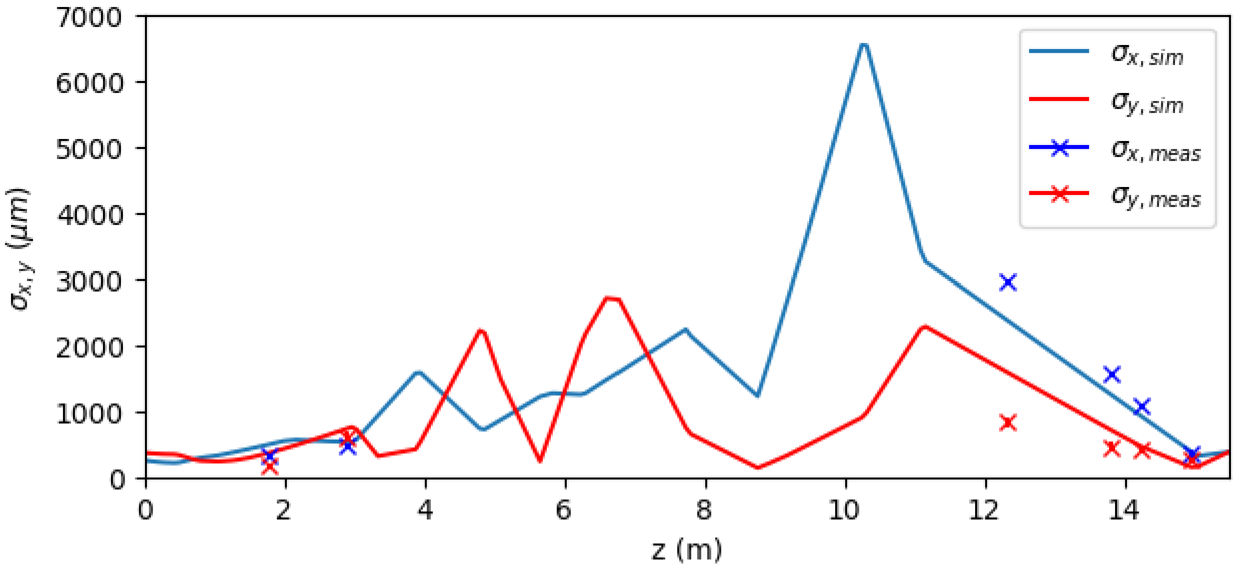
- Phase space tomography applied to AWAKE beam



Phase space tomography

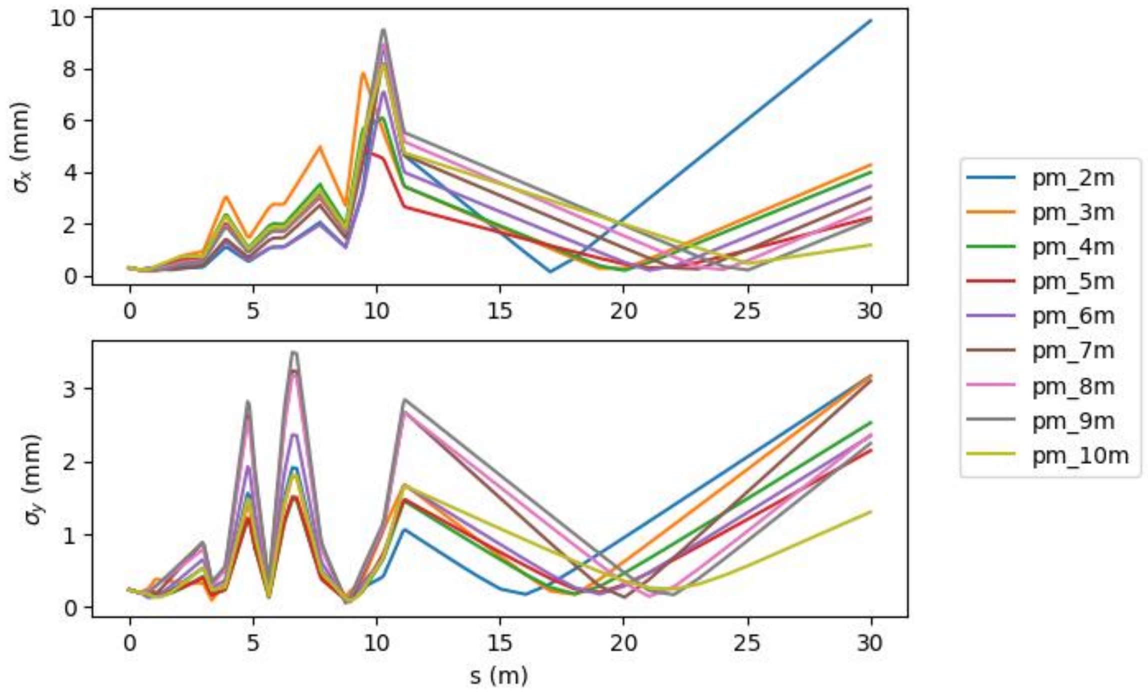
- Phase space tomography applied to AWAKE beam
- Result validated with measurements at screens along the line





New optics for side injection

- Beam from tomographic reconstruction was used to generate the new optics for side injection
  - New optics needed to shift the waist forward in the range between 1m and 10m downstream the iris
  - Matching performed using Genetic Algorithm



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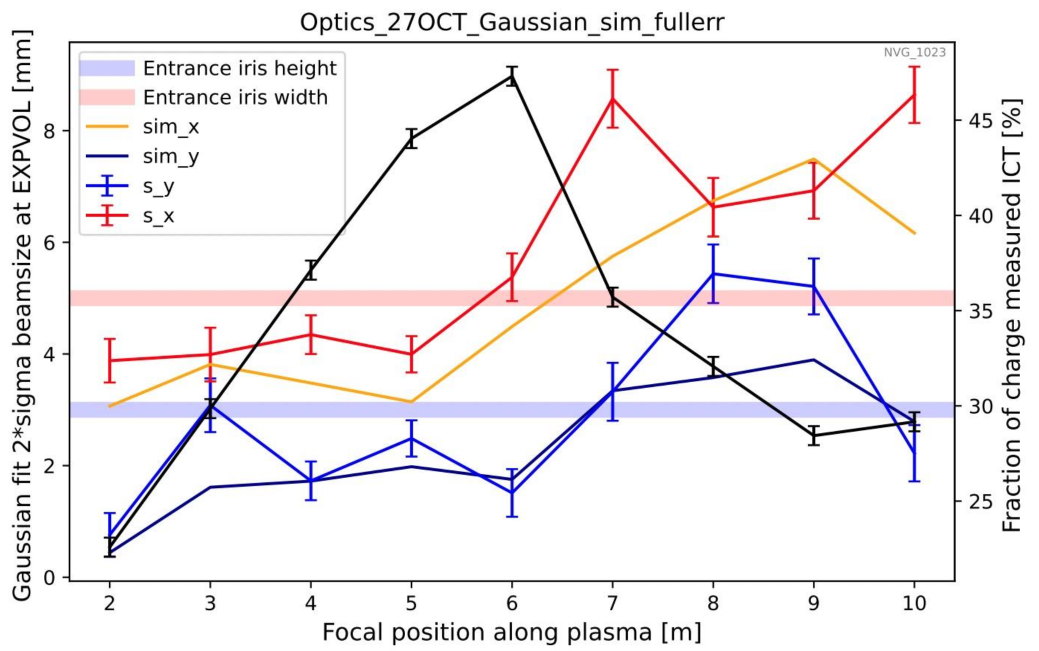
- Beam tested measuring:
  - Beam size at last BTV before plasma cell
  - Current at the exit of the plasma cell
- The expected behavior was observed
  - Current increasing moving the focal point toward the end of the cell
  - Current drops when beam size becomes bigger than aperture



Conclusions

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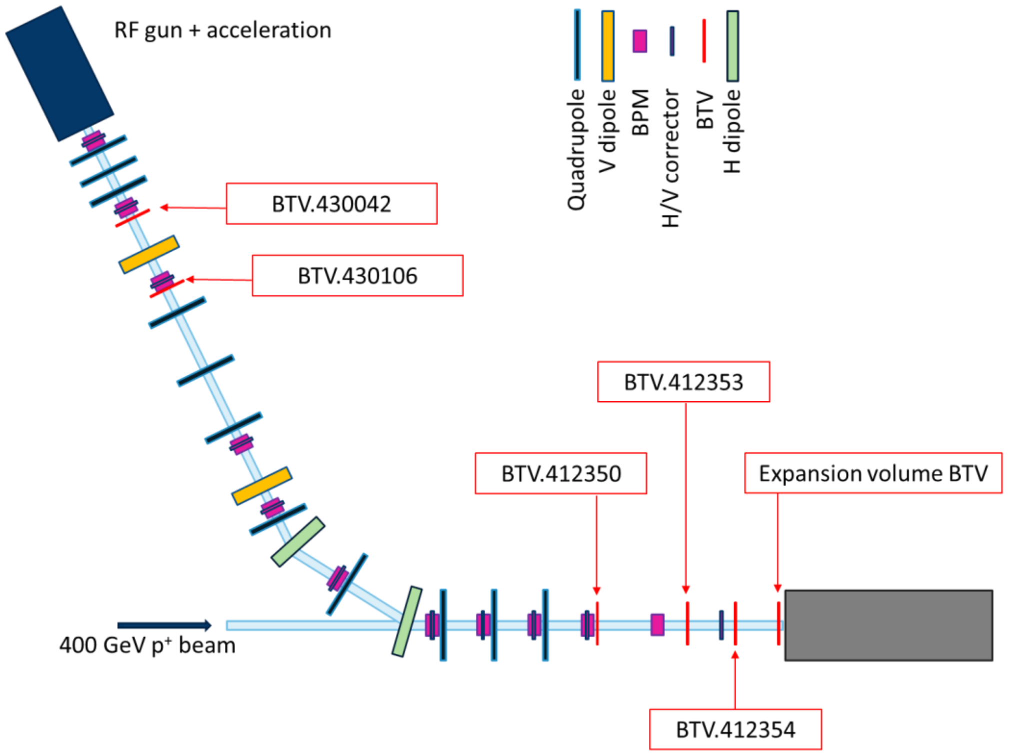
- New refined operational methods were developed to match the flexibility required by Run2b experimental goals.
- Quick degaussing and orthogonal steering allowed to achieve high reproductivity and precision in controlling beam position and angle at injection.
- Phase space tomography improved the accuracy of the simulations, allowing for better beam matching and for the creation of new optics for side injection.
- All tools were tested and validated experimentally and were successfully used during last operations in the last runs

Thank you for your attention!

Tomographic reconstruction

To test the validity of tomographic reconstruction:

- Quad scan at BTV.430042 and tomography
- Measure beam distribution at BTVs along the line
- Track reconstructed beam using MADx
- Compare results



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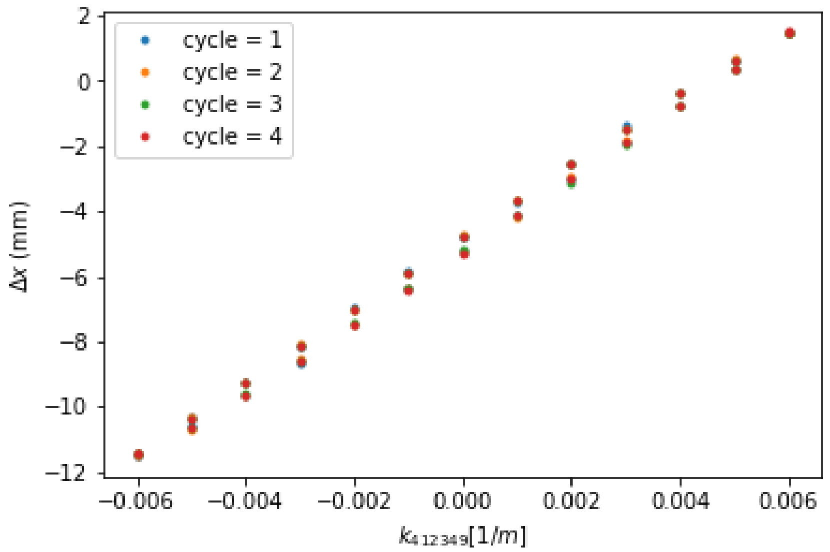
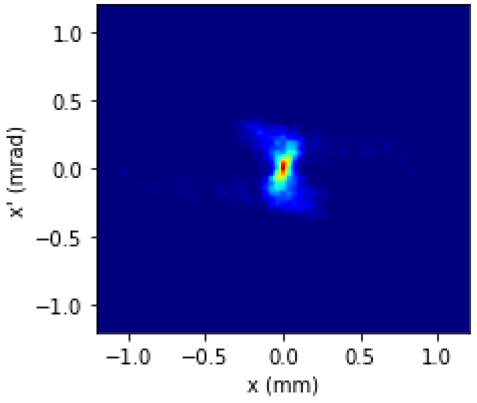
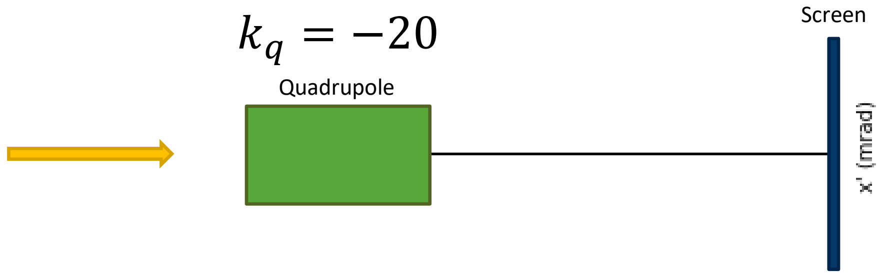
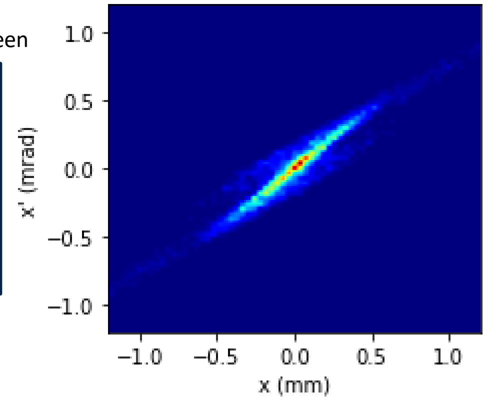


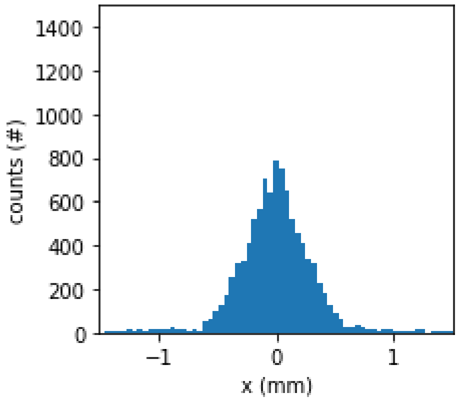
How this applies to beam physics?



$k_q = -20$







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

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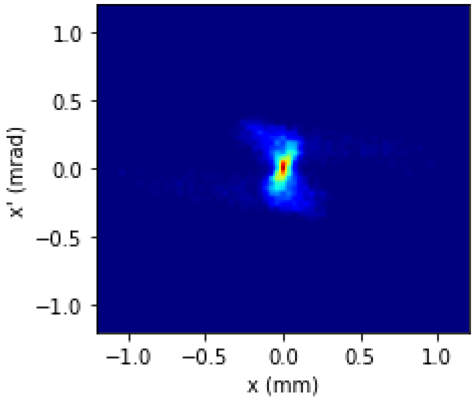

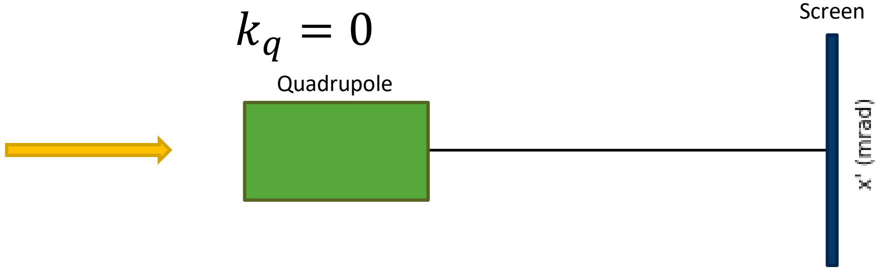

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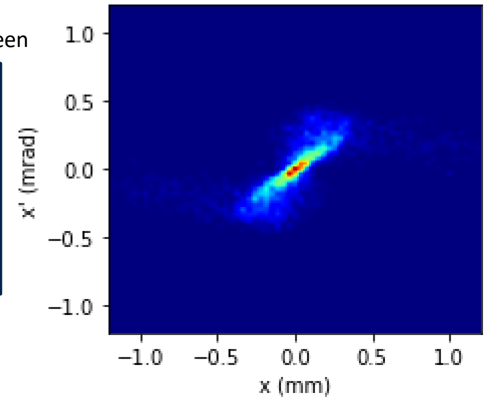

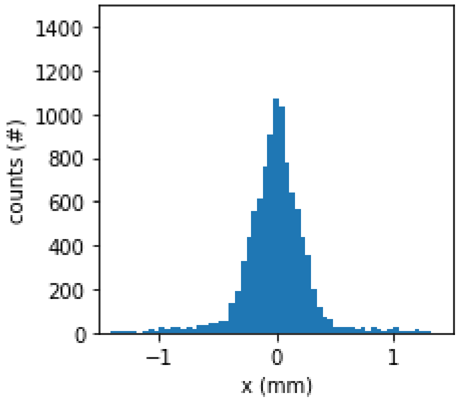

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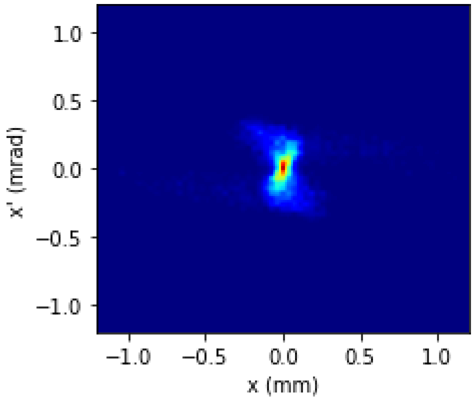

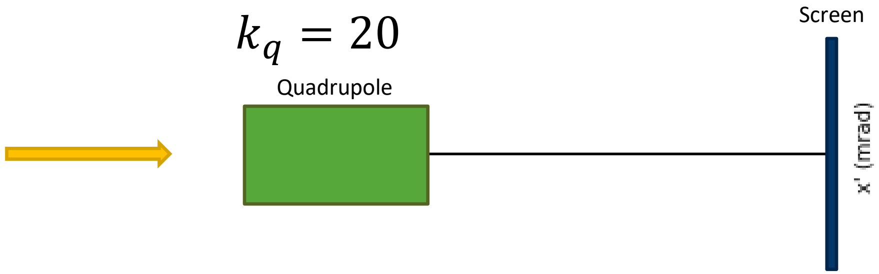

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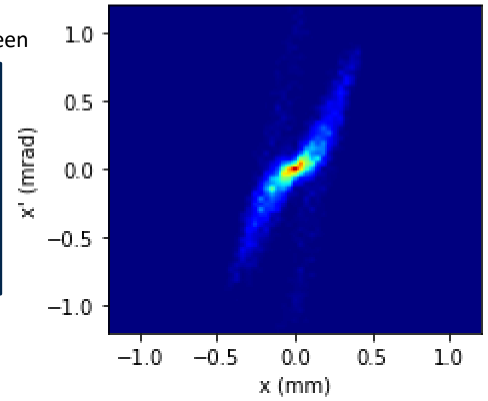
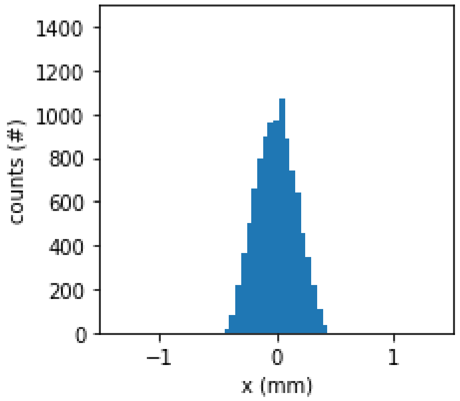
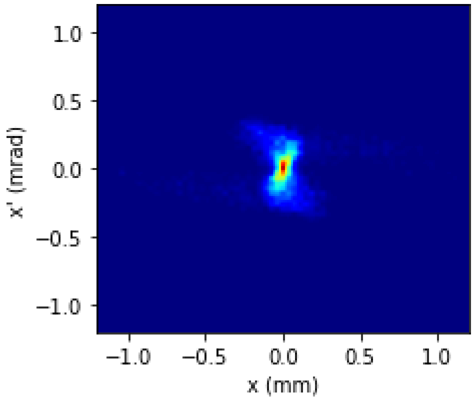
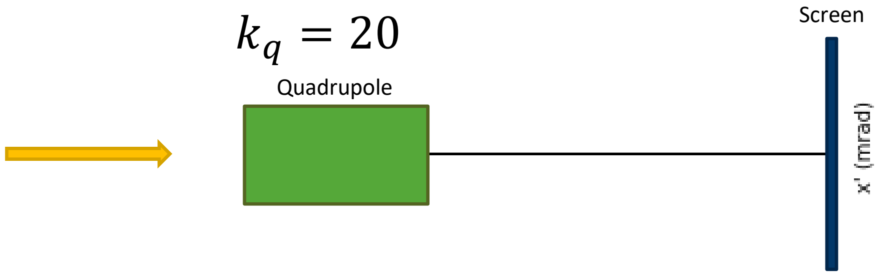
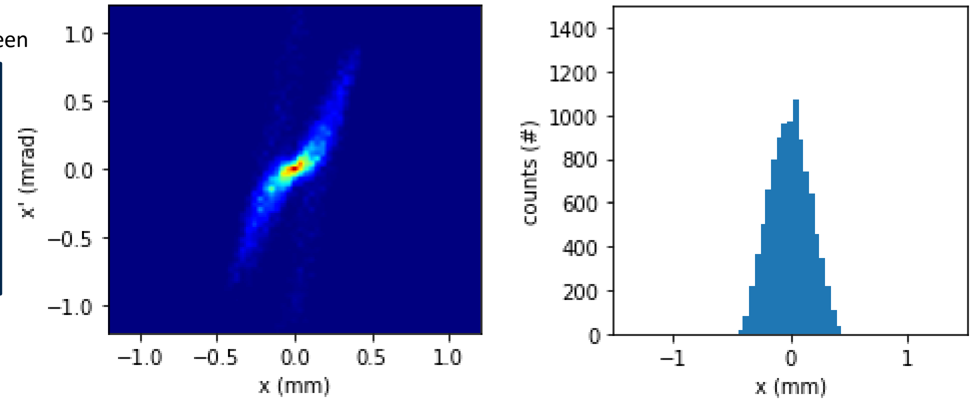




How this applies to beam physics?







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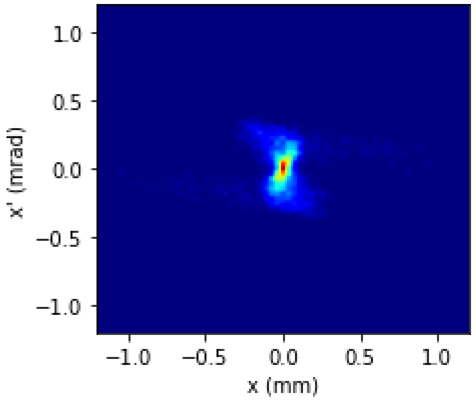
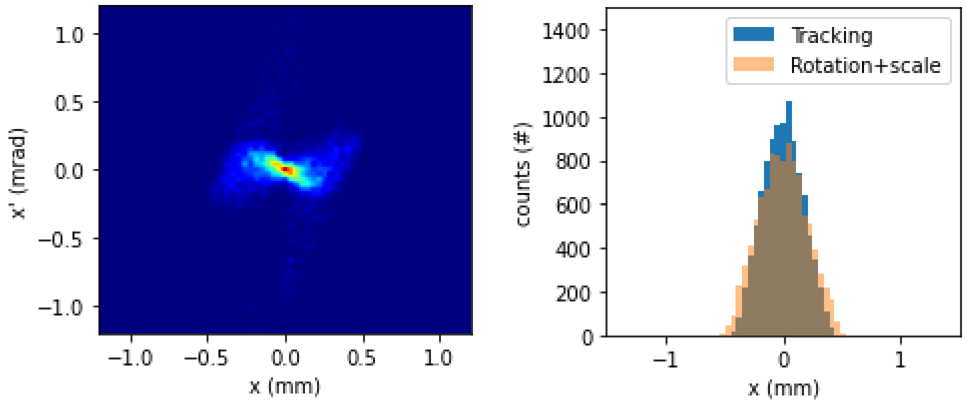


ROTATE

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

$\theta = 101°$



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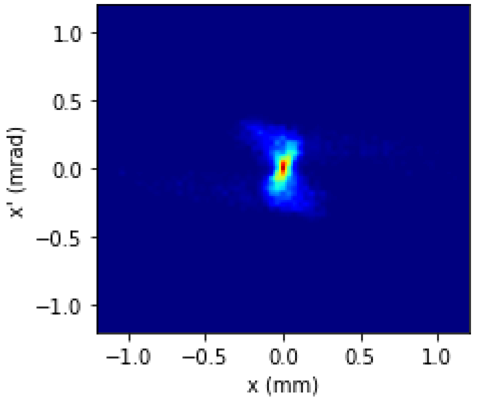
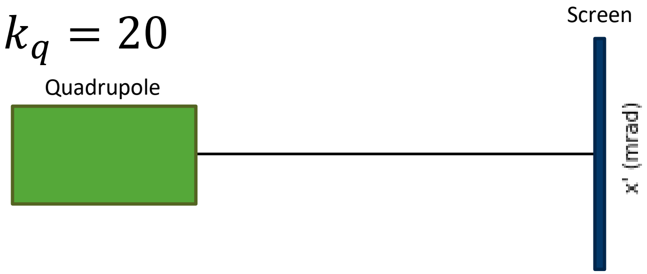
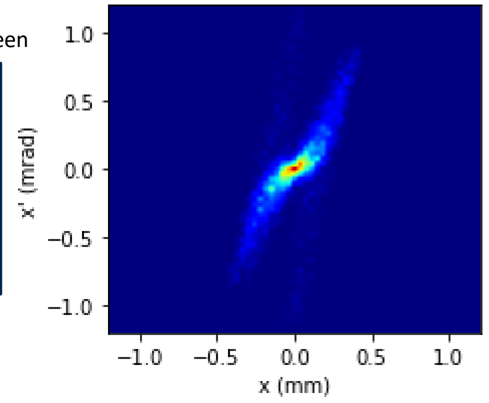
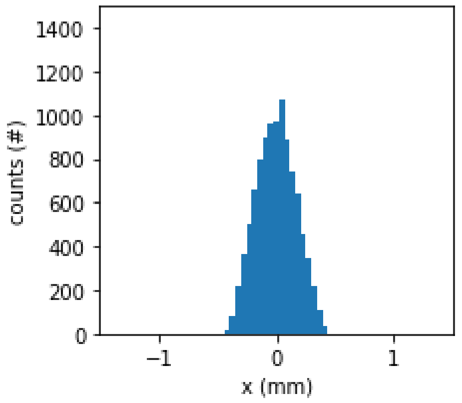


$k_q = 20$







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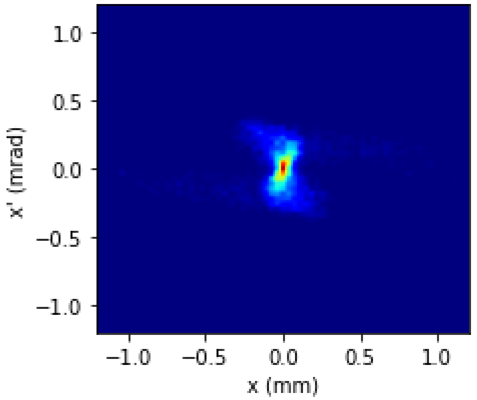


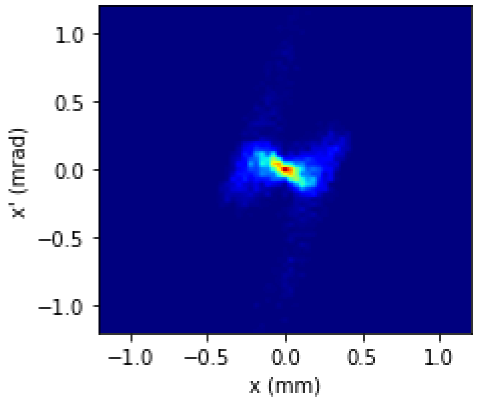
ROTATE

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

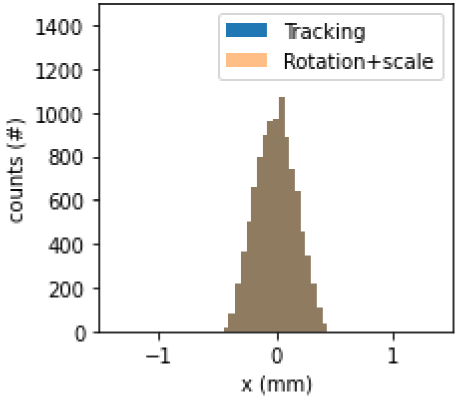
SCALE

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

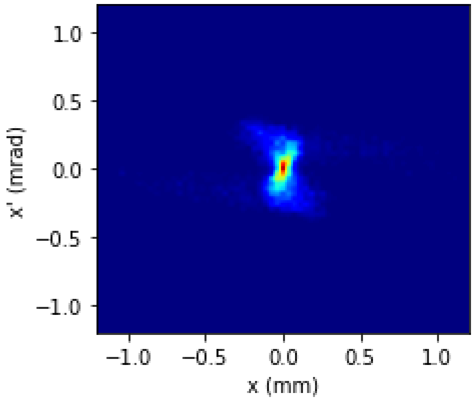
$\theta = 101°$



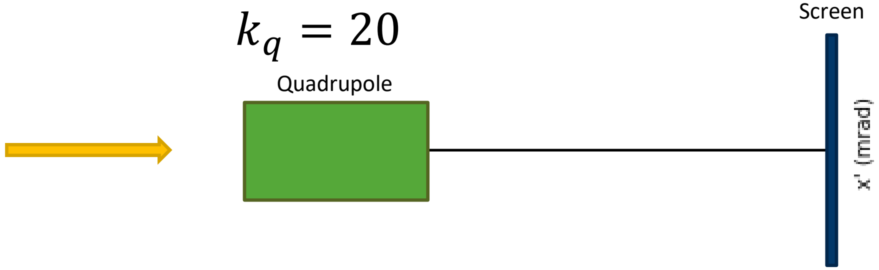
$s = 0.84$

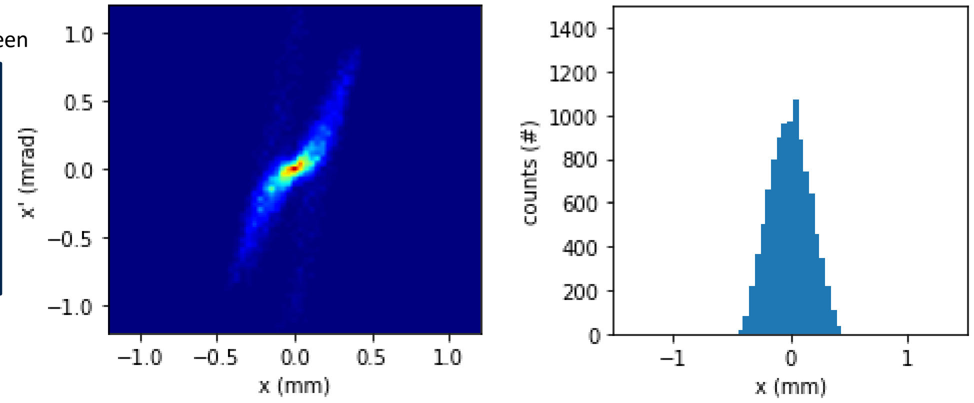


How this applies to beam physics?



$k_q = 20$





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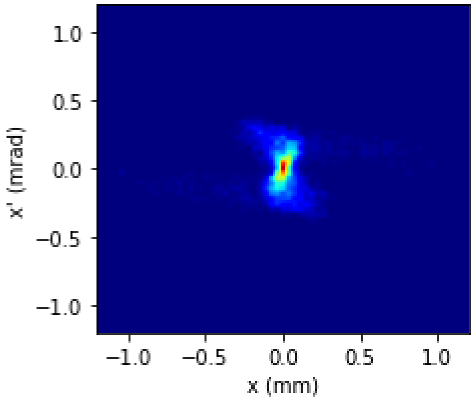
THANKS TO THIS TRANSFORMATION WE TREAT IT AS A TOMOGRAPHY PROBLEM!



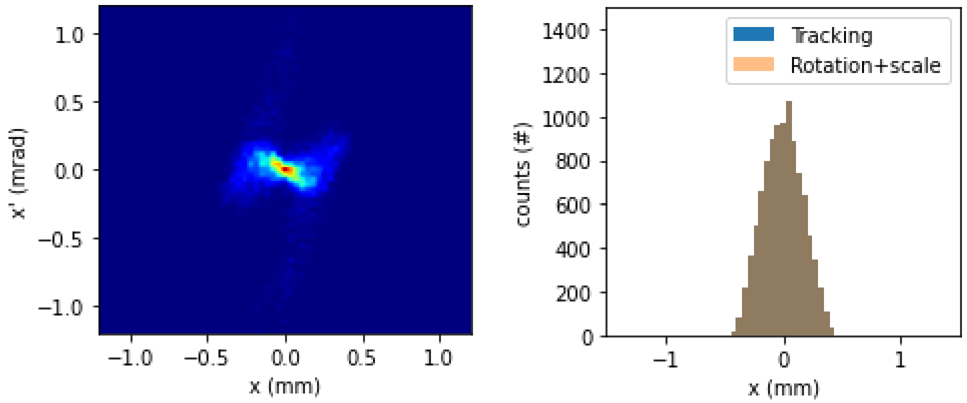
ROTATE

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

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

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