BSM IN THE TK: CONTROL OF THE MOMENTUM SPREAD AND REAL-TIME RECONSTRUCTION

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17 December 2025

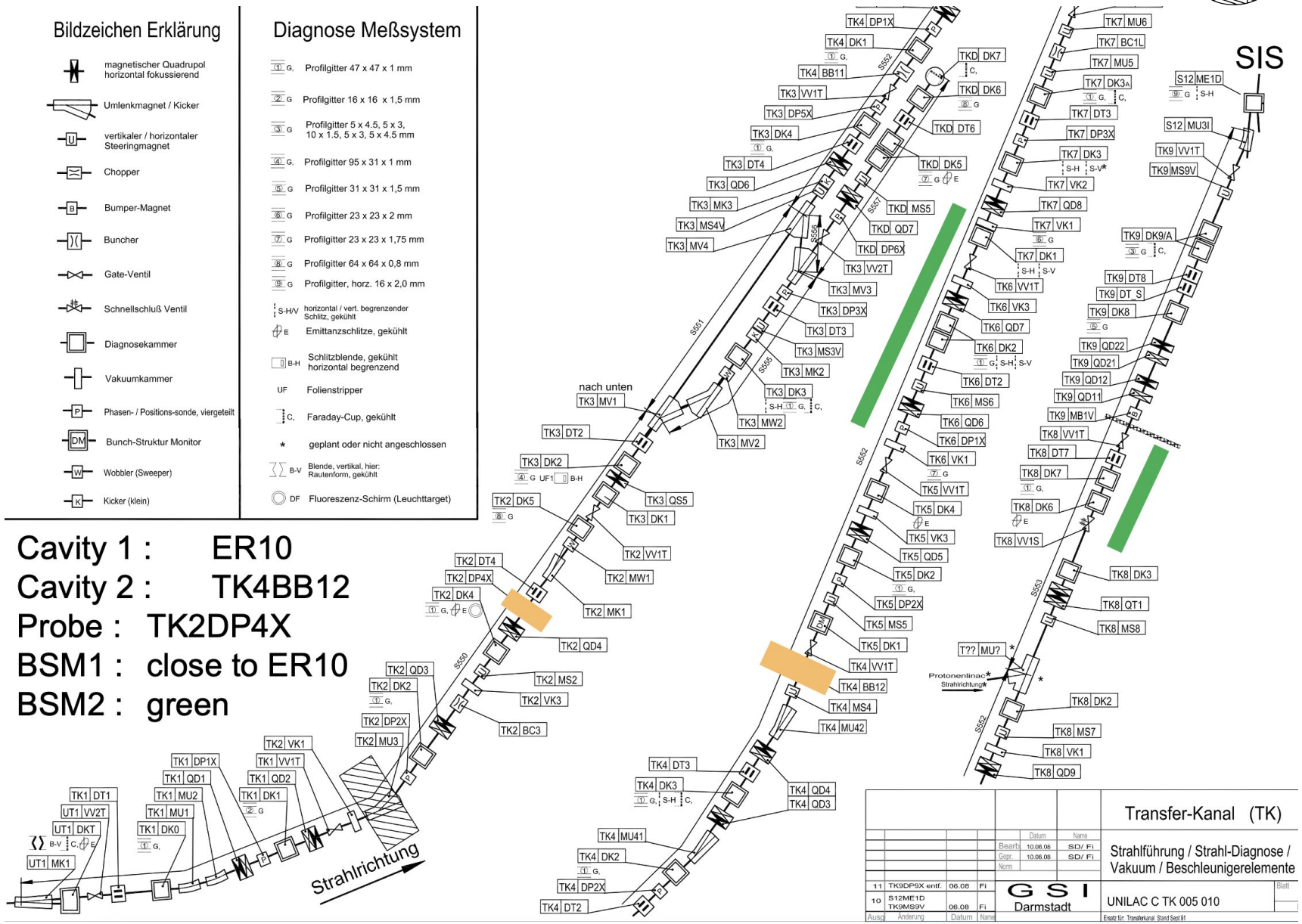
PURPOSE OF THE MEETING

- After the Machine Meeting 4. Nov 2025, issues and open question were identified:
  - Device protection (0.1mm wire) – today not addressed.
  - Transverse aperture (63mm)
  - Positions of the BSM installation in TK
  - Demonstration of the BSM data processing using the HLI measurements data
  - Features of the proposed real-time reconstruction software for the two-BSM system in TK

- The task: the issues and open questions should be clarified until Feb’26 (another discussion at the Machine Meeting) so that the installation can be started in March’26.

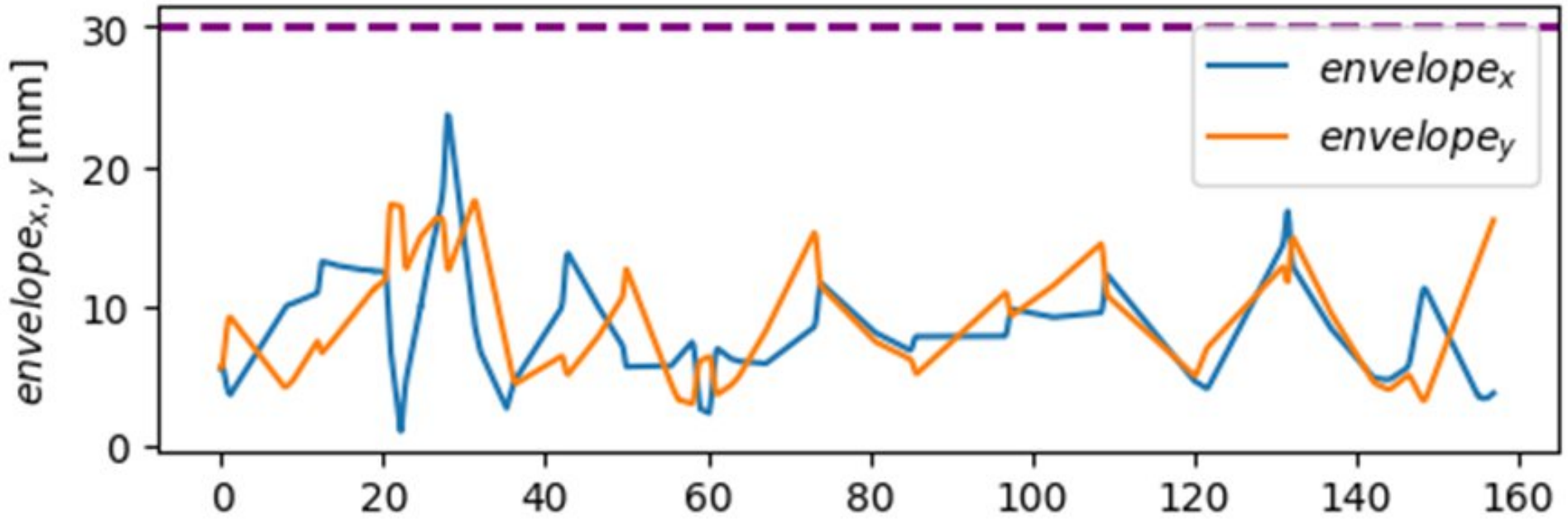
MOTIVATION

- dp/p of the beam injected into SIS (<1×10^{-3}) is crucial for low-loss high-intensity operation.
- Direct measurements of dp/p, and are needed for the optimal UNILAC, TK and SIS (rf capture) settings.
- Prioritized by FAIR TI and in the UNILAC upgrade matrix.
- BMFTR funded (RECON project) PhD TU Darmstadt: Sergei Sherstiuk


Bildzeichen Erklärung
magnetischer Quadrupol horizontal fokussierend
Umlenkmagnet / Kicker
vertikaler / horizontaler Steeringmagnet
Chopper
Bumper-Magnet
Buncher
Gate-Ventil
Schnellschluß Ventil
Diagnosekammer
Vakuumkammer
Phasen- / Positions-sonde, viergeteilt
Bunch-Struktur Monitor
Wobbler (Sweeper)
Kicker (klein)
Diagnose Meßsystem
Profilgitter 47 x 47 x 1 mm
Profilgitter 16 x 16 x 1,5 mm
Profilgitter 5 x 4.5, 5 x 3, 10 x 1.5, 5 x 3, 5 x 4.5 mm
Profilgitter 95 x 31 x 1 mm
Profilgitter 31 x 31 x 1,5 mm
Profilgitter 23 x 23 x 2 mm
Profilgitter 23 x 23 x 1,75 mm
Profilgitter 64 x 64 x 0,8 mm
Profilgitter, horz. 16 x 2,0 mm
horizontal / vert. begrenzender Schlitz, gekühlt
Emittanzschlitze, gekühlt
Schlitzblende, gekühlt horizontal begrenzend
Folienstripper
Faraday-Cup, gekühlt
geplant oder nicht angeschlossen
Blende, vertikal, hier: Rautenform, gekühlt
Fluoreszenz-Schirm (Leuchttarget)
Cavity 1 : ER10
Cavity 2 : TK4BB12
Probe : TK2DP4X
BSM1 : close to ER10
BSM2 : green
SIS
nach unten
Strahlrichtung
Protonenlinac
Strahlrichtung
Transfer-Kanal (TK)
Strahlführung / Strahl-Diagnose / Vakuum / Beschleunigerelemente
GSI Darmstadt
UNILAC C TK 005 010

APERTURE

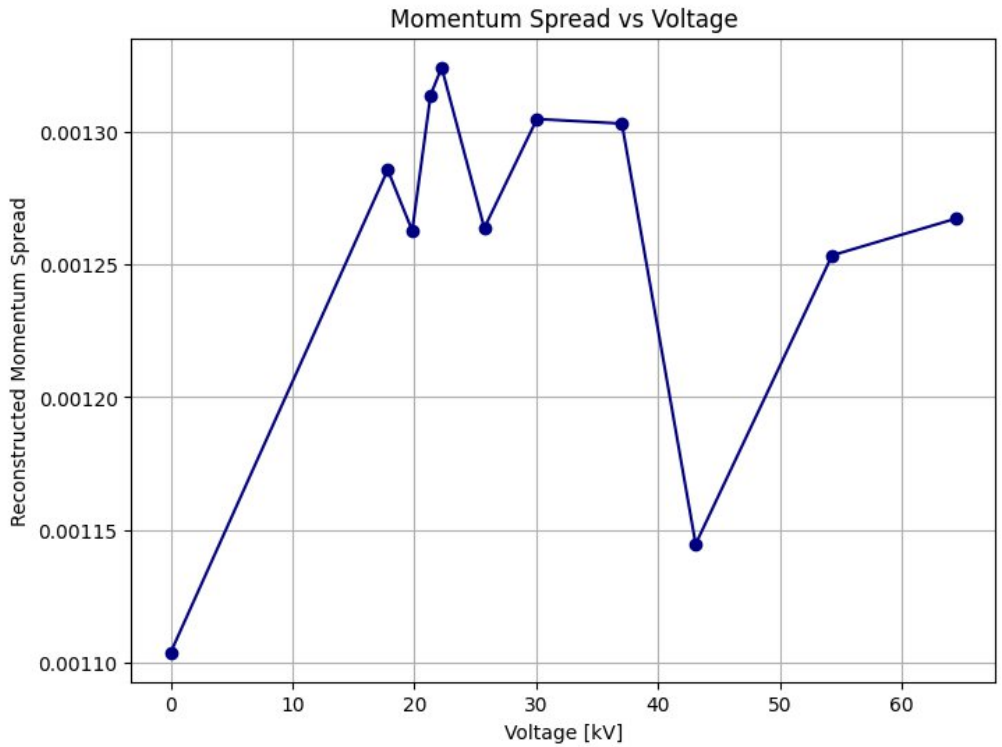
The violet line marks 30 mm aperture

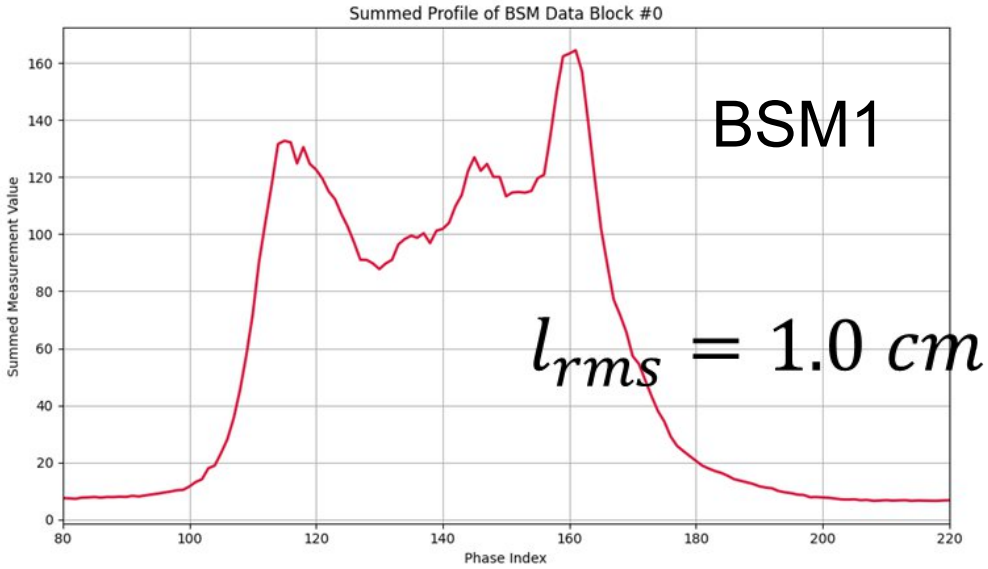


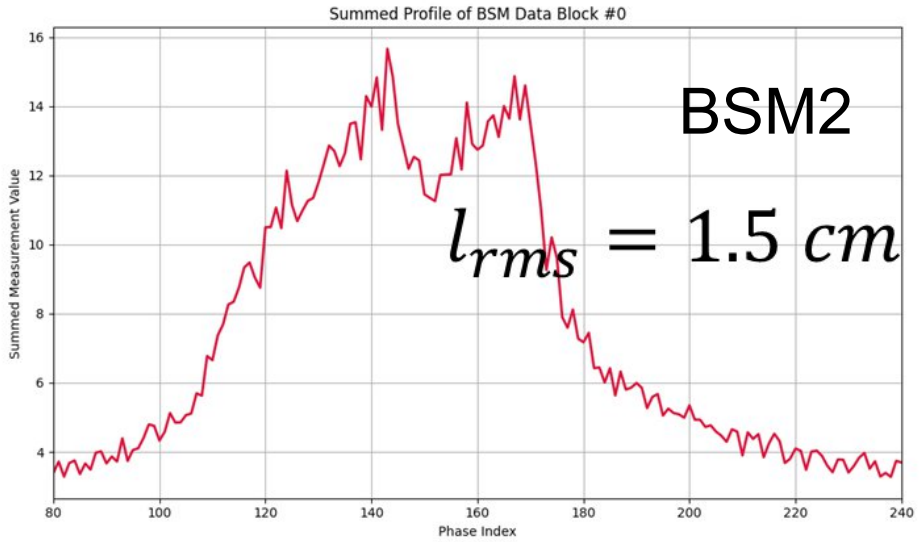
MOMENTUM SPREAD FROM TWO PROFILES

An example from the HLI measurement data:

- dp/p from two profiles BSM1 and BSM2
- Single-pass measurement
- Similar usage for TK with the complete beam dynamics (TK optics, space charge, beam loading)



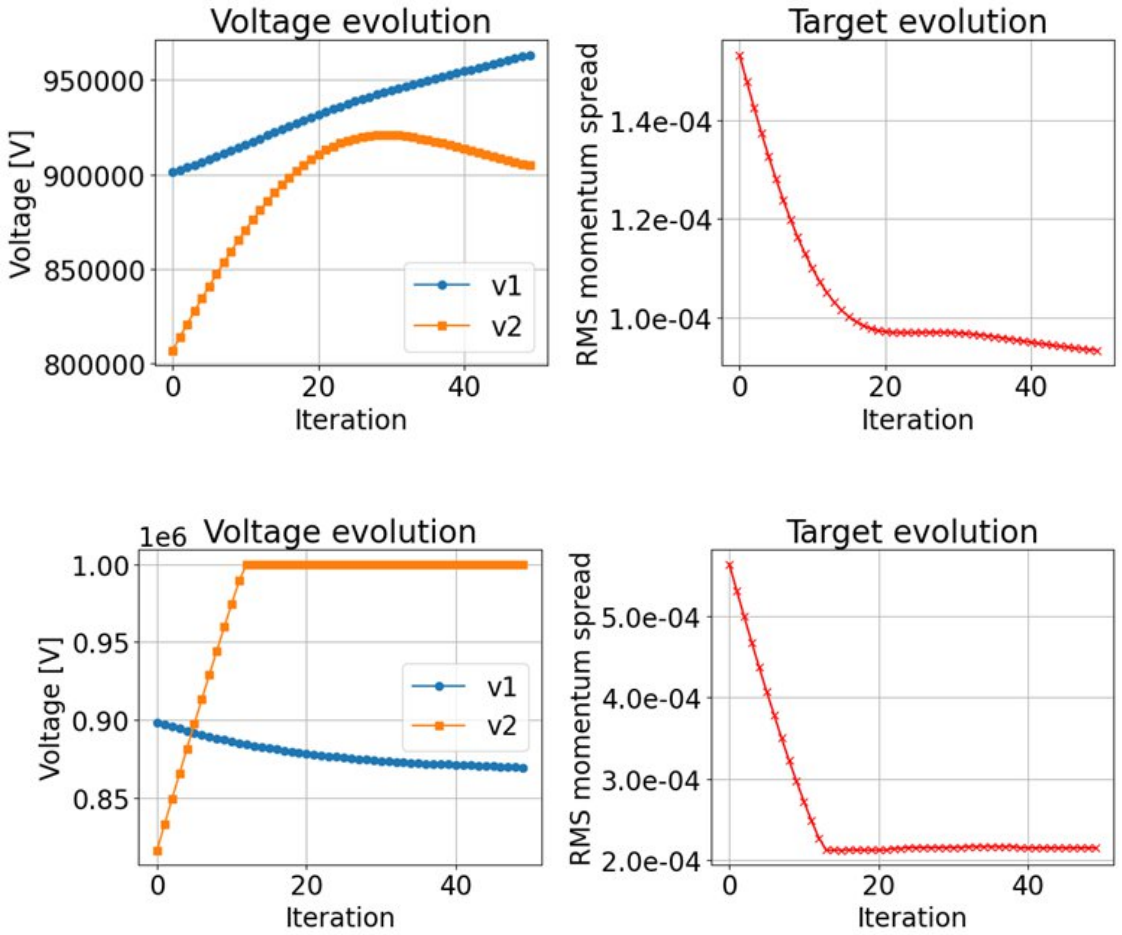




VOLTAGE OPTIMIZATION

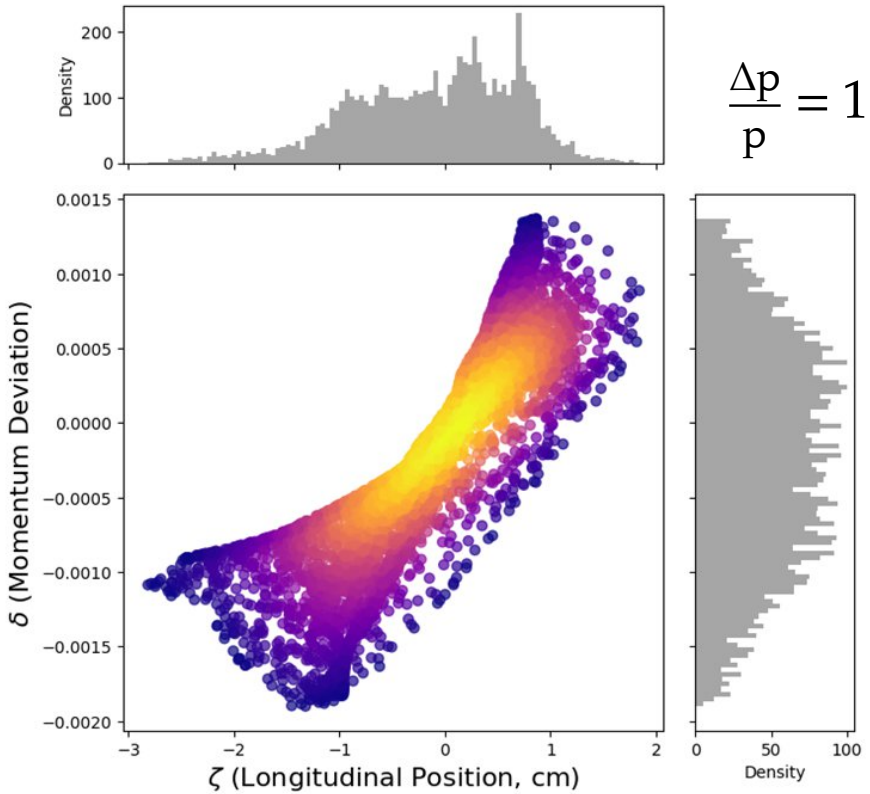
Example for the TK

- Optimized voltages for TK current of 0 and 11 mA
- Assumption: results for BSM1 and BSM2 are available.
- V1 is ER10, V2 is BB12.
- First buncher helps to elongate the bunch for maximum efficiency of the second buncher. Space charge additionally elongates the bunch.
- The algorithm uses a realistic beam-dynamics model (TK optics, space charge, beam loading)
- For an rms-equivalent Gaussian bunch a similar algorithm will be implemented for fast TK real-time application

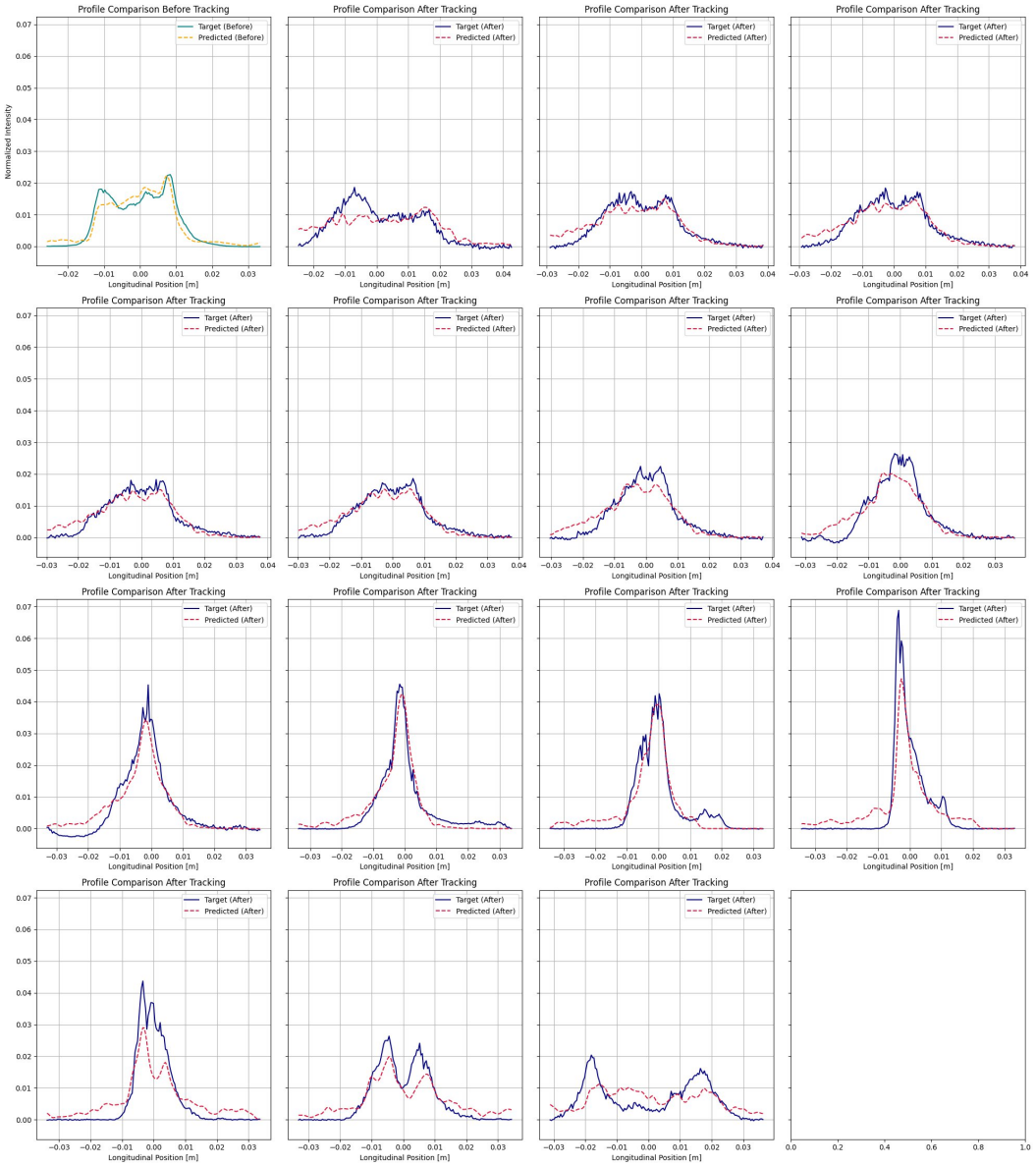


Reconstruction from series of measurements

An example from the HLI measurement data:
Details of the phase-space distribution.
Neural network is used to generate the distribution.
Profiles: blue-measured, red-reconstructed.
The phase-space at the position of BSM1.
Algorithm run time: 4 min

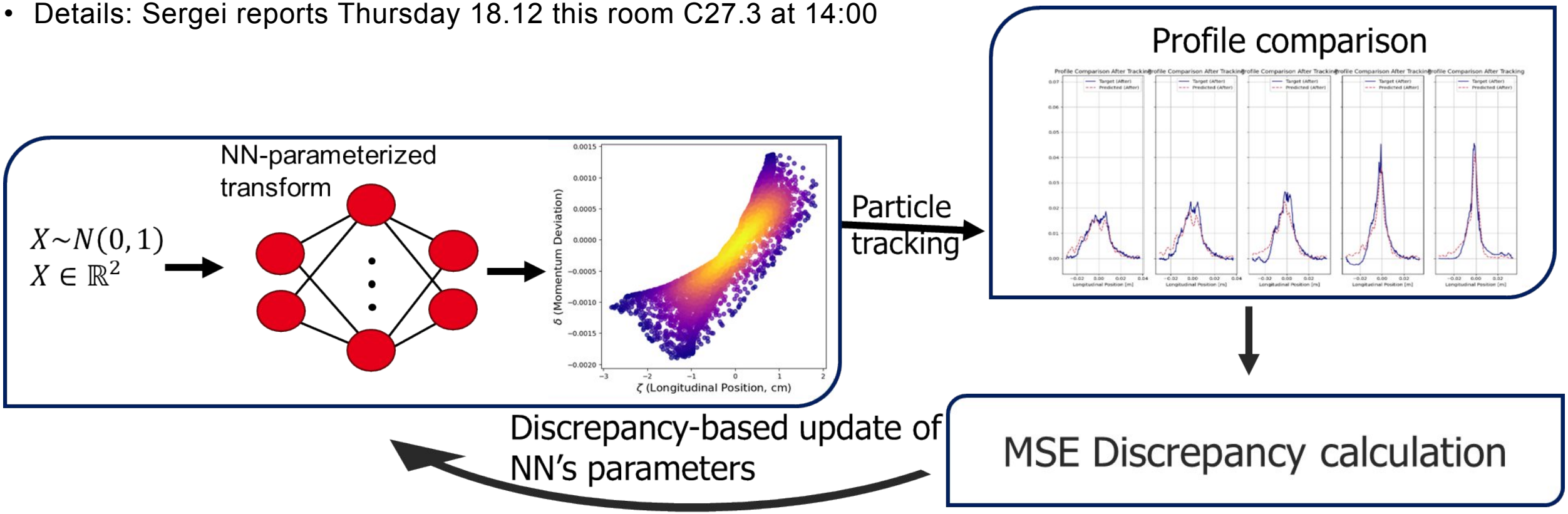


$$\frac{\Delta p}{p} = 1.1 \cdot 10^{-3}$$



RECONSTRUCTION

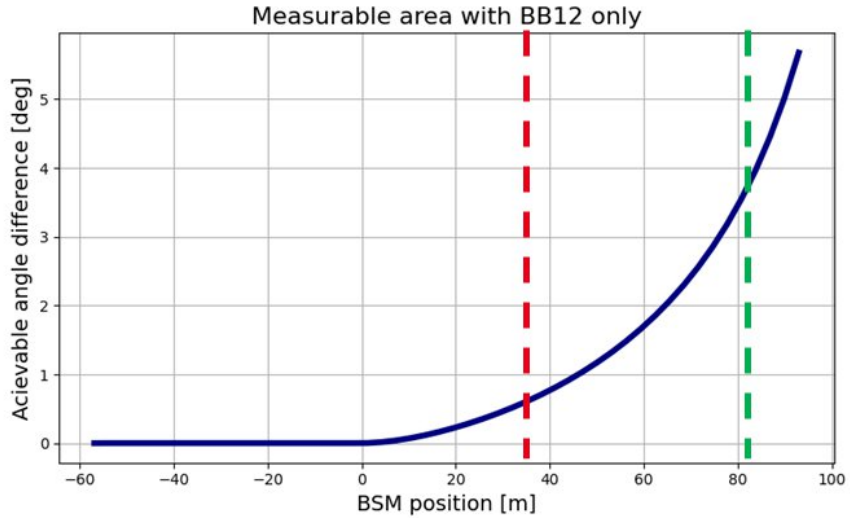
- Neural network-based particle generation for a wide variety of initial distributions
- Finding best-describing parameters with gradient decent
- Iterative trackings to ensure self-consistency
- Details: Sergei reports Thursday 18.12 this room C27.3 at 14:00

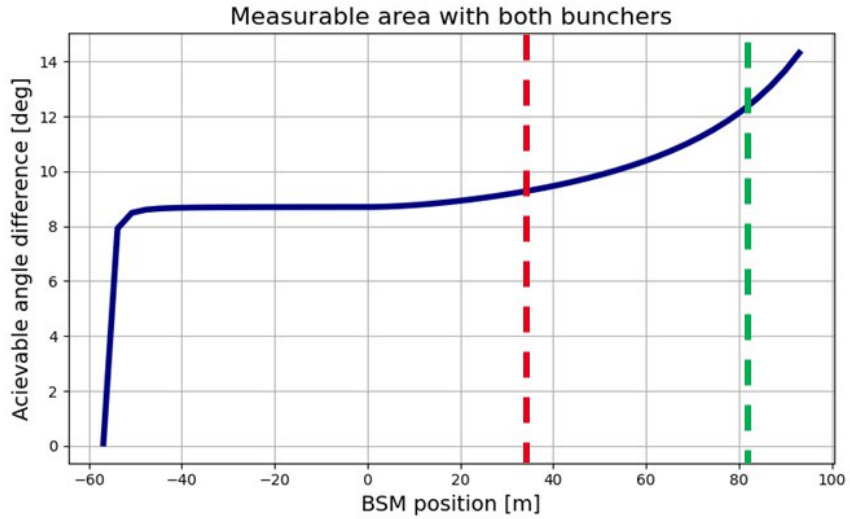


BSM POSITIONING IN THE TK

BSM2 in TK8 allows for a usage of the BB12 buncher in the phase-space reconstruction

Red dashed line - TK6
Green dashed line - TK8

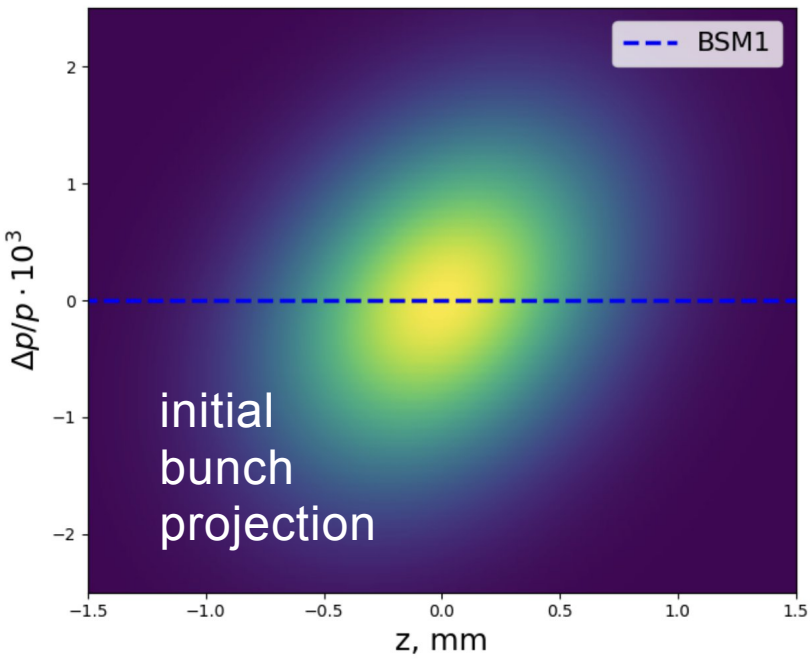


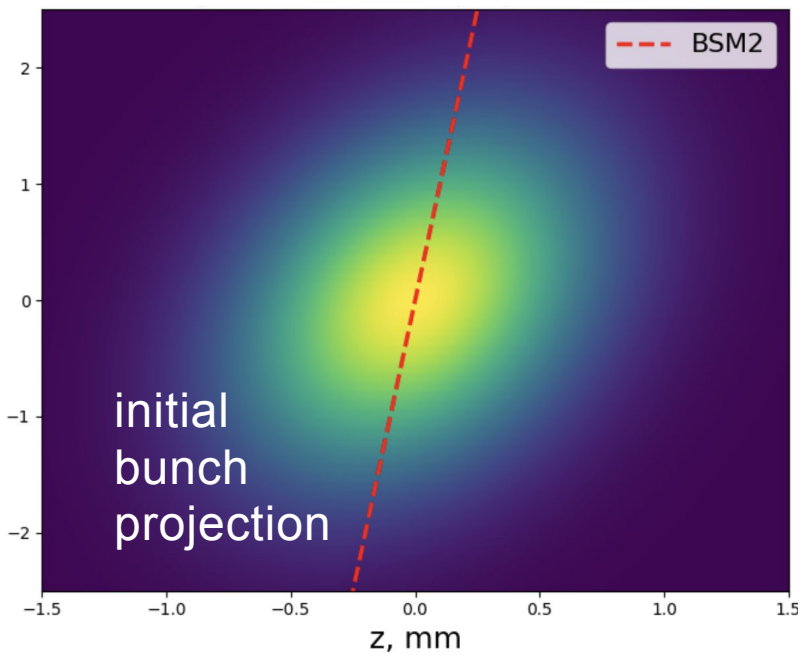


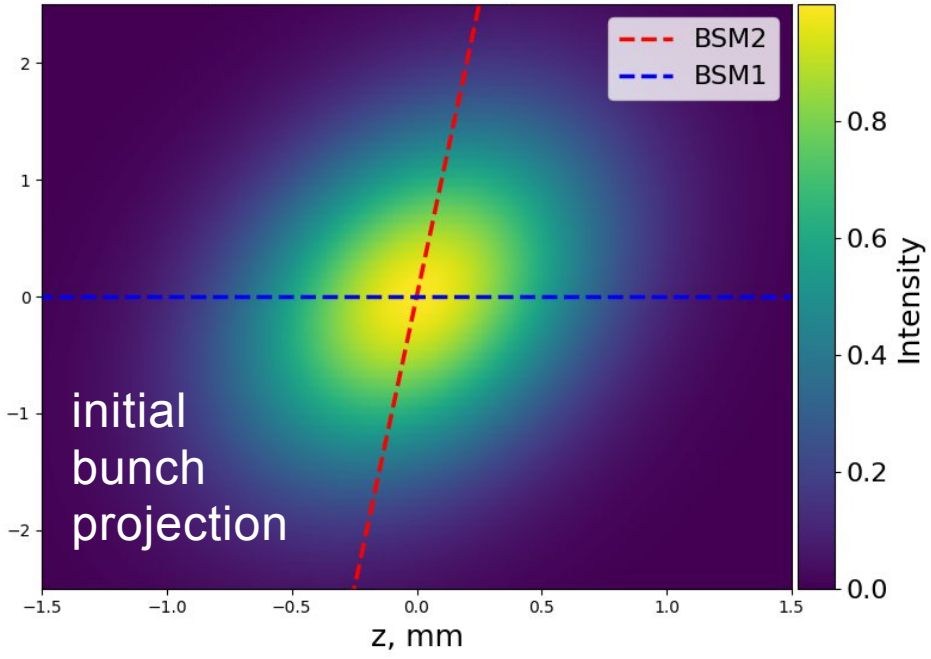
OUTLINE

- The momentum spread of the beam injected into SIS (dp/p<1×10^{-3}) is crucial for low-loss high-intensity operation.
- Direct measurements of dp/p are needed for the optimal UNILAC, TK and rf capture settings.
- Prioritized by FAIR TI and in the UNILAC upgrade matrix.
- New: Development of a “real-time” phase-space reconstruction software for TK bunch quality measurements and dp/p control.
- The basis of the software is a comprehensive beam-dynamics model
- Here: demonstration examples using the HLI data
- Two BSMs in the TK will enable:
  - Single-pass real-time dp/p measurement and voltage optimization
  - Real-time phase-space reconstruction after a few (<20) measurements
- BSM integration into the control system (FESA class) is needed

- A single pass scheme requires 2 BSM
- A real-time reconstruction requires 2 BSM for reliable operation
- Phase space deformations due to beam loading, space charge, etc





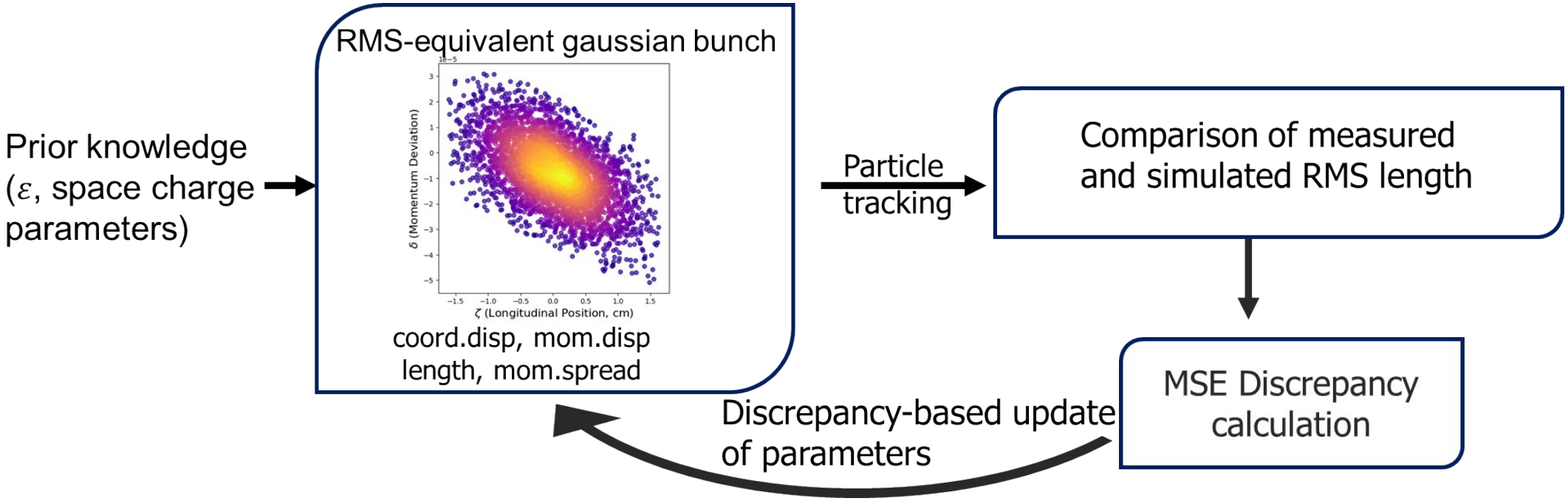


Each BSM measurement provides a slice of the phase space distribution

Phase space distribution can be reconstructed

REAL-TIME RECONSTRUCTION

- A faster and simplified version
- Use of prior knowledge to reduce the number of measurements needed



PHYSICS MODEL

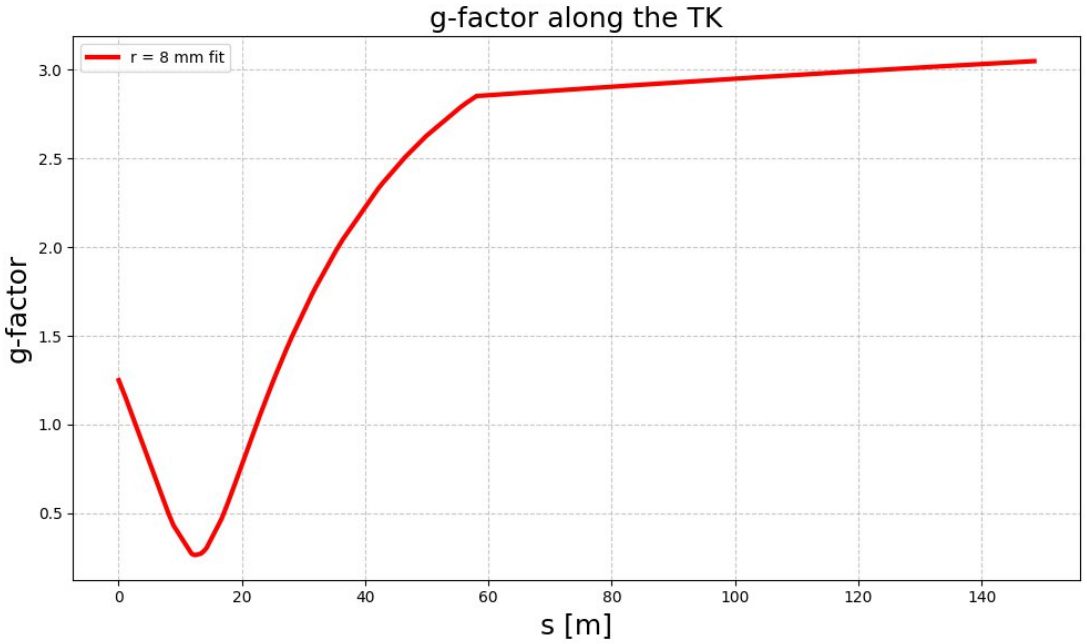
- Evolution of $f(z, \delta, l)$ in drifts with space charge forces:

$$\frac{\partial f}{\partial l} + \delta \frac{\partial f}{\partial z} - \frac{qE_z}{\gamma^2 p_0 c} \frac{\partial f}{\partial \delta} = 0$$

- A grid-less longitudinal space charge solver for accurate representation of distribution's details:

$E_z = -\frac{\partial \varphi}{\partial z}$ is longitudinal electric field in rest-frame:

$$\begin{cases} \Delta\varphi = -4\pi\rho \\ \varphi(r = b) = 0 \end{cases}$$



- With occasional thin-cavity kicks:

$$\Delta W = qU \cdot \sin\left(\frac{2\pi}{\lambda\beta} z - \phi_0(I)\right)$$

- PyTorch implementation to use gradient decent in reconstruction