Longitudinal tomography at the HElmholtz LInear ACcelerator

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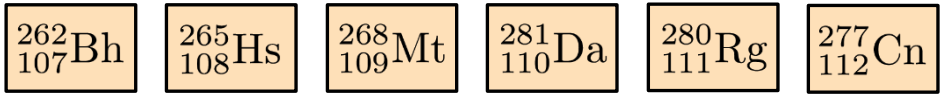
[3]JGU Johannes Gutenberg-Universität, Mainz, Germany

Introduction

- GSI Helmholtzzentrum at Darmstadt is the worldwide leading center for heavy ion research.
- Since 50 years the heavy ion UNILAC is the main accelerator at GSI.
- The GSI Super Heavy Element (SHE) user program led to the discovery of six elements for the periodic table.



- but UNLIAC is going to be upgraded…

UNILAC - Requirements for FAIR and the SHE-Program

FAIR requirements

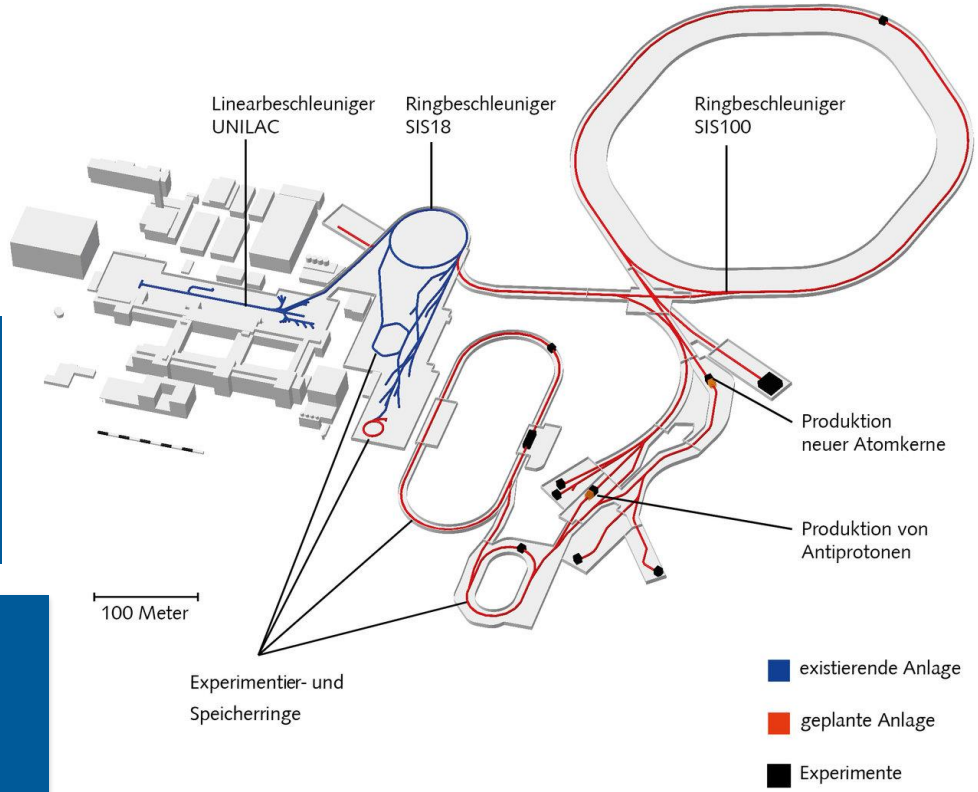
- high beam currents
- low repetition rate (max. 3 Hz)
- low duty factor

Super Heavy Element (SHE) requirements

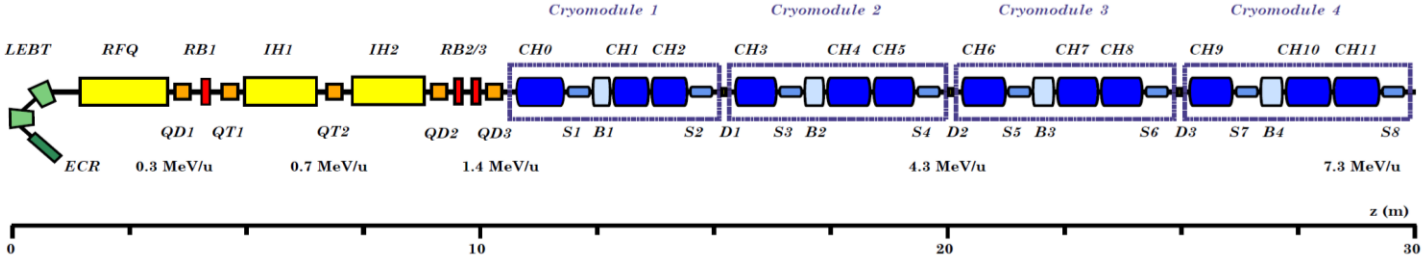
- relatively low beam currents
- high repetition rate (50 Hz)
- high duty factor (100 %, pulse length up to 20 ms)

Material Science at GSI requirements

- heavy ions (m > 200)
- beam energy (up to 10 MeV/u)
- smoothly variable beam energy (1.5 – 10 MeV/u)



Design Layout for the HELIAC



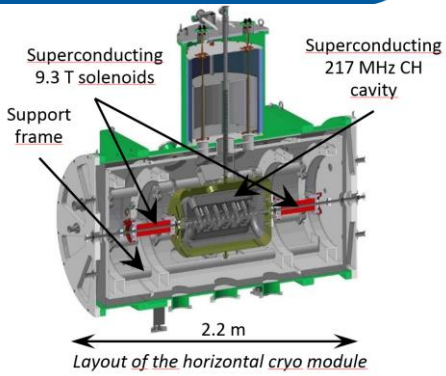
Therefore, a new dedicated CW capable accelerator is under construction:

***HE**lmholtz **LI**near **AC**celerator (**HELIAC**)*

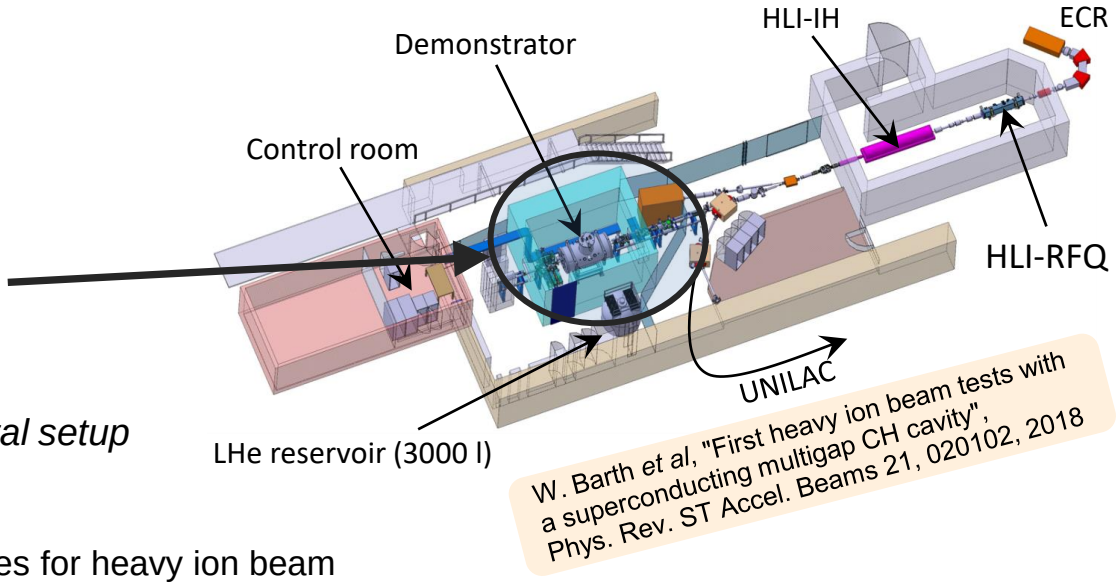
, which is a common project of HIM and GSI under key support of GUF-IAP and JG-U.

	Design Value
Mass/Charge	6
Frequency	108.4 (216.8) MHz
Max. beam current	1 mA
Operation mode	continuous wave (CW)
Injection energy	1.4 MeV/u
Output energy	3.5–7.3 MeV/u
Output energy spread	±3 keV/u

Recent Experimental Setup at GSI



Layout of the horizontal cryo module



W. Barth *et al*, "First heavy ion beam tests with a superconducting multigap CH cavity", Phys. Rev. ST Accel. Beams 21, 020102, 2018

Successful commissioning of experimental setup with SC CH cavity in 2017

GSI High Charge State injector (HLI) provides for heavy ion beam

HLI consists of ECR ion source, RFQ and IH-DTL cavity

IH-DTL design with KONUS (Kombiniert Null Grad Struktur) beam dynamics (0° synchronous phase)

- providing efficient acceleration
- deformation of the bunch shape in the longitudinal phase plane
- output beam parameters are (very) sensitive to cavity RF settings

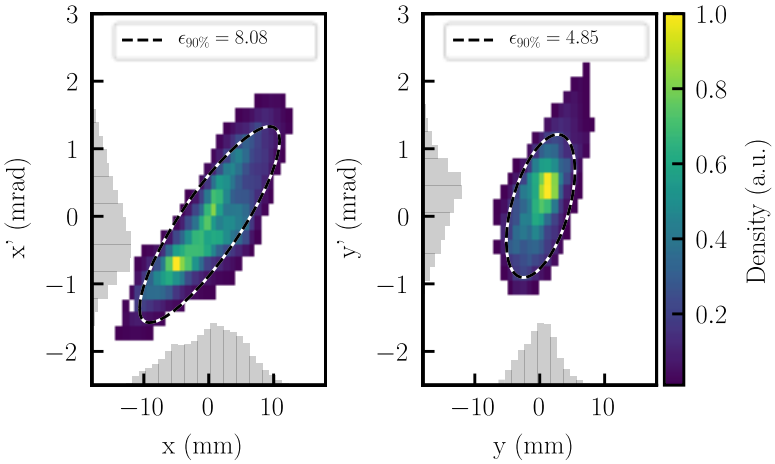
Motivation

6D matching of the beam to the cavity acceptance is required

- Transverse beam parameters already measured (x-x' and y-y' phase planes)

- Projection to the time axis (phase) measured with a Bunch Shape Monitor

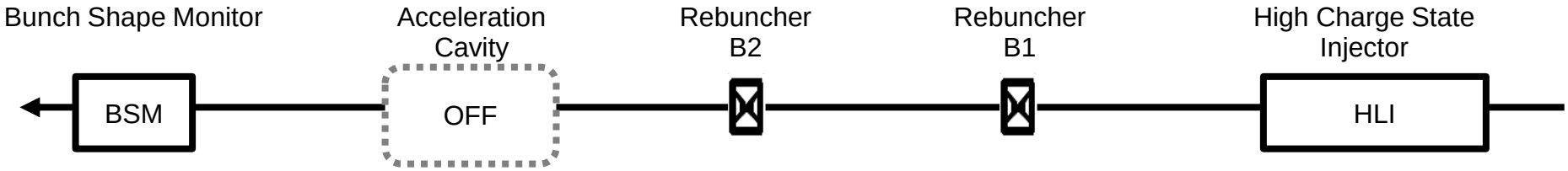
- Mean beam energy measured with phase probe sensors



The so far not measured longitudinal bunch shape is of special interest due to the intrinsic nonlinearity of longitudinal KONUS beam dynamics

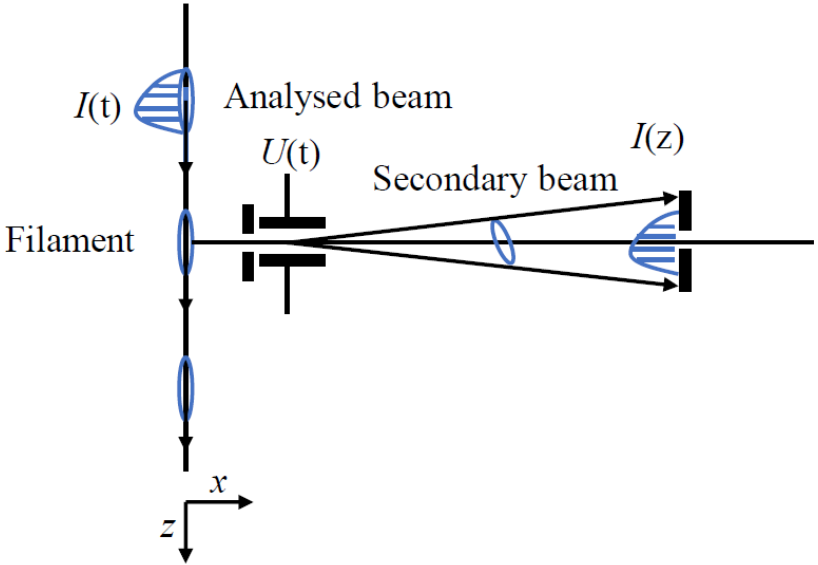
Therefore, a dedicated investigation for the longitudinal beam parameters is required

Simplified Scheme of the Recent Setup



- Beam provided by the injector GSI-High Charge State Injector (HLI)
- Two rebuncher cavities used for longitudinal beam focusing
- Accelerating cavity not in use for the presented investigations
- Feschenko Monitor (BSM) for longitudinal beam diagnostics

Bunch Shape Monitor of Feschenko-type



Minimally invasive

Fixed wire in beam line

Secondary Electron (SE) emission time dependent

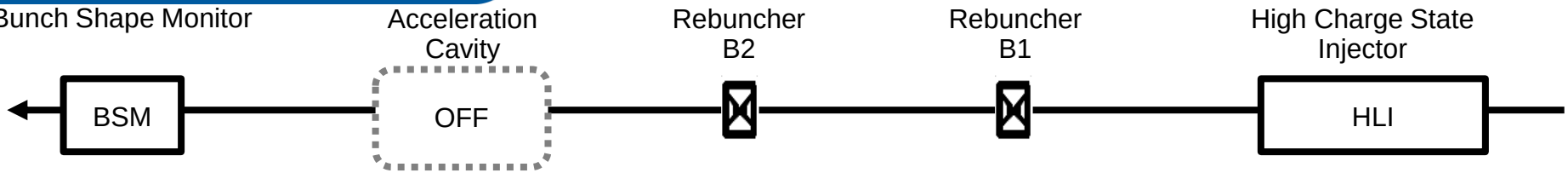
RF field deflects SE → spatial signal

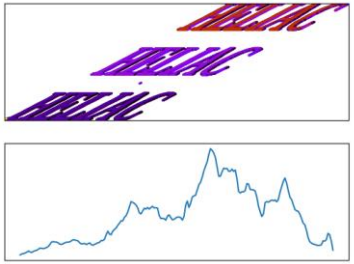
Spatial signal → Secondary Electron Multiplier

Sufficient resolution (1° at 108 MHz)

Feschenko, A.V., "Technique and instrumentation for bunch shape measurements", in *Proc. RuPAC'12*, Russia, 2012

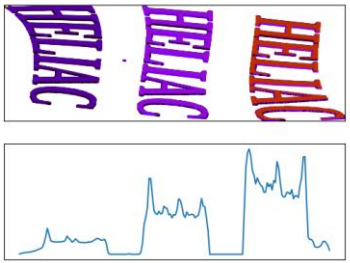
Reconstruction Goal



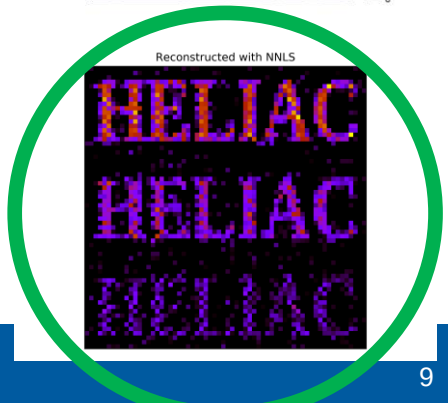


Rebuncher Setting A

Rebuncher Setting B



Reconstruct longitudinal bunch shape from measurements



Overview: Reconstruction Algorithms

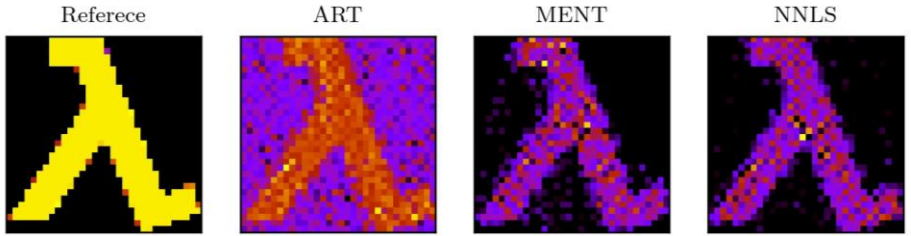
Related approaches:

- Quadrupole / Rebuncher Scan Technique → only Twiss parameters
- ART / SART → requires lots of projections, e.g. @CERN
  Algebraic Reconstruction Technique
- FBP → for linear mapping
  Filtered Back Projection
- MENT Reconstruction → memory intense, e.g. @DESY
  Maximum ENTropy

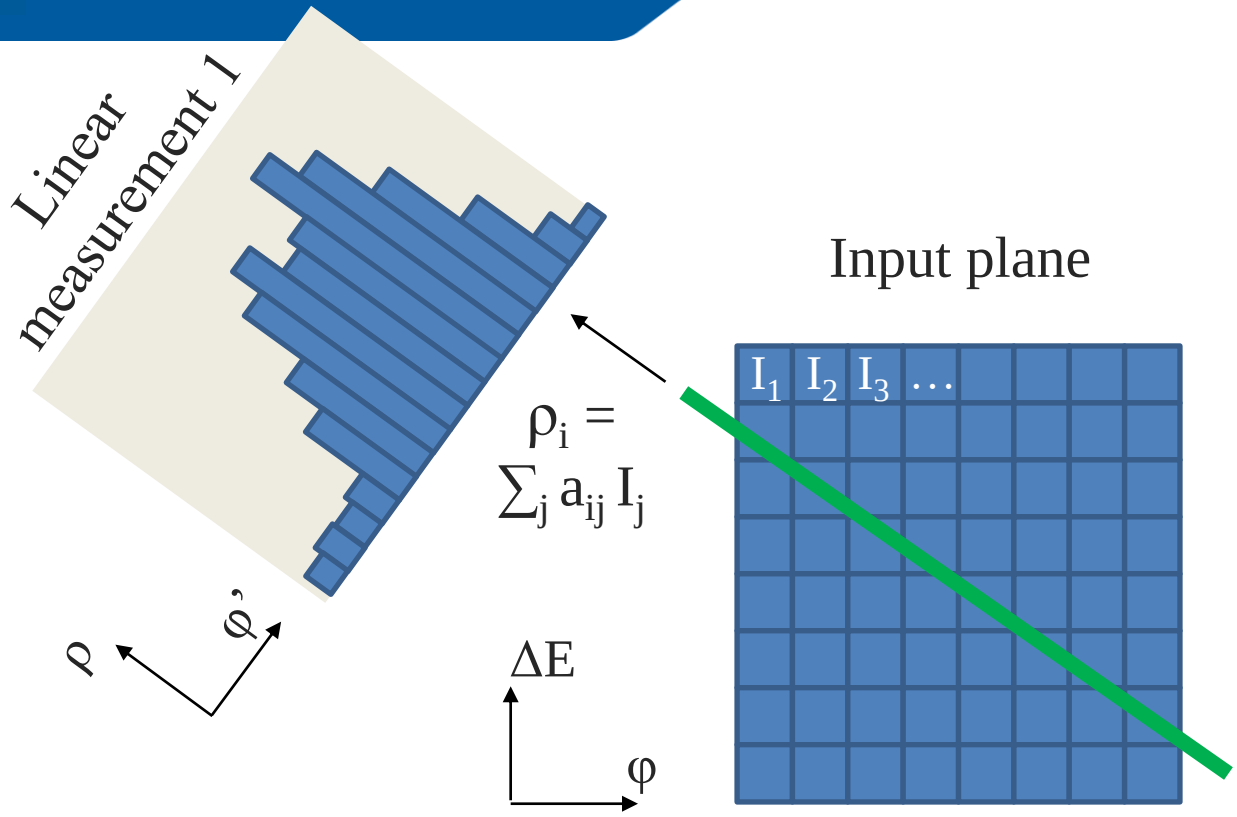
NNLS Reconstruction → close to least square
Non Negative Least Squares

J. Lallement *et al.*, "Linac4 transverse and longitudinal emittance reconstruction in the presence of space charge", *in Proc. LINAC'14*, Geneva. Switzerland, pp. 913, 2014

G. Asova *et al.*, "Design of a tomography module for the PITZ facility" in *Proc. EPAC08*, pp. 1038, 2008



Reconstruction Algorithm

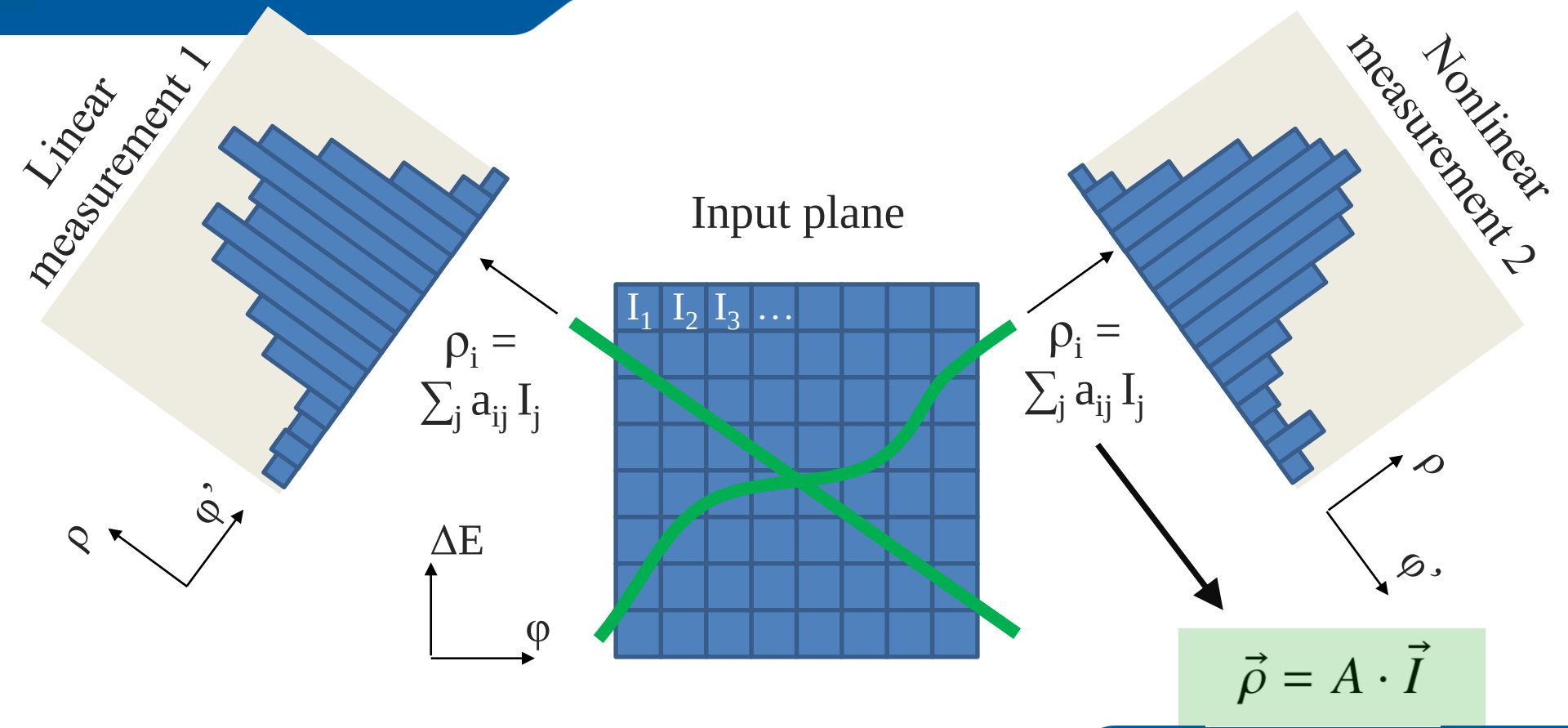


The measurements must be connected to the input plane.

Each measurement bin corresponds to a sum (line integral) along the input

The mapping from *input* to *measurement* can be derived from beam dynamics simulations

Reconstruction Algorithm



Reconstruction Algorithm

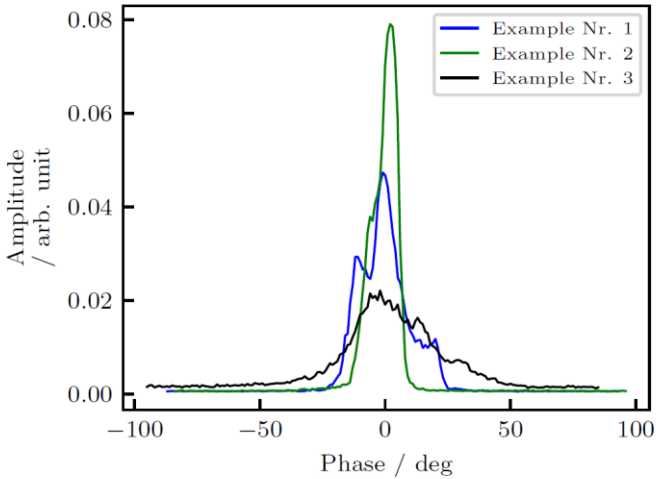
Linear system of equations obtained:

$$\vec{\rho} = A \cdot \vec{I}$$

Connects all measurements ρ with input grid intensities I.

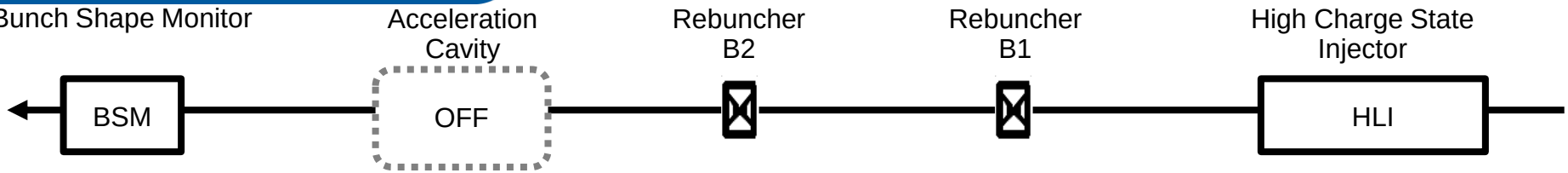
Solve for intensities:

$$\begin{aligned} &\text{minimize} \quad f(\vec{I}) = \left| A \cdot \vec{I} - \vec{\rho} \right| \\ &\text{subject to} \quad \vec{I} \geq 0 \end{aligned}$$

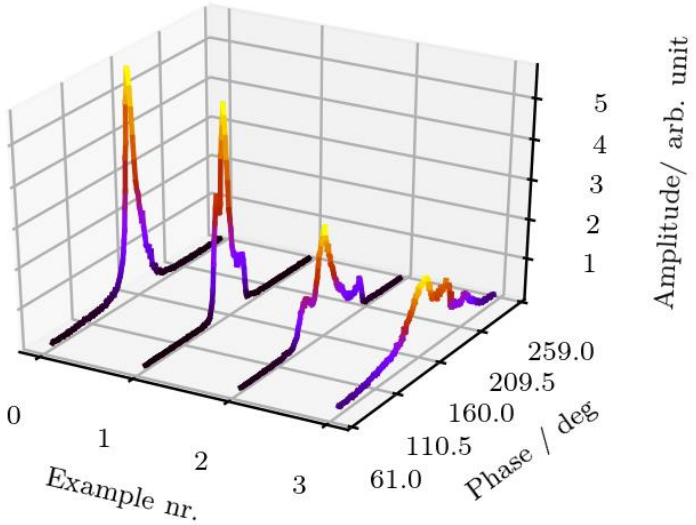


Solved by Non-Negative Least Squares algorithms from the scientific python library.

Measurements



Example Measurements



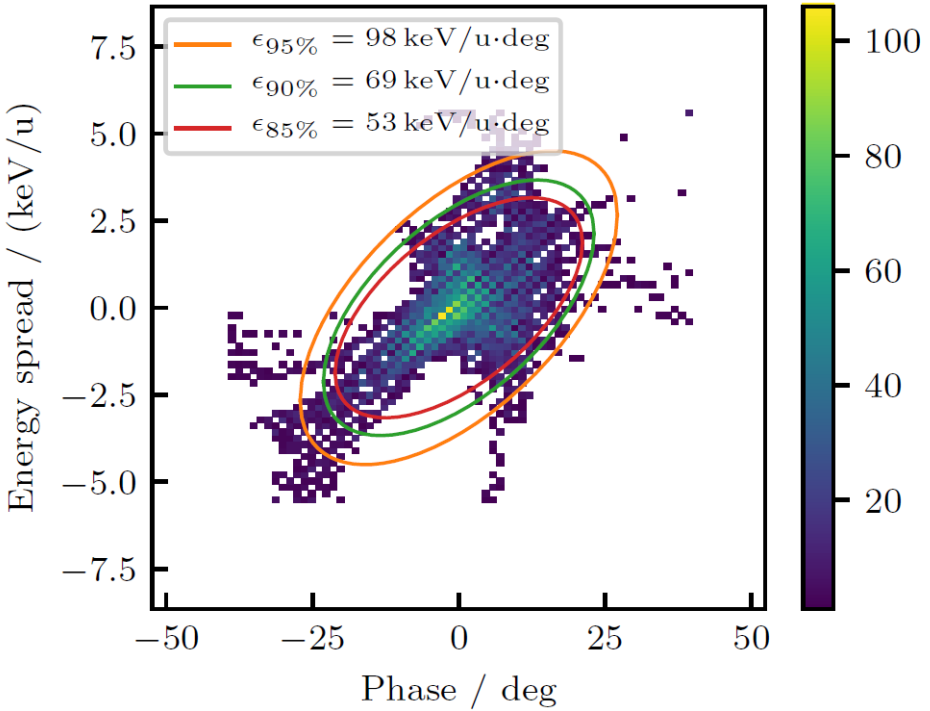
Injector at fixed parameters

- ~100 sets measured in one shift
- Almost full transmission achieved
- Buncher voltages varied
- Cavity OFF

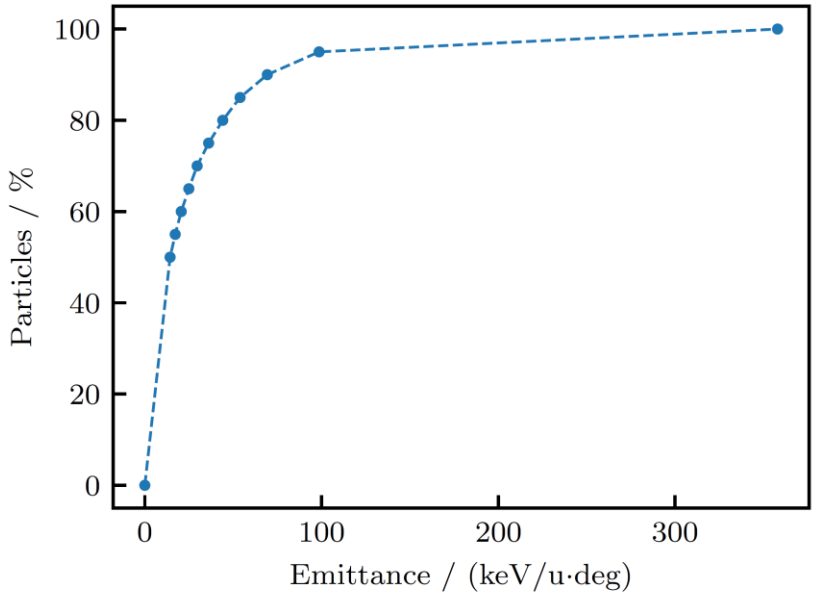
Non-elliptic shape is evident

Results

Reconstructed particle distribution
at HLI injector exit

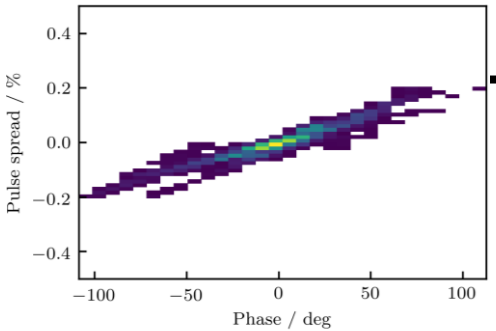


Clearly visible core



Results

Simulated at BSM



Acceleration Cavity

OFF

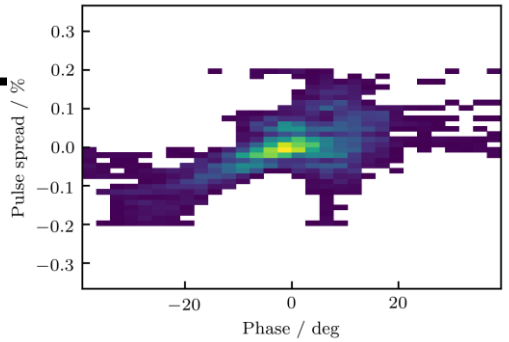
Rebuncher B2

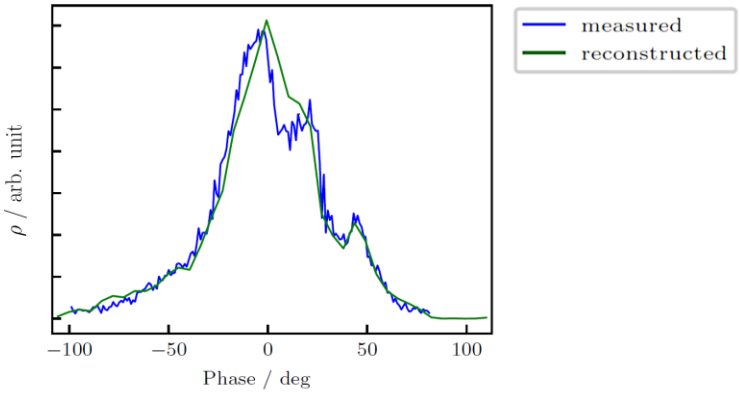
0 a.u.

Rebuncher B1

0 a.u.

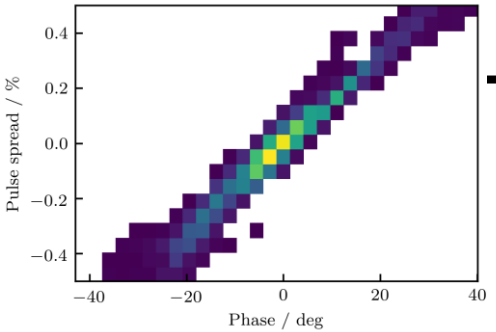
Reconstructed at HLI exit





Results

Simulated at BSM



Acceleration Cavity

OFF

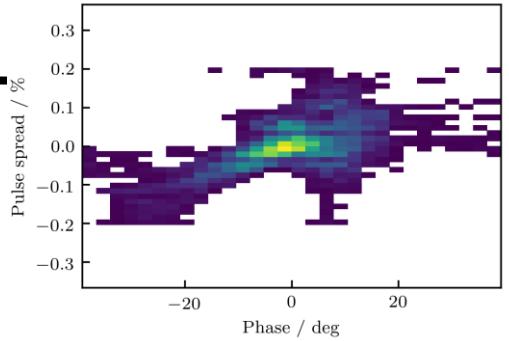
Rebuncher B2

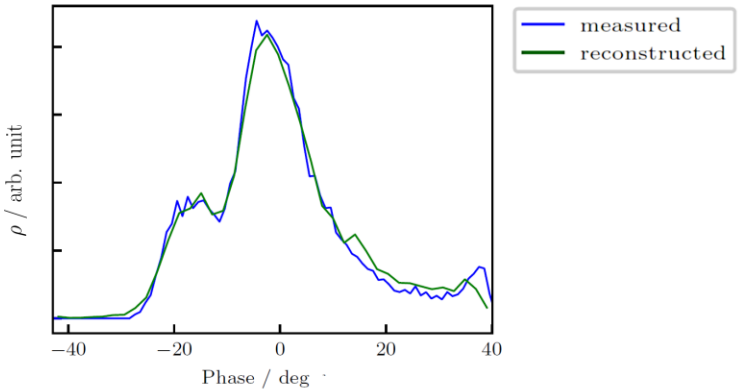
1 a.u.

Rebuncher B1

3.5 a.u.

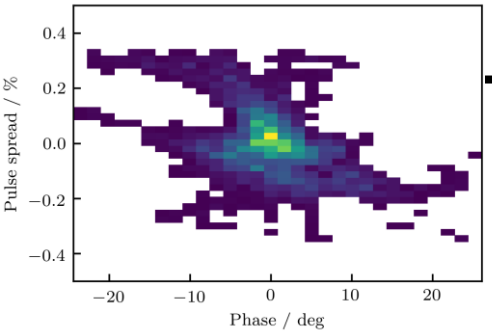
Reconstructed at HLI exit





Results

Simulated at BSM



Acceleration Cavity

OFF

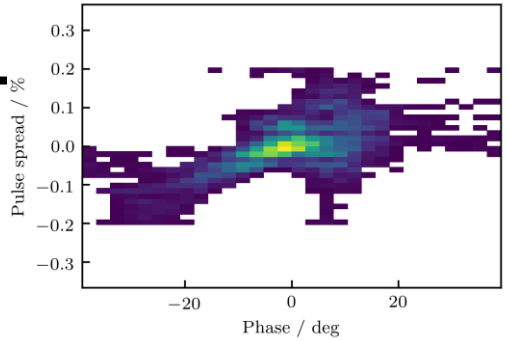
Rebuncher B2

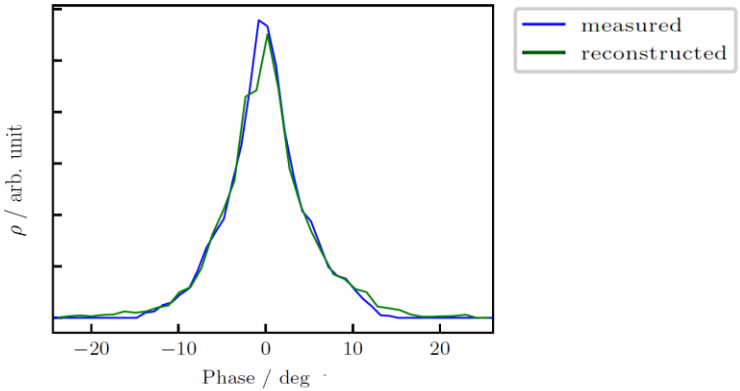
1.3 a.u.

Rebuncher B1

1.5 a.u.

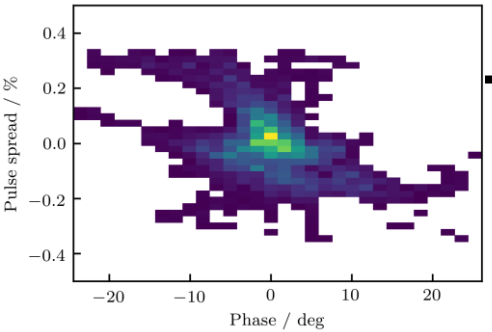
Reconstructed at HLI exit

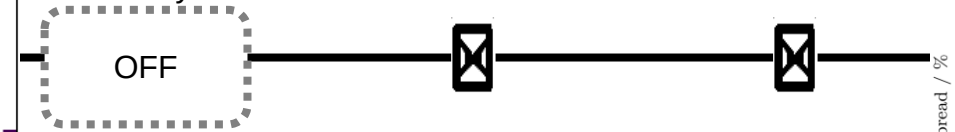




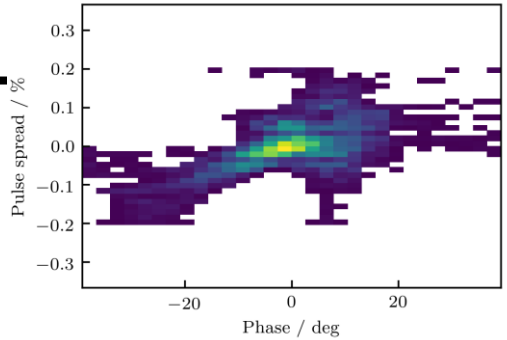
Results

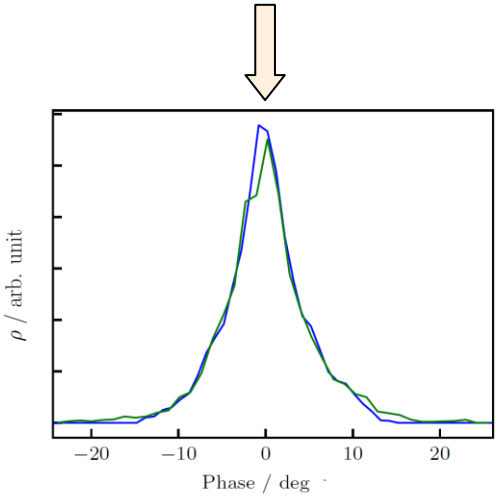
Simulated at BSM





Reconstructed at HLI exit



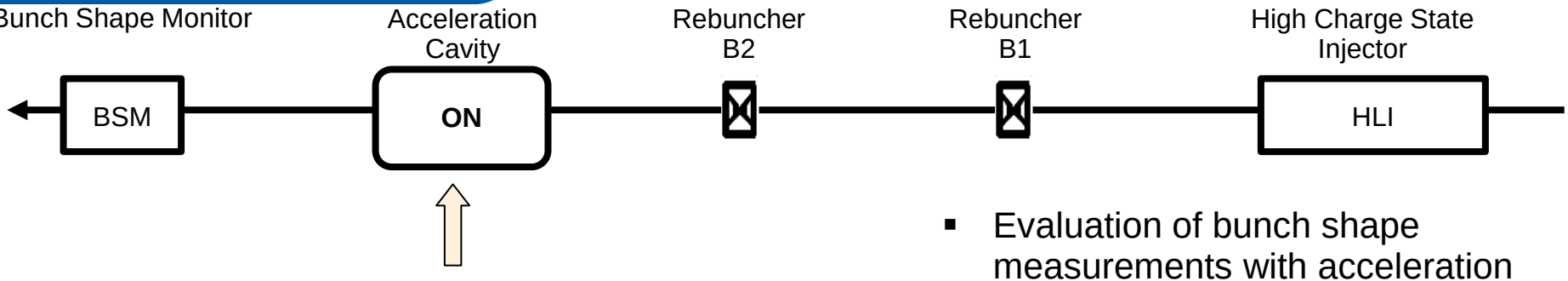


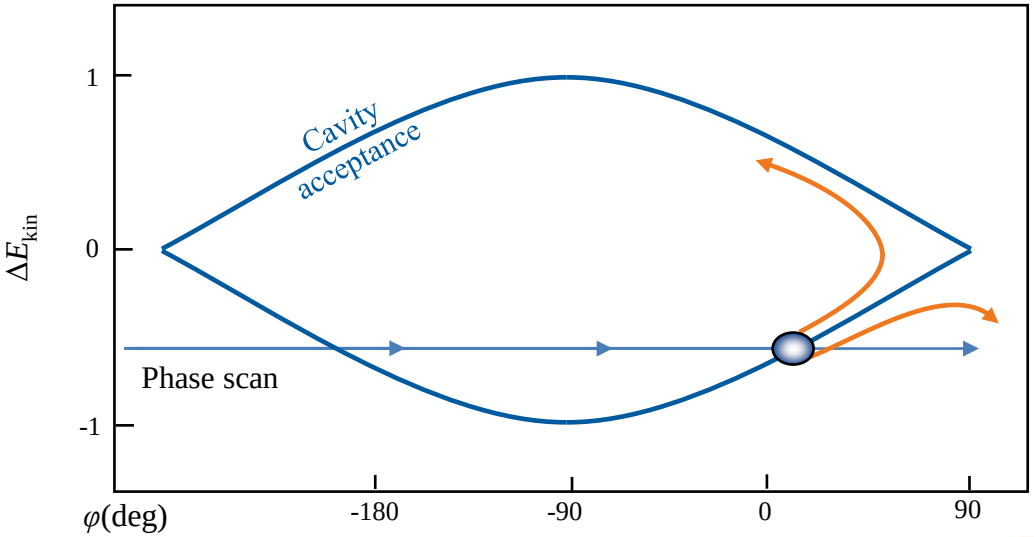
Coefficient of determination

$$R^2 = 1 - \sum_i \frac{(\rho_{i,\mathrm{meas}} - \rho_{i,\mathrm{rec}})^2}{(\rho_{\mathrm{meas,mean}} - \rho_{i,\mathrm{meas}})^2} = 0.98$$

Reconstructed bunch shape fits precisely to measurements

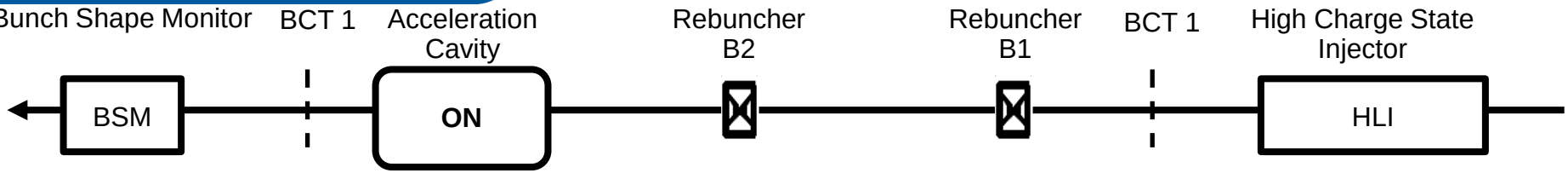
Verification I

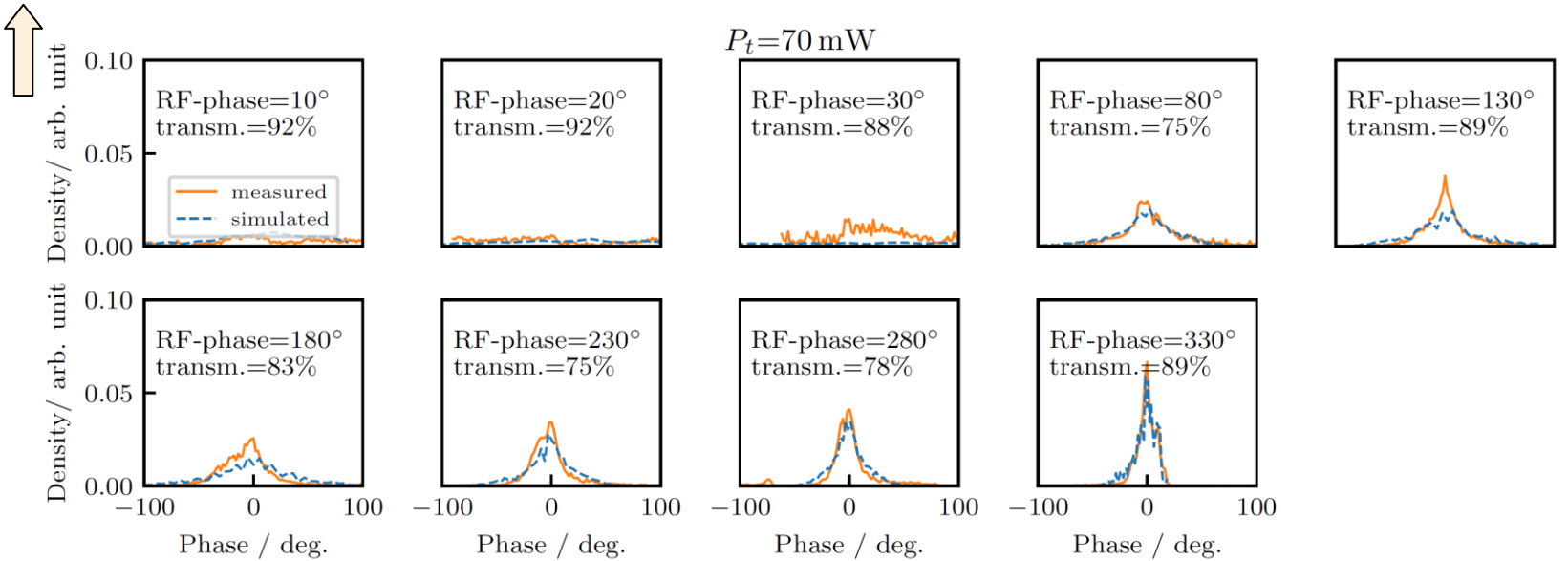




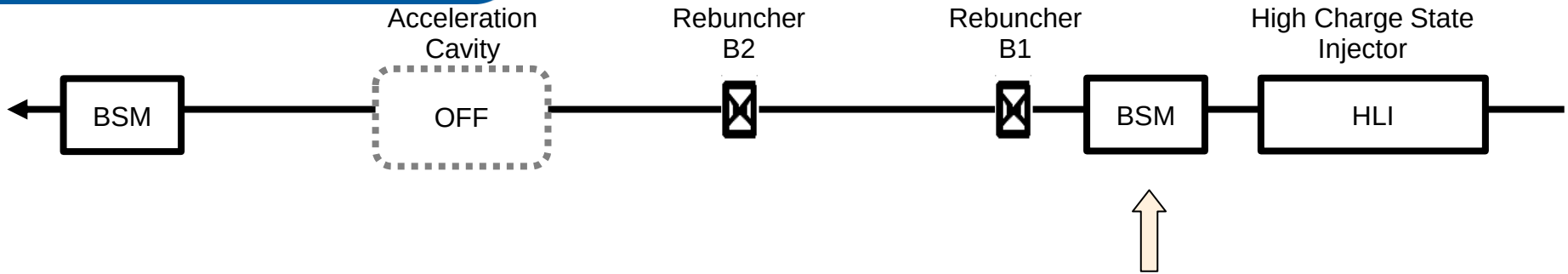
- Evaluation of bunch shape measurements with acceleration cavity switched ON, which provides for independent measurements
- Verification of reconstruction algorithm
- Verification of reconstructed bunch shape

Verification I



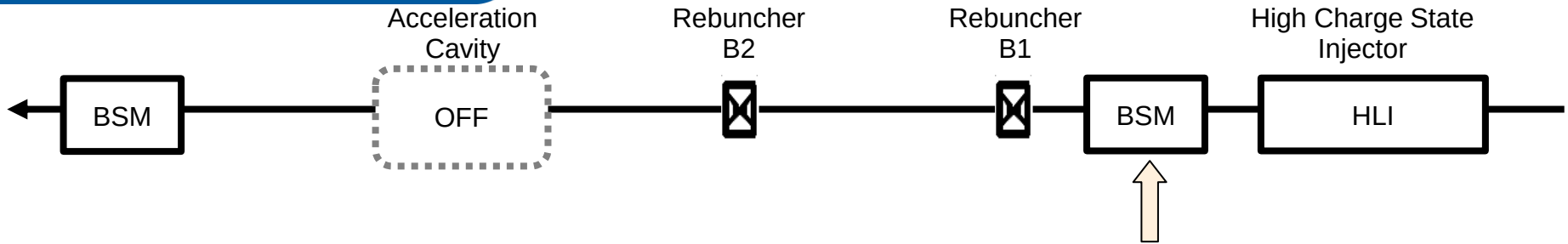


Verification II

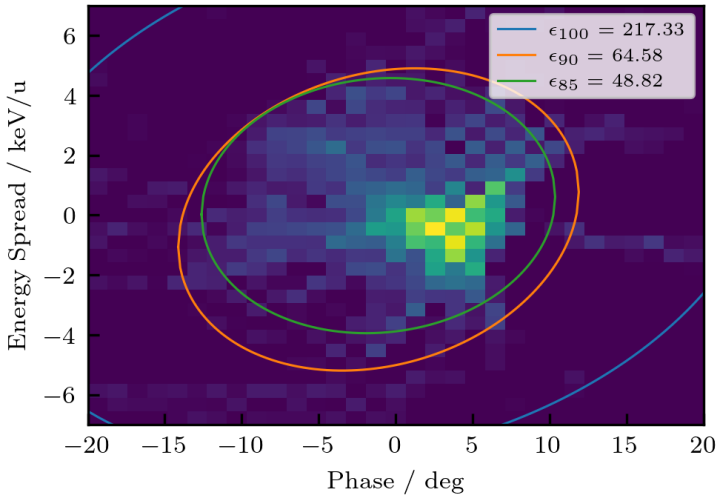


- New position of the BSM
- Measurements directly at reconstruction point
- Verification of reconstruction algorithm and results
- Measurements were repeated after one year later
  - Injector tuned differently
  - New reconstruction

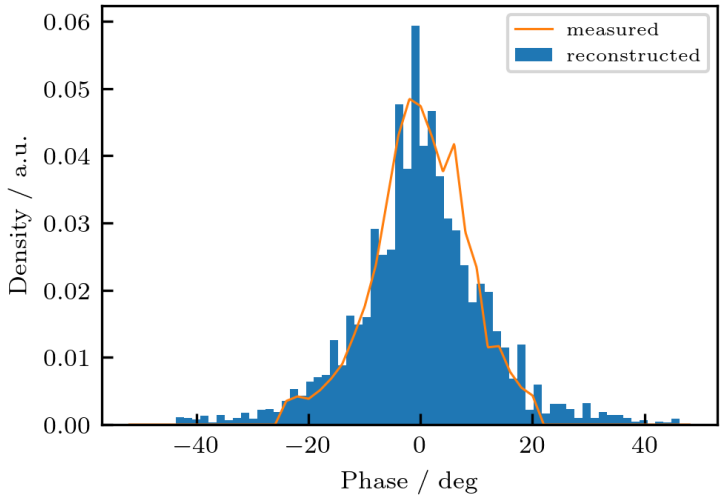
Verification II



Reconstructed at HLI exit



Phase projection vs. measurement



$R^2 = 0.96$

Summary & Outlook

- Analysis procedure for reconstruction developed
- Reconstruction method has been carried out
- Validation measurements accomplished
- Reduction of measurement number is envisaged
- A new tool (based on BSM measurements) for further optimization of HLI injector is under investigation
- Faster bunch shape measurements applying Fast Faraday Cup are going to be investigated

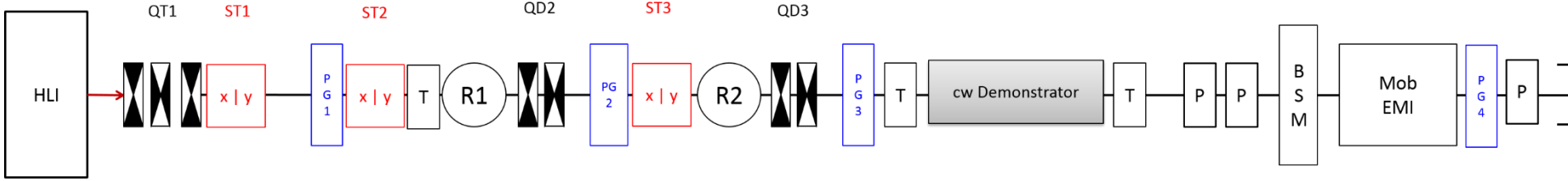
S. Lauber *et al*, "Longitudinal phase space reconstruction for a heavy ion accelerato", Phys. Rev. Accel. Beams 23, 114201, 2020

R. Singh *et al*, "Comparison of feschenko bsm and fast faraday cup withl ow energy ion beams", In Proc. IBIC 2021

Thank you for your attention!

Matching Line - BSM

HLI provides Ar^{11+}, Ar^{9+}, Ar^{6+}, He^{2+} @ 1.4 MeV/u



QT:	Quadrupol triplet
R:	Re-Buncher (QWR)
QD:	Quadrupole doublet
x|y:	Steering magnets
G:	Profile Grid
T:	Beam current transformers for transmission measurement
P:	Phase probes for TOF measurement
BSM:	Bunch shape monitor (Feschenko monitor)
EMI:	Slit-Grid emittance measurement device