Longitudinal Phase Space Reconstruction for the Heavy Ion Accelerator HELIAC

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Introduction

GSI Helmholtzzentrum at Darmstadt is the worldwide leading center for heavy ion research.

Since 50 years the heavy ion high current UNILAC is the main accelerator at GSI.

The GSI Super Heavy Element (SHE) program led to the discovery of six elements.

$^{262}_{107}\mathrm{Bh}$	$^{265}_{108}\mathrm{Hs}$	$^{268}_{109}\mathrm{Mt}$	$^{281}_{110}\mathrm{Da}$	$^{280}_{111}\mathrm{Rg}$	$^{277}_{112}\mathrm{Cn}$

Recently, UNILAC is upgraded as FAIR injector with increased intensity but shortened pulse length.

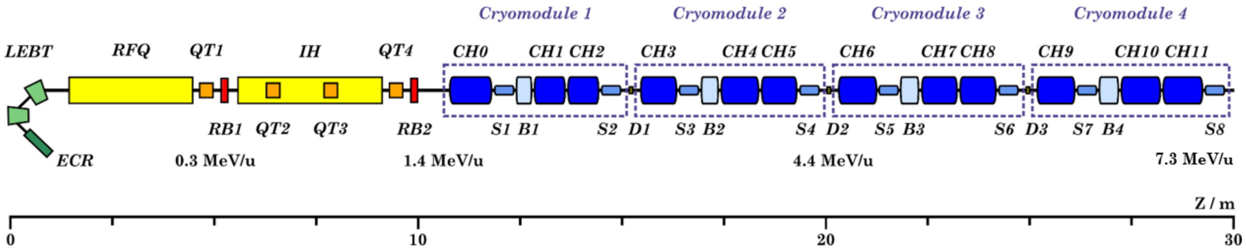
Therefore, a dedicated superconducting continuous wave heavy ion linac is under construction:

- continuous wave (CW) for increased SHE production rate
- superconducting (SC) for efficient acceleration

__HE__lmholtz __LI__near __AC__celerator (__HELIAC__)

is a common project of GSI and HIM under key support of IAP

Design Layout for the HELIAC



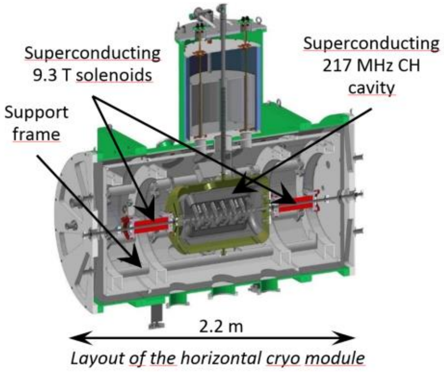
Superconducting part

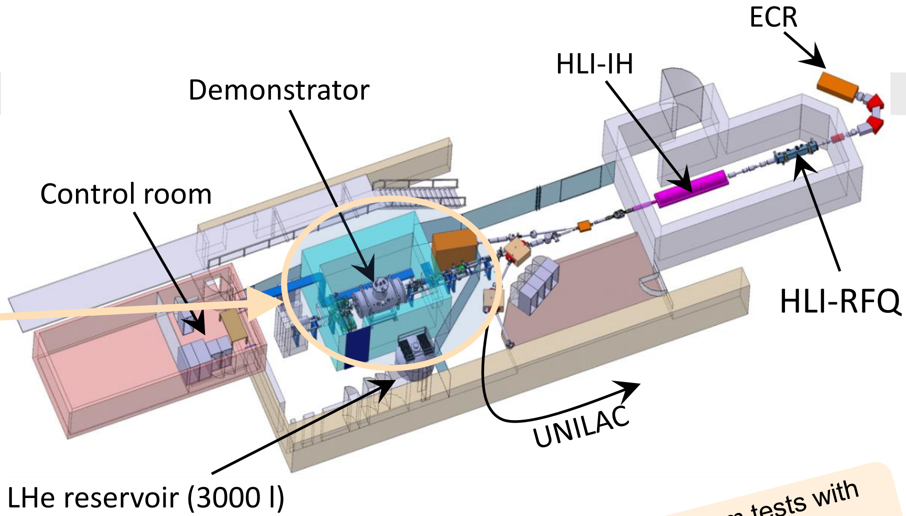
	Design Value
Mass/Charge	6
Frequency	216.816 MHz
Max. beam current	1 mA
Injection energy	1.4 MeV/u
Output energy	3.5–7.3 MeV/u
Output energy spread	±3 keV/u
Operation mode	continuous wave

Dedicated CW capable beam diagnostics:

- Cold / warm Beam Position Monitor
- Phase Probe Sensor
- Beam Current Transformer

Recent Experimental Setup at GSI





Successful commissioning of experimental setup with SC CH cavity in 2017

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

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 beam dynamics (synchronous phase around about 0°)

- provides for efficient acceleration
- leads to 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)

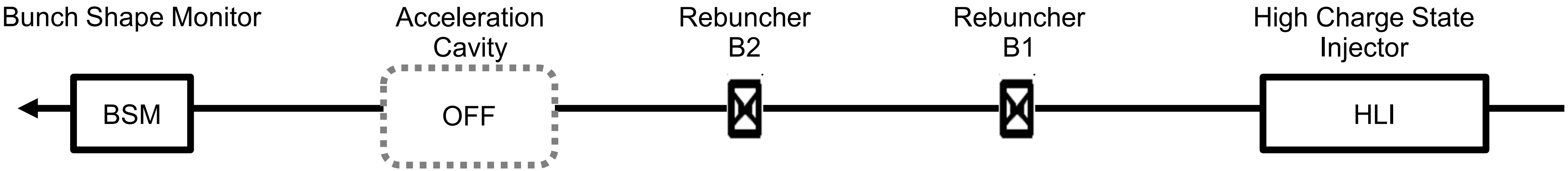
Projection to the time axis (phase) measured with the BSM

Mean beam energy measured with phase probe sensors

The bunch shape in the longitudinal phase plane is not known, but 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



Only elements acting on the longitudinal phase plane shown

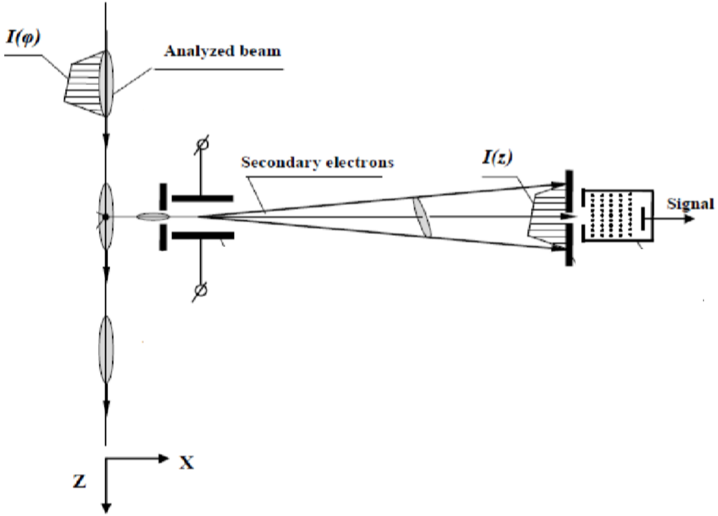
Beam provided by the injector HLI

Two rebuncher cavities used for longitudinal beam focusing

Accelerating cavity subject for other experiments

Feschenko Monitor as Bunch Shape Monitor for longitudinal beam diagnostics

Feschenko Monitor



Minimally invasive

Fixed wire in beam line

Secondary Electron (SE) emission time dependent

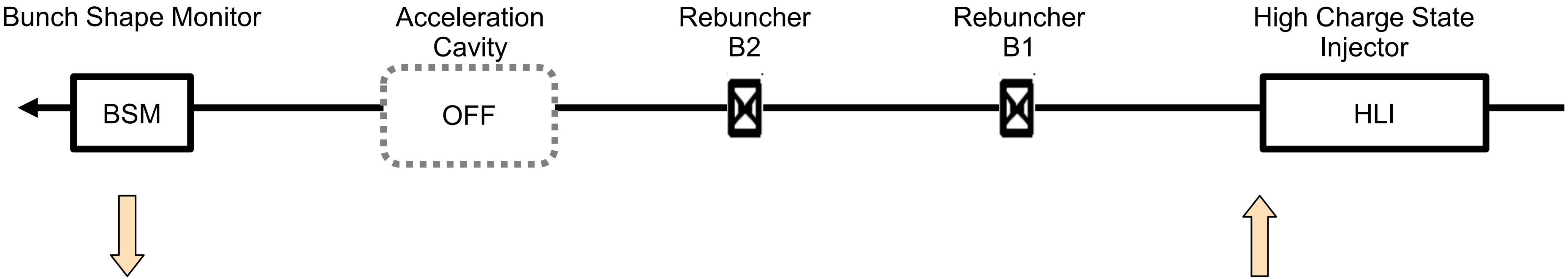
RF field deflects SE → spatial signal

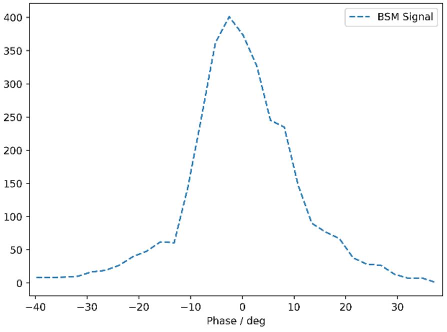
Spatial signal → Secondary Electron Multiplier

Sufficient resolution (1° at 108 MHz)

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

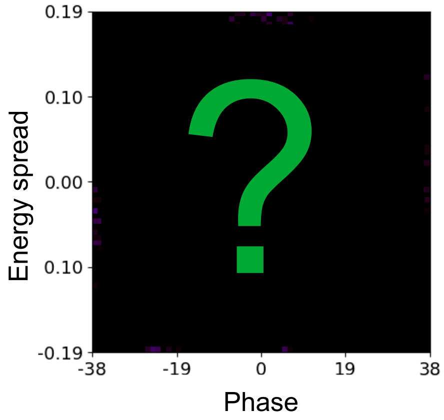
Reconstruction Goal



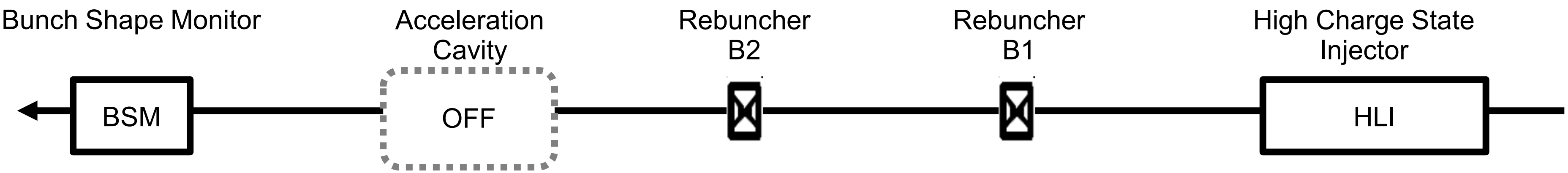


Determine beam shape including density distribution in the longitudinal phase plane

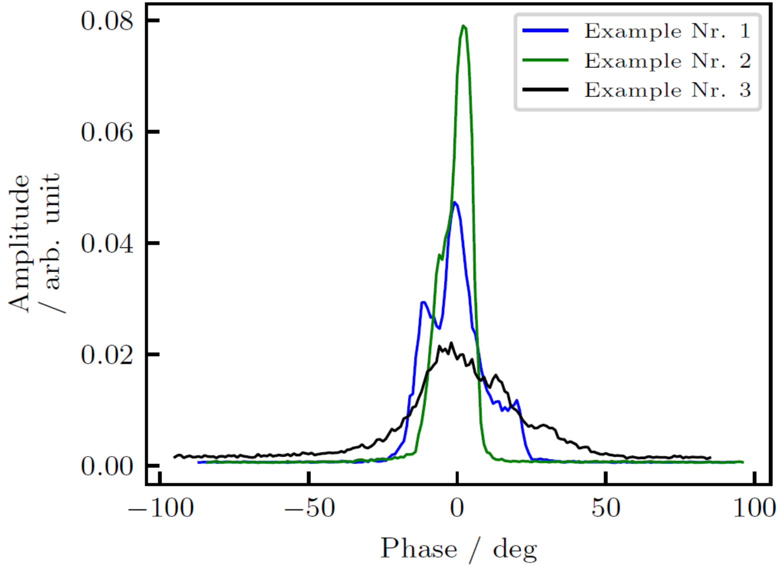
Provide for particle distribution for further HELIAC beam dynamics simulations



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

Overview: Reconstruction Algorithms

Related approaches:

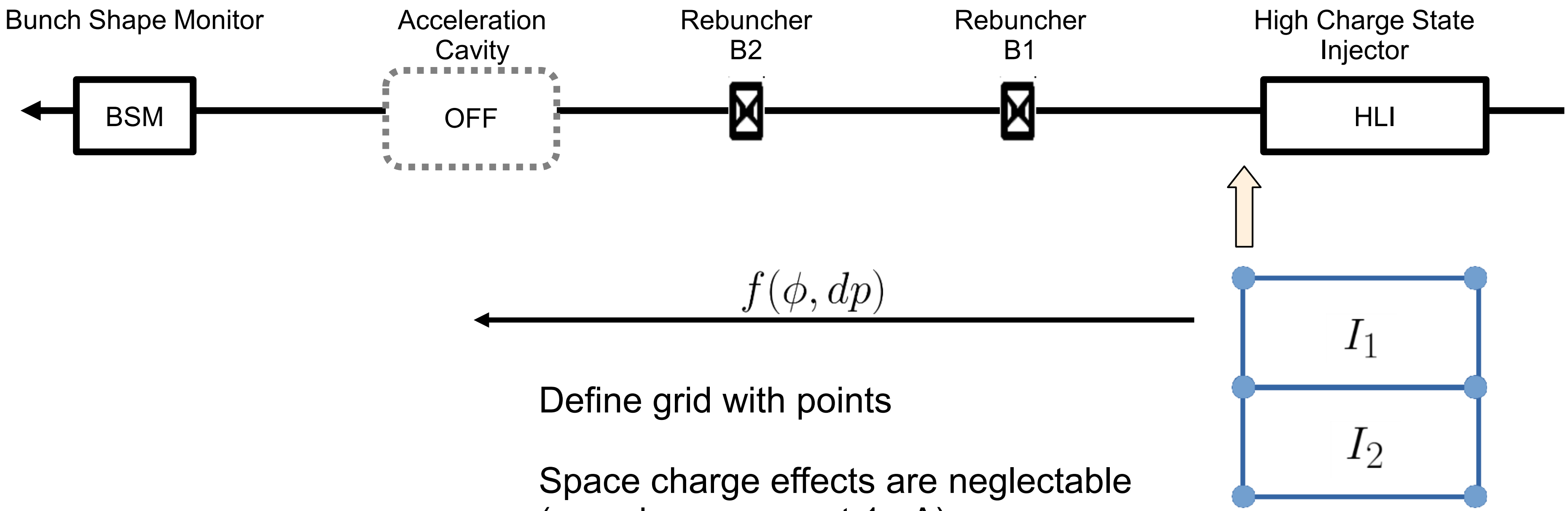
- Quadrupole/Rebuncher Scan Technique → only twiss parameters
- ART / SART → requires lots of projections, e.g. @CERN
  Algebraic Reconstruction Technique
- FBP → for linear mapping
  Filtered Back Projection
- MENT Reconstruction → memory intense, e.g. @DESY
  Maximum ENTropy

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

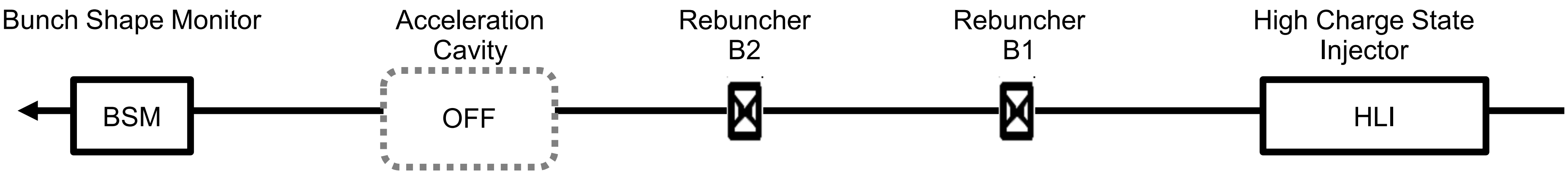


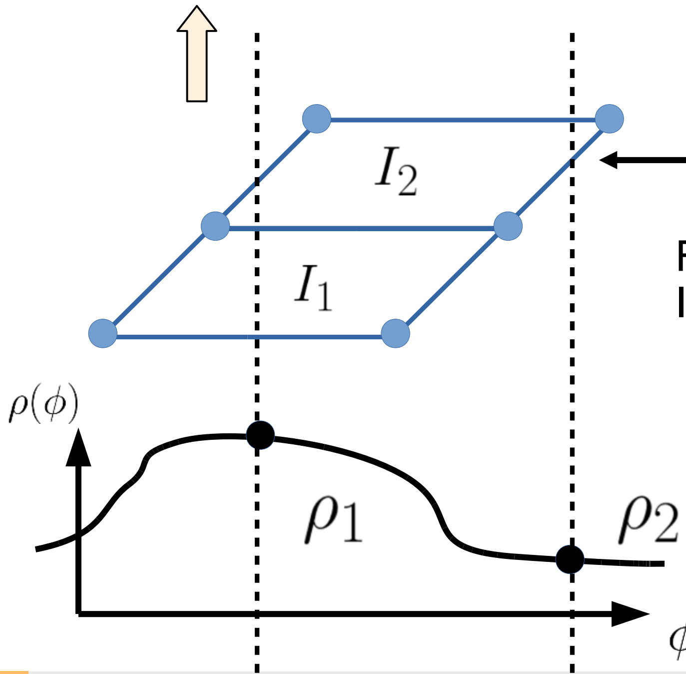
Define grid with points

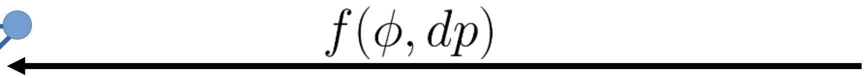
Space charge effects are neglectable (max. beam current 1mA)

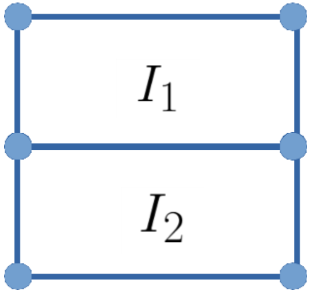
Transform grid through beamline with beam dynamics simulation (DYNAMION software)

Reconstruction Algorithm





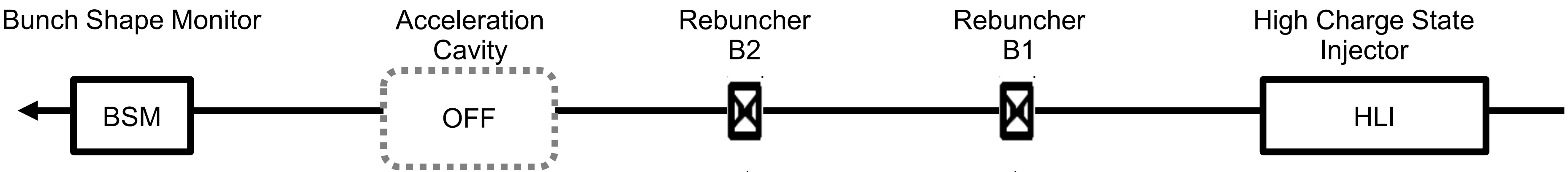


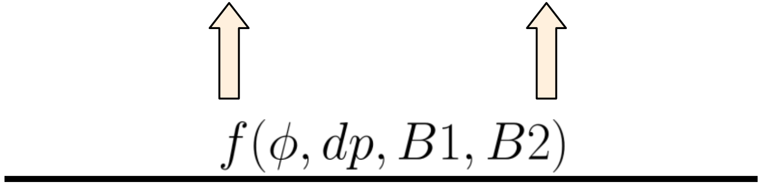


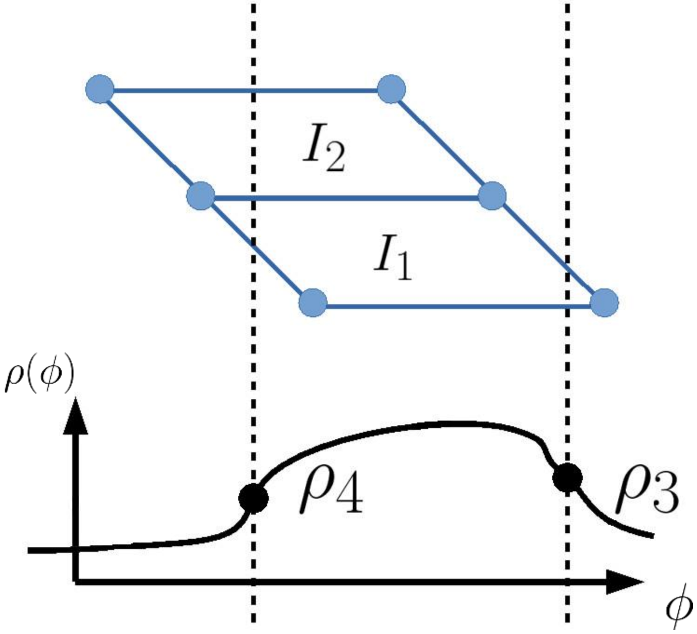
Formulate equations to connect Intensities *I* to measurements *ρ*

$$\rho_1 = 1 \cdot I_1 + 1 \cdot I_2$$
$$\rho_2 = 0 \cdot I_1 + 1 \cdot I_2$$

Reconstruction Algorithm

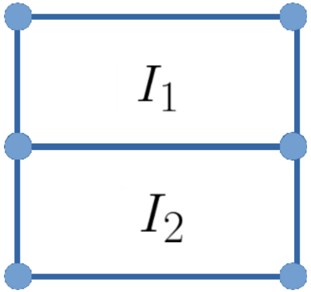


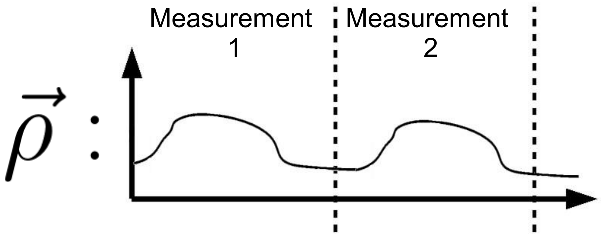




Each measurement has different mapping

Assign equations for all measurements ρ





Reconstruction Algorithm

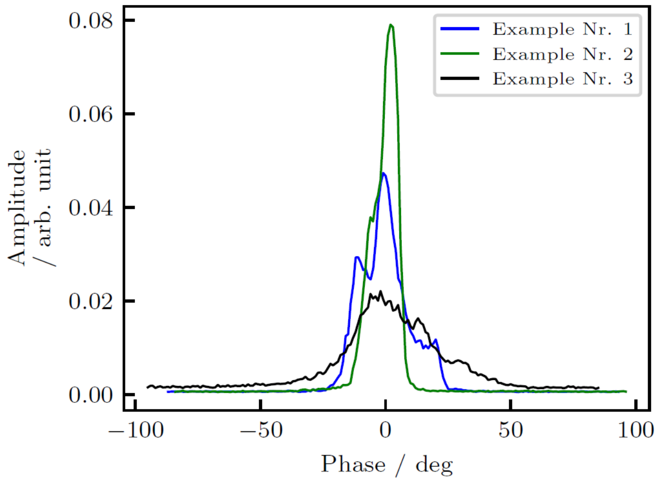
Linear system of equations obtained:

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

Connects all measurements ρ with input grid intensities I.

Solve for intensities:

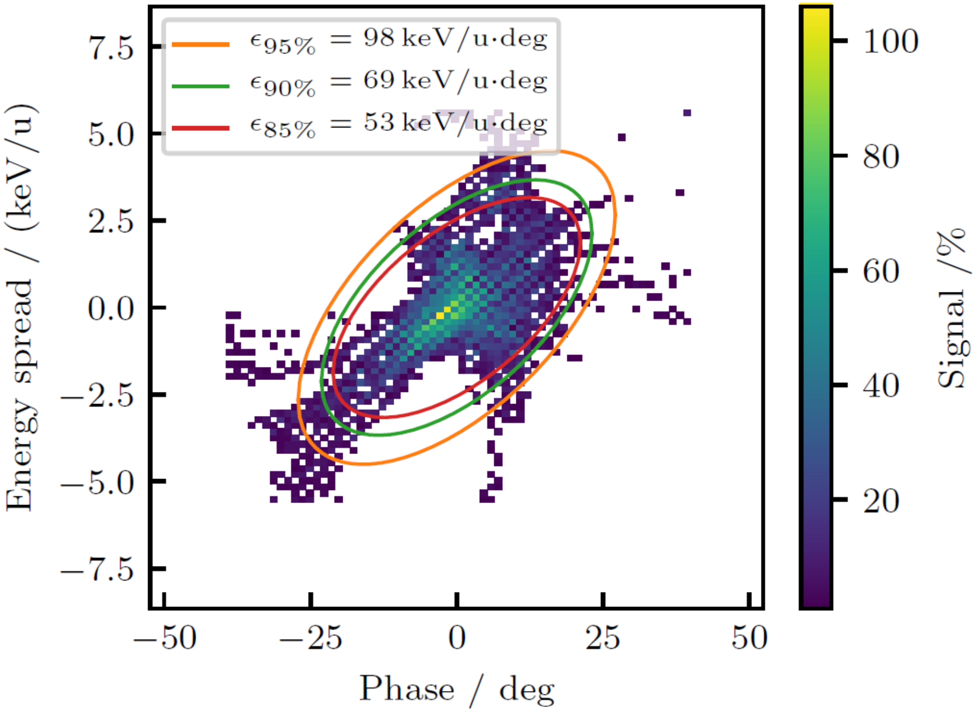
$$\text{minimize} \quad f(\vec{I}) = |A \cdot \vec{I} - \vec{\rho}|$$
$$\text{subject to} \quad \vec{I} \geq 0$$



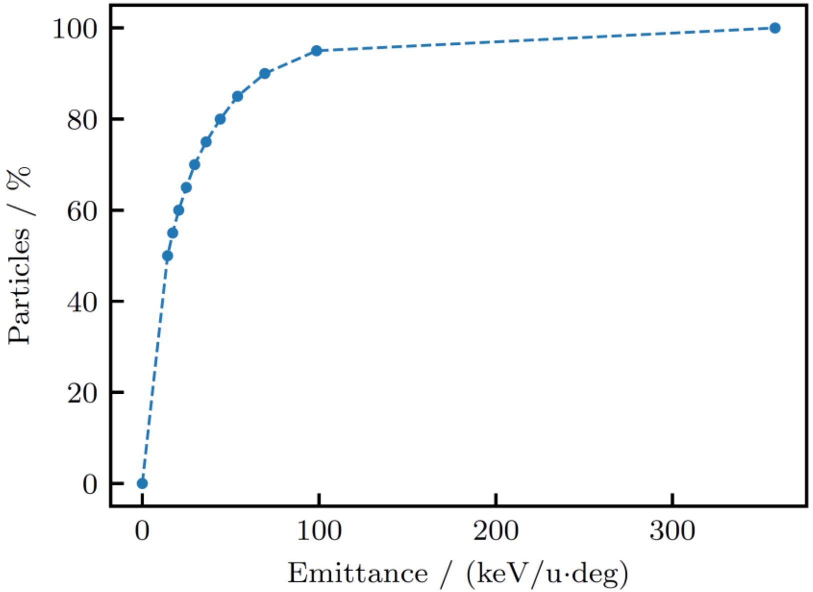
Solved by Non-Negative Least Squares algorithms from the scientific python library.

Results

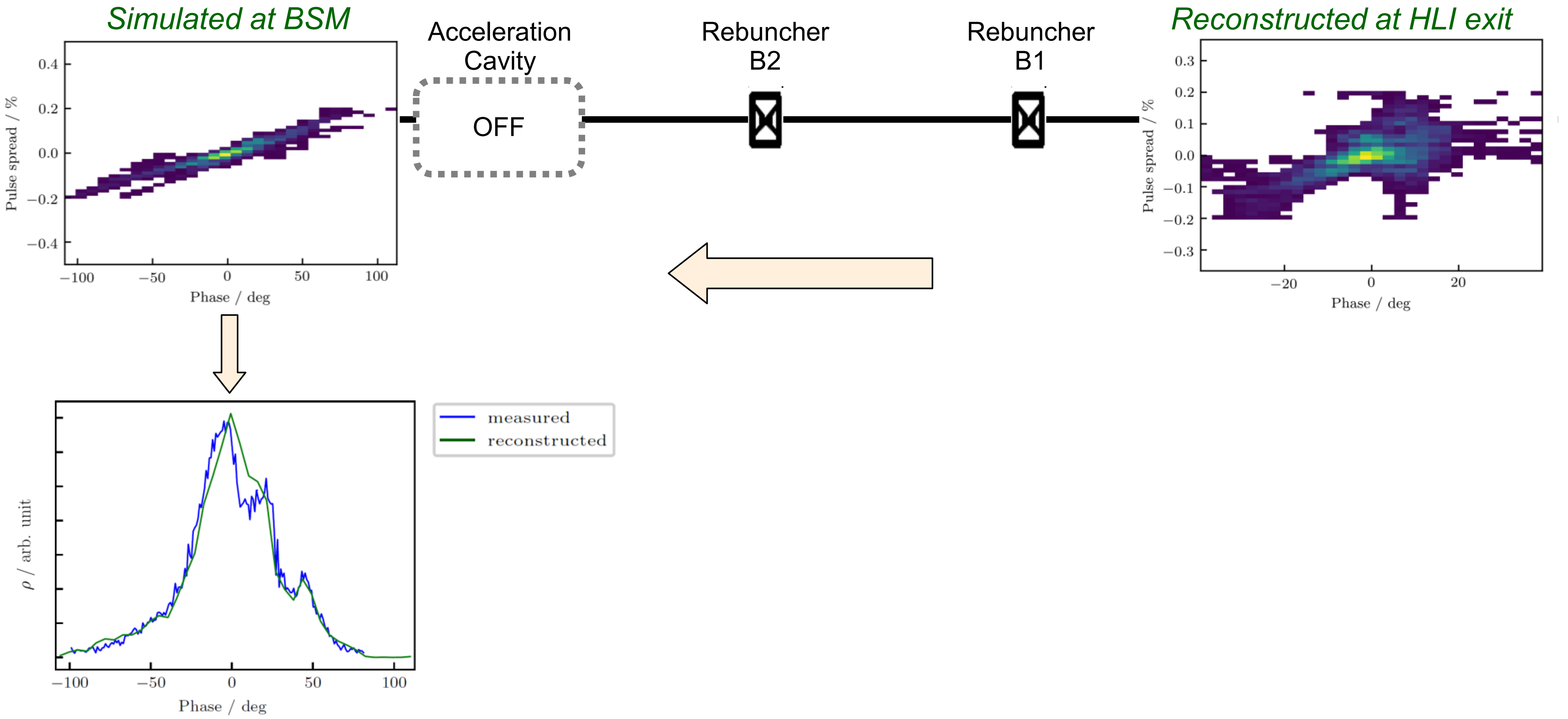
Reconstructed particle distribution at HLI injector exit



Clearly visible core

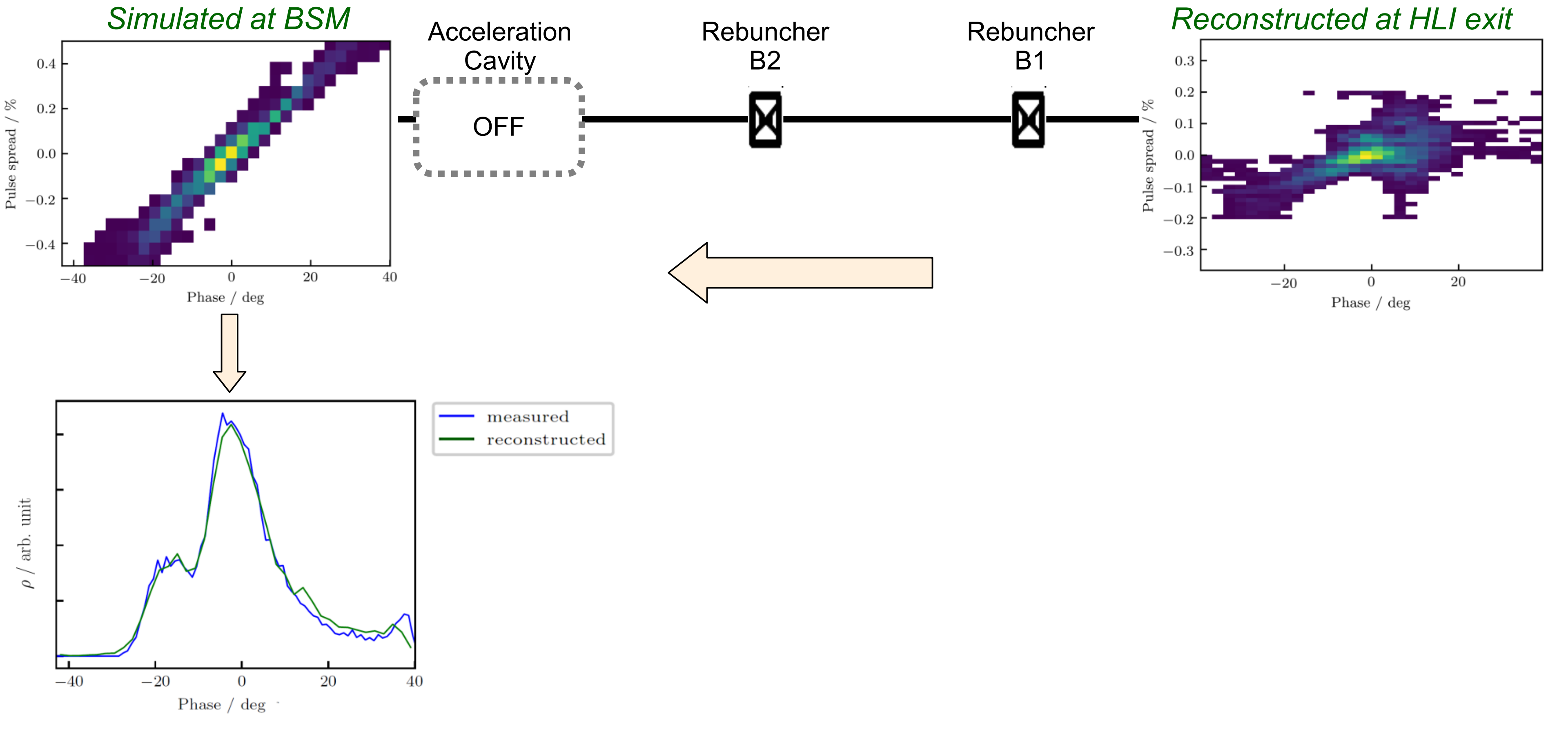


Results



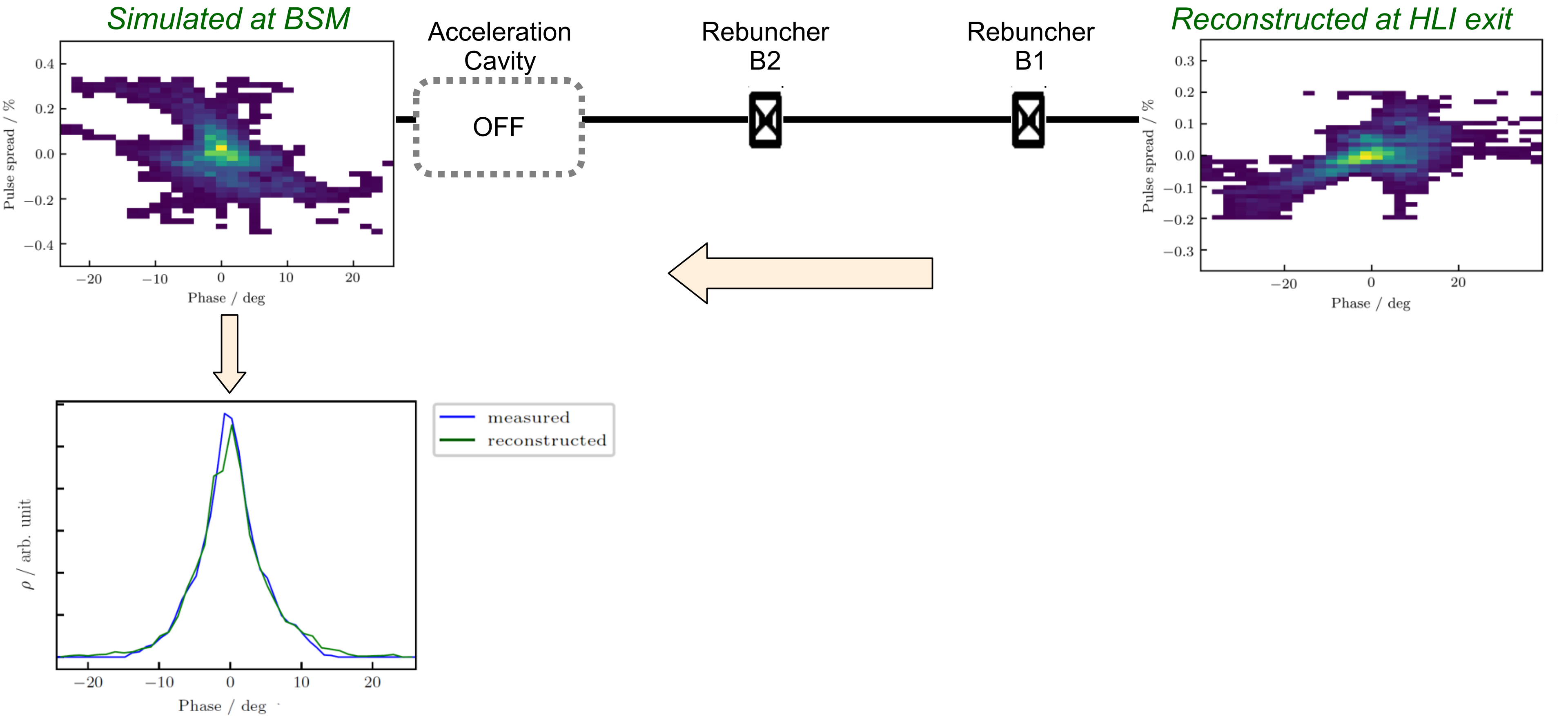
Simulated at BSM
Acceleration Cavity
OFF
Rebuncher B2
Rebuncher B1
Reconstructed at HLI exit
Pulse spread / %
Phase / deg
0.4
0.2
0.0
−0.2
−0.4
−100
−50
0
50
100
0.3
0.1
−0.1
−0.3
−20
20
ρ / arb. unit
measured
reconstructed

Results



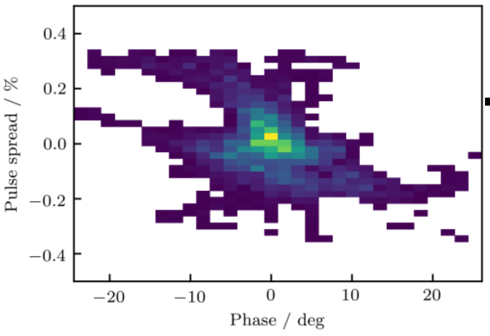
Simulated at BSM
Pulse spread / %
Phase / deg
Acceleration Cavity
OFF
Rebuncher B2
Rebuncher B1
Reconstructed at HLI exit
Pulse spread / %
Phase / deg
ρ / arb. unit
Phase / deg
measured
reconstructed

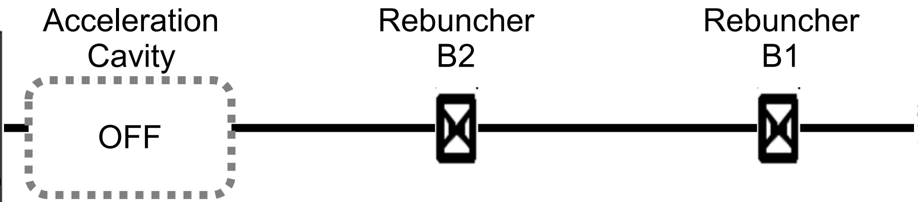
Results


Simulated at BSM
Acceleration Cavity
OFF
Rebuncher B2
Rebuncher B1
Reconstructed at HLI exit
Pulse spread / %
Phase / deg
ρ / arb. unit
measured
reconstructed

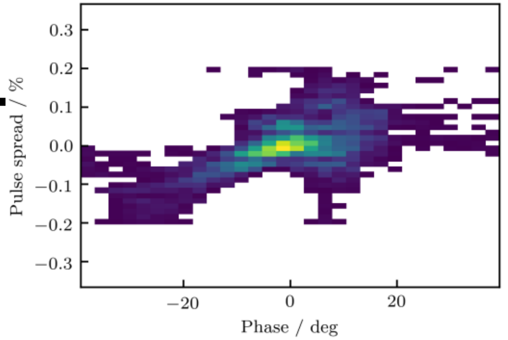
Results

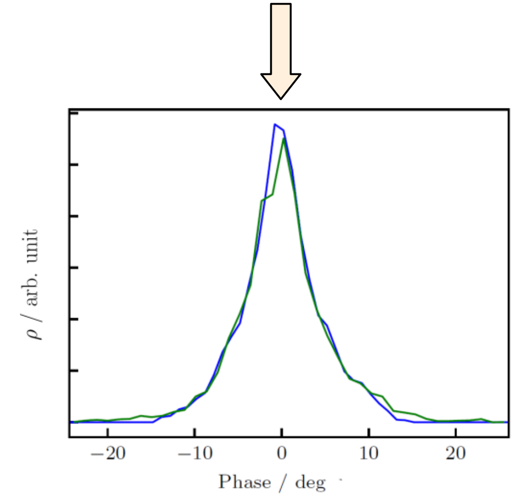
Simulated at BSM





Reconstructed at HLI exit





Coefficient of determination

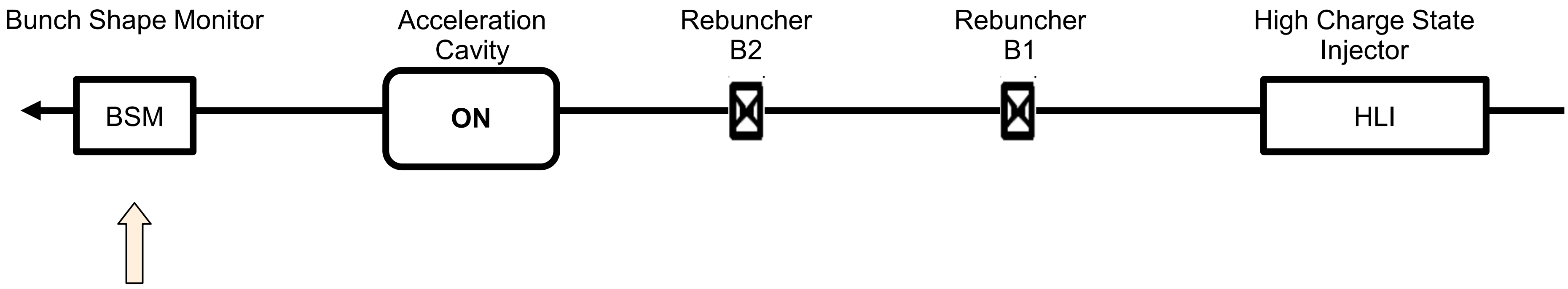
$$R^2 = 1 - \sum_i \frac{(\rho_{i,\mathrm{meas}} - \rho_{i,\mathrm{rec}})^2}{(\rho_{\mathrm{meas,mean}} - \rho_{i,\mathrm{meas}})^2} = 0.98$$

Reconstructed bunch shape fits to measurements well

Summary & Outlook

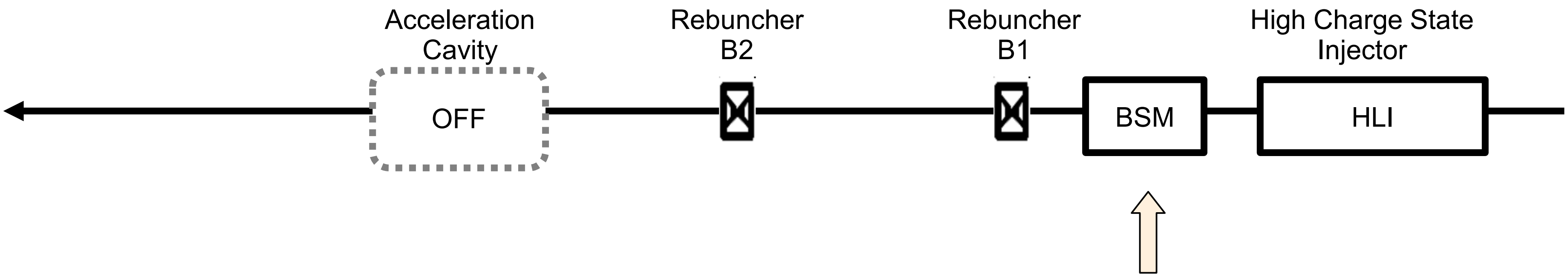
- Analysis procedure for reconstruction developed
- Reconstruction is accomplished
- Validation measurements scheduled for this year
- Reduction of measurement number is targeted
- A tool for the further optimization of HLI injector is created
- Additional dedicated beam simulations are foreseen

Future Plans I



- Evaluation of bunch shape measurements with acceleration cavity switched ON
- Verification of reconstruction algorithm
- Verification of reconstructed bunch shape

Future Plans II



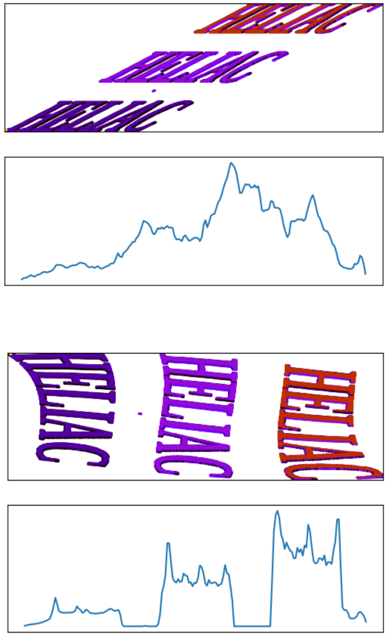
- New position of the BSM
- Measurements directly at reconstruction point
- Verification of reconstruction algorithm and results
- Optimization of HLI injector for the best HELIAC performance

Thank you for your attention!

Algorithm Testing

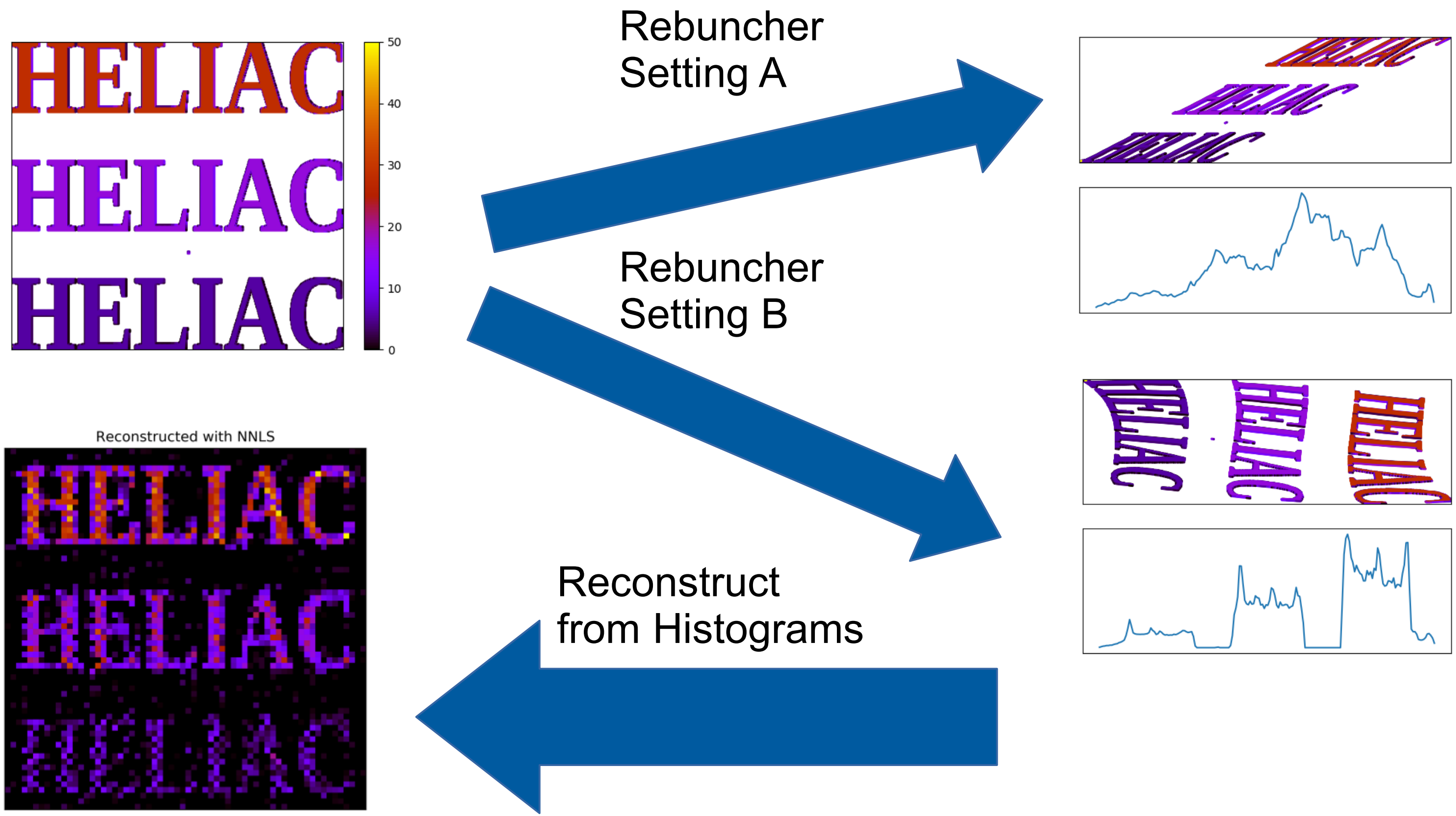
Rebuncher Setting A

Rebuncher Setting B



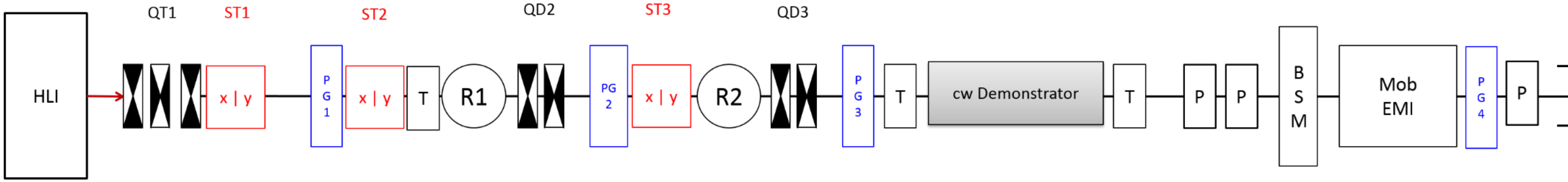
- Known input distribution transported through beamline
- Generation of the histograms is independent from the solver

Algorithm Testing



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