Bunch Struktur Messungen am UNILAC
--- Status Report ---

Operator-School, 30.10.2025

Beam Instrumentation Abteilung:

Peter Forck, Stephan Klaproth, Timo Milosic, Thomas Sieber, Rahul Singh

LINAC Abteilung:

Maksym Miski-Oglu, Uwe Scheeler, Nimue Schmidt,

Winfried Barth, Simon Lauber et al.

Messungen longitudinal Parameter:

- Beispiele zur Simulation des longitudinaler Phasenraums
- Generelles zur Bunch-Länger Messung am UNILAC
- Monitor 1: **B**unch **S**hape **M**onitor (**BSM**) von russischen Institut INR
- Monitor 2: **F**ast **F**araday **C**up (**FFC**); Design vom amerikanischen Fermilab
- Erste Ansätze zur Bestimmung des longitudinalen Emittanz
- Vergleich von BSM und FFC
- Zusammenfassung und Ausblick

Bunch shapes are very non-Gaussian

Reason: Acceleration on maximum of rf-wave to enable maximum energy gain by **KONUS** beam dynamics at CH-cavities (KoNuS = **Ko**mbinierte **Nu**ll Grad **S**truktur)

Example

325 MHz Proton LINAC:

Longitudinal phase space

simulation:

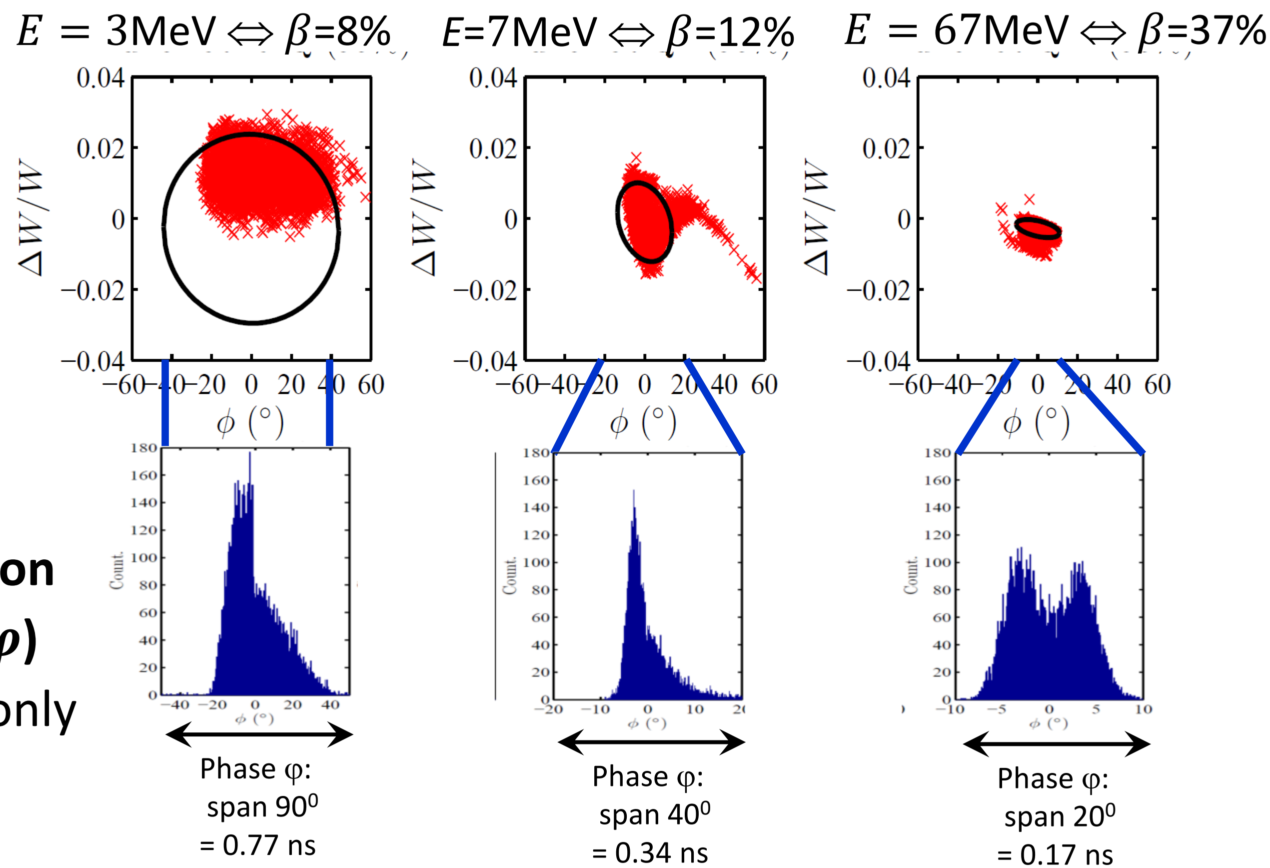
University Frankfurt

⇒ Deformed phase space

⇒ Complex bunch shape

⇒ **Sensitive to small variation of cavity setting (U and φ)**

⇒ Emittance minimization only by correct setting



Bunch shapes are very non-Gaussian

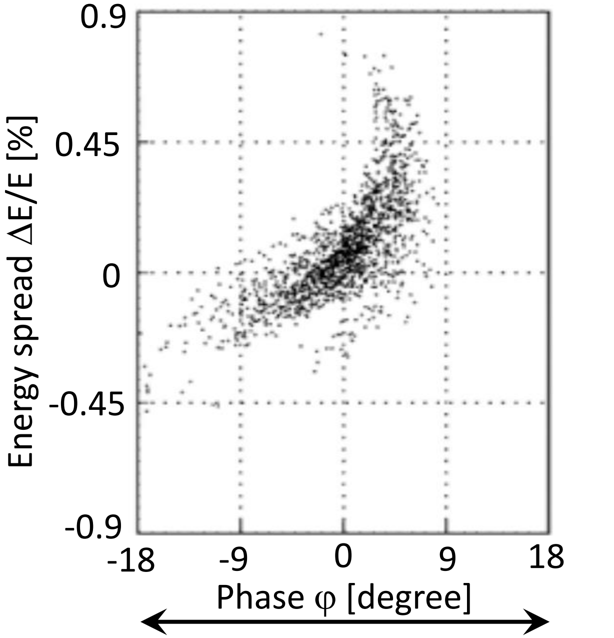
Reason: Acceleration on maximum of rf-wave to enable maximum energy gain

by **KONUS** beam dynamics at IH-cavities (KoNuS = **Ko**mbinierte **Nu**ll Grad **S**truktur)

***Simulation* example HSI exit:**

High current U^{4+}, $E = 1.4$ MeV/u

Longitudinal phase space



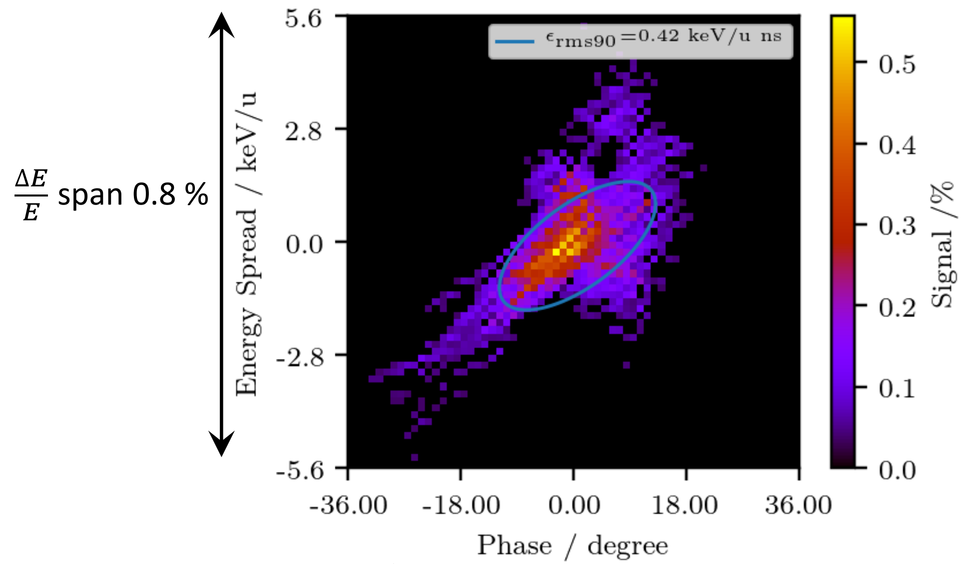
Phase φ span 36^0 = 2.8 ns @36 MHz

W. Barth, S. Yaramishev et al. LINAC'06

***Measurement* example HLI at UN6:**

Low current, E =1.4 MeV/u

Measurement: Tomographic reconstruction



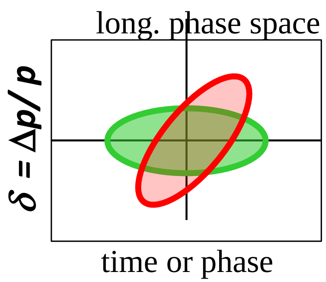
Phase φ span 72^0 = 1.85 ns

S. Lauber et al., IPAC'19 & Phys. Rev. Accel. Beams, 23, 114201 (2020)

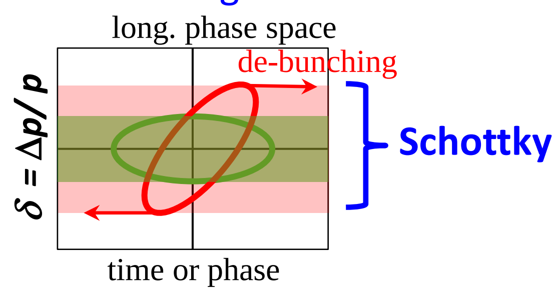
Longitudinal Schottky for Momentum Spread $\Delta p/p_0$ Analysis

Momentum spread $\Delta\, p/p_0$ after multi-turn injection
& de-bunching of t < 1ms duration
to stay within momentum acceptance during acceleration
Method: Variation of buncher voltage
i.e. rotation in longitudinal phase space
$\rightarrow$ minimizing of momentum spread $\Delta\, p/p_0$

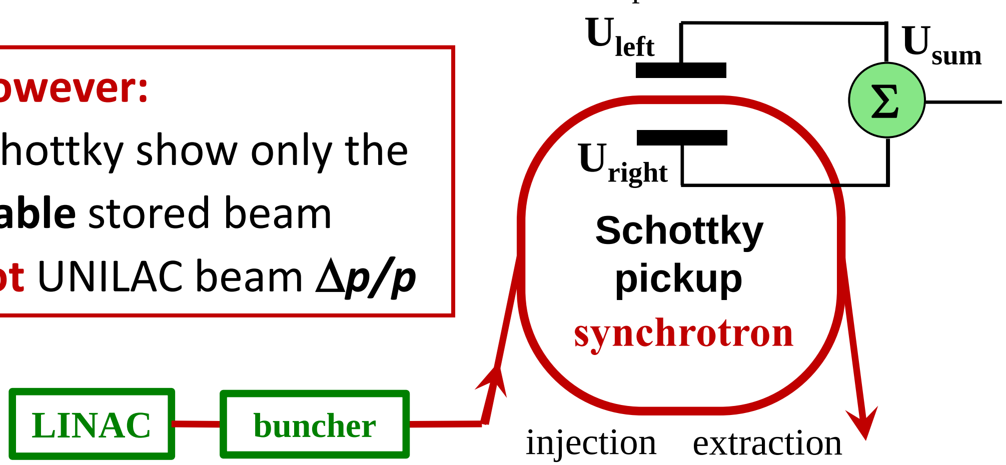
LINAC bunches at injection:



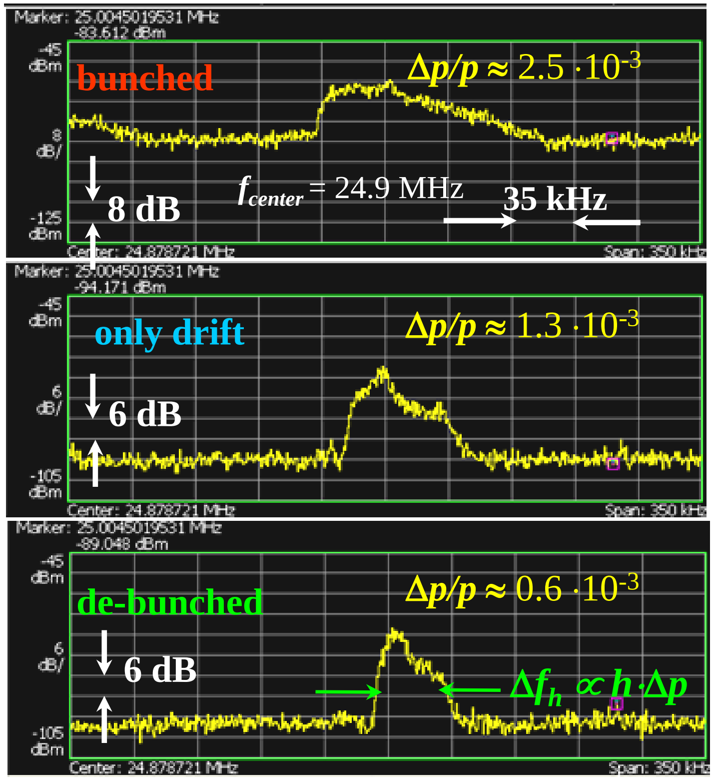
De-bunching after some ms:



However:
Schottky show only the
stable stored beam
not UNILAC beam $\Delta p/p$



Example: 10^{10} U^{28+} at 11.4 MeV/u
injection plateau 150 ms, η = 0.94
Longitudinal Schottky at harmonics h = 117
Momentum spread variation:
$\Delta p/p \approx (0.6 ... 2.5) \cdot 10^{-3}$ (1σ)



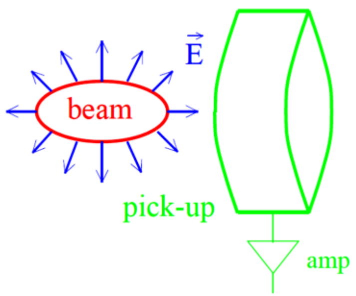
Bunch Structure at low E_{kin}: Not possible with Pick-Ups

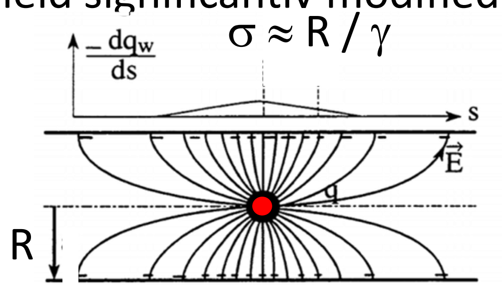
Pick-ups are used for:

➢ precise for bunch-center relative to rf

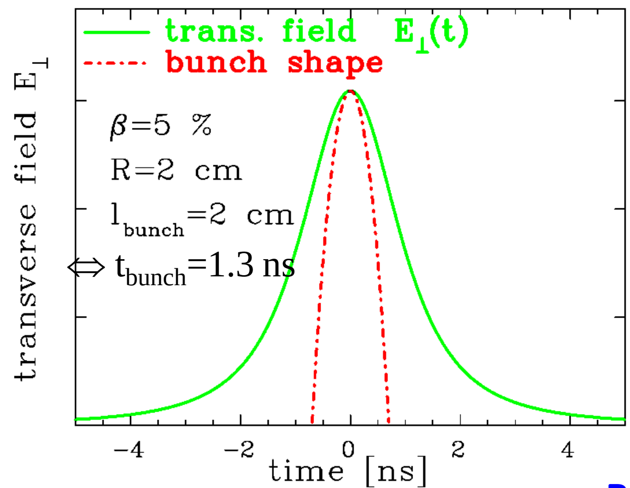
But:

For $\beta << 1 \rightarrow$ long. $\vec{E}$-field significantly modified:



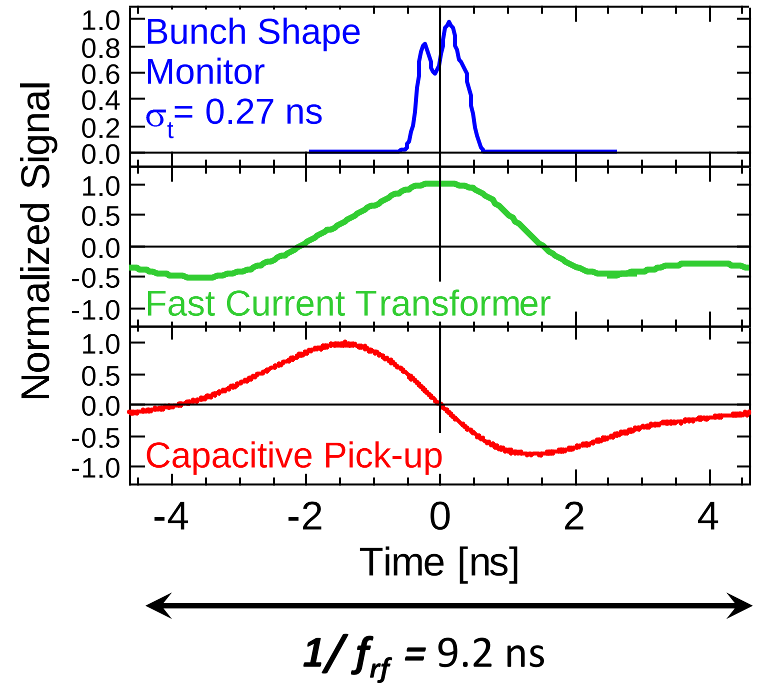


ampl.

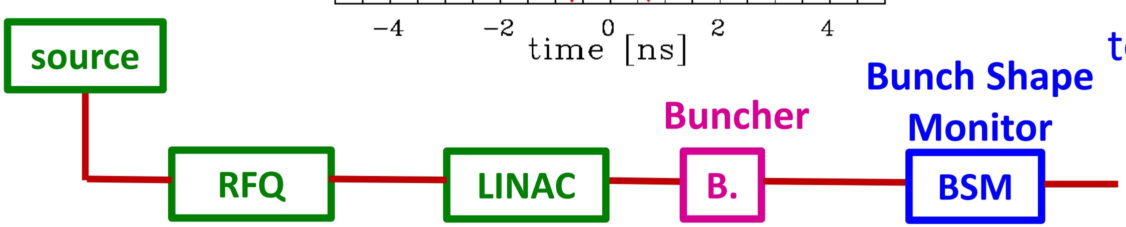


Example: Comparison pick-up – Bunch Shape Monitor:

HLI: Ar beam, E =1.4 MeV/u (β = 5.5%) , f_{rf} = 108 MHz



$\Rightarrow$ the pick-up signal is insensitive to bunch 'fine-structure'



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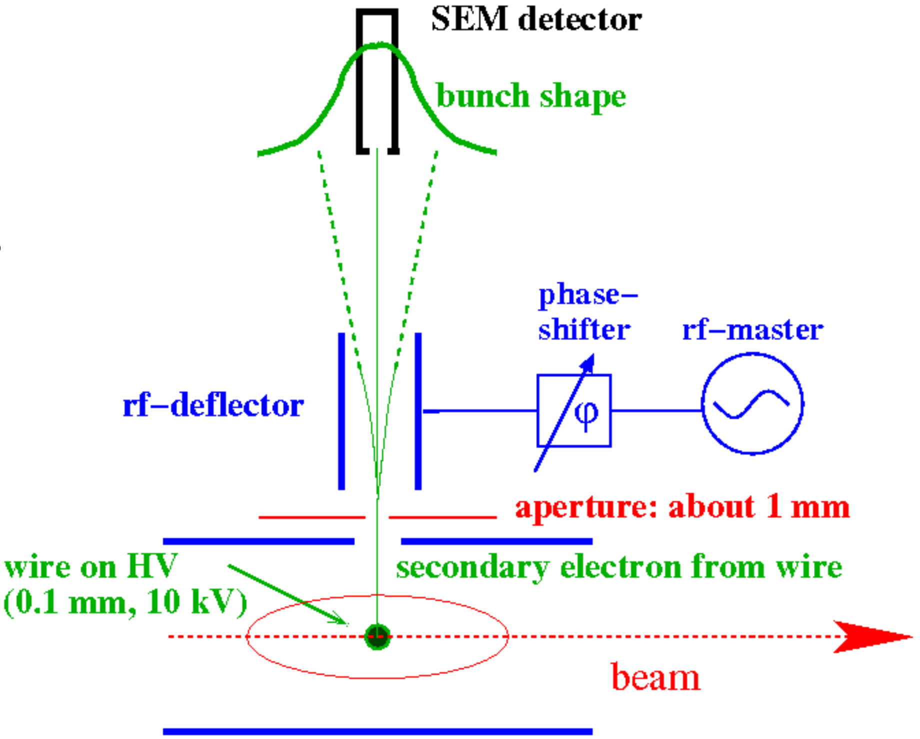
Bunch Structure using secondary Electrons for low E_{kin} Ions

Secondary e⁻ liberated from a wire carrying the time information.
→ Bunch Shape Monitor (BSM)

Working principle:

- Insertion of a 0.1 mm wire at U =-10 kV
- Emission of secondary e⁻ within $t \leq 10$ ps
  → accelerated toward an rf-deflector
- rf-deflector as 'time-to-space' converter
- Detector behind a thin slit
- Scanning method:
  Shift of the phase φ for each macro-pulse



Resolution ≈ 10 ps ≈ 1° @ 280 MHz

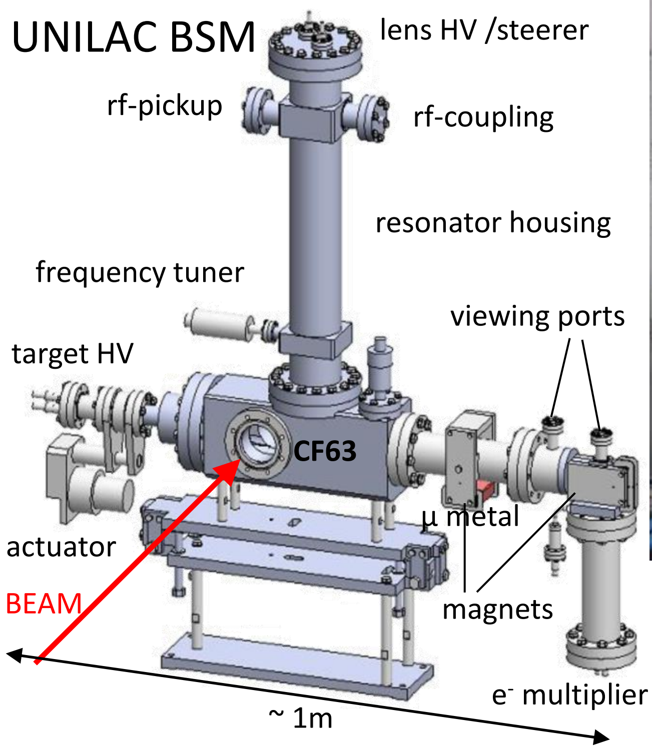
SEM: Secondary Electron Multiplier

Realization of Bunch Shape Monitor at GSI

Installation of the three BSMs:

Presently: UN6 (HLI), X2, UCW (after cavities)

Planned: UT2, TK7, UCW (after cavities)



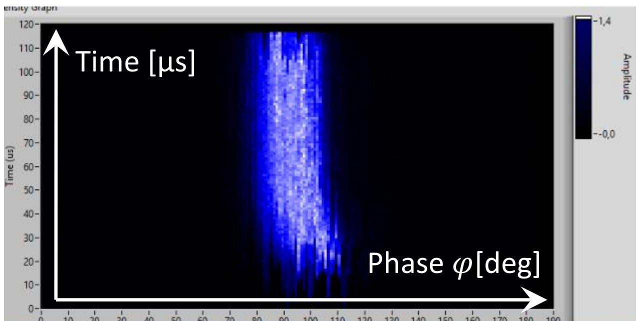
Installation at UCW: Electronics

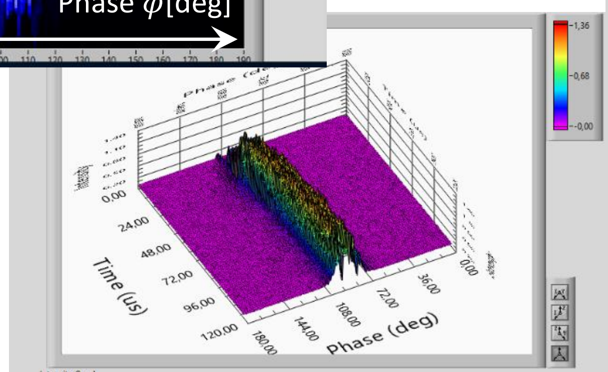
Remark:

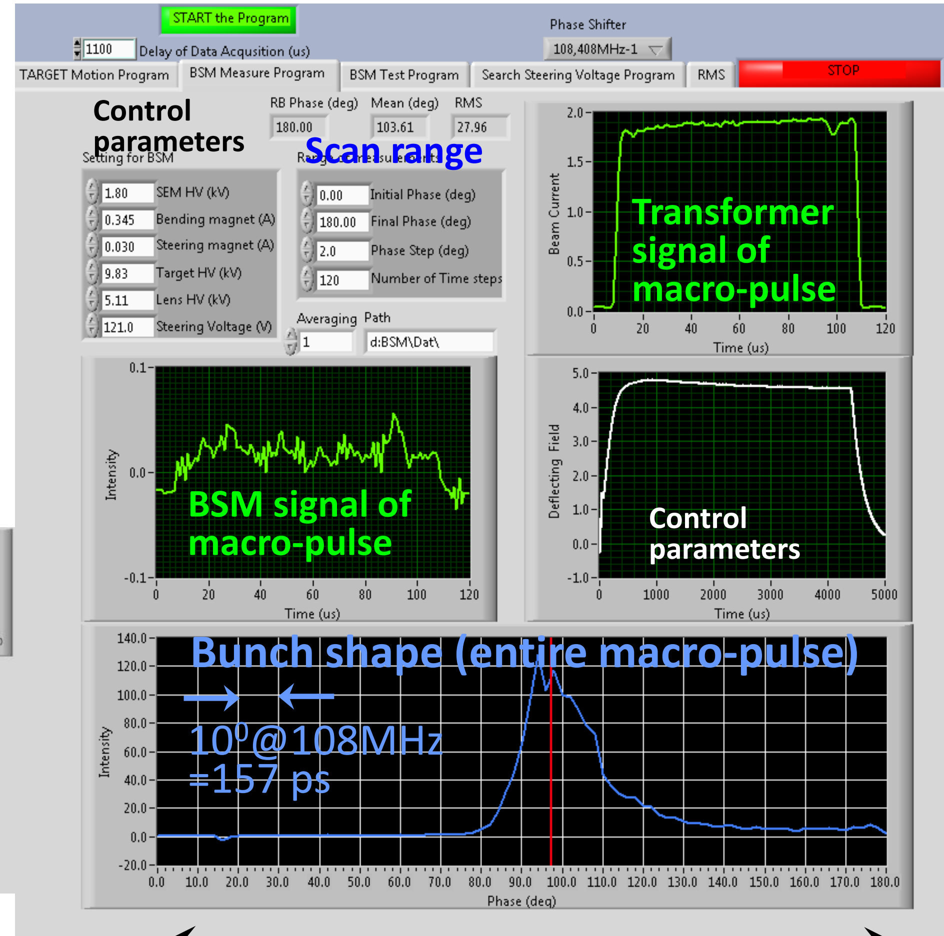
- Insertion length in beam direction: 129 mm
- Alignment with flange accuracy sufficient

Performant GUI:

- ➢Control of various monitor parameters
- ➢Bunch shape averaged over macro-pulse
- ➢Time resolved bunch with 1 μs steps







Phase φ span 180^0 = 4.6 ns

Remarks:

- ➢ BSM system responsible:
  Thomas Sieber, Pere Forck (deputy)
- ➢ Control parameters are fixed during measurements and are aligned by BEA members
- ➢ Moreover, variation during macro-pulse → should be observed and interpreted !

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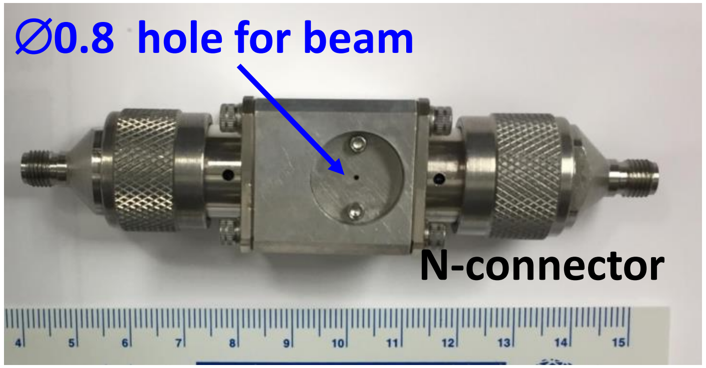
Fast Faraday Cup FFC for Bunch Shape Measurement

Fast Faraday Cup for direct bunch charge measurement:

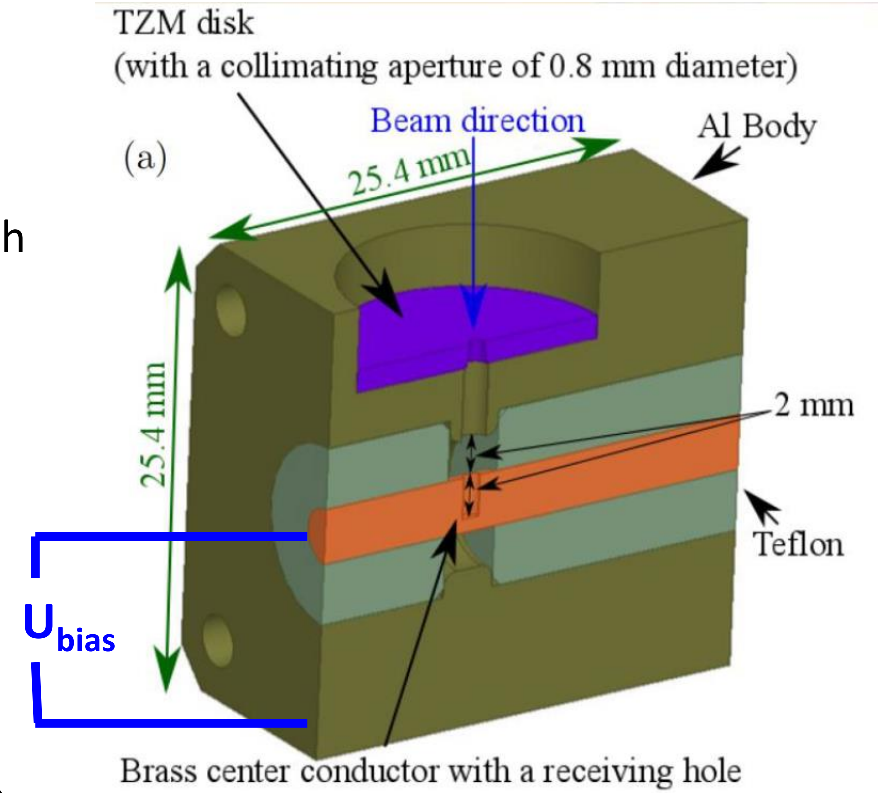
- Round 50 Ω co-axial line
- Bandwidth ≈ 20 GHz
- Collimator for beam with ∅ 0.8 mm hole
- Collimator acts as a shield for $\vec{E}$-field
- Secondary e$^-$ suppression by bias voltage

Mounting on stepping motor drive



Electronics:

- Commercial Bias-Tee (bandwidth 10 GHz)
- Broadband amplifier
- Fast oscilloscope with at least 8 GHz bandwidth



Time resolution:

- 61 ps for β = 5%
- 22 ps for β = 15%

Determined by:

- Gap between inner&outer conductor
- Electronics bandwidth

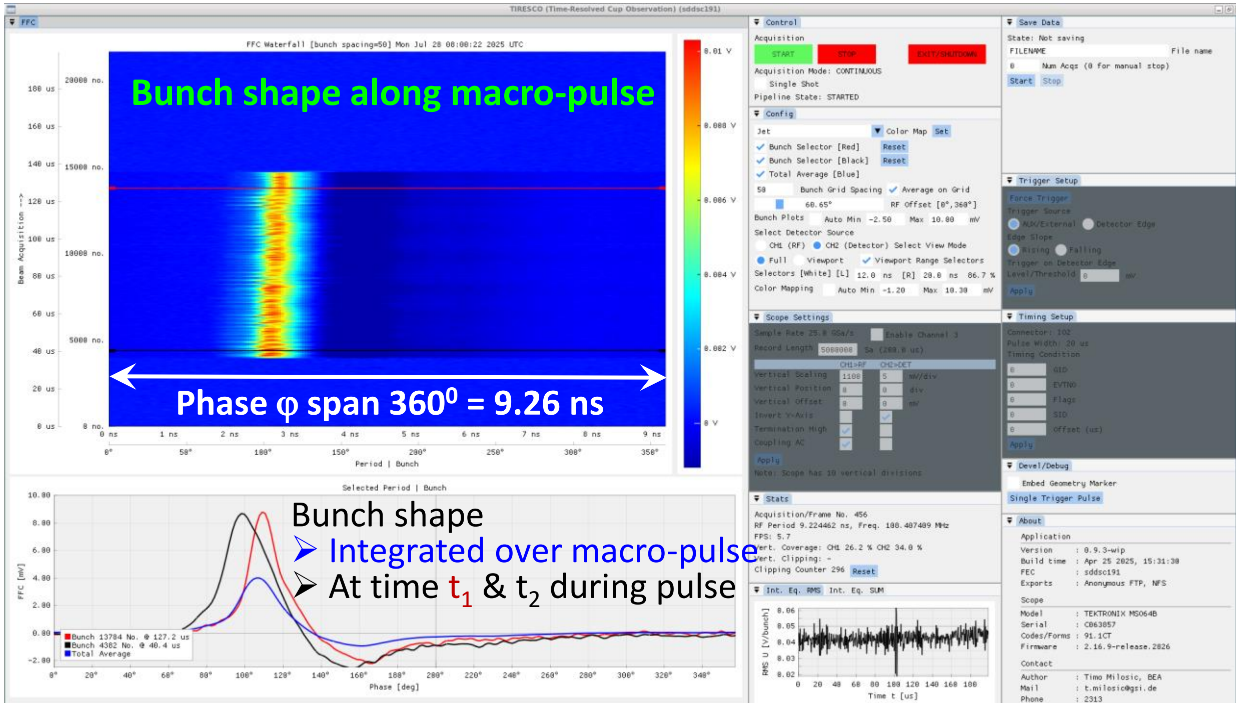
Design at Fermilab (USA) by D. Sun & A. Shemyakin,
see J-P Camiero et al. Int. J. of Mod. Phys. A, vol. 34, no. 36, 2019

Fast Faraday Cup FFC: Graphical User Interface

FFC display with TIRESCO:

Readout of Tektronix scope **MSO64B** (6 GHz, 25 GS/s)

- Bunch shape along macro pulse
  Here: variation during macro-pulse
- Average along macro pulse



Status:

- Software by Timo Milosic
- Almost finished

Installation:

- Presently:
  UN6, UCW, US3, X2
- Planned:
  UN6, UCW, X2, US3, UT2, TK7
- Broadband electronics and DAQ in preparation

Care: FFC might be destroyed by high beam power

Comparison FFC and BSM, Bunch Shape Variation

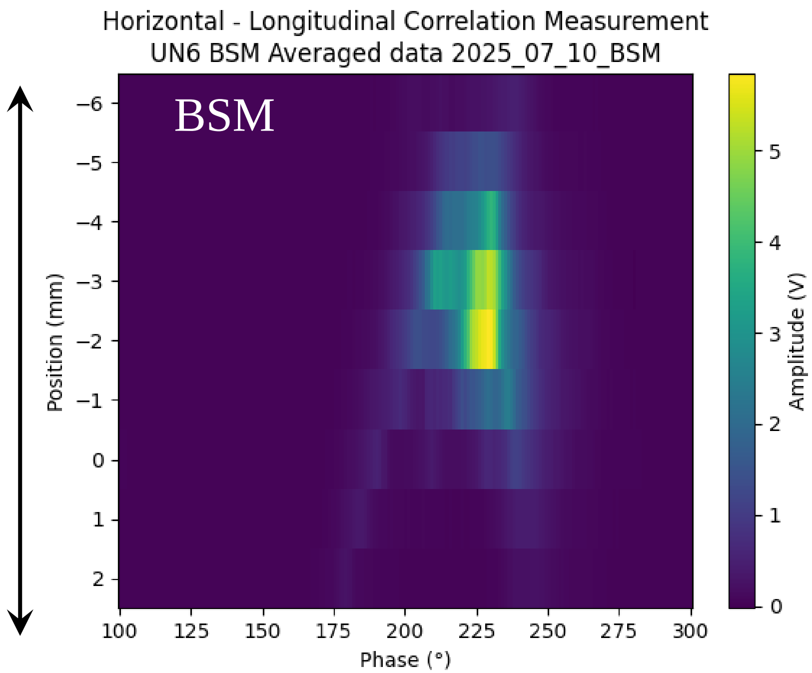
HLI @ UN6: Ar^{8+}, E =1.4 MeV/u, I = 50 µA (β = 5.5 %)

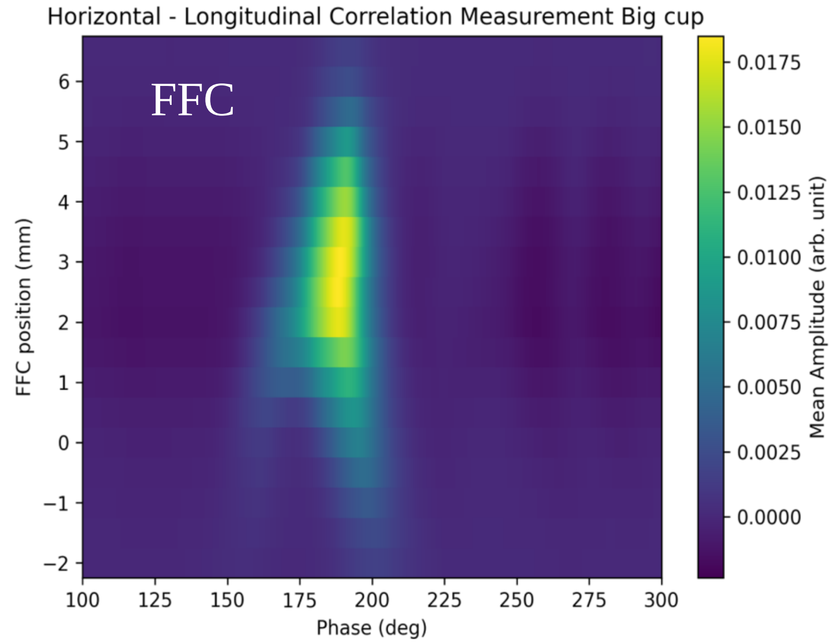
Horizontal movement by 8 mm of BSM (∅ 0.1 mm wire) and FFC (∅ 0.8 mm hole)

⇒ Horizontal – longitudinal correlation even straight after IH (unexpected)

⇒ Further investigations required

9 mm hori. movement





Phase φ span 200^0 = 5.14 ns

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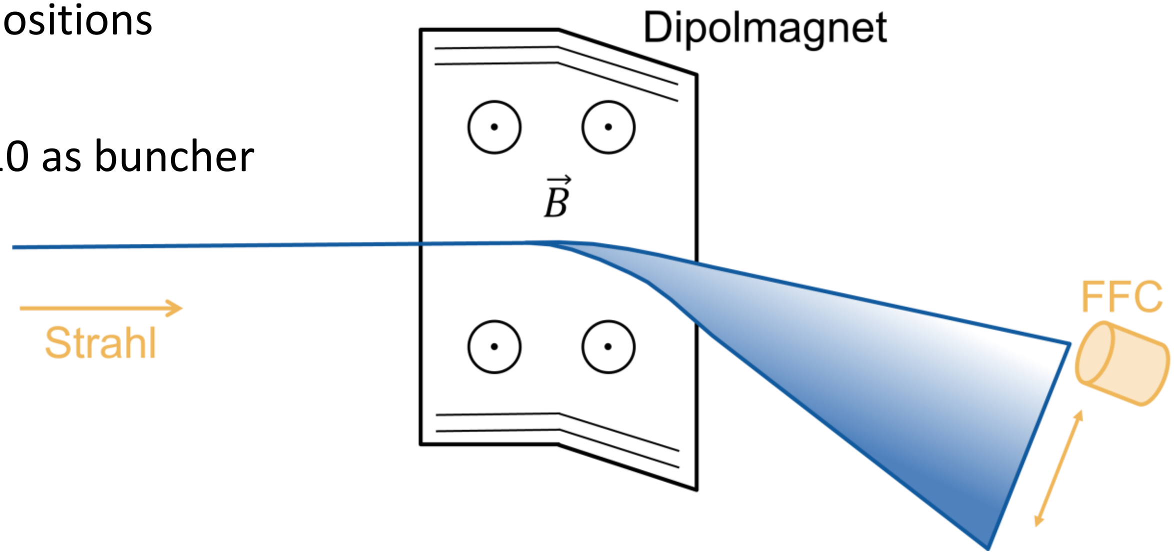
Novel investigations of longitudinal emittance:

- Location with large dispersion $\Delta x = D \cdot \frac{\Delta E}{E}$
- Bunch shape for different positions

Realized at US3 and X2

e.g. 30th July 25 at X2 using E10 as buncher



Calibration of dispersion $D = 0.90 \pm 0.1$ m using $\Delta x = D \cdot \frac{\Delta E}{E}$ at X2 via slight acceleration and profile measurement

X2 July 2025: $D = 0.90 \pm 0.1$ m $\Rightarrow \Delta x = 9$ mm for $\frac{\Delta E}{E} = 1\%$ (using $\Delta x = D\frac{\Delta E}{E}$)

N. Schmidt et al, IBIC'25 & Master Thesis

Idea for longitudinal Emittance Measurement

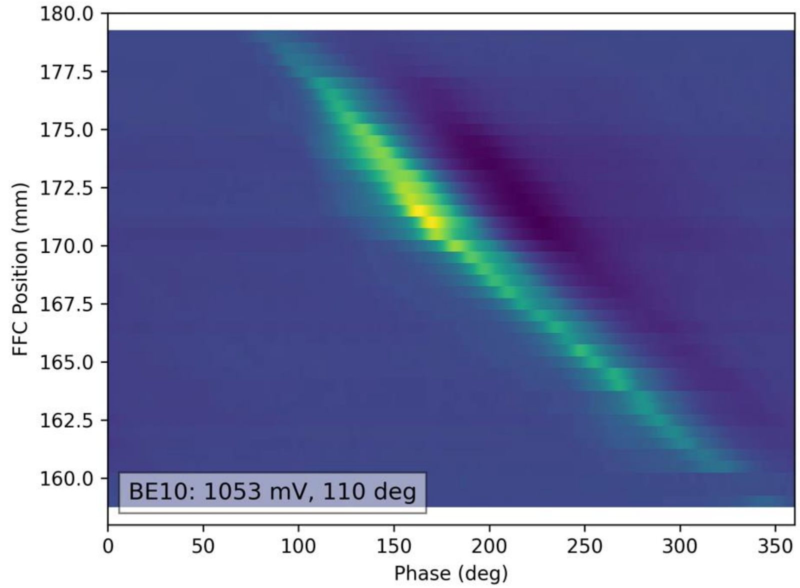
Experimental confirmation → position scan of FFC (30th July 25):

- Beam from HLI at X2: Ar^{8+} E= 11.4 MeV/u ($\beta = 15\%$), $I = 35\ \mu A$
- Variation of E10 as buncher

about $\frac{\Delta E}{E} \approx 2.2\ \%$

using measured

$D = 0.90 \pm 0.1$ m



Phase φ span 360^0 = 9.25 ns

Result:

- Method is appropriate
- Dispersion measurement by energy variation and SEM-grid detection
- Strong deformation of longitudinal phase space
- Evaluation is ongoing

Longitudinal focusing:

Variation of the bunch shape by a rf-buncher
$\rightarrow$ components 5 and 6 from 6-dim phase-space

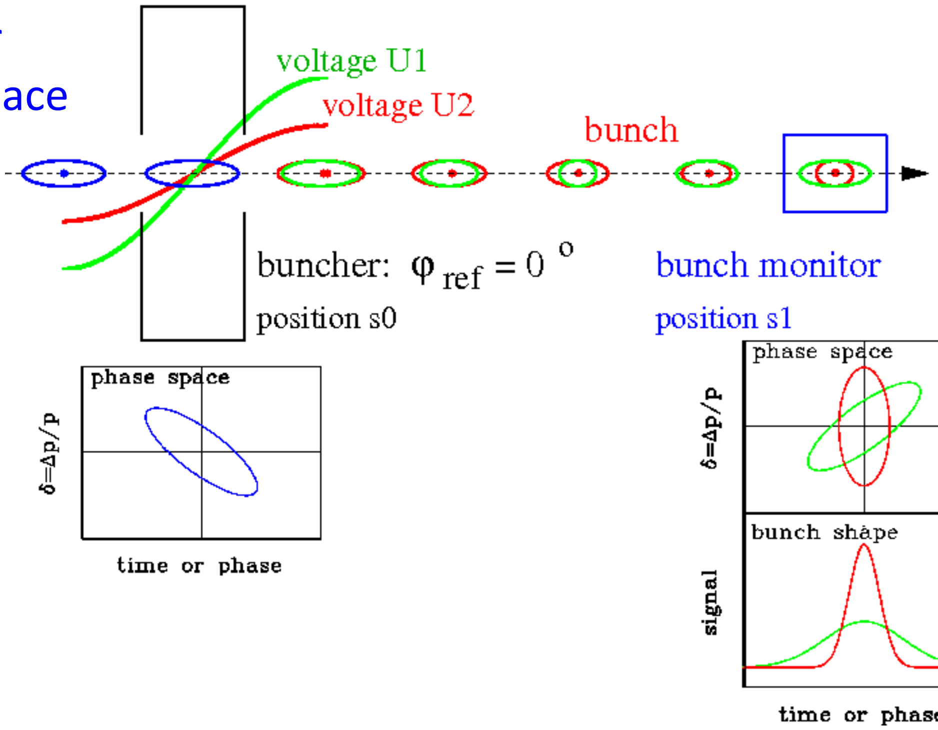
Transversal correspondence:
Quadrupole variation

- Transfer matrix of buncher & drift:

$$R_{buncher} = \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix}$$

$$R_{drift} = \begin{pmatrix} 1 & L/\gamma^2 \\ 0 & 1 \end{pmatrix}$$

with focal length $\frac{1}{f} = \frac{2\pi f_{rf}}{Apv^2} \cdot U$



- Variation of buncher amplitude U:
  - $\Rightarrow$ Different bunch width at Bunch Shape Monitor
  - $\Rightarrow$ Emittance determination by linear transformation with assumption: Bunch has Gaussian form $\Leftrightarrow$ phase space is given by an ellipse

Result of a longitudinal Emittance Measurement

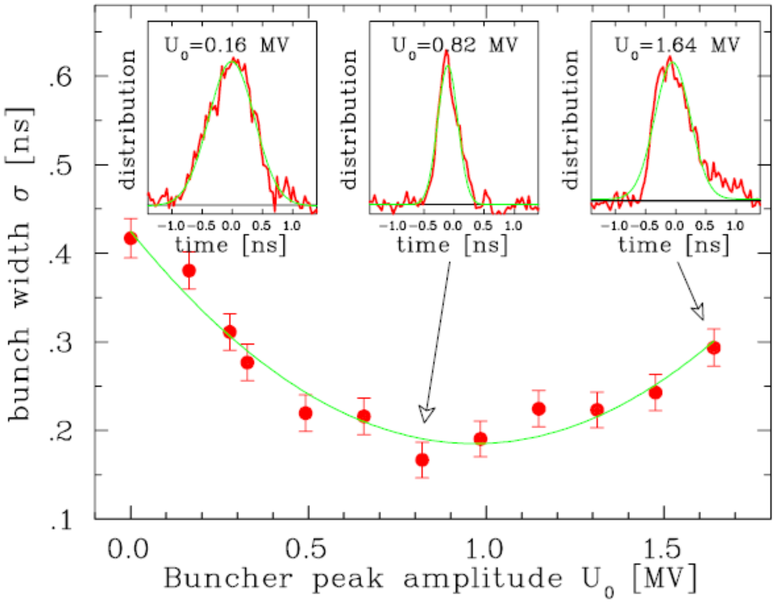
Example UNILAC-TK5: Voltage variation at E10 for 11.4 MeV/u Ni^{14+} beam, 31 m drift:

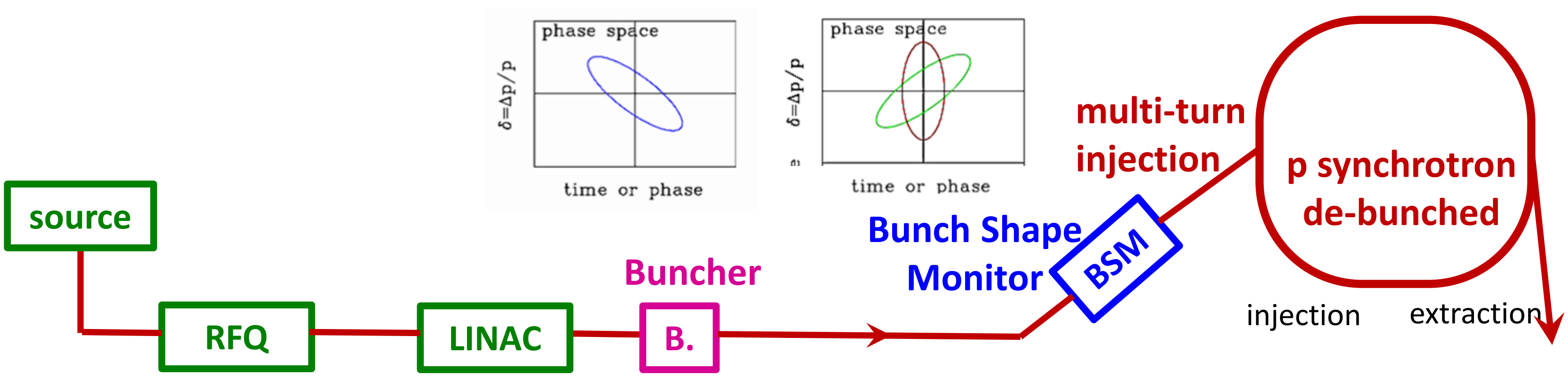
- This example: The resolution is better than 50 ps or 2° for 108 MHz
- Typical bunch length at proton LINACs:

  $\sigma_{bunch} \approx$ 0.1 to 0.5 ns
- Determination of longitudinal emittance possible
- **However:** Bunch has non-Gaussian shape!

Application for synchrotron injection:

Shaping of longitudinal phase space by buncher
i.e. long bunches ⇔ low momentum spread
to match to the synchrotron long acceptance

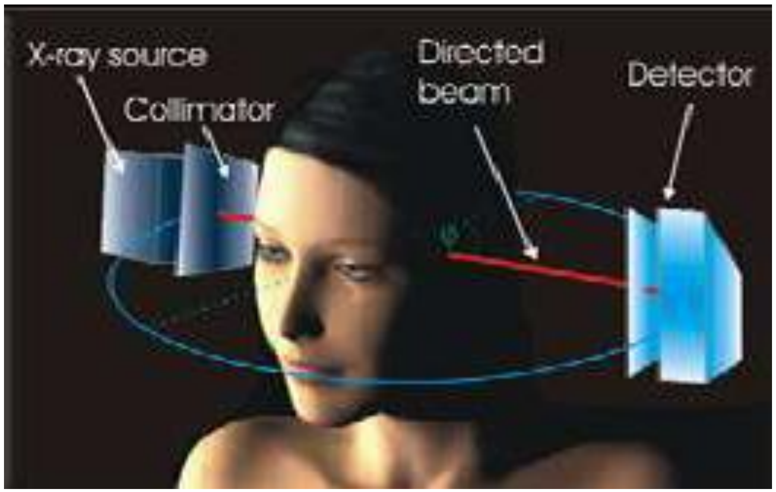


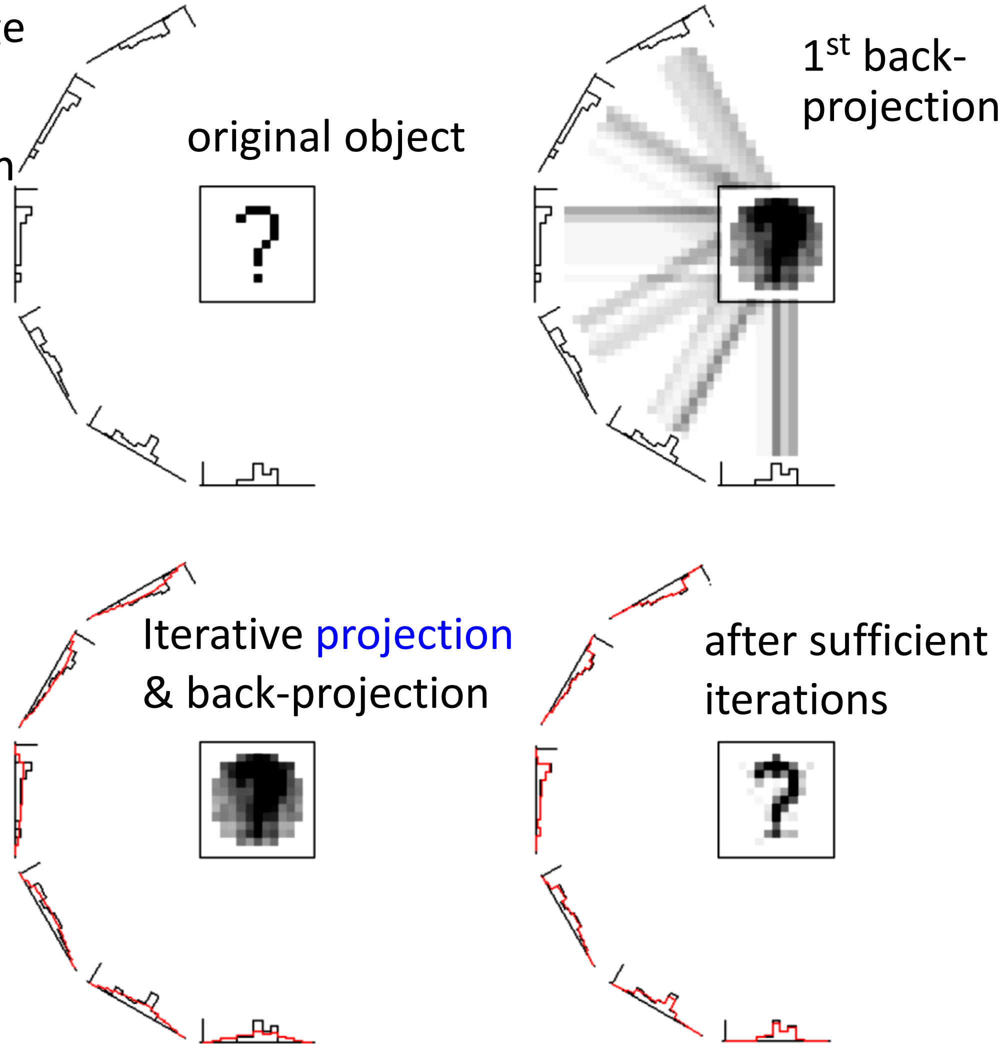


Longitudinal Emittance using tomographic Reconstruction

Tomography: Generation of a n-dim image from many lower-dim projections

Medical application: 2-dim reconstruction using sufficient 1-dim projections



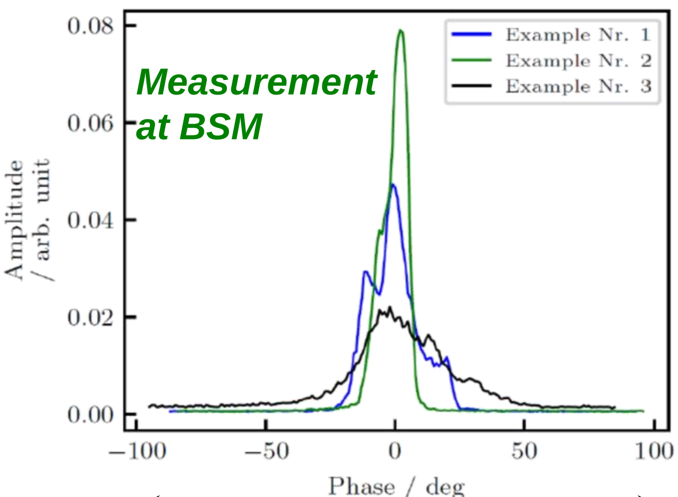


Filtered back projection:

Iterative process by redistributing the 2-dim image and considering the differences to the previous iteration step.

Example GSI HLI: Voltage variation at buncher for 1.4 MeV/u Ar^{9+} beam

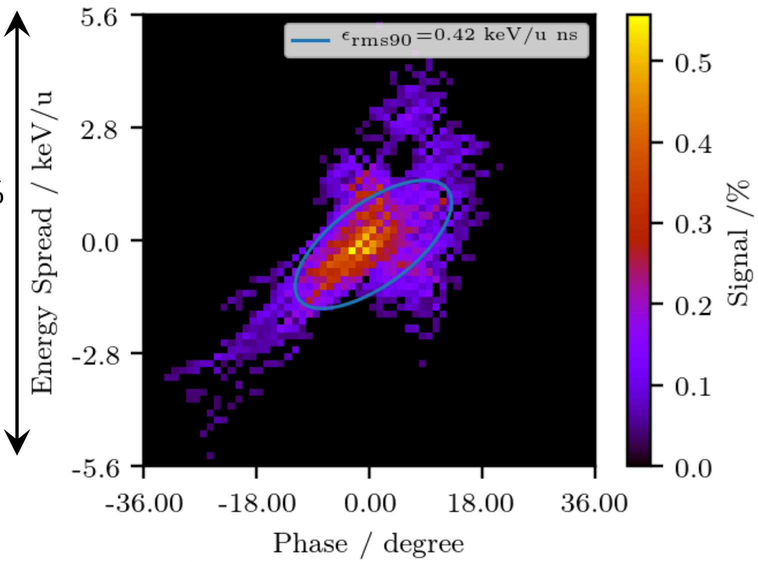
Measurement examples with BSM
for different buncher settings using 'Non-Negative Least Square' solver including space charge



Phase φ span 200^0 = 5.1 ns

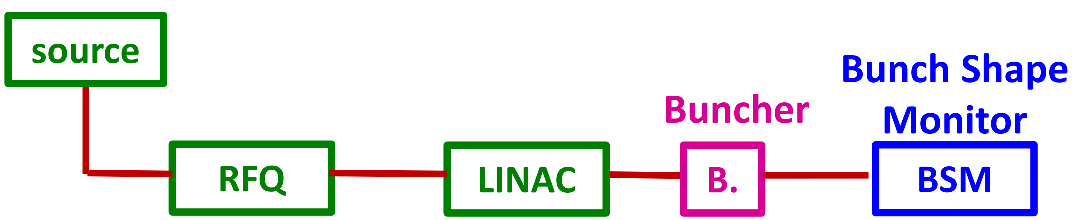
Reconstruction at HLI output

$\frac{\Delta E}{E}$ span 0.8 %



Phase φ span 72^0 = 1.85 ns

Result:
Non-regular phase-space distributions are recovered.



S. Lauber et al., Phys. Rev. Accel. Beams, 23, 114201 (2020)

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Comparison FFC and BSM

Resolution measurement at X2 (30th July 2025):

At X2 with beam from HLI:

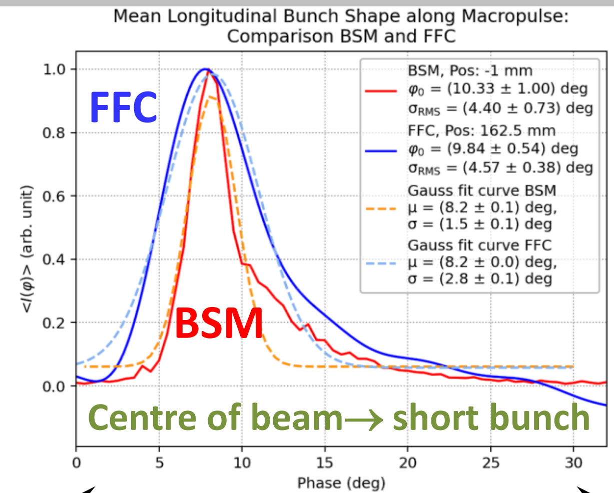
$Ar^{8+}, E = 11.4\ \mathrm{MeV/u}\ \ (\beta = 15\%), I = 35\ \mu\mathrm{A}$

Interpretation:

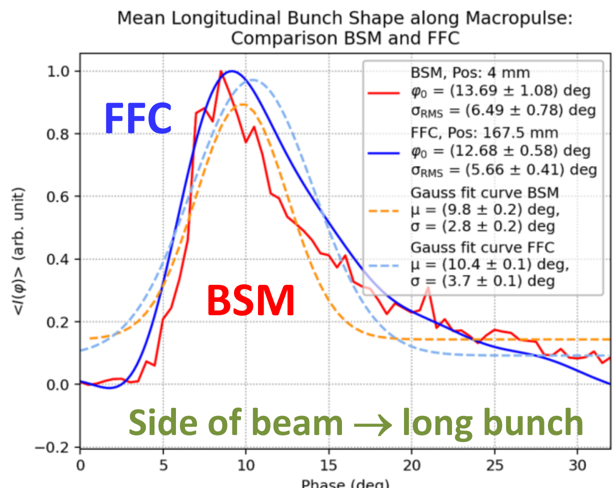
- BSM & FFC can be used for measurement
- **BSM: -** Better resolution (about ≈ 1^0 = 25 ps)
  - Long measurement time due to scan
- **FFC:** - Less resolution (about ≈ 5^0 = 125 ps)
  depending on electronics & cable bandwidth
  - Fast measurement within one macro-pulse

Applications:

- **FFC** → Fast information during operation
- **BSM** → Precise measurement
  Goal: Tomographic reconstruction etc.



Phase φ span 32^0 = 0.82 ns



Phase φ span 32^0 = 0.82 ns

Zusammenfassung und Ausblick

Messung longitudinal Parameter ist wichtig:

- Bisher sehr wenig longitudinale Messung am UNILAC durchgeführt
- Komplexe KONUS Strahldynamik ist sehr sensitiv auf U und φ Werte
- Optimale Parameter (insbesondere $\frac{\Delta p}{p} \rightarrow min$) für SIS-Injektion erfordert genauer Einstellung
- Strahldynamisches Verständnis muss erarbeitet werden

Zwei Messsysteme detailliert getestet (Fast Faraday Cup & Bunch Shape Monitor):

- **FFC**: - Messung innerhalb eines Makro-Pulses
  - Auflösung ca. 100 ps (abhängig von β, Elektronik & Kabel)
- **BSM**: - Scan-Verfahren, benötigt min. ≈ 100 Pulse, komplexerer Monitor-Aufbau
  - Auflösung ca. 10 ps = 0.5^0@108MHz
  - Geeignet für genaue Messung und Tomographie etc.

Einbau:

- **FFC**: UN6, UCW, US3, UT2, TK7oder 8, X2
- **BSM**: 3 Monitore vorhanden;
  bisher: UN6, UCW, X2;   zukünftig: UCW, UT2, TK7 oder 8 (parallel zu FFC)
- Tests durch LINAC- und BEA-Team in 2026 bei Engineering Runs & Operation bei Bedarf

Bemerkung: Variationen über den Makro-Puls detektiert; dies ist auch bei den Phasensonden sichtbar (passender GUI wird hoffentlich installiert) $\Rightarrow$ bitte im Operating beobachten.

Vielen Dank für die Aufmerksamkeit. Gibt es Fragen & Bemerkungen?

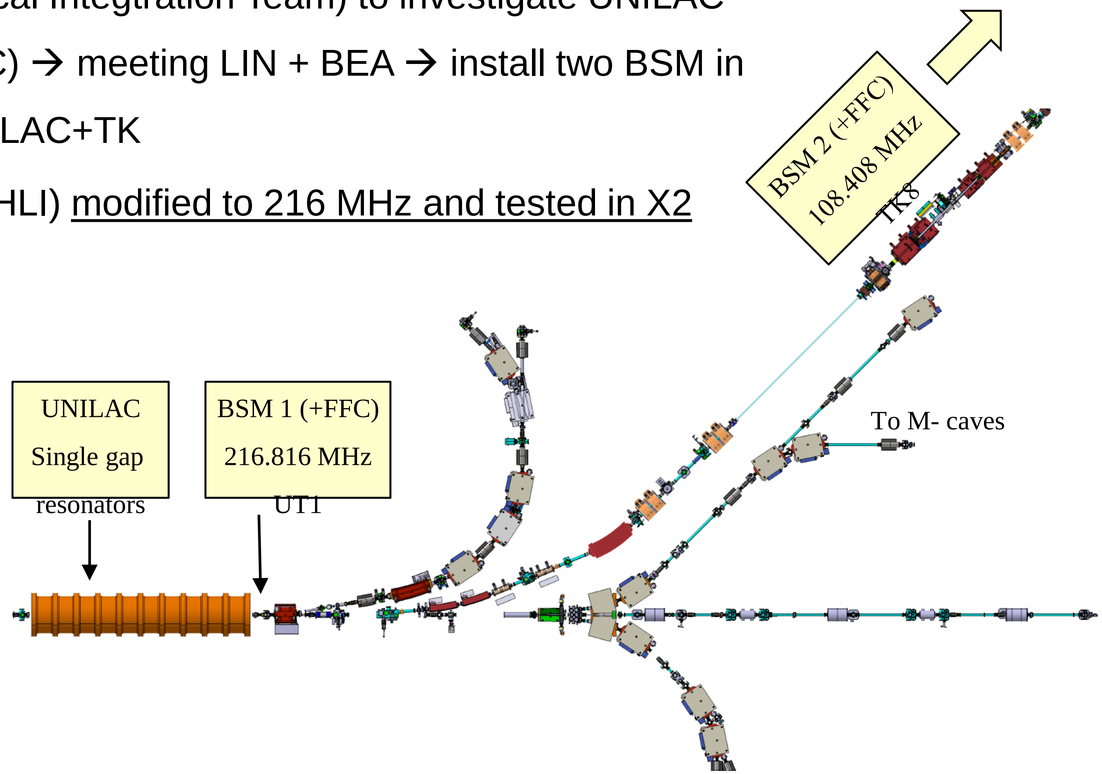
Back-up slides

BSM at GSI, current situation:

- 3 BSM at GSI: UNILAC- (2017, 108, 216, 325 MHz); cw- (2020, 108 MHz), pLinac- (2020, 325 MHz)
- UNILAC and cw-BSM frequently (and currently) in operation at HLI/HELIAC
  - Recommendation 22/23 (MAC / Technical Integtration Team) to investigate UNILAC longitudinal beam properties (BSM +FFC) → meeting LIN + BEA → install two BSM in UNILAC+TK
  - pLinac BSM (after commissioning at HLI) modified to 216 MHz and tested in X2

Locations and measurements

- Installation at UT1 (pLinac BSM) and TK8 (UNILAC BSM) to investigate beam behind UE1 and TK debuncher (SIS18 injection optimization)
- Longitudinal emittance studies by reproduction technique
  - Investigate effect of bunch shift during macropulse in X2
  - Investigate position dependent bunch shape (including FFC measurement)



Low Velocity Effect: General Consideration

Lorentz transformation of single point-like charge:

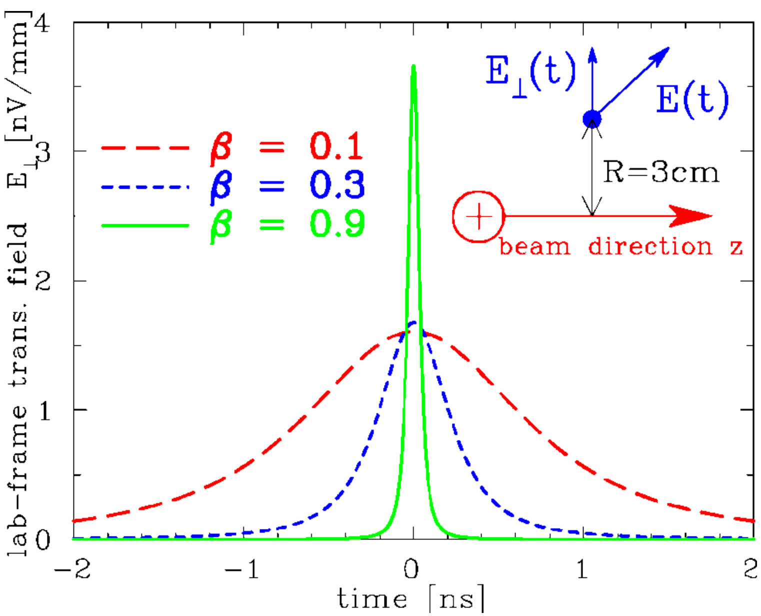
Lorentz boost ***and*** transformation of time: $E_\perp(t) = \gamma \cdot E'_\perp(t') \text{ and } t \to t'$

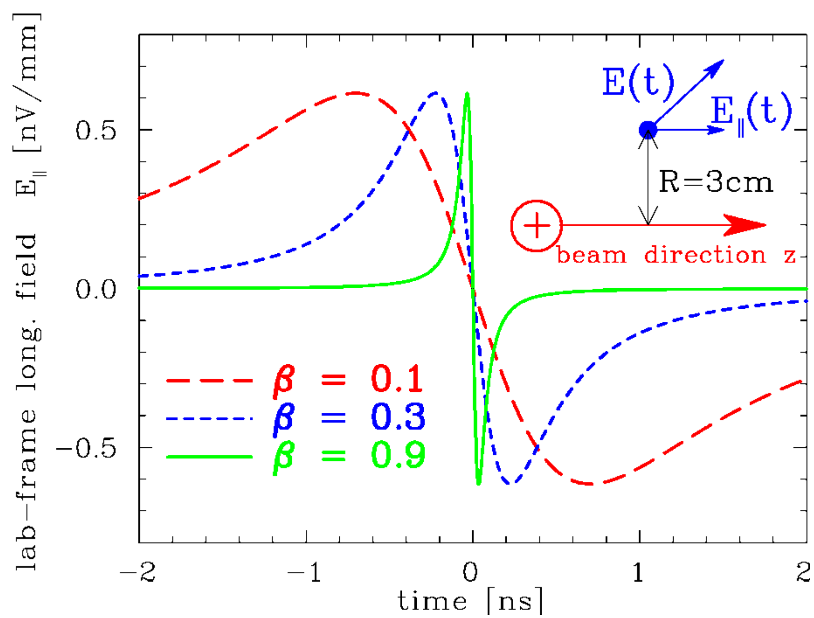
Trans. $\boldsymbol{E}_\perp$ lab.-frame of a point charge:

$$E_\perp(t) = \frac{e}{4\pi\varepsilon_0} \cdot \frac{\gamma R}{\left[R^2 + (\gamma\beta c t)^2\right]^{3/2}}$$

Long. $\boldsymbol{E}_{||}$ lab.-frame of a point charge:

$$E_{||}(t) = -\frac{e}{4\pi\varepsilon_0} \cdot \frac{\gamma\beta c t}{\left[R^2 + (\gamma\beta c t)^2\right]^{3/2}}$$

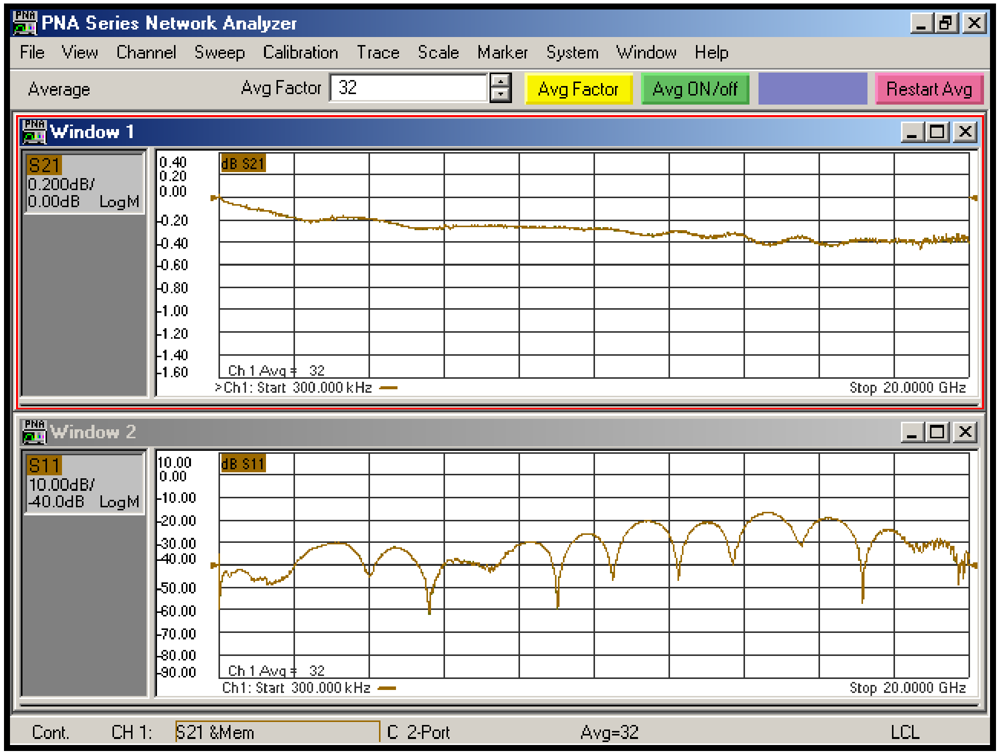


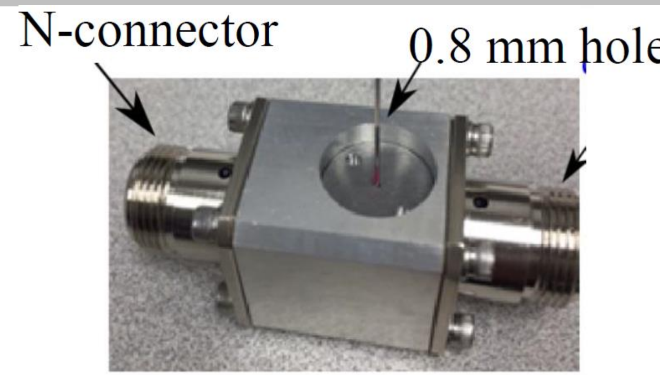


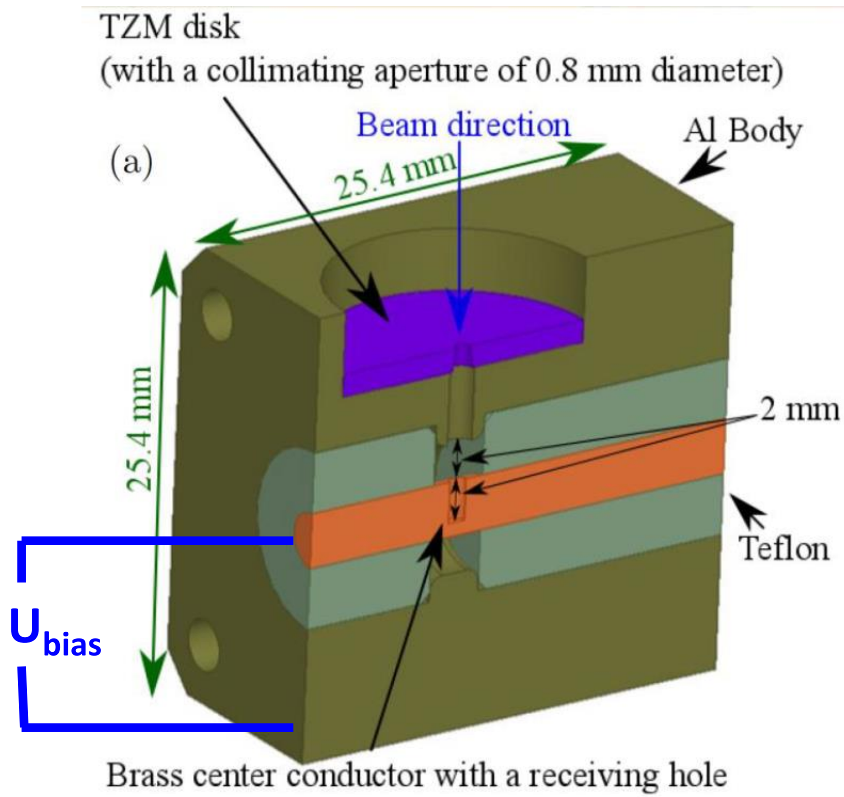
Fast Faraday Cup FFC Bandwidth

Fast Faraday Cup for direct bunch charge measurement:

- Round 50 Ω co-axial line
- Bandwidth ≈ 20 GHz







Design at Fermilab (USA) by D. Sun & A. Shemyakin, see J-P Camiero et al.
Int. J. of Mod. Phys. A, vol. 34, no. 36, 2019

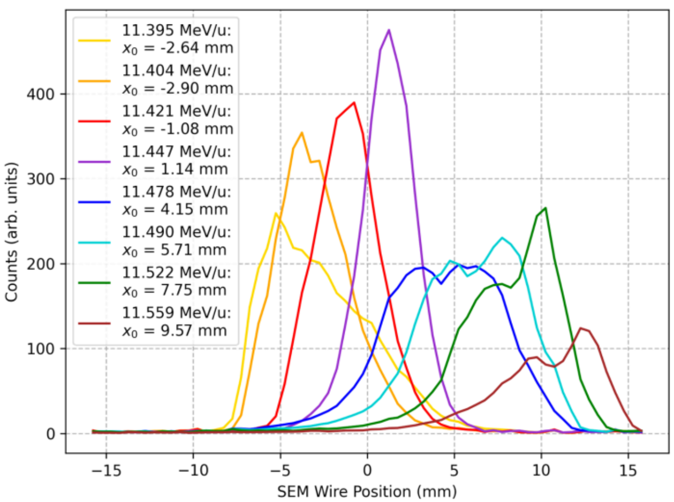
Measurement of Dispersion at X2

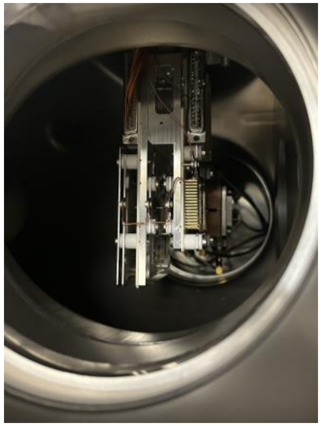
Experimental determination dispersion at X2 using $\Delta x = D \cdot \frac{\Delta E}{E}$:

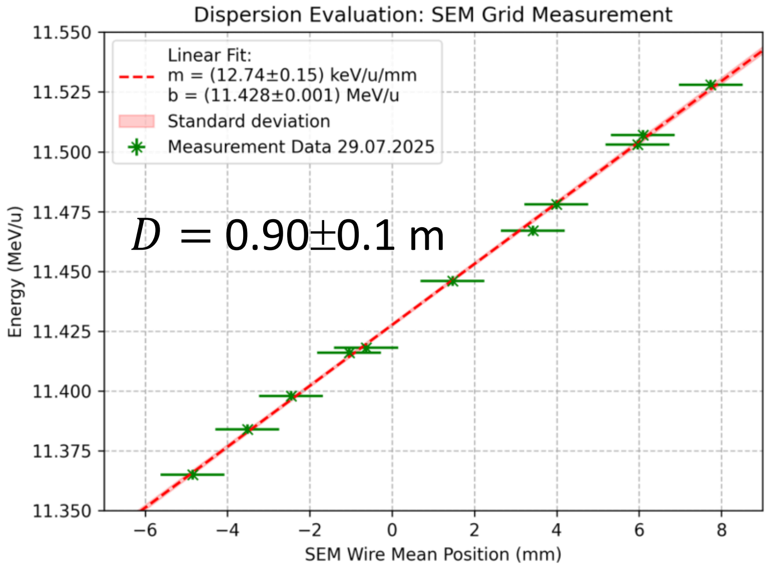
- Slight acceleration with E10
- ToF measurement with Pasensonden in UT
- Profile measurement at X2 with 0.5 mm wire spacing, 64 wires (from pLINAC)

Beam from HLI at X2: Ar^{8+} E= 11.4 MeV/u ($\beta = 15\%$), $I = 35\ \mu\mathrm{A}$

Exp. errors determined by transmission variation







SEM-grid described at: Juan Herranz et al., IBIC‘22

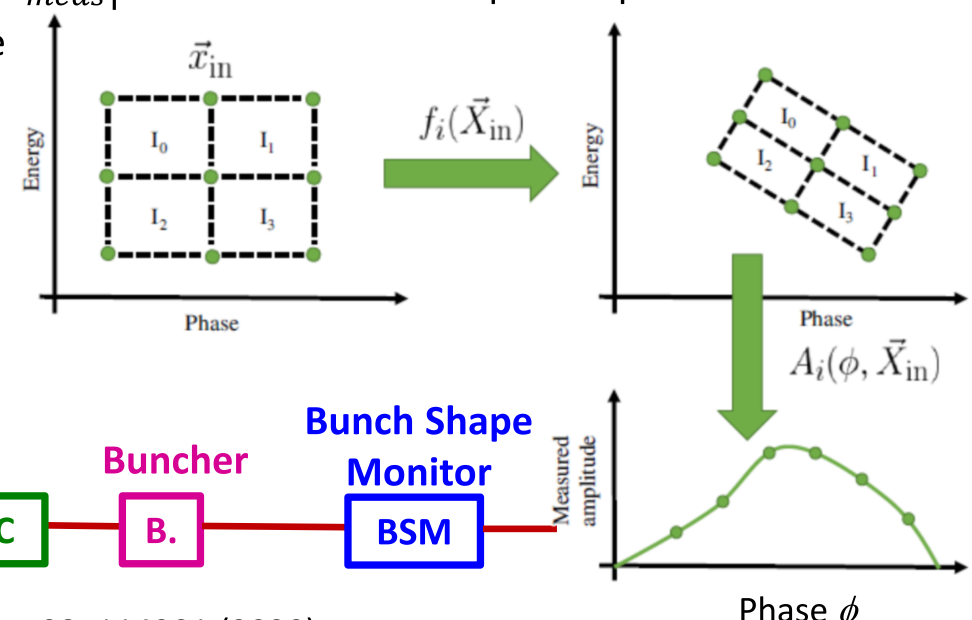
Example GSI LINAC: Voltage variation at buncher for 1.4 MeV/u Ar^{9+} beam

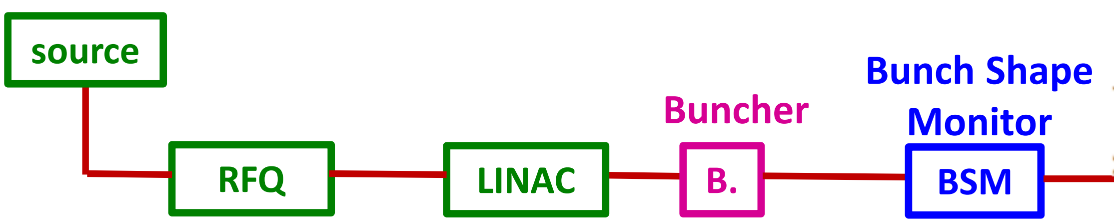
- Arbitrary phase space shapes can be recovered by reconstruction techniques (within some uncertainty)
- Phase space at buncher in discrete areas with ***m*** grid points $\vec{X}_{in}$ with intensities I_{in} $\rightarrow$ called mapping
- With particle tracking codes transferred to BSM $f_i(\vec{X}_{in})$ for **different** buncher setting ***i***
- Projection to time axis $A_i(\phi, \vec{X}_{in})$ for all buncher setting ***i*** to form a vector $\vec{A} = (A_1, A_2 \dots A_n)^t$

  $\Rightarrow$ Can be interpreted as vector-matrix equation $\vec{A} = \mathbf{B} \cdot \vec{X}$

  Matrix $\mathbf{B}$ of dimension (***n x m***) = length of all phases $\sum_{i=1}^{n} \phi_i$ ***x*** number of grid points ***m***

  resolution for phases $\boldsymbol{\phi}$***:*** 100 , number of measurement***:*** $\boldsymbol{i} = 50 \Rightarrow$ ***n = 5000***
- Best fit by minimizing $\left|\mathbf{B}\vec{X} - \vec{A}_{meas}\right| \rightarrow \mathbf{min}$ for the best phase space distribution $\vec{X}$ by **N**on-**N**egative **L**east **S**quare (NNLS) method



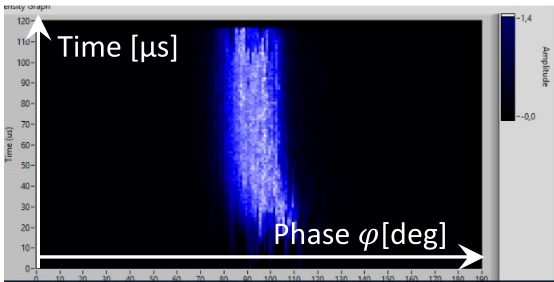


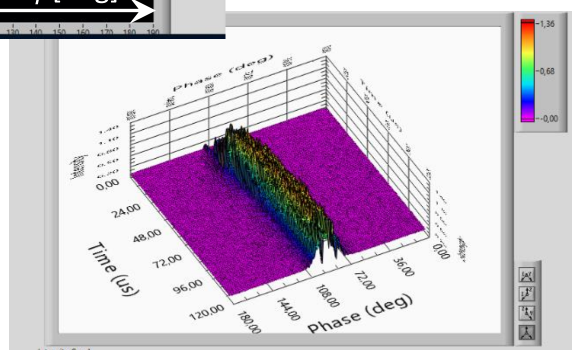
S. Lauber et al., Phys. Rev. Accel. Beams, 23, 114201 (2020)

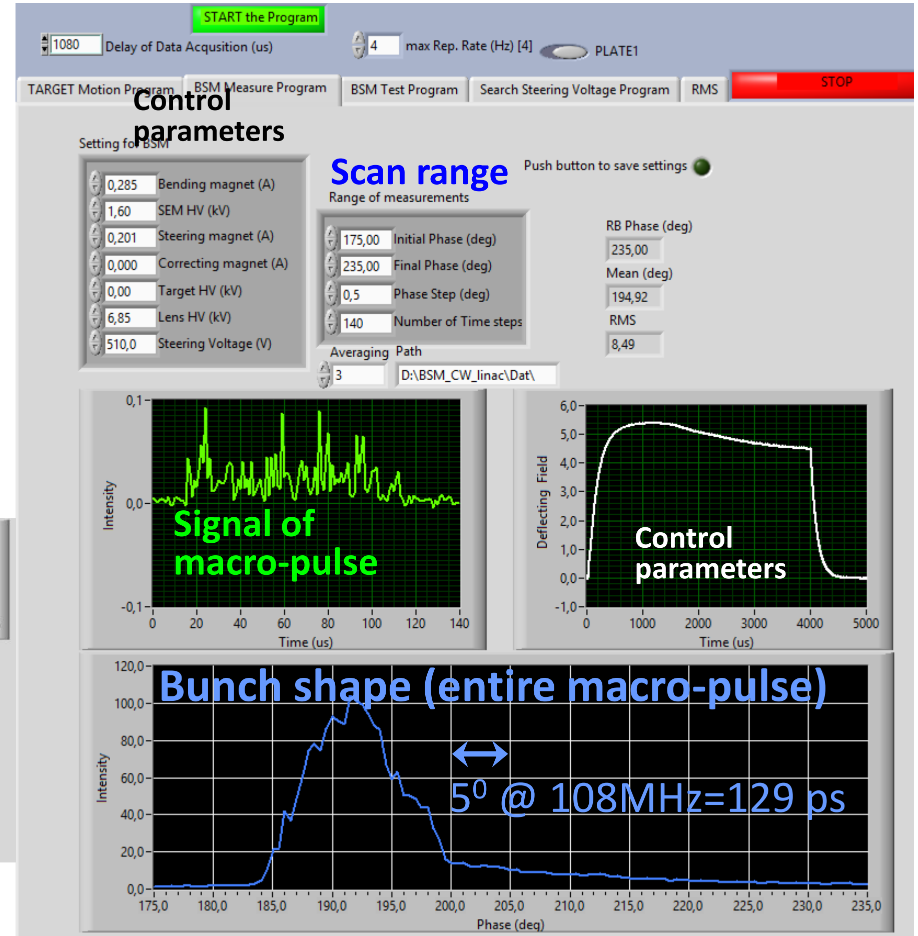
Bunch Shape Monitor: Graphical Unser Interface

Performant GUI:

- ➢Control of various monitor parameters
- ➢Bunch shape averaged over macro-pulse
- ➢Time resolved bunch with 1 µs steps







Phase φ span 60^0 = 1.54 ns

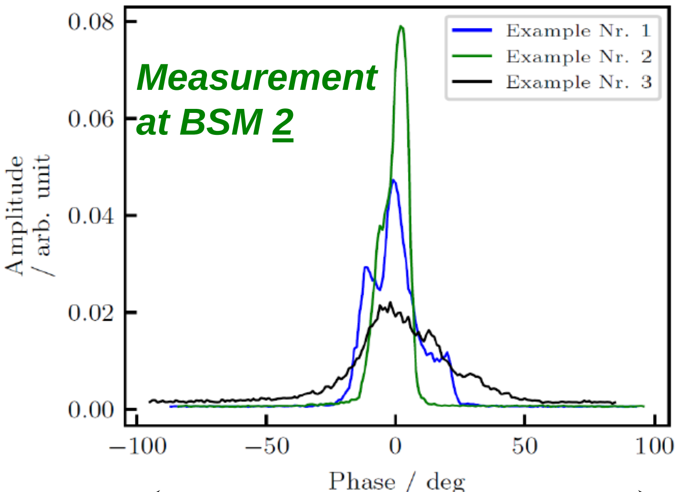
Remarks:

- ➢ BSM system responsible:
  Thomas Sieber, Pere Forck (deputy)
- ➢ Control parameters are fixed during
  measurements and are aligned by BEA members

Longitudinal Profile & Emittance: Algebraic Reconstruction

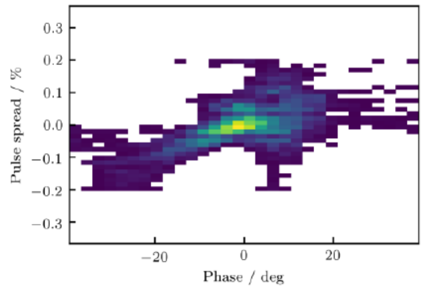
Example GSI HLI: Voltage variation at buncher for 1.4 MeV/u Ar^{9+} beam

Measurement examples with BSM
for different buncher settings:

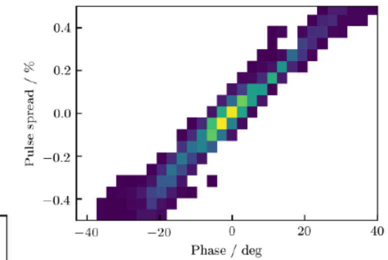


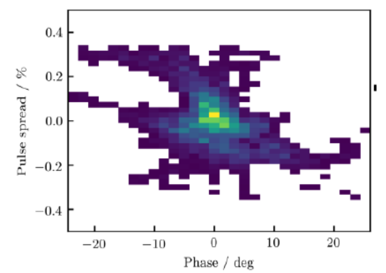
Phase φ span 200^0 = 5.1 ns

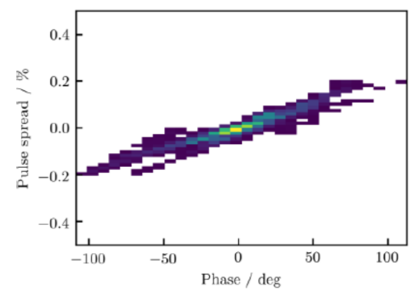
Reconstructed at HLI exit



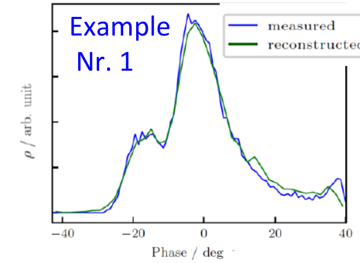
Simulated at BSM

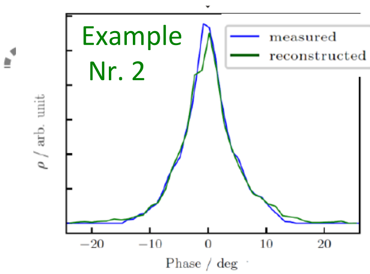


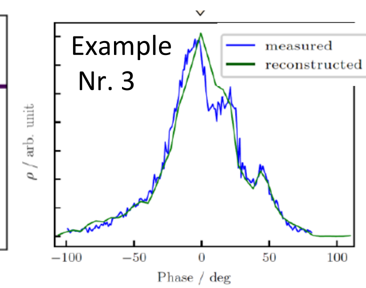




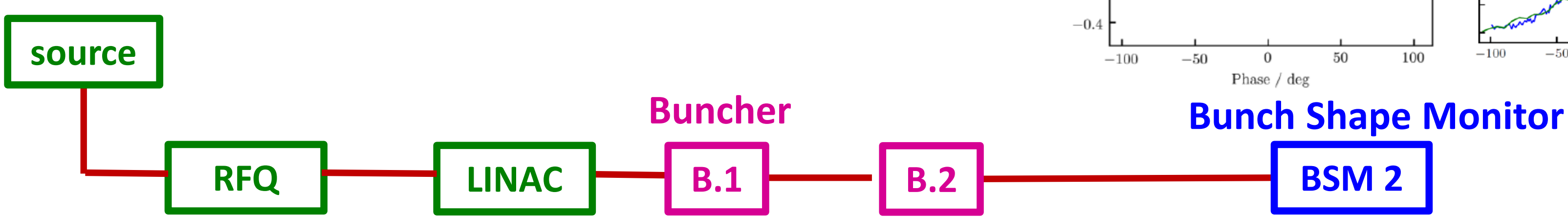
Measurement at BSM







Result: Non-regular phase-space distributions recovered
Test by changing Buncher 2 ⇒ trustful reconstruction



S. Lauber et al., Phys. Rev. Accel. Beams, 23, 114201 (2020)