Longitudinal beam diagnostics R&D at GSI UNILAC

HIAT 2022, Darmstadt

Rahul Singh

GSI Darmstadt

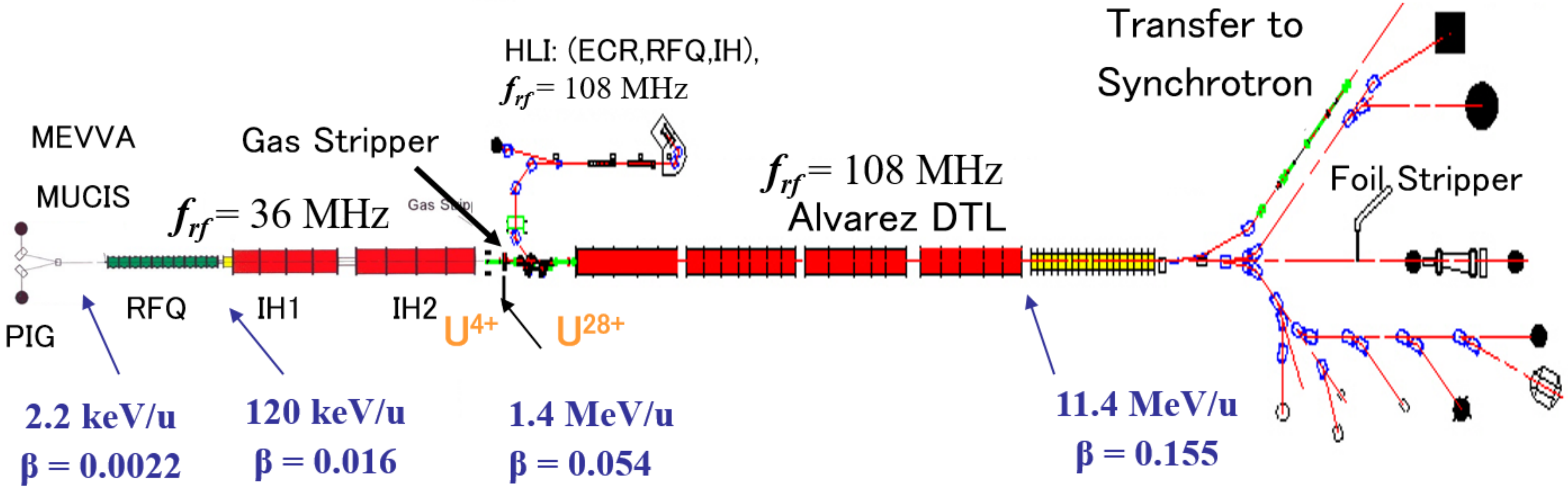
Contributors:

P. Forck, T. Reichert

Outline

- **Introduction to UNILAC longitudinal diagnostics**
  - Needs and challenges
  - Phase probes
- **Past/Existing devices**:
  - Particle detectors w.r.t. RF
  - Time-to-space conversion: Feshenko BSM , Gas ionization BSM
- **Recent developments:** Direct time-domain
  - Fast Faraday Cups (FFC)
  - GHz Transition Radiation (GTR)
- **Conclusion/Outlook**

UNILAC



HLI: (ECR,RFQ,IH), f_{rf} = 108 MHz

Transfer to Synchrotron

MEVVA

MUCIS

PIG

Gas Stripper

f_{rf} = 36 MHz

f_{rf} = 108 MHz Alvarez DTL

Foil Stripper

RFQ

IH1

IH2

U^{4+}

U^{28+}

2.2 keV/u $\beta = 0.0022$

120 keV/u $\beta = 0.016$

1.4 MeV/u $\beta = 0.054$

11.4 MeV/u $\beta = 0.155$

- UNILAC: Complex set of resonators (RFQ, IH and Alvarez) with charge stripping sections. **Two injectors** HLI and HSI served by several ion sources
- Upto 50 Hz operation, several beam types and parameters available in time multiplexed or "parallel" operation
- Significant upgrades over the last years to achieve FAIR parameters → RFQ electrodes, H2 gas strippers, beam brilliance optimization

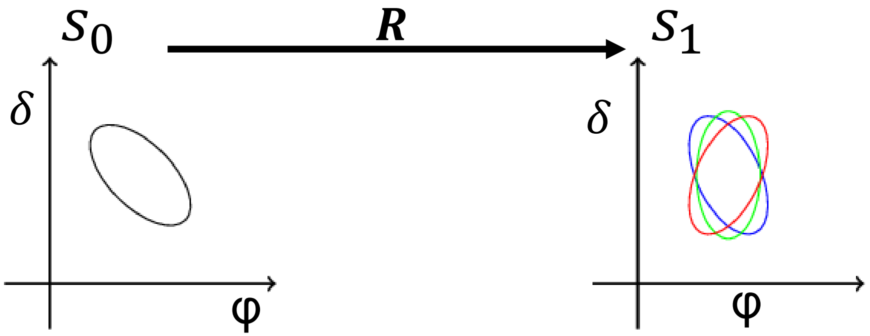
[1] W. Barth et al., High brilliance beam investigations at Universal linear accelerator, PRAB 25, 04101 (2022)

Longitudinal diagnostics and emittance

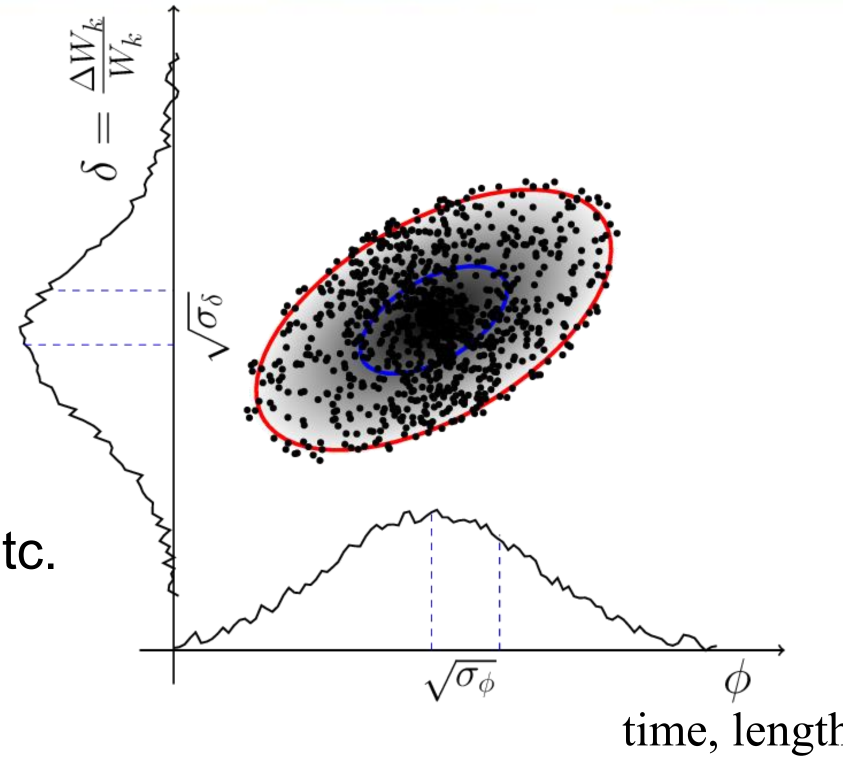
- Energy and time of arrival with respect to RF form correlated distributions
- Emittance represents the area of the phase space ellipse

$$\begin{pmatrix}\varphi\\ \delta\end{pmatrix}_{s_1} = \boldsymbol{R}\begin{pmatrix}\varphi\\ \delta\end{pmatrix}_{s_0}$$

Transfer matrix ***R*** represents buncher, drift etc.



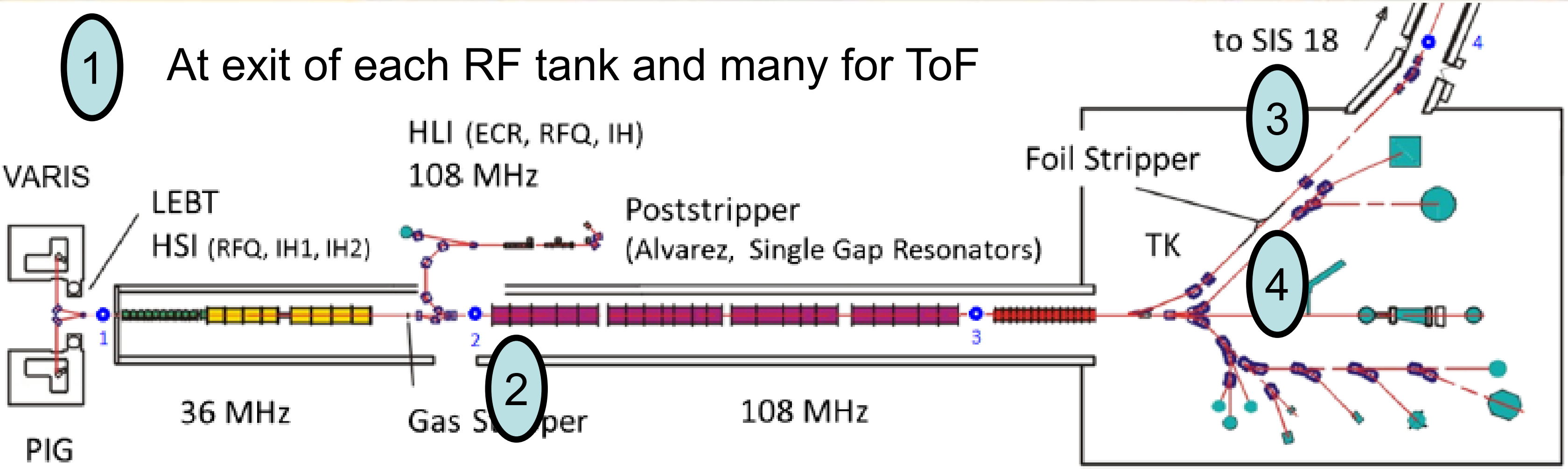
Rotation of the ellipse in phase space



- Multiple measurements of one projection enough to reconstruct both distributions → **Tomography**
- Typically only time/phase w.r.t to RF measured

Longitudinal diagnostics at UNILAC

① At exit of each RF tank and many for ToF



Need for longitudinal diagnostics : Frequent changes

- Injection from HSI into the Alvarez
- Min. energy spread while injection into the SIS-18
- Max. energy spread at stripper for countering straggling effects

Devices for longitudinal diagnostics

① Phase probes / Pick-ups

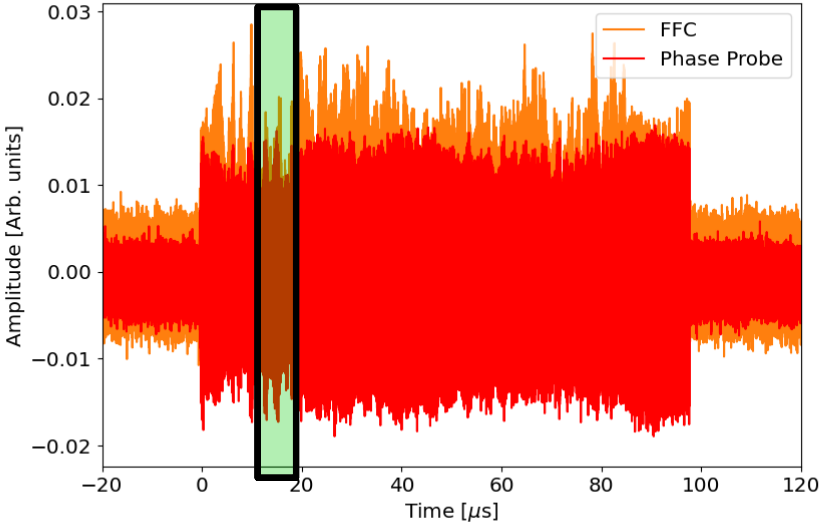
② Particle detectors

③ Residual gas ionoization monitors

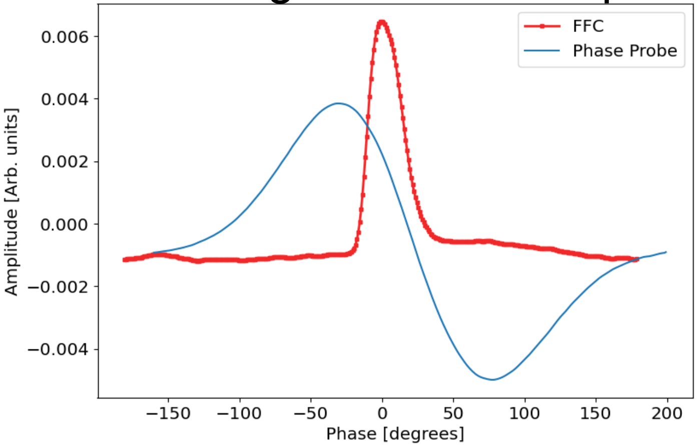
④ RF deflector and dispersion with screen

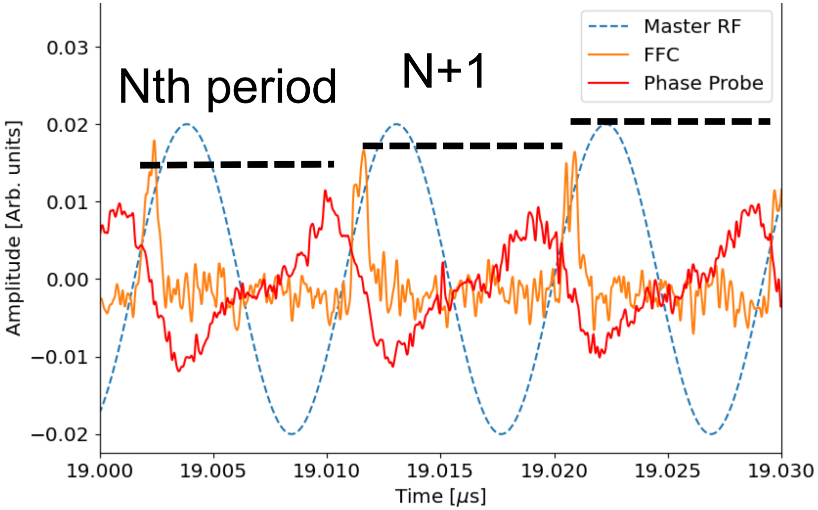
Macropulse and bunch phase w.r.t RF

100 µA He^{1+} after HLI @ 108 MHz rf

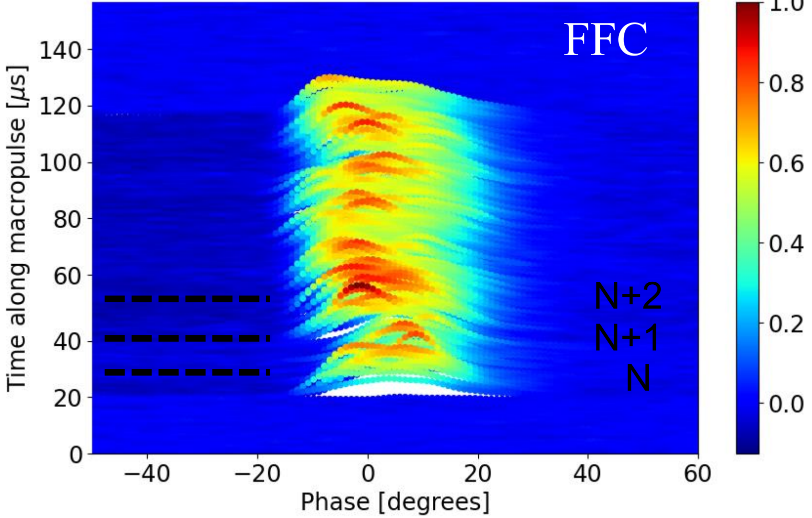


Slow averaged over macropulse



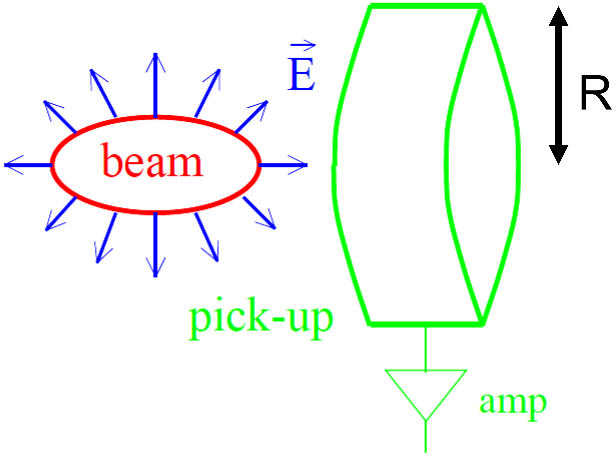


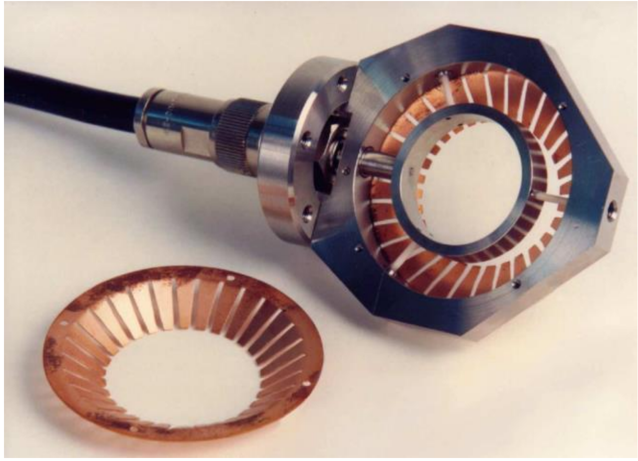
Fast



[2] R. Singh et al., Proc of IBI

Low velocity effect on phase probes



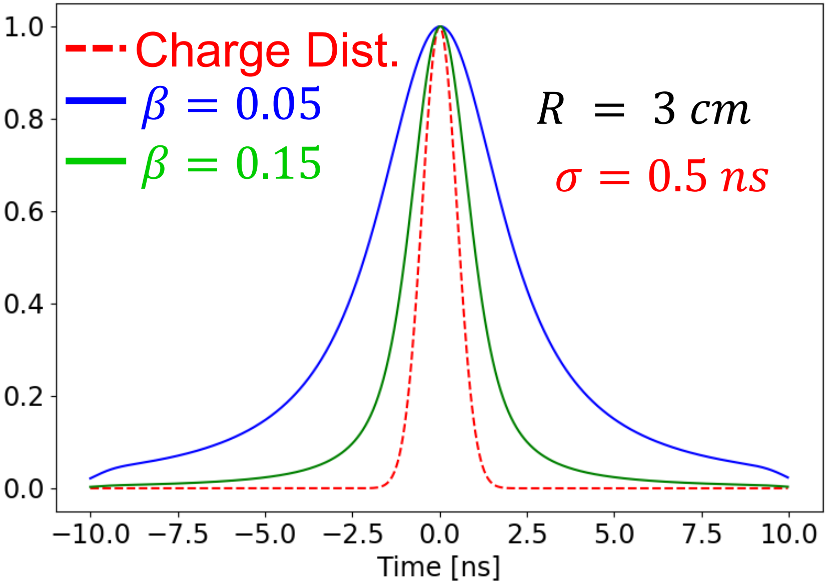


[4] P. Forck: Lecture notes on beam instrumentation

Lorentz boost ***and*** transformation of time for point charge:

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

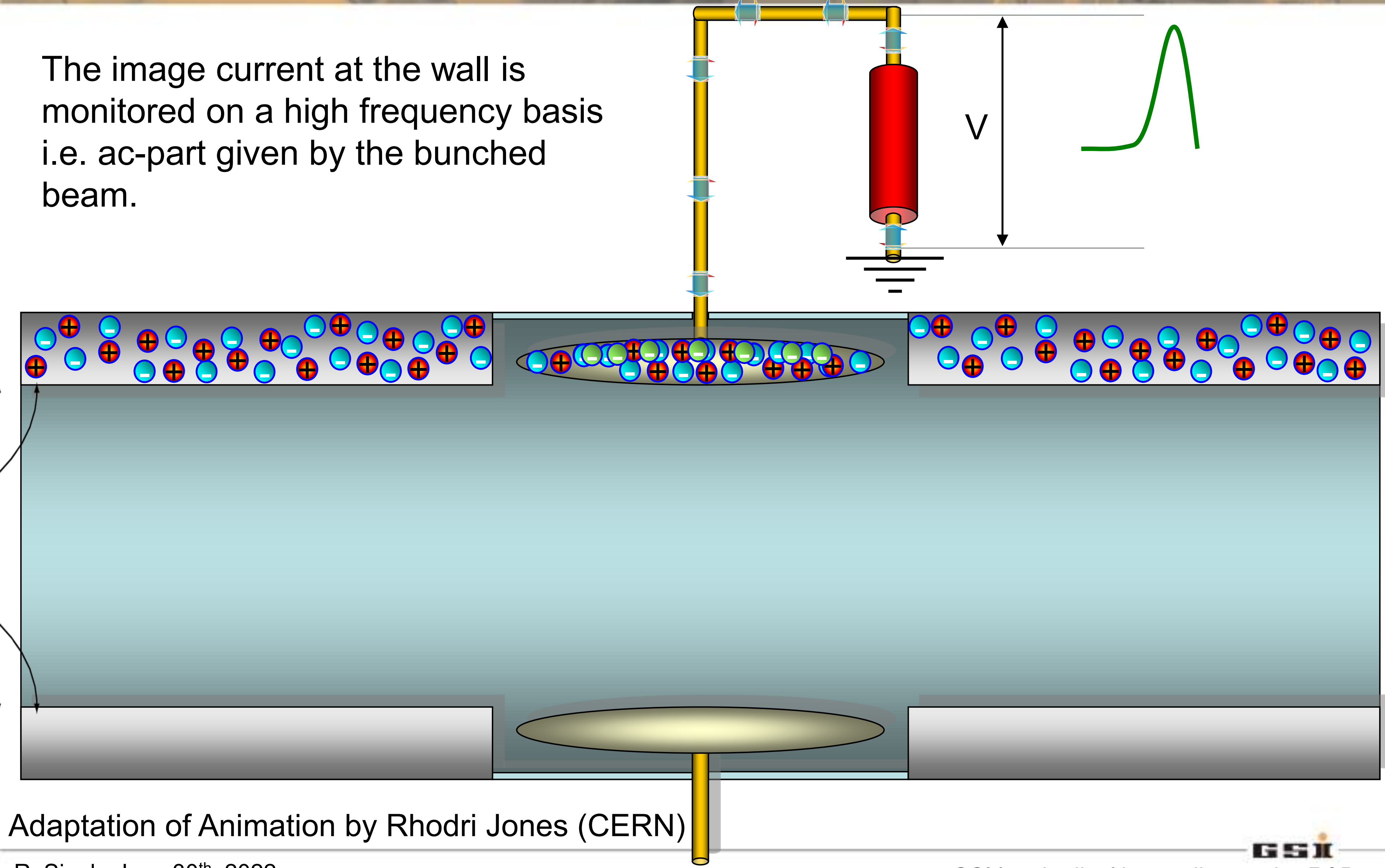
$$E_\perp(t) = \frac{e}{4\pi\varepsilon_0} \cdot \frac{\gamma R}{\left[R^2 + (\gamma\beta c t)^2\right]^{3/2}}$$



For $\boldsymbol{\beta} < 1$ → Field distribution is not the same as charge distribution. Effect visible for shorter bunches < few ns

Signal Generation in Phase Probes ($\beta < 1$)

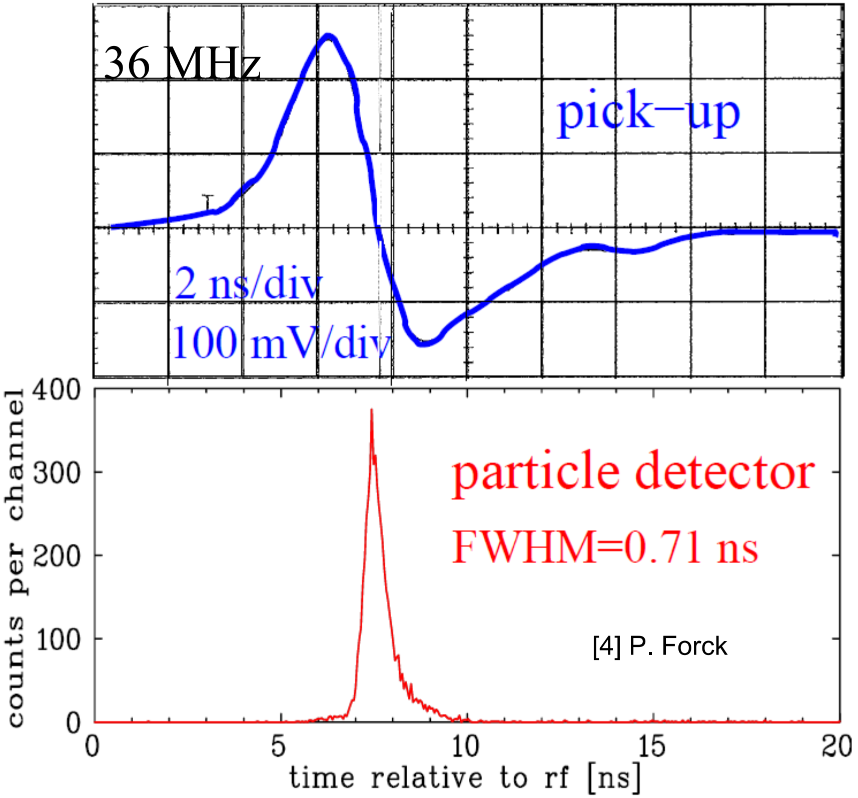
The image current at the wall is monitored on a high frequency basis i.e. ac-part given by the bunched beam.



Adaptation of Animation by Rhodri Jones (CERN)

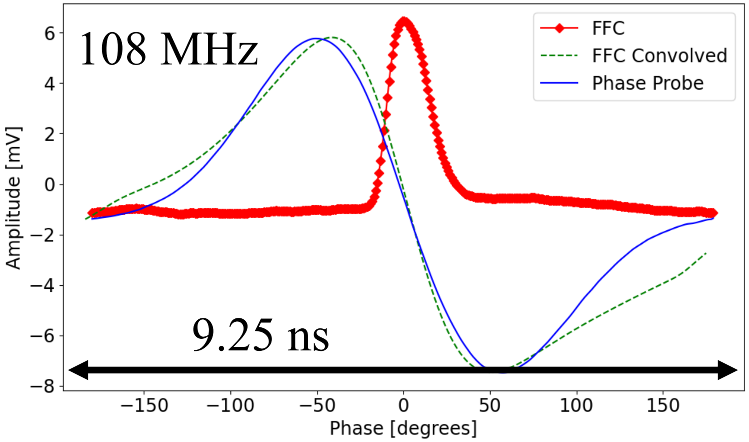
Bunch structure at low E_{kin}

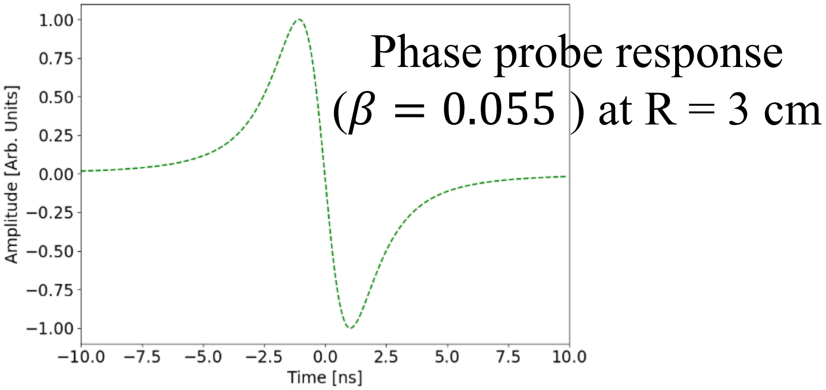
pick-up – particle counter:
Ar^{1+} with 1.4 MeV/u (β = 5.5%)



[4] P. Forck

pick-up – FFC:
He^{1+} with 1.4 MeV/u (β = 5.5%)



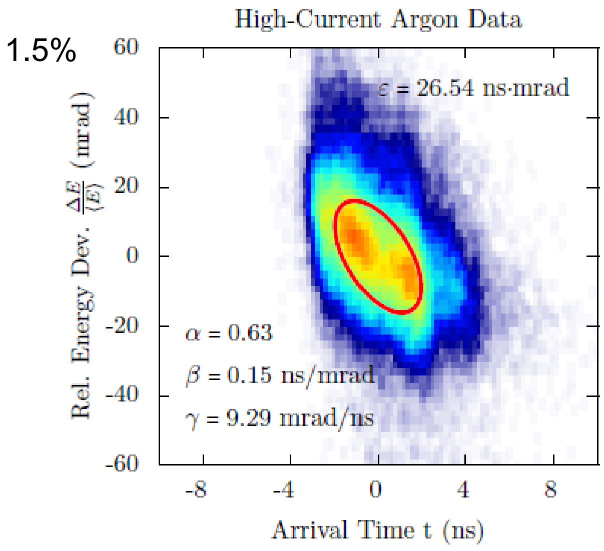


Pick-ups are used for:

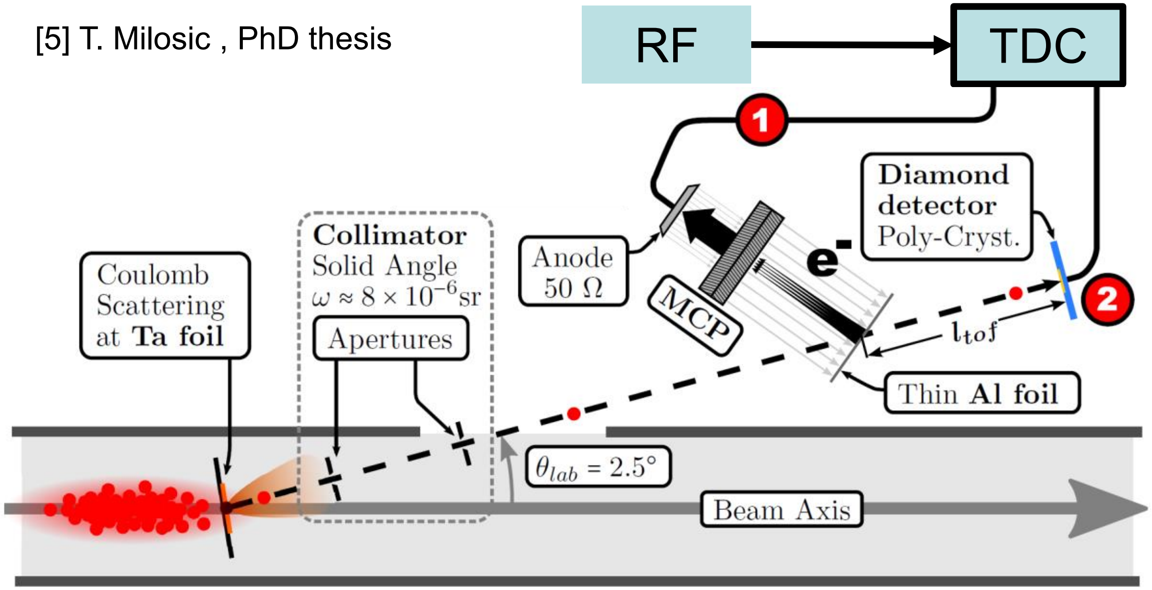
- Bunch-center relative to rf for the whole macropulse
- Does not show the detailed bunch structure although **directly related it**

Particle detectors as bunch shape monitor

The time of arrival of the particle is determined relative to the accelerating rf:



[5] T. Milosic , PhD thesis



Foil (130 nm): attenuation ≈10^{-9} by Rutherford scat.
Start-detector: Thin Al foil (50 nm) for secondary e^- acc. toward an MCP +50 Ω anode
Stop-detector: Diamond detector with 1 ns pulse width
TDC: Time relative to rf, resolution less than 25 ps

Result: Correct determination of phase spread ***but** measured* energy spread much larger than expected values → Foil non-uniformities, straggling on apertures.

Bunch structure using secondary electrons

Bunch Shape Monitor (BSM): Secondary e^- liberated from a wire or gas ionization carrying the time information.

[4] P. Forck, [6] B. Zwicker , PhD thesis

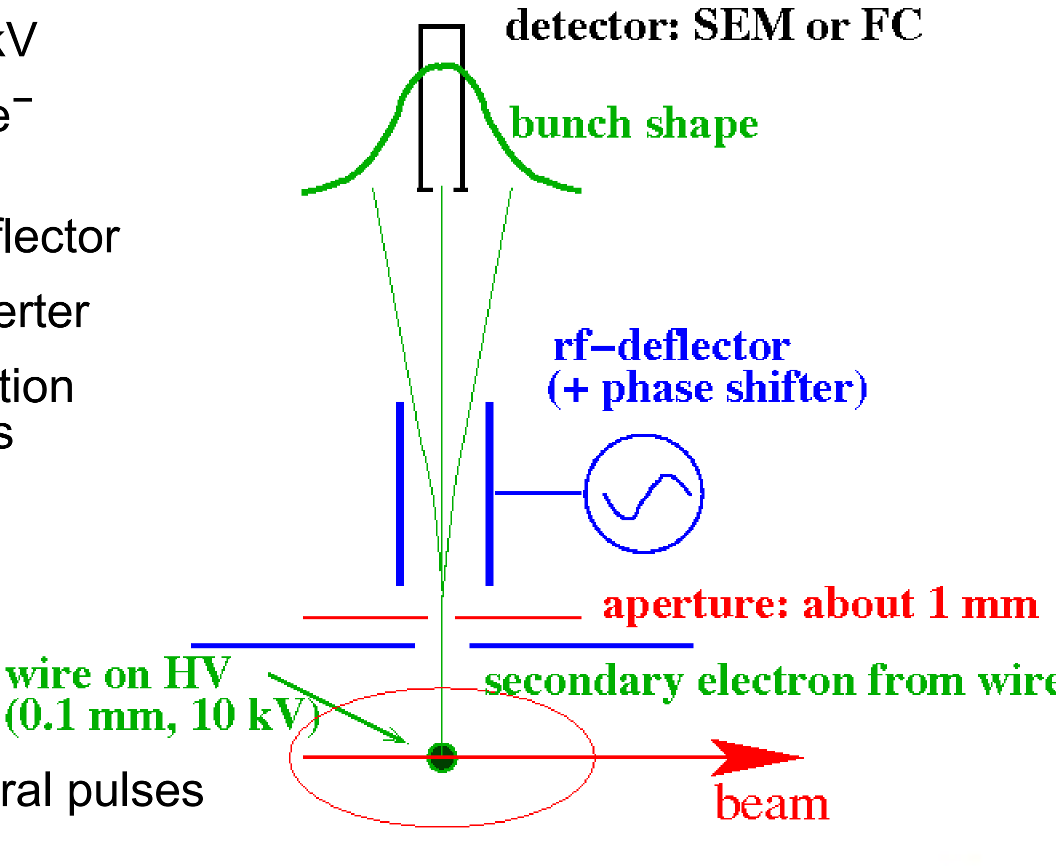
Working principle:

- insertion of a 0.1 mm wire at ≈ 10 kV
- immediate emission of secondary e^- (within < 10 ps)
- e^- are accelerated toward an rf-deflector
- rf-deflector as ’time-to-space’ converter
- either slow shift of the phase resolution ≈1° < 10 ps or "streak" the electrons

Challenges:

- Stray fields and beam fields
- Complex installation/maintenance
- Current designs: Average over several pulses

SEM: secondary electron multiplier



[2] Comparison with FFC, R. Singh et al., Proc of IBIC 2021

Fast Faraday Cups (FFC)

Faraday cup designed to measure fast bunch structures

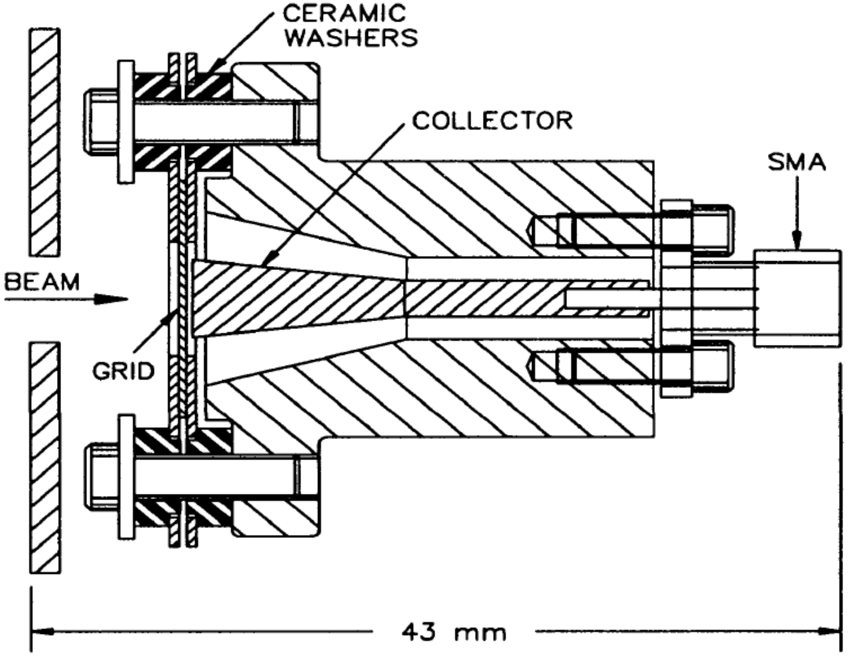
Challenges:

- Signal out-coupling should be very well matched until high frequencies , fast digitizers

  i.e. BW > $5\sigma_f = \frac{5}{2\pi\sigma_t}$

- Avoid measuring the self-field of the bunch
- Suppress distortion due to e$^-$ secondaries
- Heating/Melting of cups

Axially coupled co-axial (AC-Co FFC)



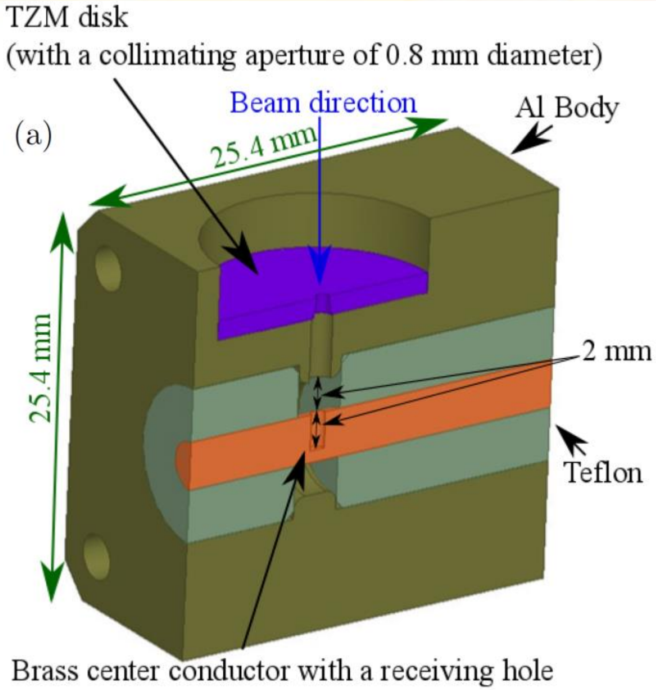
[7] P.Strehl, Beam instrumentation and diagnostics

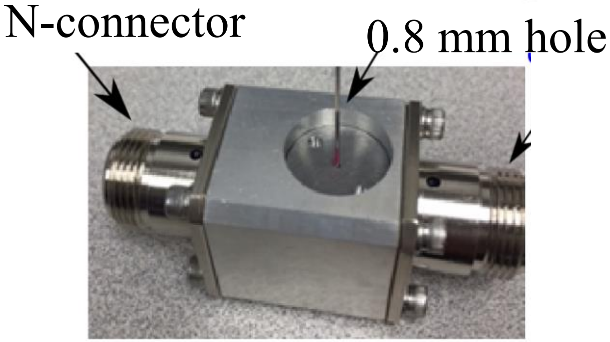
[8] Rawnsley et al. https://doi.org/10.1063/1.1342629

About18 US patent applications!

[9] J. M. Bogaty et al. (1990): A very wide bandwidth Faraday cup suitable for measuring GHz structure on ion beams with velocities to beta < 0.01

Radially coupled co-axial (RC-Co FFC)



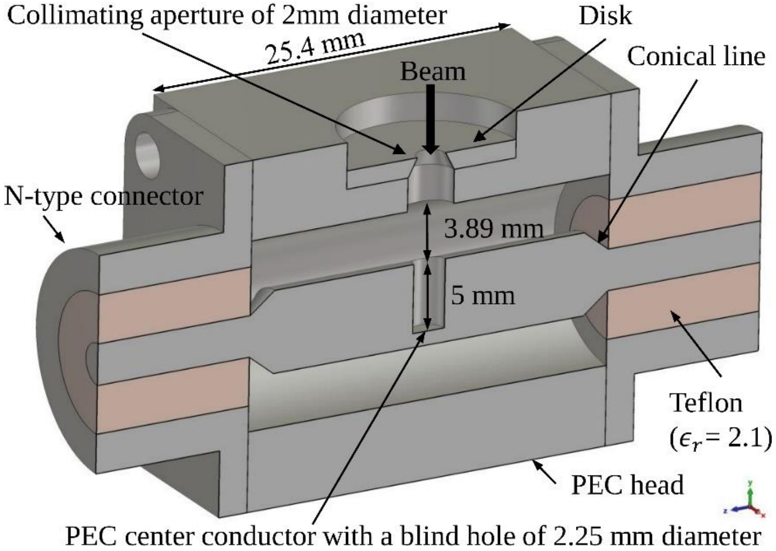


[11] J. –P Carniero et al., (2019)

D. Sun and A. Shemyakin

- Hole from the side in a co-axial cable
- 2mm distance from the ground to the central conductor → avoid pre-field
- Large depth to width ratio to avoid emission of secondaries

Minor modification of previous design

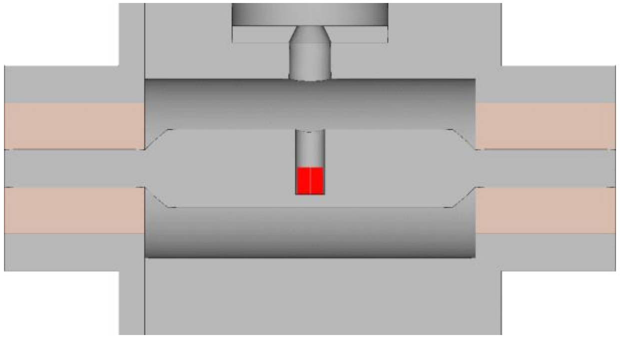


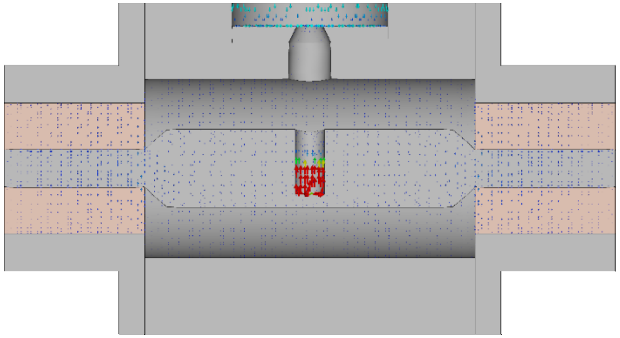
IUAC+GSI

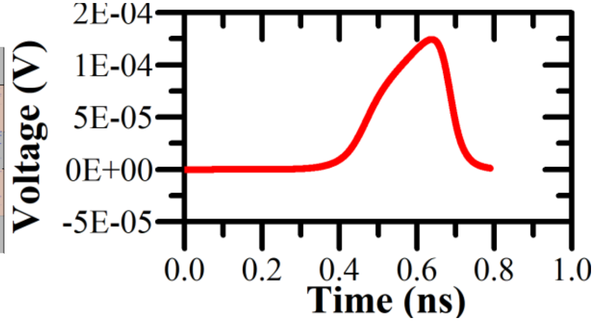
[3] K. Mal et al.

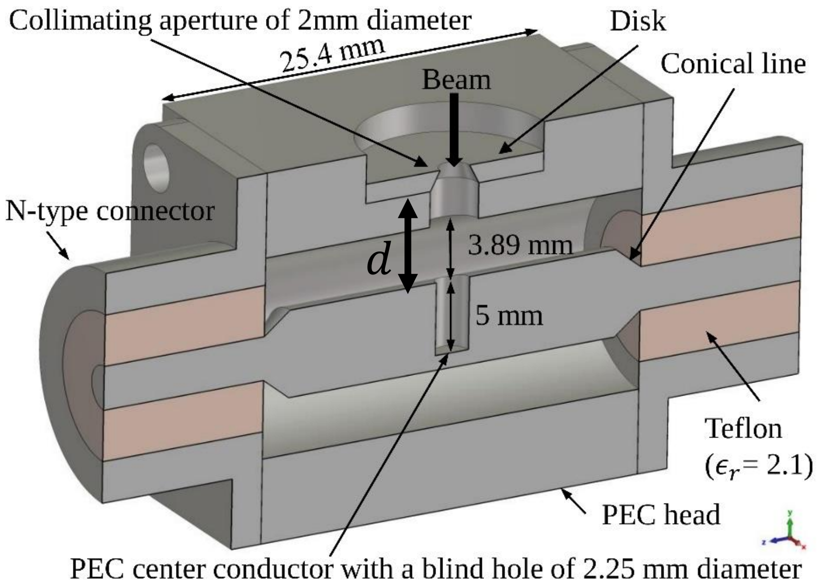
RC Co-ax FFC simulations

Simulations by [13] K. Mal et al. (IUAC)

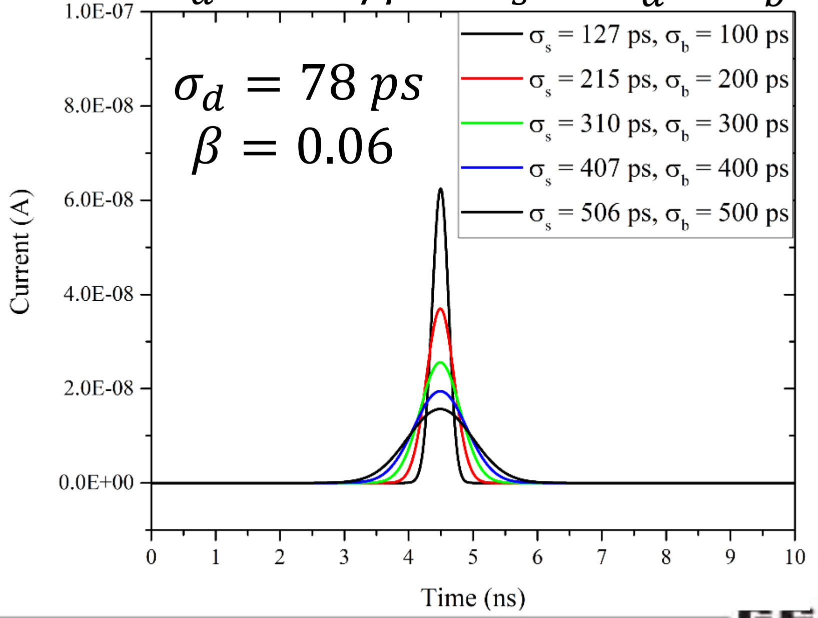






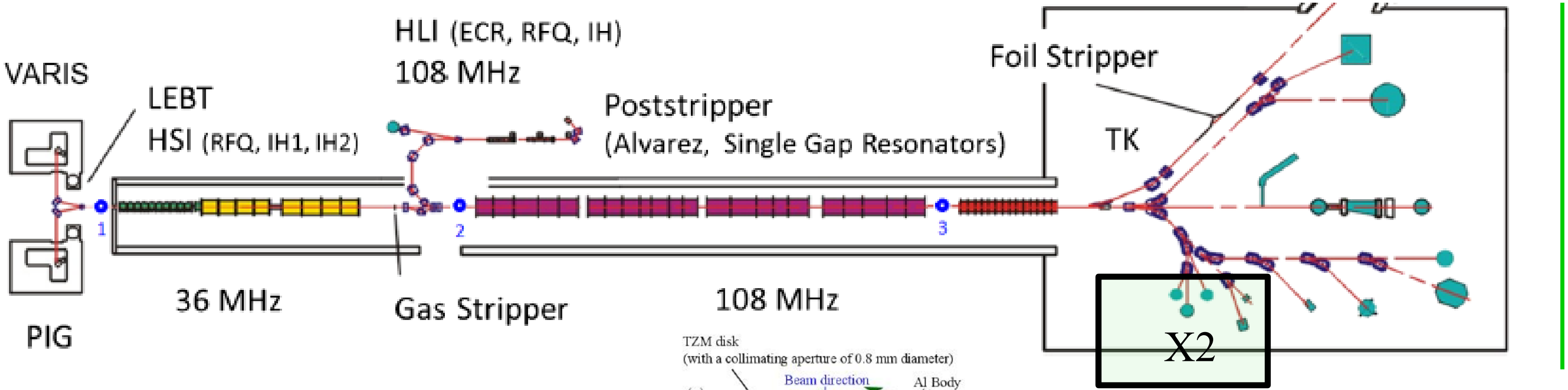


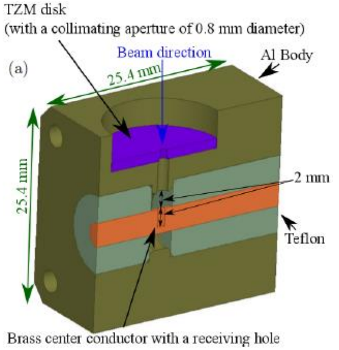
$$\sigma_d \sim 0.3d/\beta c \quad \sigma_s^2 = \sigma_d^2 + \sigma_b^2$$



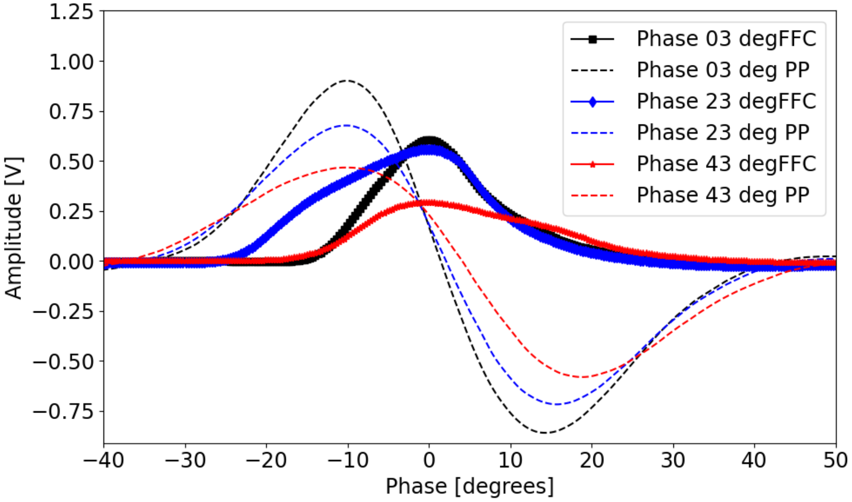
$$\sigma_d = 78\ ps$$
$$\beta = 0.06$$

RC- Coax FFC validation measurements@ X2



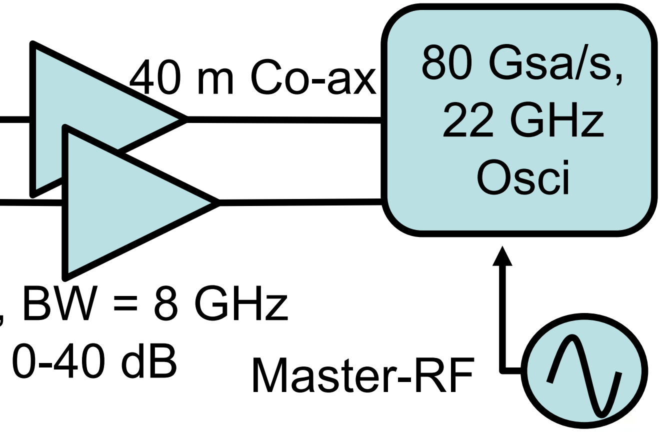


Ar^{10+}, 0.6 mA, 8.6 MeV/u



FFC

PP


40 m Co-ax

80 Gsa/s,
22 GHz
Osci

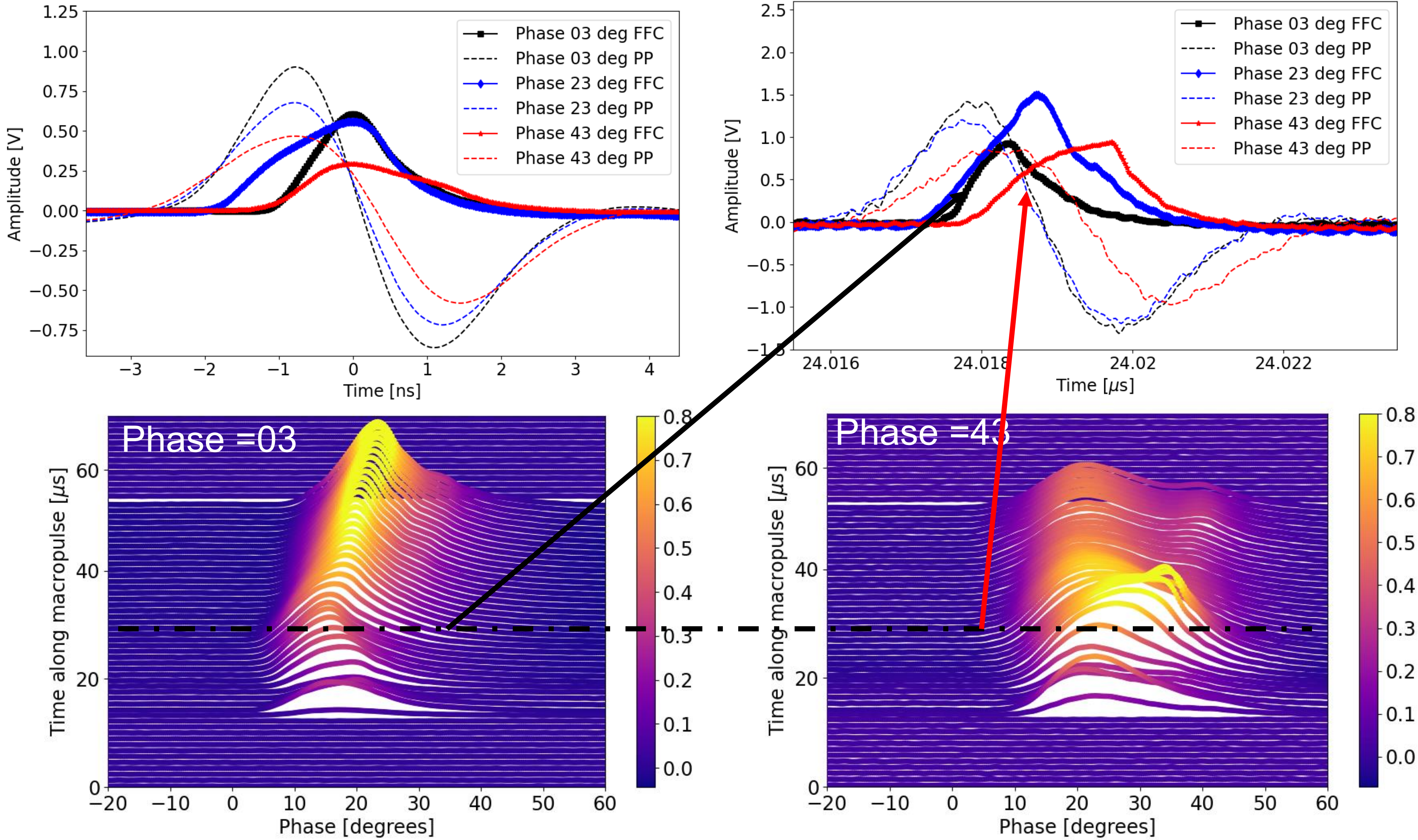
LNA, BW = 8 GHz
0-40 dB

Master-RF

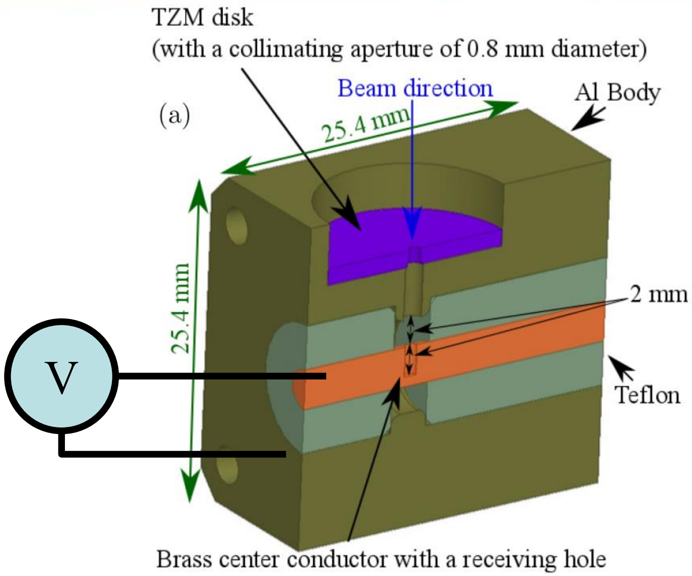
RC Coax FFC validation measurements

Averaged along macropulse

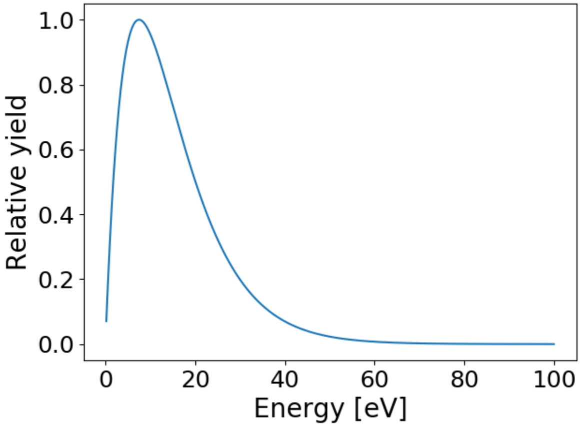
Single shot

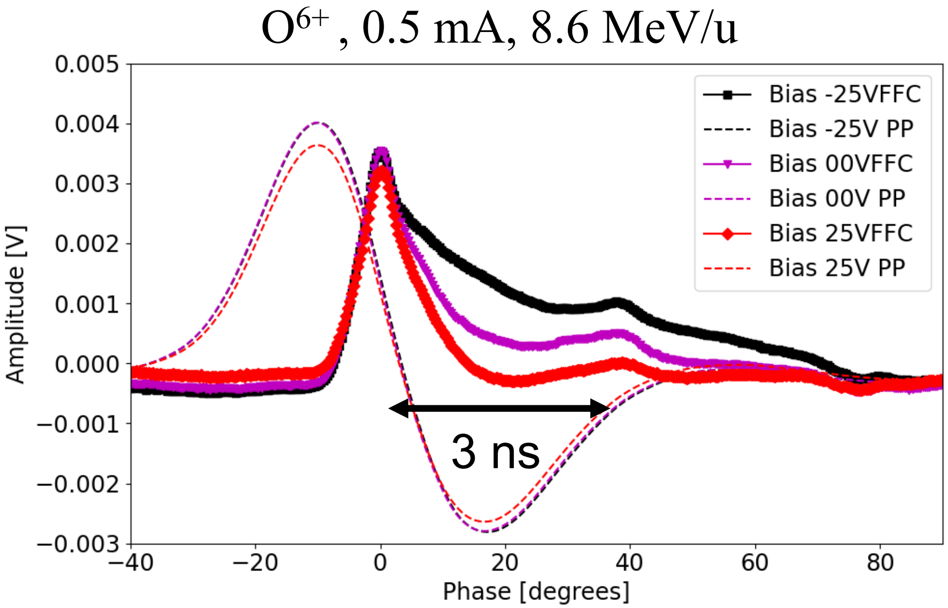


RC- Coax FFC SEE measurements



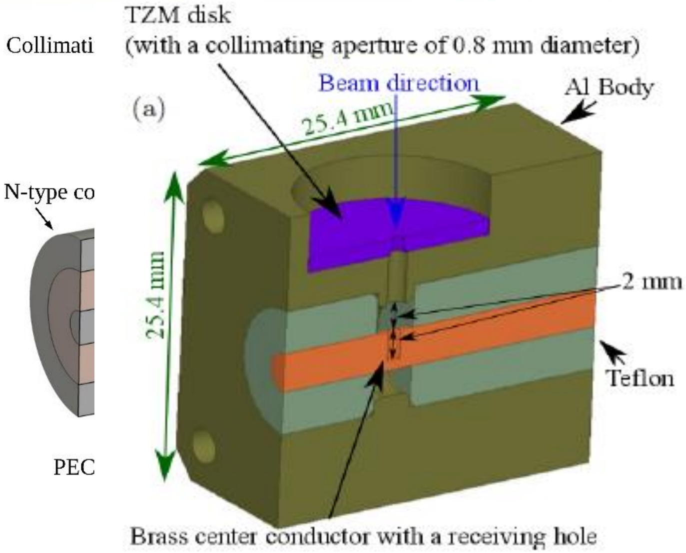
- Empirical estimates : 95% SEEs < 50 eV, Integrated SEE yield for 1-10 MeV/u p+ beam ~0.6-0.1 on metals. **Scales with ion charge state**
- Measured bunch shape is a strong function of DC bias voltage

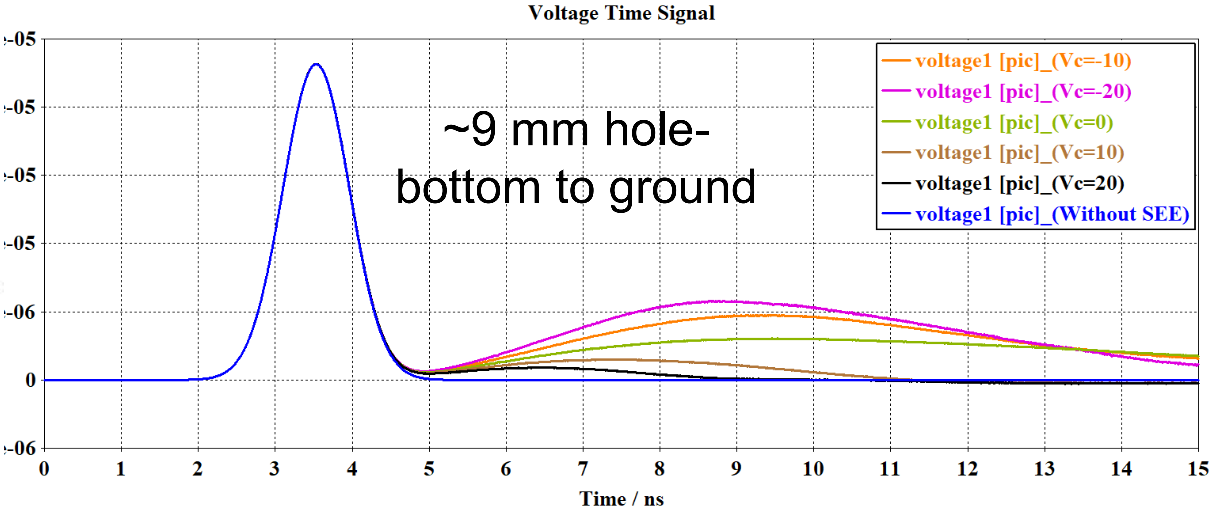




[14] J. R. Vaughan. Secondary Emission Formulas
[8] W. R. Rawnsley et al. AIP Proceedings (2000)
[15] A.Reiter et al., Investigation of Cross Talk in Secondary Electron Emission Grids. Technical Note LOBI-TN-SEM-2012-001

RC- Coax FFC SEE measurements

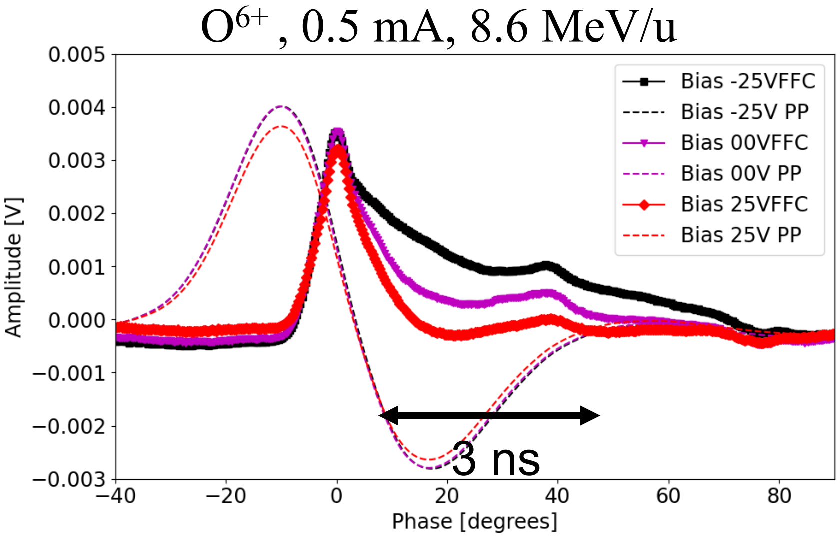




~9 mm hole-bottom to ground

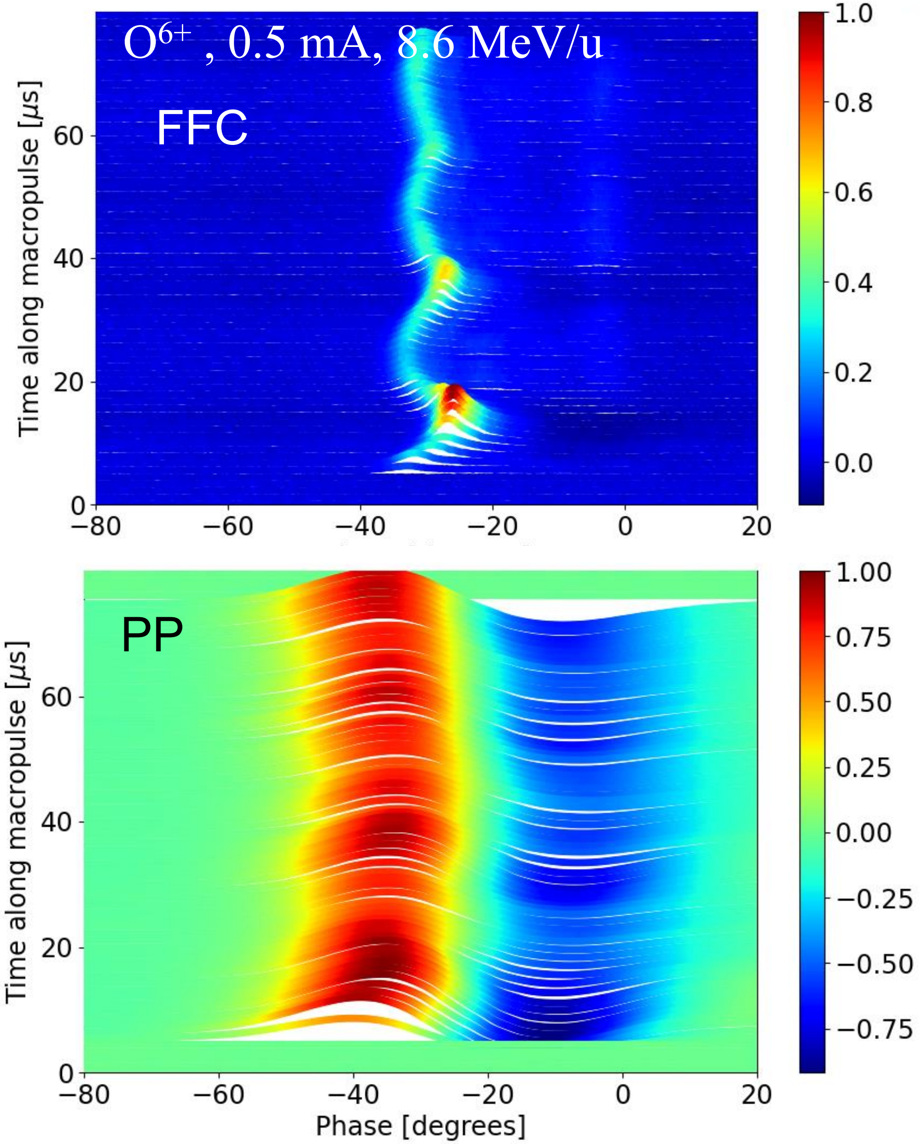
Simulations by K. Mal (IUAC)

- Speed of 1-10 eV electrons is 0.6- 2 mm/ ns.
- Bottom of the hole to ground distance in the installed device is 4mm, e.g. 1 to 2 ns delay in peak sec. e- emission
- 30 V DC bias on central conductor enough to suppress the secondaries, however risk of pulling secondaries generated in the blind hole

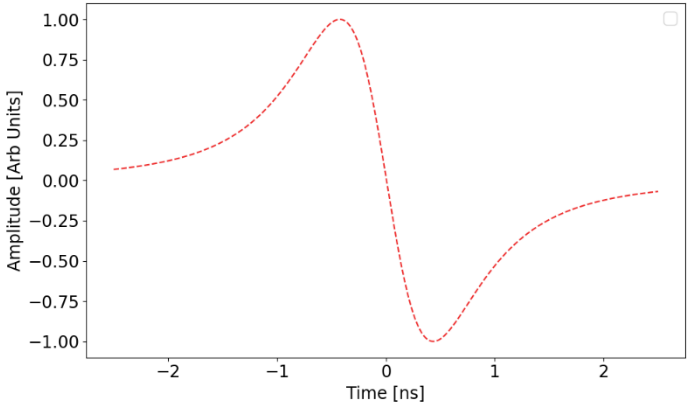

O^{6+}, 0.5 mA, 8.6 MeV/u

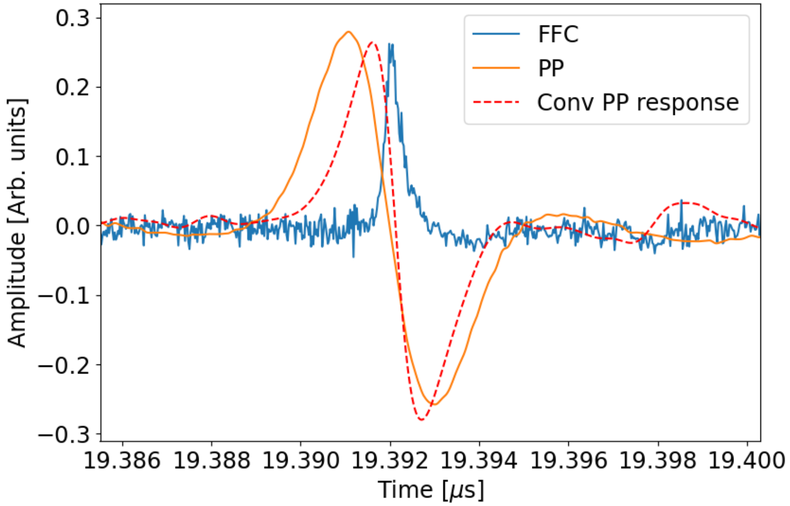
3 ns

FFC at dispersive location



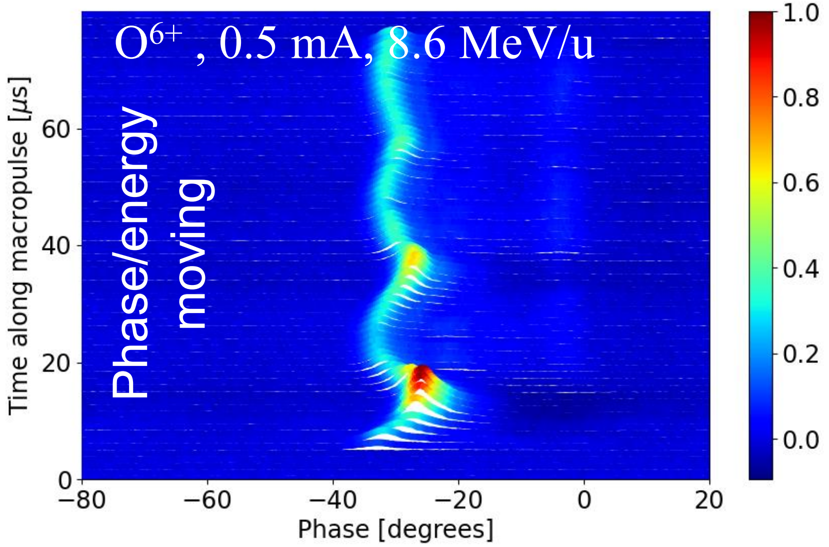
Phase probe low velocity beam response ($\beta = 0.134$) at R = 3 cm

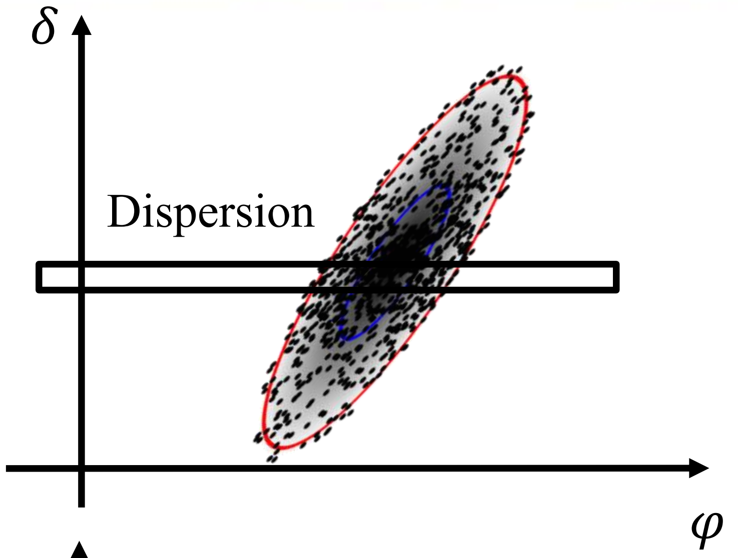


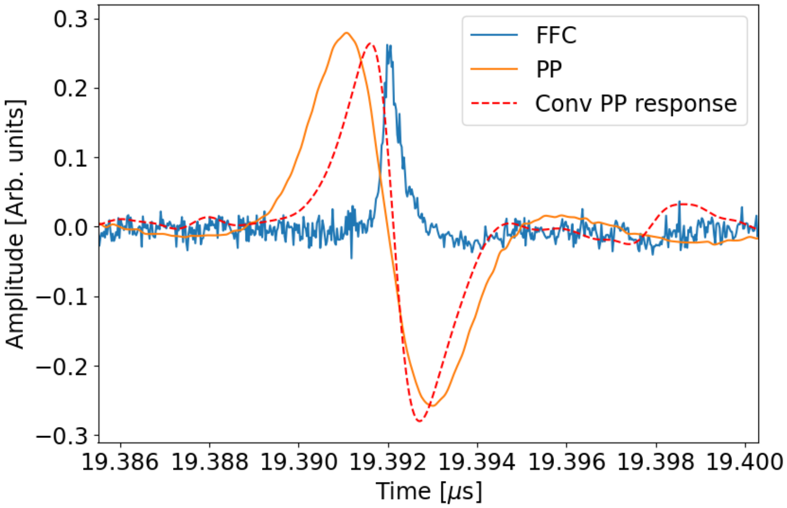


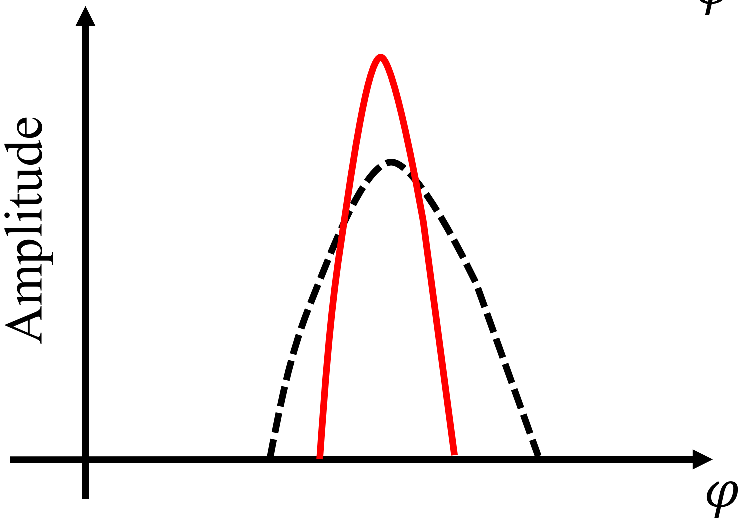
Phase probe remains a validation device!

FFC at dispersive location







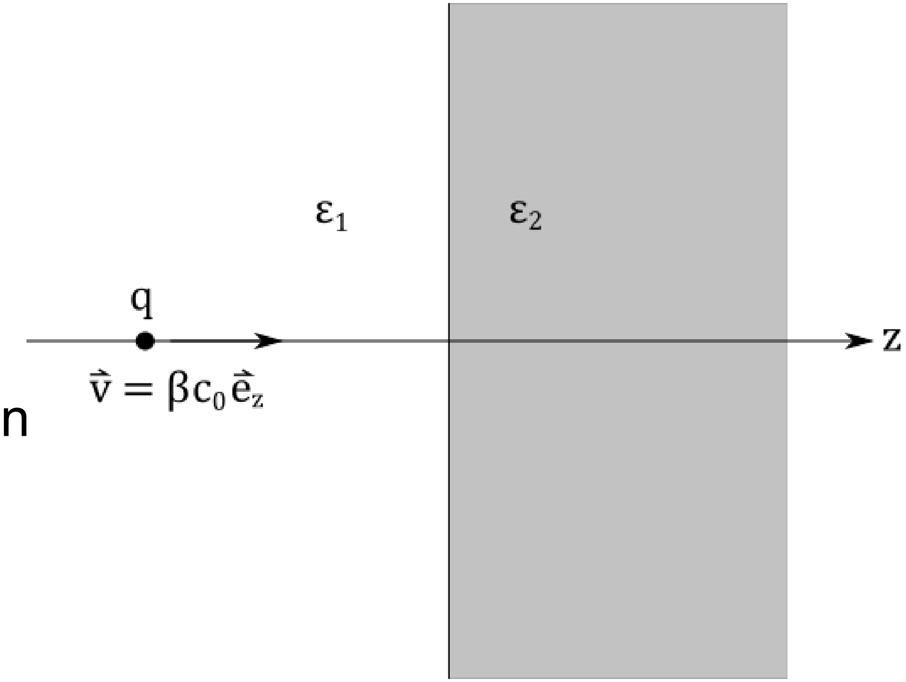


Careful placement of the FFC or simulation supported interpretation!

Fundamentals of GHz Transition Radiation (GTR)

Transition Radiation: A charge with velocity v = const. crossing an interface between two media radiates.

- an interface (z = 0) separating two half-spaces of different media
- solving MW-equations subject to interface conditions exhibit radiation field
- Surface electromagnetic phenomenon → prompt radiation
- In GHz regime, **coherent** transition radiation for ~ns bunches



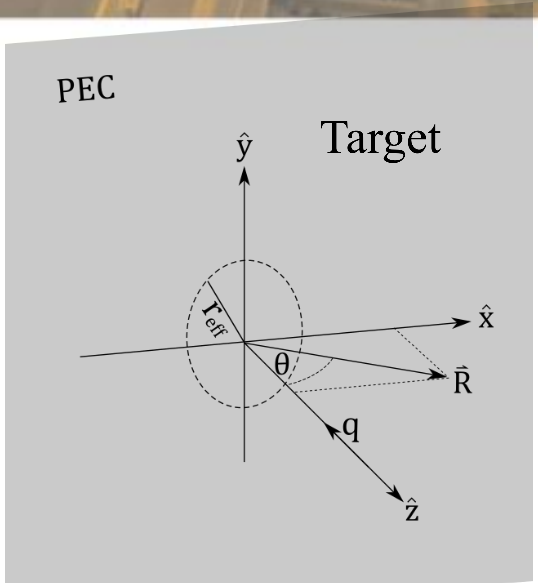
A potential method un-affected by pre-field and secondary emission

Properties of (GHz) Transition Radiation

GTR electric field for single charge:

$$\vec{E} = \frac{q\beta}{2\pi\varepsilon_0 c R}\,\frac{\sin\theta\,\delta\left(\frac{R}{c}-t\right)}{1\;-\beta^2\cos^2\theta}\left(\hat{e}_x\cos\theta+\hat{e}_z\sin\theta\right)$$

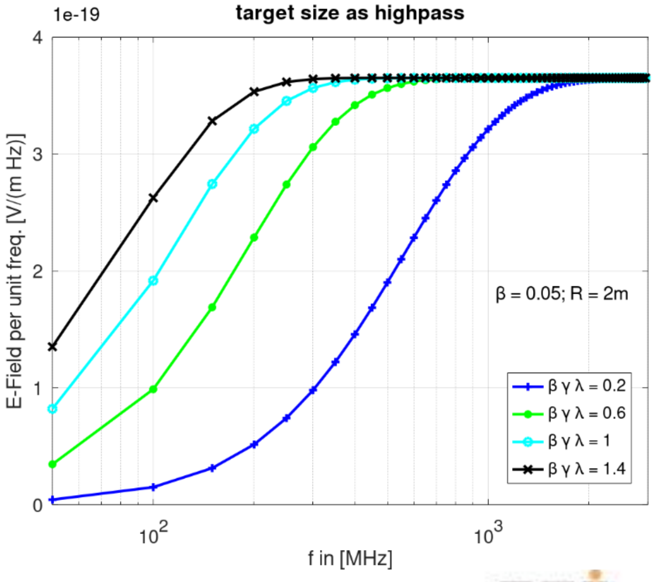
- Linear q and β dependence
- Parallel polarization for normal incidence
- Good signal: 10pC charges in 100 ps (σ) with β=0.15 → 10 mV peak



Target Size: Effective trans. extent of incident field: $r_{\text{eff}} \sim \beta\gamma\lambda$

For targets < r_{eff}: strong deviation from Far-Field

In practice: finite targets yield f–dependence

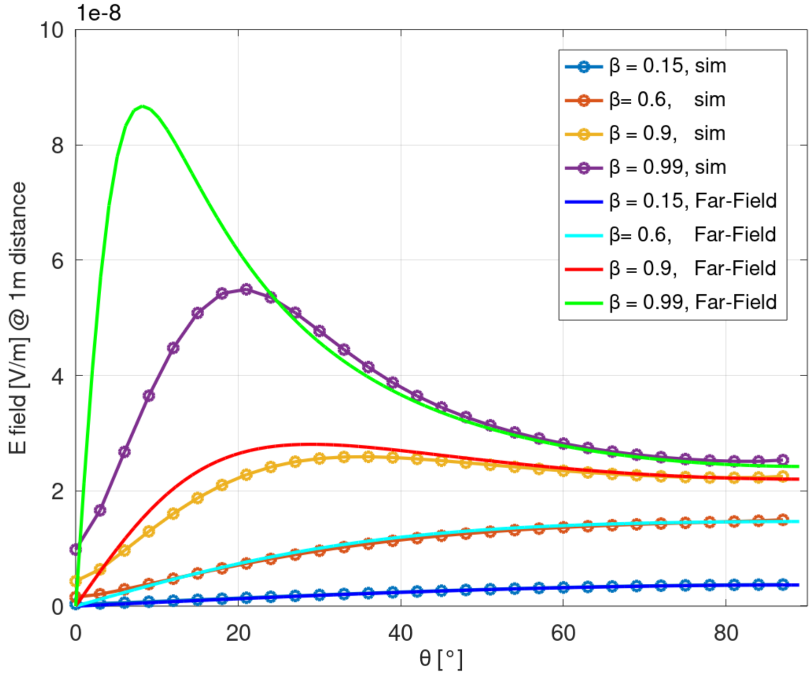


Formation Length: Distance from interface to reach Far-Field distribution (spherical wave)

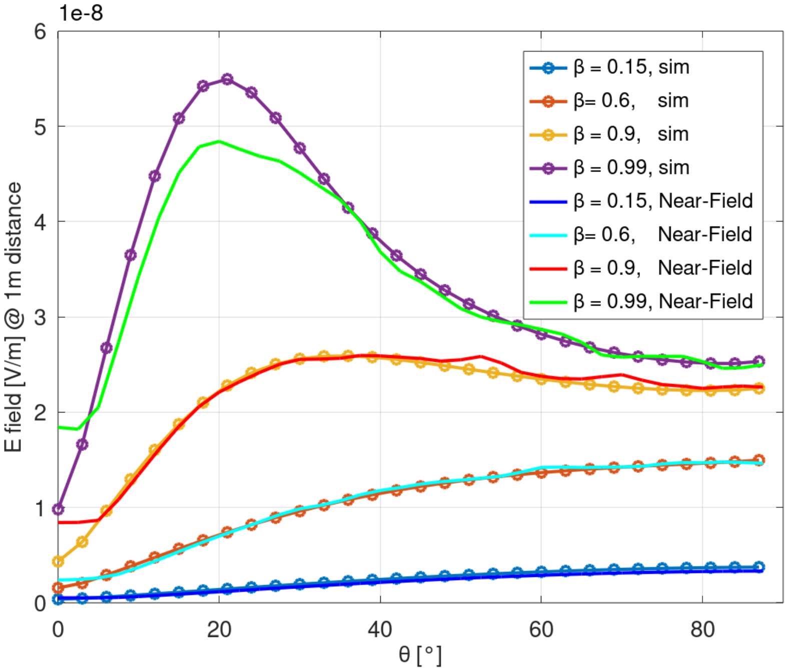
conservative estimate: $R \gg \gamma^2\lambda$, also depends on θ

Angular distribution: CST simulation and analytical

Far –field , R > Formation length



Near –field , R < Formation length



- Simulation: $\sigma_t = 100\text{ps}$, $L_z = Ltr = 1\text{m}$
- Far-Field Distribution recovered for all β @ $\theta > 55°$
- Up to $\beta \sim 0.8$ Far-Field Distribution for all θ

CST Simulations match with near and far field analytical models for all distances.

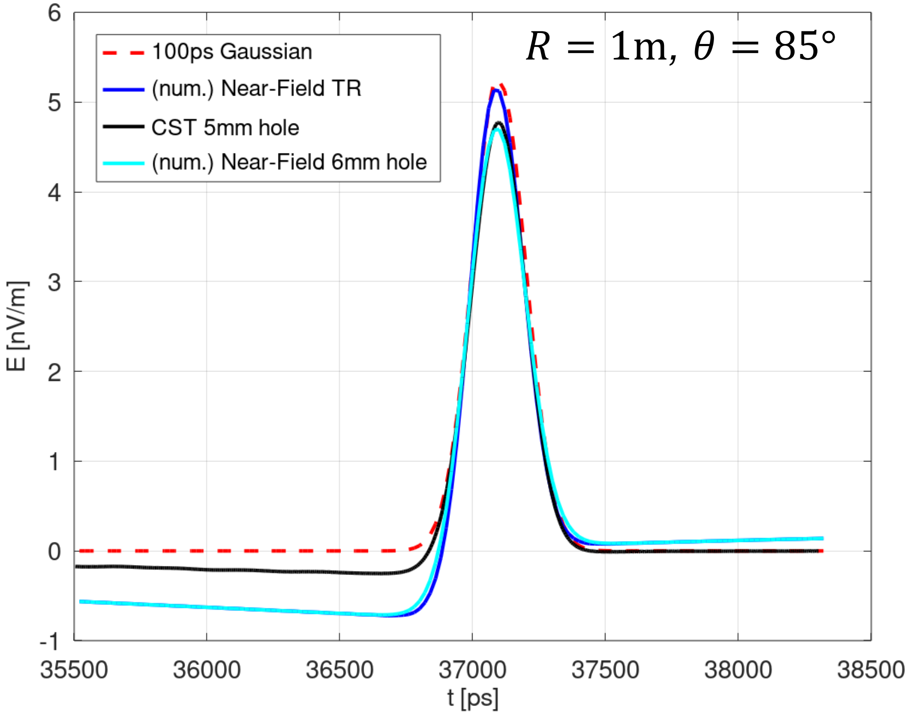
Near field models:

[16] A. G. Shkvarunets and R. B. Fiorito, Phys. Rev. ST Accel. Beams 11, 012801

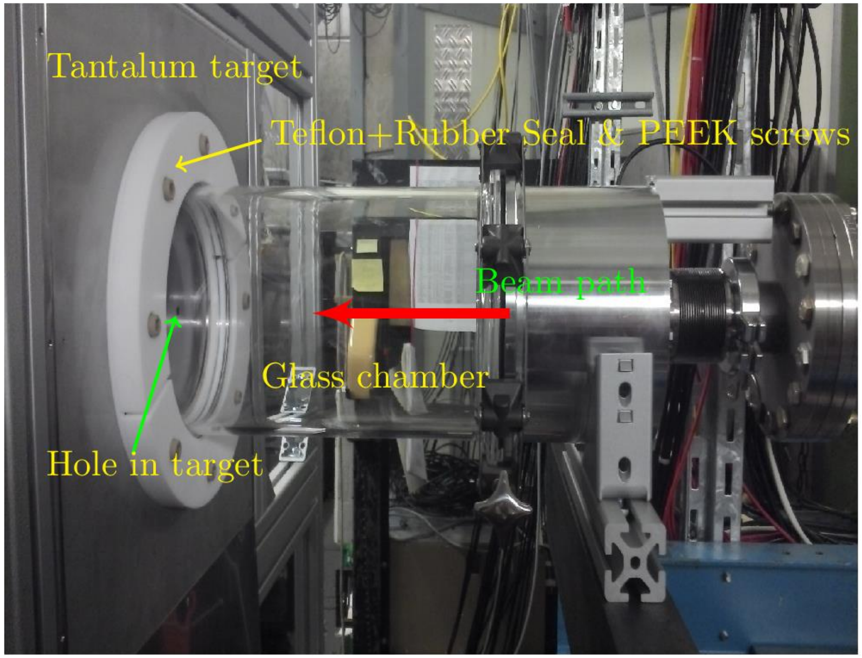
[17] R. Singh and T. Reichert, Phys. Rev. Accel. Beams 25, 032801

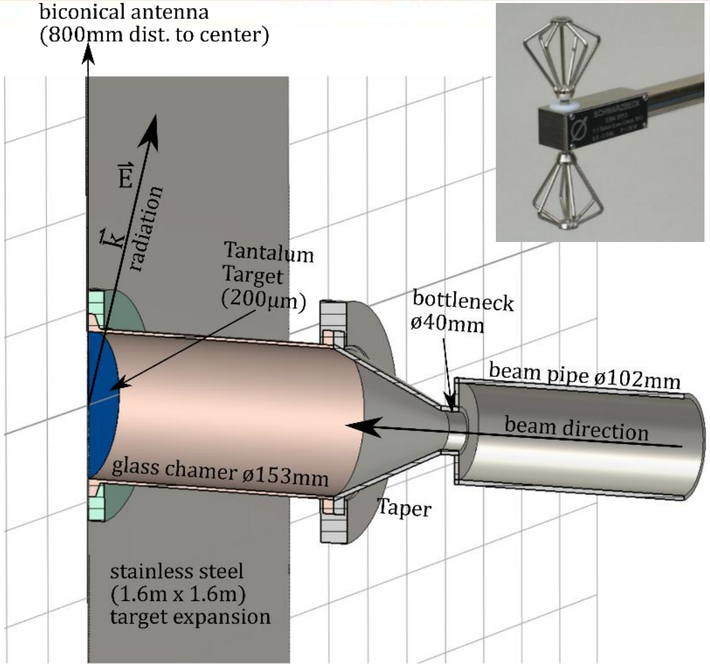
Diffraction Radiation (DR) makes it non-invasive

- DR is very similar to TR but charge traverses close to the media interface
- Here: Instead of impacting on the target bunch can go through hole
- Allowable hole size: Ø ↓ for β ↓
- For $\beta \sim 0.15$, $Ø \leq 6\text{mm}$
- **Non-destructive measurements possible!**

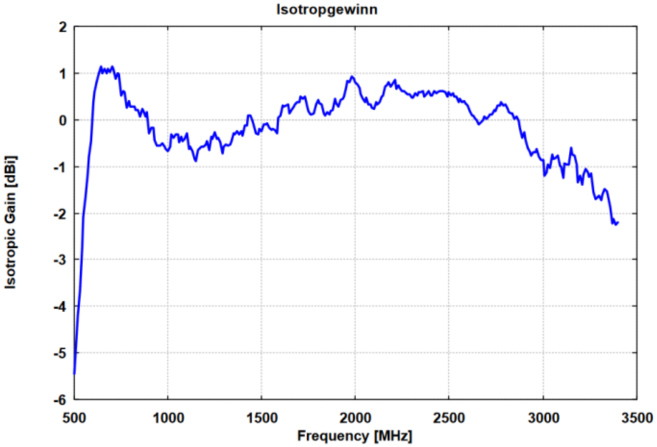


GTR setup in X2

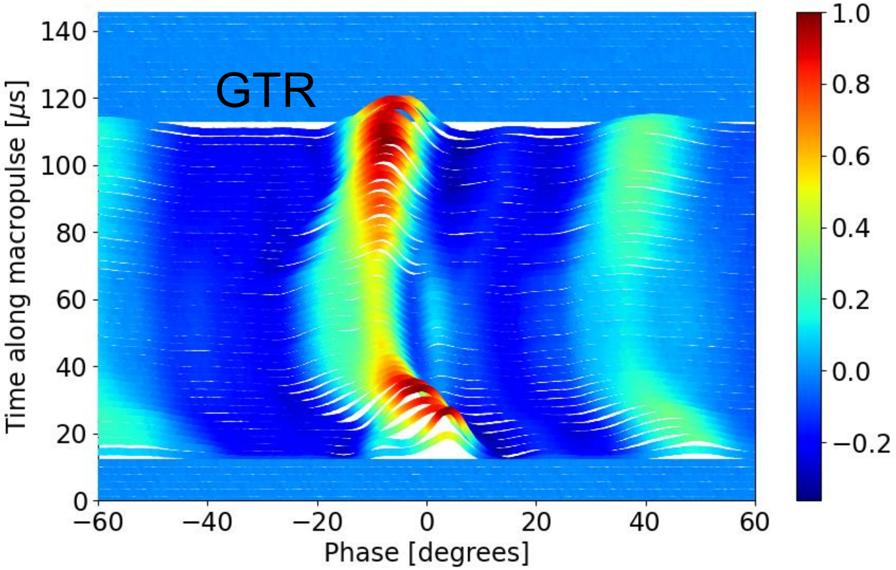


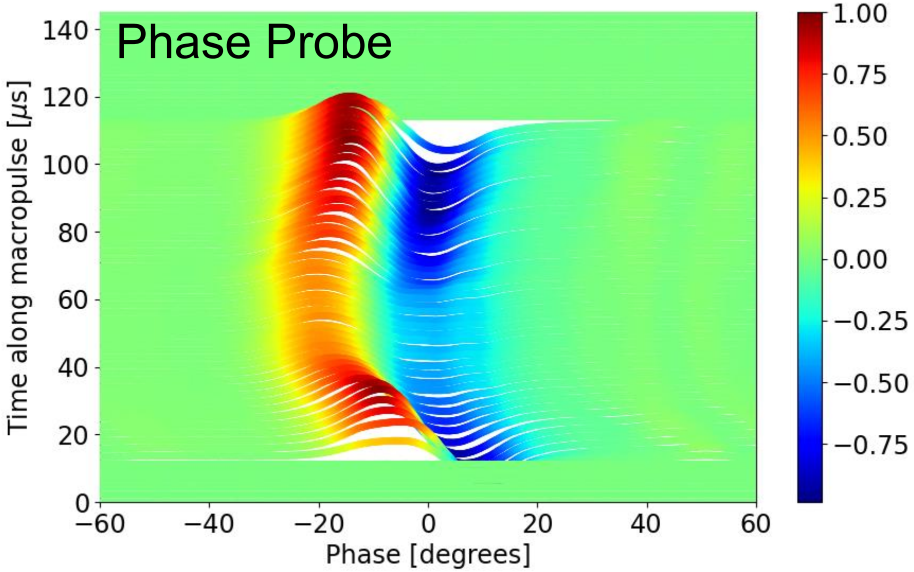


- An EM window to couple out the TR signal
  → Vacuum tolerance → critical
- Absorbers to avoid reflections
- Linear phase antenna designs

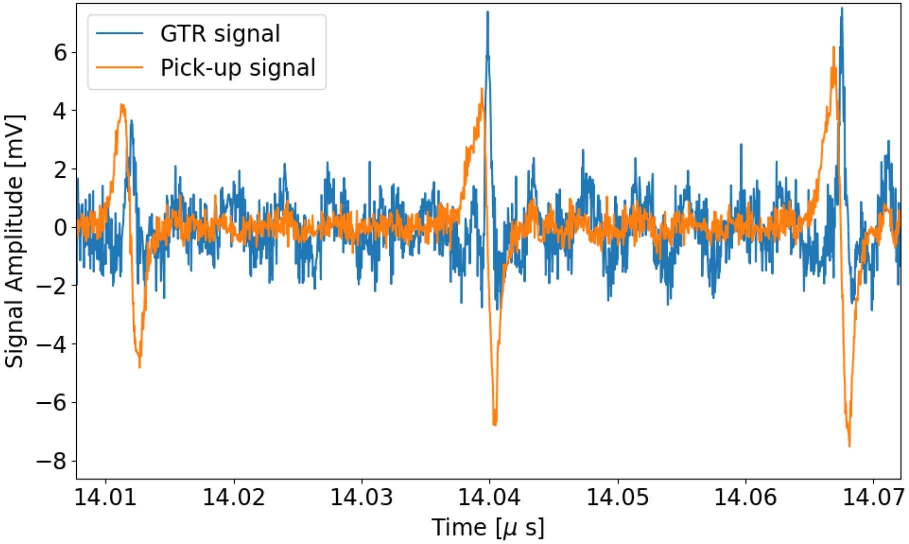


First results





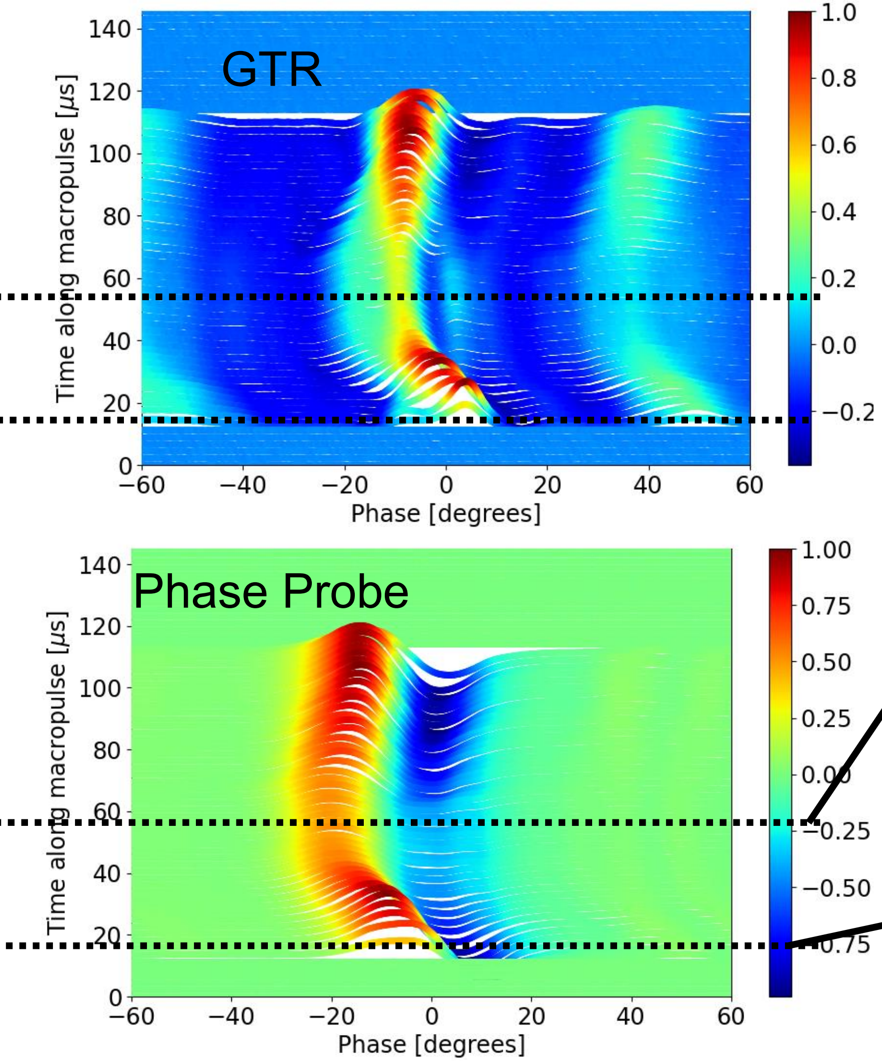
Bi^{26+} 11.4MeV/u, ~400μA,
100μs pulse length, 36MHz RF
Antenna angle (θ) = 40 deg,
Antenna distance to target (R) = 1.0 m

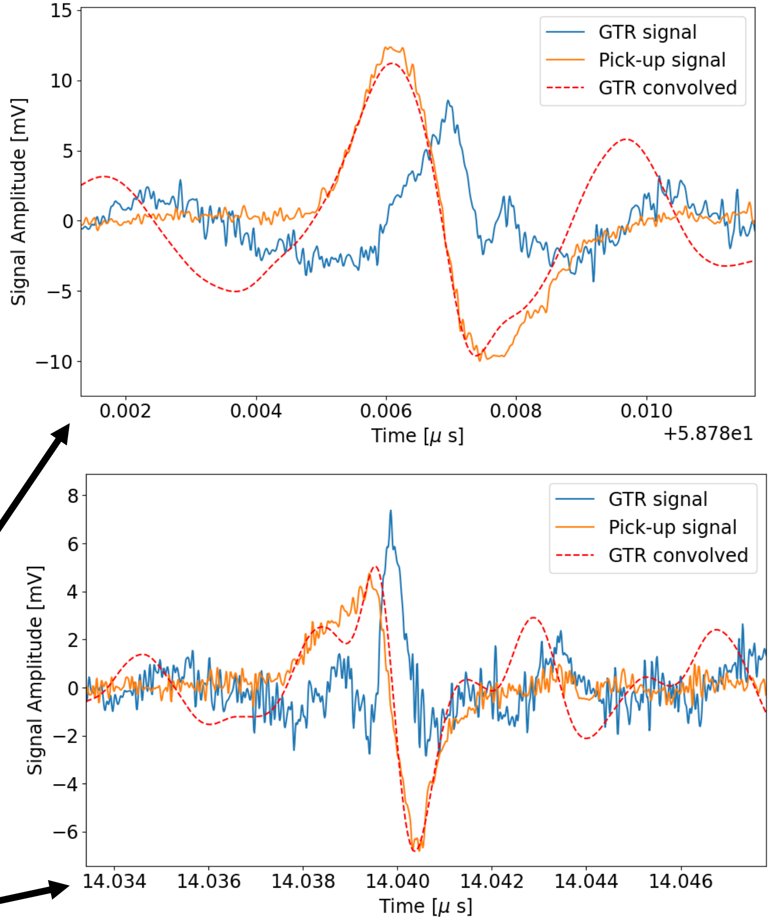


- Good correlation with the pick-up data
- Mean beam energy matches with ToF between pick-up and GTR

Comparison to phase probe data

Bi^{26+} 11.4MeV/u, ~400μA, 100μs pulse length, 36MHz RF, theta = 40 deg,(R) = 1.0 m



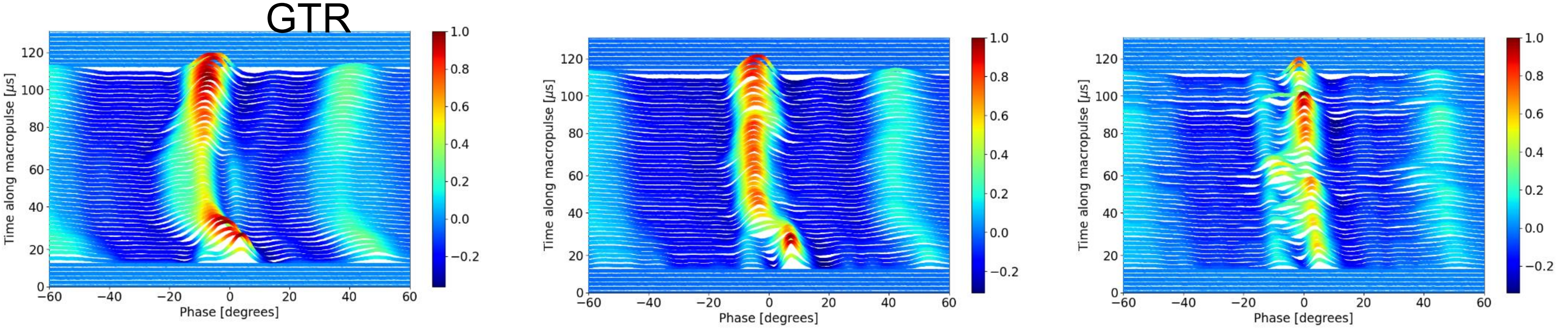


Convolved GTR has **precise** agreement with phase probe signal!

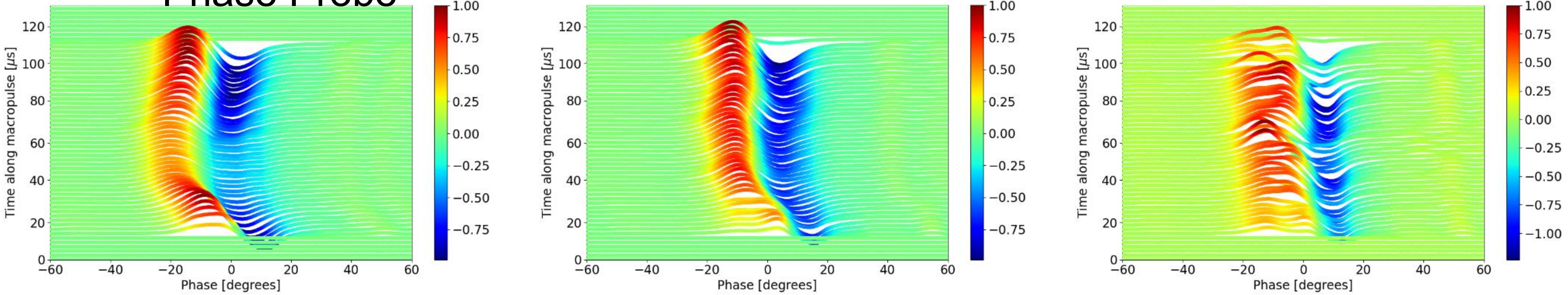
Pulse-to-pulse variation in bunch shapes

Bi^{26+} 11.4MeV/u, ~400µA, 100µs pulse length, 36MHz RF, theta = 40 deg,(R) = 1.0 m

GTR



Phase Probe



- Three consecutive macropulses show different charge distributions
- Longitudinal diagnostics need to be prepared for such fast changes

[17] R. Singh and T. Reichert, Phys. Rev. Accel. Beams 25, 032801

Conclusion and Outlook

- Fast and robust longitudinal diagnostics is important for various alignments in UNILAC.
- Lot of interesting efforts in the past → limitations for intra-macropulse and high intensity beam monitoring
- Advent of fast acquisition electronics allow devices with time domain monitoring → FFC and GTR with minimal user parameters
- FFC is a promising **compact option** *but* requires careful placement and biasing is essential in UNILAC energy regimes. New designs being tested, comparison with calculated phase space needed
- GTR a promising **non-invasive option for high currents** *but* not a compact installation. Further investigation under BMBF project ongoing

Acknowledgements :

Machine operating team!!!

BI Deptt.: C. Dorn , S. Fielder, S. Klaproth, C. Krueger, T. Luckhardt, W. Maier, T. Milosic, M. Mueller, A. Reiter, T. Sieber, B. Walasek-Hoehne **LINAC Deptt.:** W. Barth, M. Miski-Oglu, S. Lauber, U Scheeler, H. Vormann, M. Vossberg, S. Yaramyshev

IUAC: K. Mal, G. Rodrigues, S. Kumar , **FNAL:** V. Scarpine, A. Shemyakin,D. Sun

References

1. W. Barth et al., High brilliance beam investigations at Universal linear accelerator, PRAB 25, 04101 (2022)
2. R. Singh et al. Comparison of Feschenko BSM and Fast Faraday Cup with Low Energy Ion Beams , Proc of IBIC 2021,
3. S. Lauber et al., Longitudinal phase space reconstruction for a heavy ion accelerator, Phys. Rev. Accel. Beams 23, 114201
4. P. Forck, JUAS Lecture notes on beam instrumentation, 2021
5. T. Milosic , Feasibility Study on Longitudinal Phase-Space Measurements at GSI UNILAC using Charged-Particle Detectors, PhD thesis
6. B. Zwicker, Design of a Bunch Shape Monitor for High Current LINACs at GSI, PhD thesis, University Frankfurt 2016
7. P. Strehl, Beam instrumentation and diagnostics, ISBN: 978-3-540-26404-0
8. W. R. Rawnsley et al., AIP Conference Proceedings 546, 547 (2000) https://doi.org/10.1063/1.1342629
9. J. M. Bogaty et al.: A very wide bandwidth Faraday cup suitable for measuring GHz structure on ion beams with velocities to beta < 0.01, Proc. of Linear Accelerator Conference 1990, Albuquerque, New Mexico, USA
10. M. Ferianis et al., Characterization of Fast Farday cups at the ELETTRA LINAC, Proc. of DIPAC'03
11. J. Matthew and A. Bajaj, An improved strip-line fast Faraday cup for beam bunch measurements, Review of Scientific Instruments 91, 113305 (2020) https://doi.org/10.1063/5.0025457
12. J.-P. Carniero et al, International Journal of Modern Physics A, Vol. 34, No. 36 (2019)
13. K. Mal et al., Study and improvements of a radially coupled coaxial Fast Faraday cup design towards lower intensity beams, Under preperation
14. J. R. Vaughan. Secondary Emission Formulas. IEEE Transactions on Electron Devices, 40(4), 1993
15. A. Reiter et al., Investigation of Cross Talk in Secondary Electron Emission Grids. Technical Note LOBI-TN-SEM-2012-001
16. A. G. Shkvarunets and R. B. Fiorito, Phys. Rev. ST Accel. Beams 11, 012801
17. R. Singh and T. Reichert, Phys. Rev. Accel. Beams 25, 032801