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TECHNISCHE HOCHSCHULE MITTELHESSEN

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LIGHT Collaboration Meeting 2023

Longitudinal Beam Profile Measurement Methods

UNIVERSITY OF APPLIED SCIENCES

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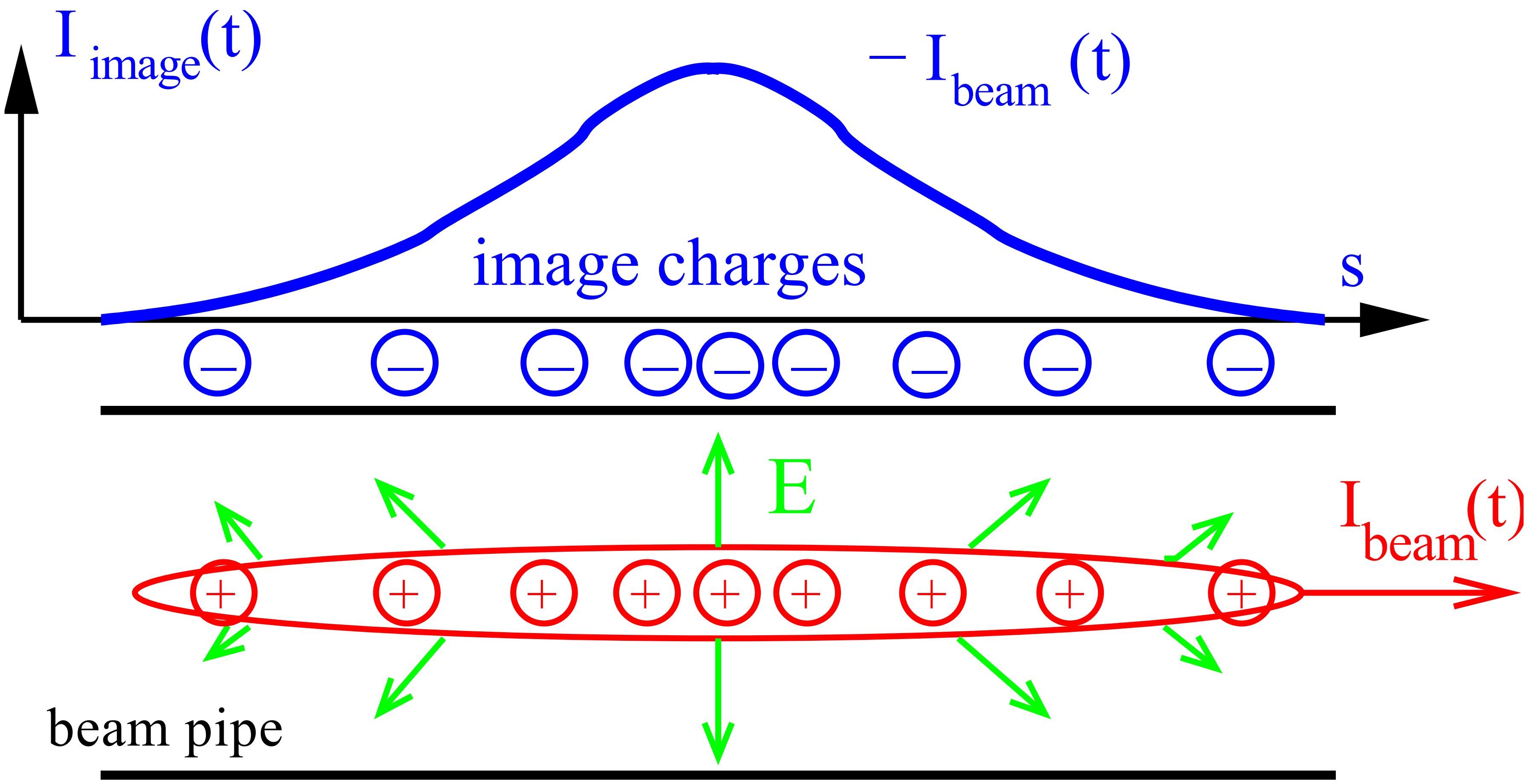
Stephan Klaproth

Outline

- Pick-Ups
  - Default Design
  - General Working Principle
  - Use Cases
- GHz Transition Radiation Monitor
  - General Properties of Transition Radiation
  - Basic Principle
  - Measurement Results at GSI X2
- Fast Faraday Cups
  - Axial vs. Radial Coupled FFC

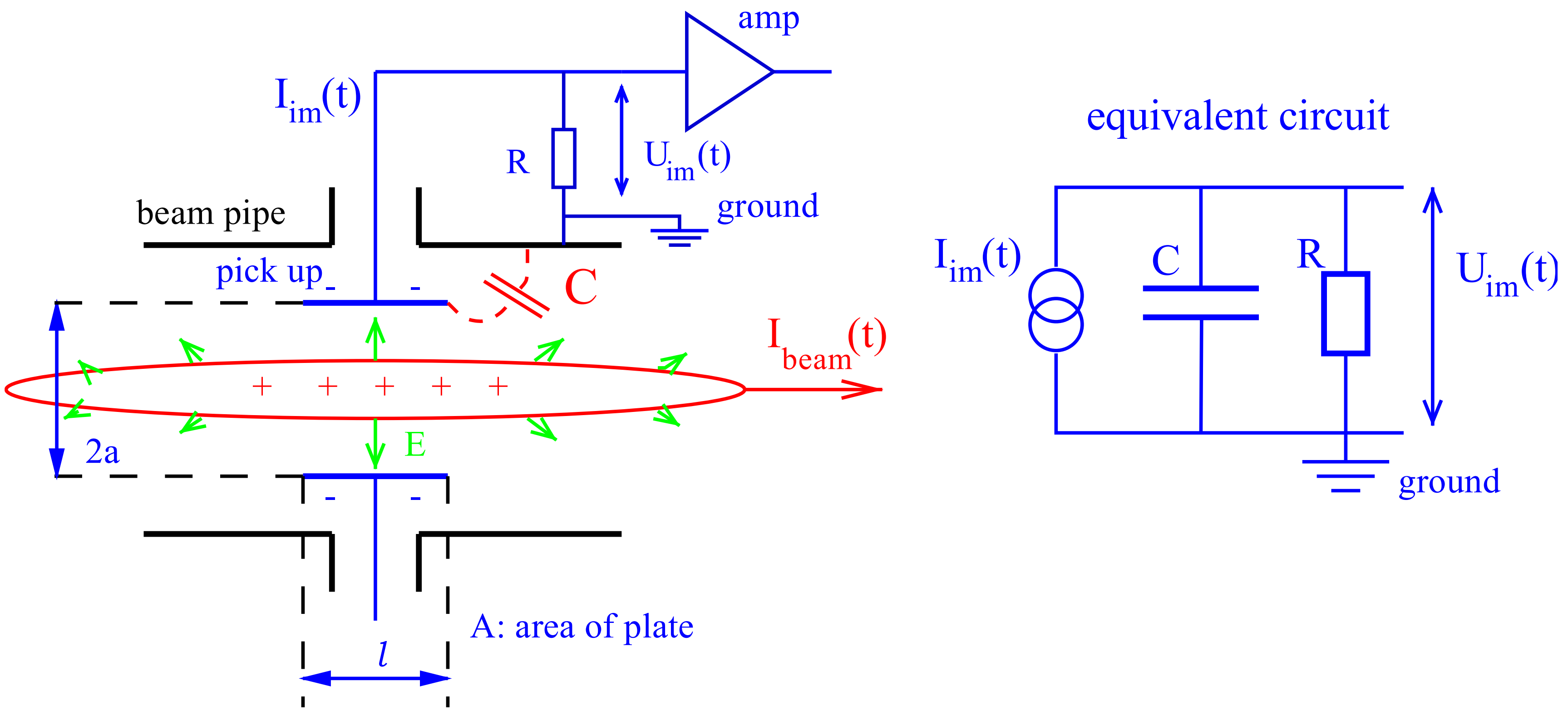
Pick-Ups

Pick-Ups - General Working Principle



[1]

Pick-Ups - General Working Principle



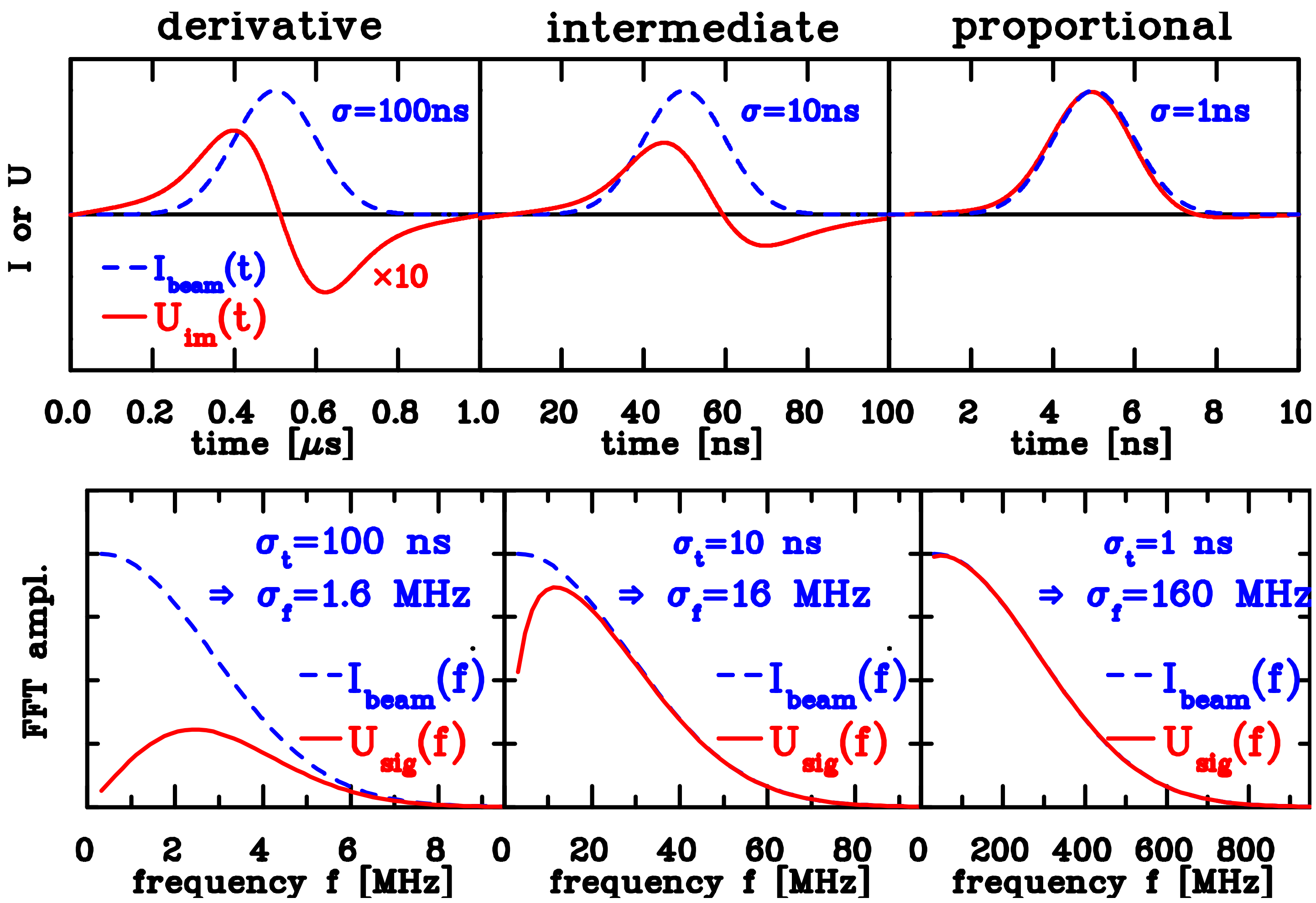
$$I_{im}(t) \equiv \frac{dQ_{im}}{dt} = -\frac{A}{2\pi a l} \cdot \frac{dQ_{beam}(t)}{dt}$$

[1]

Pick-Ups - General Working Principle

$$I_{im}(t) \equiv \frac{dQ_{im}}{dt} = -\frac{A}{2\pi a l} \cdot \frac{dQ_{beam}(t)}{dt}$$
$$= \frac{1}{\beta c} \cdot \frac{A}{2\pi a} \cdot i\omega I_{beam}$$

$$U_{im}(\omega) = R \cdot I_{im}(\omega) = Z_t(\omega, \beta) \cdot I_{beam}(\omega)$$
$$= \underbrace{\frac{1}{\beta c}\frac{1}{C}\frac{A}{2\pi a}\frac{i\omega RC}{1 + i\omega RC}}_{\text{Transfer Impedance}} I_{beam}(\omega)$$

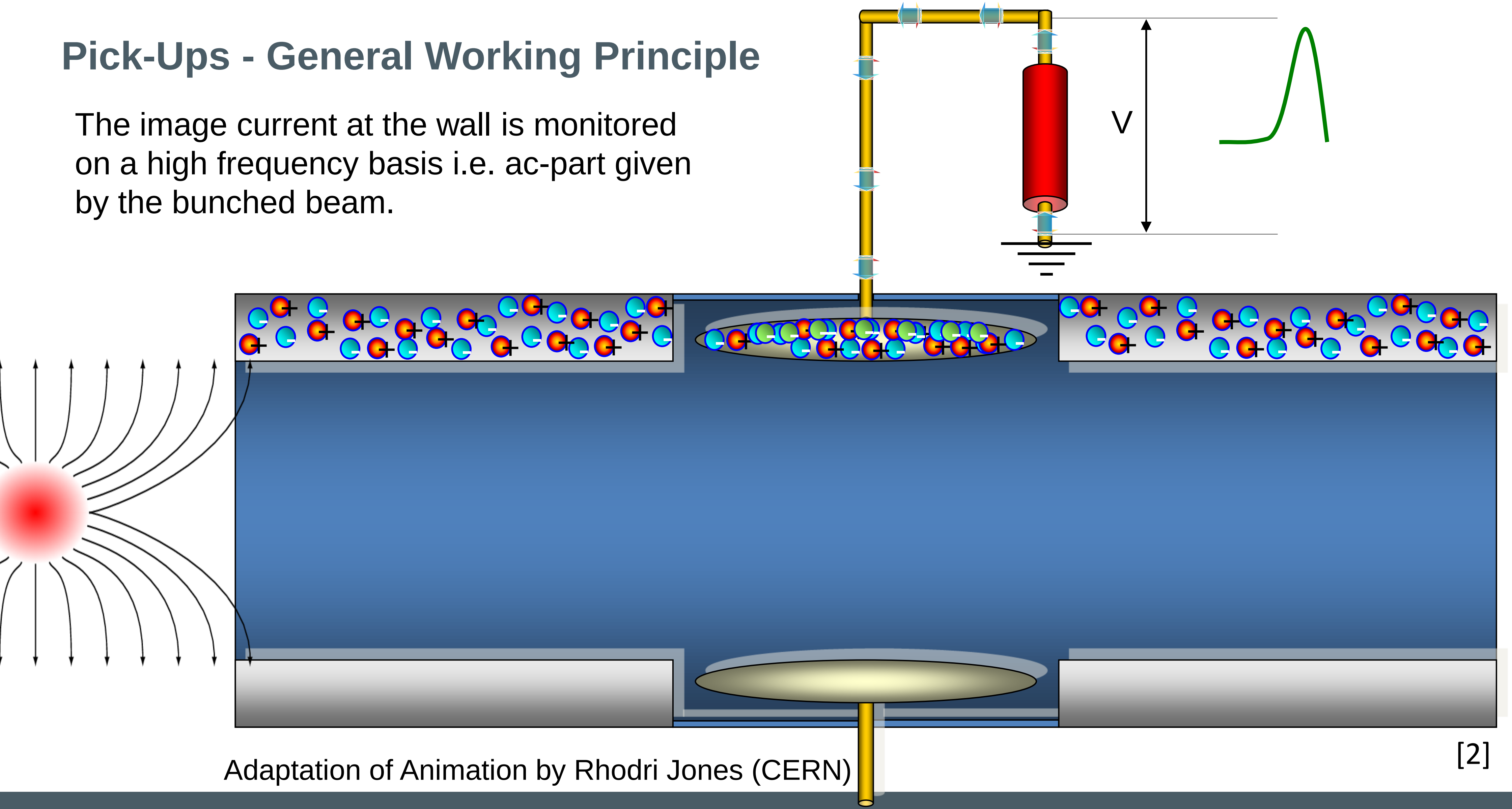


[1]

Signal Generation in Phase Probes (β < 1)

Pick-Ups - General Working Principle

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)

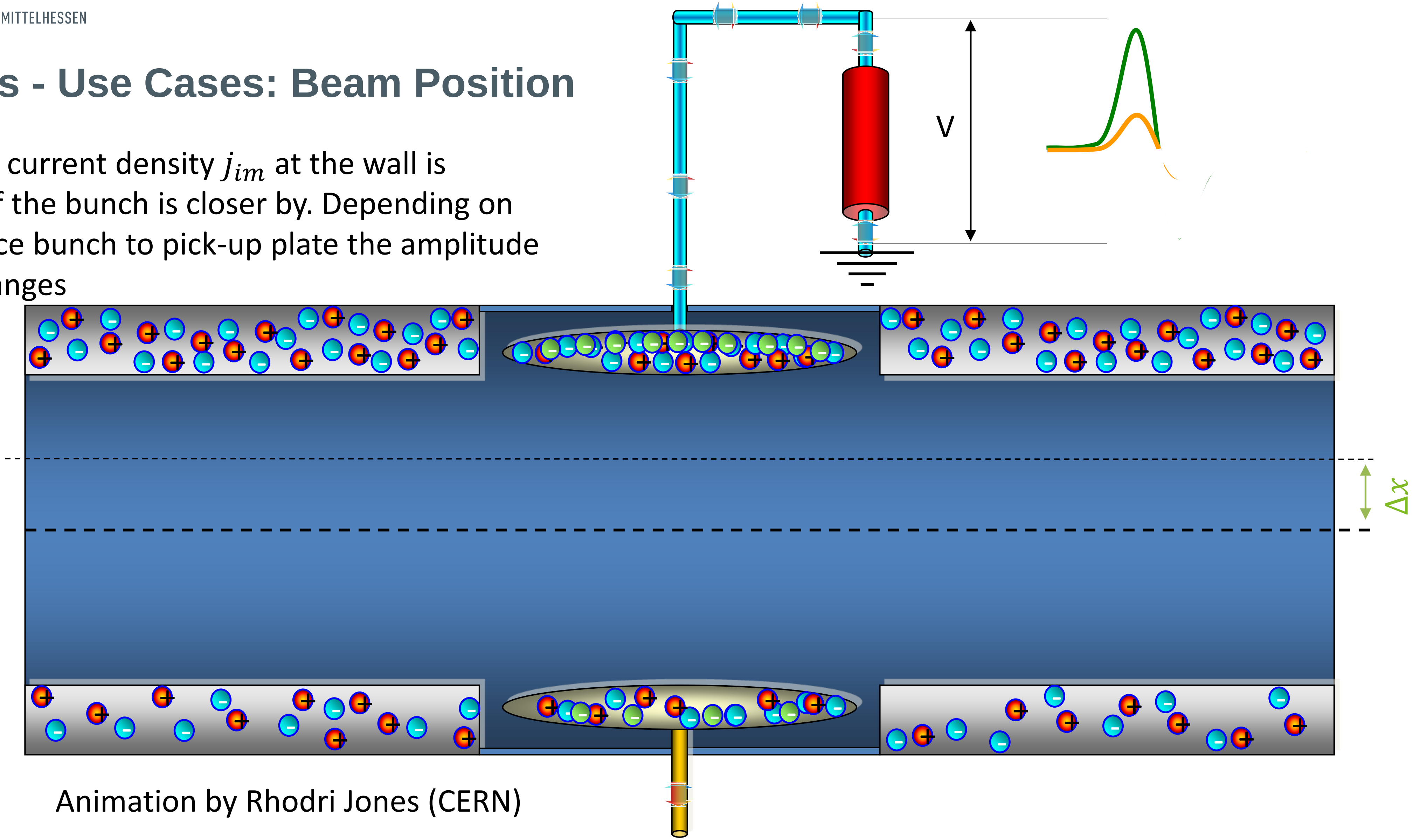
[2]

Pick-Ups - Use Cases

- Pick-Ups can be used for many purposes
- For each purpose there are specialized designs
- Some use cases are:
    - Beam Position
    - Beam Velocity (ToF)
    - Bunch Arrival (BAM)
    - Bunch Shape
    - Total Charge

Pick-Ups - Use Cases: Beam Position

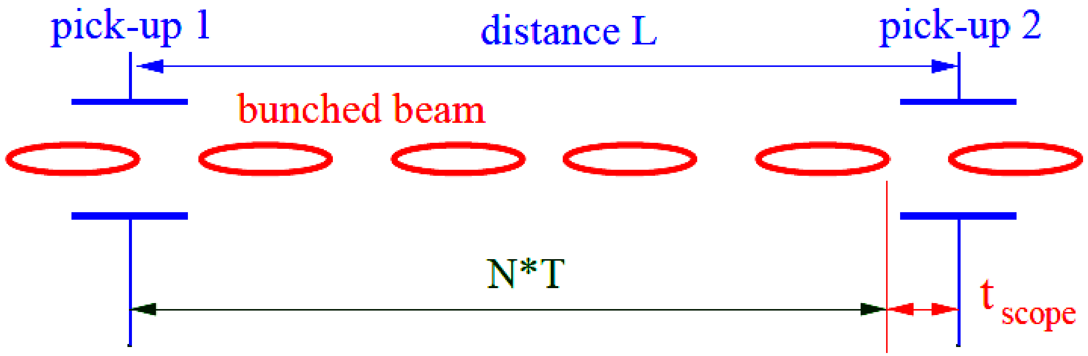
The image current density j_{im} at the wall is stronger, if the bunch is closer by. Depending on the distance bunch to pick-up plate the amplitude of U_{im} changes



Animation by Rhodri Jones (CERN)

Pick-Ups - Use Cases: Beam Velocity (ToF)

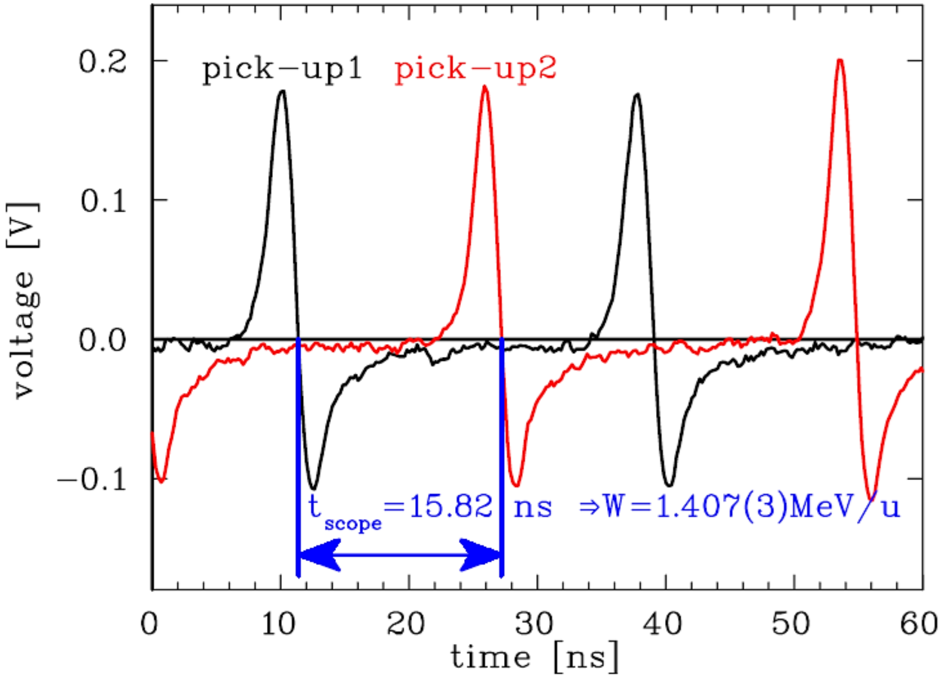
- RF-Frequency f_{rf} ⇔ Period T
- Known number of bunches in between N
- $\beta c = \frac{L}{NT + t_{scope}}$



Example: ToF at proton LINACS:

- Estimated kinetic energy 1.4MeV/u
- $t_{scope} = 15.82(5)$ns
- $f_{rf} = 36.136$MHz ⇔ $T = 27.673$ns
- $L = 1.629(1)$m
- $N = 3$

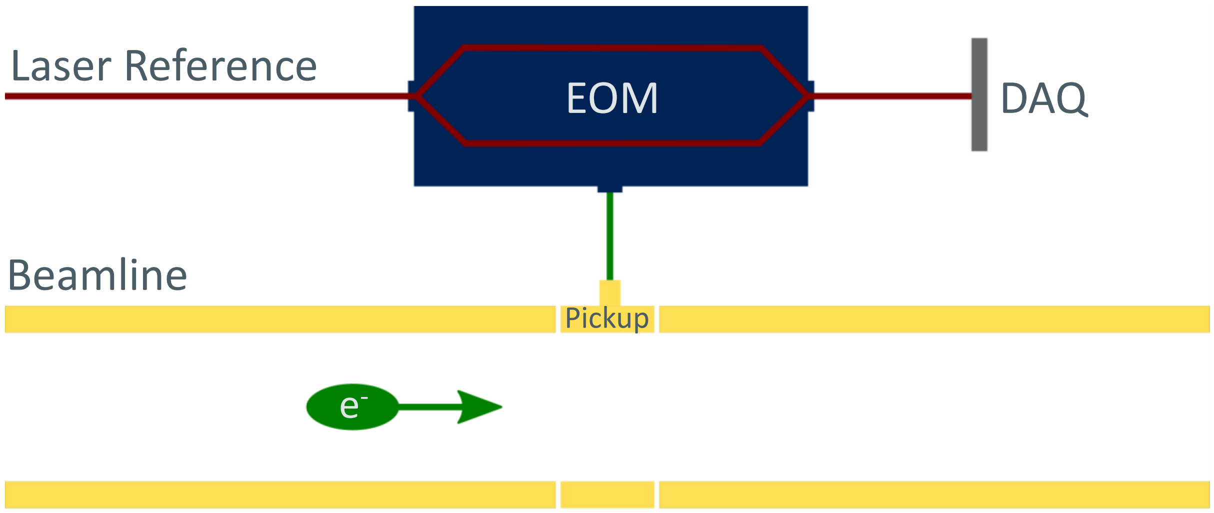
⇒ $\beta = 0.05497(7)$ ⇔ $E_{kin} = 1.407(3)$MeV/u



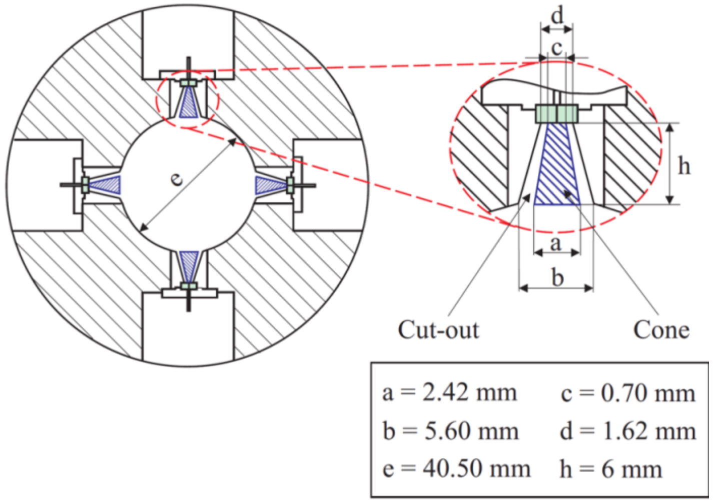
[1]

Pick-Ups - Use Cases: Bunch Arrival Monitor (BAM)

- Button pickups
  - Transient electric fields → voltage signal
- (Main) laser oscillator
  - Pulsed laser reference
- Electro-optical modulator
  - Laser amplitude modulated according to voltage signal
- Data acquisition
  - Decoding the timing information

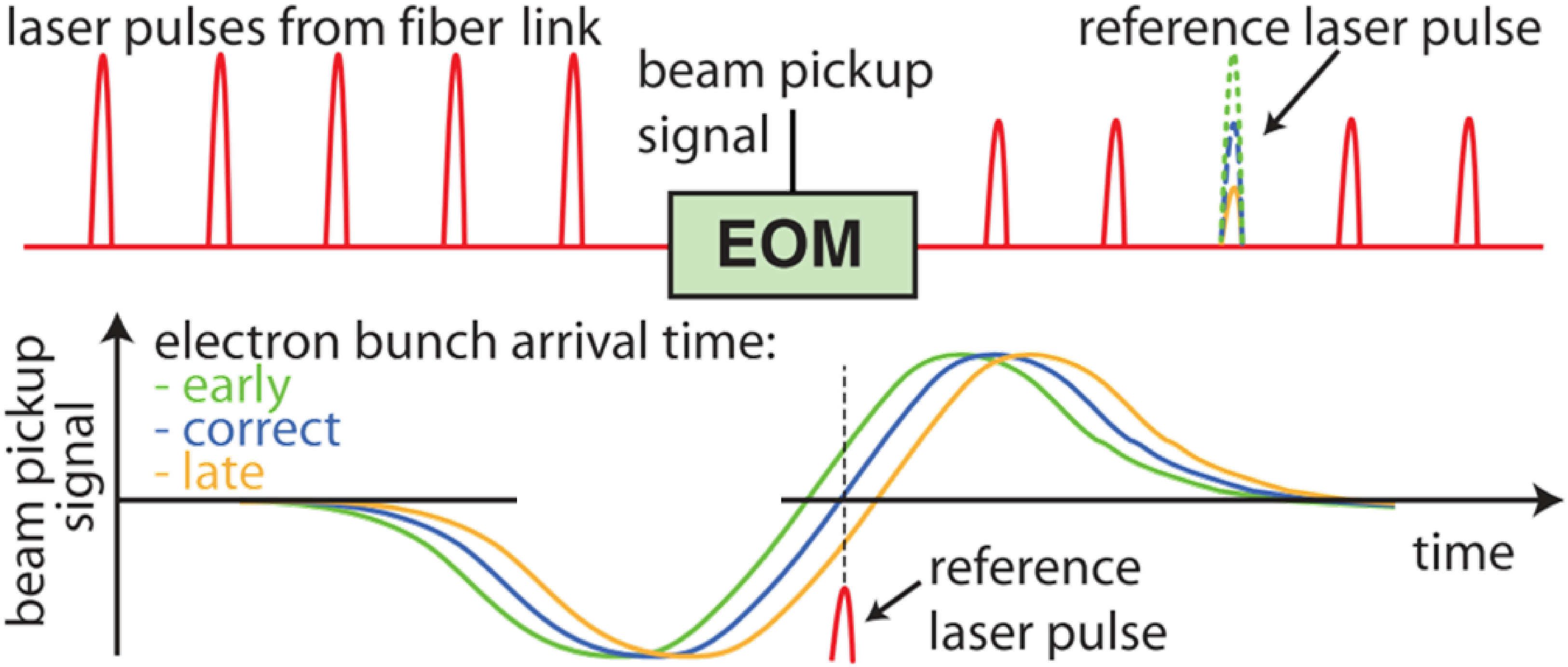


By B. Scheible



Pickup-Geometry [10]

Pick-Ups - Use Cases: Bunch Arrival Monitor (BAM)



by Löhl et al. [9]

Pick-Ups - Use Cases: Bunch Shape

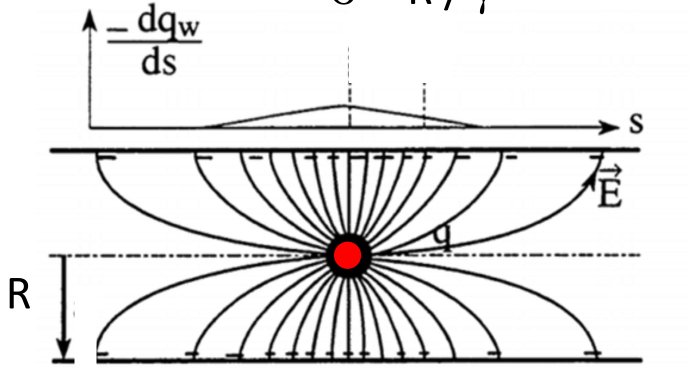
- $\boldsymbol{\beta = 1}$ Pick-Ups may be used for bunch shape measurements
- $\boldsymbol{\beta < 1}$ E-field is significantly modeled smearing out the actual longitudinal shape
- Transversal $\mathrm{E}_\perp$ lab.-frame of a point charge

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

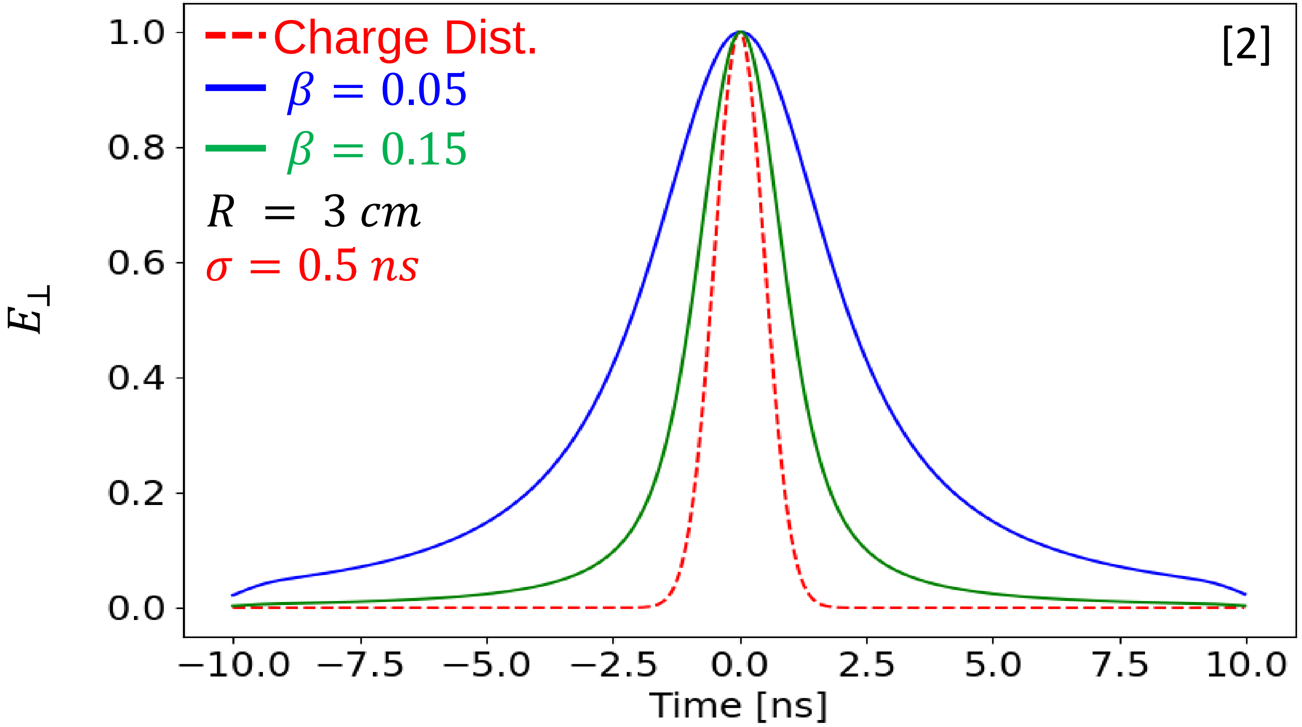
- Longitudinal $E_\parallel$ lab. frame of a point charge

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

$\sigma \approx R / \gamma$



[1]



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

Pick-Ups - Use Cases: Total Charge

- Total charge $Q_b = \int_V \rho dV = \frac{l}{\beta c} I_b(t)$

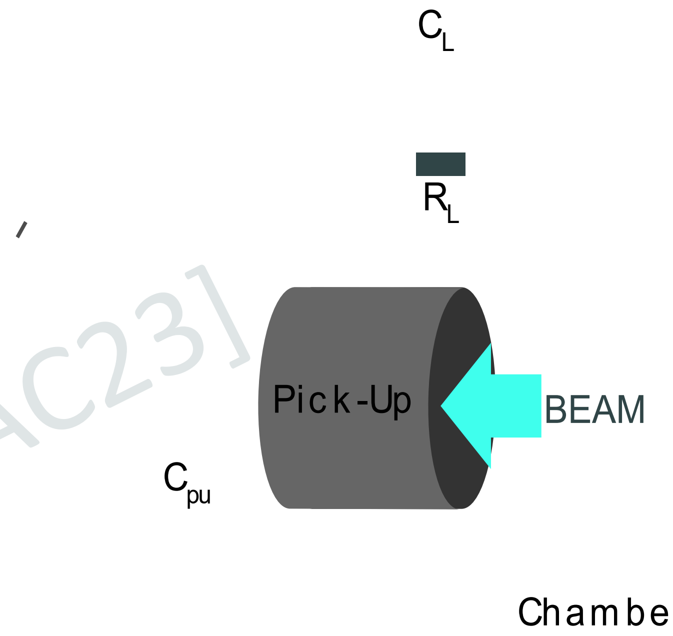
- Mirror current $I_e(t) = \frac{l}{\beta c}\frac{d}{dt} I_b(t) \equiv \frac{l}{\beta c}\, i\omega\, I_b(\omega)$

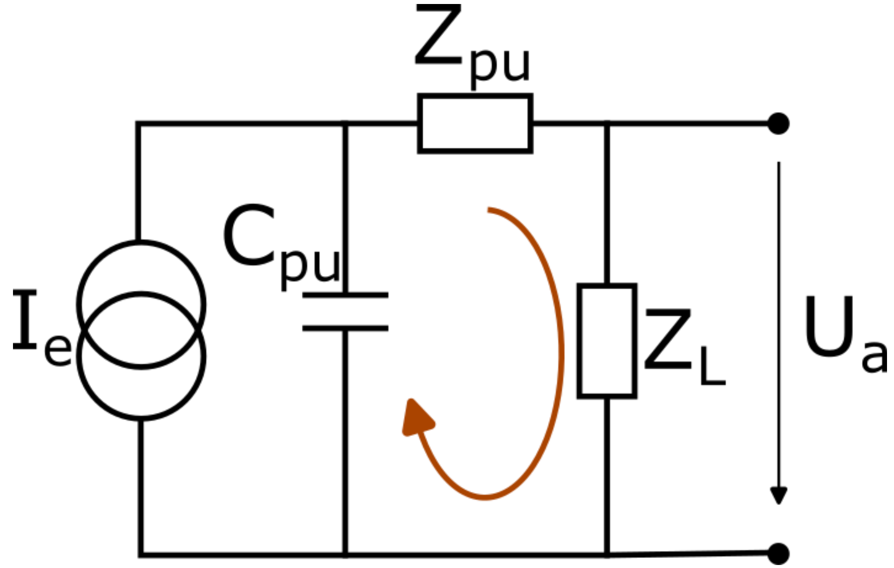
$$I_e(\omega) = \underbrace{\frac{1+i\omega C_{pu}[Z_L+Z_{pu}]}{Z_l}}_{\text{transfer function}} U_a$$

- The total charge can be calculated by measuring U_a

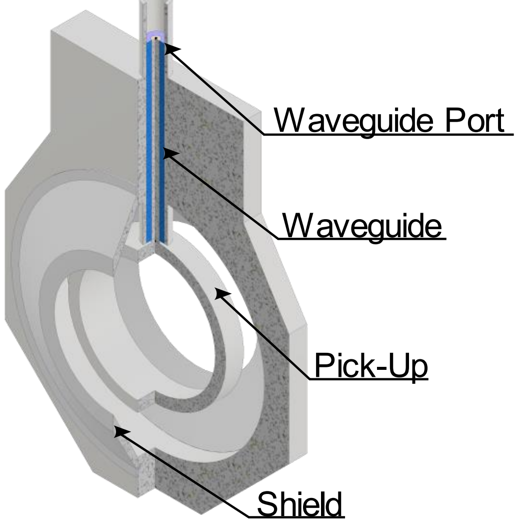
$$Q_b = \int_t I_b(t)dt$$
$$= \frac{\beta c}{l}\left(\frac{1}{Z_L}\int_t \int_\tau U_a(\tau)d\tau dt + C_{pu}\frac{Z_L+Z_{pu}}{Z_L}\int_t U_a(t)dt\right)$$

- Two cases arise for the calculation of Q_b
  - Low impedance Z_L
  - High impedance Z_L



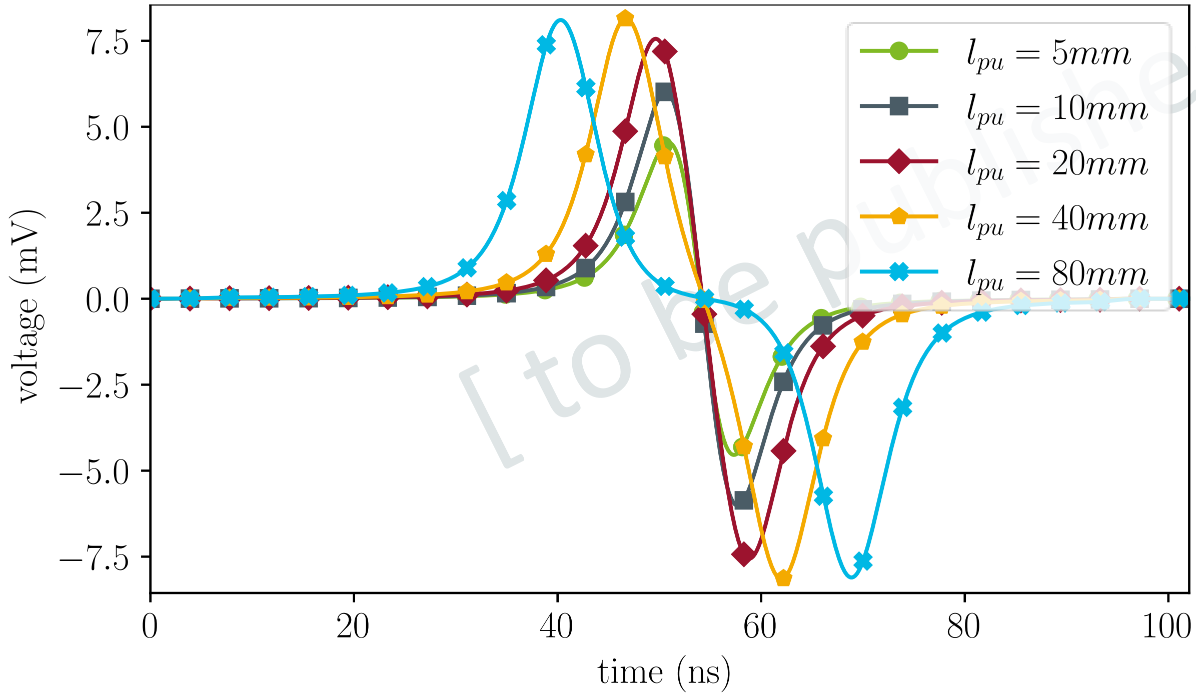


Pick-Ups - Use Cases: Total Charge

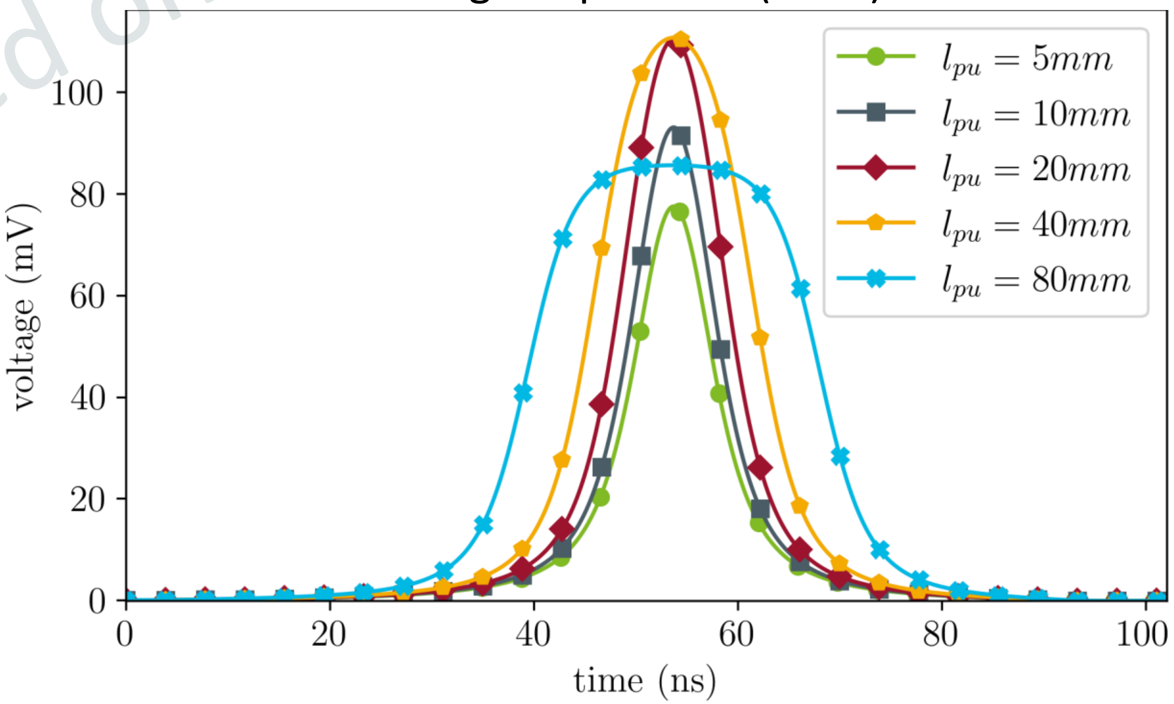


Simulations performed with CST with $1E6$ particles on simplified model

Low Impedance (50Ω)



High Impedance (1MΩ)



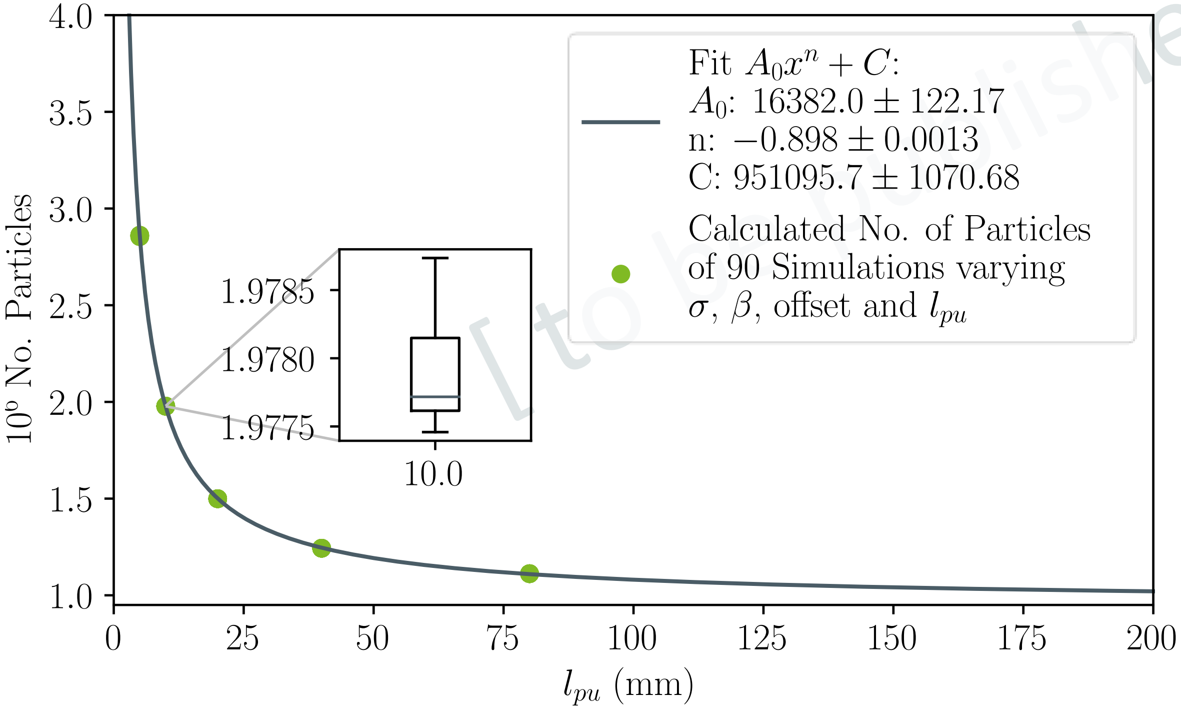
σ 1ns, $\Delta y =$ 0mm, β 0.01

$N_{sim} = 1E6$
$\sigma = [1\text{ns}, 10\text{ns}]$,
$\Delta y = [0\text{mm}, 5\text{mm}, 10\text{mm}]$
$\beta = [0.01, 0.05, 0.2]$

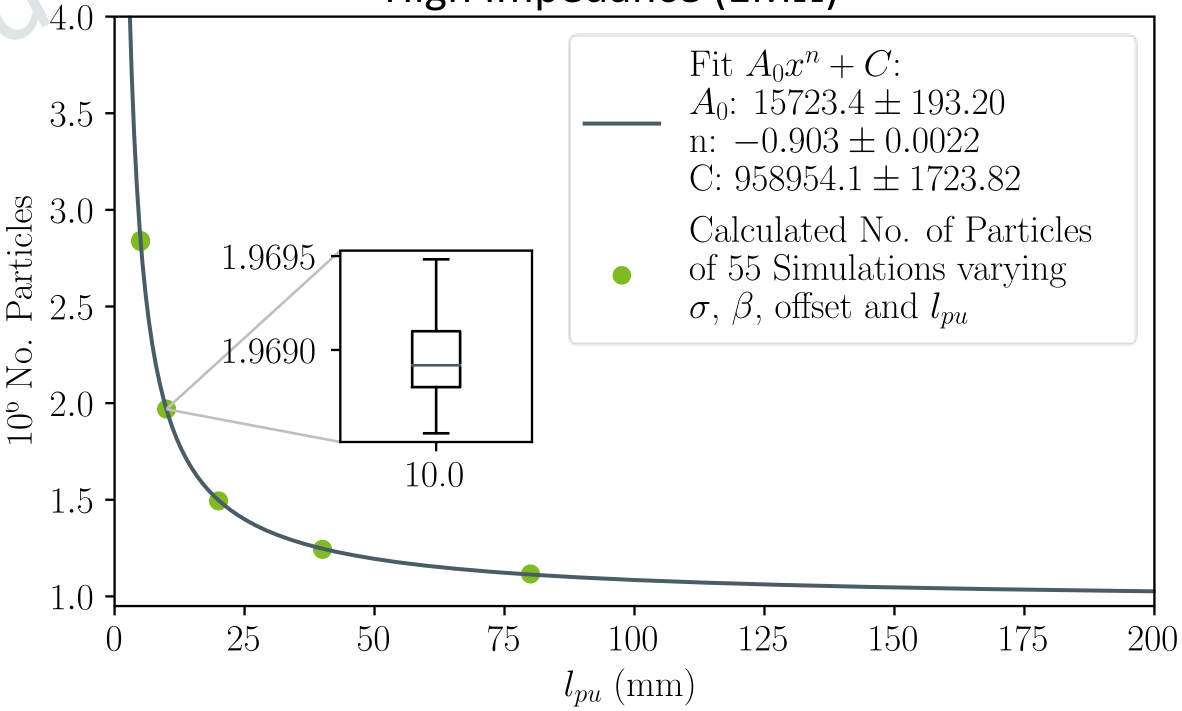
Pick-Ups - Use Cases: Total Charge

- Raw calculated $Q_b = \frac{\beta c}{l_{pu}} \left(\frac{1}{Z_L} \int_t \int_\tau U_a(\tau) d\tau dt + C_{pu} \frac{Z_L + Z_{pu}}{Z_L} \int_t U_a(t) dt \right)$
- Strong dependency on PU length l_{pu}, very low dependency on velocity βc, bunch width σ and beam axis offset Δy

Low Impedance (50Ω)



High Impedance (1MΩ)

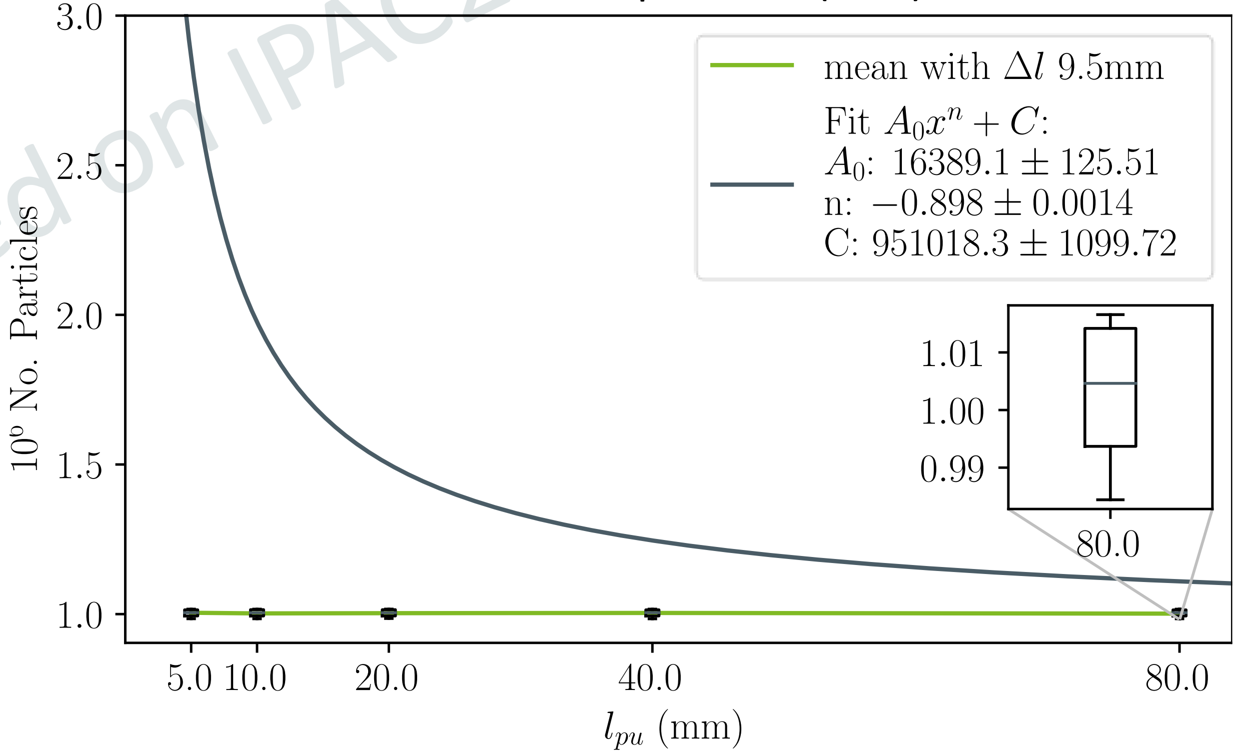


$N_{sim} = 1E6$
$\sigma = [1\text{ns}, 10\text{ns}],$
$\Delta y = [0\text{mm}, 5\text{mm}, 10\text{mm}]$
$\beta = [0.01, 0.05, 0.2]$

Pick-Ups - Use Cases: Total Charge

- Ignored fringe fields effects of the PU in the derivation.
  ⇒ An effective length should replace the PU length.
  $Q_b = \frac{\beta c}{l_{eff}}\left(\frac{1}{Z_L}\int_t \int_\tau U_a(\tau)d\tau dt + C_{pu}\frac{Z_L+Z_{pu}}{Z_L}\int_t U_a(t)dt\right)$
- A simple model $l_{eff} = l_{pu} + \Delta l$ may be used to compensate the fringe field effects up to an error of $\pm 1.7\%$ for $\Delta l = 9.5\text{mm}$
- Calibration is needed for absolute values, otherwise only relative charge measurement possible
- Alternative calibration: Test bench with known signal
- Applicable also on shoe-boxes and other types of capacitive PUs

Low Impedance (50Ω)



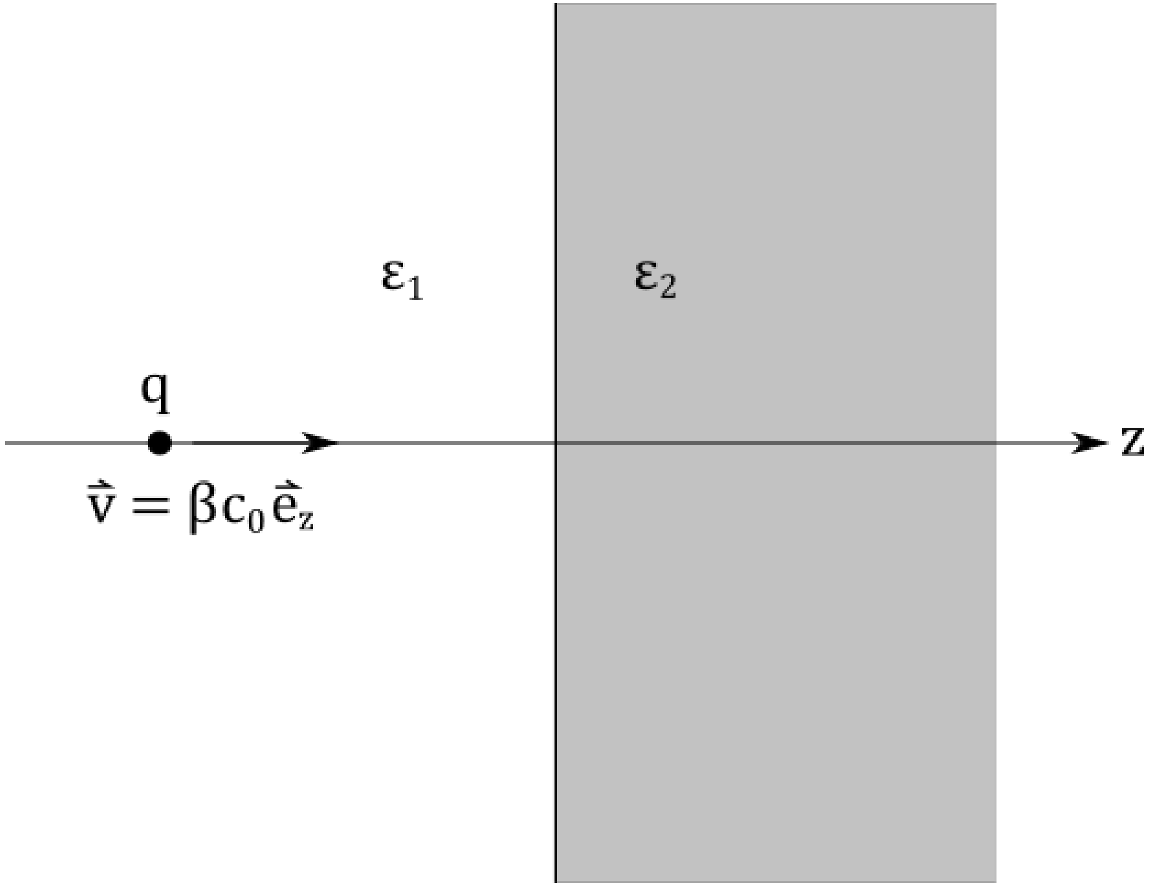
Transition Radiation Monitors

Transition Radiation (TR)

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



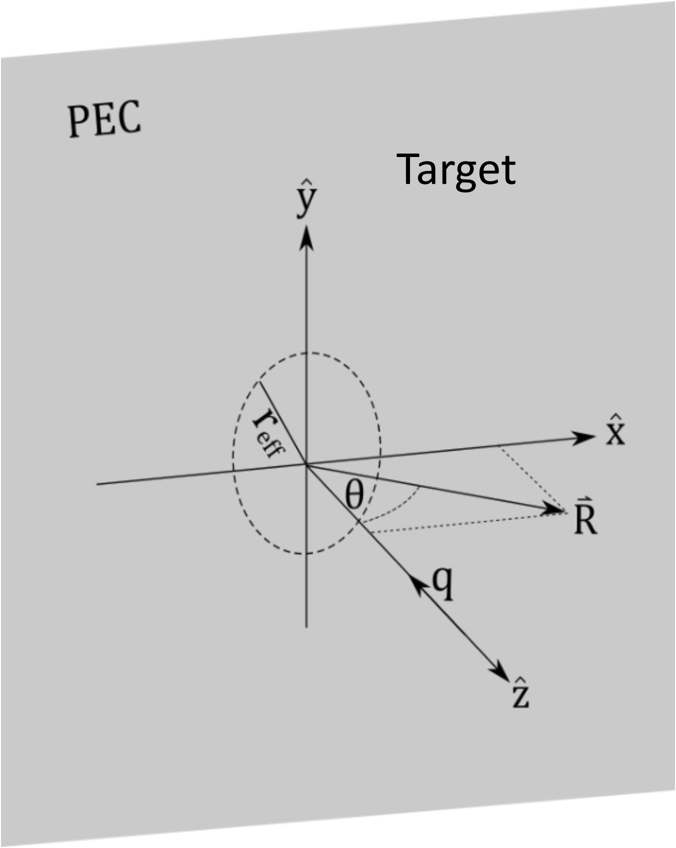
[2]

Transition Radiation (TR) – Properties in the GHz Regime

GTR electric field for single charge:

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

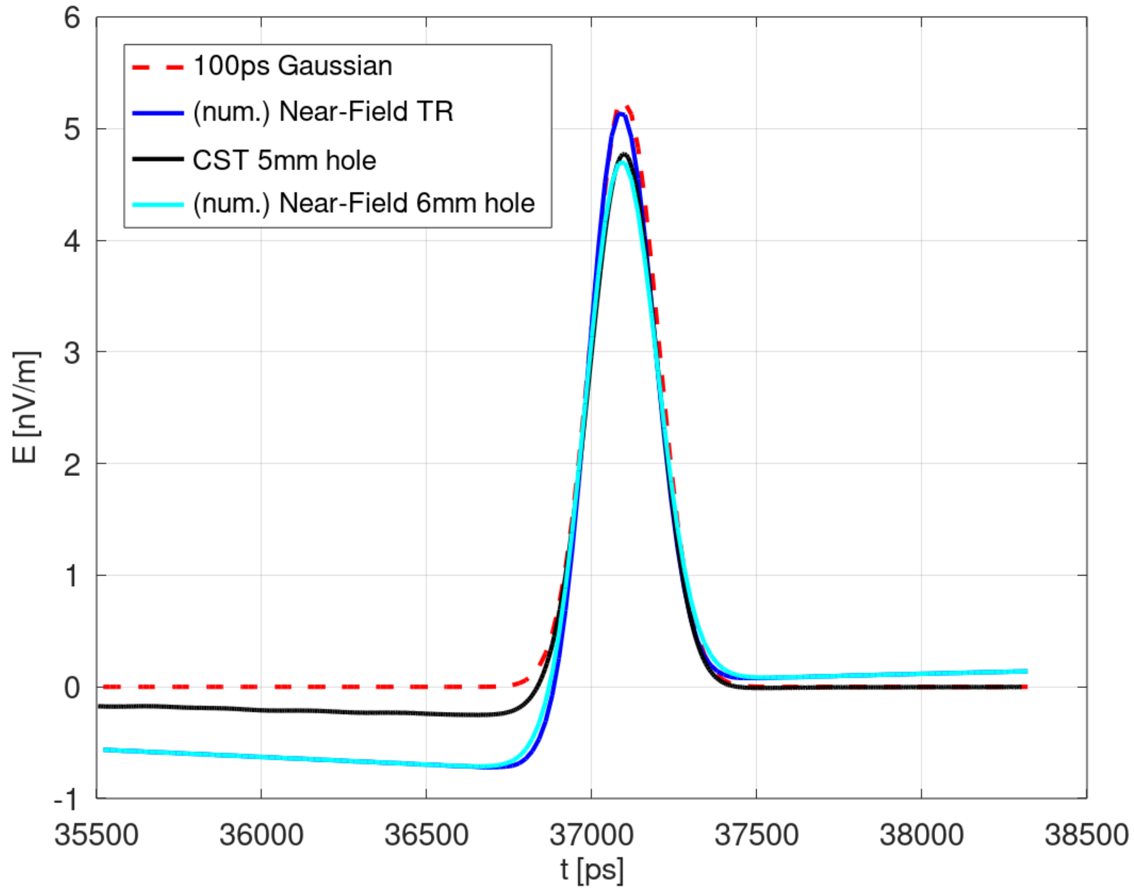
- Linear q and β dependence
- Parallel polarization for normal incidence
- Good signal: 10pC charges in 100 ps (σ) with β=0.15
  → 10 mV peak



[2]

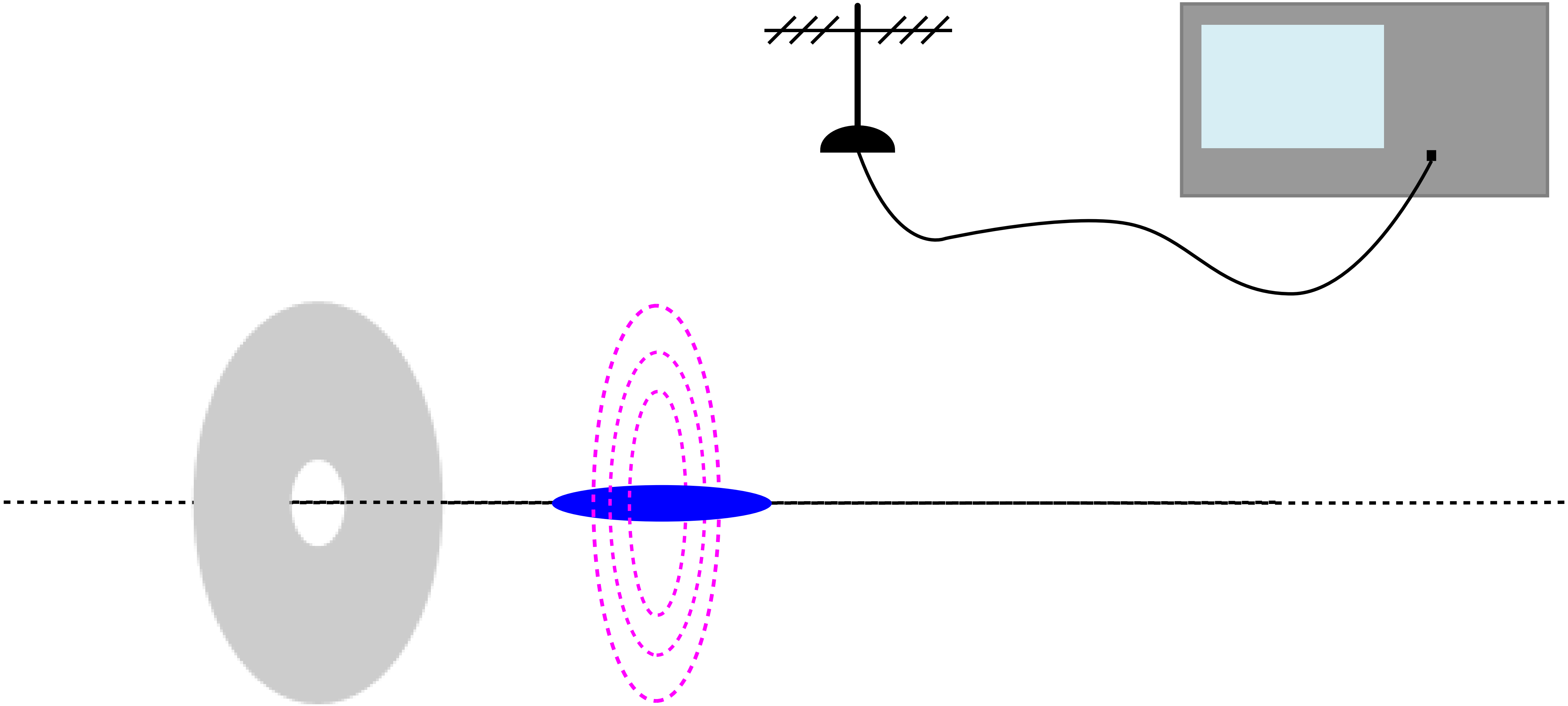
Transition Radiation (TR) – Properties in the GHz Regime

- Diffraction Radiation 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!**



[2]

Transition Radiation Monitors Basic Concept



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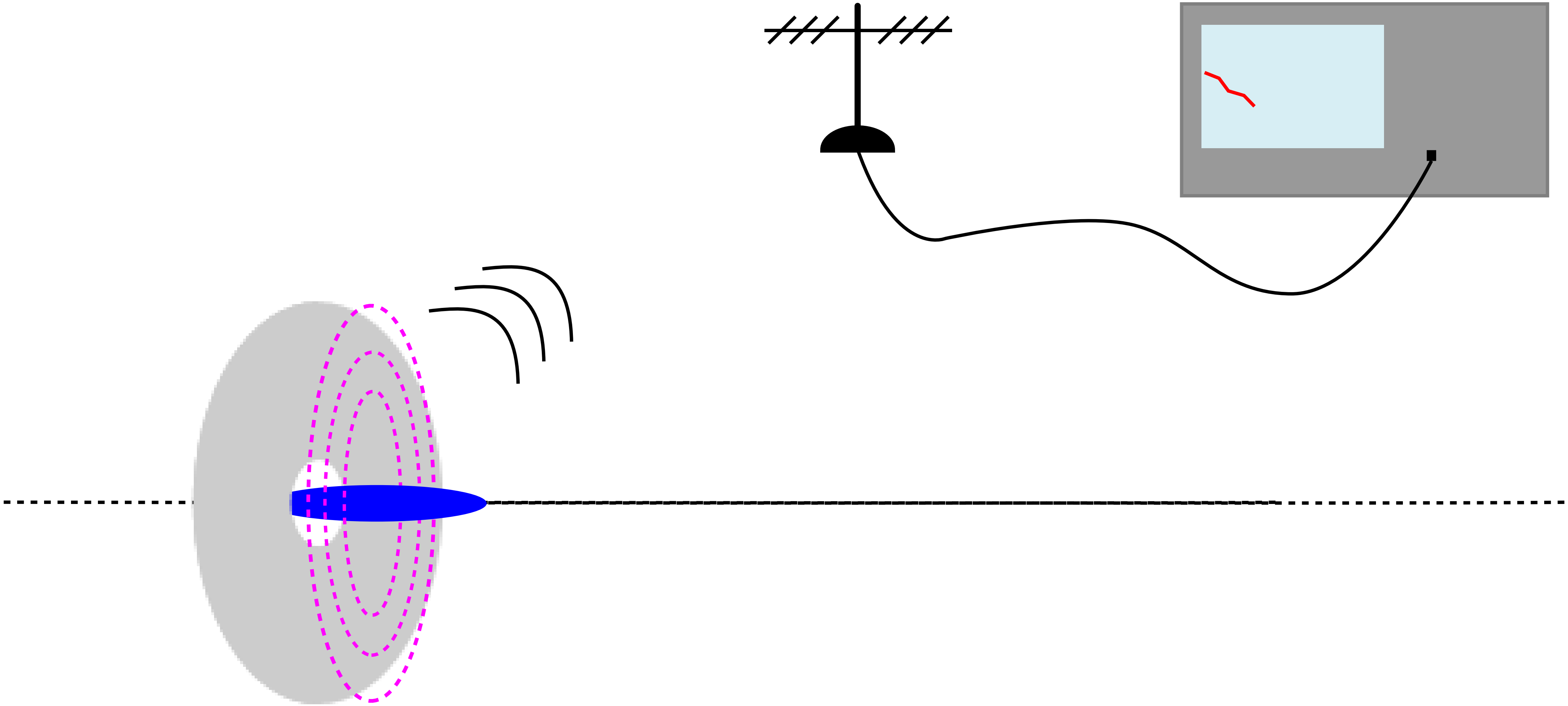
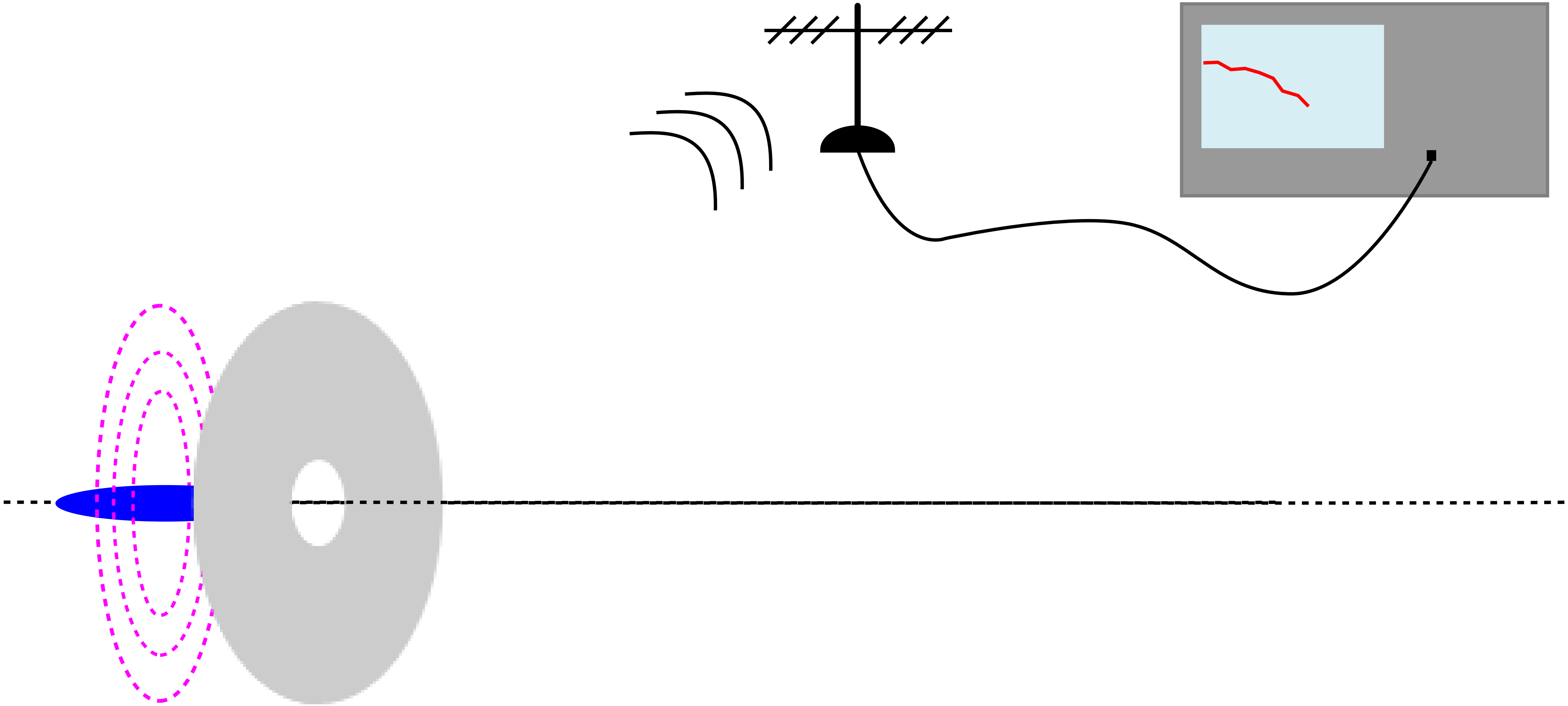
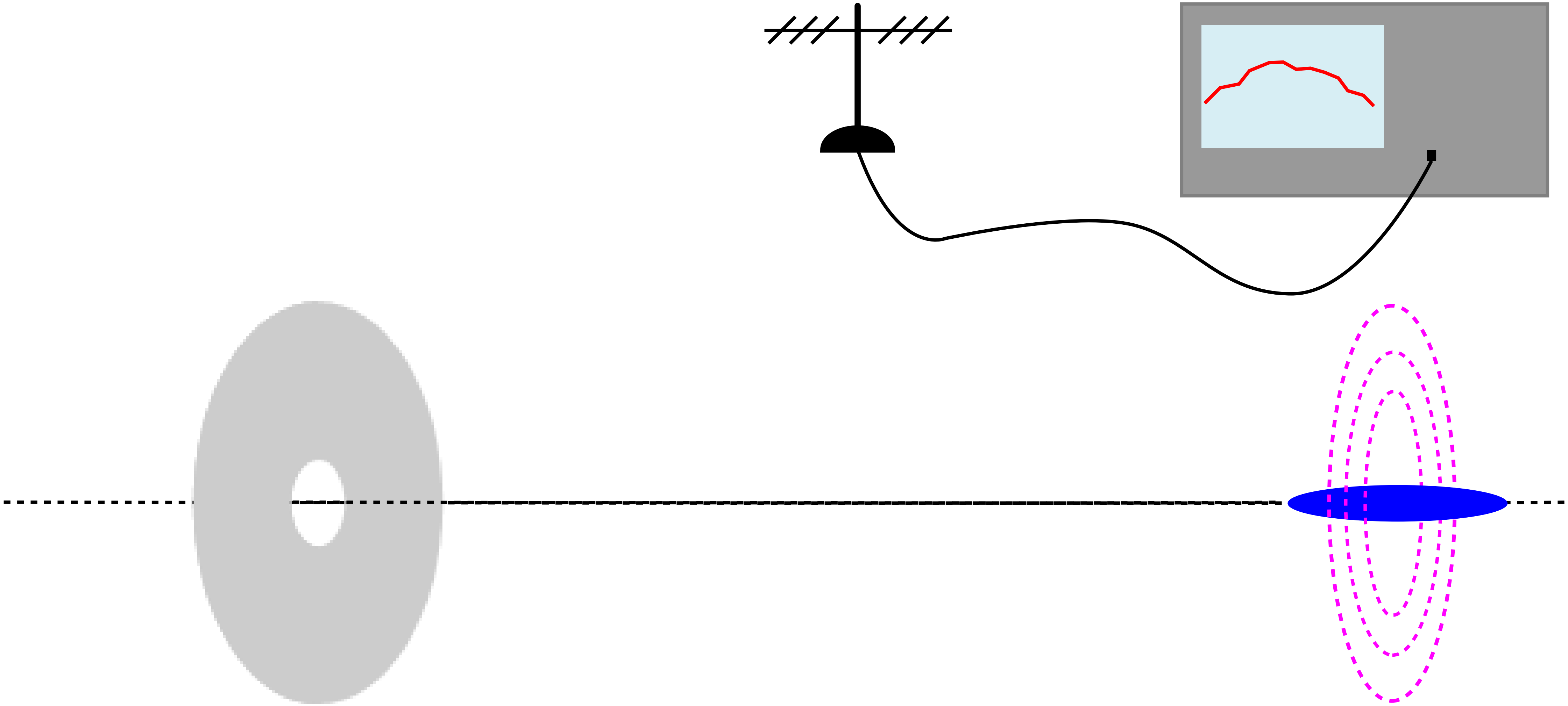


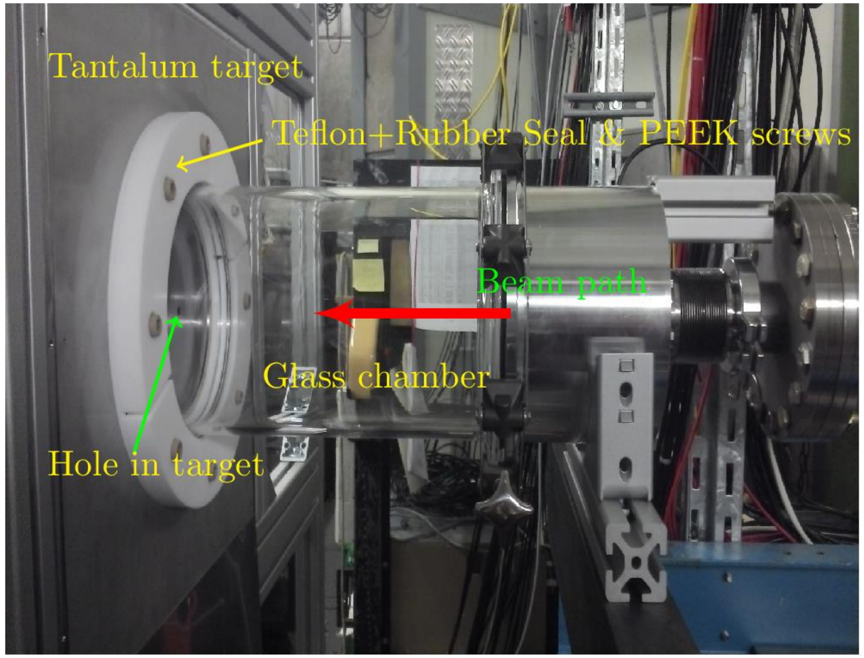
Transition Radiation Monitors Basic Concept

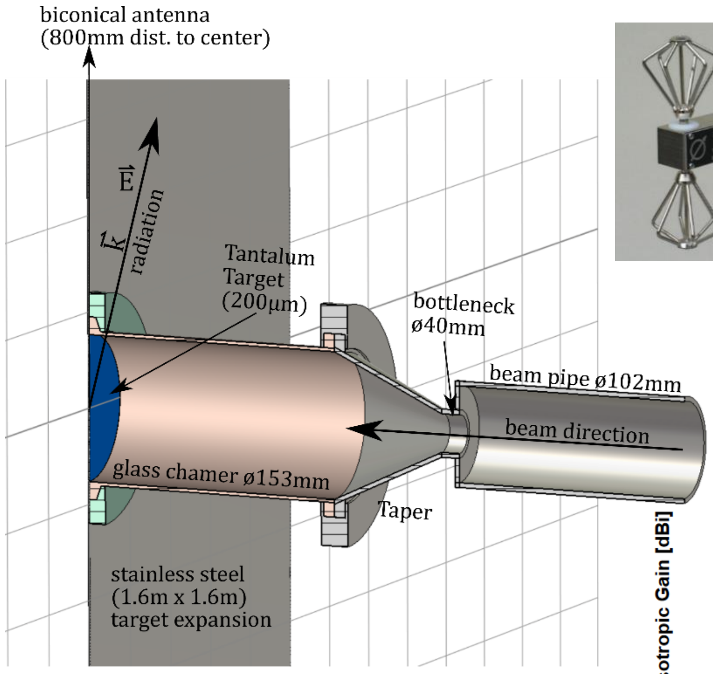


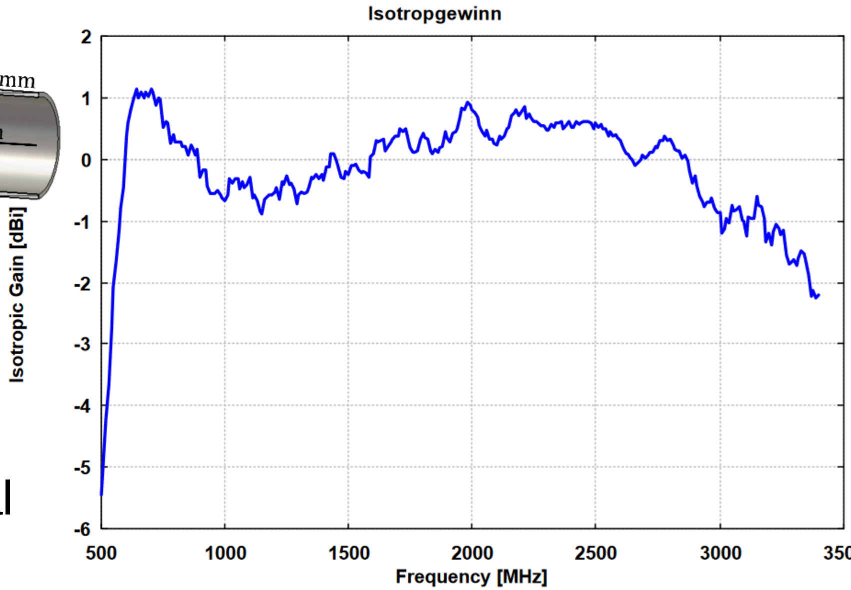
Transition Radiation Monitors Basic Concept



Transition Radiation (TR) – Measurements at X2 (GSI)





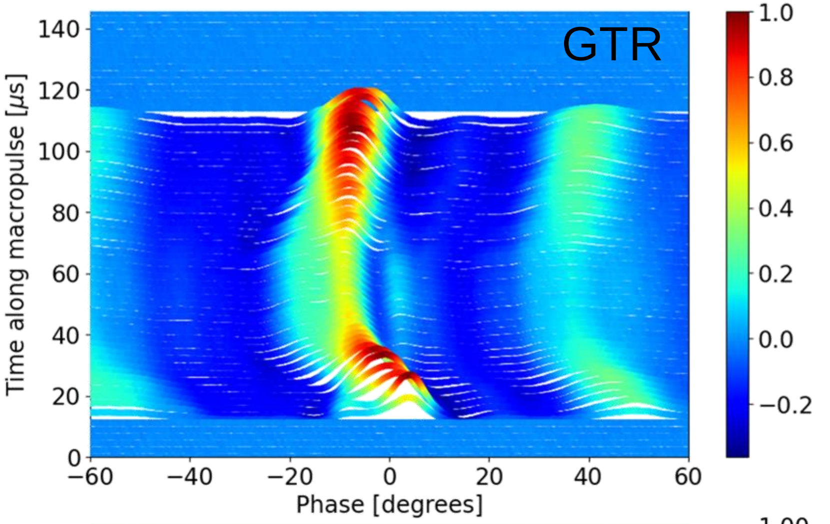


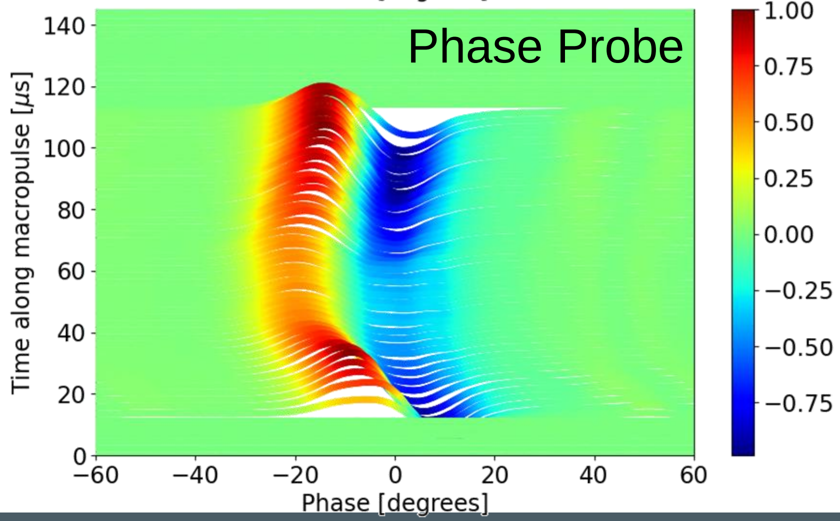
- An RF window to couple out the TR signal → Vacuum tolerance → critical
- Absorbers to avoid reflections
- Linear phase antenna designs

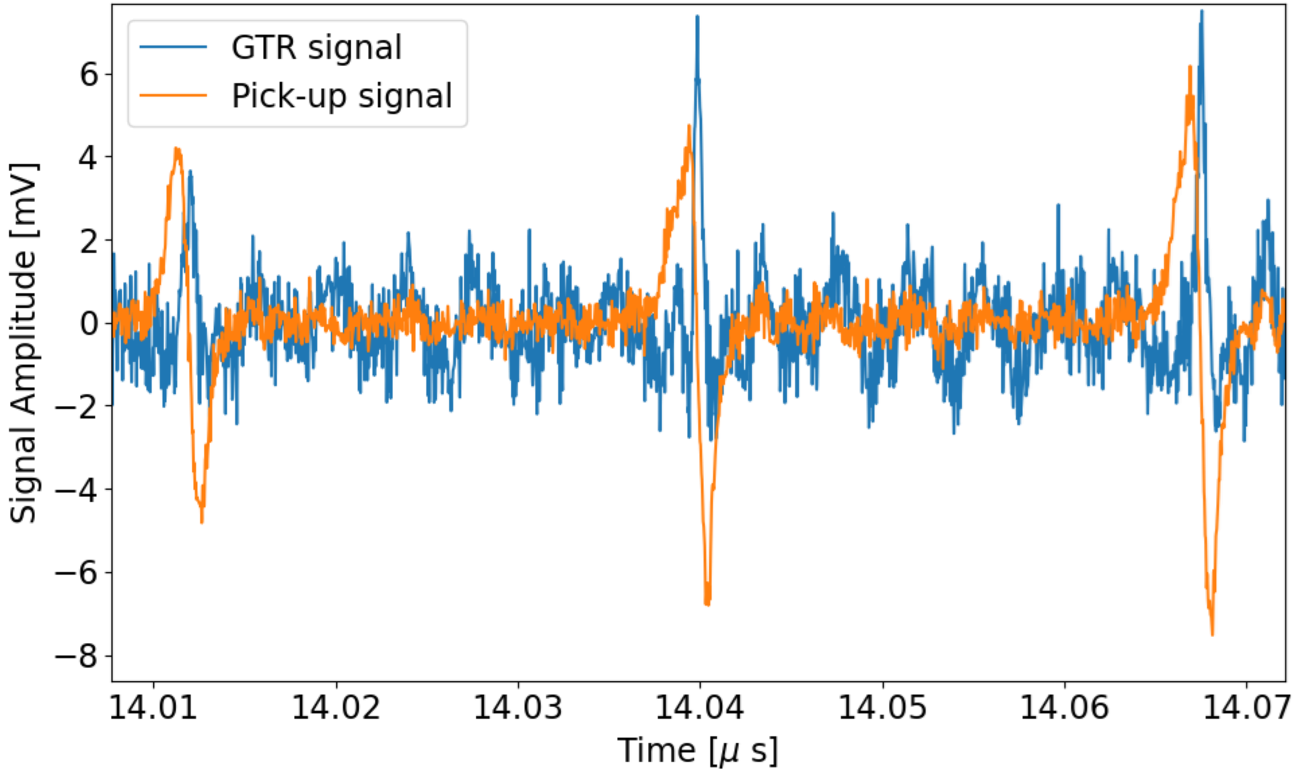
[2]

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

Transition Radiation (TR) – Measurements at X2 (GSI)







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

[2]

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100µs pulse length, 36MHz RF
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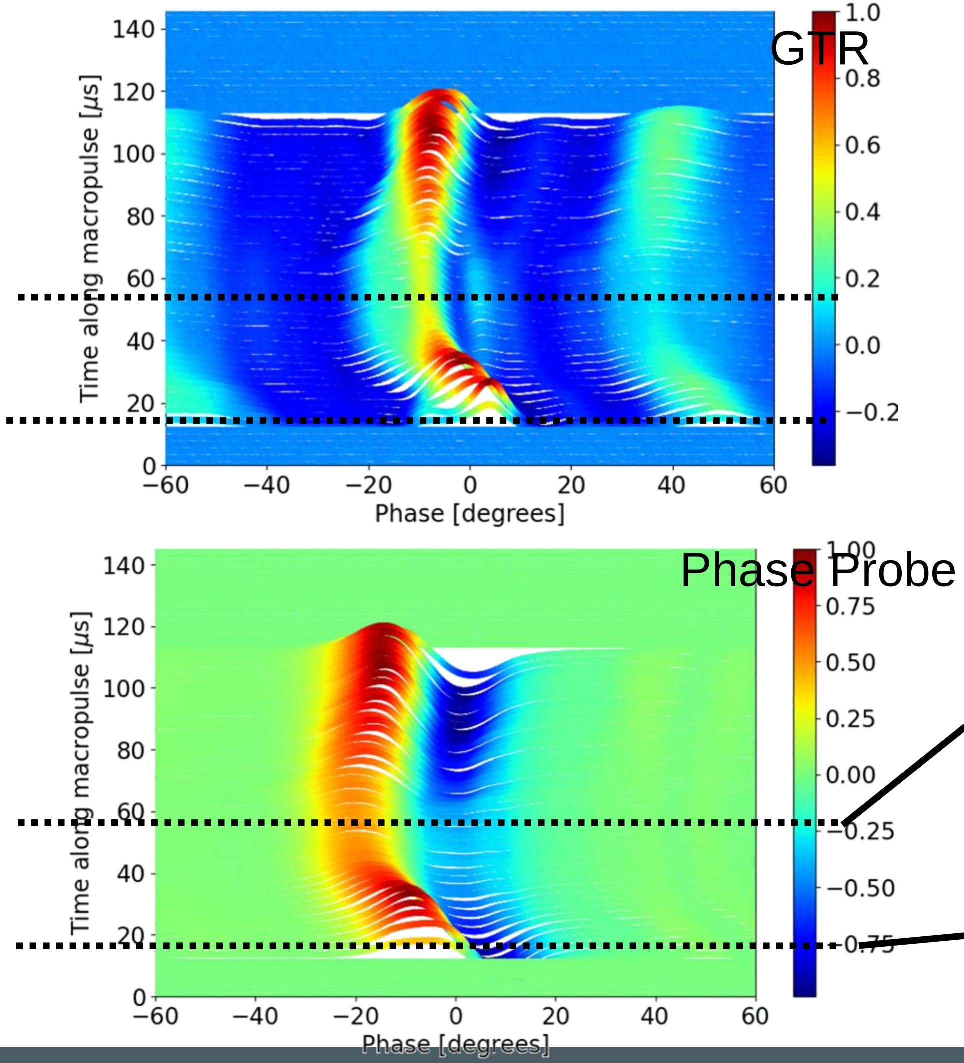

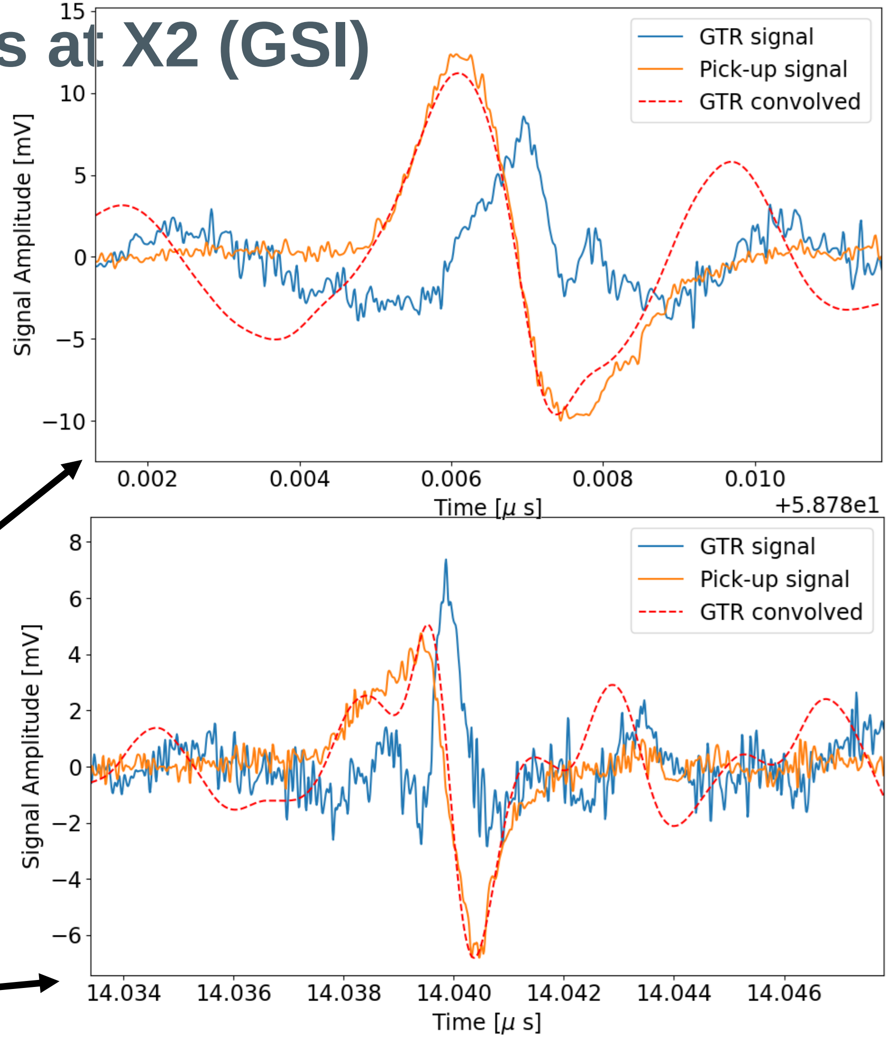

[2]

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

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100μs pulse length, 36MHz RF
Antenna angle (θ) = 40 deg,
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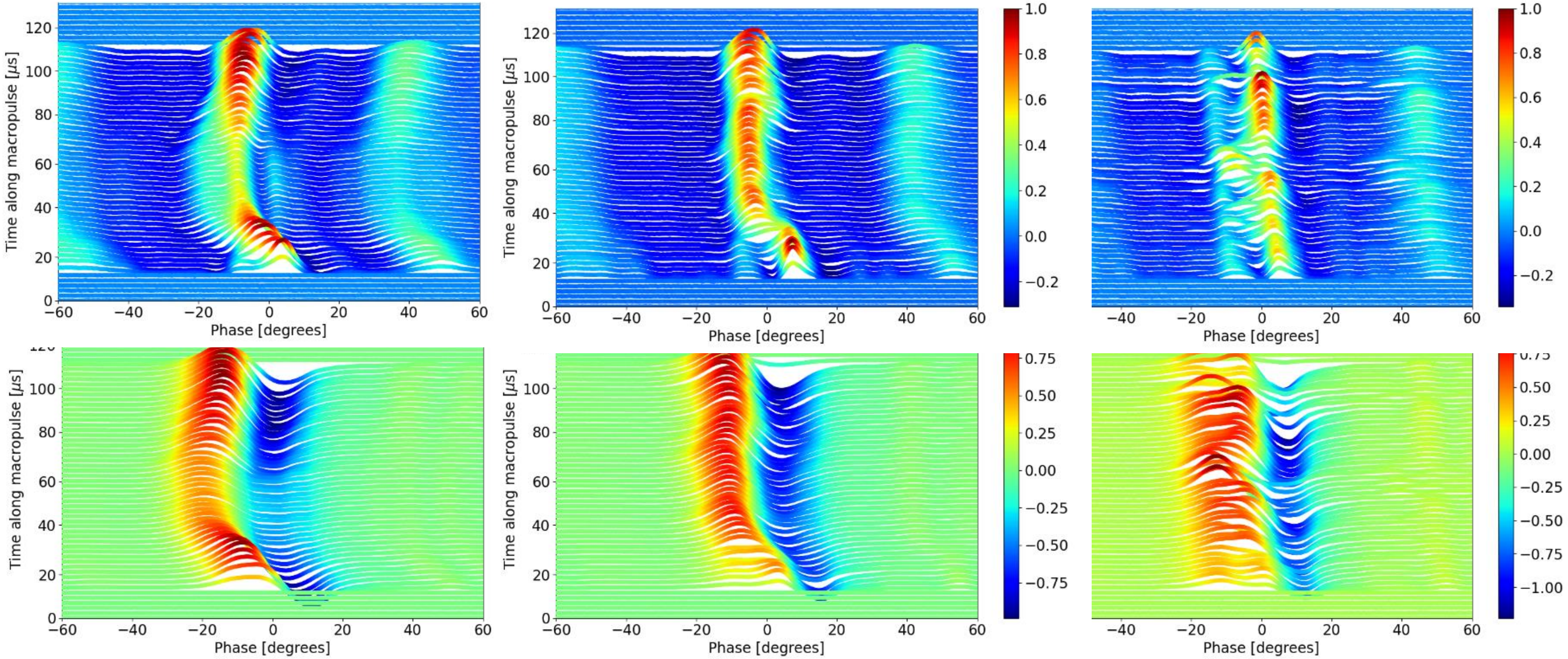
Transition Radiation (TR) – Measurements at X2 (GSI)

GTR

Phase Probe



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

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

Fast Faraday Cups

Fast Faraday Cups (FFC)

- FFCs are design to measure fast longitudinal bunch structures
- Challenges:
  - Matching of the out-coupling should be done very well till high frequencies

    i.e. $BW > 5\sigma_f = 5\frac{1}{2\pi\sigma_t}$
  - Measuring the self-field should be avoided
  - Suppress distortion of the signal caused by secondaries
  - Cooling of the FFC / avoid melting of the FFC
- Despite being known for decades, FFCs are still under research in many shapes and use cases.

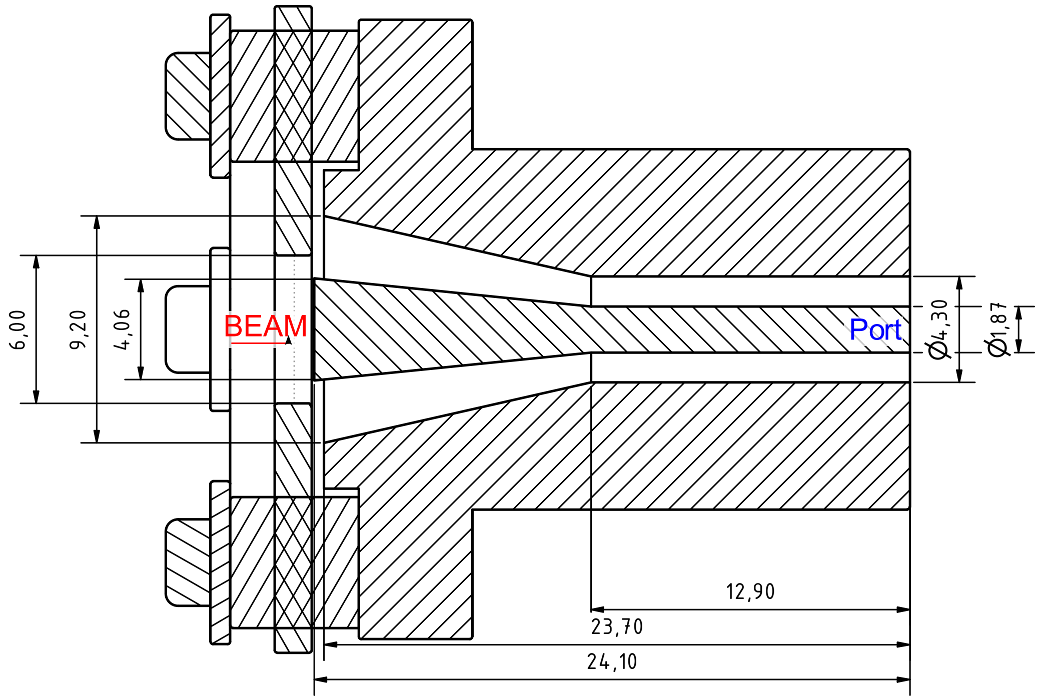
  Axial, Radial, Strip-Line, …

[7] 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

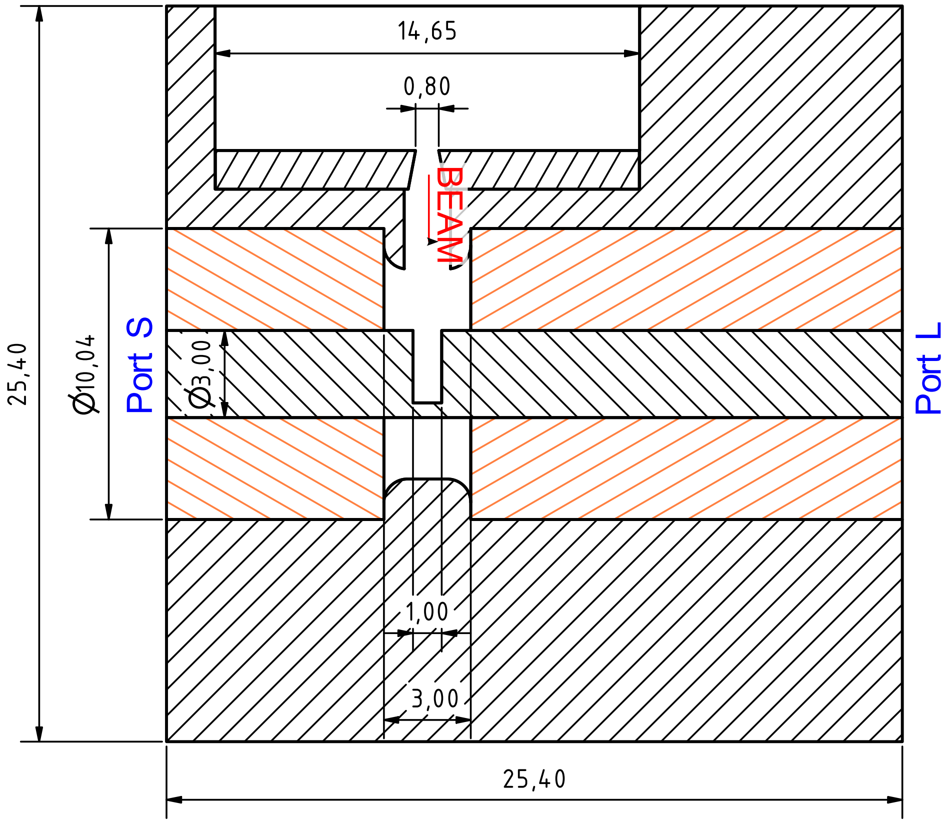
[2]

Fast Faraday Cups (FFC) – Comparing Axially Coupled and Radially Coupled FFC

ACFFC



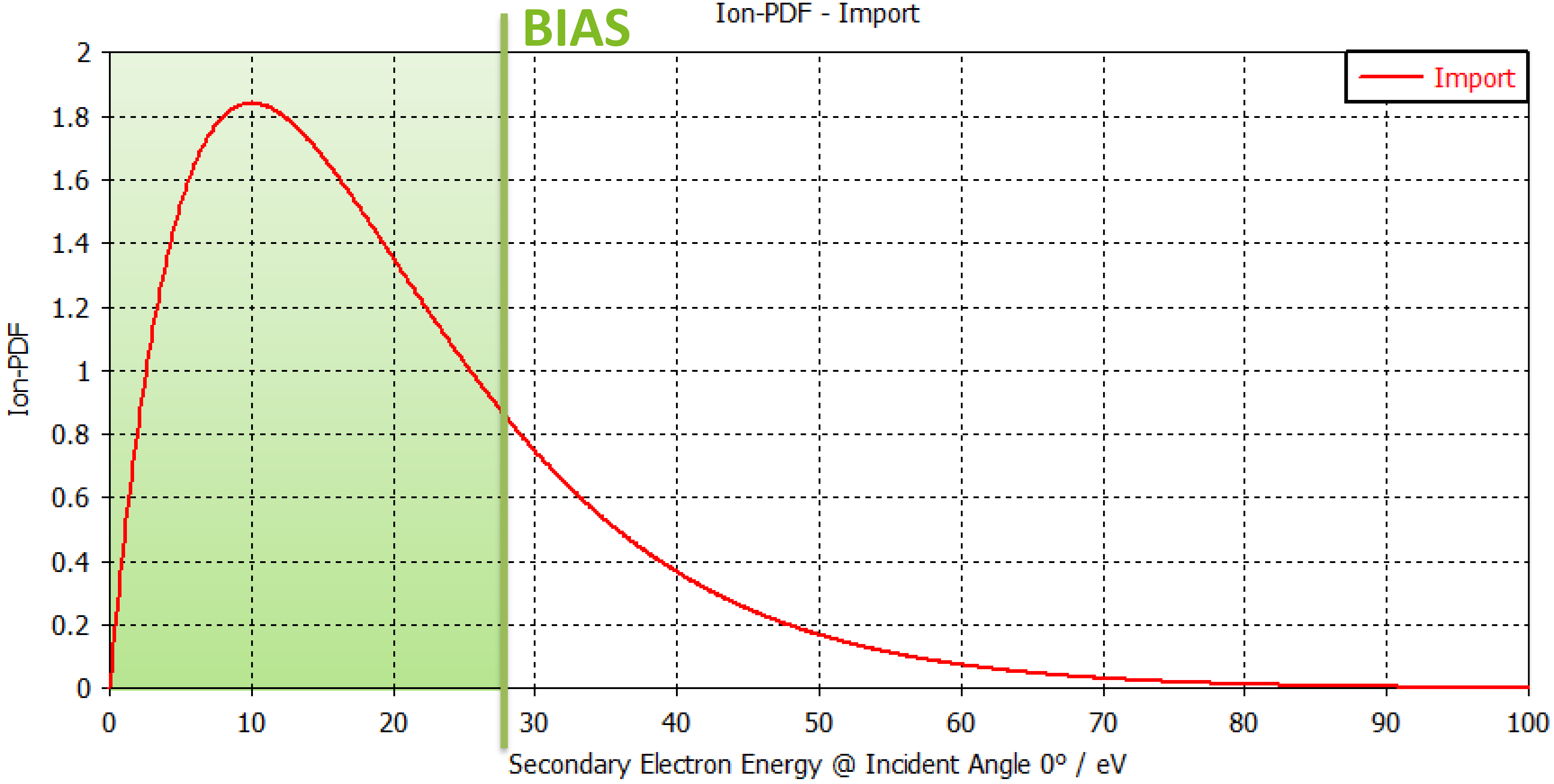
RCFFC



[8,11,12]

Fast Faraday Cups (FFC) – Comparing Axially Coupled and Radially Coupled FFC

- Simulation Settings:
  - $T_e = 10eV$
  - 50 SE/Ion
  - No SE through electrons
  - SE emitted only from central conductor
- Suppression of SEE:
  - BIAS reattracts SE to central conductor
  - RCFFC recollects SE within drill hole. These SE will not contribute to signal.



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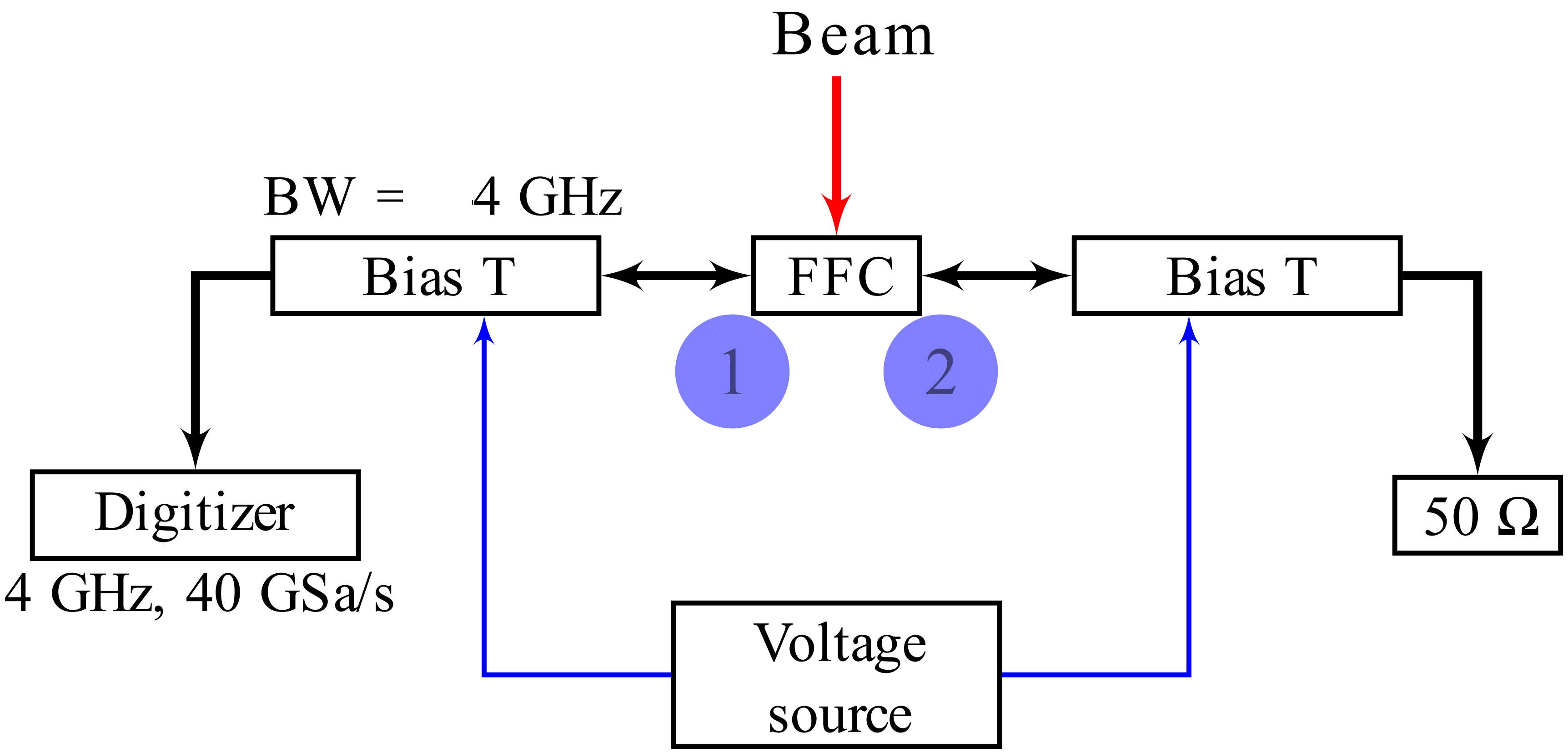

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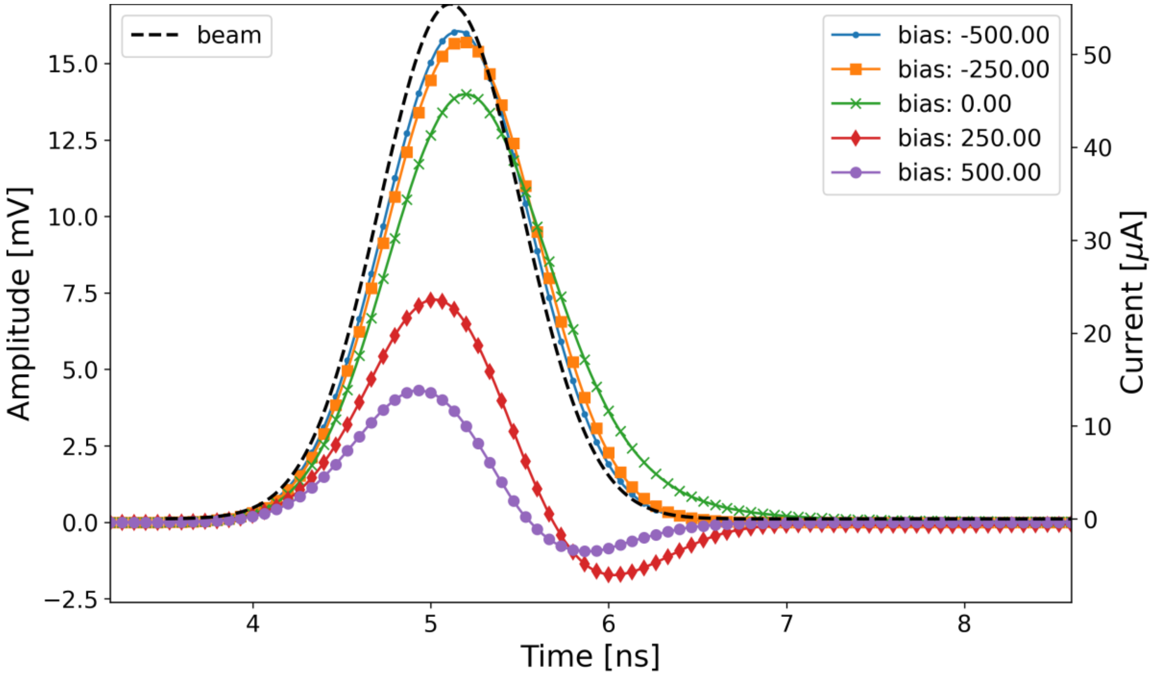
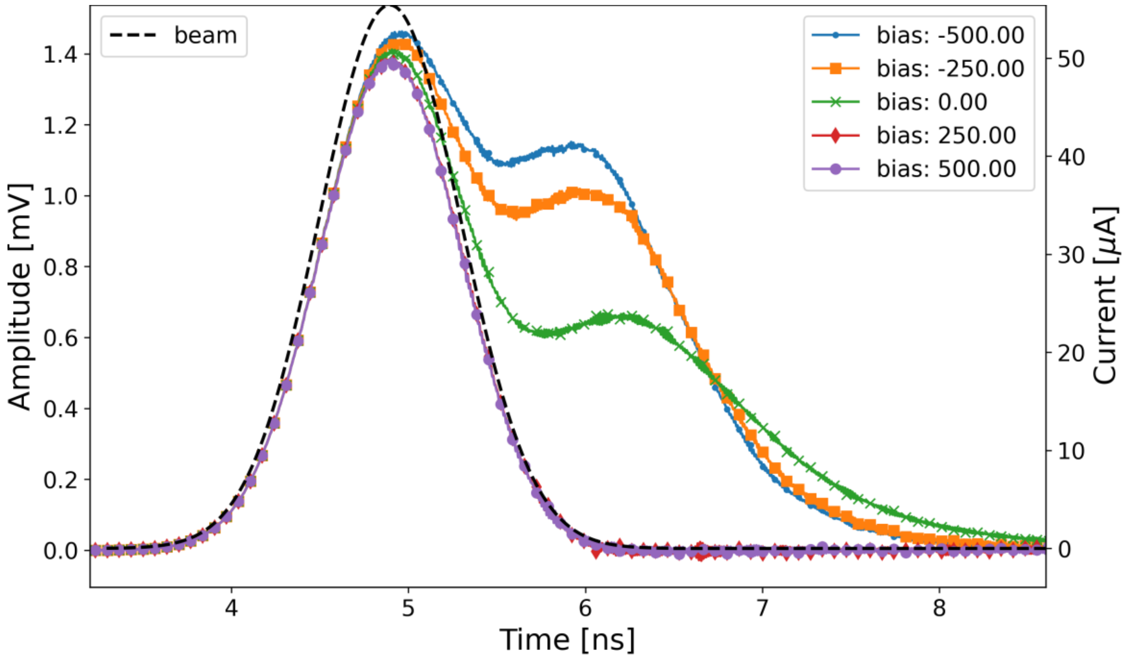
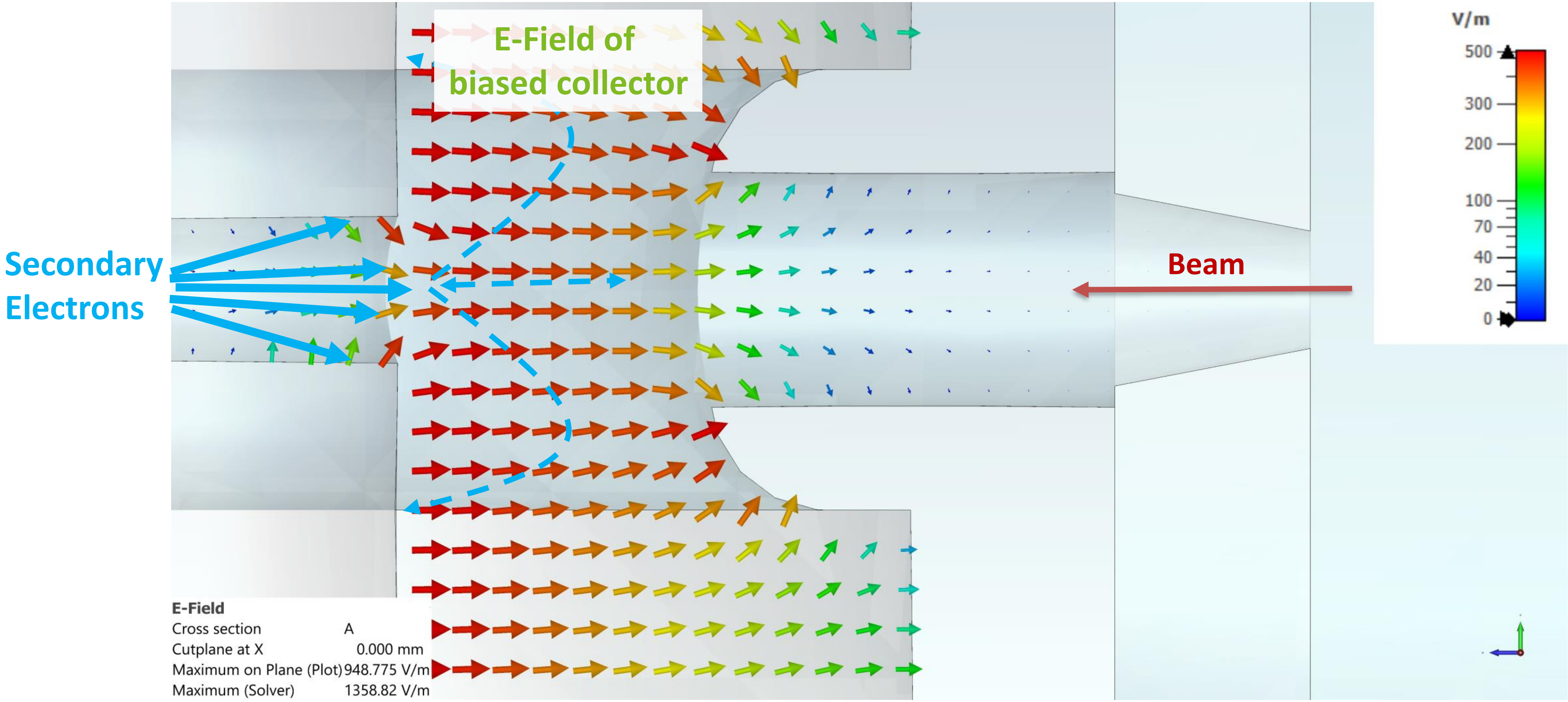


RCFFC



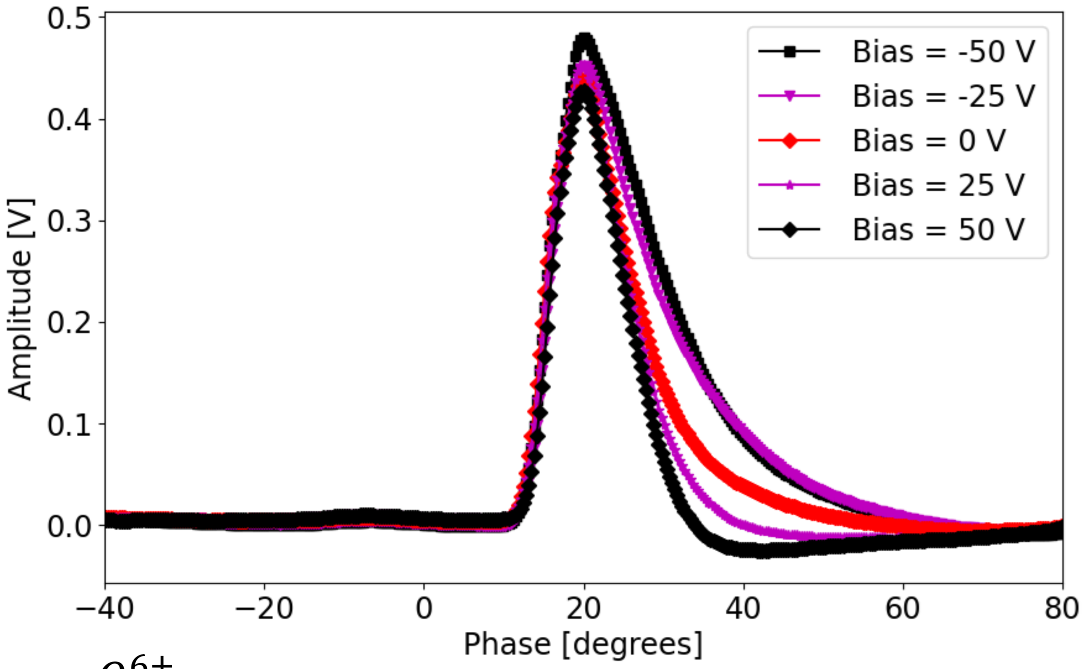
[8]

Fast Faraday Cups (FFC) – Comparing Axially Coupled and Radially Coupled FFC



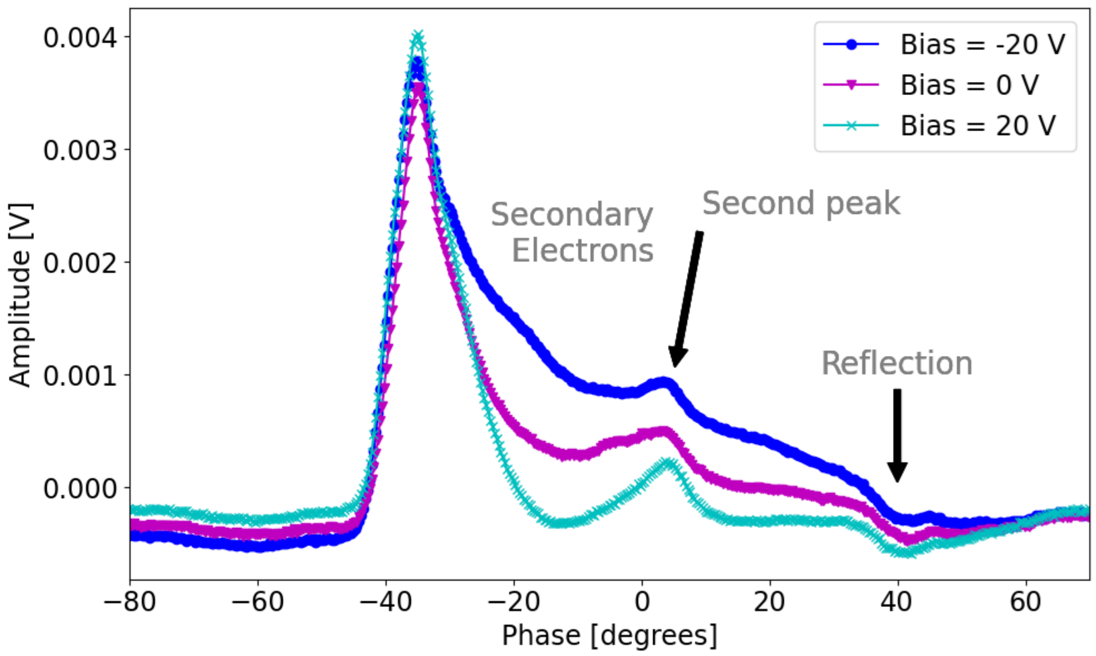
Comparing Axially Coupled and Radially Coupled FFC

ACFFC



O^{6+}
8.6 MeV/u
0.4 mA

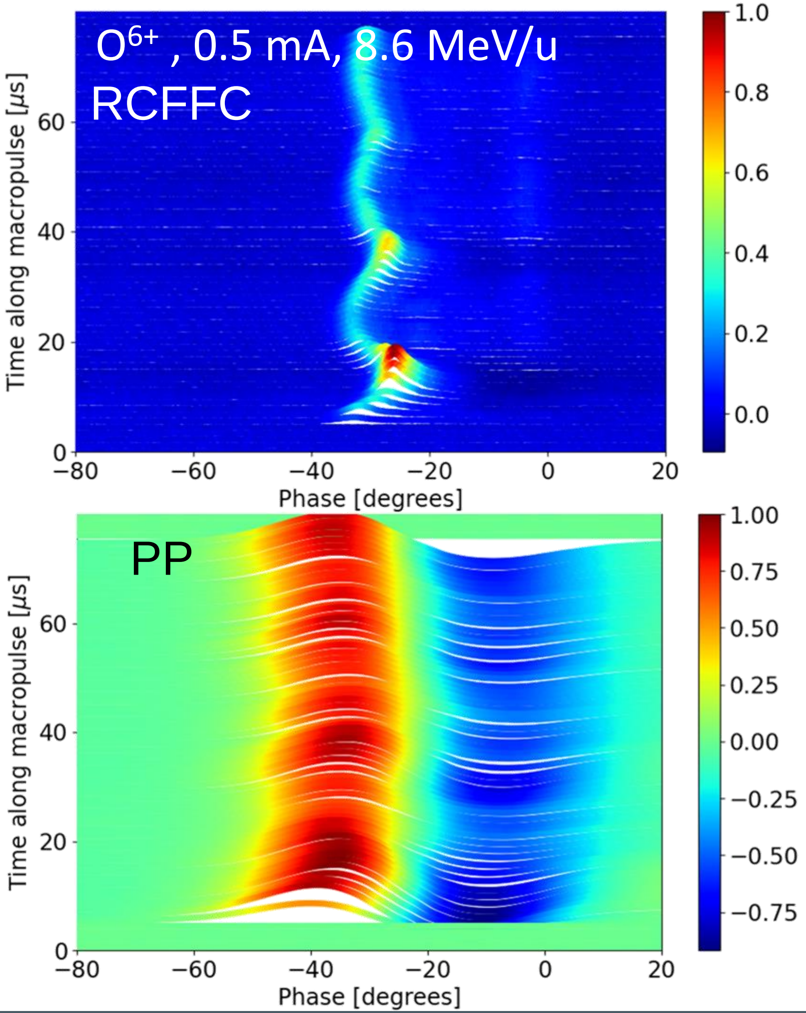
RCFFC



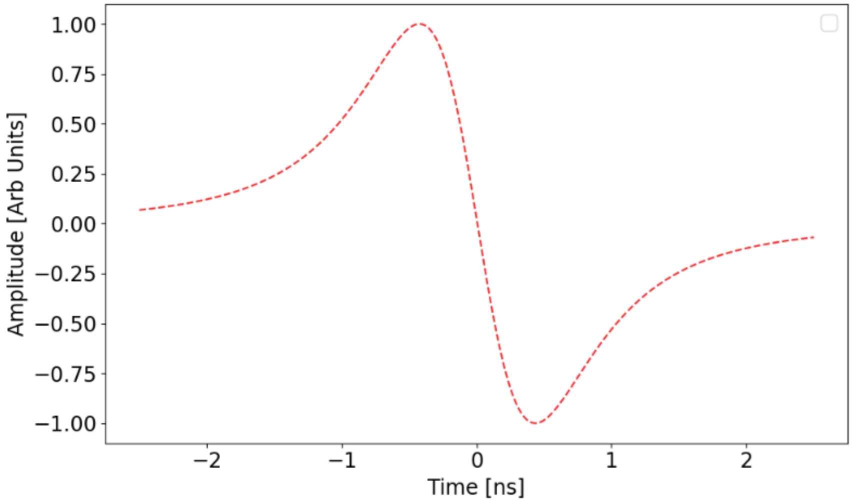
Ar^{10+}
8.6 MeV/u
0.4 mA

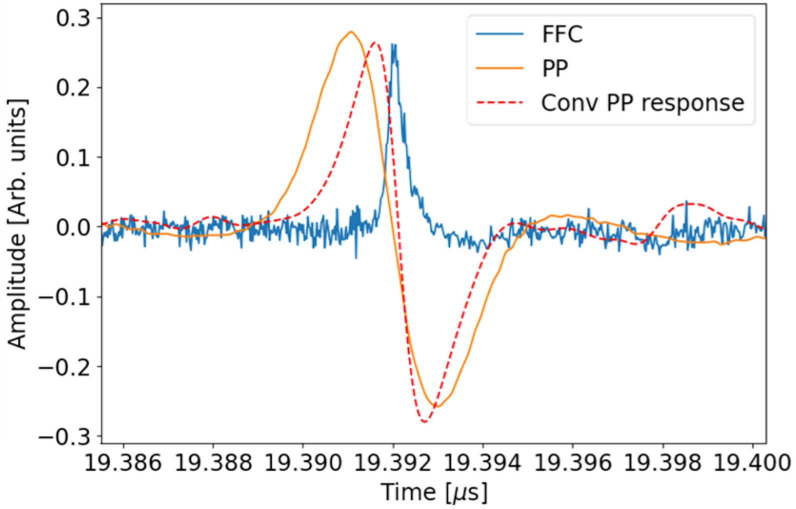
[8]

Comparing Phase Probe and Radially Coupled FFC



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





Phase probe remains a validation device!

[2]

Conclusions

- Fast and robust longitudinal diagnostics is important for various alignments.

- Pick-Up field distribution is not equal to the charge distribution for $\beta < 1$
- Total charge measurements are possible and insensitive to other beam parameters
- Combined purpose possible: e.g., TOF, BAM, Total Charge with just two Pick-Ups

- GTR a promising **non-invasive option for high currents** *but* not a compact installation. Further investigation under BMBF project ongoing

- FFC is a promising **compact option** *but* requires careful placement and biasing is essential depending on the energy regimes. New designs being tested, comparison with calculated phase space needed

[2]

Room for Questions!

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