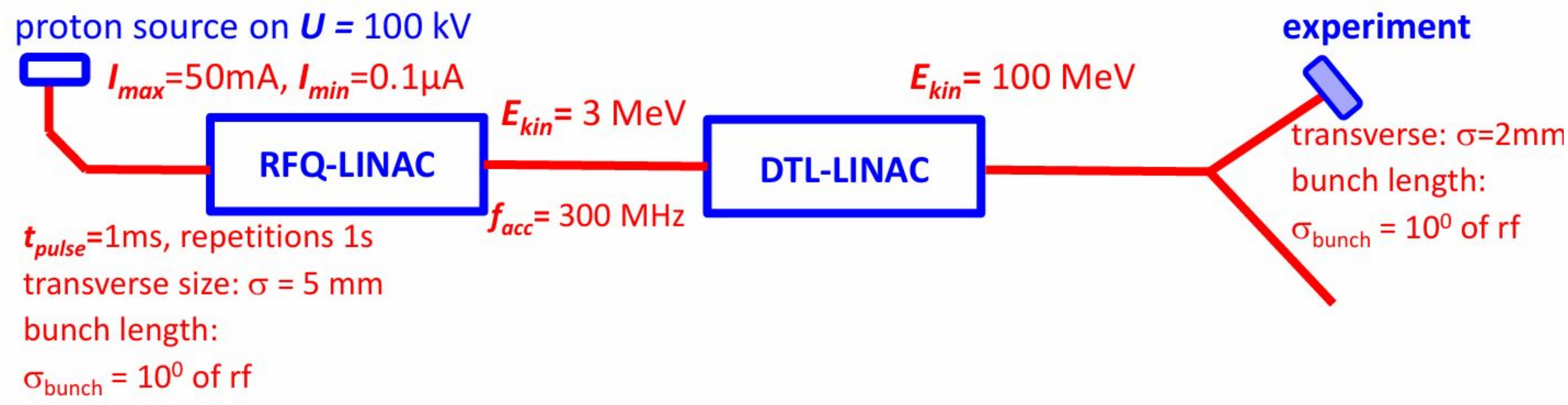
Beam diagnostics design for a proton facility

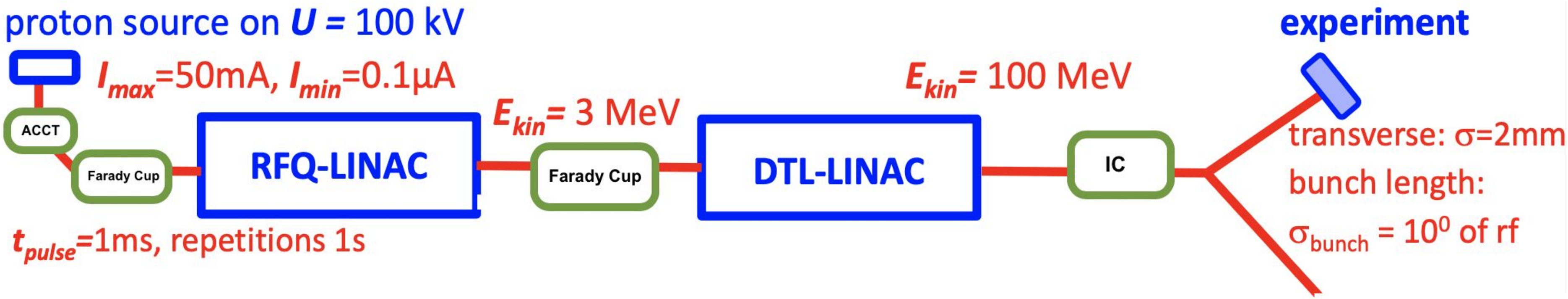
Beam Instrumentation - JUAS 2025

LINAC



proton source on U = 100 kV
Imax=50mA, Imin=0.1µA
tpulse=1ms, repetitions 1s
transverse size: σ = 5 mm
bunch length:
σbunch = 10⁰ of rf
RFQ-LINAC
Ekin= 3 MeV
facc= 300 MHz
DTL-LINAC
Ekin= 100 MeV
experiment
transverse: σ=2mm
bunch length:
σbunch = 10⁰ of rf

Beam current



<u>Active Current Transformer</u>

capture pulse current (macropulses)

+ good resolution 0,2 µA
+ suited for long pulse > 10µs
+ non-destructive

<u>Faraday Cup</u>

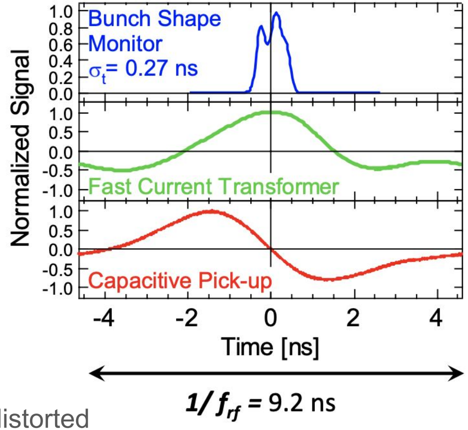
capture bunch current

+ low energy beams
+ low current measurement
- totally destructive

<u>Ionization Chamber</u>

captures bunch current

+ high energy beams
+ low current measurement
- partly destructive



Signal distorted

Beam Profile

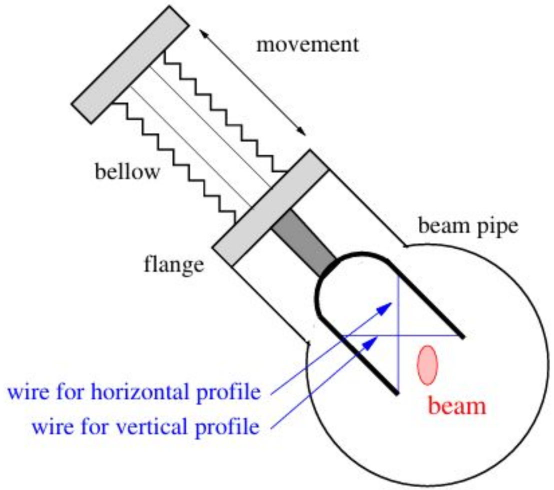
Combined system (example LINAC4 at CERN)

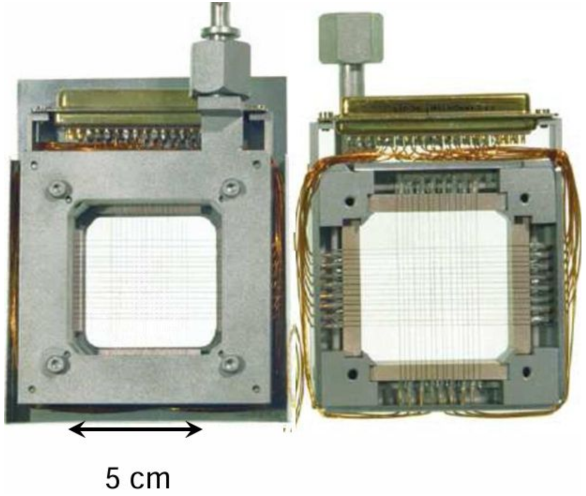
SEM-grid (Fast, real-time monitoring. Placed in Low Energy sections)

Slow Wire Scanner (Accurate, high-resolution measurements. Placed in High Energy sections.)

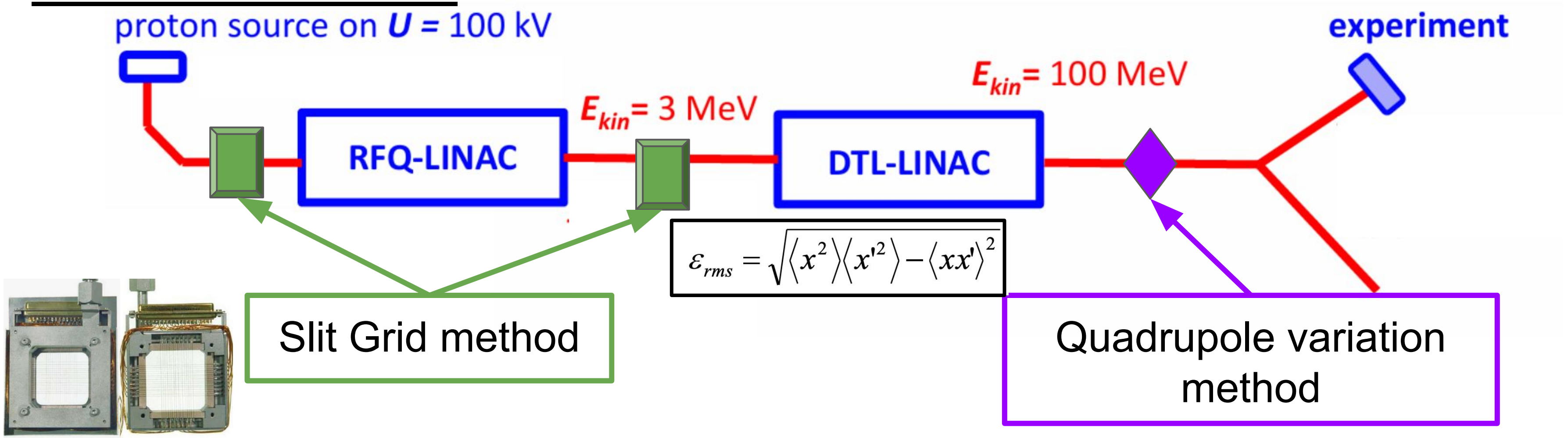
Together, they compensate for each other's temporal, spatial, and cost-related limitations to measure beam profile (σ^2)

Location	Device
Source - RFQ	SEM
RFQ - DTL	SEM
DTL - Extraction	SEM - Wire Scanner





Transverse emittance



$$\varepsilon_{rms} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2}$$

Diagnostics Methods	Placement	Why	Type
Slit Grid	RFQ Entrance	Proton Energy <100 MeV	Invasive
Slit Grid	DTL Entrance	Proton Energy <100 MeV	Invasive
Quadrupole Variation	DTL Exit	Proton Energy >100 MeV	Non-Invasive

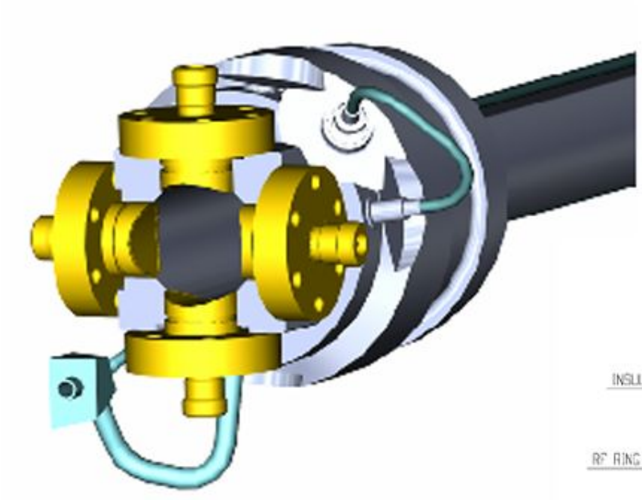
For longitudinal emittance :

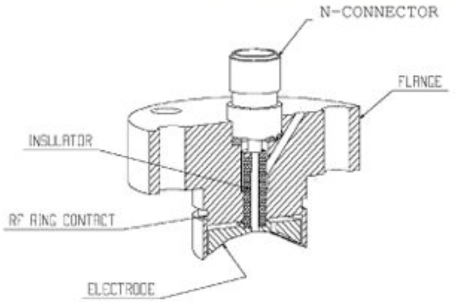
Linear transformation using Rf buncher ⇄ Quadrupolar Variation

Beam position

Capacitive button BPM - Used for LINACs and electron accelerators, for high frequencies (100MHz < f < 3GHz), so suitable for this case!

Placed at the entrance and exit of major accelerating sections (RFQ, DTL)



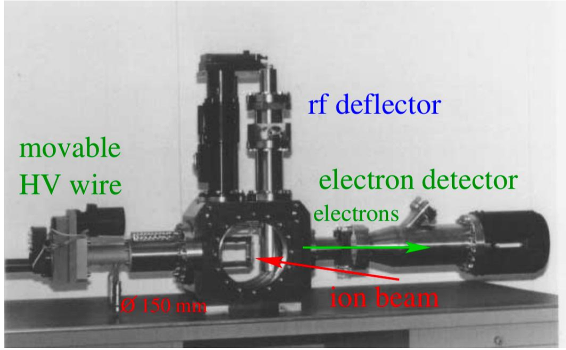


Beam Losses

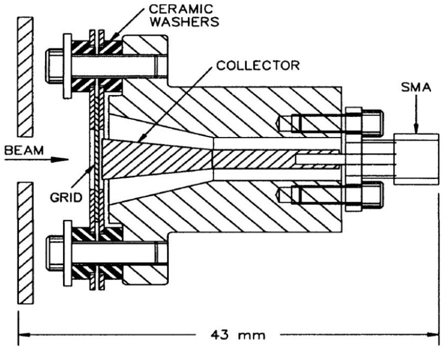
Beam Loss Monitor Type	Placement	Effects monitored	WHY 🤔
Ionization chamber	RFQ Exit	• RF Acceptance • Ionization losses	• sensitive to slow ionization effects
Scintillator / Photomultiplier tubes	DTL (near quadrupoles)	• Misalignment losses • Space charge	• prevents beam scraping
Ionization chamber	DTL Exit	• Residual beam losses • Ionization losses	• integrated ionization losses over time

Bunch Length

Measurement method	Placement	WHY 🤔
Bunch Shape Monitor	RFQ Exit	• best for low energy proton LINAC • direct measurement of bunch profile
Coaxial Faraday Cup	DLT Exit - Experiment	• direct measurement of bunch structure



BSM



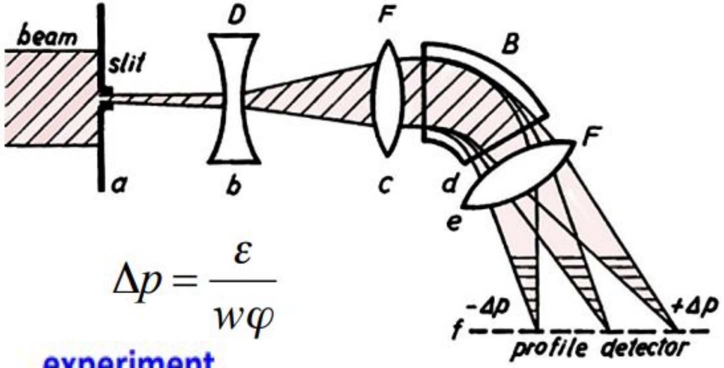
Coaxial Faraday Cup

Momentum Spread

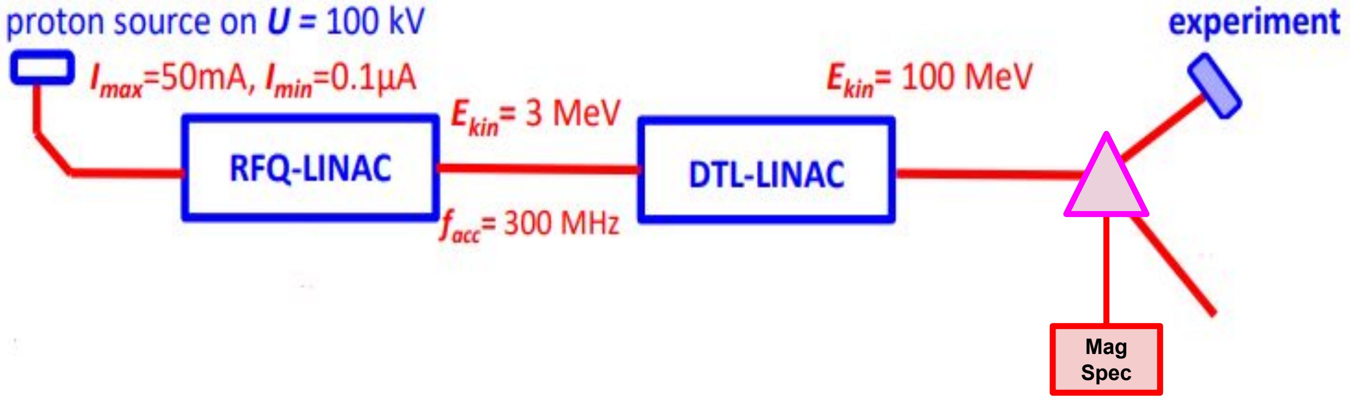
Characterize momentum spread of 100 MeV proton beam after DTL.

Magnetic Spectrometer.

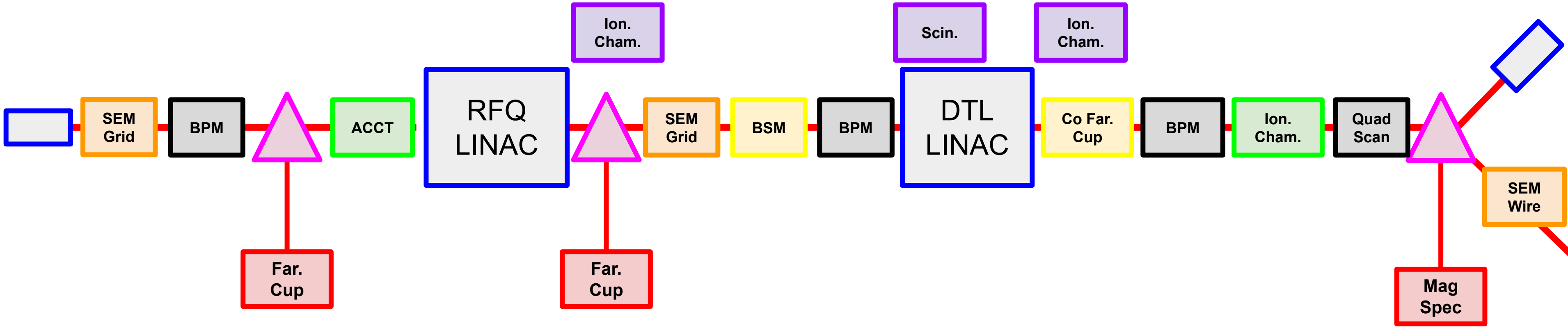
- **Dipole magnet:** Momentum separation
- **Detector array:** Trajectory-based measurement
- **Invasive:** Precise, requires dedicated beam time



$$\Delta p = \frac{\varepsilon}{w\varphi}$$



Summary



SEM Grid
BPM
Far. Cup
ACCT
RFQ LINAC
Ion. Cham.
Far. Cup
SEM Grid
BSM
BPM
Scin.
DTL LINAC
Ion. Cham.
Co Far. Cup
BPM
Ion. Cham.
Quad Scan
Mag Spec
SEM Wire

Appendix 1

An example of beam instrumentation for a proton linac:

1.2.2 Beam instrumentation for LINAC4

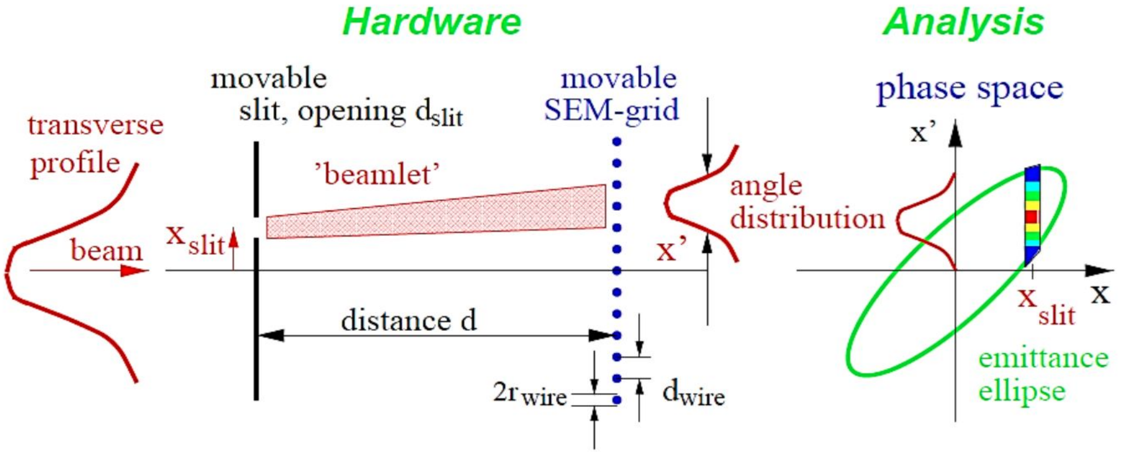
Location	Energy [MeV]	BPM	BCT	SEM grids	WBS BLM	
diagn. Bench	3 and 12	3	2	3	-	-
LEBT	0.045	-	1	3	-	-
MEBT	3	-	2	-	2	1
DTL	3 to 50	2	-	2	-	2
CCDTL	50 to 102	7	1	4	2	4
PIMS	102 to 160	6	1	6	2	3

Table 1.1: LINAC 4 diagnostics overview.

Appendix 2

Slit-Grid Emittance Measurement

- **Principle**: A **thin slit (0.1–0.5 mm)** selects a small fraction of the beam at a fixed position x, while the full beam is transmitted perpendicularly for a strong signal.
- **Angle Measurement**: A **SEM-grid** placed **10 cm to 1 m** from the slit measures the angular distribution x'. In the drift space, particle trajectories remain straight.
- **Beam Scanning**: The slit is moved across the beam to capture the full phase-space distribution. Data is **normalized** to ensure consistency.
- **Emittance Calculation**:
  - The **rms emittance** eps(rms) is derived from statistical moments.
  - An **elliptical fit** is used to extract **Twiss parameters (Courant-Snyder functions)**.



Why: used for protons for kinetic energy less 100MeV/u

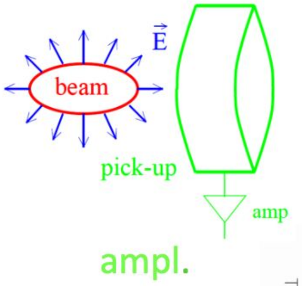
Bunch Structure at low E_{kin}: Not possible with Pick-Ups

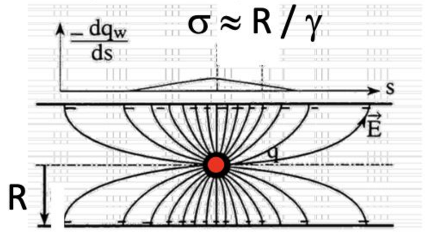
Pick-ups are used for:

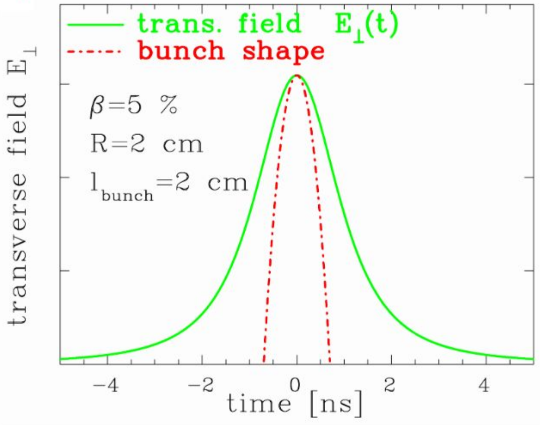
- precise for bunch-center relative to rf
- course image of bunch shape

But:

For $\beta << 1 \rightarrow$ long. ***E***-field significantly modified:

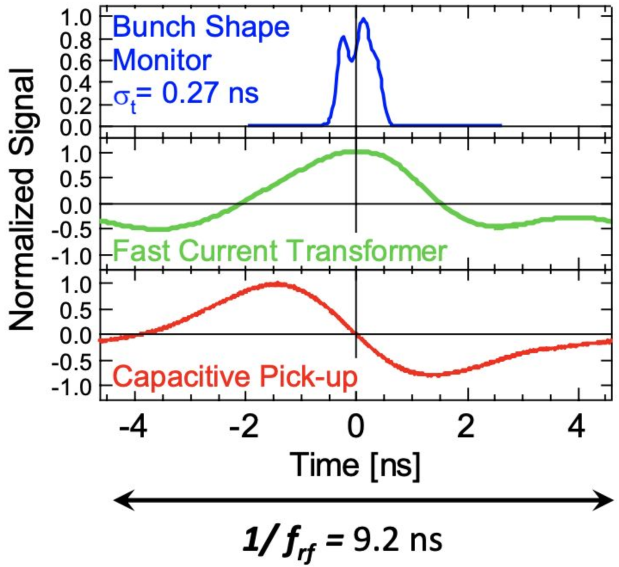






Example: Comparison pick-up – particle counter:

Ar beam of 1.4 MeV/u ($\boldsymbol{\beta}$ = 5.5%) , $\boldsymbol{f_{rf}}$ = 108 MHz



⇒ the pick-up signal is insensitive to bunch 'fine-structure'