Beam Diagnostics and Instrumentation

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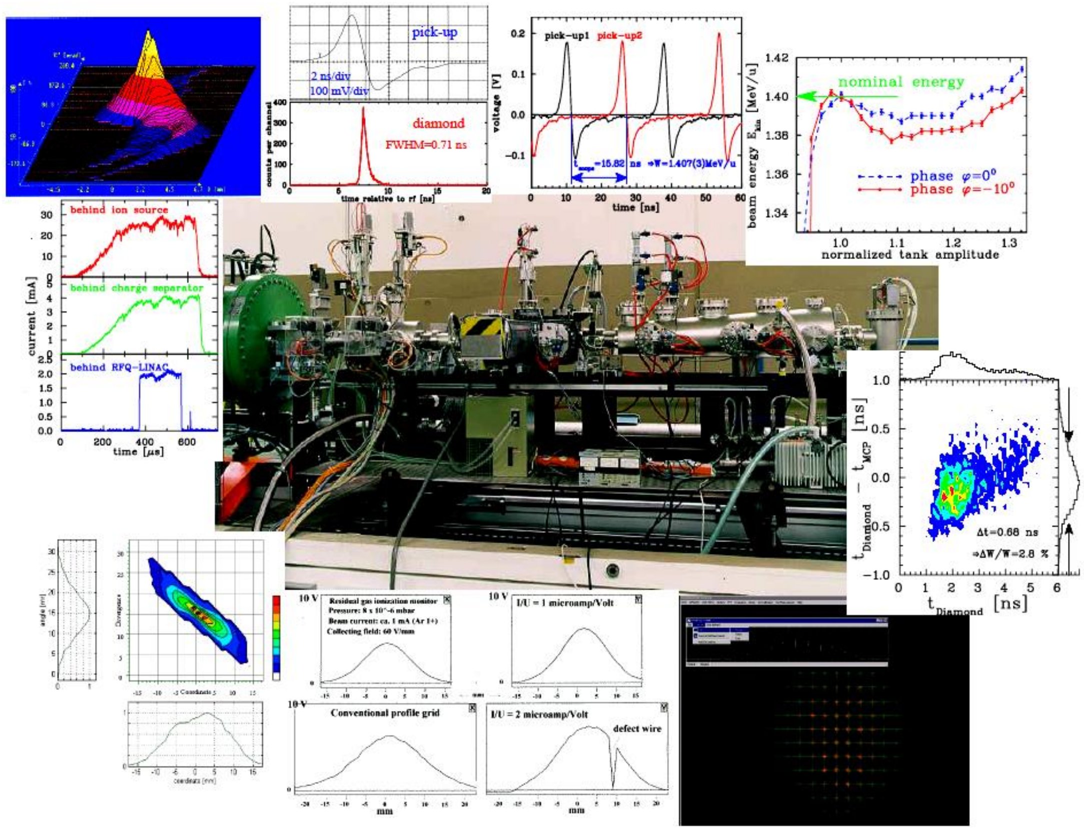
Peter Forck

Gesellschaft für Schwerionenforschnung (GSI) and University Frankfurt



Diagnostics is the 'sensory organs' for the beam.

It deals with *real* beams in *real* technical installations including all imperfections.

Three types of demands lead to different installations:

- Quick, non-destructive measurements leading to a single number or simple plots
  Used as a check for online information. Reliable technologies have to be used
  Example: Current measurement by transformers
- Instruments for daily check, malfunction diagnosis and wanted parameter variation
  Example: Profile measurement, in many cases 'intercepting' i.e destructive to the beam
- Complex instruments for severe malfunctions, accelerator commissioning & development
  The instrumentation might be destructive and complex
  Example: Emittance determination

General usage of beam instrumentation:

- Monitoring of beam parameters for operation, beam alignment, acc. development.....
- Instruments for automatic, active beam control
  Example: Closed orbit feedback using position measurement by BPMs

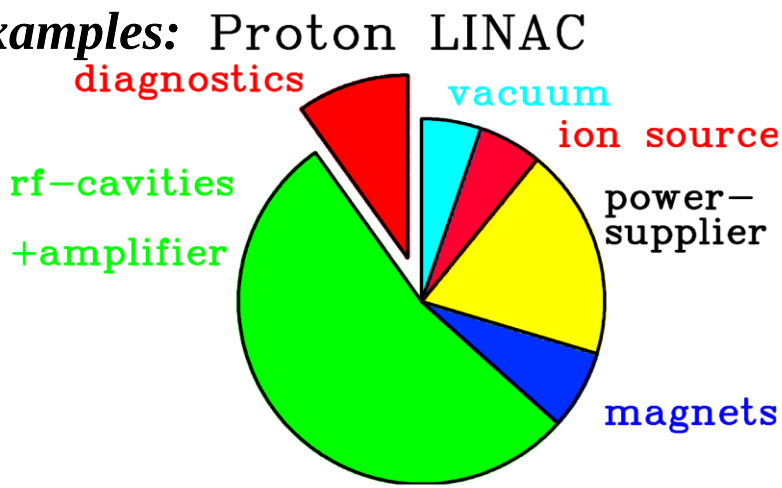
Non-destructive ('non-intercepting') methods are preferred:

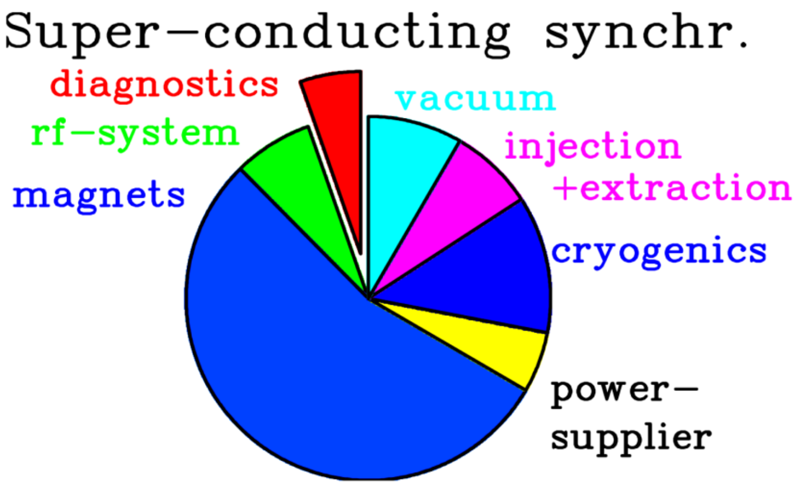
- The beam is not influenced
- The instrument is not destroyed

The cost of diagnostics is about 3 to 10 % of the total facility cost:

- ≈ 3 % for large accelerators ***or*** accelerators with standard technologies
- ≈ 10 % for versatile accelerators ***or*** novel accelerators and technologies.

Cost Examples:





The amount of man-power is about 10 to 20 %:

- very different physics and technologies are applied
- technologies have to be up-graded, e.g. data acquisition and analysis
- accelerator improvement calls for new diagnostic concepts.

Relevant physical Processes for Beam Diagnostics

- **Electro-magnetic influence by moving charges:**
  → **Physics: classical electro-dynamics. Technique: *U* and *I* meas., low & high frequencies**
  Examples: Faraday cups, beam transformers, pick-ups
- **Emission of photon by accelerated charges: (only for high relativistic electrons and p)**
  → **Physics: classical electro-dynamics. Technique: optical techniques (from visible to x-ray)**
  Example: Synchrotron radiation monitors
- **Interaction of particles with photons:**
  → **Physics: optics, lasers. Technique: optical techniques, particle detectors**
  Examples: laser scanners, short bunch length measurement, polarimeters
- **Coulomb interaction of charged particles with matter:**
  → **Physics: atomic and solid state physics. Technique: *I* meas., optics, particle detectors**
  Examples: scintillators, viewing screens, ionization chambers, residual gas monitors
- **Nuclear- or elementary particle physics interactions:**
  → **Physics: nuclear physics. Technique: particle detectors**
  Examples: beam loss monitors, polarimeters, luminosity monitors
- **And of cause accelerator physics for proper instrumentation layout.**

Beam diagnostics deals with the full spectrum of physics and technology,
⇒ this calls for experts on all these fields and is a challenging task!

LINAC & transport lines: Single pass ↔ **Synchrotron:** multi pass

Electrons: always relativistic ↔ **Protons/Ions:** non-relativistic for E_{kin} < 1 GeV/u

Depending on application: Low current ↔ high current

Overview of the most commonly used systems:

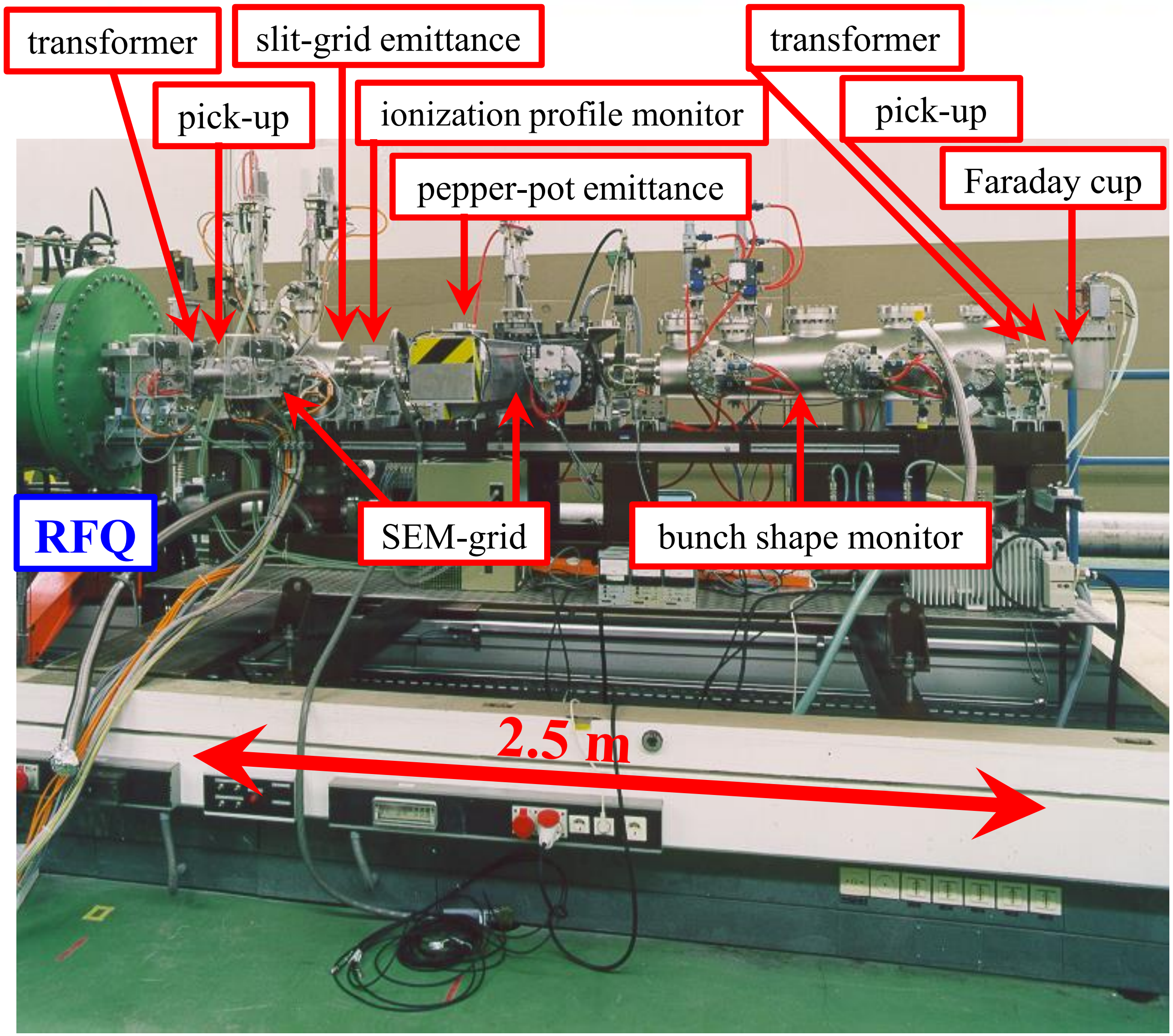
Beam quantity		LINAC & transfer line	Synchrotron
Current *I*	*General* *Special*	**Transformer, dc & ac** **Faraday Cup** **Particle Detectors**	**Transformer, dc & ac** Pick-up Signal (relative)
Profile x_{width}	*General* *Special*	**Screens, SEM-Grids** **Wire Scanners, OTR Screen** MWPC, **Fluorescence Light**	**Ionization Profile Monitor** **Wire Scanner,** **Synchrotron Light Monitor**
Position x_{cm}	*General* *Special*	**Pick-up (BPM)** Using position measurement	**Pick-up (BPM)**
Transverse Emittance ε_{trans}	*General* *Special*	**Slit-grid** **Quadrupole Variation** **Pepper-Pot**	**Ionization Profile Monitor** **Wire Scanner** Transverse Schottky

Beam Quantities and their Diagnostics II

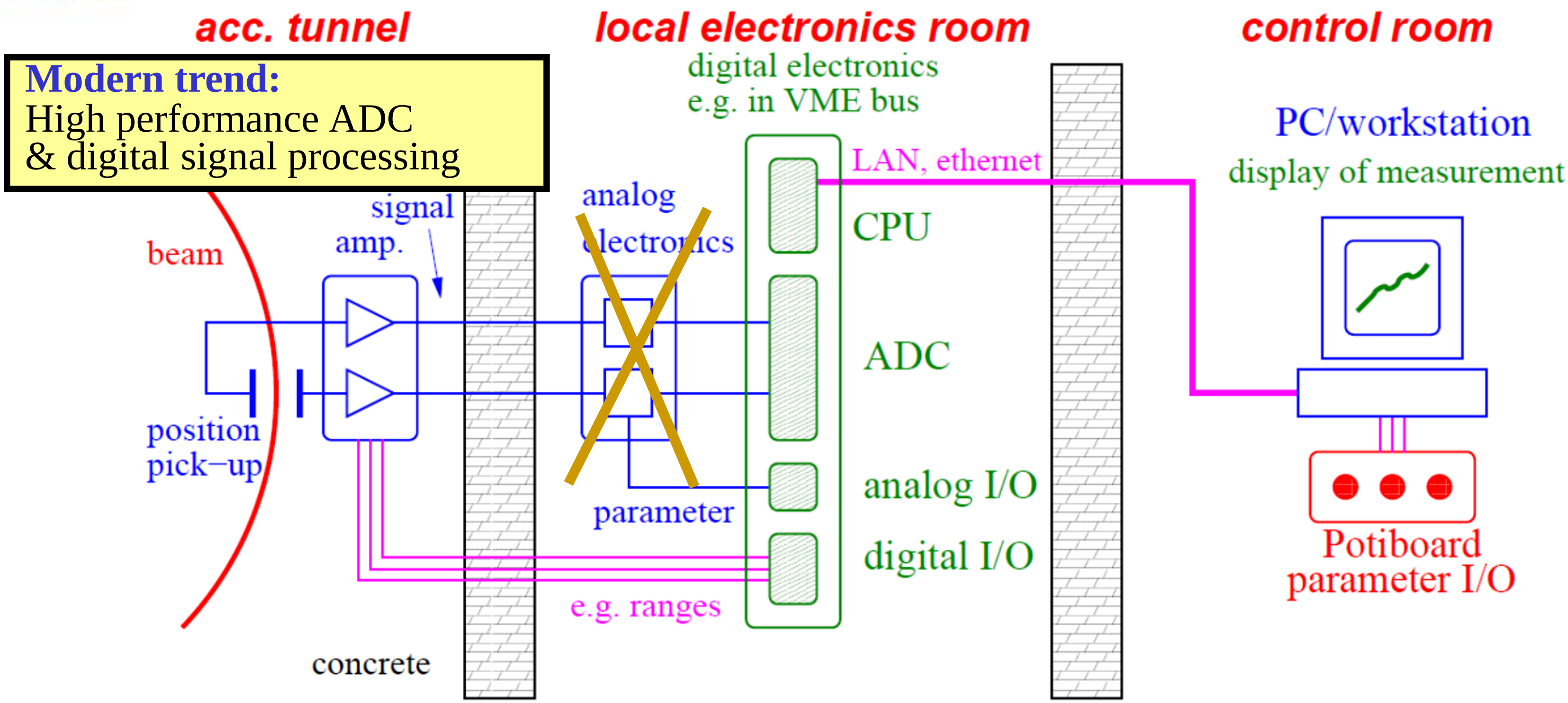
Beam quantity		LINAC & transfer line	Synchrotron
Bunch Length $\Delta\varphi$	*General* *Special*	**Pick-up** **Secondary electrons arrival** **Electro-optical laser mod.**	**Pick-up** **Wall Current Monitor** **Streak Camera** **Electro-optical laser mod.**
Momentum p **and Momentum Spread** $\Delta p/p$	*General* *Special*	**Pick-ups (Time-of-Flight)** Magnetic Spectrometer	**Pick-up (e.g. tomography)** Schottky Noise Spectrum
Longitudinal Emittance ε_{long}	*General* *Special*	**Buncher variation** Magnetic Spectrometer	 **Pick-up & tomography**
Tune and Chromaticity Q, ξ	*General* *Special*	--- ---	**Exciter + Pick-up** Transverse Schottky Spectrum
Beam Loss r_{loss}	*General*	**Particle Detectors**	
Polarization P	*General* *Special*	Particle Detectors Laser Scattering (Compton scattering)	
Luminosity L	*General*	Particle Detectors	

- Destructive and non-destructive devices depending on the beam parameter.
- Different techniques for the same quantity ↔ Same technique for the different quantities.

Example: Diagnostics Bench for the Commissioning of an RFQ



Typical Installation of a Diagnostics Device

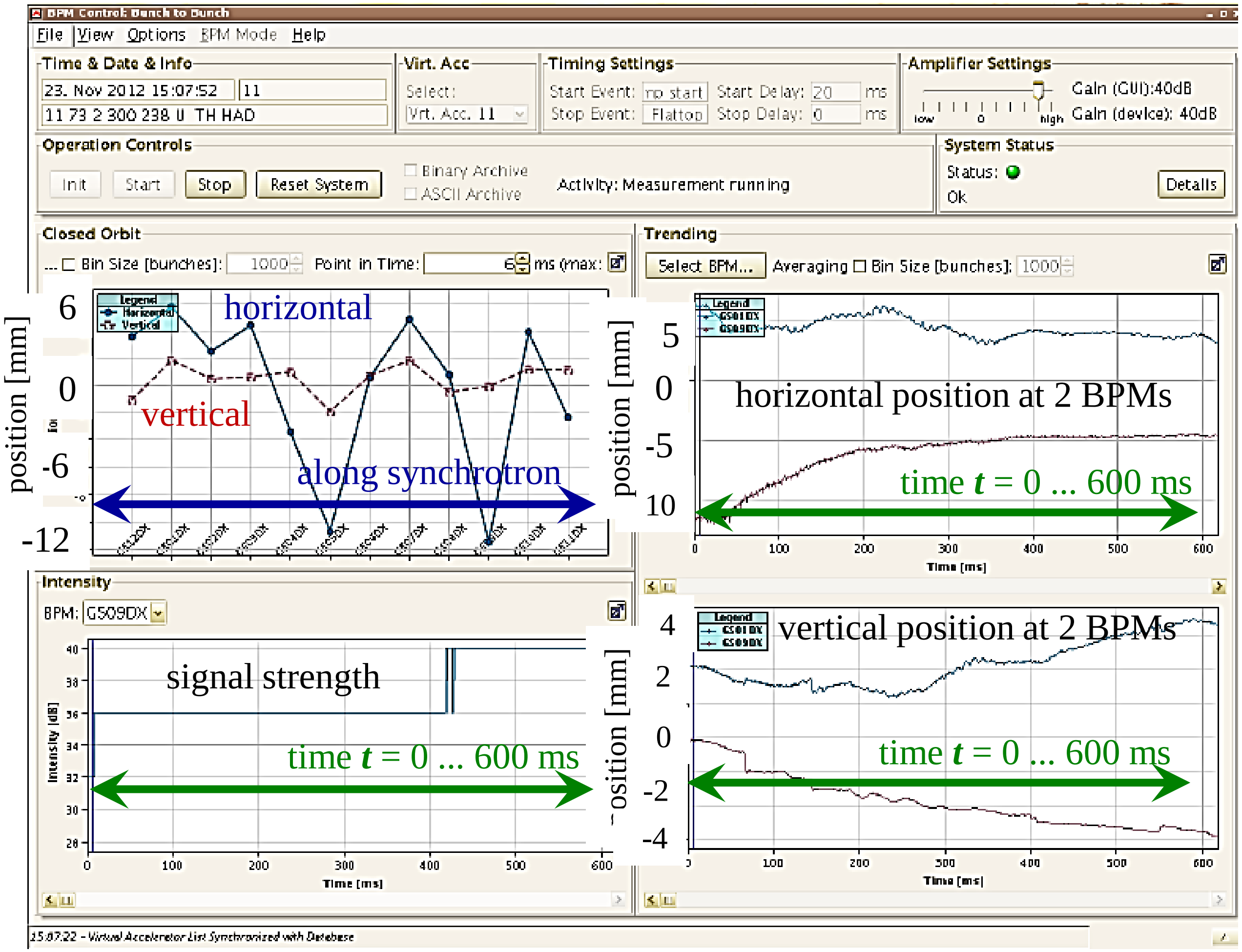


accelerator tunnel:
→ action of the beam to the detector
→ low noise pre-amplifier and first signal shaping

local electronics room:
→ analog treatment, partly combining other parameters
→ digitalization, data bus systems (GPIB, VME, cPCI, μTCA...)

control room:
→ visualization and storage on PC farm
→ parameter setting of the beam and the instruments

Single bunch position averaged over 1000 bunches → closed orbit with ms time steps.
It differs from ideal orbit by misalignments of the beam or components.
Example: GSI-synchrotron at two BPM locations, 1000 turn average during acceleration:



Closed orbit:
Beam position
averaged over many turns
(i.e. betatron oscillations).

The result helps to align the accelerator!
Some device parameters
are shown to prove functionality.

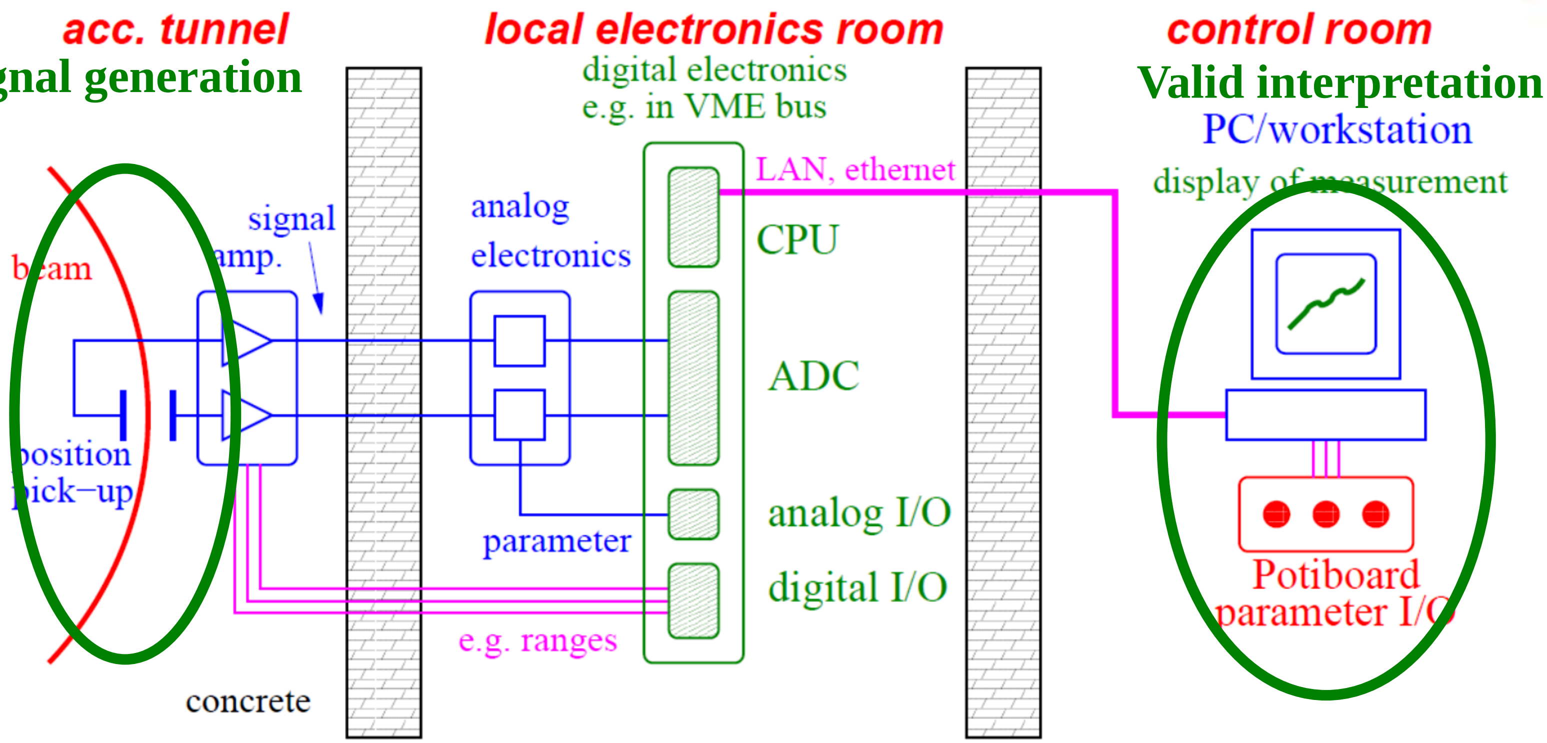
The ordering of the subjects is oriented by the beam quantities:

- **Current measurement:** Transformers, cups, particle detectors
- **Profile measurement:** Various methods depending on the beam properties
- **Transverse emittance measurement:** Destructive devices, determination by linear transformations
- **Pick-ups for bunched beams**: Principle and realization of rf pick-ups, closed orbit and tune measurements
- **Measurement of longitudinal parameters:** Beam energy with pick-ups, time structure of bunches for low and high beam energies, longitudinal emittance
- **Beam loss detection:** Secondary particle detection for optimization and protection

It will be discussed: The action of the beam to the detector, the design of the devices, generated raw data, partly analog electronics, results of the measurements.

It will not be discussed: Detailed signal-to-noise calculations, analog electronics, digital electronics, data acquisition and analysis, online and offline software....

General: Standard methods and equipment for stable beams with moderate intensities.

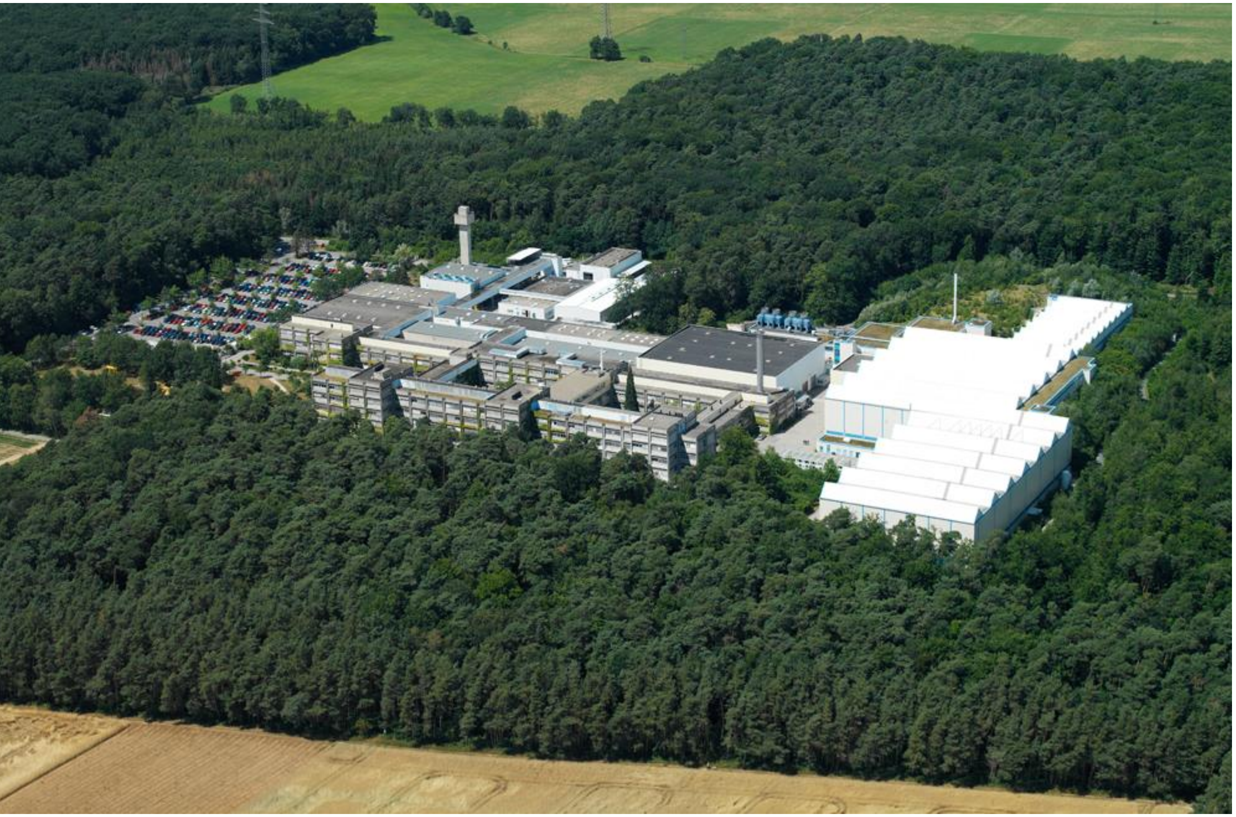


The goal of the lecture should be:

- **Understanding the signal generation of various device**
- **Showing examples for real beam behavior**
- **Enabling a correct interpretation of various measurements.**

Excurse: GSI Heavy Ion Research Center

German national heavy ion accelerator facility in Darmstadt



Accelerators:

Acceleration of all ions

LINAC: up to 15 MeV/u

Synchrotron: up to 2 GeV/u

Research area:

- Nuclear physics ≈ 60 %
- Atomic physics ≈ 20 %
- Bio physics (e.g. cell damage) incl. cancer therapy ≈ 10 %
- Material research ≈ 10 %

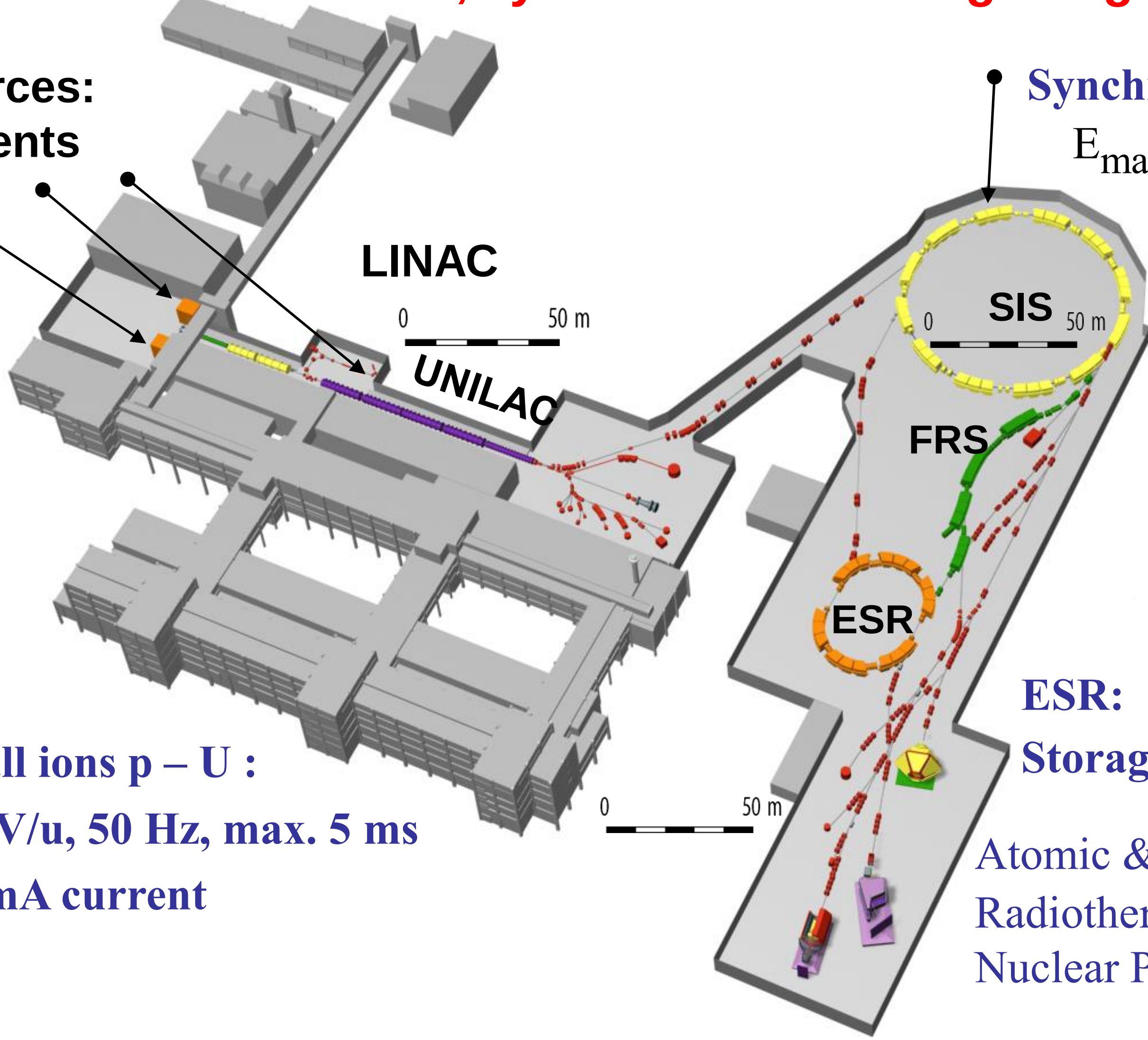
Extension by <u>international</u> FAIR facility

GSI is one of 18 German large scale research centers.

The Accelerator Facility at GSI

The GSI linear accelerator, synchrotron & storage ring for heavy ions

Ion Sources:
all elements



Synchrotron, Bρ=18 Tm

E_{max} p: 4.7 GeV
U: 1 GeV/u

Achieved e.g.:

Ar^{18+}: $1 \cdot 10^{11}$
U^{28+}: $3 \cdot 10^{10}$
U^{73+}: $1 \cdot 10^{10}$

ESR:
Storage Ring, Bρ=10 Tm

Atomic & Plasma Physics
Radiotherapy
Nuclear Physics

LINAC: all ions p – U :
3 – 12 MeV/u, 50 Hz, max. 5 ms
Up to 20 mA current