High Current Diagnostics at the GSI Heavy Ion LINAC and Synchrotron

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Used diagnostics at the GSI facility: (disregarding slow extraction)

Beam quantity	**LINAC**	**Synchrotron**
current I	**ac-transformer**	**ac- and dc-transformer**
profile x_{width}	SEM-grid residual gas monitor **residual gas fluorescence**	**residual gas monitor**
trans. emittance ϵ_{trans}	**slit grid** **pepper-pot**	residual gas monitor transverse Schottky
position x_{cms}	pick-up	pick-up
long. para. φ_{width}, $\Delta p/p$	pick-up **particle detector** bunch shape monitor	pick-up **longitudinal Schottky** tomography
tune Q etc.		exciter + pick-up (BTF) transverse Schottky
beam loss r_{loss}		**plastic scintillator**

The GSI heavy ion facility

Heavy ions are accelerated to about 18 MeV/u (LINAC) or 2 GeV/u (synchrotron)

The LINAC 'UNILAC', 50 Hz and up to 5 ms

- Ion sources: Penning, MUCIS (gas) or MEVVA (metals): up to 20 mA
- RFQ and IH (2.2 keV/u to 1.4 MeV/u) for **high current** , 36 MHz
- Alternative: ECR source (low current) and RFQ/IH, 108 MHz
- Alvarez structure up to 11.4 MeV/u, 108 MHz
- 15 einzel-resonators up to 18 MeV/u, 108 MHz

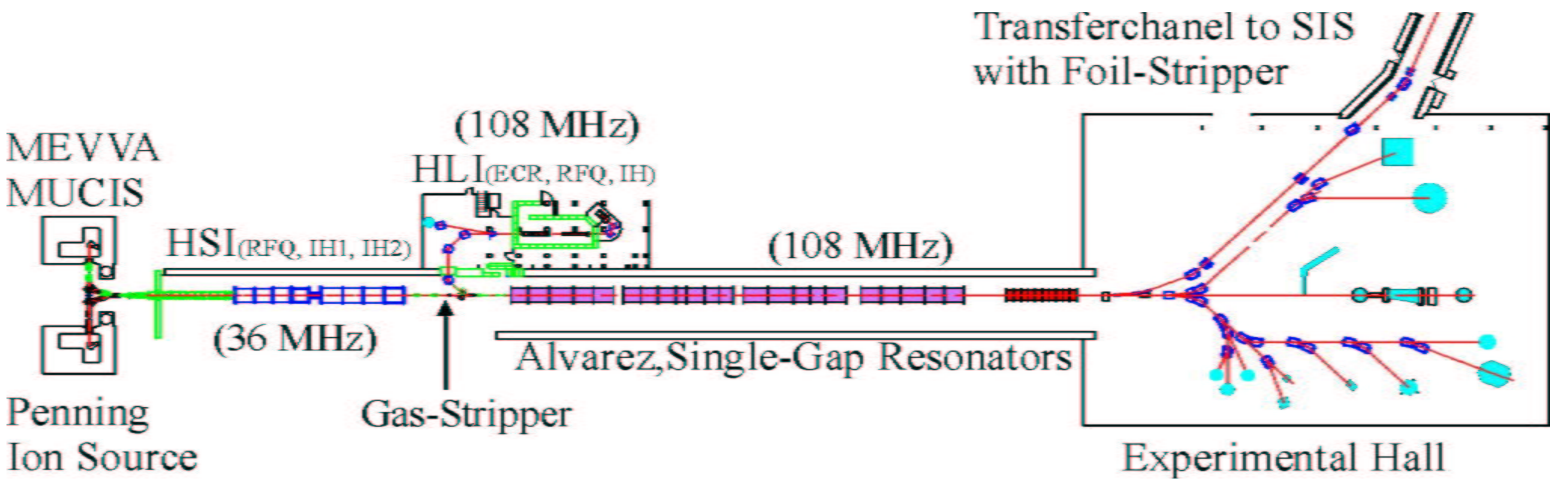
The synchrotron 'SIS'

- maximum energy 2GeV/u for q/A=1/2
- maximum rigidity $B\rho = 18$ Tm
- currents up to 10^{11} particles (space charge limit)

The storage ring 'ESR'

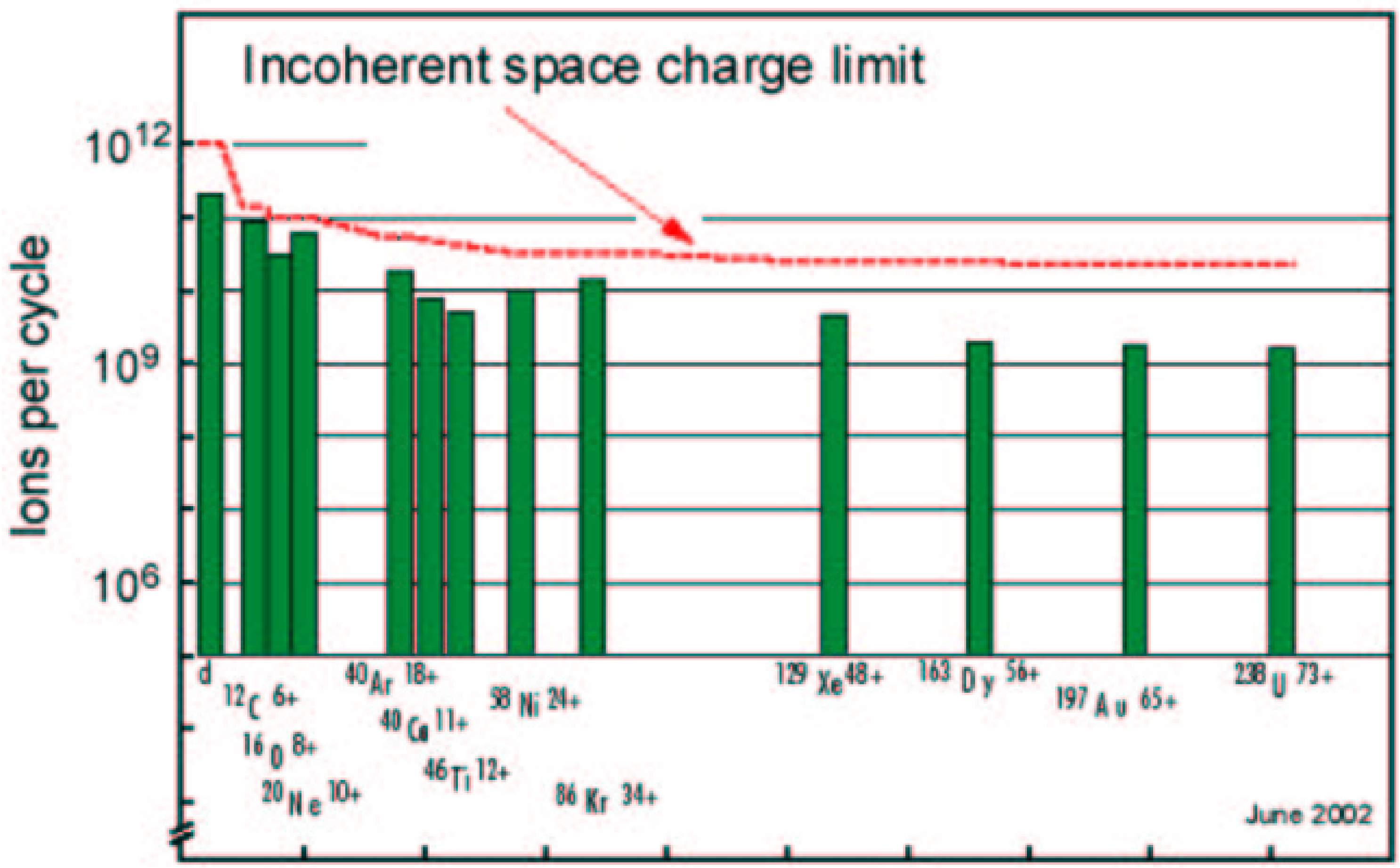
- Accelerator development: e.g. beam cooling (electron, stochastic)
- Atomic and nuclear physics experiments with circulating beams

The high current LINAC: Design parameters for Uranium



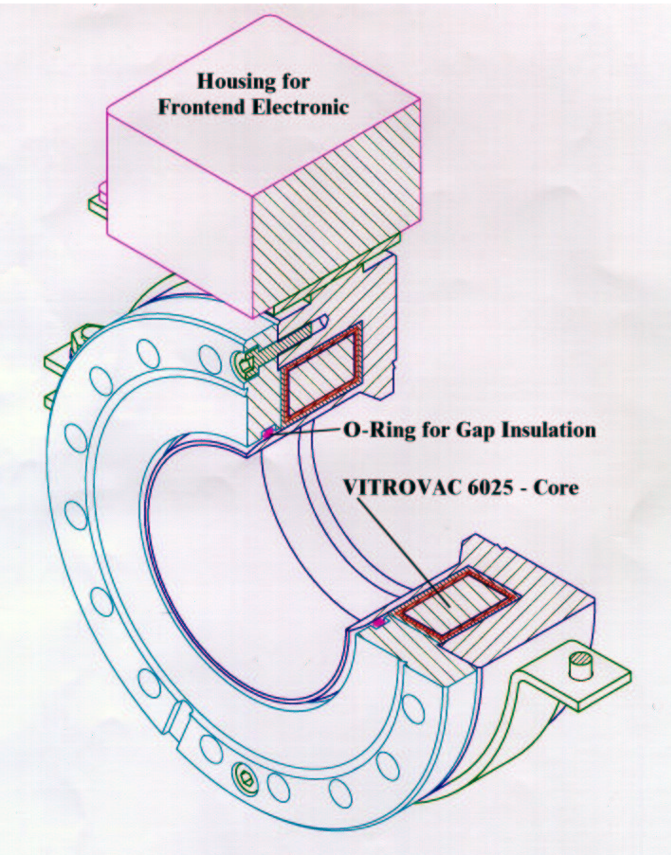
cavity	RFQ in	IH2 out	Alv. out	SIS in
Energy [MeV/u]	0.0022	1.4	11.4	11.4
Ion species	U^{4+}	U^{4+}	U^{28+}	U^{73+}
Electrical current [mA]	16	15	12	4
Part. per 100 μs	$3 \cdot 10^{12}$	$2 \cdot 10^{12}$	$2 \cdot 10^{11}$	$4 \cdot 10^{10}$
Beam power per 100 μs [MW]	0.003	1.1	0.9	0.2
Energy spread $\Delta W/W$	–	$\pm 4 \cdot 10^{-3}$	$\pm 2 \cdot 10^{-3}$	$\pm 2 \cdot 10^{-3}$
Norm. emit. $\epsilon_{norm,x}$ [mm mrad]	0.3	0.5	0.75	0.8
Norm. emit. $\epsilon_{norm,y}$ [mm mrad]	0.3	0.5	0.75	2.5 (accept)

The expected SIS currents → filling to space charge limit



Development of SIS beam intensities

Active pulse current transformer for LINAC

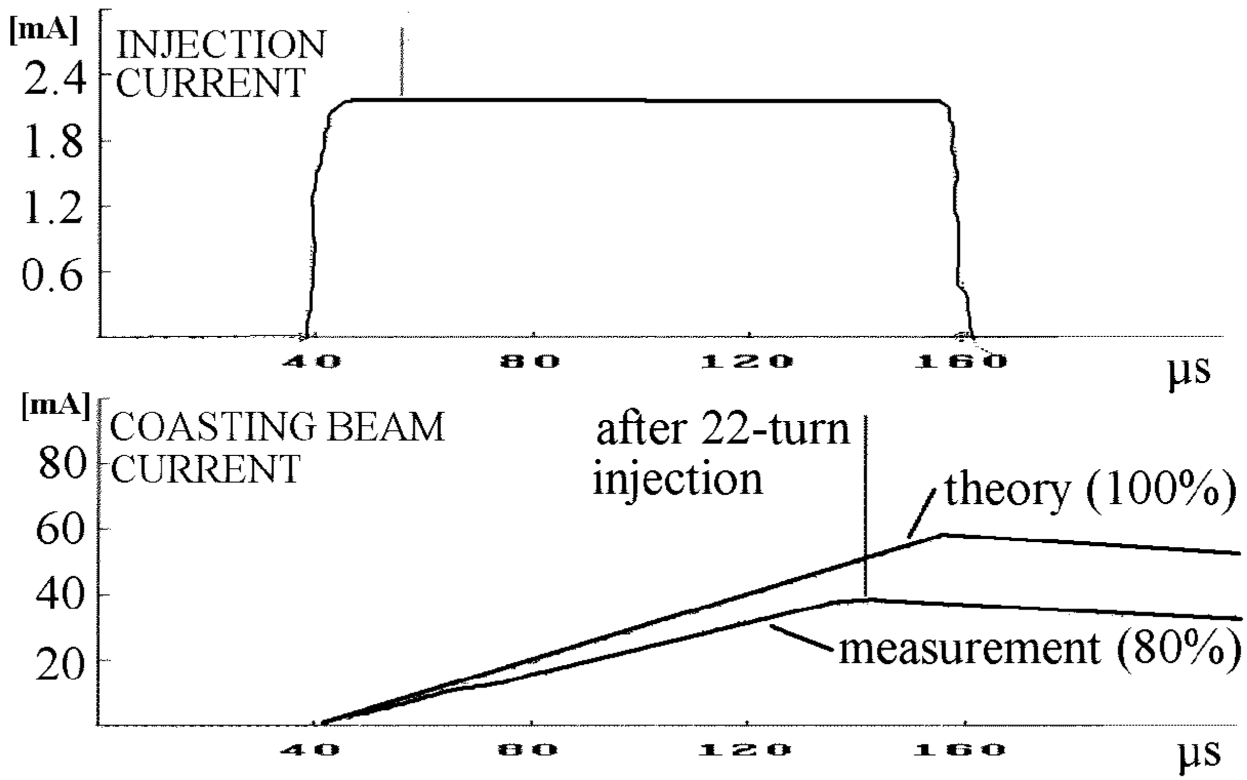


Inner core radii	$r_{in} = 30$ mm
Outer core radii	$r_{out} = 45$ mm
Core thickness	$l = 25$ mm
Core material	Vitrovac 6025, $\mu_r \simeq 10^5$ $(CoFe)_{70\%}(MoSiB)_{30\%}$
Number of windings	2×10 crossed
Beam current range	10 μA to 100 mA
Resolution	0.2 μA_{rms} (full BW)
Bandwidth	500 kHz
Droop	< 0.5 % for 5 ms
digitalization rate	10 MHz

The transformers are used (nearly) everywhere, substituting Faraday Cups.

Online control of transmission to prevent damage of the intersecting devices:
Analog output → U/F converter → up or down counter
Two consecutive transformers are compared by digital comparator
⟶ if the difference is above a calculated threshold the beam is aborted by a copper.

AC-transformers for multi-turn injection into SIS synchrotron



One transformer is located in the transfer line
the second in the synchrotron.

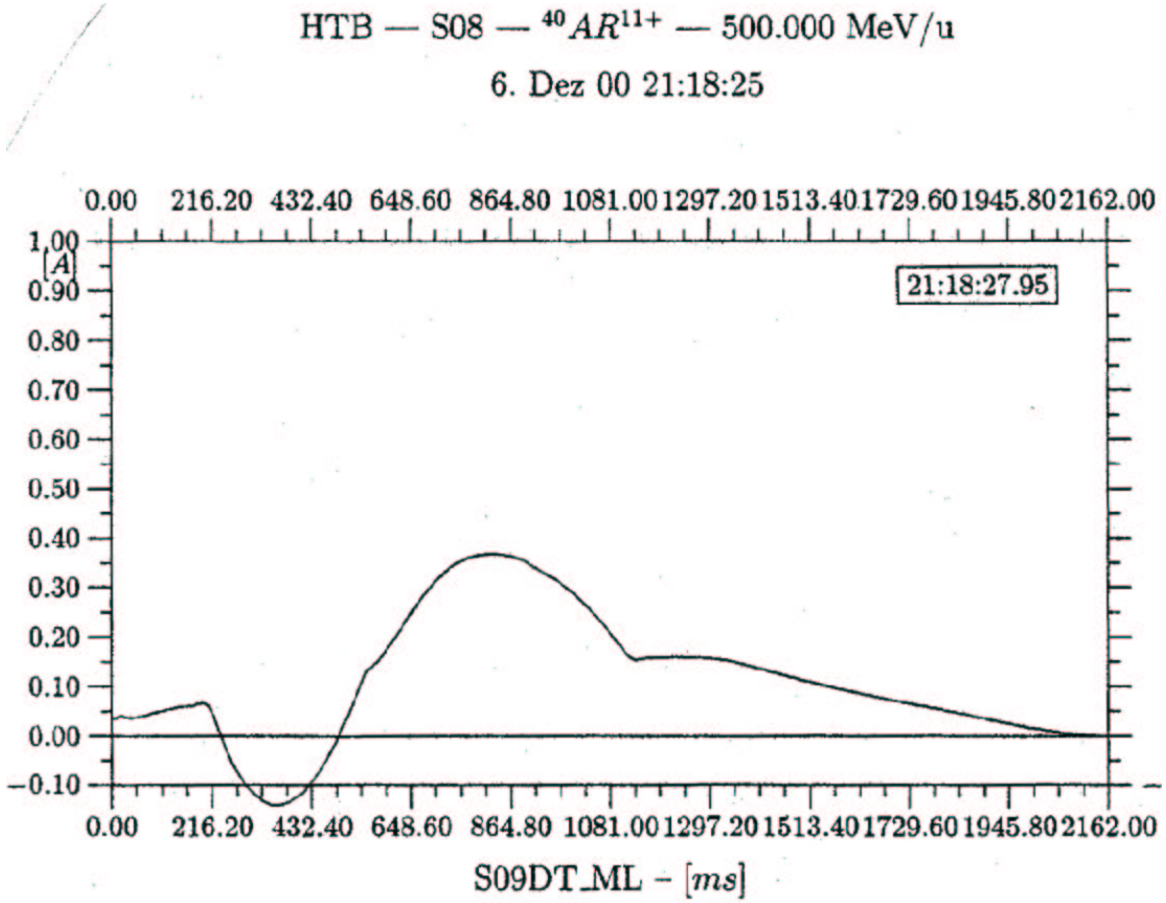
The efficiency of the multi-turn injection has to be optimized.

The dc-transformer for synchrotron

The most important online device for synchrotron!
It runs (nearly) without *any* problems!

full scale: 1 A
resolution: 2 μA

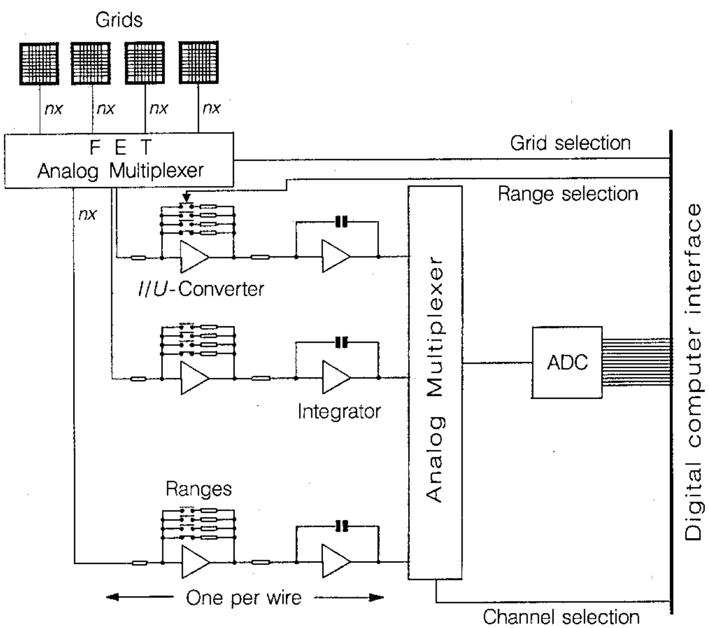
General problem:
For high **bunched** currents (100 mA dc)
→ feedback loop runs in a resonance.
(bunch 0.5 to 2 MHz)
→ can **not** be solved by improvement of control loop parameters.



SEM grids for profiling at LINAC and fast extraction

Specification of a SEM-grid for the GSI-LINAC:

Diameter of the wires	0.1 mm
Spacing	1 mm (typ.)
Length	100 mm (typ.)
Material	W-Re alloy
Insulation of the frame	Al_2O_3
number of wires	32 (typ.)
Max. power rating in vacuum	1 W/mm
Min. sensitivity of I/U-conv.	1 nA/V
Dynamic range	$1:10^6$
Number of ranges	10 typ.
Integration time	0.5 or 5 ms



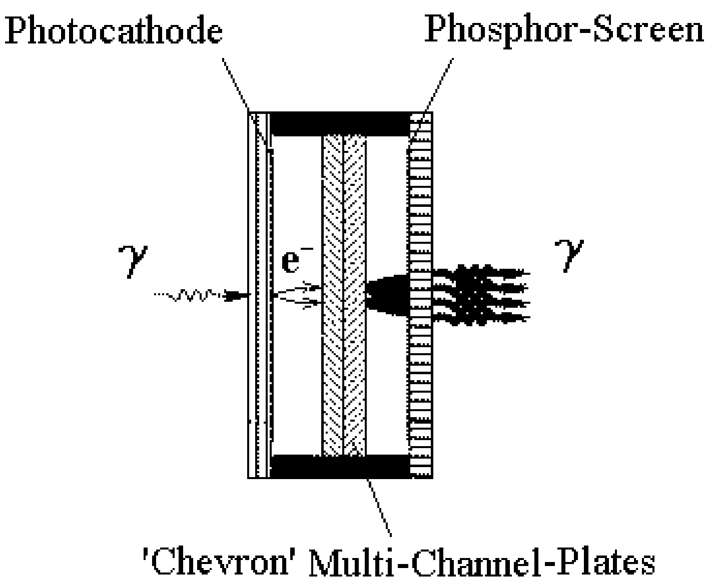
Low energy beam: Ratio of spacing/thickness $\simeq 10 \rightarrow$ only 10 % loss.
The standard method so far.

To prevent damage: The macro-pulse is shorted dynamically by the copper as determined by the ac-transformer (U/f-conv. + up/down counter + digital comparator).

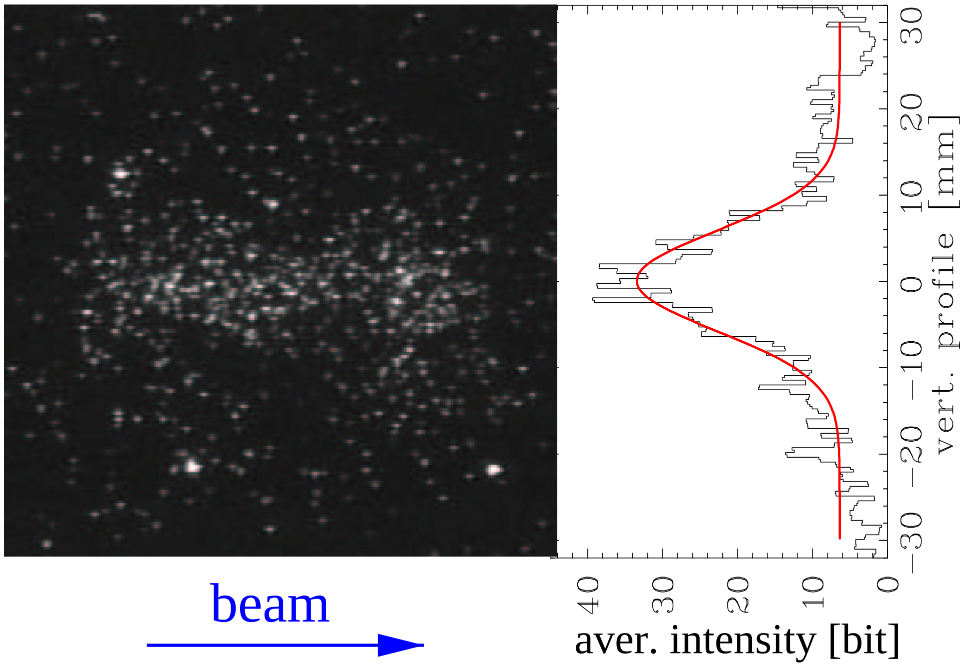
First tests with residual fluorescence monitor

Due to the beam's energy loss, the residual gas molecules are excited to fluorescent levels:
$\longrightarrow$ N_2 and N_2^+ between 390 nm $< \lambda <$ 470 nm.

Image intensifier:
photo cathode S20 + Chevron-MCP
+ phosphor screen P46



Ar^{11+} beam $I = 700\ \mu$A,
$t = 200\mu$s, $E_{kin} = 6$ MeV/u, $p = 10^{-5}$ mbar



Number of photons: $N_{photon} \propto \frac{dE}{ds} \Delta s \cdot p \cdot \frac{f}{h\nu} \cdot \frac{\Omega}{4\pi} \cdot \frac{I_{beam}}{qe}$

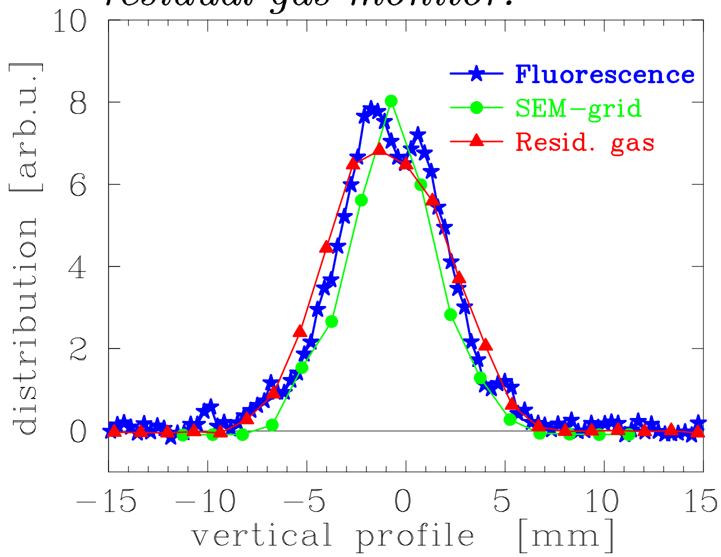
Advantage: Nothing installed in the vacuum pipe.

Further results of residual fluorescence monitor

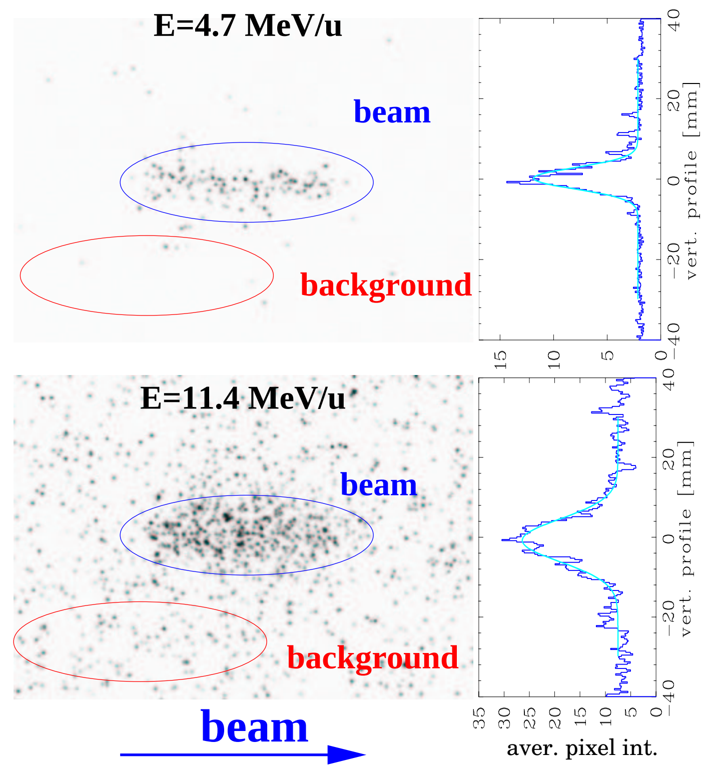
Possible Problems:

- Ruination of the CCD by neutron or γ rays
- Some background due to neutron or γ rays:

Comparison to SEM-grid and residual gas monitor:



Good correspondence!



The amount of (diffuse) background is energy dependent.

Residual gas monitor

Ion detection with $E \sim 1$ kV/cm are used at GSI:

LINAC type:

- no MCP due to high pulse current and $p \sim 10^{-7}$ mbar
- 23 strip readout on slitted PCB
- *no* significant broadening due to large beam size

SIS synchrotron type:

- Chevron MCP due $p \sim 10^{-11}$ mbar
- large aperture
  (due to multi-turn injection)
- 63 strip readout, 0.5 ms integration

ESR storage ring type:

- installed inside a dipole magnet
- Chevron MCP due $p \sim 10^{-11}$ mbar
- wedge and strip readout (ions)
  particle detector electronics (μs integr.)
- vertical profile: TOF ions – e^-
- *Problem:* Small distance to vacuum chamber → noise due to rf-pick-up

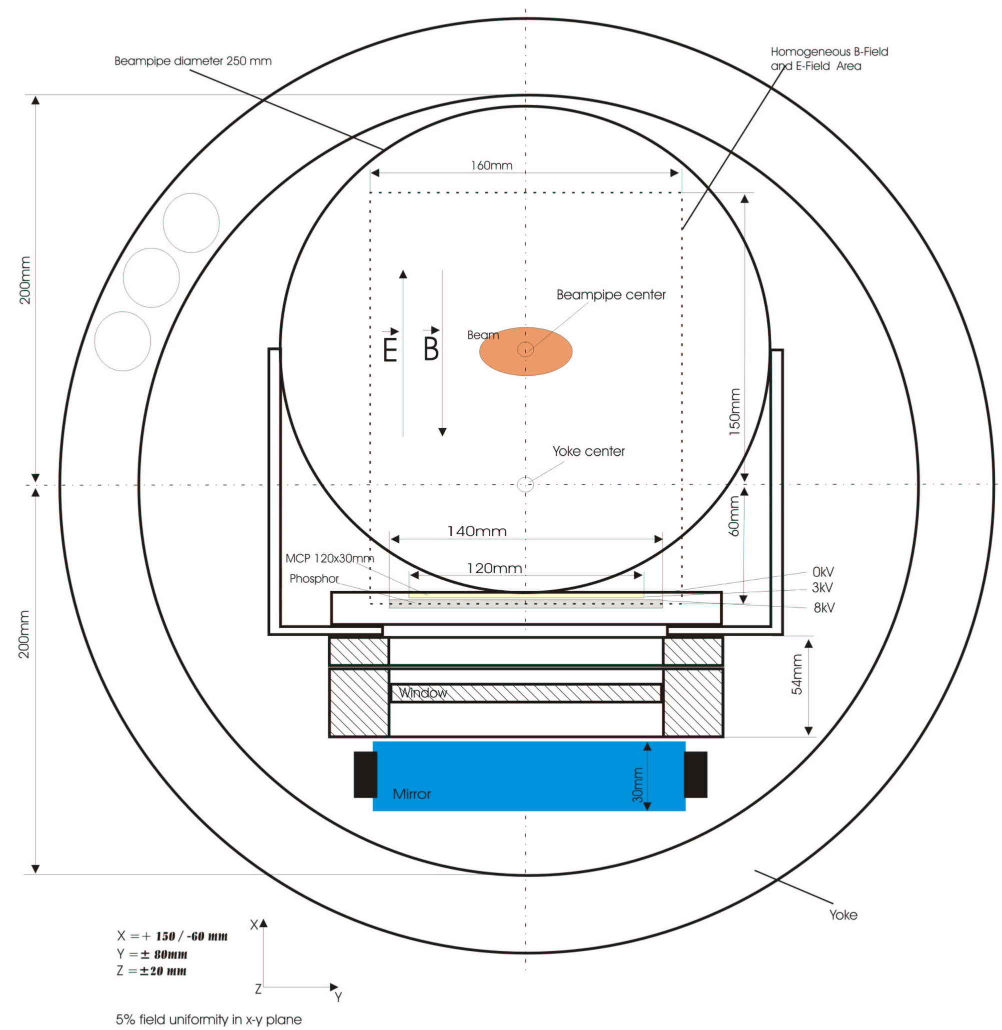
New development:

$\vec{E} \| \vec{B}$ monitor (with permanent magnets or coils) are foreseen.
Revolution synchronous readout for injection mismatch.

Idea of new residual gas monitor for synchrotron

- *Best* readout by
  MCP + phosphor + CCD
  ⇒ high resolution
- Fast readout
  (revolution synchronous)
  ⇒ injection mismatch
  → fast avalanche diodes
- Due to space charge
  a magnetic field is needed:
  Using permanent magnets ?
  Compact design ?

(Possible collaboration with Skachkov, Liakin et al., ITEP)



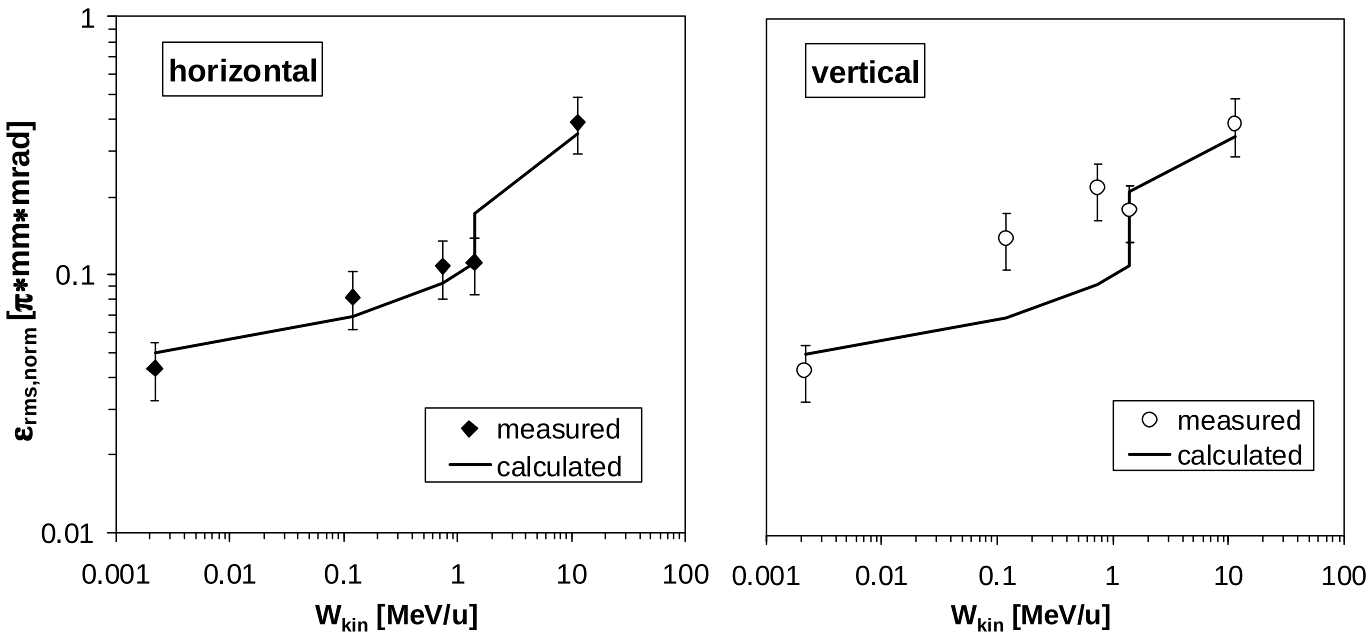
Transversal emittance: slit-grid device

Direct determination of position and angle distribution.

Slit width: 0.1 mm

SEM-grid: 1mm spacing, but step motor driven intermediate positions

The working horse, but only for short pulses:

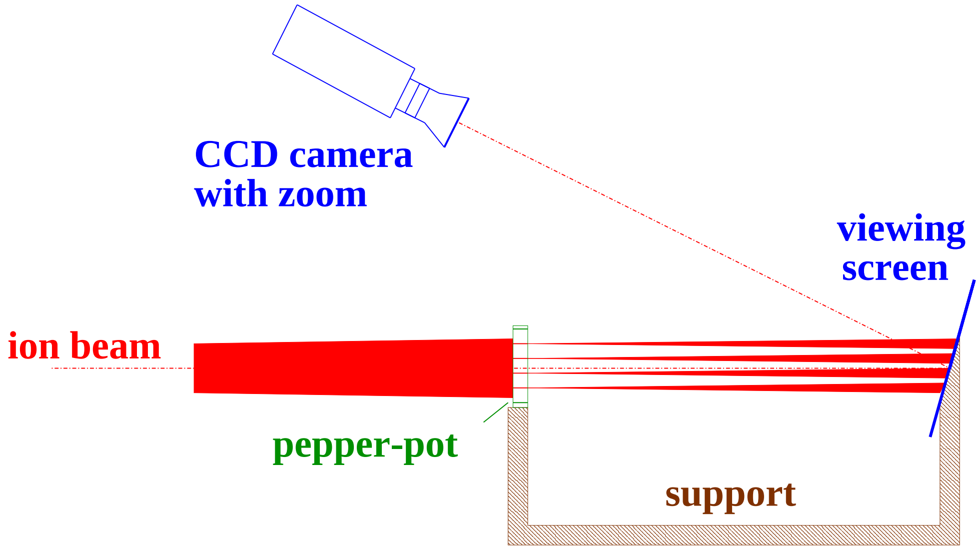


Emittance blow-up due to space charge forces.

Parameters: 10 mA Ar^{1+} up to 1.4 MeV/u, 7 mA Ar^{10+} form 1.4 MeV/u to 11.4 MeV/u

Transversal emittance: the pepper-pot device

Measurement within *one* LINAC pulse!



Pepper-pot: 15 × 15 holes with 0.1 mm diameter on a 50 × 50 mm^2 copper plate

Screen: Al_2O_3 25 cm from the pepper-pot

Data acquisition: high resolution CCD camera

Data analysis: Projection one hor. and vert. axis; i.e. same as slit-grid

Calibration: Using HeNe laser to determine the image of the holes

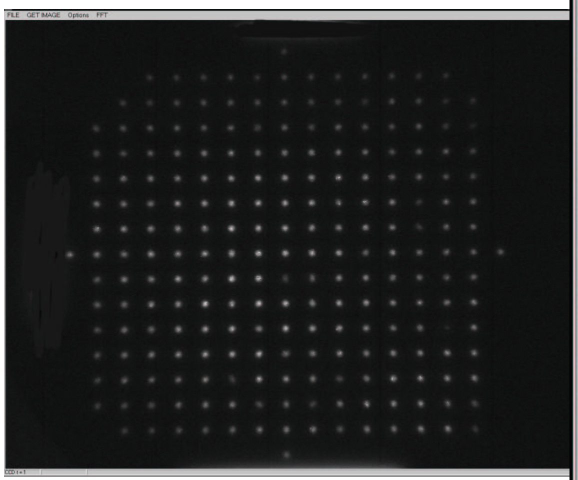
Good spatial resolution if many holes are illuminated.

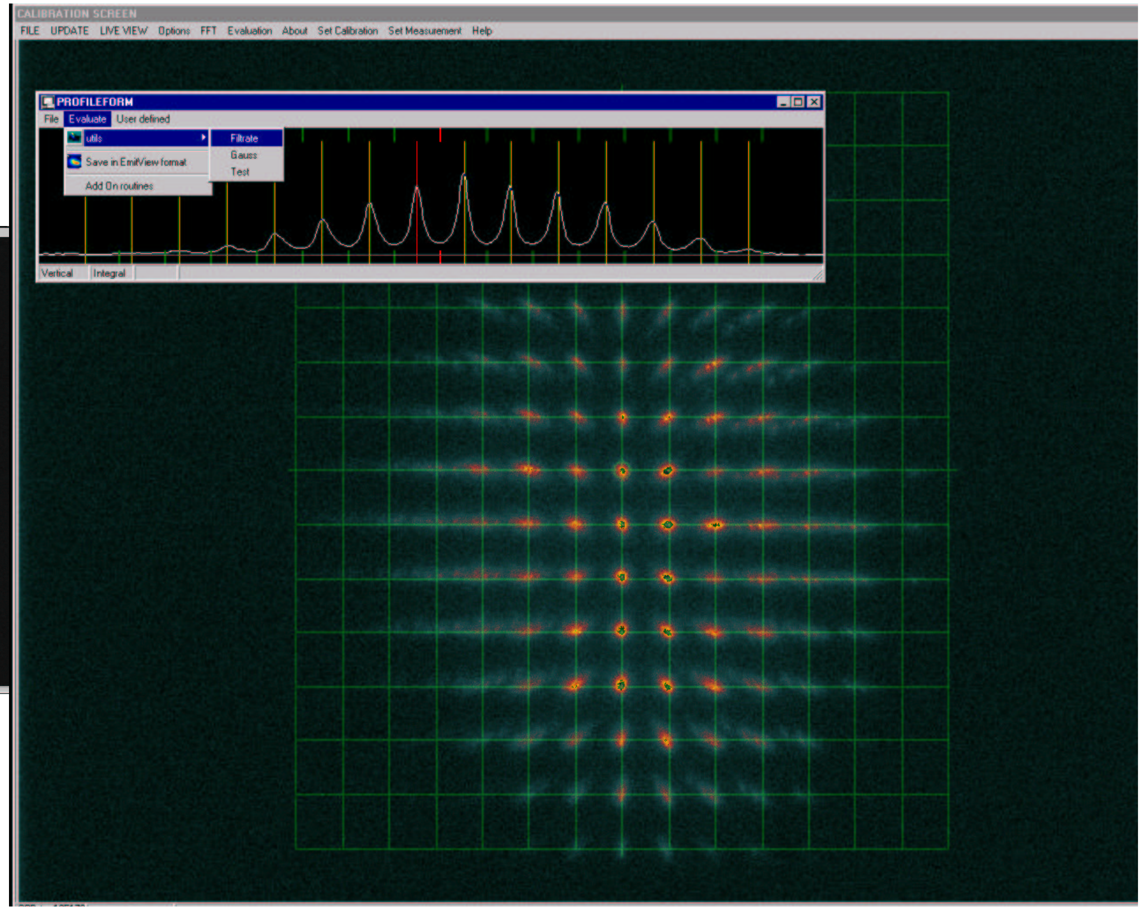
Problem due to viewing screen: No good scintillator found, which tolerate high current.

Results of a pepper-pot measurement

Ar^{1+} ion beam at 1.4 MeV/u:

Laser image for calibration:





Optical saturation or internal light scattering
→ factor 1.5 larger result as compared to slit-grid.

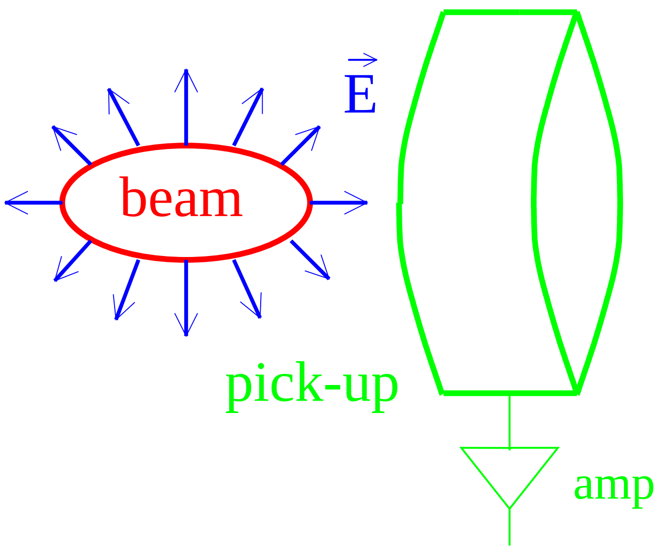
Bunch structure at low E_{kin}: Not Possible with pick-ups

Pick-ups:

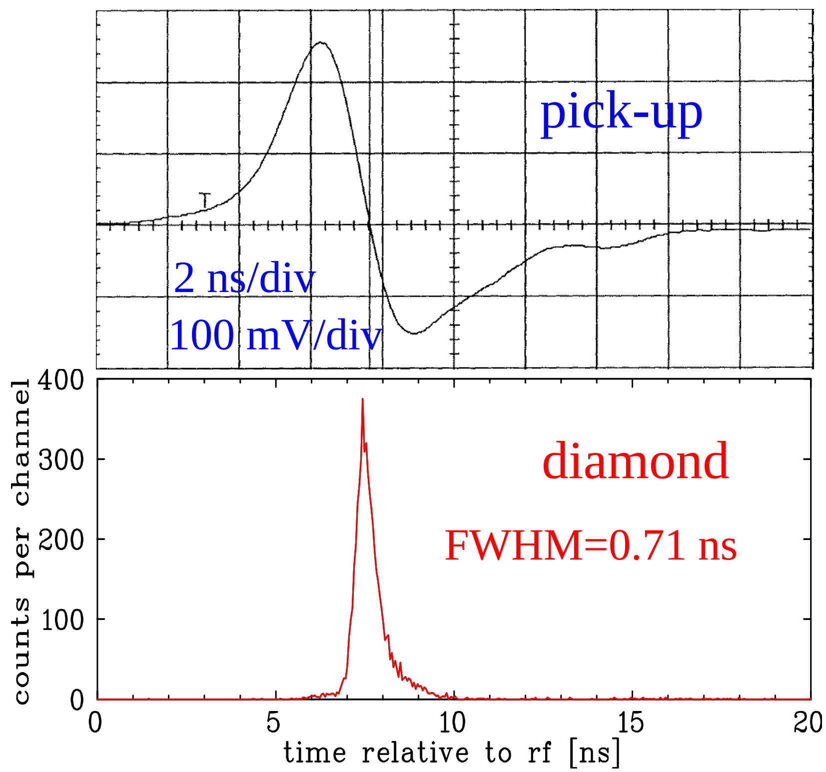
- precise for bunch-center relative to rf
- course image of bunch shape
- electrical field is measured via image charge

But:

For $\beta \ll 1 \Rightarrow$ long. $\vec{E}$ field



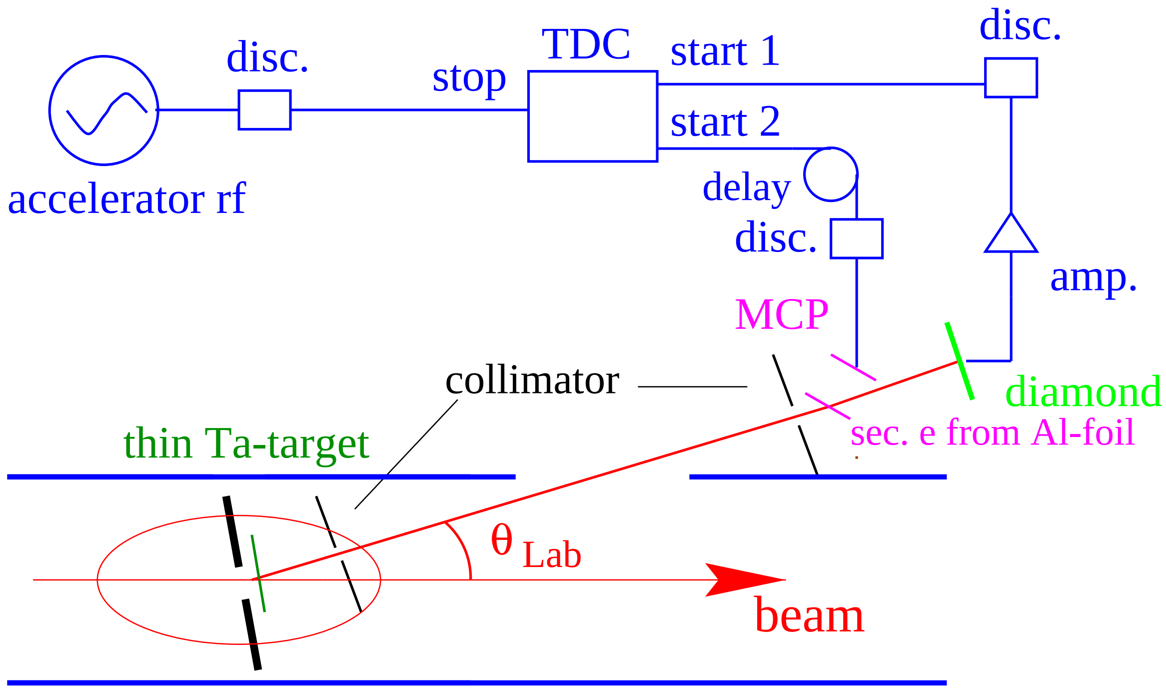
Comparison pick-up – particle counter:
Ar^{1+} with 1.4 MeV/u ($\beta = 5.5\%$)



$\Rightarrow$ the pick-up signal is independent on 'fine-structure'

TOF with particle detector

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



Less than *one* particle per bunch is required due to single particle counting:

→ Foil (Tantalum 130 nm) for attenuation $\sim 10^{-9}$ by Rutherford scattering and finite solid angle ($\Delta\Omega_{lab} = 2.5 \cdot 10^{-4}$).

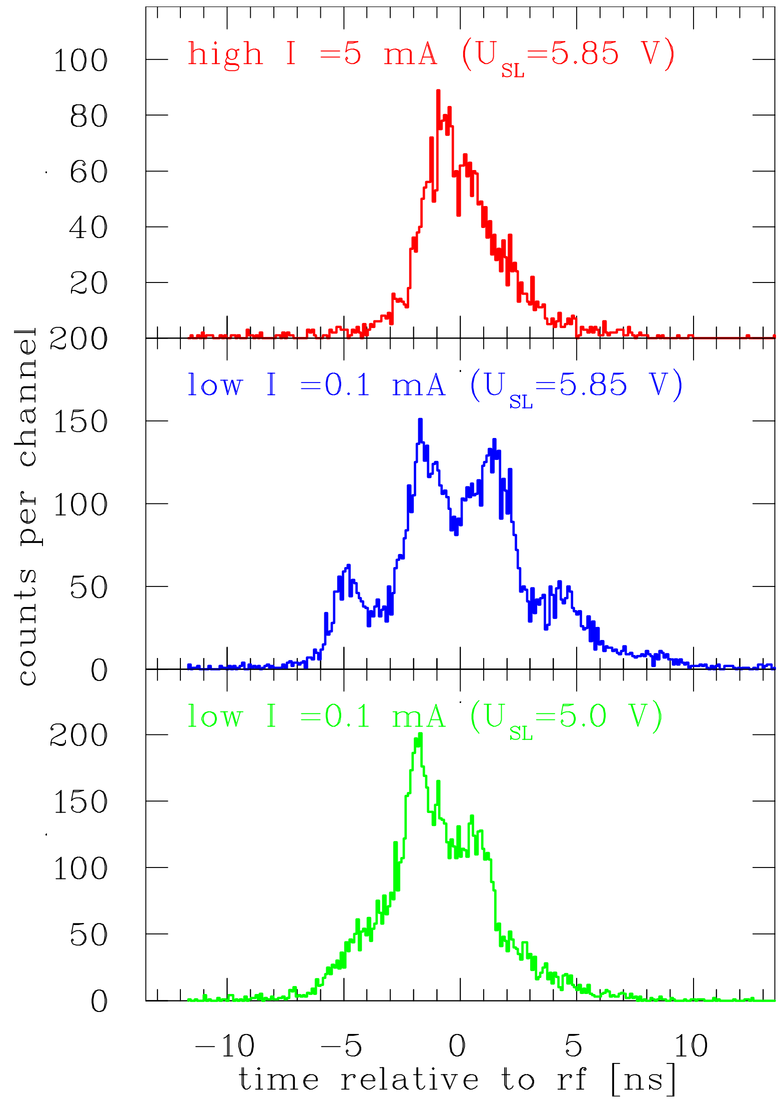
→ Fast detector with 1 ns pulse width (MCP+50Ω anode, diamond).

→ Time relative to rf, resolution less than 25 ps (corresponding to 0.3^o in phase).

→ Second detector with thin Al foil (50 nm) for secondary e^- acc. toward an MCP
⇒ determination of phase and energy of individual particles.

Results for a bunch structure behind RFQ at $E_{kin} = 120$ keV/u

The bunch structure is dependent on the amplitude or phase setting
→ wrong bunching (RFQ),
emittance blow-up, filamentation...



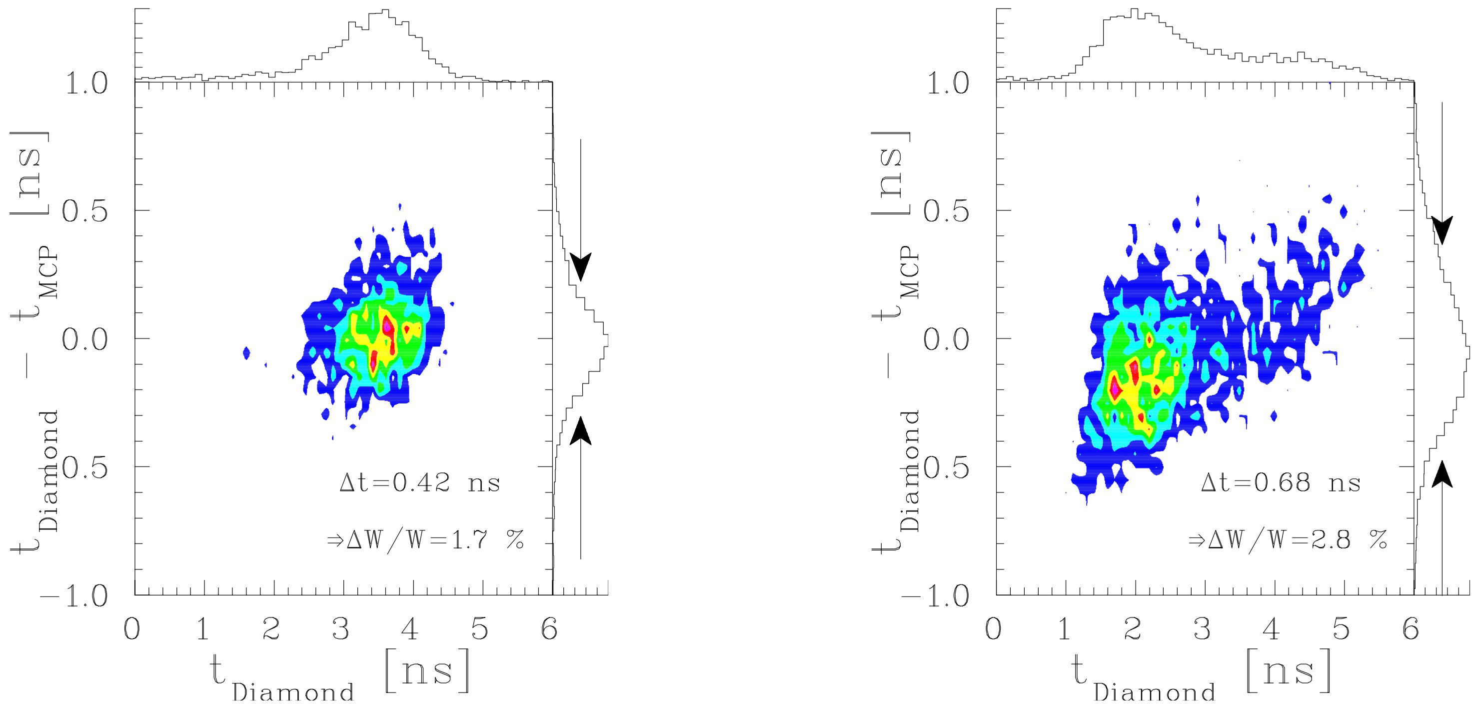
The bunch shape at 120 keV/u RFQ with different rf amplitudes and currents. One rf-period is shown.

→ **Significant emittance blow-up at low energy acceleration.**

Results for longitudinal emittance at low E_{kin}

Using two detectors *in coincidence* and a drift space in between, the phase and the energy of a *individual* particle can be determined.
⇒ for many particles the longitudinal phase space can be spanned.

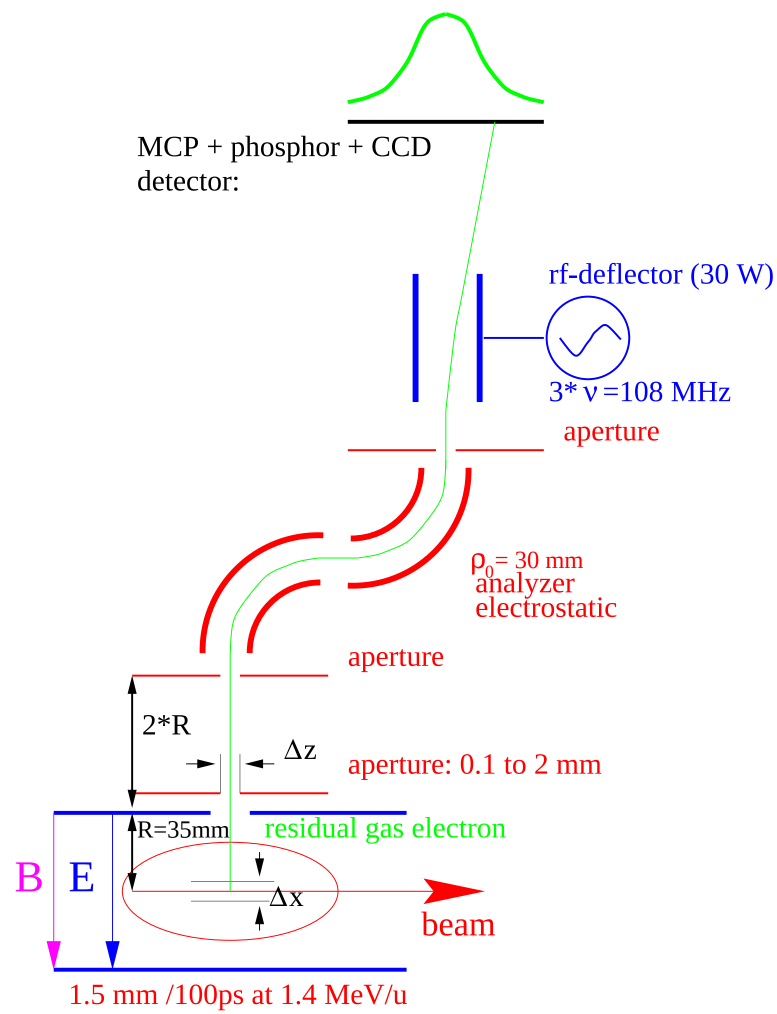
GSI-LINAC at 1.4 MeV/u with low and high current Ar beam behind the stripper (nominally $Ar^{1+} \rightarrow Ar^{10+}$). The effect of the emittance blow-up due to the large charge-density in the stripper region is seen.



Detector resolution $\sim 10ps$ ⇒ useful for lower energies and lower rf frequencies.

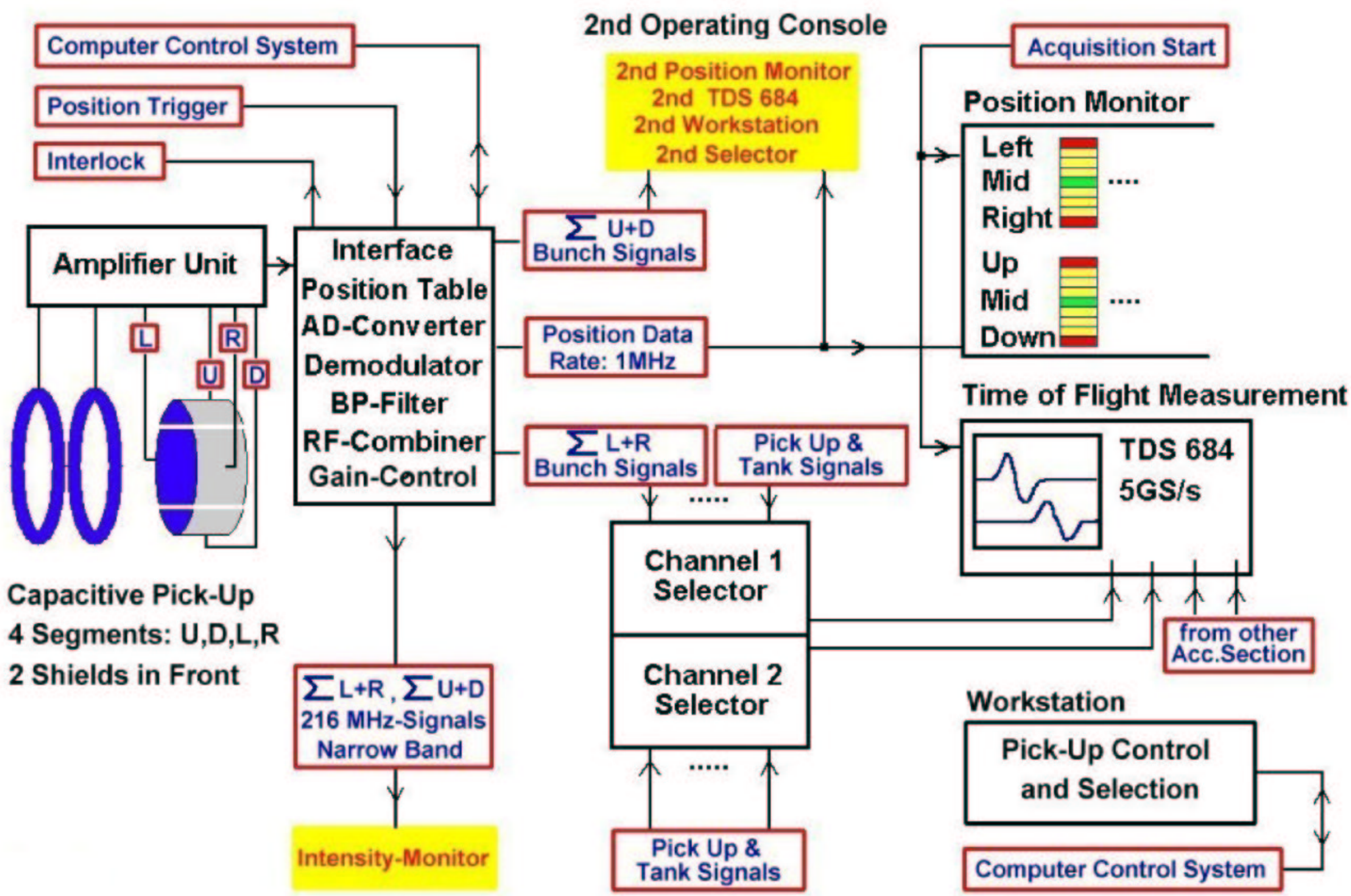
Idea for *non-intersecting* bunch shape measurement

- electron acceleration done by homogeneous electric field ($\mathcal{E} = 5$ kV/cm)
- target location done by electrostatic analyzer ($\Delta x = 0.5..2$ mm)
- rf-deflector as time-to-space converter
- readout by MCP + phosphor + CCD
- measurement done within one macro-pulse
- magnetic field might necessary: space charge of ion beam influence the electron's path
- complex device : in preparation



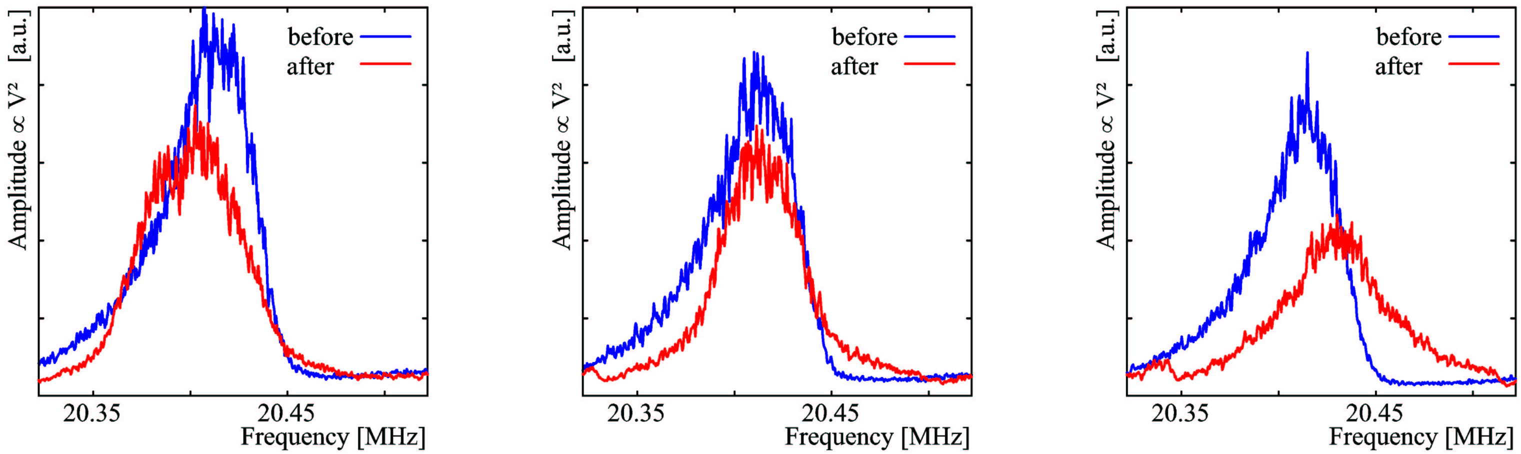
Online position control at LINAC: BPM

BPM are used for: Position, bunch shape and energy (TOF) measurements:

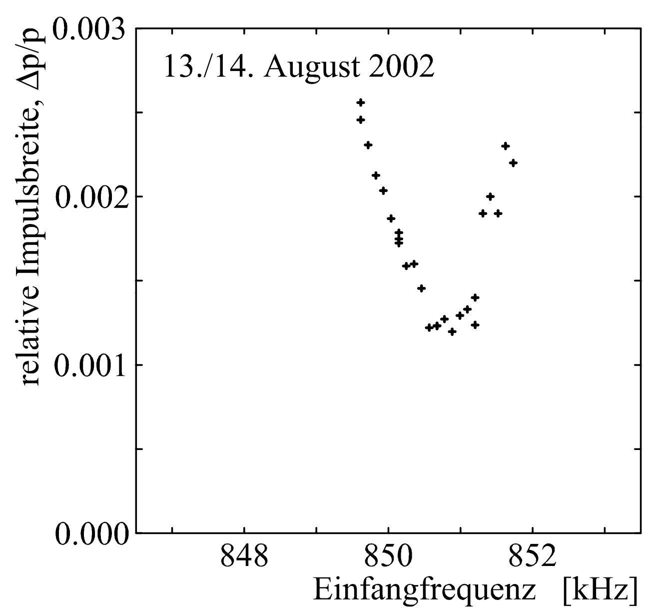


Schottky scans for momentum spread

Long. Schottky spectrum (cw beam) before / after rf-capture + dedunching:



With slightly detuned rf frequency
a emittance blow up is visible:
$\Rightarrow$ control of right synchrotron rf
$\Rightarrow$ $\Delta p/p$ i.e rebuncher setting from LINAC.
Also control of adiabatic rf-capture.

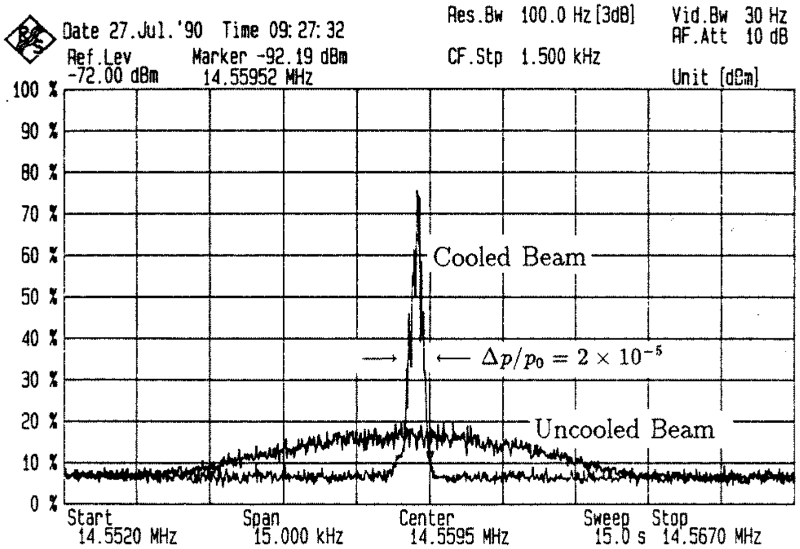


Further use of Schottky scan:

- Control of cooling
- Tune and transverse emittance by *transverse* Schottky

Schottky scans for momentum spread and tune

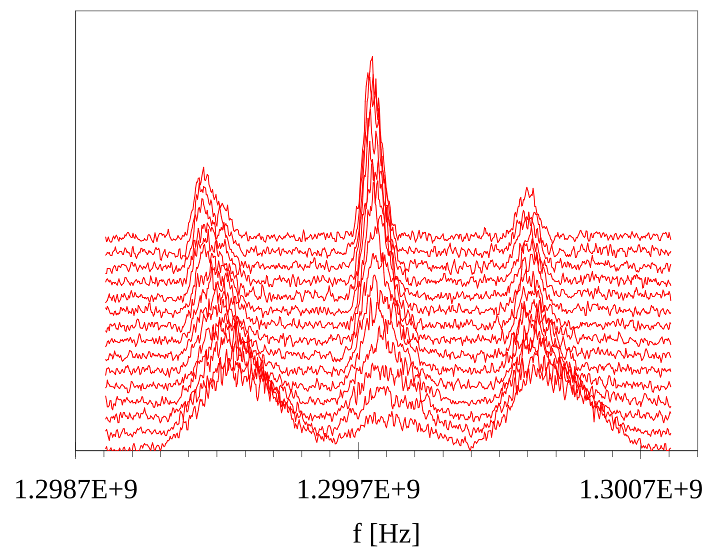
Long. Schottky scan for a cw beam:



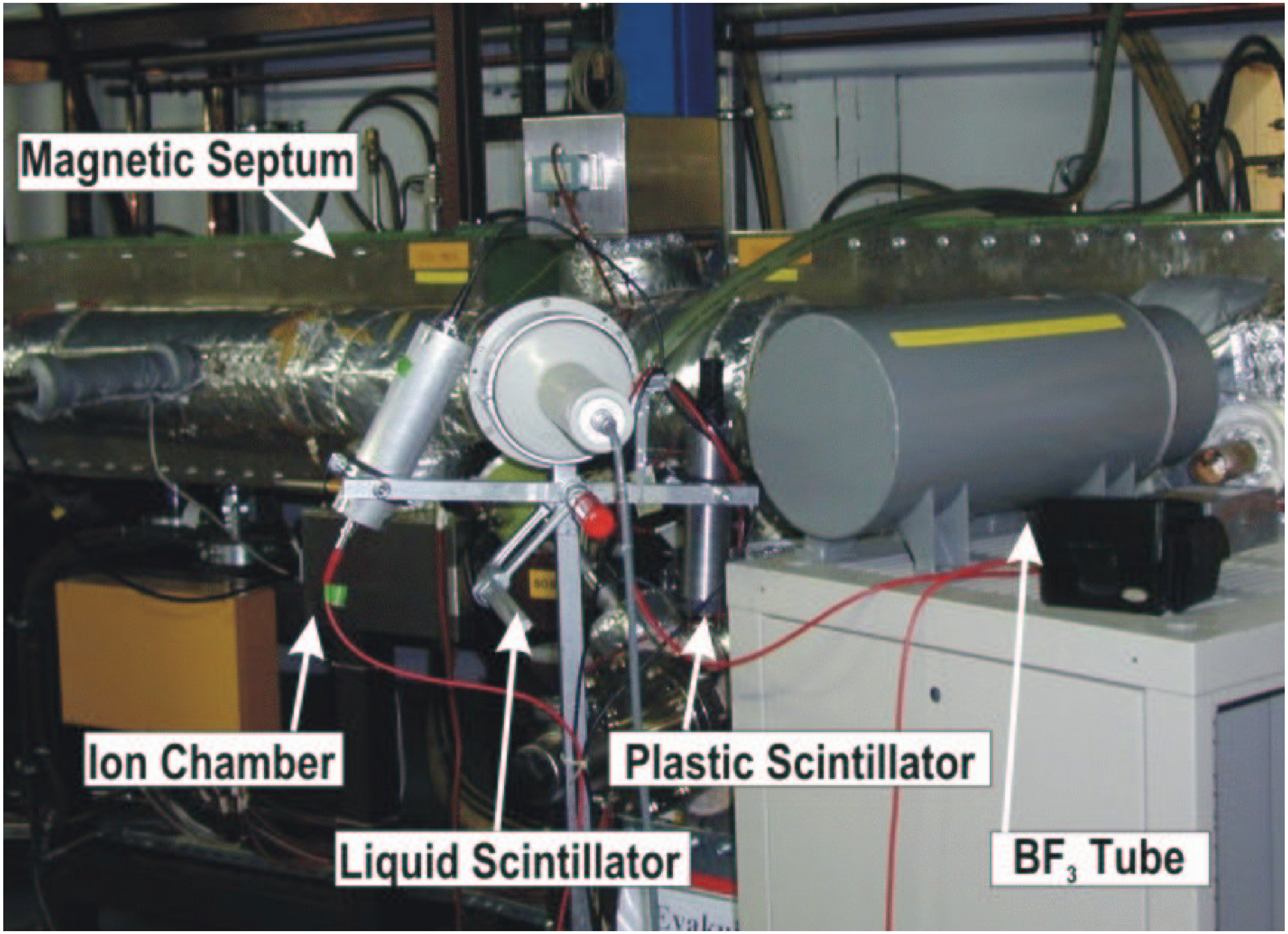
Mainly used for

- cooling control
- $\Delta p/p$ at injection (LINAC para.).

Transverse Schottky spectra recorded every 80 ms during stochastic cooling
$\rightarrow$ decrease of sidebands $\Leftrightarrow$ trans. cooling

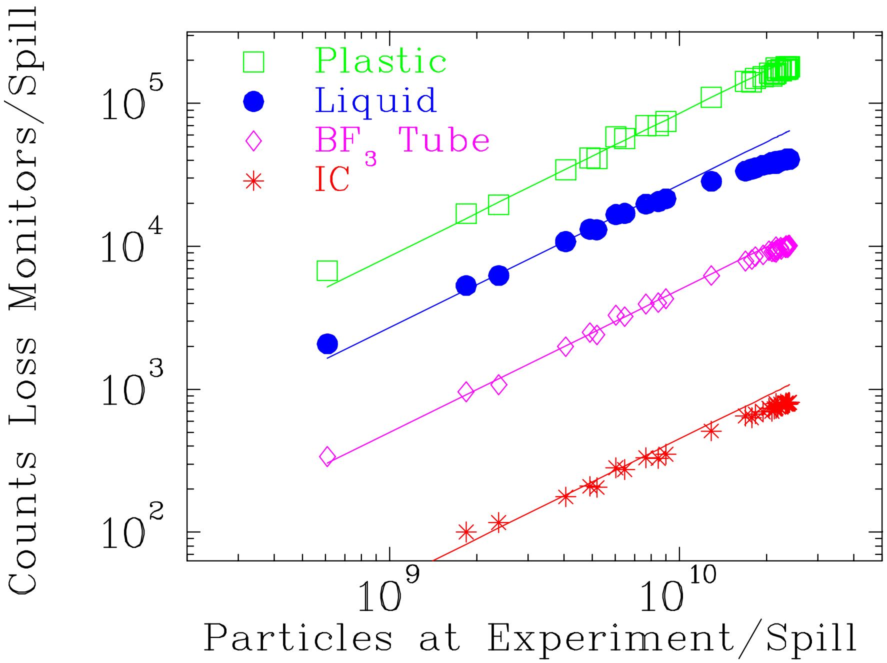


Test of different beam loss detectors at the SIS



Different beam loss detectors

Different detectors are sensitive to various physical processes.

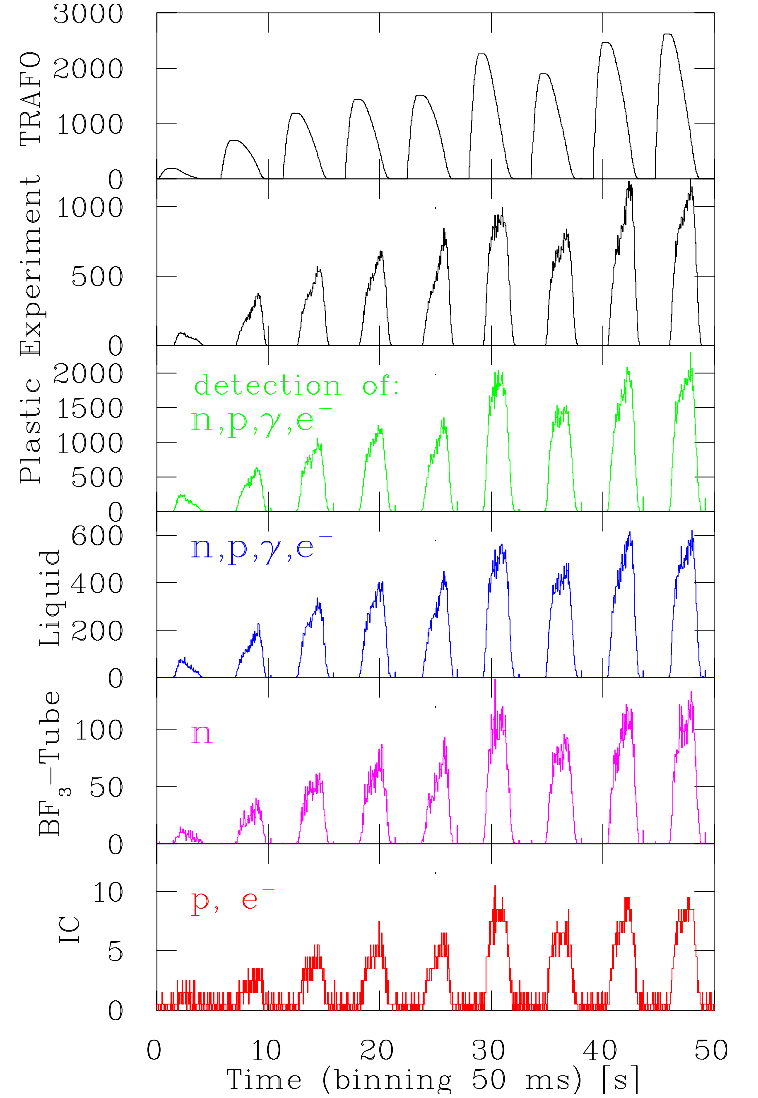


⟶ Linear behavior for all detectors but quite different count rate.

Usage:

Alignment of injection and slow extraction.

Beam loss for 800 MeV/u O^{8+} up to 10^{10} 1/s:



List of wishes for beam diagnostics

1. *Operating based on more complex measurements than current*
   - Availability of complex methods on a day & night basis
   - easy use of these measurements (e.g. well interpretable data analysis)
   - close connection between measurement and theory (ABS etc.)
2. *Non-destructive methods for all parameters*
   - problems with transversal and longitudinal emittance (LINAC)
   - partly problems with transversal profile (LINAC)
3. *Reliable detectors to be used by the operators*
   - problems for particle detector based systems, like residual gas monitor (synchrotron)
   - problems for rf techniques based systems, like Schottky, BTF, tune-meter etc.