Momentum Spread Determination of Linac Beams Using Incoherent Components of the Bunch Signals

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Beijing, September 20th, 2011

Outline

Introduction

- The GSI facility
- Examples of methods of longitudinal phase space measurements at Linacs

Non-invasive longitudinal bunch shape measurement

- measurement principle
- Exemplary results

Concept of momentum spread determination from incoherent bunch signals

Description of the experimental setup

Recent results and interpretation

Summary and outlook

The Accelerator Facility at GSI

Synchrotron, Bρ=18 Tm

E_{max} p: 4.7 GeV

U: 1 GeV/u

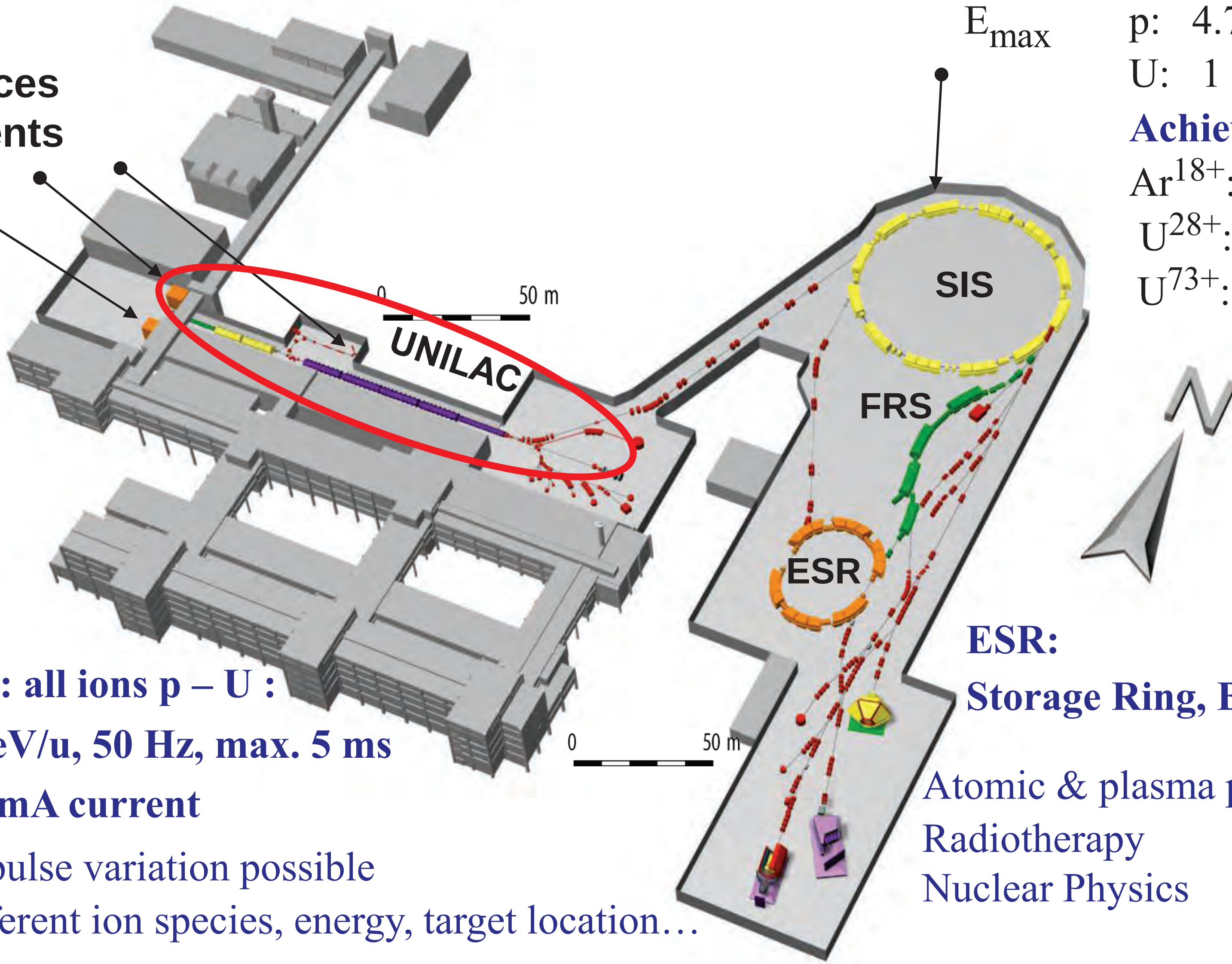
Achieved e.g.:

Ar^{18+}: $1 \cdot 10^{11}$

U^{28+}: $3 \cdot 10^{10}$

U^{73+}: $1 \cdot 10^{10}$

Ion sources all elements



ESR:

Storage Ring, Bρ=10 Tm

Atomic & plasma physics

Radiotherapy

Nuclear Physics

UNILAC: all ions p – U :

3 – 12 MeV/u, 50 Hz, max. 5 ms

Up to 20 mA current

Pulse-to-pulse variation possible

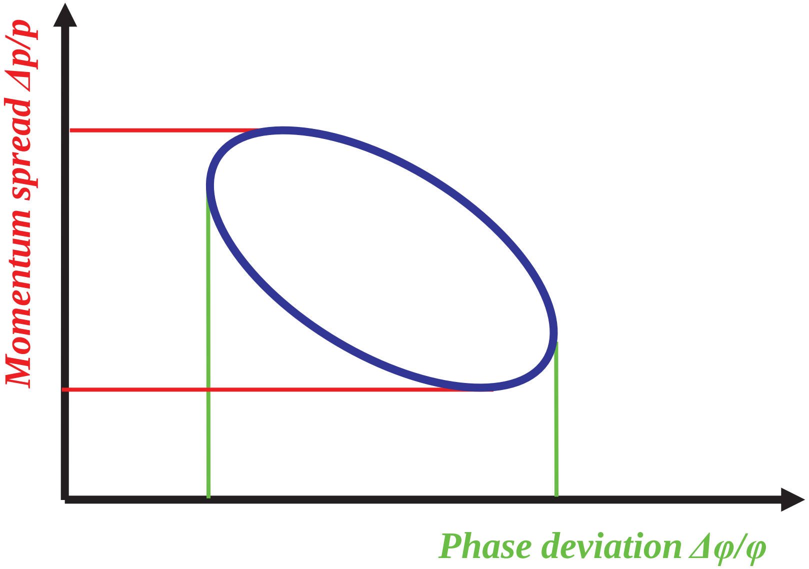
⇒ different ion species, energy, target location…

Motivation

- *The longitudinal phase space is very sensitive to parameter variation*
- *In the case of **linear accelerator** its knowledge is extremely important for beam dynamics calculations*

➔ *measurement is required*

- *There are different available methods but they are either beam destructive or costly in realization:*



Meth.1 Longitudinal Emittance using two Particle Detectors

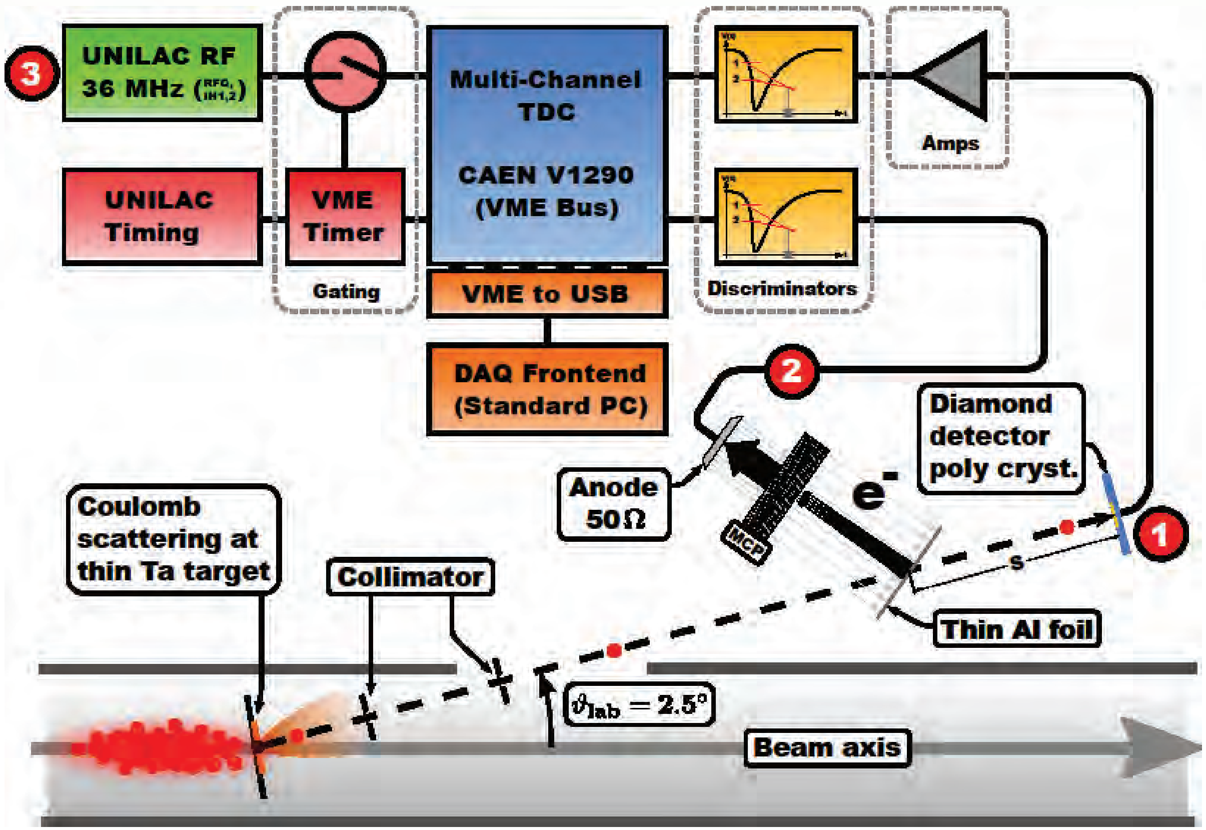
Observables: Arrival time and time-of-flight between two particle detectors:

Bunch shape:

via arrival at diamond (1) detector compared to rf delivers

Energy:

via different arrival times at det. (1) and (2)



Resolution:

- ➢Very good for bunch shape and energy distribution
- ➢ In-sufficient for phase space
- ➢ **However:**

Invasive method:
Rutherford scattering to achieve single particles.

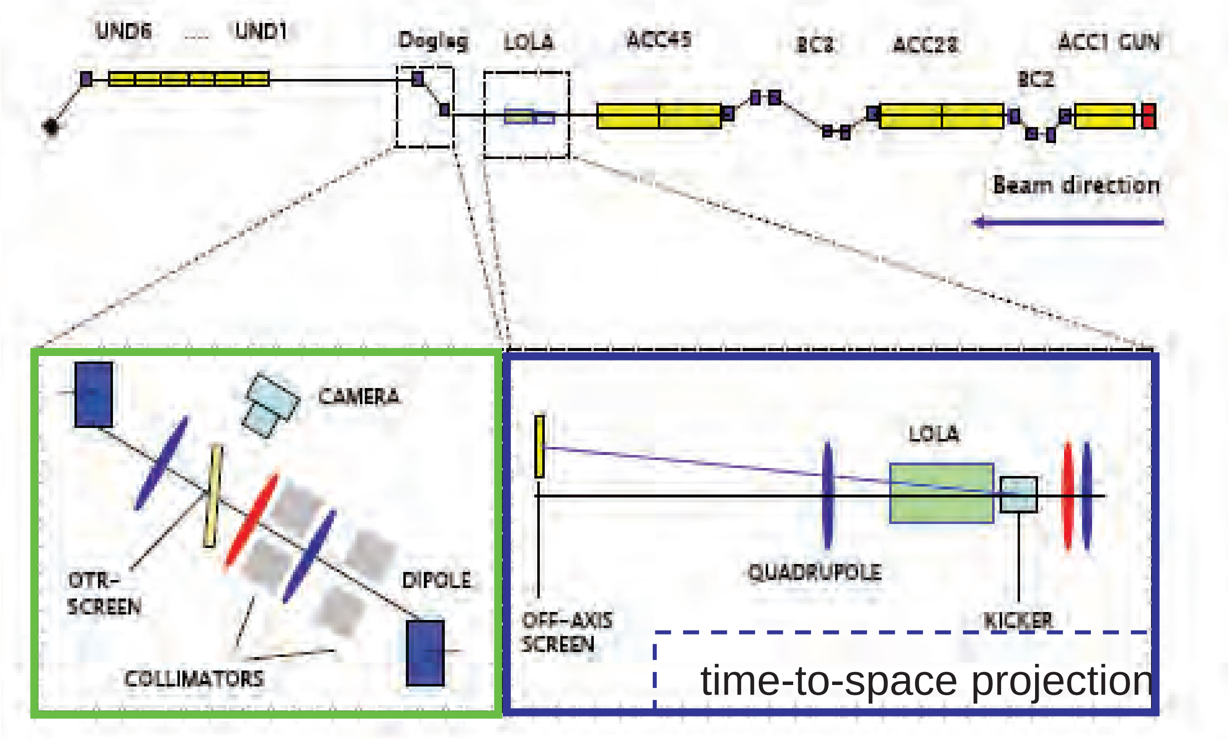
Further reading:

Peter Forck, Legnaro, October 2010

Meth.2: Longitudinal Emittance Using Dipole Magnet and Kicker

- ***Long. bunch shape:*** measured on off-axis screen using deflection in kicker (Figure middle right)

- ***Energy spread:*** via OTR screen in dispersive section behind the dipole (Figure middle left)



However:

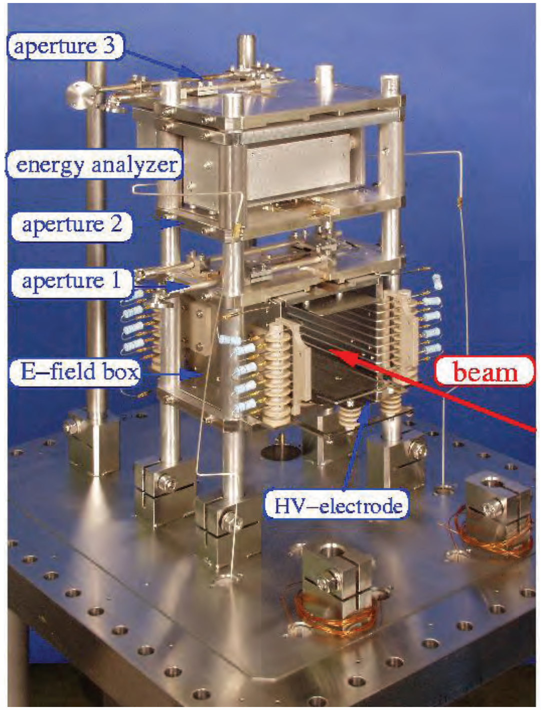
- Slightly invasive method: (OTR screen in beam)
- Requires, besides diagnostic elements, an installation of the dedicated kicker

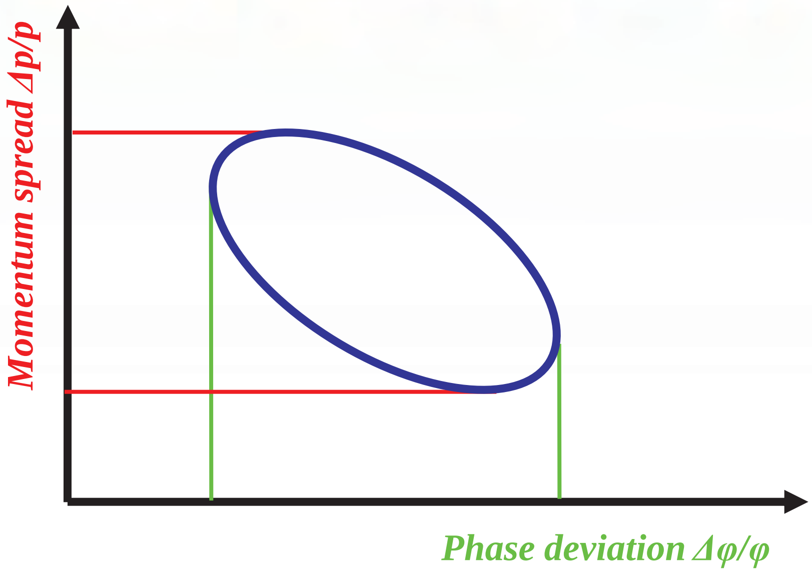
Michael Röhrs, et al., "INVESTIGATIONS OF THE LONGITUDINAL ELECTRON BUNCH STRUCTURE AT THE FLASH LINAC WITH A TRANSVERSE DEFLECTING RF-STRUCTURE", Proceedings of FEL 2006, Berlin, Germany

Measurement of phase space projections in two independent systems

➢ ***Distribution of the long. phase*:**

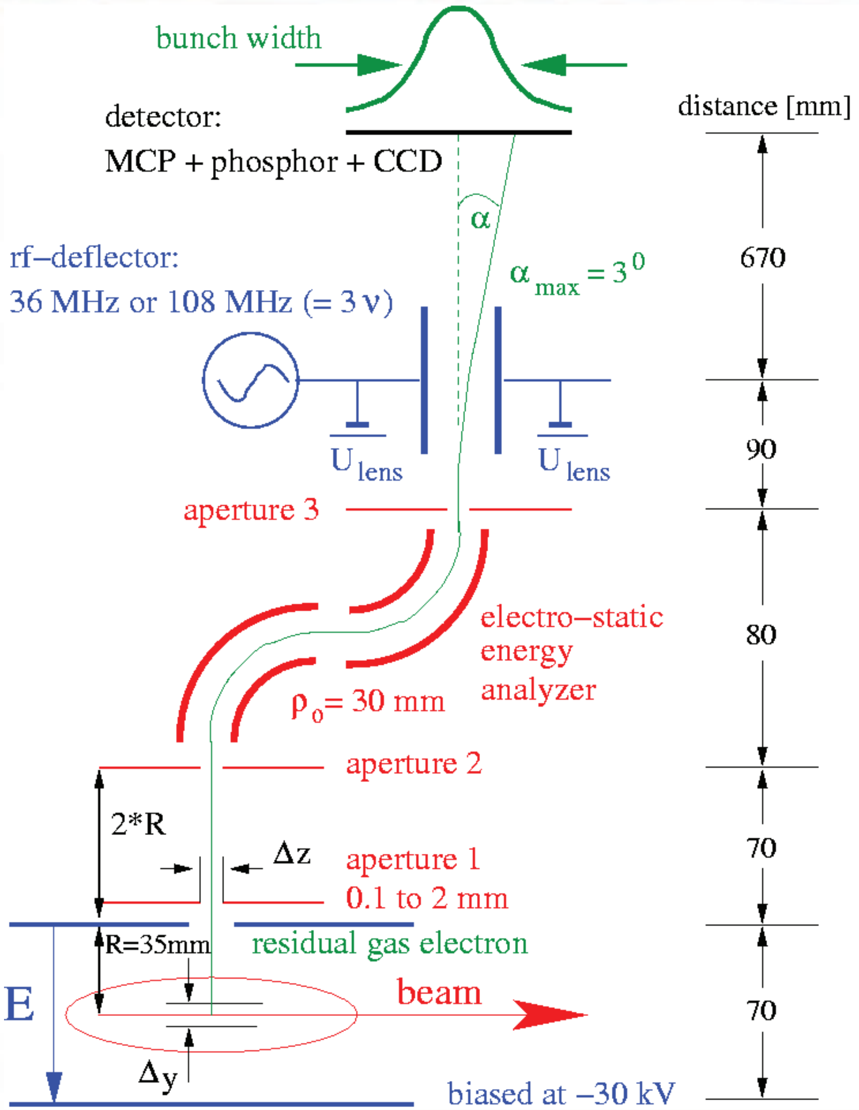
using Non-intercepting
Bunch Shape Monitor





Bunch Shape Monitor

Non-intercepting Bunch Shape Monitor



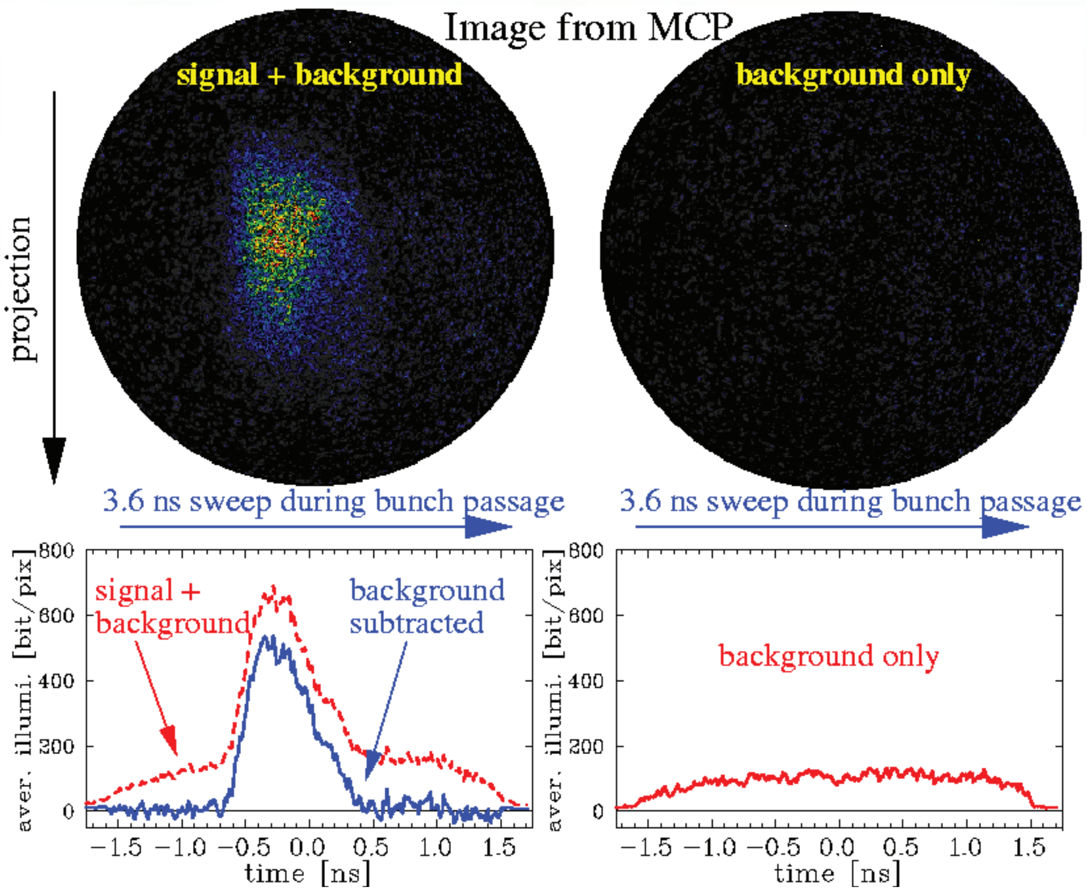
Scheme for novel device:

- Secondary electrons from residual gas
- Acceleration by electric field
  (like for Ionization Profile Monitor)
- Beam height localization by apertures and electro-static analyzer
- rf-resonator as 'time-to-space' converter
  $\lambda/4$ resonator, $Q_0 \approx 300$, P_{in}=50 W max.
- Readout by MCP + Phosphor + CCD

More details: Peter Forck, et al.
ABI Workshop, December 12st, 2008

Results from non-intercepting Bunch Shape Measurement

Time information carried by the secondary e^- is transferred to spatial differences:



Features:

- Single electron detection
- Recorded within few macro-pulses
- Pressure bump required
- Background should be suppressed

Beam parameters:

Ni^{14+} at 11.4 MeV/u

I=1.5 mA, 200 µs macro pulse

Average: 8 macro pulses

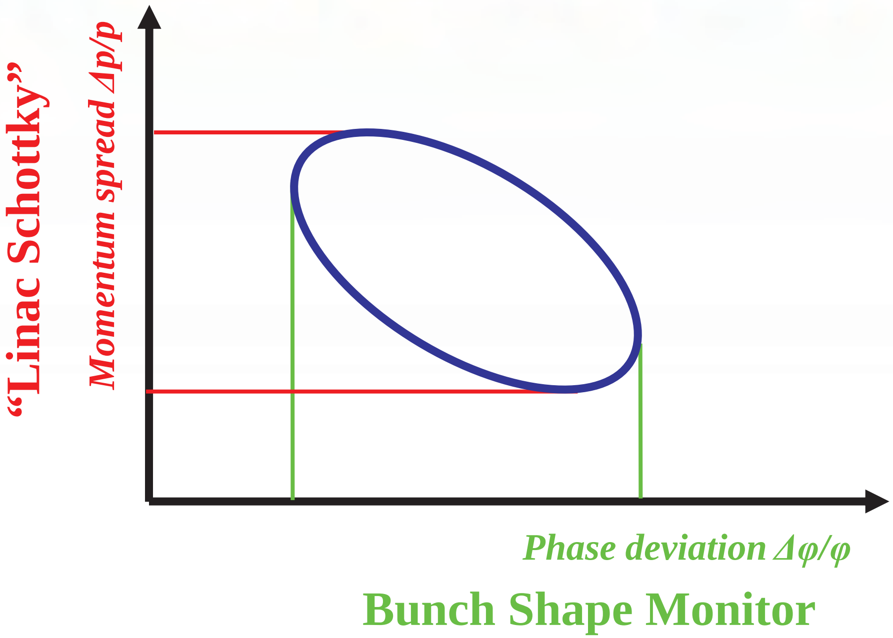
Pressure $p=2*10^{-6}$ mbar

Deflector power P=15 W

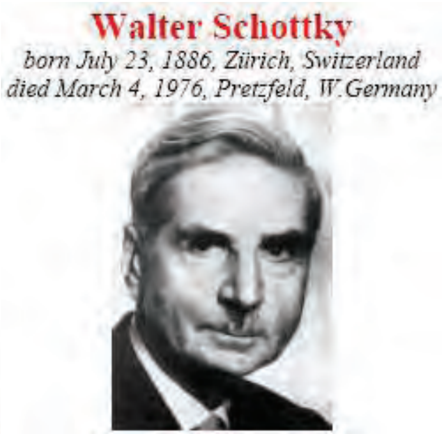
Measurement of phase space projections in two independent systems

➢ ***Distribution of the long. phase*:**
using Non-intercepting
Bunch Shape Monitor

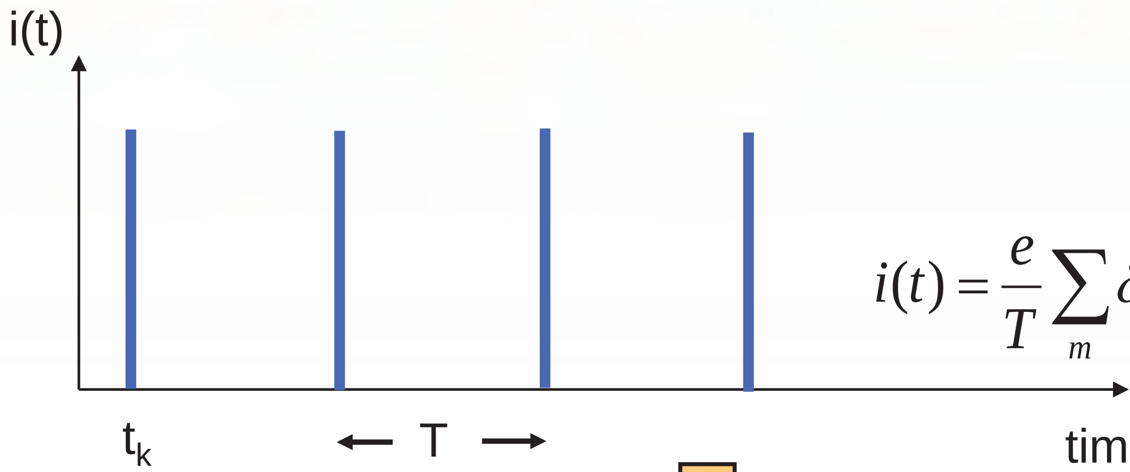
➢ ***Momentum spread***
via Analysis of Incoherent
Components of the Bunch Signals
(let us call it "Linac Schottky")



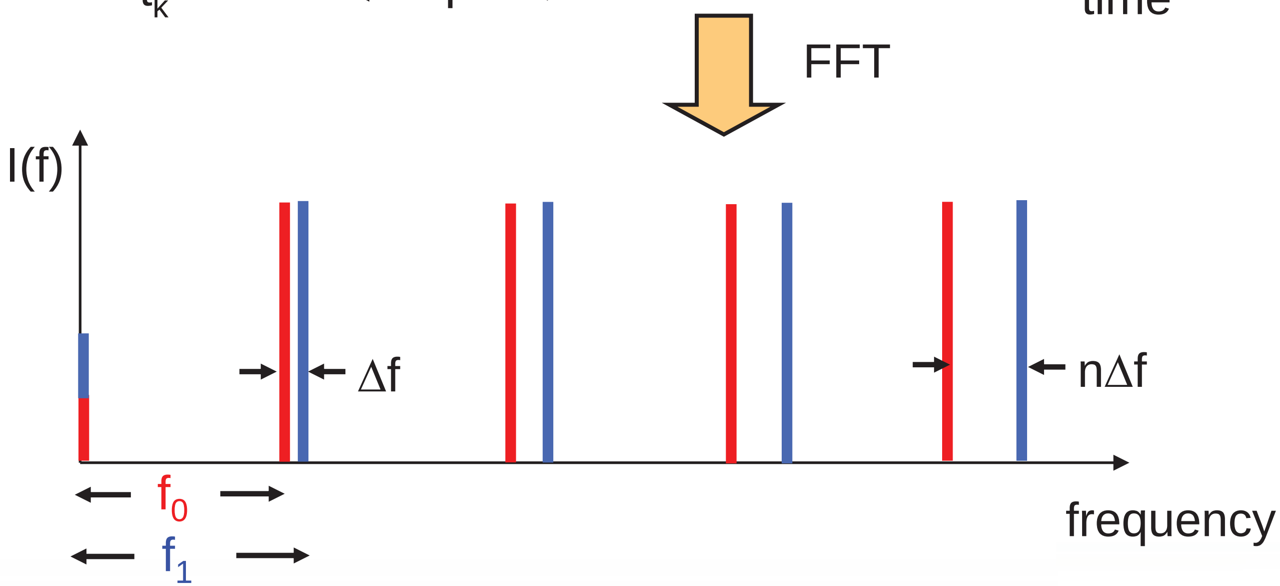
Its sounds strange but originally W. Schottky
described spontaneous current fluctuations
from DC electron beams for e.g. vacuum diodes
which can be considered as a kind of linear accelerator



Time and frequency domains (synchrotron case)



$$i(t) = \frac{e}{T}\sum_m \delta(t - t_k - mT)$$

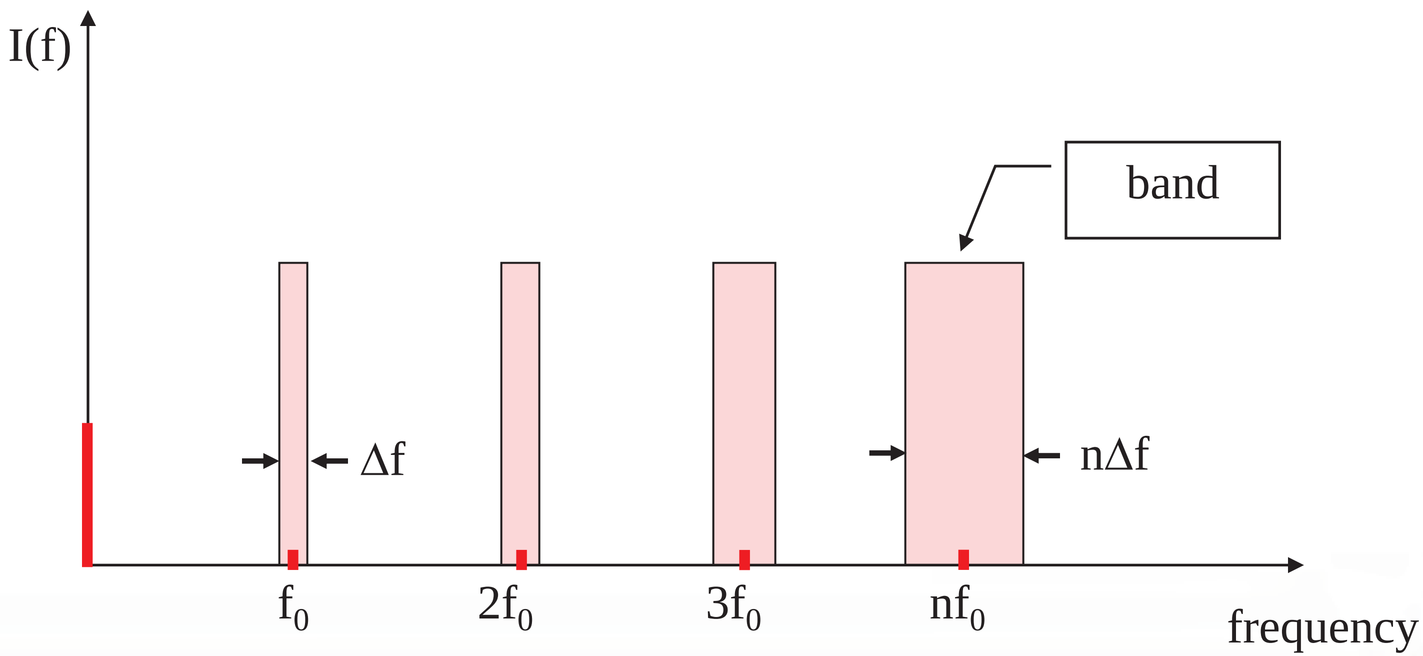


$$\Delta f = f_0 \times \eta \frac{\Delta p}{p}$$

A second particle of revolution frequency $f_1 = f_0 + \Delta f$

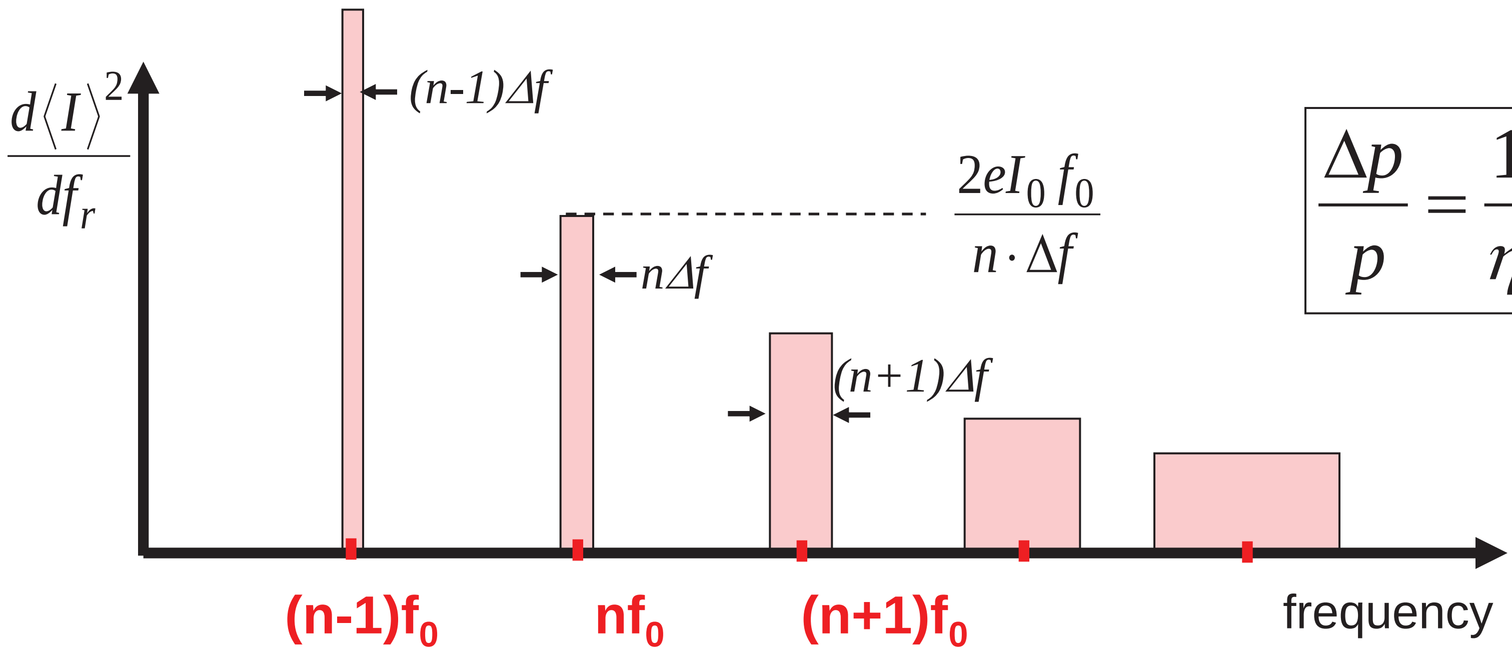
Coasting beam : frequency Domain (synchrotron case)

- N particles with a distribution of revolution frequencies $f_0 \pm \Delta f/2$
- One expects a spectrum with bands around each **harmonic** nf_0
- The band height is arbitrary at this stage



Schottky bands (synchrotron case)

- In a diagram $\left(\frac{d\langle I\rangle^2}{df_r}\right)$ versus f the area of each Schottky band is constant
- Since the n^th band has a width $(n \times \Delta f)$, the spectral density decreases with $1/f$

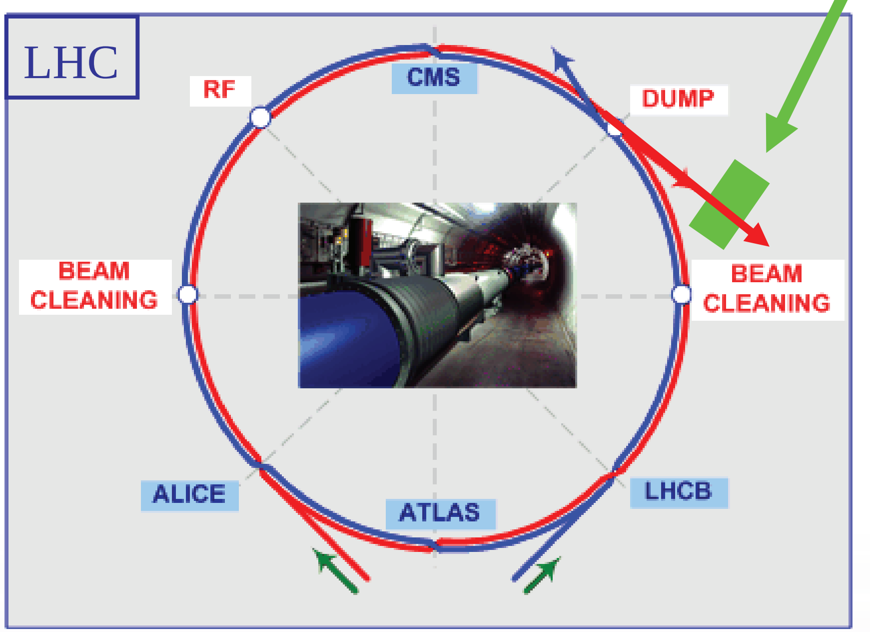


$$\frac{\Delta p}{p} = \frac{1}{\eta}\frac{\Delta f}{f_0}$$

Each longitudinal Schottky band has the same „area“ = integrated power

“Gedankenexperiment”

- Consider a quite large synchrotron with big number of circulating bunches like e.g. LHC.
- At injection revolution frequency is f_0 = 11.24 kHz which gives a period of T_{rev}=89 µs.
- Can we see any Schottky like signal if we do a measurement for let say 80µs only, i.e. each bunch pass our pick-up only once?
- If yes, the signal measured in the beam dump should have the same structure.
- What happen if we “skip” the synchrotron in the front of the dump?
- Is it only question of dispersion?



Parameters:

2808 bunches

E_{inj}=@450 GeV

f_0=11.24kHz

T_{rev}=89µs

γ_{tr}=55.67

α=3.2e-4

γ_{inj}=480

η=-=3.2e-4

Momentum Spread vs. Frequency Spread (Linac case)

- The generalization of the momentum compaction function ***α*** of the transfer line as a function of position ***s*** can be applied well also in particular case of Linac.
- The relative change in the orbit length per relative momentum change is given by:

$$\alpha(s,s_0)=\frac{\Delta L/L_0}{\Delta p/p_0}=\frac{1}{L_0}\int_{s_0}^{s}\frac{D(t)}{q(t)}dt \quad \text{with} \quad L_0=\int_{s_0}^{s}dt$$

- The relative change in time of flight per relative momentum deviation is:

$$\eta(s,s_0)=\frac{\Delta t/t_0}{\Delta p/p_0}=\frac{p_0}{t_0}\frac{\Delta(\frac{L}{v})}{\Delta p}=\alpha(s,s_0)-1+\frac{v^2}{c^2}$$

- If there is no dispersion (no dipole in lattice):

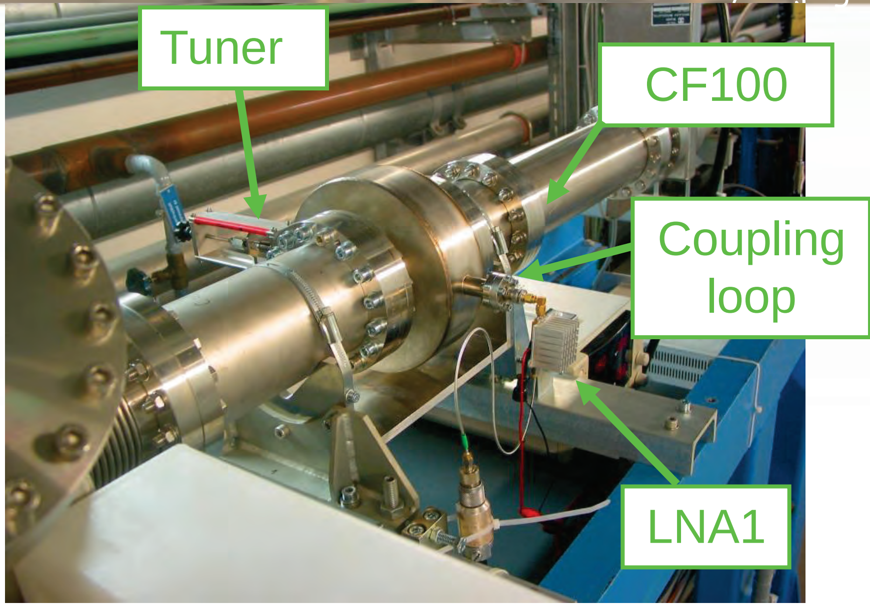
$$\eta(s,s_0)=-1+\frac{v^2}{c^2}$$

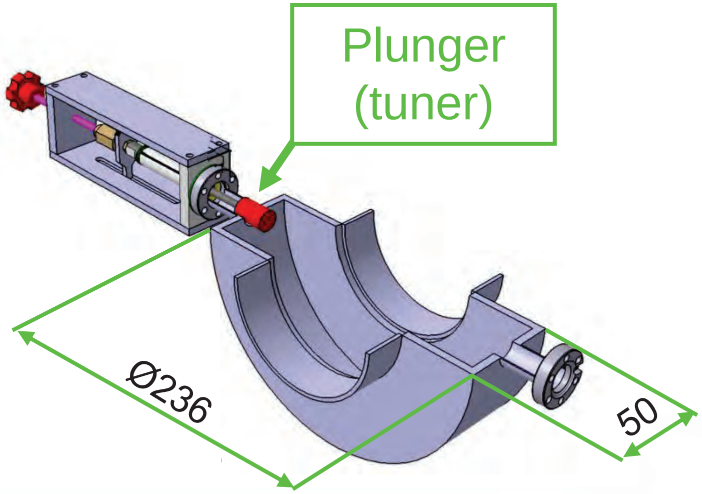
- If the beam were ultrarelativistic the Linac would be isochronous i.e. all particle would arrive simultaneously.
- However, for Unilac $v/c \approx 15\%$. Therefore: eta = -0.98 => faster particle arrives earlier, and:

$$\frac{\Delta p}{p_0}=\frac{1}{\eta}\frac{\Delta f_n}{nf_0}$$

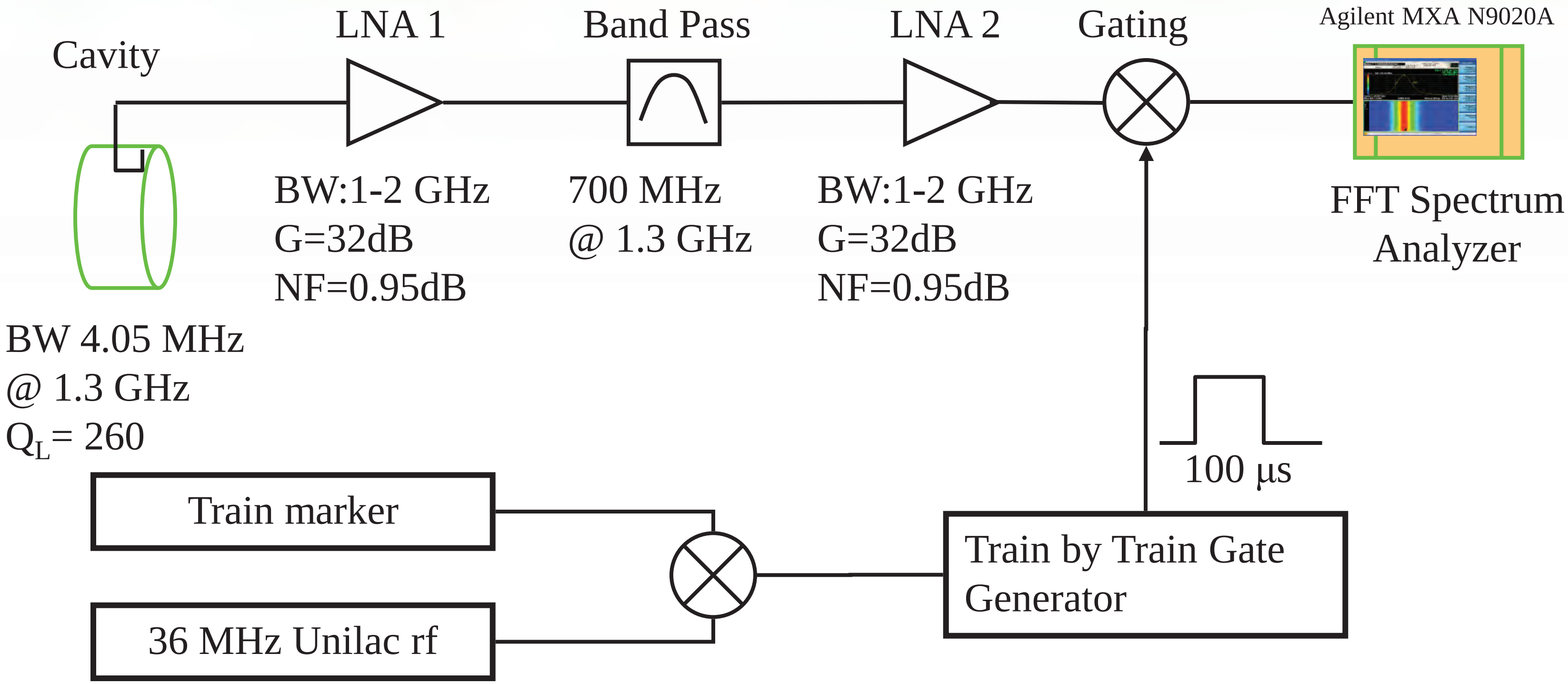
“Linac Schottky” Pick-up

- Pillbox cavity used as a Pick-up to increase measurement sensitivity.
- Loaded quality factor Q_L=260.
- Frequency of TM_{010} mode tuned to 1.30089 GHz, i.e. to 36 harmonic of Unilac RF. (rejection of coherent signal)
- Bandwidth 4 MHz
- Tuner allows fine tuning in range of $\Delta f_{res} \pm 2$ MHz.





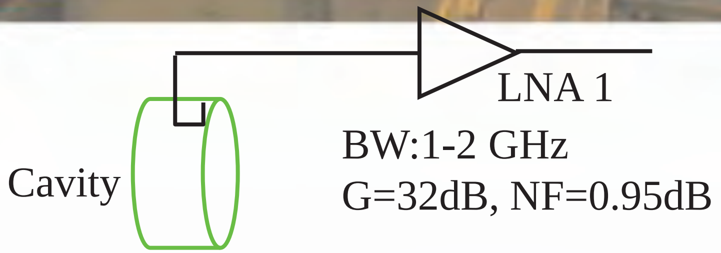
Signal treatment



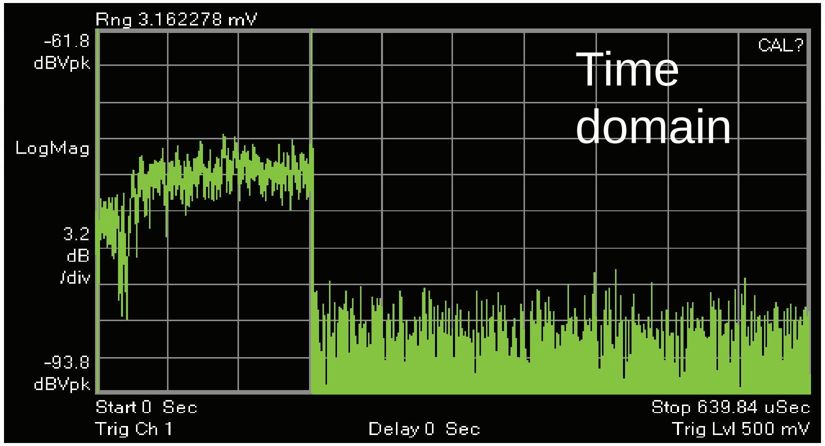
- ➢ Gating on bunch train allows significant reduction of noise contribution
- ➢ Modern FFT spectrum analyzers make possible signal analysis even in the relatively short time (~100 µs)

System Sensitivity

- Gating on bunch train allows significant reduction of noise contribution

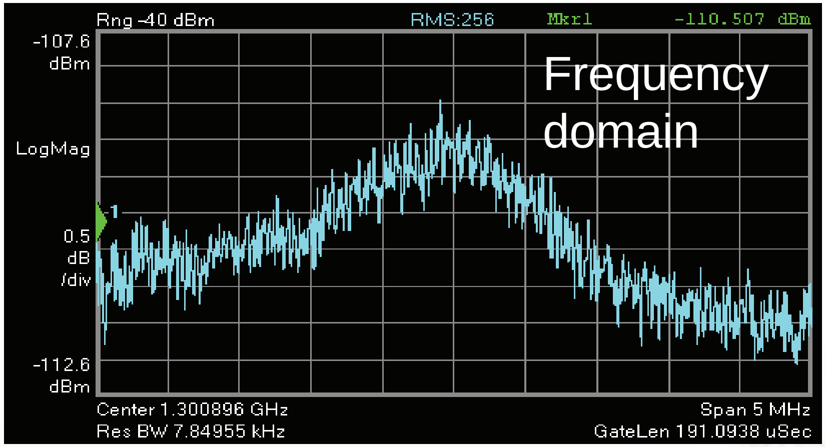


- Modern FFT spectrum analyzers make possible signal analysis even in the relatively short time (~100 μs)



- Within this time we can acquire a signal at the level of -110 dBm

Prove: measurement of the thermal noise of LNA (input) amplified in the cavity



General Idea of Experiment

Intensity: $1.2 \cdot 10^{10}$ U^{28+} Ions/cycle (train)

$E_{inj(SIS18)} = E_{ext(Unilac)}$: 11.43 MeV/u

Train length: 100µs

Synchrotron, Bρ=18 Tm

Used as energy analyzer

f_{rev} = 214.7 kHz

H = 4^{th}

f_{rf} = 858.88 kHz

Cavity installed in July 2012 →

"Schottky" Cavity

f_{res} = 1.30089 GHz

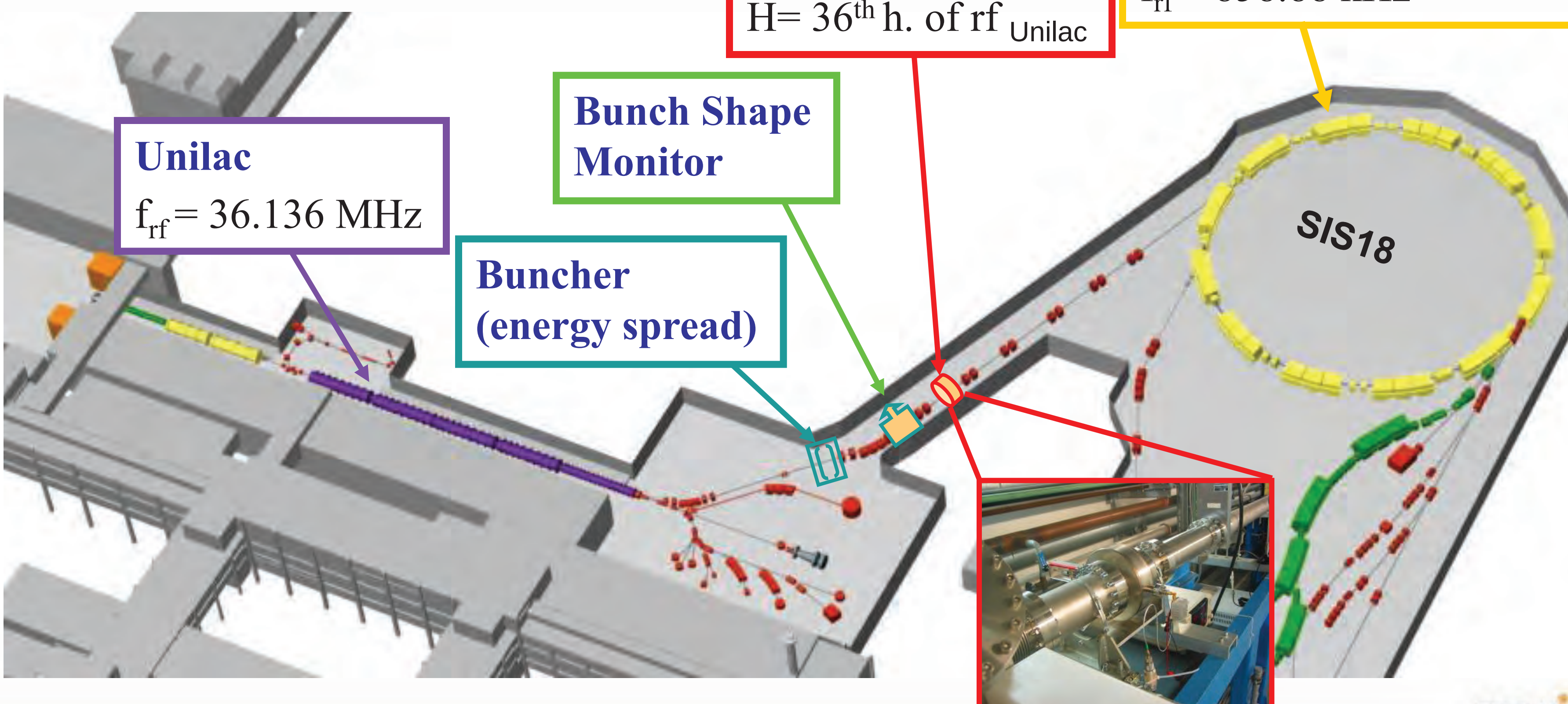
H= 36^{th} h. of rf $_{Unilac}$

Bunch Shape Monitor

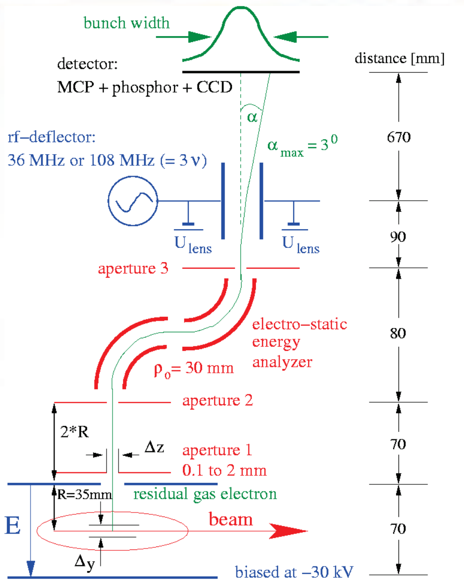
Unilac

f_{rf} = 36.136 MHz

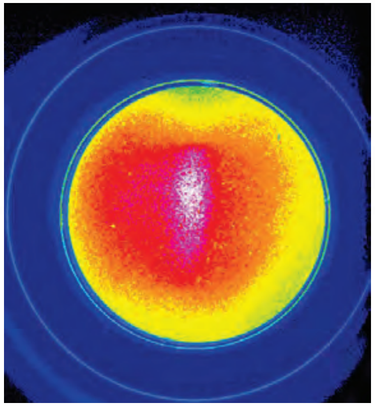
Buncher (energy spread)



Results from Bunch Shape Monitor



Data taken on 12th Sept 2012!



Beam parameters:

U^{28+} at 11.4 MeV/u

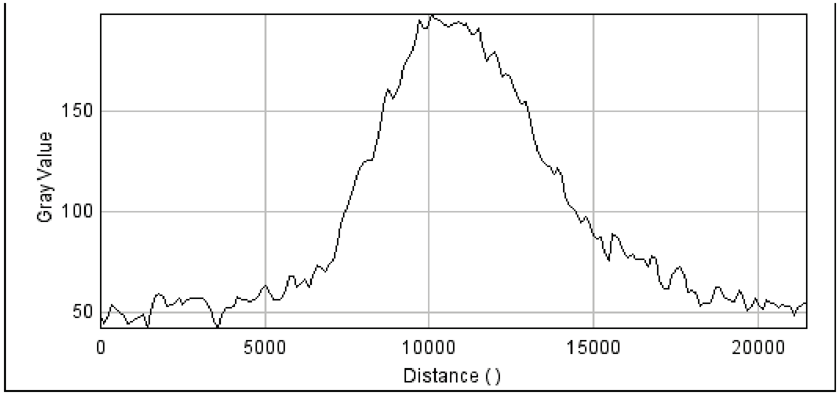
I=0.78 mA, 100 µs macro pulse

Average: 8 macro pulses

Pressure p=2*10-6 mbar

Measurement done by: Benjamin Zwicker
Beam Diagnostics Group GSI Darmstadt

Longitudinal bunch profile



Very preliminary results!

Momentum Spread Measured at SIS18

Data taken on 12th Sept 2012!

- Very preliminary data!
- Measurements done by means of SIS18 Schottky system and analyzed with Real-Time Spectrum Analyzer for the different buncher settings.

Beam parameters:

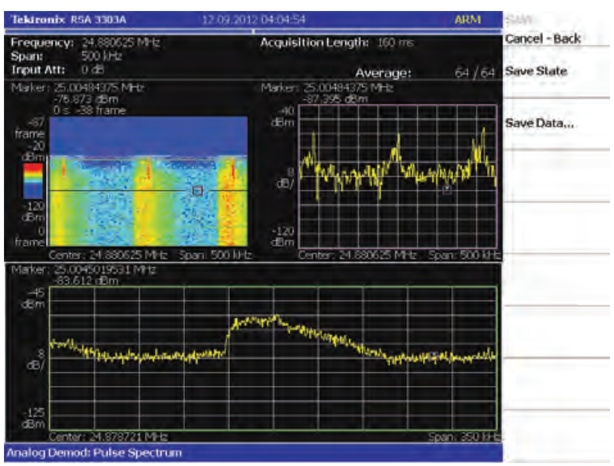
U^{28+} at 11.4 MeV/u (SIS18 injection)

$1.2 \cdot 10^{10}$ ions per spill

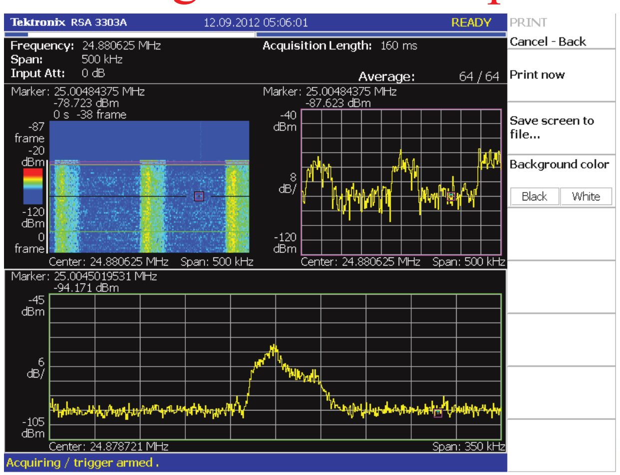
injection plateau 150 ms

$\eta = 0.94$

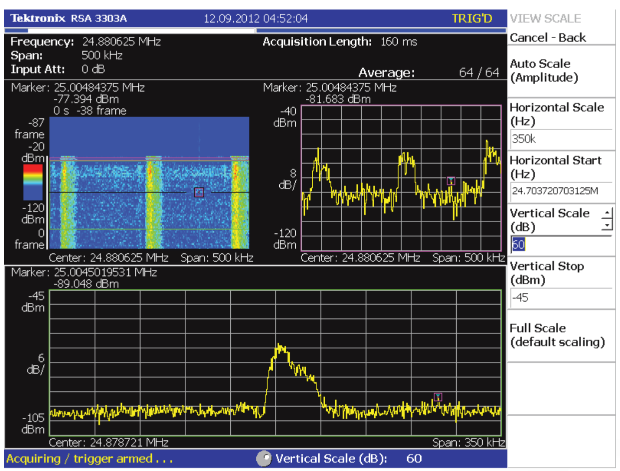
Decreasing momentum spread →→



Debunching



Buncher turned off



Bunching

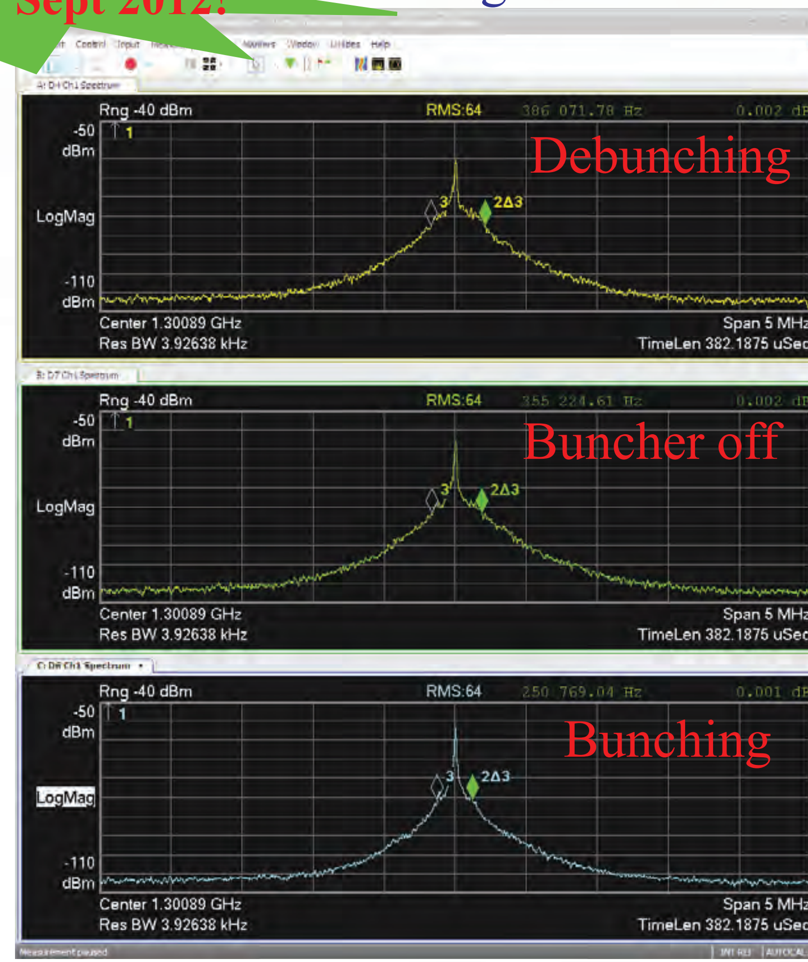
Results of the "Linac Schottky" measurements

Data taken on 12th Sept 2012!

Linear scale

Decreasing momentum spread ↓↓

Logarithmic scale



Very preliminary data! => precise data analysis needed.

Summary and outlook

Knowledge of longitudinal phase space is important for beam dynamics calculations and requires precise measurement.

Non-invasive measurement methods are preferred.

GSI type bunch shape monitor allows non-invasive determination of the longitudinal bunch profile and was successfully operated during recent measurement.

The analysis of incoherent components of the Linac bunch signals could be very elegant and cheap method for momentum spread determination.

Very preliminary results of resent experiment are still not be yet consider as a prove of principle but one can state: "there is something which seems to be systematical".

Anyhow:

Further careful data analysis is required to get quantitative results

A solid theoretical model is highly desired!

Authors owe a great thanks to:

- **Diagnostics Group:** C. Dorn, K. Gütlich, M. Schwickert, B. Zwicker
- **LINAC Group:** W. Barth, W. Bayer, H. Vormann, L. Dahl
- **Operating Group:** U. Scheeler, C. Wetzel, H. Rödl
- **Vacuum and Montage Group**: P. Horn, D. Acker

For help in preparation and performing of this "just-in-time" experiment.

- **HB2012 Editors:**

for patience…;)

and last but not least:

Thank you for your attention!

Spare transparencies

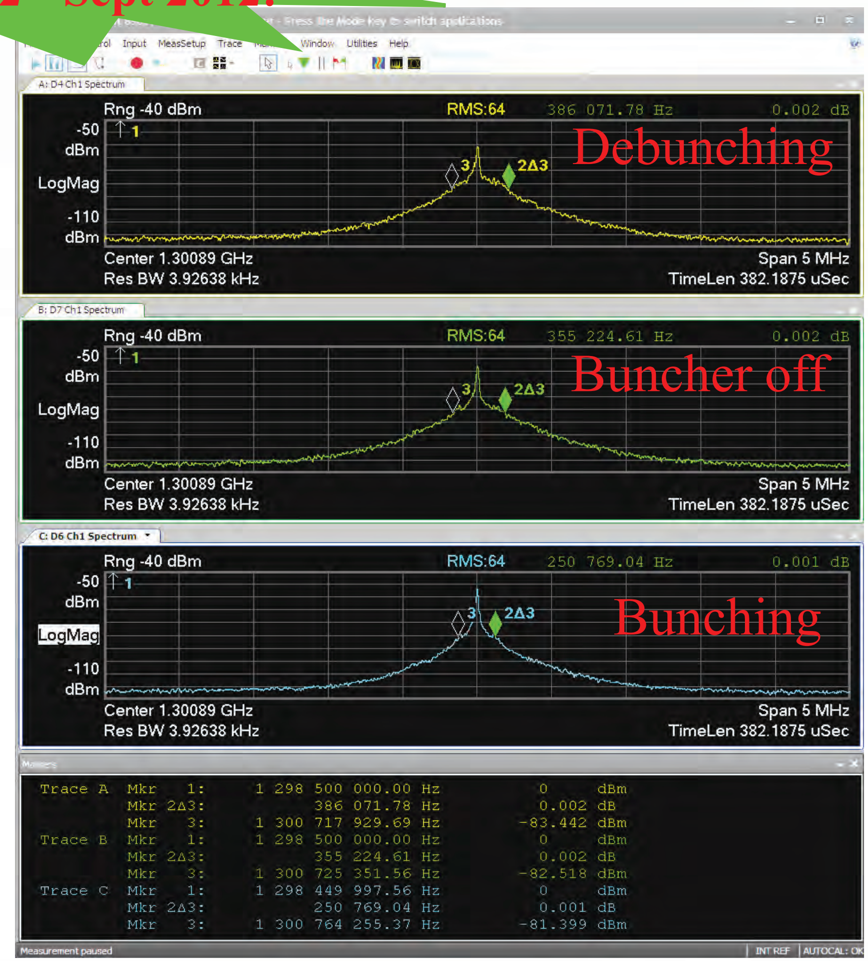
Results of the "Linac Schottky" measurements

Data taken on 12th Sept 2012!

Linear scale

Decreasing momentum spread ↓↓

Logarithmic scale



Very preliminary data! => precise data analysis needed.

Shot noise in a vacuum diode (1)

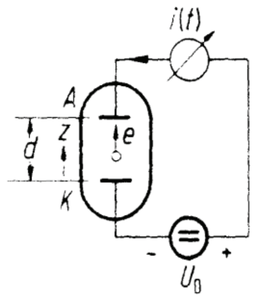


Abb. 8.1/5. Ebene Zwei-Elektrodenstrecke einer Vakuumdiode

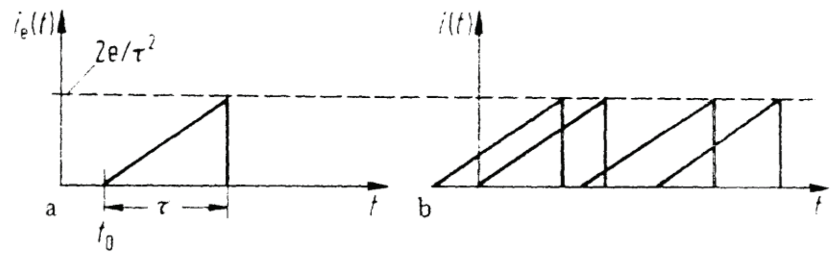


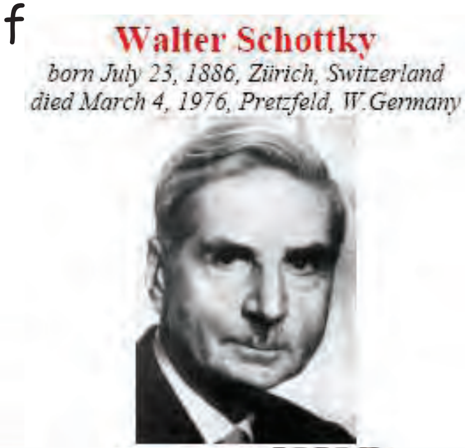
Abb. 8.1/6a u. b
a Zeitfunktion des Influenzstroms $i_e(t)$ eines einzelnen Elektrons; b Superposition von $i_e(t)$ zum Gesamtstrom $i(t)$

$S_i(\omega) = 2I_0 e$

- Consider a vacuum diode where single electrons are passing through in a statistical manner (left figure) with the travel time τ
- Due to the dD/dt (D = εE) we get a current linearly increasing vs time when the electron approaches the flat anode.
- We assume a diode in a saturated regime (space charge neglected) and obtain after some math for frequencies with a period >>τ f the spectral density S_i (ω) of the short circuit current the Schottky equation:

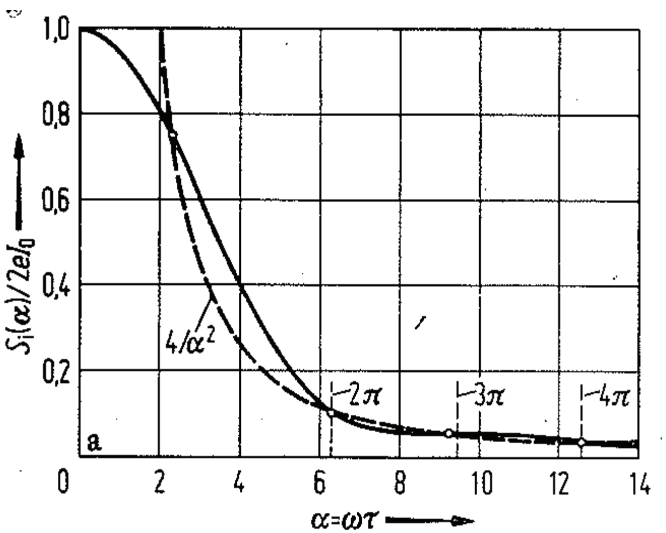
$$S_i(\omega) = 2I_0 e$$

with e= $1.6e^{-19}$ As and the mean current I_0 =e v_{mean}



Shot noise in a vacuum diode (2)

- obviously the travel time τ plays a very important role for the frequency limit
- The value for τ in typical vacuum diodes operated at a few 100 Volts is around a fraction of a ns. This translates to max frequencies of 1Ghz



From:Zinke/Brunswig: Lehrbuch der Hochfrequenztechnik, zweiter Band , Page 116

Single-particle current (2)

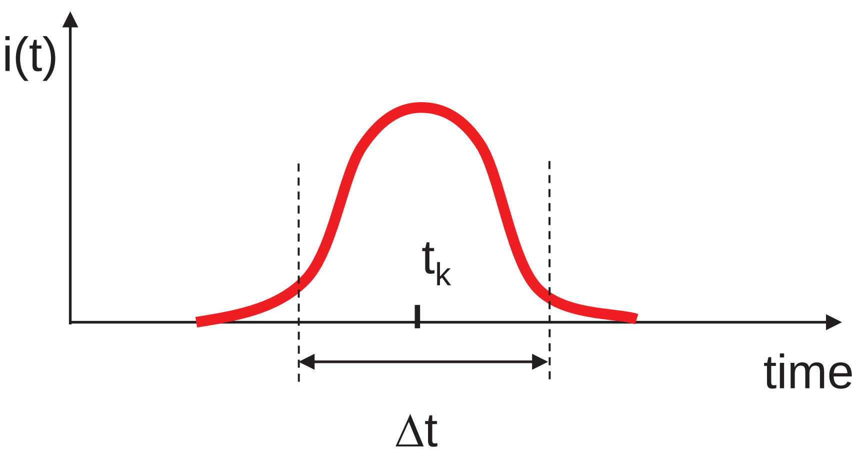
- Approximation by a Dirac distribution.
- Periodic signal over many revolutions $$i_k(t) = \frac{e}{T} \sum_m \delta(t - t_k - mT)$$
- Applying the Fourier expansion to $i_k(t)$:

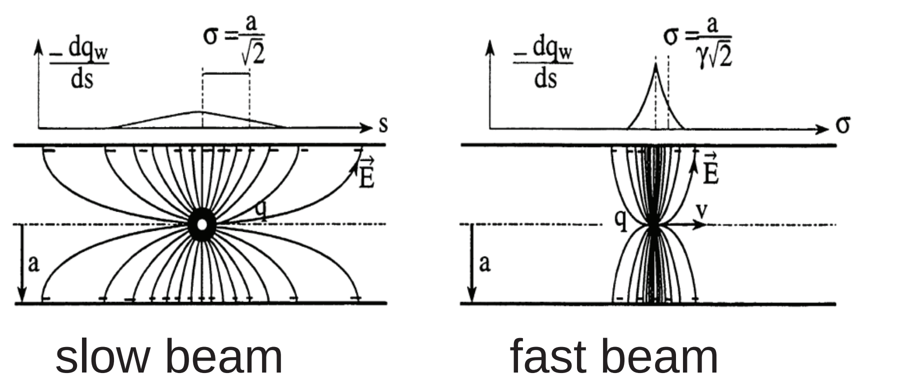
$$i_k(t) = i_0 + 2i_0 \sum_{n=1}^{\infty} a_n \cdot \cos n\omega_0 t + b_n \cdot \sin n\omega_0 t$$

with $$\begin{cases} i_0 = ef_0 \\ a_n = \cos n\varphi_k \quad \text{and} \quad b_n = \sin n\varphi_k \end{cases}$$

Single-particle current (synchrotron case)

- A single particle rotating in a storage ring
- Constant frequency $\omega_0 = 2\pi f_0 = 2\pi/T$
- Signal induced on a pick-up at passage time t_k; *Dirac response smeared out due to low pass effect from the pickup itself and due to not TEM wave if* $v \ll c$



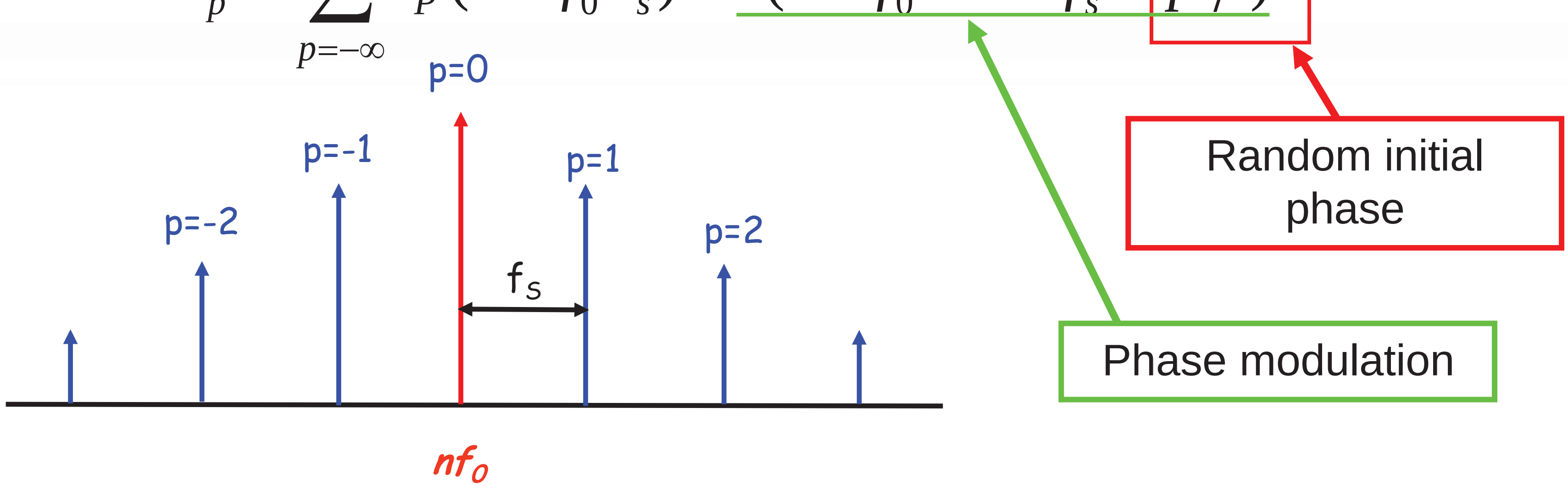


From: A.Hofmann: Electromagnetic field for beam observation CERN-PE-ED 001-92

Bunched beams (synchrotron case)

For each of those modulation lines with index p the amplitude of the current, I_P can be expressed as

$$I_p = \sum_{p=-\infty}^{n} J_P(2\pi n f_0 A_s)\cos(2\pi n f_0 + 2\pi n f_s + p\psi)$$

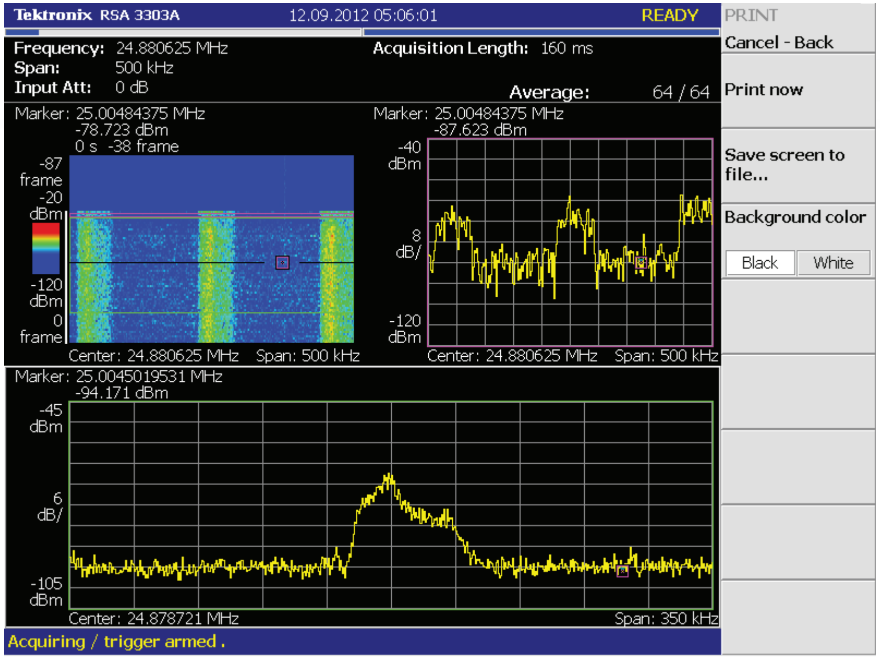


Here J_P stands for the Bessel function of order p

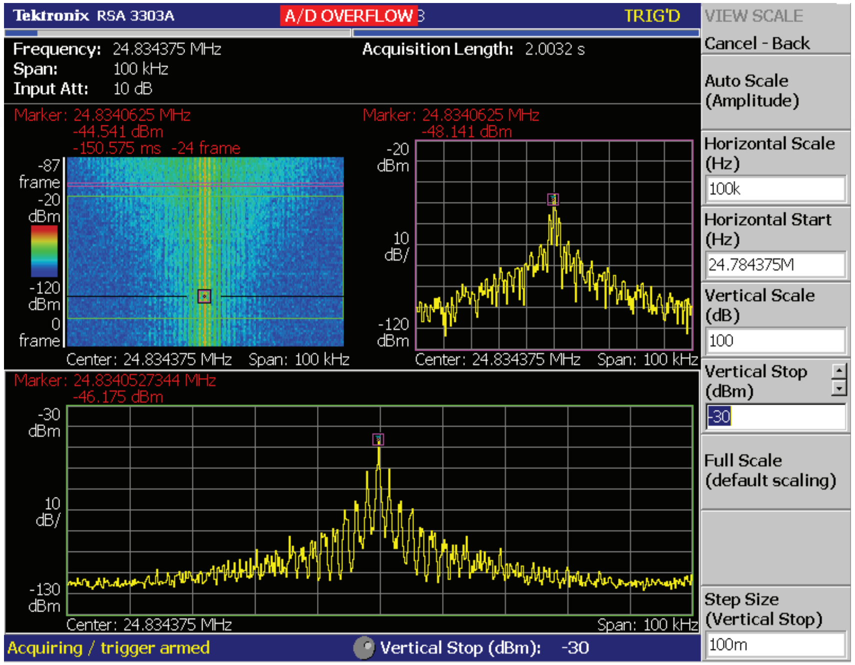
How does it look like in the case of Linac beam?

Examples of Schottky Spectrum for Synchrotron Beam

Coasting beam



Bunched beam



Longitudinal Emittance using two Particle Detectors

Arrival time and time-of-flight between two particle detectors:

Two detectors:

Arrival at diamond detector compared to rf delivers

Bunch shape:

Time resolution: ≈50 ps

⇔ phase resol. 1^0 for 36MHz

Energy via different arrival times

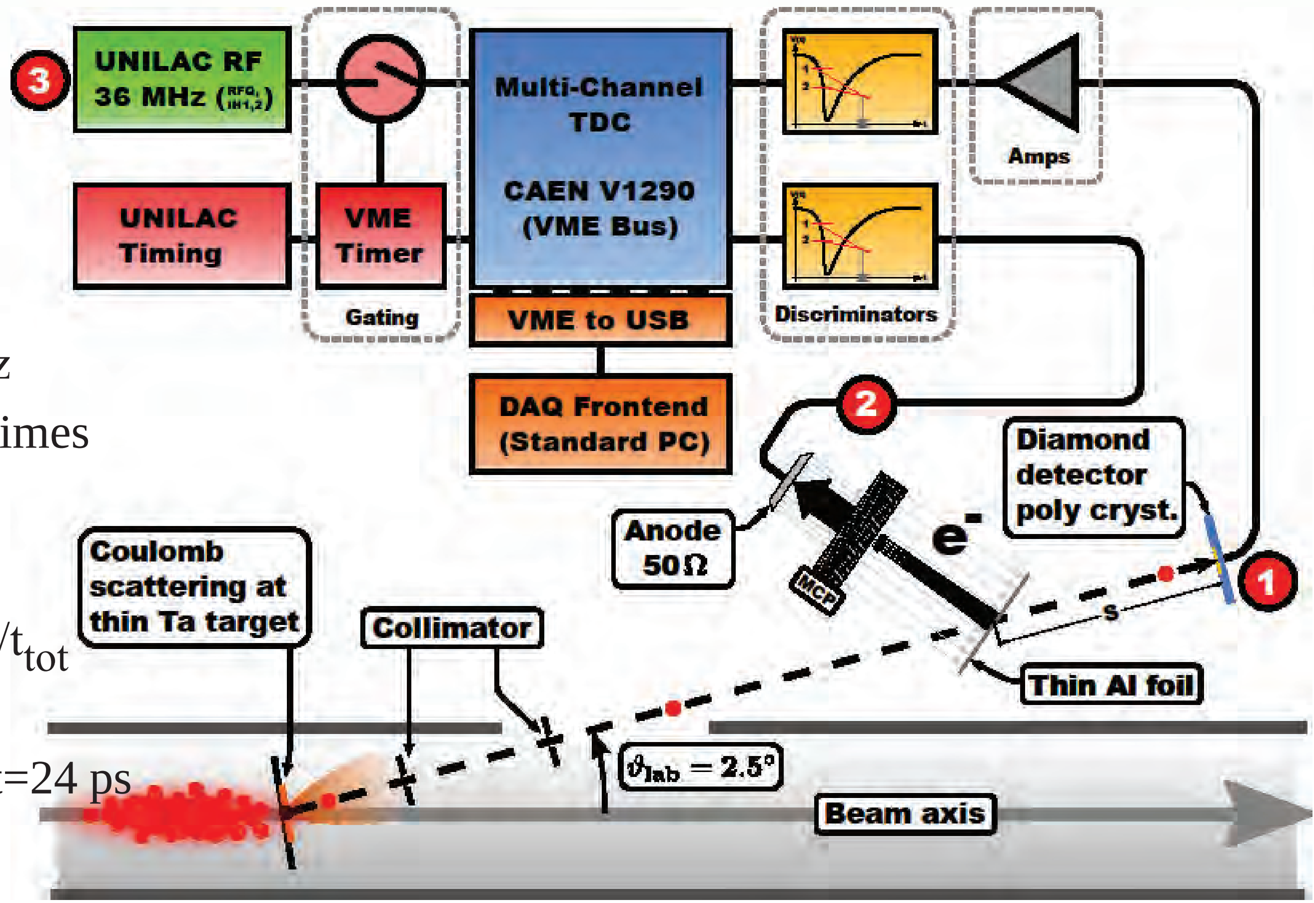
⇔ energy resolution 0.5%

for 1.4MeV/u

$\Delta E/E = -2 * (t_{MCP} - t_{Diamond})/t_{tot}$

t_{tot}=48 ns

Required $\Delta E/E$=0.1% ⇒ $\Delta t/t$=24 ps



Important information for comparison to beam dynamics

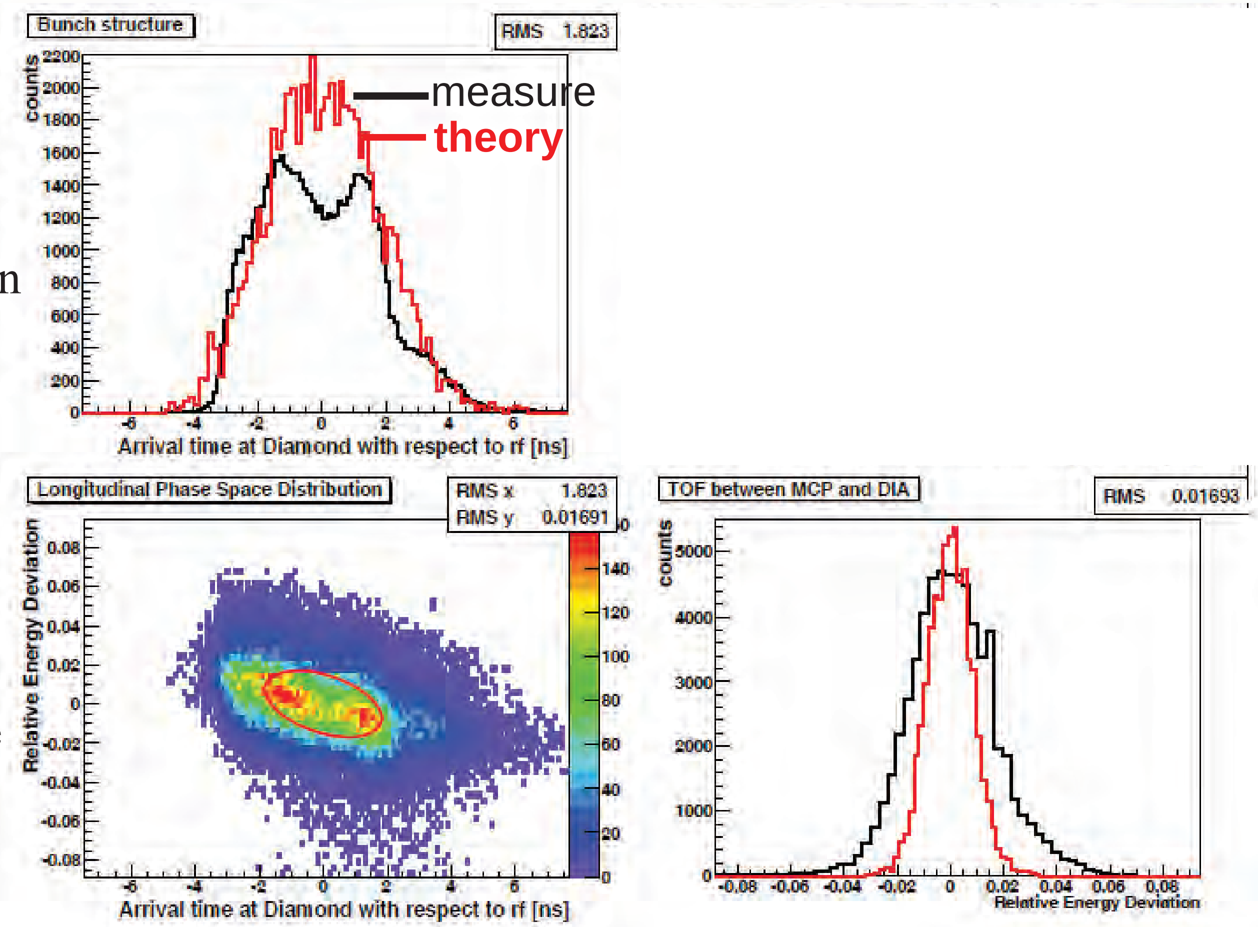
Example of Measurement

Phase space measurement:

Particle detection, ≈10 min

Result:

- Non-Gaussian bunch shape,
- Gaussian energy distribution
- Comparison to theory:
  Too low correlation i.e. **α**



Resolution:

- Very good for bunch shape
- Sufficient for total energy
- In-sufficient for phase space

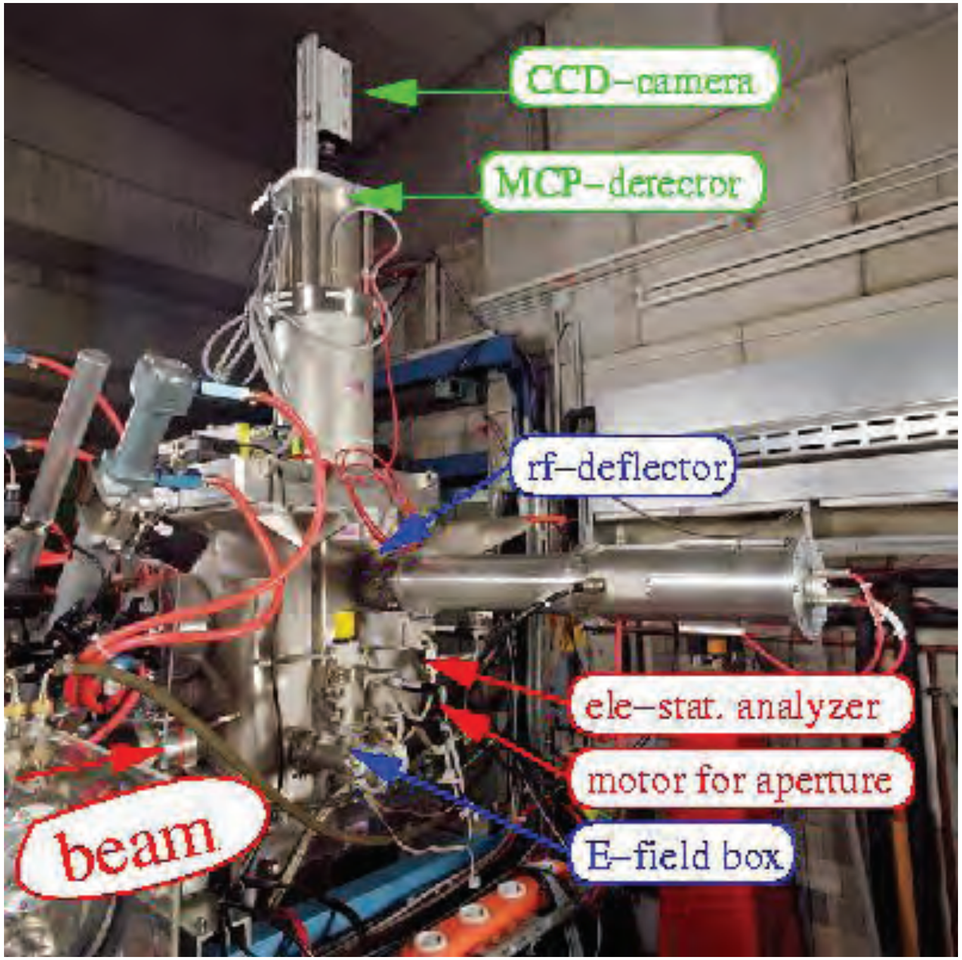
Never-the-less:

Used diagnostics for

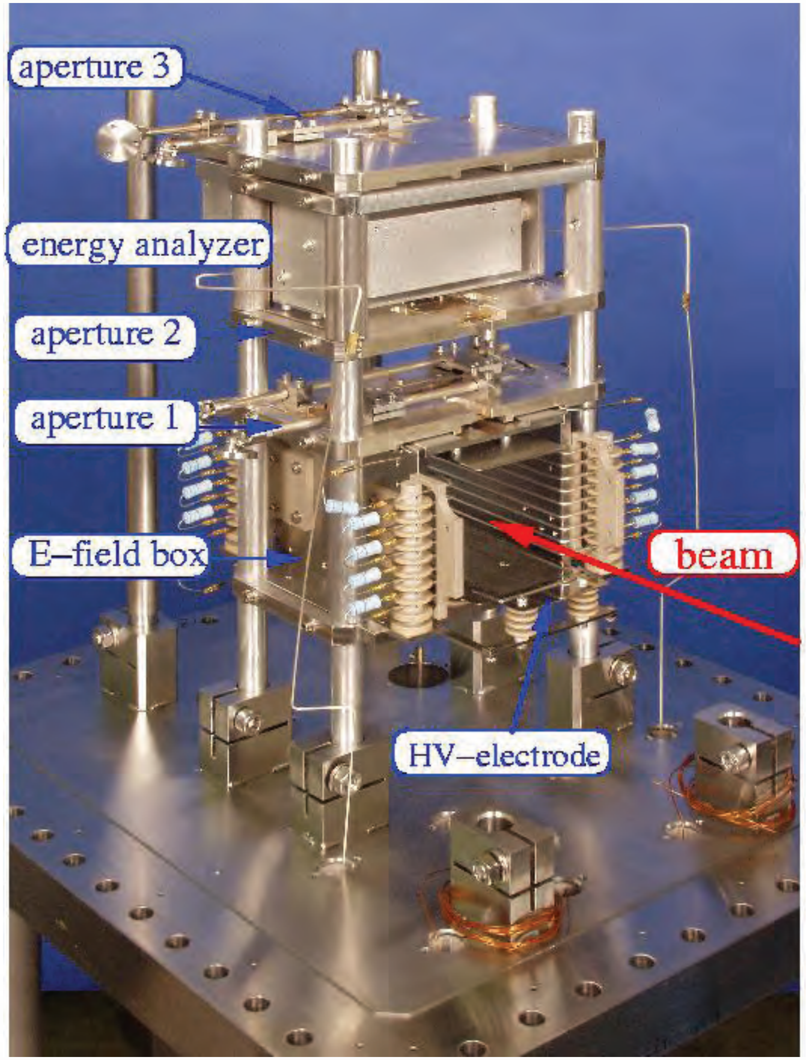
bunch shape & energy distribution (i.e. Twiss parameter β and γ)

Realization for non-intercepting Bunch Shape Monitor

The installation for beam based tests:



E-field box and energy-analyzer:

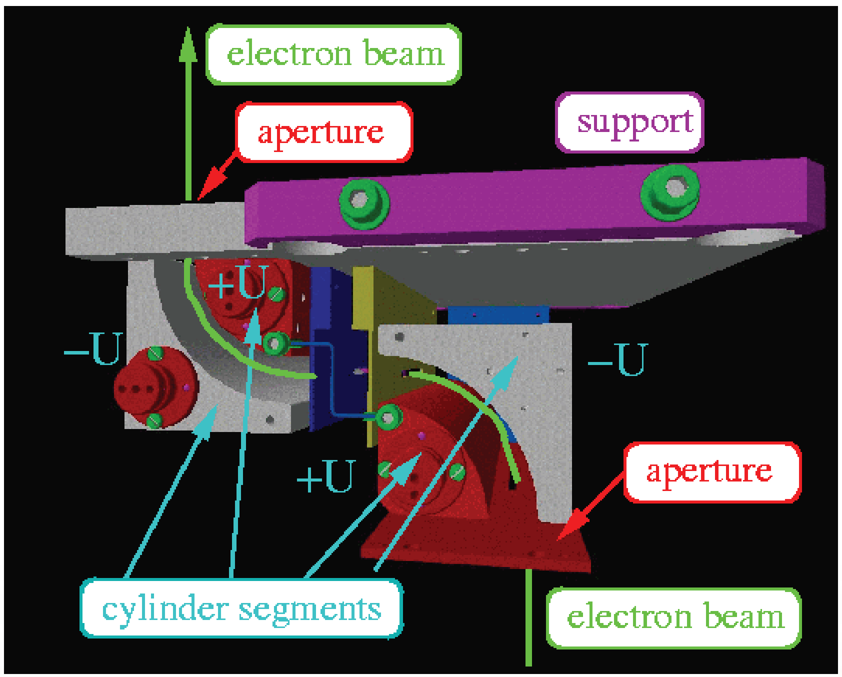


Hardware for Bunch Shape Monitor: Energy Analyzer

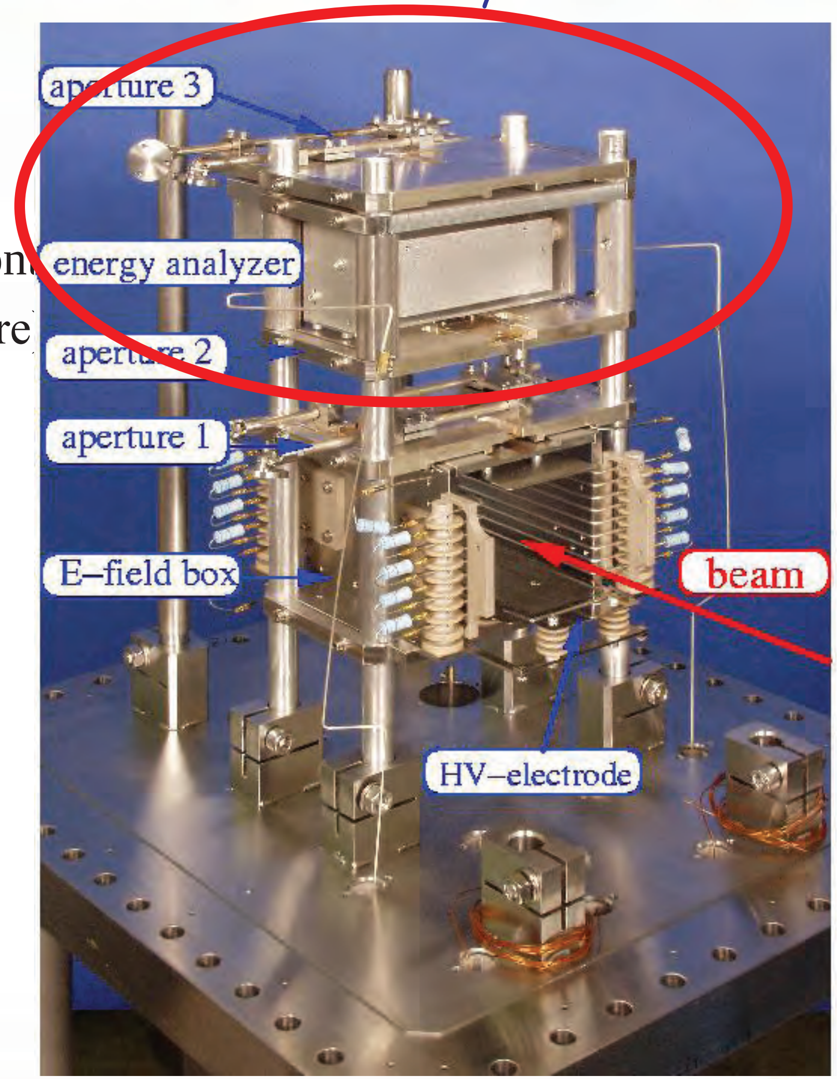
Energy analyzer for source volume restriction:

- Radius ρ=30 mm, 90^0 bending, $\pm$5.5 kV
- Remote controlled aperture: 0.1 to 2 mm
- point-to-point focusing
- for $\pm$0.25mm and $\pm$0.5mm aperture (remote con

  $\Rightarrow$ ±0.2 mm vert. prolongation (comparable to wire

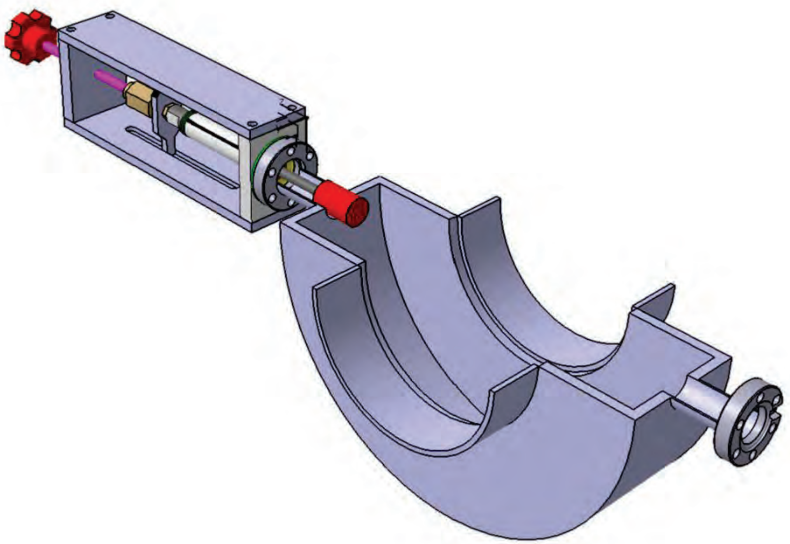


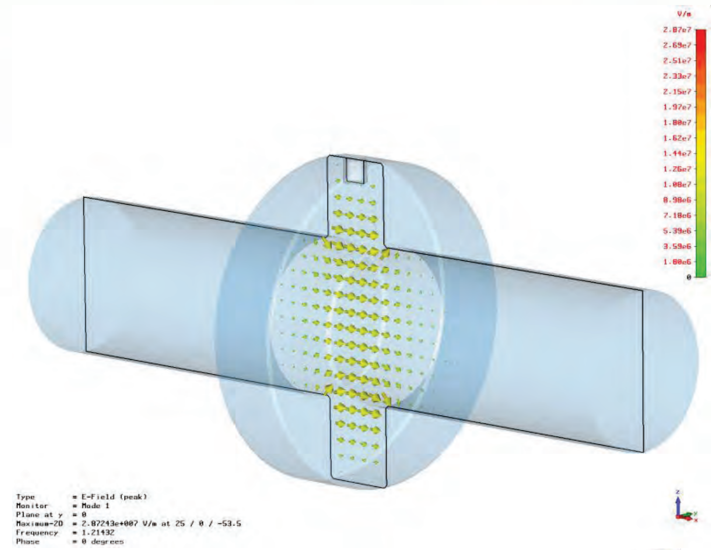
The E-field and analyzer:

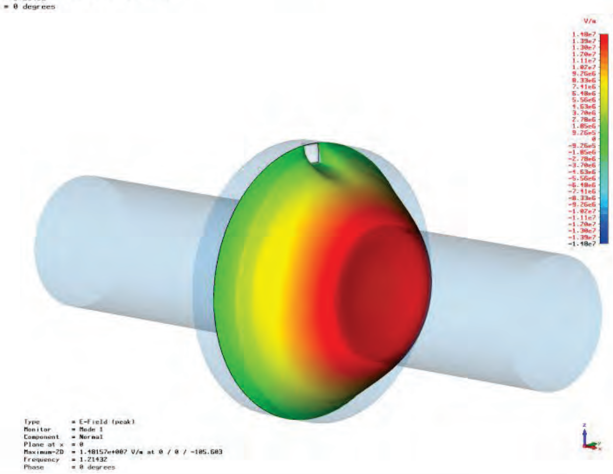


FEM Simulations of the Cavity Modes

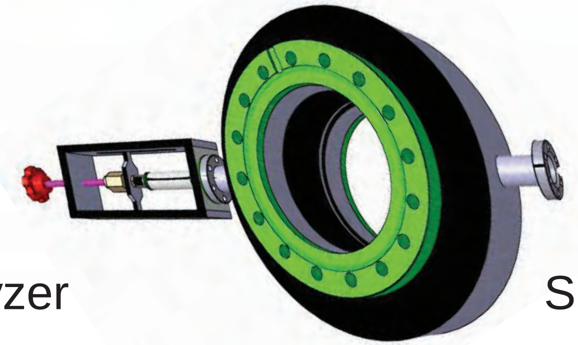
- TM010 mode simulated for different tuner position.
- No significant mode deformation found due to the tuner.





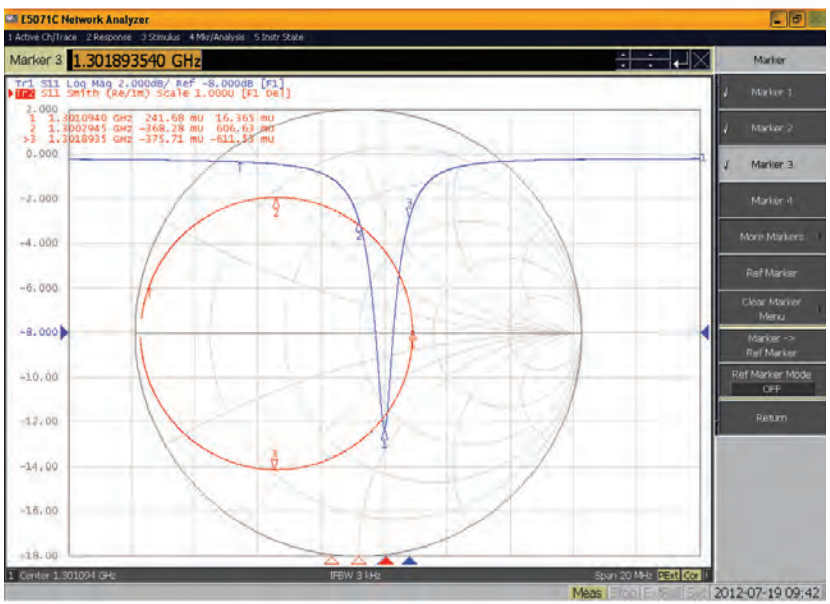


RF measurements of the cavity



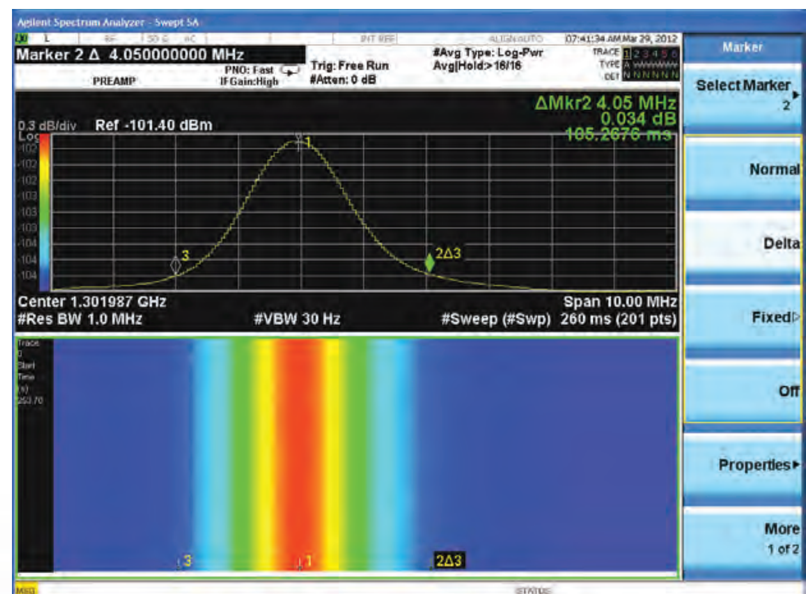
Network analyzer

(measured with coupling loop only)



Spectrum analyzer

(measure with whole el. chain)



General Idea of Experiment

Intensity: $1.2 \cdot 10^{10}$ U^{28+} Ions/cycle (train)

$E_{inj(SIS18)} = E_{ext(Unilac)}$: 11.43 MeV/u

Train length: 100µs

Synchrotron, Bρ=18 Tm

Used as energy analyzer

$f_{rev} = 214.7$ kHz

$H = 4^{th}$

$f_{rf} = 858.88$ kHz

Cavity installed in July 2012 →

"Schottky" Cavity

$f_{res} = 1.30089$ GHz

$H = 36^{th}$ h. of rf $_{Unilac}$

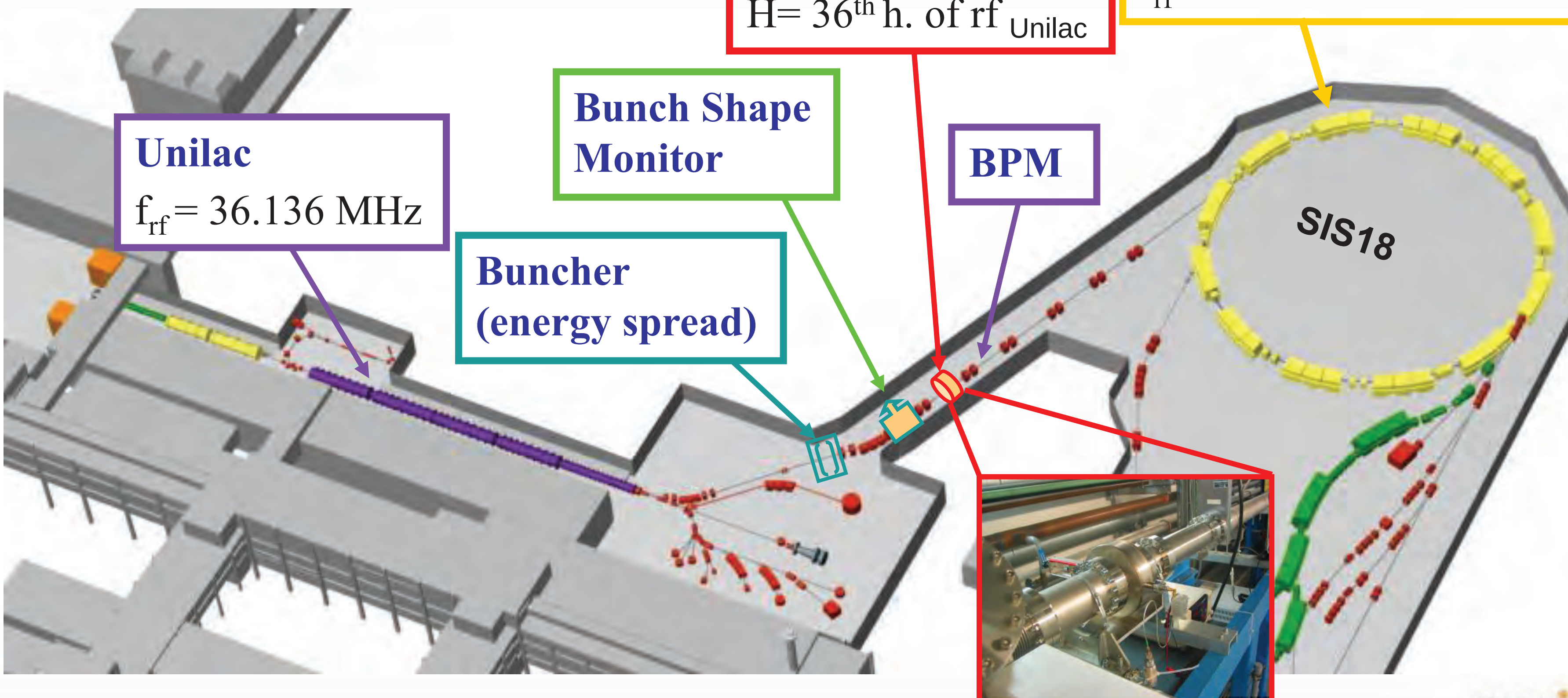
Bunch Shape Monitor

BPM

Unilac

$f_{rf} = 36.136$ MHz

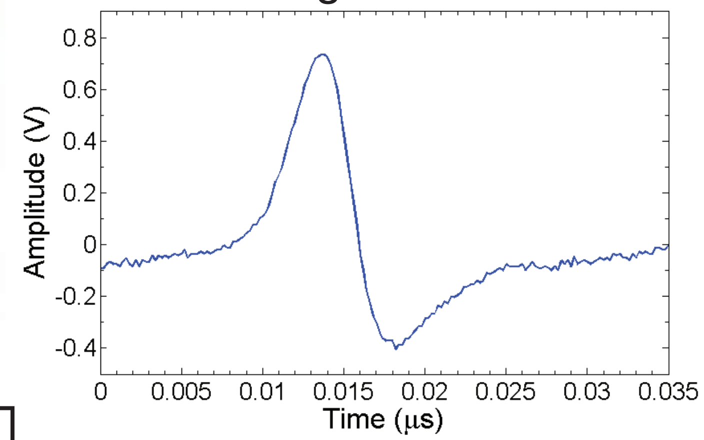
Buncher (energy spread)



Fourier transformation of Unilac bunch spectrum

- Signal measured by Unilac BPM
- Measurements done by means of 40GS/s oscilloscope
- No power in coherent lines for higher RF harmonics

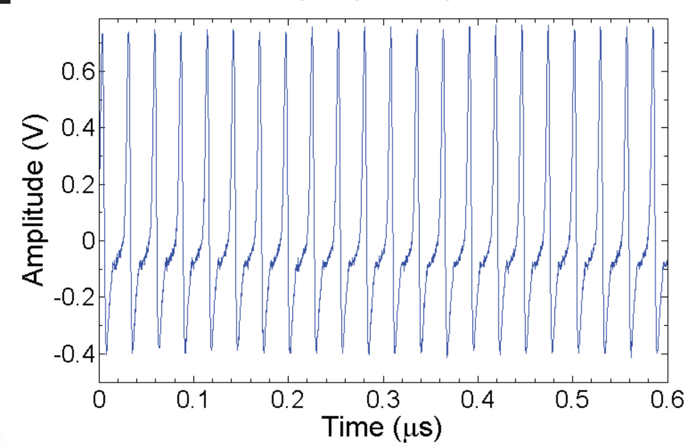
Single bunch



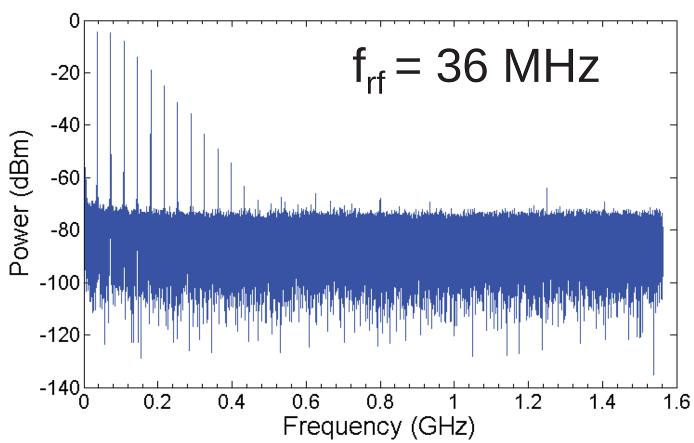
Beam parameters: U^{28+} at 11.4 MeV/u

$1.2*10^{10}$ ions per spill

Bunch train

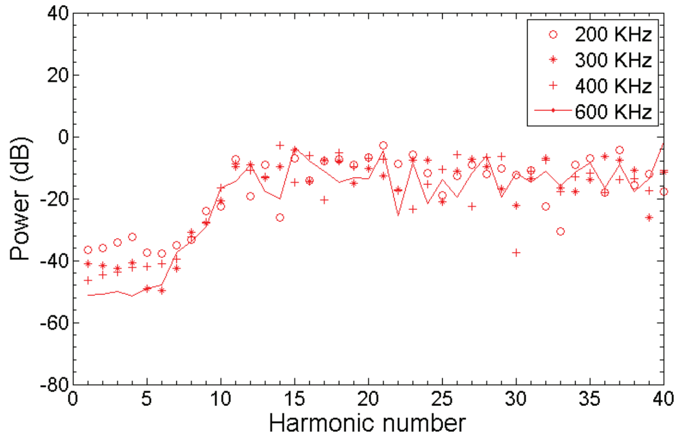


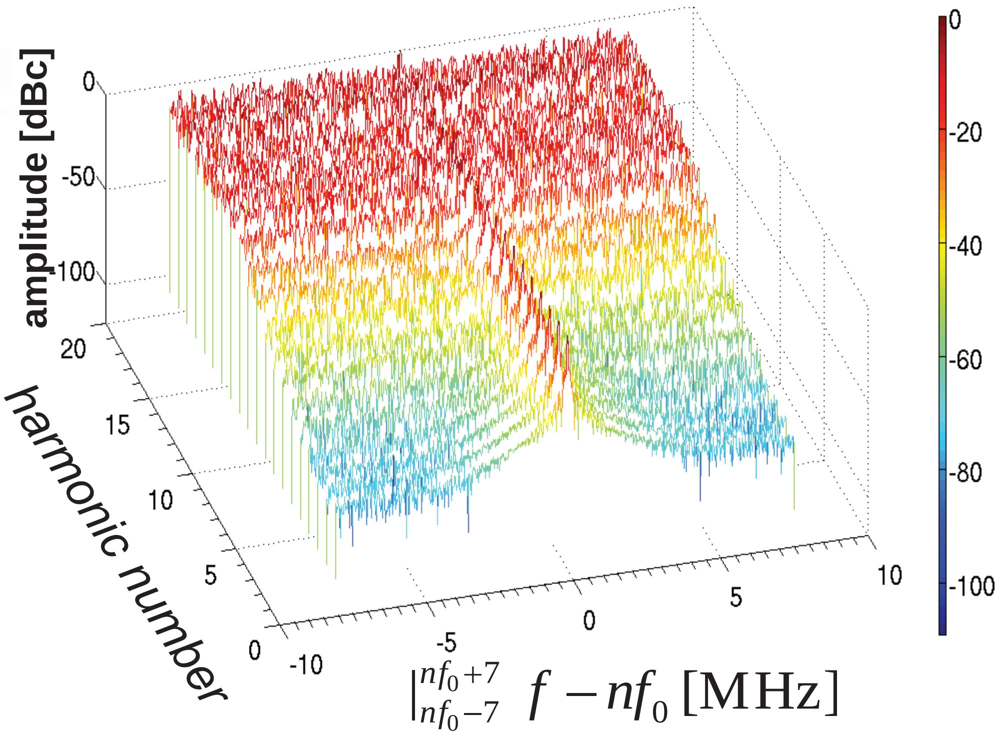
FFT



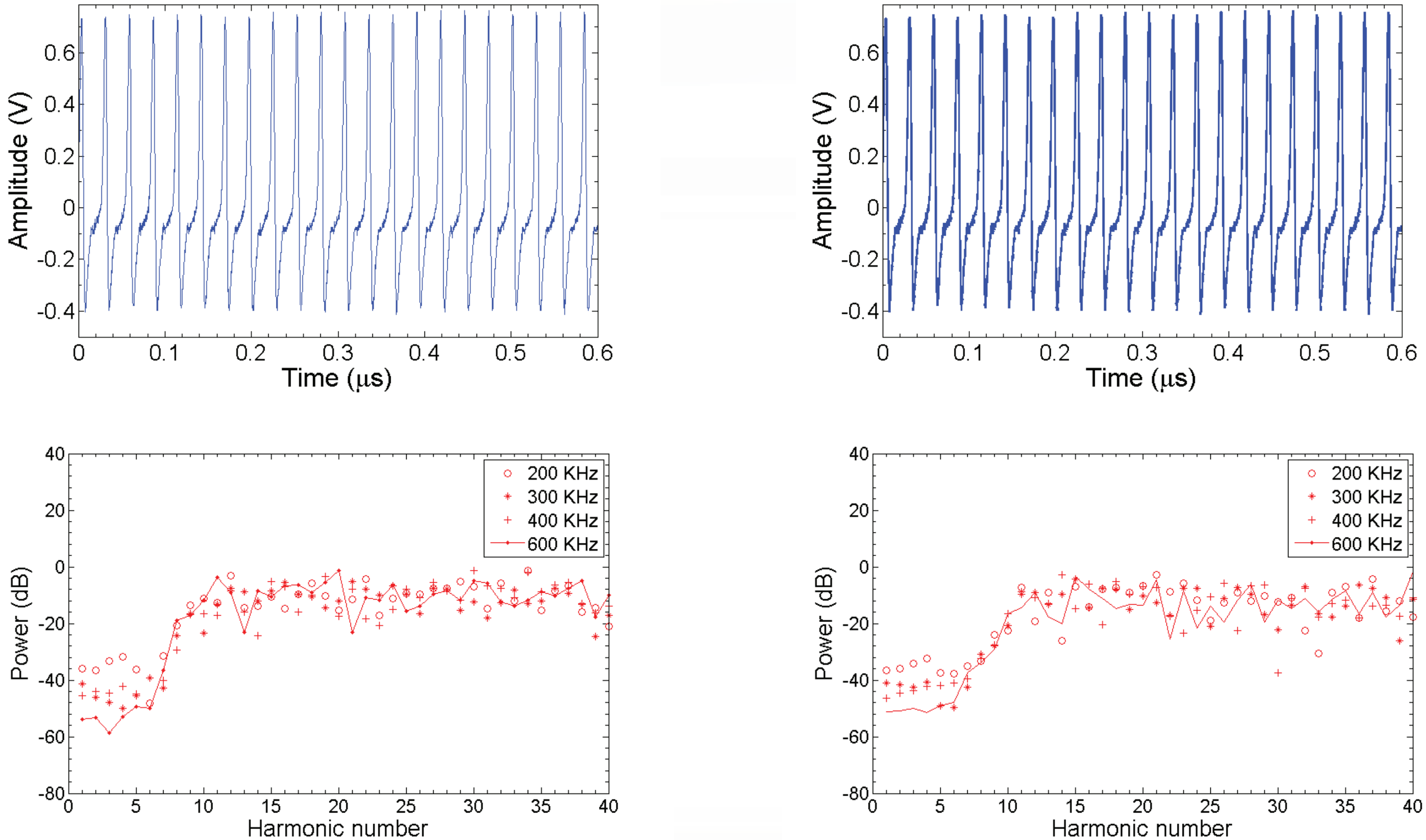
Harmonic analysis of BPM data

- Data from Unilac BPM
- No power for higher RF harmonics no coherent lines staring from n = 18)
- However sensitivity too small to see any incoherent (Schottky) signal





Harmonic analysis of BPM data (2)



Observation of the plasma modulations in the ion source

- System is extremely sensitive on any sour of beam modulation!
- Each modulation causes a coherent lines in the frequency spectrum.
- Here: modulation due to plasma fluctuations in the PIG ion source