Bunched Beams –
Longitudinal Beam Dynamics

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Helmholtz-Rosatom school for young scientists at FAIR 2011

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Table of Content

Parameters of the Longitudinal Beam Dynamics

V_0: Rf (peak) voltage

dp/p: Momentum spread (coasting, bunched)

Bf: Bunching factor (mean current/ peak current) – Bunch (phase) length: $\phi_B = 3/2\, \pi$ Bf

ϕ_s : Phase of synchronous particle

ω_s: Synchrotron frequency (beam in rf bucket)

h_{bunch}: Harmonic number of the bunches

h_{Rf}: Harmonic number of the Rf system (may be different to h_{bunch} , e.g. kicker gap)

α: Momentum compaction factor = $$\frac{1}{\gamma_t^2} = \alpha_p = \frac{1}{C}\oint \frac{D(s)}{\rho(s)} ds$$ $\gamma_T \sim Q$

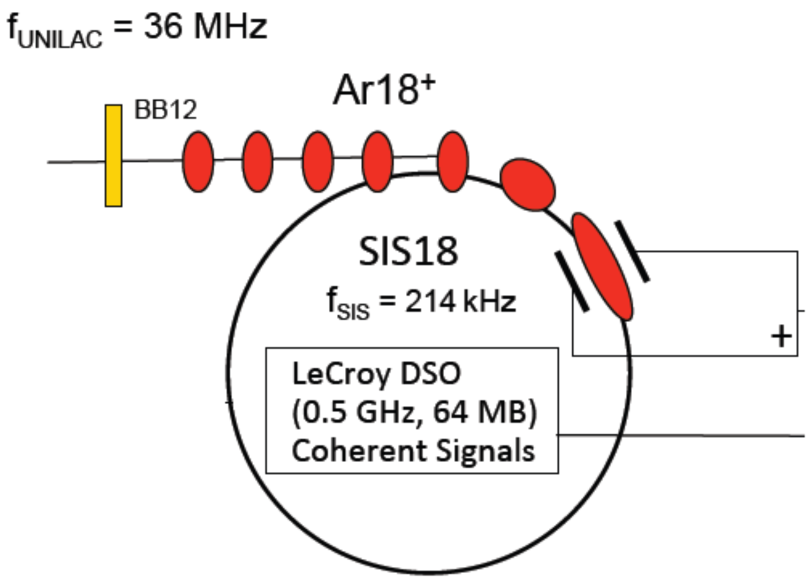
(Density of particle tracks with different momenta – function of the ring lattice)

η: Slip factor $= 1/\gamma^2 - 1/\gamma_T^2$

$\eta = 0$: All particles, independent from the momentum deviation have the same revolution time

(isochronous mode > storage rings)

Injection and Debunching



$$z_m'' + k_{z0}^2 z_m - \frac{K_L}{z_m^2} - \frac{\epsilon_L^2}{z_m^3} = 0$$

$$E_{||} \sim -K_L z$$

Longitudinal Envelope Equation

z_m: bunch length

ε_L: longitudinal emittance

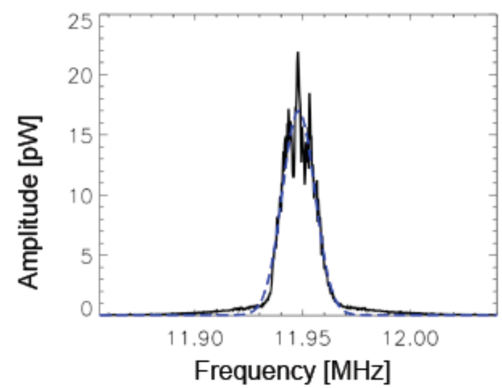
K_L: space charge parameter

k_z : longitudinal focusing (Rf system)

Coasting (debunched) beam:

Debunched, dc beam, „equally“ distributed over the circumference with a „flat“ longitudinal distribution. The linac beam has a microstructure, given by the linac Rf system – normally of much higher frequency than the ring Rf system.

The (micro)bunches from the linac are debunching after injection until they overlap. The momentum spread of the coasting beam is defined by the momentum spread of the microbunches (without space charge and debunching Rf system).

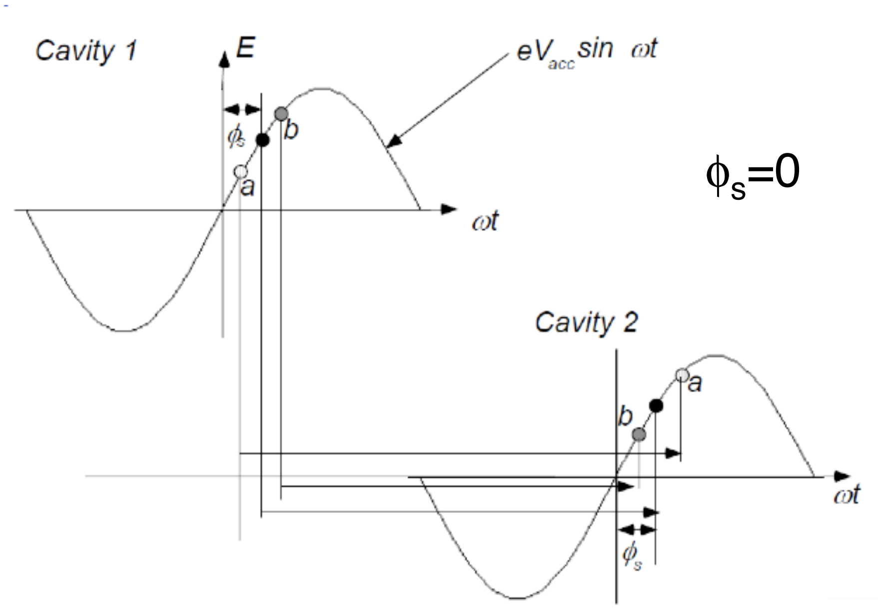


Schottky Spectrum

Longitudinal Profiles in Circular Accelerators

Bunched beam (stationary):

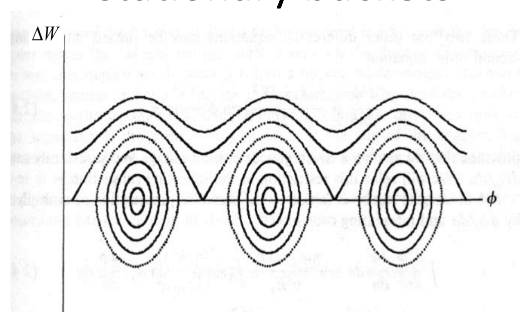
Particles capture in the Ring Rf bucket. Parabolic longitudinal distribution. Number of bunches are defined by the ratio of Rf frequency/ revolution frequency = harmonic number h.



ϕ_s=0

$$T = h\frac{2\pi}{\omega_{\mathrm{RF}}}$$

'stationary buckets'

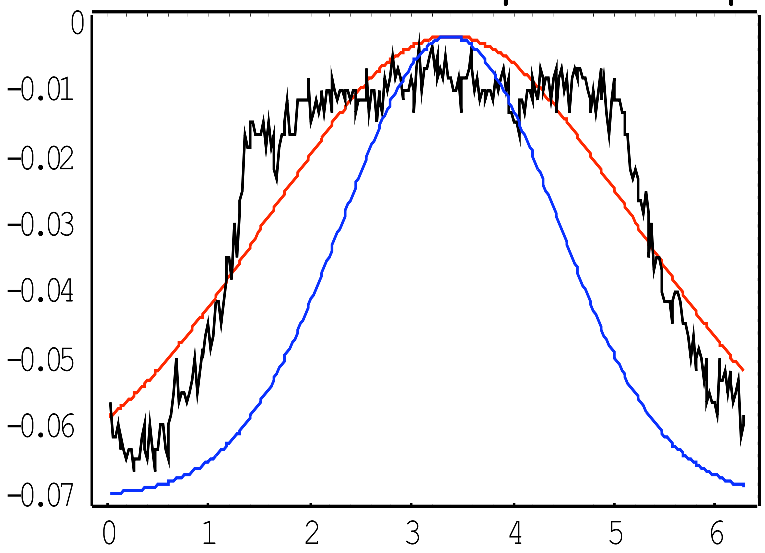


Particles inside the separatrix: bunch

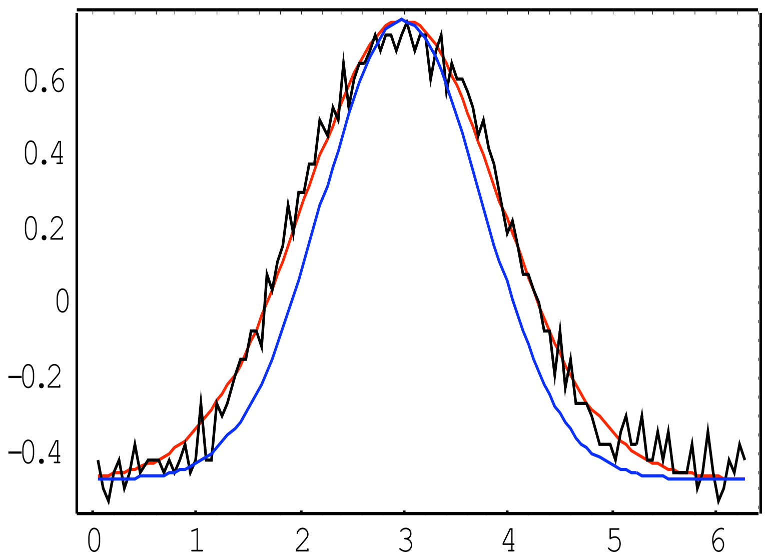
The run time T of the particle between two cavities must be an integer number h of oscillations.

Observed bunch profiles in SIS 18 after rf capture

SIS-MODI rf amplitude ramp



self-generated adiabatic rf ramp



Distorted bunch form.

Bunch area blow-up: ≈100 %

Matched bunch.

Bunch area blow-up: ≈30 %

Longitudinal Phase Space Conservation

The longitudinal phase space ε_L is invariant.

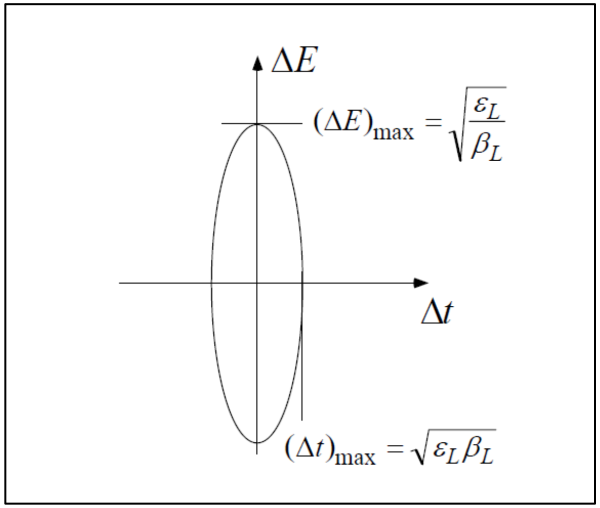
Even nonlinear systems do not change the emittance.

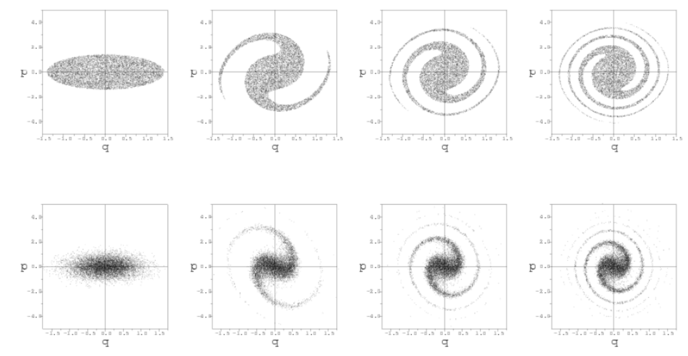
Only mechanisms changing the total energy of the systems change the emittance,

- e.g. acceleration (damping with $\varepsilon \sim \beta\gamma$), cooling etc.

Other mechanisms which may potentially change the emittance:

- charge exchange (stripping, stripping injection ...)





Phase space diagrams with equal emittances but increasing „effective emittance“.

However, the effective emittance can be changed. E.g. „air“ in the phase space generated by e.g. instabilities, coherent longitudinal oscillations, mismatch, Rf phase jumps etc. increases the effective emittance.

Since beam loss has to be avoided, the effective emittance is the only important parameter.

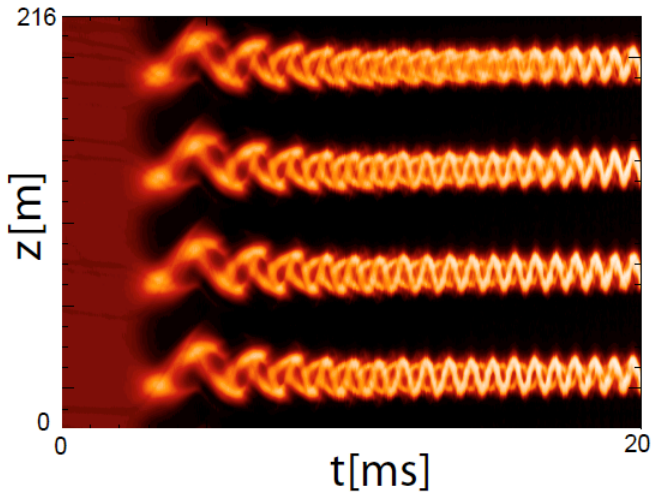
Bunching: Coasting Beam > Bunched Beam

The Rf frequency must be matched to the revolution frequency of the beam (schottky measurement).

The bunching process must be performed (iso)adiabatically.

The bunch must be matched to the bucket at any time.

The capture time must be a multiple of the synchrotron period (e.g. 30x). The change in synchrotron frequency must be small with respect to the synchrotron period.



Observation:
Persistent dipolar or quadrupolar bunch oscillations above a threshold intensity.

Persistent dipole oscillations in SIS 18: $\sum \approx 0.2$

Phase space conservation

$(dp/p)_c \times C = Ff \times h_B \times (dp/p)_B \times z_B$

$(dp/p)_B = 8/3 \times (dp/p)_C / (\pi\ Bf)$

Stationary Bunches

$$V_0 = \frac{(dp/p)^2}{d\phi^2} \times \frac{2\pi h\eta}{qe} mc^2 \beta\gamma \left(1+\Sigma_0\right)$$

$$\Sigma_0 = \frac{3Qhgqe}{8\pi\varepsilon_0 mc^2 \beta^2 \gamma^3 \eta \left(dp/p\right)^2 R d\phi}$$

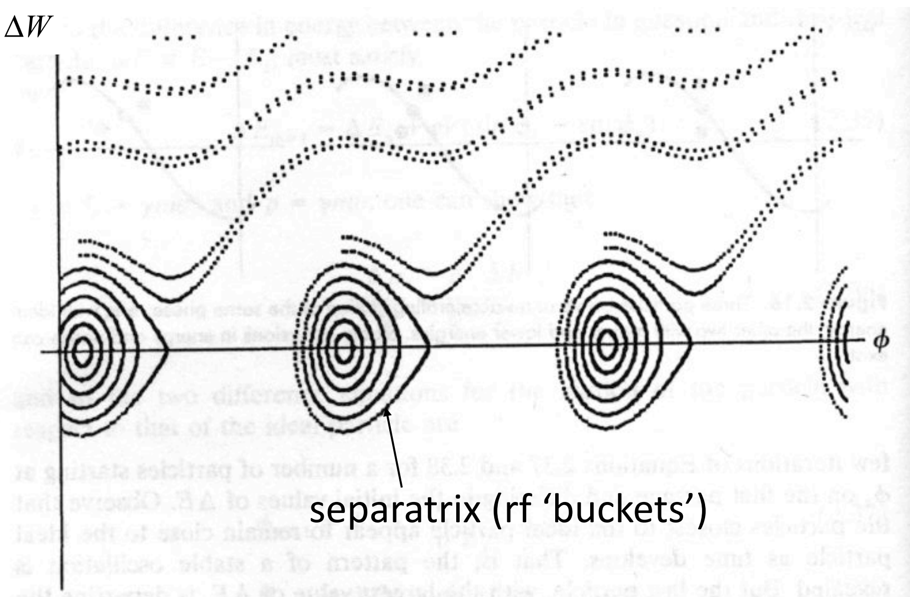
Rf voltage with space charge parameter

R: mean ring radius

g: form factor= ½ + 2ln (r_{tube}/r_{beam})

Acceleration

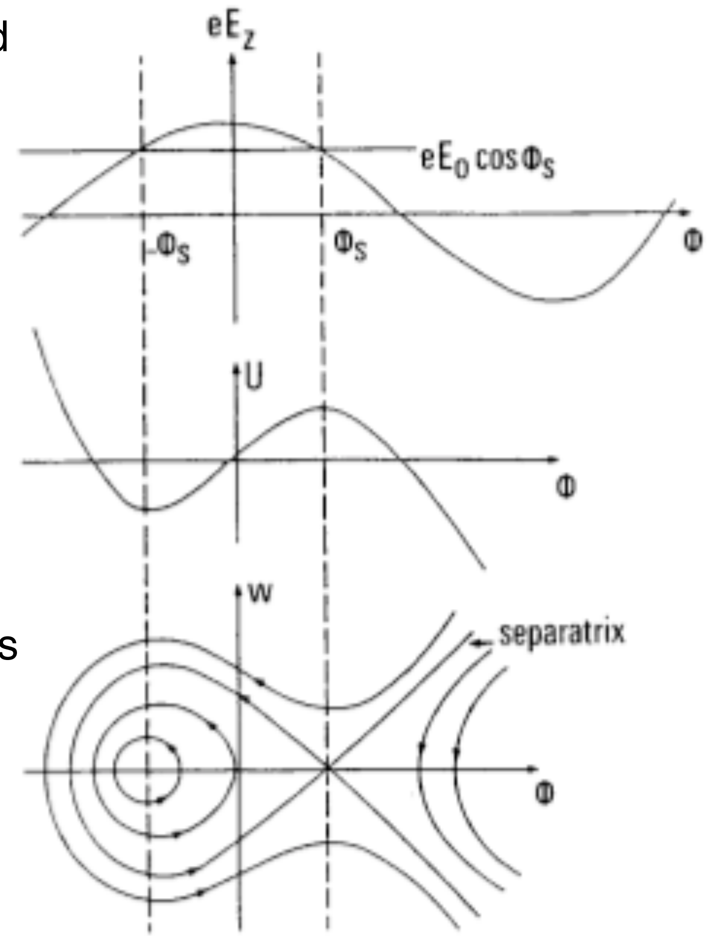
'accelerating buckets'



Electric Field

Potential

Trajectories



Stationary Rf Bucket

Synchrotronfrequency

$$\omega_S = \sqrt{\frac{qVh\sin\phi_S\eta}{2\pi R^2\gamma m}}$$

SIS18: typically 1 kHz

SIS100: proton operat. > ∞

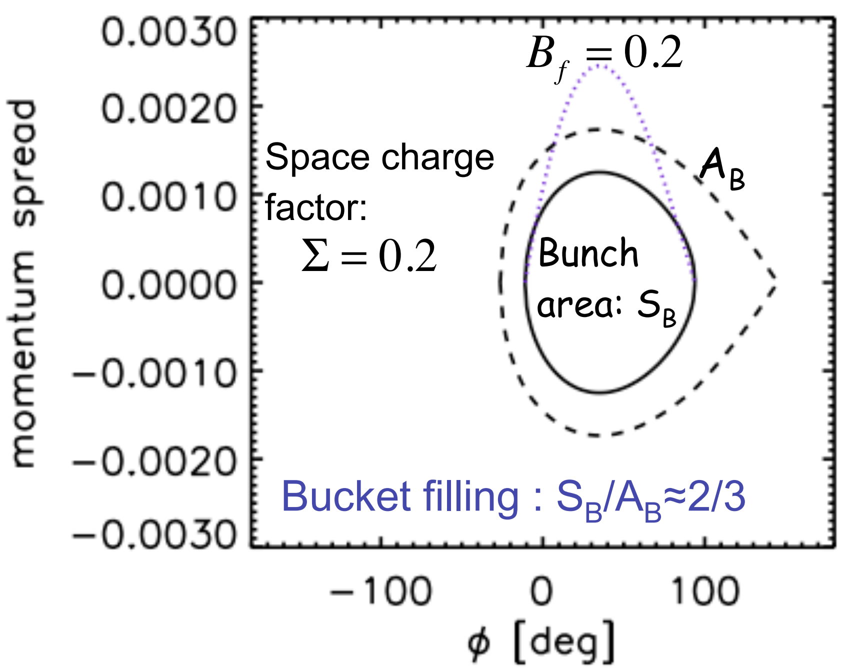
Bucket Area (Phase Space Acceptance)

$$A_B \propto \frac{1}{h^2}\sqrt{\frac{qhV_0}{M\cos\phi_s}}\,\frac{1-\sin\phi_s}{1+\sin\phi_s}$$

SIS18/SIS100 Rf Bucket Area and Beam Quality

Bucket area: $$A_B \propto \frac{1}{h^2}\sqrt{\frac{qhV_0}{M\cos\phi_s}}\frac{1-\sin\phi_s}{1+\sin\phi_s}$$

$= 4$ T/s: $V_0 = 400$ kV, h=10, $\phi_s = 35^0$



Bunch area and equivalent coasting beam momentum spread

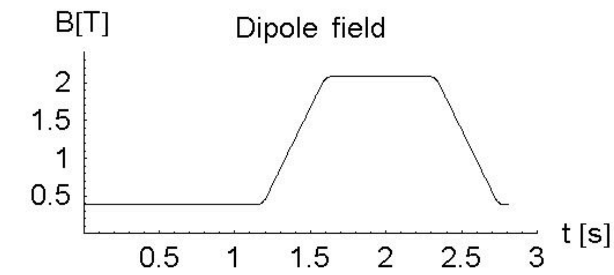
$$S_B = C\left(\frac{\Delta p}{p}\right)_{dc} \propto N_{inj}\left(\beta_0\gamma_0\right)^{-1}$$

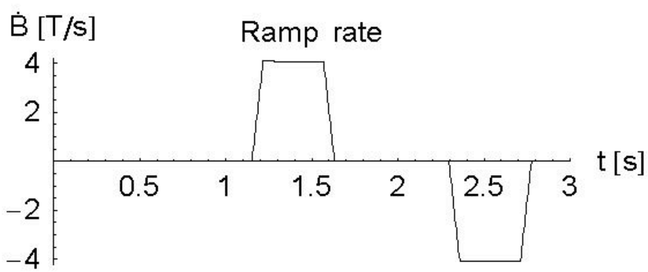
	FAIR design	today (e.g. M.Kirk, H.Damerau)
SIS 18 injection	10^{-3}	1-2 x 10^{-3}
SIS 18 extraction	4x 10^{-4} (dilution factor: 2)	1-2 x 10^{-3} (dilution factor: 5)
SIS 100 injection	4x 10^{-4}	1-2 x 10^{-3}

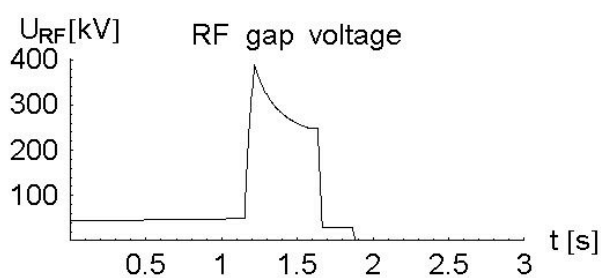
The budget for longitudinal blow-up in SIS 18/100 is tight (factor 2-3) !

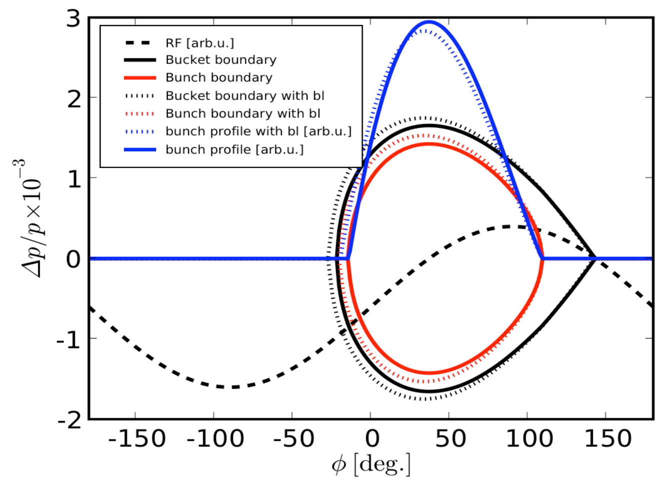
The present blow-up (> factor 5) in SIS 18 is not acceptable for FAIR !

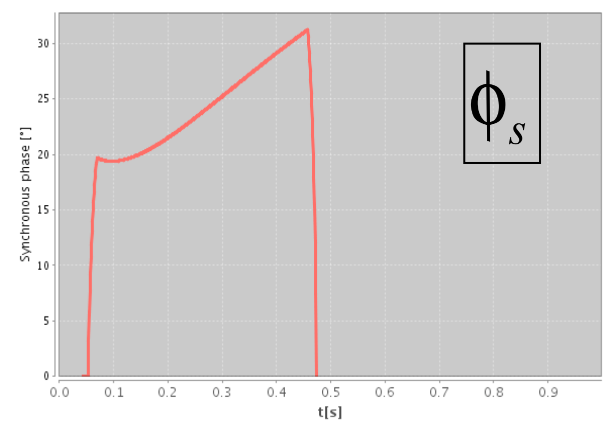
Acceleration in SIS100







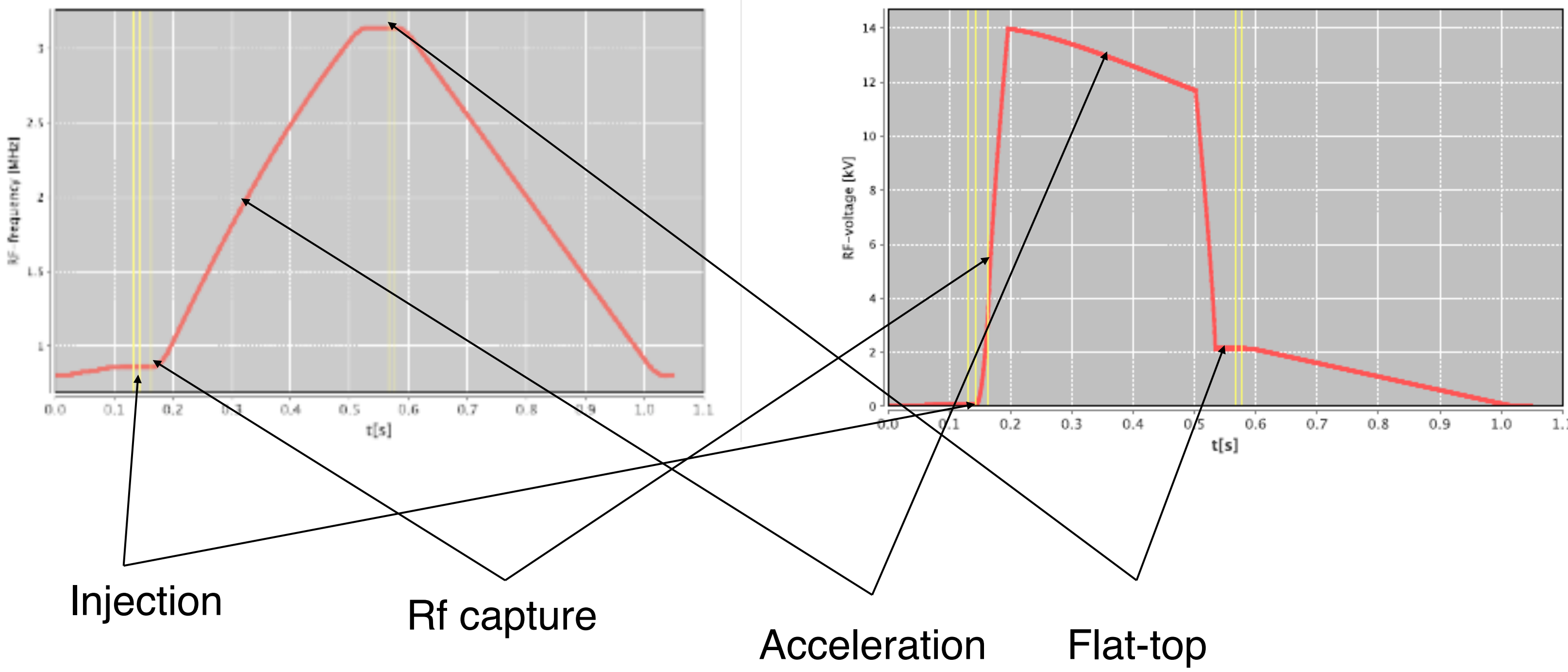




Realistic Rf Cycles (fast extraction)

Rf frequency cycle

Rf voltage cycle



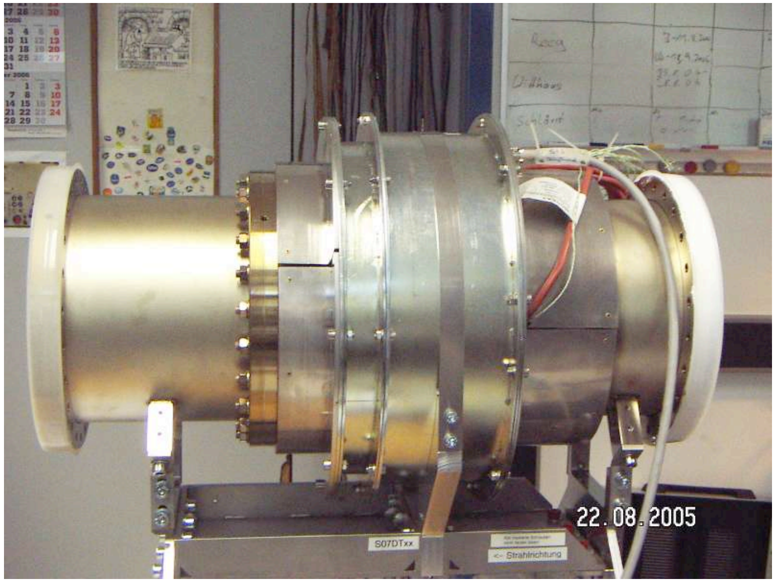
dB/dt = const

η: decreasing

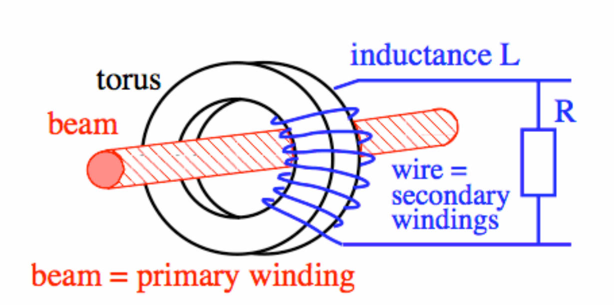
$\varepsilon_{L:}$ decreasing

Broadband Current Transformers

Transformer with beam pipe for average (dc) and bunch (ac) current

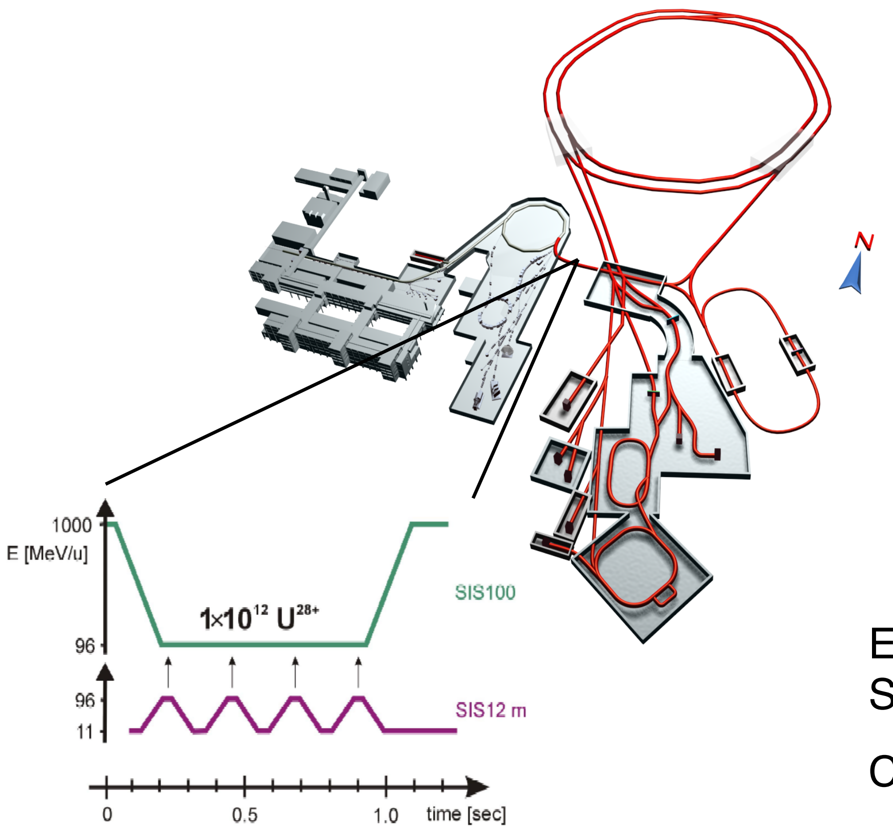


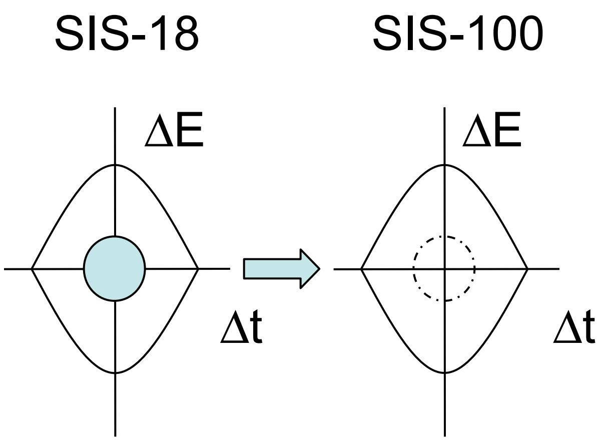
$$V = L \frac{dI_b}{dt}$$



- BERGOZ Instrumentation, France
- Bandwidth: 1 kHz ~ 650 MHz
- Rise time: 540 ps
- cost: 8000 Euro

SIS18 > SIS100 Bunch to Bucket Transfer





Extraction kicker is triggert according to beat between SIS18 and SIS100 bucket phase.

Circumference relation must by slightly non-integer.

Barrier Bucket Injection (temporary concepts)

Barrier Bucket System in SIS18 :

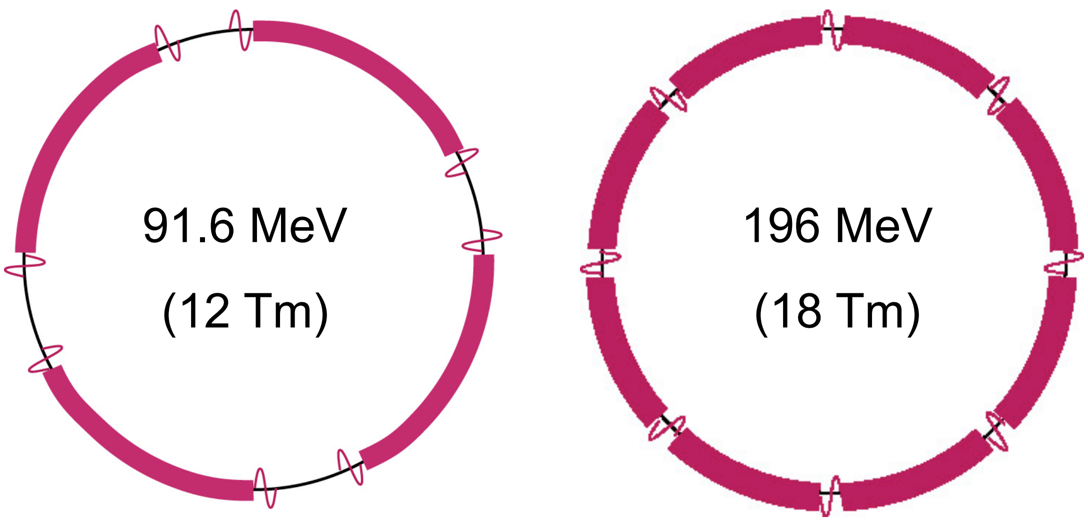
Debunching before transfer to SIS100

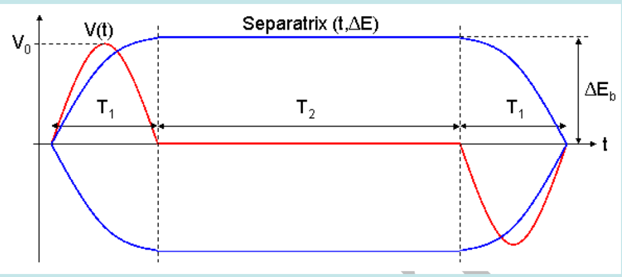
Inc. Tune Shift $dQ \propto 1/(\beta^2 \gamma^3)$

and $dQ \propto I_{spitze}/\langle I \rangle$

$dQ < 0.25$ (1 Sek.)

Synchrotron ≠ Storage Ring





Separatrix in a barrier bucket

Barrier bucket injection system in SIS100 :

2 individual systems of MA loaded cavities

15 kV at 2,4 MHz

(Cavity under development at GSI)

Rf Cycle in SIS100 (temporary concepts)

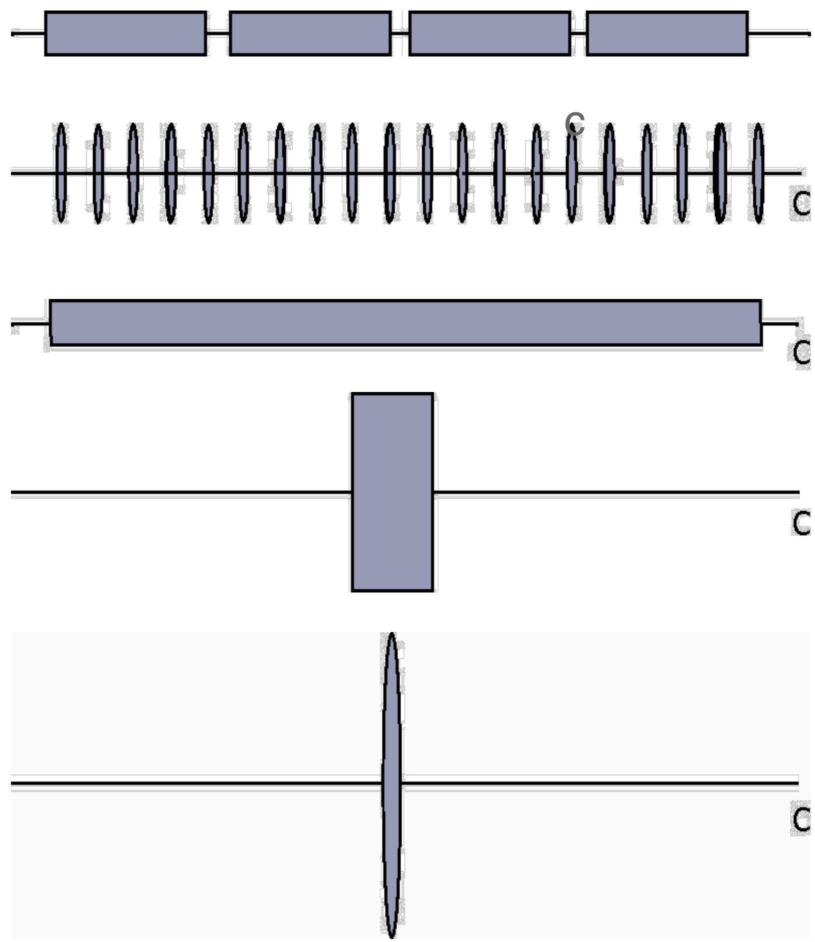
Barrier Bucket Injection
(RF System 1)

Acceleration at h = 20
(RF System 2)

Debunching in Barrier Bucket
(RF System 1)

Precompression in Barrier Bucket
or Harmonic Potential
(RF system 1/2)

Compression at h = 2
(RF system 3)



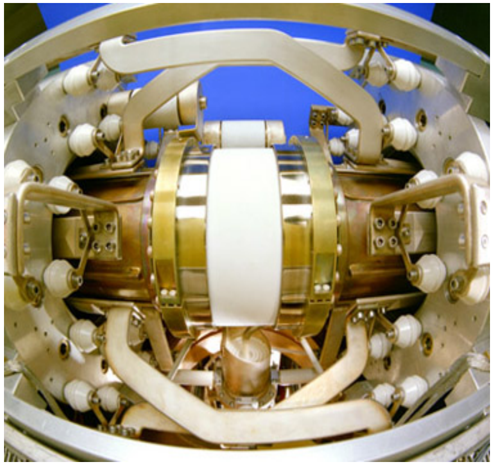
Rf Systems in SIS100

- ***Acceleration Systems***
  18 ferrite loaded Cavities
  $V_{a,tot}$ = 300 kV - Frequency Range : 2.28 – 5.34 MHz

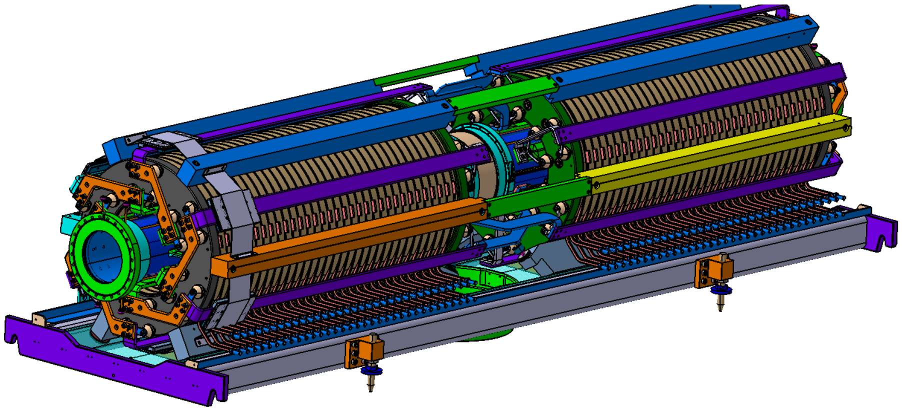
- ***Compression Systems***
  38 MA-loaded Cavities
  $V_{c,tot}$ = 1.3 MV – Frequency Range : 465 kHz (±70)

- ***Barrier Bucket Systems***
  Broad band MA-loaded Cavities
  V_b = 2x 15 kV – Frequency = 2.4 MHz.

  Total Length of RF-Systems ~ 120 m
  (11% of Circumference)

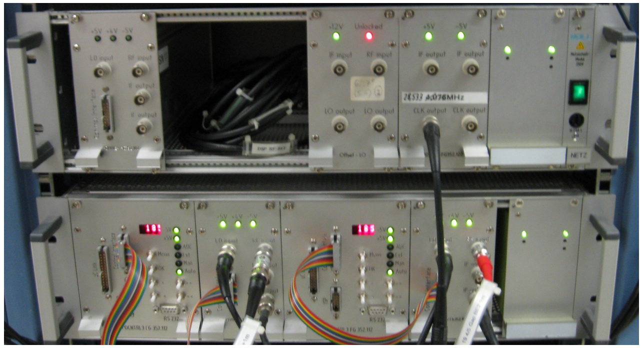


SIS18 and SIS100 Inductively Loaded Rf Cavities



Ferrite loaded SIS18 acceleration cavity

MA loaded SIS18 bunch compressor cavity



Phase control unit for two harmonic operation of the ferrit loaded SIS18 cavities and the MA loaded h=2 cavity

New LLRF modules developed:

Flexible Direct Digital Synthesis (DDS) unit for RF signal generation,

Programmable distribution amplifier for the switching of RF reference signals,

FPGA interface board that distributes information from the central control system via optical networks to the target devices (e.g. to the DSP system for closed-loop phase control)

Rf System Developments

- Digital Cavity Control

  Synchronization of cavities > Increased longitudinal acceptance at high ramp rates and rigidities

  Synchronization of cavities running at different harmonics

  Bunch phase feed back

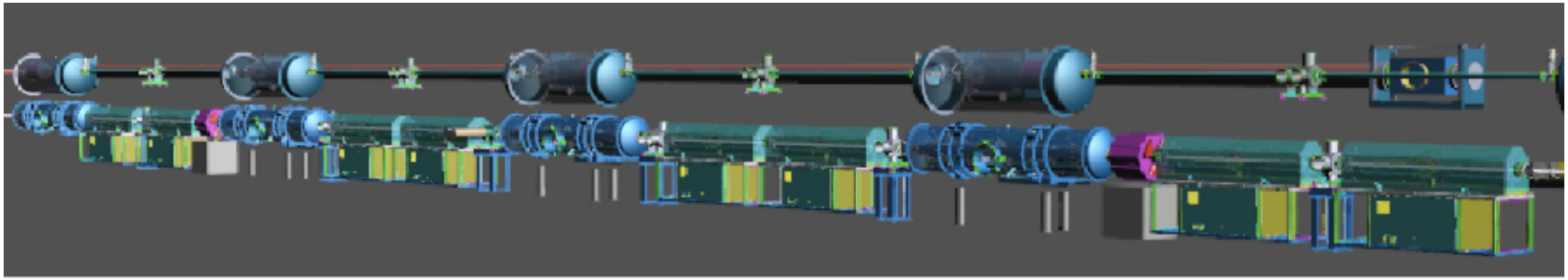
- Longitudinales feed back system (separate broad band cavity)

  Damping of coupled bunch modes

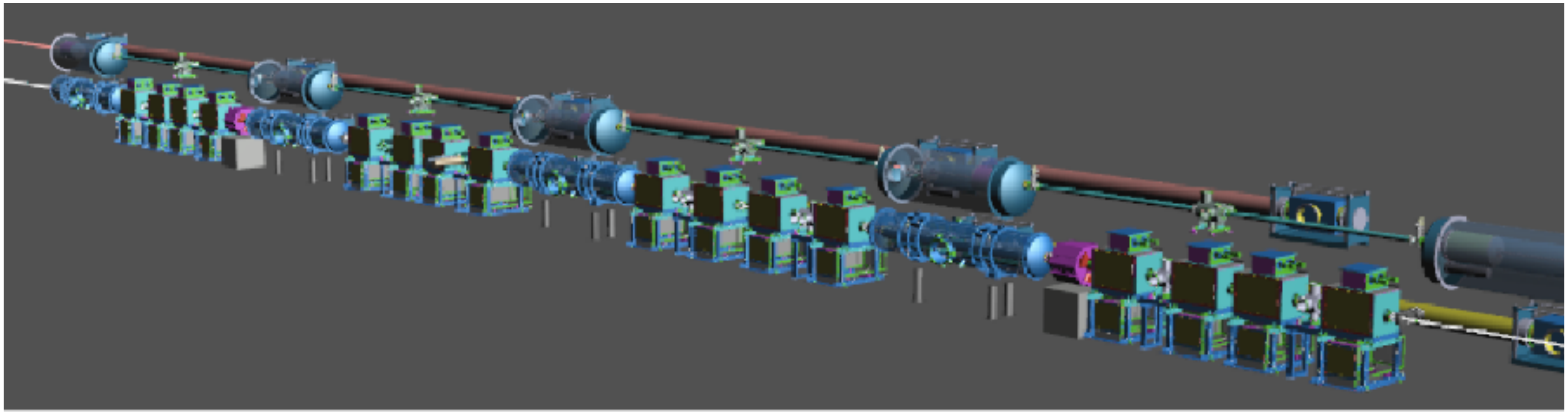
  Damping of instabilities in the coasting beam phase

- Fast semiconductor gap switches for low and high duty cycle cavities

SIS100 Rf Sections



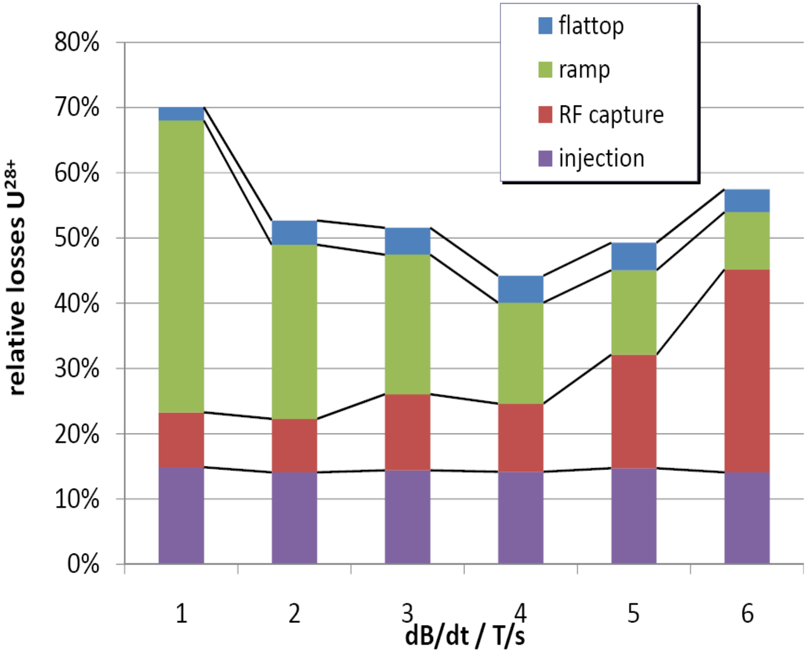
Rf acceleration section



Rf compression section

SIS18 - U^{28+} Beam Loss at High Ramp Rates

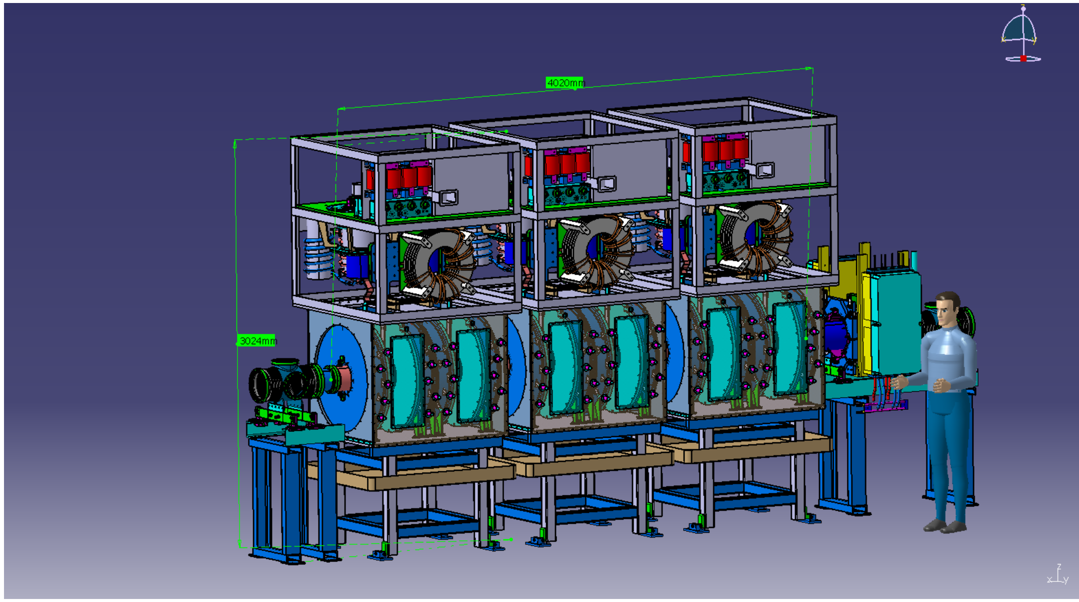
Insufficient bucket area creates beam loss. The bucket area depends on the phase of the synchronous particle which increases with increasing ramp rate.



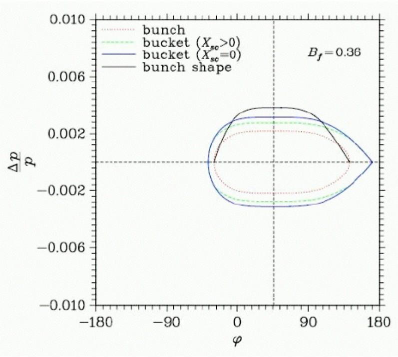
$$V_{acc,\min} = V_0 \sin\phi_s = 2\pi\ R_{syn}\rho_B \times dB/dt$$

Fractional loss of different mechanisms during fast ramping

New h=2 Acceleration System



- Sufficient Rf voltage for fast ramping with low charge state heavy ions
  - *U^{73+} acceleration with 4 T/s ($2x10^{10}$ ions)*
  - *U^{28+} acceleration with 10 T/s ($2x10^{11}$ ions)*
- Sufficient bucket area for minimum loss
  (30 % safety)
- Flat bunch profile (high Bf) for lower inc. tune shift
  - *two harmonic acceleration*
  - *h=4 (existing cavity) and h=2 (new cavity)*
- Compatibility with SIS100 Rf cycle



Design studiy for the new, high duty cycle MA loaded, h=2 acceleration cavities (0.5 MHz - 50 kV)

Dual Harmonic Operation

Dual harmonic test operation with the existing SIS18 cavities at h= 4 and h= 8 with the new LLRf system.

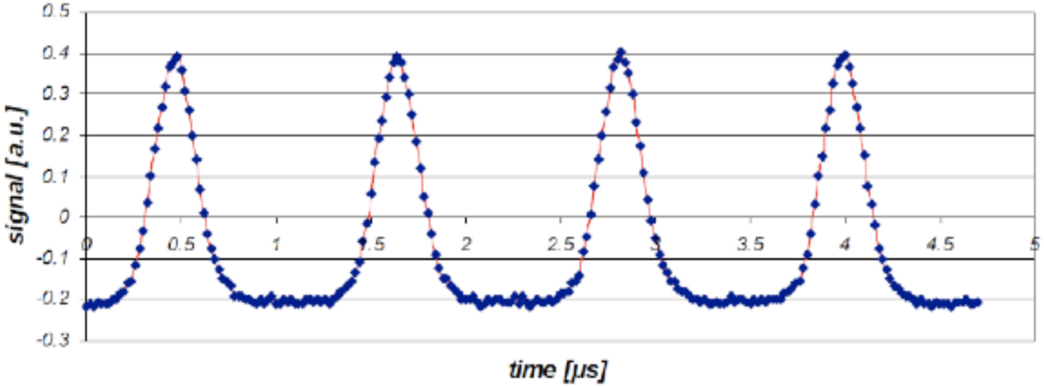


Figure 4: Bunch Profile Single-Harmonic Operation (B. Zipfel)

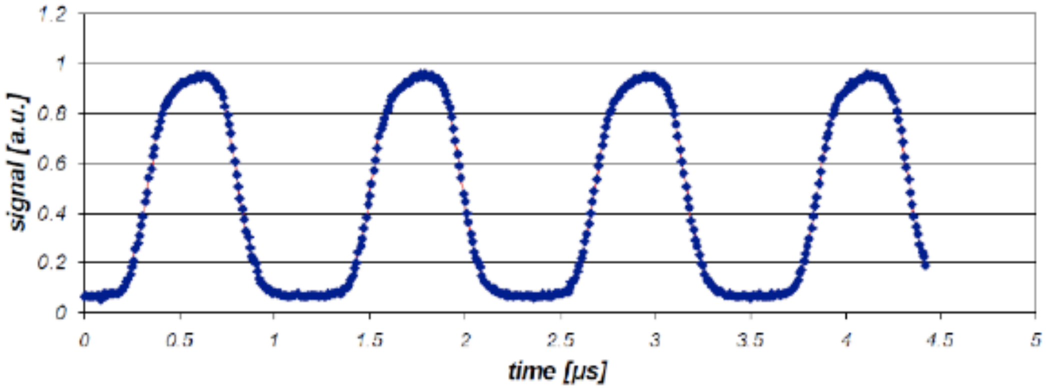
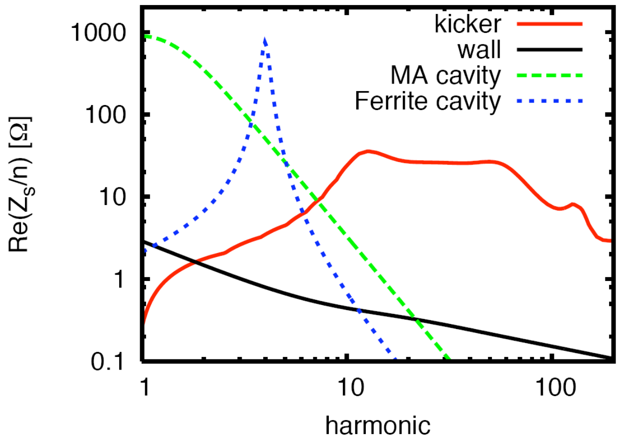
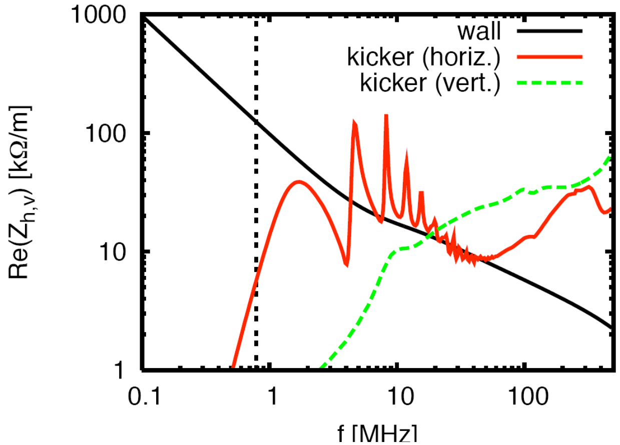


Figure 5: Bunch Profile Dual-Harmonic Operation (B. Zipfel)

Single Bunch Generation

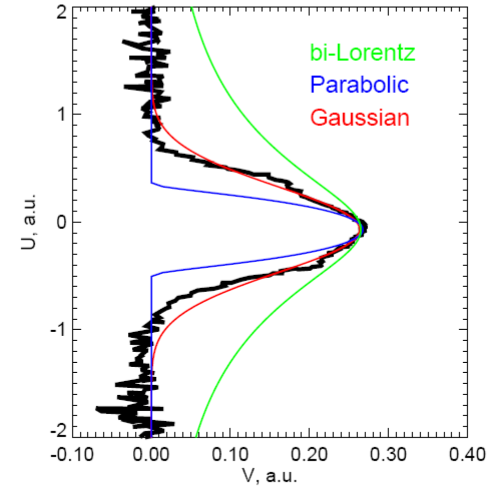
Impedance and Beam Stability

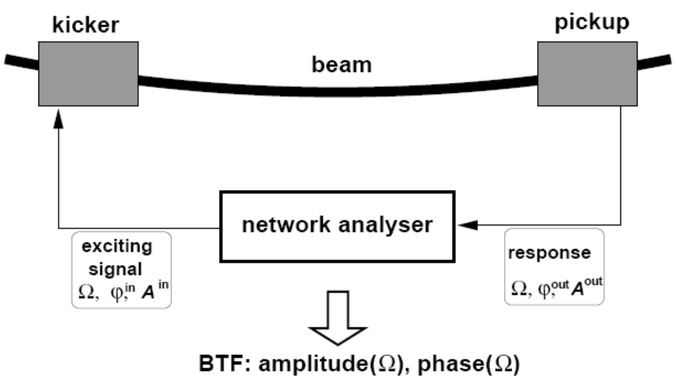




Measurement of

- Beam stability diagram
- Betatron tune Q,
- Chromaticity ξ
- Momentum spread dp/p

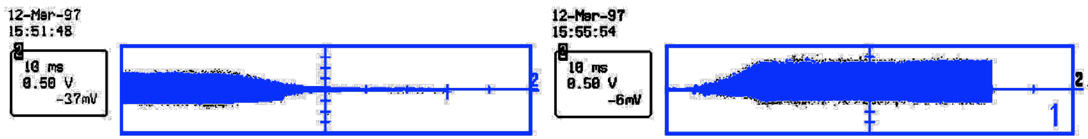




Goal: Determination of impedance spectrum - Measurement of kicker- and resistive wall impedance and their influence on beam stability

Beam Instability in the Coasting Beam Phase

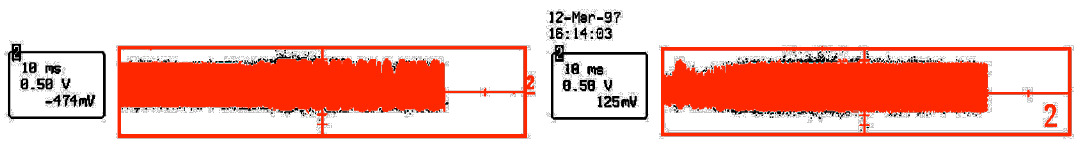
Cavity impedance : 3 kOhm – Resistive Wall Impedance : 1.5 kOhm



Bunch Amplitude before Debunching (h=4)

Niedriger Strom

Bunch Amplitude after Rebunching (h=1)

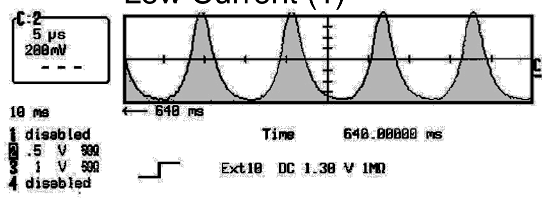


Bunch Amplitude before Debunching (h=4)

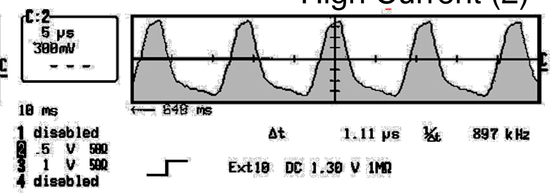
Hoher Strom

Bunch Amplitude after Rebunching (h=1)

Final Bunch Profil at Low Current (1)



Final Bunch Profil at High Current (2)



Ne^{10+}-beam $1x10^9$ and $2x10^{10}$ Teilchen

- Fast detuning the cavity during or after debunching
- Operatíon with slightly bunched beams during slow extraction
- Broad band feed back system (under development)

Bunch Merging

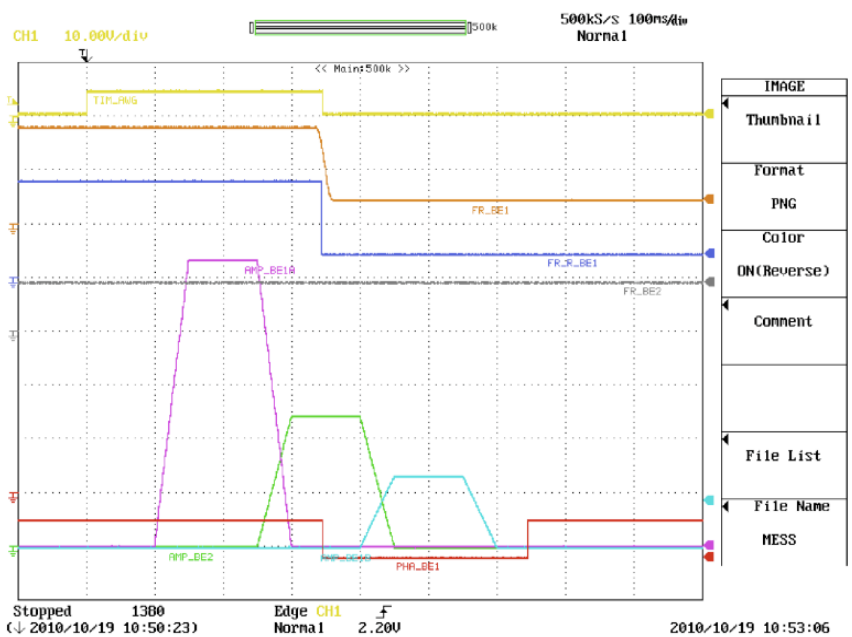


Figure 2: Oscilloscope plot of the generated ramps

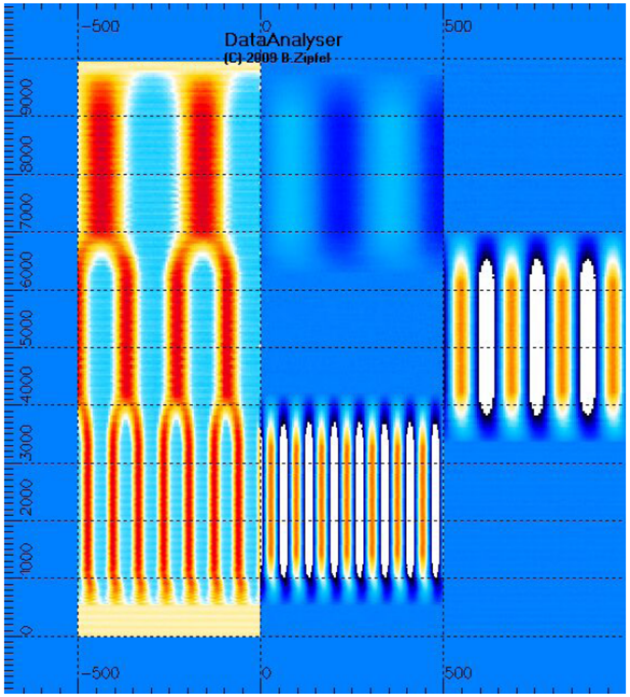


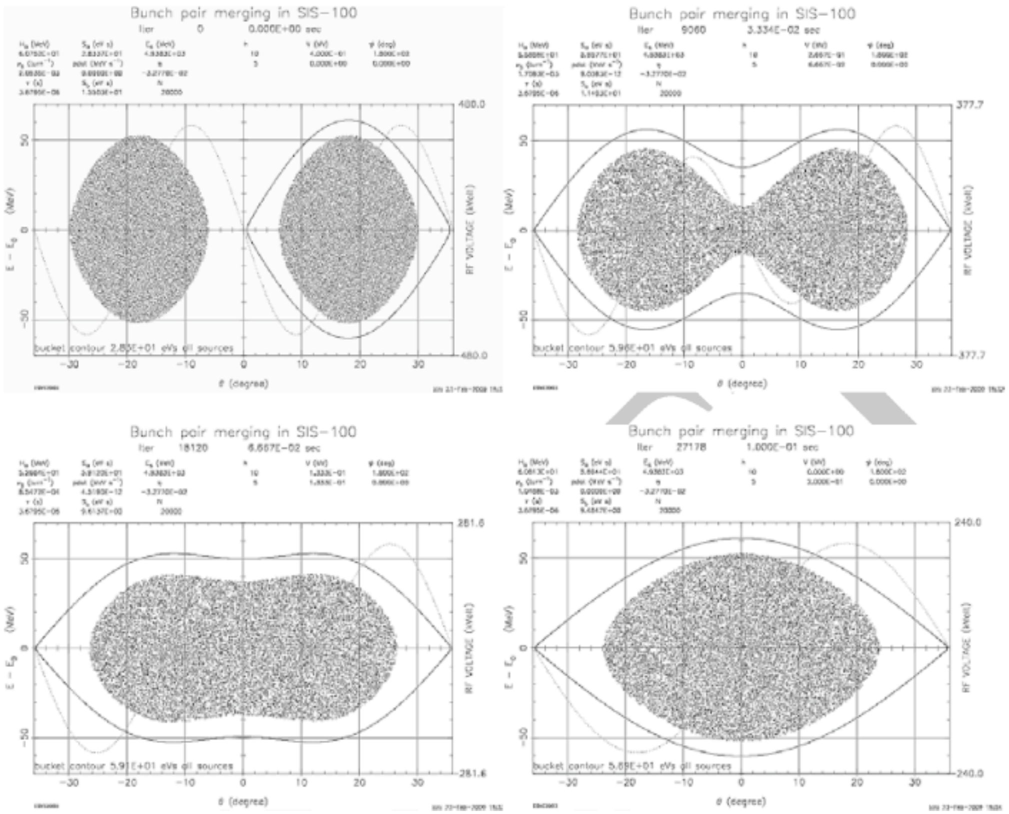
Figure 4: Waterfall plot (leftmost section: Beam signal (beam phase monitor S05DP3P), section in the middle: Gap voltage S02BE1, right section: Gap voltage S08BE2)

The cavity S02BE1 was temporarily operating at h=4 and temporarily at h=1, the cavity S08BE2 was permanently operating at h=2.

The height (amplitude) of two subsequent overlapping trapezoidal ramps differs by a factor of ½. This ratio was chosen in order to keep the overall bucket area (proportional to $\sqrt{U_{RF}/h}$) constant.

Proton Bunch-Merging in SIS100

Figure 4. Simulated phase space plots of the beam during bunch merging of 4 GeV protons. The plots below correspond to the times t=0 (top left), $t=T_{merge}/3$ (top right), $t=2T_{merge}/3$ (bottom left), $t=T_{merge}$.

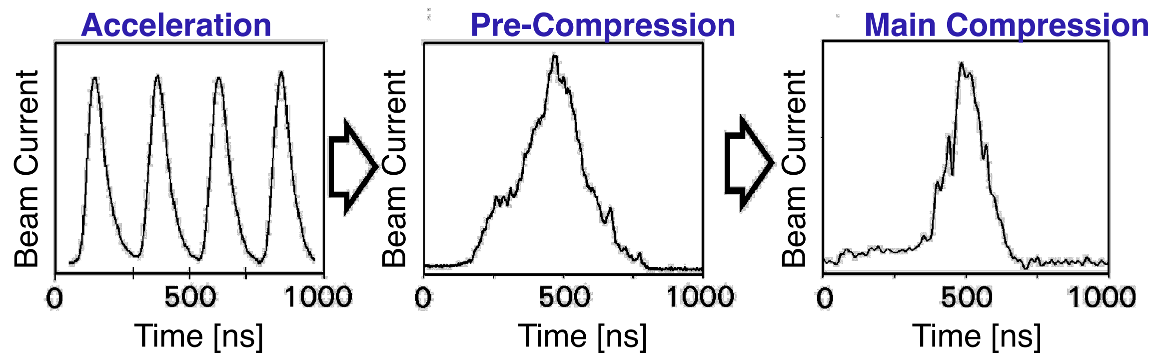


Since the synchrotron frequency at extraction level ist too low, proton bunch merging (single bunch generation) in SIS100 must be performed on injection level

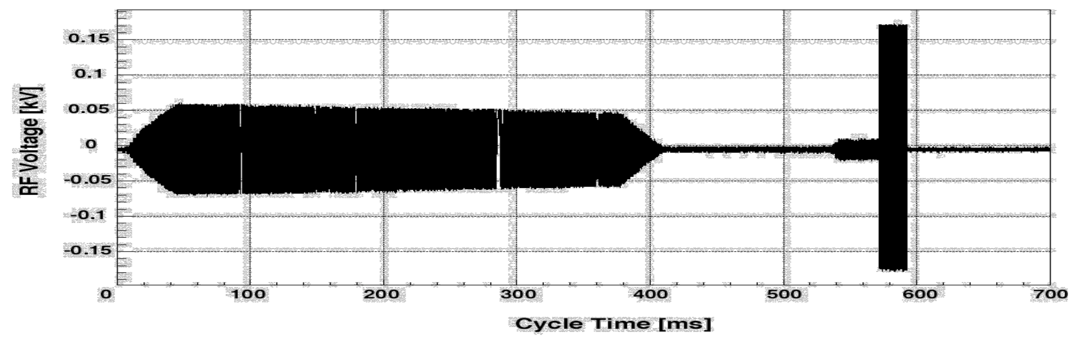
Bunch Compression and Target Matching

Single Bunch Generation and Compression in SIS18

Measured Beam Currents

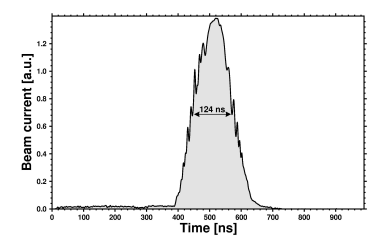


RF- Cycle



Fast Compression $t_{b,f} = \sqrt{(Vi/Vf)} * t_{b,i}$ | Adiabatic Compression $t_{b,f} = \sqrt{\sqrt{(Vi/Vf)}} * t_{b,i}$

Dec. 2003 : Compression of 4×10^{9} U-Ions to 120 ns



HELMHOLTZ | GEMEINSCHAFT GSI FAIR

Bunch Compression in SIS18

- **Proposal (1996):**

  Compression of U^{28+} at 200 MeV/u for PP experiments

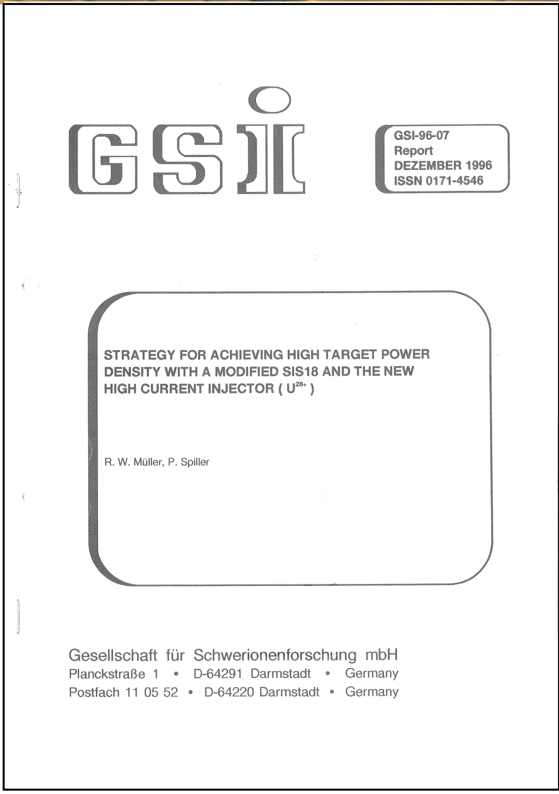
  Proposed compression voltage: 240 kV

- **Present Situation:**

  Realized is one Rf system with: 40 kV

- **Application change:**

  Compression of U^{73+} at 1000 MeV/u for FAIR stage 1



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STRATEGY FOR ACHIEVING HIGH TARGET POWER DENSITY WITH A MODIFIED SIS18 AND THE NEW HIGH CURRENT INJECTOR (U^{28+})

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Bunch Compressor is a Low Duty Cycle Cavity

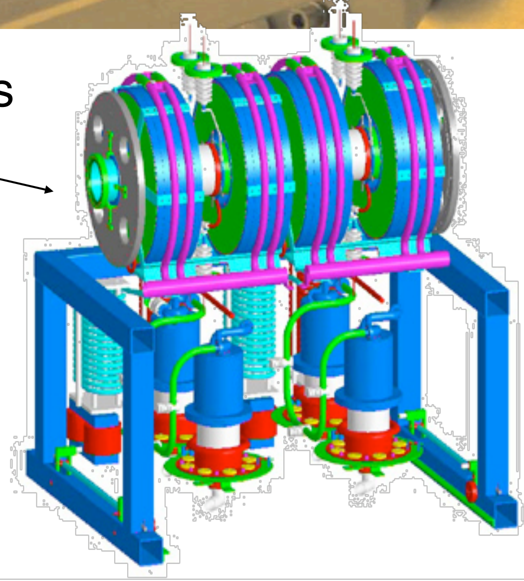
Operation frequency can only be adjusted via the gap capacitor and is almost fixed.

Rf pulse length of 500 μs just sufficient for the long compression time (1 ms)

> combined compression with existing Ferrite cavities

Compression Cavity and MA Research for SIS18

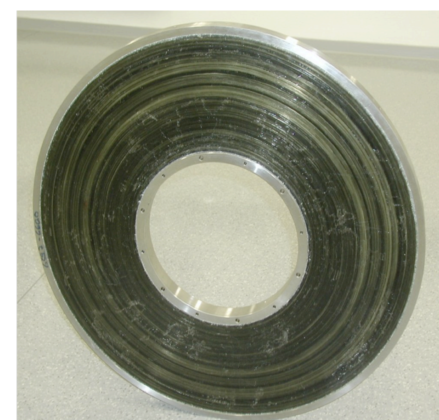
Amorphous MA Cores
Cobalt based



40 kV per Gap

Low Duty Cycle System
(Rf pulse 500 μs) > air cooling

Original Goal: μQf = 6 GHz



For an optimization of shunt impedance and inductivity, a large variety of nanocristalline (Fe based) and amorphous (Co based) core materials have been investigated

(Vitrovac, Honeywell, Finemet)

MAGNETIC ALLOY (MA) versus FERRITE

Properties of MA - Materials

- High saturation flux density (0.8 T) (higher gap voltage)
- Linear permeability μ(B)
- Constant power loss product 1/μQf at high flux densities
- Low power density at high voltages
- High Curie Temperature (570°C)

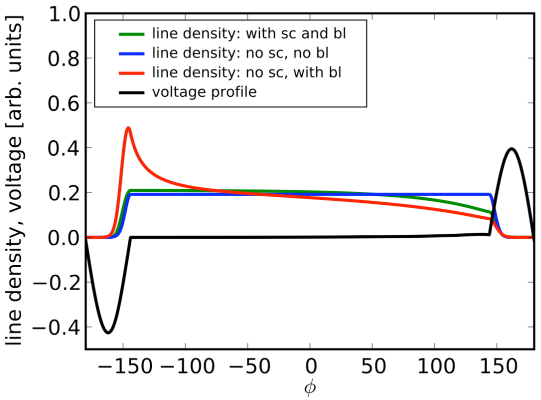
Properties of Ferrites

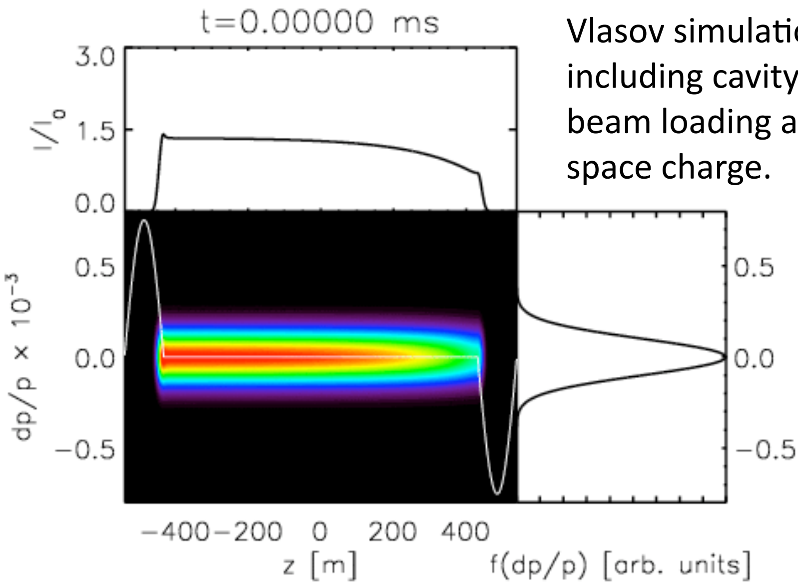
- Lower saturation flux density (0.3 T) (lower gap voltages)
- Decreasing power loss product 1/μQf at high flux densities
- Higher power loss density at high voltages
- Low Curie Temperaturw (100° - 250°C)

MA - Typen: z.B. Vitrovac (VAC), Vitroperm (VAC), Finemet (HITACHI)

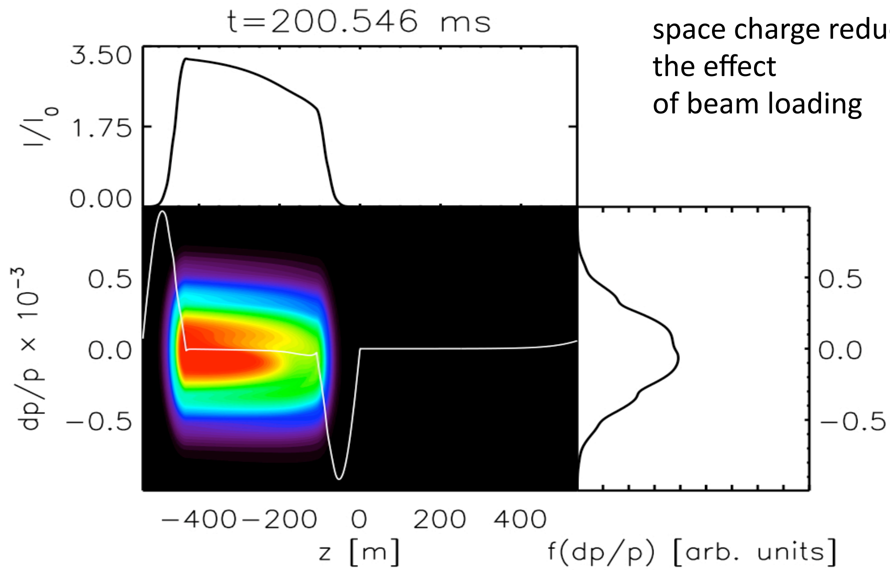
Pre-Compression in SIS100

	# cavities	R_s/cavity [kΩ]	Q_s	f_{res}
acceleration	20	3	10	$10f_0$
barrier	2	1	0.4	1.5 MHz
compression	16	1	2	1.5 MHz





Vlasov simulation including cavity beam loading and space charge.

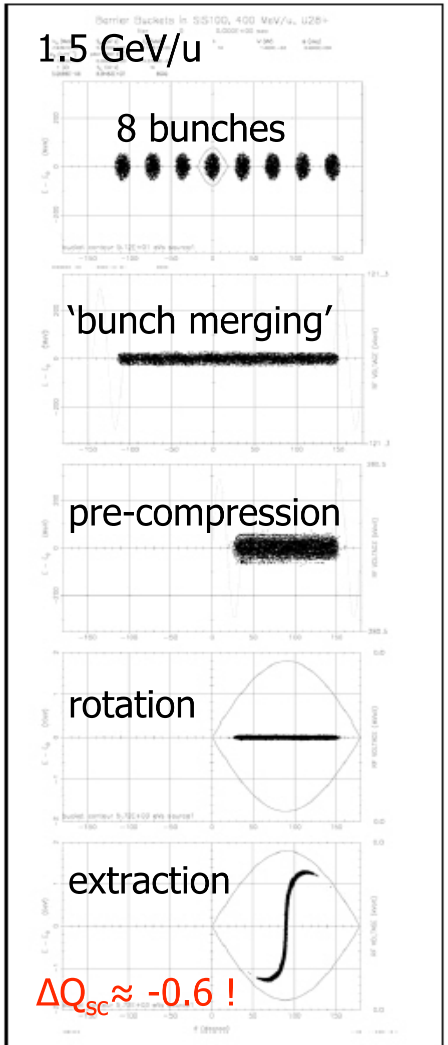


space charge reduces the effect of beam loading

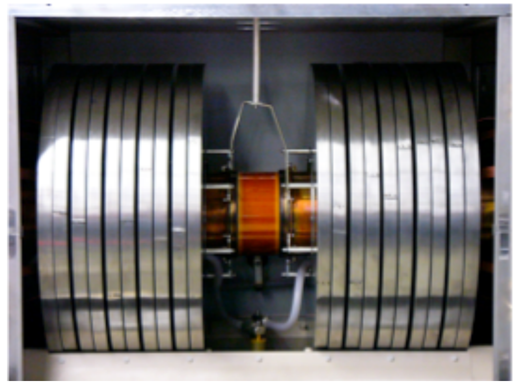
Bunch area increases by 20 % during pre-compression. Longitudinal dilution budget in SIS-100: Factor 2.

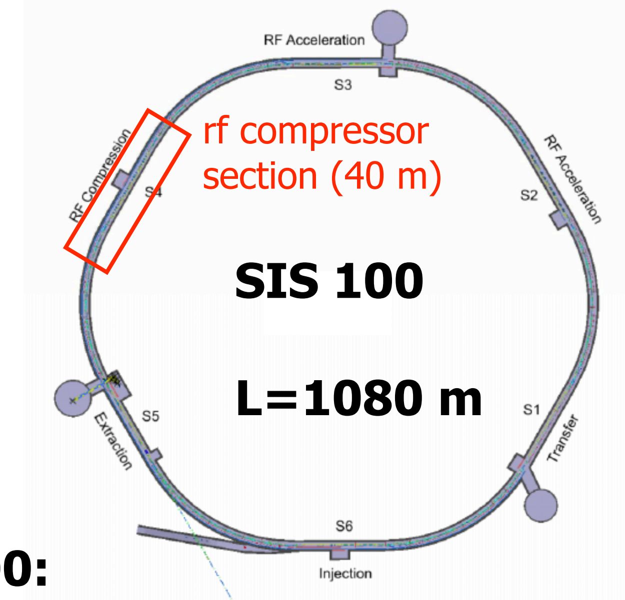
Bunch Compression in SIS100

Single bunch formation



SIS-18 bunch compressor loaded with 20 MA cores





RF cavity systems in SIS 100:

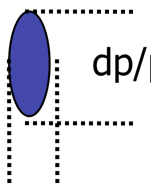
	#cavities	Voltage [kV]	Frequency [MHz]	Concept
Acceleration	20	400	1.1-2.7 (h=10)	Ferrite
Compression	16	600	0.4-0.5 (h=2)	MA (low duty cycle)

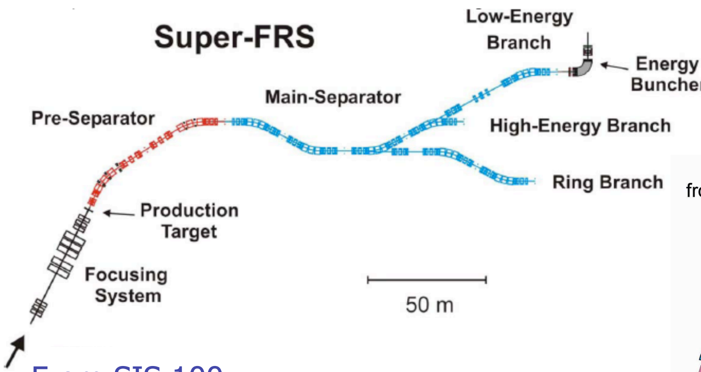
Final bunch parameters:

	Particles/bunch	bunch length
1.5 GeV/U U^{28+}	$5x10^{11}$	60 ns
29 GeV/u p	$2\text{-}4x10^{13}$	25 ns

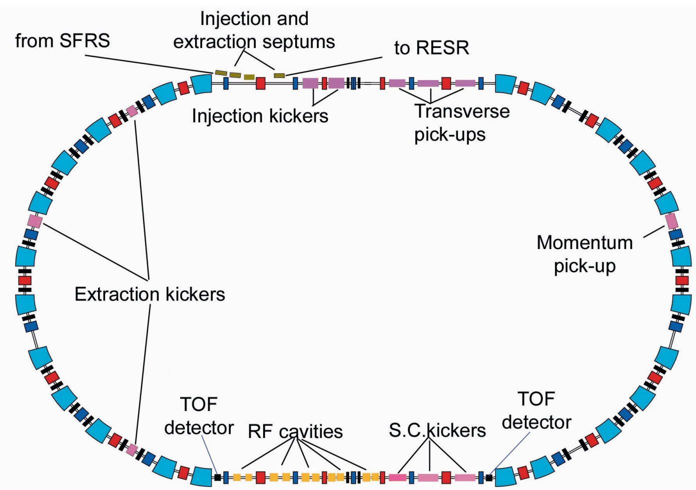
Target Matching and Bunch Rotation

Short SIS 100 bunches:
- target matching
- RIB/pbar pre-cooling

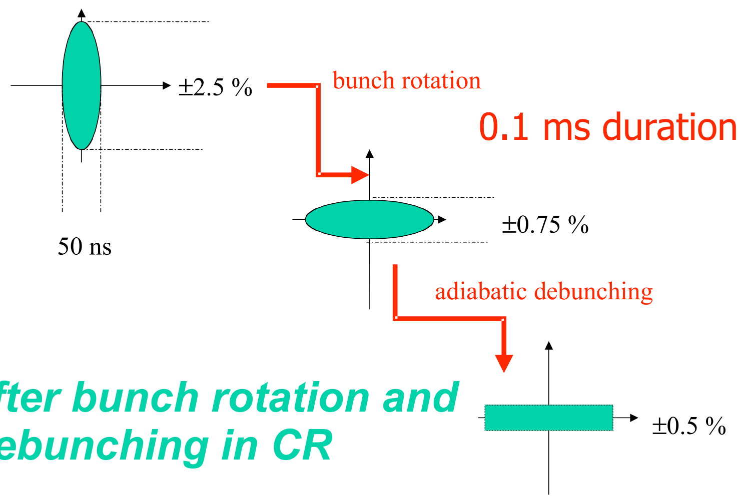




Collector Ring (CR)
circumference 212 m
rigidity 13 Tm



RF voltage in the CR: 200 kV (1.5 MHz)



after bunch rotation and debunching in CR

CR ring properties:

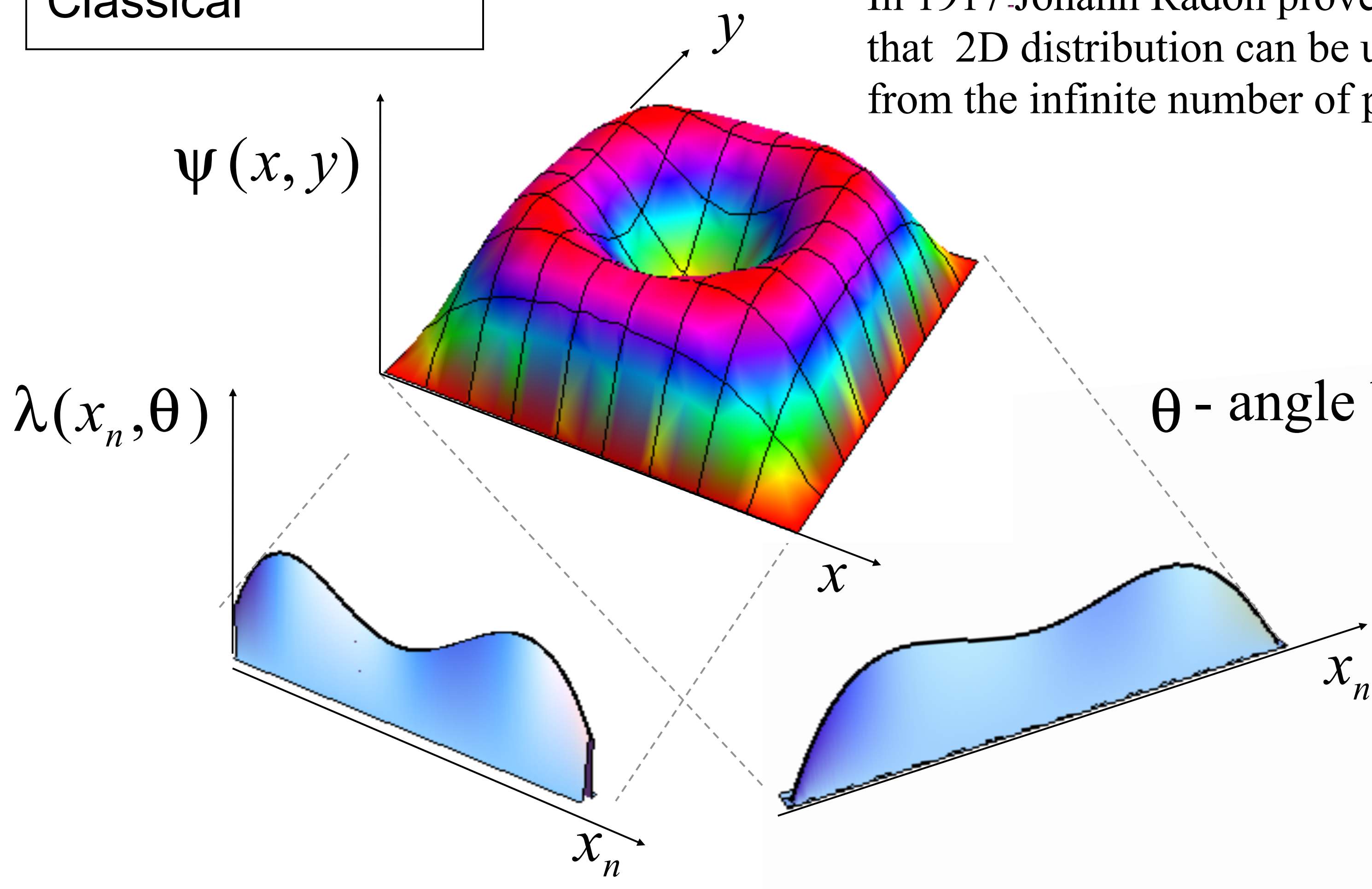
	RIB	**pbar**
energy	740 MeV/u	3.0 GeV
mom. accept.	± 1.5 %	± 3.0 %
transv. accept.	200×10^{-6} m	240×10^{-6} m
Cooling down time	1.5 s	10 s

M. Steck, TUOBM01 (oral)

Tomographic Reconstruction of 2D Objects

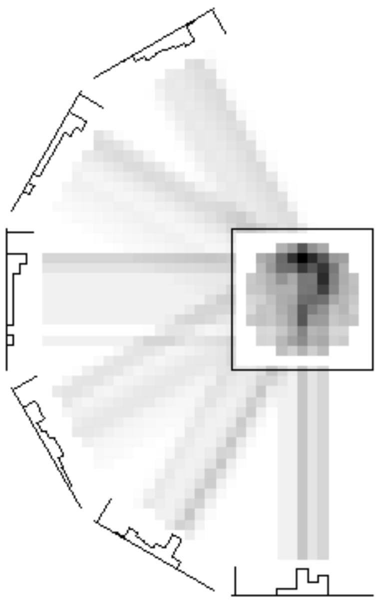
Classical

In 1917 Johann Radon proved for general case that 2D distribution can be uniquely restored from the infinite number of projections



θ - angle between x, x_n

Longitudinal Phase Space Reconstruction

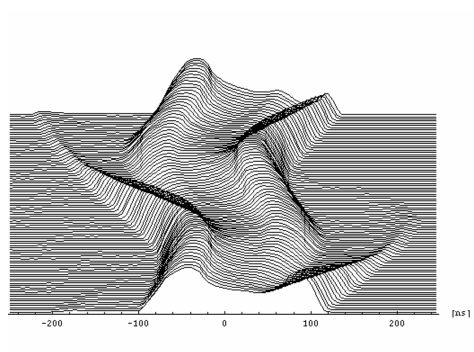


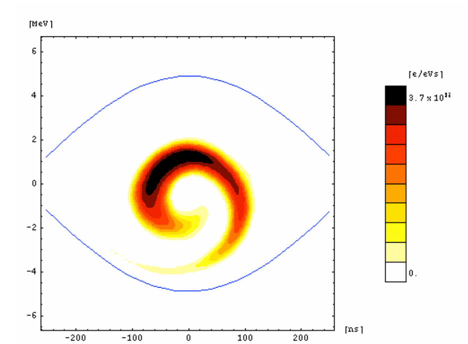
S. Hancock, CERN

Tomograhic reconstruction of phase space requires views from different sides onto the phase space distribution.

Synchrotron oscillation generates projections of the phase space distributions (line density) which can be measured by a beam transformer.

A mountain range (watefall) plot (turn by turn monitoring of the bunch profile) can be used to reconstruct the phase space distribution.

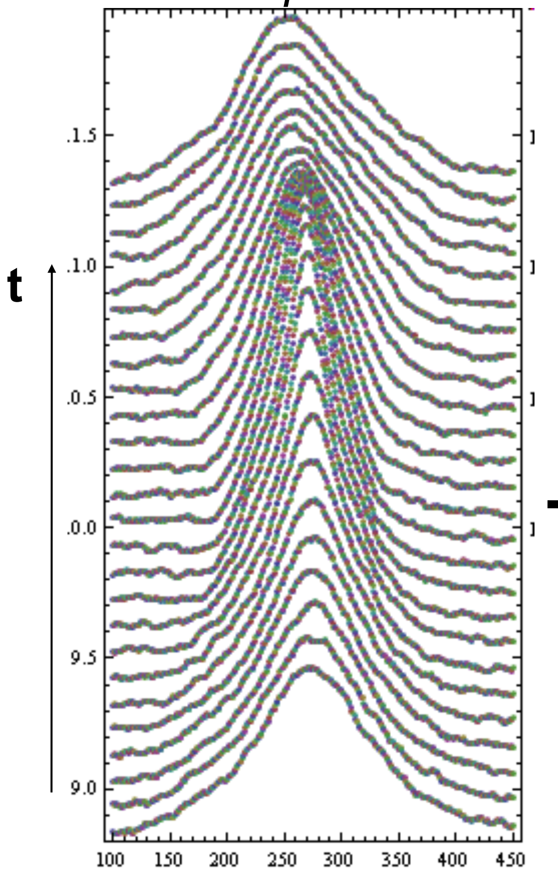




TOMO Phase Space Reconstruction

Input parameters:
line density in ascii format

example

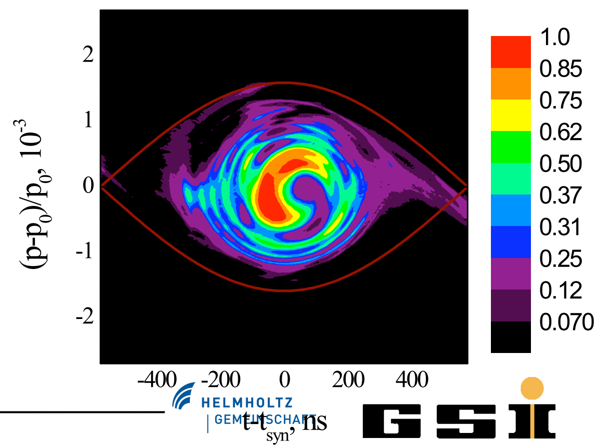


Input parameters:
Header information of the line density file
Machine parameters in ascii fromat

Number of bins
Number of frames
...
Harmonic
Voltage amplitude
...

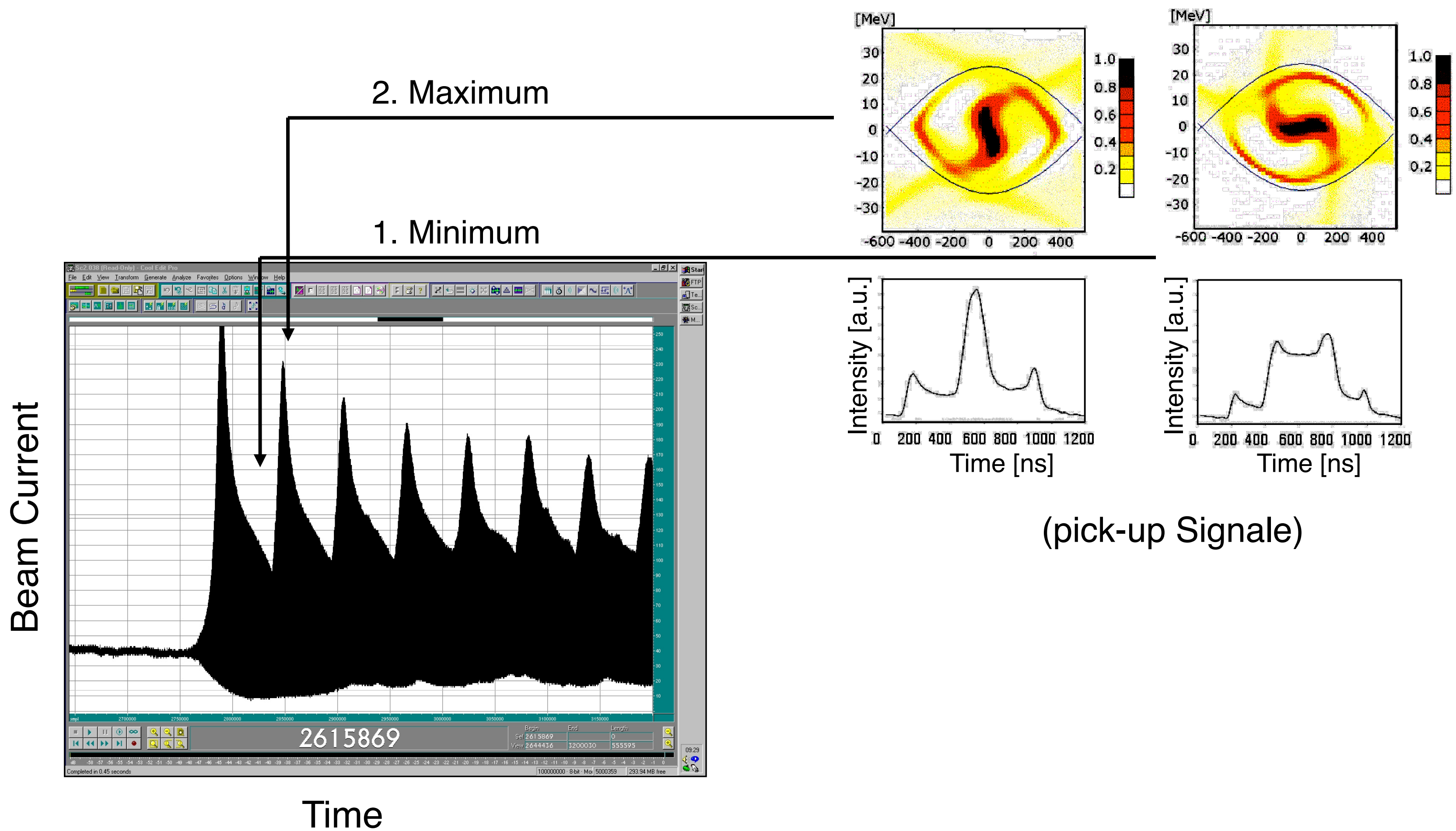
"TOMO"

example



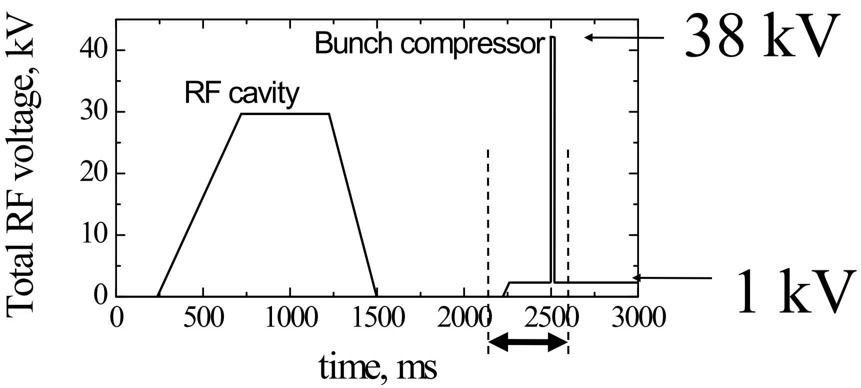
Tomography of Bunch Compression

Reconstructed Phase Space

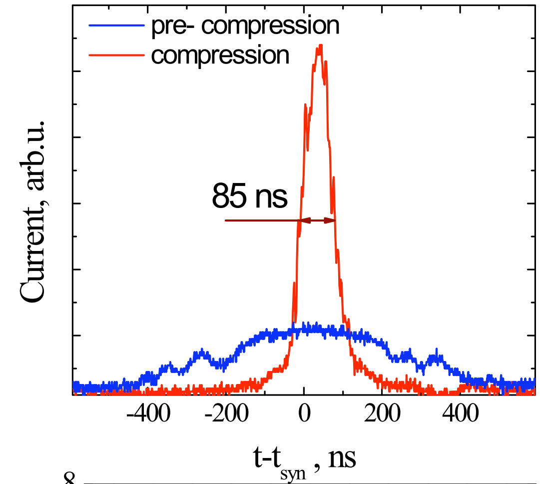


Tomography of Bunch Compression

RF cycle in SIS18



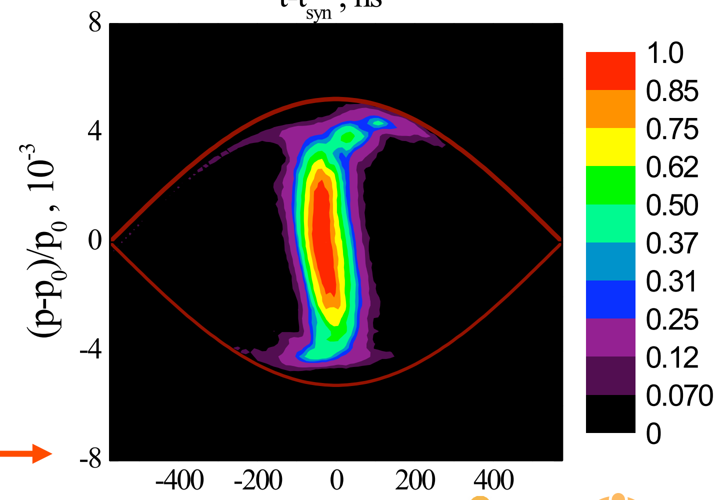
Measurements before and during compression



Main parameters

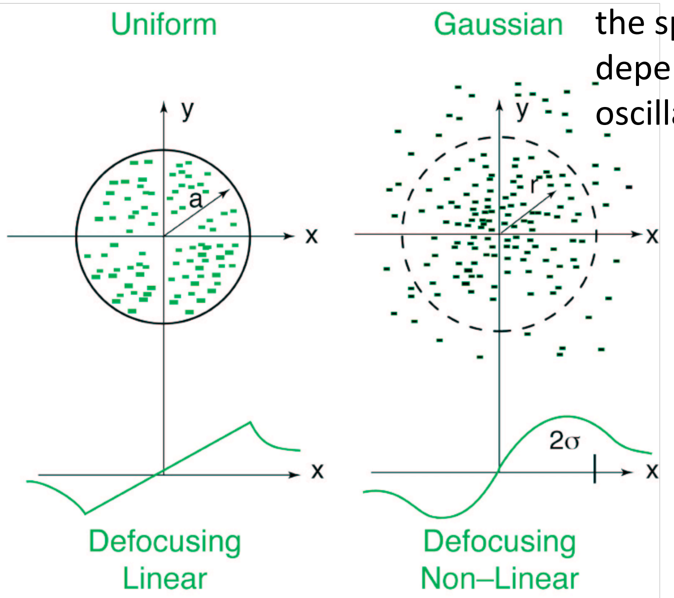
Ion:	U^{+73}
Energy:	295 MeV/u
Pre-bunching RF amplitude:	1 kV
Bunch Compressor amplitude:	38 kV
Particles in the ring:	1×10^{9}

Tomographically reconstructed phase space of the compressed bunch



Transverse-Longitudinal Effects

Transverse Space Charge



the space charge tune shift depends on the betatron oscillation amplitude **a**.

Amplitude dependent tune shift:

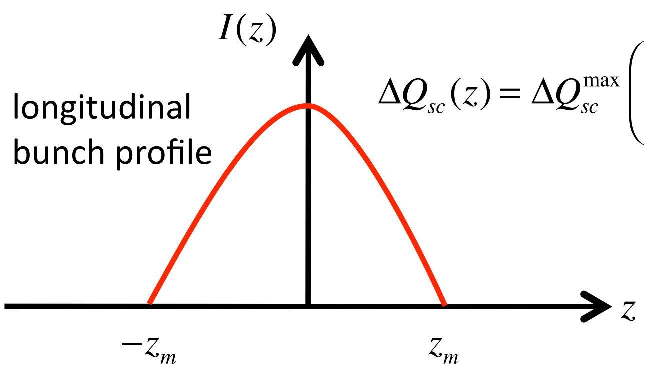
$$Q(a_x, a_y) = Q_0 - \Delta Q_{sc}(a_x, a_y, z)$$

Maximum space charge tune shift:

$$\Delta Q_{sc}^{\max} \propto -\frac{g_f}{B_f} \frac{qN}{\varepsilon_x \beta_0^2 \gamma_0^3} \frac{2}{1+\sqrt{\varepsilon_x/\varepsilon_y}}$$

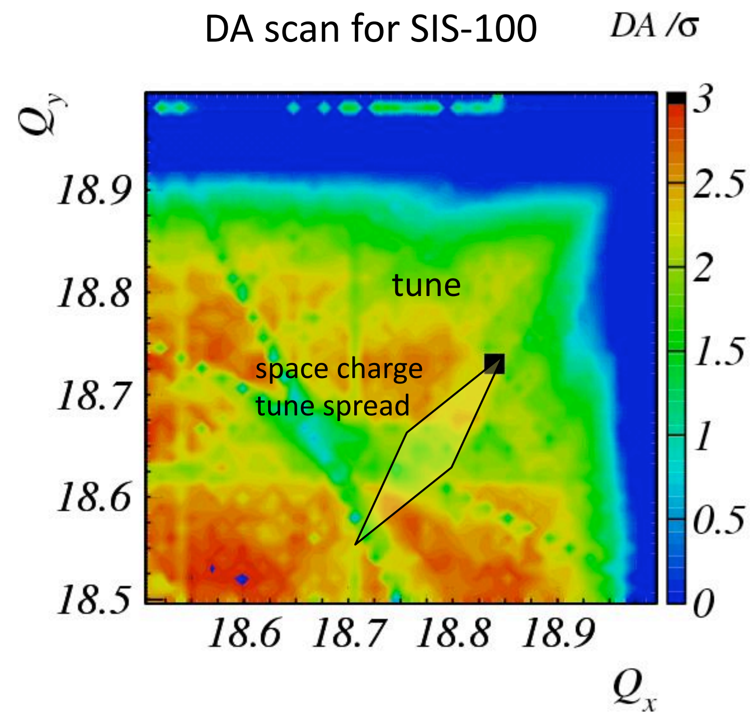
$g_f = 1 - 2$ (1: uniform, 2: Gaussian)

Space charge force changes along the bunch:

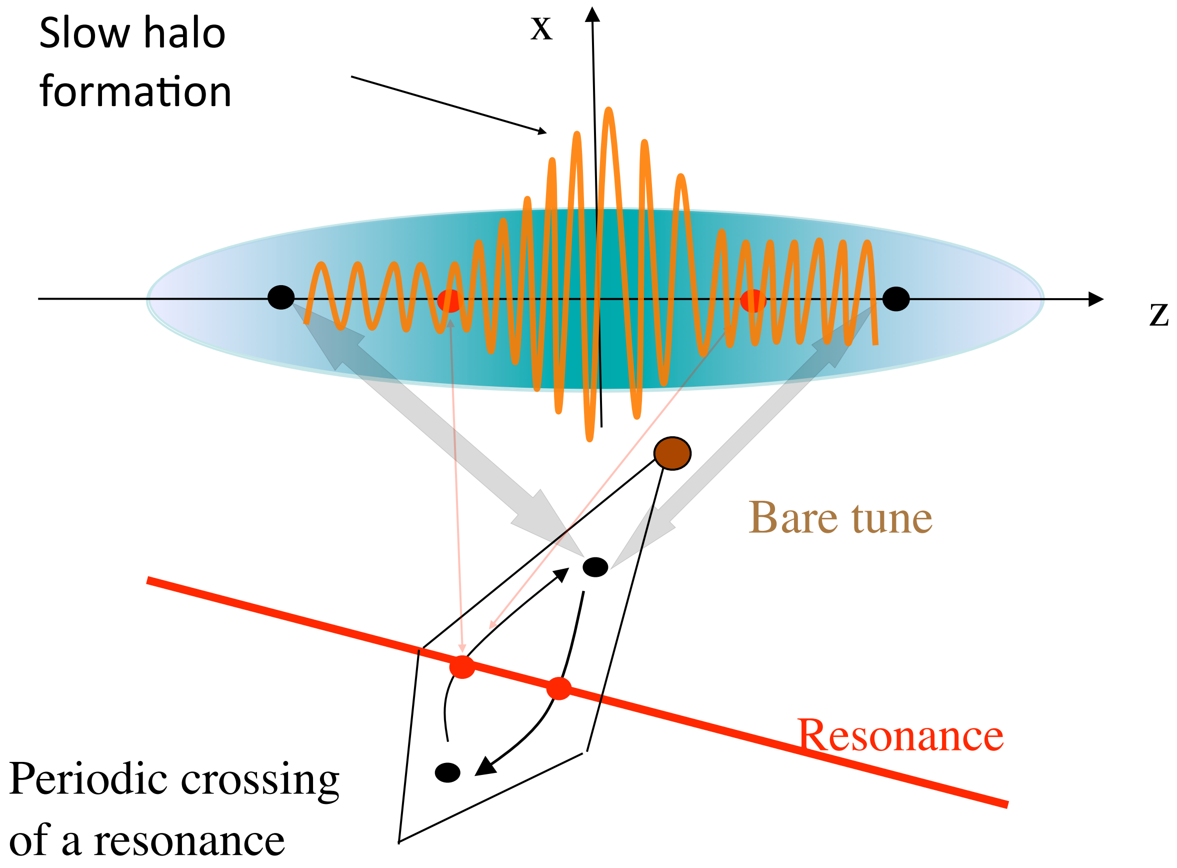


$$\Delta Q_{sc}(z) = \Delta Q_{sc}^{\max}\left(1 - \frac{z^2}{z_m^2}\right)$$

DA scan for SIS-100



Beam Loss by Resonance Trapping



Bunch Profile Reformation by Resonances

Dual harmonic operation was supposed to reduce beam loss by resonance trapping.

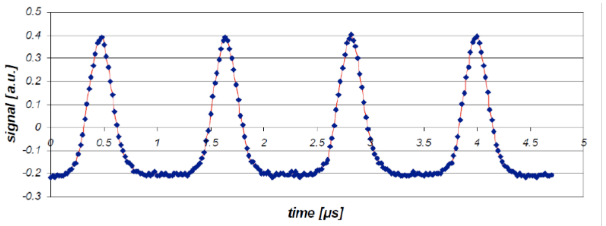
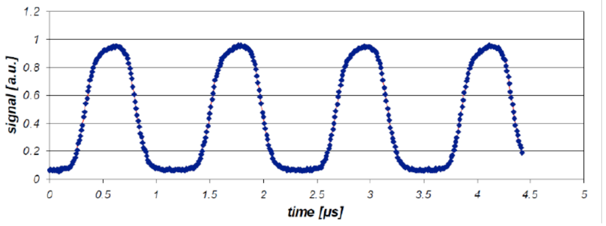
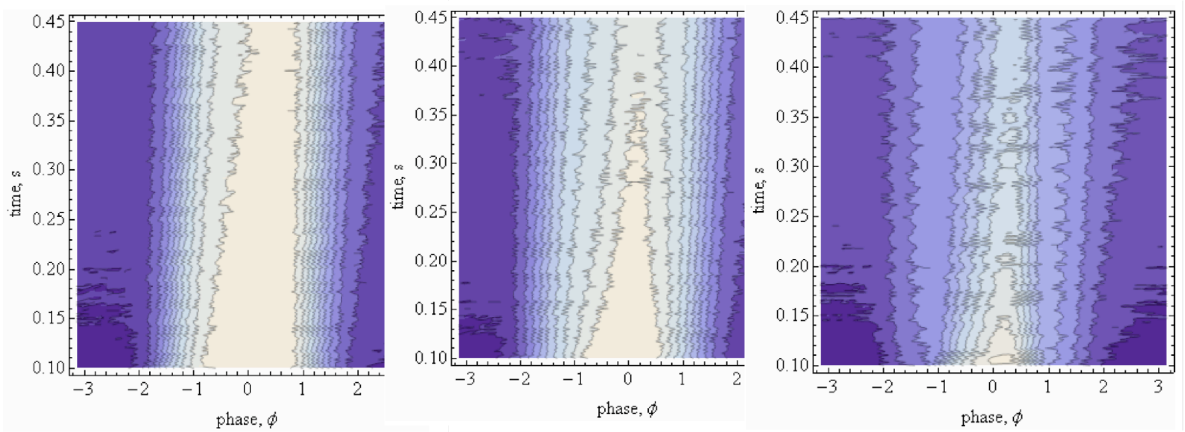


Figure 4: Bunch Profile Single-Harmonic Operation (B. Zipfel)



„single harmonic bunch“

Flat, dual harmonic bunch



Different working points

Acceleration

The bucket area A_0 becomes reduced by factor $\alpha_s(\phi_s)$.

$$A_B = A_0 \alpha_S(\phi_S)$$

The bucket factor $\alpha_s(\phi_s)$ is given by the numerical solution of the elliptic integral

$$\alpha_S(\phi_S) = \frac{\sqrt{2}}{8} \int_{\phi_1}^{\phi_2} \left| \sqrt{\cos\phi + \cos|\phi_S| + (\phi + |\phi_S| - \pi)\sin|\phi_S|} \right| d\phi$$