RF Systems for Ring Accelerators

TECHNISCHE UNIVERSITÄT DARMSTADT

517. WE-Heraeus-Seminar on Accelerator physics for intense ion beams

Contents

- Basic Cavity Considerations
- Ferrite Cavities
  - Magnetic properties, hysteresis
  - Simplified ferrite cavity model
  - Lumped-element circuits
  - Cavity parameters
  - Example: SIS18 ferrite cavity
- System Aspects
  - Tetrode amplifiers
  - Supply units
  - Low-level RF control (LLRF)
- Basics of Longitudinal Beam Dynamics
- Examples for Advanced Beam Manipulations

Basic Cavity Considerations

Special Relativity

- The velocity v of the particles is not negligible in comparison with the speed c_0 of light
  $\Rightarrow$ relativistic effects:

$$\beta = \frac{v}{c_0} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$m = m_0 \gamma$$

$$W_{rest} = m_0 c_0^2 \qquad W_{total} = m c_0^2 = m_0 \gamma c_0^2$$

$$W_{kin} = W_{total} - W_{rest} = m_0 c_0^2 (\gamma - 1)$$

- For the revolution frequency one obtains:

$$f_R = \frac{c_0}{l_R} \frac{\gamma\beta}{\sqrt{1+(\gamma\beta)^2}} \quad \text{with} \quad \gamma\beta = \frac{QrB}{m_0 c_0}$$

B=magnetic field (dipoles)
r=bending radius
Q=charge of particle
l_R=synchrotron circumference

In spite of increasing energy, the velocity does not increase significantly under highly relativistic conditions ($\beta \approx 1$).

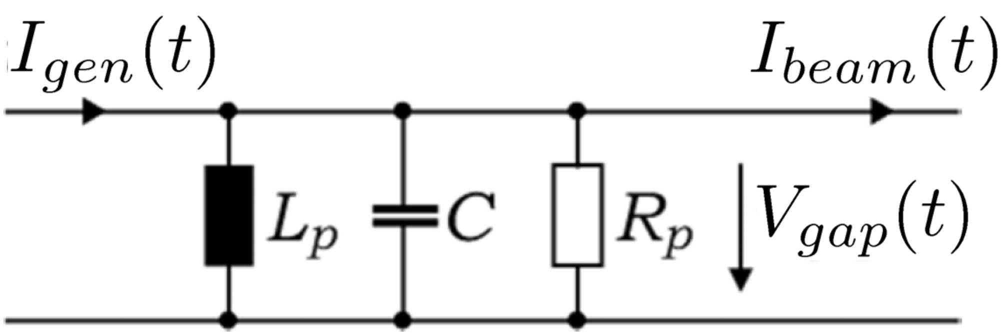
Principle of RF Acceleration

TECHNISCHE UNIVERSITÄT DARMSTADT

- An acceleration in the sense of an increase of kinetic energy is only possible by means of electric fields, not with magnetic fields:

$$\Delta W = \int \vec{F}\cdot d\vec{r} = Q \int \left(\vec{E} + \vec{v}\times\vec{B}\right)\cdot d\vec{r} = $$
$$= Q \int \left(\vec{E} + \underbrace{\dot{\vec{r}}\times\vec{B}\right)\cdot\dot{\vec{r}}}_{0}\, dt = Q \int \vec{E}\cdot d\vec{r} = QV$$

- If we want to generate high voltages with only moderate power, resonators are a good choice:



$$\omega_0 = \frac{1}{\sqrt{L_p C}}, \qquad P = \frac{\hat{V}_{gap}^2}{2R_p}$$

- However, a large R_p may be harmful for high beam currents

Basic Types of RF Cavities

- Pillbox cavity may be considered as a basic type:
  - standing wave
  - E_{010} Mode (= TM_{010}) is used for acceleration
  - longitudinal electric field, transverse magnetic field
  - typical operating/resonant frequency: a few 100 MHz
  - typical Q: 100...50000 (or higher for superconducting cavities)
- In practice, modifications are necessary (e.g. rounded shape)
- Several cells may be coupled or combined
- Based on this principle, one may produce fixed-frequency (or slightly tunable) cavities for synchrotrons and storage rings
- Example LHC: 2 x 8 superconducting single-cell cavities, 2 MV each, 400 MHz, mechanical tuning, tuning range≈180 kHz

Basic Types of RF Cavities

LHC 4-Cavity Unit
(source: R. J. Gonsalves: „Particle Acceleration, Resonant Cavities and Klystrons“)

Classification of Ring RF Systems

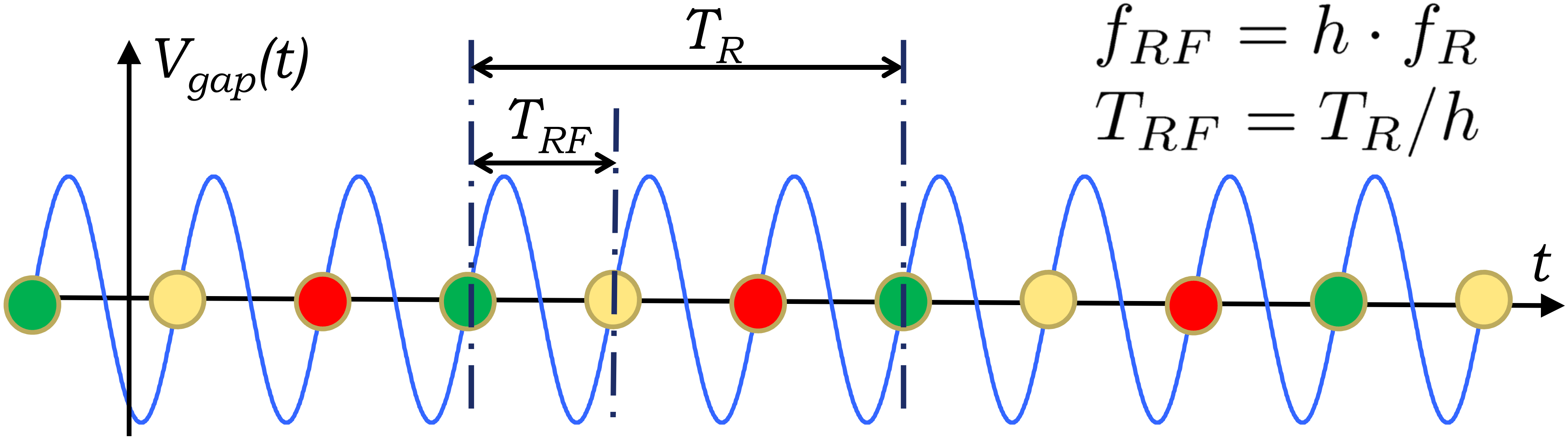
TECHNISCHE UNIVERSITÄT DARMSTADT

- Bandwidth
  - narrowband (e.g. for acceleration)
  - wideband (e.g. for barrier bucket operation or for bunch compression)
- Operating frequency
  - fixed frequency
  - tunable
- Material
  - normal conducting
  - superconducting
  - ferrite-loaded
  - ...
- Duty cycle
  - CW
  - Pulsed operation

Principle of RF Acceleration

TECHNISCHE UNIVERSITÄT DARMSTADT

- Each rising slope of $V_{gap}(t)$ is a stable region for a particle bunch:

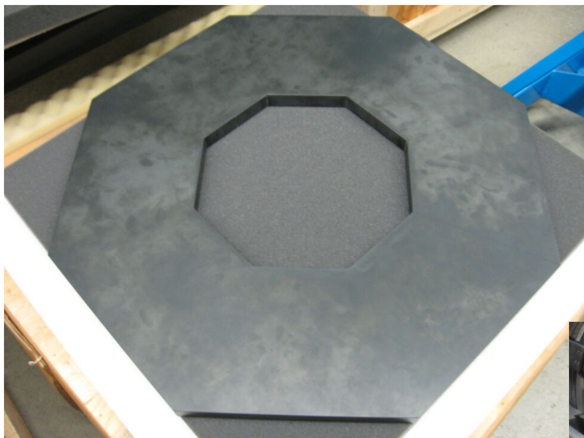


$$f_{RF} = h \cdot f_R$$
$$T_{RF} = T_R/h$$

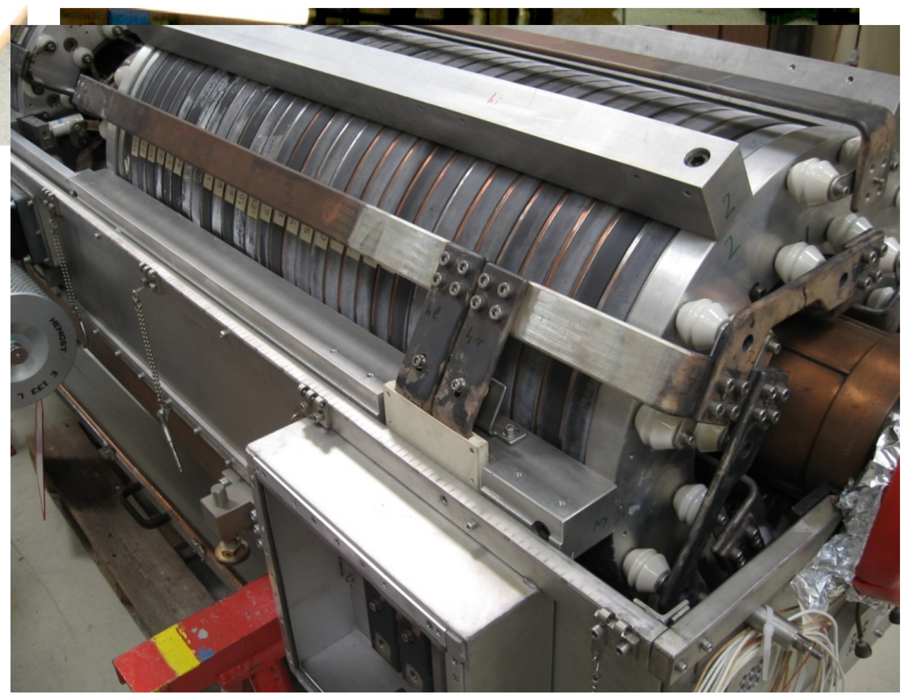
- Synchrotron circumference > 60 m $\Rightarrow$ revolution time >200 ns (5 MHz)
- If only a few bunches shall circulate, the harmonic number h must be small such that the RF frequency is only a few MHz (counter-example LHC: 400 MHz, h≈35600!).
- Classical cavity resonators have dimensions of the order of the wavelength $\lambda = c/f_{RF} = c \cdot T_{RF}$
- Even for f_{RF}=30 MHz one obtains λ=10 m!

Principle of RF Acceleration

- Solution: Load the cavity with magnetic material



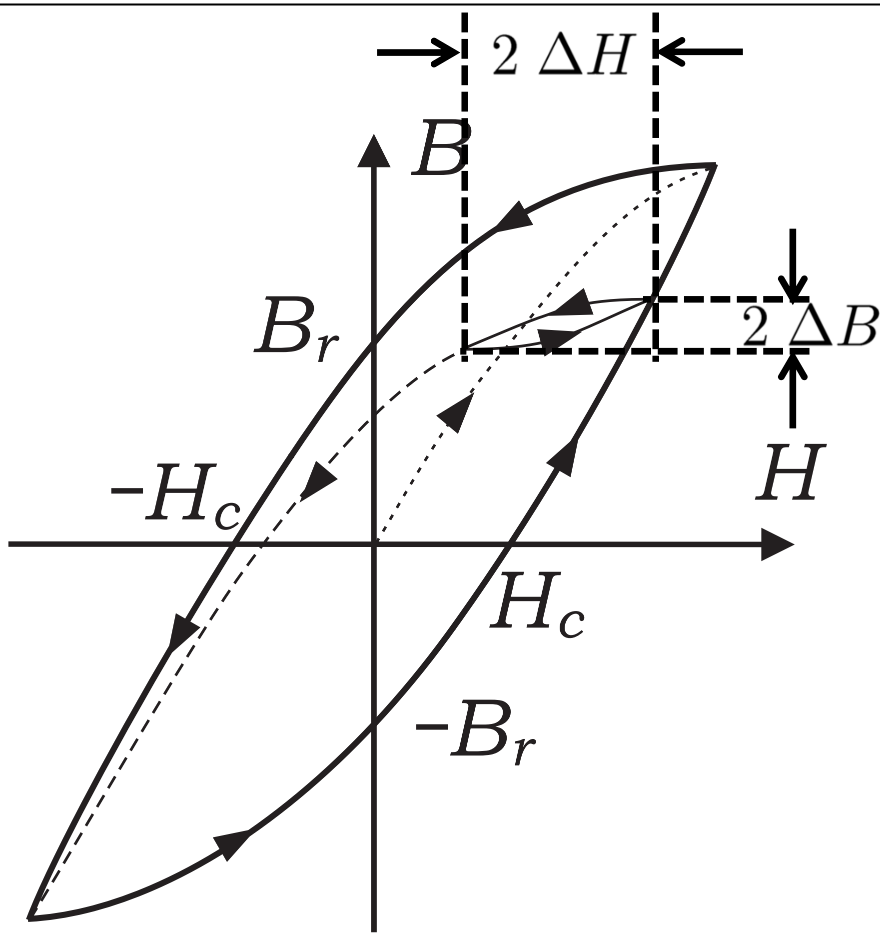
$$c = \frac{1}{\sqrt{\mu\epsilon}}$$



Bildquelle: GSI Helmholtzzentrum für Schwerionenforschung, A. Zschau

Ferrite Cavities

Hysteresis Loop



H_c: coercive magnetizing field
B_r: residual induction

- soft magnetic material:
  narrow hysteresis loop
- hard magnetic material:
  wide hysteresis loop
  (limits between soft and hard
  are not strictly defined)

Bias current → H_{bias} ⟶ modification of incremental/differential permeability:

$$\mu_\Delta = \frac{\Delta B}{\Delta H}$$

Index Δ is now left out...

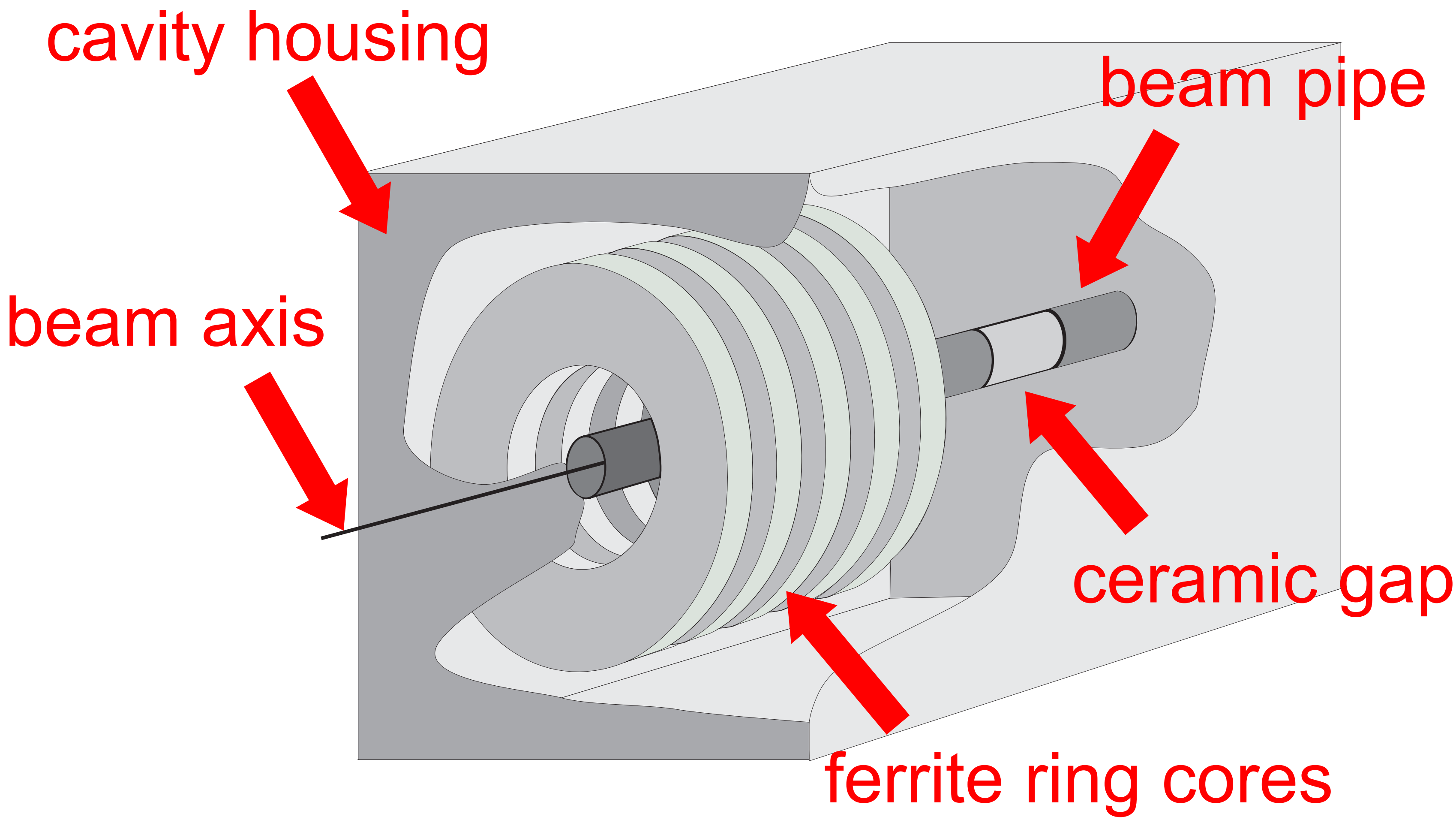
Magnetic Losses

- Hysteresis may be described by Preisach model
- Losses:
  - Hysteresis Loss
  - Eddy Current Loss
  - Residual Loss
- Description of losses by complex permeability:

$$\underline{\mu} = \mu_s' - j\mu_s''$$

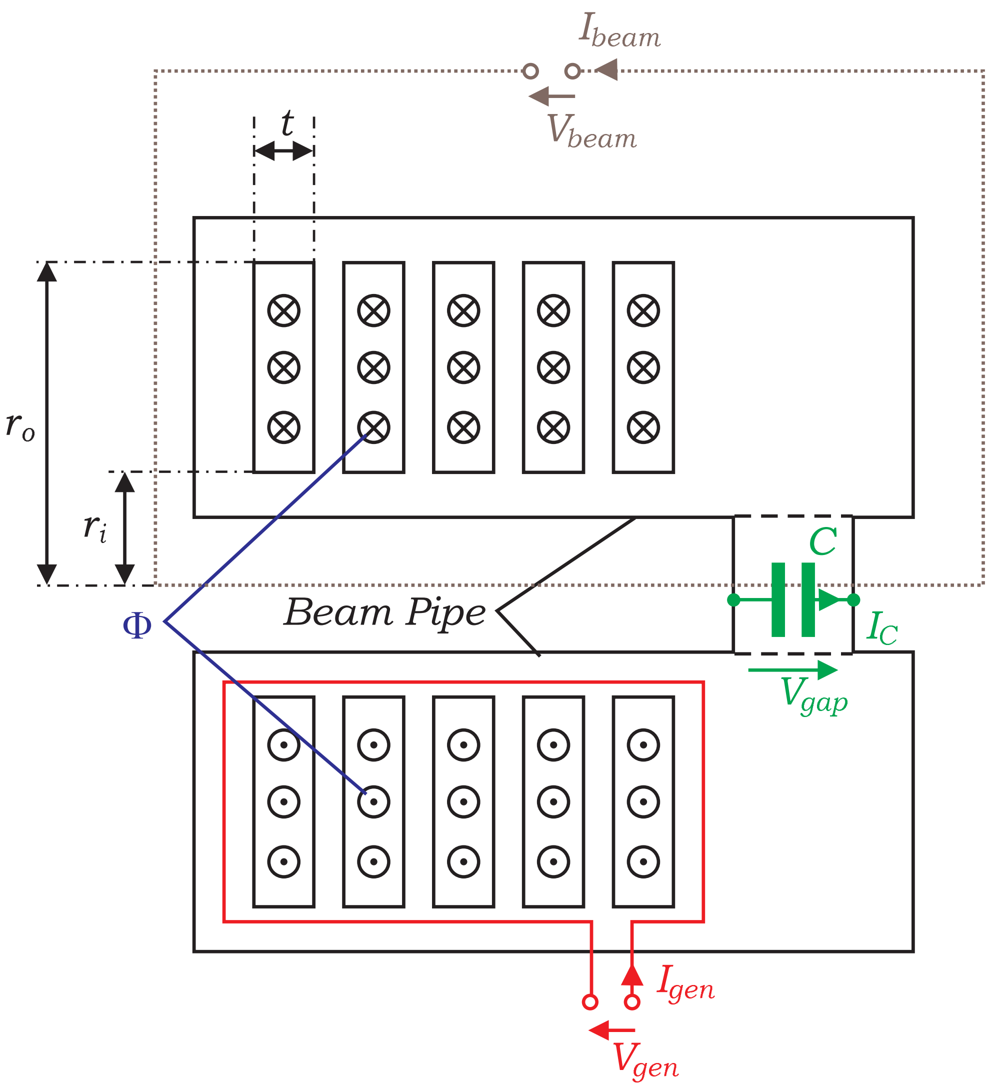
- The behavior of magnetic materials is rather complicated, thorough measurements are always needed.

Ferrite Cavity – Main Components



Simplified Ferrite Cavity Model

TECHNISCHE UNIVERSITÄT DARMSTADT



Faraday's law of induction:

$$\oint_{\partial S} \vec{E} \cdot d\vec{l} = -\int_S \dot{\vec{B}} \cdot d\vec{S}$$

$$\Rightarrow V_{gen} = +j\omega\Phi_{tot}$$

$$V_{gap} = +j\omega\Phi_{tot}$$

$$V_{gap} = V_{gen}$$

$$V_{beam} = +j\omega\Phi_{tot} = V_{gap}$$

$$I_{tot} = I_{gen} - I_C - I_{beam}$$

Simplified Ferrite Cavity Model

TECHNISCHE UNIVERSITÄT DARMSTADT

Now we have to determine the magnetic flux:

Ampère's law:

$$\oint_{\partial S} \vec{H} \cdot d\vec{l} = \int_S \vec{J} \cdot d\vec{S}$$

$$\rightarrow \quad H\ 2\pi r = I_{tot} \quad \rightarrow \quad B = \mu \frac{I_{tot}}{2\pi r}$$

Flux through one ring core:

$$\Phi_1 = \int \vec{B} \cdot d\vec{S} = t \int_{r_i}^{r_a} B\ dr = \frac{t \mu I_{tot}}{2\pi}\ ln \frac{r_o}{r_i}$$

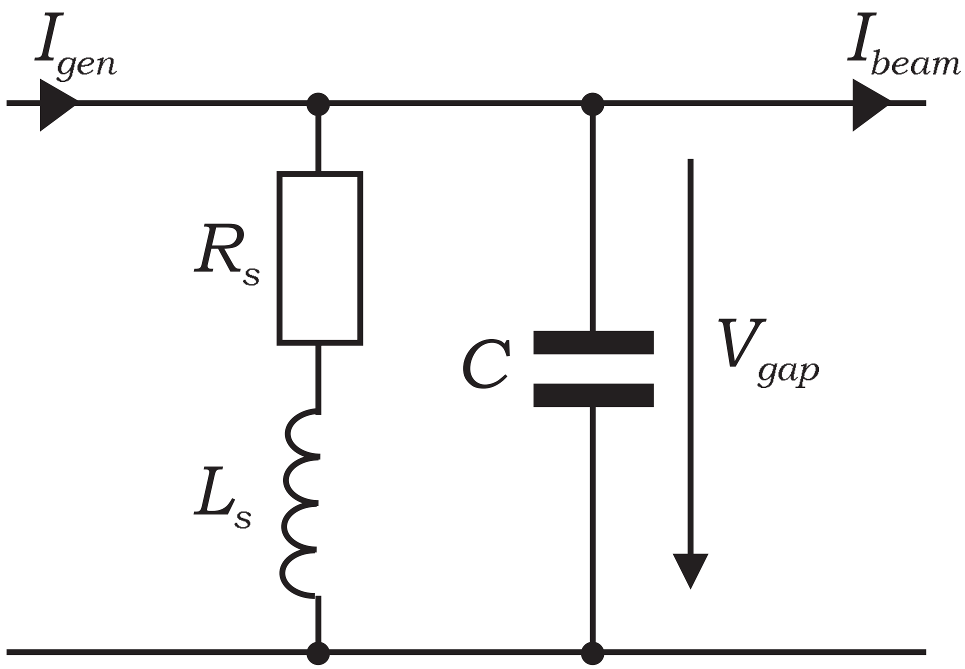
$$V_{gap} = j\omega \Phi_{tot} = j\omega N\ \Phi_1 = j\omega \frac{Nt(\mu_s' - j\mu_s'')I_{tot}}{2\pi}\ ln \frac{r_o}{r_i}$$

$$V_{gap} = I_{tot}(j\omega L_s + R_s) = I_{tot} Z_s$$

Lumped Element Circuit

TECHNISCHE UNIVERSITÄT DARMSTADT

This leads us to the following equivalent circuit:



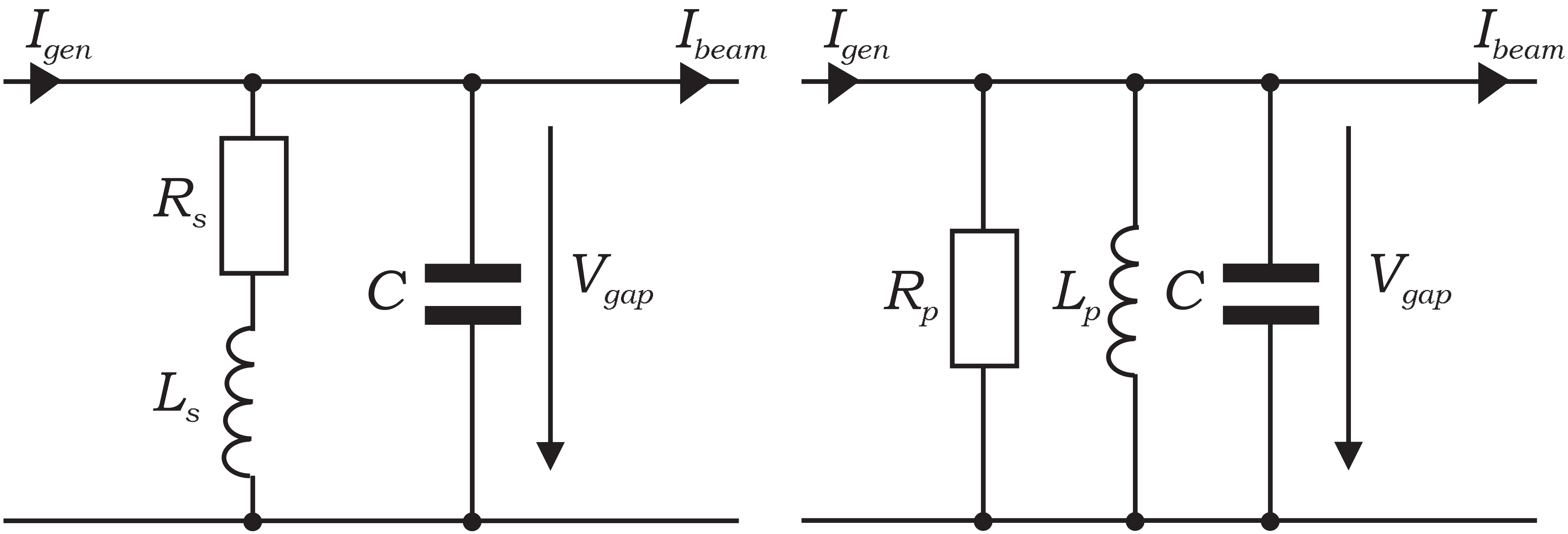
Beam current comparable with generator current
⇒Beam Loading

$$L_s = \frac{N t \mu'_s}{2\pi} \ln \frac{r_o}{r_i}$$

$$R_s = \omega \frac{N t \mu''_s}{2\pi} \ln \frac{r_o}{r_i} = \omega \frac{\mu''_s}{\mu'_s} L_s = \frac{\omega L_s}{Q}$$

Equivalence of Series and Parallel Representation

In the vicinity of the resonant frequency, the following circuits are equivalent:



$$Y_{tot} = j\omega C + \frac{1}{R_s + j\omega L_s} = j\omega C + \frac{1}{R_p} + \frac{1}{j\omega L_p}$$

Series and Parallel Lumped-Element Circuit

Conversion formulas for impedance:

$$R_p = \frac{R_s^2 + (\omega L_s)^2}{R_s}$$

$$\omega L_p = \frac{R_s^2 + (\omega L_s)^2}{\omega L_s}$$

Frequency dependence of parameters is different!

Also complex permeability may be defined based on the parallel lumped-element circuit:

$$\frac{1}{\underline{\mu}} = \frac{1}{\mu_p'} + j\frac{1}{\mu_p''}$$

Series and Parallel Lumped-Element Circuit

$$Q = \frac{\mu_s'}{\mu_s''} = \frac{\omega L_s}{R_s} = \frac{R_p}{\omega L_p} = \frac{\mu_p''}{\mu_p'}$$

Conversion formulas:

$$\mu_p' = \mu_s' \left(1 + \frac{1}{Q^2}\right)$$

$$\mu_p'' = \mu_s'' \left(1 + Q^2\right)$$

$$\begin{aligned} R_p &= R_s(1+Q^2) \\ L_p &= L_s\left(1 + \frac{1}{Q^2}\right). \end{aligned}$$

Approximation for Q>5:

$$R_p \approx R_s\, Q^2, \qquad L_p \approx L_s, \qquad \mu_p' \approx \mu_s', \qquad \mu_p'' \approx \mu_s''\, Q^2$$

$\mu_r Qf$ Product

Using these formulas we get:

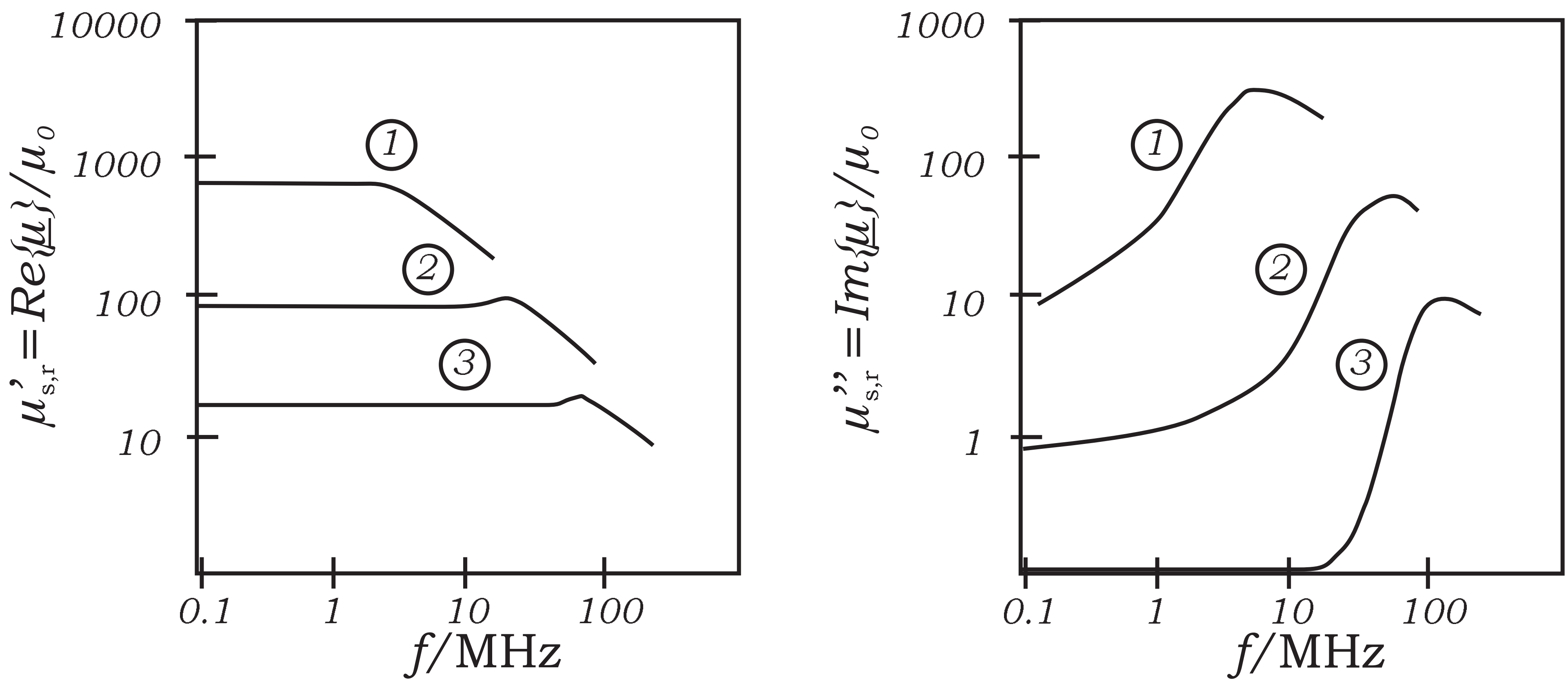
$$R_p = \omega \frac{N t \mu_p' Q}{2\pi} \, ln \frac{r_o}{r_i} = N t \underbrace{\mu_p' Q f}_{\mu_0 \mu_r Q f} \, ln \frac{r_o}{r_i}$$

Ferrite manufacturers often specify the $\mu_r Q f$ product.

R_p is often called 'shunt impedance'.

Behavior of the Permeability

Example: Ferroxcube 4 for small B fields and no biasing
(①: Ferroxcube 4A, ②: Ferroxcube 4C, ③: Ferroxcube 4E)

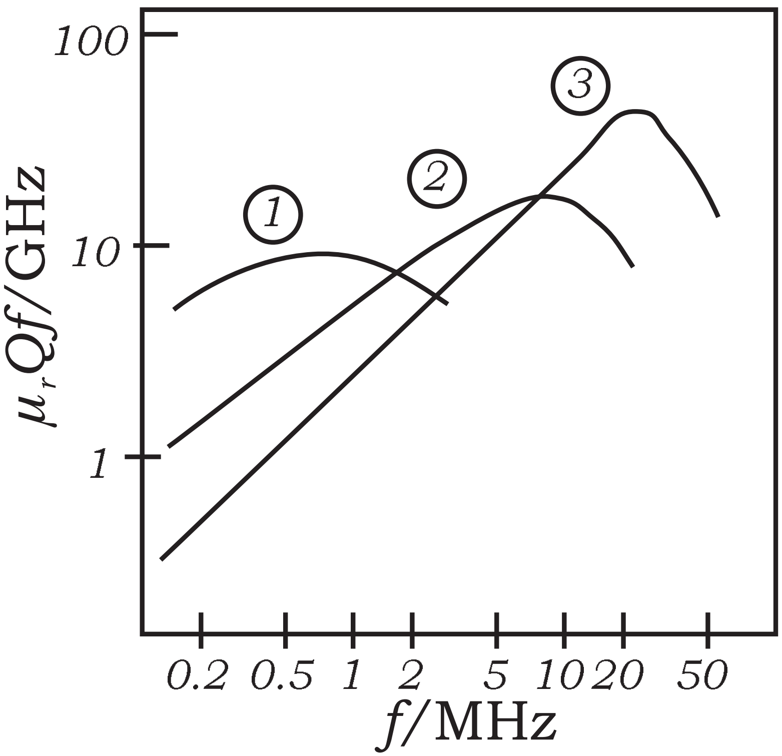


Source: F. G. Brockman, H. van der Heide, M. W. Louwerse: Ferroxcube für Protonensynchrotrons, Philips Technische Rundschau 30, pp. 323-342, 1969/70.

Low-frequency range: constant $\mu'_{s,r}$, Q factor decreases with frequency

Ferrite Properties

Example: Ferroxcube 4 for small B fields and no biasing
(①: Ferroxcube 4A, ②: Ferroxcube 4C, ③: Ferroxcube 4E)



Source: F. G. Brockman, H. van der Heide, M. W. Louwerse: Ferroxcube für Protonensynchrotrons, Philips Technische Rundschau 30, pp. 323-342, 1969/70.

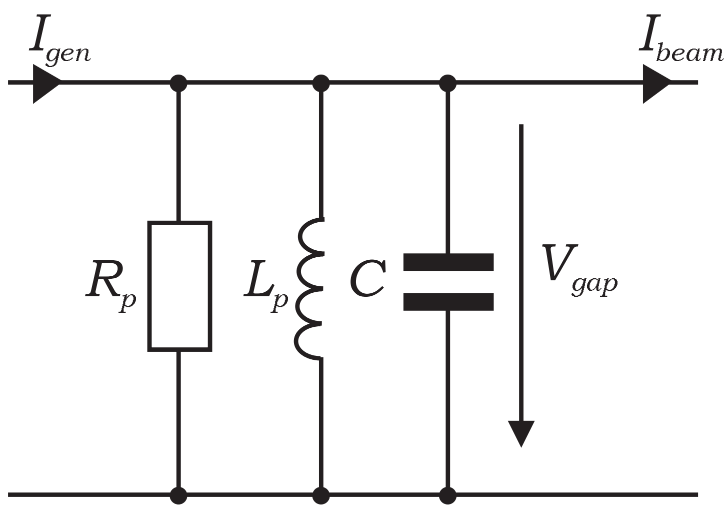
Ferrite Properties

TECHNISCHE UNIVERSITÄT DARMSTADT

Dependence of parameters on:

- Material type
- Frequency
- Strength of magnetic field
- Biasing
- History of magnetization
- ...

Cavity Description



$$\omega_0 = 2\pi f_0 = \frac{1}{\sqrt{L_p C}}$$

$$Q_0 = \omega \frac{W_{tot}}{P_{loss}}$$

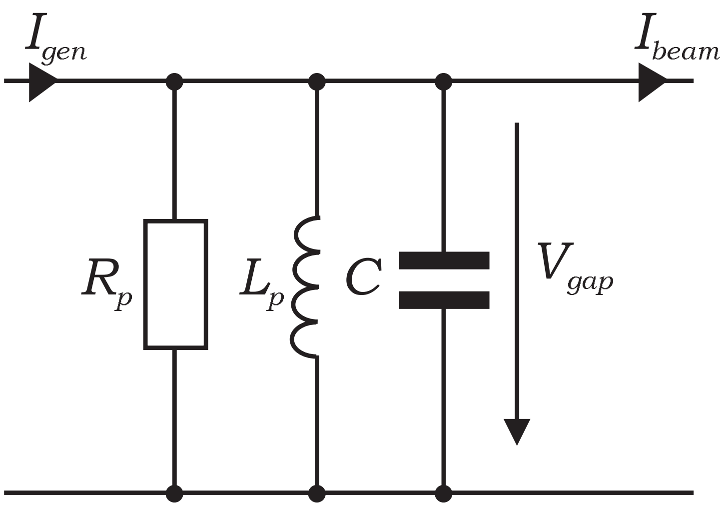
$$Q_0 = R_p \sqrt{\frac{C}{L_p}}$$

$$Z_{tot} = \frac{R_p}{1 + j\, Q_0 \left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \right)}$$

$$P_{loss} = \frac{|V_{gap}|^2}{2R_p}$$

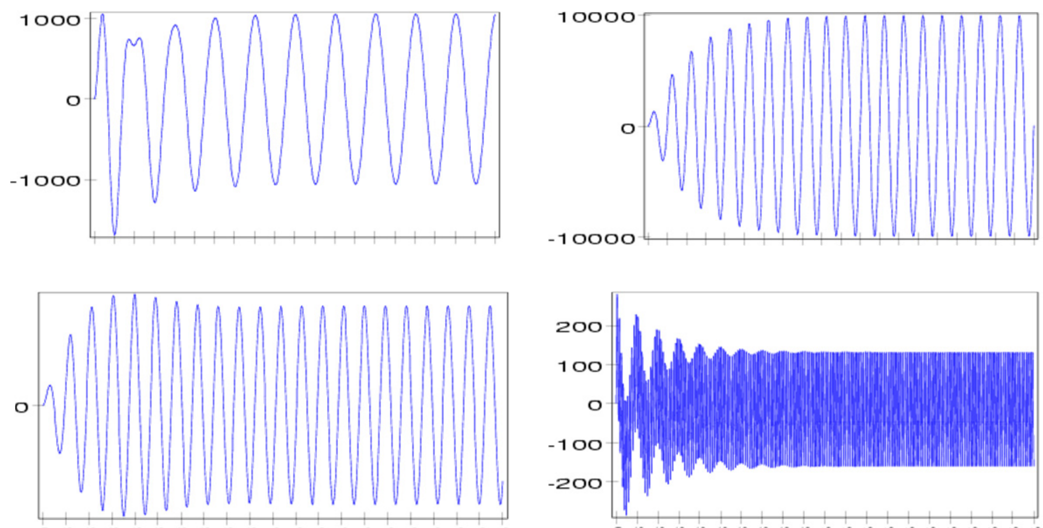
Cavity Time Constant, Cavity Filling Time

$$\ddot{V}_{gap} + \frac{2}{\tau}\dot{V}_{gap} + \omega_0^2 V_{gap} = \frac{1}{C}\frac{d}{dt}(I_{gen} - I_{beam})$$



$$\tau = 2R_pC$$

$$\tau = \frac{2Q_0}{\omega_0} = \frac{Q_0}{\pi f_0}$$



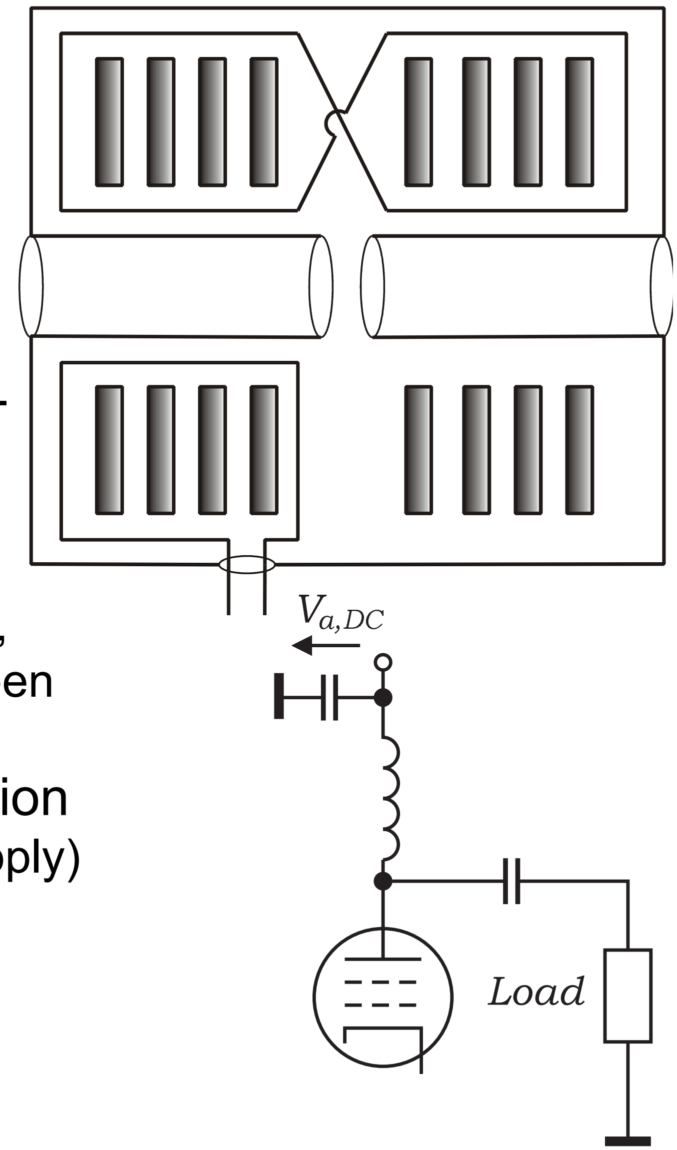
RF Power Amplifier, Cooling

TECHNISCHE UNIVERSITÄT DARMSTADT

- Up to now, we only dealt with the 'unloaded Q' factor of the cavity
- RF power amplifier may often be described as a voltage-controlled current source
- The impedance of this source reduces R_p
- This leads to the 'loaded Q' factor
- 50 Ω matching is not required in general
- Cavity impedance in the order of a few hundred or a few thousand Ohms allows direct connection of tetrode amplifiers (without long cables, which would modify the overall impedance/capacitance)
- In this case, amplifier and cavity should not be designed independently – they are one unit
- Both, the cavity and the power amplifier need active cooling (Curie temperature of ferrites typically >100°C)
- Depending on the operating conditions (e.g. CW or pulsed), forced air cooling may be sufficient or water cooling may be required. For the ring cores, cooling may be realized by cooling disks in-between the ring cores (requires good thermal contact)

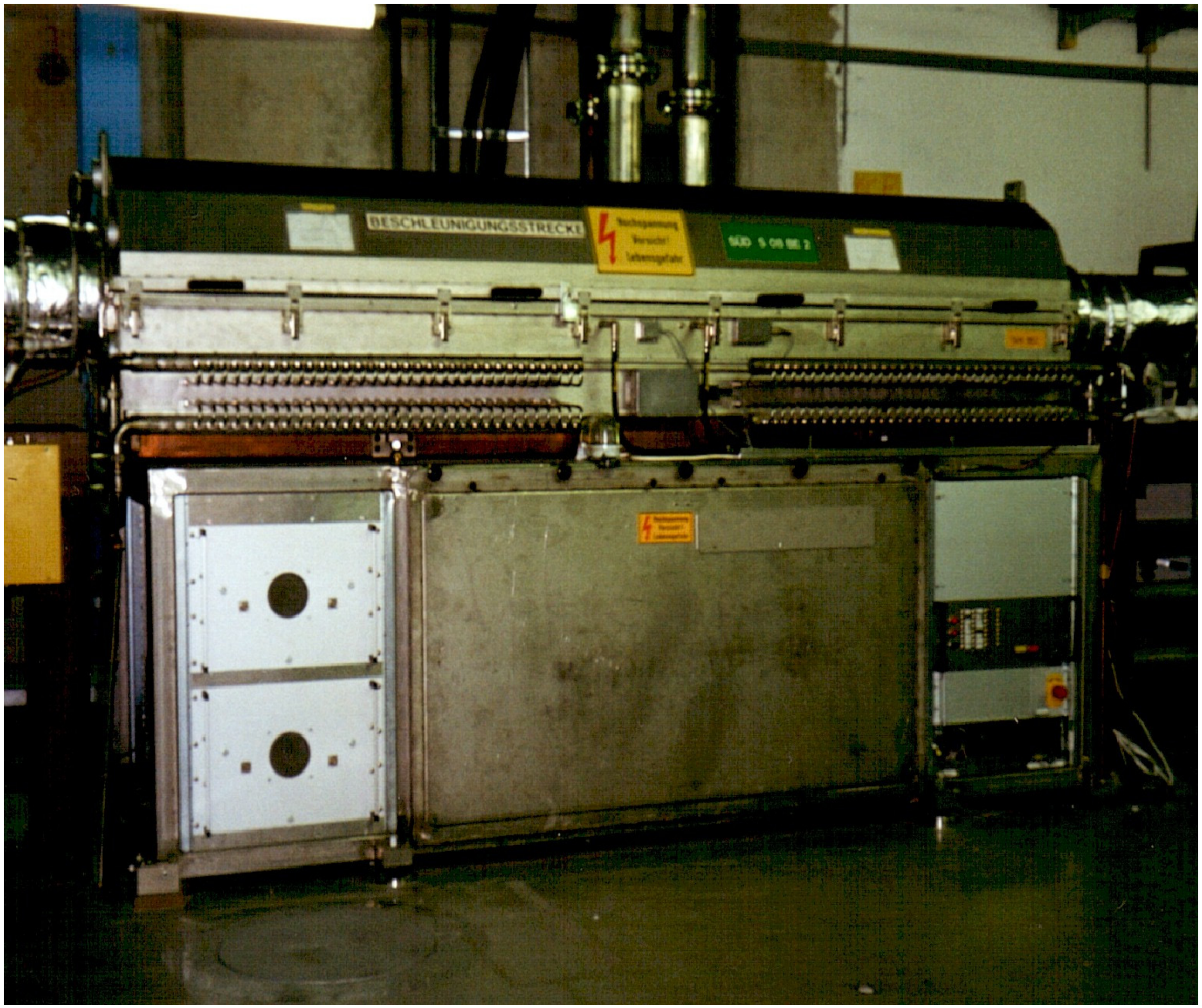
Different Cavity Configurations

- Tuning (e.g. capacitive or bias-current tuning)
- Different number of ferrite stacks and gaps
  - Copper bars may be used to connect gaps (connections as short as possible)
  - Coupling loops may be used to couple ferrite stacks
- Often-used configuration:
  - Two ferrite stacks with one gap in the middle, figure-of-eight bias current windings around both stacks
  - With respect to RF, both ferrite stacks are excited due to bias current windings although the coupling loop surrounds only one of them → 1:2 transformation ratio, impedance seen by the beam is 4 times impedance seen by the amplifier (saves power for same gap voltage)
- Inductive coupling or capacitive coupling or combination (capacitive coupling requires choke coil for high-voltage supply)
- Individual ring core coupling (e.g. 50 Ω)
- External tuners
- ...



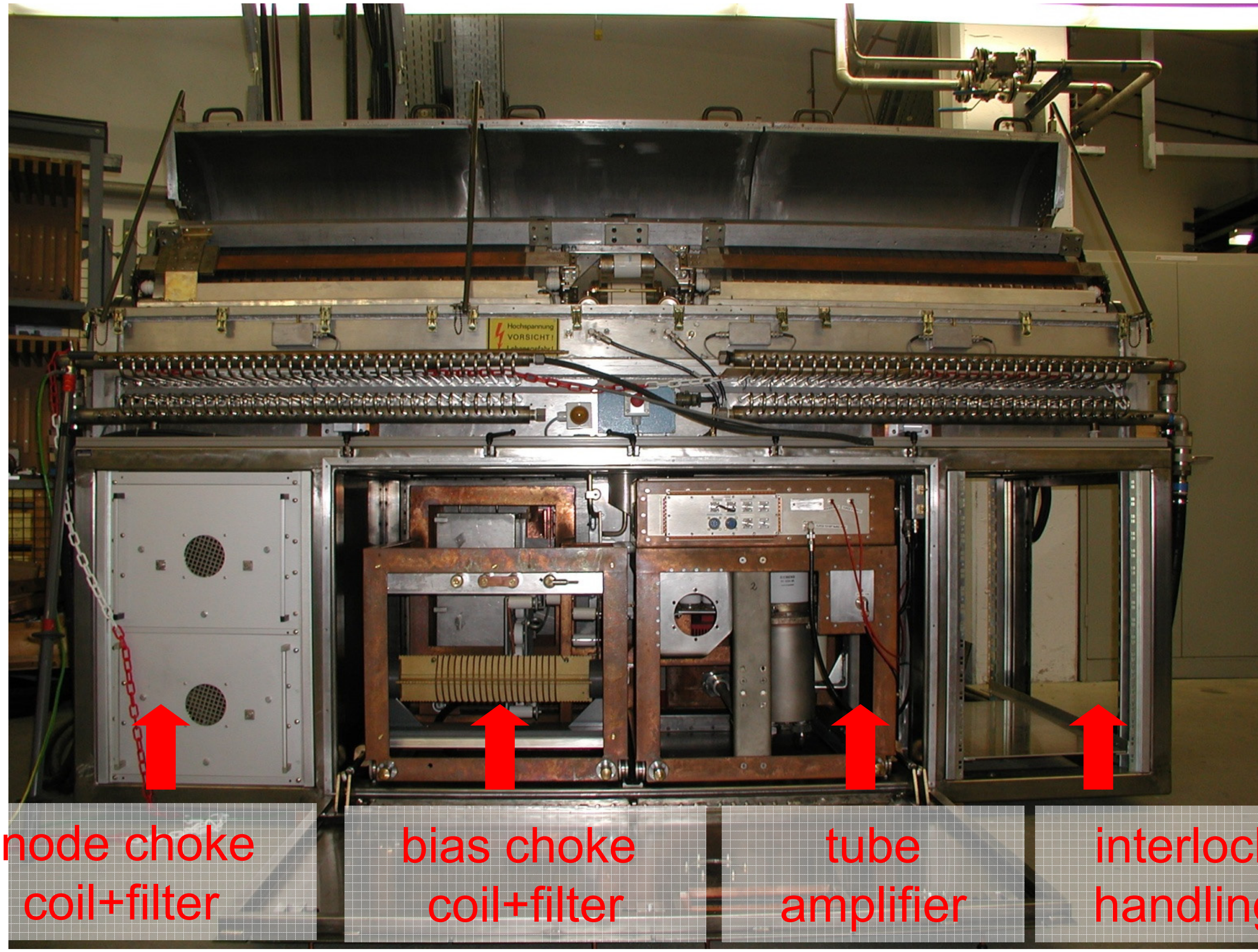
Example: SIS18 Ferrite Cavity at GSI

TECHNISCHE UNIVERSITÄT DARMSTADT



Example: SIS18 Ferrite Cavity at GSI

TECHNISCHE UNIVERSITÄT DARMSTADT



anode choke coil+filter

bias choke coil+filter

tube amplifier

interlock handling

Example: SIS18 Ferrite Cavity at GSI

TECHNISCHE UNIVERSITÄT DARMSTADT

- Ring cores: Ferroxcube 8C12m, d_o =498 mm, d_i =270 mm, t =25 mm
- N_{bias}=6 figure-of-eight bias current windings (up to I_{bias}=800 A bias current)
- Total capacitance C =740 pF
- Ring cores cooled by copper cooling disks
- Maximum amplitude: 16 kV

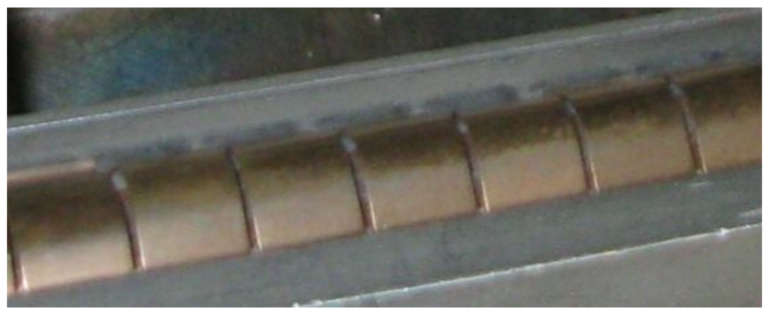
Some realistic parameters (cavity without power amplifier):

Resonant frequency f_0	620 kHz	2.5 MHz	5 MHz
Relative permeability $\mu'_{p,r}$	450	28	7
Magnetic bias field at mean radius H_{bias}	25 A/m	700 A/m	2750 A/m
Bias current I_{bias}	4.8 A	135 A	528 A
$\mu'_{p,r} Q f$ product	$4.2 \cdot 10^9\ \mathrm{s}^{-1}$	$3.7 \cdot 10^9\ \mathrm{s}^{-1}$	$3.3 \cdot 10^9\ \mathrm{s}^{-1}$
Q-factor Q	15	53	94
L_s	88.2 μH	5.49 μH	1.37 μH
L_p	88.5 μH	5.49 μH	1.37 μH
R_s	22.8 Ω	1.63 Ω	0.46 Ω
R_p	5200 Ω	4600 Ω	4100 Ω
Cavity time constant τ	7.7 μs	6.7 μs	6.0 μs

Note: All parameters have comparatively high tolerances

Some Practical Aspects

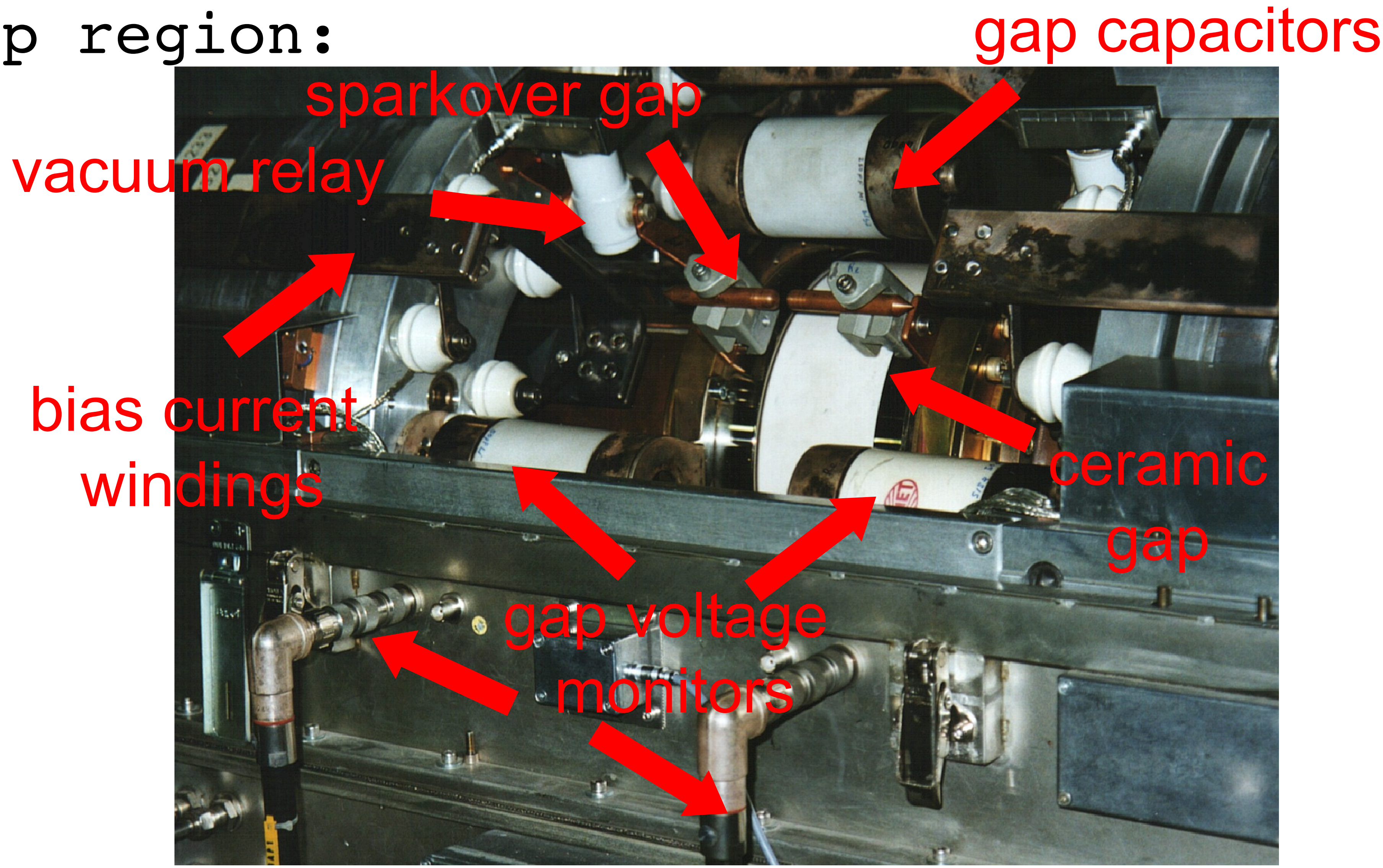
- Gap periphery
  - Gap voltage dividers are required to measure on a safe voltage level → e.g. capacitive dividers
  - Gap relays to temporarily short-circuit unused cavities
  - Solid-state switches for cycle-by-cycle switching
- Impedance of all these devices and of other parasitic elements has to be considered in the lumped-element equivalent circuit
- Cavity should be EMC tight → e.g. RF seals between metal parts



- Bakeout to fulfill vacuum requirements: heating jackets (magnetic material must not be over-heated)
- Radiation hardness of materials

SIS18 Ferrite Cavity

Gap region:

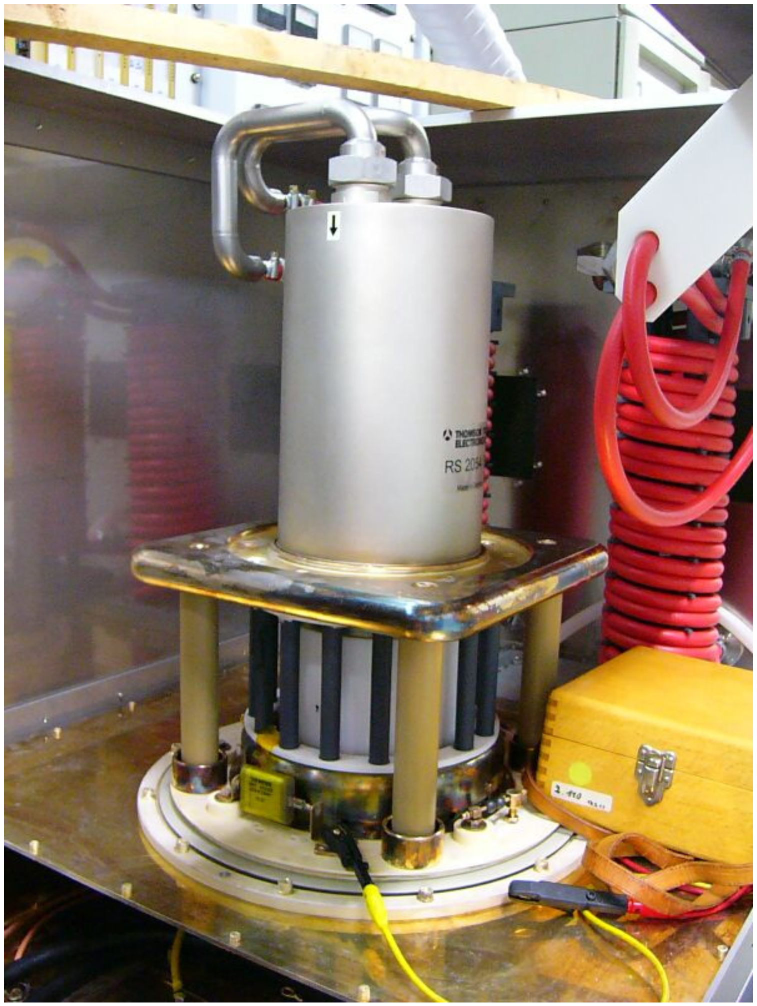


System Aspects

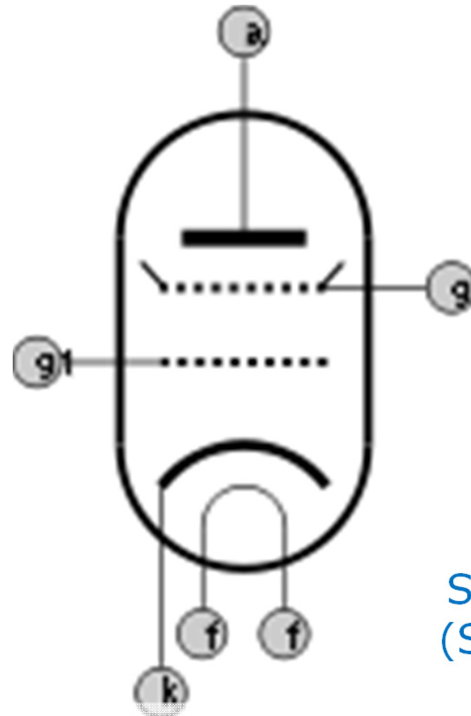
Required RF Subsystems

- RF power generation (vacuum tubes, high-voltage power supplies/power converters, solid-state amplifiers)
- RF power transport & coupling
- Media supply (cooling air, cooling water, electrical power)
- Vacuum subsystem
- Cryogenics (for superconducting cavities)
- Low-Level RF system (electronics, closed-loop control)
- Interface to central control system (hardware & software)

RF Power Generation



Tetrode RS2054
(THALES ELECTRON DEVICES)



Schematics symbol
(Source: Wikipedia)

Tetrode Properties:

- High power
  (~100 kW anode dissipation)
- High radiation hardness

Klystrons are used at higher frequencies (above 300 MHz).

Power Supply Unit

Supply Unit of SIS18 Bunch Compressor, GSI

Power supplies for tetrodes:
- Anode voltage
- Screen grid voltage
- Control grid voltage
- Filament current

A so-called Programmable Logic Control (PLC) unit (German: SPS, Speicherprogrammierbare Steuerung) is used to switch on all voltages and currents in the required order and to monitor failures.

Classical scheme for power supply:
- Transformer
- Rectifier
- Capacitor bank

Modern solution: Switch mode power supply (SMPS)

Further Sub-Systems

TECHNISCHE UNIVERSITÄT DARMSTADT

Solid-state power amplifiers as drivers for tetrodes

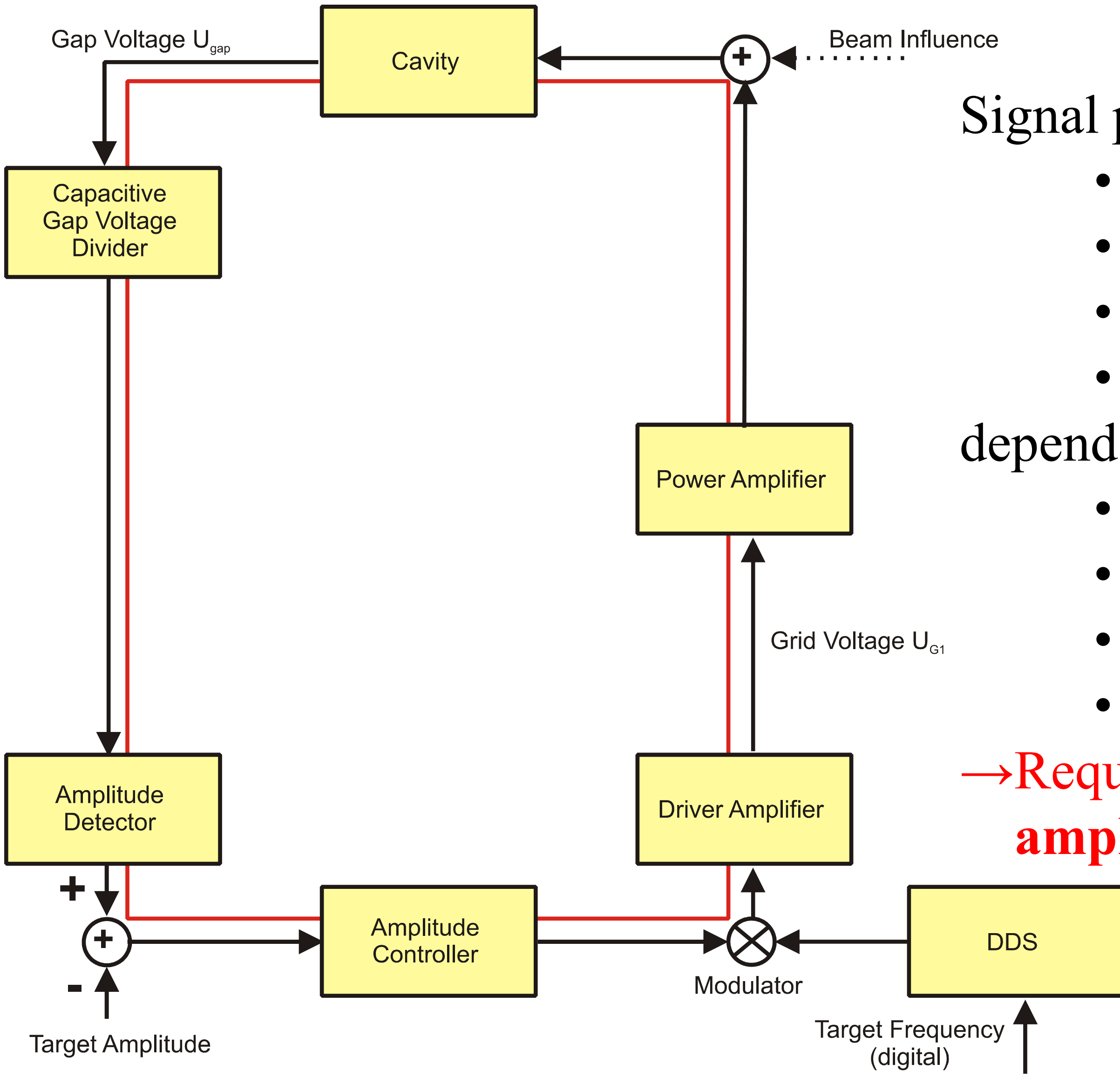
Solid-state pre-amplifier,
barthel HF-Technik GmbH

LLRF System, Control Loops

- Operating parameters must be controlled in real-time
  - RF frequency
  - RF amplitude
  - RF phase
- Some quantities must be stabilized by means of closed-loop control:
  - Amplitude
  - Resonant frequency
  - Phase

Control Loops (Example SIS18)

TECHNISCHE UNIVERSITÄT DARMSTADT



Challenge

Signal processing chain consisting of

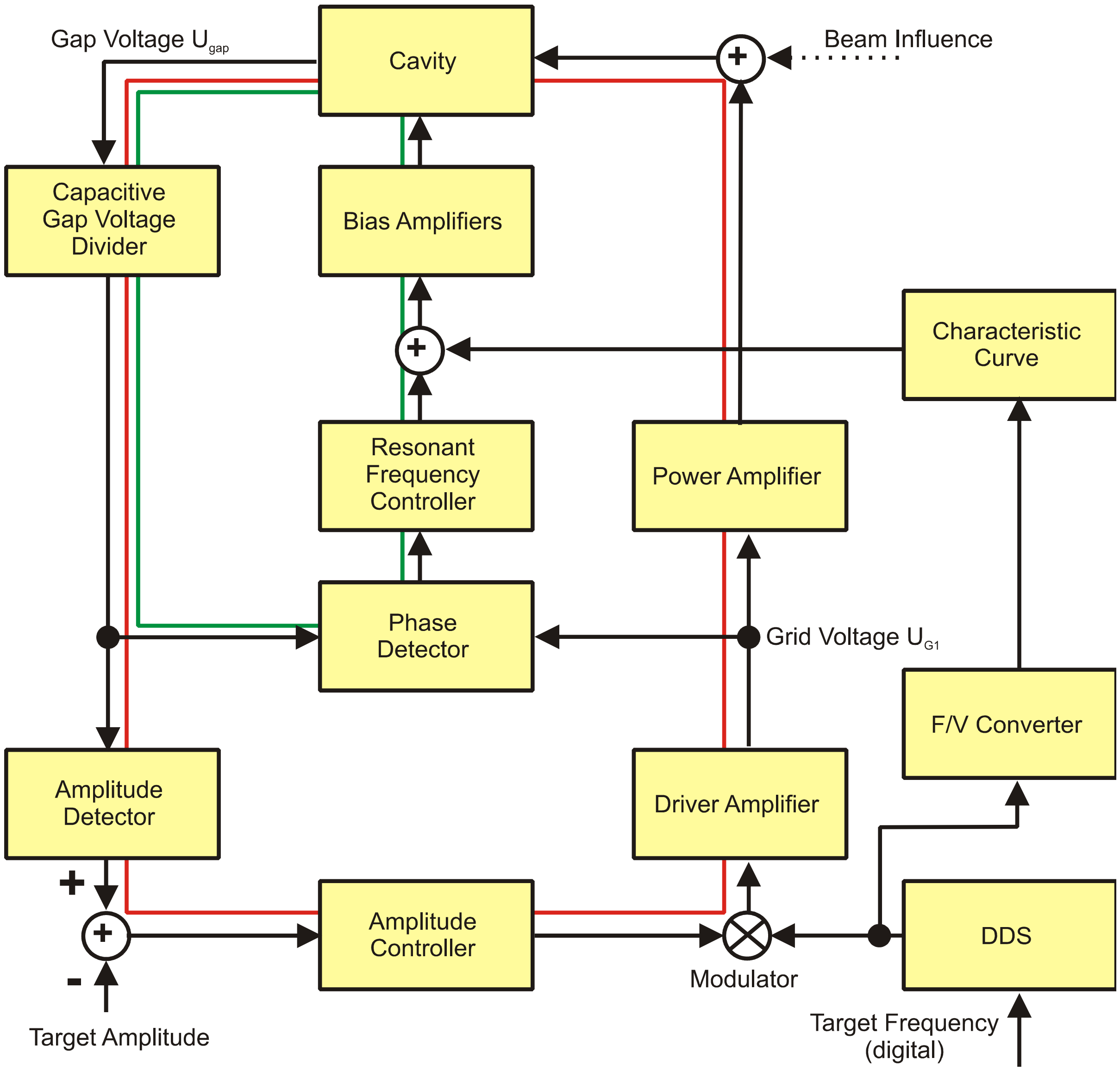
- Amplitude modulator
- Driver amplifier
- Power amplifier and
- Cavity

depends on

- Temperature
- Frequency
- Amplitude
- …

→Requirement for **amplitude control** and …

Control Loops (Example SIS18)



...resonant frequency control

Next problem:
The phase of the DDS signal does not necessarily determine the phase of the gap voltage
→ Active cavity synchronization required

Control Loops

- Summary:
  - Even though the equivalent circuit is rather simple, the system behavior is rather complicated
  - The beam current makes the behavior even more complicated (requires stationary and transient beam loading compensation)
  - The power amplifier (e.g. a tetrode) and the magnetic material introduce nonlinear impedances
- In practice, the following cavity-oriented control loops may, e.g., be present:
  - Amplitude control loop to stabilize the amplitude
  - Resonant frequency control to tune the cavity to resonance
  - Phase control/cavity synchronization to adjust the gap voltage to the correct phase (with respect to the beam current)
  - Fast feedback/feedback around the amplifier (for transient beam loading reduction, reduction of shunt impedance)

Control Loops

- Further loops:
  - Beam Phase Control
    (damping of coherent dipole modes of oscillation - dipole oscillations may e.g. be induced by timing imperfections during the transfer from one synchrotron to another one or by real instabilities)
  - Longitudinal Feedback Systems
    (damping of higher-order modes: dipole, quadrupole, sextupole, octupole, etc.)
  - Radial Loop
    (measures and corrects radial position of the beam, e.g. by modifying RF frequency)

Basics of Longitudinal Beam Dynamics

Longitudinal Beam Dynamics

- Behavior of particles may be described by difference equations

$$\Delta t_n = \Delta t_{n-1} + \frac{l_R \eta_R}{\beta_n \beta_{Rn}^2 c_0} \frac{\Delta \gamma_n}{\gamma_{Rn}} \qquad \Delta \gamma_n = \Delta \gamma_{n-1} + \frac{Q}{m_0 c_0^2} \Delta U_{n-1}$$

or differential equations:

$$\frac{d(\Delta t)}{dt} = \frac{\eta_R}{W_R \beta_R^2} \Delta W \qquad \frac{d(\Delta W)}{dt} = \frac{Q}{T_R} \left(U(t_R + \Delta t) - U(t_R) \right)$$

- Dynamical systems of this type obey Hamilton’s equations:

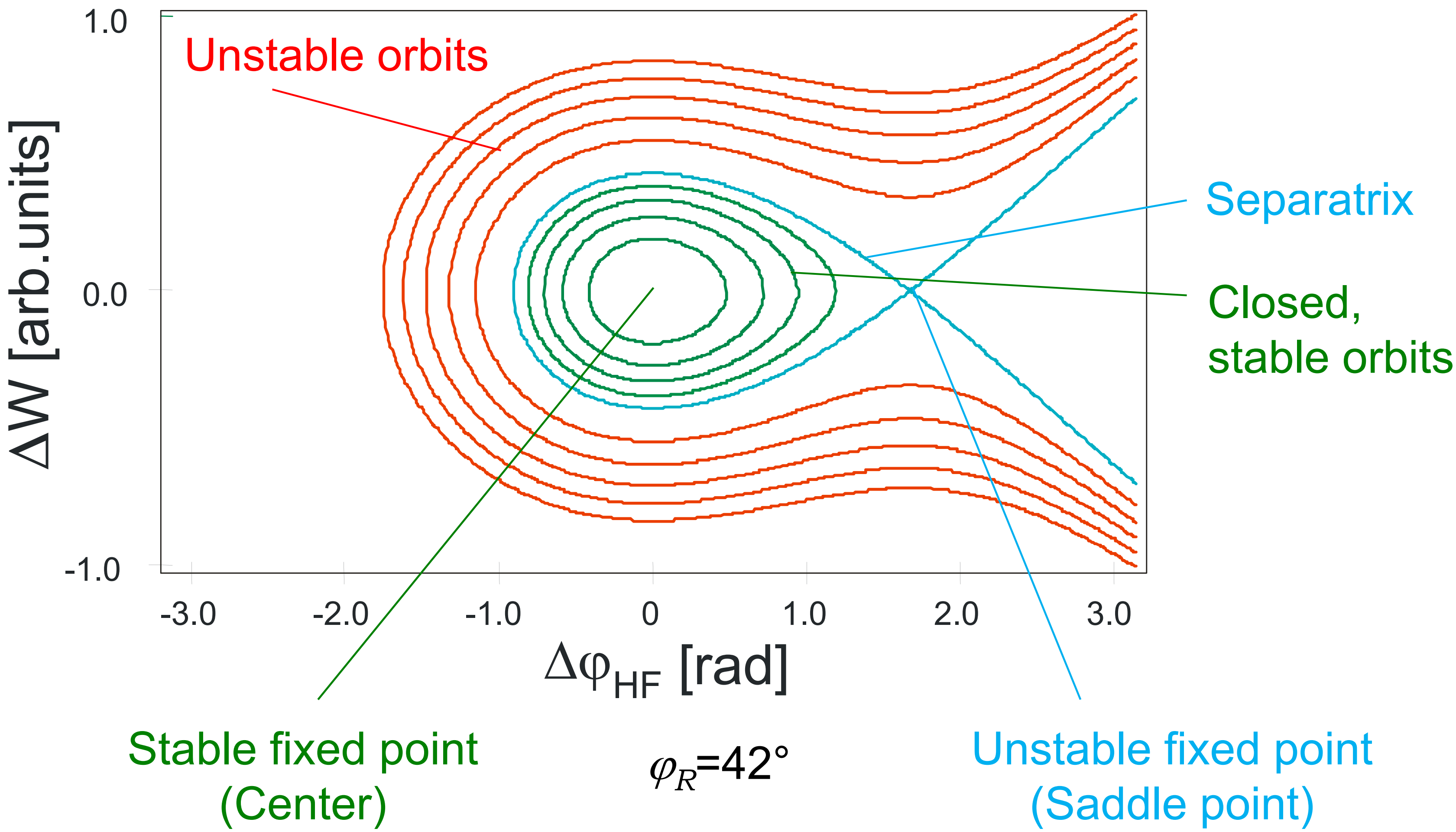
$$\frac{\partial H}{\partial p} = \dot{q} \qquad \frac{\partial H}{\partial q} = -\dot{p}$$

- In our case, the Hamiltonian reads:

$$H(\Delta W, \Delta t) = -\frac{\eta_R}{W_R \beta_R^2} \frac{\Delta W^2}{2} - \frac{Q\hat{u}}{T_R} \left(\frac{1}{\omega_{HF}} [\cos(\omega_{HF} \Delta t + \varphi_R) - \cos \varphi_R] + \Delta t \sin \varphi_R \right)$$

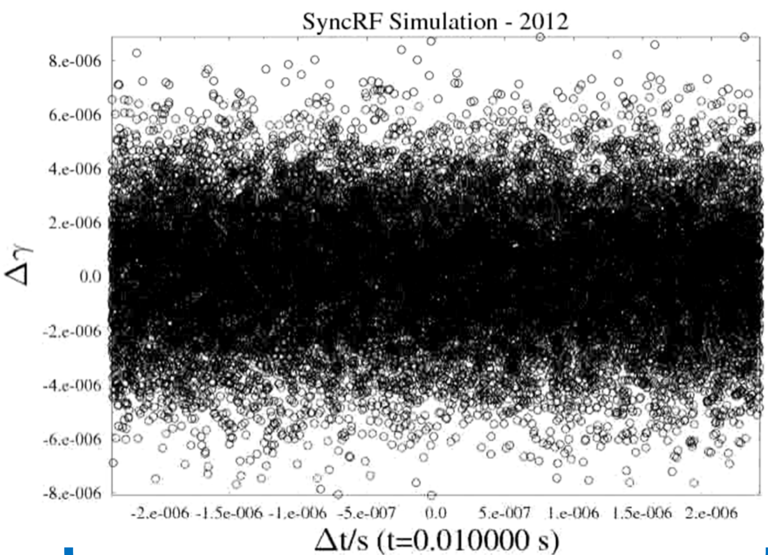
- It specifies particle trajectories in phase space...

Longitudinal Beam Dynamics

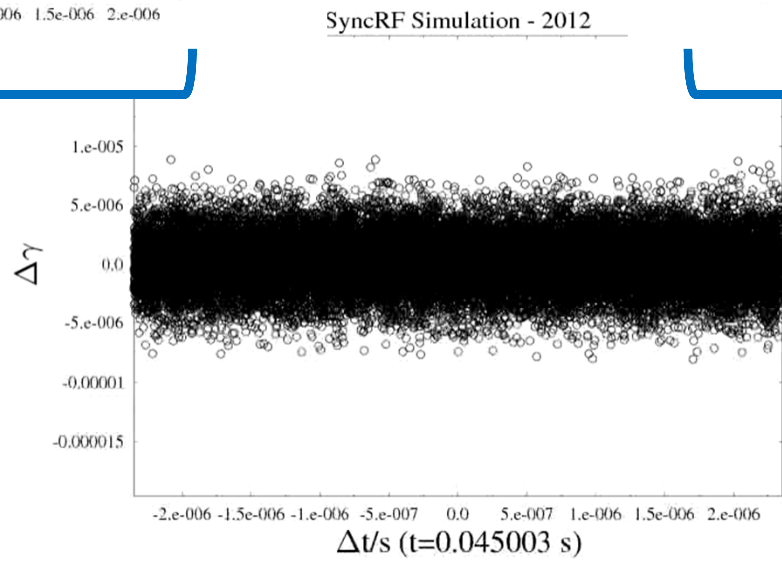


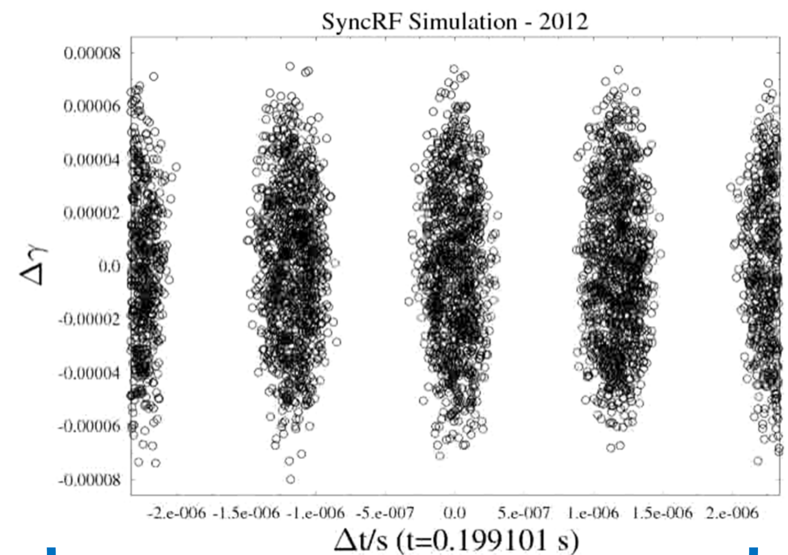
For high-intensity beams, space charge effects have to be included in the description

Longitudinal Beam Dynamics



Coasting Beam

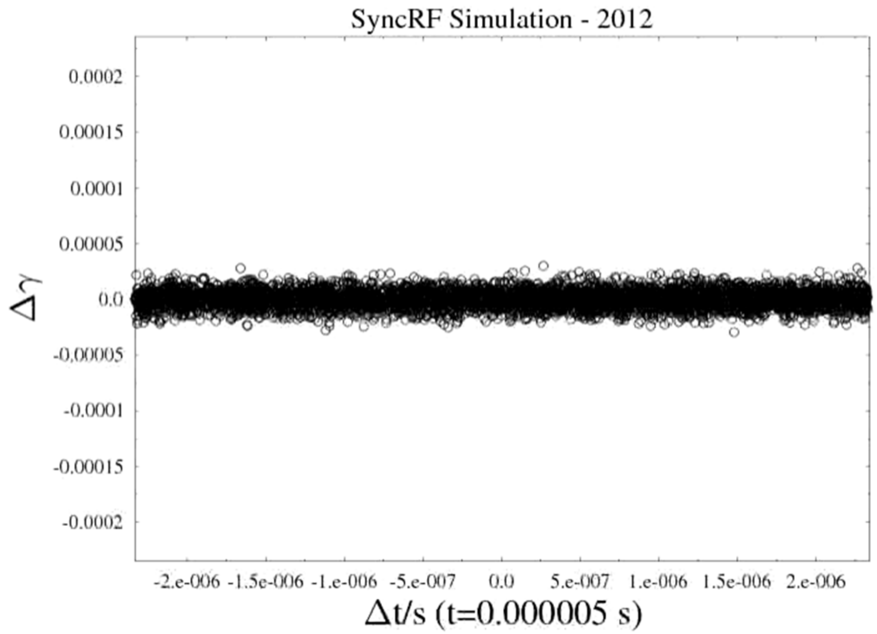


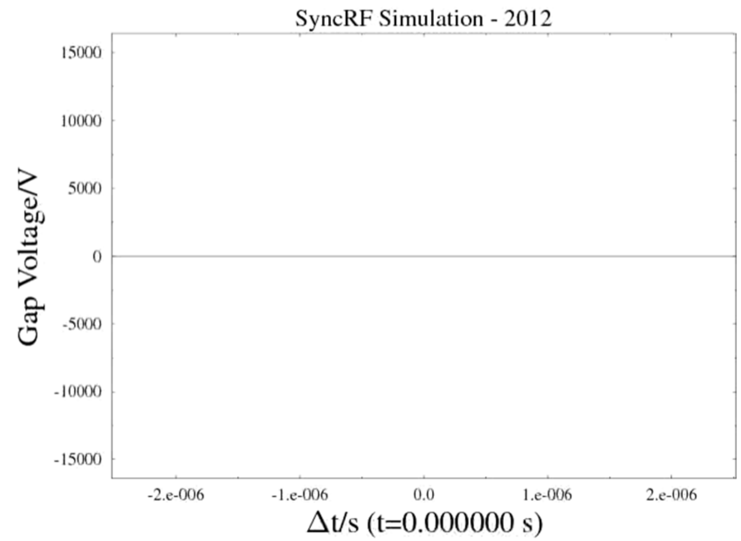


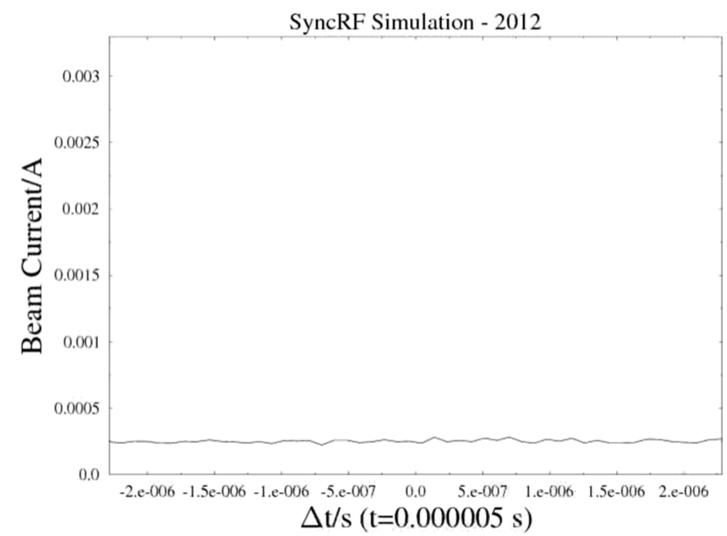
Bunched Beam

A Typical Machine Cycle

TECHNISCHE UNIVERSITÄT DARMSTADT







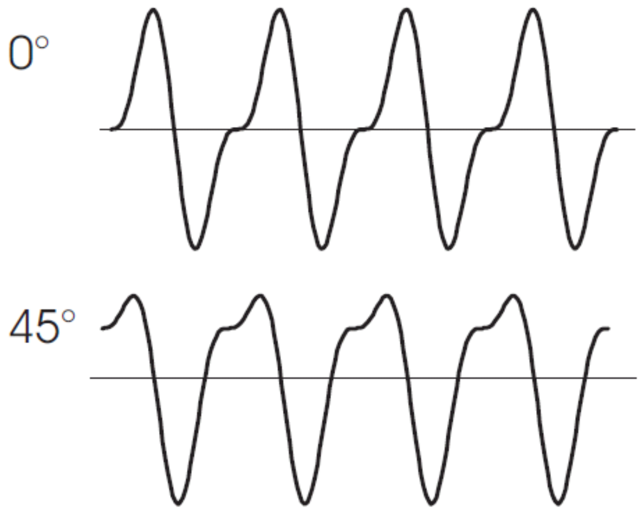
- Injection
- Adiabatic Capture (Bunching)
- Acceleration
- Debunching
- Slow Extraction

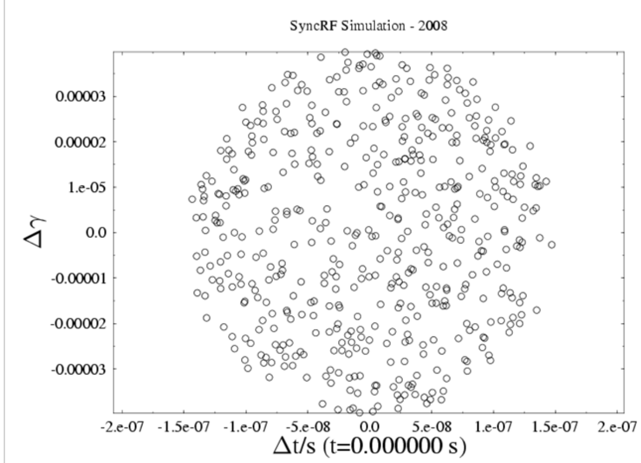
Examples for Advanced Beam Manipulations
“RF Gymnastics”

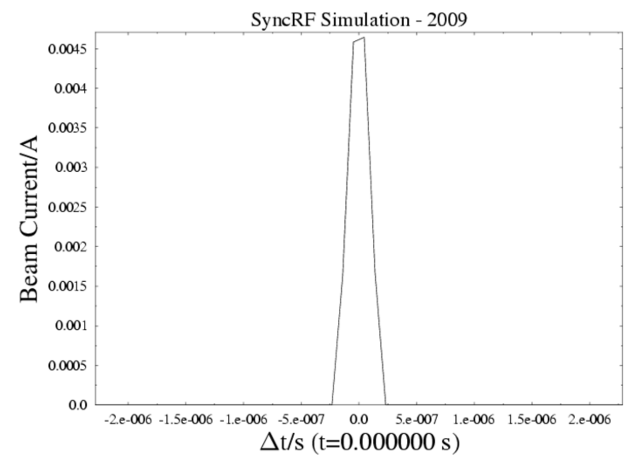
Examples for "RF Gymnastics"

- Bunch compression, bunch rotation (90° rotation in phase space by means of large RF amplitude applied for ¼ of a synchrotron period) – not presented here
- Barrier bucket operation (mixture between coasting beam and bunched beam by means of single-sine RF pulses) – not presented here
- Dual-harmonic operation (increases bunching factor $B_f = \frac{\bar{I}}{I_{max}}$ and hence, decreases space-charge effects)
- Bunch merging, bunch splitting

Dual Harmonic Operation



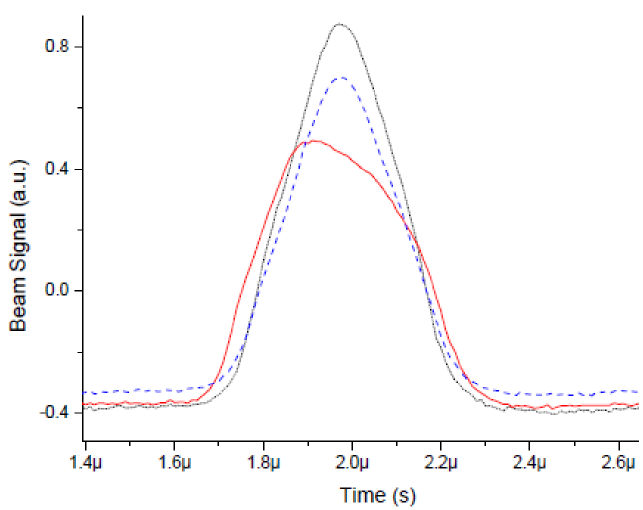


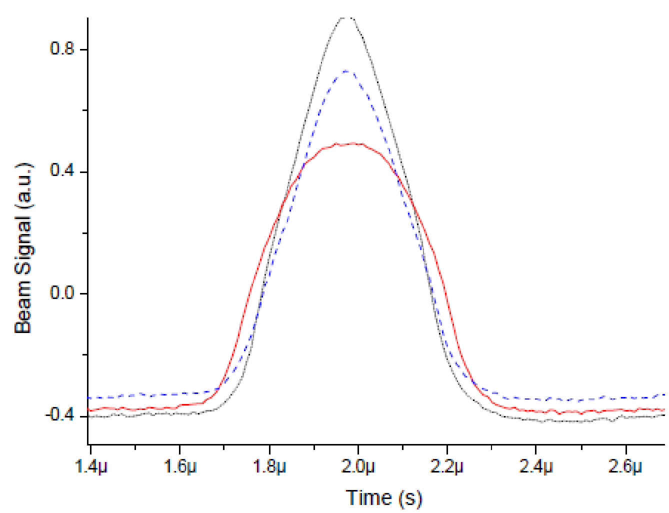


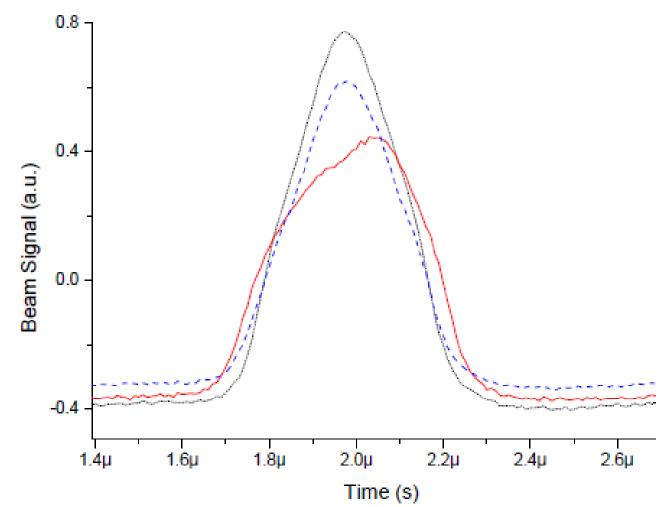
Phase 5° too low

Phase ok

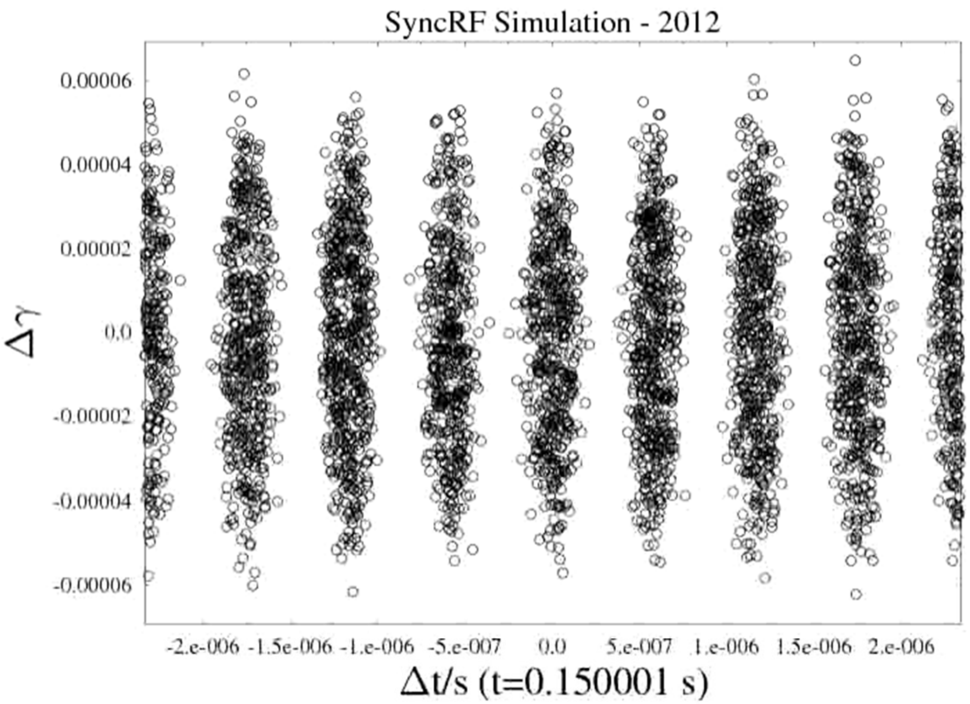
Phase 5° too large:

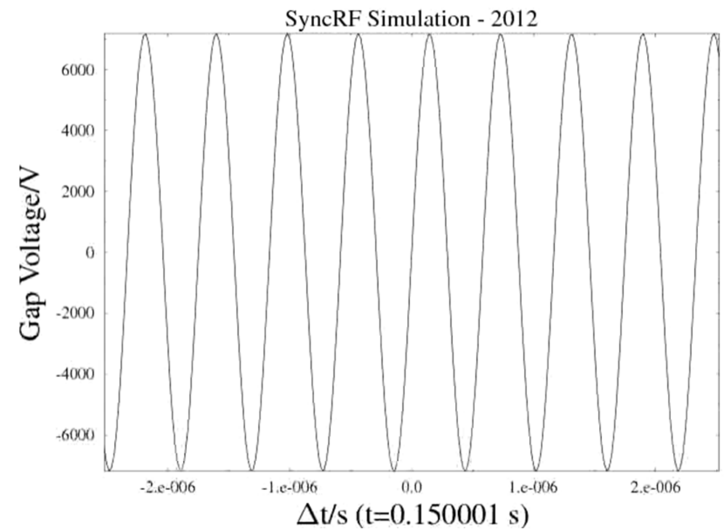


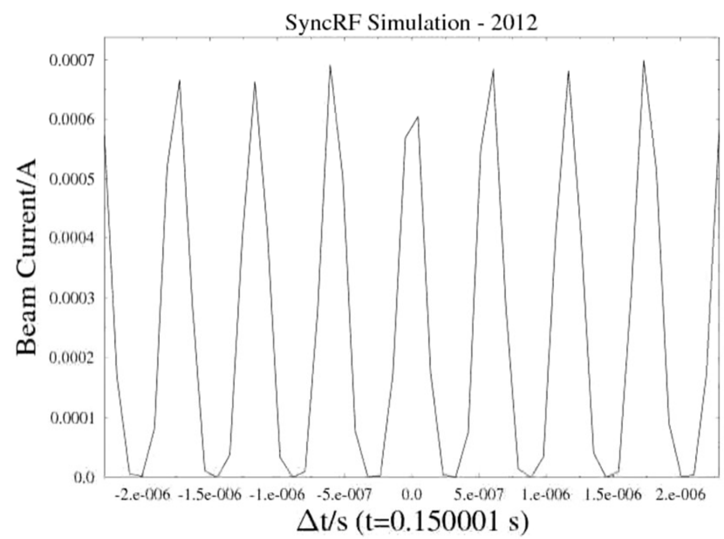




Bunch Merging



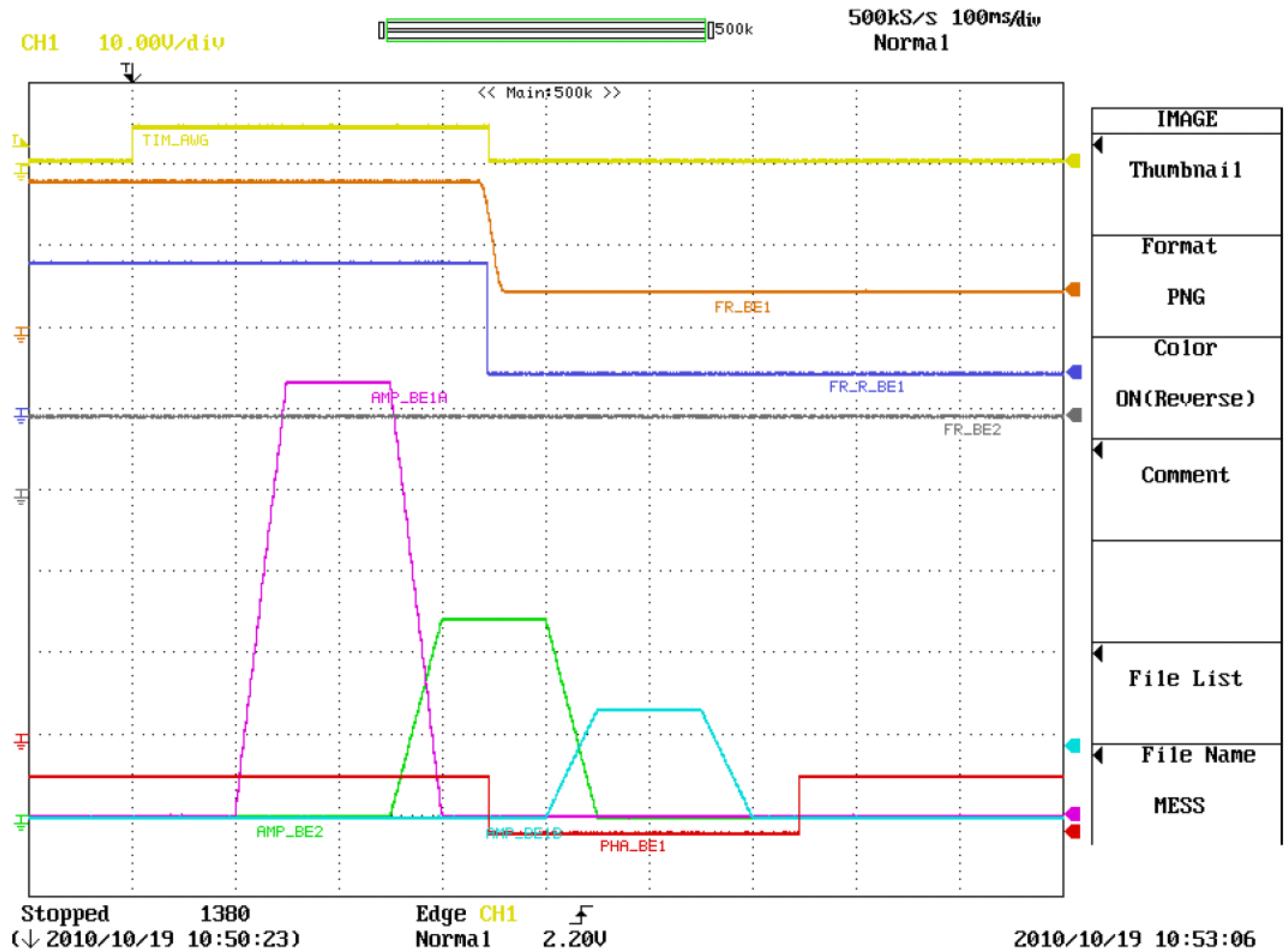




Bunch Merging

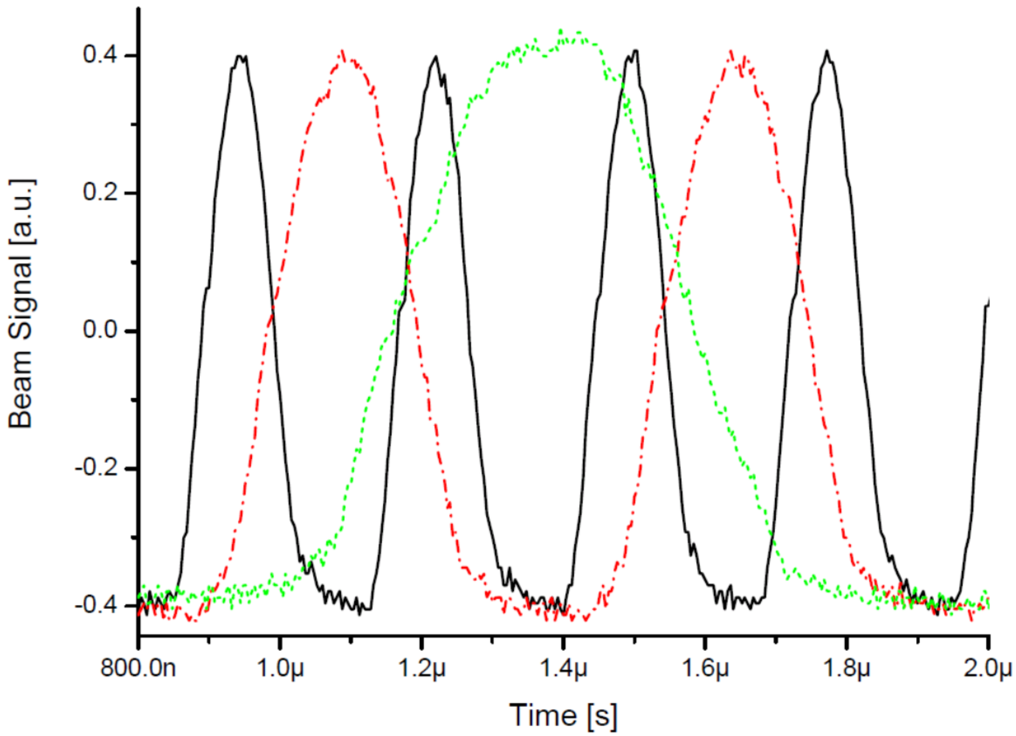
Bunch Merging, 19.10.2010

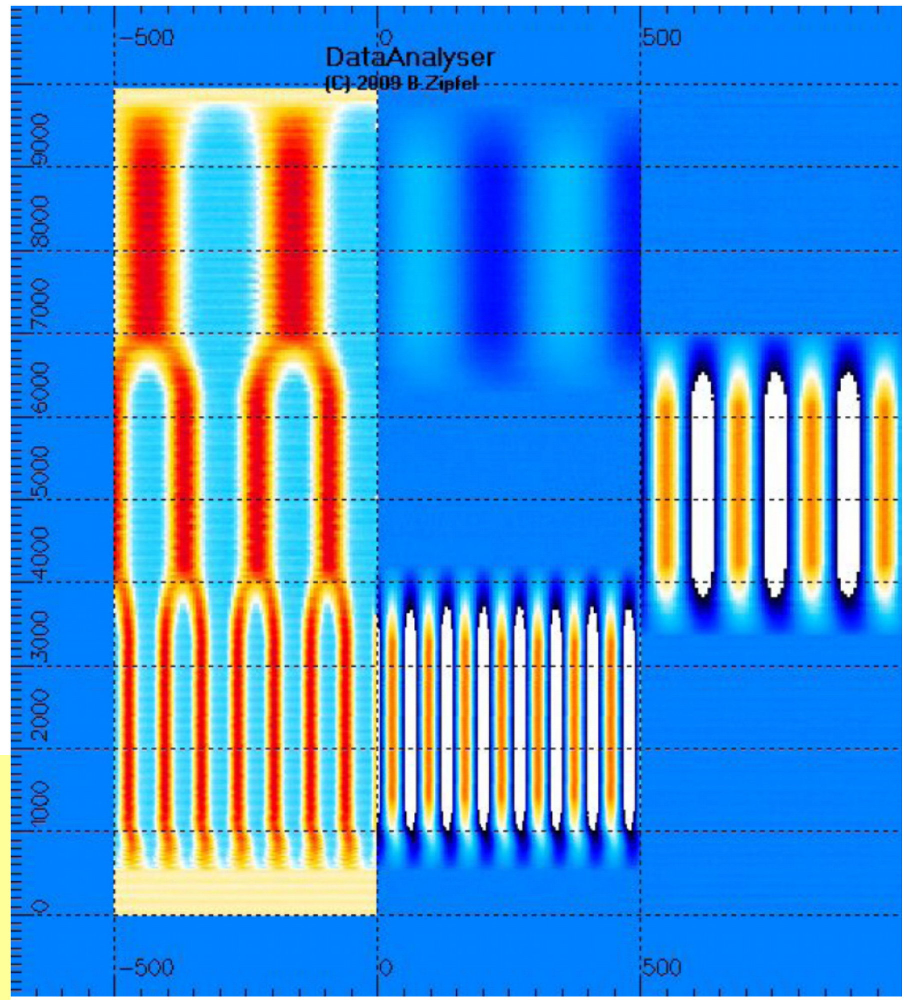
- $^{238}U^{73+}$
- h=4→2→1
- Different extraction energies



Bunch Merging

Bunch Merging, 19.10.2010

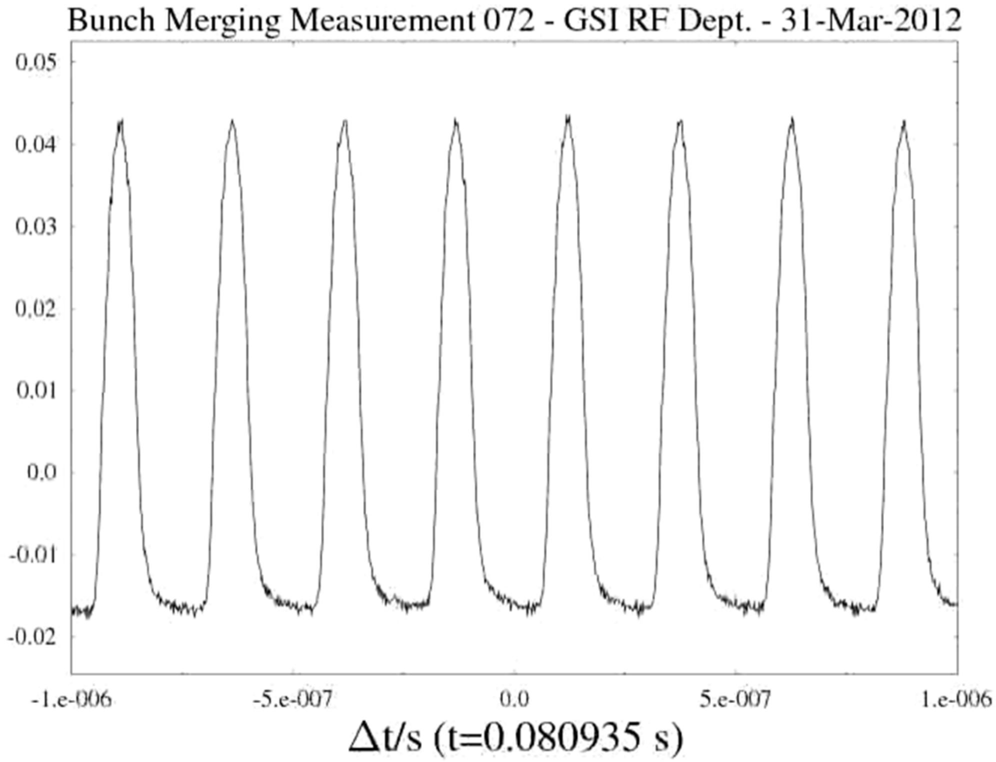




Contributors: Kainberger, Klingbeil, Laier, Mondry, Moritz, Ningel, Reimann, Riehl, Schäfer, Schütt, Spiller, Thielmann, Winnefeld, Wollmann, Zipfel

Bunch Merging

Bunch Merging, 31.03.2012
($^{238}U^{73+}$, 400 MeV/u, $1 \cdot 10^9$ ions per cycle)



Contributors: Hartel, Kaufmann, Klingbeil, Laier, Lens, Mondry, Moritz, Ningel, Reeg, Reimann, Riehl, Schäfer, Schütt, Spiller, Thielmann, Winnefeld, Zipfel

Acknowledgements

Many colleagues contributed to this presentation by several discussions. It is impossible to mention all of them here but with some colleagues I had many fruitful discussions:

Current staff:
Priv.-Doz. Dr. habil. Peter Hülsmann, Dr. Hans Günter König,
Dr. Ulrich Laier, Dr. Klaus-Peter Ningel, Dr. Gerald Schreiber,
Dr. Bernhard Zipfel

Former staff:
Dr. Norbert Angert, Dr. Klaus Blasche, Dipl.-Phys. Martin Emmerling,
Dr. Bernhard Franzke, Dr. Klaus Kaspar

(literature references are provided on the following slides)

Thank you very much for your attention!

References

[1] J. M. Brennan, in Handbook of Accelerator Physics and Engineering, Eds. A. W. Chao and M. Tigner (World Scientific, Singapore, 1999), pp. 570–2.

[2] I. D. Mayergoyz, Mathematical Models of Hysteresis and Their Applications, 2nd ed., e-book (Elsevier, San Diego, 2003).

[3] F. G. Brockman, H. van der Heide, and M. W. Louwerse, Ferroxcube für Protonensynchrotrons, Philips Technische Rundschau, 30 (1969/70) 323–342.

[4] S. Papureanu, Ch. Hamm, A. Schnase, and H. Meuth, Performance test of a ferrite-loaded cavity under operation conditions, in 15th IEEE Particle Accelerator Conference, Washington, DC, USA, 1993 (IEEE, Piscataway, NJ, 1994), pp. 962–964.

References

[5] M. Morvillo, R. Garoby, D. Grier, M. Haase, A. Krusche, P. Maesen, M. Paoluzzi, and C. Rossi, The PS 13.3–20 MHz RF system for LHC, in 20th IEEE Particle Accelerator Conference, Portland, OR, USA, 2003, Ed. J. Chew (JACoW, Geneva, 2003), pp. 1724–1726.

[6] P. Hülsmann, G. Hutter, and W. Vinzenz, The bunch compressor system for SIS18 at GSI, in EPAC, Luzern, 2004, pp. 1165–1167.

[7] W. R. Smythe and T. G. Brophy, RF cavities with transversely biased ferrite tuning, IEEE Trans. Nucl. Sci. NS-32 (1985) 2951–2953.

[8] J. E. Griffin and G. Nicholls, A review of some dynamic loss properties of Ni-Zn accelerator RF system ferrite, IEEE Trans, Nucl. Sci. 26 (1979) 3965–3967.

[9] K. Kaspar, H. G. König, and T. Winnefeld, Studies on maximum RF voltages in ferrite-tuned accelerating cavities, in EPAC, Luzern, 2004, pp. 985–987.

References

[10] H. G. König and S. Schäfer, Reduction of Q-loss effects in ferrite-loaded cavities, in EPAC, Genoa, Italy, 2008, pp. 985–987.

[11] V. S. Arbuzov et al., Accelerating RF station for HIRFL-CSR, Lanzhou, China, in RuPAC XIX, Dubna, 2004, pp. 332–334.

[12] X. Pei, S. Anderson, D. Jenner, D. McCammon, and T. Sloan, A wide tuning range RF cavity with external ferrite biasing, in 15th IEEE Particle Accelerator Conference,Washington, DC, USA, 1993 (IEEE, Piscataway, NJ, 1994), pp. 1421–1423.

[13] A. Susini, Low frequency ferrite cavities, in EPAC, Rome, 1988, Ed. S. Tazzari (World Scientific, Singapore, 1989), pp. 1416–1417.

[14] I. S. K. Gardner, Ferrite dominated cavities, in CAS - CERN Accelerator School: RF Engineering for Particle Accelerators, Oxford, 1991, S. Turner (Ed.) CERN 92-3, pp. 349–374.

References

[15] A. Schnase, Cavities with a swing, in CAS - CERN Accelerator School: Radio Frequency Engineering, Seeheim, 2000, J. Miles (Ed.) CERN 2005-3, pp. 236–272.
[16] A. Krusche and M. Paoluzzi, The new low frequency accelerating systems for the CERN PS Booster, in EPAC, Stockholm, 1998 (IOP, Bristol, 1998), pp. 1782–1783.
[17] J. Dey, I. Kourbanis, and D.Wildman, A new RF system for bunch coalescing in the Fermilab Main Ring, in 16th IEEE Particle Accelerator Conference, Dallas, TX, USA, 1995 (IEEE, Piscataway, NJ, 1995), pp. 1672–1674.
[18] R. M. Hutcheon, A perpendicular-biased ferrite tuner for the 52 MHz PETRA II cavities, in 12th IEEE Particle Accelerator Conference, Washington, DC, USA, 1987 (IEEE, New York, 1987), pp. 1543–1545.

References

[19] C. C. Friedrichs, R. D. Carlini, G. Spalek, andW. R. Smythe, Test results of the Los Alamos ferrite tuned cavity, in 12th IEEE Particle Accelerator Conference, Washington, DC, USA, 1987 (IEEE, New York, 1987), pp. 1896–1897.
[20] R. L. Poirier, Perpendicular biased ferrite-tuned cavities, in 15th IEEE Particle Accelerator Conference, Washington, DC, USA, 1993 (IEEE, Piscataway, NJ, 1994), pp. 753–757.
[21] C. Fougeron, P. Ausset, D. de Menezes, J. Peyromaure, and G. Charruau, Very wide range and short accelerating cavity for MIMAS, in 15th IEEE Particle Accelerator Conference, Washington, DC, USA, 1993 (IEEE, Piscataway, NJ, 1994), pp. 858–861.
[22] K. Saito, K. Matsuda, H. Nishiuchi, M. Umezawa, K. Hiramoto, and R. Shinagawa, RF accelerating system for a compact ion synchrotron, in 19th IEEE Particle Accelerator Conference, Chicago, IL, USA, 2001 (IEEE, New York, 2002), pp. 966–968.
[23] R. Stassen, K. Bongardt, F. J. Etzkorn, H. Stockhorst, S. Papureanu, and A. Schnase, The HESR RF system and tests in COSY, in EPAC, Genoa, 2008 (JACoW, Geneva, 2008), pp. 361–363.

References

[24] L. M. Earley, H. A. Thiessen, R. Carlini, and J. Potter, A high-Q ferrite-tuned cavity, IEEE Trans. Nucl. Sci. NS-30 (1983) 3460–3462.
[25] K. Kaspar, Design of Ferrite-Tuned Accelerator Cavities Using Perpendicular-Biased High-Q Ferrites, Technical report, Los Alamos National Laboratory, New Mexico, USA, November 1984, LA-10277-MS.
[26] G. Schaffer, Improved ferrite biasing scheme for Booster RF cavities, in EPAC, Berlin, 1992 (Éditions Frontières, Gif-sur-Yvette, 1992), pp. 1234–1236.
[27] E. Jensen: Cavity basics, Proceedings of the CERN Accelerator School (CAS) – RF for accelerators, Ebeltoft, Denmark, 8-17 June 2010, pp. 259-275.
[28] F. Gerigk: Cavity types, Proceedings of the CERN Accelerator School (CAS) – RF for accelerators, Ebeltoft, Denmark, 8-17 June 2010, pp. 277-298.
[29] H. Klingbeil: Ferrite cavities, Proceedings of the CERN Accelerator School (CAS) – RF for accelerators, Ebeltoft, Denmark, 8-17 June 2010, pp. 299-317.

References

[30] R. G. Carter: RF power generation, Proceedings of the CERN Accelerator School (CAS) – RF for accelerators, Ebeltoft, Denmark, 8-17 June 2010, pp. 173-207.

[31] P. Baudrenghien: Low-level RF, Proceedings of the CERN Accelerator School (CAS) – RF for accelerators, Ebeltoft, Denmark, 8-17 June 2010, pp. 341-367.

[32] R. Garoby: RF gymnastics in synchrotrons, Proceedings of the CERN Accelerator School (CAS) – RF for accelerators, Ebeltoft, Denmark, 8-17 June 2010, pp. 431-446.

[33] A. Gamp: Beam cavity interaction, Proceedings of the CERN Accelerator School (CAS) – RF for accelerators, Ebeltoft, Denmark, 8-17 June 2010, pp. 149-171.