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Magnetic Alloy/Ferrite Cavities

Harald Klingbeil

Technical University of Darmstadt, Accelerator Technology Group,
Darmstadt, Germany

and

GSI Helmholtzzentrum für Schwerionenforschung GmbH, Department Ring RF Systems
Darmstadt, Germany

Magnetic Alloy/Ferrite Cavities

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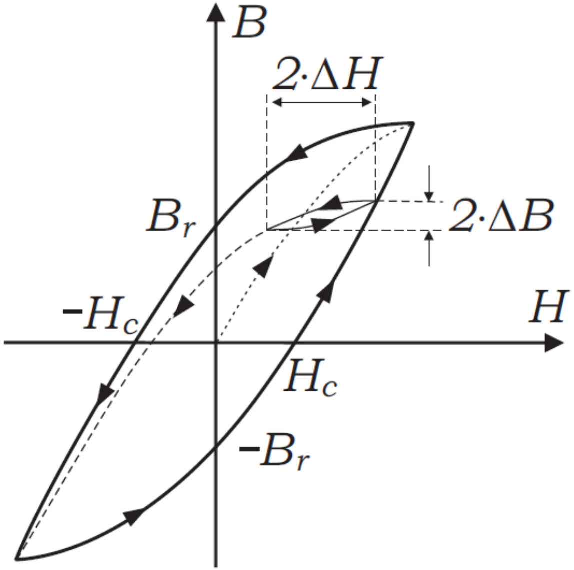
Usage of Magnetic Alloy/Ferrite Cavities in Synchrotrons and Storage Rings

- Revolution frequency in synchrotrons usually lower than 10 MHz
  (even for small synchrotrons with 20...25 m diameter and relativistic particles)
- If small harmonic numbers h are desired, also the RF frequency will be lower than 10 MHz
  → wavelength in air or vacuum >30 m
  → conventional RF resonator (e.g. pillbox cavity) not possible
- Reduction of wavelength is possible by magnetic materials
  → idea of ferrite- or MA-loaded cavities
- Nice side-effect: Frequency tuning easily possible, as we will see now...

Hysteresis Loop

- Soft magnetic material: narrow hysteresis loop
- Hard magnetic material: wide hysteresis loop
- (limits between soft and hard magnetic material are not strict)
- Bias current → H_{bias} → modification of incremental/differential permeability:

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



H_c: coercive magnetizing field
B_r: residual induction

Fig. taken from [A.1, A.2]

- 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:

$$\boxed{\underline{\mu} = \mu'_s - j\mu''_s}$$

MA/Ferrite-Loaded Cavity – Main Components

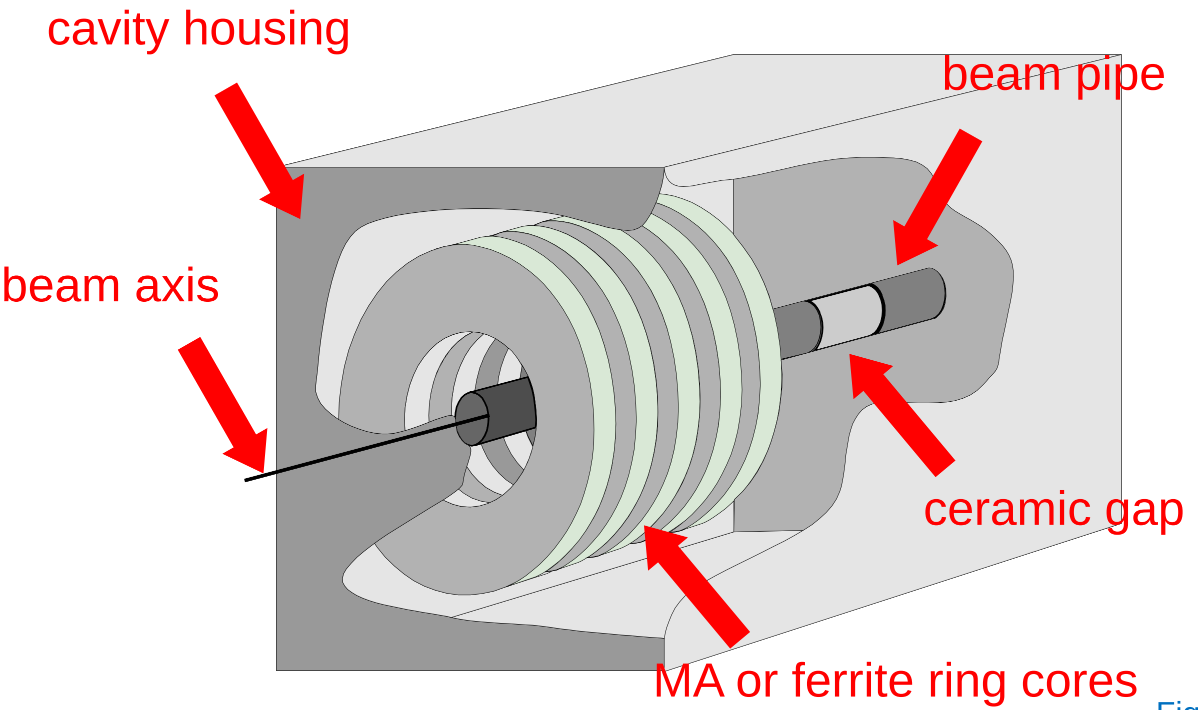


Fig. taken from [A.1, A.2]

Simplified MA/Ferrite Cavity Model

Faraday's law of induction:

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

All field and circuit quantities are phasors! Frequency: f_{RF}

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

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

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

Total current enclosed by the magnetic field lines:

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

3D cavity replaced by wire model

Magneto-quasistatic (MQS) analysis plus discrete capacitor

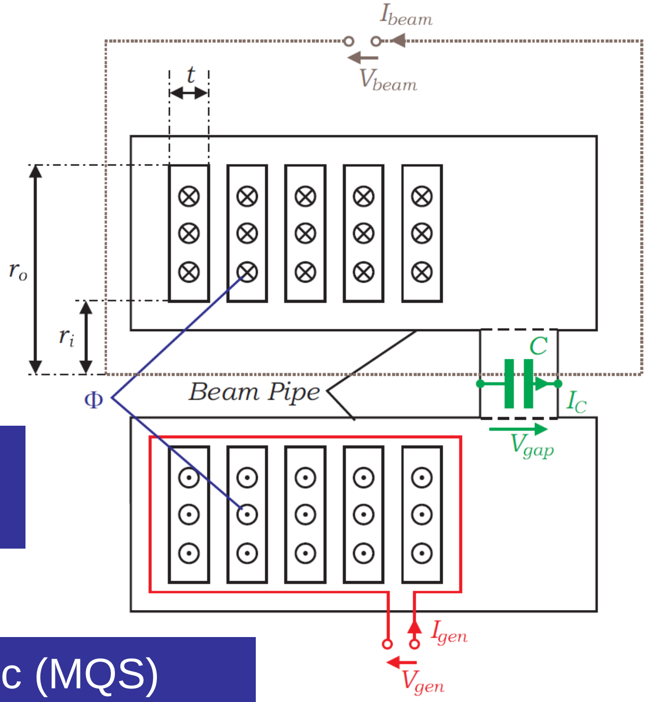


Fig. taken from [A.1, A.2]

Simplified MA/Ferrite Cavity Model

Now we have to determine the magnetic flux:

All field and circuit quantities are phasors!

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:

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

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

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

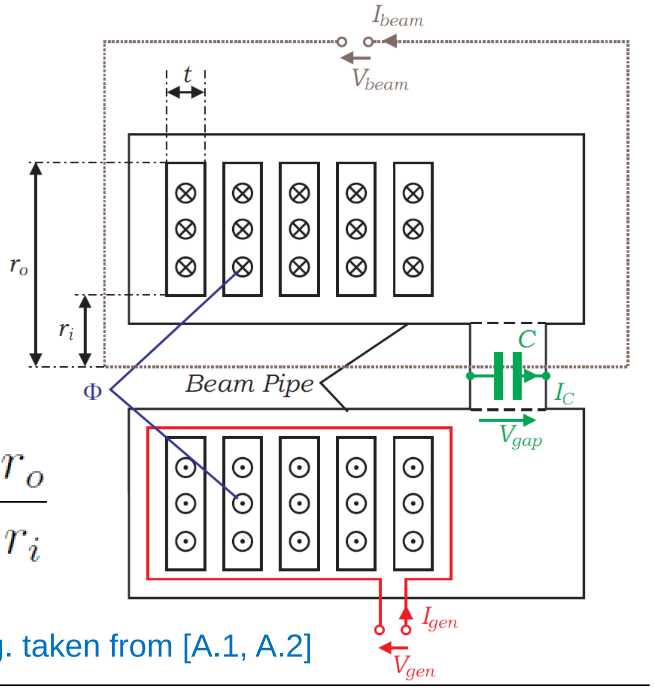


Fig. taken from [A.1, A.2]

Lumped Element Equivalent Circuit

This leads us to the following equivalent circuit:

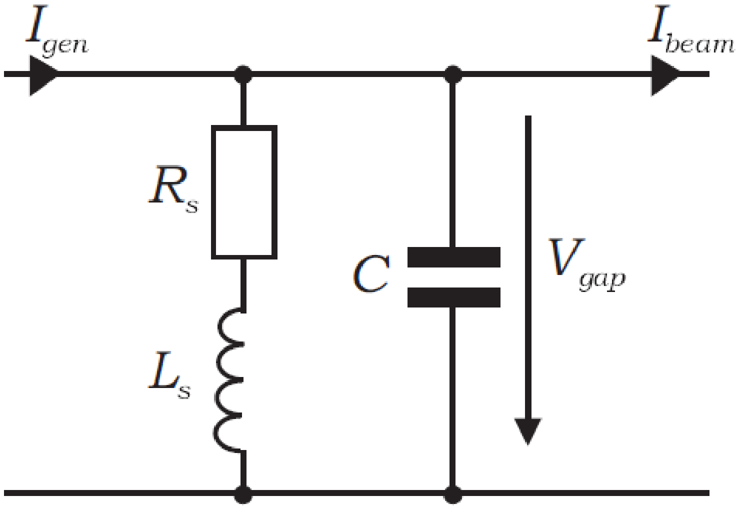


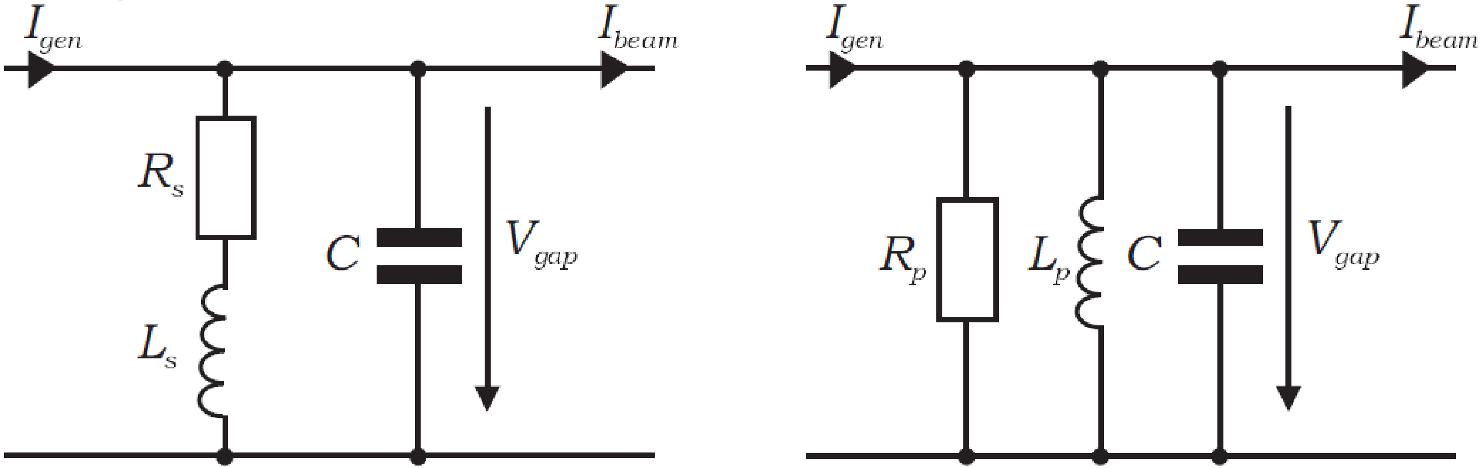
Fig. taken from [A.1, A.2]

$$\boxed{L_s = \frac{Nt\mu_s'}{2\pi}\, ln\frac{r_o}{r_i}}$$

$$\boxed{R_s = \omega\frac{Nt\mu_s''}{2\pi}\, ln\frac{r_o}{r_i} = \omega\frac{\mu_s''}{\mu_s'}L_s = \frac{\omega L_s}{Q}}$$

Equivalence of Series and Parallel Representation

In the vicinity of the resonant frequency (assuming constant circuit elements), the following circuits are equivalent:



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

Figures taken from [A.1, A.2]

Series and Parallel Lumped-Element Circuit

- Conversion formulas for impedance:

$$\boxed{\begin{aligned} R_p &= \frac{R_s^2 + (\omega L_s)^2}{R_s} \\ \omega L_p &= \frac{R_s^2 + (\omega L_s)^2}{\omega L_s} \end{aligned}}$$

- Realistic MA or ferrite material → L_s, R_s, L_p, R_p are frequency-dependent
- Frequency dependence of parameters is different if the two equivalent circuits shall be equivalent for all frequencies $f > 0$!
- Also complex permeability may be defined based on the parallel lumped-element circuit:

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

Series and Parallel Lumped-Element Circuit

- Conversion formulas:

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

- Realistic MA or ferrite material
  → μ'_s, μ''_s, μ'_p, μ''_p are frequency-dependent

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

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

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

- 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:

$$R_s = \omega \frac{N t \mu_s''}{2\pi} \, ln \frac{r_o}{r_i}$$

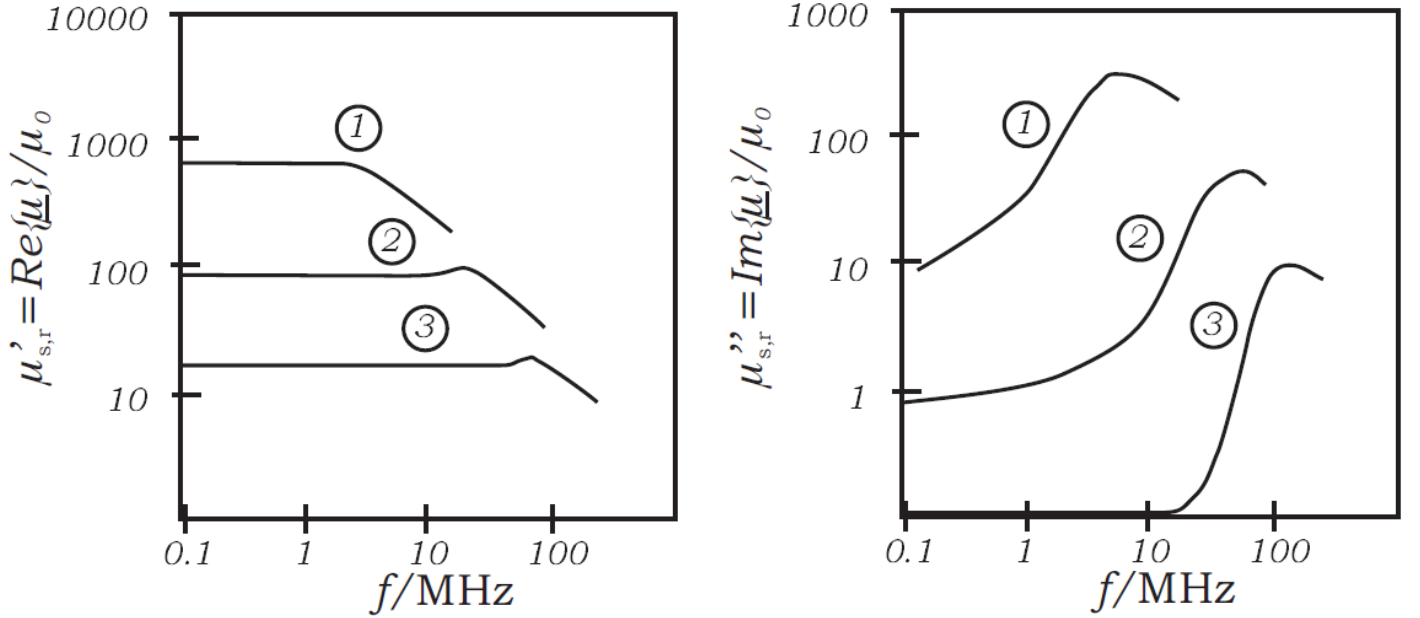
$$R_p = \omega \frac{N t \mu_p' Q}{2\pi} \, ln \frac{r_o}{r_i} = N t \underbrace{\mu_p' Q f}_{\mu_0 \mu_r Q f} \, ln \frac{r_o}{r_i}$$

Manufacturers of ferrite or MA ring cores often specify the $\mu_r Qf$ product.

R_p is often called 'shunt impedance' (this is the circuit definition which differs from the LINAC definition, cf. [1]!)

Ferrites: Behavior of the Permeability

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



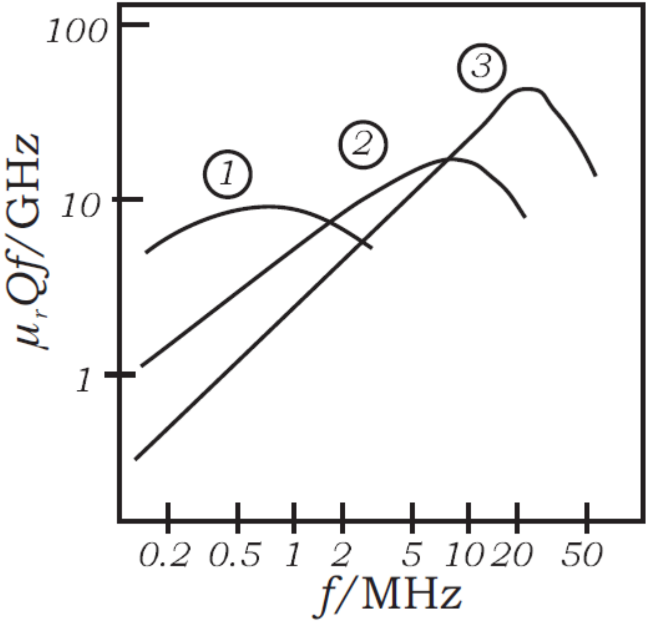
Data originally taken from [3],
Figures taken from [A.1, A.2]

Ferrites: Behavior of the Permeability

- Strong dependence on type of material
- Up to a certain frequency, $\mu'_s \approx \mu'_p$ remains constant
- Starting from 0 Hz, the Q factor decreases with frequency
  (for higher frequencies, the behavior may be more complicated)

Ferrites: Behavior of the Permeability

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



Data originally taken from [3],
Figures taken from [A.1, A.2]

Ferrites: Behavior of the Permeability

- When the magnetic RF field is increased, both Q and $\mu'_\mathrm{p}Qf$ will decrease (μ'_p increases, see hysteresis loop).
- Biasing leads to a shift of the $\mu'_\mathrm{p}Qf$ curve to the lower right side
- This may partly compensate the frequency dependence
  (assuming that the ferrite is tuned to the cavity resonance for all frequencies).

Cavity Description

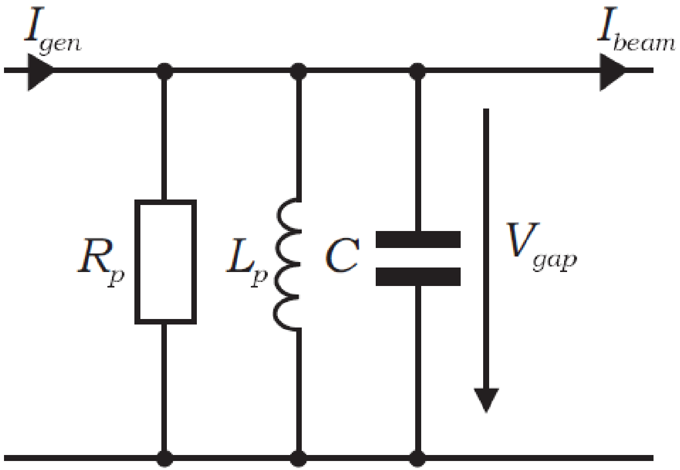


Fig. taken from [A.1, A.2]

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

(undamped natural frequency)

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

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

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

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

Cavity Time Constant, Cavity Filling Time

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

$$\boxed{\tau = 2R_pC}$$

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

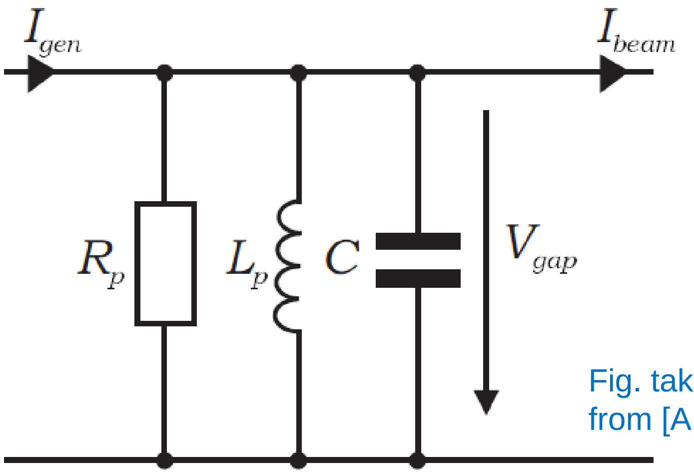
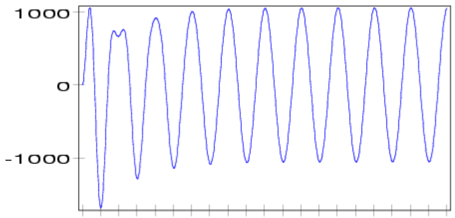
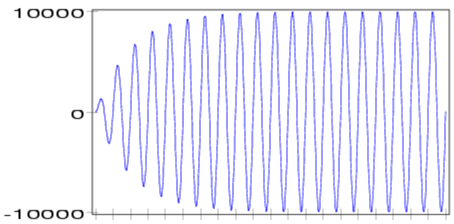


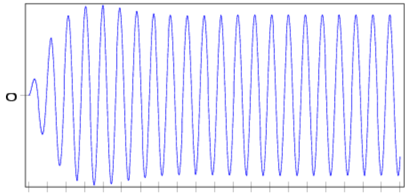
Fig. taken from [A.1, A.2]



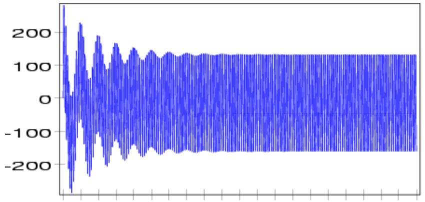
f=0.5 MHz



f=f_0=1 MHz



f=1.1 MHz



f=10 MHz

Length of the Cavity, Dimensions of the Cavity

- Example SIS18 Ferrite Cavity: At f =2.5 MHz: μ_r=28, $\varepsilon_{r,\mathrm{eff}}$=1.8 → λ=16.9 m
  64 ring cores with a thickness t=25 mm: l=1.6 m → l/λ=0.095 (34°)
- The ring core length is short in comparison with the wavelength inside the ferrite cross-section (justifying lumped-element model).
- One may also use a transmission line model of the cavity describing the ferrite sections as a homogeneously filled coaxial transmission line with a short-circuit at the end of the cavity.
  This explains the name 'shortened quarter-wavelength resonator‘
- In the SIS18 case only <10% deviation from the lumped element model
- Note: Unlike typical RF resonators, the exact dimensions of a ferrite- or MA-loaded cavity are not determined by the wavelength (e.g. the SIS18 cavity has a length of 3 m)
- Minimum distances (bias windings, gap, coupling, etc.) have to be kept to avoid high-voltage sparkovers
- The distances should not be too large to avoid resonances in the operating frequency range

Modeling/Measurement

- Further possibilities of analysis:
  - Describe all parts as lumped elements and perform circuit simulation (e.g. PSpice)
  - Full-wave simulation including lumped-element C (high computational cost, multi-scale problem)
- Note: Material properties at operating conditions are difficult to determine
  → usually larger influence than type of model
- Parameter tolerances due to manufacturing process have to be taken into account
- Thorough measurements under realistic operating conditions using a fixed setup are inevitable

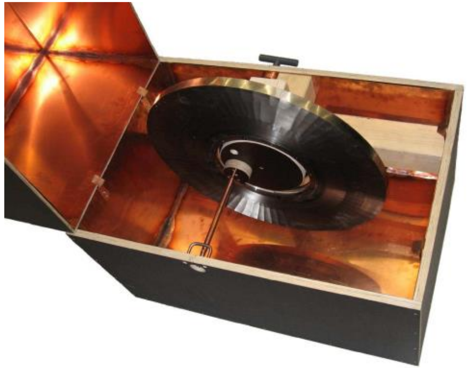
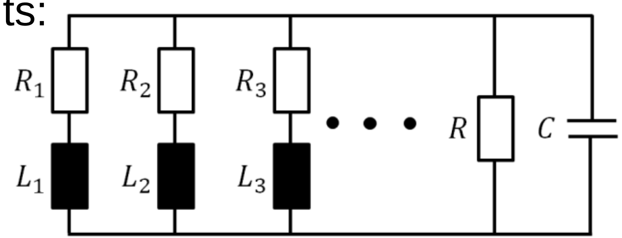
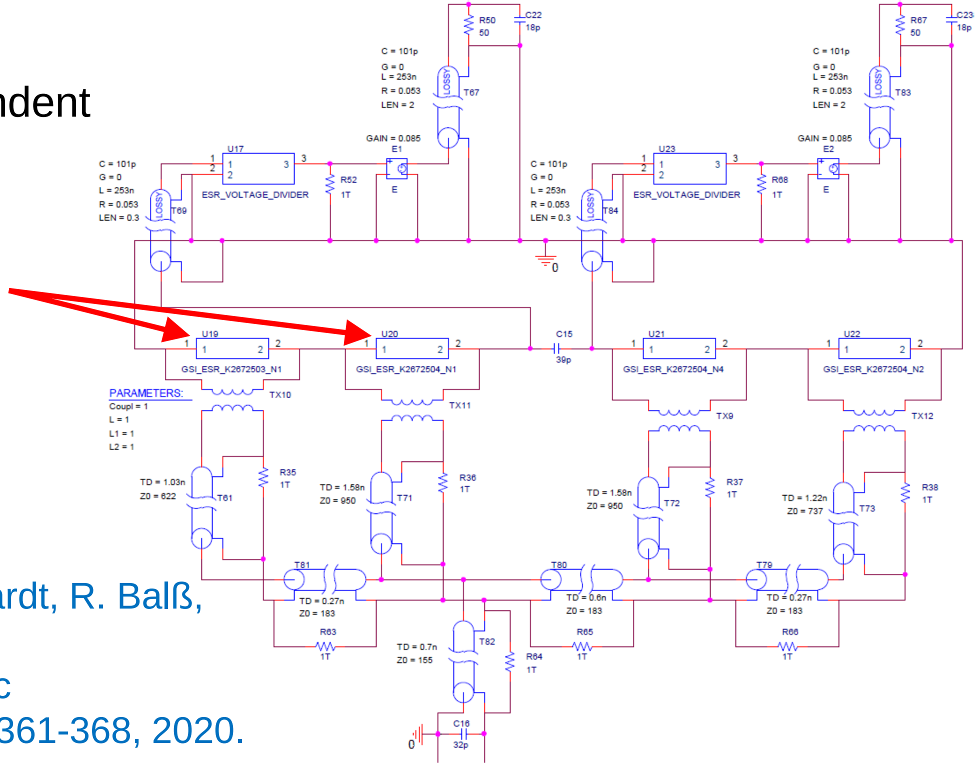


Fig. taken from: H. Klingbeil, J. Schweickhardt, R. Balß, M. Frey, P. Hülsmann: „Design Process for Synchrotron RF Cavities Loaded With Magnetic Ring Cores“, IEEE Trans. Nucl. Sc. 67 (1), pp. 361-368, 2020.

Modeling/Measurement

- Each ring core can be modeled by an equivalent circuit with frequency-independent elements:



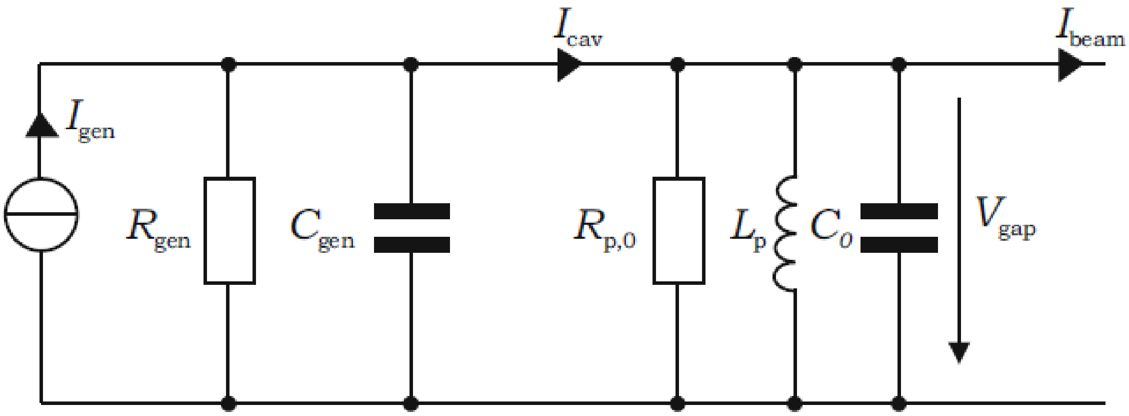


- This allows us to simulate the full cavity as a PSpice model…

Figures taken from: H. Klingbeil, J. Schweickhardt, R. Balß, M. Frey, P. Hülsmann: „Design Process for Synchrotron RF Cavities Loaded With Magnetic Ring Cores“, IEEE Trans. Nucl. Sc. 67 (1), pp. 361-368, 2020.

RF Power Amplifier

- 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



Taken from [A.2]

RF Power Amplifier, Cooling

- 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. Water cooling may be realized by cooling disks in-between the ring cores (requires good thermal contact).

Cavity Tuning

- Capacitive tuning
  - e.g. variable capacitor with stepping motor
  - usually only suitable for sporadic/slow changes
- Bias current tuning
  - Parallel biasing
    - Simple (similar to inductive coupling loop) and effective
    - Q-loss (high loss) effect may be observed
  - Perpendicular biasing
    - Q-loss effect was not observed
    - Low losses may be reached for microwave garnet ferrites in the operating range 40...60 MHz

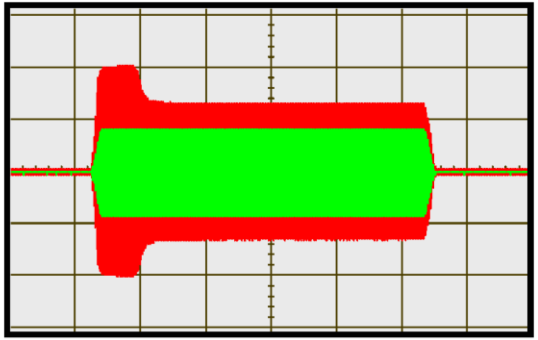


Fig. taken from: K. Kaspar, H.-G. Koenig, Th. Winnefeld: STUDIES ON MAXIMUM RF VOLTAGES IN FERRITE-TUNED ACCELERATING CAVITIES, EPAC 2004.

Cavity Tuning

An average field may be defined for the description of biasing (quasi-DC):

$$H_{bias} = \frac{N_{bias} I_{bias}}{2\pi \bar{r}} \qquad \bar{r} = \sqrt{r_i r_o}$$

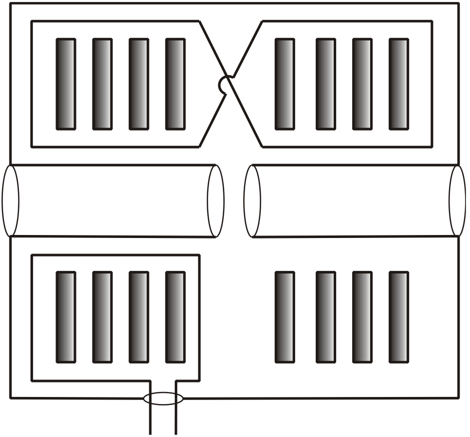
More bias windings: Less current, more symmetry, but danger of resonances and slower bias current changes (higher inductance)

Further Complications

- Problems mentioned before:
  - Permeability depends on history of biasing and RF currents
  - Range between lumped elements and distributed elements
  - Anomalous loss effects (Q loss and dynamic loss effect)
- Further complications:
  - H_{bias} shows an r^{-1} dependence. Therefore, biasing is more effective in the inner region. Therefore, μ_Δ increases with r. The magnetic RF B-field will therefore show a weaker dependence on r.
  - Maximum ratings of the material must not be exceeded, especially $B_{\mathrm{rf,max}}$
  - Permeability depends not only on frequency, RF field, and biasing but also on temperature
  - Depending on the ferrite material and the operating frequency, the fields may decay from the ring core surface to the inner regions reducing the effective volume (e.g. MnZn ferrites)
  - At high bias currents, stray fields may be significant

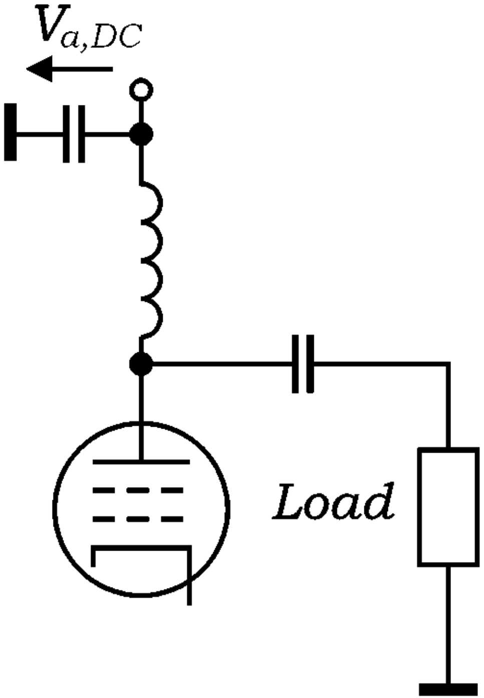
Different Cavity Configurations

- 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 ring core 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 ring core 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)



Different Cavity Configurations

- Capacitive coupling instead of inductive coupling.
  High-voltage supply of tetrodes requires choke coil.
- Combined capacitive/inductive coupling
  e.g. to influence parasitic resonances
- Individual ring core coupling may allow 50 Ω impedance
  matching (standard solid-state RF power amplifier).
- External tuners for small relative frequency modification



Example: SIS18 Ferrite Cavity at GSI

Photography: GSI Helmholtzzentrum für Schwerionenforschung GmbH, T. Winnefeld

Example: SIS18 Ferrite Cavity at GSI

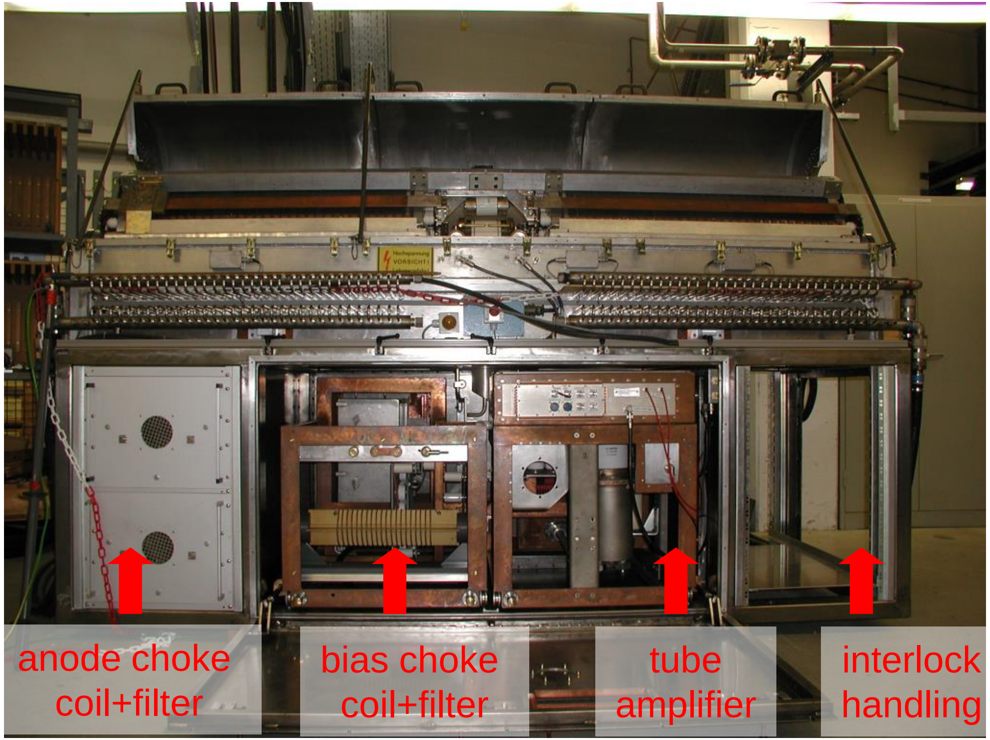


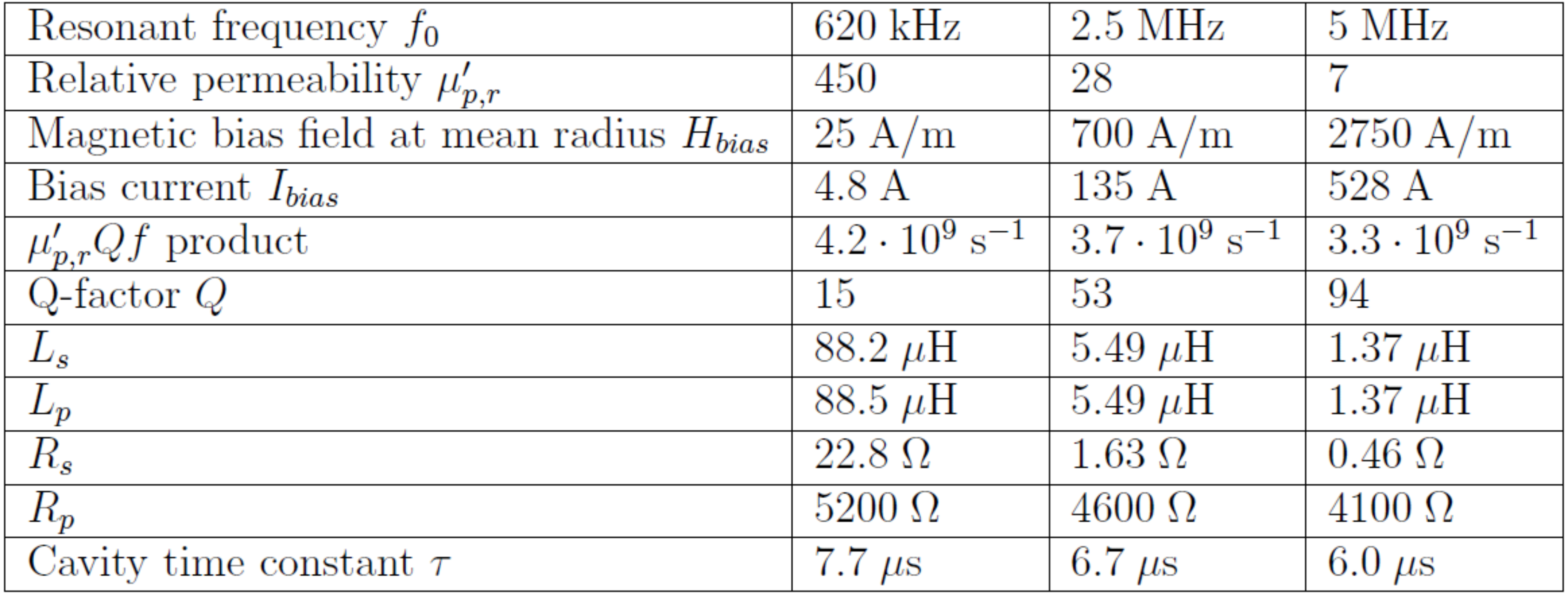
Fig. taken from [A.1, A.2],
Photography: GSI Helmholtzzentrum für Schwerionenforschung GmbH,
T. Winnefeld

Example: SIS18 Ferrite Cavity at GSI

- 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
- Large frequency range from 800 kHz to 5.4 MHz

Example: SIS18 Ferrite Cavity at GSI

Some realistic parameters (cavity without power amplifier):

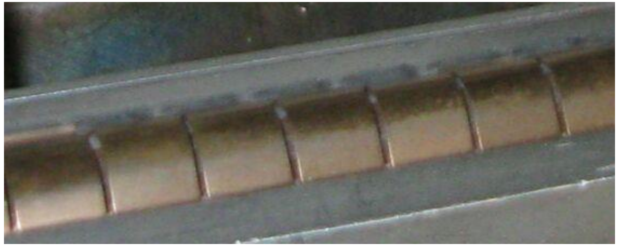


Resonant frequency f_0	620 kHz	2.5 MHz	5 MHz
Relative permeability $\mu'_{p,r}$	450	28	7
Magnetic bias field at mean radius H_{bias}	25 A/m	700 A/m	2750 A/m
Bias current I_{bias}	4.8 A	135 A	528 A
$\mu'_{p,r}Qf$ product	$4.2 \cdot 10^9\ \mathrm{s}^{-1}$	$3.7 \cdot 10^9\ \mathrm{s}^{-1}$	$3.3 \cdot 10^9\ \mathrm{s}^{-1}$
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

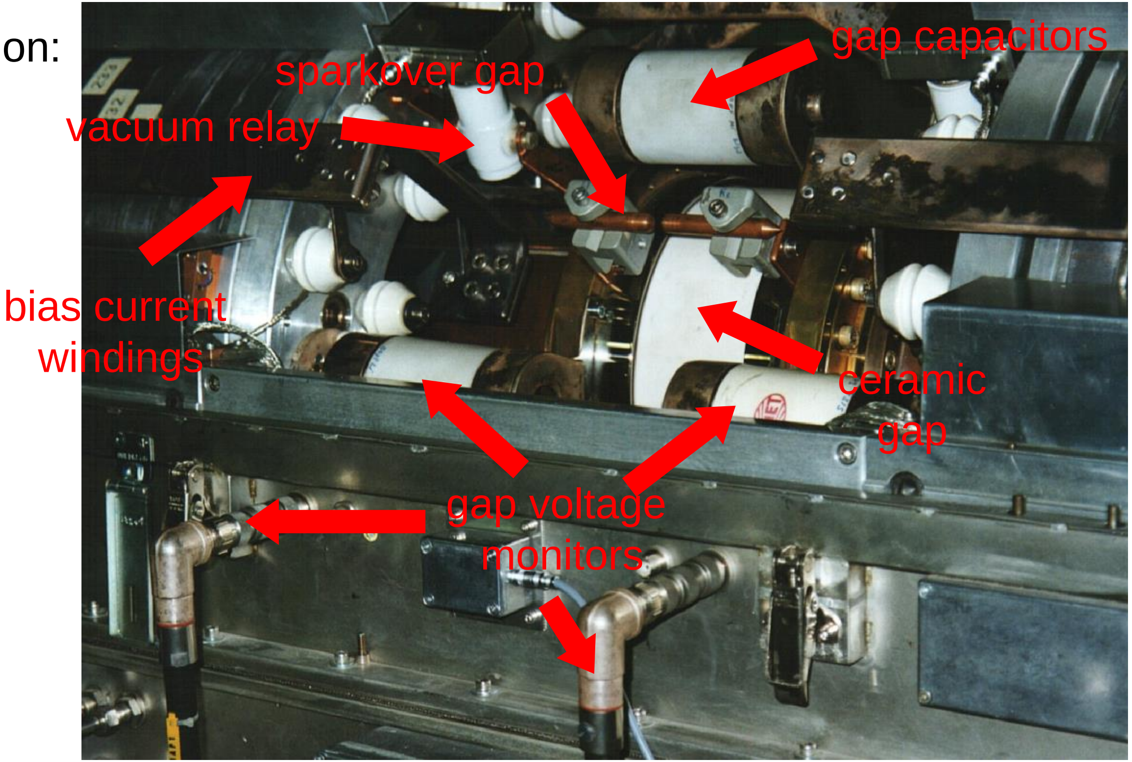


Photography: GSI Helmholtzzentrum für Schwerionenforschung GmbH, T. Winnefeld

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

SIS18 Ferrite Cavity

Gap region:



Photography: GSI Helmholtzzentrum für Schwerionenforschung GmbH, T. Winnefeld

Some Magnetic Materials

- Nickel-Zinc (NiZn) ferrites may be regarded as the traditional standard for ferrite-loaded cavities
- At least the following parameters should be considered:
  - Permeability under all operating conditions
  - Magnetic losses
  - Saturation induction (typically 200...300 mT for NiZn ferrites)
  - Maximum RF inductions of 10...20 mT (limited by power and/or Q loss effect)
  - Dielectric constant (10...15 for NiZn, large for MnZn) and dielectric losses (negligible for NiZn)
  - Maximum operating temperature, temperature dependence
  - Magnetostriction
  - Specific resistivity (very high for NiZn, very low for MnZn leading to high eddy current losses)

Some Magnetic Materials

- Amorphous and nanocrystalline metallic alloy (MA) materials are used for very compact low-frequency cavities (higher induction is possible, lower Q factor
  → lower number of ring cores, but higher power loss for the same voltage),
  arbitrary RF waveforms are possible due to low Q
- Ring cores may be cut in order to increase Q and decrease the effective permeability allowing higher operating frequencies

From: P. Hülsmann, O. Boine-Frankenheim, H. Klingbeil, G. Schreiber: Considerations Concerning the RF System of the Accelerator Chain SIS12/18 - SIS100 for the FAIR-Project at GSI.

Some Magnetic Materials for RF Purposes (100 kHz…10 MHz)

	Max. Initial permeability	Conductivity $\kappa / \mathrm{Sm}^{-1}$	B_{sat}/T	H_c/Am^{-1}
NiZn ferrite (base: $Ni_xZn_{(1-x)}Fe_2O_4$)	1500	$10^{-6}…10^{-4}$	0.2…0.5	20…200
MnZn ferrite (base: $Mn_xZn_{(1-x)}Fe_2O_4$)	15000	0.05…10	0.2…0.5	5…20
Magnetic Alloys (tape-wound cores)	$\sim 10^5$	$\sim 10^6$ [but: insulation between layers]	0.5…1.6	0.3…3

↑ Range depends on specific material

The data given here only represent typical values, no absolute limits! They are based on [2] (but not identical) and further references.

Rough Description of Ring Core Manufacturing Process

Ferrite	MA Ring Core
• Preparation of metal oxide powder • Milling to small grain sizes • Pressing • Sintering (>900°C) • Machining/finishing	• Melting of metal • Nozzle to dispose material on a cooled rotating wheel („planar flow casting“) → tape/ribbon • Insulation coating • Winding of ribbon • Annealing (>300°C) – sometimes with magnetic field • Coating/wrapping/impregnation

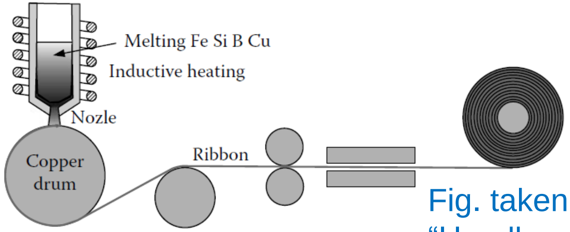


FIGURE 3.40
Technology of the amorphous ribbon production.

Fig. taken from S. Tumanski: “Handbook of Magnetic Measurements”, CRC Press, 2011. p. 135

Example for MA Cavity: SIS18 h=2 System

SIS18 h=2 cavities
(tetrode power amplifiers on top)

Here, we benefit from…

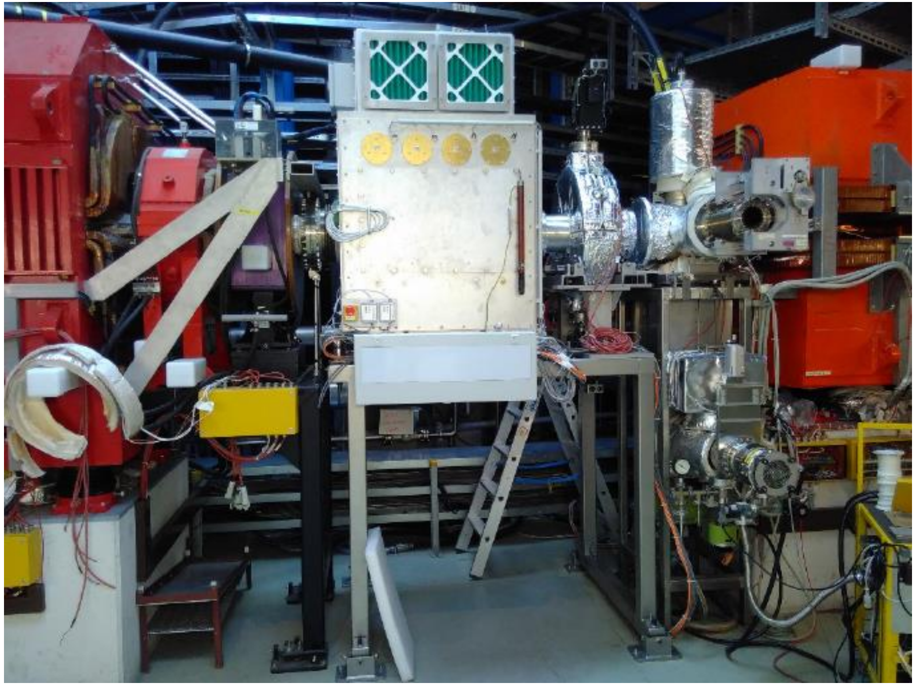
- …the large B_{RF} tolerable by the MA ring cores (up to 50 kV in 3.6 m)
- …the low Q<1 (untuned cavities, operating range 400kHz…2.7 MHz)

Concept and project management:
Priv.-Doz. Dr. Peter Hülsmann,
Robert Balß

Photographies: GSI Helmholtzzentrum
für Schwerionenforschung GmbH,
G. Otto

Platform for SIS18 h=2 power supplies (2nd floor), mains distribution (1st floor), and oil cooling system (ground floor)

Example for MA Cavity:
ESR Barrier-Bucket System



Here, we benefit from the linearity and the broadband behavior of the MA ring cores…

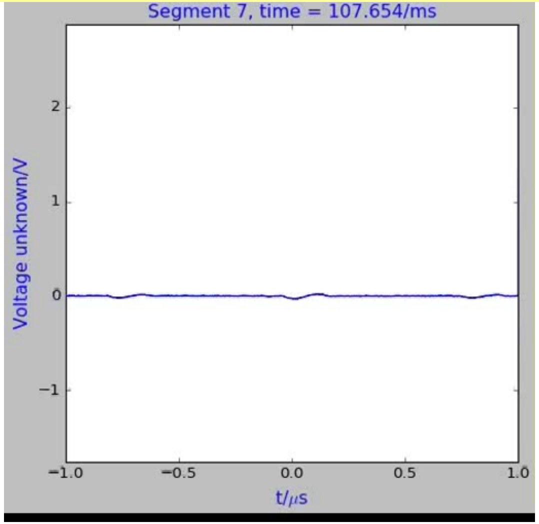
Concept and project management:
Michael Frey

Photography: GSI Helmholtzzentrum für Schwerionenforschung GmbH, M. Frey

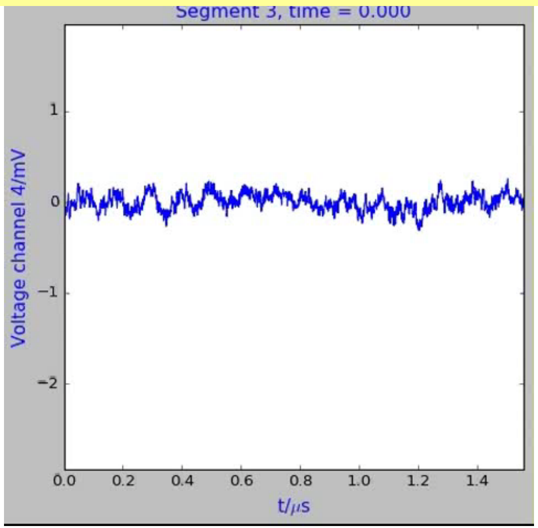
Example for MA Cavity:
ESR Barrier-Bucket System

Measurement results of machine development experiment (MDE) dated April 11th, 2019 ($^{56}Fe^{25+}$, 120 MeV/u, $3 \cdot 10^7$ Ions per Cycle)

Sum of two gap voltages



Beam signal (low-frequency components removed)



Contributors:
D. Bast, M. Frey,
H. Klingbeil, U. Laier,
D. Lens, D. Penza,
J. Schweickhardt, A. Stuhl,
G. Thomin, B. Zipfel

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[1] F. Gerigk: “RF Basics I and II”, Proceedings CAS - CERN Accelerator School: Course on High Power Hadron Machines, Bilbao, Spain, 24 May - 2 Jun 2011, 71-116

[2] M. Coey and S.S.P. Parkin (editors): “Handbook of Magnetism and Magnetic Materials”, Springer, 2021.

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

This presentation is based on the following previous publications:

[A.1] H. Klingbeil: “Ferrite cavities”, in CAS - CERN Accelerator School: RF for Accelerators, Ebeltoft, 8–17 Jun 2010, CERN Report CERN-2011-007, pp. 299–317, CC BY 3.0 Attribution License

[A.2] H. Klingbeil, U. Laier, D. Lens: “Theoretical Foundations of Synchrotron and Storage Ring RF Systems”, Springer, 2015 (open access since 2022: https://library.oapen.org/handle/20.500.12657/57000)

(for further literature references, please see proceedings)

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Magnetic Alloy/Ferrite Cavities

Thank you very much
for your attention!