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CERN Accelerator School – Ferrite Cavities

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Contents

- Usage of Ferrite Cavities
- Magnetic properties, hysteresis
- Simplified ferrite cavity model
- Lumped-element circuits
- Cavity parameters
- Amplifier considerations
- Cavity configurations
- Example: SIS18 ferrite cavity
- Magnetic materials

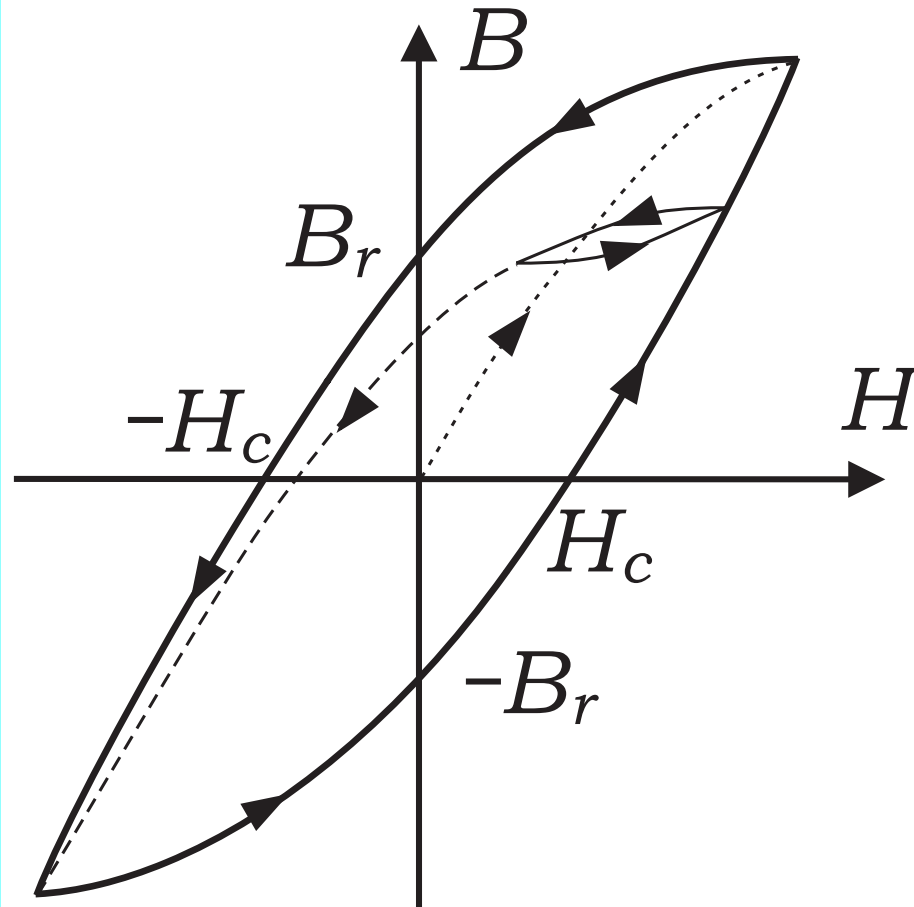


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Usage of Ferrite Cavities

- 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 $>30\text{m}$
 - conventional RF resonator (e.g. pillbox cavity) not possible
- Reduction of wavelength is possible by magnetic materials → idea of ferrite 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 are not strict)

Bias current $\rightarrow H_{bias} \rightarrow$
 modification of
 incremental/differential
 permeability:

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

H_c : coercive magnetizing field

B_r : residual induction

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:

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

Ferrite Cavity – Main Components

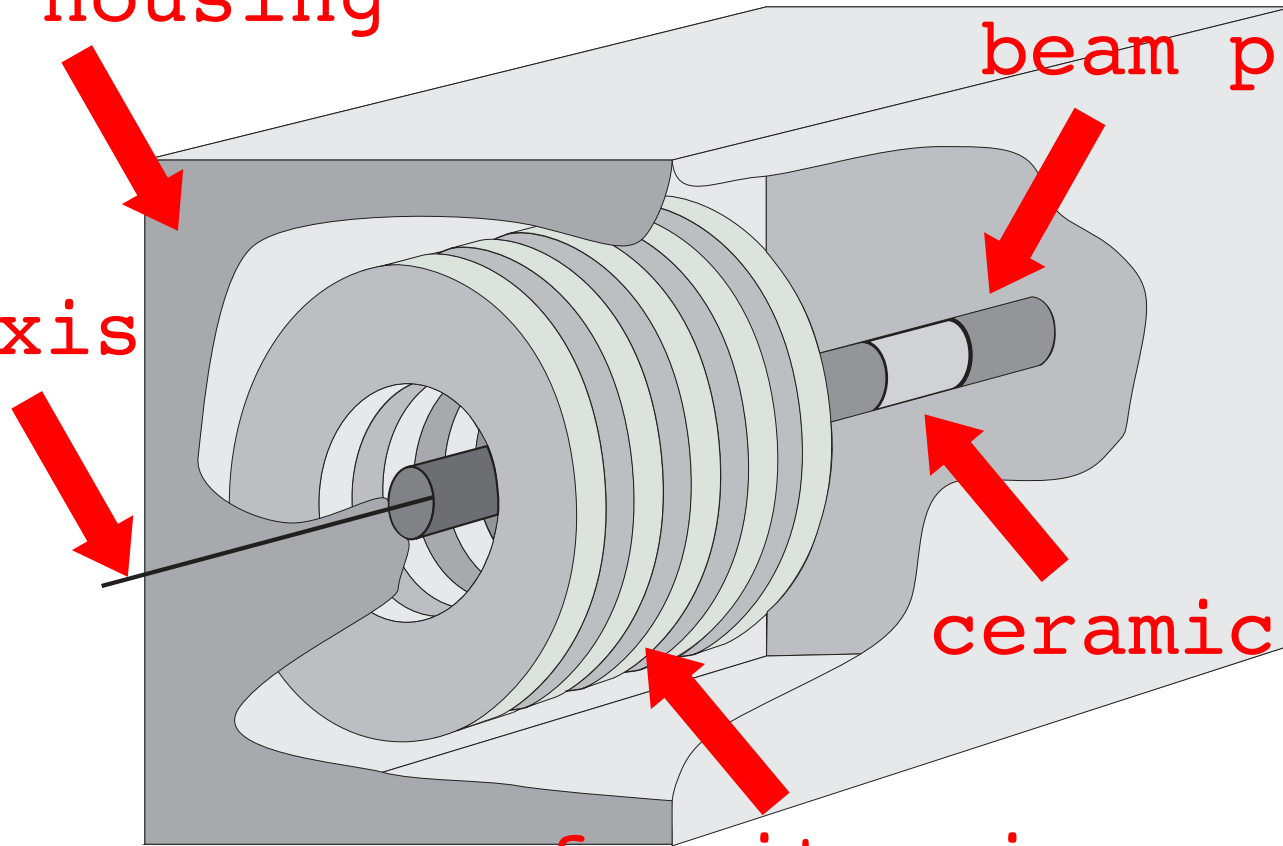
cavity housing

beam pipe

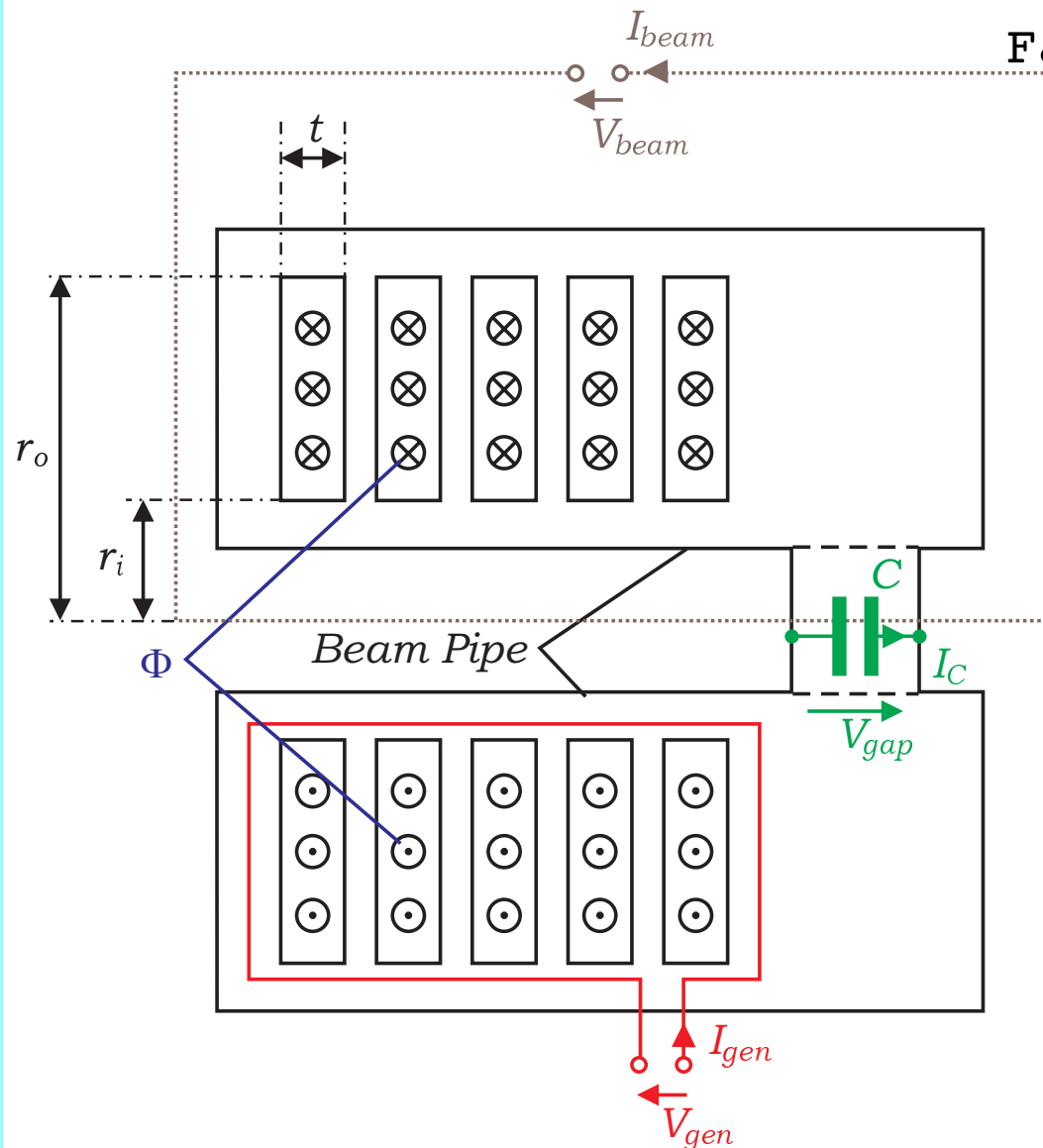
beam axis

ceramic gap

ferrite ring cores



Simplified Ferrite Cavity Model



Faraday's law of induction:

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

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

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

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

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

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

Simplified Ferrite Cavity Model

Now we have to determine the magnetic flux:

Ampère's law:
$$\oint_{\partial S} \vec{H} \cdot d\vec{l} = \int_S \vec{J} \cdot d\vec{S}$$

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

Flux through one ring core:

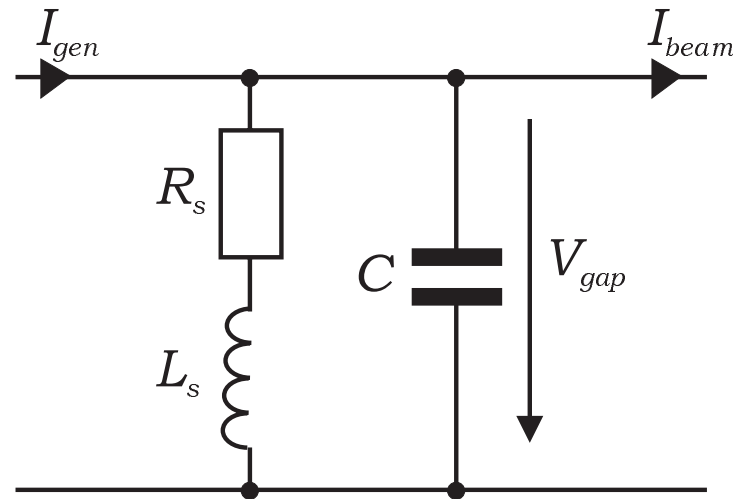
$$\Phi_1 = \int \vec{B} \cdot d\vec{S} = t \int_{r_i}^{r_o} B dr = \frac{t\mu I_{tot}}{2\pi} \ln \frac{r_o}{r_i}$$

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

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

Lumped Element Circuit

This leads us to the following equivalent circuit:

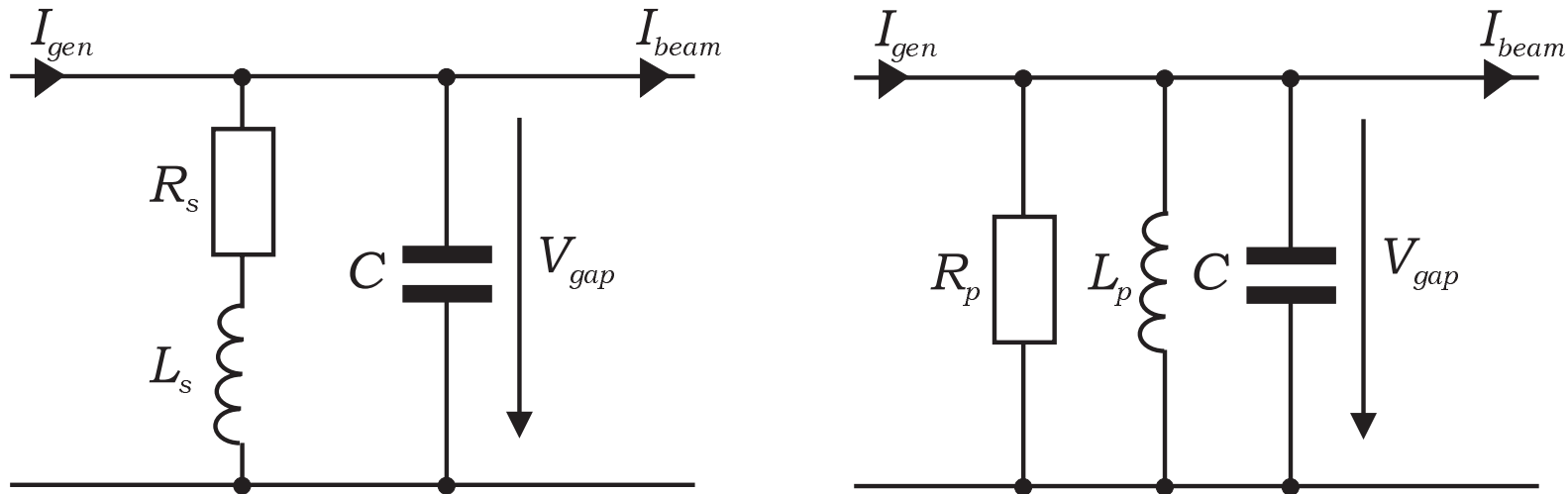


$$L_s = \frac{Nt\mu'_s}{2\pi} \ln \frac{r_o}{r_i}$$

$$R_s = \omega \frac{Nt\mu''_s}{2\pi} \ln \frac{r_o}{r_i} = \omega \frac{\mu''_s}{\mu'_s} L_s = \frac{\omega L_s}{Q}$$

Equivalence of Series and Parallel Representation

In the vicinity of the resonant frequency, 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:

$$\mu'_p = \mu'_s \left(1 + \frac{1}{Q^2} \right)$$

$$\mu''_p = \mu''_s (1 + Q^2)$$

$$R_p = R_s (1 + Q^2)$$

$$L_p = L_s \left(1 + \frac{1}{Q^2} \right).$$

Approximation for $Q > 5$:

$$R_p \approx R_s Q^2, \quad L_p \approx L_s, \quad \mu'_p \approx \mu'_s, \quad \mu''_p \approx \mu''_s Q^2$$

$\mu_r Qf$ Product

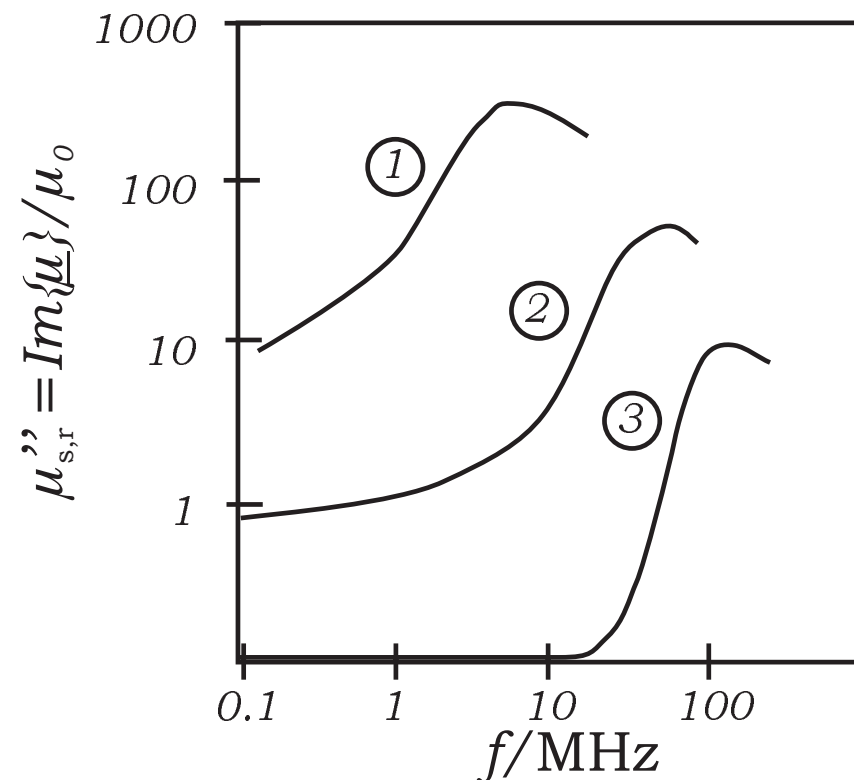
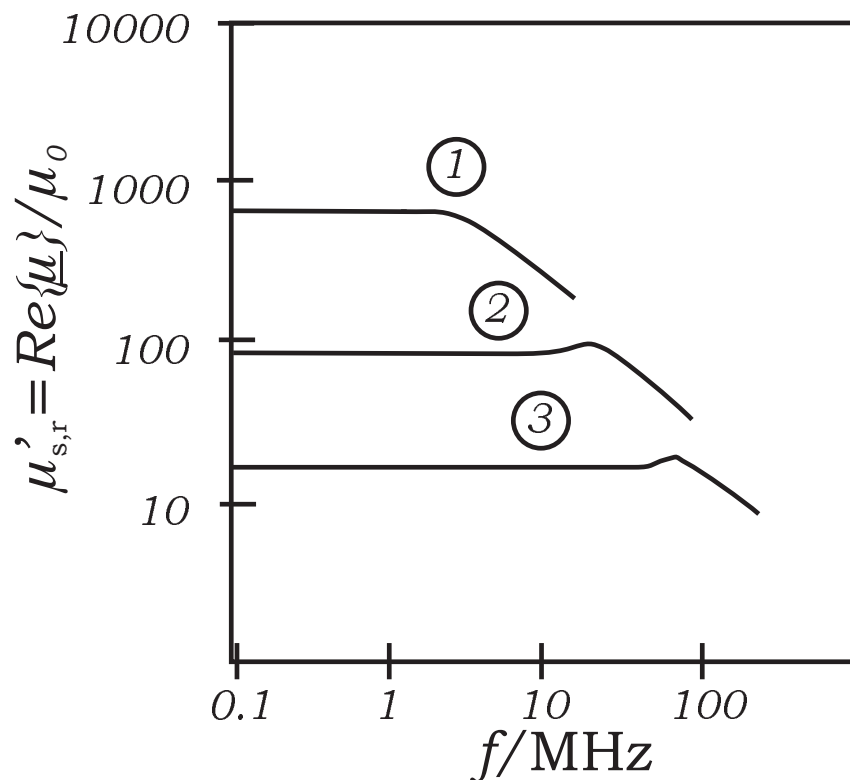
Using these formulas we get:

$$R_p = \omega \frac{Nt\mu'_p Q}{2\pi} \ln \frac{r_o}{r_i} = Nt \underbrace{\mu'_p Q f}_{\mu_0 \mu_r Qf} \ln \frac{r_o}{r_i}$$

Ferrite manufacturers often specify the $\mu_r Qf$ 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. Louwarse: Ferroxcube für Protonensynchrotrons, Philips Technische Rundschau 30, pp. 323-342, 1969/70.



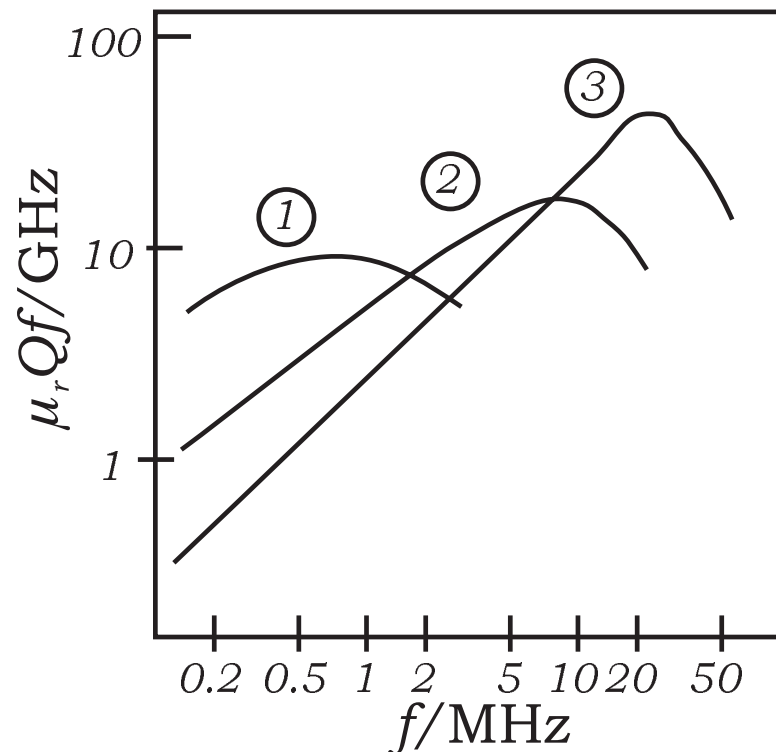
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Behavior of the Permeability

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

SIS18 Ferrite Cavity

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



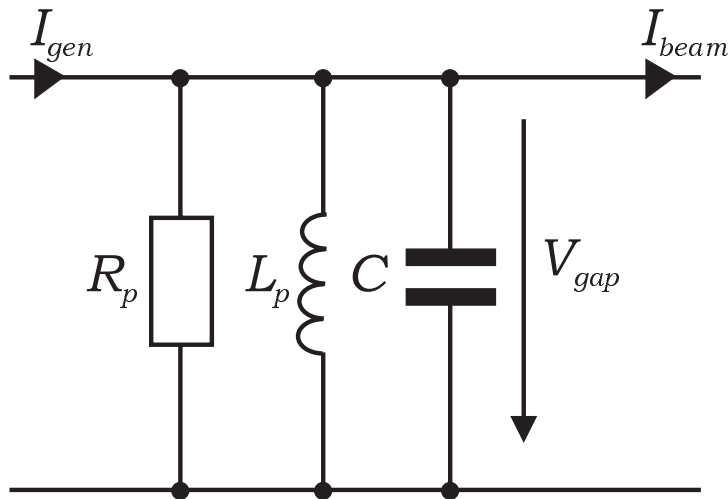
Source: F. G. Brockman, H. van der Heide, M. W. Louwerson: Ferroxcube für Protonensynchrotrons, Philips Technische Rundschau 30, pp. 323-342, 1969/70.

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Behavior of the Permeability

- When the magnetic field is increased, both Q and $\mu'_p Qf$ will decrease (μ'_p increases, see hysteresis loop).
- Biasing leads to a shift of the $\mu'_p Qf$ 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



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

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

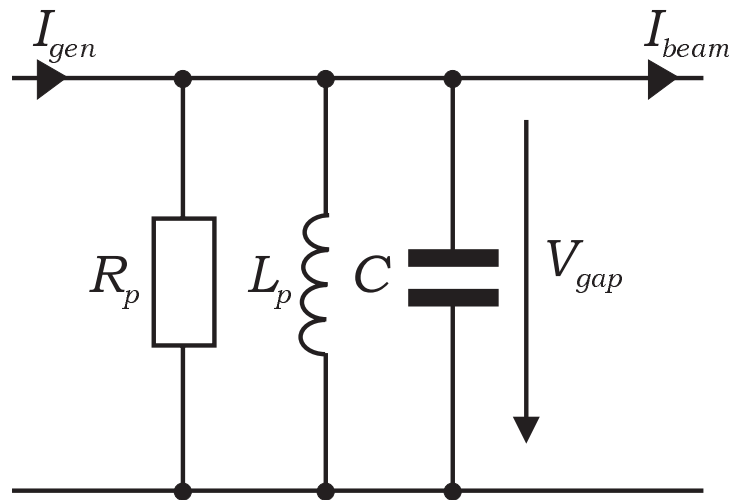
$$Q_0 = R_p \sqrt{\frac{C}{L_p}}$$

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

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

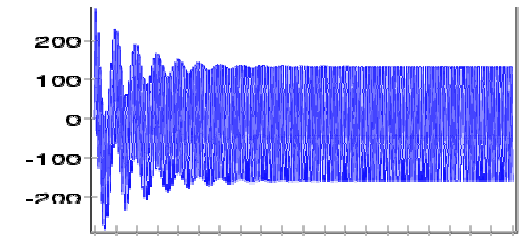
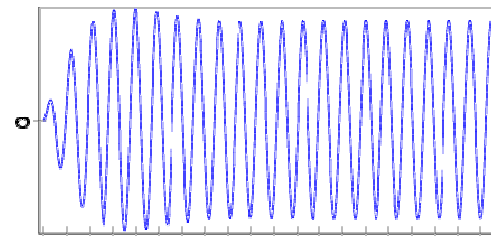
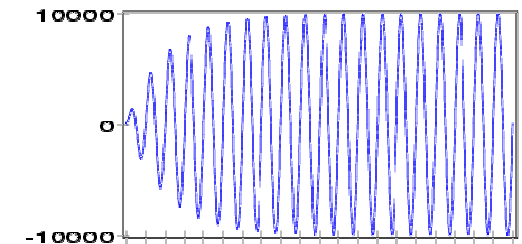
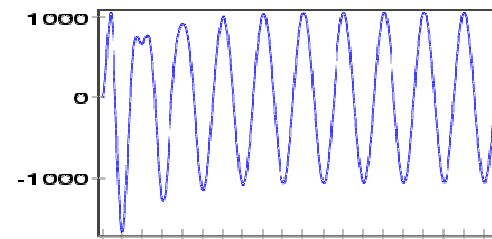
Cavity Time Constant, Cavity Filling Time

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



$$\tau = 2R_p C$$

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



Length of the Cavity

- Example SIS18 Ferrite Cavity: At $f=2.5$ MHz: $\mu_r=28$,
 $\varepsilon_{r,eff}=1.8 \rightarrow \lambda=16.9$ m
64 ring cores with a thickness $t=25$ mm: $l=1.6$ m
 $\rightarrow l/\lambda=0.095$ (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



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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
- Note: Material properties at operating conditions are difficult to determine
 - usually larger influence than type of model
- Thorough measurements under realistic operating conditions using a fixed setup are inevitable
- Parameter tolerances due to manufacturing process have to be taken into account



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Length of the Cavity

- Note: Unlike typical RF resonators, the exact length of a ferrite-loaded cavity is not determined by the wavelength (e.g. the SIS18 cavity has a length of 3 m)
- Minimum distances have to be kept to avoid high-voltage sparkovers
- The distances should not be too large to avoid resonances in the operating frequency range



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RF Power Amplifier

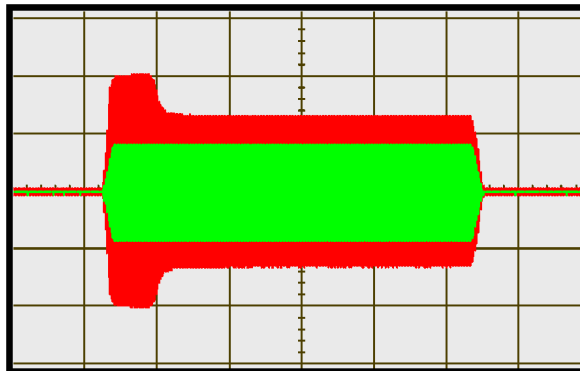
- Up to now, we only dealt with the 'unloaded Q' factor of the cavity
- RF power amplifier may often be described as a voltage-controlled current source
- The impedance of this source reduces R_p
- This leads to the 'loaded Q' factor

RF Power Amplifier, Cooling

- 50Ω 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 $>100^\circ\text{C}$).
- 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).

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



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

- Perpendicular biasing
 - Q-loss effect was not observed
 - Low losses may be reached for microwave garnet ferrites in the operating range 40...60 MHz



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Cavity Tuning

An average field may be defined for the description of biasing:

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

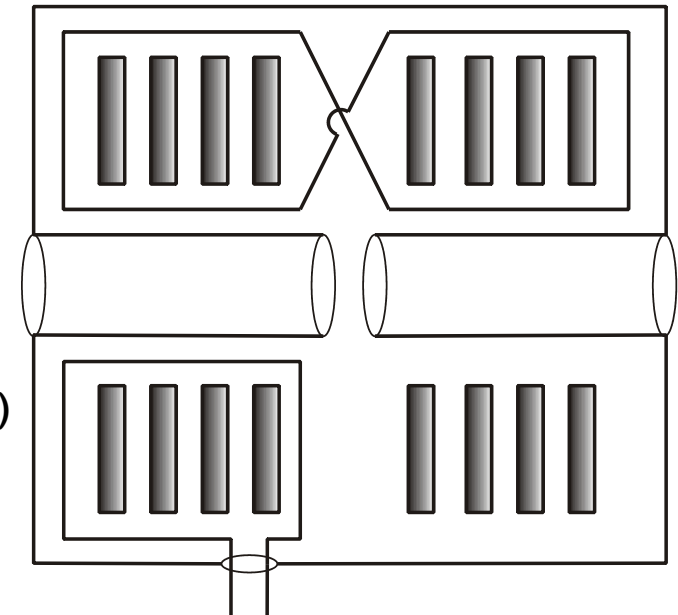
More bias windings: Less current, more symmetry, but danger of resonances and slower bias current changes

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. 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 $B_{rf,max}$
 - 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 surface to the inner regions reducing the effective volume (e.g. MnZn ferrites)
 - At high bias currents, stray fields may be significant

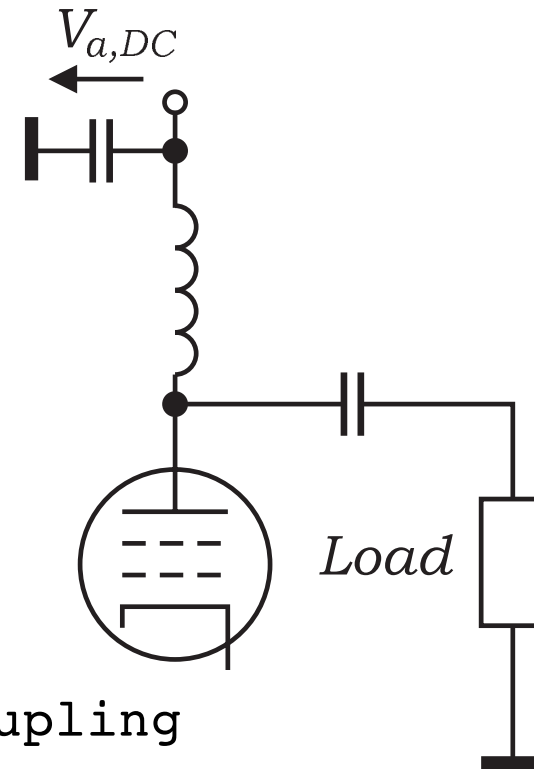
Different Cavity Configurations

- 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 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)



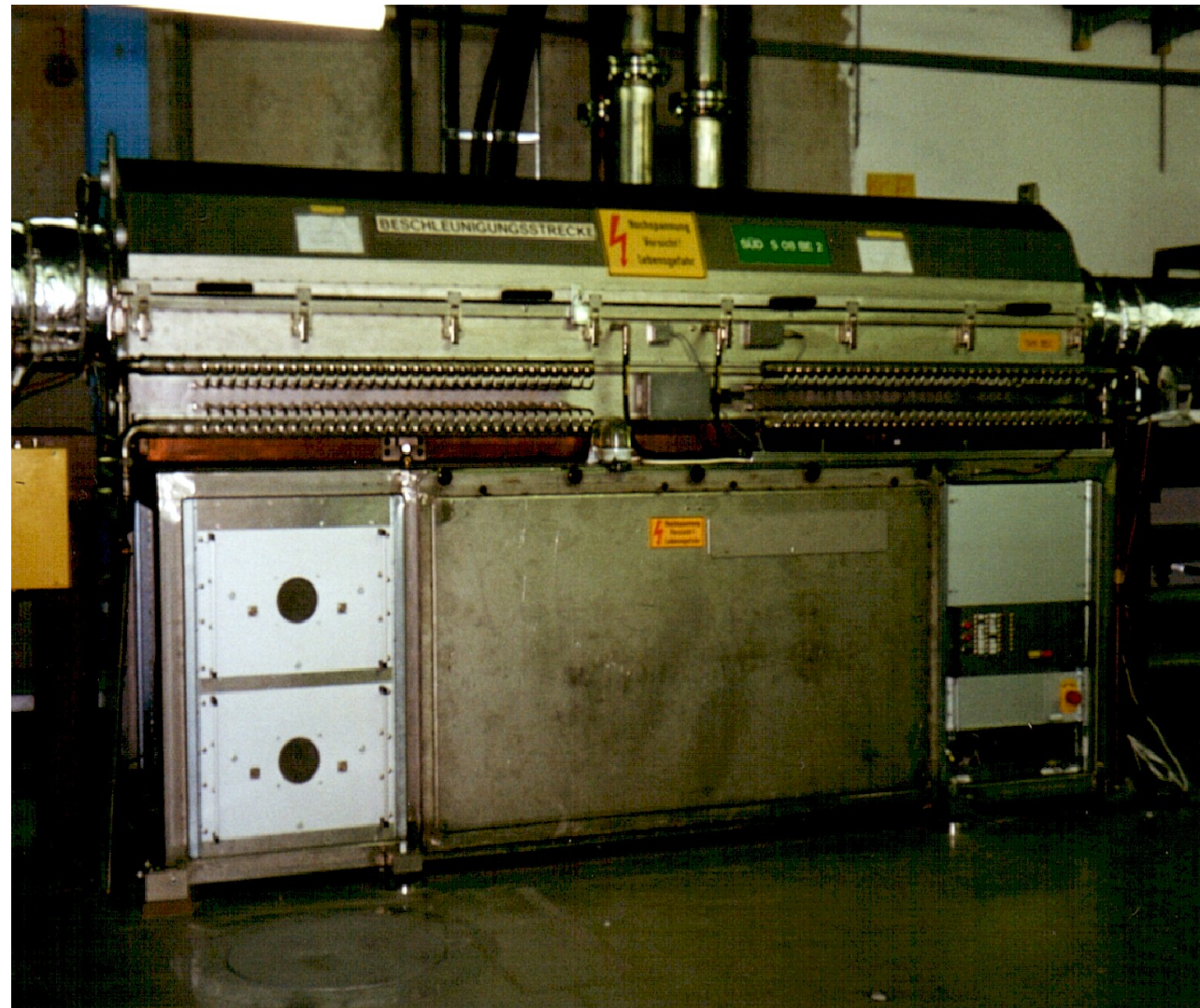
Different Cavity Configurations

- Capacitive coupling instead of inductive coupling. High-voltage supply of tetrodes requires choke coil.

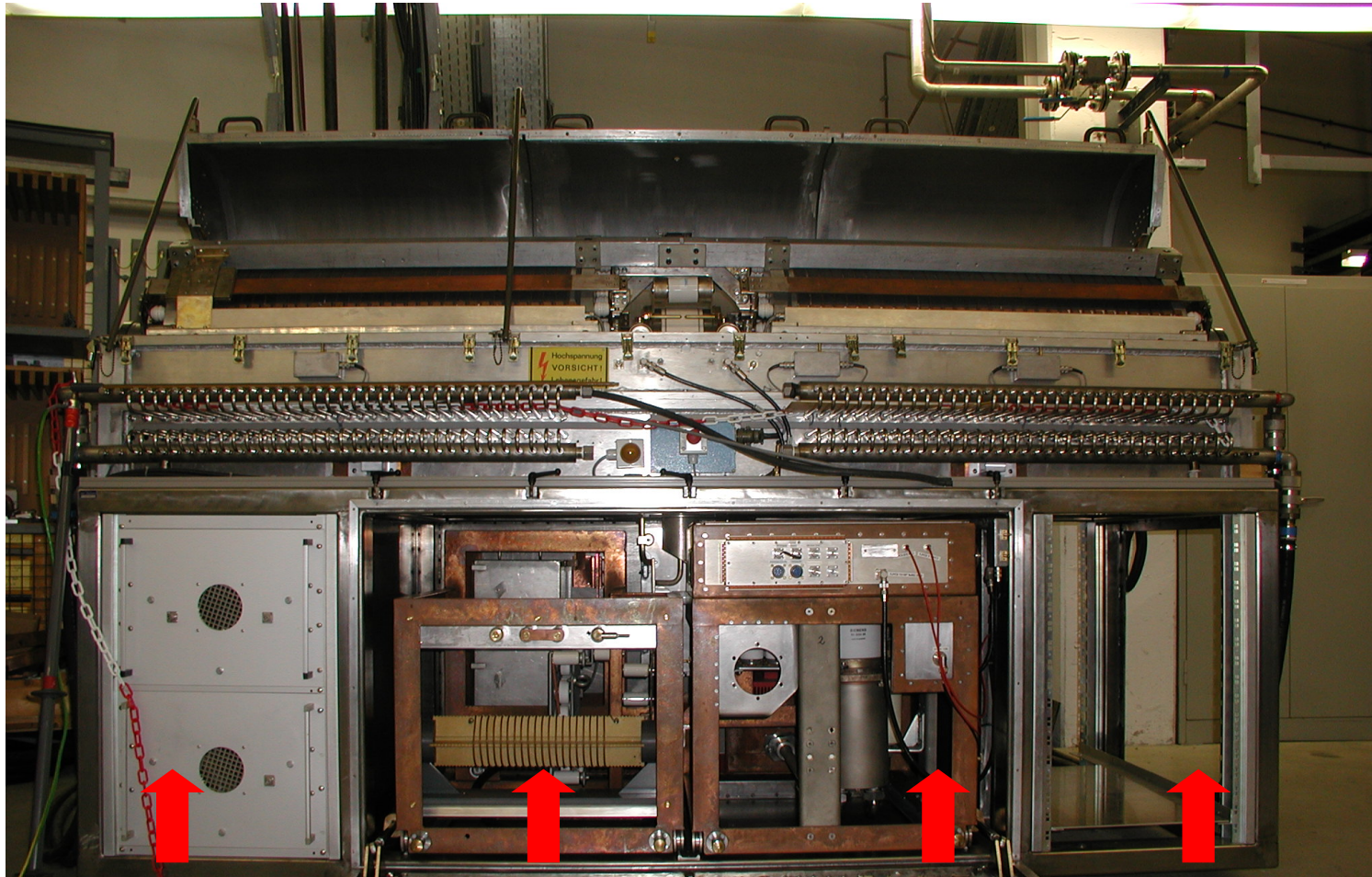


- Combined capacitive/inductive coupling e.g. to influence parasitic resonances
- Individual ring core coupling may allow 50Ω impedance matching (standard solid-state RF power amplifier).
- External tuners for small relative frequency modification

Example: SIS18 Ferrite Cavity at GSI



Example: SIS18 Ferrite Cavity at GSI



anode choke
coil+filter

bias choke
coil+filter

tube
amplifier

interlock
handling



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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

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
$\mu'_{p,r} Q f$ product	$4.2 \cdot 10^9 \text{ s}^{-1}$	$3.7 \cdot 10^9 \text{ s}^{-1}$	$3.3 \cdot 10^9 \text{ s}^{-1}$
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:

gap capacitors

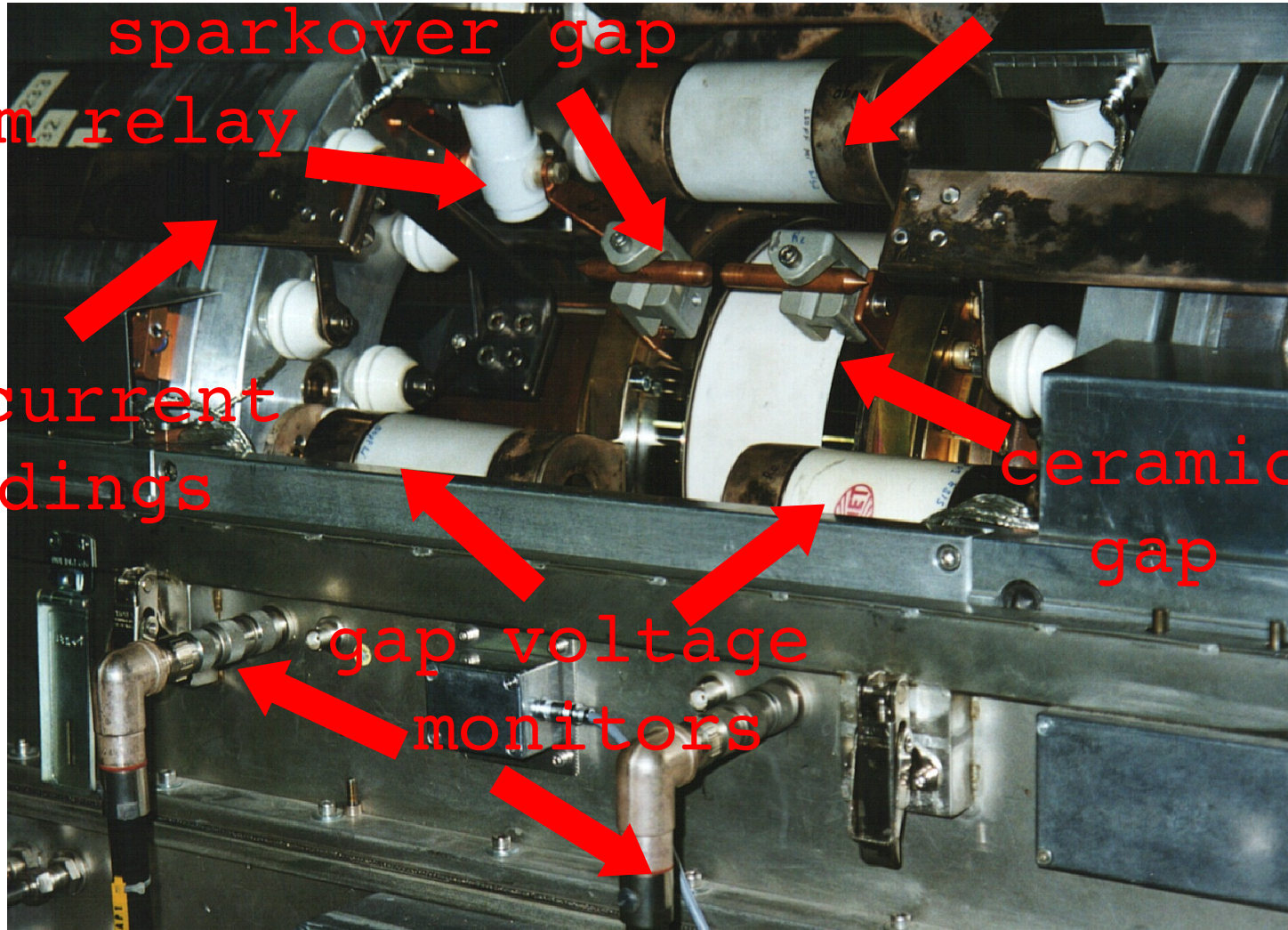
sparkover gap

vacuum relay

bias current
windings

ceramic
gap

gap voltage
monitors



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) and dielectric losses (negligible for NiZn)
 - Maximum operating temperature, temperature dependence
 - Magnetostriction
 - Specific resistance (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
- Microwave garnet ferrites with perpendicular biasing at 40...60 MHz (comparatively low losses)



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.



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Former staff:

Dr. Klaus Blasche, Dipl.-Phys. Martin Emmerling,
Dr. Klaus Kaspar

(for literature references, please see proceedings)



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**Thank you very much
for your attention!**