RF HARDWARE OPTIONS

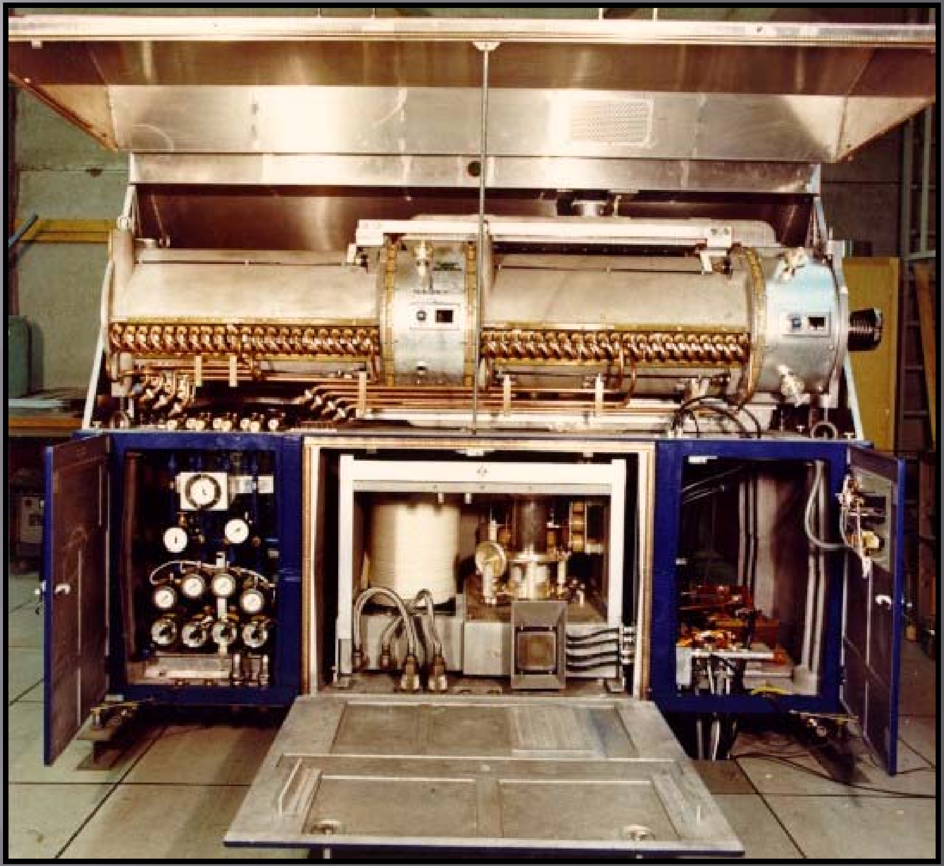
Very preliminary!

E. Jensen, 29-May-08

The 10 MHz route

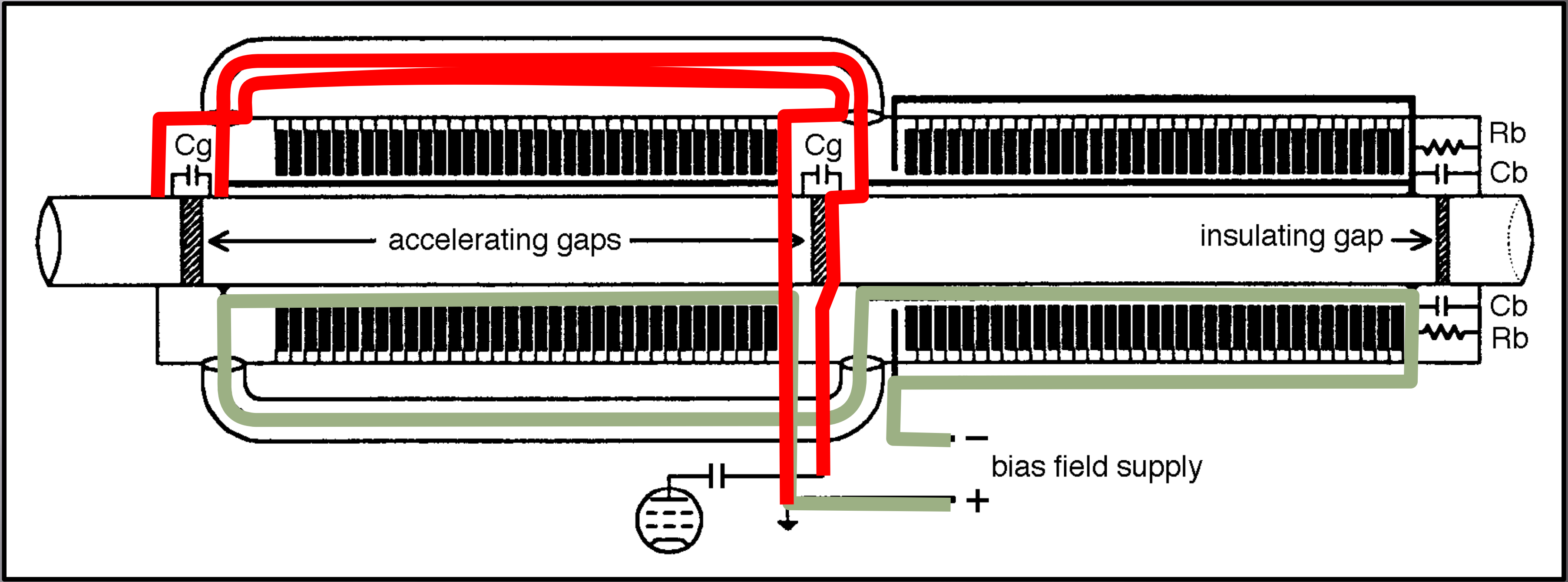
- Present PS 10 MHz system:
  - 10+1 cavities, 2 gaps/cavity, 10 kV/gap
  - 2.7 … 10 MHz tuning range
  - longitudinal imp. 3.5 kΩ/gap, reduced to 110 Ω with FB. (total 70 kΩ w/o FB, 2.2 kΩ with FB)
  - 2.4 m length/cavity (24 m long straight sections)
- Required in PS2 @ 10 MHz:
  - 500 kV (i.e. around 26 of these cavities or 60 m straight sections)
  - 13, 20, 40 and 80 MHz system, similar to present systems would also be required.
  - If the space is available, this can be done; no significant R&D required.

Present PS 10 MHz cavity



Installed around 1971

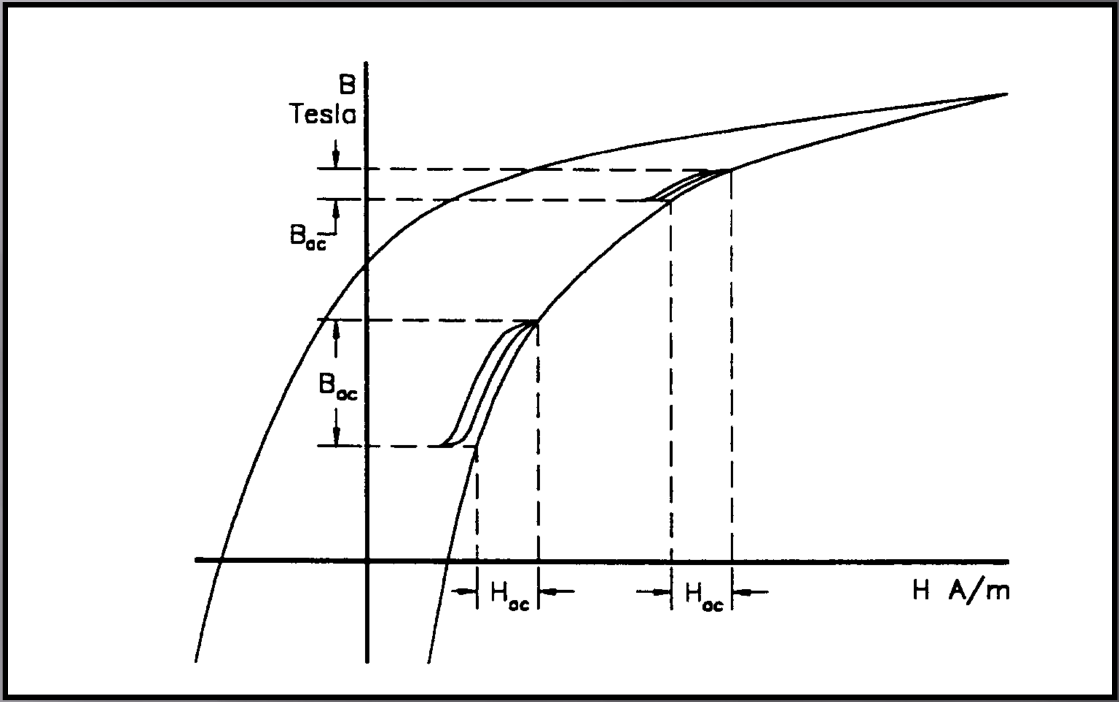
“standard” ferrite cavity



Tuning bias current circuit: azimuthal magnetization, ferrite toroid stacks in anti-series and with figure-of-8 current.

RF: 2 gaps (Cg) and input of coaxial lines (variable L) in parallel for the amplifier (in series for the beam). The RF magnetic field is azimuthal (parallel to DC magnetization).

μ: slope of magnetization curve



$$f \propto \frac{1}{\sqrt{L}} \propto \frac{1}{\sqrt{\mu}}$$

But: area inside hysteresis loop corresponds to losses. Loaded *Q* about 30.

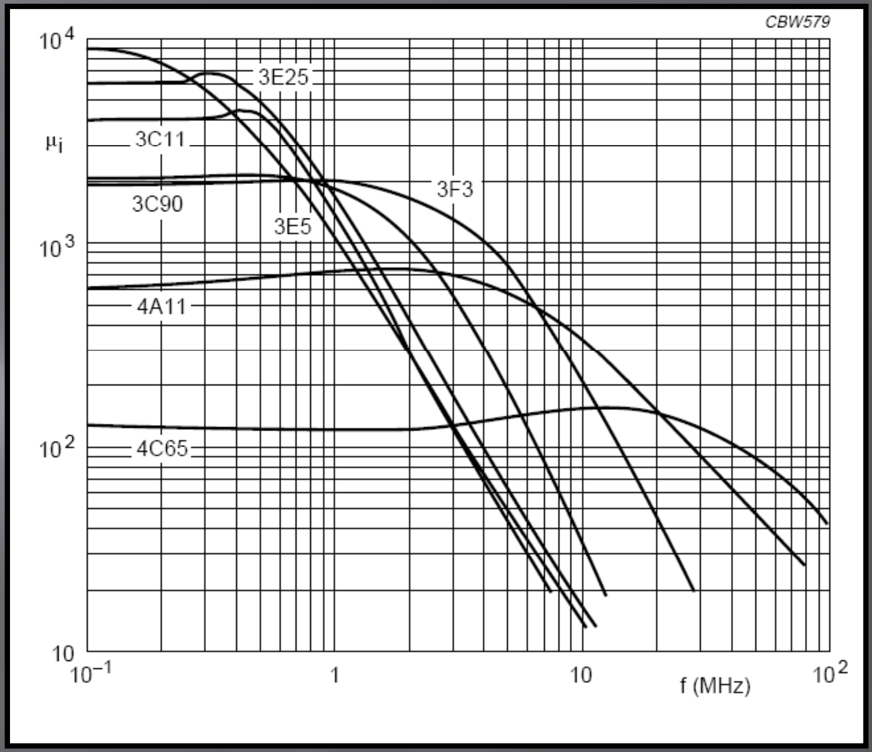
The 40 MHz route

- Required:
  1.5 MV, 18.5 … 40 MHz
- Also required: new LEIR h=10 system, 10 … 18.5 MHz, ≈15 kV; not considered here (easier than the PS RF system). Straight section available in LEIR? Alternative?

- Obvious question: can the concept of "standard" ferrite cavities be extrapolated to higher frequencies?

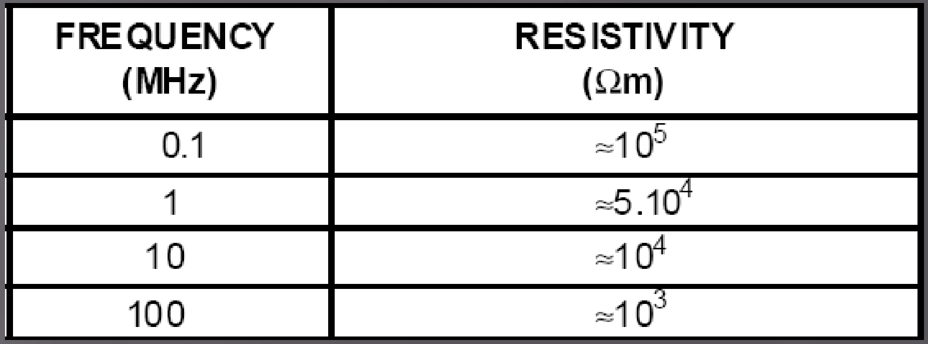
“Standard” ferrite cavity at higher *f*?

- In principle yes, but
  - μ_i decreases with *f*!
  - smaller μ_i, smaller tuning range



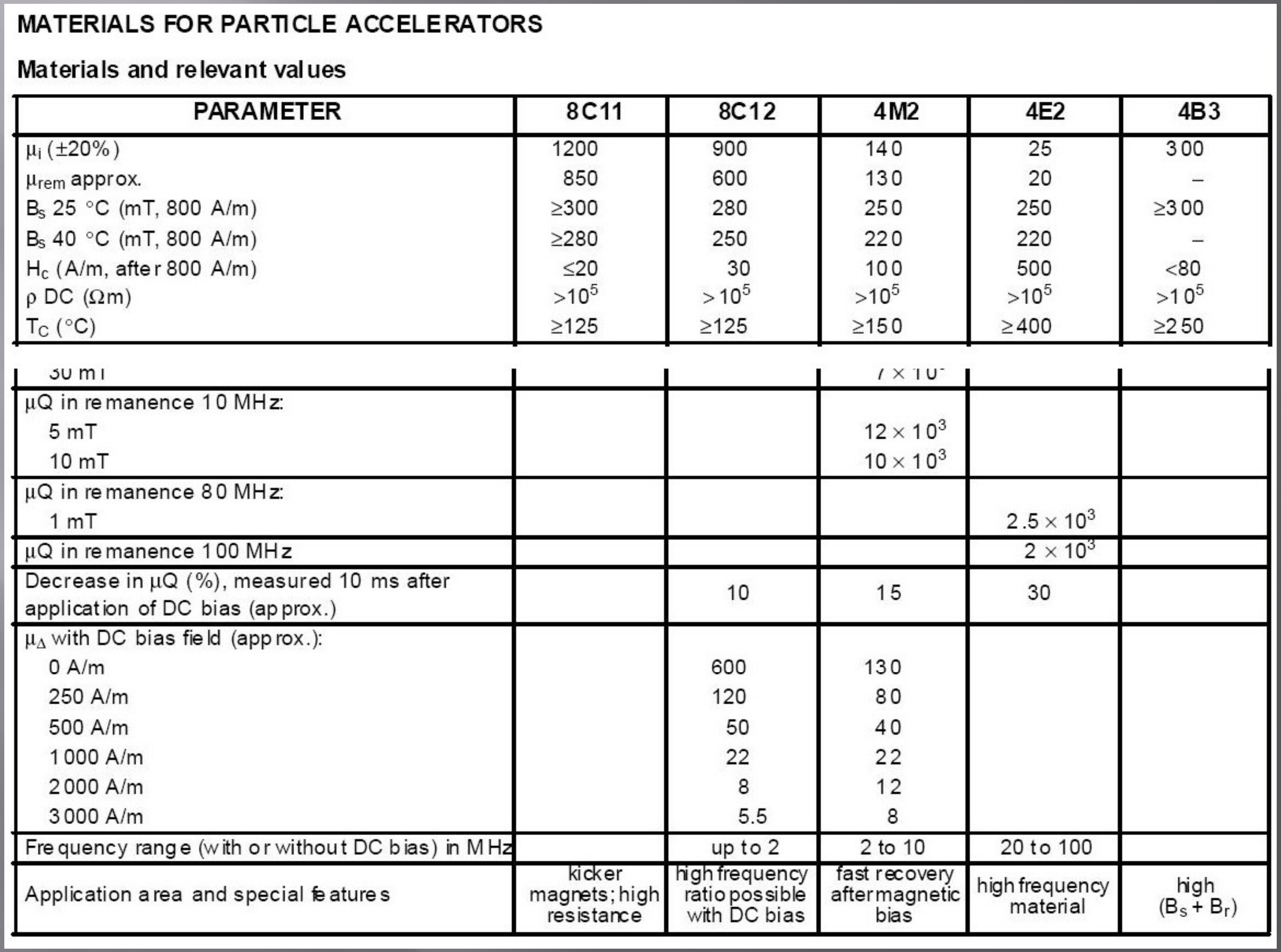
- Losses grow with *f*!

e.g. decreasing resistivity for NiZn ferrites:



FREQUENCY (MHz)	RESISTIVITY (Ωm)
0.1	$\approx 10^5$
1	$\approx 5.10^4$
10	$\approx 10^4$
100	$\approx 10^3$

Excerpt from Ferroxcube® catalog



MATERIALS FOR PARTICLE ACCELERATORS

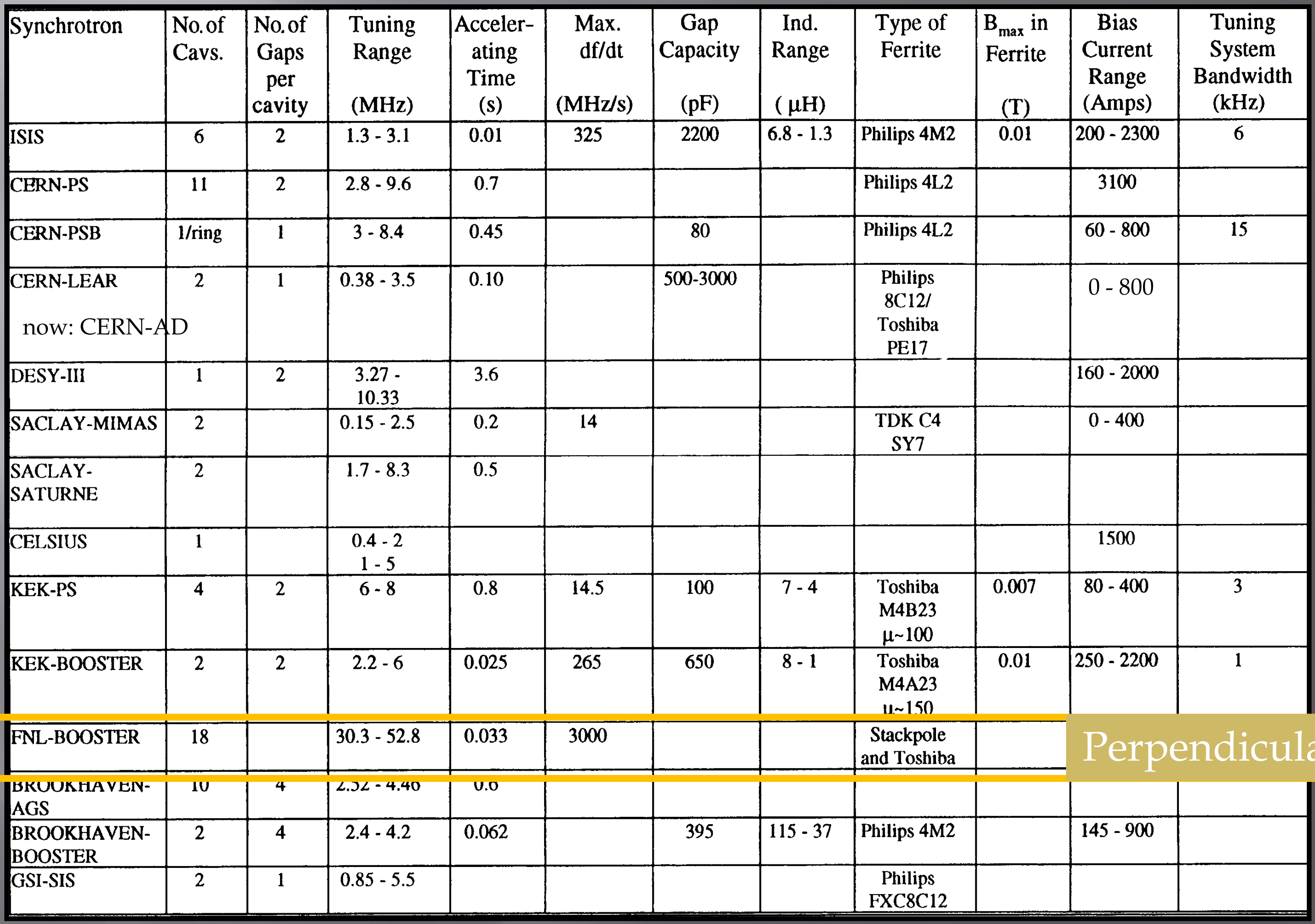
Materials and relevant values

PARAMETER	8C11	8C12	4M2	4E2	4B3
μ_i (±20%)	1200	900	140	25	300
μ_{rem} approx.	850	600	130	20	–
B_s 25 °C (mT, 800 A/m)	≥300	280	250	250	≥300
B_s 40 °C (mT, 800 A/m)	≥280	250	220	220	–
H_c (A/m, after 800 A/m)	≤20	30	100	500	<80
ρ DC (Ωm)	$>10^5$	$>10^5$	$>10^5$	$>10^5$	$>10^5$
T_C (°C)	≥125	≥125	≥150	≥400	≥250
30 mT			7×10		
μQ in remanence 10 MHz:					
5 mT			12×10^3		
10 mT			10×10^3		
μQ in remanence 80 MHz:					
1 mT				2.5×10^3	
μQ in remanence 100 MHz				2×10^3	
Decrease in μQ (%), measured 10 ms after application of DC bias (approx.)		10	15	30	
μ_Δ with DC bias field (approx.):					
0 A/m		600	130		
250 A/m		120	80		
500 A/m		50	40		
1000 A/m		22	22		
2000 A/m		8	12		
3000 A/m		5.5	8		
Frequency range (with or without DC bias) in MHz		up to 2	2 to 10	20 to 100	
Application area and special features	kicker magnets; high resistance	high frequency ratio possible with DC bias	fast recovery after magnetic bias	high frequency material	high (B_s + B_r)

"Standard" ferrite cavity at higher *f*?

- Due to reduced μ_i, the tuning range will become smaller.
- Due to higher losses, the shunt impedance will become smaller, i.e. more power is needed for the same voltage.
- This increased power will not only have to be produced, but also cooled away.
- The table of existing systems confirms that a reasonable upper *f*-limit for "standard" ferrite cavities is around 20 MHz.
- Alternatives? → Perpendicular bias!

Some existing ferrite RF systems

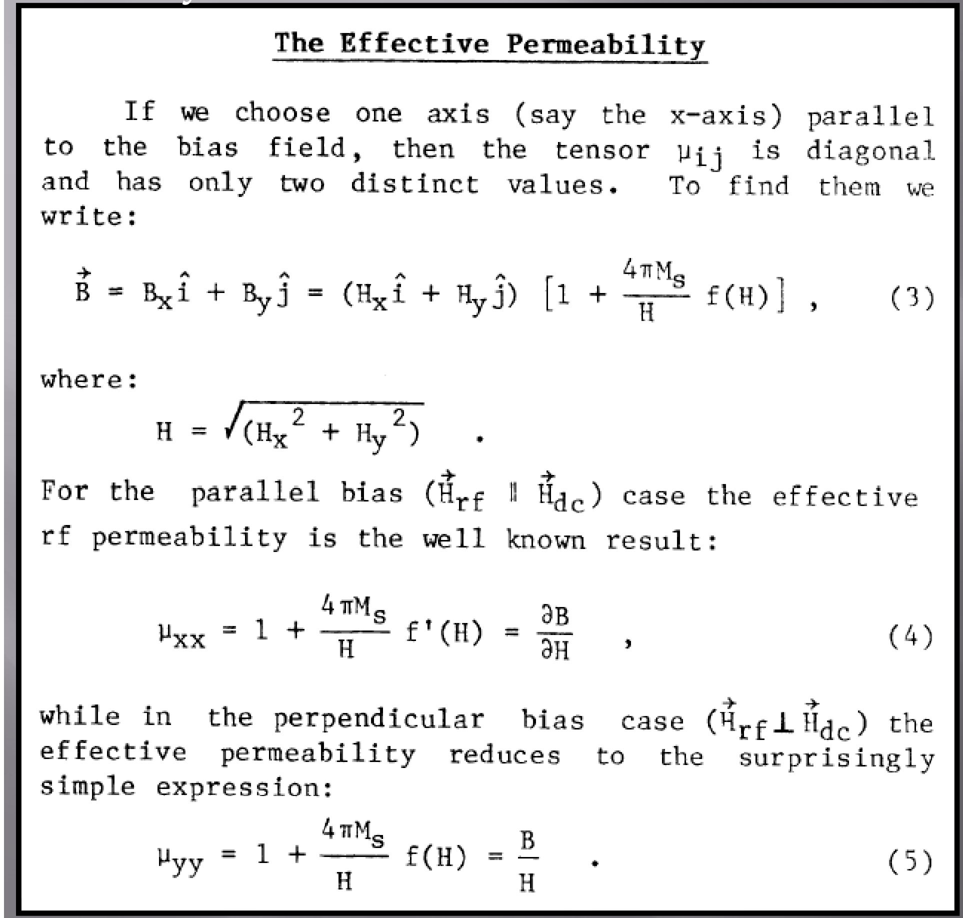


Synchrotron	No. of Cavs.	No. of Gaps per cavity	Tuning Range (MHz)	Acceler-ating Time (s)	Max. df/dt (MHz/s)	Gap Capacity (pF)	Ind. Range (µH)	Type of Ferrite	B_{max} in Ferrite (T)	Bias Current Range (Amps)	Tuning System Bandwidth (kHz)
ISIS	6	2	1.3 - 3.1	0.01	325	2200	6.8 - 1.3	Philips 4M2	0.01	200 - 2300	6
CERN-PS	11	2	2.8 - 9.6	0.7				Philips 4L2		3100	
CERN-PSB	1/ring	1	3 - 8.4	0.45		80		Philips 4L2		60 - 800	15
CERN-LEAR now: CERN-AD	2	1	0.38 - 3.5	0.10		500-3000		Philips 8C12/ Toshiba PE17		0 - 800	
DESY-III	1	2	3.27 - 10.33	3.6						160 - 2000	
SACLAY-MIMAS	2		0.15 - 2.5	0.2	14			TDK C4 SY7		0 - 400	
SACLAY-SATURNE	2		1.7 - 8.3	0.5							
CELSIUS	1		0.4 - 2 1 - 5							1500	
KEK-PS	4	2	6 - 8	0.8	14.5	100	7 - 4	Toshiba M4B23 µ~100	0.007	80 - 400	3
KEK-BOOSTER	2	2	2.2 - 6	0.025	265	650	8 - 1	Toshiba M4A23 µ~150	0.01	250 - 2200	1
FNL-BOOSTER	18		30.3 - 52.8	0.033	3000			Stackpole and Toshiba			
BROOKHAVEN-AGS	10	4	2.32 - 4.46	0.6							
BROOKHAVEN-BOOSTER	2	4	2.4 - 4.2	0.062		395	115 - 37	Philips 4M2		145 - 900	
GSI-SIS	2	1	0.85 - 5.5					Philips FXC8C12			

Perpendicular bias!

Perpendicular bias

Smythe 1983:



The Effective Permeability

If we choose one axis (say the x-axis) parallel to the bias field, then the tensor μ_{ij} is diagonal and has only two distinct values. To find them we write:

$$\vec{B} = B_x\hat{i} + B_y\hat{j} = (H_x\hat{i} + H_y\hat{j})\left[1 + \frac{4\pi M_s}{H} f(H)\right] , \qquad (3)$$

where:

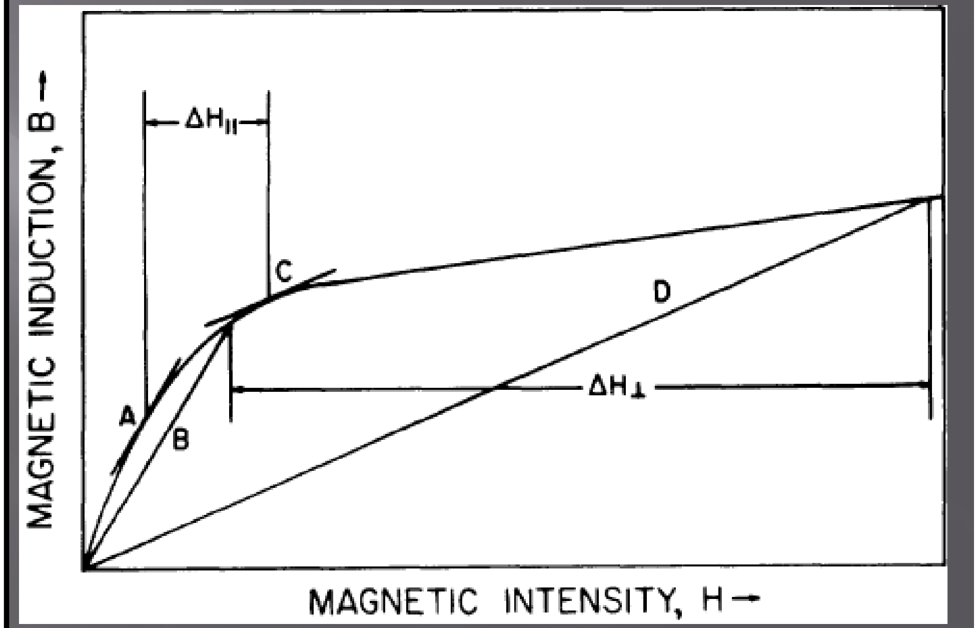
$$H = \sqrt{(H_x{}^2 + H_y{}^2)} \quad .$$

For the parallel bias ($\vec{H}_{rf} \parallel \vec{H}_{dc}$) case the effective rf permeability is the well known result:

$$\mu_{xx} = 1 + \frac{4\pi M_s}{H} f'(H) = \frac{\partial B}{\partial H} \quad , \qquad (4)$$

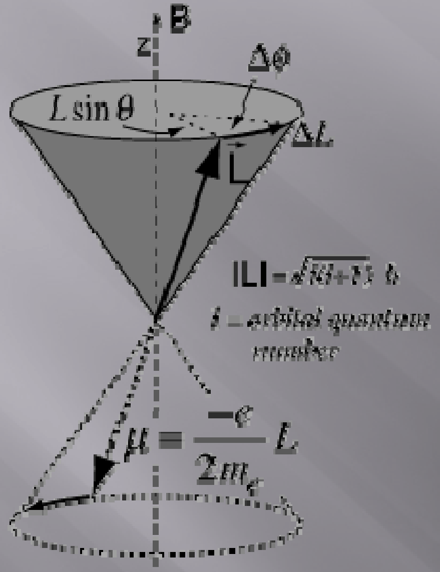
while in the perpendicular bias case ($\vec{H}_{rf} \perp \vec{H}_{dc}$) the effective permeability reduces to the surprisingly simple expression:

$$\mu_{yy} = 1 + \frac{4\pi M_s}{H} f(H) = \frac{B}{H} \quad . \qquad (5)$$



Advantage: always in saturation, i.e. reduced hysteresis loss → potentially higher Q

Gyromagnetic resonance



Poirier, PAC 1993:

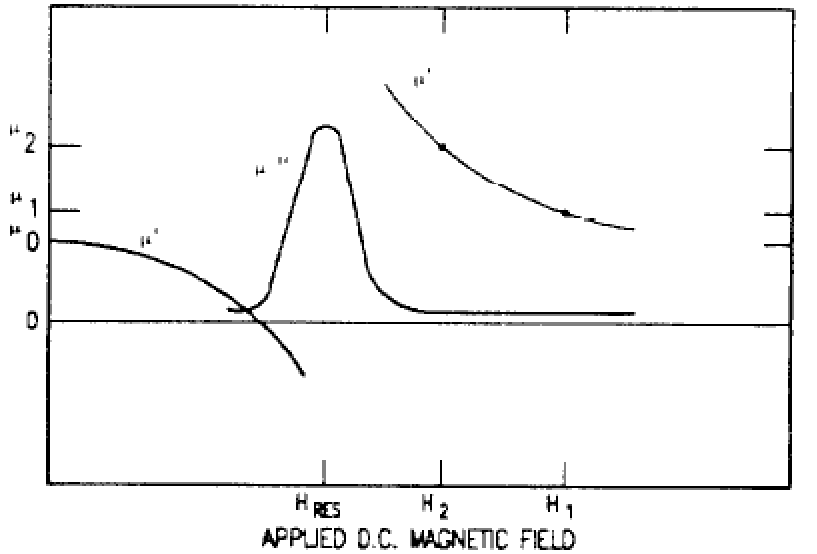


Figure 3. Plot of permeability vs applied magnetic field.

resonance at:

$$f \approx 35\,\mathrm{kHz}\,\frac{H}{\mathrm{A/m}}$$

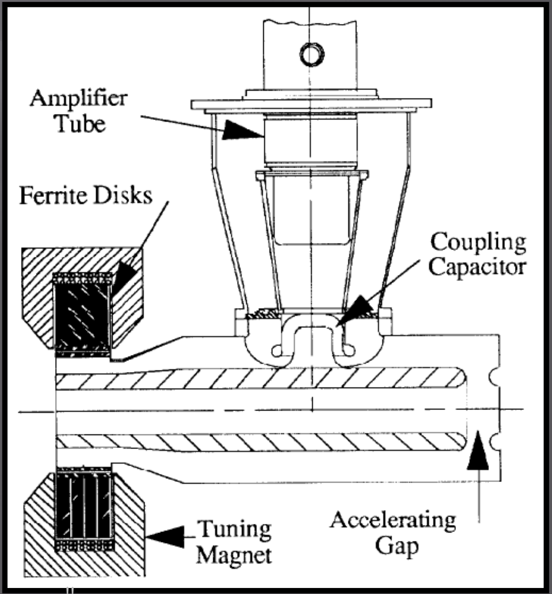
typical bias: 10 … 200 kA/m

At fields above the gyromagnetic resonance, this is consistent with the $\mu \propto H^{-1}$ dependence in saturation given by Smythe.

Perpendicular bias RF systems

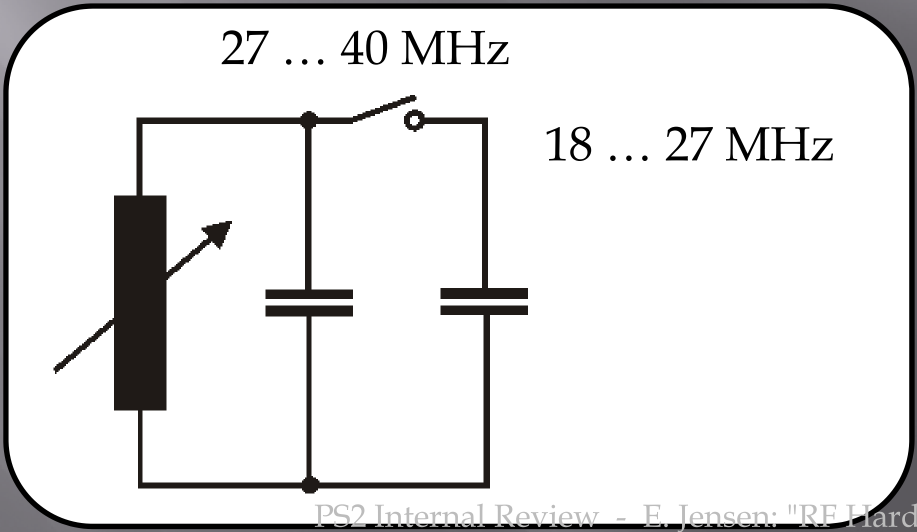
- FNAL Booster (2001)
  - 100 kV with 150 kW, 36 … 53 MHz, bias < 1000 A
- LAMPFF, later SSCL LEB, 1984 - 1993
  - 127 kV with 150 kW, 47…60 MHz, *Q* above 1000
- TRIUMF Kaon Factory Booster (1998)
  - 62 kV, 46 … 62 MHz

"generic" conceptual design:



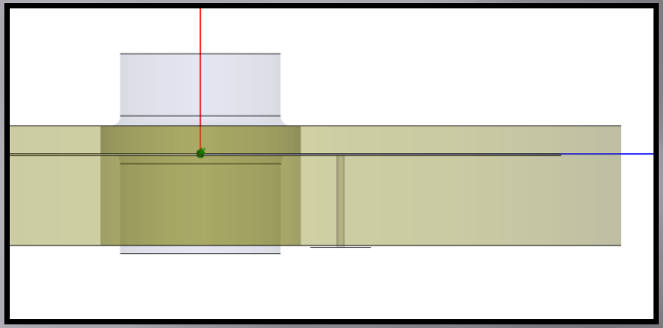
Concluded from these:

- Systems around 50 MHz with a tuning range of 1.5 can be done.
- For our *f* range (18 … 40 MHz), things would be simpler rather than more complicated.
- With a switchable gap capacitor it should be possible to make the tuning range in 2 sub-ranges – is this acceptable?



Can 1 octave tuning range be reached?

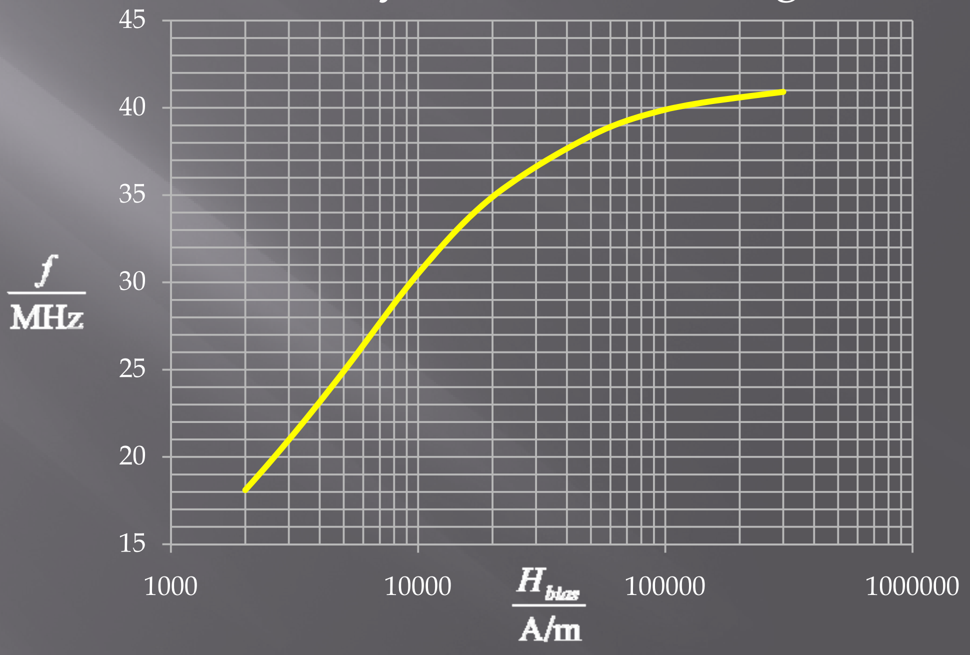
- Simplified geometries tried in HFSS, e.g.



Ferrite: YIG
(Yttrium-Iron-Garnet)
with (realistic)

$\tan\delta_\varepsilon = 2\,10$ [illegible]
$M_{\text{sat}} = 1$ [illegible]
$\Delta H = 1\ \text{Oe}$

Preliminary result for a tuning curve:



Preliminary answer:
Octave can be reached, **but:** for bias below 5000 A/m, the *Q* becomes very small!

YIG ferrites can be taylored

E.g.:

- Substitution of some Y with Gd (see plot), Vd or Ca reduces the saturation magnetization.
- Substitution of some Fe with In reduces the linewidth.

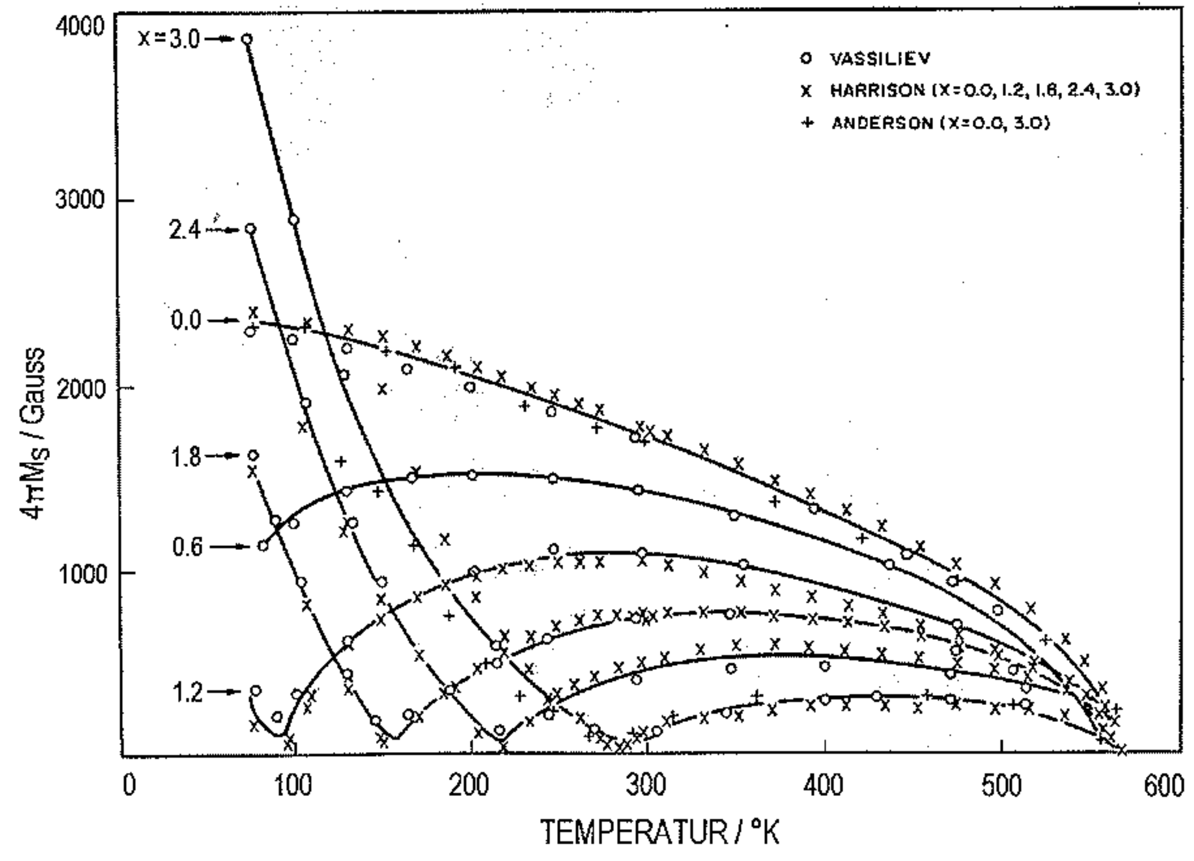
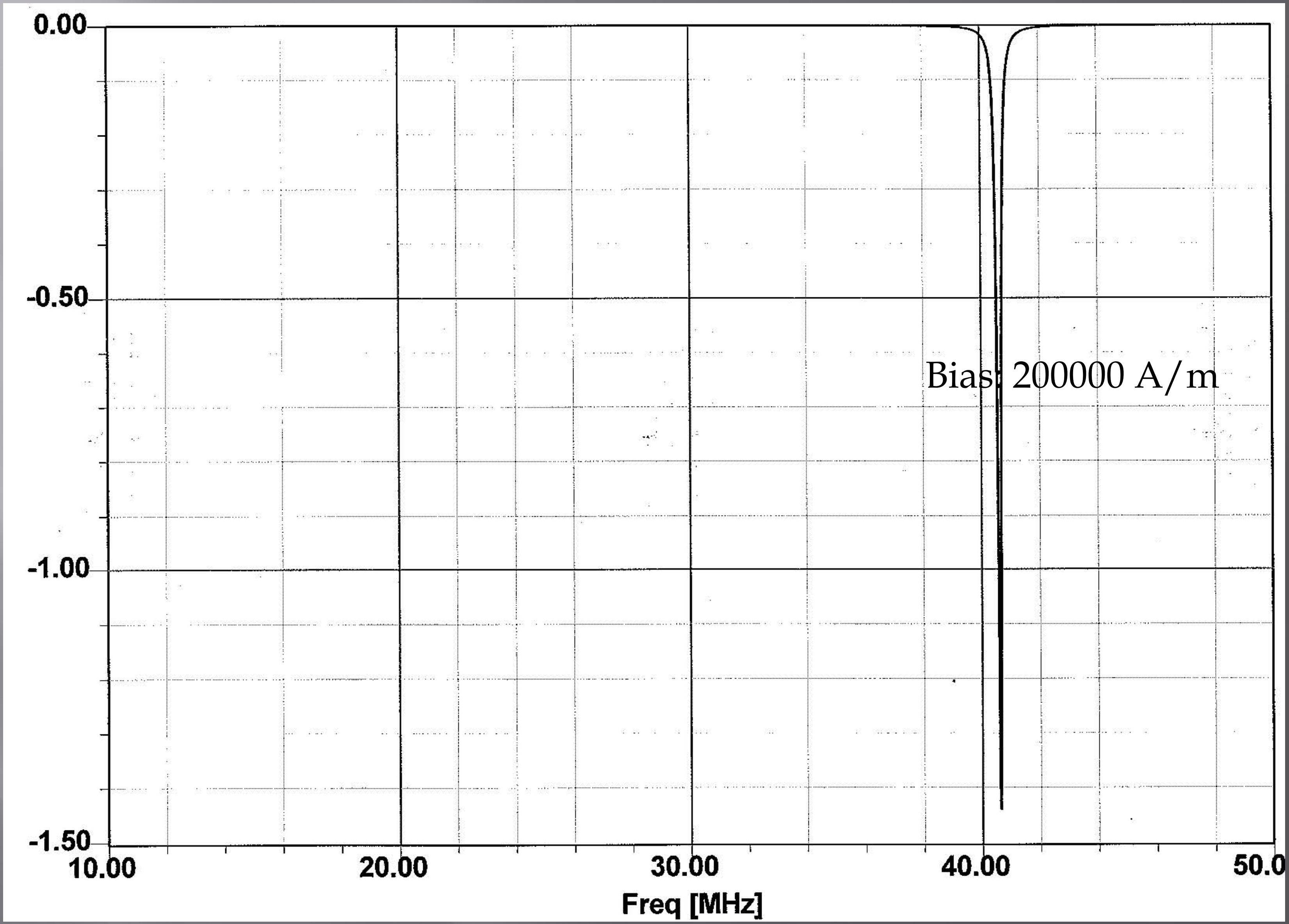


Bild 8.7: Gd-Substitution in YIG:
Sättigungsmagnetisierung über der Temperatur
für verschiedene x in $Gd_xY_{3-x}Fe_5O_{12}$

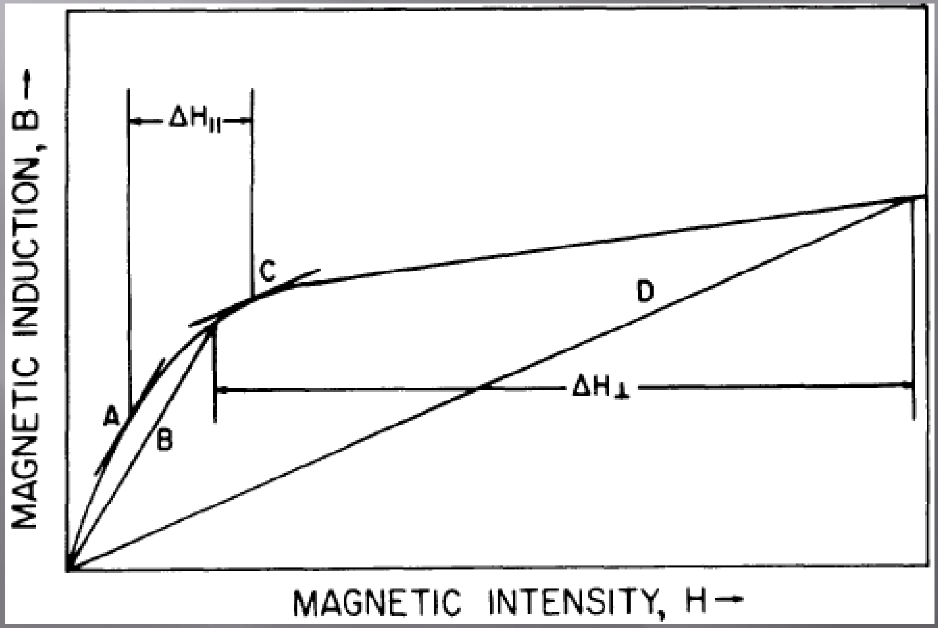
from L. Michalowsky: “Weichmagnetische Ferrite”, expert verlag, Renningen, 2006

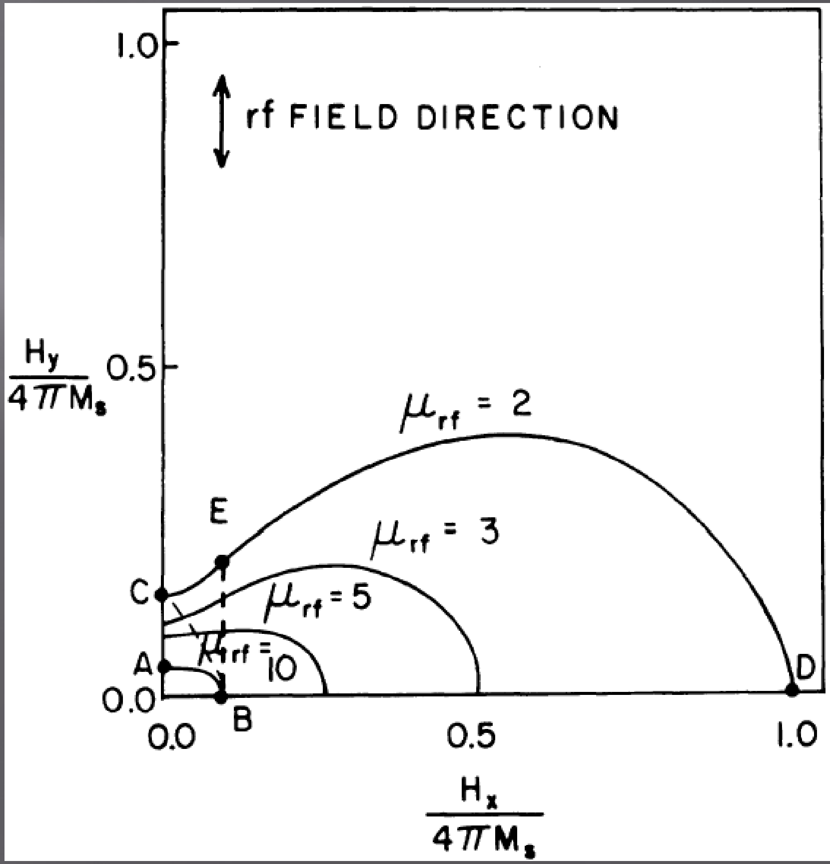
Preliminary HFSS results:



Parallel plus perpendicular biasing?

- Smythe suggested in 1983 to use
  - transverse bias to get into saturation (lower losses)
  - add’l. parallel bias for tuning (less bias).
- Could this work? (I’d like to try!)





Next steps

- Characterize YIG ferrite samples with different saturation and line width under different bias conditions in our *f*-range. (This requires a dedicated test set-up).
- This will allow to advance a cavity design.
- My guess today: If the split *f*-range is possible, 40 kV, 50 kW units should be possible; this would require around 40 systems for the 1.5 MV requirement.