RF Acceleration
RF Systems

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KEK

Contents

RF Acceleration

- Direc tvoltage and RF accelerations
  - Electrostatic accelerators: Cockcroft&Walton, Van de Graaf
  - RF accelerations: Linac, synchrotron(+FFAG)
- Electron and Proton/ions
  - β=1 vs. β<1
  - Cavities (high-Q, ferrite, MA)
- Beams
  - Synchrotron motion
  - Phase stability & transition
  - Dual harmonic acceleration
  - beam loadings

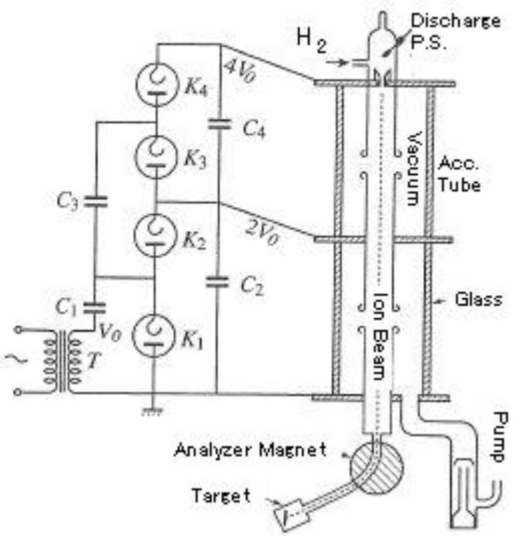
RF Systems

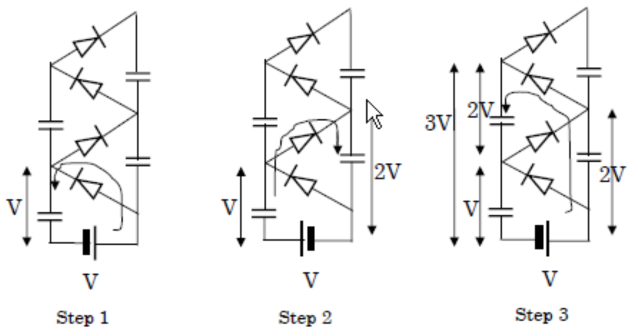
- Cavities
  - Designing of MA Cavities
- LLRF
- FFAG cavities

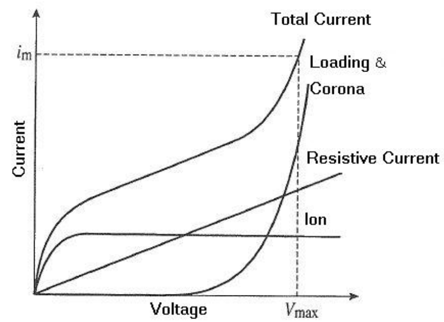
1.1 Direct voltage and RF accelerators

Electrostatic accelerator

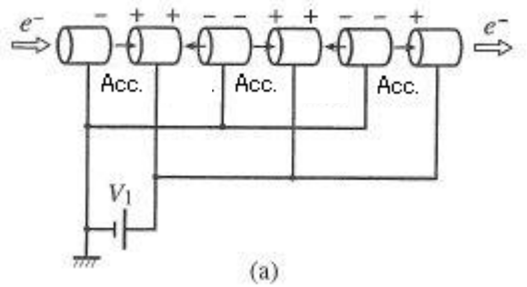
- Voltage is limited to 10MV because of corona discharge.

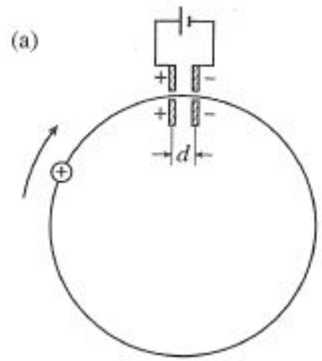




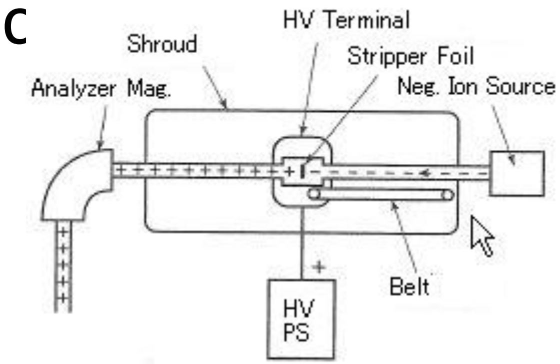


- Static accelerator can not be combined with other static ac





- Idea of Tandem acc

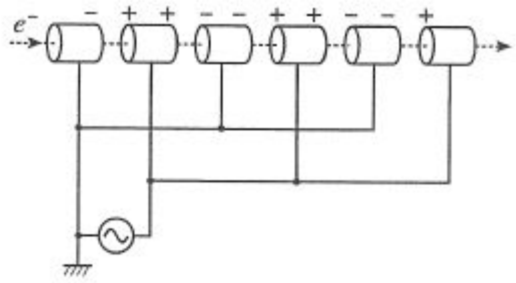


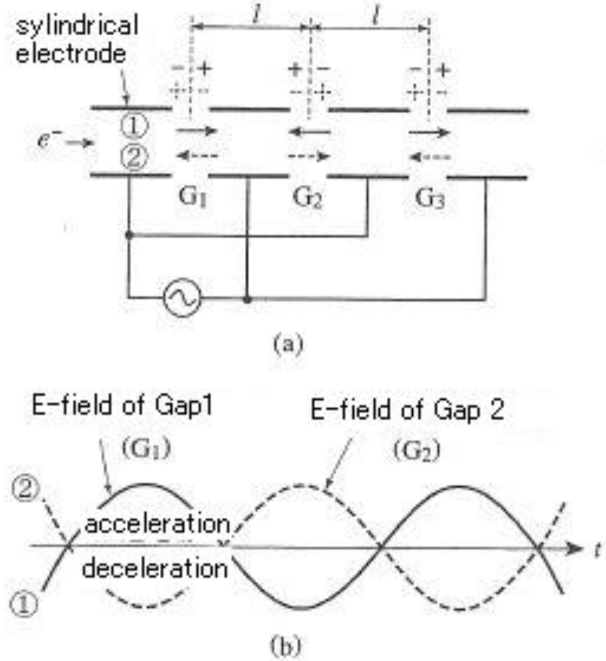
Question: If static acceleration is applied to a circular accelerator, what happens ?

RF acceleration

- Direction of RF voltage changes regularly.
- RF field can be confined in RF structure (cavity).
- 1928 Wideroe K+, N+
- 1931 Sloan, Lawrence Hg+ (10 MHz RF ⇒Long tubes)
- 1937-45 Hansen, Varian Klystron
- 1945- Alvarez 200 MHz Linac(DTL)

  ⇒Higher Energy
- 1947- disk-loaded linac 2856 MHz
- 1965 Wilson superconducting linac

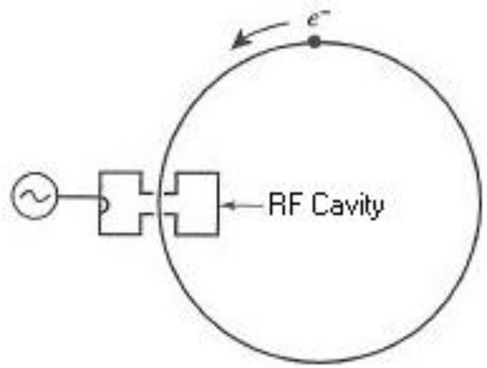


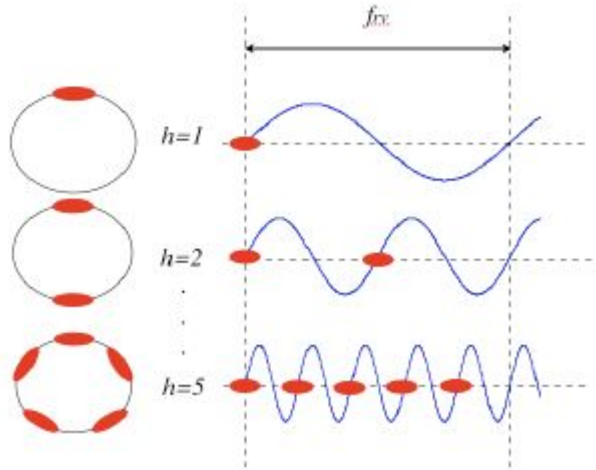


Circular machines

- RF cavity (RF is confined in it).
- $f_{rf}=h\ f_{rev}$

  h:Harmonic number
- Beam forms a bunch structure.





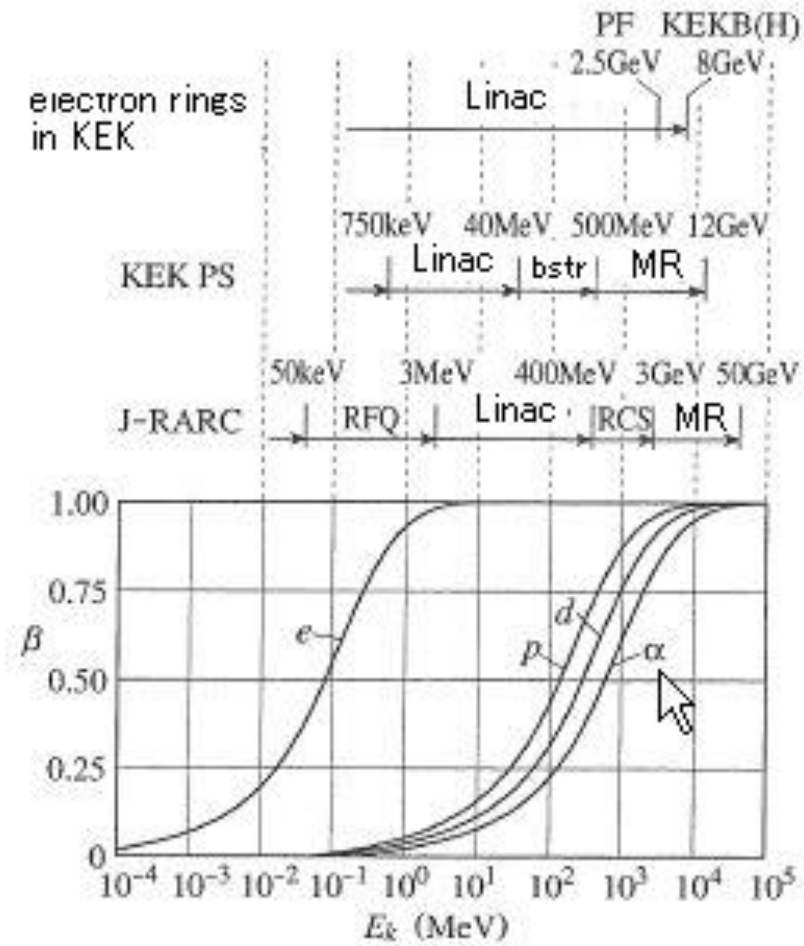
RF parameter of accelerators

Accelerators	Energy (GeV)	Circumference (m)	Revolution time(μs)	frev(MHz)	f_{RF}(MHz)	H
J-PARC RCS	0.18-3	348	2.1-1.2	0.47-0.84	0.94-1.67	2
J-PARC MR	3-50	1568	5.37-5.23	0.186-0.191	1.67-1.72	9
KEK Photon Factory	2.5	187	0.624	1.603	500.1	312
SP-8	8	1436	4.79	0.209	508.6	2436
SP-8 booster	1-8	396	1.32	0.757	508.6	672
KEK-B	3.5,8	3018	10.1	0.099	508.9	5120

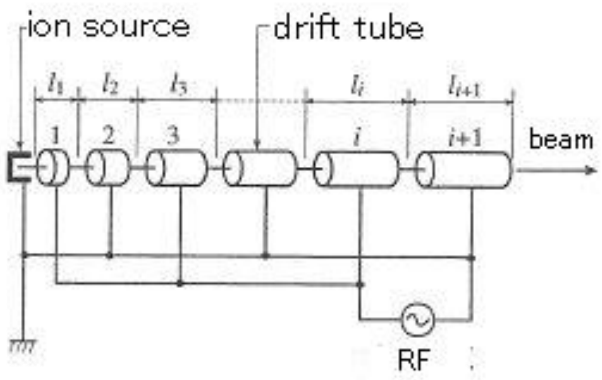
J-PARC : proton machines
Others: electron machines

1.2 Electron and proton accelerations

- Mass
  - Electron: 0.511 MeV
  - Proton: 938 MeV
- In electron machines (E>10 MeV), β~1
- For proton, E>20 GeV to be β~1
- For many electron linac, fixed cavity structure.
- For many proton linac, need to change structure according to acceleration.
- For many electron rings, fixed rf frequency.
- For many proton rings, need to change rf frequency.



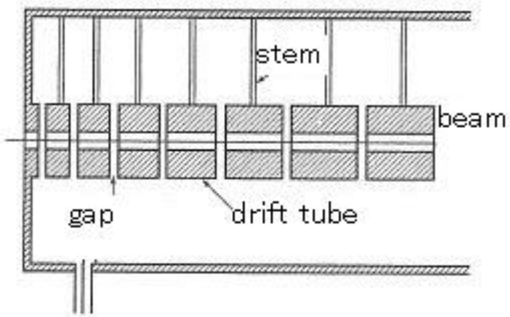
- Proton linac needs to change length of drift tube according to acceleration.

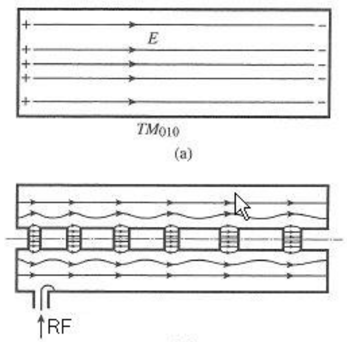


R. Wideroe-type linac
Below 10 MHz, in a glass
li=βλ/2

Over 100 MHz RF high power sources become available after WWII. High energy acceleration became possible.

Particle	E(MeV)	β	βλ (200MHz)	βλ (3000MHz)
P	0.75	0.04	**6**	0.4
P	10	0.14	**22**	1.4
P	100	0.43	**64**	4.3
e	0.1	0.55	82	5.5
e	1	0.94	141	9.4
e	10	0.999	150	**10.0**
e	100	0.99999	150	**10.0**





Alvarez linac (DTL) in KEK PS
About 200 MHz, cavity structure
TM(Transverse Magnetic)010 mode
li=βλ

- Electron linac uses a fixed structure and higher frequency.
  - Alvarez type does not fit as β=1 and drift tube becomes long.
- TM01 mode is used.
- For multi-cell structure, traveling wave type cavity is used.
  - Standing wave type has higher shunt impedance, but difficult for multi-cell.

TMmnp

m: circumferential

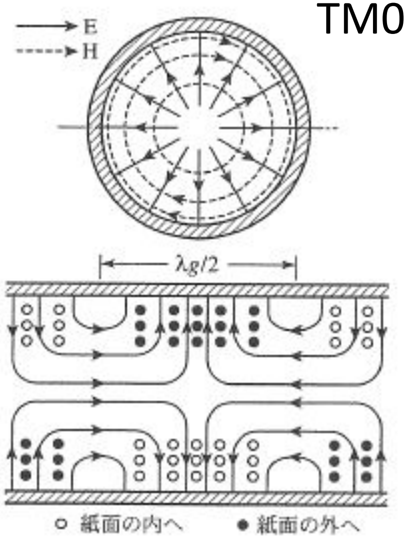
n: radial

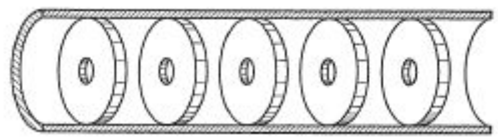
p:longitudinal

TM010:Only longitudinal E-field

TM01 : Simplest mode in waveguide

TM01

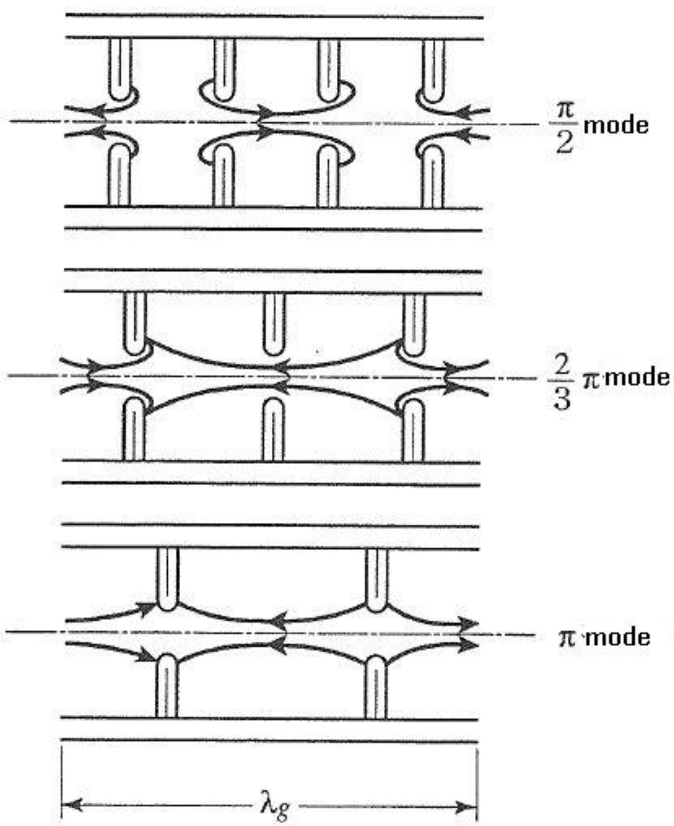




Putting discs for slow-wave structure.

Phase velocity of RF matches velocity of electron

Acceleration Mode

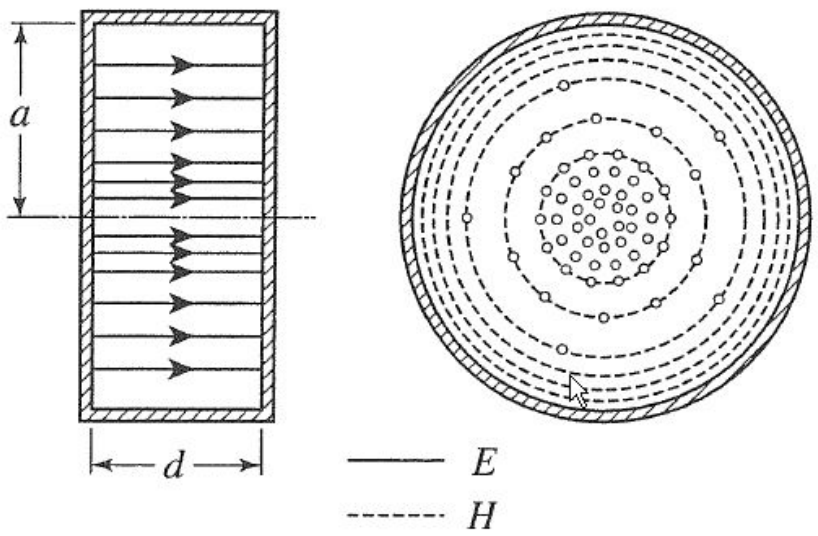


m (disc/wave length)	λ (wave length)	2π/m (phase /disc)
2	2d	π
3	3d	2π/3
4	4d	π/2

2 π/3 mode has a large shut impedance.

Cavity for Electron ring

Fixed frequency
 same structure as linac cavity
But,
Low voltage because of high duty
Standing wave type cavity for high shunt impedance



- Pill box cavity
- TM010 mode is excited.
- Resonant frequency is

$$\lambda_r = \frac{2\pi a}{q_{01}}, \qquad f_r = \frac{q_{01} c}{2\pi a}$$

independent on d.

- To resonate at 500 MHz, a = 0.2295 m
- Toresonate at 18.1 MHz, a =6.347 m

- Transit time factor

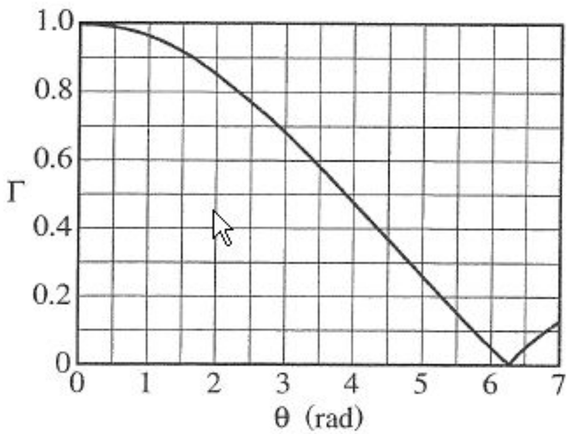
  E field which particle sees

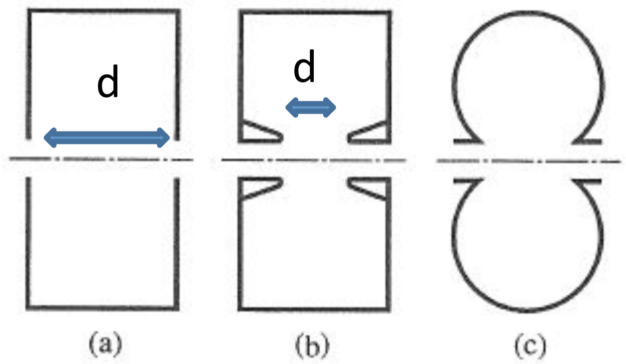
$$V = \int_{-d/2}^{d/2} E_0 \cos\left(\omega t + \phi\right) dz$$

$$= \left[\frac{\sin(\omega d/2\beta c)}{\omega d/2\beta c}\right] E_0 d \cos\phi$$

$$\Gamma = \frac{\sin(\omega d/2\beta c)}{\omega d/2\beta c} = \frac{\sin(\theta/2)}{\theta/2}$$

$$\theta = \frac{\omega d}{\beta c} = \frac{2\pi d}{\beta\lambda}$$





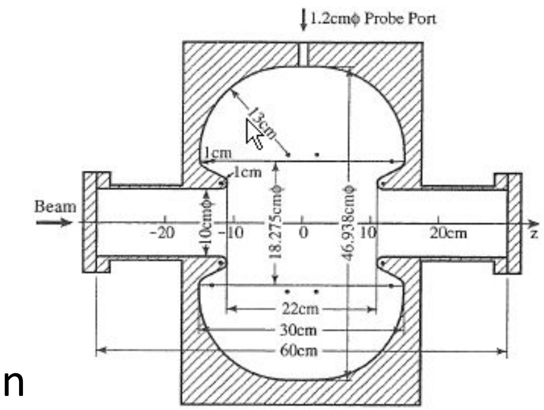
(a)Pill box

(b) With nose cone

large Γ

(c) Curved surface

High shunt impedance

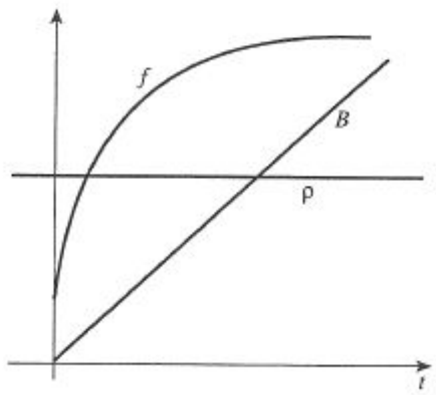


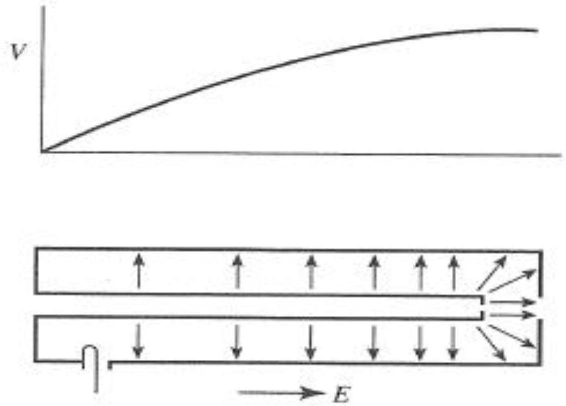
KEK-PF cavity

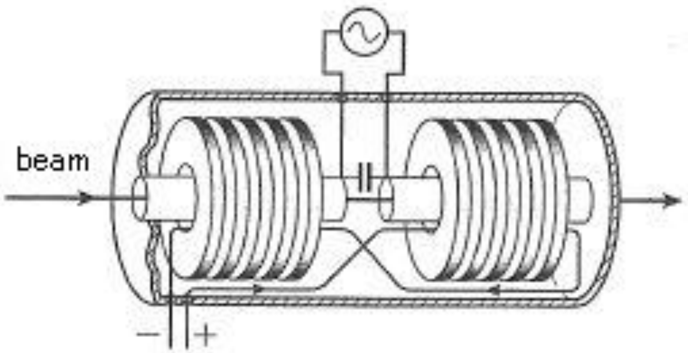
Original design

Cavity for Proton/Ion ring

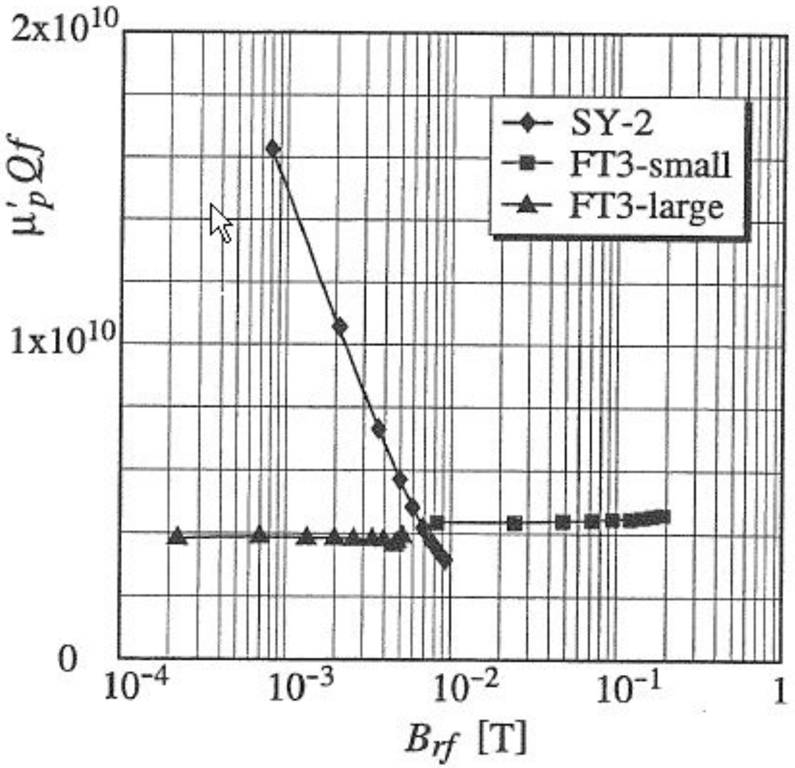
- Proton synchrotron needs to change RF frequency according to acceleration.
- λ/4resonator
- Ferrite cavity needs bias circuit to tune cavity.







Magnetic Alloy Cavity



- Stable μQf at high RF field
- Low Q (frequency sweep w/o bias circuit)
- High Curie temperature

μQf and Brf
are proportional to
shunt impedance and RF voltage

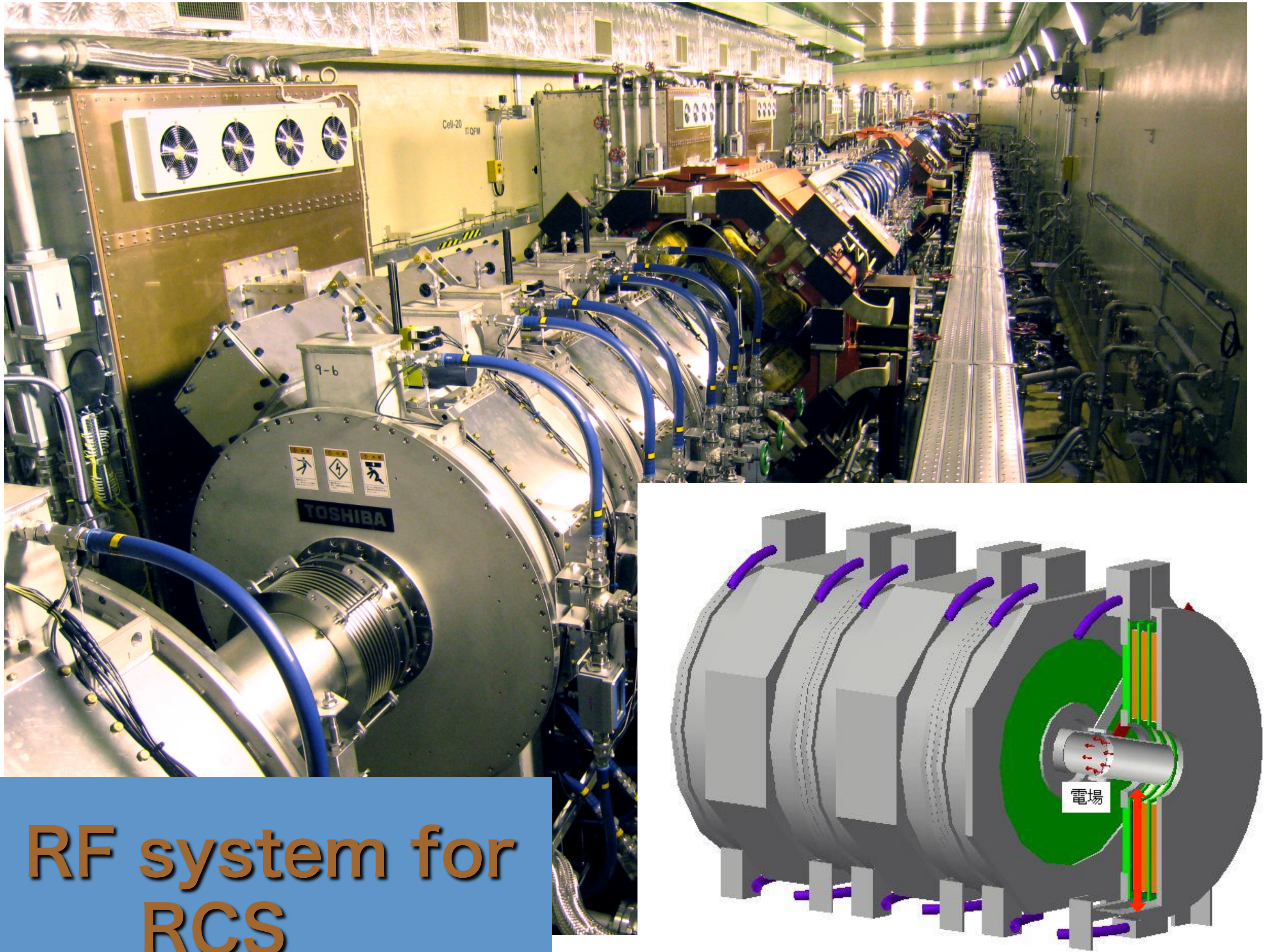
MA cavities

Q-value

- Low Q (~0.6)
  CERN LEIR cavity
- Hybrid cavity
  - With external inductor Q~2
  J-PARC RCS
- Cut core cavity
  - High Q
  J-PARC MR

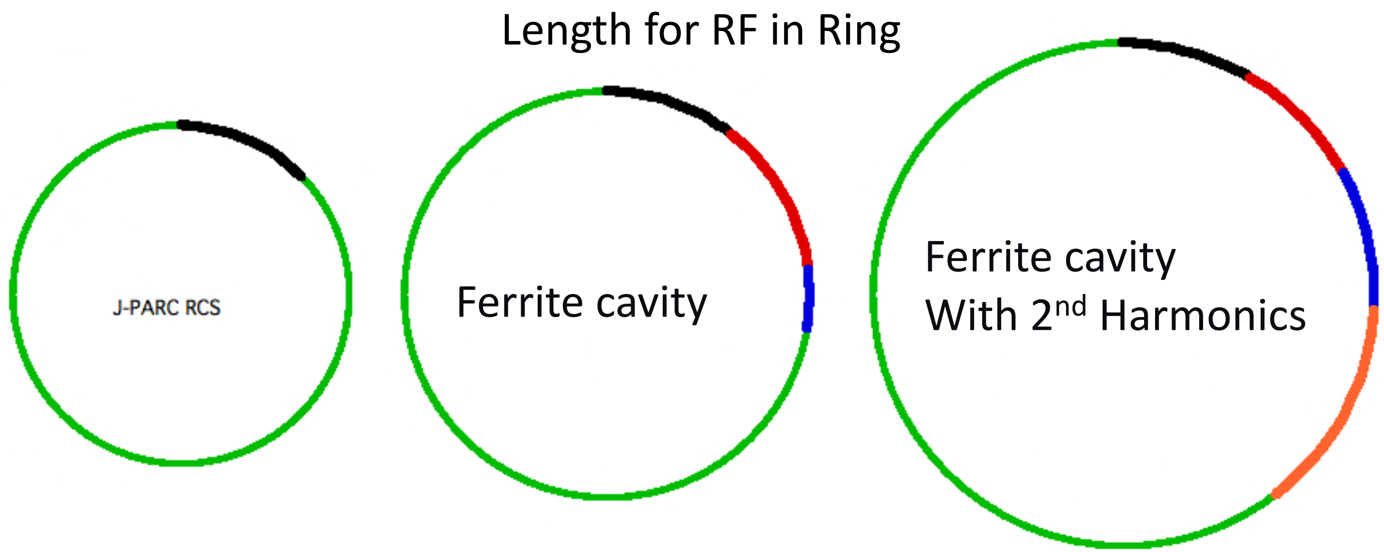
Cooling

- Air
  PRISM cavity, (EMMA MA cavity)
- Forced air
  PS booster cavity, many MA cavities for medical use
- Indirect water cooling
  Gunma U. medical acc.
- Direct water cooling
  J-PARC RCS&MR, LEIR cavities
- Oil/Fluorinate cooling
  KEK PS 2^{nd} H cavity
  KEK induction cavity



11 RF system for RCS

Impact on RCS design by High Field Gradient



Left: J-PARC RCS has about 350 m circumference. Black line means the space for RF (44 m, including Q-magnets).

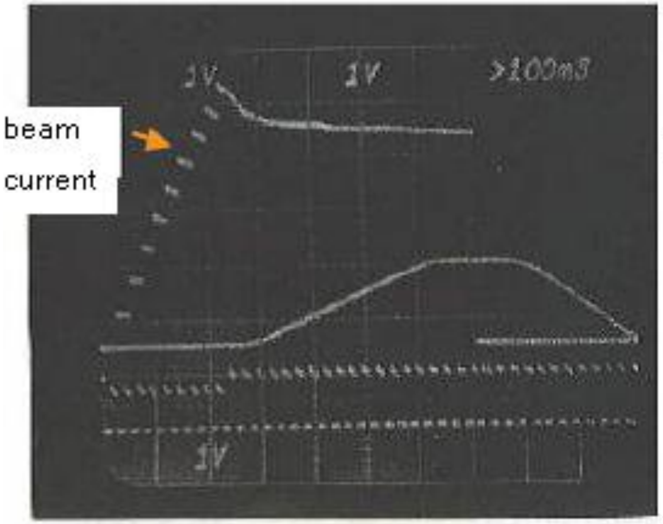
Middle: 3 GeV Ring using ferrite cavity. Red line means additional space by low gradient. Blue is by the extended circumference.

Right: 3 GeV ring using ferrite cavity with 2nd H system (orange).

RF acceleration in Ring

High Power Operation of
KEK PS 2000/3/7

25mA at Ion Source
1.4x10^{12} /bunch from BR
1.2x10^{12} /bunch 3msec after injection

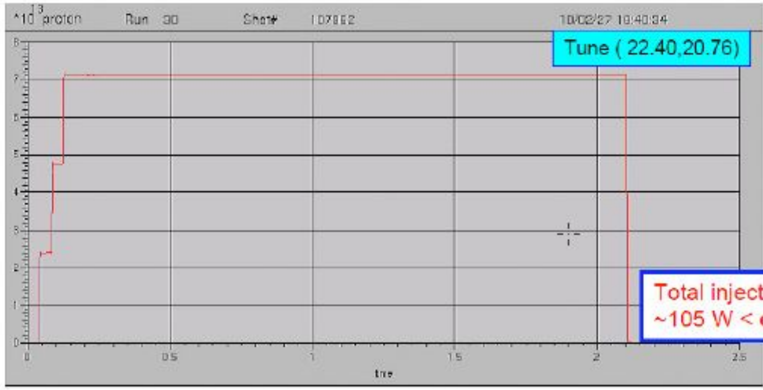


9.3x10^{12} at start of acceleration
8.0x10^{12} just at end of acceleration
7.4x10^{12} just after extraction 13

When α-1/γ2=0, it is "transition".

$$\gamma_T = \frac{1}{\sqrt{\alpha}}$$ transition gamma

Electron ring does not have it as g is much larger than transition gamma.



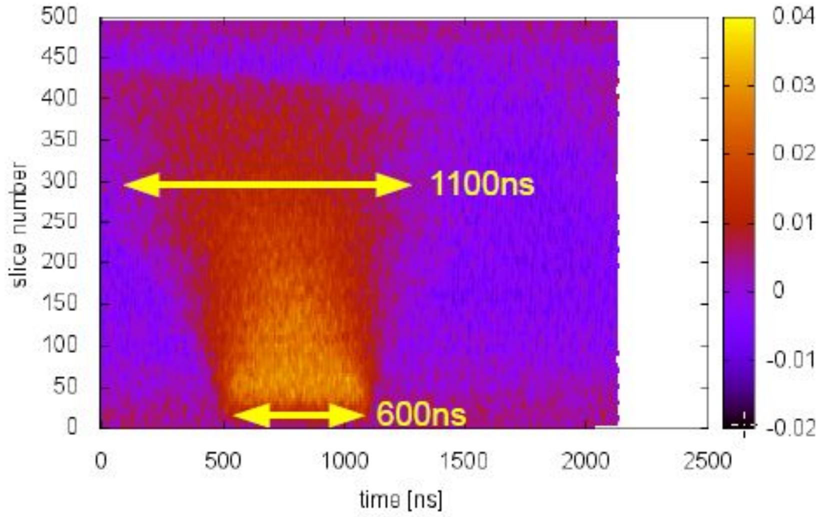
On Feb. 27

The extracted particles to abort dump is 7.2e13 ppp, it corresponds to 100 kW if operated in 3.52 sec cycle.

Total injection loss is 7.7 e11
~105 W < collimator limit 450 W

J-PARC has no transition.

- Slippage factor



Contour plot shows
de-bunching of beam in RCS.

Momentum spread (Full width) is given by

$$\frac{\Delta p}{p} = -\eta \left(\Delta\omega / n \right) f_{rev}$$

In RCS, h=-0.69, frev=0.469 MHz at injection.

Bunch is lengthen by 500 ns in 300 turns.

Momentum spread (full width) is 0.11 %

Synchrotron motion

- Synchrotron motion
  - Synchronous particle

$$\Delta E = eV\sin(\phi_s)$$

  - Non-synchronous particle

$$\Delta E = eV\sin(\phi_s + \Delta\phi)$$

- Equations

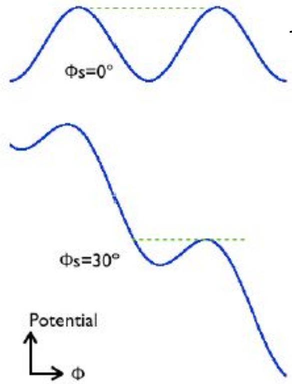
$$\frac{d}{dt}\left(\frac{\Delta E}{\omega_{rf}}\right) = \frac{eV}{2\pi h}\left[\sin(\phi_s + \Delta\phi) - \sin(\phi_s)\right]$$

$$\frac{\Delta T}{T_s} = \left(\alpha - \frac{1}{\gamma_s^2}\right)\frac{\Delta p}{p} = \eta_s\frac{\Delta p}{p}$$

give

$$H' = \mathrm{sgn}(\eta)\left\{\frac{1}{2}\frac{\omega_{rf}^2\eta}{\beta_s^2 E_s}W'^2 + \frac{eV}{2\pi h}\left(\cos\phi + \phi\sin\phi_s\right)\right\}$$

$$W' = \mathrm{sgn}(\eta)\frac{\Delta E}{\omega_{rf}}$$



For small amplitude,

$$\frac{d^2(\Delta\phi)}{dt} - \frac{\omega_{rf}^2\eta_s eV\cos(\phi_s)}{2\pi h\beta_s^2 E_s}\Delta\phi = 0$$

$$\omega_{syn} = \sqrt{-\frac{\omega_{rf}^2\eta_s eV\cos(\phi_s)}{2\pi h\beta_s^2 E_s}}$$

Synchrotron oscillation

Stable RF phase

for stability.

$$\eta_s \cos(\phi_s) < 0$$

Below transition, (η<0)

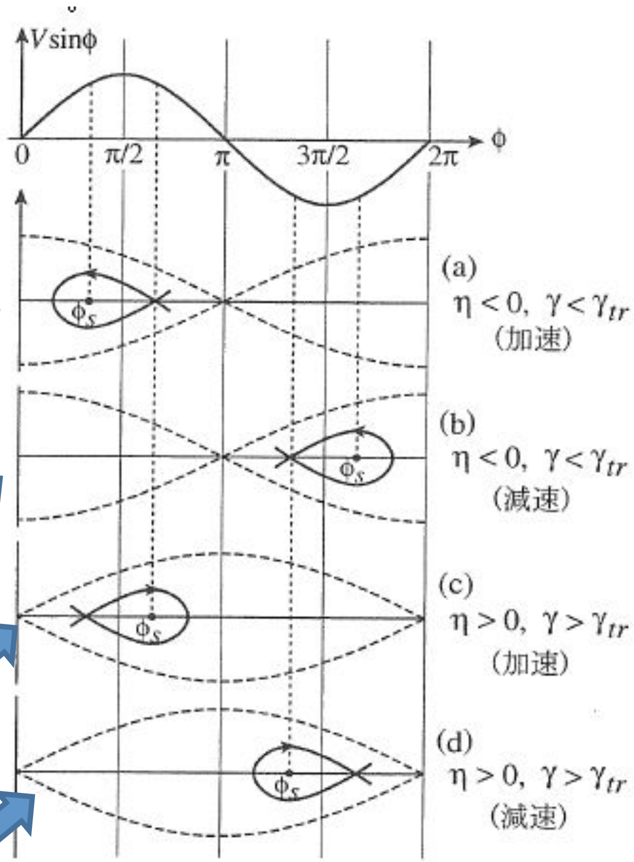
Acceleration $0 < \phi_s < \frac{\pi}{2}, \sin\phi_s > 0$

Deceleration $\frac{3\pi}{2} < \phi_s < 2\pi, \sin\phi_s < 0$

Above transition, (η>0)

Acceleration $\frac{\pi}{2} < \phi_s < \pi, \sin\phi_s > 0$

Deceleration $\pi < \phi_s < \frac{3\pi}{2}, \sin\phi_s < 0$



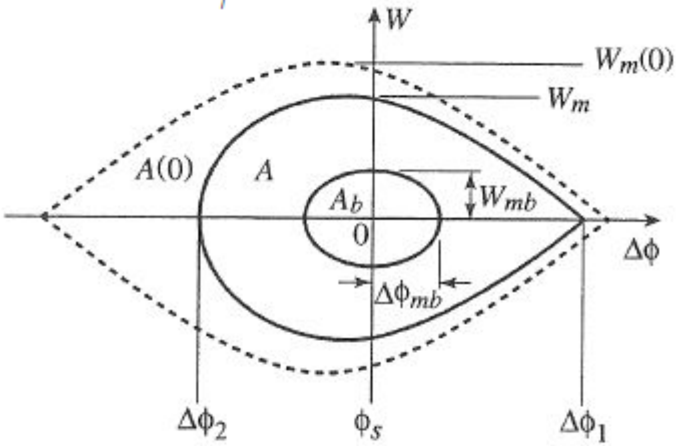
At transition crossing,
RF phase φs will move to π−φs

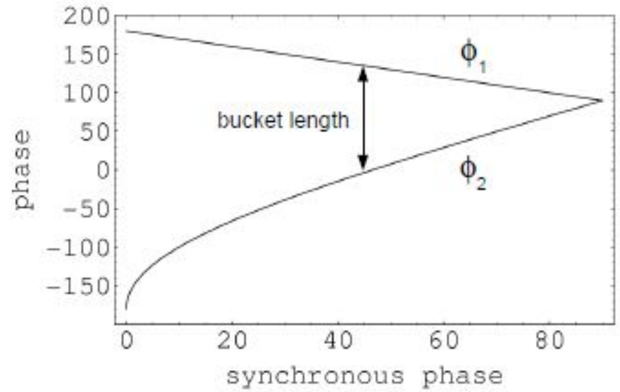
RF Bucket

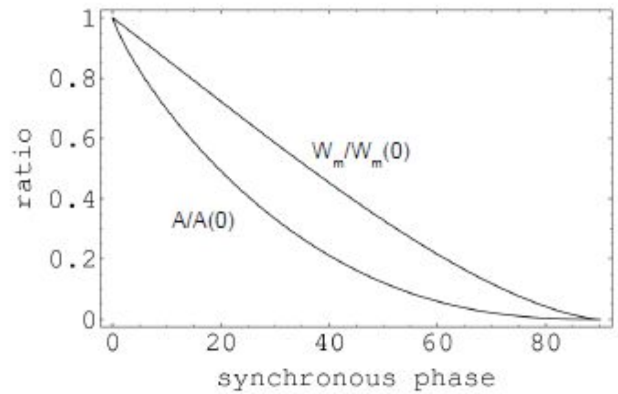
Bucket height, Wm and Acceptance, A
for moving bucket

Particles are oscillating in the bucket.

$$e\frac{dB\rho}{dt} = \frac{1}{\beta c}\frac{dE}{dt} \qquad E = V\sin\phi_s$$







$$\phi_1 = \pi - \phi_s$$

$$\cos(\phi_2) + \phi_2 \sin\phi_s = (\pi - \phi_s)\sin\phi_s - \cos\phi_s$$

Bucket height and acceptance for stationary bucket

$$W_m(0) = \sqrt{\frac{2eV\beta_s^2 E_s}{\pi h |\eta_s| \omega_{rf}^2}} \qquad A(0) = 8\sqrt{\frac{2eV\beta_s^2 E_s}{\pi h |\eta_s| \omega_{rf}^2}}$$

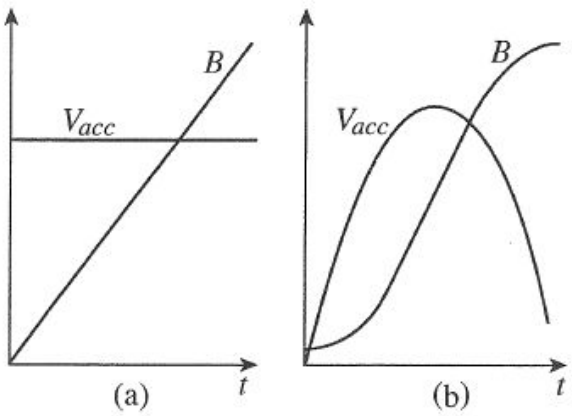
- When acceleration starts, φs is increasing, then Wm and A reduced.
- Large RF voltage is necessary to accelerate high intensity beam.

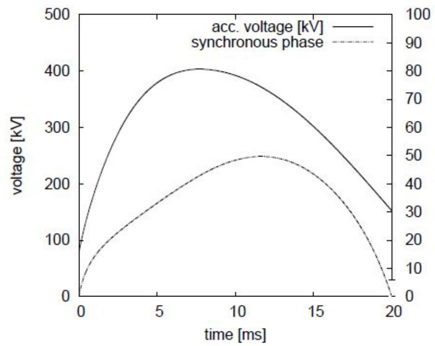
RF voltage pattern for proton ring

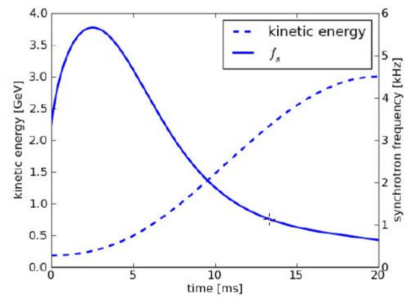
- In proton synchrotrons, bunch length is gradually shortened by adiabatic damping. Momentum spread is increasing and emittance is constant.
- In electron ring, synchrotron oscillation is damped by synchrotron radiation. But, the radiation also excites the particles. Emittance is given by two effects.
- In proton ring, emittance matching is important as no synchrotron radiation.

$$\Delta E = qC\rho \frac{dB}{dt}$$

(a): dB/dt = c
(b): RCS

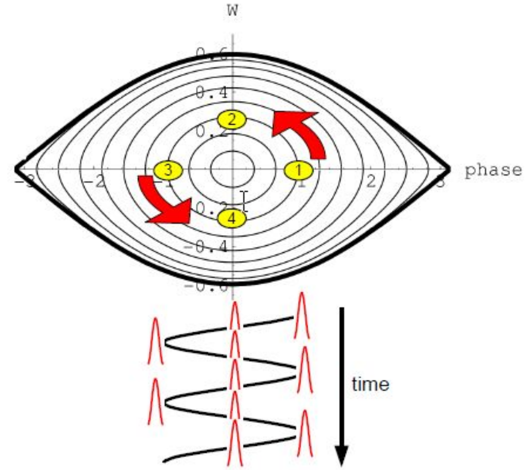


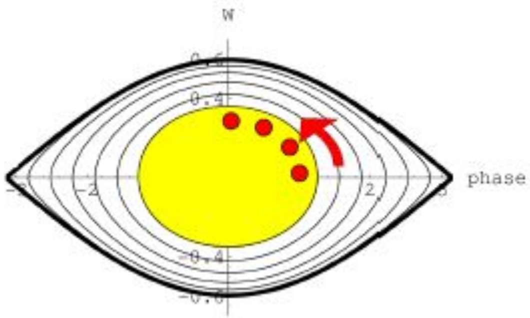




- A computer code, RAMA, is suitable to estimate the bunch size and energy spread during acceleration from magnet pattern.
  - Developed by Rick Baartman, TRIUMF.
- The emittance given by a booster accelerator can be used for another accelerator (Main Ring).
- It also gives longitudinal beam impedance and instability effects.
- Hoffman-Pedersen distribution is used to estimate the longitudinal space charge.

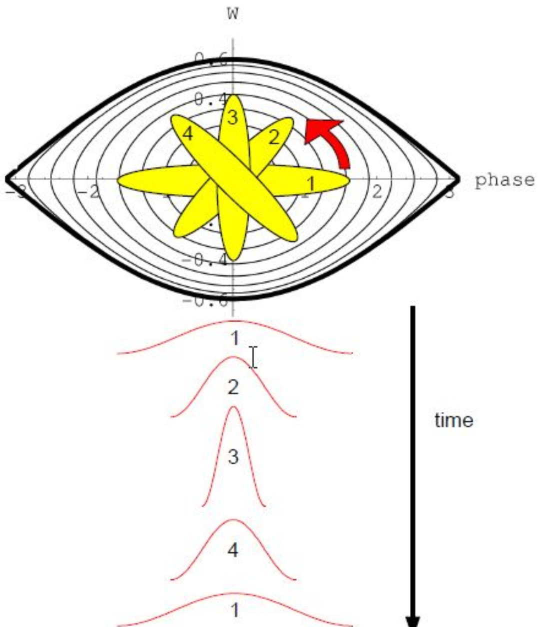
Motion of particles

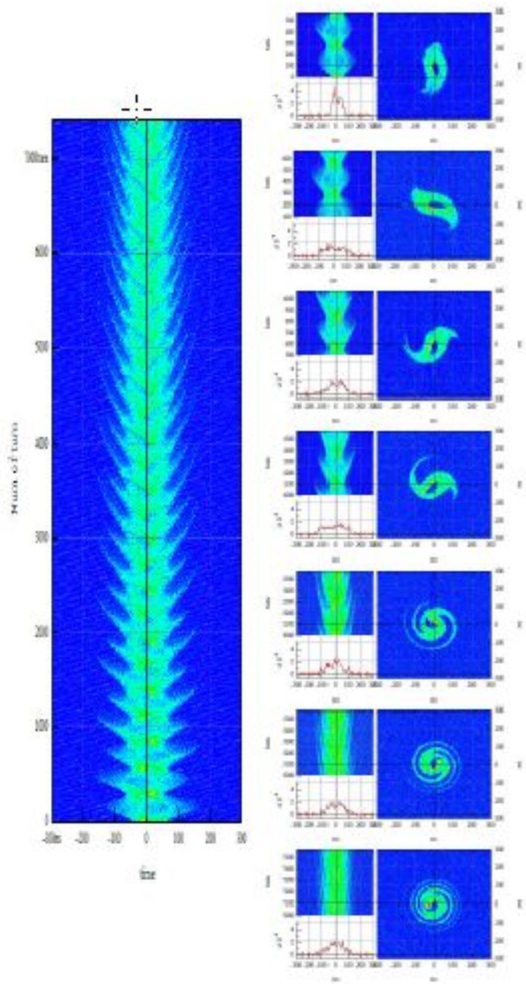




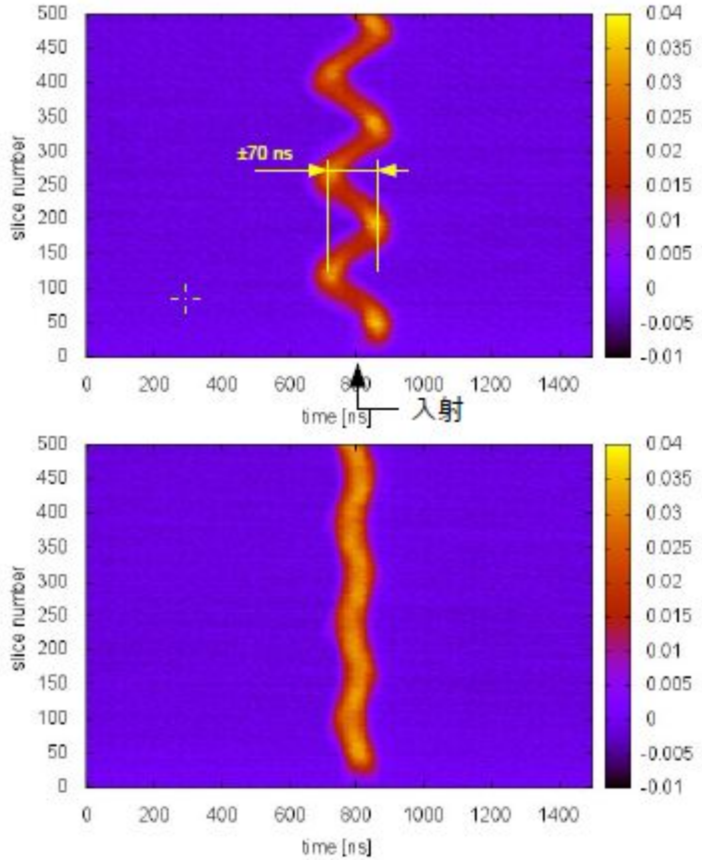
If bunch is matched to rf ucket, dipole and quadrupole oscillations will not be excited .

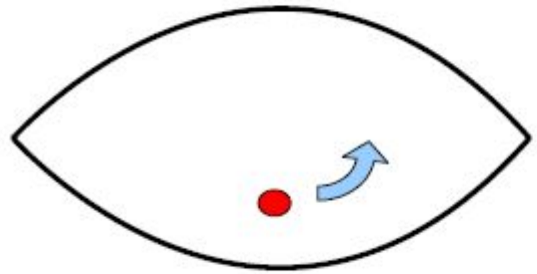
If it is not matched, filamentation and emittance growth occur.





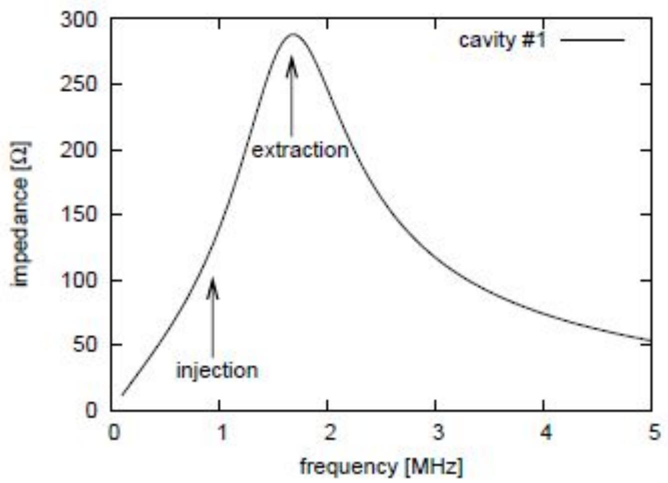
Way to adjust RF frequency to initial energy





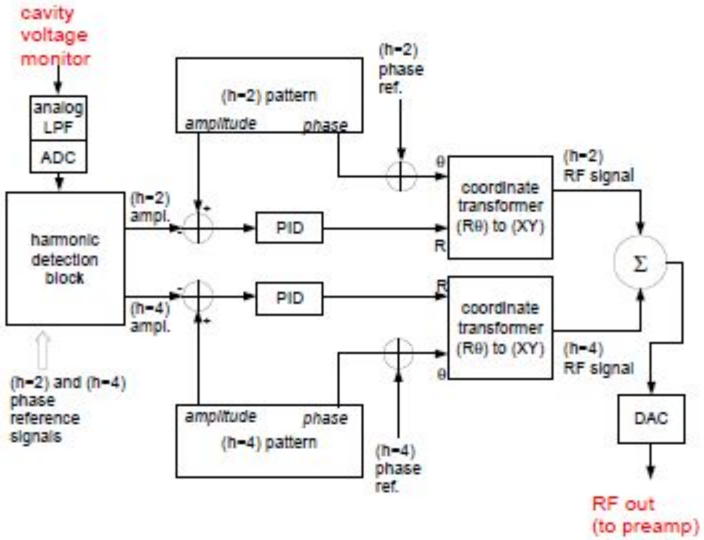
When bea was injected to RCS, dipole oscillation was observed. It suggests, rf frequency is high. The frequency was reduced to 938175Hz from 939471Hz to match.

Dual Harmonic RF

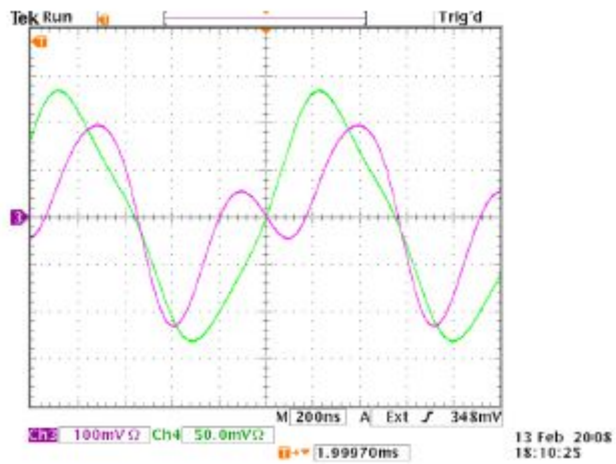


As tuning-circuit is not used for cavity, MA cavity is assumed a passive circuit. But, impedance at injection is much smaller than that at extraction. AVC gain is changed during acceleration.

In case of ferrite cavity, two different RF system have to be handle.



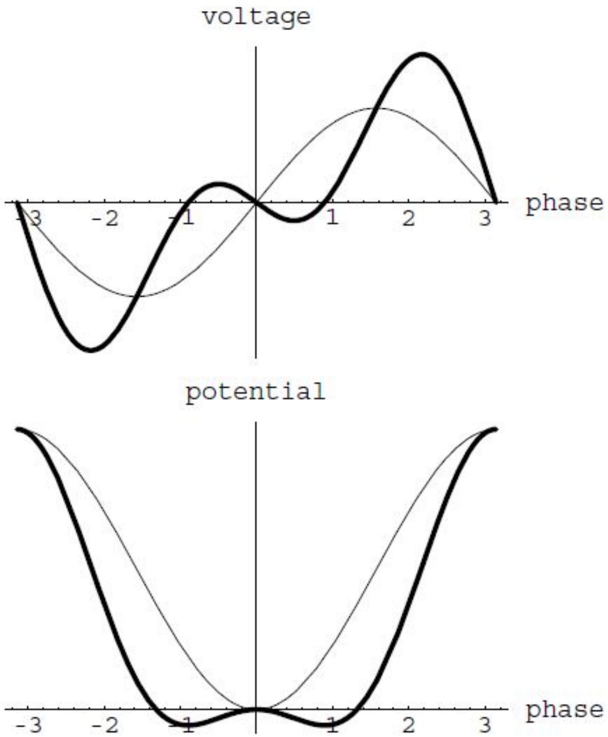
Dual harmonic AVC

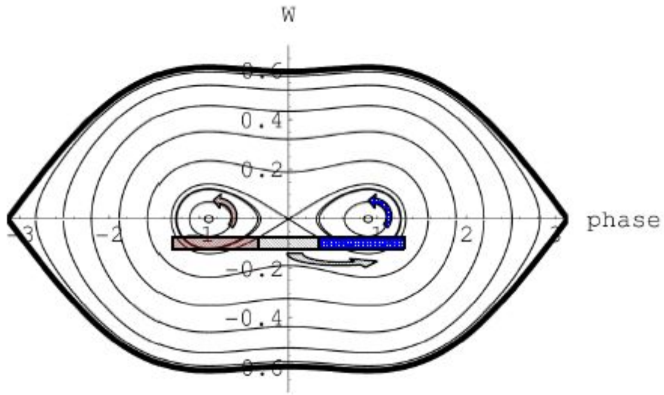


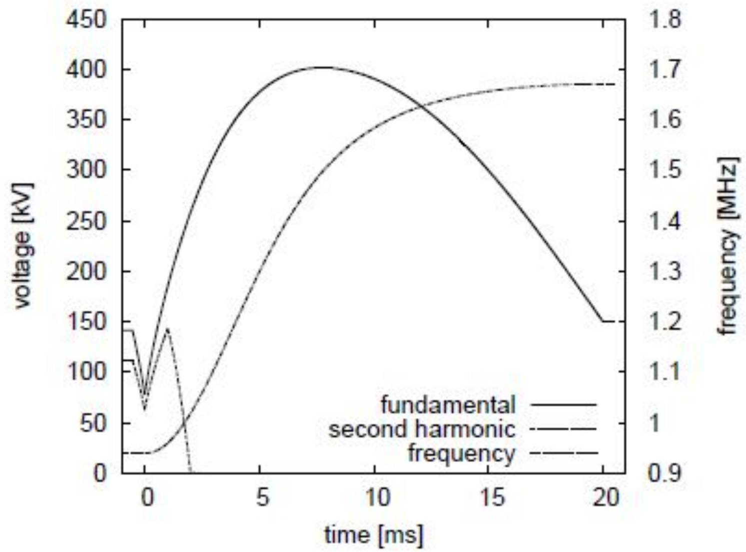
Dual harmonic RF voltage (red)

Space charge effects

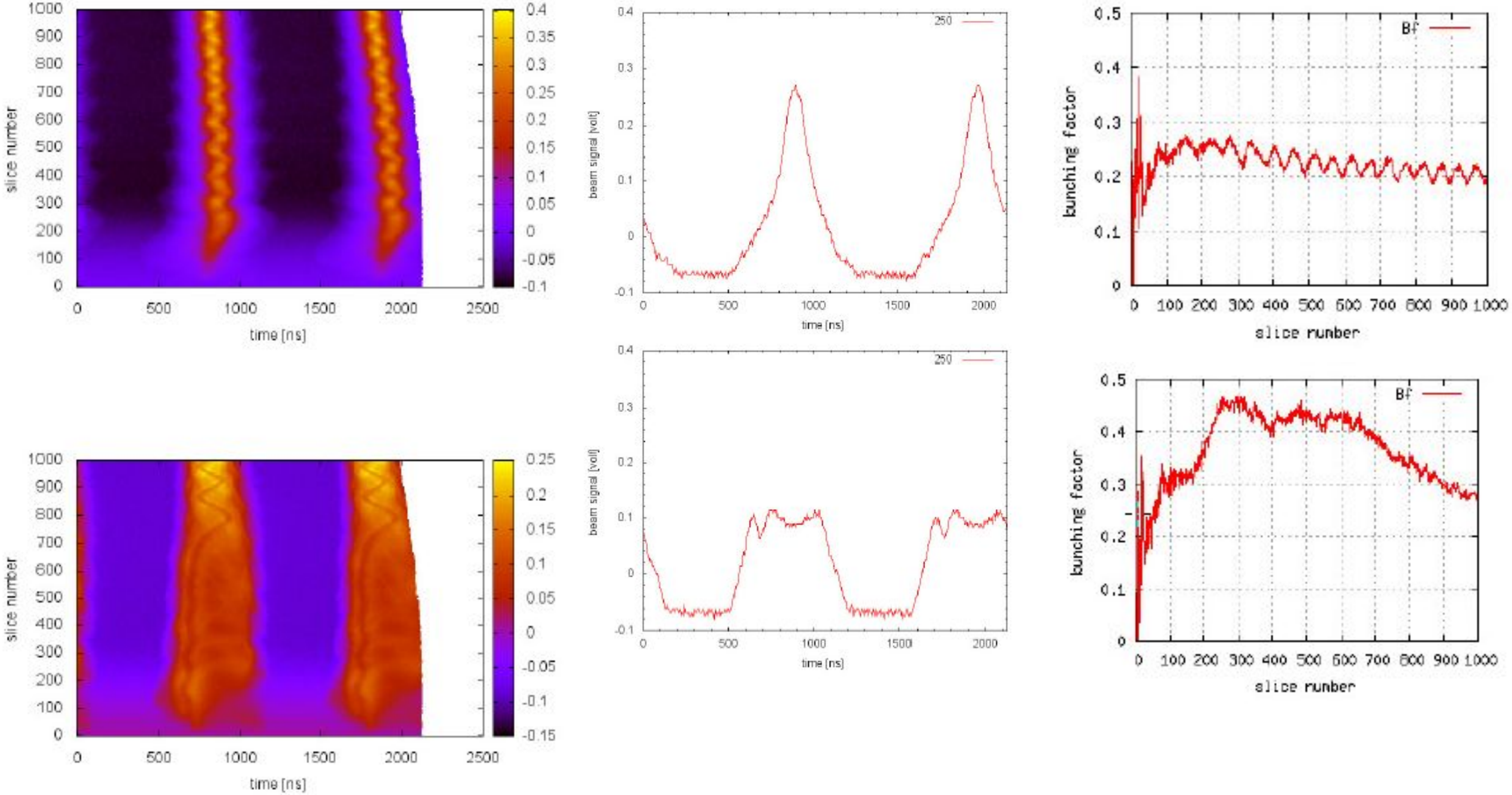
- Dual Harmonic is a powerful tool to reduce the space charge effects







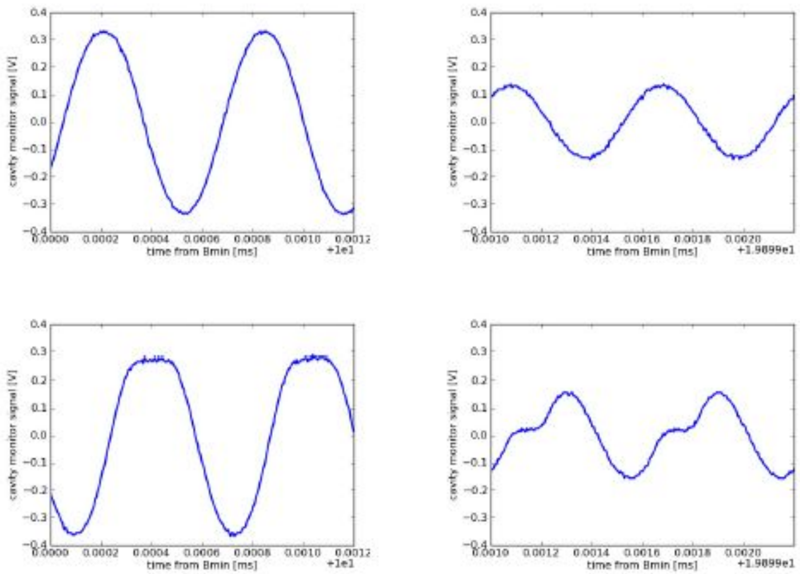
- Effects on beam



High intensity beam

- To accelerate high intensity beam,
  - Beam loading on RF sys.
  - Space charge effects
  - Instability
  - others

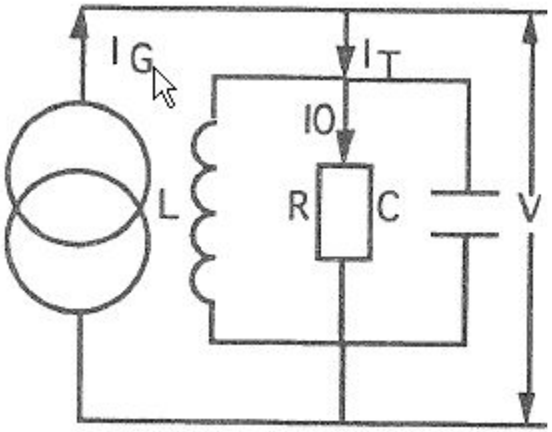
should be care.

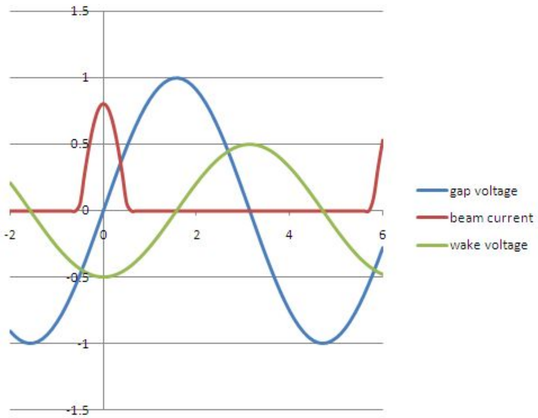


Example of beam loading on RCS cavity.
300 kW beam is accelerated.

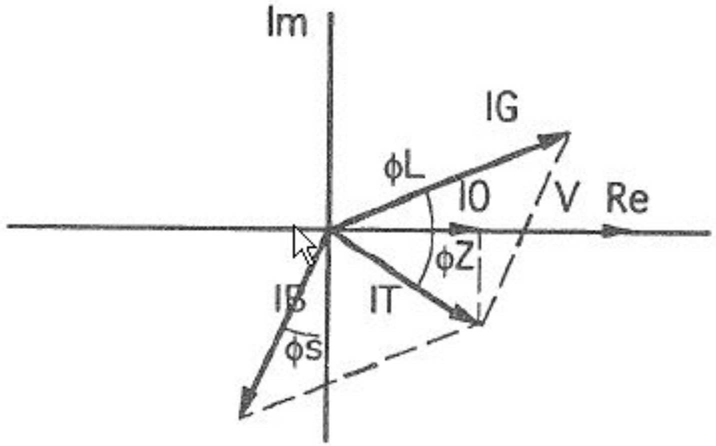
Beam loading

- Assuming cavity is parallel circuit of LCR,



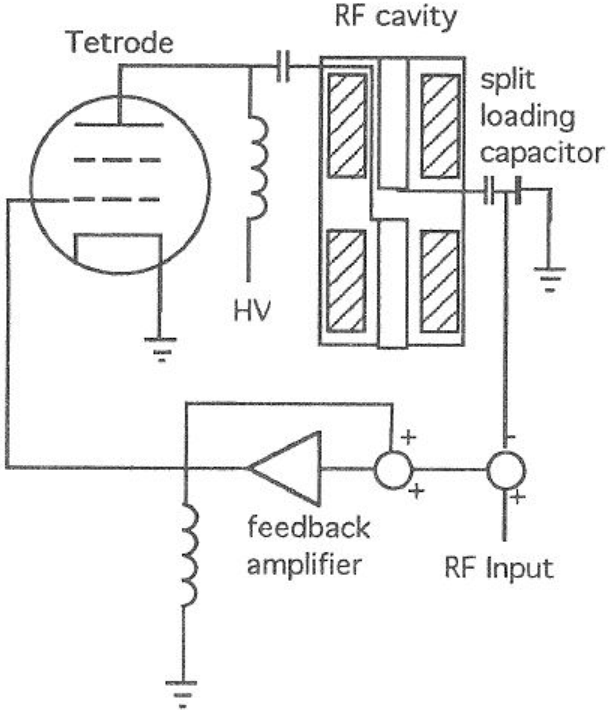


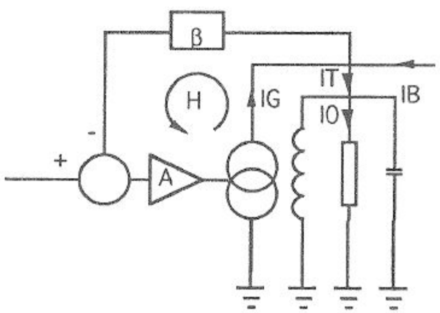
- Phase of beam is 90 deg late from RF phase.



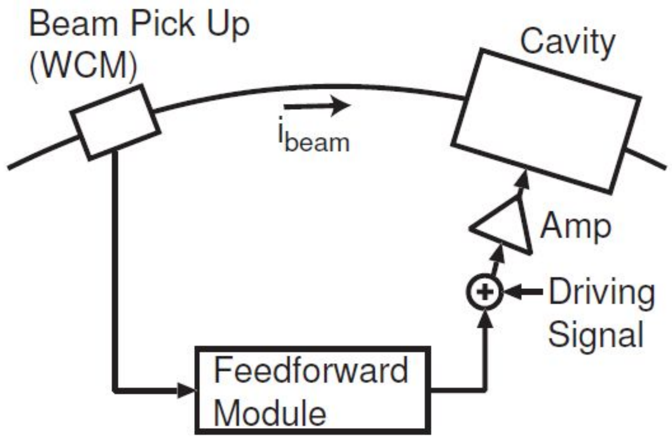
High Q system: a phaser of RF frequency
Low Q system : phaser diagrams for higher components

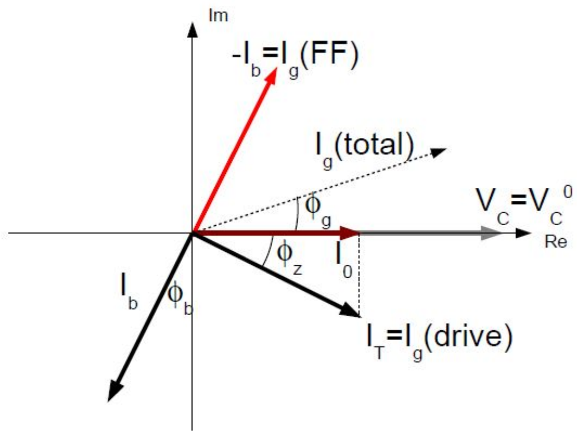
- Direct Feedback





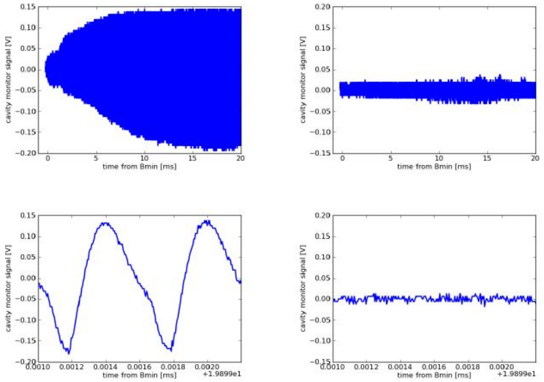
- Feed forward



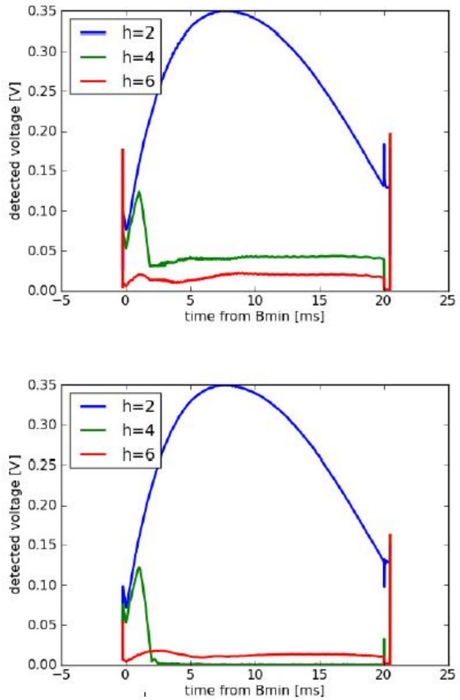


In case of ferrite system, tuning loop makes the system complicated.

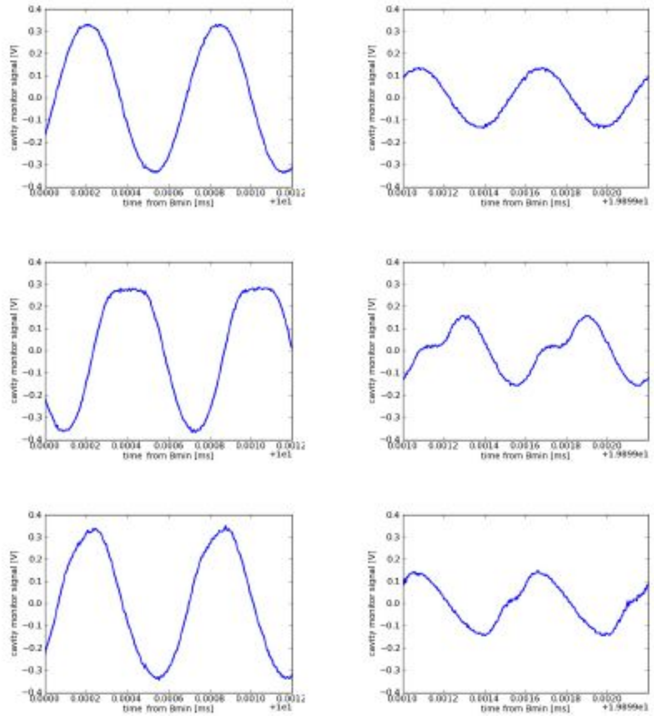
- Feed forward



10 cavities for acceleration,
1 for measuring wake voltage
Left FF OFF, Right FF ON

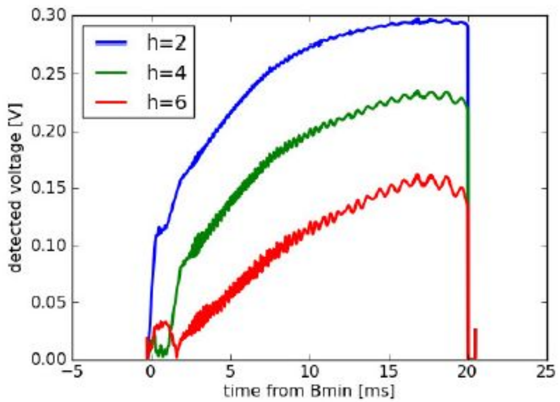


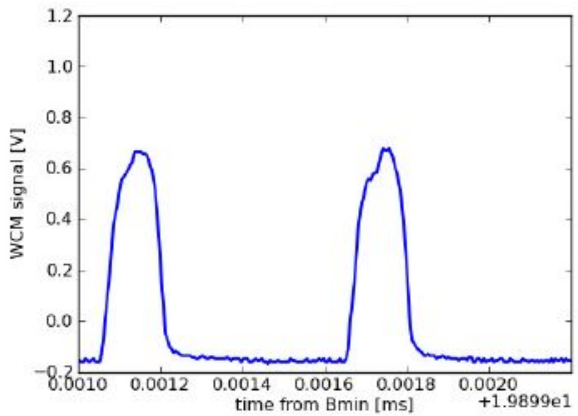
Gap voltage for each RF component
Upper FF OFF,
Lower FF ON

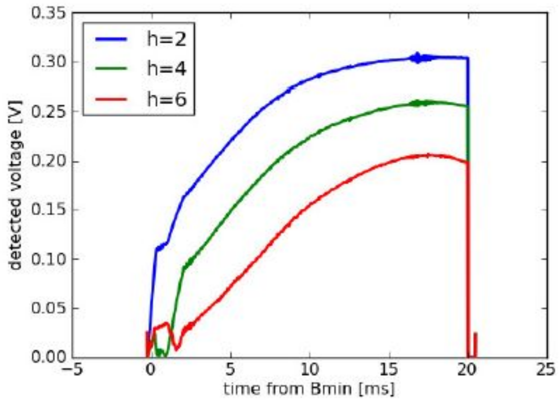


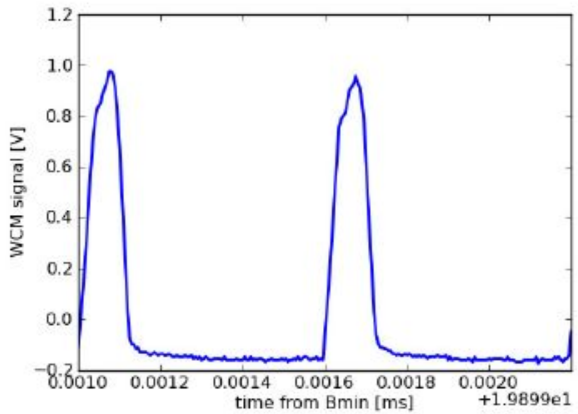
Gap voltage
Right acceleration, Left Extraction
Upper w/o beam
Middle with 300kW beam FF OFF
Lower with 300 kW beam FF ON

- # Effects on beam









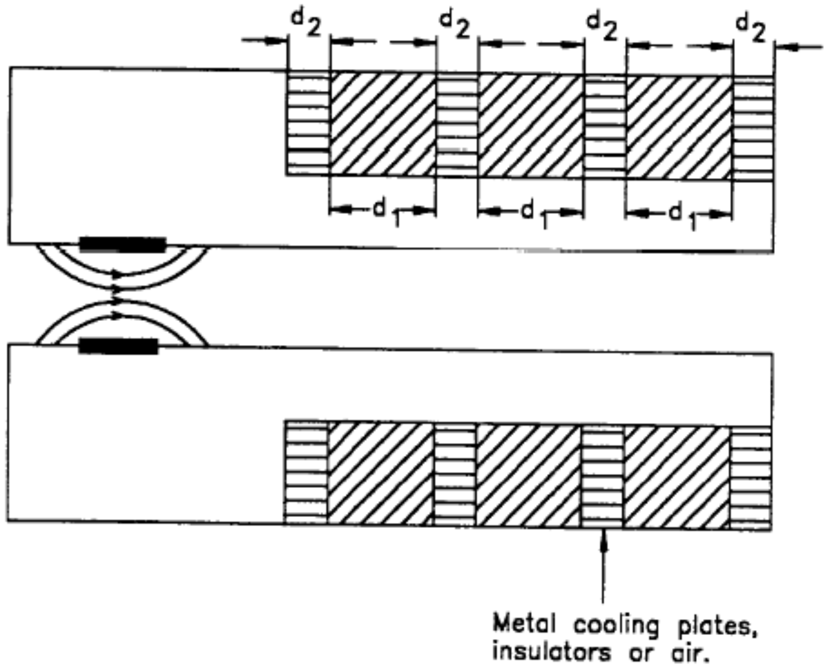
After 2 ms, h=4 and 6 show oscillation.
It is quadrupole (or higher).

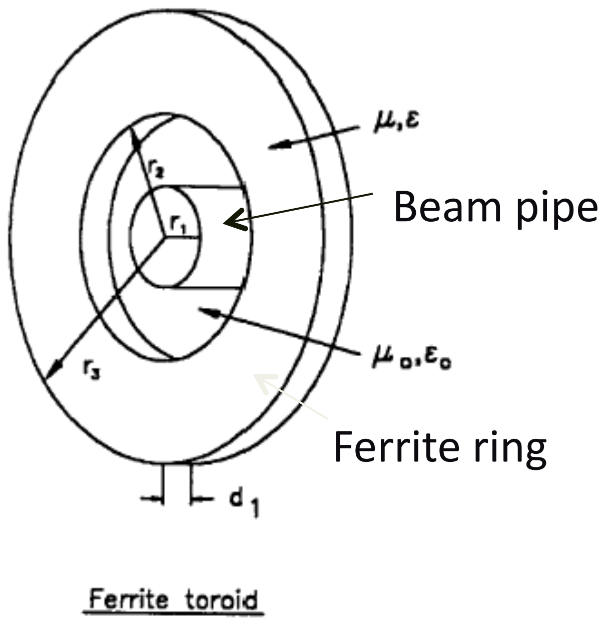
Beam bunch becomes narrow
(emittance growth was reduced)

RF Systems

Proton Rings
Ferrite cavities

- In hadron accelerators, velocity of particle changes (not β=1 as electron accelerators). When synchrotron was developed ferrite cavity was the most possible scheme to sweep the rf frequency.

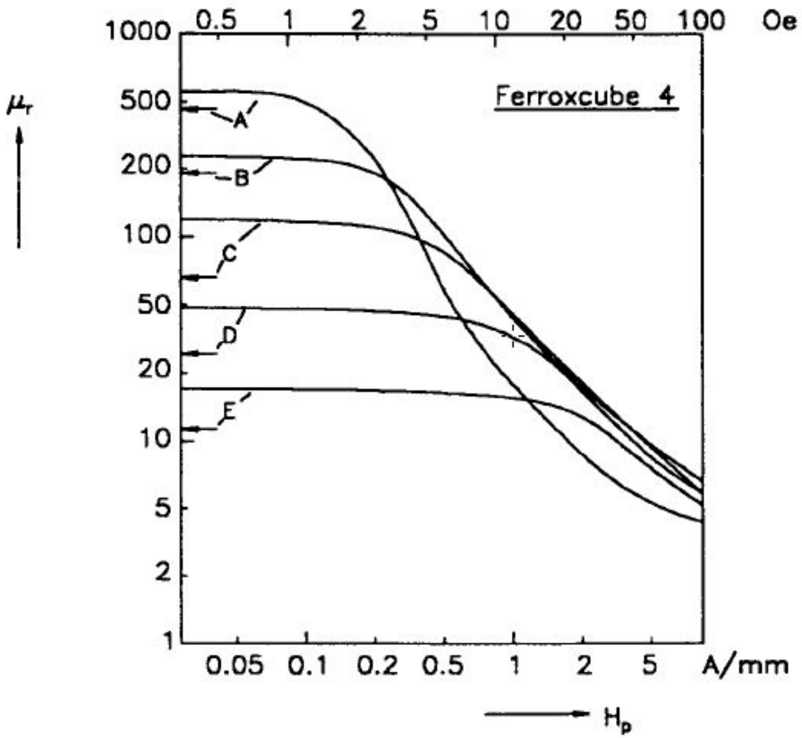


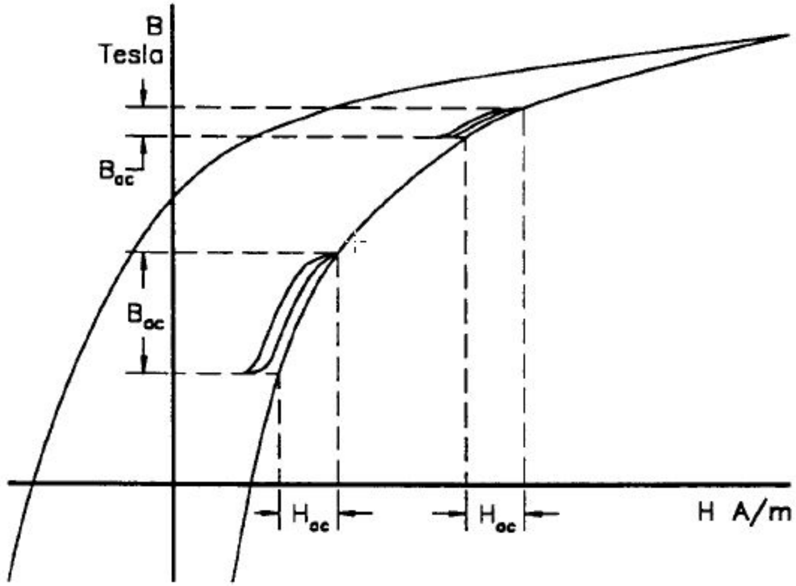


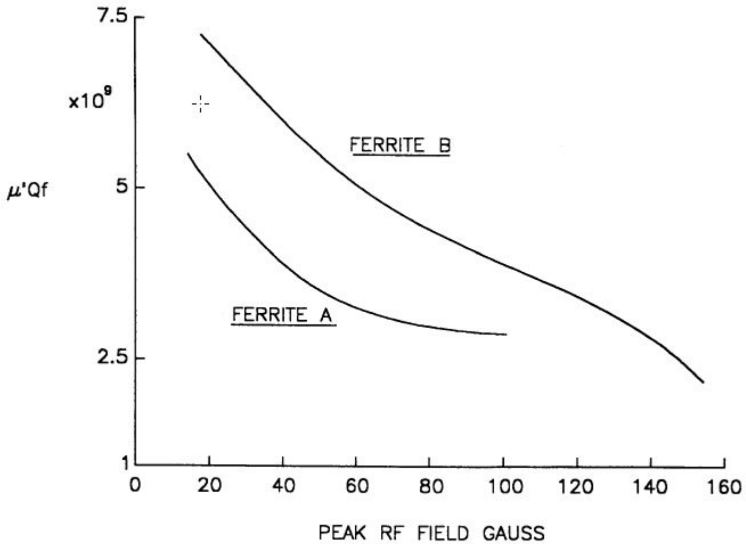
Ferrite cavity

HIMAC Ferrite Cavity & AMP
Courtesy of M. Kanazawa

Characteristics of ferrite

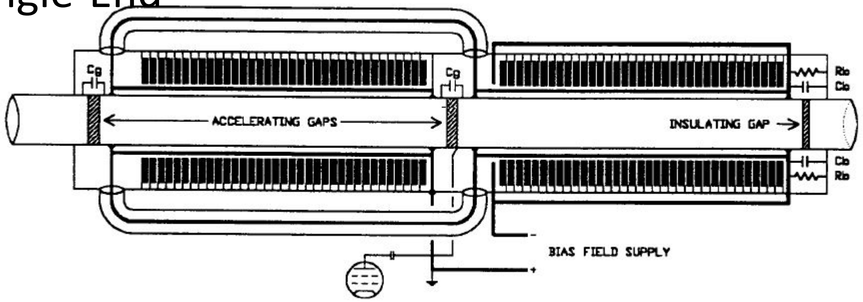


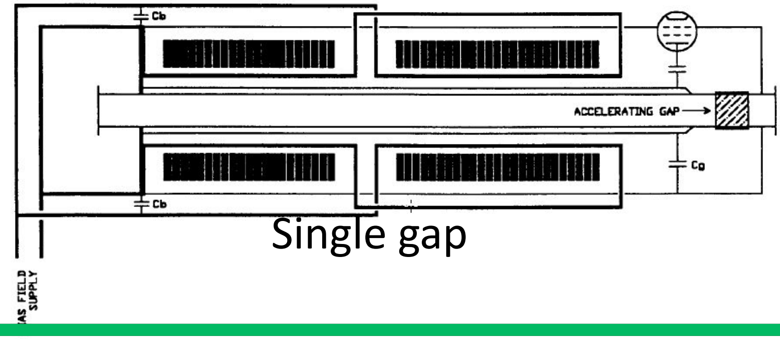




Ferrite Cavities

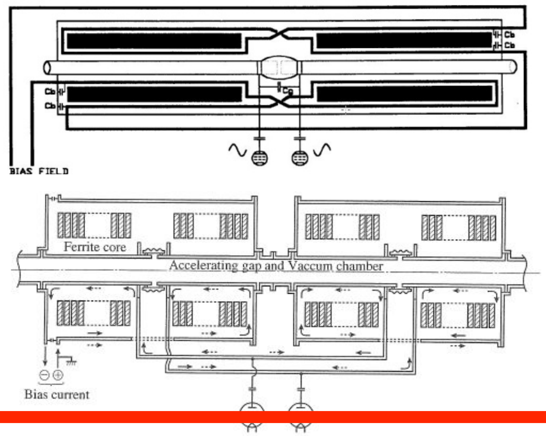
Single-End



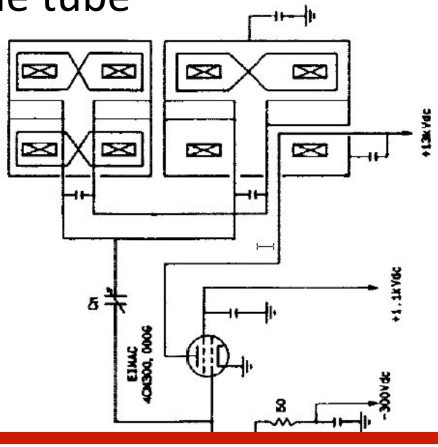


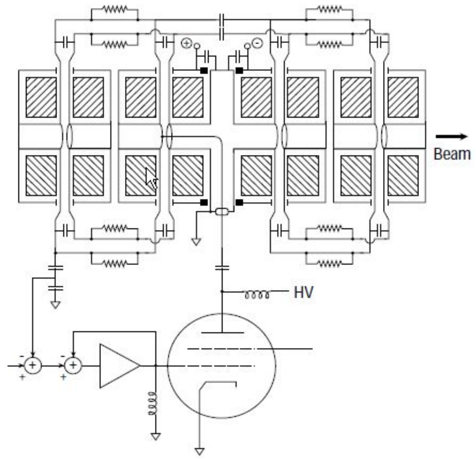
Single gap

Push-pull

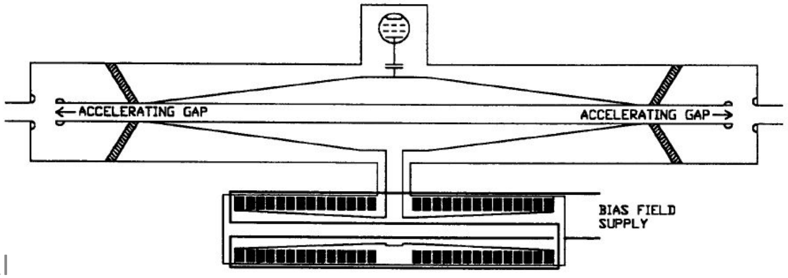


Single tube



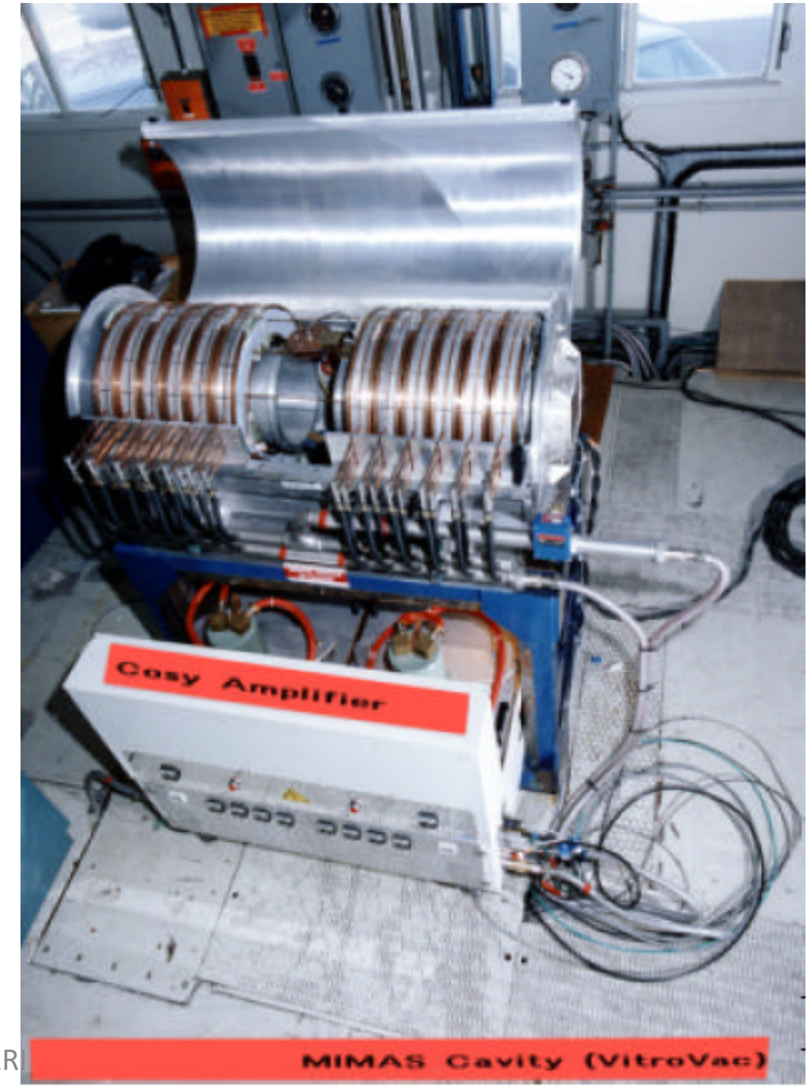


Drift-tube



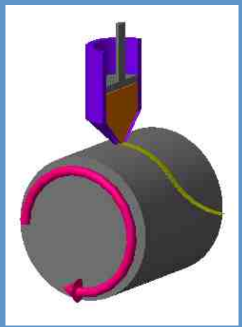
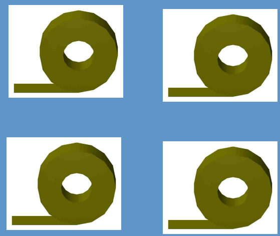
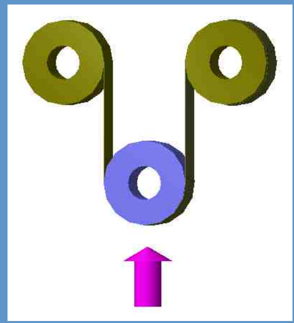
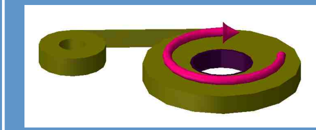
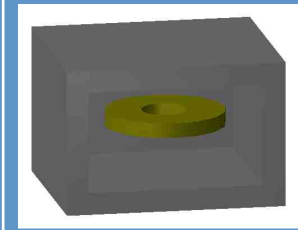
Magnetic Alloy cavity

- MIMAS Cavity
- Probably, this is the first MA cavity.



Courtesy of A. Schnase

Production of MA

				
①Amorphous→	②Ribbon→	③SiO2 Coating→	④Winding of large core→	⑤Annealing

Production of Ferrite Core

Ferrite powder with glue
Forming a ring core shape
High pressure press
Annealing
Polishing surface

Comparison

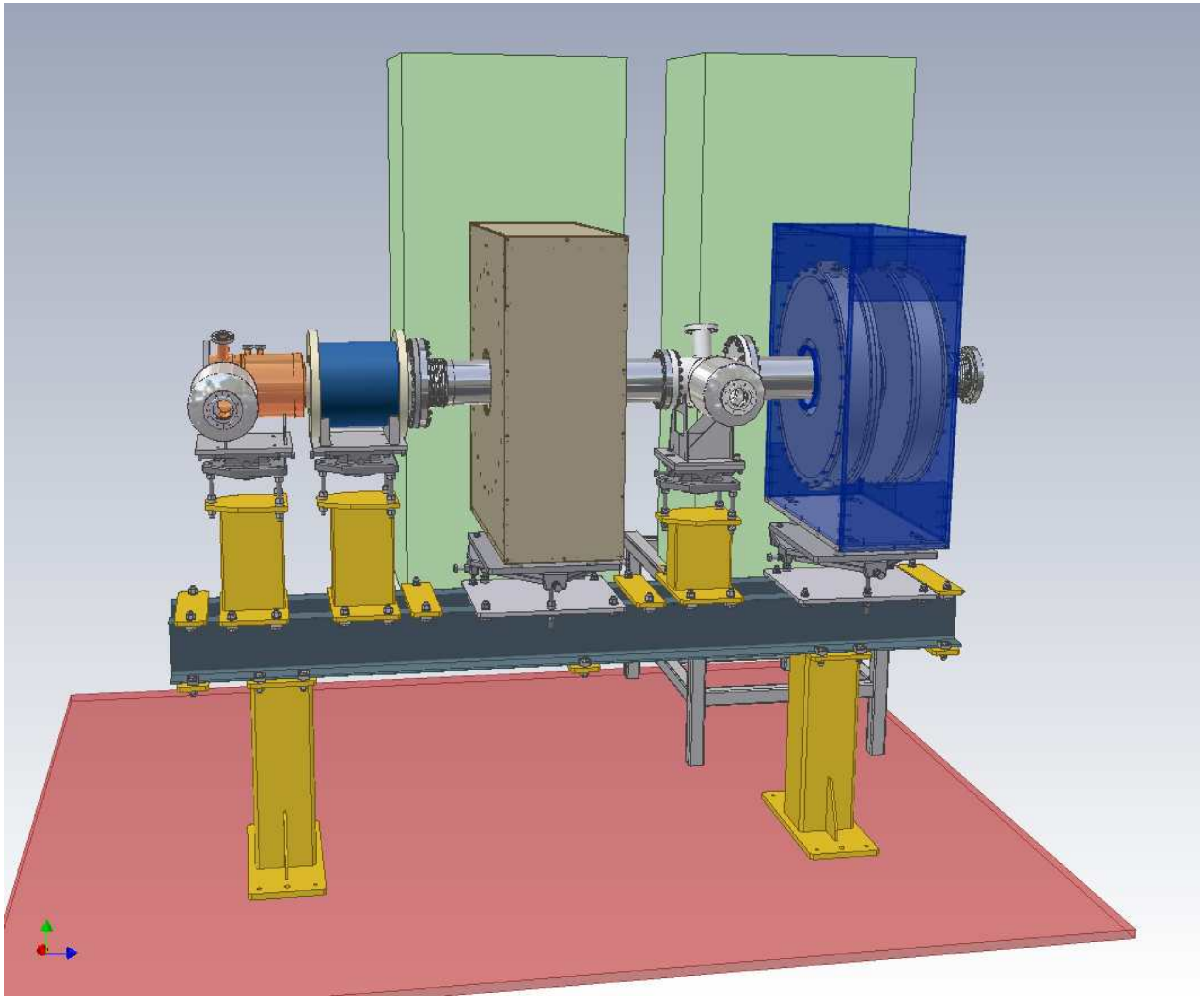
	MA	Ferrite (Ni-Zn)
Saturation flux density	1.2 T	0.4 T
Possible Acc. Field gradient	High (25kV/m for J-PARC) (depend on duty factor)	Below ~15kV/m (depend on freq. and I.D.)
Permeability	~3000	~500
Core impedance	Few 100 Ω/core	Few 100 Ω/core depend on voltage
Q-value	~0.6	Few 100
Bandwidth	Wide	Narrow

Designing of MA Cavity

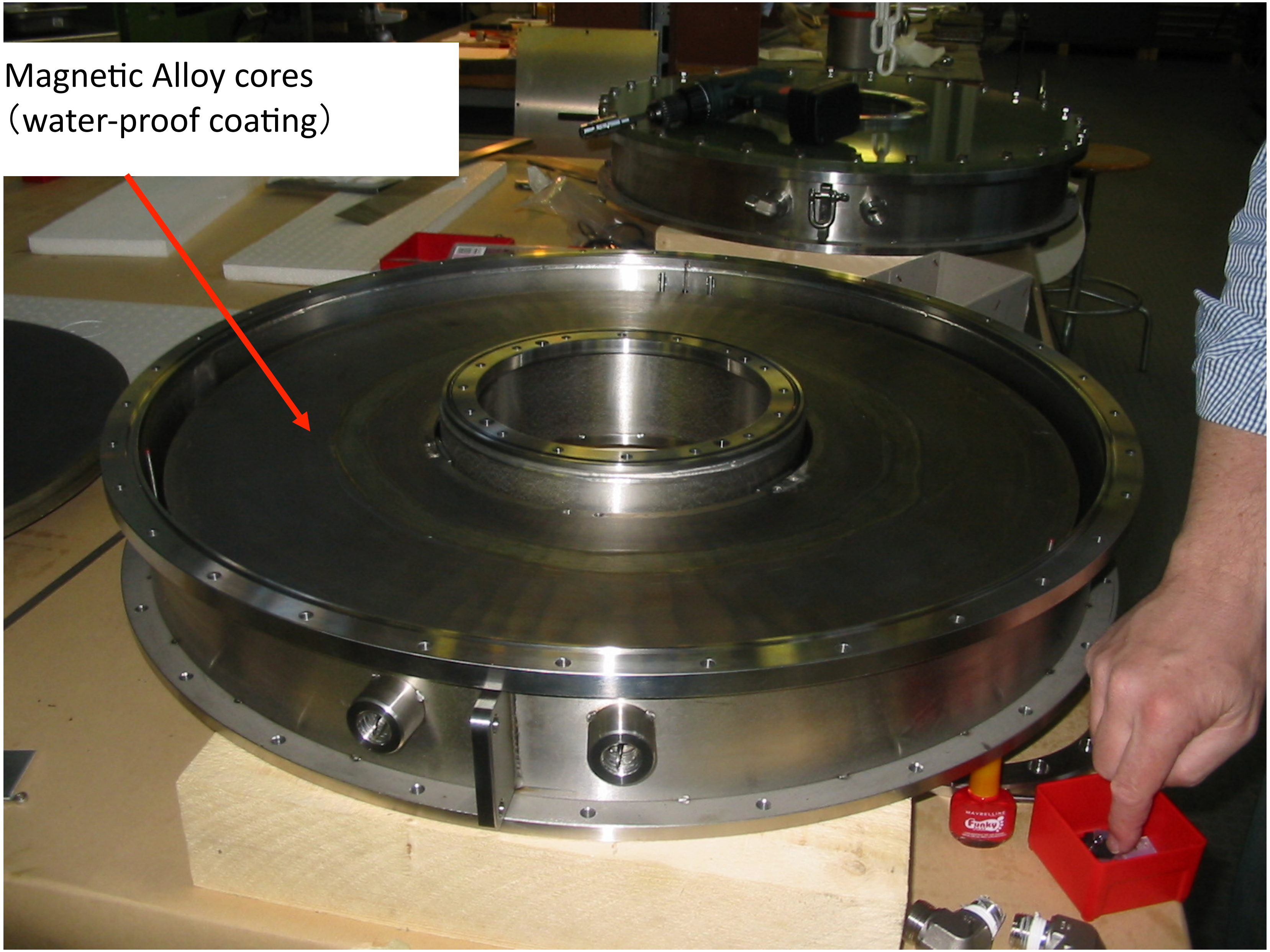
- Keys
  - Bandwidth
  - RF voltage
  - Beam current

	High gradient	Medium gradient
Wideband	Un-cut core	Un-cut core
	LEIR cavity AGS Barrier cavity	Gunma U. Medical machines
Medium	Un-cut + inductor	
	J-PARC RCS PRISM	
Narrow band	Cut core	
	J-PARC MR EMMA MA cavity	

LEIR RF SYSTEM – RING SECTION

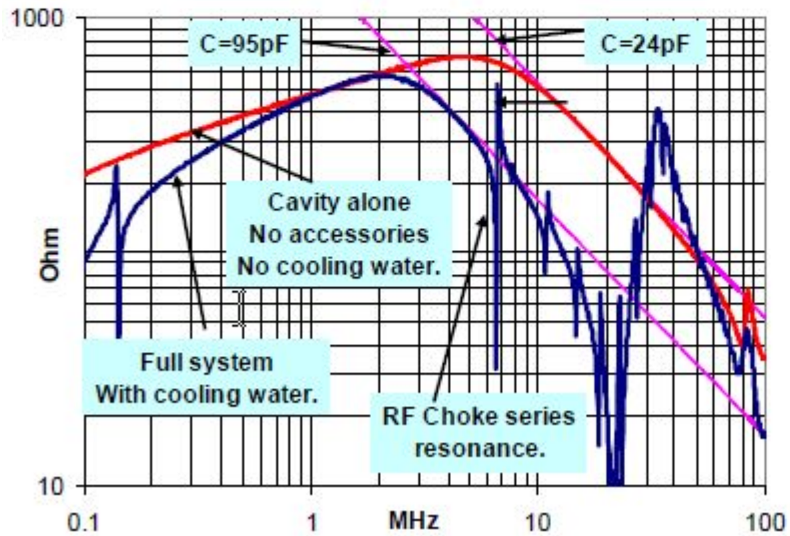


Free space is used for H=2 RF system, now.

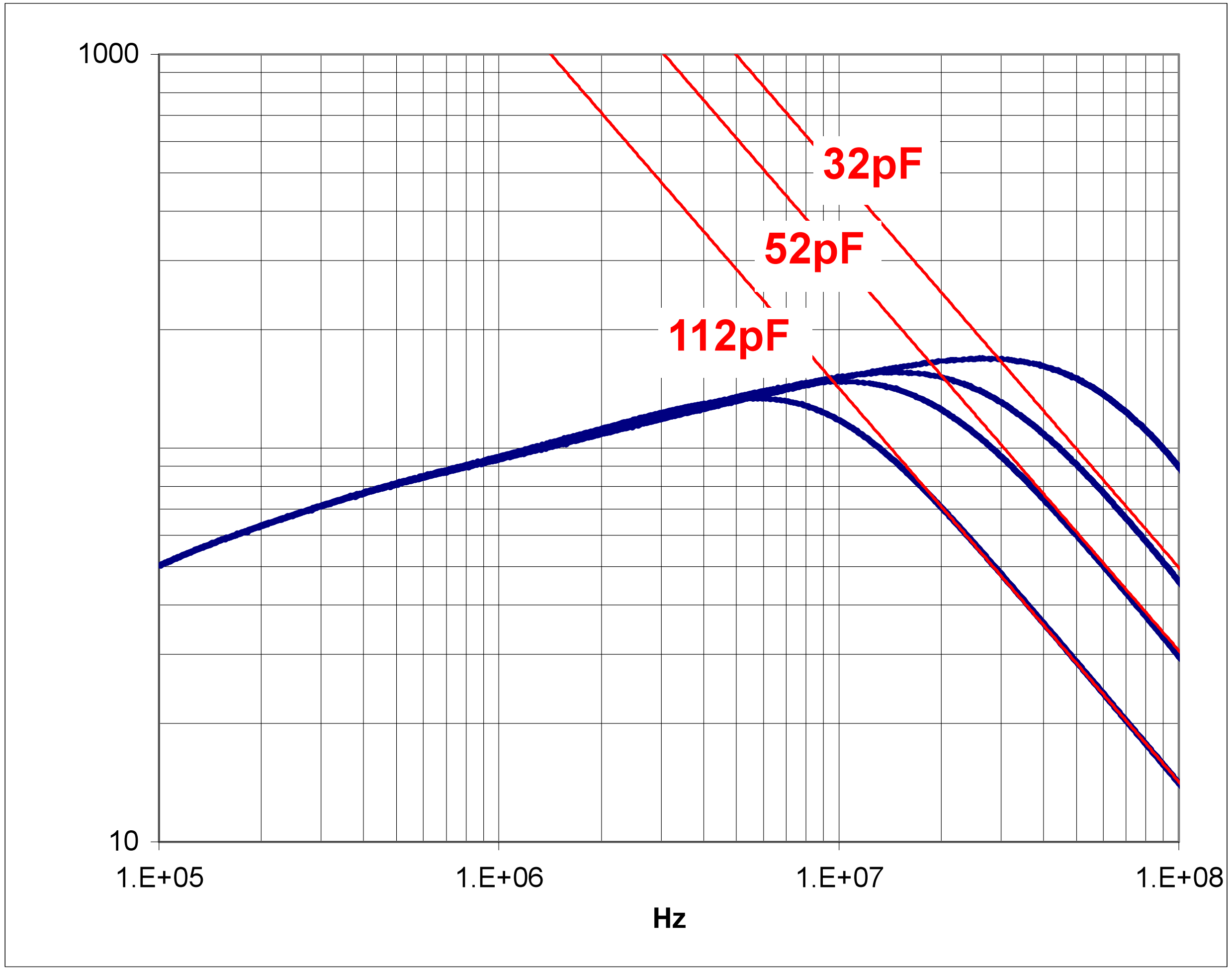

Magnetic Alloy cores
（water-proof coating）

Bandwidth

- Wideband uncut core cavity
- Bandwidth (upper) is limited by floating and tube capacitances.



LEIR RF SYSTEM
Cavity Model: Half Cavity Z (1 Core)



M. Paoluzzi

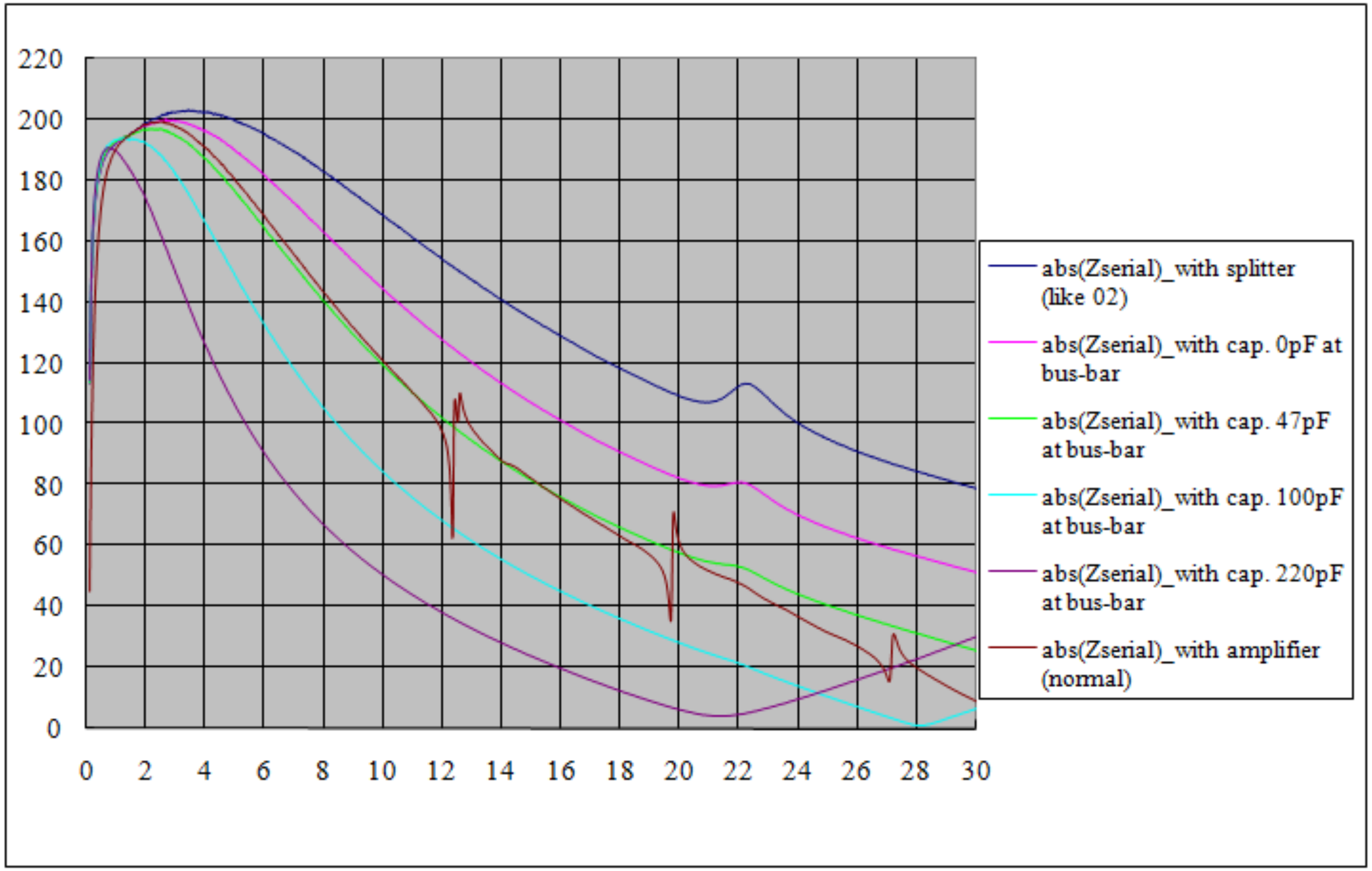
Additional C:
0
+20pF
+40pF
+100pF

Response similar to that of an RC circuit.

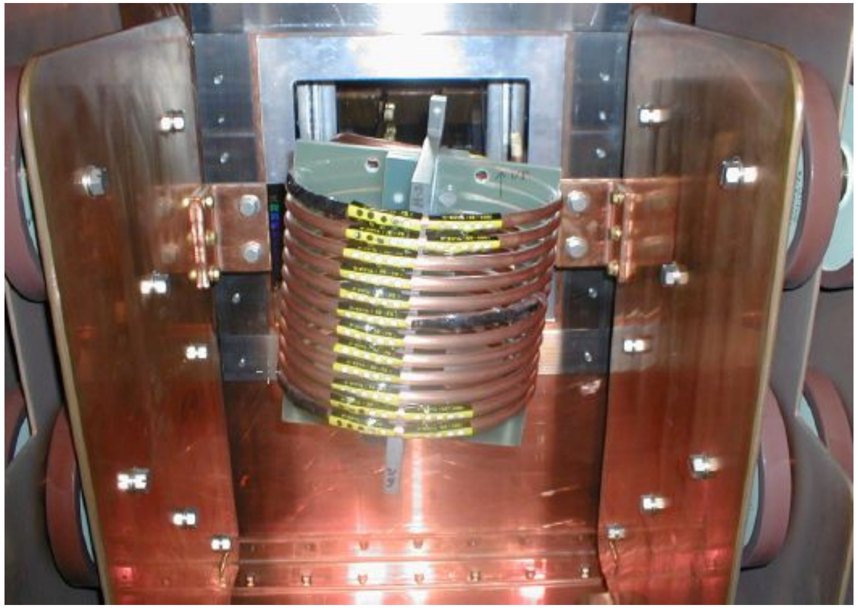
Above cutoff the slope is mainly dependent on C value.

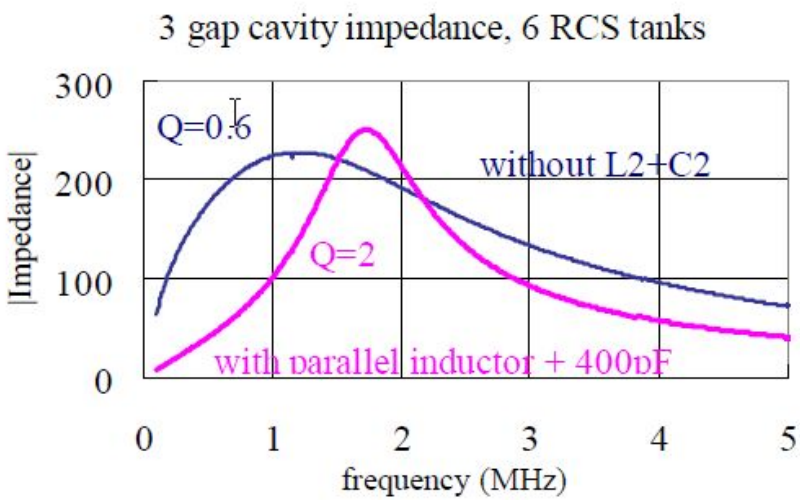
Structure capacitance is ~12pF.

Capacitance from AMP



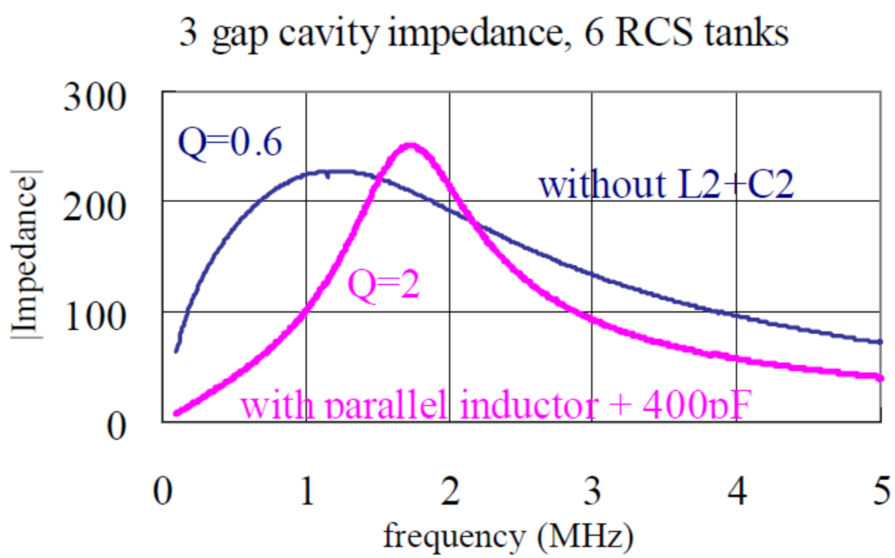
Uncut + inductor for medium bandwidth

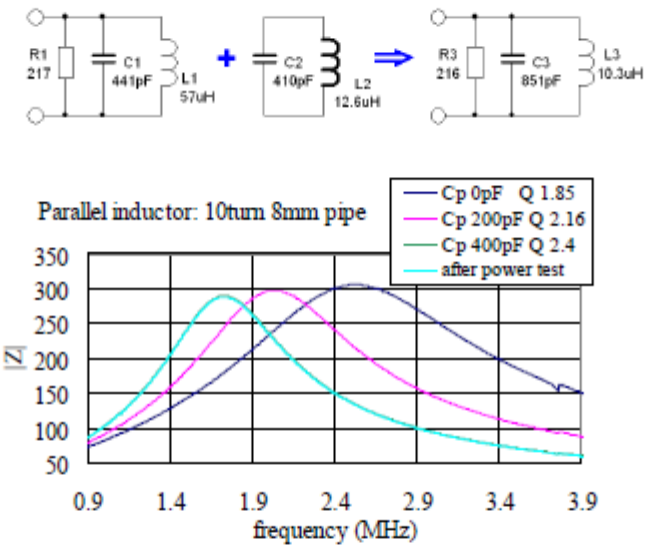




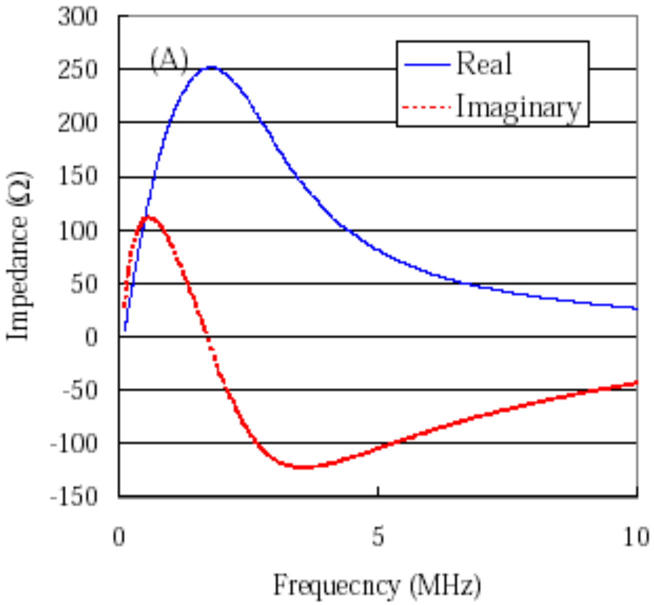
Control of Q-value w/o cutting

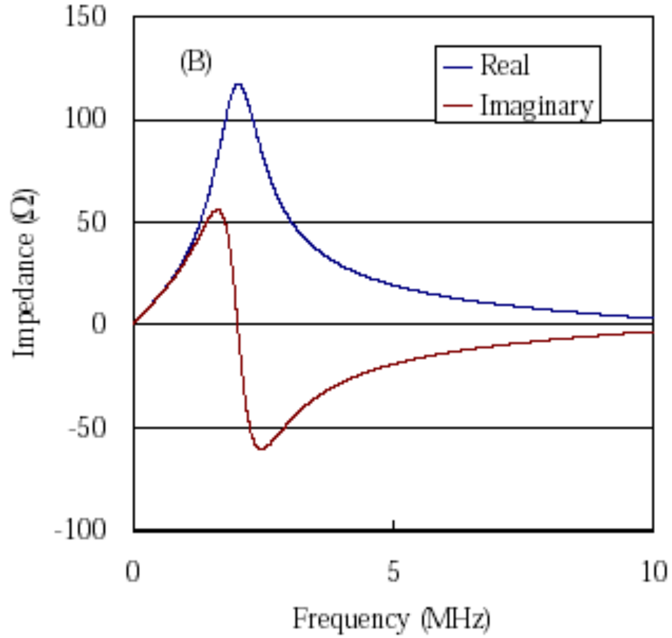
- Parallel inductance reduces inductance of resonant circuit. Additional capacitor
- Preferable Q-value for RCS, 2, for BL and dual H.
- It is too high for uncut core and too low for cut core.

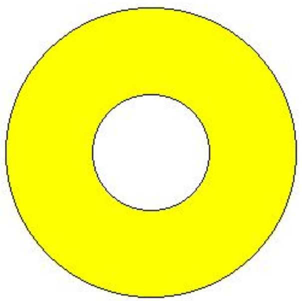


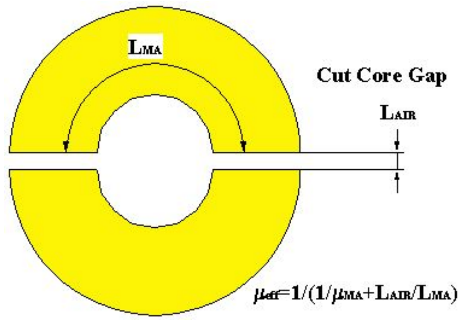


Cut Core Configuration for higher Q

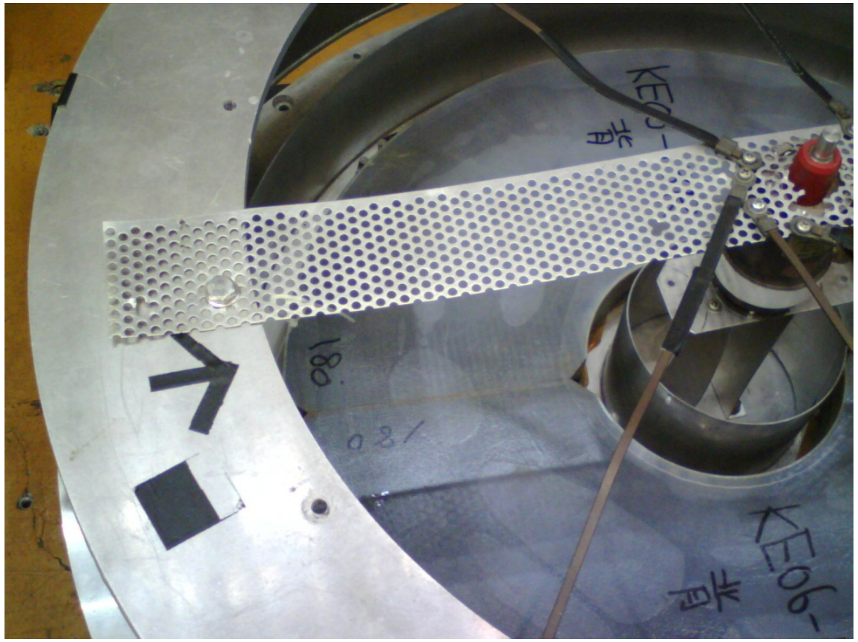


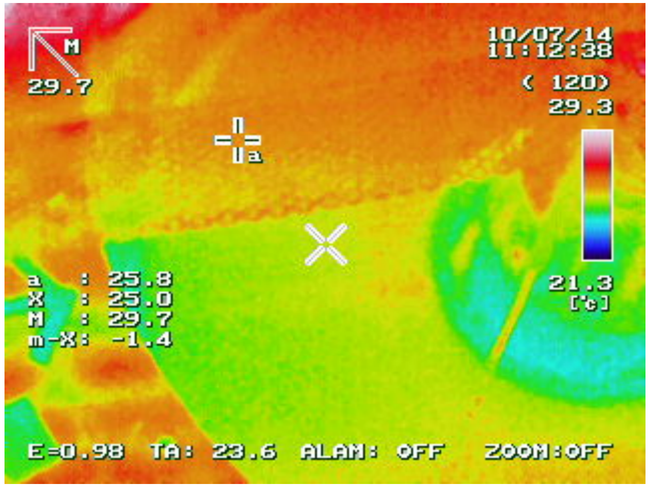




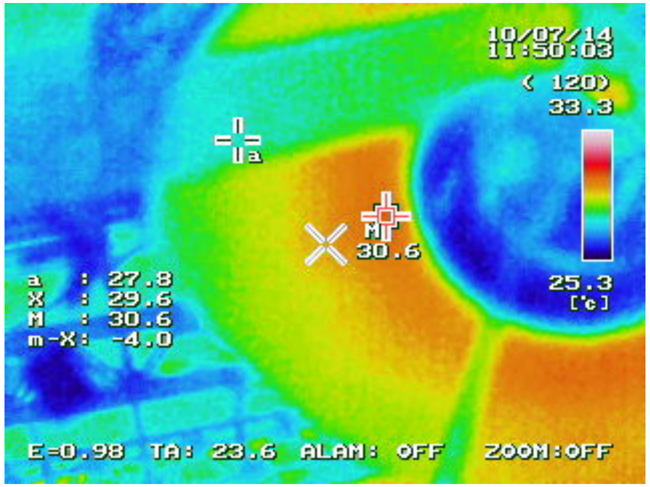


Cut Surface

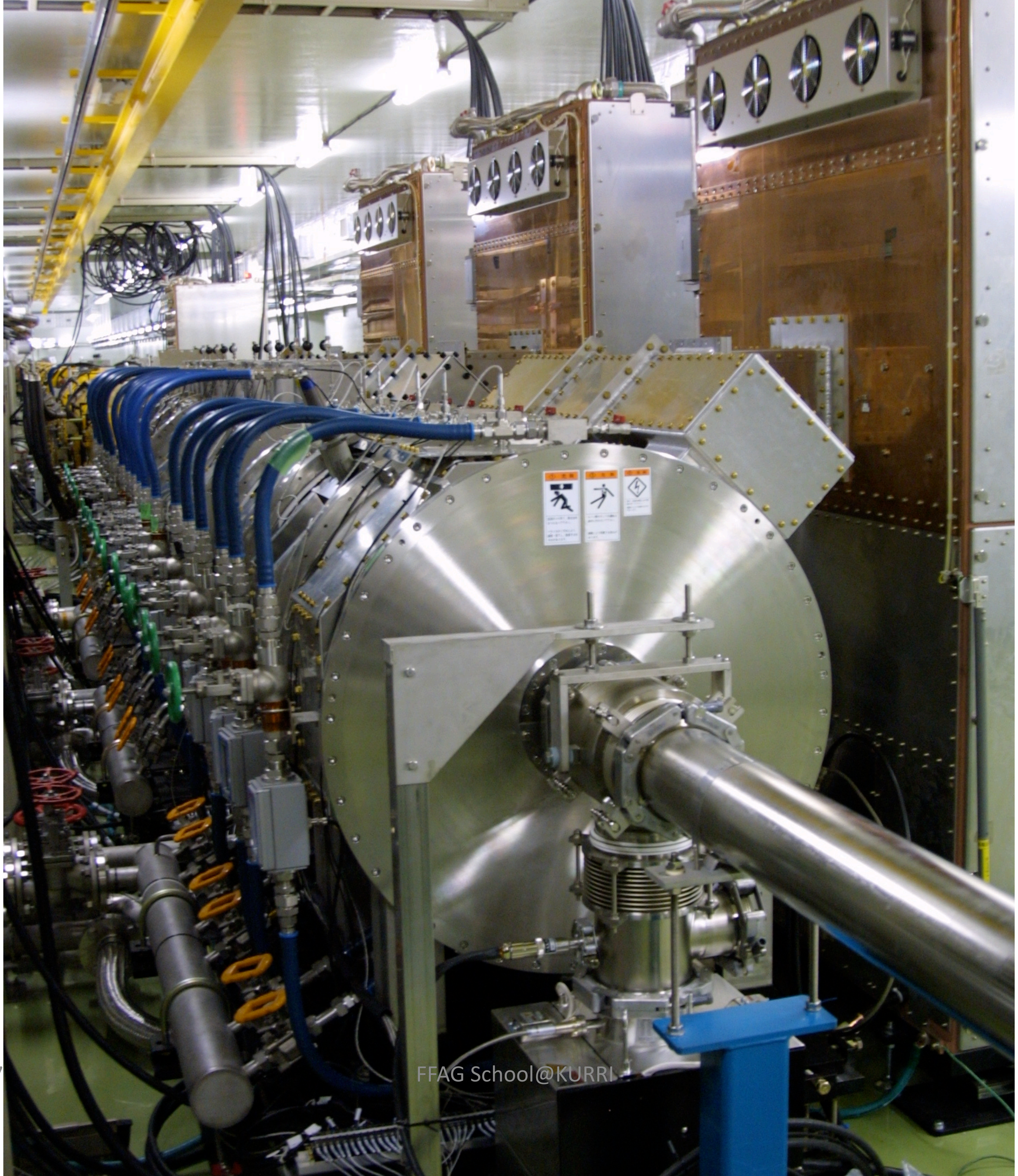




Bad polishing

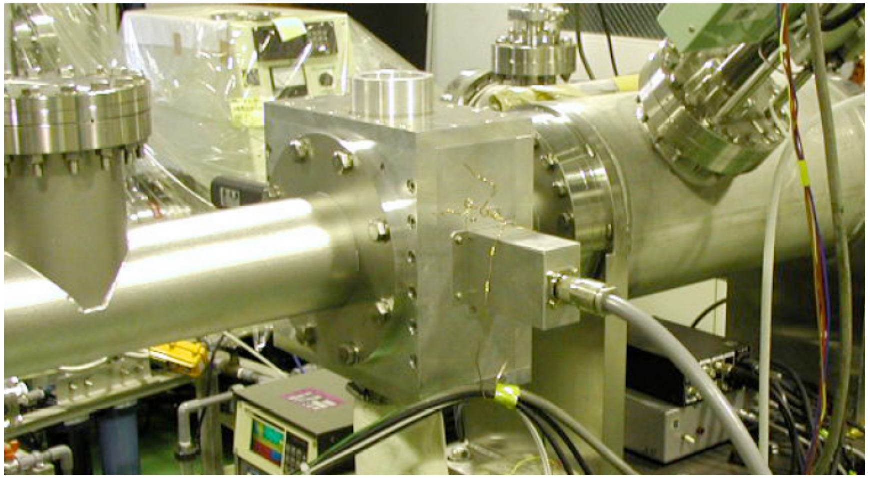


Good Polishing



Cut Core cavity

- Cut core cavity is used for
  - Accelerator with transient beam loading + very short beam …………J-PARC MR
  - Accelerator with high resonant frequency and narrow band ……….RIKEN beam chopper
- High voltage and high power use requires a good cutting scheme to avoid destruction of ribbon insulation. Destruction of insulation of 2μm will cause local heating of cut surface.

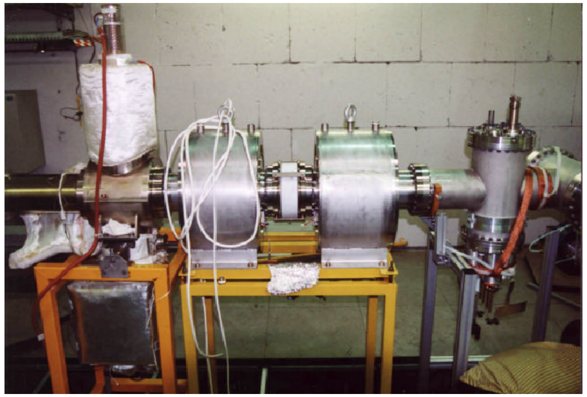


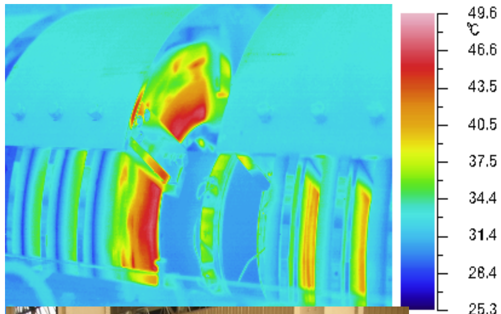
Q-value of MA cavity

Core	Q	Frequency	Uses	Accelerators
Uncut core	~0.6	300kHz-3MHz	Low energy, Ion synchrotron, Bunch manipulation	KEK PS booster, CERN LEIR, Medical use, AGS (Barrier bucket, Bunch Stacking)
Hybrid	2-	Few MHz -	Medium energy High intensity w/o transient B.L.	J-PARC RCS
Cut core	5-	Few MHz-(few 10MHz)	High energy High intensity with transient B.L., High frequency use	J-PARC MR, Riken beam Chopper

Cooling Scheme

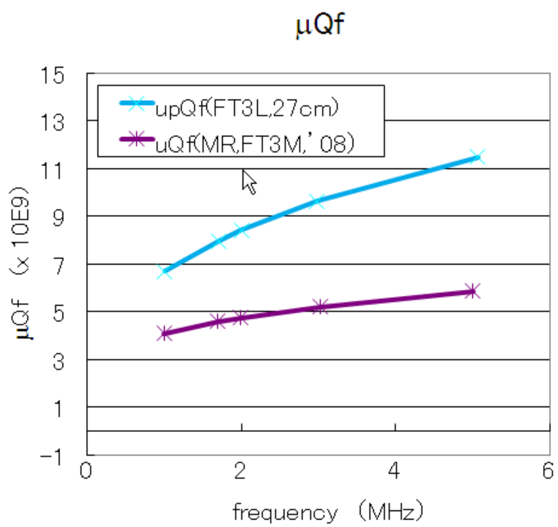
Air	Low duty	<0.2 W/cc		AGS barrier Medical use	Simple
Forced Air	High duty	? 0.5 W/cc		KEK PS booster	
Indirect	High duty	< 0.5 W/cc		JHF R&D Medical use	
Direct-water	High duty	1 W/cc	Water	J-PARC MR, RCS	High power use
Direct-other	Low duty	?	Florinate Silicon oil	KEK PS 2nd KEK PS induction	Good for higher freqeuncy

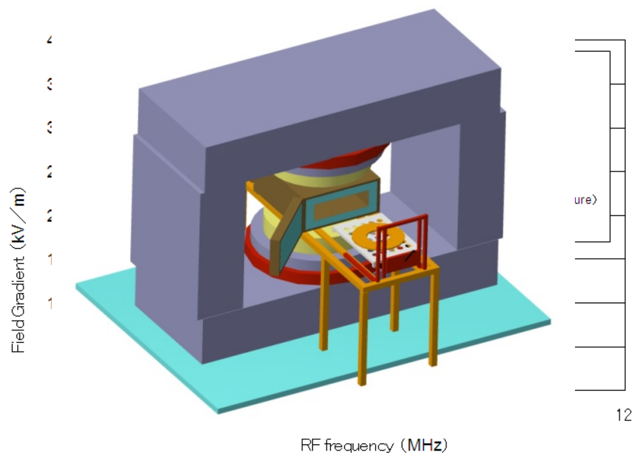




Materials

Materials	Impedance	use	Ribbon Insulation	Maker
Fe- amorphous	Low	MIMAS		VAC, Allied, Hitachi-Metal
Co- amorphous	High	Gunma Medical		Allied, Toshiba
Nano- crystalne	High	J-PARC, AGS, CERN, Riken	SiO_2 2μm	Hitachi-Metal
New MA	Higher		SiO_2 2μm	
Ferrite	High at low voltage	Many		





A large MA core using new material, FT3L,
Is under developing at J-PARC

RF System

MA Cavity

- MA cavity
  - Passive LCR circuit
- Final stage AMP
  - Wideband circuit, multi-H
  - CG: all pass network
- Driver AMP
  - Few kW
- Low Level RF
  - Multi-H
  - ALC, (phase, orbit), beam loading

Ferrite loaded cavity

- Ferrite Cavity
  - Bias PS for tuning cavity
- Final stage AMP
  - Narrow band
- Driver AMP
  - About 1 kW
- Low Level RF
  - Single H
  - ALC, phase, orbit, tuning loop, beam loading

LLRF

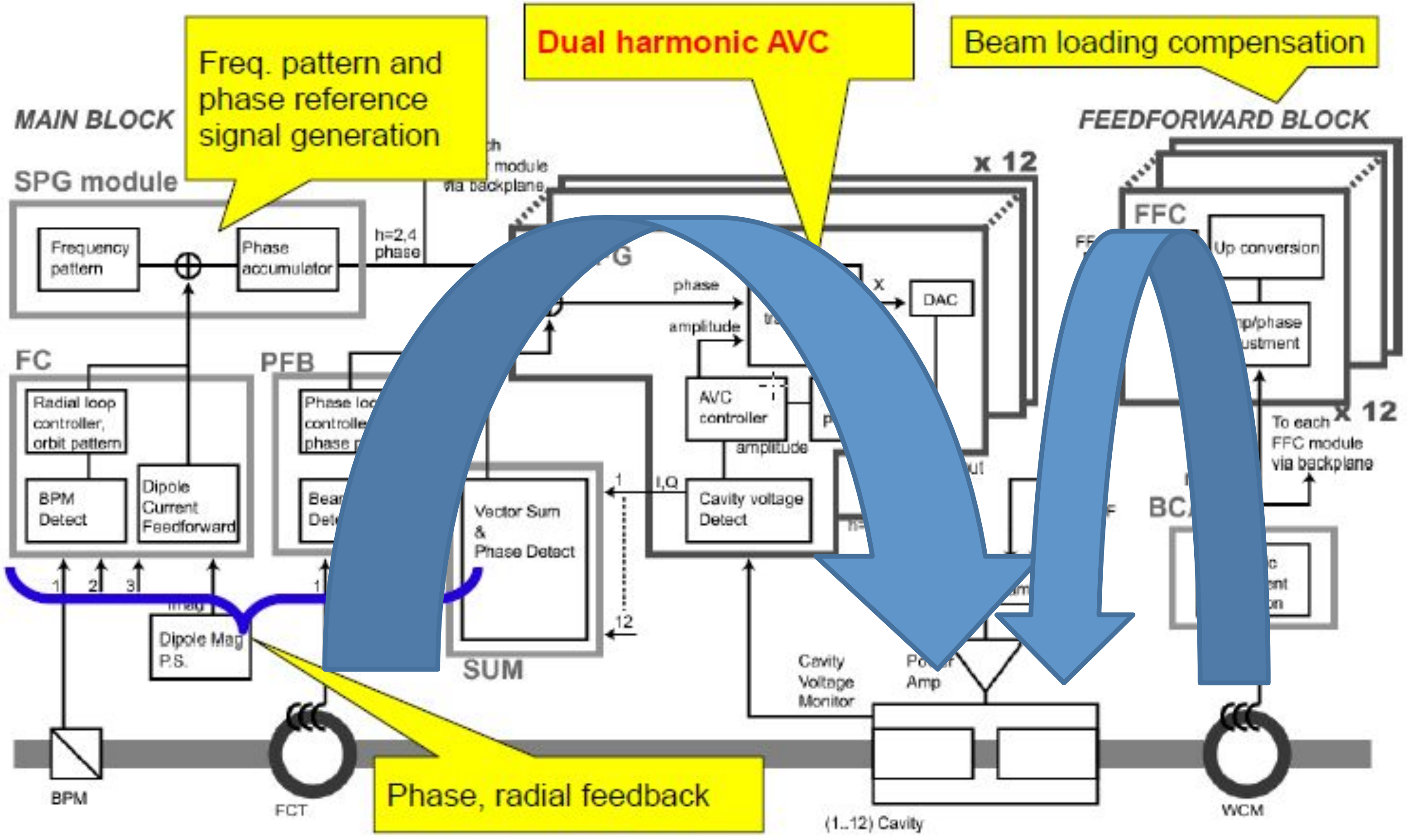
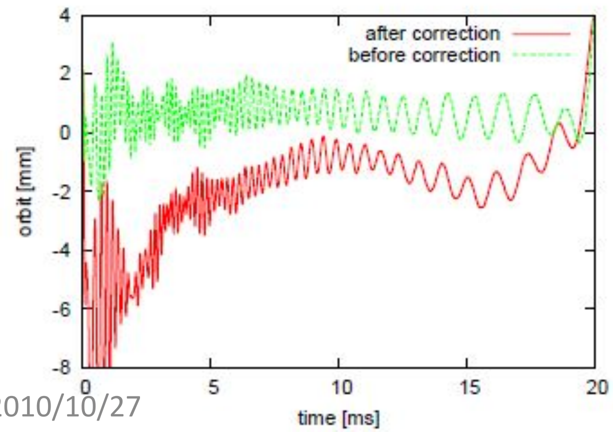
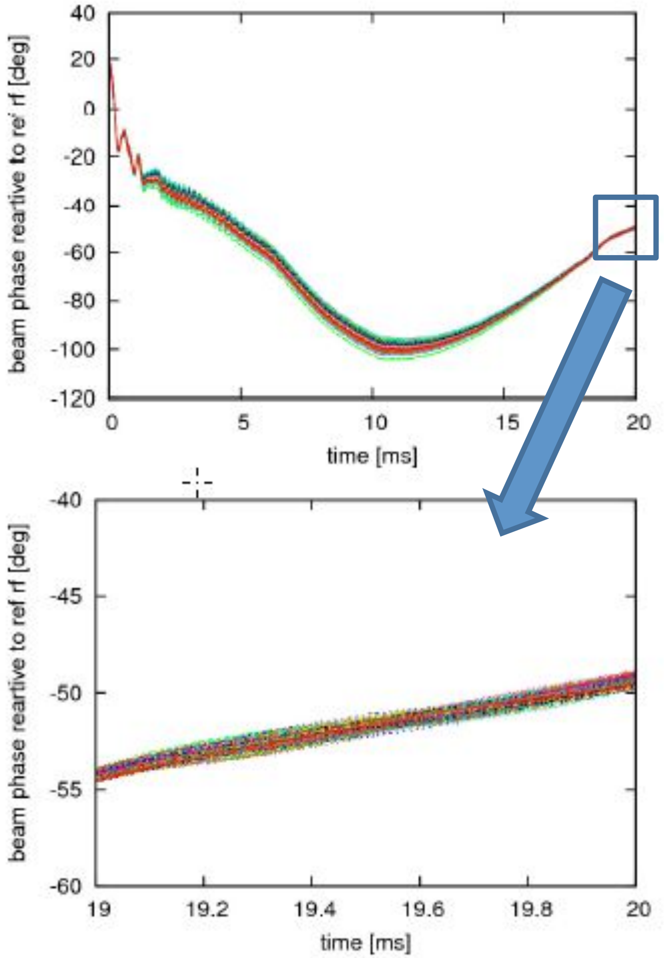


図 19 RCS LLRF block diagram (MR is similar).

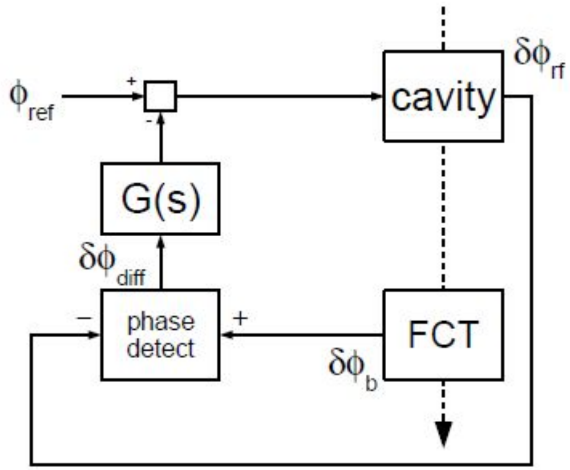
- Frequency tuning during acceleration (RCS)
- B-field becomes stable after few days from restart.
- Digital LLRF + MA cavity give a very stable RF system. (MA cavity is passive system)
- Usually, orbit feedback is necessary for high intensity ring.
- In RCS, orbit remain stable whole cycle after tuning.

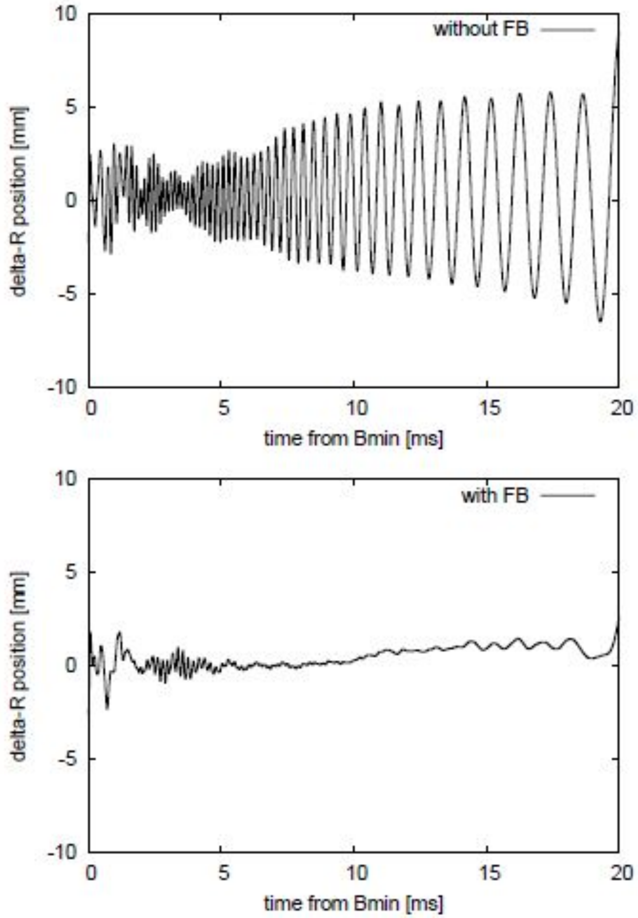




Stability of orbit during high power test (300 kW). The time jitter is only 1.7 ns.

- Phase feedback damps dipole oscillation.
- Upto 100 kW beam, still phase feedback is not necessary for operation.
- Above 300 kW, beam loading compensation using feed forward technique is necessary.





FFAG Cavities

- MA cavities
  - PoP, 150 MeV
  - PRISM
  - EMMA MA
- EMMA cavities

FFAG cavities

Air cooling	PoP FFAG PRISM FFAG
Indirect water cooling	150 MeV FFAG
Induction	Ion beta FFAG
Normalconducting RF	EMMA (non-scaling FFAG in UK)

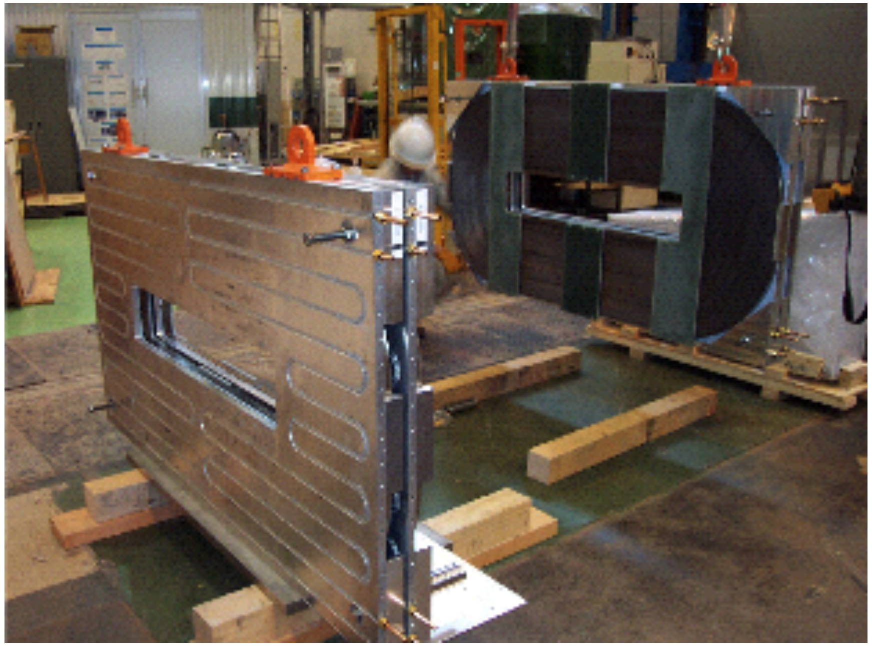
Air-cooled uncut core cavity PoP
FFAG cavity

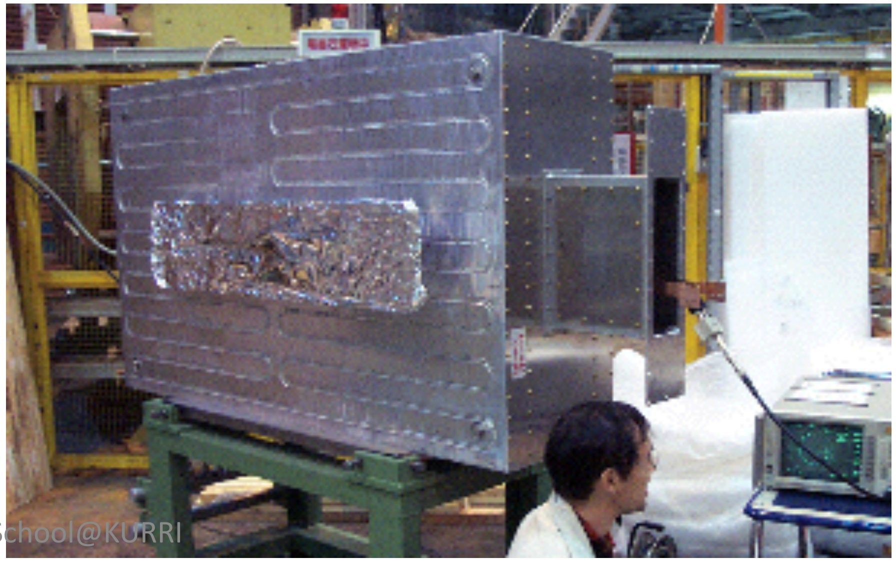
Indirect cooling

Cavity assembly

150 MeV FFAG

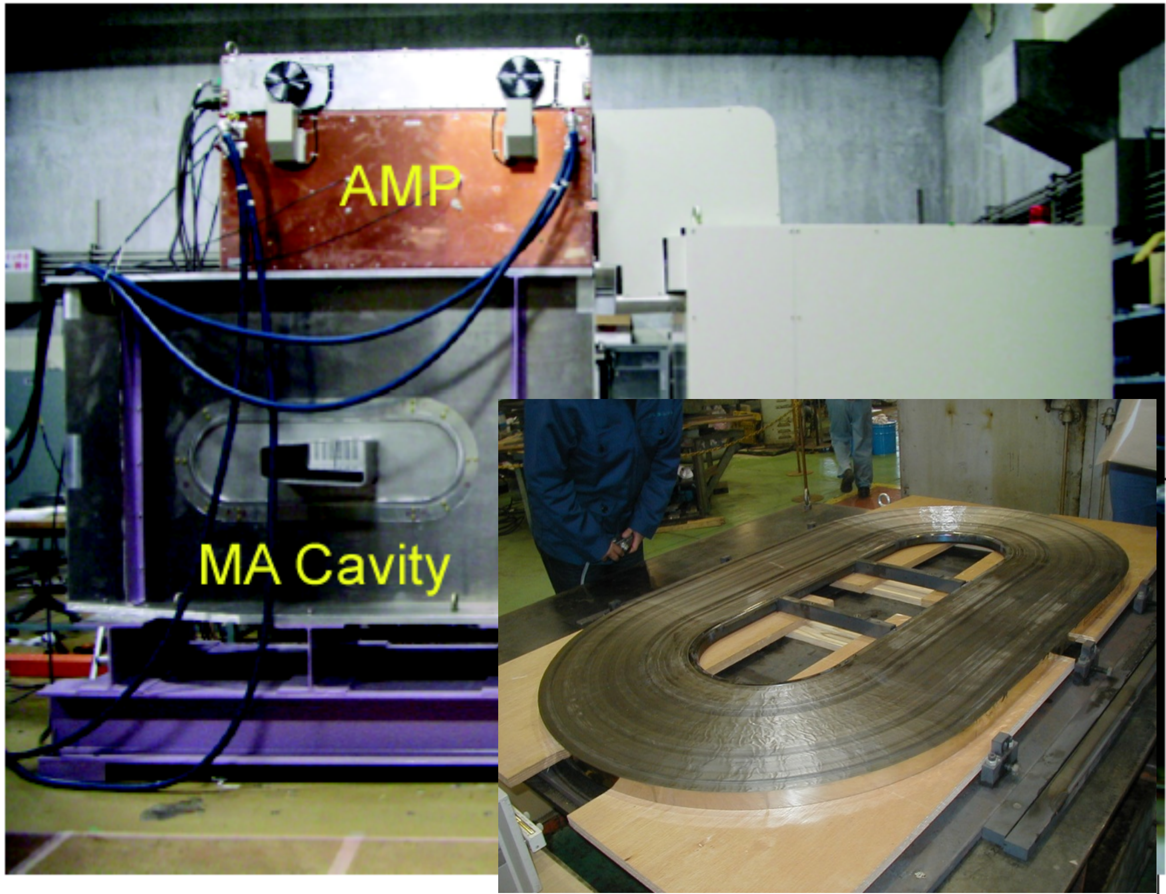
- Number of cores 2~4
- Outer size 1.7m x 1m
- Inner size 1m x 0.23m
- RF frequency 1.5 - 4.6 MHz
- RF voltage 9 kV
- RF output 55 kW
- Power density 1 W/cm^3
- Cooling water 70 L/min

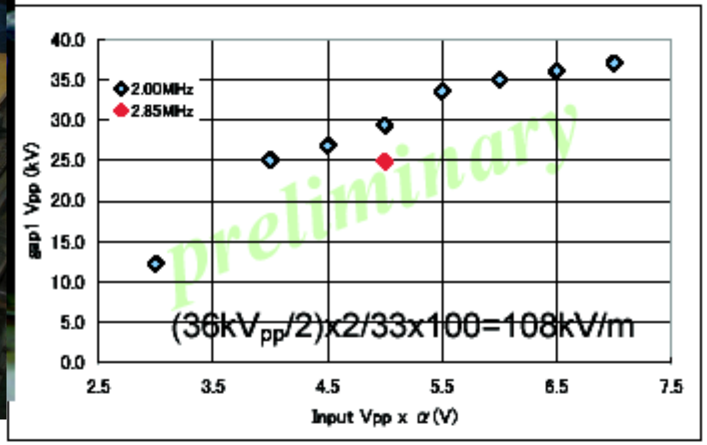




Air cooling

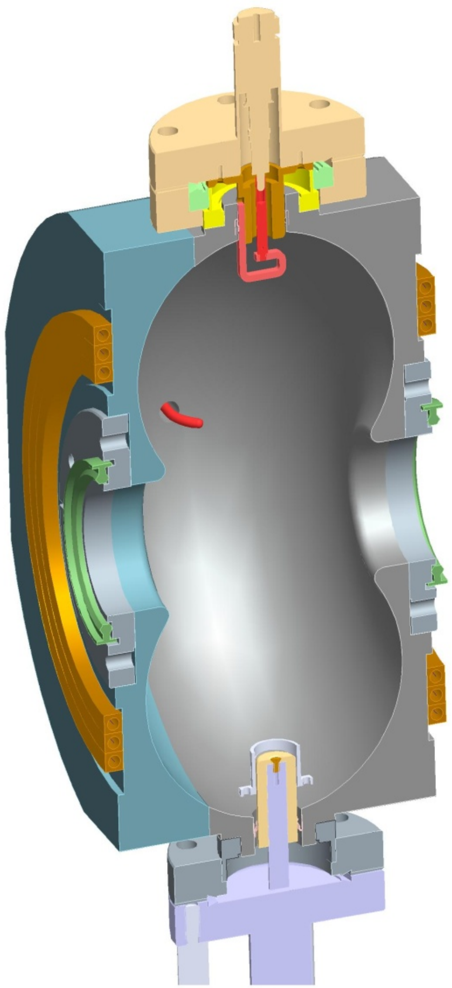
RF for 6cell-FFAG





RF system for 6cell-FFAG has been developed.
100kV/m @ 2MHz is promising.

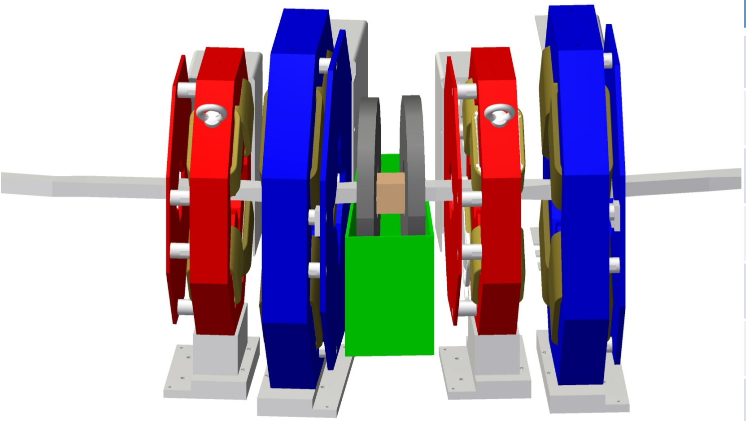
Cavity Design Parameters

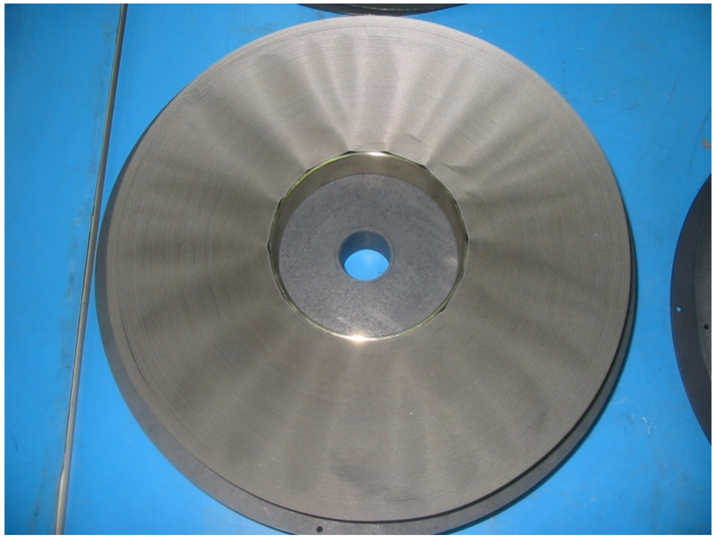


Parameter	Value	
Frequency (MHz)	1300	
Shunt impedance (MΩ)	2.05	
Q_0	20500	
R/Q	100	
Tuning Range (MHz)	-4.0 to +1.6	
Accelerating Voltage (kV)	120	180
Power to generate voltage (kW)	3.6	8.1
Power including overhead#	4.7	10.5

Includes Distribution losses and LLRF Control

EMMA MA CAVITY





frequency	18 MHz	=1.3 GHz/72
frequency sweep	3 %	
df/dt	97.2 GHz/s	Phase shift $=\pi/37$ turns
Total Voltage	100 kV per turn	100 turns/cycle
Number of cavities	3	
Voltage	33.3 kV	
Length of cavity	10 cm	
Number of MA cores	2 per cavity	
Size of MA core	27 cm O.D, 12 cm I.D x 2.5 cm	
MA core	Cut core	
Q-value	About 9	
Cavity impedance	600 Ω (1.4 k Ω)	
Core material	FT3M (FT3L)	

Beam Acceleration in FFAG

Beam acceleration in Synchrotron

- Pattern of frf is given by B field.
- Required rf voltage is given by dB/dt and ϕs

Beam acceleration in FFAG

- B-field is constant.

Scaling FFAG

- Pattern of frf is given by energy gain; rf voltage and ϕs

Very fast acceleration in Non scaling FFAG

- Constant rf frequency.
- RF voltage is given by top and bottom energy

Summary

In this lecture,

- RF Acceleration
- RF System