# Review of Magnetic Alloy Cores for RF Resonant Cavity

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# Contents





FFA'20 Virtual Workshop

# Ferrite Cavities

## 28 years ago.

Table 1 - Parameters of some synchrotrons that use ferrite-tuned cavities

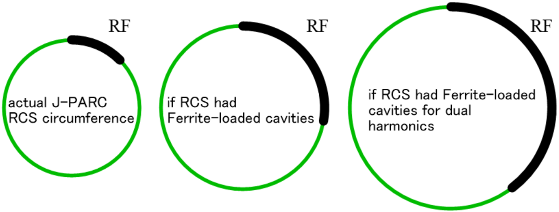
| Synchrotron | No. of Cavs. | No. of Gaps per cavity | Tuning Range (MHz) | Acceler-ating Time (s) | Max. df/dt (MHz/s) | Gap Capacity (pF) | Ind. Range (μH) | Type of Ferrite | $B_{max}$ in Ferrite (T) | Bias Current Range (Amps) | Tuning System Bandwidth (kHz) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 | 2 | 1 | 0.38 - 3.5 | 0.10 | | 500-3000 | | Philips 8C12/ Toshiba PE17 | | | |
| 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<br>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 | | 50 - 2250 | |
| BROOKHAVEN-AGS | 10 | 4 | 2.52 - 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 | | | |

I. Gardner, CERN Accelerator School(1992)

# Background

- Japan Hadron Facility (JHF) project started in 1994.
  Accelerator issues: RF, RCS mag., inj., ext.....
  RF R&D started. We need high gradient.

Length ratio for RF stations in an accelerator

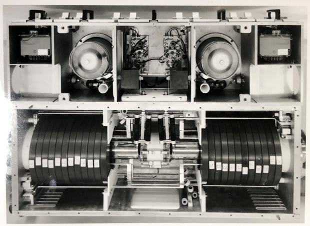



- In JHF design, ferrite- and MA-cavity (1998)
  merged with JAEA project, J-PARC started (2000).
  MA-cavity design for RCS and MR (2002).

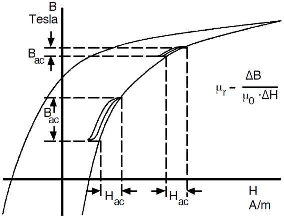
# Why not Ferrite ?

## Ferrite Cavites were standard. But,

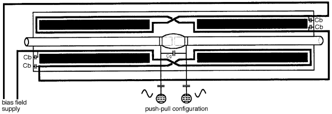
- Narrow band system and tuning circuit is inevitable.



PSB Ferrite Cavity




B-H Curve



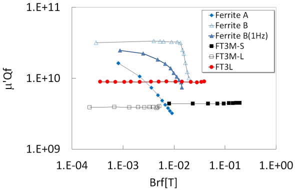

$$f = \frac{1}{2\pi\sqrt{LC}}$$
$$L = \frac{\mu_0\mu'}{4\pi} \ln \frac{b}{a} tN$$

b:O.D., a:I.D., t:thickness,N:# of cores

# Why not Ferrite ?

## Ferrite Cavity was standard. But,

- Narrow band system and tuning circuit is inevitable.
- Cavity impedance depends on RF amplitude.
- Temperature dependence




- $R_p = \mu_0 \mu' Q f \ln \frac{b}{a} t$
- $B_{rf} = \frac{V}{\omega S} = \frac{V}{2\pi f S}$

  b:Outer diameter

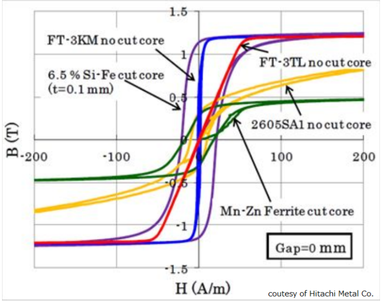
  a:inner diameter

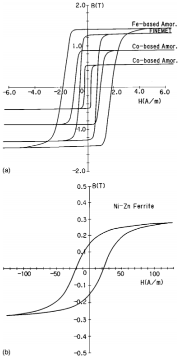
  t:thickness

  S:cross section =(b-a)t/2

- ferrite cav.: $\mathrm{V} = \mathrm{Z}(\mathrm{I_{bias}}, \mathrm{V_{RF}}, \mathrm{T}) \times \mathrm{I}$
- MA cavity: $\mathrm{V} = \mathrm{Z} \times \mathrm{I}$

# $B_s$




Y. Yoshizawa, KEK Acc. Seminar (2017)

K. Watanabe et al., Rev. Sci. Instr. **69**,12 (1998).

B-H Curve shows :

- Ferrite $B_s$ : 0.3 T
- Finemet FT3: 1.2 T
- Co. Amorphous: 0.6 T



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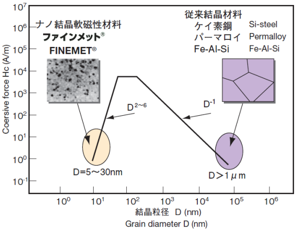
# Nano-Crystalline Material



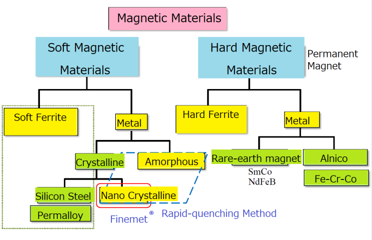


## Crystalline Materials

Relationship between crystal grain diameter (D) and coercive force ($H_c$)




## Magnetic Alloys & Ferrites

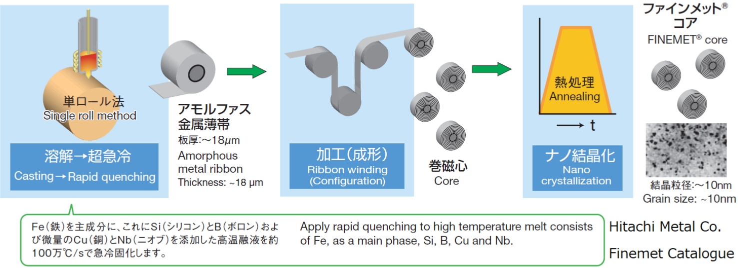



- Thin Ribbon by Rapid-quenching makes Less Eddy current power loss.
- Large grain size materials show soft magnetism.
- Nano-crystalline materials show soft magnetism.

* Y. Yoshizawa, J. Appl. Phys., 64 6044 (1988).

# Amorphous to Nano-Crystalline Material

- Rapid-quenching makes amorphous phase.
- High temperature annealing makes nano-crystalline in amorphous.




Hitachi Metal Co.

Finemet Catalogue

For Magnetostriction, $\lambda_s \sim 0$

$$\lambda_s = V_{crystal} \times \lambda_{crystal} + (1 - V_{crystal}) \times \lambda_{amorphous}$$

$\lambda_{crystal}$ and $\lambda_{amorphous}$ have different sign



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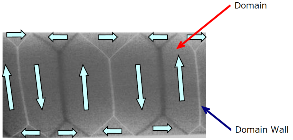
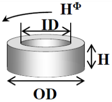
# Nano-crystalline

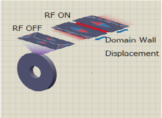
Magnetic annealing affects Mag. Domain.

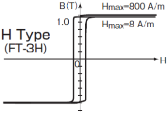



Annealing | Motion of Mag. Domain in use | B-H Curve | Applications

H Type (Longitudinal)



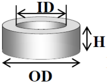



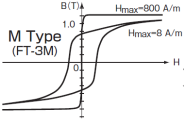




Surge Blocker

Saturable core

M Type (w/o B-field)



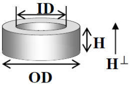



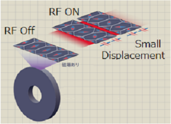

Shielding

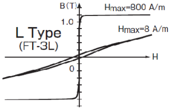
Common mode

Choke

L Type (perpendicular)




RF Cavity

Transformer



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# Applications

## RF applications

$$P_{loss} = P_{eddy\ current} + P_{domain\ wall} + P_{magnetic\ rotation}$$

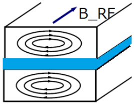
foil thickness — mag. annealing affects this.

Insulation between foils is necessary to avoid large eddy loss.

However, thin foil reduces packing factor.

$$f_p = V_{material}/V_{all}$$

$$V_{all} = V_{material} + V_{insulation} + V_{air,others}$$




So far, 10 $\mu$m thickness still has advantage to use.

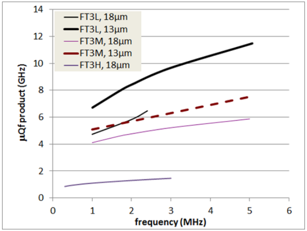
## DCCT

Type M seems good as it needs hysteresis.

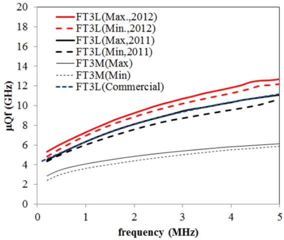
## Switching devices

Packing factor seems more important.

# Power Loss




small core samples




80-cm core samples

$$R_p = \mu_0 \mu' Q f \ln \frac{b}{a} t$$

- H-type has large loss. L-type has low loss.
- Combination of Mag. Annealing and thin ribbon
- Large mag-annealed core also has good quality





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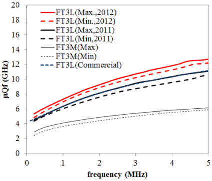
# Large L-Type Core Production

However, it was not very easy to make a large core, because there was not such production system.

Our solution was DIY.


Production test

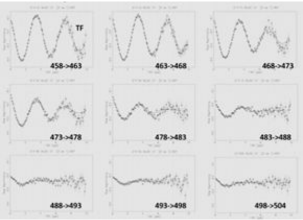
Mass production system



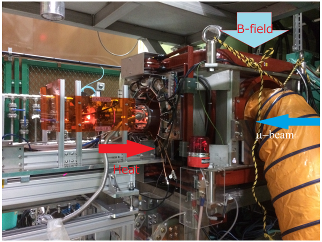

C. Ohmori et al., Phys. Rev. ST Accel. Beams 16 112002(2013).

# The other difficult part

It was not easy to build a magnetic annealing system because we were not sure if we could. A $\mu$SR experiment gave us confidence to proceed !



$\mu$SR results. Crystallization can be measured in situ condition.




Experimental setup

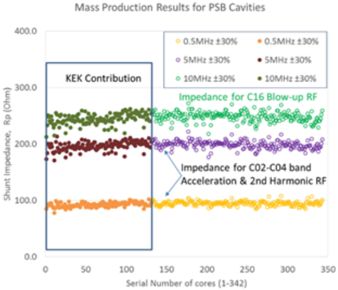
muon is a good tool to study magnetism of materials.
$\mu$SR results also pushed to build a mag. annealing oven!

C. Ohmori, JPS Conf. Proc. 8, 012025 (2015)

# Mass Production Issues

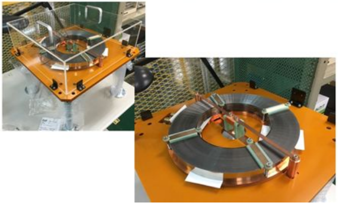
Quality control becomes important in mass production.

- Core impedance measurements




CERN PSB Core production(324 cores)

J-PARC-oven makes better cores!

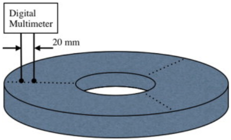


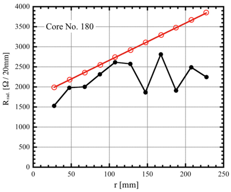
PSB Core under power test

# Mass Production Issues

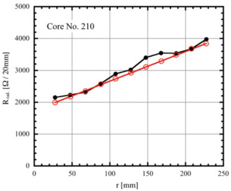
Quality control becomes important in mass production.

- Core impedance measurements
- Insulation between layers,




bad core

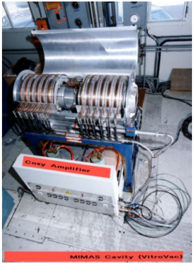



good core

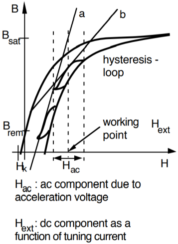
Nomura et al., NIM A, **668** p. 83-87, https://doi.org/10.1016/j.nima.2011.11.092

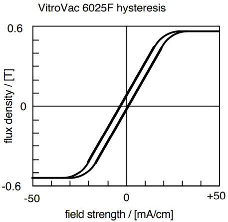
# Amorphous Cores

Cobalt-base amorphous is also used for cavities.




First MA Cavity
for MIMAS
VitroVac 6025F



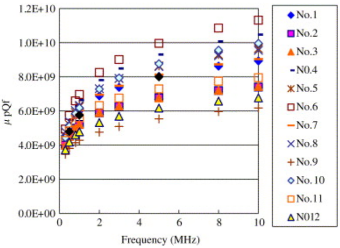

$B_{sat}$ is below 0.6 T.

$B_{sat,ferrite} < B_{sat,Co} < B_{sat.nano}$

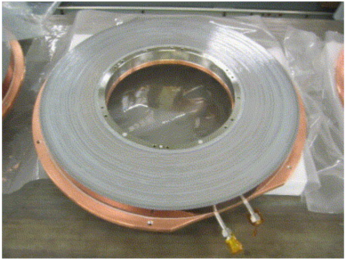
0.2-8 MHz bandwidth
with biasing.

A. Schnase, CAS 2005, p. 236, https://cds.cern.ch/record/386544/files/CERN-2005-003.pdf

# Characteristics of Co-base Amorphous Cores




high impedance cores.



Cobalt core on cooling disc.

$$(\mu \mathrm{Qf})_{\mathrm{nano}} \leq (\mu \mathrm{Qf})_{\mathrm{Co}} < (\mu \mathrm{Qf})_{\mathrm{nano-mag-annealing}}$$

Co-base amorphous for medical uses; HIMAC, HIMAT etc.

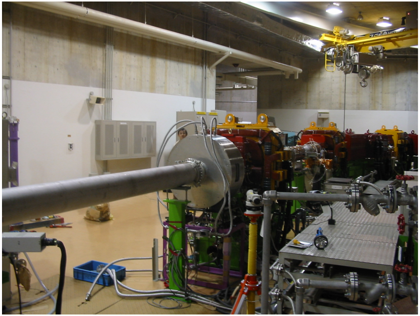
M. Kanazawa et al., NIM A, **566**, 2, p. 195-204, https://doi.org/10.1016/j.nima.2006.05.276

# Cavity Applications

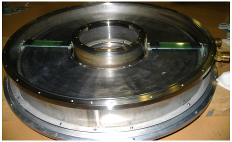
- Wideband applications
  - FFA
  - Medical uses
  - Latest Wideband Cavities
- Control of bandwidth
  - Medium band
  - Narrow band
- Beam Control

# Wideband Cavies:Acceleration

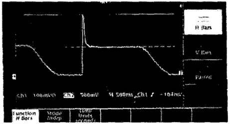
HIMAC water-cooled wideband cavity was installed in 1998 and demonstrated acceleration, dual harmonic and beam manipulations(bunch rotation, barrier).



HIMAC Wideband Cavity



MA cores in water tank

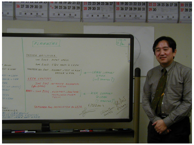


Beam acceleration w/o ALC, $\Delta\phi$, $\Delta R$ and biasing

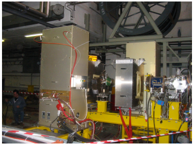
Proc. PAC99, p. 798-799(1999)
NIM A, **547**, 2–3, p. 249-258(2005)

# Wideband Cavies:Acceleration

Low Energy Ion Ring (LEIR) cavity Collaboration for Pb+Pb collision at LHC

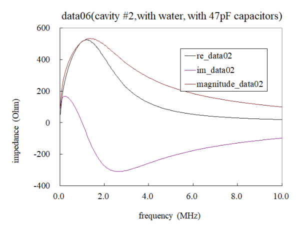


started in 2002.



LEIR cavities

| Parameters | Capture | Extraction |
|---|---|---|
| Energy | 4.2 MeV/u | 72 MeV/u |
| Frequency | 361 kHz | 1.423 MHz |

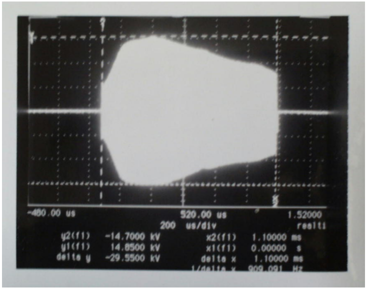



Wideband cavity impedance

# Wideband Cavities for FFA

Fast RF freq. sweep on wideband cavity inspired FFA.

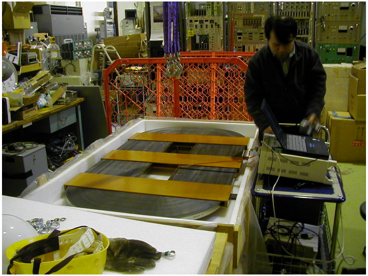
Jim Griffin pointed to check fast frequency sweep. Then, we tried...




MA cavity system showed very fast frequency sweep of ∼kHz!

# Wideband Cavities for FFA

Cavity for PoP FFA 0.05-0.5 MeV:2000

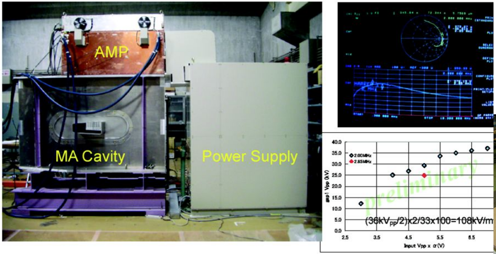


proof-of-principle, scaling (DFD) FFA
proton machine
MA rf cavity

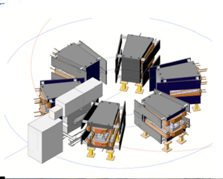
# Wideband Cavities for FFA

## PRISM FFA

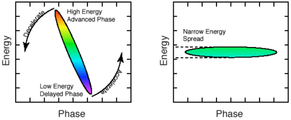
RF for 6cell-FFAG



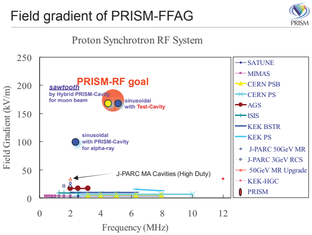

RF system for 6cell-FFAG has been developed.
100kV/m @ 2MHz is promising.



Bunch rotation cavity for low-momentum spread $\mu$ beam 3-5 MHz, 100-kV/m



# Wideband Cavities for PRISM FFA

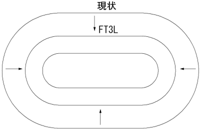



$\alpha$ beam experiment suggests that the real voltage might be 20% less because of monitor problem. MEA CULPA

A. Sato, Nufact2009.

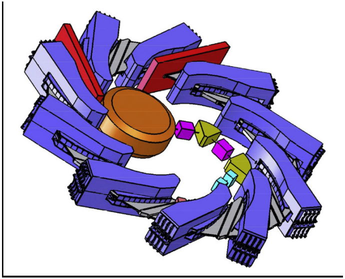
Assuming it has same impedance,
total weight of core will be 1/3.
Core cost will be 1/3 ?

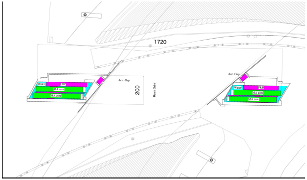
Mag. annealing also makes FFA cores smaller!

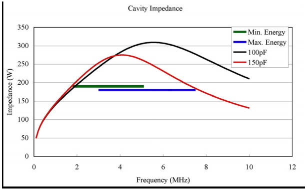


# Wideband Cavities for FFA

## Medical spiral FFA, RACCAM





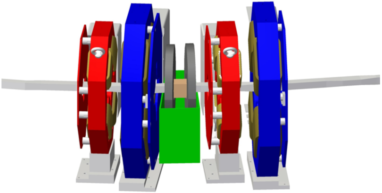



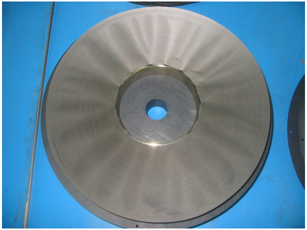

2$\times$3 kV cavity, direct water cooling,
vacuum tube amplifier-driven, 1.86-7.54 MHz ,
$\leq$100 Hz repetition rate, Core loss$\leq$0.5 W/cc

S. Antoine et al, NIM A, **602**, 2, p. 293-305, https://doi.org/10.1016/j.nima.2009.01.025

# Wideband Cavities for FFA

Slow EMMA acceleration

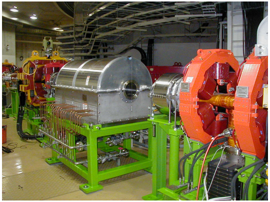




EMMA MA cavity was not made. However production of mag.-annealed cores for EMMA was the first step to start to build mag.-annealing oven.

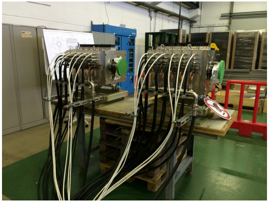
# Wideband Cavities for Medical Uses

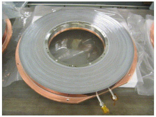
Amorphous cav.@HIMAC

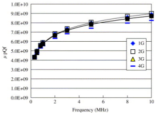


Courtesy of Dr. M. Kanazawa

MedAustron Finemet Cav.








Finemet FT3L cavities under test at CERN in 2013.

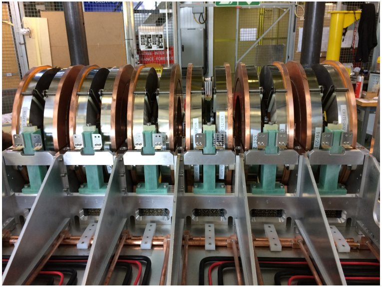
Co amorphous core also has high impedance.

https://doi.org/10.1016/j.nima.2005.10.118

# FT3L Cavities for CERN PS Booster

Mag. annealing, FT3L, cores are used for Booster

4 Rings $\times$
3 sets of 12-cell cavity
$3 \times 8$ kV for multi-H.

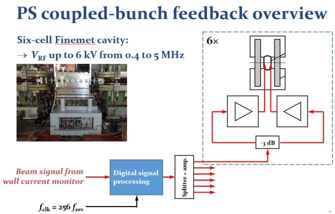


12 FT3L cores in 6-cell cav.
Driven by SSA
Indirect cooling

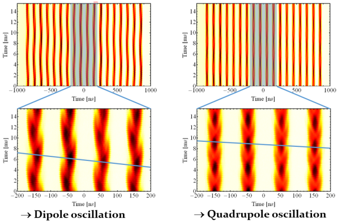
M. Paoluzzi et al., IPAC19(2019), pp. 3063-3065.

# FT3L Cavities for CERN PS

Damping Long. Coupled Bunch Instability
CBI causes Long. emittance growth
Problem for HiLumi LHC.




6-cell damper cavity in PS to damp harmonic components of CBI.



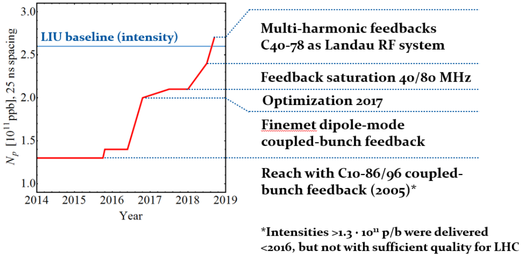

Dipole mode was damped.

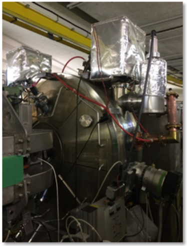
Quad. mode was not

M. Paoluzzi et al., CERNACC-NOTE-2013-0019(2013).

# FT3L Cavities for CERN PS

## Damping Long. Coupled Bunch Instability



40 MHz Landau cav.

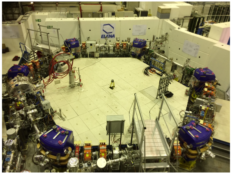
Dipole modes are damped by FT3L cavity.
Quadrupole ones by Landau cavity.

H. Damerau, et al., ICFA Mini-workshop, Benevento, Italy, 2017.

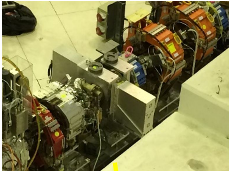
H. Damerau et al., IPAC18, p. 728-731(2018).

# FT3L Cavities for CERN

Decelerations of antiprotons



ELENA
5 MeV-100 keV!



100 kHz at
100 keV!


AD reuses PSB
test cav.

Both AD and ELENA use Finemet Cavities for deceleration of $\overline{p}$





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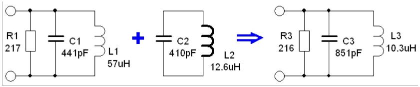
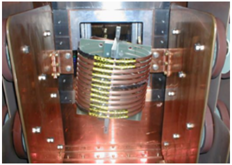
# J-PARC RCS: Hybrid System with External Inductor



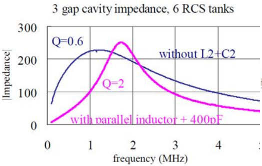
Low Q = High R/Q is an issue for very high intensity.

External inductor can increases Q.

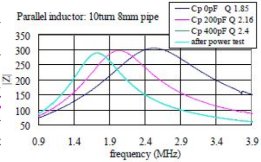


External inductor under testing




Controlling bandwidth



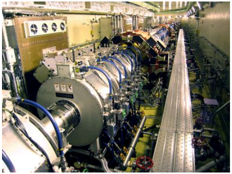

Changing resonant frequency

Optimum Q-value of 2 is used at J-PARC RCS.

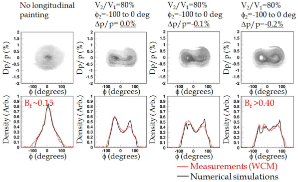
A. Schnase et al., Proc. PAC07, p. 2131–2133(2007).

# Hybrid System with External Inductor

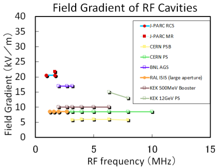
- Direct water cooled cavities for high field gradient of $\sim$ 20 kV/m.



J-PARC RCS Cavities




Dual harmonic RF

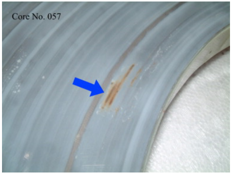


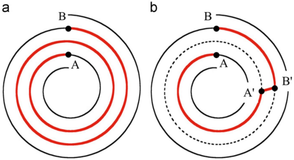


RCS demonstrated 1-MW beam operation!

# Solved Issues

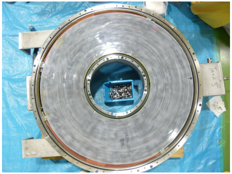
- Layer insulation

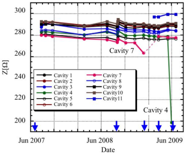


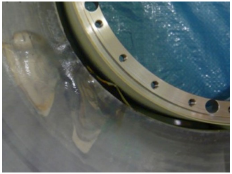




Solved by improving core production

- buckling





Solved by softening





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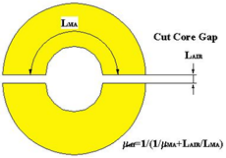
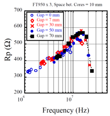
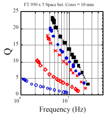
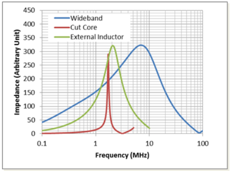
# J-PARC MR: Cut Core Scheme

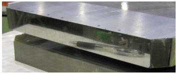


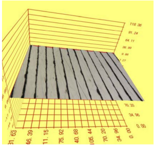



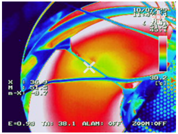



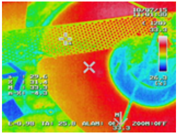




Reducing inductance w/o reducing $\mathrm{R_p}$ increases Q.







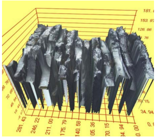


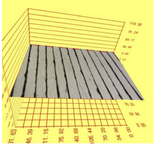
Cut surface is polished with diamond powder.
All cores were power-tested.

EPAC 2006, TUPCH128

# Solved Issues

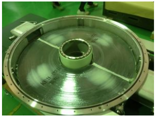
- Hot Spots on Cut Surface





Solved by water-jet cutting, epoxy-immersion and diamond-polishing.

- Water Quality and Surface Protection



Cu ions from magnet sticked on surface and became rusty.
Solved by separate water line and surface protection





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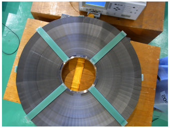
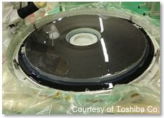
# Cut Core Production

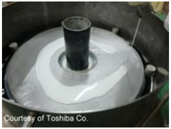


measurements

investigation

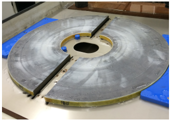



epoxy immersion

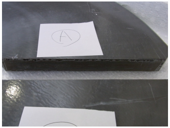



coating

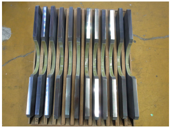
coated core



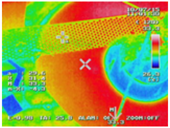
water jet cutting



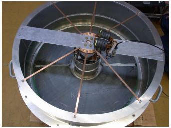
epoxy immersion



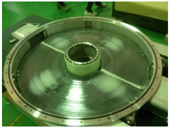
diamond polishing



power test



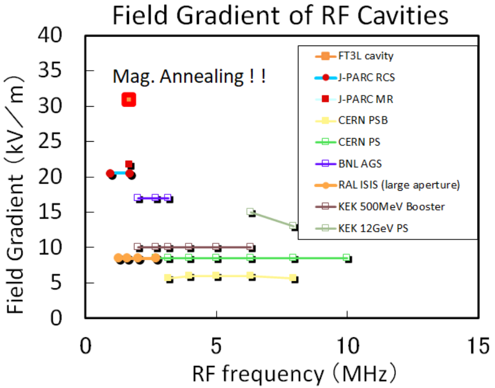
impedance measurements



installatin

power test

# J-PARC MR Cavity




- By magnetic annealing and thin 13 $\mu$m ribbon, MR cavities achieved 32 kV/m as a field gradient!
- RCS is also planning to use mag. annealing cores for over 1 MW.



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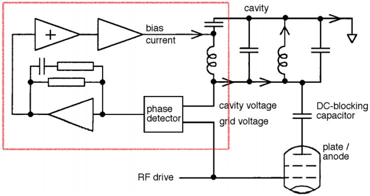
# Beam Control

- MA system Simplifies LLRF




Ferrite system needs tuning [] and AVC loops.

- J-PARC RCS demonstrated 1 MW beam delivery to MLF.
- J-PARC MR delivered 510 kW ($2.6 \times 10^{14}$ ppp to T2K target



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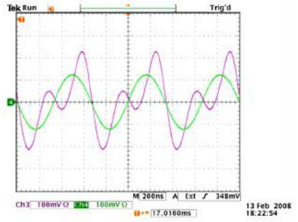
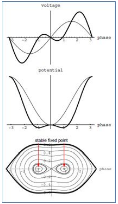
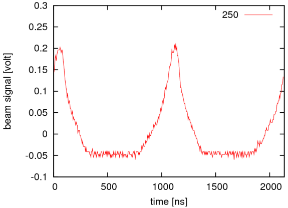
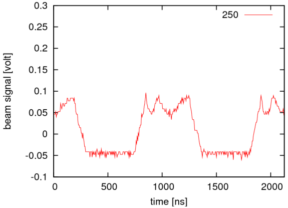
# Beam Control

- Multi-harmonic RF is available.

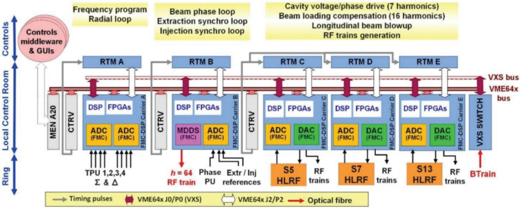


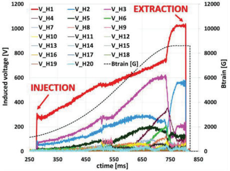



# PSB LLRF




- Control 3 HLRF
- Each HLRF deliver 8 kV total voltage
- Wake voltages were compensated by LLRF.

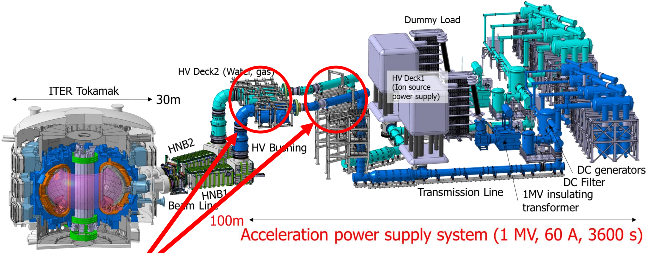
M. E. Angoletta et al., IPAC2019, doi:10.18429/JACoW-IPAC2019-THPRB068

# Other Applications

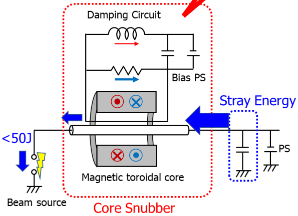
- Surge Protection for Fusion Facility
- Transportation System

# Surge Protection for ITER

## ITER Neutral Beam Injector




Acceleration power supply system (1 MV, 60 A, 3600 s)



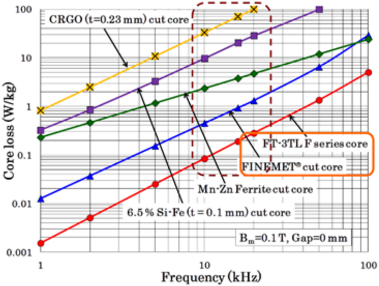

- Surge protection is one of important function for 1 MV acceleration power supply for ITER.
- Core snubbers play an important role for surge absorber to protect the beam source and the power supply at break downs.


<Reference>

- A. Kojima, et.al., Progress of R&D for 1 MV acceleration power supplies toward ITER heating neutral beams based on the neutral beam test facility, 31st Symposium on Fusion Technology (SOFT2020) #517.
- K. Watanabe, et.al., Development of a dc 1 MV power supply technology for NB injectors, Nucl. Fusion **46**(2006) S332–S339


Courtesy of Dr. A. Kojima

# Transformer using Low-Loss Core

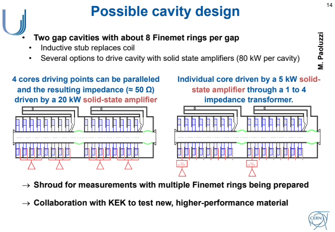


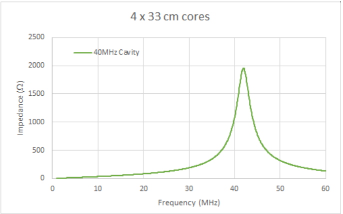

Courtesy of Hitachi Metal Co.

- Mag.-annealed core shows low loss as high frequency transformer
- KEK and HM agreed use of Mag.-annealing oven for transportation systems R&D.

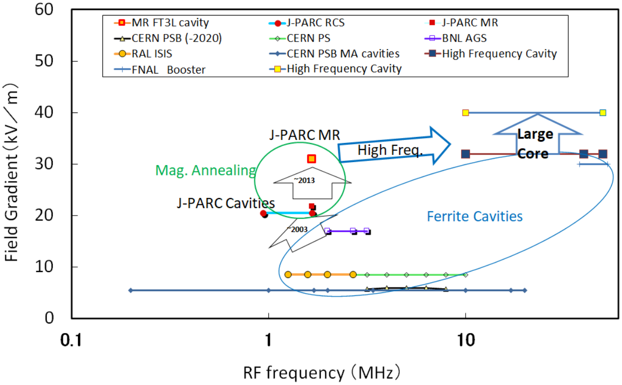
# High Frequency Cavity R&D

- Wideband 40 MHz Cavity for Quad-mode of Long. CBI
- 10 $\mu$m ribbon improves impedance.
- Lower Loss and High Field Gradient
  13$\mu$m core at 10 MHz : 250 $\Omega$
  10$\mu$m core at 40 MHz : $\sim 500\ \Omega$
- High Power GaN SSA to drive



# High Frequency Cavity




- Higher Frequency Cavity may achieve higher gradient $\sim 40\ kV/m$.
- New applications for accelerators

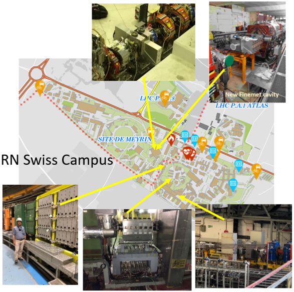
# Improvements of materials

- Material development and ribbon thickness improvement are important.
- Recent nano-crystalline research using $\mu$SR at J-PARC MLF gives more understanding for magnetic field effects during annealing.
  It shows the magnetic field may affect crystallization process itself and important role of Si atoms.
- $\mu$SR experiments using pulse and CW muon may be useful ! We are interested in TRIUMF muon beam.

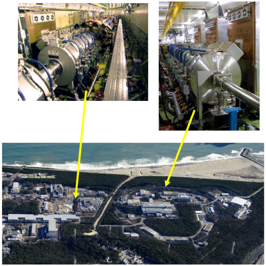
M. Ohta et al., 2nd J-PARC Symposium

# Summary

- MA Cavity technology has been spreading.
- It changes the proton/hadron beam acceleration/deceleration because of its flexibility.
- New idea of applications from CERN: Damper cavity and deceleration



CERN Swiss Campus


J-PARC Tokai



FFA'20 Virtual Workshop

# Summary



## And, now

Table 1 - Parameters of some synchrotrons that use ferrite-tuned cavities

| Synchrotron | No. of Cavs. | No. of Gaps per cavity | Tuning Range (MHz) | Accelerating 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 | +MA | 3100 | |
| CERN-PSB | 1/ring | 1 | 3 - 8.4 | 0.45 | | 80 | | MA | | 60 - 800 | 15 |
| CERN-LEAR<br>LEIR<br>ELENA, AD | 2 | 1 | 0.38 - 3.5 | 0.10 | | 500-3000 | | MA | | | |
| DESY-III | 1 | 2 | 3.27 - 10.33 | 3.6 | | | | | | 160 - 2000 | |
| SACLAY-MIMAS | 2 | | 0.15 - 2.5 | 0.2 | 14 | | | 1st MA cavity | | 0 - 400 | |
| SACLAY-SATURNE | 2 | | 1.7 - 8.3 | 0.5 | | | | | | | |
| CELSIUS | 1 | | 0.4 - 2<br>1 - 5 | | | | | | | 1500 | |
| KEK-PS<br>J-PARC MR | 4 | 2 | 6 - 8 | 0.8 | 14.5 | 100 | 7 - 4 | MA | 0.007 | 80 - 400 | 3 |
| KEK-BOOSTER<br>J-PARC RCS | 2 | 2 | 2.2 - 6 | 0.025 | 265 | 650 | 8 - 1 | MA | 0.01 | 250 - 2200 | 1 |
| FNL-BOOSTER | 18 | | 30.3 - 52.8 | 0.033 | 3000 | | | Stackpole and Toshiba | | 50 - 2250 | |
| BROOKHAVEN-AGS | 10 | 4 | 2.52 - 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 | +MA | | |

COSY is also using MA cavity for many years.

FAIR and heavy ion machines in China are also planning to use.

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