The 20th ICFA Advanced Beam Dynamics Workshop
on High Intensity and High Brightness Hadron Beams
(ICFA-HB2002)

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WG I: Circular Accelerators –
Longitudinal dynamics and rf hardware

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Longitudinal Dynamics

Emittance and Bunching factor controls

Requirement:

- Bunching factor B_f should be greater than **0.4** at RCS injection, and **0.3** at MR injection, which is equivalent to **0.3** at RCS *extraction.*

  < to keep a moderate $\Delta\nu$.

- Emittance should be greater than **10 eV·s** before 50GeV flat-top. During injection and early accelerating period, controlled emittance blow-up is necessary.

Difficulties:

- Small synchrotron tune, even high gamma transition lattice.
- Heavy beam loading (Y~7) at RCS extraction. Slippage and harmonic ratio between two rings ~ about 5
- , , ,

Solutions:

- Full cycle particle tracking has been done to check the possibility.

  According to,,, > 2^{nd} harmonic system, Feedforward system are essential.

Beam Injection for RCS

Linac Beam

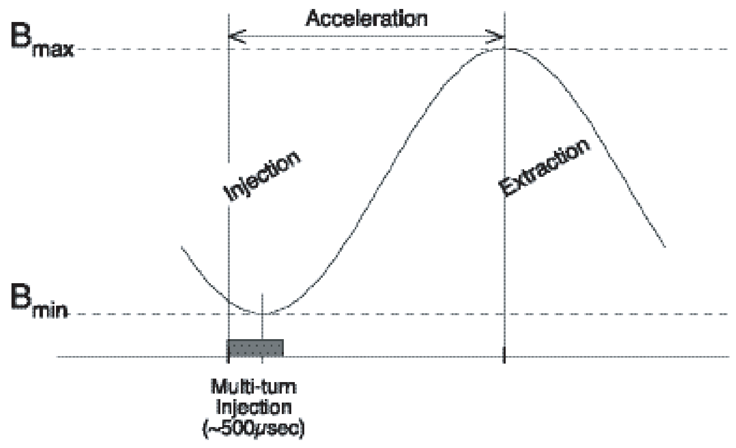
····· **50mA peak current**
····· **500μsec pulse width**
····· $\Delta p/p \sim \pm 0.1\%$.

Injection

·····**Multi-turn injection (Transverse painting)**
·····**Chopped beam injection (longitudinally)**

Pulse will be chopped by RCS injection frequency
Duty is 40~60%

>> ***Optimizations for Timing/Width/Duty/Offset necessary.***

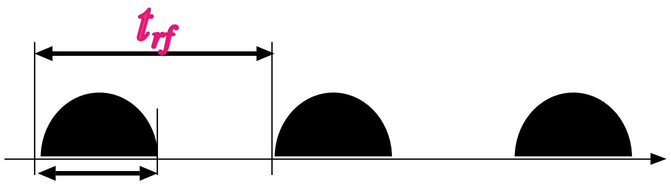


Requirements for RCS Injection

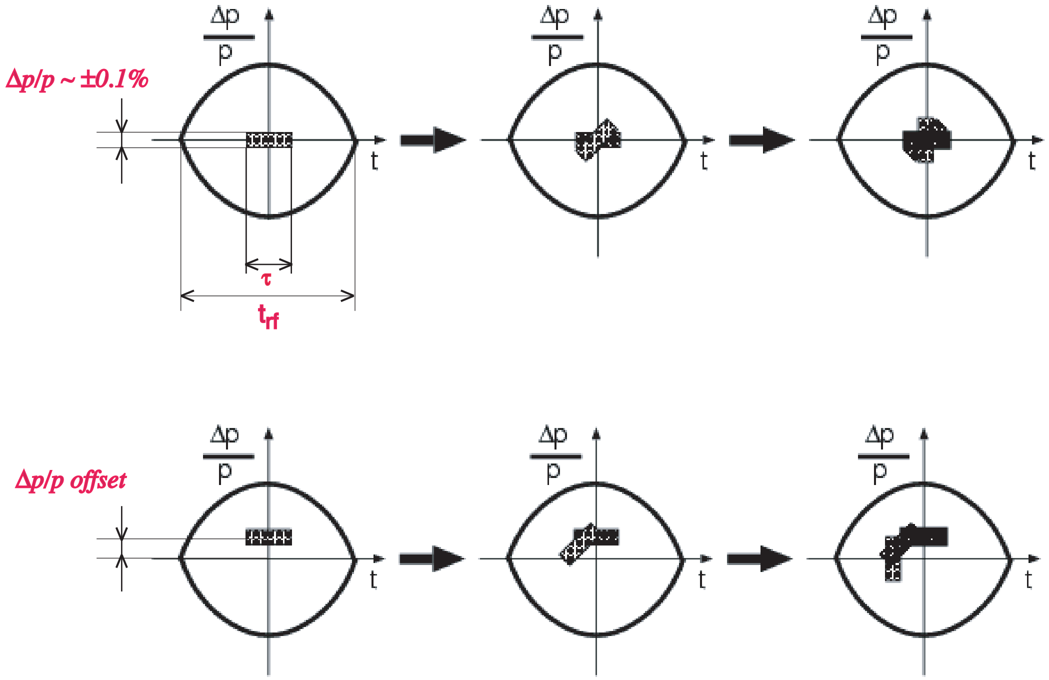
To keep Bunching Factor of >0.4 at Injection

Chopped beam injection	*40 ~ 60%*
Momentum offset injection	*0.3 ~ 0.5%*
2nd.harmonic mixture	*50 ~ 80 %*

Injection RF period 814 ns @ B_{bottom}



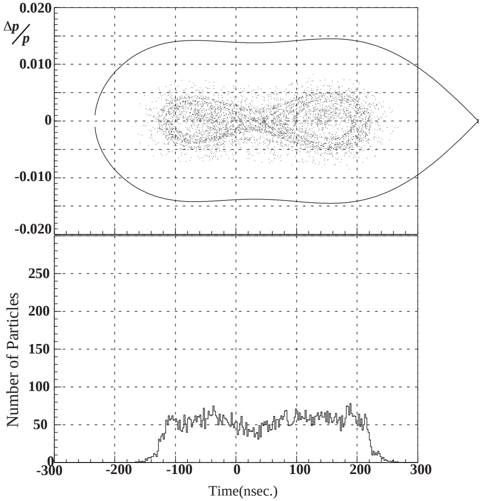
chopping factor = τ / t_{rf}



Summary of Particle Simulations for Momentum Offset Injections

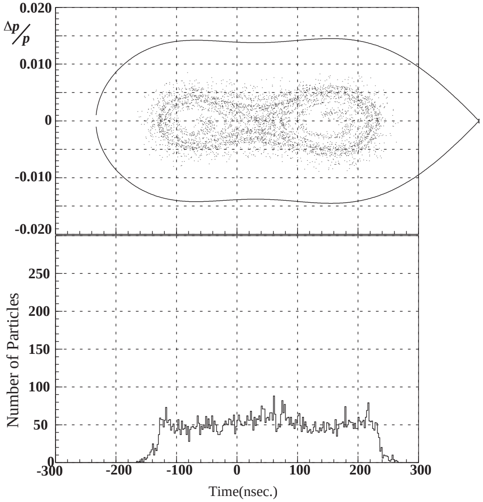
Momentum offset: 0.3%

3 GeV Injection(Chop=500 ns, 2nd=80%)



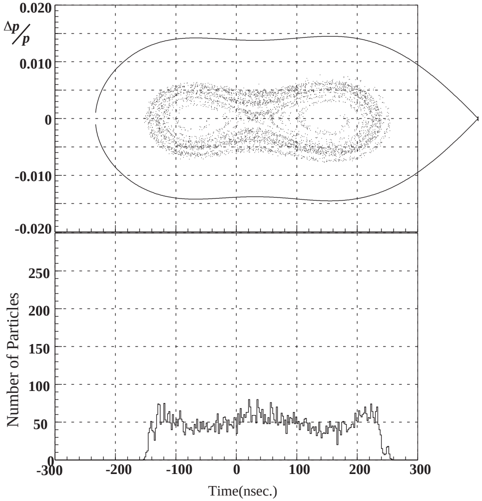
Momentum offset: 0.4%

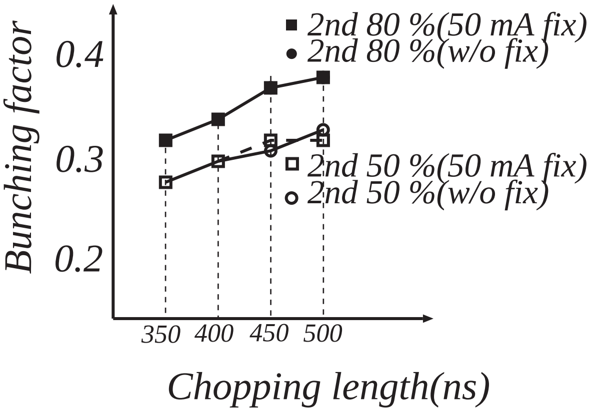
3 GeV Injection(Chop=500 ns, 2nd=80%)

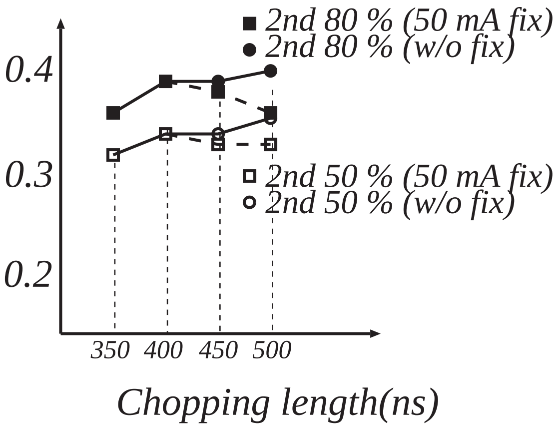


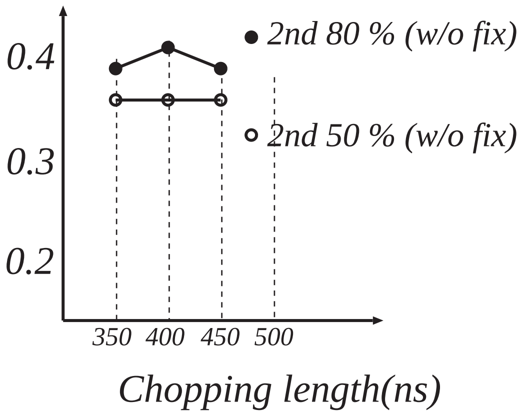
Momentum offset: 0.5%

3 GeV Injection(Chop=400 ns, 2nd=80 %)

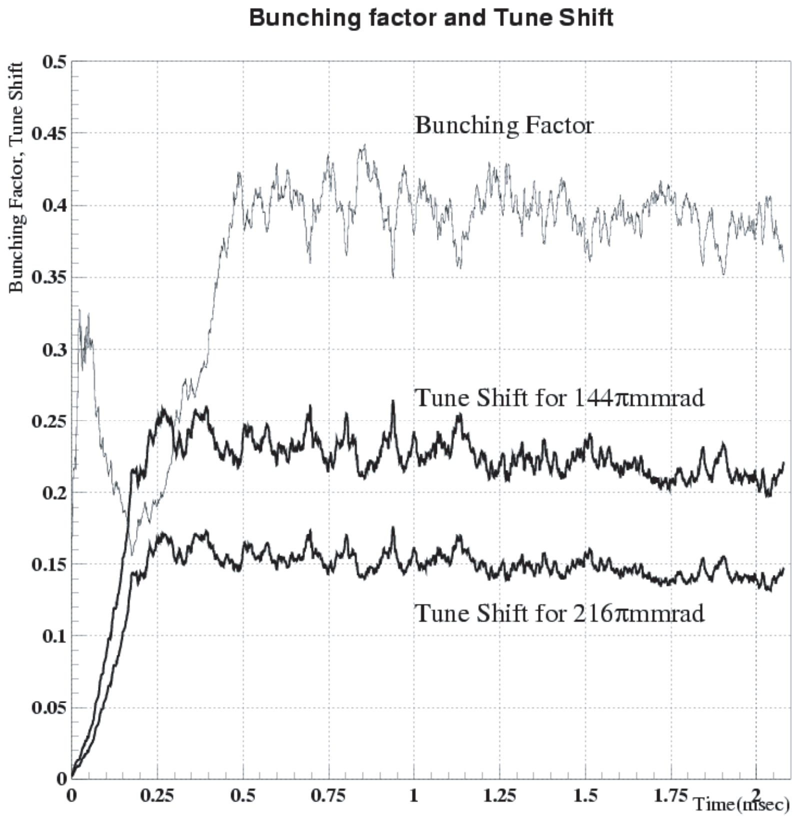






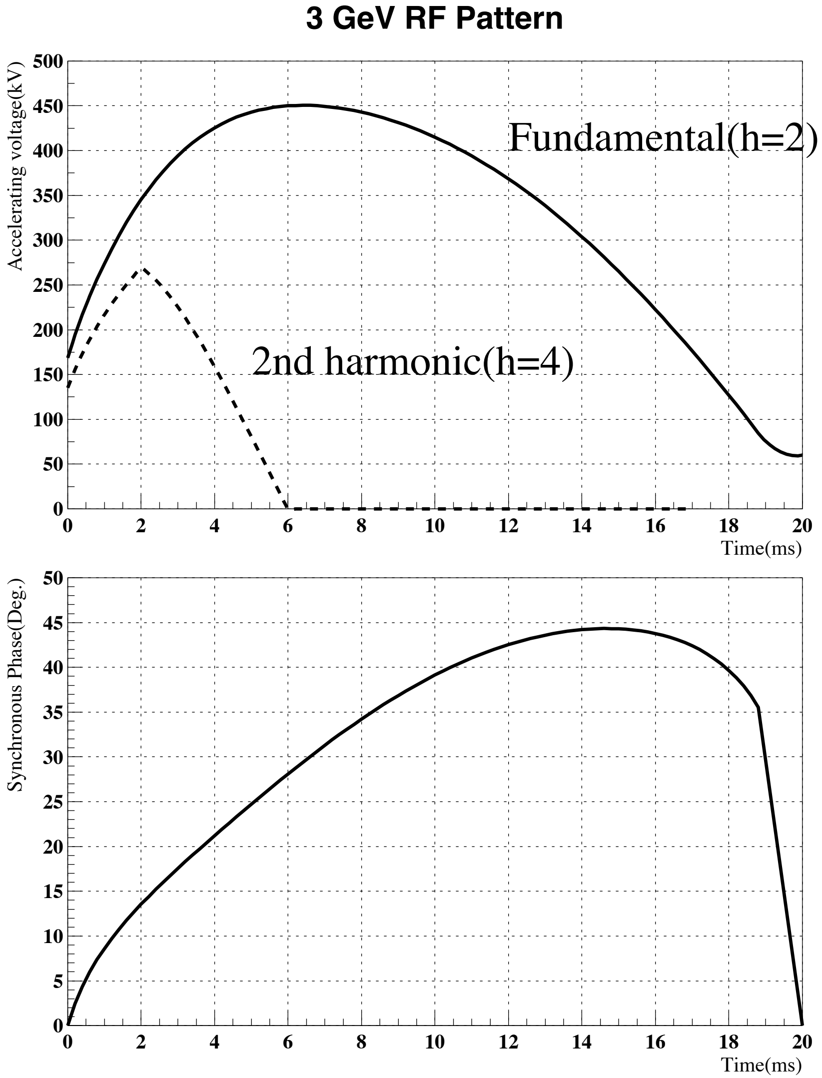


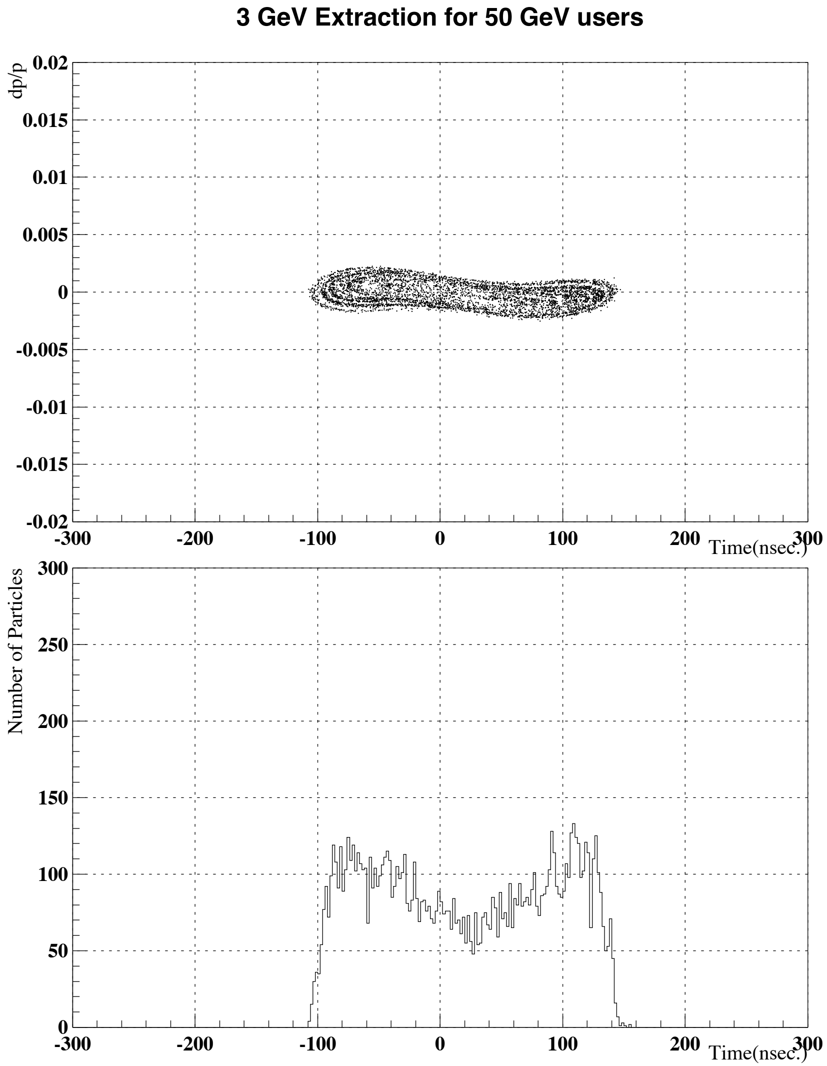
Time variations of Bunching factor and Tune shift



The transverse incoherent tune shift caused by the space charge and the bunching factor in early injection

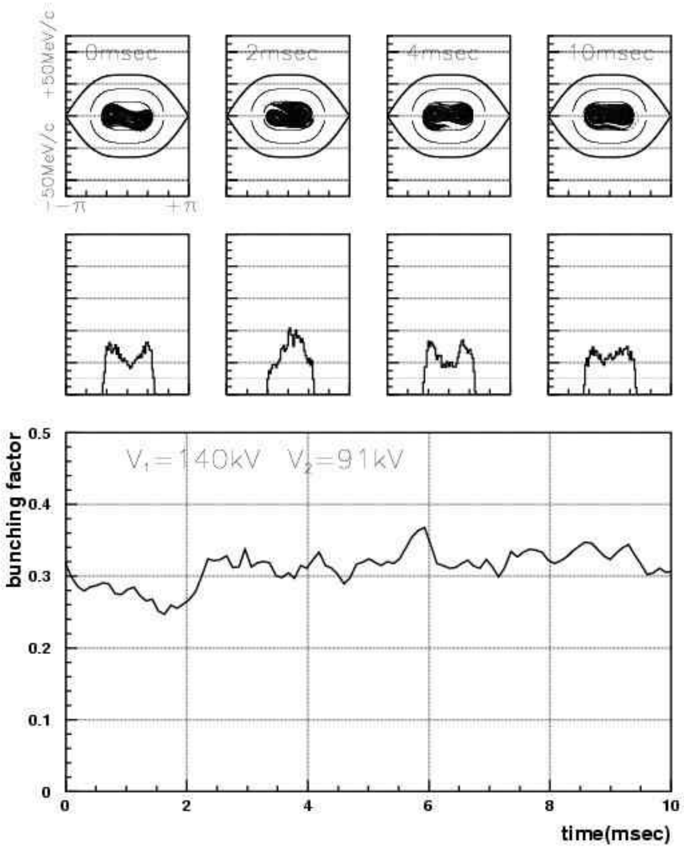
3GeV RF Pattern for 50 GeV Injection Beam



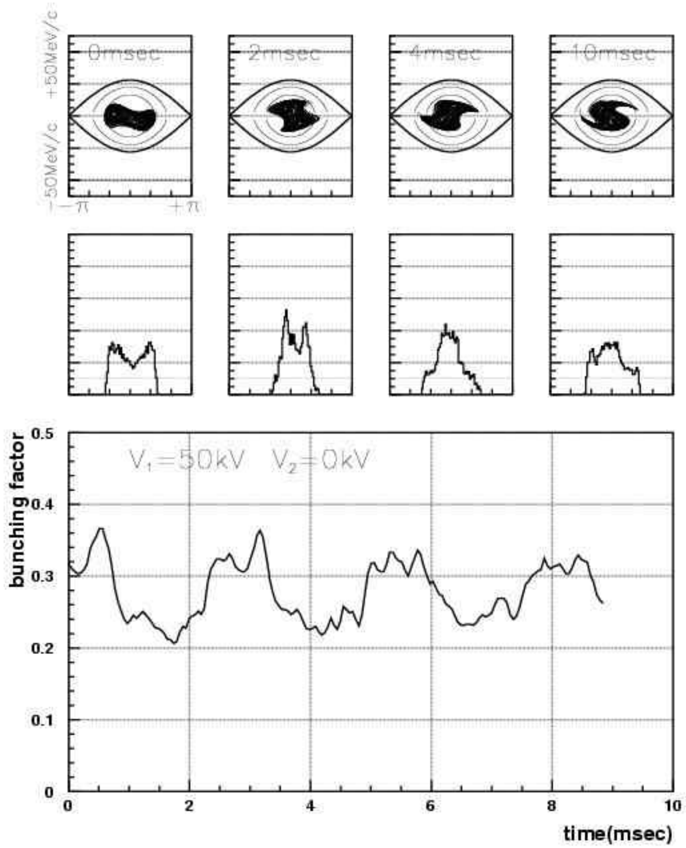


Keeping B_f more than 0.3 is important.

Particle Simulation for Longitudinal Matching at 50GeV MR Injection



Dual Harmonic RF



Single Harmonic RF

Short Summary of Longitudinal emittance control

- Longitudinal full tracking in RCS shows that B_f control in RCS seems to be possible by adding 2nd harmonic system and the phase and amplitude modulations are also effective.
- For bucket matching to 50 GeV MR, the extraction RF voltage must be reduced to 60kV. To compensate a heavy beam loading, the feedforward system is indispensable.
- Because of small synchrotron tune at RCS extraction, synchronization for beam transfer needs more consideration as well as an emittance control.
- 50GeV injection also needs 2nd harmonic system for longitudinal matching and for keeping B_f above 0.3.

RF Hardware

RF Cavity

- MA loaded High Gradient Cavity. Q-value of system is around 2 for 3GeV RCS (ref. CB, frequency range) and 10 for 50GeV (ref. Transient, one missing bucket).
- *Cut core configuration.*
- Prototype of direct cooled cavity installed in KEK-PS: 30kV at 12 MHz, 1m long.
- Cooling is the most technical issue.
- New *indirect cooling* cavity is developing.

RF Amplifier and DC Power Supply

- To minimize an undesired beam loss, fluctuations of power system and beam must be separated. Synchrotron frequencies are low in two rings.
- 1.2MW final stage RF amplifier is required to supply the accelerating power and beam power.
- An IGBT inverter power supply has achieved ±0.1% of voltage ripple.

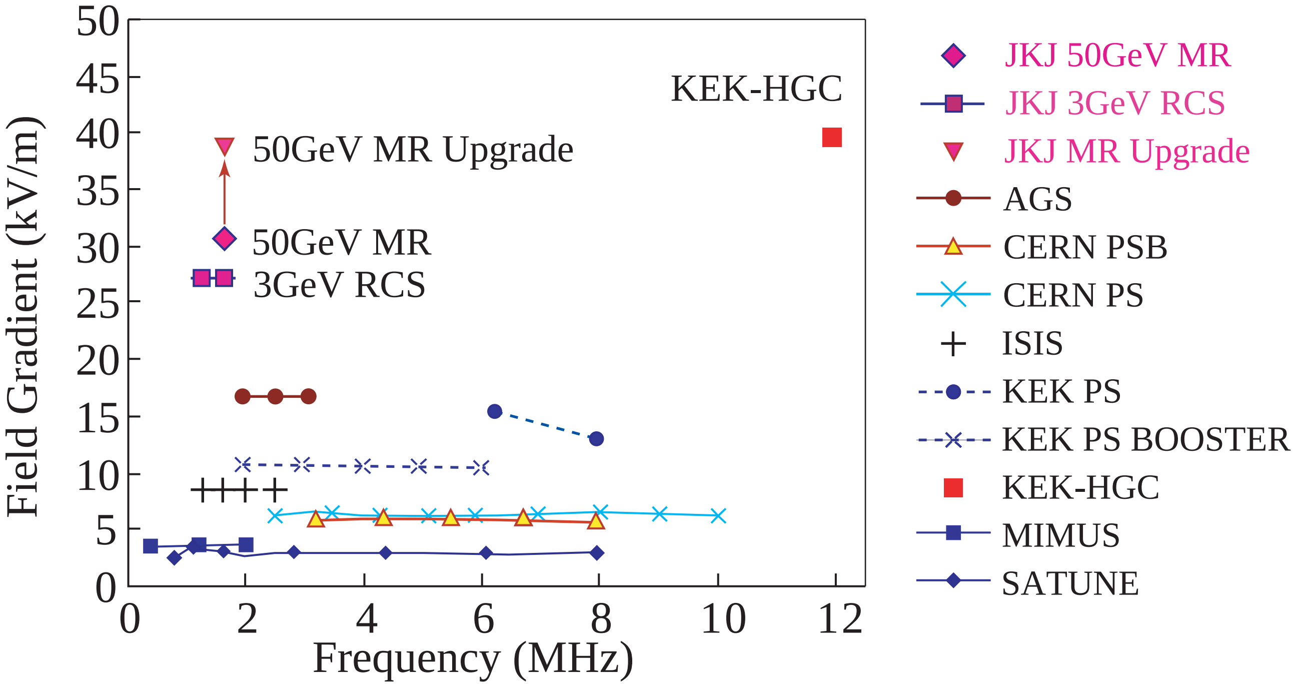
Digital low level RF control

- Reliability, Stability, Accuracy and Reproducibility are keys for RF control.
- Full digital control is considered.
- Feedforward system is key control component.
- DDS based dual harmonic RF signal generator, Digital phase detector and *Feedforward* module

Main Parameters of 3GeV RCS and 50 GeV MR RF System

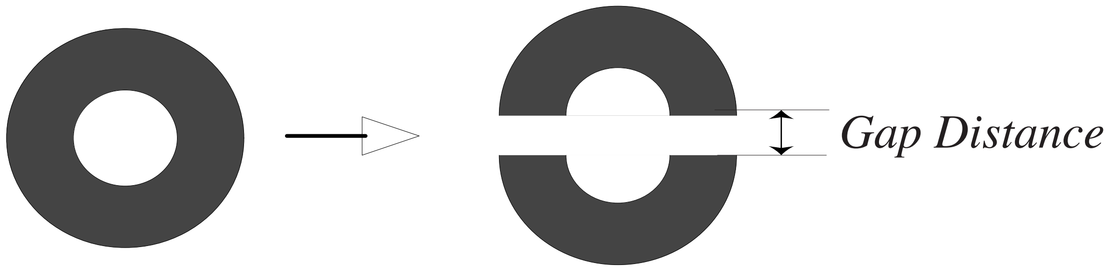
	3GeV RCS	50GeV MR
Number of cavities	11	7
Voltage per cavity	45kV	47kV
Number pf gaps	3	3
Length of cavity	1.996 m	1.846 m
Number of core per cavity	24	24
Cavity impedance	840 ohm for each 3 gaps	1000 ohm for each 3 gaps
Core type/ sizes	Magnetic Alloy, cut core OD80cm, ID37.5cm, T3cm	Magnetic Alloy, cut core OD80cm, ID24.5cm, T3cm
Core impedance	100 ohm	125 ohm
Power dissipation per core	17.5kW	15.1kW
Duty	50% (RF on time) 30% (power consumption)	60% (RF on time)
Average dissipation / core	5kW	9.1kW

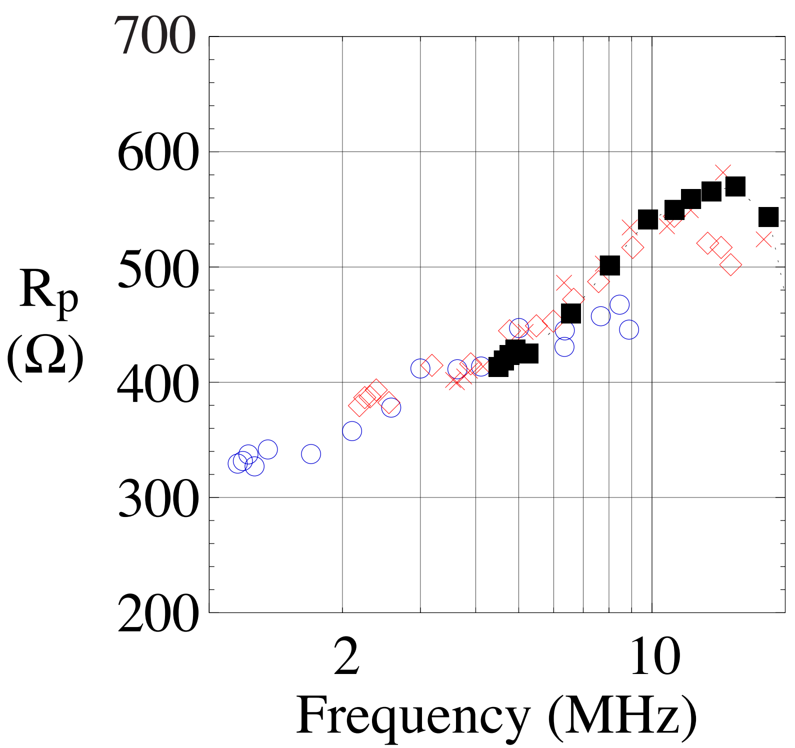
The field gradient of RF cavities for the proton synchrotrons

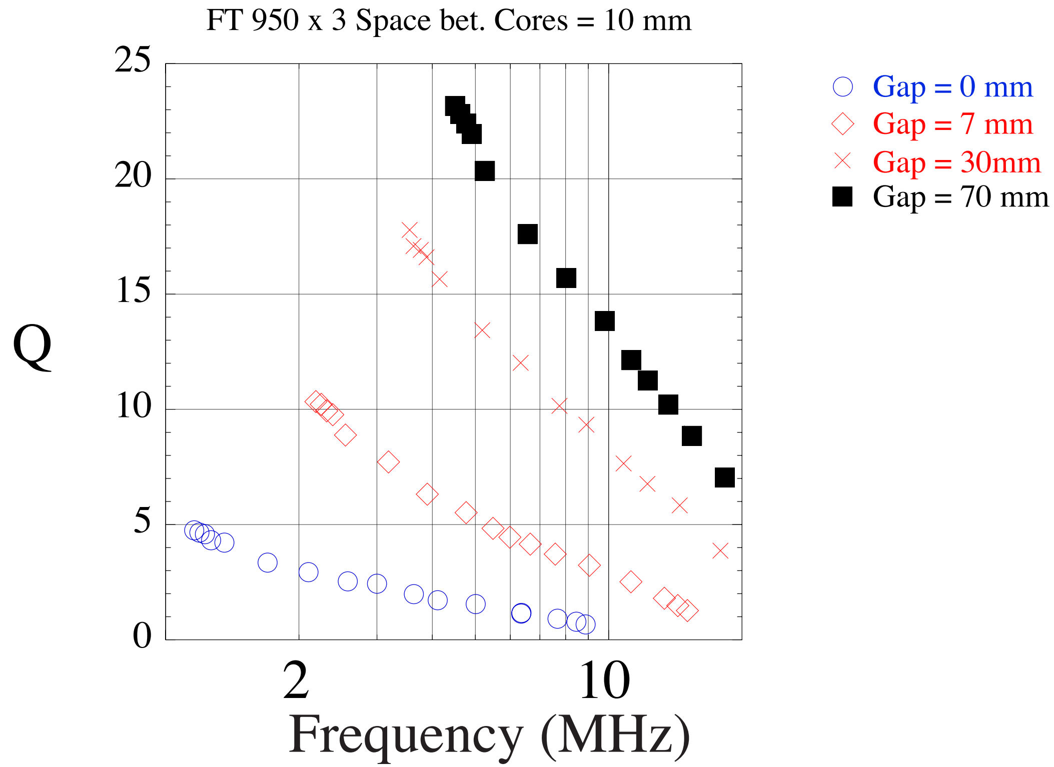


Impedance and Q-value Variations as Functions of Gap Distance and Frequency

Cut core impedance stays constant !
Gap distance could control R/Q value widely.







JKJ RING-RF Cavity Design

Average power dissipations per core are

5kW ---- (3GeV), 9kW ---- (50GeV)

Key Point of Design is how to cool the cavity.

(1) Direct-water cooling cavity

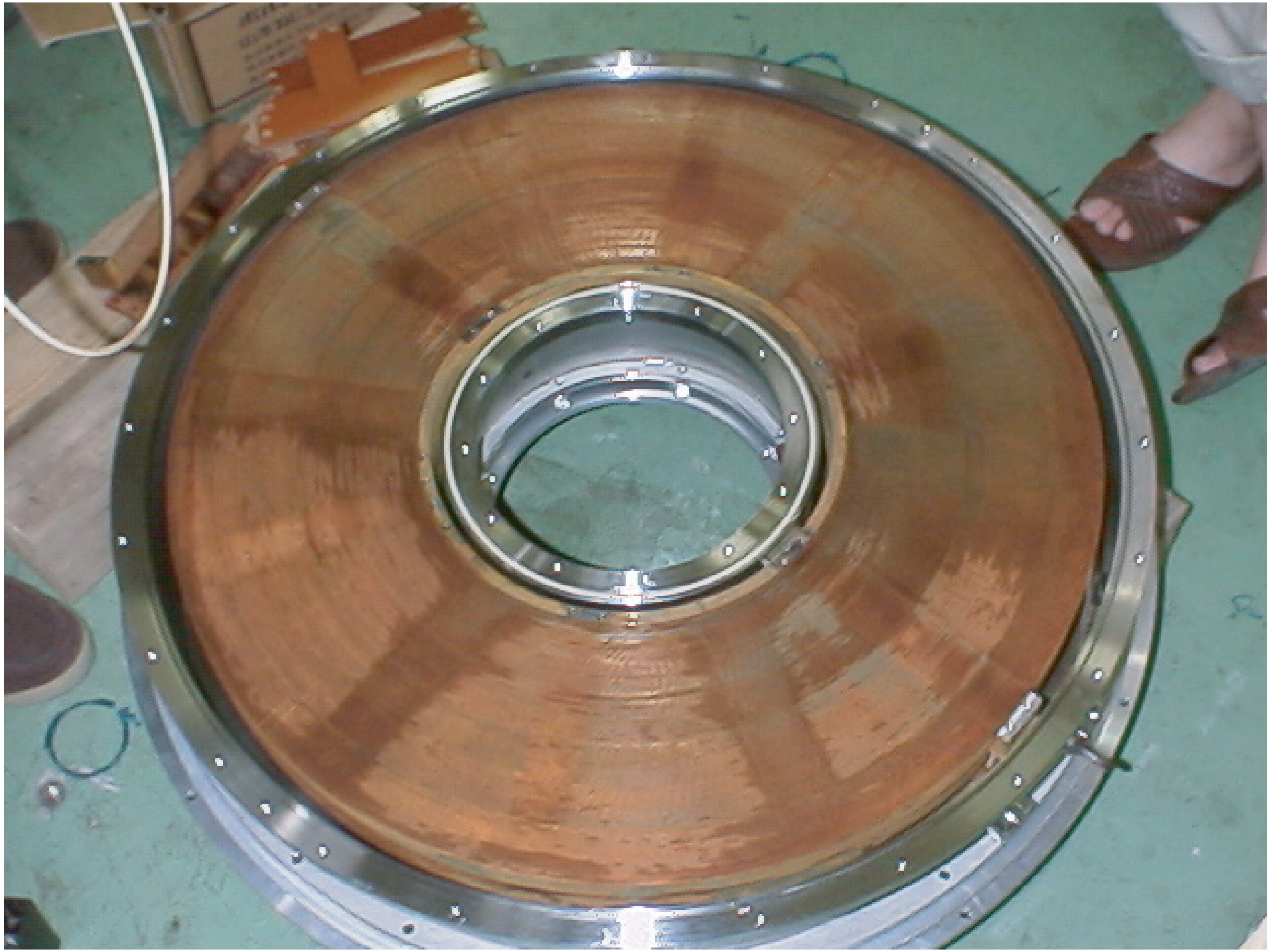
Direct-water cooled by puttning cores into water-tank
The most effective cooling
however,
Double structure to seal water > a troublesome work
High di-electric water affects impedance of cavity
Rusting may become serious after long operation

(2) In-direct cooling cavity

Water cooled Cu-plate removes heat.
Cavity Q-value could be optimized easily.
however,
Good thermal contact and electical insulation between core and Cu-plate are essential.

Direct Cooling

Water Tank and MA Cores for Direct Cooling Cavity

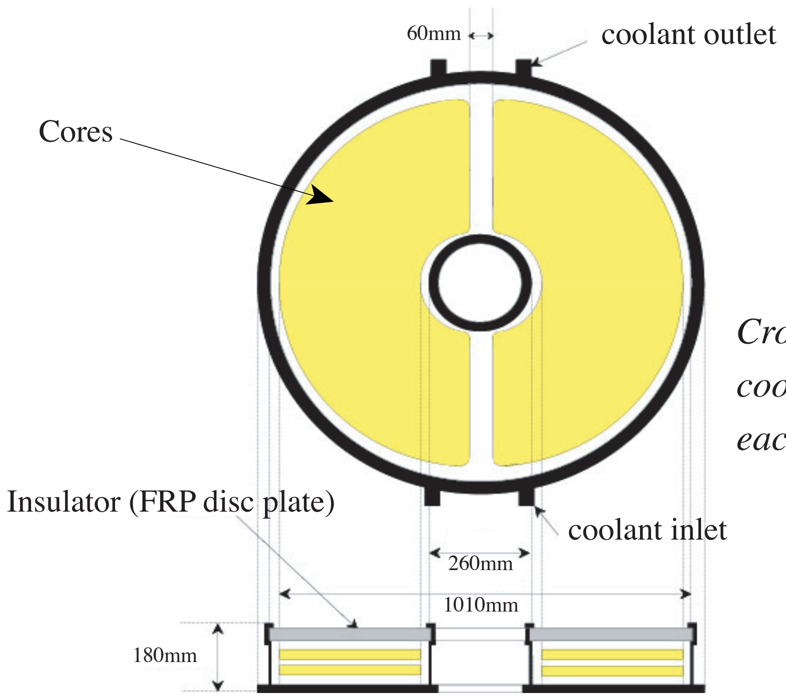


This is the first water coolded model, no cut cores used.

High Gradient MA Caviry RF system at KEK 12 GeV PS

Specifications

Resonant Frequency	: 12.04MHz
Accelerating Voltage	: 30 kV
Q-value	: 10
Cavity Impedance	: 1000Ω per gap
Number of Gaps	: 2
Cavity Length	: 920 mm (F to F)
Number of Cores	: 8 (outer 950, Inner 260, Thickness 25 in mm)
Cooling	: Direct fluiod cooling with Perfluorinated liquid (FC3283)
Flow Rate	: 400 liters/min



Cross-sectional view inside the cut-core cooling cell. There are two facing cells at each acceleration gap.

The cavity anf the amplifier installed in KEK-PS tunnel.

Indirect Cooling

Indirect Cooling Test using smaller cores

Each stack was bonded with Plyimide(BT) resin + AlN

Bonding

Thermal analysis results in in-direct cooling could possible.
Good surface contact between > essensial
Inorganic compound is rather hard and sticky, then it is hard to remove bubbles inside

Finally, a polyimide resin and an alumium nitride are the best to achieve both good contact and good thermal conductive.
Polyimide resin and an alumium nitride are mixed. 25%/75%
Themal conductivity around 2 ~ 4 W/m/K.

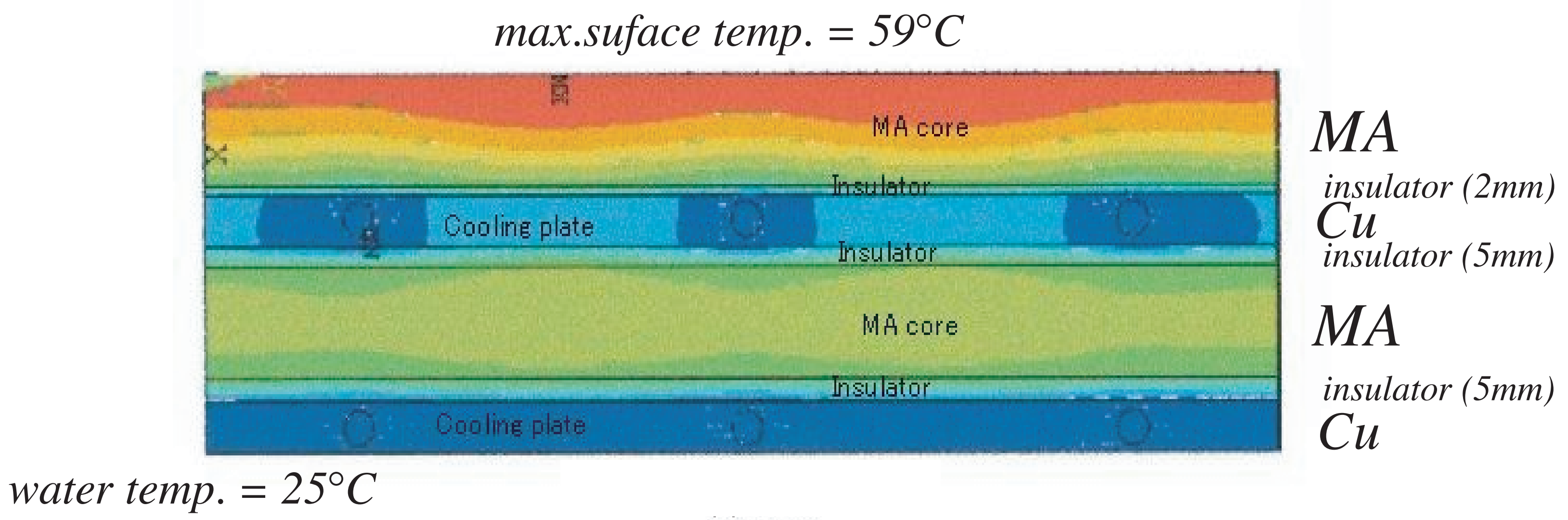
Indirect Cooling using Water cooled Cu-plates

- MA core + polyimide resin (BT-resin) + Cu cooling plate
- *Developement of High Thermal-conductive Insulation Material (BT-resin)*

  → polyimide resin + Aluminum Nitride (*AlN*)

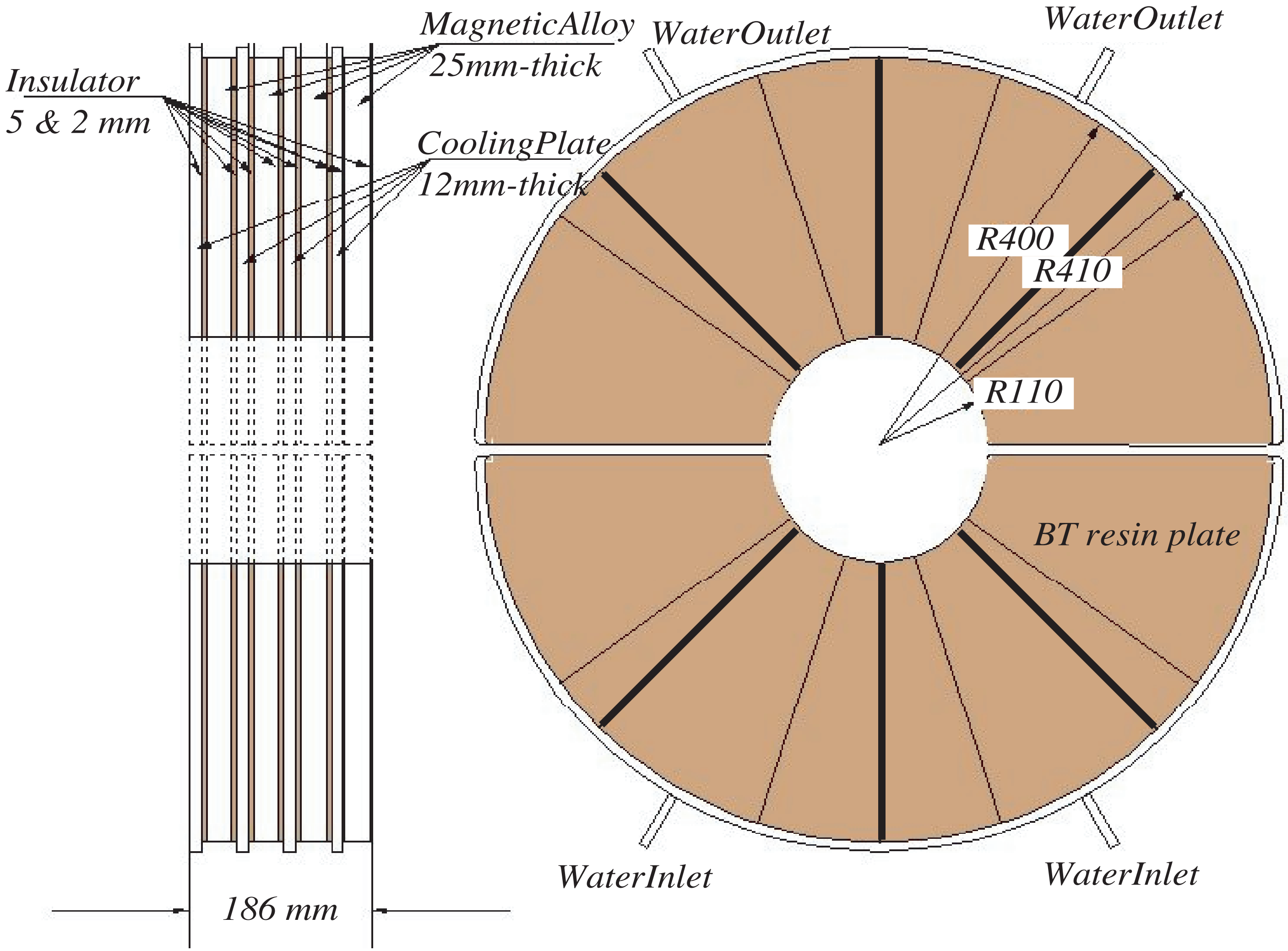
  25% + 75%(AlN) >> 2 ~ 4 W/m/deg.

The most important thing is how to contact/bond together.



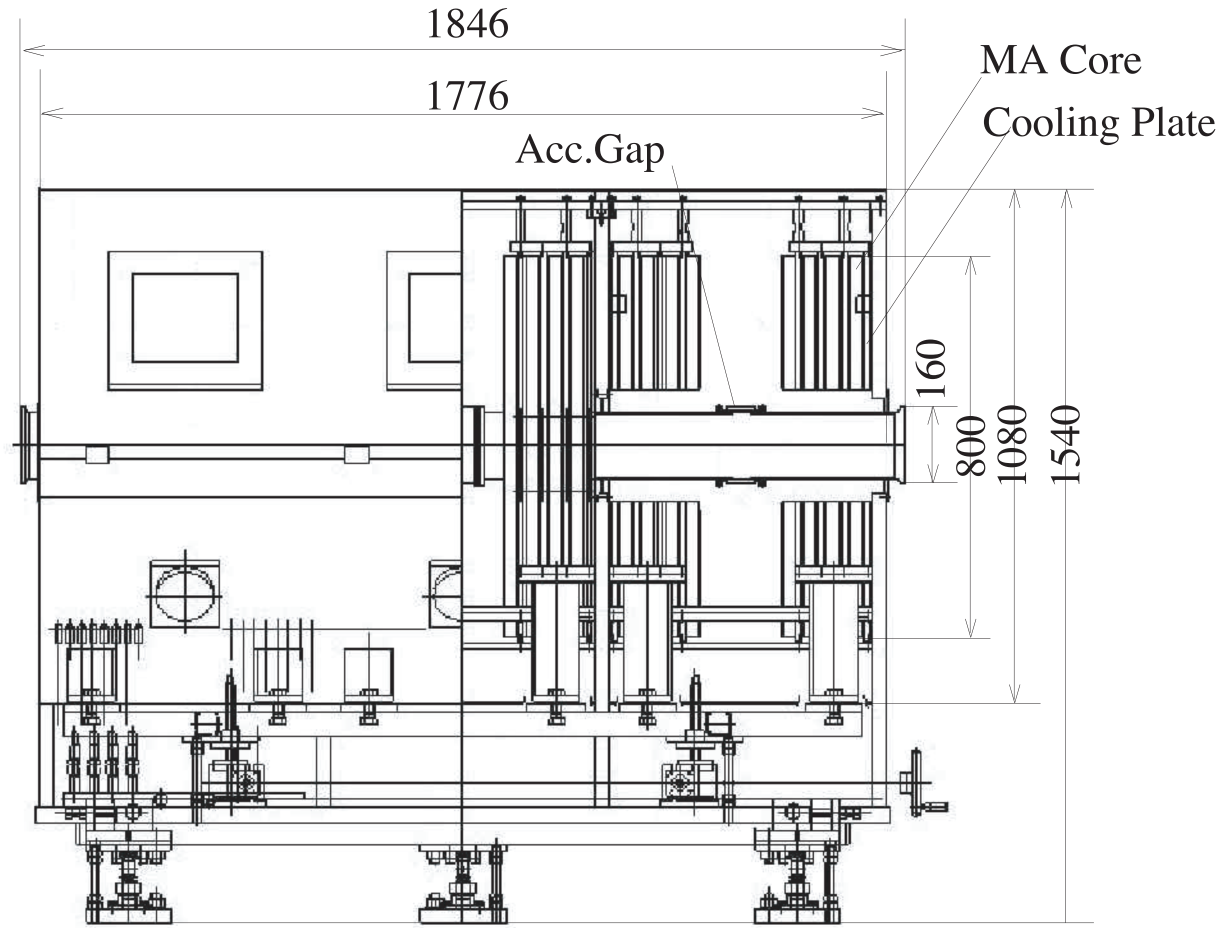
Thermal Analysis in case of Indirect Cooling: by *ANSYS*

MA Stack (indirect cool type)

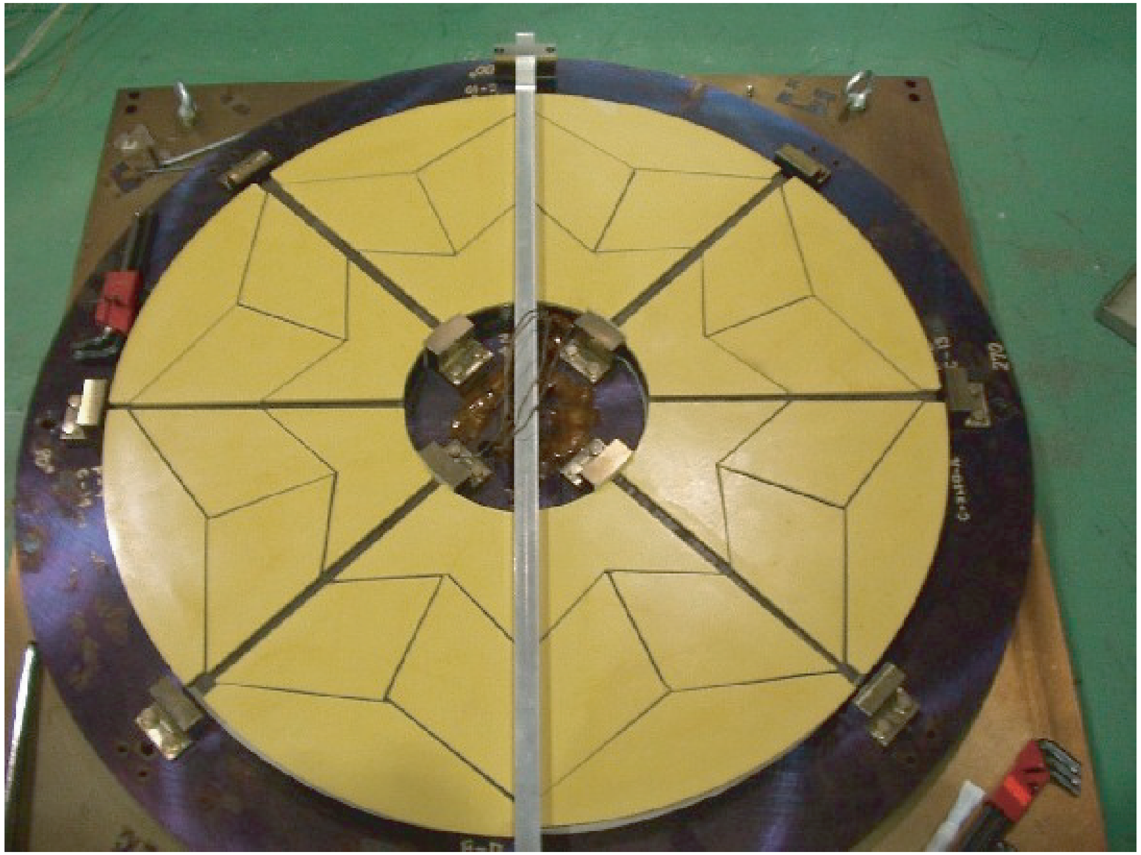


- *A stack consists of 4 MA cores, and each gap has two MA stack.*
- *BT-resin plates are segmented by 8*

High Gradient RF system for 50GeV MR
Indirect Cooling Type:



Improved BT-resin Plates



Each gap between BTs could release the thermal stress.

Cutting Core with Cooling Plates

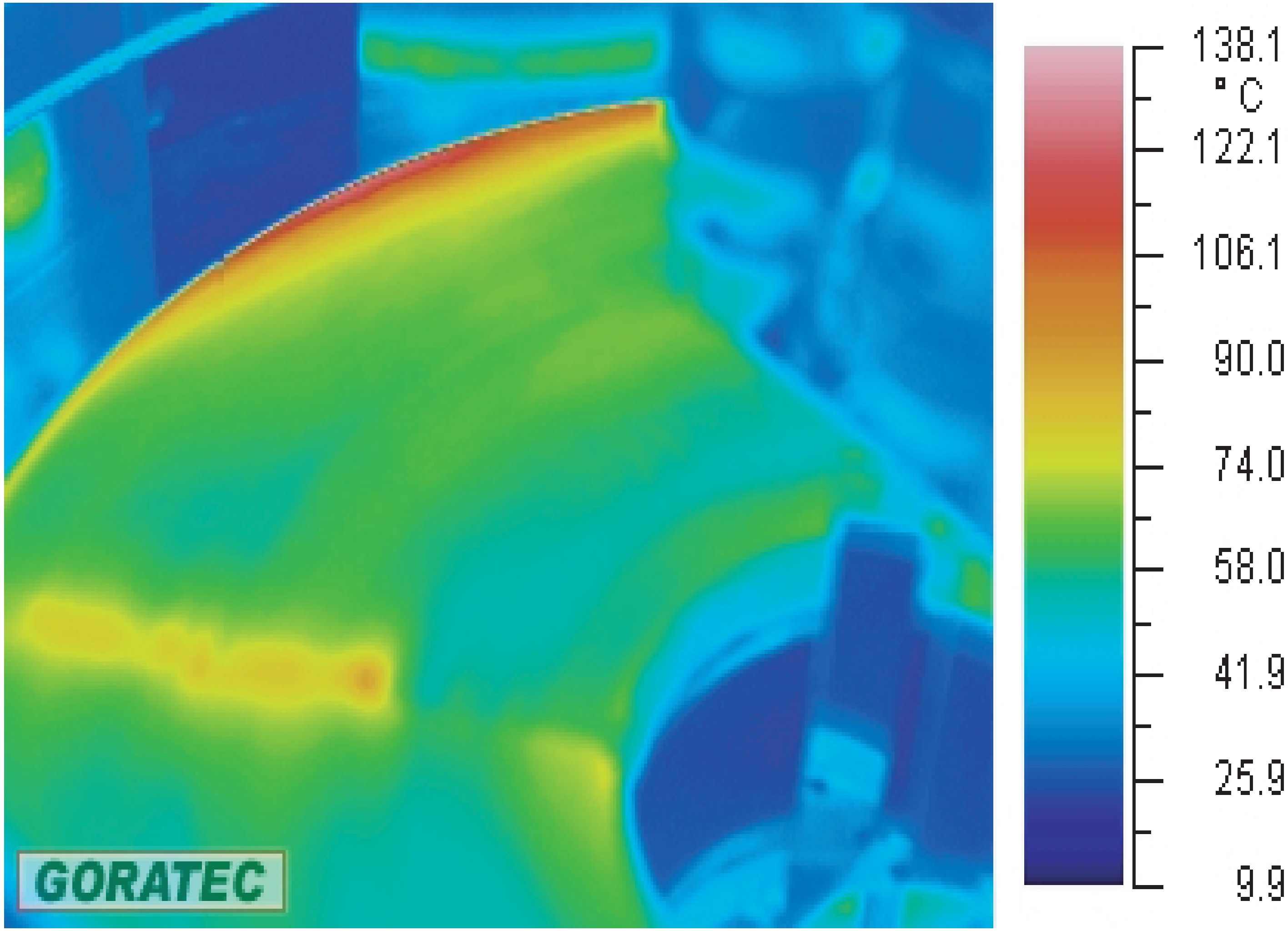
Cu-cooling plates have been segmented at a cutting position. The plate was bonded by Inorganic compound glue.

Magnetic Alloy Cut-Cores with Cu Cooling Plates

Sizes: 800*o.d.*-235*i.d.*-25*t*, in mm

MA core is cut after bonded with already segmented cooling plates by water-jet cutter.

High Power Test to check Cu-plate Contact



There is observed "hot spot" may due to bad contact.

RF Amplifier and Anode DC PS

Specifications of RF Amplifier

	3 GeV	50 GeV
Output tube Tetrode (TH558)	Tetrode (TH558)	
Number of output tubes	2	2
Operation		
Class	AB_1	AB_1
Arrangement	push-pull	push-pull
Peak RF current of each tube	200 A	190 A
Output impedance of each tube	260 Ω	260 Ω
DC plate voltage	10 kV	10.5 kV
Robinson Impedance		
per Cavity	1.4 kΩ	1.8 kΩ
per Ring	15.4 kΩ	10.8 kΩ
Beam Intensity	8.3×10^{13} ppp	3.3×10^{14} ppp
μ Coulomb/pulse	13.3	53.2
Revolution frequency		
Injection	613.79 kHz	185.69 kHz
Extraction	835.87 kHz	191.16 kHz
Beam Current		
Average	8.16 – 11.1 A	9.82 – 10.1A
RF fundamental	14 – 19 A	19 – 25 A
RF fundamental (peak)	23 A	25 A
Peak power dissipation per gap	147 kW	122 kW
Peak output in total	930 kW	970 kW
(RF output)	602 kW	650 kW
(Plate dissipation)	328 kW	320 kW
Operation duty factor	60 %	60 %
Cooling water		
Tubes	$18\ m^3/hr$	
G1	$0.3\ m^3/hr$	

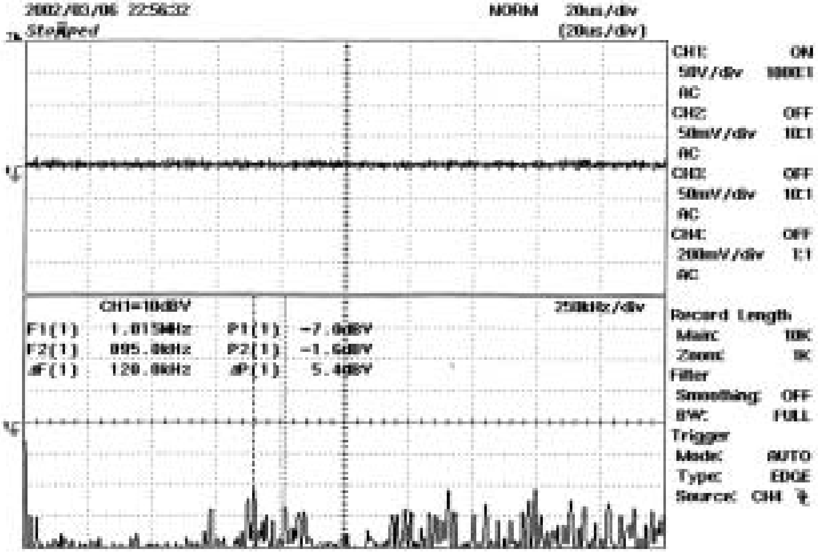
Specification of Anode DC Power Supply

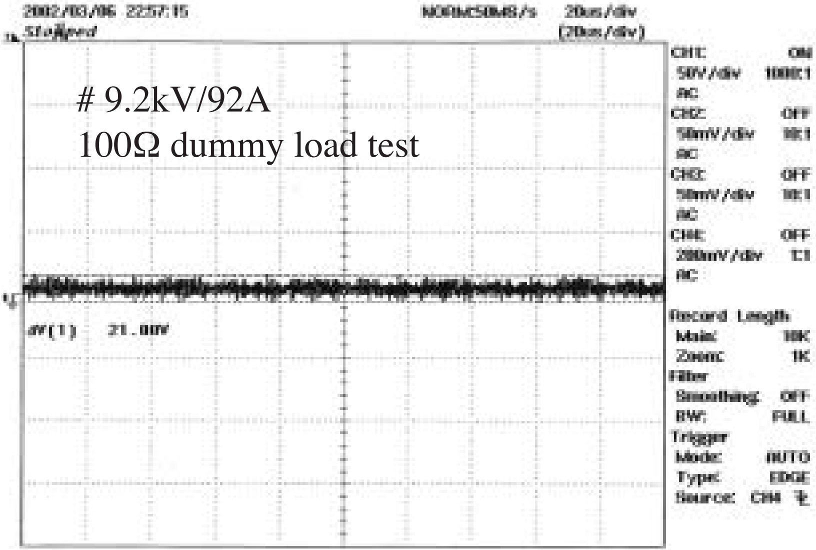
■Peak output power		1.2MW
■Output voltage		9 ~ 13 kV
■Output current		92 A
■Voltage ripple	less than	±0.2%
■Voltage sag	less than	1%
■Duty	more than	60%

RF Power Source

This is an RF amplifier for 50GeV RF.
Two TH558 tetrodes are used at output.

1.2MW Anode DC Power Supply *(consisting 15 IGBT-inverter units)*





9.2kV/92A
100Ω dummy load test

Low Level RF Control

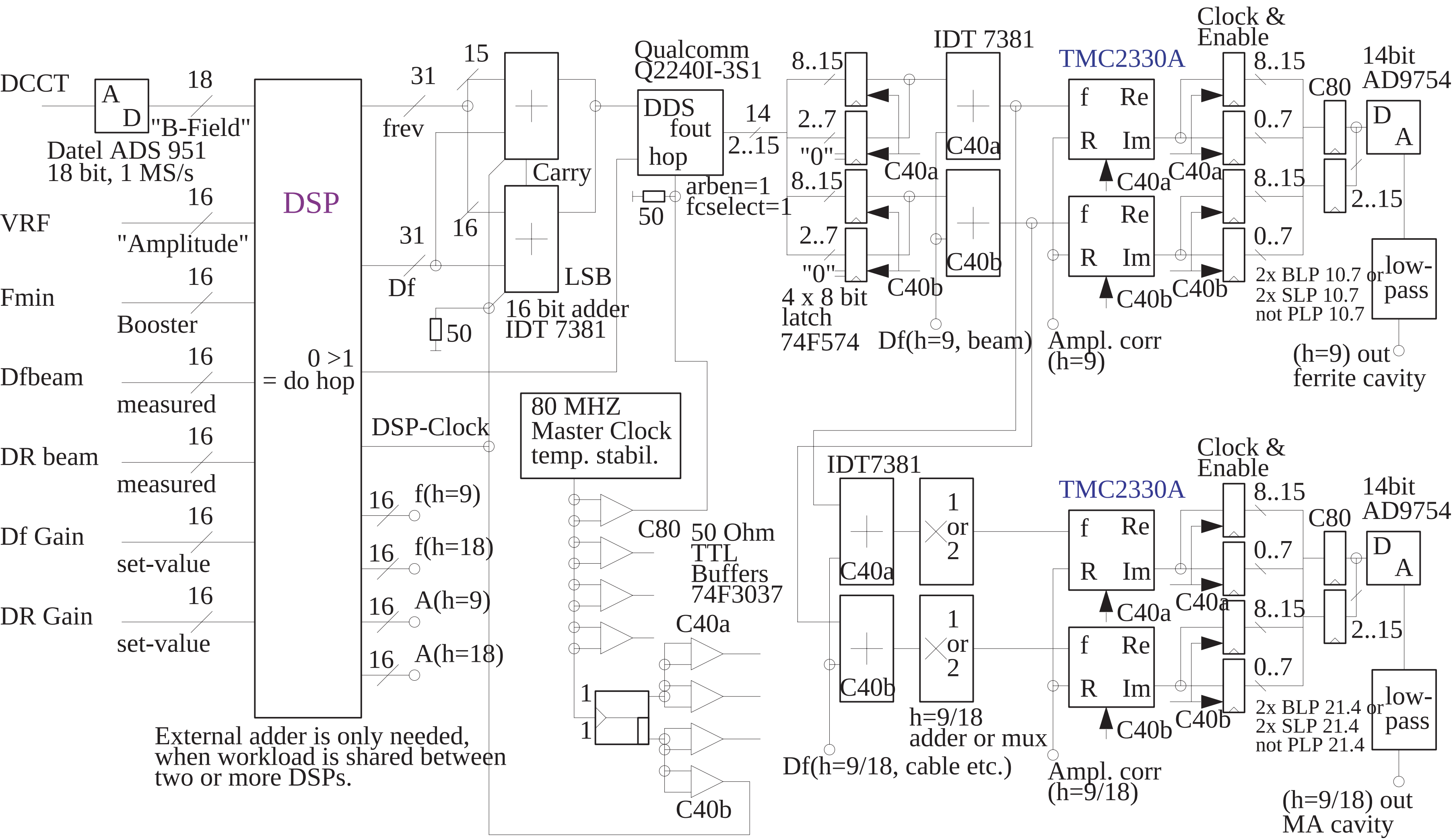
Low Level RF Control

= *Reproducible Contorl*

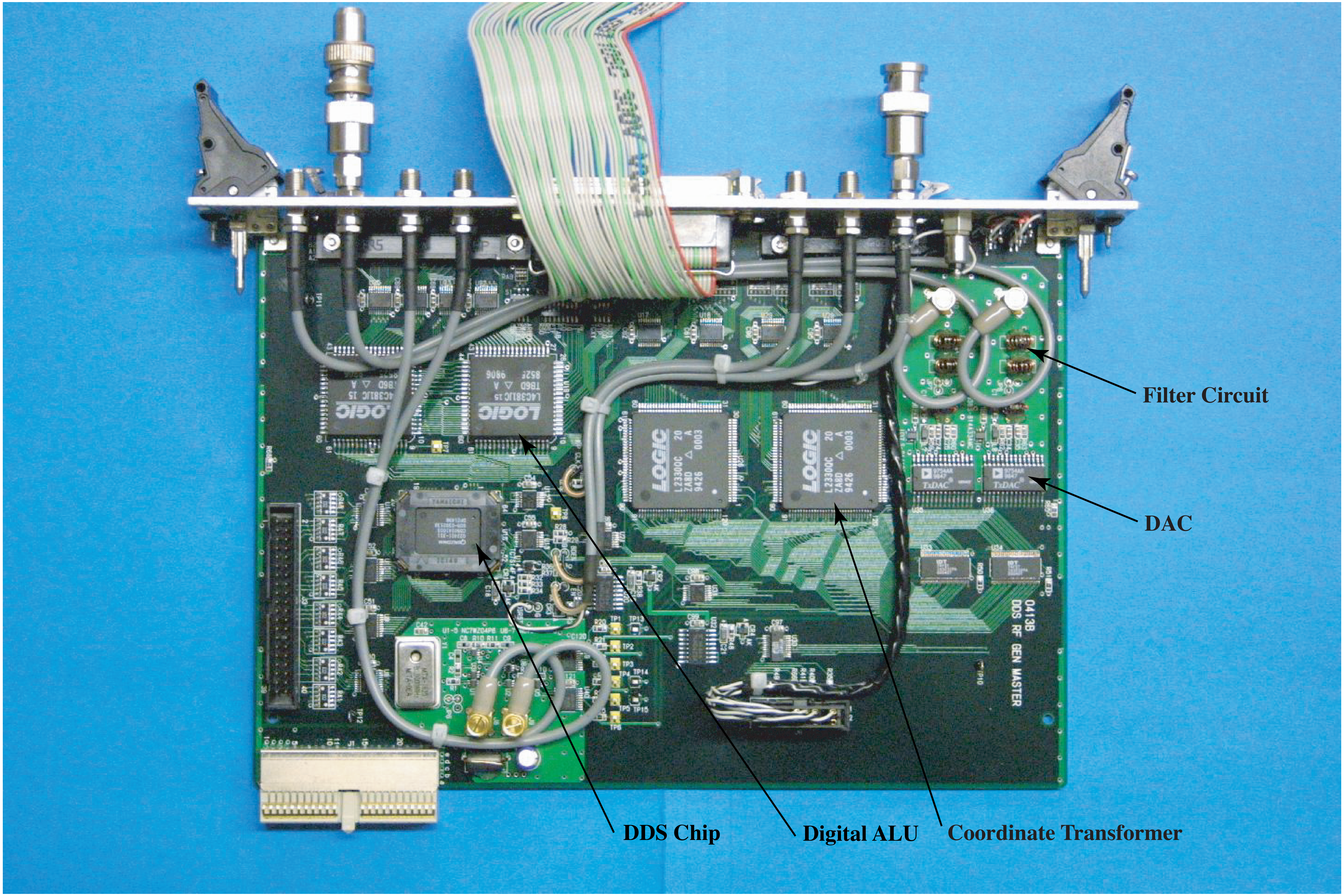
Considering "Accuracy", "Stability" and "Reproducibility", developing
Direct Digital Synthesis based RF Low Level Control,
Fully Digital Control

- *DDS: <1ppm o low phase noize.*
- *Digital feedback (orbit correction and phase feedback)*
- *Digital feedfoward system to compensate beam induced signal*
- *Digital synchronization system*
- *Digital pattern generations*

Block diagram of DDS-based Dual RF Signal Generator Module



DDS RF Generator Master Board

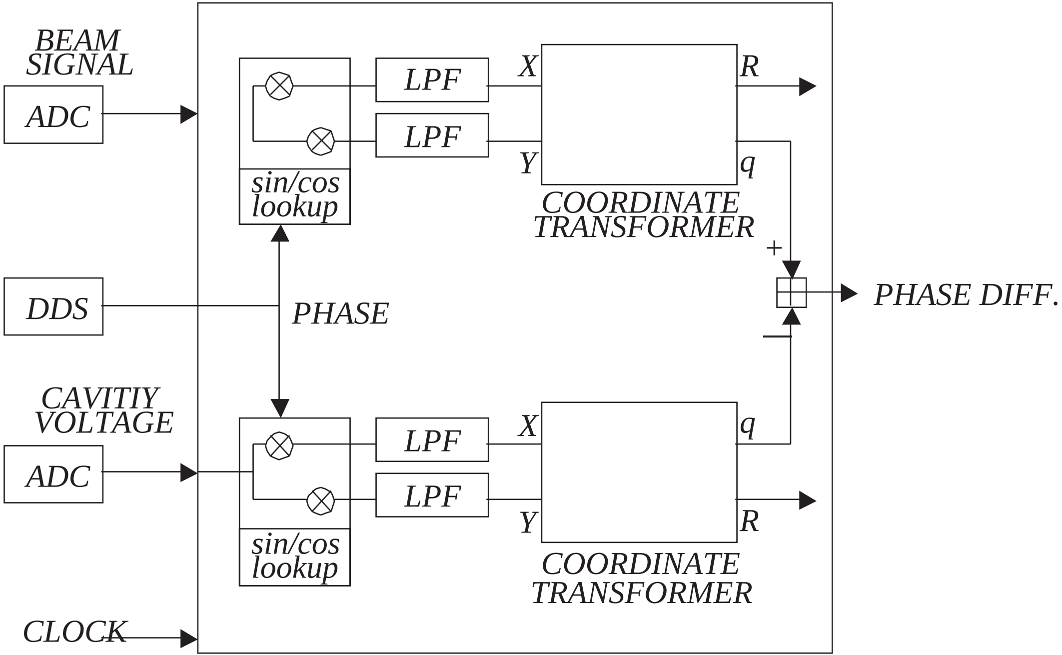


Developement of Fast Digital Phase Detector Module

I/Q modulation is applied to measure a beam phase error respect to the accelerating RF phase.

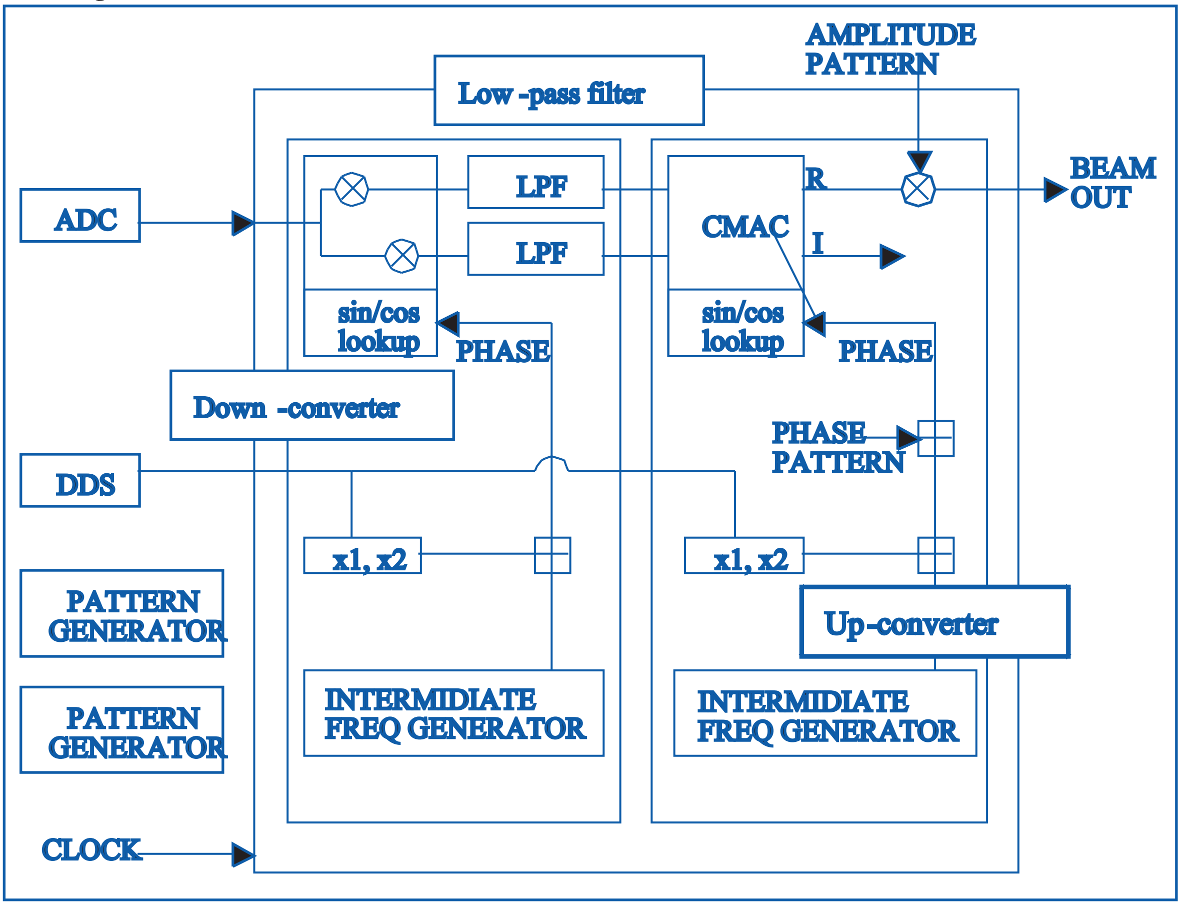
Module is under tunnig.

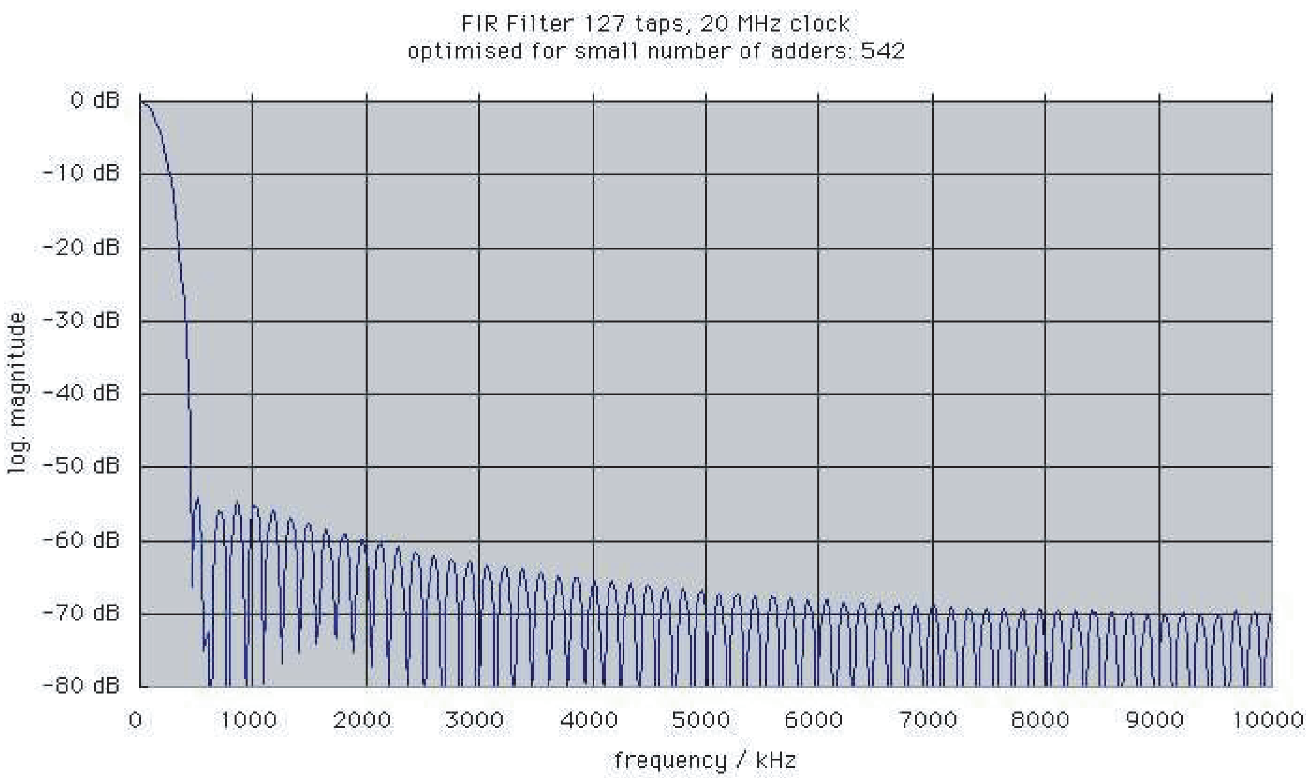
This will be tested at KEK-PS.



Digital Feed-forward Beam Control Circuit

Block Diagram





drawn by A.Schnase and F.Tamura

Summary

Longitudinal emittance control:

- Longitudinal full tracking shows that B_f control in RCS seems to be possible by using 2^{nd} harmonic system. Phase and amplitude modulations are also effective.
- Feed-forward system is necessary to compensate the beam loading in both rings.
- 50GeV injection also needs 2^{nd} harmonic system for longitudinal matching and for keeping B_f above 0.3.
- Emittance blow-up in 50GeV is necessary in early stage of acceleration. This tracking work needs more realistic optimization.

Cavity

- R&D's of both direct and indirect cooled type cavities are going on.
- Prototype of direct cooled cavity installed in KEK-PS has achieved the field gradient of > 30kV/m, 15kW dissipation per core. However, dielectric property of coolant (water) and corrosive issue should be solved.
- Indirect cooling is very attractive. Recent work is concentrated to this development.
- Bonding MA cores and Cu-cooling plate together is the most important issue.
- High power test of prototype indirect cavity will start soon.

continued

Anode DC power supply/RF amplifier

- To minimize an undesired beam loss, fluctuations of power system and beam must be separated in such a machine with low synchrotron tune. We have developed an extremely stable 1.2MW anode DC power supply for final stage RF amplifier.
- An IGBT inverter power supply has achieved ±0.1% of voltage ripple.

Digital low level RF control

- Reliability, Stability, Accuracy and Reproducibility are keys for RF control.
- Full digital control is considered.
- DDS based dual harmonic RF signal generator has been built.
- Digital phase detector and Feedforward module are designed.

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