OPPOSITE FIELD SEPTUM MAGNET SYSTEM FOR THE J-PARC MAIN RING INJECTION

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I. INTRODUCTION

- The septum conductor and its support are required to be as thin as possible.
- High intensity / high energy accelerators require the large aperture high field septum magnets.
- In the case of a high-field septum magnet, the severe electromagnetic force on the septum conductor and leakage flux to outside of the septum are serious problems
- To solve these problems, an opposite-field septum-magnet system has been developed for the beam injection / extraction.
- In this case, the same grade of opposite magnetic field is produced outside of the septum, which is on the side of the circulating beam.
- The electromagnetic force on the septum conductors and leakage flux cancel out each other. Furthermore, the beam-separation angle is twice as large as that of the conventional single septum magnet.
- To use this opposite-field septum magnet for beam injection / extraction for a circulating beam accelerators, the magnetic field of the circulating beam side must be compensated by other sub-bending magnets.
- Fortunately, these sub-bending magnets increase the separation angle of the injection / extraction beam orbit with the circulating beam orbit. We need a half-length opposite-field septum magnet and two quarter-length sub-bending magnets located up-stream and down-stream of the main opposite-field septum magnet
- The opposite field septum magnet system has been applied to the injection system of the J-PARC Main ring (50-GeV) proton synchrotron.

Configuration of Magnetic Field

- In Fig. 1, the opposite-field septum magnet has three conductor blocks in a pole gap. The central conductor forms a septum conductor on which double current flows and makes an opposite magnetic field in both side gaps
- These magnetic fields have the same value of opposite signs and face each other across the central septum conductor.

- In Fig. 2, a comparison of the magnetic field distribution between the normal septum magnet and the opposite-field septum magnet by a simulation using the computer program “Poisson” is shown.

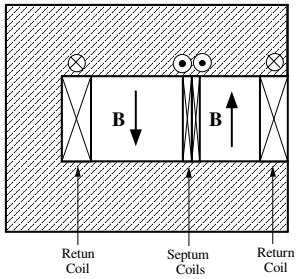


Fig. 1 Cross-sectional view of opposite-field septum magnet

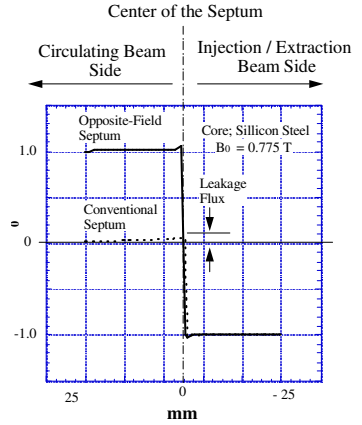
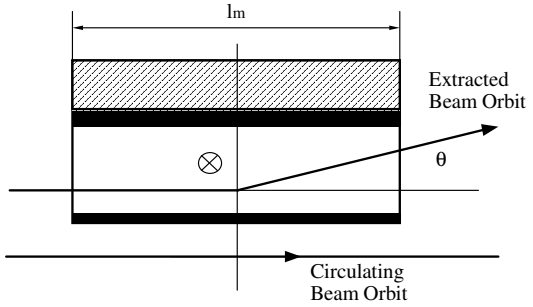
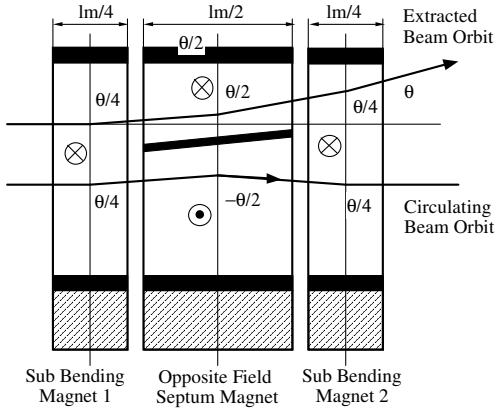


Fig. 2 Comparison of the magnetic field distribution between the conventional septum magnet and the opposite-field septum magnet by a 2D simulation

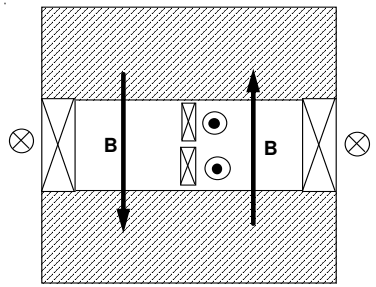
Opposite Field Septum Magnet and Sub-Bending Magnets System

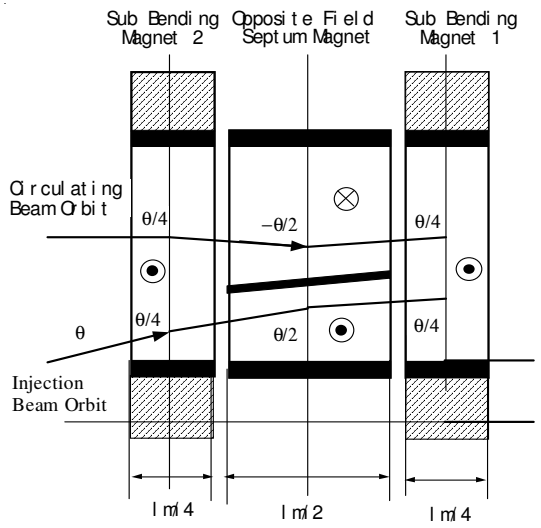
- The conventional septum magnet produces a magnetic field only inside the septum magnet.
- On the other hand, the opposite-field septum magnet makes a magnetic field of opposite sign on the circulating beam orbit.
- To use this opposite-field septum magnet for beam injection / extraction, the magnetic field of the circulating-beam side must be compensated by other sub-bending magnets.
- The horizontal aperture of these sub-bending magnets covers the injection / extraction beam orbit, so that the injection / extraction angle of the beam orbit with the circulating beam orbit is enhanced to the same amount as the opposite-field septum magnet.
- To obtain the same injection / extraction angle as the conventional septum magnet, we need only half the length of the opposite-field septum magnet and two quarters of the length of the sub-bending magnets.





The concept of the opposite-field septum magnet system





The same grade of opposite magnetic field is produced both inside and outside of the septum.

The electromagnetic force on the septum conductors is canceled out by each other by opposite magnetic fields on both side of the septum.

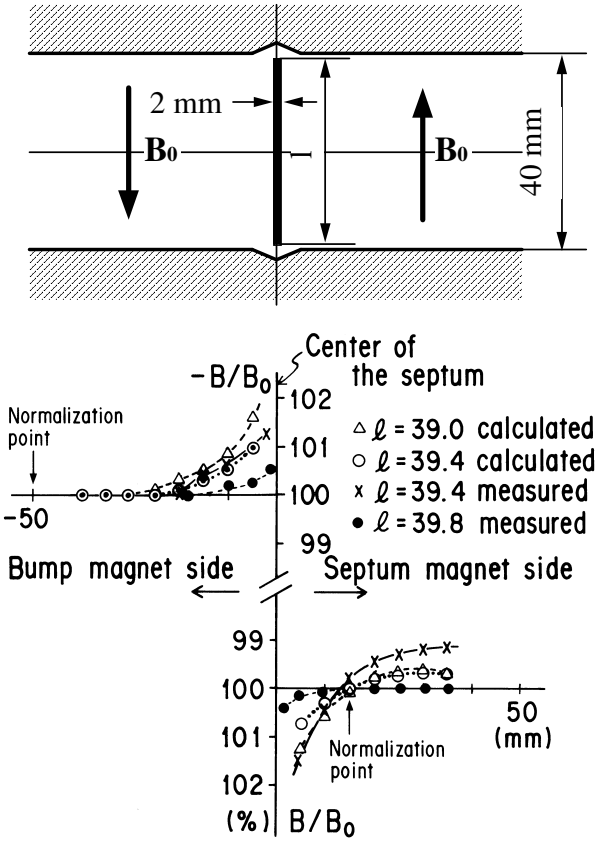
The magnetic field of the circulating beam side is compensated by two sub-bending magnets set up-stream and down-stream of the opposite-fields septum magnet.

These three magnets are connected in series and excited by the same power supply for simultaneous excitation.

The thin septum conductor will be available without any mechanical support, and pulse excitation for power saving becomes easier than that for the normal septum magnet.

Field Quality Near the Septum

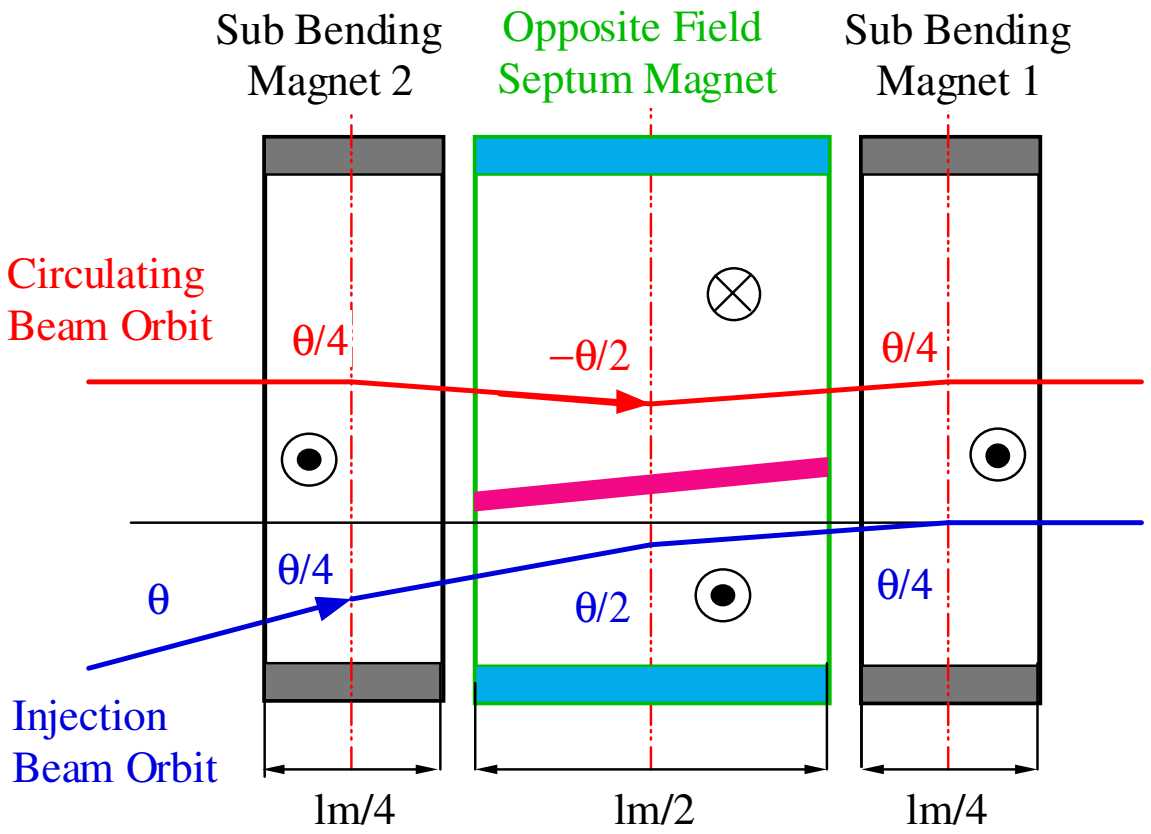
- At the septum conductor, the pole face is notched to make the insulation gap with the septum conductor.
- Fortunately, however, regarding the disturbance of the field distribution, the notched pole face and the cut-off septum are complementary to each other.
- The notched shape of the pole face, was fixed in advance, and the size of the septum conductor was changed by trial and error. The calculated values by “Poisson” were agreed well with the measured value. The field distribution near the septum is very sensitive to the cut-off quantity of the septum.
- In this way, the optimum shapes of the pole face and the septum conductor were decided.



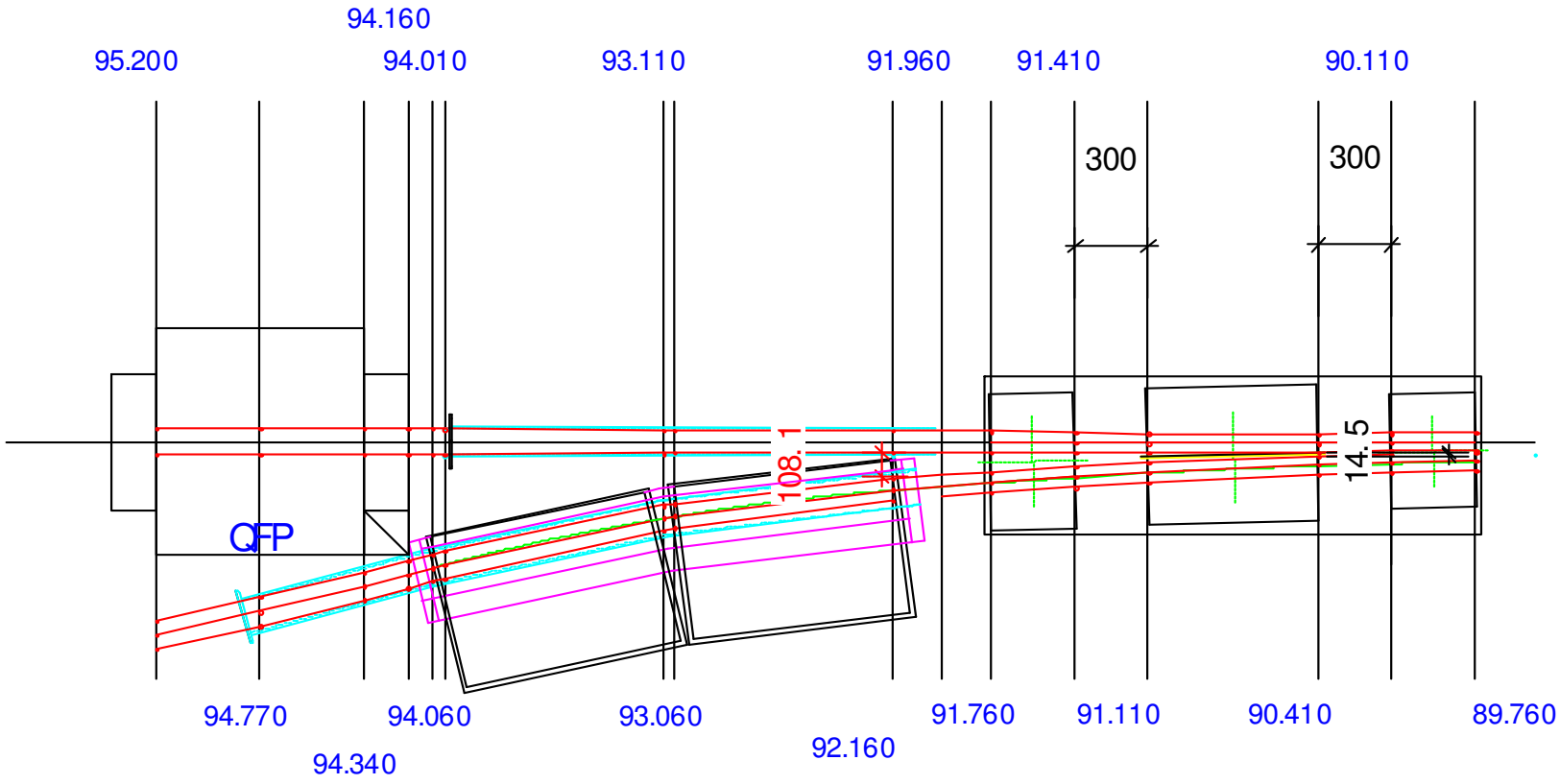
Application of opposite field septum magnet to JPAERC Main Ring Injection

- The J-PARC Main Ring is 50-GeV proton synchrotron which is designed to accelerate 8.3×10^{13} protons (8 bunches) every 3.64 sec repetition.
- The injection energy is 3 GeV.
- The incoming beam emittance from the 3-GeV rapid cycling synchrotron (RCS) is shaped to 54p mm mrad in both the horizontal and vertical planes using a scraper and collimator system.
- The acceptance of the transfer line from the RCS and the ring of the 50-GeV synchrotron are designed to be 81p mm mrad in both the horizontal and vertical planes.
- High-intensity high-energy accelerators impose tight demands on the injection / extraction septum magnets because of its large aperture and high magnetic field.
- Especially regarding the injection system, their large-size injection beam and a circulating beam, before adiabatic damping, must be separated in the limited length of the straight section.
- A thin structure, large aperture and high operating magnetic field septum magnet are required.
- To cope with these tight demands, a new design concept of the opposite-field septum magnet system has been invented[1].

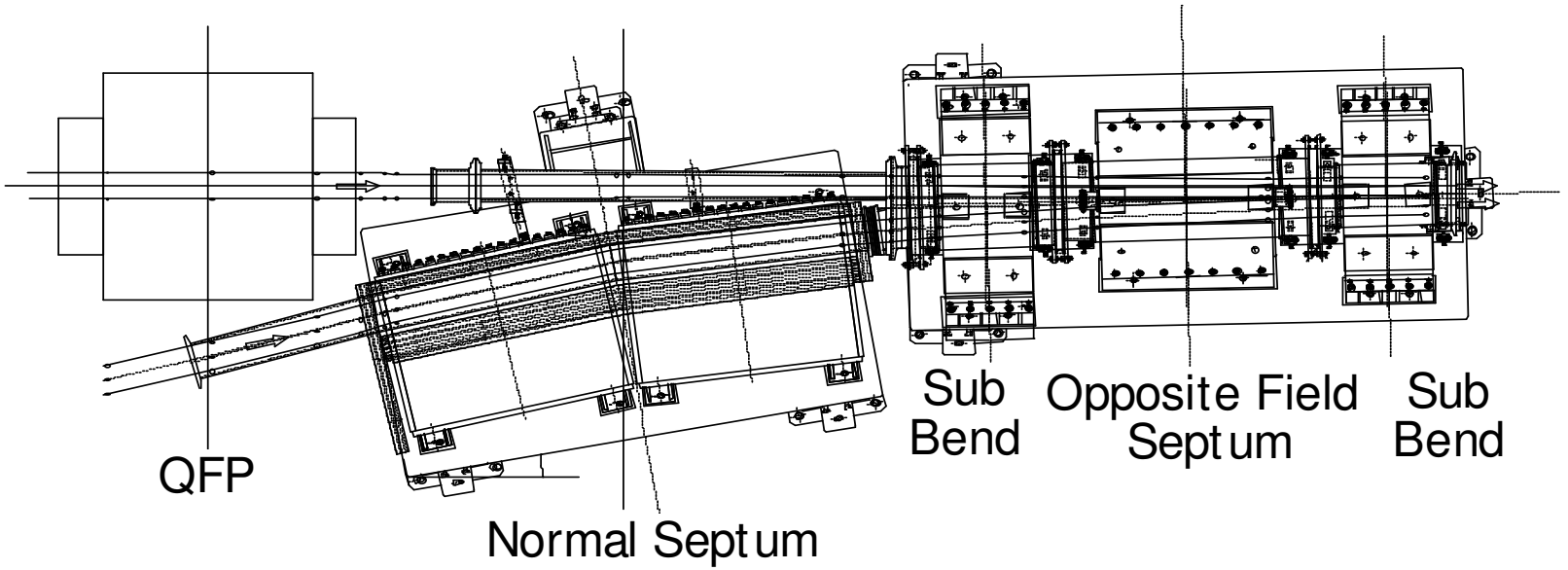
Opposite field septum magnet system for beam injection



Injection beam line



Outline of the injection magnets system



Outline of the injection system

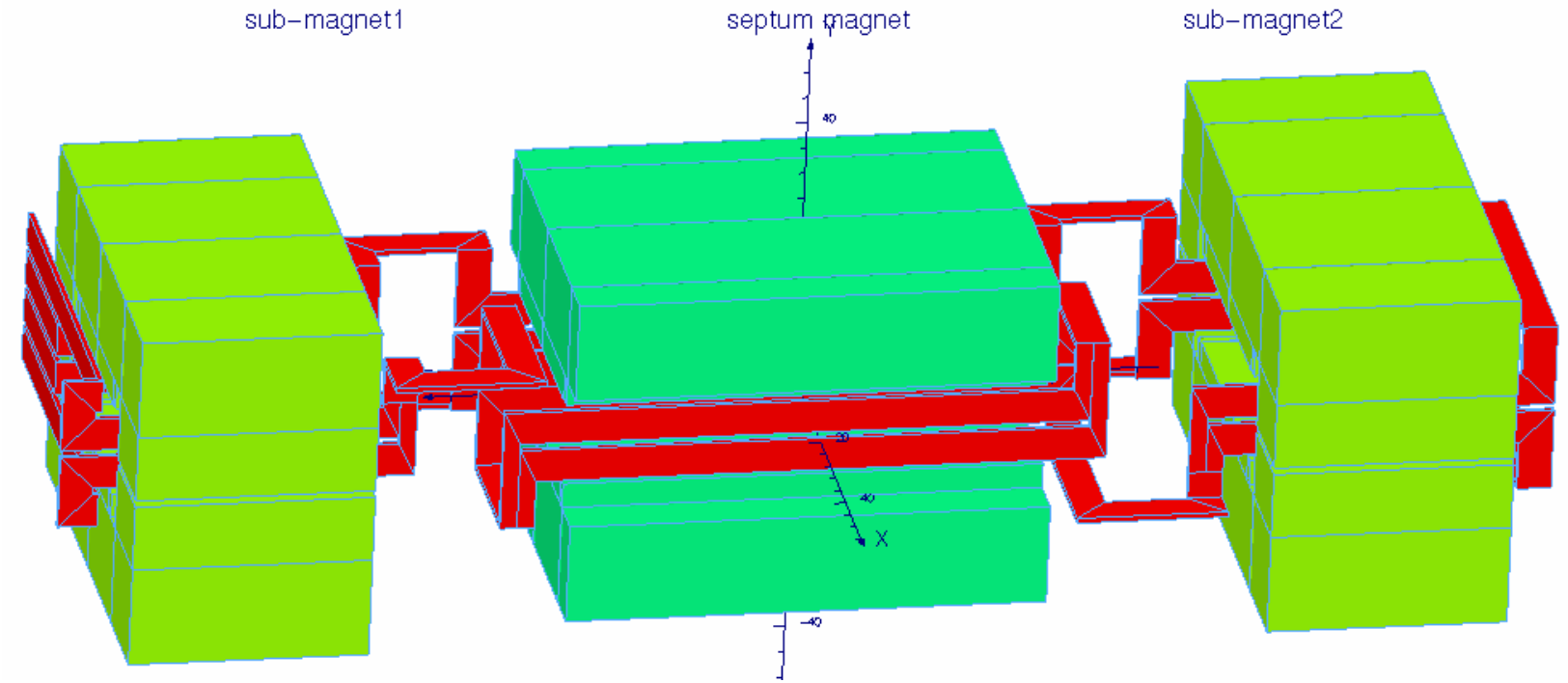
The injection system is composed of a high field (1.36T) normal septum magnet, the opposite field septum magnet system (0.60T)
and 7 kicker magnets (0.065T) not shown in Fig.2.

Parameters of the magnets for the injection system

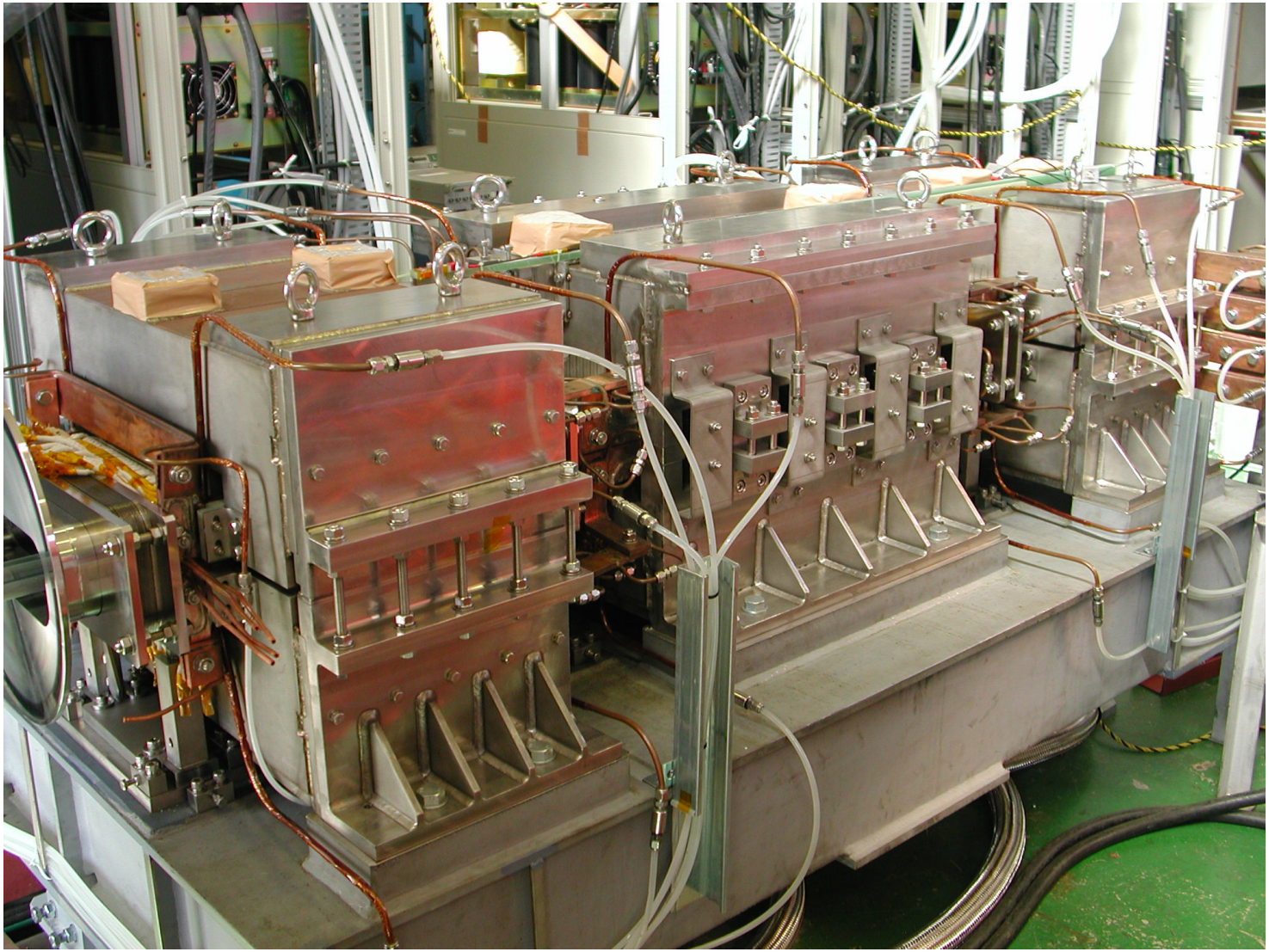
- The injection system is composed of a high field (1.36T) normal septum magnet, the opposite field septum magnet system (0.60T) and 7 kicker magnets（0.065T）
- The opposite-field septum magnet has a thin structure (8mm). The beam apertures of the injection beam and circulating beam at the injection septum magnet for the 50-GeV ring are 90 π mm mrad, which is larger than the full acceptance (81p mm mrad) of the ring.
- This high field and thin septum magnet makes the injection system simple and compact.

	Gap	Length	B	Angle
Septum I	**98 mm**	**1800 mm**	**1.36 T**	**191 mrad**
Sub-bend 1	**120 mm**	**350 mm**	**0.60 T**	**17 mrad**
Septum II	**120 mm**	**700 mm**	**0.60 T**	**34 mrad**
Sub-bend 2	**120 mm**	**350 mm**	**0.60 T**	**17 mrad**
Kicker (x7)	**~90 mm**	**300~680**	**0.065T**	**15.4mrad**

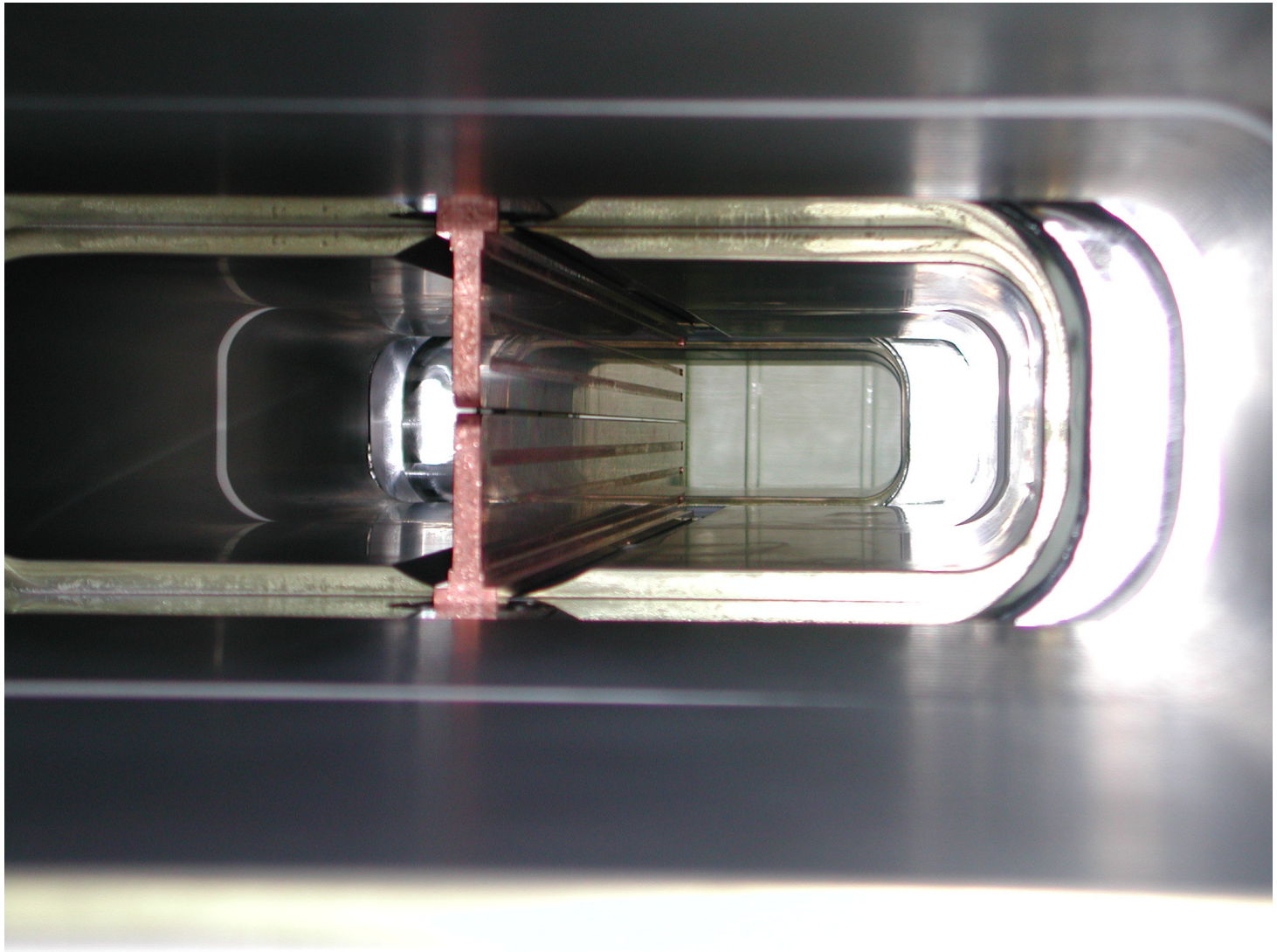
Structure of the opposite field septum magnet system for the 50GeV Main ring injection



Exterior of the opposite field septum magnet system



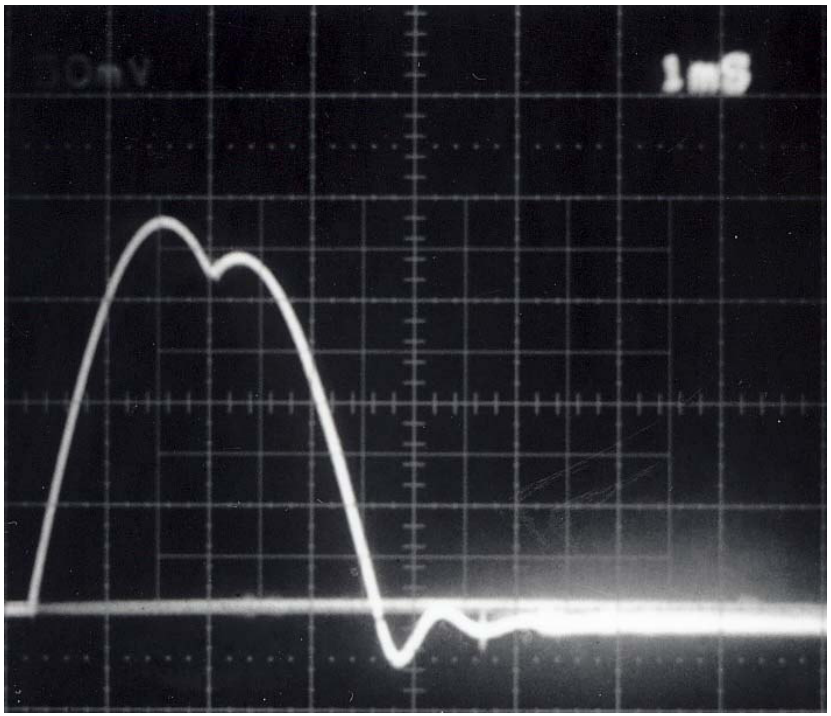
Inside of the vacuum chamber



Parameters of the opposite field septum magnet

		Sub Bend1	Opposite Field Septum	Sub Bend2
Bending angle	mrad	15	30	15
Magnetic field	T	0.60	0.60	0.60
Pole length	mm	350	700	350
Pole gap	mm	120	120	120
Pole width	mm	374	355	272
Inductance	μH		5293	
Resistance	mΩ		0.221	
Current	kA		53.5	
Voltage	V		356	

Waveform of magnetic field



•The opposite field septum magnet has a force-free structure.

• Pulse excitation is easily acceptable to escape the problem of heat generation at the septum.

•The thin septum structure is available because of its pulse operation.

Required repetition rate of excitation

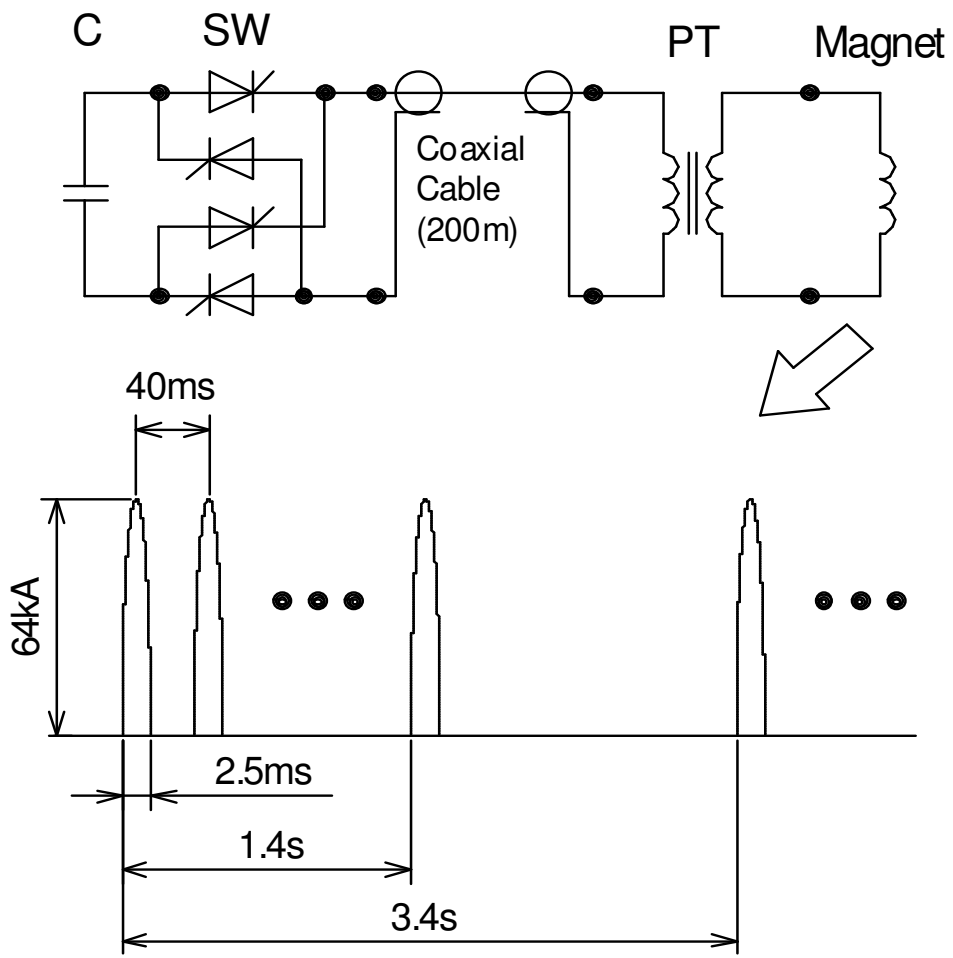
- The injection septum magnets are required to operate at a period of 900ns x 4 repetition for the two bunches x 4 repetition mode injection with a repetition cycle of 25 Hz of the 3-GeV RCS.
- Further the maximum repetition rate of 16 for the one bunch x 16 repetition mode injection with a repetition cycle of 25 Hz.

Required accuracy of the excitation current

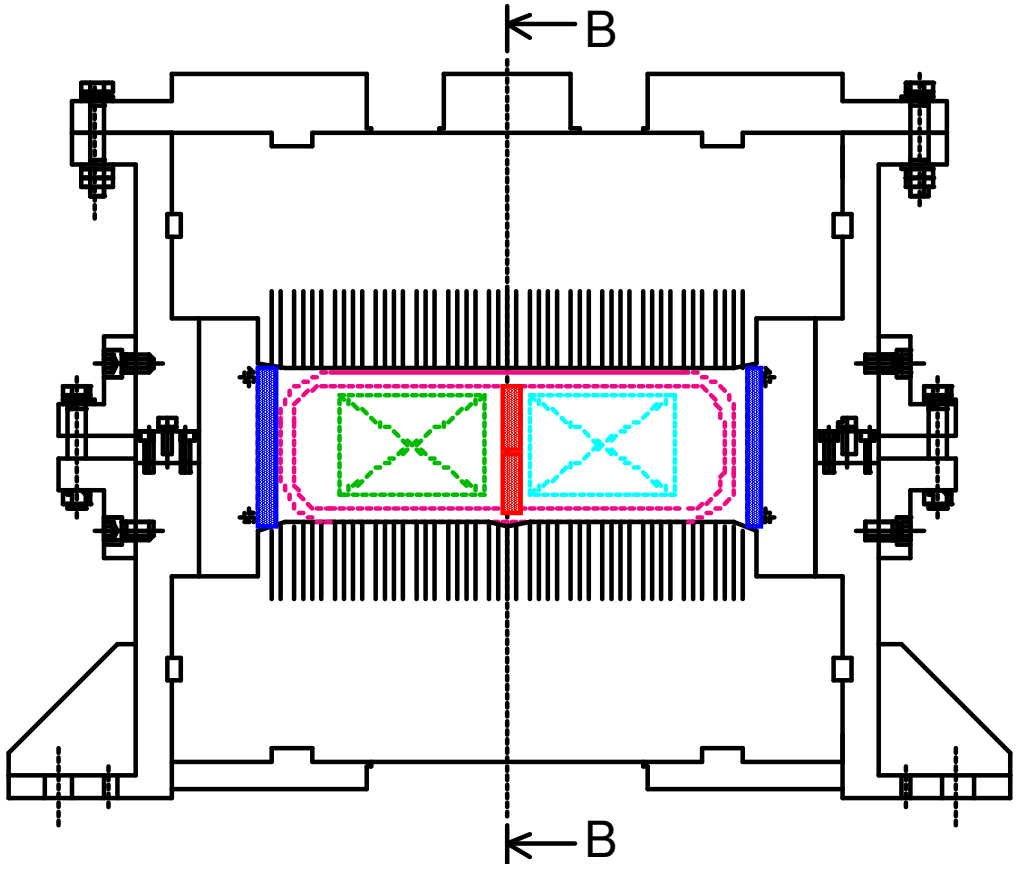
The injection system is designed to suppress the emittance growth by injection errors to be less than 2%.

The stability of the magnetic field is required to be less than 2 x 10E -4. The output voltage of the power supply is fed backed by the current monitor of the excitation current.

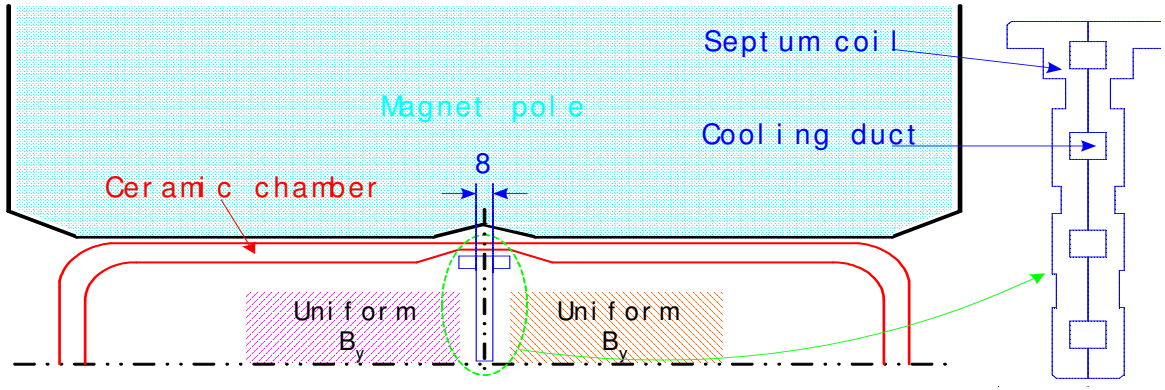
Outline of the power supply

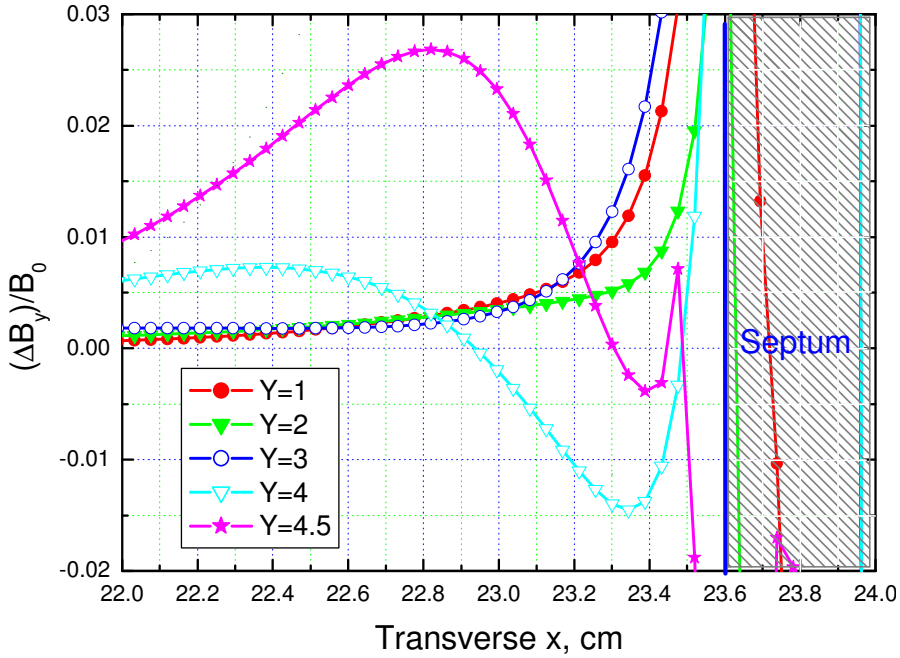


Transverse cross-sectional view of the opposite field septum magnet for 50GeV Ring injection



Conductor shape and magnetic field distribution

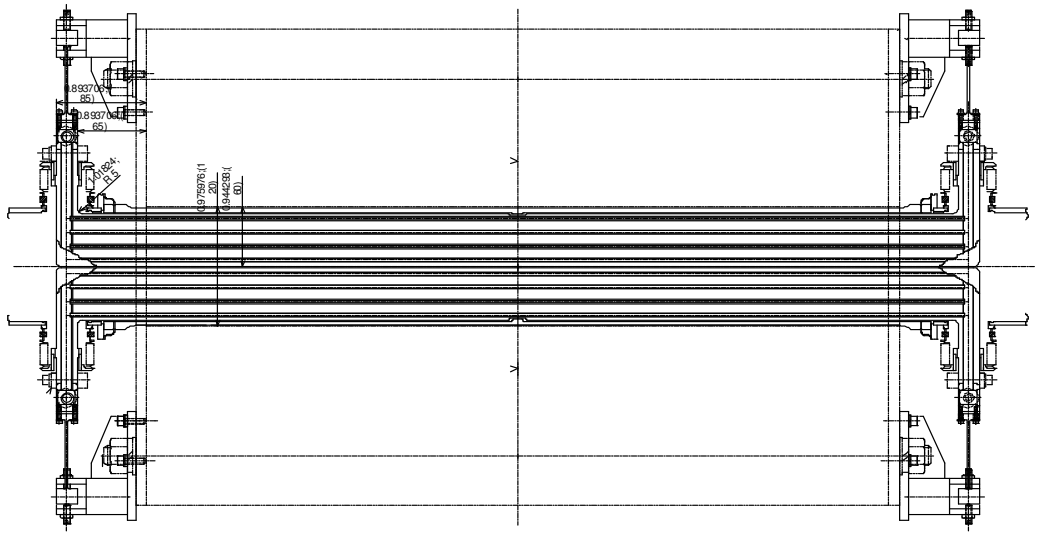




The shape of septum conductor

- The incoming beam and the circulating beam both have rectangular shapes.
- A uniform magnetic field distribution is required not only near the medium plain but also at the edge of the septum.
- To obtain a uniform magnetic field, the thickness of the ceramic vacuum chamber is a partially thin structure so as to approach the septum conductor to the pole surface as close as possible.
- The minimum gap between the septum coil and the magnet pole is 6 mm.
- Four stainless-steel cooling water pipes, which are gathered to one pipe at the end of the conductor, are sandwiched in the septum conductor (copper) by the Hot Isostatic Pressing (HIP) technique.
- These gaps and holes in the conductor disturb the uniformity of the magnetic field near to the septum.
- The cross section of the conductor is shaped so as to form a uniform distribution of the average current along the vertical axis of the septum.

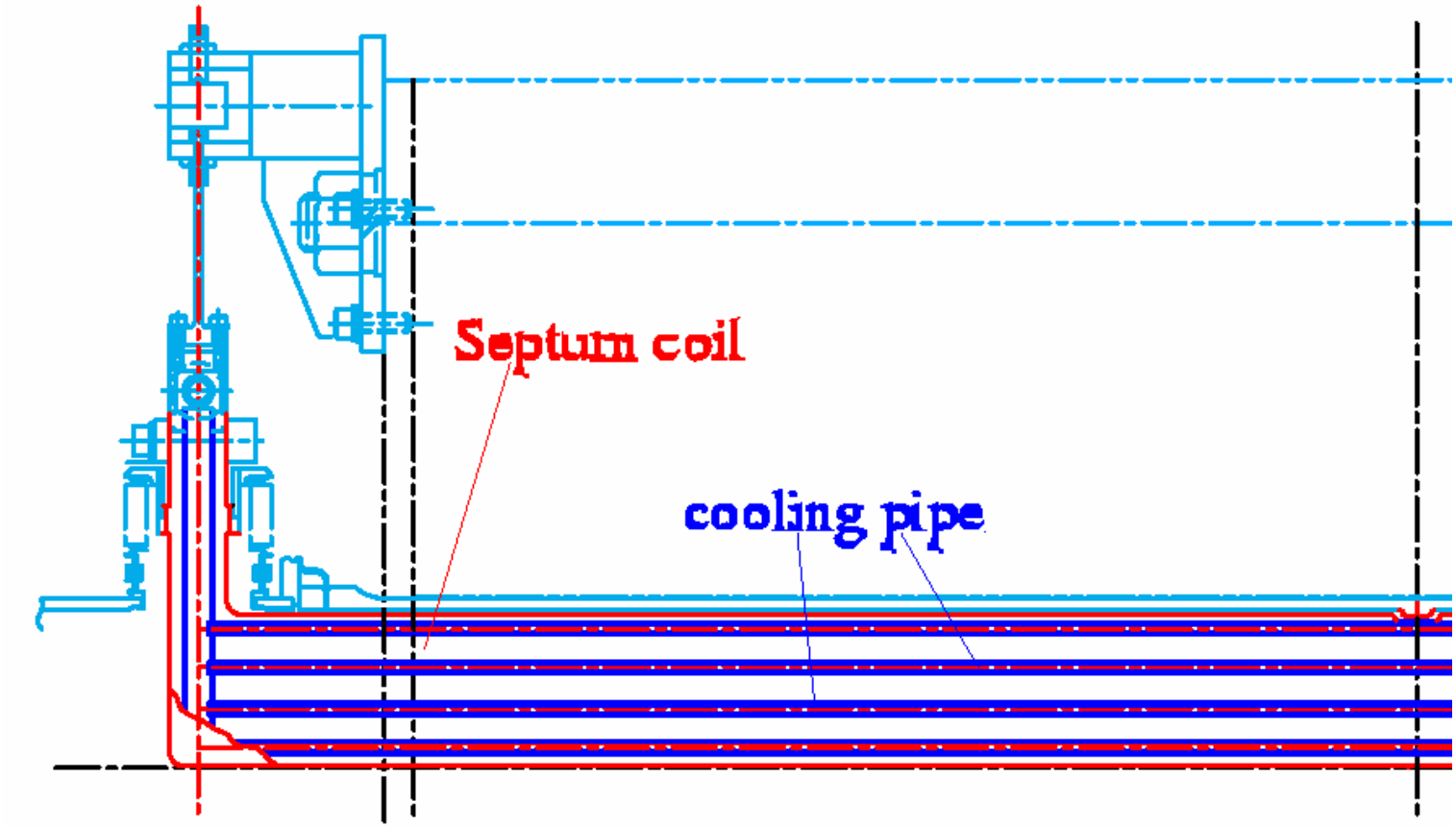
Longitudinal cross-sectional view of the septum conductor



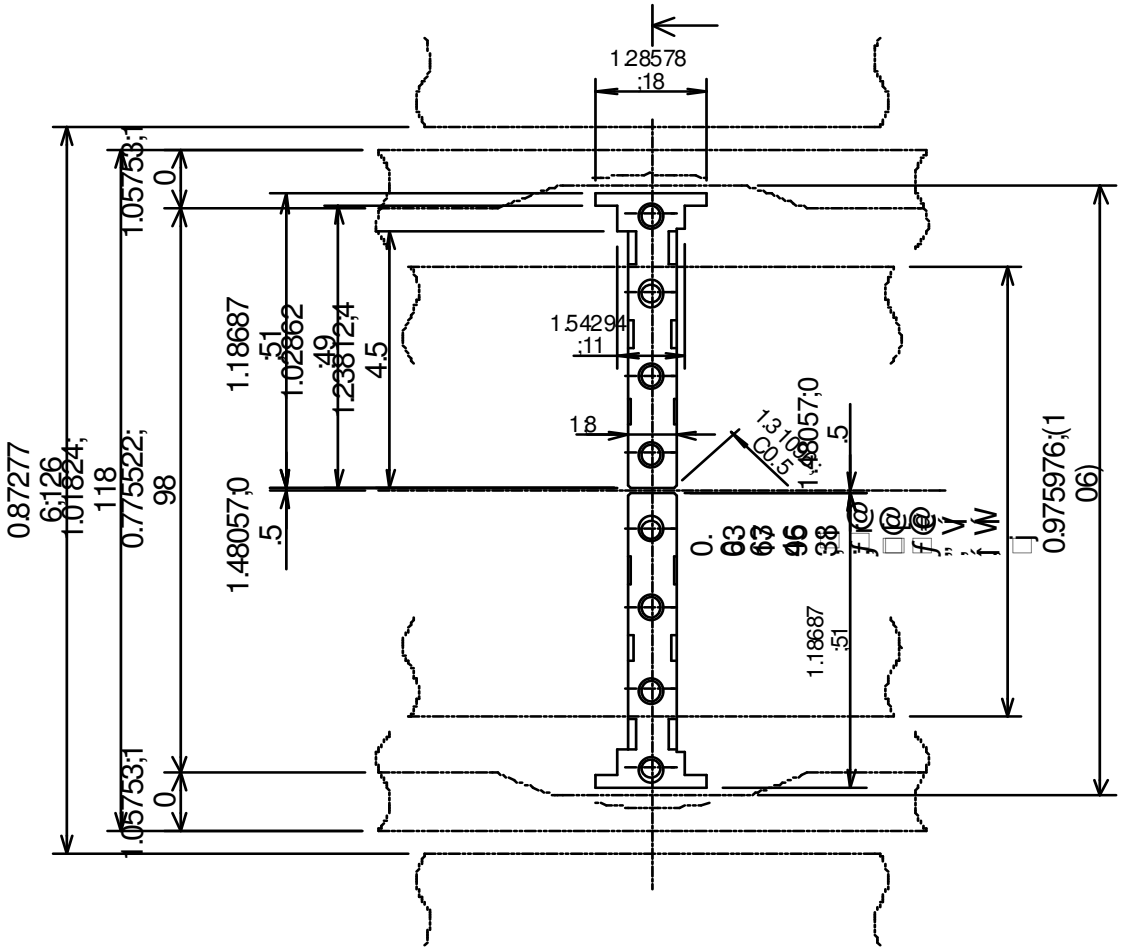
The core of the magnet and the return coils are set outside of the vacuum chamber to decrease the out-gassing rate from the septum magnet.

Only the septum conductors are set inside of the vacuum chamber, which is made of alumina ceramic.

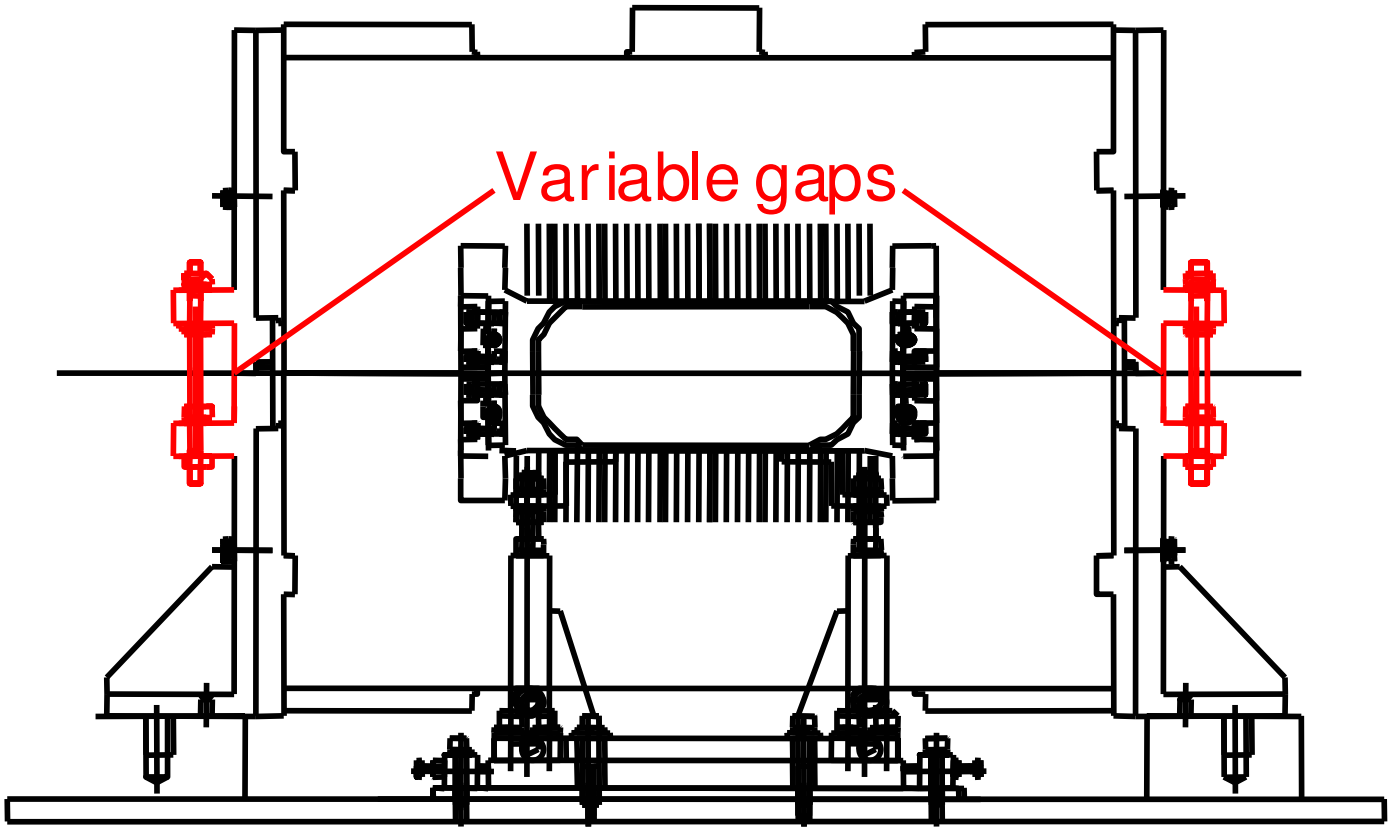
Detailed structure of the septum coil support



Transverse cross-sectional view of the septum conductor



Transverse cross-sectional view of the sub-bending magnet

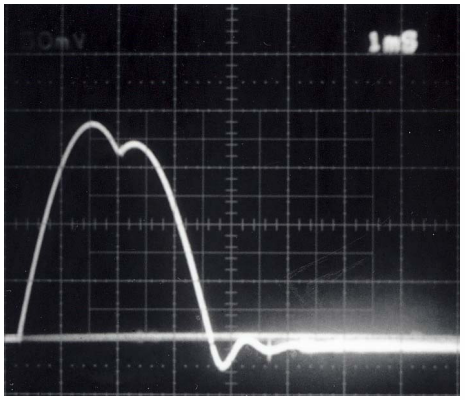


Compensation of error fields

- The opposite field septum magnet system is composed of the main septum magnet and two sub-bending magnets. The integrated magnetic field along the circulating beam axis is designed to be zero to suppress the closed-orbit distortion around the whole ring.
- The fabrication errors and the difference in the effective length will be compensated by a fine adjustment of the sub bending magnets, which are initially designed to have variable gaps.
- The disproportion of the eddy current will be compensated by back-leg windings on the return yoke of the sub bending magnets, which have a short circuit, including a variable resistor and inductance to control the self-induced counter phase current.

- (These compensation techniques have already been verified by the experiments on the H^- injection bump magnets for the 500-MeV booster synchrotron in the KEK 12-GeVPS.)

The error field of the circulating beam side is suppressed to be less than 0.1% of the total kick angle of the injection side by gap adjustment of the sub-bending magnets and the back-leg winding of the opposite septum magnet.



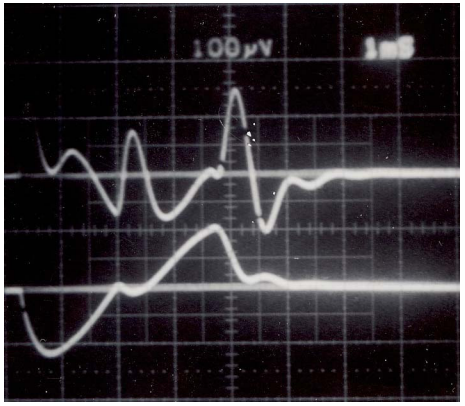
BL integration of the injection beam side

50 mV/div, 1 ms/div

Calculated value of BL = 0.93 Tm.

Kick angle = 72.9 x 10^{-3} rad

(Designed value = 65.9 x 10^{-3} rad)



BL integration of the circulating beam side

Upper line is BL integration

100 μ V/div, 1 ms/div

Measured value of BL = 7.34 x 10^{-4} Tm

Calculated value of BL = 7.34 x 10^{-4} Tm

Kick angle = 5.76 x 10^{-5} rad (0.8% of the injection side)

(Designed value = 0 rad)

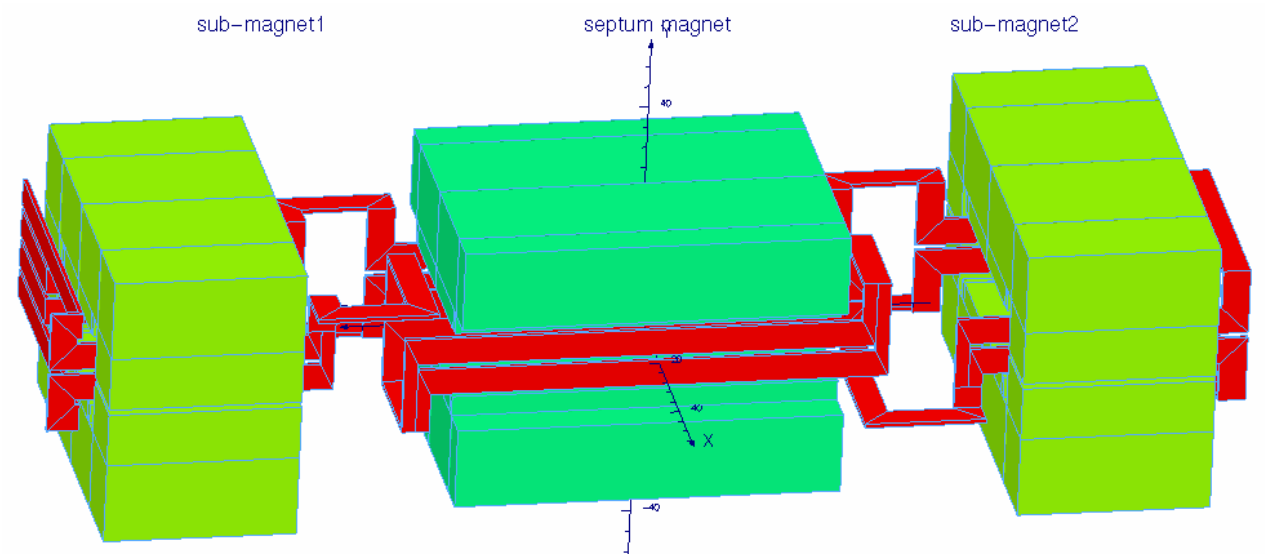
Induced maximum C.O.D. ≈ 0.8 mm

Lower line is self-induced current on the back-leg winding to compensate error field induced by eddy current.

The C.O.D. in the whole is expected less than 1mm !!

Summary

- The opposite-field type septum magnet combined with sub-bending magnets has unique features compared with normal septum magnets as a force-free structure and cancellation of the leakage flux at the septum.
- The force-free structure permits thin septum magnets, pulse excitation and a structure such that the septum conductor is set inside of the vacuum for a low evacuating load.
- In the case of the injection septum magnet for the J-PARC 50-GeV proton synchrotron, the larger beam aperture than the full acceptance of the ring can be obtained for low-loss injection.
- The system is applicable to injection / extraction septum magnets for many kinds of accelerators.


sub-magnet1
septum magnet
sub-magnet2
40
40
X
40