방사광 가속기 전자석

다목적 방사광 가속기
Magnets Group

Dong-Eon Kim (金東彦)
dekim@postech.ac.kr

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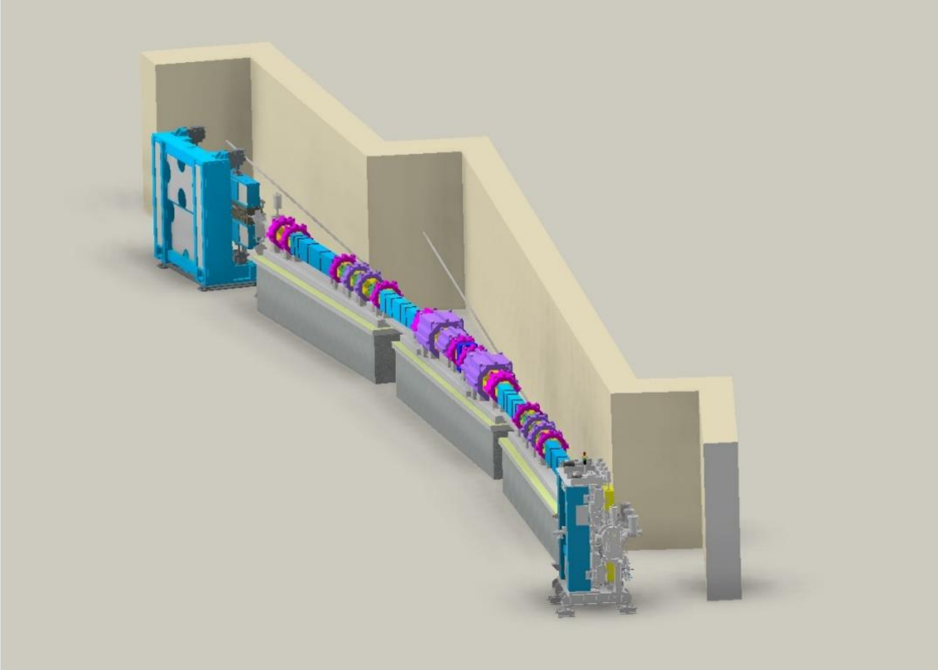


PAL POHANG ACCELERATOR LABORATORY

Magnets Technology for Accelerators

- Contents from 2009 Bruges CERN Accelerator School on Magnets.

- CAS 에서 찾을 수 있는 가장 광범한 Magnet 관련 자료.
- 8일간의 강의, 약 40개의 강좌,
- Topic 으로는
- Maxwell Equations, Beam Optics, 자성물질의 물리와 측정, 수치해석, 자장측정
- 자석설계 기초, 초전도 자석, 와전류, 입사/Extraction Magnet
- 영구자석 (Wiggler/Undulator), Specification QA, Metrology Alignment
- Insulation, 도체, 자장측정 과 calibration, 안정성과 반복성.

- 위 자료 중 주로 방사광 가속기용 전자석의 설계 관련 부분
- 자체 자료 및 다목적 산업용 방사광 가속기 전자석에 관해서 주로 설명.

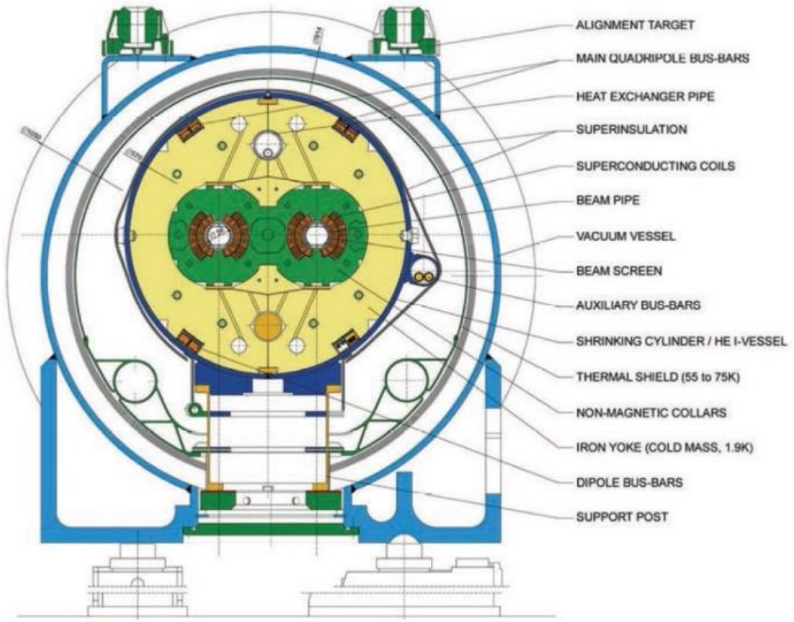
Contents

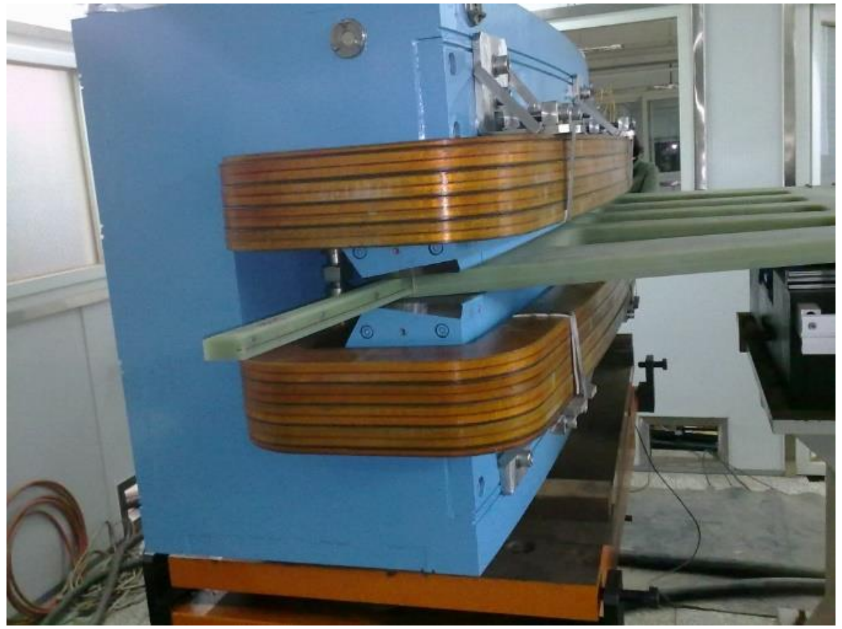
- Functions of Magnets (Dipoles, Quadrupoles…)
- Design of Magnets meeting the requirements.
  - Determination of Parameter
  - NI (Ampere Turns), Current, Voltage, Power, ΔT, L ,R etc.
- Pole, Yoke shaping,
- Magnetic Saturation and the impact of magnetic saturation.
- Methods to reduce the magnetic saturation.
- Cooling of Magnets (Air Cooling, heat sink, Water cooling using Hollow conductor..)
- Factors affecting the total Costs
- Tools for Magnetic Modelling and their pros and cons.
- Fiducialization and example
- Magnetic measurement methods and their advantages and disadvantages

- Korea 4GSR Magnets Status

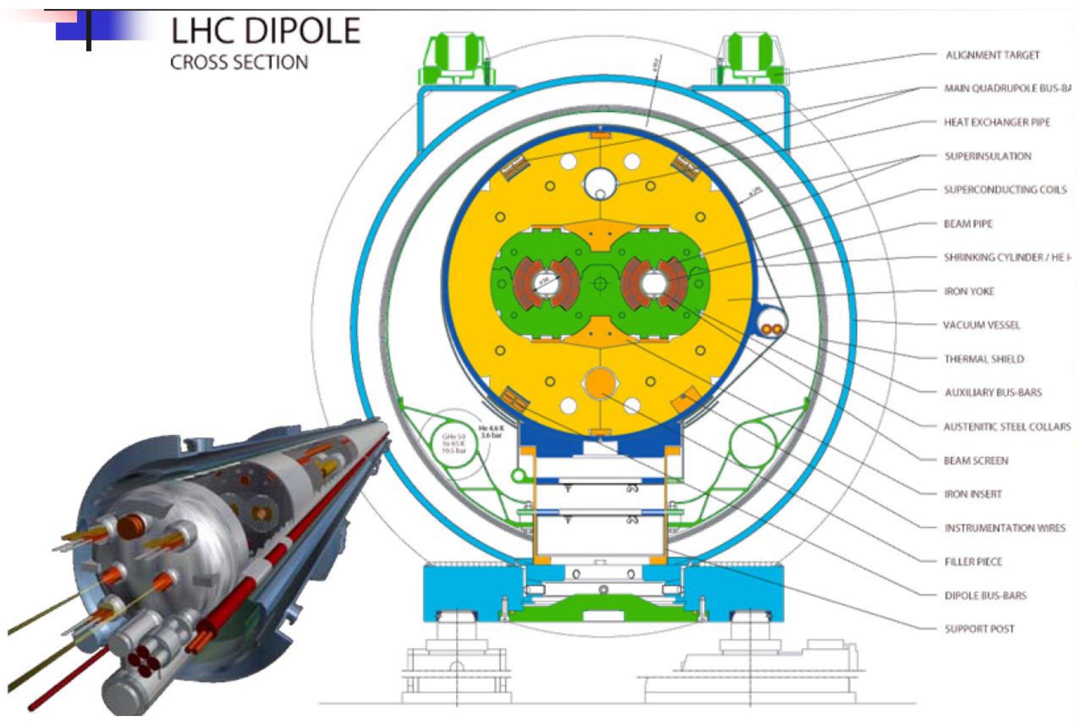
Application of Magnets?

- Charged particles should be controlled using magnets.
- For collider like LHC, high field superconducting magnets are used. (can reach up to ~10 Tesla)
- For smaller accelerator, like synchrotron light sources, iron dominated room temperature electromagnets are mostly used. (can reach up to ~1.8 Tesla limited by saturation)
- For special purpose, High T Superconducting magnets can be used.

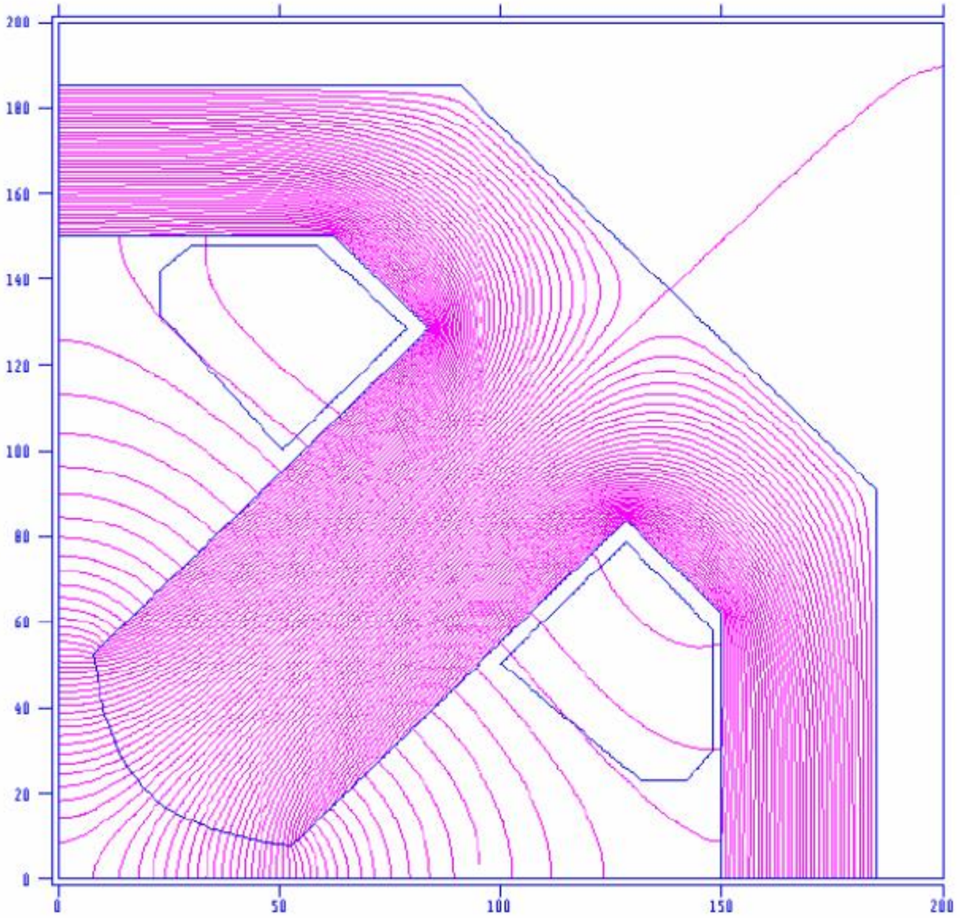




Types of Magnets for Accelerators



Current Dominated Magnet (Mostly Superconducting)



Iron dominated Magnet (Field mostly coming from magnetized iron)

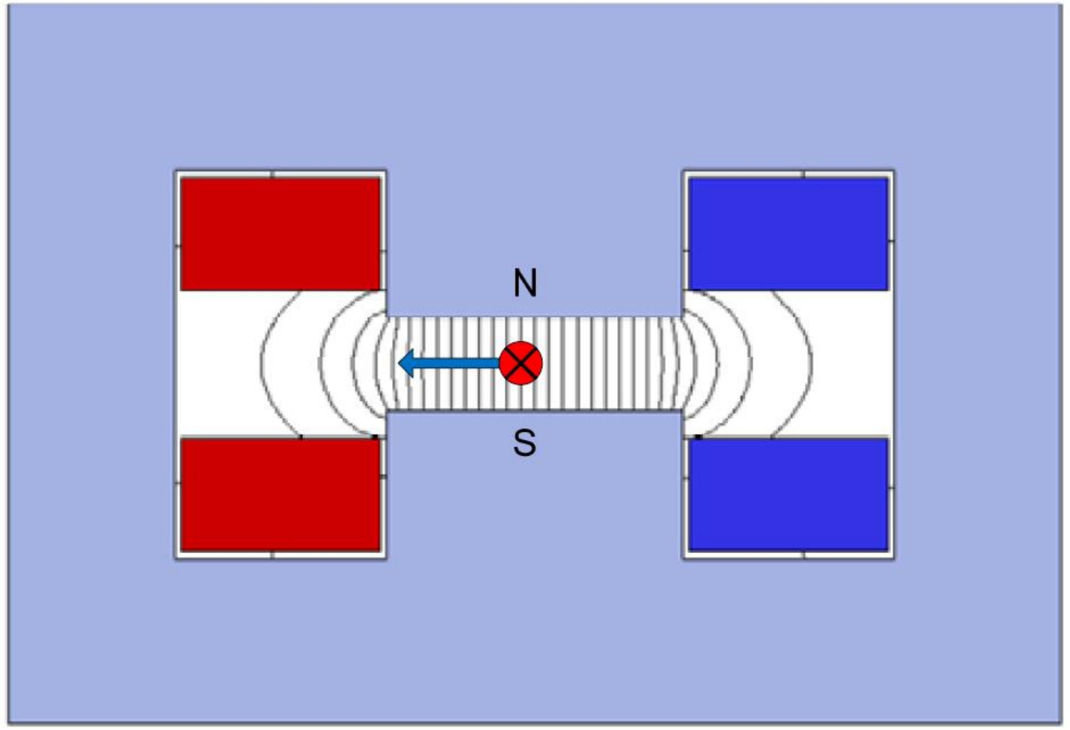
Figure 4: Comparison of resistive and superferric magnets.

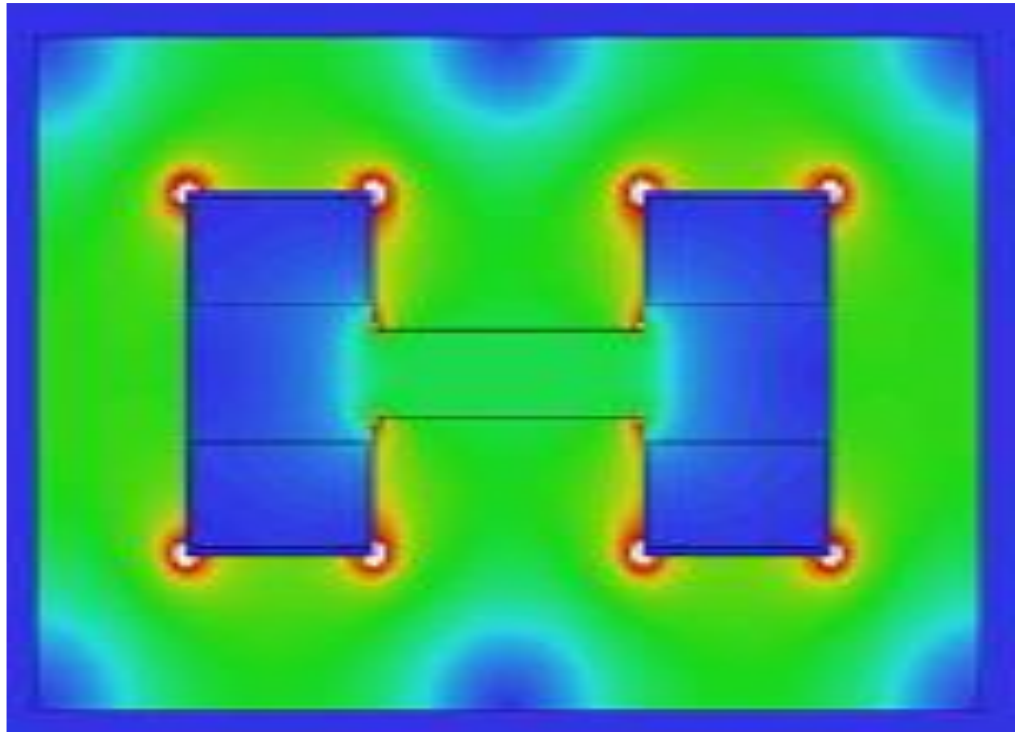
Superferric Magnet (SC but helped by iron magnetization)

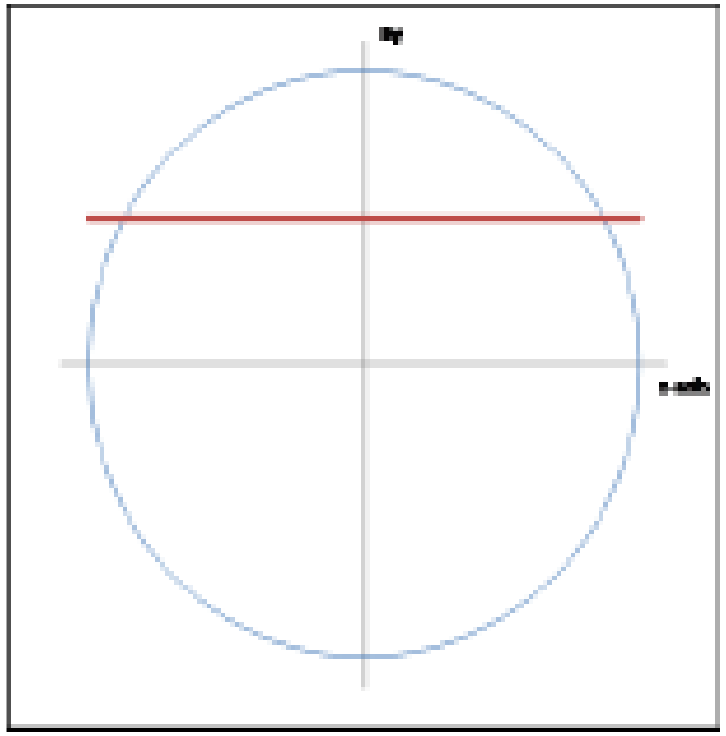
In this talk, we concentrate on the “iron dominated electromagnet” for light sources.

Dipole Magnet 의 기능 (1)

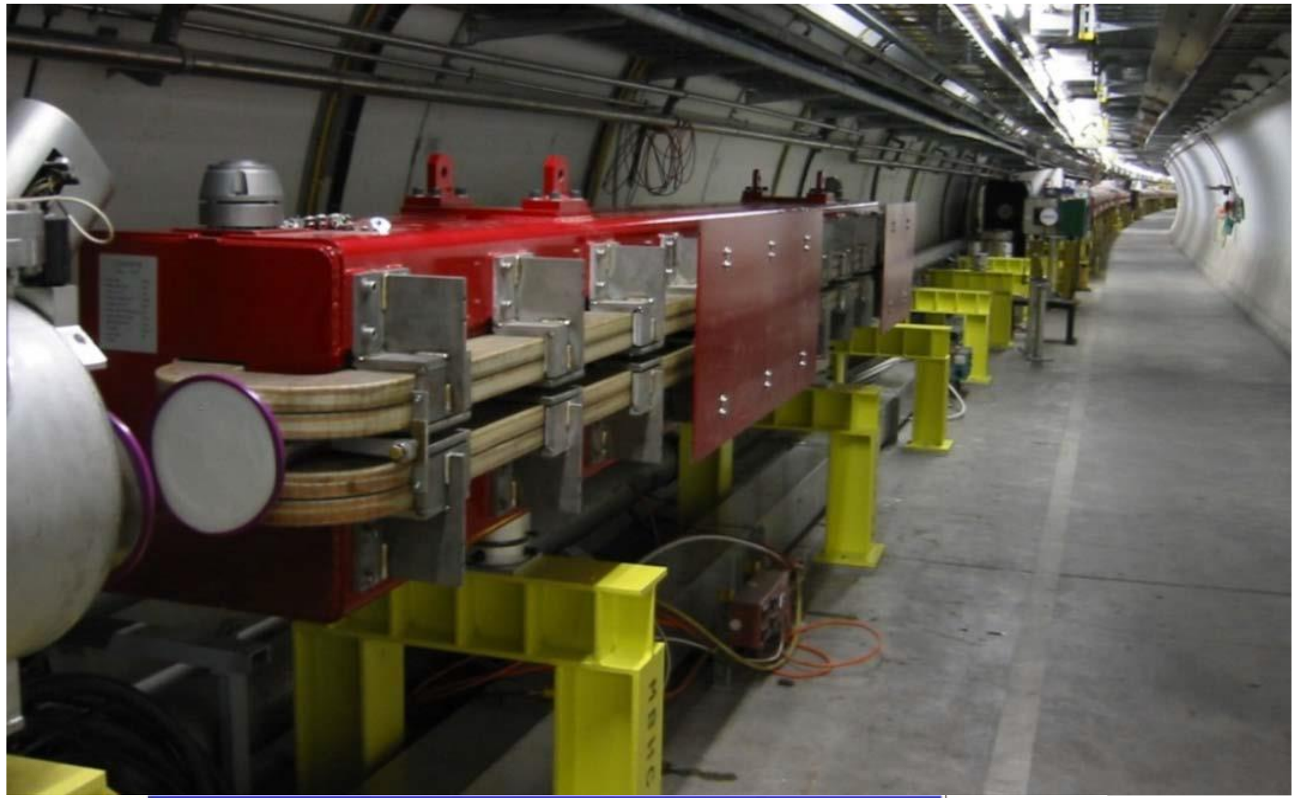
- Purpose : bend or steer the particle beam
- Equation for normal ideal poles : y = ±r (r =half gap height)
- Magnet flux density : By=a1=B0-const.
- Allowed harmonics : n=1,3,5,7..

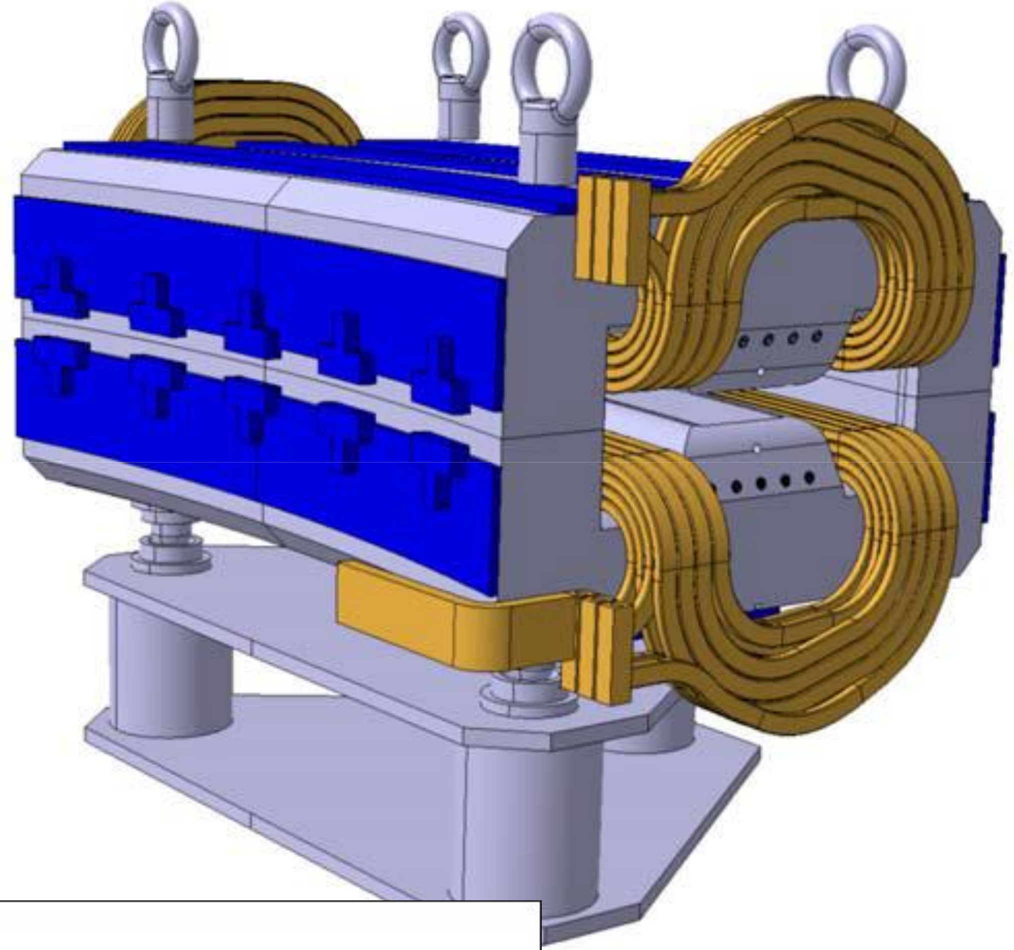


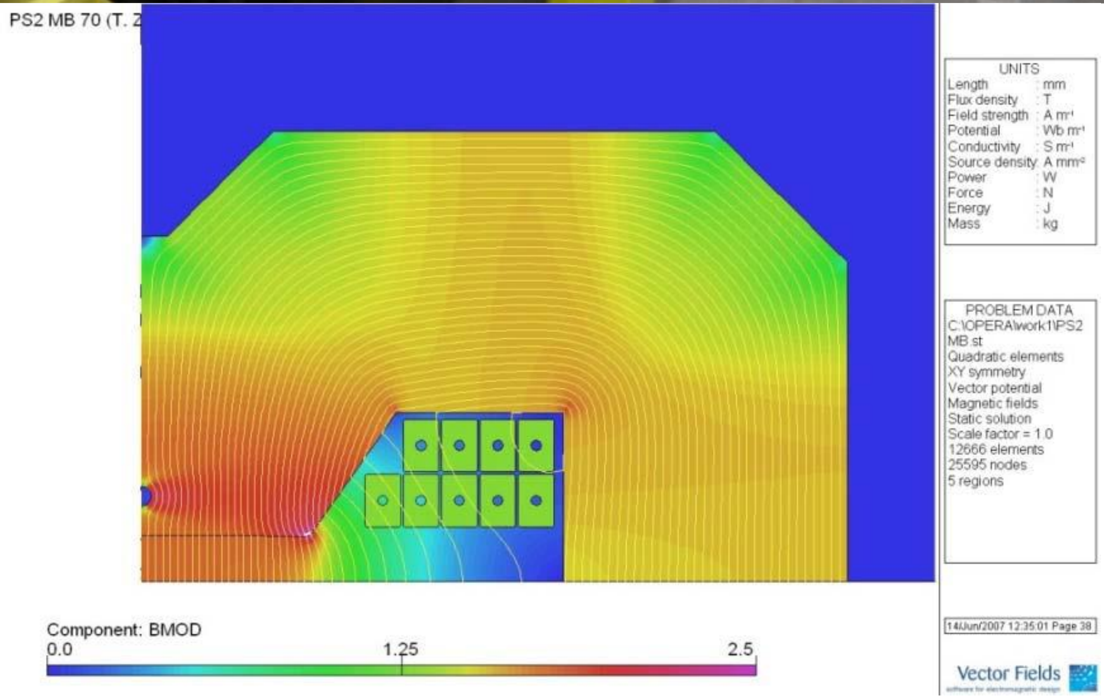


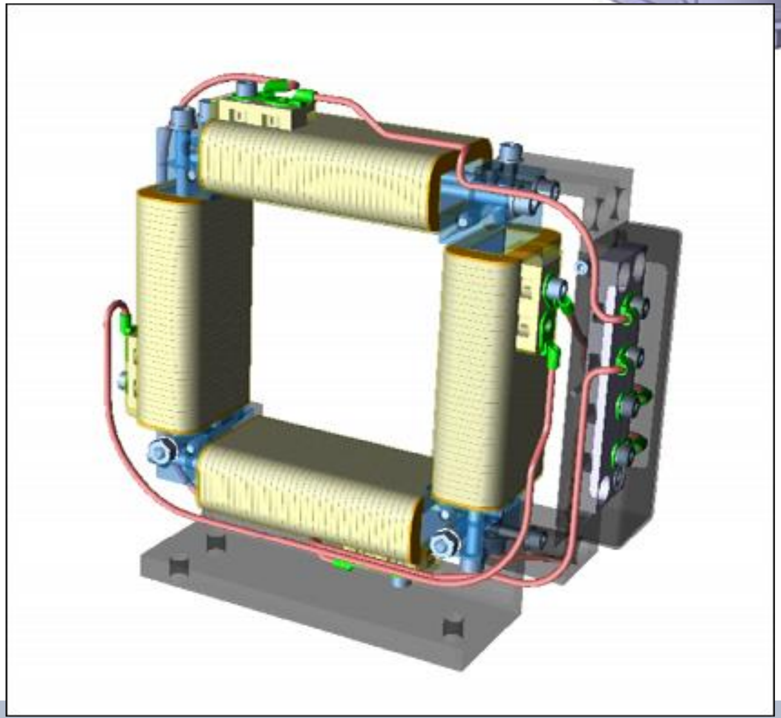


Some Examples of Dipoles



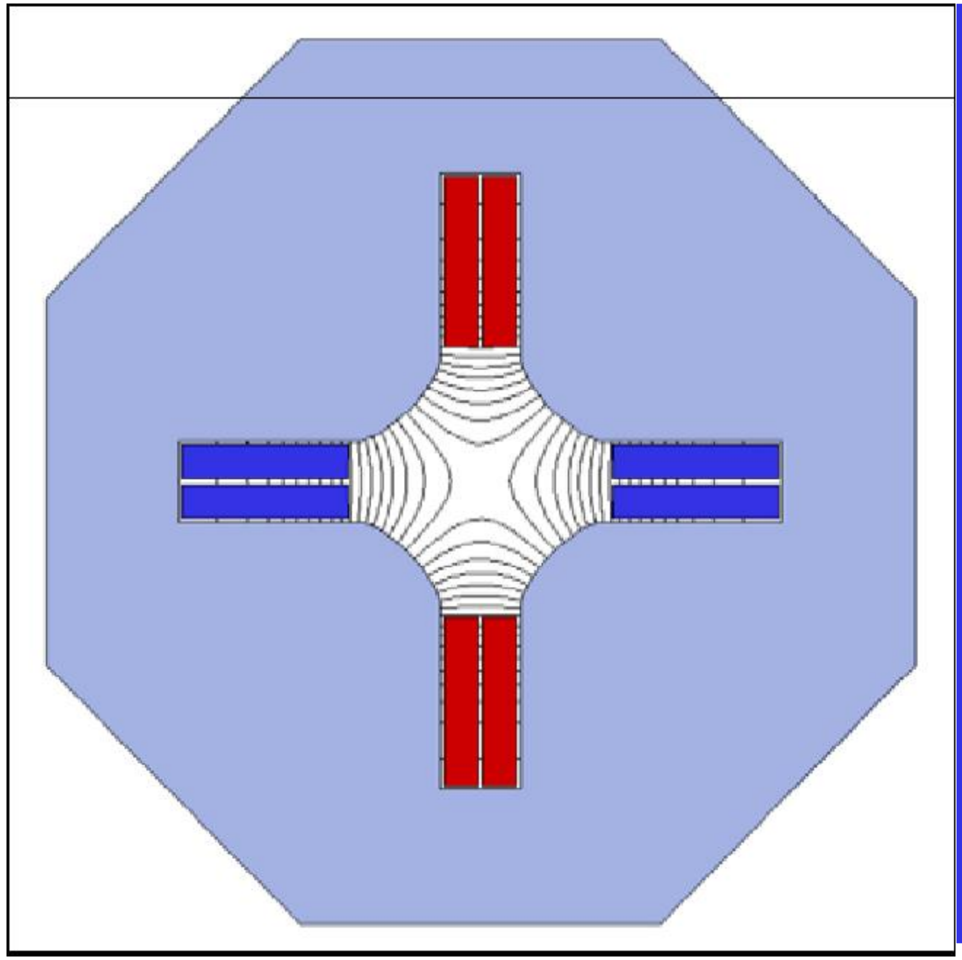


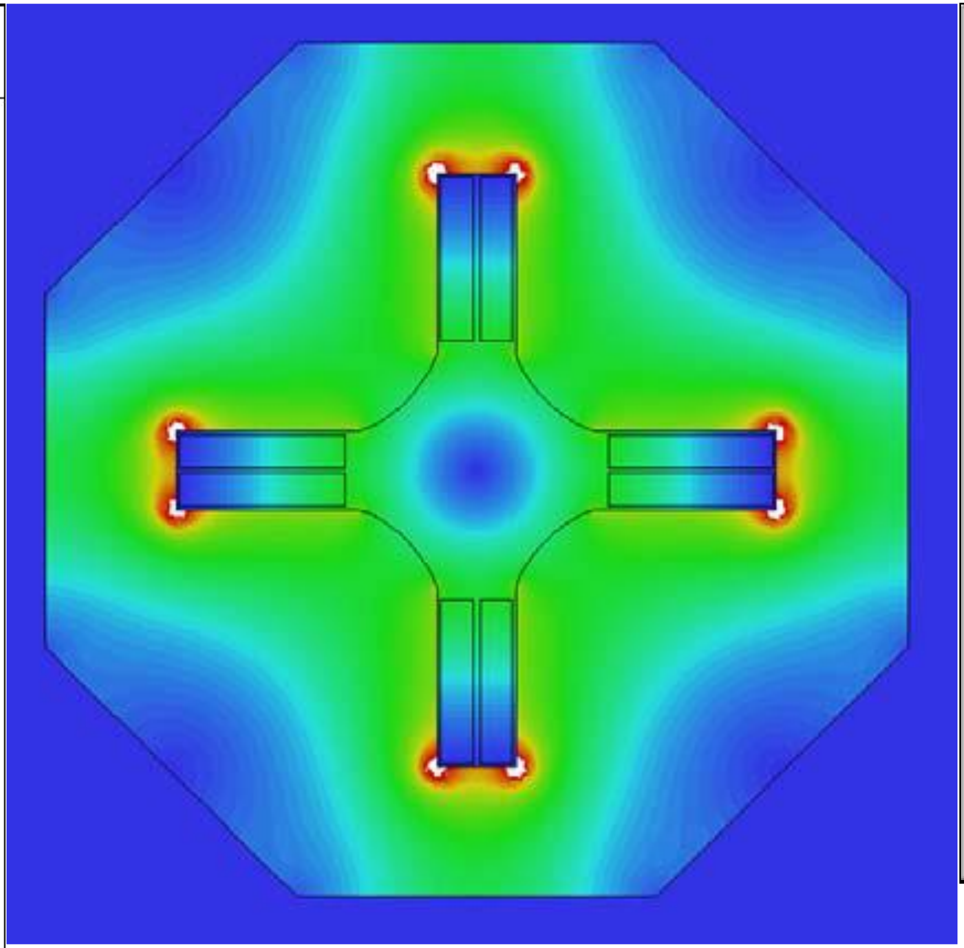


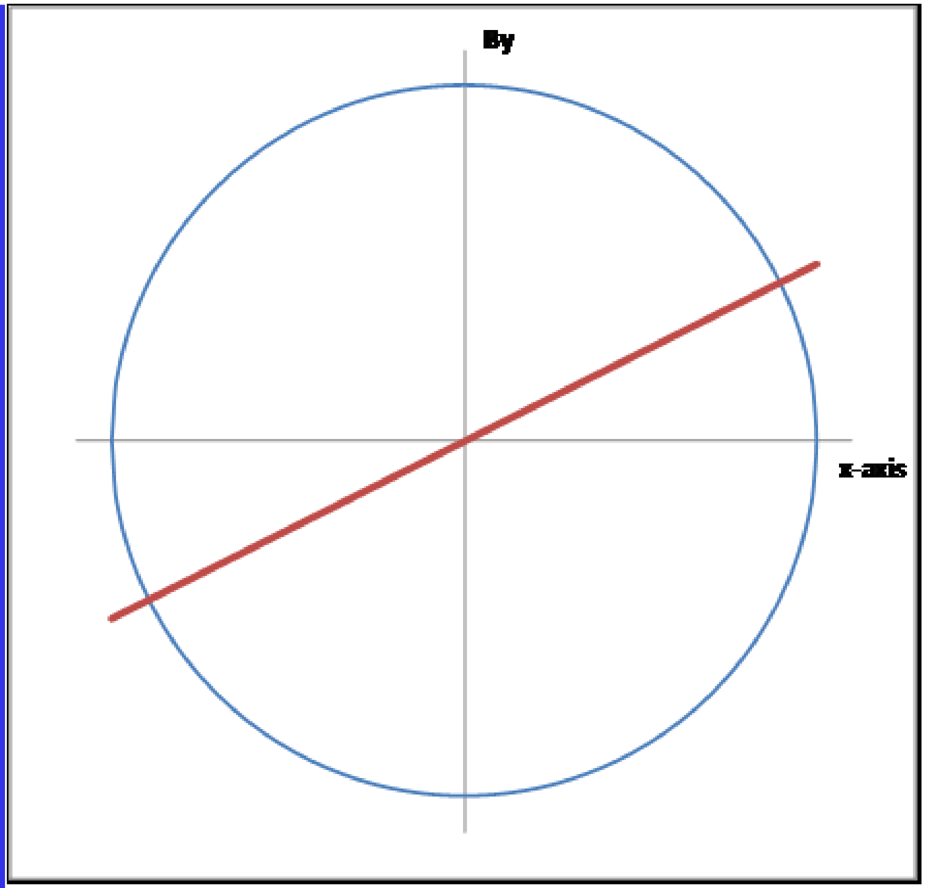


Quadrupole Magnet 의 기능 (1)

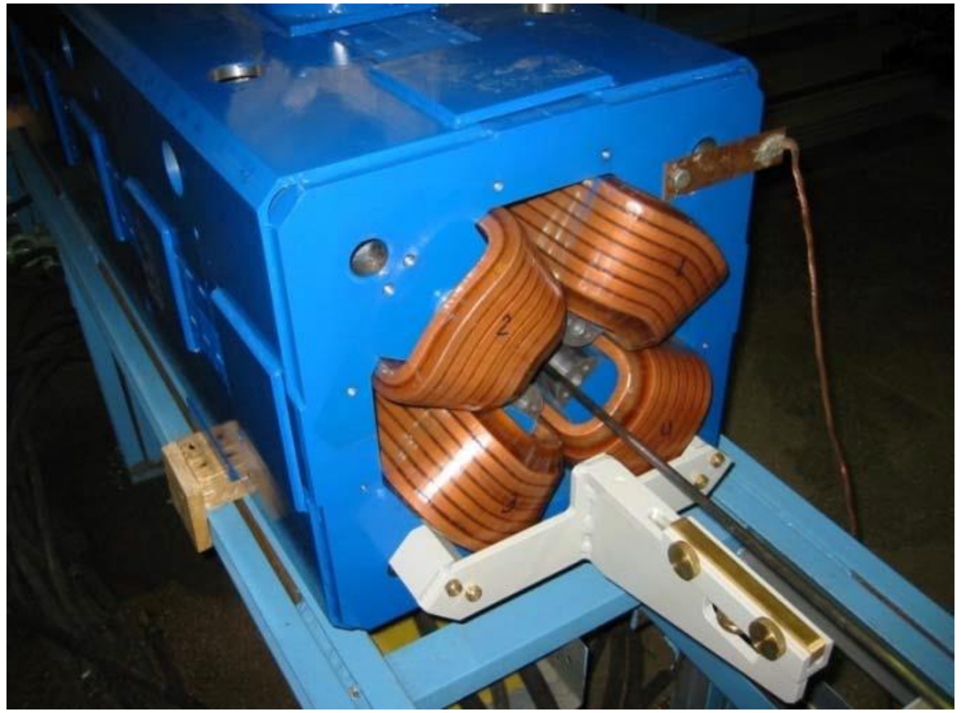
- Purpose : focusing of the beam (h-focusing is v-defocusing)
- Equation for normal (non-skew) ideal (infinite) poles: $2xy = \pm r^2$ (r = aperture radius)
- Magnetic flux density: $B_y = a_2\, x$
- ‘Allowed’ harmonics: n = 2, 6, 10, 14, ... (= 2n pole errors)

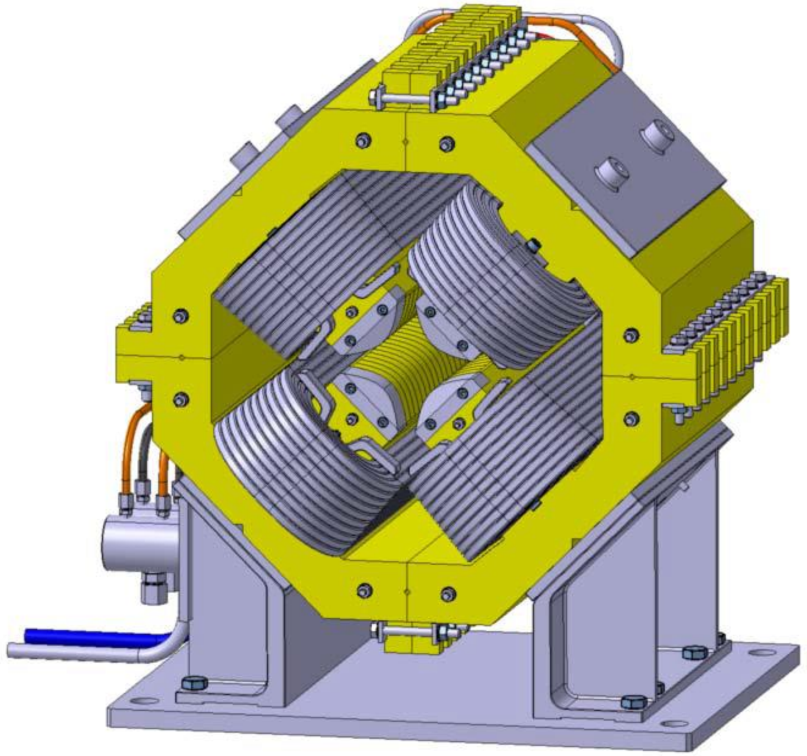


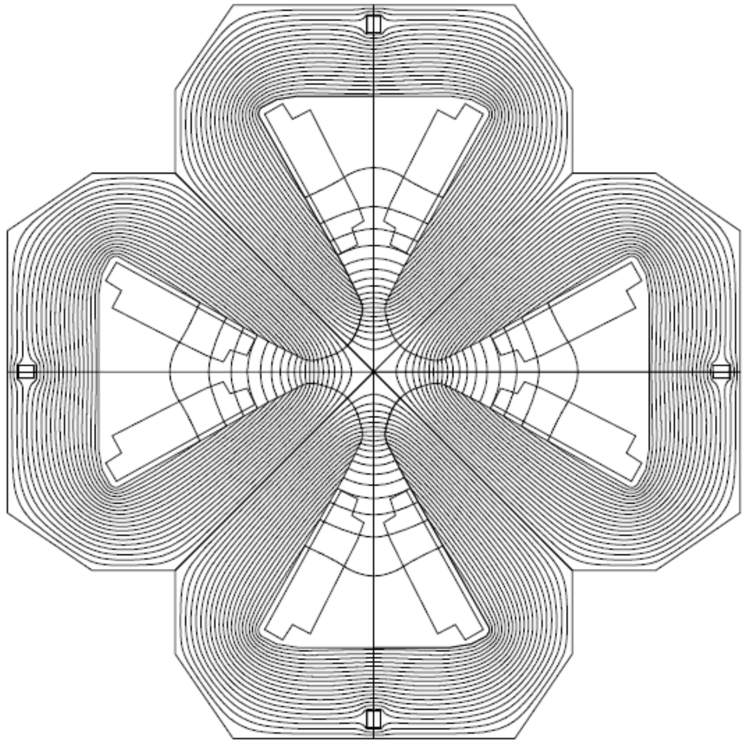




Some Examples of Quadrupoles

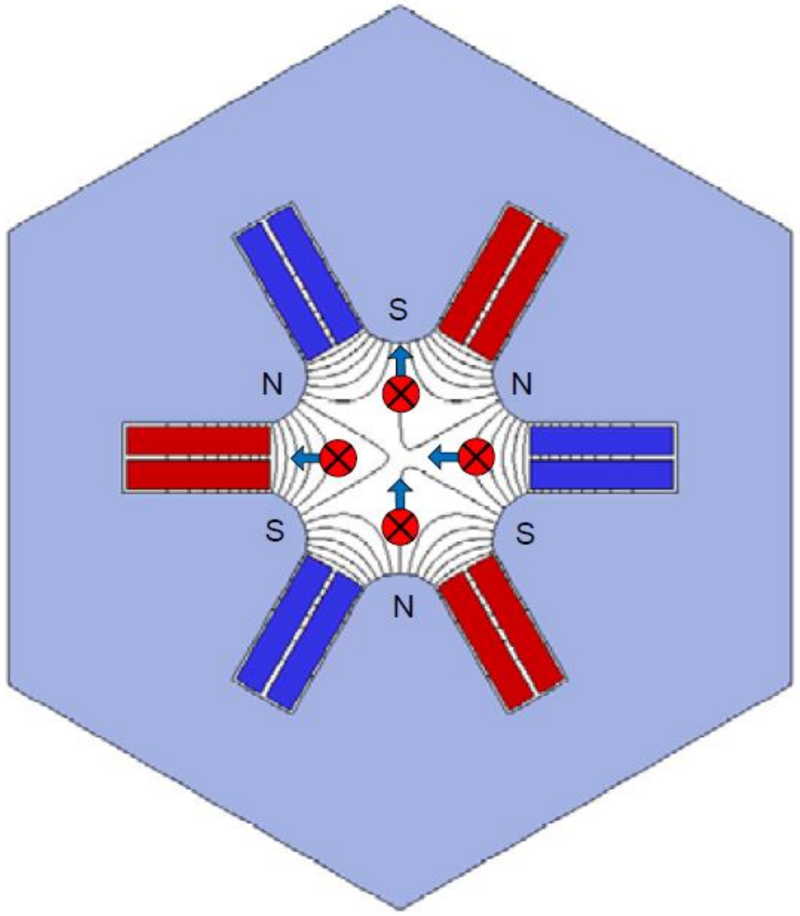


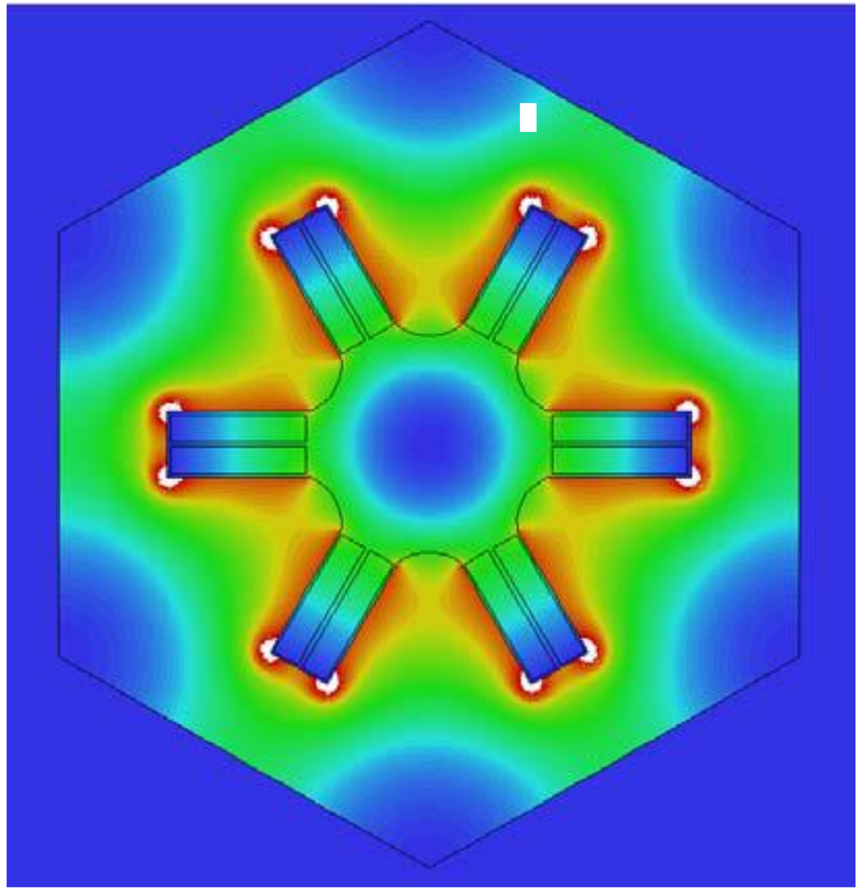


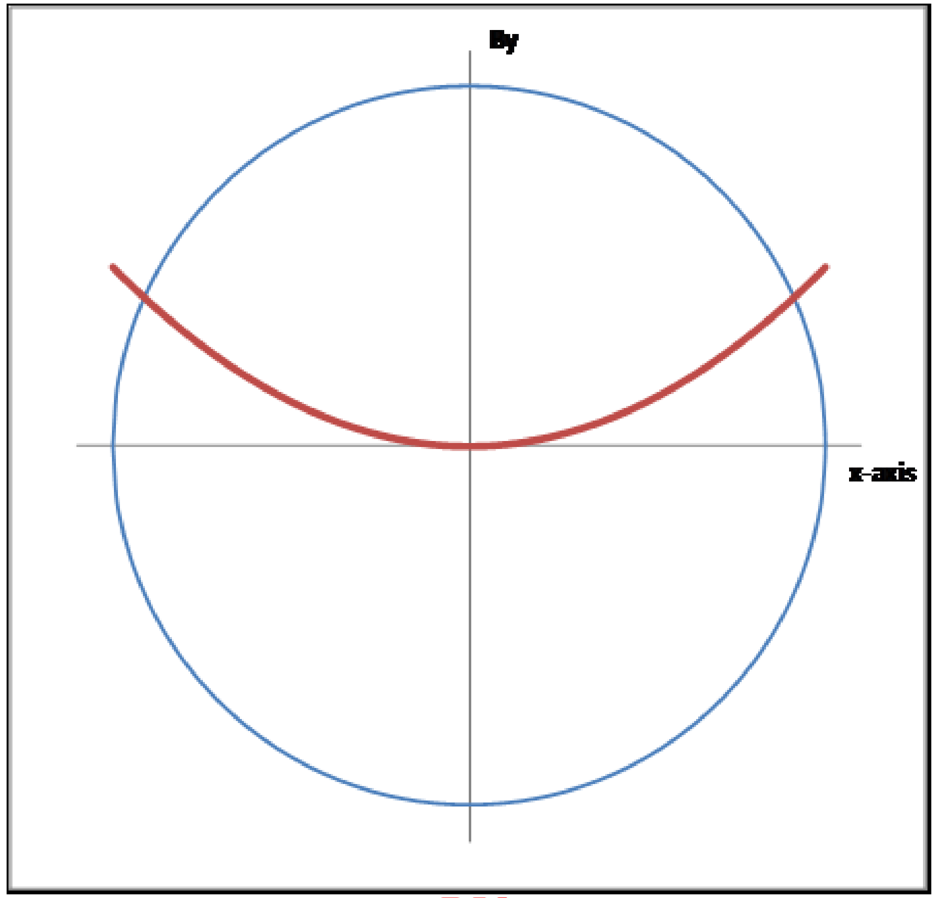


Sextupole Magnet 의 기능 (1)

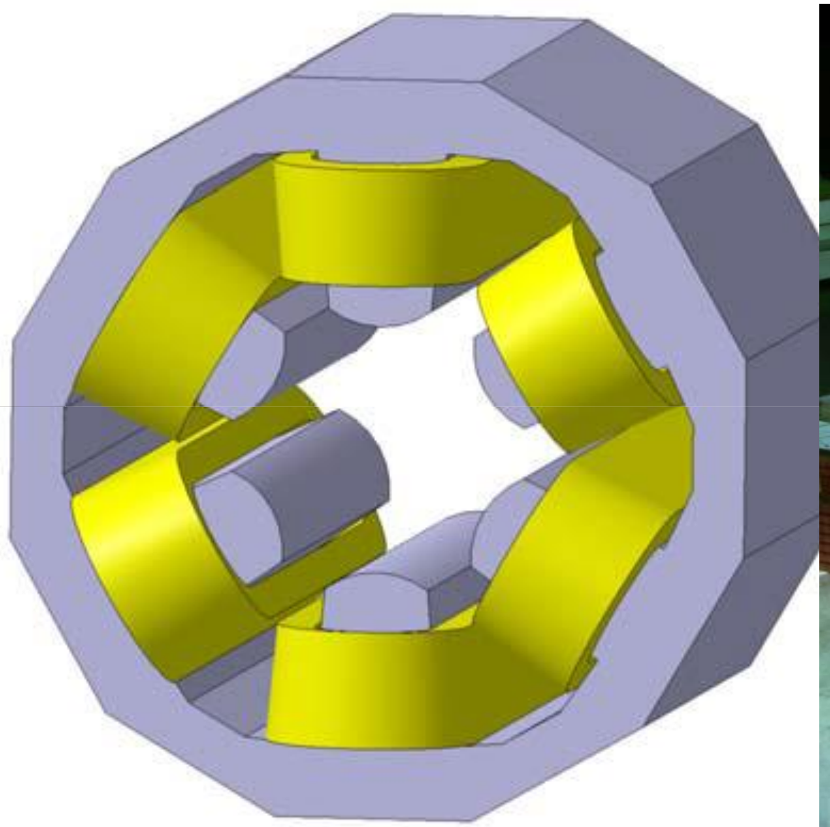
- Equation for normal (non-skew) ideal (infinite) poles: $3x^2y - y^3 = \pm r^3$(r = aperture radius)
- Magnetic flux density: $B_y = a_3(x^2 - y^2)$
- 'Allowed' harmonics: n = 3, 9, 15, 21, ... (= 2n pole errors)





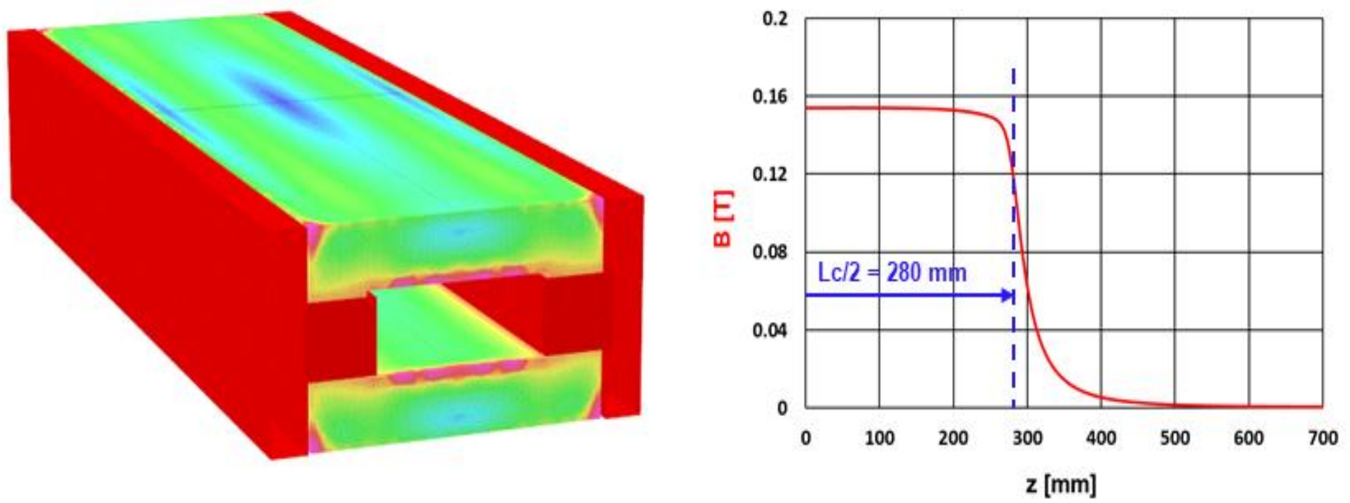


Some Examples of Sextupoles

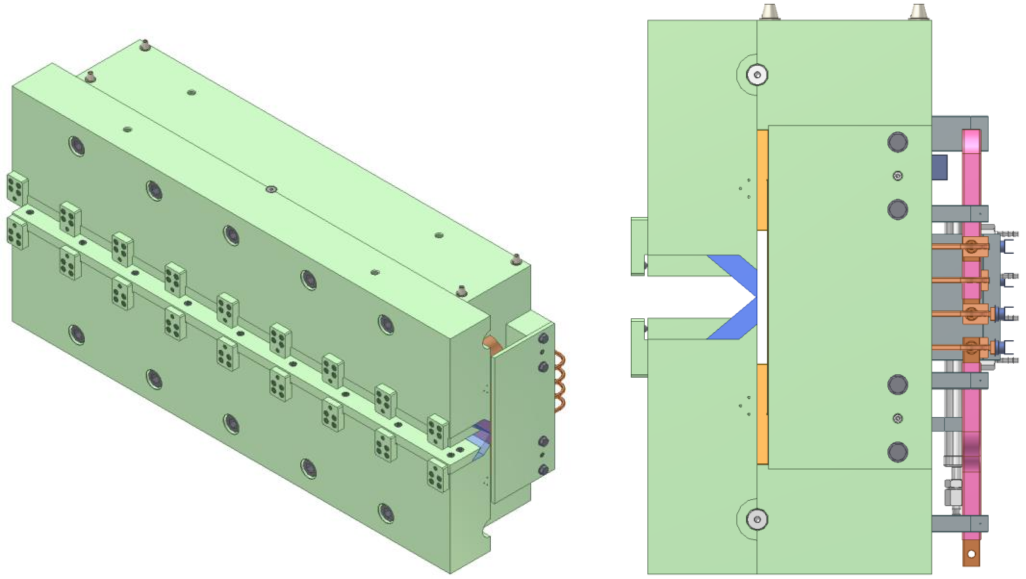


Other Magnets

- Octupole : landau damping
- Skew quadrupole : coupling horizontal-vertical betatron oscillation
- Skew quadrupole is 45degree rotated quadrupole magnet
- Combined function magnet:
  - Dipole+Quadrupole+(Sextupole) combined function magnet.
  - Quadrupole+(Corrector)
  - Sextupole+(H/V Corrector)+(Skew Quadrupole) combination
- Kicker, Septa Magnet : For injection/extraction

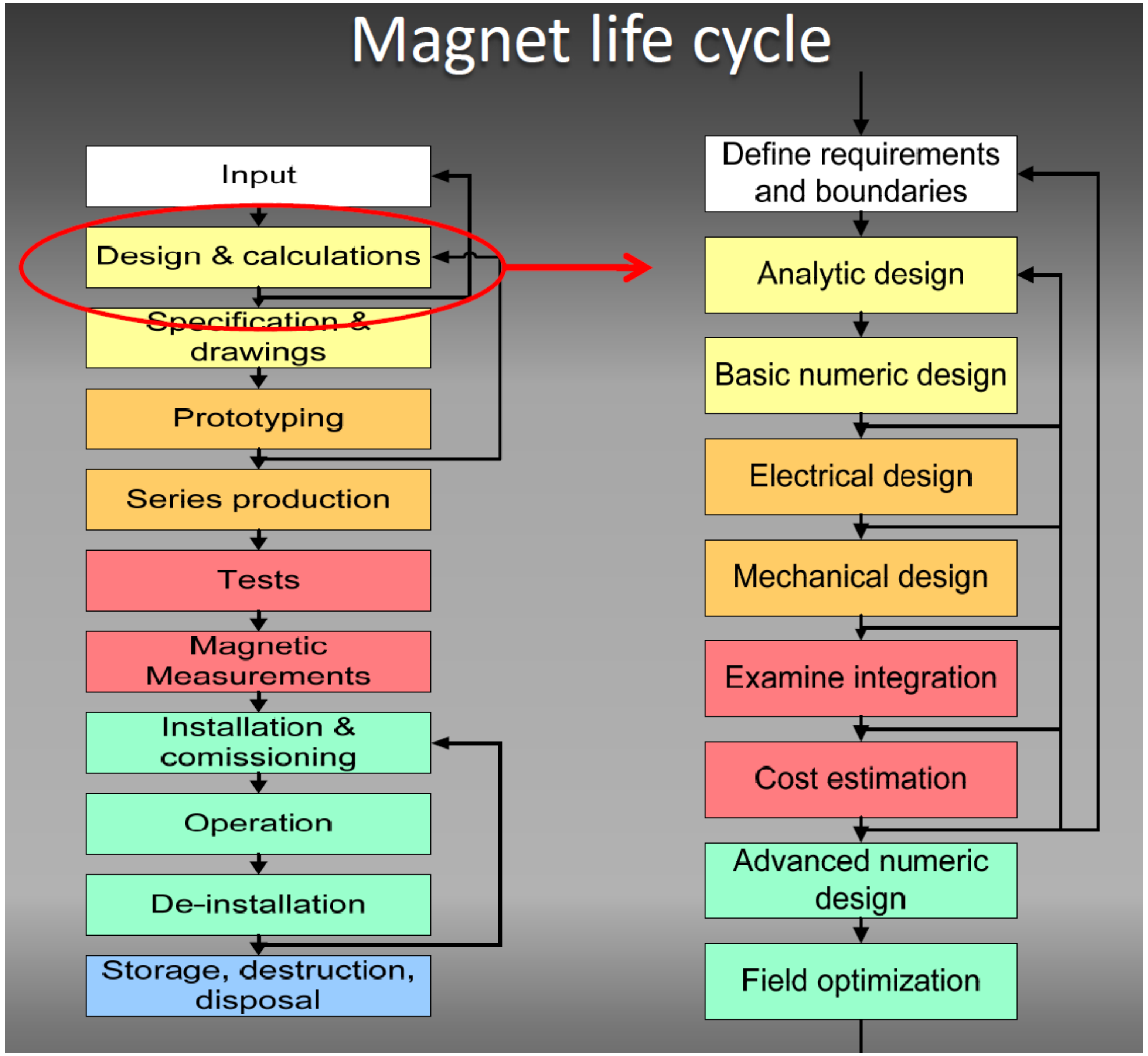


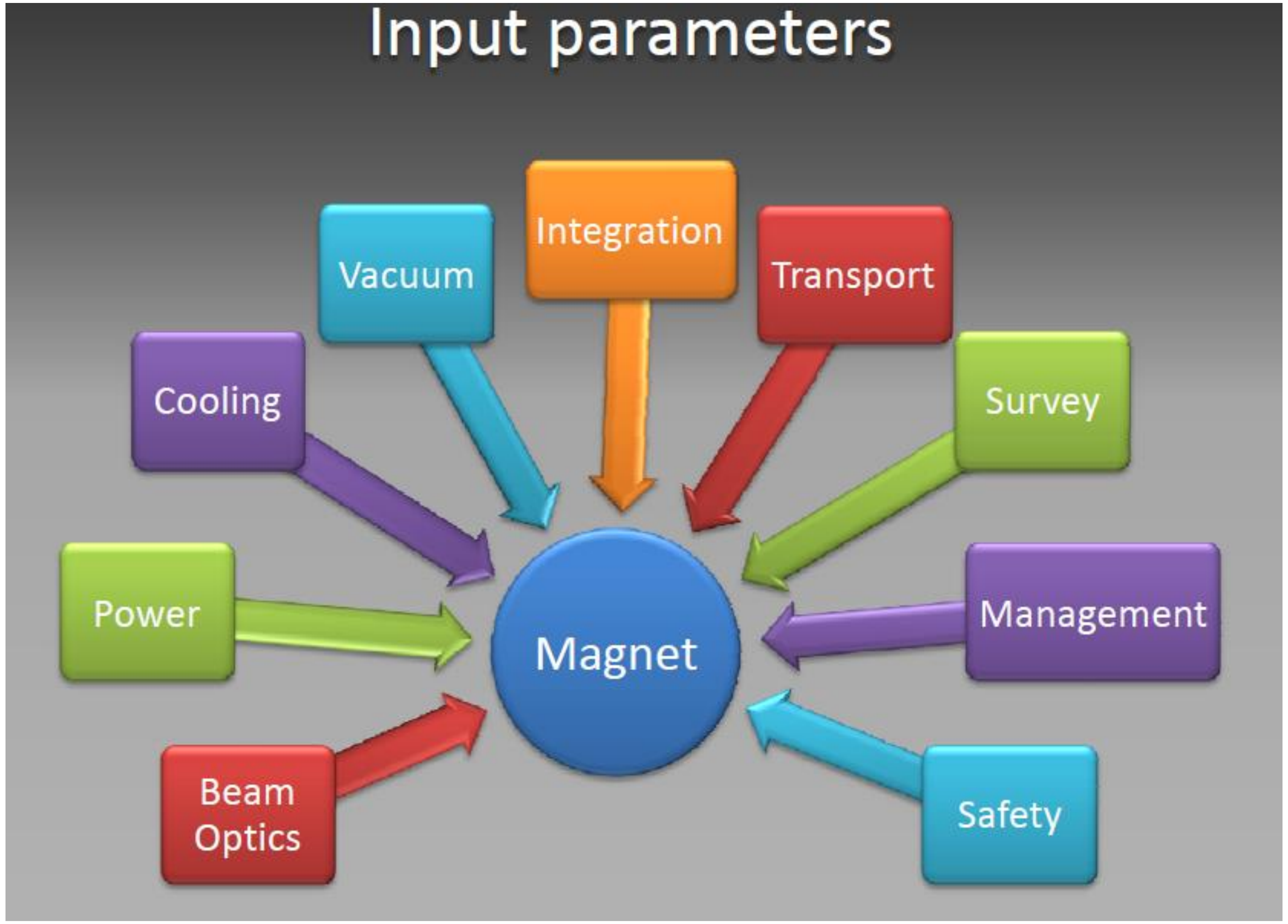
Kicker magnet (6 usec, half sine, 10kA)



1.1 T Lambertson Septum

Magnet Project Life Cycle

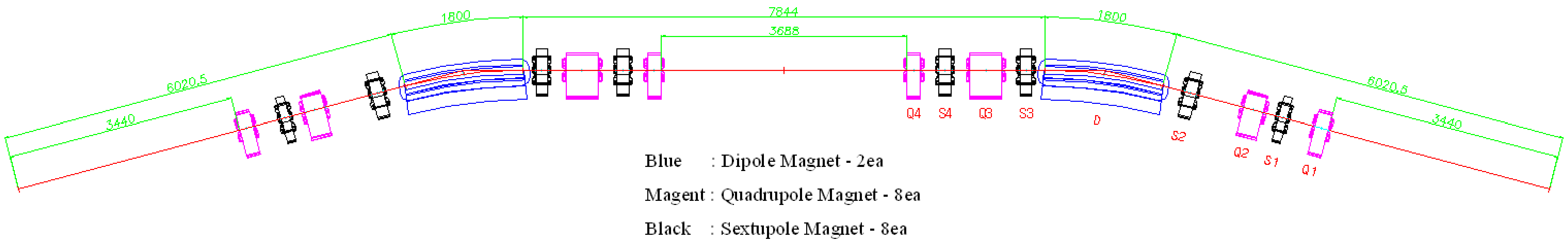


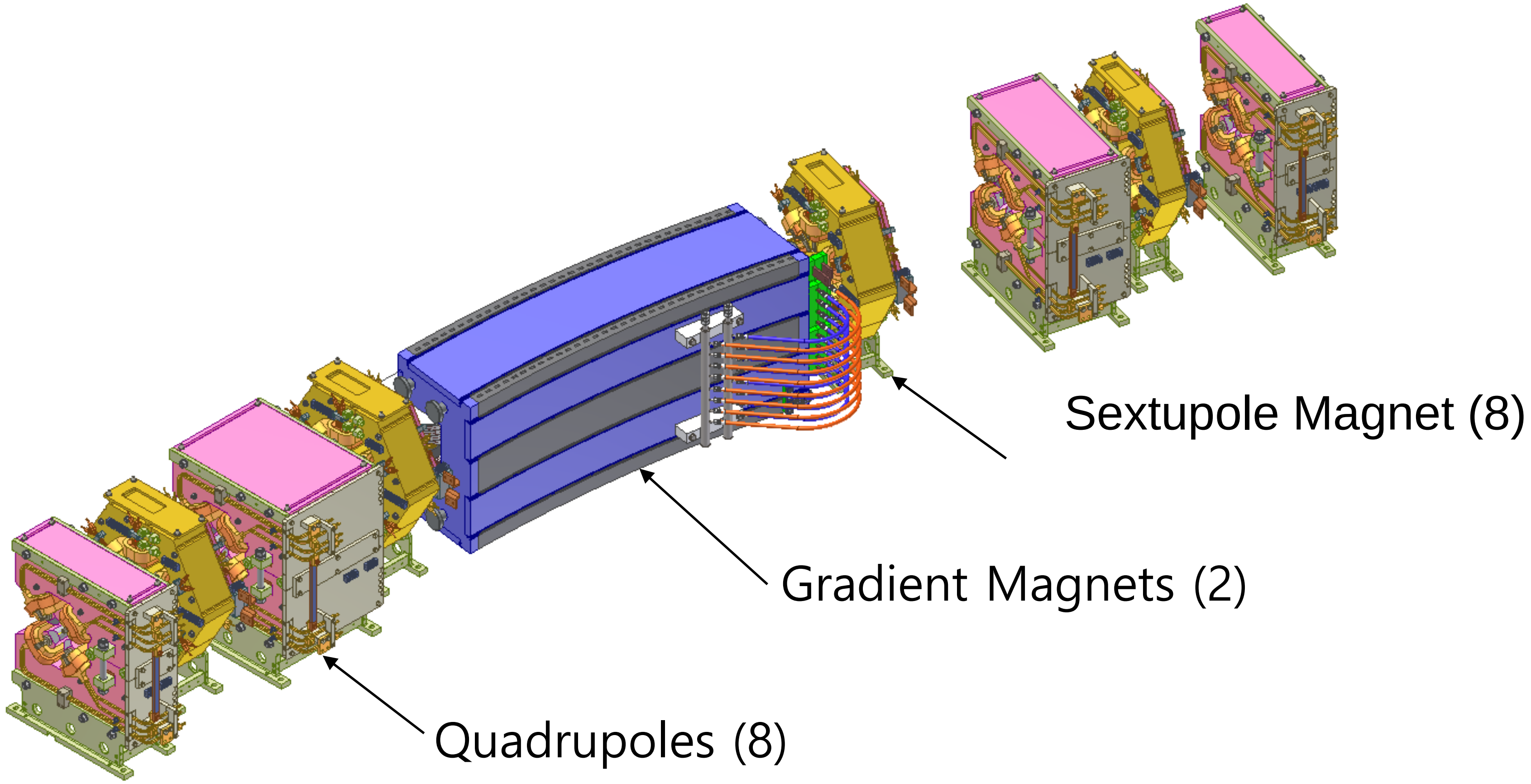


Magnet Requirements

- Beam Parameter (angle, k-value).
- Integrated strength
- Local Field and magnetic length
- Operation Mode (Continuous, Pulse, Ramp.. Etc)
- Field Quality (Uniformity, Harmonic content, stability,…)
- Sextupole+(H/V Corrector)+(Skew Quadrupole) combination
- Space, Transport, Weight limitation
- Crane, Connections, Alignment target
- Aperture, Good field region
- Radiation level,
- Fringe field, magnetic interference.
- Safety, interlocks.
- Cooling, Flow rate, inlet temperature, Pressure drop.
- Vacuum chamber size, interference with vacuum components.
- Max current, Voltage, max dI/dt.

PLS-II Magnet System Layout





Example of Magnet Requirements

	Q1	Q2	Q3	S1	D1	Remark
Nominal Gap or Aperture Radius [mm]	31.25mm	64.0mm	104.0 mm	104.0 mm	68 mm	
Field Integral	7.408 T	3.870 T	2.352 T	7.2 T/m	2.042 Tm	
Effective Length	0.250 m	0.300 m	0.300 m	0.100 m	1.571 m	
Good field radius or Good field region	21.9 mm	44.8mm	72.8 mm	72.8 mm	±70 mm	
Allowed normalized multipole or uniformity	1.00E-03	1.00E-03	1.00E-03	1.00E-03	1.00E-03	
Max Strength	25.6 T/m	12.5T/m	7.7 T/m	72 T/m2	1.30 T	
Max Pole tip field	0.8 T	0.8 T	0.8 T	0.39 T		
Ref particle					132Sn+47 18.9 MeV/u	

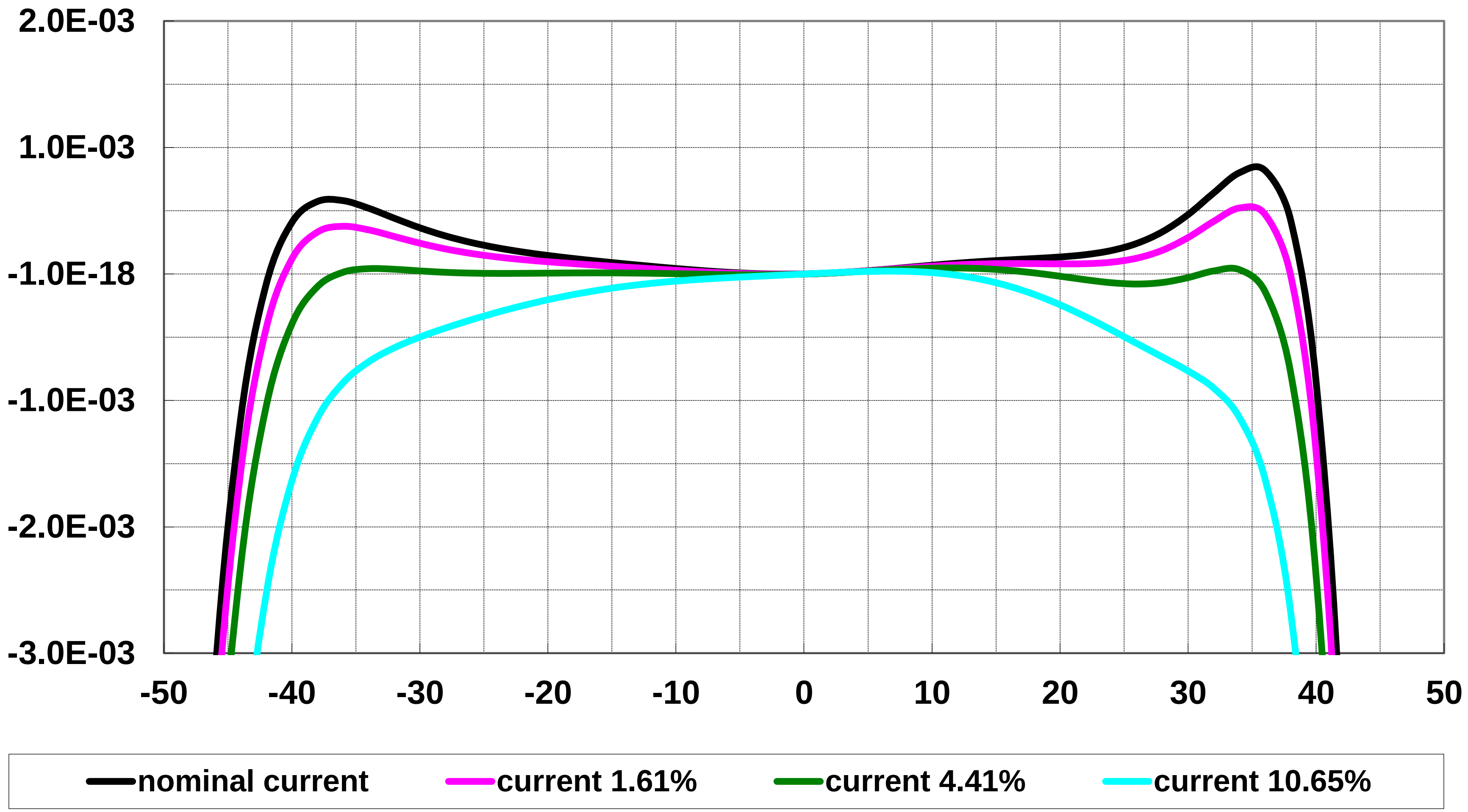
Caution: Some physicist require un-achievable requirements. Long discussion with BD people for realizable system is needed!

Uniformity

Uniformity is defined by

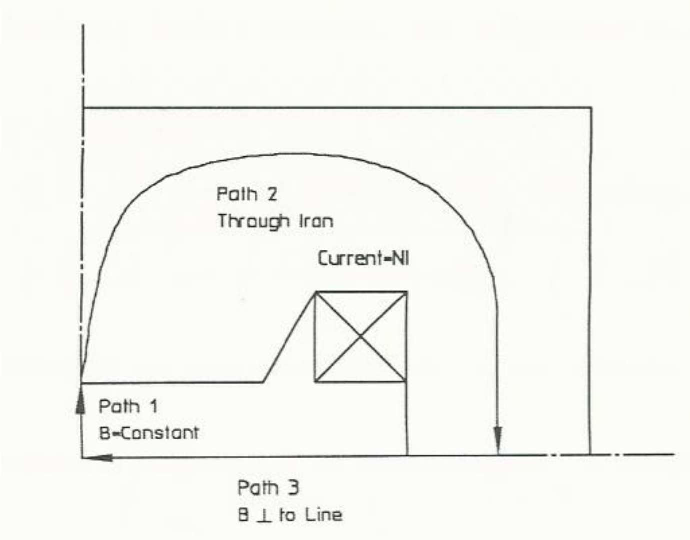
$$\frac{\Delta B}{B}=\frac{B_y(x)-(B_0-G_0x)}{B_0-G_0x}$$

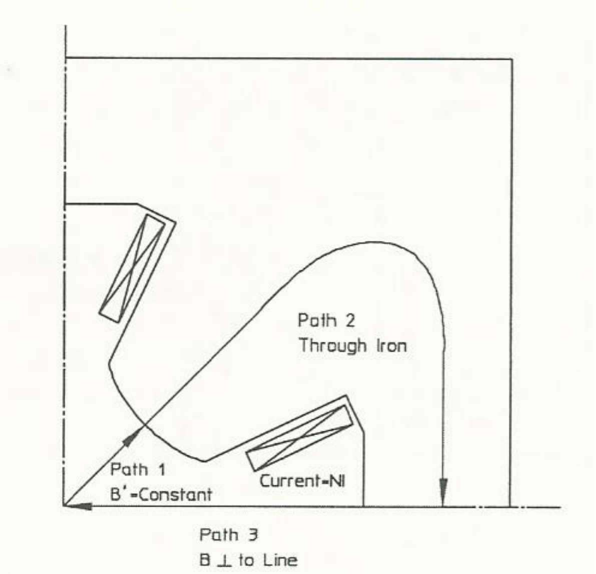
As expected, for higher excitation, the effect of the pole shaping is decreasing.



Required Ampere Turns around a pole

- Calculated from Ampere's Law: $\oint \frac{1}{\mu\mu_0} B \bullet dl = NI$
- For dipole: $B\frac{g}{2} \cong \mu_0 NI \Rightarrow NI = B\frac{g}{2}\frac{1}{\mu_0}$ g is a full gap.
- Neglecting small contribution for path inside the core because of high μ. NI is the required ampere-turn per coil.
- For Quadrupole: $\int_0^{r_c} \frac{1}{\mu_0} B' r\, dr = \frac{1}{2}\frac{B'}{\mu_0} r_c^2 \cong NI$ r_c is the bore radius
- For Sextupole: $\int_0^{r_c} \frac{1}{\mu_0}\frac{B'' r^2}{2} dr = \frac{1}{6}\frac{B''}{\mu_0} r_c^3 \cong NI$ r_c is the bore radius





Integration path for dipole and quadrupole

Magnet Resistance, Power, Inductances

Resistance = $R = \frac{\rho L}{A_c} = \frac{\rho N L_0}{A_c}$ Ac : Conductor cross section

Here, $\rho = \rho_0 (1 + \alpha \Delta T)$ $\rho_0 = 1.70 \times 10^{-8}$ Ωm, $\alpha = 4.2 \times 10^{-3} / K$

Power : $P = I^2 R = I^2 \frac{\rho N L_0}{A_c} = \left(\frac{I}{A_c} \right) \rho (NI) L_0 = J \rho (NI) L_0$

Note NI is determined by the gap (bore radius), therefore Power is linearly proportional to current density (j=I/Ac)

Inductance : $U_{mag} = \frac{1}{2} L I^2$, $L = 2 \times U_{mag} / I^2 = \frac{2 \times U' \times L_{eff} \times N_{symm}}{I^2}$

For example: $N_{symm} = 8, U' = 217.3 J/m, I = 101.5 A,$ $L = 0.0844 mH$

From Power, $R=P/I^2$(Cross check), V=I X R (Voltage drop)

Lamination, Solid ?

- Lamination:
  1. For many magnets, the costs can be reduced.
  2. After punching, the punched lamination can be sorted/shuffled to achieve uniform magnetic properties between magnets reducing magnet to magnet error.
  3. For AC magnets, or ramped magnets (like synchrotron magnets), lamination is essential.
  4. Initial costs for a mold, and jig, fixtures are high. Therefore, the 1st magnet costs is high and delivery is long.
- Solid Magnet:
  1. Can be prototyped relatively quickly.
  2. Magnetic property of the material can vary between the Lot, and the magnet to magnet deviation can be higher.
  3. Due to eddy current, and Hysteresis effect, solid magnet is not adequate for AC magnet or ramped magnet.

Total Costs of Ownership

Total cost=M1+M2+M3+….M0

M1: Cost of Power Supply

M2: Cost of Coil

M3: Cost of Yoke

…

M0: Cost of electricity based on the assumed operating hour

Power: $$P = I^2 R = I^2 \frac{\rho N L_0}{A_c} = \left(\frac{I}{A_c}\right) \rho (NI) L_0 = J \rho (NI) L_0$$

- L_0 is an approximate one turn length and it does not change much with design. Therefore, with given Ampere Turn (NI), the power P is proportional to J. low J means high coil costs, expensive MPS , and lower operating costs (lower power).

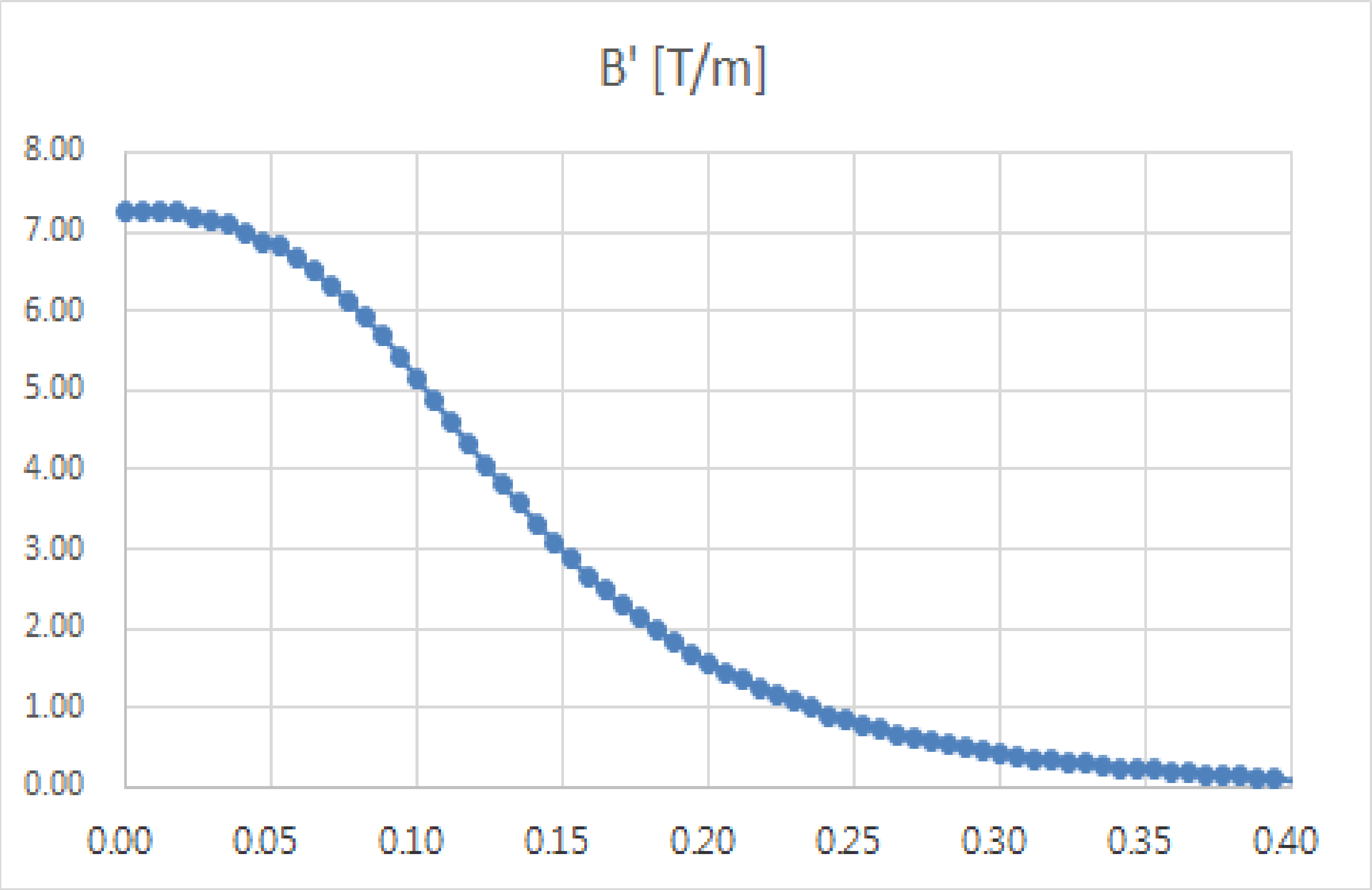
- With same NI, the current I can be different depending on the number of turns, and it can affect the costs of power supply.

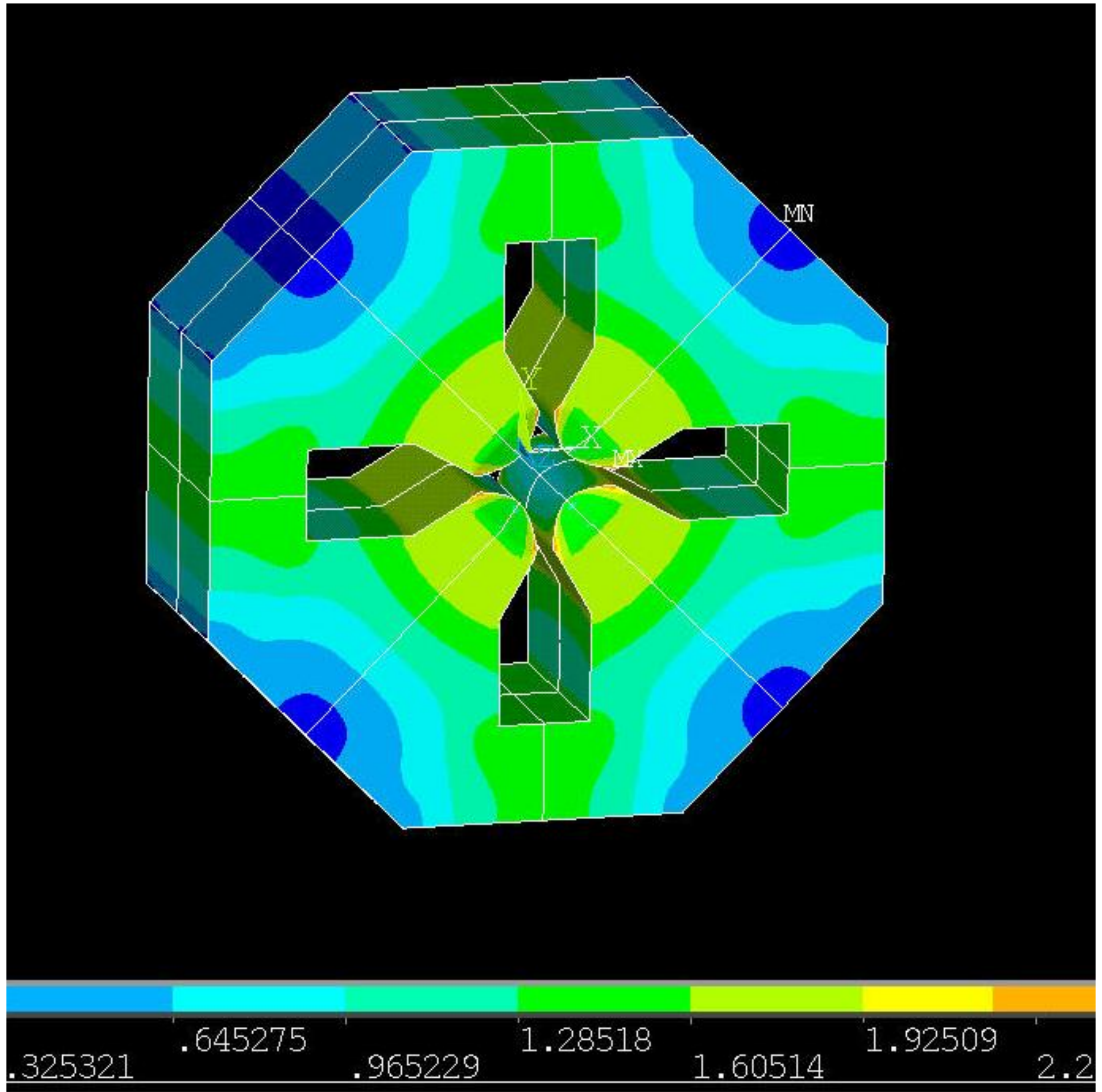
- Optimum current density J can vary depending on the cases. In most cases, optimum J is about 4~6 A/mm2 for water cooled magnet.

Tools for Design

- POISSON: (Free, relatively easy to learn)
  1. 1st 2D Finite Difference Magneto static Program by Klaus Halbach, Ron Holsinger at LBNL, Berkeley. (1987)
  2. Consists of POISSON (Magneto static), PANDIRA (Permanent magnet), MIRT (Optimization Code), Superfish (RF).
  3. 1st Practical Magnet design Computer Code, and said to be the 1st Computer Application next to the trajectory calculation.
- Opera Series:
  1. Vector Fields Company's 2D 3D Electromagnetic FEM Code
  2. Consists of Opera2D, 3D, Elettra (AC), Soprano (HF) etc modules.
  3. AT PAL 1 copy is used for Magnet Calculation.
  4. Expensive and need some experience (or training)
- ANSYS :
  1. General 2D, 3D FEM program (Can solve structure, heat transfer, magneto static, electrostatic, AC, RF, Fluid etc problems.)
- RADIA : BEM (Boundary element Program) code developed at ESRF based on the Mathematica. Optimized for Undulator analysis

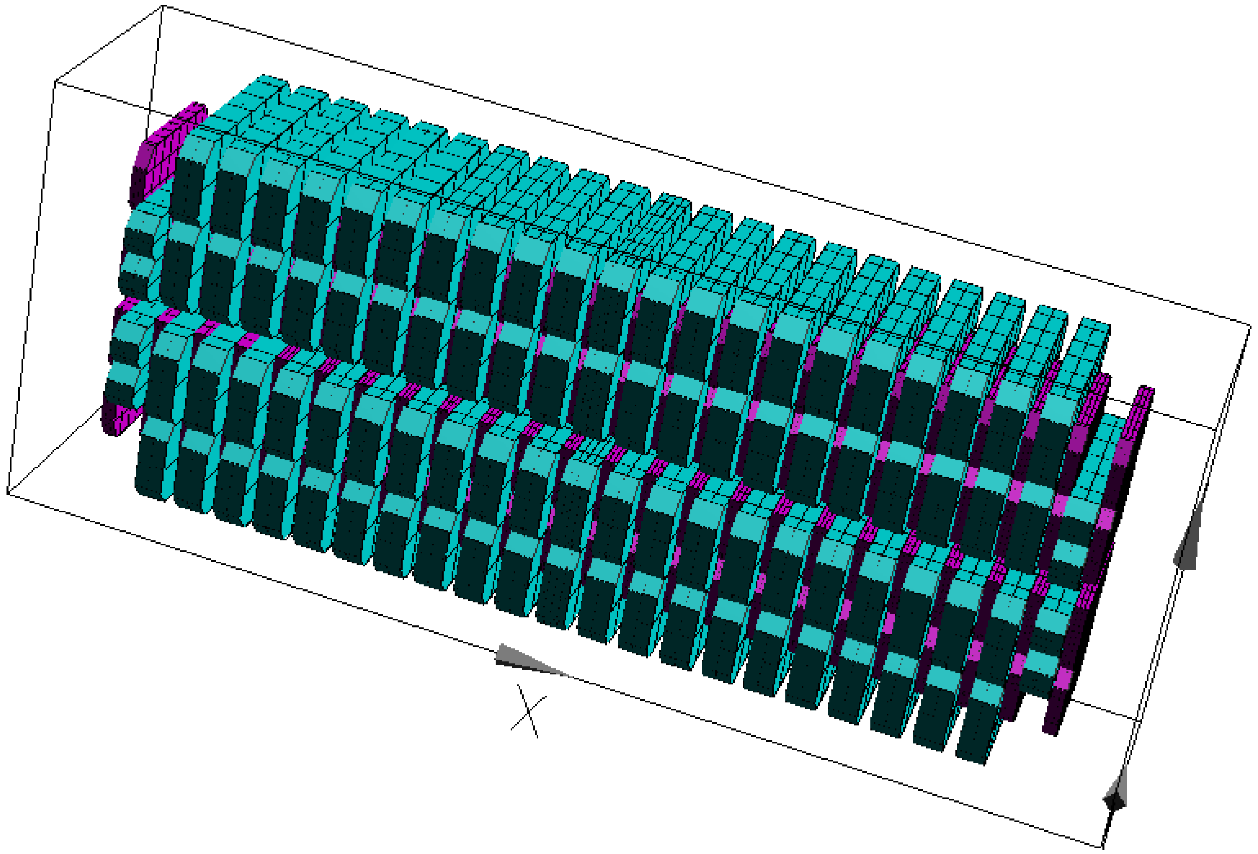
Results of the 3D calculation



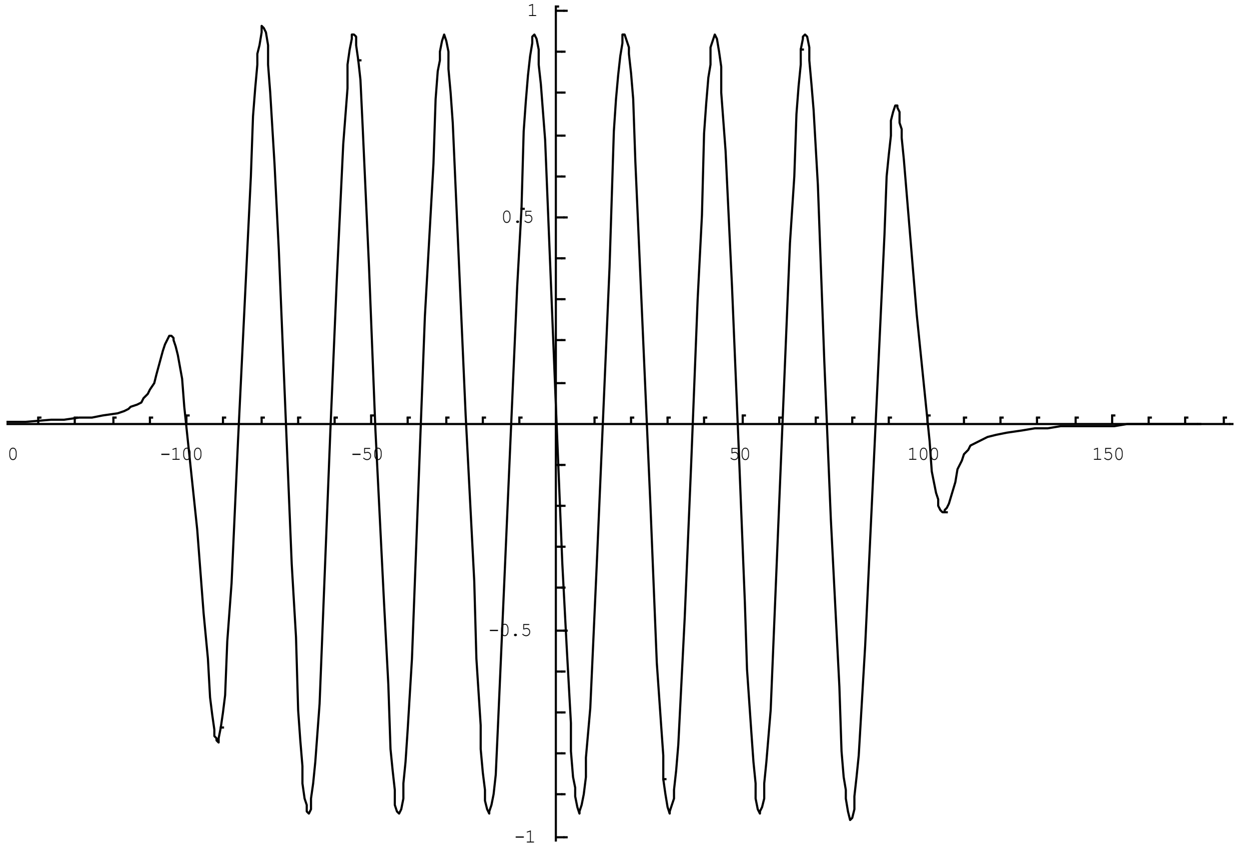


- Longitudinal profile of B' (strong 3D feature due to short core length), L_{core}=259 mm for L_{eff}=300mm.
- |B| distribution on the surface of the Q1

Short Radia Model of the HX undulator

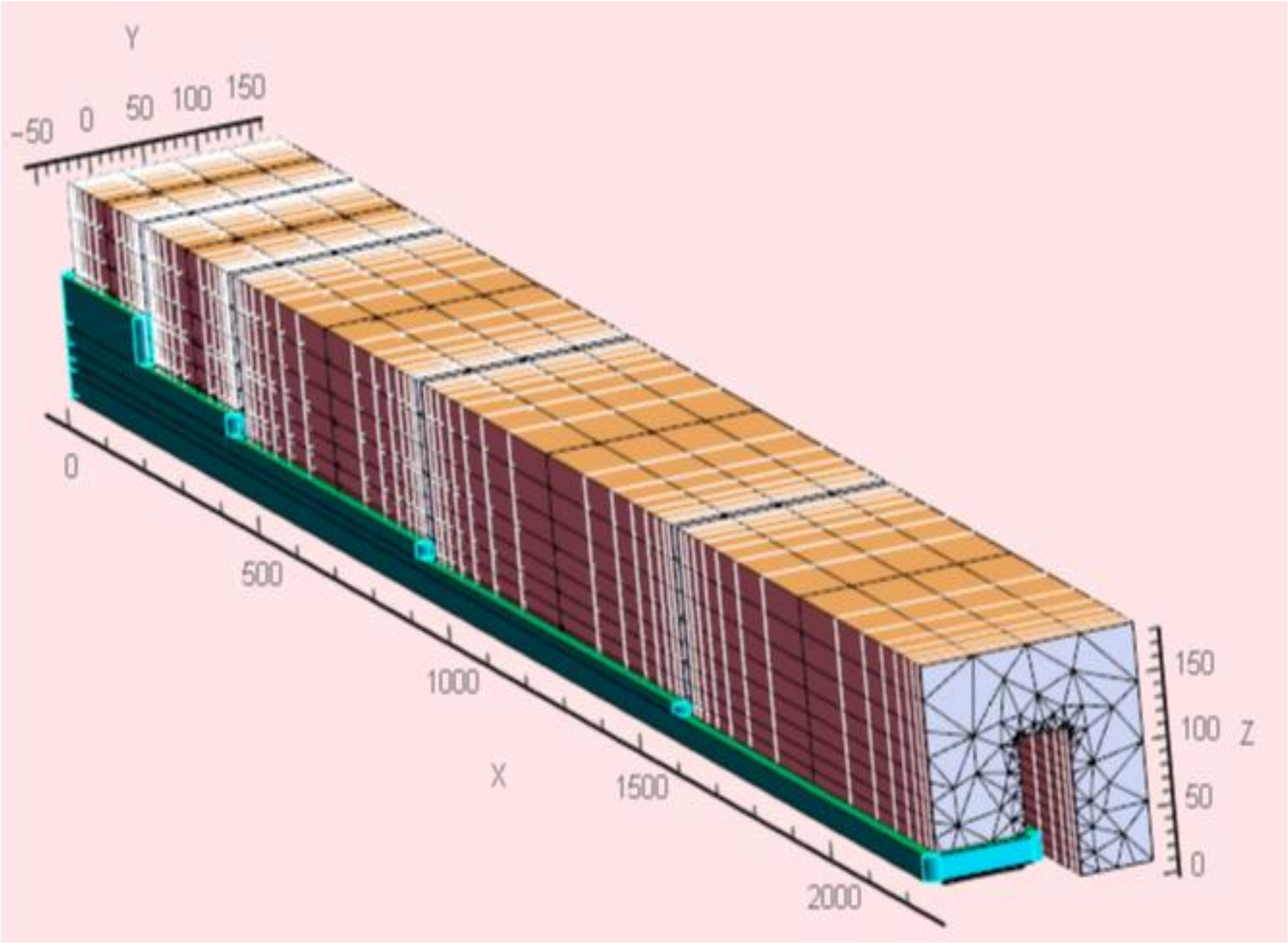


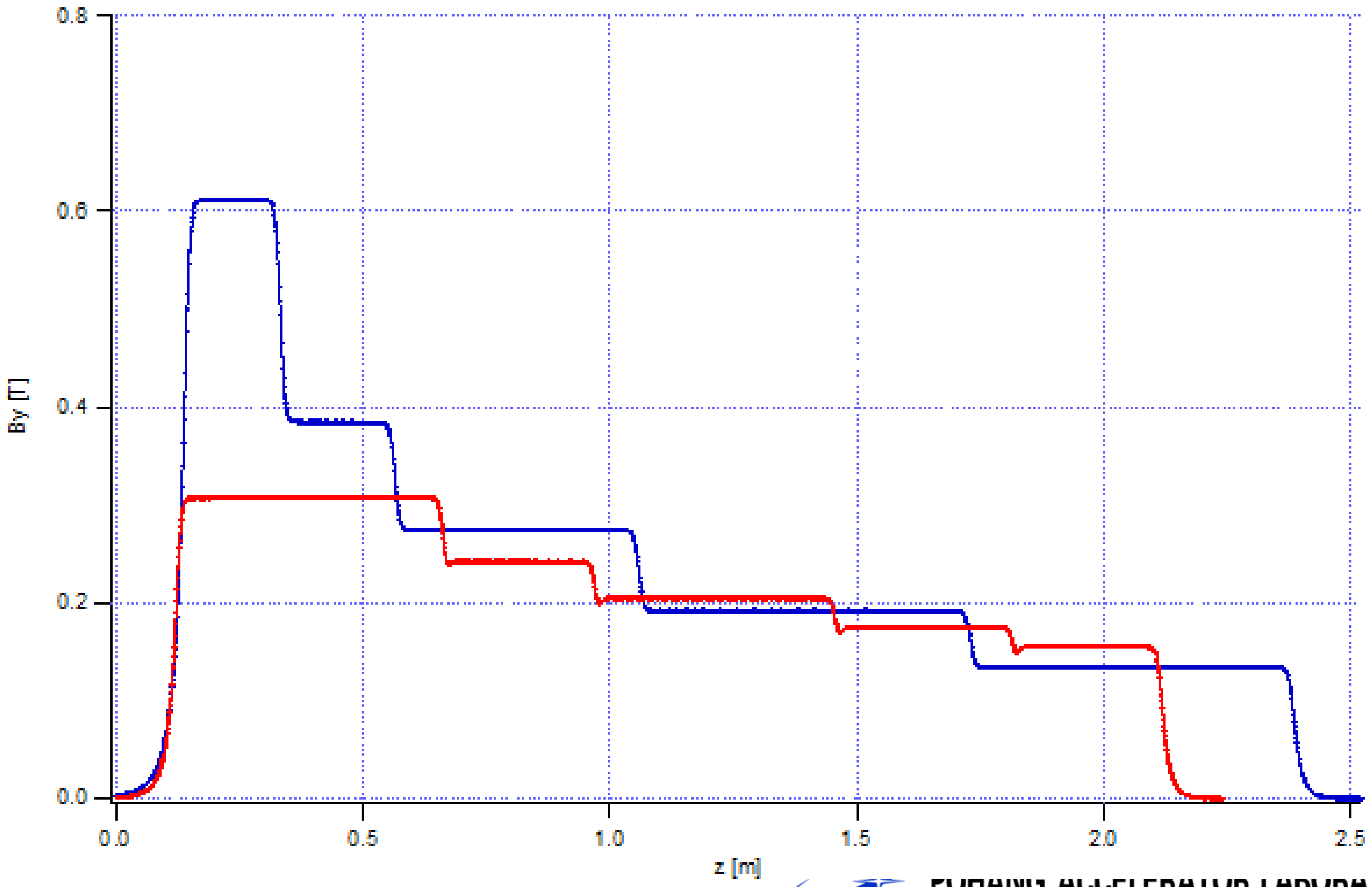
Example of Radia calculation



Longitudinal Gradient Dipole (LGBM) : 3D

- The spacing between the section is compromised for current density and profile accuracy. The spacing is 14mm for LGBM1, and 12mm for LBGM2.
- Due to quantized nature of the coil turns, reluctant air gap is introduced in the return yoke to achieve the design field.
- Following show the 3D Raida model, and longitudinal field profiles of BM1, BM2.
- It’s also simulated using ANSYS 3D.





2D Magnetics Basic

Many accelerator magnets are long compared to the gap, and can be described as 2D magnets.

Using Scalar Potential: $B_x = -\frac{\partial V}{\partial x}, \quad B_y = -\frac{\partial V}{\partial y}$

Using Vector Potential: $B_y = -\frac{\partial A}{\partial x}, \quad B_x = \frac{\partial A}{\partial y}$

A, V pair satisfies Cauchy Riemann Condition:
->> Complex Potential F=A(x,y)+iV(x,y) is analytic, expand F in series

$$F = A + iV = \sum_{n=1} C_n \left(\frac{z}{r_0}\right)^n = \sum_{n=1} (a_n + ib_n)\left(\frac{z}{r_0}\right)^n, \quad z = x + iy$$

$$B^* = B_x - iB_y = i\frac{dF}{dz} = i\sum_{n=1} \frac{nC_n}{r_0}\left(\frac{z}{r_0}\right)^{n-1} = i\sum_{n=1} \frac{n(a_n + ib_n)}{r_0}\left(\frac{z}{r_0}\right)^{n-1}, z = x + iy = r\exp(i\theta)$$

Here, r_0 is normalization radius to make all C_n to be same unit (Tesla-m), F and B* is analytic, z can be Cartesian or polar.

Symmetry in Magnets

Midplane Symmetry : Normal magnet or skew magnet?
or Bx only or By only at the midplane.
(a_n is normal component, b_n is the skew..)

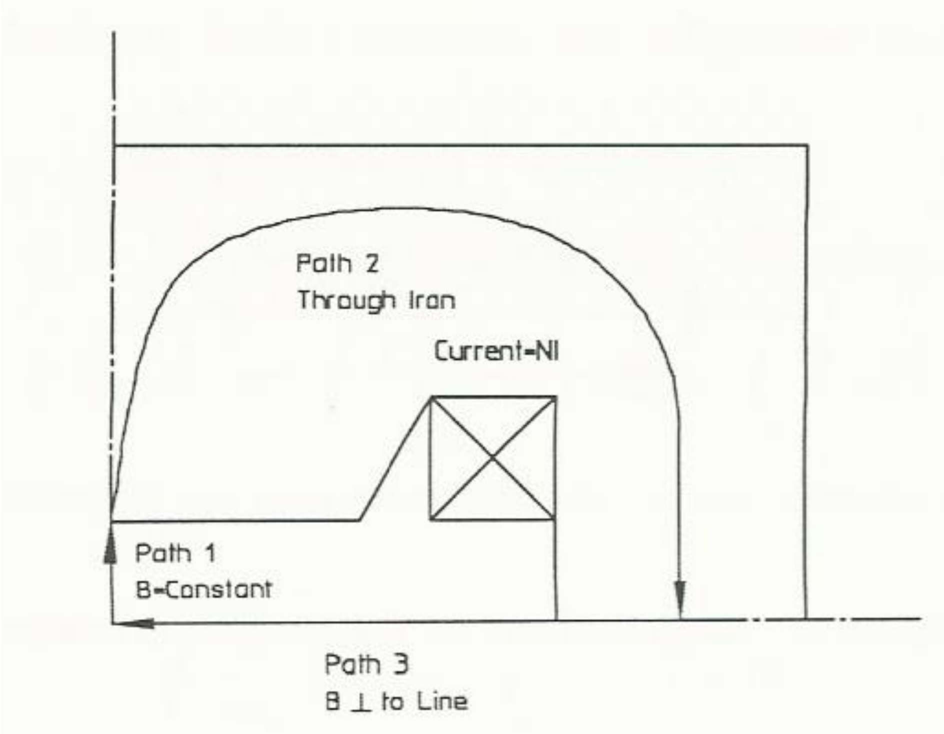
Rotational Symmetry : invariance in rotation.
for example rotating dipole 180 degree
or rotating quad in 90 degree
Left right symmetry(?): Mirror reflection on the symmetry axis

Only harmonics satisfying the symmetry exists: allowed harmonics.
For example: H-type dipole : n=1,3,5.. (n=1 is dipole)
Symmetric quad : n=2,6,10… (n=2 is quadrupole)

For XFEL quad: only consider n=2,6.. n=10 is too high and even not measured during the rotating coil measurement.

Magnetic Saturation (1)

- How efficiently magneto motive force MMF (Ampere Turn) is used in the gap region?
- Ampere's law (Integral form): $NI = \oint \frac{B}{\mu\mu_0} \cdot dl$



$$NI = \oint \frac{B}{\mu\mu_0} \cdot dl = \oint_{gap} \frac{B}{\mu\mu_0} \cdot dl + \oint_{yoke} \frac{B}{\mu\mu_0} \cdot dl = NI_{gap} + NI_{yoke}$$

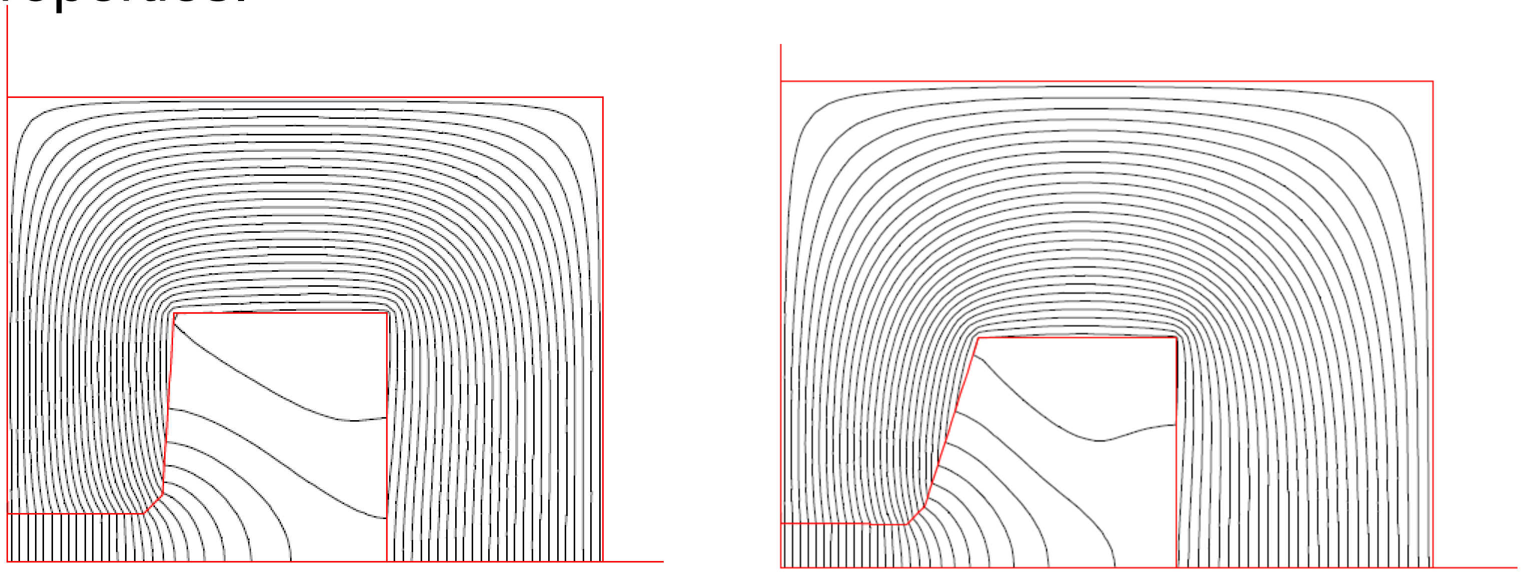
Magnetic Efficiency : $$\eta = \frac{NI_{gap}}{NI_{gap} + NI_{yoke}}$$

- Assuming Lyok=10 * gap, average relative permeability in the yoke is NI_{yoke}=10/1000 * NI_{gap}. Using these values, approximate magnetic efficiency is about 0.99.

- Low magnetic efficiency can be tolerated if it's cost effective. For example, a dipole in a collider can be 1.7 Tesla with 0.8 efficiency.

Magnetic Saturation (2)

- If magnetic efficiency is low, we need higher operating current. But other impacts are more important.
- The optimized pole shape is not good for the whole excitation if the magnet is saturated since the impact of pole shims change with saturation.
- Therefore, if we need magnet which changes very little with excitation, we need to design a non-saturated magnet.
- Pole root saturation: for parallel pole, magnetic flux is collected at the root of the pole causing saturation. Tapering the root of the pole can reduce this effect. (See Figure)
- In longitudinal direction, same problem may happen like “root saturation”, To minimize the saturation impact, the longitudinal end chamfering is helpful.
- One more advantage of an unsaturated magnet is that the error fields of the magnet is not so sensitive to the material properties.



Tapering of the pole root to reduce saturation

Cooling of room Temperature Magnet

- The cooling of room temperature magnets are done by:
- Air cooling: with current density J=1.0~2.0 A/mm2
- low costs, high reliability, limited to low current density

- Indirect water cooling using a Heat sink: Cooling upto J=2.0 ~5.0 A/mm2 is possible. Additional costs for heat sink, cooling plate is necessary. Can reduce the operating current of the magnet using small conductors reducing power supply costs.

- Direct water cooling using a Hollow conductor: Cooling up to J=4.0 ~ 10 A/mm2 is possible. Cooling using Low conductivity water LCW is the most reliable, safe, and predictable. However hollow conductor is expensive, and minimum size is large requiring higher current, and possibility of water leaks at the LCW joints..

- In any case, the magnet coil should be protected using a temperature interlock to connected to the power supply to avoid coil damage.

Coolant Flow in Hollow Conductor

- Coolant Flow velocity and pressure drop inside cooling channel
- Darcy formula : Used to estimate V with given pressure drop.

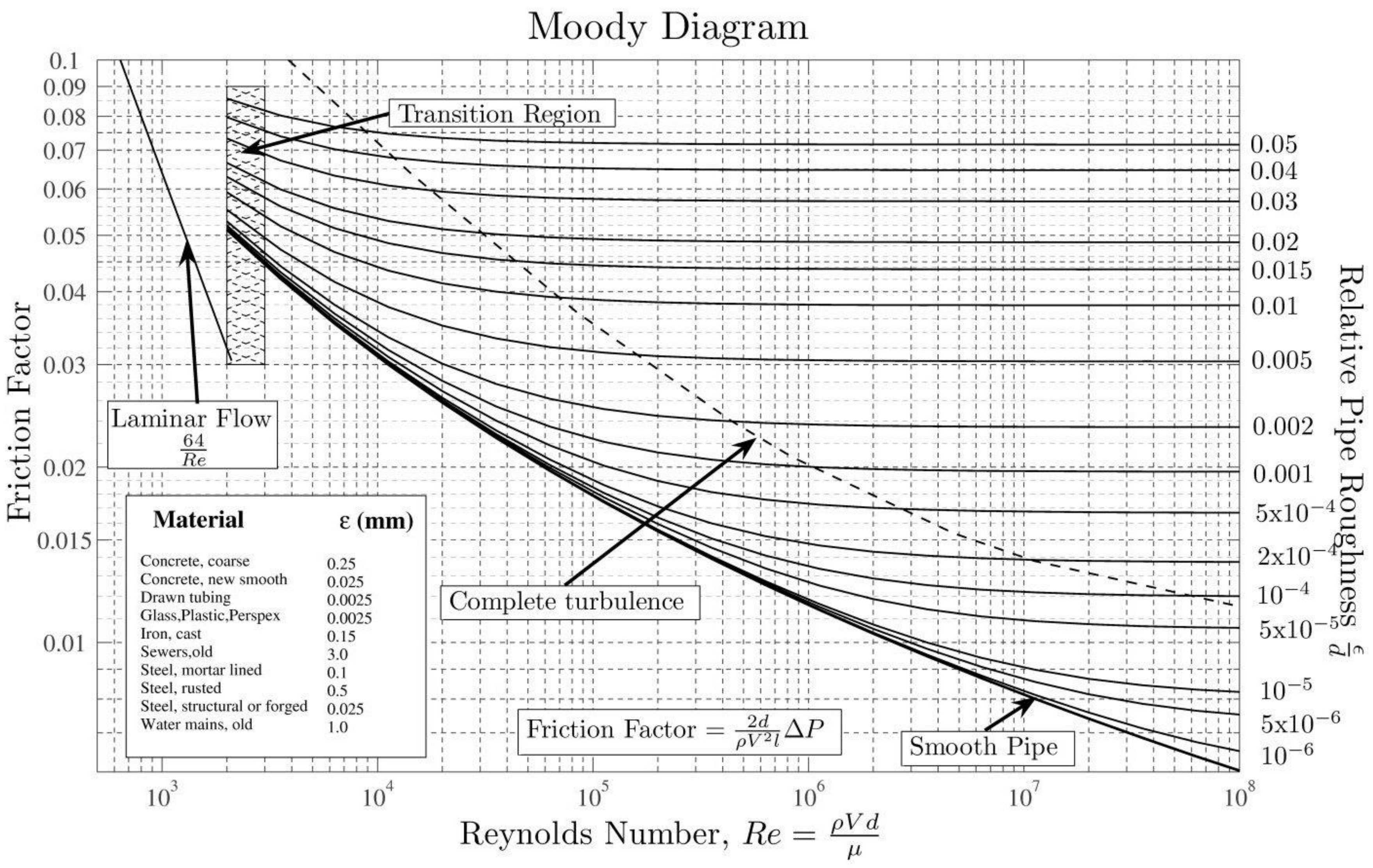
$$\Delta P = \frac{\rho V^2}{2} \times \frac{fl}{d}$$

- Friction factor f is determined by Reynolds number Re= ρVD/ μ , surface roughness, and Moody's diagram.
- Here, ρ is coolant density, V is coolant bulk velocity, d is coolant diameter, l is the length of the cooling path.
- Coolant temperature rise is determined from the heat balance equation.

$$\dot{m} C \, \Delta T = Power$$

- Here $\dot{m}$ is mass flow rate, C is specific heat capacity, ΔT is the temperature rise, Power is heating power per the cooling circuit.

Moody Diagram



$$\frac{1}{\sqrt{f}} = -2.0\log_{10}\left(\frac{\frac{\epsilon}{d}}{3.7} + \frac{2.51}{Re\sqrt{f}}\right), \text{turbulent flow}$$

From Wikipedia

Magnetic Measurement (1)

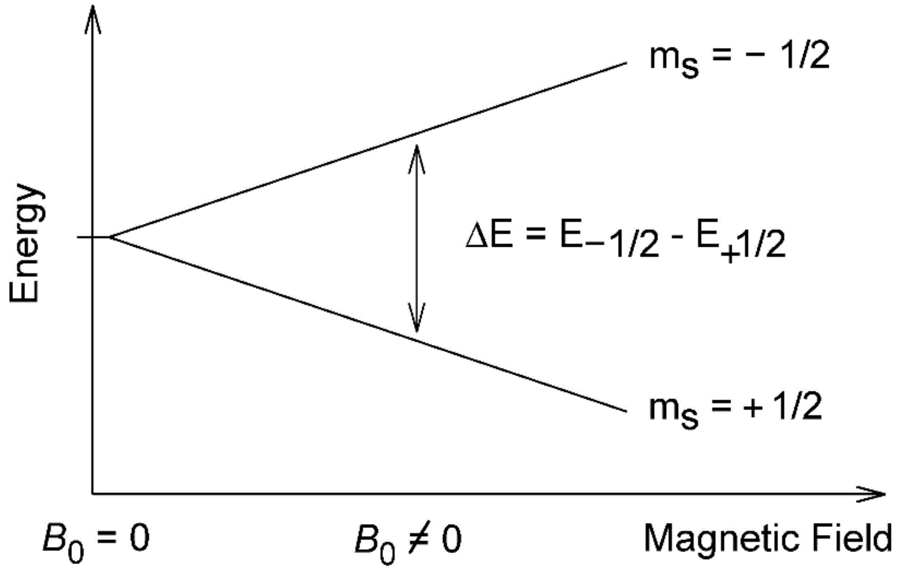
NMR (Nuclear Magnetic Resonance)

-Theory: Measure the splitting of energy level of a nucleus under external B.

-Pros: Absolute accurate measurement with ppm precision.

-Cons : Depending on the Field level, probe should be changed.
The field should be uniform to lock the signal at the probe position.
Therefore, can not be used for magnets other than the dipole
probe is rather large and spatial resolution is low.
Expensive and only magnitude is measureable.

-Used mostly to calibrate other probes.



Metrolab NMR Teslameter

Magnetic Measurement (2)

Hall probe

-Theory : Measurement of Hall voltage under the influence of external B

-Pros : Wide measurement range, low costs, accuracy,

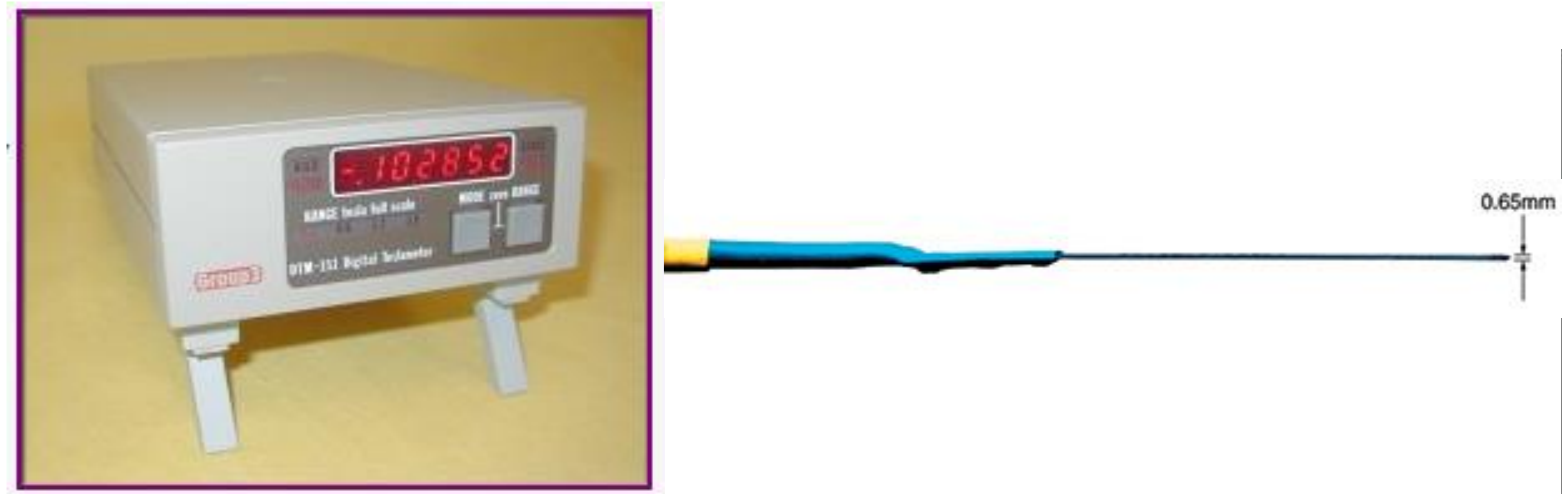
-Cons : Nonlinearty between V, B.

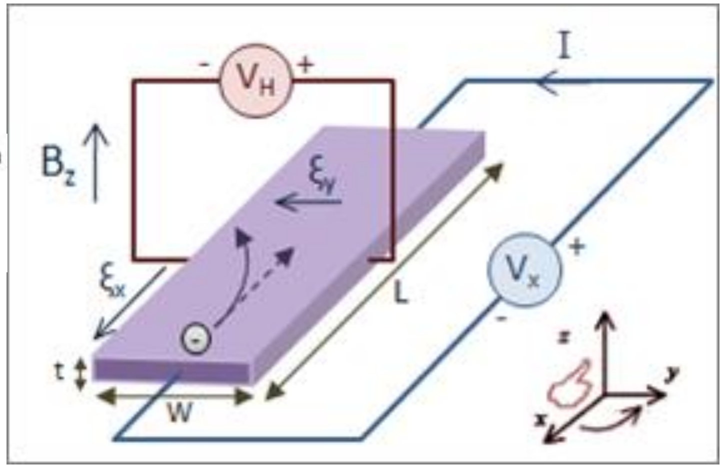
Temperature Sensitivity (T compensation, or Const T sink)

Planar hall Effect (Vx is affected by By), Flip-Flop Difference.

Calibration Difficulty.

-If used carefully, it’s most cost effective, and flexible method





GMW Hall Gaussmeter, 100ppm/K

Magnetic Measurement (3)

Rotating coil

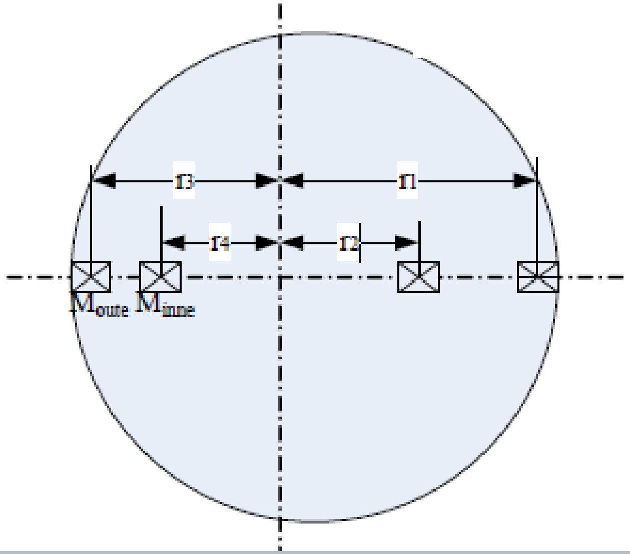
-Theory : Rotate a coil inside a magnet and analyze the induced voltage.

-Pros : Fast and precise fundamental, multipole error measurement.

-Cons :

- -Need a specific rotating coil for each type of magnet. (costly)
- -Base of the coil should be non magnetic, non conducting like engineering ceramic or glass fiber. Precision machining is difficult.
- -Integrator has a intrinsic drift which should be minimized, compensated.
- -Absolute value need calibration using Hall probe measurements.
- -Other coil methods other than the rotating coil is also possible.

-For multipole field error estimation, rotating coil measurement is mandatory



$$V_o(\theta) = \frac{1}{RC}\int V_i(t)dt = \frac{1}{RC}\int d\Phi = \frac{L}{RC}\int B_\theta dr$$

$$= \frac{L}{RC}\int \frac{\partial A(\theta)}{\partial r}dr = \frac{L}{RC}A(\theta)$$

Multipole measurements of the PLS quad at PLS-II excitation

N	Q1 (PLS)	Q1 (PLSII)	Q2 (PLS)	Q2 (PLSII)		
2	1.1630E-1	1.4668E-1	1.7527E-1	2.4378E-1		
3	2.96E-04	6.23E-05	3.58E-04	1.02E-04		
4	4.35E-06	3.07E-05	1.25E-04	2.72E-05		
5	9.52E-05	1.21E-04	1.83E-04	1.69E-04		
6	3.50E-04	6.35E-04	1.72E-04	6.54E-04		
10	1.71E-04	2.00E-04	8.51E-05	1.69E-04		

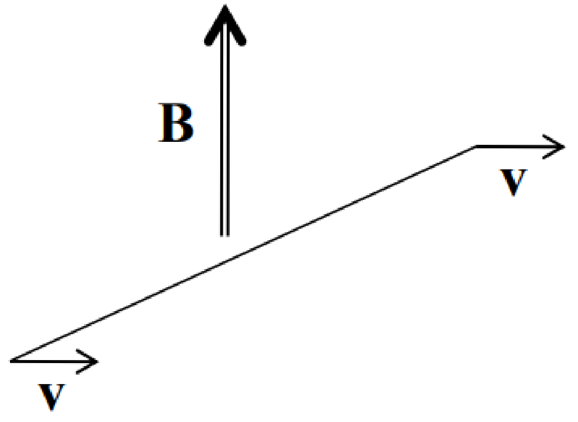
- All field is based on the normalization radius r_0 =30 mm.
- N=3,4,5,6,10.. Values are normalized to the fundamental component.
- For N=2, unit is T m (=B’ r_0 L_{eff}).
- Increase in n=6 (dodecapole) component is significant.

Magnetic Measurement (4)

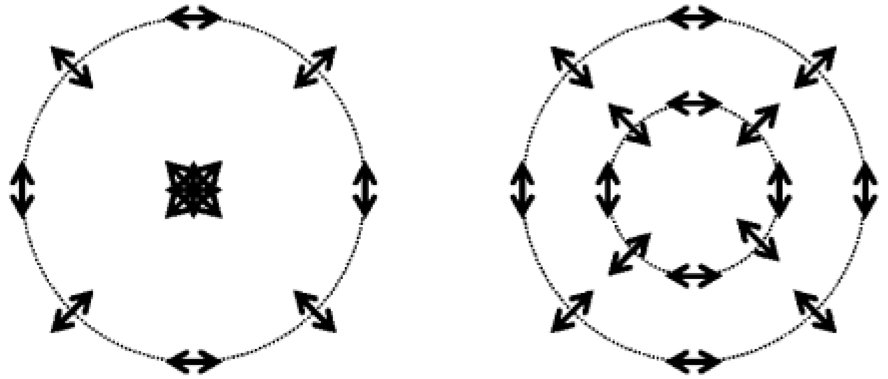
Wire Measurements (ESRF developments since 2012)
PRST AB, vol. 15, p. 022401, 2012.
-Theory : Measure integrated voltage along a wire trajectory
-Pros : Fundamental/multipole measurement for arbitrary rc.
-Cons :
- -Calibration difficulty
- -Need to optimize the measurement trajectory for precise bucking of the fundamental components
- -Accuracy of multipole about $2X10^{-4}$ of fundamental.

Integration and time averaging

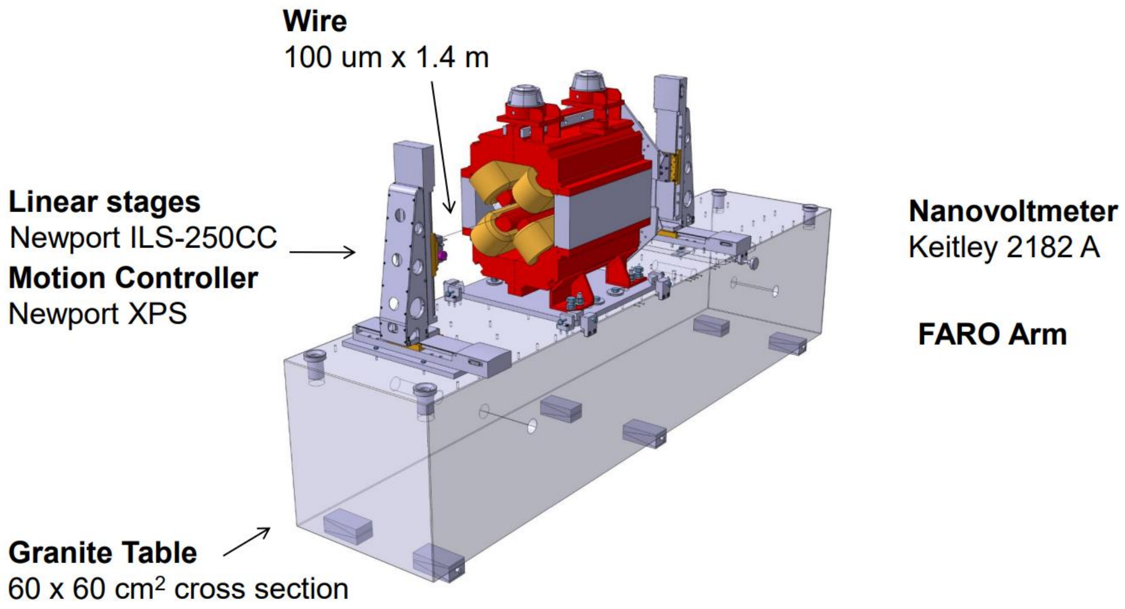
$$I = \frac{1}{L}\int e\,dt \qquad I \approx -\frac{\langle e\rangle T}{L}$$



SW field integral measurement

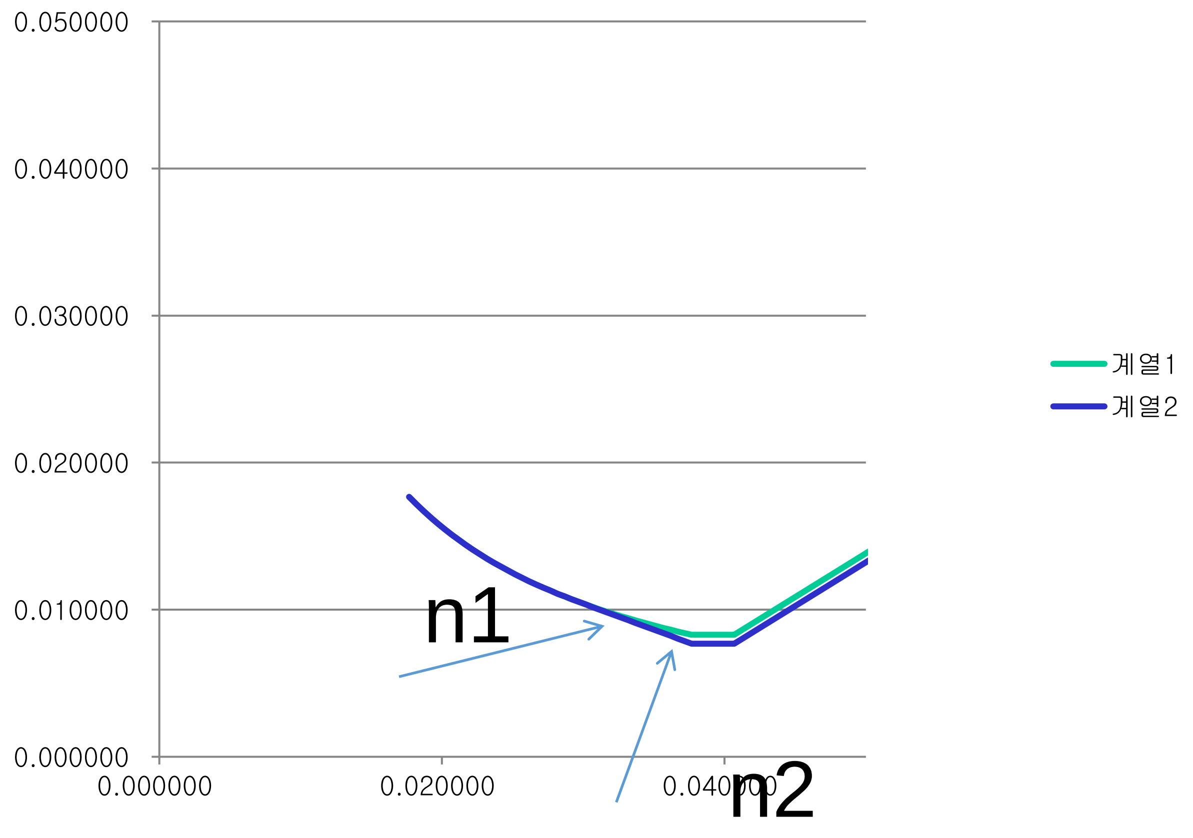


Example of wire trajectory for measurements



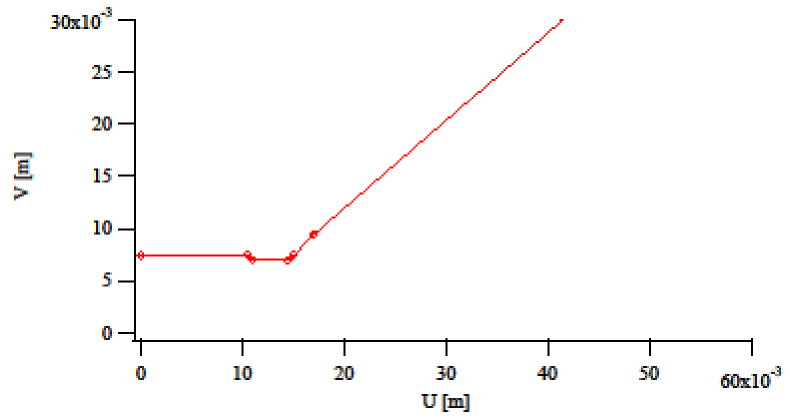
Measurement bench

Pole Shape Optimization

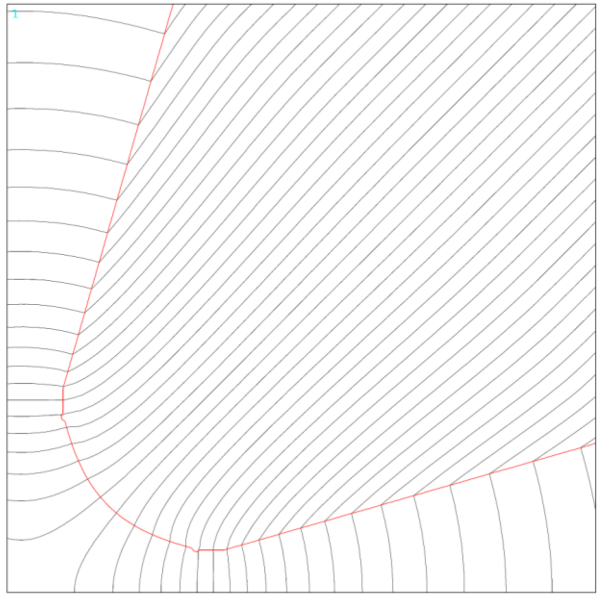


Alternatively,

Add shims in dipole geometry (W plane)
Conformal transform to z plane (real)
Calculate field quality to check the impact of the shims.



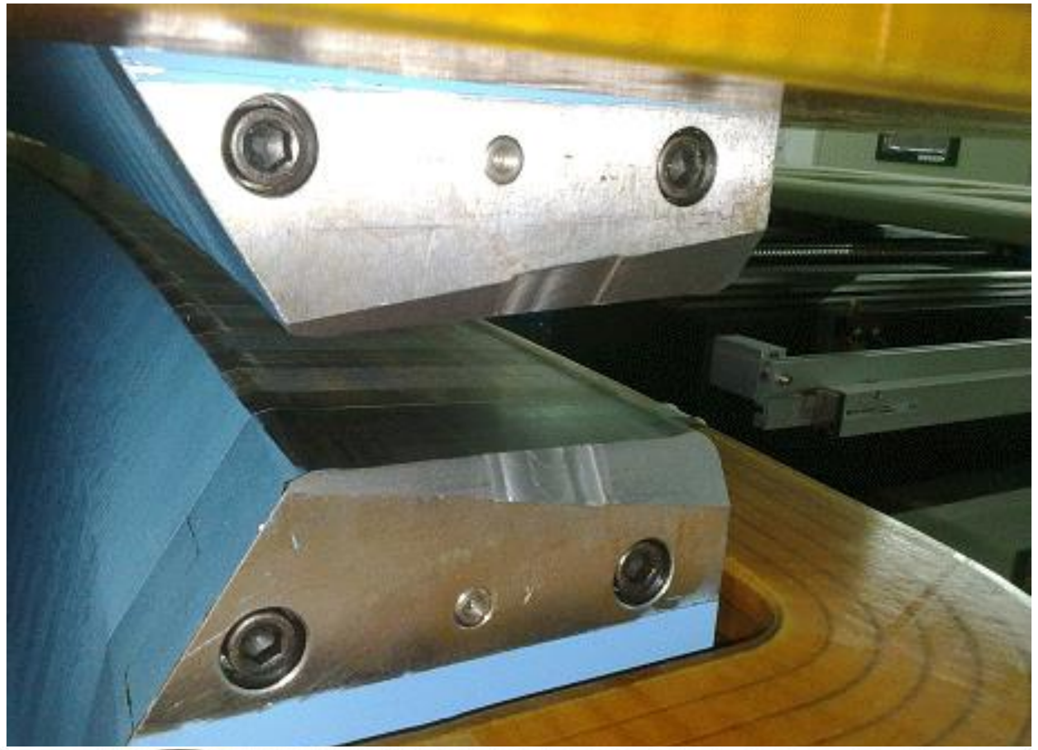
W plane

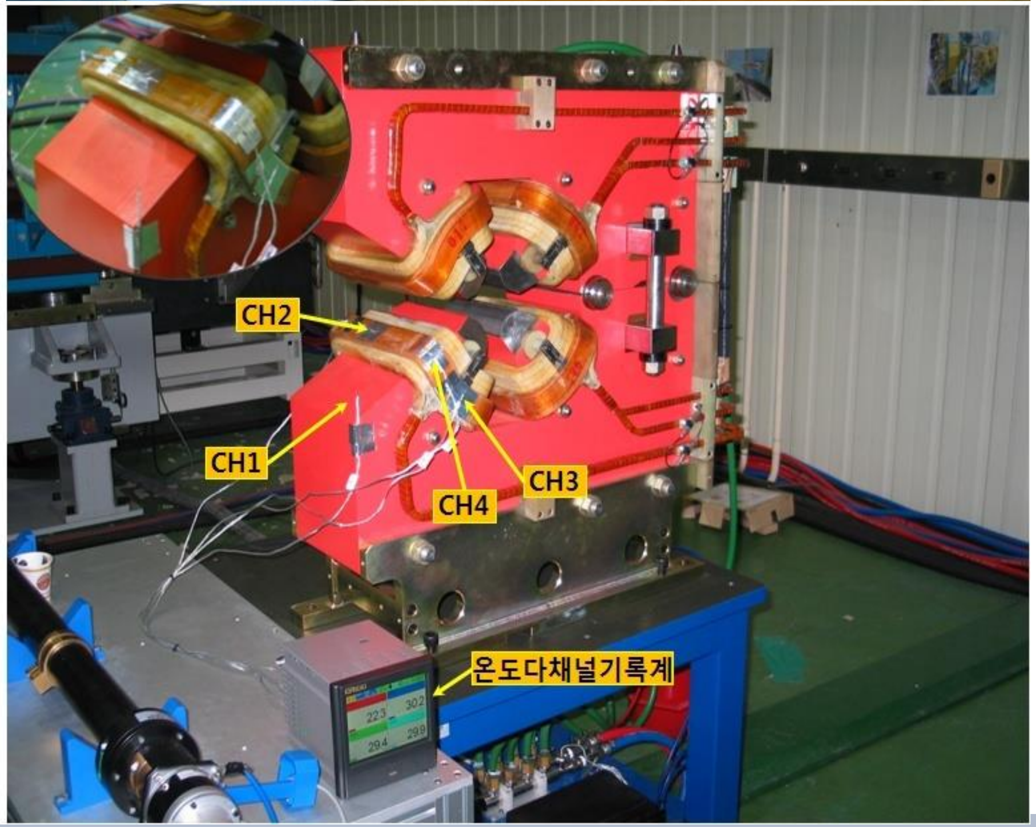


Z plane

Green : Ideal Pole profile for infinite pole width, and infinite m
Blue : Optimization for finite pole width
Ideal profile : xy=r0^2/2
Optimized Pole profile: Tangent at the mid point,
Add flat region to reduce the saturation (remove acute angle)

End Chamfering, Shimming





PLS-II Gradient magnet:
Chamfering : Straight Cut

Shimming : 0.5 mm deep near the central part

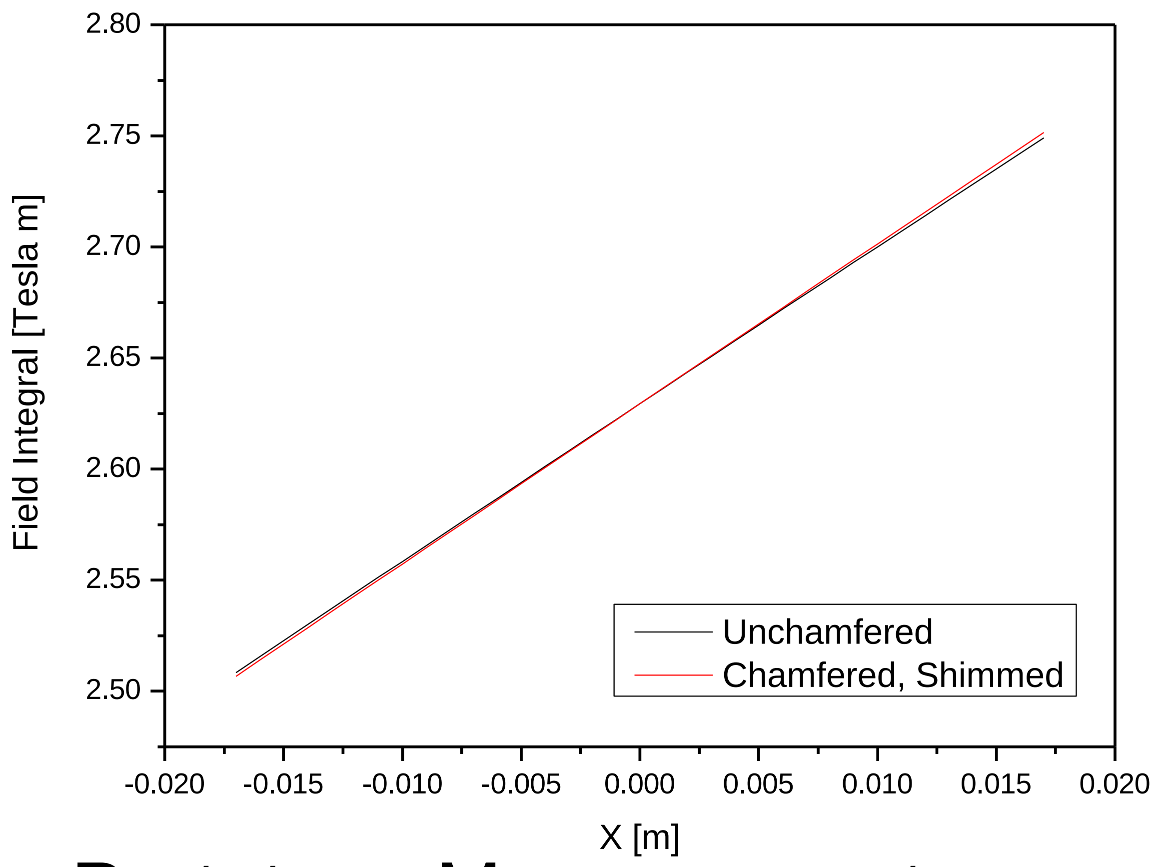
Reduce end saturation, improve multipole errors

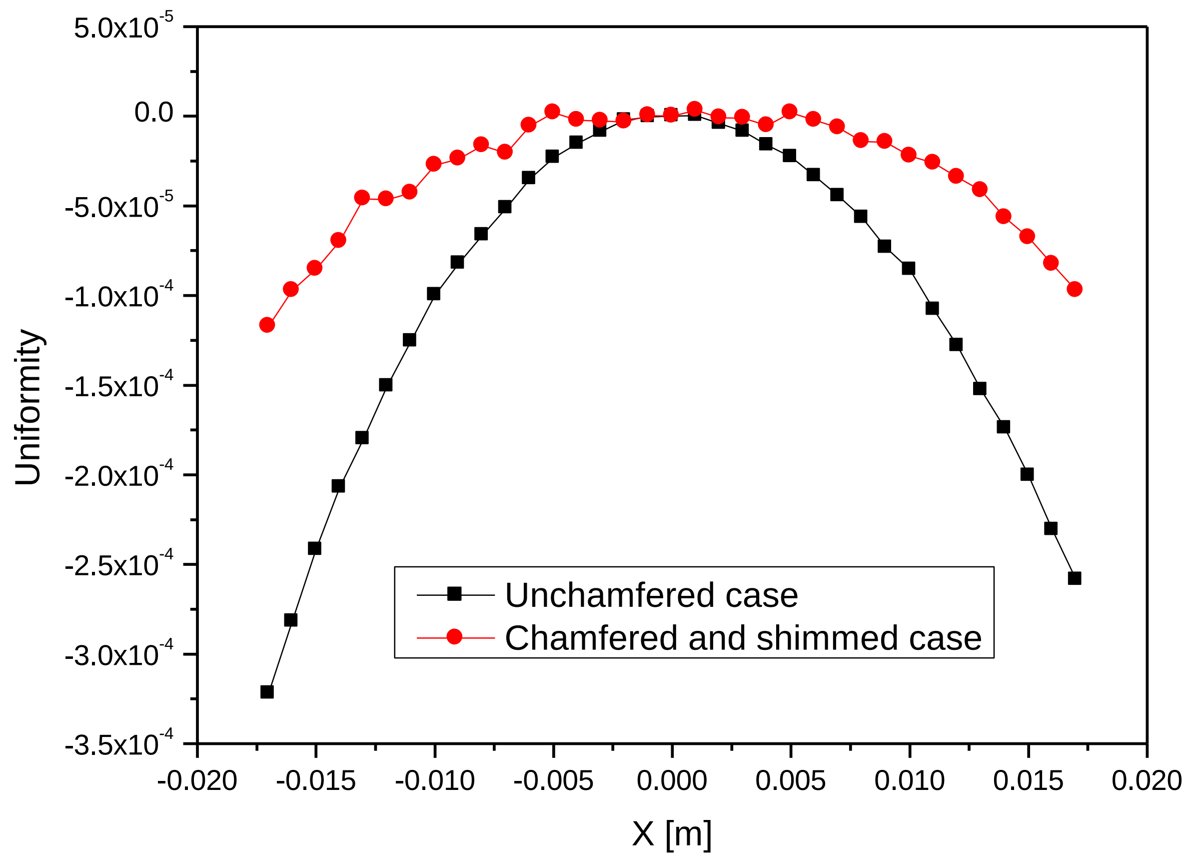
PLS-II Quadrupole
Chamfering : Straight Cut

Reduce end saturation, improve multipole errors

Removable end pole shoe can be used. Several cuts are tested for final decision.

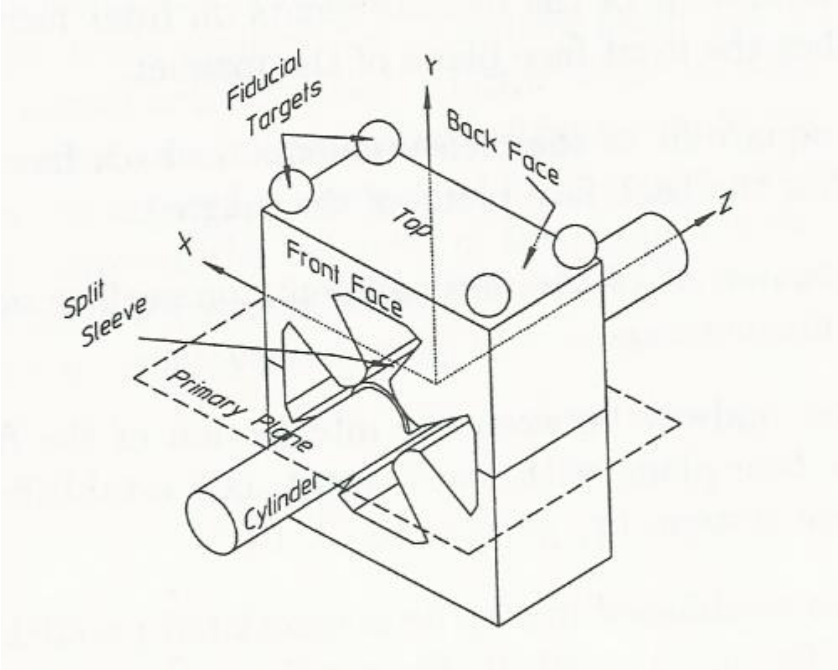
Field integral, Uniformity (Translating coil measurement)





- Prototype Measurement
- Measurement shows good dipole+ quadrupole properties.
- Initial uniformity of 3.2E-4 is improved to 1.2 E-4 after chamfering and shimming meeting the 2.0E-4 requirements.

Fiducialization

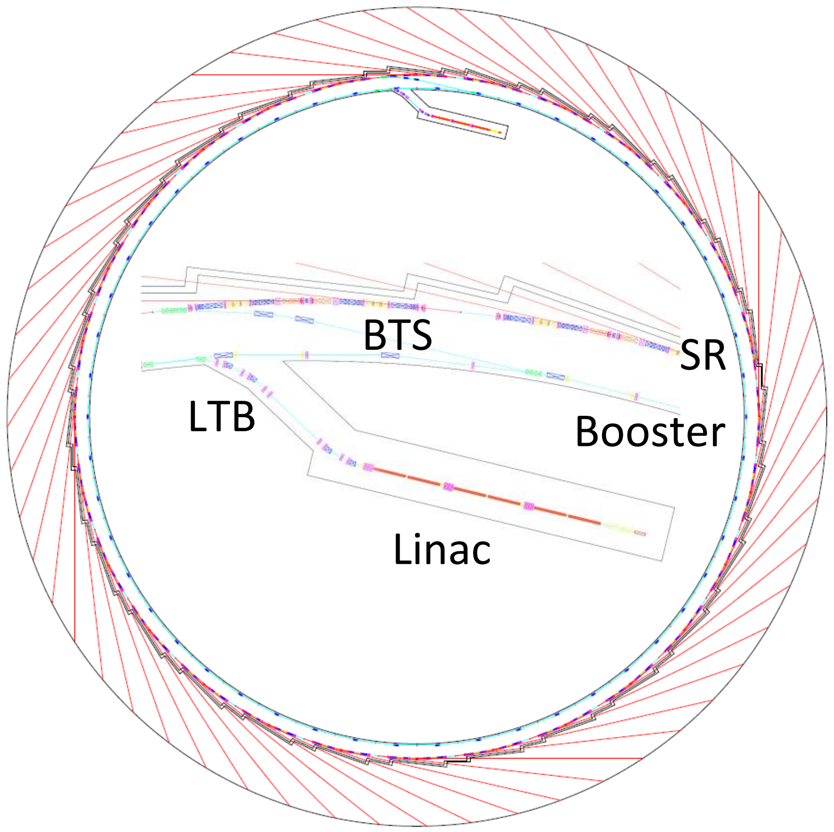


Fiducialization is a procedure acquiring the coordinates of the fiducial targets relative to the magnet center (which is usually in the air!).

- Using the center plane of the front face and the back Face, with the cylinder axis, determine the magnet origin.
- Translate the top face to the origin to define the midplane
- Using this coordinate, measure the coordinates of the center of the target balls.
- 3 balls are enough, but 4 balls are used for redundancy, cross-check, and possible damage, to work around the visibility problem of all the balls.

Introduction

- Korea is trying to develop 4th Generation SR based light source starting construction on 2022.
- It features 4 GeV, 7BA, 800 m circumference, 58 pm emittance, 28 superperiods, full energy booster injection, 2 T center bends for harder X-ray source.
- The project is now on CDR v0 phase, and TDR efforts will continue to 2022. After 2 years of full technical design, the actual construction will start on 2024 lasting 5 years for the completion.
- In this report, 0.5th version of the magnet system designs are summarized.



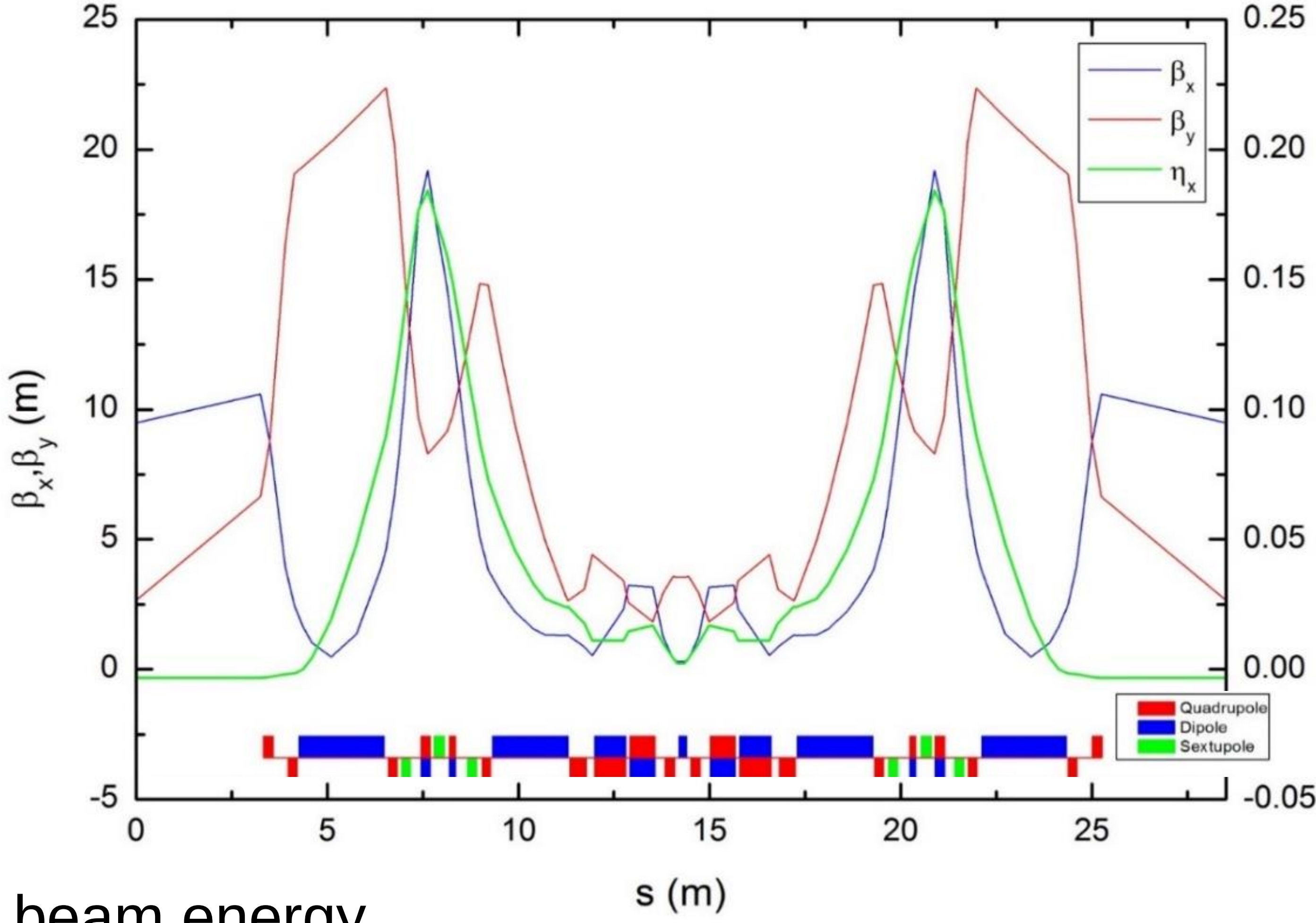
Total # of BL: 52 (60)

4GSR Ring		Value	Unit
Design Parameters	Cell Number	28	-
	Circumference	**798.84**	**[m]**
	Electron Energy	**4**	**[GeV]**
	Natural Emittance	**58**	**[pm rad]**
Tune and Chromaticiy	Horizontal Tune	67.395	-
	Vertical Tune	24.275	-
	Natural Horizontal Chromaticity	-115.344	-
	Natural Vertical Chromaticity	-84.693	-
	Horizontal Chromaticity	3.5	(target)
	Vertical Chromaticity	3.5	(target)
Radiation related quantities	**Energy Loss per Turn**	**1009**	**[keV]**
	Energy Spread	0.1197	[%]
	Horizontal Damping Time	11.075	[ms]
	Vertical Damping Time	21.127	[ms]
	Longitudinal Damping Time	19.342	[ms]
Twiss functions at the ID	Horizontal beta function at the ID center	8.564	[m]
	Vertical beta function at the ID center	2.459	[m]
	Dispersion function at the ID center	1.3	[mm]

Injector: Booster

Lattice design

- ESRF-EBS type
  - Dispersion bump w/sextupoles.
  - Longitudinal gradient dipoles.
  - Phase advance of $\Delta\varphi_x = 3\pi$ and $\Delta\varphi_y = \pi$ between corresponding sextupole.
- APS-U type: Reverse bends in Q4, Q5, and Q8.



1. Achieving 58 pm with 800 m circumference at 4.0 GeV beam energy.
2. Natural evolution of ESRF-EBS, and APS-U.
3. Massive use of combined function magnet for quad focusing and bending using “Offsetted” quadrupole.
4. Application of reverse bend with strong quad focusing (DQ51)
5. 6.5 m straight section and 2 T Center-bend as bending source (ec=21 keV).

Magnet Summary for Booster and SR

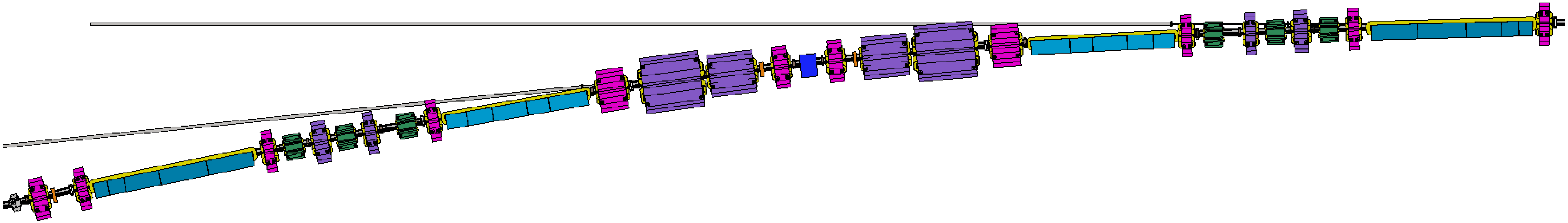
Magnet	Required Number	Remark
Combined Dipole	72	2*36 cell
Quadrupole	72	2*36 cell
Sextupoles	72	2*36 cell
Corr.	?	TBD
Total	216+	Total number of magnets

Booster Magnet Summary

Magnet	Required Number	Remark
Central BM	28	1*28
Long. BM	112	4*28
Reverse Bend	168	2*3*28 (should have B, B')
Quad Bend	56	2*28 (should have B, B')
Quadrupoles	336	6*2*28
Sextupoles	168	6*28 (should have B", H/V Corr, Skew Quad)
Fast Corr.	112	4*28 (H/V combined corrector)
Magnets/Sec	35	31+4 (fast Corr.)
Total	980	Total number of magnets

Booster Magnet Summary

Additional magnets are required for LTB (Linac to Booster), and BTS (Booster to SR) and injection/extraction.



General Design Requirements

- LGBMs mirror symmetric in longitudinal direction with respect to center bend.
- Dipole Quadrupole (DQ) series operational range is 95% to 105% of the nominal value.
- Quadrupole operational range is 75% to 110% of the nominal value.
- Sextupole magnets operational range is 50 to 120% of the nominal value.
- More than 98% magnetic efficiency for sextupole for min cross-talk btw the H/V/SQ coils.
- QD, RB, Quads should have 90% min efficiency.
- Coolant pressure drop is 6bar (or 90 psi) with inlet temperature of 25C.
- Coolant temperature rise is limited to less than 20 K.
- Min H/V apertures are decided based on BD simulation and vacuum requirements.
- Typical Quad aperture radius is 15 mm with good field radius of 11.0 mm except DQ51, DQ32.
- DQ51 ro/rc=15mm/30mm, DQ32 ro/rc=10mm/20mm.
- For Quadrupoles, multipole requirements are < 1.0E-3 at good field radius.
- For Sextupoles ro/rc=12mm/16mm with multipole < 1.0E-3 at good field radius.
- For Dipoles, the uniformity requirement is DB/B < 1.0E-3 for +-13.0 mm.
- Vertical half gap for center bend, LGBM1, LGBM2 are 7.0/13.9/12.2 mm, respectively.
- Fast correctors need about 1.0 mrad kick but detailed requirements are not fixed yet. Therefore it's not treated here

Magnet Summary 2

- In addition to SR magnets, we need 341+ magnets for the booster and LTB (Linac to Booster), BTS (Booster to SR) line.
- Parameters of the magnets are being optimized for BD, and manufacturing aspects. (For example, the field strength, and length of the dipole magnets in the booster).
- Physical parameters (eg, miminum pole gap, required uniformity) are being summarized to start actual design.
- No technical difficulties are expected for these magnets since the magnets are more easily realizable compared to SR magnets.

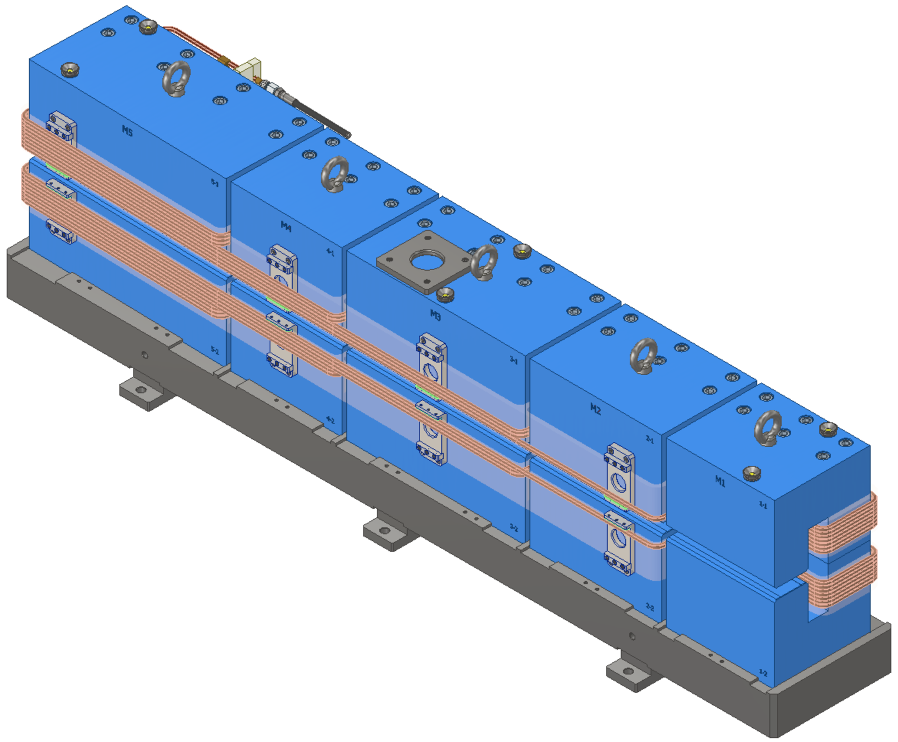
Magnet	Required Number	Remark
Gradient Bend	100	2*50
Quadrupoles	100	2*50
Sextupoles	100	H/V Correctors Combined
Fast Corr.	?	
Total	300+	Total number of magnets

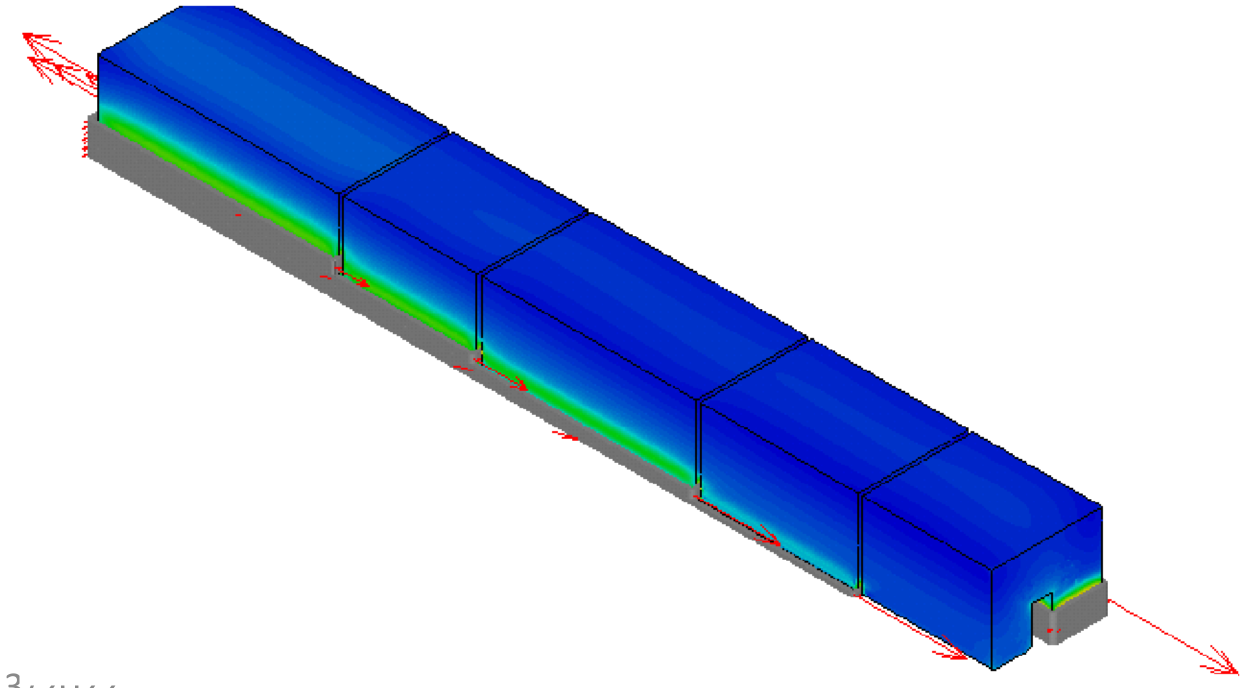
Booster Magnets

	Magnet	Required Number	Remark
LTB Magnets	BM	4	0.5m, 0.35 T
	Septum	1	0.8 m, 0.30 T
	Kicker	1	0.8m, 0.0125 T
	Quad	10	0.2 m, 5.7 T/m
	Correctosr (H/V)	4	0.1 m, 0.01 T
BTS Magnets	BM	2	1.6 m, 0.73 T
	Septum	5	0.6 m, -1.17 T
	Quad	10	0.5 m, 21 T/m
	Correctors (H/V)	4	0.3 m, 0.08 T

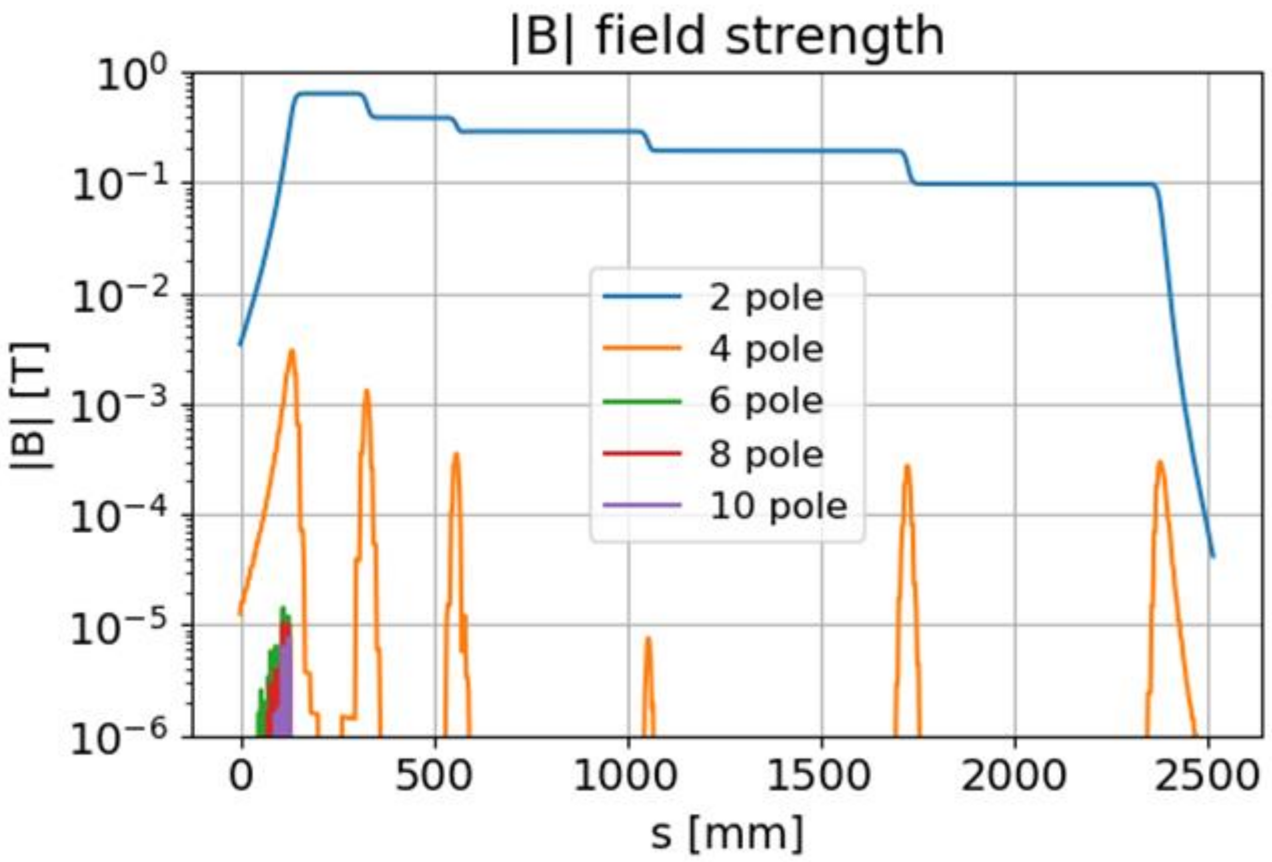
LTB, BTS Magnets (41+ Magnets)

Longitudinal Gradient Dipole (LGBM) : 3D



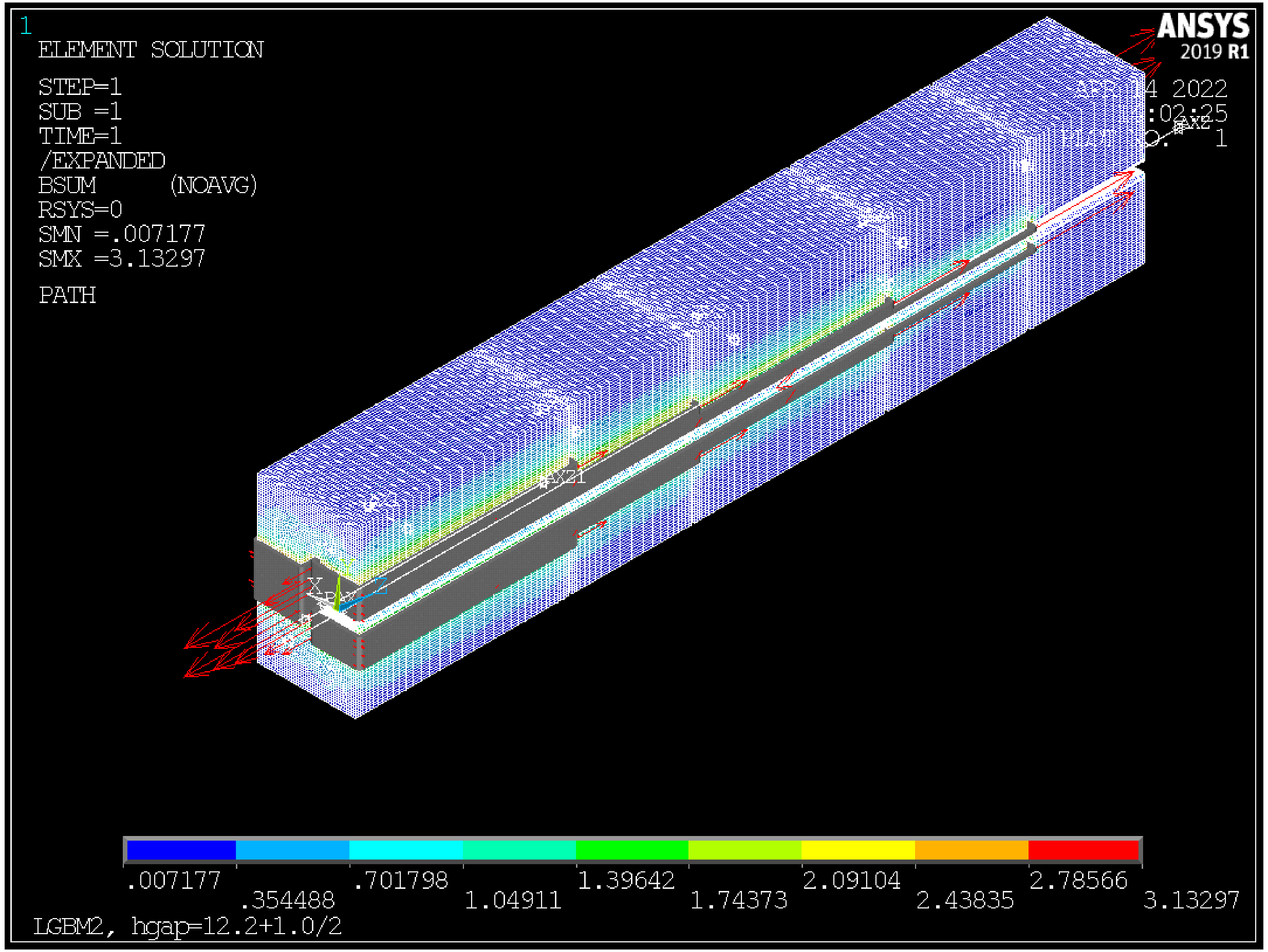


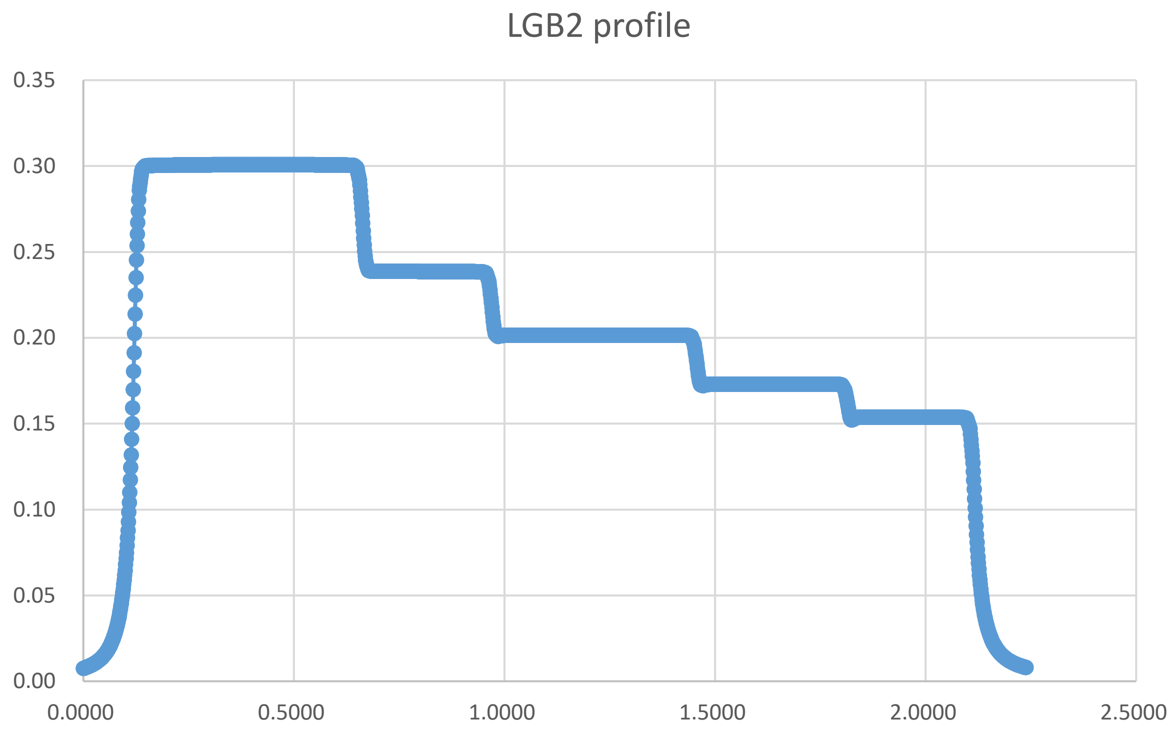
Dipole and higher order multipole along the orbit.



- EM version is selected for construction costs and total cost of operation during the lifetime.
- 3D field map with 1mm step size is calculated, and the multipole along the orbit is calculated.
- Except the quadrupole component which comes from the edge focusing, higher order was negligible.
- To match the design field, reluctance gap at the return yoke is implemented for each magnet section

Example of LGB2 Analysis

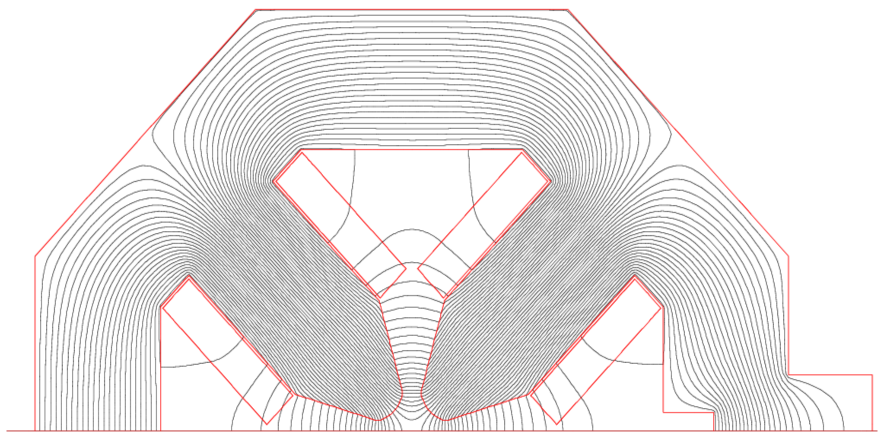




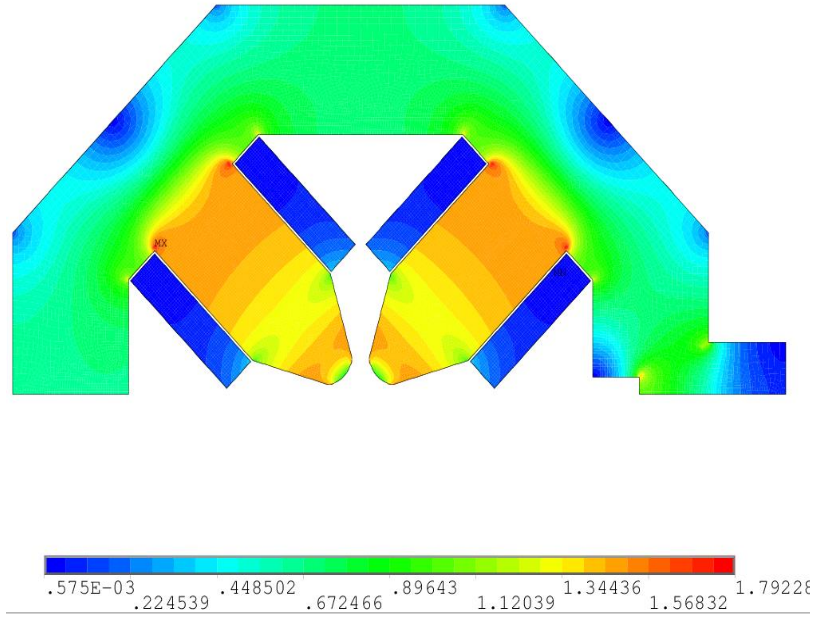
3D FEM model and results (left), and the calculated field profile (above) of LGB2 magnet.

Dipole Quadrupole (DQ), Reverse Bends Quadrupoles

- Dipole Quadrupoles, Reverse Bend Quadrupoles are basically offsetted quadrupoles for design simplicity.
- The offset for dipole component reaches from 20.1 mm to 2.74 mm.
- DQ51 which has the largest offset has an aperture radius of 30 mm, DQ32 has an aperture radius of 20 mm to avoid mechanical interference. The max B'=30 T/m (DQ51), 23 T/m (DQ32) which is achievable without any difficulty using standard low carbon steel with untampered pole.
- Other types DQ52, DQ31 has an aperture radius of 15 mm which is same with regular quadrupoles with Max B'=60 T/m.
- The poles are optimized for min harmonic content and maximum B' with tapering (See next quad page)
- All DQ should have trim windings for dipole component that will be used to keep the dipole component while quad component changes.
- Each type may have a slot for photon extraction depending on the lattice position.
- All DQ use solid core.



Flux distribution

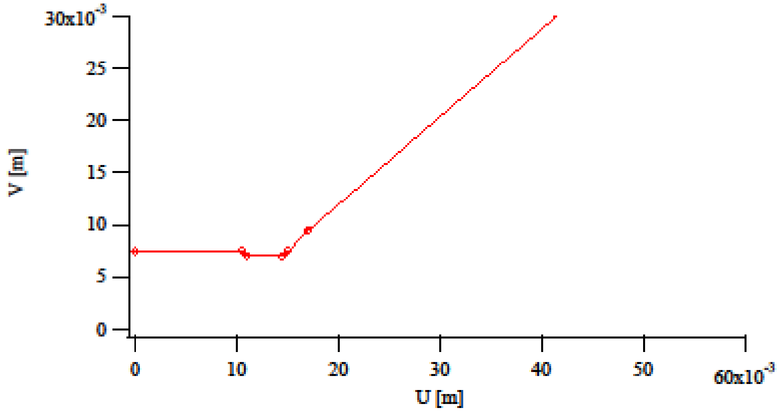


|B| distribution

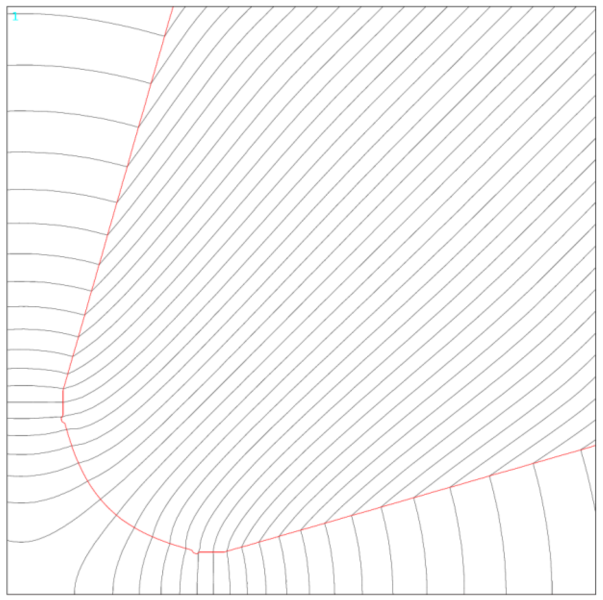
DQ and Quadrupole Magnet

Conformal map

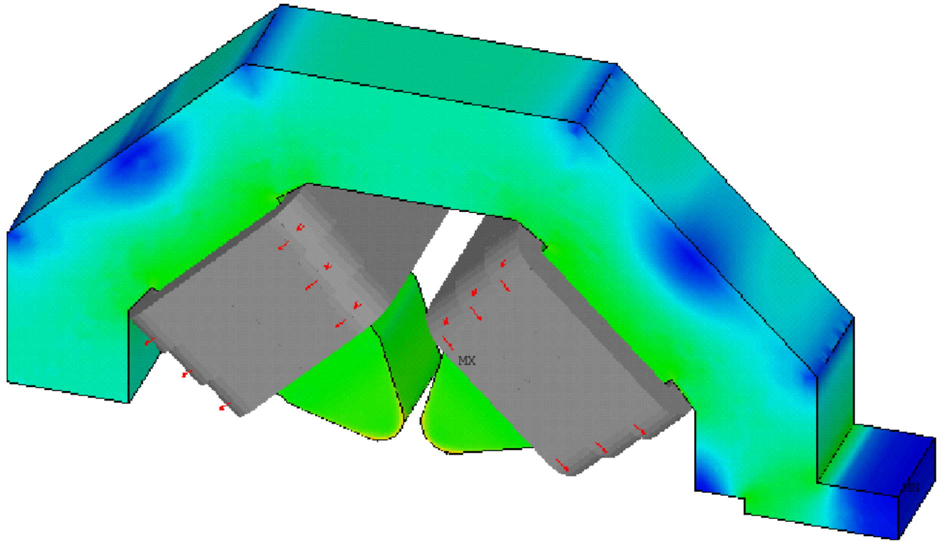
$$w = u + iv = \frac{z^2}{2r_c} = \frac{(x+iy)^2}{2r_c}$$



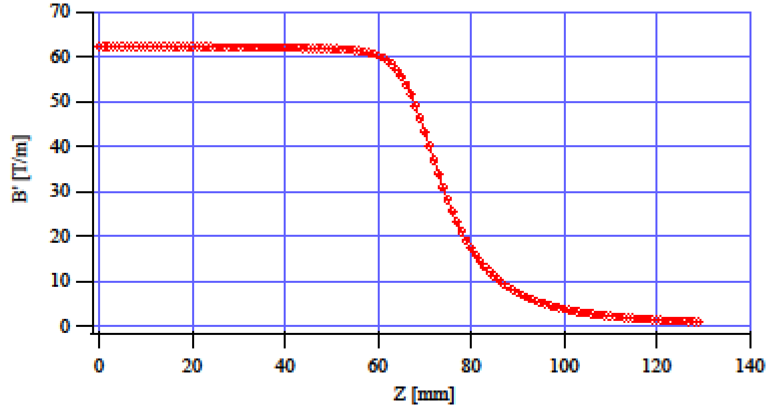
U plane



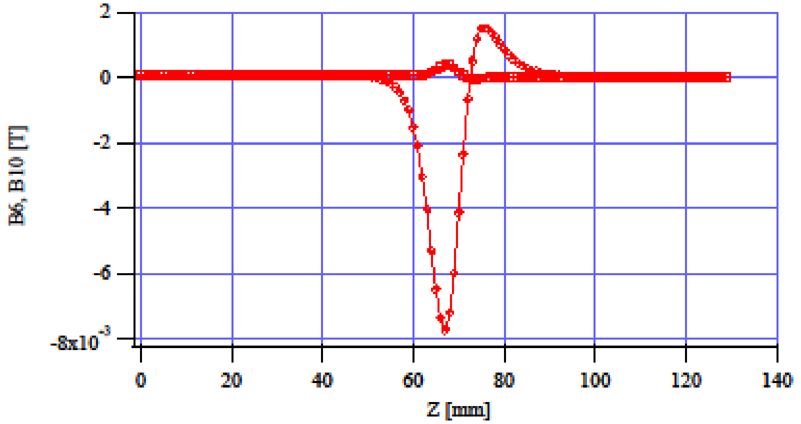
z plane



3D FEM Model



B’ along the magnet



b6, b10 along the magnet

- Quad, and DQ magnets are similar design. Two DQ types have longer effective length and decided to be arc shape. Other quad, DQs have straight shape.
- Apertures are all 15 mm for quad, and 15, 20, 30 mm for DQ magnets.
- Shims are introduced in w plane, and transformed to z plane and the geometry is analyzed in 2D, and 3D with real permeability.
- The fundamental component, and two first allowed harmonics b6, b10 along the magnet is calculated for each 1mm slices which were well within requirements.
- Each quadrupole and DQ types have different photon exit slot size

Major Parameters of (DQ), and Reverse Bends

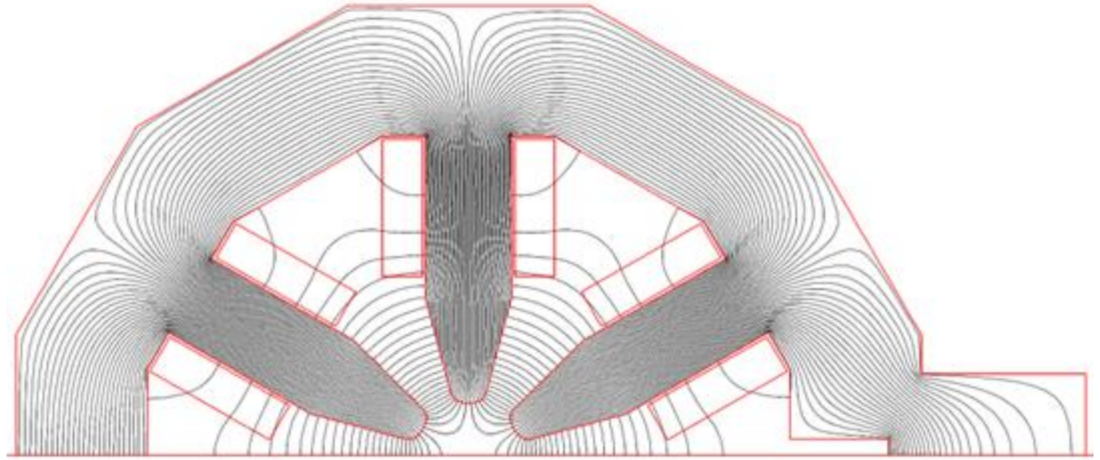
Parameter	DQ32	DQ31	DQ51	DQ52	Units/Remark
B'=	23	60	30	60	
Rc=	20	15	30	15	mm
Req. Number	56	56	56	56	
Leff=	0.145	0.200	0.820	0.626	m
Efficiency=	0.97	0.94	0.97	0.94	
Ampere Turns=	3.78	5.71	11.43	5.71	kA
Conductor=	6.5X6.5-4.0Φ	6.5X6.5-4.0Φ	9.0X9.0-5.0Φ	6.5X6.5-4.0Φ	mm
N/pole=	56	56	56	56	
Current=	67.4	102.0	204.1	102.0	A
Voltage/Mag=	5.08	9.31	26.34	21.91	V
Power/Magnet=	0.17	0.95	5.38	2.24	kW
# Cooling Cha=	2	2	4	4	
Coolant V=	1.53	1.37	1.26	1.24	m/sec
Flow rate=	2.31	2.07	5.94	3.74	Liters/min
DT=	2.1	6.6	13.0	8.6	K
dP=	6.0	6.0	6.0	6.0	Kg/cm^2
Reynolds #=	9300	8400	9600	7600	

Major Parameters Quadrupole Magnets

Parameter	Q12/Q31/Q32	Q11/Q52	Q51	Units/Remark
B’=	60	60	60	
Rc/Ro=	15/10	15/10	15/10	mm Aperture/GFR
Req. Number=	56+56+56	56+56	56	
Leff=	0.145	0.200	0.384	m
Efficiency=	0.94	0.94	0.94	
Ampere Turns=	5.71	5.71	5.71	kA
Conductor=	6.5X6.5-4.0Φ	6.5X6.5-4.0Φ	6.5X6.5-4.0Φ	mm
N/pole=	56	56	56	
Current=	102.0	102.0	204.1	A
Voltage/Mag=	7.70	9.31	14.76	V
Power/Magnet=	0.78	0.95	1.51	kW
# Cooling Cha=	2	2	4	
Coolant v=	1.51	1.40	1.53	m/sec
Flow rate=	2.28	2.11	4.61	Liters/min
DT=	4.9	6.5	4.7	K
dP=	6.0	6.0	6.0	Kg/cm^2
Reynolds #=	9250	8570	9670	

Sextupole Magnets

- Sextupole magnet has a marginal strength (2nd derivative) B"=2212 T/m2 with aperture radius of 16 mm, and effective length 250 mm.
- Pole tip field is about 0.29 T which is well acceptable.
- All sextupoles should have H-corr/V-corr/Skew Quad windings.
- To minimize the interference between the coils, the magnetic efficiency should be kept high (about 98%) which is achievable due to low pole tip field.
- For extraction of photons, there is minimum vertical clearance between the poles at 30 degree and -30 degree. This limits the maximum possible pole width which affects the allowed multipole.
- Sextupole may need very wide photon extraction slot. This will be confirmed soon.
- No 3D simulation yet.
- Lower figure shows 2D flux distribution, and right table shows the key parameters of the sextupole magnet.

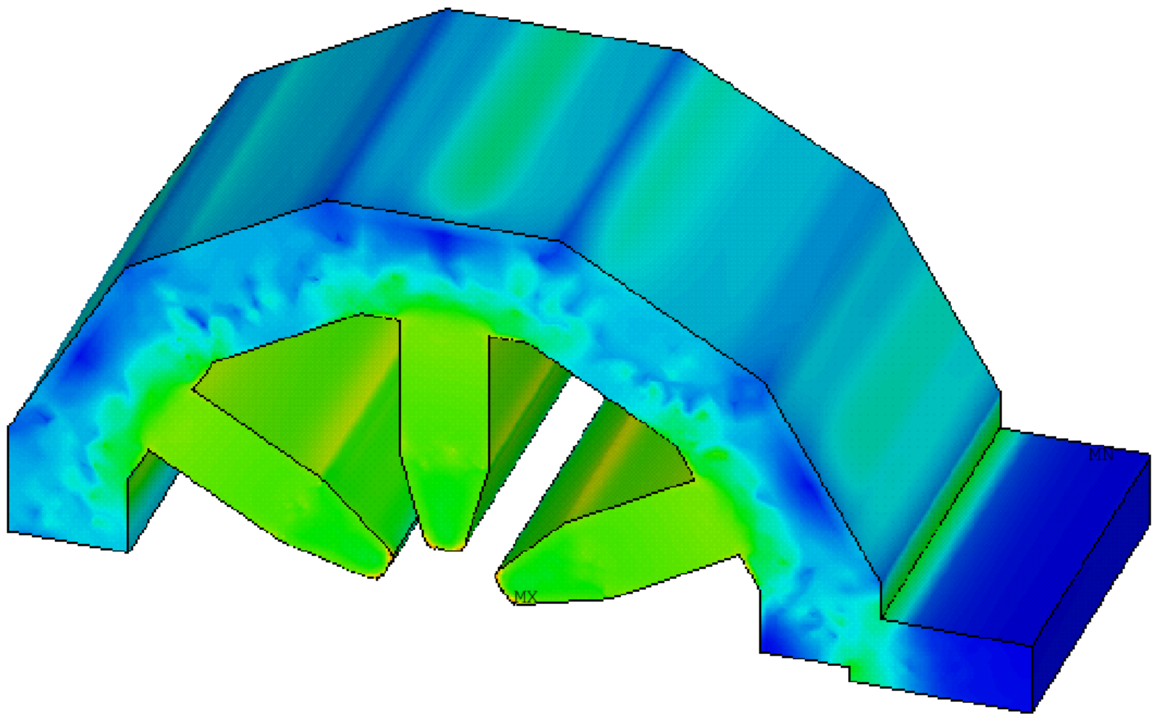


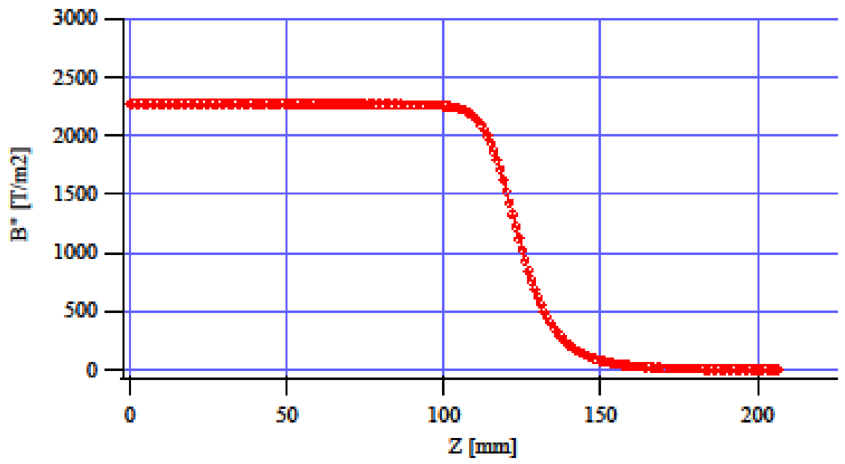
Parameter	S1	Units/Remark
B''_{max}=	2212	
Rc/Ro=	22/12	mm Aperture/GFR
Req. Number=	6*28	
Leff=	0.250	m
Efficiency=	0.94	
Ampere Turns=	1.28	kA
Conductor=	6.5X6.5-3.5Φ	mm
N/pole=	12	
Current=	106.6	A
Voltage/Mag=	3.2	V
Power/Magnet=	0.341	kW
# Cooling Cha=	2	
Coolant v=	2.20	m/sec
Flow rate=	2.54	liters/min
DT=	1.9	K
dP=	6.0	Kg/cm^2
Trim Windings	Yes	H/V/SQ

Sextupole Magnets

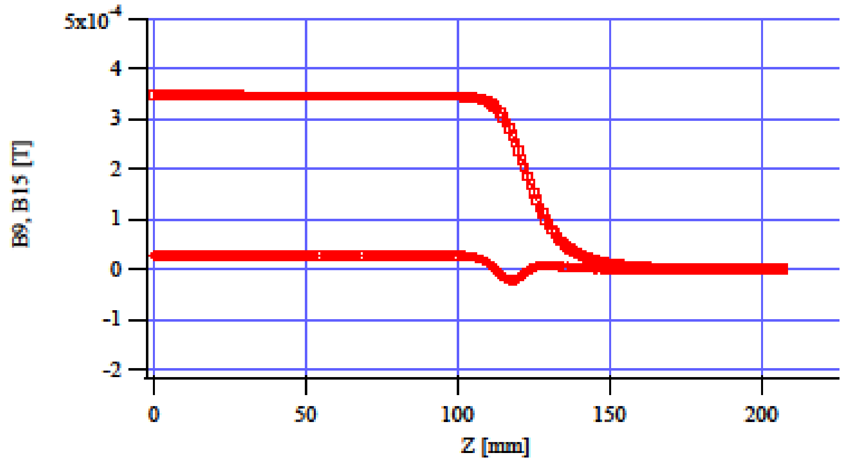
Conformal map

$$w = u + iv = \frac{z^3}{3r_c^2} = \frac{(x+iy)^3}{3r_c^2}$$





B" along the magnet



b9, b15 along the magnet

- Like quadrupole, shims are introduced in w plane, and transformed to z plane and the geometry is analyzed in 2D, and 3D with real permeability.
- Max B"=2212 T/m2, with effective length 250 mm.
- Apertures are all 22 mm to meet the minimum vertical photon slot size requirements.
- The fundamental component, and two first allowed harmonics b9, b15 along the magnet is calculated for each 1mm slices which were well within requirements.
- All sextupoles should have H-corr/V-corr/Skew Quad windings.
- To minimize the interference between the coils, the magnetic efficiency should be kept high (about 98%) which is achievable due to low pole tip field.

4GSR Magnet Status Summary

- Korea is planning a 4 GeV, 4th generation SR based light source.
- SR needs 35*28(cell #)=980 magnets, and 272 booster magnets with additional correctors and LTB, BTS, injection/extraction magnets.
- For LGBMs, staggered coil, and reluctance gap in the return yoke is chosen to reproduce the design field as accurately as possible. 2D and 3D calculations are carried out using RADIA and ANSYS. Reluctance gap is introduced in the return yoke to match the design field. A sensitivity study is going on, and if the emittance is so sensitive on the field profile, the field profile can change without the cumbersome reluctance gap in the return yoke.
- For Dipole Quads (DQ) and Quadrupoles, shims are introduced in the dipole geometry and mapped to real quadrupole geometry for analysis. The most demanding rc=15mm, L=145 mm quad, DQ are fully studied in 3D to assess the fundamental and higher harmonics with acceptable results.
- For sextupoles, the aperture is increased to 22 mm to meet the photon slot neck problem. 3D analysis is done to calculate the longitudinal dependence of the fundamental and higher harmonics.
- Other magnets including center bends, correctors, quad DQs with different parameters are also being carried out.
- Prototyping of LGBM, and one DQ, Quadrupole magnet is planned in this year.
- In summary, 0th order realistic design for Korea 4GSR magnets are carried out.

Summary of the talk

- Introduced the function (or purpose) of magnets in an accelerator.
- Magnet design starts from the "realistic" requirements from Beam Dynamics group like minimum gap, peak field, effective length, good field region, uniformity (or allowed multipole errors).
- Also, high magnetic efficiency with low magnetic saturation is helpful if the magnet needs to have small magnet errors from low excitation to high excitation.
- Also, unsaturated core has advantage of "less" sensitivity to the characteristic of the material.
- Calculation of key parameters should be done, with detailed FEM calculations to define the core, and coil geometry of the magnet.
- The core, and coil should be optimized to meet the requirements with minimum total expected operating costs including the costs of power supply, and the power consumption.
- A few measurement methods are introduced with pros and cons.

- Thank you for your attention!

Thank you!