Normal Conducting FAIR Magnets –
Basics and Examples

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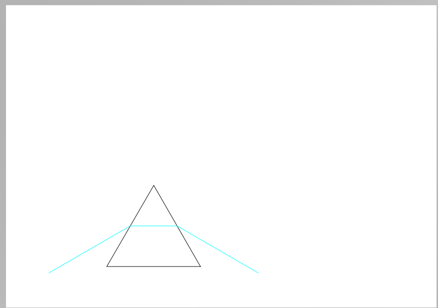
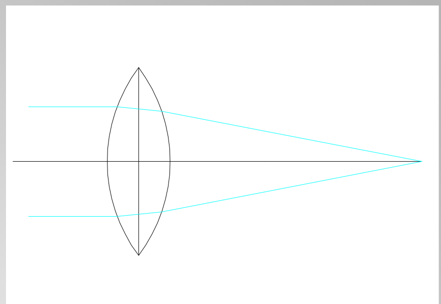
Storage Rings Meeting

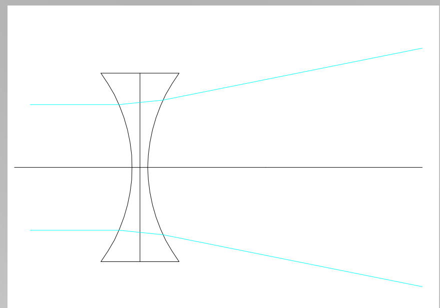
25.06.2015

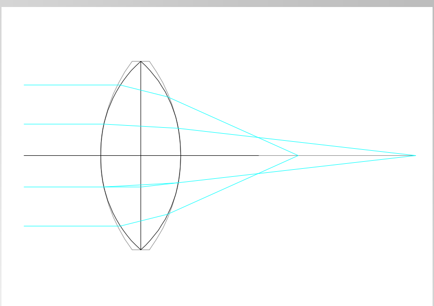
Thank you for beeing here and not looking for an alternative

Why?





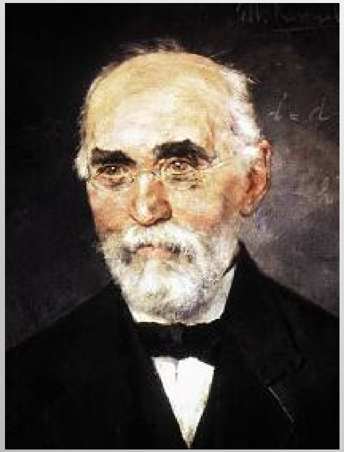




- Dipoles:
  - Bending beams
  - Separation of particles with other magnetic rigidity
  - Spectrometer
- Quadrupoles:
  - focusing and defocusing of beams
- Sextupoles, Octupoles, Steerer, ...:
  - Corrections

Lorentz-equation

Charles Augustin de Coulomb
(1736 – 1806)
Coulomb force
$\mathbf{F} = q\mathbf{E}$



Hendrik Antoon Lorentz
(1853 – 1928)
Lorentz force
$\mathbf{F} = q\mathbf{v} \times \mathbf{B}$

$$\mathbf{F} = q\mathbf{E} + q\mathbf{v} \times \mathbf{B}$$

with v = c/2, E must be $1.5 \cdot 10^6$ V/cm to get same effect as 1 Tesla

Accelerator magnets

Current dominated

cos nθ

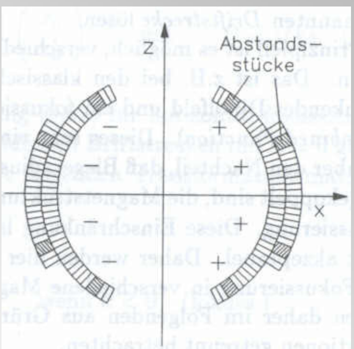
overlapping ellipses

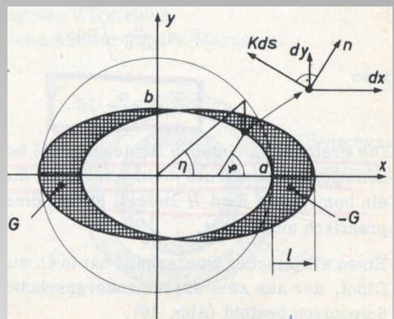
Iron dominated

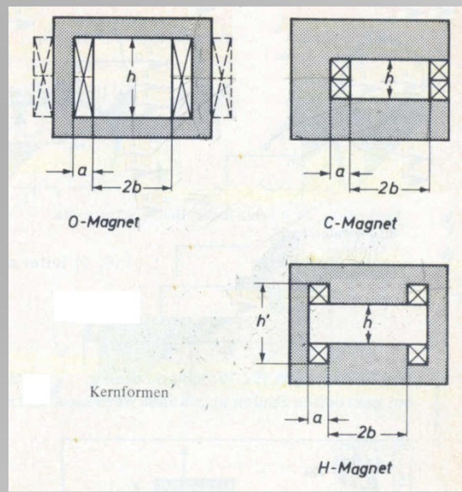
H-magnet

C-magnet

Window frame





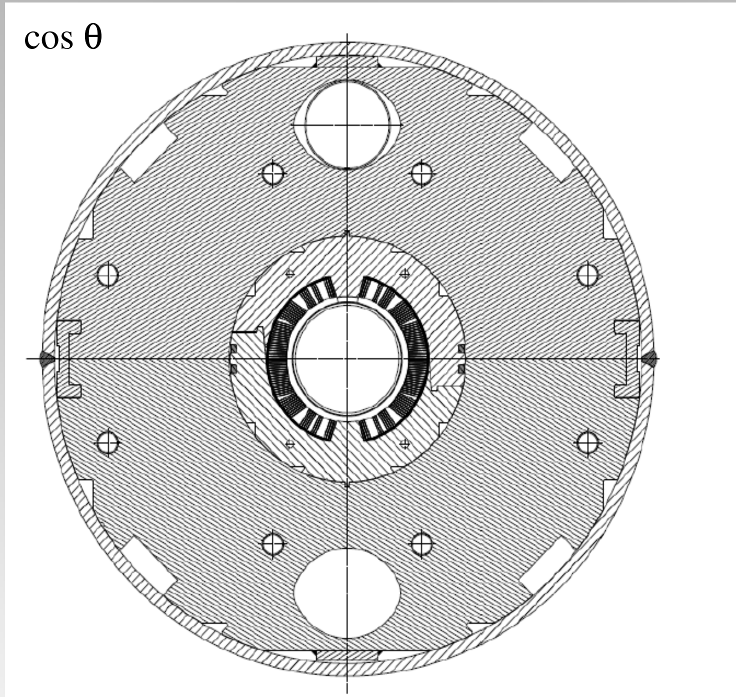


Biot and Savart‘s law

$$\mathrm{d}\boldsymbol{B}(\boldsymbol{r}) = \frac{\mu_0}{4\pi} I \,\mathrm{d}\boldsymbol{l} \times \frac{\boldsymbol{r} - \boldsymbol{r}'}{|\boldsymbol{r} - \boldsymbol{r}'|^3}$$

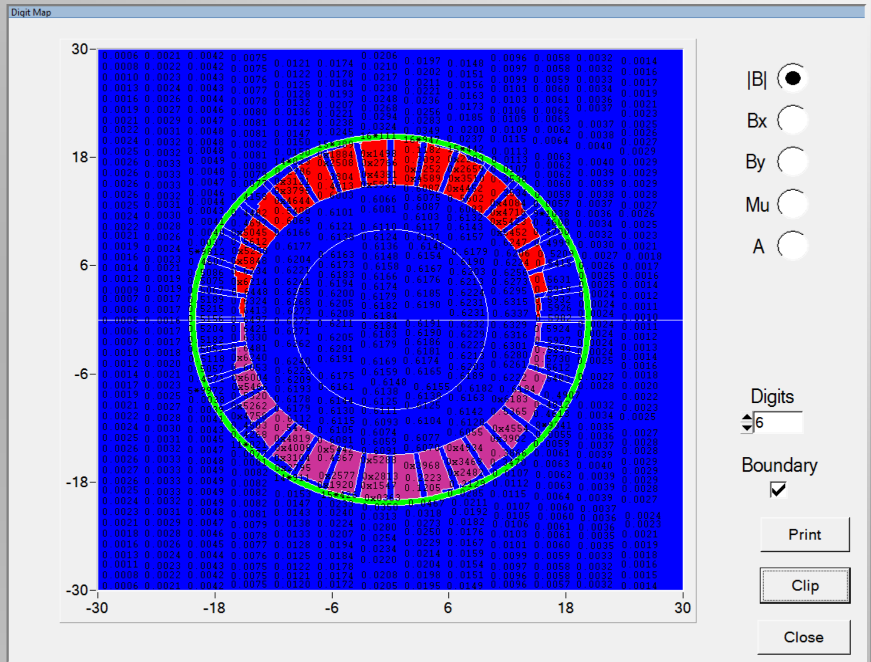
Examples of current dominated magnets

Full size curved short SIS 300 dipole prototype (superconducting)



aperture radius	43 mm
cold mass outer radius	250 mm
current density	460 A/mm²
peak field on coil	4.9 T

Steering magnet for CR (vertical, BINP 2015)



aperture radius	100 mm
outer radius	~200 mm
current density	1.4 A/mm²
dipole field	0.06 T

Pros and conts

Current dominated

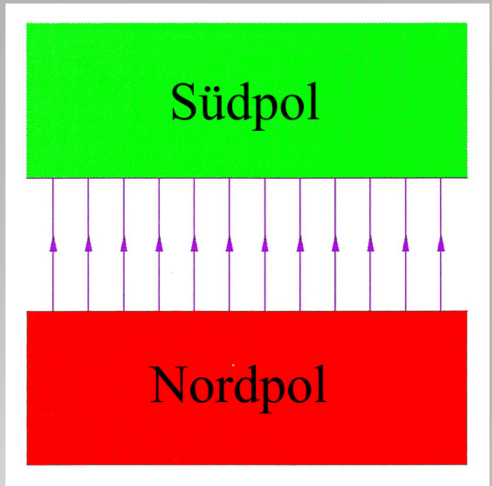
- No/low saturation effects
- High flux densities possible with no/low change of field quality
- Easy combination of independend multipoles

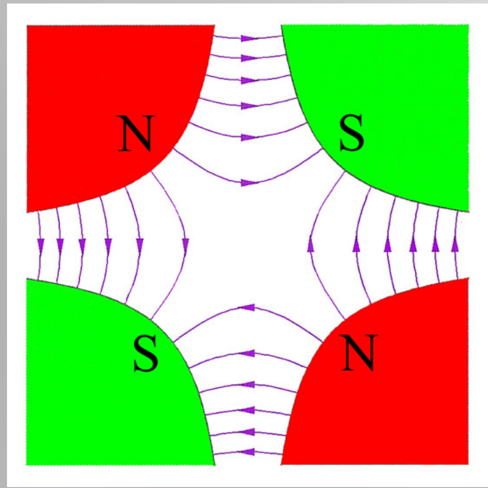
- More ampere turns required for same field level => higher power consumption
- Field quality depends strongly on position of conductors
- Complex coil winding

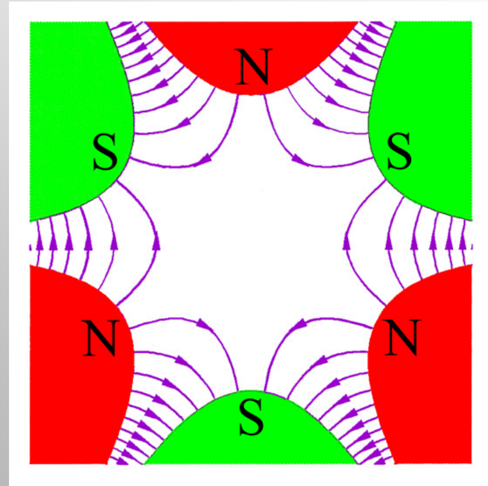
Iron dominated

- Saturation effects above 1.6 Tesla in iron
- Hard to reached good field quality within a wide range of field level
- Complicated to include independend multipoles inside dipoles or quadrupoles
- Less ampere turns required for same field level => lower power consumption
- Field is mainly shaped by iron => better control on the relevant parts for the fiel quality during production

Flux lines of iron dominated magnets







Dipole
B = const.

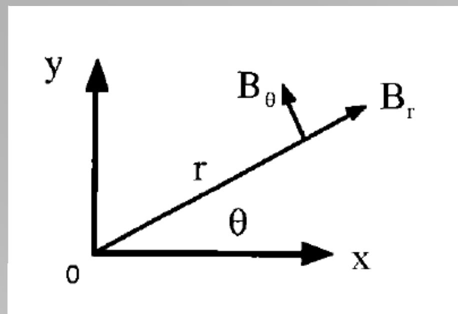
Quadrupole
$B = g \cdot r = B' \cdot r$

Sextupole
Sextupol: $B = B'' \cdot r^2/2$
Octupol: $B = B''' \cdot r^3/6$

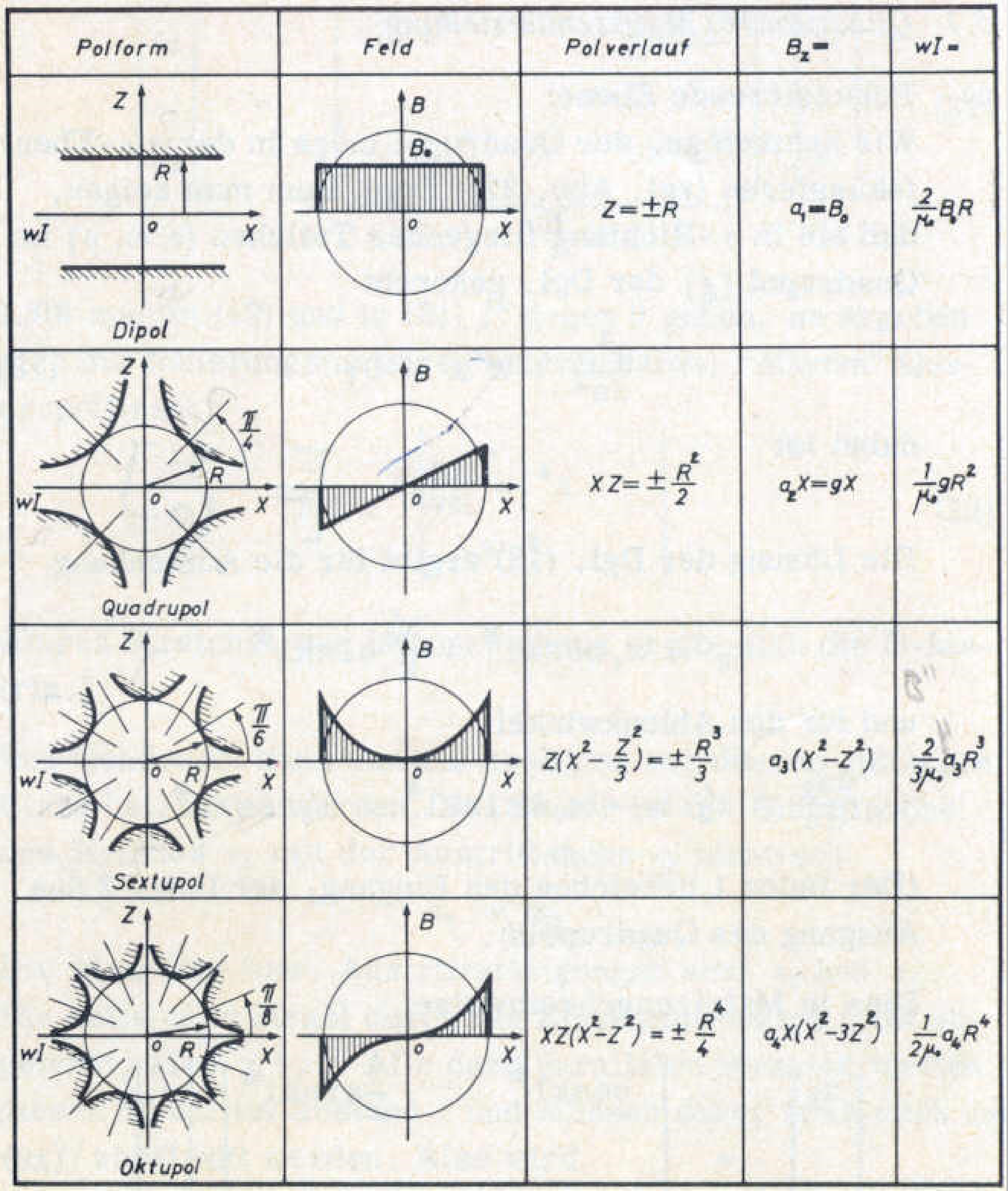
$$B_r = -\sum_n \left(A_n r^{n-1} \cos n\theta + B_n r^{n-1} \sin n\theta \right)$$

$$B_\theta = -\sum_n \left(-A_n r^{n-1} \sin n\theta + B_n r^{n-1} \cos n\theta \right)$$

Dipole: n = 1, Quadrupol: n=2, ...



Multipole

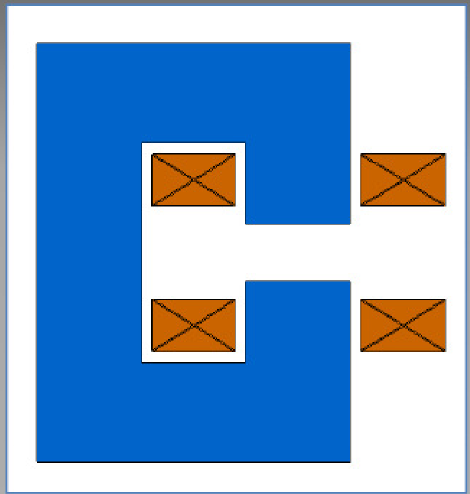


Polform	Feld	Polverlauf	$B_z =$	$wI =$
Dipol		$Z = \pm R$	$a_1 = B_0$	$\frac{2}{\mu_0} B_0 R$
Quadrupol		$XZ = \pm \frac{R^2}{2}$	$a_2 X = gX$	$\frac{1}{\mu_0} g R^2$
Sextupol		$Z(X^2 - \frac{Z^2}{3}) = \pm \frac{R^3}{3}$	$a_3(X^2 - Z^2)$	$\frac{2}{3\mu_0} a_3 R^3$
Oktupol		$XZ(X^2 - Z^2) = \pm \frac{R^4}{4}$	$a_4 X(X^2 - 3Z^2)$	$\frac{1}{2\mu_0} a_4 R^4$

But size of magnets are not infinite

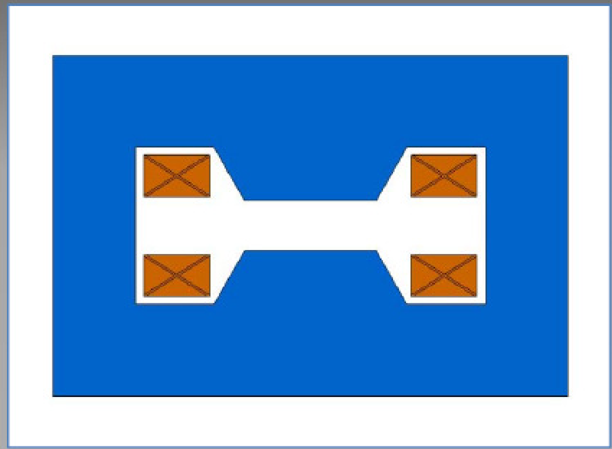
Dipole types

C-Shape



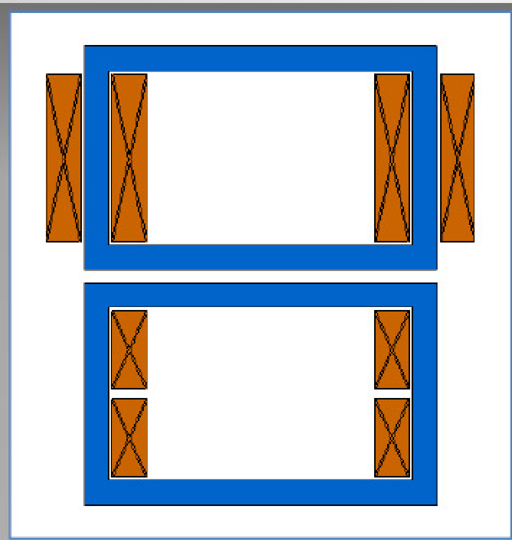
Accessibility: very good
Shims required: yes
Mechanical stability: poor
Iron weight: high
coil shape: race track

H-Shape



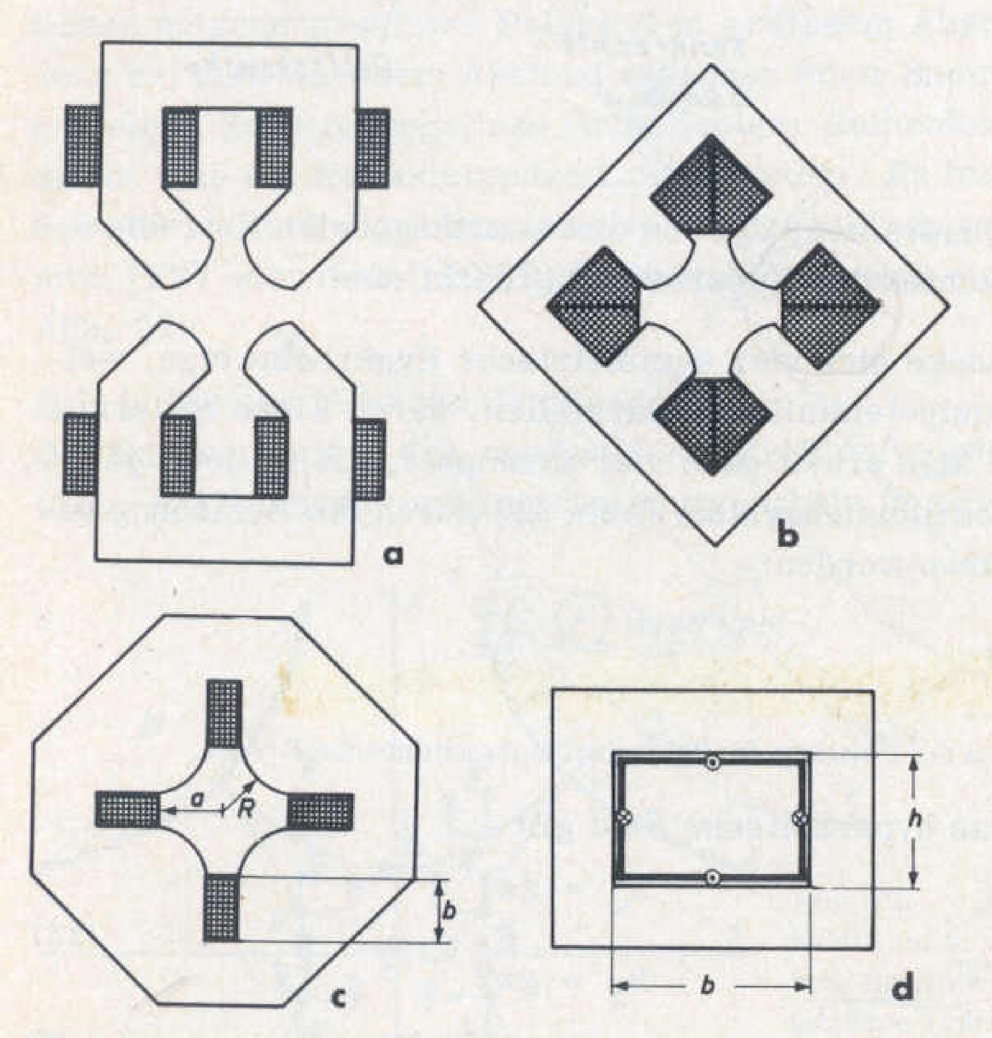
Accessibility: poor
Shims required: yes
Mechanical stability: good
Iron weight: medium
coil shape: race track

window frame



Accessibility: very poor
Shims required: no
Mechanical stability: good
Iron weight: low
coil shape: bedstead

Quadrupol Typs



- a) **Collins quadrupole (≈„Figure of 8“-quadrupole)**
- b) **1. Standard quadrupole (no widening of pole basis)**
- c) **2. Standard quadrupol (maximum widening of pole basis => reducing of saturation in pole)**
- d) **Panofsky quadrupole**

Quadrupol doublet

- Quadrupoles focus in one direction but defocus in the other direction
- Solution: Two quadrupoles (doublet) focus in both directions

The focal length for a combined system is given by:

$$\frac{1}{f_{\mathrm{ges}}} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 \cdot f_2}$$

Combination of focusing and defocusing quadrupole with same focal length *f* und –*f*:

$$\frac{1}{f_{\mathrm{ges}}} = +\frac{d}{f^2}$$

(distance between two lenses: *d*)

Exotic Magnets

Solenoid
- Simple coil
- Magnetic field along beam direction
- Focusing in both direction due to fringe effects

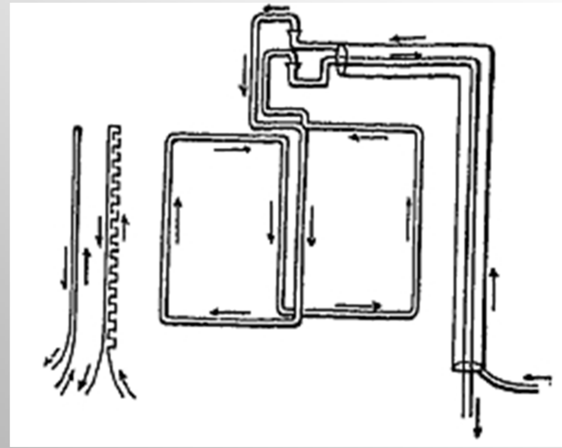
Septum
- Dipole magnets with small blade between injected / extracted beam and circulating beam
- Blade: coil and shield
- as low as possible influence on circulating beam

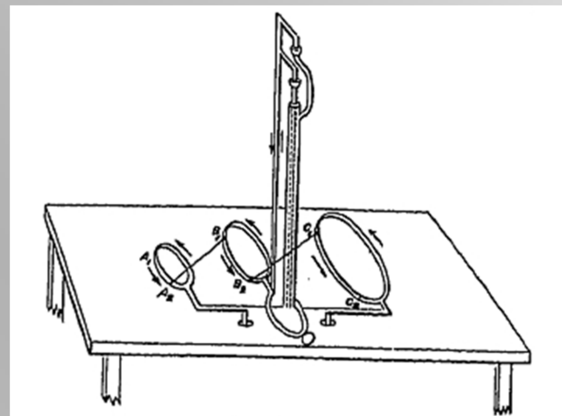
Einschub zur Bestimmung des notwendigen Erregungsstromes

Ampere‘s circuital law:

André-Marie Ampère
(1775 – 1936)

Maxwell‘s experimental setup to illustrate Ampère‘s law





$$\oint_{\partial A} \mathbf{H} \cdot d\mathbf{s} = \int_A \mathbf{j} \cdot d\mathbf{A} + \frac{d}{dt} \int_A \mathbf{D} \cdot d\mathbf{A}$$

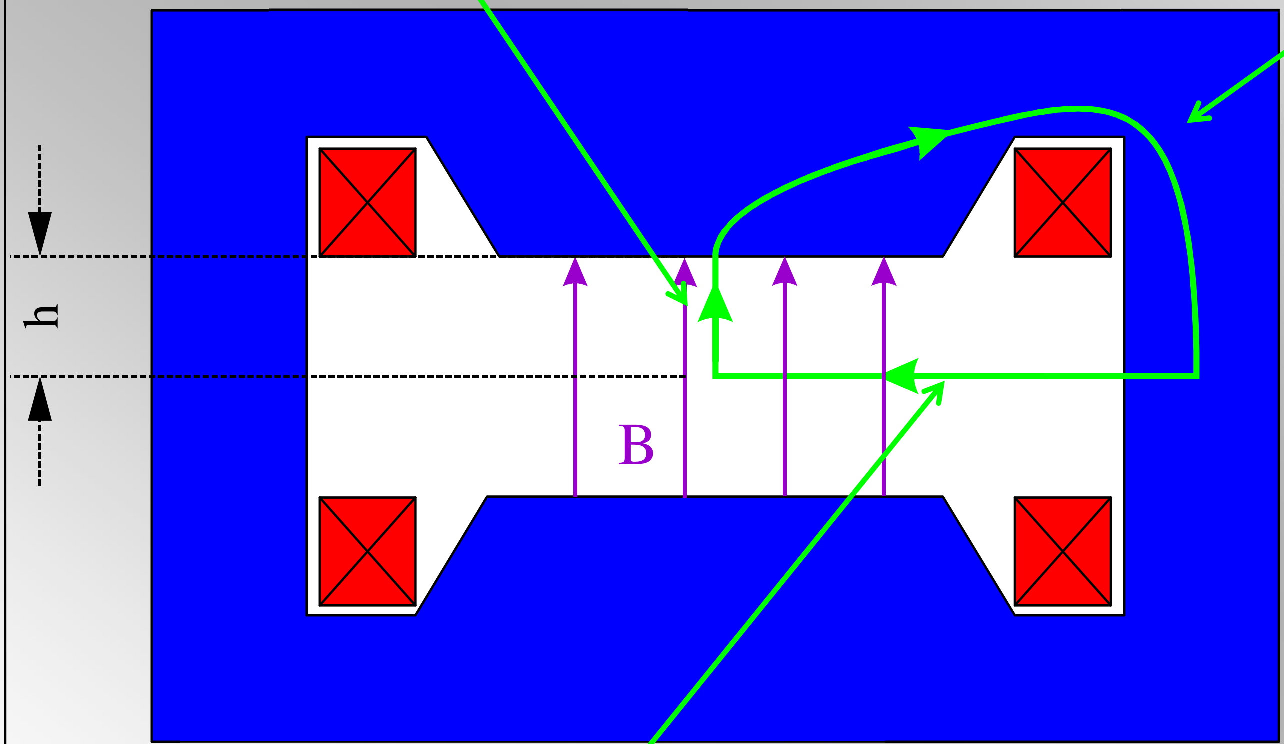
the line integral of the magnetic field H around a closed curve ∂A equals the current *I* through the surface *A*

Estimation of ampere turns with Ampere‘s circuital law (H = B/μ)

$$\int \frac{\vec{B}}{\mu\mu_0} \cdot d\vec{l} = \frac{Bh}{\mu\mu_0}$$

ist klein, da μ groß

$$\int \frac{\vec{B}}{\mu\mu_0} \cdot d\vec{l} = \frac{Bh}{\mu_0}$$



$$\int \frac{\vec{B}}{\mu\mu_0} \cdot d\vec{l} = 0, \quad \text{weil } \vec{B} \perp \vec{l}$$

Ampère‘s law:

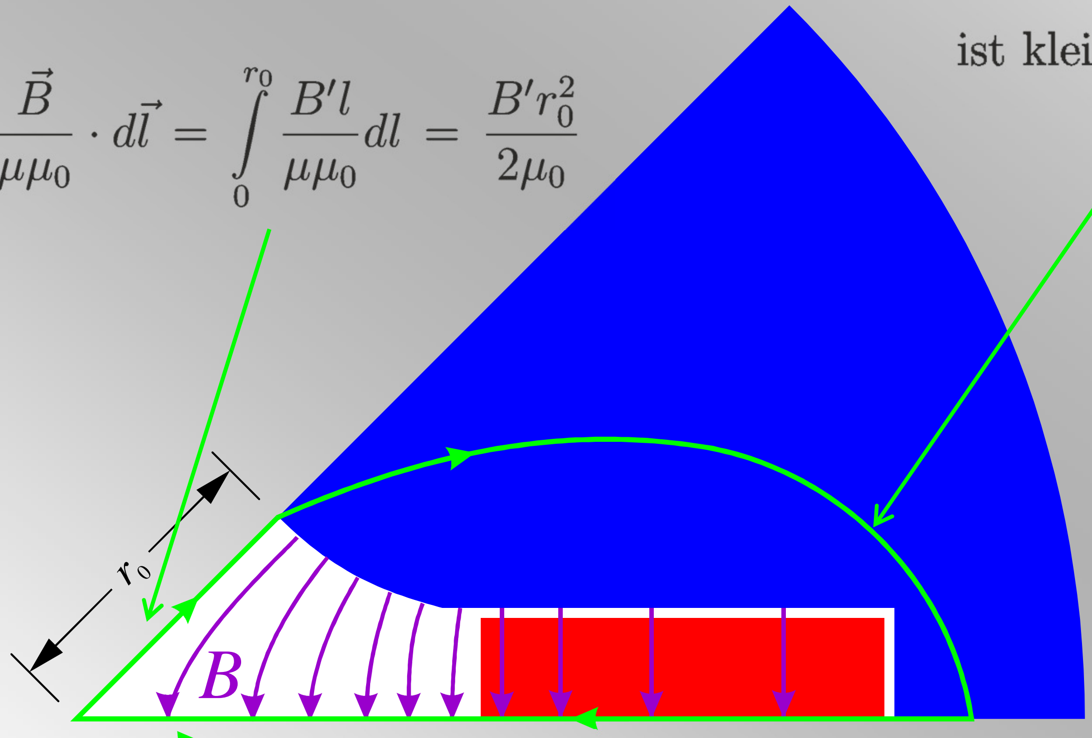
$$NI \approx \frac{Bh}{\mu_0}$$

Estimation of ampere turns with Ampere's circuital law (H = B/μ)

$$\int \frac{\vec{B}}{\mu\mu_0} \cdot d\vec{l} = \frac{Bh}{\mu\mu_0}$$

ist klein, da μ groß

$$\int \frac{\vec{B}}{\mu\mu_0} \cdot d\vec{l} = \int_0^{r_0} \frac{B'l}{\mu\mu_0} dl = \frac{B' r_0^2}{2\mu_0}$$



$$\int \frac{\vec{B}}{\mu\mu_0} \cdot d\vec{l} = 0, \quad \text{weil } \vec{B} \perp \vec{l}$$

Ampère's law:

$$NI \approx \frac{B' r_0^2}{2\mu_0}$$

Analog für Sextupol:

$$NI \approx \frac{B'' r_0^3}{6\mu_0}$$

Leitermaterialien

	Aluminium (rein, > 99.5%)	**Kupfer** (OFHC- Oxygen free high conductivity)
Preis (01/2003)	2,70 – 3,0 EUR/kg	8 – 16 EUR/kg
Leitfähigkeit	36 S m/mm^2	58 S m/mm^2
Dichte	2,70 g/cm^3	8,96 g/cm^3
Linearer Ausdeh-nungskoeffizient	$23 \cdot 10^{-6}$ K^{-1}	$17 \cdot 10^{-6}$ K^{-1}
Elastizitätsmodul	72.000 N/mm^2	123.000 N/mm^2
Keystoning-Effekt	Geringer	Höher
Oxydation	An Luft, löst sich elektrochemisch in gemischten Kühlkreisläufen mit Kupferspulen	Gering
Schlussfolgerungen (auf der Basis eines identischen $N \cdot I$)	◆ Größer ◆ Leichter ◆ Größere Transparenz f. Teilchen ◆ Geringere Investitionskosten ◆ Höhere Betriebskosten ⇒ Eher für Detektormagnete	◆ Kleiner ◆ Schwerer ◆ Verringerte Transparenz f. Teilchen ◆ Höhere Investitionskosten ◆ Geringere Betriebskosten ⇒ Eher für Beschleunigermagnete

Cooling of coils

Cooling

Air

Water

natural convection

forced air flow

direct

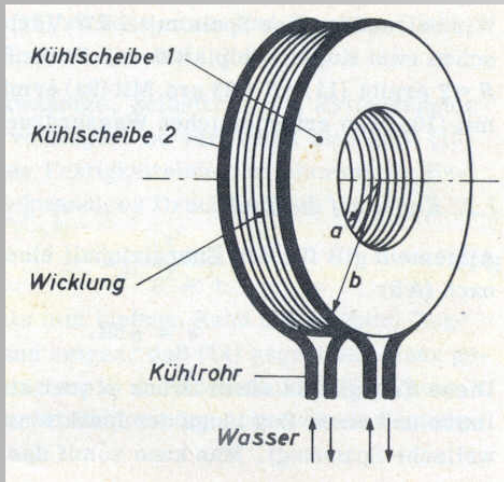
indirect

no measures

cooling fan

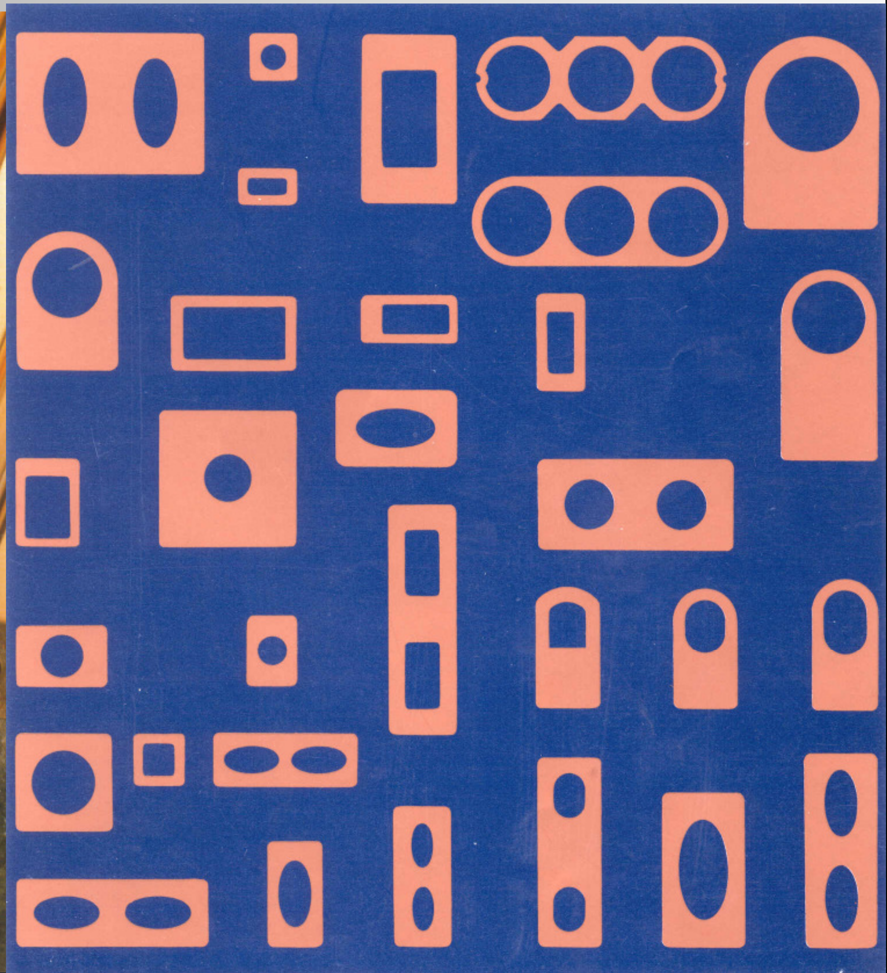
conductor with cooling channel

current density < 2 A/mm^2

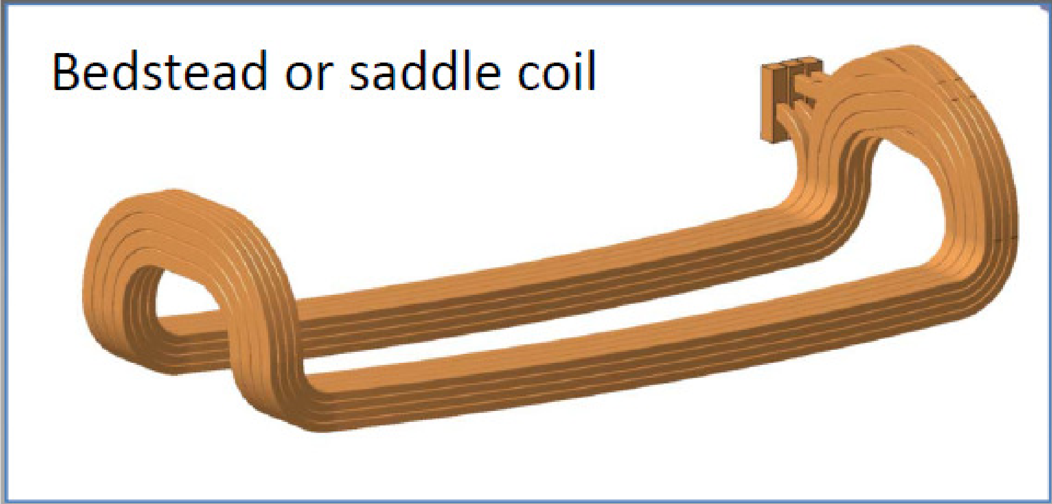


current density < 10 A/mm^2
our standard: 5 A/mm^2

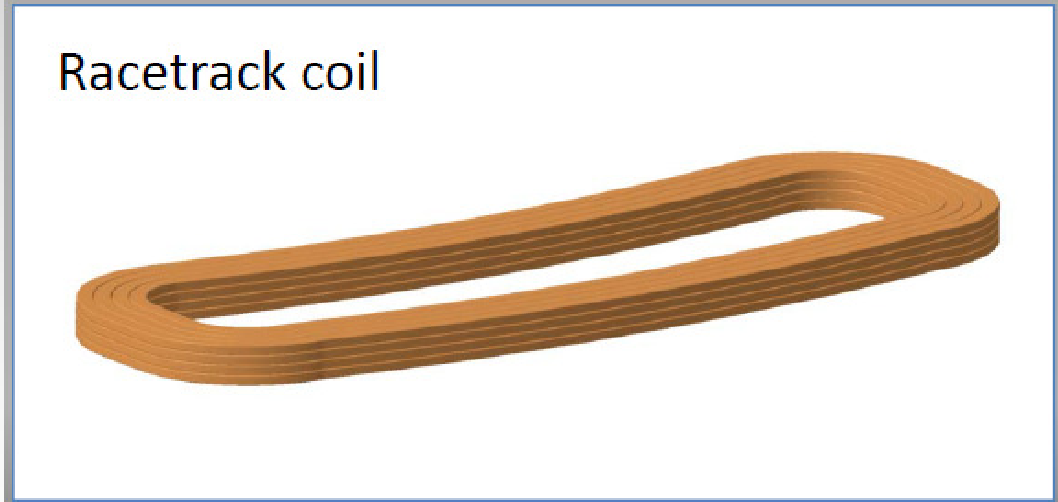
Cross section of copper conductor



Coil shapes

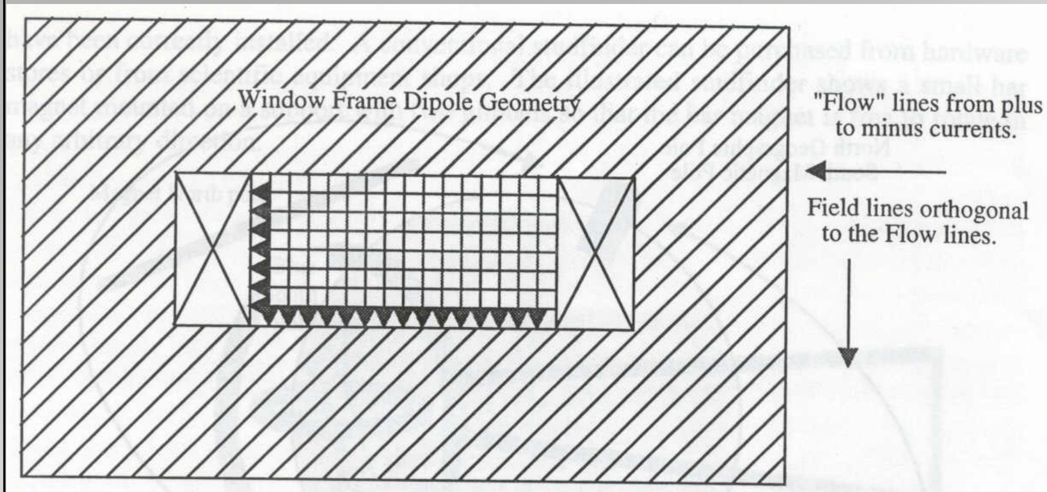


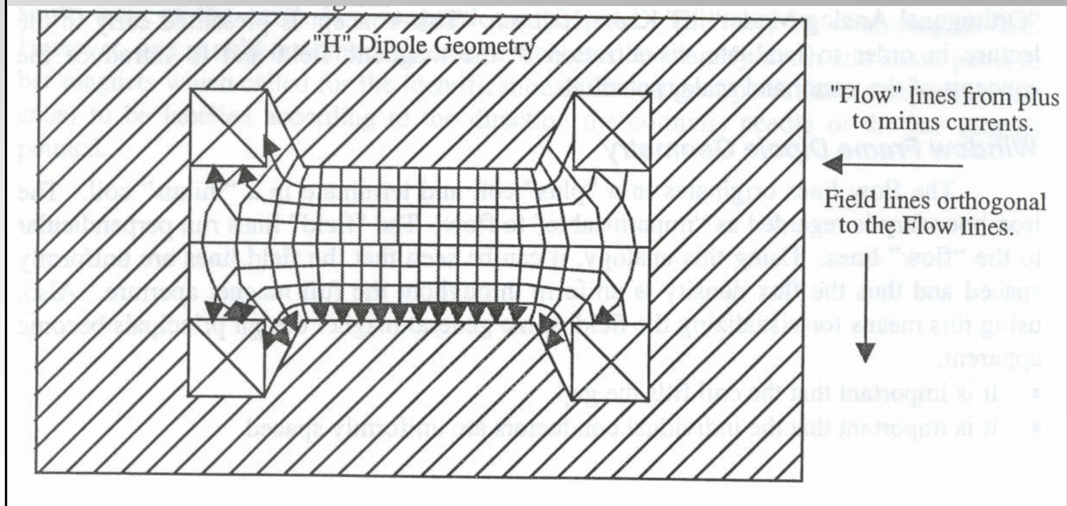
for example for
Window frame dipoles
Quadrupoles with widened pole basis



for example for
H-type dipoles
Quadrupoles without widened pole basis

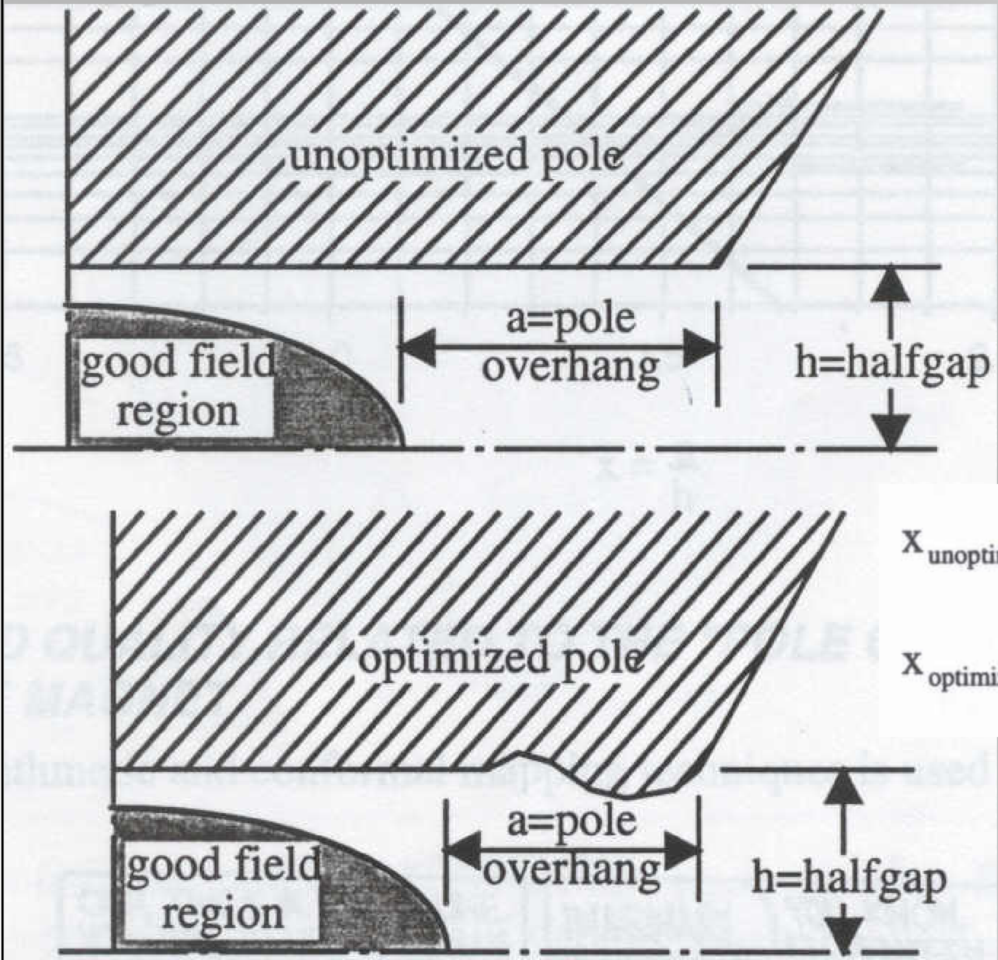
Orthogonal analog model





- For fast estimation of field quality
- Draw ‚flow lines‘ from plus to minus current
- Field lines are orthogonal to ‚flow lines‘
- In prinziple window frame dipole gives better field quality theoretically

Improvement of field quality with shims



$$\left(\frac{\Delta B}{B}\right)_{unoptimized} = \frac{1}{100}\exp[-2.77(x-0.75)]$$

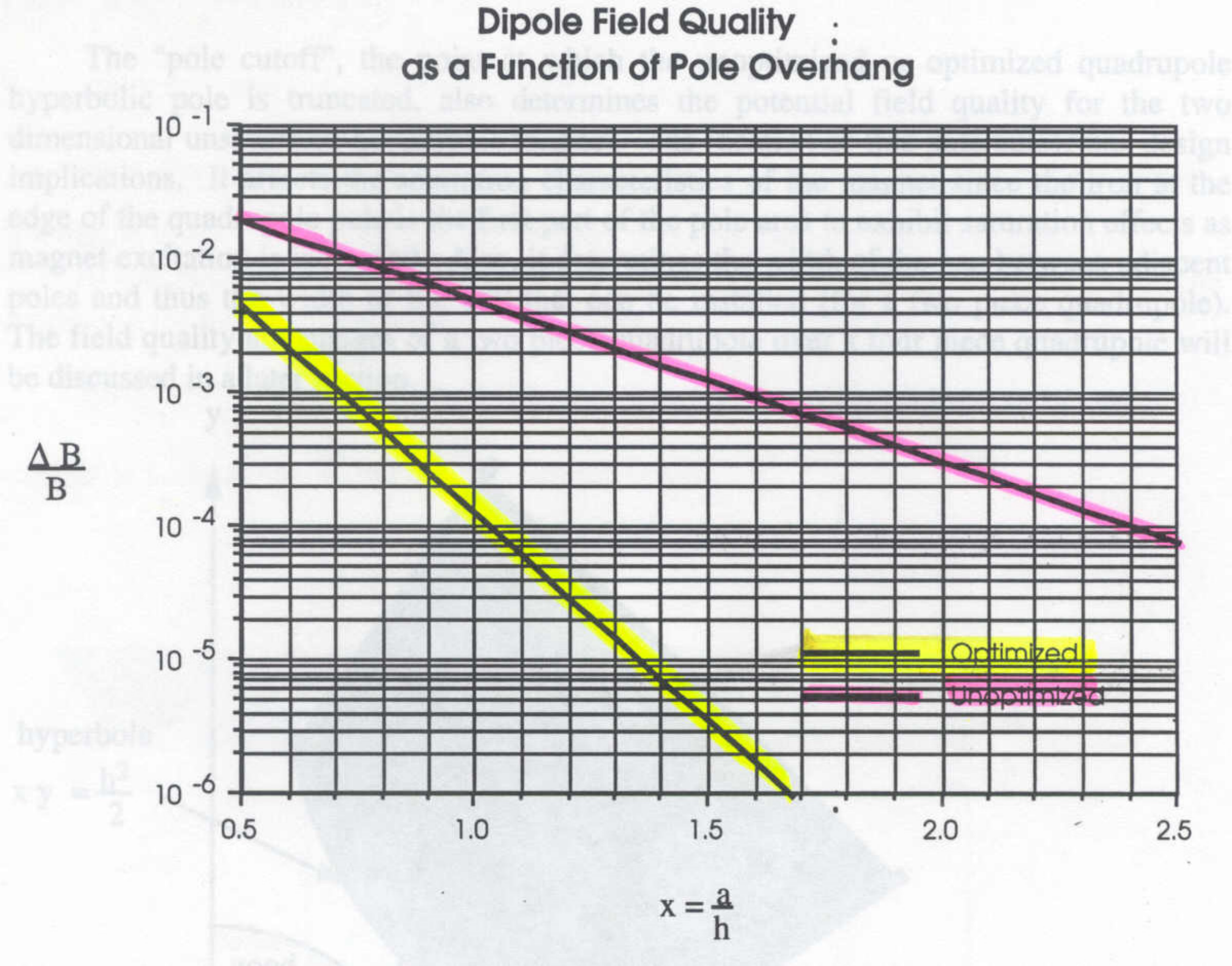
$$\left(\frac{\Delta B}{B}\right)_{optimized} = \frac{1}{100}\exp[-7.17(x-0.39)]$$

$$\text{where } x = \frac{a}{h} = \frac{\text{"pole overhang"}}{\text{half gap}}$$

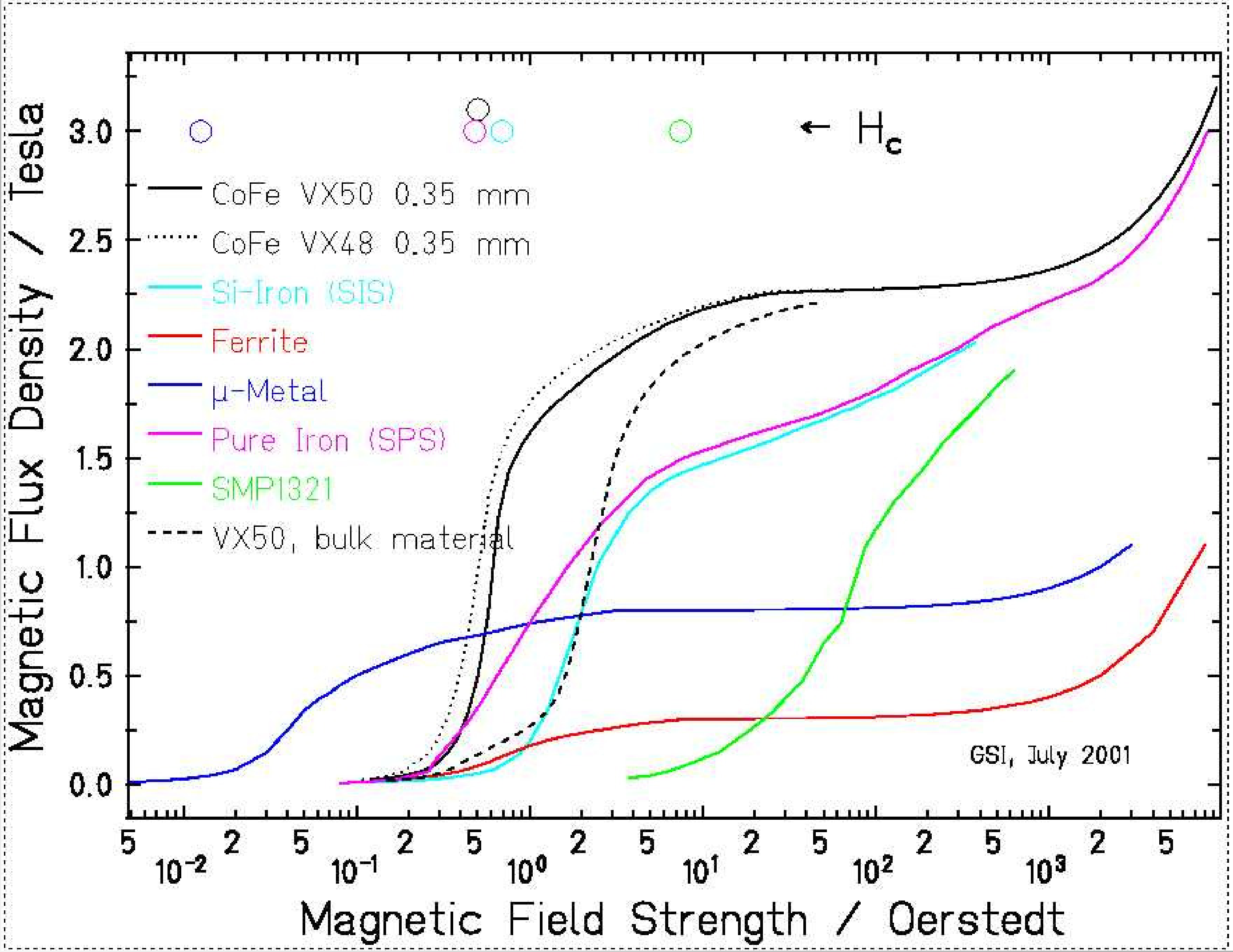
$$x_{unoptimized} = \left(\frac{a}{h}\right)_{unoptimized} = -0.36\ \ln\frac{\Delta B}{B} - 0.90$$

$$x_{optimized} = \left(\frac{a}{h}\right)_{optimized} = -0.14\ \ln\frac{\Delta B}{B} - 0.25$$

Field quality with and without optimization



B-H-Kurven



← H_c
CoFe VX50 0.35 mm
CoFe VX48 0.35 mm
Si-Iron (SIS)
Ferrite
μ-Metal
Pure Iron (SPS)
SMP1321
VX50, bulk material
GSI, July 2001
Magnetic Flux Density / Tesla
3.0
2.5
2.0
1.5
1.0
0.5
0.0
5 10^{-2} 2 5 10^{-1} 2 5 10^{0} 2 5 10^{1} 2 5 10^{2} 2 5 10^{3} 2 5
Magnetic Field Strength / Oerstedt

Saturation effects

- $\mu_r = \mu_r(B)$, for $B > 1.5$ T, μ_r is getting smaller

- saturation effects
  - reduced flux density (less efficiency)
    - more $N \cdot I$
    - widening yoke
  - reduced field quality
    - enlarge pole
    - use cut outs
    - active correction

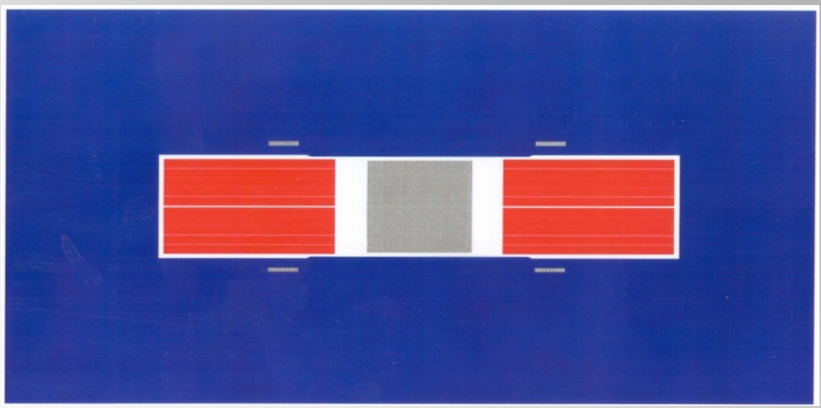
Cut outs in yoke

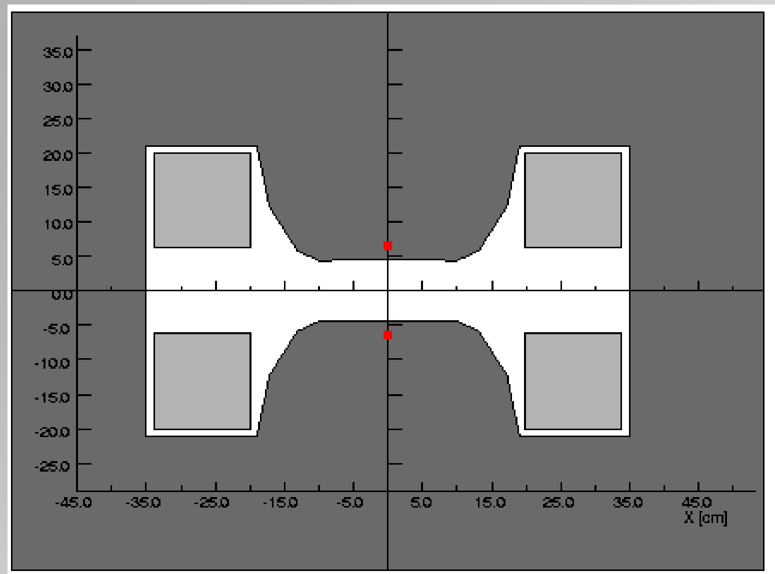
- Reducing influence of saturation effects on the field quality

cut outs

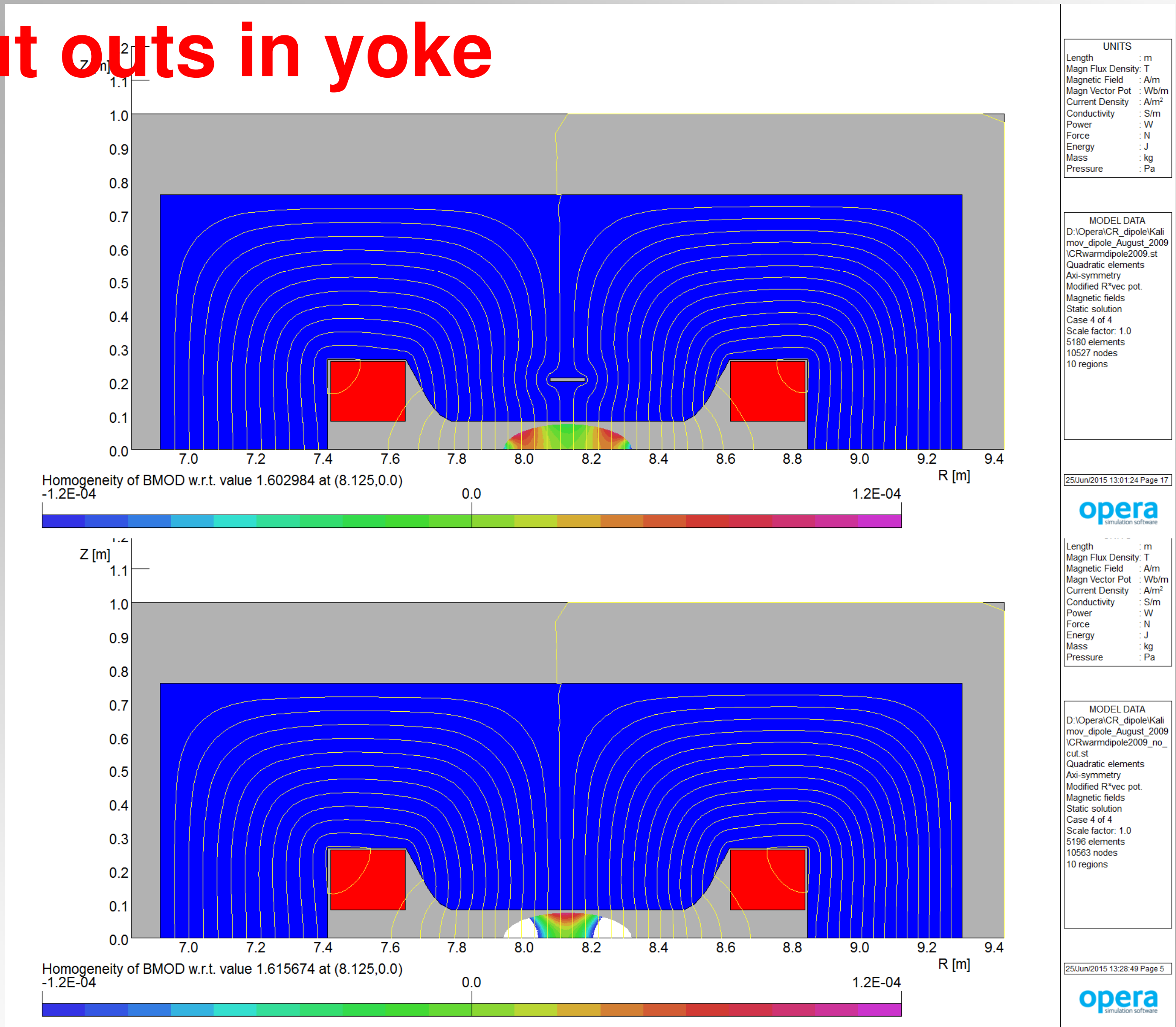
leading flux lines

compensation of saturation effects





Cut outs in yoke



Pulsed or fast ramped magnets

dB/dt induces eddy currents. This could lead to

- **reduces field quality**
- **reduces flux density (delay of peak field)**
- **could be avoided by using sinter materials (high electric resistivity but with reduced μ_r) and laminated yoke.**

Ampere's circuital law:

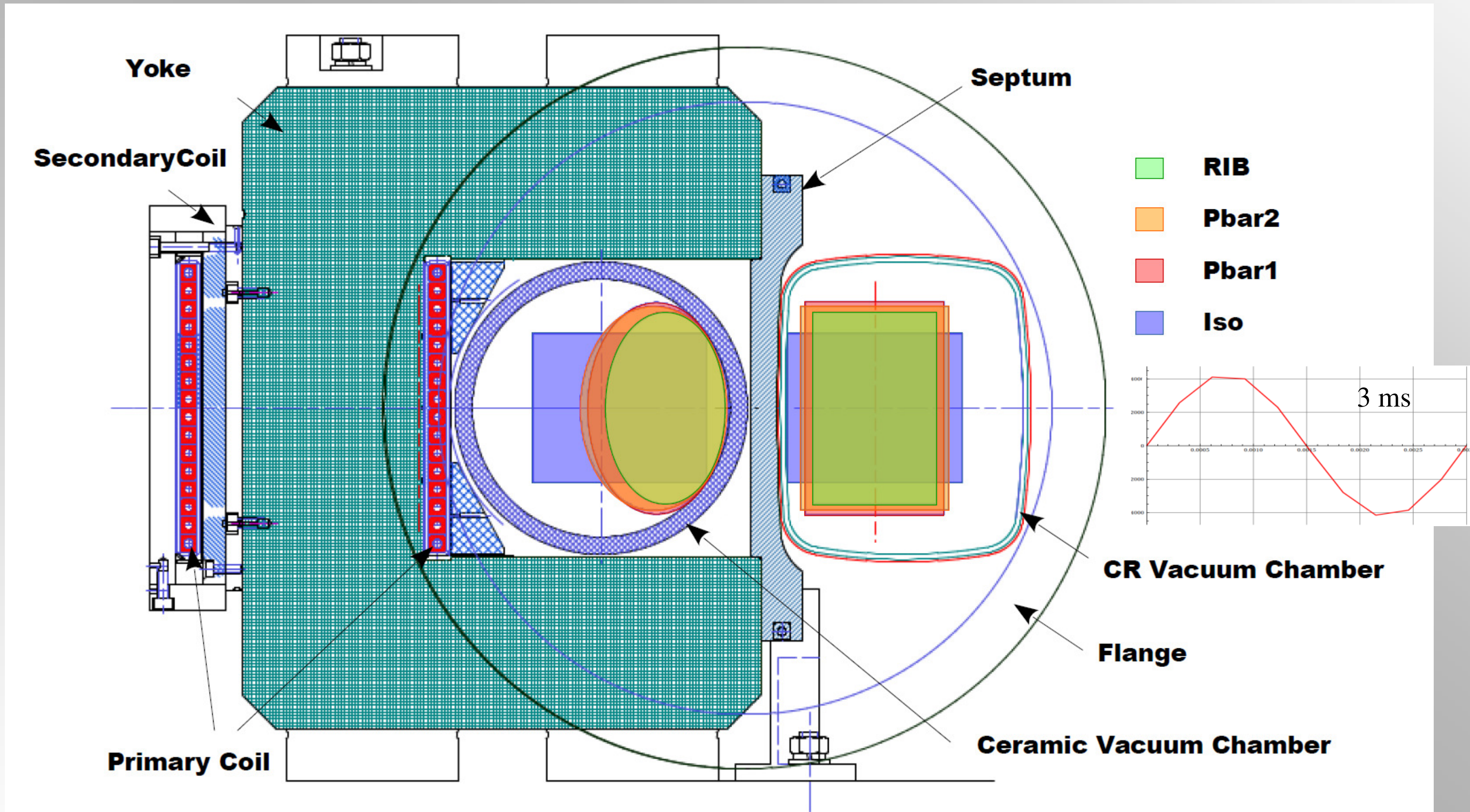
$$\oint_{\partial A} \mathbf{H} \cdot d\mathbf{s} = \int_A \mathbf{j} \cdot d\mathbf{A} + \frac{d}{dt} \int_A \mathbf{D} \cdot d\mathbf{A} \quad \text{aus} \quad \nabla \times \mathbf{H} = \mathbf{j} + \frac{\partial}{\partial t}\mathbf{D}$$

Faraday's law of induction:

$$\oint_{\partial A} \mathbf{E} \cdot d\mathbf{s} = -\frac{d}{dt} \int_A \mathbf{B} \cdot d\mathbf{A} \quad \text{aus} \quad \nabla \times \mathbf{E} = -\frac{\partial}{\partial t}\mathbf{B}$$

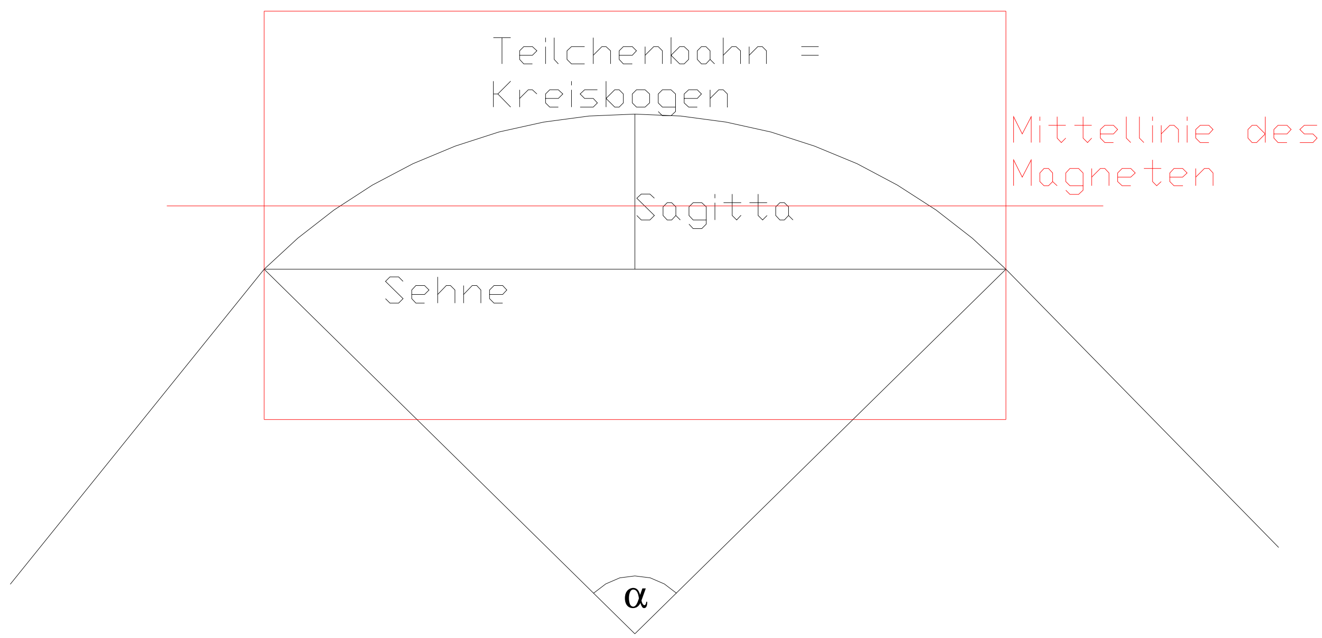
Welcome eddy currents

Pulsed CR septum magnets



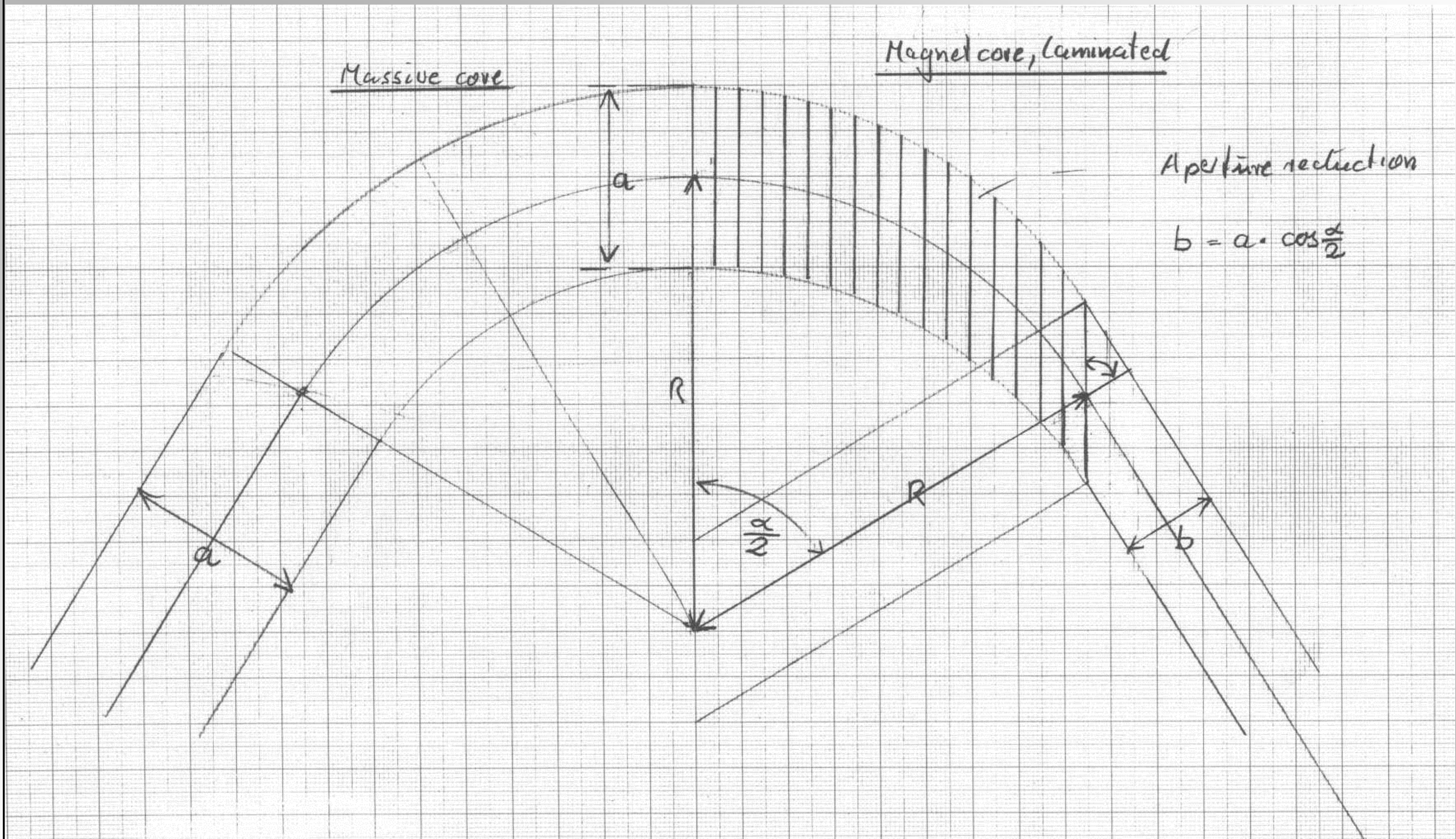
Sagitta

- Asymmetrischer
  Einschuss i
  gestreckten
- Sagitta h, R
  Ablenkwinl
- Magnet mu
  Apertur bel
  oder gebog
  werden



$$h = r * (1 - \cos(\alpha / 2))$$

Aperturverlust für geblechte Magnete



- **Lamellen werden im Bogen gestapelt => Apertur wird reduziert**

Design (1/2)

- **Requirements**
  - Maximum field/minimum field, effective length, bending radius, bending angle
  - Aperture
  - Field quality
  - Ramp rate
- **Iron blocks or laminated yoke?**
  - Depends on ramp rate
- **Which type of magnet?**
  - Depends on field quality, flux density, environment
- **Curved or straight dipole?**
  - Depends on bending angle
- **Ampere turns**
  - Depends on aperture and maximum strength

Design (2/2)

- **Coil**
  - Cross section depends on N*I
- **First draft of 2d design**
  - with μ_r=const.
- **Improved 2d design**
  - Non linear 2d simulations ($\mu_r=\mu_r(B)$)
- **3d design and simulation**
  - Check of field quality
- **Making parameter table**
  - Detailing of yoke, coil, dimenions, cooling, power consumption, etc.

- **Its a iterative process.**

Example of parameter table

G[illegible] S[illegible]

HSP010498.MA

Parameter des 15°-Magneten
im gepulsten UNILAC Ladungsseparator

B.Langenbeck

Darmstadt, den 01.04.1998

Tel.: +49 6159 71 2369
Fax: +49 6159 71 2785

V[illegible]

D[illegible] T[illegible] f[illegible] die [illegible] Mag[illegible] e[illegible] die Tabellen vom 27.11.1997. In der von d[illegible] eine Optimierung der Jochlänge vorgenommen. Die Spulen liegen jetzt stirnseitig am Joch an und der Biegeradius des Kupfers wird in den Spulenfenstern aufgefangen, siehe anliegende Skizze. Flußdichte, Betriebsstrom und Pulsleistung liegen deutlich niedriger, die für die Pulsung erforderliche Spannung ändert sich nicht. Der Nennstrom beträgt 960 A. Für die Aufnahme von Ladungsspektren hinter dem ersten dieser Magneten sind Ströme bis 1100 A erforderlich. Ergänzt wurde eine Tabelle für die Auslegung von Demagnetisierspulen, die in einer Lage unter der Grundisolierung der Hauptspulen gewickelt werden.

Es wird darauf hingewiesen, daß die Außenabmessung der Kammerhöhe 59.9 mm nicht überschreiten darf. Das Maß 62.5 mm der Gaphöhe im Aperturzentrum muß für die Planung der verzweigten Vakuumkammern um die doppelte Shimhöhe (1.3 mm), an den Polrändern) reduziert werden.

Datenauszug des H-Magneten

Ablenkwinkel	15.000	°
Bahnradius	1.313	m
Flußdichte im Gap	1.104	T
Rampensteilheit	73.600	T/s
Luftspalthöhe	62.500	mm
maximale Kammerhöhe	59.900	mm
Luftspaltbreite	112.500	mm
Homogenitätsbereich	52.500	mm
für $\Delta B/B$	.200	%
effektive Magnetlänge	.340	m
Baulänge des Jochs	.340	m
Baulänge des Magneten	.477	m
Stahlgewicht	.560	to
Leitergewicht	.095	to
gespeicherte Energie (nur Gap)	2.303	kJ
Windungszahl	60	
Strom	960.898	A
Widerstand	13.187	mΩ
Grund - Induktivität	5.500	mH
dc - Verluste	12.176	kW
Wirbelstromverluste auf der Rampe	1.113	kW
Hystereseverluste/Zyklus	16.413	J
Tastverhältnis	100.000	%
mittlere Verluste	12.176	kW
Kühlwasserbedarf	11.689	ℓ/min
bei Temperaturanstieg	15.000	°C
Druckdifferenz	1.659	at

Jochdaten des H-Magneten

Ablenkwinkel	15.000	°
Bahnradius	1.313	m
Flußdichte im Gap	1.104	T
Rampensteilheit	73.600	T/s
Tastverhältnis	100.000	%
Flußdichte im Joch	1.411	T
Jochbstärke	90.000	mm
mittlere Flußdichte im Pol	1.215	T
Polbasisbreite	195.000	mm
Luftspalthöhe	62.500	mm
Luftspaltbreite (einschließlich Shims)	115.000	mm
Shimbreite	14.500	mm
Shimhöhe	1.300	mm
Homogenitätsbereich	52.500	mm
für $\Delta B/B$	.200	%
Endprofil	Rogowski-Profil	
Bauart	Lamellen, im Bogen gestapelt	
Sagitta	11.233	mm
effektive Länge des Bahnbogens	.344	m
effektive Magnetlänge	.340	m
Baulänge des Jochs	.340	m
Baulänge des Magneten	.477	m
Breite der Jochkonstruktion	735.000	mm
Höhe des Magneten	435.000	mm
Spulenfenster Breite	180.000	mm
Spulenfenster Höhe	255.000	mm
Feldvolumen	.005	m^3
Lamellendicke	1.000	mm
max.Verschiebung benachb.Lamellen	.132	mm
Lamellenzahl	666	
Füllfaktor	.980	
Gewicht pro Blech	.841	kg
Gewicht des ganzen Joches	.560	to
Ampere-Windungsverluste	5.000	%
gespeicherte Energie (nur Gap)	2.303	kJ
Wirbelfeld-Zeitkonstante	11.968	μs
Wirbelfeld-Amplitude	-7.140	G
rel. Permeabilität im Pol	3191.046	
rel. Permeabilität im Joch	2149.371	
Hysteresefläche	226.768	J/m^3
diff. Permeabilität im Joch	512.323	
Faktor für $\Delta H_c/H_c$, mittl. Wert	18.800	
Divisor für $\Delta\mu/\mu$	22.318	

Daten des Spulensystems

Windungszahl, gesamt	60	
Spaltenzahl	5	
Zeilenzahl, gesamt	12	
Kühlkreisläufe, gesamt	6	
Strom	960.898	A
Spulenbreite	68.000	mm
bzw.	81.000	mm
Spulenhöhe	81.000	mm
horiz. Abstand vom Pol	40.000	mm
vertik. Abstand vom Fenster	6.500	mm
axialer Abstand vom Pol	0.500	mm
Abstand der Spulen	80.000	mm
Leiterisolierung	.500	mm
Grundisolierung	1.500	mm
Leiterbreite	12.000	mm
Leiterhöhe	12.000	mm
Durchmesser des Kühlkanals	5.000	mm
Kantenradius des Leiterprofils	2.000	mm
Leiterquerschnitt	120.931	mm^2
Stromdichte	7.946	A/mm^2
mittlerer Spulenumfang	1.456	m
Widerstand	13.187	mΩ
mittlere Verlustleistung	12.176	kW
Kühlwasserbedarf	11.689	ℓ/min
bei: Tastverhältnis	100.000	%
bei: Rampenanstieg	73.600	T/s
bei: Temperaturanstieg um	15.000	°C
und für Druckdifferenz von	1.659	at
Strömungsgeschwindigkeit	1.654	m/s
Wärmeübergang	.887	W/cm^2
Leiterfüllfaktor	65.867	%
Leitergewicht	.095	to

Betriebsdaten

Strom	960.898	A
Stromanstieg	64.060	kA/s
Widerstand	13.187	mΩ
Grund-Induktivität	5.500	mH
dc-Spannung	12.671	V
ac-Spannung	352.352	V
dc-Verlustleistung	12.176	kW
Wirbelstromverluste, Spule		
und Magnet, auf der Rampe	1.113	kW
Hystereseverl. pro Zyklus	16.413	J
Rampendauer	15.000	ms
Zyklusdauer	**********	ms
Tastverhältnis	100.000	%
mittlere Verluste	12.176	kW
moment.Verlustl.Rampenende	13.289	kW
Gesamtspannung,Rampenende	365.023	V
gespeicherte Energie (Gap)	2.303	kJ

Demagnetisierspulen

Anzahl	2	
Position: unter die Grundisolierung		
der Hauptspule gewickelt.		
Windungszahl pro Spule	16	
Zeilenzahl	1	
Strom	5.500	A
Feldhub	35.000	Gauß
Leiterbreite	4.000	mm
Leiterhöhe	2.000	mm
Kupferquerschnitt	7.637	mm^2
Lackisolierung	0.110	mm
mittlerer Spulenumfang	1.456	m
Spulenbreite	66.000	mm
Widerstand (32 Windungen)	0.119	Ω
Spannung	0.660	V
Leistung	3.600	W
Gewicht pro Spule	1.595	kg

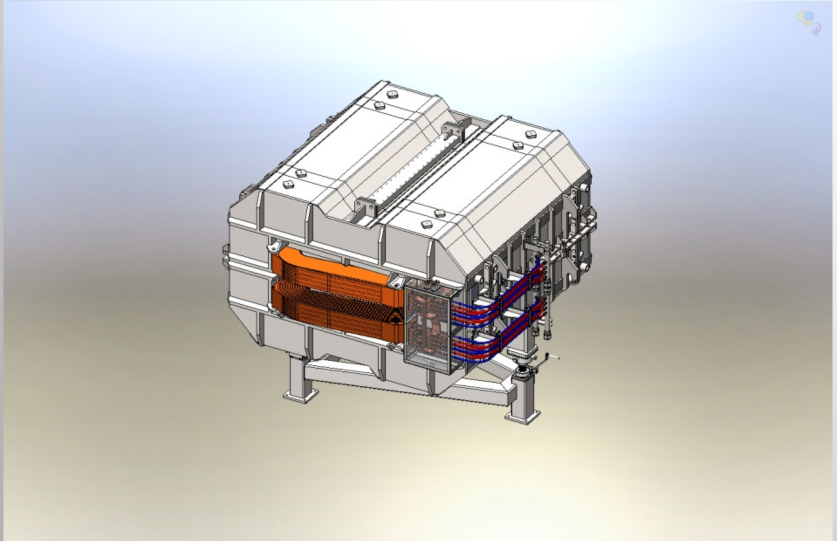
dc-Betrieb für Ladungsspektren

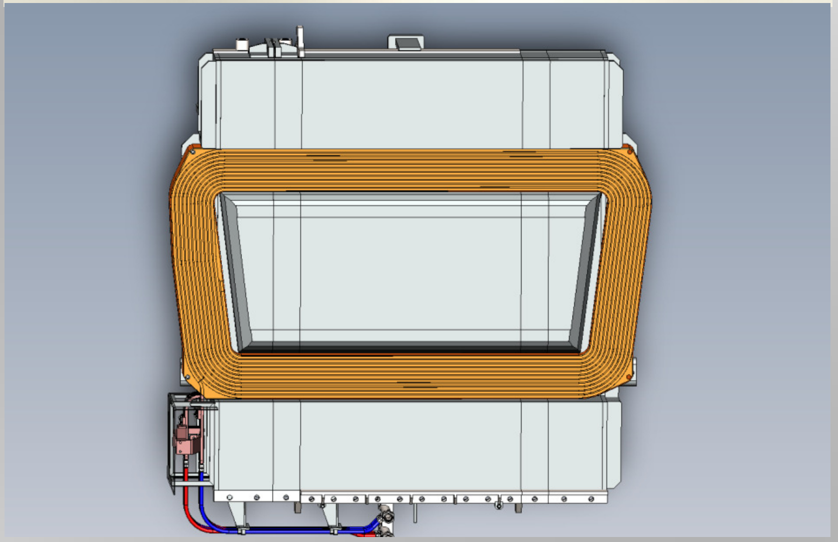
Flußdichte in der Apertur	1.265	T
Flußdichte im Joch	1.623	T
Strom	1105.000	A
Stromanstieg	0.000	kA/s
Widerstand	13.187	mΩ
Grund-Induktivität	5.500	mH
dc-Spannung	14.572	V
ac-Spannung	0.000	V
dc-Verlustleistung	16.102	kW
Wirbelstromverluste, Spule		
und Magnet, auf der Rampe	0.000	kW
Hystereseverl. pro Zyklus	16.413	J
Rampendauer	0.000	ms
Zyklusdauer	**********	ms
Tastverhältnis	100.000	%
mittlere Verluste	16.102	kW
moment.Verlustl.Rampenende	16.102	kW
Gesamtspannung,Rampenende	14.572	V
gespeicherte Energie (Gap)	3.046	kJ
Kühlwasserbedarf	15.458	ℓ/min
bei: Tastverhältnis	100.000	%
bei: Rampenanstieg	0.000	T/s
bei: Temperaturanstieg um	15.000	°C
und für Druckdifferenz von	2.706	at
Strömungsgeschwindigkeit	2.187	m/s
Wärmeübergang	1.173	W/cm^2

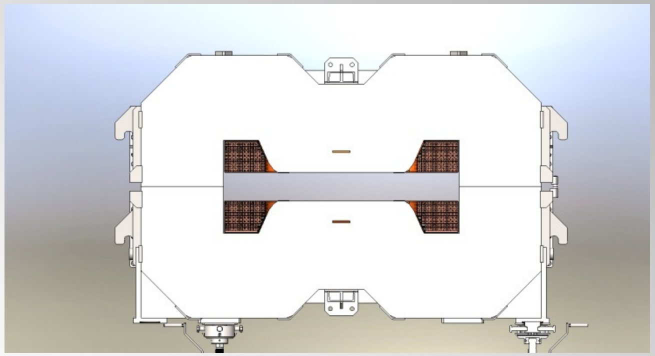
More examples

CR Dipole

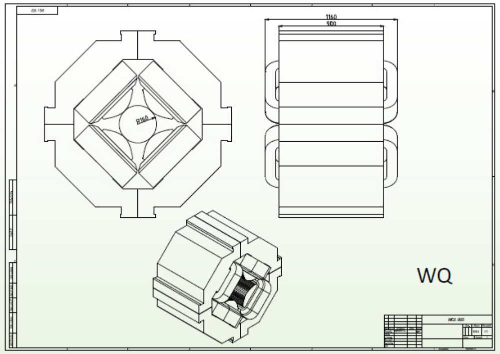
- H-type
- Sector magnet
- Weight: ca. 60 tons
- Flux density within gap: 1.6 T
- Bedinge angle 15°
- Bending radius 8.125 m
- Integral field non-uniformity $\Delta \int B\, dl / \int B\, dl = \pm 1 \cdot 10^{-4}$
- Aperture 380 × 140 mm²



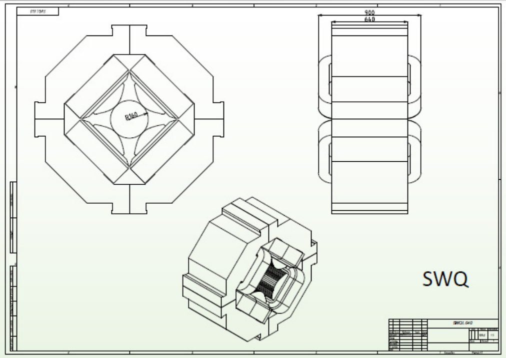




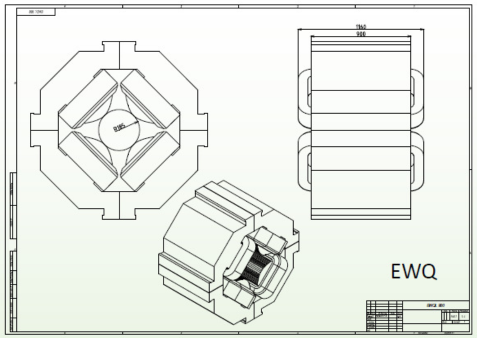
Other not mentioned CR magnets



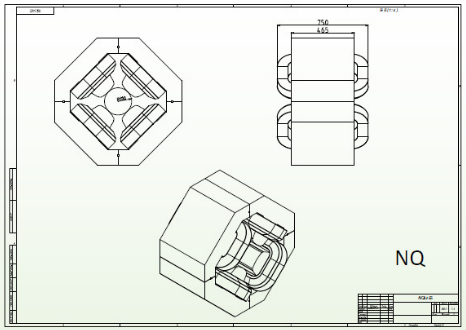
Maximal integral gradient $G_{max} \cdot l_{eff}$ (T)	4.7	Overall yoke width / height (m)	1.6
Effective magnet length l_{eff} (m)	1	Total weight (to)	10.6
Inscribed radius (mm)	160	Current (A)	1470
Total magnet length (m)	1.16	Power consumption (kW)	57



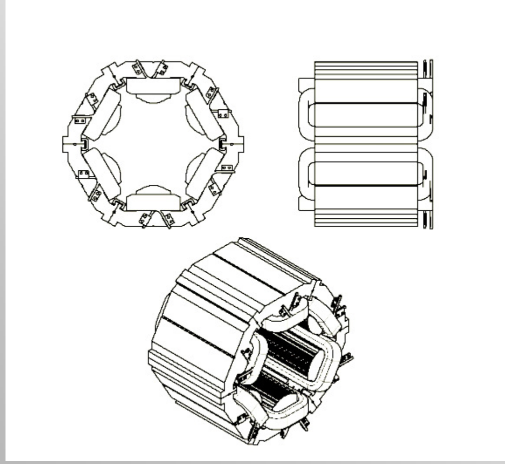
Maximal integral gradient $G_{max} \cdot l_{eff}$ (T)	3.29	Overall yoke width / height (m)	1.6
Effective magnet length l_{eff} (m)	0.7	Total weight (to)	6.7
Inscribed radius (mm)	160	Current (A)	1480
Total magnet length (m)	0.9	Power consumption (kW)	47.5



Maximal integral gradient $G_{max} \cdot l_{eff}$ (T)	3.5	Overall yoke width / height (m)	1.6
Effective magnet length l_{eff} (m)	1	Total weight (to)	10.2
Inscribed radius (mm)	185	Current (A)	1380
Total magnet length (m)	1.16	Power consumption (kW)	50.1



Maximal integral gradient $G_{max} \cdot l_{eff}$ (T)	3.1	Overall yoke width / height (m)	0.88
Effective magnet length l_{eff} (m)	0.545	Total weight (to)	1.2
Inscribed radius (mm)	100	Current (A)	1210
Total magnet length (m)	0.75	Power consumption (kW)	14.8



Aperture radius – 201 mm

Sextupole strength – 10 T/m^2

Field homogeneity (in radius 190 mm) $\pm 5 \times 10^{-3}$

Yoke length – 500 mm

Current – 500 A

Usable aperture $\pm$215 / $\pm$90 mm

Power – 8,75 kW

Total weight – 1350 kg

Total length with coils – 629 mm

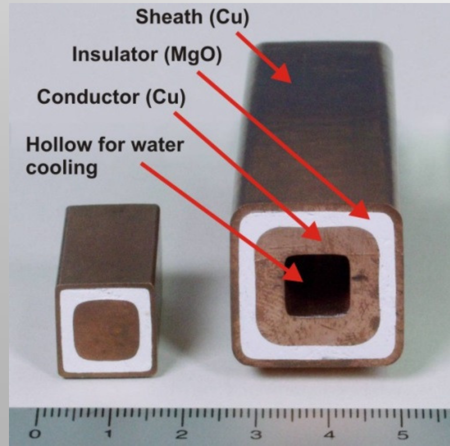
Overall width – 884 mm

Overall height – 807 mm

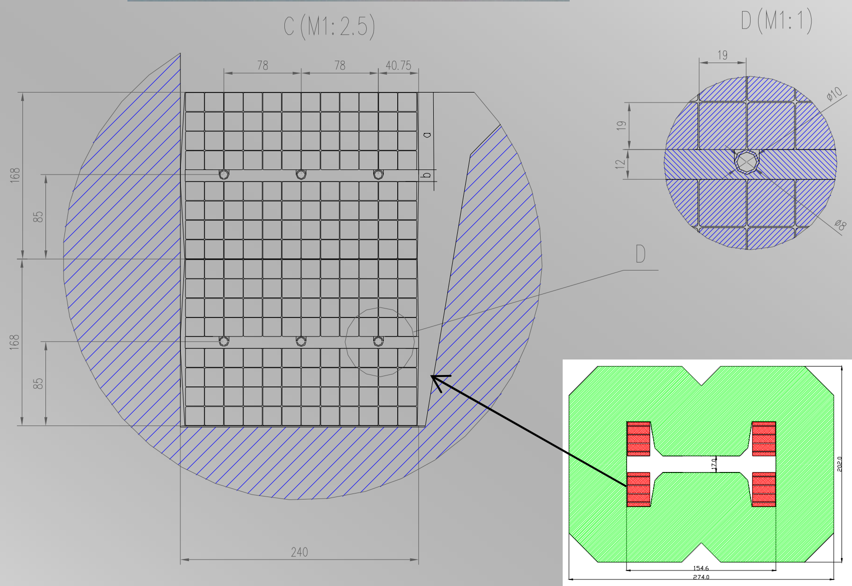
Copper bar – 10x10 mm^2

with hole Ø5mm

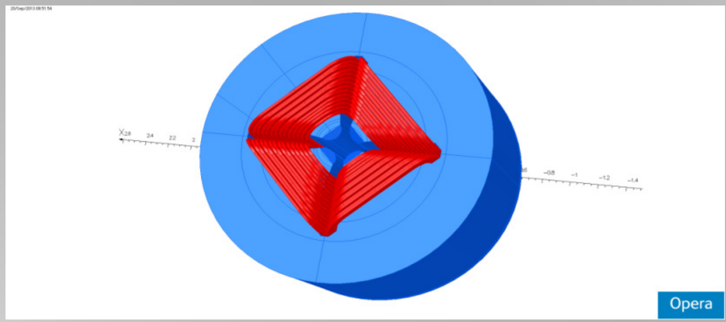
Radiation resistant Super-FRS Dipole

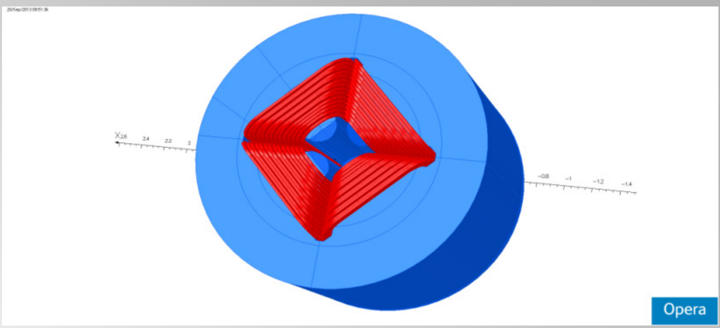


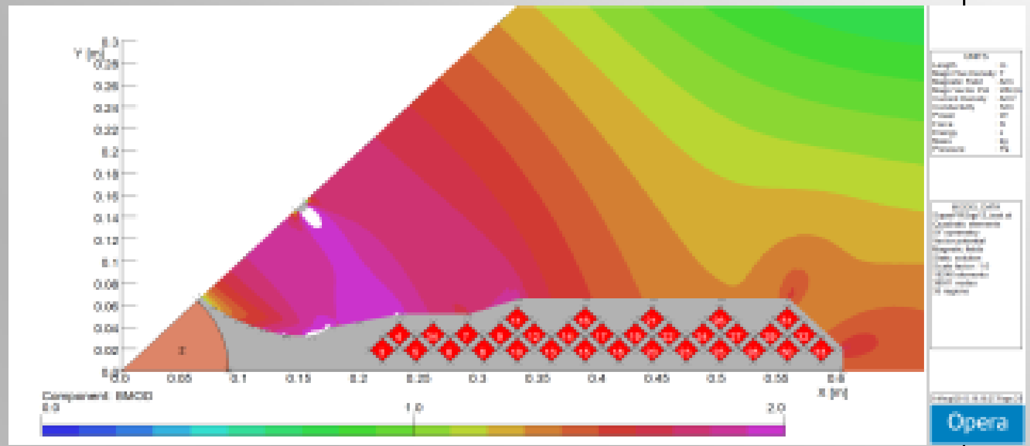
MgO is hygroscopic



Radiation resistant Super-FRS Quadrupoles

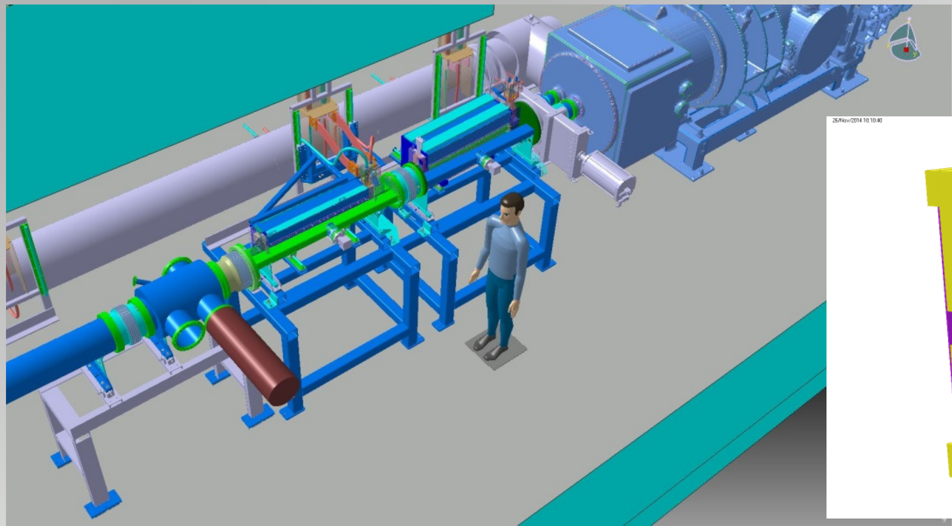


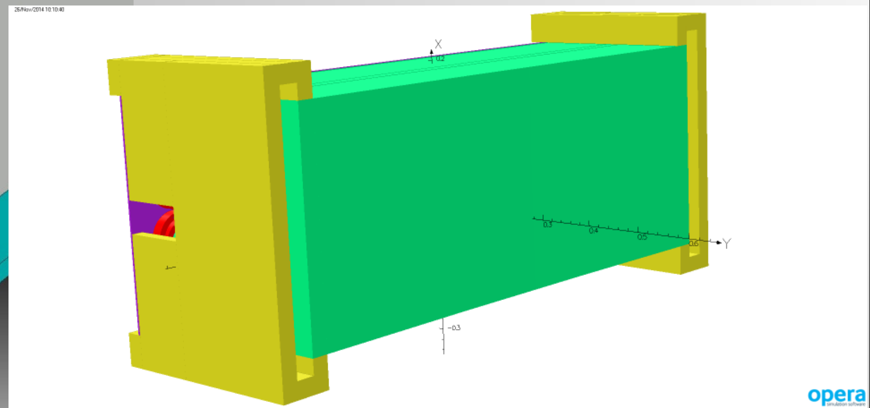


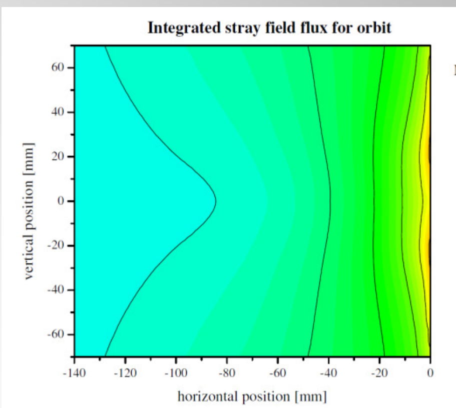


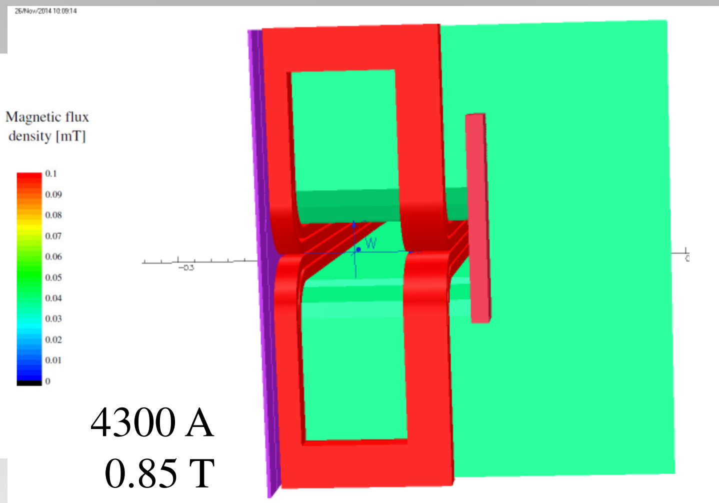
PSP code	Magnet	Pole gap (mm)	Dimension (m) (x,y,z)	Max. current	inductance (mH)	Resistance (mOhm)	Total weight (tons)	Power (kw)	Flow rate (l/min)
2.4.2.1.1	Dipole 1	180	3.2 / 3.0 / 2.1	640	2100	300	96	121	72
2.4.2.2.1	Quadrupole 1a	70	1.186/1.80/1.80	981	72	49	20.2	47	27
2.4.2.2.1	Quadrupole 1b	95	1.149/1.80/1.80	1408	80	59	26.6	116	67
2.4.2.2.2	Quadrupole 2	163	1.34/1.50/1.50	1944	57	43	18.3	163	94
2.4.2.3.1	Sextupole 1	195	0.84 / 1.6 / 1.6	1800	20	27	6	86	50

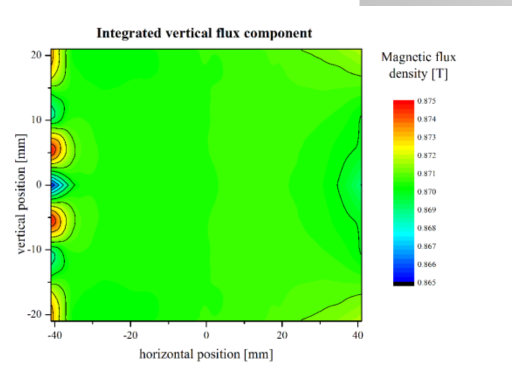
SIS 100 Septum 1









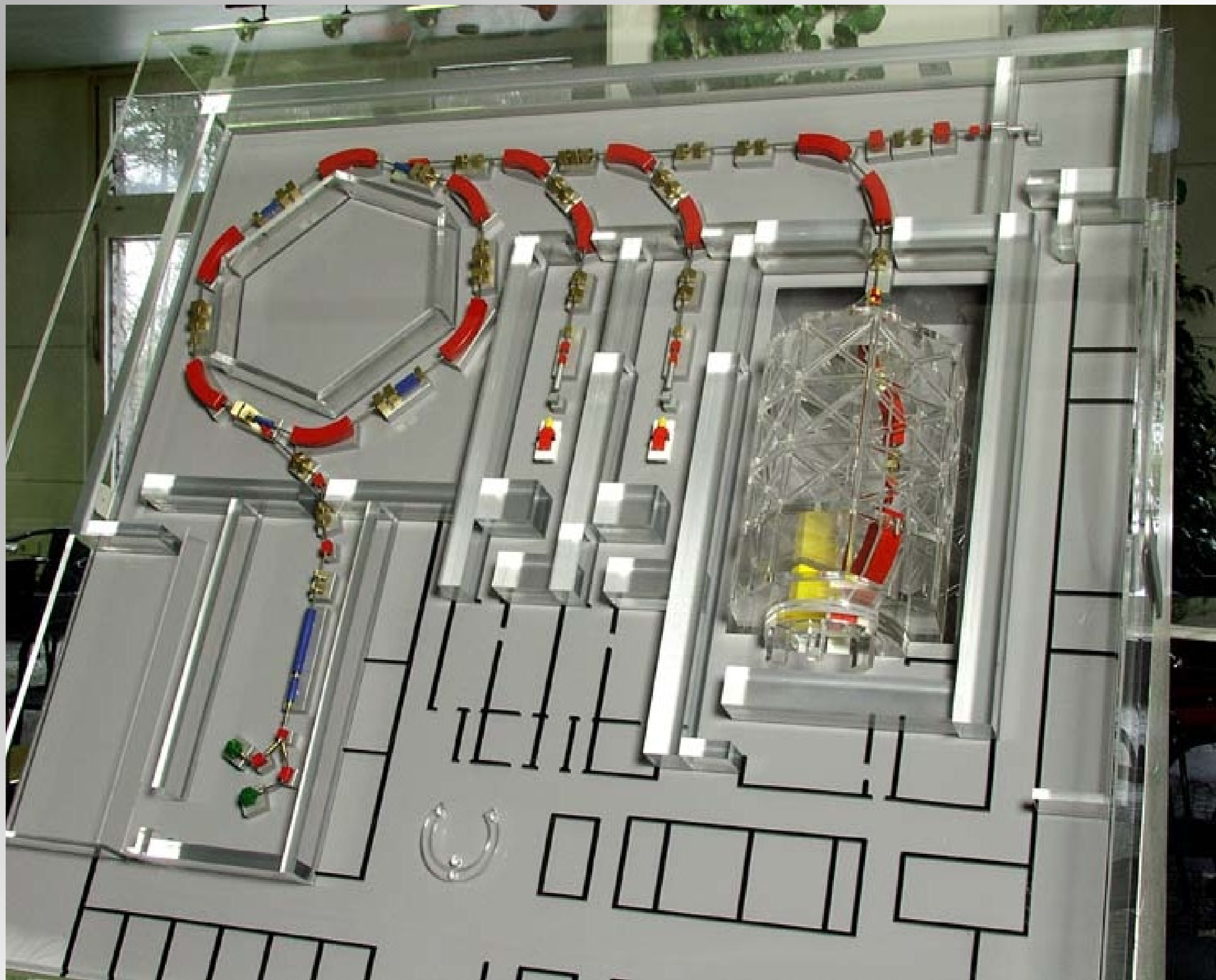


Some Numbers

- more than 100 different types of NC-magnets
- each magnet type must be designed and specified
- number of NC-magnets (without experiments): > 630
- estimated sum of costs: ca. 70 million Euro

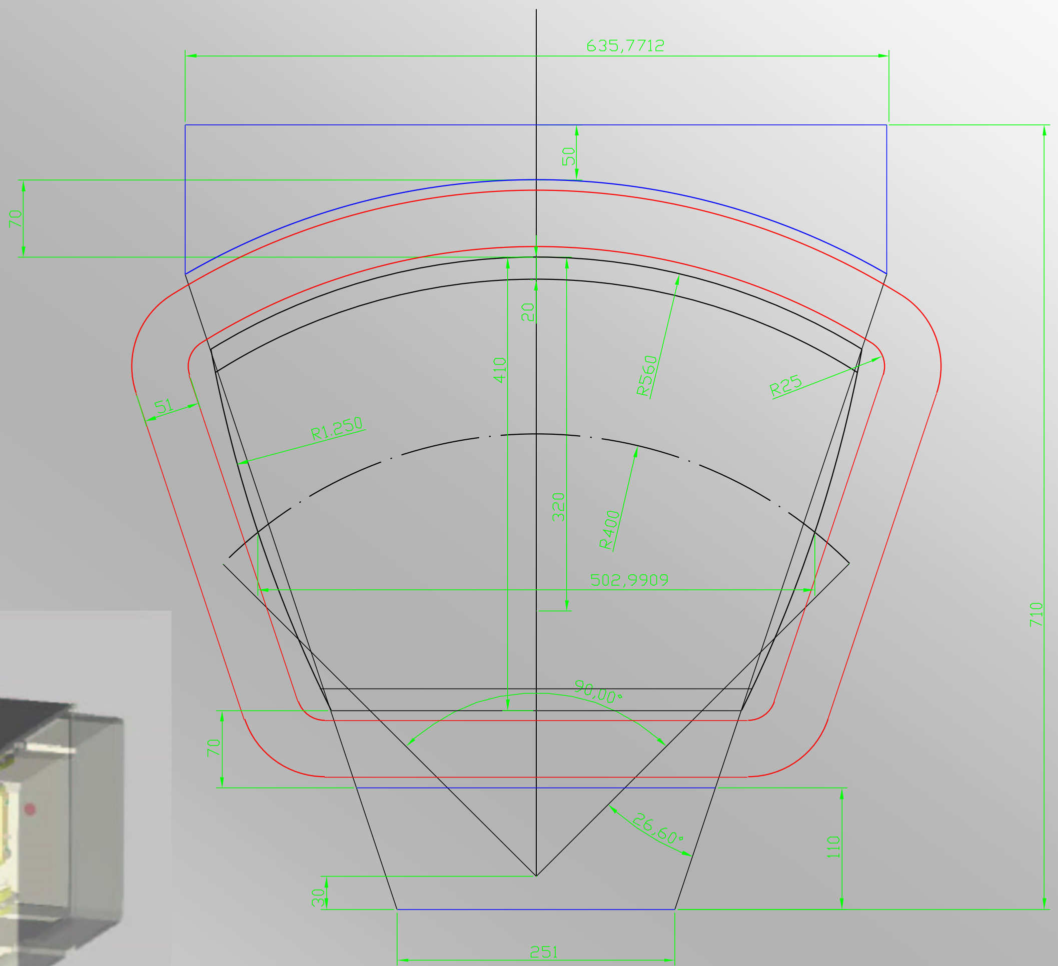
Magnete HIT (Heidelberger Ionentherapie)

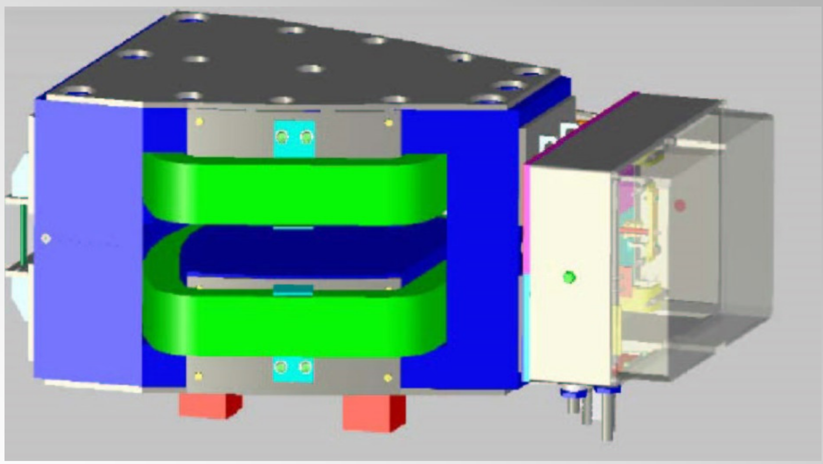
- Dedizierte Anlage für die Tumortherapie mit Ionen in Heidelberg
- Entwickelt von der GSI
- Inbetriebnahme des Beschleunigers durch GSI
- Erste Patienten-bestrahlung Ende 2009
- Kommerzielle Anlagen im Bau bzw. in Inbetriebnahme
- Weitere Anlagen in Planung



Analysierdipol

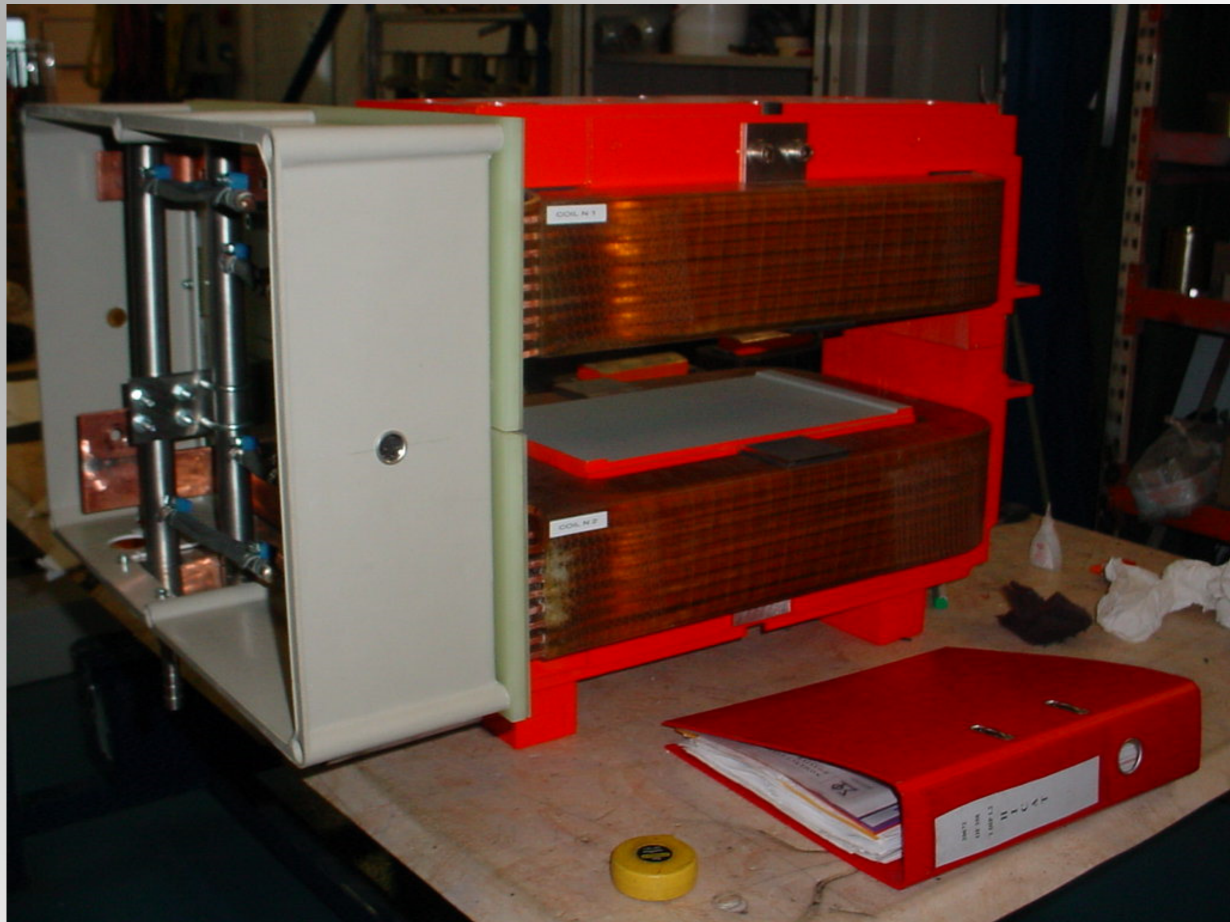
- H-Magnet
- D-förmig
- Polradius
- 0.2T





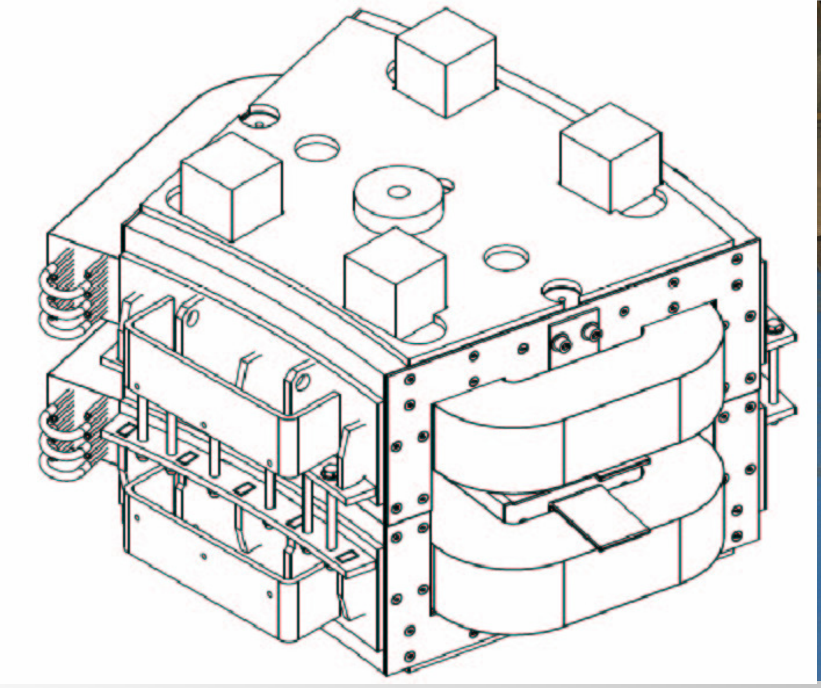
Schaltdipol

- H-Magnet
- Gestreckt
- 0.1T



MEBT-Dipol (Medium Energy Beam Transport)

- H-Magnet
- Gebogen
- 0.57T

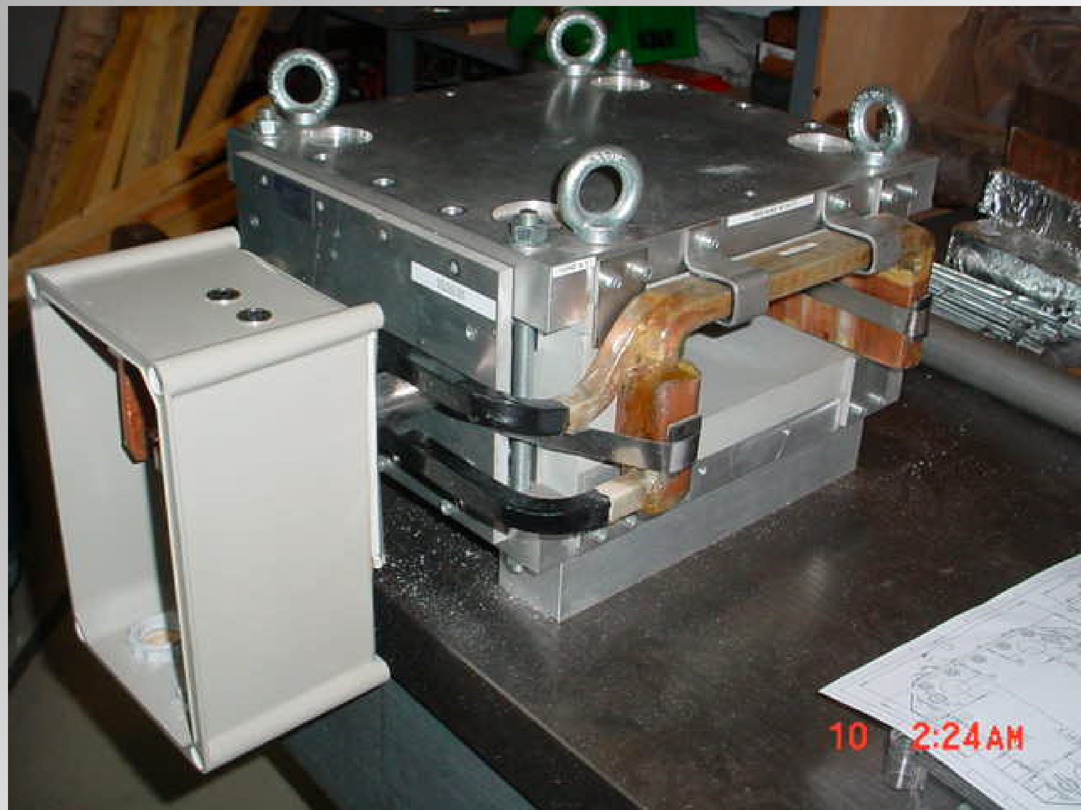


Inflektor

- Window-Frame-C-Magnet
- Gebogen
- 0.42T

Bumper

- Window-Frame-Magnet
- Sehr schnell:
  - Joch aus Sintermaterial
  - Nur 2 Windungen
- 0.0195T

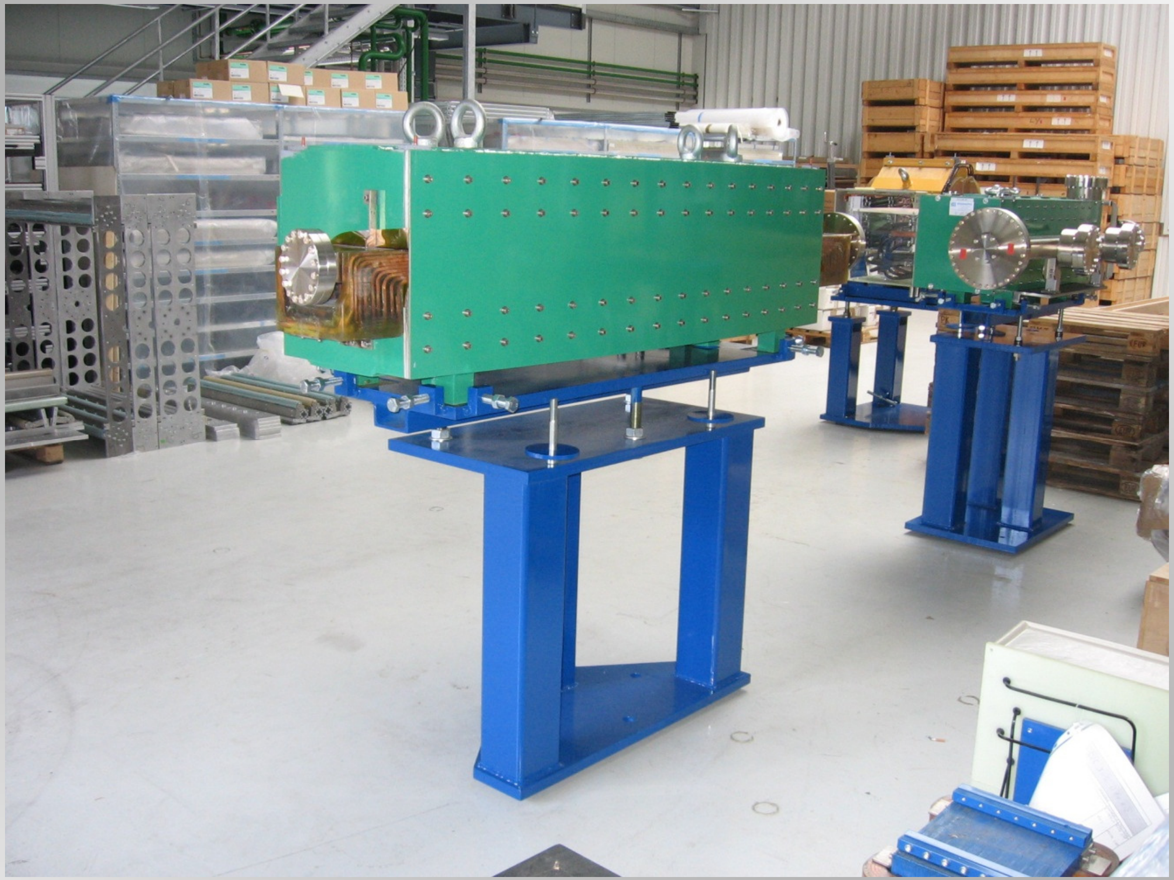


Septum I

- Window-Frame-C-Magnet
- Gestreckt mit Knick
- Septum
  - Trennt Bereiche mit konstantem Feld von feldfreien Bereichen
  - Geringe Spulenbreite an der Schneide
  - Spule aus Einzelteilen zusammengelötet
- 0.75T

Septum II

- Window-Frame-C-Magnet
- Gebogen
- Septum
  - Geringe Spulenbreite an der Schneide
  - Spule aus Einzelteilen zusammengelötet
- Betrieb in Serie mit Synchrotron-Dipolen
- 0.9T

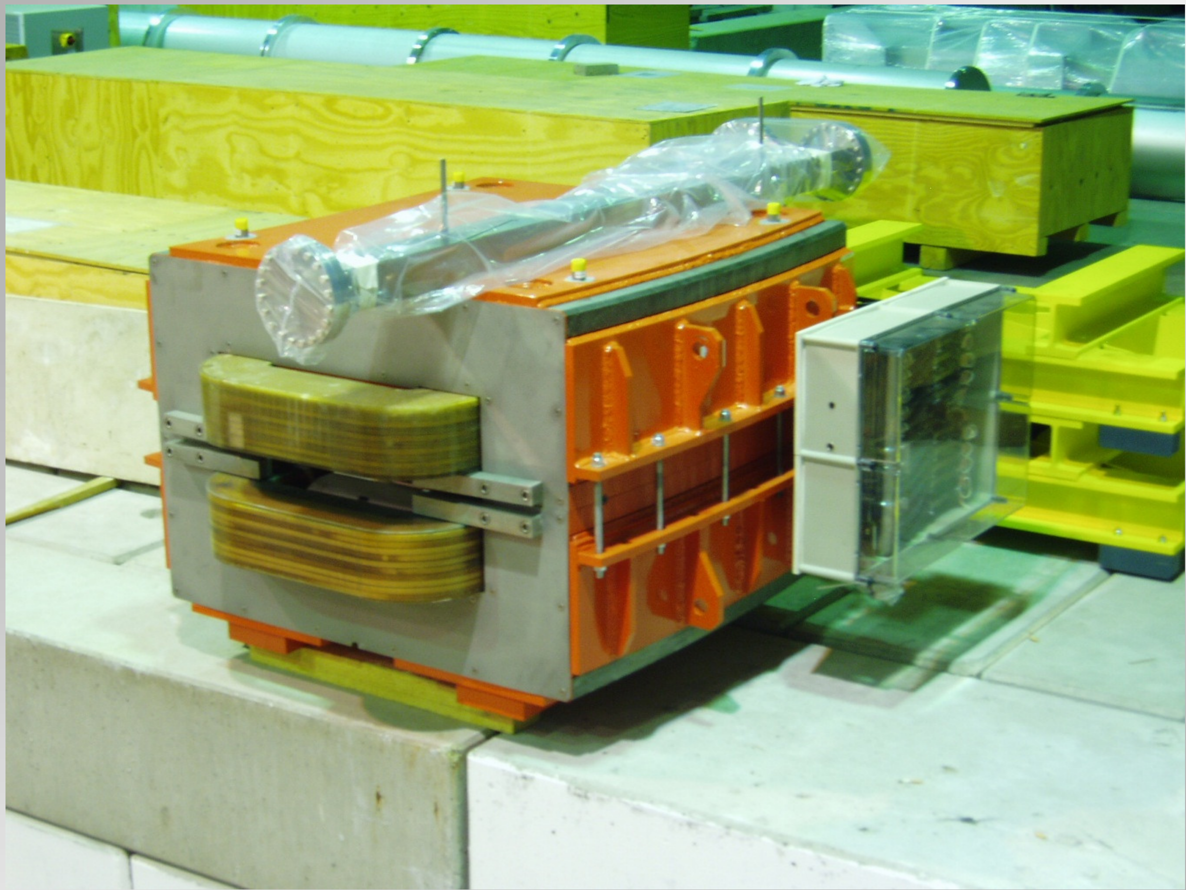


Synchrotron-Dipol

- H-Magnet
- Gebogen
- Demontierbare Endplatten für Längenschimming
- Korrekturwindung integriert
  ⇒ Horizontalsteerer
- 1.53T

15°-HEBT-Dipol (High Energy Beam Transport)

- H-Magnet
- Gebogen
- Gleicher Querschnitt wie der folgende Magnet
- Nullfeldspule für geraden Durchschuss integriert
- 1.51T

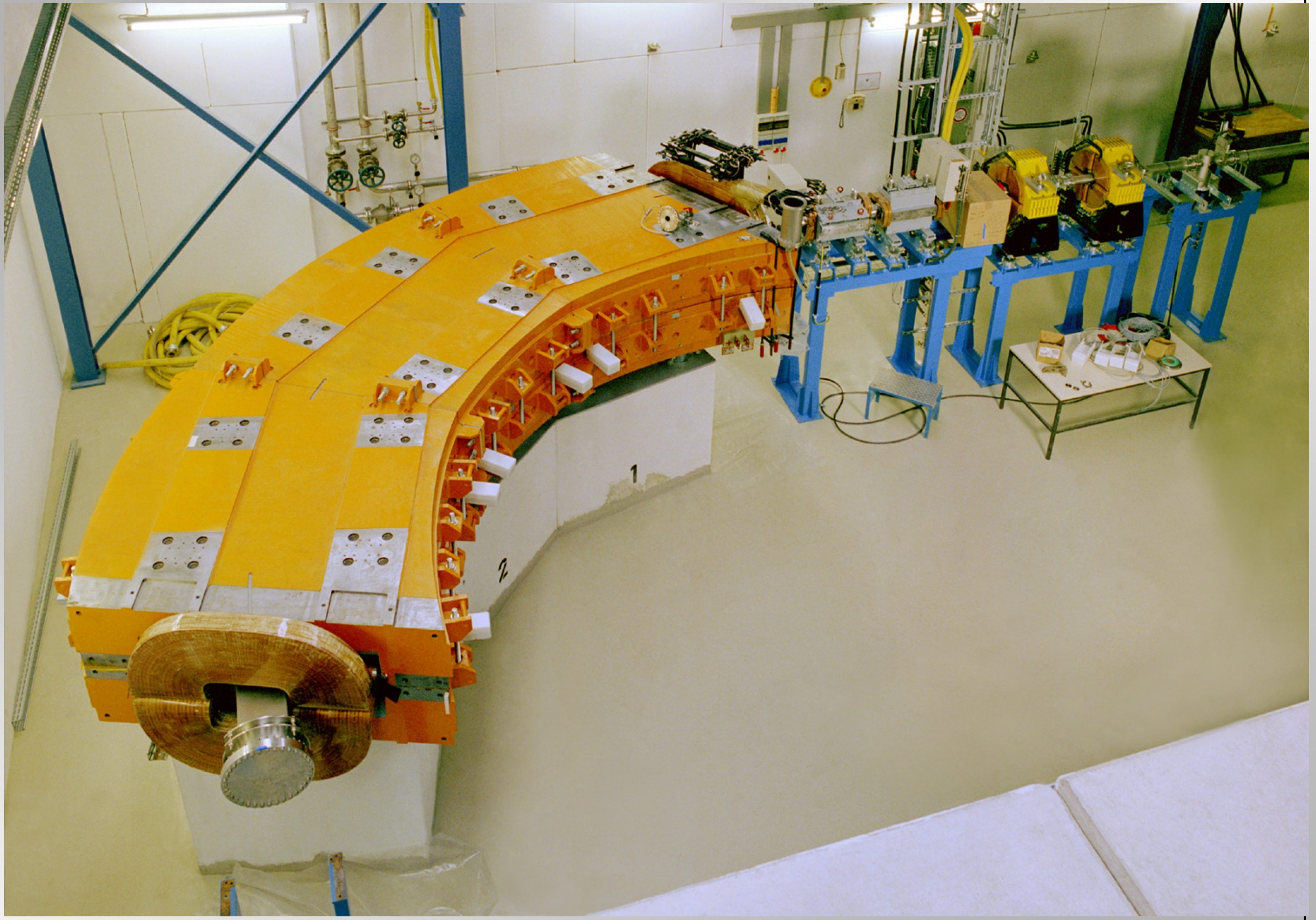


45°-HEBT-Dipol

- H-Magnet
- Gebogen
- Öffnung für Gerade-ausstrahl bei 3 Magneten
  - Jochverstärkung zur Kompensation der Öffnung
  - Nullfeldspule integriert
- 1.51T

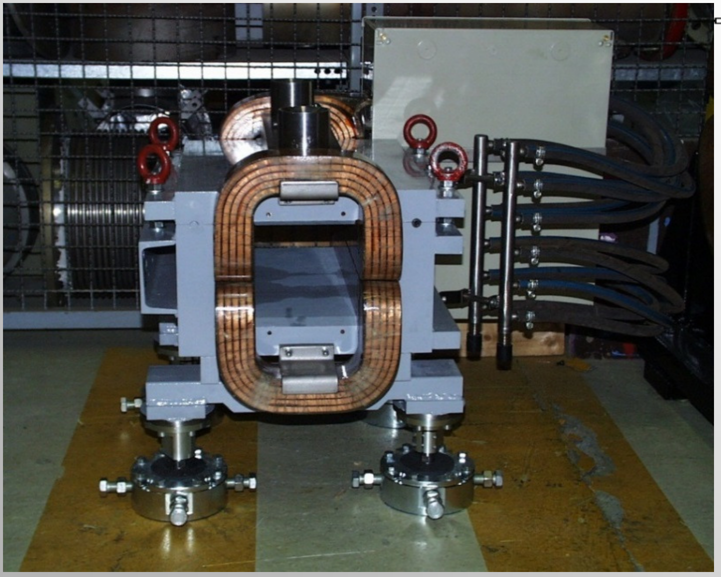
90°-Gantry-Dipol

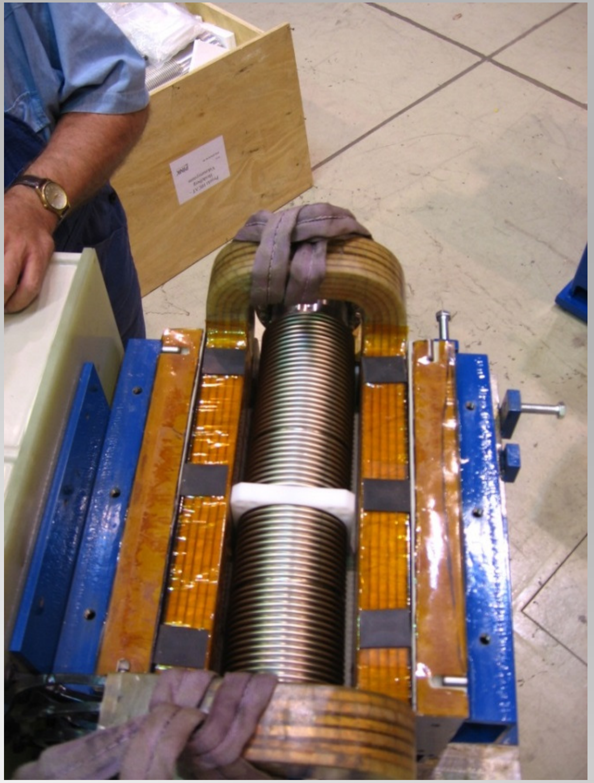
- Window-Frame-Magnet
- Extrem große Apertur
- 1.81 T

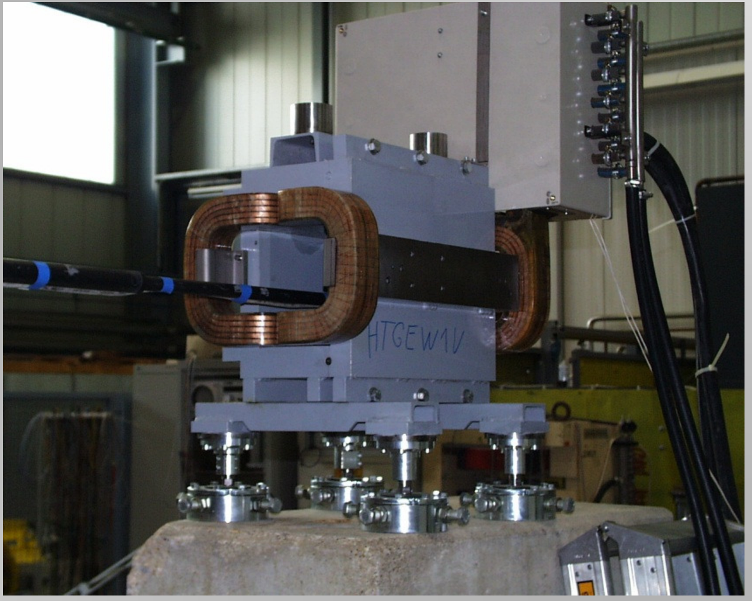


Scanner

- Window-Frame-Magnet
- Lamellendicke 0.35 mm
- Dünnwandige Kammer
- 0.31T

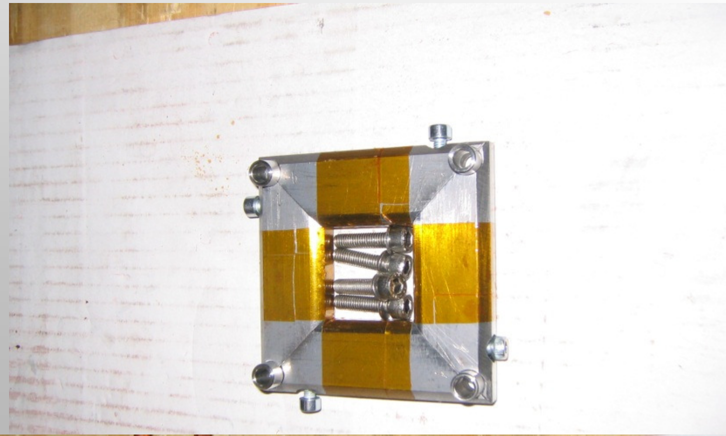


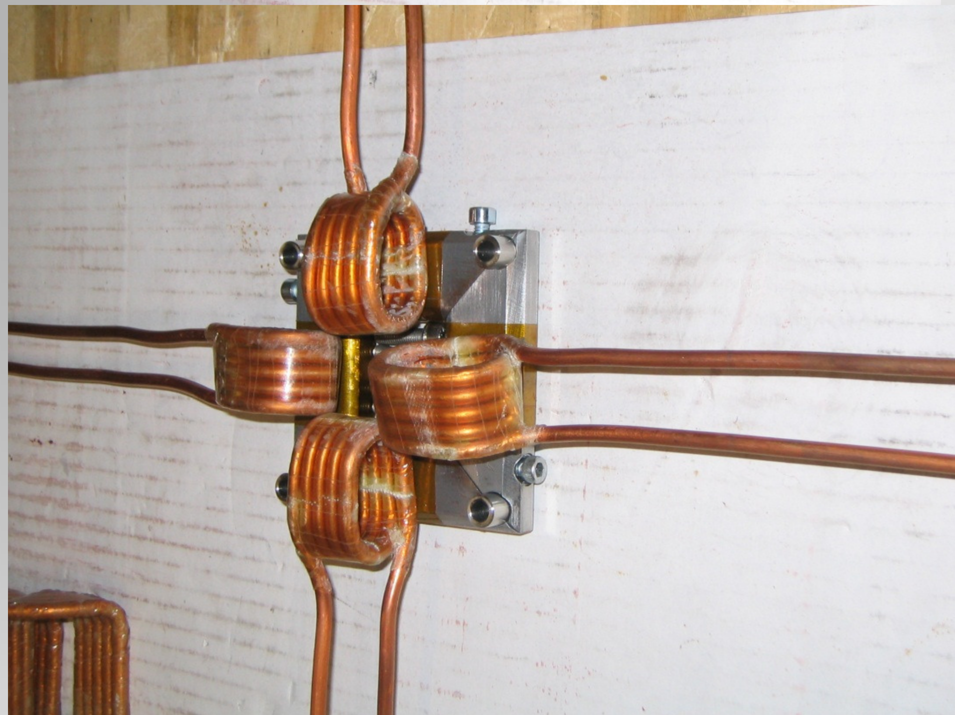




Matching Steerer

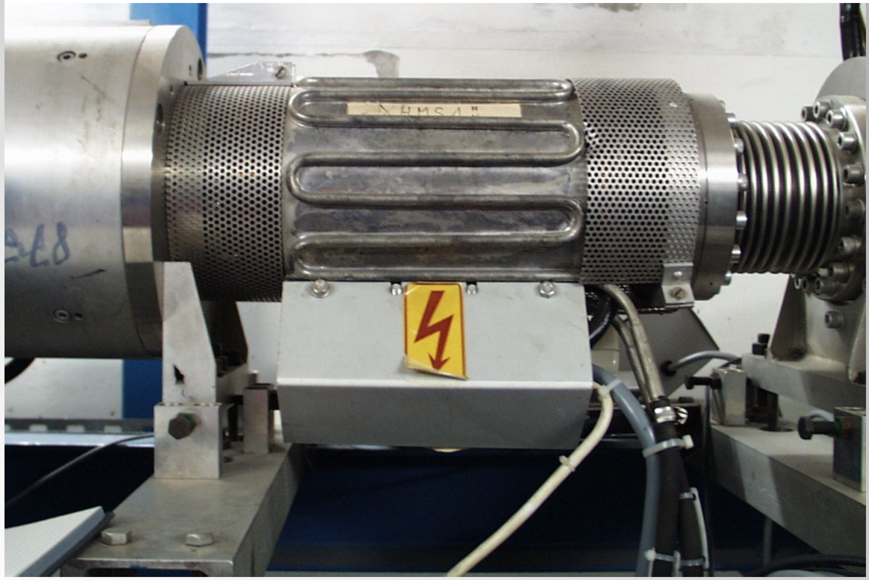
- Doppelsteerer
- Window-Frame-Magnet = Rahmensteerer
- 0.085T

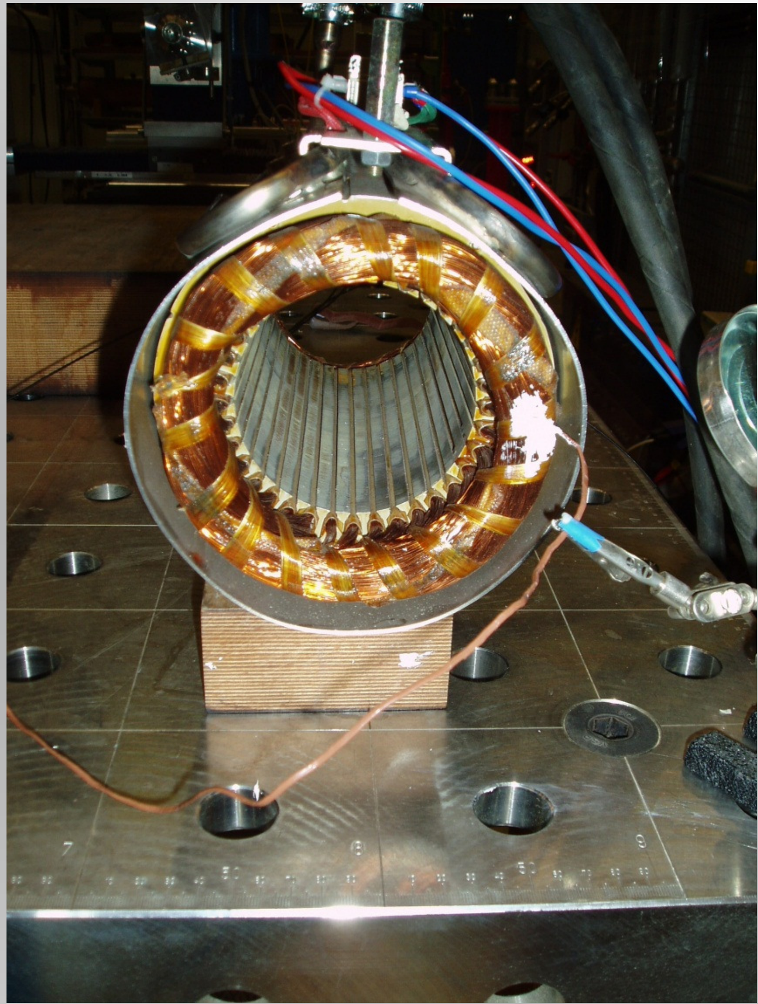




Rohrsteerer

- Stromdominiert im cosθ-Design
- Doppelsteerer
- In den 70er Jahren als Low-Cost-Steerer entwickelt
  - Joch: Standard E-Motor-Stator
- Indirekte Kühlung mit Kühlhemd
- 0.05T





Synchrotron-(Vertikal-)Steerer

- Einfachsteerer -> vertikal
- Window-Frame-Magnet
- Erhöhte Spulensymmetrie
- 0.134T

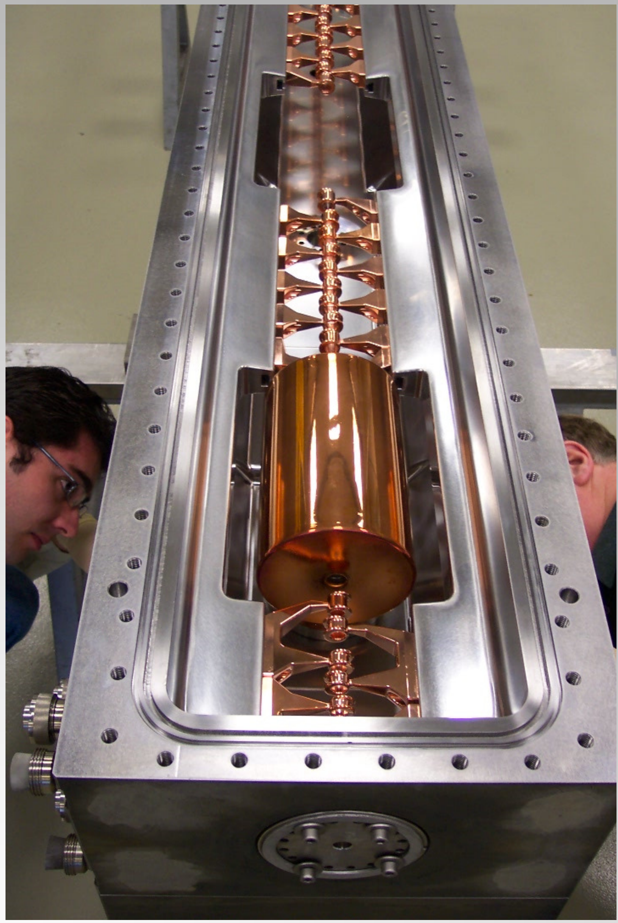
HEBT-Steerer

- Window-Frame-Magnet
- Einfachsteerer = Einbau sowohl vertikal als auch horizontal
- Bild: Horizotal-steerer Gantry
- 0.1 T

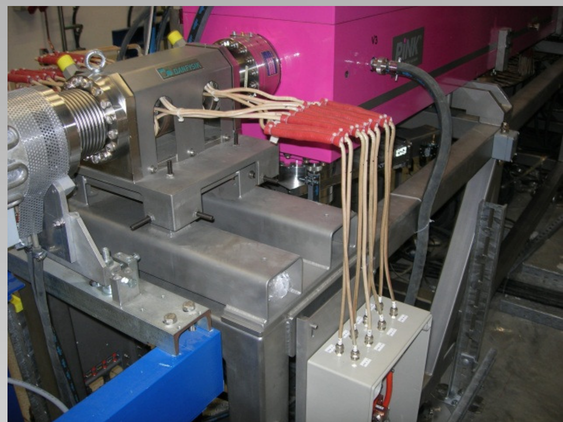
LEBT-Quadrupol

- Quadrupol ohne Polbasisver-breiterung
- Singulett und Triplett
- 3.2T/m

IH-Quadrupole

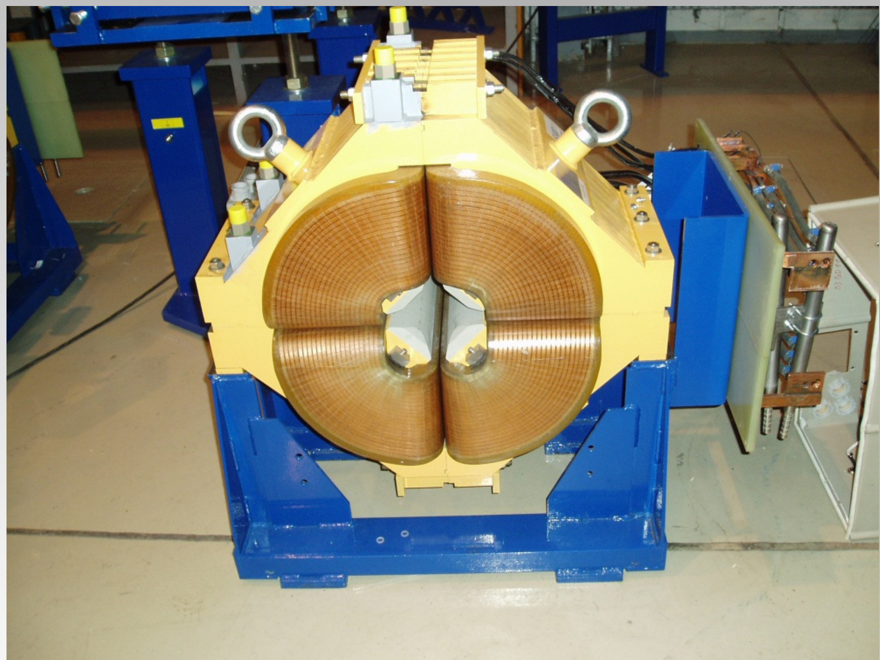


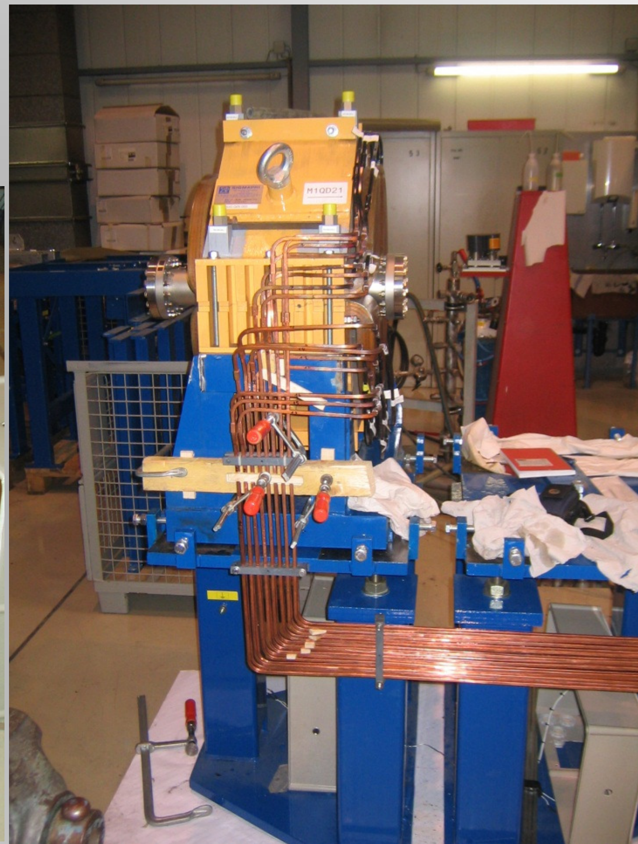
- Kompakte Bauform bei höchsten Gradienten
  - Maximale Polbasisverbreiterung
  - Joch CoFe mit 0.35mm Dicke
  - Einlagige Spule
- Bis 124T/m



MEBT-Quadrupol (3.5)

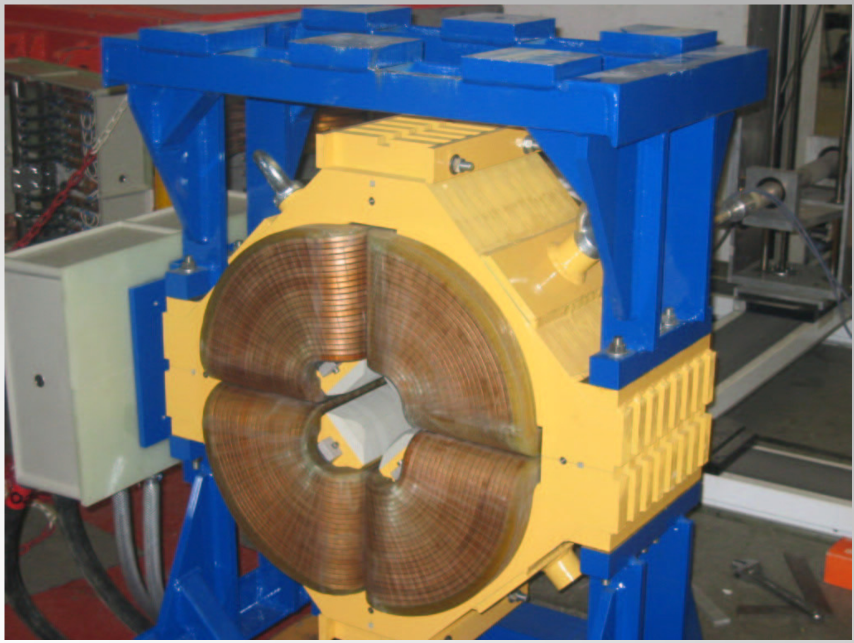
- Maximale Polbasisverbreiterung
- Gleicher Querschnitt wie 3.6 und 3.7
- 18.8T/m





Gantry-Quadrupol (3.6)

- Magnet ist baugleich zu 3.5
- Doppelgestell
- 1 schiefer Quadrupol
- 18.8T/m



HEBT-Quadrupole (3.7)

- Wie 3.5 und 3.6 aber mit längerem Joch
- 19.3T/m

Synchrotron-Quadrupol

- „Figure of 8“-Quadrupol
- Demontierbare Polendstücke für Feldoptimierung und Längenshimming
- 7.0T/m

Solenoid

- 0.54T
- Feld in Strahl-richtung

Sextupol

- Joch dreiteilig aufgebaut
- $d^2B/dx^2=26.7$ T/m^2