Caucasian - German School and Workshop on Hadron Physics

Tbilisi, Georgia

Development of modern magnet systems

a tutorial by

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Development of modern magnet systems

Customer requirements

1) *Charged particles, mass, charge*

- a) Energy, momentum, rigidity B ρ (s. tab.)
- b) Intensity, phase space ε_x, ε_y , δp / p
- c) Time structure, DC, AC beams, macro-, microcycle

2) *Purpose and aims*

- a) Beam transport
- b) Applications e. g.

  Irradiations (food …)

  Isotope production (incl. mass separation..)

  Spectroscopy (energy, mass, time ..

  Medical treatments (voxel scanning, application of

3) *Available space and limitations*

- a) New buildings or tunnels, new radiation shielding
- b) Existing or annexes (*multifloor layout…*)

4) *Expenditures* (*periphery omitted here !*)

I *Hardware*

a) Overall new investments

b) Usage of existing magnets, possibly to be modified

II *Manpower*

a) Customer's manpower *(e.g. formulation of optics concept, engineering, acceptance tests - field mapping - alignment, commissioning…..)*

b) Outside or commercial manpower

III *Operation costs*

a) Power

b) Cooling

c) Backup & spares, preservation investments

d) Maintenance

e) System aspects *(controls, documentation …)*

5) *Performance and reliability*

a) Availibility *(short term ….)*

b) Reprocucibility

6) *Delivery aspects*

ad 1)

a) *The requested <u>rigidity</u> prejudices the technology*:

normal conducting (n. c.) 0.3 T $< B <$ 1.2 (1.5) T

superconducting (s. c.) > 1.5 T

permanent magnet (p. m.) B ~ 1 T

The deflection radius ρ determines size, weight, power and Costs.

b) *The <u>emittances</u> fix apertures, magnet gaps, quadrupole and sextupole … bores.*

N. B. Liouville theorem :

Phase space conservation connects size to divergence :

E. g. For typical ε_x = 5 mm mrad a requested spot of 100 μ

leads to 50 mrad ~ 3 ° duivergence!

c) <u>Time structure</u> of beams lead to specific technologies :

DC : Solid low C iron (n. c.), Rare Earth Co (p. m.)

AC : Laminated poles, yokes

(Ramping, hysteresis effects… steel specs)

ad 2 & 3)

The application of the charged particle beam requires an ion optical concept :

In general:

Start :
A beam of momentum p and emittances ε_x, ε_y, $\delta p / p$.

Destination:

That beam with specified spot size, divergence, momentum and $\Delta p / p$*, as well as time structure.*

In between topological requests and others (shielding, monitoring..)

as well as beam deflection angles, beam rotation have to be met.

Also some optical conditions have to be observed e. g.

$p / dp = D / M \, x \, \rho / x_0$ D = R_{16} - Dispersion

M = R_{11} - Magnification

x_0 - spot size, ρ = bending radius

For economy the beam should be small inside the magnets (axial waist in dipoles) and symmetric in quadrupoles.

Generally one starts with a first order approach using *<u>matrix algebra</u>* *:*

The beam is specified by a 6 - dimensional vector, the elements (magnets and drifts in between etc…) by (6 x 6) matrices, whose elements are derived from a solution of the equation of motion.

$$\boxed{\begin{pmatrix} x_1 \\ x'_1 = \theta_1 \\ y_1 \\ y'_1 = \phi_1 \\ l_1 \\ \delta_1 \end{pmatrix} = \begin{pmatrix} R_{11} & R_{12} & 0 & 0 & 0 & R_{16} \\ R_{21} & R_{22} & 0 & 0 & 0 & R_{26} \\ 0 & 0 & R_{33} & R_{34} & 0 & 0 \\ 0 & 0 & R_{43} & R_{44} & 0 & 0 \\ R_{51} & R_{52} & 0 & 0 & 0 & R_{56} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} x_0 \\ x'_0 = \theta_0 \\ y_0 \\ y'_0 = \phi_0 \\ l_0 \\ \delta_0 \end{pmatrix}}$$

For a particle travelling from A (index 0) to B (index 1)

through drifts L_1 to L_3. a dipole and a quadrupole

the matrices are to be multiplied in <u>opposite</u> direction.

A **L_1** **M_1** **L_2** **Q_1** **L_3** **B**

$$\xrightarrow{\hspace{10cm}}$$

$$\boxed{\begin{pmatrix} x_1 \\ \theta_1 \\ \cdots \\ \delta_1 \end{pmatrix} = R_{L3} * R_{Q1} * R_{L2} * R_{M1} * R_{L1} \begin{pmatrix} x_0 \\ \theta_0 \\ \cdots \\ \delta_0 \end{pmatrix}}$$

The elements of the product matrix defines the optical constraints – typical for single ray optics e. g.

<u>Achromaticity :</u> R_{16} = R_{26} = 0

<u>Isochronicity :</u> R_{51} = R_{52} = R_{56} = 0

<u>Focussing conditions :</u>

<u>*Point to point :*</u> R_{12} = R_{34} = 0

<u>*Parallel to point :*</u> R_{11} = R_{33} = 0

<u>*Parall. to parall.*</u> : R_{21} = R_{43} = 0

<u>*Point to parall.:*</u> R_{22} = R_{44} = 0

(from K. L. Brown, Transport CERN 80 – 04)

Another formulation of this first order matrix is given by

$$\boxed{\begin{pmatrix} R_{11} & R_{12} & .. & R_{16} \\ R_{21} & R_{22} & .. & R_{26} \\ R_{33} & R_{34} & .. & .. \\ R_{43} & R_{44} & .. & .. \end{pmatrix} = \begin{pmatrix} c_x & s_x & .. & d_x \\ c'_x & s'_x & .. & d'_x \\ c_y & s_y & .. & \\ c'_y & s'_y & .. & \end{pmatrix}}$$

These functions of the line element t are called cosine and sinelike of the radial (x) and the axial (y) planes

e. g. in a focus :

$s_x = 0$ and c_x is the radial magnification, also

$$\boxed{c'_x = -\frac{1}{f_x}}$$

and

$$\boxed{\begin{aligned} d_x &= s_x \cdot \int c_x d\alpha \\ d\alpha &= d\tau / \rho_0 \end{aligned}}$$

To enlarge d 'make'
sin-like function large !

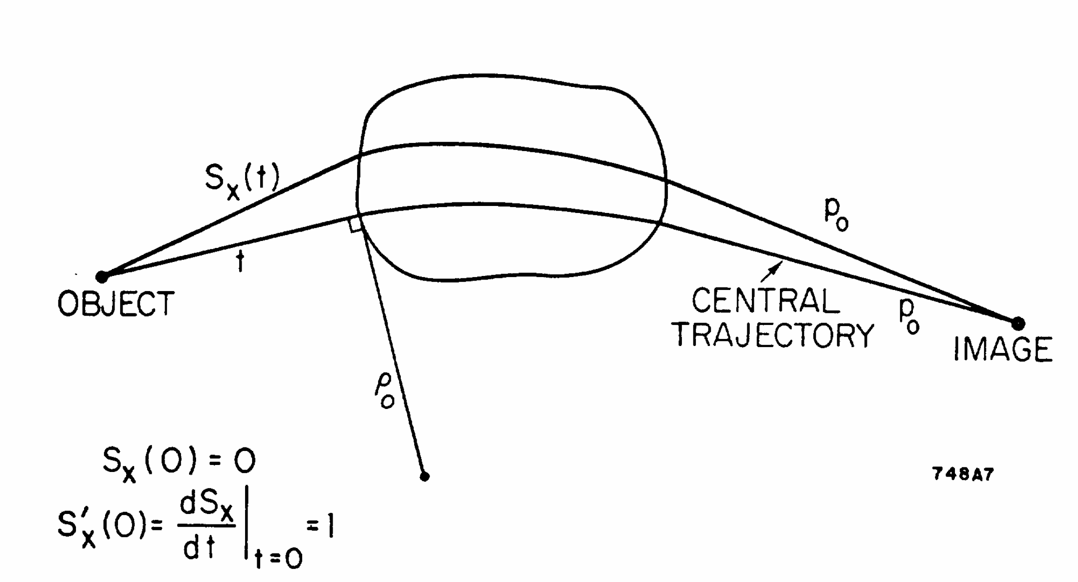


FIG. 4--SINE-LIKE FUNCTION $s_x(t) = R_{12}$ IN MAGNETIC MIDPLANE. $s'_x(t) = R_{22}$.

A beam of particles is assumed to lie in the the boundaries of an ellipse.

With a beam matrix σ_{nm} a beam from A (index 0) to B (index 1) as

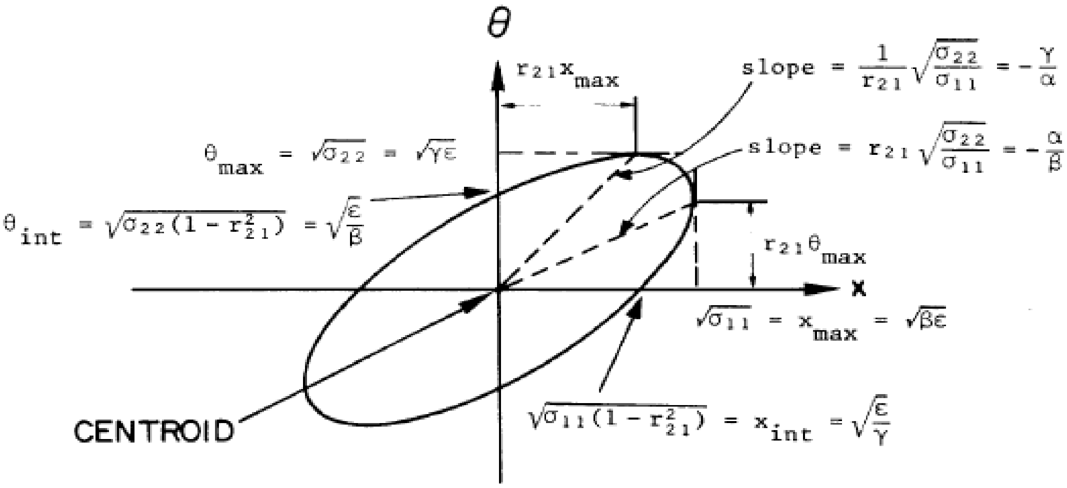
$$\sigma(1) = R\,\sigma(0)\,R^T$$

where T denotes the transpose. The ellipse area equals the phase space.

$$A = \varepsilon_x = \pi\,(\det\sigma)^{1/2} = \pi\,x_{max}\,\theta_{int} = \pi\,x_{int}\,\theta_{max}$$

and $\boxed{x_{max} = \sqrt{\beta_x * \varepsilon_x}}$ $\boxed{\theta_{max} = \sqrt{\gamma_x * \varepsilon_x}}$

(equivalently for axial coordinates)



A TWO-DIMENSIONAL BEAM PHASE ELLIPSE

The equation of the ellipse is

$$\boxed{\gamma\cdot x^2 + 2\cdot\alpha\cdot\theta\cdot x + \beta\cdot\theta^2 = \varepsilon}$$

where

$$\boxed{\sigma = \begin{pmatrix} \sigma_{11} & \sigma_{21} \\ \sigma_{21} & \sigma_{22} \end{pmatrix} = \varepsilon * \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}}$$

The determinant of ***<u>this TWISS matrix</u>*** is given by :

$$\boxed{T = \begin{vmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{vmatrix} = \left(\beta\cdot\gamma - \alpha^2\right)}$$

The transformation of TWISS with R – matrix elements is

$$\boxed{\begin{pmatrix}\beta\\ \alpha\\ \gamma\end{pmatrix}_1 = \begin{pmatrix} R_{11}^2 & -2\cdot R_{11}\cdot R_{12} & R_{12}^2 \\ -R_{11}\cdot R_{21} & R_{11}\cdot R_{22}+R_{12}\cdot R_{21} & -R_{12}\cdot R_{22} \\ R_{21}^2 & -2\cdot R_{21}\cdot R_{22} & R_{22}^2 \end{pmatrix}\cdot\begin{pmatrix}\beta\\ \alpha\\ \gamma\end{pmatrix}_0}$$

*Example:* The TWISS matrix elements for a symmetric drift ($\alpha = 0$) with ist R – matrix is:

$$\boxed{R = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}} \qquad \boxed{\beta_1 = \beta_0 + {\frac{L}{4\cdot\beta_0}}^{2}}$$

In addition we need an additional parameter, the phase shift $\Delta\psi$

$$\boxed{\Delta\psi = \int \tfrac{1}{\beta}\, ds}$$

s - line element along o.a.

(E. D. Courant & H. S. Snyder, Ann. Phys. 3 (1958))

For the beam – characterised by the σ – matrix - there are also constraints, e. g.

Horizontal beam waist $\sigma_{21} = 0$
^ Vertical beam waist $\sigma_{43} = 0$

*In this tutorial we postpone here second and higher order calculations*

Examples for optical modules

A) A telescope

It consists of two thin lenses (in one dimension)

separated by a distance equal to the sum of their

focal length providing simultaneous parallel to parallel
and point to point imaging i. e. $R_{21} = R_{12} = 0$
and a phase shift always equal to n π and $\alpha_1 = \alpha_2$!

For a two - dimensional system 4 quadrupoles are needed

The magnifications of the beam envelopes may either
be the same or different as for

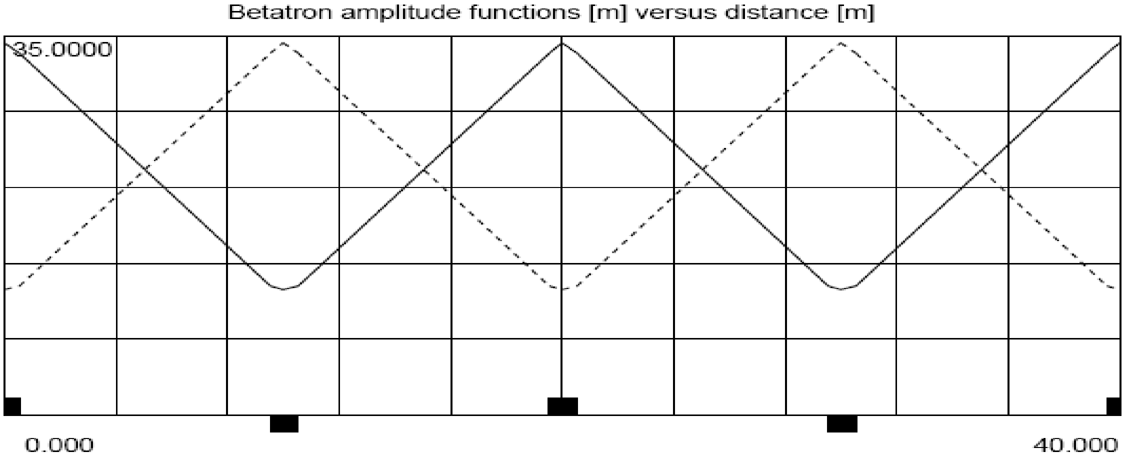
an ideal matching system

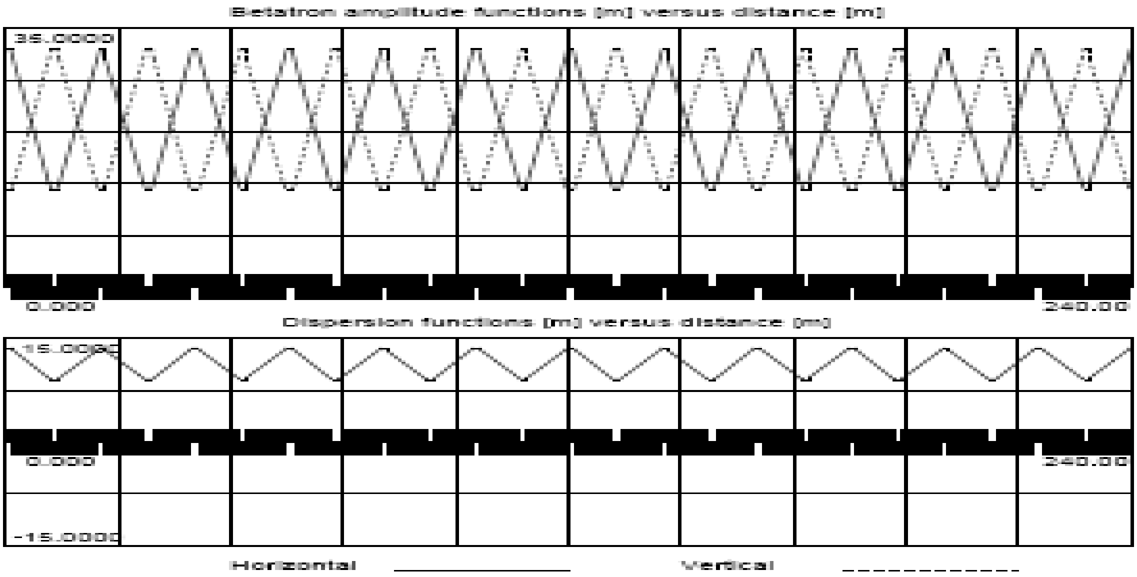
(For further details s. K. L. Brown)

B) An application: The F - O - D - 0 system

The most economic beam transport system consists of idendical cells with focussing (F) and defocussing (D) components separated by a drift (O) .

It may be built with standard n. c. magnets of with permanent magnets.





ad 4)

I Hardware - layout and engineering

This implies another tutorial with lots of details on

- detailed material specifications
- layout considerations (e. g. choice of special design)
- engineering recipes (partly commercial secrets)
- availibility of suppliers and their competence
- fabrication details and involved costs

Before a discussion of detailed results as provided by UGS some useful layout comments:

Relations between particle velovity, momentum and energy (from Bovet, CERN)

In terms of	β	c p	T	E	γ
β =	β	$\underline{((E_0/cp)^2 + 1)^{-1/2}}$ cp / E	$(1 - (1 + T/E_0)^{-2})^{1/2}$	$\underline{(1 - (E0/E)^2)^{1/2}}$ cp / E	$(1 - \gamma^{-2})^{1/2}$
cp =	$\underline{E_0 (\beta^{-2} - 1)^{-1/2}}$ $E \beta$	cp	$\underline{(T (2 E_0 + T))^{1/2}}$ $T ((\gamma + 1) / (\gamma - 1))^{1/2}$	$\underline{(E^2 - E_0^2)^{1/2}}$ $E \beta$	$E_0 (\gamma^2 - 1)^{1/2}$
E_0 =	$\underline{cp / \beta \gamma}$ $E (1 - \beta^2)^{1/2}$	$cp (\gamma^2 - 1)^{-1/2}$	$T (\gamma - 1)$	$(E^2 - c^2 p^2)^{1/2}$	E / γ
T =	$((1 - \beta^2)^{-1/2} - 1) E_0$	$\underline{(E_0^2 + c^2 p^2)^{1/2} - E_0}$ $cp ((\gamma - 1) / (\gamma + 1))^{1/2}$	T	$E - E_0$	$E_0 (\gamma - 1)$
γ =	$(1 - \beta^2)^{- 1/2}$	$\underline{cp / E_0 \beta}$ $(1 + (cp / E_0)^2)^{1/2}$	$1 + T / E_0$	E / E_0	γ

T kinetic energy E total energy E_0 rest energy

$$p\ (\mathrm{GeV}/c) = \underline{0{,}2997925\ B \rho\ (\mathrm{T\,m})} \quad \text{or} \quad p\ (\mathrm{V\,A\,s^2\,m^{-1}}) = e B \rho\ (\mathrm{A\,s\,T\,m})$$

Magnetic elements

Dipole magnet

Rigidity: $B \rho$ (T m) = 3.3356 p (GeV / c)

= 3.1297 $\beta \gamma$ for protons

Deflection angle: θ (deg) = ($L_t / \pi \rho$) 180 L_t - length of particle trajectory

θ (rad) = $B L_t / (B \rho)$

Excitation current: N x I (A turns) = $B h_B / \mu_0$ (mT / H m^{-1}) h_B - mean gap height

e.g. 800 Ampere turns / 0.1 T x 1 cm gap

Stored energy: W_S (W s) = $B^2 h_B w l_B$ ($T^2 m^3 / H m^{-1}$)

l_B - total magnetic length

w – inductance

Power : $\sim I^2 \sim h_B^2$ (proportional to oper. Costs)

Fe - volume :~ length x area (proportional to invest. Costs)

$\sim 1 / B \times B^2$

$\sim 1 / B$

But lower B – field corresponds to larger layout and building costs !

Quadrupole lens

Excitation current per pole : $N_Q \times I$ (Aturns) = $g\ r_Q^{\ 2} / 2\ \mu_0$ (T m / H m^{-1})

g - gradient

r_Q - bore radius

e. g. 400 Aturns/
10 T / m @ 1 cm bore radius

Stored energy: W_Q (W s) = $g^2 r_Q^2 y_{max}$ (y_{max} + 2/3 w_Q) l_Q / μ_0

l_Q – quad length

w_Q - inductance

Power: $\sim\ I^2\ \sim r_Q^4$

Estimate of Magnet Costs by UGS

Magnet type:	**Dipole**	**HEBT DIP1 (fast)**
Quantity		

I. Magnet Parameters

A. Dipole: Magnetic and mechanical specifications

Item		*Unit*	*Customer Req.*
Gapheight	**80**	**mm**	**yes**
Beam radius max	35	mm	
B-field max (gap)	**1,600**	**T**	**yes**
B-field max (yoke)	**1,77**	**T**	**yes**
Width (good field region)	**122,5**	**mm**	**yes**
Field quality dB/B	**0,004**		**yes**
Magnet strength (B x Leff)	2,355	Tm	
Effective field length	**1,473**	**m**	
Length of steel body	1,416	m	
Length total	1,758	m	
Horizontal size total	0,946	m	
Vertical size total	0,746	m	
Total weight (Fe& Cu)	7,159	t	
Provision of shims			**yes**
Shim width relative	0,2500		
Shim width abs	**10,0000**	**mm**	**yes**
Shim height relative	0,0475		
Shim height abs	**1,9000**	**mm**	**yes**
Chamfer in	**83**	**deg**	**yes**
Rogowski radius ratio	0,209		

B x rho max	18,00	Tm	
Bend angle	**7,500**	**deg**	**yes**
Bend angle	0,131	rad	
Bending radius	**11,250**	**m**	**yes**
Edge angle entrance	0,00	Grad	
Edge angle exit	0,00	Grad	

B. Dipole: Electric specifications

Item		*Unit*	*Customer Req.*
Number of coils	**2**		
B-field ramp rate	**8**	**T/s**	**yes**
B-field rise time	**0,2**	**s**	
Pulse rep. rate	**10**	**Hz**	
Resistance per magnet	**0,029359323**	**Ohm @ 20deg**	
Current (max)	**1086**	**A**	
Voltage per dipole (max)	**31,9**	**V**	
Driving voltage	**4163**	**V**	
Inductivity	**95**	**mH**	
Power per magnet	**35**	**kVA**	

Copper conductor specs

Current density	**4,476**	**A/mm^2**	**yes**
Copper layers hor.	**8**		**yes**
Copper layers vert.	**6**		**yes**
Material (Outukumpu No.)	**8473**		
Insulation thickness	**0,5**	**mm**	**yes**
Pancake insulation (ground)	**1**	**mm**	**yes**

C. Dipole: Cooling specifications

Delta T in	**30**	**deg**	**yes**
Temp Coolant in	28	deg	
Pressure max in	12	at	

II. Dipole engineering design

A. Estimated working time

Magnet design (total)	10	weeks
Drafts man design	400	mh (technician)
Engineering design	24	mh (engineer)
Documentation, specs	16	mh (engineer)
3 D field design for higher quality magnet	40	mh (engineer)

B. Relevant salaries

Engineer	120	k€/y
Technician	100	k€/y
Trained workman	80	k€/y
working hours per year	1760	h

III. One- time investment for the magnet type

A. Tools and other provisions

1. Iron: yoke and poles

Stamping tool	remark 1	22000	€
Table for stapling of lam.	remark 2	50000	€
Frame for stapling	remark 3	2000	€
Oven for glueing	remark 4	240	€
Lifting console	remark 5	800	€
		75040	

Remark 1 : 50 000 stamps per tool are asumed. Control and sharpening after 5000 stampings:
1 man day (workman) + 0.5 man day (engineer) are assumed.
Remark 2: The stacks of laminations have to be stored in suitable forms before they are inserted
into the oven with a suitable lifting tool. The costs vary with size and weight. Here the
share for this magnet type has been roughly estimated.
Remark 3: The number stapling frames depends on the efficient manufacturing process.
Here 2 frames for each magnet type are assumed.
Remark 4: The operational costs for the oven are roughly estimated.
Remark 5: The lifting console is used for manipulating the magnet during stapling and remachining.

2. Coils

Winding frame (2)	remark 3	800	€
Oven for bakeout	est. share in cost	400	€
Coil support table	"	500	€
Vessel for glueing	"	370	€
		2070	

B. Working time

1. Iron: yoke and pole pieces

Stamping tool control, sharpening	see remark 1	1	md W / 5000 punches
		0,5	md E / 5000 punches
Preparations	remark 6	500	€
		*workman	**engineer

Remark 6: The stacks of laminations have to be stored in suitable forms before they are inserted
into the oven with a suitable lifting tool. The costs vary with size and weight. Here the
share for this magnet type has been estimated.

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2. Coils

Preparations winding frames	remark 3	400	€

IV. Material costs

1. Iron: yoke and poles

Lamination	number of laminations	1374	
Lamination	thickness	1	mm
Coated lamination	price per kg (20% loss)	1,30	€
Weight (total)		5384	kg
Cost steel	per magnet	8399	€
Dowel pins	3 per yoke	360	€

2. Coils

Raw conductor cost	price per kg	14	€
Weight (total)		834	kg
Insulation	ins. coating (glas fiber)	0,4	€/m
inlets	no. of inlets per magnet	2	
cost copper before winding		23639	€
Connector box	electr. & water	2080	€
Coil fix. to yokes	8 per coil	524	€

3. Periphery

Magnet support	gross price frame	2216	€
Aligment feet (incl. fixings)	3 per magnet	2550	€
Alignment target+sockets	3 sockets 1 target	810	€
Crating	for shipping	454	€

V. Working costs

1. Iron: yoke and poles

Estim. labour costs	stamping	420	€
	stacking	4165	€
	welding of belt	364	€
	machining of pole profiles	736	€
	fix. for coils	364	€
	maching of ref. surfaces	0	€
	dowel pin fitting	552	€
	assembling	318	€
	mech. tests/ qual.control	170	€
	prep. for shipment	182	€
	onsite acceptance	227	€

2. Coils

Estim. labour costs	winding	503	€
	insulation	150	€
	bake-out	288	€
	soldering of connectors	142	€
	prep. for shipment	182	€
	onsite acceptance	1364	€

3. Periphery

Estim. labour costs	machining of suppport	4,46	K€
	prep. for shipment	294,48	€

VI. Operational costs for 1 dipole

Assumed operation	hours	5000	h / a.
Estim. annual expenditures	cooling	5,2	k€
"	power	17,3	k€
"	renewal (10%)	16,6	k€
Total operation cost		39,1	k€ / a.
Ratio invest. to ann. op.	see VII.	4,2	

VII. Total investment costs

Estim. price per magnet	**steel & coils & support**	**75**	**K€**

Magnet price x quantity	**"**	**822**	**K€**

Magnet & p.s.+cooling	**investment cost**	**166**	**K€ / magnet**

Rel.cost (breakdown)	**price / kg magnet**	**14**	**€/Kg magnet**
	Price / kg coil	**31**	**€/Kg coil**

Costs depending on manufacturer

Shipment incl. handling	**?**	**€**
Add. charges (e.g.insurance)	**?**	**€**
Profit and risk factor	***?***	
Inflation (scaling formula)	**?**	**for next n years**