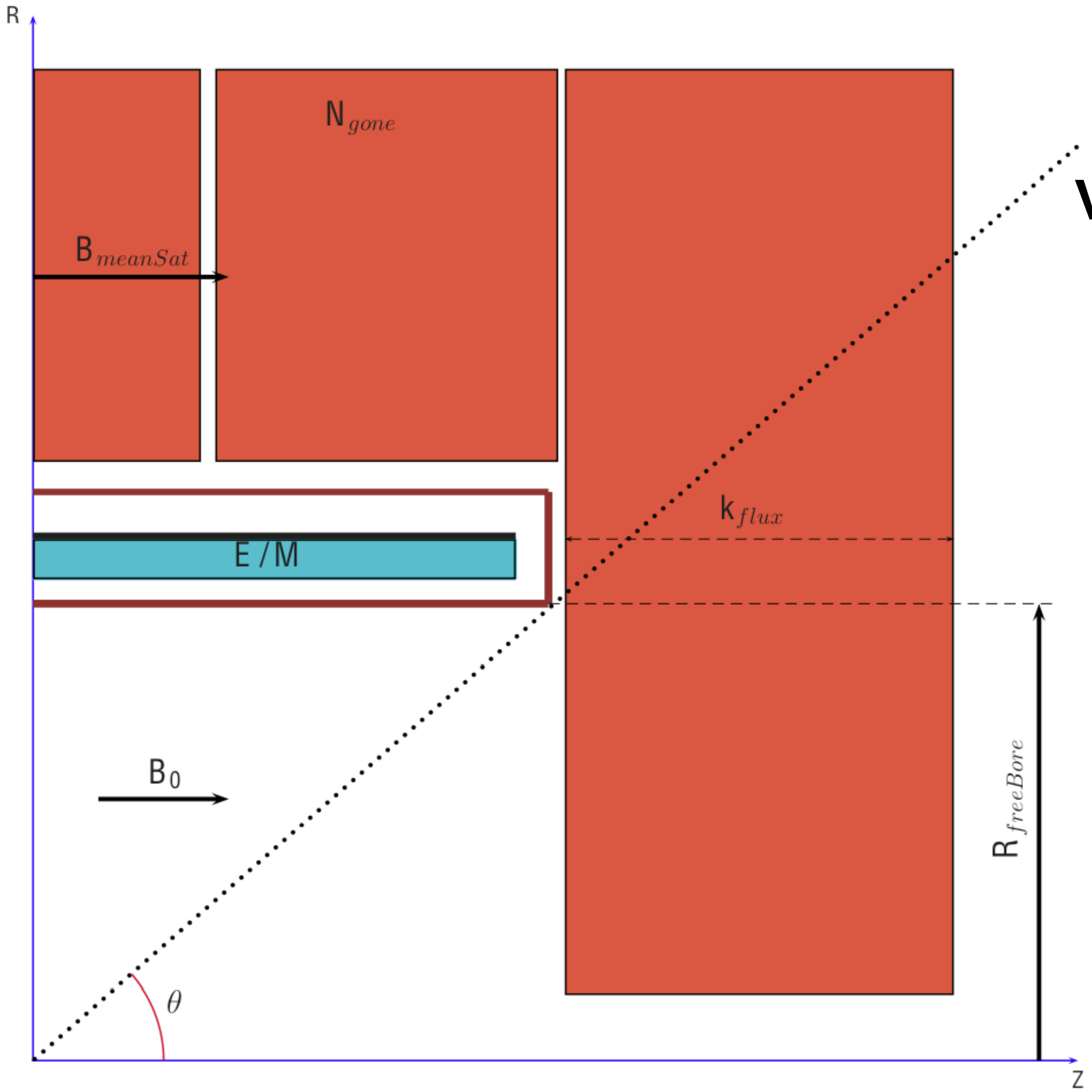
Parametric Model for Yoke + Coil

A. Hervé/ETH Zürich @ CERN

Parametric Model for Coil+Yoke



Valid for CMS SiD ILC and CLIC

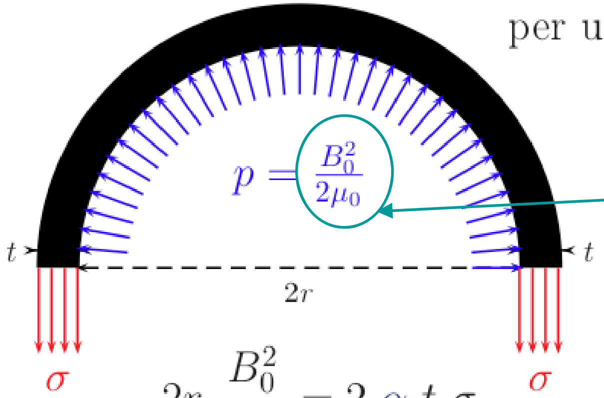
Definition of Main Parameters

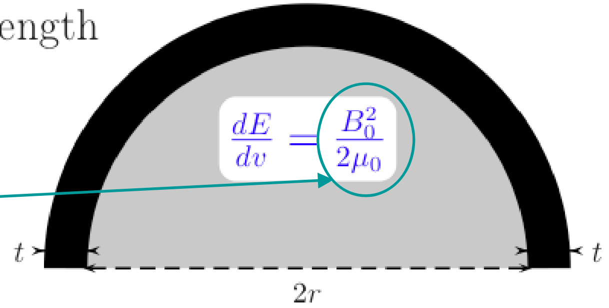
- B0: Central Induction
- RfreeBore: Inner Radius of Vac tank
- theta: Distribution Barrel/Endcap
- BmeanSat: Mean Saturation of Iron in Central Plane
- kflux: Fraction of Flux crossing Endcap at RoutWinding
- Ngone: Yoke number of sides of polygon
- E/M: Ratio of Magnetic Stored Energy per kg of Cold Mass

Specific Stored Energy Vs. Strain Coil is a Thin Tube

Force consideration | **Energy consideration**

per unit length





$$2r \, \frac{B_0^2}{2\mu_0} = 2 \, \alpha \, t \, \sigma$$

α : ratio of structural material

$$\frac{B_0^2}{2\mu_0} \, \pi r^2 = 2\pi r t \, \rho \, \frac{E}{M}$$

ρ : density of aluminum

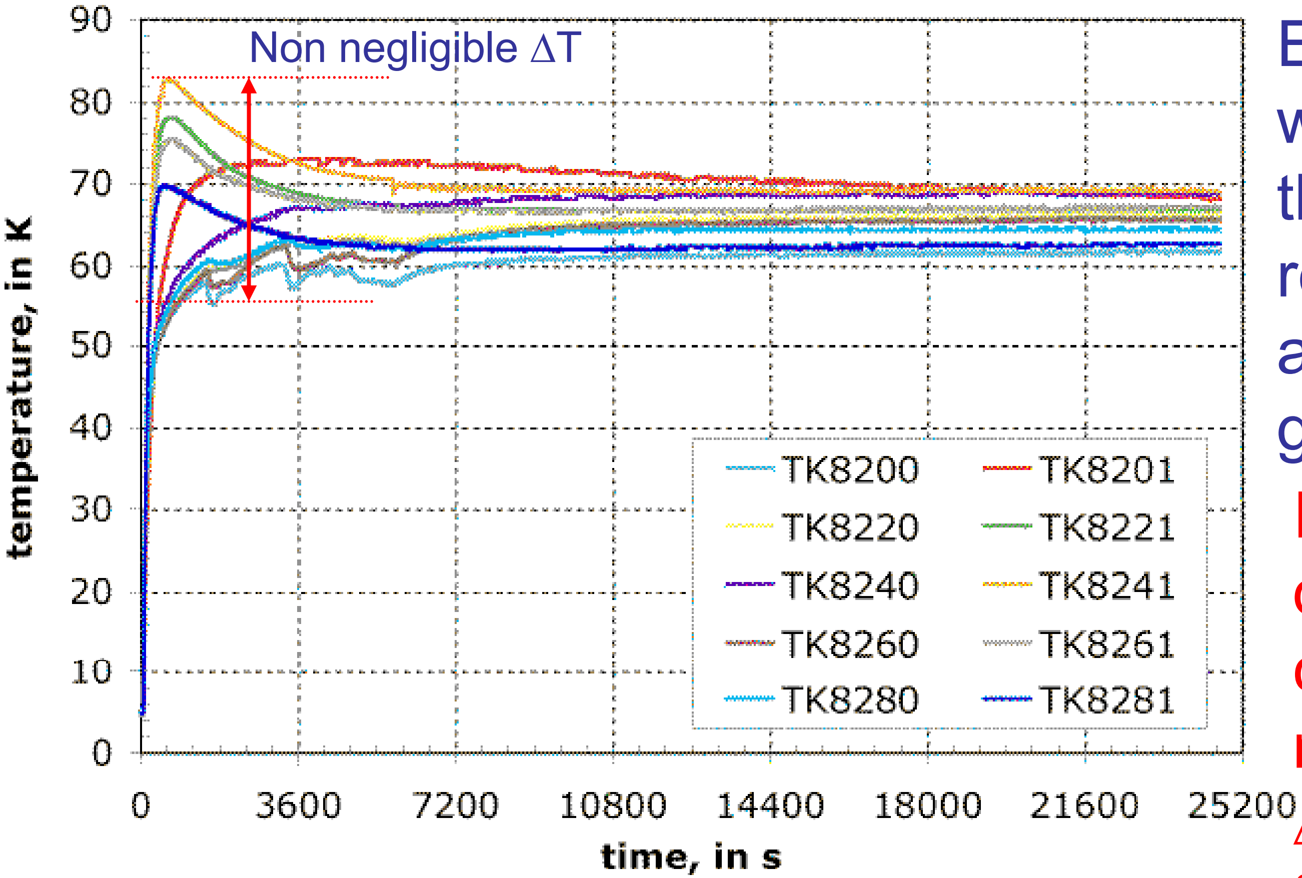
with hoop strain $\epsilon = \frac{\sigma}{Y}$ then : $$\frac{E}{M} = \alpha \, \frac{Y}{2\rho} \, \epsilon$$

Y : Young's modulus of aluminum

This is the limiting factor!

Temperature distribution in CMS coil during a fast dump with 50% extraction and E/M=12kJ/kg

Fast dump analysis in CMS



With E/M=12kJ/kg, when all is OK, the mean Temp. reaches 70K with a thermal gradient of 25K.

If all the energy is dumped in the coil the Temp. reaches 130K + ΔT, and this is a 'safety limit'!

B_0 and r do not appear in the Formula

$$\frac{E}{M} = \alpha \frac{Y}{2\rho} \epsilon$$

0.6 in CMS conductor **< 1**

Neither B_0 nor r appear in the formula!

$\Rightarrow$ When increasing B_0 or r more material has to be added to maintain E/M at the same value of 12 kJ/kg.

$\Rightarrow$ This material is available to limit the strain at 0.15 %, or less if α can be increased.

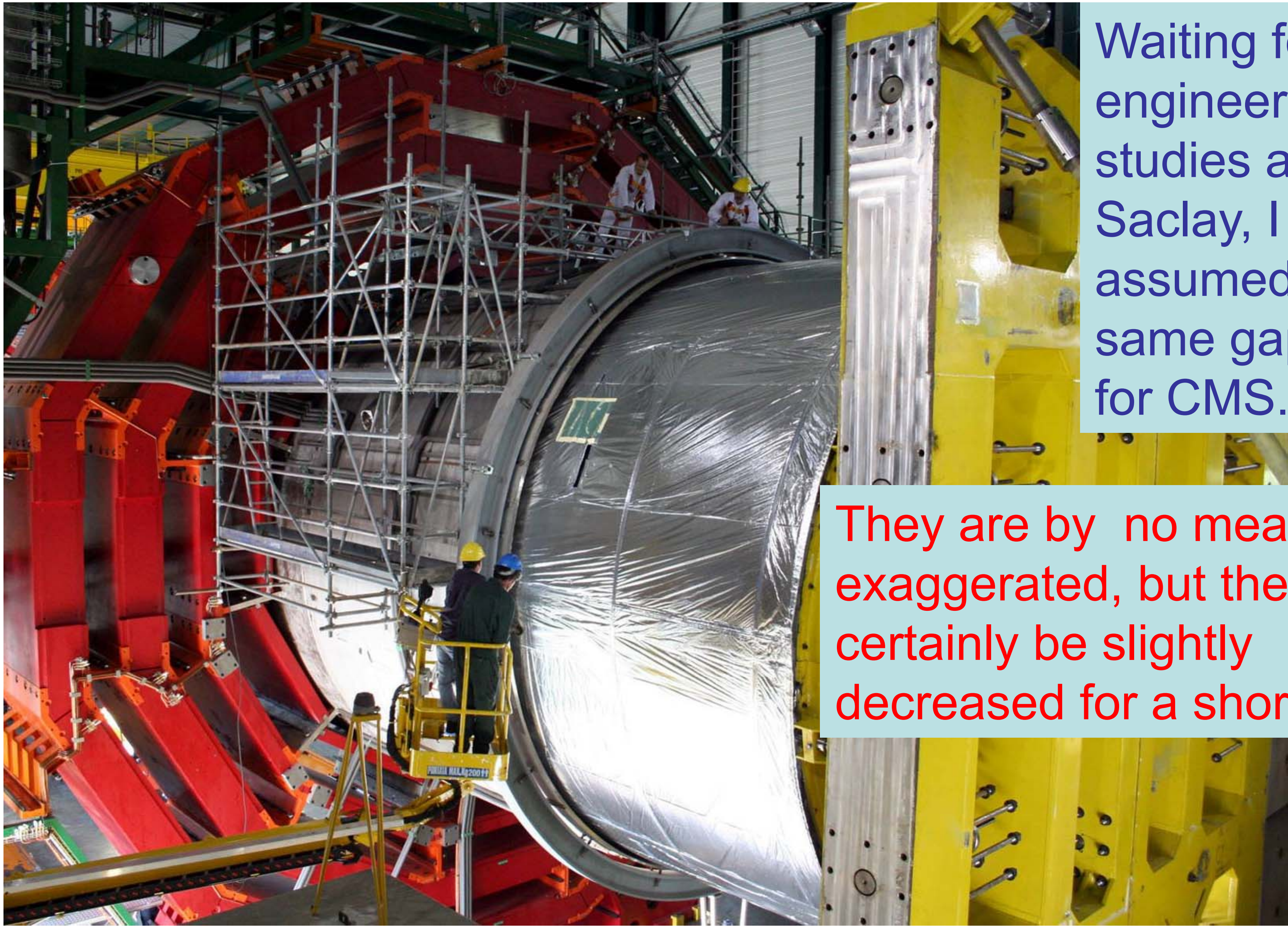
B_0 and r do not appear in the Formula

Thus there is nothing magic with B_0 or r!

However, B_0 and r are not without influence on difficulties and cost!

Not forgetting the cost of the return yoke if one wants to limit the stray field!

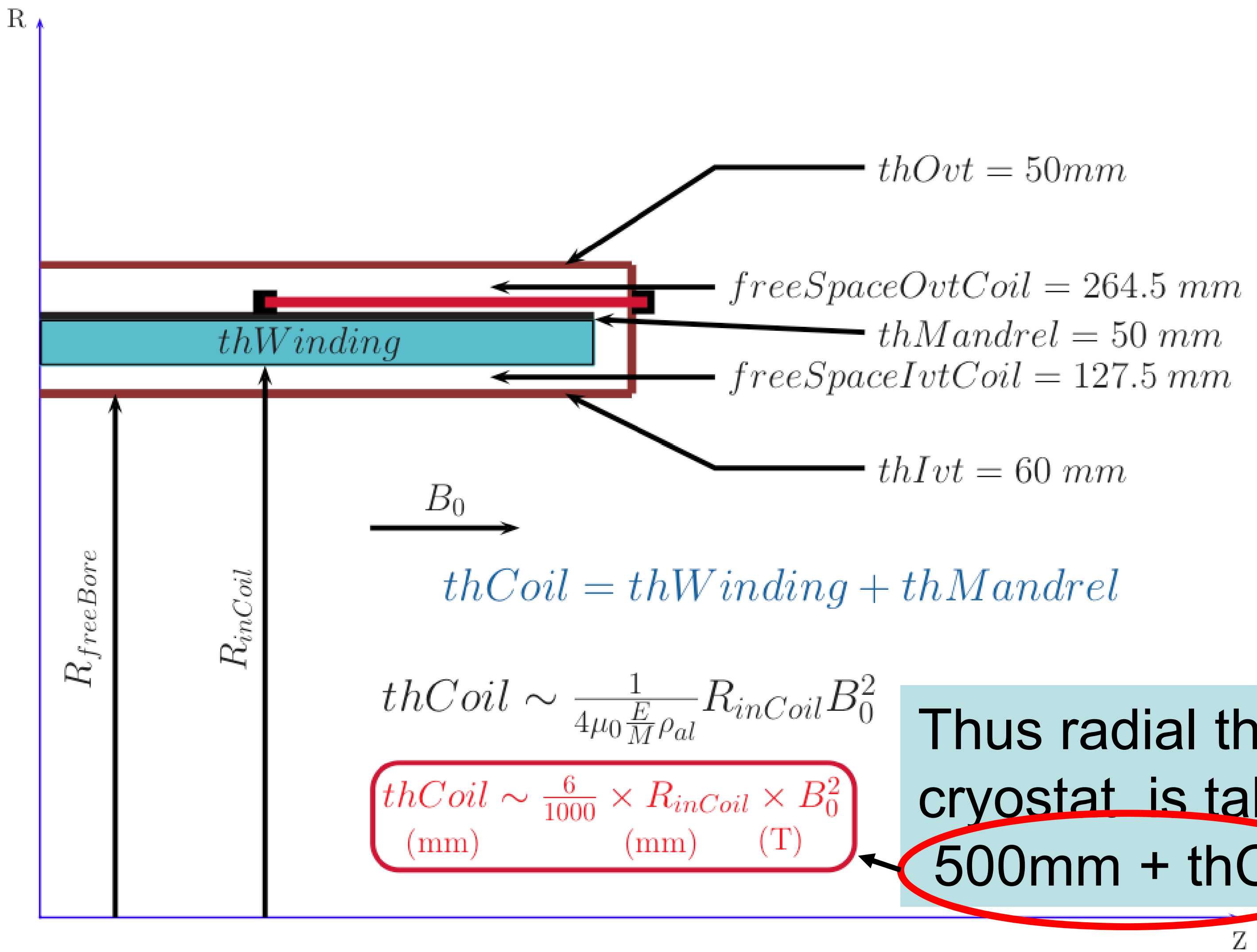
Radial gaps in Coil System



Waiting for new engineering studies at Saclay, I have assumed the same gaps as for CMS.

They are by no means exaggerated, but they can certainly be slightly decreased for a shorter coil.

Radial gaps in Coil System



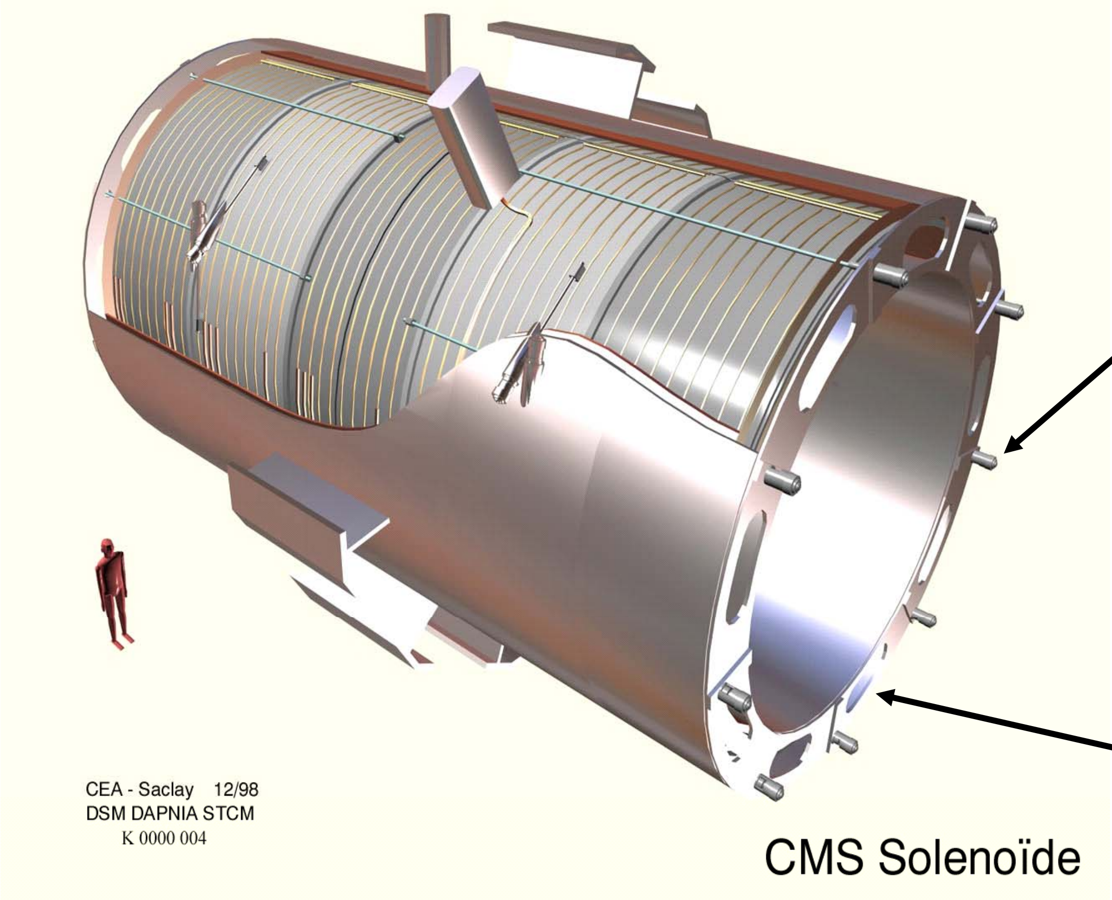
$$thCoil = thWinding + thMandrel$$

$$thCoil \sim \frac{1}{4\mu_0 \frac{E}{M} \rho_{al}} R_{inCoil} B_0^2$$

$$\underset{(mm)}{thCoil} \sim \frac{6}{1000} \times \underset{(mm)}{R_{inCoil}} \times \underset{(T)}{B_0^2}$$

Thus radial thickness of cryostat is taken as 500mm + thCoil

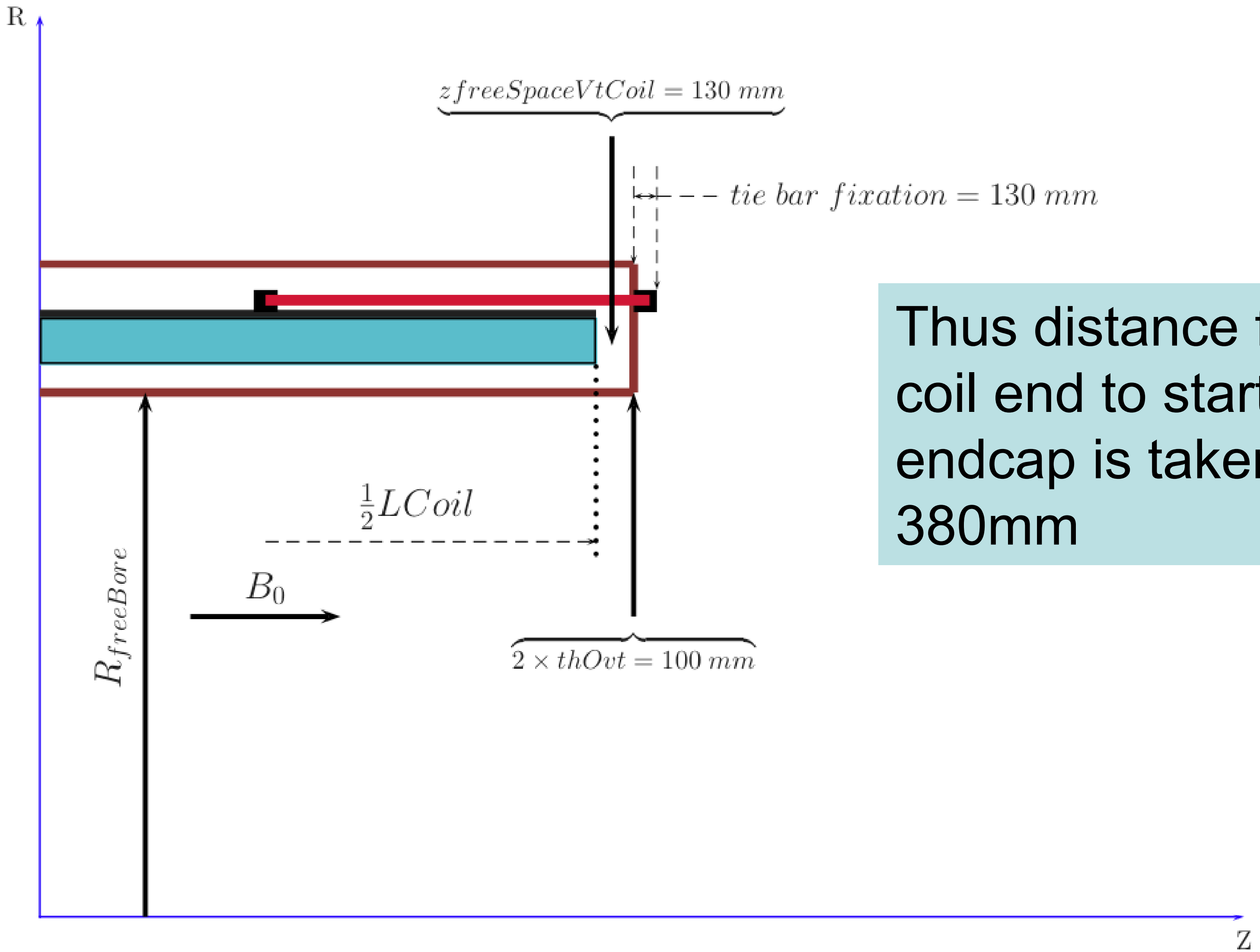
Z gaps in Coil System



Tie bars to stabilize the cold mass inside the Vac Tank. They protrude!

The flange is a complex structure

Z gaps in Coil System



Thus distance from coil end to start of endcap is taken as 380mm

Parametric Model for ILD-Results-I

For exemple here: 4T and RfreeBore=3440mm 1/2LBarrel= 3.992 m (ILD0)

Status	Input	Name	Output	Unit	Comment
					Simulation of ILD 4T/3.44m/4m -- 17 January 2009
					--
	4	B0		T	Central field
	3,44	RfreeBore		m	IVT inner radius
	41,2903511	θ		deg	Tan(θ)=RfreeBore/LoutOVT
	12	EoverM		kJ/kg	Specific magnetic energy=>Temperature after Dump
	2	BsatBarrel		T	Mean saturation in central plane of Barrel Yoke
	,712	coefFlux		-	percentage of Flux going through Endcap
	12	Ngone		-	Number of sides for Barrel yoke
					--

Parameters adjusted to get the yoke thicknesses of ILD0

Parametric Model for ILD-Results-II

	RoutIvt	3500	mm	IVT outer radius	
	RinCoil	3627,5	mm	Coil inner radius	← **+50 mm**
	RoutWinding	3930,1	mm	Winding outer radius	
	RoutCoil	3980,1	mm	Coil outer radius	← **+50 mm**
	RinOvt	4244,6	mm	OVT inner radius	
	RoutOvt	4294,6	mm	OVT outer radius	← **+100 mm**
	RinBarrel	4444,6	mm	Yoke inner radius	
	ThIroninBarrel	2390,3	mm	Thickness of iron in Barrel	← **+100 mm**
	ThBarrel	2790,3	mm	Thickness of Barrel Yoke	
	RoutBarrel	7235	mm	Outer radius of Barrel on flats	← **+100 mm**
				--	
	LoutOVT	3917	mm	Half outer length of OVT	
	LCoil	3667	mm	Half length of coil	
	LBarrel	3992	mm	Half length of Barrel	
	ZbeginEndcap	4042	mm	Start iron for Endcap	
	ThIroninEndcap	2588,3	mm	Thickness of iron in Endcap	
	ThEndcap	3088,3	mm	Thickness of Endcap	
	ZendEndcap	7130,3	mm	Stop iron for Endcap	

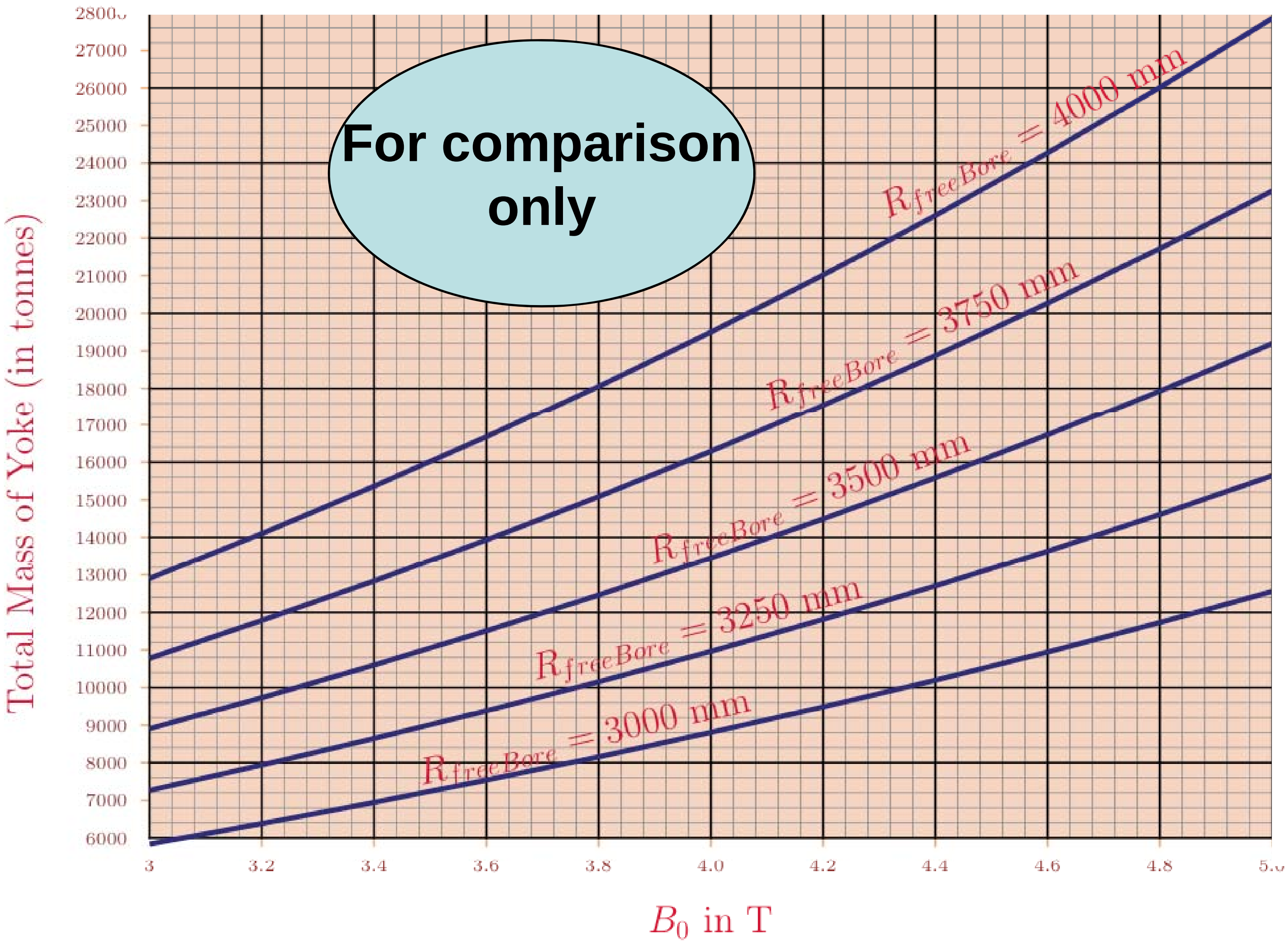
Parametric Model for ILD-Results-III

	ThWinding	302,6	mm	Thickness of Winding
	ThCoil	352,6	mm	Coil thickness (Winding + Mandrel)
	Flux	179,54	Wb	Flux
	StoredEnergy	2,04	GJ	Stored Magnetic Energy
	MassCoil	170	t	Mass of the coil including mandrel
	MassBarrel	5520	t	Mass of Barrel
	MassOneEndcap	3398	t	Mass of one Endcap
	MassYoke	12316	t	Mass of Yoke = Barrel + 2*Endcaps

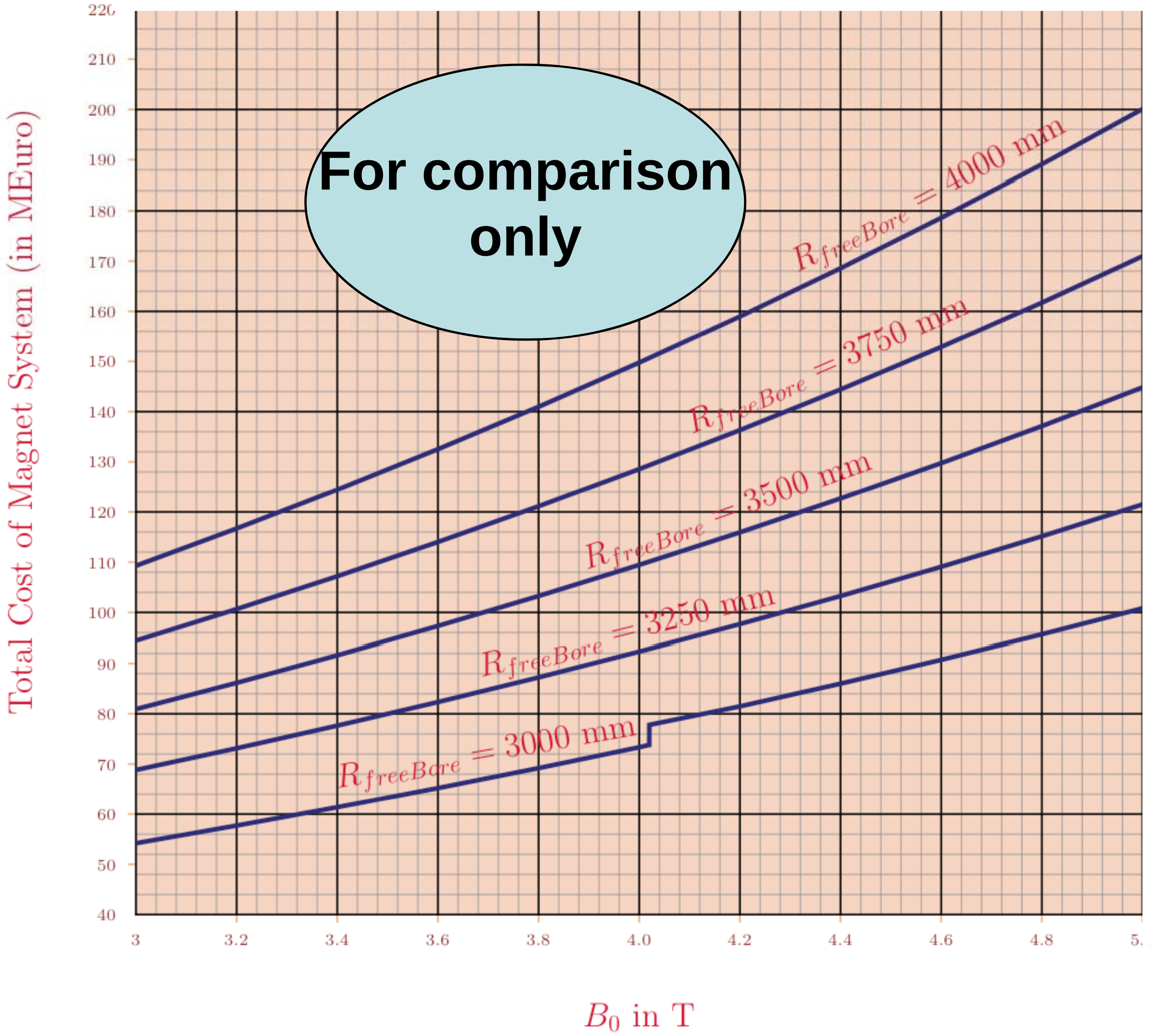
Parametric Model for ILD-Results-IV

Status	Input	Name	Output	Unit	Comment
					--
	3,5	PriceIronperKg		Euro	unit price of iron yoke including assy: 2000 prices
		PriceYoke	43,1	MEuro	2000 price of Yoke Structure, including assembly
		PriceYokeAncillaries	8,5	MEuro	2000 price of Yoke ancillaries and moving system
		PriceCoil	37,6	MEuro	2000 price of Coil + VT plus all ancillaries
		overCostSiteWinding	4,8	MEuro	=>Site winding if RoutCoil > 3.5 m
		TotalCost2000	94	MEuro	2000 price of Magnet System
	10	CumulativeInflation		%	cumulative inflation since 2000
		TotalCostActualized	103,4	MEuro	Actual Cost of Magnet System

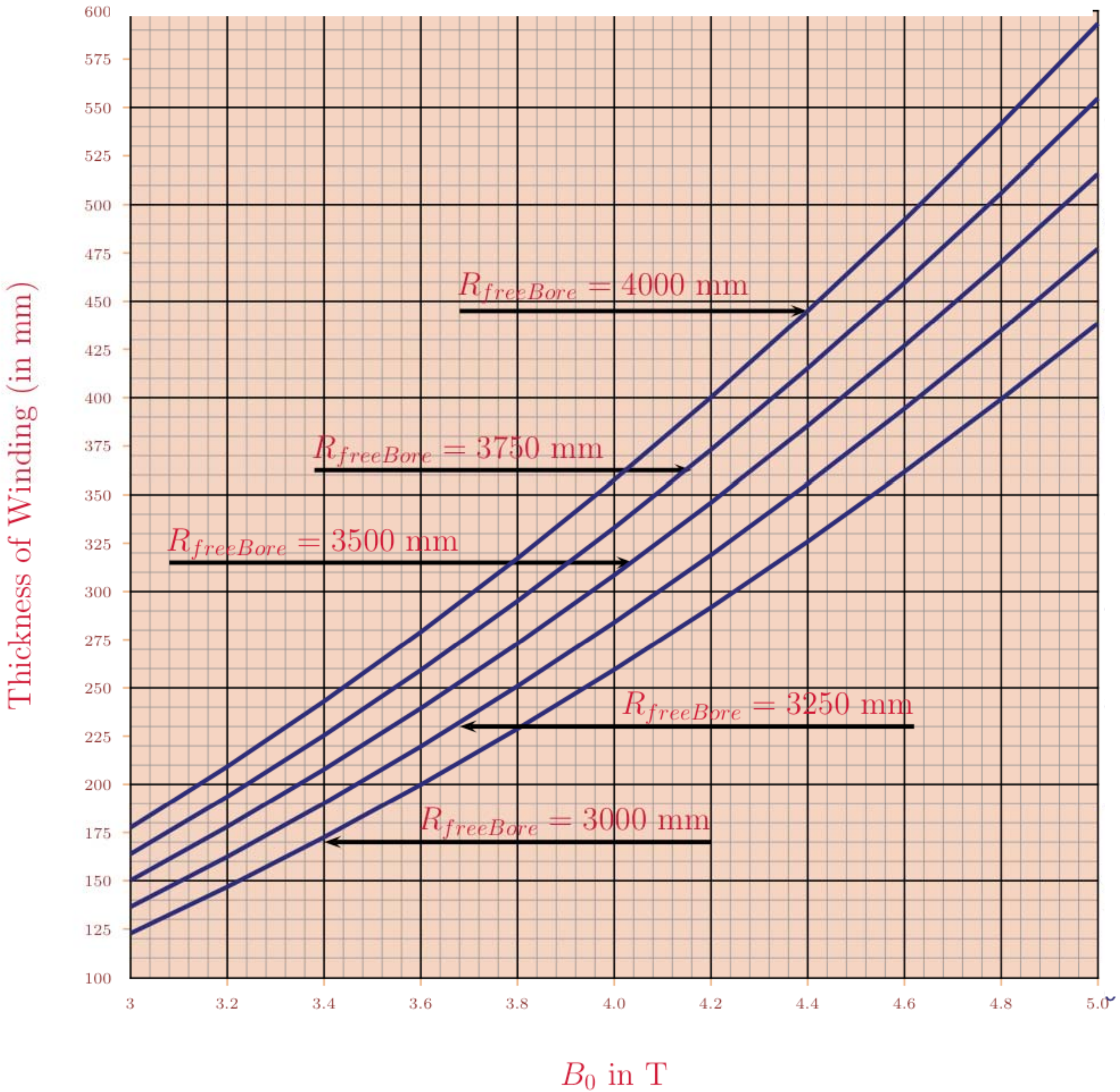
Mass of Yoke in tonnes



Total Cost of Magnet System in M€



Thickness of Winding (in mm)



Conclusions-I

- The only parameter to watch is the non negligible increase of current in the side modules to better homogeneity.
  As mentioned by Kircher, to respect both E/M and strain in these modules without increasing the coil thickness, the use of the upgraded conductor proposed by CMS two years ago, is mandatory
- It is thus important to launch the industrial R&D development program proposed already one year ago by CERN, Saclay and Genova, to replace pure aluminum by “Yamamoto’s alloy”.

Conclusions-II

- There is large penalty in cost to increase RfreeBore
- There is another one to increase B0, and technical difficulties for the coil are increased for B0 > 4T
- A heavy yoke brings further penalties in logistics in particular in the push-pull scenario
- The increase of current in the side modules to better homogeneity needs to be confirmed by the R&D program
- Otherwise I find the ILD choice (3.5 -- 4T, 3440mm) a good choice