Mini-workshop

DESIGNING A SYNCHROTRON LIGHT SOURCE

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Introduction

- **AIM:**
  Upgrade a synchrotron light facility with a new 3 GeV high-brightness ring. Keep the existing 2 GeV injector.

- **ASSUME:**
  The existing injector operates at 500 MHz. It ejects pulses of 225 consecutive bunches with 4×10^{10} electrons per bunch with a duty cycle of 5 s, 1-σ, emittances of 0.15 π mm mrad horizontally and vertically, 1 per mil momentum spread and a full bunch length of 40 ps (12 mm).

- **REQUIREMENTS FOR THE NEW RING :**
  Space limitations restrict the new light source ring to a circumference of less than 700 m. The lattice should have 2 superperiods connected by 2 dispersion-free regions to be used for RF, injection, extraction and any other special functions.

  Each superperiod should have 12 bending cells of the DBA type. The RF system shall operate at 500 MHz and be able to accelerate from 2 GeV to 3 GeV and to compensate radiation losses.

  Aim for the smallest possible equilibrium horizontal emittance and indicate how to improve the brilliance.

Strategy

- **We will start by working together in the Computer Laboratory.**
- **We will follow a written recipe for building a Basic DBA Cell and then copying this cell to make a Basic Ring.**
- **This will provide everyone with a simple working design, introduce them to the DBA culture and will familiarize them with the program WinAGILE.**
- **The use of MAD or any other program is encouraged. It is always good practice to compare results.**
- **We will then distribute the work between Task Working Groups. Each group will try to improve and embellish the basic design. The working groups should be flexible.**
- **Please use the lectures, the library and the internet and question JUAS lecturers and the staff when visiting laboratories to learn what you need to know.**
- **We will now choose a Project Leader and the Task Working Groups…**

Organisation

Project Leader :

Organizes the parameter list, coordinates the design, co-ordinates the presentation, and makes executive choices between proposals.

Task Working Groups :

1. **Lattice.** **Try to improve the cell design. Define apertures. Get radiation parameters.**
2. **Lattice links.** **Create dispersion-free, 1:1 1:-1 modules to link the 2 half arcs and create the final ring with the Lattice Group.**
3. **RF system.** **Define RF system. Define the RF programmes (frequency, voltage and phase).**
4. **Chromaticity control.** **Start with basic cell.**
5. **Tune control.** **Work with Lattice links.**
6. **Resonance excitation/Dynamic aperture.** **Work with Chromaticity Control Group.**
7. **Closed orbit correction and prognosis.** **Start with basic cell.**
8. **Injection and extraction insertions.** **Start with basic ring.**
9. **Effects of space charge.**
10. **Magnets design.**
11. **Vacuum system.**
12. **Theory.**
13. **Other proposals.**

Parameter List spreadsheet

	A	B	C	D	E	F
1		**Parameter List for Synchrotron Light Source**				
2	***Bold entries can be edited and the spreadsheet will recalculate.***					
3						
4	**Constants:**					
5	Electron mass [GeV]		**0.000510999**			
6	Velocity of light [m/s]		**2.9979E+08**			
7	Electronic charge [A s]		**1.6022E-19**			
8	Free space permeability [H/m]		**1.2566E-06**			
9	Free space permittivity [F/m]		**8.8542E-12**			
10	Free space impedance [Ω]		**3.7673E+02**			
11	Planck's constant/π [J s]		**1.0546E-34**			
12	Classical electron radius [m]		**2.81794E-15**			
13						
14	**Beam from**	Kinetic Energy [GeV]	**2**		Momentum [GeV/c]=	1.999999935
15	**Existing Injector :**				Relativistic beta =	0.999999967
16					Relativistic gamma=	3913.901984
17					Magnetic rigidity [Tm]=	6.671336
18						
19		RF [MHz]	**500**		Bucket spacing [m]=	0.59957998
20					Bucket spacing [s]=	2.0000E-09
21					Free space wavelength [m] =	5.9958E-01
22		No. of bunches in a train	**225**			
23		No. of electrons in a train	**5.00E+10**		No. of electrons per bunch=	2.2222E+08
24					Length of bunch train [m]=	134.905496
25					Duration of bunch train [s]=	4.5000E-07
26		Duty cycle [s]	**5**			
27						
28		Geom. H emit. [π mm mrad]	**0.15**		These values describe beam quality at injection.	
29		Geom. V emit. [π mm mrad]	**0.15**		The values will decrease due to damping after	
30		Energy spread *ΔE/E*	**1.00E-03**		injection in the Main ring.	
31		Full bunch lgth [ps] =	**40**		Full bunch lgth [m] =	0.0120

- **You will find this Parameter List on your CD-ROM. It is incomplete, but holds the input data for the project. The first part shown above concerns the injected beam.**
- **The left hand side is input data that can be edited and the right hand side is calculated.**
- **The Project Leader's job is to add the new data of the team's design and to make it all work!**

Parameter List continued

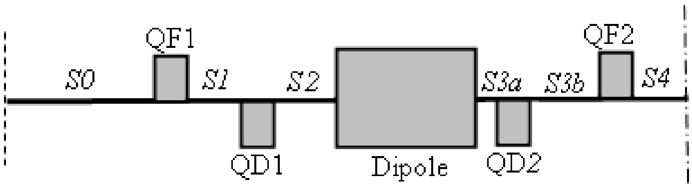
BASIC RING DESIGN				
Main Synchrotron:	Bunch to bucket transfer.		Assume beam is matched, no blowup and no loss.	
	Kicker rise/fall time [ns]	**50**	Gap needed between trains	
			[no. of empty buckets]	25
	No. of trains injected	**4**		
			Total no. of electrons injected=	2.0000E+11
			Circumference [m]=	599.579980
			Average radius [m]=	95.42611766
	No. cells	**24**	Length of cell [m]=	24.982499
	Dipoles per cell	**2**	Dipole bending angle[rad]=	0.130900
	Magnets :			
	Length of dipole along orbit [m]	**1.2**	Total dipole length [m]=	57.6
			Bending radius [m]=	9.167324722
	Length of quadrupole [m]	**0.4**		

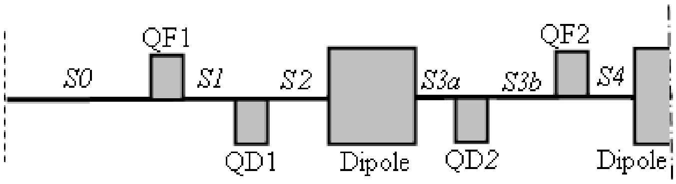
- **Here is the start of the Basic Ring parameters.**
- **The new and improved ring is below awaiting your additions…**

REFINED DESIGN			
Main Ring			
		PLEASE ADD NEW DATA	

Improving the Basic Ring

- The Basic Cell can be further improved by varying the input matching conditions, using a gradient in the dipole, and/or changing the layout.





etc.

- A more fundamental possibility is to use a Möbius ring to share the stronger cooling in the vertical plane with the horizontal plane.
- To do this add two rotator sections on opposite sides of the ring.
- The rotators have to be scaled to an integer number of RF wavelengths and the gaps between the pulses increased to absorb the extra length.
- Use one rotator on rollers to switch the planes when needed. Modify the other rotator to obtain a phase shifter for tune control with injection and extraction included.

Theoretical task

- In Lecture 6, Slides 4 - 7 derive a simple matching condition for minimum *H(s)* in the dipole.
- Can this be extended,
  - Either as a simplified calculation for a dipole with a gradient,
  - Or a simplified calculation with finite dispersion at the entry. The aim here is see how to match other dipoles introduced inside the cell (MBAs Multi-bend Achromats).
  - Or a complete analysis with the full transfer matrix elements with the help of 'Mathematica' perhaps.?
- This refers back to (6.3)

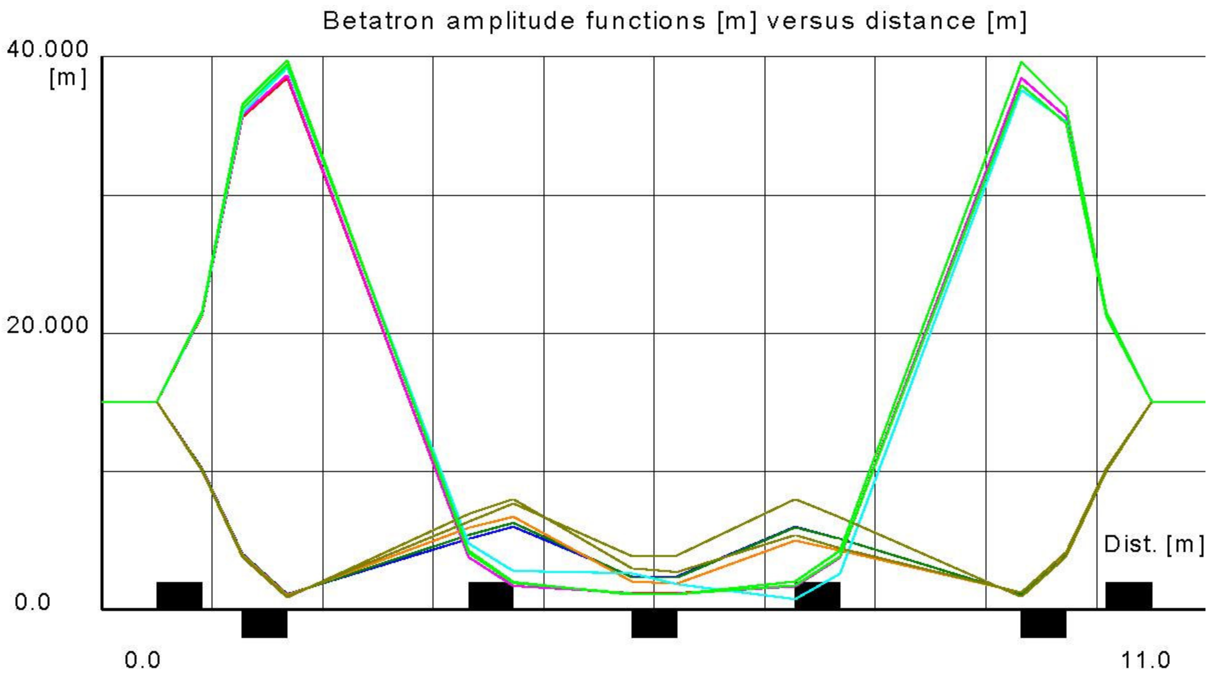
$$E_{x,eq} = A\left[\frac{\int_{\text{Dipole}} \boldsymbol{H}(s)\,\mathrm{d}s}{L\rho_0 + 2\rho_0^2 k \int_{\text{Dipole}} D_x(\mathrm{s})\,\mathrm{d}s}\right] \qquad (6.3)$$

Vacuum

- **The first step is to calculate the beam aperture.**
- **The aperture is dominated by the injected beam. Typically the injected beam will NOT be damped down to its minimum size, but will be blown up by earlier handling. In DESY for example, the injection lines to HERA were specially orientated to prevent coupling in the proton line, but not for the electron line because it would damped down later in the main ring.**
- **Set the aperture at say ±5 sigma and then specify the vacuum chambers. This will define the images for the space charge tune shifts and the surface areas for determining the base vacuum pressure.**
- **The base vacuum pressure (without beam) would ideally be close to 10^{-10} torr. Many hours of beam time will then be needed to clean the chamber further with synchrotron radiation.**
- **The pump speeds and pump spacing for the base vacuum can be calculated in WinAGILE.**

Phase shifter

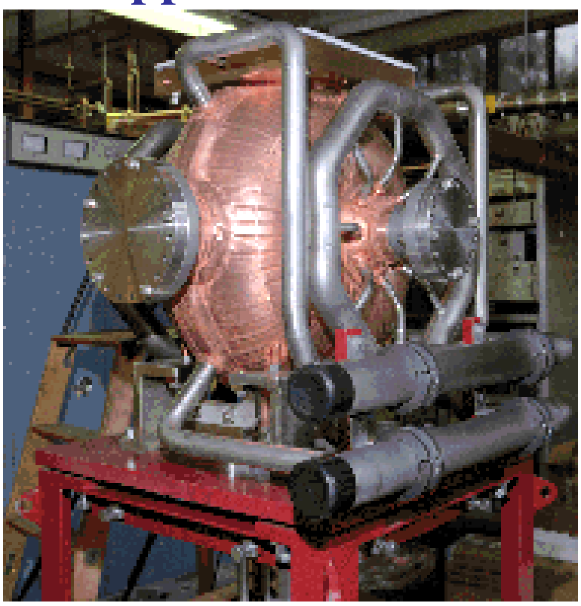
- Start with the scaled rotator. There are 7 quadrupoles. Strictly speaking 6 are required to match the 6 conditions for β_x, β_z, α_x, α_z, μ_x and μ_z, but the 7th automatically becomes free, so it can be used.
- The diagram shows how the betatron amplitude functions would change for some small phase shifts in a similar insertion.



RF system

- Medium and high-energy electron accelerators are ultra-relativistic. The velocity of the electrons is quasi-constant from injection up to the top energy.
- The Parameter List includes the calculations that confirm this.
- Consequently, the cavities can be high-Q and need only the slightest tuning.
- Basing the cavity design on a pill box means the radius will be of the order of a quarter free-space wavelength.
- Water cooling on the outer cavity surface should be needed. Can this be confirmed numerically? This also indicates that the cavity should be well-rounded and made of copper.

Cavity at LBL



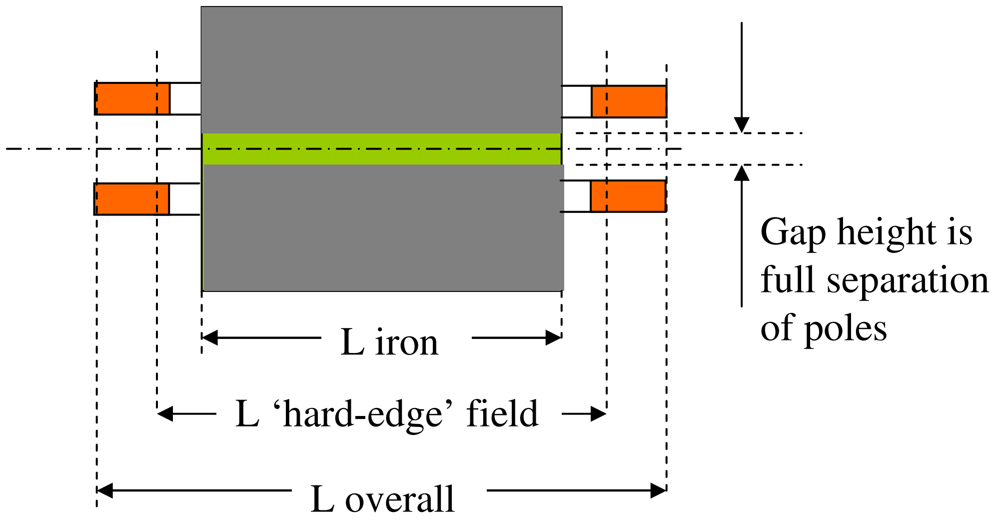
Injection

- The injection is specified in the Parameter List as 'bucket-to-bucket'.
- In the Basic Ring, 4 beam pulses of 225 bunches will be injected with gaps of 25 empty RF buckets between pulses.
- Use this scenario to define the kicker rise, flat-top and fall times. The improved ring with customized insertions will have larger beam gaps.
- Injecting within a single drift space makes the extraction independent of the machine optics.
- For a horizontal injection with a quadrupole between the septum and kicker choose a defocusing unit, so that its kick aids the injection. If the quadrupole is focusing, then inject vertically and use a Lambertson septum (see Lecture 2 slide 25).
- A horizontal radial bump will ease requirements.
- In the Basic Ring, the lack of space makes it necessary to study the installation of the injection and extraction in the same drift space.

Extraction

- There are no downstream facilities after the new light source, but it would still be advantageous to be able to extract the beam for secure dumping at the end of a run.
- Machine activation may not be a big problem in absolute terms, but even low-level activation is important for 'hands-on' maintenance, especially as there will be a lot of outside workers entering the beam area to service the experimental beams.
- Extracting within a single drift space makes the extraction independent of the machine optics.
- For a horizontal extraction with a quadrupole between the kicker and septum choose a defocusing unit, so that its kick aids the extraction. If the quadrupole is focusing, then extract vertically and use a Lambertson septum (see Lecture 2 slide 25).
- A radial bump eases requirements but reduces reliability. Note that the kicker only needs a rapid rise time and a flat-top of one turn. The fall time and quality of the flat-top are less important.

Estimating a dipole



- **Effective field length of 'hard-edge' model**

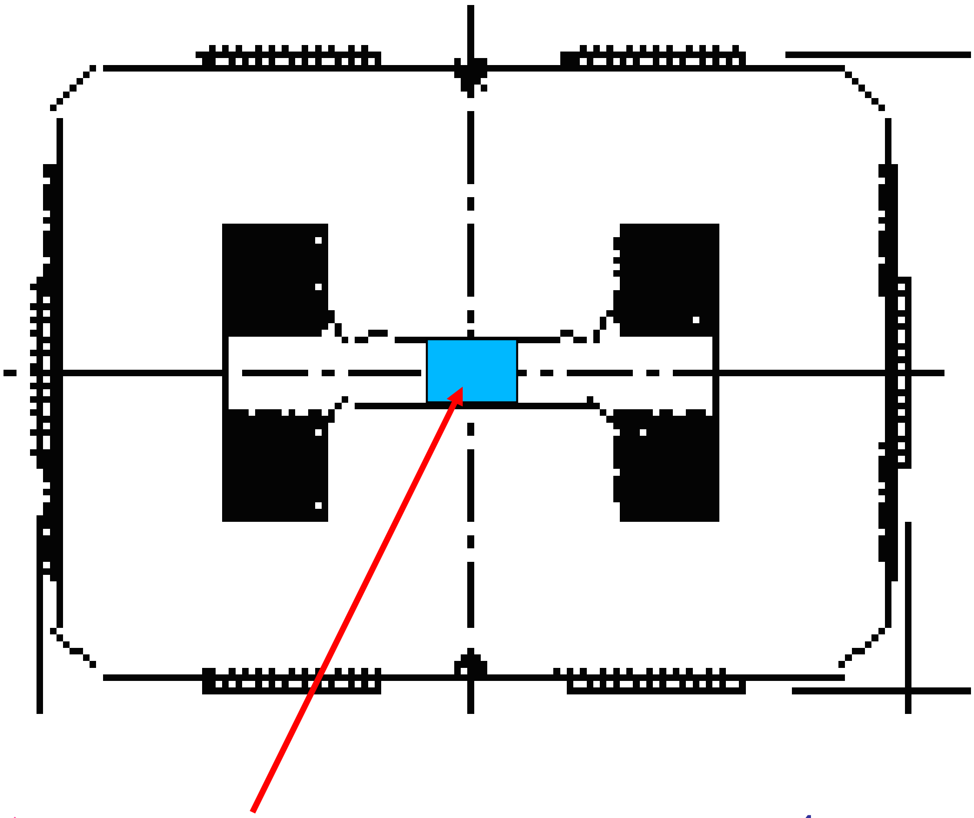
  $= L_{iron} + 1.3 \times$ gap height (unsaturated)

  $= L_{iron} + 0.7 \times$ gap height (saturated).

- **Overall length is more variable, but until a design is made, assume**

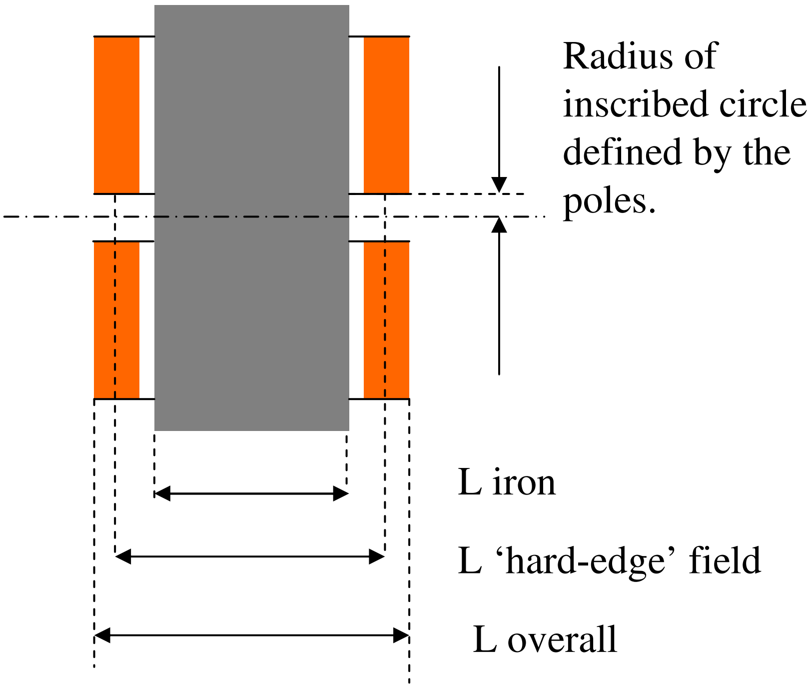
  $= L_{iron} + 4 \times$ gap height.

Estimating a dipole continued



- Good field : $\Delta B/B = \pm 2\times 10^{-4}$; B = 1.5 T; gap height (vert.) × 2 gap height (horiz.).
- Pole width ~ 5 × gap height.
- Coil X-section ~ [1.5-2 ×gap height]^2.
- Overall width ~ 13-15 ×gap height.
- Overall height ~ 10-11 × gap height.
- Side, top and bottom yokes = half of pole width +15%.

Estimating a quadrupole



- **Effective field length of ‘hard-edge’ model**

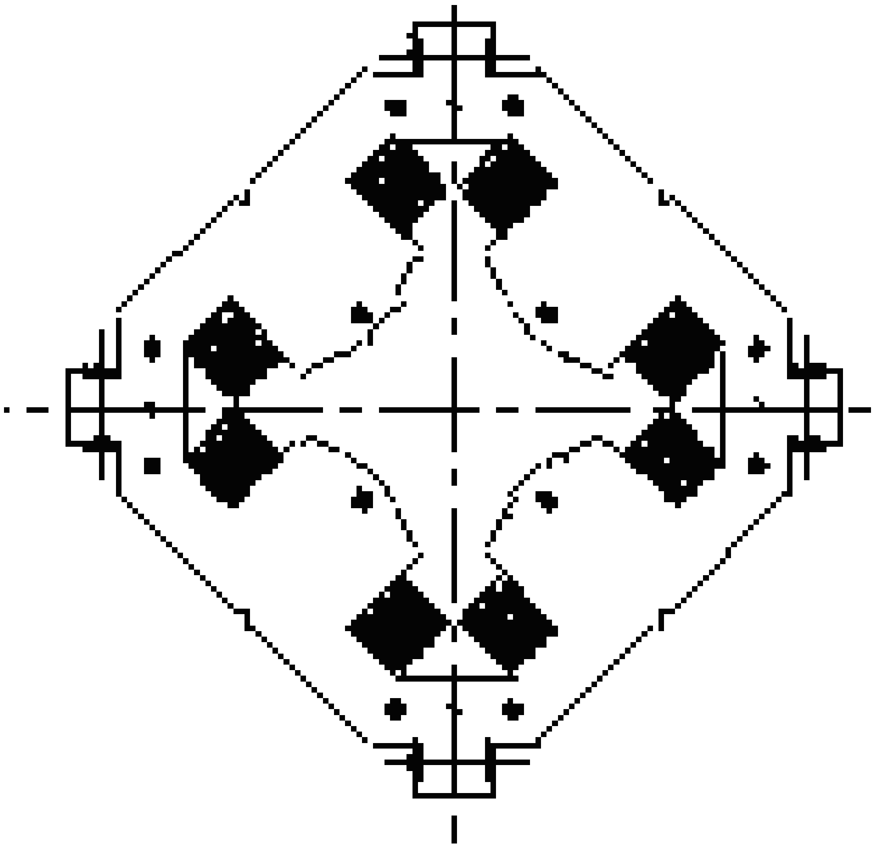
  $= L_{iron} + 1.0 \times$ inscribed radius (unsaturated)

  $= L_{iron} + 0.6 \times$ inscribed radius (saturated).

- **Overall length is more variable, but until a design is made, assume**

  $= L_{iron} + 2 \times$ inscribed radius.

Estimating a quadrupole continued



- Good field : $\Delta G/G = \pm 5\times 10^{-4}$;
  G = 6 T/m; 0.5 T on pole; over region of radius 0.6-0.7 × inscribed radius of poles.

- Overall width ~ 7-8 × inscribed radius of poles.

Powering magnets

- **Dipole:**

  $NI = (\text{gap height})\, B/\mu_0$

- **Quadrupole:**

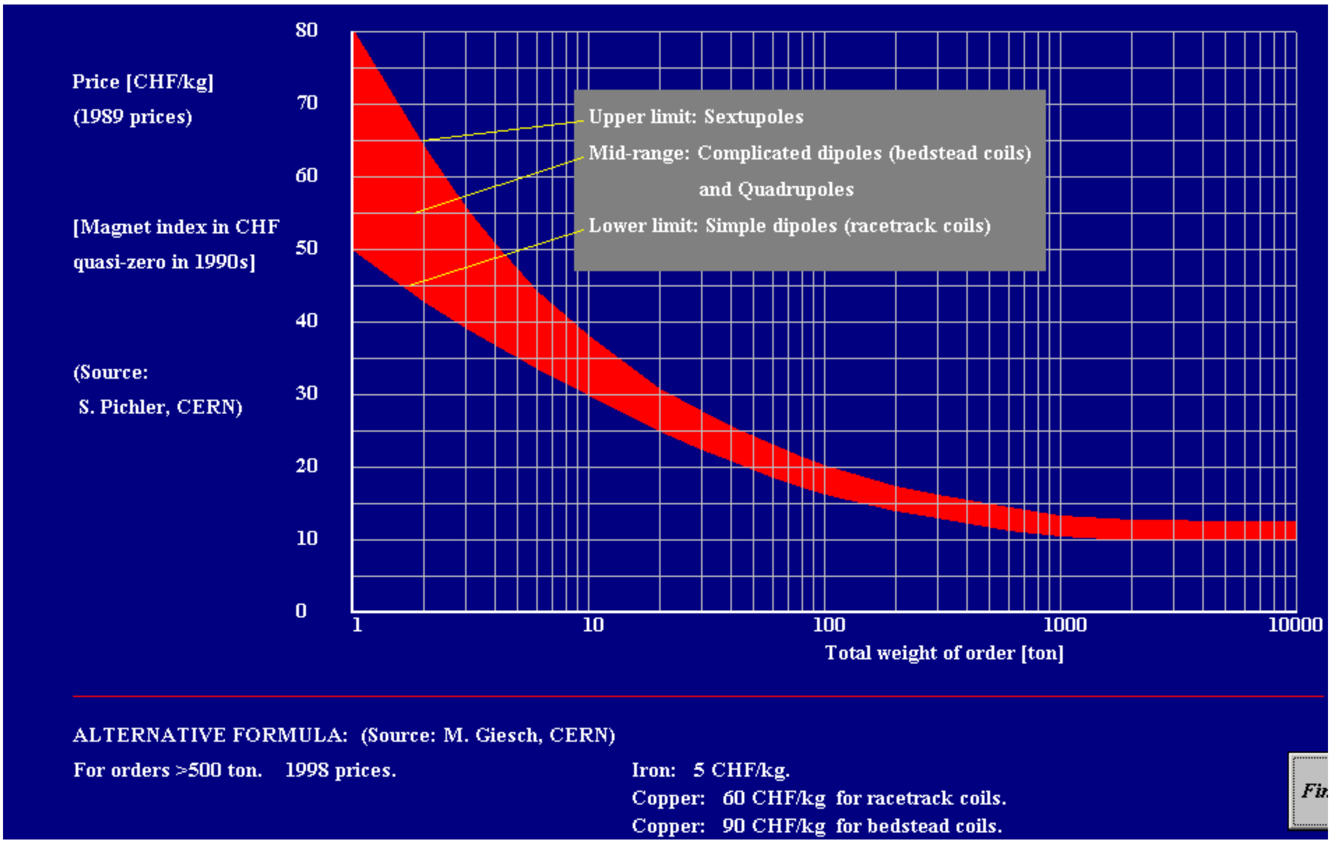
  $NI_{\text{per pole}} = (1/2)\, G\, (\text{inscribed radius})^2 / \mu_0$

- **More ampere-turns will be needed if iron is saturated.**

- **More voltage will be needed to pulse the magnets.**

- **For water-cooled coils see design aid in WinAGILE.**

Magnet cost



Graph can be found in WinAGILE

Conclusion of Mini-Workshop

- **Please use the course lectures as much as possible to fill out the design study of the light source synchrotron.**
- **This project will act as a sort of revision.**
- **The Project Leader and the various Task Working Groups should present their reports in the Concluding Meeting in Week 4 (see the lecture programme).**
- **The reports should be tailored to fit the one hour lecture period.**