SC magnets for Future HEHIHB Colliders

presented by L. Bottura

WAMS, Archamps, March 22-23,2004

Overview

- Few selected examples of
  - **drivers for R&D in the next 10 years …**
    - LHC upgrades scenarios (why ? how ?)
    - GSI-IAF for Beams of Radioactive Ions (objectives and overview)
    - Other special developments (combined function magnets, wigglers, focussing magnets in background field, …)
  - **… and associated needs**
    - maximum field
    - aperture
- A summary and a perspective

LHC Upgrades - Why

- After initial running at the nominal energy and luminosity, the quest at the LHC will continue to:
  - **extend the discovery potential of new particles (SUSY particles, new gauge bosons, ???)**
  - **access a larger number of particle interaction channels to understand better the underlying physics**
  - **increase the precision of measurements of particle masses, interactions, couplings, cross-sections, ...**
- This will be achieved by:
  - **increasing the rate of particles collisions at the experimental vertices: luminosity** L
  - **increasing the energy** E **of the beams**

Physics Discovery Potential

- The Physics Discovery Potential (PDP) is a quantitative scaling for the probability of discovering a new particle (e.g. Higgs at the LHC experiments)
- In the case of a light Higgs (120 GeV) the PDP scales in the range 4 TeV < E < 7 TeV as(*):

$$PDP = \boxed{(E-1)}\sqrt{L}$$

- The PDP increases with ***E*** and ***L***, hence one needs to push both to *see* more interesiting stuff

Too bad for the Tevatron folks…

(*)Prof. A. Verdier, Proceedings of Chamonix XII, CERN, 2003

Energy upgrade

- in a circular accelerator the magnetic rigidity ($B\,\rho$) is proportional to the to the particle momentum (p):

$$B\rho = \frac{p}{e}$$

- for a given tunnel geometry (major cost in modern colliders !) demanding an energy increase is equivalent to demanding an increase of the bending field strength

$$B[\mathrm{T}] = \frac{1}{0.2998}\frac{p[\mathrm{GeV/c}]}{\rho[\mathrm{m}]}$$

LHC example:
$p = 7000$ [TeV/c]
$\rho = 2800$ [m]
$B = 8.33$ [T]

- the integrated focussing strength also increases proportionally ! (stronger or/and longer quads)

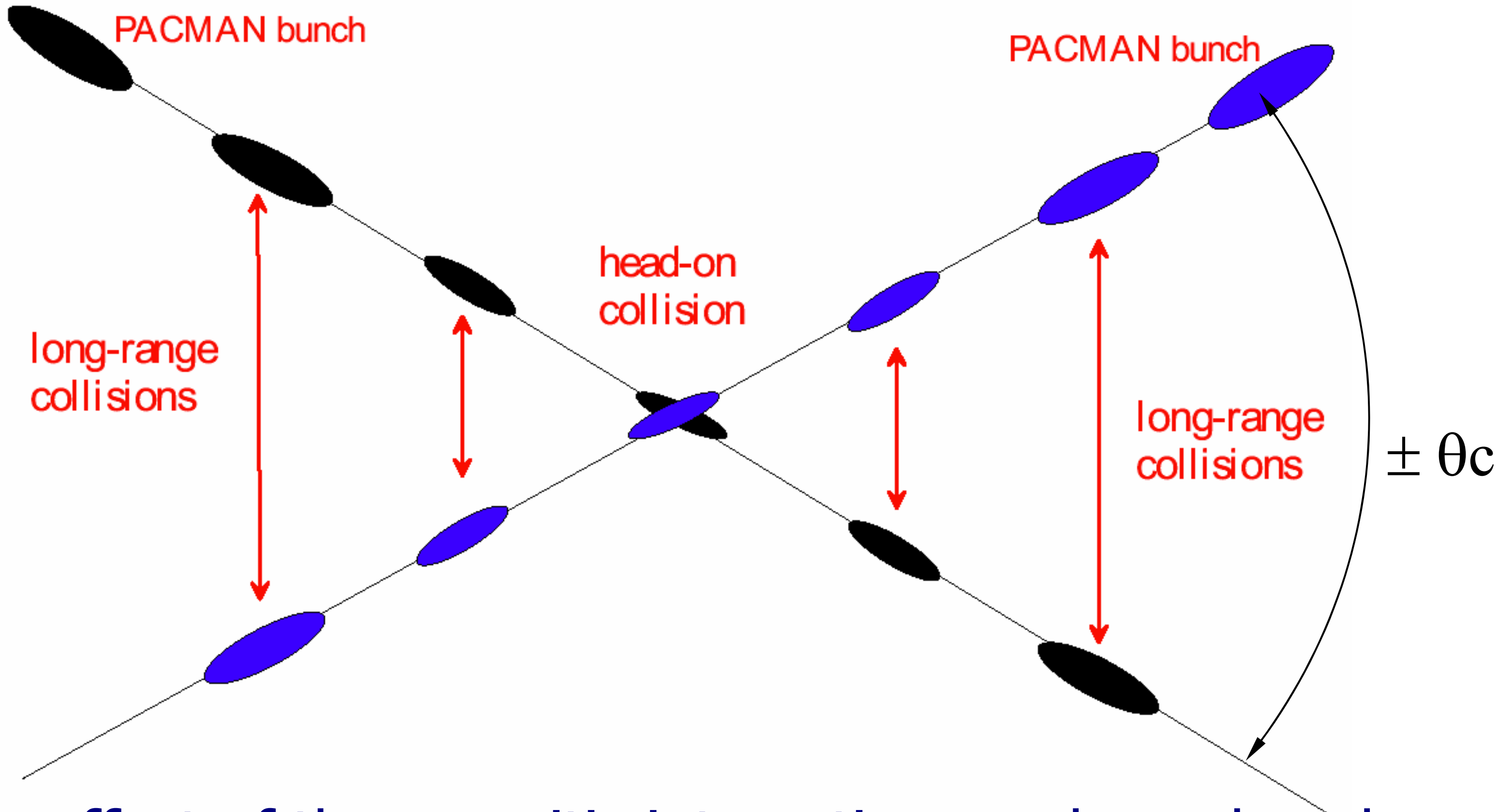
Luminosity upgrade

- the beam luminosity L [cm^{-2} s^{-1}] is defined as:

$$L = \frac{N_b^2 f_{rep}}{4\pi\sigma^{*2}} F(\theta_c)$$

- N_b number of protons/bunch
- f_{rep} average bunch repetition frequency $f_{rep} = n_b f_0$
- n_b number of bunches
- f_0 revolution frequency
- F geometric factor, depending on crossing angle θ_c decrease ↓
- σ^* r.m.s. transverse beam size $\sigma^* = \sqrt{\varepsilon\beta^*}$ decrease ↓
- ε beam emittance
- β^* betatron oscillation function at the interaction point decrease ↓

Parasitic interactions and θ_c



the effect of the parasitic interaction can be reduced increasing the distance of the beams outside of the IP

increase the crossing angle θ_c

increase magnet aperture !

courtesy F. Ruggiero

Side effects of luminosity increase

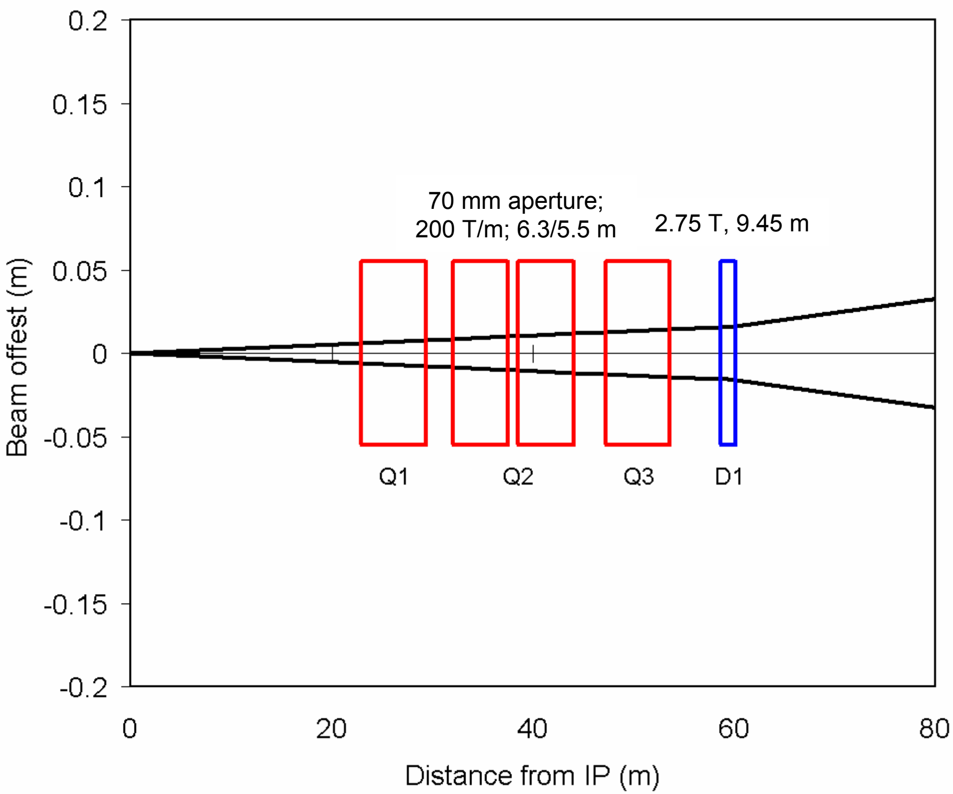
- reduce the beam size σ^*: $\sigma^* = \sqrt{\varepsilon\beta^*}$
  - **lower β^* in the interaction point (IP) can be achieved**
    - increasing the focussing strength of the quads in front of the IP
      - **Increase the peak field in the coil**
    - increasing β in the focussing quads in front of the IP
      - **increase the magnet aperture *and* peak field in the coil**
- to reduce beam-beam scattering, increase the crossing angle θ_c:
  - larger beam divergence
    - **increase the magnet aperture**

A scenario for an LHC upgrade

- nominal parameters: $E = 7$ TeV, $L = 1 \times 10^{34}$ cm^{-2}s^{-1}
- a staged plan:
  - **phase 0: push the collider to its ultimate performance by exploiting all expected margins on field and aperture**
    - objective $E = 7.54$ TeV, $L = 2.3 \times 10^{34}$ cm^{-2}s^{-1}
  - **phase 1: luminosity upgrade modifying β^* (0.5 to 0.25 m) and crossing angle θ_c ($\approx$ 300 to $\approx$ 500 mrad)**
    - objective $L = 4.6 \ldots 9.2 \times 10^{34}$ cm^{-2}s^{-1}
  - **phase 2: luminosity *and* energy upgrade increasing bending and focussing field (B $\approx$ 15 T), injecting at higher energy (0.5 TeV to 1 TeV)**
    - objective $E = 14$ TeV, $L = 1 \times 10^{35}$ cm^{-2}s^{-1}

whatever the upgrade sequence, it will involve a **major change** in the magnets (dipoles and quadrupoles) at the IP's and/or in the arcs and/or in the injector chain

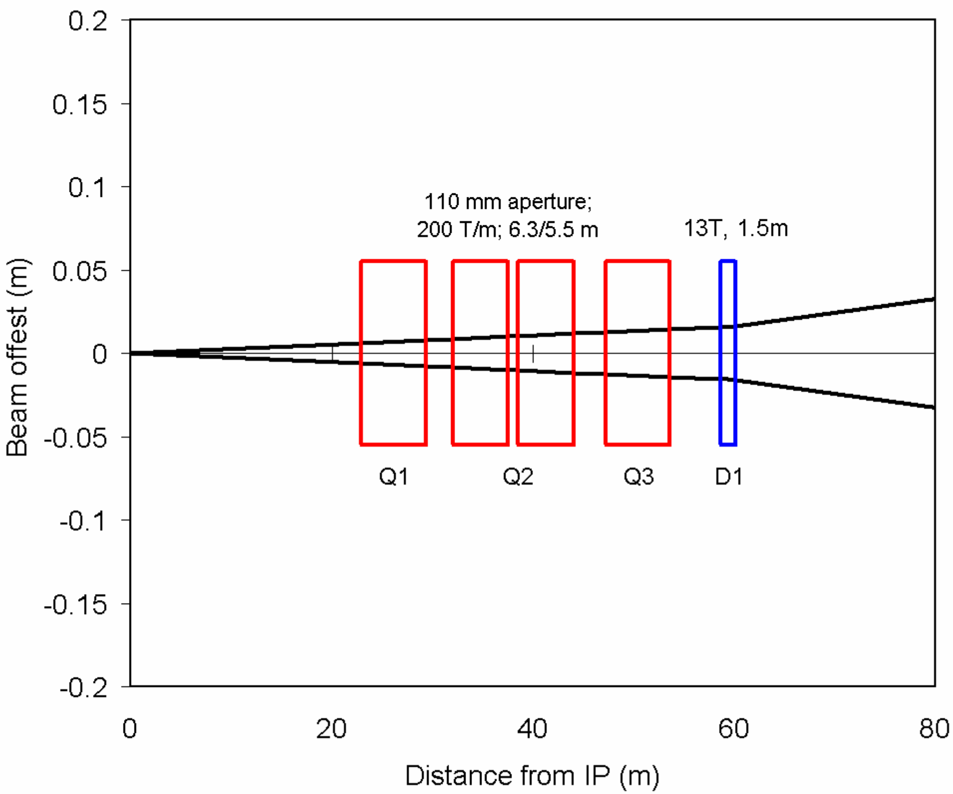
Present scheme (quads first)



- aperture
  - coil diameter in Q1/Q2/Q3 is the limiting factor for β^* (0.5 m)
- field quality requirements
  - feed-down from off-axis orbit
  - tight tolerances for Q1/Q2/Q3 (D1)
  - correction difficult as field errors affect both beams
- parasitic interactions
  - very long distance between IP and D1, many parasitic beam-beam interactions

courtesy T. Taylor

Upgrade based on present scheme



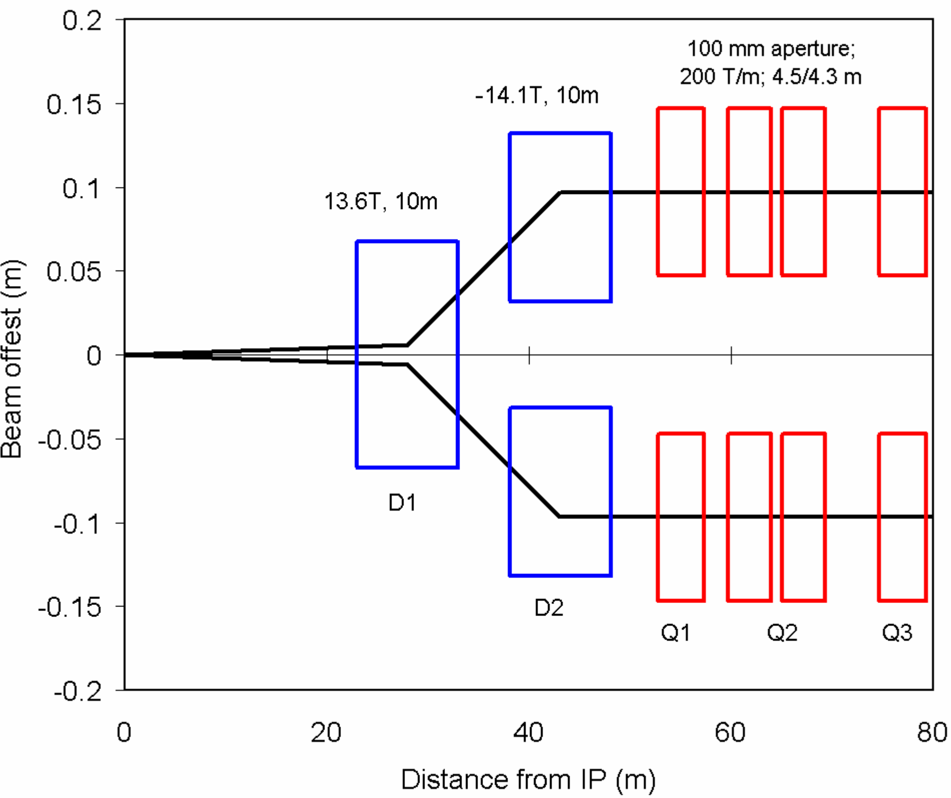
- increase Q1/Q2/Q3 aperture to 110 mm (β^* =0.25 m)
- increase B in D1 to 13 T (gain space in the IR)
- straightforward, logical
- aperture limited by coil diameter of Q1/Q2/Q3
- tight requirements for field quality in Q1/Q2/Q3 (D1)
- many parasitic interactions
- heat load removal at Q1
  - **9 kW/beam from *pp* collisions at the IP**

courtesy T. Taylor

Quads first - comments

- drawbacks:
  - **beams off-axis in quadrupoles and dipoles**
    - Feed-down of multipole errors is important and only small field errors, up to high order (10) can be tolerated
    - Corrections affect both beams, coupling the controls
  - **magnet aperture is a hard limit on the crossing angle and results in many parasitic crossings**
    - beam-beam interaction degrades and can limit beam performance
- remedies:
  - **separate beams earlier (dipoles)**
  - **use twin-aperture quadrupoles**
  - **bring the quadrupoles closer to the IP (space ?!?)**

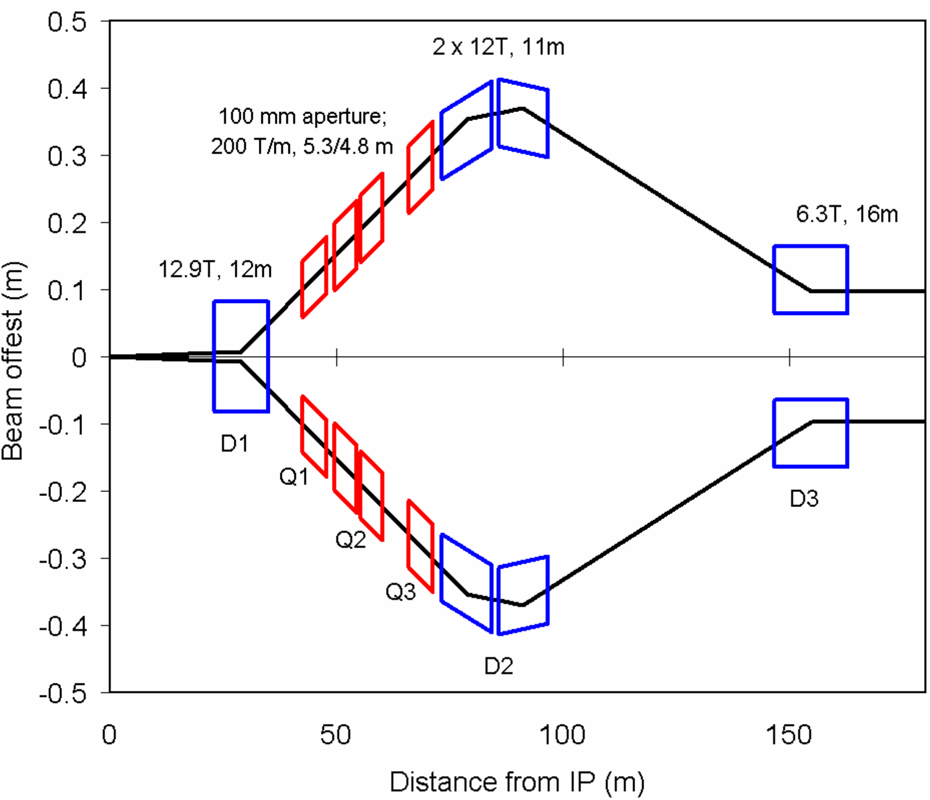
Dipoles first



- high B separation dipoles in front of the IP
- reduces parasitic collisions (lower beam-beam effect by a factor 3)
- field quality requirements on twin aperture Q1/Q2/Q3 are decoupled
- distance of Q1/Q2/Q3 from IP is large (increase β and coil diameter)
- heat load on D1 from *pp* collisions *and* charged particle showers
- field quality for the high-field, twin aperture D2 ?

courtesy T. Taylor

Quads between dipoles



- separate the beam close to the IP
- focus beam right after to reduce the aperture requirement

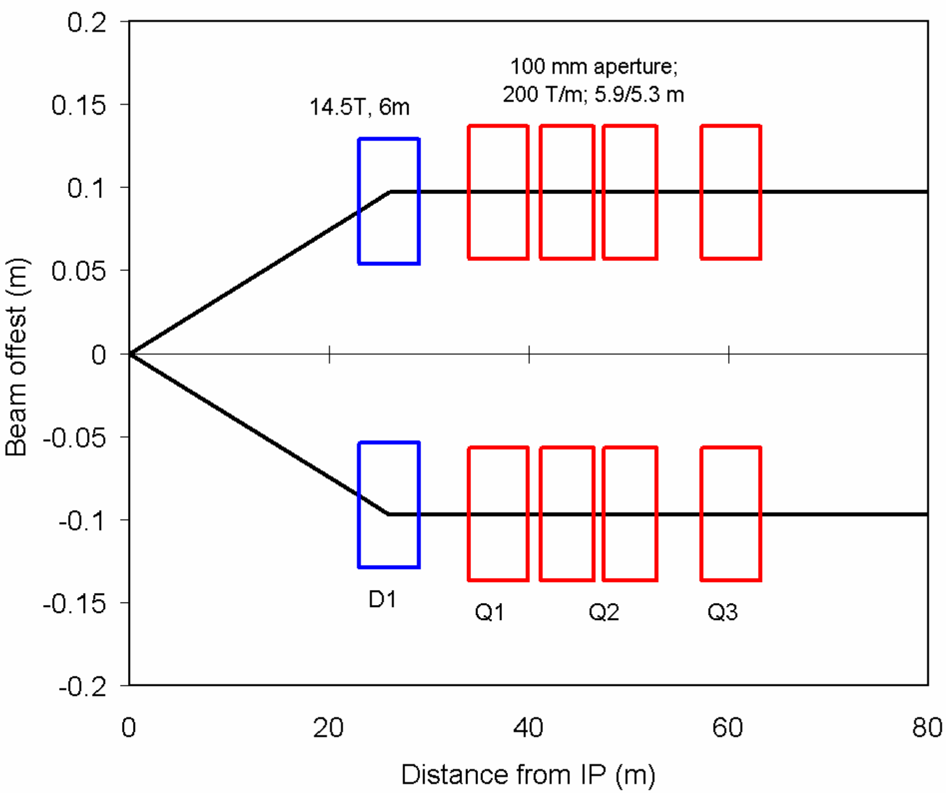
- reduces parasitic collisions (lower beam-beam effect by a factor 3)
- field quality requirements on twin aperture Q1/Q2/Q3 are decoupled
- coil diameter of Q1/Q2/Q3 reduced

- heat load on D1 from *pp* collisions *and* charged particle showers

- tapered aperture Q1/Q2/Q3 ?
- field quality for the high-field, twin aperture D2 ?

courtesy T. Taylor

Dipole first with large x-ing angle



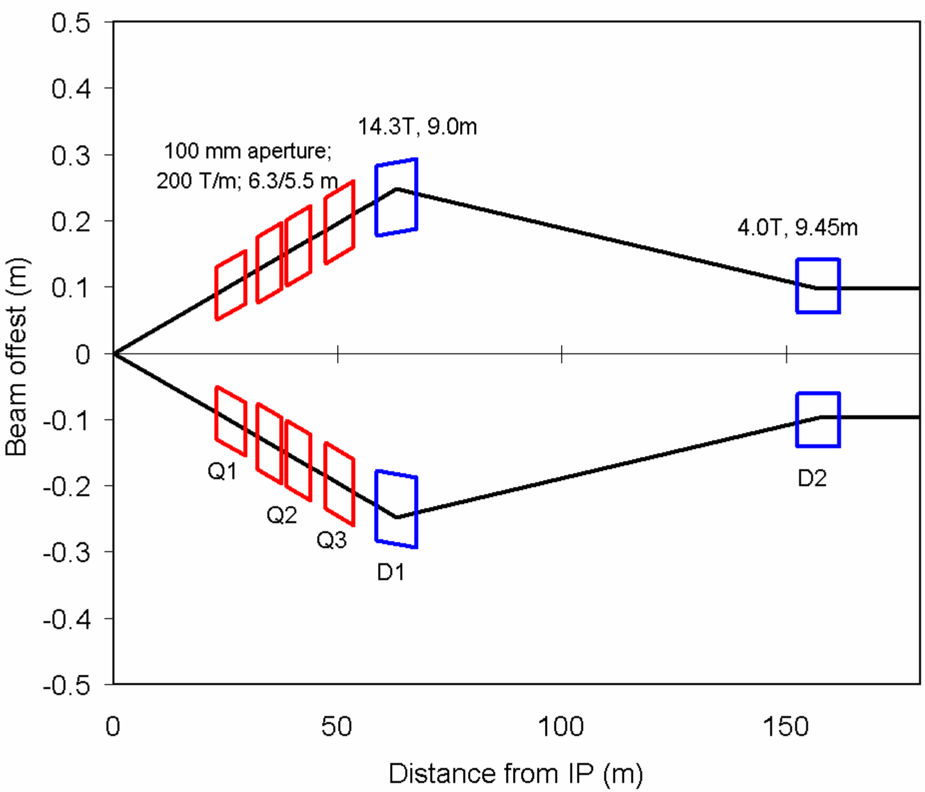
- very large crossing angle ($\pm$ 4 mrad) would solve beam-beam if this appears to be **the** limiting factor

- much reduced parasitic collisions
- field quality requirements on twin aperture Q1/Q2/Q3 are decoupled
- coil diameter of Q1/Q2/Q3 reduced

- heat load on D1 from *pp* collisions *and* charged particle showers *and* neutrals impinging on the magnet structure

courtesy T. Taylor

Quads first with large x-ing angle



- very large crossing angle (± 4 mrad) would solve beam-beam if this appears to be **the** limiting factor
- much reduced parasitic collisions
- field quality requirements on twin aperture Q1/Q2/Q3 are decoupled
- coil diameter of Q1/Q2/Q3 reduced
- further reduction of β^* may be possible (10 cm)
- heat load on Q1/Q2/Q3
- tapered aperture Q1/Q2/Q3 ?

courtesy T. Taylor

LHC IR Upgrade - Overview

	baseline	quads first	dipole first	quads between dipoles	dipole first large θ_c	quads first large θ_c
IP to Q1 (m)	23	23	52.8	42.5	34	23
D_{quad} (mm)	70	110	100	100	100	100
β^*_{min} (cm)	50	16	26	19	15	10
β_{max} (km)	5	15	23	23	23	23
B_{D1} (T)	2.75	15.3	15	14.6	14.5	14.3
L_{D1} (m)	9.45	1.5	10	12	6	9
D_{D1} (mm)	80	110	135	165	75	105

LHC Upgrades - other ideas

- increase injection energy into the LHC (SPS extraction), typically from 0.45 TeV to ≈ 1 TeV
  - **will make life easier in the present configuration**
    - smaller, stiffer beam injected
    - aperture limitation relaxed
    - decrease dynamic range of acceleration from 15 to 7
  - **could provide additional mean to increase luminosity (pack more particles in a smaller beam)**
  - **definitly needed if an energy upgrade is envisaged**
  - **implies a major upgrade of the injector chain**
    - Super-SPS (B ≈ 4 T, D ≈ 50 mm, dB/dt ≈ 1 T/s) plus transfer lines, as well as previous chain of injectors
    - LHC booster (B ≈ 1…2 T, D ≈ 50 mm)

LHC Upgrades - Roadmap

1 develop hi-tech dipoles and quadrupoles for an LHC IR upgrade, IP radiation and heat load compliant

- **quads: G ≈ 200 T/m, D ≈ 100 mm, (B ≈ 11.5 T)**
- **dipole: B ≈ 15 T, D ≈ 75…100 mm**

2a develop low-tech, cost-effective pulsed dipoles and quadrupoles for the LHC injector (see also later discussion on GSI-IAF)

- **dipole: B ≈ 2…4 T, dB/dt ≈ 5…1 T/s**

2b as an alternative, develop low-tech, cost-effective dipoles and quadrupoles for an LHC booster ring

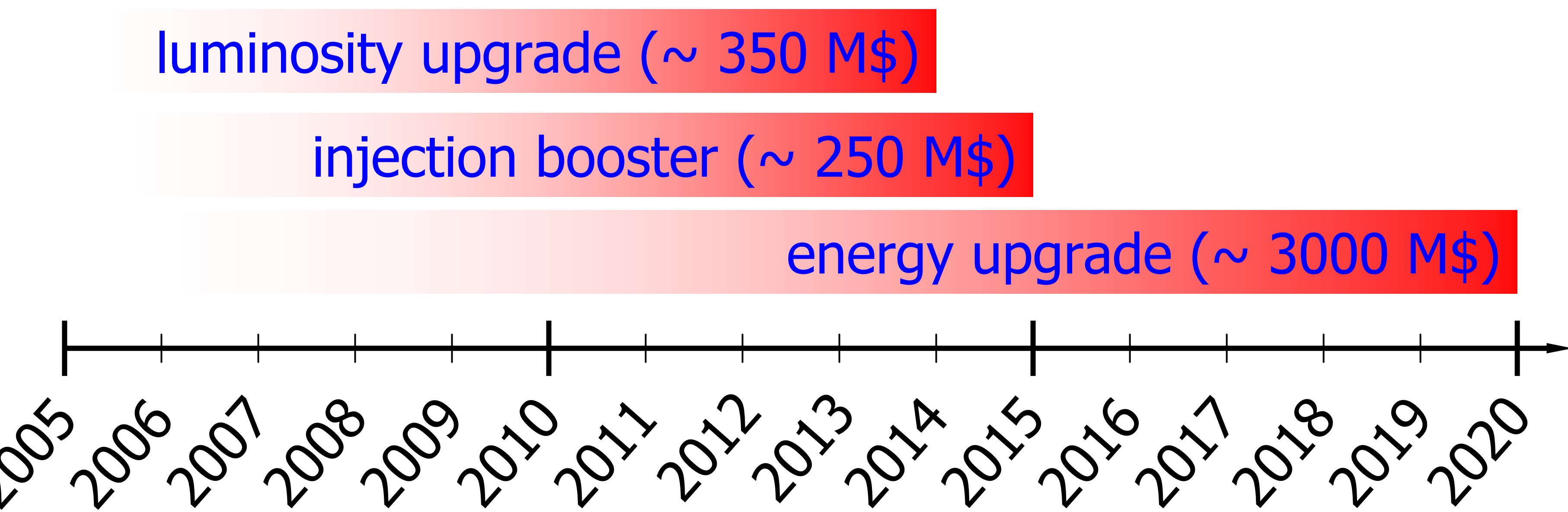
- **dipole: B ≈ 2 T, D ≈ 50 mm**

3 develop cost-effective dipoles and quadrupoles of a new LHC lattice for an energy upgrade

- **dipole: B ≈ 15 T, D ≈ 50 mm**
- **quads: G ≈ 400 T/m, D ≈ 50 mm, (B ≈ 12 T)**

When ?

- maximum machine potential (target luminosity) exploited within ~ 5 years
- present IR magnets will reach radiation damage limit by 2015…2017



What is this LHC ?

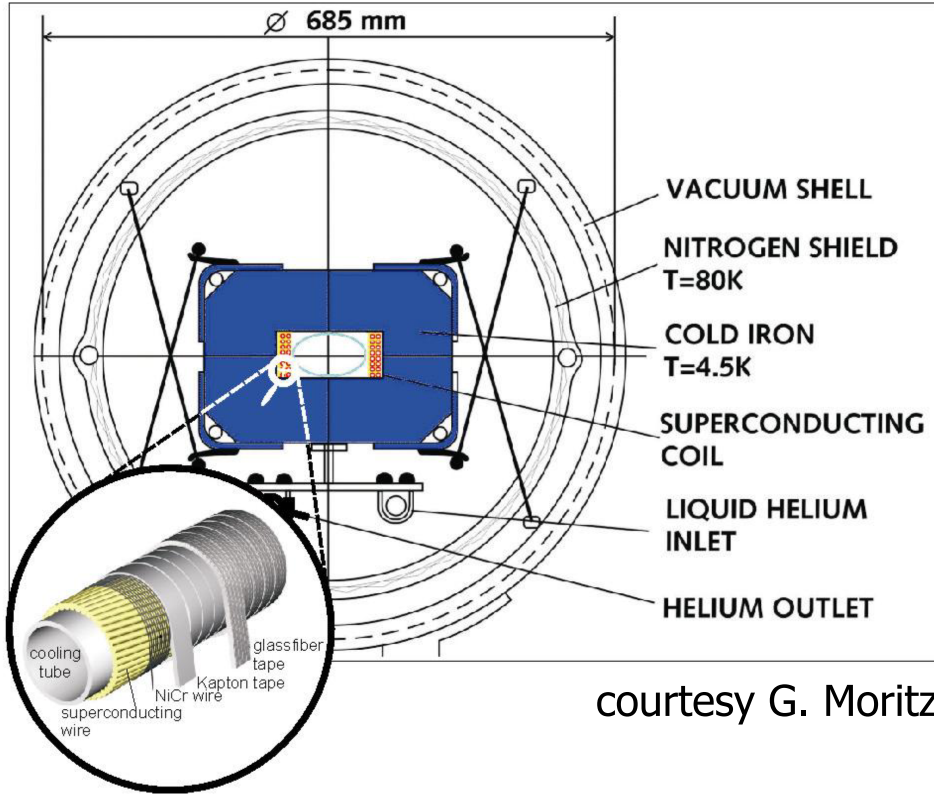
Lucio's Hadron Collider

GSI-IAF

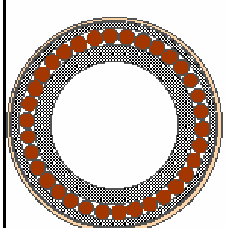
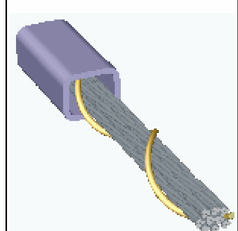
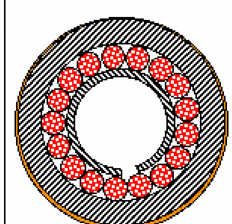
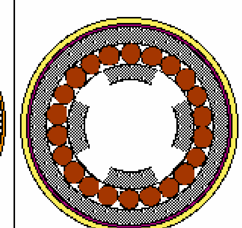
- an accelerator facility for research on radioactive ion beams far from stability
  - **structure of nuclei**
  - **nuclear astrophysics**
  - **study of fundamental interactions and symmetries exploiting the properties of specific radioactive nuclei**
- 8 years R&D and construction, on line around 2010 … 2012
- 2 main rings …
  - **SIS-100 (100 Tm rigidity)**
  - **SIS-300 (300 Tm rigidity)**
- … and many auxiliary rings (HESR, CR, NESR, super FRS)

SIS-100

- rigidity $B\,\rho = 100$ T m
- dipole field $B = 2$ T
- ramp-rate in nominal operation $dB/dt = 4$ T/s
- 130 x 65 mm aperture
- continuous operation, resulting in cycle time of approximately 1 s
- large number of cycles during the machine lifetime (few 10^8)
- super-ferric design



courtesy G. Moritz

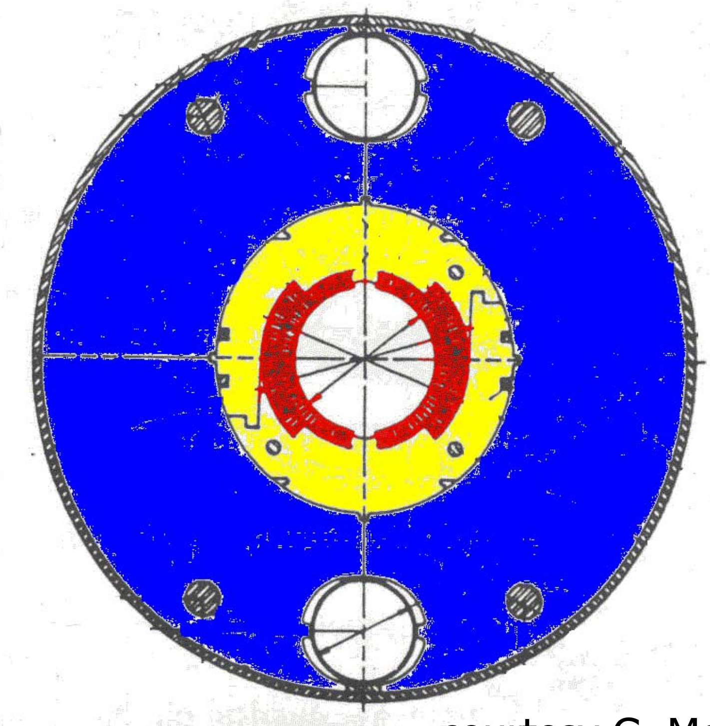
Original Nuclotron type	CICC Kurchatov	Modified Nuclotron with C channel	Modified Nuclotron with central spiral
			

courtesy P. Bruzzone

SIS-300

- bending strength (rigidity) $B\,\rho = 300$ T m
- dipole field $B = 6$ T
- ramp-rate in nominal operation $dB/dt = 1$ T/s
- 100 mm aperture
- storage ring

- two-layers, cos(θ) design, (cored) Rutherford cables

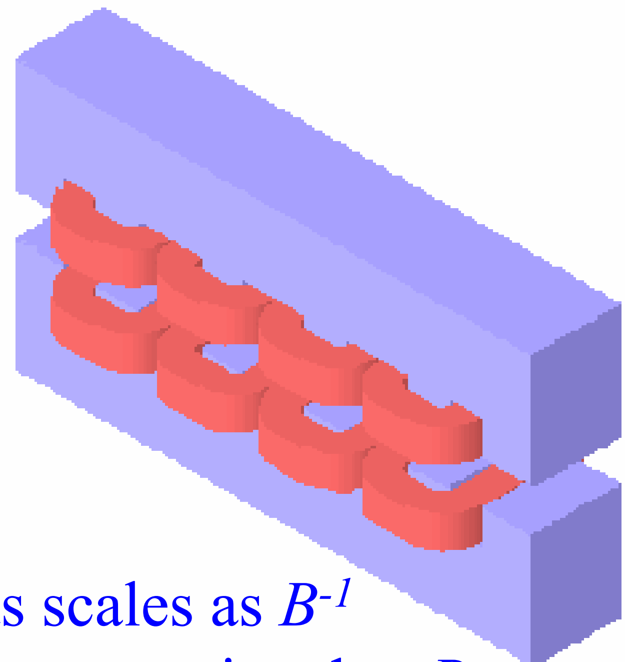


courtesy G. Moritz

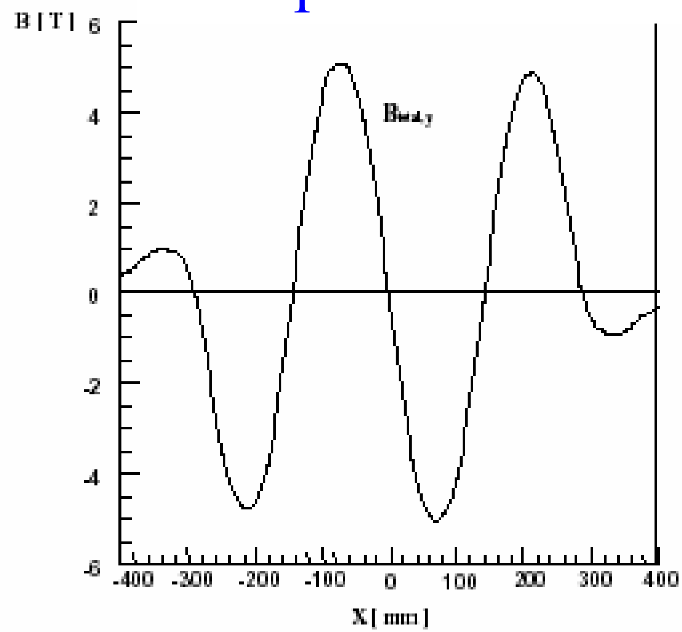
the SIS-100 and SIS-300 magnets cover the envelope of specifications for an injector doubler at the LHC

Wigglers

- what for ?
  - **SR monitor for beam profile measurements**
  - **damp the beam (reduce emittance) stimulating SR emission**



example of a 5 T design



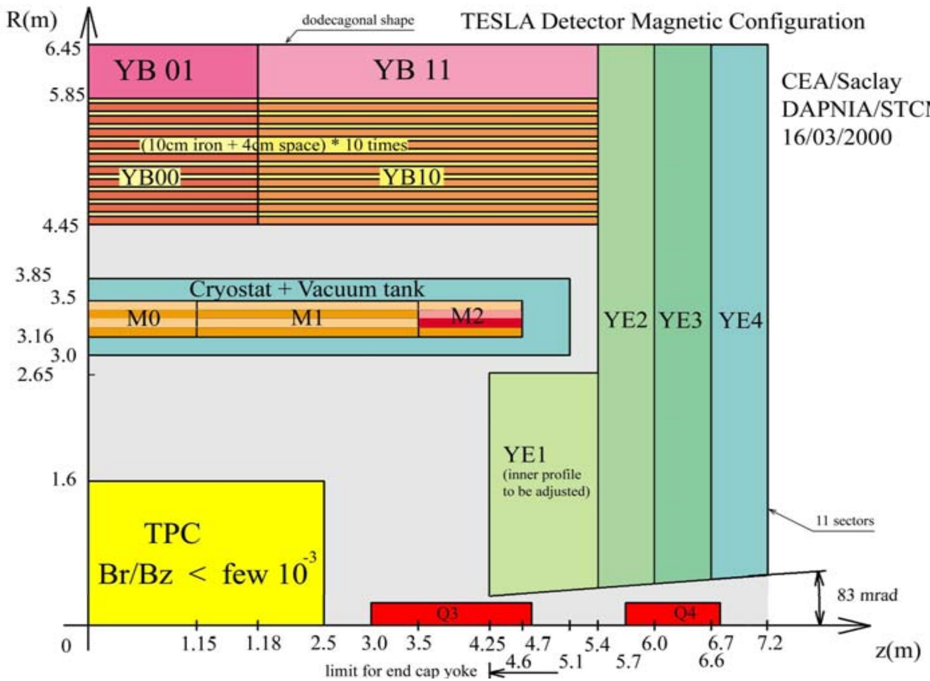
bending radius scales as B^{-1}

emitted power proportional to B

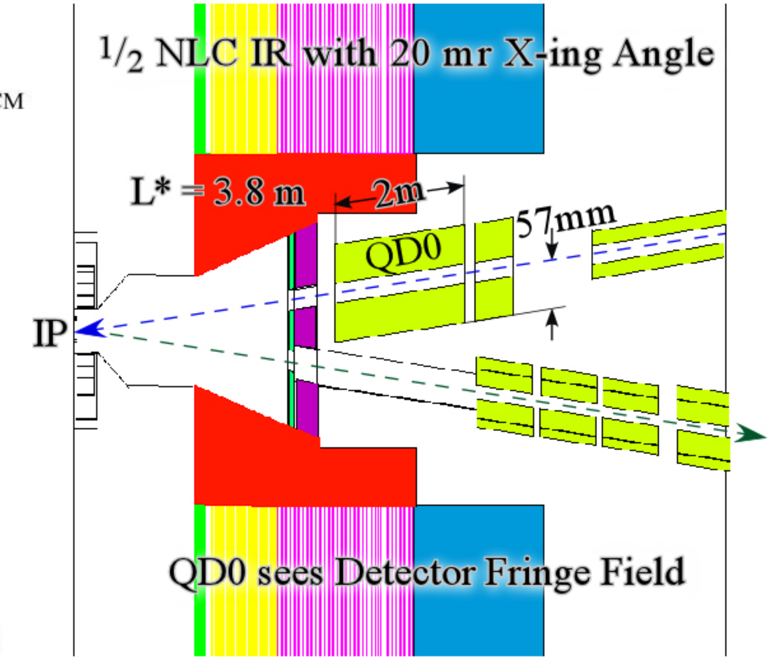
courtesy D. Tommasini

higher field (> 7 T) needed for an efficient design

Magnets for Linear Collider IR's



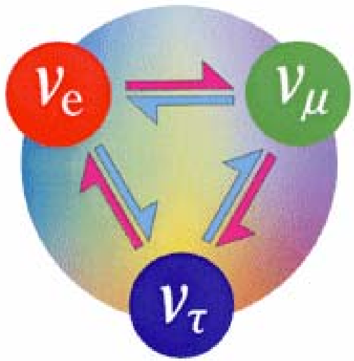
TESLA first IR requires LHC-type quadrupole magnets to be operated in a 4-T solenoidal background field (from F. Kircher)



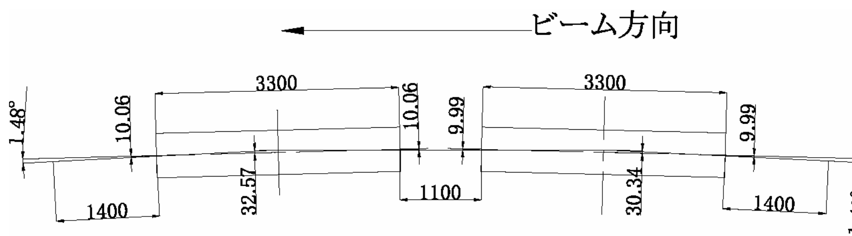
NLC IR with large crossing angle requires strong but very compact quadrupole magnets to clear the way for crossing beam (from B. Parker)

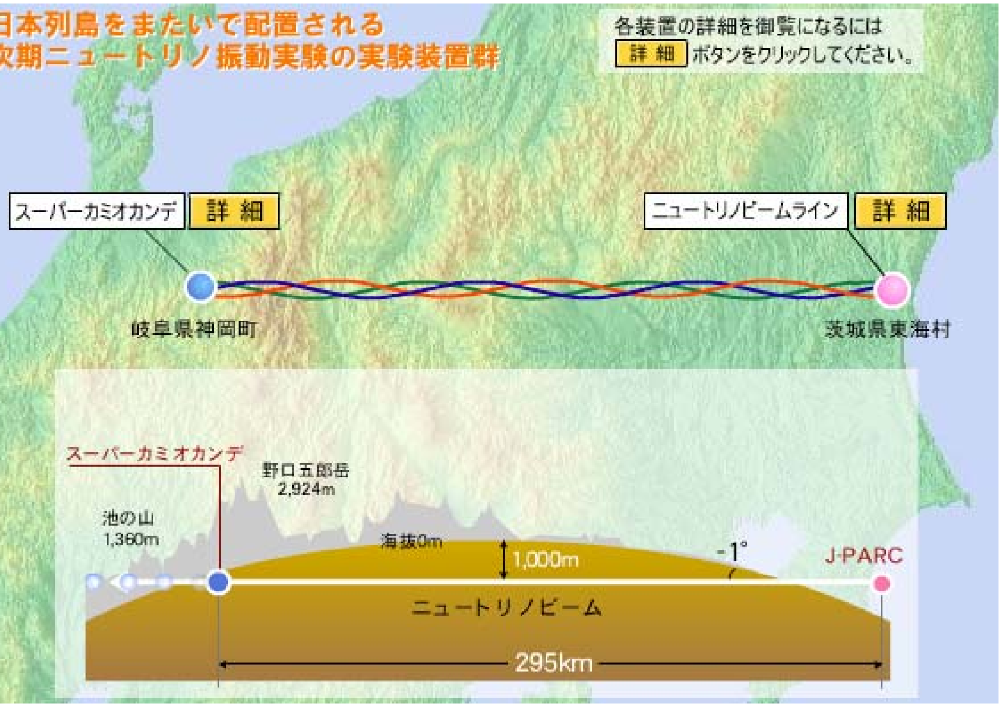
courtesy A. Devred

J-PARC combined function optics



次期ニュートリノ振動実験が
発見を目指す3世代間の
ニュートリノ振動現象の模式図。



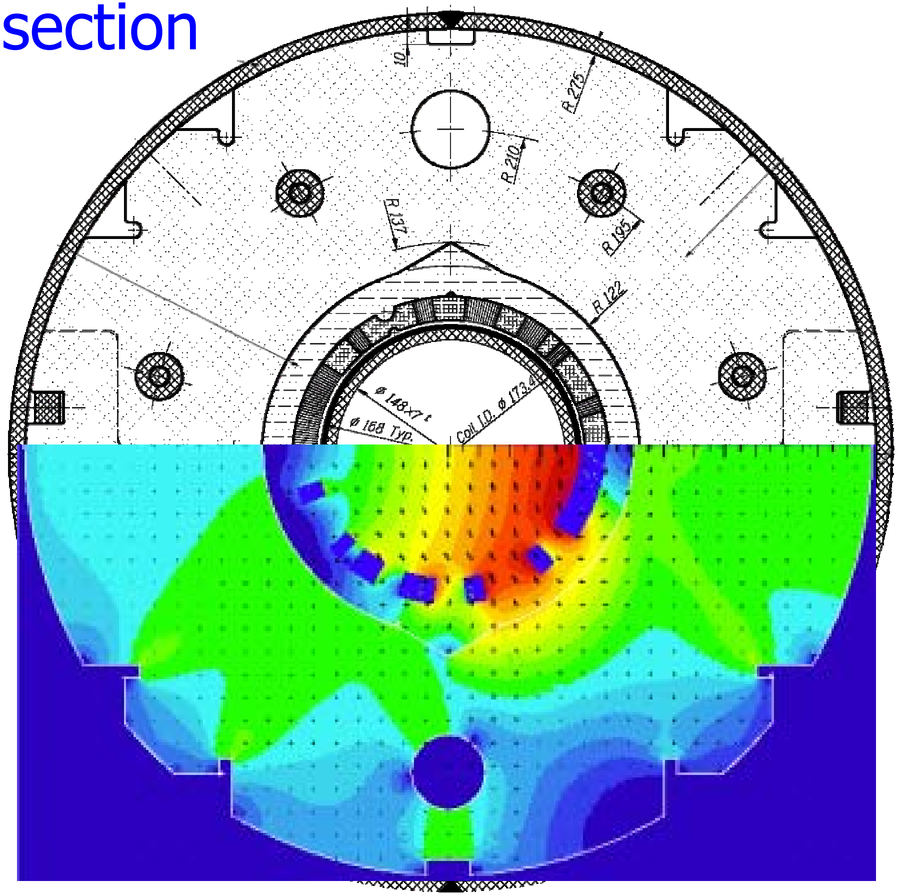


doublet optics
combined function magnets

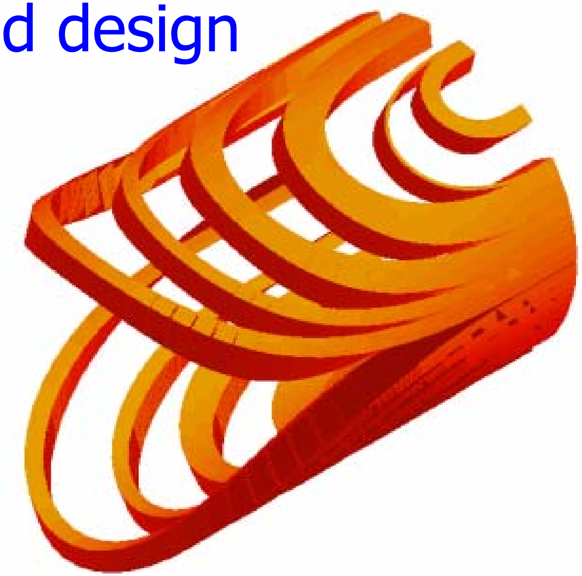
Dipole: B = 5.6 T
Quadrupole: G = 18.6 T/m

Combined functions SC magnet

x-section



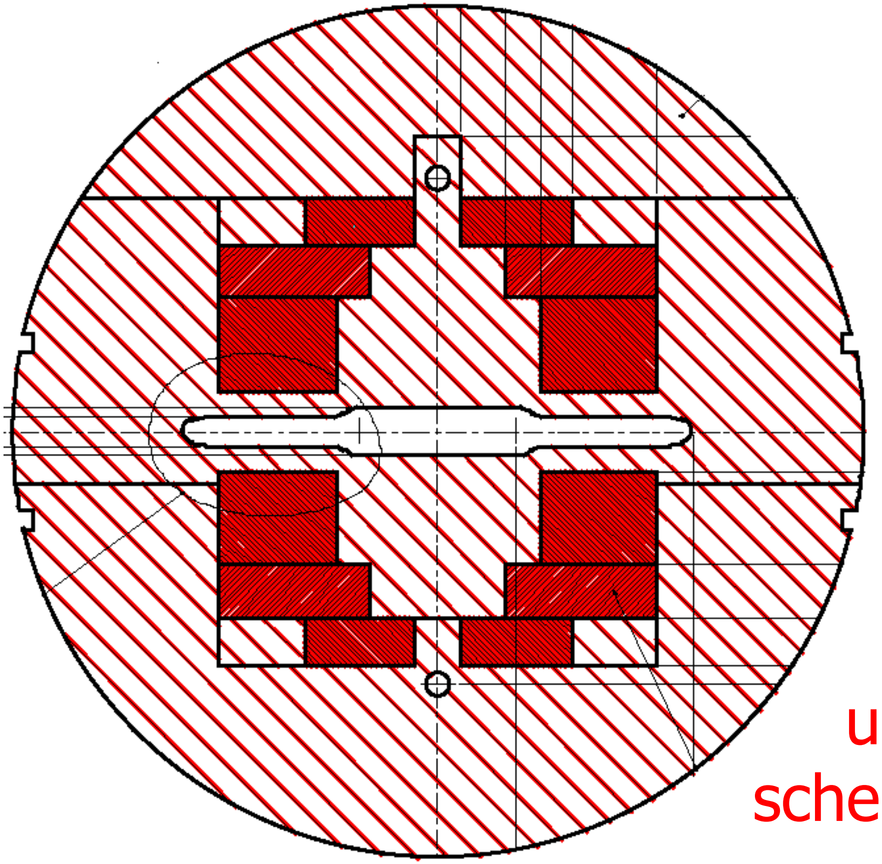
non-symmetric
end design



free slit space on the midplane
could be used for a SR window ?

courtesy T. Ogitsu

Magnets for high SR loads



central slit allows radiation and charged products of the interactions at the IP to exit without heating the coil

use in IR region (dipole first scheme) or for high energy beams

N.V. Mokhov, et al., Energy Deposition Limits in a Nb3Sn Separation Dipole in Front of the LHC High-Luminosity Inner Triplet, PAC 2003

courtesy T. Taylor

Summary - where are we heading to ?

- high performance, high field/gradient dipoles and quadrupoles for final focus magnets
  - **dipole B = 15 T, D = 50 … 100 mm,**
  - **quadrupole G = 200 T/m, D = 100 mm (B = 12 T)**
  - **accelerator quality field (100's of ppm)**
  - **radiation heat and dose resistant**
- pulsed dipoles and quadrupoles for new rings and upgrades
  - **dipoles B = 2…6 T, D = 50 … 100 mm, dB/dt = 4…0.5 T/s**
- *difficult* magnets in the mid-field range (5…10 T)
  - **combined functions**
  - **wigglers**
  - **final focus quads in background field**

cost !

Summary - what are the challenges ?

- critical current $J_c \propto 1/B^{1/2}\ (1-B/B_c)^2$
  - **operating margin and cable current density**
- electromagnetic force $F \propto B^2$
  - **stability of the cable vs. mechanical energy release in the perturbation spectrum**
  - **mechanical design**
- stored magnetic energy $E \propto B^2\ D^2\ L$
  - **quench protection**
- beam heating through radiation $Q \propto B^4\ I_{beam}$
  - **cooling scheme and additional devices (e.g. photon stops)**
  - **stability of the cable vs. heat inputs in the perturbation spectrum**
- radiation dose $RD_{IP} \propto L$; $RD_{arc} \propto I_{beam}$
  - **radiation hardness**

innovation on materials <u>and</u> design is needed !

References

[1] O. Bruening, et al. LHC Luminosity and Energy Upgrade: A Feasibility Study, LHC PR 626, 2002.

[2] F. Ruggiero, LHC Accelerator R&D and Upgrade Scenarios, LHC PR 666, 2003.

[3] T.M. Taylor, Superconducting Magnets for a Super LHC, Proc. of EPAC 2002, xx-xx.

[4] J. Strait, et al., Towards a New LHC Interaction Region Design for a Luminosity Upgrade, Proc. of PAC 2003, 42-44.

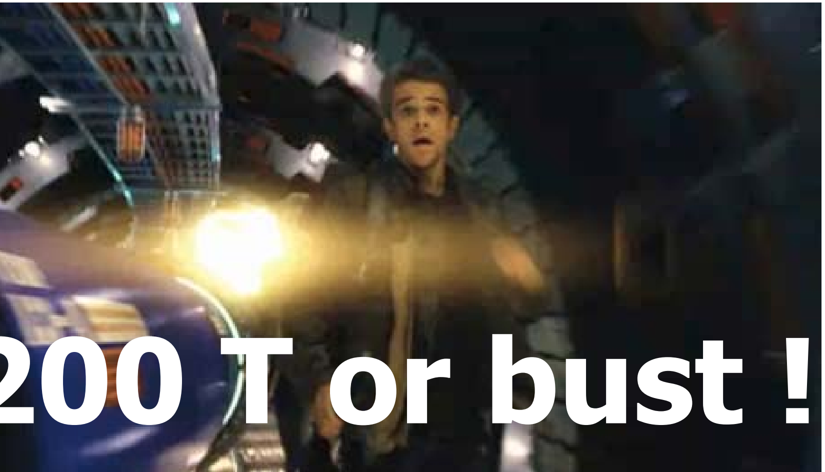
[5] A. Devred, High Field Accelerator Magnets Beyond LHC, Proc. of PAC 2003, 146-150.

[6] P. Spiller, et al., The GSI Synchrotron Facility Proposal for Acceleration of High Intensity Ion and Proton Beams, Proc. of PAC 2003, 589-591.

A very far future...

$$B[\mathrm{T}] = \frac{1}{0.2998}\,\frac{p[\mathrm{GeV/c}]}{\rho[\mathrm{m}]}$$

100 m radius, 6 TeV synchrotron requires a 200 T bending field…



200 T or bust !

… but is the **<u>best way</u>** to get rid of a T-X Terminator model of the third generation