Baseline Scenario for the LHC Luminosity Upgrade

Summary of CARE-HHH LHC-LUMI-06

(concentrating on magnet-related issues)

Thanks to Frank Zimmermann, Walter Scandale and Jean-Pierre Koutchouk for supplying essential material

T. Taylor, KEK, February 2007

CARE-HHH APD workshop 'LUMI 06'
Towards a Roadmap for the Upgrade of the LHC and GSI Accelerator Complex

IFIC, Valencia (Spain), 16-20 October 2006

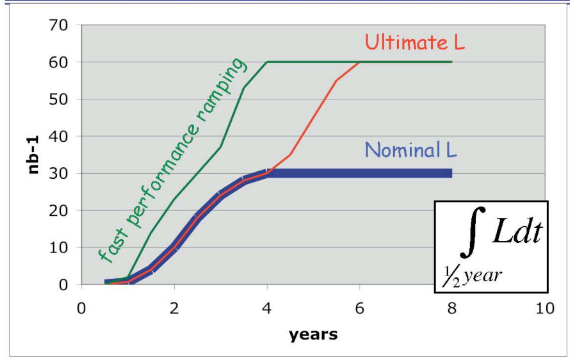
- about 70 participants
  (including 13 from US-LARP and 2 from KEK)
- 53 presentations, 10 discussions, 4 posters

<u>topics:</u>

- interaction-region upgrade
- beam parameters
- intensity limitations
- injector upgrade

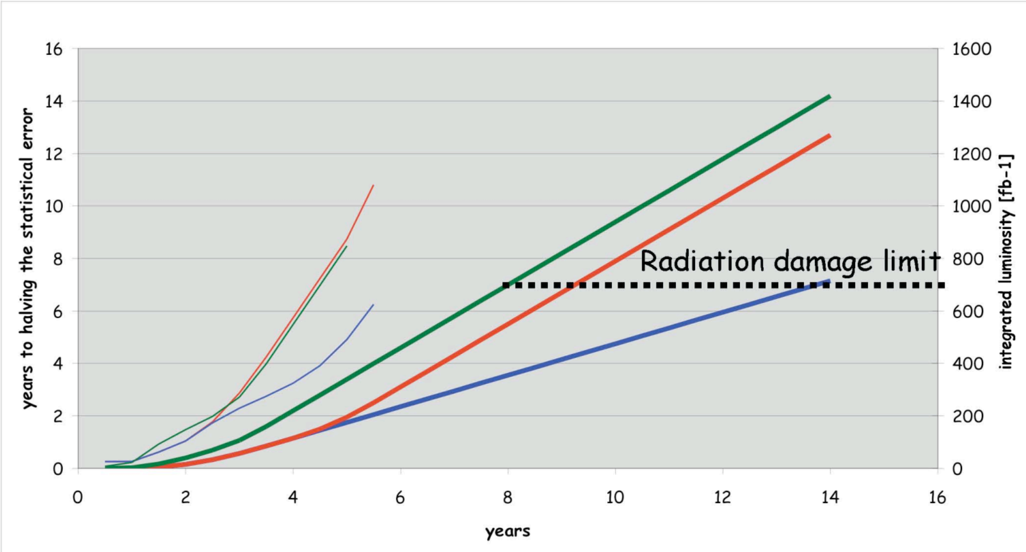
Walter Scandale: status of upgrade

LHC luminosity upgrade: why and when?



How fast performance is expected to increase:

- 4 y up to nominal *L*
- 4 y up to nominal *L* & 2 y up to ultimate *L*
- 4 y up to ultimate



- IR quadrupole lifetime ≥ 8 years owing to high radiation doses
- halving time of the statistical error ≥ 5 y already after 4-5 y of operation
- luminosity upgrade to be planned by the middle of next decade

The plans for a (× 10) luminosity upgrade assume:

- × 2 by increasing the bunch charge from 1.15 to 1.7 10^{11}
- × 2 by doubling the number of bunches
- × 1.5 by reducing the bunch length (harmonic RF system)
- × 1.5 with a stronger focusing

(Now excluded: large angle crab crossing, long bunches, …)

Increasing the beam current is difficult in a collider):

- It couples with all limits (beam instabilities, heat load, …)
- For the LHC, it increases hazards due to beam losses (collimation, machine protection)

- Experience shows that to improve luminosity is hard…

- Also NB: the present limit to ~ 40% of the nominal current due the collimator impedance, which is related to the insertion quadrupole inner diameter.

Per Grafstrom: ATLAS Perspective of Upgrade

- **Inner detector - high luminosity upgrade issues**
  - luminosity x 10 $\Rightarrow$ most sensors die in a couple of months

    $\Rightarrow$ 10 000 charged particles in η < 3.2

    The TRT will have occupancy close to 100%

  $\Rightarrow$ need a complete replacement

  i.e. a **NEW Inner Detector !**

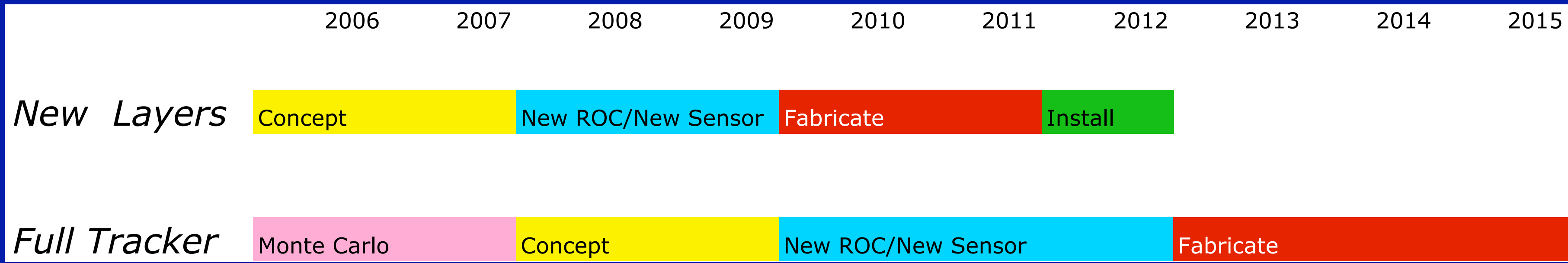
- Need to reduce background

  replace SS beam pipe with Al or Be beam pipe

- There are potential **slots for "slim" magnets inside**

Jordan Nash: CMS Perspective of Upgrade

- Roadmap for tracker/trigger upgrades

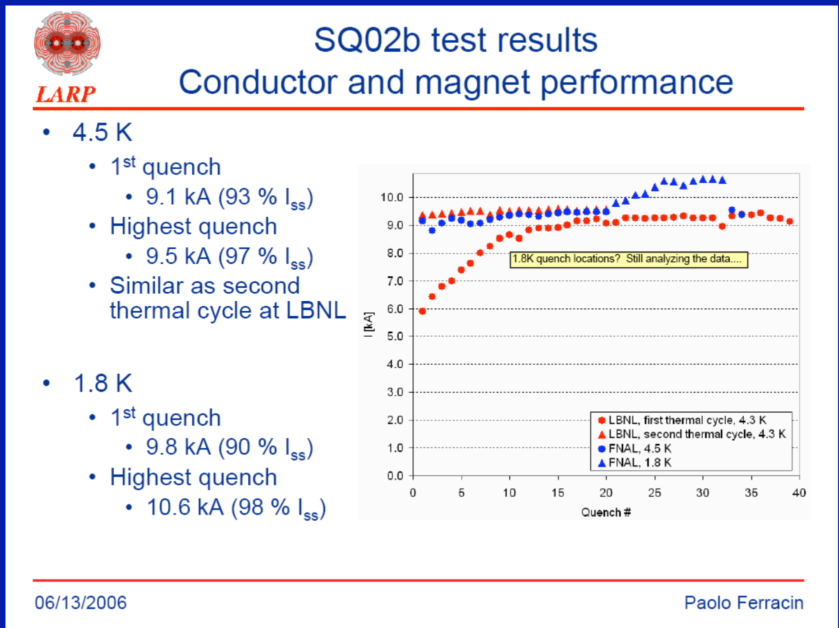


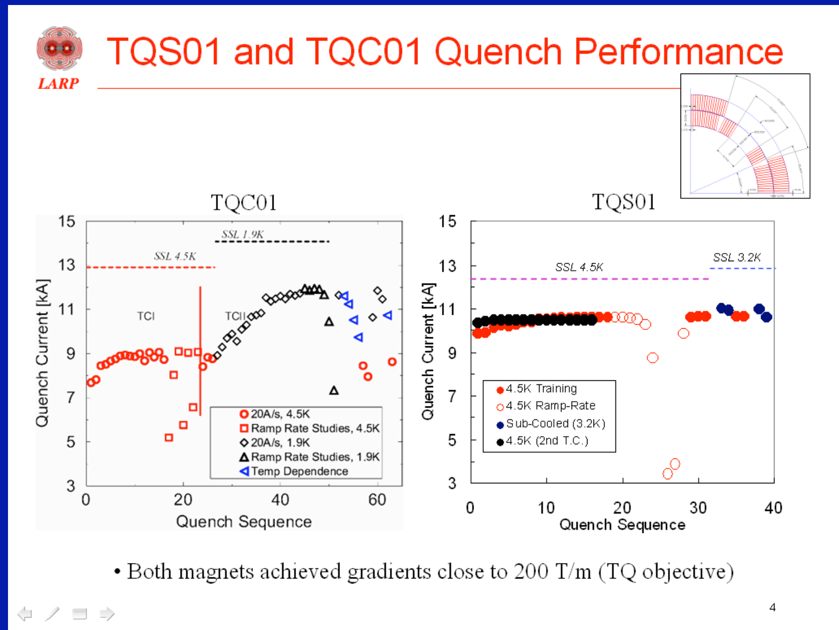
- **Upgrade to full new tracker in 8-10 years (for SLHC)**

NB: Both experiments emphasize “We want maximum annual integrated luminosity at minimum peak luminosity”

Jim Strait: LHC Upgrade from a US Perspective

- LHC program, including LHC upgrade, is high-priority component of US HEP program.
- US participates in R&D towards upgrades of experiments (ATLAS and CMS) and of LHC accelerator.
- US contributions to accelerator upgrade focus on IR, in particular on Nb_3Sn magnet development.. Recent successes: fields 10-12 T reached in different prototype magnets

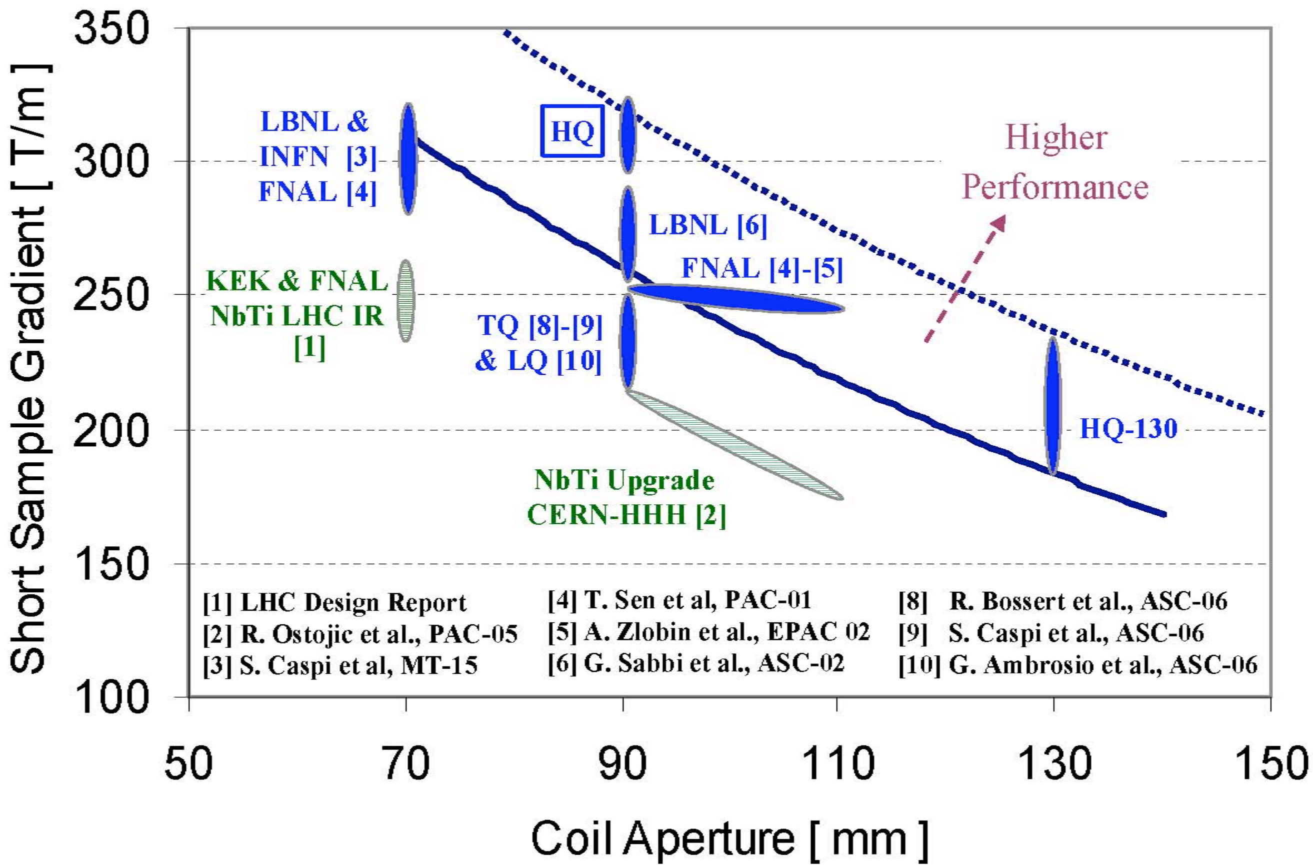




GianLuca Sabbi: Nb_3Sn Quad Development in US

LARP

Quadrupole Designs for the LHC IR



LHC-LUMI-06 Workshop, October 2006 Gian Luca Sabbi 3

LARP Magnet Program Goals

Investigate viability of Nb_3Sn technology for the LHC luminosity upgrade

1. Capability to deliver predictable and reproducible performance:

TQ (Technology Quads, 2005-07) D = 90 mm, L = 1 m, G_{nom} > 200 T/m

2. Capability to scale-up the magnet length:

LQ (Long Quadrupoles, 2008-09) D = 90 mm, L = 4 m, G_{nom} > 200 T/m

3. Capability to reach high gradients in large apertures:

HQ (High Gradient Quads, 2008-09) D = 90 mm, L = 1 m, G_{nom} > 250 T/m

Oct 25, 2005	Type	Length [m]	Gradient [T/m]	Aperture [mm]	FY05	FY06	FY07	FY08	FY09
MODEL MAGNETS									
Technology Quad (TQ)	cos(2θ)	1	> 200	90		3N+1R	2N+1R		
Long Quad (LQ)	cos(2θ)	4	> 200	90				1N	1N
High Gradient Quad (HQ)	cos(2θ)	1	> 250	90					2N
SUPPORTING R&D			**Peak Field** [T]						
Sub-scale Quad (SQ)	block	0.3	10-11	110	1N+1R	1N+1R	1N+1R	1N	
Short Racetrack (SR)	block	0.3	10-12	N/A		1N	1N	1N	
Long Racetrack (LR)	block	4	10-12	N/A			2N+1R		

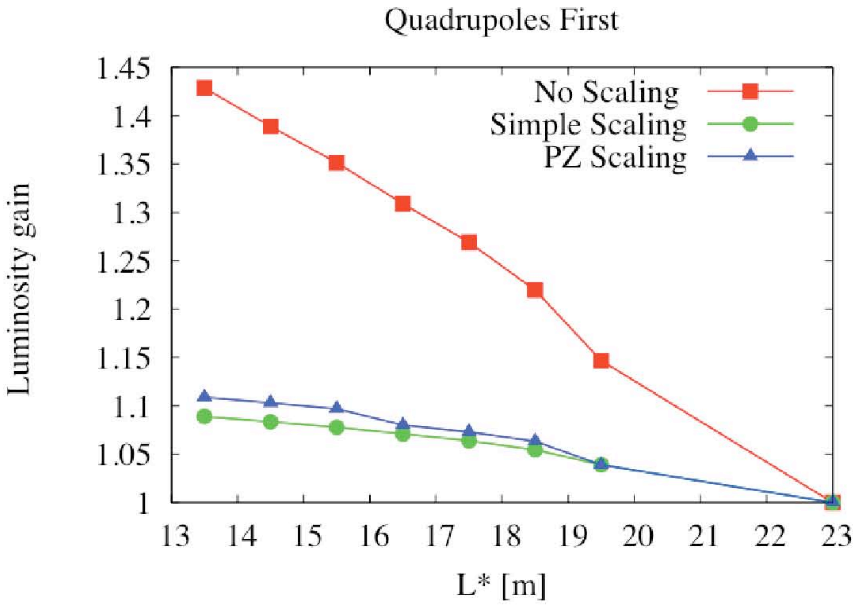
Tanaji Sen: IR Upgrade with Quadrupoles

LARP

Luminosity vs Lstar

Matching conditions
- From Q4 left to Q4 right
- β^{max} kept the same
- Quad lengths changed, gradient constant.

L* [m]	β* [m]
23	0.25
19.5	0.22
18.5	0.205
17.5	0.197
16.5	0.191
15.5	0.185
14.5	0.180
13.5	0.175

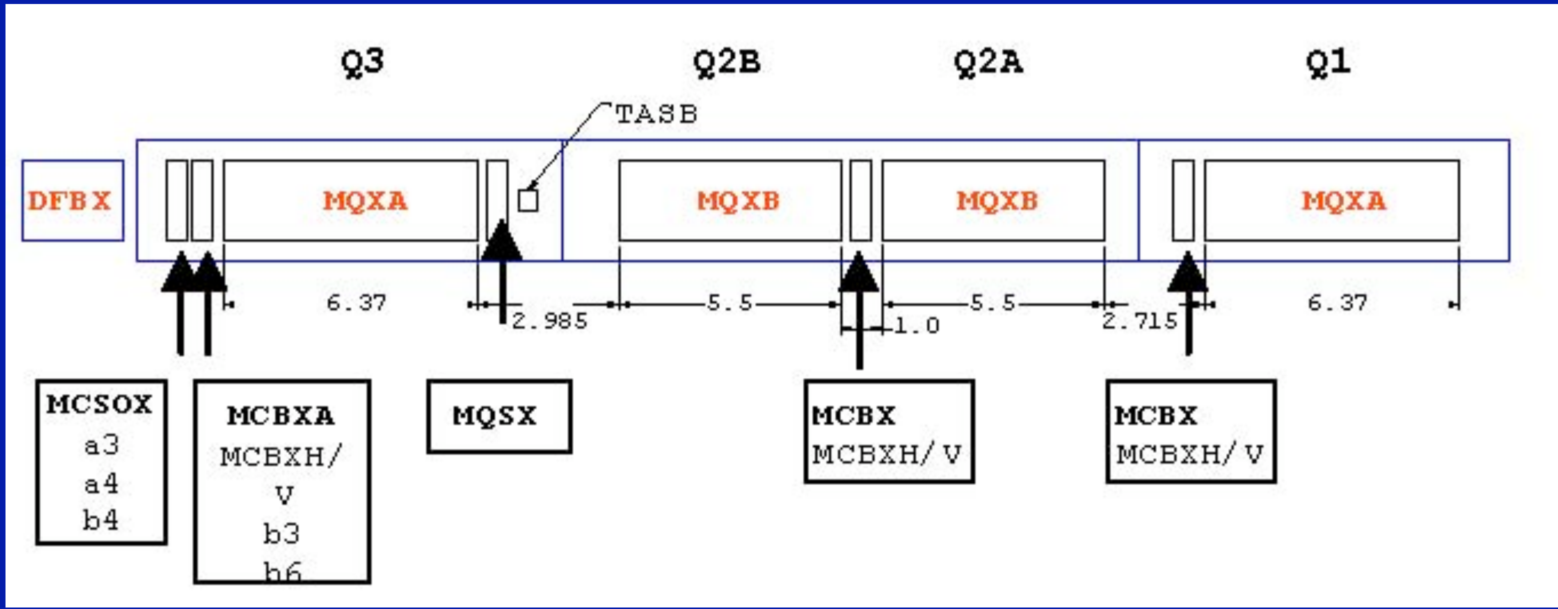


PZ: Y. Papaphilippou & F. Zimmermann

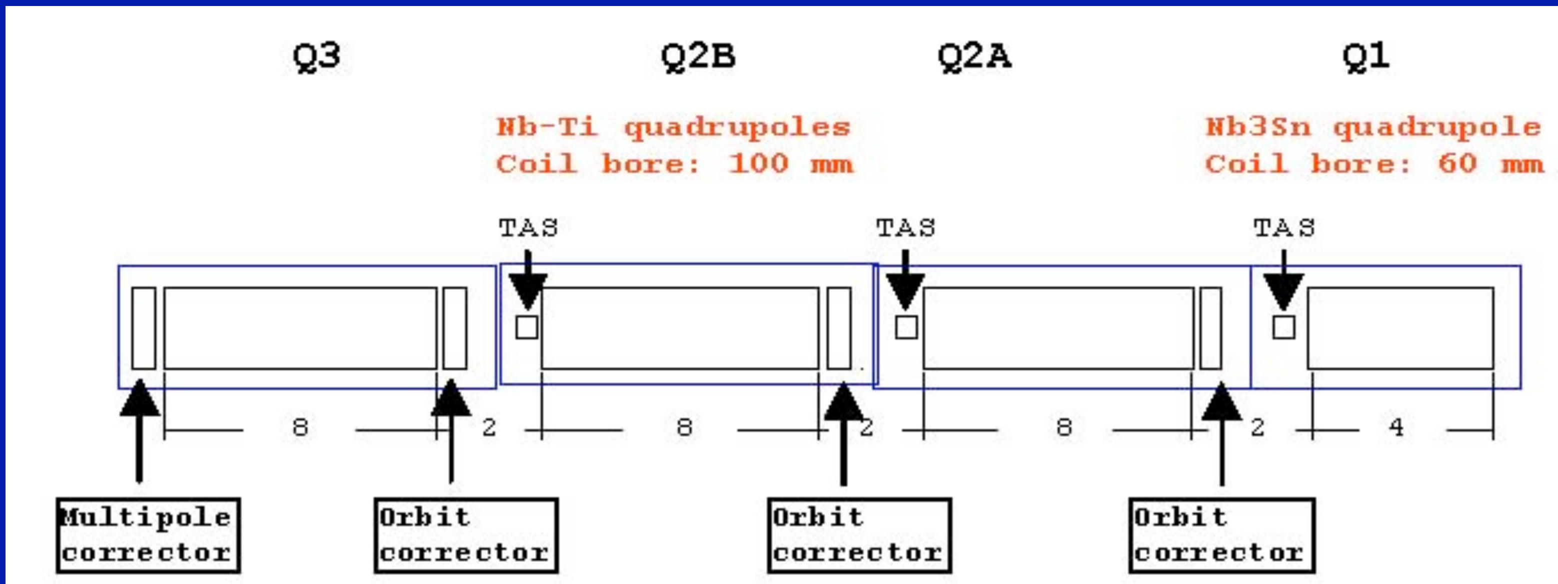
At constant N_b, reducing L* is worthwhile only if the crossing angle does not have to scale as $1/\sqrt{\beta^*}$. Else, weaker bb effects may allow increase in intensity as L* is reduced.

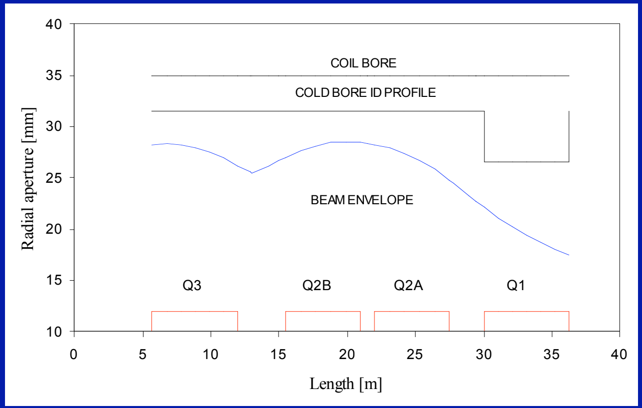
Tom Taylor & Ranko Ostojic: Nb_3Sn & NbTi Hybrid IR

Present layout



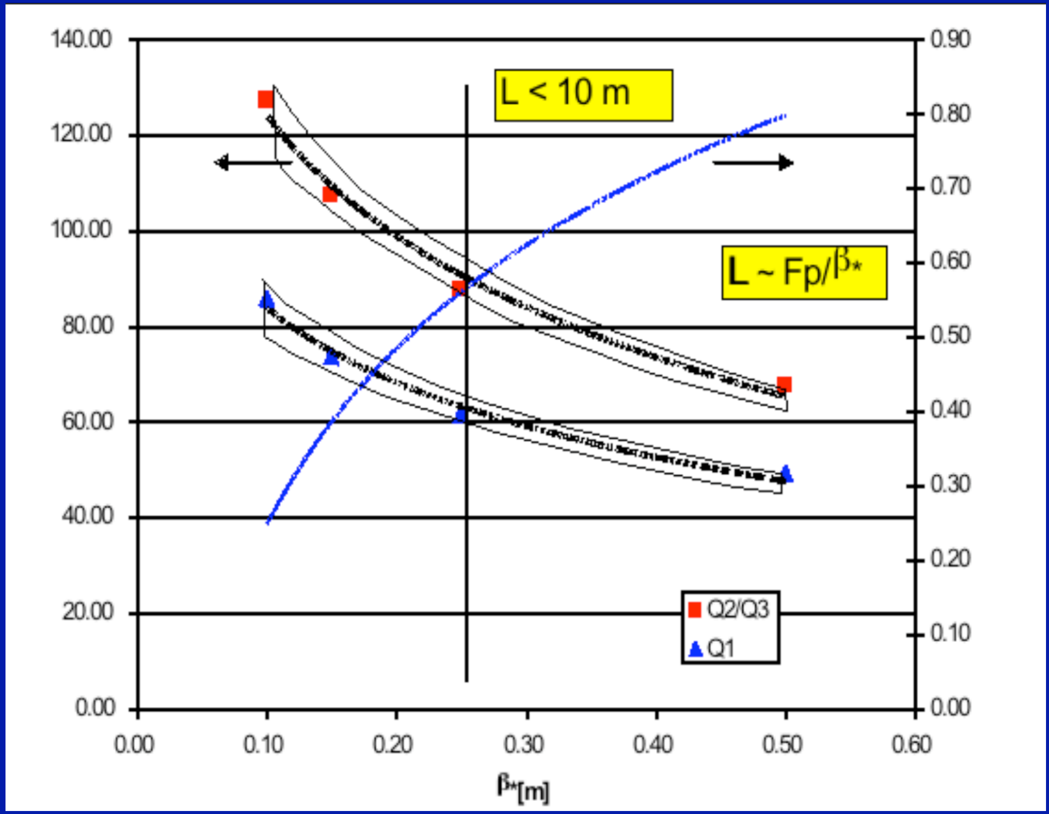
Proposed layout





Aperture requirement through present triplet with $\beta^* = 0.55$ m

With a triplet layout with l* ~ 20 m, and for magnets of up to 10 m long, increasing the bore D and decreasing the Piwinski factor F_p lead to a practical lower limit for β^* of 0.25 m.



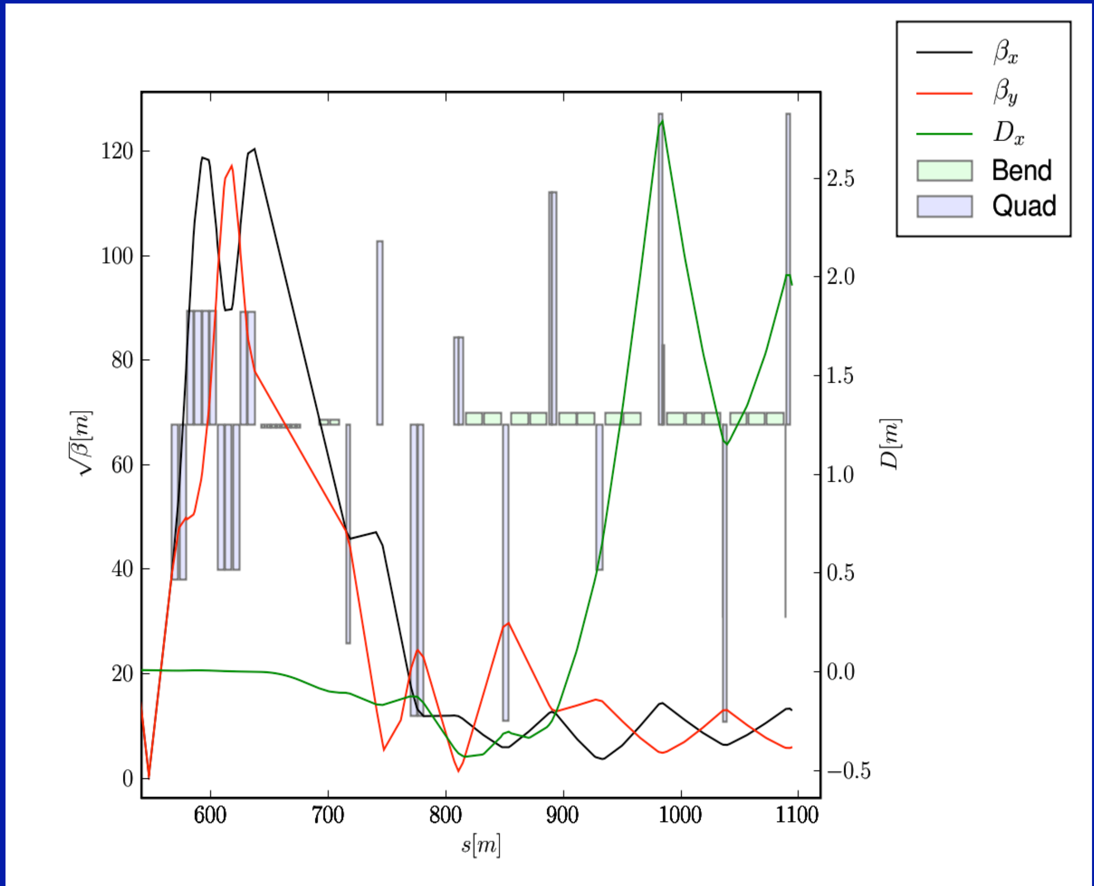
Oliver Bruning & R. de Maria: Low-Gradient Triplets

Solution with Modular 'Triplet' Layout

β-max < 15 km

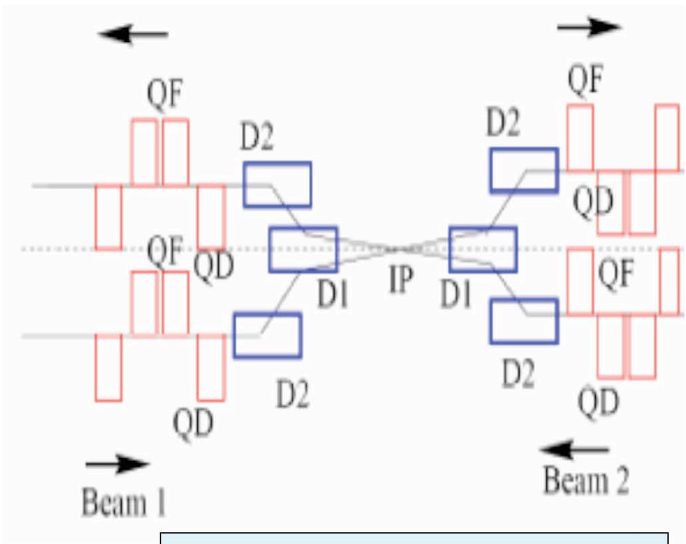
QX1 → 100T/m
QX2 → 80 T/m
QX3 → 100T/m
QX4 → 80 T/m

peak field: 9 T,
aperture: 180 mm,
(10% margin)

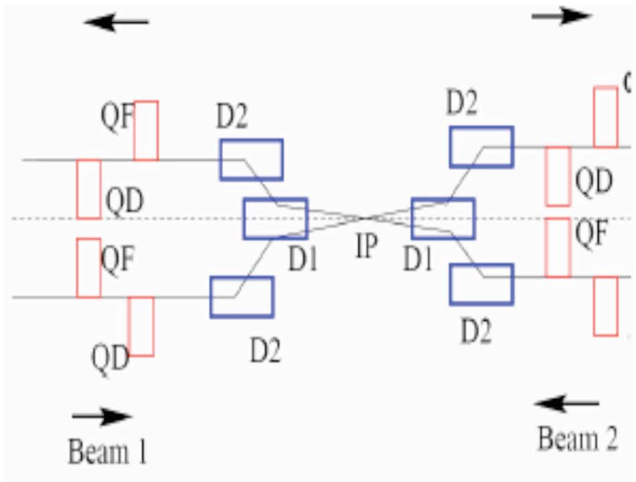


Tanaji Sen: US "Dipole First" Optics

Dipoles First: Two Flavours



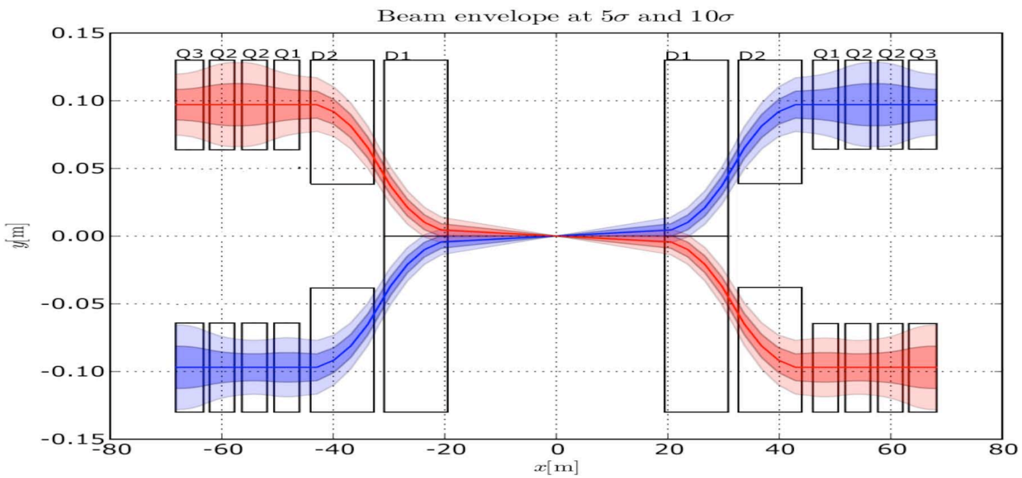
Triplet Focusing
Anti-symmetric about IP



Doublet Focusing
Symmetric about IP

Riccardo de Maria: Dipole 1st Optics optimizing Chromaticity and Dynamic Aperture

Layout specifications



Mag.	Pos.	Length	Field	Inner D.
D1	19.45m	11.4m	15.0T	0.130m
D2	32.653m	11.4m	15.0T	0.080m
Q1	46.05m	4.5m	231.0T/m	0.080m
Q2A	51.87m	4.5m	-256.6T/m	0.080m
Q2B	57.69m	4.5m	-256.6T/m	0.080m
Q3	63.25m	5.0m	280.0T/m	0.080m

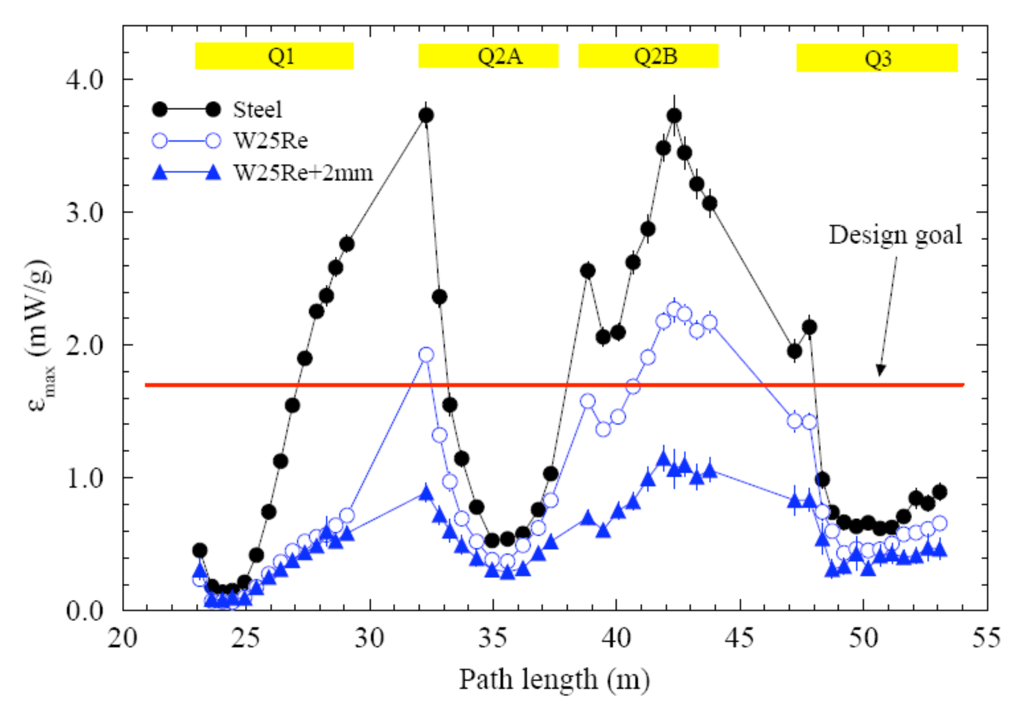
Ramesh Gupta: Open Mid-plane Dipoles

Open Mid-Plane Designs using HTS

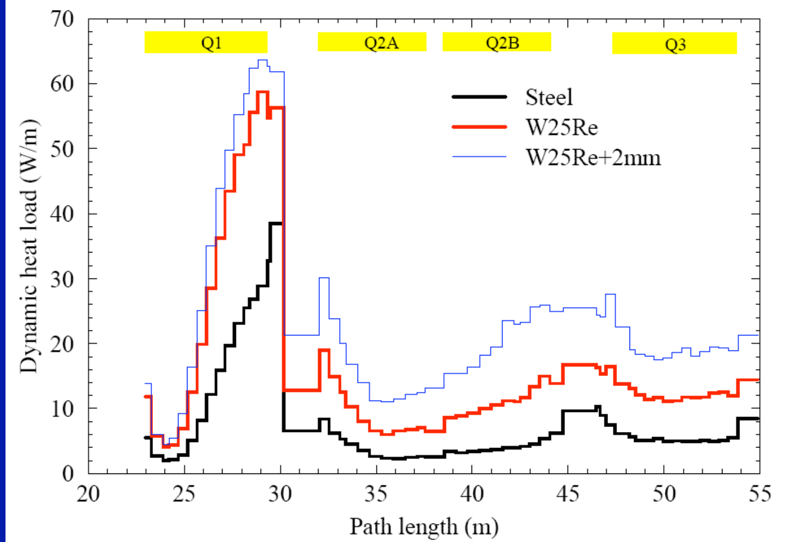
- **HTS in a hybrid design with Nb3Sn coils**
- **Such magnets could operate at very high field (>16 T)**
- **HTS would tolerate large energy deposition**

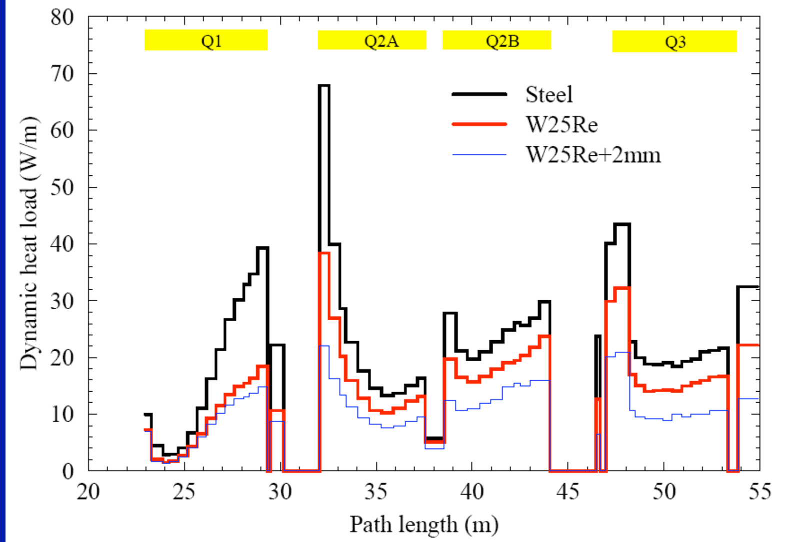
Nikolai Mokhov: Handling Collision Debris

High-Z Liner (Inner Absorber)

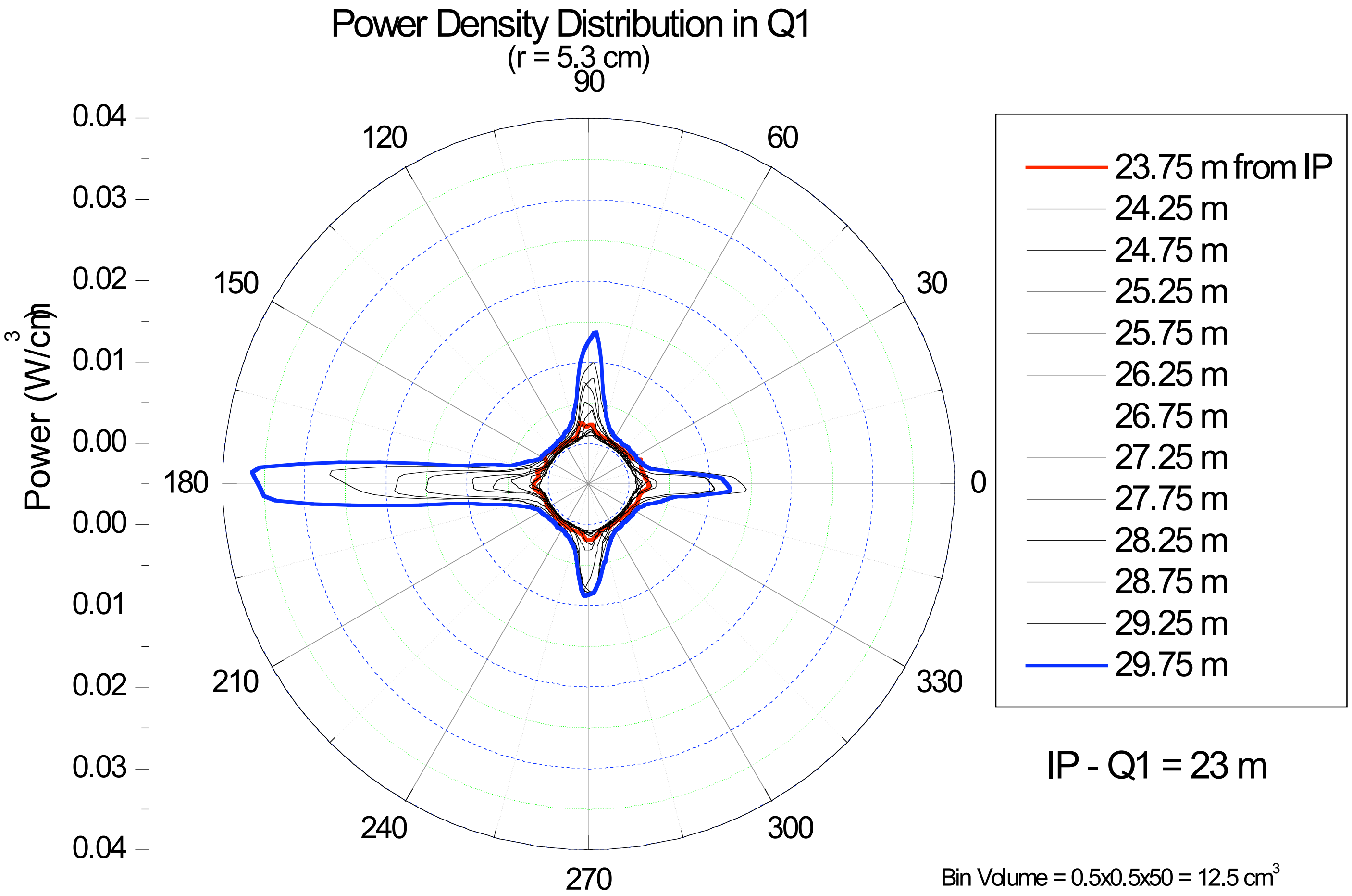


Energy deposition design goal for Nb3Sn quads is reached with **W25Re liner 7.2 mm thick** (+1.5 mm) in **Q1** and 1 mm thick (+1.5 mm) in the rest of triplet





Francesco Broggi: Energy Deposition in Triplet



peak power deposition almost constant for all cases

4- Solutions to reach a higher luminosity

Full beam current upgrade and "practical" early separation (reduction of the angle at IP by a factor of two). β_{max} around 16 km. Q' corrected.

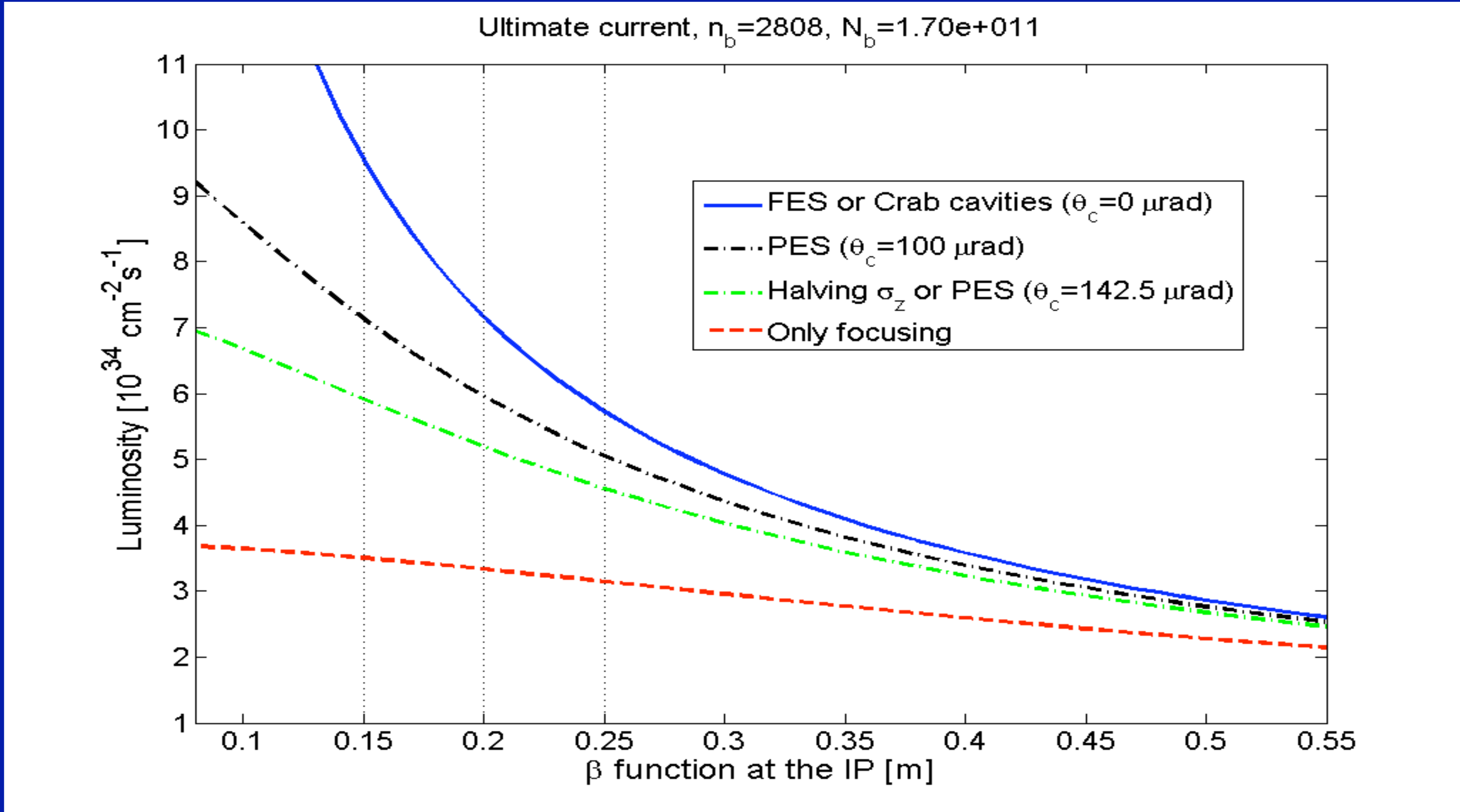
l^*	β^*	ϕ_{coil}	L_{PES}	L_{NES}	$<L_{PES}>$ 5 hours	Multiplicity
[m]	[m]	[mm]	[10^{34} $cm^{-2}s^{-1}$]			
13	**0.087**	**126**	**20.5**	12.2	× **1.5***	196
19	0.124	130	17.3	11.4		
23	0.15	131	15.3	10.7		

* With respect to L/L_0=10

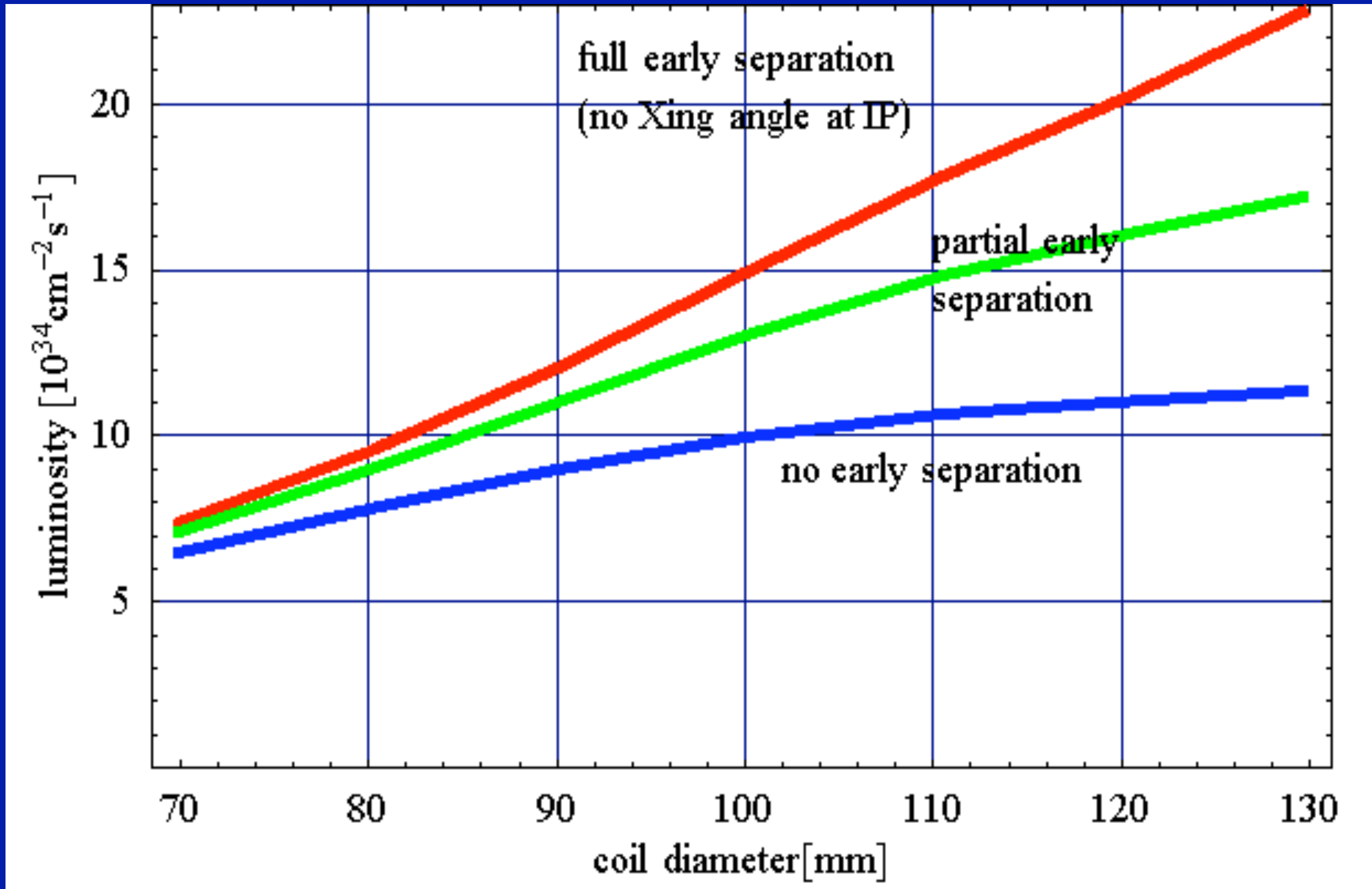
The Nb_3Sn quadrupole length is 6 to 7 m. Note the quadrupole aperture around 130 mm.

This means as well L/L0 = 10 e.g. for the **nominal bunch current**.

Note that the crossing angle couples β* and F



The geometric loss factor F is important for luminosity;
Reducing β is more useful if F is acted upon too.



Gain in luminosity from ×1.8 to ×3 for quadrupole ID 70 → 130 mm. The maximum of 130 mm is set by the

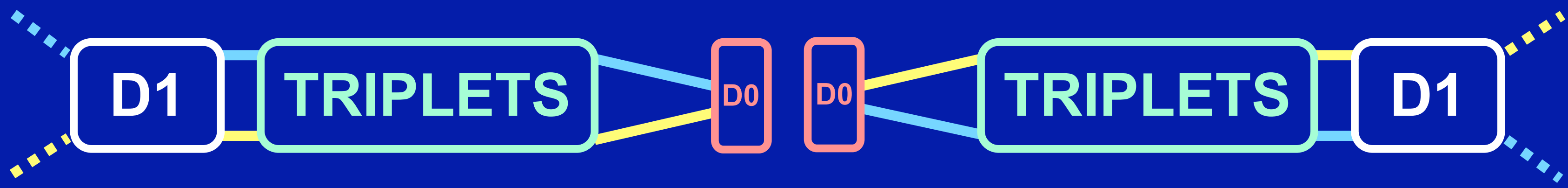
- *chromaticity correction*
- *the internal stresses for the Nb3Sn*

(Parameters used: "Ultimate beam" with 5616 × 1.7 10^{11} p and σ_s = 3.7 cm; l=19m, Nb_3Sn technology)*

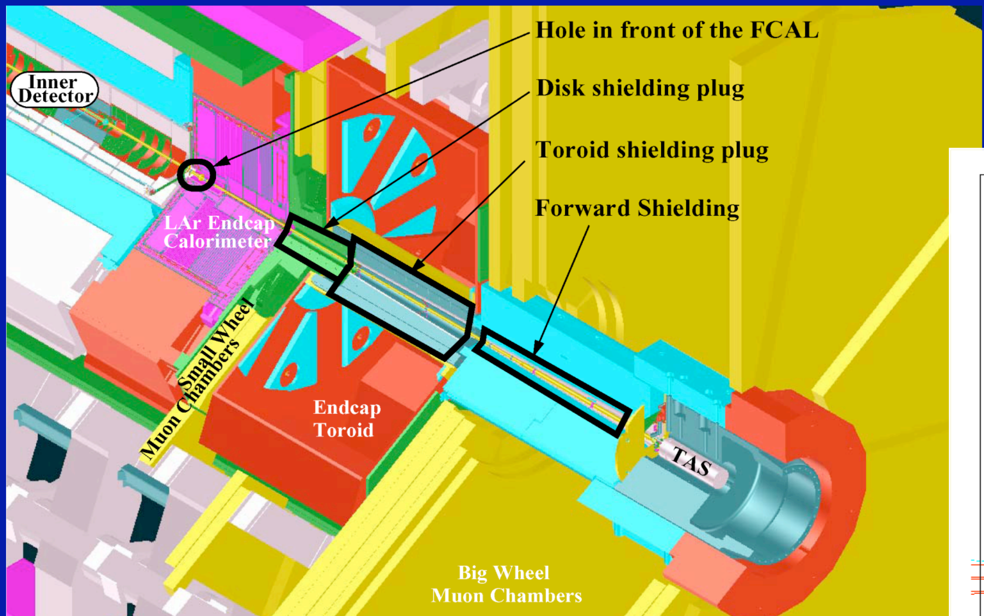
Jean-Pierre Koutchouk: Insertions - Parametric Study

1. **A very large aperture quadrupole** is the first key to increasing the luminosity. A quadrupole of ~125 mm aperture, 6 to 7 m long for 15 T peak field **would satisfy all insertion solutions investigated here.**
2. The Nb_3Sn technology offers 30% more luminosity for 50% more gradient and a significantly larger temperature margin *(see also E. Todesco talk)*.

Guido Sterbini: D0 and its Integrability

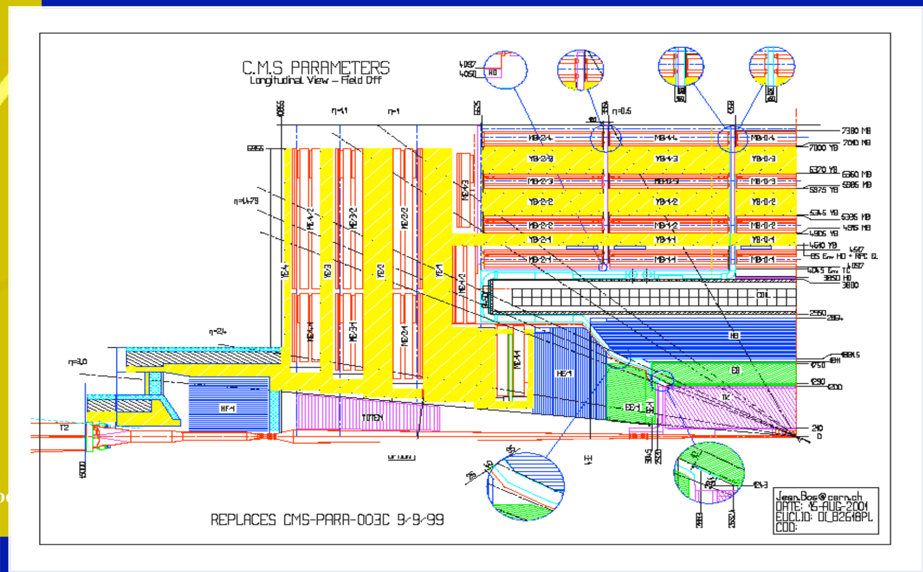


vanishing crossing angle & early separation

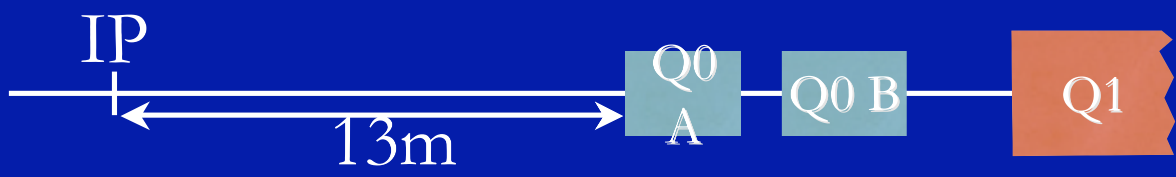


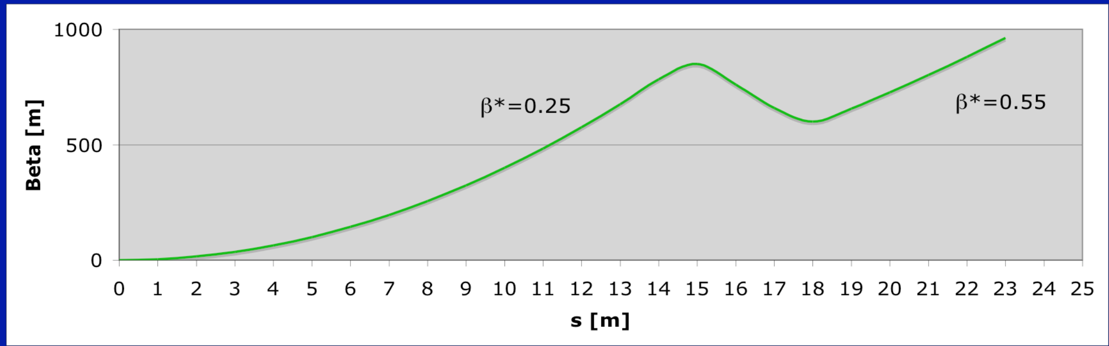
Courtesy of M. Nessi, 'Machine upgrade, ATLAS considerations', June 2006

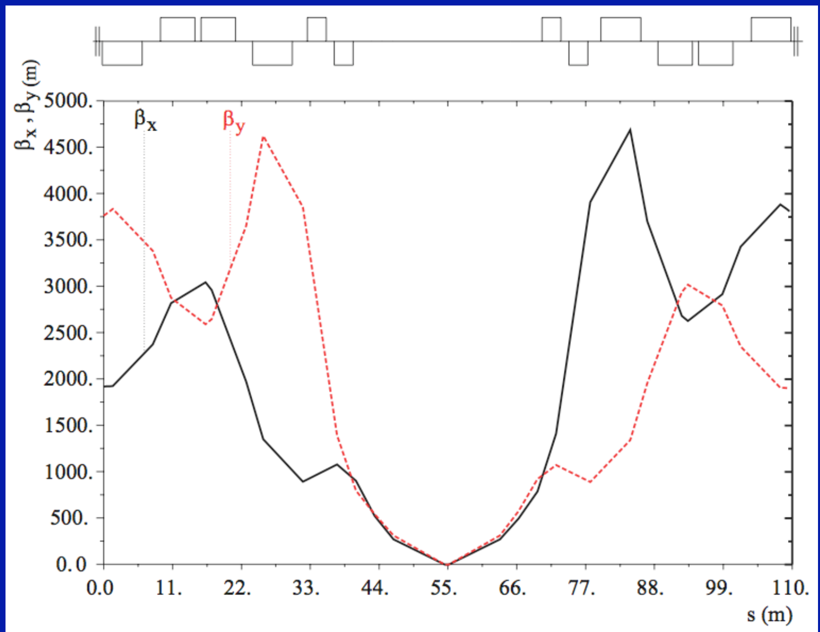
Space (?) for D0 in expts



Emanuele Laface: Q0 with l* = 13 m







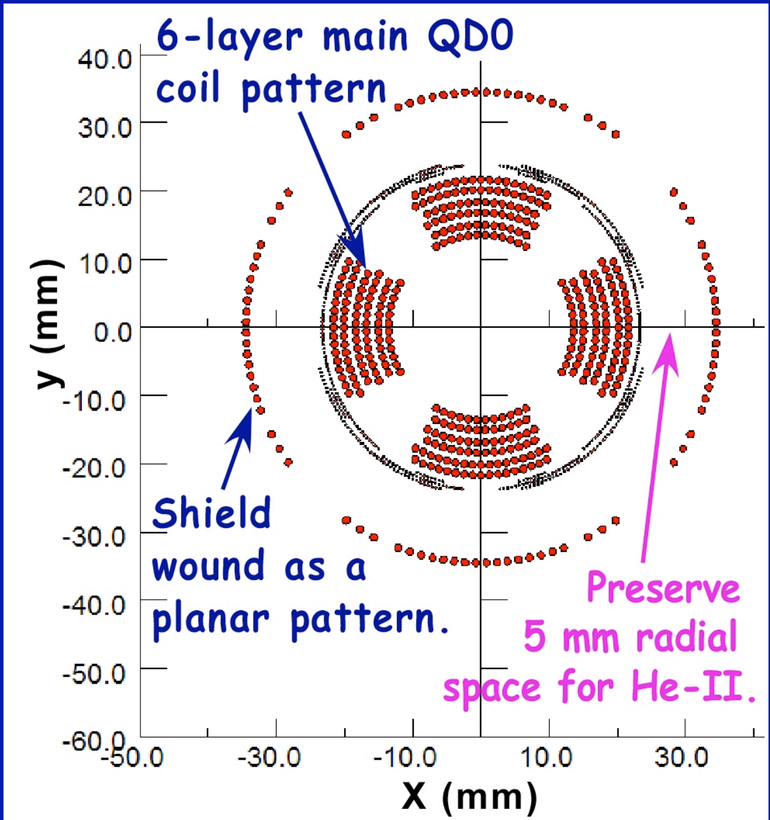
Magnet	Bore	Gradient
Q0 A	> 40 mm	165 T/m
Q0 B	> 40 mm	165 T/m

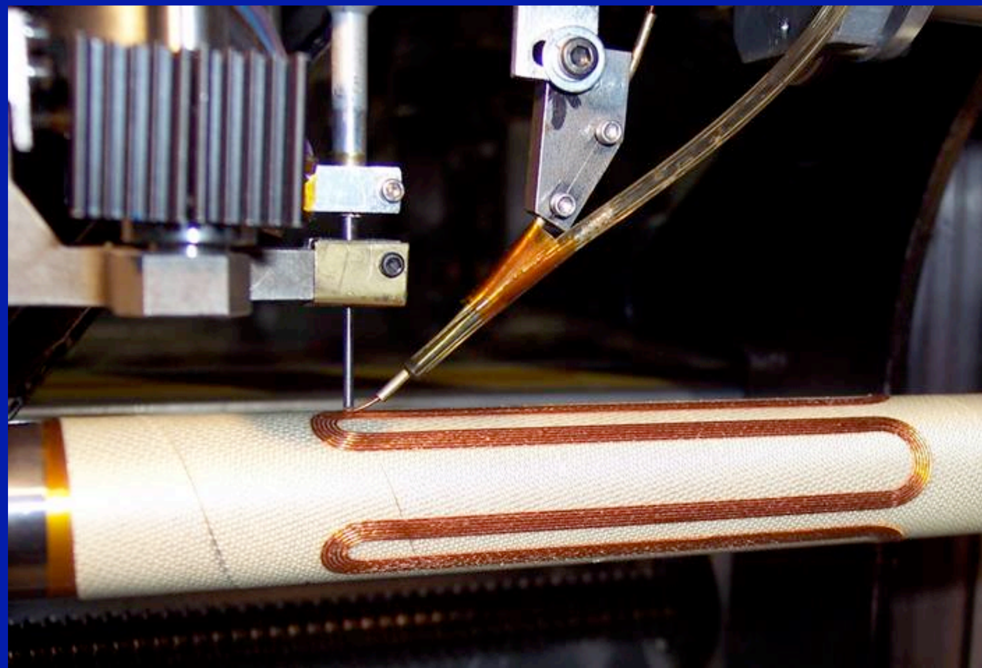
Peter Wanderer: Direct-wind slim quadrupoles

LHC Slim Quadrupole Specifications

Magnet	Length	Gradient	Diameter
SQ1	~ 3 m	~ 118 T/m	> 32 mm
SQ2	~ 3.5 m	~ 163 T/m	> 35 mm

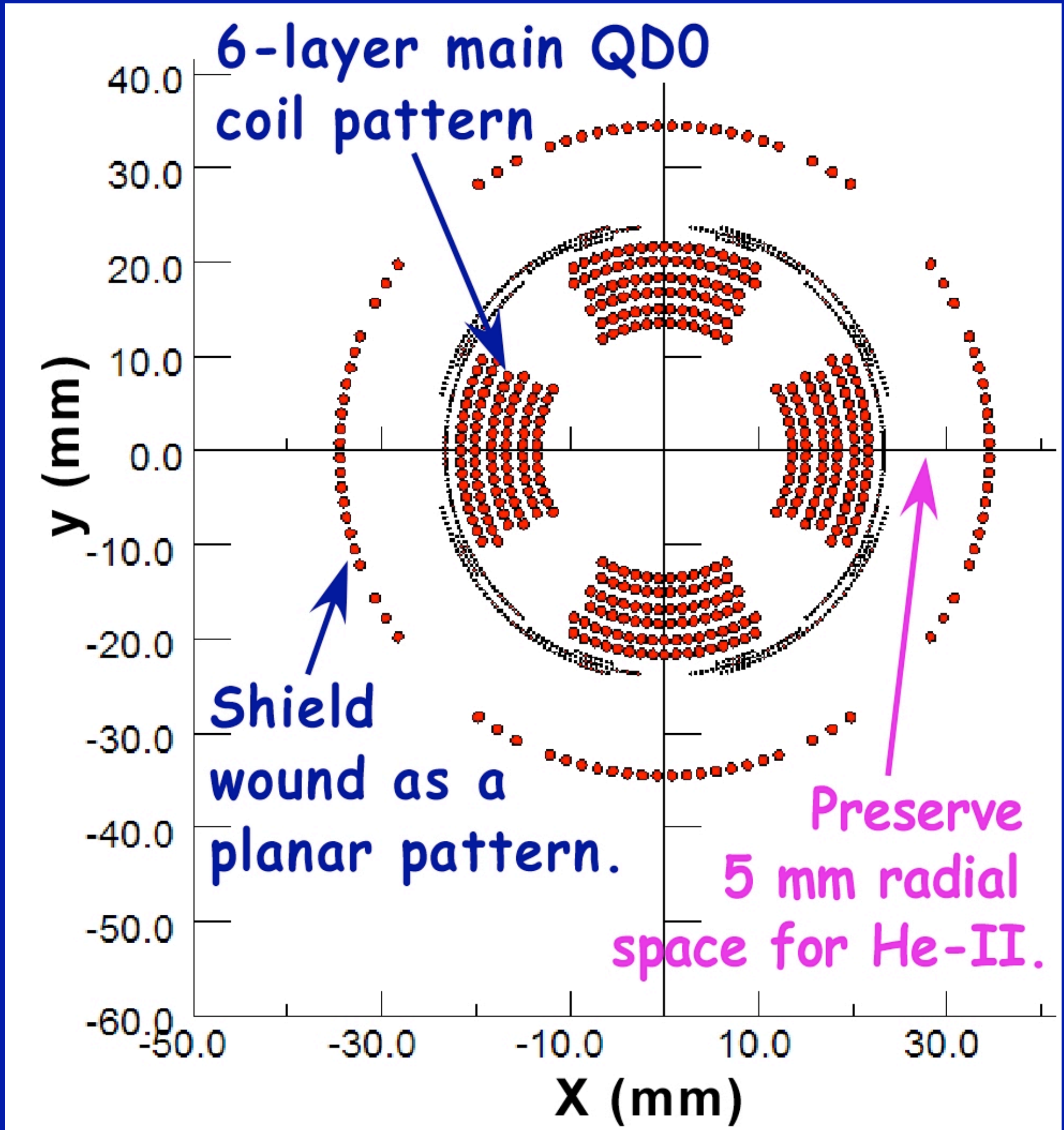
Compare
ILC actively shielded QD0 coil





It's worth following up for LHC

ILC direct-wind quadrupole



The inner and outer coils are wound on separate tubes (not shown) with a 5 mm space left inside the outer support tube for He II cooling. Running both coils at ~ 700 A gives 148 T/m from the inner coil and - 8 T/m from the outer coil.

Net gradient = 140 T/m

Peter Limon: LHC Luminosity Upgrade Using Quads

List of R&D topics

Continue & expand Nb_3Sn magnet R&D

Model quads, Long quadrupoles

More Nb_3Sn magnet R&D

Even more aggressive Nb_3Sn magnet R&D !

What else?

Much more work on energy deposition
cooling
support structure
alignment techniques
etc.

+ Lots of detector R&D

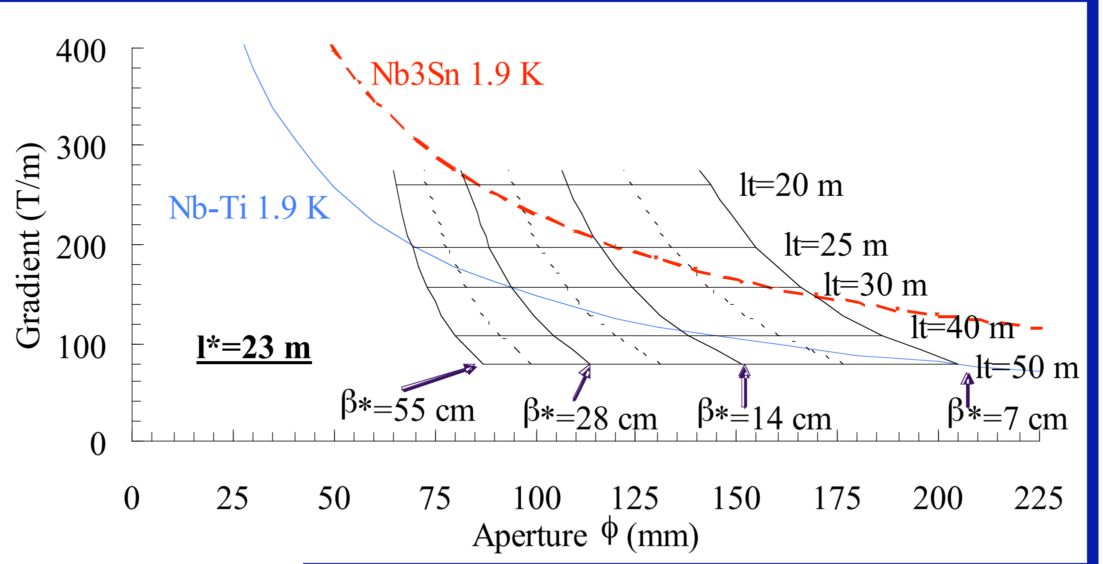
Ezio Todesco: Scaling Laws for β* in LHC IR

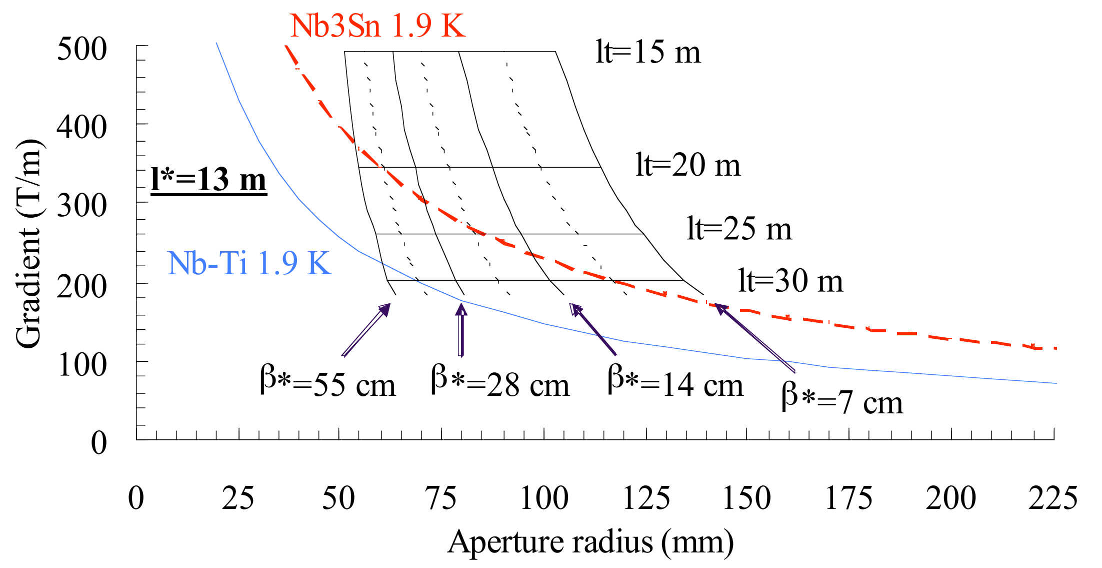
Triplet aperture and length vs *β**, technology, *l**

Ex.: *l** = 23 m *β** = 0.28 cm

Nb-Ti: aperture 94 mm,
triplet length 30 m,
gradient 160 T/m

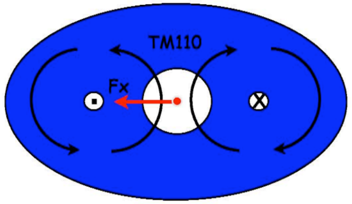
Nb_3Sn: aperture 81 mm,
triplet length 20 m,
gradient 275 T/m

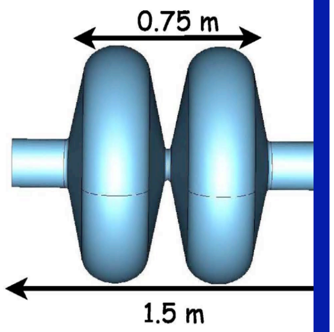




- Solutions can be found for both materials
- Large aperture: is this possible for Nb_3Sn ?
- Stresses, aberrations ?

Rama Calaga: Crab Cavities

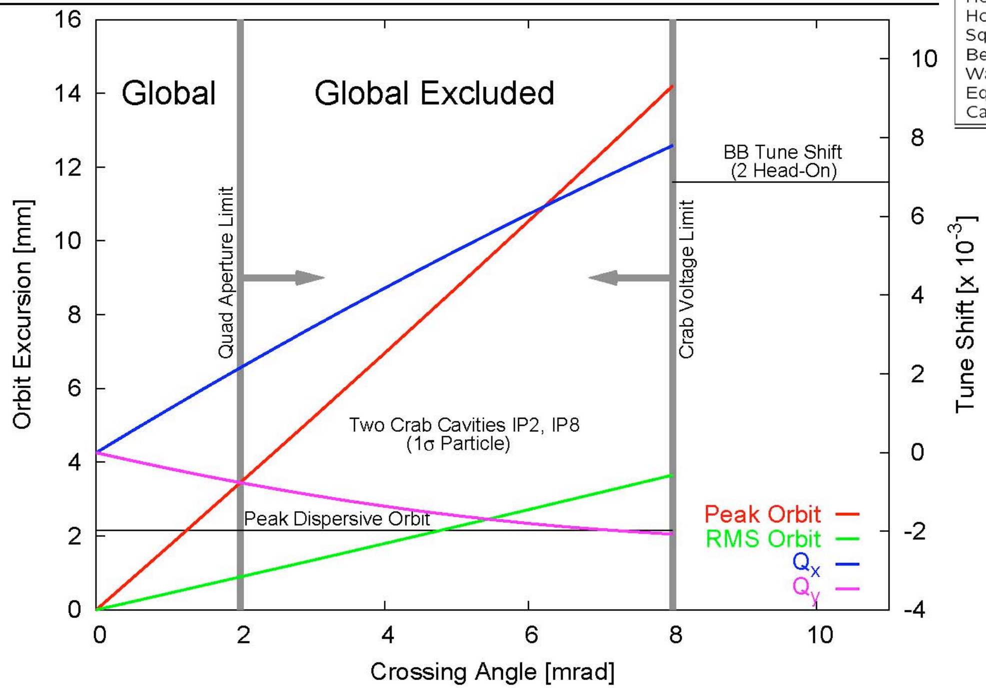




Half Cell Length, $L = \frac{\lambda\beta}{4}$	18.75 [cm]
Two Cells + Beam Pipe	~ 1.5 [m]
Horizontal Eq. Radius, R_{iris}	53 [cm]
Horizontal Eq. Radius, R_{iris}	37.5 [cm]
Squash Ratio	0.75
Beam Pipe Radius	15 [cm]
Wall Angle, α	~ 6 [deg]
Equator Dome Radius	12.0 [cm]
Cavity Beta, $\beta = \frac{v}{c}$	1.0

- Two Cells ~ 5 MV/Structure
- LOM + HOM Couplers
- Polarize for mode separation
- Tuners, Cryostat, ···

Orbit Excursion & Tune Spread



0.4-2 mrad	4-6 mrad	8 mrad
Nom. Quad-First	Sep. Quads (Exotic)	Sep. Quads (Simple)
$V_{crab} < 15$ MV Cavity Simple	$V_{crab} \sim$ 50-70 MV Exotic Cavity	$V_{crab} \sim 111$ MV Voltage Limit

Laurent Tavian: LHC Cryogenic System Upgrade

Local cooling limitations

Scenario	BS cooling loop [W/m/aperture]	1.9 K cooling loop [W/m]
Nominal	1.5	0.40
Ultimate	1.7	0.44
Short-bunch	**16**	0.81
Long-bunch	1.6	0.45
Local limitation	2.4 *	0.9 **

***: limited by the hydraulic impedance of the cooling channels and calculated for a supply pressure (header C) of 3 bar.**
****: limited by the sub-cooling heat exchanger capacity**

"The Short-bunch scenario requires an increase of sector cooling capacity by a factor 4 and shows local limitations in the beam screen cooling circuits.
- These two effects make **this scenario not cryogenically feasible**"

Outcome of LUMI'06 Part 1
IR upgrade and beam parameters

- Quadrupole-first preferred over dipole-first
- Pushed NbTi or Nb_3Sn still pursued, or hybrid solution – ***new***
- Slim magnets inside detector ("D0 and Q0") – ***new***
- Wire compensation ~established; electron lens – ***new***
- Crab cavities: large angle rejected; small-angle – ***new***
- 12.5-ns scenario seems to be impossible (cryogenic load)
- e-cloud/pile-up compromise: 25-ns & b*~8 cm, or 50-ns spaced long bunches – ***new***

Roland Garoby: Limitations of the Injectors

	Maximum energy	Number of pulses for the next machine	Repetition period for LHC	Intensity/bunch within required emittances (at ejection)	Limitations*
Linac2	50 MeV	1	1.2 s		Too low energy
PSB	1.4 GeV	2	1.2 s	~ ultimate beam	Too low injection energy (space charge)
PS	25 GeV	3-4	3.6 s	$1.5\ 10^{11}$ p/b (~ 90 % of ultimate beam)	Transition / Impedance ? Poor longitudinal match with SPS Reliability (age)
SPS	450 GeV	12	21.6 s	$1.15\ 10^{11}$ p/b (nominal beam)	Too low injection energy e-cloud Impedance
LHC				???	Too low injection energy (DA, Snap-back) ? e-cloud ?

Unexpected beam loss: > 10 %

* More in G. Arduini's talk on Friday morning

Main line of action

Guidelines: economy / reliability / timing / flexibility

Stage		Main effect	Additional benefits
1	Linac4 [160 MeV, H⁻]	▪ PSB beam brightness x2 => ultimate beam in PS in a single pulse	▪ Easier operation, flexibility ▪ New accelerator ▪ Possibility of > ultimate beam from the PS
2	New PS [~50 GeV, PS2]	▪ Higher injection energy in the SPS => better SPS performance ▪ New accelerator + less demand on the PS => higher reliability	▪ Shorter injection flat porch in SPS and LHC ▪ Potential injector for a new (higher energy) SPS
2'	New injector for PS2	▪ Reach full potential of PS2 (brightness & intensity) ▪ No PS any more => higher reliability	▪ Easier operation (minimum RF gymnastics in PS2 + shorter injection flat porch in SPS and LHC) ▪ New accelerator ▪ Flexibility
3	New SPS [>500 GeV]	▪ Reach full potential of LHC ▪ New accelerator => higher reliability	▪ Easier operation ▪ Potential injector for a DLHC

Michael Benedikt: General Design Aspects for PS2

- The PS2 is proposed as a replacement for the PS. It is a presently a normal conducting synchrotron with an injection energy of around 4 GeV and a maximum energy of around 50 GeV, twice that of the present PS. Why?

1. Assure reliability and availability of the injector chain for LHC. The present PS is the 50 year old: the frequency of breakdowns is increasing.
2. Improve the performance of the injector chain for LHC. PS2 will allow faster filling of the SPS, and produce LHC beams with greater brightness;
3. Improve beam performance for non-LHC physics in range 20 to 450 GeV;
4. The combination of cycling rate, size, beam density and extraction energy will give PS2 nearly an order of magnitude more beam power;
5. Prepare for a long-term energy upgrade of the SPS and possibly the LHC. The higher PS2 extraction energy will reduce the energy swing required from an SPS successor, allowing to approach 1 TeV at high energy.

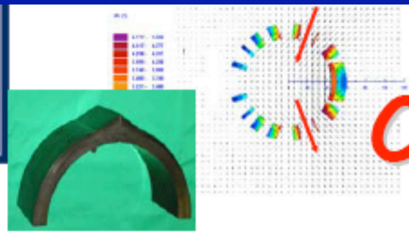
Parameter	Unit	PS2/PS2+	PS
Injection energy kinetic	GeV	3.5 – 4.0	1.4
Extraction energy kinetic	GeV	~ 50/75	13/25
Max. intensity LHC (25ns)	ppb	4.0×10^{11}	1.7×10^{11}
Max. intensity FT	ppp	1.2×10^{14}	3.3×10^{14}
Max. stored energy	kJ	1000/1500	70
Max ramp rate	T/s	1.5	2.2
Repetition time (50 GeV)	s	~ 2.5	1.2/2.4
Max. effective beam power	kW	400	60

- Twice average line density of PS
- Twice longer machine
- Twice extraction energy
- Identical acceleration time
- Shorter cycle time in some cases (LHC without double batch)
- Actual performance will depend on the level of the injector upgrade

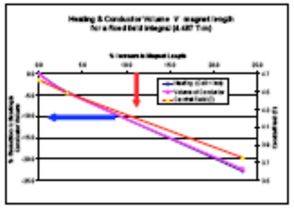
In case of staged approach, i.e. PS2 before injector upgrade

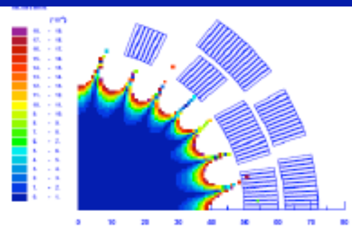
- Line density limited to achievable PS density
- Increased cycling time because of double batch filling from PS.

Glyn Kirby: Superconducting SPS

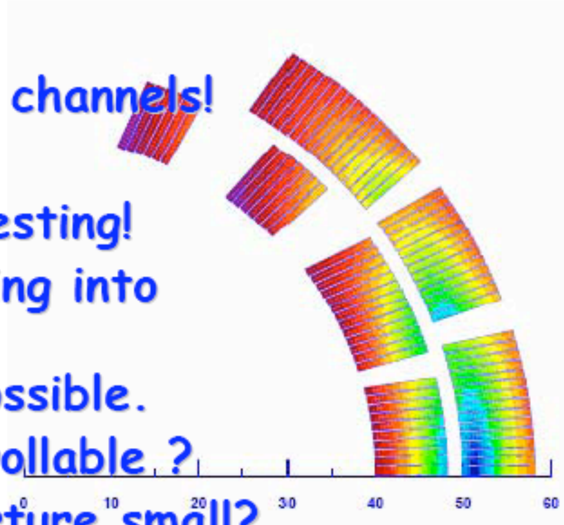


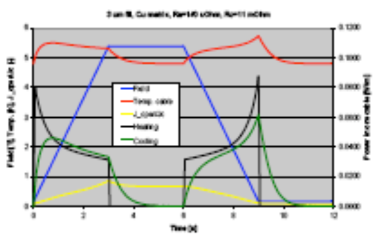
Conclusions

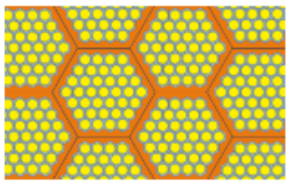


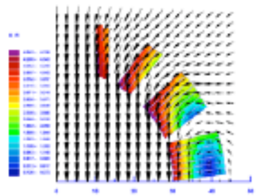


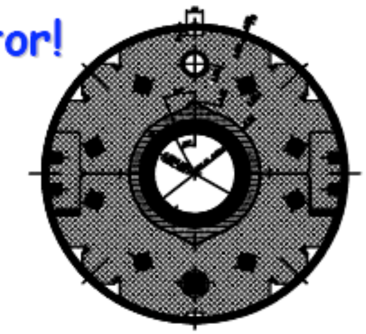
- 2 layer design!
- GRP or Stainless steel wedges with big channels!
- Cold Iron!
- Fatigue is important! Needs design & testing!
- Aperture keep as small as possible taking into account the beam? 60 80 100?
- Beam losses push aperture as big as possible.
- Field quality during ramping seem controllable ?
- Bend the magnet to help keep the aperture small?
- Get the heat out! Very open coil / insulation.
- Long Magnets have lower heating & less conductor! a CFM design?











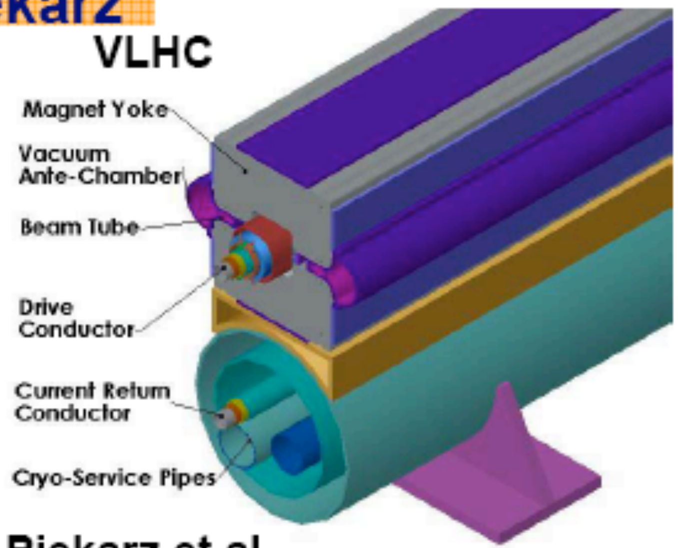
G.A.Kirby, CERN, LUMI-06, 19th October 2006 Valencia

Pipetron - VLHC magnets FNAL

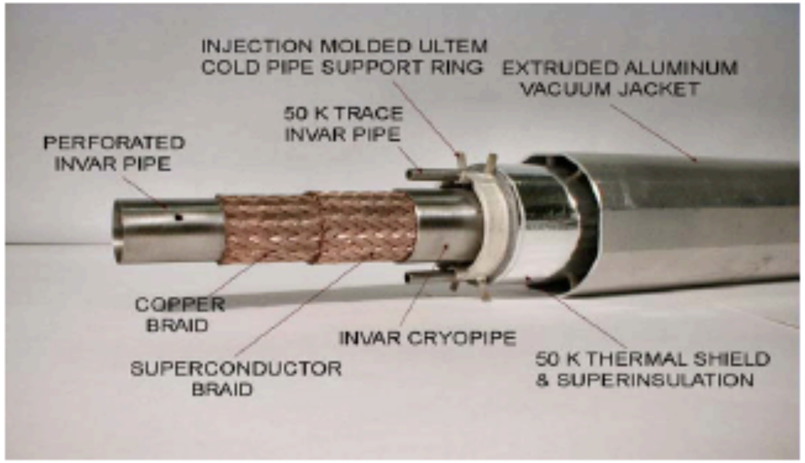
LARP

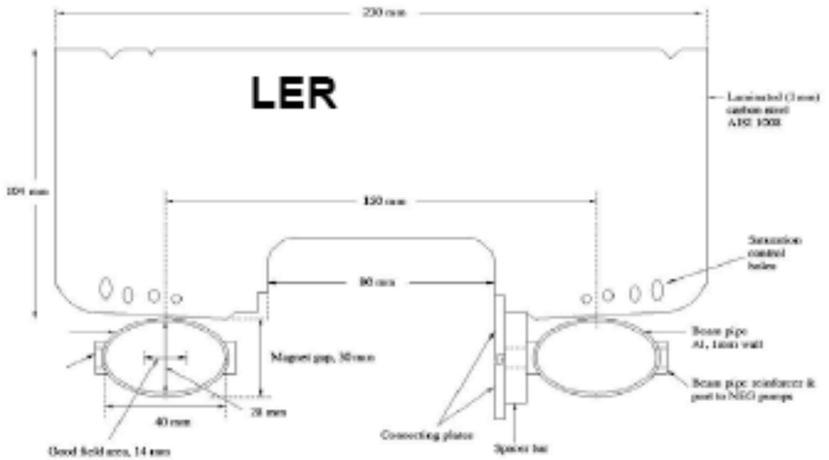
H.Piekarz

- 0.45 TeV injection at 0.48 T
- 1.5 TeV top at 1.595 T (72kA)
- Gradient ~ 3%
- Enlarged magnet aperture v 28 mm x h 40 mm



H. Piekarz et al.





Ralph Assmann: Collimation

Collimation: LHC Intensity Limitations I

Issue for protons	Prediction	Consequences
Collimator impedance	LHC impedance determined by collimators	≤ 40% of nominal intensity
Dispersion suppressors IR7	Losses of off-momentum p (single-diffractive scattering)	≤ 30-40% of nominal intensity for ideal cleaning
Unavoidable imperfections	Efficiency reduced to less than ideal	Set up time versus reduced efficiency
Efficient BLM thresholds	Factor 3-10 uncertainty from BLM reading on knowledge of beam loss	Thresholds at least factor 3 below intensity limit for quench
Radiation dose IR7 magnets (MBW, MQW)	2-3 MGy per year	Limited lifetime of magnets (specified for 50 MGy)
SC link in IR3	Risk of quench for losses of uncaptured beam	≤ 3.5% of nominal intensity in uncaptured beam
Dose on personnel	High remanent radiation	Limited access for modifications and upgrades in cleaning insertions
Environmental impact	OK for ultimate intensity	Review needed for any upgrade above ultimate → bypass galleries

Outcome of LUMI'06 Part 2
Tentative Conclusions on Injectors

- Intensity limitations in the PSB, SPS are the injector bottlenecks
- The LINAC4 will help to cure the space-charge problem in the PSB
- PS2/PS2+ should be successor of PS:
  reliability & availability; better technology
- Optimum extraction energy, layout, etc. to be determined (for SPS intensity, ion acceleration, nu-physics)
- Measures needed to improve the SPS until its successor is provided
- Comparison PS2/PS2+ required (eventually launch SC magnet R&D - superferric and 3.5-4.5 T, 2 T/s rate)
- Superferric LER in SPS to be investigated
- Studies to be made on space-charge compensation (e-lens) ?
- Effect of e-cloud in the upgraded injector to be cross-checked

Thank you for your attention