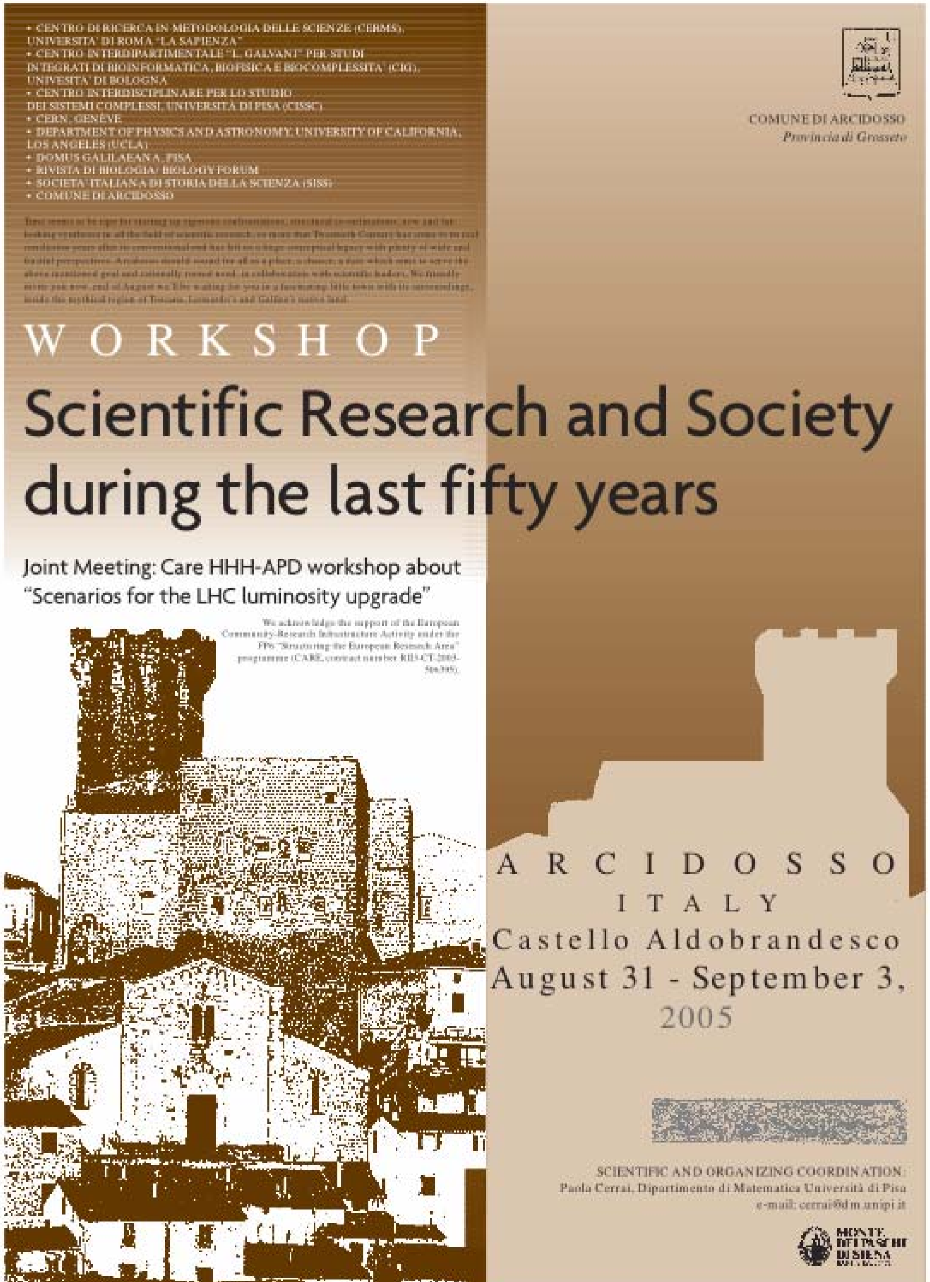
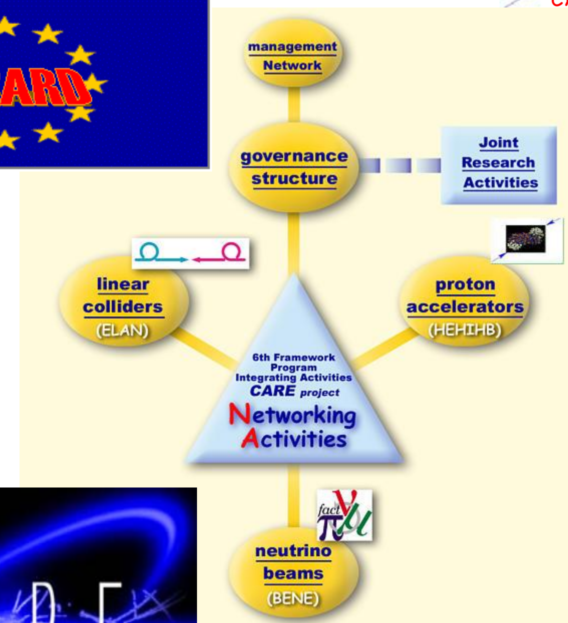
Scenarios for the LHC Luminosity Upgrade: Interaction Region Upgrade

- Report from the CARE-HHH-APD LHC-LUMI-2005 workshop (Arcidosso, 31 Aug–3 Sep 2005)
- Luminosity upgrade paths and IR design: dipole-first vs quadrupole-first, energy deposition, minimum crossing angle and beam-beam compensation, Crab cavities or early beam separation, flat beams
- Highlights from the US-LARP mini-workshop IR-2005 (Fermilab, 3–4 Oct 2005) and recent developments
- Tentative conclusions: R&D, milestones, convergence towards a Reference Design Report

http://care-hhh.web.cern.ch/CARE-HHH/

Future upgrade





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LHC-LUMI-2005 WORKSHOP PROGRAMME

Opening Session, convener E. Tsesmelis helped by F. Zimmermann

- Physics Motivation for an LHC Luminosity Upgrade, M. Mangano
- Machine-Detector Interface, F. Palla (INFN)
- LHC beam parameters and IR upgrade options, F. Ruggiero
- Fast pulsed High Energy injectors, W. Scandale

Session 1: Optics & Layout, convener P. Raimondi (INFN) helped by R. Tomas

- Progress of US-LARP activities on LHC IR Upgrade, T. Sen (FNAL)
- Possible Dipole-First Options and Challenges, O. Brüning
- Optics Design for Dipole-First Options, R. De Maria
- Possible Quadrupole-First Options with $\beta^* <= 0.25$ m, J.-P. Koutchouk
- Magnetic lattice for the High Energy injectors, G. Arduini

Session 2: High-Intensity Effects, convener F. Ruggiero helped by G. Rumolo

- Progress of Beam-Beam compensation schemes, F. Zimmermann
- High brilliance and closer bunches from the LHC injectors, E. Shaposhnikova
- Beam collimation and control in the High Energy injectors, N. Catalan
- New RF systems for the Super-ISR and Super-SPS, J. Tuckmantel

WG 1 on LHC IR Upgrade, convener O. Brüning helped by E. Todesco

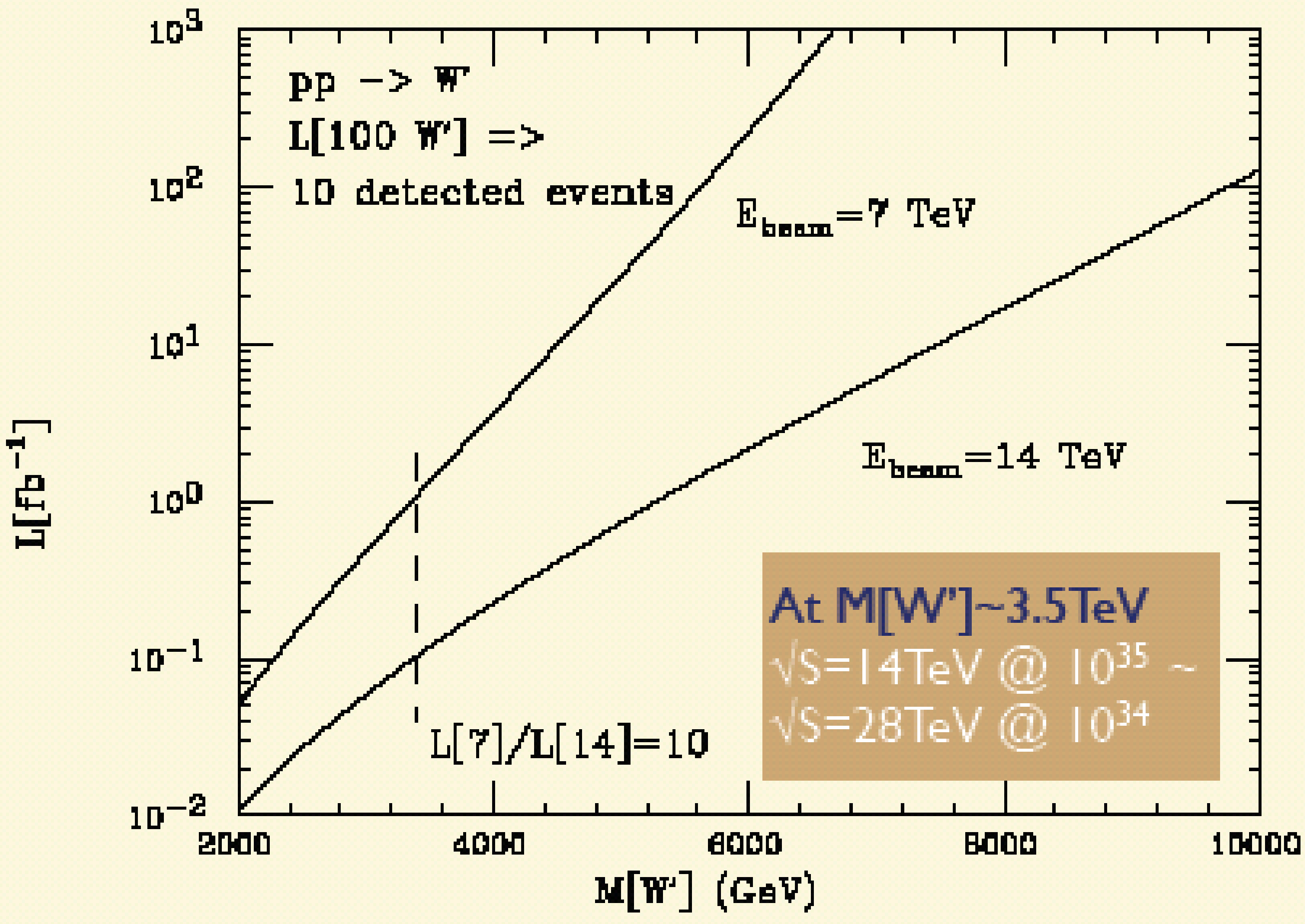
WG 2 on High Energy Injectors, convener W. Scandale helped by G. Arduini

Closing Session, Summary talks by the Sessions and WG's conveners

luminosity versus energy upgrade

Courtesy of Michelangelo Mangano

At low mass, the energy-dependence of the cross section is weaker, and a factor x10 in Lum is better than a factor of x2 in Ebeam



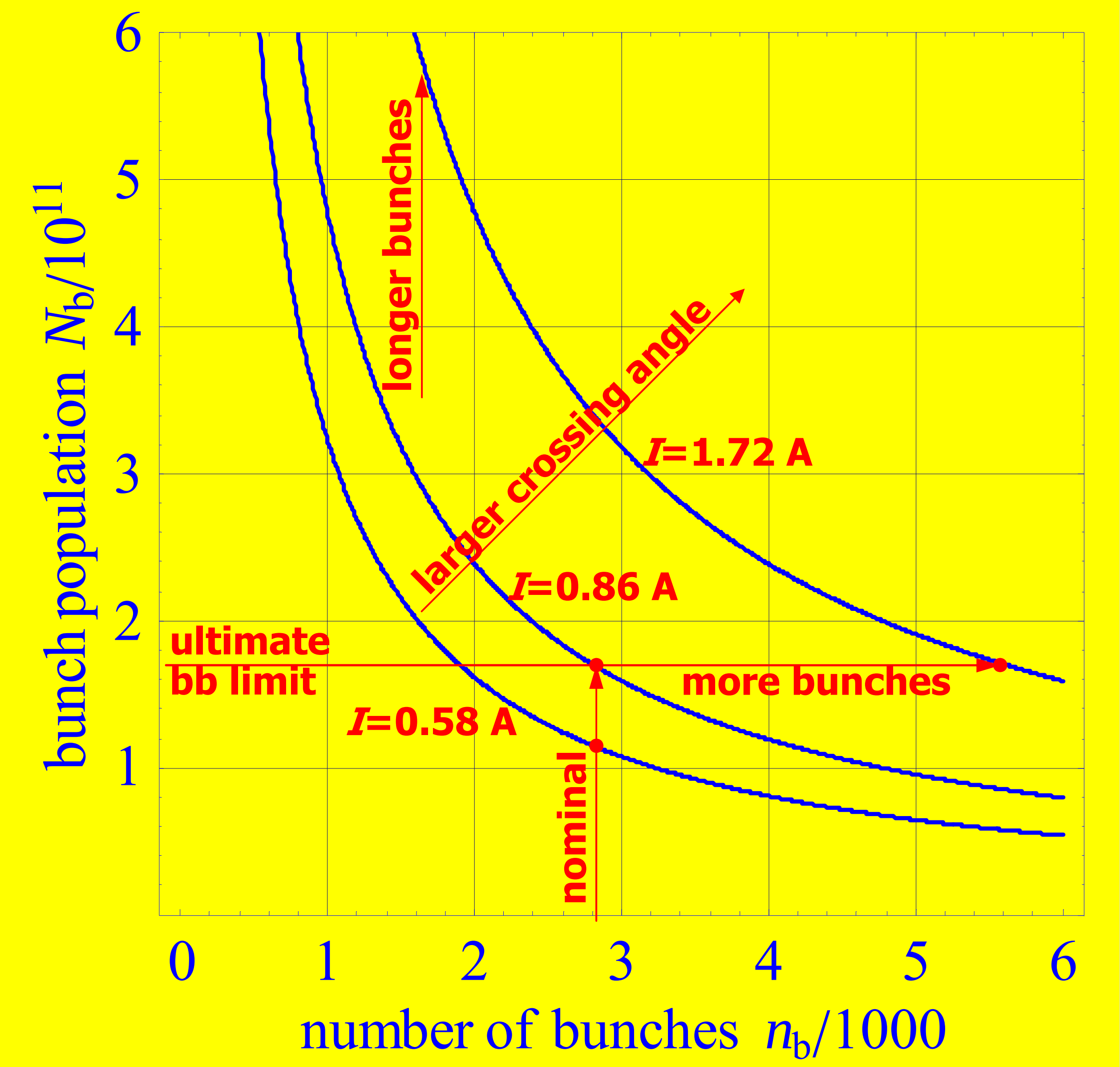
At M[W']~3.5TeV
√S=14TeV @ 10^{35} ~
√S=28TeV @ 10^{34}

At high masses, the E upgrade is essential

Nominal LHC parameters

collision energy	E_{cm}	2x7	TeV
dipole peak field	B	8.3	T
injection energy	E_{inj}	450	GeV
protons per bunch	N_b	1.15	10^{11}
bunch spacing	Δt	25	ns
average beam current	I	0.58	A
stored energy per beam		362	MJ
radiated power per beam		3.7	kW
normalized emittance	ε_n	3.75	μm
rms bunch length	σ_z	7.55	cm
beam size at IP1&IP5	σ^*	16.6	μm
beta function at IP1&IP5	β^*	0.55	m
full crossing angle	θ_c	285	μrad
luminosity lifetime	τ_L	15.5	h
peak luminosity	L	10^{34}	$cm^{-2}s^{-1}$
events per bunch crossing		19.2	
integrated luminosity	$\int L\,dt$	66.2	fb^{-1}/year

LHC upgrade paths/limitations



- Peak luminosity at the beam-beam limit $L \sim I/\beta^*$
- Total beam intensity I limited by electron cloud, collimation, injectors
- Minimum crossing angle depends on beam intensity: limited by triplet aperture
- Longer bunches allow higher bb-limit for N_b/ε_n: limited by the injectors
- Less ecloud and RF heating for longer bunches: ~50% luminosity gain for flat bunches longer than β^*
- Event pile-up in the physics detectors increases with N_b
- Luminosity lifetime at the bb limit depends only on β^* ⇒ reduce $T_{turnaround}$ to increase integrated lumi

Various LHC upgrade options

parameter	symbol	nominal	ultimate	shorter bunch	longer bunch
no of bunches	n_b	2808	2808	5616	936
proton per bunch	N_b [10^{11}]	1.15	1.7	1.7	6.0
bunch spacing	Δt_{sep}[ns]	25	25	12.5	75
average current	I [A]	0.58	0.86	1.72	1.0
normalized emittance	ε_n [μm]	3.75	3.75	3.75	3.75
longit. profile		Gaussian	Gaussian	Gaussian	flat
rms bunch length	σ_z [cm]	7.55	7.55	3.78	14.4
ß* at IP1&IP5	ß* [m]	0.55	0.50	0.25	0.25
full crossing angle	θ_c [μrad]	285	315	445	430
Piwinski parameter	$\theta_c \sigma_z/(2\sigma^*)$	0.64	0.75	0.75	2.8
peak luminosity	L [10^{34} cm^{-2} s^{-1}]	1.0	2.3	9.2	8.9
events per crossing		19	44	88	510
luminous region length	σ_{lum} [mm]	44.9	42.8	21.8	36.2

Interaction Region upgrade

goal: reduce β^* by at least a factor 2

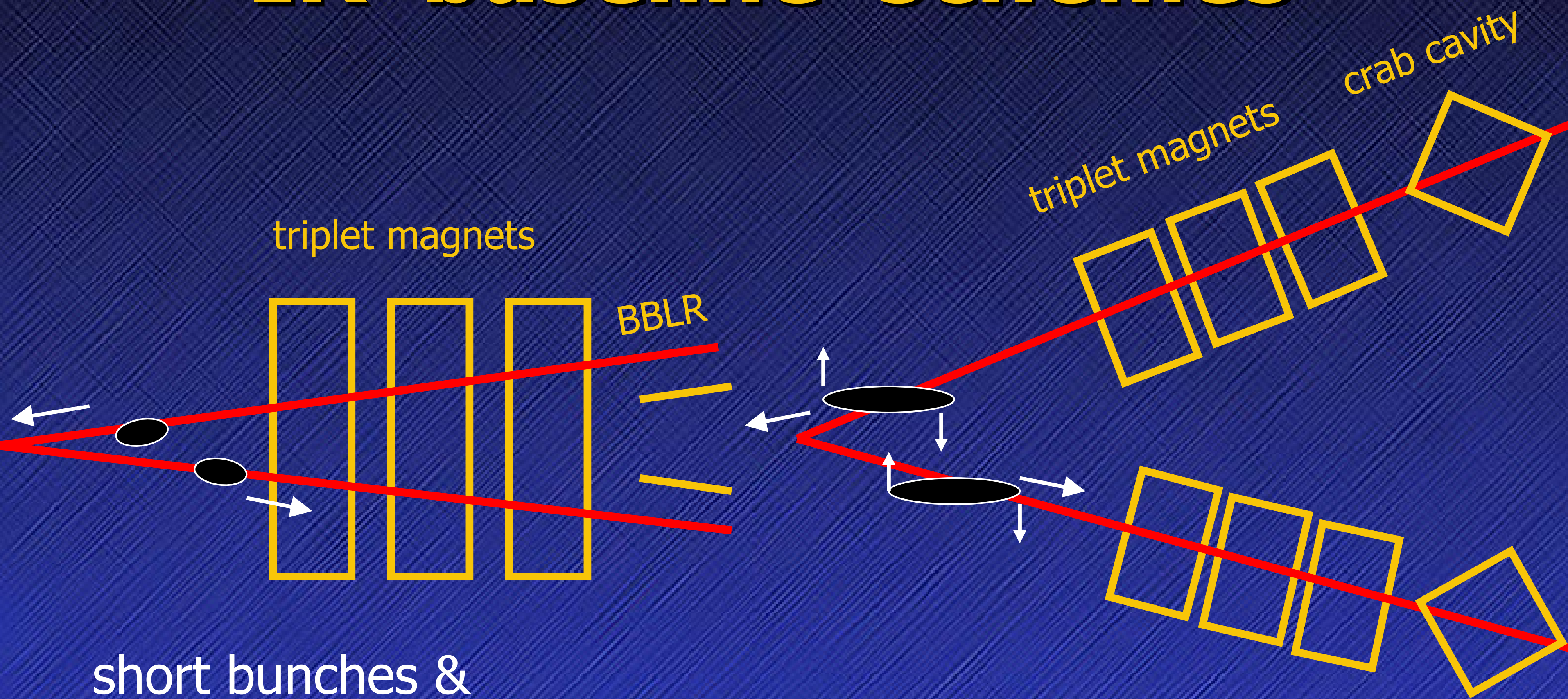
options: NbTi 'cheap' upgrade, NbTi(Ta), Nb_3Sn
new quadrupoles
new separation dipoles

maximize magnet aperture, minimize distance to IR

factors driving IR design:

- minimize β^*
- minimize effect of LR collisions
- large radiation power directed towards the IRs
- accommodate crab cavities and/or beam-beam compensators. Local Q' compensation scheme?
- compatibility with upgrade path

IR 'baseline' schemes



short bunches &
minimum crossing angle &
BBLR

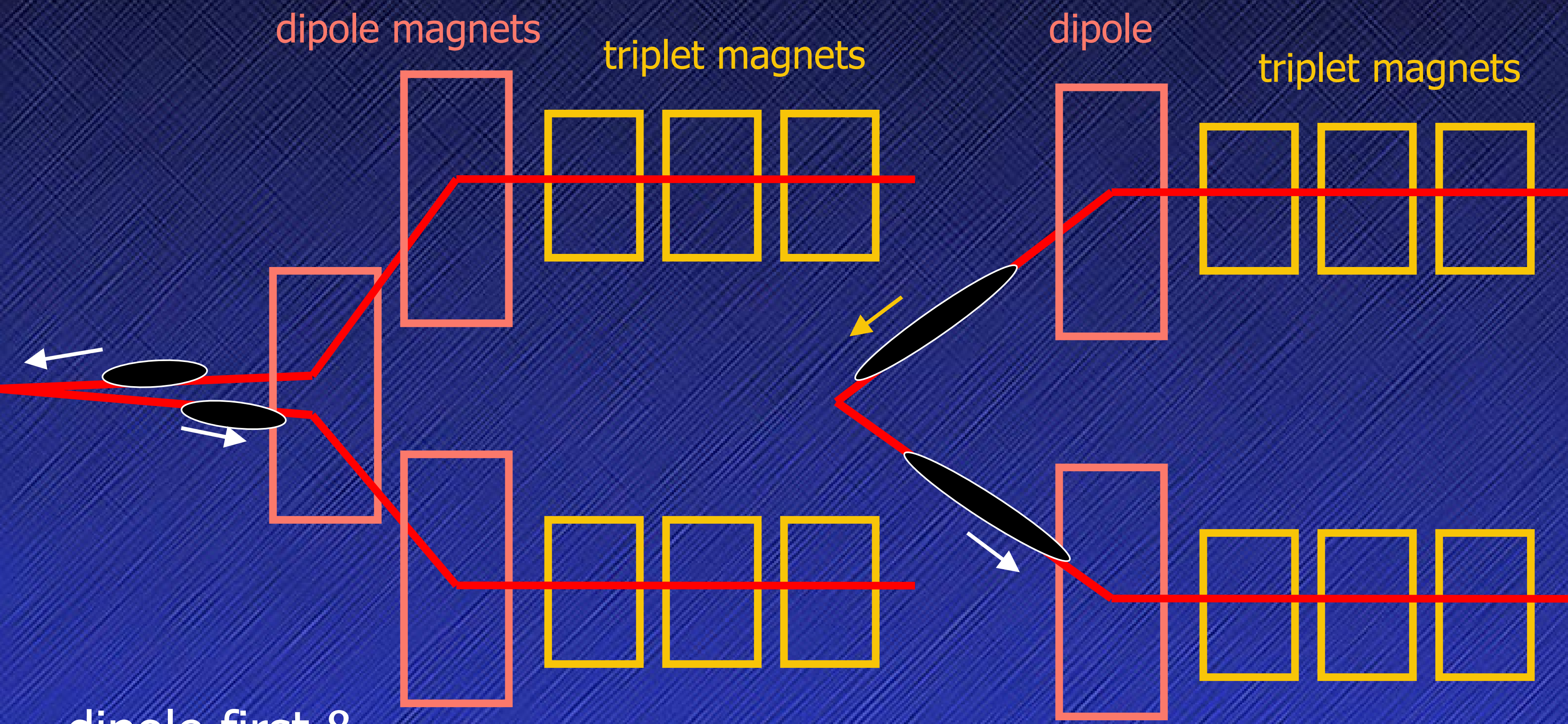
crab cavities &
large crossing angle
(what is minimum crossing
angle for separate channels?)

Conclusions (quad first, small angle)

1. The scaling of the beam separation and of the heat deposition are two critical issues for the definition of the triplet quadrupoles→checks welcome.
2. The Nb-Ti-Ta solutions have very limited scope and have potential chromatic problems. The Q aperture shall be at least 100 mm.
3. At 23m, the Nb3Sn solutions require a quad aperture larger than 100 mm and suffer from the same chromatic problems. The BBLR reduces the demand to 90mm but no guaranty today.
4. At 19 m from IP, a 90 mm quad is OK with good luminosity and potential for significant improvements with BBLR and D0 or shorter bunches.
5. At 12m and **16m**, the performance and potential are somewhat improving and the chromaticity issue totally disappears.
6. An early separation scheme (D0) is under evaluation.
7. The possibility of moving the triplet towards/in the detectors will be investigated

J.P. Koutchouk

alternative IR schemes



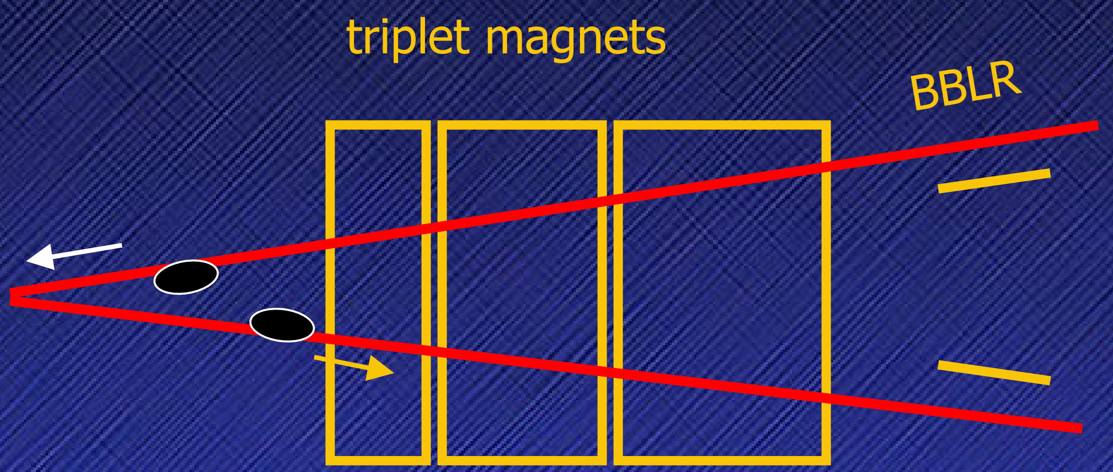
dipole first &
small crossing angle

reduced # LR collisions
collision debris hit D1

dipole first &
large crossing angle &
long bunches or crab cavities

‘cheap’ IR upgrade

in case we need to double LHC luminosity earlier than foreseen



short bunches &
minimum crossing angle &
BBLR

each quadrupole individually optimized (length & aperture)
reduced IP-quad distance from 23 to 22 m
conventional NbTi technology: β=0.25 m seems possible*

Triplet aperture requirements

The minimum coil aperture D_{min} of the low-β quadrupoles for the baseline scheme can be roughly estimated by assuming:

- 9σ beam envelope (or more to relax constraints on collimation)
- 7.5σ beam separation (at mid of Q2 -> $\theta_c \sim 9.5\text{-}10\ \sigma_\theta$)
- 3-4 mm spurious dispersion orbit d_s (depending on θ_c)
- 20% β-beating
- 3 mm peak orbit excursion
- 1.6 mm mechanical tolerances
- 10 mm margin for beam tube and beam screen

$$D_{min} \geq 1.1*(7.5+ 2*9)\sigma + 2*(d_s + 3\text{ mm}+1.6\text{ mm}) + 10\text{ mm}$$

Nominal LHC: $\beta^* = 0.5$ m, $\sigma = 1.54$ mm $\Rightarrow D_{min} \sim 68$ mm

Baseline upgrade: $\beta^* = 0.25$ m, $\sigma = 2.2$ mm $\Rightarrow D_{min} \sim 89$ mm

- Drop 7.5σ beam separation for separate channels (e.g. dipole-first)
- Add safety margin from heat deposition $\Rightarrow$ approximate scaling?
- Add $1.5\text{-}2\sigma$ beam separation for I =1.7 A (12.5 ns spacing, no BBLR)
- Multiply σ by $\sqrt{2}$ for 2 x bunch intensity and 2 x emittance (Super-SPS)

Quadrupole-first layout: an example

Main parameters of the quadrupoles at 7 TeV in different arrangements of the low-β triplet. The spacing between the quadrupoles is 2 m and ℓ^* is 23 m (Table 2 from R. Ostojic et al, PAC05 and CARE Conf-05-005-HHH).

The short Q1 in the last column assumes Nb_3Sn cable, all others NbTi.

	LHC triplet		Symmetric triplet		Long Q3		Short Q1	
	Q2, Q3	Q1	Q2, Q3	Q1	Q2, Q3	Q1	Q2, Q3	Q1
β^* [m]	0.50	0.50	0.25	0.25	0.25	0.25	0.25	0.25
β_{peak} [m]	4750	1265	11520	5400	11840	5440	9500	3600
θ_c [μrad]	315	315	445	445	445	445	445	445
σ [mm]	1.5	0.8	2.4	1.6	2.4	1.6	2.2	1.3
d_s [mm]	2.8	1.4	4.2	2.9	4.3	2.9	3.9	2.4
D_{min} [mm]	67.6	44.2	94.5	70.8	95.5	70.9	87.6	61.3
g [T/m]	198.5	198.5	151.8	151.8	137.8	161.1	151.8	338.6
L [m]	5.5/6.3	6.3	8.0	8.0	8.0/10.0	8.0	8.0	4.0

LHC-LUMI-05 workshop: some conclusions on the IR Upgrade

- Local correction à la Raimondi, via dispersion inside triplet magnets and two pairs of sextupoles, can correct chromaticity and geometric aberrations ⇒ **look for a solution that can be implemented and removed anytime by varying quads and sexupole strengths**
- Three IR layout options were identified that should be studied in more detail:

1) dipole-first based on **Nb3Sn technology** with ℓ* = 19 m
2) quad-first layout based on **Nb3Sn technology** ℓ * = 19 m
3) low gradient quad-first layout based on **NbTi technology**

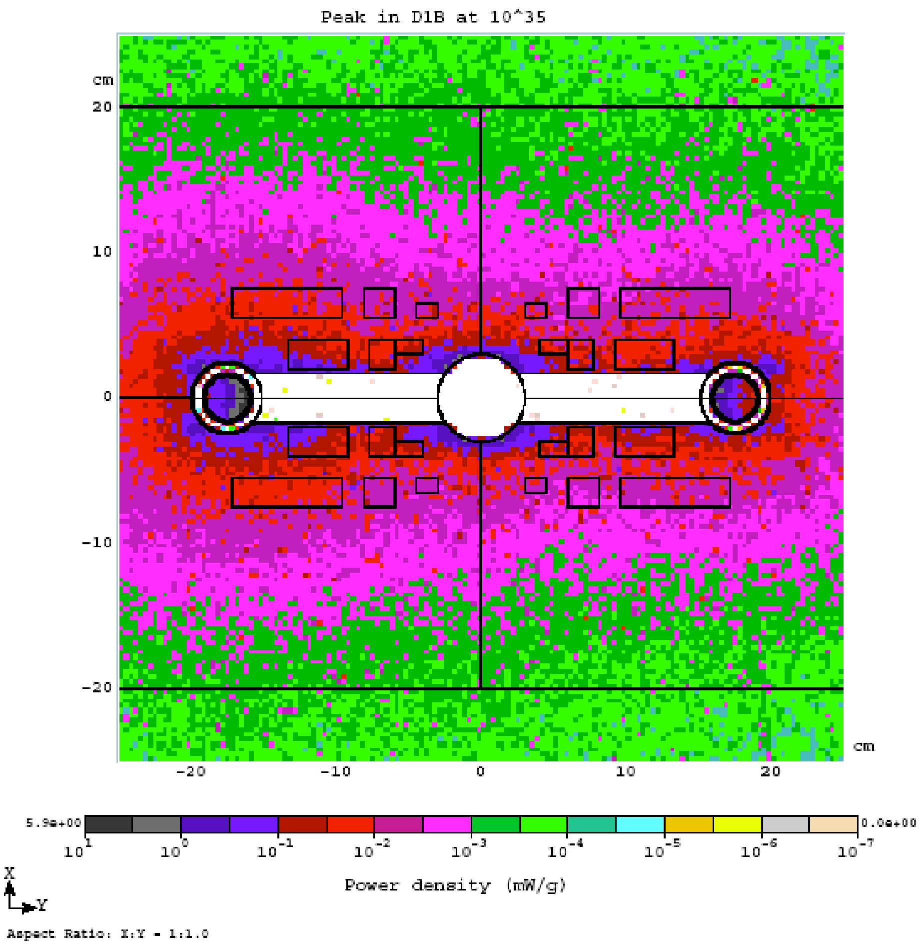
- Still need to fix ℓ* and required length for TAS upgrade. Agreement to assume ℓ* = 19 m as a reasonable estimate
- CARE-HHH web repository with optics solutions is very desirable ⇒ we should all use the same input (MADX)
- Update the 3 proposals by the **end of 2005**

Dipole-First optics (R. De Maria)

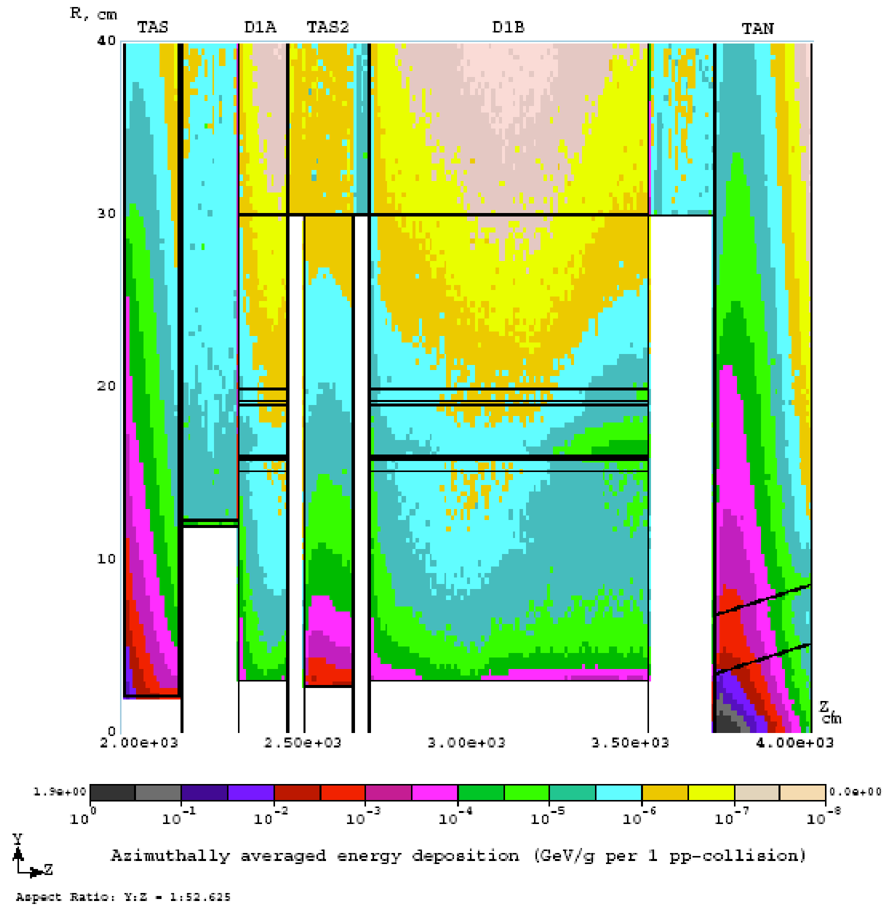
- matched optics solution for dipole-first layout for Beam1 and Beam2 with squeeze and tunability study:
  - 18 km β-max requires additional Q′ correction
  - dispersion of 15 cm from D1/D2 arrangement for free
  - could be increased for D′ ≠ 0 at the IP
  - dispersion changes sign left and right from IP
  - S. Fartoukh proposed a `kissing scheme′ could allow equal signs of D but vertical D is quite small
- optics study relies on Nb3Sn technology:
  - ➔ 10 m long dipole magnets with B = 15 T
  - ➔ quadrupole magnets with 260 T/m and 80 mm aperture ➔ 11 T coil field
  - ➔ IR layout provides magnetic TAS for “free”

Energy Deposition in Open Midplane Dipole in Dipole First Optics

Courtesy: Nikolai Mokhov, FNAL



Power density isocontours at the non-IP end of the D1B.



Azimuthally averaged energy deposition iso-contours in the dipole-first IR.

Energy Deposition Summary (Mokhov, 04/05)

SUMMARY

- The open midplane dipole is very attractive option for the LARP dipole-first IR at $\mathcal{L} = 10^{35}$. The design accommodates large vertical forces, has desired field quality of 10^{-4} along the beam path and is technology independent.
- After several iterations with the BNL group over last two years, we have arrived at the design that – being more compact than original designs – satisfies magnetic field, mechanical and energy deposition constraints.
- We propose to split the dipole in two pieces, 1.5-m D1A and 8.5-m D1B, with a 1.5-m long TAS2 absorber in between.
- With such a design, peak power density in SC coils is below the quench limit with a safety margin, heat load to D1 is drastically reduced, and other radiation issues are mitigated. This is a natural two-stage way for the dipole design and manufacturing.

Fermilab N. Mokhov

Summary of Design Iterations (A to F)

	A	B	C	D	E	F
H(mm)	84	135	160	120	80	120
V(mm)	33	20	50	30	34	40
V/H	0.39	0.15	0.31	0.25	0.43	0.33
B_o(T)	13.6	13.6	13.6	13.6	15	13.6
B_{ss}(T)	15	15	15	14.5	16	15
J_c(A/mm^2)	2500	3000	3000	3000	3000	3000
Cu/Sc	1	1,1.8	0.85	0.85	0.85	1
A(cm^2)	161	198	215	148	151	125
R_i(mm)	135	400	400	320	300	300
R_o(mm)	470	800	1000	700	700	700
E(MJ/m)	2.2	4.8	9.2	5.2	4.1	4.8
F_x(MN/m)	9.6	10.1	12.3	9.5	10.4	9.6
F_y(MN/m)	-3.0	-6.8	-8.7	-7.0	-5.1	-5.4

Alternative Quad-First optics (O.Brüning)

proposal of a low-gradient solution that could be realized with NbTi technology

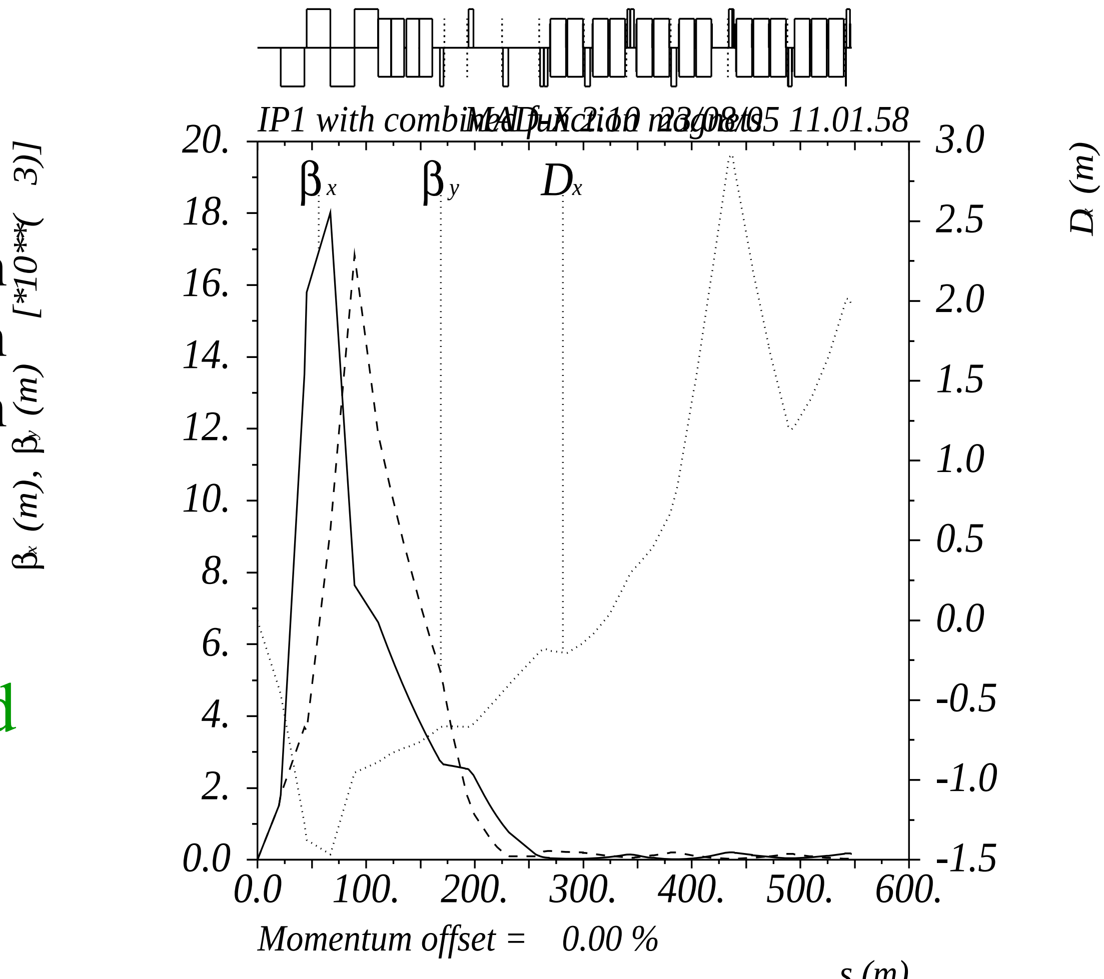
- 18 km β-max requires additional Q′ correction
- maximum gradient of 70 T/m allows more than 200 mm diameter with a peak coil field of 5.5 T
- Dispersion inside the triplet could be increased for D′ ≠ 0 at the IP
- Layout still requires an improved TAS absorber

Options for a Quadrupole First Layout

- Layout and optics derived from Combined function solution:

D1/D1 ➔ 3.7 T
Q1 ➔ 47T/m ➔ d = 212mm
Q2 ➔ 70T/m ➔ d = 143mm
Q3 ➔ 47T/m ➔ d = 212mm
Q3b ➔ 6T/m

➔ aperture estimate assumes a peak coil field of 5 T!



➔ dispersion matched to 1.5m in ‘triplet’ for Q’ correction!

More conclusions of WG1

1) Modular IR design: D0 magnet inside experiment for x-ing angle generation, beam-beam wire compensators and crab cavities benefit any IR design (dipole-first or quad-first) and should be studies/pursued independently of the final IR layout choice
2) Any IR upgrade requires a TAS upgrade. A dipole-first layout offers the natural combination of a TAS absorber and spectrometer dipole
3) We saw two interesting proposals for dipole magnet designs that could be used for such a magnetic TAS. Both proposals come from the USA: BNL - Gupta and Peter McIntyre. This important R&D on high field dipoles should continue.
4) Future R&D efforts should not only focus on Ni_3Sn but also continue NiTi developments and designs as a fall back solution in case Ni_3Sn technology is not ready by the time a (first) IR upgrade becomes necessary. Any IR upgrade implies also an upgrade of several NiTi insertion quads (larger aperture Q4 to Q7).

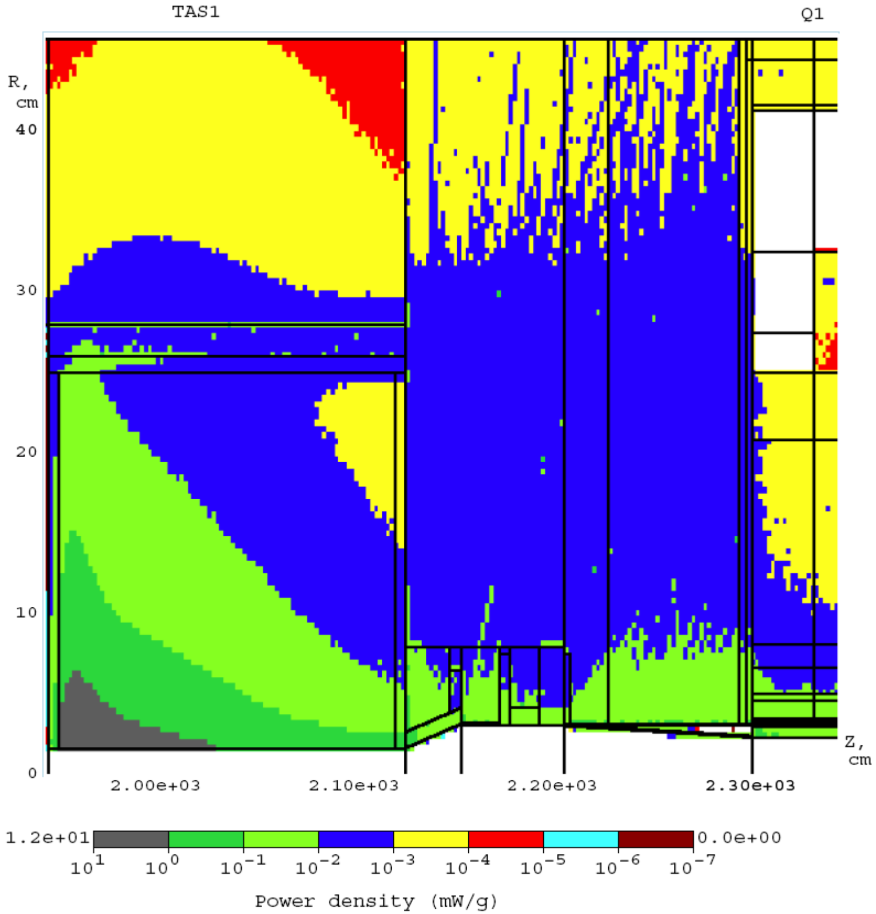
Energy Deposition Issues in LHC IR Upgrades, N. Mokhov (FNAL)

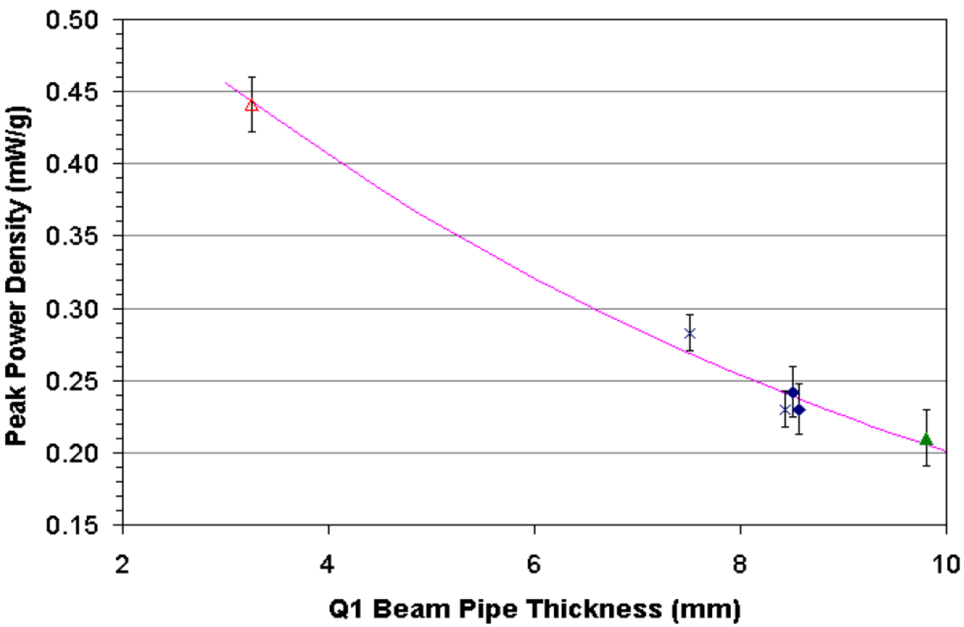
- All three aspects, i.e. *i)* quench limit, *ii)* radiation damage (magnet lifetime), and *iii)* dynamic heat load on the cryo system should be simultaneously addressed in the IR magnet design. *i)* and *ii)* are linked
- Peak power deposition at non-IP end of IR magnets ~proportional to $\int B d\ell \Rightarrow$ **FDFD "quadruplet" focusing?**
- Estimated dipole field with TAS in quad-first option to reduce peak energy deposition "well below" quench limits

  $\Rightarrow$ **15-20 Tm for magnetic TAS**
- Estimated thickness of internal absorbers $\Rightarrow$ **a 5 mm thick SS absorber reduces peak power by a factor ~2**
- Impact of orbit corrector D0 inside the experiment on energy deposition in downstream magnets, including detector solenoid field

  $\Rightarrow$ **more work needed, modest impact of solenoid field on energy deposition (more from fringe fields)**

TAS AND LINER OPTIMIZATION





Beam screen together with cold bore

Reduces power density at IP-end of Q1 300 times and dynamic heat load to inner triplet by 185 Watts. 5% of incoming energy punch through 1.8-m copper TAS body

Chosen: 6.5 mm in Q1 and 3 mm in Q2-Q3

Action items/comments on energy deposition, Nikolai Mokhov

- Refine and test scaling law for energy deposition in IR magnets with MARS simulations (including dependence on ℓ^*)
- Introduce quench limits to JPK's spreadsheet for NbTi and Nb_3Sn
- Address radiation damage/lifetime issues in all IR magnet design analyses: 7 years at 10^{34} become 8 months at 10^{35} with currently used materials ⇒ new (ceramic type) materials for 10^{35}?
- Launch R&D program on beam tests for SC and insulating materials asap: BNL, FNAL, MSU
- Arrive at a clear picture on Dynamic Heat Load limits. How serious is the current 10 W/m limit or 120 W on each side of IR? This becomes 100 W/m and 1.2 kW for 10^{35}. Cooling scheme? Cryoplant capability?

Magnet R&D: Gianluca Sabbi and Paolo Ferracin

- R&D models with 90 mm aperture address the critical design issues (magnetic, mechanical, quench etc)
- Using a larger aperture for magnet R&D would likely be less effective (due to cost considerations and other practical constraints)
- There is good confidence that successful results of 90 mm models can be extended to the range of apertures under consideration
- The maximum coil field is a critical parameter to establish the performance characteristics
- "High-gradient" models with 90 mm aperture (HQ) will be used to establish the maximum design field
- IR optimization studies should assume constant pole tip field and optimize aperture/gradient accordingly
- Using 13 T peak field (JPK) is ok for now, but the program aims at 15 T
- JPK model calibration using TQ design: 11 T peak field corresponds to 210 T/m in the 90 mm aperture

LARP Magnet Program Goals

FY09 Milestone:

Demonstrate viability of Nb_3Sn technology for "Quad-first" option

1. Capability to deliver predictable, 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 gradient (pole tip field) in large aperture:

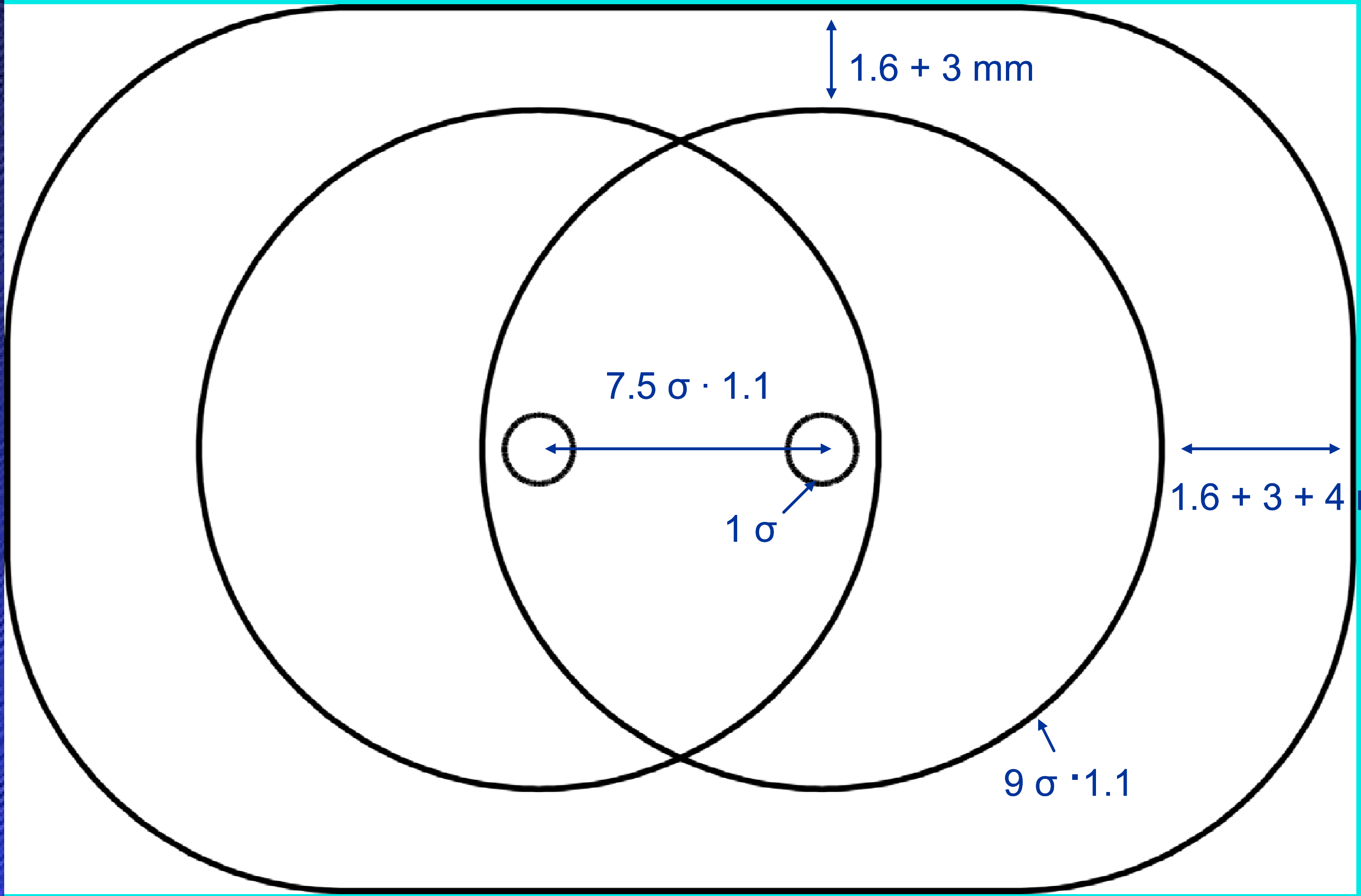
HQ (HighGradient Quads, 2008-09) D = 90 mm, L = 1 m, G_{nom} > 250 T/m

- *Fabrication of the first two TQ quads (TQS01 and TQC01) has started*
- *TQS01 test in February/March 2006; TQC01 test in April/May 2006*

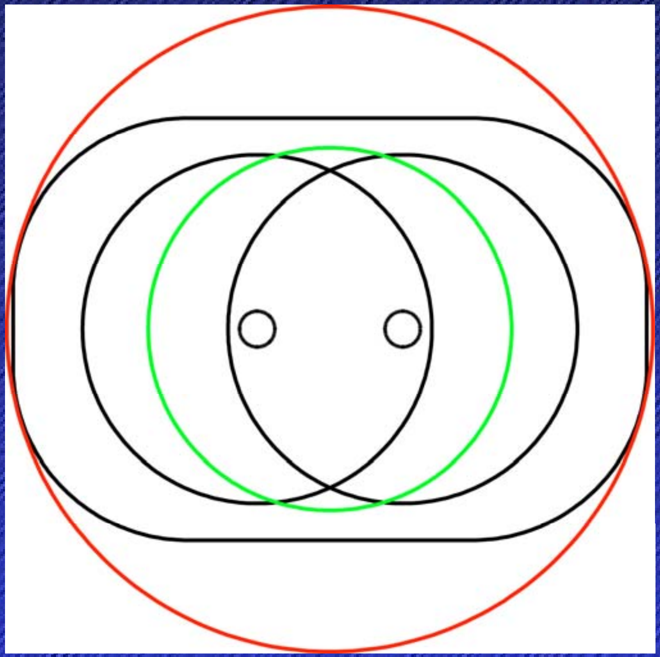
Coil aperture requirements

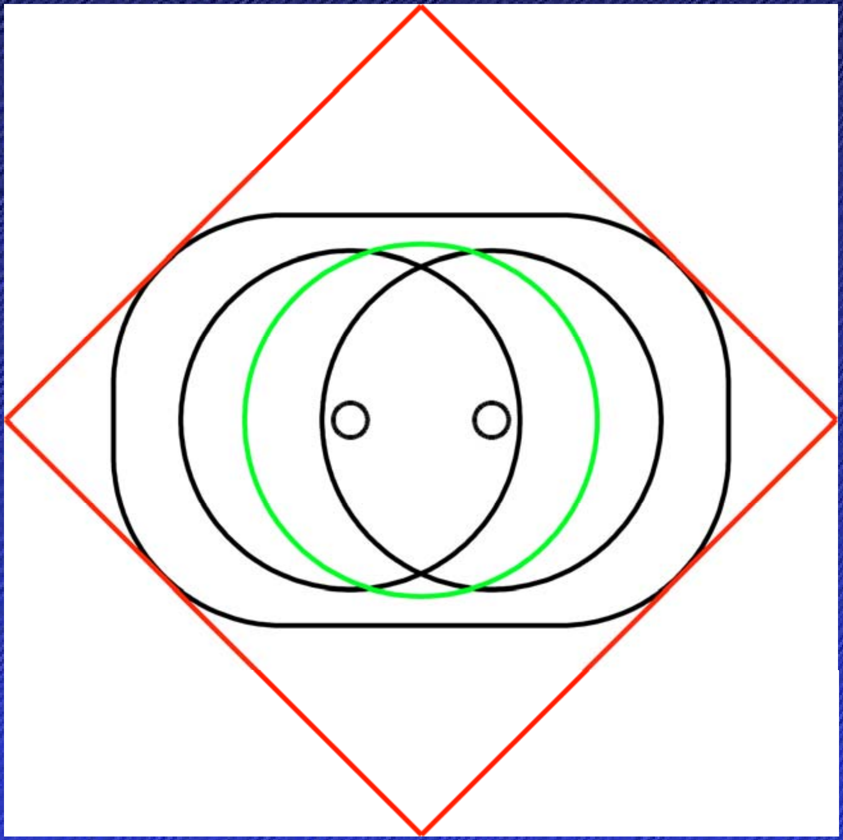
Coil aperture estimates need to be clarified/debugged/improved

$D_{trip} > 1.1 \times (7.5 + 2 \times 9) \cdot \sigma + 2 \times (1.6 + 3 + 4)$ mm



- The beam envelope formula does not correspond to a good field region (green circle)
- Equivalent aperture comparisons should include heat deposition considerations





Action Items from the IR-2005 mini-workshop

- CERN beam physicists will circulate a draft proposal for aperture and field quality requirements
- CERN beam physicists will circulate a draft proposal to assess and compare the performance of any IR solution, including quantitative considerations for luminosity or lifetime (possibly based on tune footprints for off-momentum particles)

Questions to WG1 - Magnets

1. What is the limit on quad aperture from magnet design at constant pole tip field? Is the aperture limit different for NbTi and Nb_3Sn?
2. Is there a quad design with either an absorber or low-Z spacers in the horizontal and vertical planes? to minimize energy deposition.
3. Are there lower limits to the systematic errors on b_6 and b_{10} with Nb_3Sn? How does this scale with the pole tip field and aperture?
4. If 90 mm quads with 11-12 T field are demonstrated by 2009, how much confidence is there that larger aperture quads can be built with the same pole tip field?

2. Energy deposition issues

- Absorbers and mid-plane spacers can be included in all magnet designs
- Additional space for absorbers (in particular at mid-plane) can be obtained by increasing the coil aperture

3. Field Quality

- Geometric errors are very small and comparable in Nb_3Sn and NbTi quadrupole designs
- Fabrication tolerances will likely dominate the field errors
- Further studies are needed to determine the practical limits on field quality achievable in Nb3Sn quads
- Conventional scaling with aperture applies; field errors can be minimized for all operating fields

4. Aperture scaling

- There is good confidence that the 90 mm models will address the critical R&D issues, applicable to the entire range of apertures being considered
- Based on results from R&D, it will be possible to fabricate prototypes of larger aperture in the same time frame as for 90 mm aperture quads

Potential impact of novel magnet technology for IR elements, Peter McIntyre

- Designs have been suggested for novel magnet technology to mitigate limitations from heat deposition and radiation damage from deposition of secondary particles in the quadrupole triplet and separation dipole. One example is an ironless quadrupole using structured-cable Nb3Sn conductor, which could provide 390 T/m gradient at a location as close as 12 m from the IP, and compatibility with supercritical helium flowing throughout the coils. A second example is a 9 T levitated-pole dipole for D1, which would open the transverse geometry so that secondaries are swept into a room-temperature flux return.
- In order to evaluate the potential benefit of these concepts it is necessary to model the heat deposition and radiation damage in the more compact geometries, and to examine potential interference with the performance of the detectors.
- Of particular importance is to undertake a consistent examination of the impact of reducing ℓ^* on the ensemble of issues that impact achievable β^* the interface of the IR with the machine lattice (chromaticity and dispersion, multipole errors, orbit errors, etc.), and the strategy for accommodating long-range beam-beam effects.
- Also of interest is to evaluate the pros and cons of the alternatives for operating temperature (superfluid, two-phase, or supercritical cooling) for the IR elements that must operate with substantial heat loads.

Tentative conclusions for the LHC IR Upgrade

- We do need a back-up or intermediate IR upgrade option based on NbTi magnet technology. What is the maximum luminosity?
- A vigorous R&D programme on Nb_3Sn magnets should start at CERN asap, in parallel to the US-LARP programme, to be ready for 10^{35} luminosity in ~2015
- Alternative IR layouts (quadrupole-first, dipole-first, D0, flat beams, Crab cavities) should be rated in terms of technological and operational risks/advantages

Several LHC IR upgrade options are currently being explored: we need to converge to a baseline configuration and identify a few alternative options

- quadrupole-first and dipole-first solutions based on conventional NbTi technology and on high-field Ni_3Sn magnets, possibly with structured SC cable
- energy deposition, absorbers, and quench limits
- schemes with Crab cavities as an alternative to the baseline bunch shortening RF system at 1.2 GHz to avoid luminosity loss with large crossing angles
- early beam separation by a "D0" dipole located a few metres away from the IP may allow operation with a reduced crossing angle. Open issues: integration and compatibility with detector layout, reduced separation at first parasitic encounters, energy deposition by the collision debris
- local chromaticity correction schemes
- flat beams. Open issues: compensation of long range beam-beam effects with alternating crossing planes

Towards a baseline design

Following the approach proposed by Barry Barish for the ILC, I suggest to:

- **Define a Baseline,** **i.e. a *forward looking* configuration which we are reasonably confident can achieve the required LHC luminosity performance and can be used to give an accurate cost estimate by mid-end 2006 in a "Reference Design Report"**
- **Identify Alternative Configurations and rate them in terms of technological and operational risks/advantages**
- **Identify R&D (at CERN and elsewhere)**
  - **To support the baseline**
  - **To develop the alternatives**

Reference LHC Luminosity Upgrade: workpackages and tentative milestones

accelerator	WorkPackage	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	after 2015
LHC Main Ring	Accelerator Physics											
	High Field Superconductors											
	High Field Magnets											
	Magnetic Measurements											
	Cryostats											
	Cryogenics: IR magnets & RF											
	RF and feedback											
	Collimation&Machine Protection											
	Beam Instrumentation											
	Power converters											
SPS	SPS kickers											
	Tentative Milestones	Beam-beam compensation test at RHIC	SPS crystal collimation test	LHC collimation tests	LHC collimation tests	Install phase 2 collimation	LHC tests: collimation & beam-beam			Install new SPS kickers	new IR magnets and RF system	
	Other Tentative Milestones	Crab cavity test at KEKB	Low-noise crab cavity test at RHIC	**LHC Upgrade Conceptual Design Report**		LHC Upgrade Technical Design Report	Nominal LHC luminosity 10^34			Ultimate LHC luminosity 2.3x10^34	beam-beam compensation	Double ultimate LHC luminosity 4.6x10^34

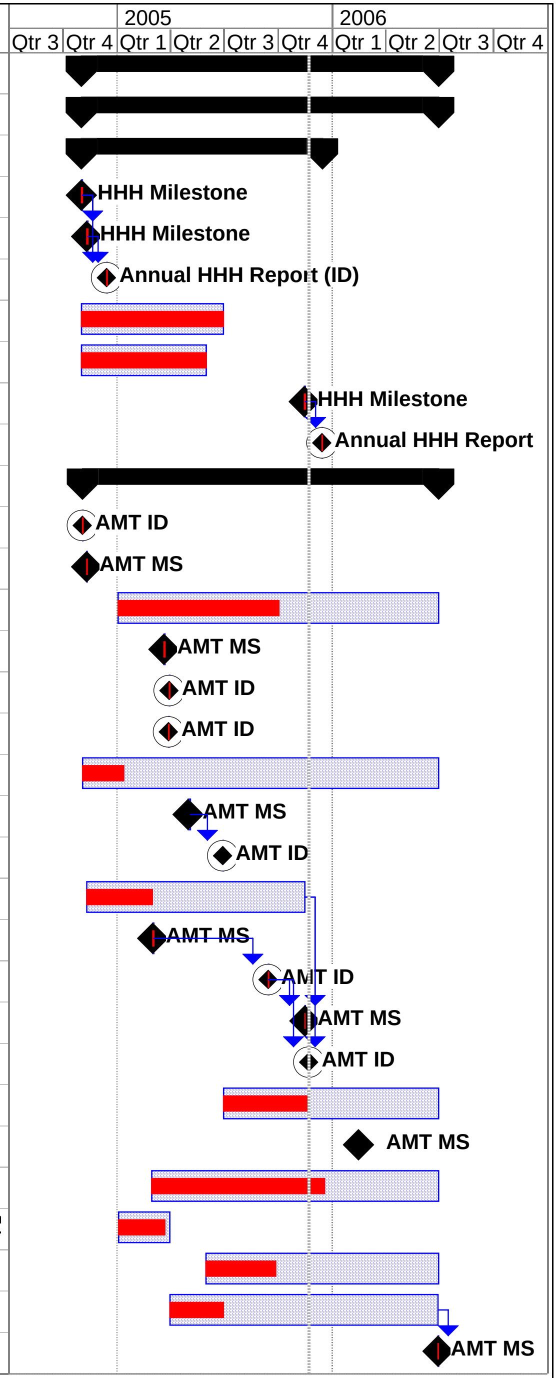
LHC Upgrade Reference Design Report

R&D - scenarios & models	
specifications & prototypes	
construction & testing	
installation & commissioning	

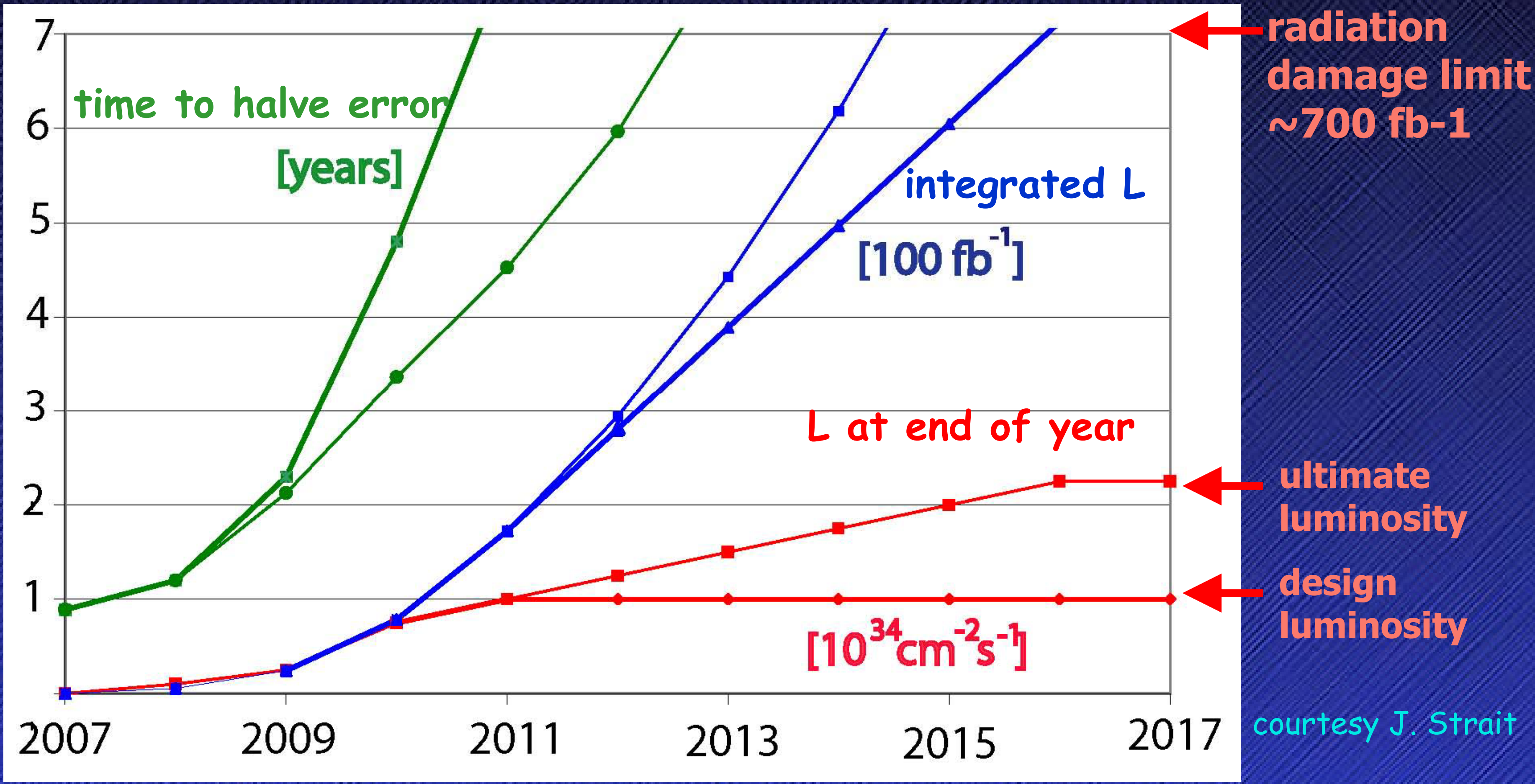
Reference LHC Upgrade scenario: peak luminosity 4.6x10^34/(cm^2 sec)
Integrated luminosity 3 x nominal ~ 200/(fb*year) assuming 10 h turnaround time
new superconducting IR magnets for beta*=0.25 m
phase 2 collimation and new SPS kickers needed to attain ultimate LHC beam intensity of 0.86 A
beam-beam compensation may be necessary to attain or exceed ultimate performance
new superconducting RF system: for bunch shortening or Crab cavities
hardware for nominal LHC performance (cryogenics, dilution kickers, etc) not considered as LHC upgrade
R&D for further luminosity upgrade (intensity beyond ultimate) is recommended: see Injectors Upgrade

Additional Slides

ID	Task Name
1	**N3: HHH Networking Activities**
2	**All Work Packages**
3	**Network coordination, dissemination, and outreach**
4	MS: Joint HHH/NED meeting at CARE04
5	General HHH meeting at CERN including non-EU partners
6	***ID: HHH Annual Report 2004***
7	Reinforce connections between Labs and Universities in all WP's
8	Revisit priorities for all WP, improve HHH web site
9	MS: Annual HHH meeting
10	***ID: HHH Annual Report 2005***
11	**WP1 Accelerator Magnet Technology (AMT)**
12	***ID: Interim report on AMT activities and reporting at the general CARE meeting***
13	MS: General AMT meeting
14	Coordinate conductor development and tests
15	MS: AMT topical meeting on Insulation and Impregnation Techniques
16	***ID: Proceedings of the 1st AMT topical workshop on Accelerator Magnet Superconductors***
17	***ID: Report on AMT organization and conductor development roadmap***
18	Development of Web based database for SC Cables and Magnets
19	MS: Specific meeting on database
20	***ID: First report on Web based database***
21	Codes and models for design, stability and protection studies for AMT1 and AMT4
22	MS: AMT mini-workshop on Beam Generated Heat and Magnet Quench Level
23	***ID: Proceedings of AMT mini-workshop on Beam Generated Heat and Magnet Quench Level***
24	MS: establish a catalog of existing codes for design, stability and protection studies
25	***ID: Interim report on AMT activities and reporting at the general CARE meeting***
26	Catalog and comparison of different IR options (AMT4)
27	MS: AMT workshop on Contact Tooling
28	Studies of fast pulsed SC magnets for Super-SPS
29	Review of developments in the US and for ITER on conductors and magnet technology relevant for AMT1-2
30	Comparative studies of alternatives using low field magnets for AMT2 and AMT3
31	Determination of scaling law for magnet and cryogenic cost for AMT5
32	MS: Preliminary report on scaling law for magnet and cryogenic cost (roadmap)



Time scale of LHC upgrade



- the **life expectancy of LHC IR quadrupole magnets** is estimated to be **<10 years** owing to high radiation doses
- the **statistical error halving time** will exceed 5 years by 2011-2012
- therefore, it is reasonable to plan a **machine luminosity upgrade based on new low-ß IR magnets before ~2015**

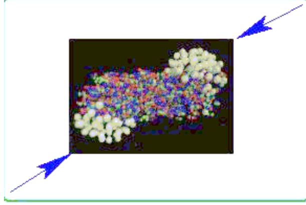
Chronology of LHC Upgrade studies

- **Summer 2001**: two CERN task forces investigate physics potential (CERN-TH-2002-078) and accelerator aspects (LHC Project Report 626) of an LHC upgrade
- **March 2002**: LHC IR Upgrade collaboration meeting http://cern.ch/lhc-proj-IR-upgrade
- **October 2002**: ICFA Seminar at CERN on "Future Perspectives in High Energy Physics"
- **2004**: CARE-HHH European Network on

  High Energy
  High Intensity
  Hadron Beams

- **November 2004**: first CARE-HHH-APD Workshop (HHH-04) "Beam Dynamics in Future Hadron Colliders and Rapidly Cycling High-Intensity Synchrotrons", CERN-2005-006

The CARE-HHH Network



Mandate

Coordinate and integrate the activities of the accelerator and particle physics communities, in a worldwide context, towards achieving superior High-Energy High-Intensity Hadron-Beam facilities for Europe

- Roadmap for the upgrade of the European accelerator infrastructure (LHC and GSI accelerator complex)
  - luminosity and energy upgrade for the LHC
  - pulsed SC high intensity synchrotrons for the GSI and LHC complex
  - R&D and experimental studies at existing hadron accelerators
  - select and develop technologies providing viable design options
- Coordinate activities and foster future collaborations
- Disseminate information

- **HHH coordination: F. Ruggiero (CERN) & W. Scandale (CERN)**

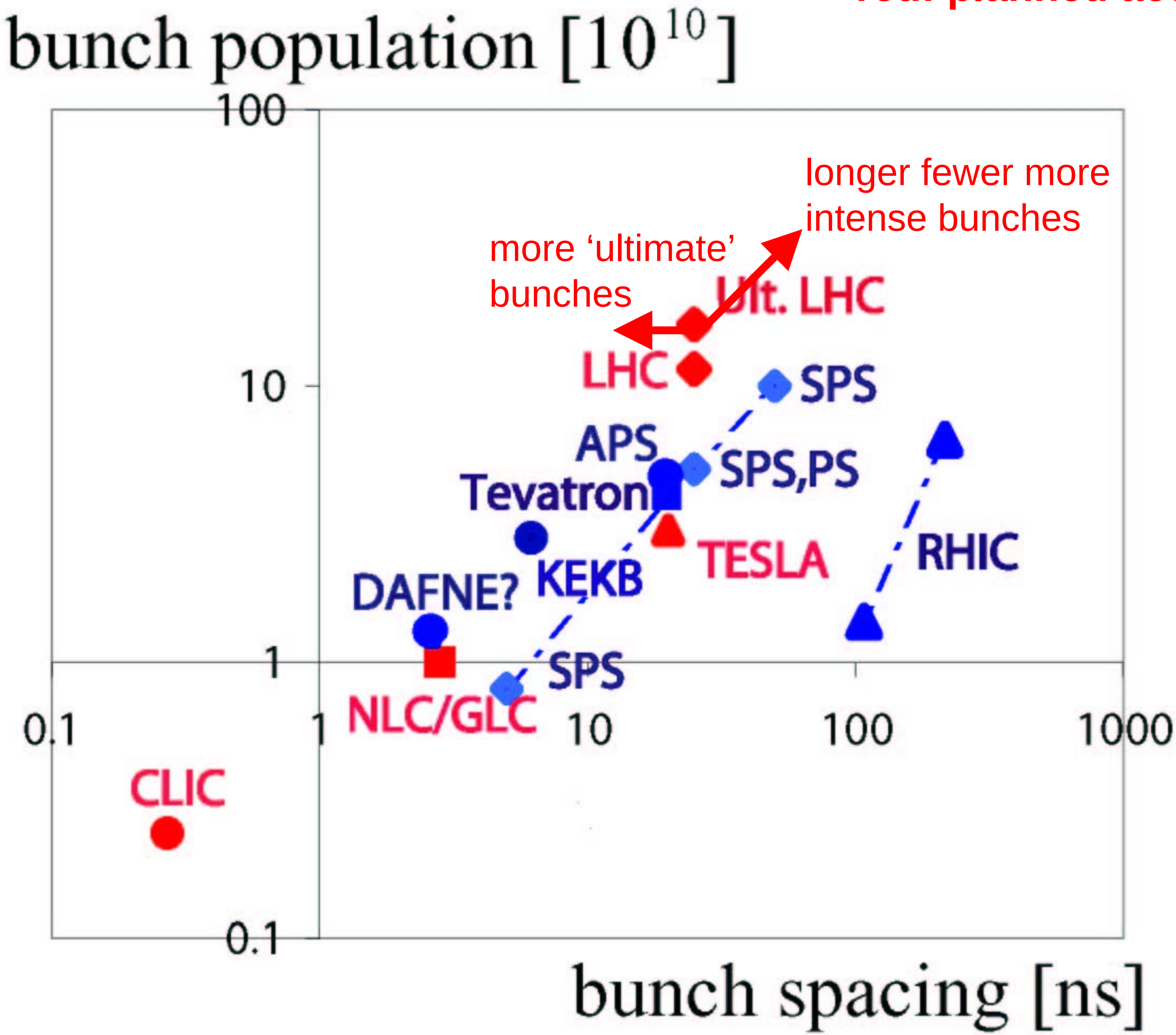
1. Advancement in Acc. Magnet Technology (AMT): L. Rossi (CERN) & L. Bottura (CERN)
2. Novel Meth. for Acc. Beam Instrumentation (ABI): H. Schmickler (CERN) & K. Wittenburg (DESY)
3. Accelerator Physics and Synchrotron Design (APD): F. Ruggiero (CERN) & F. Zimmermann (CERN)

Effective luminosity for various upgrade options

parameter	symbol	nominal	ultimate	shorter bunch	longer bunch
protons per bunch	N_b [10^{11}]	1.15	1.7	1.7	6.0
bunch spacing	Δt_{sep}[ns]	25	25	12.5	75
average current	I [A]	0.58	0.86	1.72	1.0
longitudinal profile		Gaussian	Gaussian	Gaussian	flat
rms bunch length	σ_z [cm]	7.55	7.55	3.78	14.4
ß* at IP1&IP5	ß* [m]	0.55	0.50	0.25	0.25
full crossing angle	θ_c [µrad]	285	315	445	430
Piwinski parameter	$\theta_c \sigma_z/(2\sigma^*)$	0.64	0.75	0.75	2.8
peak luminosity	L [10^{34} cm^{-2} s^{-1}]	1.0	2.3	9.2	8.9
events per crossing		19	44	88	510
IBS growth time	$\tau_{x,IBS}$ [h]	106	72	42	75
nuclear scatt. lumi lifetime	$\tau_N/1.54$ [h]	26.5	17	8.5	5.2
lumi lifetime (τ_{gas}=85 h)	τ_L [h]	15.5	11.2	6.5	4.5
effective luminosity	L_{eff} [10^{34} cm^{-2} s^{-1}]	0.4	0.8	2.4	1.9
($T_{turnaround}$=10 h)	T_{run} [h] optimum	14.6	12.3	8.9	7.0
effective luminosity	L_{eff} [10^{34} cm^{-2} s^{-1}]	0.5	1.0	3.3	2.7
(T_{turn}=5 h)	T_{run} [h] optimum	10.8	9.1	6.7	5.4

electron cloud

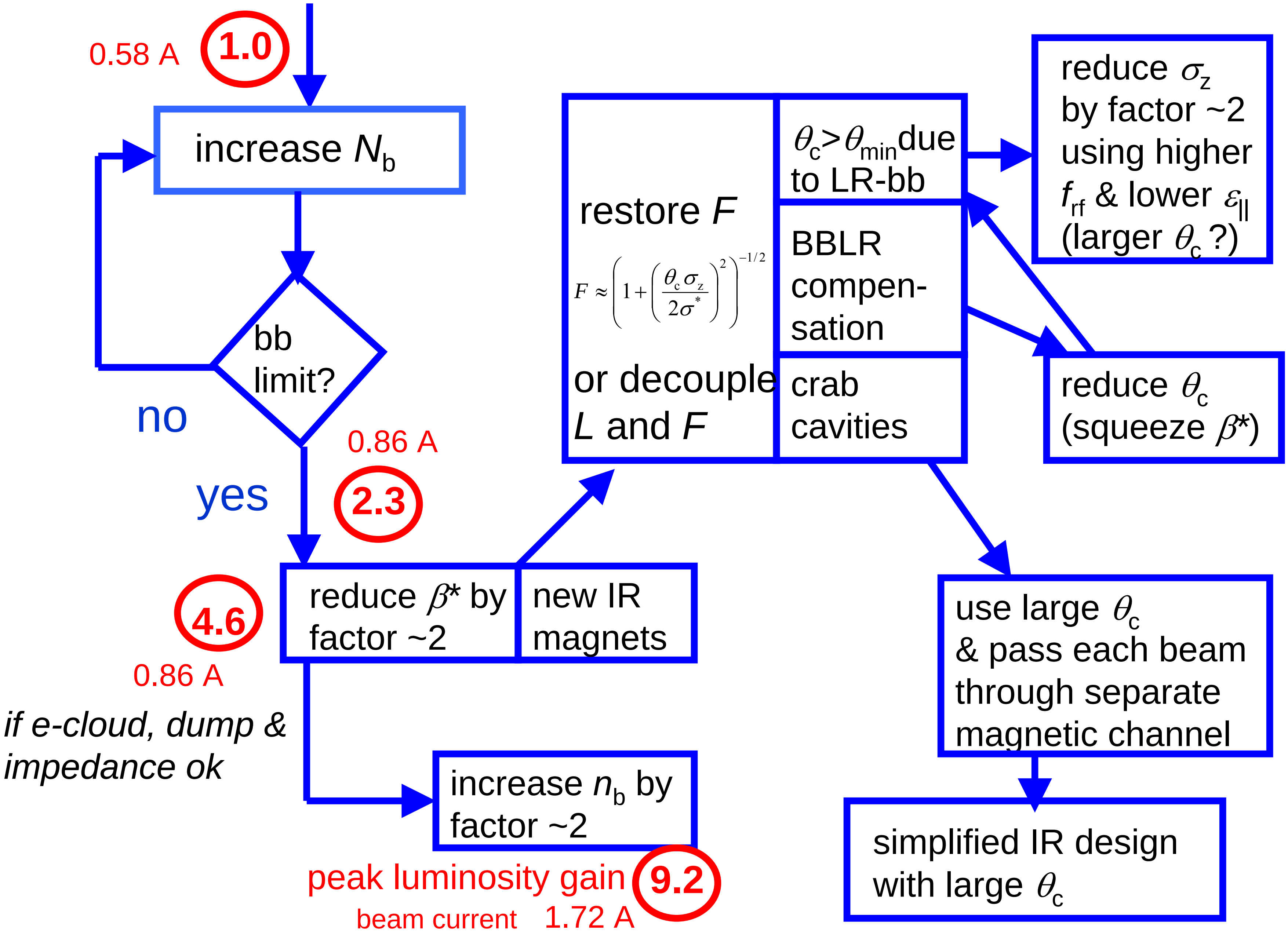
blue: e-cloud effect observed
red: planned accelerators



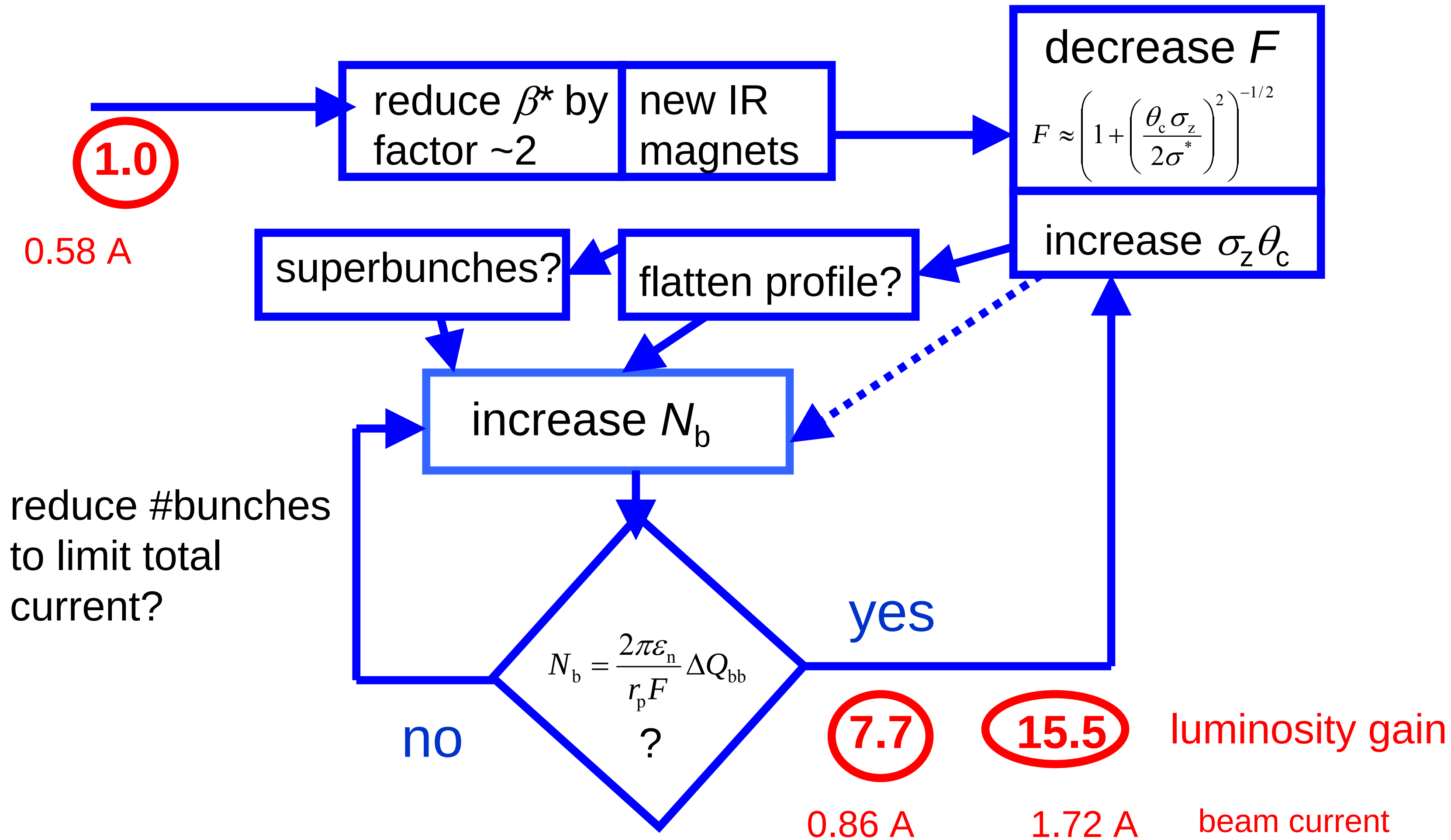
experience at several storage rings suggests that the e-cloud threshold scales as $N_b \sim L_{sep}$;

possible LHC upgrades consider either smaller L_{sep} with constant N_b, or they increase L_{sep} in proportion to N_b

luminosity upgrade: baseline scheme



luminosity upgrade: Piwinski scheme



If bunch intensity and brightness are not limited by the injectors or by other effects in the LHC (e.g. electron cloud) ⇒ luminosity can be increased without exceeding beam-beam limit ΔQ_{bb}~0.01 by increasing the crossing angle and/or the bunch length

Express beam-beam limited brilliance N_b/ε_n in terms of maximum total beam-beam tune shift ΔQ_{bb}, then

$$L \cong \frac{\gamma}{2r_p}\frac{\Delta Q_{bb} I}{\beta^*} \cong \frac{\gamma\pi f_{rev}}{r_p^2}\frac{\Delta Q_{bb}^2 n_b \varepsilon_n}{\beta^*}\sqrt{1+\left(\frac{\theta_c\sigma_z}{2\sigma^*}\right)^2}$$

At high beam intensities or for large emittances, the performance will be limited by the angular triplet aperture

$$L \cong \frac{\gamma}{2r_p}\Delta Q_{bb} I \min\left\{\frac{1}{\beta^*},\frac{1}{\varepsilon}\left(\frac{D_{tripl}/\ell^*}{20+\theta_c/\sigma_\theta}\right)^2\right\}$$

Quadrupole aperture with BBLR

case14-2a: Nb3Sn triplet at 23m, ultimate bunch current, bunch spacing halfed
Papaphilippou/Zimmermann angle scaling with current

β_{IP} 0.25 m	N_{bunch} 1.7 10^{11} p	k_b 5616	Xing HV	$\mathcal{L}/\mathcal{L}_0$ 5.83
$\ell_{IP \to Q1}$ 23. m	$<\ell_Q>$ 5.5 m	ℓ_{LR} 54. m	31. – 0.12 Ic 44. – 0.35 Ic	
Gradient 234. T / m	coil oversize 1.	ϕ_{inner} coil 98.4 mm	B_{max} 11.5 T	power dens 4.29 mW / g
Efficiency:	NbTi 134. %	NbTiTa 125. %	Nb3Sn 88. %	
β_{max} 9373.1 m	K2[Q'] 84.9 %	K2[Q', Q''] 111. %	coef.b6 10.3	coef.b10 46.7
ϕ_{beam} 89.7 mm	$\sigma_{\beta max}$ 2.17 mm	$a_{disp,max}$ 5.05 mm	beam sep Q2 24.9 mm	θ_c 515. μrad

case14-3: Nb3Sn triplet at 23m, bunch charge doubled, HH Xing with BBLR

β_{IP} 0.25 m	N_{bunch} 2.3 10^{11} p	k_b 2808	Xing BBLR	$\mathcal{L}/\mathcal{L}_0$ 6.14
$\ell_{IP \to Q1}$ 23. m	$<\ell_Q>$ 5.5 m	ℓ_{LR} 54. m	31. – 0.12 Ic 44. – 0.35 Ic	
Gradient 234. T / m	coil oversize 1.	ϕ_{inner} coil 88.4 mm	B_{max} 10.4 T	power dens 3.91 mW / g
Efficiency:	NbTi 121. %	NbTiTa 112. %	Nb3Sn 79. %	
β_{max} 9373.1 m	K2[Q'] 84.9 %	K2[Q', Q''] 111. %	coef.b6 10.3	coef.b10 46.7
ϕ_{beam} 79.7 mm	$\sigma_{\beta max}$ 2.17 mm	$a_{disp,max}$ 2.48 mm	beam sep Q2 20.5 mm	θ_c 423. μrad

Wire compensation has the potential to reduce the aperture required significantly