A Strongly Focused High-Luminosity Insertion for the LHC Upgrade

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Thanks to R. Aßmann, E. Metral, L. Rossi, G. Sterbini, E. Todesco, F. Zimmermann,…

Outline

1. Motivations
2. How to increase performance
3. The early separation scheme
4. The parametric insertion model:
    - The model
    - Luminosity prospects versus inner diameter, l* and technology
5. The issue of energy deposition
6. Solutions
7. **Quad aperture and collimator impedance**
8. **Integrated versus peak luminosity**
9. **Conclusions**
10. **Work plan**

1.1- Motivations

The plans for a luminosity upgrade assumed so far *10 largely based on a beam current increase:

- *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 with an harmonic RF system
- *1.5 with a stronger focusing

Other options were gradually ruled out (large angle crab crossing, long bunches)

Increasing the beam current is in practice complicated in a collider, (unless designed in a conservative way):

- It couples with all limits all around the machine (beam instabilities, heat load,…)
- For the LHC, it increases the hazards related to beam losses, whether from the collimator or machine protection viewpoints
- Experience shows that the progress in luminosity is slow, with a significant impact on the integrated luminosity actually produced.

1.2- Motivations

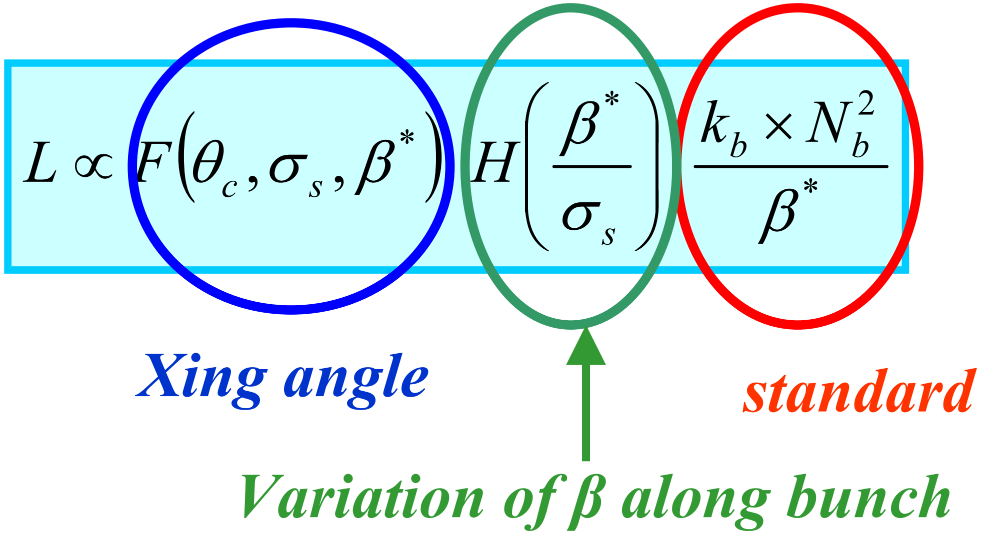
An additional consideration of importance is the present limit imposed by the collimator impedance to about 40% of the nominal current: this is related to the insertion quadrupole inner diameter.

All these considerations point to the question:

Is it possible to imagine a new insertion that would provide the requested luminosity increase without or with a much reduced increase of the beam current, i.e. that would localize the added complexity ONLY in the insertion region??

As I will try showing, the answer is probably **yes**, but it is a significant **technological** challenge.

2.1- The luminosity formula



$$L \propto F\left(\theta_c,\sigma_s,\beta^*\right) H\left(\frac{\beta^*}{\sigma_s}\right) \frac{k_b \times N_b^2}{\beta^*}$$

Xing angle

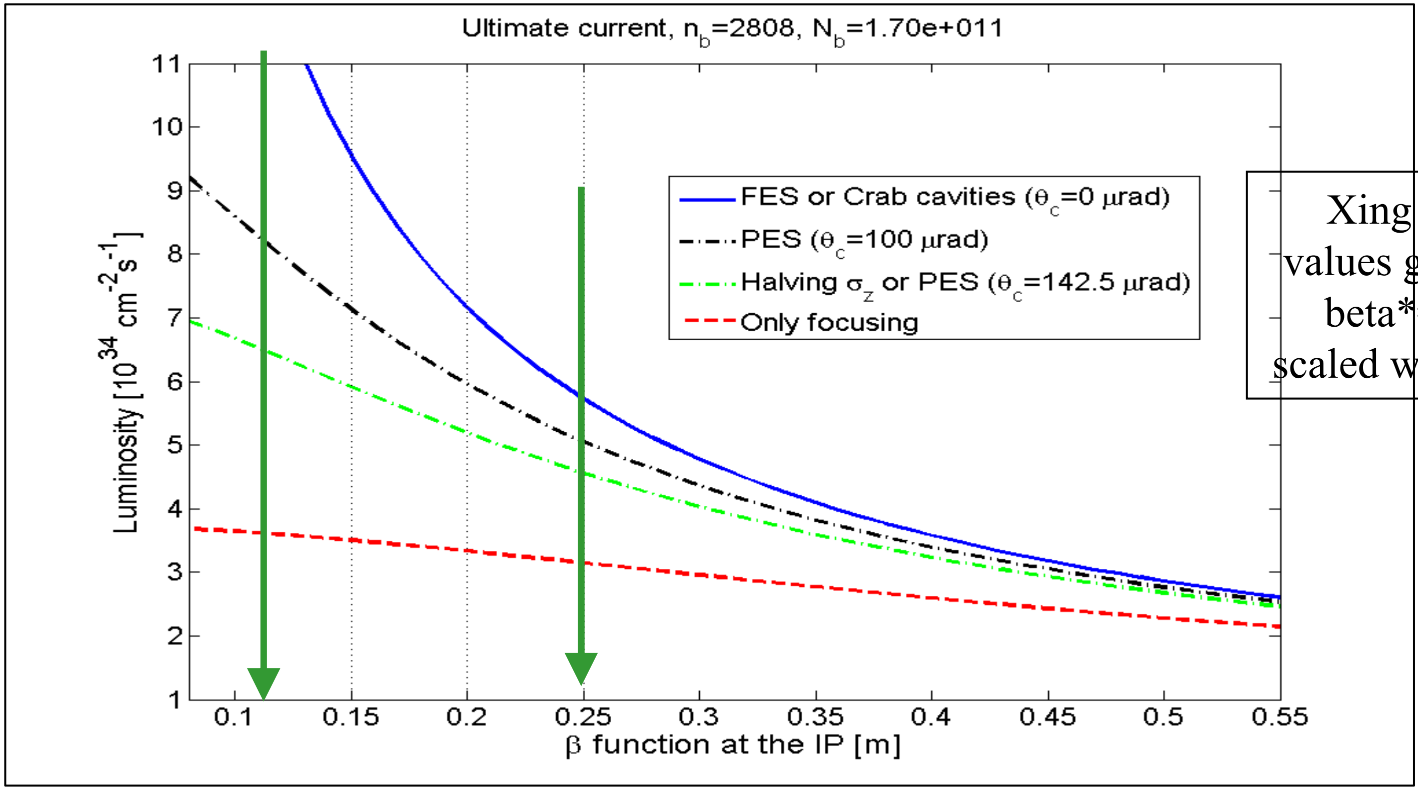
standard

Variation of β along bunch

Indeed the most evident and efficient way to increase luminosity is thru the beam current contribution $k_b \times N_b^2$

We are left with β* and F()…but θ_c is fully constrained by β * , k_b and N_b

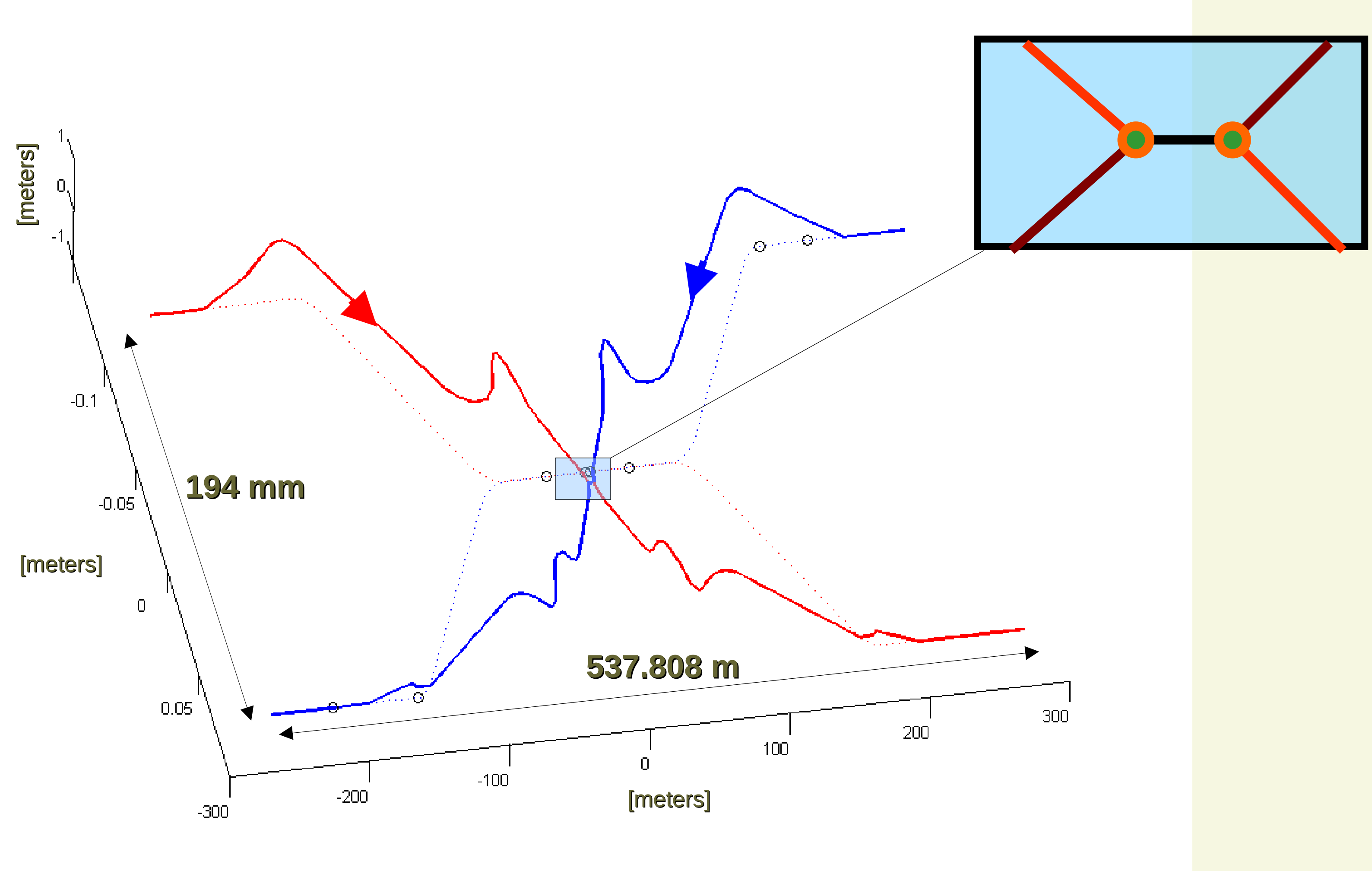
2.2- The Xing angle couples β* and F



Xing angle values given for beta*=.5m, scaled with beta*

Pushing the low-β makes sense if simultaneously the impact of the luminosity geometrical loss factor F is acted upon.

3.1- A way out: the early separation scheme



Courtesy G. Sterbini

3.2- Performance prospects with early separation

1. **With dipoles at 2 m from the IP, F=1** and no beam dynamics issue for target luminosity…*but inner detector "killed"* (meetings with experimenters).

2. **With dipoles at 3.5m or spread starting from 3.5 m, 50% of improvement obtained** with a scheme that is not a priori rejected by the experimenters. The Xing angle is 40 to 50% of nominal. Beam dynamics issue under study. *Excellent case for a small angle crab crossing to make the effective residual angle vanish (F=1) or increase the beam separation.*

4.1- Insertion design: out to deal with so many requirements?

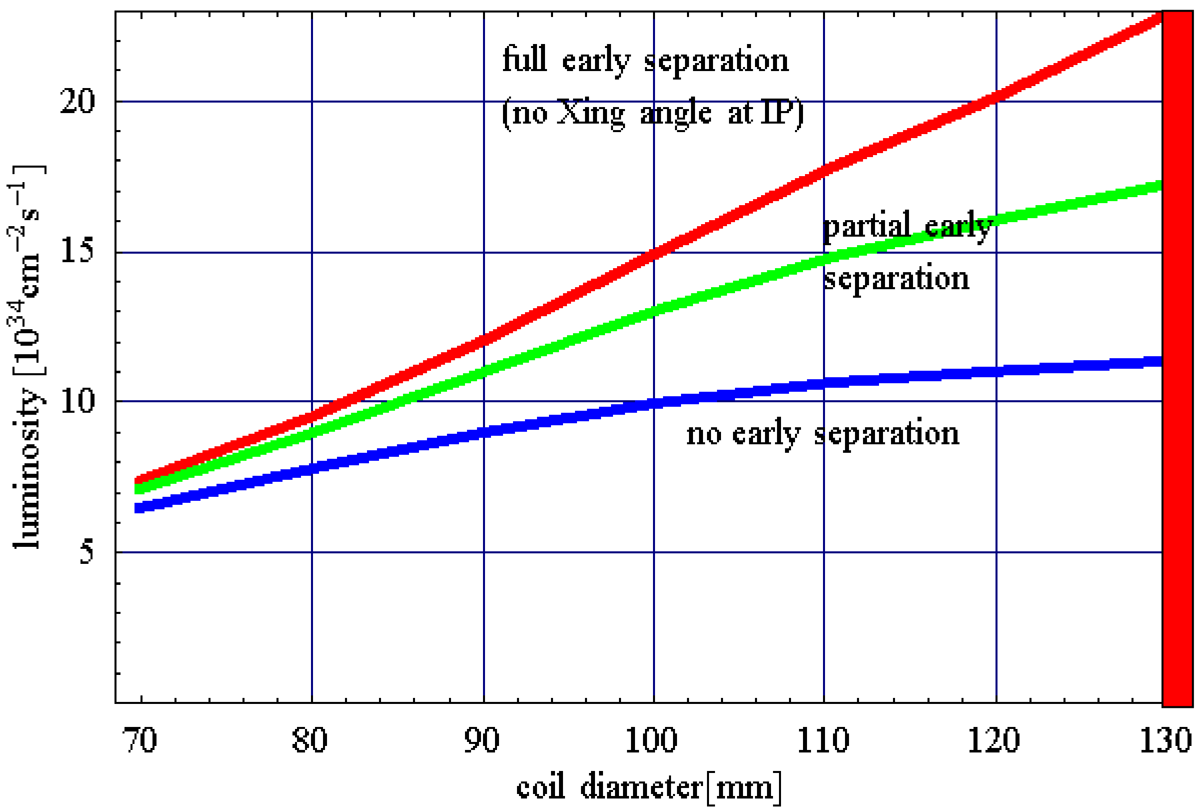
A parametric insertion model (Arcidosso, EPAC2006) solves in a simplified but self-consistent way the problems of layout, optics, aberrations, beam-beam, quadrupole technology and gives hints on energy deposition (*waiting for scaling laws*).

The parameters adjusted are l^*, B_{max}, Φ_{quad}, l_{quad}, β^*, k_b, N_b, θ_c, σ_s

to maximize the ***peak luminosity*** , respecting constraints:

- ***10σ*** betatron aperture in the triplet,
- Maximum peak field of technology respected with margin: 75% of quench fields (Nb-Ti:10T; Nb_3Sn:15T)
- ***Head-on and LR Beam-beam limits*** respected
- ***Linear*** chromaticity correctable by the lattice sextupoles
- “Reasonable” geometric aberrations
- Operational heat deposition limits: 0.5 mW/g for Nb-Ti, 1.9 mW/g for Nb_3Sn (with safety margin of 3).

4.2- Luminosity vs triplet aperture



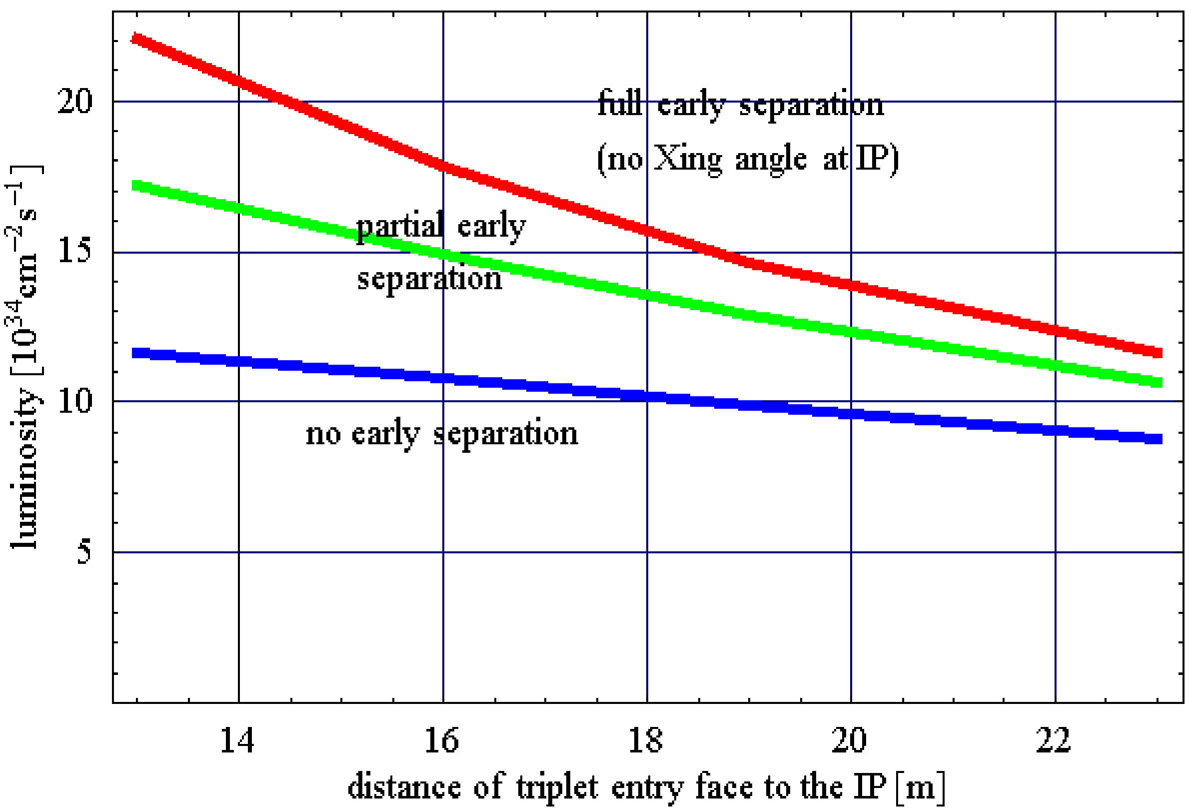
Gain in luminosity from 85% to × 3 for

Φ 70 → 130 mm.

The maximum of 130 mm is set by the Q' correction AND by the internal stresses for the Nb$_3$Sn (Fessia/Todesco)

Defaults: Ultimate beam parameters: 5616 × 1.7 10^{11} p, σs = 3.7 cm, l*=19m, Nb$_3$Sn

4.3- Luminosity vs triplet position



Gain in luminosity from 35% to 90% *when l* is reduced from 23 m down to 13 m at constant aperture.*

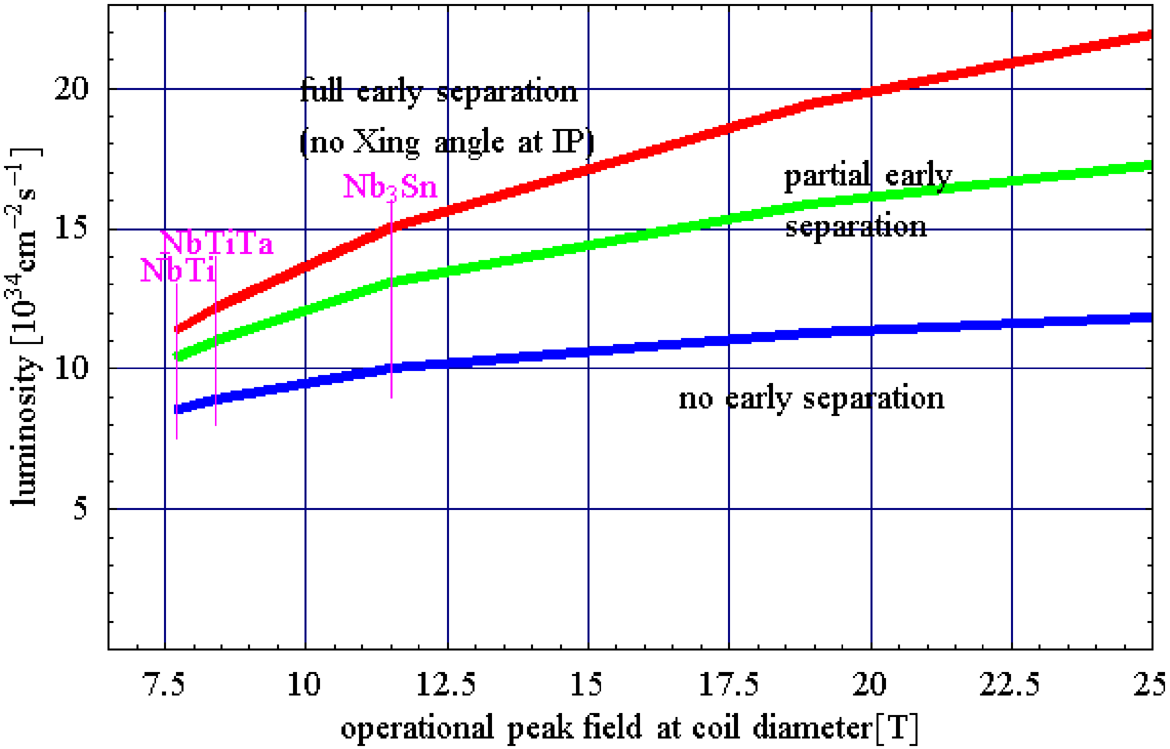
Issues: space in the detector volume, supports and stability, TAS, backscattering,…

Defaults: ***Ultimate beam parameters: 5616 × 1.7 10^{11} p,***

σs = 3.7 cm , Nb_3Sn, Φ =100 mm

4.4- Luminosity vs quad. technology

Temperature margin for heat deposition not included



Gain in luminosity from 15% to 30% between NbTi and Nb$_3$Sn due to more compact triplet (increased gradient by ~50%).

LHC as built can still take advantage of much higher gradients.

Defaults: Ultimate beam parameters: 5616 × 1.7 10^{11} p, σs = 3.7 cm , l*=19 m, Φ =100 mm

5- The issue of energy deposition

The present triplet is able to cope with L=10^{34} with a safety factor of 3 established as necessary: accuracy of the models for energy deposition and extraction, accuracy of the simulations, imperfections.

For the present knowledge (Zlobin et all) of energy deposition, thermal performance of the insulation and heat extraction:

	Nb-Ti	Nb_3Sn
L/L_0	**8.6**	**10**
Heat/Quench*	**3.75**	**1.4**

Defaults: ***Ultimate beam parameters: 5616 × 1.7 10^{11} p, σs = 3.7 cm, NO EARLY SEPARATION., Φ=100 mm, l*=19 mm***

The measurements planned on fragments of coils are essential.

The issue of heat deposition and removal has to be tackled at the magnet design stage →Team on heat deposition calculation started at CERN.

6.1- Solutions based on strong focusing

2808 bunches with 7.5 cm length; assume *practical early separation, Nb3Sn*.

Smaller aberrations!

l* **[m]**	*β** [cm]	***Np*** **[10^{11}p]**	***L***	*L*
				[10^{34} cm^{-2}s^{-1}]
13	8.7	**1.7**	**7.5**	→**13.7** (FES or + $\sigma_s/2$) →***3.1*** (NES)
		1.15	**3.6**	→ 6.2 (FES or + $\sigma_s/2$)
16	10.7	**1.7**	**7.5**	→11 to **12**. (FES or + $\sigma_s/2$)
		1.15	**3.6**	→ 5.4 (FES or + $\sigma_s/2$)
19	13	**1.7**	**7.3** ~~(2.3)~~	→9.7 to **10.5** (FES or + $\sigma_s/2$)
		1.15	**3.5**	→ 4.9 (FES or + $\sigma_s/2$)

Quadrupole aperture 120 mm

βmax 16500 m

6.2- Strong focusing with 50 ns spacing

50 ns spacing allows almost full early separation

Ultimate bunch current of 1.7 10^{11} assumed

l^* [m]	β^* [m]	Φ_{coil} [mm]	L [10^{34} cm^{-2}s^{-1}]	$L_{\sigma/2}$
13	**0.088**	**117**	**6.8**	8.0
19	0.122	120	5.5	5.8

The ratio (peak heat deposition/quench level) is 1 for L=6.8 (Nb_3Sn).

7- Quadrupole aperture and collimator impedance (hint)

The collimator gap is a function of the rms beam size. At collision, where it is very small, the collimators create an impedance that limits the beam current to 40% of nominal.

At collision, the aperture limit to protect against beam losses is in the triplet.

If the triplet aperture is increased, for a given protection level, the collimator gap can be increased, reducing the impedance seen by the beam.

Hence, larger aperture quadrupoles could be considered as elements of collimation phase 2.

8.1- Considerations on integrated luminosity

What really matters is the INTEGRATED luminosity.

Why talking about peak L?: because accelerator design can say something on peak L, while integrated L relies on many practical issues and assumptions

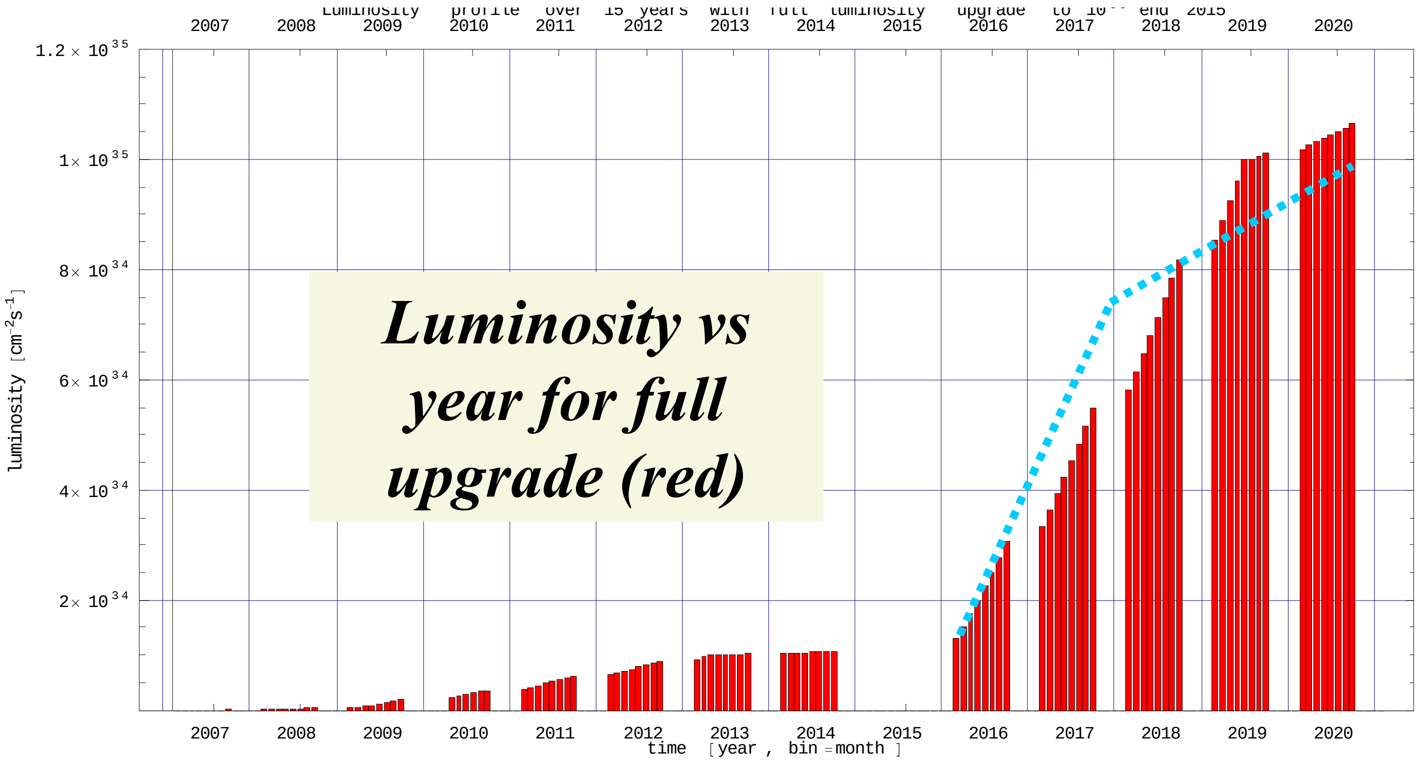
But something can be said about the consumption of protons: **the decay of L produced by optics is faster than L produced by the beam current:**

$$\tau_{nuclear} \propto \frac{N_b k_b}{L}$$

At this few*10% level, there are several other phenomena or options, e.g. variable beta*, and…

8.2- Considerations on integrated luminosity

The rise time of the performance must be taken into account: Scenario based on CPT th. (Shiltsev) with complexity from 0.7 (TeV I was 0.9) to 2 (RHIC, SppS but HERA and ISR around 4).



Luminosity vs year for full upgrade (red)

$$L_{eff}=\eta L_{eff0}$$

$$\eta\in(0.5,\sim1)$$

9.1- Conclusions

These estimates made with a simplified model need be checked against detailed studies. For the time being:

1) **For the strong focusing option, the early sep. scheme is critical**: it requires compact dipoles submitted to very high heat deposition(70W/m) placed in a position where they are not really wanted, that shall be either transparent with no magnetic leak or act like a shielding block. *But it is a key for safe high L. In addition, they open the way to a "mild" crab crossing scheme with another potential yield of ×2 in L.*
2) **Quadrupoles with an aperture significantly larger than foreseen: 120 to 150 mm** are needed for luminosity; they are liable to significantly simplify collimation phase 2 and MP. *If the aperture is limited, a Q0 option brings the same advantages with more quads of smaller aperture.*

9.2- Conclusions

3) The Nb_3Sn technology offers 30% more luminosity for 50% more gradient and a significantly larger temperature margin, though still insufficient.

4) **The calculation and optimization of heat deposition and removal becomes a key issue for the upgraded luminosity (the doses as well):** expected impact on triplet position, geometry, materials, shielding. *Not only the heat but a detailed knowledge of the impacting particles and their energy spectra.*

5) *Even if Nb_3Sn is successful, the* ***LHC performance remains limited first by quad magnet technology*** *(critical field, temperature margin) and* ***can be increased*** *if these limitations are overcome.*

10.1- Work plan

For PAC07, study one or two solutions in detail (e.g. l*=23m, l*=16m). “A concept for the LHC luminosity upgrade based on strong b* reduction combined with a minimized geometrical luminosity loss factor”, *JPK, R. Assmann, R. de Maria ,E. Metral ,G. Sterbini ,E. Todesco ,F. Zimmermann*

- Stresses in large aperture quads: *F. Borgnolutti (PhD), E. Todesco, P. Fessia, F. Regis* and optimized design vs stresses and luminosity.
- Field quality in large aperture quads: *B. Bellesia, JPK, E. Todesco*
- Calculation of energy deposition from collision debris & scaling laws: *C. Hoa, G. Sterbini, E. Wildner, E. Laface, with support of CERN FLUKA team., F. Broggi/Milano*
- Early separation scheme: first iteration of design: *G. Sterbini (PhD) with help by JPK, D. Tommasini, F. Zimmermann;*
- Q0 focusing booster: *E. Laface (PhD), W. Scandale*

10.2- Work plan

- Integration of magnets in detectors: *G. Sterbini, E. Laface, P. Limon, G. Kirby, E. Tsesmelis, ATLAS & CMS physicists*

Will benefit from work done in a more general framework:

- Measurement of heat transfer: *D. Richter*
- Thermal optimization of insulation: *e.g. M La China, D. Tommasini*
- Thermal calculations
- Of course US/LARP

+ work by ABP or in collaboration with ABP or RHIC:

- Optical design of insertions
- Calculation of aberrations and minimization
- Requirements for the collimator gap
- Requirements for the quad aperture for collimation
- RHIC experiment on required beam separation at long-range encounters

Annex1: Solutions for ultimate beam current

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 $L/L_0=10$

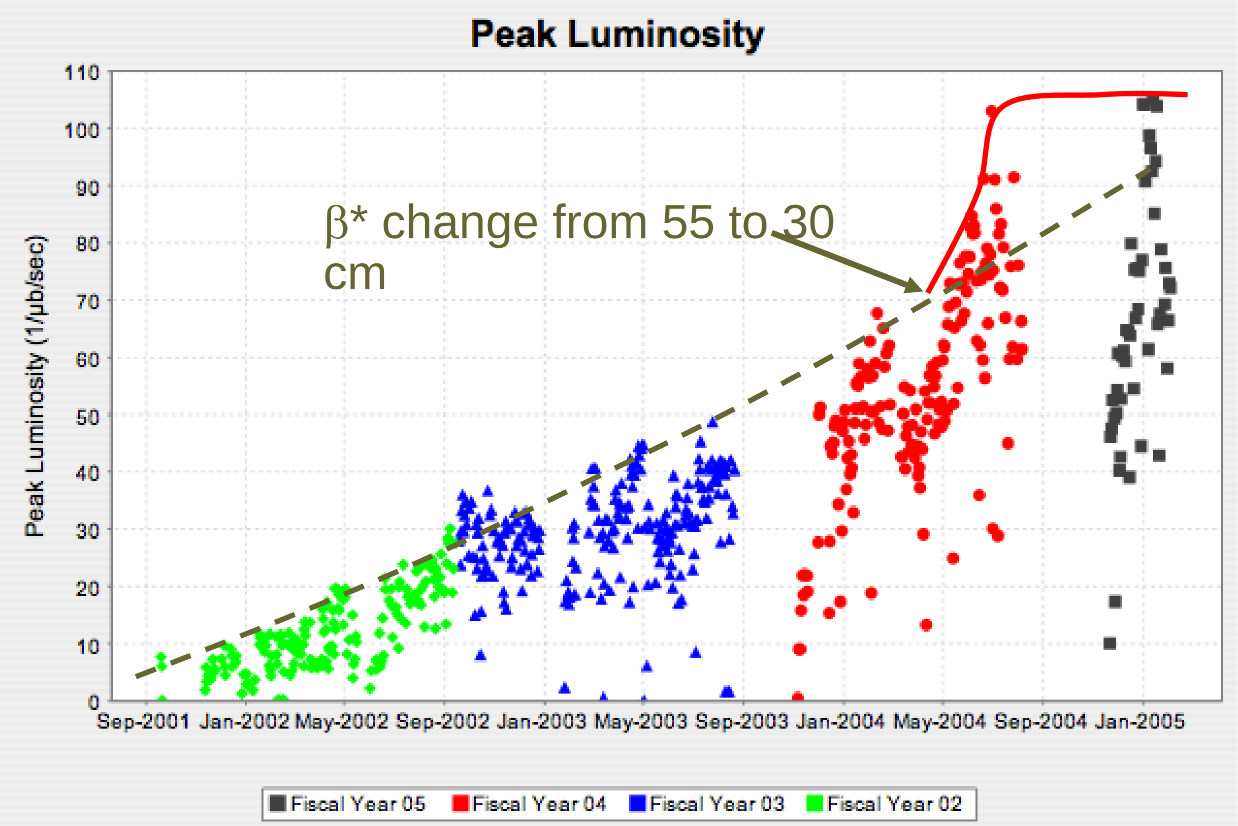
The Nb_3Sn quadrupole length is 6 to 7 m. Note the quadrupole aperture around 130 mm.

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

Annex 2: faster increase with optics)

ISR: Increasing the luminosity with the sc low-beta insertion took months: probably less than 2 years for 7 times more luminosity

TEV:



Courtesy V. Shiltsev & E. Todesco