LHC Machine Upgrades

Roger Bailey, CERN, Geneva

The plans for increasing the integrated luminosity of the LHC beyond its nominal parameters are well under way. The first upgrade is based on improvement of the collimation system, probably the most limiting factor at present. This will allow to reach and to pass the nominal 10^{34} cm^{-2} s^{-1}. Other improvements in the injector chain (Linac4, PSB at 2 GeV, SPS upgrade) and in the LHC ring (a new cryo-plant for cooling of SC RF cavities, removal of radiation limitation in electronic equipment, etc.) should be able to bring us around 1.7-2 10^{34} $cm^{-2}s^{-1}$. Then, in the longer term a major upgrade involving :

- New Inner Triplets and insertion magnets
- A revision of the matching region and of the corrector system
- Crab Cavities to allow full exploitation of the low β^* of the new triplets
- New cryoplants dedicated to the cooling of the new magnets and cavities

The implementation of this new scheme accompanied by other possible improvements under consideration (shorter bunches, etc.) should allow a peak luminosity of ~ 5 10^{34} cm^{-2} s^{-1} and improved luminosity lifetime by “luminosity leveling”. Finally, the very preliminary outcome of first discussions and studies on a LHC energy upgrade to around 28-33 TeV cm will be presented.

Instantaneous luminosity

$$L = \frac{N^2 k_b f}{4\pi\sigma_x\sigma_y} F = \frac{N^2 k_b f\gamma}{4\pi\varepsilon_n\beta^*} F$$

"Thus, to achieve high luminosity, all one has to do is make (lots of) high population bunches of low emittance to collide at high frequency at locations where the beam optics provides as low values of the amplitude functions as possible." PDG 2005, chapter 25

- Nearly all the parameters are variable (and not independent)
  - Number of bunches per beam k_b — Total Intensity
  - Number of particles per bunch N } Beam Brightness
  - Normalised emittance ε_n } Beam Brightness
  - Relativistic factor (E/m_0) γ — Energy
  - Beta function at the IP β^* } Interaction Region
  - Crossing angle factor F } Interaction Region
    - Full crossing angle θ_c
    - Bunch length σ_z
    - Transverse beam size at the IP σ^*

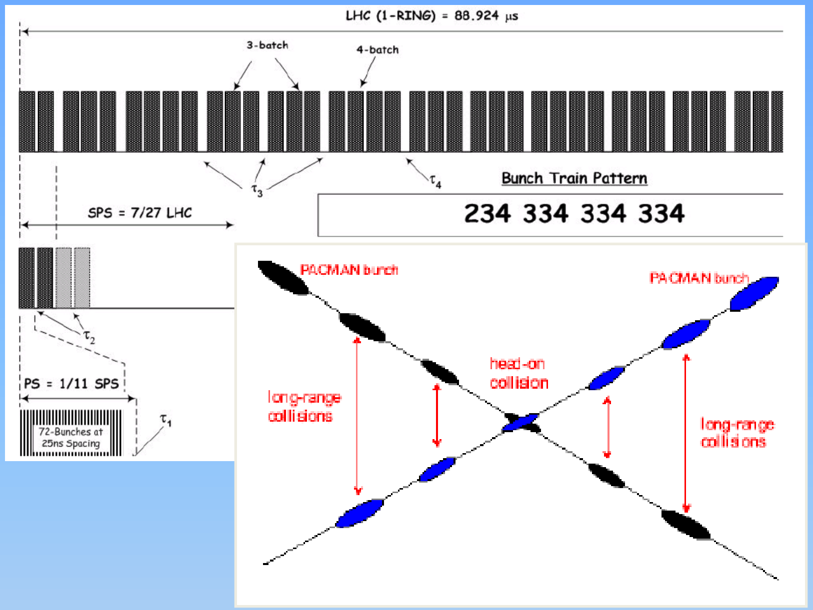
$$F = 1/\sqrt{1+\left(\frac{\theta_c\sigma_z}{2\sigma^*}\right)^2}$$

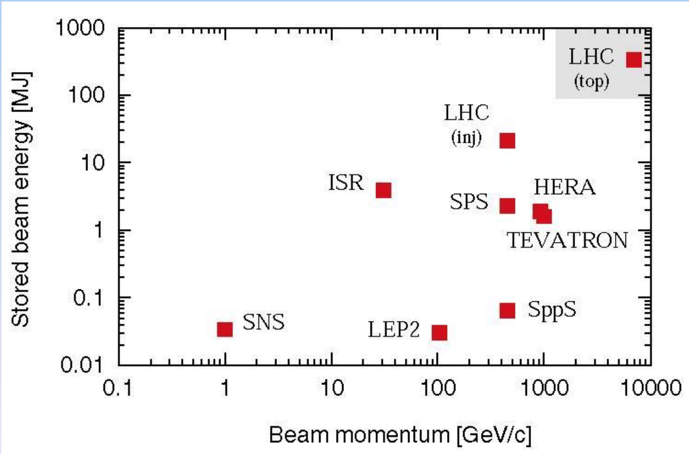
LHC nominal performance

Nominal settings	
Beam energy (TeV)	7.0
Number of particles per bunch	$1.15\ 10^{11}$
Number of bunches per beam	2808
Crossing angle (μrad)	285
Norm transverse emittance (μm rad)	3.75
Bunch length (cm)	7.55
Beta function at IP 1, 2, 5, 8 (m)	0.55,10,0.55,10

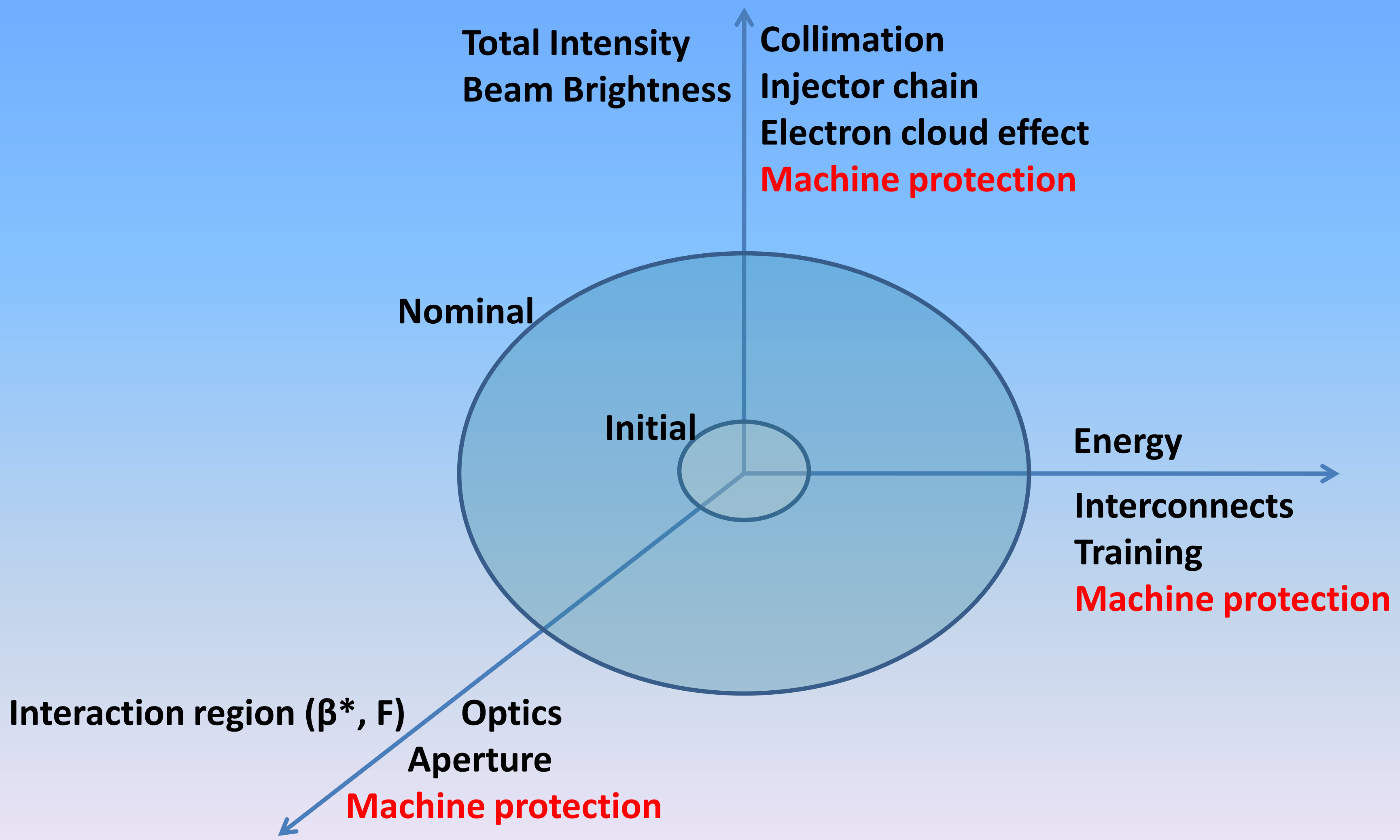
Derived parameters	
Luminosity in IP 1 & 5 ($cm^{-2}\ s^{-1}$)	10^{34}
Luminosity in IP 2 & 8 ($cm^{-2}\ s^{-1}$)*	$\sim 5\ 10^{32}$
Transverse beam size at IP 1 & 5 (μm)	16.7
Transverse beam size at IP 2 & 8 (μm)	70.9
Stored energy per beam (MJ)	362

* Luminosity in IP 2 and 8 optimized as needed





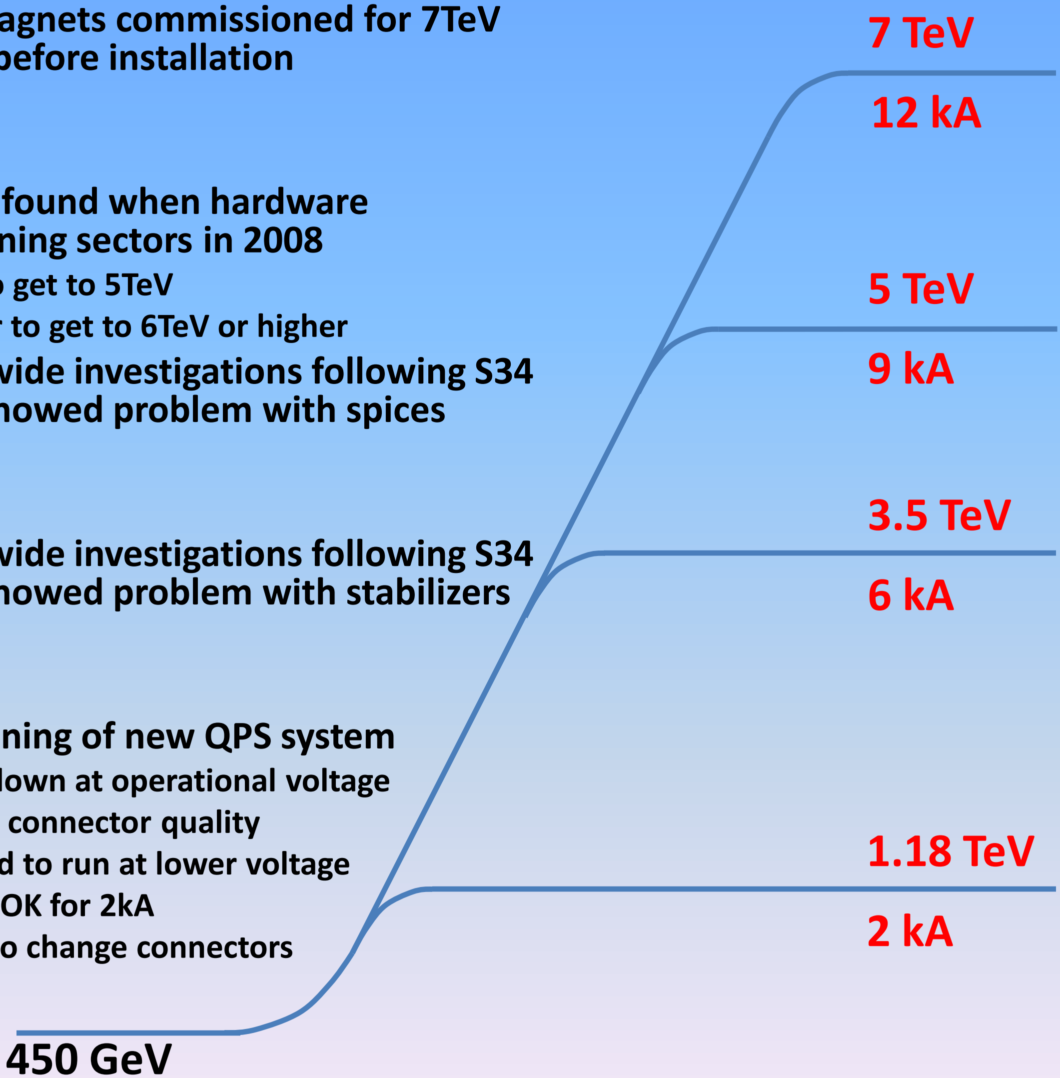
LHC performance drivers



7/22/2010

Evolution of target energy during commissioning

- All main magnets commissioned for 7TeV operation before installation
- Detraining found when hardware commissioning sectors in 2008
  - Easy to get to 5TeV
  - Harder to get to 6TeV or higher
- Machine wide investigations following S34 incident showed problem with spices
- Machine wide investigations following S34 incident showed problem with stabilizers
- Commissioning of new QPS system
  - Breakdown at operational voltage
    - connector quality
  - Obliged to run at lower voltage
    - OK for 2kA
  - Need to change connectors



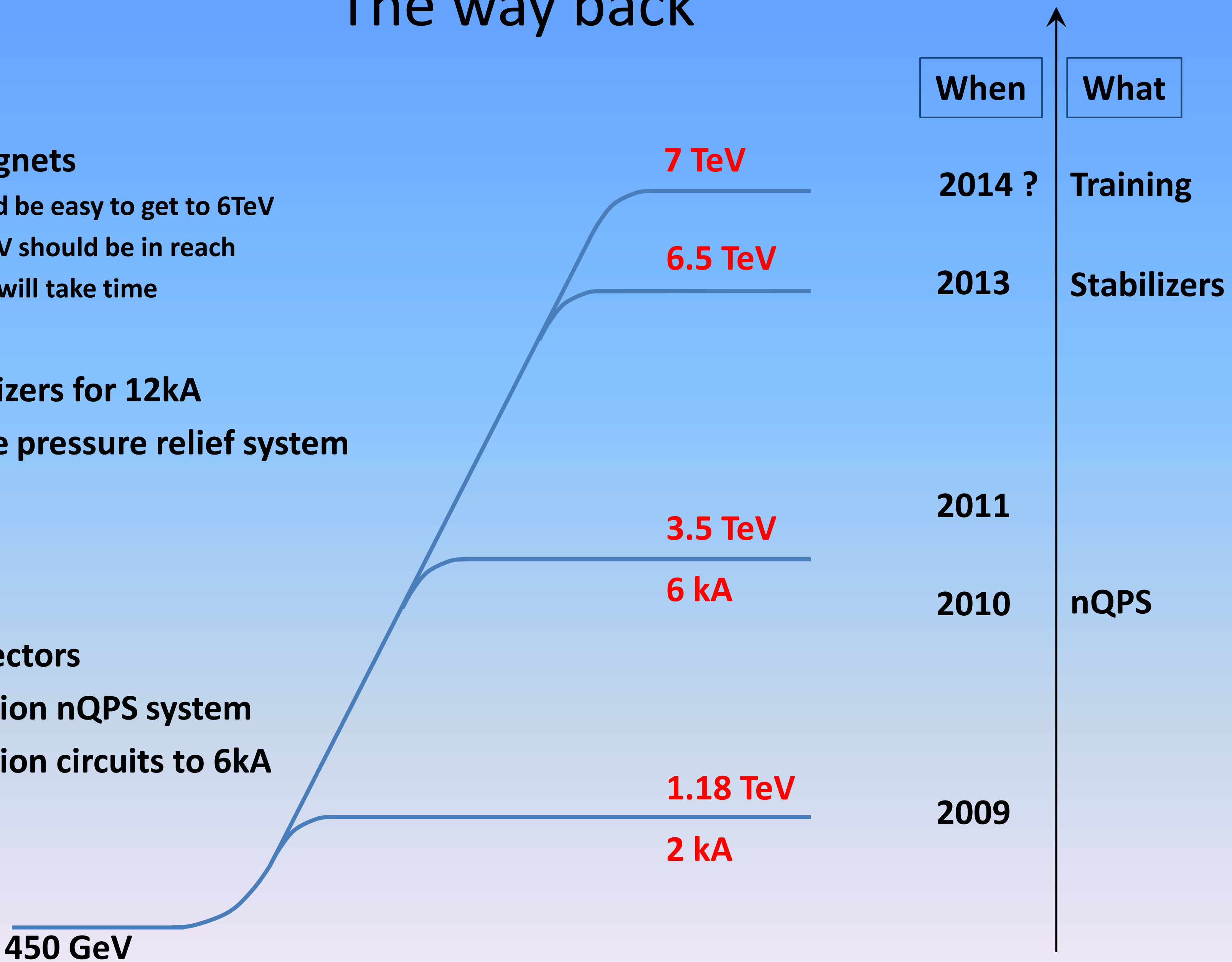
When	Why
2002-2007	Design
Summer 2008	Detraining
Late 2008	Splices
Summer 2009	Stabilizers
October 2009	nQPS

The way back

- **Train magnets**
  - Should be easy to get to 6TeV
  - 6.5 TeV should be in reach
  - 7 TeV will take time

- **Fix stabilizers for 12kA**
- **Complete pressure relief system**

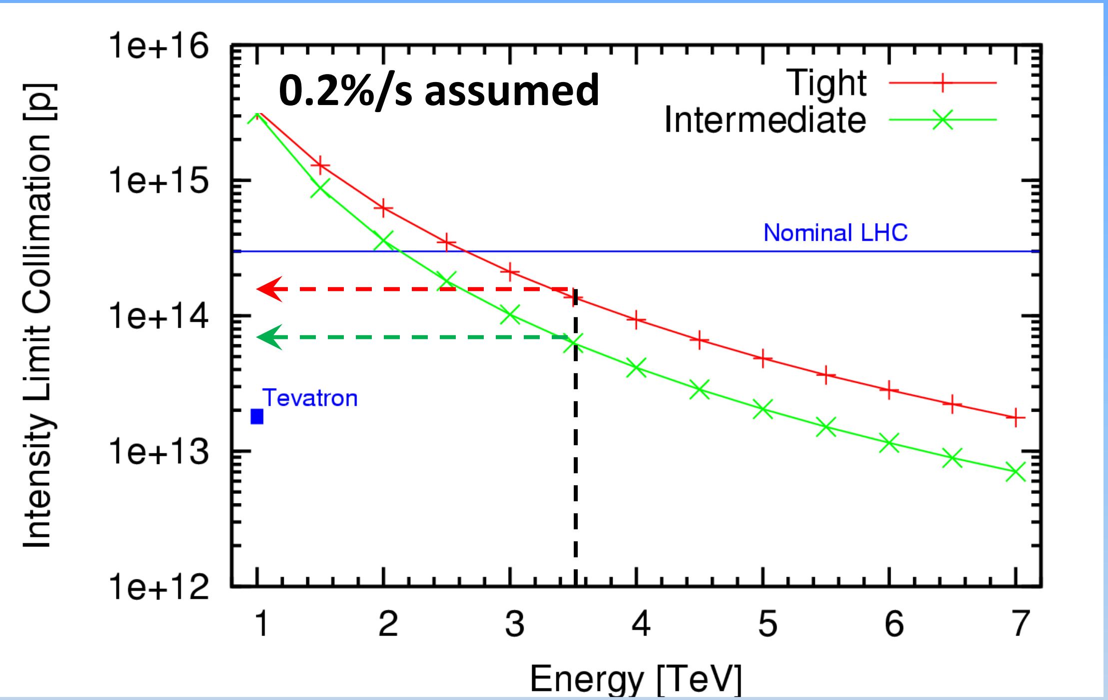
- **Fix connectors**
- **Commission nQPS system**
- **Commission circuits to 6kA**



LHC Intensity limits 2010 2011

- Collimation system conceived as a staged system

- **First stage installed and allows 40% of nominal intensity at 7TeV**
  - **Under certain assumptions**
    - **LHC lifetimes and loss rates**
    - **0.1%/s assumed (0.2h lifetime)**
    - **Ideal cleaning**
  - **Imperfections bring this down**
    - **Deformed jaws**
    - **Tilt & offset & gap errors**
    - **Machine alignment**
  - **Machine stability**
    - **Tight settings a challenge early**
    - **Intermediate settings make use of aperture to relax tolerances**



Fix I_{max} to 6 10^{13} protons per beam at 3.5TeV (about 20% nominal intensity)

30MJ stored beam energy

- At higher energies cleaning gets harder !!!

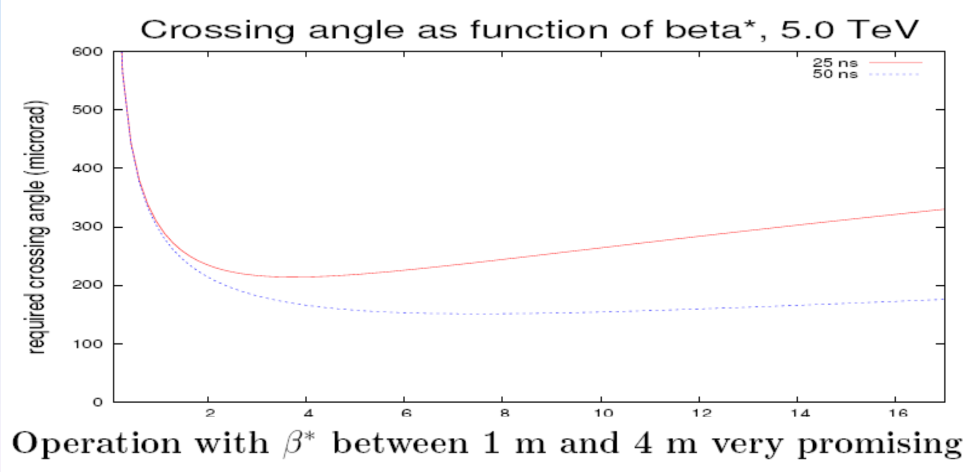
Higher intensities

- With experience assume that we can
  - Move to tight settings
  - Achieve 0.1% loss rates
  - Get the imperfection factor down
    - Should allow to push to higher intensities at 3.5 TeV
    - Still have the 40% limit expected at 7 TeV

- Then need to install something more
  - Collimators in the cold regions of the machine in 2012
    - Using "missing magnet" space in the dispersion suppressors
    - Requires moving magnets in LSS3 and LSS7 (24 magnets each)
    - Being pursued with high priority

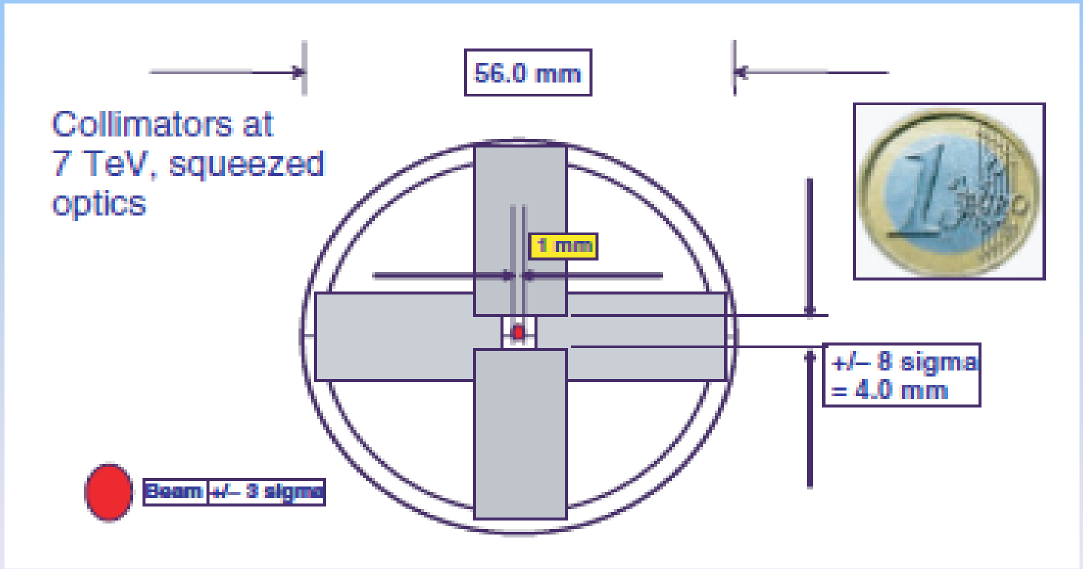
β* and F in 2010 2011

- Lower energy means bigger beams $\varepsilon_n = \varepsilon\gamma$ $\sigma = \sqrt{\varepsilon\beta}$
  - Less aperture margin around the IP
  - Higher β* helps in this
- > 150 bunches requires crossing angle
  - Requires more aperture
  - Higher β* again helps
- Targets for 3.5TeV
  - 2m no crossing angle
  - 3m with crossing angle



β* evolution

- The squeeze is always going to be challenging
  - Changing optics with dangerous beams
  - Follow / anticipate with collimators
  - Particularly tricky below 1m
- With experience, should be easier, but still …



Early beam operation

2009			2010			2011		
Repair of Sector 34	1.18 TeV	nQPS 6kA	3.5 TeV $I_{safe} < I < 0.2\ I_{nom}$ $\beta^* > 2$ m	Ions		3.5 TeV $\sim 0.2\ I_{nom}$ $\beta^* \sim 2$ m	Ions	
No Beam	B		Beam			Beam		

- Energy limited to 3.5 TeV
- 2010
  - Intensity carefully increased to collimation limit
  - β^* pushed as low as possible
  - Target luminosity 10^{32} $cm^{-2}s^{-1}$
- 2011
  - Run at established limits
  - Target integrated luminosity 1 fb^{-1}

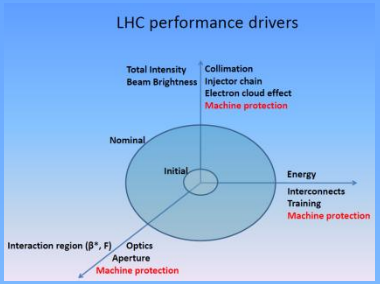
Energy	TeV	3.50	3.50	3.50	3.50
Bunch intensity	1.E+10	10.0	10.0	10.0	10.0
Bunches per beam		4	24	432	792
Emittance	µm	3.75	3.75	3.75	3.75
β*	m	3.50	3.50	3.50	3.50
Luminosity 1 and 5	cm-2 s-1	1.0E+30	6.1E+30	1.1E+32	2.0E+32
Total inel X section	cm2	6.0E-26	6.0E-26	6.0E-26	6.0E-26
Event rate	Hz	6.1E+04	3.7E+05	6.5E+06	1.2E+07
Event rate / Xing	Hz	1.4	1.4	1.3	1.3
Protons		4.0E+11	2.4E+12	4.3E+13	7.9E+13
% nominal		0.1	0.7	13.4	24.5
Current	mA	0.7	4.3	77.7	142.5
Stored energy	MJ	0.2	1.3	24.2	44.4
Beam size 1 and 5	um	59.3	59.3	59.3	59.3

40% efficiency for physics → 10^6 seconds collisions per month

10^6 seconds @ <L> of 10^{32} cm^{-2} s^{-1} → 100 pb^{-1}

Getting to nominal (dates indicative)

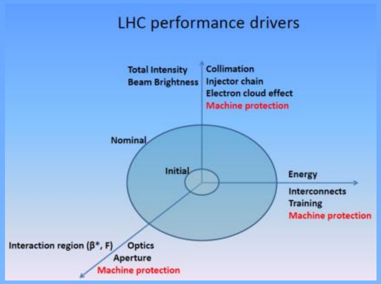
$$L = \frac{N^2 k_b f}{4\pi\sigma_x\sigma_y} F = \frac{N^2 k_b f\gamma}{4\pi\varepsilon_n\beta^*} F$$



2010	2011	2012	2013	2014	2015	2016
Energy3.5TeV		Splices, Collimators in IR3	Increase Beam Energy to 7TeV			
β^* of 2m			Decrease β^* to 0.55m			
20% of I_{nom}			Increase k_b to 2808			
Initial			Nominal			
10^{32}			10^{34}			
1 fb^{-1}			≤ 50 fb^{-1}/yr			

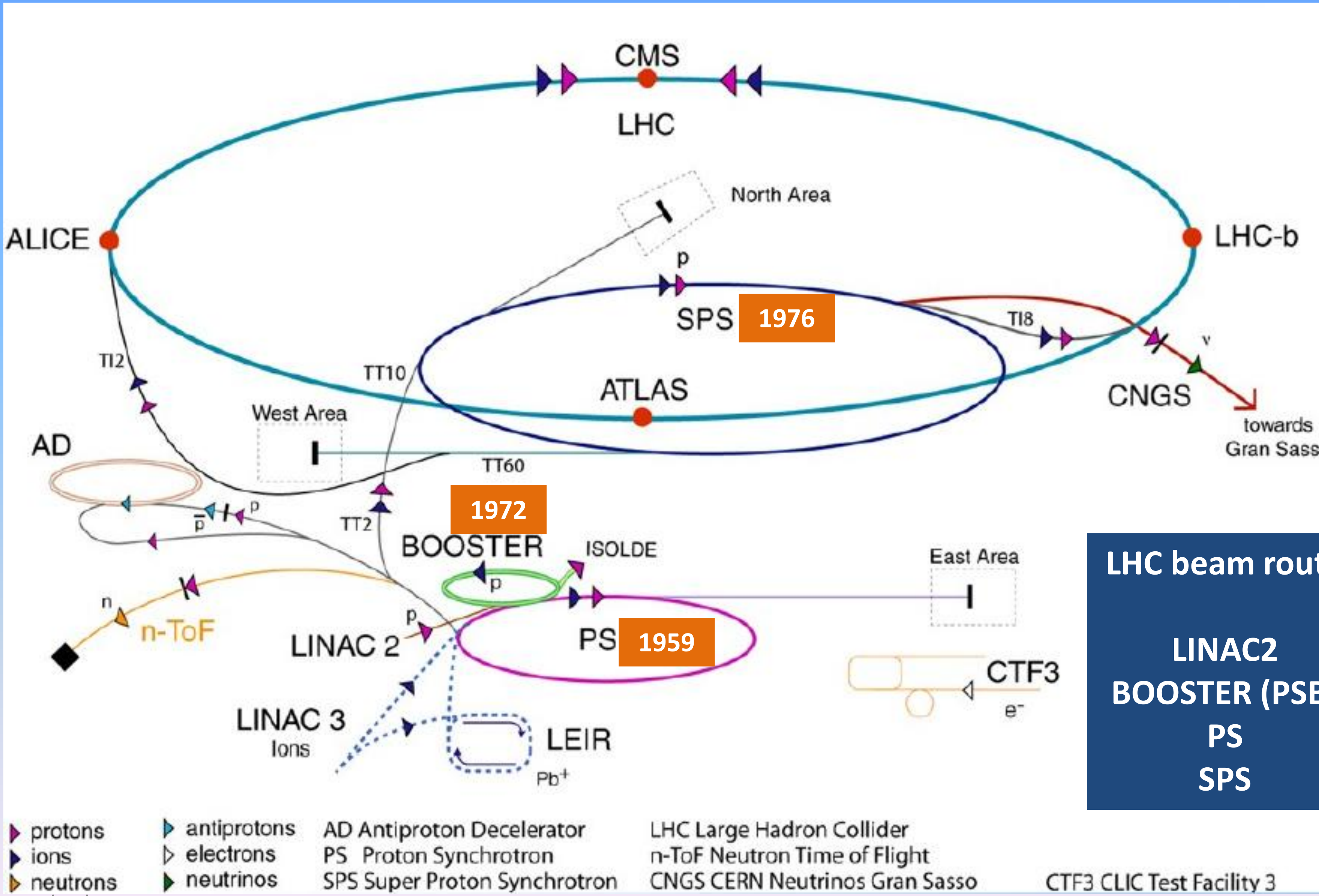
Overall strategy beyond 2016 (dates indicative)

$$L = \frac{N^2 k_b f}{4\pi\sigma_x\sigma_y} F = \frac{N^2 k_b f\gamma}{4\pi\varepsilon_n\beta^*} F$$



2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	etc.
														Increase Beam Energy to 16.5 TeV					
				New interaction region ($\beta^*$to 0.2m, luminosity leveling)															
Increase beam brightness																			
Ultimate				**HL-LHC**										**HE-LHC**					
2.3 10^{34}				**5 10^{34}**										**2 10^{34}**					
≤ 100 fb^{-1}/yr				**≤ 200 fb^{-1}/yr**										**≤ 100 fb^{-1}/yr**					

Present accelerator complex



LHC beam route

LINAC2
BOOSTER (PSB)
PS
SPS

Injector chain

- The present accelerators are getting old (PS is 50 years old…) and they operate far beyond their initial design parameters

- Luminosity depends directly upon beam brightness N/ε^*

$$L \propto \frac{1}{\beta^*} \frac{N_b}{\varepsilon_{X,Y}} \cdot N_b \cdot k_b$$

N_b : number of protons/bunch

$\varepsilon_{X,Y}$: normalized transverse emittances

k_b : number of bunches per ring

- Brightness is limited by space charge at low energy in the injectors

$$\Delta Q_{SC} \propto \frac{N_b}{\varepsilon_{X,Y}} \cdot \frac{R}{\beta\gamma^2}$$

N_b : number of protons/bunch

$\varepsilon_{X,Y}$: normalized transverse emittances

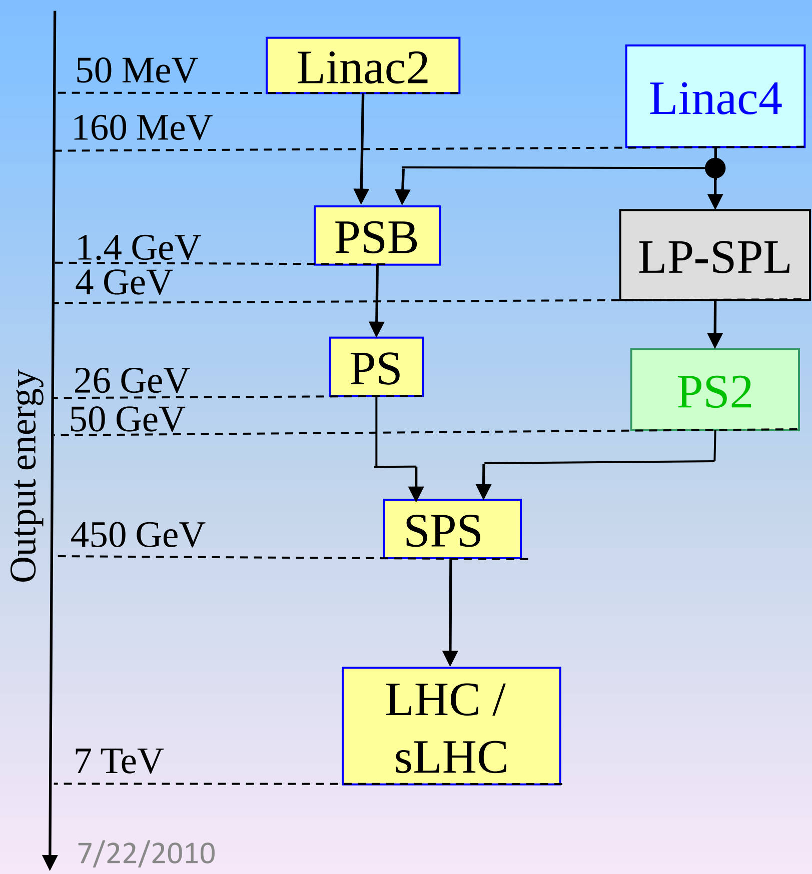
R : mean radius of the accelerator

$\beta\gamma$: classical relativistic parameters

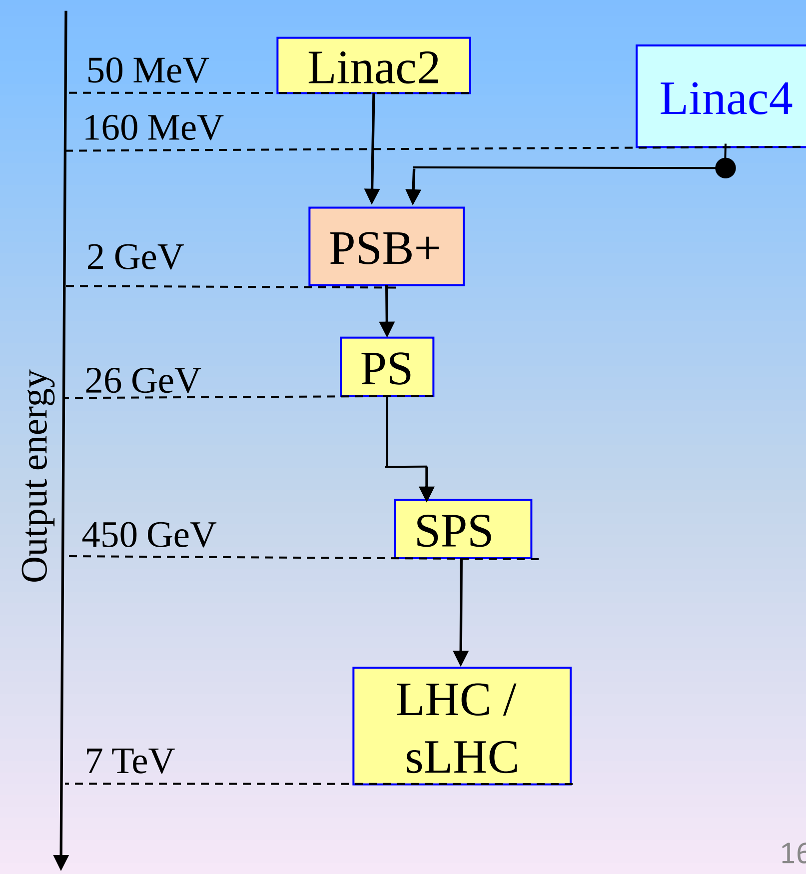
$\Rightarrow$ Need to increase the injection energy in the injection synchrotrons

Injector chain

- Scenario 1 (pre 2010)
  - Replace old machines
  - Consolidate SPS
  - **Realistic planning 2020**



- Scenario 2 (2010)
  - Consolidate all machines
  - Upgrade PSB energy
  - **Realistic planning 2015**



Intensity Limits

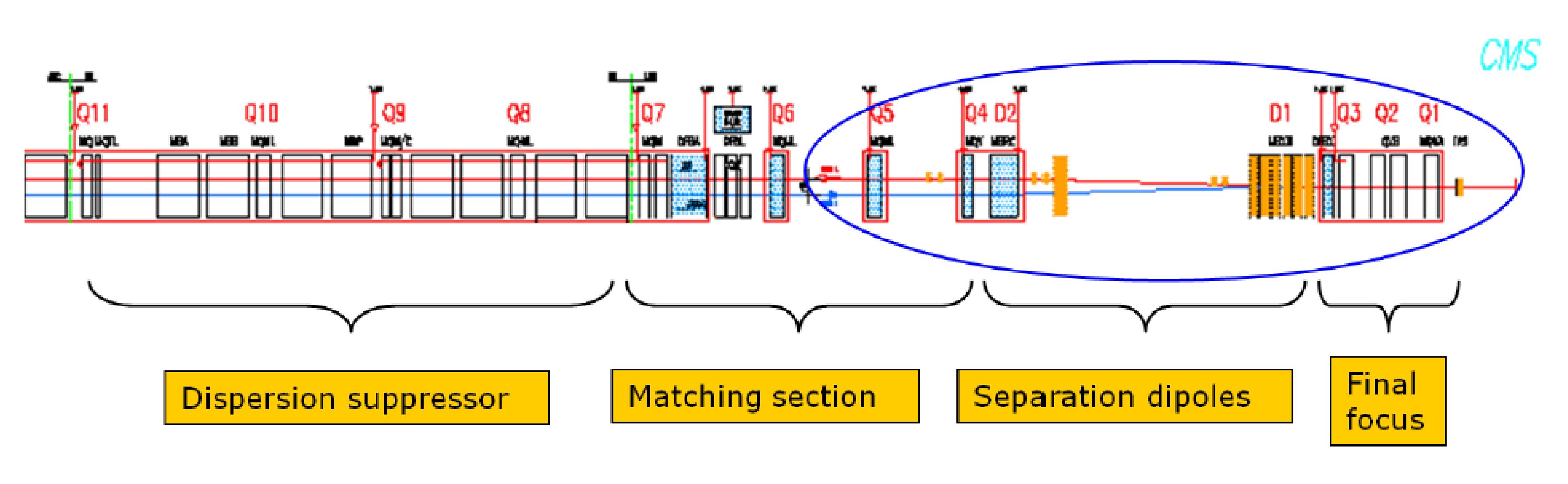
Reminder design = 1.15 (for 10^{34}); Ultimate = 1.7 (for $2.3x10^{34}$)

Intensity Limitations (10^{11} protons per bunch)			
	Present	SPL-PS2	2GeV in PS
Linac2/LINAC4	4.0	4.0	4.0
PSB or SPL	3.6	4.0	3.6
PS or PS2	1.7	4.0	3.0
SPS	1.2	>1.7?	>1.7?
LHC	1.7-2.3?	1.7-2.3?	1.7-2.3?

Conclusion from (or just after) Chamonix workshop in February 2010:

- We continue (as planned) and finish the study for LP-SPL/PS2
- Study in parallel the PS Booster energy upgrade
- Decision can be taken when we have the results of these studies

High Luminosity Interaction Regions



Goals of Phase I of the original upgrade project:

- flexibility & performance
- improve spares count
- cope with radiation damage
- enable focusing of the beams to β^*=0.3 m in IP1 and IP5

Scope of the project:

1. Upgrade of ATLAS and CMS interaction regions: Interfaces between LHC and experiments remain unchanged.
2. Cryogenic cooling capacity and other infrastructure in IR1 and IR5 remain unchanged and will be used to full potential.
3. Replace present triplets with wide aperture quadrupoles based on the LHC dipole (Nb-Ti) cables cooled at 1.9 K.
4. Upgrade D1 separation dipole, TAS and other beam-line equipment (also TAN) so as to be compatible with the inner triplets.
5. Modify matching sections (D2-Q4, Q5, Q6) to improve optics flexibility, and introduce other equipment to the extent possible.

Reconstructed at Chamonix 2010

1. Will the phase 1 upgrade produce an increase in useful integrated luminosity?
2. Do we have the resources to complete on a time scale which is reasonable with respect to phase 2?

- Key preliminary findings (report forthcoming)
  - Can expect 1.2 to 1.35 better luminosity with present limitations
    - 30 cm β^* is more difficult than 55 cm of the present LHC. Better solution found with β^* = 40 cm offering a 3 sigma margin per beam (which was part of the initial goal) but only 1.2 gain in lumi over nominal. Today we are limited by a single element. IR upgrade will use all the margins in the whole ring.
  - Radiation damage not an issue till 2020 with evolution now expected
  - In any case the Triplet cannot be built before 2016 at best (resources)

New study underway

- **High Gradient/Large Aperture Quads, with B_{peak} 13-15 T.** US-LARP engaged to produce proof using Nb_3Sn by 2013. Construction is 1 year more than Nb-Ti : 2018 is a reasonable assumption. Nb-Ti remains as a backup solution.

- Higher field quadrupoles translate into
  - higher gradient/shorter length
  - larger aperture/same length
  - or a mix of the two

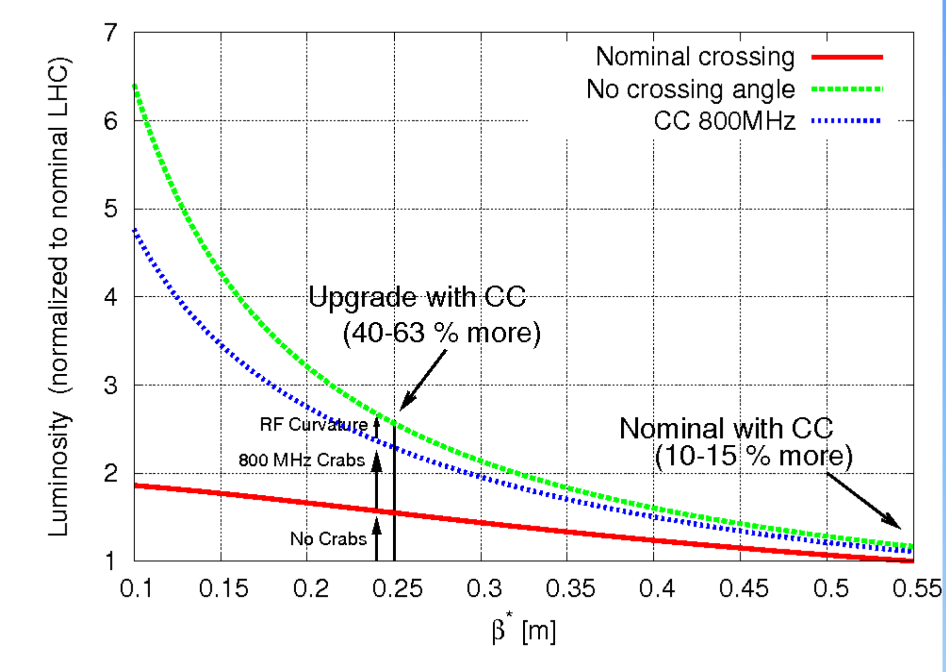
- β^* as small as 22 cm are possible with a **factor ~2.5** in luminosity by itself, **if coupled with a mechanism to compensate the geometrical reduction**

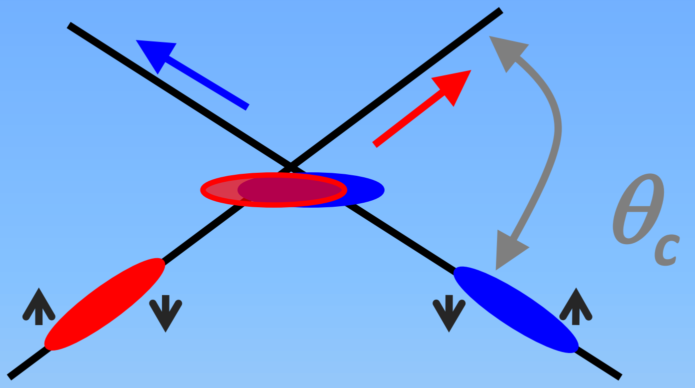
- **Crab Cavities**: this is the best candidate for exploiting small β^* (for β^* around nominal only +15%). However it should be underlined that today Crab Cavities are not validated for LHC , not even conceptually: **the issue of machine protection should be addressed with priority**

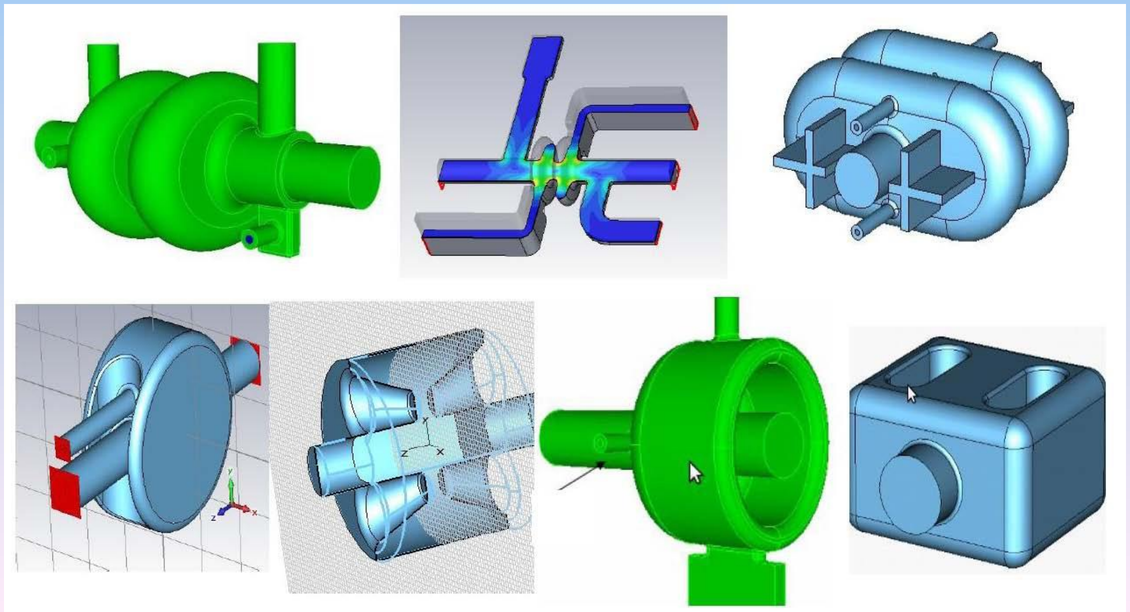
- **SC links** to replace at the surface electronic equipment today in the tunnel and exposed to high radiation

- **New Cryoplants** in IP1 & IP5: for power AND to make independent Arc- IR: 2.8 kW @ 1.8 K scales as 5.2 kW @ 2 K (for 1 set of cold compressor)

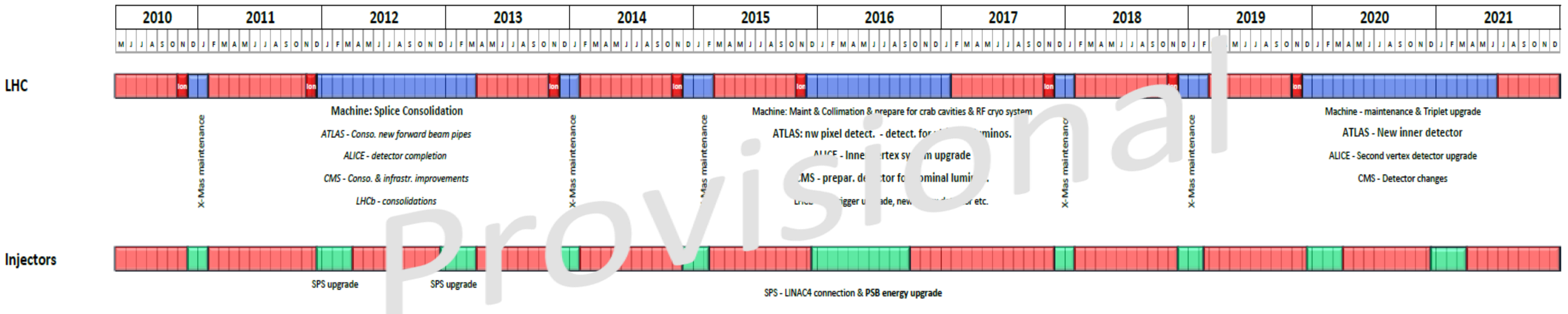
Crab cavities for exploiting low β^*







Provisional route to achieving all this



Shutdowns

	2012	2016	2020
LHC machine	Splices for 7 TeV Collimators in IR3 R2E driven modifications	Collimation phase II Prepare for crab cavities New RF cryogenic system	New Triplets Crab cavities
LHC experiments	ALICE – TID and calorimeter ATLAS – forward beam pipes CMS – infrastructure LHCb – conical beam pipe	Assuming 30 to 50 fb^{-1} ALICE – new vertex detector ATLAS – pixel detector + upgrades CMS – many improvements LHCb – full trigger upgrade, new vertex detector	Assuming 300 to 600 fb^{-1} ALICE – vertex detector upgrade ATLAS – new inner detector CMS – new inner detector LHCb –
Injectors	In two 3-4 month shutdowns • Preparations for PSB energy upgrade • SPS upgrade	Linac 4 connection to PSB Completion of PSB energy upgrade for 2 GeV operation PS and SPS consolidation	Consolidation of all machines in 3-4 month injector shutdowns

HE-LHC

"First Thoughts on a Higher-Energy LHC"

Ralph Assmann, Roger Bailey, Oliver Brüning, Octavio Dominguez Sanchez, Gijs de Rijk, Miguel Jimenez, Steve Myers, Lucio Rossi, Laurent Tavian, Ezio Todesco, Frank Zimmermann

Abstract:

We report preliminary considerations for a higher-energy LHC ("HE-LHC") with about 16.5 TeV beam energy and 20-T dipole magnets. In particular we sketch the proposed principal parameters, luminosity optimization schemes, the new HE-LHC injector, the magnets required, cryogenics system, collimation issues, and requirements from the vacuum system.

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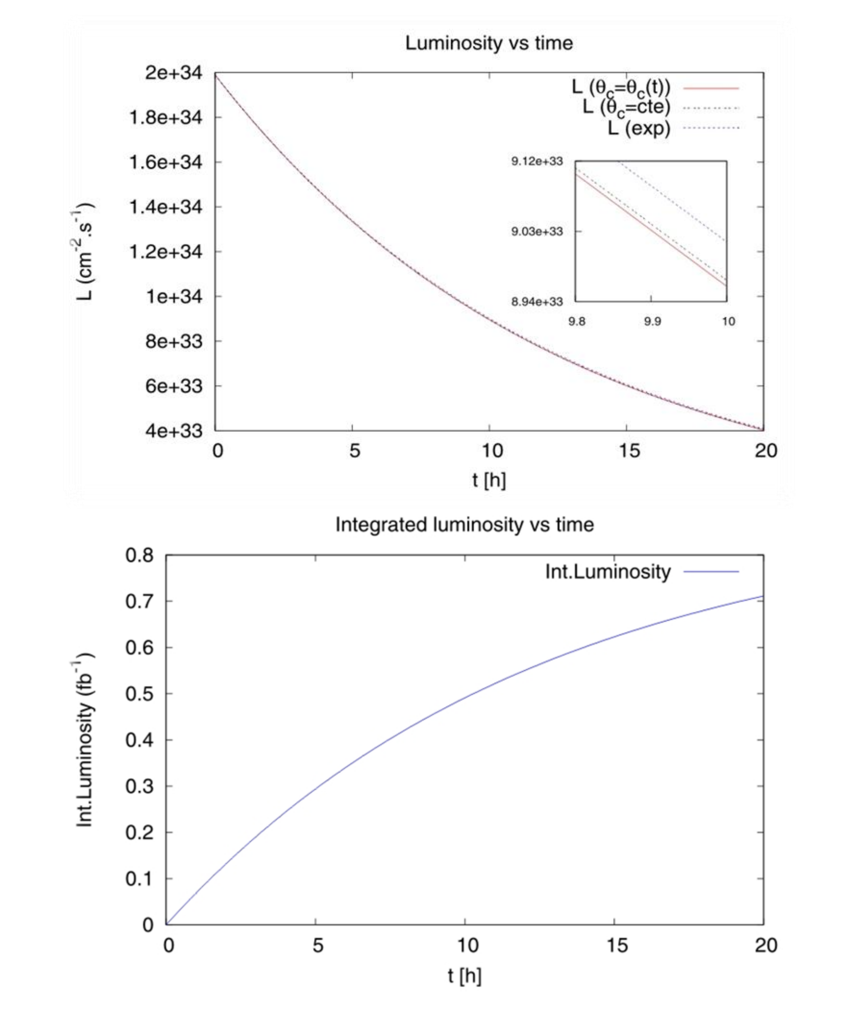


EuCARD-AccNet mini-workshop on a higher-energy LHC
"HE-LHC'10" –14-16 October '10, Malta

HE-LHC

Provisional parameter list for LHC energy upgrade at 33 TeV centre-of-mass energy

	nominal LHC	LHC energy upgrade
beam energy [TeV]	7	16.5
dipole field [T]	8.33	20
dipole coil aperture [mm]	56	40
beam half aperture [cm]	2.2 (x), 1.8 (y)	1.3
#bunches	2808	1404
bunch population [10^{11}]	1.15	1.29
initial transverse normalized emittance [μm]	3.75	3.75, 1.84
initial longitudinal emittance [eVs]	2.5	4.0
number of IPs contributing to tune shift	3	2
initial total beam-beam tune shift	0.01	0.01 (x & y)
maximum total beam-beam tune shift	0.01	0.01
RF voltage [MV]	16	32
rms bunch length [cm]	7.55	6.5
rms momentum spread [10^{-4}]	1.13	0.9
IP beta function [m]	0.55	1 (x), 0.43 (y)
initial rms IP spot size [μm]	16.7	14.6 (x), 6.3 (y)
full crossing angle [μrad]	285 (9.5 $\sigma_{x,y}$)	175 (12 σ_{x0})
Piwinski angle	0.65	0.39
geometric luminosity loss from crossing	0.84	0.93
stored beam energy [MJ]	362	478.5

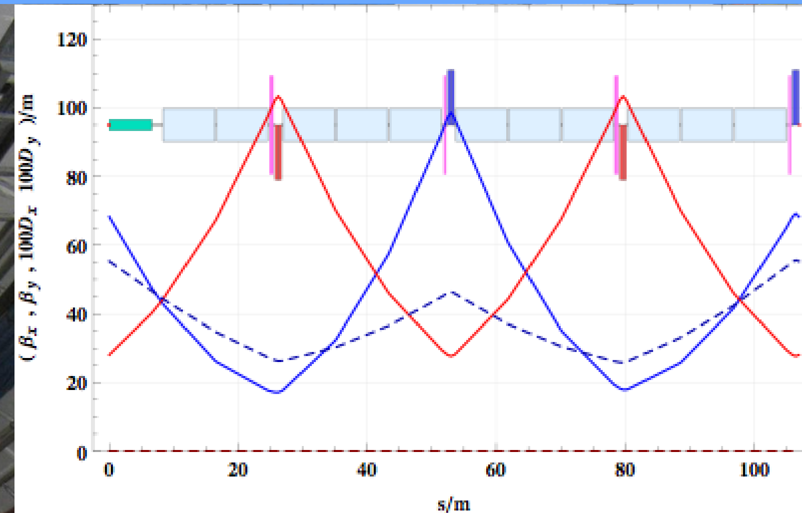
LHeC

- 2 options on the table
  - Ring-Ring
    - e-p and e-A (A=Pb, Ar, …) collisions, limited possibilities for polarized e
    - More "conventional" solution, like HERA, no difficulties of principle at first sight but constrained by existing LHC in tunnel
    - Steady progress with detailed design
  - Linac-Ring
    - e-p and e-A (A=Pb, Ar, …) collisions, polarized e from source, poorer Luminosity/Power
    - No previous collider like this (at present)
    - Comparisons of layouts

Ring-Ring

- No interference with LHC
- Meets design parameters
- Synchrotron radiation energy loss < 50 MW (maximum dipole filling)
- 2 quadrupolesfamilies
- Reasonable sextupole strength and length

- Dedicated injector at 10GeV

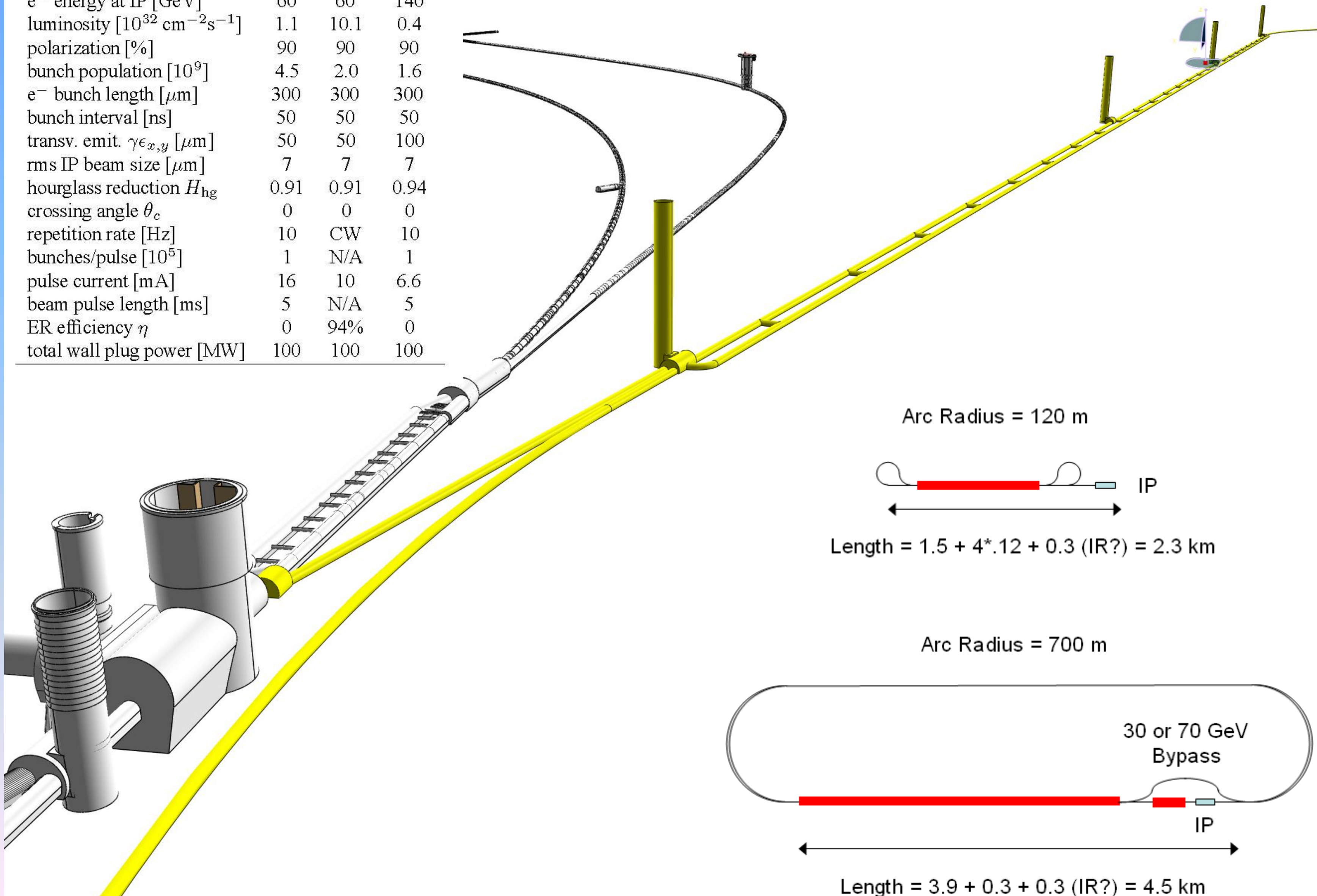


$$10^{33}\, cm^{-2} s^{-1}, \int L = 100\ fb^{-1}, E_e = 60\, GeV$$

Linac-Ring

Table 4: Lepton beam parameters and luminosity.

	p-60	erl	p-140
e^- energy at IP [GeV]	60	60	140
luminosity [10^{32} cm^{-2}s^{-1}]	1.1	10.1	0.4
polarization [%]	90	90	90
bunch population [10^9]	4.5	2.0	1.6
e^- bunch length [μm]	300	300	300
bunch interval [ns]	50	50	50
transv. emit. $\gamma\epsilon_{x,y}$ [μm]	50	50	100
rms IP beam size [μm]	7	7	7
hourglass reduction H_{hg}	0.91	0.91	0.94
crossing angle θ_c	0	0	0
repetition rate [Hz]	10	CW	10
bunches/pulse [10^5]	1	N/A	1
pulse current [mA]	16	10	6.6
beam pulse length [ms]	5	N/A	5
ER efficiency η	0	94%	0
total wall plug power [MW]	100	100	100



Summary

- Clear goals for 2010 and 2011
- Route to nominal pretty clear (E, k_b, β^*)
  - Needs collimation upgrade in 2012
- Pragmatic upgrade of the injectors for around 2016
  - Linac 4, upgraded booster
- Single upgrade of the HL IRs around 2020
- Planning will be finalised during second half of 2010
  - Ongoing HL-LHC task force (Chamonix 2011 if not before)
  - Ongoing HE-LHC study group (Chamonix 2011 if not before)
  - Ongoing LHeC machine study group (CDR Q4 2010)