LHC Machine Upgrades

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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^*

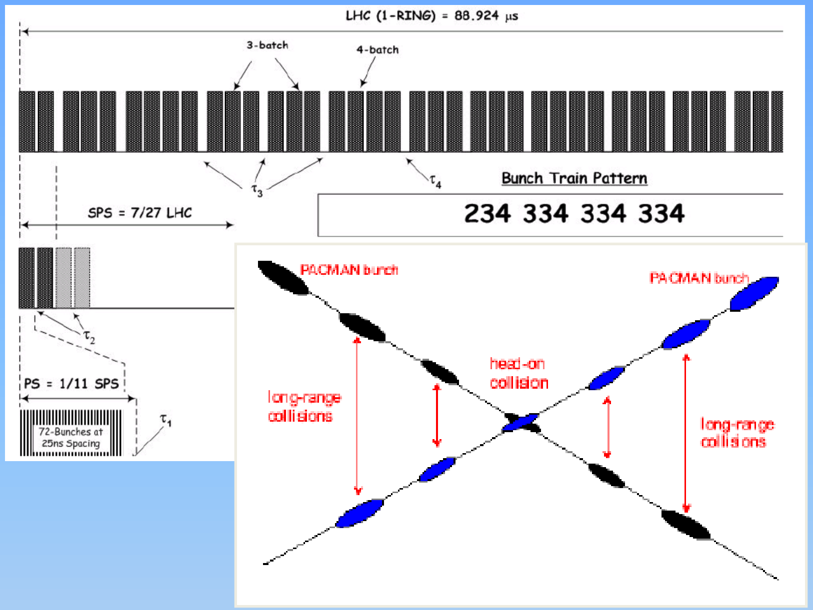
$$F = 1/\sqrt{1 + \left(\frac{\theta_c\sigma_z}{2\sigma^*}\right)^2}$$

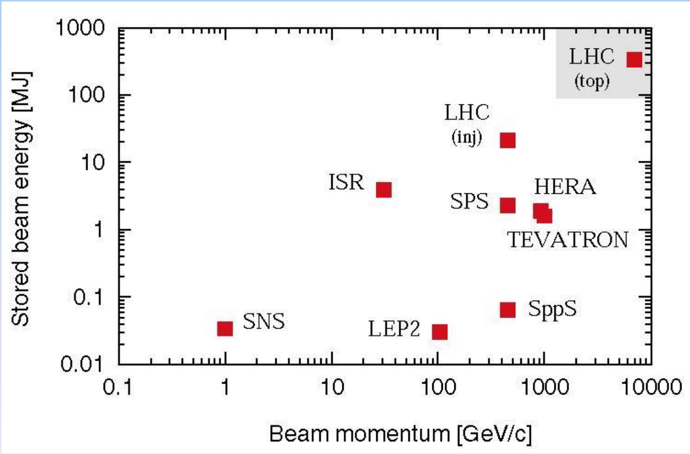
LHC nominal performance

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

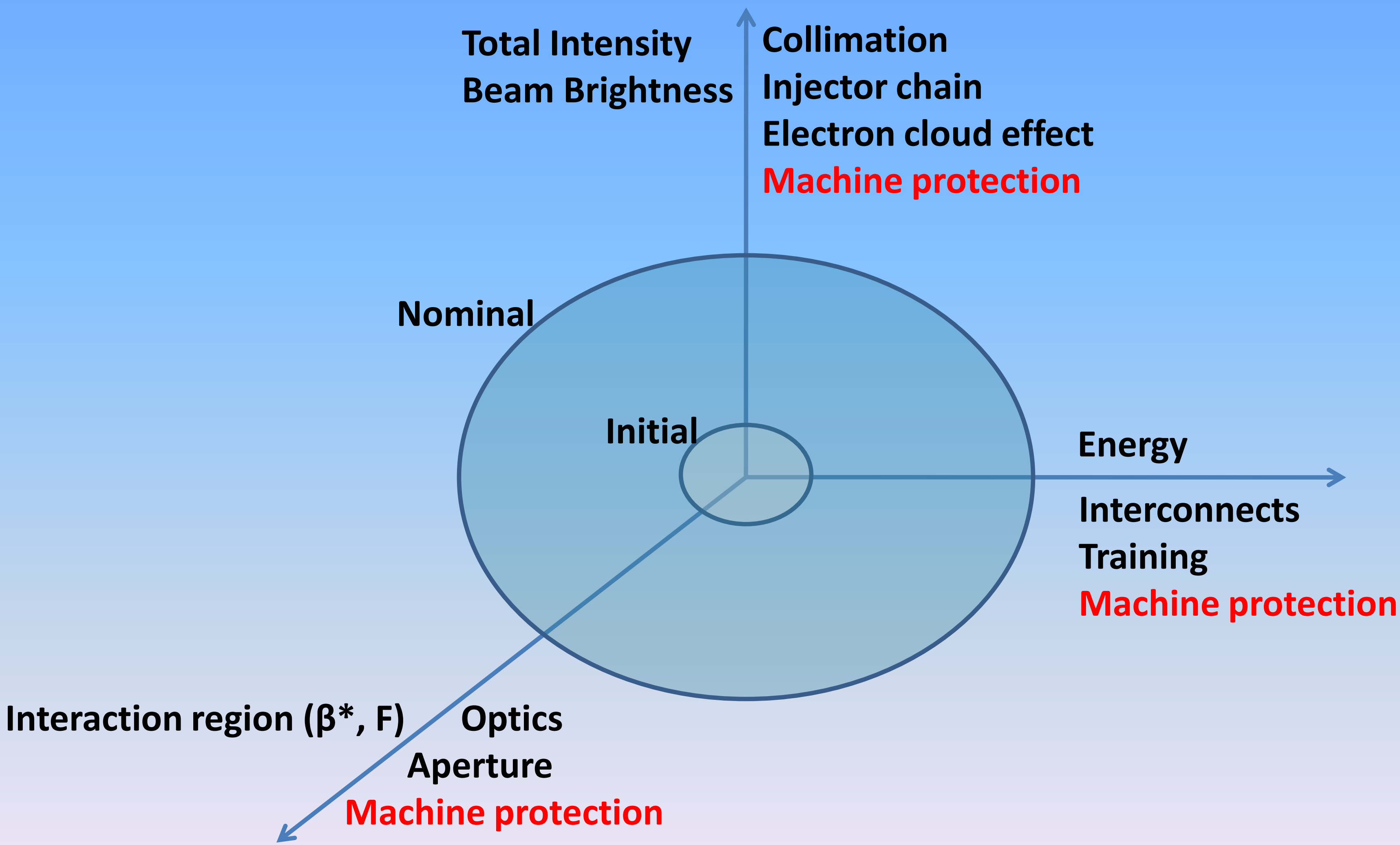
Derived parameters	
Luminosity in IP 1 & 5 ($cm^{-2}\ s^{-1}$)	10^{34}
Luminosity in IP 2 & 8 ($cm^{-2}\ s^{-1}$)*	$\sim 5\ 10^{32}$
Transverse beam size at IP 1 & 5 (μm)	16.7
Transverse beam size at IP 2 & 8 (μm)	70.9
Stored energy per beam (MJ)	362

* Luminosity in IP 2 and 8 optimized as needed





LHC performance drivers



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

Energy	Current	When	Why
7 TeV	12 kA	2002-2007	Design
5 TeV	9 kA	Summer 2008	Detraining
		Late 2008	Splices
3.5 TeV	6 kA	Summer 2009	Stabilizers
1.18 TeV	2 kA	October 2009	nQPS

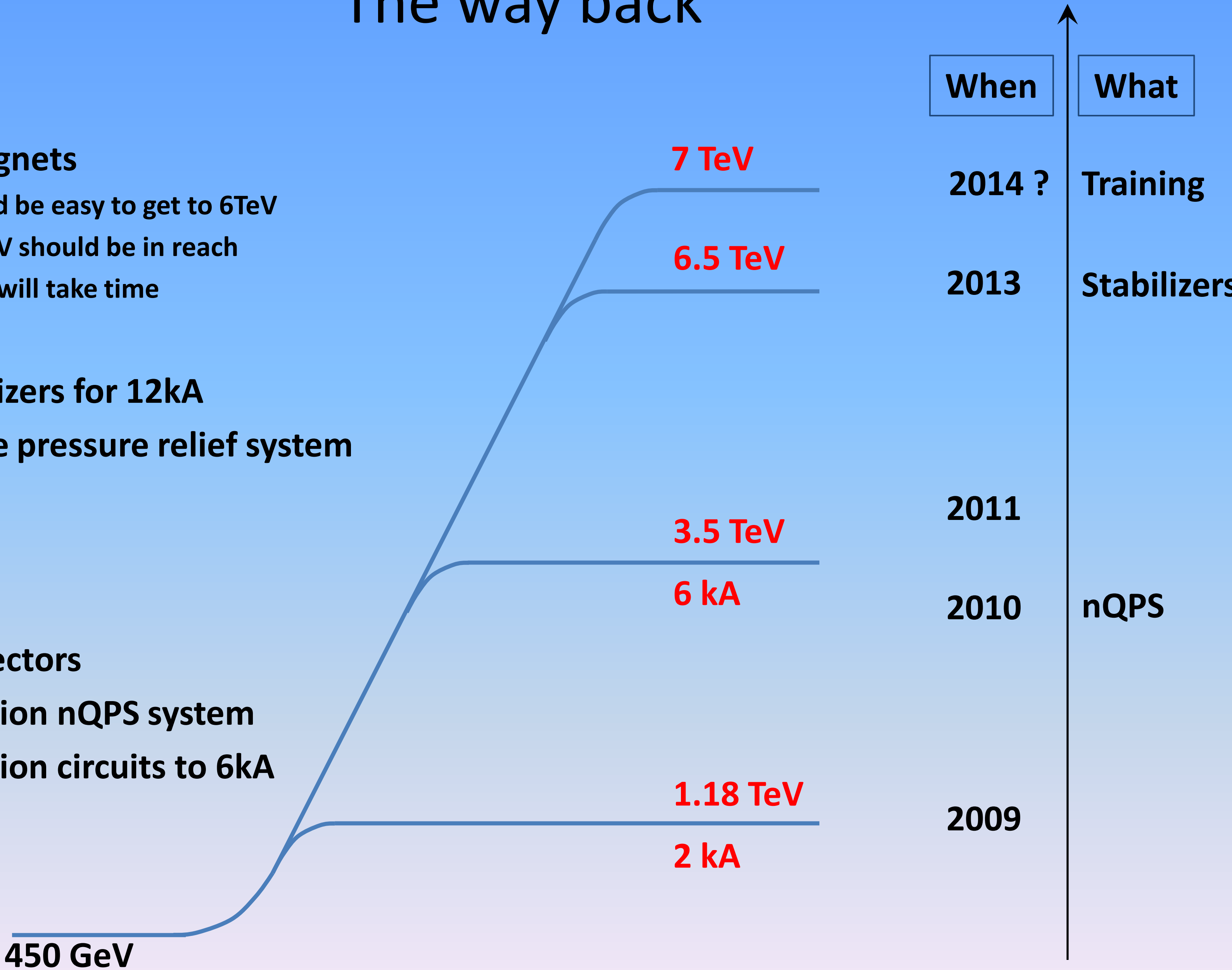
450 GeV

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

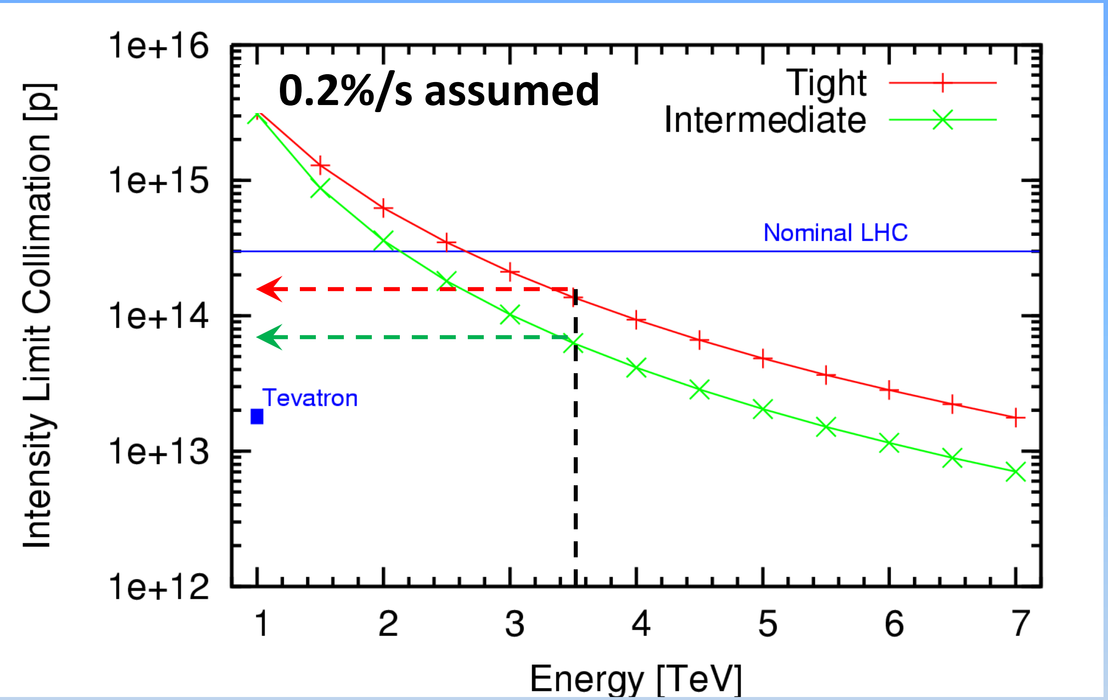
- Fix connectors
- Commission nQPS system
- Commission circuits to 6kA



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

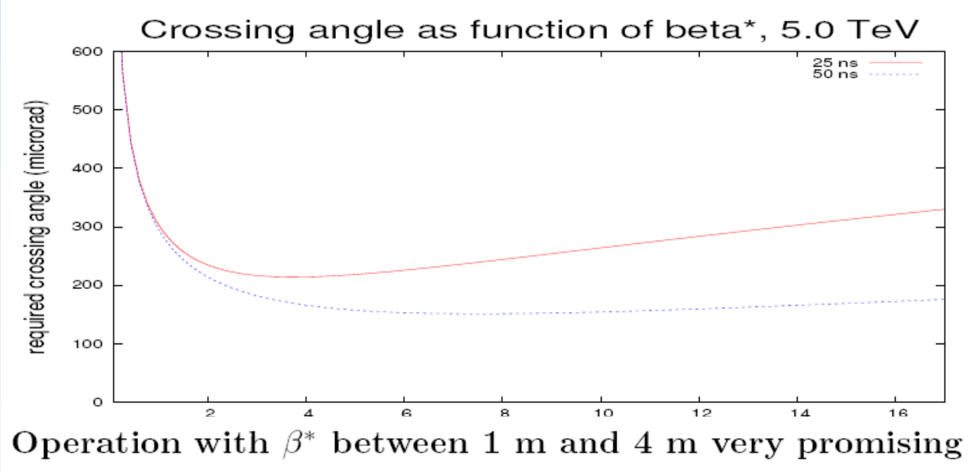
- At higher energies cleaning gets harder !!!

Higher intensities

- Limited in LHC by collimation system to ~ 20% at 3.5TeV
  - Under certain assumptions on loss rates, imperfections
  - Injectors can deliver nominal beams
- With experience assume that we can
  - Move to tight collimator settings
  - Improve loss rates
  - Get the imperfection factor down
    - Should allow to push to higher intensities (to ~40% nominal)
- 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)
    - Should allow us to get to nominal intensity at 7TeV
  - Phase II collimators installed in 2016 or so

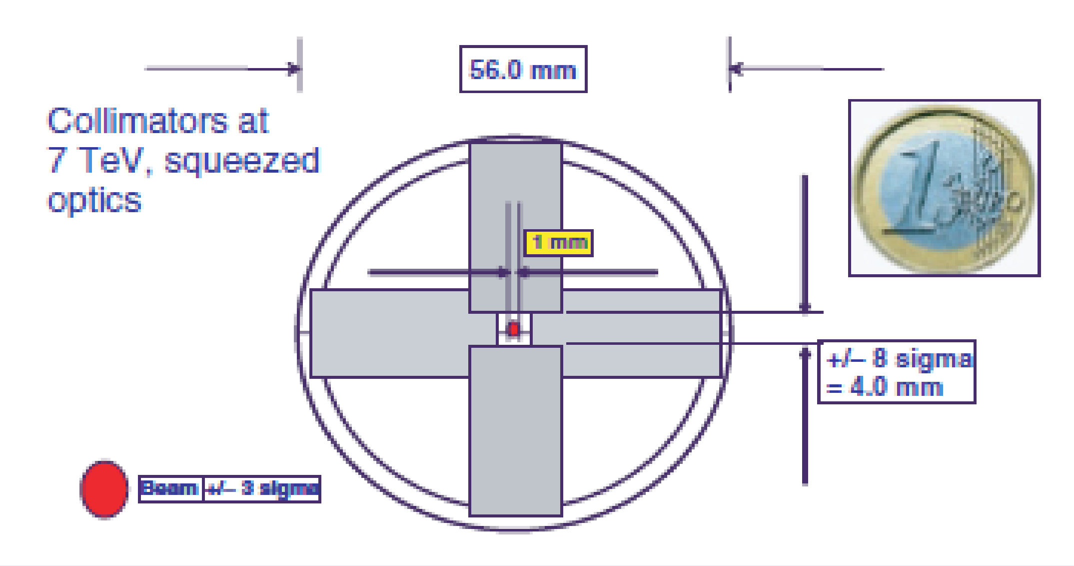
β* and F in 2010 2011

- 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}

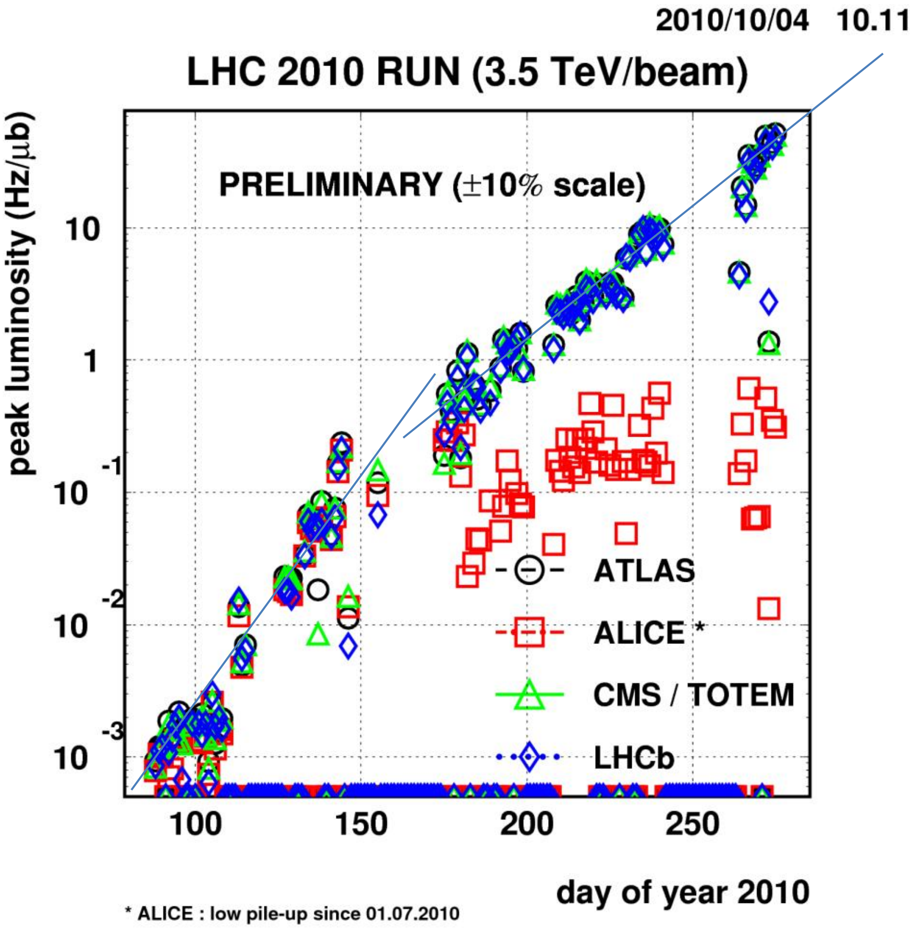
Energy	TeV	3.50	3.50	3.50	3.50
Bunch intensity	1.E+10	10.0	10.0	10.0	10.0
Bunches per beam		4	36 (48)	432	792
Emittance	µm	3.75	3.75	3.75	3.75
β*	m	3.50	3.50	3.50	3.50
Luminosity 1 and 5	cm-2 s-1	1.0E+30	9.0E+30	1.1E+32	2.0E+32
Total inel X section	cm2	6.0E-26	6.0E-26	6.0E-26	6.0E-26
Event rate	Hz	6.1E+04	2.4E+05	6.5E+06	1.2E+07
Event rate / Xing	Hz	1.4	1.3	1.3	1.3
Protons		4.0E+11	4.8E+12	4.3E+13	7.9E+13
% nominal		0.1	1.5	13.4	24.5
Current	mA	0.7	8.6	77.7	142.5
Stored energy	MJ	0.2	2.7	24.2	44.4
Beam size 1 and 5	um	59.3	59.3	59.3	59.3

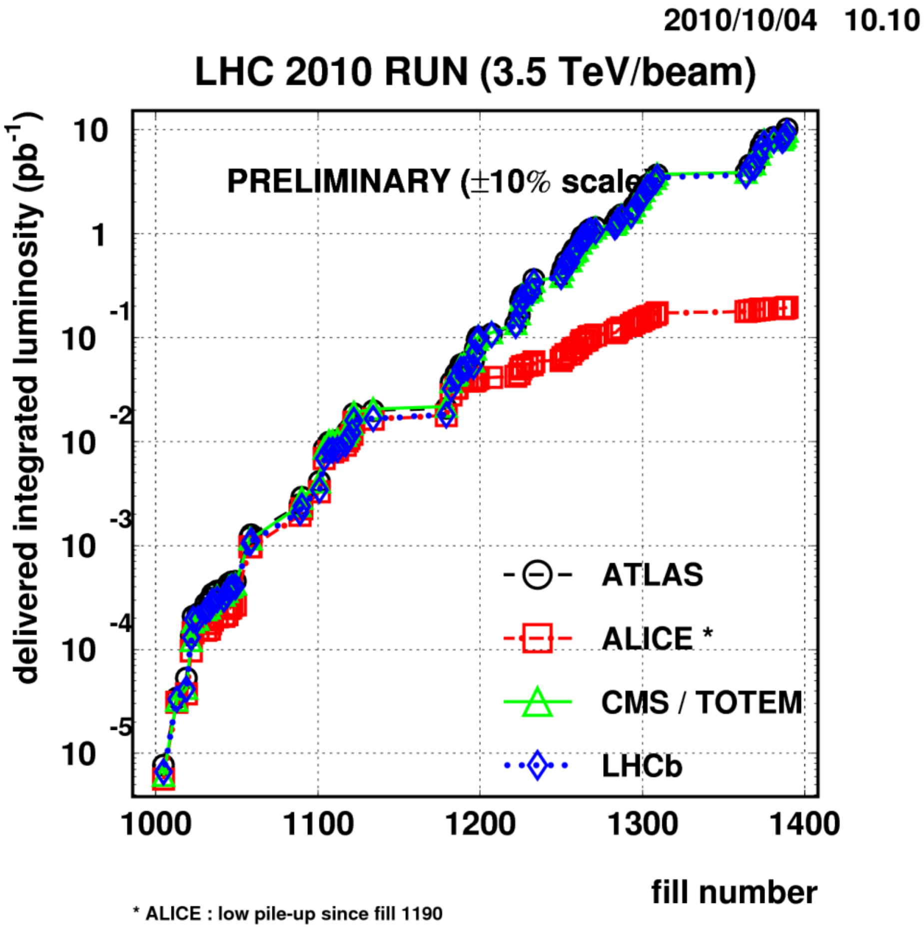
40% efficiency for physics → 10^6 seconds collisions per month

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

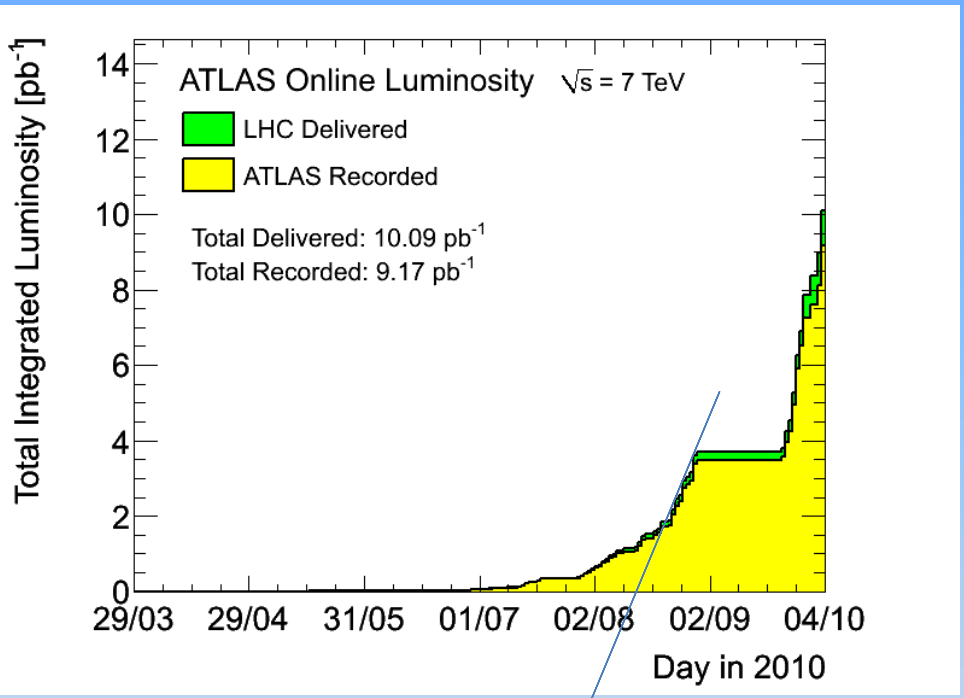
Luminosity evolution

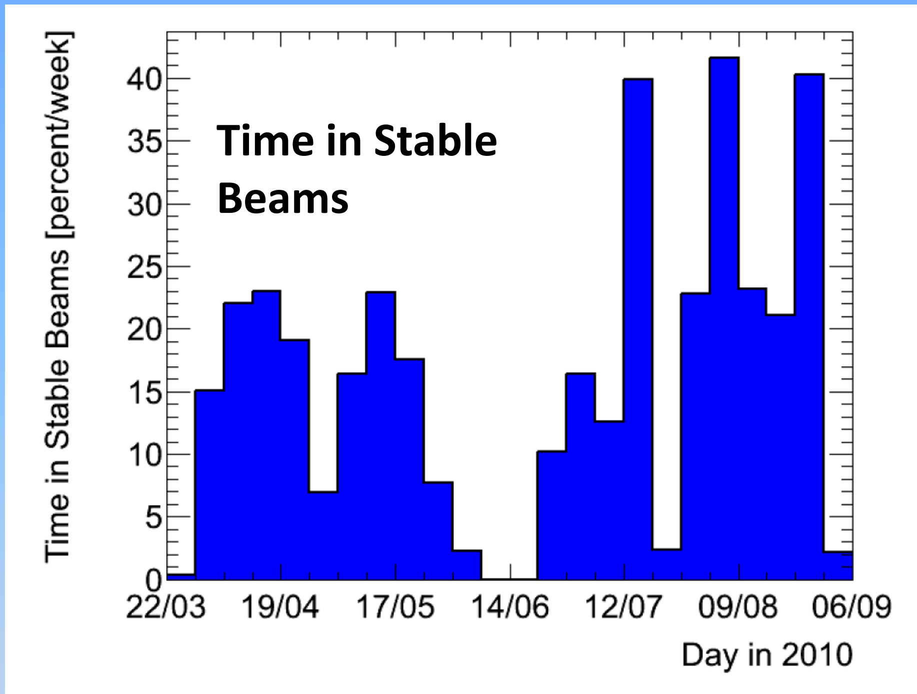
4 orders of magnitude in ~180 days





Efficiency for physics





$60 nb^{-1}$ per day

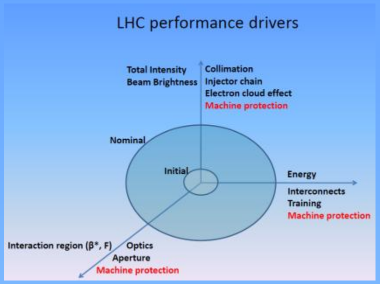
$< \mathcal{L} >$ ~$1.5\ 10^{30}$

10h physics per day

40% efficiency

Getting to nominal (dates indicative)

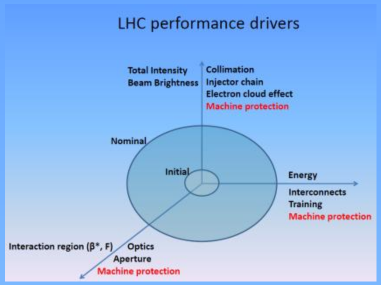
$$L = \frac{N^2 k_b f}{4\pi\sigma_x\sigma_y} F = \frac{N^2 k_b f\gamma}{4\pi\varepsilon_n\beta^*} F$$



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

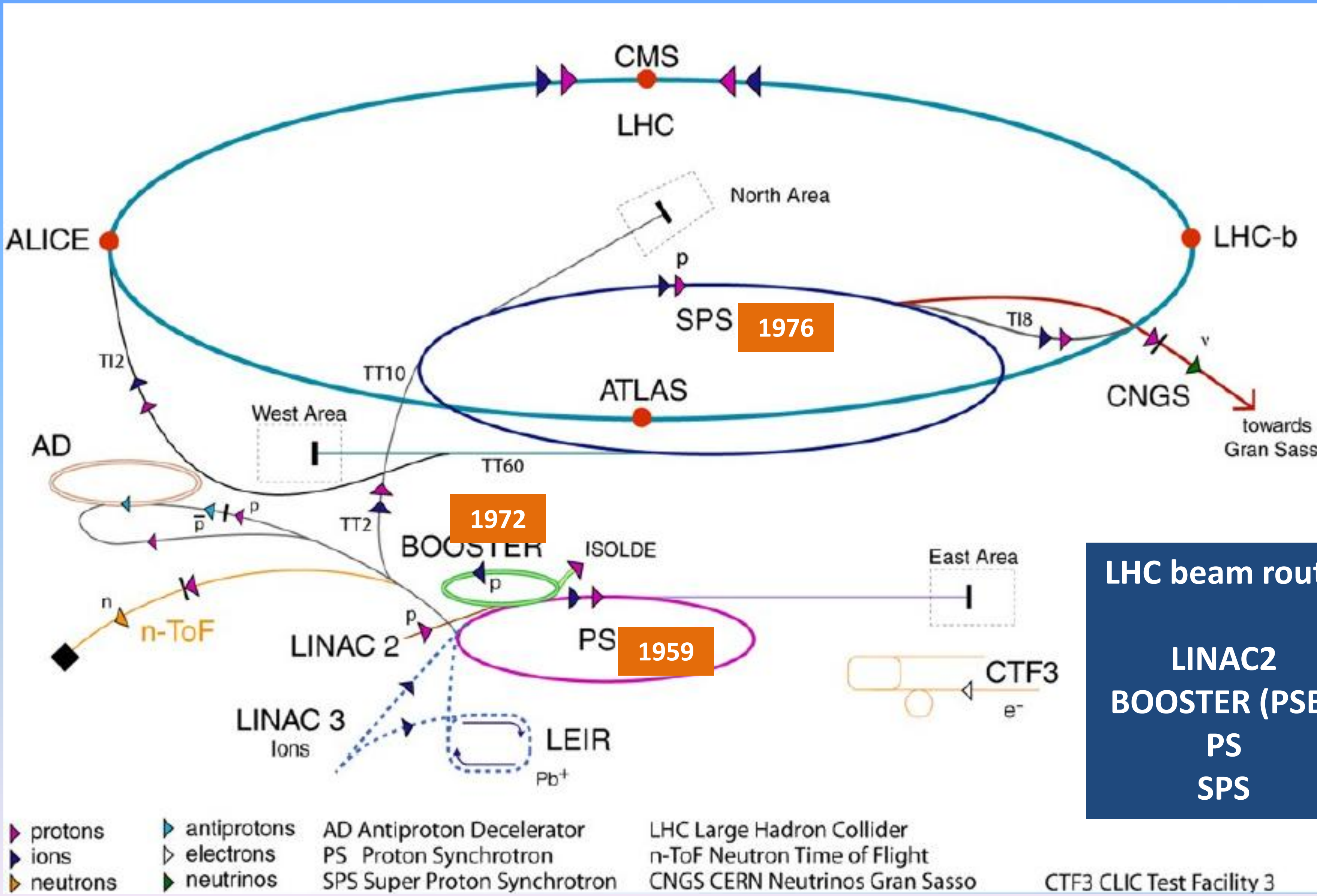
Overall strategy beyond 2016 (dates indicative)

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



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 (β*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

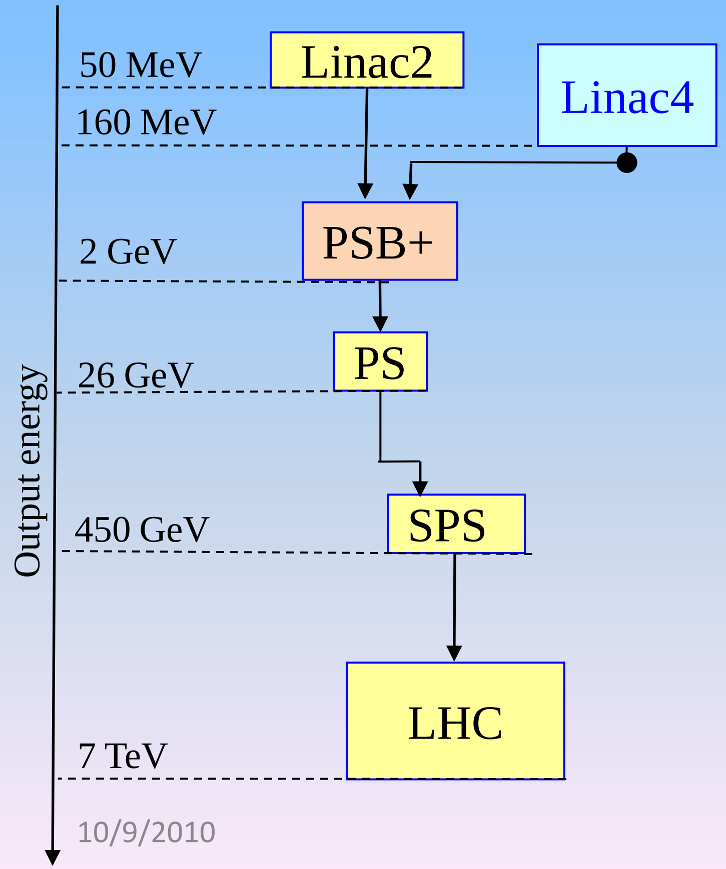
R : mean radius of the accelerator

$\beta\gamma$: classical relativistic parameters

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

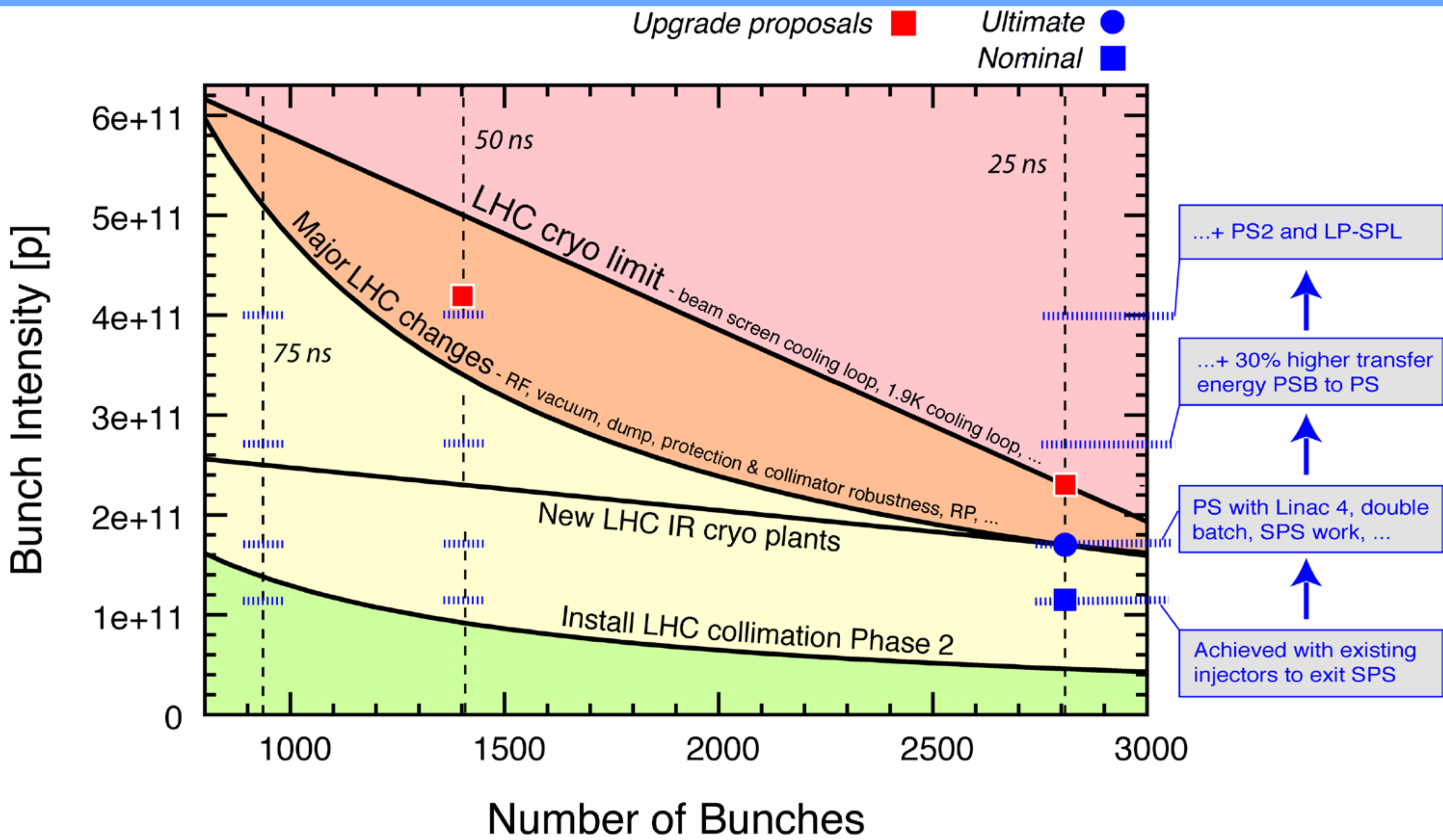
Strategy for injector chain upgrade

- Replace Linac 2 with Linac 4
- Consolidate all machines
- Upgrade PSB energy to 2 GeV (PSB+)
- Realistic planning OK for 2015

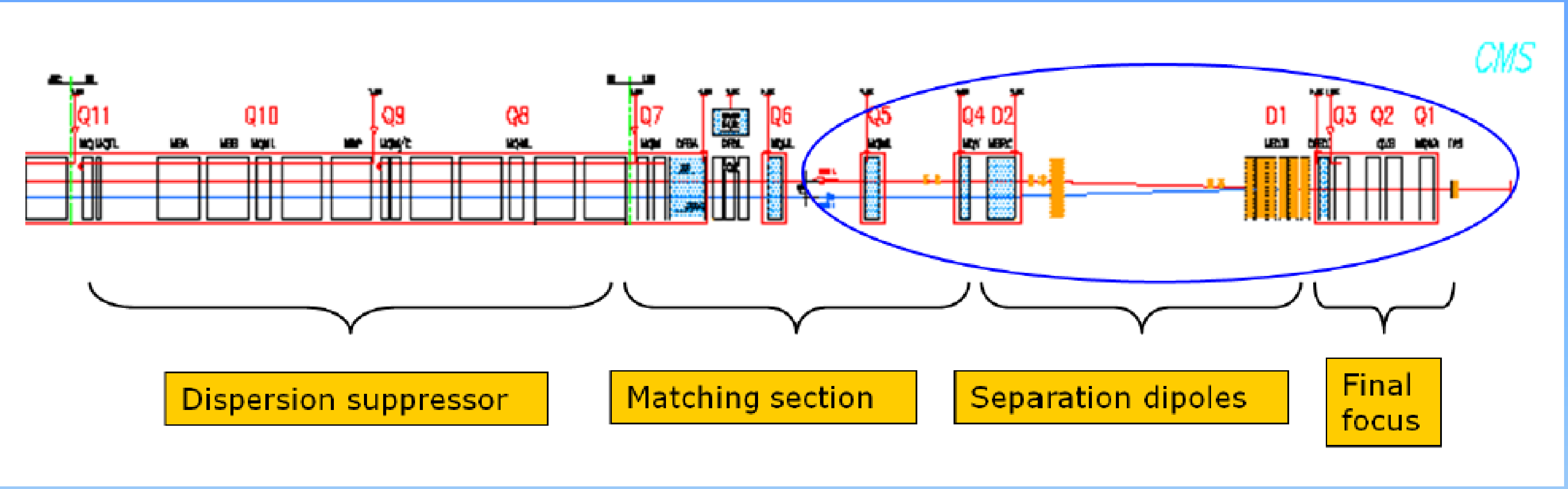


Intensity Limitations (10^{11} protons per bunch)	
Nominal = 1.15 (for 10^{34}) Ultimate = 1.7 (for $2.3x10^{34}$)	
Machine	Bunch intensity delivered (10^{11})
Linac4	4.0
PSB+	3.6
PS	3.0
SPS	2.5
LHC	1.7-2.3

Intensity limits in the LHC



High Luminosity Interaction Regions



- Original upgrade project (plan until 2010)
  - Phase I around 2015
  - Phase II around 2020
- New studies underway
  - High gradient large aperture quadrupoles
  - New thinking on machine optics limitations

Original upgrade project (phase I)

Goals of Phase I of the original upgrade project:

- flexibility & performance
- improve spares count
- cope with expected 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.

Key preliminary findings of recent review (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 intensity evolution now expected

– In any case the Triplet cannot be built before 2016 at best (resources)

High gradient large aperture quads

- **High Gradient/Large Aperture Quads, with B_{peak} 13-15 T.** US-LARP engaged to produce proof using Nb3Sn 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**

- **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)

New thinking on machine optics limitations

1. Replace 96 MB's in sectors 81/12/45/56 by shorter Nb3Sn dipoles equipped with strong sextupoles. Huge impact and very expensive.
2. Maximize the β function at the existing sextupoles, with a closed β -beat scheme. There is a large aperture margin in the arcs at 7 TeV, which means it is possible to increase the β by a factor of about 16.
   - Effectively the actual insertions IR1 and IR5 are replaced by two 7 km long low-β insertions containing
     - the low-β IRs proper (optically passive below a certain β^*)
     - two LHC sectors (chromatic correction sections)
     - two "auxiliary" insertions (resembling matching sections)

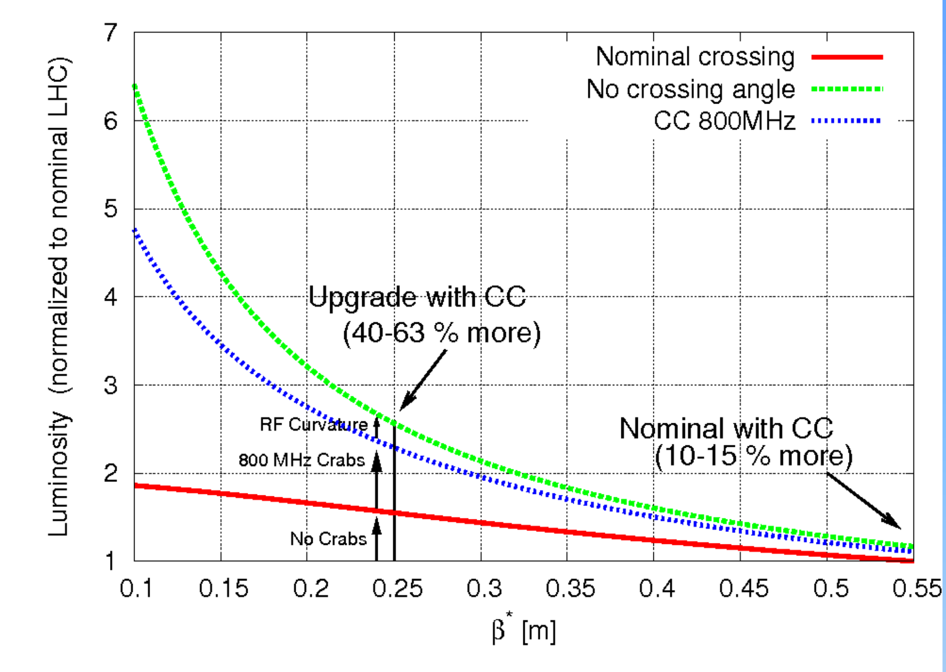
Injection optics: β^* = 14 m in IR1 and IR5 (round beam)

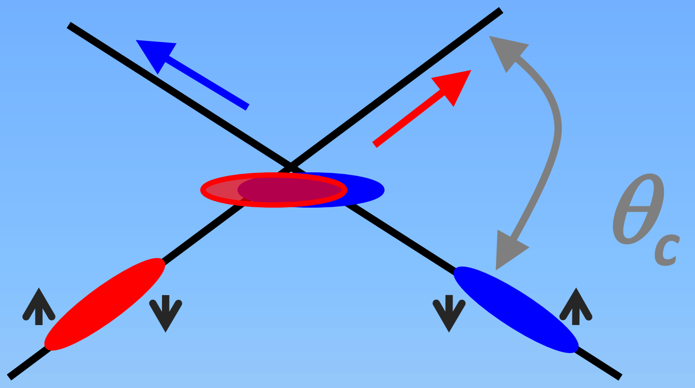
Pre-squeezed optics: β^* = 60 cm in IR1 and IR5 (round beams)

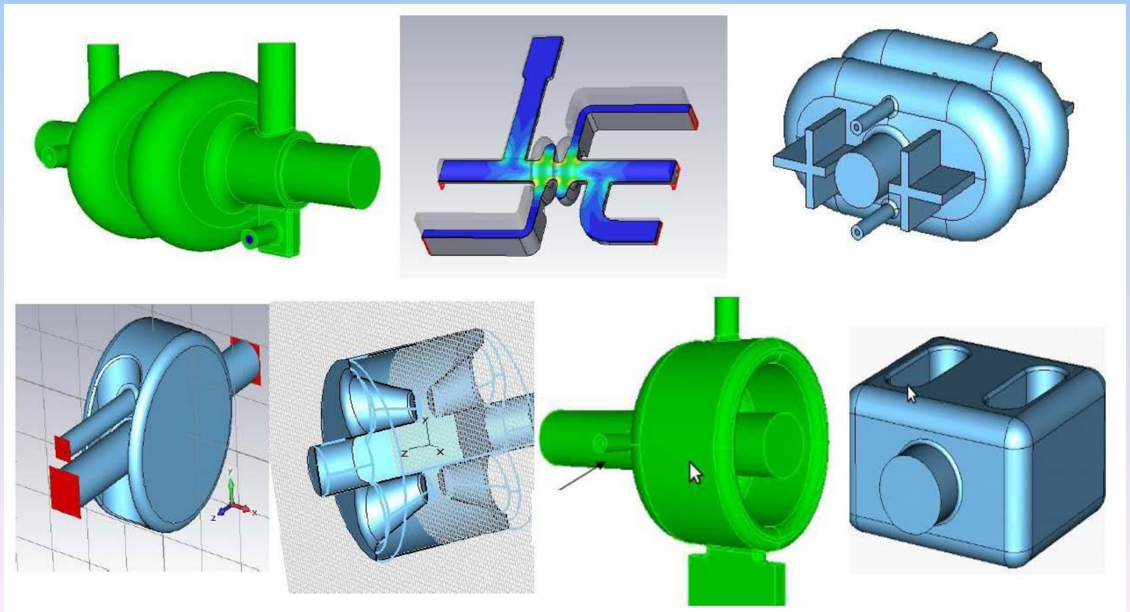
Intermediate squeezed optics: β^* = 30 cm in IR1 and IR5 (round beam)

Squeezed optics: $\beta^*_{x/y}$ = 7.5/30 cm (flat beam) alternated in IR1 and IR5

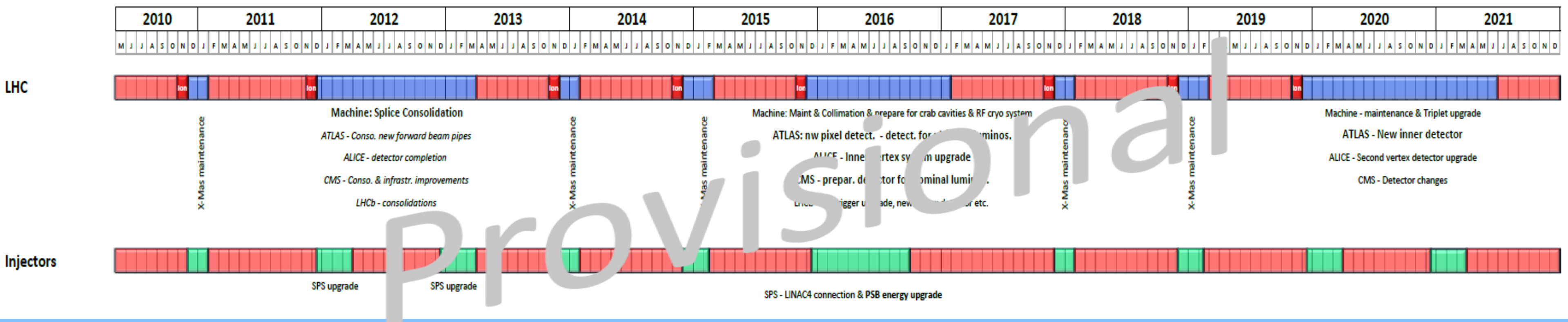
Crab cavities for exploiting low β^*







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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2. Luminosity optimization
3. Injector
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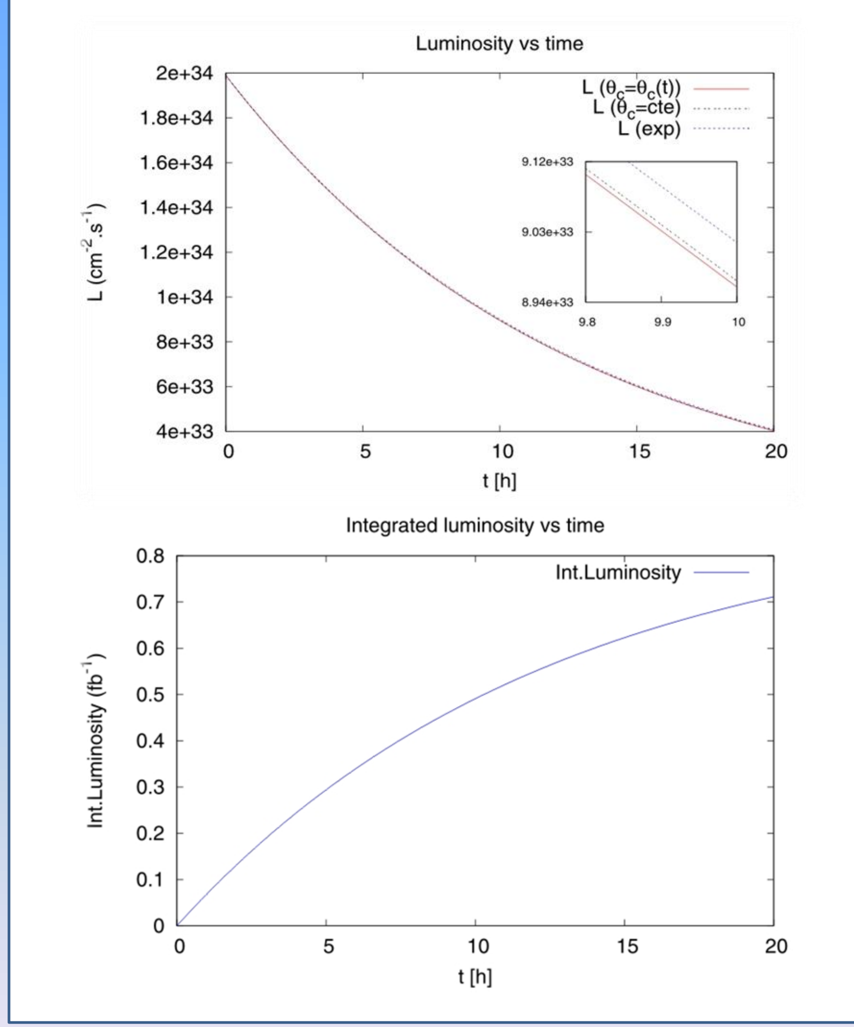
6. Vacuum system
7. Collimation issues



HE-LHC

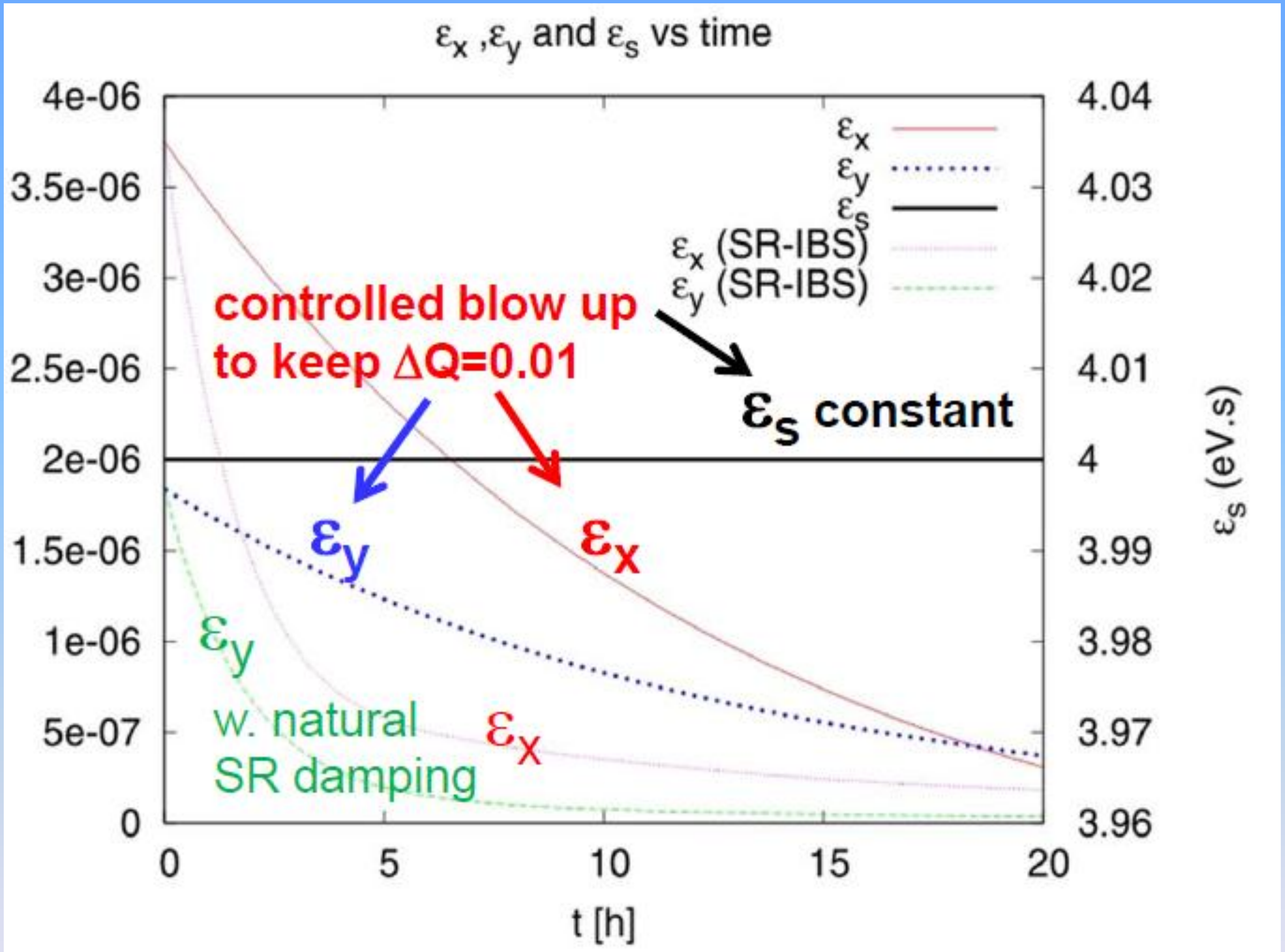
Provisional parameter list for LHC energy upgrade 33 TeV centre-of-mass energy

	nominal LHC	HE-LHC
beam energy [TeV]	7	16.5
dipole field [T]	8.33	20
dipole coil aperture [mm]	56	40
#bunches / beam	2808	1404
bunch population [10^{11}]	1.15	1.29
initial transverse normalized emittance [μm]	3.75	3.75 (x), 1.84 (y)
number of IPs contributing to tune shift	3	2
maximum total beam-beam tune shift	0.01	0.01
IP beta function [m]	0.55	1.0 (x), 0.43 (y)
full crossing angle [μrad]	285 (9.5 $\sigma_{x,y}$)	175 (12 σ_{x0})
stored beam energy [MJ]	362	479
SR power per ring [kW]	3.6	62.3
longitudinal SR emittance damping time [h]	12.9	0.98
events per crossing	19	76
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	2.0
beam lifetime [h]	46	13
integrated luminosity over 10 h [fb^{-1}]	0.3	0.5

HE-LHC

- Main issues
  - high-field 20-T dipole magnets based on Nb_3Sn, Nb_3Al, and HTS
  - high-gradient quadrupole magnets for arc and IR
  - fast cycling SC magnets for 1-TeV injector
  - emittance control in regime of strong SR damping and IBS
  - cryogenic handling of SR heat load (this looks manageable)
  - dynamic vacuum
- Provisional dates
  - 2022 start of 20-T magnet procurement
  - 2022-30 building/preparing new 1.3-TeV injector
  - 2030-33 installation of HE-LHC ring in LHC tunnel

Emittance control

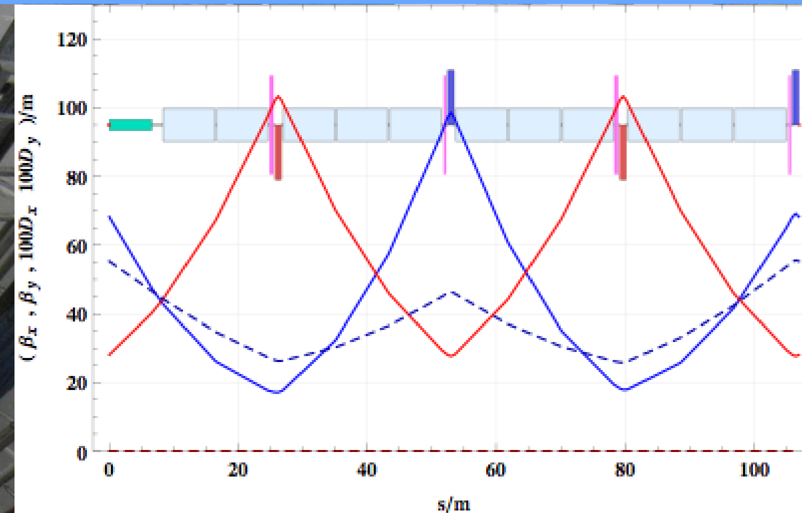


LHeC

- 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



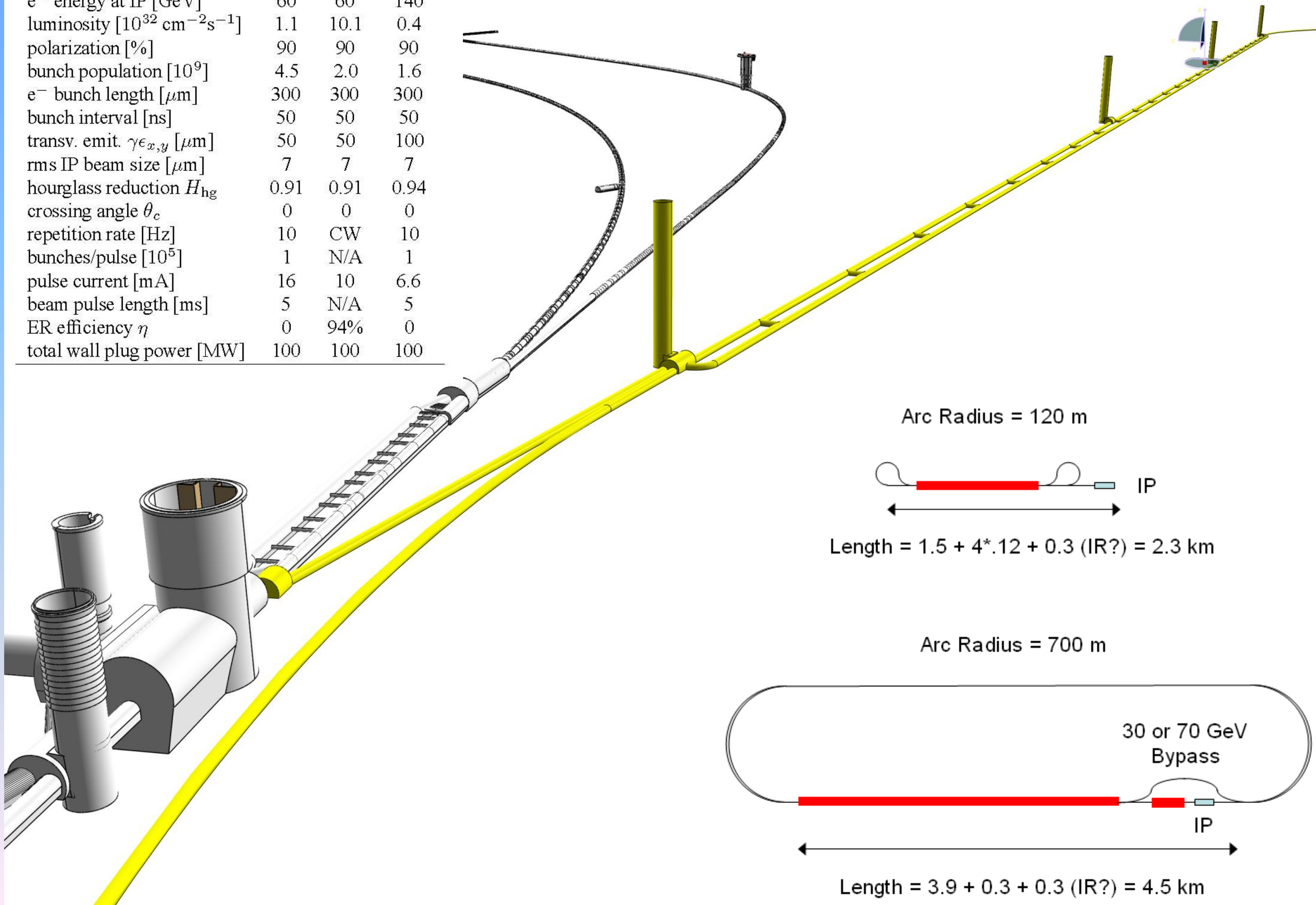
- Dedicated injector at 10GeV

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

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



Arc Radius = 120 m

Length = 1.5 + 4*.12 + 0.3 (IR?) = 2.3 km

Arc Radius = 700 m

Length = 3.9 + 0.3 + 0.3 (IR?) = 4.5 km

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
  - Optimum solution still to be defined
- 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)