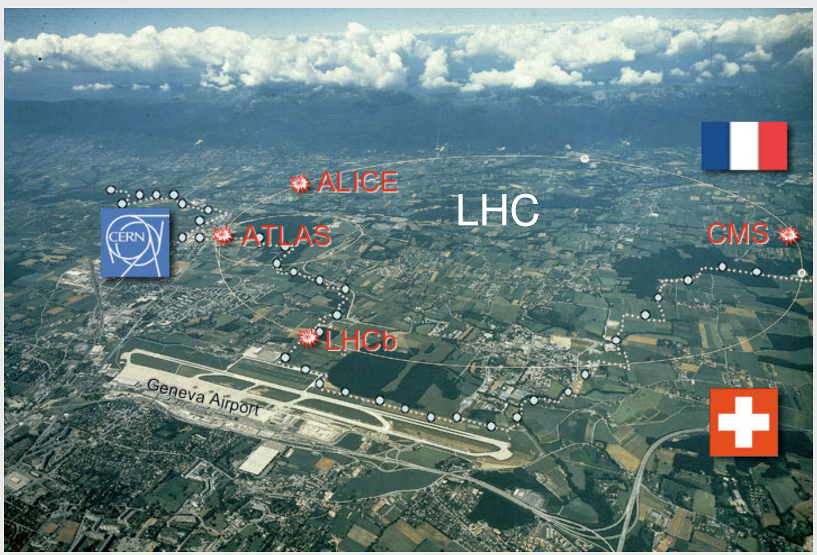
The LHC: Status and Outlook



Islamabad

October 15, 2009

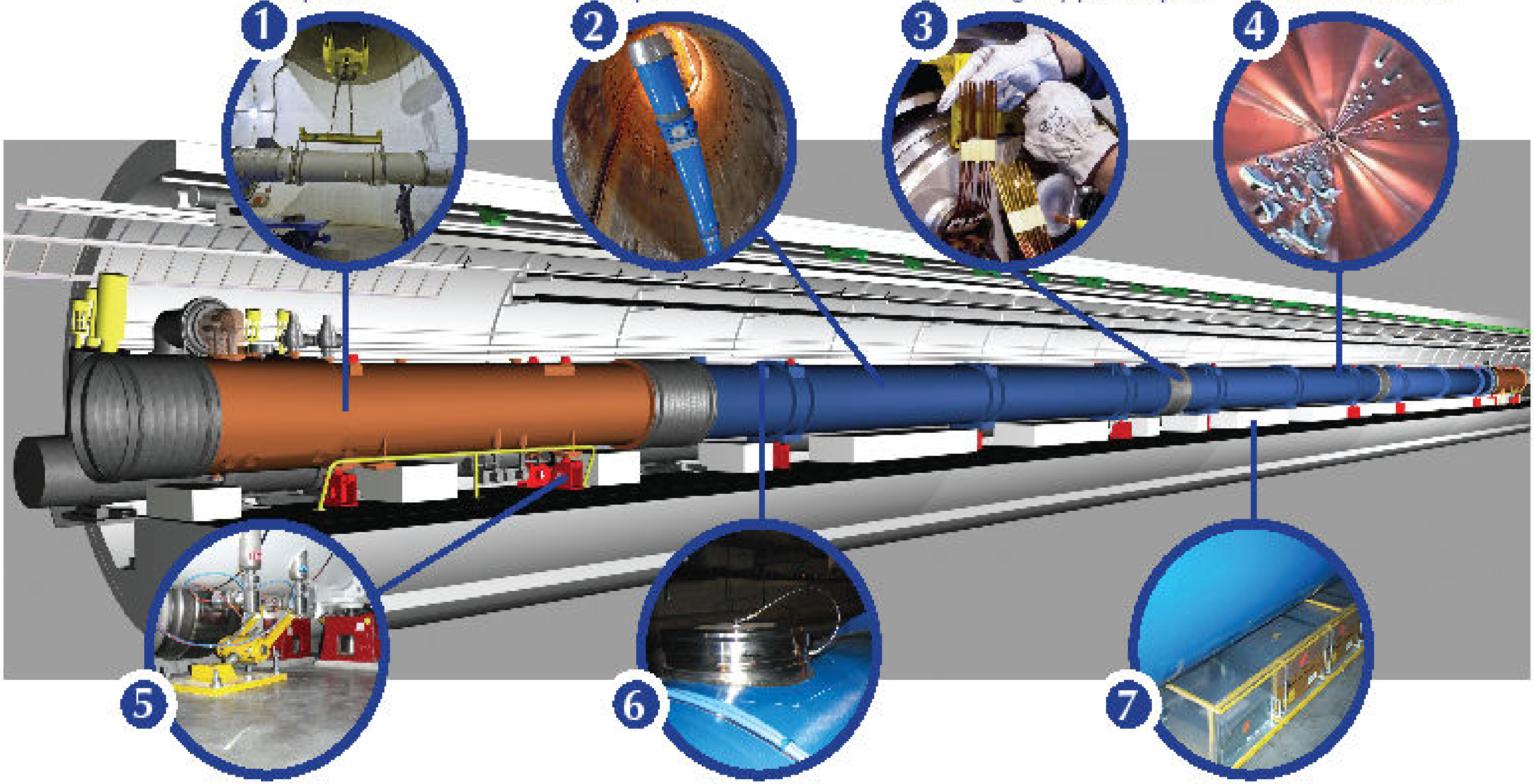
Sergio Bertolucci

CERN

Our agony and ecstasy: the LHC

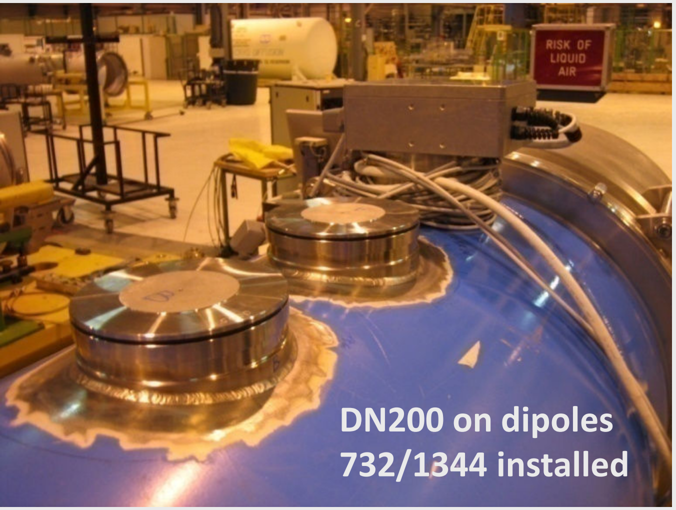
- **Status**
- Schedule
- Commissioning plans
- Early Physics
- **The future**

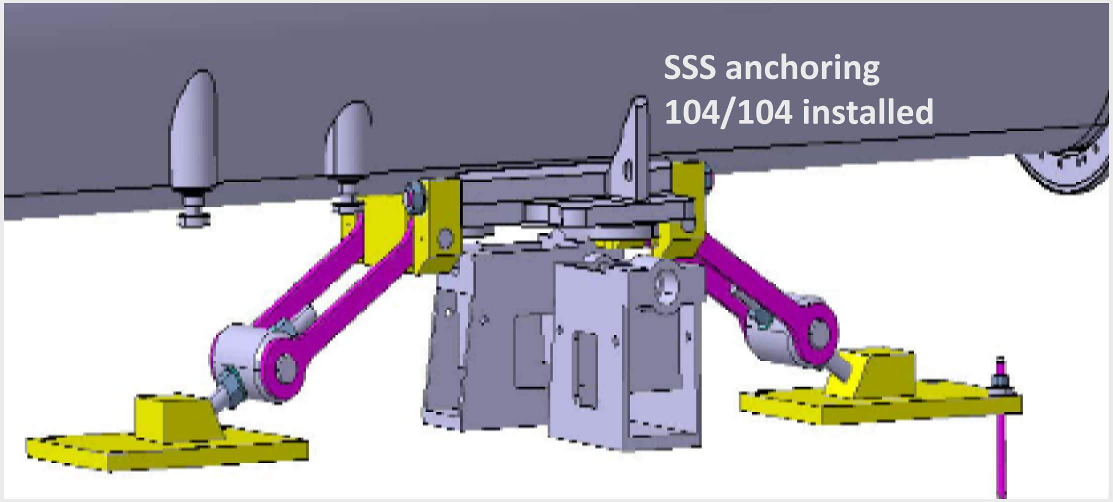
The LHC repairs in detail



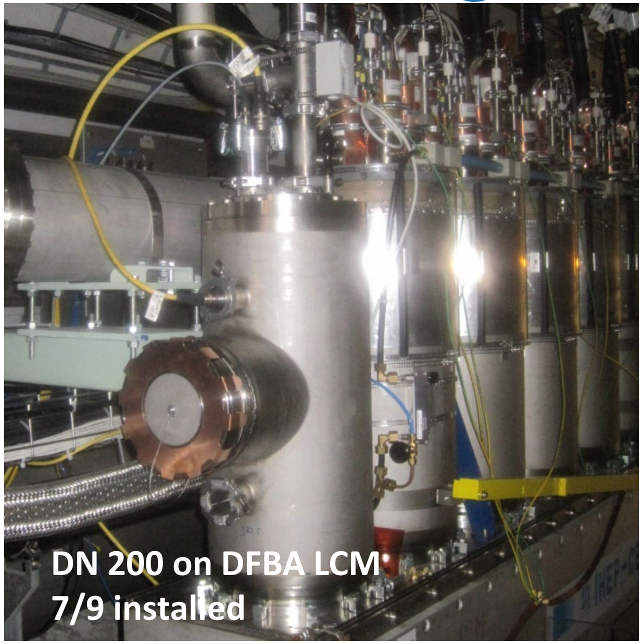
CERN

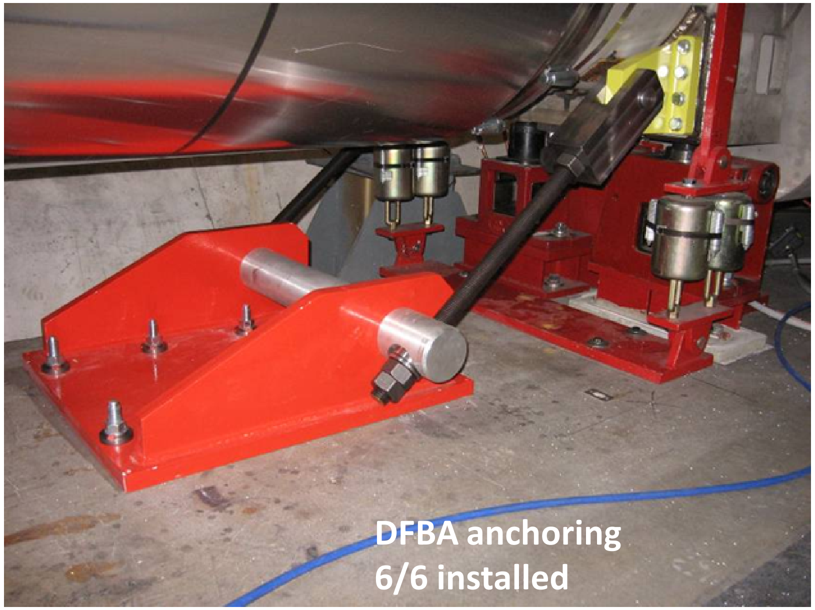
Magnet protection and anchoring





Magnet protection and anchoring





DSLC protection

Enhanced QPS

Role of the Enhanced QPS System

- **To protect against the new 'problems' discovered in 2008:**
  - The Aperture-Symmetric Quench feature in the Main Dipoles and
  - Defective Joints in the Main Bus-bars, inside or in-between the magnets.

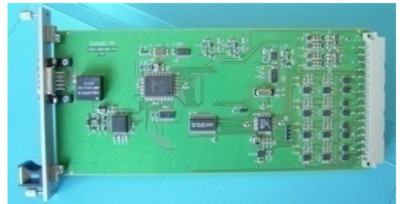
Reminder

- **QPS Upgrade also allows:**
  - **Precision measurements of the joint resistances at cold (sub-nΩ range) of every Busbar segment**. This will allow complete and **continuous** mapping of the splice resistances (the bonding between the s.c. cables)
  - To be used as the basic monitoring system for future determination of busbar resistances at warm (min. 80 K), to measure regularly the continuity of the copper stabilizers.

The nQPS project

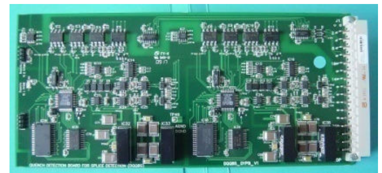
DQQTE board for ground voltage detection

(total 1308 boards, 3 units/crate)



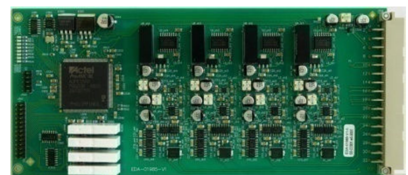
DQAMG-type S controller board

1 unit / crate, total 436 units



DQQBS board for busbar splice detection

5 such boards / crate, total 2180 units



DQQDS board for SymQ detection

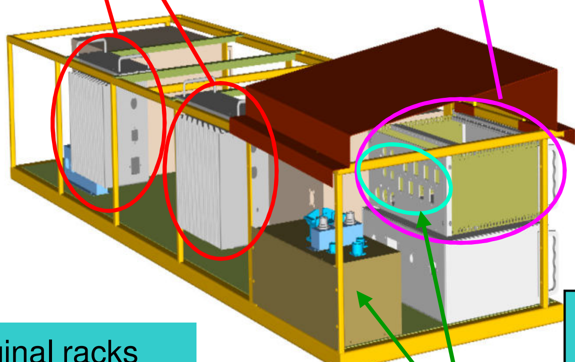
4 boards / crate, total 1744

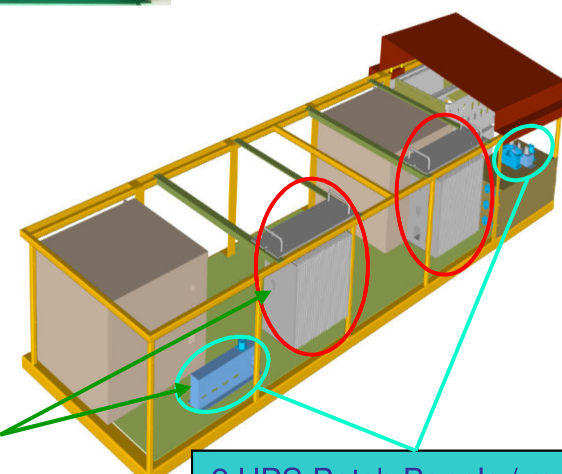
DQLPUS Power Packs

2 units / rack (total 872 units)

DQLPU-type S crate

total 436 units





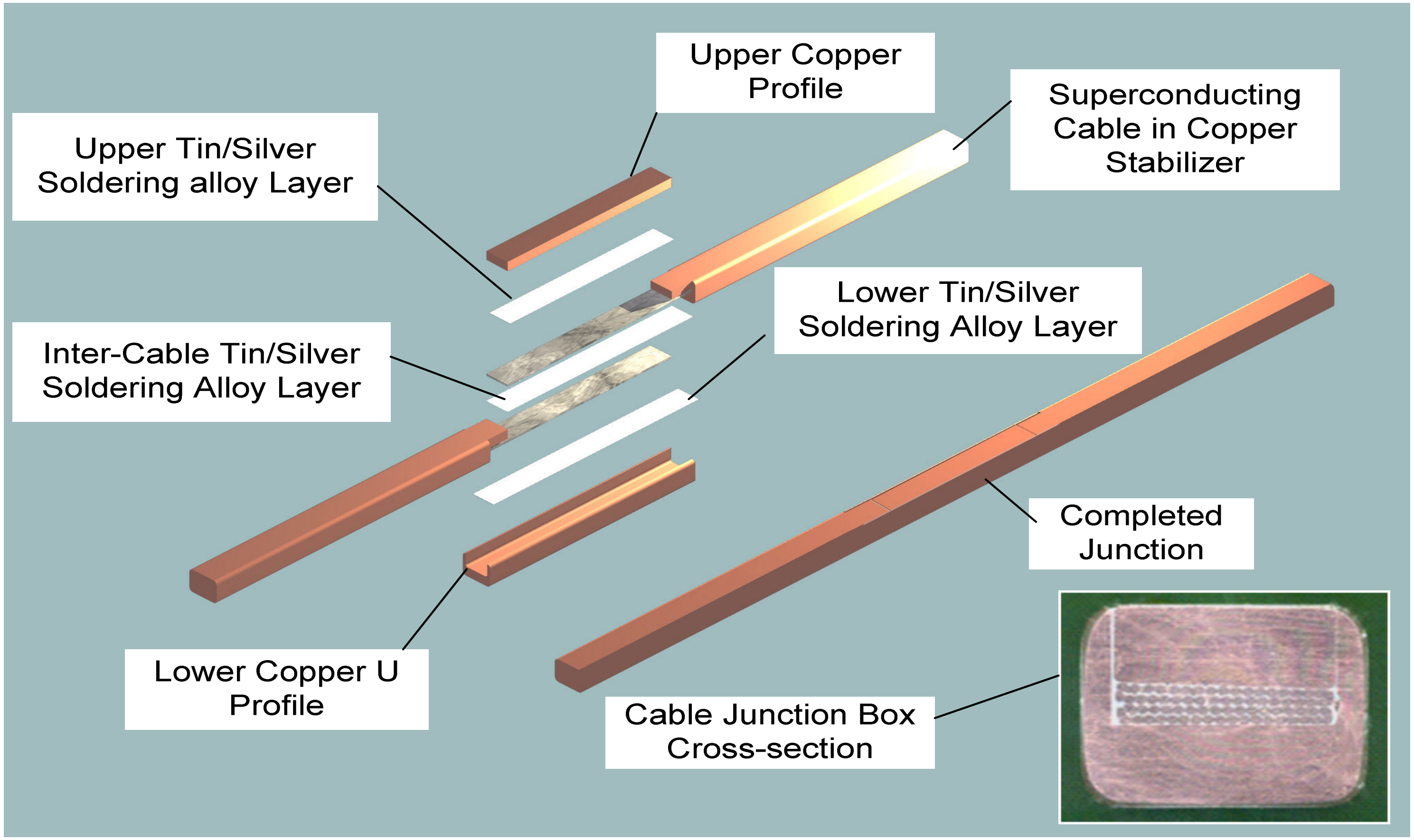
Original racks

'Internal' and 'external' **cables** for sensing, trigger, interlock, UPS power, uFIP (10'400 + 4'400)

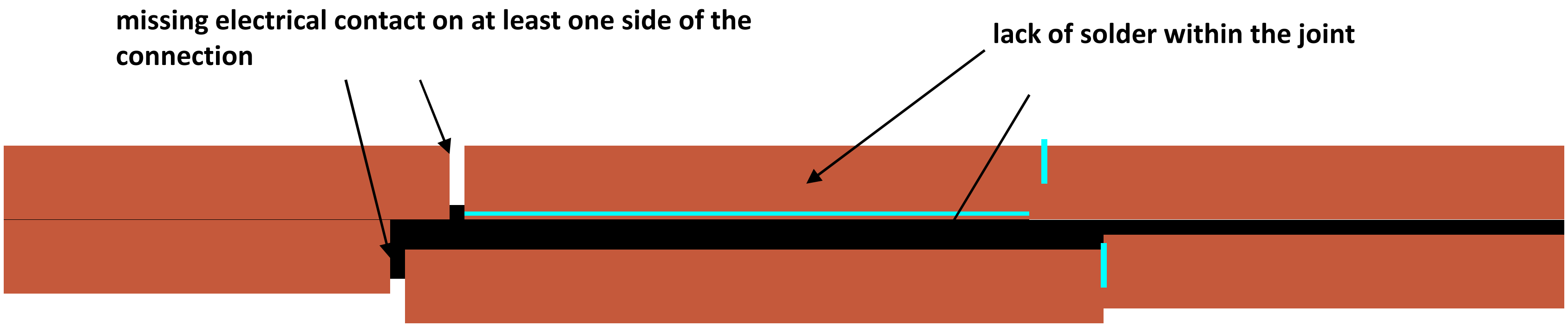
2 UPS Patch Panels / rack &
1 Trigger Patch Panel / rack
total 3456 panel boxes

Sc cable Splices

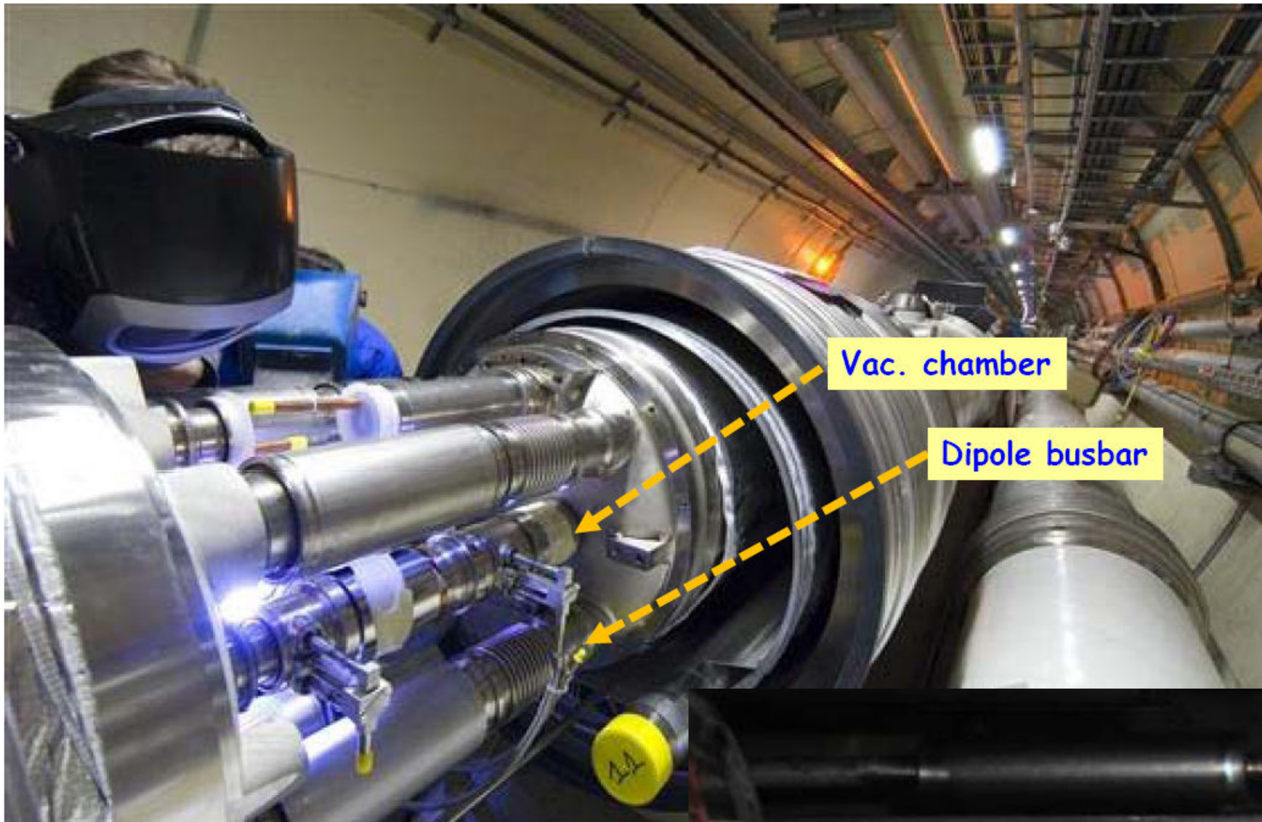
Show sample

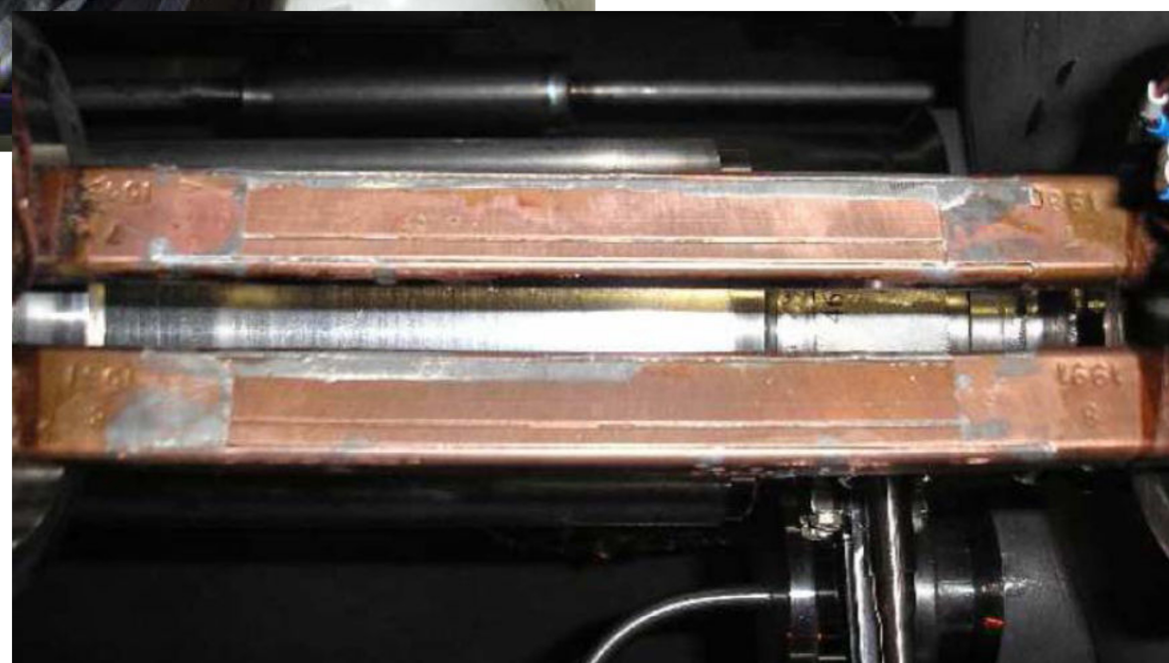


Upper Copper Profile
Superconducting Cable in Copper Stabilizer
Upper Tin/Silver Soldering alloy Layer
Lower Tin/Silver Soldering Alloy Layer
Inter-Cable Tin/Silver Soldering Alloy Layer
Completed Junction
Lower Copper U Profile
Cable Junction Box Cross-section



missing electrical contact on at least one side of the connection
lack of solder within the joint


Vac. chamber
Dipole busbar



Number of splices in RB, RQ circuits

circuit	splice type	splices per magnet	number of units	total splices
RB	inter pole	2	1232	2464
RB	inter aperture	1	1232	1232
RB	interlayer	4	1232	4928
RB	internal bus	1	1232	1232
RB	interconnect	2	1686	3372
RQ	Inter pole	6	394	2364
RQ	internal bus	4	394	1576
RQ	interconnect	4	1686	6744
total				23912

Methods for testing splices

- The methods we have at our disposal to measure spice resistances (either directly or indirectly) are four:
  - The ‘Keithley’ method
  - The ‘QPS snapshot’ method
  - The calorimetric method
  - *The ultrasound method*

Decision: Beam Energy at Start-up (August 2009)

- Avoidance of thermal runaway (during a quench)
  - Maximum safe current flowing in joint (beam energy)
    - Electro-magnetic, thermo-dynamic simulations
    - Probability of simultaneous quench in magnet and joint (?beam losses FLUKA)
    - Quench propagation time from the magnet to the joint
  - Resistance of the copper stabilizers (measurements)
  - Quality of the copper in the sc cable and the Cu stabiliser (RRR)
  - Energy extraction time (modification of dump resistors quads and dipoles)
  - Gaseous cooling of the joint?

Choices

- Stick to 5TeV/beam and repair all necessary Cu stabilizer joints => warm up of several sectors and delay start of physics till 2010
- Aim for maximum safe energy with no additional repairs on CU stabilizers => allows us to gain experience up to this maximum energy (accelerator and detectors)

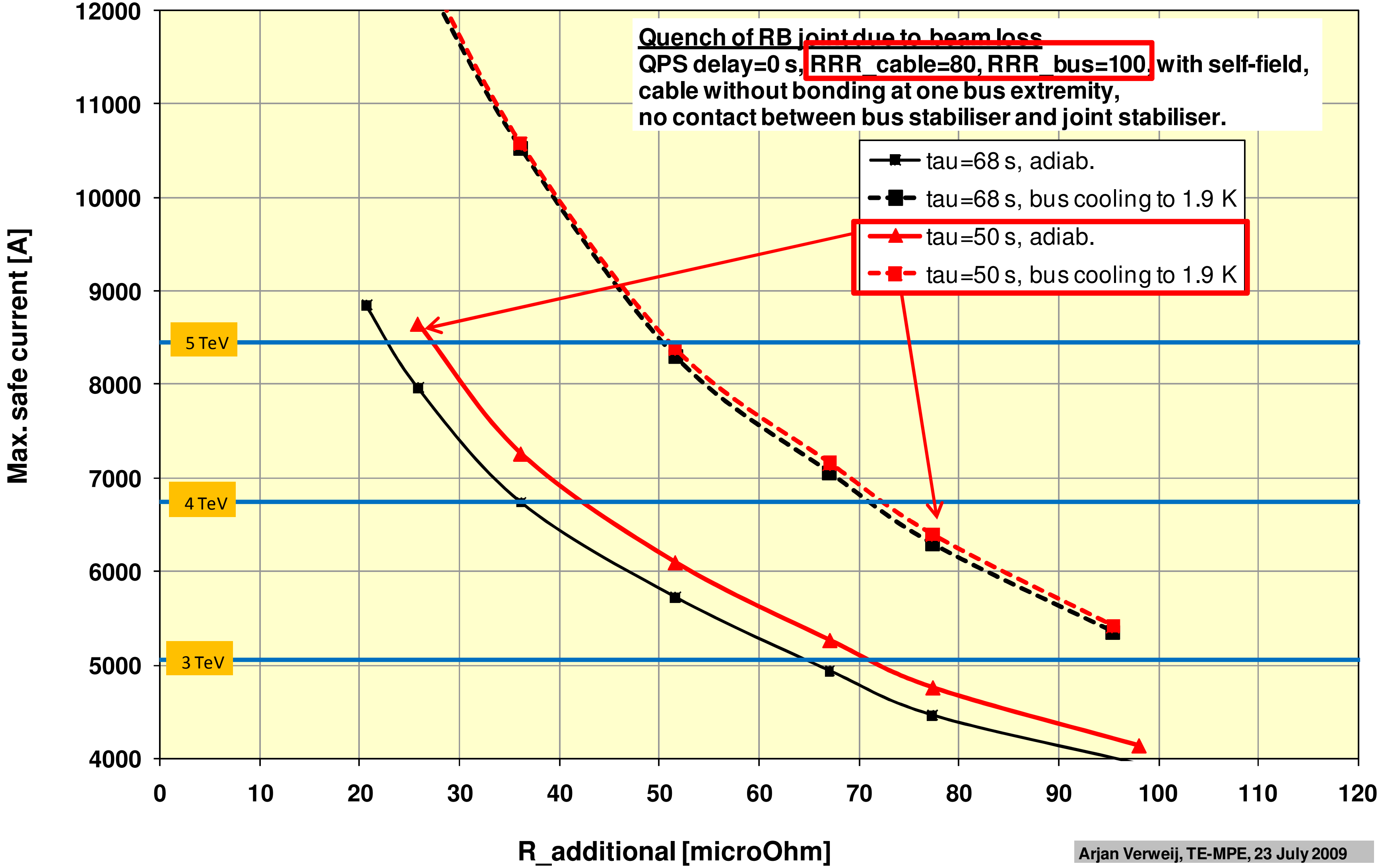
Simultaneous busbar and magnet quench?

FLUKA Simulations

- **Combined busbar and magnet quench <u>cannot</u> be excluded but is <u>highly unlikely</u>**
- **Magnet will quench at a significantly lower level** of beam loss than adjacent bus bars (in inter-connects or the empty cryostat)
  - **10^6** protons sufficient to quench the magnets
  - **10^9-10^{10}** protons required to quench the busbars
- According to the present studies it is **very unlikely to quench the busbar only (not observed in these studies)**

New RQ dump resistors; preparation was launched immediately

RB: case 1 (instantaneous quench in busbar/magnet)



Thermal propagation time (for case 2)

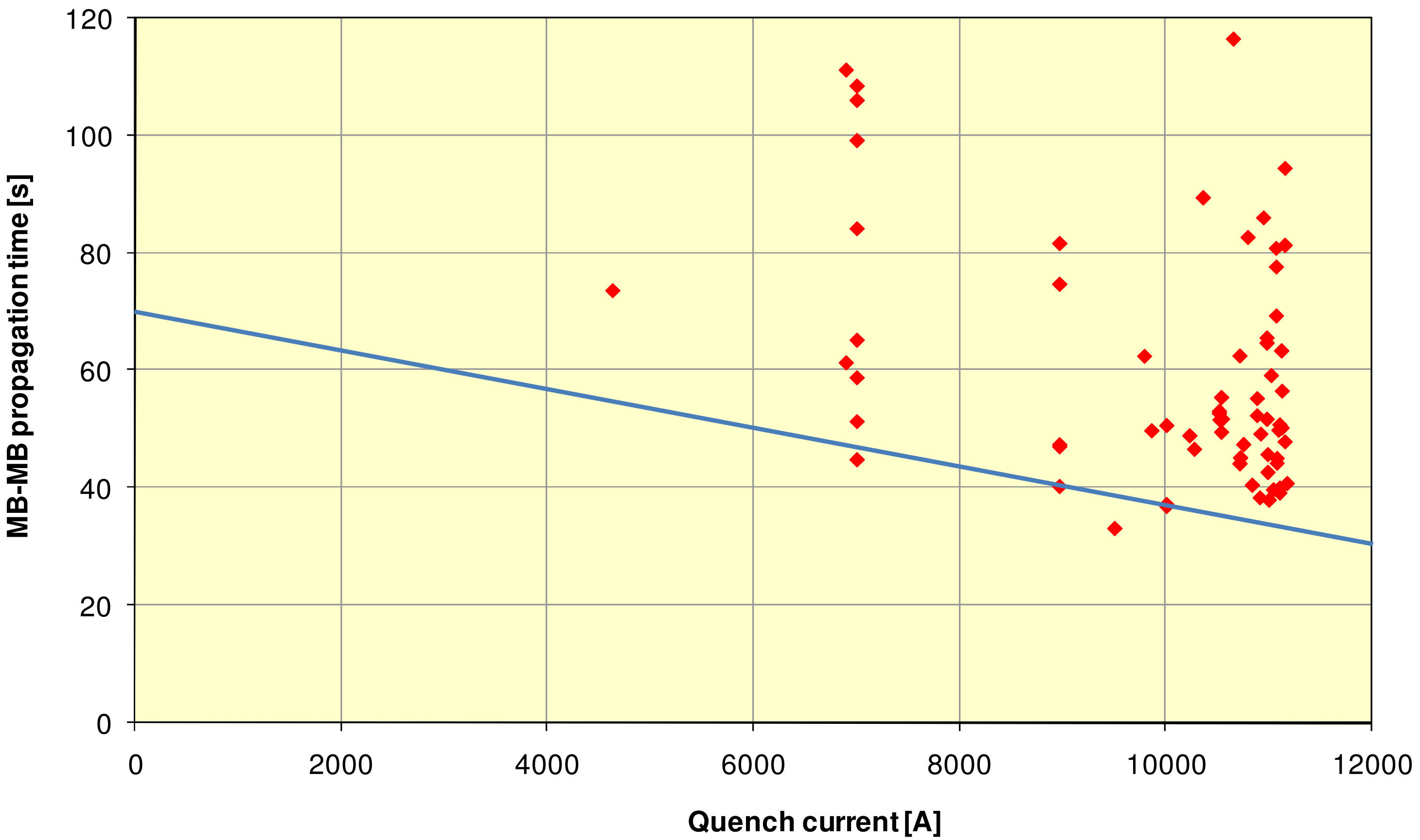
Experience from HWC for RB quenches at 7-11 kA.

Assume that the joint quenches after half the MB-MB thermal propagation time,

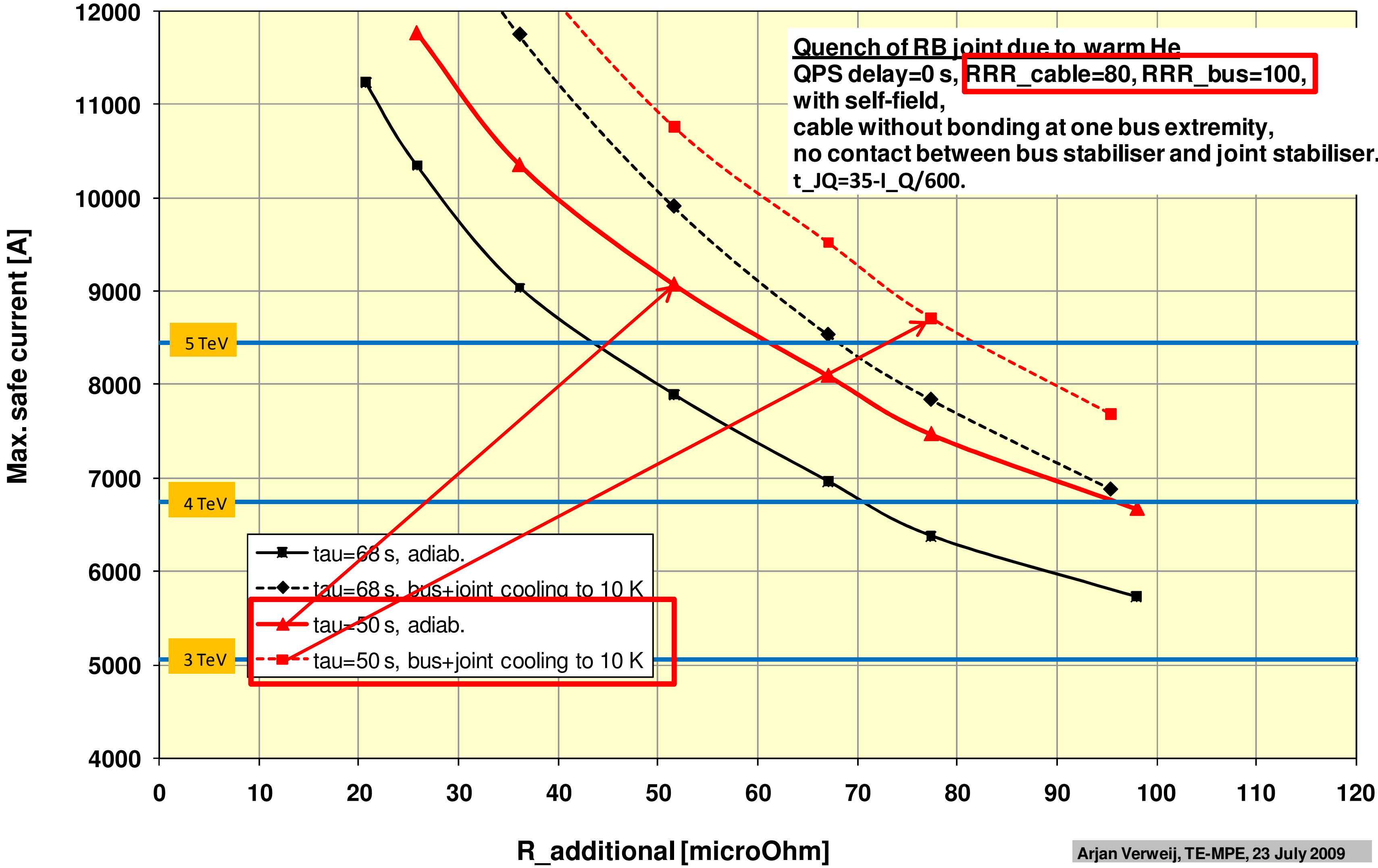
so $t_{JQ}=0.5*(70-I_Q/300)$

?

Maybe possible to get more accurate value from thermal analysis…..



RB: case 2 (quench propagation from magnet to busbar)



Decision on Initial Beam Operating Energy

(August 2009)

- Highest measured value of excess resistance (R_{long}) in 5 sectors measured at 300K was **53μΩ**.
- Operating at 7TeV cm with a energy extraction times of **50s, 10s** (dipoles and quadrupoles)
  - Simulations show that resistances of ≤120μΩ are safe from thermal runaway under conservative assumed conditions of worst case conditions for the copper quality (RRR) and no cooling to the copper stabilizer from the gaseous helium
- Operating at 10TeV cm with a dipole energy extraction time of 68 s
  - Simulations show that resistances of ≤67μΩ are safe from thermal runaway under conservative assumed conditions of worst case conditions for the copper quality (RRR), and with estimated cooling to the stabilizer from the gaseous helium

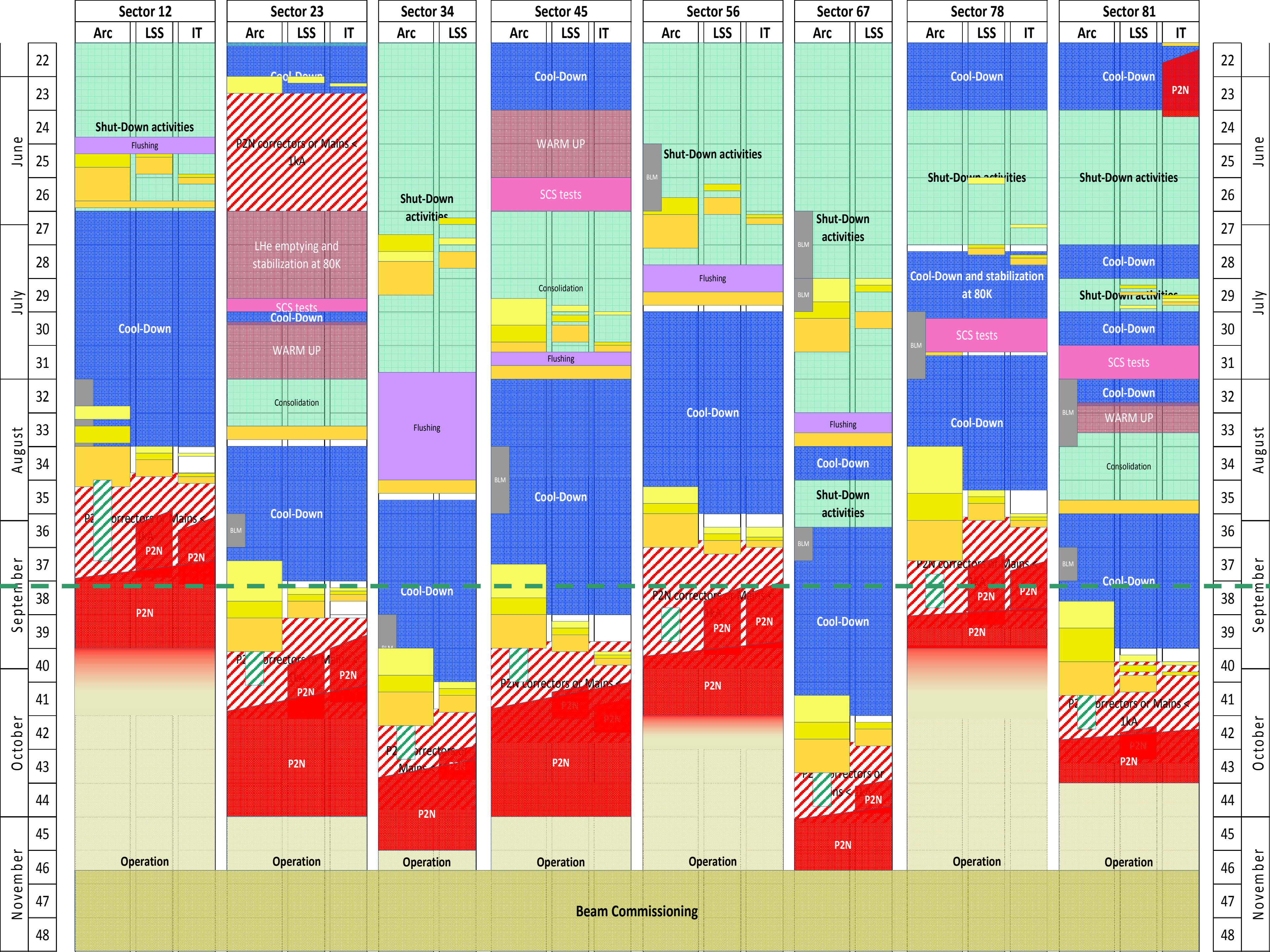
Decision:

- **Operation initially at 7TeV cm (energy extraction time of 50s,10s) with a safety factor or more than 2 for the worst stabilizers. During this time**
  - **monitor carefully all quenches to gain additional information.**
  - **Continue simulations and validation of simulations by experimentation (FRESCA)**
- **Then operate at around 10TeV cm.**

Since August

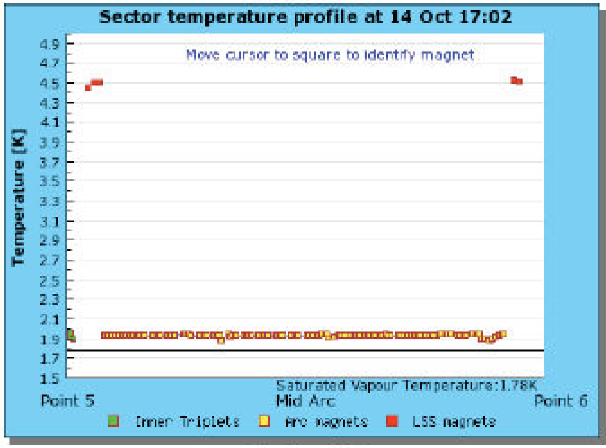
- Start of re-establishment of spares situation as it was before the incident
- Helium leak (flexible in the DFBs) in S45, S23, and S81. All repaired
- Super-insulation fire in S67 (minimum damage)
- Magnet/busbar short to earth in S67 (detected and repaired)

LHC Schedule

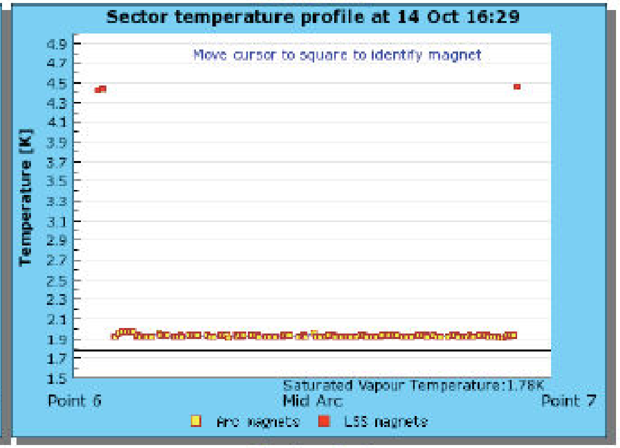


Sector 12
Sector 23
Sector 34
Sector 45
Sector 56
Sector 67
Sector 78
Sector 81
Arc
LSS
IT
June
July
August
September
October
November
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
Shut-Down activities
Flushing
Cool-Down
P2N
Operation
WARM UP
SCS tests
LHe emptying and stabilization at 80K
Consolidation
P2N correctors or Mains < 1kA
BLM
Cool-Down and stabilization at 80K
Beam Commissioning

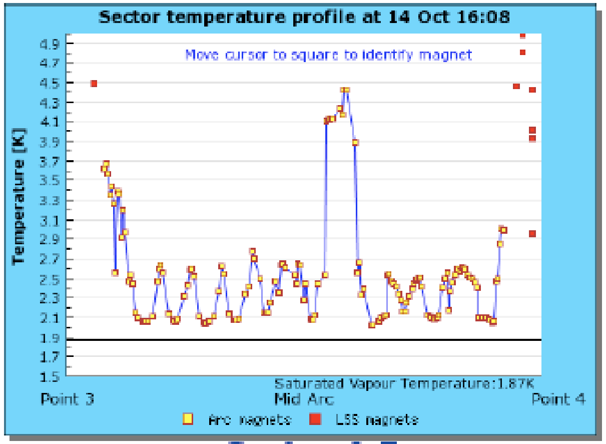
Sector 5-6



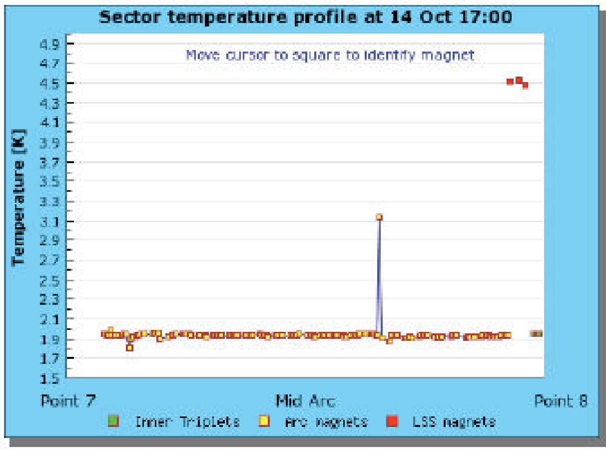
Sector 6-7



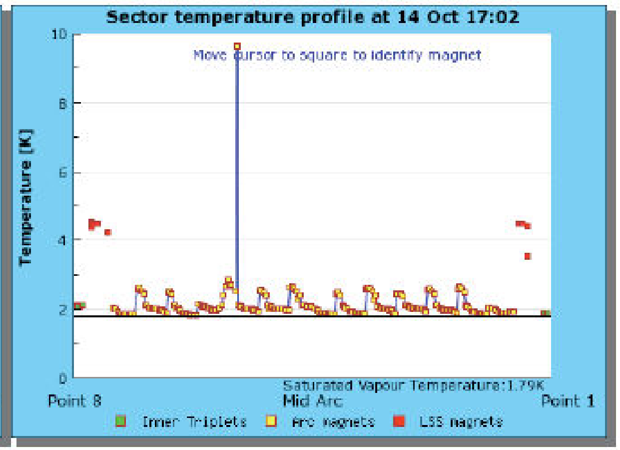
Sector 3-4



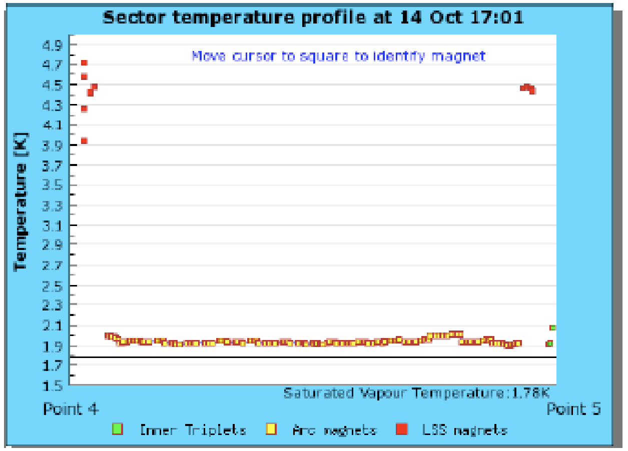
Sector 7-8



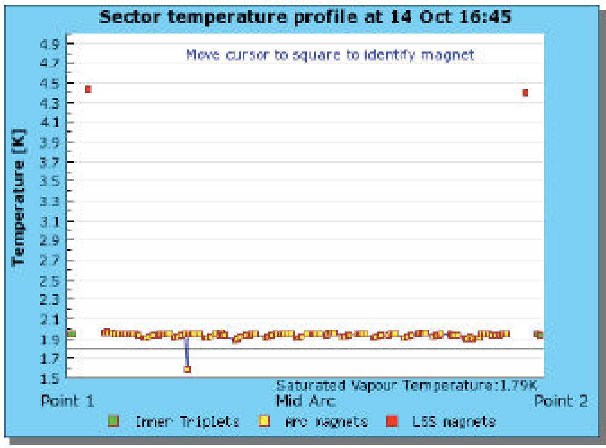
Sector 8-1



Sector 4-5

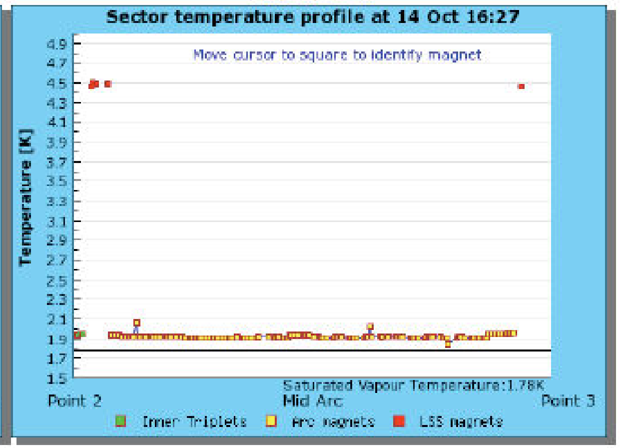


Sector 1-2



Sector 3-4

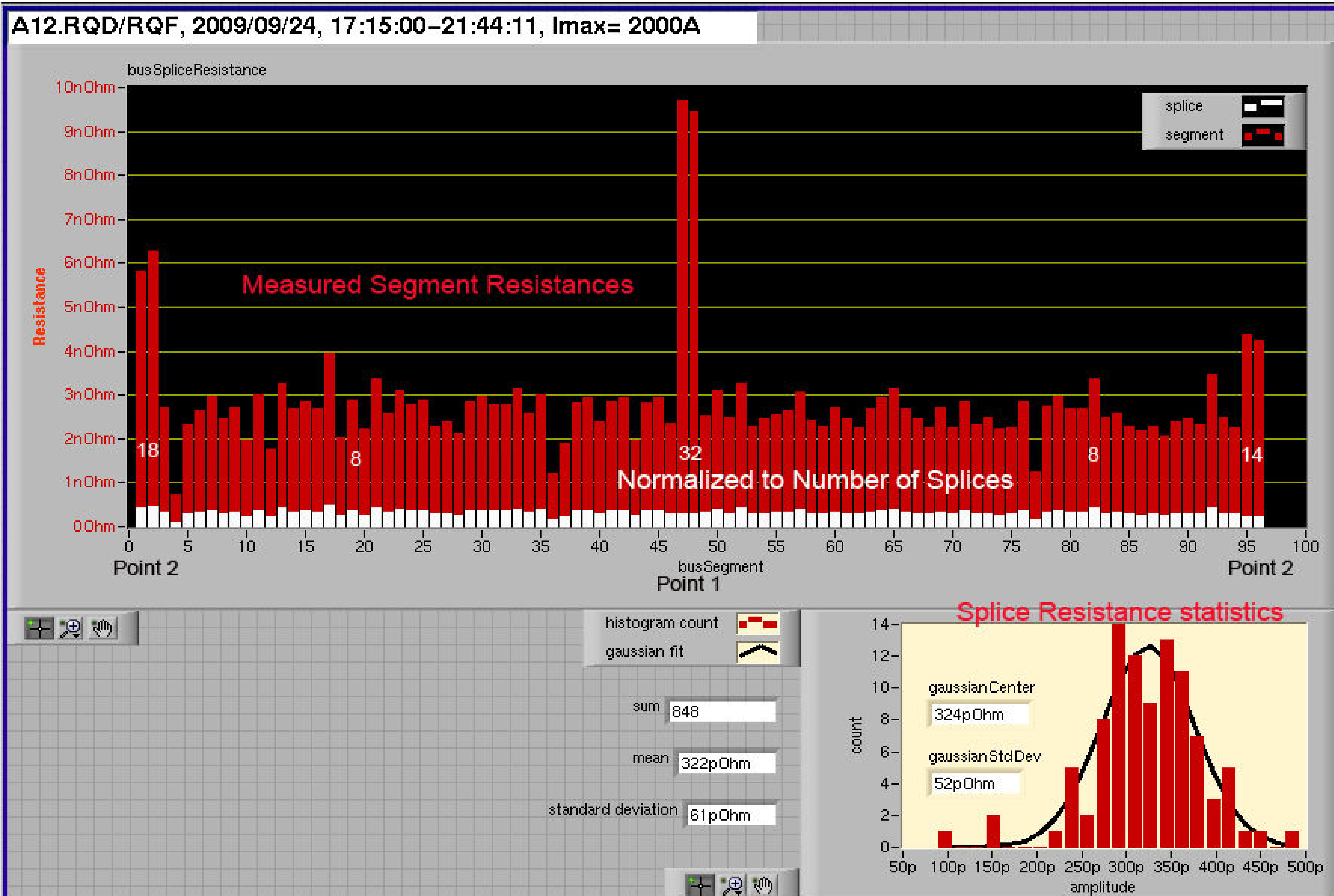
Sector 2-3



Sector 4-5

Cool down status on 14nd October 2009

Sector 1-2 splice measurement with the nQPS



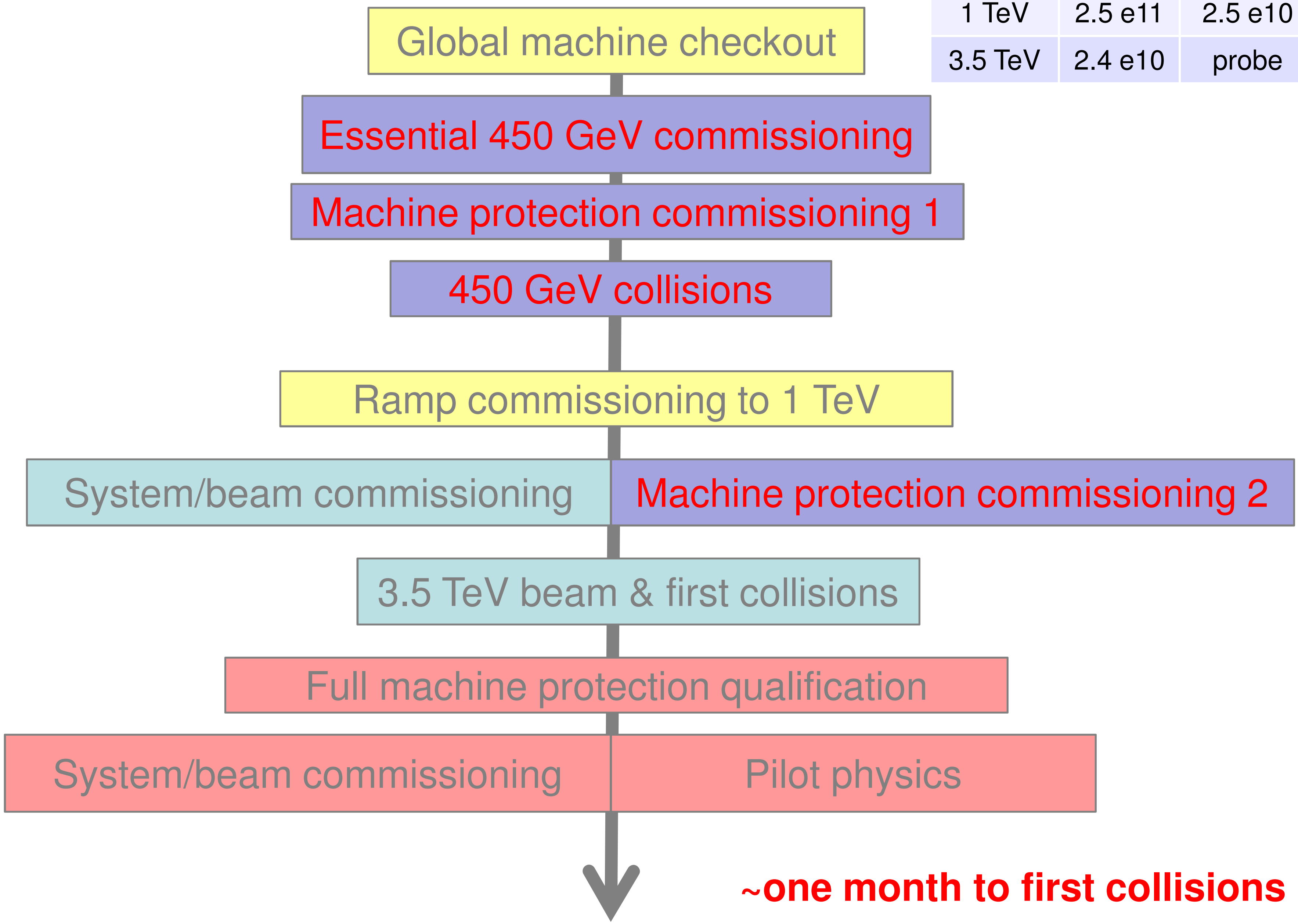
LHC 2009/2010 – running scenarios

This is the present plan:

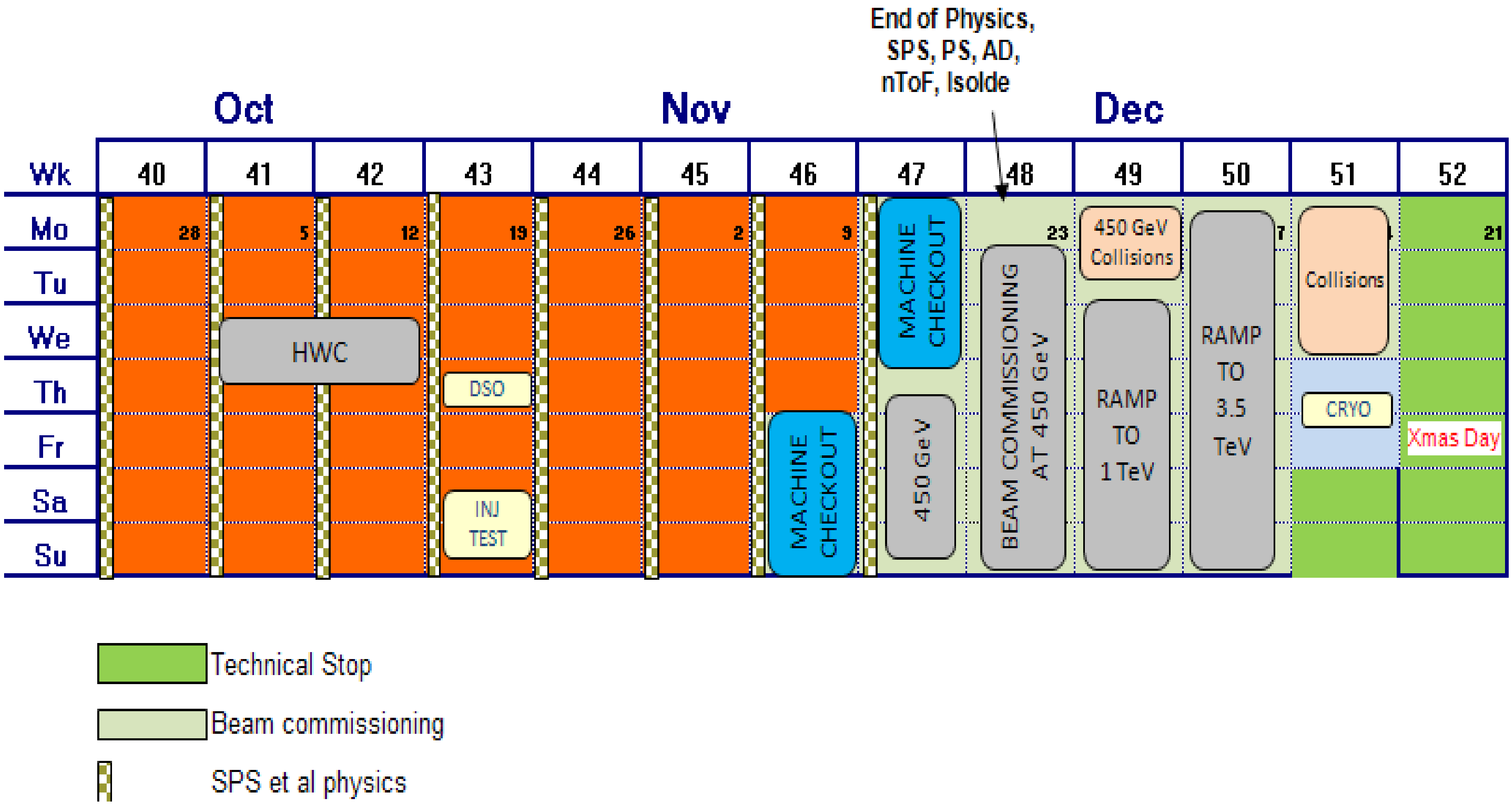
- It will almost certainly be modified on a daily/weekly basis, once we start with beam commissioning.
- …BUT we need a plan!

LHC beam commissioning

Energy	Safe	Very Safe
450	1 e12	1 e11
1 TeV	2.5 e11	2.5 e10
3.5 TeV	2.4 e10	probe



~one month to first collisions



- All dates approximate…
- Reasonable machine availability assumed

Possible evolution

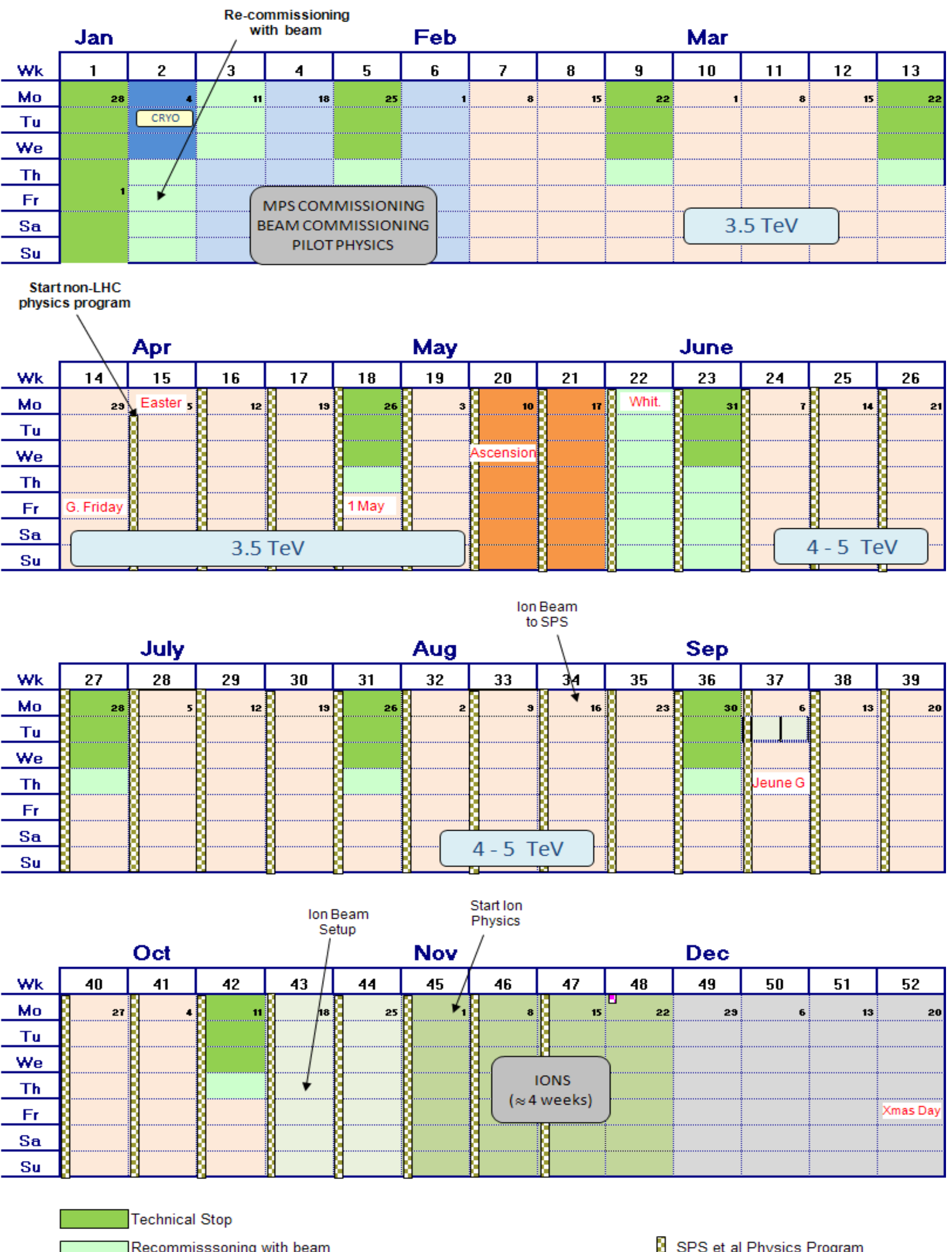
Physics at 3.5 TeV
beta* = 2 m
no crossing angle, 156 bunches

Step up in energy

Ramp, squeeze, ramp to 4-5 TeV
beta* = 2 m
no crossing angle, 156 bunches

Ramp, squeeze at 4-5 TeV
beta* = 2 m
crossing angle, 50 ns

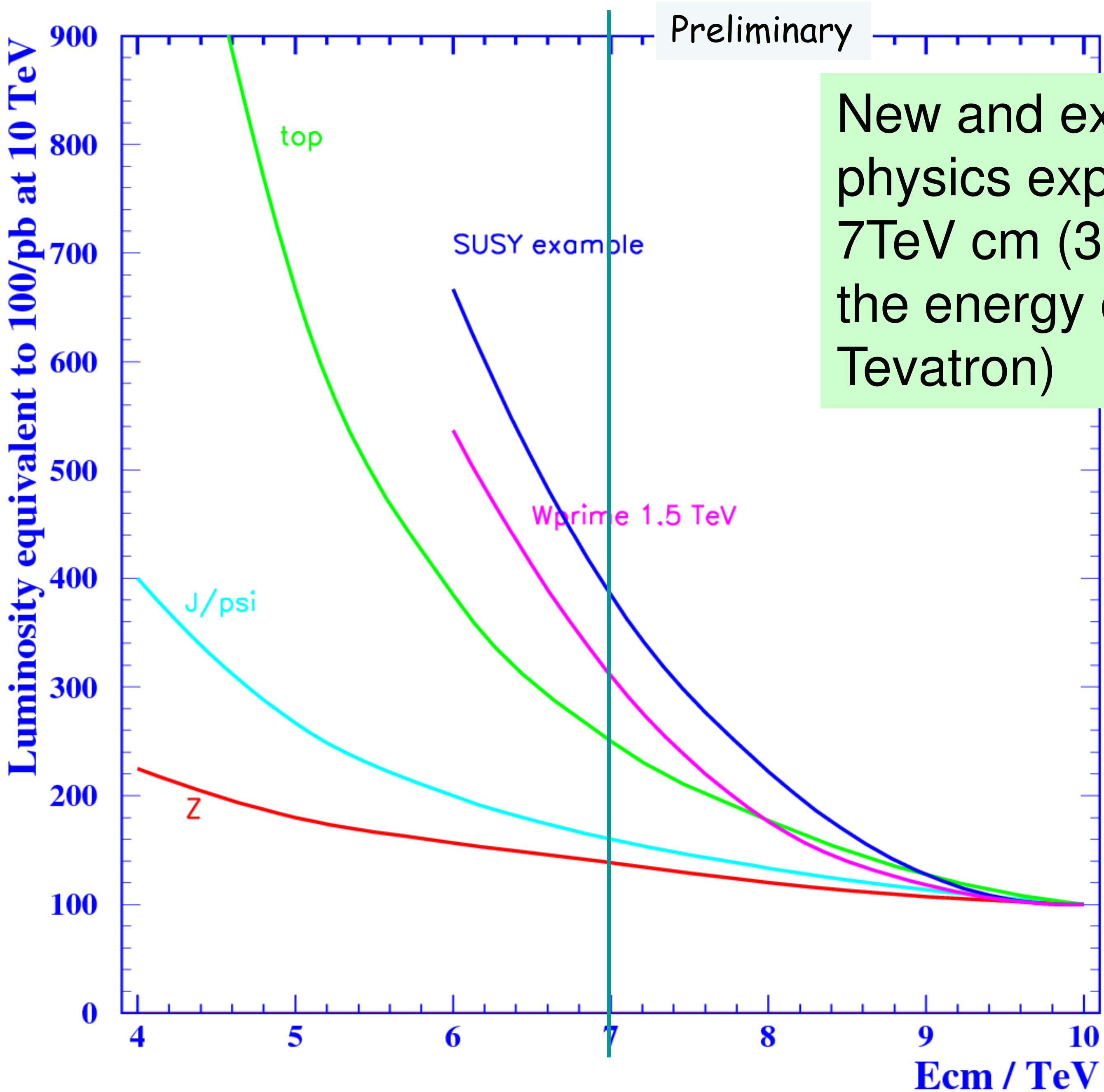
LHC 2010 – **very draft**



- **2009**:
  - 1 month commissioning
- **2010**:
  - 1 month pilot & commissioning
  - 3 month 3.5 TeV
  - 1 month step-up
  - 5 month 4 - 5 TeV
  - 1 month ions

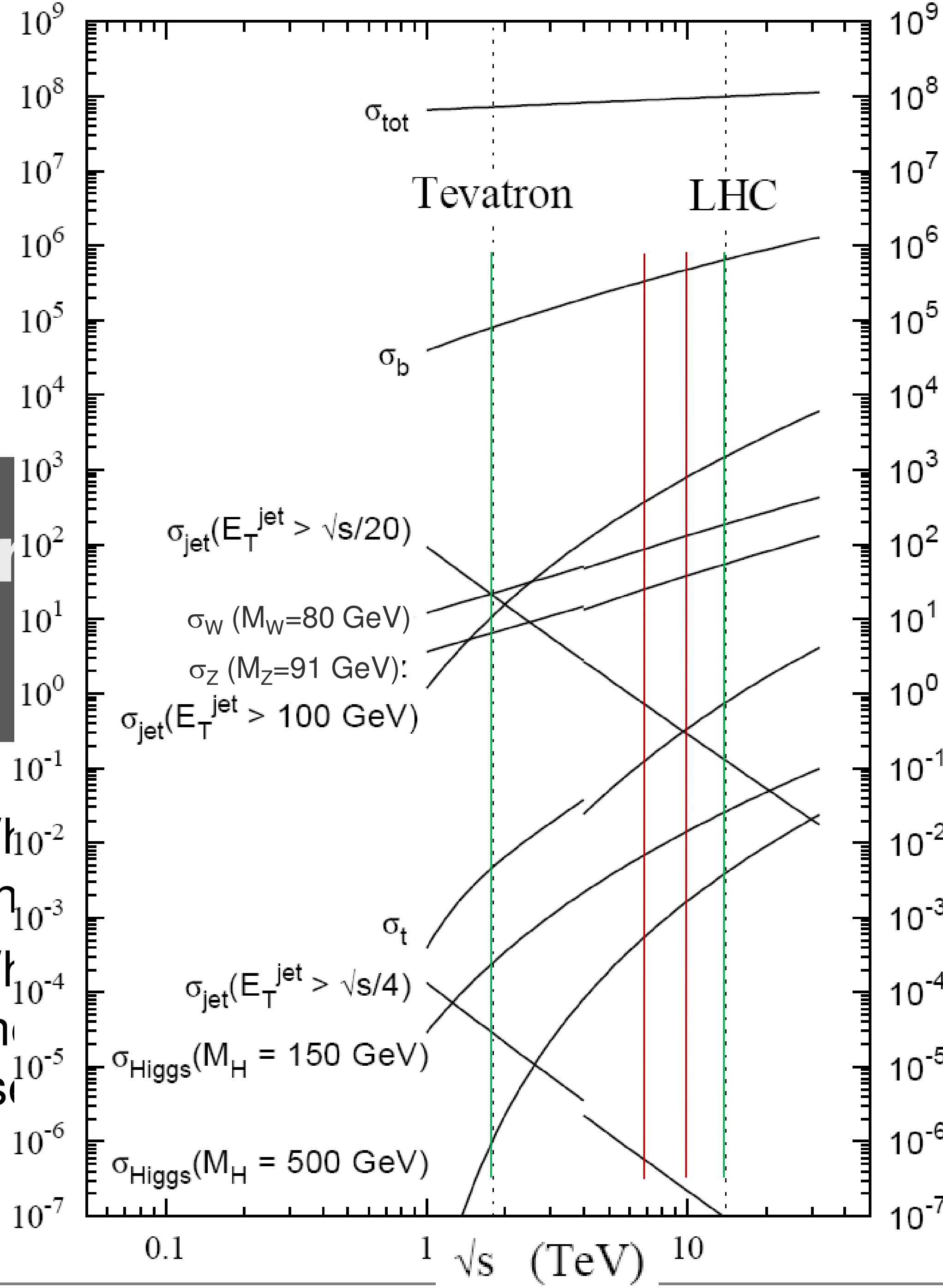
Plugging in the numbers with a step in energy

Month	OP scenario	Max number bunch	Protons per bunch	Min beta*	Peak Lumi	Integrated	% nominal
1	Beam commissioning						
2	Pilot physics combined with commissioning	43	3×10^{10}	4	8.6×10^{29}	~200 nb^{-1}	
3		43	5×10^{10}	4	2.4×10^{30}	~1 pb^{-1}	
4		156	5×10^{10}	2	1.7×10^{31}	~9 pb^{-1}	2.5
5a	No crossing angle	156	7×10^{10}	2	3.4×10^{31}	~18 pb^{-1}	3.4
5b	No crossing angle – pushing bunch intensity	156	1×10^{11}	2	6.9×10^{31}	~36 pb^{-1}	4.8
6	Shift to higher energy: approx 4 weeks	Would aim for physics without crossing angle in the first instance with a gentle ramp back up in intensity					
7	4 – 5 TeV (5 TeV luminosity numbers quoted)	156	7×10^{10}	2	4.9×10^{31}	~26 pb^{-1}	3.4
8	50 ns – nominal Xing angle	144	7×10^{10}	2	4.4×10^{31}	~23 pb^{-1}	3.1
9	50 ns	288	7×10^{10}	2	8.8×10^{31}	~46 pb^{-1}	6.2
10	50 ns	432	7×10^{10}	2	1.3×10^{32}	~69 pb^{-1}	9.4
11	50 ns	432	9×10^{10}	2	2.1×10^{32}	~110 pb^{-1}	12



New and exciting physics expected at 7TeV cm (3.5 times the energy of the Tevatron)

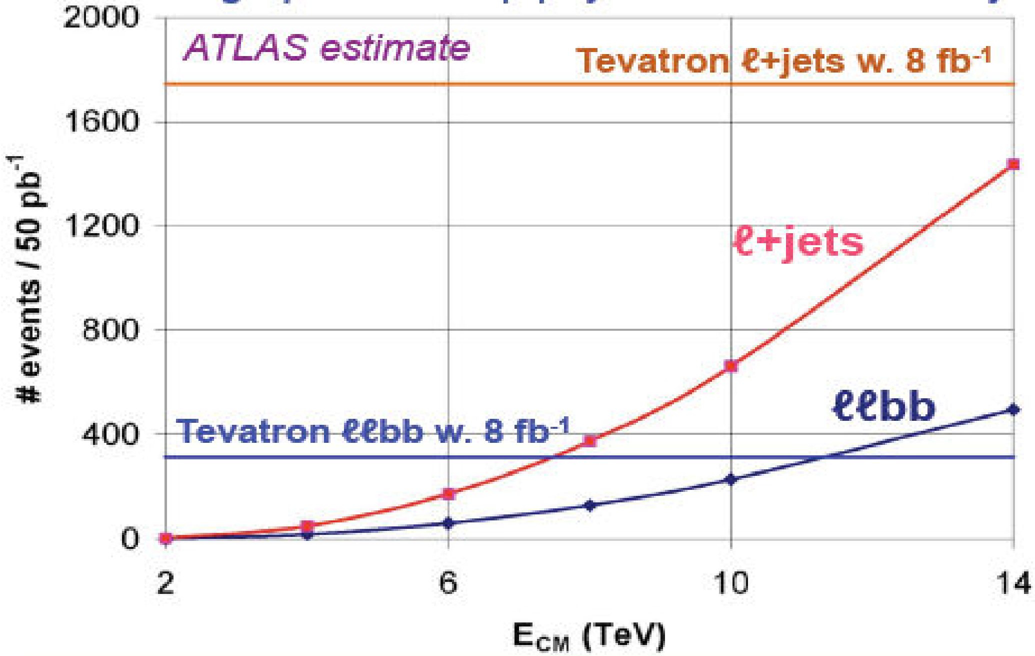
Integr… section



- Wh… , wh…
- Wh… en en… cs run us… eV)

Top quark

- Background to new physics searches – must measure cross-section & properties in data
- Expected Tevatron statistics provide a benchmark:
  - Cross-section statistical precision will then be comparable to other uncertainties
  - High-precision top physics will be underway



~50 pb^{-1}@14 TeV would match full Tevatron sample
- lose ~factor 2 in cross-section dropping to 10 TeV
- lose ~another factor 2 dropping to 8 TeV

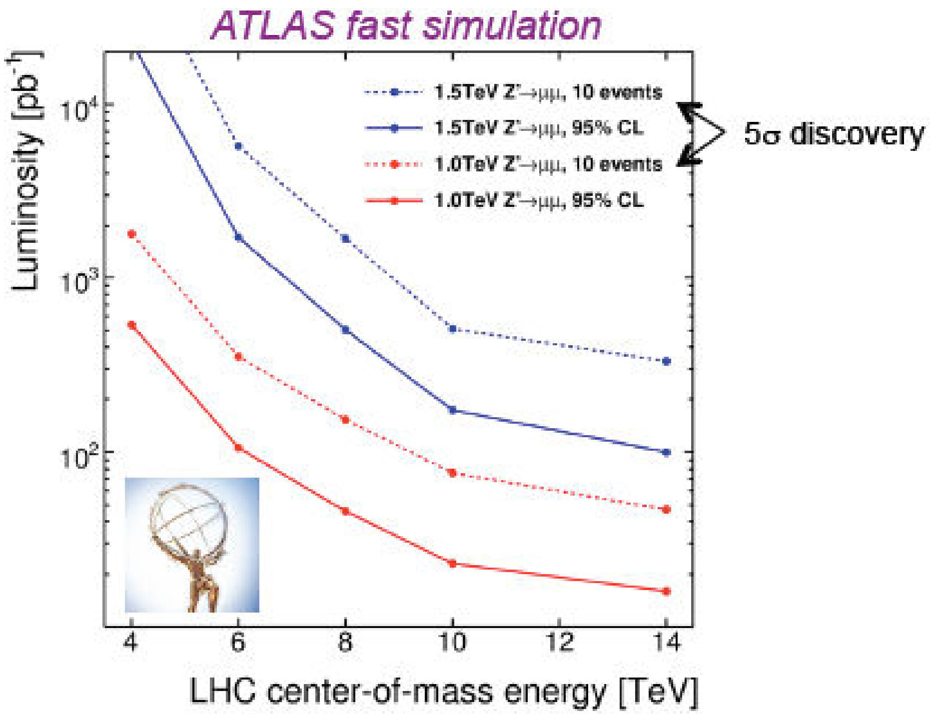
Below 8 TeV samples will be rather small, with a few tens of pb^{-1}

Catch up with Tevatron with **$s^{1/2}$ = 8-10 TeV** and ~**200-100 pb^{-1} g.d.**

Z'

Z': Heavy partner of the Z (SSM)

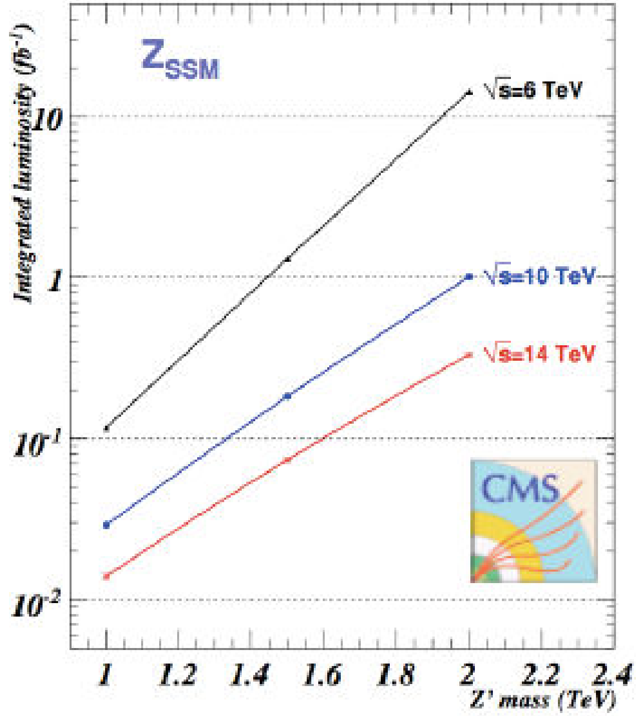
- Very clean experimental signal: $Z' \rightarrow \ell\ell$
- Tevatron 95% CL limit at $m_{Z'}$ =1 TeV



Needed luminosity for 95%CL exclusion at $m_{Z'}$ = 1 TeV :

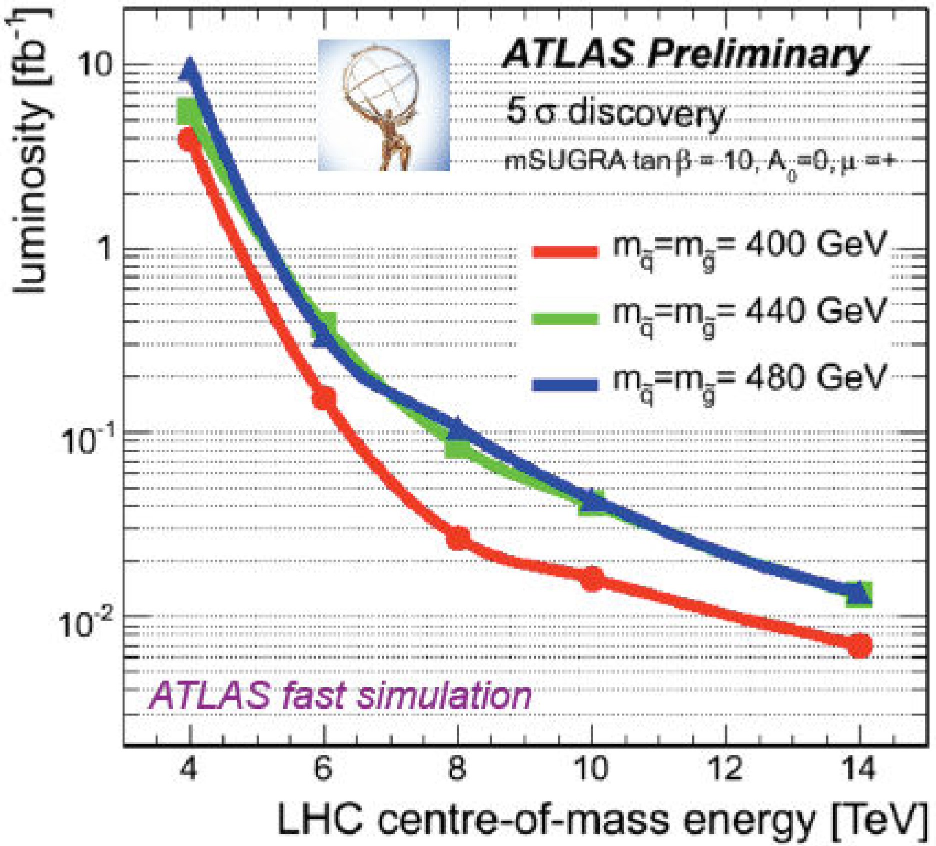
$s^{1/2}$: 14 → 10 → 6 TeV

Lumi: 13 → 30 → 110 pb^{-1}



SUSY, an example

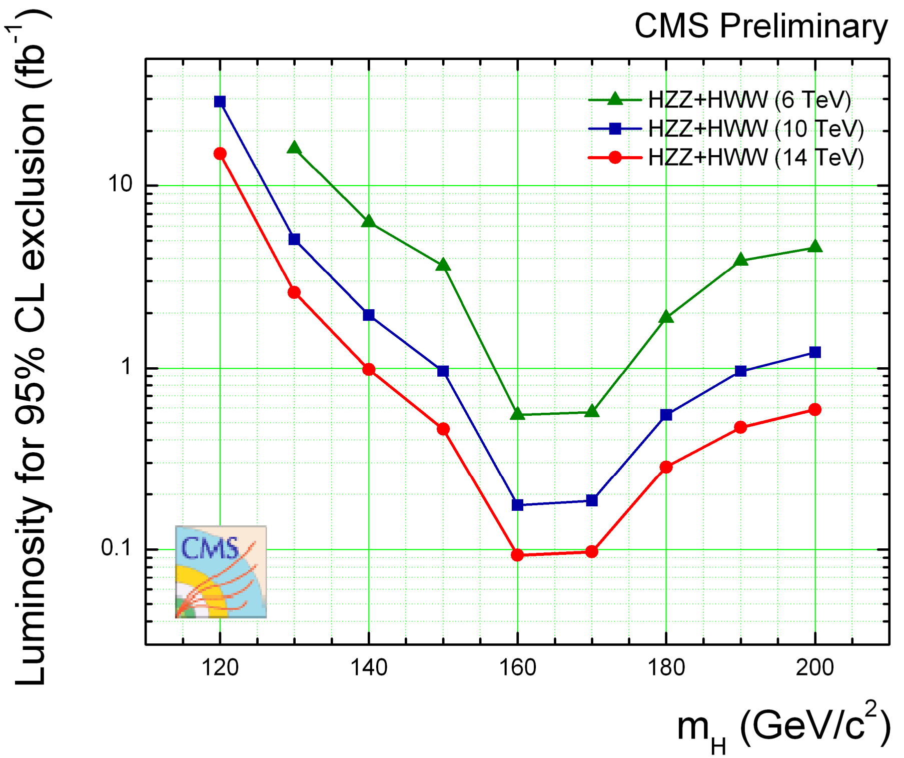
- ℓ+jets+missing-E_T channel
  - Not most sensitive, but will be usable before inclusive jets +missing-E_T analysis
- Tevatron limit currently is 380 GeV in this model ($m_{\tilde{q}} = m_{\tilde{g}}$)
  - plot shows 3 masses above this
- We will be sensitive to a region overlapping with ultimate Tevatron reach
- Below E_{cm}≈8 TeV, the sensitivity collapses



5σ discovery beyond current Tevatron limits is possible with $s^{1/2}$ = 8-10 TeV and ~30-15 pb^{-1} g.d.

Higgs 95% CL at LHC GPD , H→ weak bosons, indicative

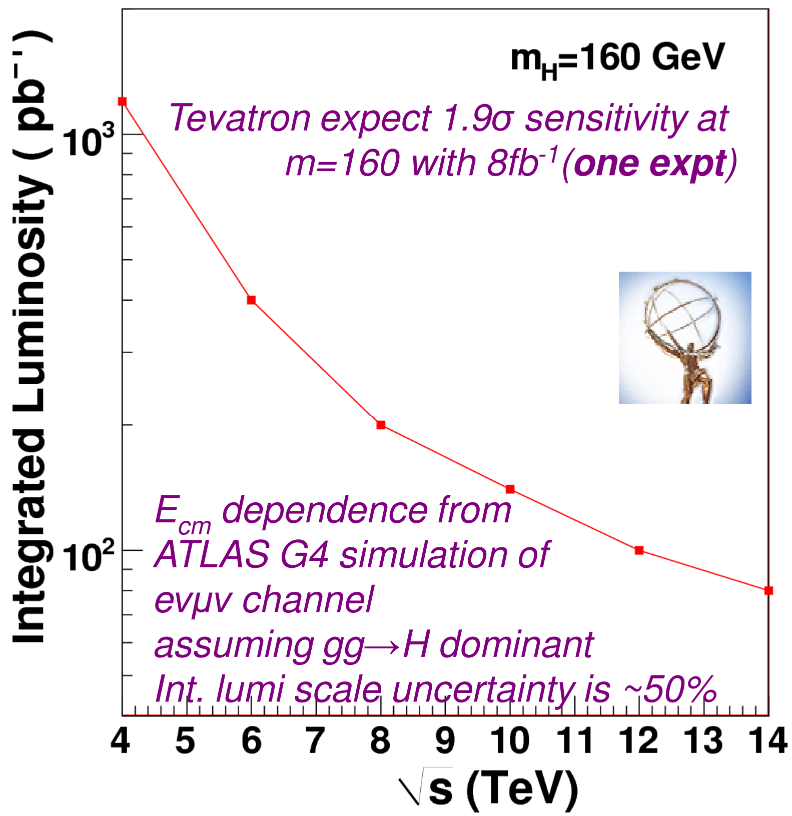
Combined H→WW + H→ZZ: lumi for 95% CL



- Energy $s^{1/2}$ 14 → 10 → 6 TeV
- Lumi needed 0.1 → 0.2 → 0.6 fb^{-1}

Compare sensitivity to Tevatron with 8 fb^{-1}

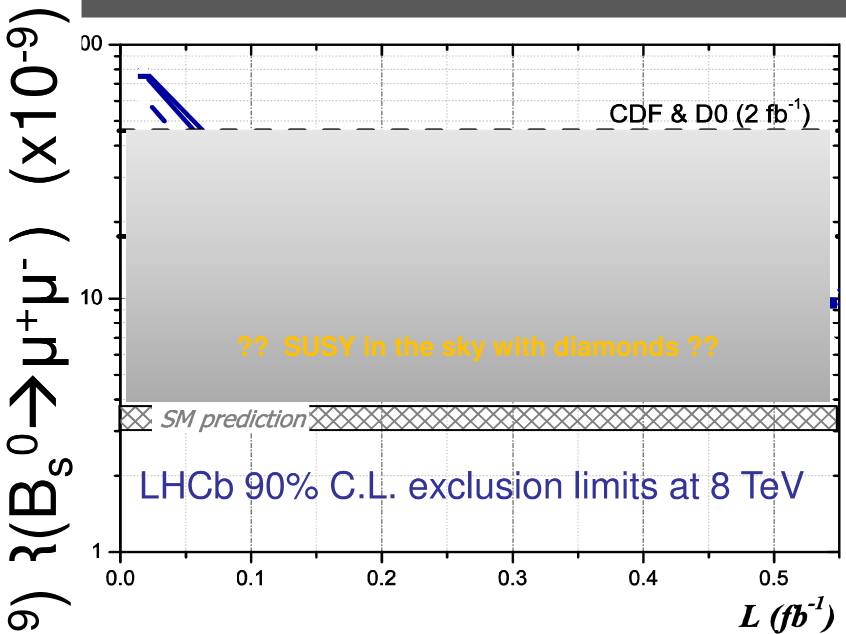
(only H→WW→ $\ell\nu\ell\nu$)



- Massive loss of sensitivity below 6 TeV

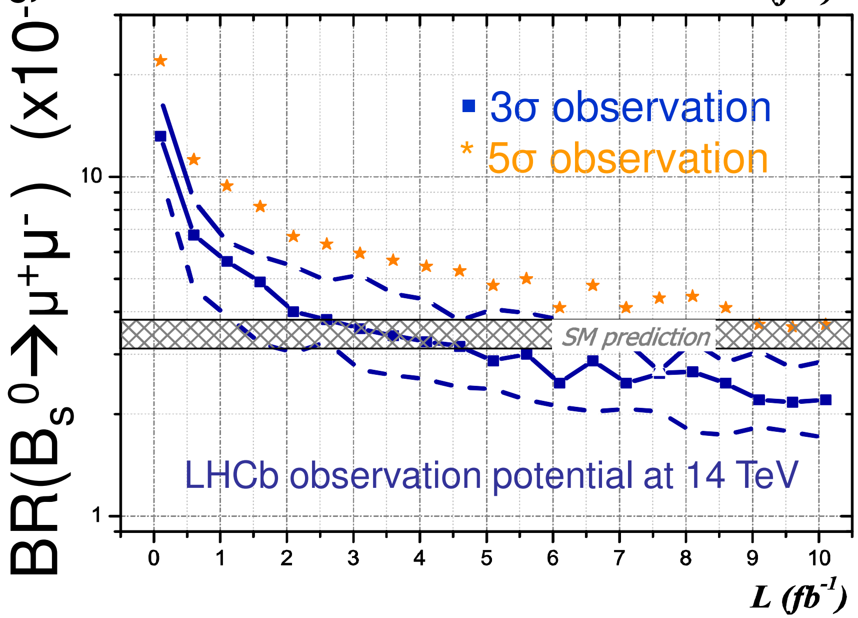
To challenge Tevatron with $s^{1/2}$ = 8-10 TeV, we need ~300-200 pb^{-1} g.d.

Physics reach for BR($B_s^0 \rightarrow \mu^+\mu^-$)



- as function of integrated luminosity (and comparison with Tevatron)

At $s^{1/2}$ = 8 TeV , need ~**0.3-0.5 fb^{-1} g.d.** to improve on expected Tevatron limit



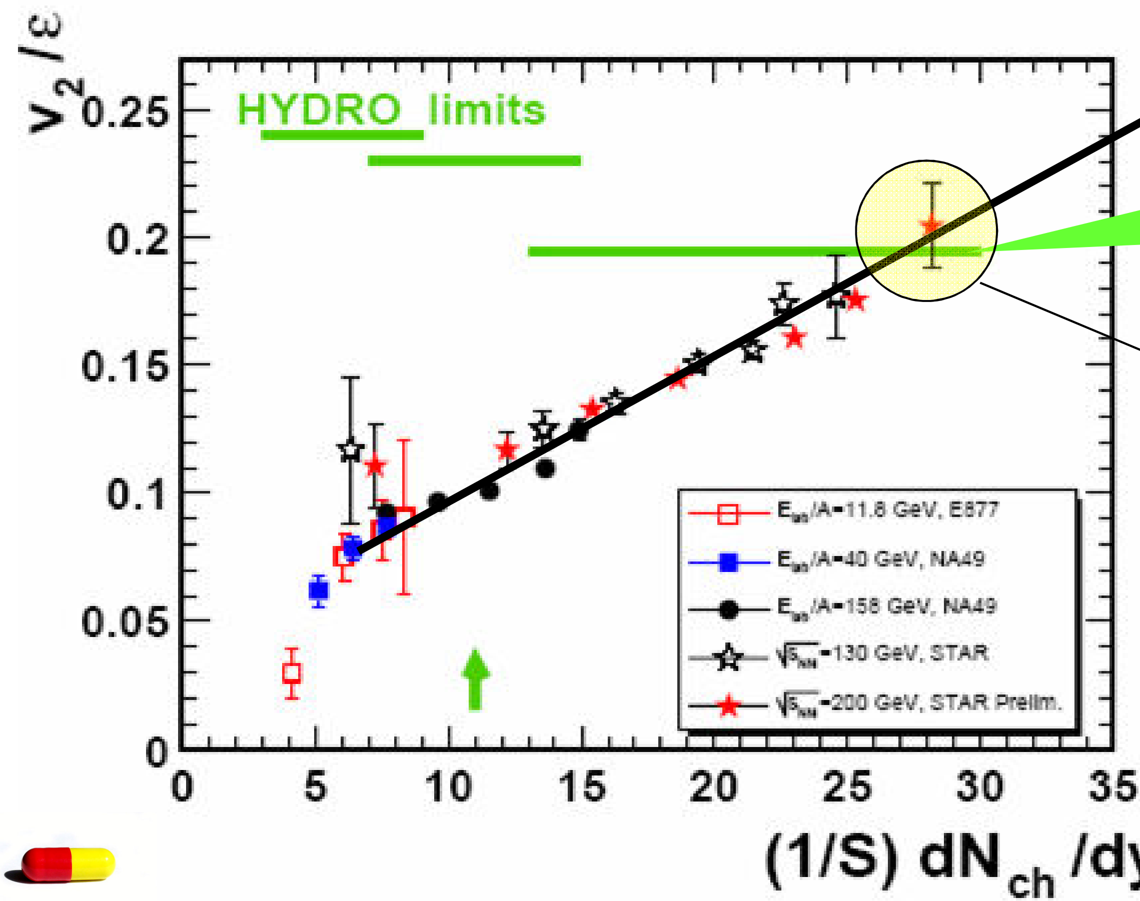
Collect ~3 fb^{-1} for 3σ observation of SM value

Heavy Ions: Flow at LHC

- one of the first and most anticipated answers from LHC
  - 2nd RHIC paper: Aug 24, 22k MB events, **flow surprise** (v_2)
    - Hydrodynamics: modest rise (Depending on EoS, viscosity, speed of sound)

LHC ?

increase of flow



BNL Press release, April 18, 2005:

Data = ideal Hydro

"Perfect" Liquid

New state of matter more remarkable than predicted – raising many new questions

LHC will either

confirm the RHIC interpretation

(and measure parameters of the QGP EoS)

OR

……………………..

Summary of beam commissioning

- First injection test – 24/25 October
- With a bit of luck - first high energy collisions just before Christmas
- Step up in energy would take ~4 weeks physics to physics
- Would start at higher energy with a flat machine before bringing on crossing angle and exploiting 50 ns.
- Interesting times.

Preparations for the Future

Operational Consolidation

Operational Consolidation : Strategy

1. we have prepared an inventory of
   a) the existing spares and spare components for the LHC
   b) the existing spare components of the LHC infrastructure
   c) Consolidation needed to increase the efficiency of safe operation of the machine in the longer term
2. we have prepared a preliminary estimate of the total materials cost
3. In the MTP, we have planned a budget of 25MCHF/year to carry out this programme
4. The time prioritization of the operational consolidation work is being done by Risk Ranking of the inventory. Two passes finished and the “final” ranking in a few weeks
5. The manpower needed to carry out this programme has not yet been identified

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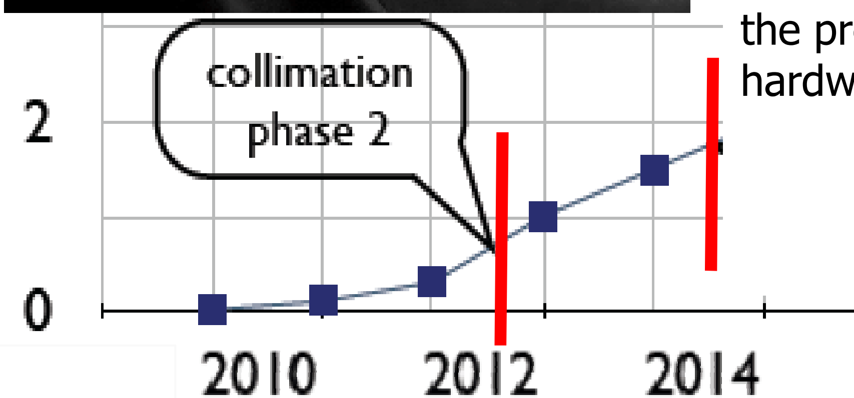
How will the next few years develop ?



✓ Through a sequence of long runs alternated to relative long shutdowns

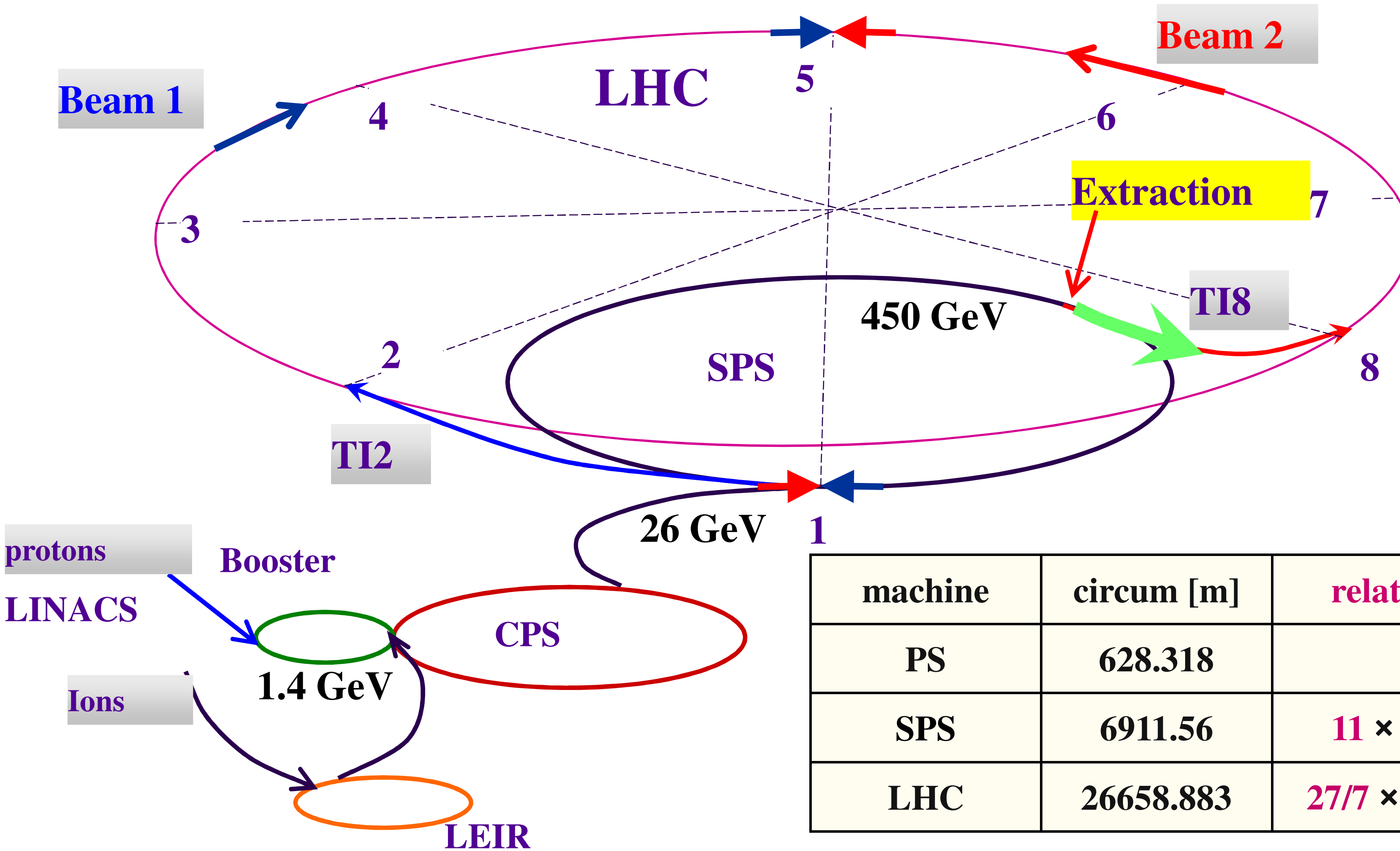
✓ Initial runs to tune and get to know machine and experiments (7 TeV -> 10 TeV -> 14 TeV)

✓ Shutdowns to upgrade the energy to 7 TeV (probably in steps, fix known problems, re-train magnets,…), but also to increase luminosity and machine protection (collimation upgrade)

✓ 200-300 fb^{-1} is the integrated Luminosity level where the pp experiments expect some aging of the present pixel innermost layer and when new hardware might become necessary

New discoveries will eventually influence this path

The CERN accelerator complex : injectors and transfer



machine	circum [m]	relative
PS	628.318	
SPS	6911.56	11 × PS
LHC	26658.883	27/7 × SPS

simple rational fractions for synchronization
… on a single frequency
…ator at injection

Beam size of protons decreases with energy : area $\sigma^2 \propto 1 / E$

Beam size largest at injection, using the full aperture

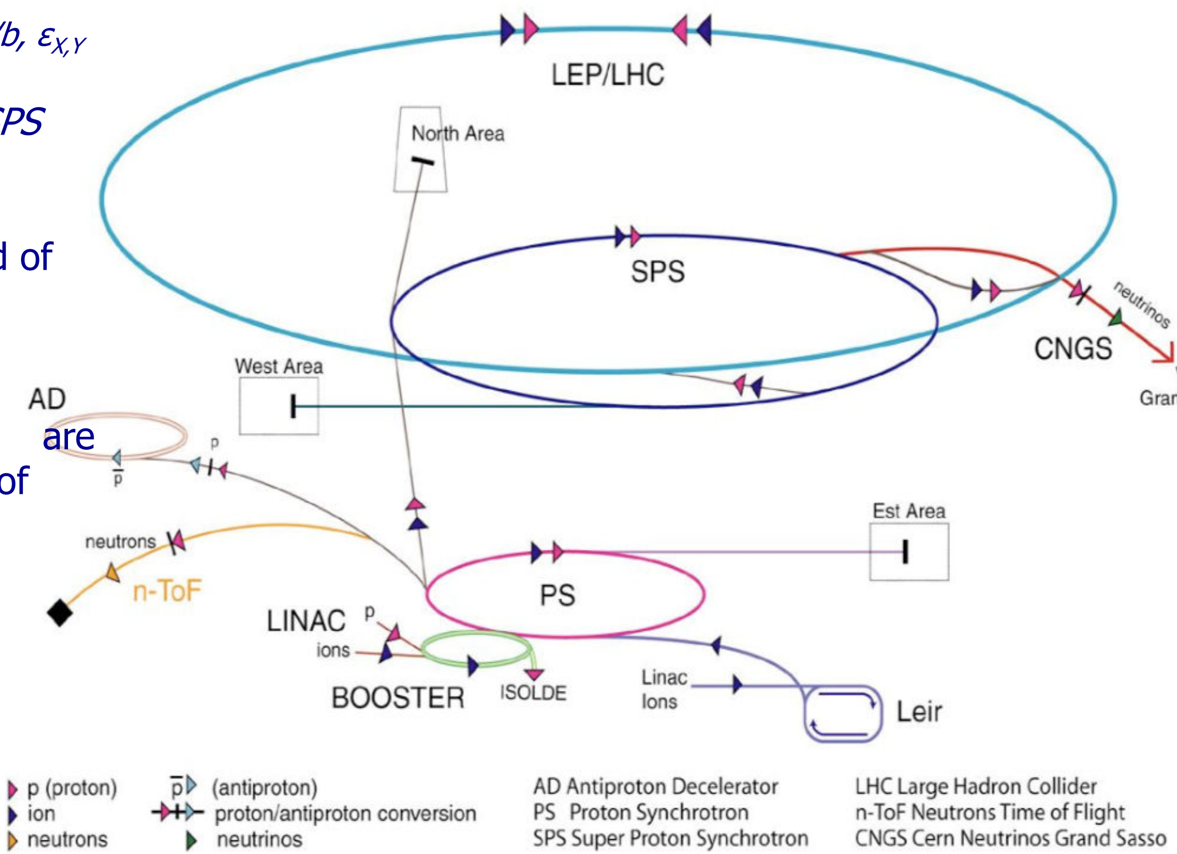
The CERN accelerators complex upgrade

✓ *The LHC-imposed beam brightness ($N_b / \varepsilon_{x,y}$) must be present from the lowest energy on (Liouville's theorem)*

- Beam loss is higher than foreseen: ultimate beam characteristics ($N_b = 1.7\ 10^{11}$ *p/b*, $\varepsilon_{X,Y} = 3.5$ *mm.mrad)cannot be obtained.* *Nominal* $N_b = 1.15\ 10^{11}$ *p/b achieved in the SPS*

- Operation is complicated and involves the control of many RF systems: risk of drift and of long duration of repair/re-adjustment

- Reliability is uncertain: many equipments are old (e.g. PS magnets) and used at the limit of their capability



Maximum beam intensity LHC year 1

design LHC intensity : 3.23×10^{14} protons / beam

1st years, limited by magnet quench / collimation

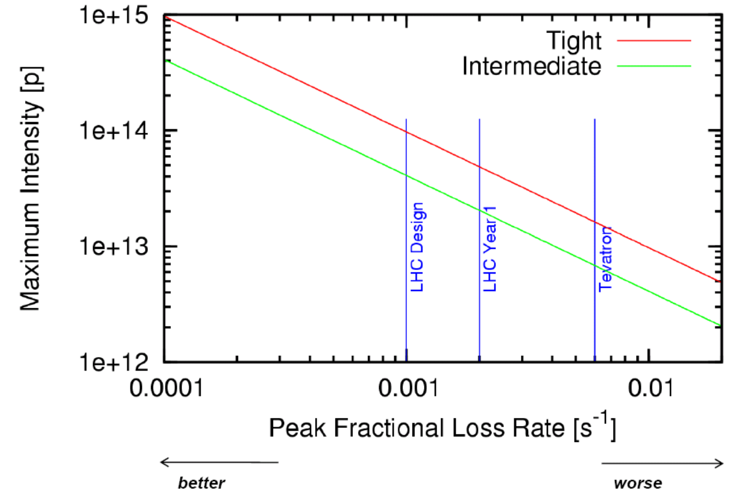
maximum beam loss rate ~ 10^{-3} /s fraction or ~4×10^{11} p/s

Examples for 0.001/s Loss Rate

- It is really the loss rate that matters above a few ms. So what counts is the ratio of loss amount over loss duration (short loss spikes are very dangerous). We get the peak loss rate 0.001/s from:
  - **1% of beam lost in 10 s.**
  - **0.1% of beam lost in 1 s.**
  - **0.01% of beam lost in 100 ms.**
  - **0.001% of beam lost in 10 ms.**
- Stick with the official loss rate 0.001/s from now on, adding some evolution.
- Assume 0.002/s is achieved in the first year of LHC operation at 5 TeV, as shown in following slides.

Ralph Assmann 21

Result: Intensity Limit vs Loss Rate 5 TeV



Ralph Assmann 18

 # bunches : nominal is 2808 bunches, 25 ns spacing

LHC year 1 : Important to go in small steps - minimize beam losses. Max. total intensity at 5 TeV roughly ~ 1/10 nominal.

start of physics run : $I < 2\times10^{13}$ p with intermediate coll. settings

later : $I < 5\times10^{13}$ p with tight coll. settings.

3.5 TeV intensities could be a bit higher - details remain to be worked out

Scaling of beam parameters with energy

Baseline beam parameters for E_b = 5 TeV have been worked out, discussed and agreed, LPC 7/5/09
Details for 3.5 TeV still need to be defined.

		scale factor 3.5 to 5 TeV
intensity	more critical at high E	take 1 ; conservative
emittance	E^{-1}	1.43
β*	~ E^{-1} triplet aperture	1.43
Luminosity	~ E^{-2}	2
beam-beam tune shift	constant	1

Luminosity estimates : roughly 2× less at 3.5 TeV compared to 5 TeV
this should be conservative and does not take into account that lower energies are less critical for protection, shorter ramp time and faster turnaround.

Beam-beam tune shift parameter ξ
for head-on collisions depends only
on intensity (not energy, β*)

$$\xi = \frac{r_p N}{4\pi \epsilon_N}$$

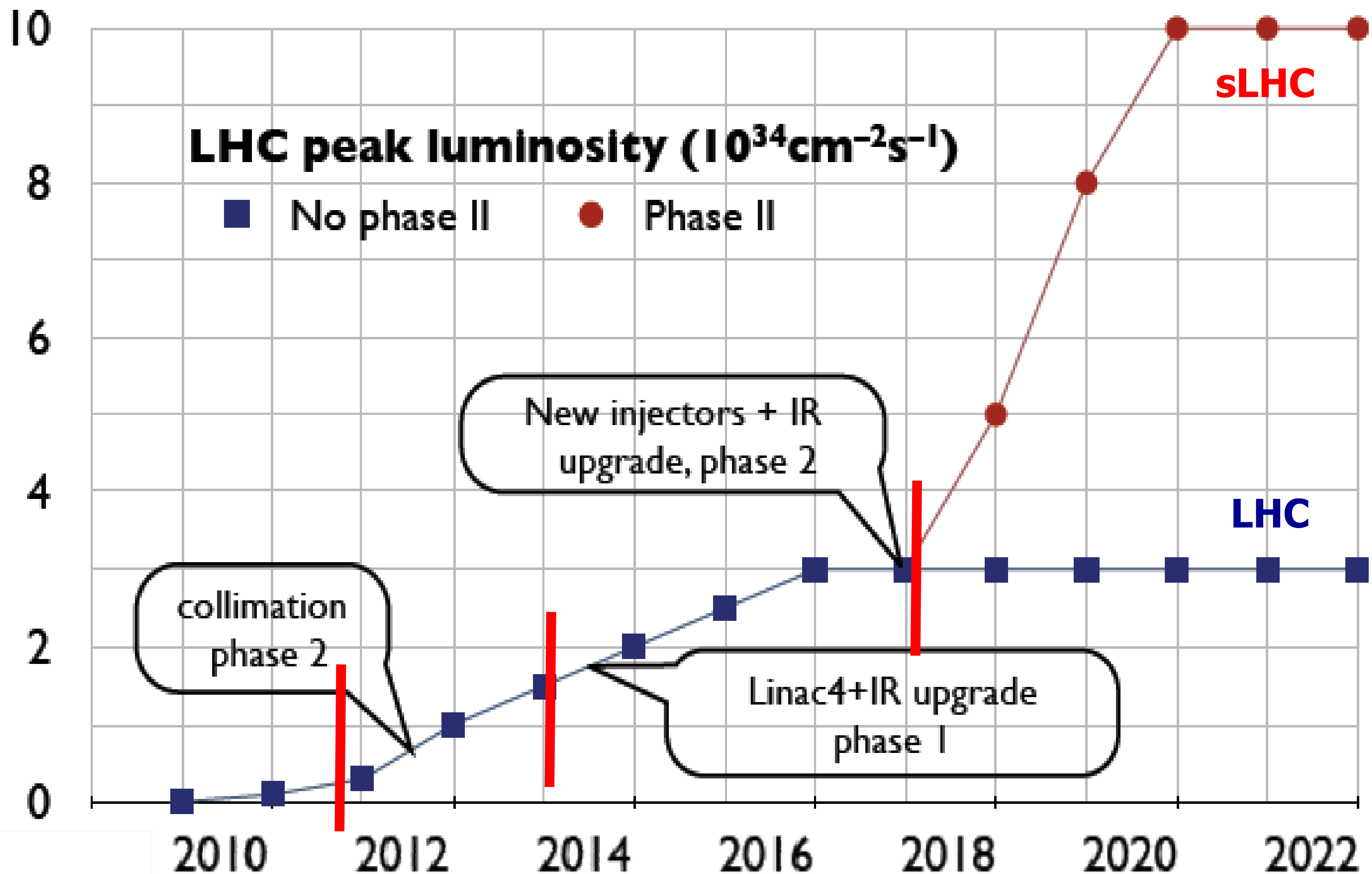
nominal LHC : round beams and const ε_N

$$\sigma_{x,y} = \sqrt{\beta_{x,y}\,\epsilon_N/\gamma}$$

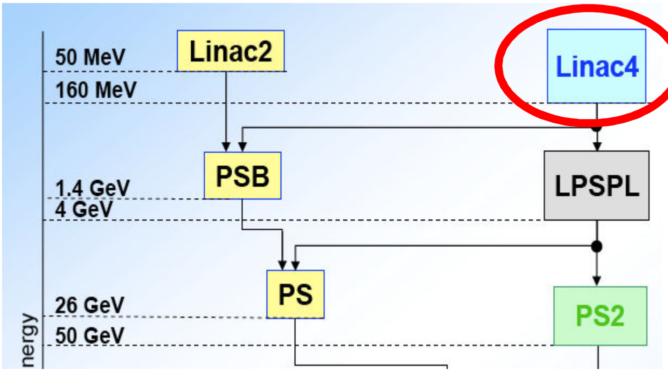
N	ξ
5×10^9	0.000163
4×10^{10}	0.00130
1.15×10^{11}	0.00374

at the design emittance

Luminosity road map in 2 phases



Phase I upgrade brings us to end of the LHC mandate

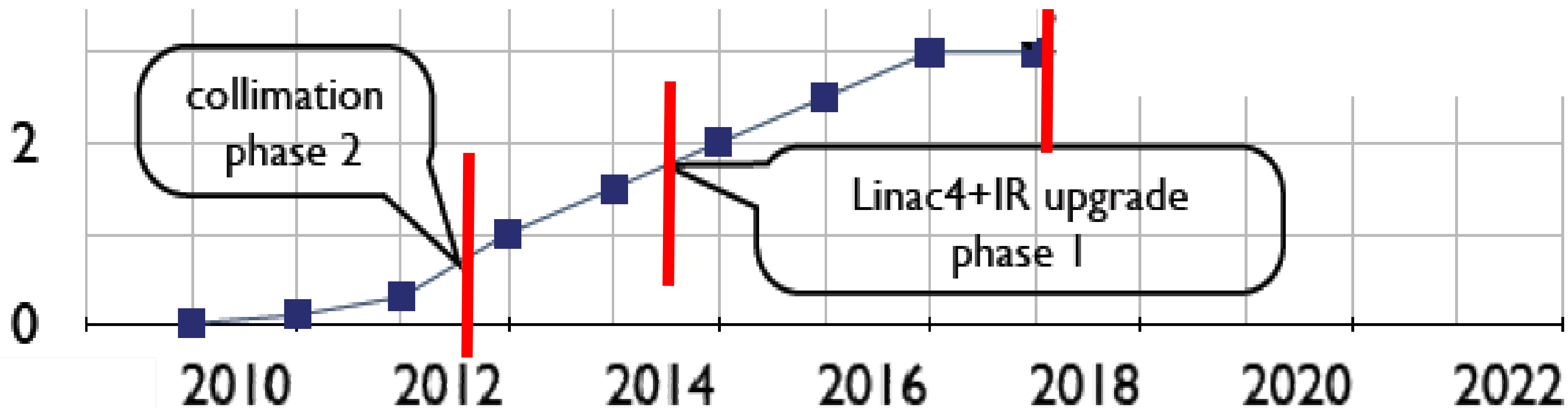


Linac4 higher performance:

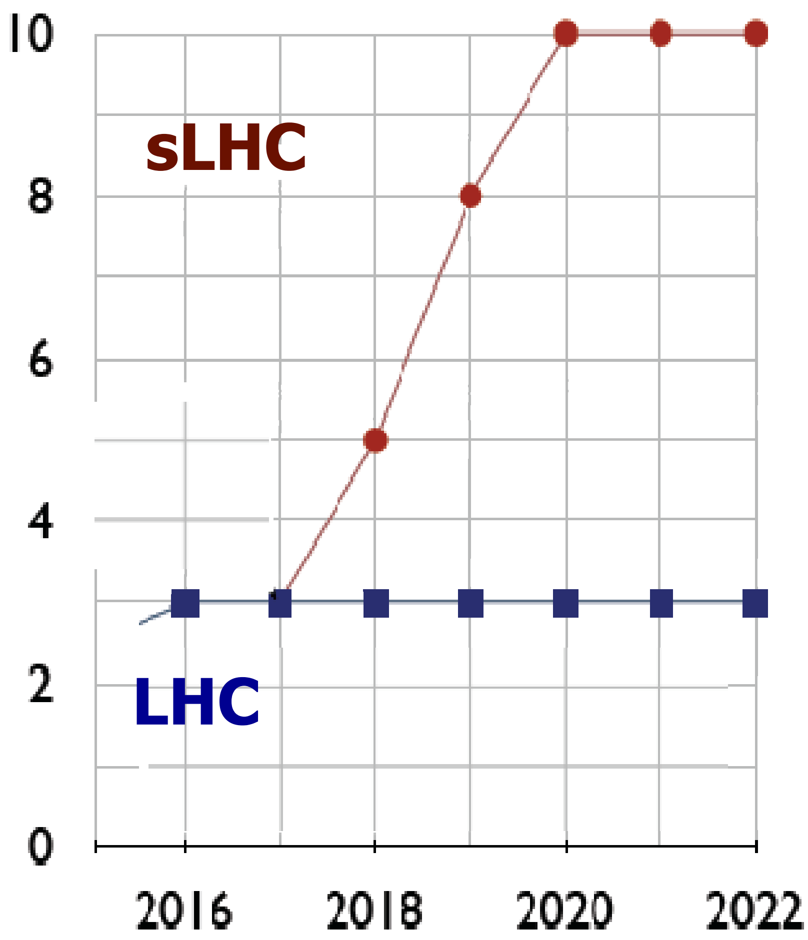
Space charge decreased by a factor of 2 in the PSB, factor 2 gain in $\beta\gamma^2$

$\Rightarrow$ potential to double the beam brightness at constant tune shift and fill the PS with the LHC beam in a single pulse

- ✓ *Linac-4 approved and construction work has started*
- ✓ *Allows to increase the LHC current to "ultimate" which is 2.3 times the nominal*
- ✓ *New Inner Triplet focusing magnets. Larger aperture, allows β^* of 0.25 m, L x 2 !*
- ✓ ***The expectation is that these two improvements will allow a ramp-up to 3 x nominal Luminosity, 120-180 fb^{-1} /year***



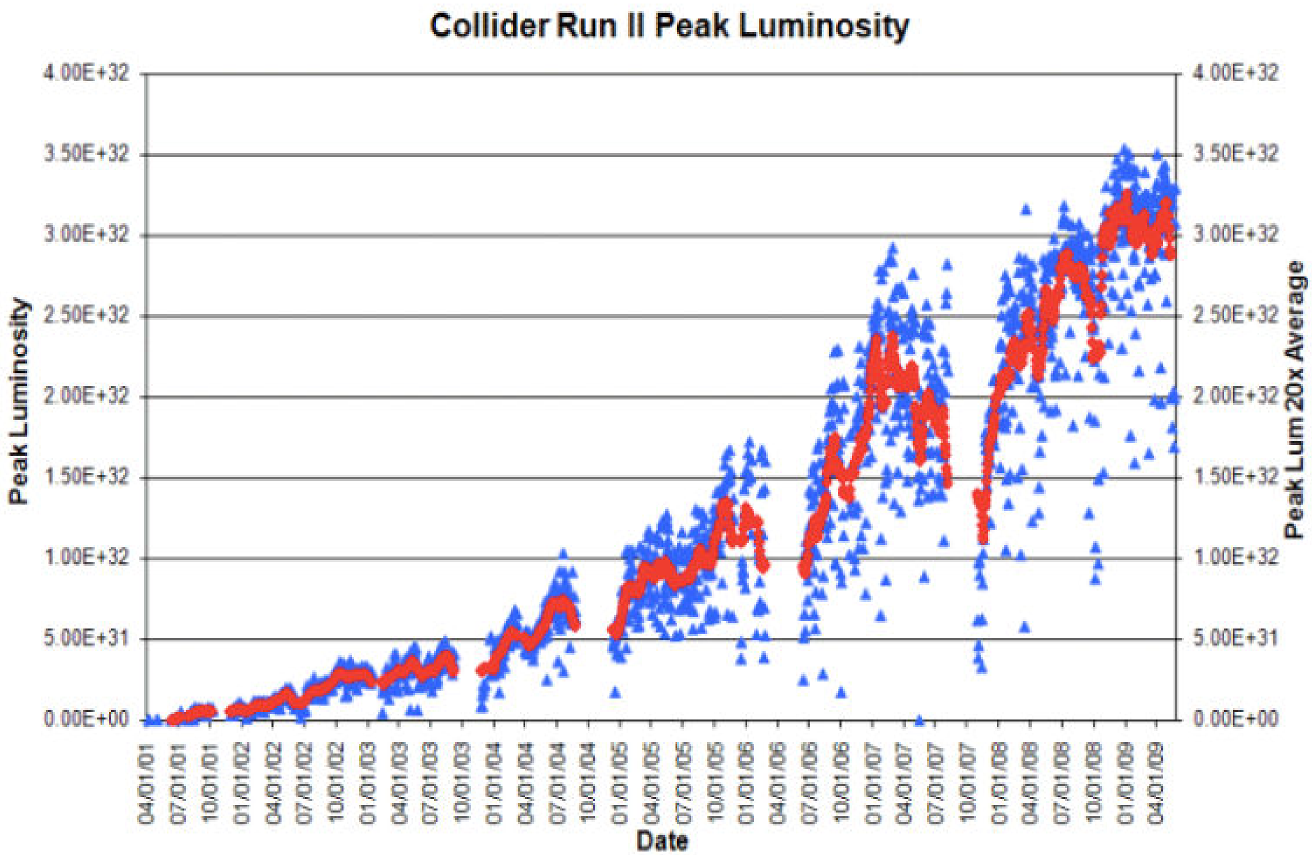
Why should we go beyond 600 fb^{-1}: sLHC ?



10 times more statistics, is there a physics motivation for 3000 or more fb^{-1}?

Whatever the decision will be, in 8-9 years from now the pp detectors will need a major upgrade; some components like the Inner Detectors will be suffering from aging and radiation damage

Lesson from the Tevatron



The lesson from the Tevatron is that once data are available, the experimental ingenuity can deliver the "impossible" (M.Mangano)

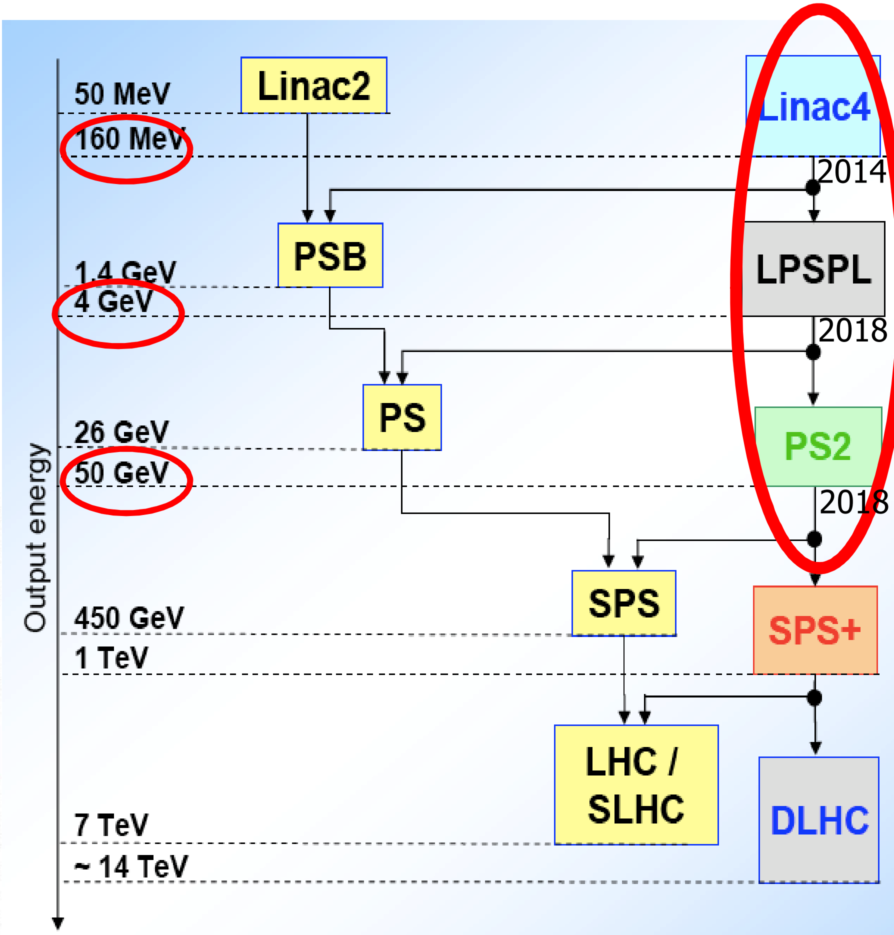
..but it also says that it takes time

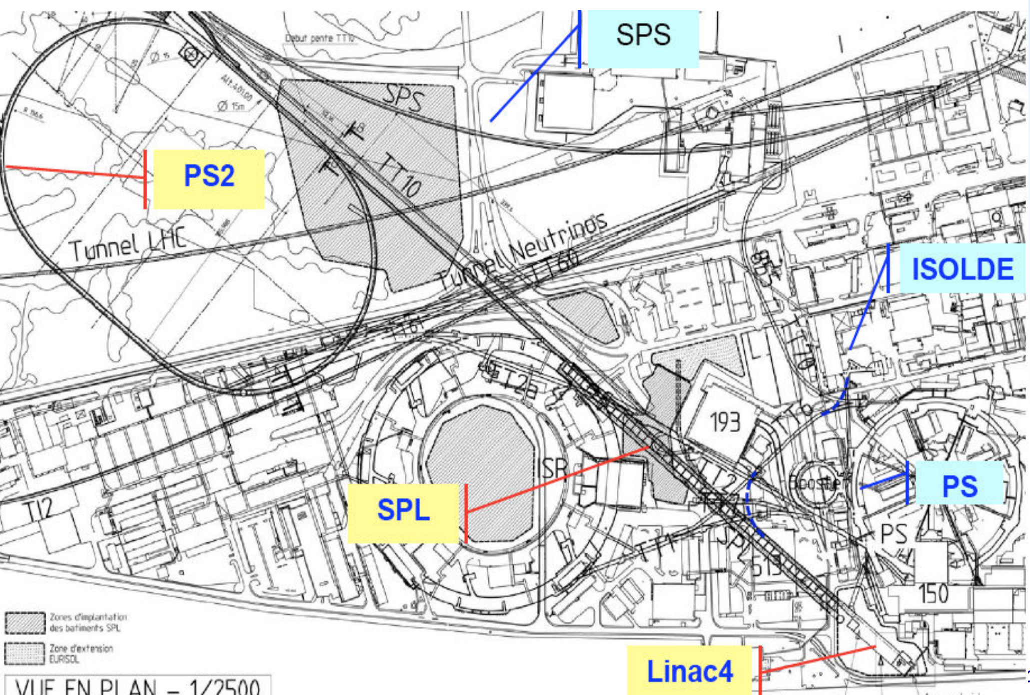
The CERN injectors complex upgrade

✓ Beam at sLHC injection shall have up to twice the ultimate brightness

(N_b =3.4$10^{11}$ p/b, $\varepsilon_{X,Y}$ =3.7 mm.mrad)

⇒ Simple operating mode
⇒ Margin in beam performance
⇒ Margin in equipment ratings
⇒ Advantage of shorter LHC filling time





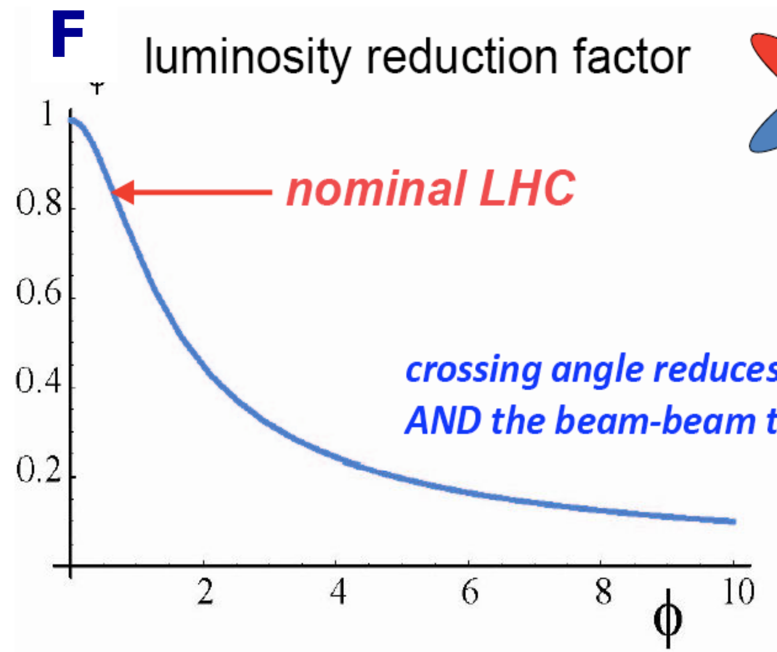
✓ Linac4 project has started, ready in 2014 for phase I

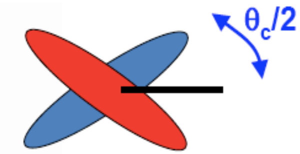
Peak Luminosity also depends on the IR properties

$$L = \frac{N_b^2 n_b f_r \gamma}{4\pi\varepsilon_n \beta^*} F$$

N_b number of particles per bunch
n_b number of bunches
f_r revolution frequency
ε_n normalised emittance
β^* beta value at Ip
F reduction factor due to crossing angle

N_b, ε_n → injector chain
β^* → LHC insertion
F → beam separation schemes
n_b → electron cloud effect





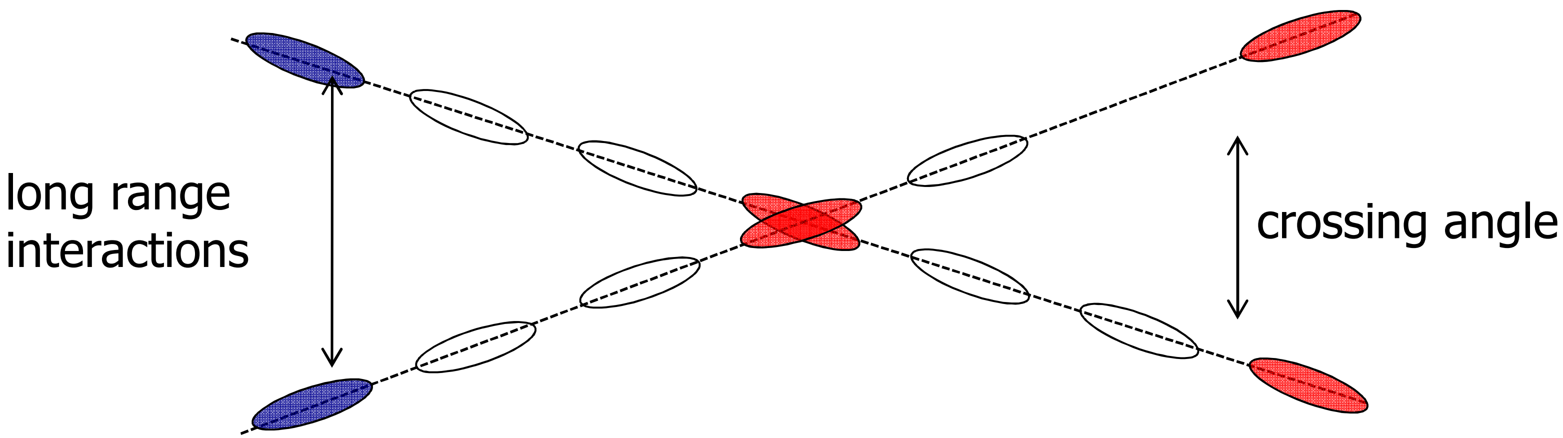
effective beam size $\sigma \rightarrow \sigma/F$

crossing angle reduces the luminosity AND the beam-beam tune shift

$$\mathbf{F} = \frac{1}{\sqrt{1+\phi^2}}; \quad \phi \equiv \frac{\theta_c \sigma_z}{2\sigma_x} \quad \text{"Piwinski angle"}$$

beam-beam tune (ΔQ) shift proportional to **F** *and beam brightness (beam stability)*

Crossing angle : the LHC solution !



~30 long range beam beam interaction per IP

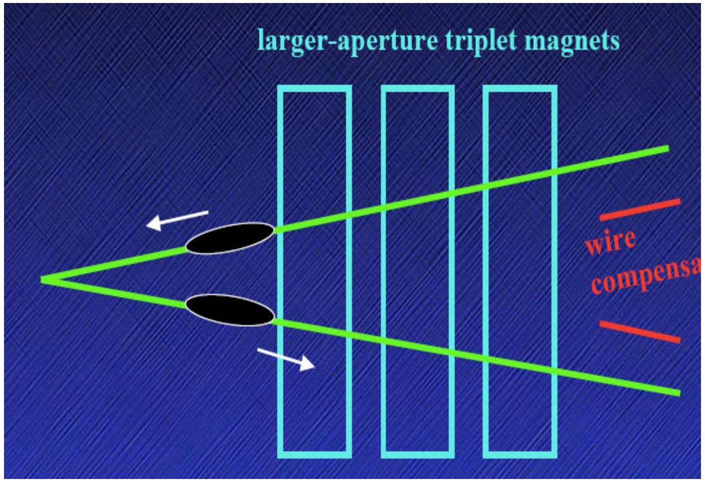
tune shift would increase 30 times without crossing angles

To increase Luminosity choose between head-on collisions, large beam brightness, minimize transverse emittance …. or a combination of them …

… but minimize beam beam tune shift ΔQ_{bb}

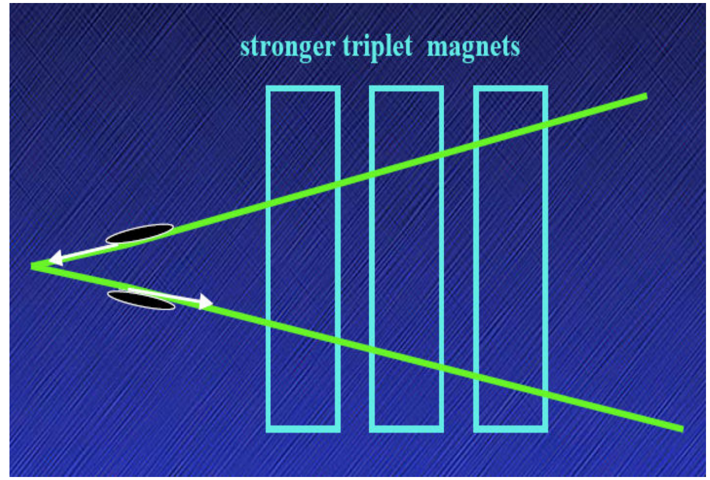
Several solutions still possible !!

Large Piwinski angle (LPA)



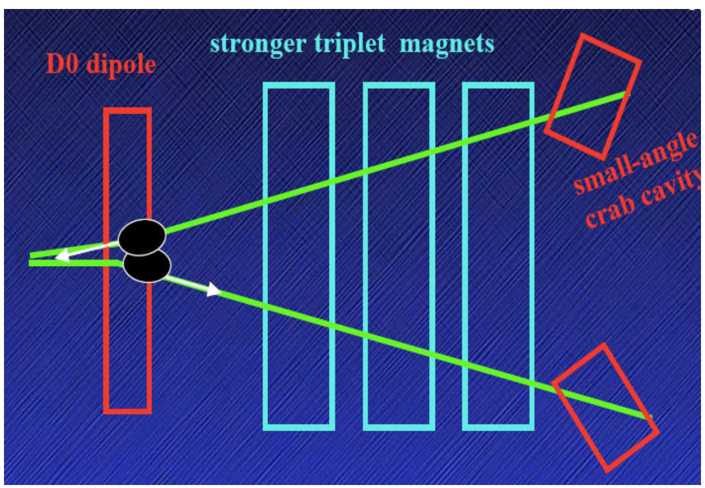
50ns, flat intense bunches, $\theta_c \sigma_z >> 2 \sigma_x$

Low transverse emittance (LE)



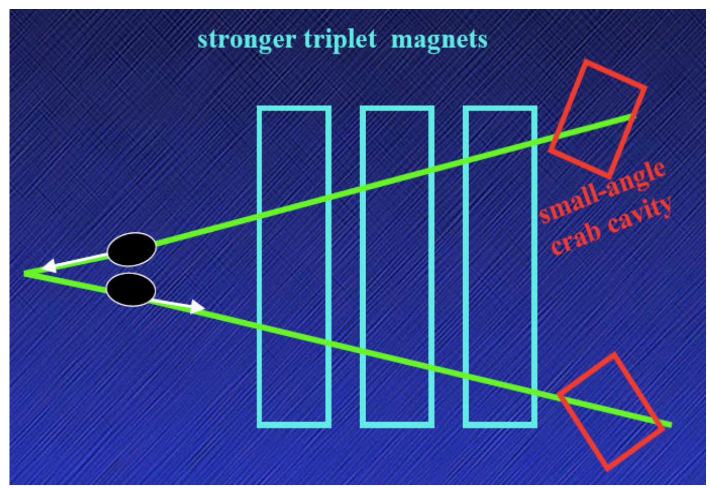
Constraint on new injectors, γε~*1-2 μm*

Early separation + crab cavities (ES)



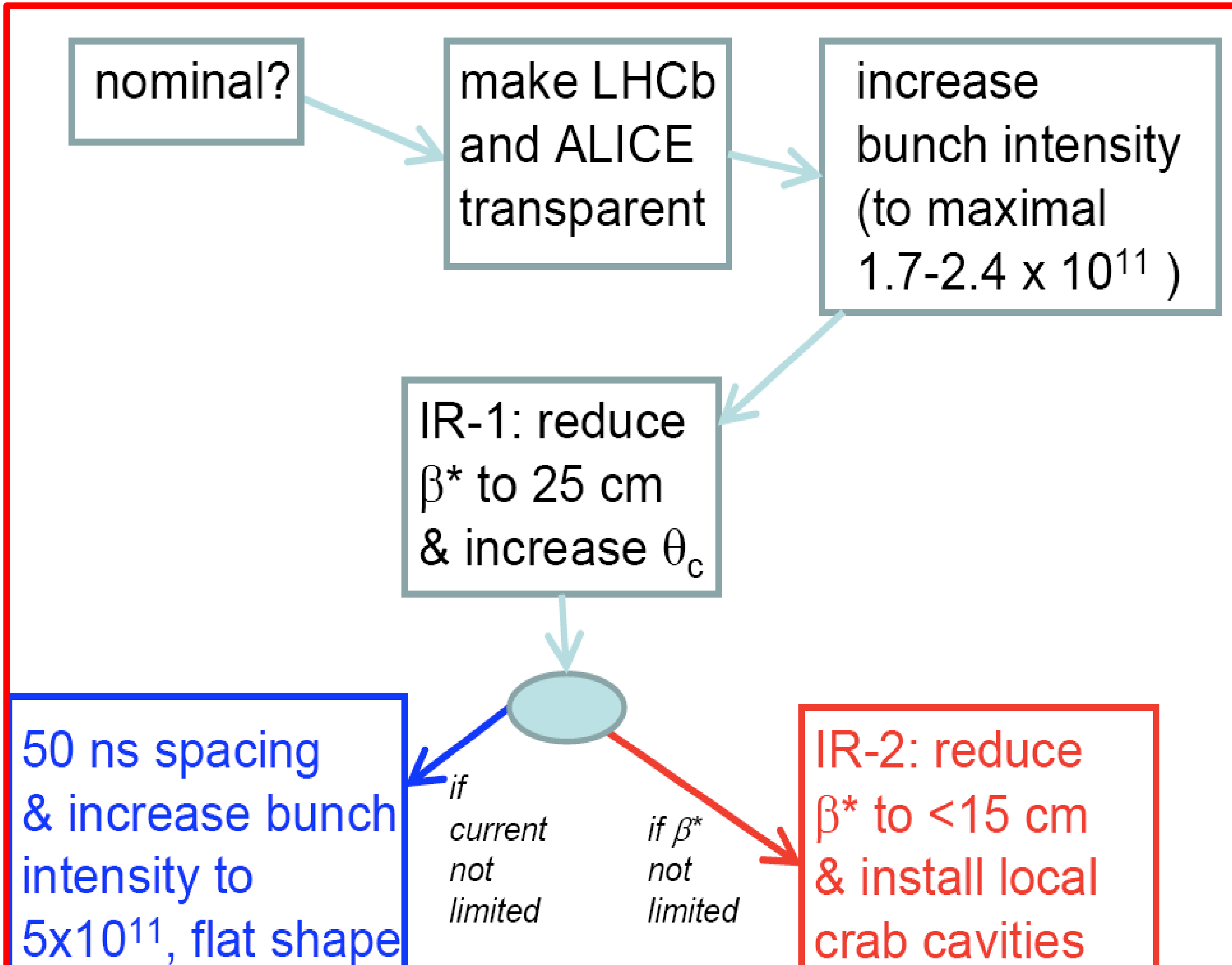
Dipoles inside the experiments

Full crab crossing (FCC)



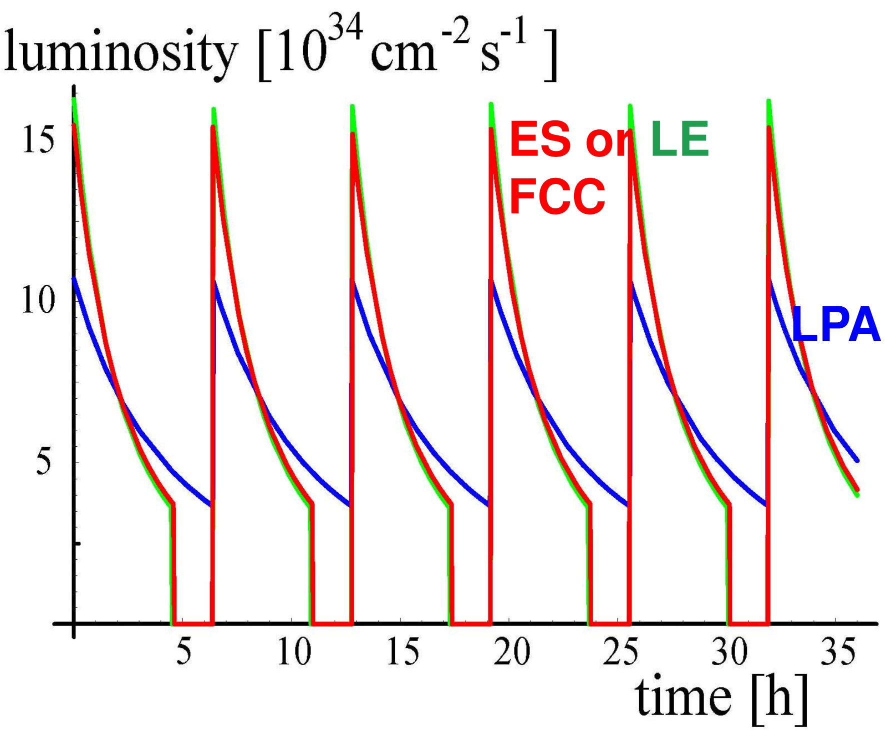
Crab cavities with 60% higher voltage

Possible Luminosity Upgrade road map

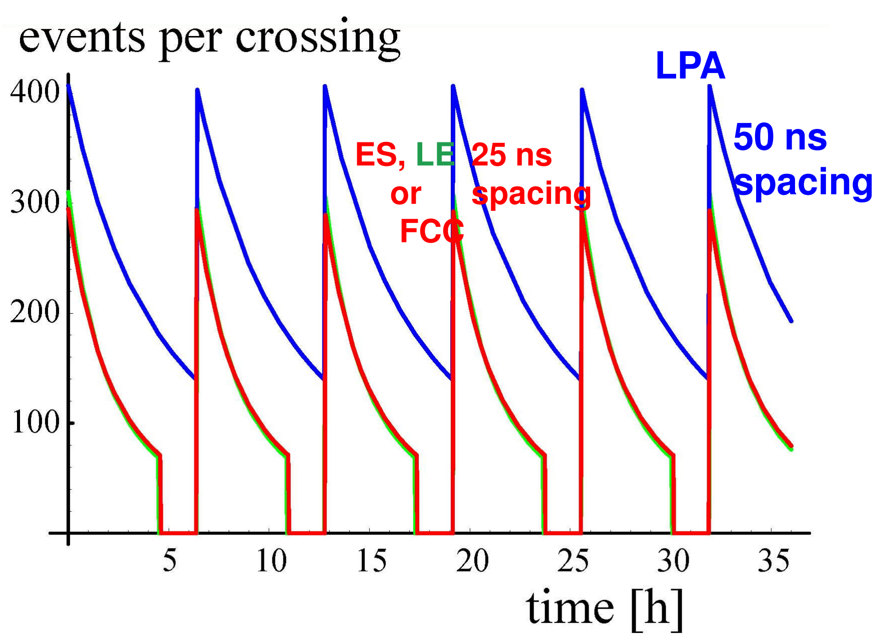


F. Zimmerman 2009

Luminosity life time



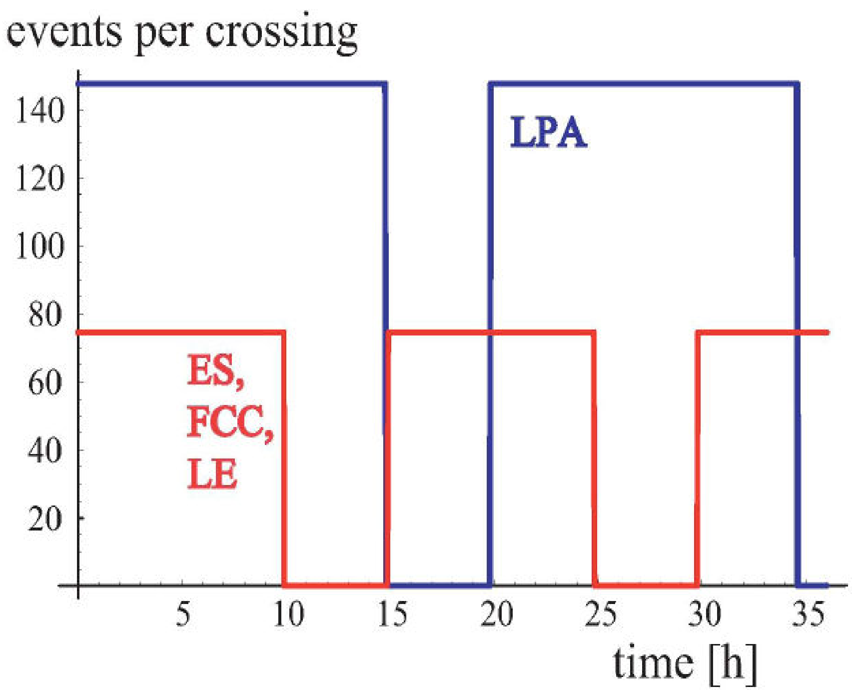
Very inefficient way to use the beam, very difficult experimental environment at the very beginning of the fill, short cycles (5-6 hours)



expected very fast decay of luminosity (few hours) dominated by proton burn-off in collisions

$$\tau_{eff} = \frac{N_b n_b}{n_{IP} \hat{L} \sigma_{tot}}$$

The solution : Luminosity Leveling



Flat luminosity profile (~80 events per crossing, ~10 h fill lifetime for leveling with crossing angle

Optimize Integrated Luminosity vs. Peak Luminosity

***Luminosity leveling* (changing dynamically θ_c , β^* or σ_z in store to keep** luminosity constant) becomes a powerful strategy to reduce event pile up in the detector & peak power deposited in IR magnets

Leveling with crossing angle has distinct advantages:

- increased average luminosity if beam current not limited
- operational simplicity

Natural option for early separation or crab cavities

Planning the future

- **Workshop on new injectors** (Chamonix 2010?)
- Tests/studies on the different IP schemes
- Tests on the luminosity leveling
- ……

….and for the experiments

- Improve detector and background modeling, based on the real LHC environment experience
- Minimize cavern background (new TAS, forward shielding)
- Assess and understand detectors performances as luminosity grows
- Improve the trigger capabilities to cope with ~ factor 5-10 higher amount of hard collisions, in particular at level 1 (μseconds scale)
- Build new low mass beam pipes
- Prepare to rebuild the inner detectors (tracking), mostly using silicon technology

To conclude

- By year 2013, **experimental results** will be dictating the agenda of the field.
- Early discoveries will greatly accelerate the case for the construction of the next facilities (sLHC, Linear Collider, ν-factory …)
- No time to idle, no time to be shy!

Very exciting years are ahead of us!