An application for research
LHC

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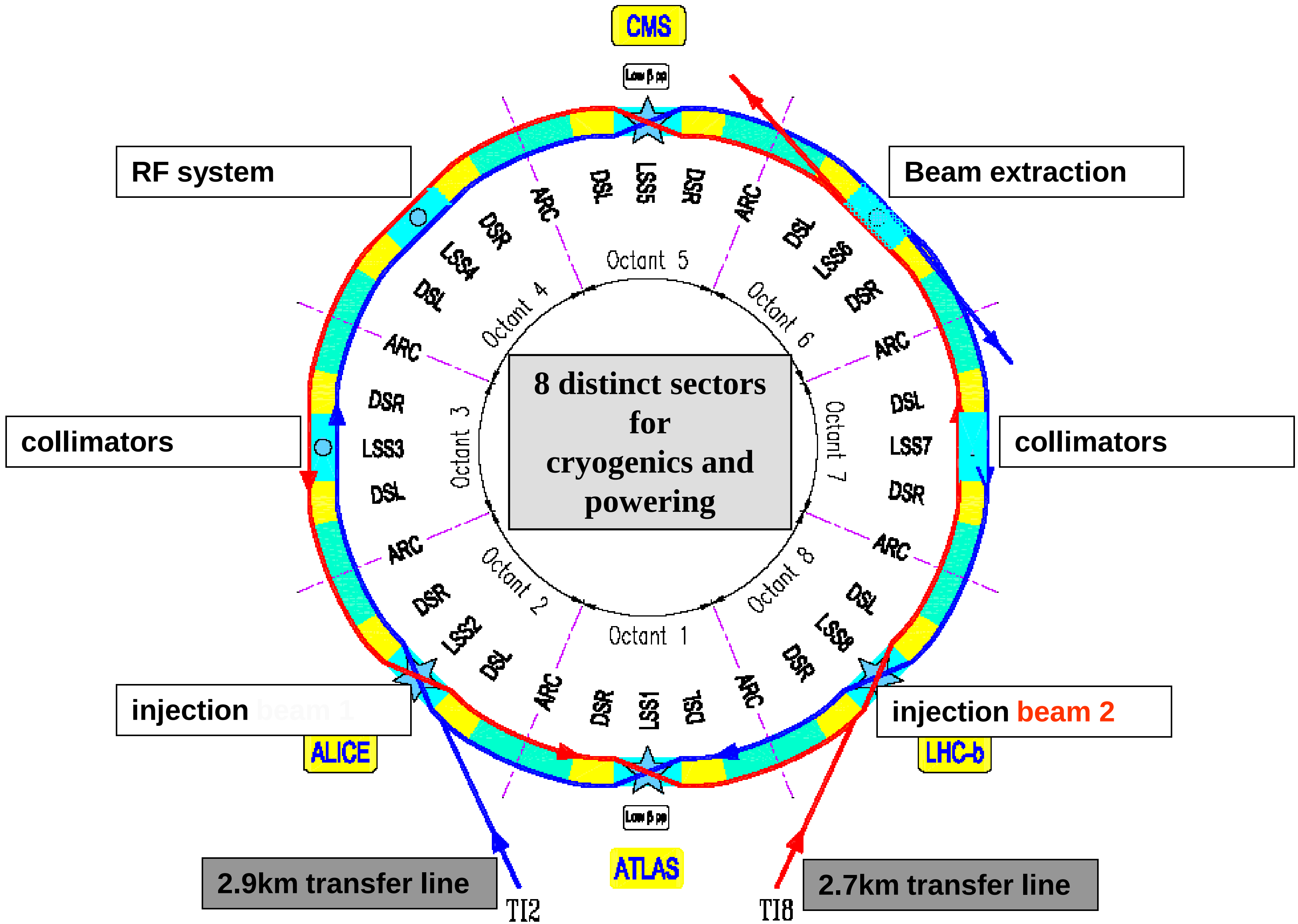
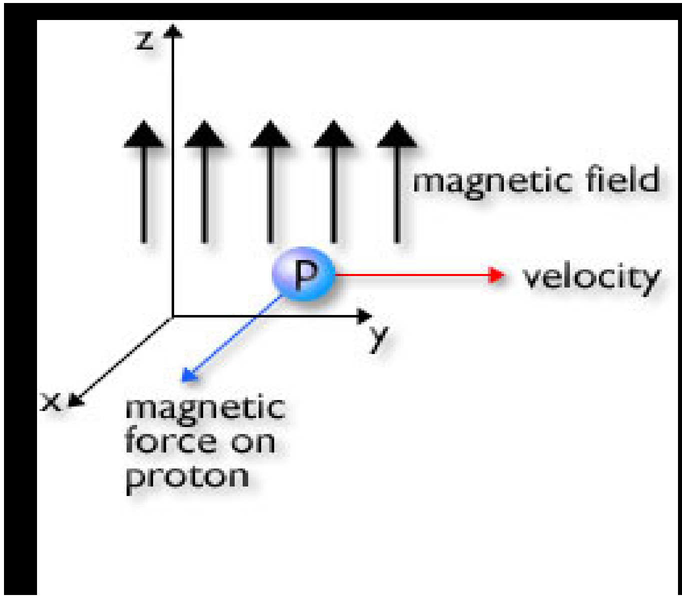
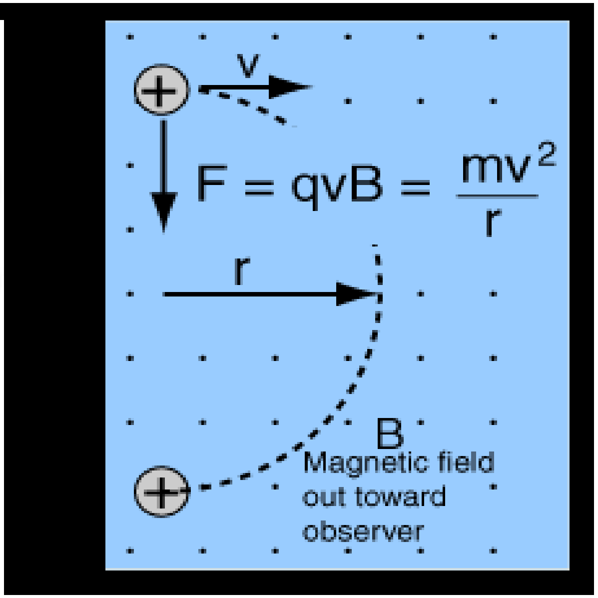
Schematic of the LHC



Most of the 27km is filled with magnets

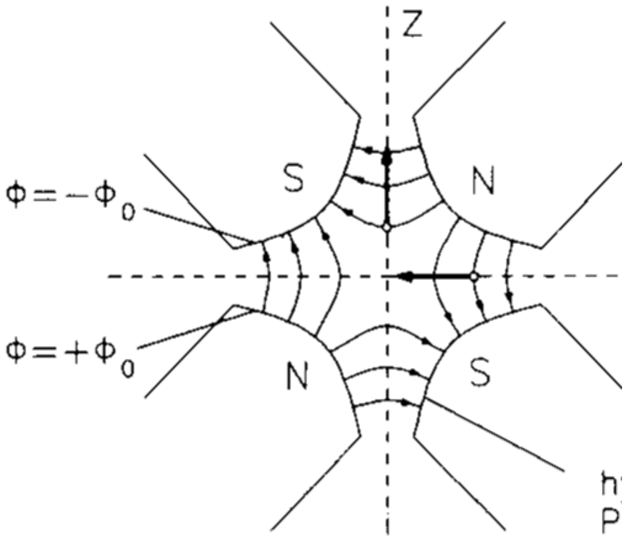
- Dipole magnets bend the beam
- The more energy, the greater the magnetic field
- P and Pbar would counter-circulate

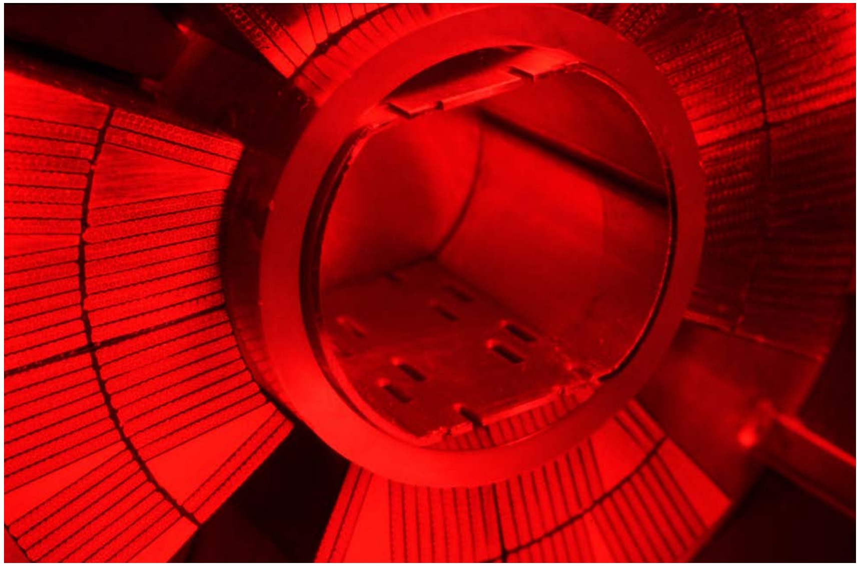




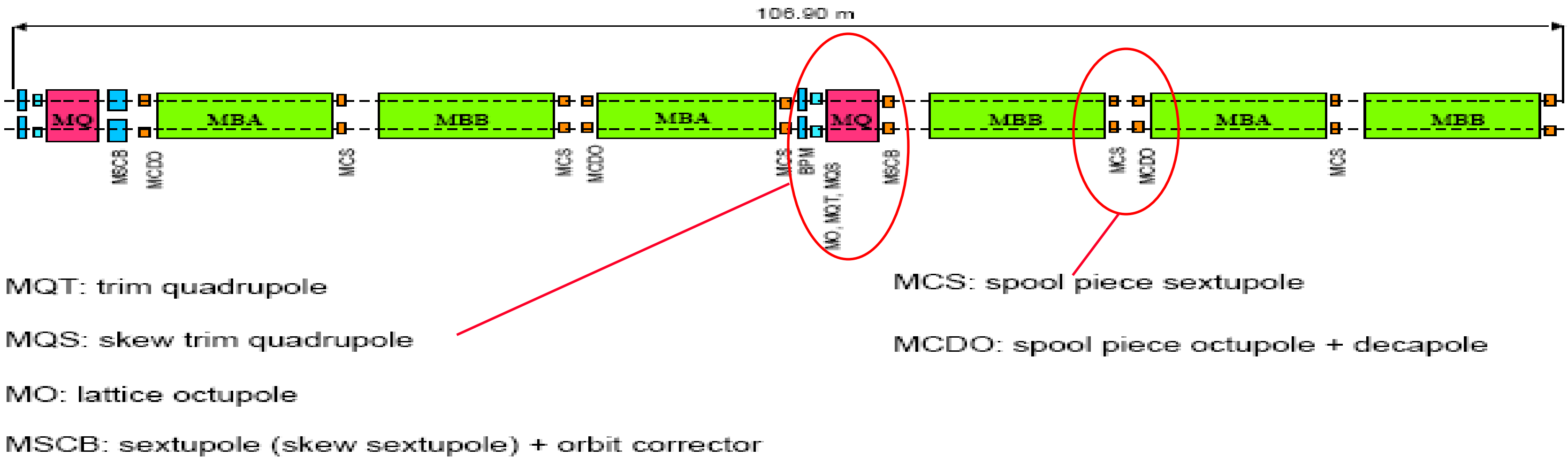
Most of the 27km is filled with magnets

- Quadrupole magnets focus the beam
- Focus in one plane, defocus in the other
- FODO cell (alternate gradient focusing)





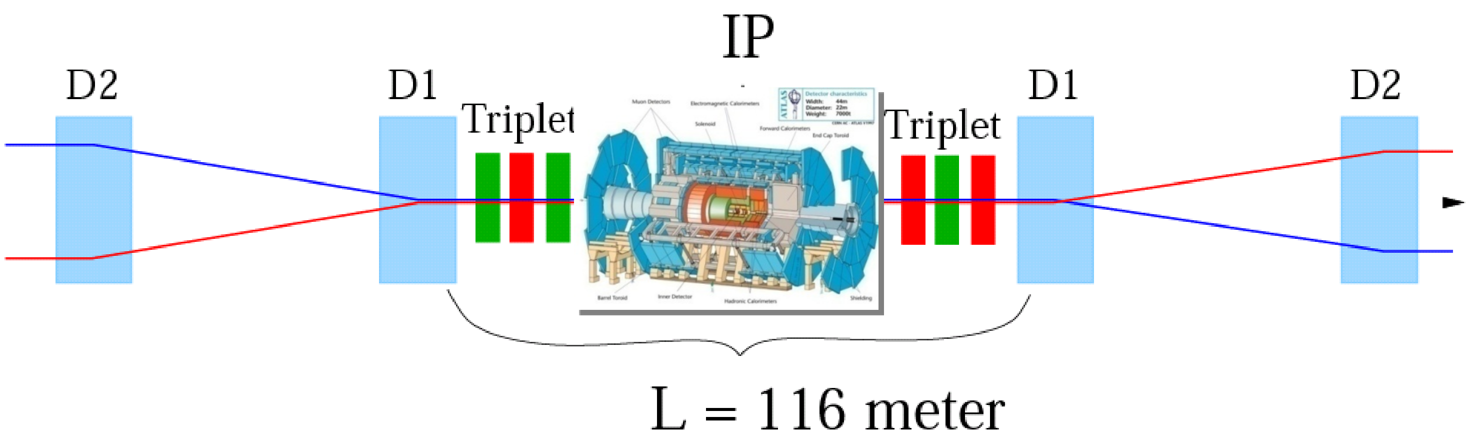
The arcs

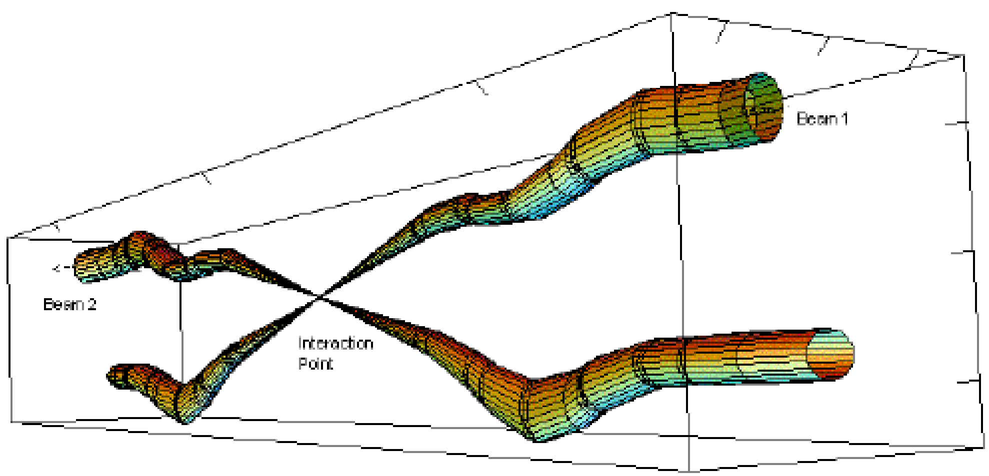


- 23 regular FODO cells in each arc
- 106.9m long, made from two 53.45m long half-cells
- Half cell
  - 3 15m cryodipole magnets, each with spool-piece correctors
  - 1 Short Straight Section (~6m long)
    - Quadrupole and lattice corrector magnets

Insertion regions (points 1, 2, 5, 8)

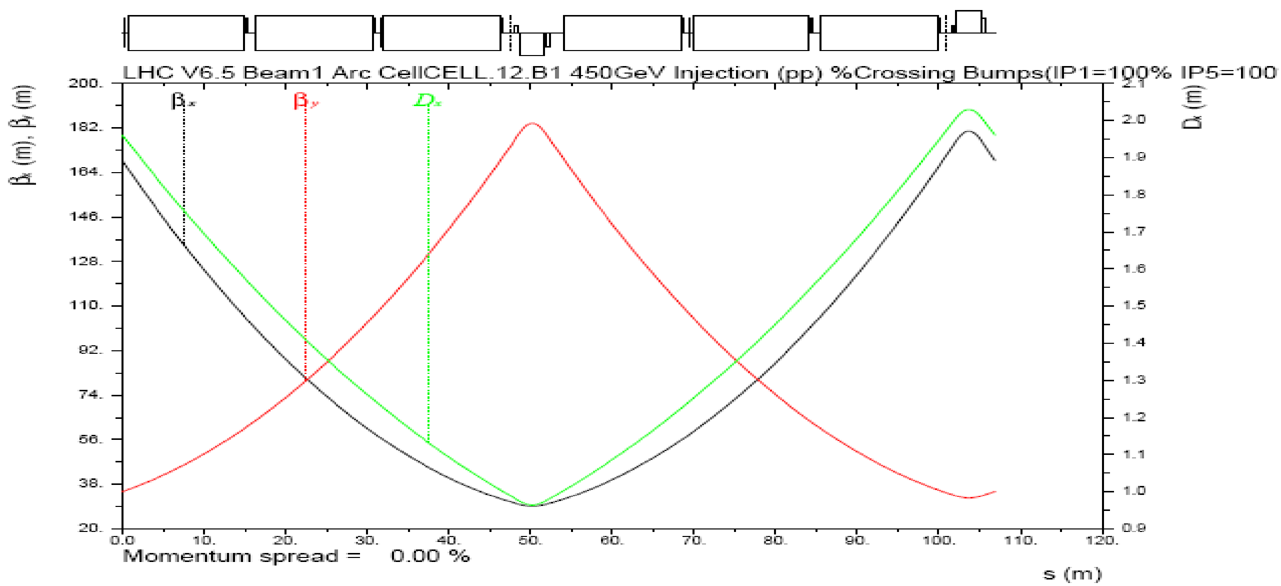
Bring beams on axis and focus them at the interaction point

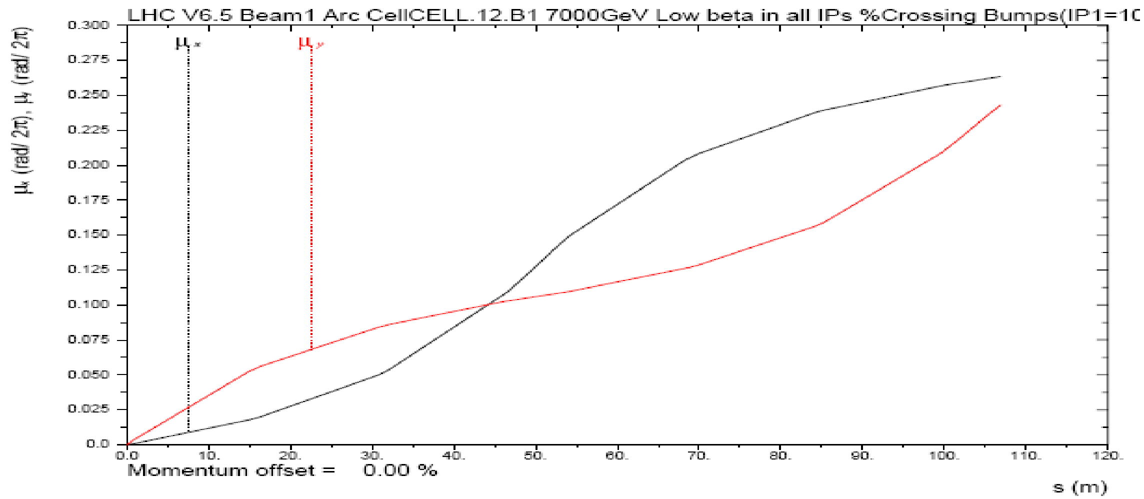




Relative beam sizes around IP1 (Atlas) in collision

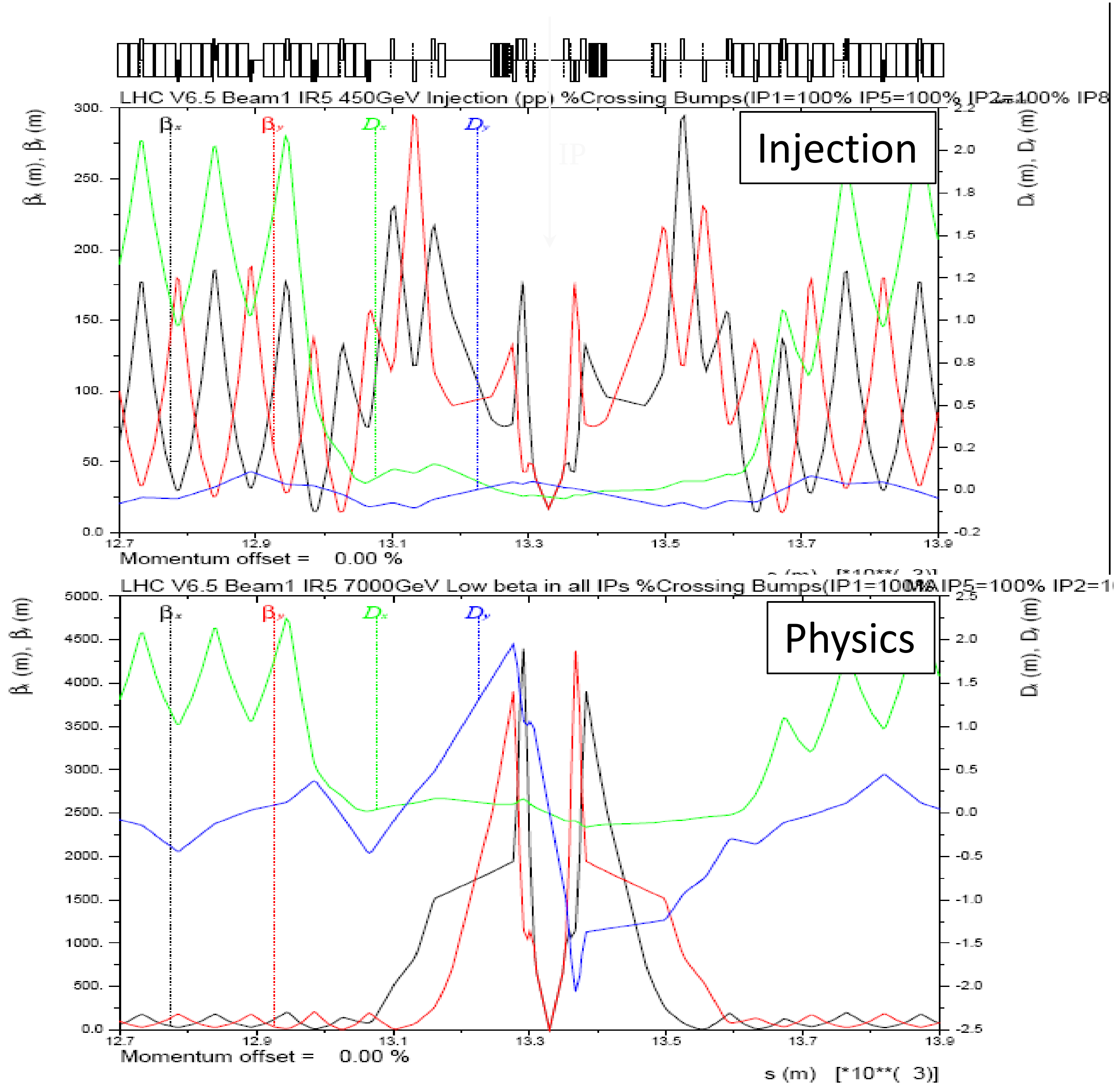
Optics in the arc cell





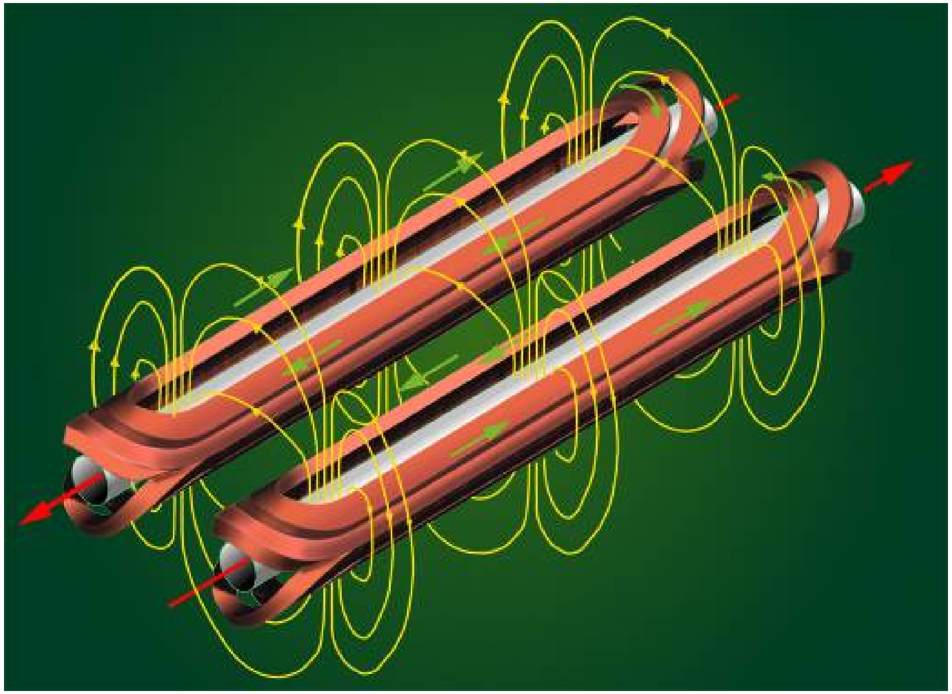
Optics in IP5

$$\sigma = \sqrt{\varepsilon\beta}$$



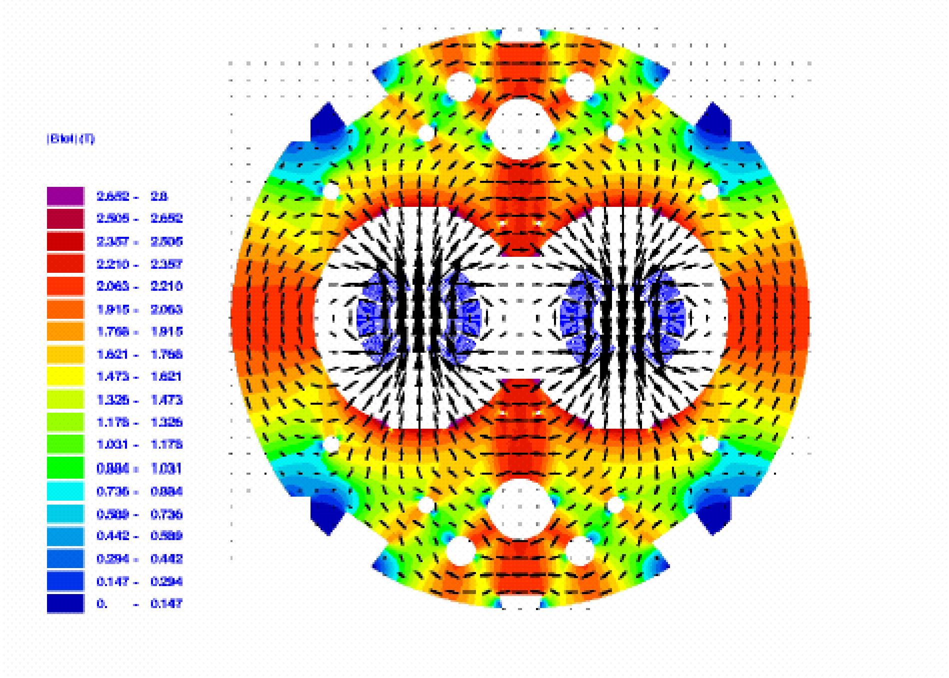
Principal LHC design parameters

- Luminosity (defines rate of doing physics) 10^{34} cm^{-2} s^{-1}
  - Need lots of particles to achieve this rate
  - Hence proton – proton machine (unlike Tevatron or SppbarS)
  - Separate bending fields and vacuum chambers in the arcs

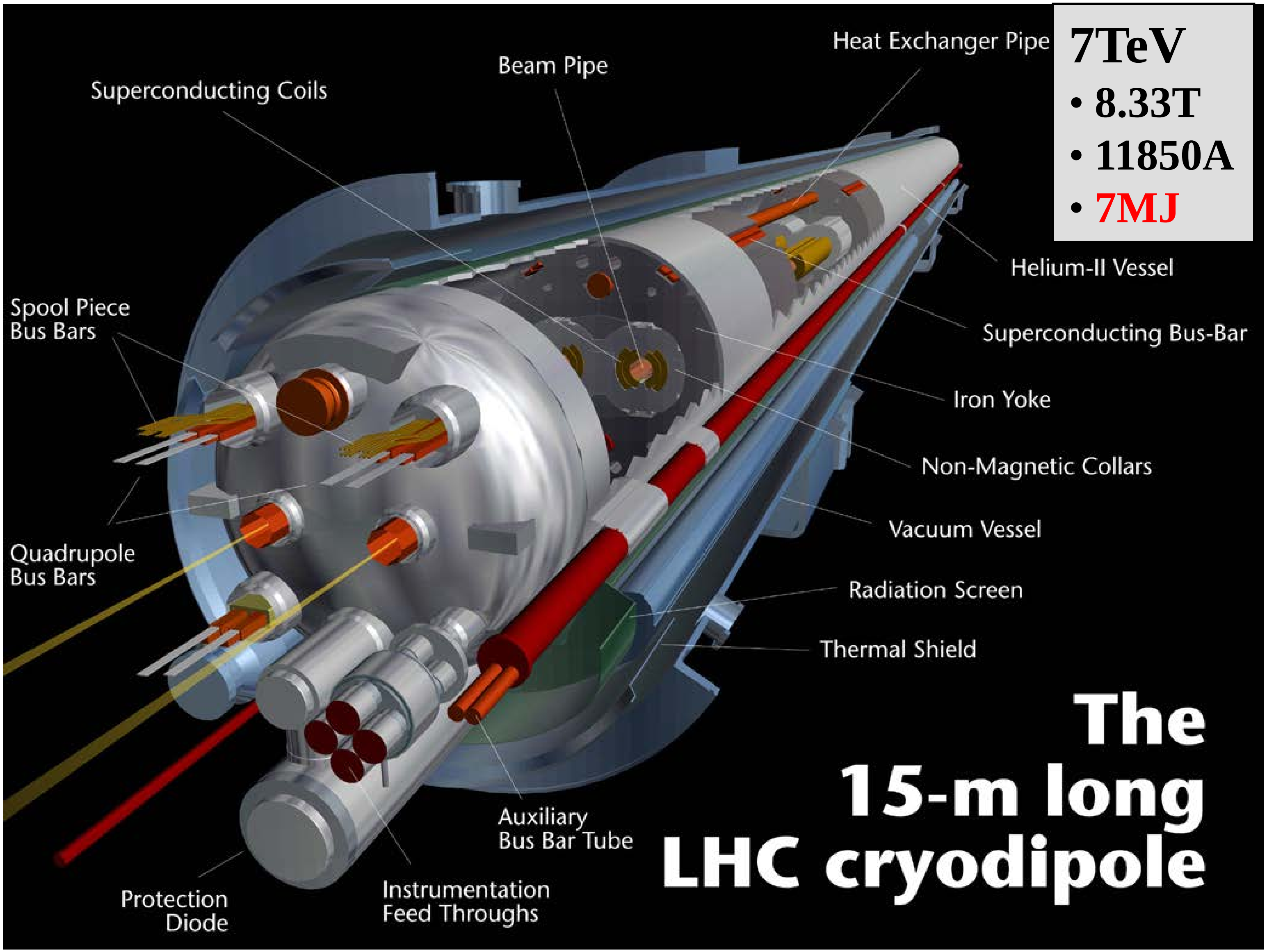


Principal LHC design parameters

- Energy 7TeV per beam ⬄ Dipole field 8.33Tesla
  - Superconducting technology needed to get such high fields
  - Tunnel cross section (4m) excludes 2 separate rings (unlike RHIC)
  - Hence twin aperture magnets in the arcs



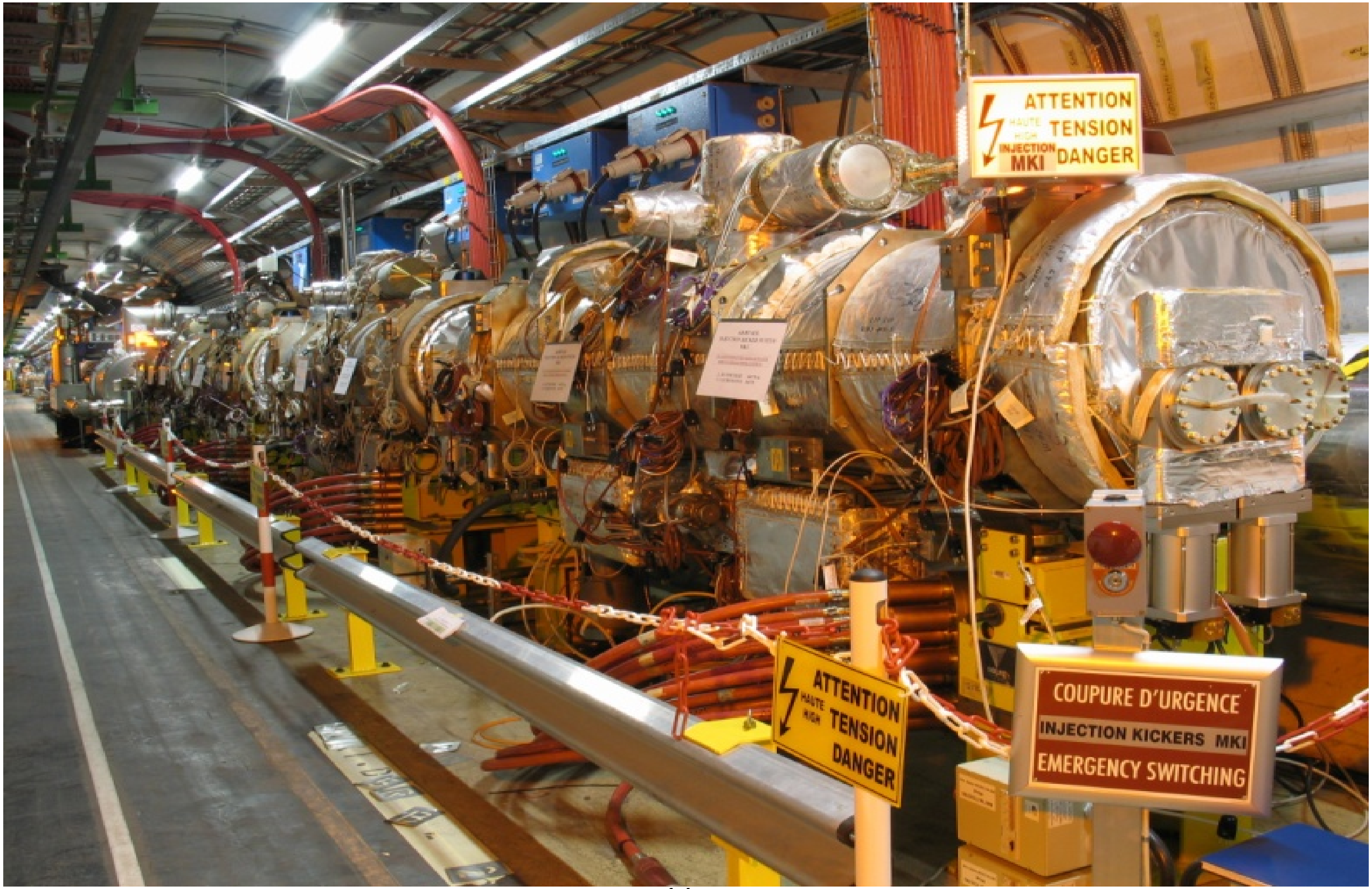
LHC dipoles (1232 of them) operating at 1.9K



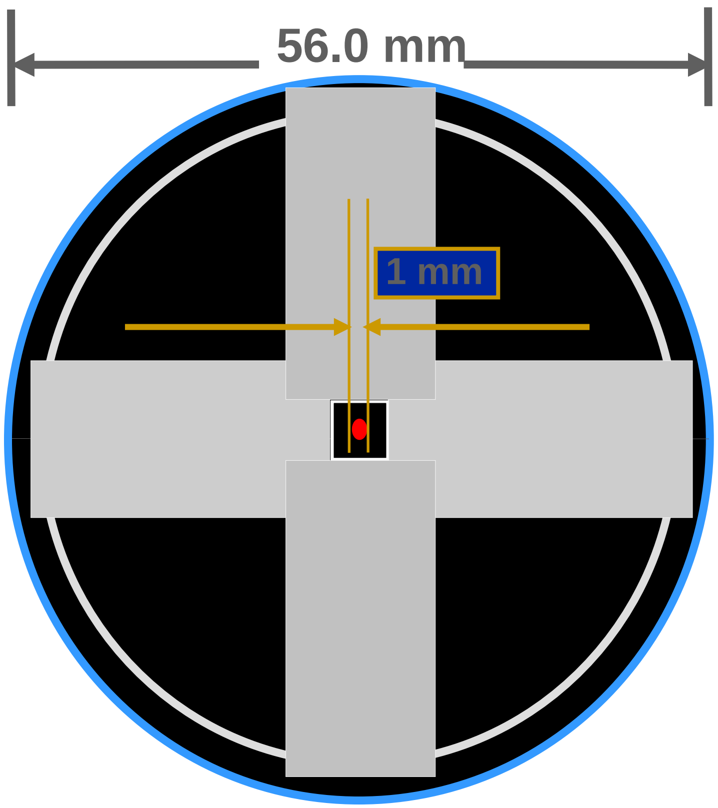
Cooled by liquid helium, distributed over 27km

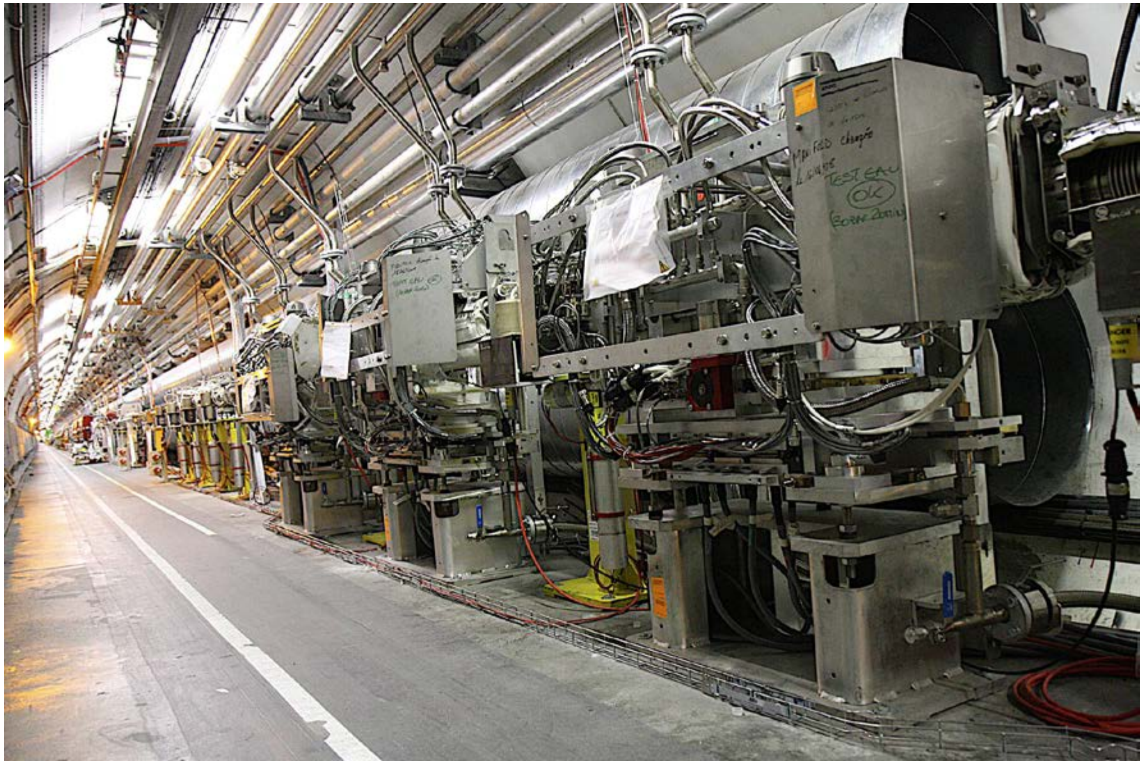
LHC arc

Injection systems (points 2 and 8)

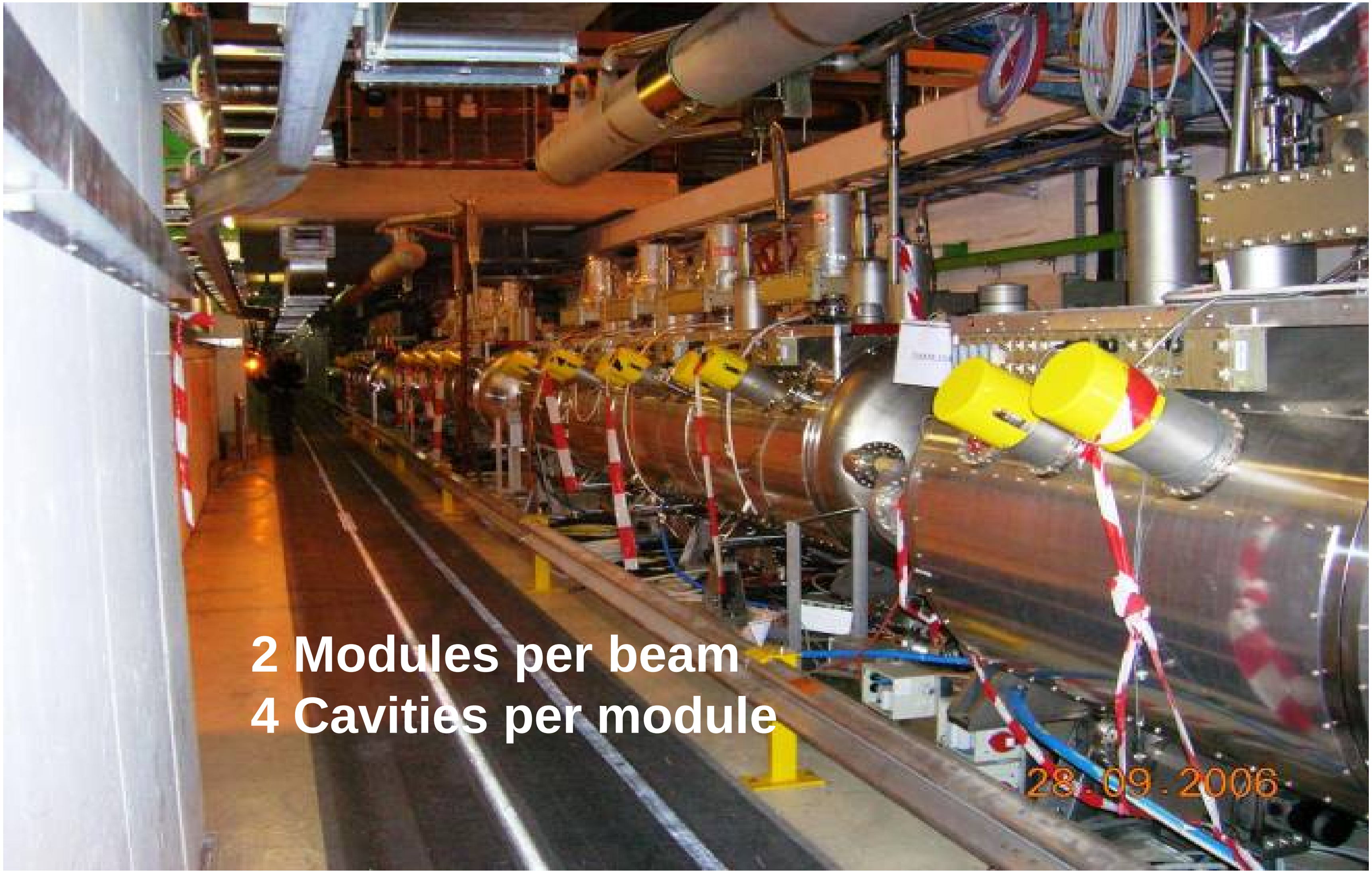


Collimators (points 3 and 7)

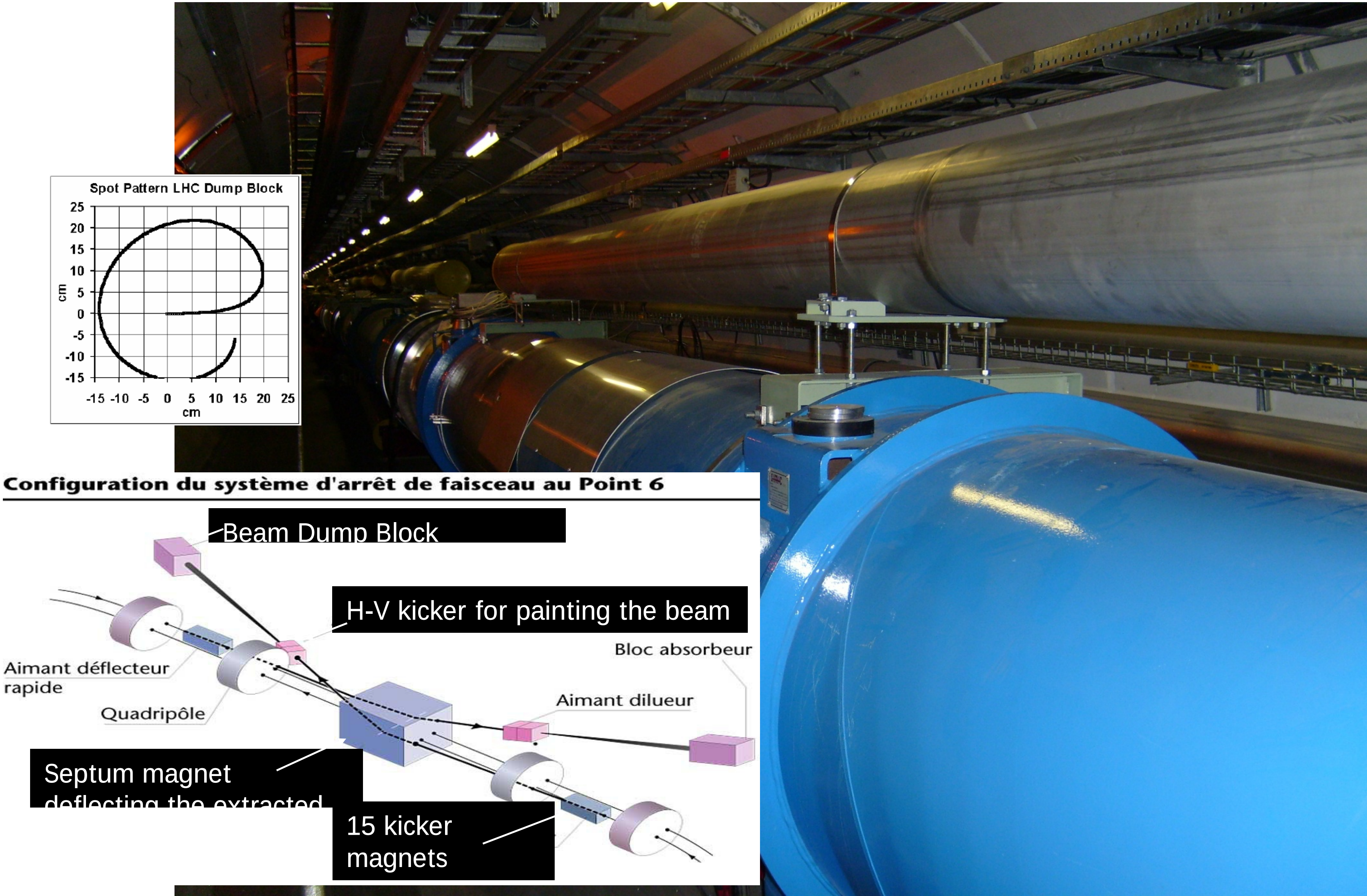




RF systems (point 4)

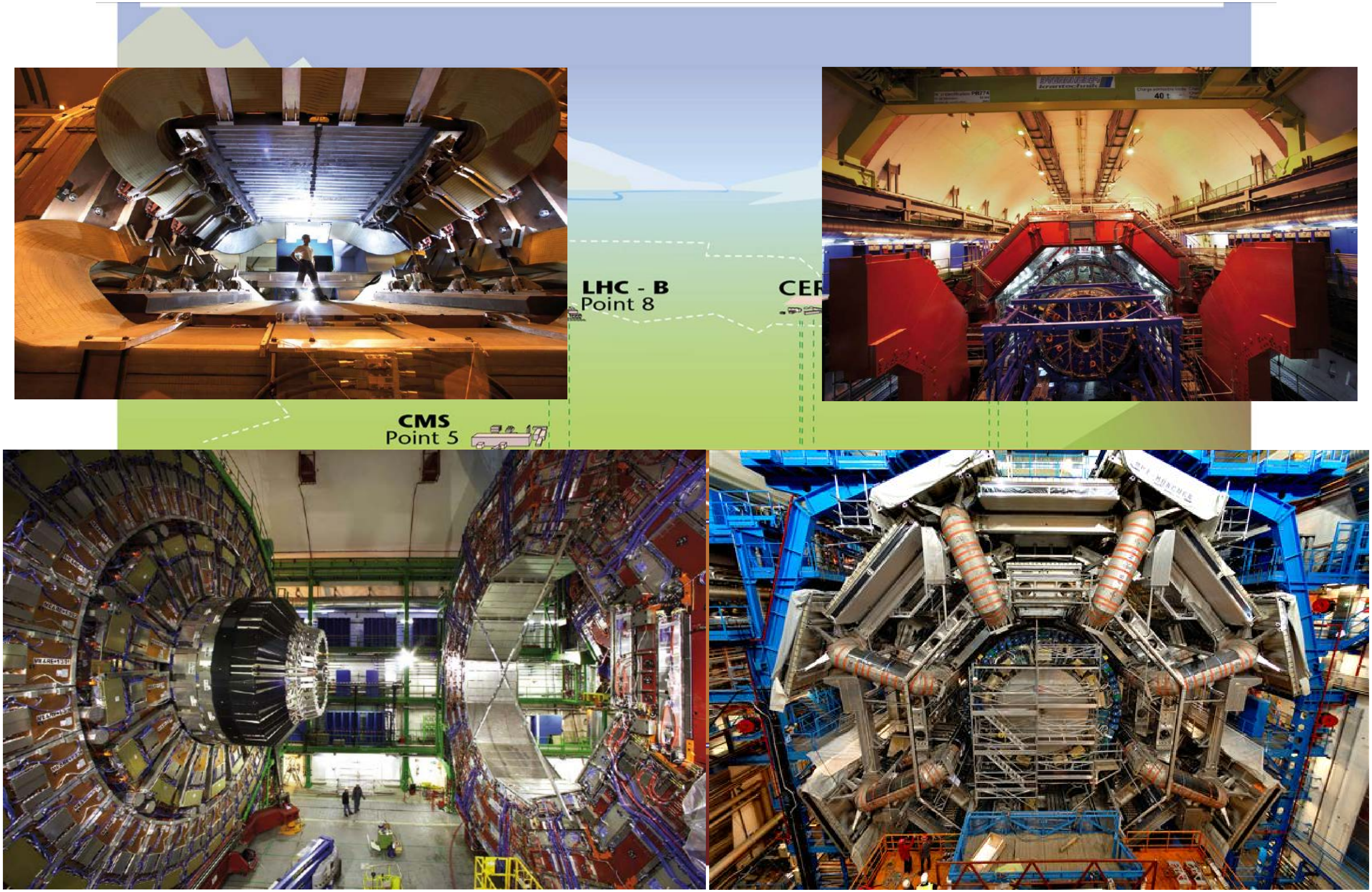


Beam extraction (point 6)



Triplets (points 1, 2, 5, 8)

Experiments (points 1, 2, 5, 8)



So what is the LHC for ?

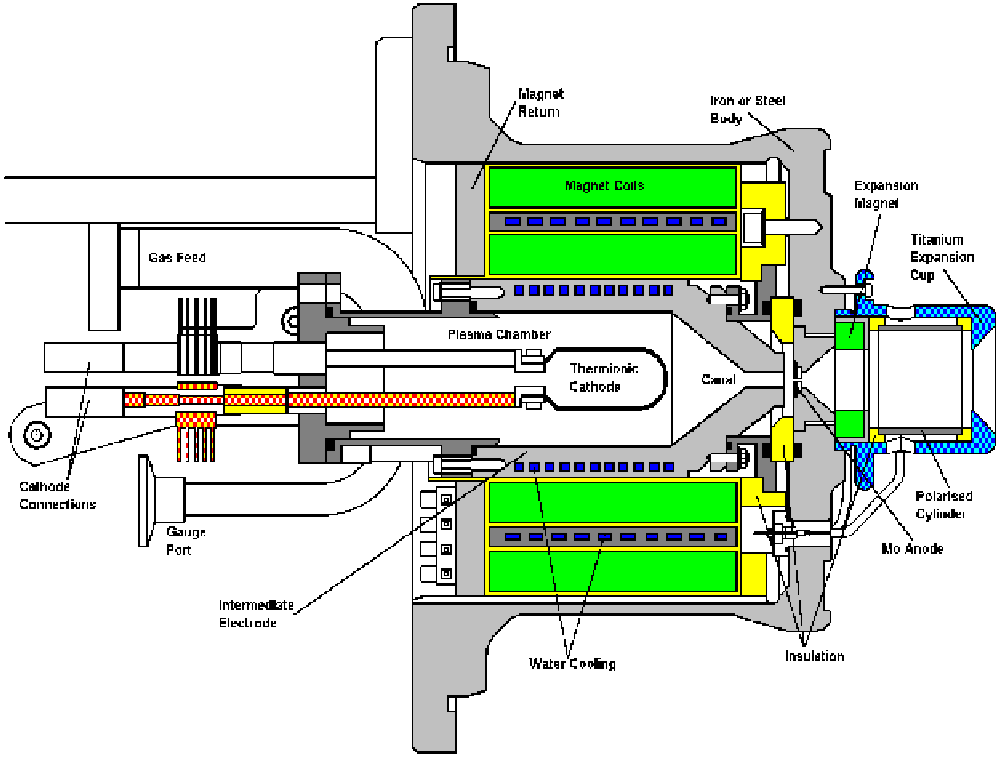
- Despite the Standard Model's effectiveness at describing the phenomena within its domain, it is nevertheless incomplete

- The LHC was built to help answer some key unresolved questions in physics

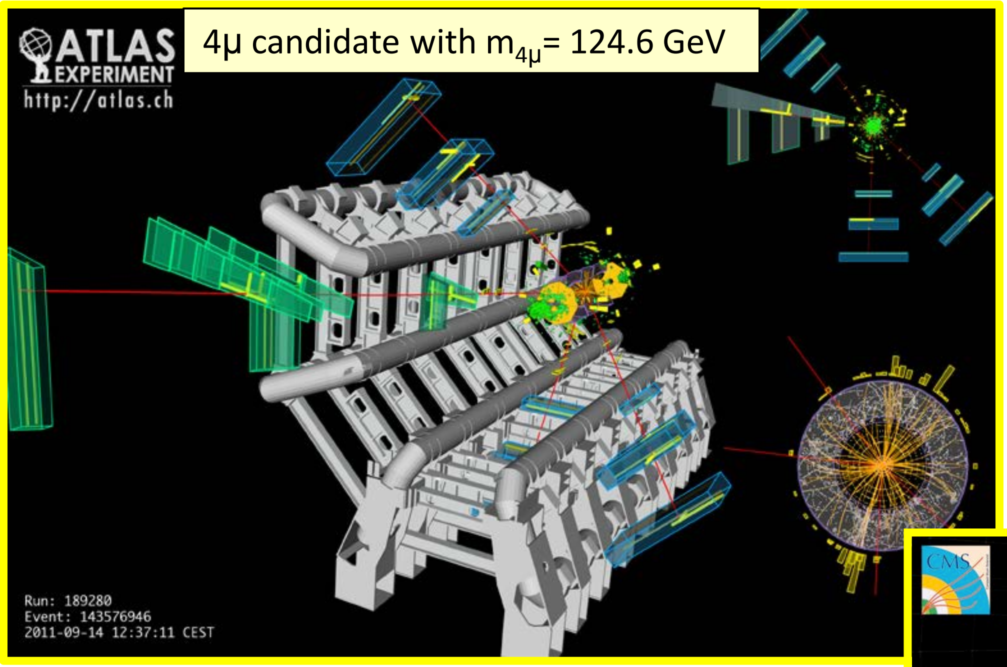
  – What is the origin of mass ? Is it the Higgs boson ?
  – What is 96% of the universe made of ?
  – Why is there no more antimatter ?
  – What was matter like in the first second of the Universe ?

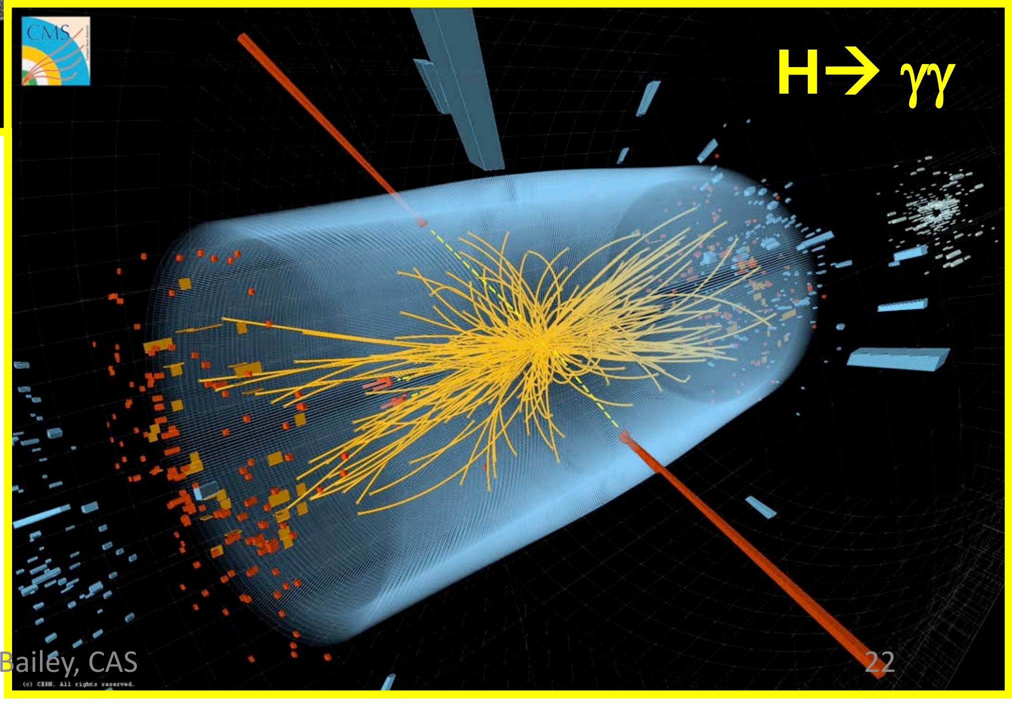
The question is: How do we get from this,

The CERN Duoplasmatron Proton Ion Source

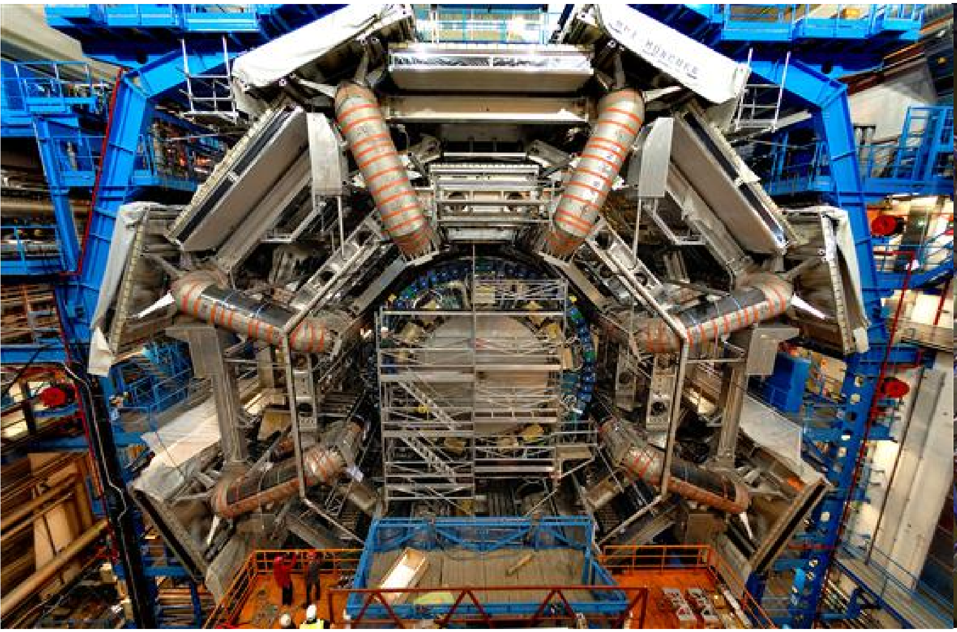


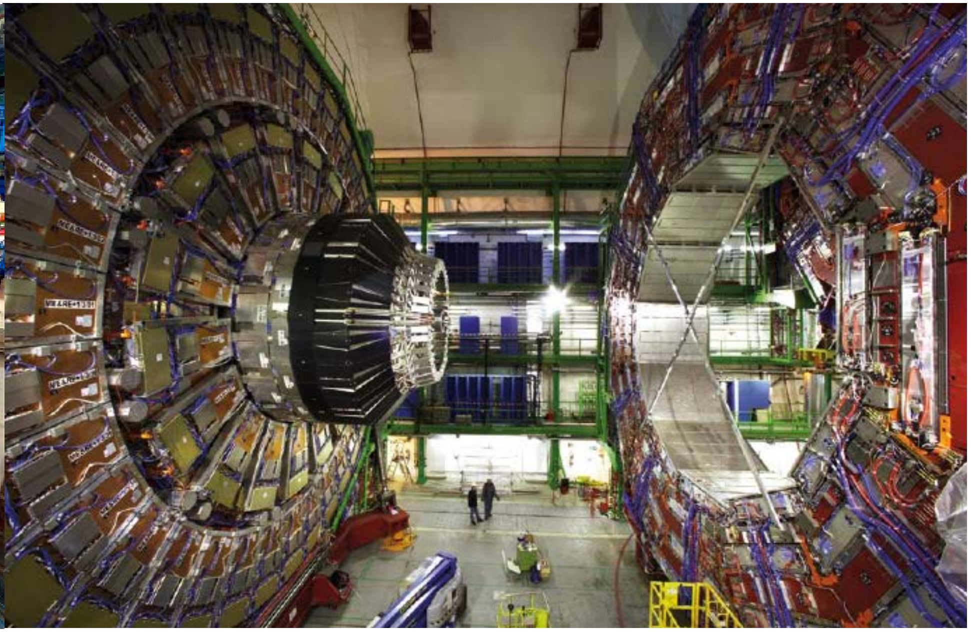
to this ?


ATLAS EXPERIMENT
http://atlas.ch
4μ candidate with $m_{4\mu}$= 124.6 GeV
Run: 189280
Event: 143576946
2011-09-14 12:37:11 CEST


CMS
H→ γγ

LHC





- The LHC was built (primarily) to find (or exclude) the Higgs boson
- To do this it needs to deliver a lot of data; what does *a lot of data* mean ?
- Answer depends on a number of things
  - Beam energy
  - Higgs mass
  - Production cross section
  - Decay channel branching ratio

Cross sections

- Cross section σ measured in barns (1 barn = 10^{-28} m^2)

/1000	mb
/1000	μb
/1000	nb
/1000	pb
/1000	fb

Increasingly rare processes

- 12 orders of magnitude difference in range above

Delivered luminosity

- Performance level of a collider is defined by
  - luminosity *L* measured in $cm^{-2}\,s^{-1}$

- Average luminosity *<L>* delivered over time *t* yields
  - $L_{DEL} = <L> . t$ cm^{-2}

    $barn^{-1}$

mb^{-1}

μb^{-1}

nb^{-1}

pb^{-1}

fb^{-1}

Increasingly more data

Number of events

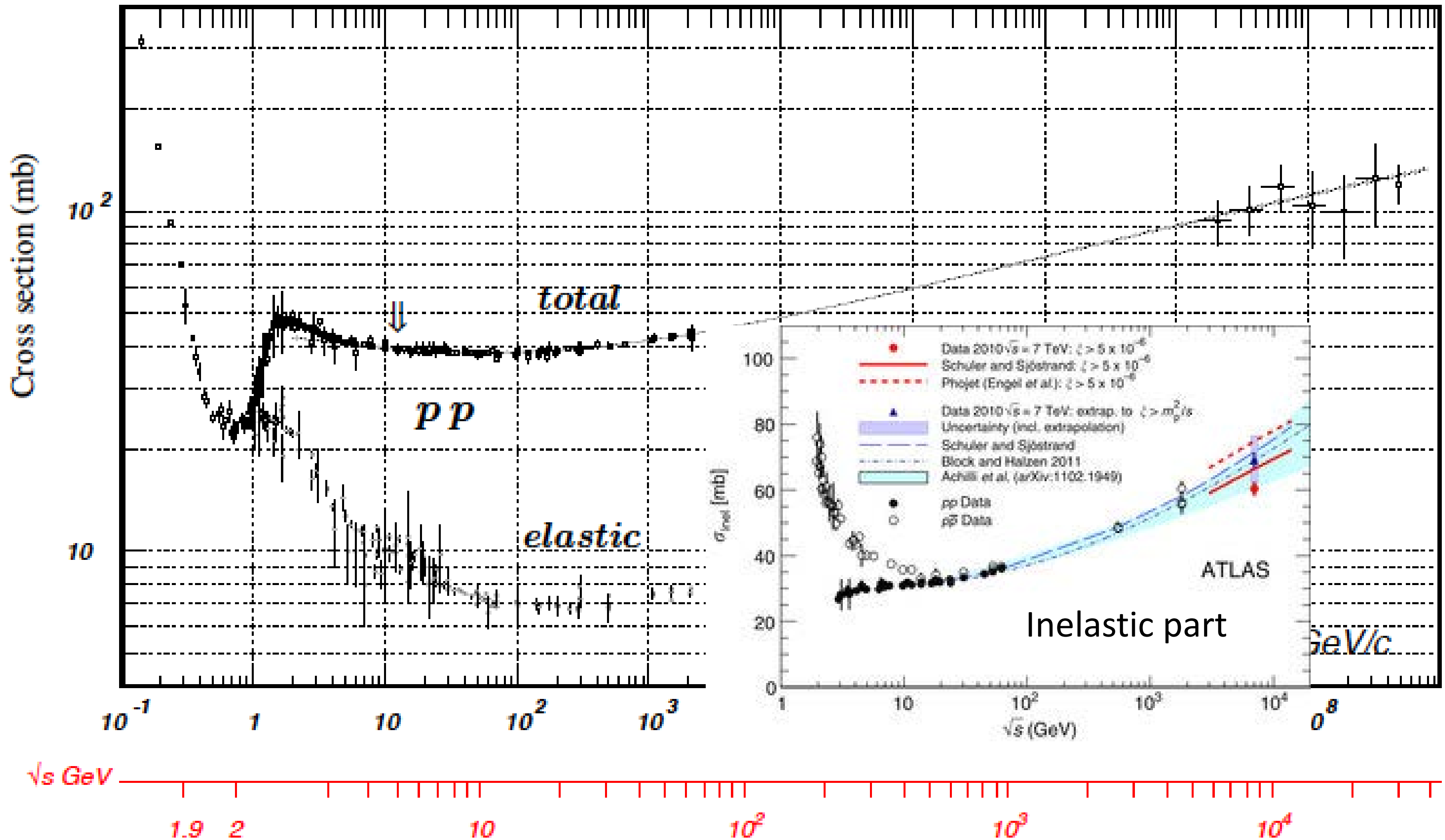
- Any given particle is produced with a cross section σ
  - It can decay through a variety of channels
  - Any given channel has a branching ratio BR
- The cross section for *seeing a given channel* is σ.BR

- For a delivered luminosity L_{DEL}

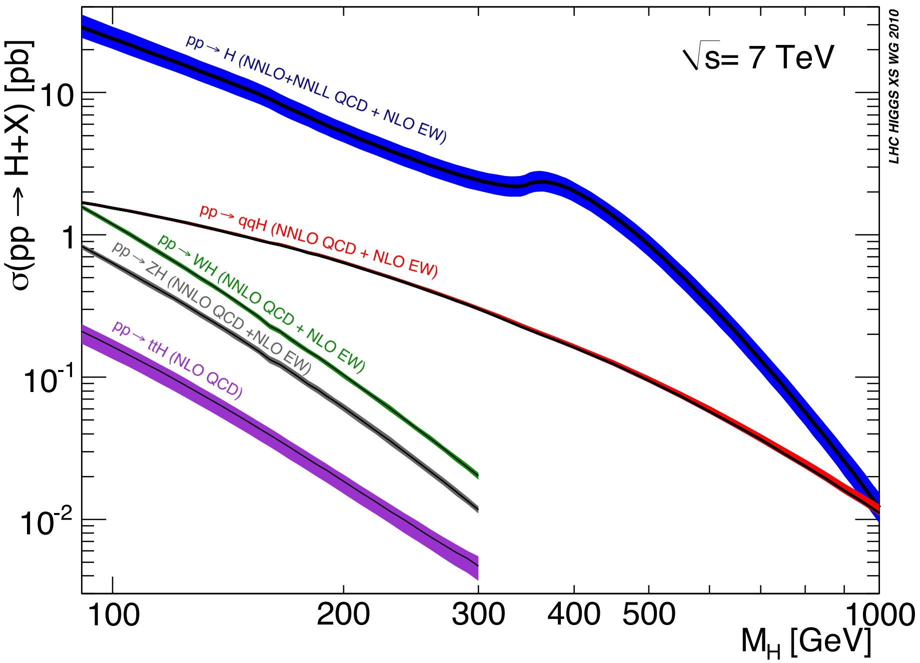
The number of these events detected is

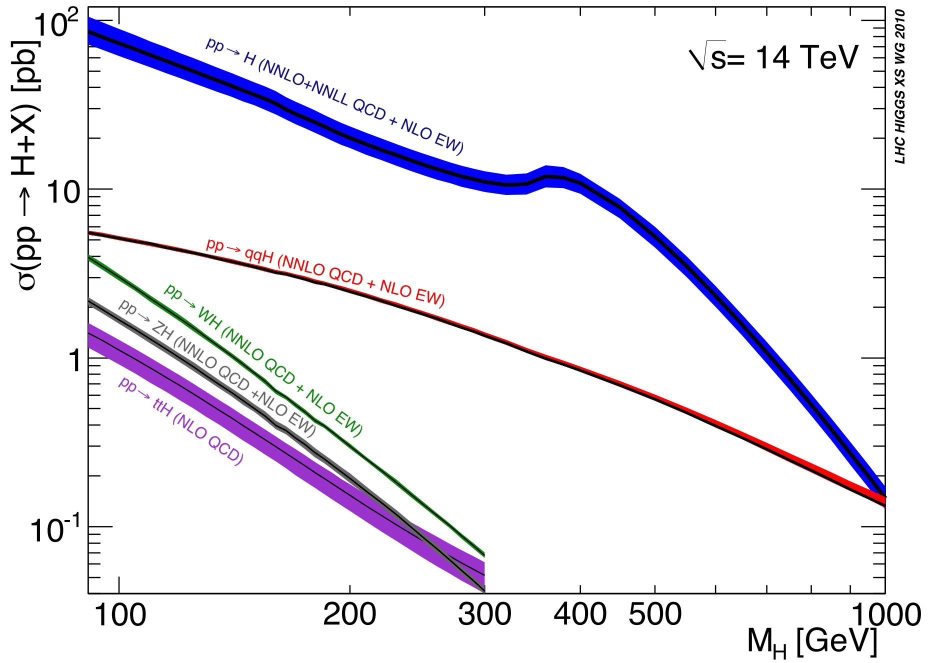
$$N_{event} = \sigma . BR . L_{DEL}$$

Total pp cross section



Expected Higgs production cross sections

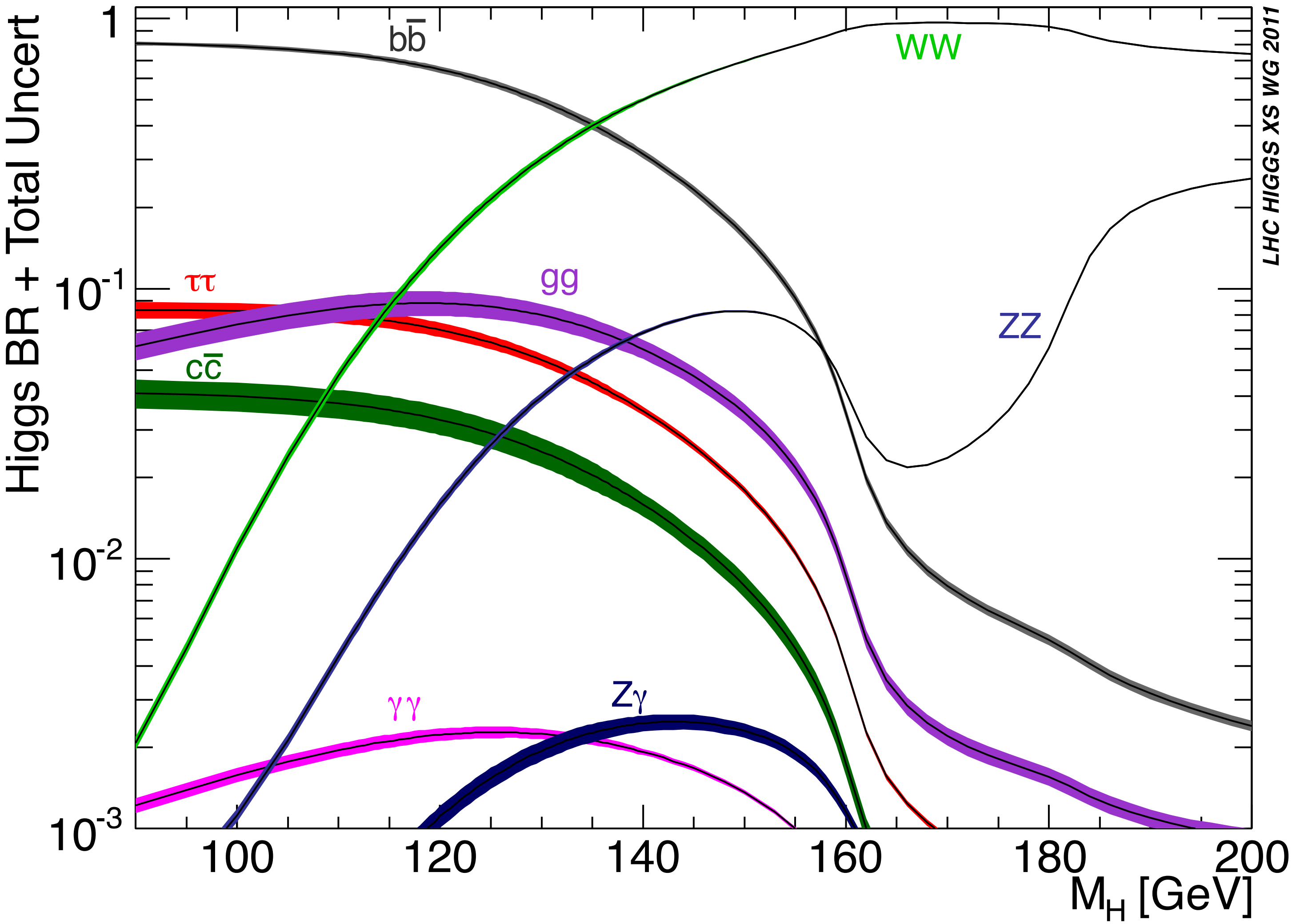




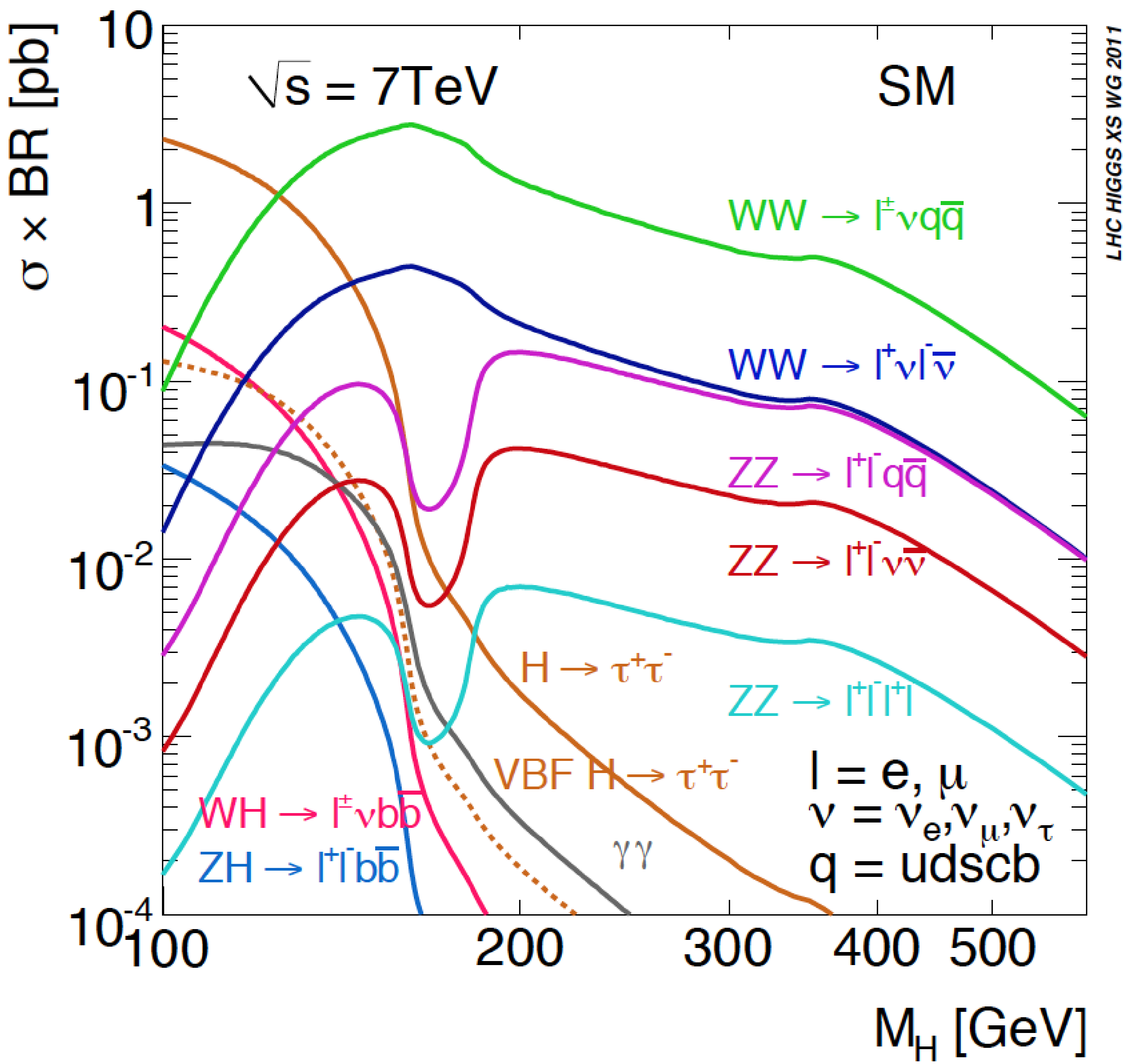
Different production mechanisms contribute (log scale)

Cross section dominated by gluon fusion for M_H < 1TeV

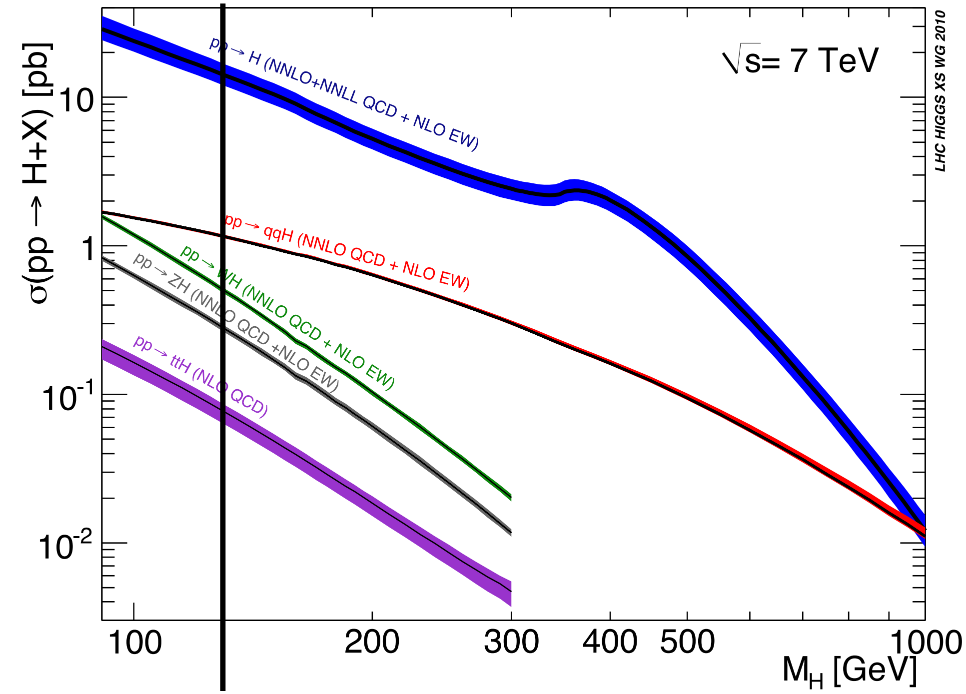
Expected Higgs decay branching ratios



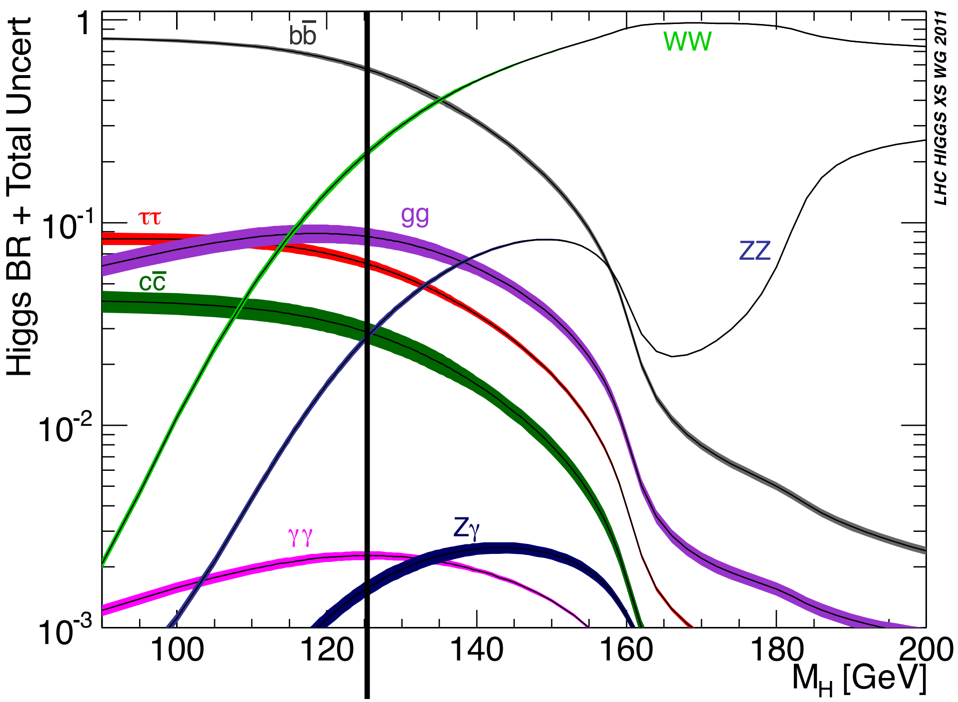
Cross section times branching ratio



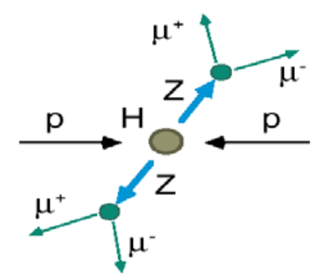
LHC 2011



- 3.5 TeV per beam
- Higgs mass ~ 125 GeV
  - Cross section σ ~ 10pb
  - cf ~ 60 mb total inel cross section

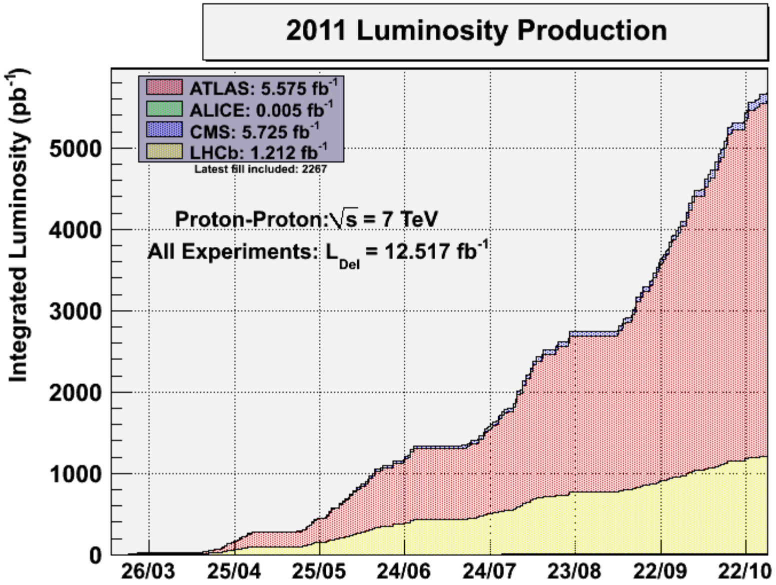


- Higgs to ZZ to 4 leptons
  - Higgs to ZZ ~ 2 10^{-2}
  - 2*(Z to l) ~ 10^{-1} x 10^{-1}
  - Higgs to 4l ~ 2 10^{-4}

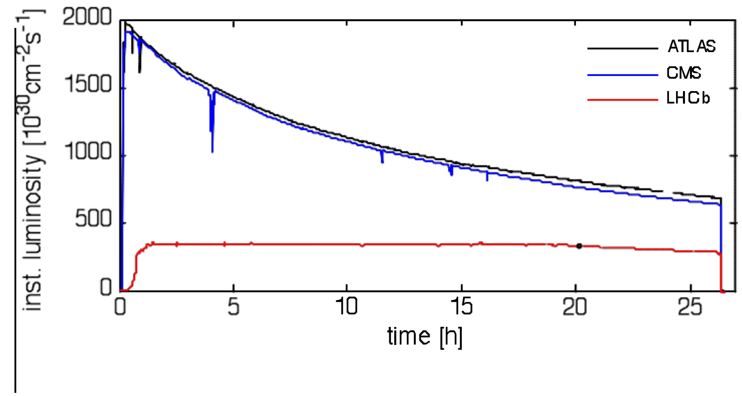


- σ.BR ~ 10 x 2 10^{-4} pb = 2 fb
- N_{event} = σ.BR x delivered luminosity
- 5 fb^{-1} of data gives ~ 10 Higgs / 4l events

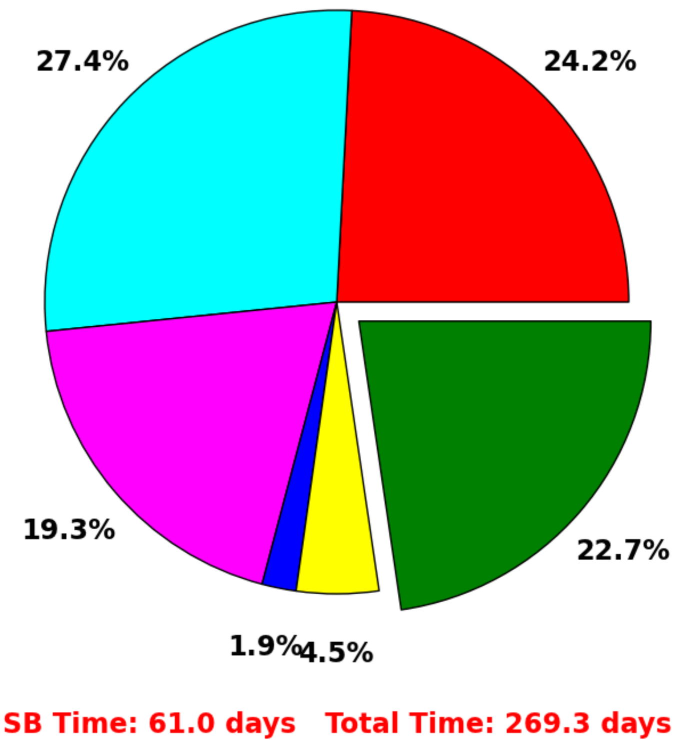
Luminosity



- 5 fb^{-1} delivered in 2011
- 5 10^6 s of colliding beams
- L_{DEL} = <L> . (Time in collision)
- Hence for 5 fb^{-1} of data we need <L> = 10^{33} cm^{-2} s^{-1}



- So we need L_{Peak} >> 10^{33} cm^{-2} s^{-1}
- Aiming in 2012 for
  - L_{Peak} > 5 10^{33} cm^{-2} s^{-1}
  - 15 to 20 fb^{-1} of data



Luminosity

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

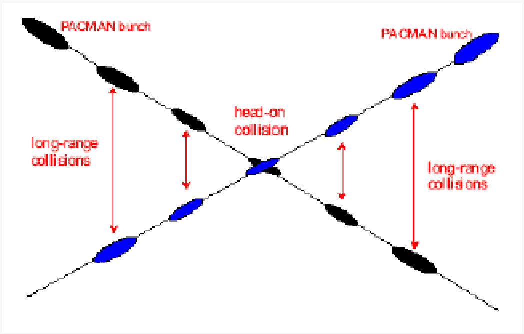
$$\sigma = \sqrt{\varepsilon\beta}$$

$$\varepsilon_n = \varepsilon\gamma$$

"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
  - Number of particles per bunch N
  - Number of bunches per beam k_b
  - Relativistic factor (E/m_0) γ
  - Normalised emittance ε_n
  - Beta function at the IP β^*
  - Crossing angle factor F
    - 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 performance

Controlled parameters	Nominal	2011	Aim for 2012
Beam energy (TeV)	7.0	3.5	4.0
Number of particles per bunch	$1.15\ 10^{11}$	$1.5\ 10^{11}$	$1.5\ 10^{11}$
Number of bunches per beam *	2808	1380	1380
Bunch spacing (ns)	25	50	50
Crossing angle (μrad)	285	240	290
Norm transverse emittance (μm rad)	3.75	2.5	2.5
Bunch length (cm)	7.55	10.1	10.1
Beta function at IP 1, 2, 5, 8 (m)	0.55,10,0.55,10	1,3,1,10	0.6,3,0.6,3

Derived parameters	Nominal	2011	Aim for 2012
Luminosity in IP 1 & 5 ($cm^{-2}\ s^{-1}$)	10^{34}	$3.5\ 10^{33}$	$6\ 10^{33}$
Luminosity in IP 8 ($cm^{-2}\ s^{-1}$) **	$\sim 5\ 10^{32}$	$3\ 10^{32}$	$4\ 10^{32}$
Transverse beam size at IP 1 & 5 (μm)	16.7	25.9	18.8
Stored energy per beam (MJ)	362	116	132

* A few % of bunches do not contribute to luminosity

** Luminosity in IP 8 optimized as needed

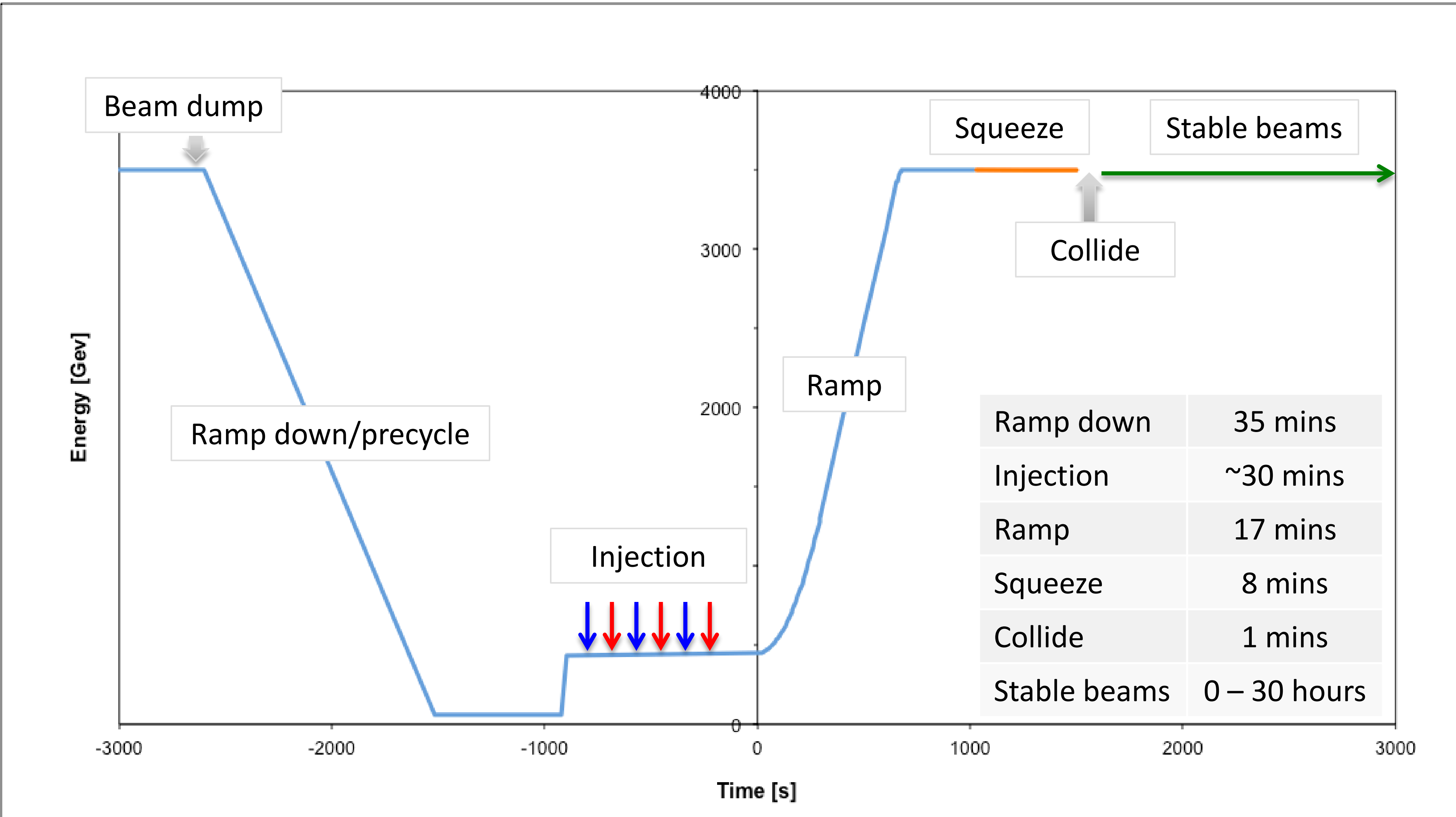
So we need High Luminosity

"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

- How do we do this ?
  - LHC ramps from 450 GeV to collision energy (γ)
  - LHC squeezes from injection optics to physics optics (β^*)
  - It needs from the injectors
    - Thousands of bunches (k_b) at 450 GeV with
      - High intensity (N)
      - Low transverse emittance (ε_n)
      - Correct bunch length (σ_z)
      - Correct bunch spacing

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

The LHC cycle 2011

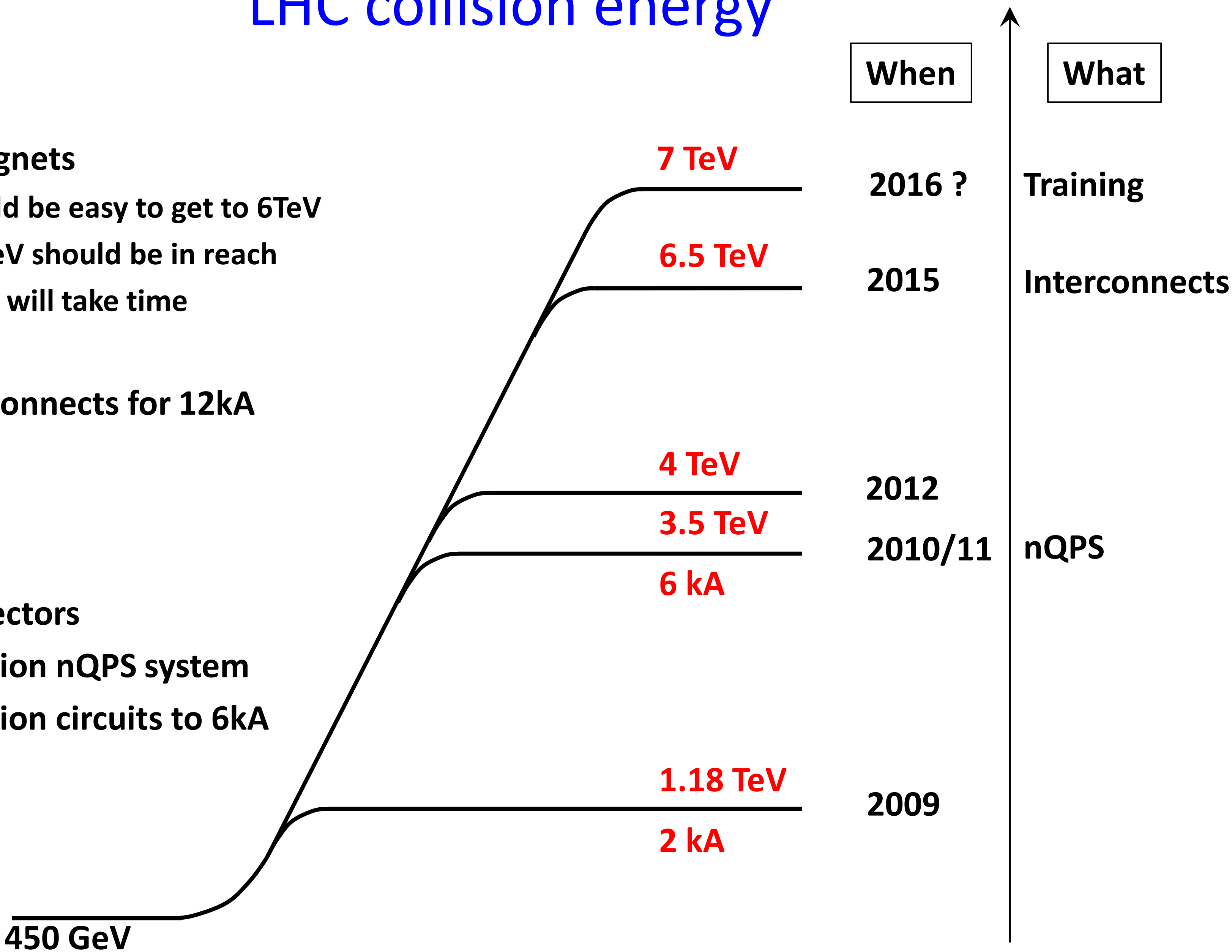


Ramp down	35 mins
Injection	~30 mins
Ramp	17 mins
Squeeze	8 mins
Collide	1 mins
Stable beams	0 – 30 hours

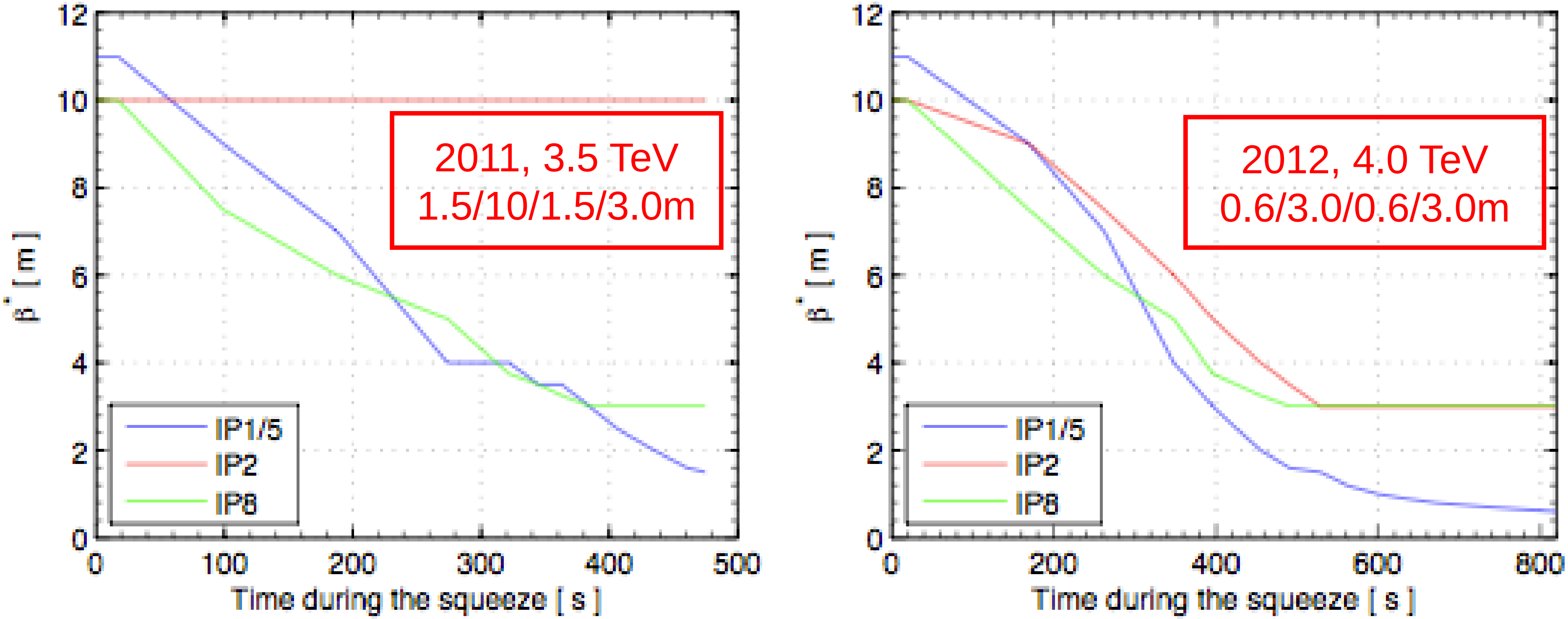
Fastest turn around down from 3h40m in 2010 to 2h7m in 2011 after optimization

LHC collision energy

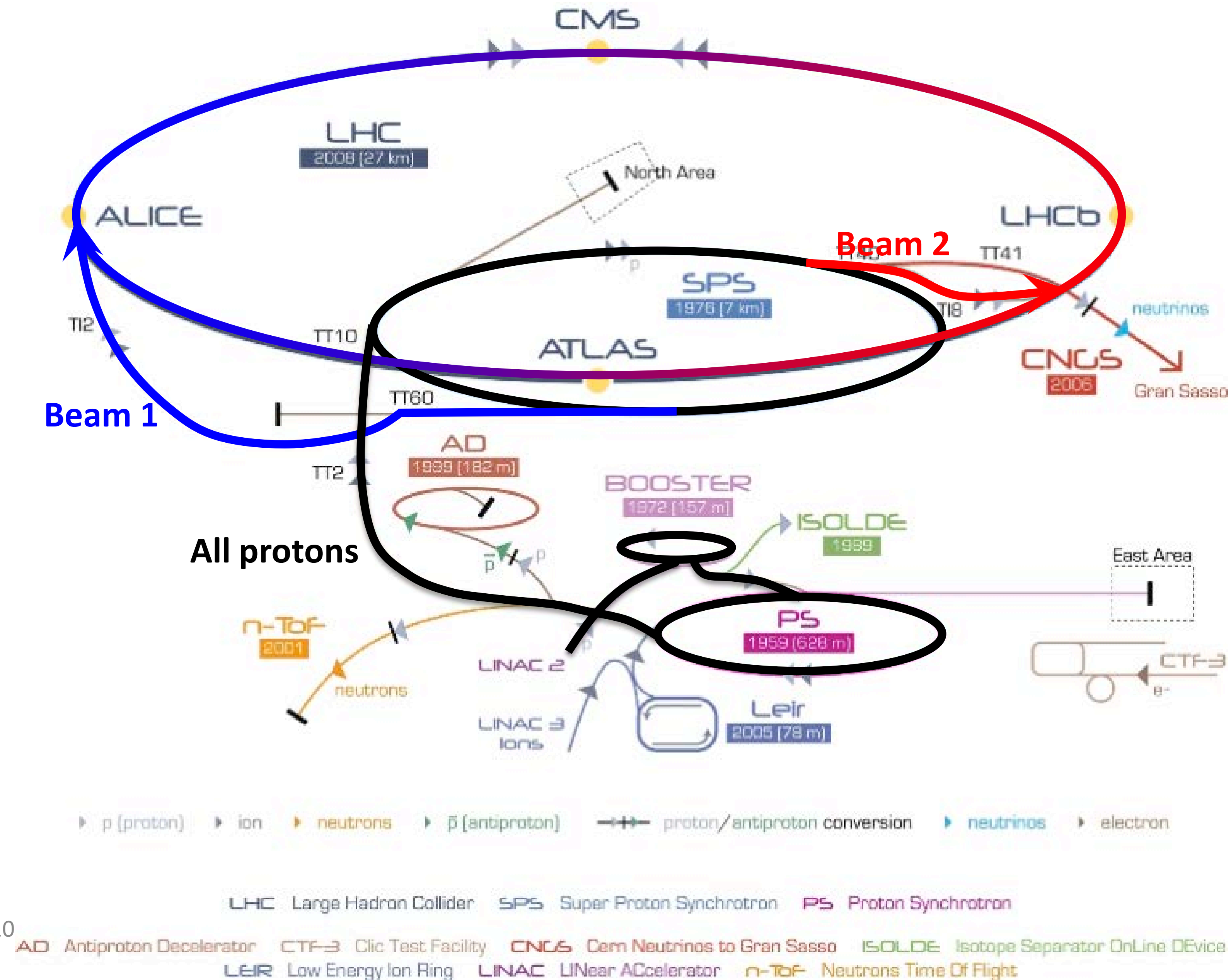
- Train magnets
  - Should be easy to get to 6TeV
  - 6.5 TeV should be in reach
  - 7 TeV will take time
- Fix interconnects for 12kA
- Fix connectors
- Commission nQPS system
- Commission circuits to 6kA



LHC squeeze from injection to physics optics



Thousands of bunches (k_b) at 450 GeV



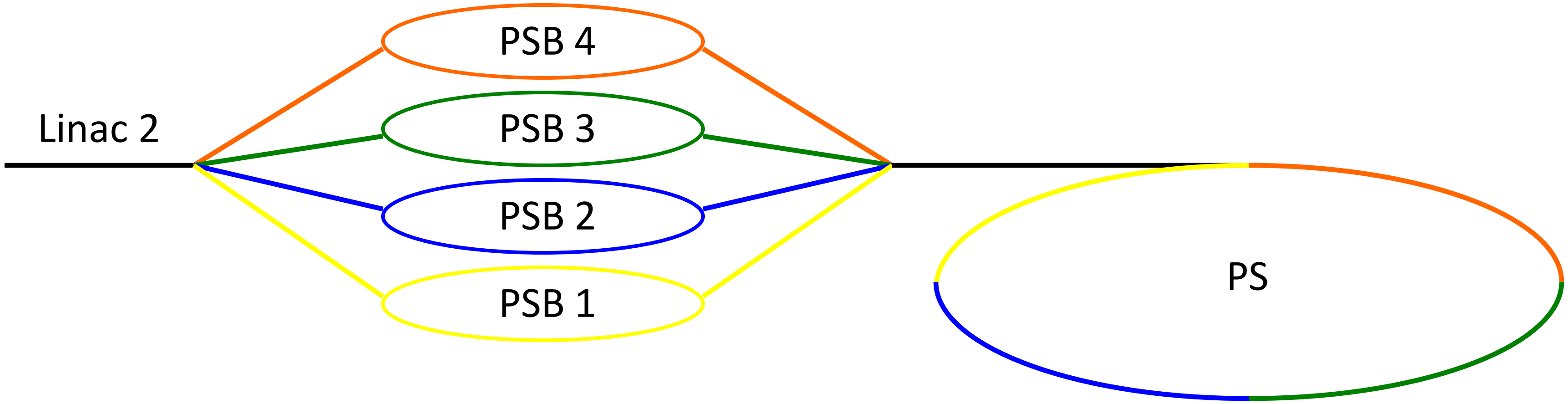
(SPS physics beams

Linac 2 →

Machine	E_{inj}	γ	Circumference (m)	Factor	T_{rev} (μs)
PSB	50 MeV	1	157		1.67
PS	1.4 GeV	2.5	628	4	2.29
SPS	14 GeV	27.6	6911	11	23
LHC	450 GeV	480	26658	27/7	89

- PSB (actually 4 rings)
  - Increases energy from 50 MeV to 1.4 GeV
  - Fills PS machine with successive extraction from 4 rings
- PS
  - Increases energy from 1.4 GeV to 14 GeV
  - Fills SPS machine with 2 x 5 turn slow extraction
- SPS
  - Increases energy from 14 GeV to 450 GeV
  - Delivers a continuous stream of 450 GeV protons (slow extraction)

SPS physics beams)



Linac2 provides a stream of protons which are sequentially injected into all 4 PSB rings
This is using phase-space painting and is typically over 13 turns. Emittance is not a big issue
So Linac 2 has to deliver to the PSB the protons injected/turn*13*4. Allow for losses !
Also has to provide a long enough pulse to allow 13 turns * 4 in the PSB (Trev at 50 MeV is 1.67 µs)

Linac2	PSB	PS
> 87 µs	Injection over 13 turns, into each ring	Takes beam from 4 PSB rings
$4\ 10^{13}$	$7\ 10^{11}$ injected per turn	$7\ 10^{12}$ injected per PSB ring

Typical parameters are 70 mA during the pulse over 100 µs which results in $4.4\ 10^{13}$ ppp in Linac2

LHC nominal beams

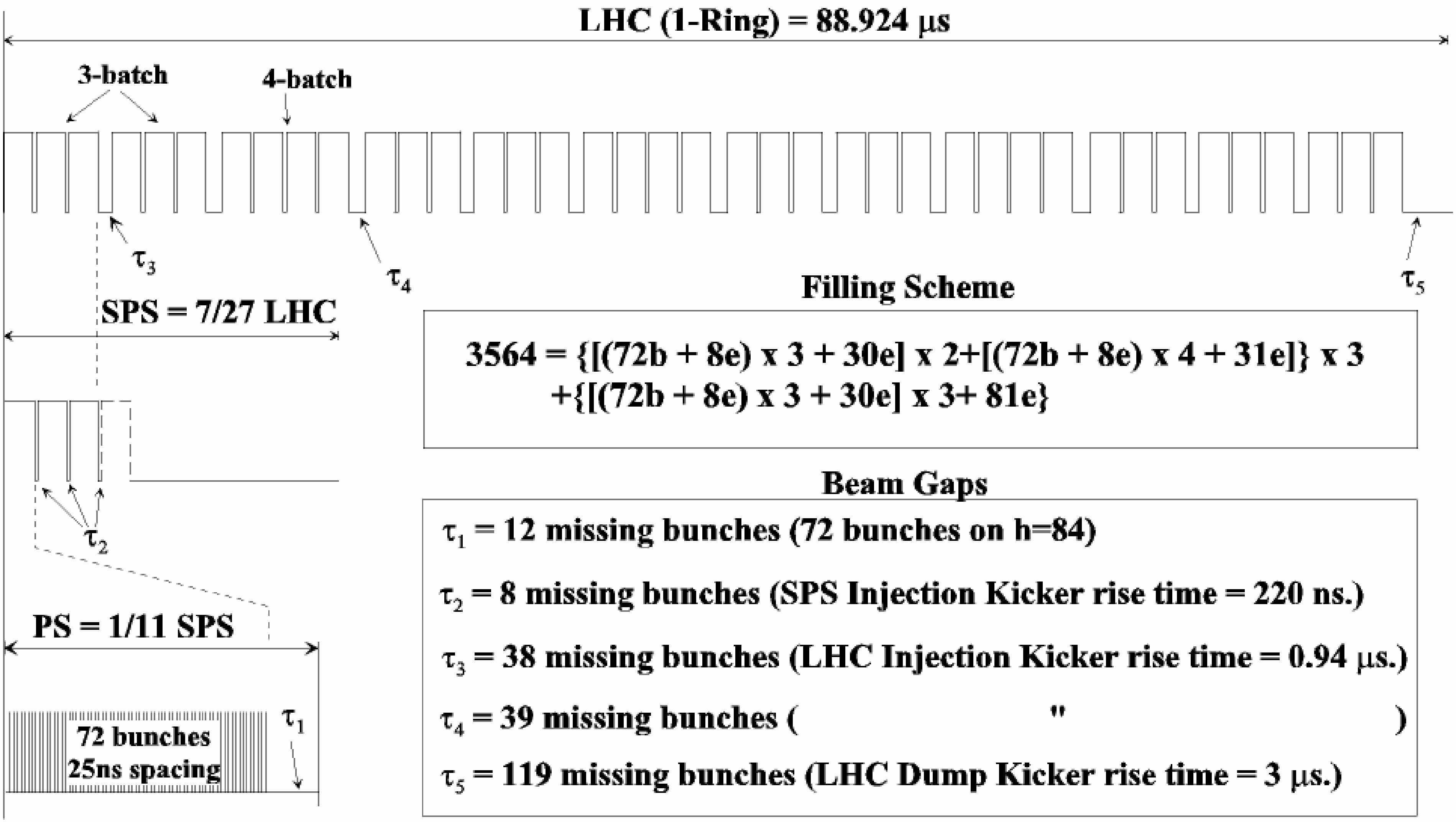
Linac 2 →

	E_{ext}	γ	Circ (m)	T_{rev} (μs)	F_{rev} (Hz)	h	f_{RF} (MHz)
PSB	1.4 GeV	1	157	.572	$1.75\ 10^{6}$	1	1.75
PS	25 GeV	2.5	628	2.09	$4.37\ 10^{5}$	84	40
SPS	450 GeV	27.6	6911	23	$4.33\ 10^{4}$	4620	200
LHC	7000 GeV	7462	26666	89	$1.1\ 10^{4}$	35640	400

- LHC needs
  - 2808 distinct high intensity bunches spaced by 25 ns
  - Spread around the circumference
  - One in ten buckets can be filled
  - Gives 3564 available bunch spaces

Where do all the bunches come from ?

Bunch Disposition in the LHC, SPS and PS



Filling Scheme

3564 = {[(72b + 8e) x 3 + 30e] x 2+[(72b + 8e) x 4 + 31e]} x 3
+{[(72b + 8e) x 3 + 30e] x 3+ 81e}

Beam Gaps

τ_1 = 12 missing bunches (72 bunches on h=84)

τ_2 = 8 missing bunches (SPS Injection Kicker rise time = 220 ns.)

τ_3 = 38 missing bunches (LHC Injection Kicker rise time = 0.94 μs.)

τ_4 = 39 missing bunches (")

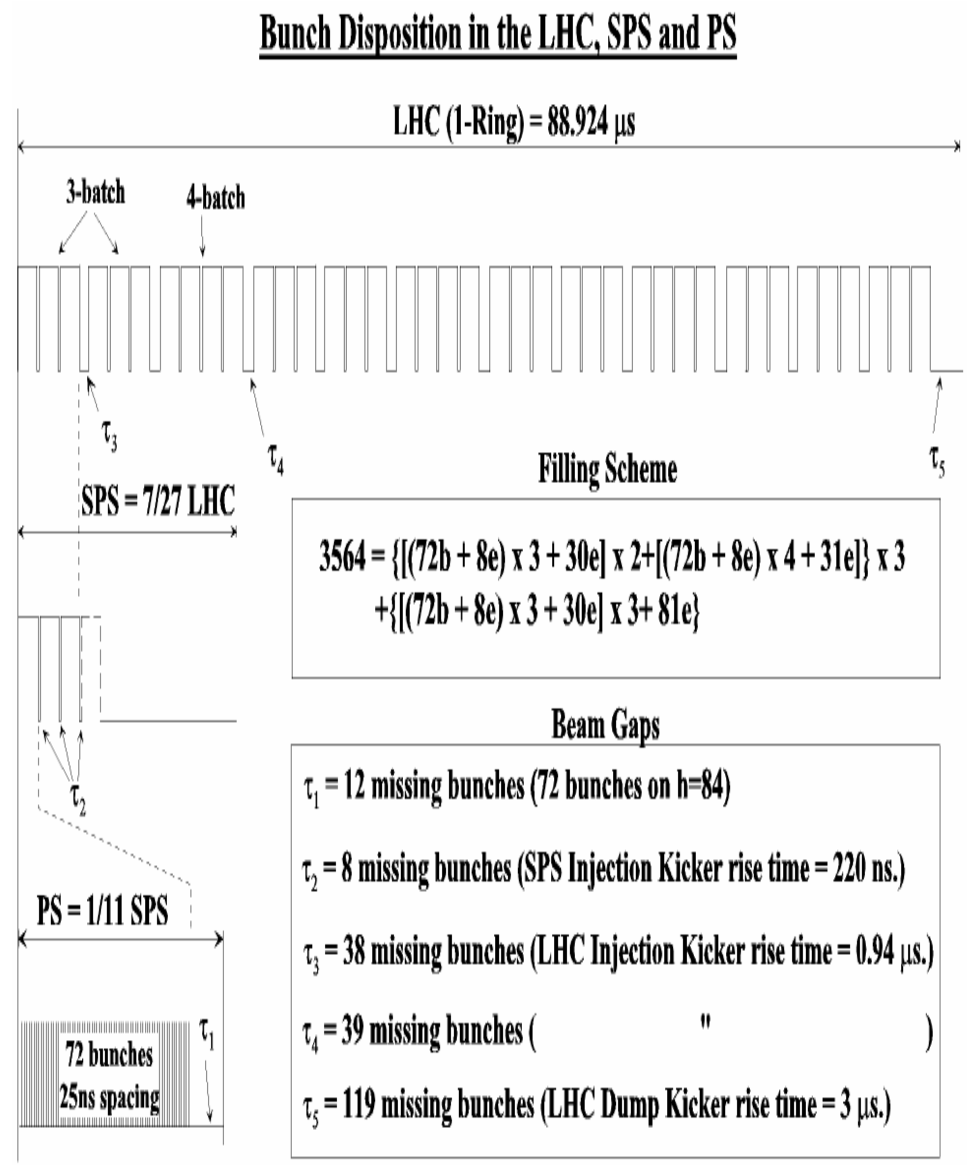
τ_5 = 119 missing bunches (LHC Dump Kicker rise time = 3 μs.)

PS to SPS to LHC

- 12 LHC injections per ring
  - 3 or 4 PS batches
  - 39 PS batches in total
- PS batch
  - 72 PS bunches

2808

- SPS circumference used
  - 4 * 72 * 25 ns = 7.2 µs

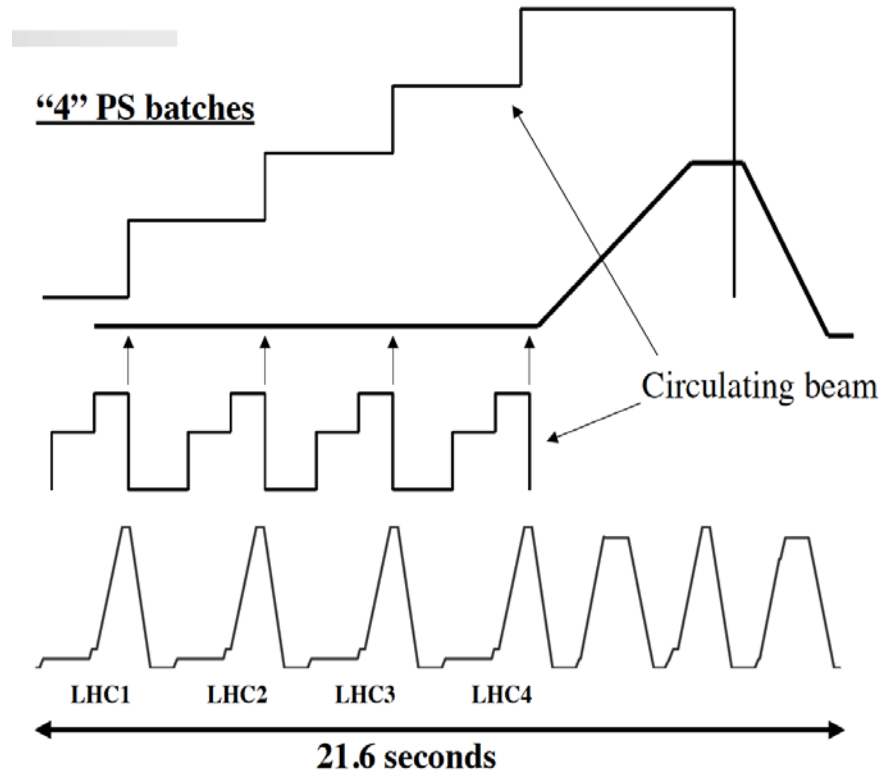


PS and SPS cycles

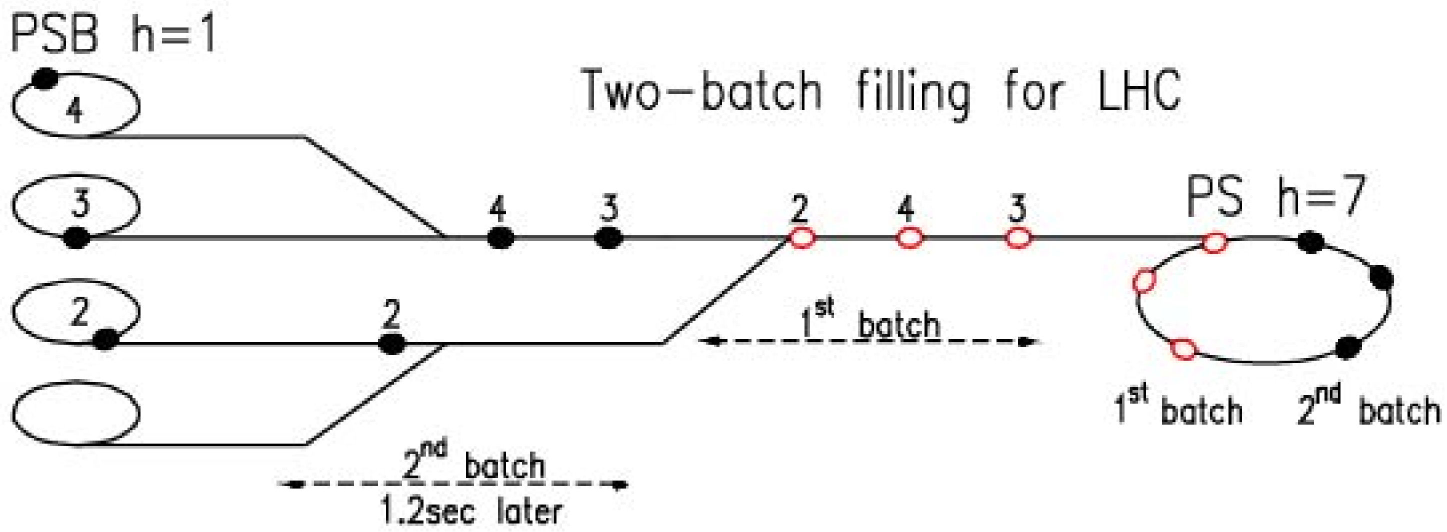
- 4 injections into SPS
- 2 injections into PS

- 21.6 seconds SPS cycle
- 12 of these per LHC ring

- 10 minutes to fill LHC



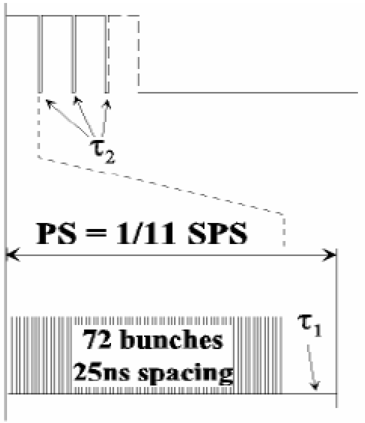
PSB to PS



Note; could also do this with 4 + 2. Indeed this might be preferred
Either way we get 6 bunches into the PS

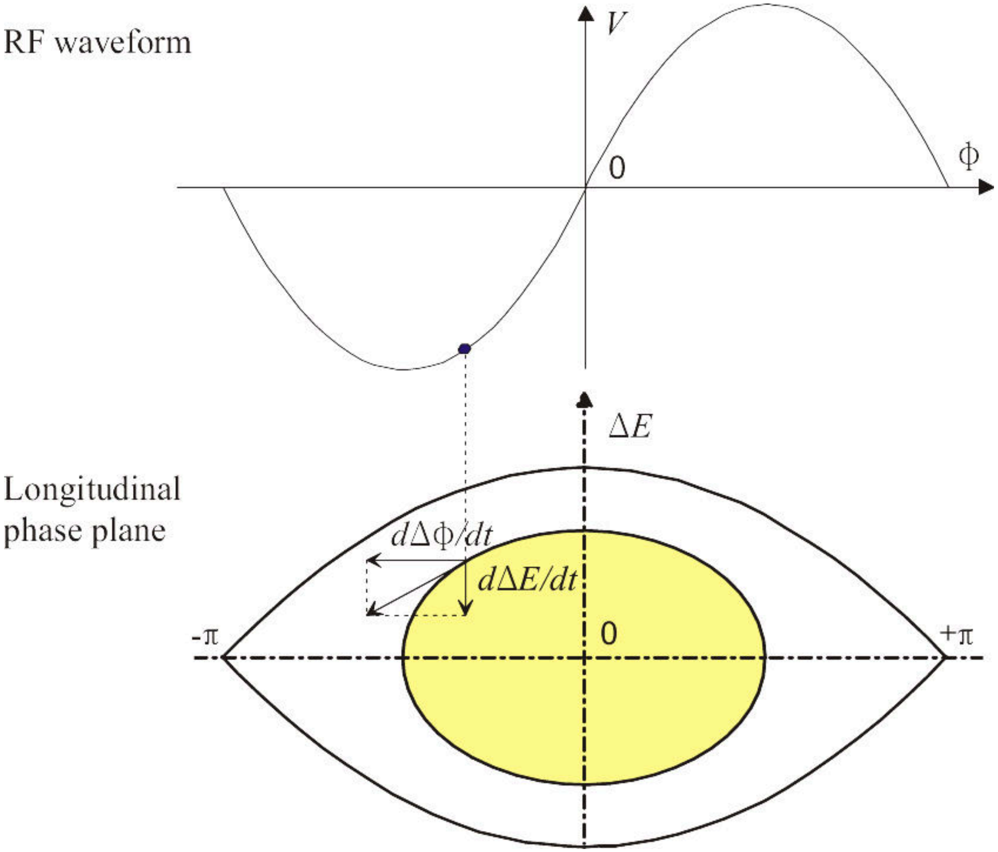
Recall; PS delivers 72 bunches per transfer to the SPS

How does 6 become 72 ?



Phase stability

- Sinusoidal voltage and stationary bucket
- Bunch is captured in the RF bucket

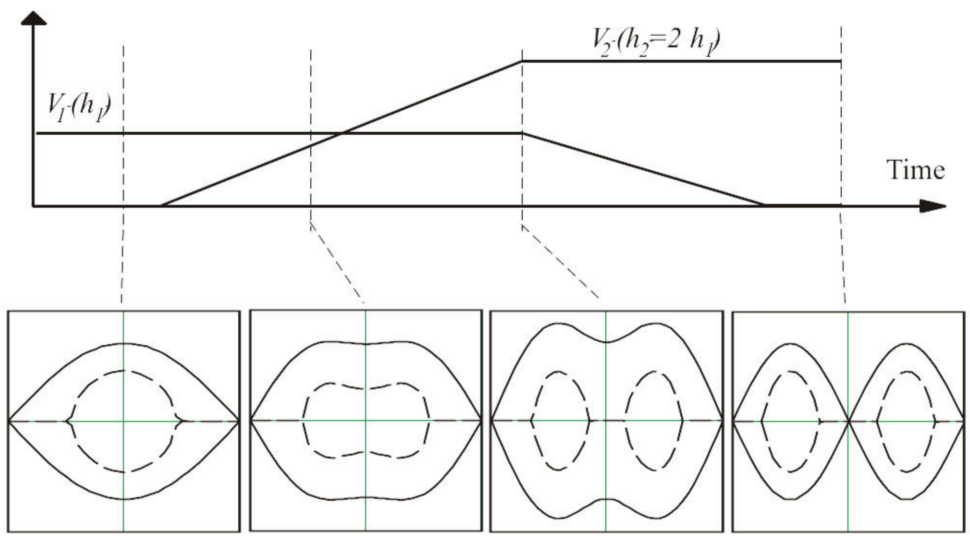


Multi-bunch gymnastics

- Apply simultaneously 2 (or more) RF voltages on h and 2h
- Adiabatically change the voltages

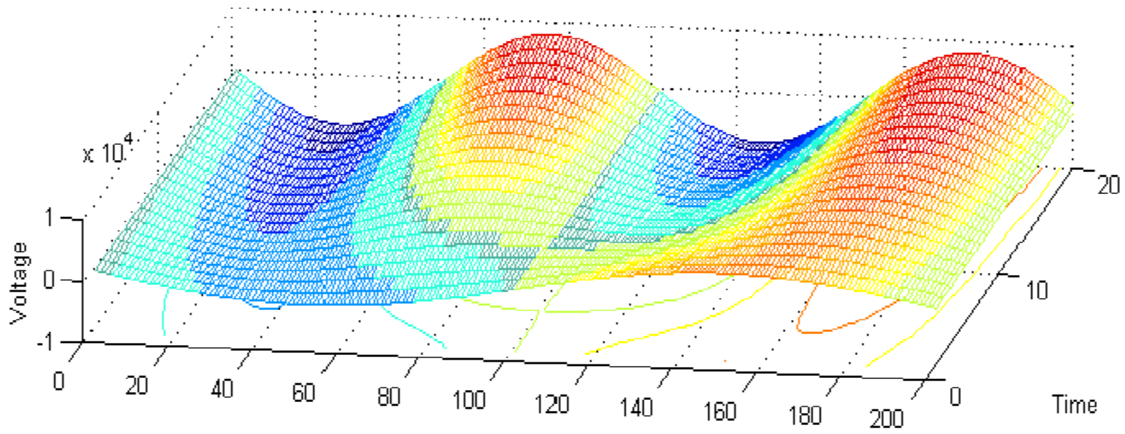
$$V_1 = \hat{V}_1 \sin(h\omega_R t)$$

$$V_2 = \hat{V}_2 \sin(2h\omega_R t + \pi)$$

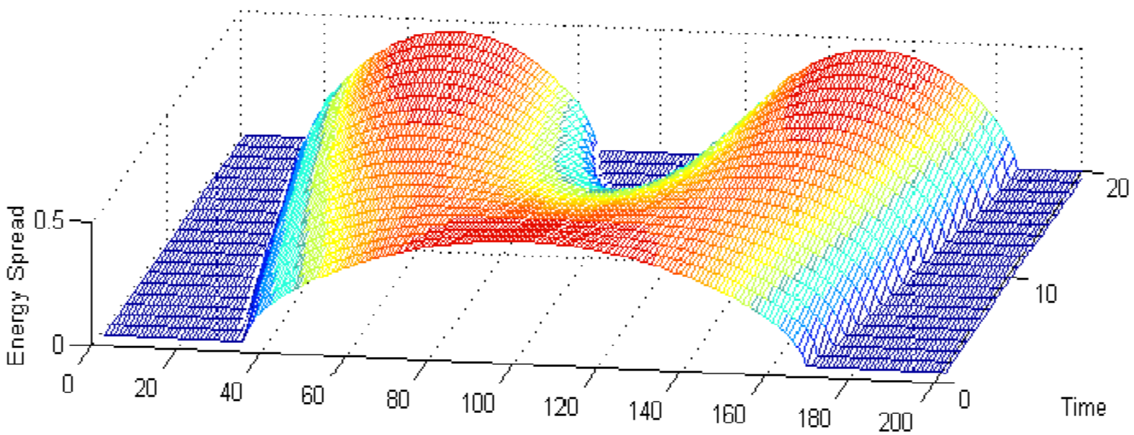


Splitting in two (simulation)

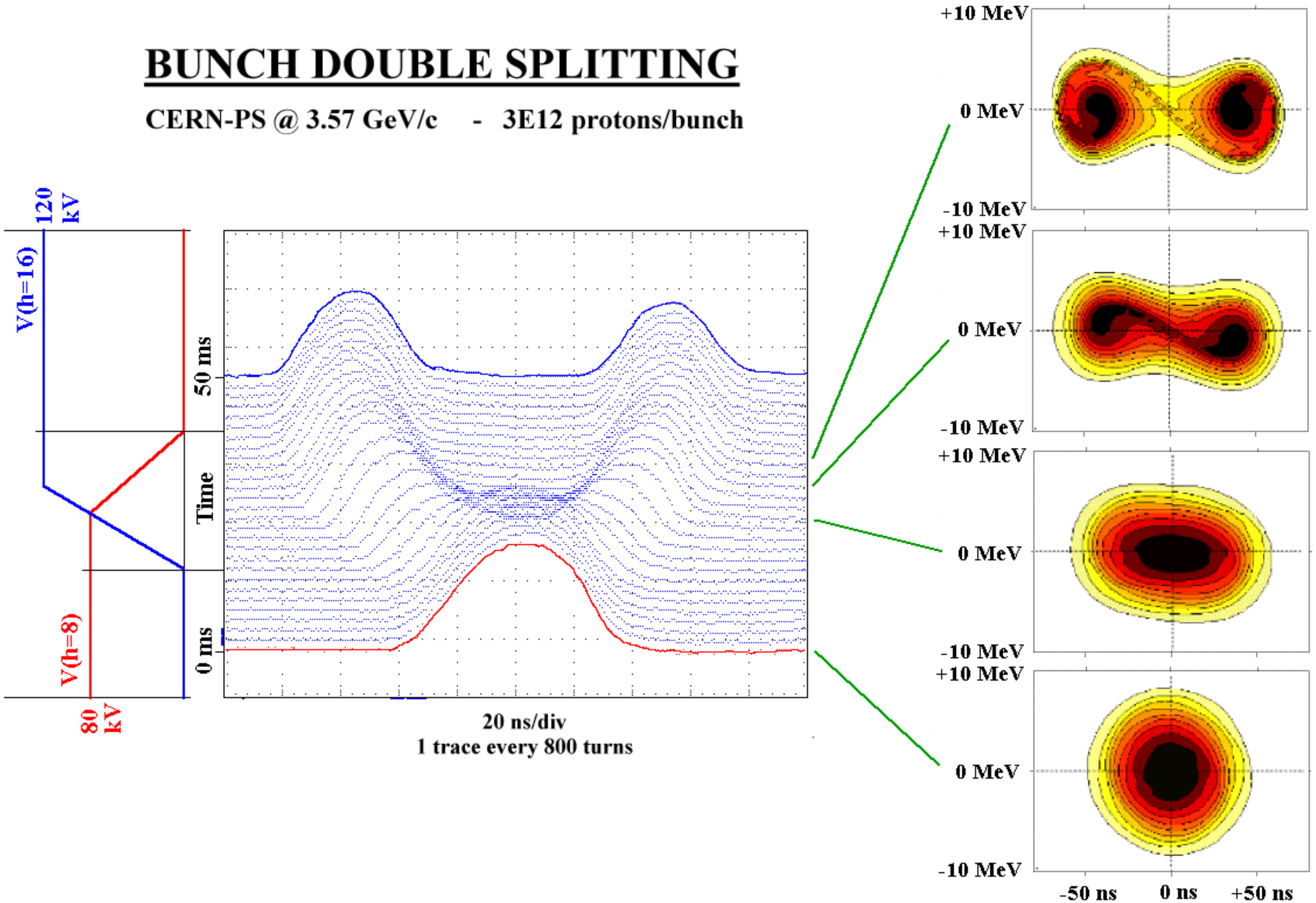
Time evolution of the RF voltage



Time evolution of the bunch(es)



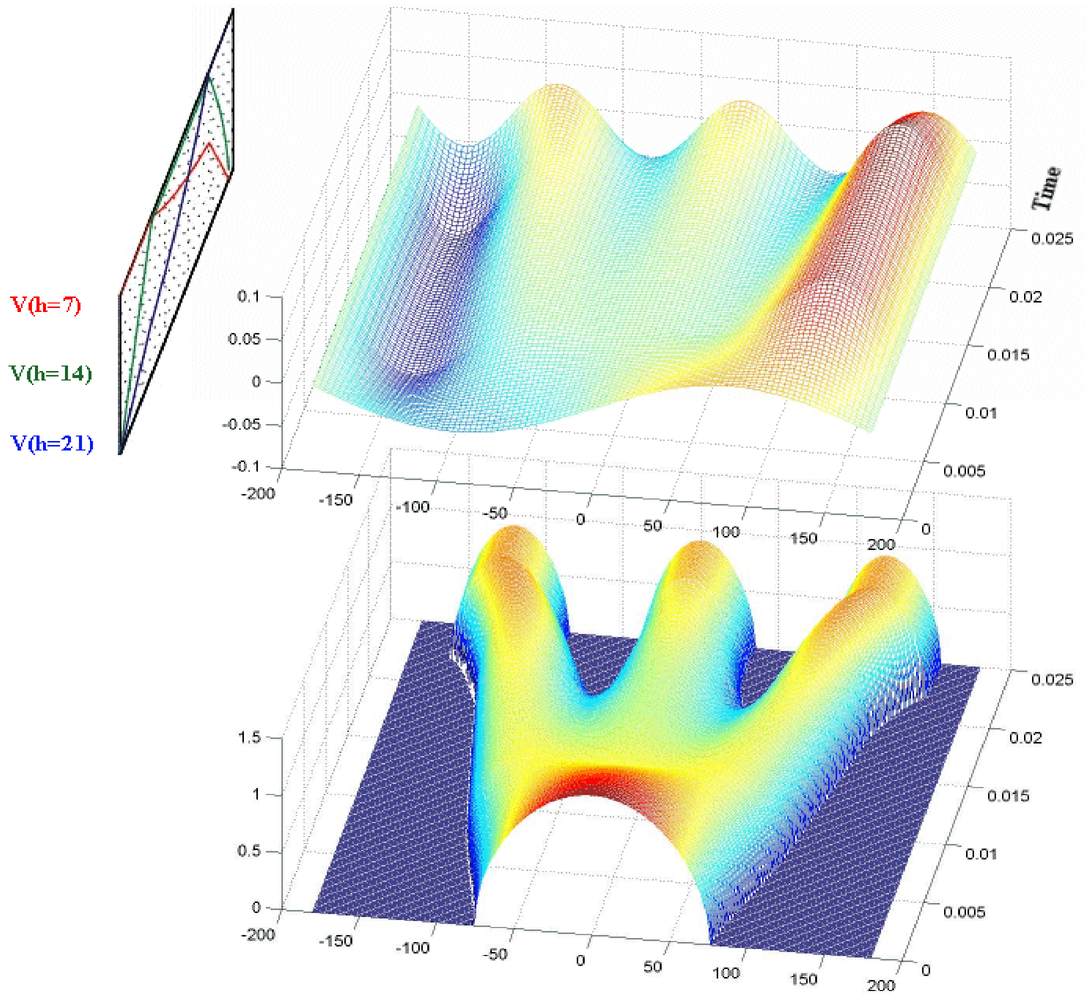
Splitting in two (data)



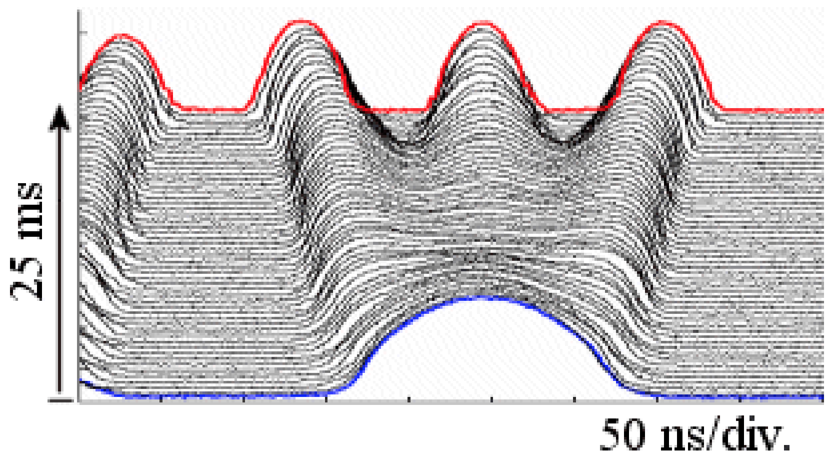
Triple splitting (simulation)

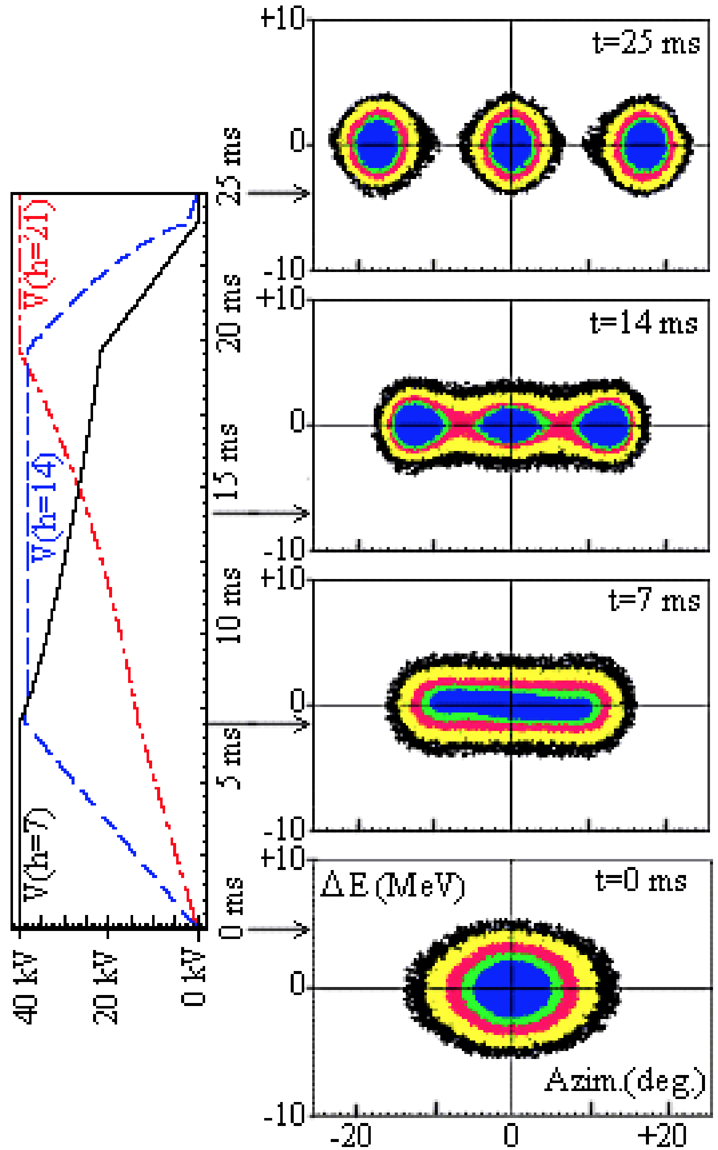
Time evolution of the RF voltage

Time evolution of the bunch(es)

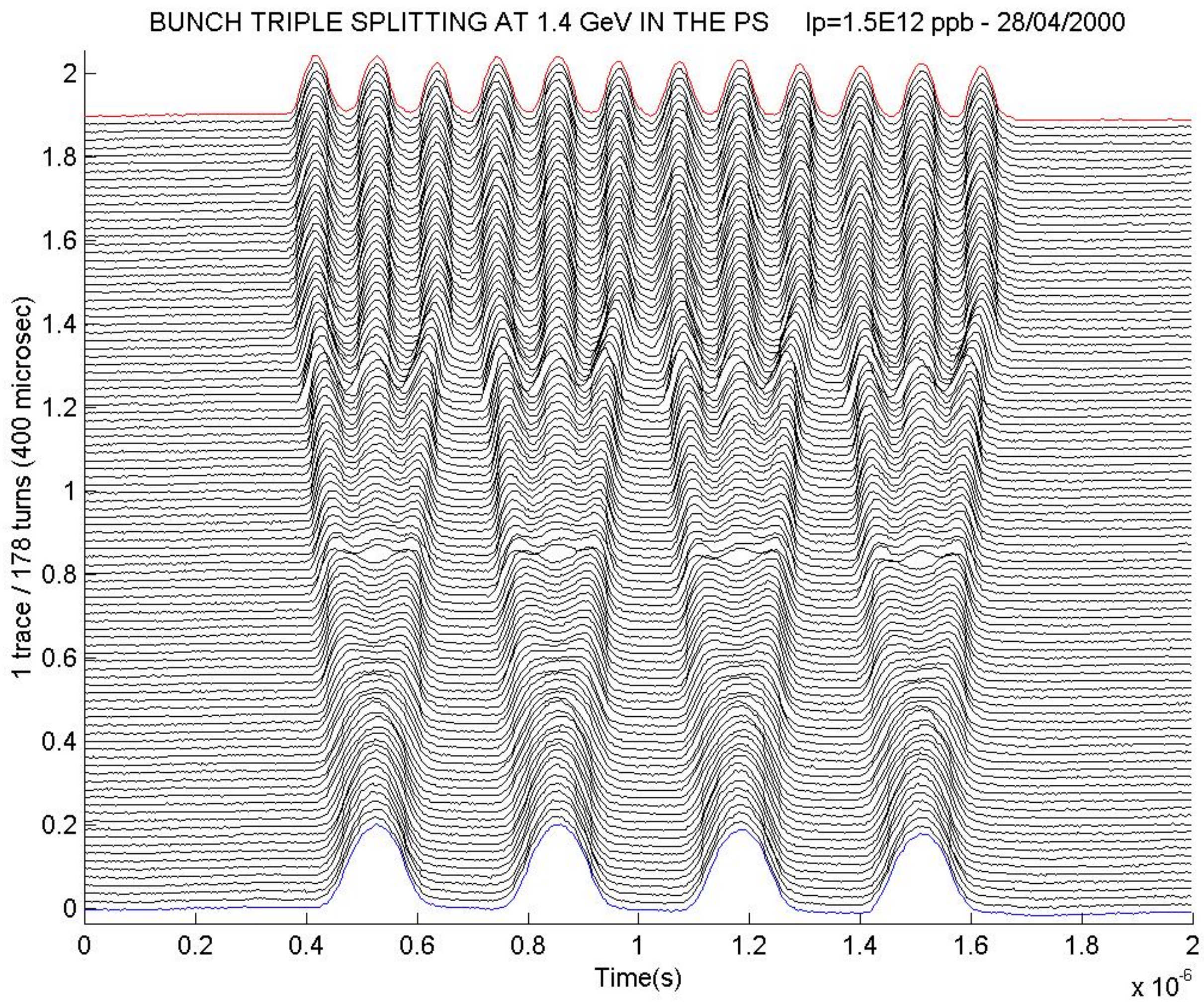


Triple splitting at 1.4 GeV (data)

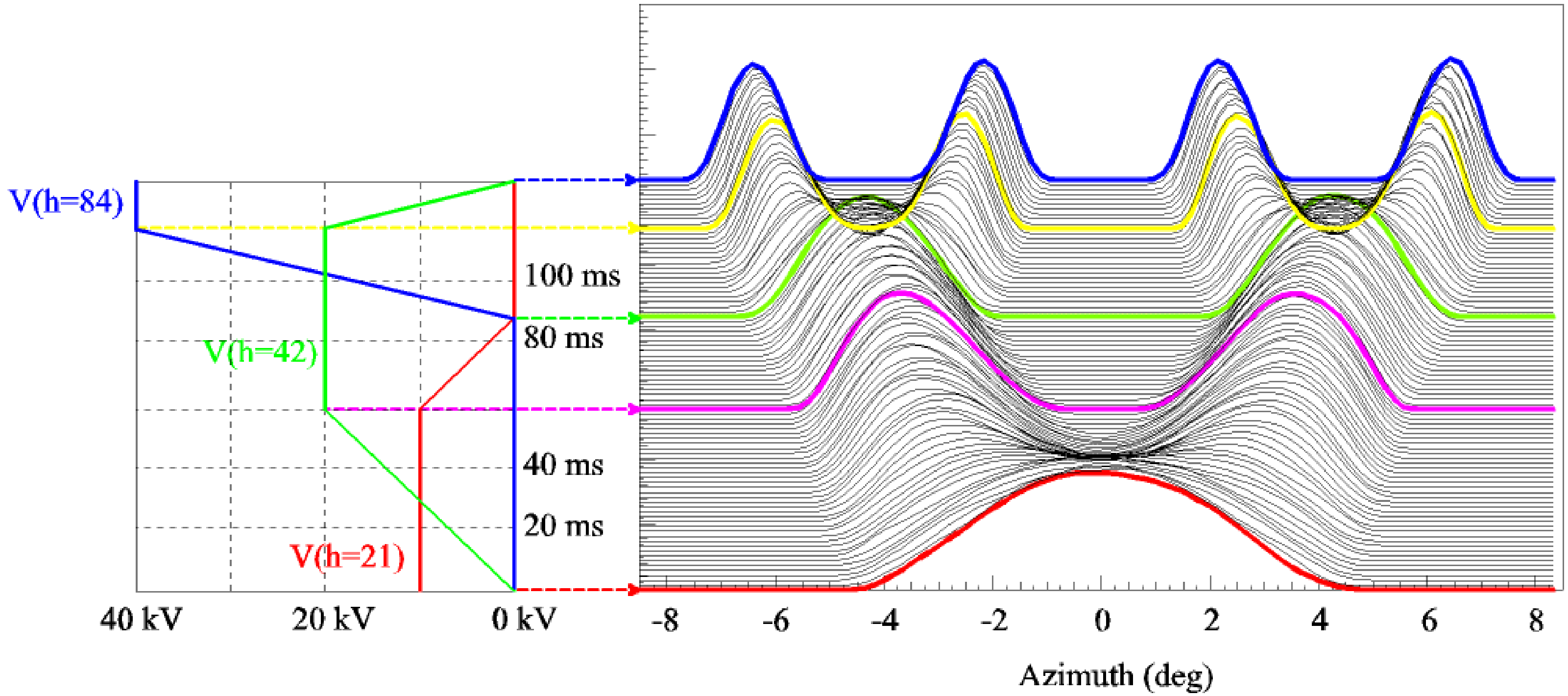


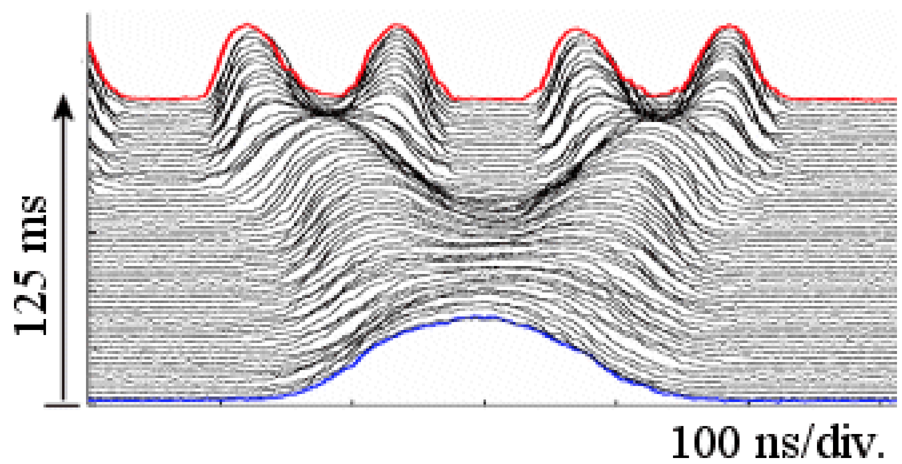


Splitting of 4 bunches into 12 (test in 2000)

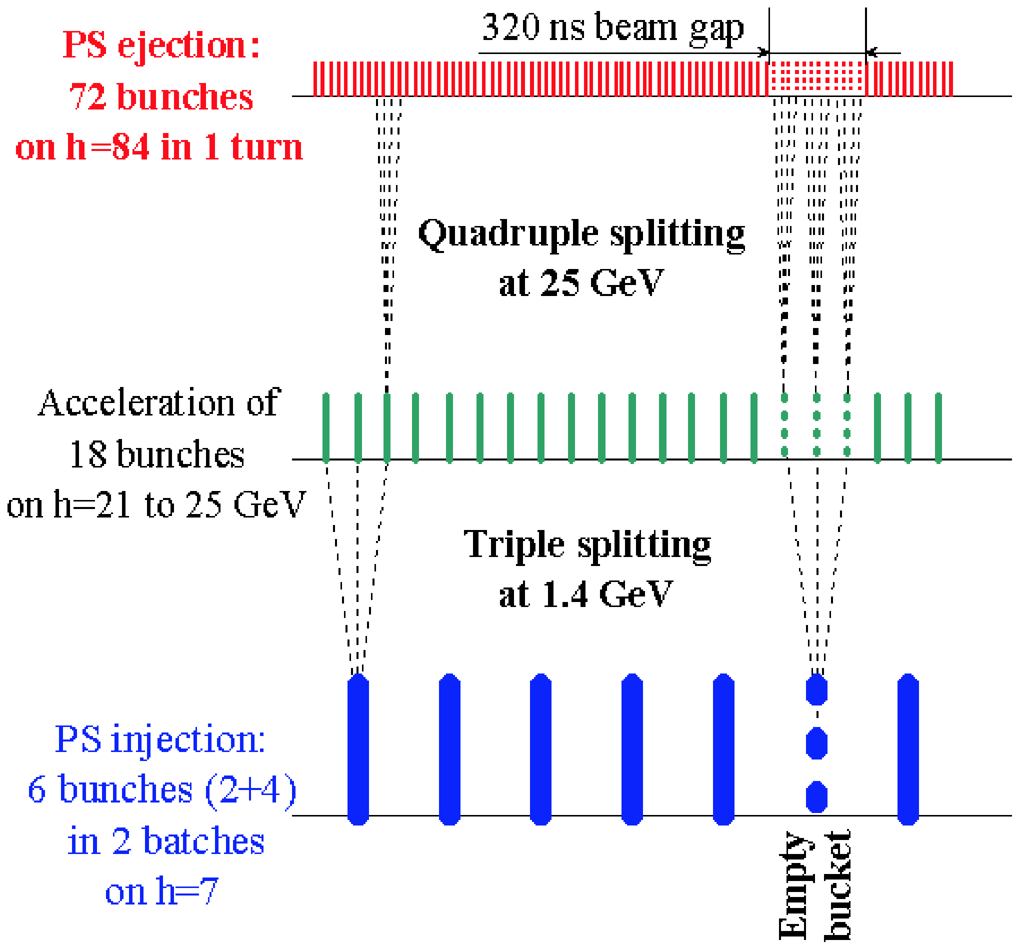


Splitting in four (actually 2 x 2)

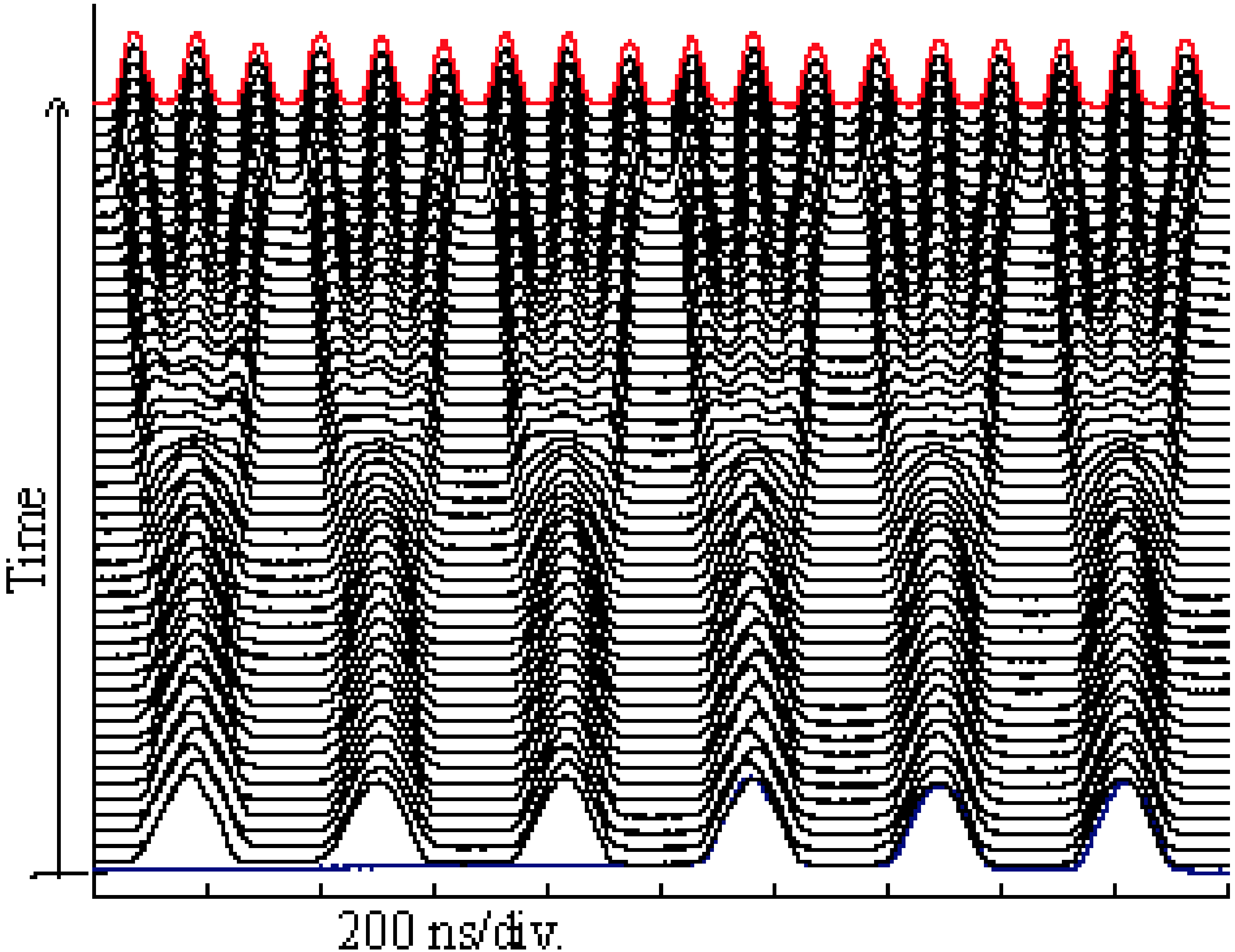




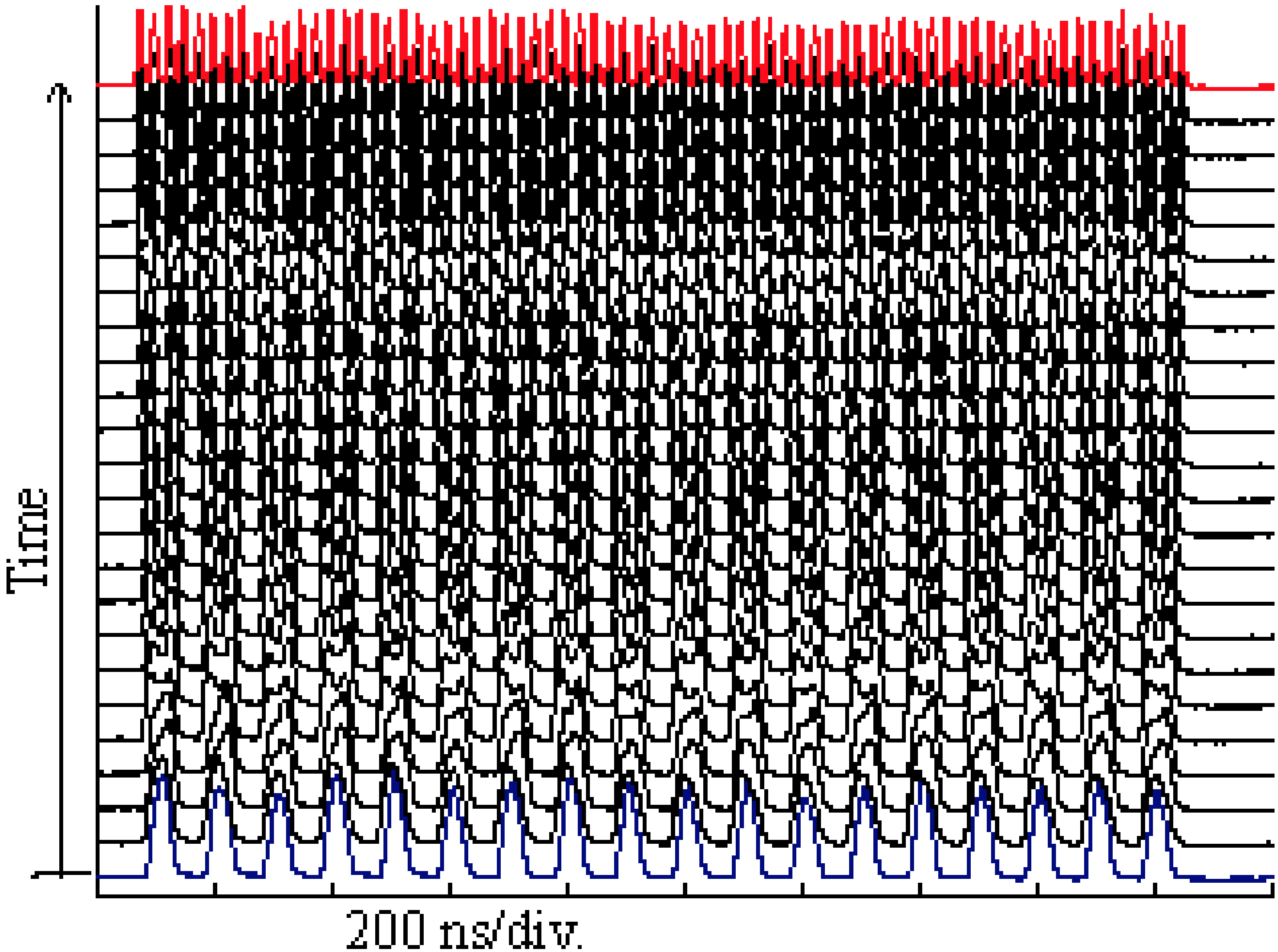
Bunch splitting in the PS



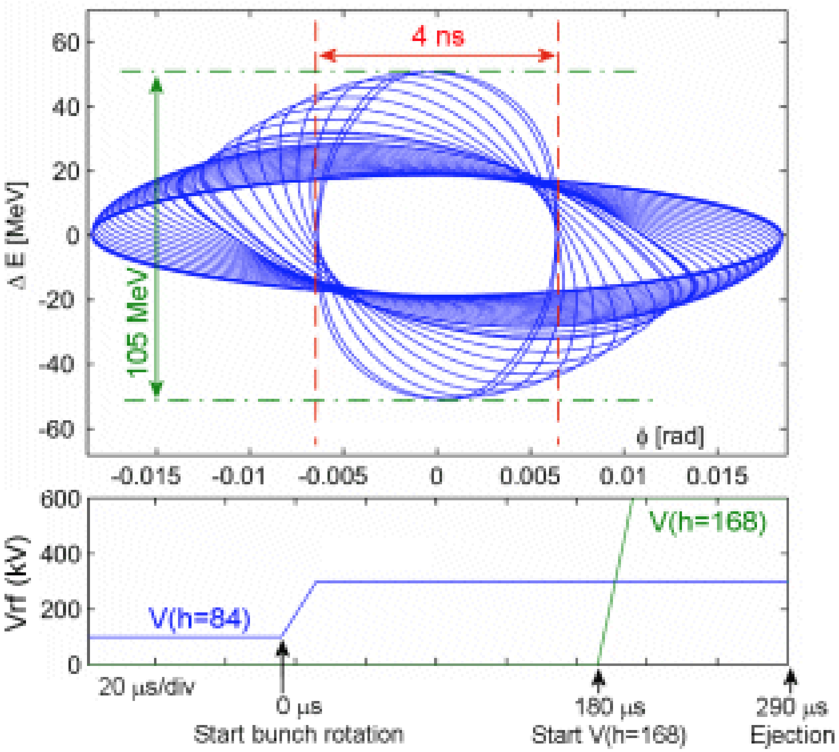
Thus 6 becomes 18 (at 1.4 GeV)

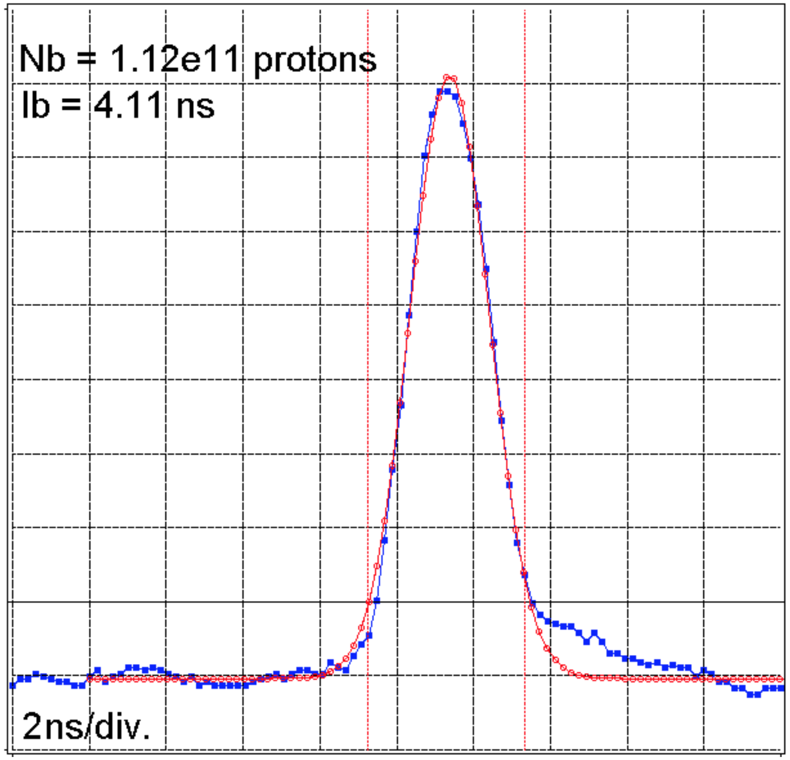


And 18 becomes 72 (at 25 GeV)



Bunch rotation at 25 GeV before extraction





Recap and intensities

- 1 bunch per PSB ring
- 6 injections into PS
- Triple and quadruple splitting in PS for 72 bunches
- 3 or 4 injections into SPS, up to 288 bunches in SPS
- 12 cycles for 39 injections of 72 for 2808 bunches in LHC

Nominal intensities for LHC and associated space charge at injection, emittance is critical, no losses						
	N	kb	Itot	Ibunch inj	Scheme	SC
LHC	1.150E+11	2808	3.229E+14	1.150E+11	12 SPS cycles, 234 334 334 334 = 39	-3.474E-08
SPS	1.150E+11	288	3.312E+13	1.150E+11	4 PS cycles	-1.051E-05
PS	1.150E+11	72	8.280E+12	1.380E+12	bunch splitting *3 and *2 and *2	-1.693E-02
PSB	1.380E+12	1	1.380E+12	1.380E+12	2 PBS cycles per PS cycle, injecting 3+3 or 4+2	-2.764E-01

Nominal intensities for LHC and associated space charge at injection, emittance is critical, 10% losses everywhere						
	N	kb	Itot	Ibunch inj	Scheme	SC
LHC	1.150E+11	2808	3.552E+14	1.392E+11	12 SPS cycles, 234 334 334 334 = 39	-4.204E-08
SPS	1.392E+11	288	4.408E+13	1.684E+11	4 PS cycles	-1.538E-05
PS	1.684E+11	72	1.334E+13	2.223E+12	bunch splitting *3 and *2 and *2	-2.726E-02
PSB	2.223E+12	1	2.445E+12	2.689E+12	2 PBS cycles per PS cycle, injecting 3+3 or 4+2	-5.386E-01

Requirements on the Linac complex

- So Linac2 has to provide
  - 2 turn injection into 4 rings (most demanding case)
  - T_{rev} at injection at 50 MeV is 1.67 μs

- So Linac2 needs to provide a pulse in excess of 10^{13} protons
- Minimum pulse length 13.5 μs

	PSB	Loss(%)	ppp needed	current(mA)	Pulse(us)	ppp
Linac2	**1.08E+13**	**10**	**1.18326E+13**	**100**	**20**	**1.248E+13**
RFQ out		**10**		**110**	**20**	**1.373E+13**
Source		**50**		**165**	**20**	**2.060E+13**

- With losses between the source and the linac
- Need around 2 10^{13} protons from the source
- Typical operation is 165mA current during the pulse in a 20 μs pulse

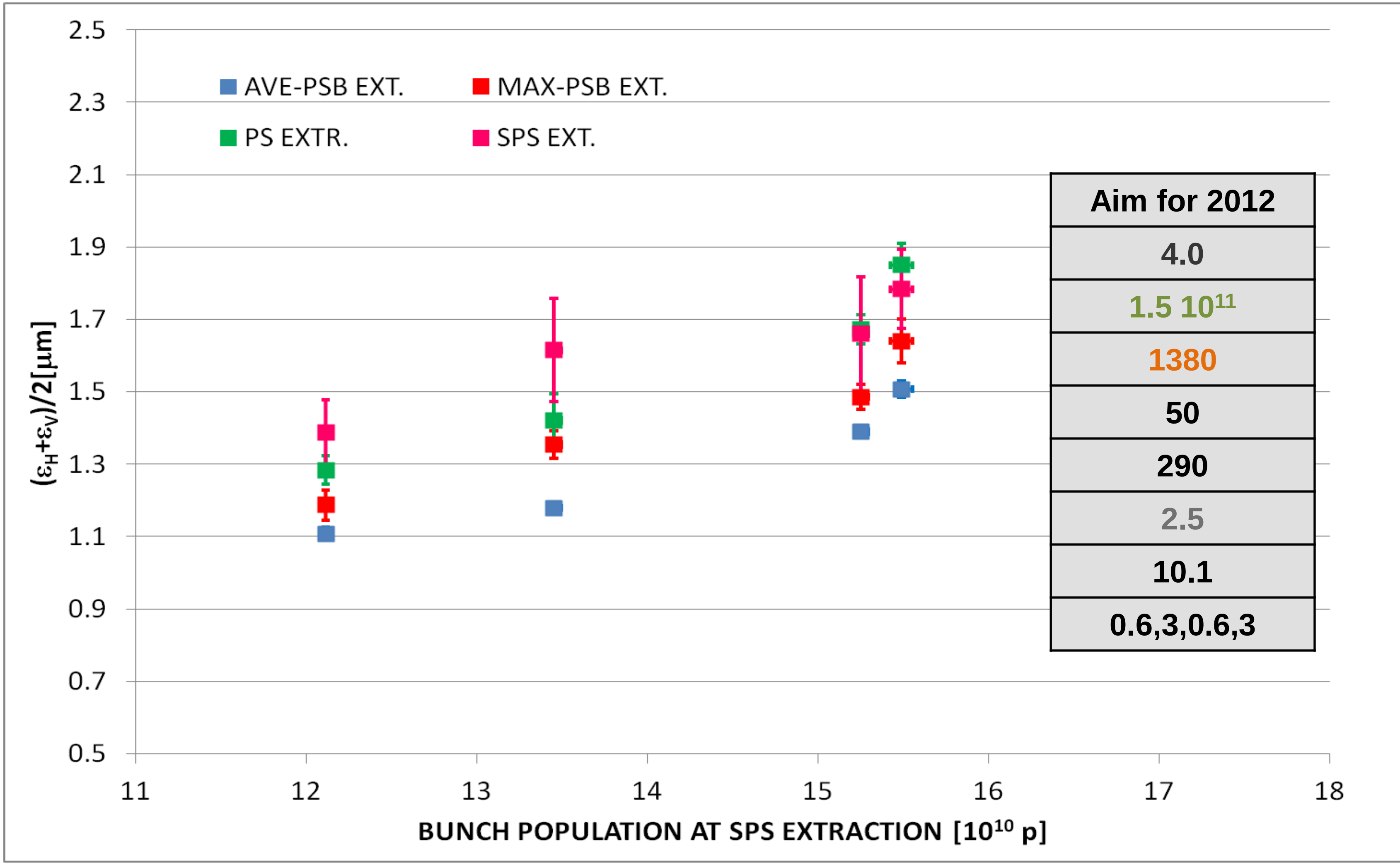
What about the transverse emittance ?

- The pulse from the source has around ε_n 1.2 μm.rad
- This is then
  - Injected into the PSB
  - Accelerated and extracted from PSB and injected into the PS
  - Accelerated and extracted from PS and injected into the SPS
  - Accelerated and extracted from SPS and injected into the LHC
  - Accelerated and squeezed in the LHC

- Each of these (and more) could lead to emittance blow up

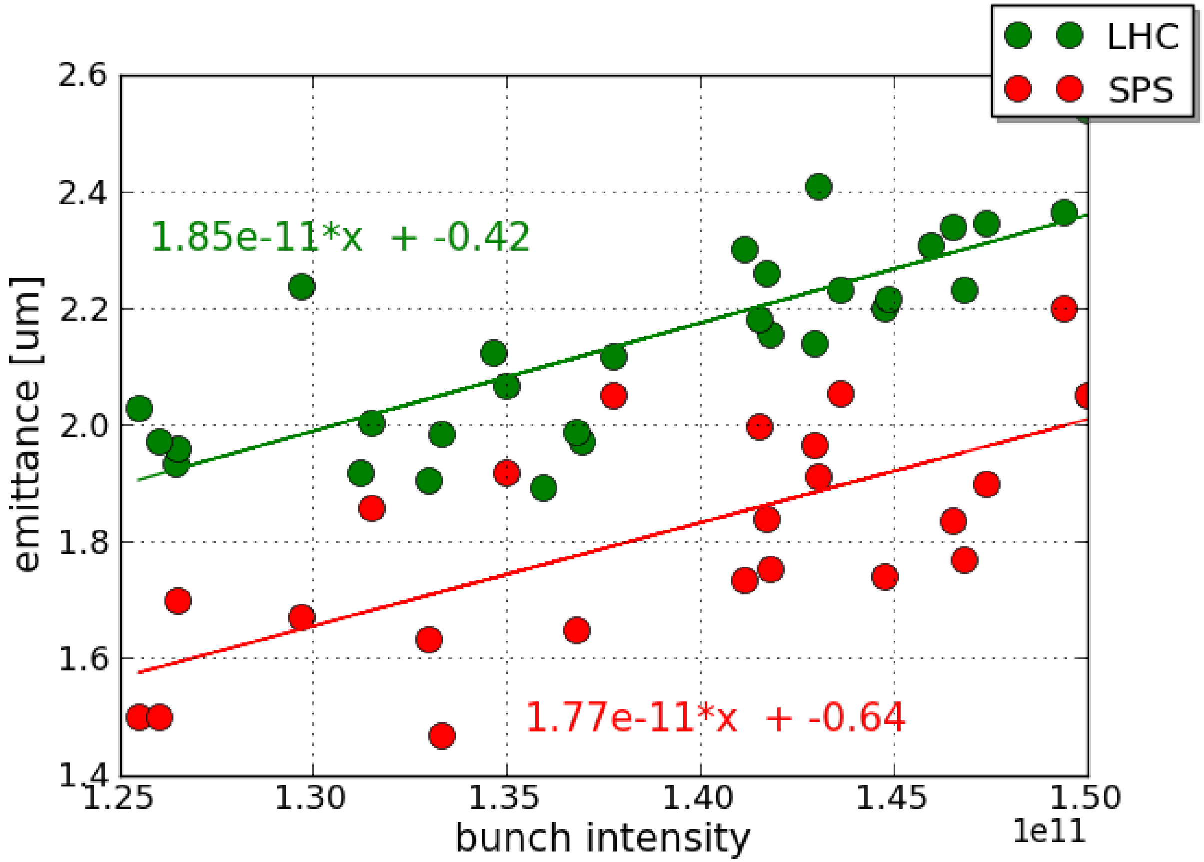
From design report (25 ns): PSB 2.5 μm – PS 3 μm – SPS 3.5 μm

Impressive injector performance 2011



LHC not bad either

Controlled parameters	Nominal	Aim for 2012
Norm transverse emittance (μm rad)	3.75	2.5



On average ~ 20 - 30 % growth between SPS flat top and collisions

Summary

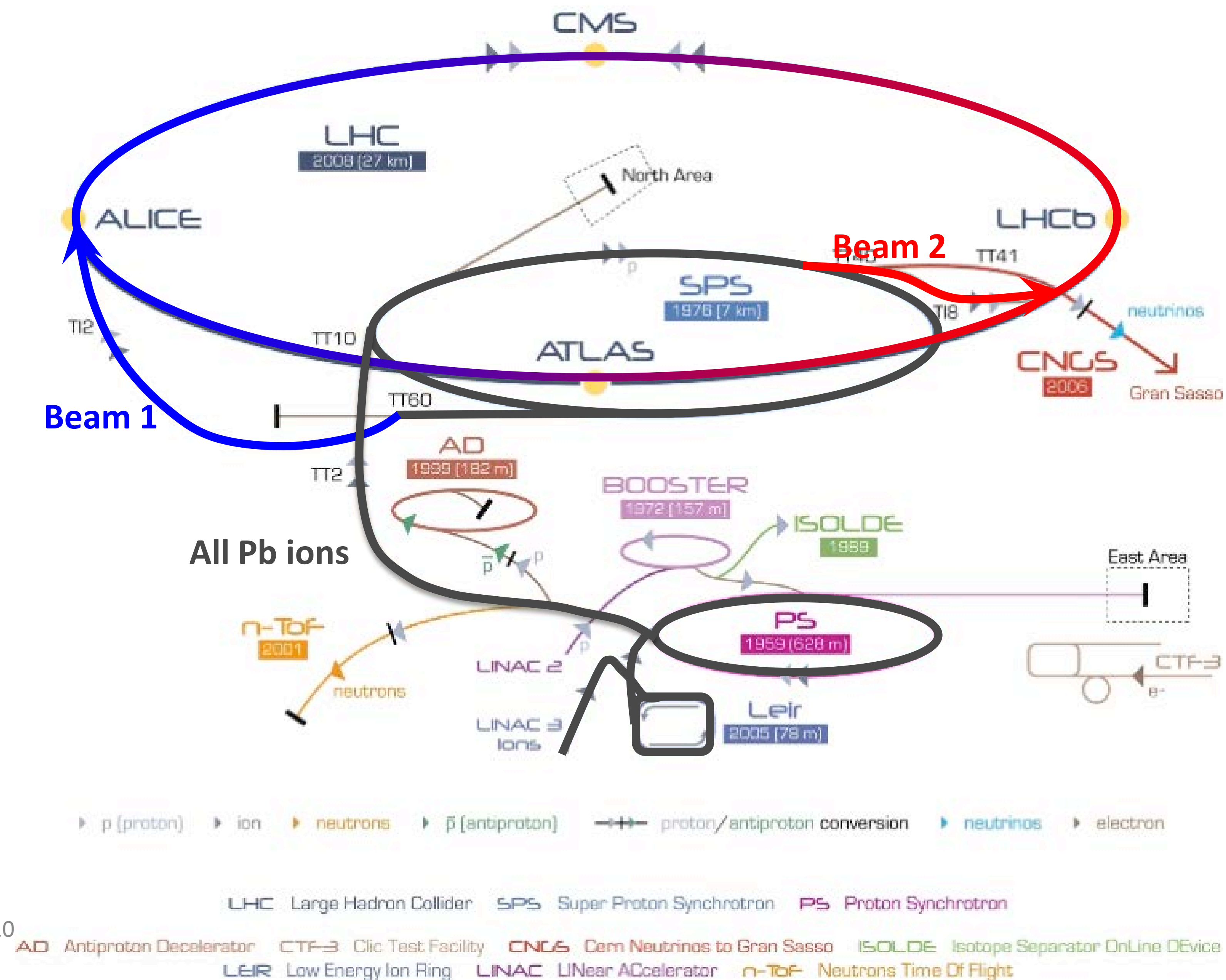
- Source has to repeatedly provide
  - 165 mA current during the pulse in a 20 μs pulse
- Corresponds to around 2 10^{13} protons per pulse

- The LHC injector chain plays a crucial role in LHC performance
- Has to provide 1000s of bunches for each physics fill
- Involves a complex series of manipulations
  - Innovative ideas that had to be realized on the machines
  - Have to be maintained throughout several months each year
  - Have to be done with no detrimental impact on transverse emittance

- LHC has to operate at high luminosity for many months per year
- Allows to deliver the 10-20 fb^{-1} needed to find or exclude the Higgs

- All this will yield (or not) a handful of events in any given channel

A word on Pb ions



Ions

- Electron Cyclotron Resonance ion source
  - producing Pb^{27+}
- RFQ
- Linac3
  - C foil stripper $Pb^{27+} \rightarrow Pb^{54+}$
- Phase space cooling in Low Energy Ion Ring
- PS again performs bunch splitting
  - Al foil stripper $Pb^{54+} \rightarrow Pb^{82+}$
- Multiple injections into SPS, and recombination
- Multiple injections into LHC

LHC Performance with ions

- Nominal scheme
- Early ion scheme (used in 2010, intermediate in 2011)
  - Much easier for LEIR, PS
  - Shorter filling time

Parameter	**Units**	**Nominal**	**Early Beam**
Energy per nucleon	TeV/n	2.76	2.76
Initial Luminosity L_0	$cm^{-2}\ s^{-1}$	$1\ 10^{27}$	$5\ 10^{25}$
# bunches/bunch harmonic		592/891	62/66
Bunch spacing	ns	99.8	1350
b^*	m	0.5	1.0
Number of Pb ions/bunch		**$7\ 10^7$**	**$7\ 10^7$**
Transv. norm. rms emittance	mm	1.5	1.5
Longitudinal emittance	eVs/charge	2.5	2.5
Luminosity half-life (1,2,3 expts.)	h	8,4.5,3	14,7.5,5.5