The Large Hadron Collider
An Introduction

R. Bailey

AB LHC Operations

An Introduction to the LHC

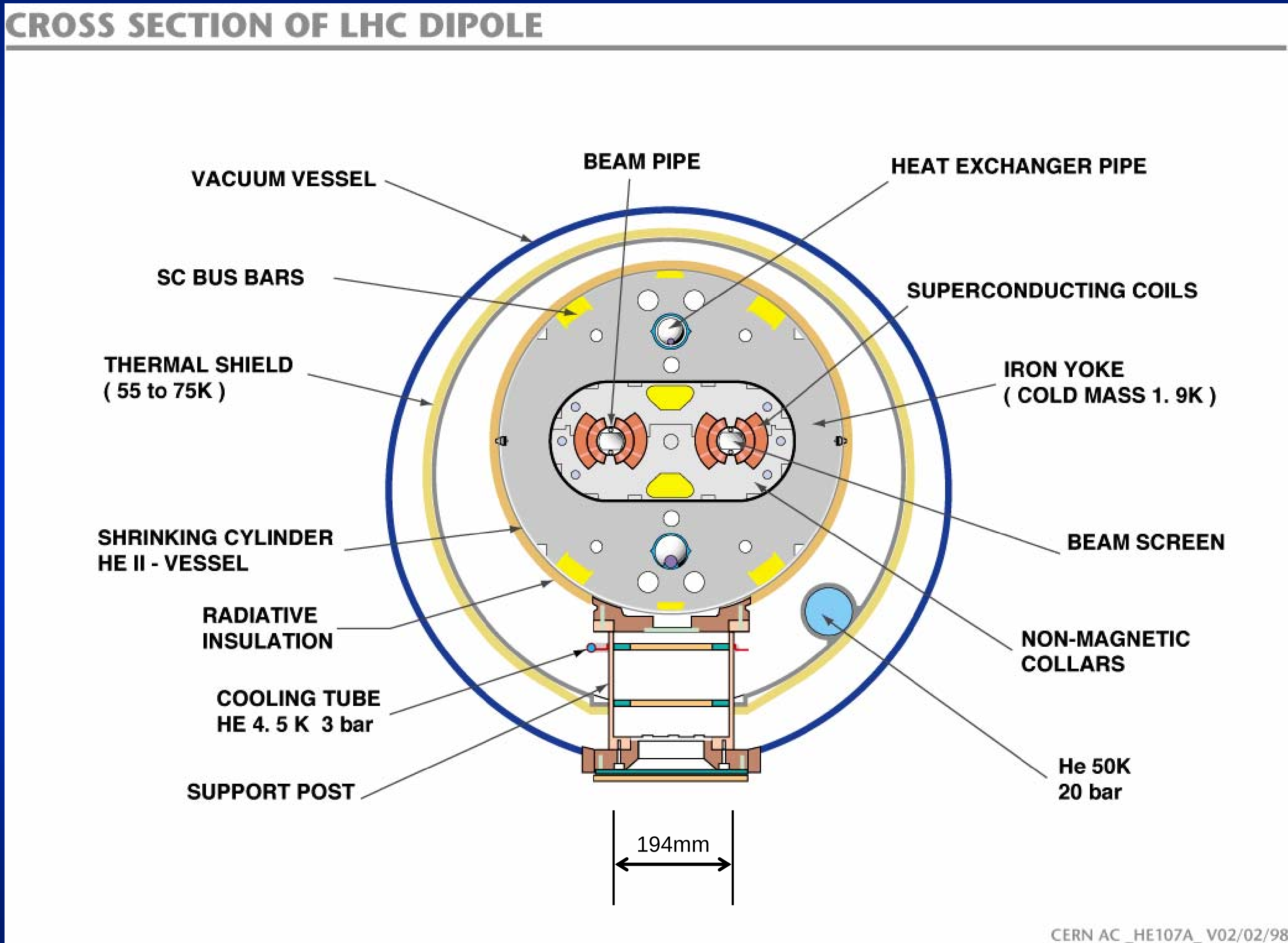
- Brief description (what and where)
- Some details of the machine layout
  - Arcs
  - Insertions
  - Dispersion suppressors
- Injectors and transfer lines
- A look at the LHC operational cycle
- Performance goals and associated parameters
- Commissioning strategy

Description

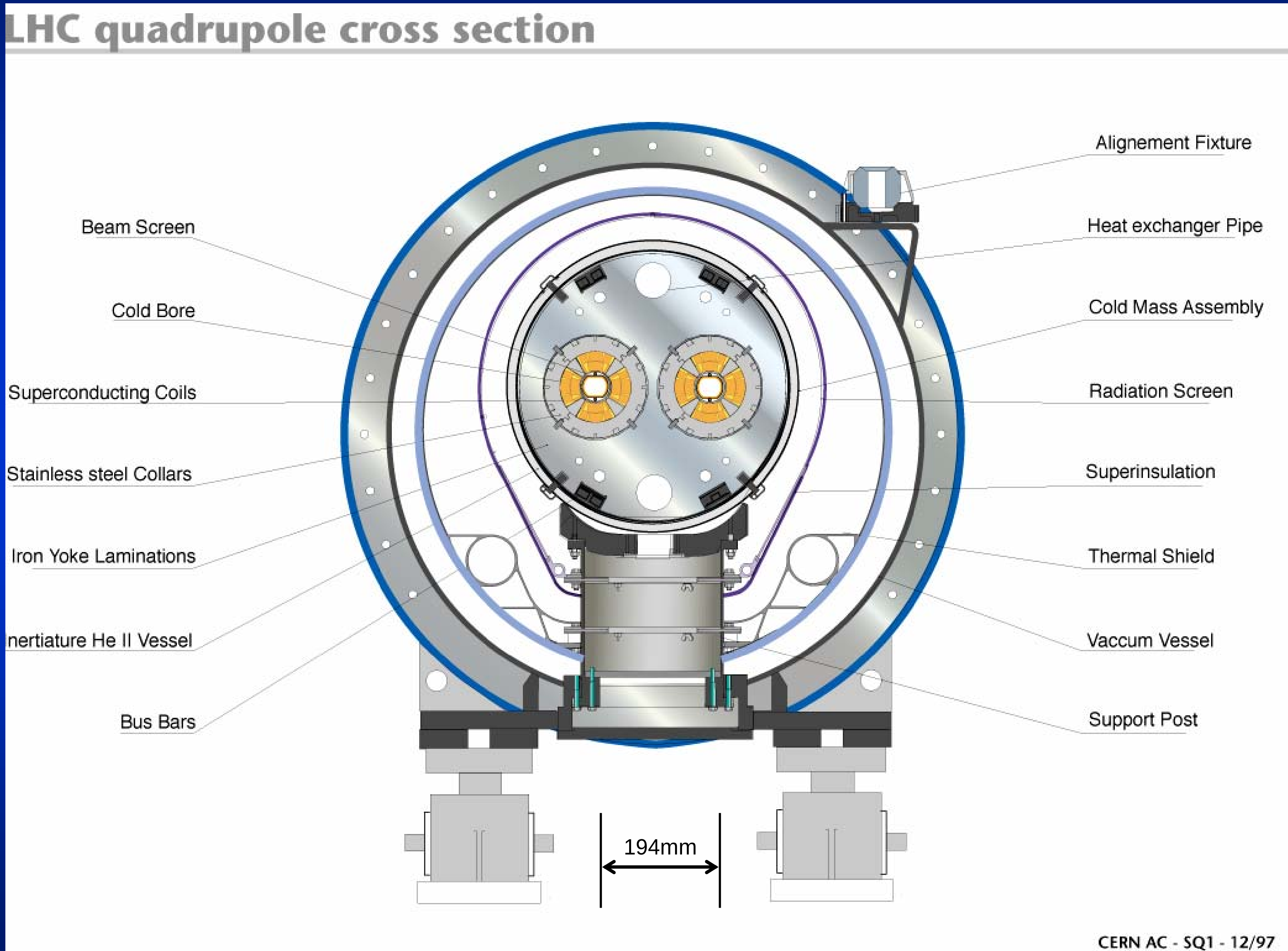
- Superconducting accelerator and collider in the LEP tunnel
  - LEP
    - Constructed 1984-89
    - Operated 1989-2000
    - Dismantled 2001/2002
  - LHC
    - Civil engineering and preparation of tunnel 1998-2005
    - Installation 2004-6
    - Commissioning 2007

- Luminosity goal 10^{34} cm^{-2} s^{-1}
- Excludes proton – antiproton in one beam pipe
  - Hence proton – proton machine
    - Separate magnetic fields and vacuum chambers in the arcs
    - Common sections in the interaction regions
    - Ion-ion collisions also possible
  - Tunnel cross section excludes 2 separate rings of magnets
    - Hence twin aperture magnets in the arcs

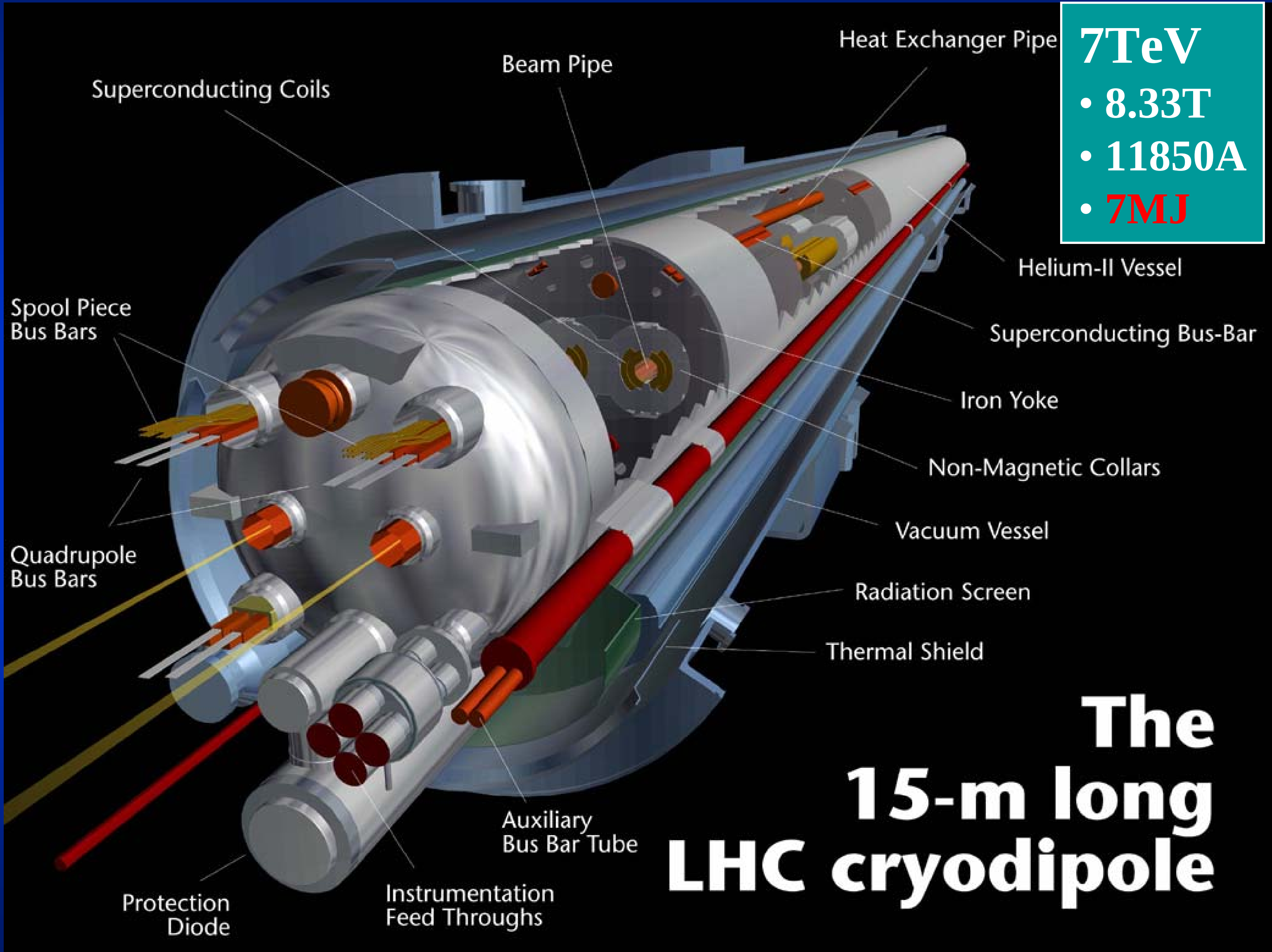
Dipole magnet cross section



Quadrupole magnet cross section



LHC dipoles (1232 of them)



7TeV

- **8.33T**
- **11850A**
- **7MJ**

And plenty more magnets besides …

Magnet Type	Order	Description	Number of Magnets
MB	1	Main Dipole Coldmass	1232
MBAW	1	Alice Spectrometer (Muon Dipole)	1
MBLW	1	LHC-b Spectrometer	1
MBRB	1	Twin Aperture Separation Dipole (194 mm) D4	2
MBRC	1	Twin Aperture Separation Dipole (188 mm) D2	8
MBRS	1	Single Aperture Separation Dipole D3	4
MBW	1	Twin Aperture Warm Dipole Module D3 and D4 in IR3 and IR7	20
MBWMD	1	Single Aperture Warm Dipole Module Compensating Alice Spectrometer	1
MBX	1	Single Aperture Separation Dipole D1	4
MBXW	1	Single Aperture Warm Dipole Module D1 in IR1 and IR5	24
MBXWH	1	Single Aperture Warm Horizontal Dipole Module Compensating LHC-b Spectrometer	1
MBXWS	1	Single Aperture Warm Horizontal Dipole Short Module	2
MBXWT	1	Single aperture warm compensator for ALICE	2
MCBCH	1	Orbit Corrector in MCBCA(B,C,D)	78
MCBCV	1	Orbit Corrector in MCBCA(B,C,D)	78
MCBH	1	Arc Orbit Corrector in MSCBA(B,C,D), Horizontal	376
MCBV	1	Arc Orbit Corrector in MSCBA(B,C,D), Vertical	376
MCBWH	1	Single Aperture Warm Orbit Horizontal Corrector	8
MCBWV	1	Single Aperture Warm Orbit Verticall Corrector	8
MCBXH	1	Horizontal Orbit Corrector in MCBX(A)	24
MCBXV	1	Vertical Orbit Corrector in MCBX(A)	24
MCBYH	1	Orbit Corrector in MCBYA(B)	44
MCBYV	1	Orbit Corrector in MCBYA(B)	44
MCD	5	Decapole Corrector in MCDO, (Spool Piece Corrector)	1232
MCO	4	Octupole Corrector in MCDO, (Spool Piece Corrector)	1232
MCOSX	3	Skew Octupole Spool-Piece Associated to MQSX in MQSXA	8
MCOX	4	Octupole Spool-Piece Associated to MQSXA	8
MCS	3	Sextupole Corrector, (Spool Piece Corrector)	2464
MCSSX	3	Skew Sextupole Spool-Piece Associated to MQSX in MQSXA	8
MCSX	3	Sextupole Spool-Piece Associated to MCBXA	8
MCTX	6	Dodecapole Spool-Piece Associated to MCBXA	8
MKA	1	Tune kicker	2
MKD	1	Ejection dump kicker	30
MKI	1	Injection kicker	8
MKQ	1	Kicker For Q And Aperture Measurement	2

Magnet Type	Order	Description	Number of Magnets
MO	4	Octupole Lattice Corrector in Arc Short Straight Section	336
MQ	2	Lattice Quadrupole in the Arc	392
MQM	2	Insertion Region Quadrupole 3.4 m	38
MQMC	2	Insertion Region Quadrupole 2.4m	12
MQML	2	Insertion Region Quadrupole 4.8 m	36
MQS	2	Skew Quadrupole Lattice Corrector in Arc Short Straight Section	64
MQSX	2	Skew Quadrupole Q3	8
MQT	2	Tuning Quadrupole Corrector in Arc Short Straight Section	320
MQTLH	2	(MQTL Half Shell Type)	48
MQTLI	2	(MQTL Inertia Tube Type)	72
MQWA	2	Twin Aperture Warm Quadrupole Module in IR3 and IR7. Asymmetrical FD or DF	40
MQWB	2	Twin Aperture Warm Quadrupole Module in IR3 and IR7. Symmetrical FF or DD	8
MQXA	2	Single Aperture Triplet Quadrupole (Q1, Q3)	16
MQXB	2	Single Aperture Triplet Quadrupole (Q2)	16
MQY	2	Insertion Region Wide Aperture Quadrupole 3.4 m.	24
MS	3	Arc Sextupole Lattice Corrector Associated to MCBH or MCBV in MSCBA, MSCBB, MSCBC and MSCBD	688
MSDA	1	Ejection dump septum, Module A	10
MSDB	1	Ejection dump septum, Module B	10
MSDC	1	Ejection dump septum, Module C	10
MSIA	1	Injection septum, Module A	4
MSIB	1	Injection septum, Module B	6
MSS	2	Arc skew Sextupole Corrector Associated to MCBH in MSCBC and MSCBD	64

Several thousand magnets

And plenty of power circuits …

Type	Number of Circuits
RB	8
RBAWV	1
RBLWH	1
RBWMDV	1
RBXWH	1
RBXWSH	2
RBXWTV	2
RCBCH10	16
RCBCH5	4
RCBCH6	12
RCBCH7	14
RCBCH8	16
RCBCH9	16
RCBCV10	16
RCBCV5	4
RCBCV6	12
RCBCV7	14
RCBCV8	16
RCBCV9	16
RCBH11	16
RCBH12	16
RCBH13	16
RCBH14	16
RCBH15	16
RCBH16	16
RCBH17	16
RCBH18	16
RCBH19	16
RCBH20	16
RCBH21	16
RCBH22	16
RCBH23	16
RCBH24	16
RCBH25	16
RCBH26	16
RCBH27	16
RCBH28	16
RCBH29	16

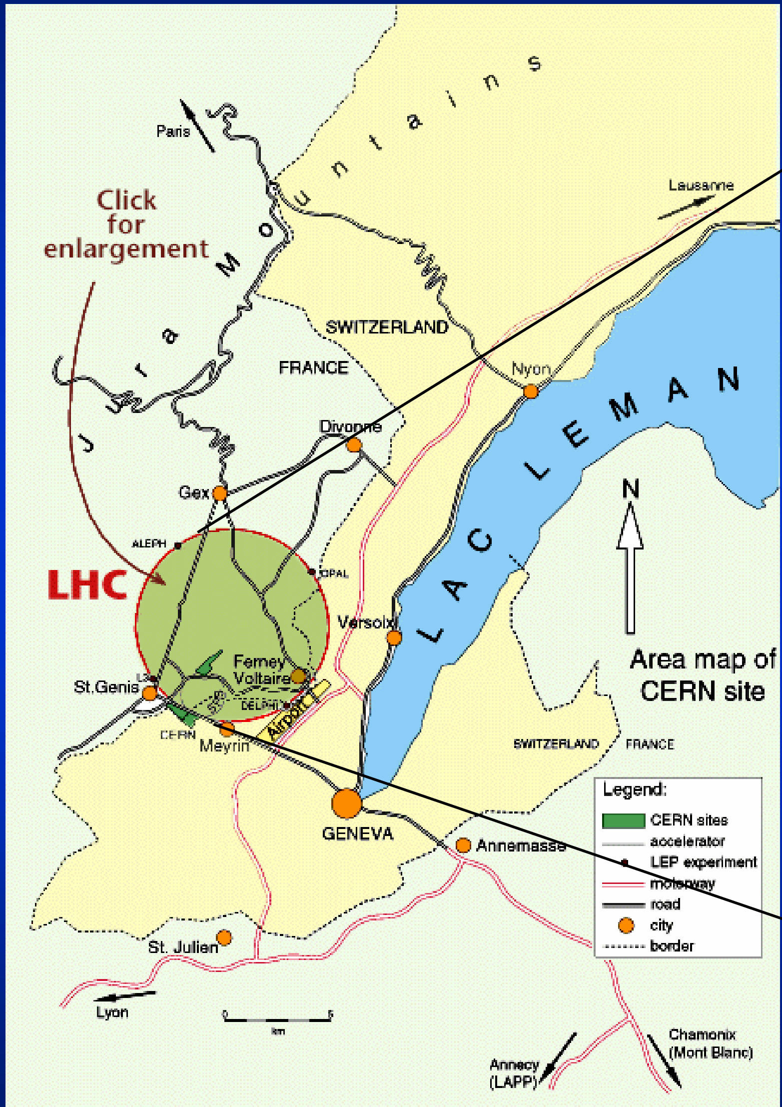
Type	Number of Circuits
RCBH30	16
RCBH31	16
RCBH32	16
RCBH33	16
RCBH34	8
RCBV11	16
RCBV12	16
RCBV13	16
RCBV14	16
RCBV15	16
RCBV16	16
RCBV17	16
RCBV18	16
RCBV19	16
RCBV20	16
RCBV21	16
RCBV22	16
RCBV23	16
RCBV24	16
RCBV25	16
RCBV26	16
RCBV27	16
RCBV28	16
RCBV29	16
RCBV30	16
RCBV31	16
RCBV32	16
RCBV33	16
RCBV34	8
RCBWH4	4
RCBWH5	4
RCBWV4	4
RCBWV5	4
RCBXH1	8
RCBXH2	8
RCBXH3	8
RCBXV1	8
RCBXV2	8
RCBXV3	8
RCBYH4	10
RCBYH5	8

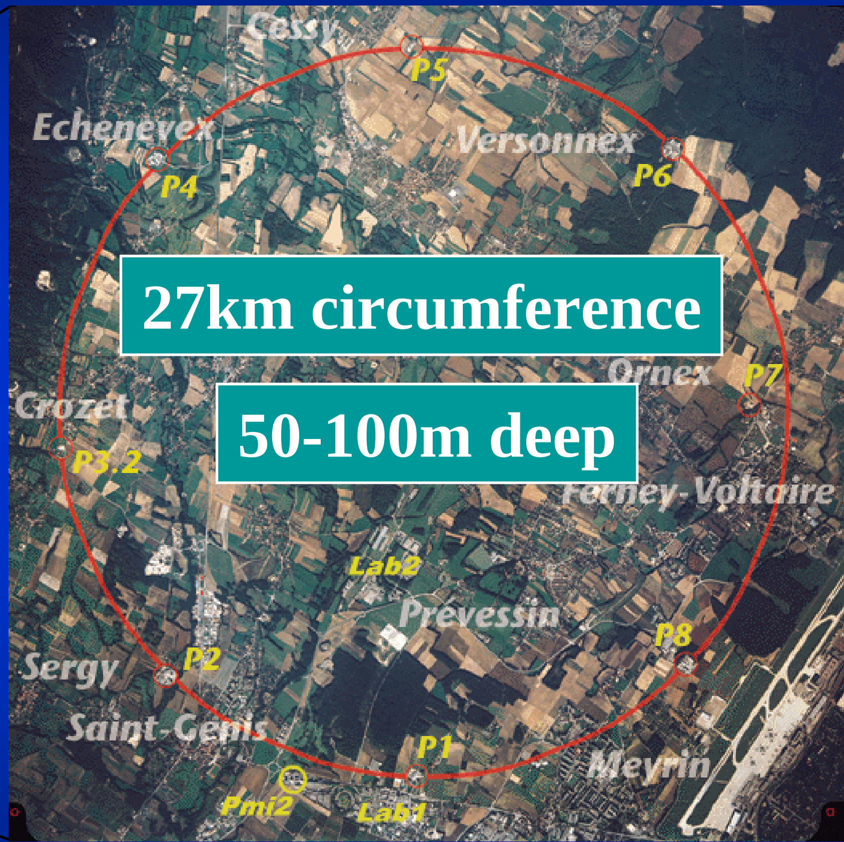
Type	Number of Circuits
RCBYH6	2
RCBYHS4	16
RCBYHS5	8
RCBYV4	10
RCBYV5	8
RCBYV6	2
RCBYVS4	16
RCBYVS5	8
RCD	16
RCO	16
RCOSX3	8
RCOX3	8
RCS	16
RCSSX3	8
RCSX3	8
RCTX3	8
RD1	6
RD2	8
RD3	2
RD34	2
RD4	2
RMSD	2
ROD	16
ROF	16
RQ10	12
RQ4	12
RQ5	14
RQ6	18
RQ7	10
RQ8	12
RQ9	12
RQD	8
RQF	8
RQS	24
RQSX3	8
RQT12	32
RQT13	32

Type	Number of Circuits
RQT4	4
RQT5	4
RQTD	16
RQTF	16
RQTL10	8
RQTL11	32
RQTL7	8
RQTL8	8
RQTL9	8
RQX	8
RSD1	16
RSD2	16
RSF1	16
RSF2	16
RSS	16

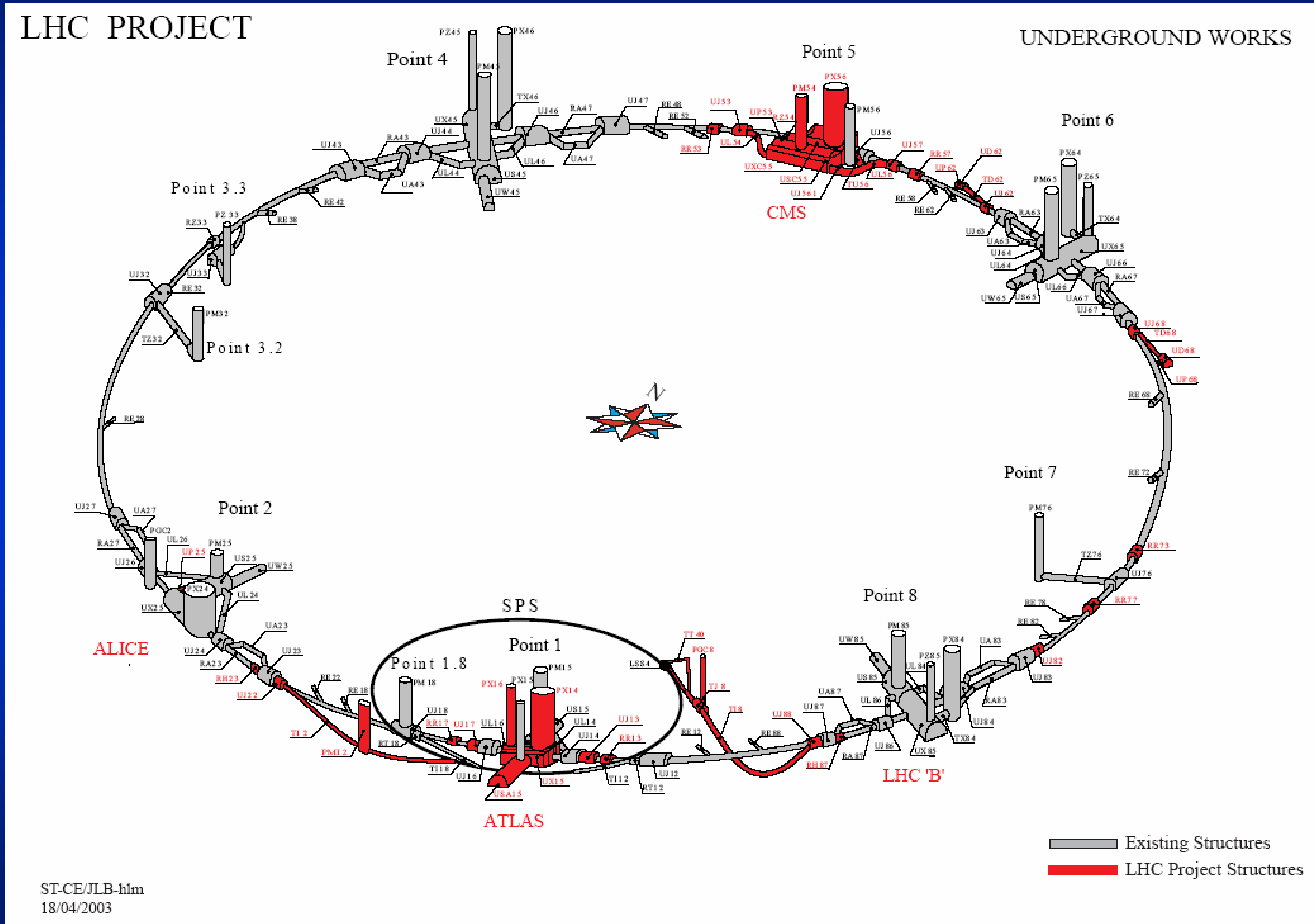
Several hundred power circuits

Geographical situation

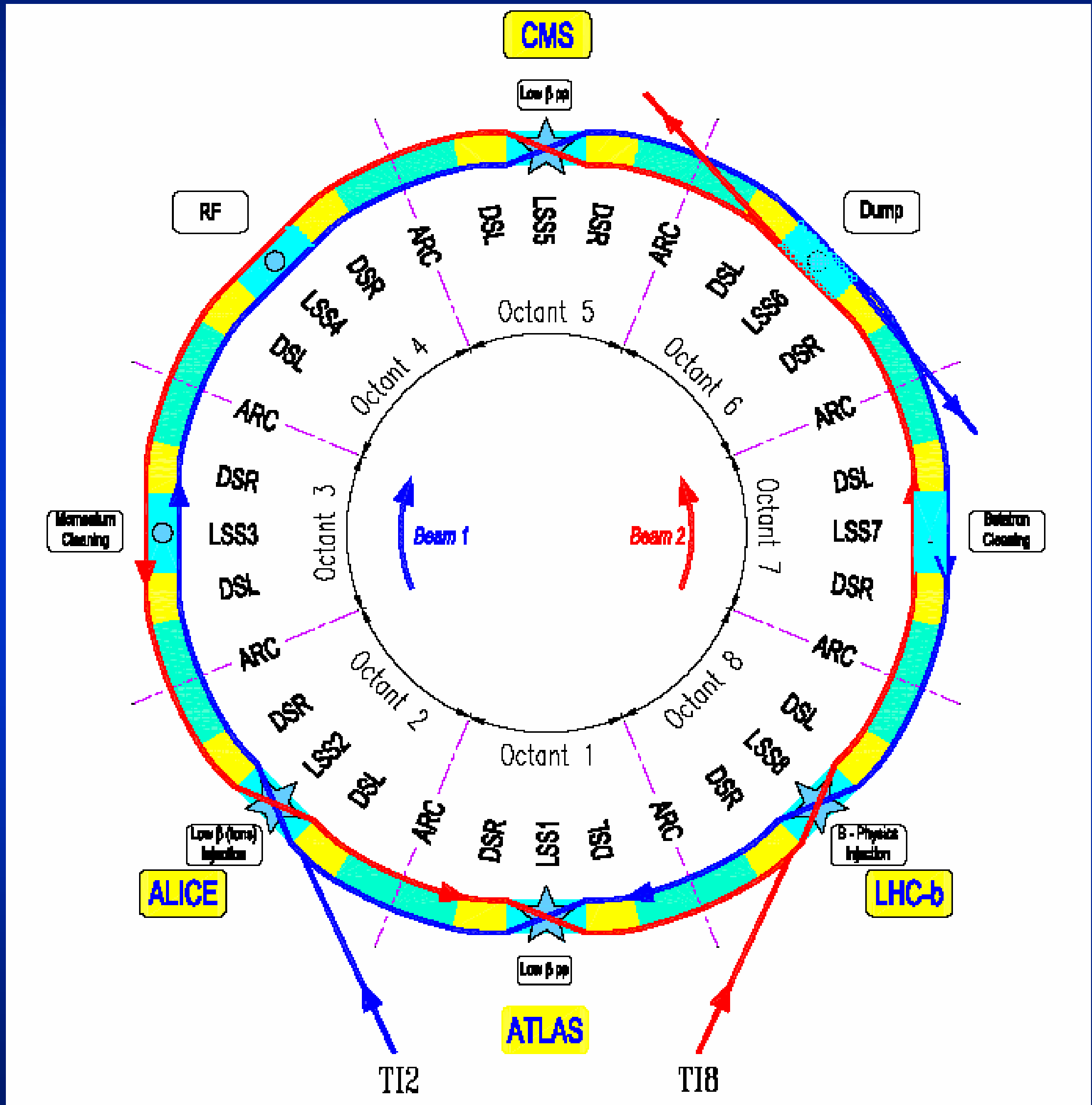




LEP and LHC underground structures

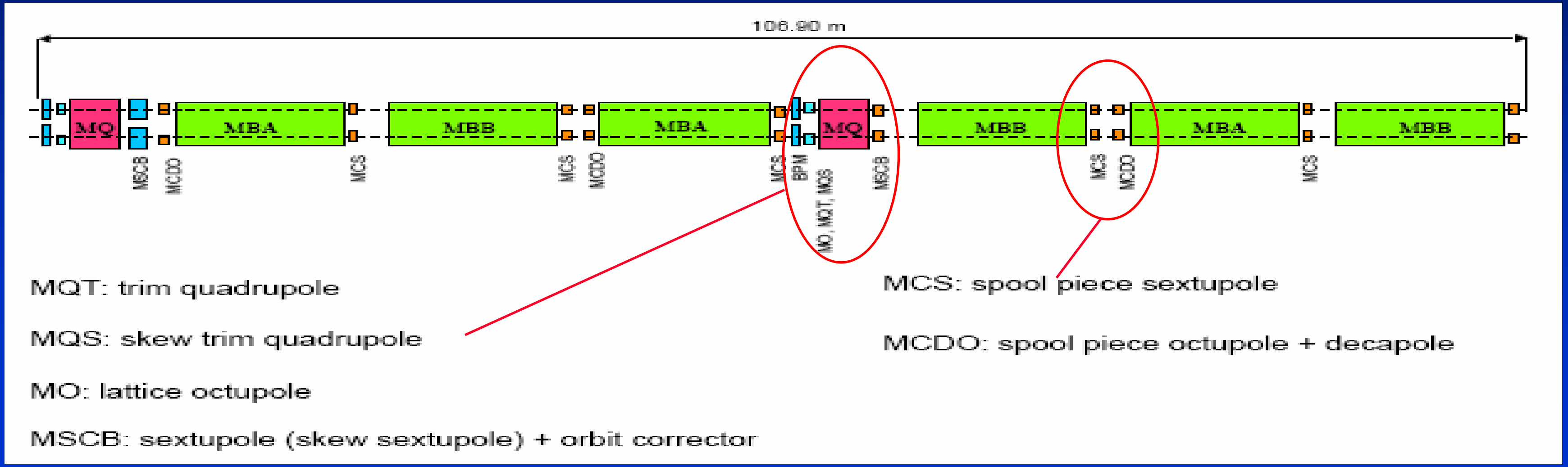


Layout schematic



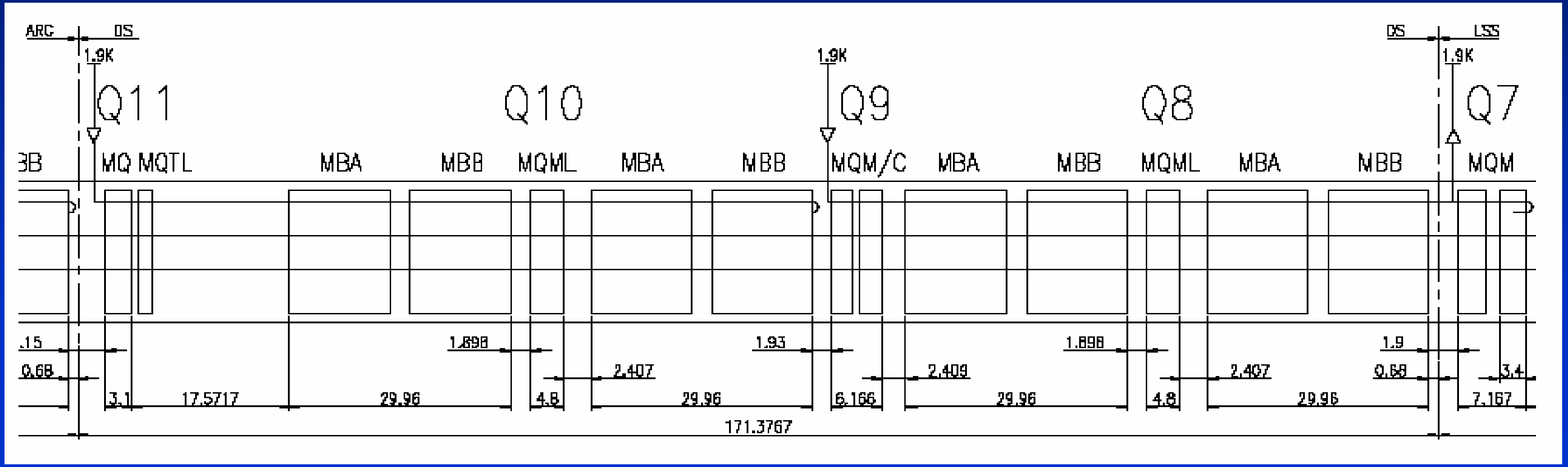
- 8 arcs
- 8 LSSS
- 16 dispersion suppressors
- 4 main experiments

The arcs



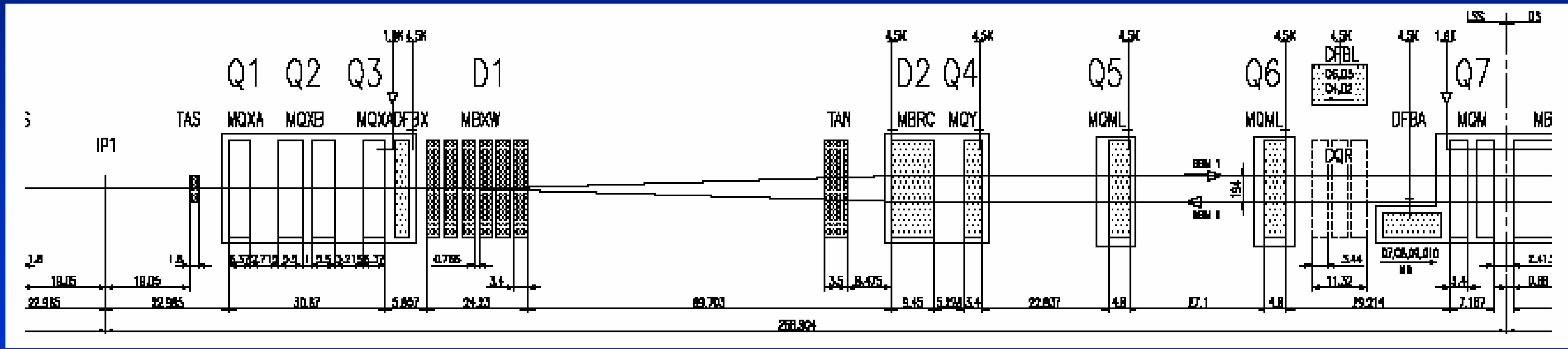
- 23 regular cells in each arc
- 106.9m long, made from two 53.45m long half-cells
- Half cell
  - 3 15m cryodipole magnets, each with spool-piece correctors
  - 1 Short Straight Section (~6m long)
    - Quadrupole and lattice corrector magnets

Dispersion suppressors



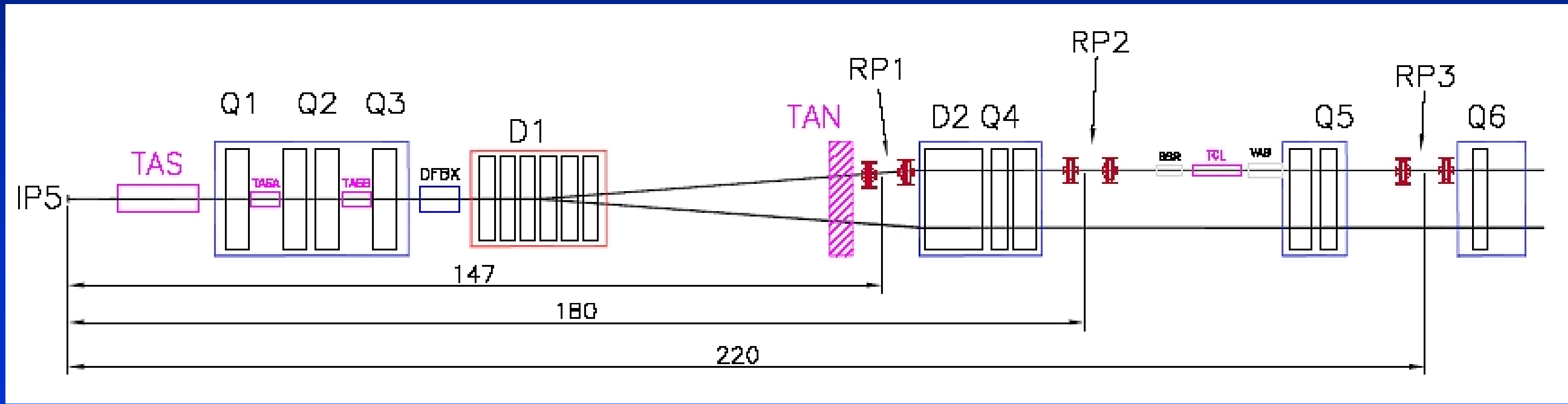
- Standard arc cells with missing dipole magnet and individually powered quadrupoles
- Threefold function
  - adapt the LHC reference orbit to the geometry of the LEP tunnel
  - cancel the horizontal dispersion arising in the arc and generated by the separation / recombination dipole magnets and the crossing angle bumps
  - help in matching the insertion optics to the periodic solution of the arc

IR1 (ATLAS)



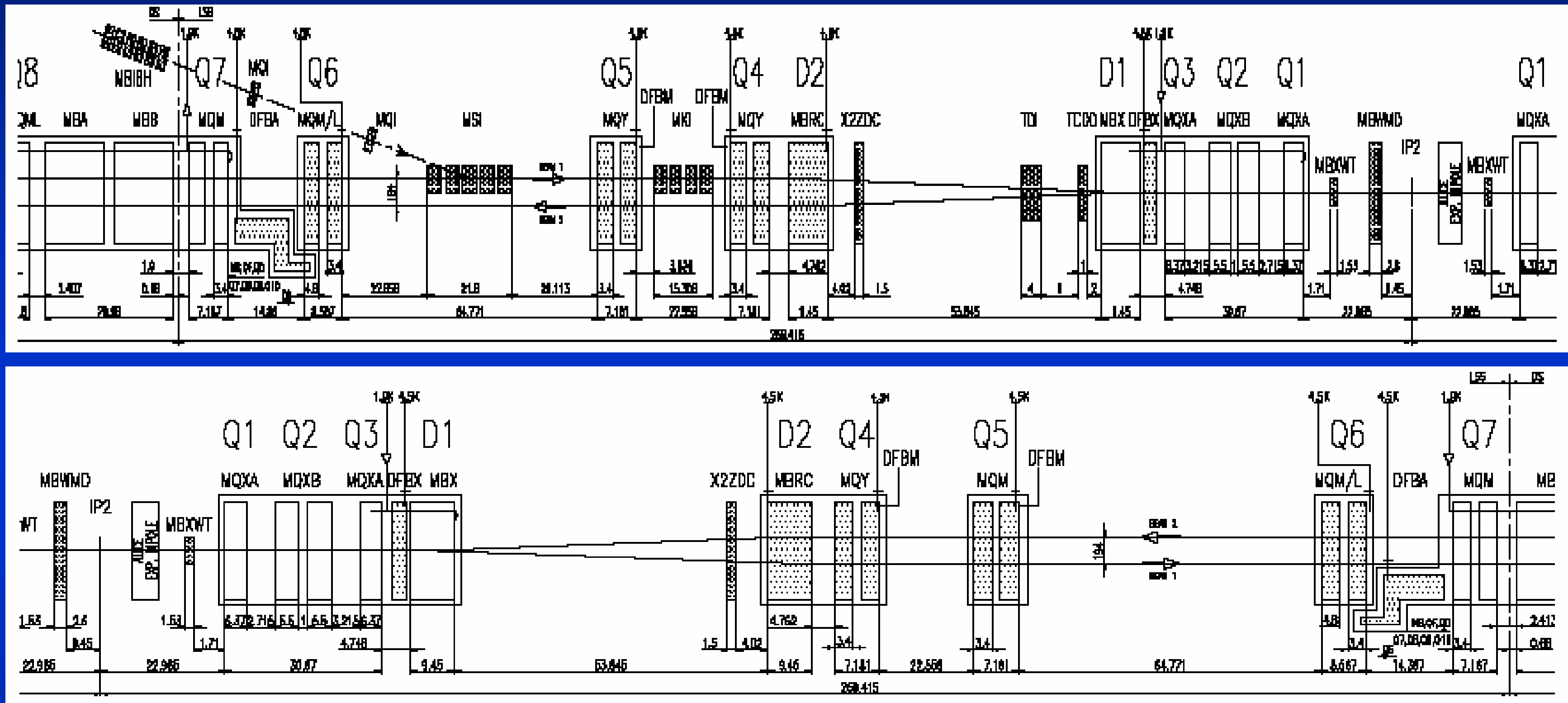
- ATLAS experiment (high luminosity)
- Symmetrical around IP (right side shown)
- Single bore low β triplet assembly
- Single bore conventional dipole D1
- Double bore superconducting dipole D2
- 4 matching quadrupoles Q4 to Q7

IR5 (CMS and TOTEM)



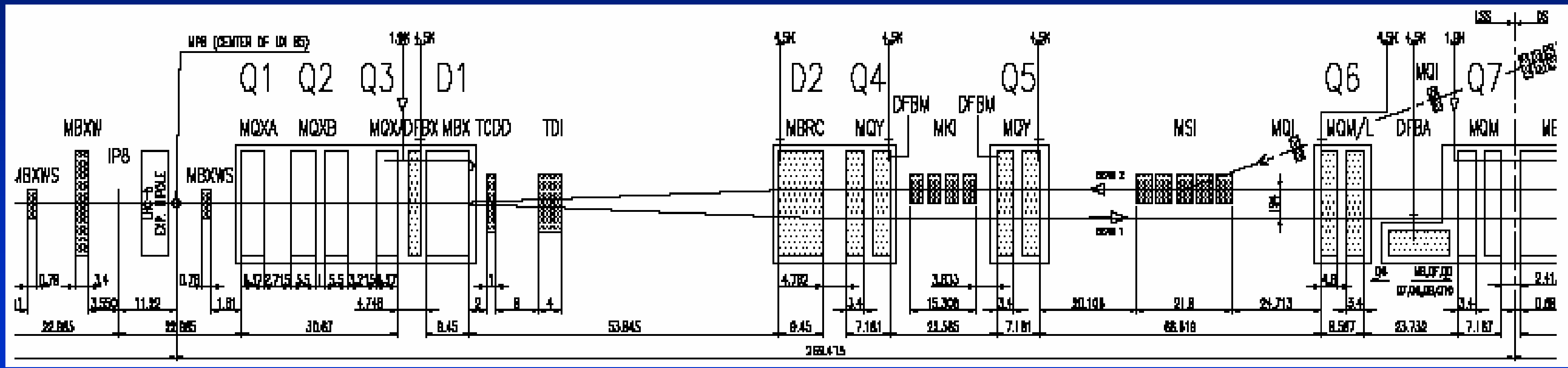
- CMS experiment (high luminosity) and TOTEM
- Basically the same layout as IR1
  - Symmetrical around IP (right side shown)
  - Single bore low β triplet assembly
  - Single bore conventional dipole D1
  - Double bore superconducting dipole D2
  - 4 matching quadrupoles Q4 to Q7

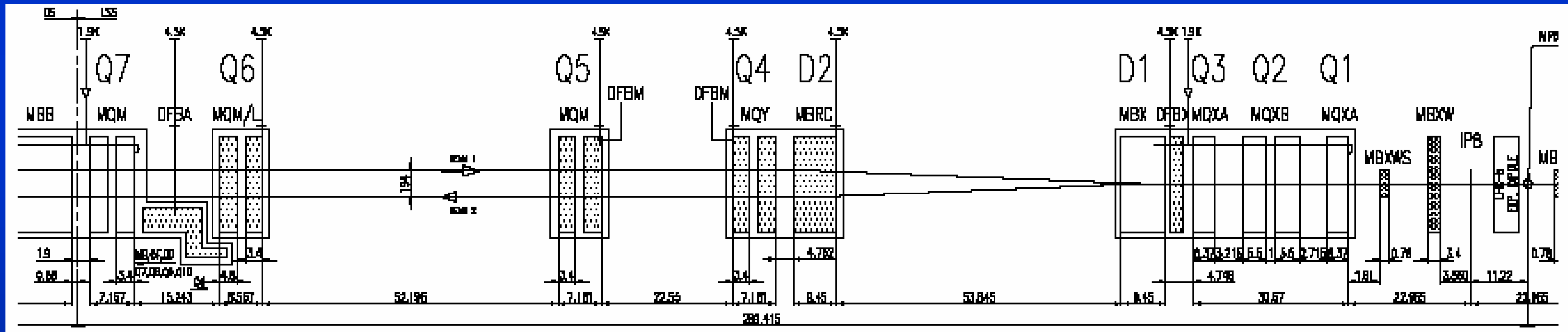
IR2 (ALICE and injection into Ring 1)



- Injection into matching section left of IP
- D2 and D1 both superconducting
- ALICE experiment (ions)
- Flexible optics to control luminosity

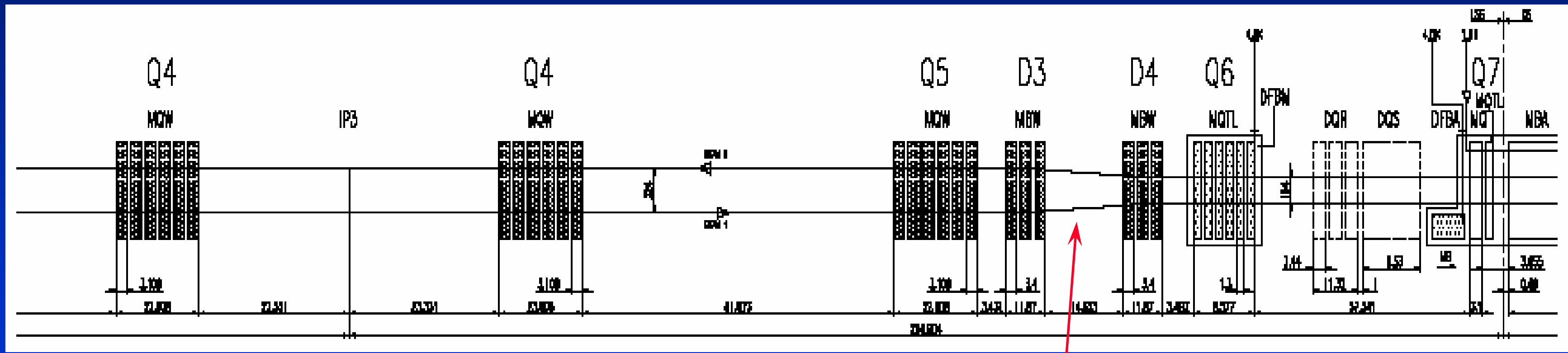
IR8 (LHCb and injection into Ring 2)





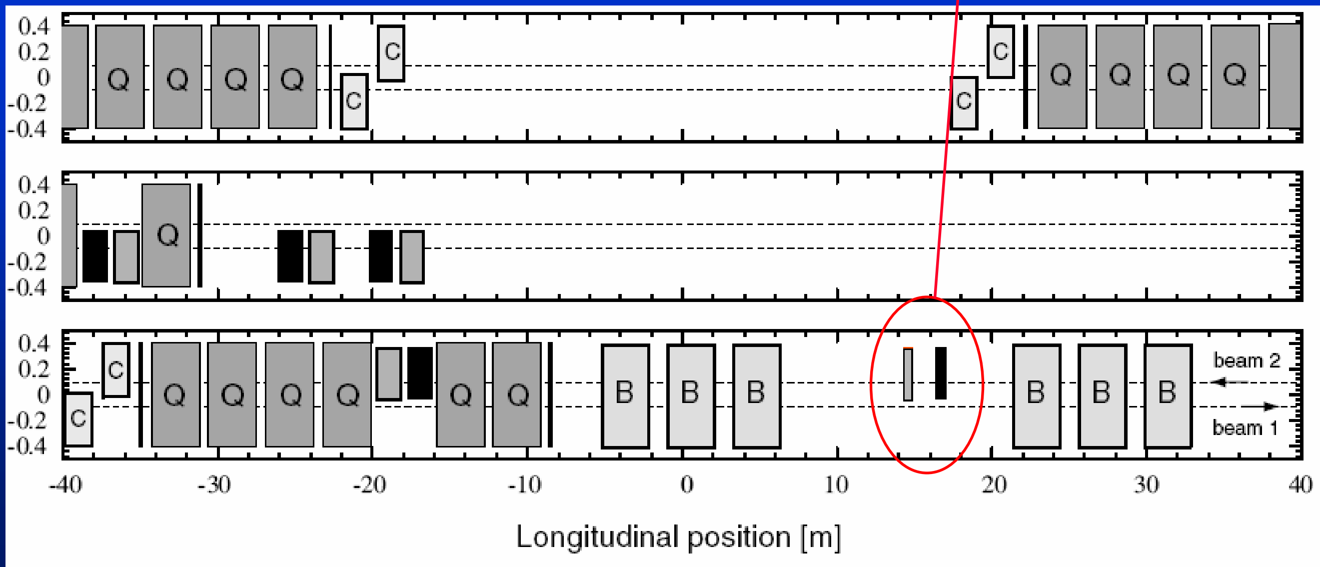
- Injection into matching section right of IP
- D2 and D1 both superconducting
- LHCb experiment (CP violation in B decays)
- Flexible optics to control luminosity

IR3 (collimators; momentum cleaning)

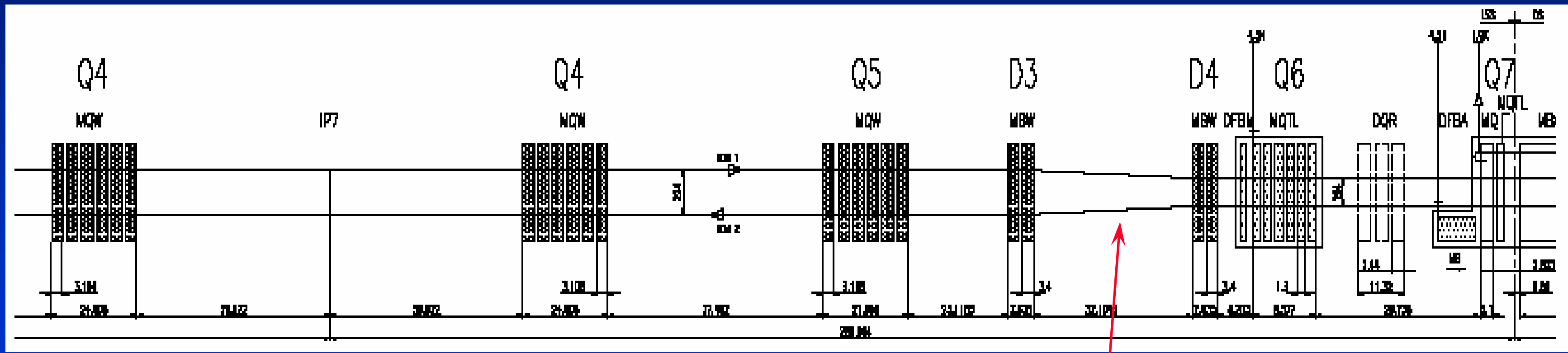


- Double bore conventional dipoles D4 and D3
- Double bore conventional quads Q5 and Q4

Primary collimators here

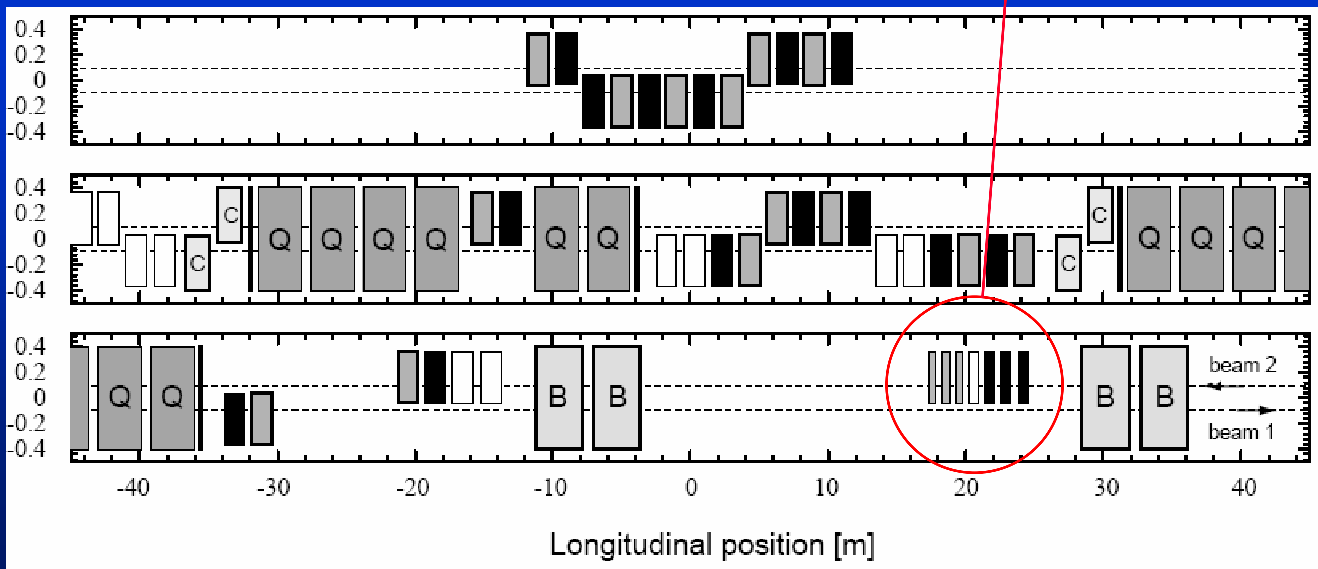


IR7 (collimators; betatron cleaning)



- Double bore conventional dipoles D4 and D3
- Double bore conventional quads Q5 and Q4

Primary collimators here



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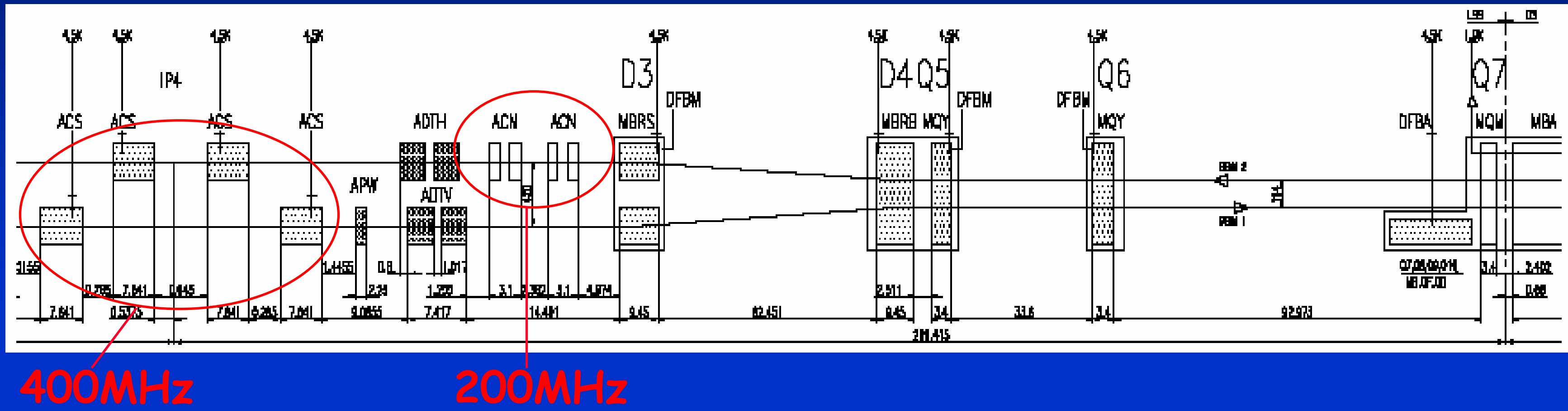
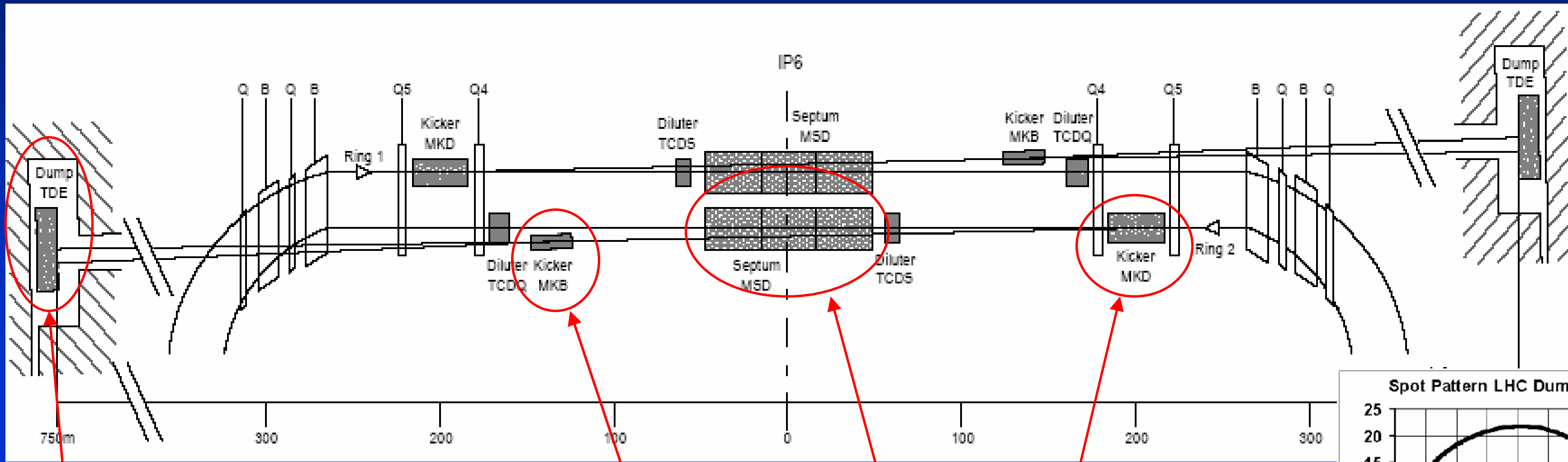
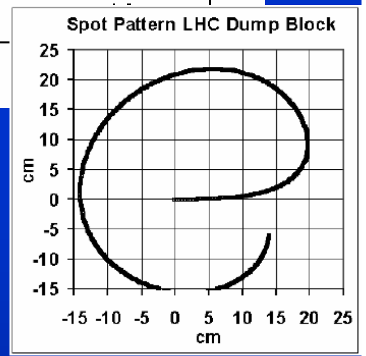
IR4 (RF)



- Symmetrical around IP (right side shown)
- Double bore superconducting dipoles D4 and D3
- 400MHz accelerating system
  - For capture, acceleration and store
  - 2 * 4-cavity cryogenic modules per beam
- 200MHz capture system (staged)
  - For injected bunches with longitudinal emittance > 1eV.s
  - Design done, space reserved for possible later installation

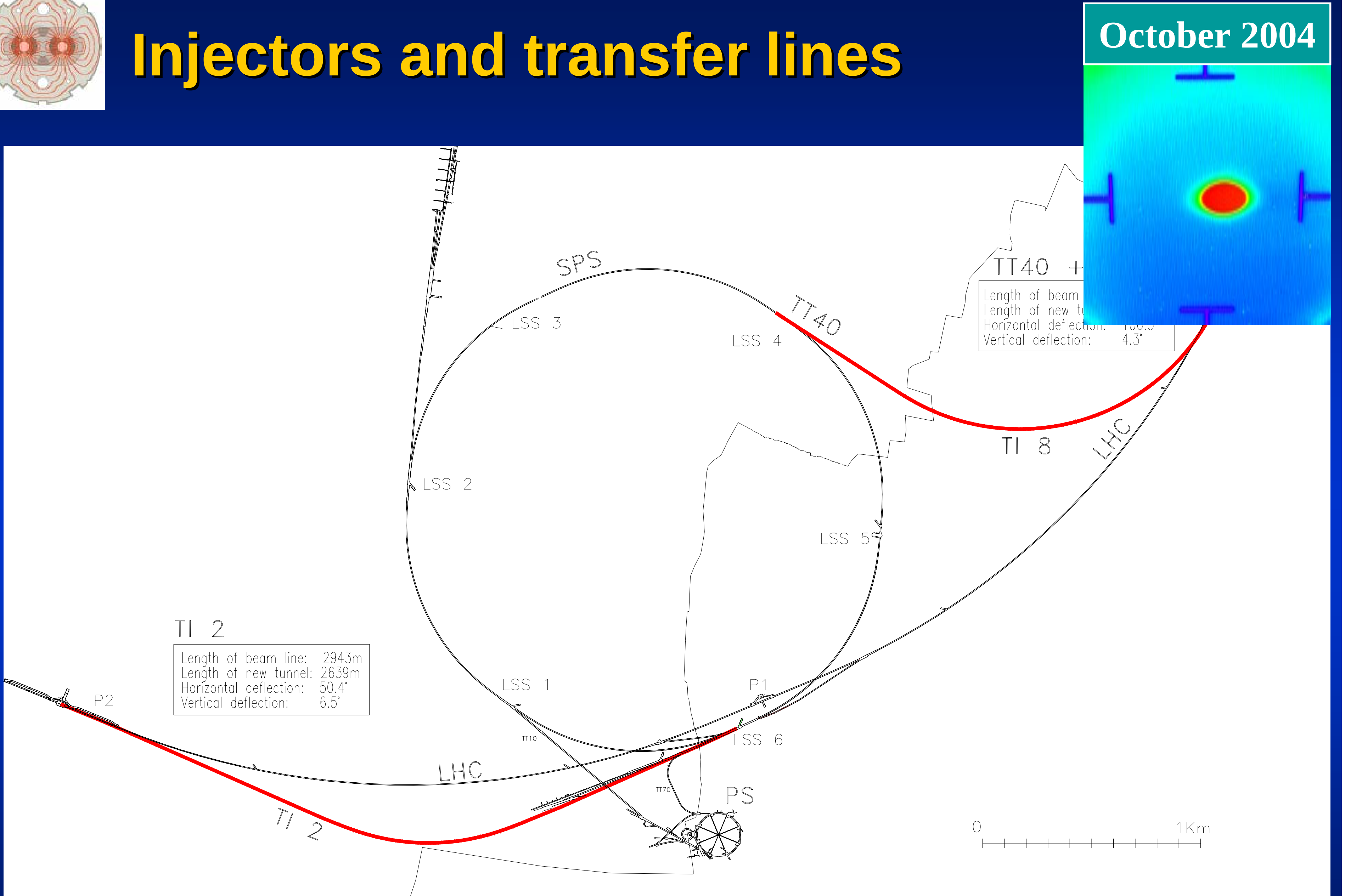
IR6 (Beam dump)



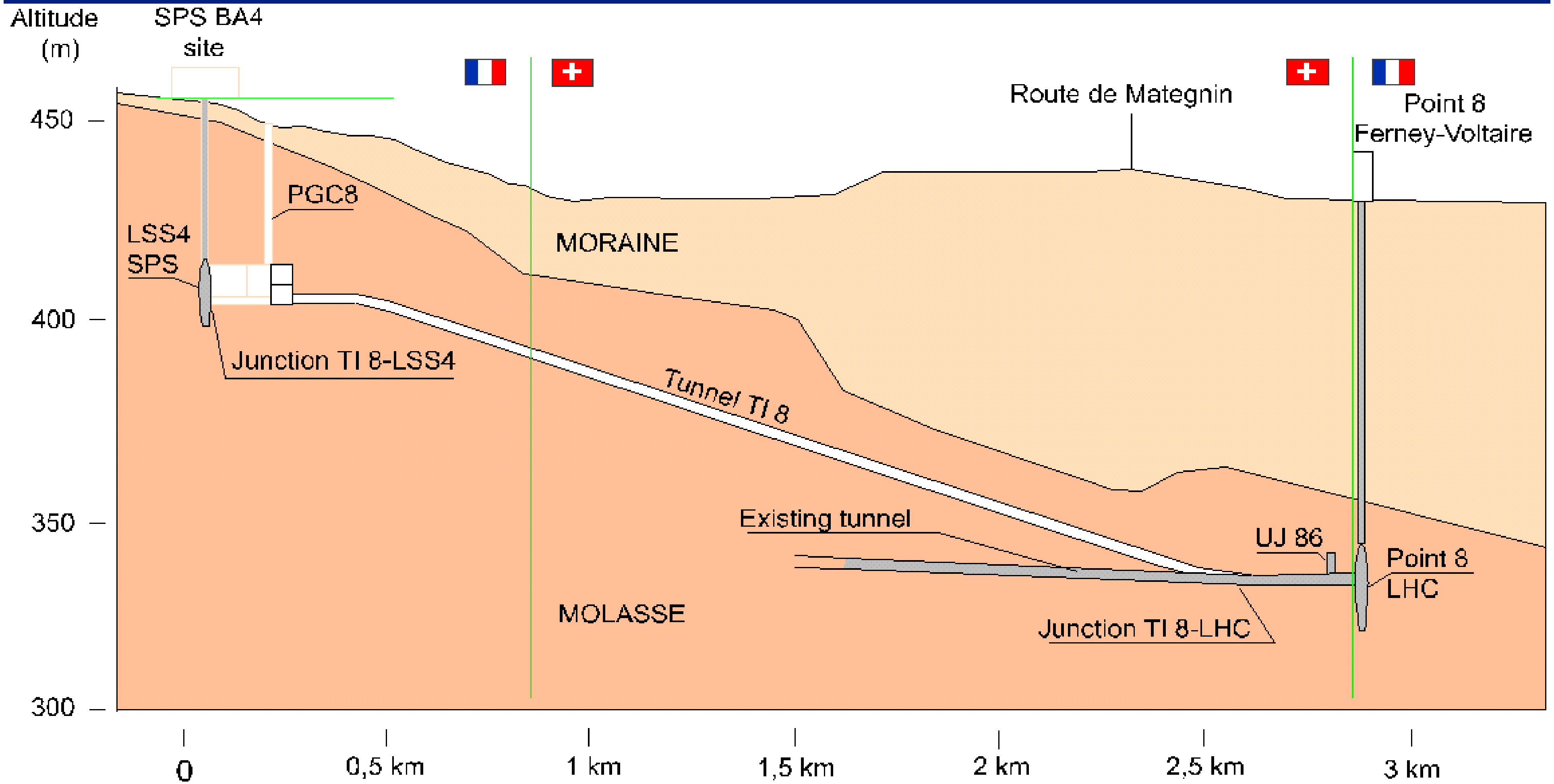


- Symmetrical around IP
- Horizontal kick by MKD into septum magnet
- Vertical deflection by MSD into transfer tunnel
- Beam dilution kicker magnets MKB to spread beam on dump
- Beam dumps TDE located 750m from the septum

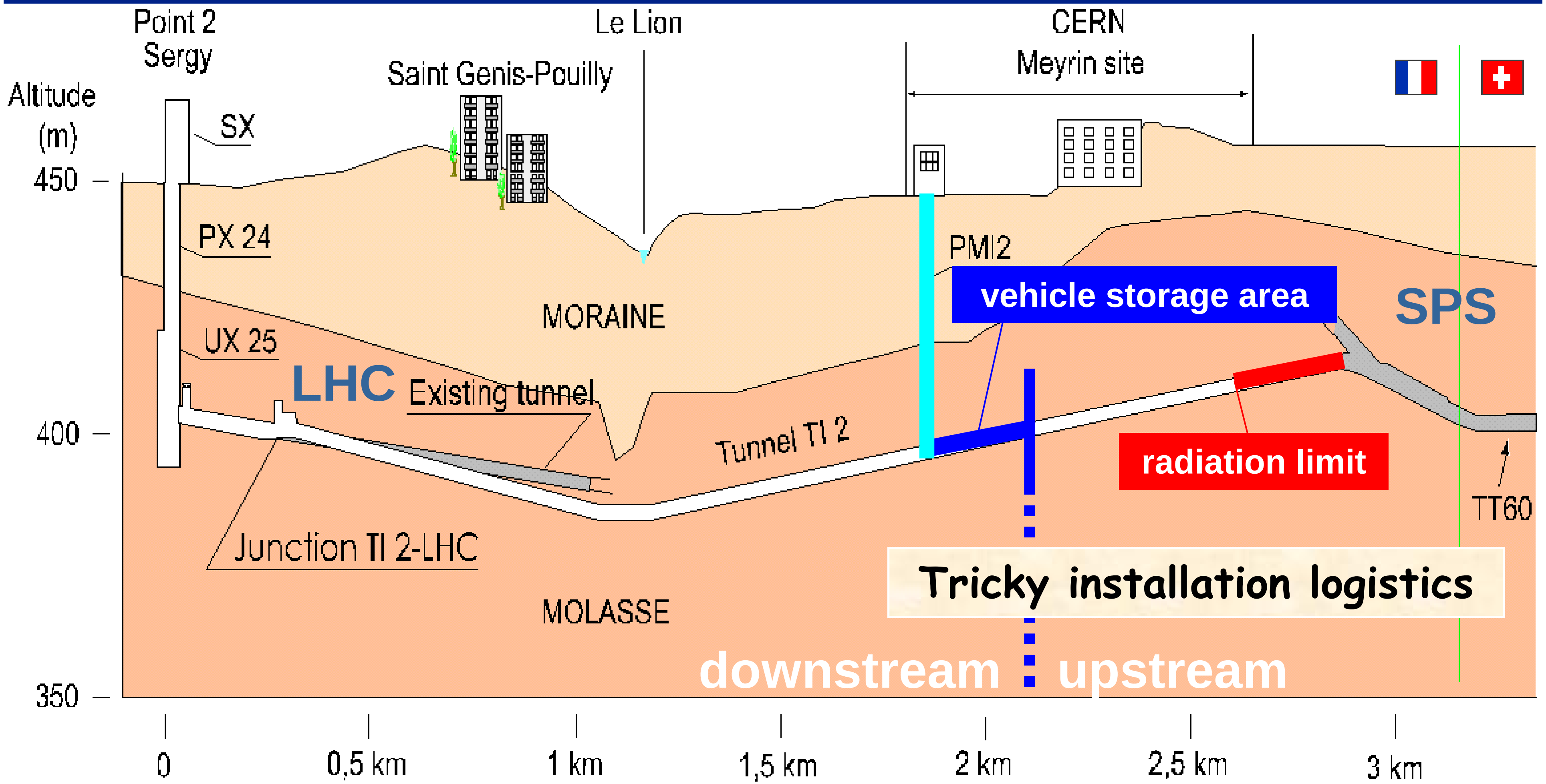
Injectors and transfer lines



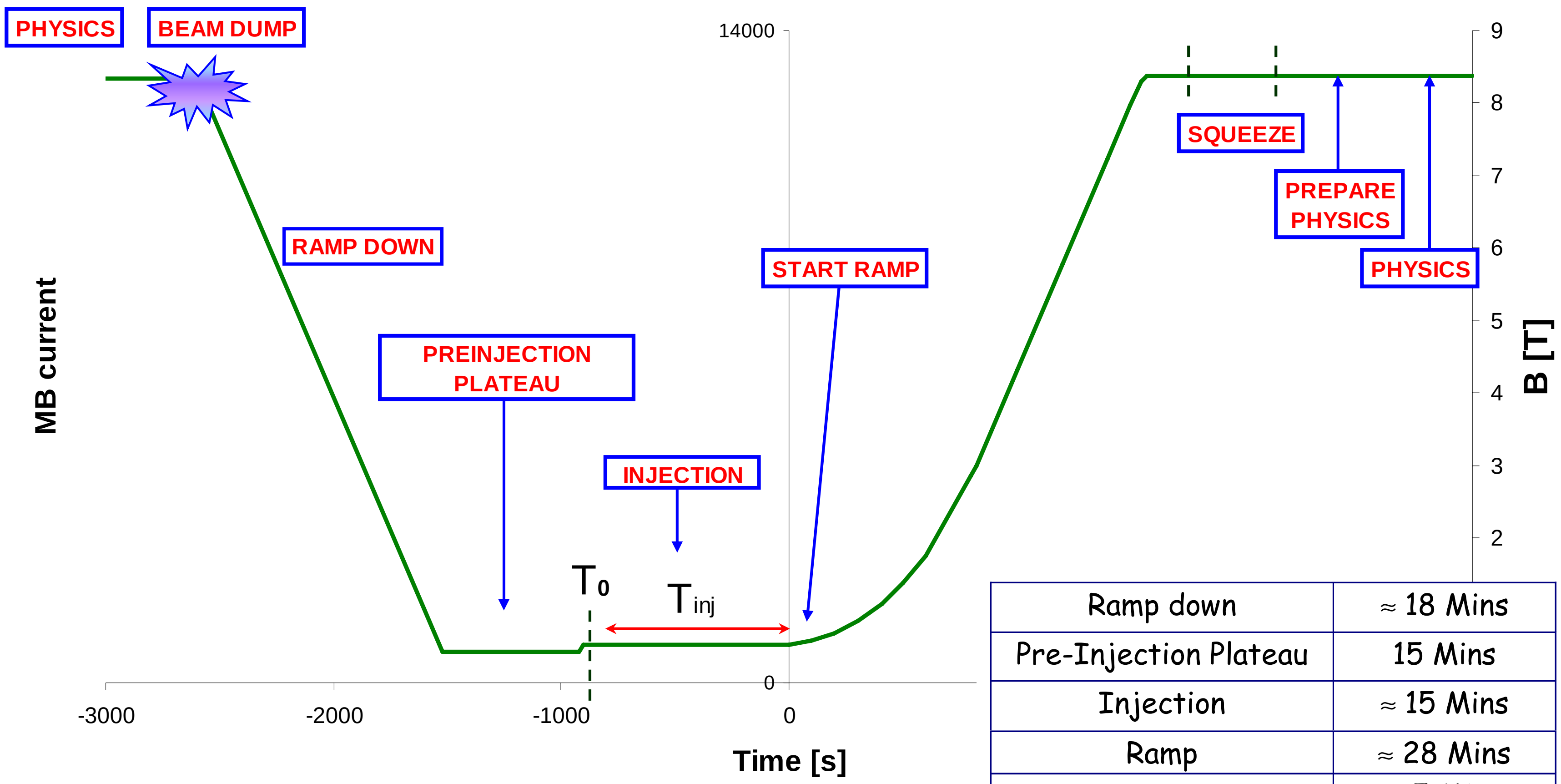
TI8 schematic



TI2 schematic



LHC Operational cycle

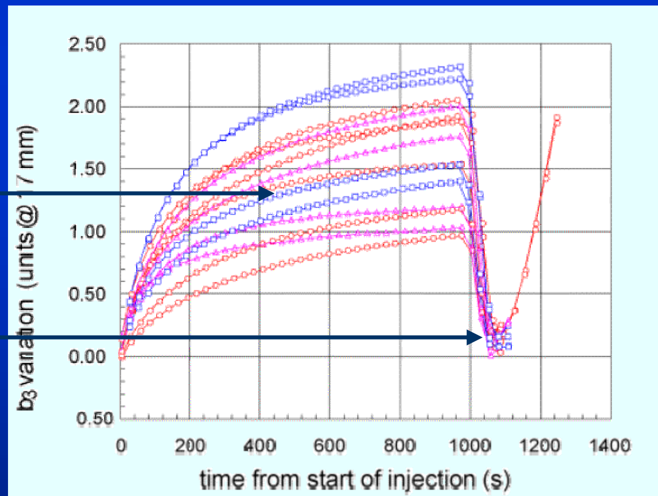


Ramp down	≈ 18 Mins
Pre-Injection Plateau	15 Mins
Injection	≈ 15 Mins
Ramp	≈ 28 Mins
Squeeze	< 5 Mins
Prepare Physics	≈ 10 Mins
Physics	10 - 20 Hrs

Phases of LHC operation

No Beam	Dump beams @ 7TeV; Ramp down to pre-injection plateau; Pre-injection tasks
Safe beam	Injection @ 450GeV — Establish injection conditions
Damage possible	Fill for physics (in the presence of decay of persistent currents)
Getting hot	Ramp (with snapback); Squeeze; Physics @ 7TeV

- Dump beams @ 7TeV
- Ramp down to pre-injection plateau
- Pre-injection tasks
- Injection @ 450GeV
  - Establish injection conditions
  - Fill for physics (in the presence of decay of persistent currents)
- Ramp (with snapback)
- Squeeze
- Physics @ 7TeV



Performance goals

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

- **Nearly all these 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^*

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

Parameters for 10^{34} cm^{-2} s^{-1}

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

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

Related 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

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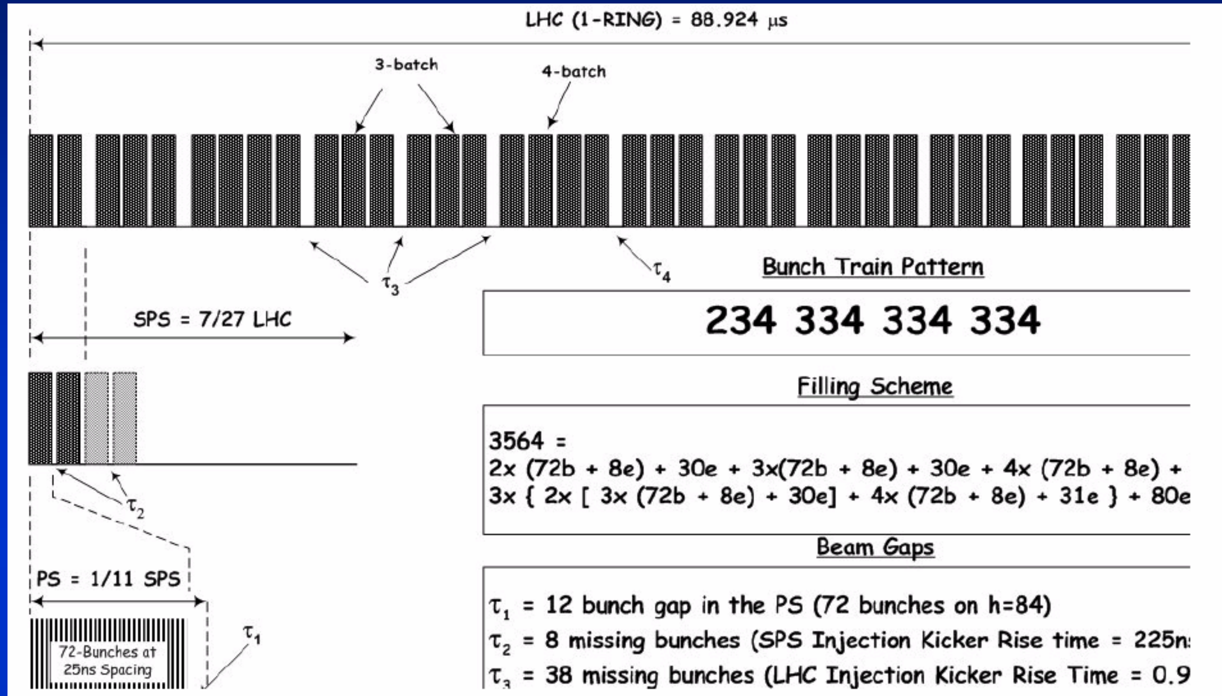
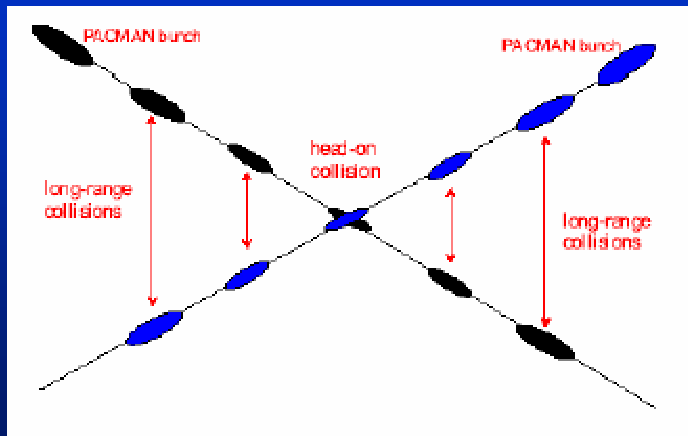
2808 is a lot of bunches per beam

- **Filling scheme requires 12 SPS cycles per beam**



- **Crossing angle needed**



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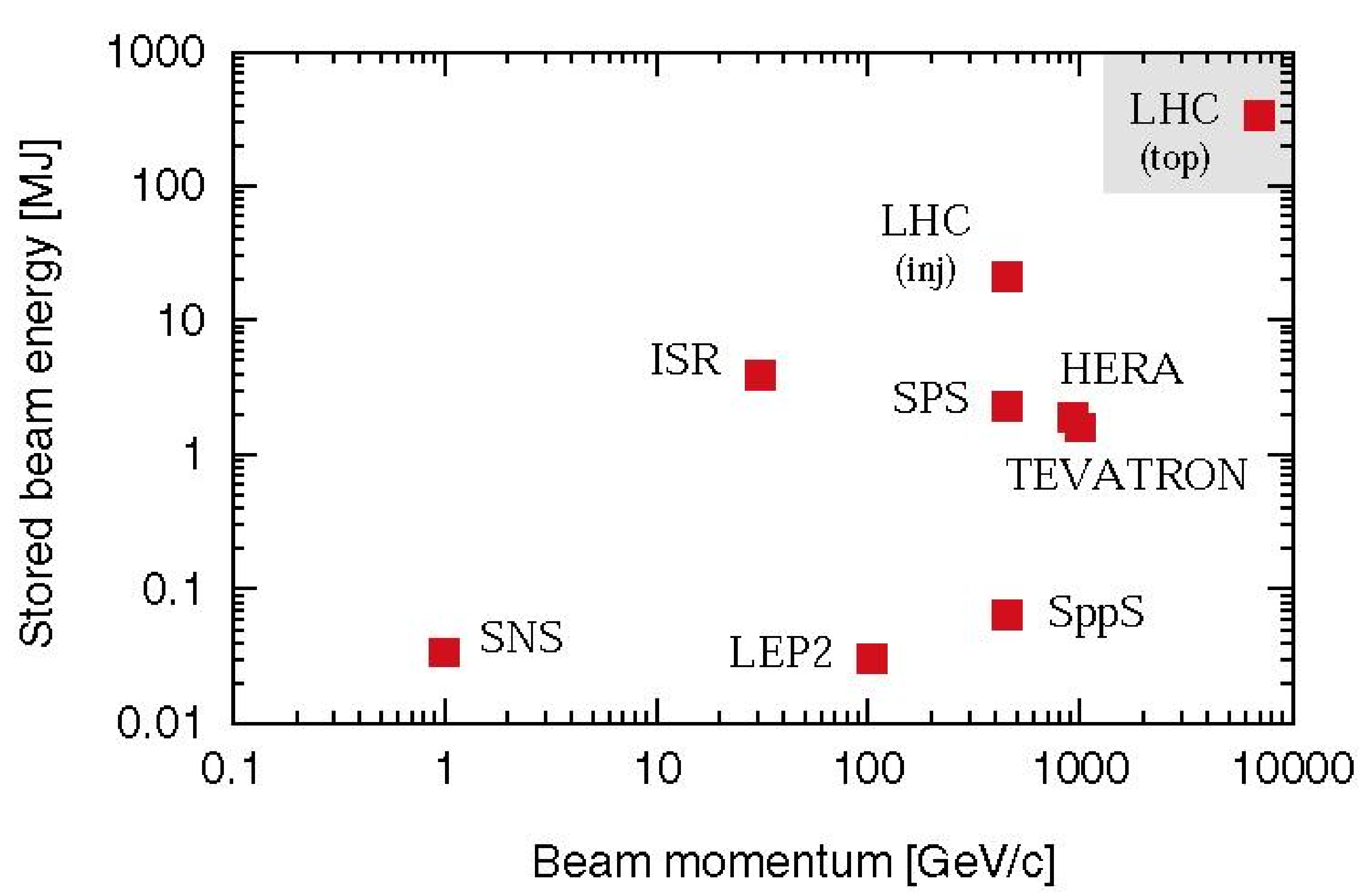
362MJ is a lot of beam energy to handle



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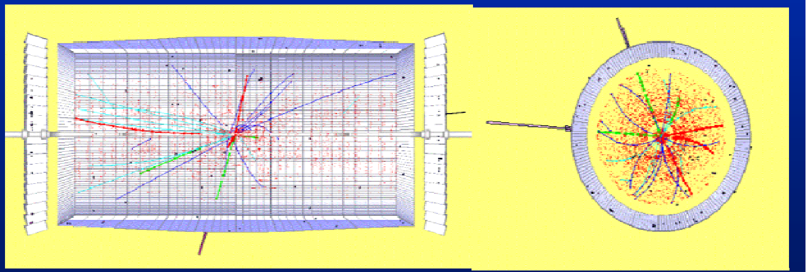
So how to get there ?

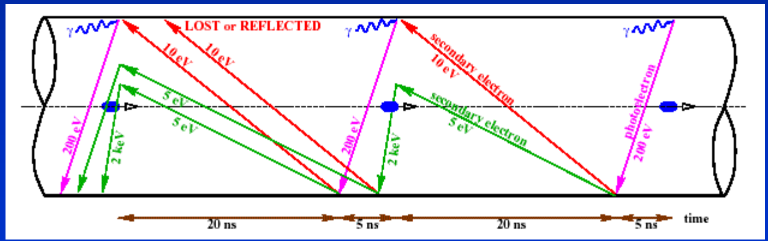
- Avoid quenches (and damage)
  - Reduce total current to reduce stored beam energy
    - Lower i_b
    - Fewer bunches (we have 25ns 50ns 75ns spacing available)
  - Higher β^* to avoid problems in the (later part of) the squeeze
  - Reduce energy to get more margin
    - Against transient beam losses
    - Against magnet operating close to training limit

- Both machine and experiments will have to learn how to stand running at nominal intensities
- An early aim is to find a balance between robust operation and satisfying the experiments
  - Maximize integrated luminosity
  - Minimize event pile-up (to event + 2)

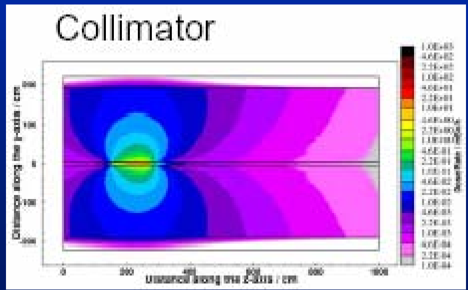


Other considerations

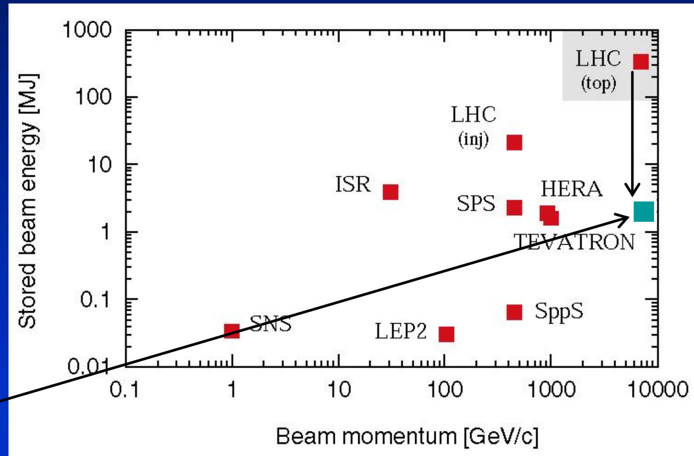
- Electron cloud (LHC simulations and SPS experience)
  - i_b < 35% nominal for 25ns spacing
  - i_b ~ nominal for > 50ns



- With lower currents in mind, two machine systems will be staged
  - Only 8 of 20 beam dump dilution kickers initially installed
    - Total beam intensity < 50% nominal
    - Install the rest when needed
  - Collimators (robustness, impedance and other issues)
    - Phased approach
    - Run at the impedance limit during phase I
      - Lower currents
      - Higher β^*



Proposal for early proton running



Phase I collimators and partial beam dump

1. **Pilot physics run with few bunches**
   - No parasitic bunch crossings
   - Machine de-bugging no crossing angle
   - 43 bunches, unsqueezed, low intensity
   - Push performance (156 bunches, partial squeeze, higher intensity)
2. **75ns operation**
   - Establish multi-bunch operation
   - Relaxed machine parameters (squeeze and crossing angle)
   - Push squeeze and crossing angle
3. **25ns operation with Phase I collimators + partial beam dump**
   - Needs scrubbing for higher intensities ($i_b > 3\ 10^{10}$)

Phase II collimators and full beam dump

25ns operation

- Push towards nominal performance

Stage 1 – pilot run luminosities

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

- No squeeze to start
- 43 bunches per beam (some displaced in one beam for LHCb)
- Around 10^{10} per bunch
- Push one or all of
  - 156 bunches per beam (some displaced in one beam for LHCb)
  - Partial optics squeeze
  - Increase bunch intensity

Beam energy (TeV)	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0
Number of bunches per beam	43	43	156
β^* in IP 1, 2, 5, 8 (m)	18,10,18,10	2,10,2,10	2,10,2,10
Crossing Angle (μrad)	0	0	0
Transverse emittance (μm rad)	3.75	3.75	3.75
Bunch spacing (μs)	2.025	2.025	0.525
Bunch Intensity	$1\ 10^{10}$	$4\ 10^{10}$	$4\ 10^{10}$
Luminosity IP 1 & 5 ($cm^{-2}\ s^{-1}$)	$\sim 3\ 10^{28}$	$\sim 5\ 10^{30}$	$\sim 2\ 10^{31}$
Luminosity IP 2 ($cm^{-2}\ s^{-1}$)	$\sim 6\ 10^{28}$	$\sim 1\ 10^{30}$	$\sim 4\ 10^{30}$

Stage 2 – 75ns luminosities

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

- Partial squeeze and smaller crossing angle to start
- Luminosity tuning, limited by event pileup
- Establish routine operation in this mode
- Move to nominal squeeze and crossing angle
- Increase bunch intensity ?
- Tune IP2 and IP8 to meet experimental needs

Beam energy (TeV)	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0
Number of bunches per beam	936	936	936
β^* in IP 1, 2, 5, 8 (m)	2,10,2,10	0.55,10,0.55,10	0.55,10,0.55,10
Crossing Angle (μrad)	250	285	285
Transverse emittance (μm rad)	3.75	3.75	3.75
Bunch Intensity	$4\ 10^{10}$	$4\ 10^{10}$	$9\ 10^{10}$
Luminosity IP 1 & 5 ($cm^{-2}\ s^{-1}$)	$\sim 1\ 10^{32}$	$\sim 4\ 10^{32}$	$\sim 2\ 10^{33}$
Luminosity IP 2 & 8 ($cm^{-2}\ s^{-1}$)	$\sim 2\ 10^{31}$	$\sim 2\ 10^{31}$	$\sim 1\ 10^{32}$

Stage 3 – 25ns luminosities

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

- Production physics running
- Start with bunch intensities below electron cloud threshold
  - Scrubbing run (1-2 weeks)
- Increase bunch intensities to beam dump & collimator limit
  - Install beam dump kickers
  - Install phase II collimators

  ← Long shutdown (6months)
- Increase bunch intensities towards nominal
- Tune IP2 and IP8 to meet experimental needs

Beam energy (TeV)	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0	7.0
Number of bunches per beam	2808	2808	2808
β^* in IP 1, 2, 5, 8 (m)	0.55,10,0.55,10	0.55,10,0.55,10	0.55,10,0.55,10
Crossing Angle (μrad)	285	285	285
Transverse emittance (μm rad)	3.75	3.75	3.75
Bunch Intensity	$3\ 10^{10}$	$5\ 10^{10}$	$1.15\ 10^{11}$
Luminosity IP 1 & 5 ($cm^{-2}\ s^{-1}$)	$\sim 7\ 10^{32}$	$\sim 2\ 10^{33}$	10^{34}
Luminosity IP 2 & 8 ($cm^{-2}\ s^{-1}$)	$\sim 4\ 10^{31}$	$\sim 1\ 10^{32}$	$\sim 5\ 10^{32}$

TOTEM luminosities

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

- Total Cross Section and Elastic scattering
- Diffraction and minimum bias
- Characterized by
  - Several 1 day runs per year (starting early)
  - Some single beam runs
  - 43 and 156 bunches per beam
  - IP5 β^* = 1540m
  - IP5 β^* = 18m

Beam energy (TeV)	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0
Number of bunches per beam	43	156	2808
β* in IP 5 (m)	1540	1540	18
Crossing Angle (μrad)	0	0	285
Transverse emittance (μm rad)	3.75	3.75	3.75
Bunch spacing (μs)	2.025	0.525	0.025
Bunch Intensity	$3\ 10^{10}$	$6\ 10^{10}$	$1.15\ 10^{11}$
Luminosity IP 5 ($cm^{-2}\ s^{-1}$)	~ $4\ 10^{27}$	~ $6\ 10^{28}$	~ $3\ 10^{32}$

ION luminosities

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

- ALICE request short run “after the first long shutdown”
- First runs with “early ion scheme”
- Move to nominal when possible

	Early	Nominal
Beam energy / nucleon (TeV)	2.76	2.76
Number of bunches (per beam)	62	592
β* in IP 2 (m)	1	0.5
Crossing Angle (μrad)	0	0
Transverse emittance (μm rad)	1.5	1.5
Bunch spacing (μs)	0.099	1.350
Bunch Intensity	$7\ 10^7$	$7\ 10^7$
Luminosity in IP2 ($cm^{-2}\ s^{-1}$)	$\sim 5\ 10^{25}$	10^{27}

Summary

- LHC is a large and complicated machine
- Performance goals are very demanding
- Damage potential is very high
- Staged approach towards nominal parameters
  - Reduced complexity
  - More robust operation
  - Damage potential is still very high, very soon
- Machine protection system mandatory
  - Needed from day 1 + not many
    - A few low intensity bunches at injection are OK
    - Everything else is dangerous
  - Has to be commissioned as an integral part of the machine