The CERN Accelerator School

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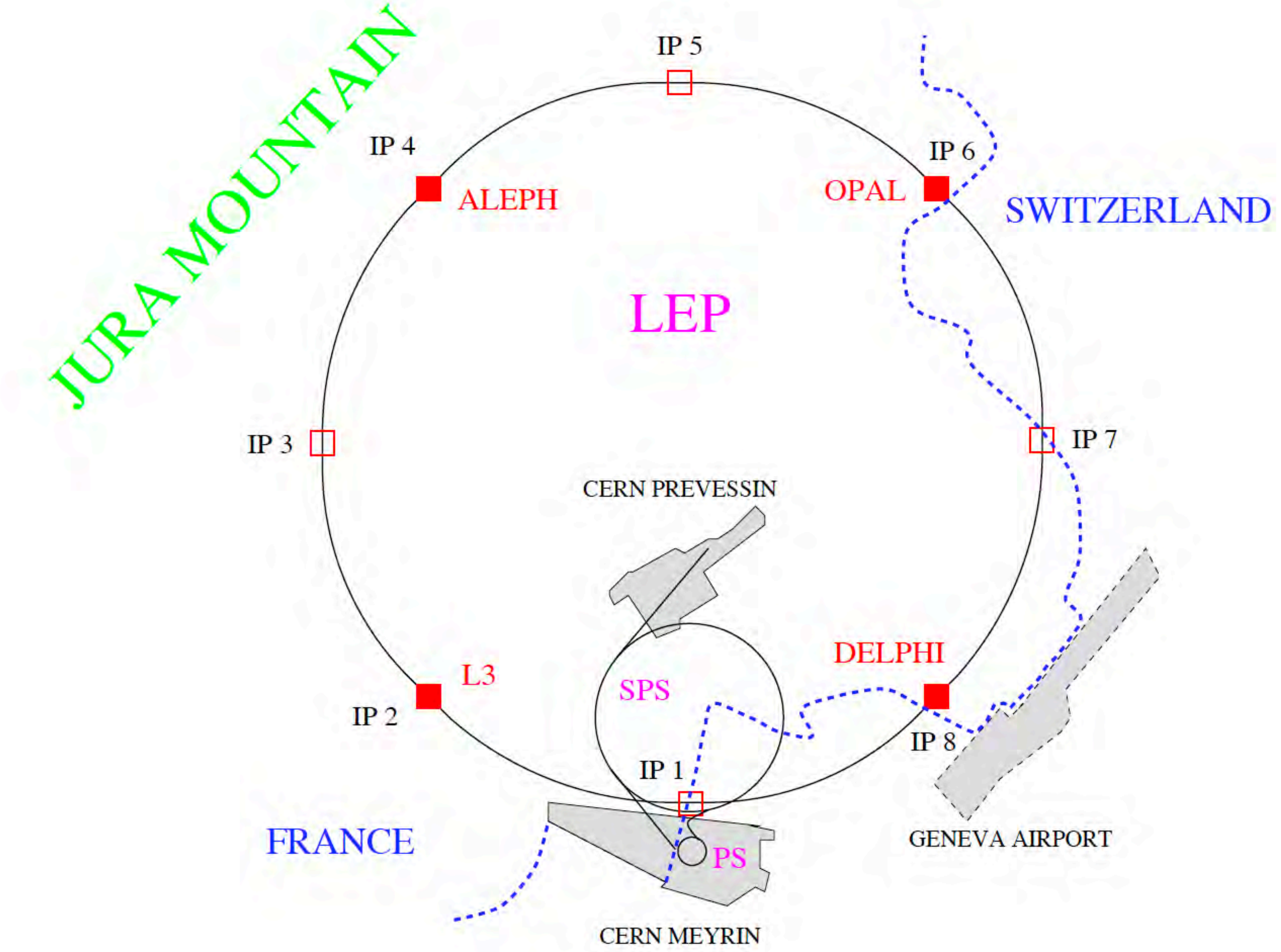
COLLIDER OPERATION

Mike Lamont 8/7/2021



JURA MOUNTAIN
IP 5
IP 4
ALEPH
IP 6
OPAL
SWITZERLAND
LEP
IP 3
IP 7
CERN PREVESSIN
L3
SPS
DELPHI
IP 2
IP 8
IP 1
FRANCE
PS
GENEVA AIRPORT
CERN MEYRIN

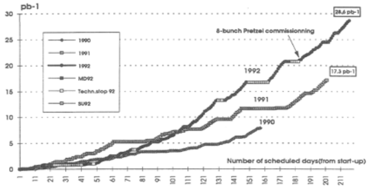
September 13, 1983
Civil engineering started

February 8, 1988
LEP tunnel finished

July 12, 1988
Injection test

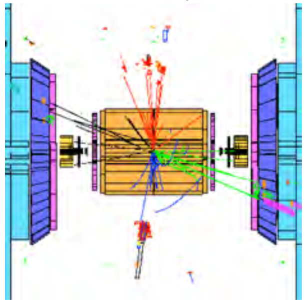
July 14, 1989
First injection

August 13, 1989
First collisions

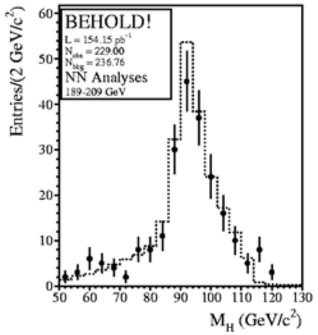


1995
LEP1.5
65, 68, 70 GeV

03:13 9th July 1996



1996
First Ws
80.5 to 86 GeV



1998
94.5 GeV
10^{32} cm^{-2}s^{-1}

2000
102 – 104.4 GeV
Discovery mode

1983 | ≈ | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000

LEP TIMELINE

LEP challenges

- 27 km of equipment and instrumentation to keep running
  - 700 or so power converters,
  - 1000s of magnets: 8 of which superconducting
  - 20 or so electrostatic separators
  - Huge RF system
  - Lots of Collimators
  - Kickers, beam dumps
  - 250 Beam Position Monitors, Bunch Current Transformers, Tune-meter, Beam Synchrotron Light Telescope, profile measurements, Beam Loss Monitors etc
  - A few interlocks
  - Communication with the experiments

All held together with a rudimentary control system

LEP challenges

- Multi-cycle injection of electrons and positrons
  - Stability of lines, steering
  - Accumulation: resonances, coherent tune shifts, wigglers, radiation in experiments, etc. etc.
- Ramp between 22 GeV and 104 GeV
  - Tune, chromaticity and orbit control (particularly the start), resonances, bunch length, wigglers
- Squeeze between β^* = 20 cm and β^* = 5 cm.
  - Tune, chromaticity and orbit control
- Physics
  - Beam-beam, control of tune, chromaticity, orbit, beam crossings, coupling, lifetimes
  - Background optimization - collimation
  - Continual optimization to maximize delivered luminosity.

1989 - commissioning

- 14th July: first beam
- 23rd July: circulating beam
- 4th August: 45 GeV
- 13th August: colliding beams

These people are to blame for what followed

First Chamonix 1991

LEP – difficult teething

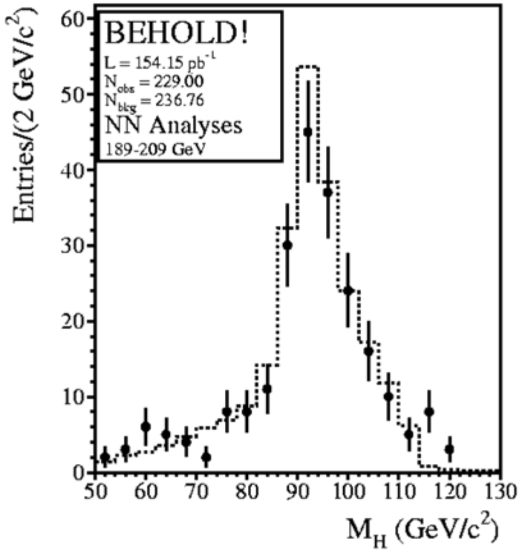
- Fractured high level control system
- It was slow (even in 2000 it took 15 s to acquire a closed orbit)
- Poor measurement facilities
  - Beam instrumentation lived in a world of its own. Very little integration.
  - Essential signals not available e.g. no beam lifetime, for example
  - Poor data management
  - Inflexible communication with experiments
  - No easy way of closing the measure/correct loop
- Poor and unreliable, incoherent data acquisition systems

- *After commissioning and 2 years of operations we were faced with just wanting to get the beam up the ramp occasionally. Operations a real struggle (turn around was around 7 hours back then)*

2000 - the end

- Total integrated luminosity of 233.05 pb^{-1} of which
  - 4.42 pb^{-1} at 45 GeV
  - 228.63 pb^{-1} over 100 GeV
  - 131.73 pb^{-1} between 103.0 and 103.5 GeV
  - 10.74 pb^{-1} at 104 GeV or above

Rather good



LEP COULD BE OPERATED BY ONE MAN!

The legacy of LEP

The physics data (luminosity, energy, energy calibration)

"It should be stressed that the whole body of knowledge accumulated by the study of LEP and SLD data is simply enormous"

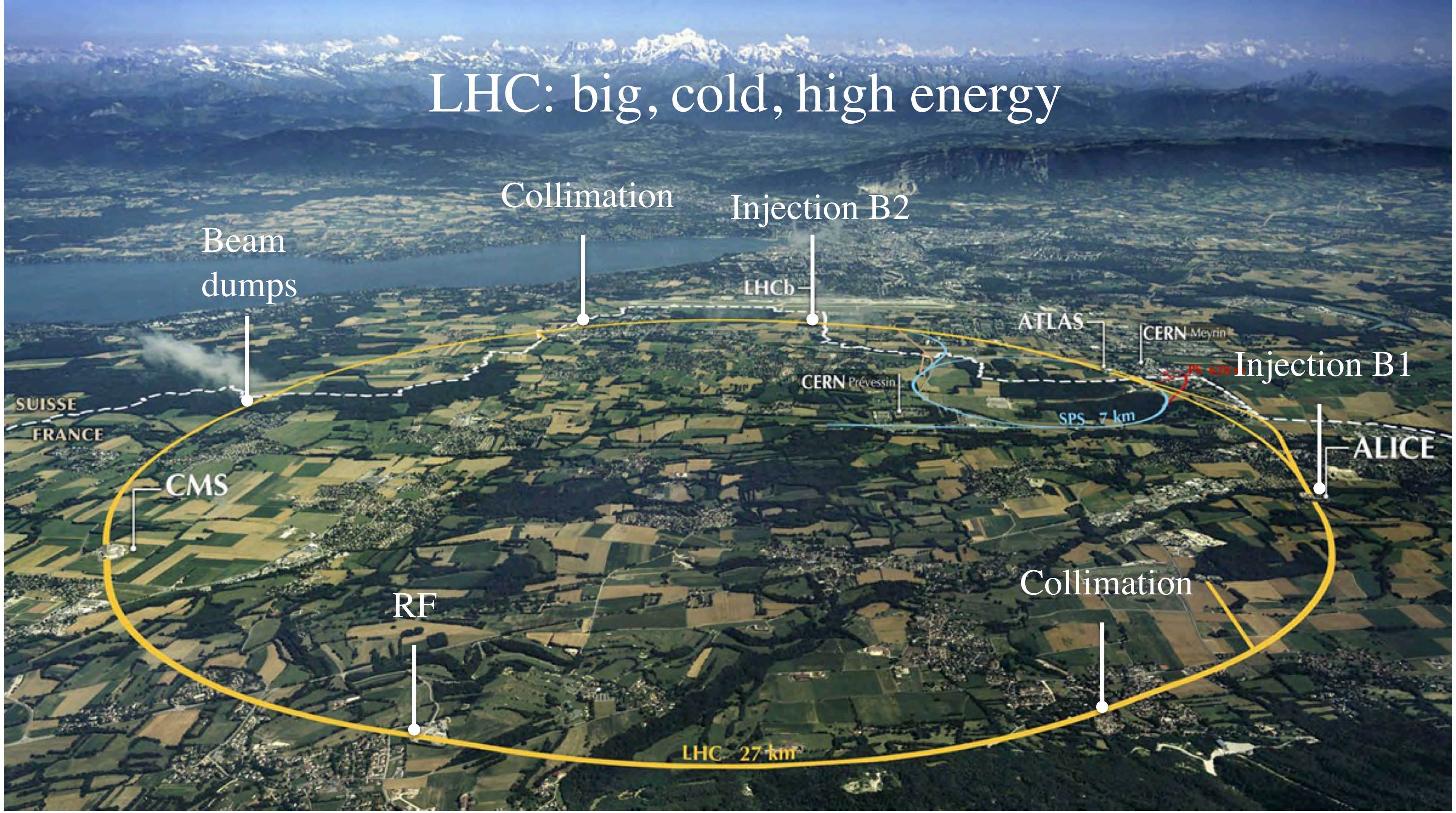
The experience in operating large accelerators

- Technical infrastructure
- Operational control (Orbit, tunes, ramp, squeeze…)
- Alignment, ground motion in deep tunnels
- Designing and running a large SC RF system.
- Impedance and beam dynamics in big machines
- Optics designs from 60/60 to 102/90 and 102/45

Operation in unique regime of ultra-strong damping:

- Vertical emittance with small solenoid effects (dispersion-dominated).
- Beam-beam limit with strong damping.
- First confirmation of theory of transverse spin polarization.

LHC: big, cold, high energy

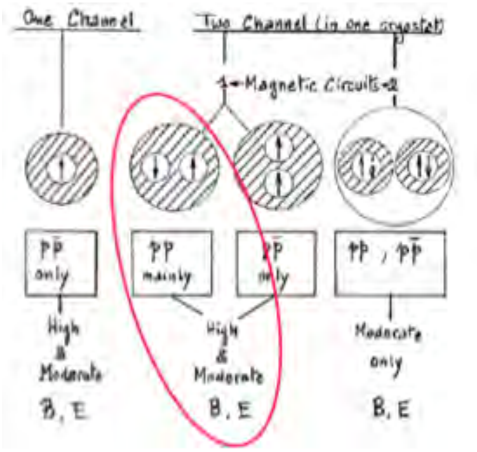


1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
~4000 Beam loss monitors

150 tonnes helium, ~90 tonnes at 1.9 K
350 MJ stored beam energy in 2016
1.2 GJ magnetic energy per sector at 6.5 TeV

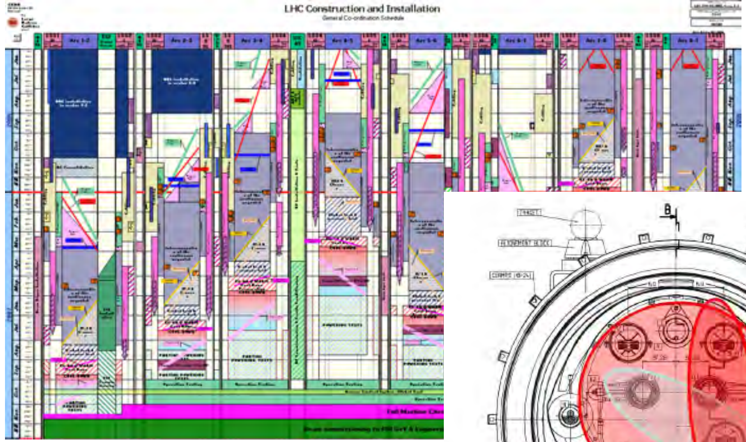
And some things that should not have been forgotten were lost. History became legend, legend became myth.

Conception

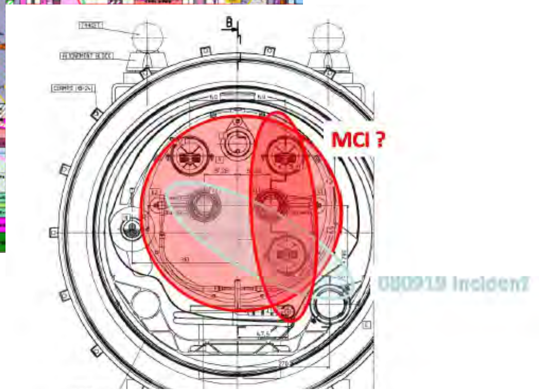


Initiation

LHC approved
by the Elders



Birth – overdue



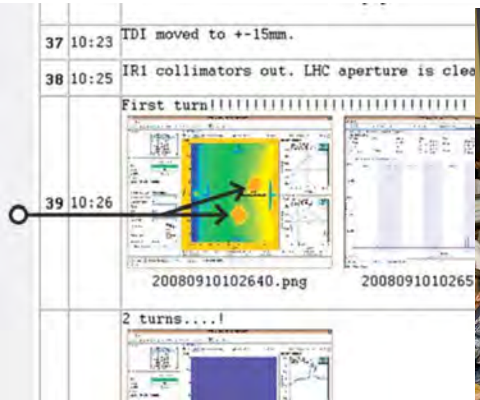
Withdrawal from community for mediation and preparation

Rival stumbles

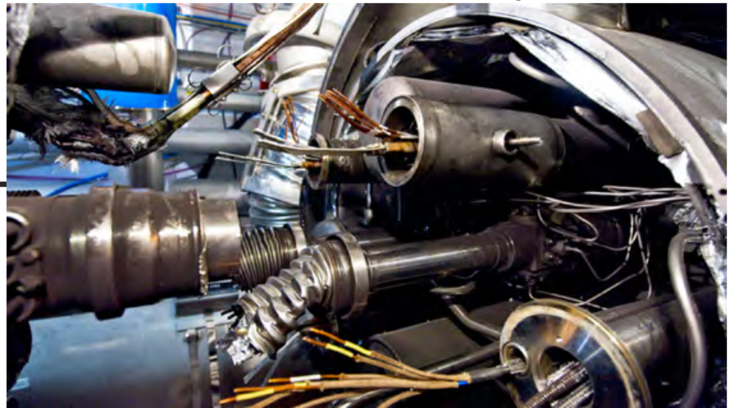
SSC cancelled

1984	//	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10

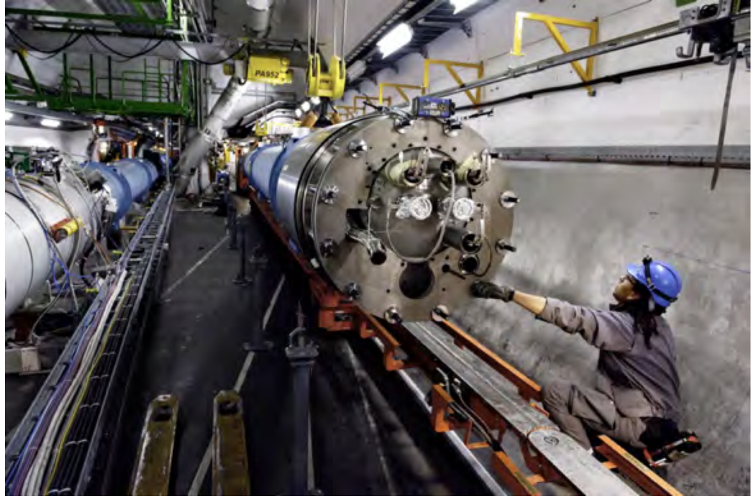
Hubris (?) September 10, 2008



Nemesis September 19, 2008



LHC



Trial/descent in the underworld

November 29, 2009

Resurrection and rebirth

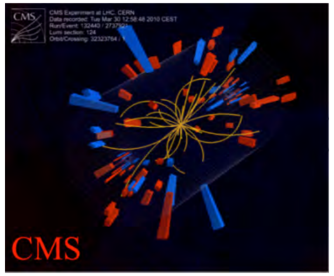
Apotheosis and atonement

4 July, 2012

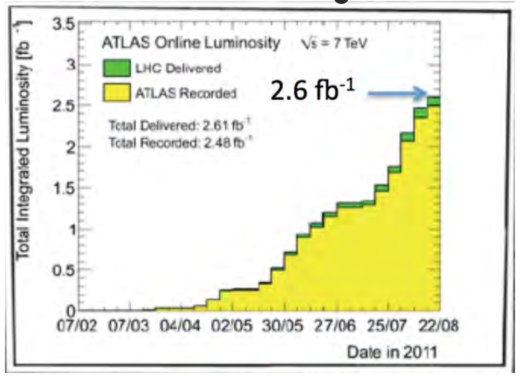
2009 | 2010 | 2011 | 2012 | 2013

March 30, 2010

First collisions at 3.5 TeV



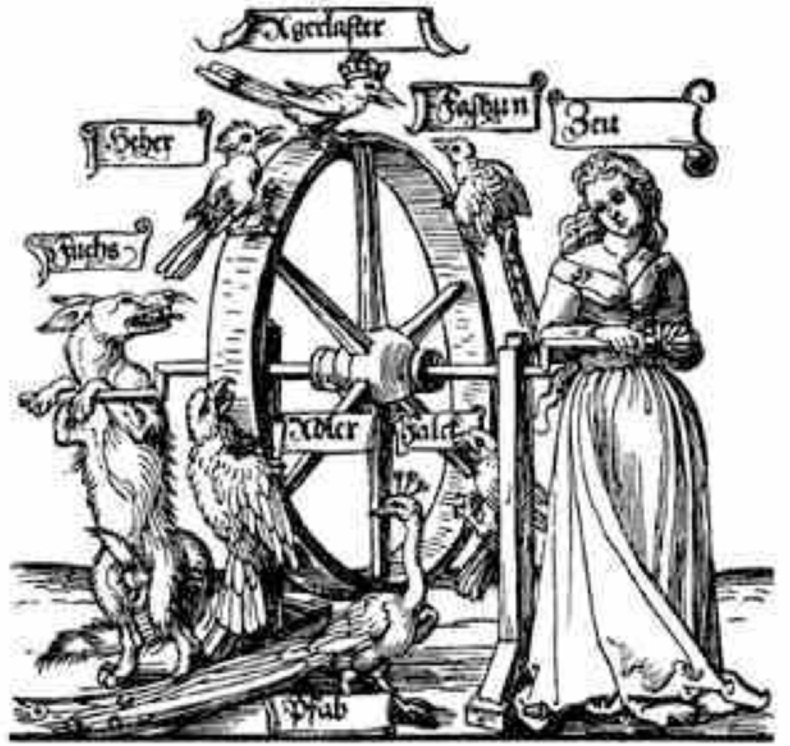
Ascension

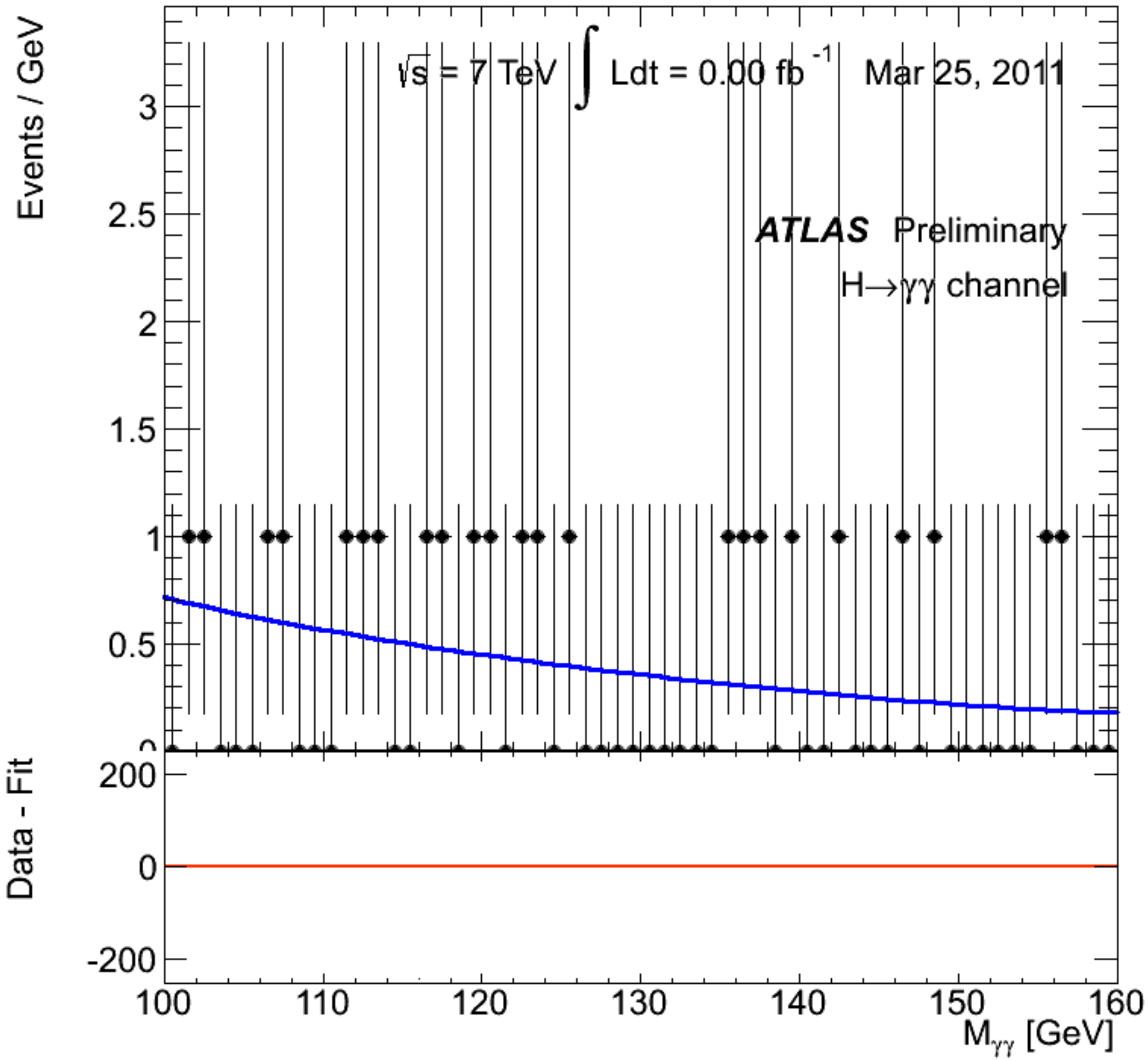


Heroic subplot

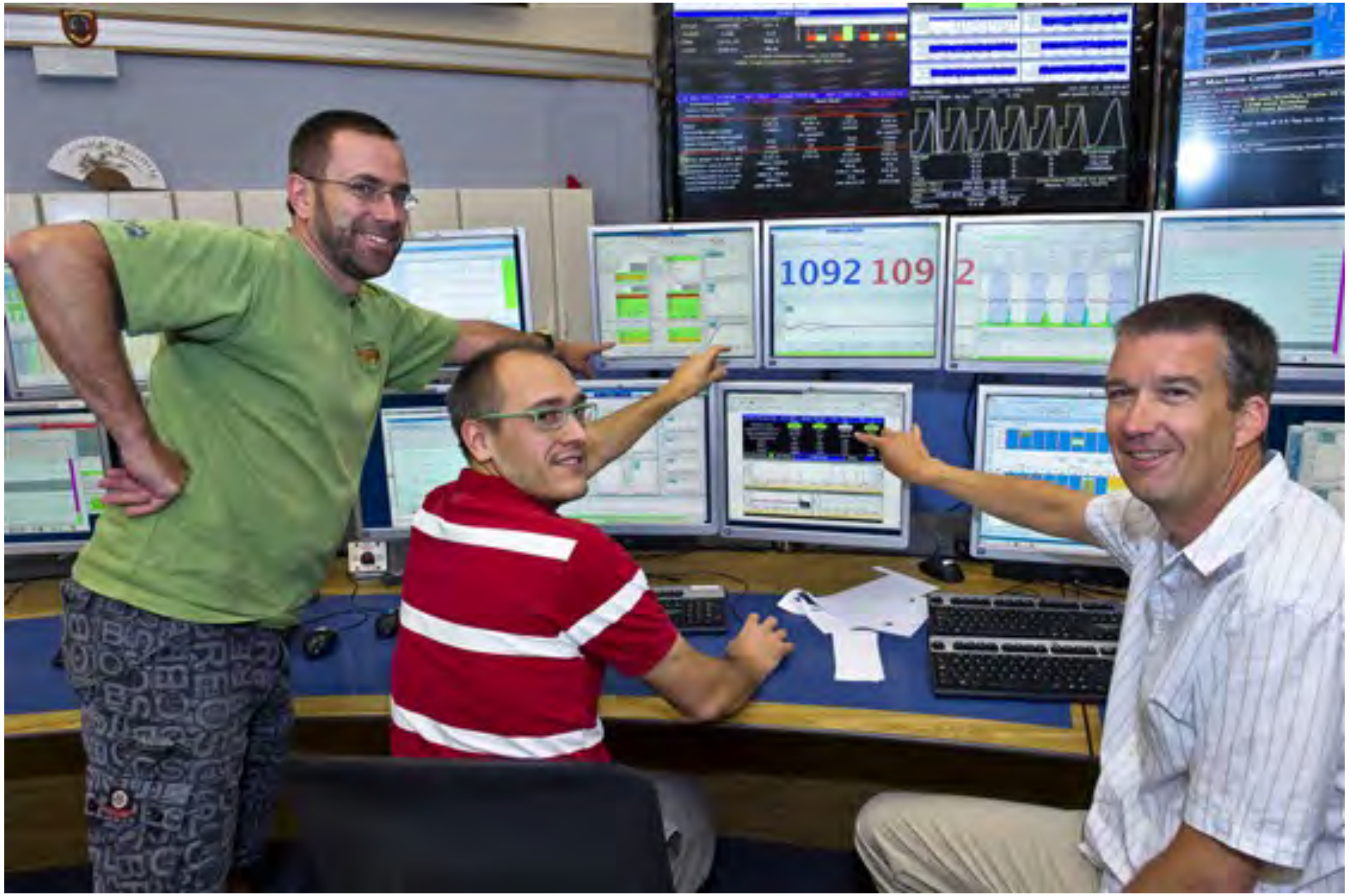
And let us not forget Fortuna

- Late
- Over budget
- Blew it up after 9 days
- Costly, lengthy repair
- Rival coming up fast on the outside
- Had to run at half energy
- And yet…



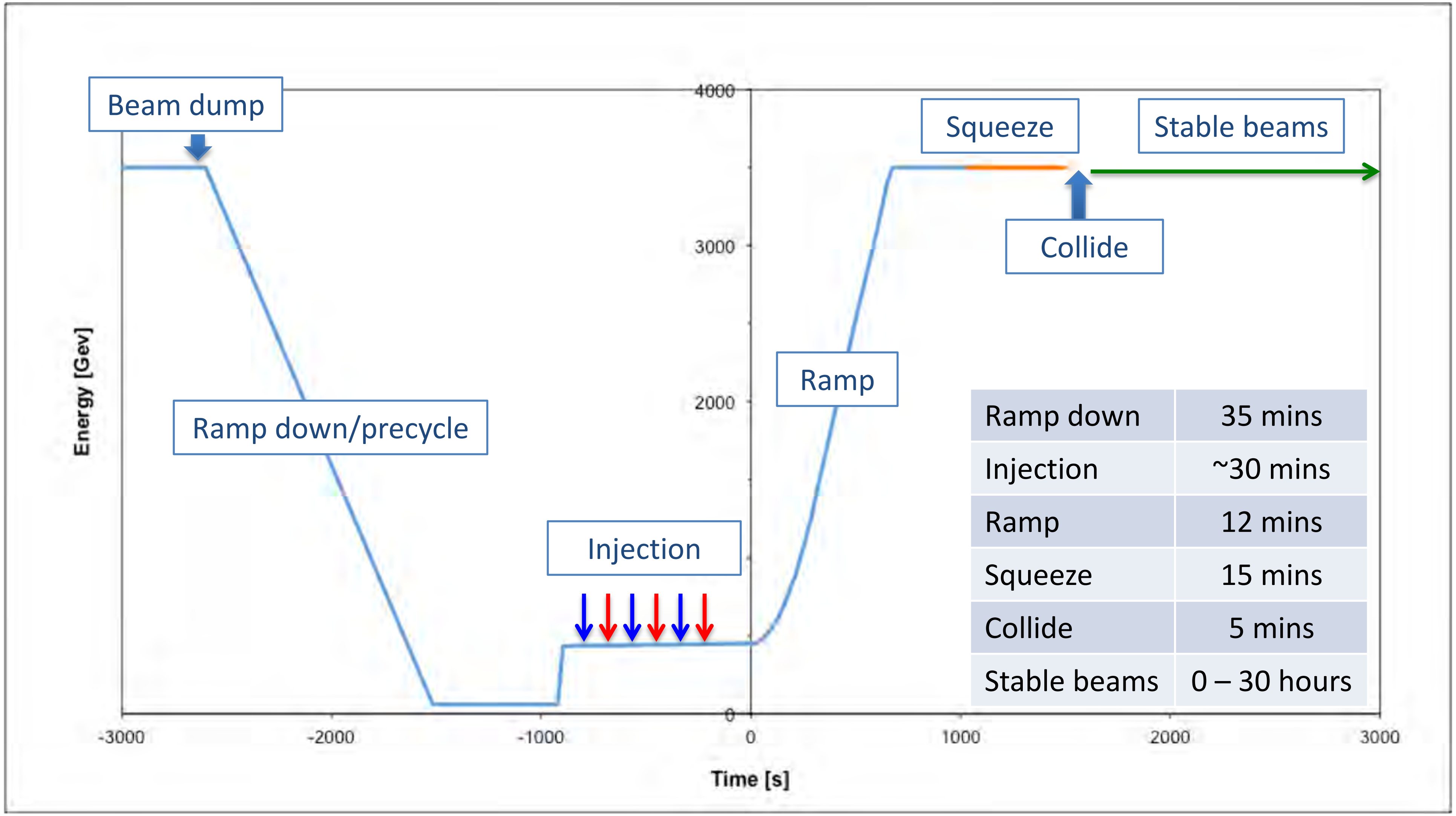


$\sqrt{s}$ = 7 TeV $\int$ Ldt = 0.00 fb^{-1} Mar 25, 2011
ATLAS Preliminary
H→γγ channel
Events / GeV
3
2.5
2
1.5
1
0.5
Data - Fit
200
0
-200
100
110
120
130
140
150
160
$M_{\gamma\gamma}$ [GeV]



LET’S GET OPERATIONAL

LHC Nominal Operational cycle



Ramp down	35 mins
Injection	~30 mins
Ramp	12 mins
Squeeze	15 mins
Collide	5 mins
Stable beams	0 – 30 hours

Turn around from stable beams to stable beams - 2 to 3 hours on a good day

The controls' challenge

- EQUIPMENT
  - Collimators/TDI/TCDQ etc.
  - Beam Dump
  - Power converters,
  - Kickers
  - RF, TFB, LFB
  - Spectrometers & compensation
- INSTRUMENTATION
  - Distributed systems:
    - BLMs, BPMs,
  - Standalone:
    - BCT, BTV, AGM, BIPM, BWS, Schottky..
  - Tune, Chromaticity, Coupling
  - Luminosity monitors
  - Radiation Monitors
- MAGNETS – RMS, errors
- MACHINE PROTECTION
- VACUUM, CRYOGENICS, QPS, EE
- EXPERIMENTS

⊗

Settings, functions, monitoring, display, post mortem, control, acquisition, concentration, archiving, alarms, interlocks

⊗

⊗

Driving the machine through the cycle

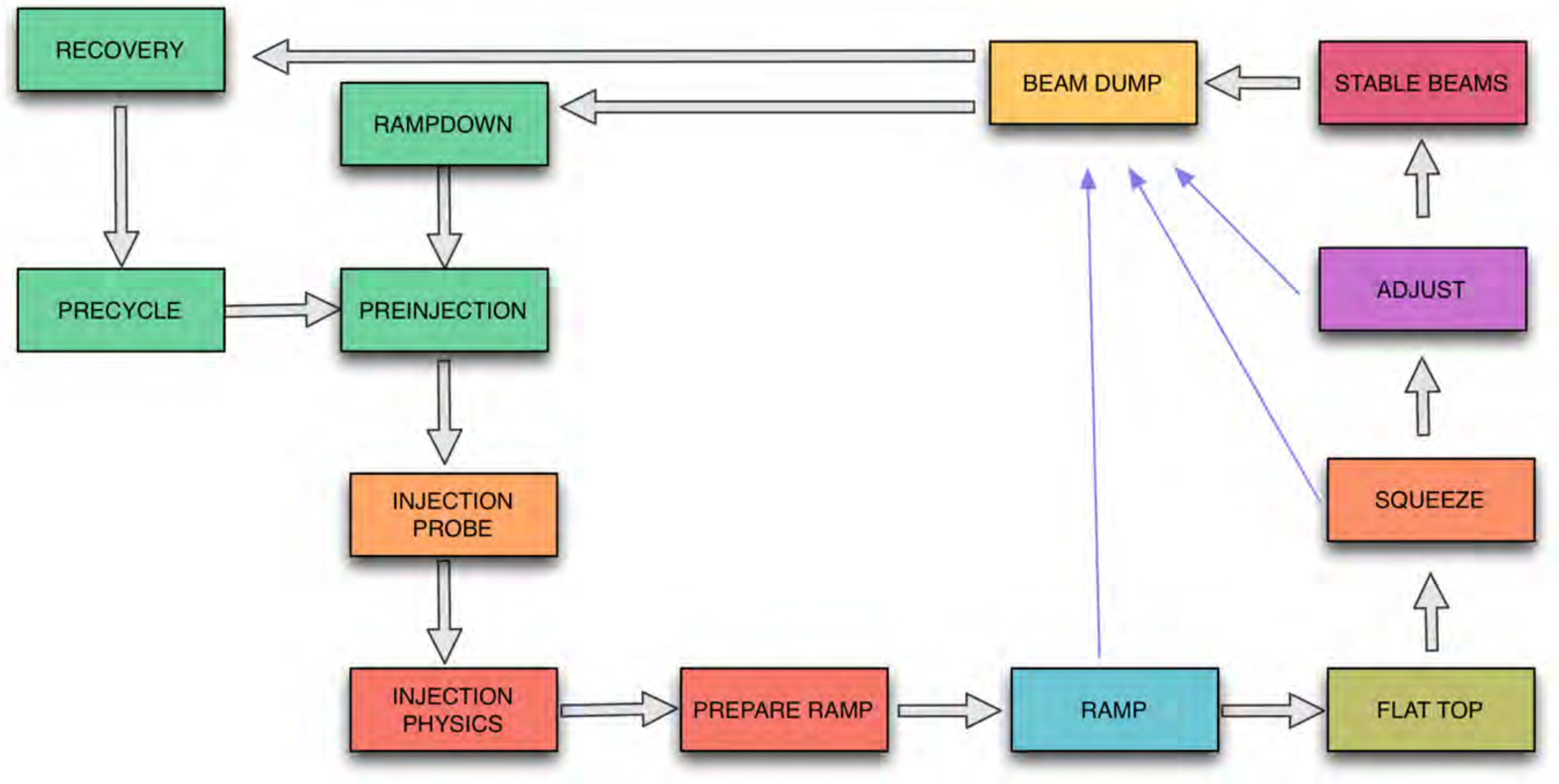
Magnet errors, crossing angles, snapback, ramping, squeezing, colliding, orbit, parameter control, optimisation etc. etc.

HIGHLY DESTRUCTIVE BEAM

TIGHT TOLERANCES

Nominal cycle

Globally the machine state is fairly well described by machine mode/beam mode combination



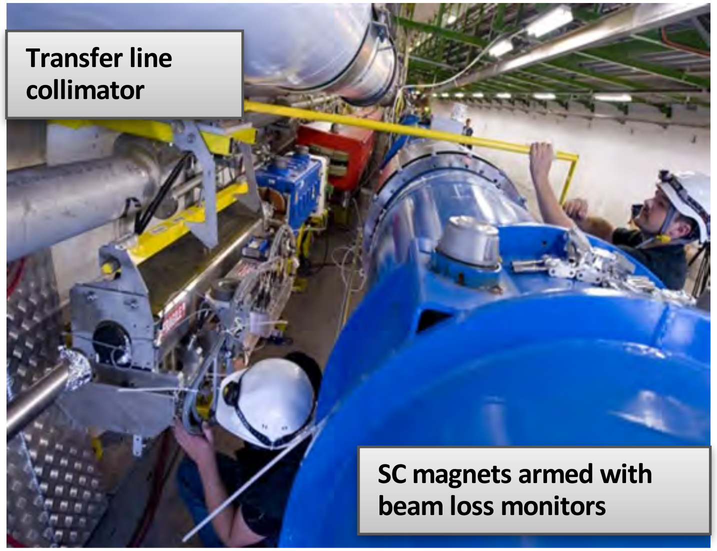
Precycle/ramp-down

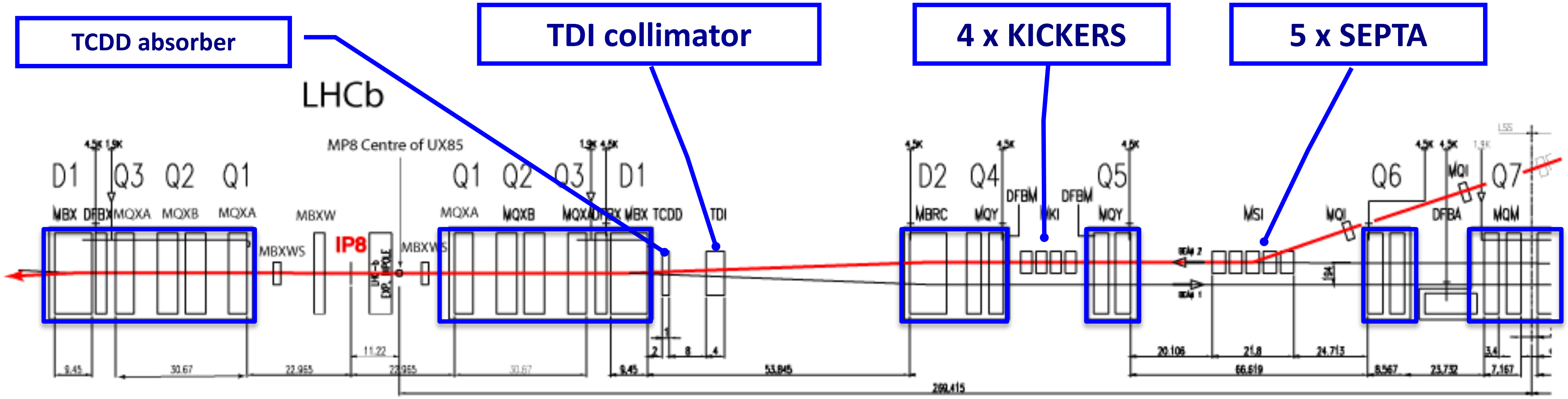
- Coming back from access
  - Full pre-cycle of all magnetic circuits
- After stable beams
  - Ramp-down/precycle combination

Aim: reproducible magnetic machine

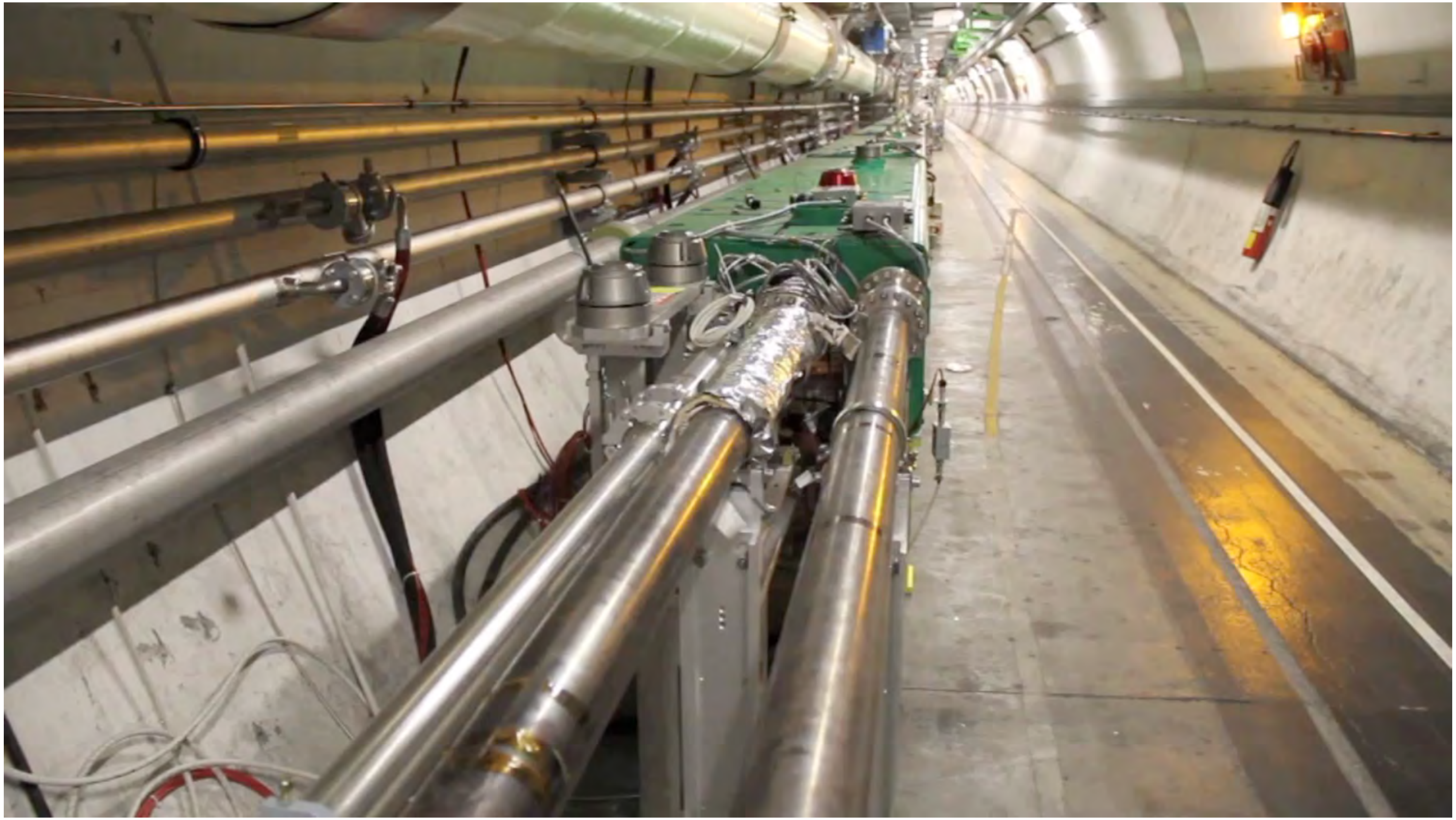
Injection

- Complex process – wrestle with:
  - RF: re-phasing, synchronization, transfer, capture
  - Timing, injection sequencing, interlocks
  - Injection Quality checks – SPS and LHC
  - Abort gap keeper
  - Beam losses at injection, abort gap cleaning
- Full program of beam based checks performed
  - Carefully positioning of collimators and other protection devices
  - Aperture, kicker waveform





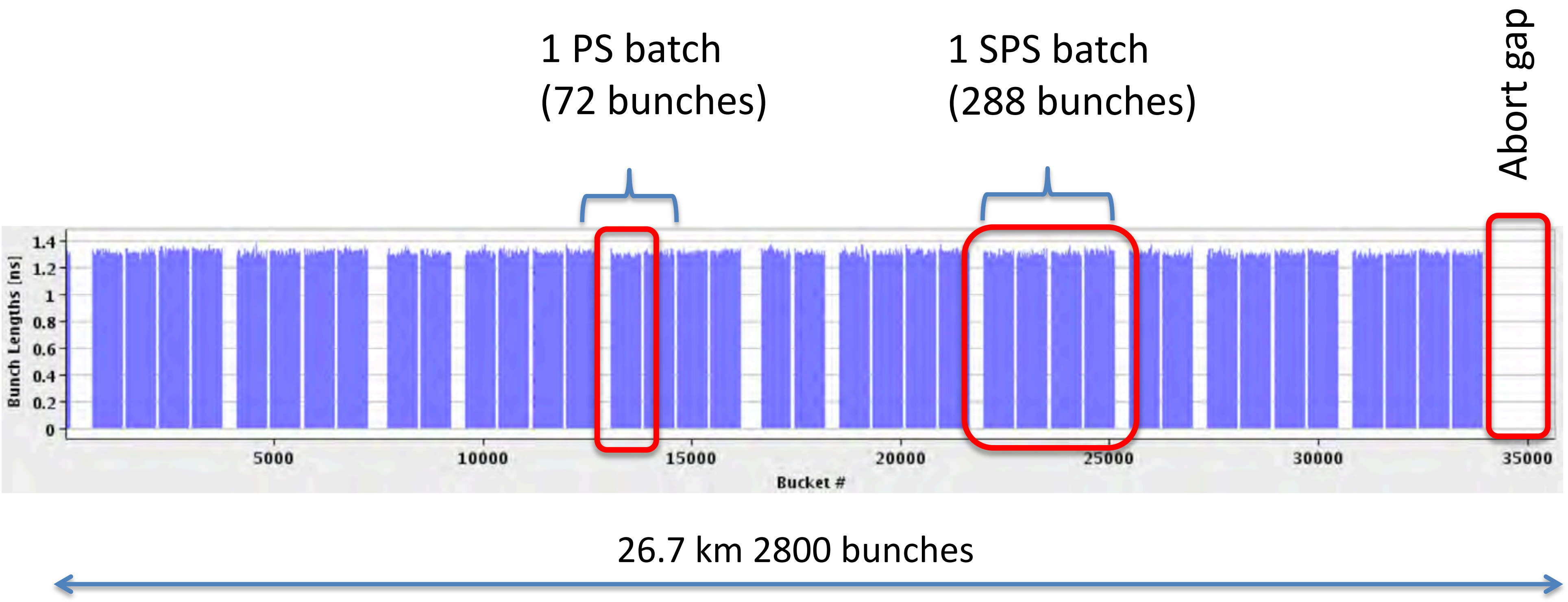
Septa and beyond



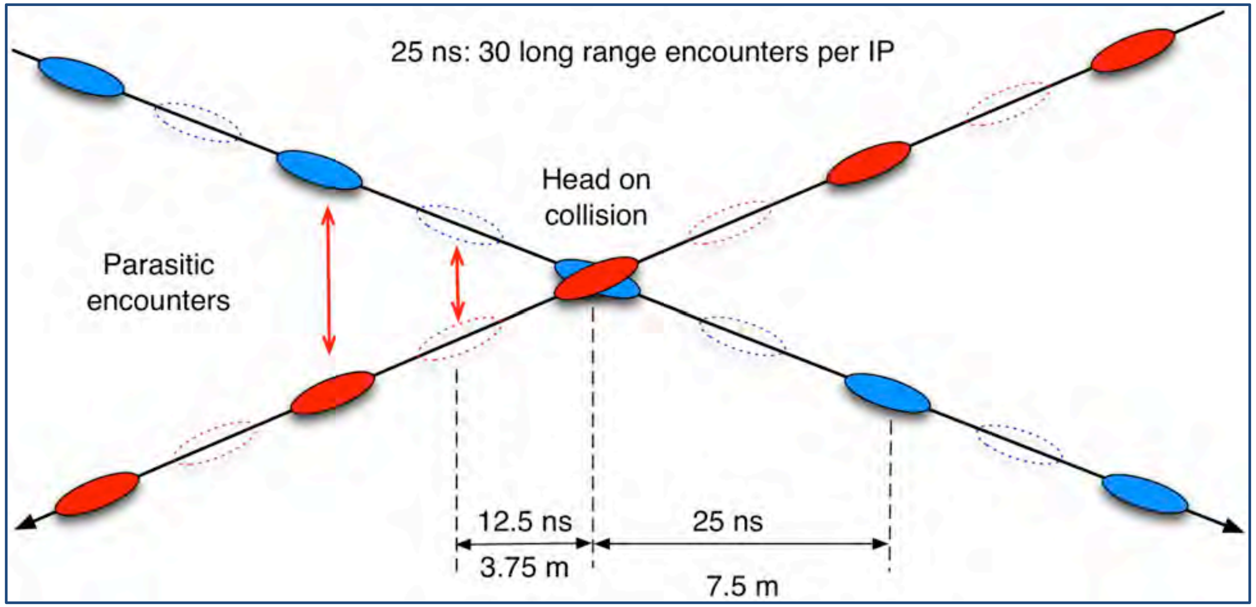
Video – 2’26’’

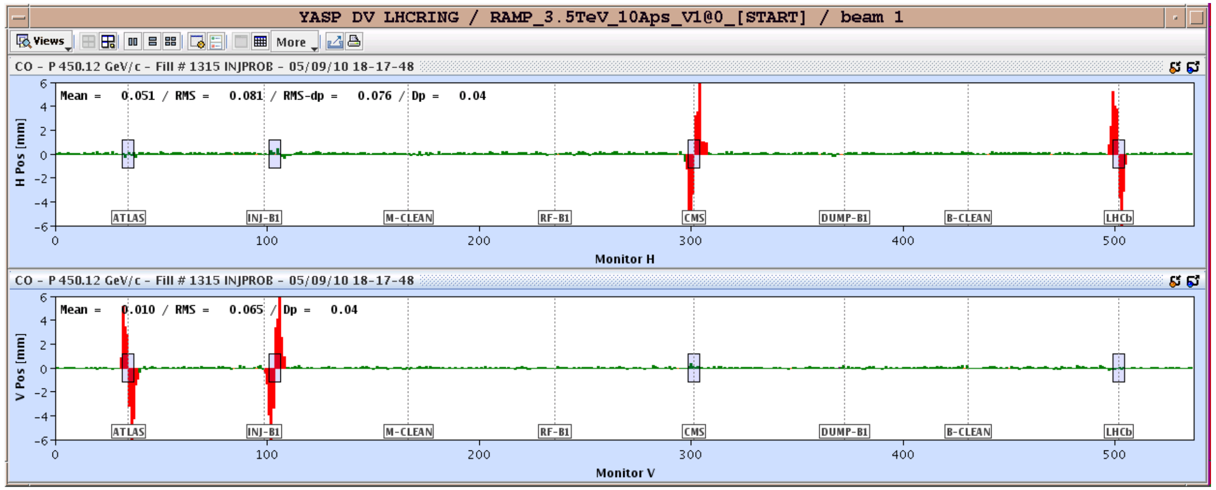
(Nominal) LHC bunch structure

- 25 ns bunch spacing
- Nominal bunch intensity 1.15 x 10^{11} protons per bunch



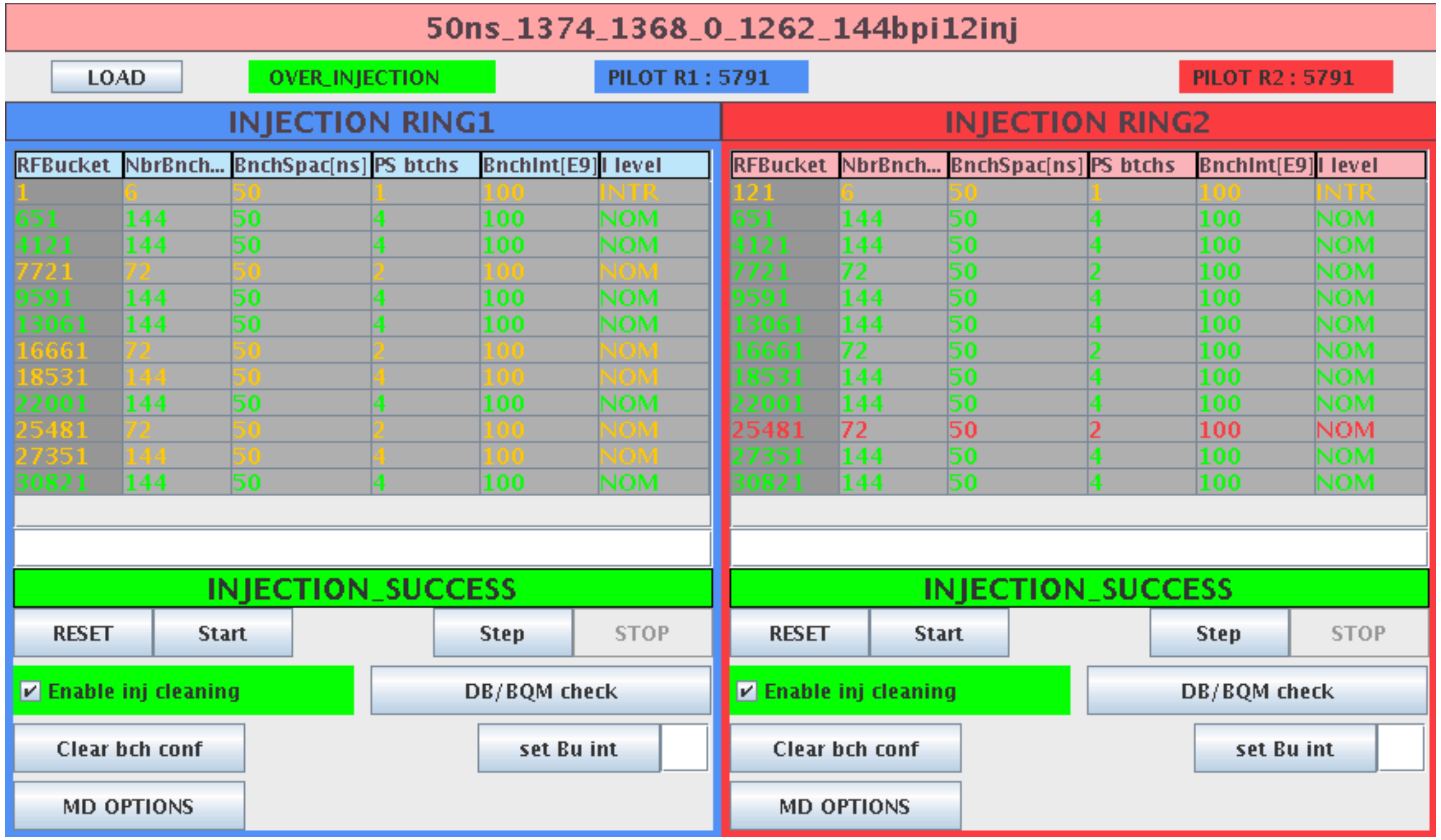
Crossing angles at interaction points

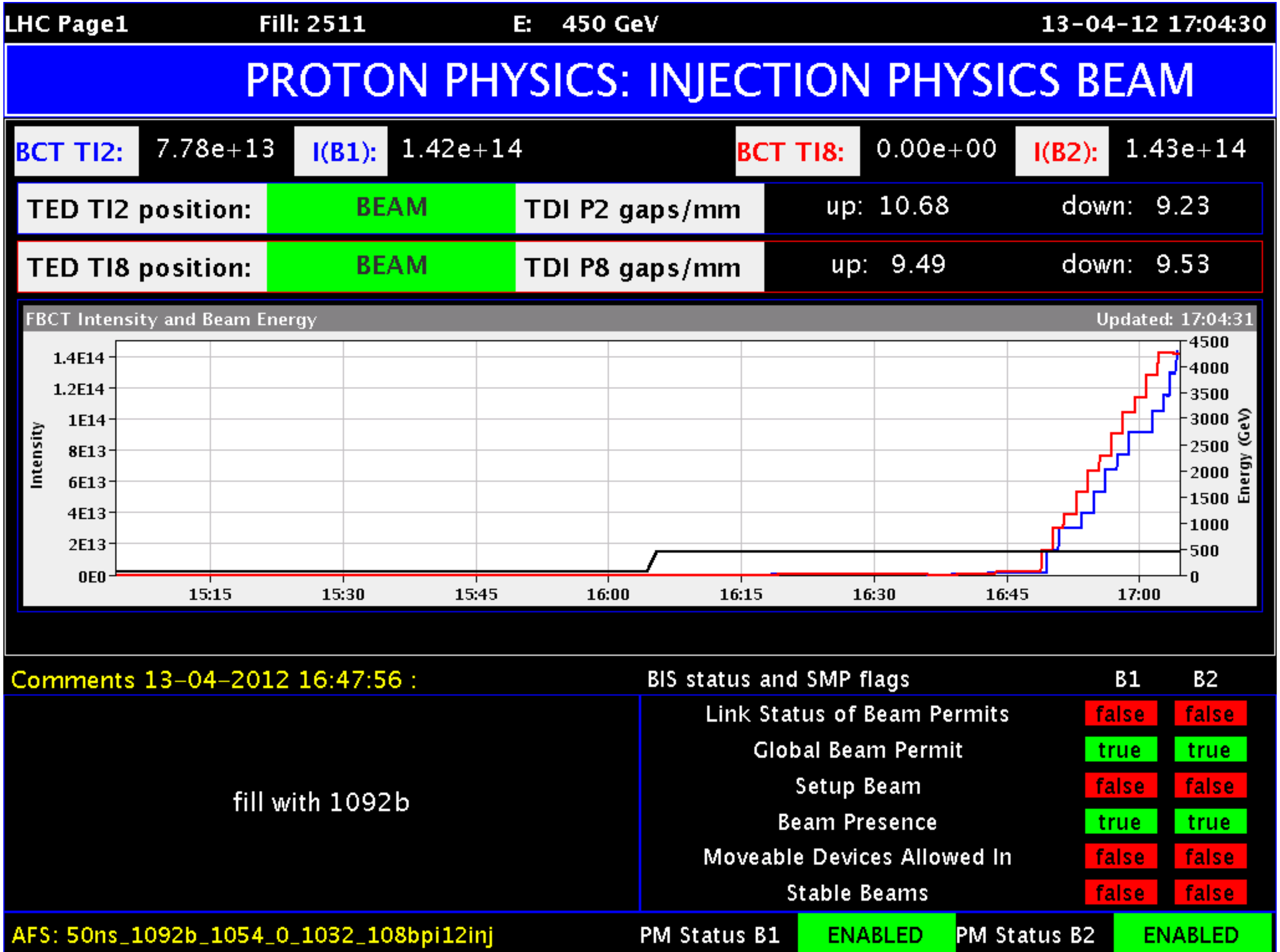




Filling

- LHC makes requests to the Central Beam and Cycle Manager (CBCM) which takes care of sorting things out in the injectors
  - Ring, number of batches, bucket number
- Injection process controlled semi-automatically by injection sequencer

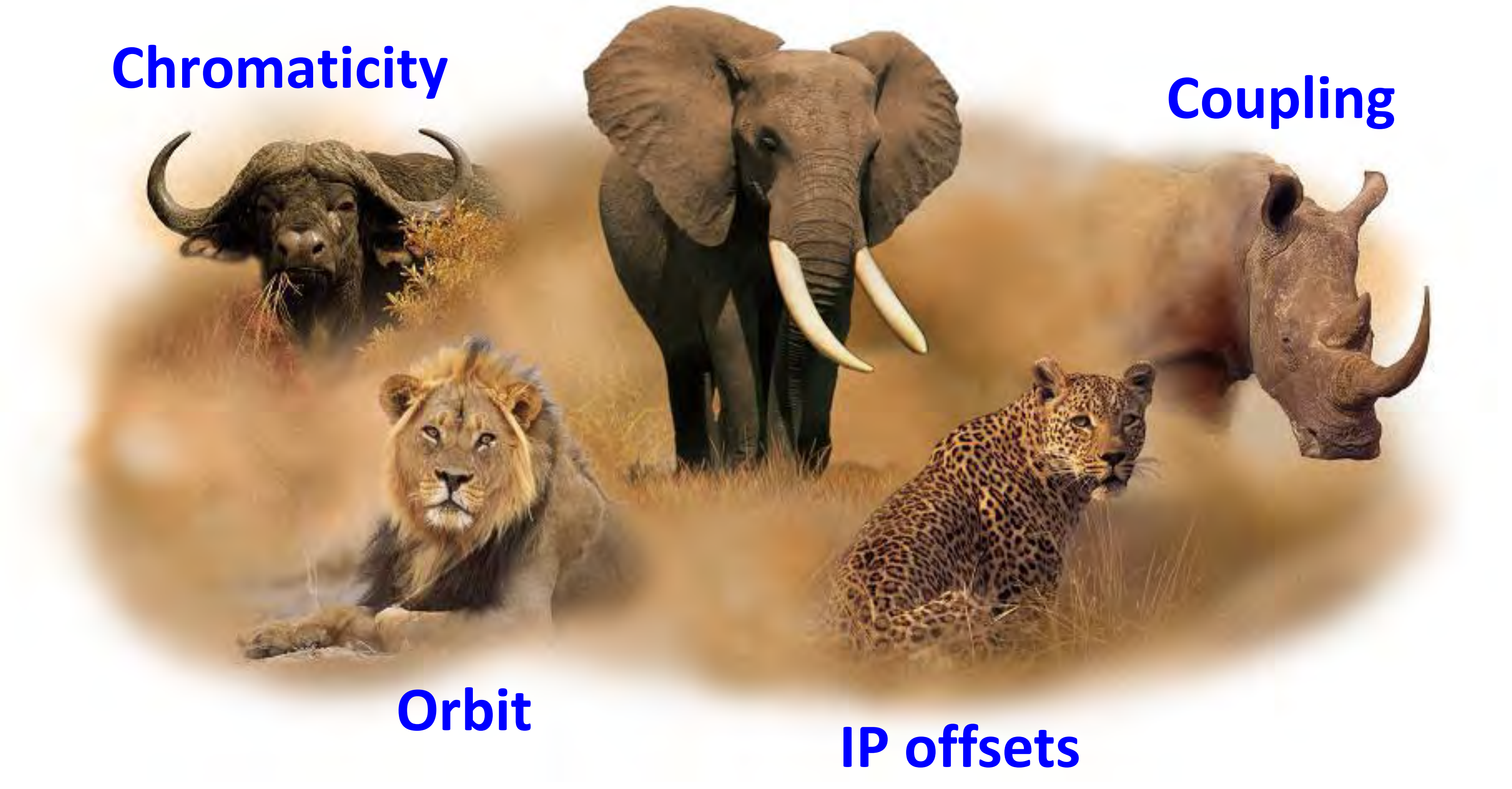



LHC Page1
Fill: 2511
E: 450 GeV
13-04-12 17:04:30
PROTON PHYSICS: INJECTION PHYSICS BEAM
BCT TI2: 7.78e+13
I(B1): 1.42e+14
BCT TI8: 0.00e+00
I(B2): 1.43e+14
TED TI2 position: BEAM
TDI P2 gaps/mm up: 10.68 down: 9.23
TED TI8 position: BEAM
TDI P8 gaps/mm up: 9.49 down: 9.53
FBCT Intensity and Beam Energy
Updated: 17:04:31
Intensity
Energy (GeV)
1.4E14
1.2E14
1E14
8E13
6E13
4E13
2E13
0E0
4500
4000
3500
3000
2500
2000
1500
1000
500
0
15:15
15:30
15:45
16:00
16:15
16:30
16:45
17:00
Comments 13-04-2012 16:47:56 :
fill with 1092b
BIS status and SMP flags
B1
B2
Link Status of Beam Permits false false
Global Beam Permit true true
Setup Beam false false
Beam Presence true true
Moveable Devices Allowed In false false
Stable Beams false false
AFS: 50ns_1092b_1054_0_1032_108bpi12inj
PM Status B1 ENABLED
PM Status B2 ENABLED

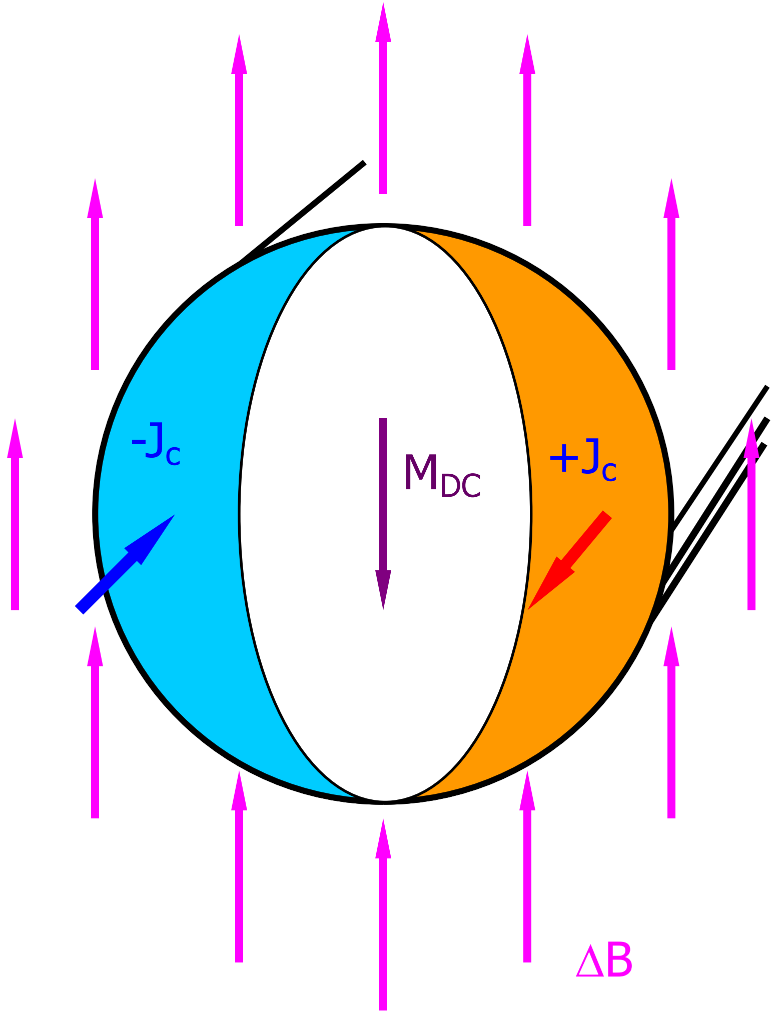
Ramp

- Load power converters (1700+)
- Load collimators
- Load RF settings
- Load transverse feedback
- Get orbit and tune feedback on
- Send timing event
- Get a cup of coffee
- BLM thresholds, beam dump - tracking energy

Parameter safari: the big five



Persistent currents



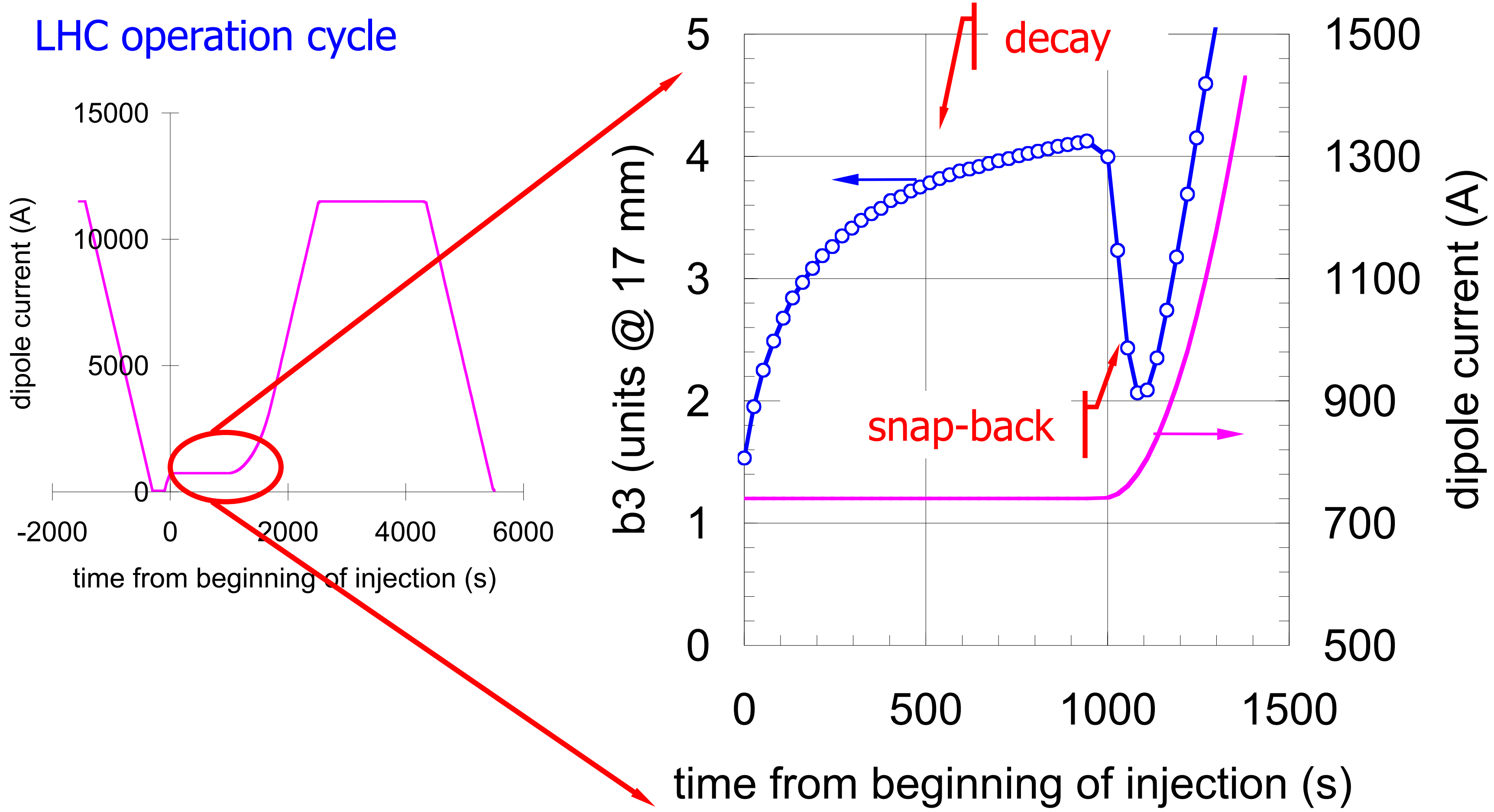
- Field change ΔB
- *Eddy* currents J_c with $\tau=\infty \Rightarrow$ *persistent*
- Diamagnetic moment at each filament: $M_{DC} \approx J_c * Dfil$

Dfil - filament diameter: 6-7 μm

This really messes with the field quality of the main dipoles. Large field errors, in particular, sextupole, are introduced.

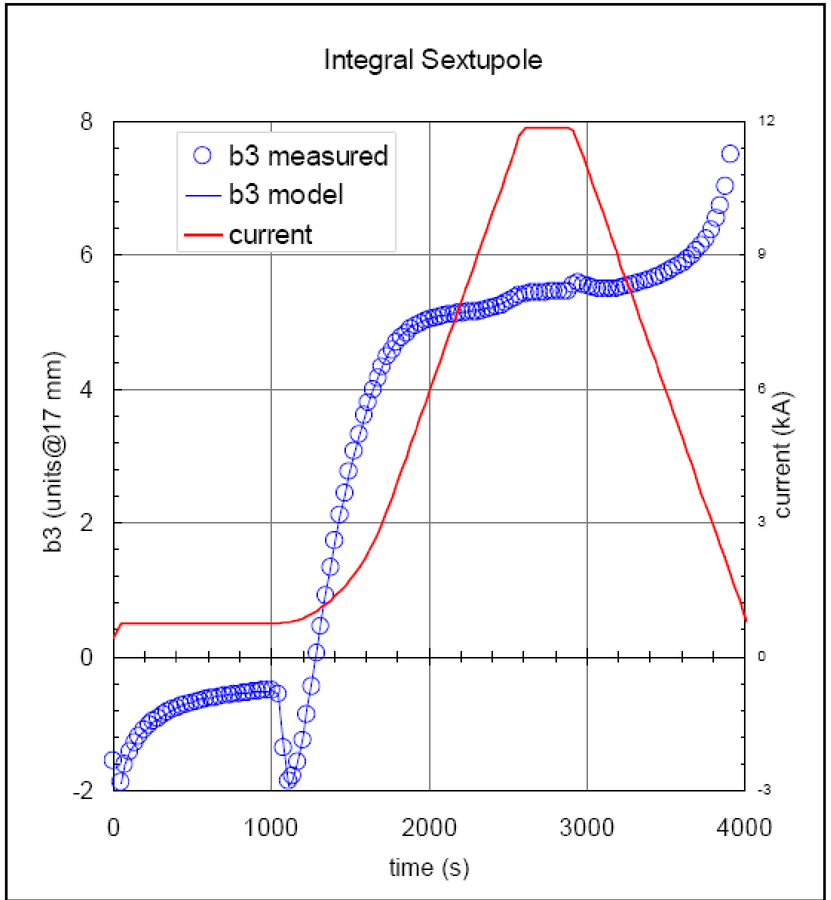
Exacerbated by the fact the effects are dynamic…

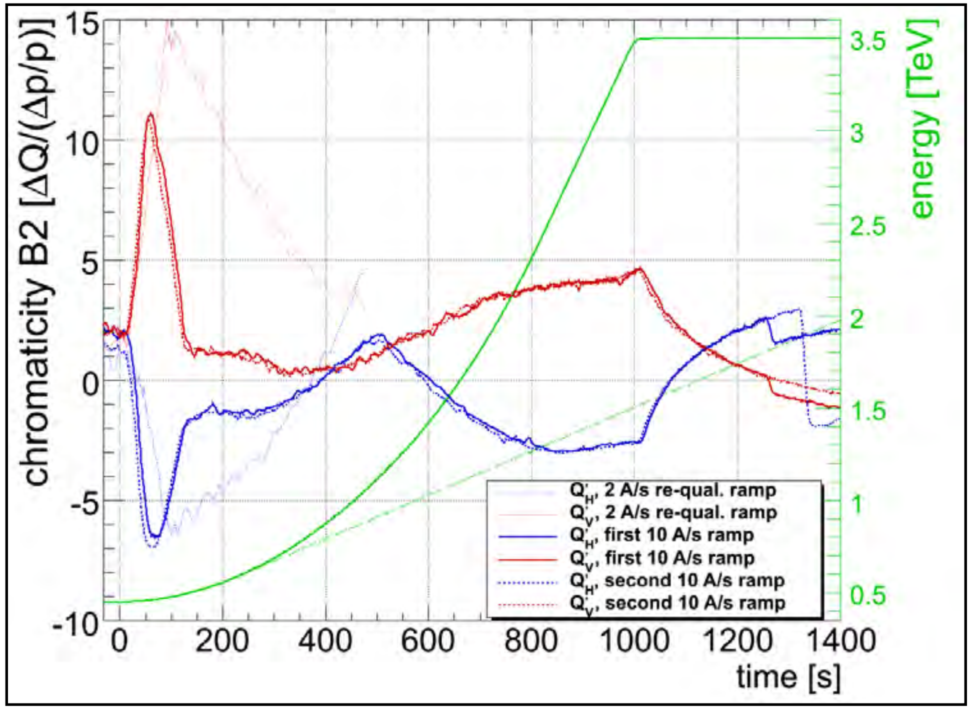
Decay and Snap-back



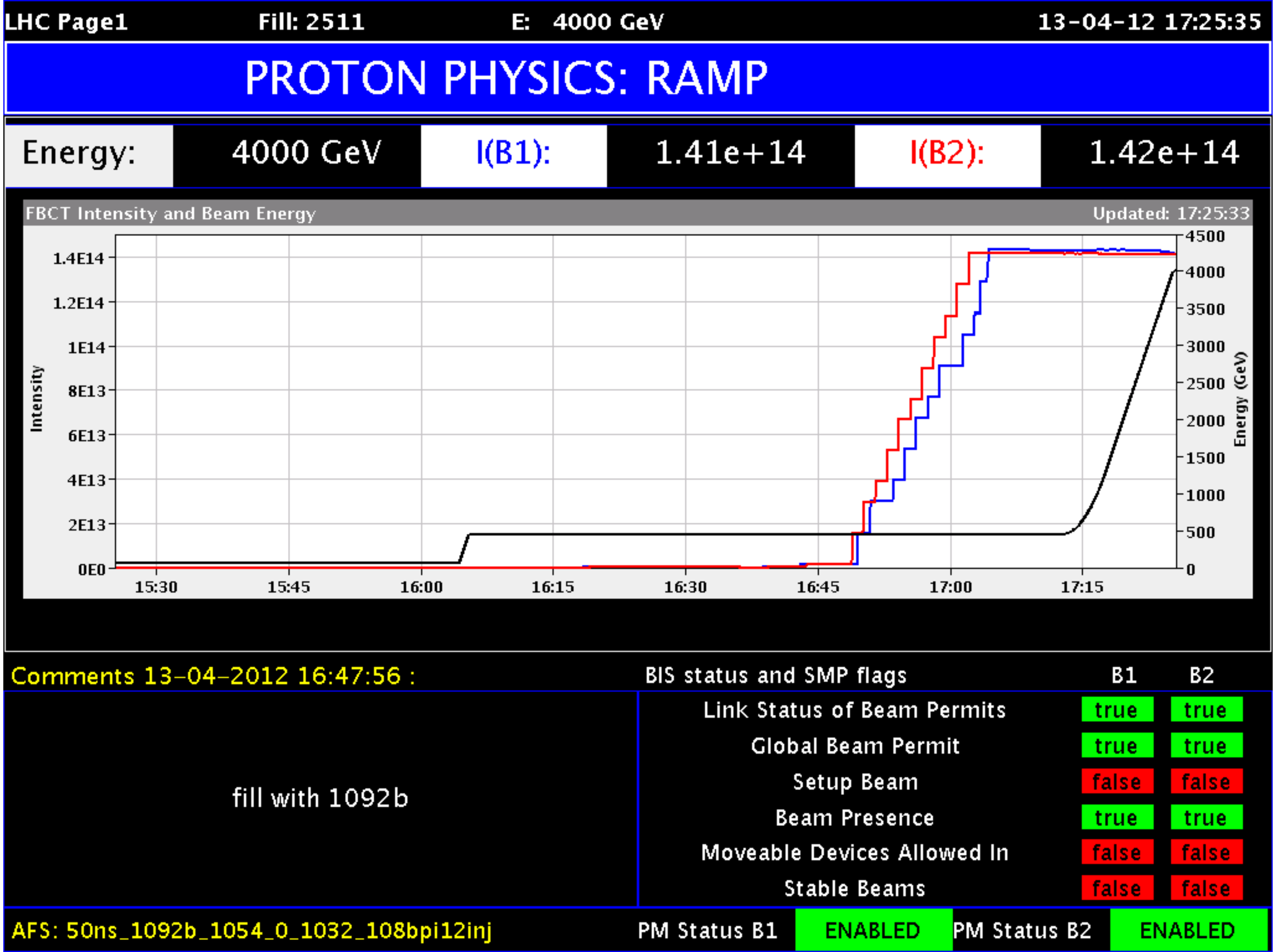
Magnet model

- Knowledge of the magnetic machine is good
- All magnet 'transfer functions', all harmonics including decay and snapback
- Tunes, momentum, optics all close to the model





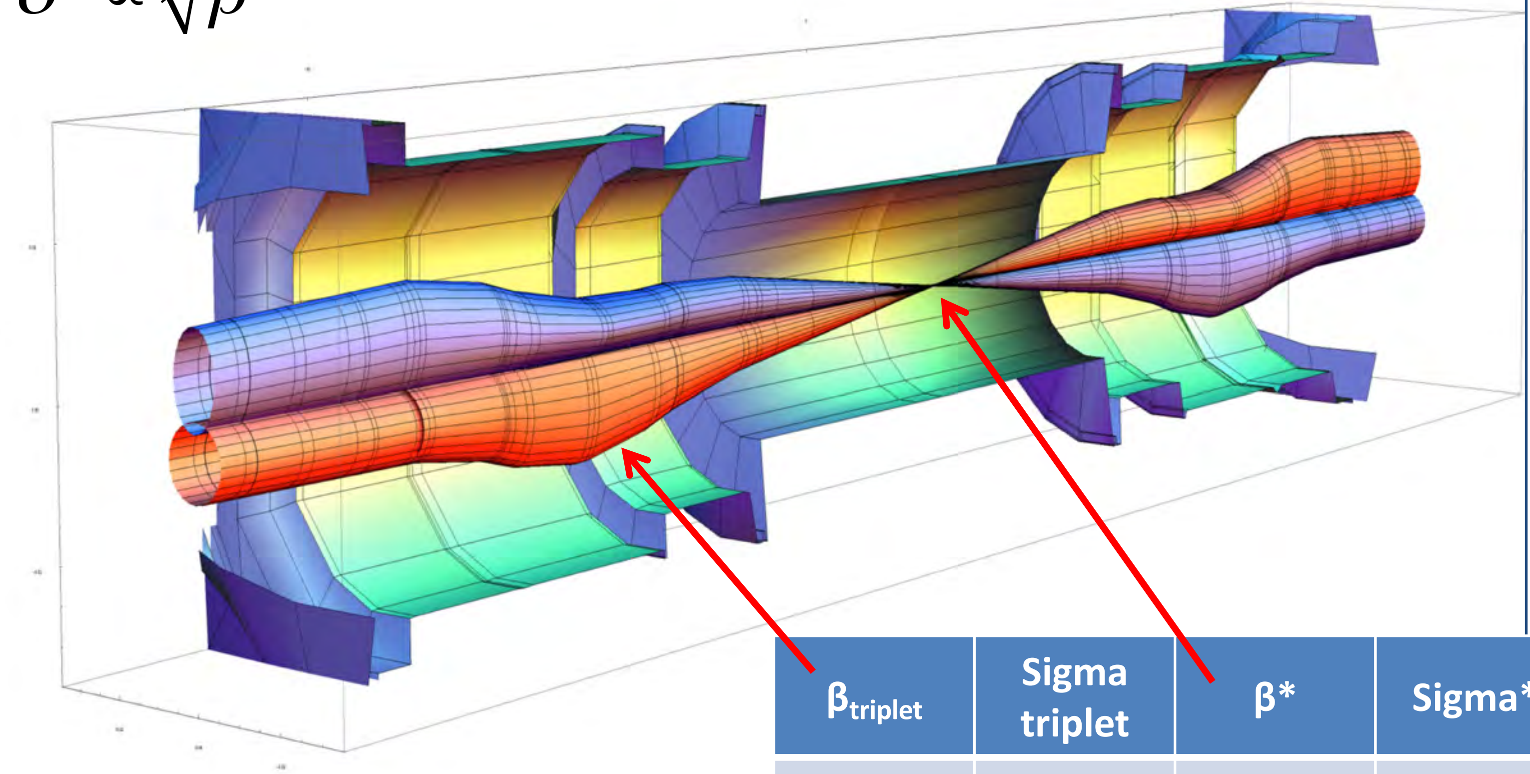
Model based feed-forward reduces chromaticity swing


LHC Page1
Fill: 2511
E: 4000 GeV
13-04-12 17:25:35
PROTON PHYSICS: RAMP
Energy: 4000 GeV
I(B1): 1.41e+14
I(B2): 1.42e+14
FBCT Intensity and Beam Energy
Updated: 17:25:33
Intensity
Energy (GeV)
1.4E14
1.2E14
1E14
8E13
6E13
4E13
2E13
0E0
4500
4000
3500
3000
2500
2000
1500
1000
500
0
15:30
15:45
16:00
16:15
16:30
16:45
17:00
17:15
Comments 13-04-2012 16:47:56 :
fill with 1092b
BIS status and SMP flags
B1
B2
Link Status of Beam Permits true true
Global Beam Permit true true
Setup Beam false false
Beam Presence true true
Moveable Devices Allowed In false false
Stable Beams false false
AFS: 50ns_1092b_1054_0_1032_108bpi12inj
PM Status B1 ENABLED
PM Status B2 ENABLED

Squeeze

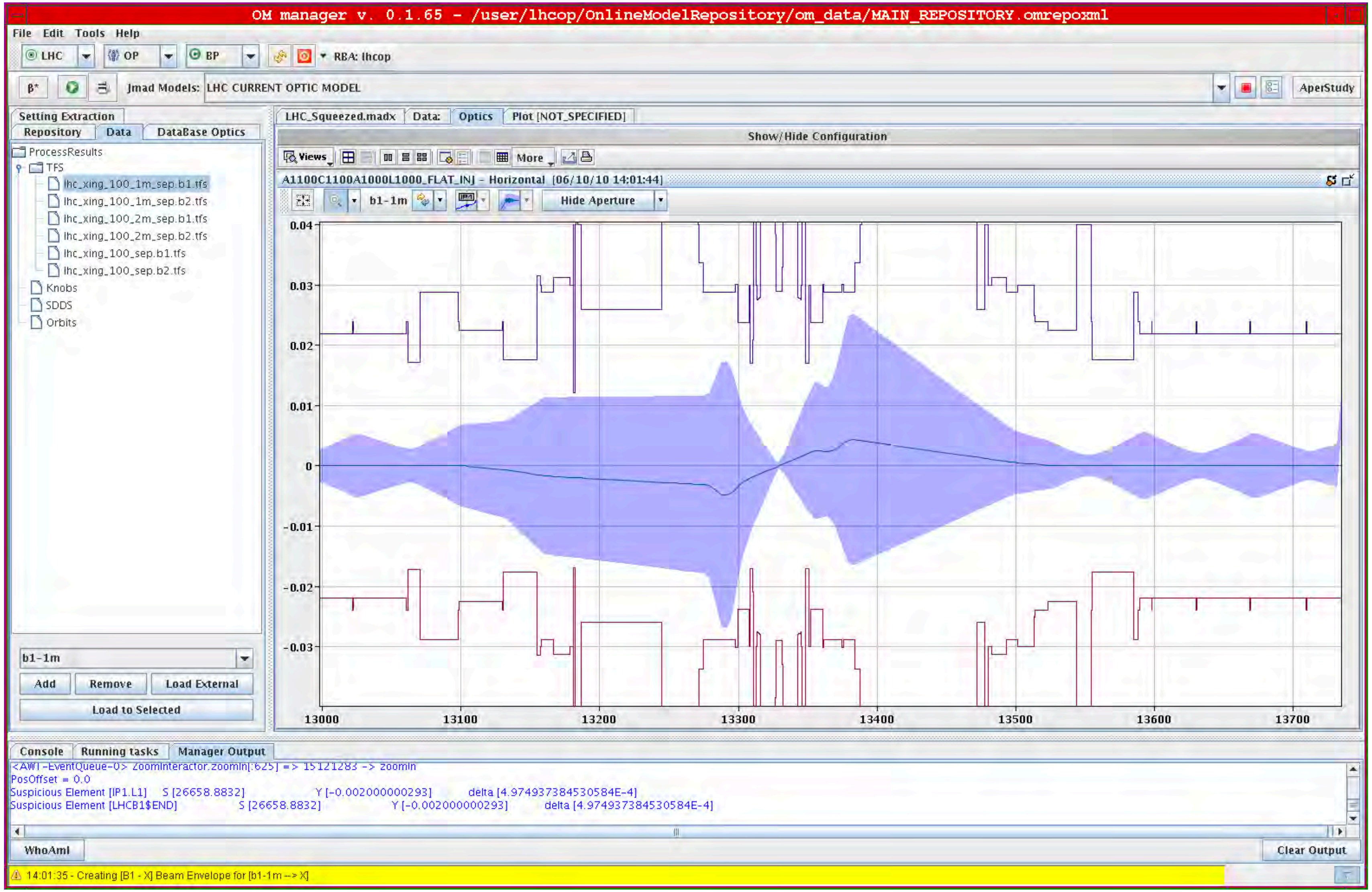
- Lower β* implies larger beams in the triplet magnets
- Larger beams implies a larger crossing angle
- Aperture concerns dictate caution (inject & ramp with high β* at IP, minimum β*)

$$\sigma^* \propto \sqrt{\beta^*}$$



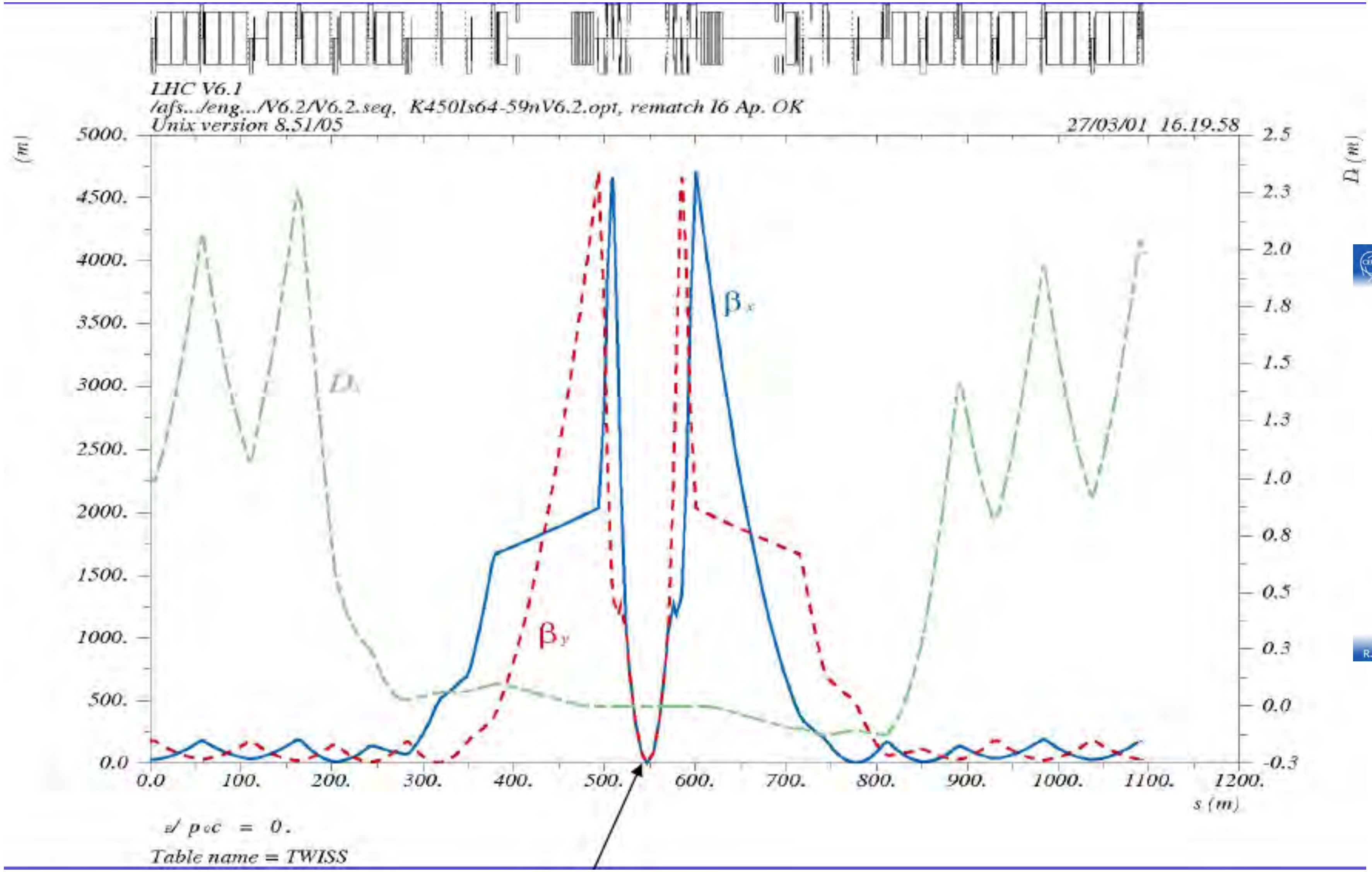
$\beta_{triplet}$	Sigma triplet	β*	Sigma*
~4.5 km	1.5 mm	55 cm	17 um

Image courtesy John Jowett



OM manager v. 0.1.65 - /user/lhcop/OnlineModelRepository/om_data/MAIN_REPOSITORY.omrepoxml
File Edit Tools Help
LHC
OP
BP
RBA: lhcop
Jmad Models: LHC CURRENT OPTIC MODEL
AperStudy
Setting Extraction
Repository
Data
DataBase Optics
ProcessResults
TFS
lhc_xing_100_1m_sep.b1.tfs
lhc_xing_100_1m_sep.b2.tfs
lhc_xing_100_2m_sep.b1.tfs
lhc_xing_100_2m_sep.b2.tfs
lhc_xing_100_sep.b1.tfs
lhc_xing_100_sep.b2.tfs
Knobs
SDDS
Orbits
b1-1m
Add
Remove
Load External
Load to Selected
LHC_Squeezed.madx
Data:
Optics
Plot [NOT_SPECIFIED]
Show/Hide Configuration
Views
More
A1100C1100A1000L1000_FLAT_INJ - Horizontal [06/10/10 14:01:44]
b1-1m
Hide Aperture
Console
Running tasks
Manager Output
PosOffset = 0.0
Suspicious Element [IP1.L1] S [26658.8832] Y [-0.002000000293] delta [4.974937384530584E-4]
Suspicious Element [LHCB1$END] S [26658.8832] Y [-0.002000000293] delta [4.974937384530584E-4]
WhoAmI
Clear Output
14:01:35 - Creating [B1 - X] Beam Envelope for [b1-1m --> X]

Squeeze


LHC V6.1
/afs.../eng.../V6.2/V6.2.seq, K450Is64-59nV6.2.opt, rematch I6 Ap. OK
Unix version 8.51/05
27/03/01 16.19.58
(m)
D (m)
βx
βy
Dx
s (m)
δE/ p0c = 0.
Table name = TWISS


β* is like toothpaste...
YOU KNOW
YOU CAN ALWAYS SQUEEZE A BIT MORE
R. Bruce, 2016.12.15
21

Squeeze in practice

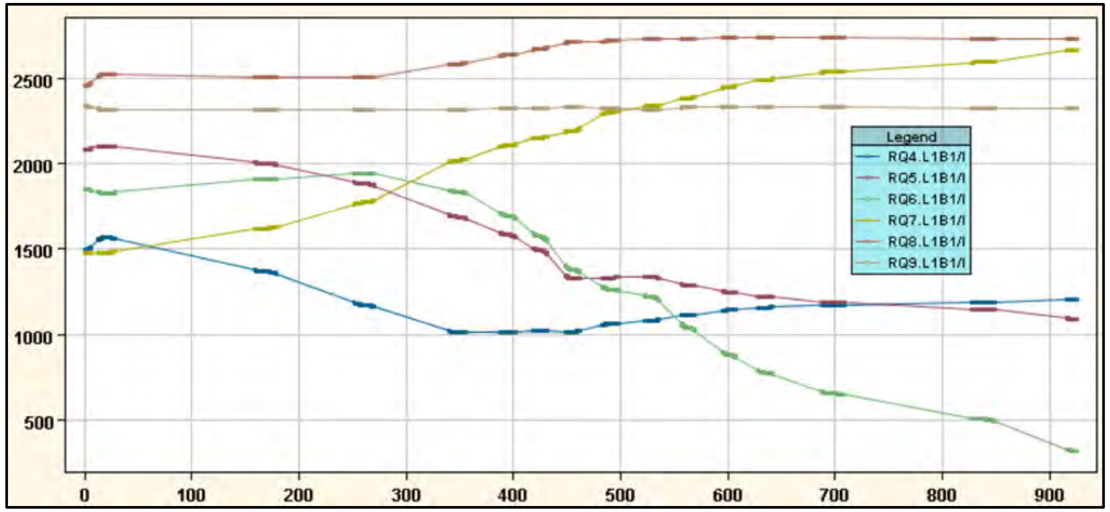
Matched optics

Time in seconds

Optic Name	Energy	Time
A1100C1100A1000L1000_INJ_2012	4000.0	0
A1100C1100A1000L1000_2012	4000.0	19
A900C900A900_0.00915L750_0.00932_2012	4000.0	169
A700C700A750_0.00897L600_0.00909_2012	4000.0	262
A400C400A600_0.00889L500_0.00900_2012	4000.0	348
A300C300A500_0.00889L375_0.00888_2012	4000.0	396
A250C250A450_0.00889L350_0.00882_2012	4000.0	425
A200C200A400_0.00889L325_0.00878_2012	4000.0	455
A160C160A350_0.00889L300_0.00875_2012	4000.0	491
A150C150A300_0.00889L300_0.00875_2012	4000.0	529
A120C120A300_0.00889L300_0.00875_2012	4000.0	563
A100C100A300_0.00889L300_0.00875_2012	4000.0	602
A90C90A300_0.00889L300_0.00875_2012	4000.0	634
A80C80A300_0.00889L300_0.00875_2012	4000.0	696
A70C70A300_0.00889L300_0.00875_2012	4000.0	840
A60C60A300_0.00889L300_0.00875_2012	4000.0	925

Beta* - 11 m ATLAS, CMS; 10 m in ALICE, LHCb

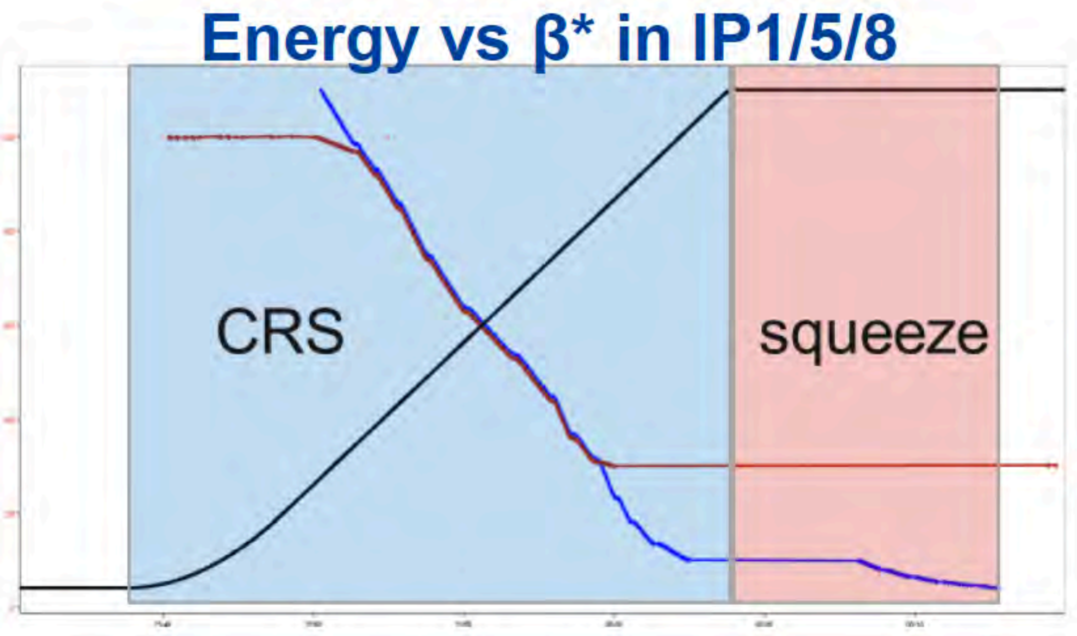
Beta* - 0.6 m ATLAS, CMS; 3 m in ALICE, LHCb



Current during the squeeze in a few quads at point 1

With practice - 2017

- ❑ Enhanced **Combined Ramp & Squeeze** (CRS) to reach β^* of 1 m (ATLAS/CMS) at flat top → further squeeze to 40 cm



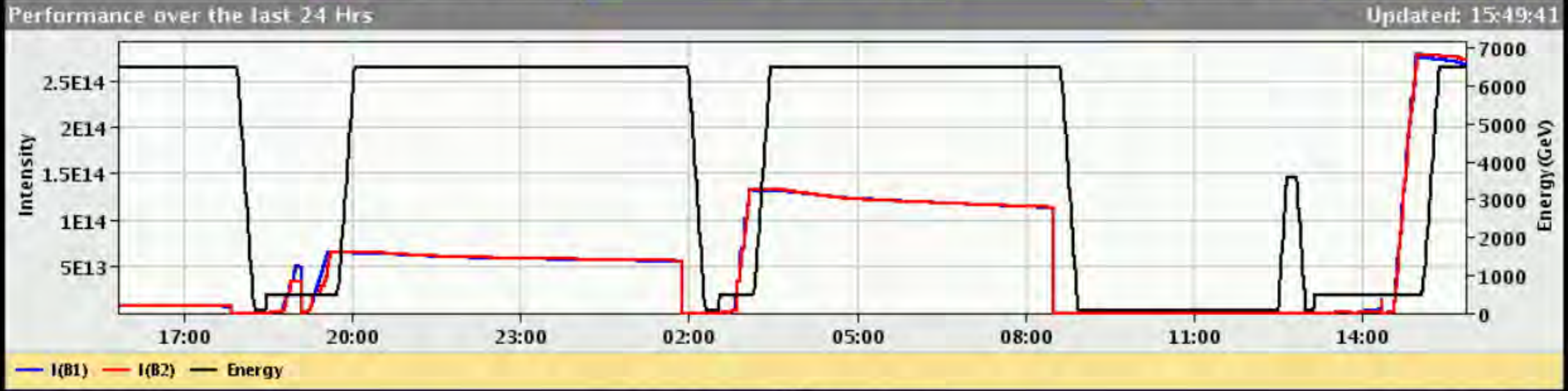
udp://multicast-bevlhc3:1234 - VLC media player

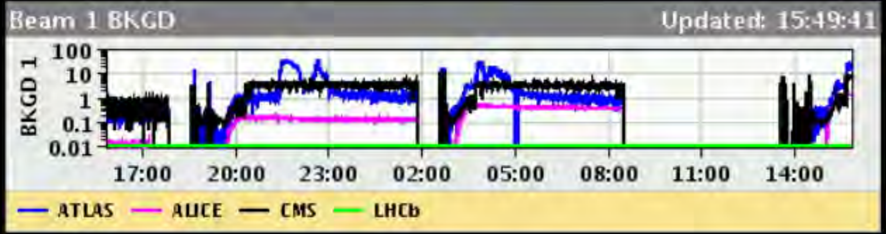
Media Playback Audio Video Subtitle Tools View Help

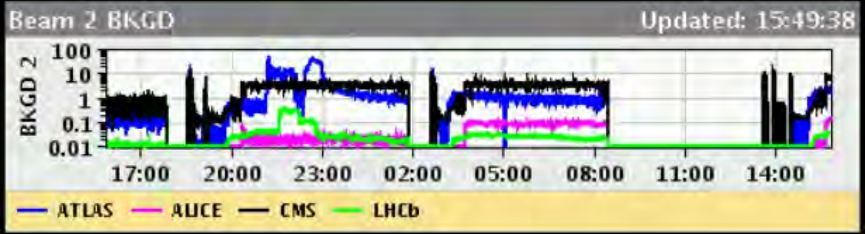
24-Sep-2018 15:49:42 Fill #: 7217 Energy: 6499 GeV I(B1): 2.67e+14 I(B2): 2.72e+14

	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	PHYSICS
Instantaneous Lumi [(ub.s)^-1]	19211.756	3.460	18467.459	262.148
BRAN Luminosity [(ub.s)^-1]	22613.0	3.3	15929.7	531.3
Fill Luminosity (nb)^-1	1361.260	0.447	3292.048	78.109
Beam 1 BKGD	15.513	1.406	8.339	0.003
Beam 2 BKGD	2.267	0.137	7.699	0.030
Beta*	0.30 m	10.00 m	0.30 m	3.00 m
Crossing Angle (urad)	160(V)	200(V)	160(H)	-250(H)

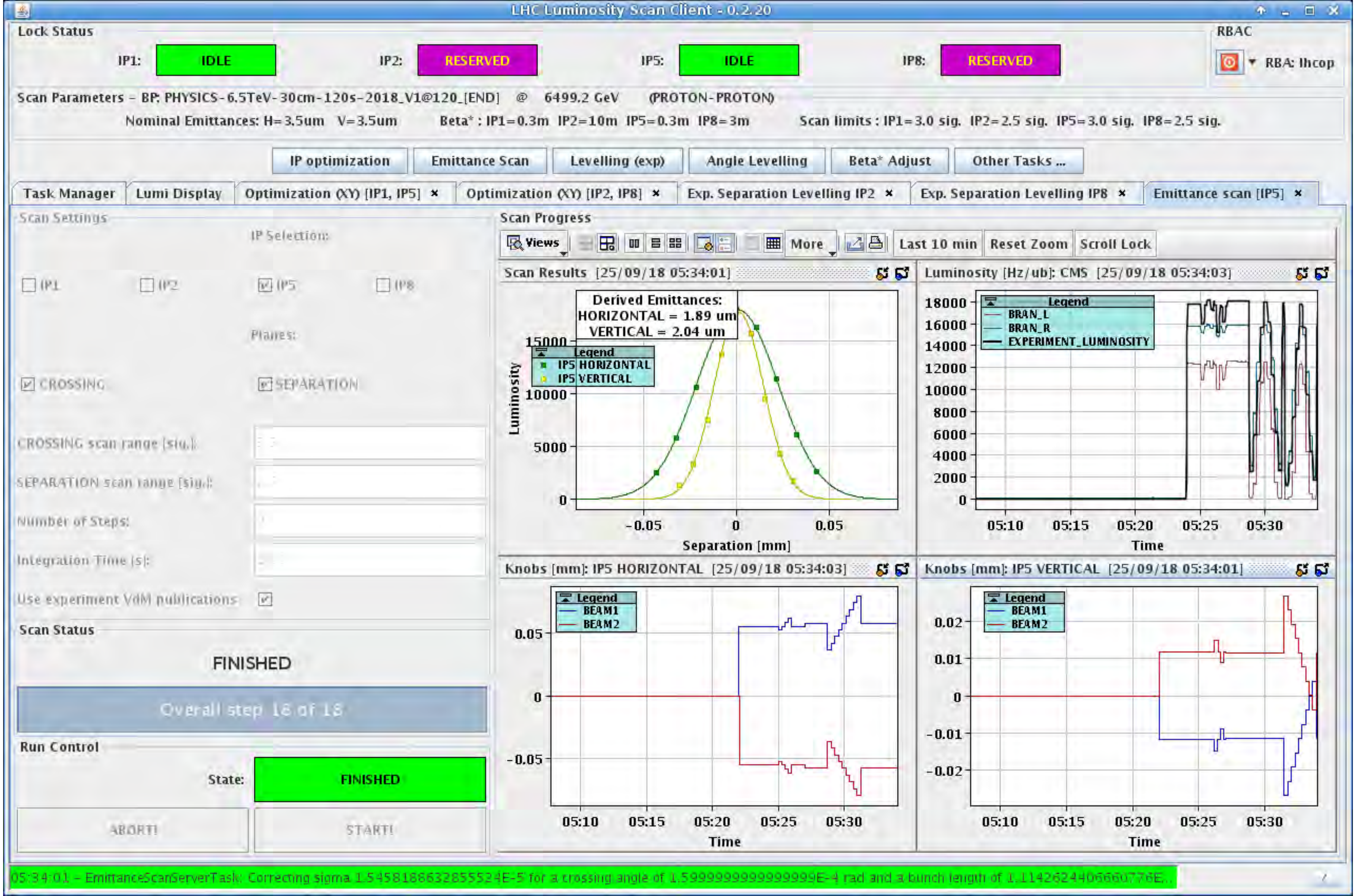
LHCb VELO Position IN Gap: 20.0 mm | STABLE BEAMS | TOTEM: CALIBRATION







00:00 00:00


LHC Luminosity Scan Client - 0.2.20
Lock Status
IP1: IDLE
IP2: RESERVED
IP5: IDLE
IP8: RESERVED
RBAC
RBA: lhcop
Scan Parameters - BP: PHYSICS-6.5TeV-30cm-120s-2018_V1@120_[END] @ 6499.2 GeV (PROTON-PROTON)
Nominal Emittances: H=3.5um V=3.5um Beta* : IP1=0.3m IP2=10m IP5=0.3m IP8=3m Scan limits : IP1=3.0 sig. IP2=2.5 sig. IP5=3.0 sig. IP8=2.5 sig.
IP optimization
Emittance Scan
Levelling (exp)
Angle Levelling
Beta* Adjust
Other Tasks ...
Task Manager
Lumi Display
Optimization (XY) [IP1, IP5]
Optimization (XY) [IP2, IP8]
Exp. Separation Levelling IP2
Exp. Separation Levelling IP8
Emittance scan [IP5]
Scan Settings
IP Selection:
IP1
IP2
IP5
IP8
Planes:
CROSSING
SEPARATION
CROSSING scan range [sig.]:
SEPARATION scan range [sig.]:
Number of Steps:
Integration Time [s]:
Use experiment VdM publications
Scan Status
FINISHED
Overall step 18 of 18
Run Control
State: FINISHED
ABORT!
START!
Scan Progress
Views
More
Last 10 min
Reset Zoom
Scroll Lock
Scan Results [25/09/18 05:34:01]
Derived Emittances:
HORIZONTAL = 1.89 um
VERTICAL = 2.04 um
Legend
IP5 HORIZONTAL
IP5 VERTICAL
Luminosity
Separation [mm]
Luminosity [Hz/ub]: CMS [25/09/18 05:34:03]
Legend
BRAN_L
BRAN_R
EXPERIMENT_LUMINOSITY
Time
Knobs [mm]: IP5 HORIZONTAL [25/09/18 05:34:03]
Legend
BEAM1
BEAM2
Time
Knobs [mm]: IP5 VERTICAL [25/09/18 05:34:01]
Legend
BEAM1
BEAM2
Time
05:34:01 - EmittanceScanServerTask: Correcting sigma 1.5458188632855524E-5 for a crossing angle of 1.5999999999999999E-4 rad and a bunch length of 1.1142624406660776E...

Beam dump system – point 6

Video 2’10”

Underpinning all this…

- RF, power converters, collimators, beam dumps, injection, magnets, vacuum, transverse feedback, machine protection
- Magnets, magnet protection & associated systems
- Beam instrumentation and beam based feedbacks
- Controls, databases, high level software
- Cryogenics, survey, technical infrastructure, access, radiation protection

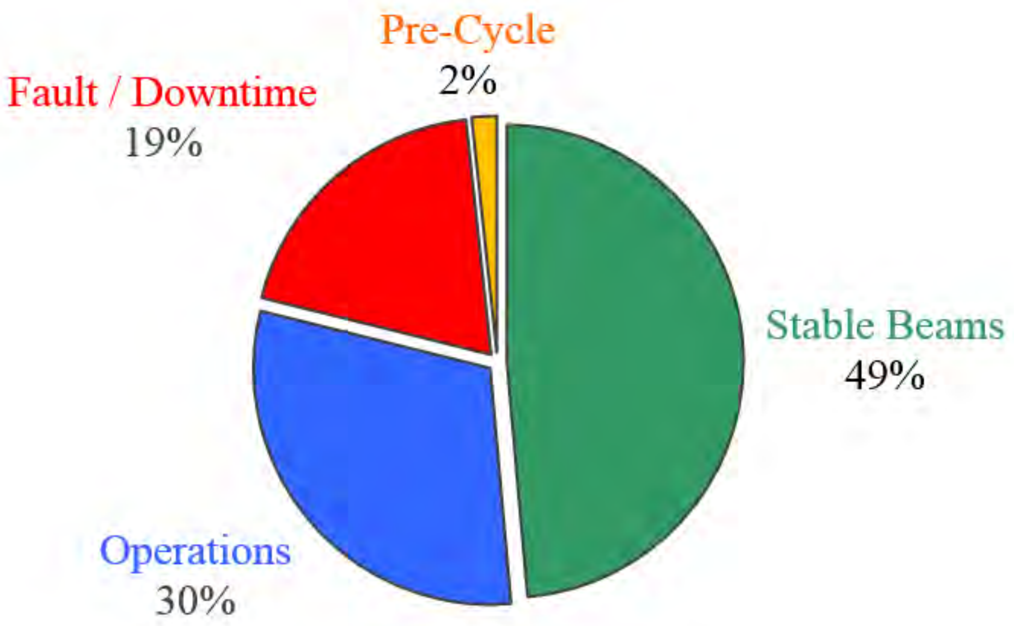
Impossible to do justice to the commitment and effort that's gone into getting, and keeping, the complex operational

Availability

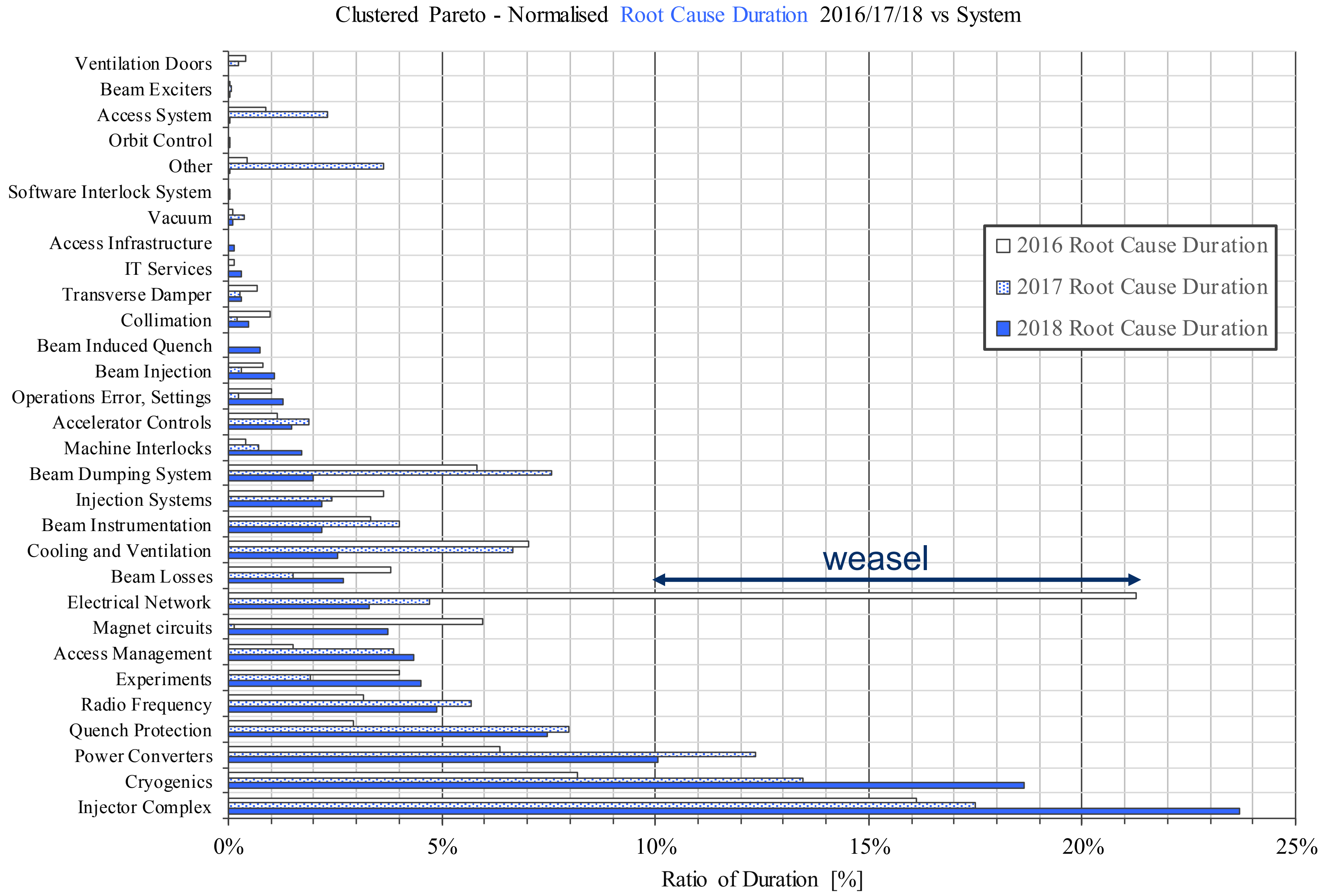
2017: 140½ days physics ≈ 3362.1 hours

	Duration [h]
Stable Beams	1633.9
Operations	1018.1
Fault/Downtime	652.9
Pre-Cycle	57.2

= 3362.1



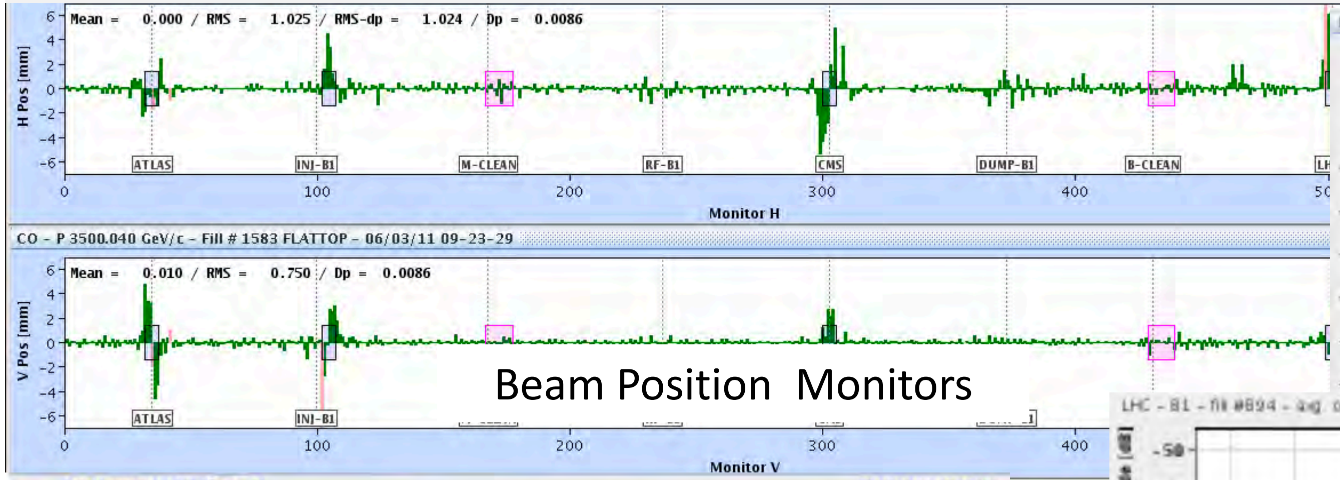
LHC 2016/17/18 Faults

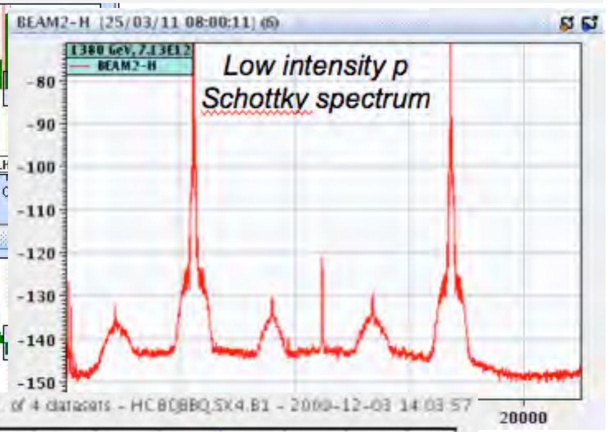


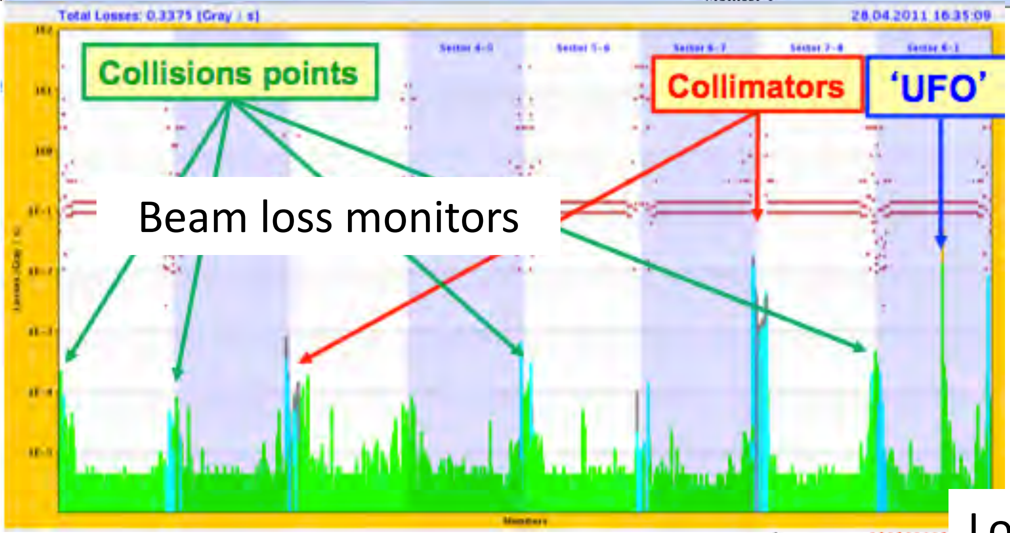
I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be. **Kelvin**

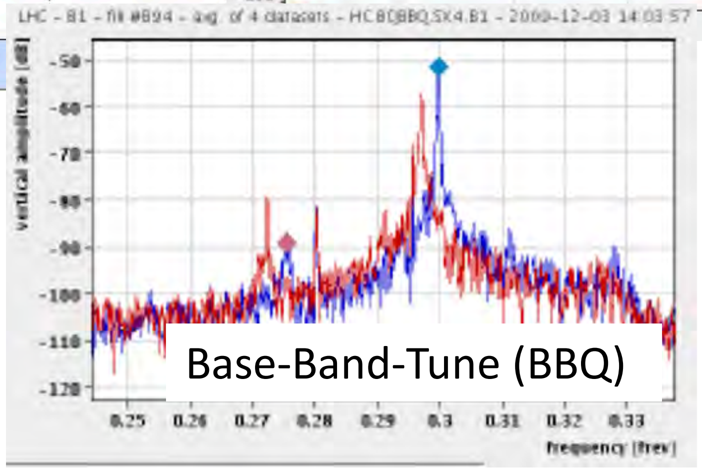
BEAM INSTRUMENTATION

Beam Instrumentation – the enabler

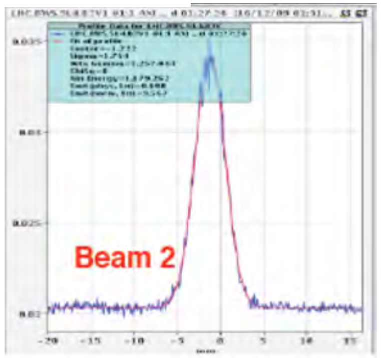


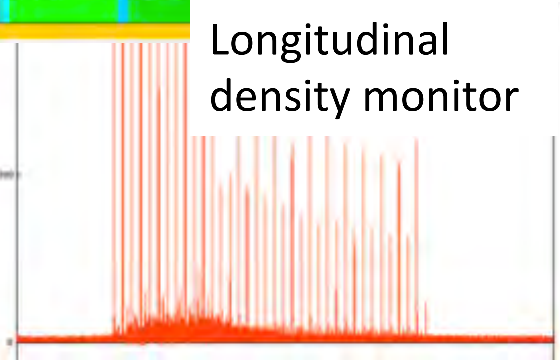




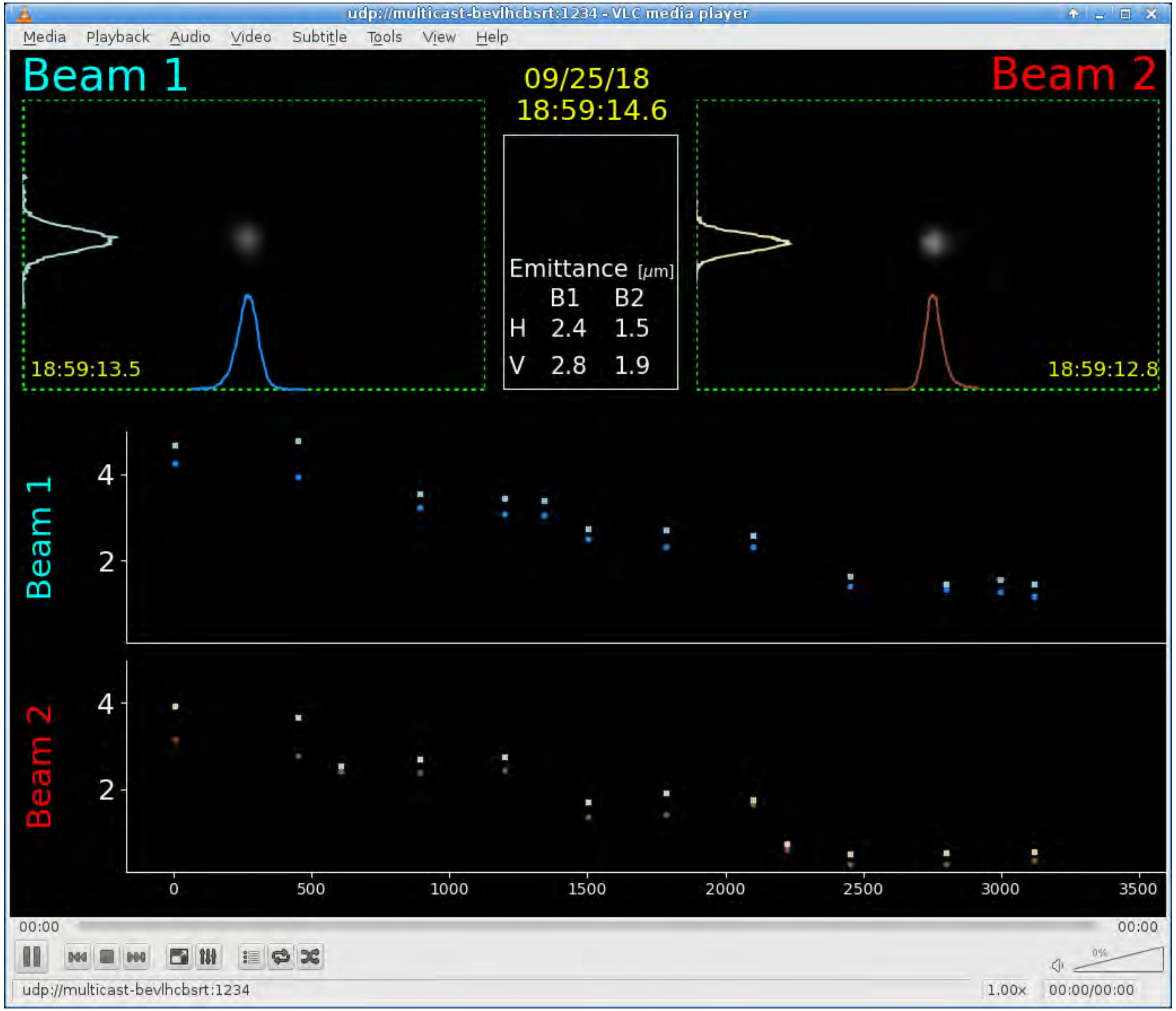


Wire scanner





Synchrotron Radiation Telescope

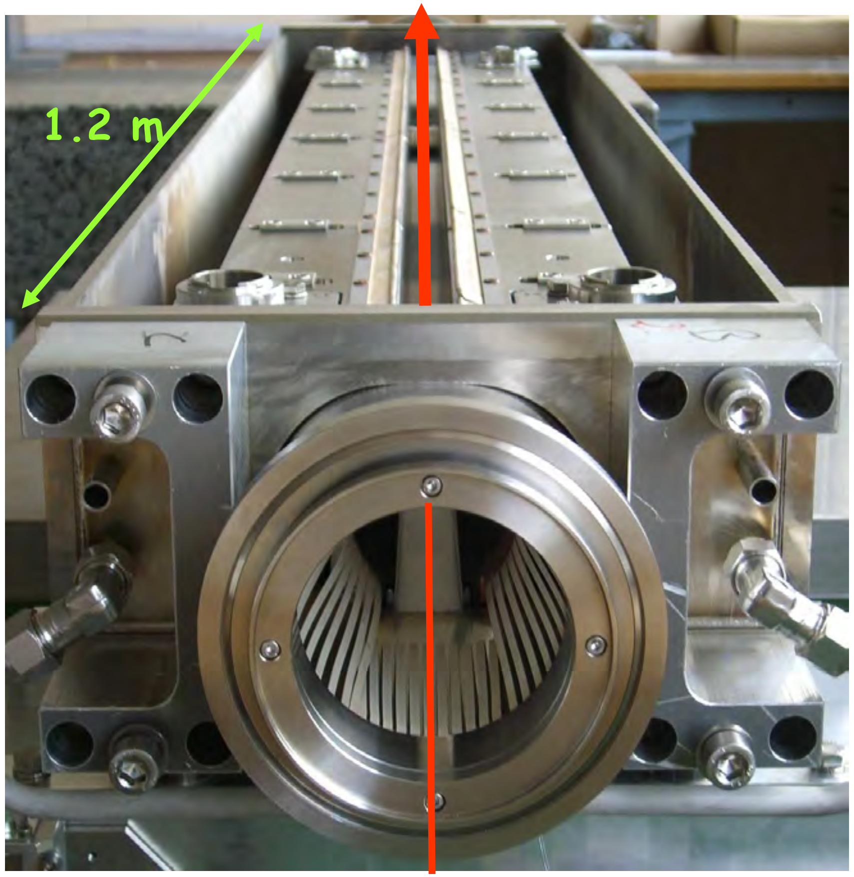


Beam Loss Monitors

EXPLOITATION

Following on from Kelvin, it can be measured, analysed, understood, and mastered…

Collimation



beam

Two warm cleaning insertions

IR3: Momentum cleaning

- **1 primary (H)**
- **4 secondary (H,S)**
- **4 shower abs. (H,V)**

IR7: Betatron cleaning

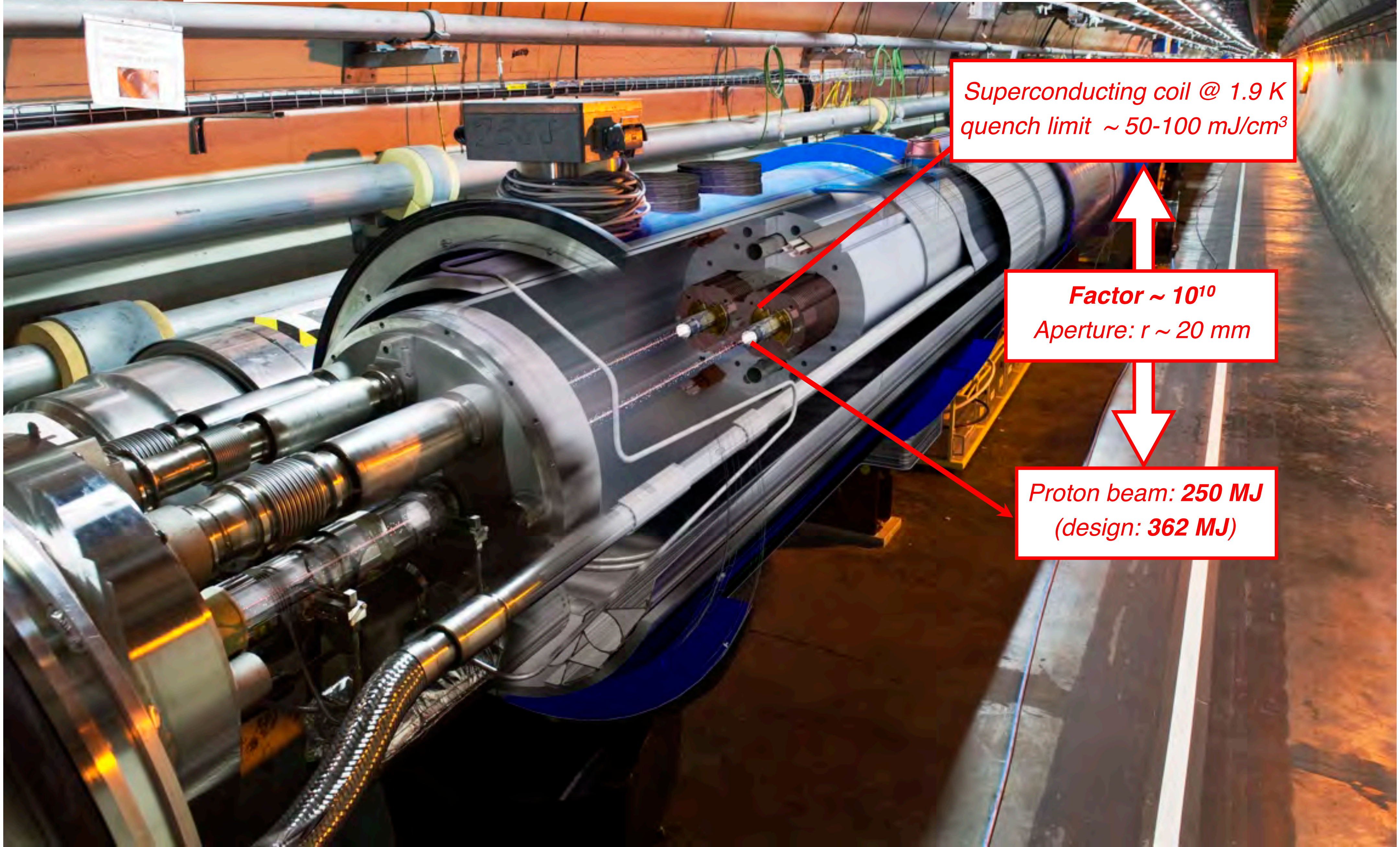
- **3 primary (H,V,S)**
- **11 secondary (H,V,S)**
- **5 shower abs. (H,V)**

Local IP cleaning: 8 tertiary coll.

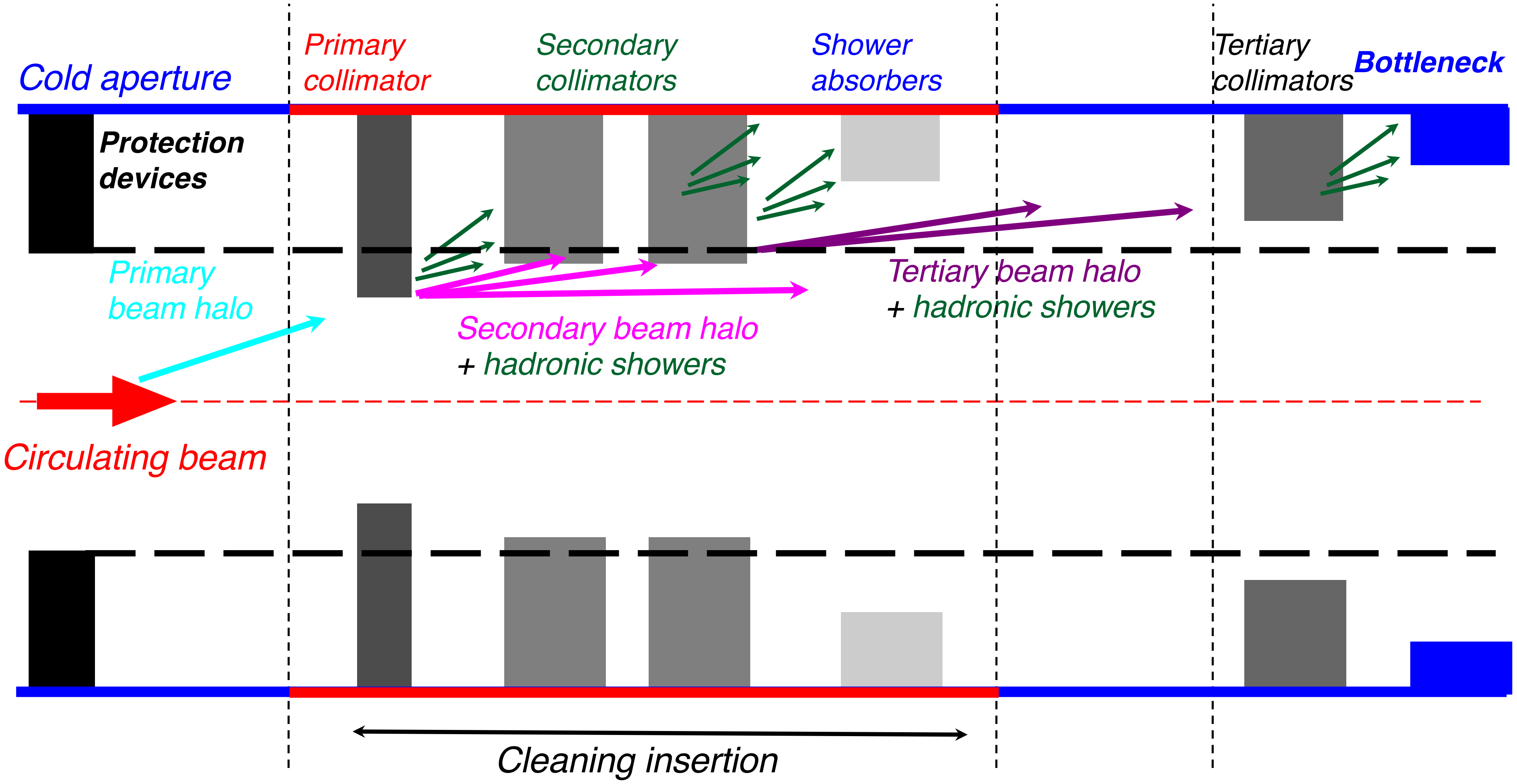
Total = 108 collimators

About 500 degrees of freedom.

Collimation at the energy frontier



Multi-stage collimation at the LHC



Including protection devices, a **5-stage cleaning** is used at the LHC !

The system performance relies on achieving the well-defined **hierarchy** between different **collimator families** and **machine aperture**.

LHC Collimators | Beam: B1 | Set: HW Group:LHC COLLIMATORS 23-05-2012 22:10:55

L(mm) MDC	IP1	PRS R(mm)
3.24	TCL.5R1.B1	-3.93
10.4	TCTH.4L1.B1	-9.11
8.96	TCTVA.4L1.B1	-3.43
	IP2	
5.05	TCTH.4L2.B1	-4.85
7.9	TCTVA.4L2.B1	-2.62
54.97	TDI.4L2	-54.91
19.92	TCDD.4L2	-20.02
27.96	TCLIA.4R2	-27.97
24.87	TCLIB.6R2.B1	-24.98
	IP3	
4.28	TCP.6L3.B1	-3.62
2.94	TCSG.5L3.B1	-3.68
1.15	TCSG.4R3.B1	-3.44
2.92	TCSG.A5R3.B1	-2.96
3.34	TCSG.B5R3.B1	-3.34
6.2	TCLA.A5R3.B1	-7.2
6.2	TCLA.B5R3.B1	-6.22
5.74	TCLA.6R3.B1	-5.72

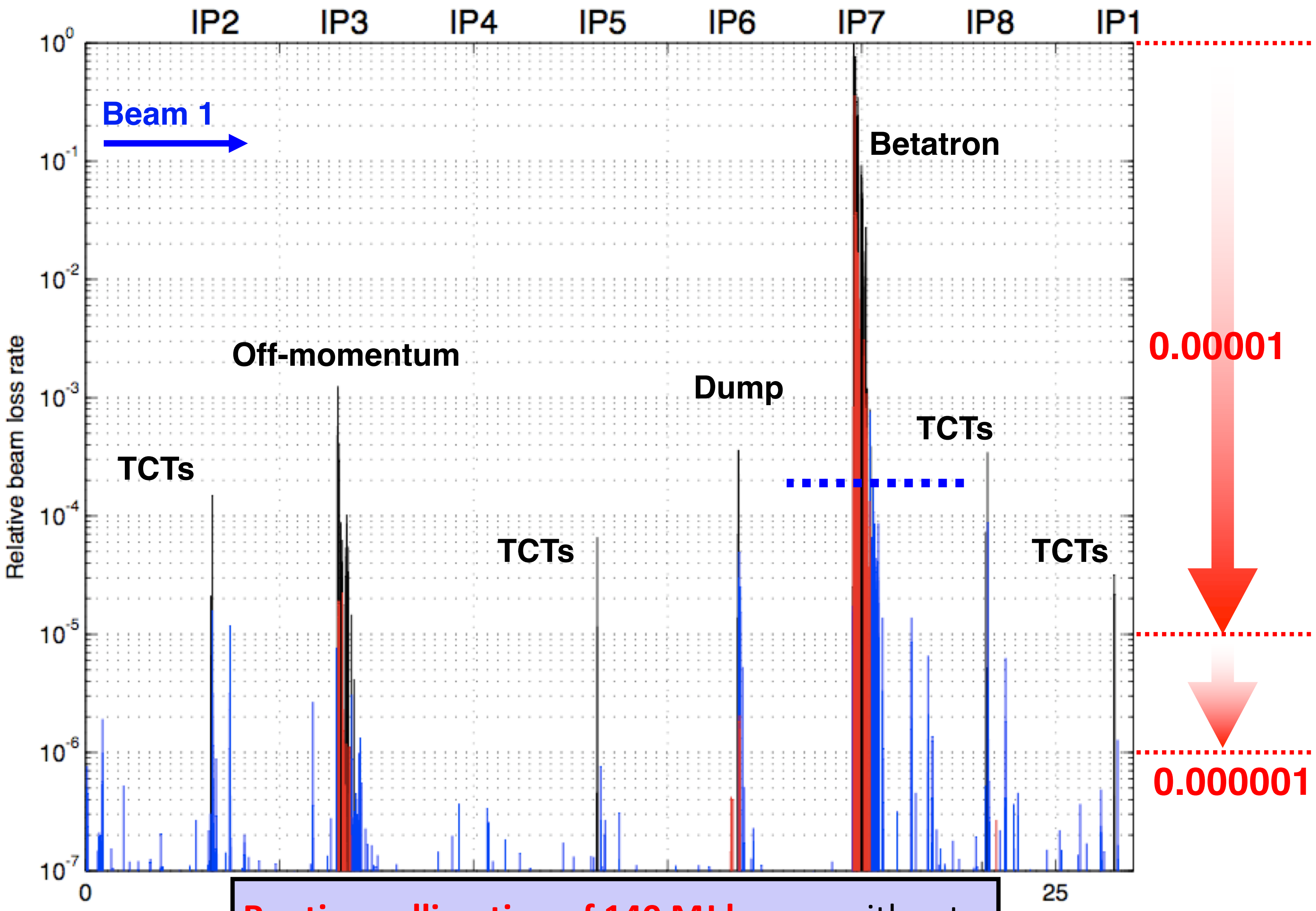
4.14	TCLA.7R3.B1	-4.11
	IP5	
5.2	TCTH.4L5.B1	-14.32
7.04	TCTVA.4L5.B1	-5.4
3.6	TCL.5R5.B1	-3.58
	IP6	
4.35	TCDQA.A4R6.B1	
4.77	TCSG.4R6.B1	-4.51
	IP7	
1.33	TCP.D6L7.B1	-0.84
1.33	TCP.C6L7.B1	-1.69
0.94	TCP.B6L7.B1	-1.61
1.85	TCSG.A6L7.B1	-2.01
1.92	TCSG.B5L7.B1	-2.66
2.1	TCSG.A5L7.B1	-2.58
1.42	TCSG.D4L7.B1	-1.55
2.98	TCSG.B4L7.B1	-1.29
2.93	TCSG.A4L7.B1	-1.27
2.8	TCSG.A4R7.B1	-1.4
2.78	TCSG.B5R7.B1	-2.02

2.22	TCSG.D5R7.B1	-2.66
2.48	TCSG.E5R7.B1	-2.39
3.08	TCSG.6R7.B1	-3.54
2	TCLA.A6R7.B1	-1.34
2.66	TCLA.B6R7.B1	-3.36
4.37	TCLA.C6R7.B1	-1.5
1.7	TCLA.D6R7.B1	-2.14
1.5	TCLA.A7R7.B1	-2.32
	IP8	
5.24	TCTH.4L8.B1	-5.43
3.3	TCTVB.4L8	-9.28
	TI2	
1.06	TCDIV.20607	-2.72
4.45	TCDIV.29012	-0.48
3.49	TCDIH.29050	-4.35
2.55	TCDIH.29205	-2.44
5.69	TCDIV.29234	-0.53
3.49	TCDIH.29465	-2.34
9.44	TCDIV.29509	-3.7

BETATRON_HOR | BETATRON_VER | OFFMOMENTUM_POS_DP | OFFMOMENTUM_NEG_DP

Collimation

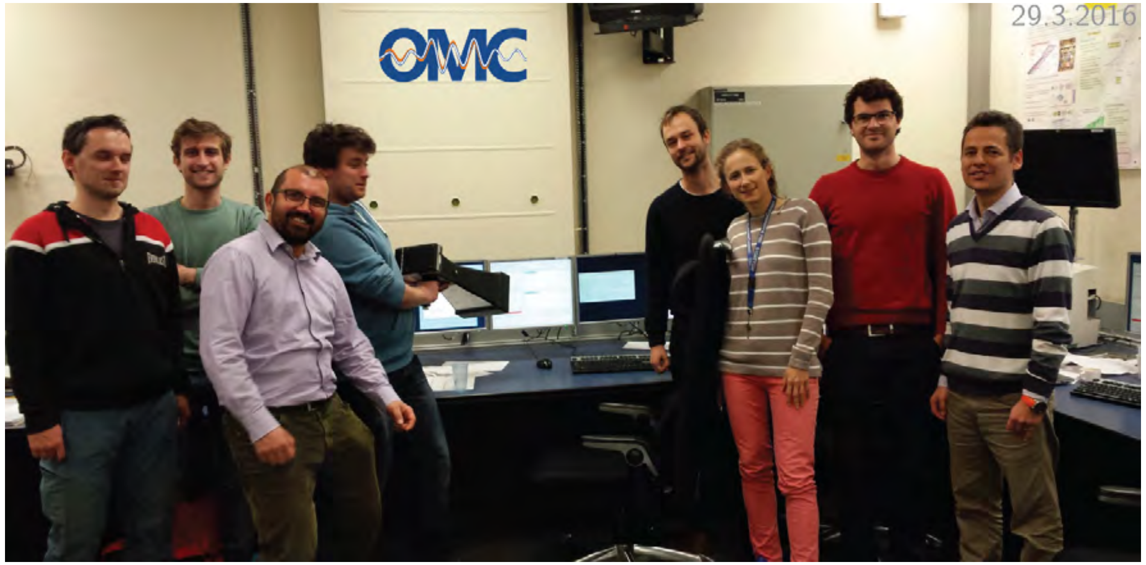
Generate higher loss rates: excite beam with transverse dampers



Legend:
Collimators
Cold losses
Warm losses

Routine collimation of 140 MJ beams without a single quench from stored beam

Stefano Redaelli

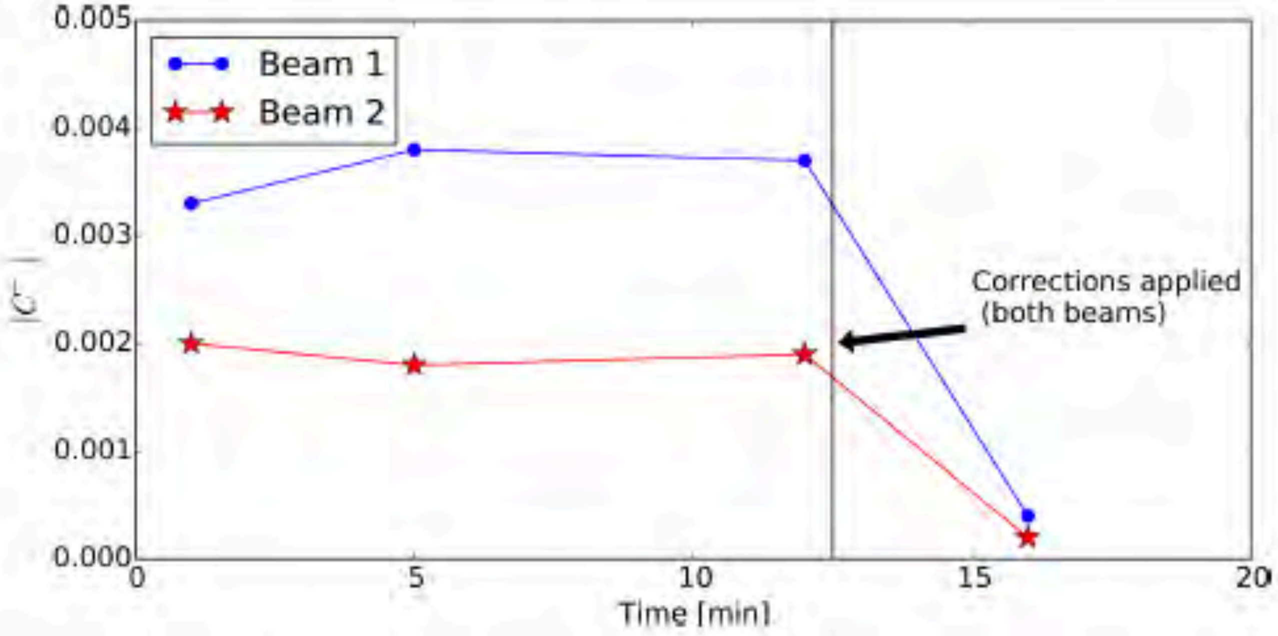


Optics Measurement and Correction (OMC) owls

ADT can now drive forced oscillations of individual bunches

→ ADT-AC dipole!

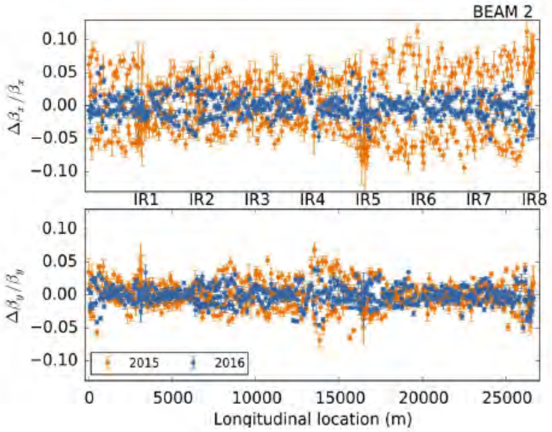
- Used in regular operation → **overcome limit of regular AC-dipole**
- Obtain spectral data all around ring → **overcome limit of BBQ**
- **Automated OMC methods used to provide online correction for $\Re$e and $\Im$m parts of coupling**



Exquisite knowledge of the machine++

Final Corrections

IP	β_{IP} [m]	β_{IP} err [m]	Waist [m]	waist err [m]
ip1b1.X	0.398	0.007	0.047	0.009
ip1b1.Y	0.401	0.002	-0.009	0.009
ip1b2.X	0.398	0.001	0.009	0.011
ip1b2.Y	0.402	0.001	0.072	0.010
ip5b1.X	0.399	0.003	-0.009	0.008
ip5b1.Y	0.400	0.001	-0.028	0.010
ip5b2.X	0.395	0.003	0.070	0.013
ip5b2.Y	0.396	0.004	-0.025	0.011
Average	**0.403**	**0.003**	**0.016**	**0.010**
RMS β-beat in IP %	**1%**			



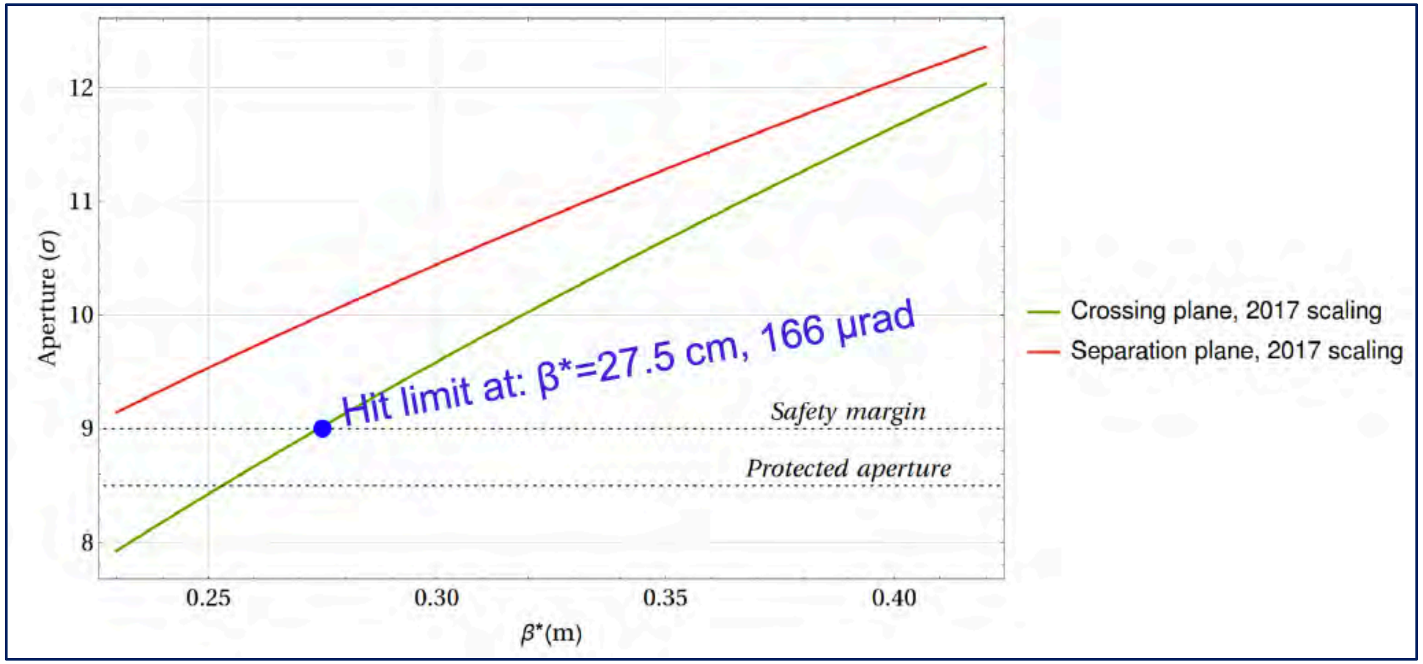
Lowest β-beat in the LHC so far!

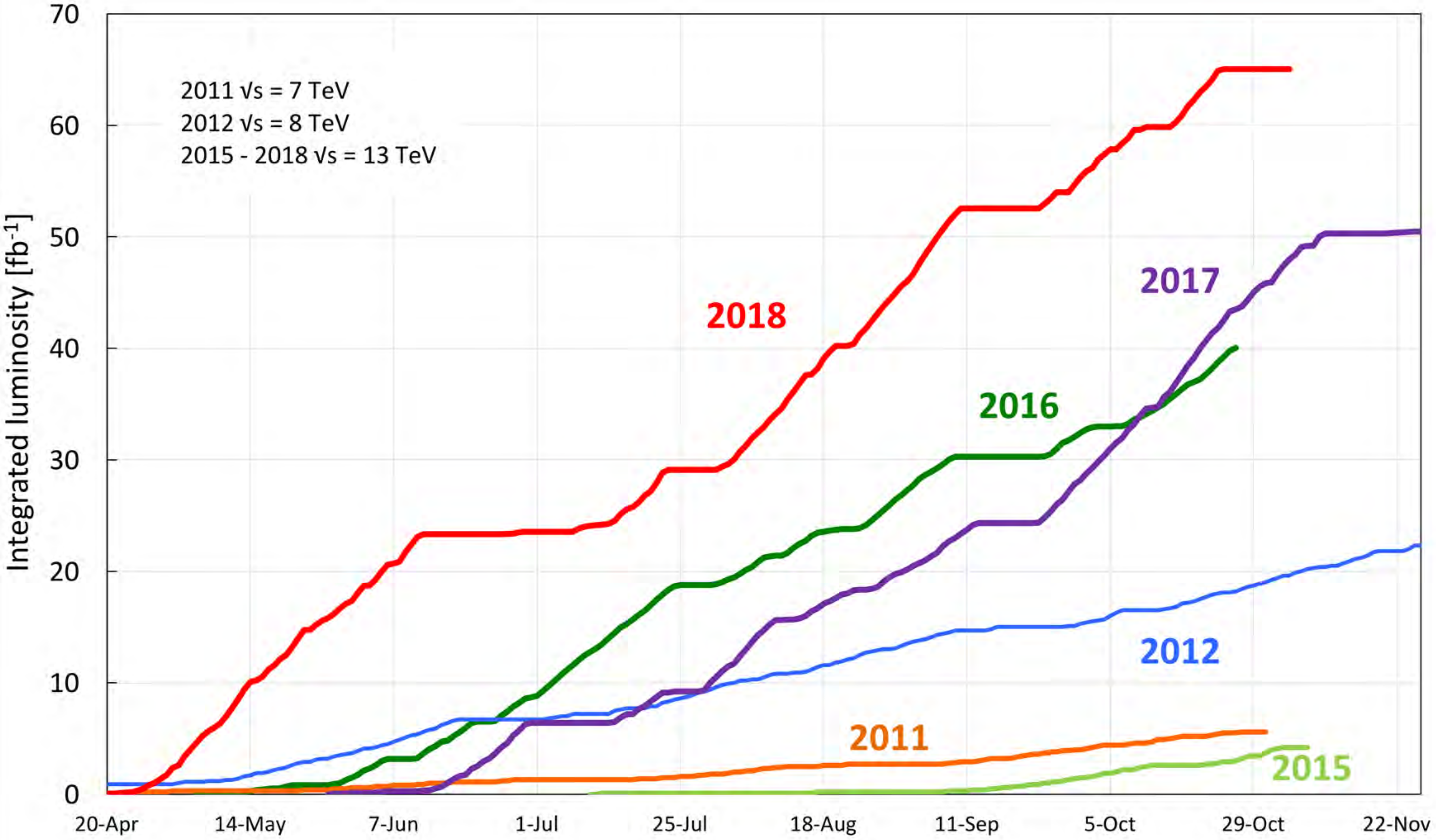
- The new approach using k-mod as input for corrections resulted in:
  - **Smallest β-beat ever achieved in LHC**
  - **1% RMS β-beat at the IP1 and IP5 (without crossing angles)**
- Coupling corrected to ≈ $2*10^{-4}$ in MD

Beta* Use Case

- Characterization of collimation system hierarchy, cleaning efficiency, validation via loss maps etc.
- Semi-automatic collimator set-up (using ML techniques)
- Accurate aperture measurements
- Optics commissioning
  - beating measurement and correction++

Opened the way to full and safe exploitation of the machine…





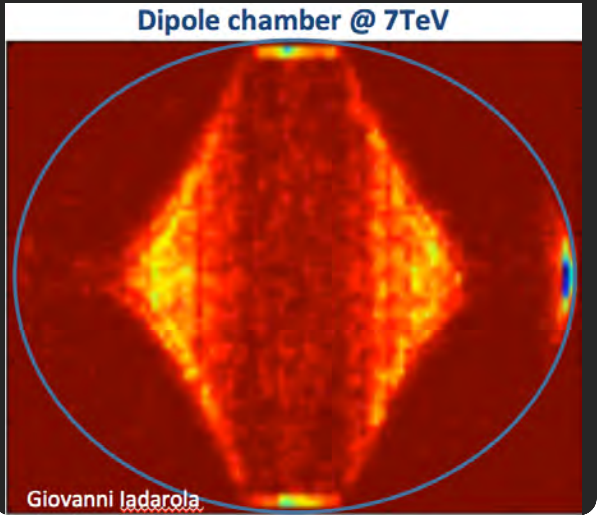
2011 √s = 7 TeV
2012 √s = 8 TeV
2015 - 2018 √s = 13 TeV
Integrated luminosity [fb-1]
2018
2017
2016
2012
2011
2015
70
60
50
40
30
20
10
0
20-Apr
14-May
7-Jun
1-Jul
25-Jul
18-Aug
11-Sep
5-Oct
29-Oct
22-Nov

It’s not what happens – it how you react.

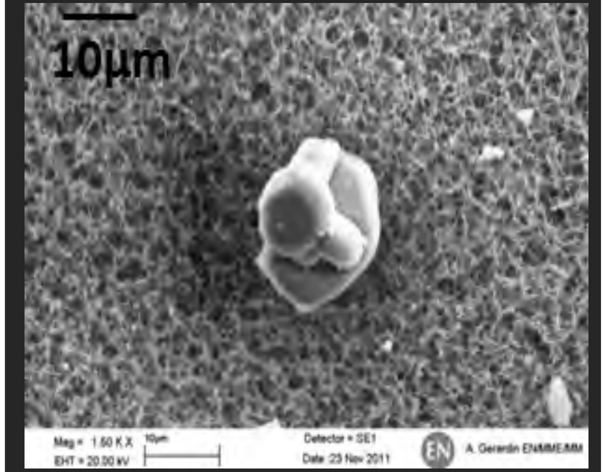
STUFF HAPPENS

2015: re-commissioning after LS1

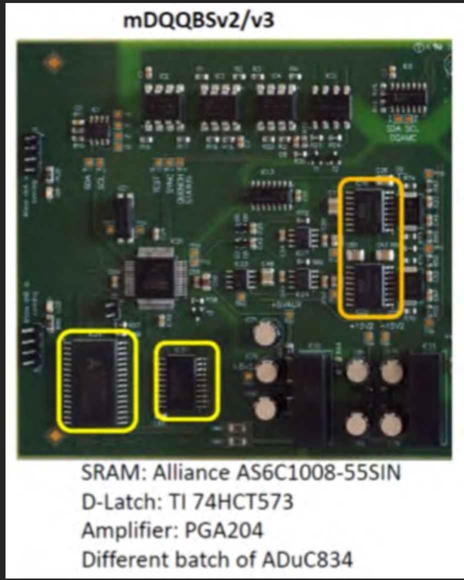
Electron cloud
- Anticipated
- Significant head load to cryogenics
- Very slow reduction despite significant dose



UFOs
- 8 UFO dumps within 2 weeks (Sep 20 to Oct 5)
- Conditioning observed



Radiation to electronics
- Mitigation measures (shielding, relocation…)
- Non-rad hard components used in LS1 upgrade



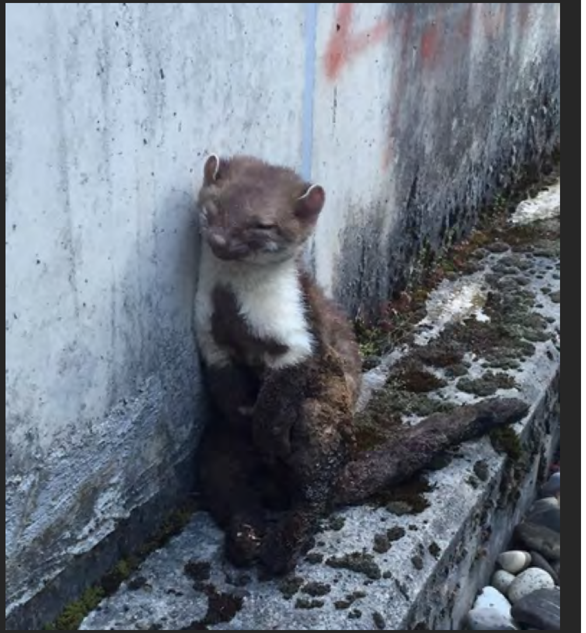
Unidentified lying objects

E-cloud…

1. **Preparation**: tools, monitoring, simulations, understanding, beams (vacuum, cryogenics, RF, injectors, ABP, OP)
2. **Scrubbing** - execution
3. **Exploitation** given the limits (heat-load, instabilities…)

Problems, problems, problems…

WEASELS



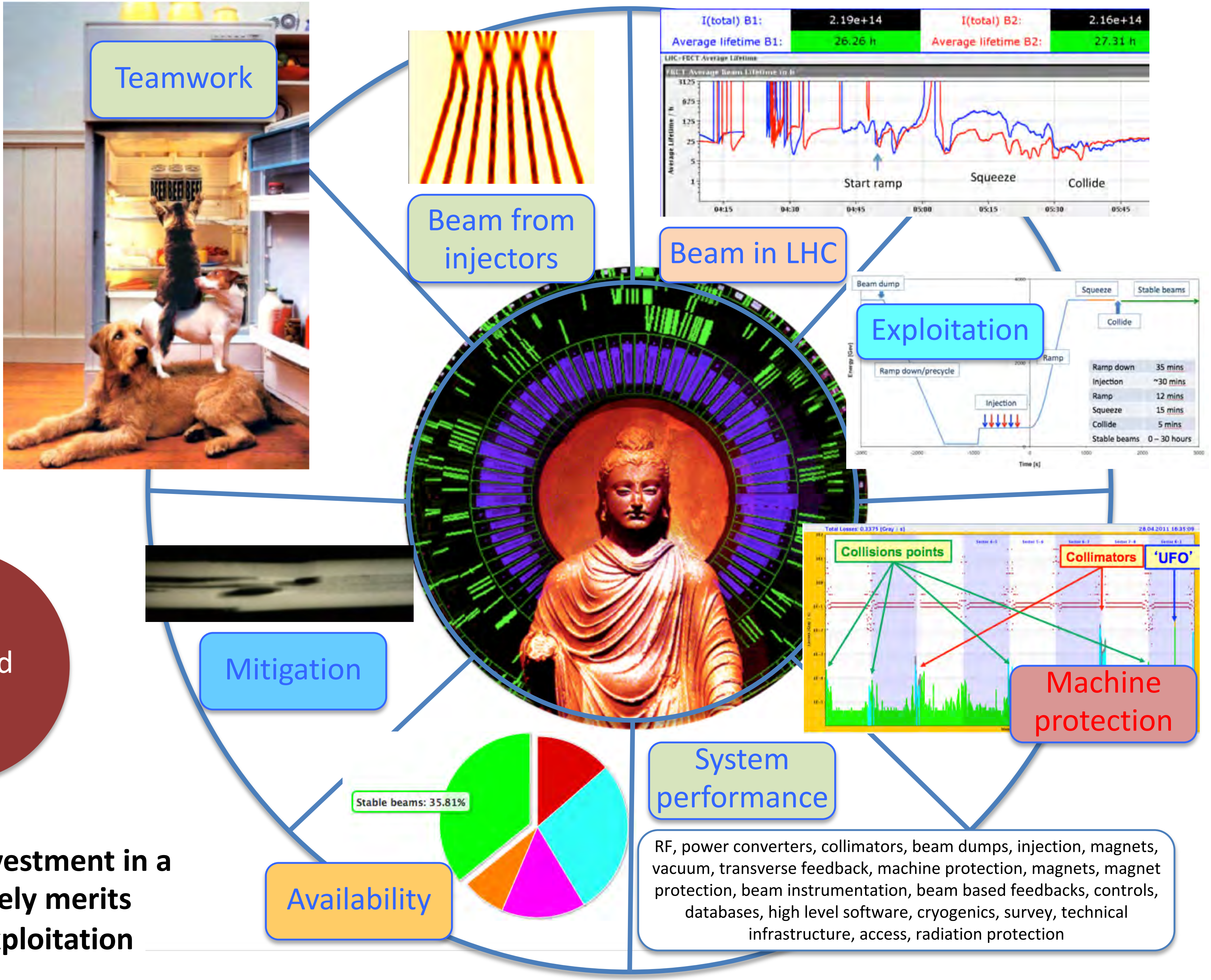
PS MAIN POWER SUPPLY

SPS BEAM DUMP

- **Limited to 96 bunches per injection**
- **2220 bunches per beam cf. 2750**

Heaven and high water is moved in response

LHC Eightfold Path



The capital investment in a collider surely merits effective exploitation

First beam at 6.5 TeV - 1 o’clock in the morning

First Stable Beams at 6.5 TeV – office hours