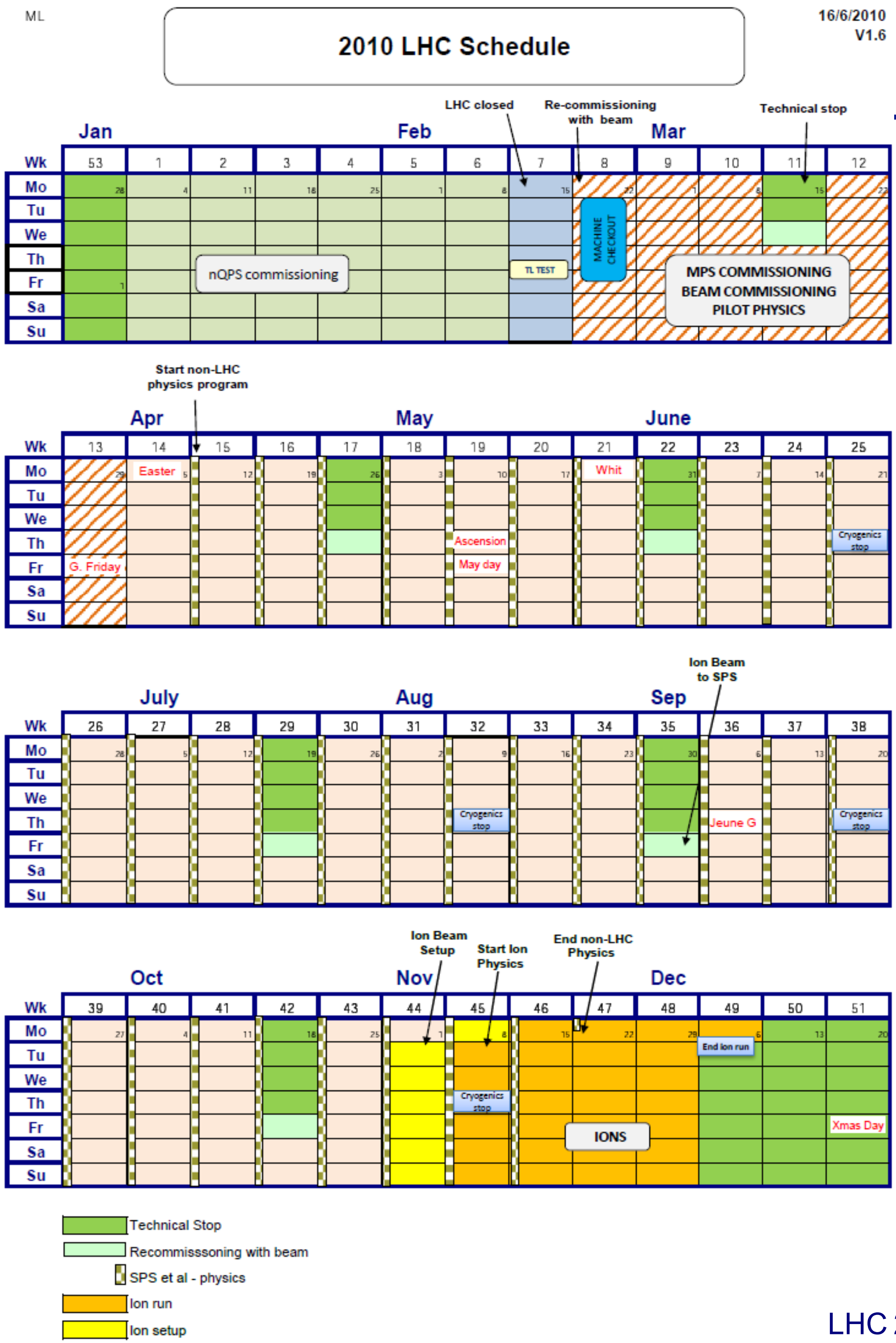
Status of the LHC

Mike Lamont
for the LHC team

COMMISSIONING PROGRESS

2010



Hardware commissioning for 3.5 TeV

Ramp beams to 3.5 TeV

Machine protection systems qualified

Colliding safe stable beams (2 on 2 pilots)

Squeeze to 2m

Low bunch currents, increase k_b

Machine protection systems qualified

13 on 13 low intensity bunches at 2m

High bunch currents, low k_b

Increase k_b

Machine protection systems qualified

50 on 50 high intensity bunches at 3.5m (Aug)

Crossing angles on, bunch trains, Increase k_b

Ions (early scheme, max 62 bunches per beam)

Same magnetic machine as for protons

1 week to switch

4 weeks ion run

Milestones - 2010

Date	Achieved	
Feb 28	Restart with beam.	
Mar 30	First collisions at 7 TeV centre of mass.	Luminosity ~ 2 10^{27} cm^{-2} s^{-1}
Apr 01	Start squeeze commissioning.	Regular physics runs 2 on 2 bunches of 10^{10} Un-squeezed 1 colliding pairs per experiment Rates around 100Hz
Apr 07	Squeeze to 2 m in points 1 and 5.	
Apr 09	Single nominal bunch of 1.1 1011 stable at 450GeV.	
Apr 13	Squeeze to 2 m in point 8.	
Apr 16	Squeeze to 2m in point 2.	
April 24	First stable beams at 7 TeV, 3 on 3, squeeze to 2m.	Luminosity ~ 2 $10^{28}$$cm^{-2}$ s^{-1}

Milestones reached 2010 (to August)

Date	Achieved	
May	Increase bunch intensity to 2 10^{10}, Increase k_b.	Regular physics runs
May 24	13 on 13, 8 colliding pairs per experiment.	Luminosity ~ 3 10^{29}cm^{-2} s^{-1}
June	Increase bunch intensity to nominal, squeeze to 3.5m.	Machine development
June 25	First stable beams at 7 TeV, 3 on 3 nominal bunch.	Luminosity ~ 5 10^{29}cm^{-2} s^{-1}
July 15	13 on 13, 8 colliding pairs, 9 10^{10} / b	Luminosity ~ 1.5 10^{30}cm^{-2} s^{-1}
July 30	25 on 25, 16 colliding pairs, 9 10^{10} / b	Luminosity ~ 3 10^{30}cm^{-2} s^{-1}
Aug 19	48 on 48, 36 colliding pairs 1 5 and 8, 9 10^{10} / b	Luminosity ~ 6 10^{30}cm^{-2} s^{-1}
Aug	Stable running period to consolidate operation and MP 50x50, 11 10^{10} / b	~2-3 MJ per beam Luminosity ~ 1 10^{31}cm^{-2} s^{-1}

Commissioning recap

- Magnetically and optically well understood
  - Excellent agreement with model and machine
- Magnetically reproducible
  - Important because it means optics and thus set-up remains valid from fill to fill
- Aperture clear and as expected
- Excellent performance from instrumentation and controls
  - Still ironing out features
- Key systems performing well
  - Injection
  - Beam dump
  - Collimation
  - Machine protection

Commissioning recap

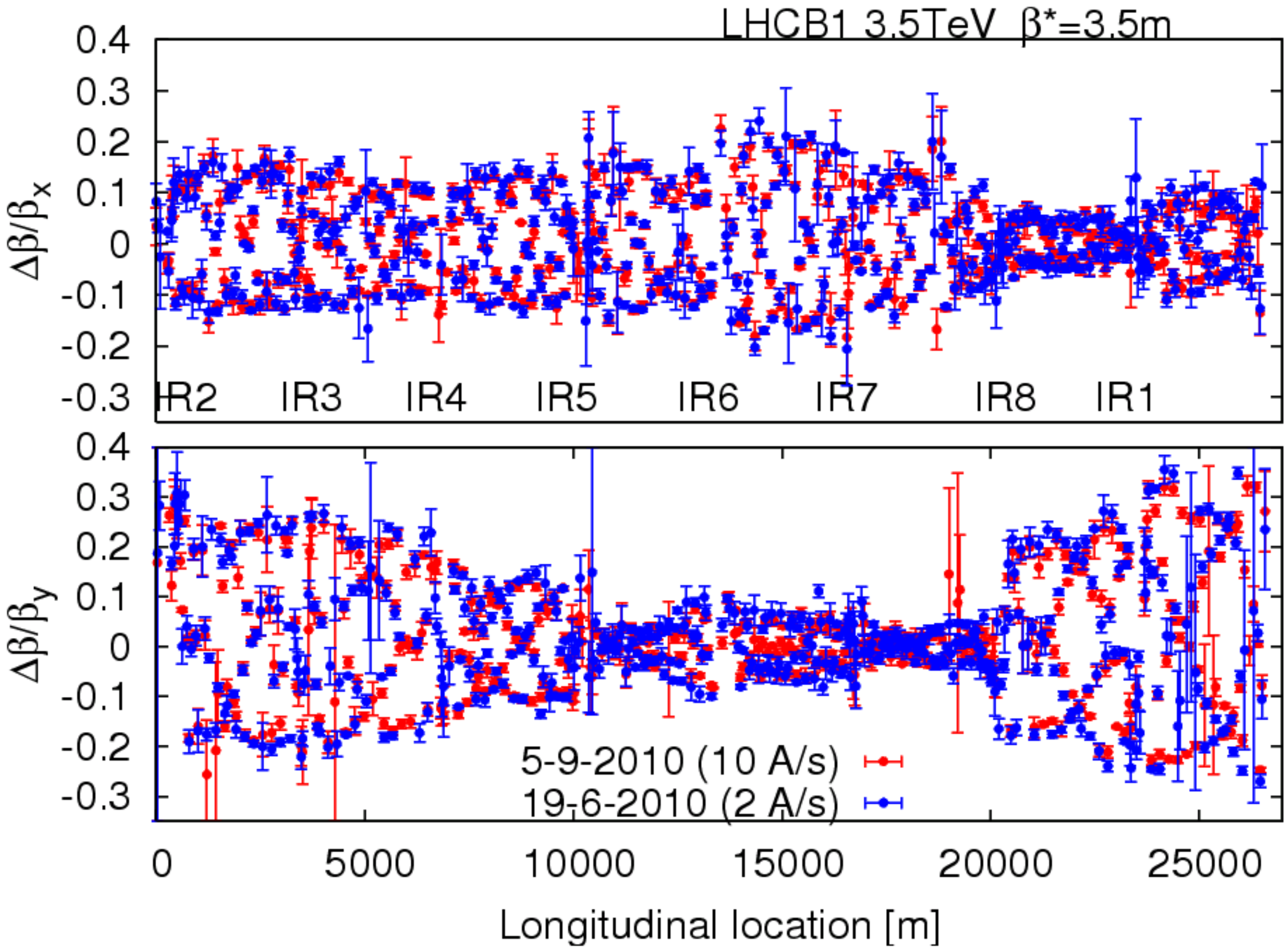
- Routinely over-inject **nominal bunch intensities**
  - Up to September 4 bunches per injection
  - September – switch to 150 ns bunch trains
- Ramp to 3.5 TeV, squeeze, bring them into collisions and deliver stable beams.
- Keep them there
- And do it again

A remarkably successful initial commissioning period

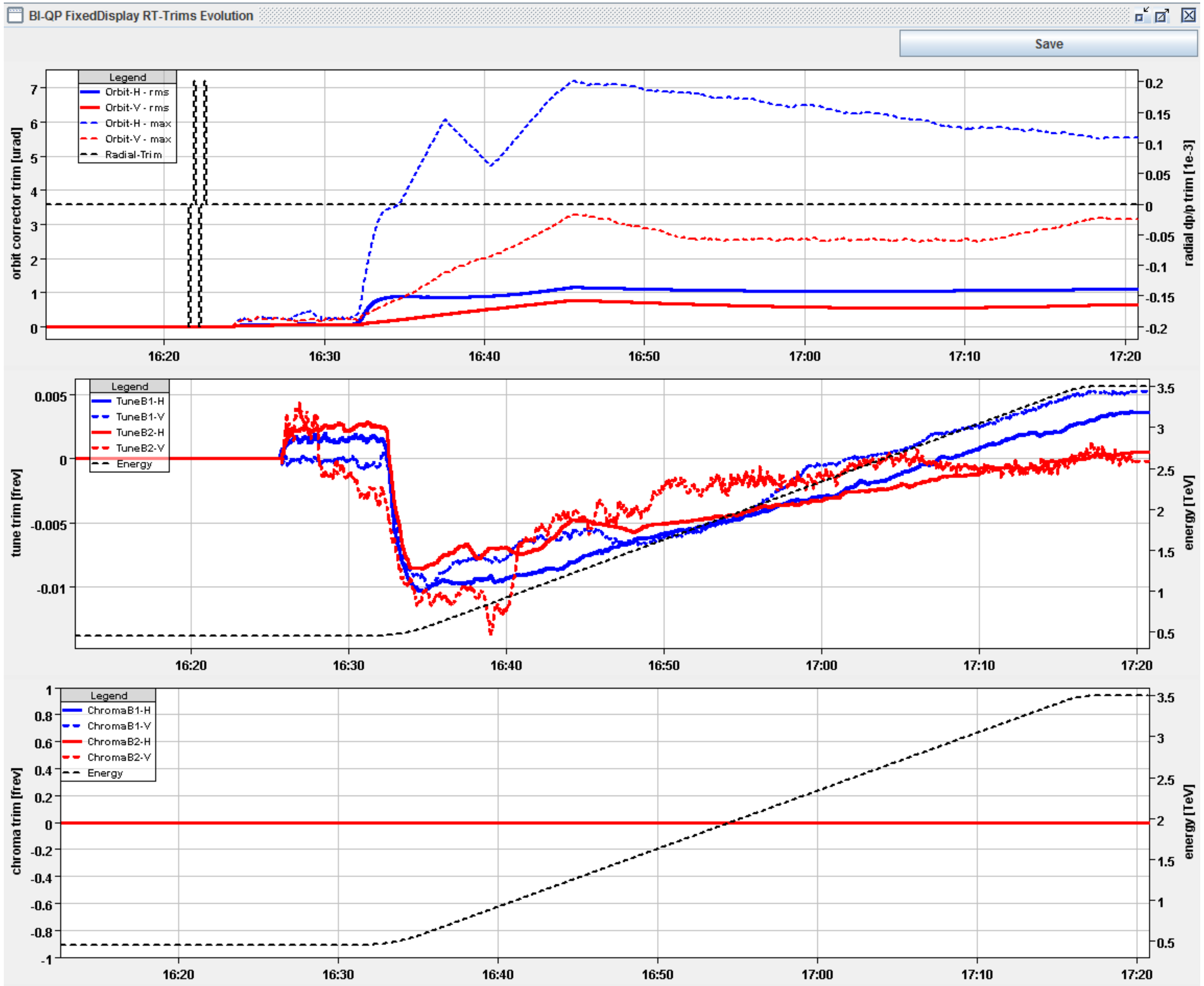
which is still ongoing… [NB]

Optics

- Stunningly stable



FBs in action : ramp



Fill 1309

29.08.2010

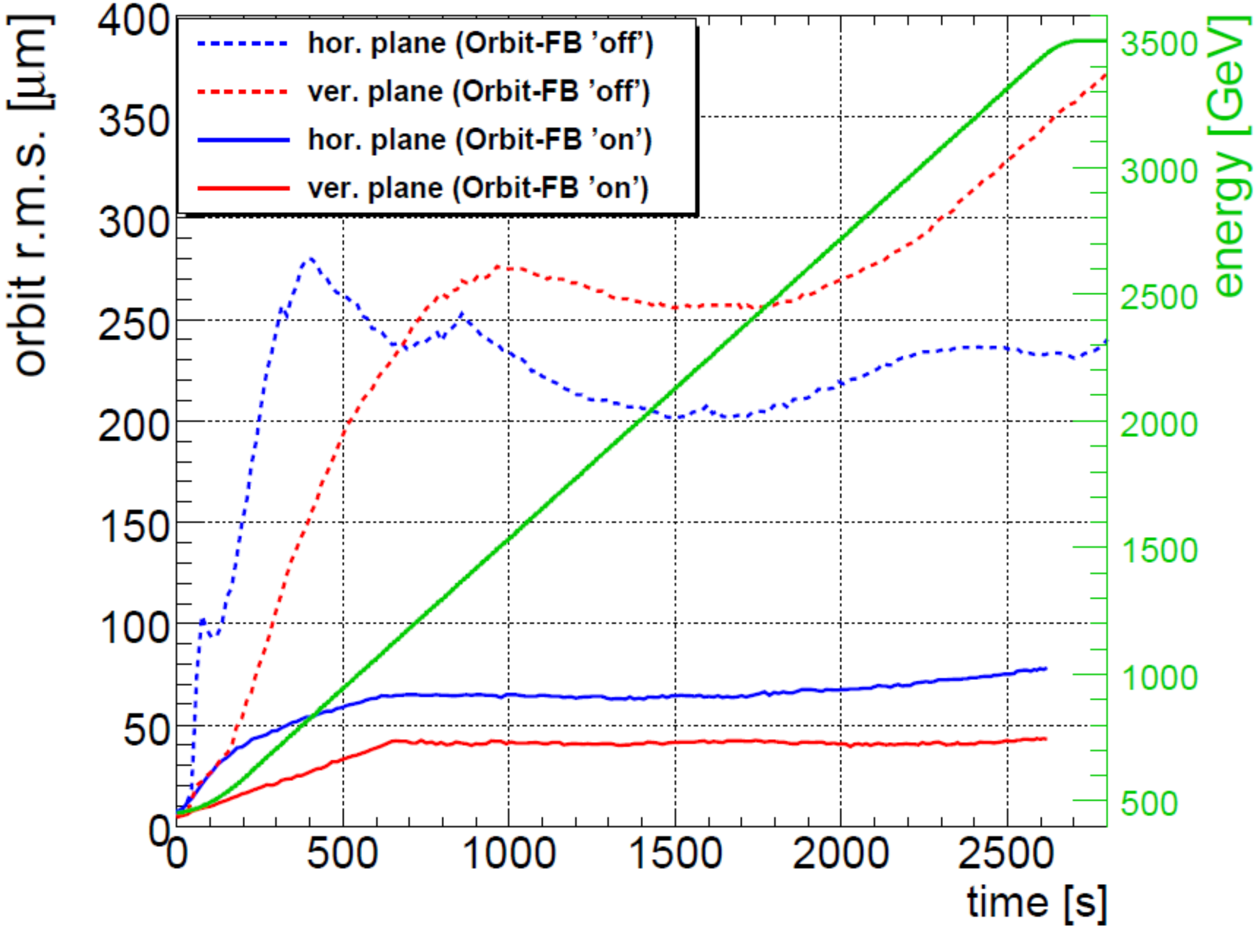
OFB trims (μrad)

QFB trims

Energy (TeV)

OFB performance : ramp

Orbit stability in the ramp: ≤ 80 μm rms



R. Steinhagen

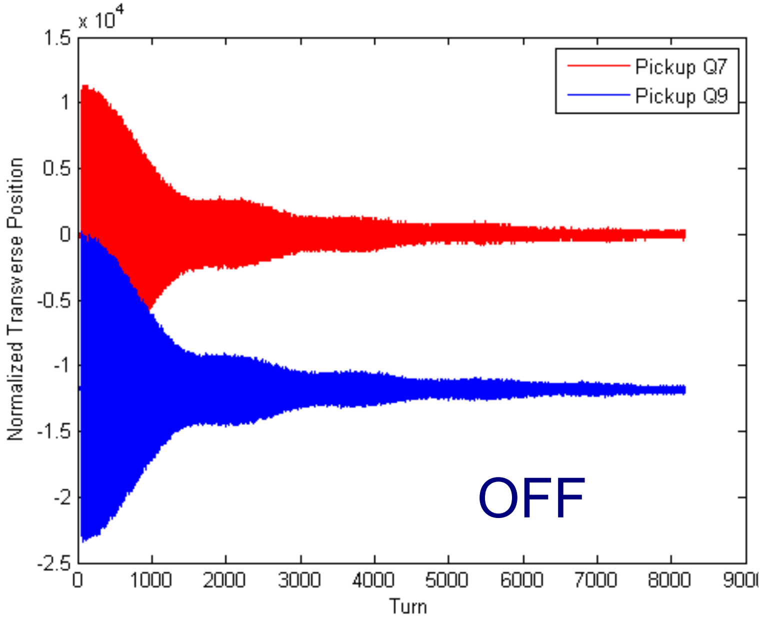
LHC and Feedbacks

- ❑ The performance of the FBs is good
- ❑ The LHC only operates reliably with both orbit and tune FBs (ramp and squeeze).
  - ○ Ramp and squeeze essentially without losses !!!!

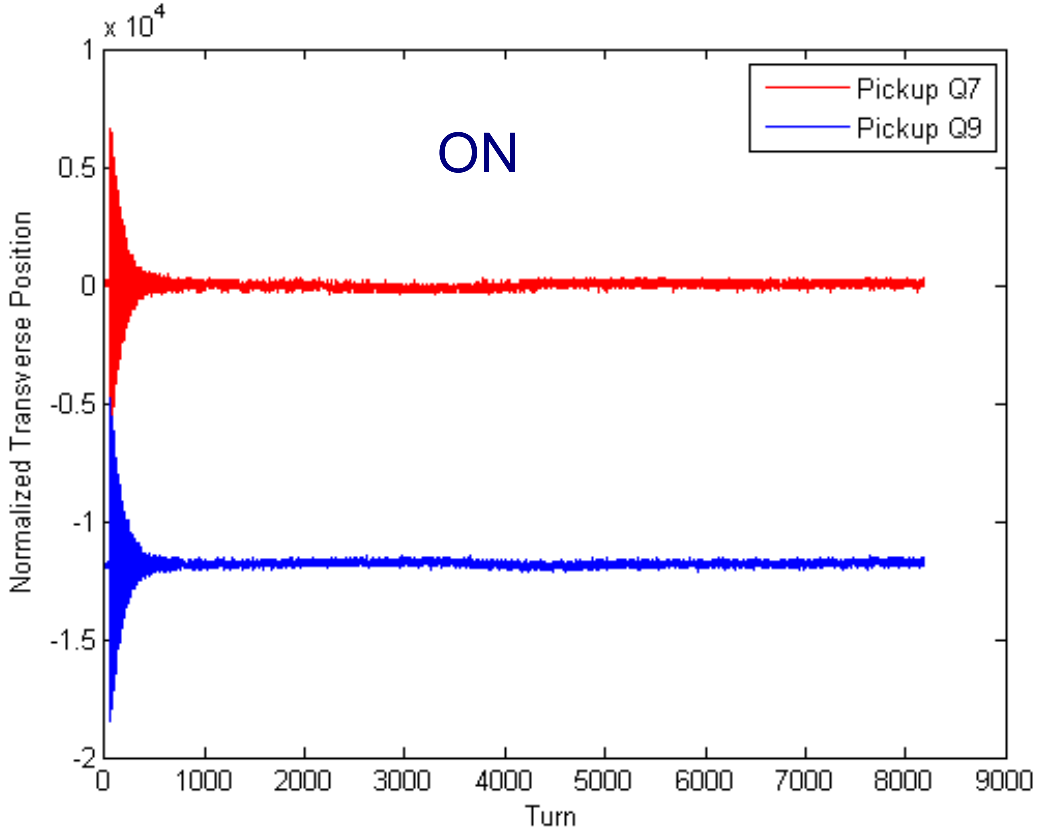
Fill 1308

28.08.2010

Transverse dampers



Crucial to keep emittance growth under control



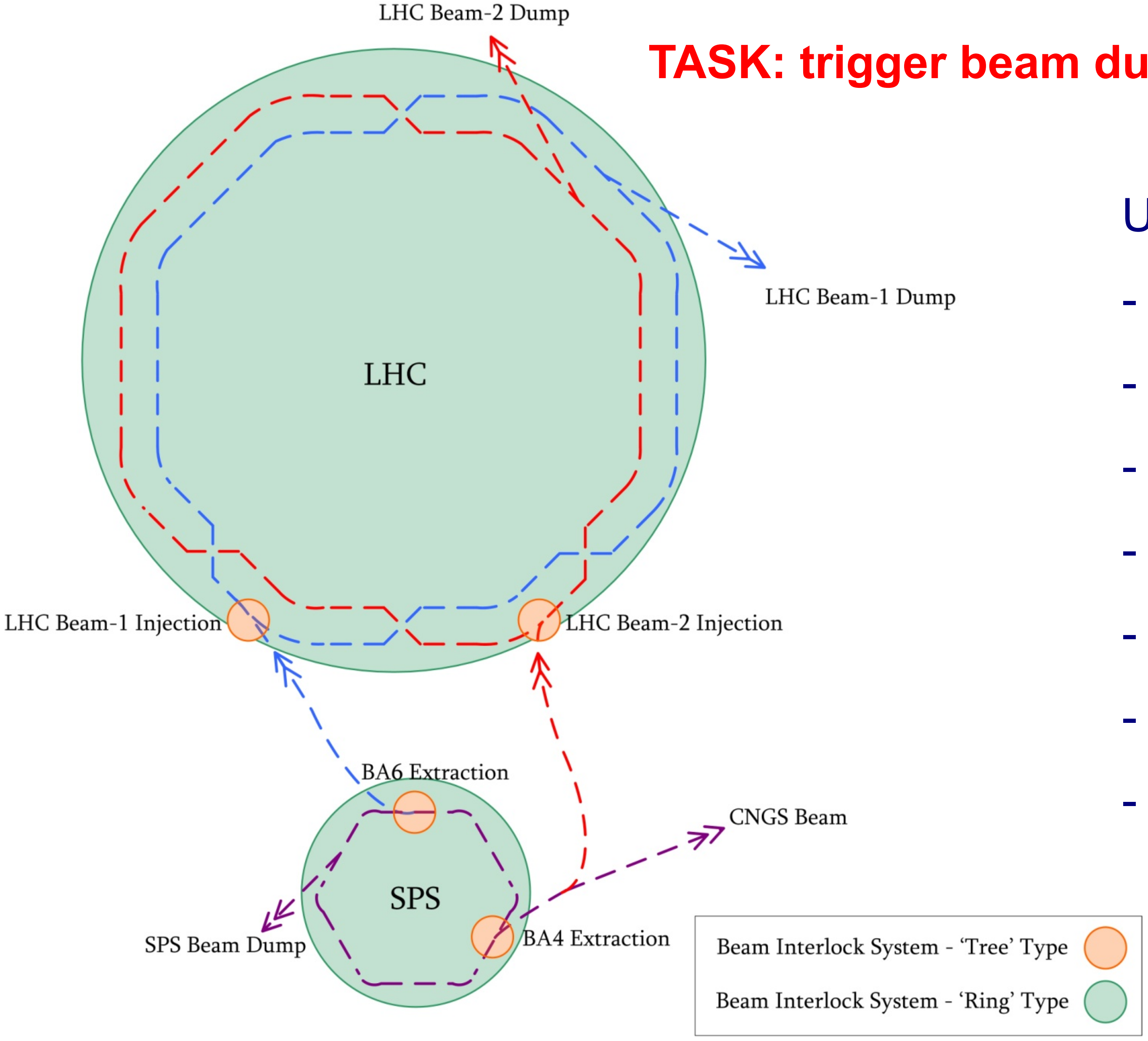
Already operational through the cycle – including stable beams

Briefly, 5 important machine things
or why we can't deliver 1e32 $cm^{-2}s^{-1}$ immediately

BEAM SAFETY

This might seem academic but it is what dominates commissioning and operations at present

Beam Interlock System

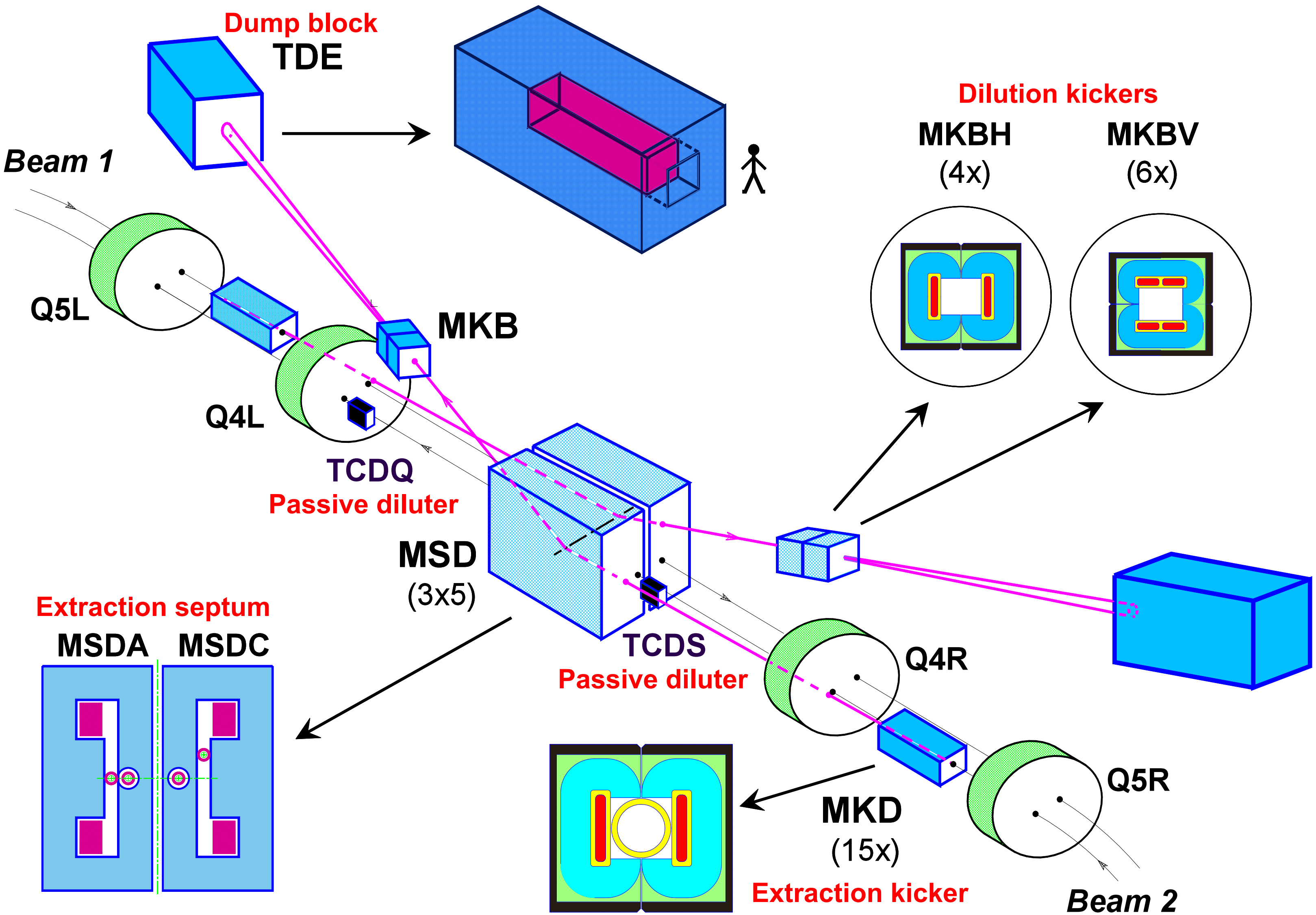


TASK: trigger beam dump within 3 turns

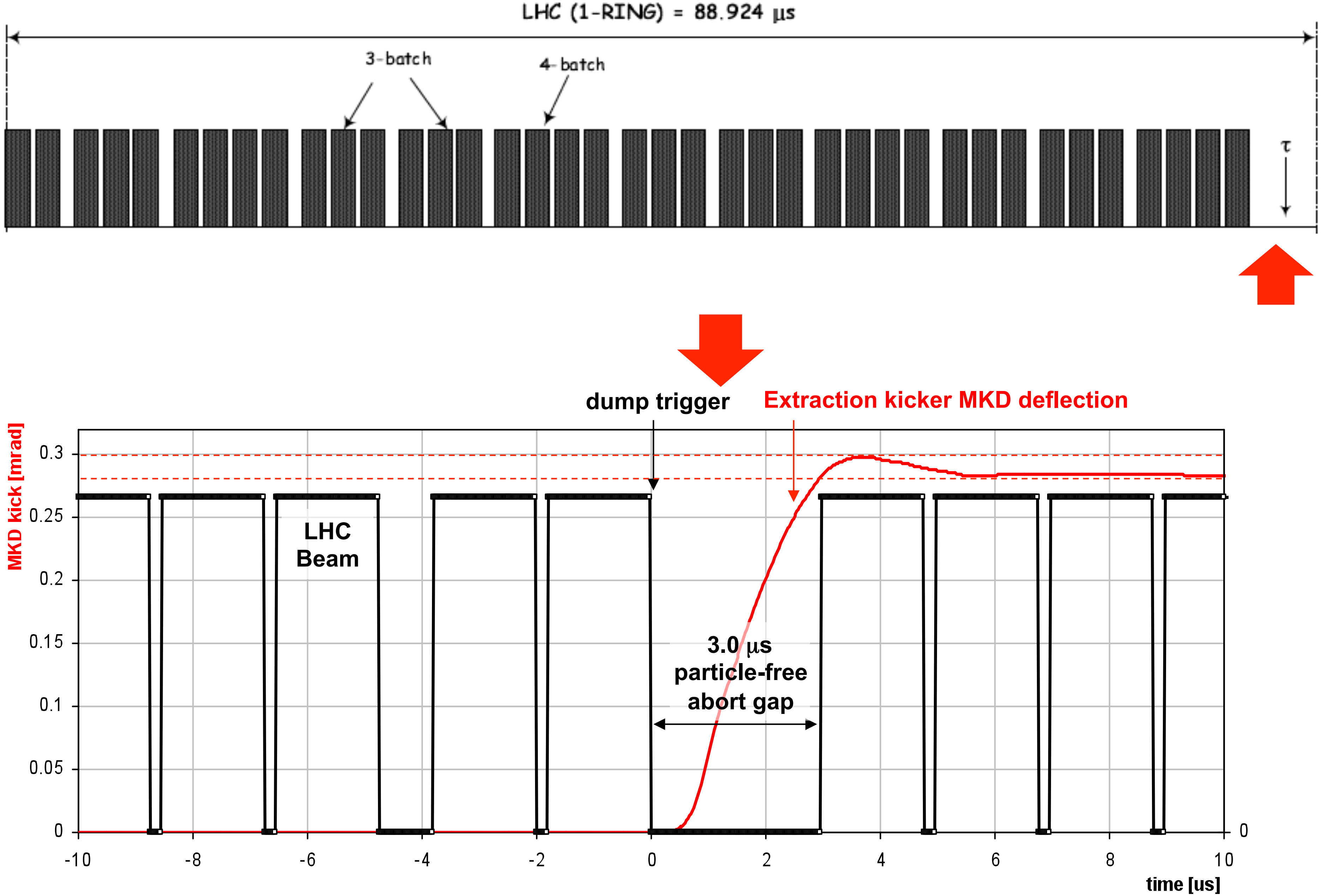
User inputs include:

- Experiments
- Beam Loss Monitors
- Powering
- Fast magnets
- Vacuum
- Beam dump
- OP

The beam dump



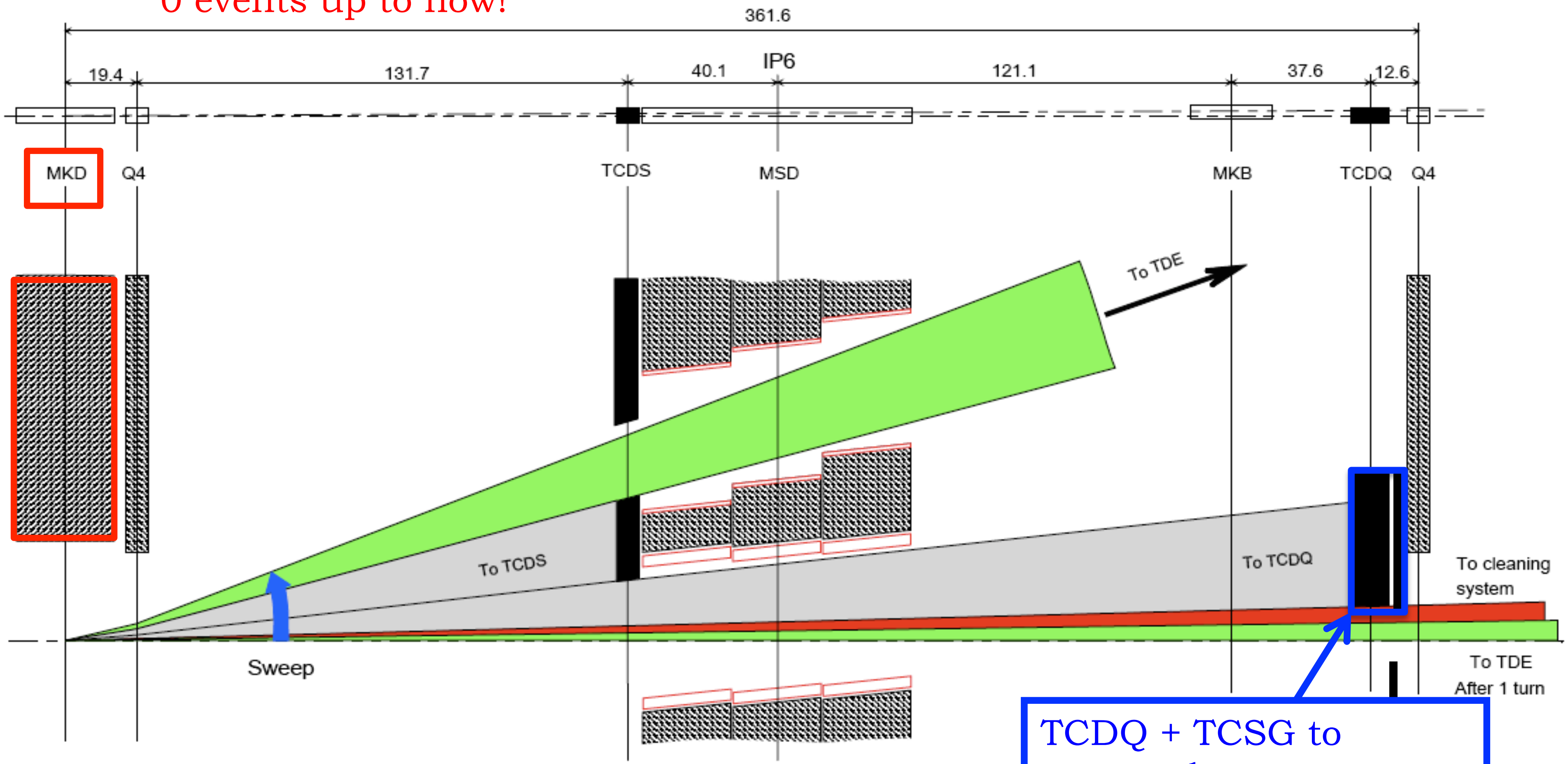
Abort Gap


LHC (1-RING) = 88.924 μs
3-batch
4-batch
τ
dump trigger
Extraction kicker MKD deflection
MKD kick [mrad]
LHC
Beam
3.0 μs
particle-free
abort gap
0.3
0.25
0.2
0.15
0.1
0.05
0
-10
-8
-6
-4
-2
0
2
4
6
8
10
time [us]

Asynchronous Beam Dump

Estimated occurrence : at least once per year,

0 events up to now!



TCDQ + TCSG to protect downstream superconducting magnets (Q4)

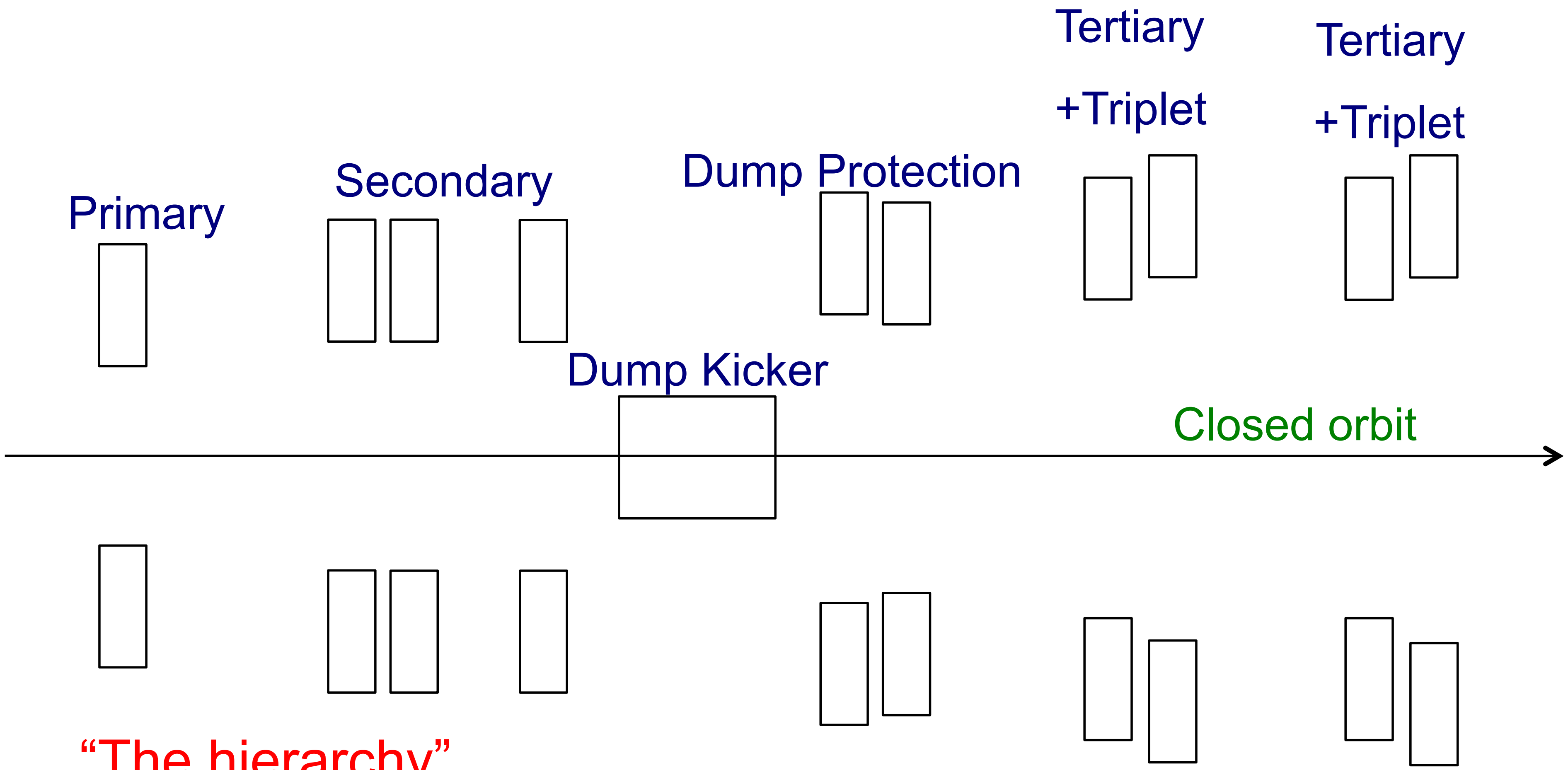
TCDQ = 6 m long CFC* one-sided collimator
TCSG = 1 m long CFC* two-sided collimator

*CFC = carbon fibre compound

Pedagogical collimation 1

Ralph Assmann

- Collimation is set up with multi-stage logic for cleaning and protection
- Let's look in normalized phase space, talking in nominal sigmas:

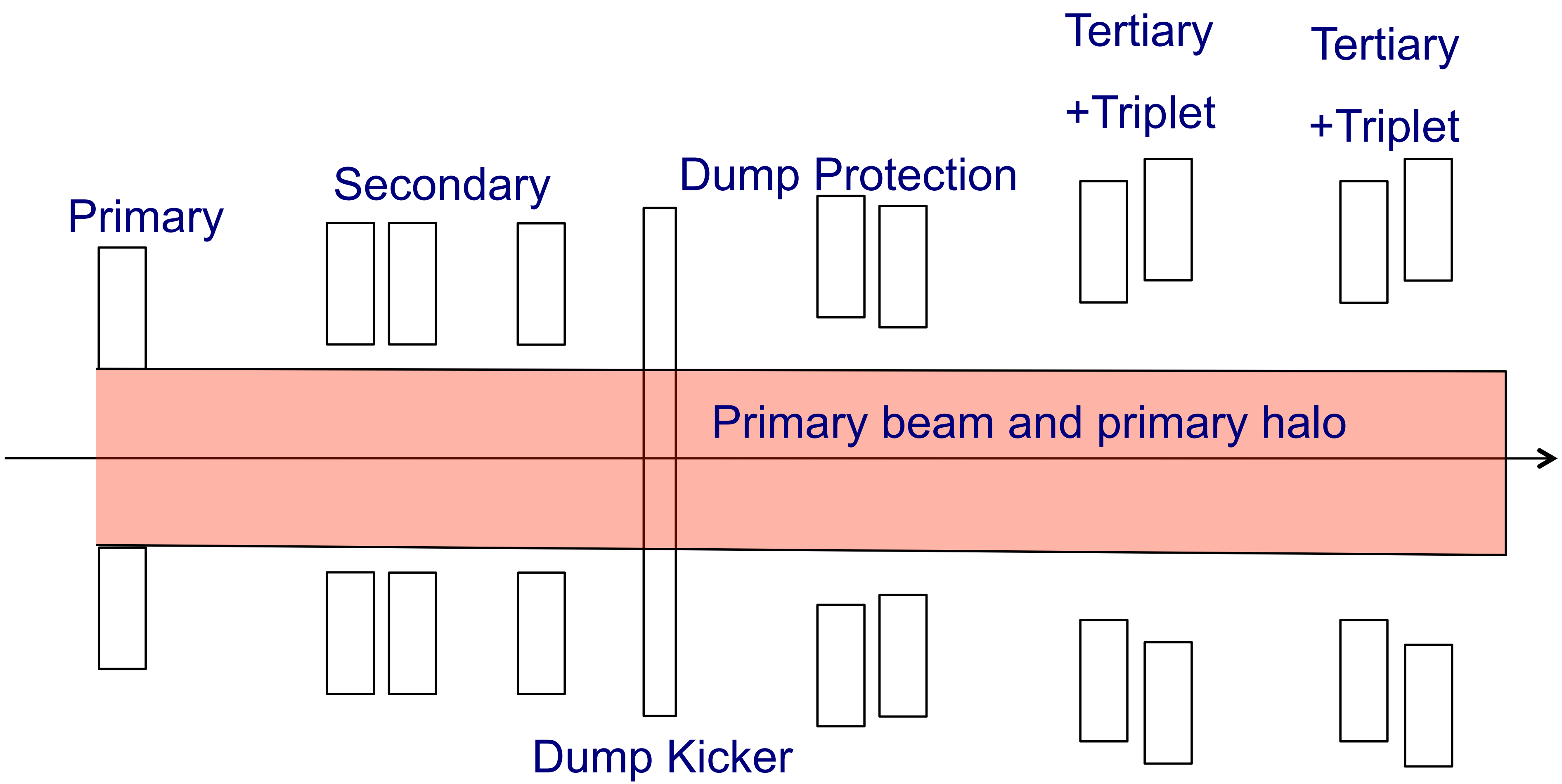


"The hierarchy"

"The jaws of power are always open to devour…"

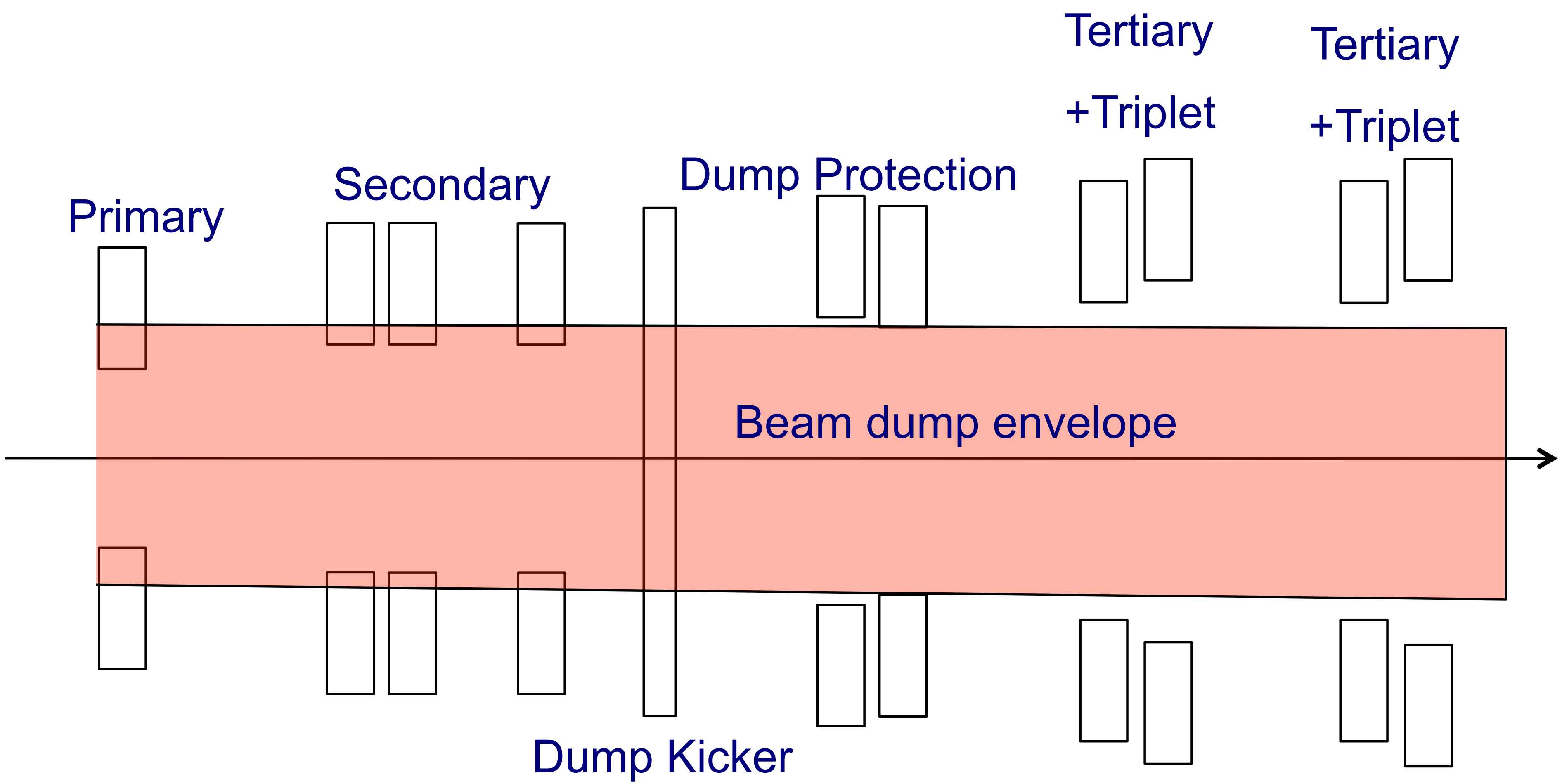
Pedagogical collimation II

- Collimation is set up with multi-stage logic for cleaning and protection
- Let's look in normalized phase space, talking in nominal sigmas:



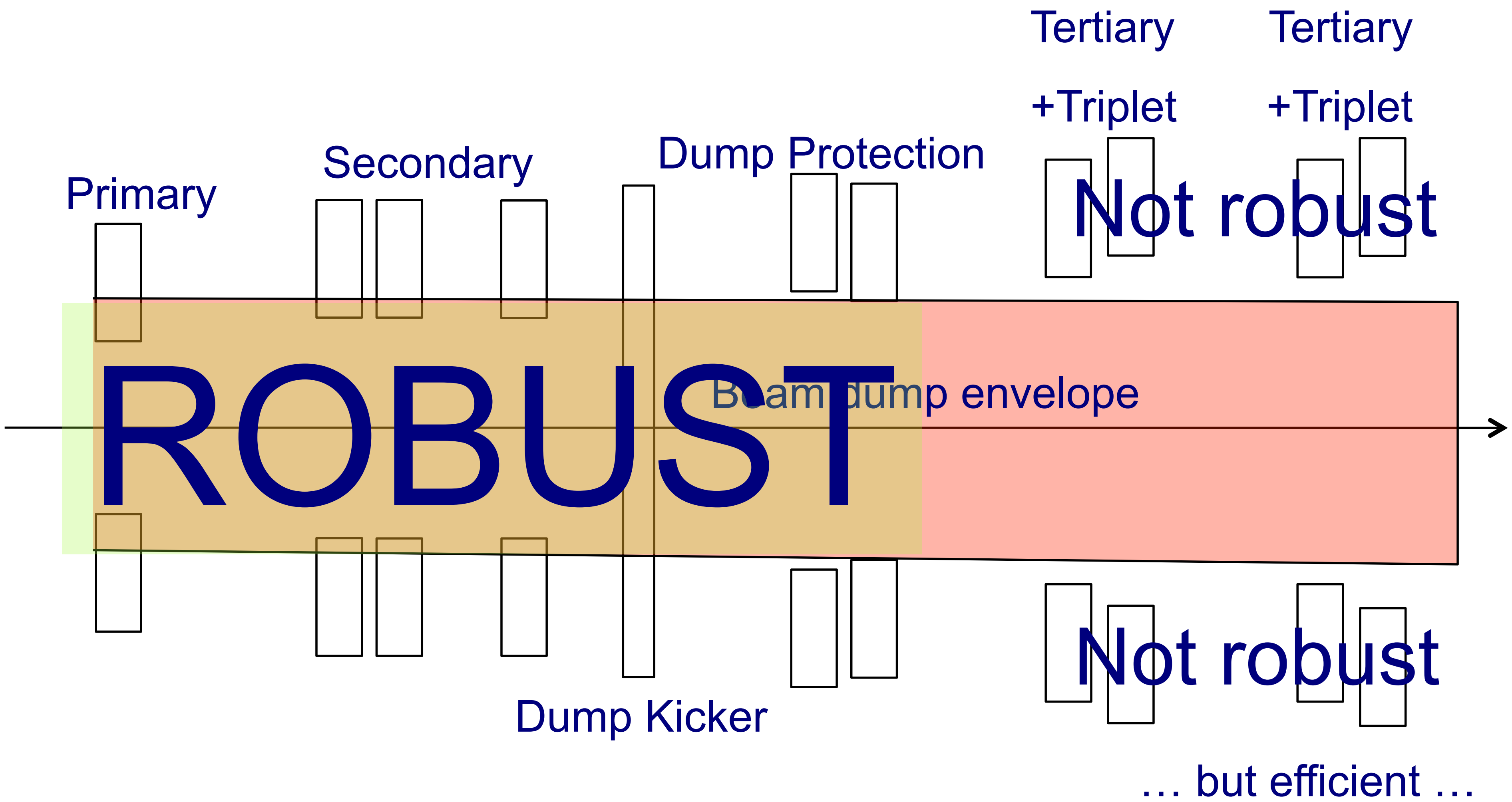
Pedagogical collimation III

- Collimation is set up with multi-stage logic for cleaning and protection
- Let's look in normalized phase space, talking in nominal sigmas:



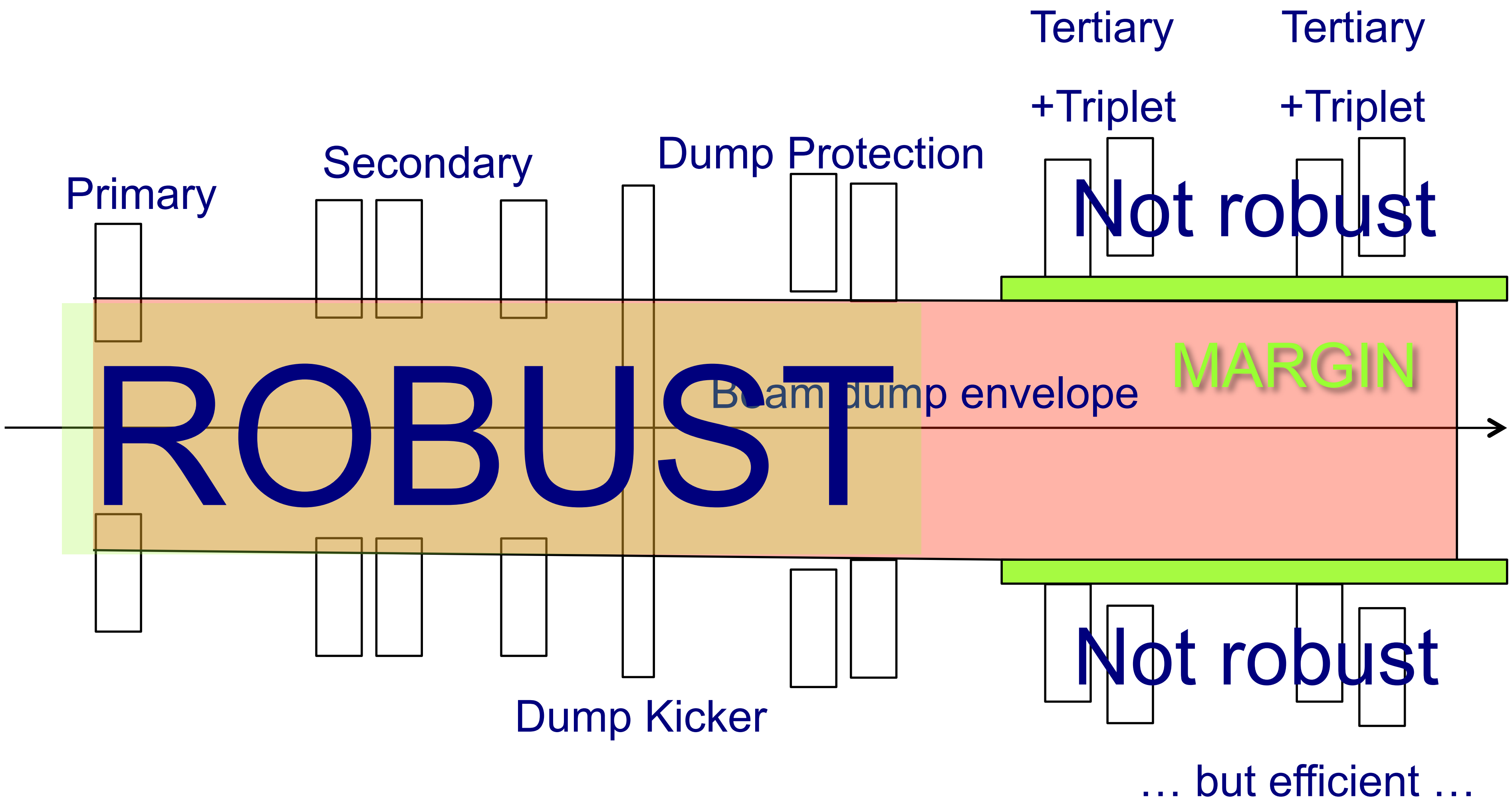
Pedagogical collimation IV

- Collimation is set up with multi-stage logic for cleaning and protection
- Let's look in normalized phase space, talking in nominal sigmas:



Pedagogical collimation V

- Collimation is set up with multi-stage logic for cleaning and protection
- Let's look in normalized phase space, talking in nominal sigmas:

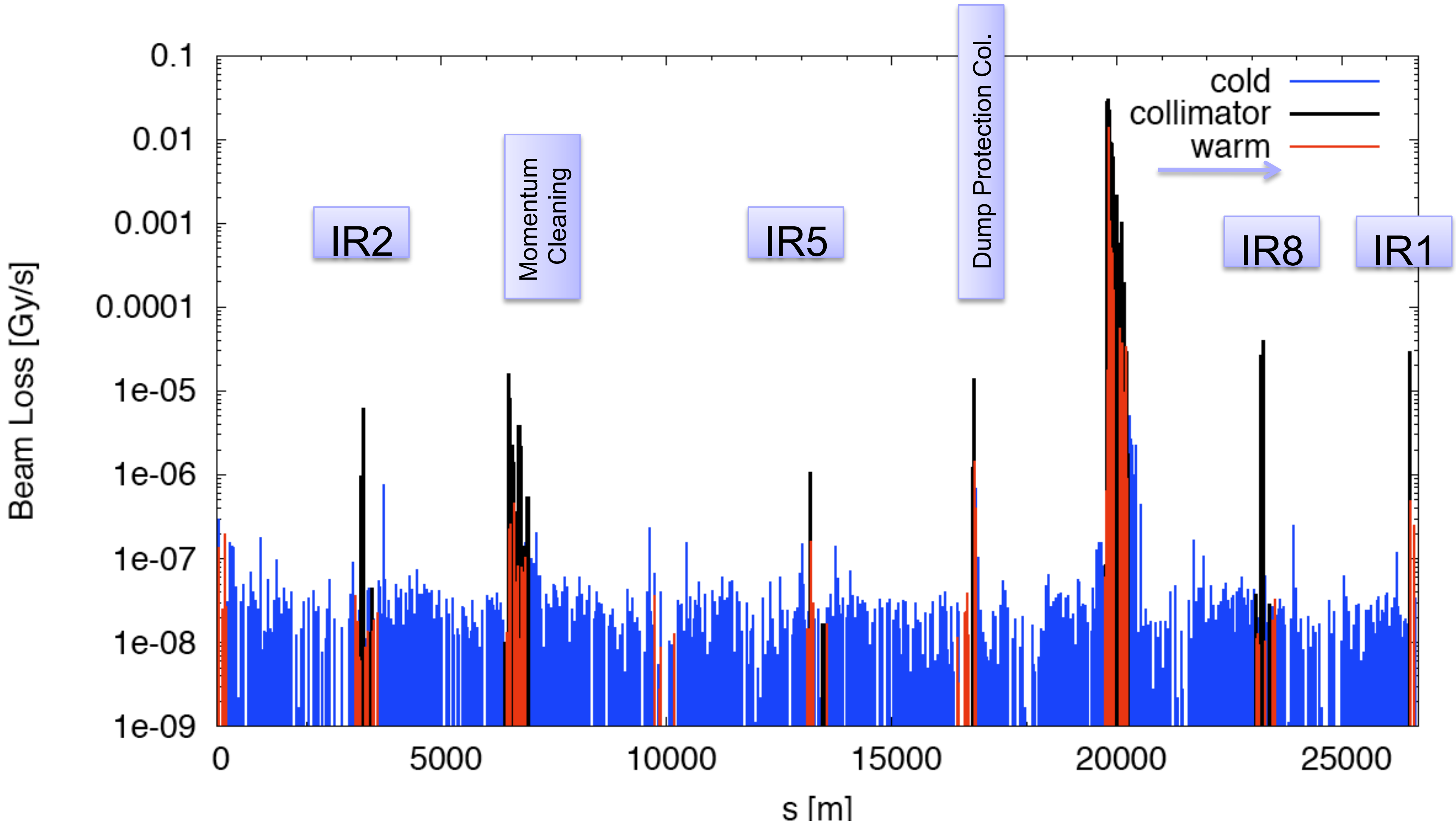


Conclusions from the pedagogical break

- The collimators and protection devices must be in position at all times
- The hierarchy must be respected
- The collimators and protection devices are positioned with respect to the closed orbit
- Therefore the closed orbit must be in tolerance at all times. This includes the ramp and squeeze.
  - Orbit feedback becomes mandatory
  - Interlocks on orbit position become mandatory
- If these rules are not respected something will get broken.
- Frequent validation to make sure that the rules are respected…

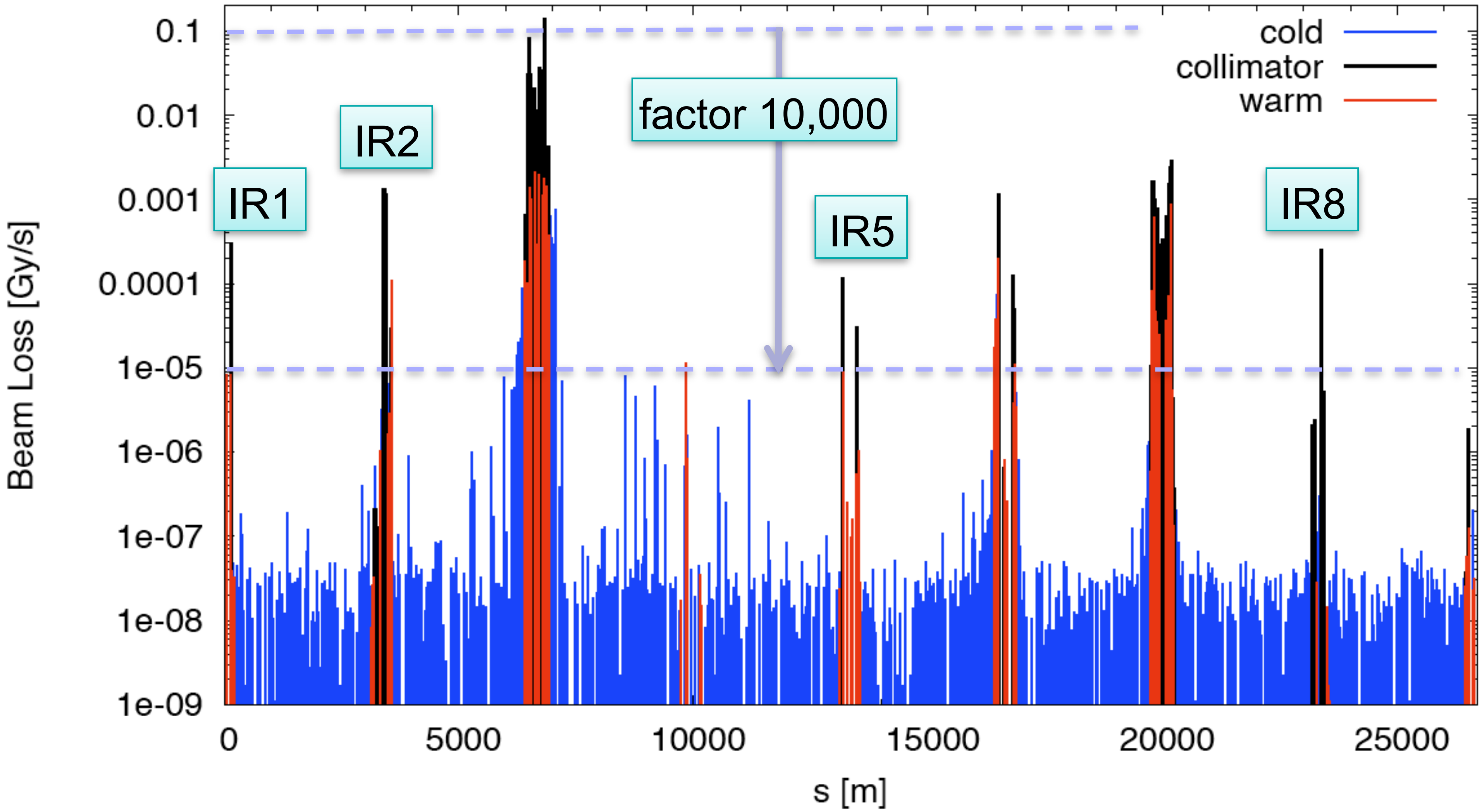
Measured Cleaning at 3.5 TeV

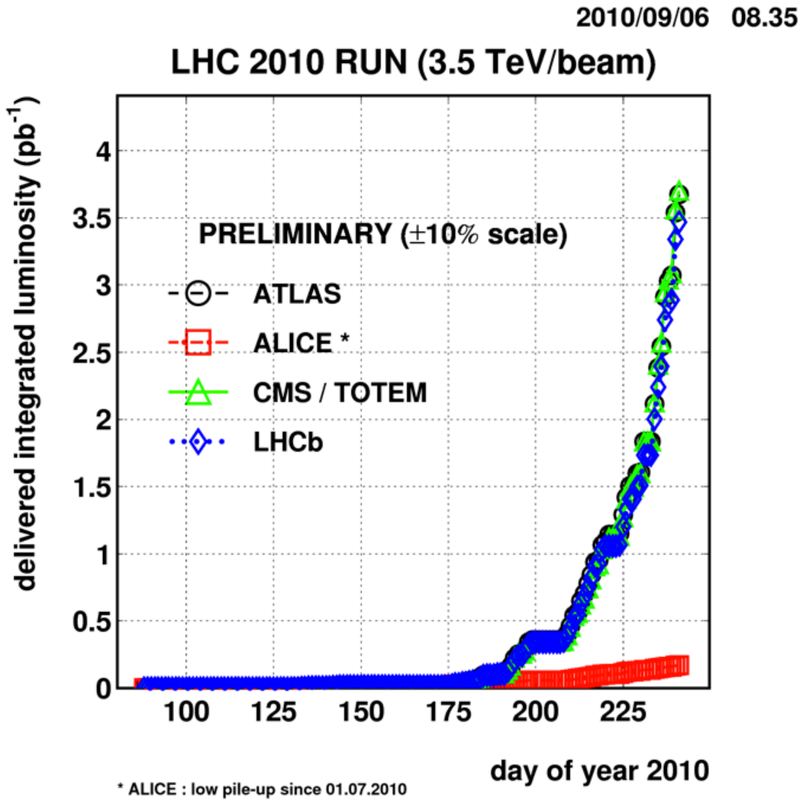
(beam1, vertical beam loss, intermediate settings)



Qualification: Off-momentum collimation

Loss map for off-momentum error. All OK. See expected low leakage to experimental IR's. OK for stable beams from coll.





LUMINOSITY PRODUCTION

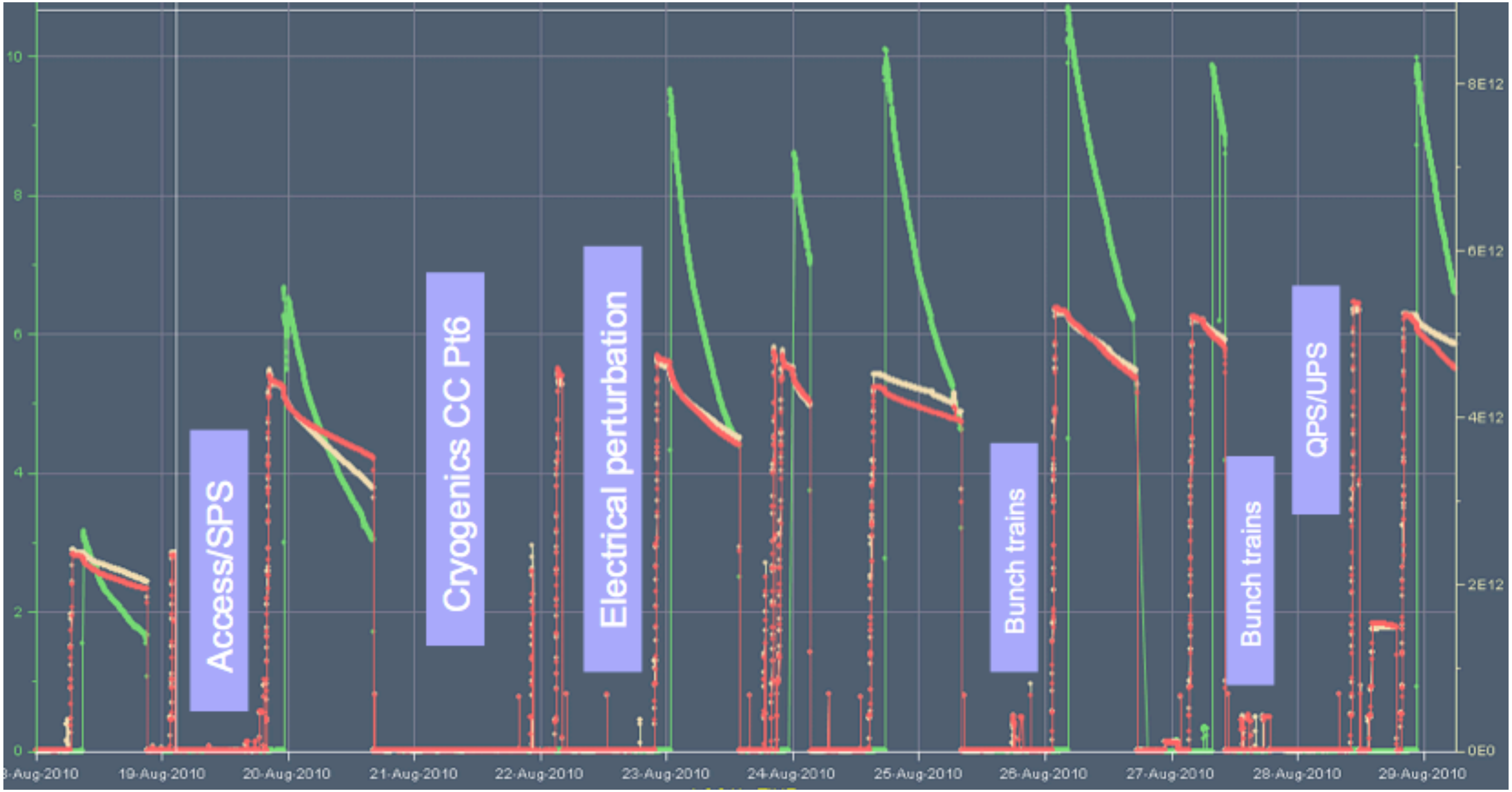
Surprises

- We were never meant to run at 3.5 TeV
  - 7 TeV studied in exquisite detail
  - 3.5 TeV - bigger beams, less aperture, less attention
- Very good single beam lifetime
  - Vacuum, non-linearities, lifetimes
  - Inject nominal bunch intensities, ramp, squeeze…
- Beam-beam
  - A lot easier than expected
  - Nominal bunch intensity collisions – resolving expected problems with predicted cures. Still surprising.
- Transverse emittance (read beam size)
  - Too small emittance from injectors!
  - Ditto longitudinal plane
- Beta* = 3.5 m

Beam current during fill 25/08/2010

Quite frankly: we're dreaming…

Two weeks in August



25b | ← 48b → | ← 50b →

W33/34

August	Fill	Bunches	Stable	nb^{-1}	EOF
18	1293	25x25	12h01	93	Programmed dump
19/20	1295	48x48	14h43	238	Programmed dump
22/23	1298	48x48	13h07	280	fast beam loss event Q22.R3.
24	1299	48x48	3h18	87	RD1.R2 trip.
24/25	1301	50x50	14h17	345	EOF studies
26	1303	50x50	13h07	369	fast beam loss event Q25.R5.
27	1305	50x50	3h30	118	EOF studies
28/29	1308	50x50	13h42	335	Programmed dump
29/30	1309	50x50	11h18	312	Programmed dump

& Totem

W34

Peak luminosity – stable beams	1.03 x 10^{31} $cm^{-2}s^{-1}$
Average luminosity – stable beams	7.08 x 10^{30} $cm^{-2}s^{-1}$
Total stable beam time	67.6 hours (40.2%)
Delivered luminosity	~1700 nb^{-1}
Luminosity lifetime	~25 hours

Hübner factor ≈ 0.29

Including some dedicated bunch train commissioning

	Availability	Physics
W33	47.3%	22%
W34	~85%	40.2%

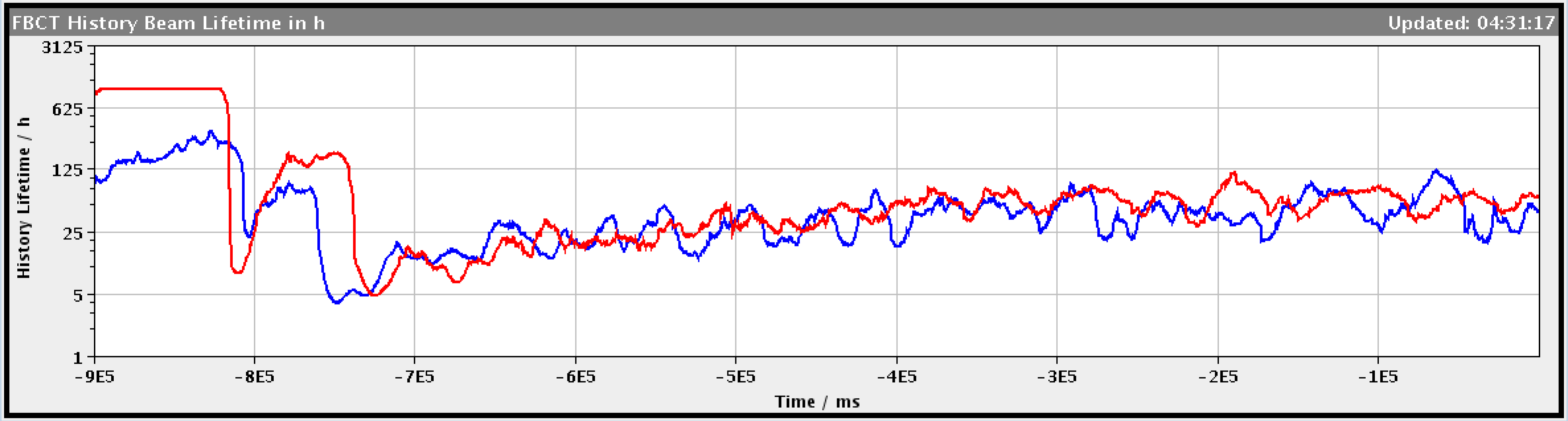
- **Remarkable machine availability**: impressive performance of cryogenics, QPS, converters, RF, instrumentation, collimators, injectors…
- **Very effective** use of available time

New Record Lumi

26-Aug-2010 04:24:46 Fill #: 1303 Energy: 3500 GeV I(B1): 5.51e+12 I(B2): 5.23e+12

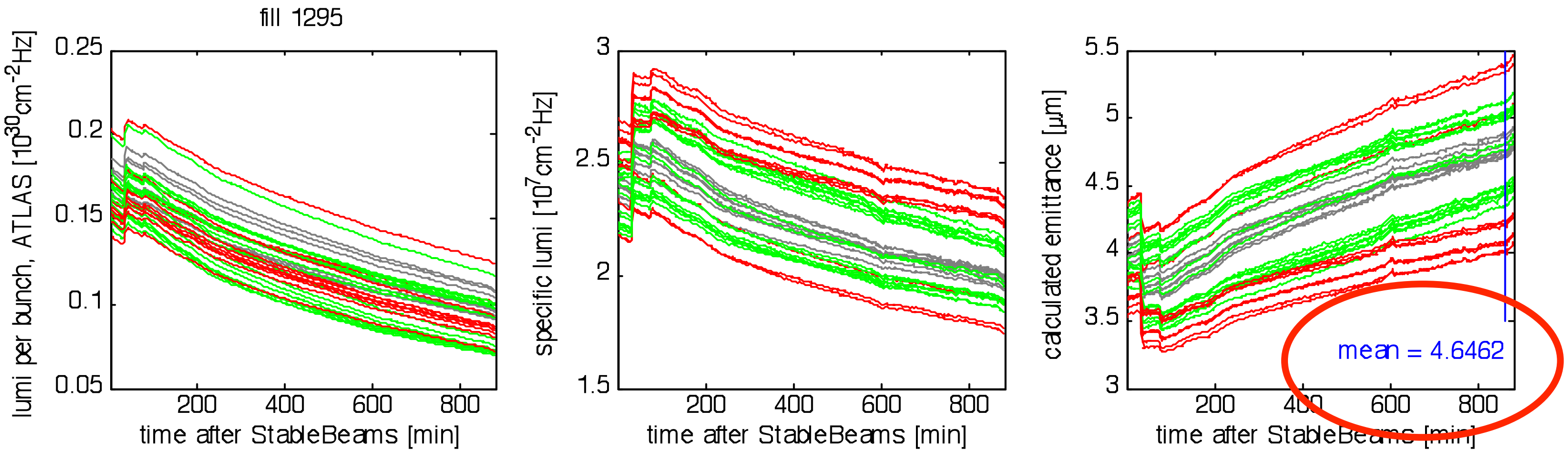
	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	NOT READY	STANDBY	PHYSICS
Instantaneous Lumi (ub.s)^-1	10.456	0.138	10.719	8.882
BRAN Luminosity (ub.s)^-1	9.573	0.137	7.914	7.327
Fill Lumiosity (nb)^-1	2.0	0.0	2.0	1.7
BKGD 1	0.018	0.019	20.644	0.197
BKGD 2	16.000	0.290	0.002	4.773
BKGD 3	5.000	0.008	0.003	0.106

LHCb VELO Position OUT Gap: 58.0 mm STABLE BEAMS TOTEM: STANDBY



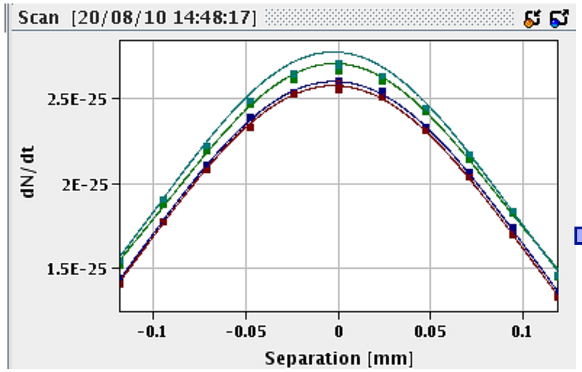
Emittance evolution during a fill

Guilia Papotti



color code:

- grey for bunches colliding in 1258;
- green for bunches colliding in 158;
- red for bunches colliding in 15.



Average emittances derived from scan IP1:
X : 4.4um
Y: 4.9um

Average 4.64um

☺

growth of 10-20% over the fill

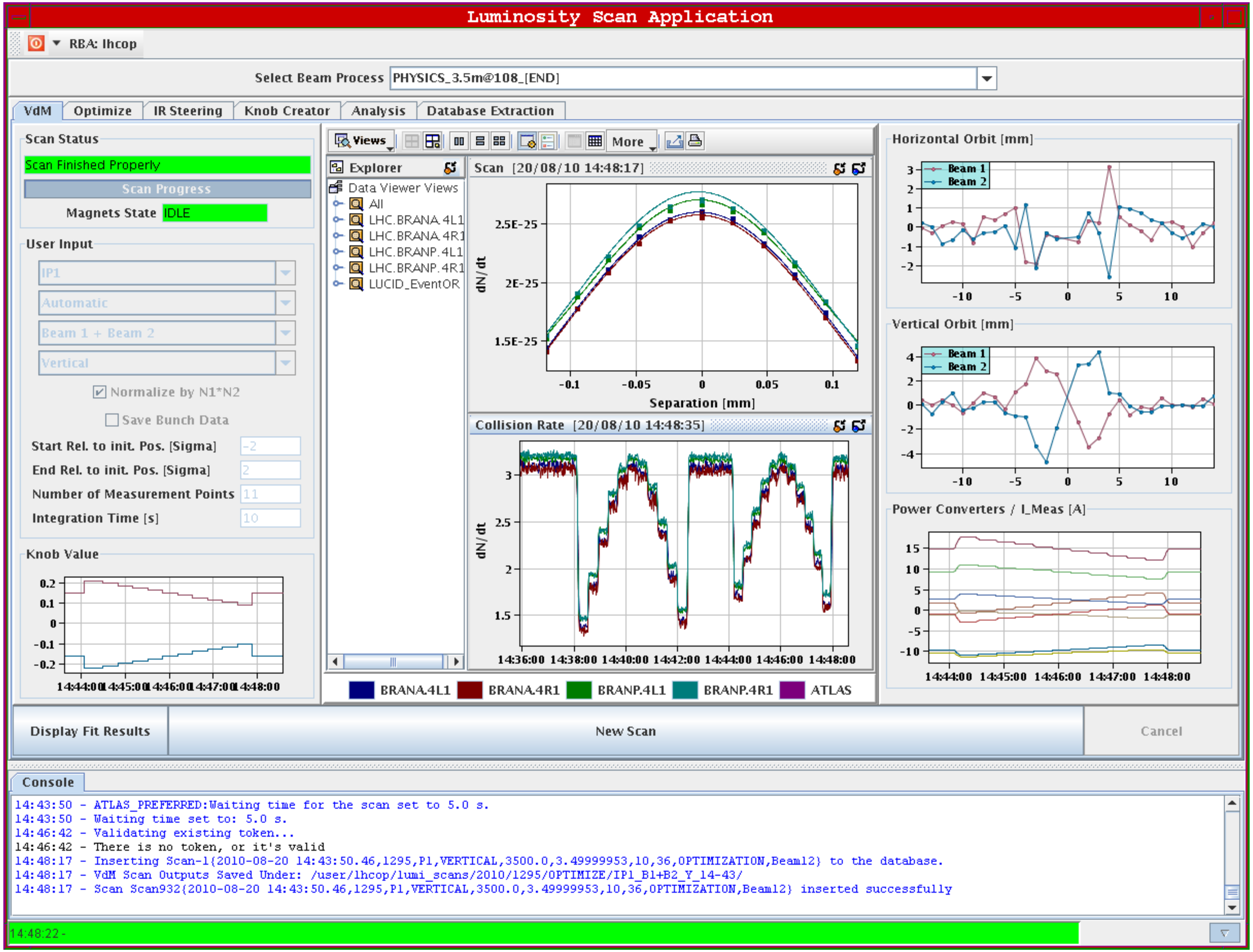
Tevatron Luminosity model on the LHC

- The major (preliminary) conclusions for the LHC fill 1303
- Luminosity lifetime – 20 hour
- Intensity loss times
  - Total 94 & 72 hour (Beam 1 & Beam 2)
    - 267 & 253 hour (Beam 1 & Beam 2) due to luminous loss (For σ =90 mbarn - need a more accurate number)
    - 170 & 112 hour (Beam 1 & Beam 2) due to longitudinal heating and clipping
- Beam loss is dominated by the longitudinal loss
  - Beam-beam loss is important for some bunches but does not dominate the average
- The transverse emittance growth is dominated by transverse noise at betatron sidebands: feedback and hump

Valeri Lebedev

Luminosity scan

Simon White



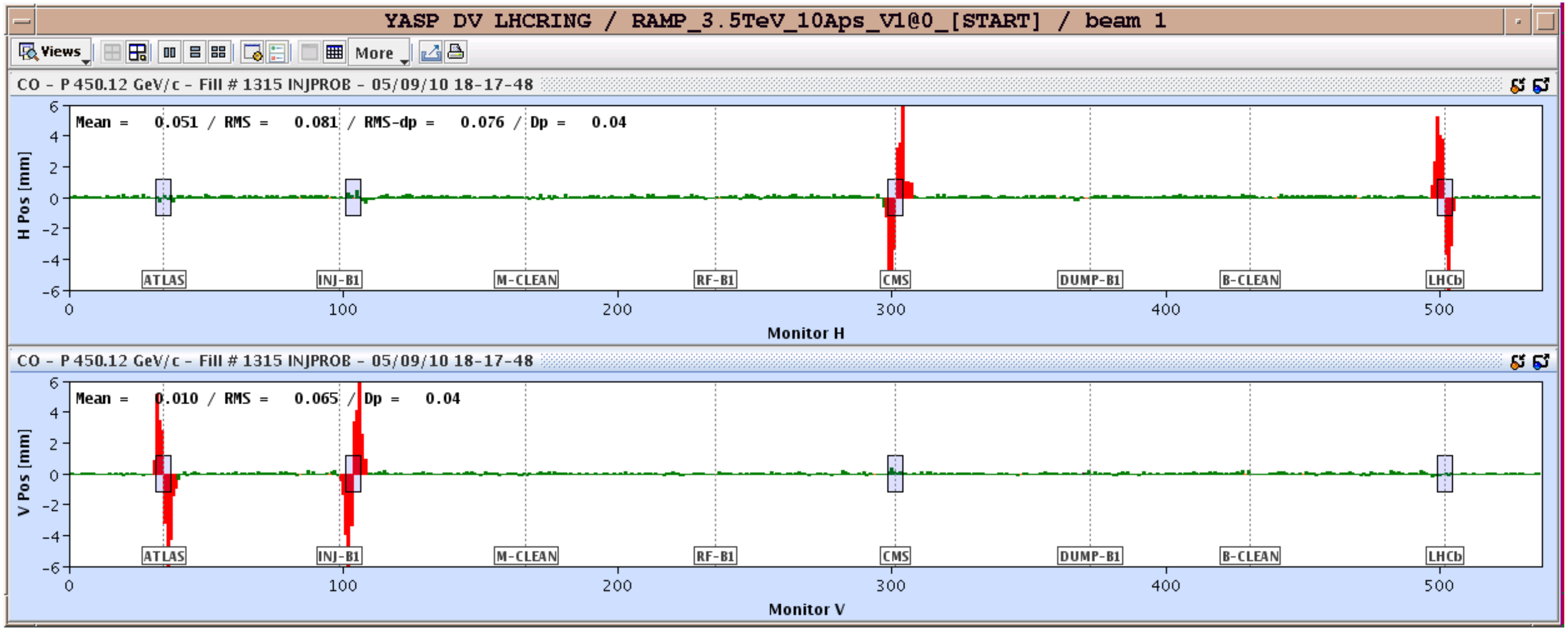
2010 INCOMING

2010 – main aims

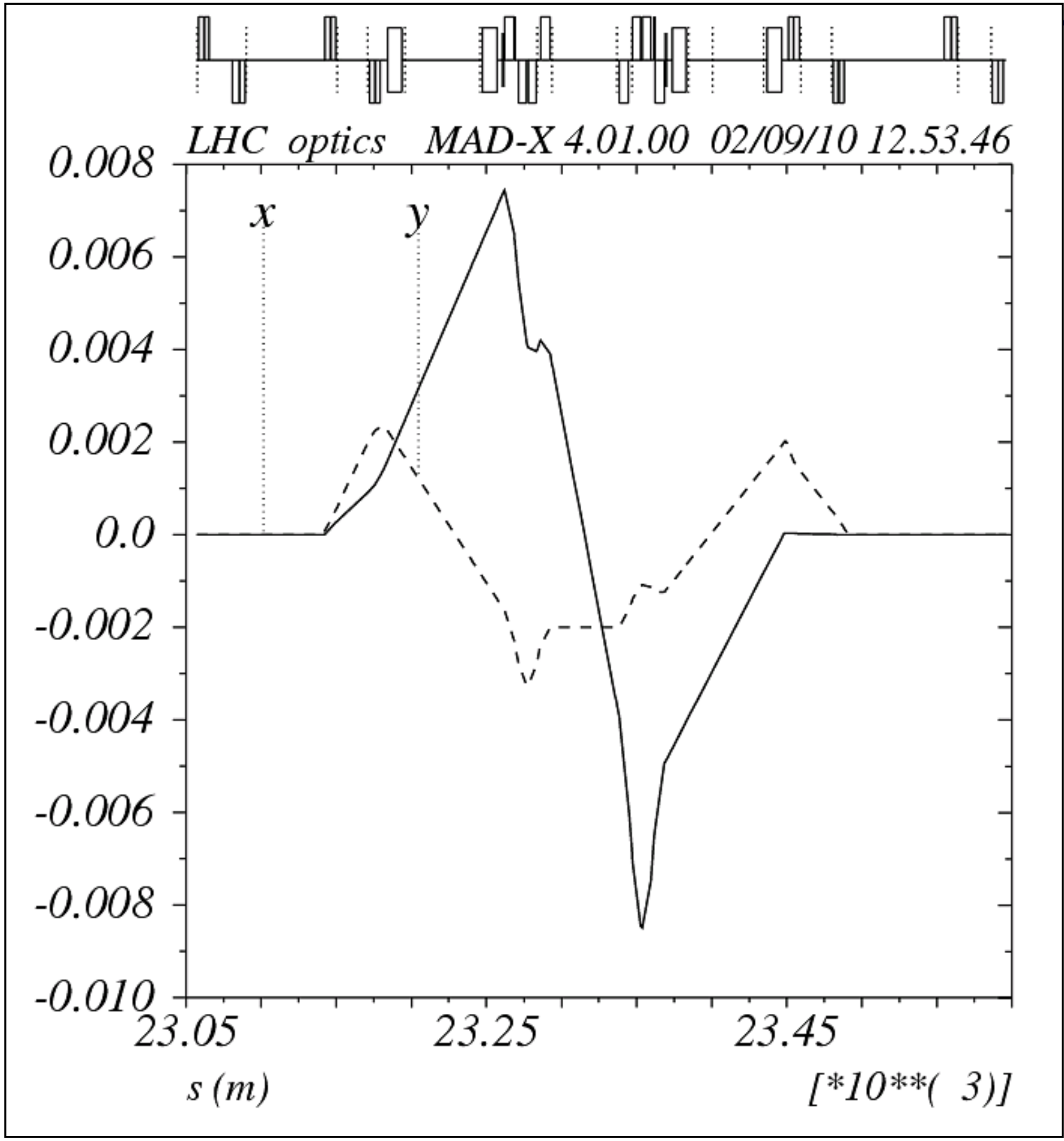
- Clear priority to lay the foundations for 2011 and delivery of 1 fb^{-1}
- Have performed a safe, phased increase in intensity with validation and a running period at each step so far
- Gained solid operational experience of [not faultlessly] injecting, ramping, squeezing and establishing stable beams
- Aimed for steady running at or around 1 MJ over the summer – around 3 weeks in the end
- Followed by commissioning of bunch trains and a comparatively fast ramp up in beam intensity

Next up - bunch trains

Step 1: bring on the crossing angles



through the full cycle and then validate with loss maps etc



on_x8 := 1;

on_sep8 := 1;

on_lhcb := 0;

Implications for machine protection

450 GeV Crossing angle at IP8 -170 microrad

High intensity bunch trains

- Bunch spacing 150 ns
- Push through 4, 12, 24 bunches per beam
- Monitor & adjust
  - ADT
  - Longitudinal blow-up
  - RF
  - Feedbacks
- First stable beams: 3x4

Brennan Goddard, Malika Meddahi

STEPS	# bunches/beam	# SPS bunch trains	# SPS bunches/train	# bunches/injection	# injections	E/inj [MJ]	I/inj (e12)	E/total (MJ @ 3.5 TeV)
A	48	1	4	4	12	0.03	0.4	2.69
	48	1	8	8	6	0.06	0.8	2.69
	96	1	8	8	12	0.06	0.8	5.38
	96	1	12	12	8	0.09	1.2	5.38
	144	1	12	12	12	0.09	1.2	8.06
B	144	2	12	24	6	0.17	2.4	8.06
	192	2	12	24	8	0.17	2.4	10.75
	240	2	12	24	10	0.17	2.4	13.44
	288	2	12	24	12	0.17	2.4	16.13
	336	2	12	24	14	0.17	2.4	18.82
C	396	3	12	36	11	0.26	3.6	22.18

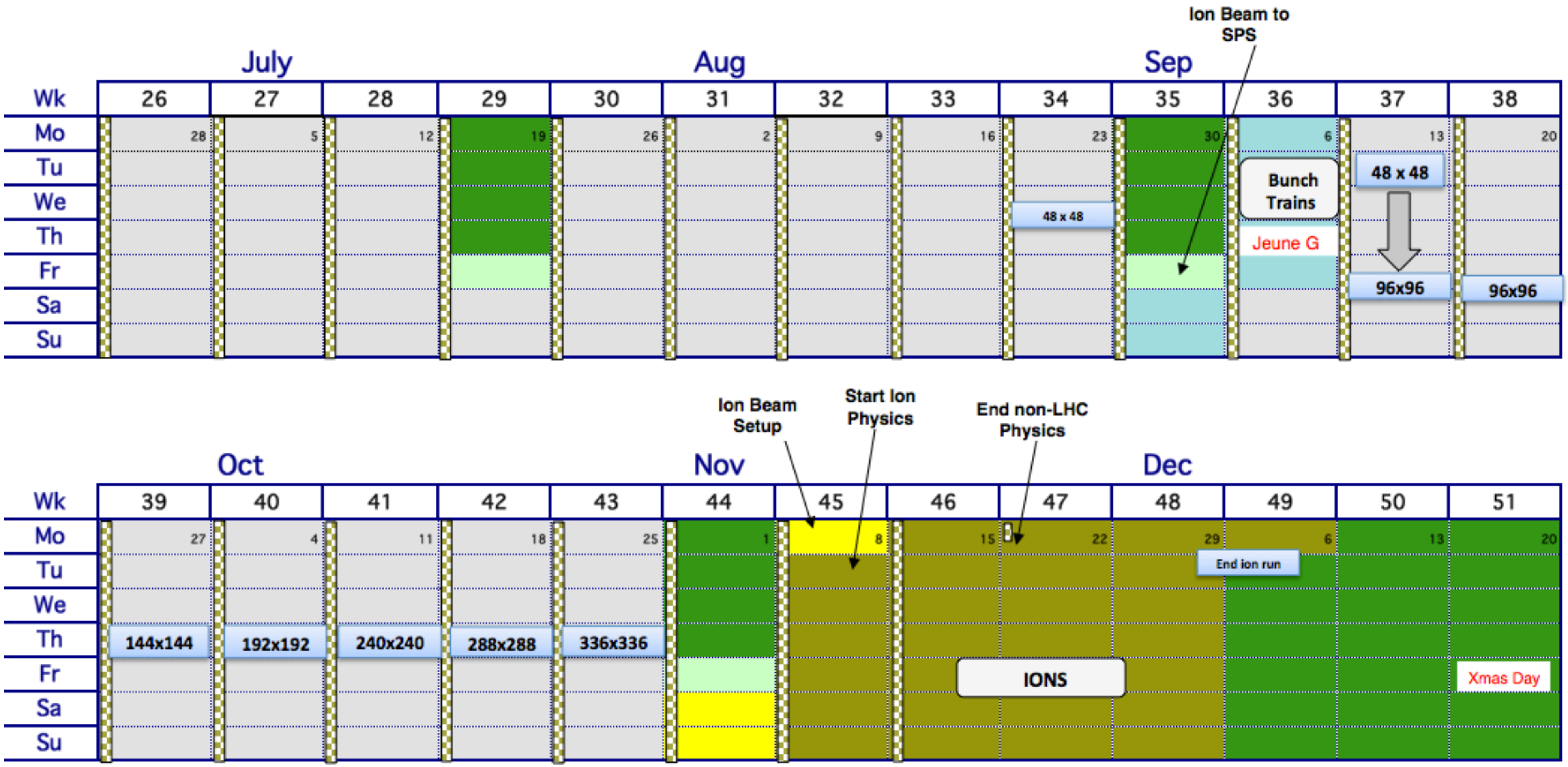
Performance

Nominal bunch intensity 1.1e11
Nominal emittance
200 microrad crossing angle
Beta* = 3.5 m
150 ns bunch spacing

Number of bunches	Peak Luminosity [$cm^{-2}s^{-1}$]	5day@0.2 [pb^{-1}]	MJ
48	1.5×10^{31}	1.3	3.0
96	2.9×10^{31}	2.5	5.9
144	4.4×10^{31}	3.8	8.9
192	5.9×10^{31}	5.1	11.8
240	7.3×10^{31}	6.3	14.8
288	8.8×10^{31}	7.6	17.7
336	1.0×10^{32}	8.9	20.7

Schedule – rest of 2010

Aggressive schedule, assuming excellent machine availability



Early Heavy Ion Run Parameters

John Jowett

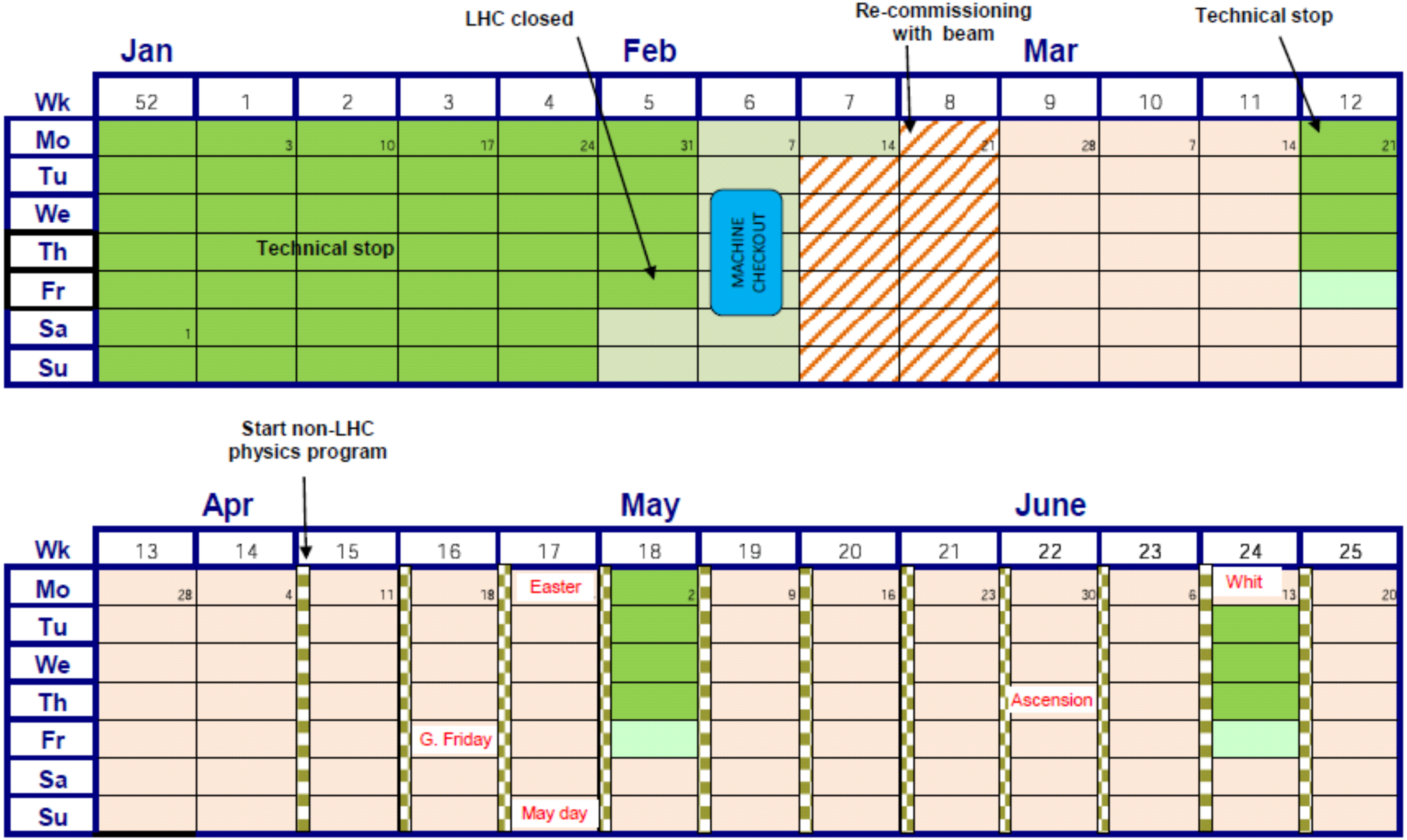
		Early (2010/11)	Nominal
$\sqrt{s}$ per nucleon	TeV	2.76	5.5
Initial Luminosity (L_0)	$cm^{-2}s^{-1}$	$\sim 10^{25}$	10^{27}
Number of bunches		62	592
Bunch spacing	ns	1350	99.8
β^*	m	3.5	0.5
Pb ions/bunch		7×10^7	7×10^7
Transverse norm. emittance	µm	1.5	1.5
Luminosity half life (1,2,3 expts.)	h	τ_{IBS}=7-30	8, 4.5, 3

Initial interaction rate: 100 Hz (10 Hz central collisions $b = 0 - 5$ fm)

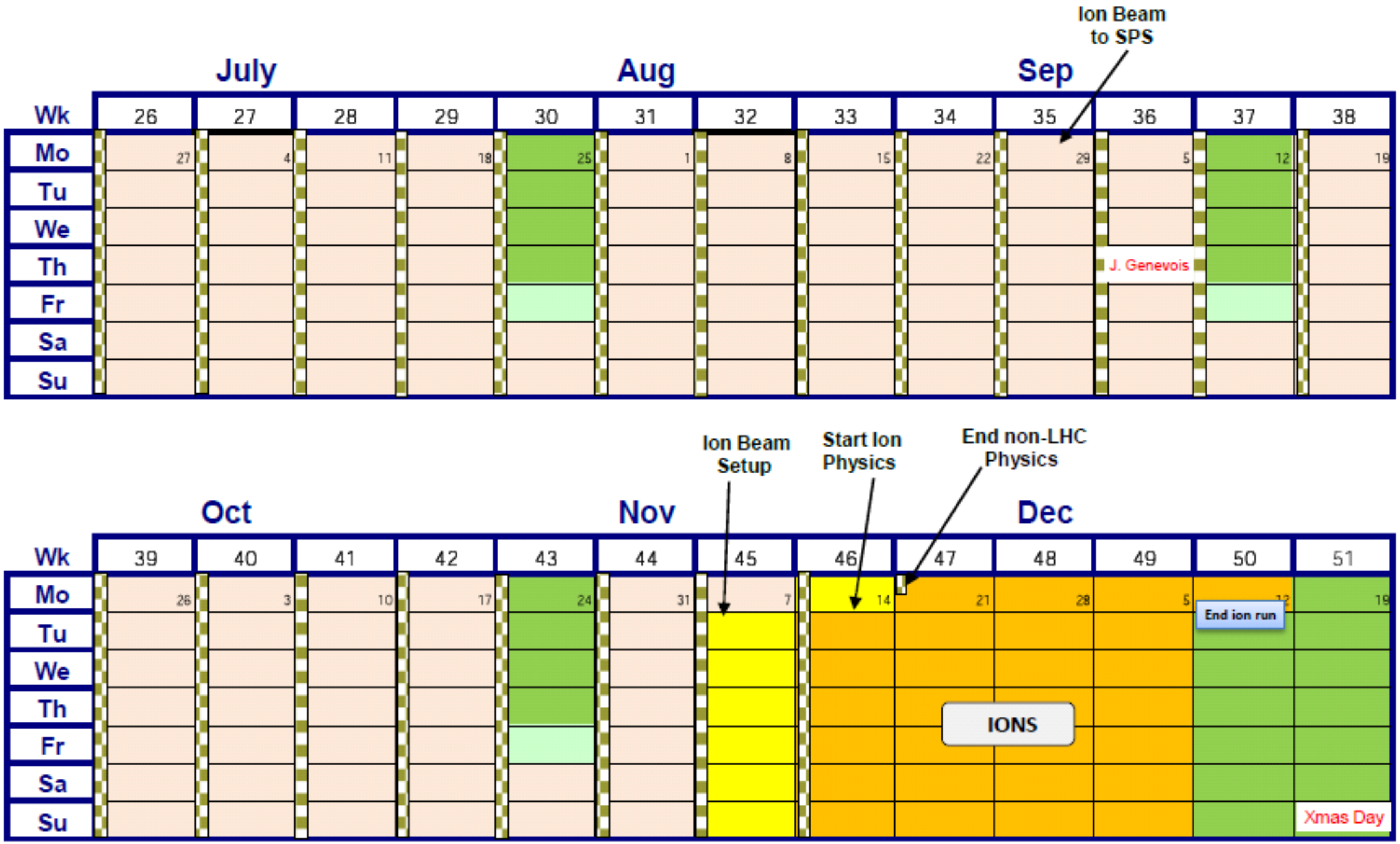
$\sim 10^8$ interaction/10^6s (~1 month)

2011

2011 Q1&2


LHC closed
Re-commissioning with beam
Technical stop
Jan
Feb
Mar
Wk
52
1
2
3
4
5
6
7
8
9
10
11
12
Mo
Tu
We
Th
Fr
Sa
Su
3
10
17
24
31
7
14
21
28
7
14
21
1
Technical stop
MACHINE CHECKOUT
Start non-LHC physics program
Apr
May
June
Wk
13
14
15
16
17
18
19
20
21
22
23
24
25
Mo
Tu
We
Th
Fr
Sa
Su
28
4
11
18
2
9
16
23
30
6
13
20
Easter
G. Friday
May day
Ascension
Whit

2011 Q3&4


Ion Beam to SPS
July
Aug
Sep
Wk
26 27 28 29 30 31 32 33 34 35 36 37 38
Mo
Tu
We
Th
Fr
Sa
Su
27 4 11 18 25 1 8 15 22 29 5 12 19
J. Genevois
Ion Beam Setup
Start Ion Physics
End non-LHC Physics
Oct
Nov
Dec
Wk
39 40 41 42 43 44 45 46 47 48 49 50 51
Mo
Tu
We
Th
Fr
Sa
Su
26 3 10 17 24 31 7 14 21 28 5 12 19
End ion run
IONS
Xmas Day

2011 – 3.5 TeV

- Restart 4th February
- 9 months protons, 4 weeks ions
- Integrated luminosity target driven – 1 fb^{-1}
- Need to run flat out above 1e32 $cm^{-2}s^{-1}$

Table 4: Possible 2011 ball-park scenarios with 1.1×10^{11} protons per bunch.

N_b	β^* [m]	Energy per beam [MJ]	Peak Luminosity [$cm^{-2}s^{-1}$]	Int. Lumi per month [pb^{-1}]
432	3.5	27	1.3×10^{32}	61
432	2.5	27	1.8×10^{32}	85
796	3.5	49	2.4×10^{32}	113
796	2.5	49	3.4×10^{32}	157

Conclusions

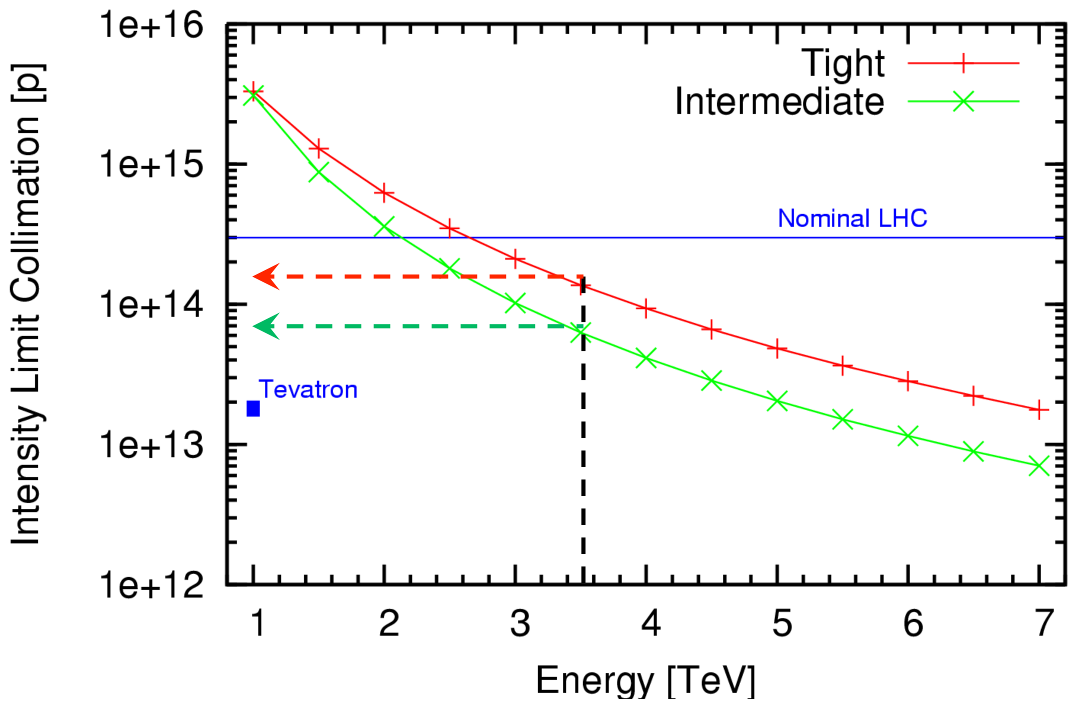
- Very successful period of initial commissioning
  - 5 months since first collisions at 3.5 TeV
  - Commissioning is still ongoing…
- All key systems performing remarkably well – some hugely complex systems out there.
  - Some commissioning still required, issues still to address
- Performance with beam (losses, lifetimes, luminosity, emittance growth etc.) is very encouraging.
- Have bedded in the nominal cycle but it remains a complex procedure with a number of critical manual actions required – mistakes still possible
- Moving towards a MJ culture.
- Aggressive planning for the rest of 2010
- Smooth running with 10s MJ in 2011 foreseen

BACKUP

LHC Intensity limits 2010 2011

- Collimation system conceived as a staged system

- First stage to allow 40% of nominal intensity at 7TeV
  - Under certain assumptions
    - LHC lifetimes and loss rates
    - 0.1%/s assumed (0.2h lifetime)
    - Ideal cleaning
  - Imperfections bring this down
    - Deformed jaws
    - Tilt & offset & gap errors
    - Machine alignment
  - Machine stability
    - Tight settings a challenge early
    - Intermediate settings make use of aperture to relax tolerances



Fix I_{max} to 6 10^{13} protons per beam at 3.5TeV (about 20% nominal intensity)

30MJ stored beam energy

0.2%/s assumed