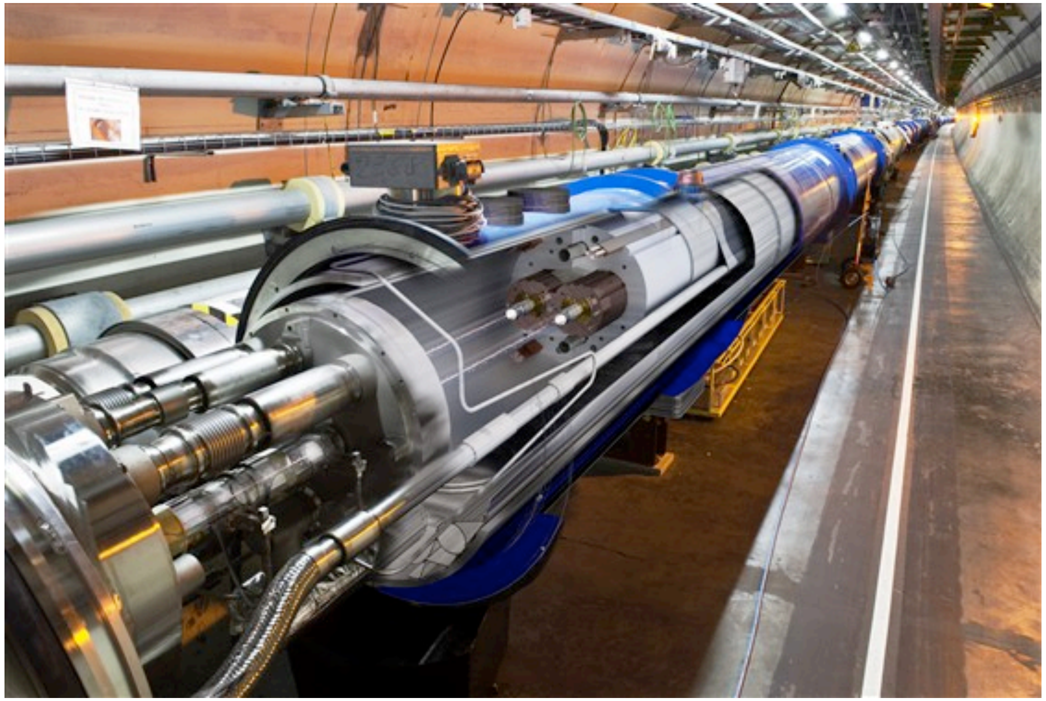
LHC near and medium term prospects

Mike Lamont
for the LHC team

Preamble

$$L = F \frac{N_b N_1 N_2 f_{rev}}{4\pi\sigma_x\sigma_y}$$

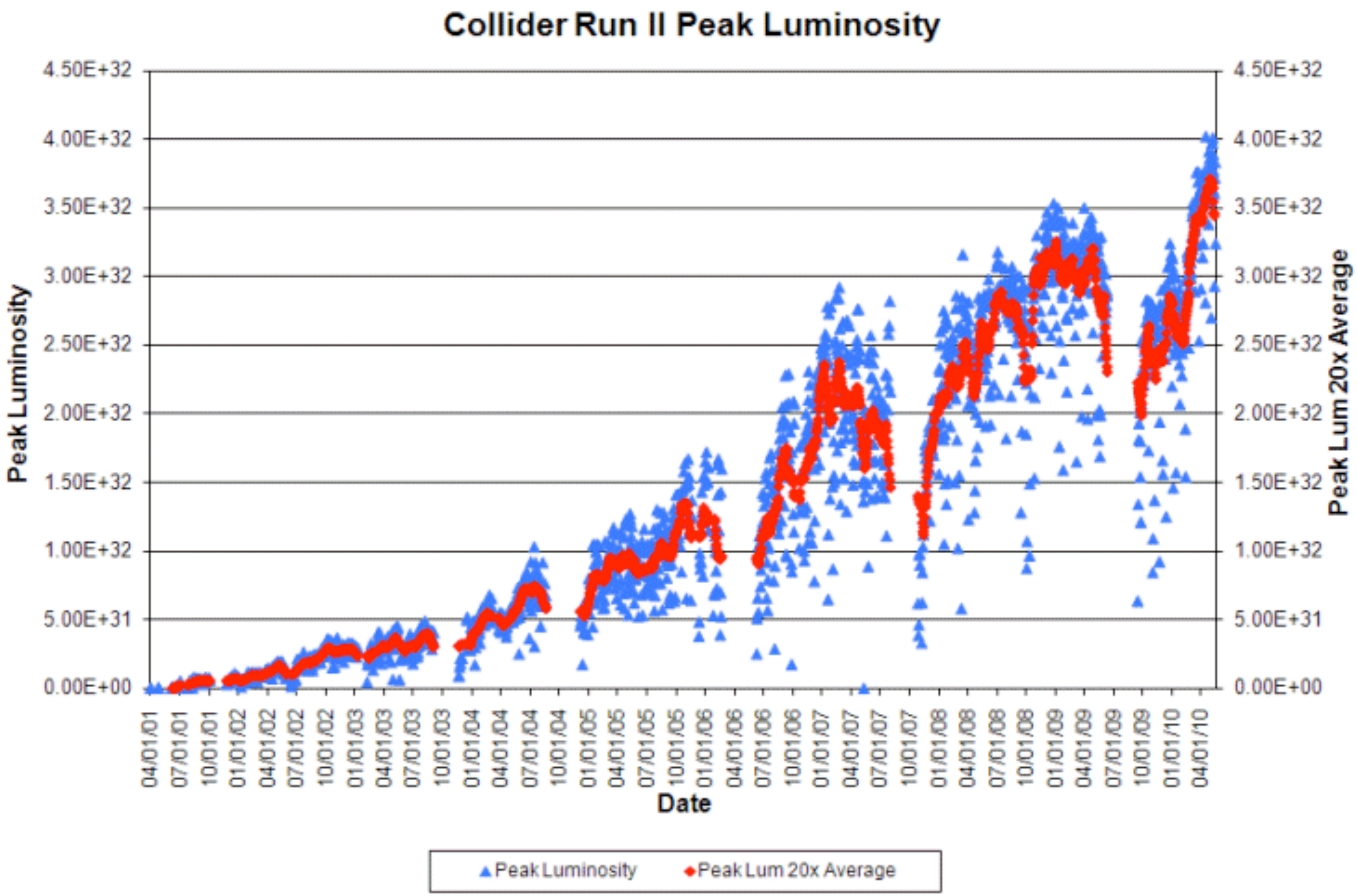
This is an equation. (a)



It is a lot easier to inject lots of high intensity bunches into a than it is b

This is a particle accelerator. (b)

Tevatron



Collider Run II Peak Luminosity
4.50E+32
4.00E+32
3.50E+32
3.00E+32
2.50E+32
2.00E+32
1.50E+32
1.00E+32
5.00E+31
0.00E+00
Peak Luminosity
Peak Lum 20x Average
Date
04/01/01
07/01/01
10/01/01
01/01/02
04/01/02
07/01/02
10/01/02
01/01/03
04/01/03
07/01/03
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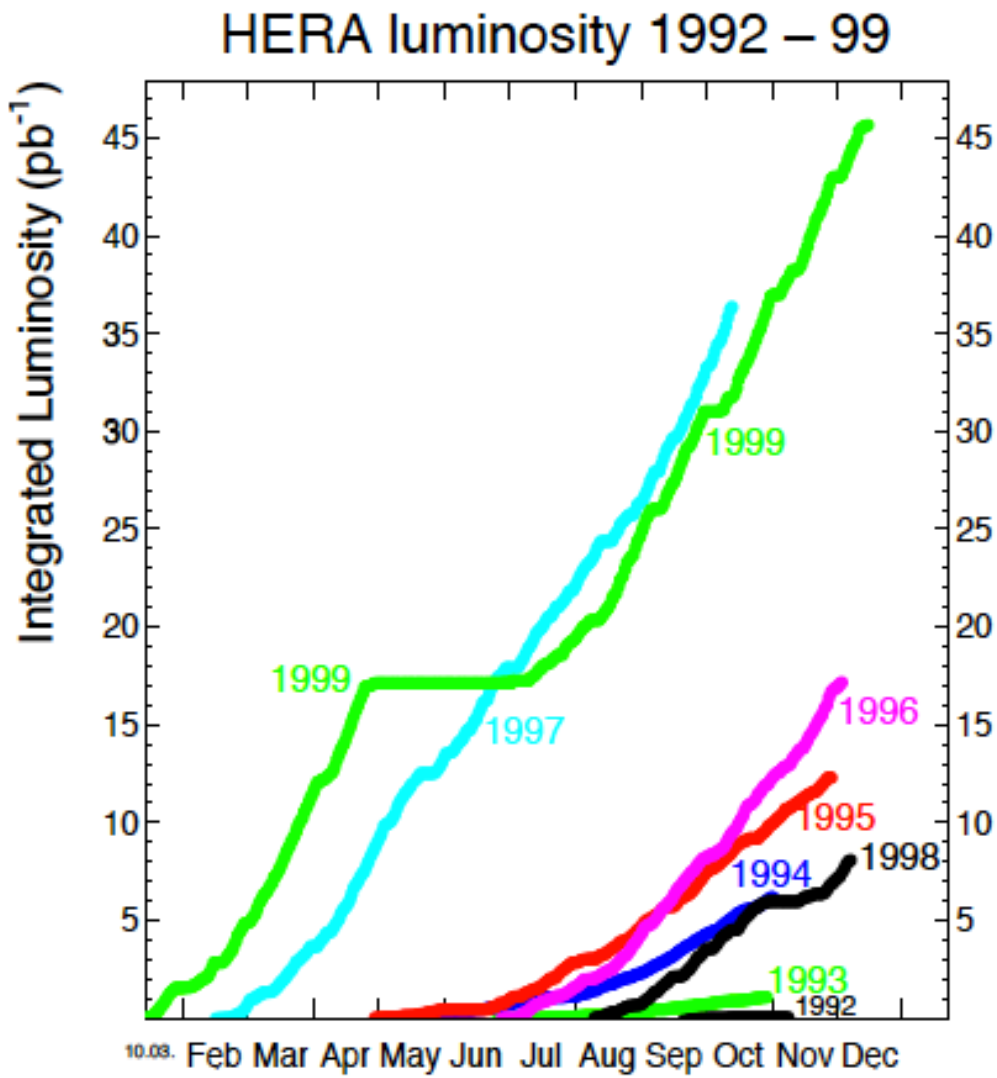
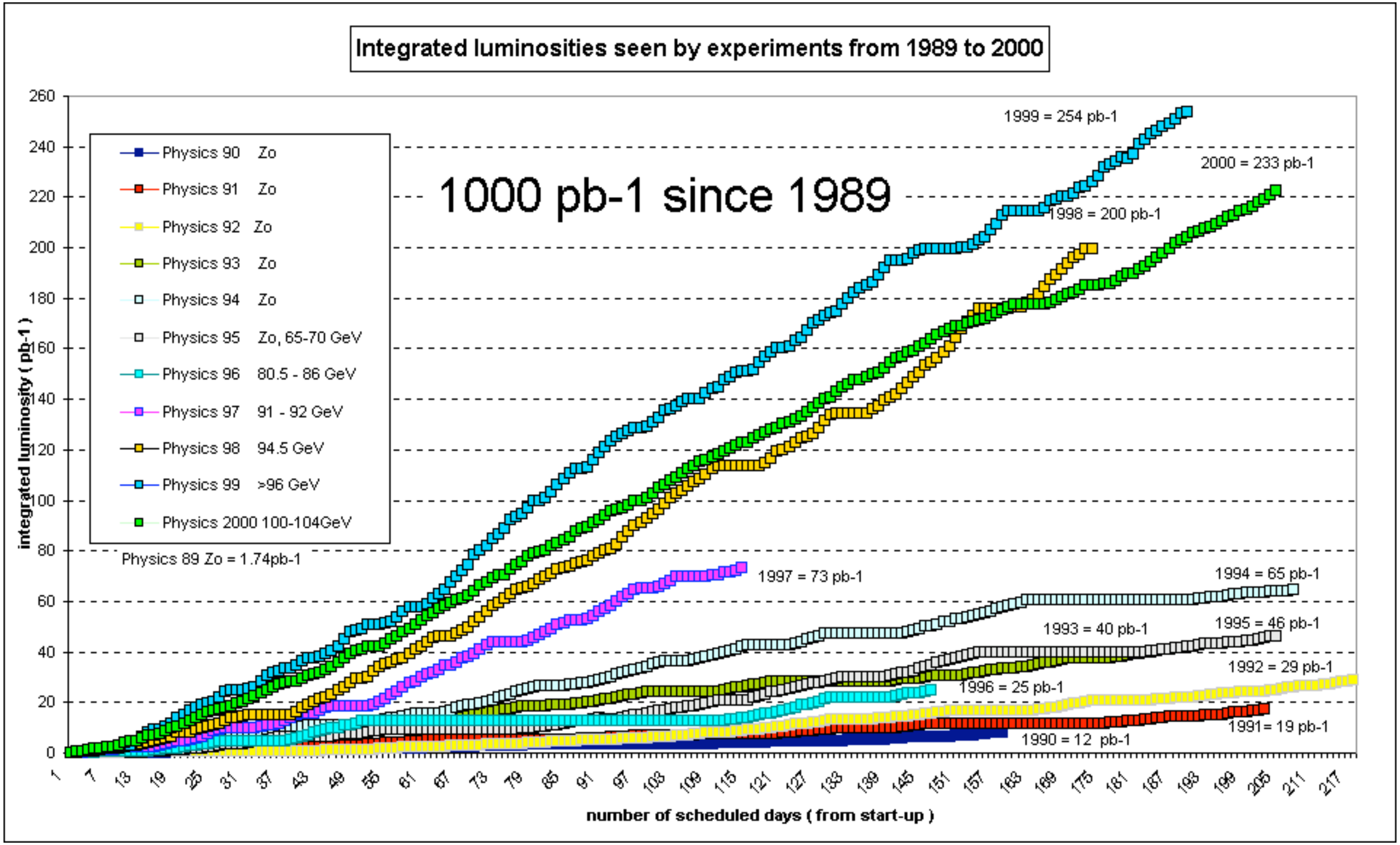
01/01/10
04/01/10
Peak Luminosity
Peak Lum 20x Average

HERA


HERA luminosity 1992 – 99
Integrated Luminosity (pb^{-1})
45
40
35
30
25
20
15
10
5
1999
1997
1999
1996
1995
1998
1994
1993
1992
10.03.
Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

LEP



MESSAGE: IT TAKES TIME!

The present - recap

- "The LHC is a fabulous machine." Lyn Evans
- 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
- Key systems performing well
  - Injection
  - Beam dump
  - Collimation
  - Machine protection

The present - recap

- Ramp and squeeze
  - In general under control
- Inject, ramp and squeeze multiple bunches and bring them into stable beams.
- Keep them there
  - Maximum fill length – a remarkable 30 hours
- And do it again
- Routinely over-inject nominal bunch intensities and ramp them to 3.5 TeV
  - Not without some problems - probing limits already

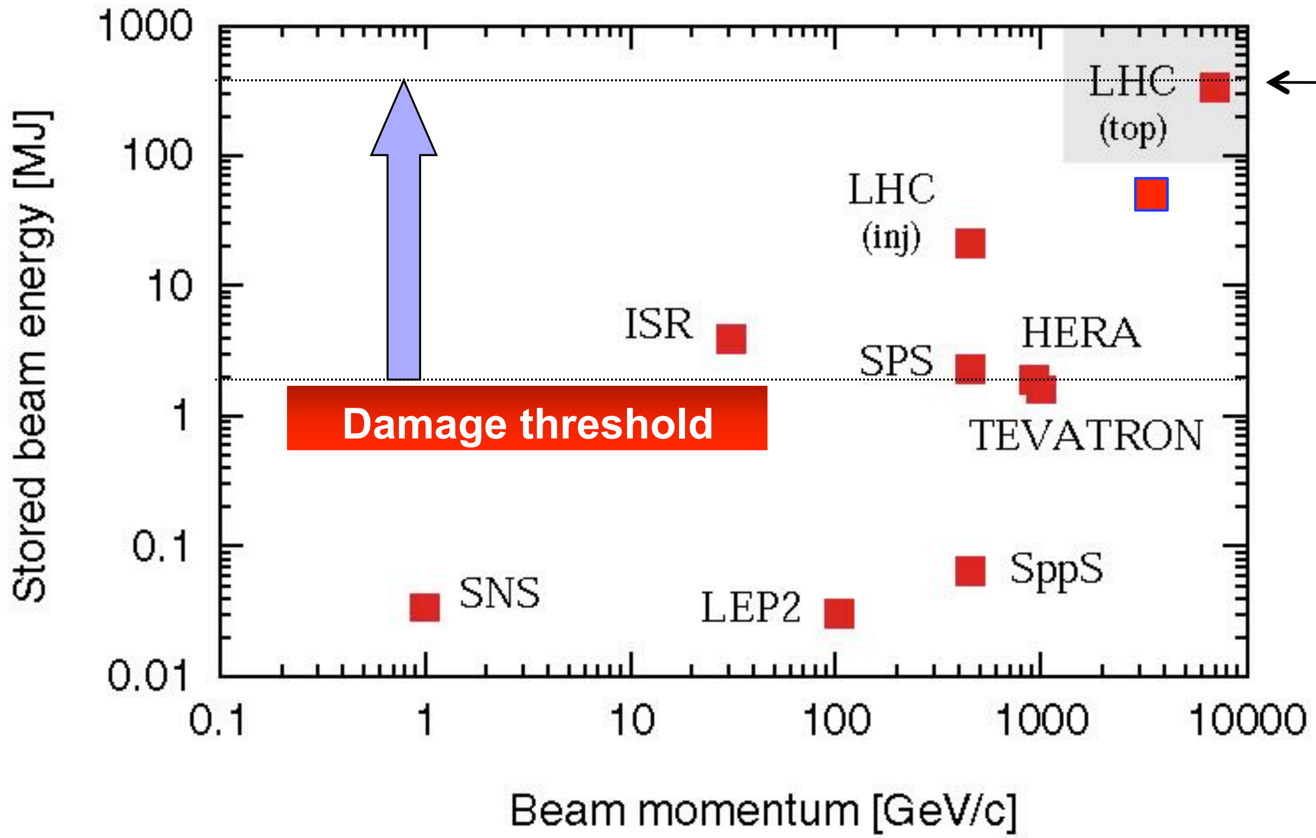
A remarkably successful initial commissioning period

But also…

- Daily challenge of operating an immensely complex machine
- Omnipresent concern for machine safety
- Dependent on some huge supporting systems :
  - cryogenics, quench protection systems, powering, access, vacuum…
- Dependent on a large number of critical sub-systems:
  - RF, synchronization, timing, transverse feedback, orbit & tune feedback, beam instrumentation – huge distributed systems, controls infrastructure, software, databases
  - Most of which are performing well but we still have some features left to iron out and commissioning to finish

Problems eat into our availability and some of it gives us pause when considering machine safety

The challenge



360 MJ

LHC quench limits:

5-30 mJ/cm^3

At less than 1% of nominal intensity LHC enters new territory.

The challenge

- The **11 GJ** of energy stored in the magnets are sufficient to heat and melt 15 tons of Copper (~1.7 m^3).
- The **360 MJ** stored in the nominal beam correspond to ~80 kg of TNT.

Plasma-hydrodynamic simulations indicate that the beam will drill a ~30 m long hole into Copper.

Something we tried earlier:

Sliced open an transfer line vacuum chamber with the impact of **~1% of a nominal LHC beam** during an "incident"

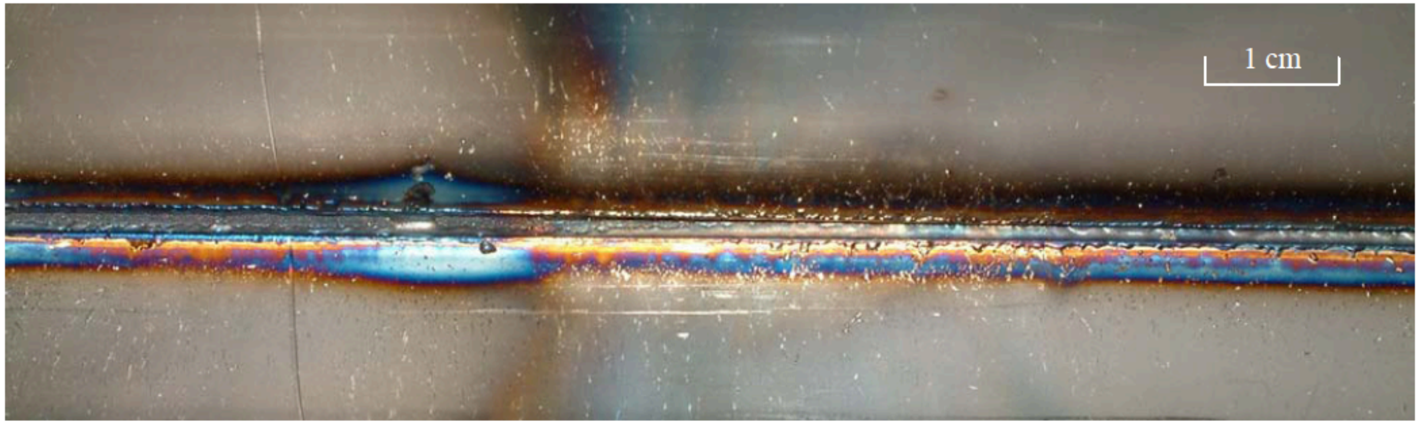


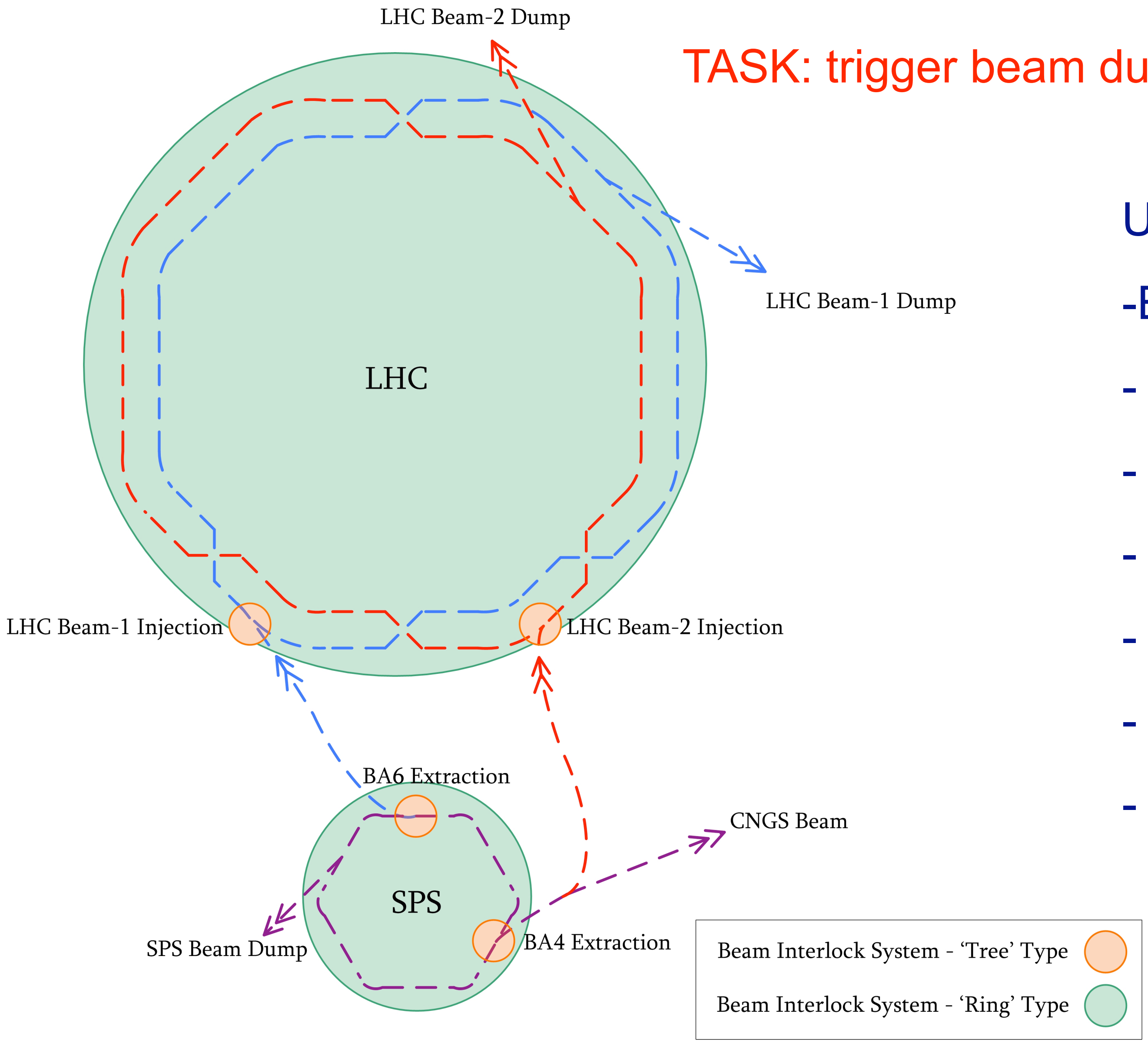
Figure 4. Damage observed on the inside of the vacuum chamber, on the beam impact side. A groove approximately 110 cm long due to removed material was clearly visible, starting at about 30 cm from the entrance.

Equivalent to around 48 bunches of 1e11 at 3.5 TeV

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

PEDAGOGICAL BREAK

Beam Interlock System



TASK: trigger beam dump within 3 turns

User inputs include:

-Experiments

- BLMS

- PIC, WIC

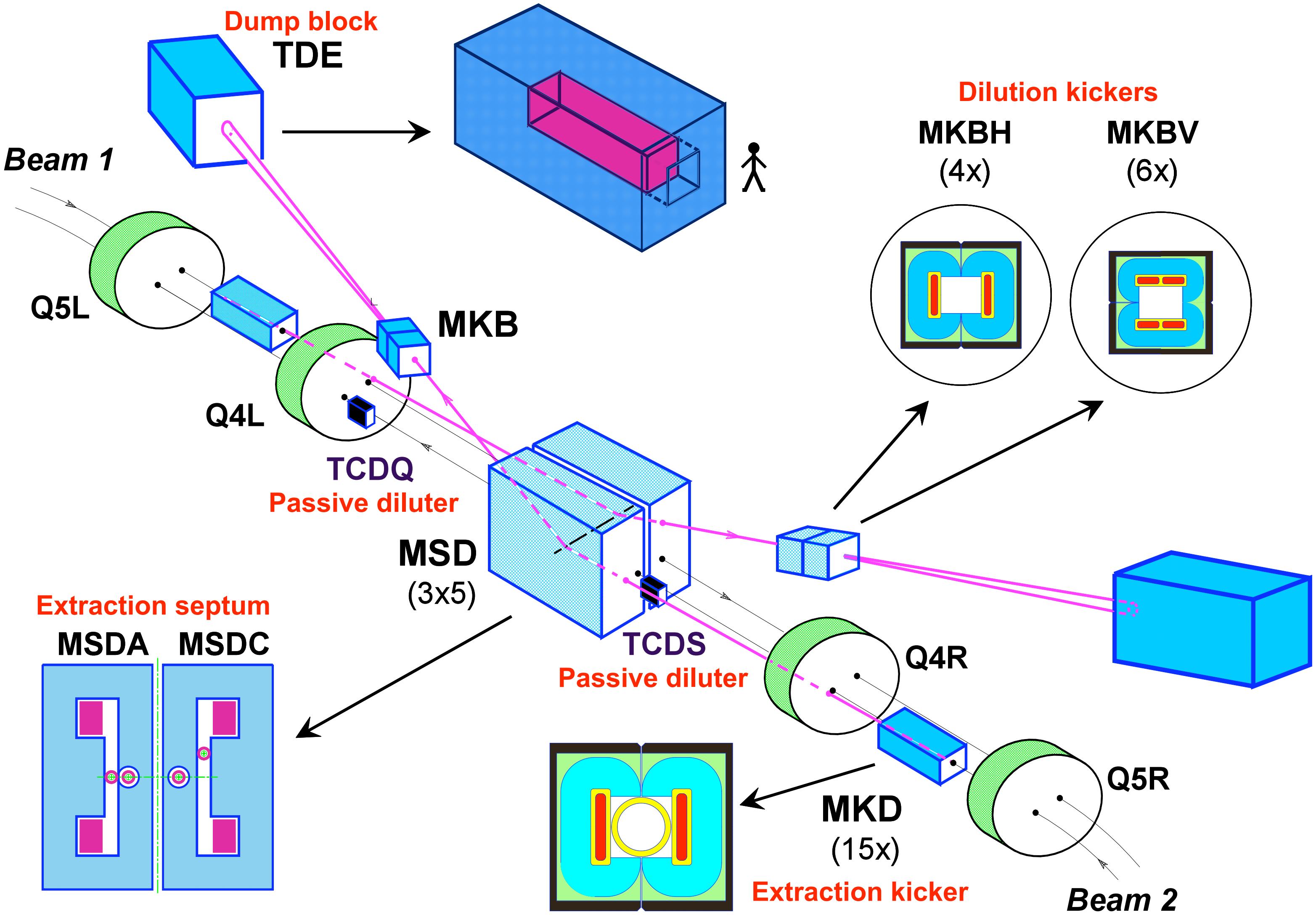
- FMCM

- Vacuum

- Beam dump

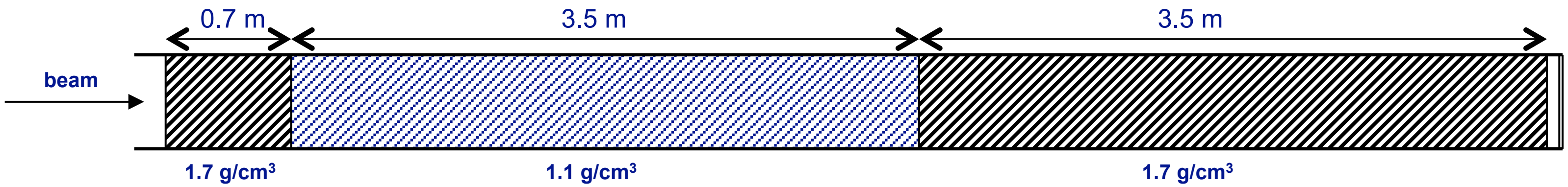
- OP

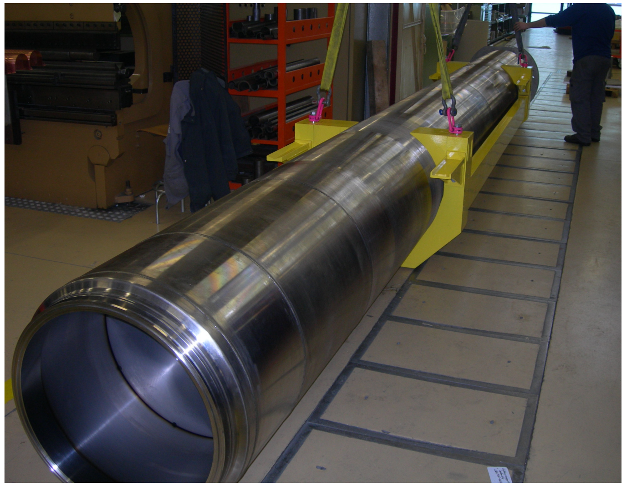
The beam dump

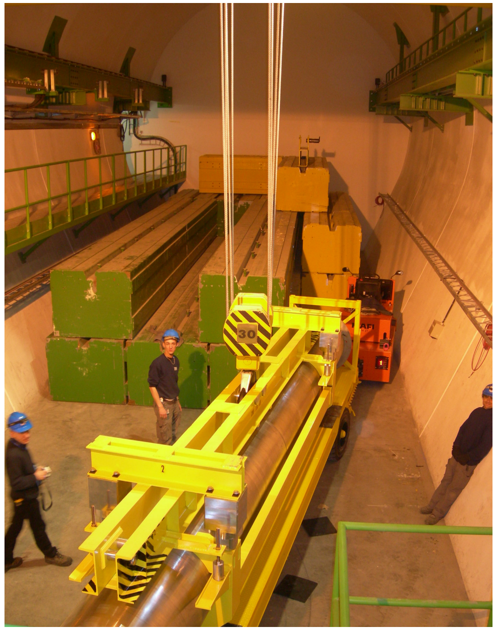


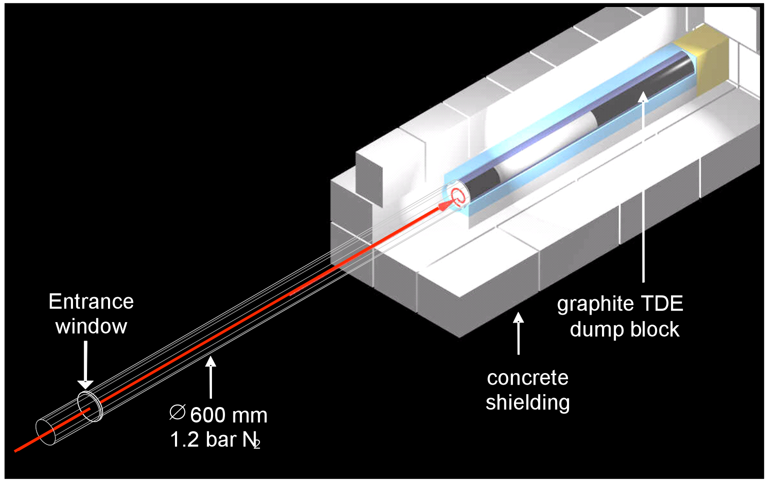
Beam dump block (TDE)

- 700 mm ∅ graphite core, with graded density of 1.1 g/cm^3 and 1.7 g/cm^3
- 12 mm wall, stainless-steel welded pressure vessel, at 1.2 bar of N_2
- Surrounded by ~1000 tonnes of concrete/steel radiation shielding blocks

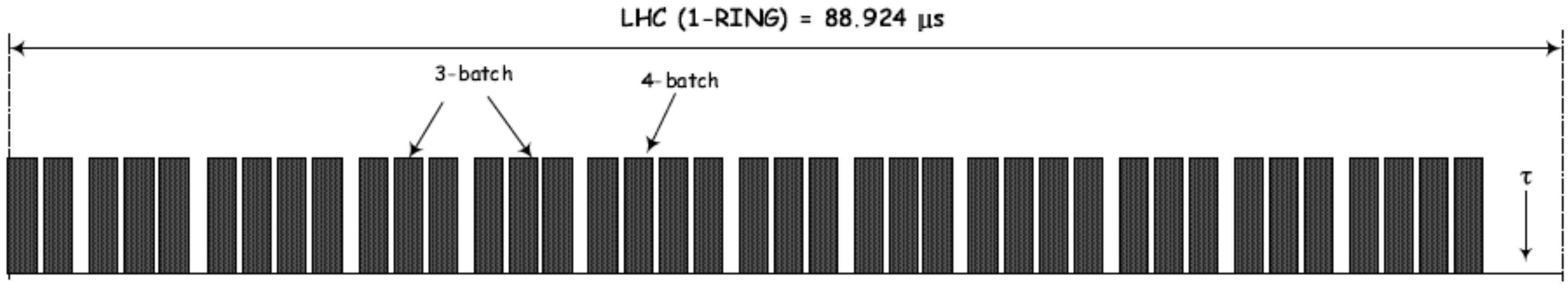




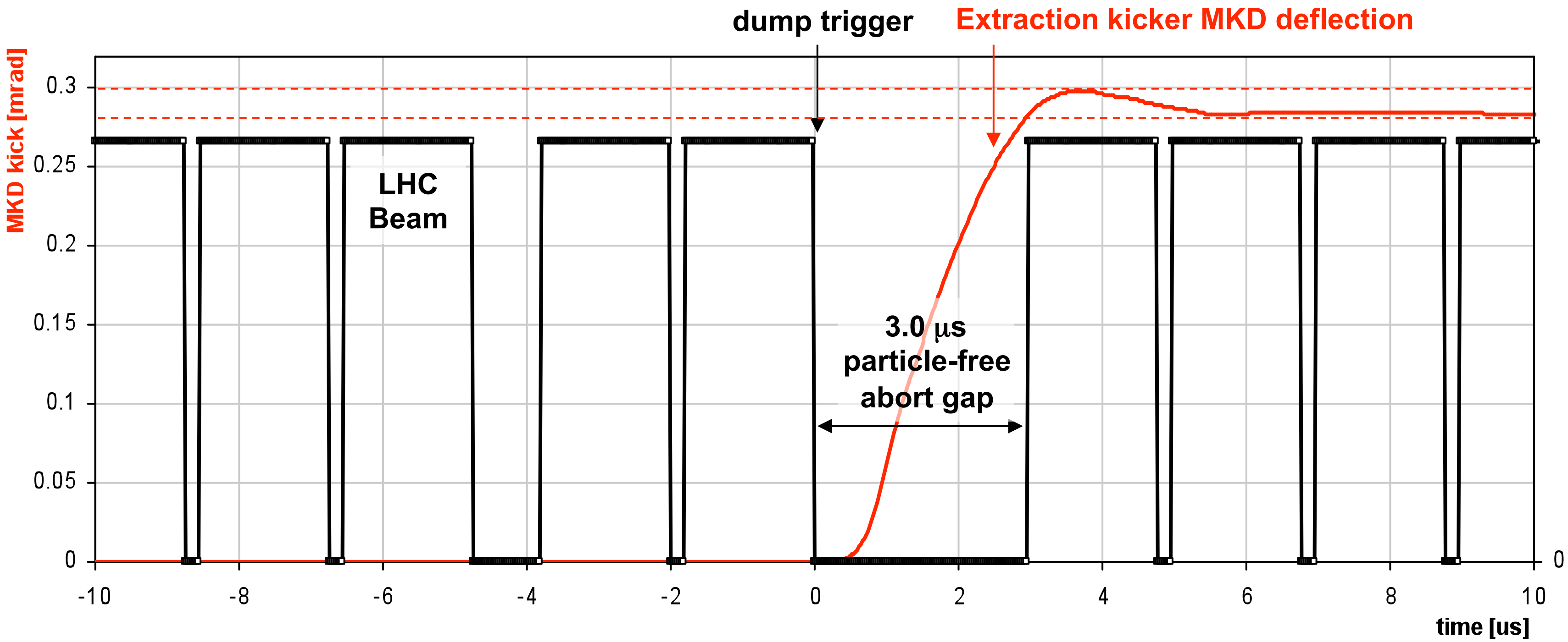




Abort Gap



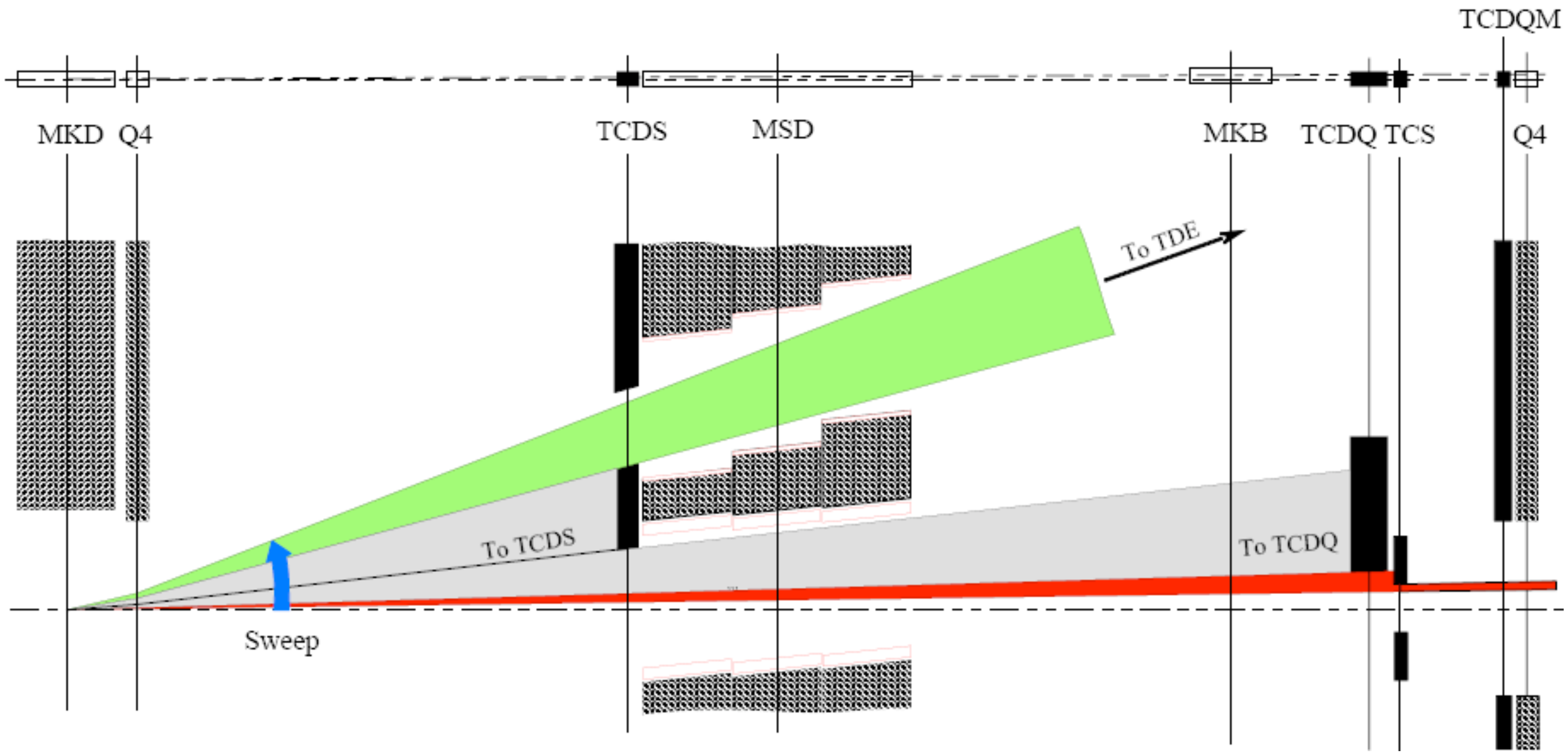
LHC (1-RING) = 88.924 μs
3-batch
4-batch
τ



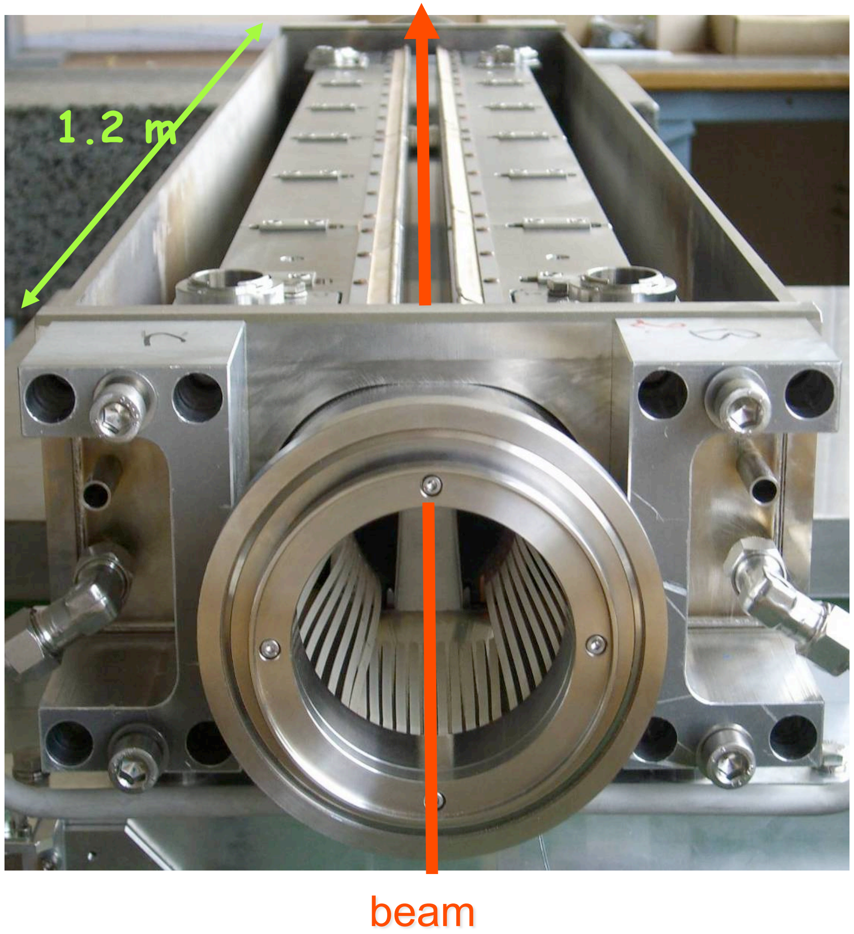
dump trigger
Extraction kicker MKD deflection
MKD kick [mrad]
LHC Beam
3.0 μs particle-free abort gap
time [us]
0.3
0.25
0.2
0.15
0.1
0.05
0
-10
-8
-6
-4
-2
0
2
4
6
8
10

Asynchronous beam dump

- Asynchronous beam dump → quench or damage
  - Several failures possible (synchronisation, MKD erratic)
- Precautionary measures include:
  - TCDS (fixed) – 6 m long diluter protects extraction septum
  - TCDQ/TCS (mobile) – 7 m long diluter kept at about 7-8 σ from the beam at all times



Collimation



Almost 100 collimators and absorbers.

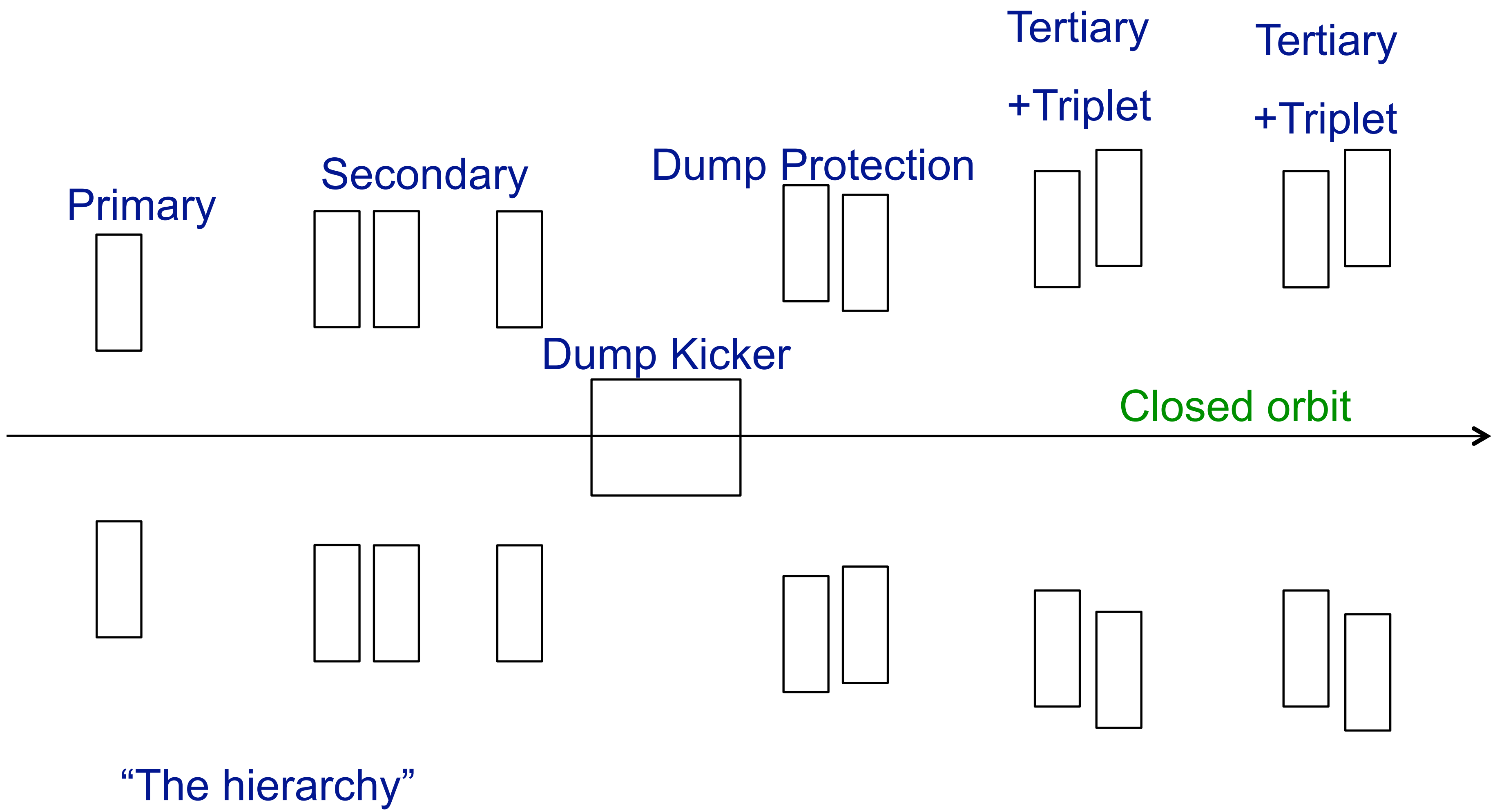
Alignment tolerances < 0.1 mm to ensure that over 99.99% of the protons are intercepted.

Primary and secondary collimators are made of reinforced graphite – robust.

Pedagogical collimation 1

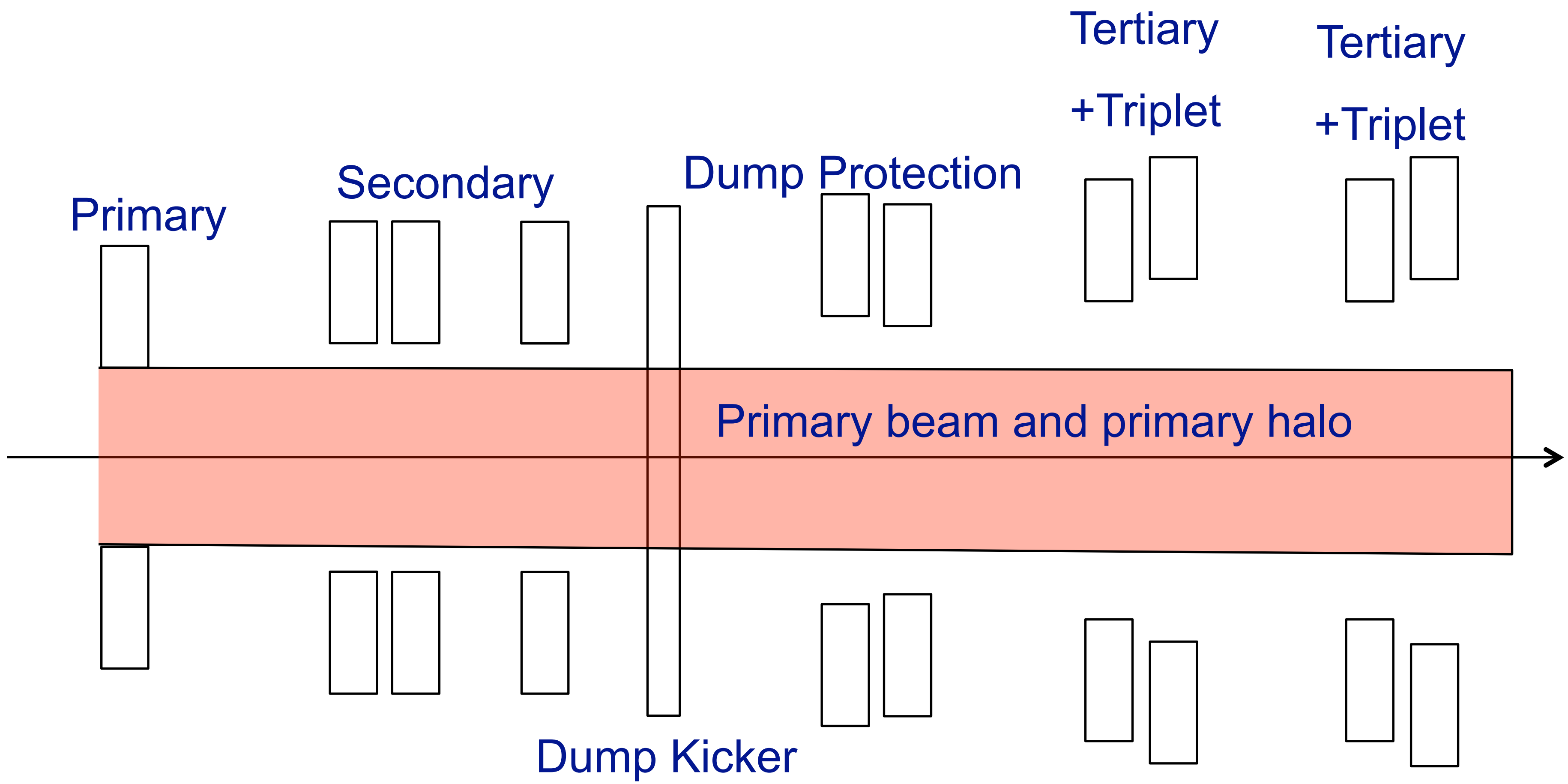
Ralph Assmann

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



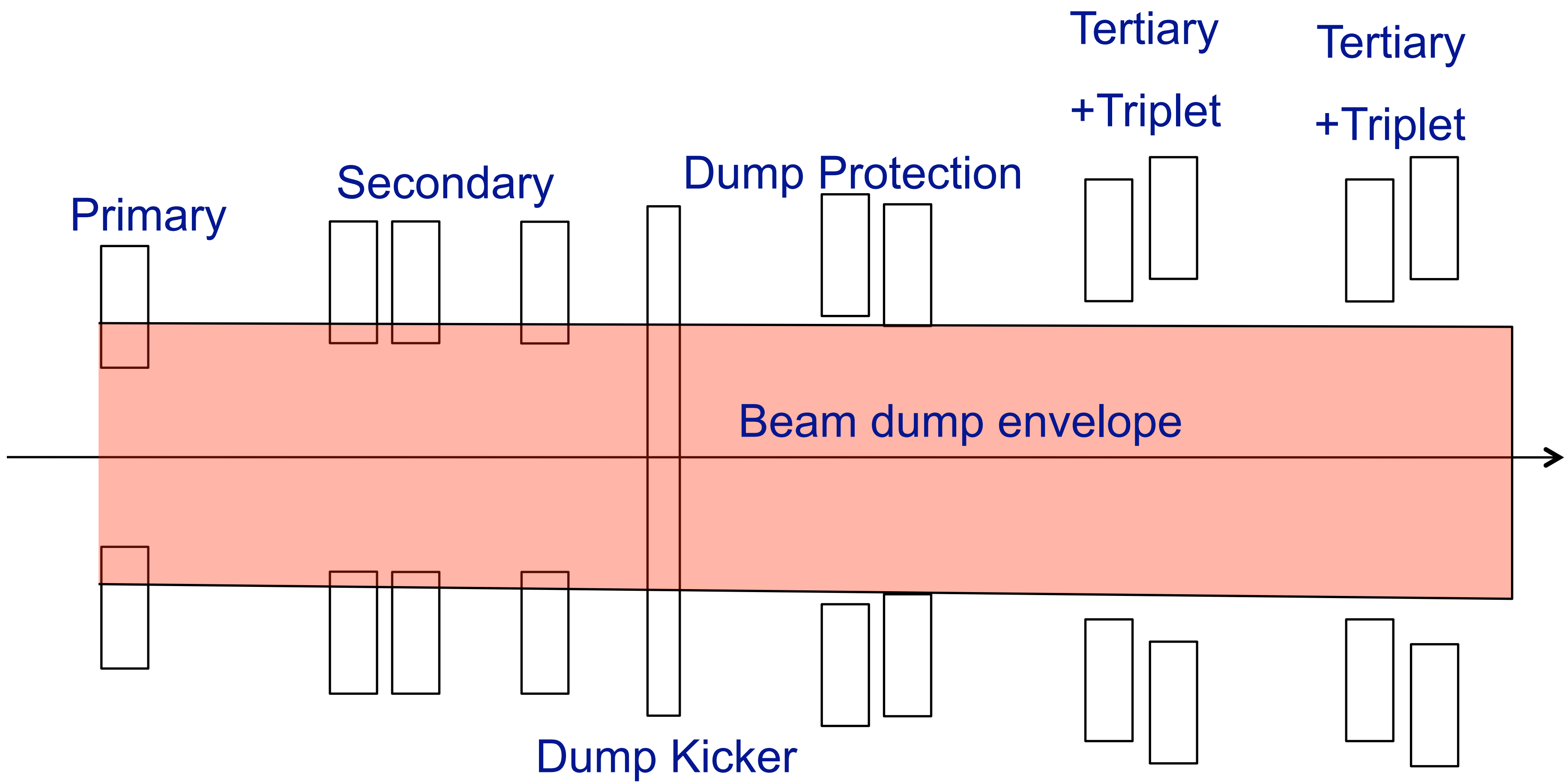
Pedagogical collimation II

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



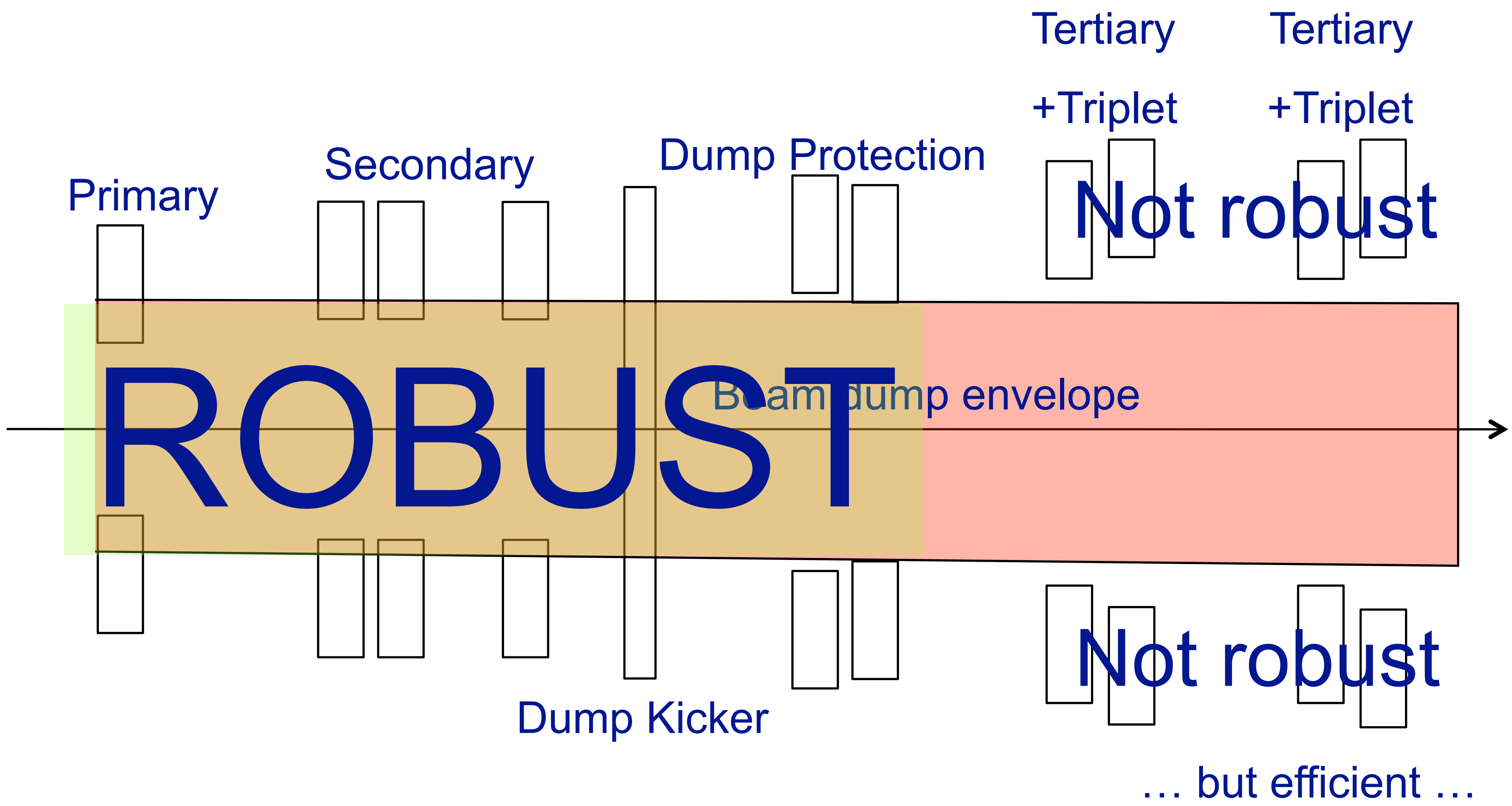
Pedagogical collimation III

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



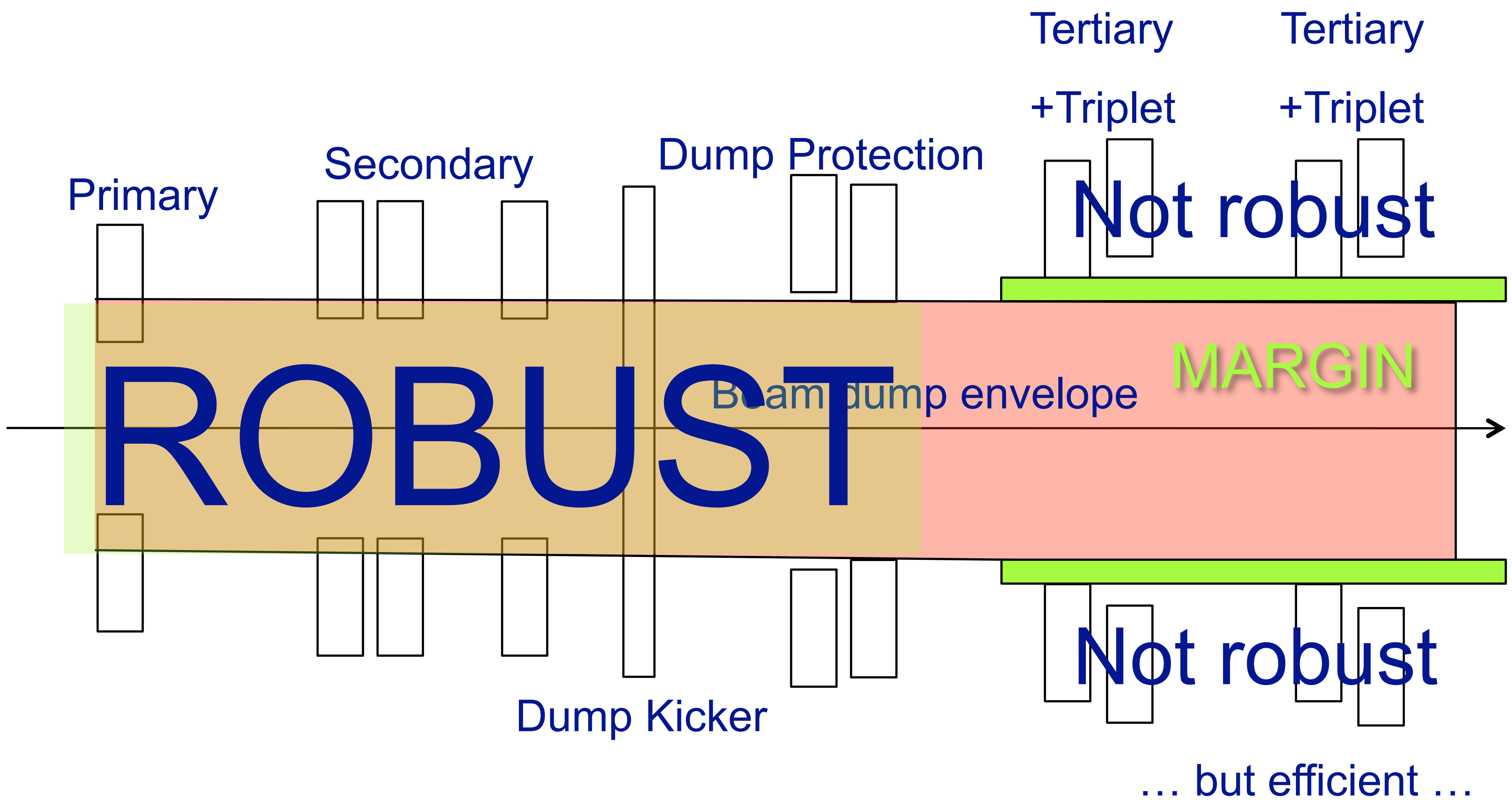
Pedagogical collimation IV

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



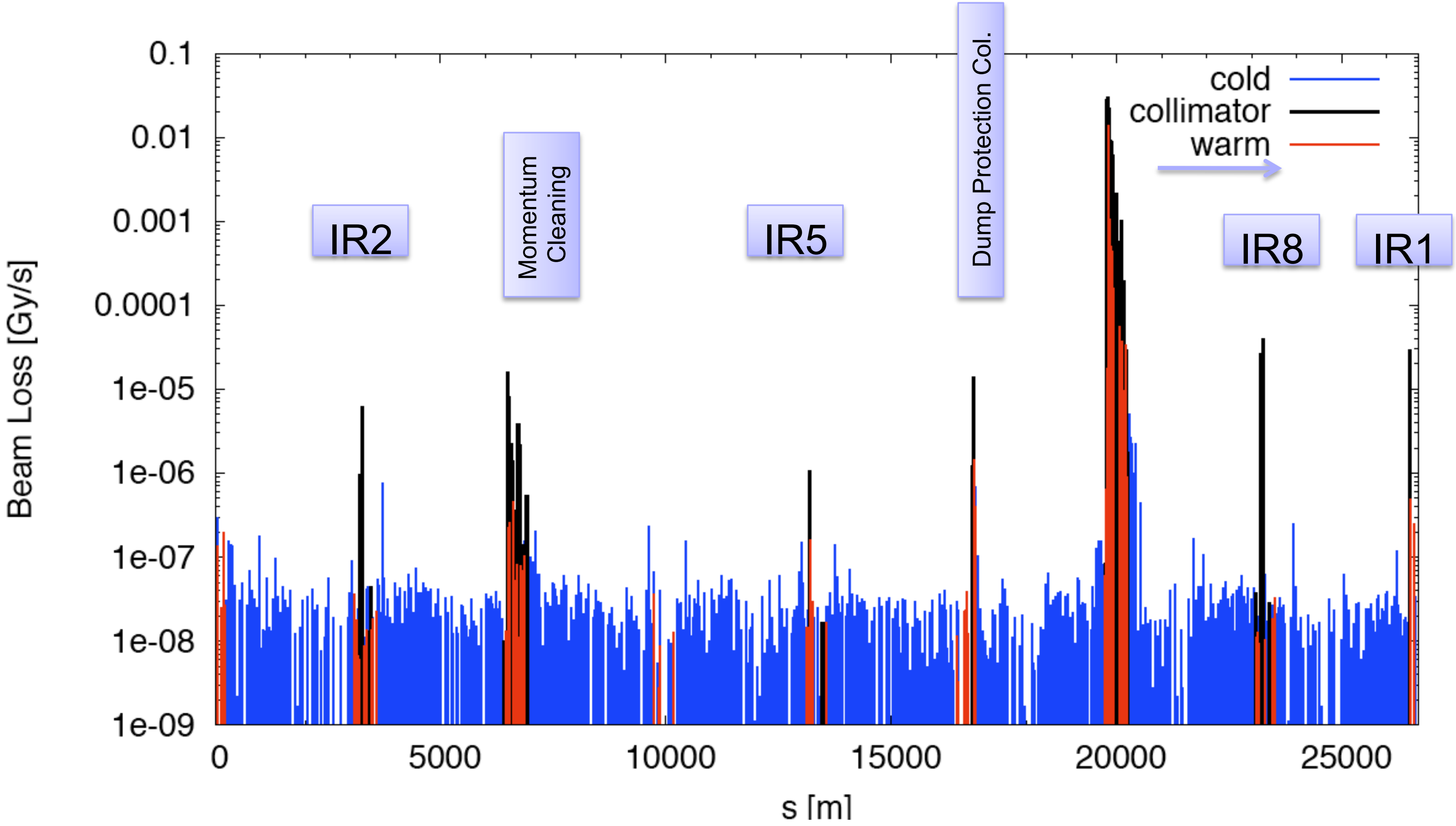
Pedagogical collimation V

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



Measured Cleaning at 3.5 TeV

(beam1, vertical beam loss, intermediate settings)



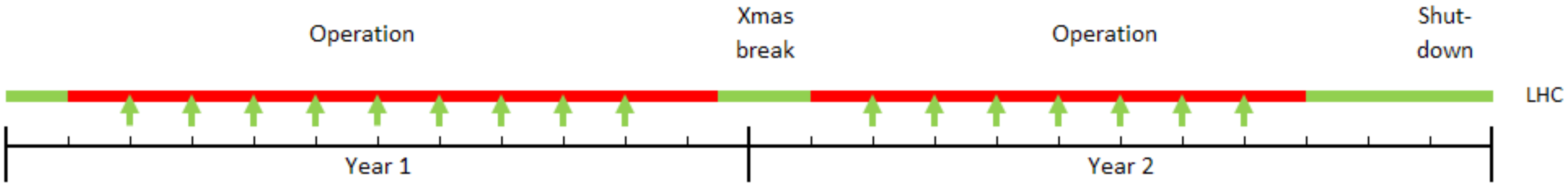
Conclusions from the pedagogical break

- 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
- If these rules are not respected something will get broken.
- It will take us some time to make sure we are fully, absolutely, completely, obeying these rules.

LOOKING AHEAD
- PLANNING

2 years cycle: global strategy

- Operate machines on a 2 year basis



- Technical stops to solve non-conformities and anticipate preventive maintenance

- Mid-period: Christmas break to perform minimum maintenance activities

- Allow a month's recommissioning after a long shutdown

Operation month/year

After a year or so…

- 30 days per month
- ~3 day technical stop & recovery
- ~2 days machine development

- ~60% machine availability
  - During which time we are dedicated to trying to do physics

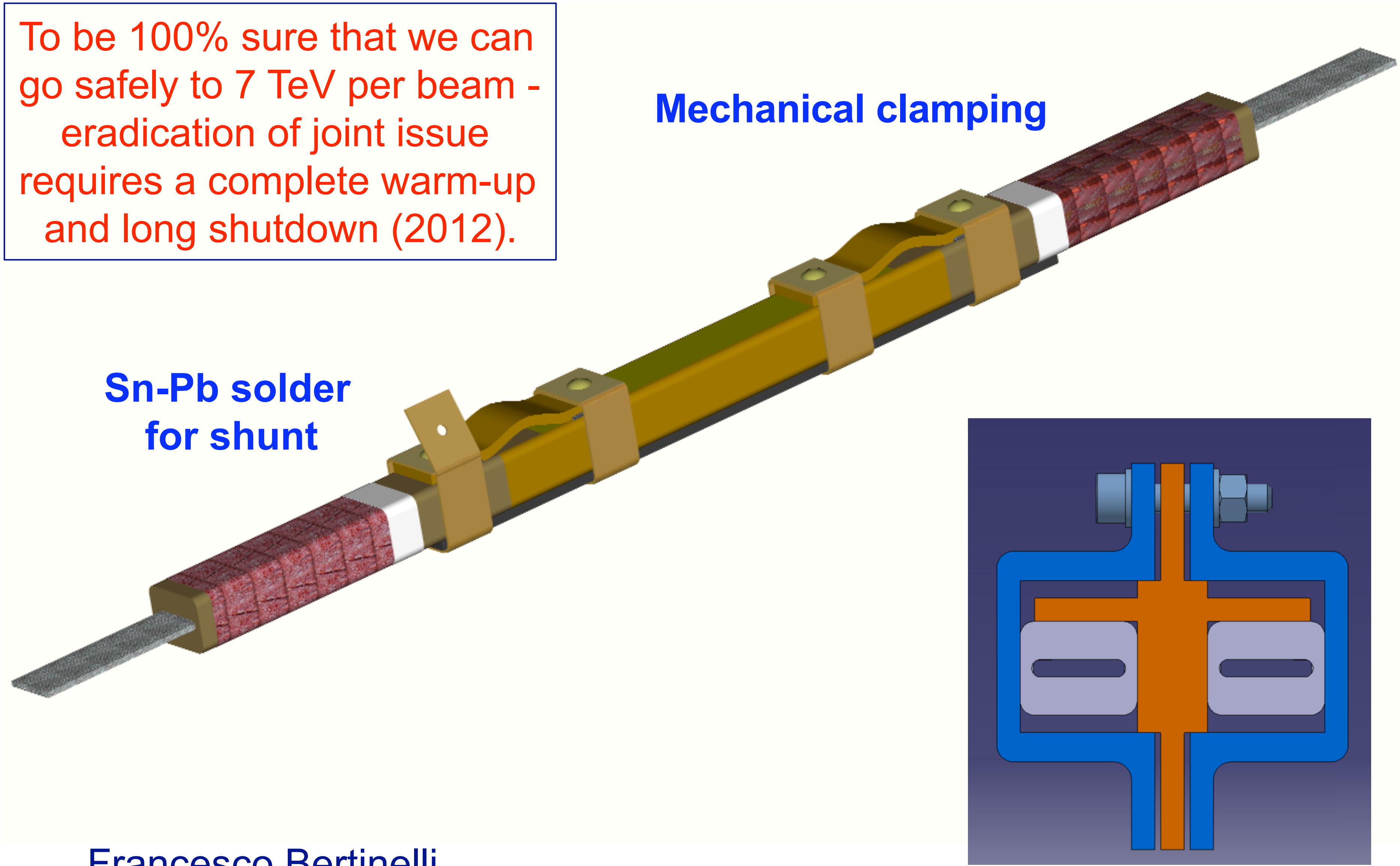
- ~4 weeks of ions
- Other requests e.g. Totem

Main shutdown drivers

Year	Main drivers	Secondary activities
2012	Splice consolidation	Possible collimation phase 2 – IR3 He Relief valves Atlas consolidation, installation of new forward beam pipes R2E
2015	Linac4 Collimation phase 2 CMS consolidation of calorimetry and forward pixel tracker	Booster upgrade RF cryogenics R2E
2017	Atlas phase 1: installation of a new pixel detector plus other upgrades	LHCb upgrade Alice inner vertex upgrade R2E Prepare for crab cavities
2020	HL-LHC upgrade	Atlas phase 2 Alice phase 2

The consolidated main IC splice

To be 100% sure that we can go safely to 7 TeV per beam - eradication of joint issue requires a complete warm-up and long shutdown (2012).



Francesco Bertinelli

Collimation phase 2

- Phase II (upgrade for nominal/ultimate intensities):
  - To be used in stable parts of operation like physics (robustness can be compromised).
  - Fixes limitations in efficiency, impedance and other issues.
- Warm leg
  - Additional secondary collimators and scrapers into IR3 and IR7 warm regions (already prepared)
- Cold leg
  - Collimators into super-conducting dispersion suppressors in IR7, IR3 and IR2.
  - Big job involving moving superconducting magnets, aim to do IR3 in 2012 shutdown

LINAC4

- Stage one LHC Luminosity upgrade program
- Linac2 giving serious reliability/sustainability worries: persistent vacuum problems, obsolete RF tube design
  - instead of an intensive consolidation program, replace with a new LINAC.
- Implement at CERN modern technologies for better injection and reduced losses (H- injection etc.).

Requires 7 months to link up with the booster and commission – no protons

LHC - medium term planning

	J	F	M	A	M	J	J	A	S	O	N	D
2010	**nQPS**										Ions	
2011											Ions	
2012	**SPLICE CONSOLIDATION**											
2013	**SPLICE CONSOLIDATION**											
2014											Ions	
2015	**COLLIMATION PHASE 2, LINAC4**											
2016											Ions	
2017	**ATLAS: new pixel detector++, ALICE inner vertex upgrade, LHCb new vertex detector**											
2018											Ions	
2019											Ions	
2020	**HL-LHC upgrade**											

Technical stop or shutdown

Proton physics

Ion Physics

NB: provisional

LOOKING AHEAD
- LUMINOSITY

2010 – main aims

- Clear priority to lay the foundations for 2011 and delivery of 1 fb^{-1}
- Need to perform a safe, phased increase in intensity with validation and a running period at each step
- Gain solid operational experience of faultlessly injecting, ramping, squeezing and establishing stable beams
- Need to finish commissioning of some critical sub-systems
  - E.g. Abort gap monitoring, abort gap cleaning, transverse damper
- Aim for steady running at or around 1 MJ over the summer

This week's news

- Obvious benefits of first increasing bunch intensity and then number of bunches – hence interest in ~1e11
- Higher intensity does bring challenges
  - Single bunch transverse instabilities, emittance blow-up, single bunch longitudinal instabilities, coupled bunch instabilities
  - Increased beam-beam
  - Machine protection issues
- These are anticipated, however causes to be understood quantitatively, cures to be deployed
- Decision this week – go for ~1e11 at 3.5 m.
  - Initial indications show 8e10 might be easier
- Will take another ~2 weeks to commission
- It is challenging… but we do have a lower intensity backup

2010 – pushing toward 1 e32 $cm^{-2}s^{-1}$

If 1e11 becomes operational…

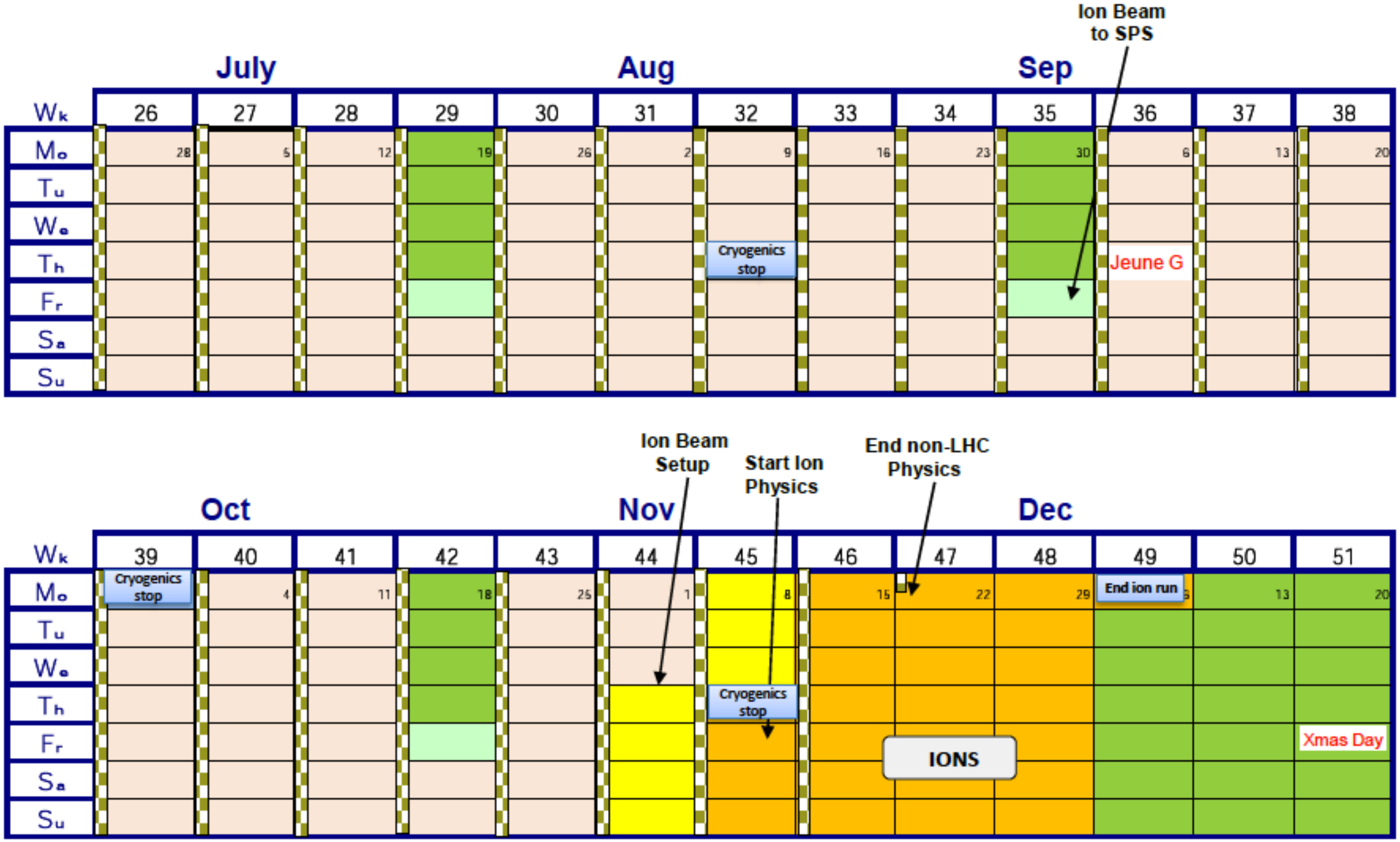
STEP	Nb	Nc	Ib	Itot	MJ	Increase	Peak lumi	Days	Int. Lumi	Approx date
4	3	1	1.E+11	3.0E+11	0.2	1.2	2.5E+29	5	0.032	W4 June
5	4	2	1.E+11	4.0E+11	0.2	1.3	5.1E+29	5	0.066	W1 July
6	8	4	1.E+11	8.0E+11	0.4	2.0	1.0E+30	5	0.13	W2 July
7	20	10	1.E+11	2.0E+12	**1.1**	2.5	2.5E+30	10	0.6	W3 & 4 July
8	24	24	1.E+11	2.4E+12	**1.3**	1.2	6.1E+30	20	3.2	August
9	48	48	1.E+11	4.8E+12	2.7	2.0	1.2E+31	10	3.1	September
10	96	96	1.E+11	9.6E+12	5.4	2.0	2.4E+31	10	6.2	September
11	144	144	1.E+11	1.4E+13	8.1	1.5	3.6E+31	10	9.3	October
12	192	192	1.E+11	1.9E+13	10.8	1.3	4.9E+31	10	12.7	October
13	240	240	1.E+11	2.4E+13	13.4	1.3	6.1E+31	7	11.1	November

if not a similar table with lower bunch intensity, more bunches.

See 1 MJ as the damage threshold hence the hold over summer (plus some experts will be away)

Also need to gain experience and confidence before moving on

2010 – second half



Early Heavy Ion Run Parameters

John Jowett

		Early (2010/11)	Nominal
$\sqrt{s}$ per nucleon	TeV	2.76	5.5
Initial Luminosity (L_0)	$cm^{-2}s^{-1}$	1.25×10^{25}	10^{27}
Number of bunches		62	592
Bunch spacing	ns	1350	99.8
β^*	m	2	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)

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

In two years: 2 x10^7 central collisions, integrated luminosity 25 μb^{-1}

2011 – 3.5 TeV

- Restart 4th February
- 9 months protons, 4 weeks ions
- Run flat out above 1e32 $cm^{-2}s^{-1}$

	Nb	Ib	Total Intensity	MJ	beta* [m]	Peak Lumi [$cm^{-2}s^{-1}$]	Int Lumi/month [pb^{-1}]
50 ns	432	7 e10	3 e13	17	2.5	7.4e31	~59 (34)
Pushing intensity limit	796	7 e10	5.1e13	31	2.5	1.4e32	~109 (63)

17% nominal

HF ~ 0.2

- Certainly need to be delivering 1e32 $cm^{-2}s^{-1}$ at least
- Should be able to deliver a total approaching 1 fb^{-1}

To 2014

- 2012: splice consolidation etc.
- 2013: 6.5 TeV ~24% nominal intensity
- 2014: 7 TeV ~27% nominal intensity

Limits from phase 1 collimation

Year	Months	Energy	Beta [m]	Ib	Nb	Peak lumi [$cm^{-2}s^{-1}$]	Lumi/ month [fb^{-1}]	Int Lumi/ Year [fb^{-1}]
2010	8	3.5	5	10e10	240	4.3e31	-	0.1
2011	9	3.5	2.5	7e10	796	1.4e32	0.1	0.9
2012								
2013	7	6.5	1	1.1e11	720	1.3e33	1	7
2014	8	7	0.55	1.1e11	796	2.9e33	2	16

NB Illustrative numbers: beta*, bunch intensity, number of bunches will be negotiable

Independent estimate

Courtesy of a more pessimistic but perhaps more realistic Massi Ferro-Luzzi who assumes a Hübner factor of 0.2

Year	Months	energy	beta	Ib	Nb	Peak Lumi [$cm^{-2}s^{-1}$]	Int Lumi/ month [fb^{-1}]	Int Lumi/ Year [fb^{-1}]
2010	6	3.5	2.5	7e10	720	1.0e32	-	0.1
2011	9	3.5	2.5	9e10	720	2.0e32	0.1	1
2012								
2013	6	6.5	1	9e10	720	9e32	0.45	2.7
2014	8	6.5	1	9e10	1404	1.7e33	0.6	5.3

In the same ball park

2015 – 2016 to nominal

Essentially dedicate 2015 to LINAC4, collimator upgrade etc.

Year	Months	energy	beta	Ib	Nb	Peak Lumi [$cm^{-2}s^{-1}$]	Lumi per month [fb^{-1}]	Int Lumi Year [fb^{-1}]
2016	~9	7	0.55	11e10	2808	1e34	6.7	~60

Might hope to hit nominal in 2016

Beyond 2016/17

- Assumptions
  - Booster, PS at increased injection energy plus LINAC4 are good for ultimate (after a suitable commissioning period)
  - ~1.7 x 10^{11} can be handled by the SPS
  - LHC can handled ultimate intensity
    - Ultimate intensity is challenging for the LHC. Many systems at technological limits with little or no margin.

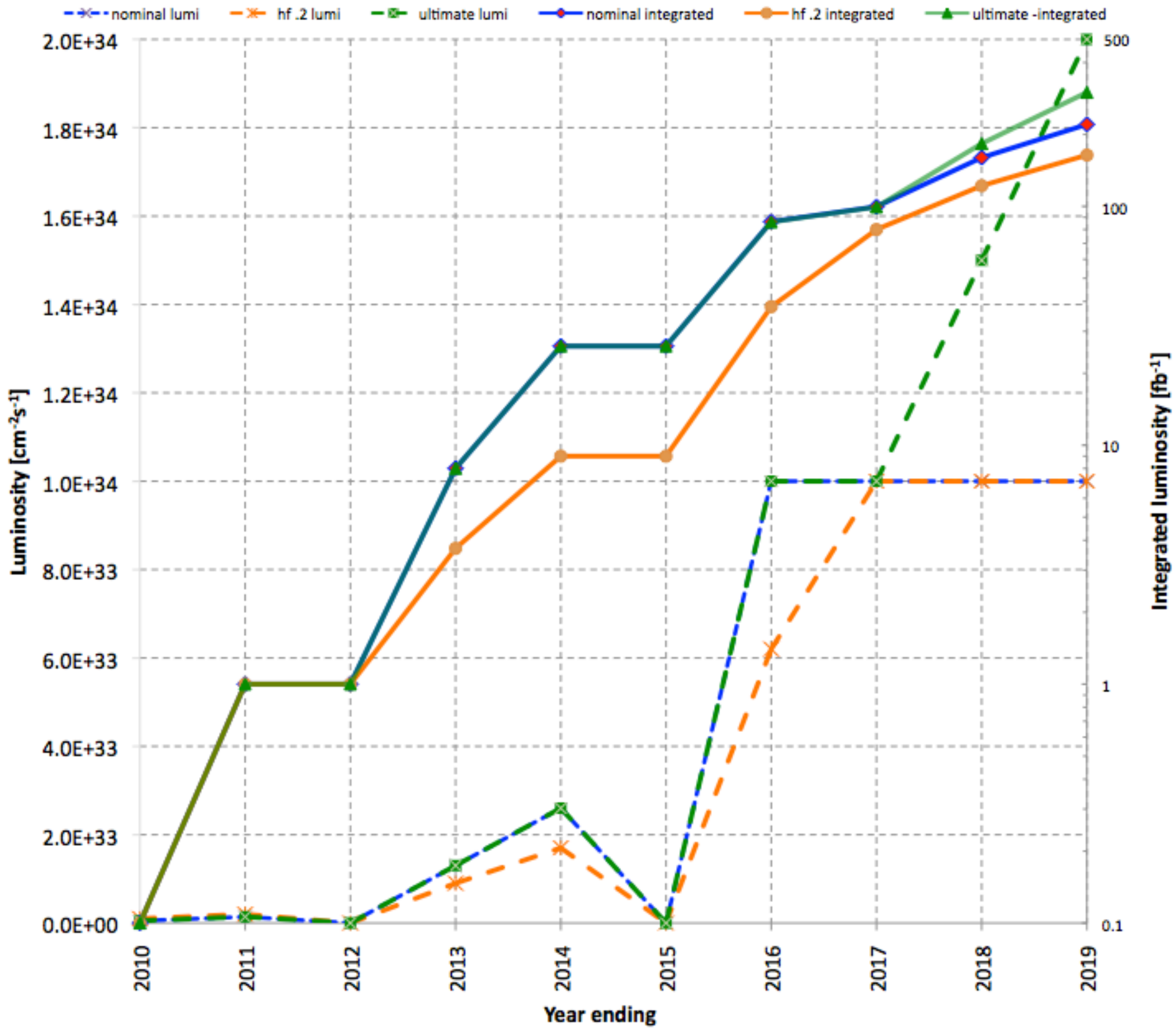
Stay at or around nominal

Year	Months	Int Lumi [fb^{-1}]
2017	2	13
2018	9	60
2019	9	60

Able to push towards ultimate

Year	Months	Int Lumi [fb^{-1}]
2017	2	13
2018	9	84
2019	9	117

2010 - 2019



nominal lumi
hf .2 lumi
ultimate lumi
nominal integrated
hf .2 integrated
ultimate -integrated
2.0E+34
1.8E+34
1.6E+34
1.4E+34
1.2E+34
1.0E+34
8.0E+33
6.0E+33
4.0E+33
2.0E+33
0.0E+00
Luminosity [cm^{-2}s^{-1}]
500
100
10
1
0.1
Integrated luminosity [fb^{-1}]
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
Year ending

Summary

- 2010 toward 1e32 $cm^{-2}s^{-1}$
- 2011 at or above 1e32 $cm^{-2}s^{-1}$
- 2012 – splice consolidation and collimation prep.
- 2013 – 6.5 TeV ~24% nominal
- 2014 – 7 TeV ~27% nominal
- 2015 – LINAC4, CMS, collimation phase 2
- 2016: 7 TeV – towards nominal performance
- 2017: long shutdown – short run
- 2018 – 2019 either:
  - a) at or around nominal luminosity
  - b) or push towards ultimate
- 2020 – 2022 – HL-LHC

Conclusions

- Good start, lots still to sort out, lots to understand.
- As we push up in stored beam energy - going to have to make sure there is 100% machine protection coverage
  - This will require some patience
- Targets for the next year and a half are clearly defined.
  - And well absorbed on the machine side
- Provisional planning until 2019 has been presented
- Ramifications of 19th September are still with us - this will take time to fix properly
- Luminosity estimates have been presented
  - All numbers to be treated with a modicum of circumspection

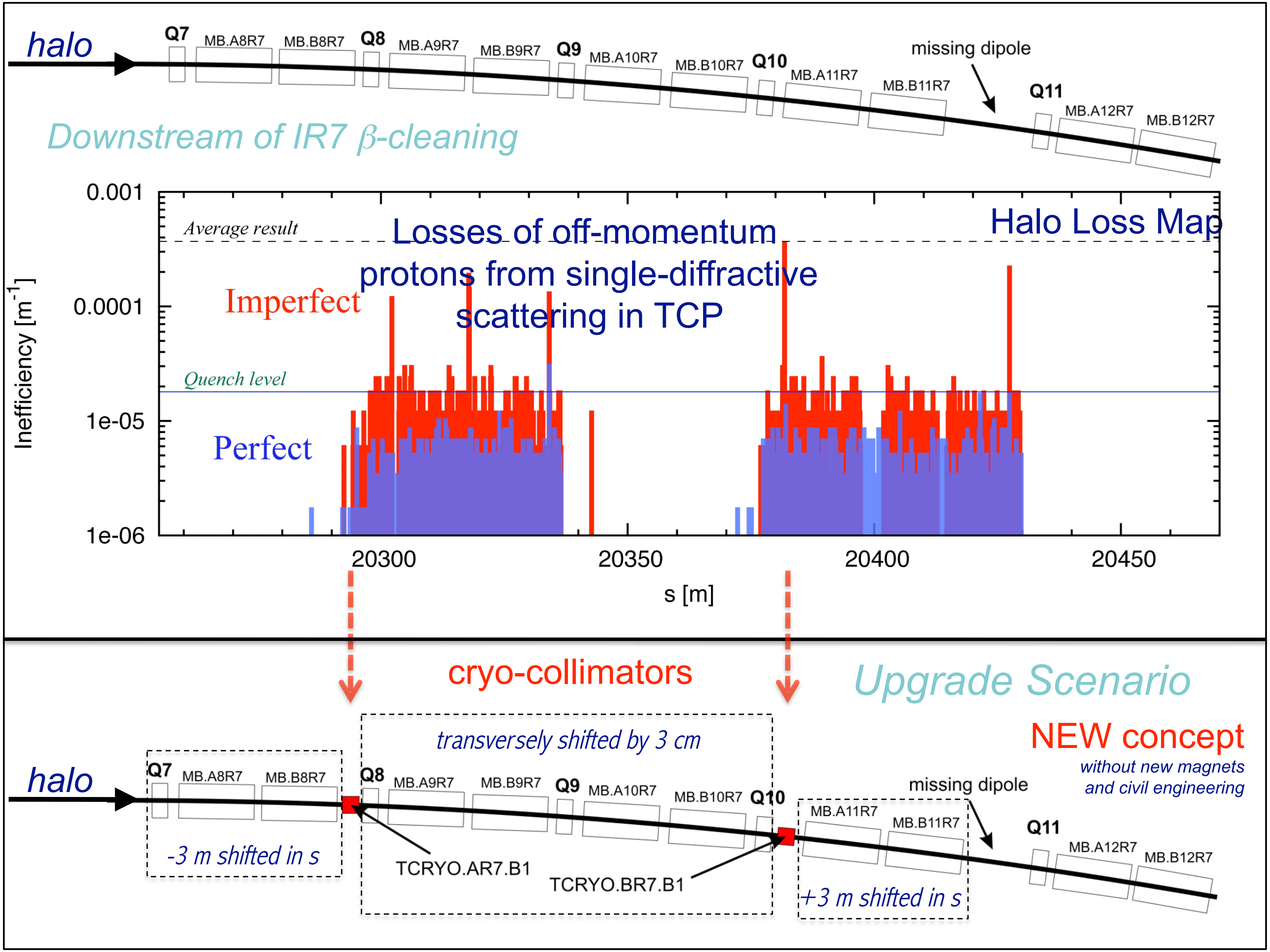
The prospects are good!

BACKUP

Safety critical aspects of the Dump System

- Signal from beam interlock system and triggering
  - No trigger = no beam dump
- Energy tracking
  - Potentially catastrophic (whole beam at “any” amplitude)
- Extraction kicker retriggering after single kicker erratic
  - No retriggering could put whole 7 TeV beam at ~10σ
- Mobile protection device setting
  - Wrong w.r.t. orbit exposes LHC arc / triplets / collimators.
- System self-tests and post-mortem
  - Undetected ‘dead’ MKD severely reduces reliability
- Aperture, optics and orbit
  - Dump with bad orbit could damage extraction elements MSD, TCDS or MKB
- Extraction – dilution kicker connection and sweep form
  - Insufficient dilution could damage TDE, BTVDD and TDE entrance window
- Abort gap ‘protection’
  - Beam in the abort gaps risks quench, or TCT/LHC damage if TCDQ position error
- Fault tolerance with 14/15 extraction kickers
  - The system is designed to operate safely with only 14 out of the 15 MKDs

Nearly all aspects need beam commissioning (validation or optimisation)



halo
Q7
MB.A8R7
MB.B8R7
Q8
MB.A9R7
MB.B9R7
Q9
MB.A10R7
MB.B10R7
Q10
MB.A11R7
MB.B11R7
missing dipole
Q11
MB.A12R7
MB.B12R7
Downstream of IR7 β-cleaning
Halo Loss Map
Losses of off-momentum protons from single-diffractive scattering in TCP
Average result
Imperfect
Quench level
Perfect
Inefficiency [m^-1]
0.001
0.0001
1e-05
1e-06
20300
20350
20400
20450
s [m]
cryo-collimators
Upgrade Scenario
NEW concept
without new magnets and civil engineering
transversely shifted by 3 cm
-3 m shifted in s
+3 m shifted in s
TCRYO.AR7.B1
TCRYO.BR7.B1