HL-LHC Options
Reasons for Embarking on 3 Additional Options in the Baseline

Oliver Brüning

Annual HL-LHC meeting – 14-16 October 2019

OPTIONS

THE NEVERLAND!

In the C&SR 2016, we presented a list of «desirable» options in the project.

Some others have been added in the last 18 months:

Where are we?

Note: LHC is approaching its real limits only now. The situation is different than a few years ago for knowledge of aperture, control of collision, head-on beam-beam limit, injector performance, pile up/PUD acceptability. **The upgrade is shooting at a moving target!**

Options that we kept open

Type P=Perfor. R=Risk mit & protect. O= Optim.	*Item description*	*WP # concerned in budget or FTE*	*Status Y=yes approved N=Not O=open*	*Date decision*	*Comments*	*Approximate Cost (MCHF) In many cases approximate*
R-O	**Full remote alignment**	**15, 3,12**	**O -> Y**	**Oct 2018**	**Reduce corrector magnets – new optimization MS – Less dose to personnel**	**Cost neutral or saving**
R	**E-lens for beam halo depletion**	**5, 13**	**O -> Y**	**Dec 2018**	**Scrutiny by C&SR3**	**10 MCHF**
P	**Crystal Collimators (for heavy ions)**	**5**	**O**	**Mar 2019**	**Depend on final quench test in 2018**	**1** ➔ 1.2MCHF
R	**Second undulator pair for Synchrotron Light Monitor (assembled in the D4 cold mass)**	**13**	**O**	**Dec 2019**	**Monitor of halo growth at injection and ...nning: currently evaluating need and technology**	**2.2** 0.4 MCHF CERN
R	**Extraction System: MKE and Dump (additional dil. Kickers, dump window, new dump materials…)**	**14**	**O**	**Dec 2020**	**Wrt to CSR2016 it doubled the cost: both MKI and TDE needs upgrade. However it must be shared with consolidation**	**7.50** ➔ 8.2MCHF after review in 2019
R	**Injection System: TDQ and BETS**	**14**	**O**	**Dec 2020**	**More for LHC flat optics (CONS)**	**0.75**
P	**Precision control EPC of S12-S45-S56-S81 main dipole circuit**	**6B**	**O**	**Dec 2020**	**NEW: This is to fight lumi unbalance**	**0.6**
P-R	**LRBB compensator via wires**	**13**	**O**	**Dec 2021**	**Mitigation of CC shortfall; Proto success; second step proto in 2018 (2.75 MCHF invested). Final solution not yet defined.**	**5-10 ?**
O	**LESS (Laser Engineered Surface Structure)**	**12**	**O**	**Dec 2021**	**Alternative to a-C coating**	**Cost neutral**

Content of this talk!

HiLumi HL-LHC PROJECT

Hardware Options that have been Integrated

Options replaced by alternative / new design modifications:

1

2 Financed by project and consolidation and integrated into the CtC!

3 fig

New Options I:

1) Fully remote alignment for matching section optimization:
   beneficial for ALARA, technical solution is being developed by CERN;
   should be cost neutral / beneficial with savings in MS upgrades

   Implemented into baseline in 2019 and ‘financed by’ MS optimization

2) Higher precision current control for PC in S12, S45, S56 and S81
   mitigation against increased tune fluctuations due to ATS optics

   Study looks very promising; but left as option for consolidation

Other approved Options since C&SR3

- **IT Quad Cold diodes**: desirable to increase robustness of protection system (not presented in C&SR 2016, stemmed out from Circuit Review 2017)
  - Replace warm diodes and is today in the baseline
  - Required R&D and validation (radiation hardness at cold)
  - Extra cost for R&D financed as baseline: 0.55 MCHF
  - Extra cost for implementation: 0.3 MCHF
    only, because of savings from warm diodes - bus bars included in WP3)

Hardware Options still considered for Baseline Integration

1), 3), and 4)

Content of this presentation:

Decided to pursue all three of them through in-kind contributions

Options motivated by recent LHC operation experience:

Decided to prepare integration into the HL-LHC baseline!!! [59th TCC – 4th October 2018]

Organized a dedicated review on the BDS: 5.2.2019

Integration into the baseline with the help of in-kind contributions

Main Points & Outcome of the BDS Review Feb'19

- MKD Type 2 erratic involving beam sweeping on TCDS and TCDQ
  ➔ Mitigation by upgrading the generators [operation at lower voltage] and implementing a new re-triggering system

- MKBV flashover with antiphase, effectively eliminating 3 dilution kicker
  ➔ Particularly problematic in horizontal plane where the LHC has only 4 dilution kicker!!!

- TDE Nitrogen leaks: movement of the beam dump core during beam dumps with high beam intensity [16L2] ➔ new Nitrogen line constantly supplying N2 to the dump; mechanical integrity of the LHC dump core?

- Energy density and hotspot temperature too high for nominal HL-LHC parameters and failure scenarios [even with the additional 2 hor. Dilution kicker] ➔ new windows and new dump core!

HL-LHC Hardware Options

H1) Considered for machine protection and risk mitigation:

O. Bruning, TCC – 8th March 2018

WP14

-**MKB or TDE upgrade**

(Dump protection in ca… …ach 3000^{o}).

…ndows

Implementation into HL-LHC project baseline

[59th TCC – 4th October]

Together with Consolidation and

in-kind contributions!!!

➔ …ng RunIII

➔ …udies and development included in WP14

➔ ~~Ca. 3.6 MCHF for dump upgrade implementation~~

➔ Integration should not be an issue

➔ 8.2 MCHF for full upgrade after review Feb. 2019

Summary of Russia Collaboration agreement

- The exact list of items is under discussion
  - First approach:
    - all hardware that is off the shelf is procured by CERN (HV components, PLCs, racks)
    - All mechanical parts, magnetic cores, coils by Russia
    - Participation of Russia in-kind to design studies and drawings production in addition to assembly and installation
    - After signature we expect more precise technical discussions and precise planning

Hollow Electron Lens

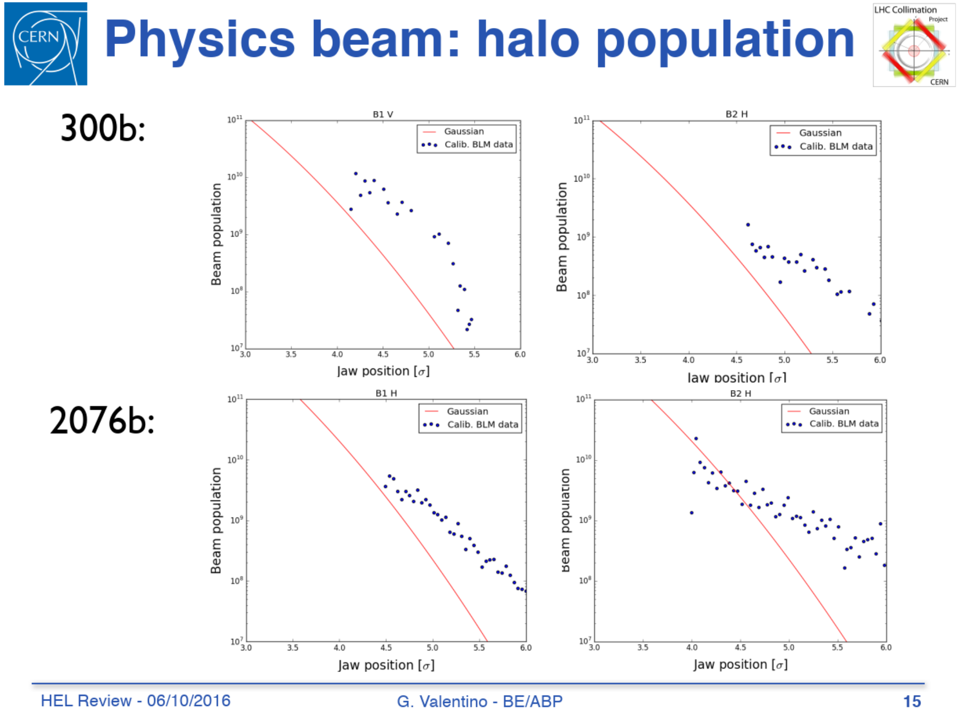
- Several reviews organized that underlined the necessity and benefit during 2012 to 2017: internal review 2012; Intern. Review on the needs in 2016; Intern. technical readiness 2017
- No clear demonstration of definite need for operation:

  Loss spikes of Run1 not evident during Run2; but beam dynamics and losses with HL-LHC beams [2x beam intensity and beam-beam] not easily predictable
- But clear outline of risk when operating with a beam with over 30MJ stored beam energy in beam halo [> 3σ]

➔ Prudent mitigation of risk for efficient operation!

Motivations

- Around 5% of the beams is in the tails (> 3.5 sigma), compared to 0.22% for Gaussian
- Factor 22 difference: scaling to HL-LHC parameters = 33.6 MJ vs 1.48 MJ
- No apparent correlation with energy

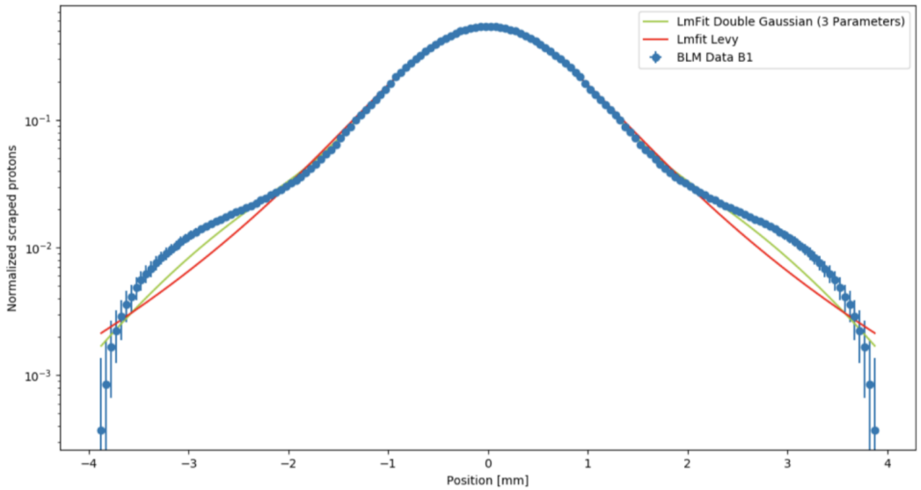


MD results

Studies at injection, step size 50um/5s, with 1 bunch

Measurements confirm overpopulation of beam tails.The fraction of particles in the **tails over 4σ** has also been evaluated, from which it has obtained that in the **horizontal plane it is in a range between 2% and 3%**, while in the **vertical plane between 3% and 6%.**

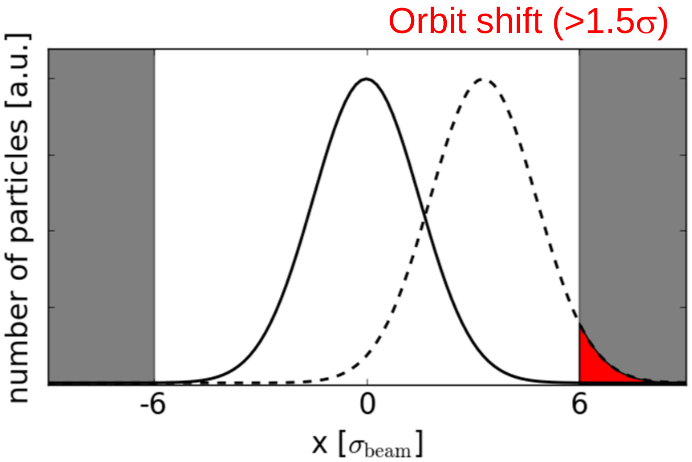
Scraping at **injection** performed with a step size of 50 µm every 5 seconds (1 Hz data)



H.Morales, P.Racano

Motivations

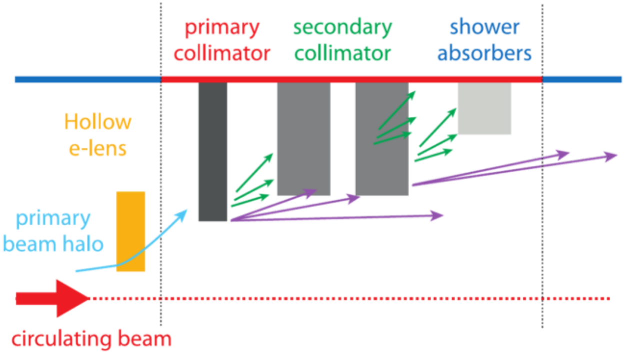
- Crab Cavity failure can induce fast (few turns) orbit shift or bunch rotation

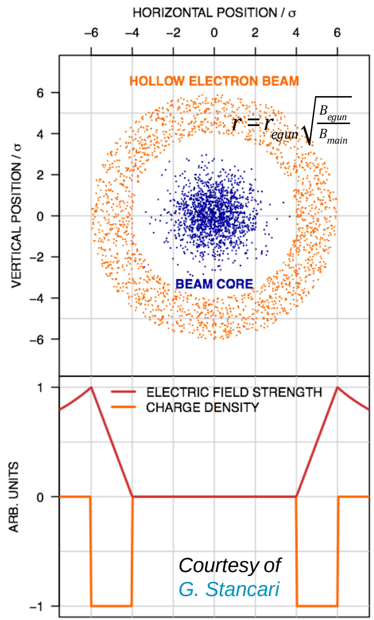


- Small earthquakes (Geothermie2020)
- In 2012 and 2016 LHC operation sometimes sudden beam losses occurred => beam dumps in HL-LHC?
- Increase of operational margin (e.g. less sensitive to transients)

Principle of Hollow Electron Lens

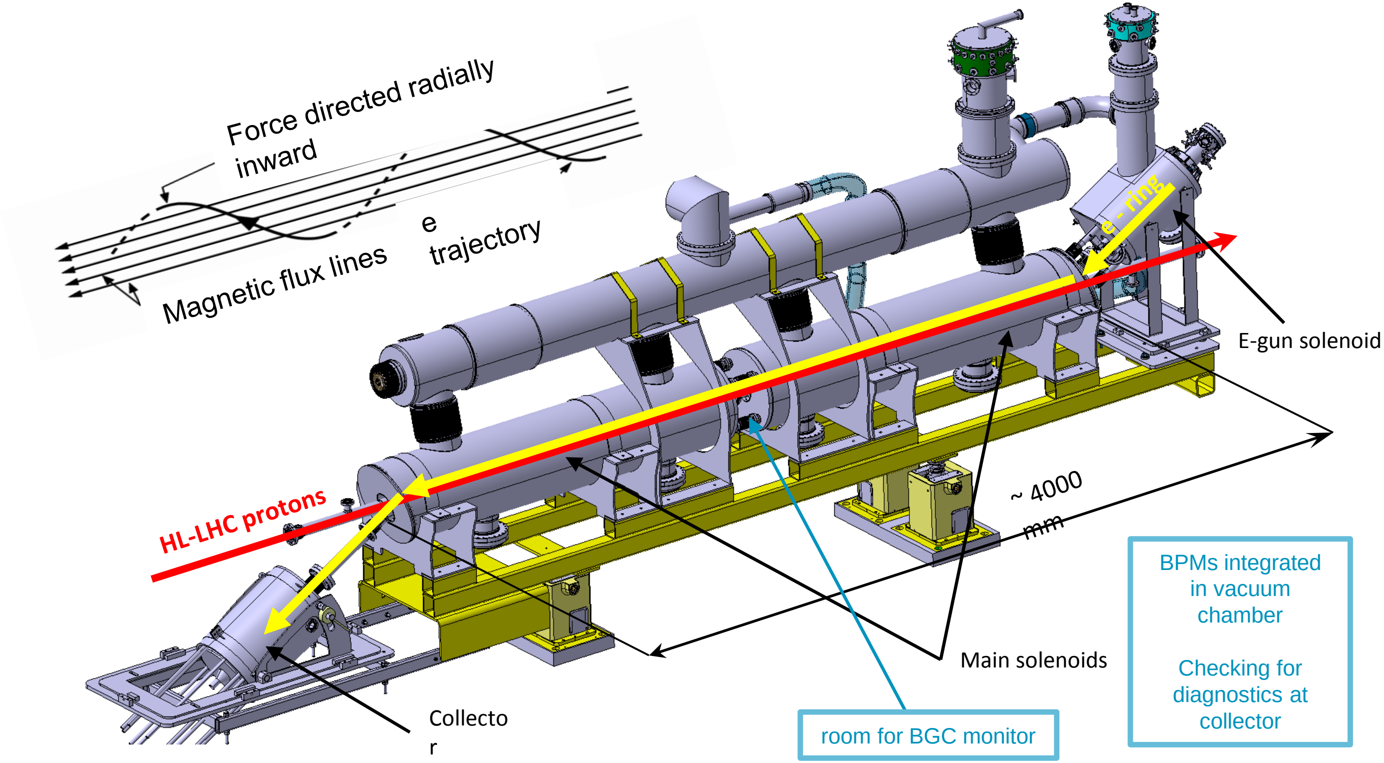
- Circulating beam travelling inside a hollow electron beam (cylindrical shell) over a short distance
- Halo particles kicked to higher amplitudes by electromagnetic field of electron beam (slow process)
- Eventually hit collimators





- Circulating beam core not affected (in field-free region)

The system configuration



Electrons are produced by the cathode of an e-gun.
A system of superconducting solenoids cooled at 4.5K generates the magnetic field to tune de size and steer the trajectory of the electron ring.

Power Converter optimization and Modulator strategy for HEL

- Power converters recovered and updated at CERN where possible
- Modulator: participation to the design by Russian personnel under BE/RF supervision (under discussion)

Hollow Electron Lens

- Organized review for technical readiness and design maturity for production in October 2018
- International Collimation Review at CERN 11-12 Feb 2019: https://indico.cern.ch/event/780182/
- Prepared resource document for CERN groups and HL-LHC Work Packages: EDMS 2186609

  ➔ lowered CERN core cost to ca. 35% of total budget
- Discussed required manpower at CERN with implied groups

Summary of Russia Collaboration agreement

- A precise list has been agreed during Summer

BINP

SYSTEM	Component	Total quantity + Spares	CERN Responsible /Group	BINP Responsible
MAGNET SYSTEM	Gun SC solenoids (0.2 to 4T)	4+2	Gijs De Rijk/TE-MCS	A.Bragin
	Bend SC solenoids (3.5T)	4+2		
	Main SC solenoids (5T)	4+2		
	Collector SC solenoids (0.2 + 1T)	2+1		
	Correctors gun (Hor and Ver)	4+2 (3H, 3V)		
	Correctors main (H and V)	24+12 (18H, 18V)		
	Dipole corrector	2+1	Gijs De Rijk	A.Bragin
	Cryostat	2+1	Vittorio Parma/TE-MCS	A.Bragin
	He vessels	12+6		
Supporting	Supports	2+1	Vittorio Parma	A.Polyansky
	Feet	6+3		
Source and collection	Gun body	2+1	Adriana Rossi/BE-BI	D. Nikiforov
	Cathodes	4+2		
	Collector	2+1		
Vacuum	Pipes	2+1	Vincent Baglin/TE-VSC	A.Krasnov
	Y chambers	4+2		
	Bellows	8+4		
	Valves DN63	4+2		
	Valves DN40	2+1		
	Turbopumps	4+2		
Beam instrumentation (electrics and cabling included)	BPM	4+2	Manfred Wendt/BE-BI	Yu. Rogovsky, E. Dementiev
	YAG screen	2+1	Adriana Rossi	O. Meshkov
	CT	4+2	Tom Levens/BE-BI	A.Chupyra
Modulator	Anode e-beam modulator	2+1	tbd	I.Gusev
TEST STAND	Test stand at BINP	1	-	
Ancillaries	Testing components at BINP		-	
	• Magnet windings		-	A. Bragin
	• Vacuum system		-	A. Krasnov
	• BPM		-	Yu. Rogovsky
	• Electron gun & collector		-	D. Nikiforov
	• Modulator		-	I. Gusev
	Testing components at CERN:		Adriana Rossi	
	• Electron gun & collector		Adriana Rossi	
	• BPM		Manfred Wendt	
	• Modulator		Wolfgang Hofler	
	Assembly at CERN		Diego Perini/EN-MME	
	• Magnets		Gijs De Rijk	
	• Mechanics		Diego Perini	
	Testing assembly at CERN		Adriana Rossi	
	• Magnets & cryogenics		Gijs De Rijk	
	• Vacuum		Vincent Baglin	
	• BPM & BGC		M. Wendt & R. Veness /BE-BI	
	• Powering & control magnets		Michele Martino/TE-EPC	
	• Powering & control HV system		Davide Aguglia/TE-EPC	
	Installation at CERN		Adriana Rossi	

CERN

SYSTEM	Component	Quantity + Spares	CERN Responsible	CERN group
POWER CONVERTERS	PC magnets high current (350A)	14+7	Michele Martino	TE-EPC
	PC magnets low current (250A)	20+10		
	PC cathode heater (40Vx10A)	2+1	Davide Aguglia	TE-EPC
	Insulator transformer	2+1		
	PC cathode (-15kV x 5A)	2+1		
	PC control electrodes	4+2		
	PC anode modulator	2+1		
	PC cathode-collector	2+1		
CABLING	Leads high current (in&out)	28+14	Davide De Luca	EN-EL
	Leads low current (in&out)	40+20		
	HV cables (in&out)	14+7	Nuno Dos Santo	EN-EL
	Power cables (3 phase)	2+1		
INTERLOCKS	Interlock controllers magnets	tbd		TE-MPE
	Interlock controllers HV	tbd		
ENERGY EXTRACTION	Dump resistors	tbd	Felix Rodriguez	TE-MPE
	Extraction systems	tbd		
CRYOGENICS	Plant		Serge Claudet	TE-CRG
	Additions			
ANCILLARIES	Cabling			EN-EL
	Integration		Paolo Fessia	ATS-DO
	Transport		Cristina Bertone	EN-HE
	Cooling		Michele Battistin	EN-CV
	Alignment		Dominique Missiaen	EN-SMM
	Testing components at CERN			
	Assembly (at CERN)			
	Testing assembly at CERN			
	Installation			

Crystal Collimation

- Organized HL-LHC Crystal Collimation day at CERN in October 2018: https://indico.cern.ch/event/752062/timetable/#20181019
- International Collimation Review at CERN 11-12 Feb 2019: https://indico.cern.ch/event/780182/
- Prepared resource document for CERN groups and HL-LHC Work Packages: EDMS Number 2186610

  → lowered CERN core cost to less than 0.5MCHF

  → can be financed by remaining R&D funds

HiLumi HL-LHC PROJECT

Simulated peak power load on DS magnets

C. Bahamonde - Tuesday's talk & 8th annual meeting Oct 2018

TCLD position		PROTONS (mW/cm^3)					IONS (mW/cm3)				
		Cell 8/9			Cell 11		Cell 8/9			Cell 11	
		*MB**	*MQ*	*11T*	*MB**	*MQ*	*MB**	*MQ*	*11T*	*MB**	*MQ*
No TCLD	0.2h	**21**	9.9	-	12	13	**57**	27	-	**57**	36
	1h	**4.2**	2	-	2.4	2.6	**11**	5.4	-	**11**	7.2
MBB.8	0.2h	6.6	8.1	11	8.7	13	5.4	15	21	**36**	33
	1h	1.3	1.6	2.2	1.7	2.6	1.1	3	4.2	**7.2**	6.6
MBA.9	0.2h	6.0	8.1	**48**	<0.3	<0.3	6.0	3.6	**33**	<0.003	<0.003
	1h	1.2	1.6	**9.6**	<0.06	<0.06	1.2	0.7	**6.6**	<0.0006	<0.0006

*Quench limit for MB estimated to be ~20 mW/cm^3 for steady state losses at 6.37Z TeV)

HiLumi HL-LHC PROJECT

Outcome of the analysis by LS2 team

	Delay in S 6-7	Delay in S 7-8
Scenario 1: First in S 6-7	-8 Weeks	+14 Weeks
Scenario 2: First in S 7-8	+8 Weeks	-2.5 Weeks

F. Savary @ 78th Meeting of the HL-LHC TCC

Impact on delayed TCLD installation in IR7 on ion runs during Run3?!

• ... full assembly after LS2 would require ... as follows:

... + ELQA @ warm

... (MB re... installation + TCLD installation)

• About 10 weeks for sector cool dow... **does not take into account the pa...**

→ Crystal Collimators as a backup plan for late TCLD installation after LS2!!!

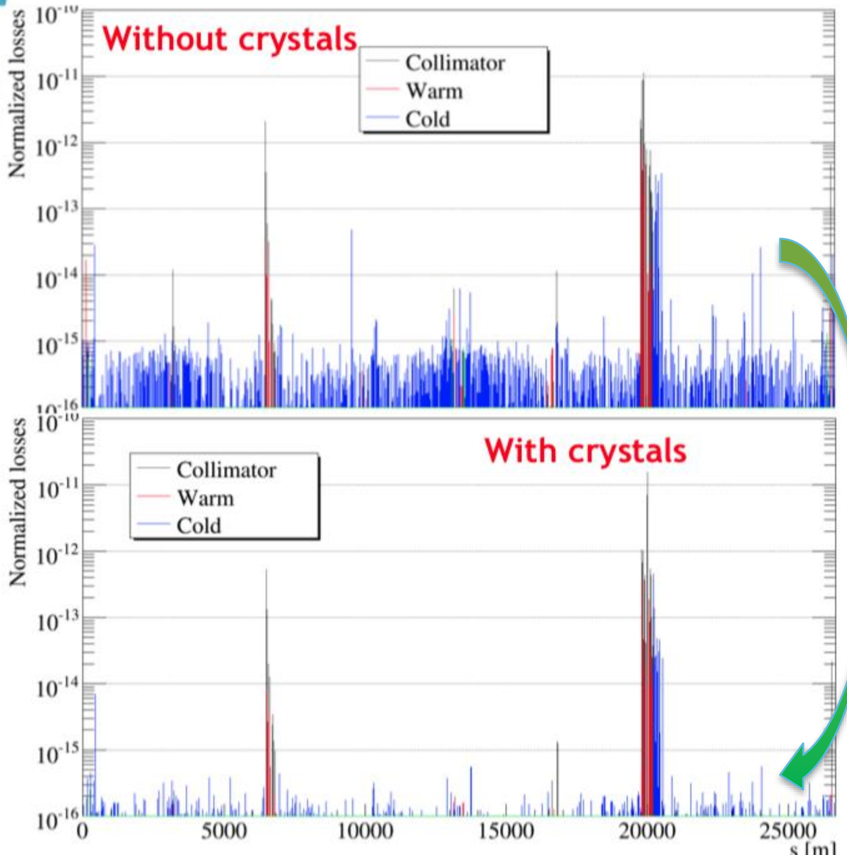
Courtesy M. Bernardini, S.E. Bustamante

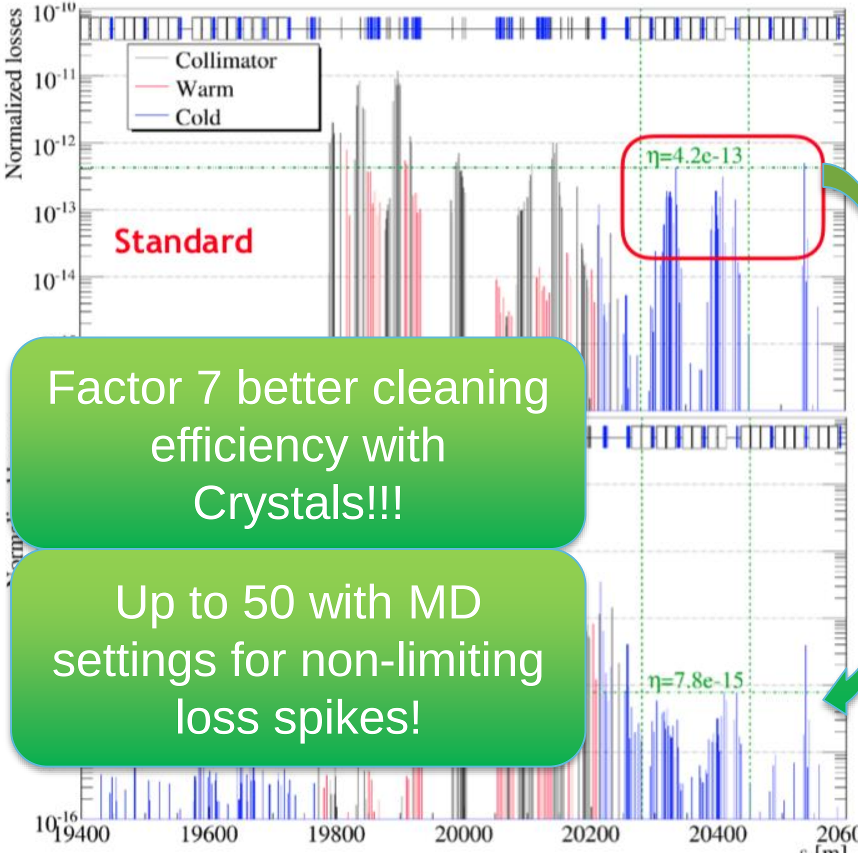
Crystal collimation cleaning of Pb beams

IR7 at operational settings

S. Redaelli @ Feb'19 Review

MD settings





Factor 7 better cleaning efficiency with Crystals!!!

Up to 50 with MD settings for non-limiting loss spikes!

Crystal Collimation System

- Discussions on the location of the 11T Collimator unit in IR7 underlined that the Pb operation during HL-LHC will create losses that will induce magnet quenches without DS collimators
- Very good MD results on the improved cleaning efficiency with crystals: ➔ factor 7 better efficiency
- Cost effective backup plan for Risk mitigation in case the 11T dipole / collimator units are late for installation in LS3!

  ➔ Strictly speaking not required if 11T collimators are on schedule
- Prepared resource document for CERN groups and HL-LHC Work Packages: EDMS Number 2186610

  ➔ lowered CERN core cost to ca. 0.4MCHF
- Definition of a reduced system with 4 crystal collimators as backup plan ➔ overall cost 1.2MCHF with 2/3rd of in-kind!

Summary of Russia Collaboration agreement

- Two Institutes in Russia shall produce 4 + 2 crystal collimation systems
- Motors and controls by CERN with reuse of material for standard collimation within a limited budget
- CERN hardware will define also how many systems can be installed
- Schedule and funding in Russia agreed with some flexibility to try to get first unit already before end LS2

Options that have been rejected

Type P=Perfor. R=Risk mit & protect. O= Optim.	Item description	WP # concerned in budget or FTE	Status Y=yes approved N=Not O=open	Date decision	Comments	Approximate Cost (MCHF) In many cases approximate
R	Cryo Beam Loss Monitor	13	N	Dec 2017	Removed from baseline not suitable	-1.2
P	Wide Feed Back System	4, 13	N	Mar 2018	Not anymore pursued	7
P	800 MHz SRF System	4	N	Jan 2017	Not anymore pursued	25 ?
P	200 MHz SRF System	4	N	Mar 2018	Not anymore pursued	25 ?
P	SRF quadrupoles for Landau damping	4	N	Mar 2018	Not pursued	15 ?
P	Second set of SRF Crab Cavity	4	N	Mar 2018	Not anymore pursued	25
R	Extra (8) low impedance collimators in IR3	5	N	Mar 2018	Removed Aug 2016;	4
R	Upgrade tertiary collimator sin IR2/8	5	N	Mar 2018	Part of consolidation	4
R	Rotatable Collimators (10 unit)	5	N	Mar 2018	Not anymore pursued	10
P	Second set of 11 T and DS collimators	5, 11	N	Mar 2018	Removed Aug 2016; No in Mar 2018	30
P	MQYY larger aperture Q4 and correctors	3	N	Mar 2018	Removed Aug 2016;	8.5
P	Stochastic cooling for heavy ions	13	N	Mar 2018	Never pursued	10 ?
R	Injection System: MKI full upgrade with new high Curie Temp. ferrite)	14	N	Mar 2018	Not pursued anymore	3.5
P-R	LRBB compensator via e-beams	13	N	Mar 2018	Not anymore pursued	25 ?

Reserve slides

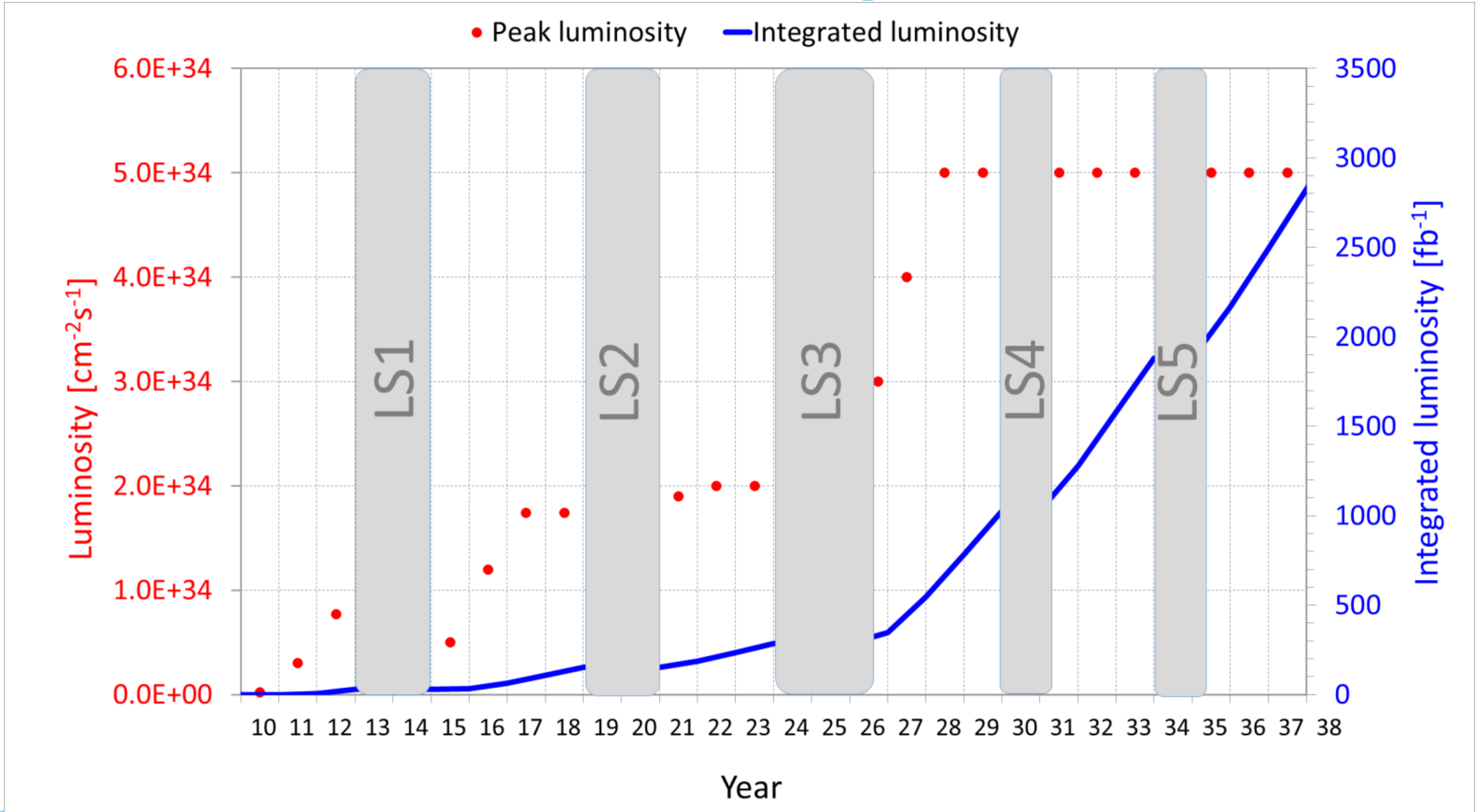
Baseline recap

- **Baseline 0** (Design Study): C&SR1 March 2015 with initial Civil Engineering and T.I. not fully finalized. No EVM, assessment of the integral sum, profile not too detailed.
- Baseline 1 (after big rebaselining of Aug. 2016; **TDR_V0.1**) : endorsed C&SR2 October 2016, first EVM and new schedule; Project complete of final C.E. + T.I.
- Baseline 2 (better granularity and more accurate time profile): after C&SR2
- Baseline 2.1: Following this C&SR3 of March 2018. It integrates all small re-scoping after C&SR2 of 2016 and schedule actualization; all extra/under-costs are noted down but NOT INTEGRATED.
- **Baseline 3.0**: End of 2018 for new final TDR: 2.1 + other possible rescoping (MS final optimization, cold diode, HEL?; Crystal?)

Options approved and will be integrated in the budget as baseline 2.1 with other re-scoping

Type P=Perfor. R=Risk mit & protect. O= Optim.	*Item description*	*WP # concerned in budget or FTE*	*Status Y=yes approved N=Not O=open*	*Date decision*	*Comments*	*Approximate Cost (MCHF) In many cases approximate*
O	**Cryogenic upgrade of existing P4 refrigerator**	**9**	**Y**	**Dec 2017**	**Replace the new 3 kW refrigerator**	**-4.7**
R	**Injection System: MKI (Cr_2O_3 coating, beam screen with ferrite rings)**	**14**	**Y**	**Mar 2018**	**Proto tested and successful**	**0.35**
P	**Coating of MS of IR2/8**	**12**	**Y**	**Mar 2018**	**NEW: decision to coat IR2L and IR8R for cryogenic power reason**	**.28**
R	**Cold diodes in the IT Quads**	**7, 3**	**Y**	**Mar 2018**	**R&D approved, (installation pending)**	**0.55 (+0.2)**
P	**Beam gas vertex detector**	**13**	**Y**	**Mar 2018**	**Real-time bunch-by-bunch beam shape measurements (5% relative accuracy) Demonstrated and needed**	**0.75**
R	**Inclinometer for vibration measurements**	**15**	**Y**	**Mar 2018**	**Funded R&D &proto ; (full system NOT pursued)**	**0.05 (+0.5)**

NOMINAL HL-LHC performance



Main open option

- **MKB and/or TDE upgrade** (prevent dump damage in case of MKB failure which could bring the temperature of TDE up to 3000º). **Decision by 2020**
  - Additional diluter kickers
  - Modifications of dump windows
  - Modification of the dump (new / additional absorber materials)