Accelerators - 1

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2015 CERN-Fermilab HCP Summer School

3 July 2015

significant input from
Mike Lamont & Lucio Rossi

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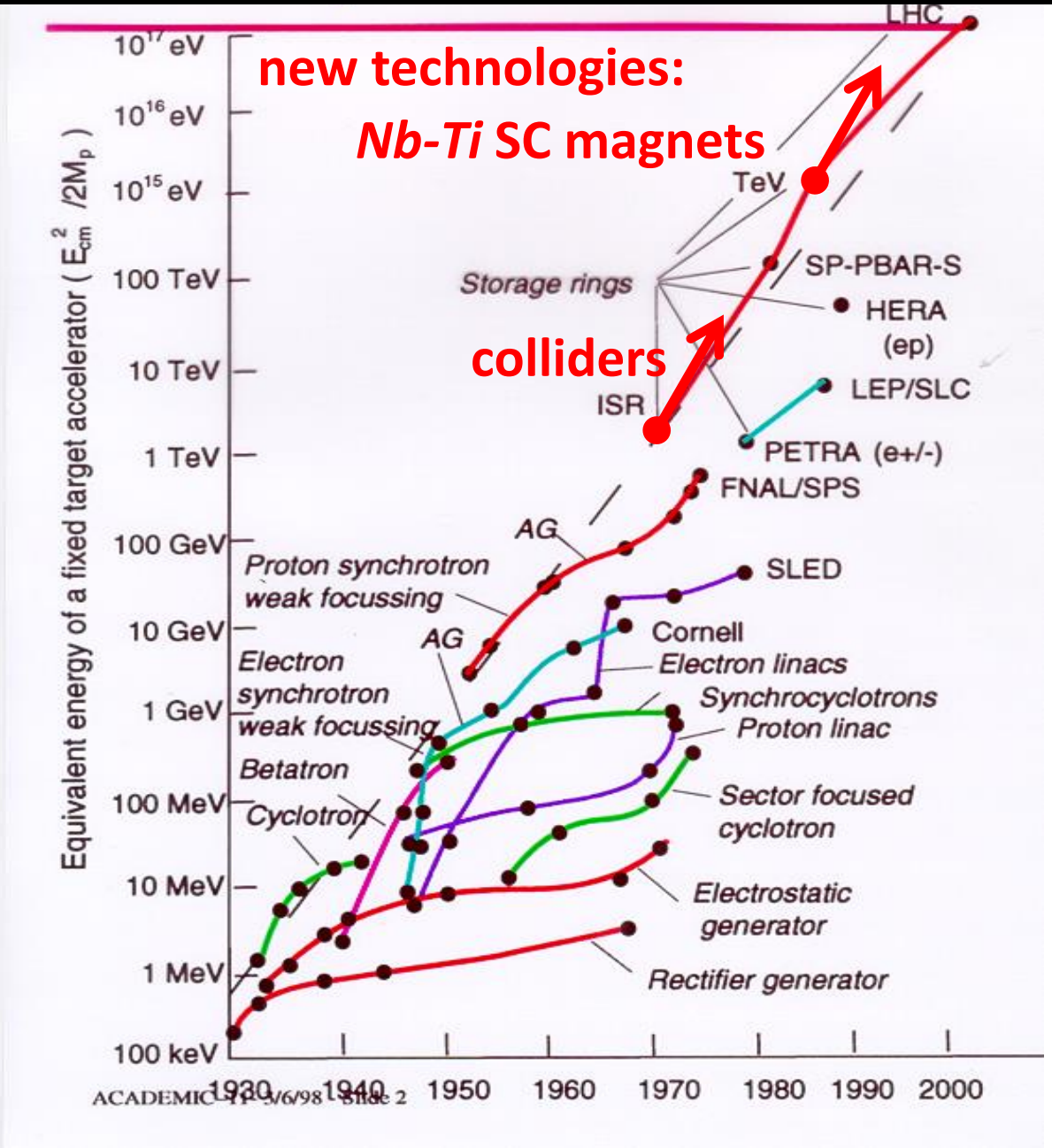
outline

- a brief history of high-energy accelerators
- LHC basics and run 1 (2010-13)
- what has changed for run 2?
  - is it really a "*new machine*"?
- run 2 highlights & challenges
- planned upgrades – LIU and HL-LHC
- LHeC option

energy frontier over 70 years



repeated jumps from saturation to new emerging technologies

storage rings have been the frontrunner technology for the last ~50 years

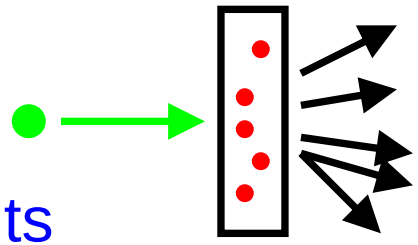
P. Lebrun

colliding beams

centre-of-mass energy:

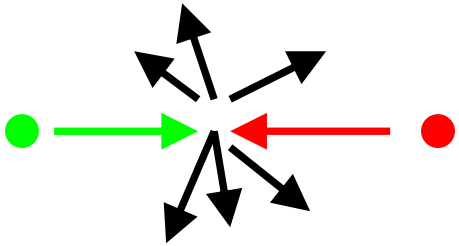
$$E_{\text{c.m.}} = \sqrt{2 E_{\text{beam}} M_{\text{target}} c^2}$$

beam hits
a “fixed target”



$$E_{\text{c.m.}} = 2 E_{\text{beam}}$$

two beams collide

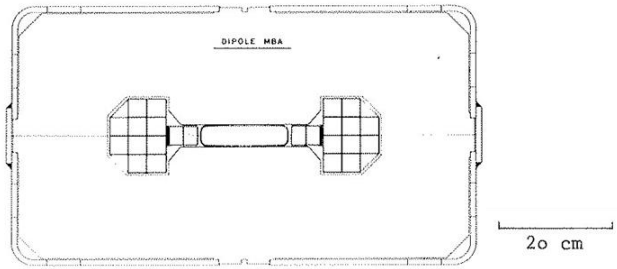


colliding two beams against each other can provide much higher centre-of-mass energies than fixed target!

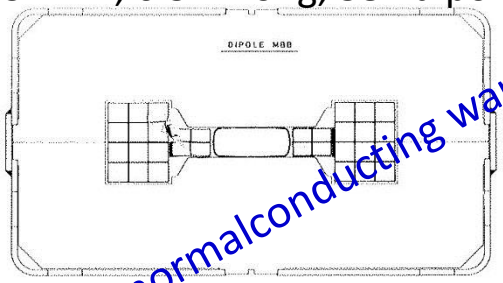
superconducting magnets

2 T

SPS MBA, 6.5 m long, 360 dipoles



SPS MBB, 6.5 m long, 384 dipoles



normalconducting warm magnets

4.5T

Tevatron,
6 m, 76 mm
774 dipoles

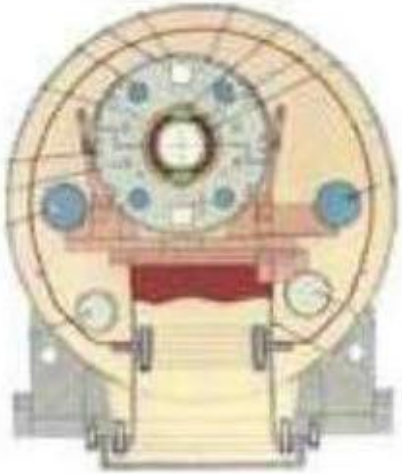
5.3T

superconducting magnets

HERA,
9 m, 75 mm
416 dipoles

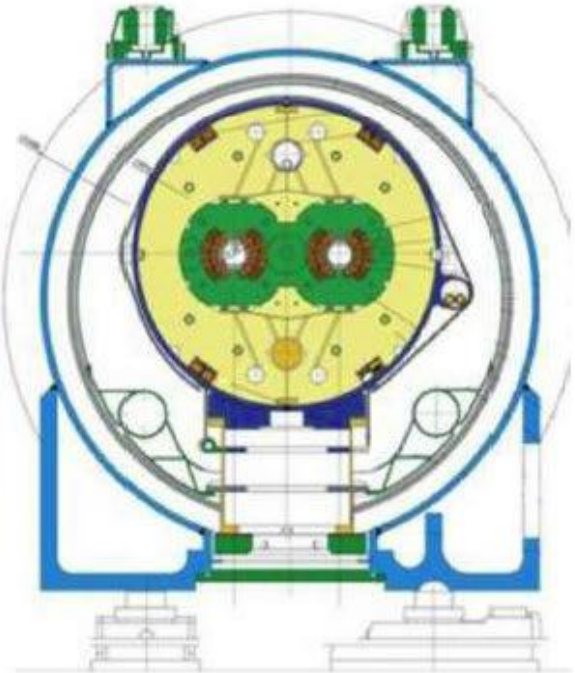
3.5T

RHIC,
9 m, 80 mm
264 dipoles



8.3T

LHC,
15 m, 56 mm
1276 dipoles

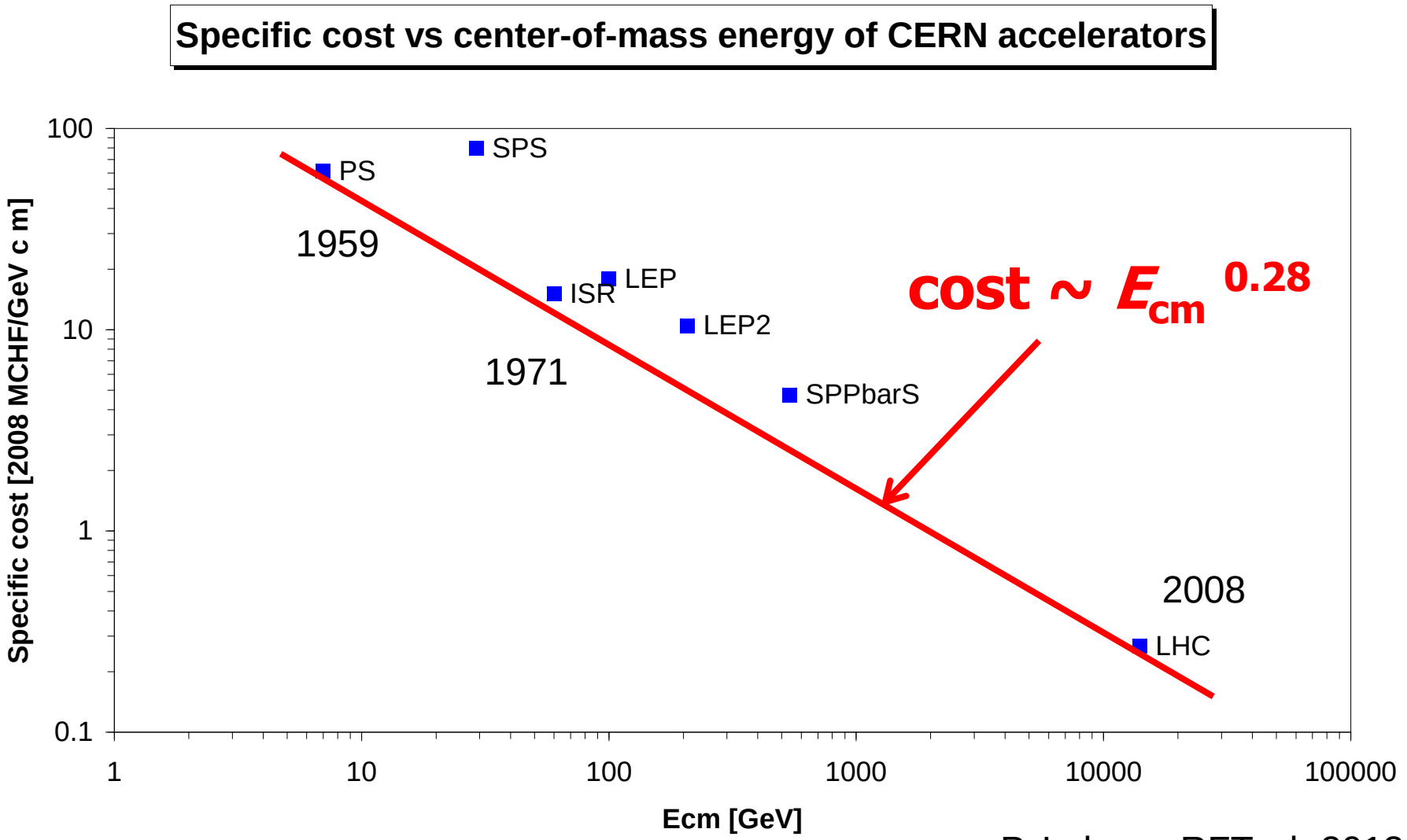


1st cyclotron, ~1930
E.O. Lawrence
11-cm diameter
1.1 MeV protons

LHC, 2015
9-km diameter
~7 TeV protons

after ~80 years
~10^7 x more energy
~10^5 x larger

remarkable advance in accelerator cost/energy
thanks to new technologies



P. Lebrun, RFTech 2013

accelerator size, energy, cost …

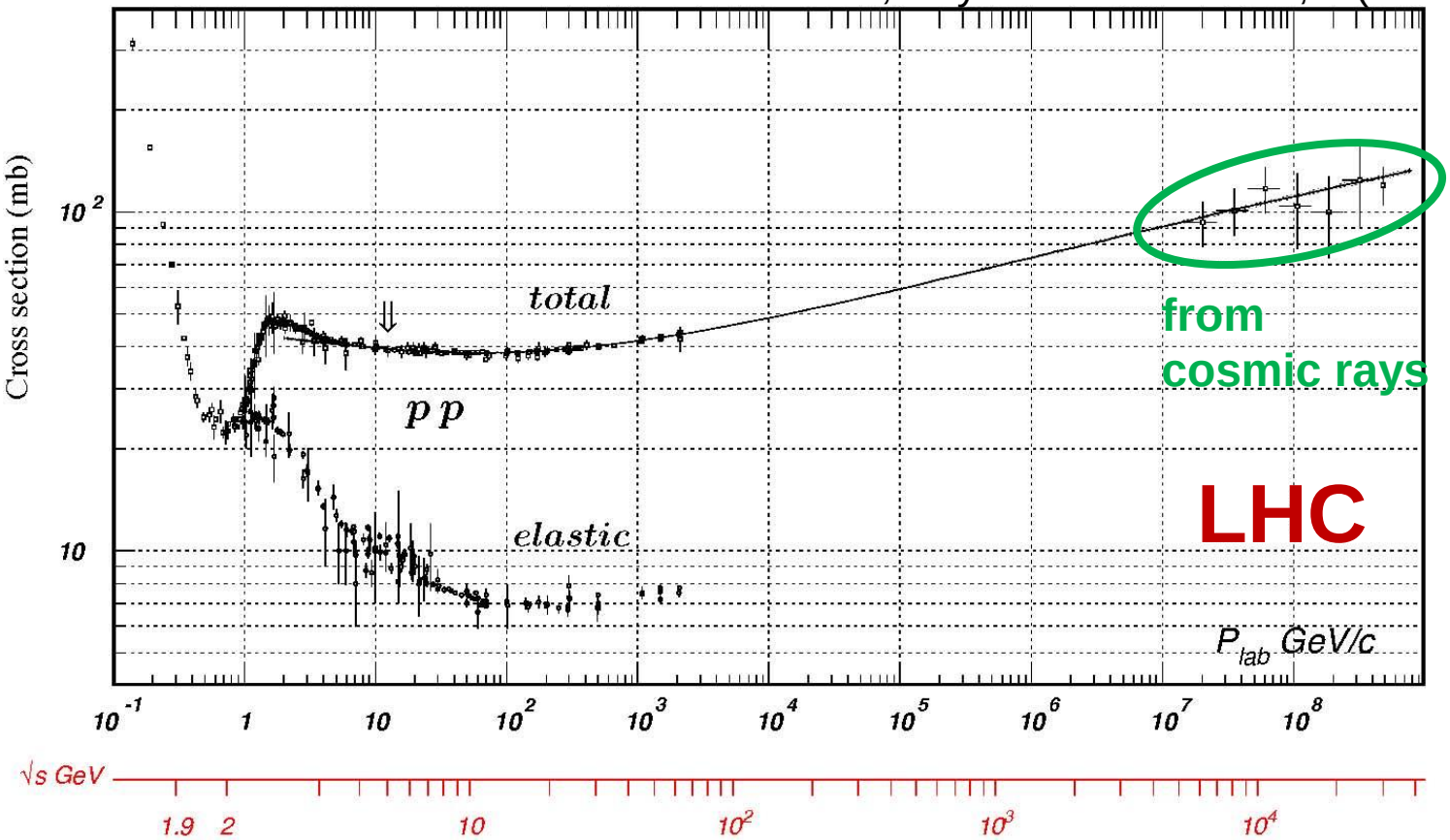
what else is there?

luminosity

$$R = \sigma L$$

reaction rate **cross section** **luminosity**

C. Amsler *et al.*, Physics Letters **B667**, 1 (2008)

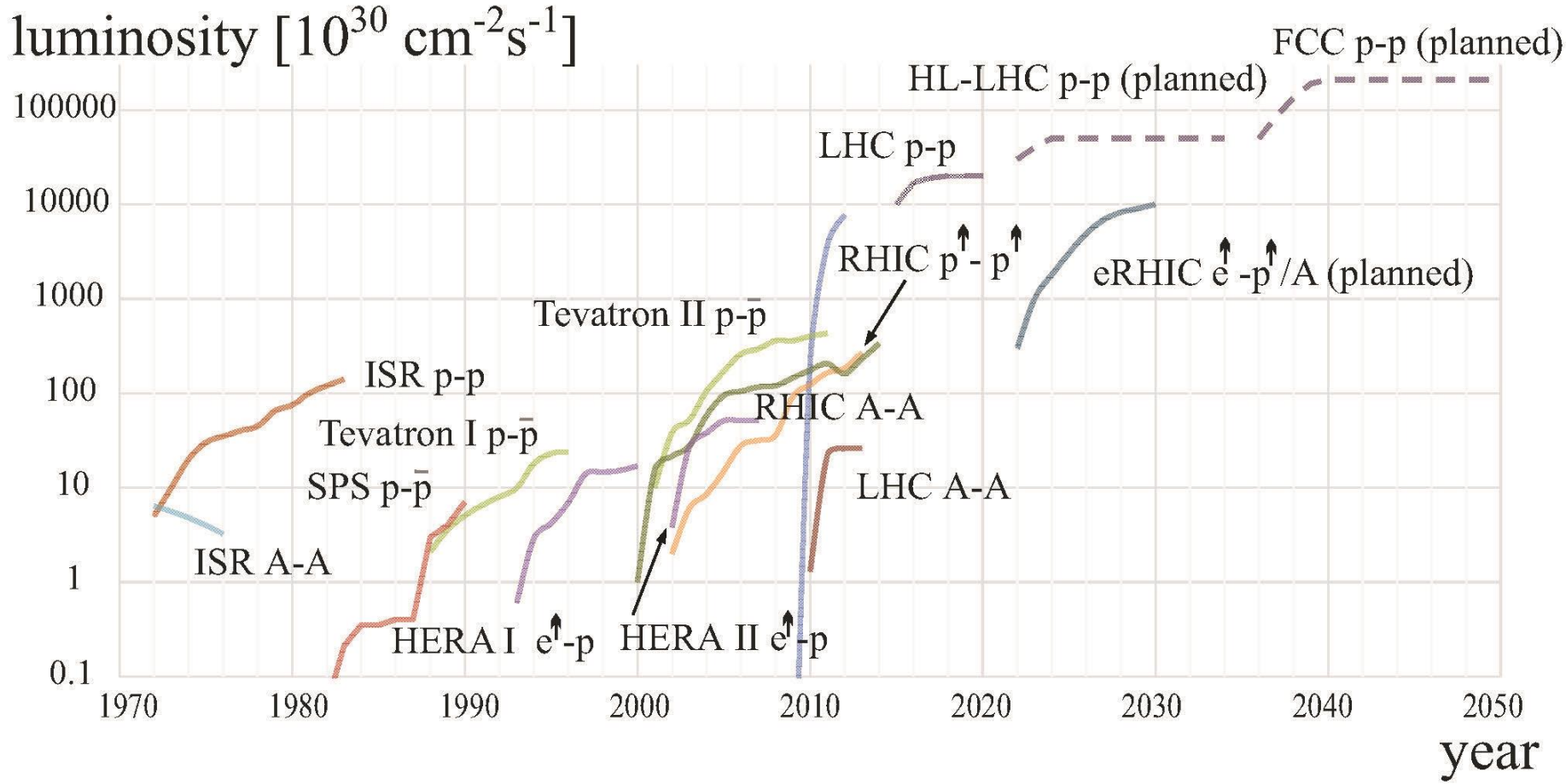


σ_{tot}~
100 mbarn
~ 10^{-25} cm^2

from cosmic rays

determines proton consumption (beam lifetime)

hadron-collider peak luminosity vs. year



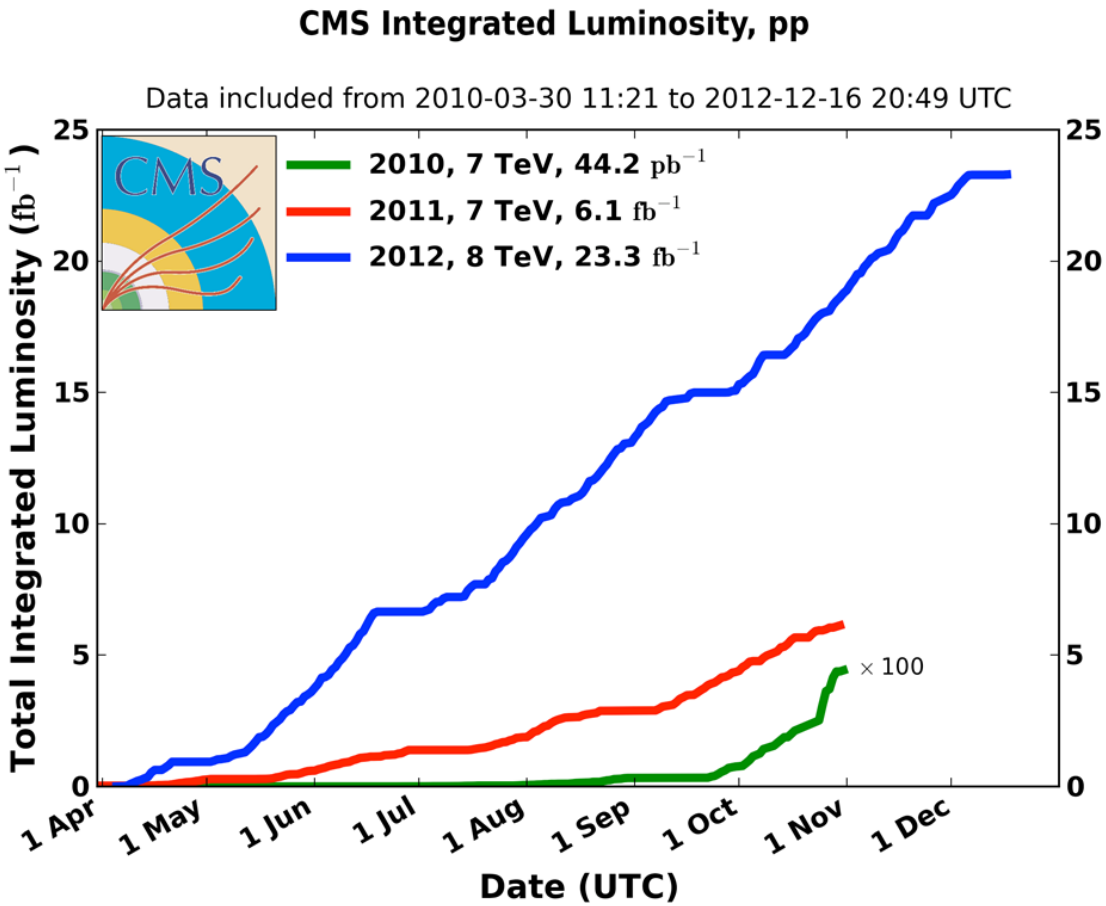
integrated luminosity = $\int L\,dt$

unit: fb^{-1}
1 fb = 10^{-43} m^2

Courtesy W. Fischer

LHC run 1 (2012-13) accumulated more integrated luminosity than all previous hadron colliders together!

LHC integrated luminosity 2010-2012



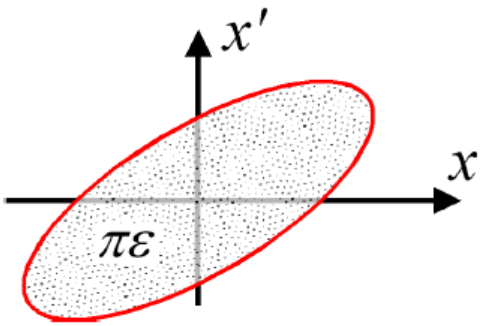
- 2010: **0.04 fb^{-1}**
  - 7 TeV CoM
  - Commissioning
- 2011: **6.1 fb^{-1}**
  - 7 TeV CoM
  - Exploring the limits
- 2012: **23.3 fb^{-1}**
  - 8 TeV CoM
  - Production

σ_{Higgs} ~ 20–50 pb → with 300 fb^{-1} LHC produces ~ 10 million Higgs

luminosity

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

N	**number of particles per bunch**
n_b	**number of bunches / beam**
f	revolution frequency
σ*	**beam size at interaction point**
F	reduction factor due to crossing angle
ε	emittance
ε_n	**normalized emittance = εγβ**
β*	**beta function at IP**



$$s^* = \sqrt{b^* e}$$

$$e_n = b g e$$

Round beams, beam 1 = beam 2

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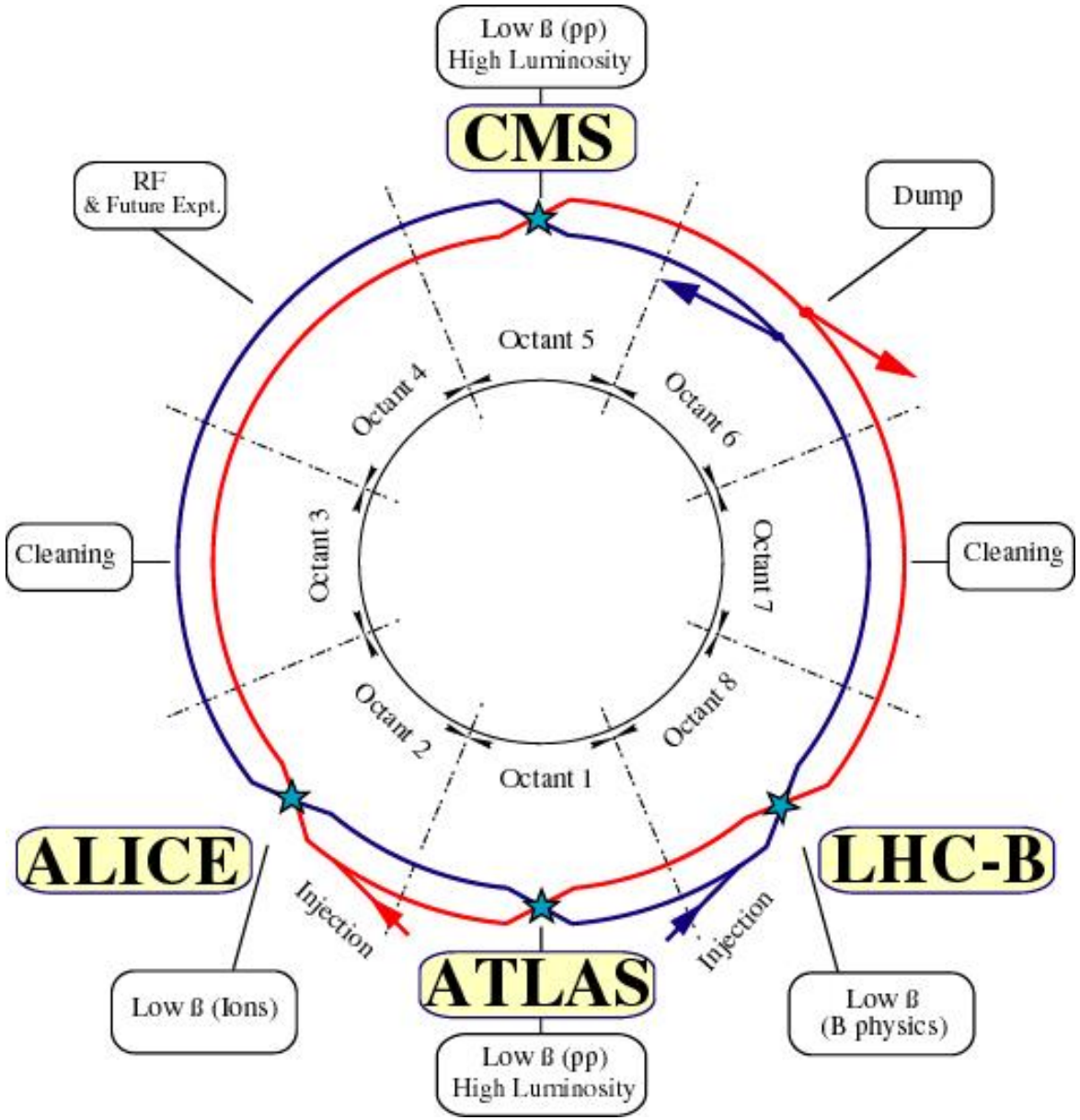
Large Hadron Collider (LHC) - design



c.m. energy
14 TeV (*pp*)

luminosity
10^{34} $cm^{-2}s^{-1}$

1.15×10^{11} p/bunch

2808 bunches/beam

~16 μm IP beam size

360 MJ / beam

dipole field 8.33 T

LHC peak performance in run 1 (2010-12)

	2010	2011	2012	Nominal
bunch spacing [ns]	150	50	50	25
no. of bunches	368	1380	1380	2808
beta* [m] ATLAS and CMS	3.5	1.0	0.6	0.55
max **bunch intensity** [protons/bunch]	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}	1.15×10^{11}
normalized **emittance** [mm.mrad]	~2.0	~2.4	~2.5	3.75
peak luminosity [$cm^{-2}s^{-1}$]	**2.1×10^{32}**	**3.7×10^{33}**	**7.7×10^{33}**	1.0×10^{34}

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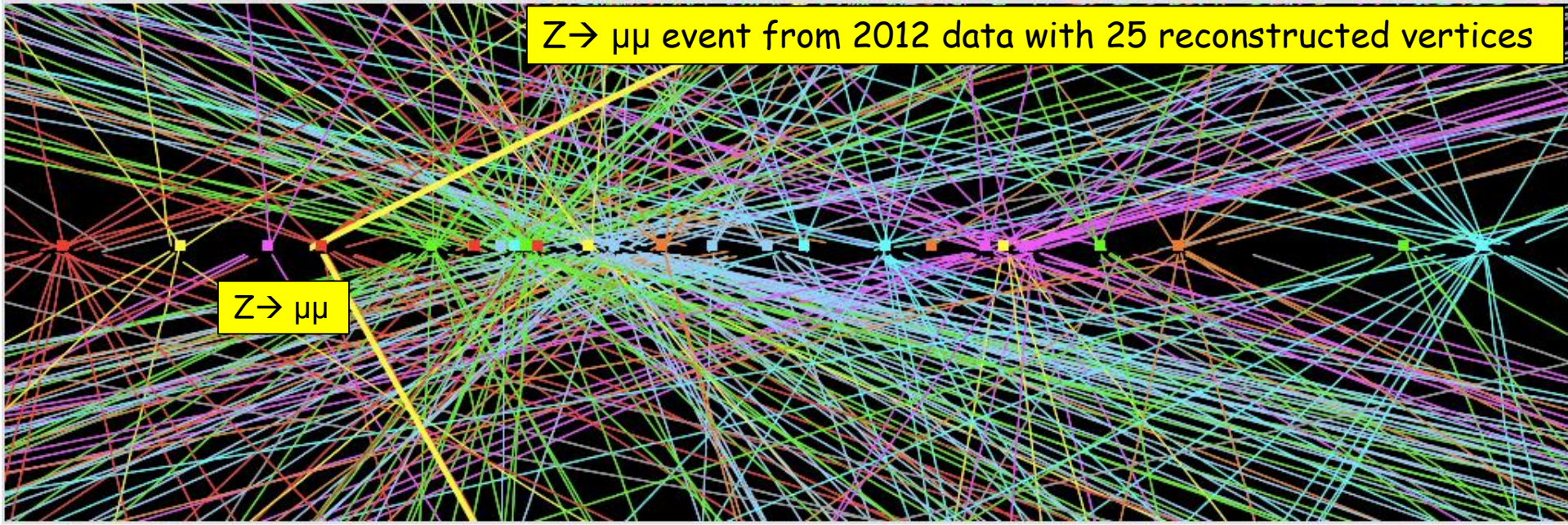
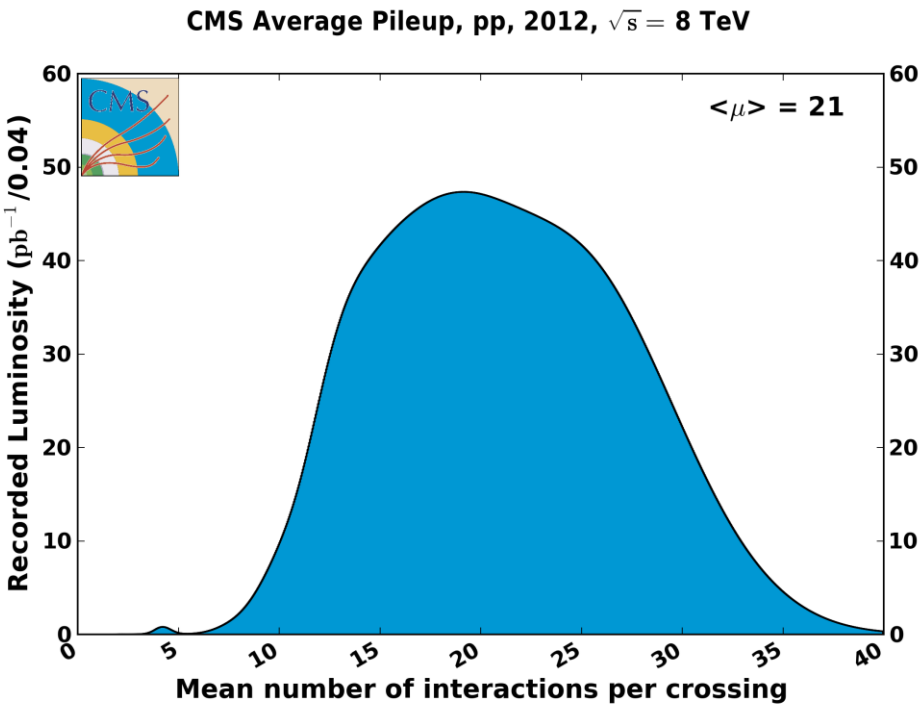
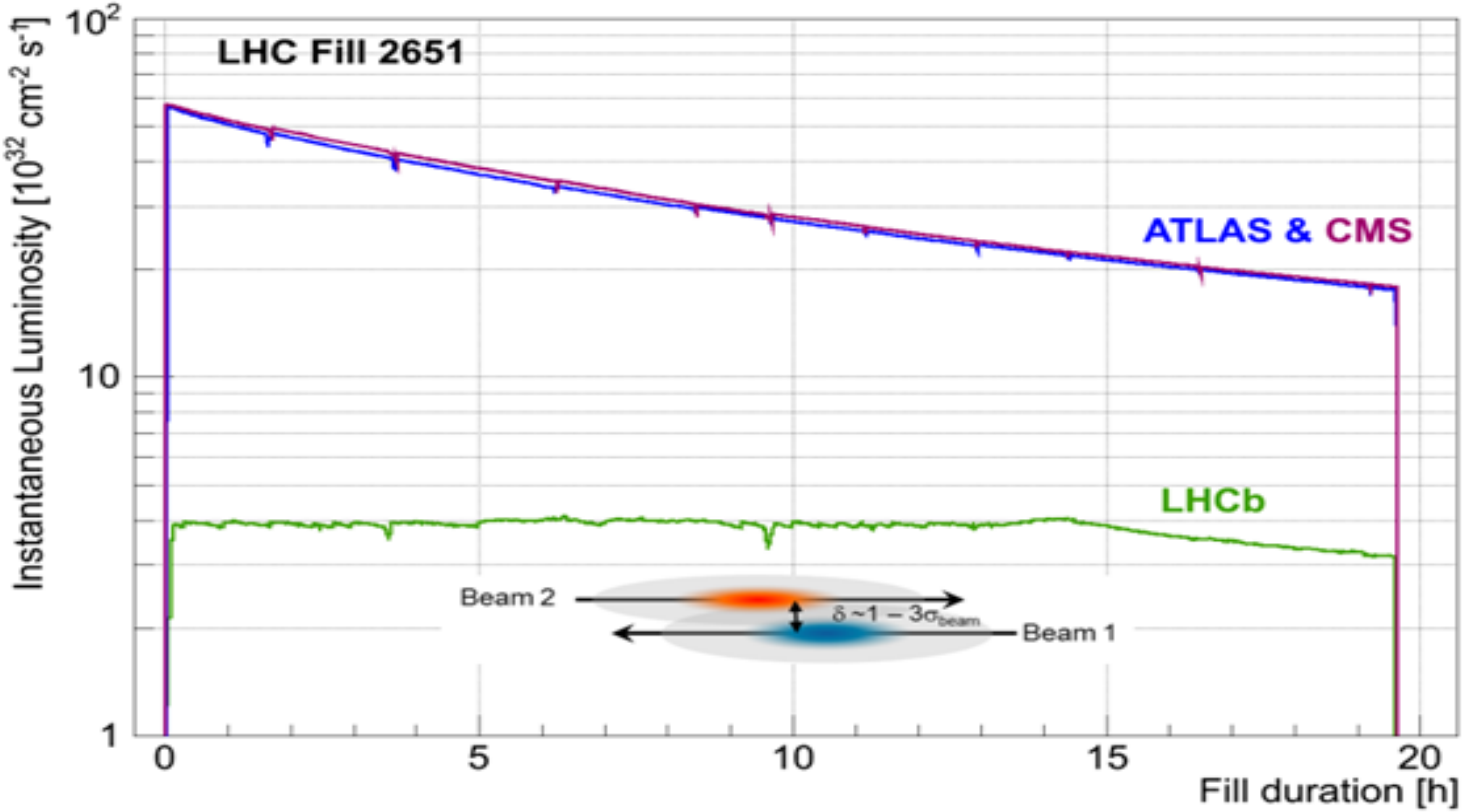




pile up will increase at higher energy → experiments request 25 ns operation in 2015

luminosity levelling for LHCb



luminosity levelling at around 4×10^{32} cm^{-2}s^{-1} via transverse separation
(with tilted crossing angle)

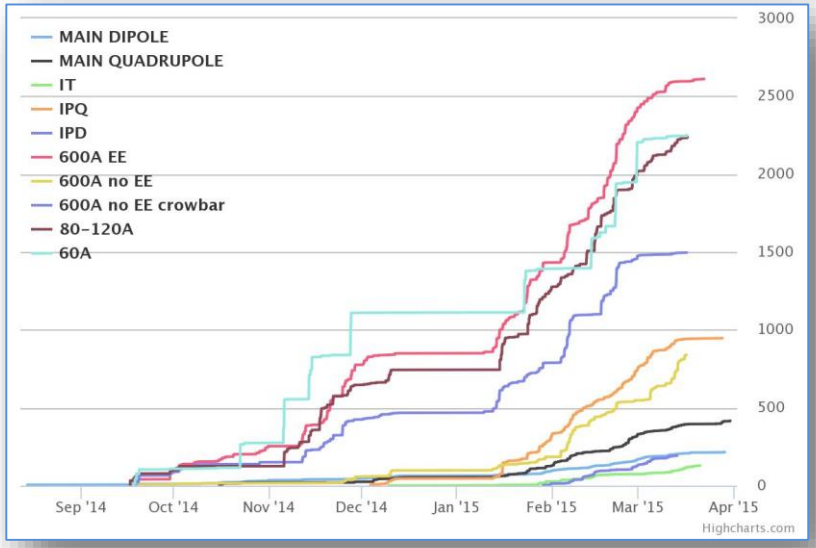
luminosity decay in ATLAS and CMS and levelled luminosity at LHCb – typical example from LHC run 1 (C. Gaspar).

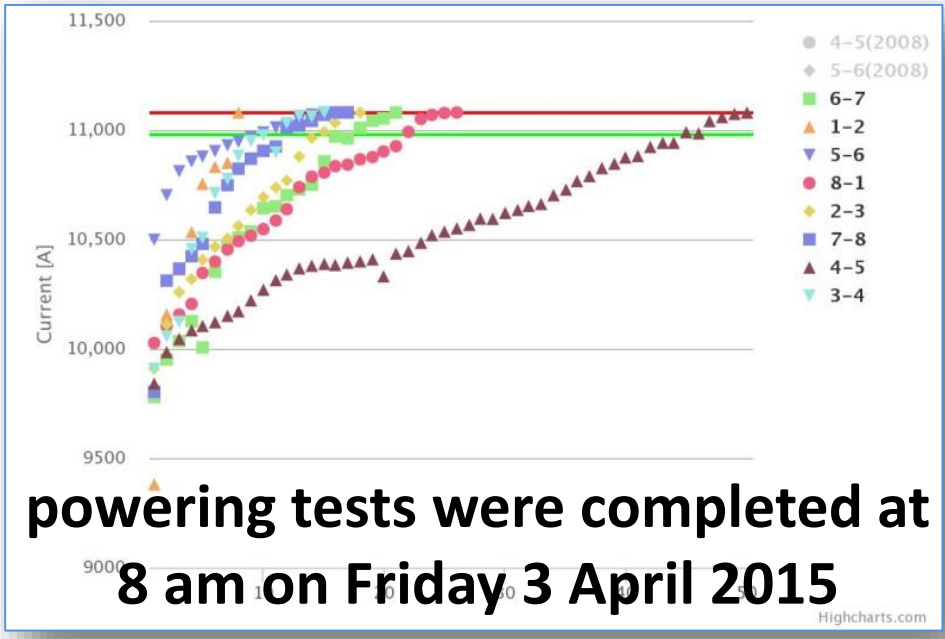
Long Shutdown 1 – SC circuit consolidation

powering tests at end of LS1

following sector by sector cool-down

M. Solfaroli et al.





powering tests were completed at 8 am on Friday 3 April 2015

Since 15 September 2014:

1566 superconducting circuits commissioned through execution and analysis of **more than 10.000 test steps** (≈13.800 test steps including re-execution)

172 training quenches on 8 dipole circuits

Circuit	Status	#M Firm 1	#M Firm 2	#M Firm 3	#MQ Firm 1	#MQ Firm 2	#MQ Firm 3	#MQ total	#CQ total
RB.A12	11080 A reached	50	95	9	2	1	4	7	7
RB.A23	11080 A reached	56	58	40	0	2	15	17	17
RB.A34	11080 A reached	44	81	29	1	7	8	16	16
RB.A45	11080 A reached	48	44	62	-	3	48	51	49
RB.A56	11080 A reached	28	42	84	0	0	18	18	17
RB.A67	11080 A reached	57	36	61	0	1	21	22	21
RB.A78	11080 A reached	53	40	61	2	10	7	19	19
RB.A81	11080 A reached	64	24	66	0	3	26	29	26

dipole training for 6.5 TeV

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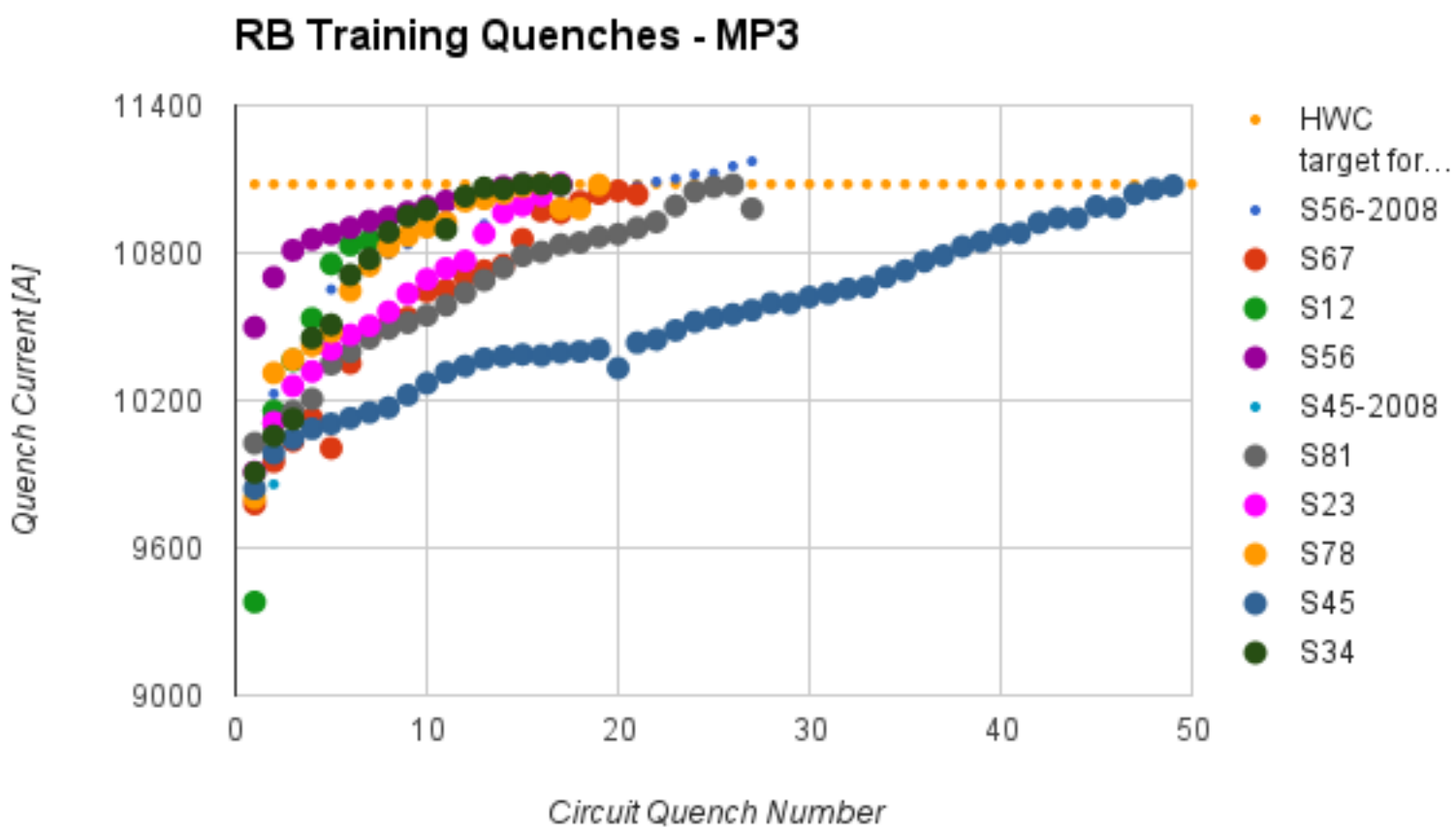
- 154 dipoles per sector, powered in series
- ramp the current until single magnet quenches - "training quench"
- usually quench 3 – 4 other dipoles at the same time
- cryogenics recovery time: 6 – 8 hours



7 TeV?

- assume all 412 firm 3 dipoles need re-training
  - some will require several re-training quenches
- firm 2 (≈5% to 6.5 TeV) and firm 1 (≈1% to 6.5 TeV) will also play a part
- detailed analysis ongoing
  - clearly hundreds further t-quenches required
  - could type test 1 sector in 2015 YETS…

target energy for 2015: 6.5 TeV

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LHC 2015

- target energy: 6.5 TeV
  - looking good
- bunch spacing: 25 ns
  - strongly favored by experiments (pile-up limit around 50)
- β^* in ATLAS and CMS: 80 to 40 cm

energy 6.5 TeV (raised from 4 TeV)

- lower quench margins
- lower tolerance to beam loss
- hardware closer to maximum (beam dumps, power converters etc.)

25 ns (decreased from 50 ns)

- electron cloud
- UFOs
- more long range collisions
- larger crossing angle, higher beta*
- higher total beam current
- higher intensity per injection

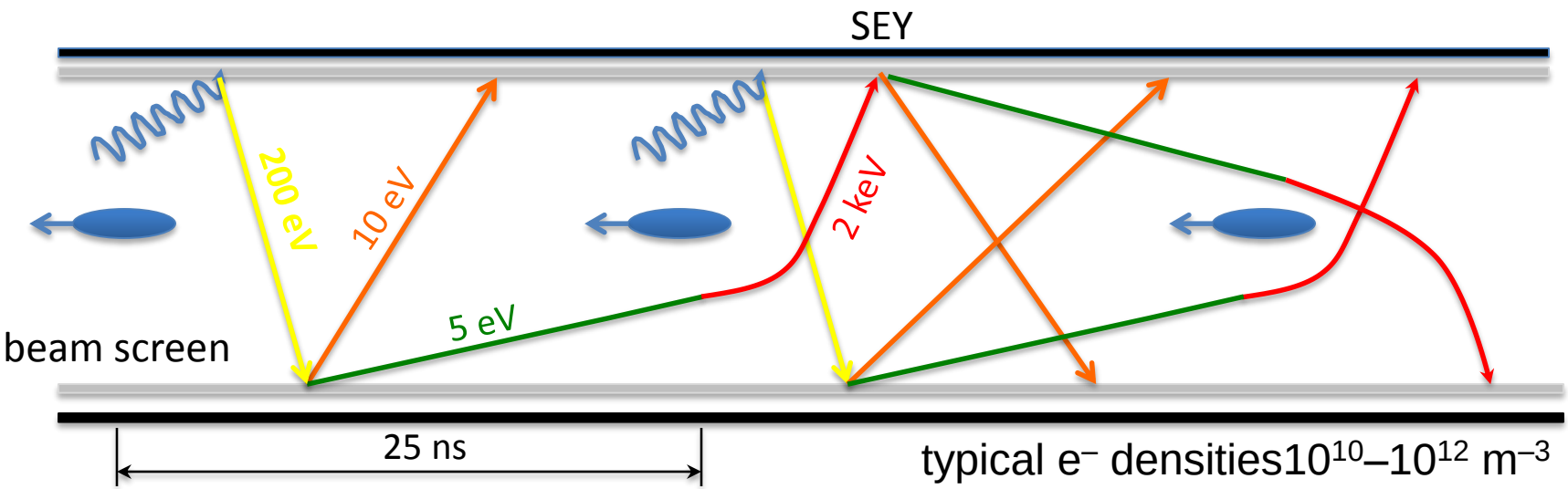
LHC bunch structure - 2015

- 25 ns bunch spacing
- ≈2800 bunches
- nominal bunch intensity 1.15 x 10^{11} protons per bunch

26.7 km 2800 bunches

new limits of ≈2 PS batches per injection from the injection protection absorbers – will reduce maximum number of bunches to ≈2500

25 ns & electron cloud



possible consequences:

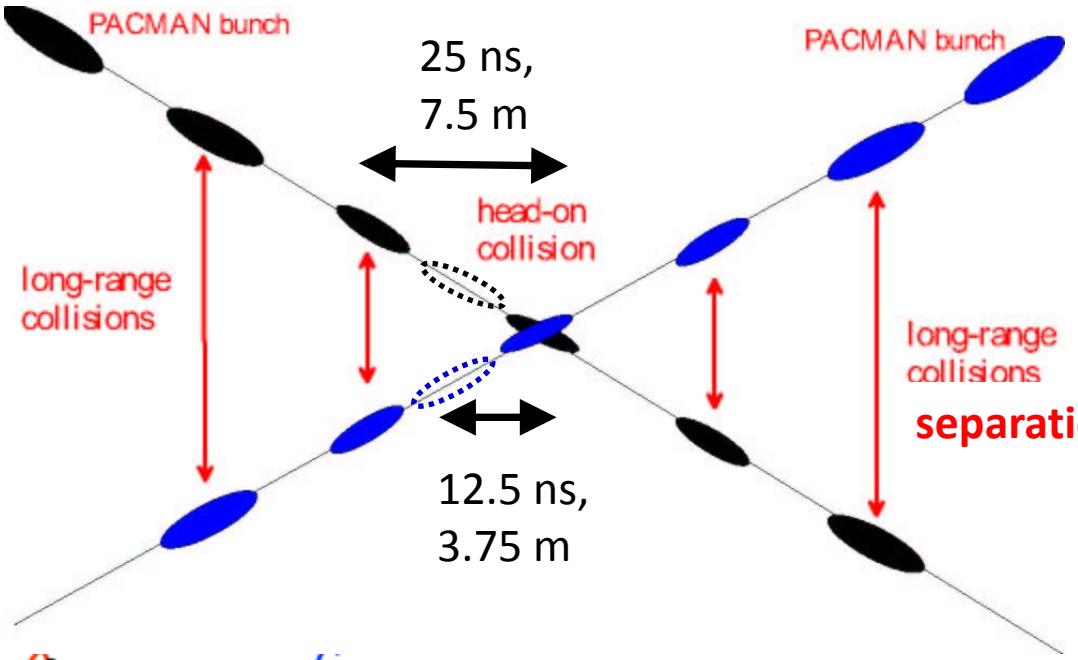
- instabilities, emittance growth, poor lifetime, desorption – bad vacuum
- excessive energy deposition in the cold sectors

electron bombardment of a surface has been proven to reduce drastically the **secondary electron yield (SEY)** of a material, this technique, known as **scrubbing**, provides a means to suppress electron cloud build-up

electron cloud significantly worse with 25 ns

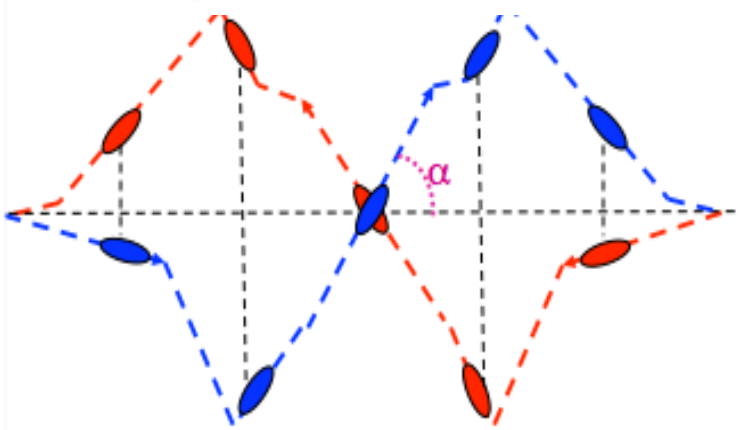
crossing angle & long-range collisions

work with a crossing angle to avoid parasitic collisions.



at 25 ns
≈30 long-range collisions per IP
(50 ns: ≈15)

separation: 10 -12 σ



geometric luminosity reduction factor:

$$F = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

2015: beta* in IPs 1 and 5

- many things have changed - starting carefully and pushing performance later
- start-up: **β*= 80 cm – (very) relaxed**
  - 2012 collimator settings
  - 11 sigma long range separation
  - aperture, orbit stability… checks ongoing
- ultimate in 2015: **β*= 40 cm**
  - **possible reduction later in the year**

$$\mathcal{L} \propto \frac{1}{\beta^*}$$

2015 commissioning strategy

- **low intensity commissioning of full cycle – 8 weeks**
- pilot physics – low number of bunches
- special physics run: LHCf and luminosity calibration
- scrubbing for 50 ns
- intensity ramp-up with 50 ns ← ***now we are here***
  - characterize vacuum, heat load, electron cloud, losses, instabilities, UFOs, impedance
- scrubbing for 25 ns
- ramp-up 25 ns operation with relaxed beta*
- possibly commission lower beta*
- 25 ns operation

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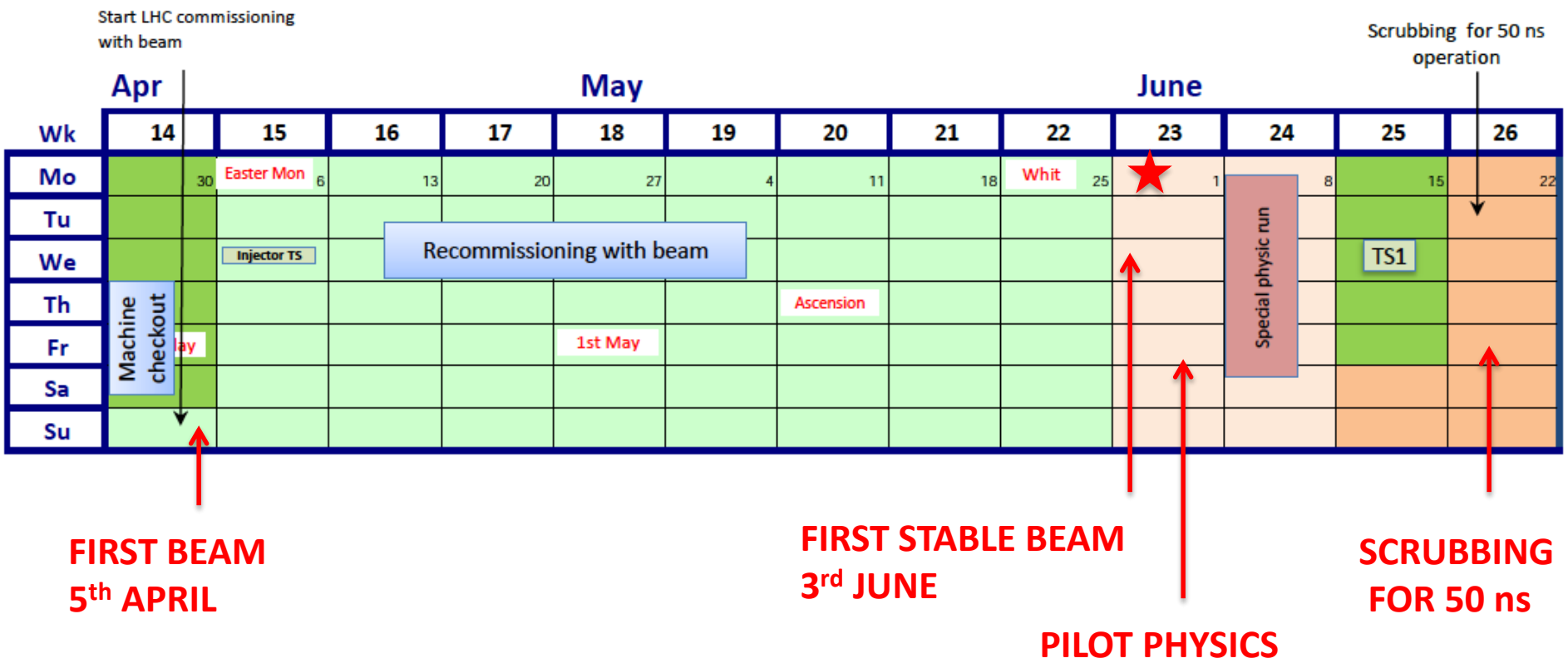
2015 Q2



- 8 weeks beam commissioning
- Pilot physics – up to at least 40 bunches per beam
- 5 days special physics at beta* = 19 m (VdM, LHCf, TOTEM & ALFA)
- Start technical stop – 15th June

2015 milestones so far

circulating beam	Sunday 5th April
ramp to 6.5 TeV	Friday 10th April
first 13 TeV collisions	Wednesday 20th May
first "Stable beams"	Wednesday 3rd June

working throughout with:

- **probes (5e9 protons per bunch) or**
- **1 or 2 nominal bunches (1.2e11 protons per bunch)**

THIS IS NOT BAD!

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6.5 TeV for the first time

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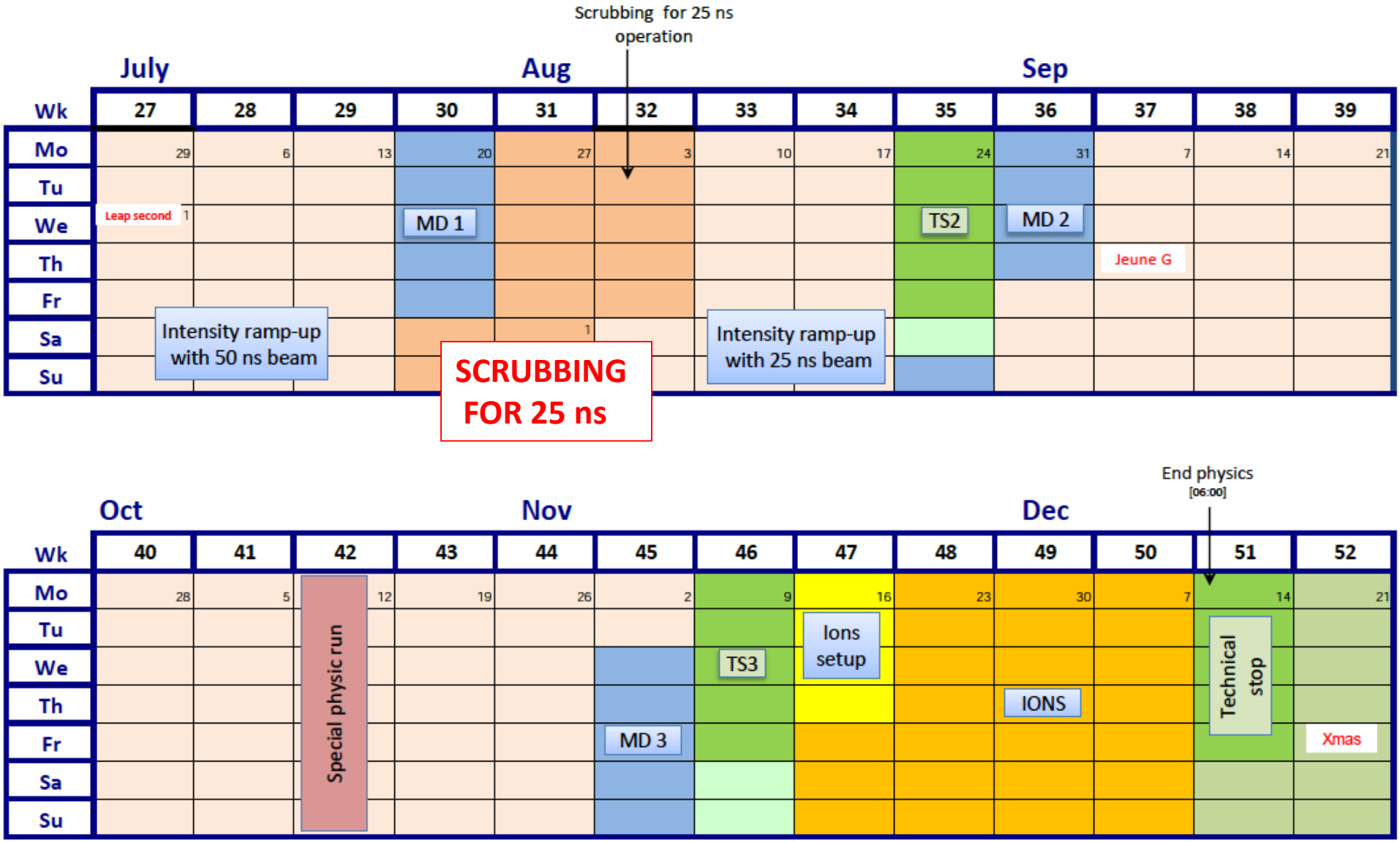
01:03 10th April

Q3/Q4 2015


Scrubbing for 25 ns operation
July
Aug
Sep
Wk
27
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36
37
38
39
Mo
Tu
We
Th
Fr
Sa
Su
Leap second
MD 1
TS2
MD 2
Jeune G
Intensity ramp-up with 50 ns beam
SCRUBBING FOR 25 ns
Intensity ramp-up with 25 ns beam
End physics [06:00]
Oct
Nov
Dec
40
41
42
43
44
45
46
47
48
49
50
51
52
Special physic run
TS3
Ions setup
IONS
MD 3
Technical stop
Xmas

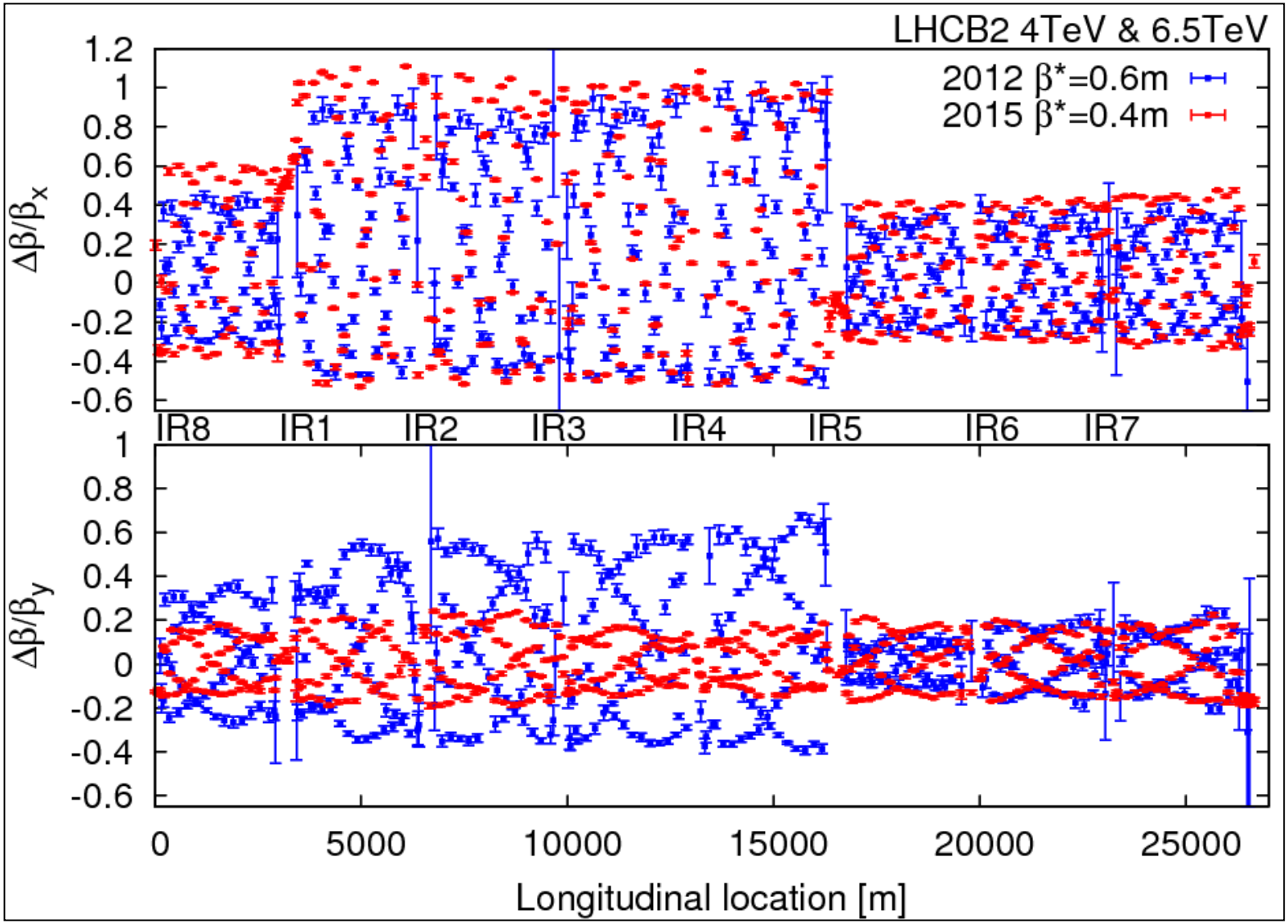
Run 2 impressions till now

- ***it's not a new machine***
  - a lot of lessons learnt from Run 1
- excellent and improved system performance
  - beam Instrumentation, transverse feedback, RF, collimation, injection and beam dump systems, vacuum, machine protection
- improved software & analysis tools
- experience!
- magnetically reproducible as ever, excellent optics
- **behaving well at 6.5 TeV**
  - only one additional training quench so far
- operationally under control
  - injection, ramp, squeeze, de-squeeze

still have to face the intensity ramp-up

- UFOs, e-cloud, vacuum, beam induced heating, instabilities

optics β*=40 cm – before correction

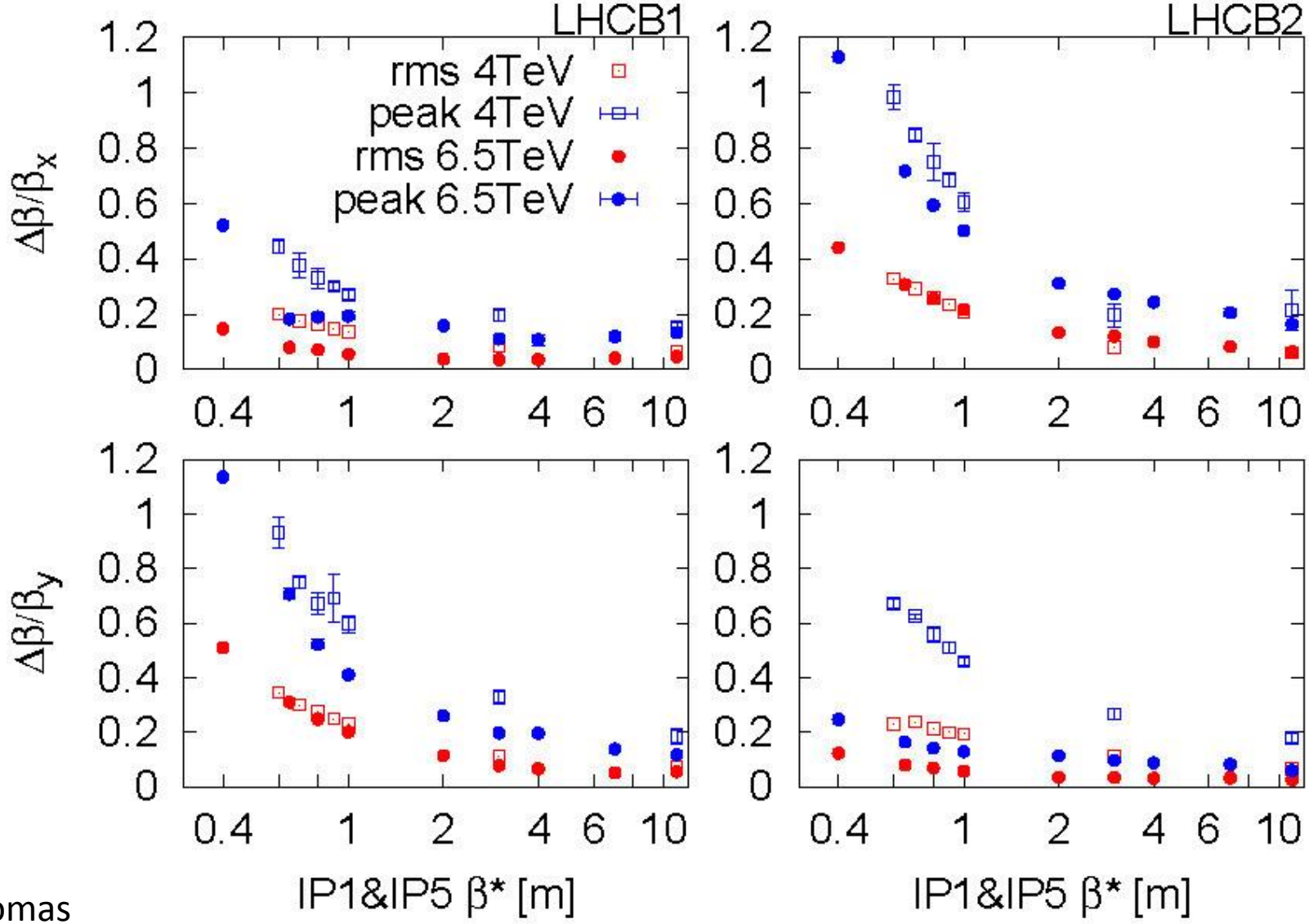


$$\sigma = \sqrt{\varepsilon\beta}$$

peak β beating of ≈120%

R. Tomas and OMC team

β beating vs β* - 2015 vs. 2012



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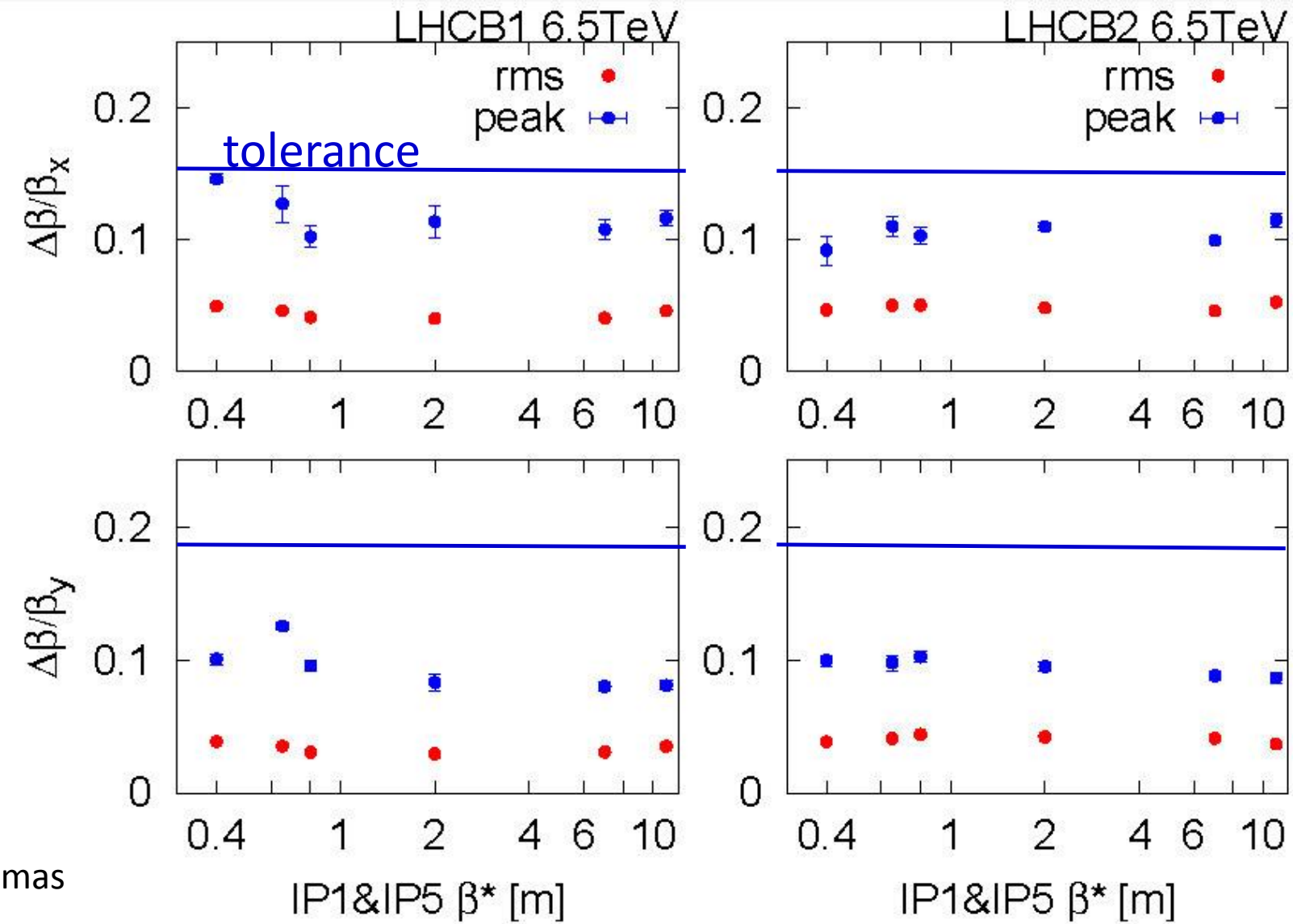
slightly lower β beating in 2015 (IP2 not squeezed)

$\Delta\beta/\beta$ vs β^* after local corrections - 2015 vs 2012



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15% β beating for beam 1 horizontal

LHC collimation system layout

two warm cleaning insertions, 3 collimation planes

IR3: Momentum cleaning
- **1 primary (H)**
- **4 secondary (H)**
- **4 shower abs. (H,V)**

IR7: Betatron cleaning
- **3 primary (H,V,S)**
- **11 secondary (H,V,S)**
- **5 shower abs. (H,V)**

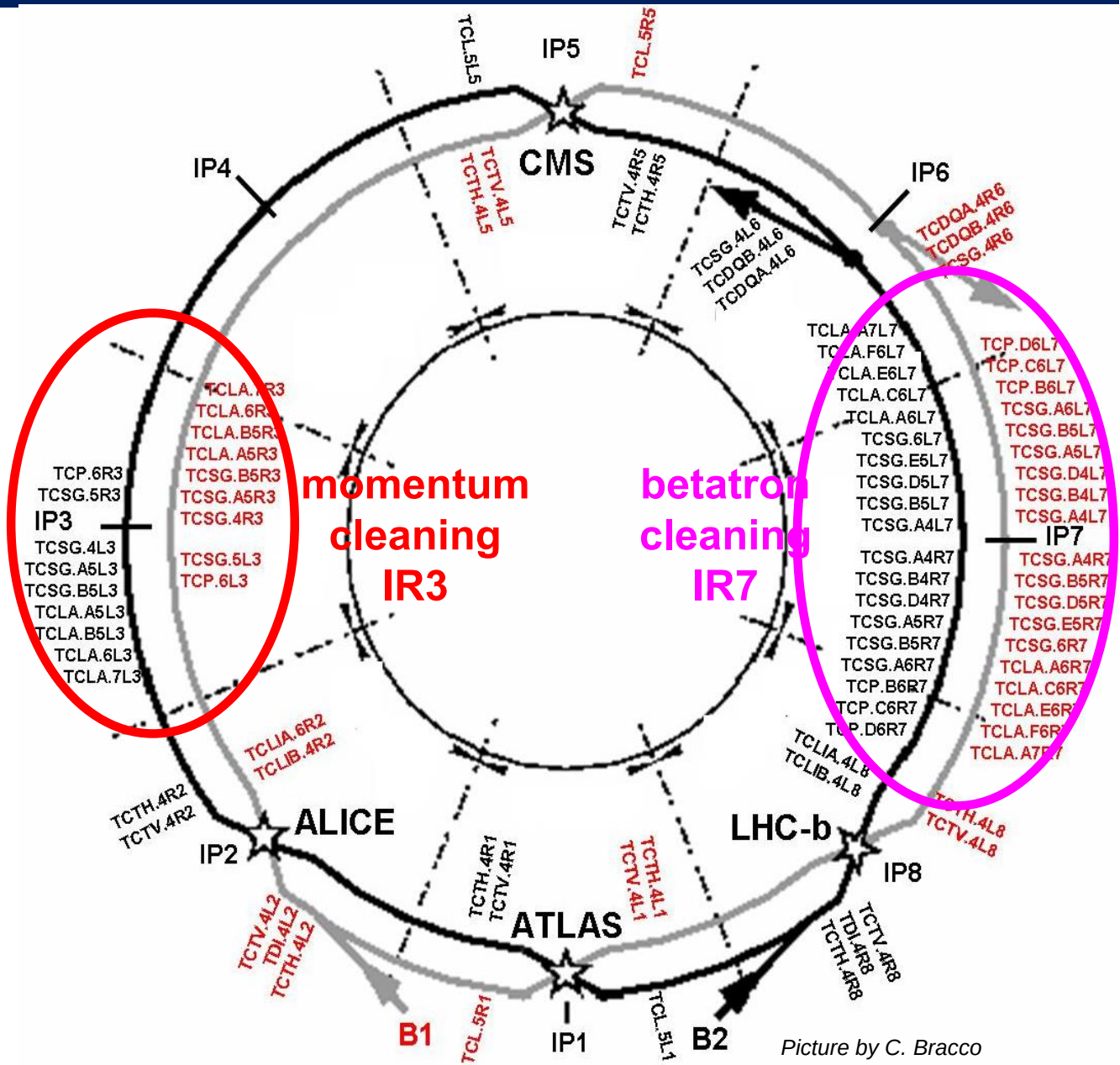
local cleaning at triplets
- **8 tertiary (2 per IP)**

passive absorbers for warm magnets

physics debris absorbers

transfer lines (13 collimators)
injection and dump protection (10)

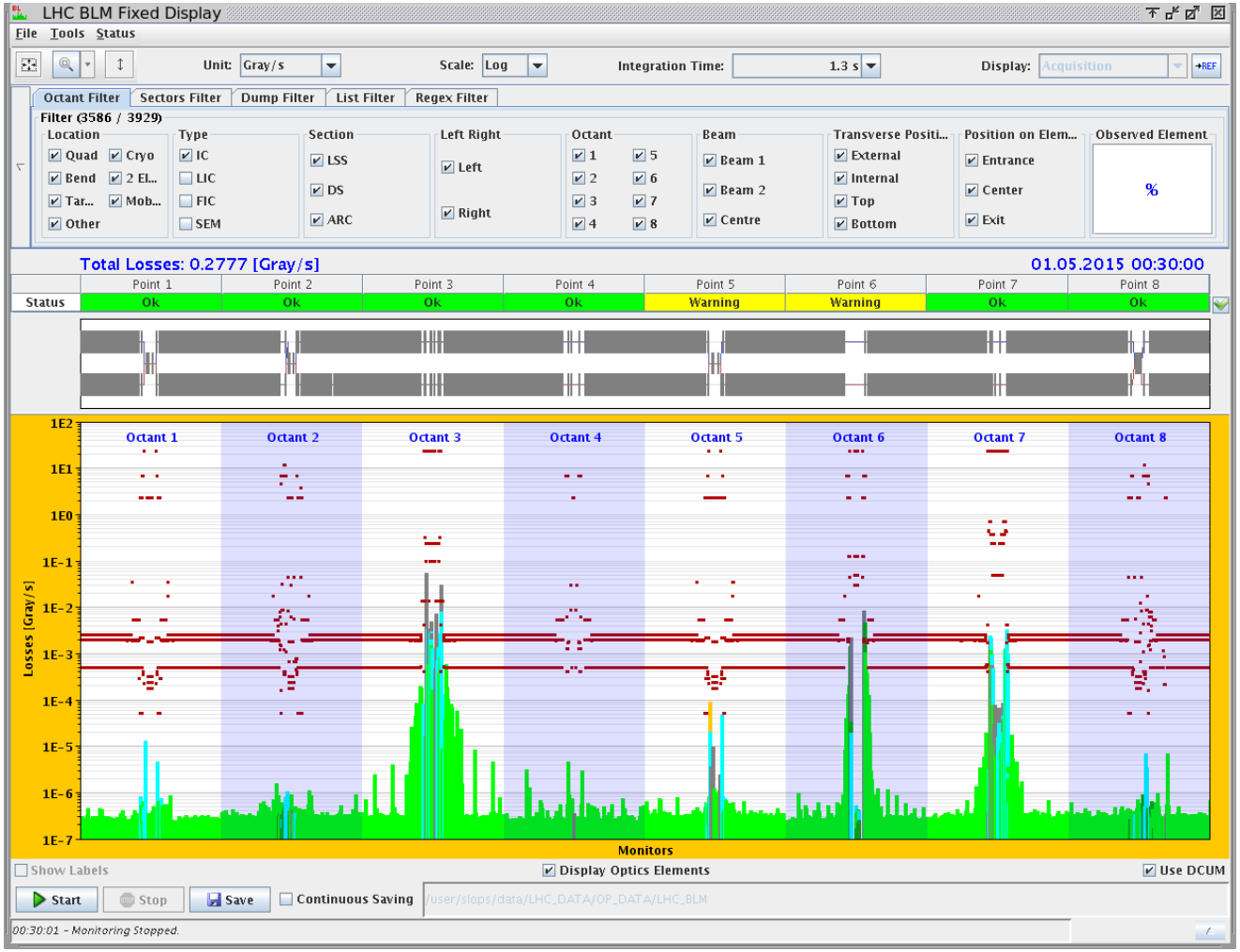
total of 108 collimators (100 movable); two jaws (4 motors) per collimator!



Picture by C. Bracco

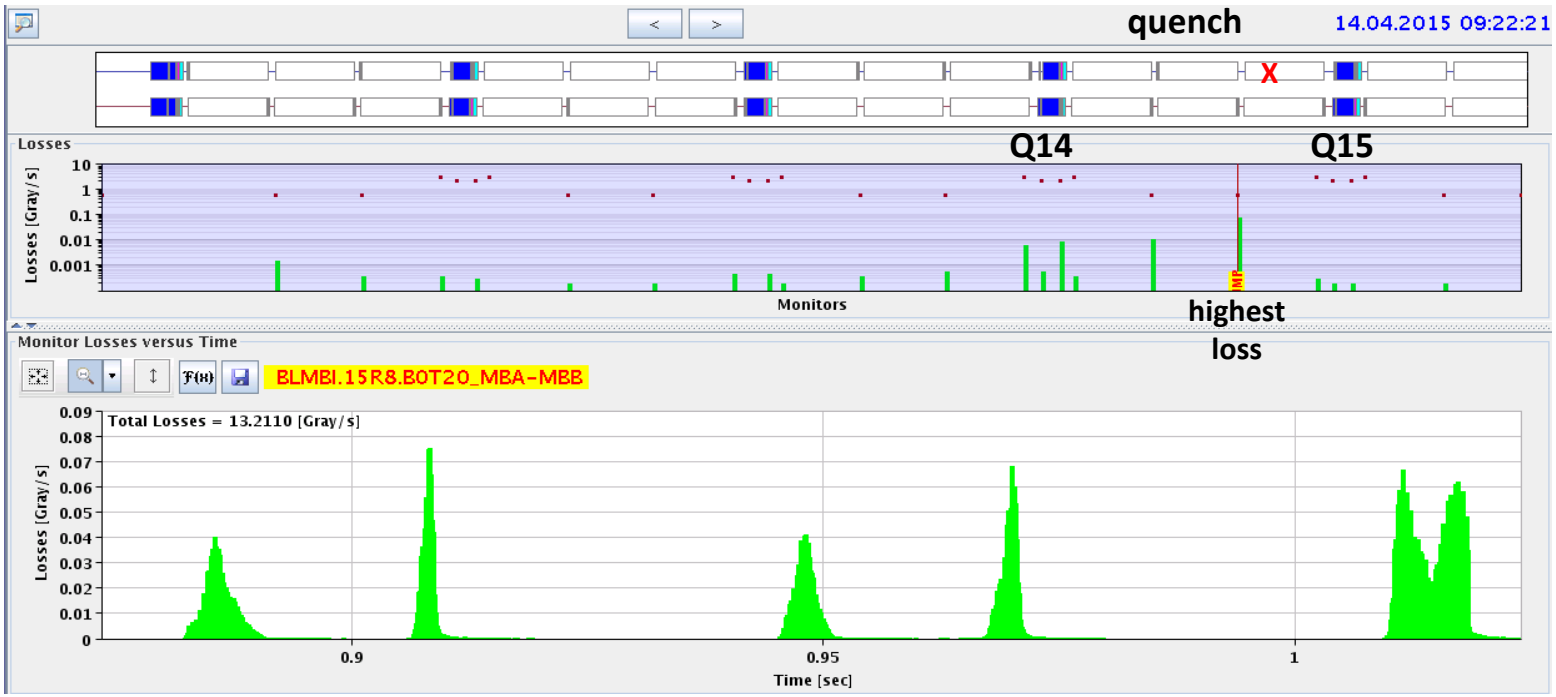
S. Redaelli

run-2 off-momentum loss map 6.5 GeV



Novel features of collimation system – BPM equipped tertiary collimators, automatic beam based set-up, …

MUFOs in 15R8



- multiple loss events after a short time at 6.5 TeV compatible with micron-size particles falling into the beam
  - loss patterns point to a specific position in the middle of a dipole magnet
  - quenched twice, numerous BLM triggered dumps…

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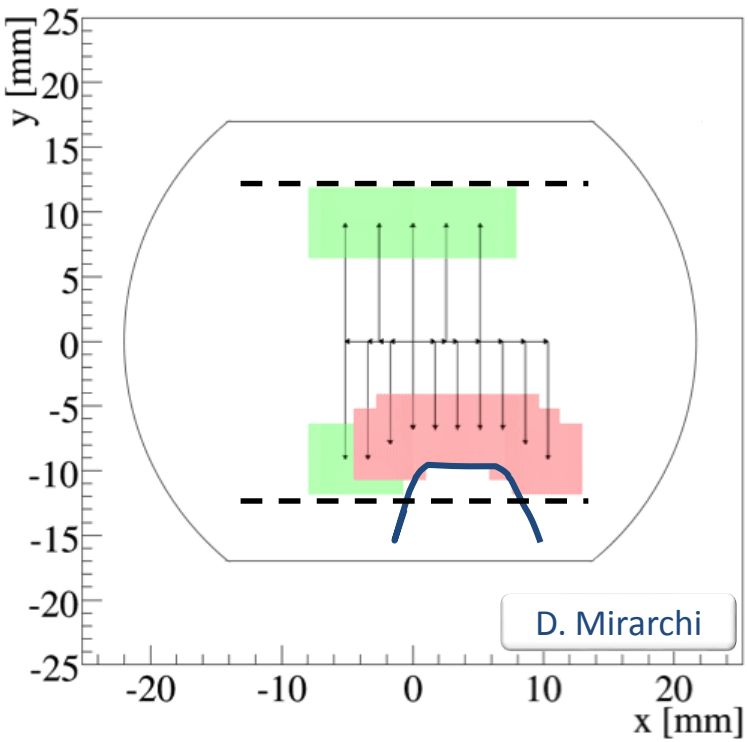
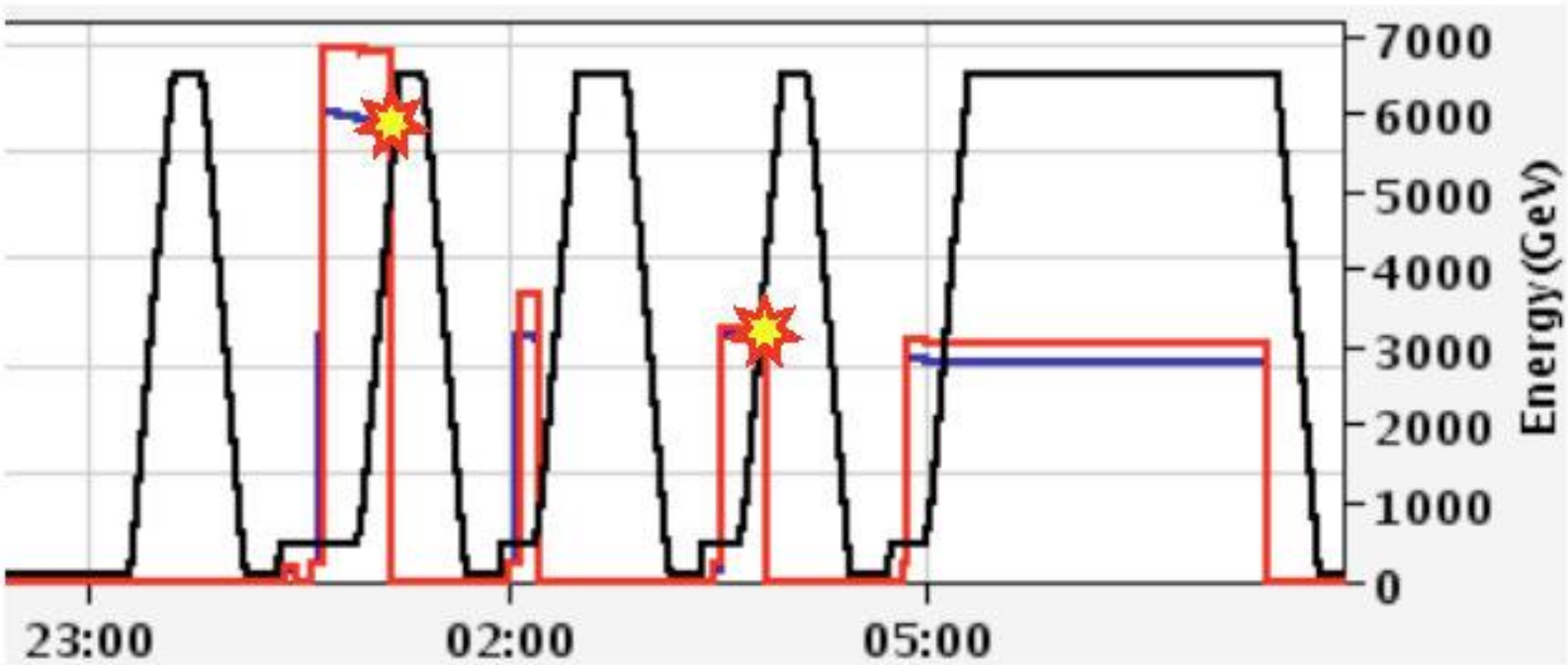
aperture restriction in 15R8

ULO (Unidentified Lying Object)

- aperture restriction measured at injection and 6.5 TeV
- presently running with orbit bumps
  - -3 mm in H, +1 in V, to optimize available aperture
  - aperture probably not limiting for operation
- behaviour with higher intensities and bunch trains still unknown
- MUFOs went away for several weeks, but returned in mid-June



UFOs in 15R8 back ?!



Dump 1: 5.1 TeV with two bunches

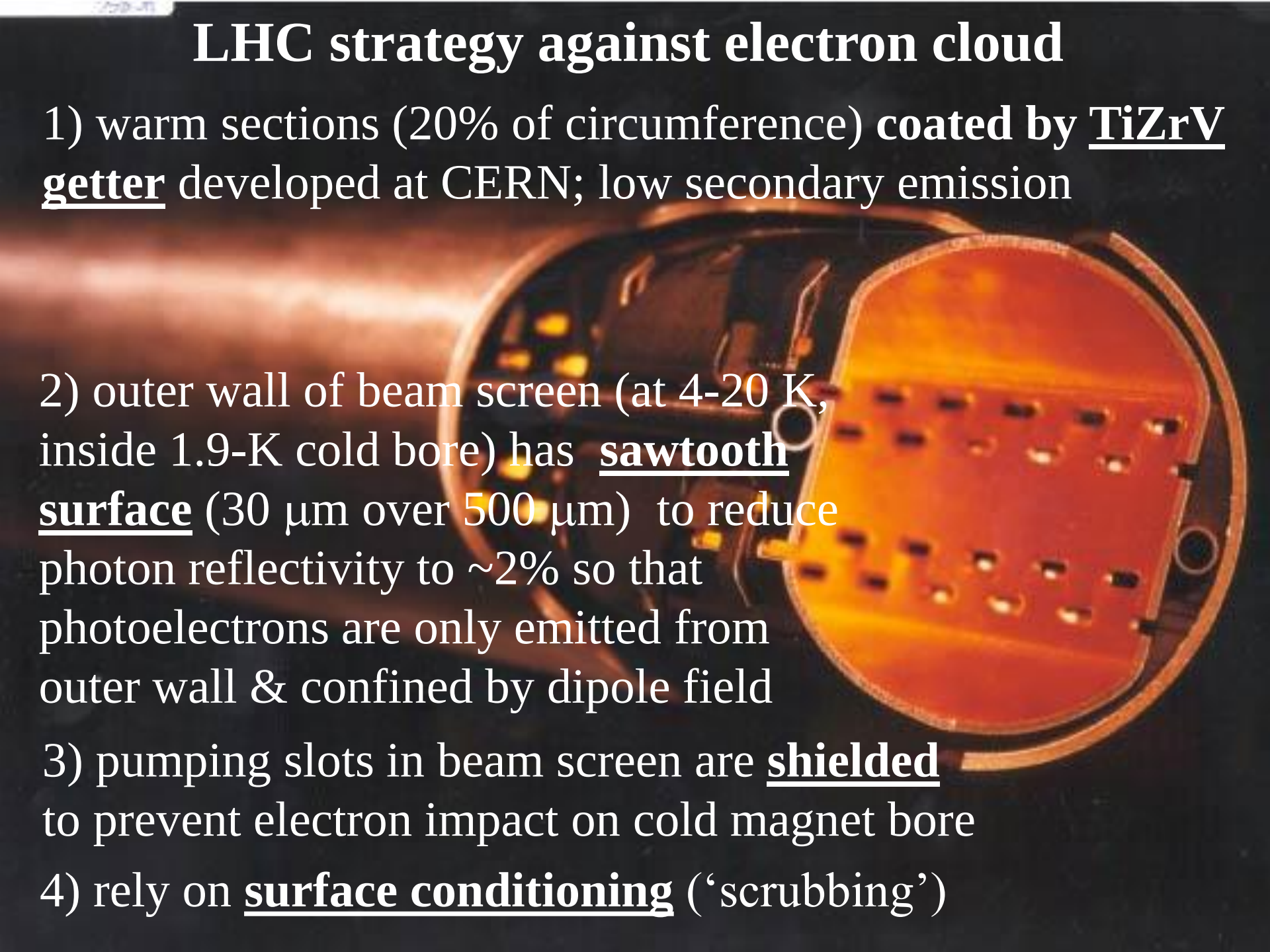
Dump 2: 4.3 TeV with one bunch

somewhat worrying

S. Redaelli

LHC strategy against electron cloud

1) warm sections (20% of circumference) **coated by <u>TiZrV getter</u>** developed at CERN; low secondary emission

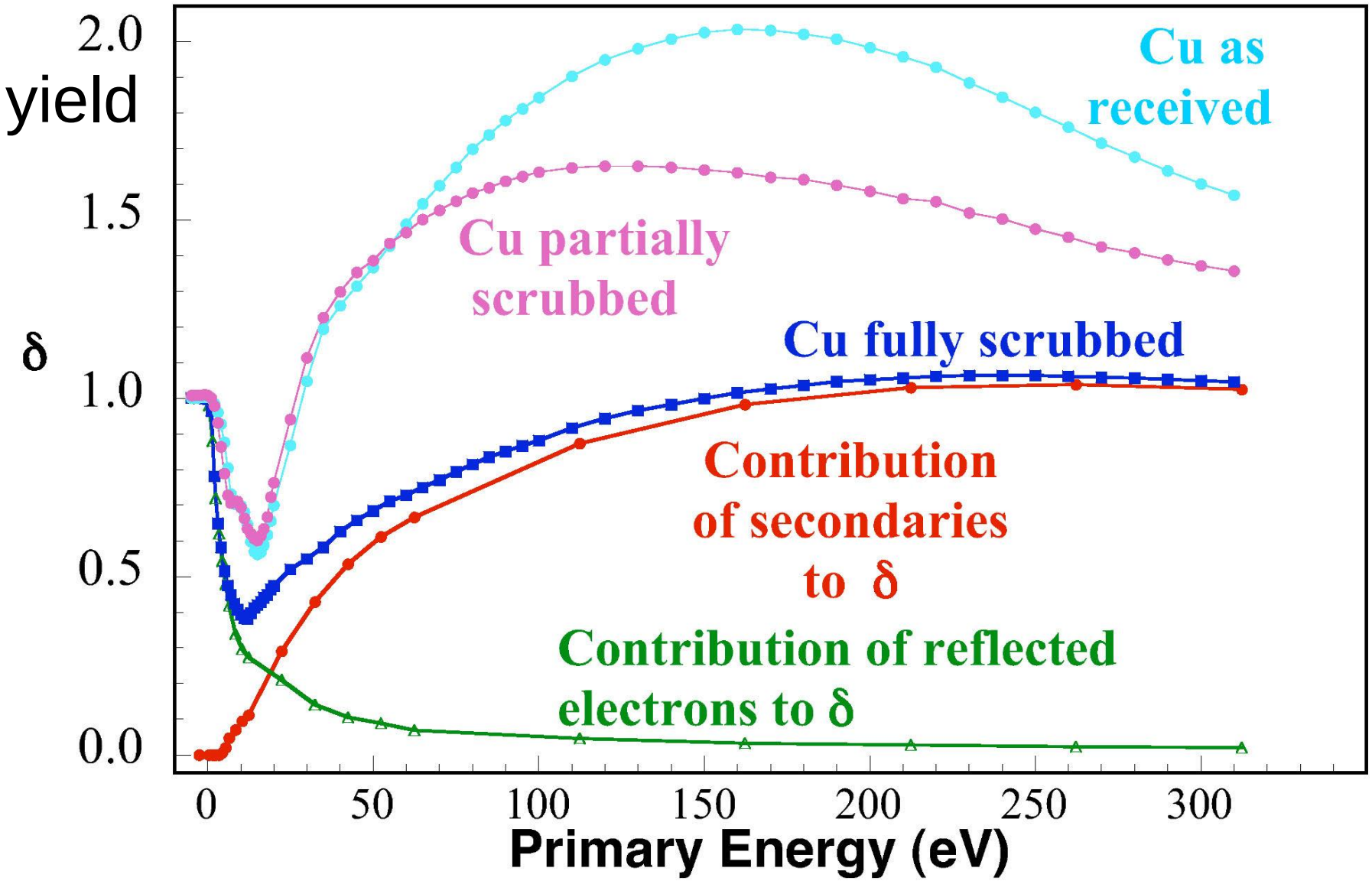


2) outer wall of beam screen (at 4-20 K, inside 1.9-K cold bore) has **<u>sawtooth surface</u>** (30 μm over 500 μm) to reduce photon reflectivity to ~2% so that photoelectrons are only emitted from outer wall & confined by dipole field

3) pumping slots in beam screen are **<u>shielded</u>** to prevent electron impact on cold magnet bore

4) rely on **<u>surface conditioning</u>** ('scrubbing')

evolution of secondary emission yield (lab meas.)

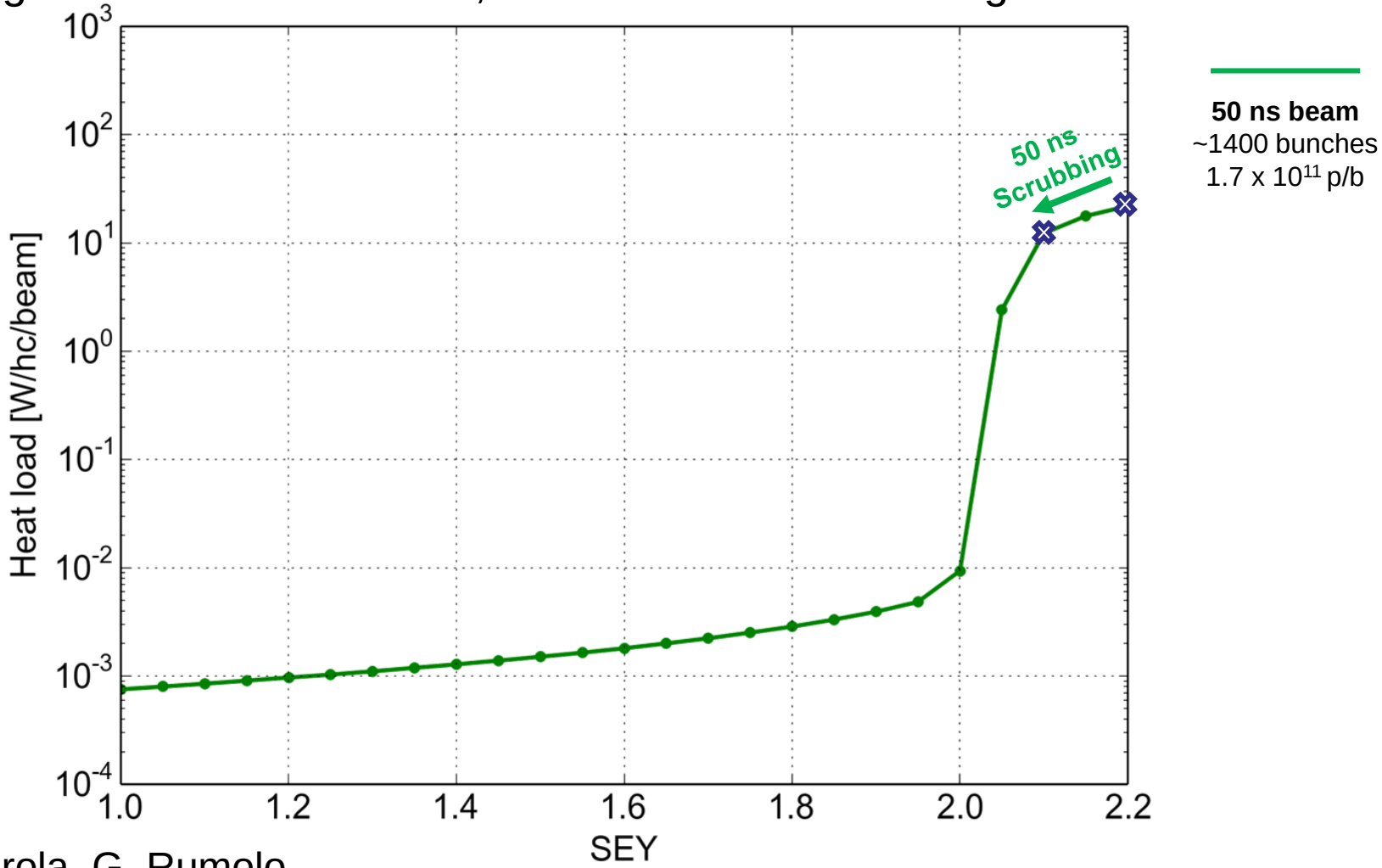


R. Cimino, I. Collins, 2003; CERN-AB-2004-012

2015 e-cloud scrubbing - goal and strategy

Goal: accumulate e^- dose on the beam chambers to mitigate e-cloud effects with 50 ns and 25 ns beams

Strategy: gradually increase the e^- flux (50 ns → 25 ns → doublets) while keeping under control vacuum, heat loads and beam degradation



G. Iadarola, G. Rumolo

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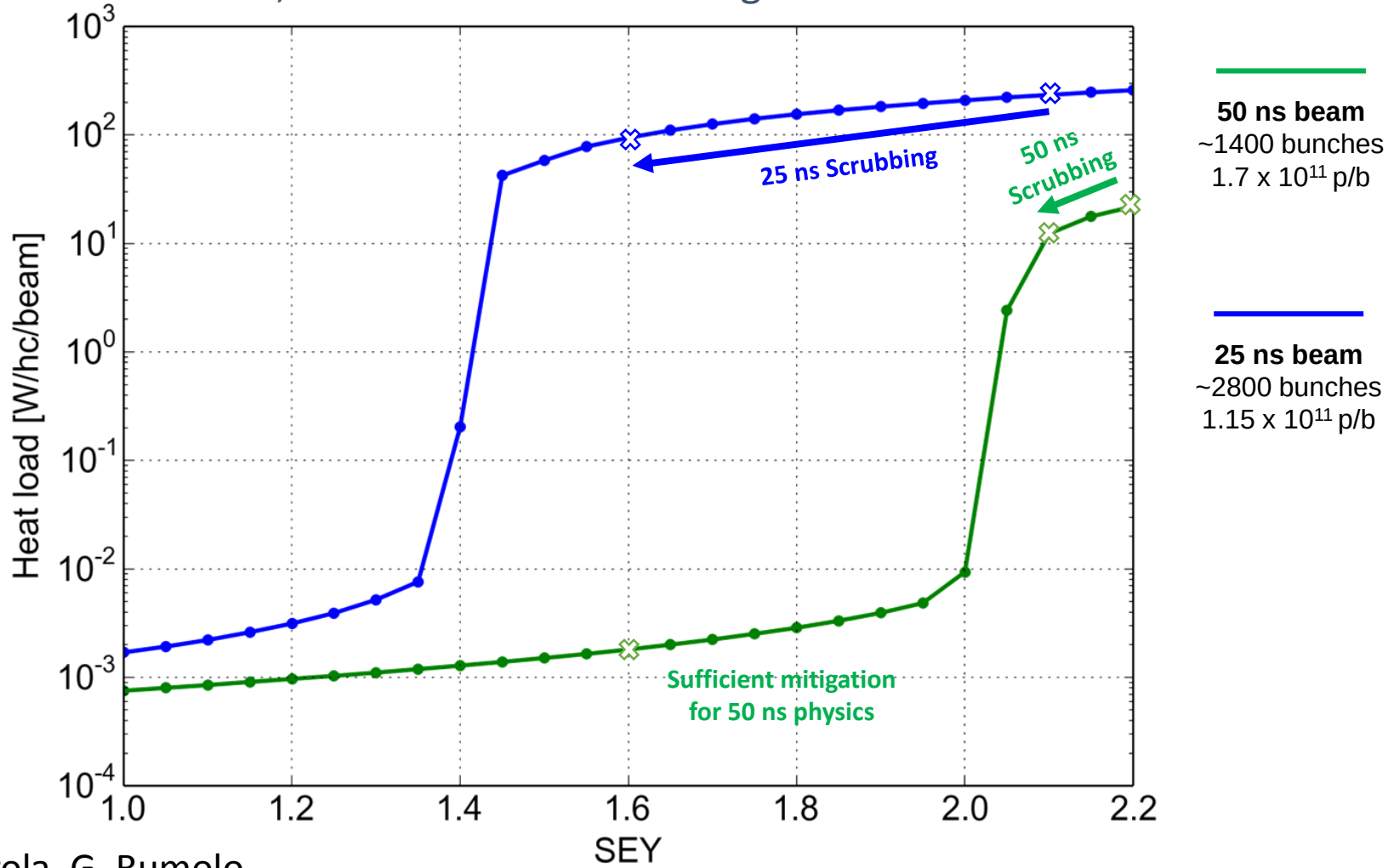

G. Iadarola, G. Rumolo

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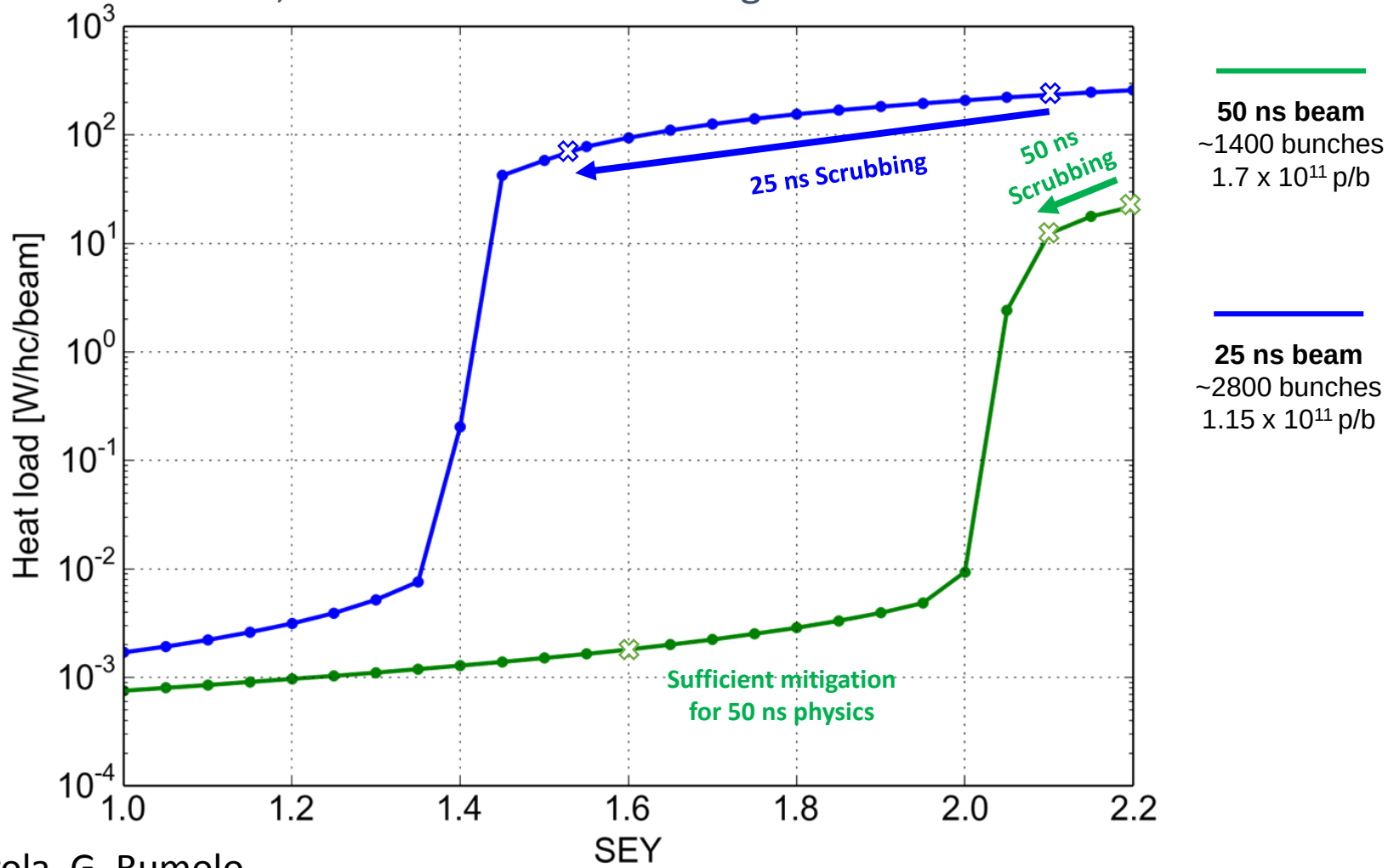

G. Iadarola, G. Rumolo

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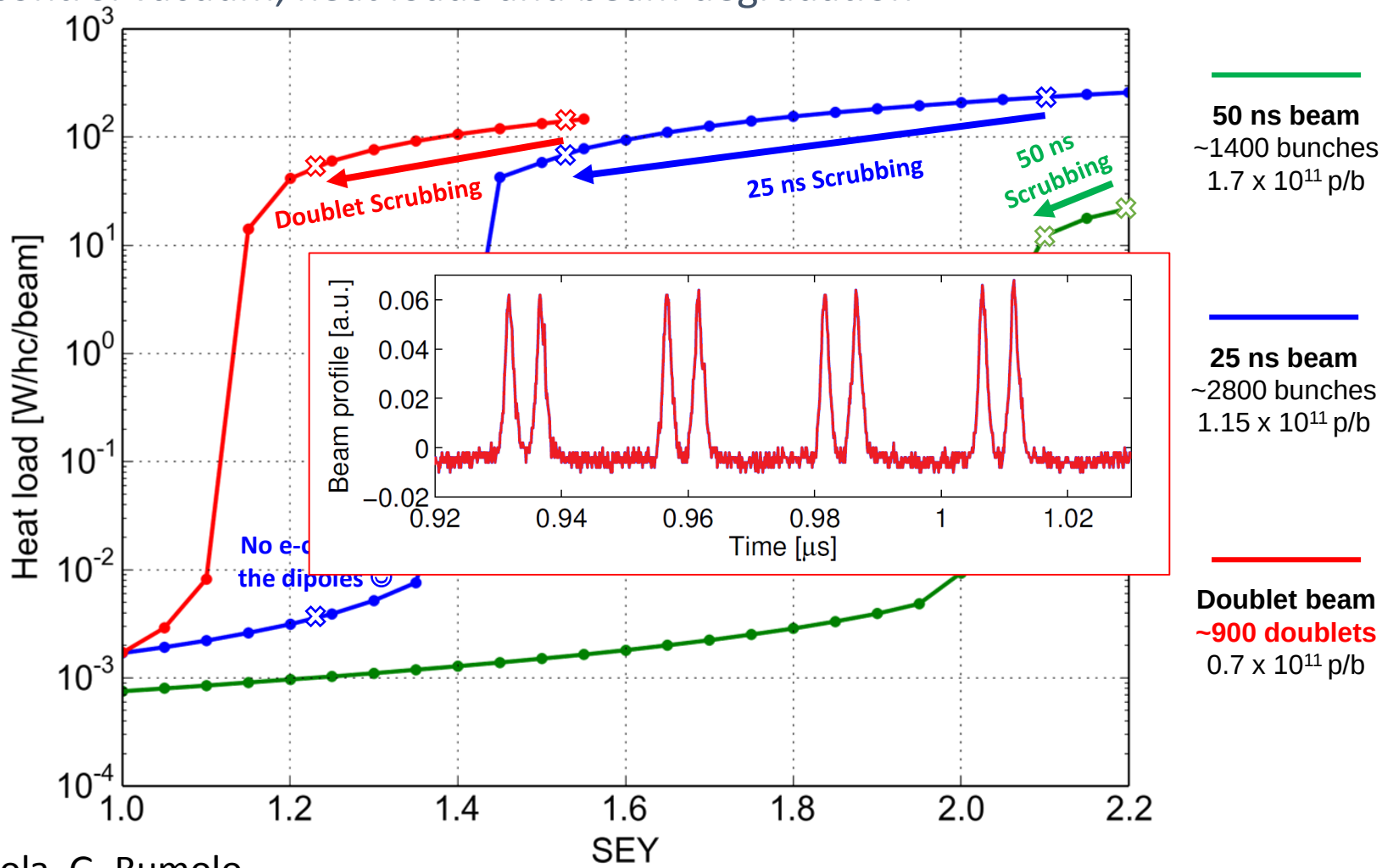
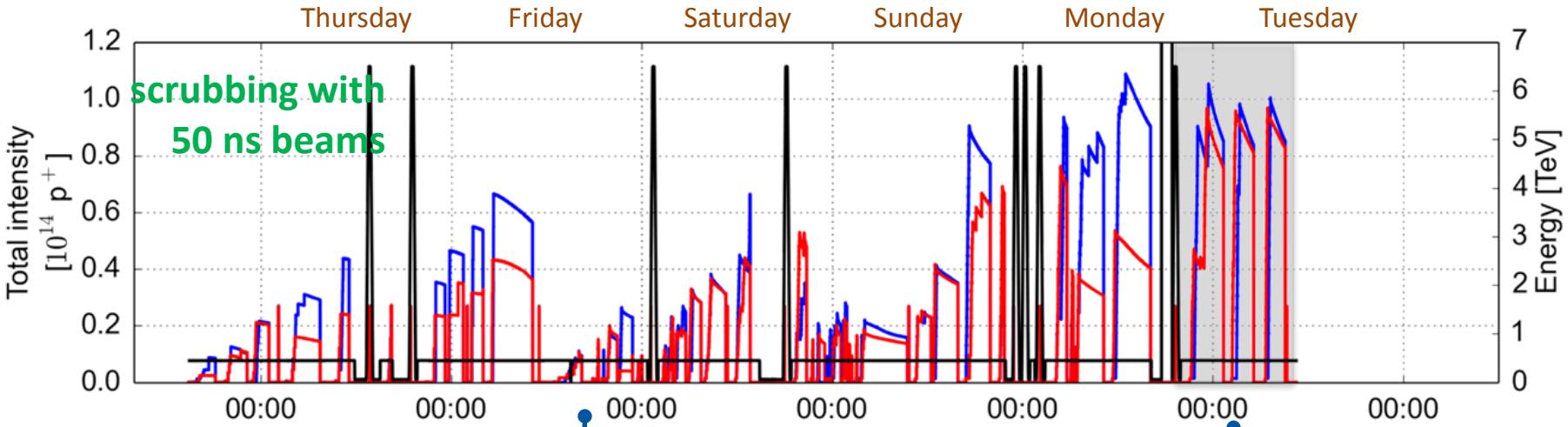


G. Iadarola, G. Rumolo

last 5 days: LHC Scrubbing Run at 450 GeV



start scrubbing with 25 ns beams

trains of 24 bunches:
698b. in beam 1,
444b. in beam 2

trains of 36 bunches

1020 870

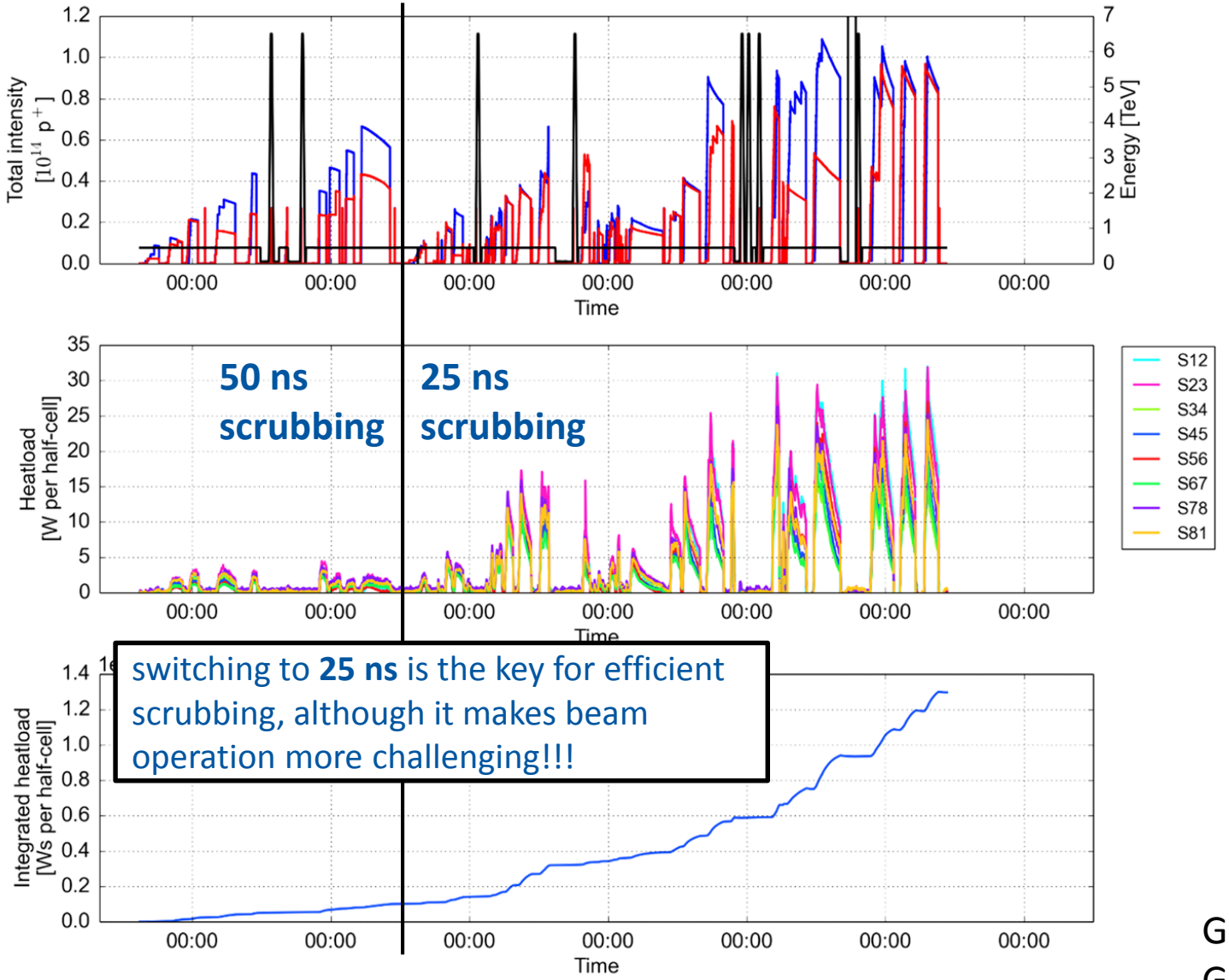
trains of 36 bunches

1200 1177

then moved to **trains of 48 bunches**

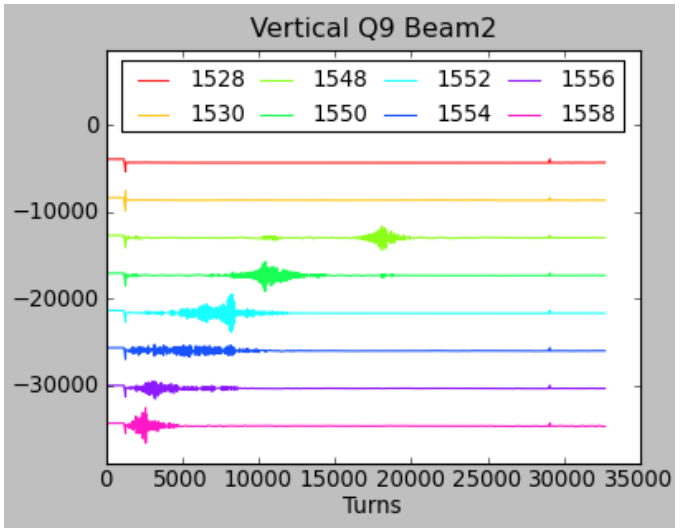
G. Rumolo,
G. Iadarola

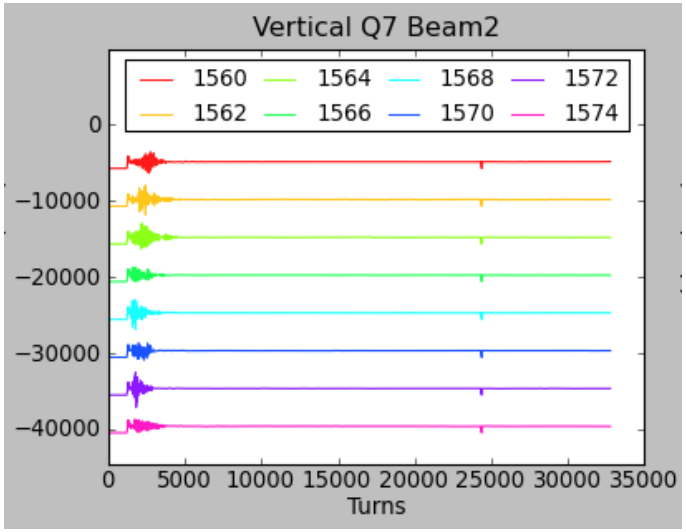
scrubbing - heat load on arc beam screens



G. Rumolo,
G. Iadarola

beam observations: coherent e-cloud instabilities





Vertical position

due to e-cloud, the 25 ns beam often **unstable at injection** (mainly in the vertical plane)

recipe to accumulate 25 ns beam in LHC:

- high **chromaticity** settings at injection ($Q'_{H,V}$≈15), but trim **$Q'_{H,V}$≈10** later to improve beam lifetime
- **octupoles** (knob value=-1.5)
- high **damper** gain

steady improvement fill after fill

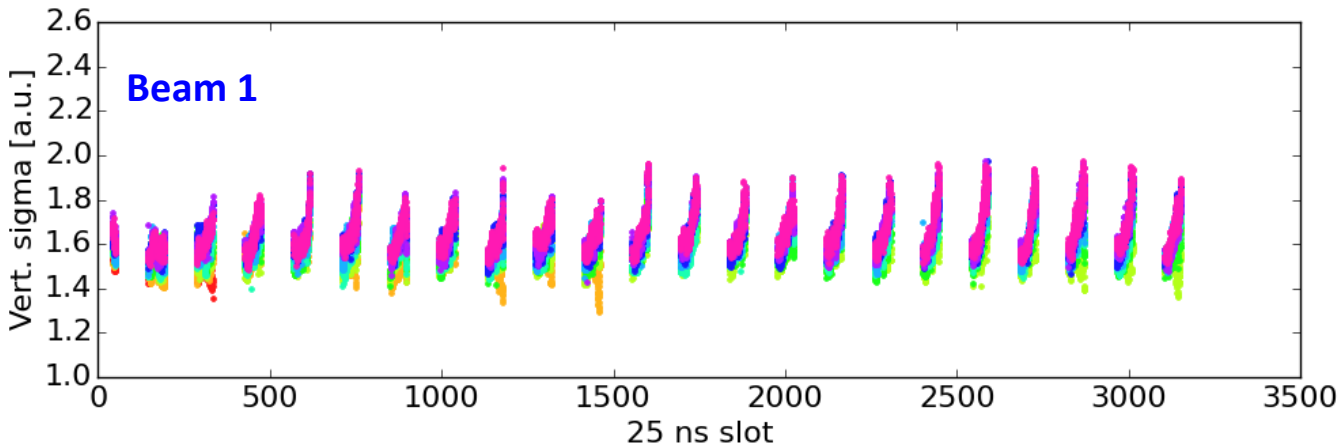
- Beam 1 (which has more accumulated dose) **hardly showed any sign of coherent instability at injection** in the last fills

beam quality degradation

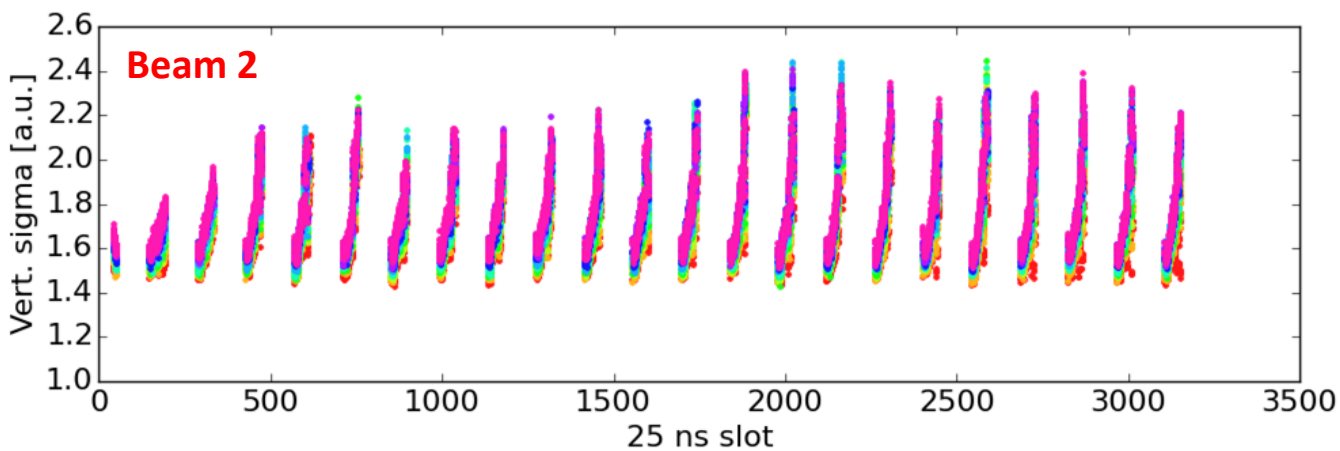
25 ns beams stored in the LHC still show a strong degradation

→ **transverse emittance blow up** along batches and from batch to batch

→ beam 2 worse than beam 1

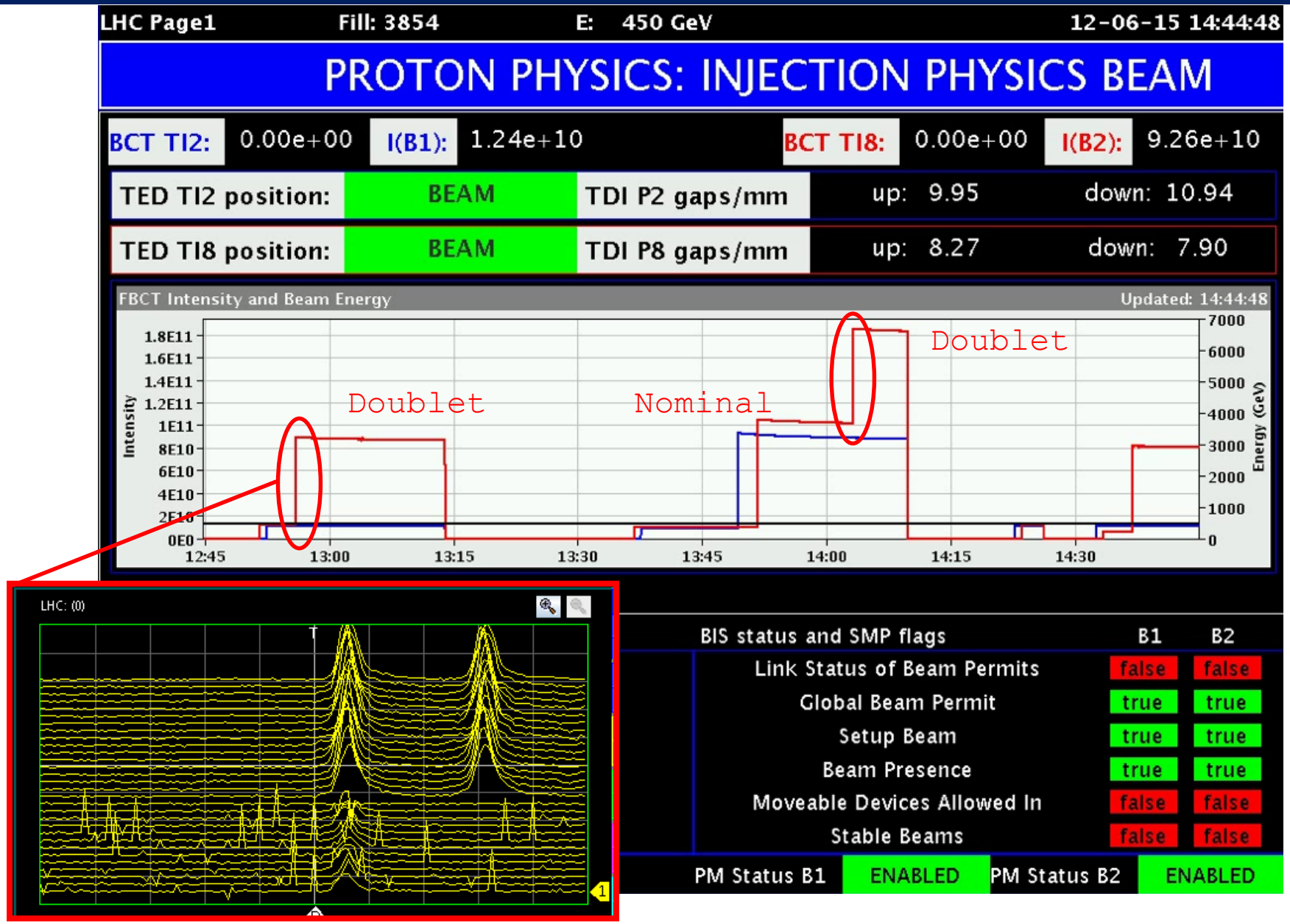


One scan every ≈20 mins



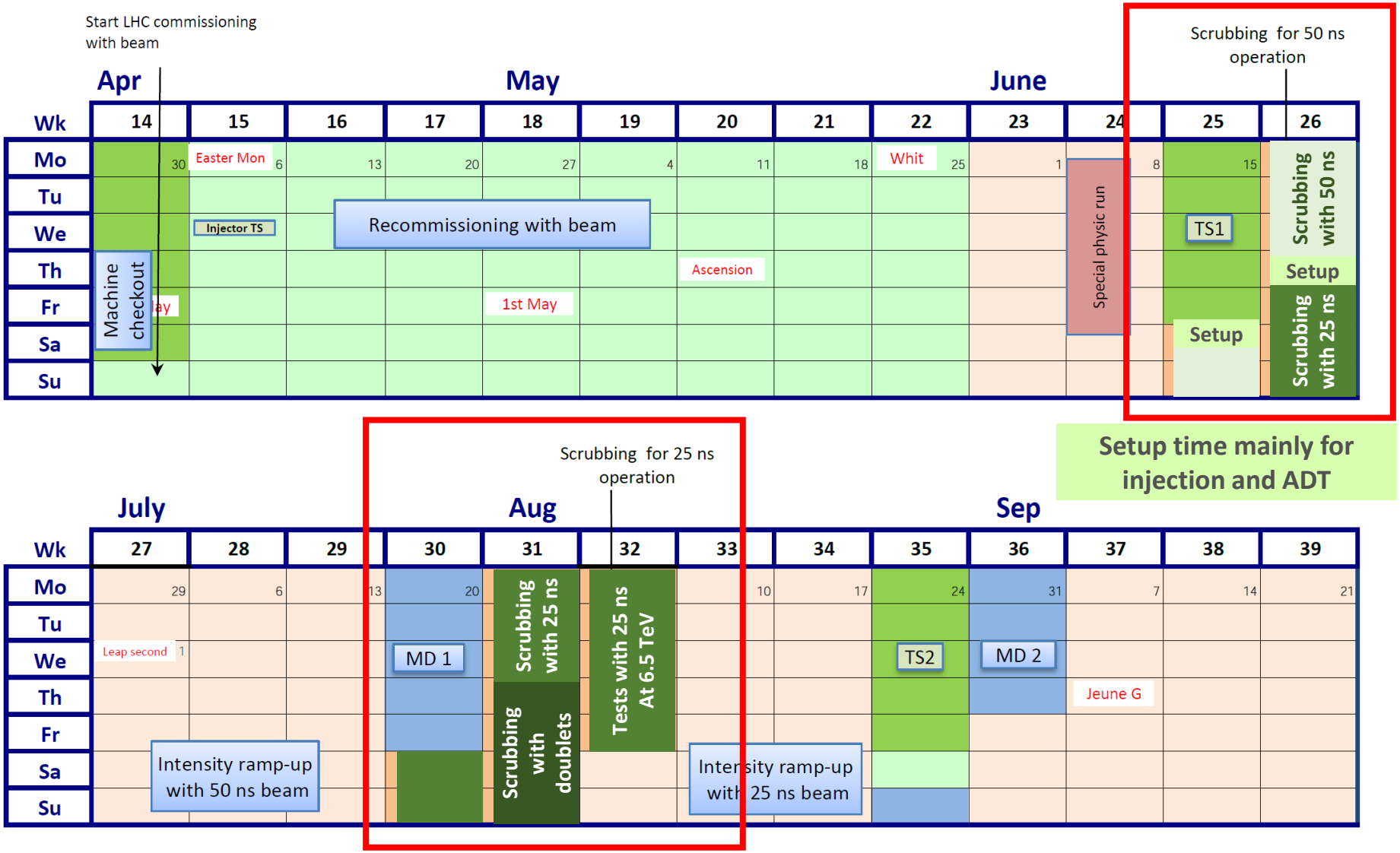
G. Rumolo,
G. Iadarola

first doublet beams in the LHC



e-cloud scrubbing time in LHC schedule (V1.4)

Two scrubbing runs: Week 26 (followed by 50 ns operation), Weeks 31-32 (followed by 25 ns operation)



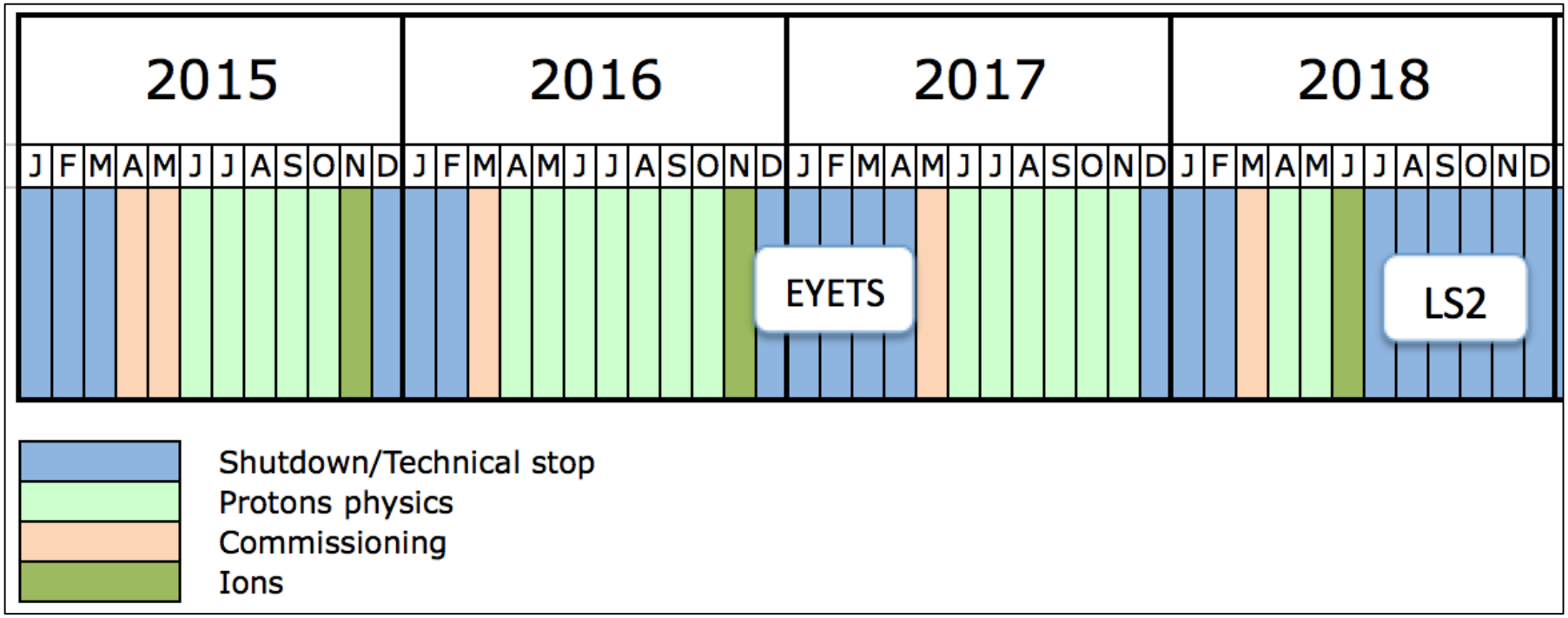
2015: ATLAS and CMS performance

- conservative beta* to start
- nominal bunch population
- reasonable emittance into collisions
- assume same machine availability as 2012

	Nc	Beta *	ppb	EmitN	Lumi [$cm^{-2}s^{-1}$]	Days (approx)	Int lumi	Pileup
50 ns	1300	80	1.2e11	2.5	4.8e33	21	≈1 fb^{-1}	25
2015.1	2448	80	1.2e11	3.1	7.1e33	35	≈4 fb^{-1}	21
2015.2	2448	40	1.2e11	3.1	1.2e34	30	≈5 fb^{-1}	35

official luminosity target for the year was 10 fb^{-1}
now on the challenging side – revised estimate 5-10 fb^{-1}

Run 2



- EYETS – Extended Year End Technical Stop – 19 weeks – CMS pixel upgrade
- **Mid-year 2018 stop will be pushed towards year end (not yet official?)**

Run 2 performance

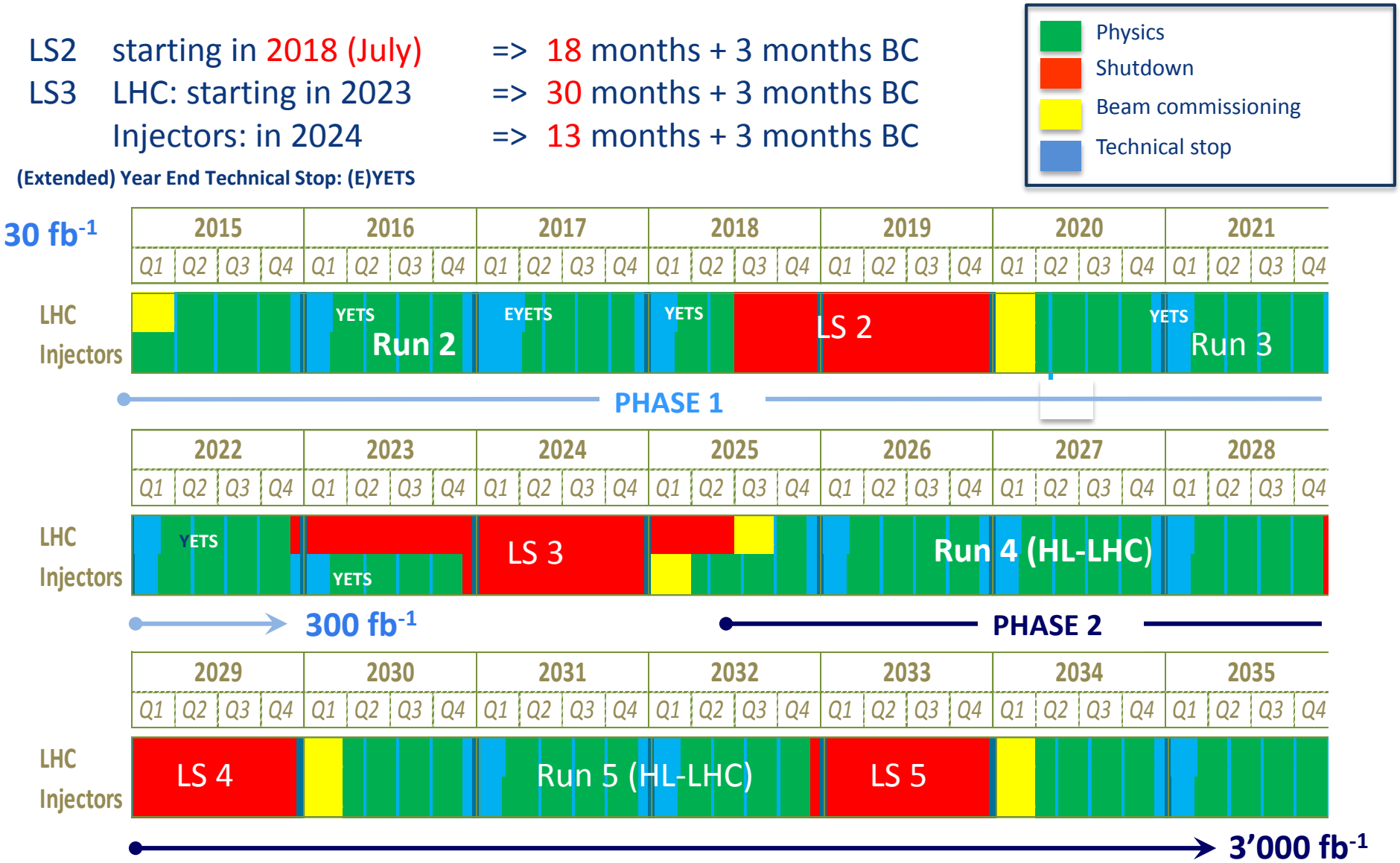
- aim to start 2016 in production mode
  - 6.5 TeV, machine scrubbed for 25 ns operation
  - β^* = 40 cm in ATLAS and CMS
  - new injection protection absorbers – full injection
  - peak lumi limited to $1.7 \times 10^{34} cm^{-2} s^{-1}$ by inner triplets

	Peak lumi 10^{34} $cm^{-2}s^{-1}$	Days proton physics	Approx. int lumi [fb^{-1}]
2015	1.2	70	5 - 10
2016	1.5	160	35
2017	1.7	160	45
2018	1.7	40	10

LHC roadmap: 20-yr schedule beyond LS1

LS2 starting in 2018 (July) => 18 months + 3 months BC
LS3 LHC: starting in 2023 => 30 months + 3 months BC
Injectors: in 2024 => 13 months + 3 months BC

(Extended) Year End Technical Stop: (E)YETS

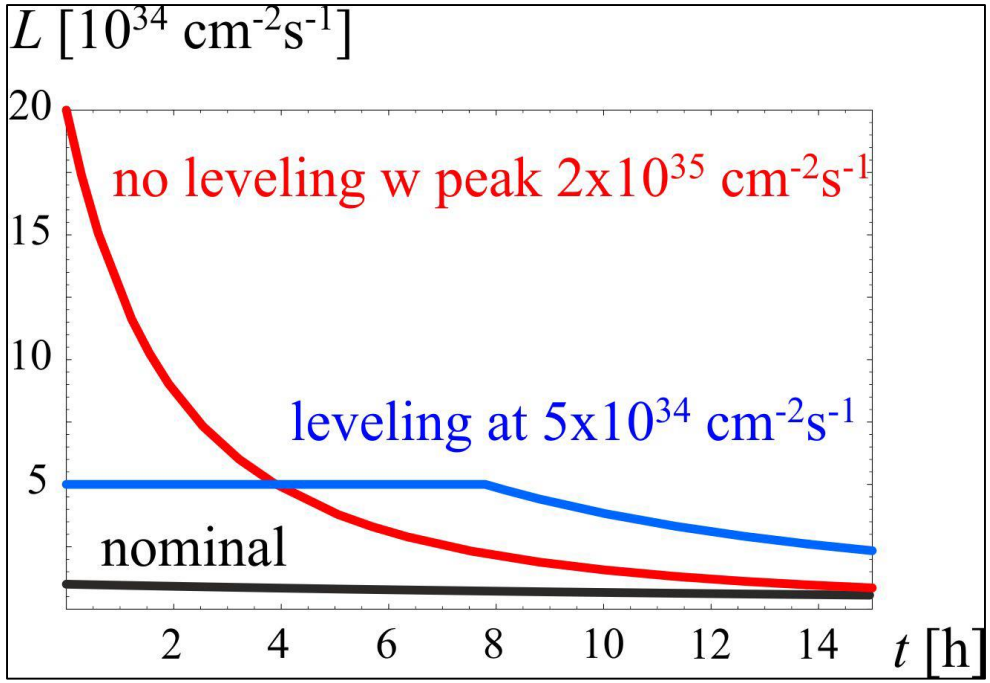


F. Bordry

HL-LHC

M. Lamont

- 3000 fb^{-1} delivered in the order of 10 years
- high "virtual" luminosity with levelling anticipated
- challenging demands on the injector complex
  - major upgrades foreseen in LS2



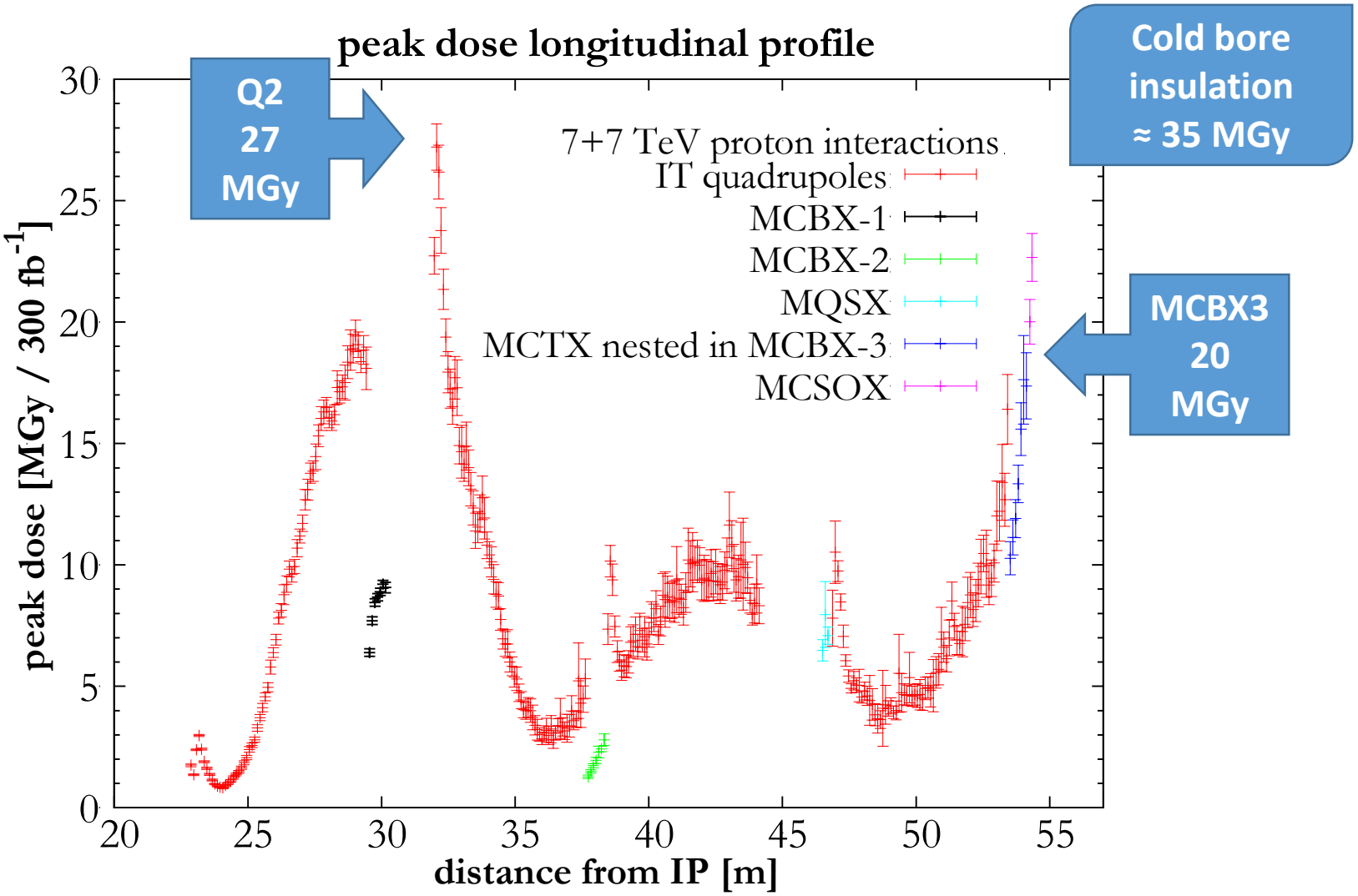
5×10^{34} $cm^{-2}s^{-1}$ levelled luminosity

pile-up ≈140

3 fb^{-1} per day

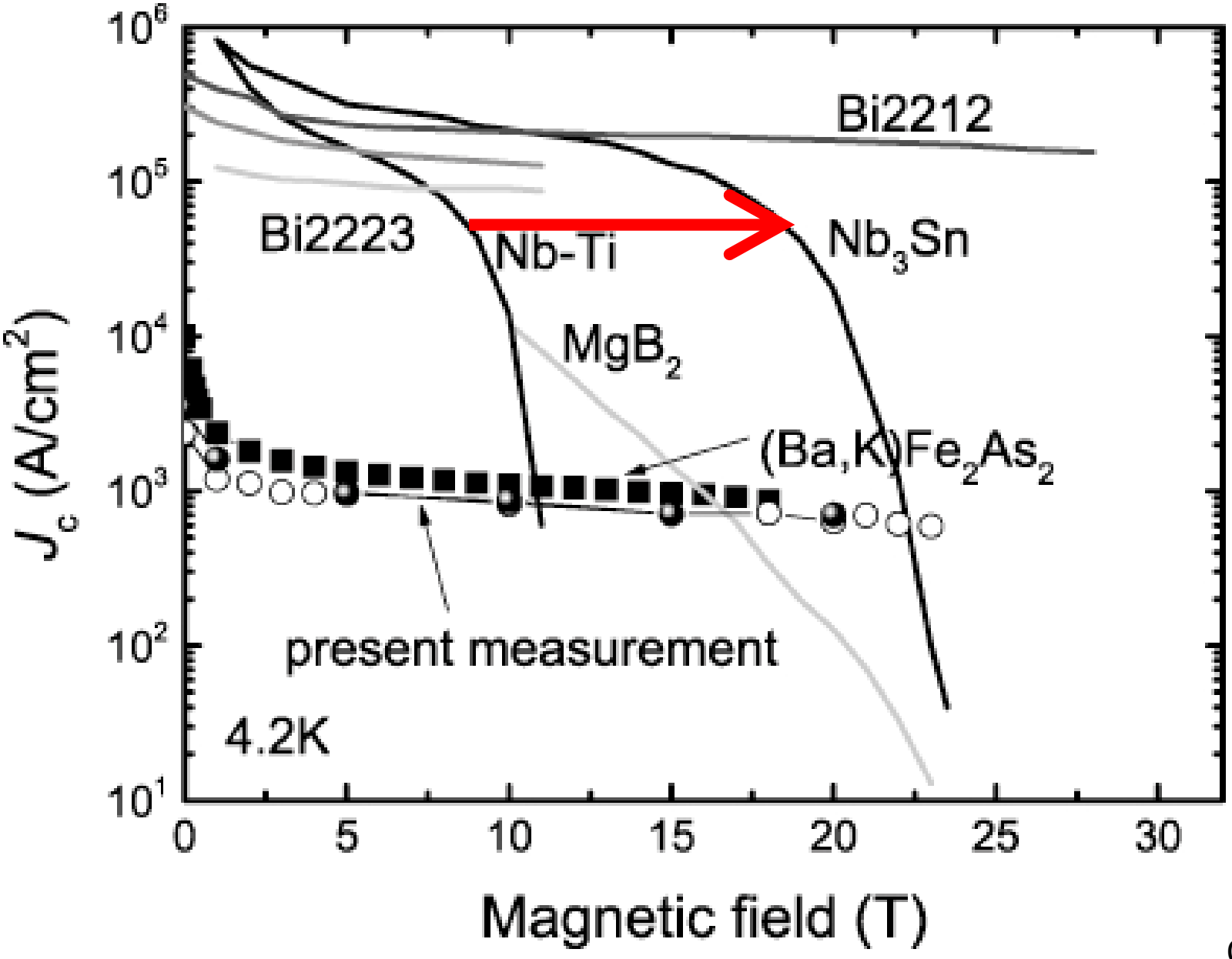
≈250 fb^{-1} /year

the technical trigger for the upgrade: radiation damage of final triplet quadrupoles



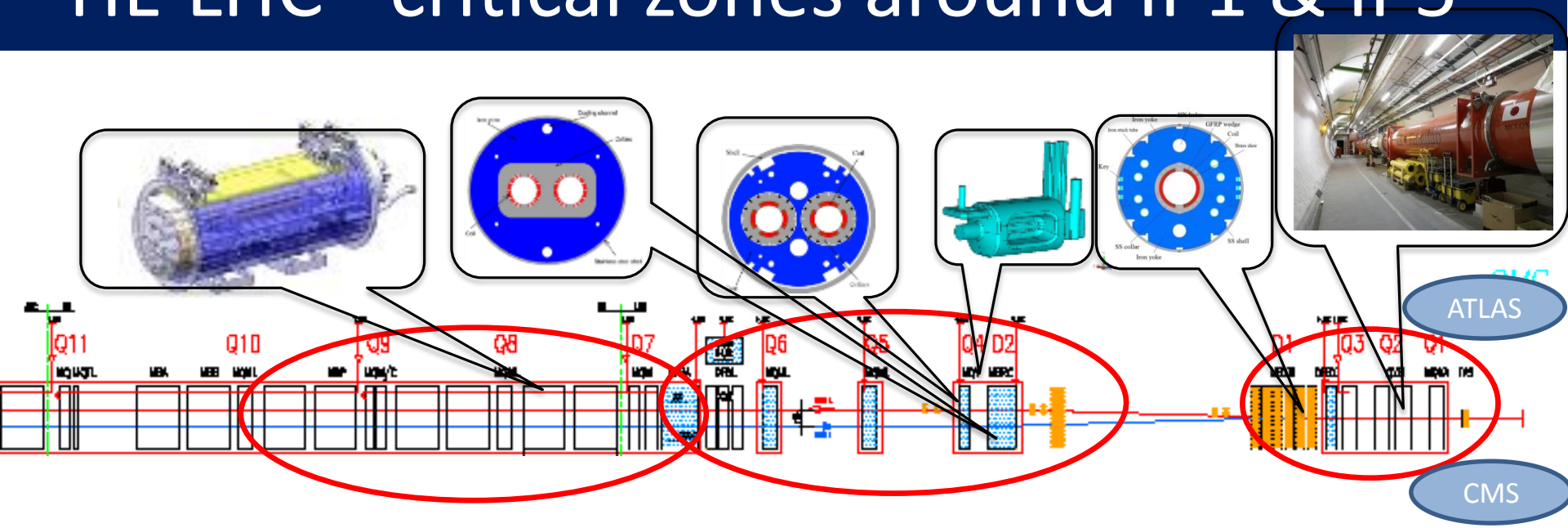
L. Rossi

technology transition: *Nb-Ti* → Nb_3Sn



O. Bruning

HL-LHC - critical zones around IP1 & IP5



3. For collimation we also need to change the DS in the continuous cryostat: **11-T Nb_3Sn dipole**

2. We also need to modify a large part of the matching section e.g. **Crab Cavities** & D1, D2, Q4 & corrector

1. **New quadrupole triplet based on Nb_3Sn (12 T at coil)** required due to:

-Radiation damage

-Need for more aperture

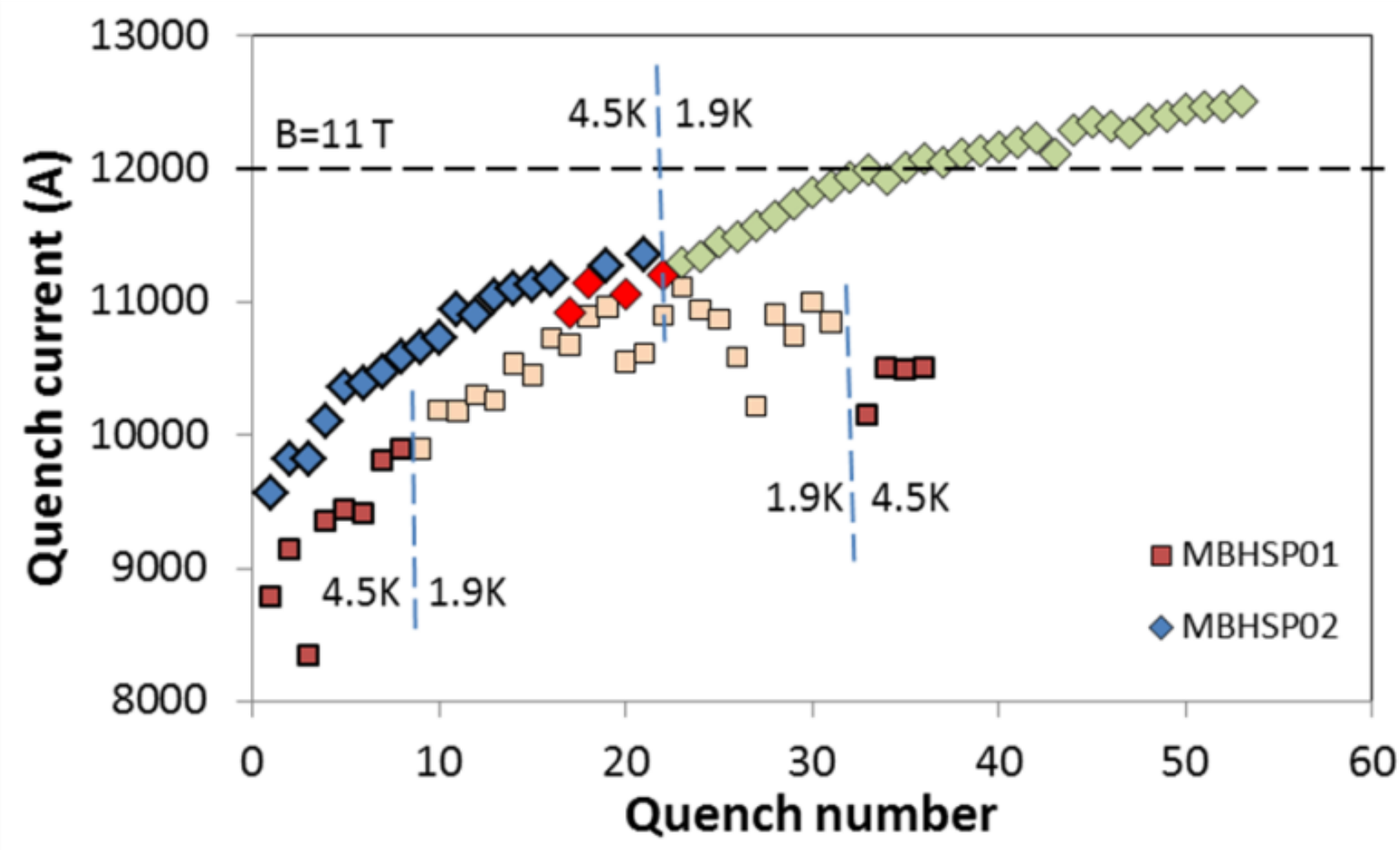
→ more than 1.2 km of LHC

→ plus technical infrastructure (e.g. Cryo and Powering)

Changing the triplet region is not enough for reaching the HL-LHC goal!

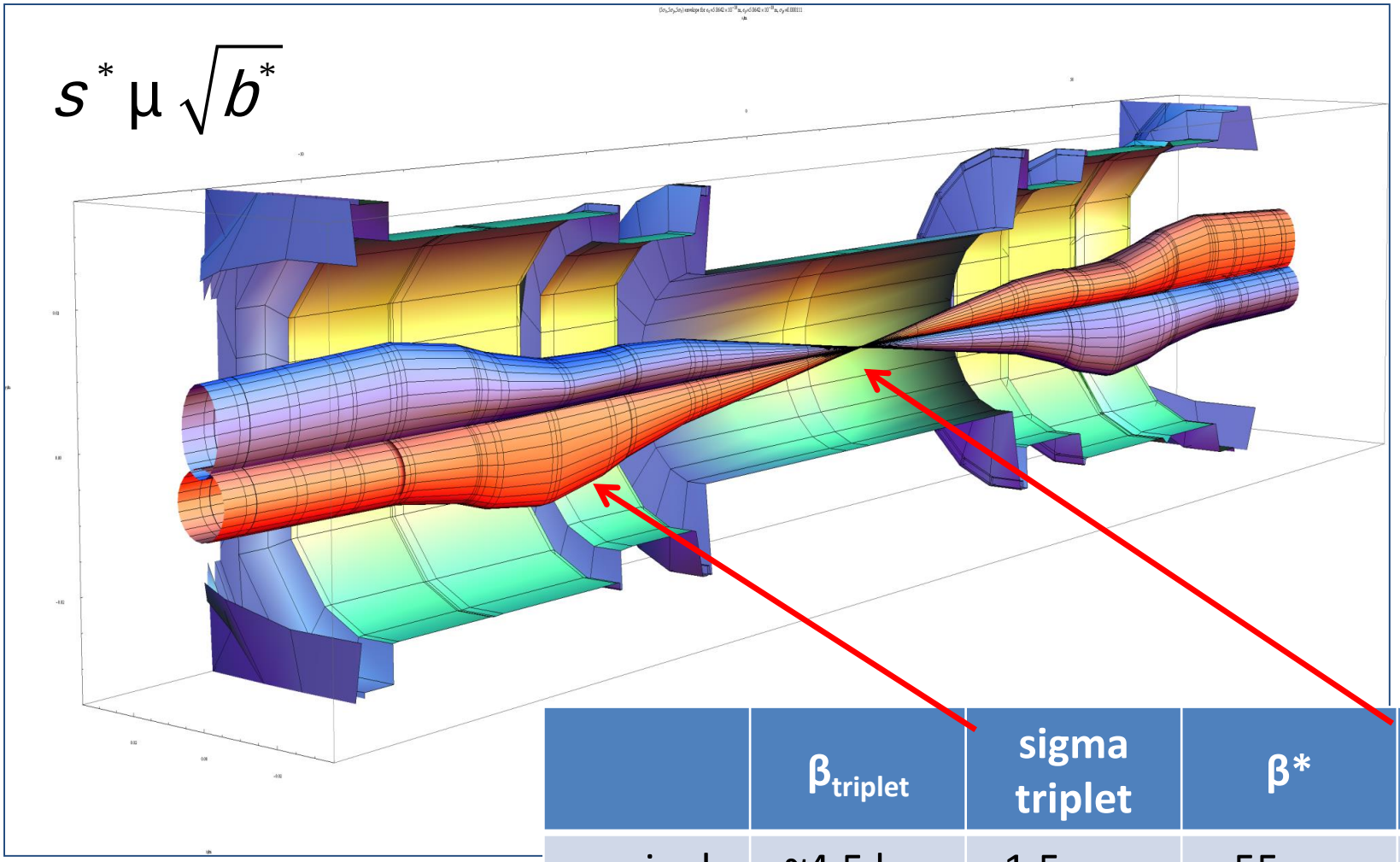
O. Brüning, L. Rossi

FNAL: Nb_3Sn dipole demonstrators



MBHSP02 (1 m) passed 11 T field during training at 1.9 K with I = 12080 A on 5 March 2013

squeeze in ATLAS: LHC vs. HL-LHC

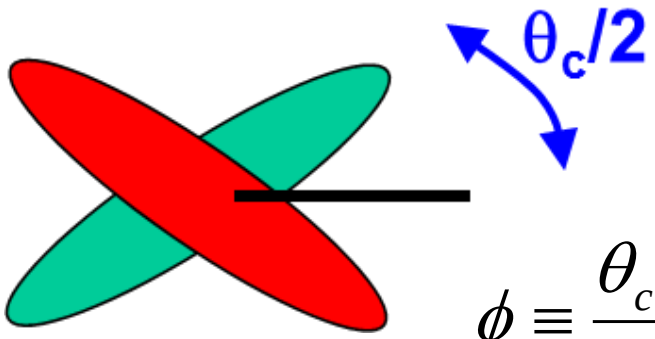


	$\beta_{triplet}$	sigma triplet	β*	sigma*
nominal	~4.5 km	1.5 mm	55 cm	17 μm
HL-LHC	~20 km	2.6 mm	15 cm	7 μm

Image courtesy John Jowett

luminosity loss due to crossing angle

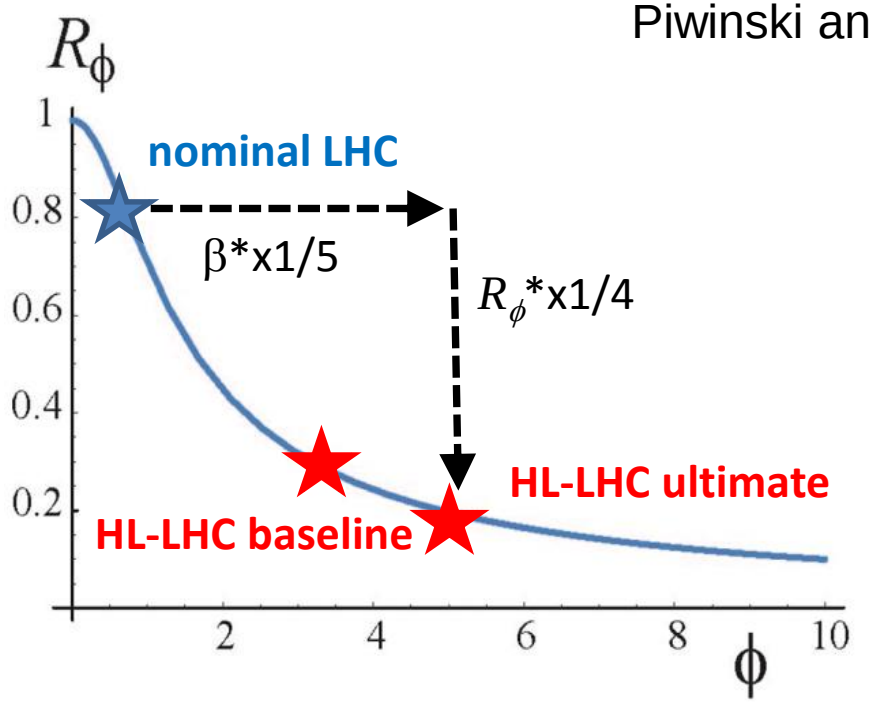
Luminosity loss due to crossing angle is related to the effective increase of the transverse beam size, $\sigma \rightarrow \sigma\sqrt{1+\phi^2}$.



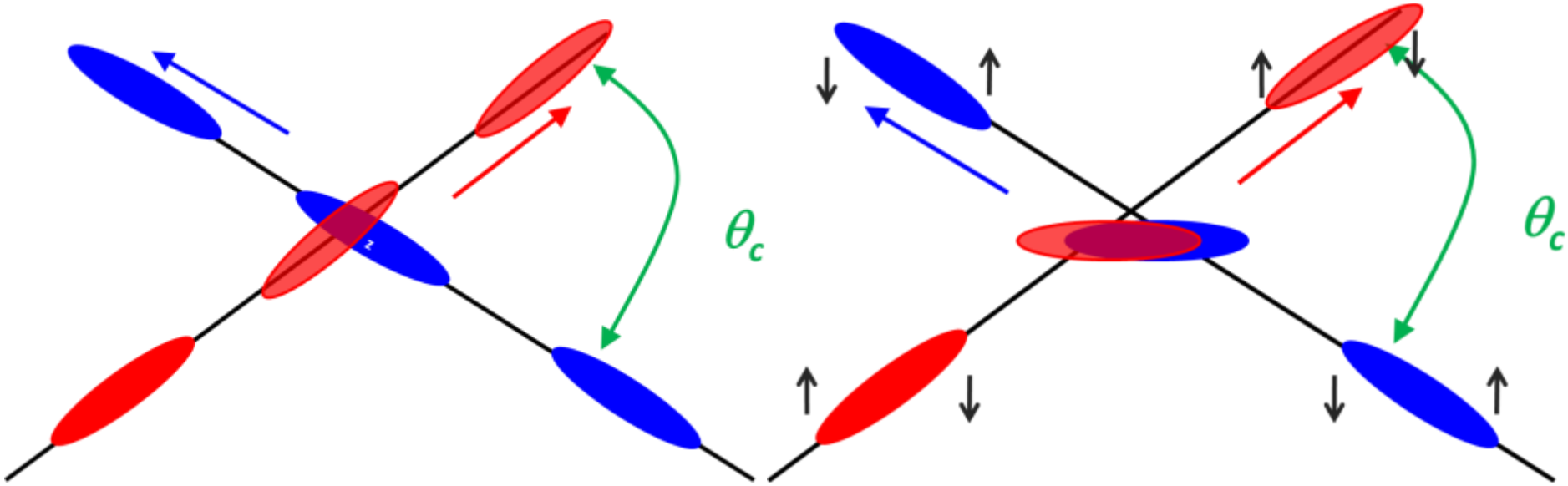
$$\phi \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

Piwinski angle

geometric luminosity loss as a function of the Piwinski angle

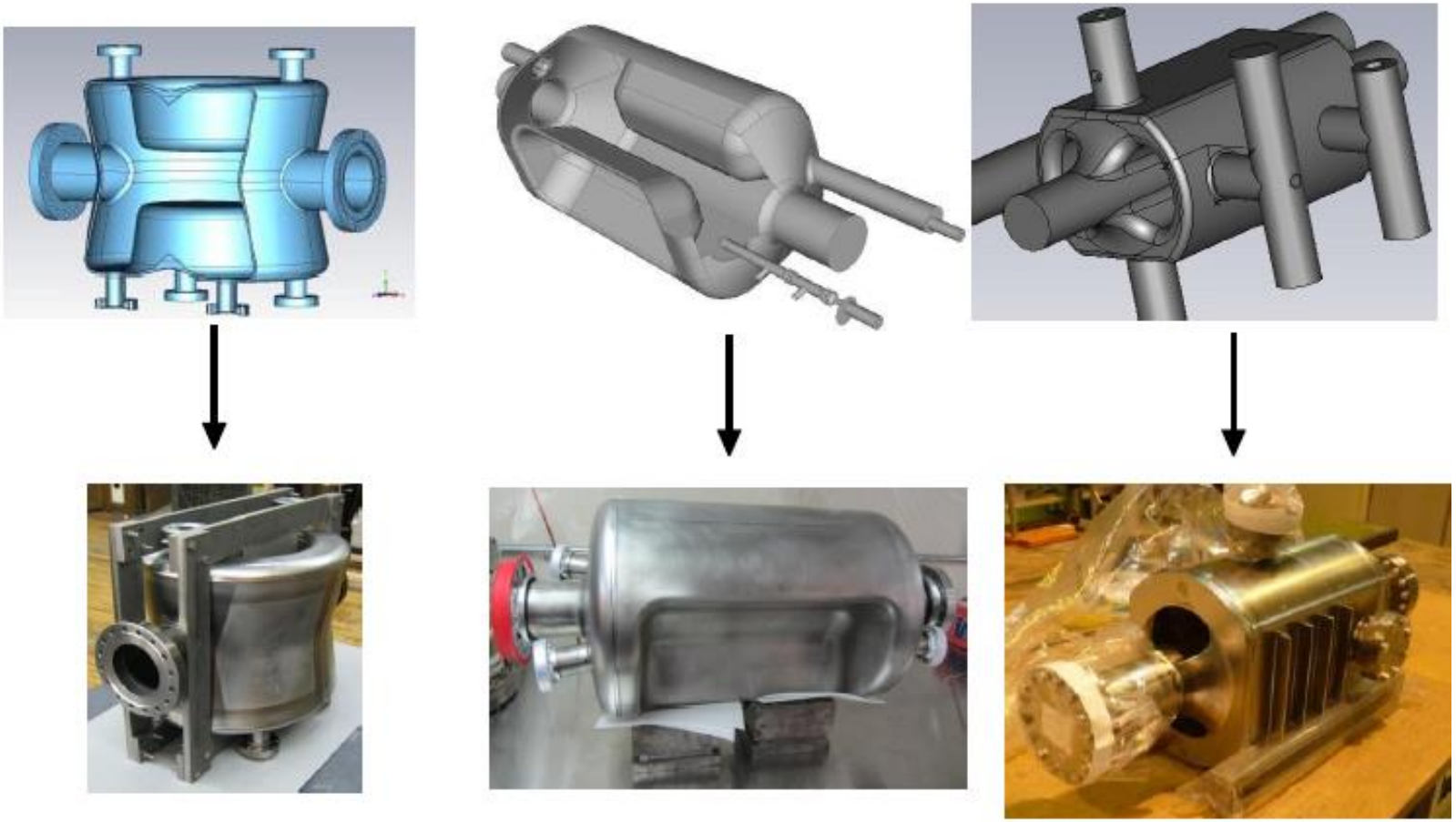


crab crossing



“Crab-crossing” configuration in the crossing plane

HL-LHC compact crab-cavity prototypes

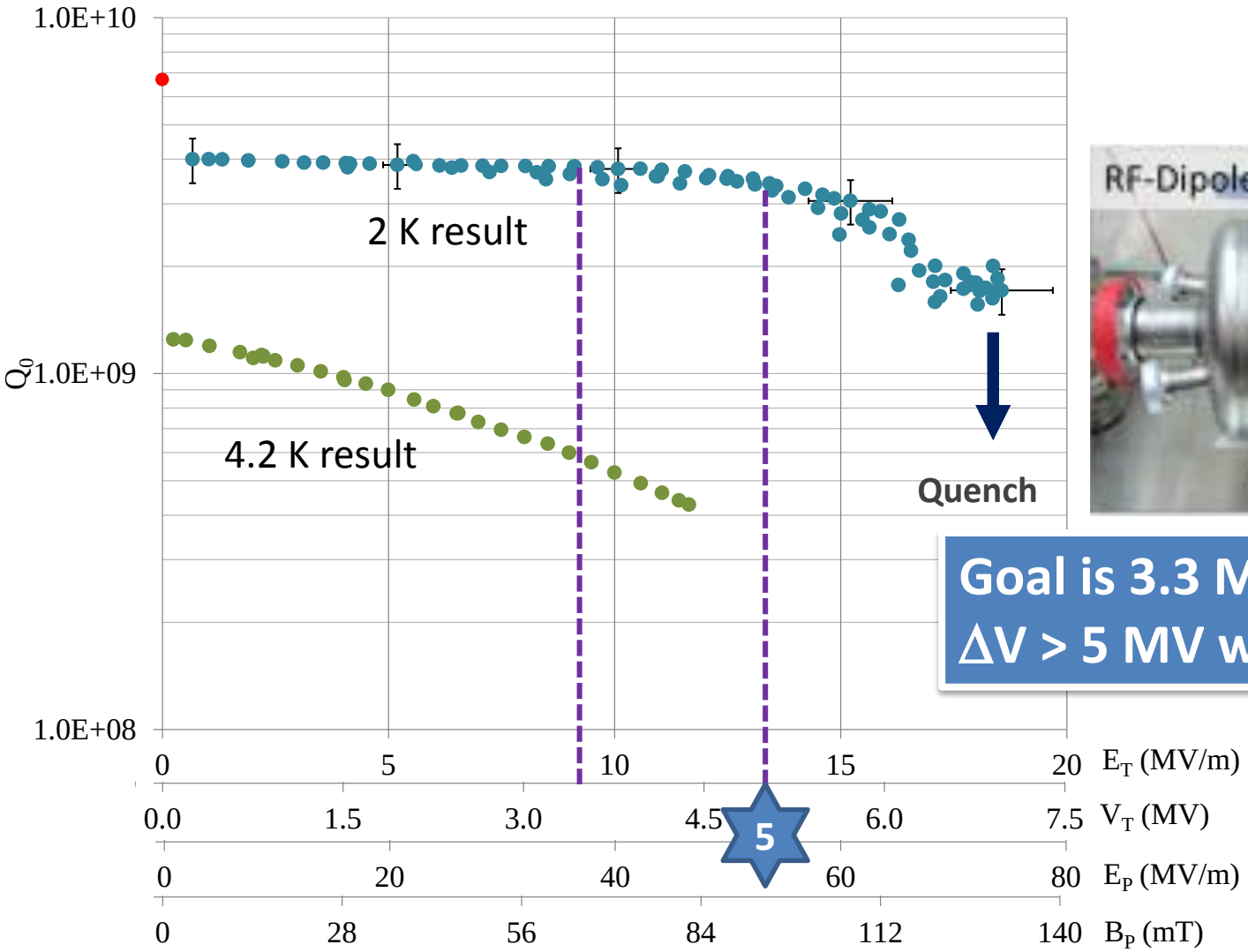


LARP-BNL

LARP-ODU-JLAB

Uni.Lancaster-CI-CERN

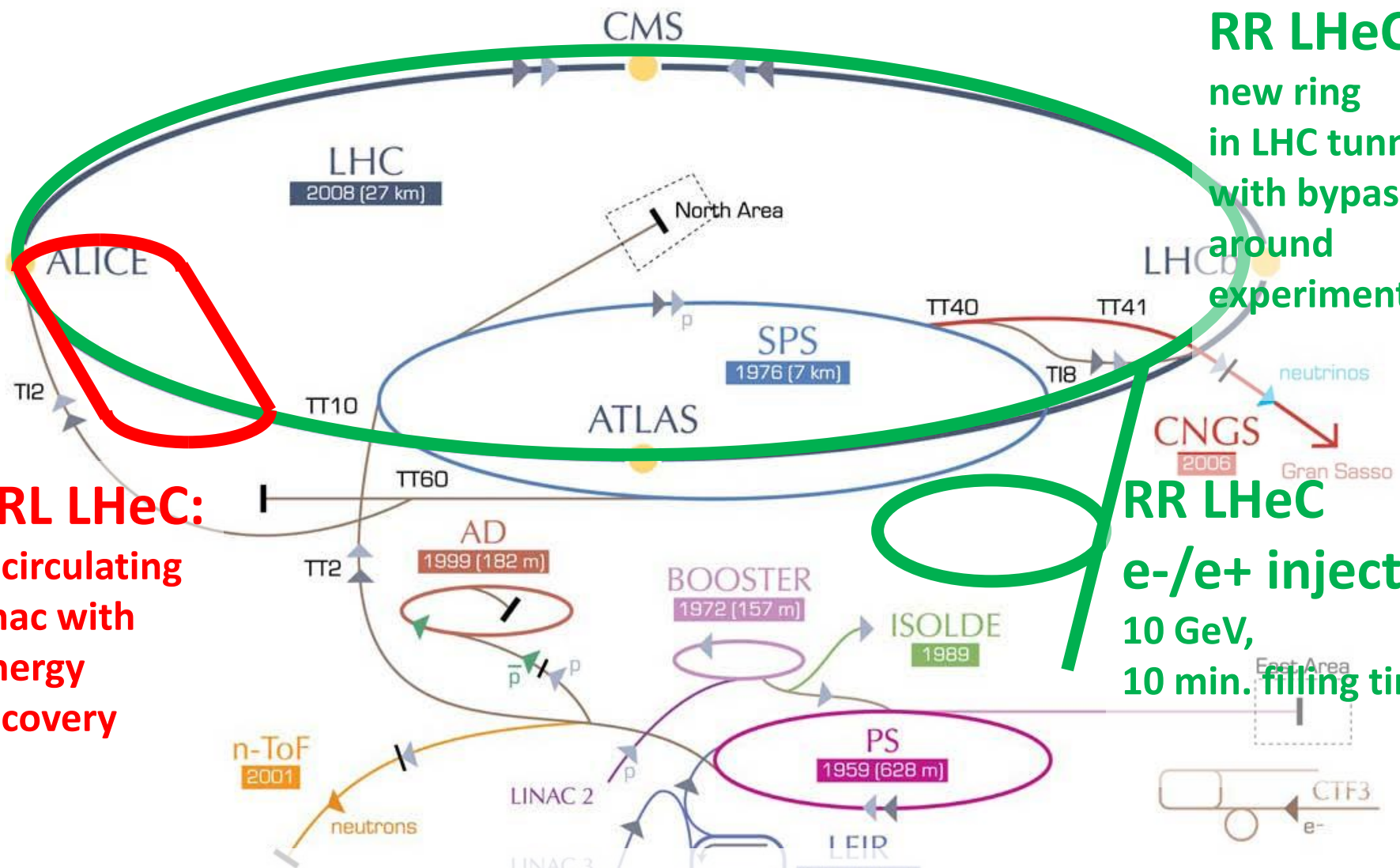
crab cavity test results: RF dipole > 5 MV



Goal is 3.3 MV
ΔV > 5 MV would be an asset

J. Delayen,
L. Rossi

Large Hadron electron Collider (LHeC)



RR LHeC:
new ring in LHC tunnel, with bypasses around experiments

ERL LHeC:
recirculating linac with energy recovery

RR LHeC e-/e+ injector
10 GeV, 10 min. filling time

At 2012 CERN-ECFA-NuPECC LHeC workshop ERL-LHeC was selected as baseline (*RR LHeC issues: HL-LHC schedule, tunnel work, interference*)

LHeC Conceptual Design Report

DRAFT 1.0
Geneva, September 3, 2011
CERN report
ECFA report
NuPECC report
LHeC-Note-2011-003 GEN

A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

LHeC Study Group
THIS IS THE VERSION FOR REFEREEING, NOT FOR DISTRIBUTION

LHeC CDR published in
J. Phys. G: Nucl. Part. Phys. 39 075001 (2012)

http://cern.ch/lhec

LHeC Study Group

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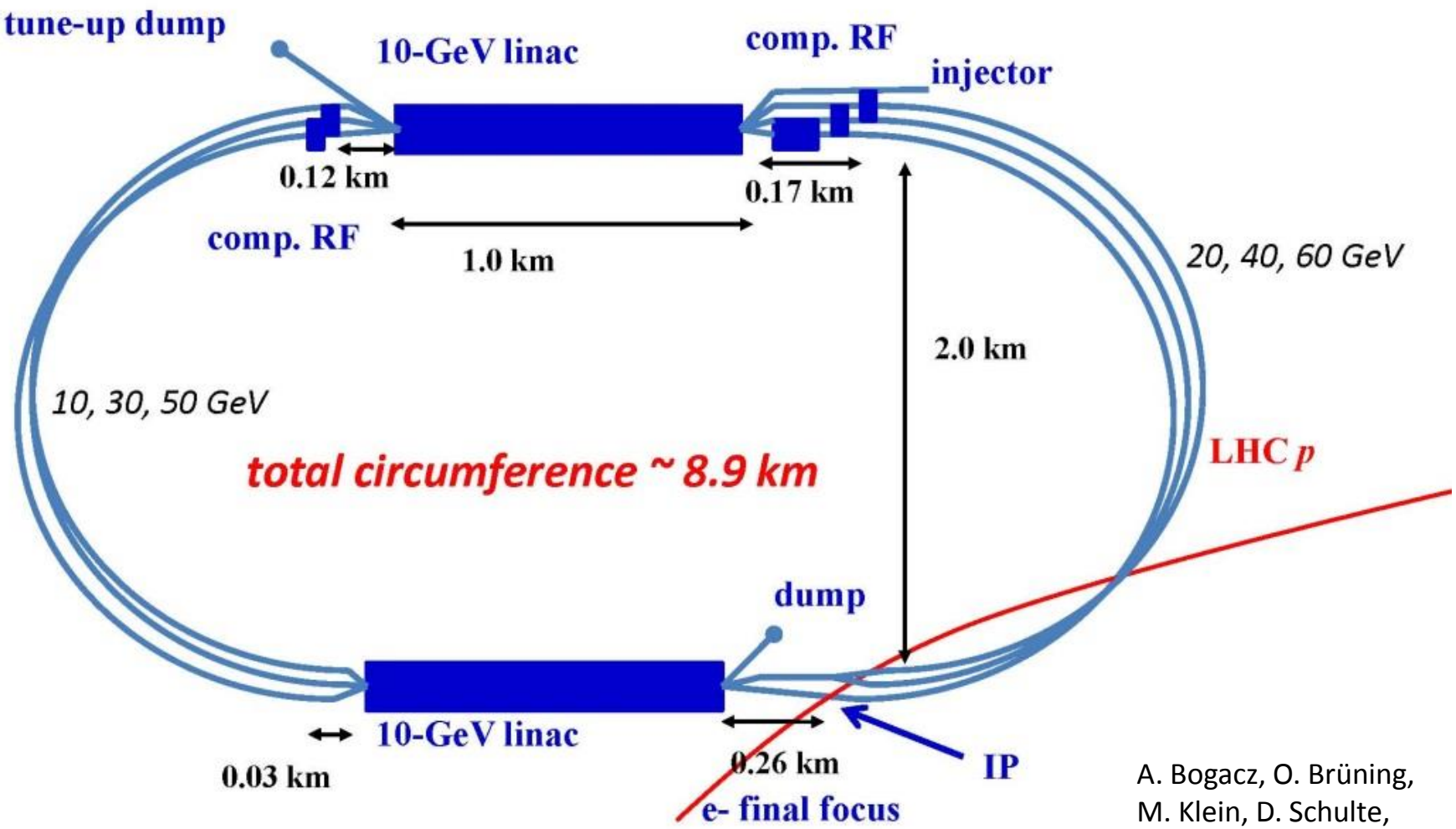
About 150 Experimentalists and Theorists from 50 Institutes
Tentative list

Thanks to all and to
CERN, ECFA, NuPECC

~600 pages

LHeC Linac-Ring ERL layout

two 10-GeV SC linacs, 3-pass up, 3-pass down; 6.4 mA, 60 GeV e-'s collide w. LHC protons/ions



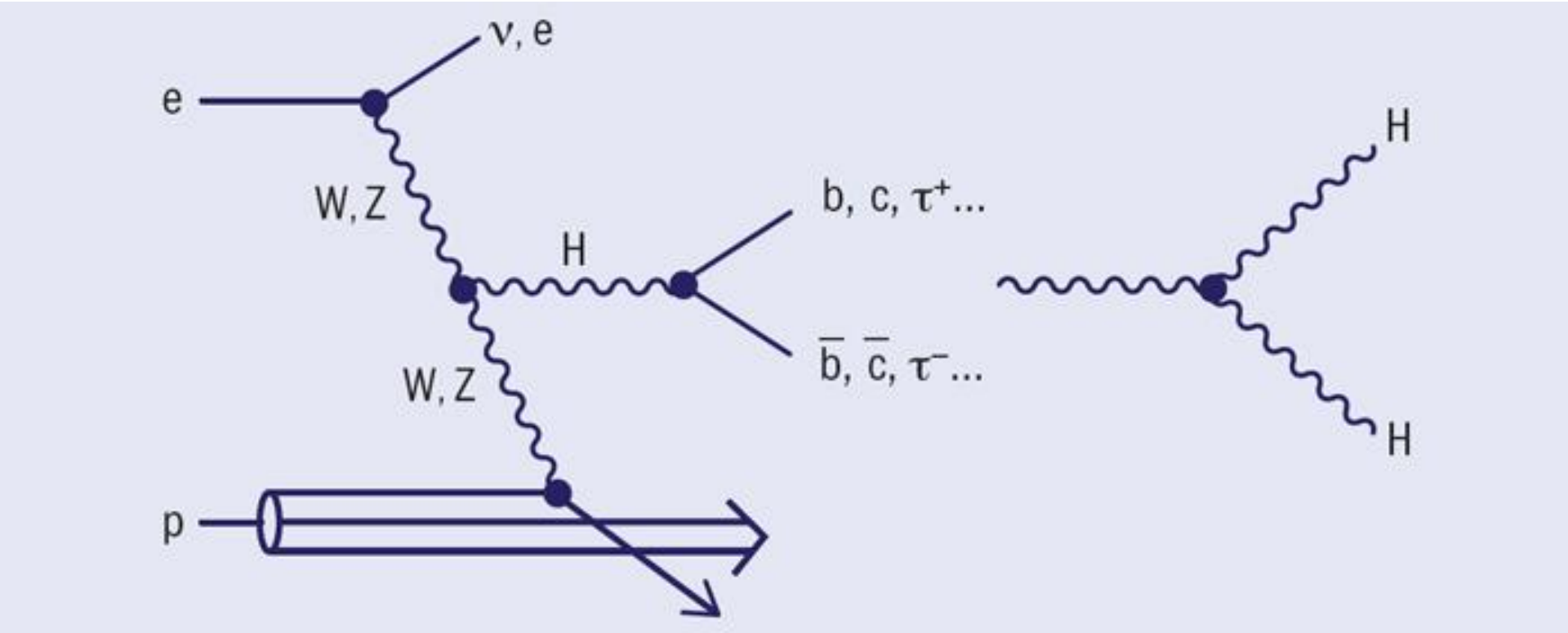
(C=1/3 LHC allows for ion clearing gaps)

A. Bogacz, O. Brüning, M. Klein, D. Schulte, F. Zimmermann, et al

LHeC → LHeC Higgs Factory

parameter [unit]		
species	***e-***	***p***
beam energy (/nucleon) [GeV]	60	7000
bunch spacing [ns]	25	25
bunch intensity (nucl.) [10^{10}]	**0.1 → 0.4**	**17 → 22**
beam current [mA]	**6.4 → 25.6**	**860 → 1110**
normalized rms emittance [μm]	50 → **20**	**3.75 → 2.5**
geometric rms emittance [nm]	**0.43 → 0.17**	**0.50 → 0.34**
IP beta function $\beta_{x,y}$* [m]	**0.12 → 0.10**	**0.10 → 0.05**
IP rms spot size [μm]	7.2 → **4.1**	7.2 → **4.1**
lepton *D* & hadron ξ	**6 → 23**	**0.0001 → 0.0002**
hourglass reduction factor H_{hg}	0.91 → **0.80**	
pinch enhancement factor H_D	1.35	
luminosity/nucl. [10^{33}cm^{-1}s^{-1}]	**1.3 → 14.4**	

Higgs physics at an LHeC



***h-e* Higgs-boson production and decay**,
precision measurements of the ***H–bb* coupling** in ***WW–H* production**

M. Klein and H. Schopper, CERN Courier June2014

Conclusions – LHC Run 2

- LHC Run 2 is looking good at 6.5 TeV
  - impressive progress so far
  - fabulous job done in LS1 and during powering tests
  - lot of lessons learnt in Run 1, not a "new machine"
- next challenge - higher intensity and e-cloud (*ongoing*!)
- sound fundamentals, no show-stoppers for the moment
  - some irritants – resolution cost time
- 2015 will be a short year for proton physics but lay foundations for production for the rest of Run 2

it takes a remarkable effort by a large number of teams to prepare and exploit the LHC

M. Lamont

Conclusions – HL-LHC

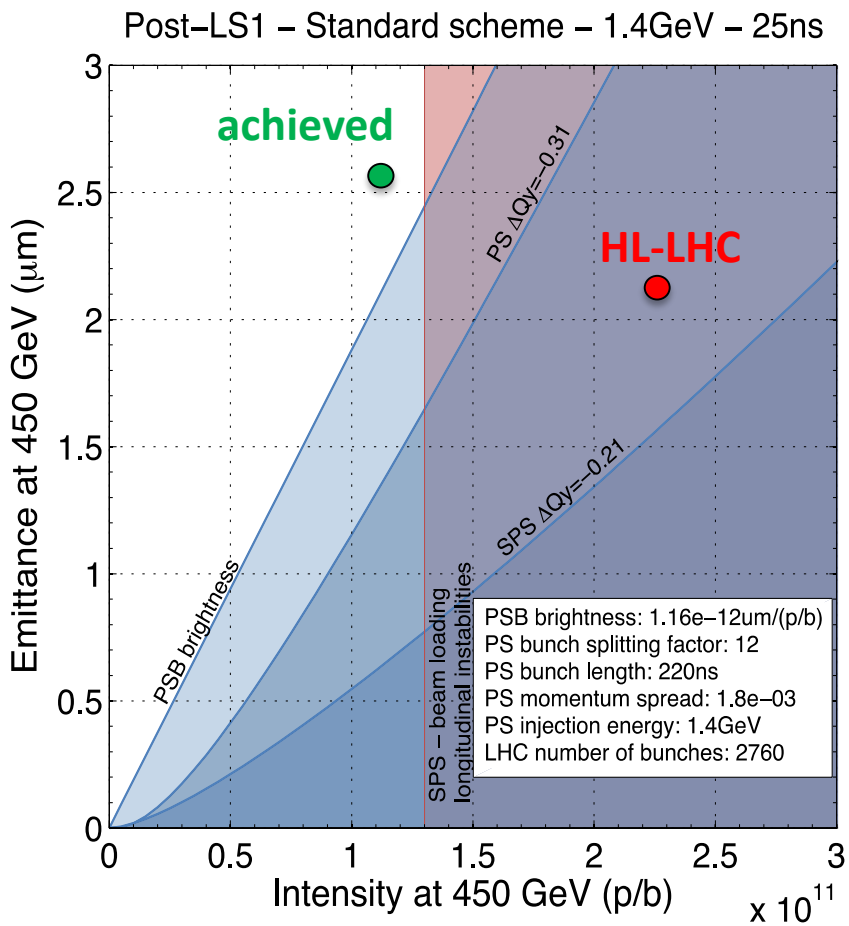
- LHC Injector Upgrade and High-Luminosity LHC Upgrade will increase annual integrated luminosity by factor 10
- new ingredients: a few tens of novel Nb_3Sn quadrupoles and dipoles (11-12 T peak field), novel compact crab cavities, SC link, luminosity leveling,…
- LHC exploitation until ≈2036, goal: 3000 fb^{-1}
- proposed option of Large Hadron electron Collider (LHeC) running concurrently with HL-LHC

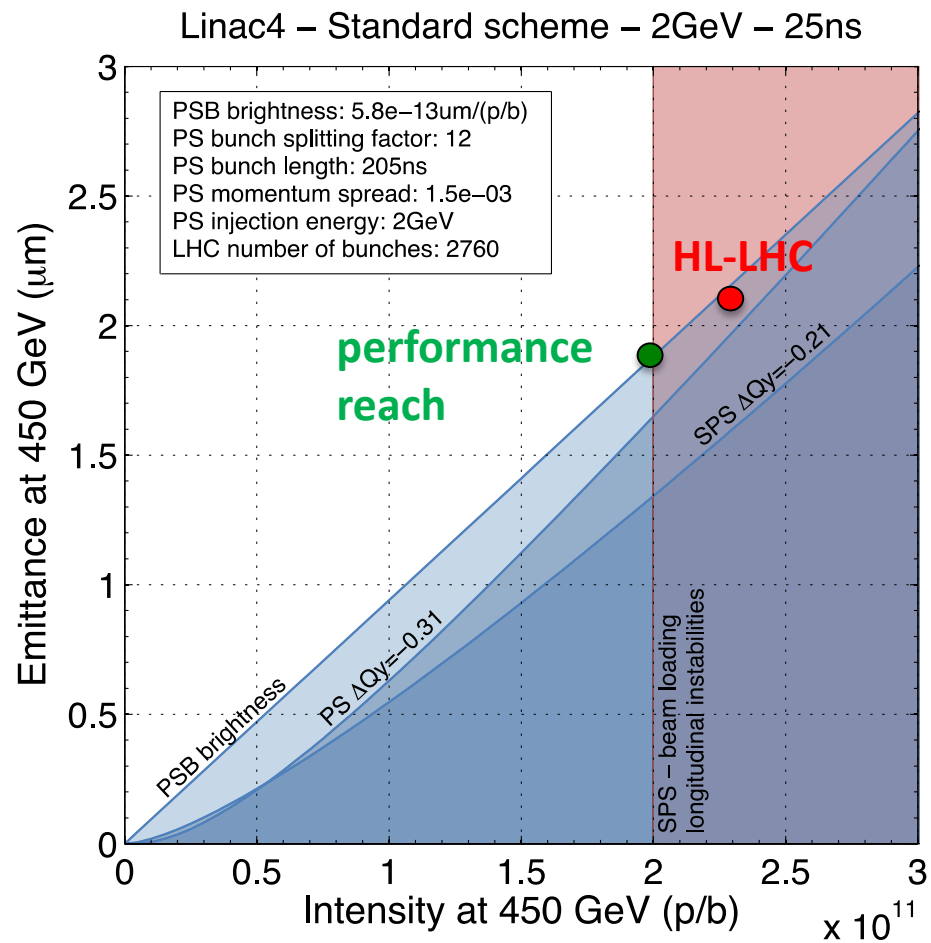
HL-LHC will prepare the technology for future proton colliders of even higher energy

seen on the internet

appendix

LHC Injector Upgrade (LS2) – 72 b trains

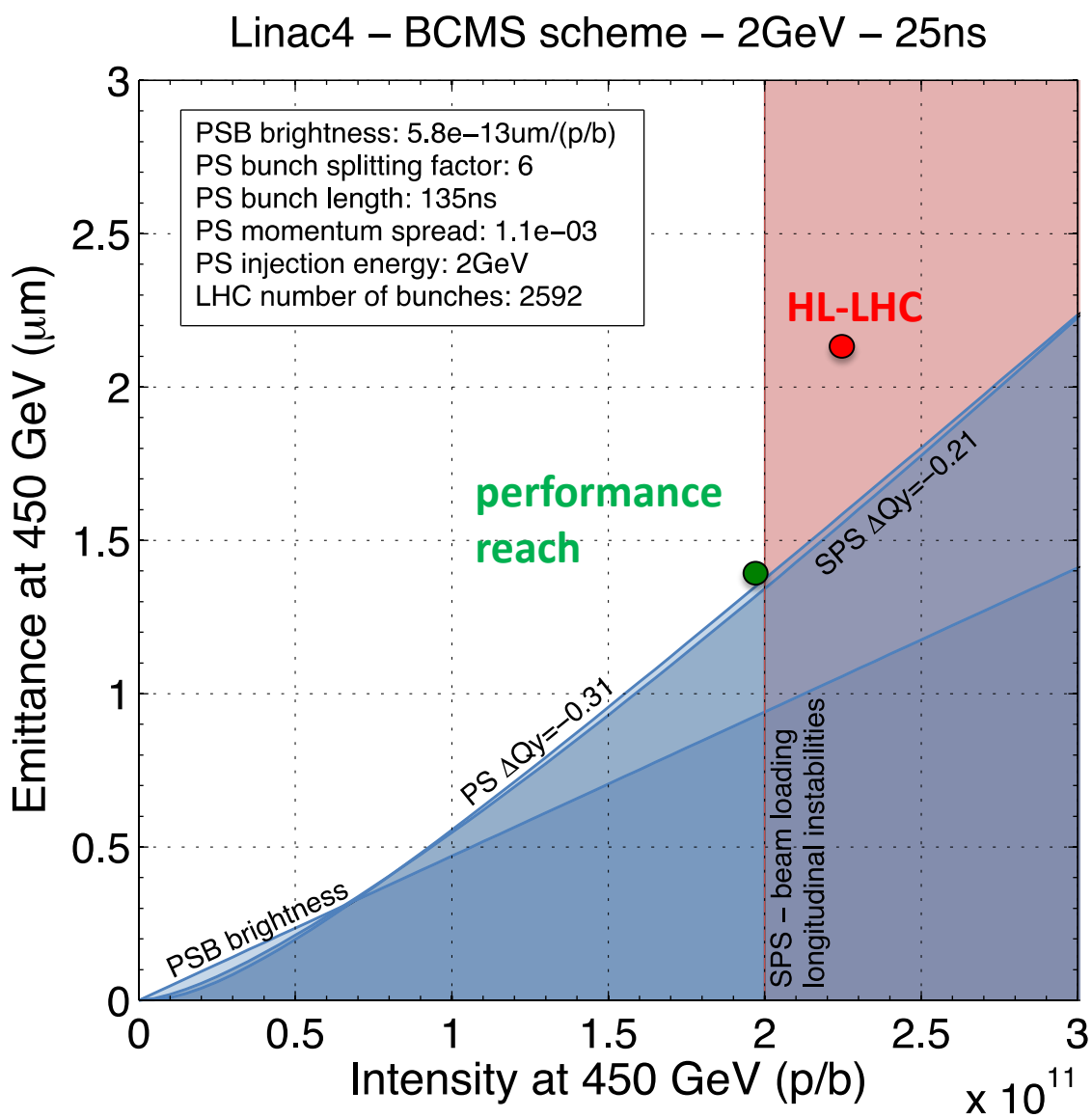




25 ns	N_b [10^{11} p/b]	ε [μm
achieved in 2012	1.2	2.6
HL-LHC goal	**2.3**	**2.1**

M. Meddahi

LIU-BCMS scheme (48 bunch trains)

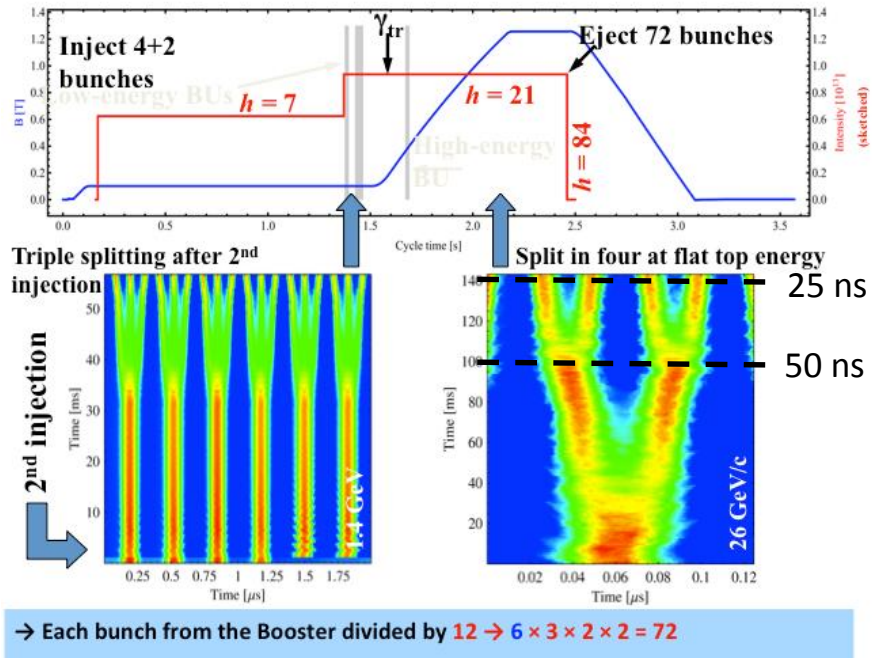


higher beam brightness than HL-LHC target

LHC beam generation in the PS

Standard scheme:

(maximum number of bunches in LHC)

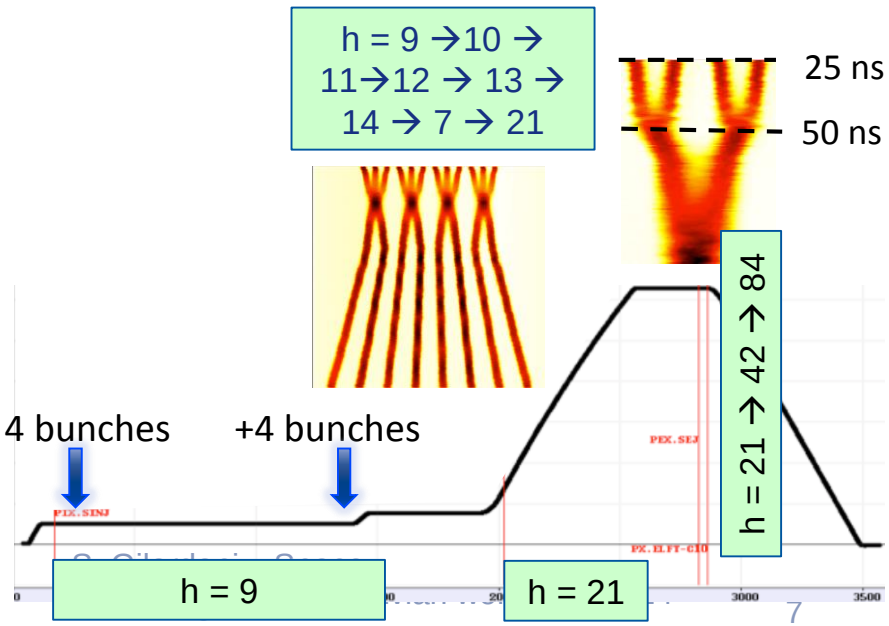


PS batches with 72 (36) bunches for 25ns (50ns)

Triple splitting up to 2013 at 1.4 GeV (moved to 2.5 GeV after LS1)

BCMS scheme:

(less bunches in LHC but higher brightness)



PS batches with 48 (24) bunches for 25ns (50ns)

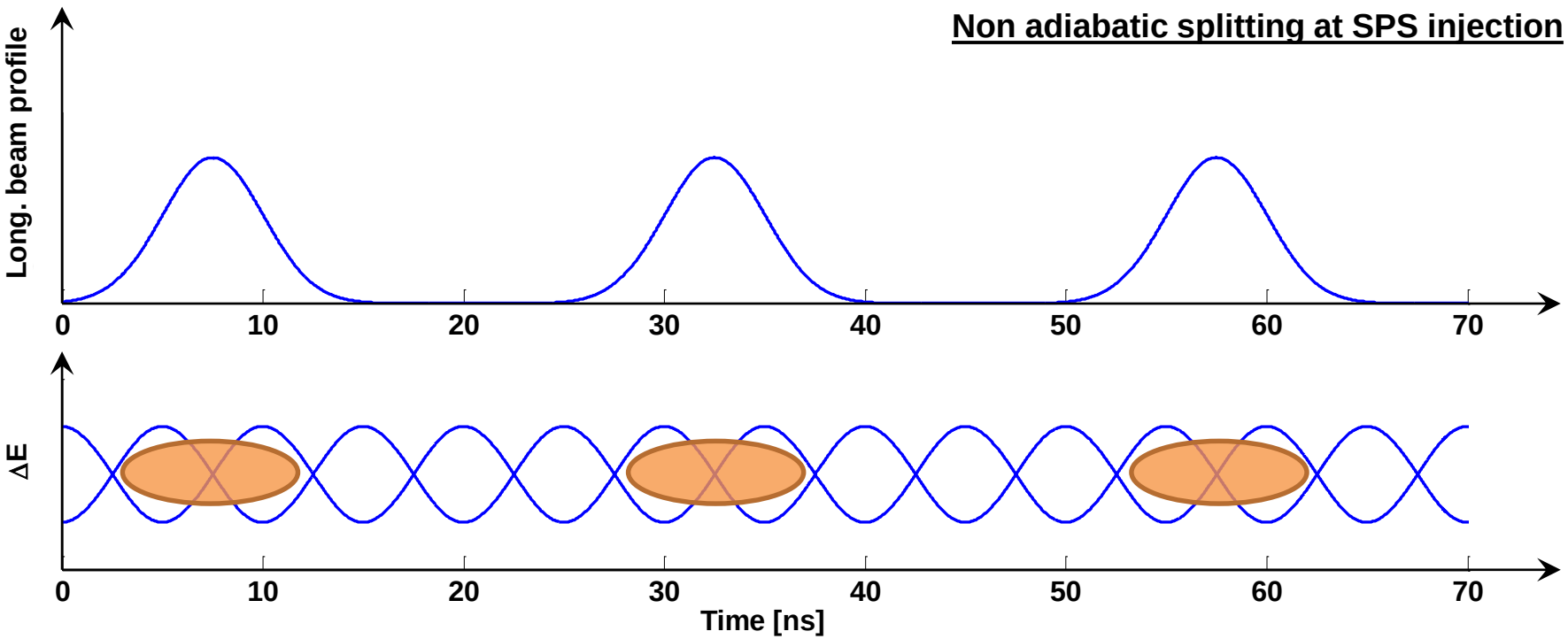
Y. Papaphilippou

“Doublet” scrubbing beam - generation in the SPS

Scrubbing with 25 ns beam allowed to lower the SEY of the dipole chambers **well below the multipacting threshold for 50 ns → e-cloud free operation with 50 ns beams**

→ **Can we go to lower bunch spacing** (e.g. 12.5 ns) **to scrub for 25 ns operation?**

- Due to RF limitations in the PS it is **impossible to inject bunch-to-bucket into the SPS with spacing shorter than 25 ns**
- An alternative is to inject long bunches into the SPS and capturing each bunch in two neighboring buckets obtaining **a (5+20) ns “hybrid” spacing**



G. Iadarola

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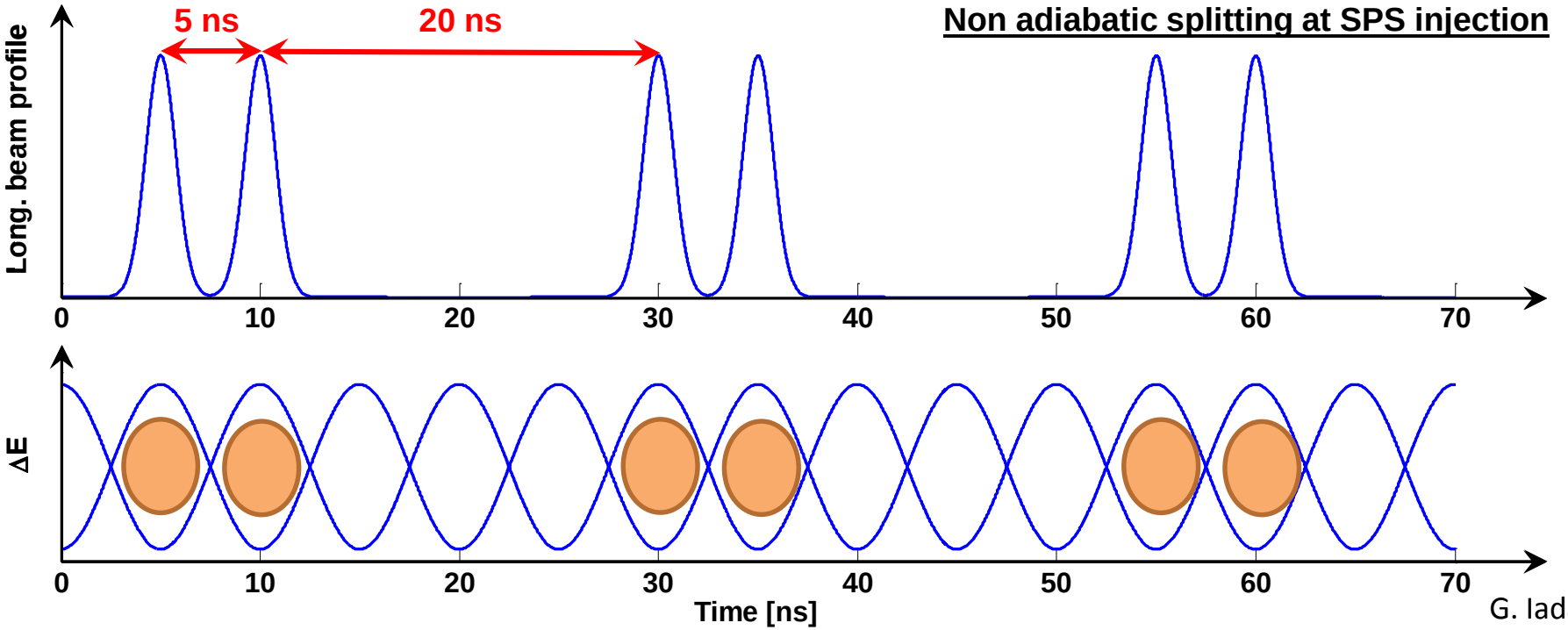
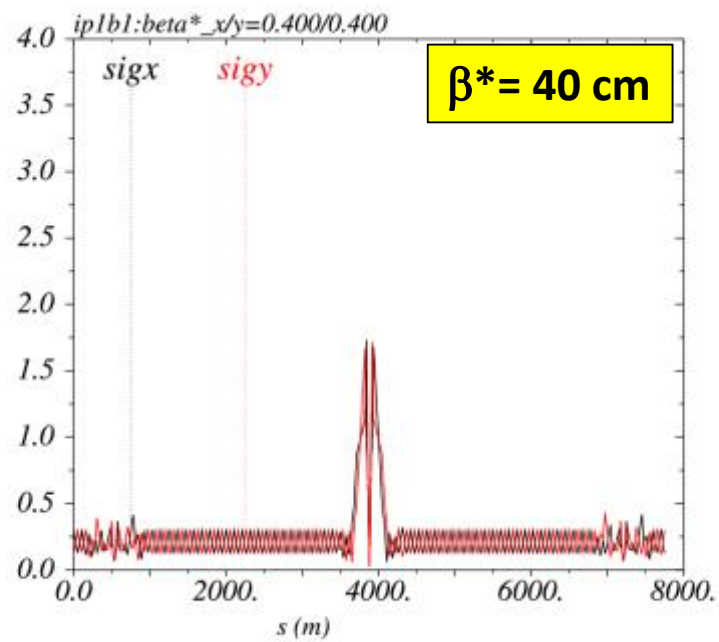


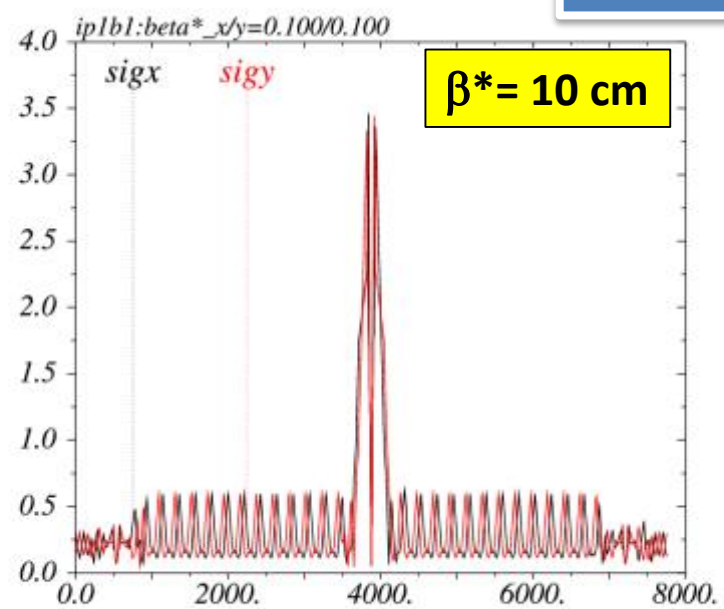
G. Iadarola

New Optics: **Achromatic Telescopic Squeeze**

- **Small β* is limited by aperture but also by** optics matching & flexibility , chromatic effects, spurious dispersion from X-angle,..
- **A novel optics scheme (ATS)** reaches un-precedent β^* w/o chromatic limit based on a generalized squeeze involving 50% of the ring

S. Fartoukh





The new IR is sort of 8 km long !

Beam sizes [mm] @ 7 TeV from IR8 to IR2 for typical ATS "pre-squeezed" optics (left) and "telescopic" collision optics (right)

“crab kissing” scheme

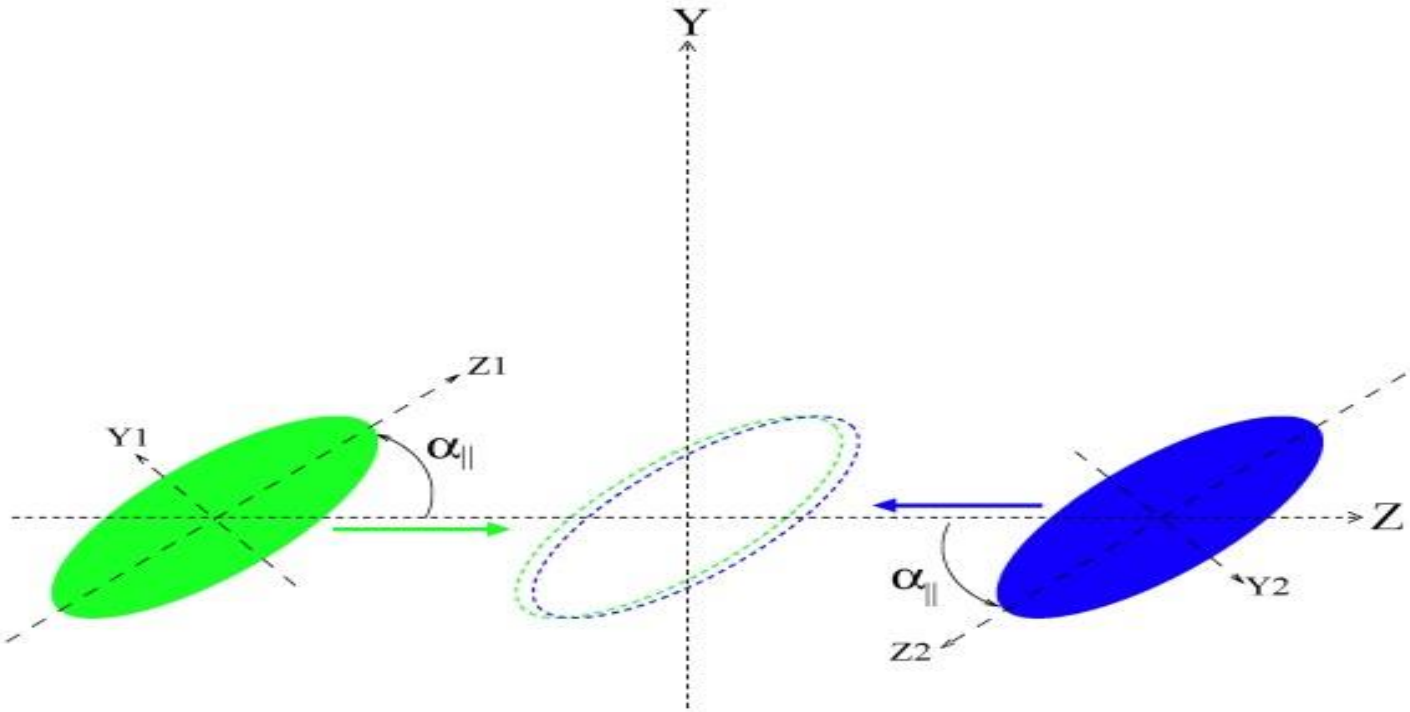


illustration of “crab kissing” configuration for luminosity levelling in the plane orthogonal to the crossing plane

a newly proposed scheme based on additional crab cavities deflecting the two beams in the non-crossing plane in anti-phase; this scheme does not reduce the longitudinal extent of the luminous region during the levelling process [S. Fartoukh, Phys. Rev. ST Accel. Beams 17, 111001 (2014)]