European Coordination for Accelerator Research and Development

PUBLICATION

High-Energy Frontier Circular Colliders

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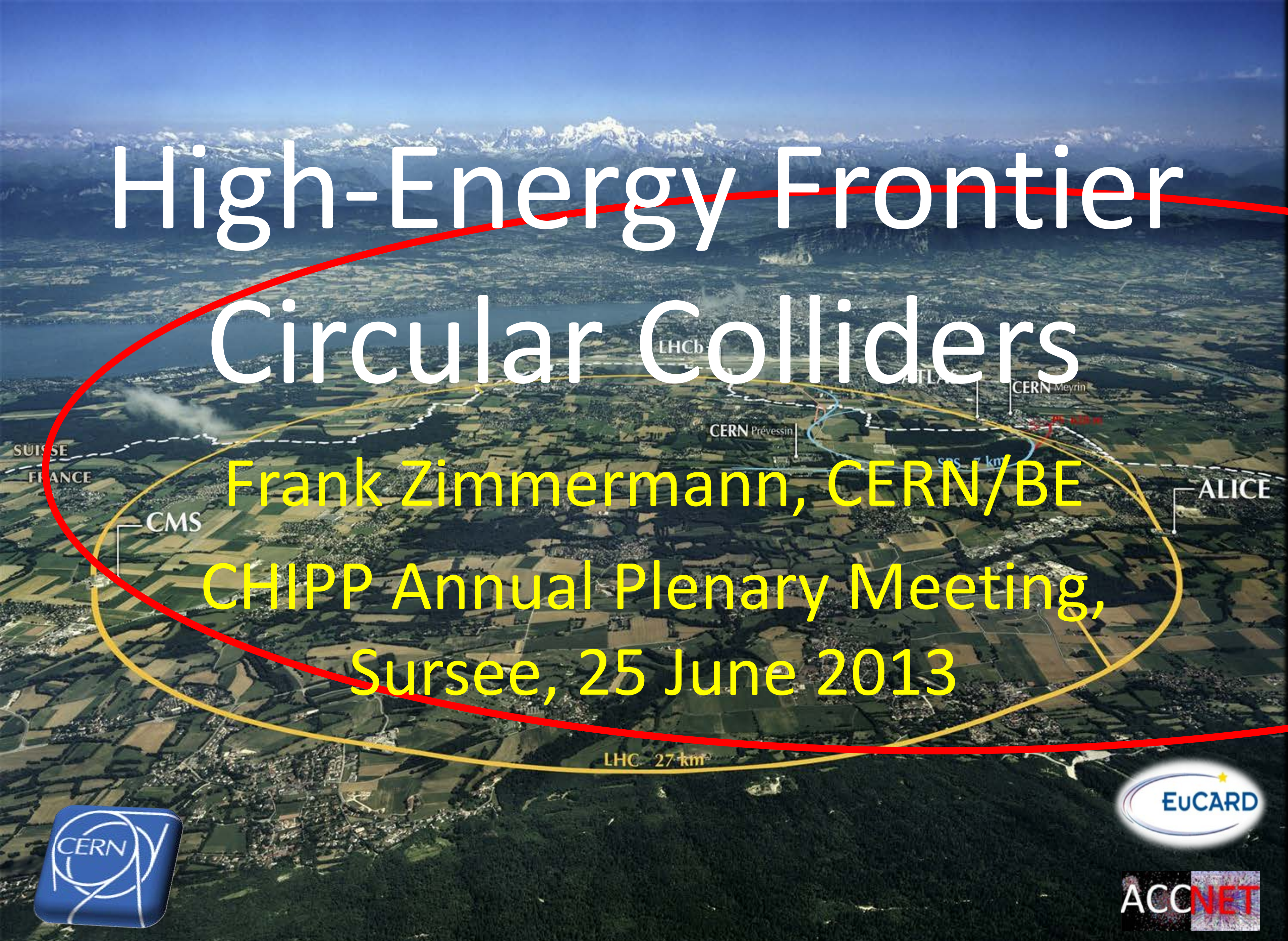
High-Energy Frontier Circular Colliders

Frank Zimmermann, CERN/BE

CHIPP Annual Plenary Meeting, Sursee, 25 June 2013



*Work supported by the **European Commission** under the FP7 Research Infrastructures project **EuCARD**, grant agreement no.~227579*

short LHC history

1983 *LEP Note 440* - S. Myers and W. Schnell propose twin-ring *pp* collider in LEP tunnel with 9-T dipoles

1991 CERN Council: LHC approval in principle

1992 EoI, LoI of experiments


CERN LIBRARIES, GENEVA

LEP/LIBRARY

SCAN-0008106

LEP Note 440

11.4.1983

PRELIMINARY PERFORMANCE ESTIMATES FOR A LEP PROTON COLLIDER

S. Myers and W. Schnell

1993 SSC termination

1994 CERN Council: LHC approval

1995-98 cooperation w.Japan,India,Russia,Canada,&US

2000 LEP completion

2006 last s.c. dipole delivered

2008 first beam

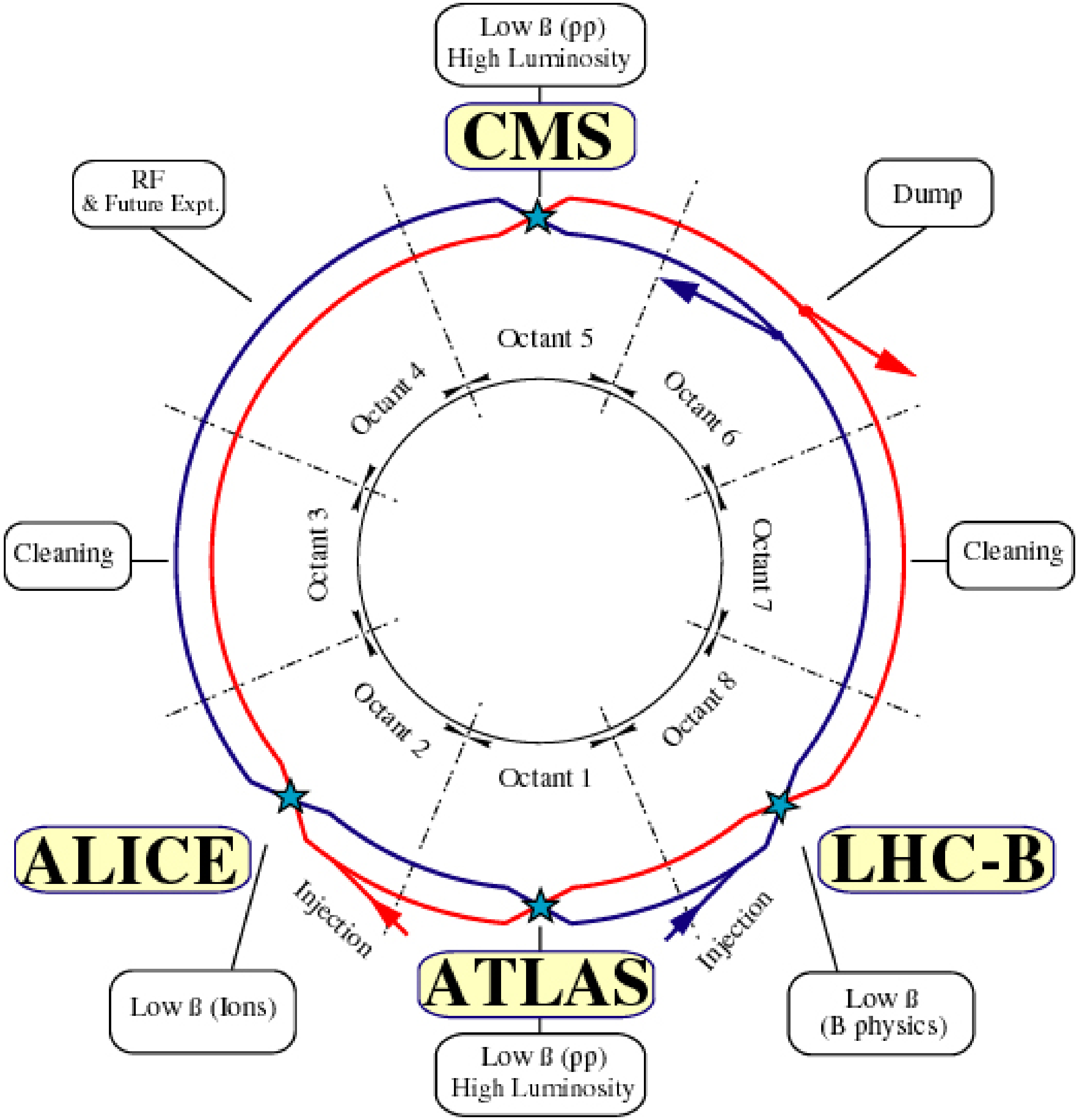
2010 first collisions at 3.5 TeV beam energy

2015 collisions at ~design energy (plan)

>30 years!

now is the time to plan for ~2040

LHC: highest energy *pp*, *AA*, and *pA* collider



design parameters

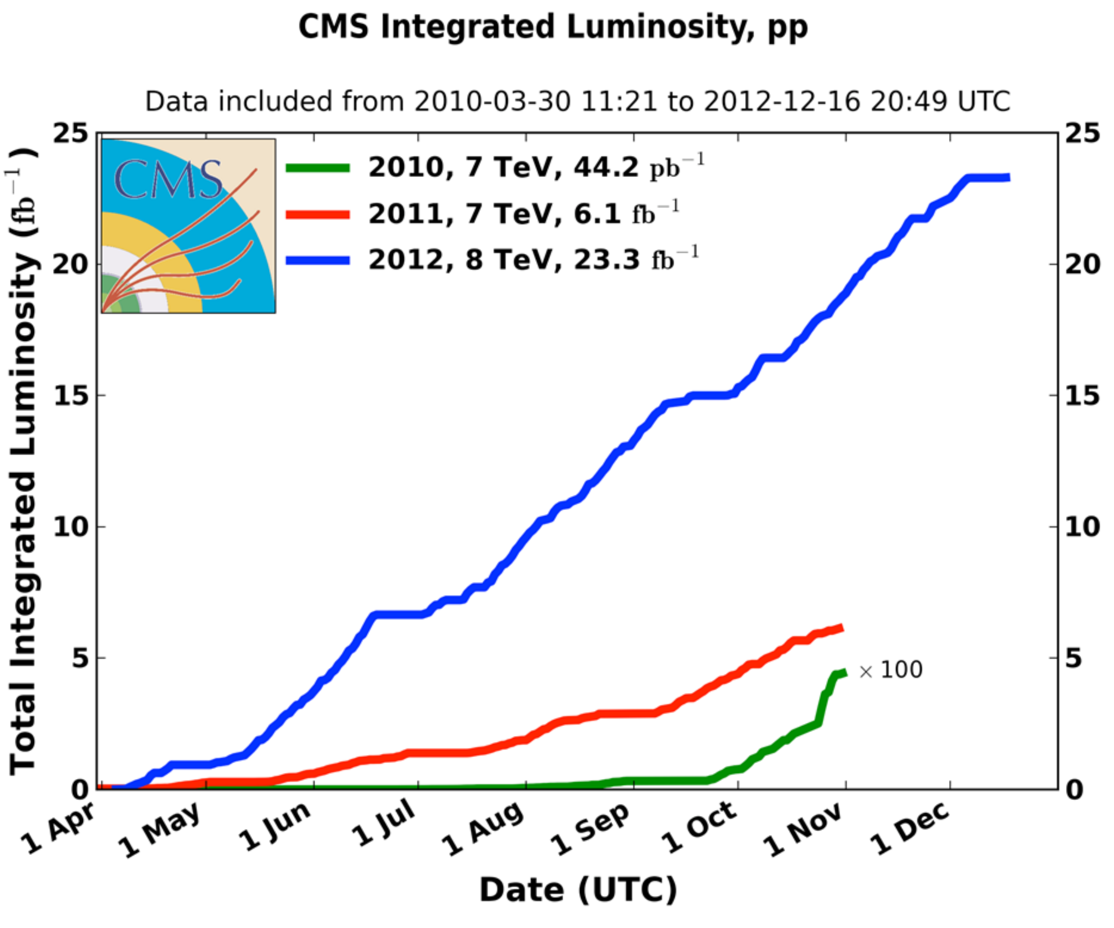
c.m. energy = 14 TeV (*p*)
luminosity $=10^{34}$ $cm^{-2}s^{-1}$

1.15×10^{11} p/bunch
2808 bunches/beam

360 MJ/beam

$\gamma\varepsilon=3.75$ μm
$\beta^*=0.55$ m
$\theta_c=285$ μrad
$\sigma_z=7.55$ cm
$\sigma^*=16.6$μm

integrated *pp* luminosity 2010-12

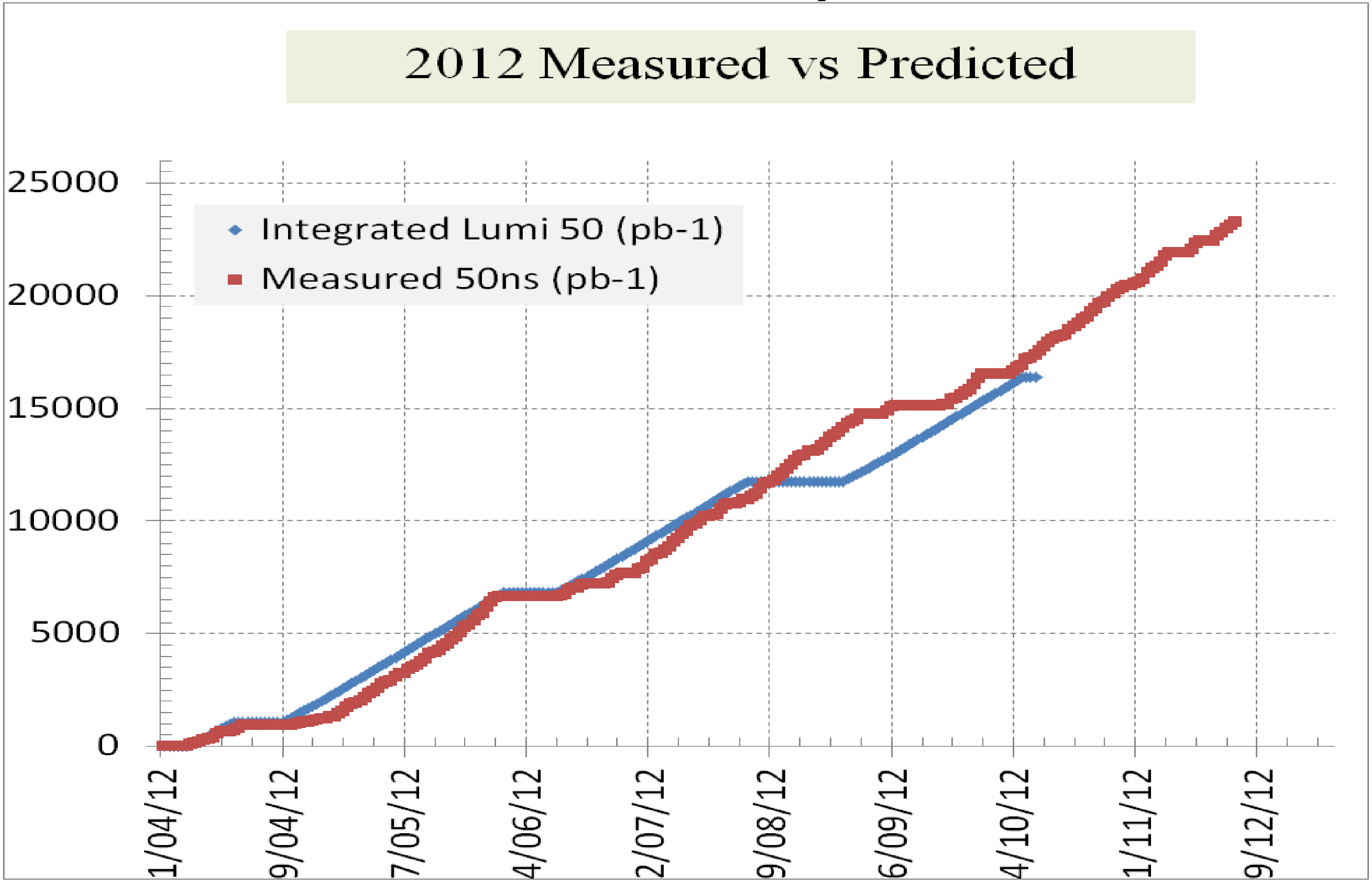


- 2010: **0.04 fb^{-1}**
  - 7 TeV CoM
  - Commissioning
- 2011: **6.1 fb^{-1}**
  - 7 TeV CoM
  - Exploring the limits
- 2012: **23.3 fb^{-1}**
  - 8 TeV CoM
  - Production

M. Lamont, IPAC'13

Steve Myers, CMAC

reliable luminosity forecasts

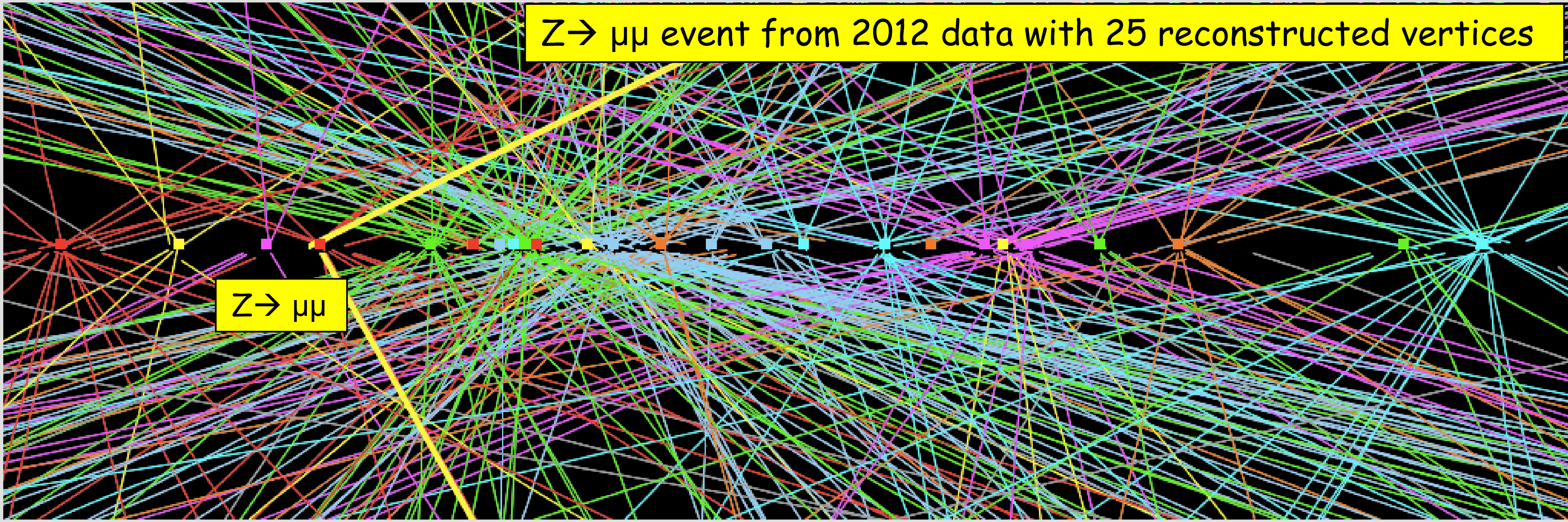


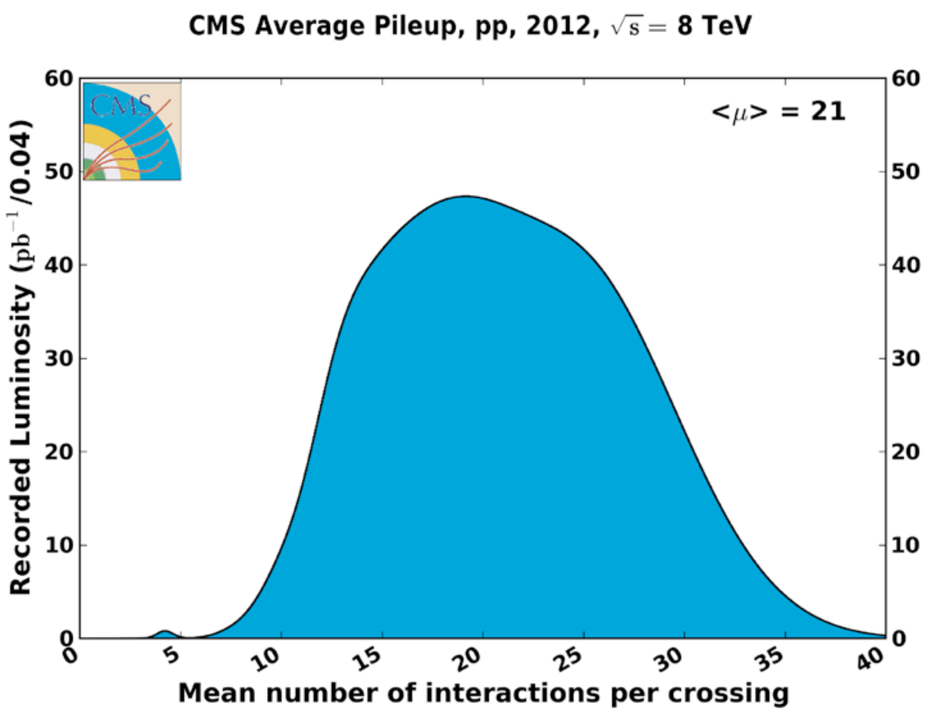
peak performance through the years

	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}

>2x design when scaled to 7 TeV

M. Lamont, IPAC'13

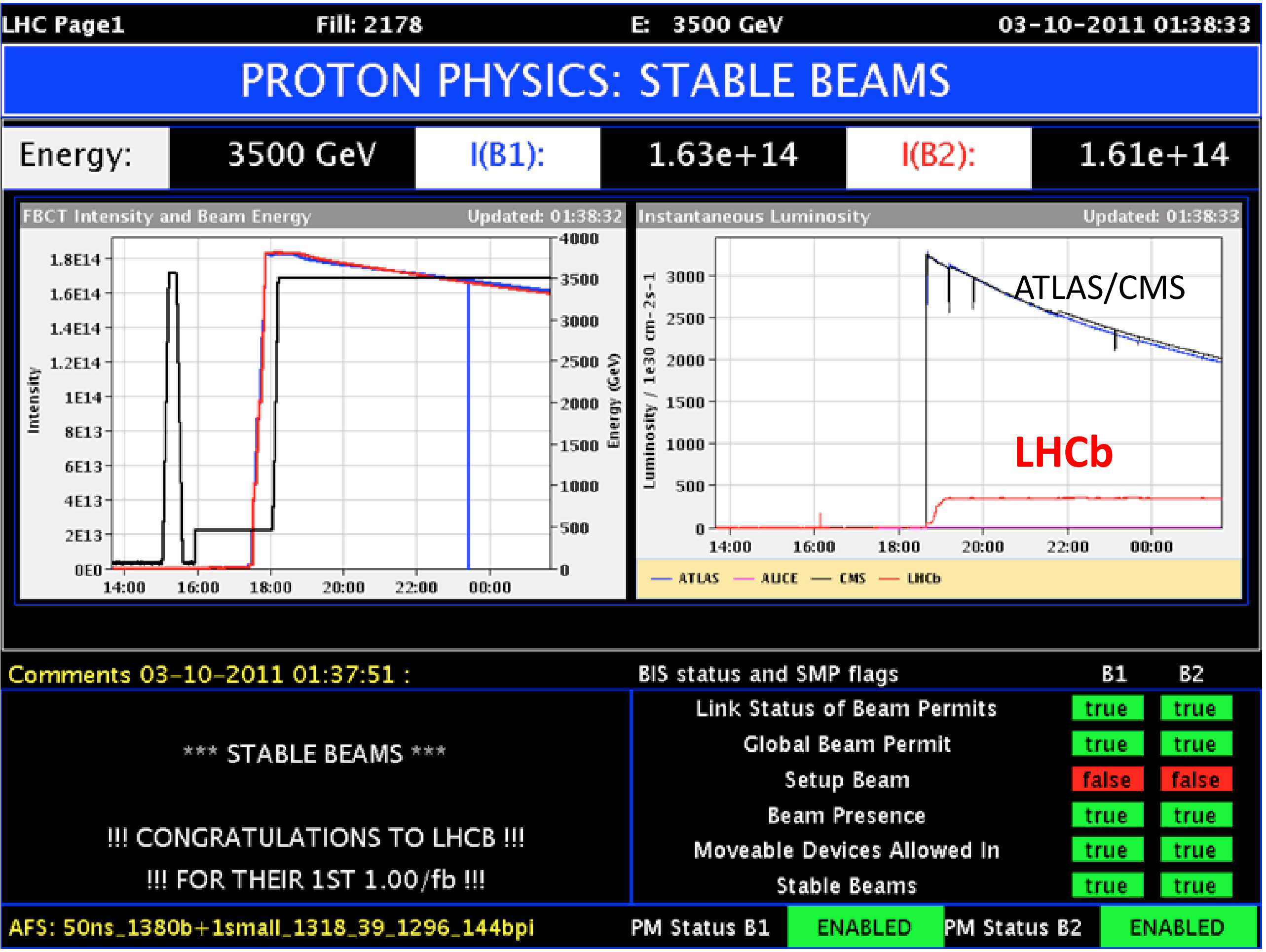




pile up
will increase
at higher energy
→
experiments
request
25 ns
operation
in 2015

M. Lamont, IPAC'13

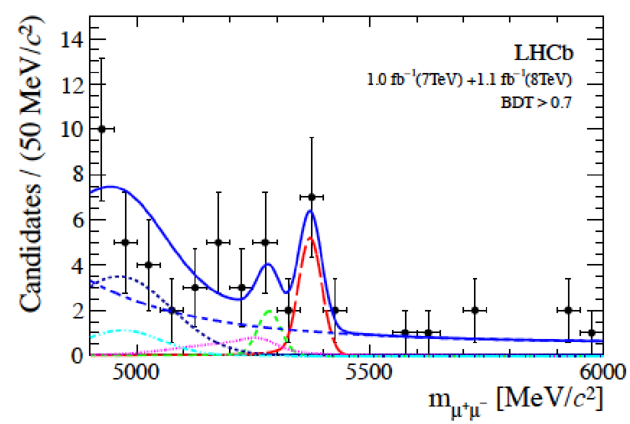
LHCb



luminosity levelling at around 4e32 $cm^{-2}s^{-1}$ via transverse separation (with a tilted crossing angle)

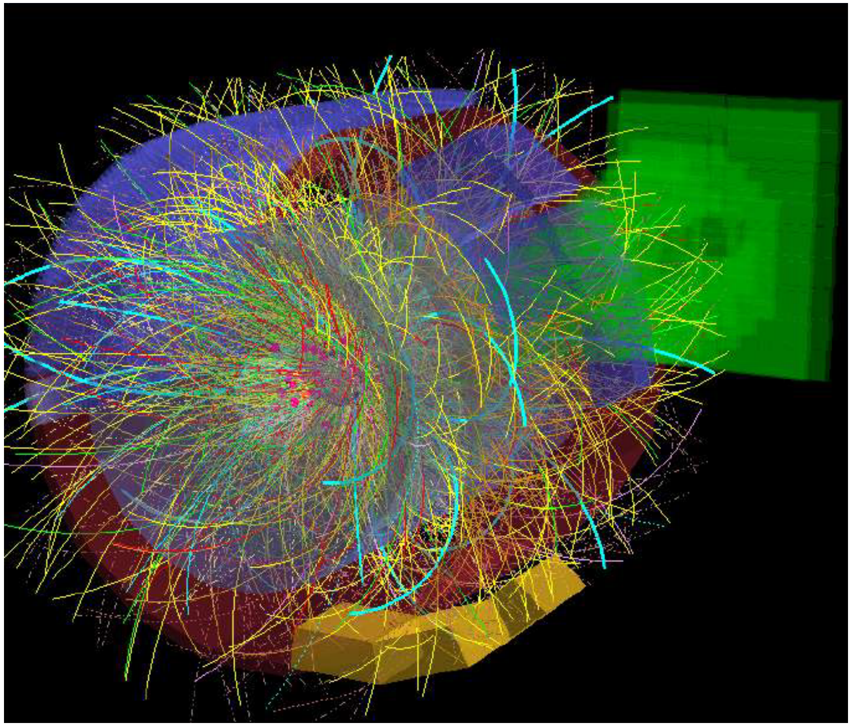
not completely trivial!

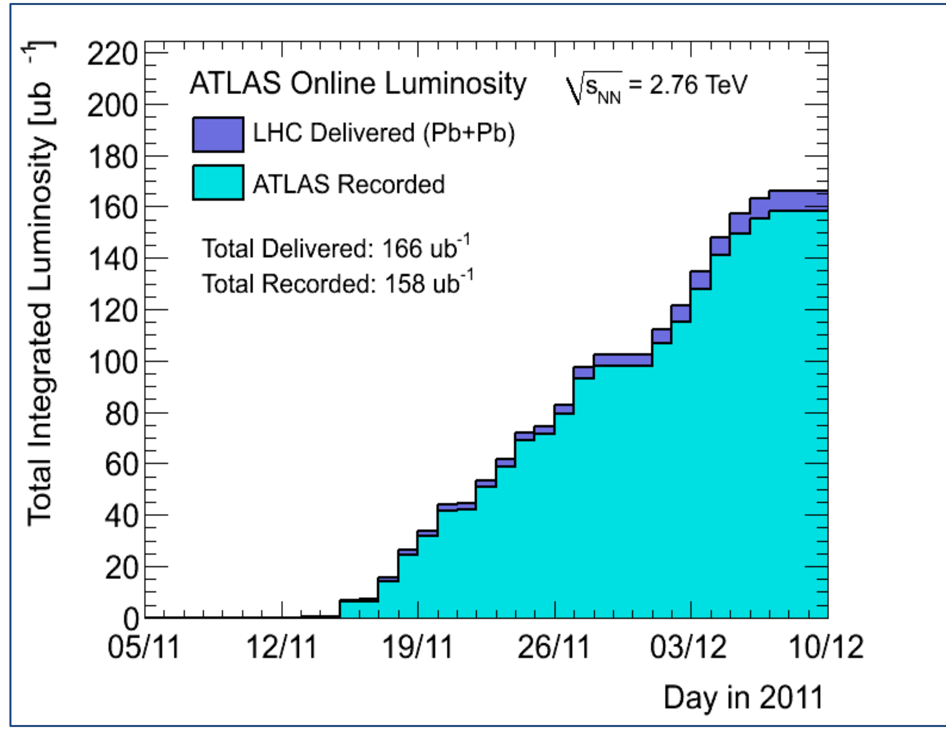
first evidence for the decay $B_s \to \mu^+ \mu^-$



M. Lamont, IPAC'13

Pb-Pb

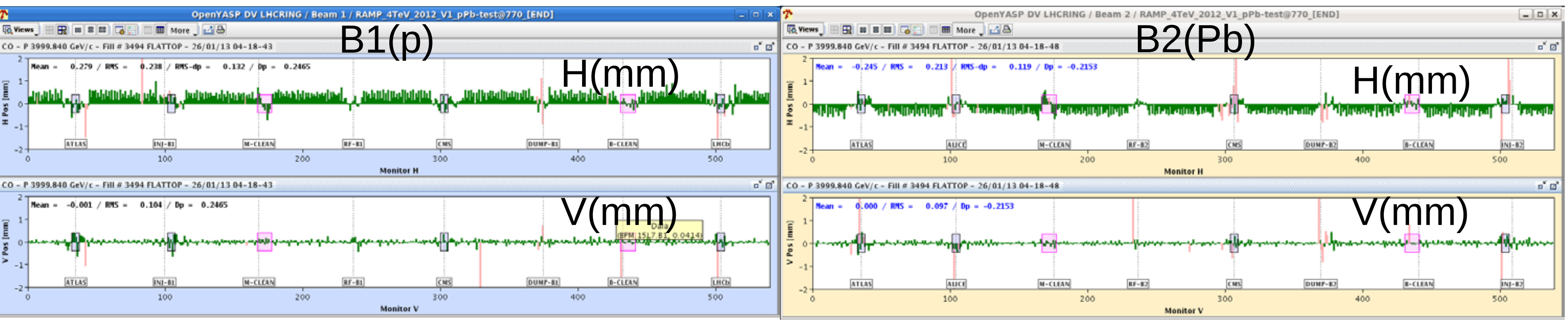




- good performance from the injectors - bunch intensity and emittance
- preparation, Lorentz' law: impressively quick switch from protons to ions
- peak luminosity around 5 x 10^{26} $cm^{-2}s^{-1}$ at 3.5Z TeV (2011) – nearly twice design when scaled to 6.5Z TeV

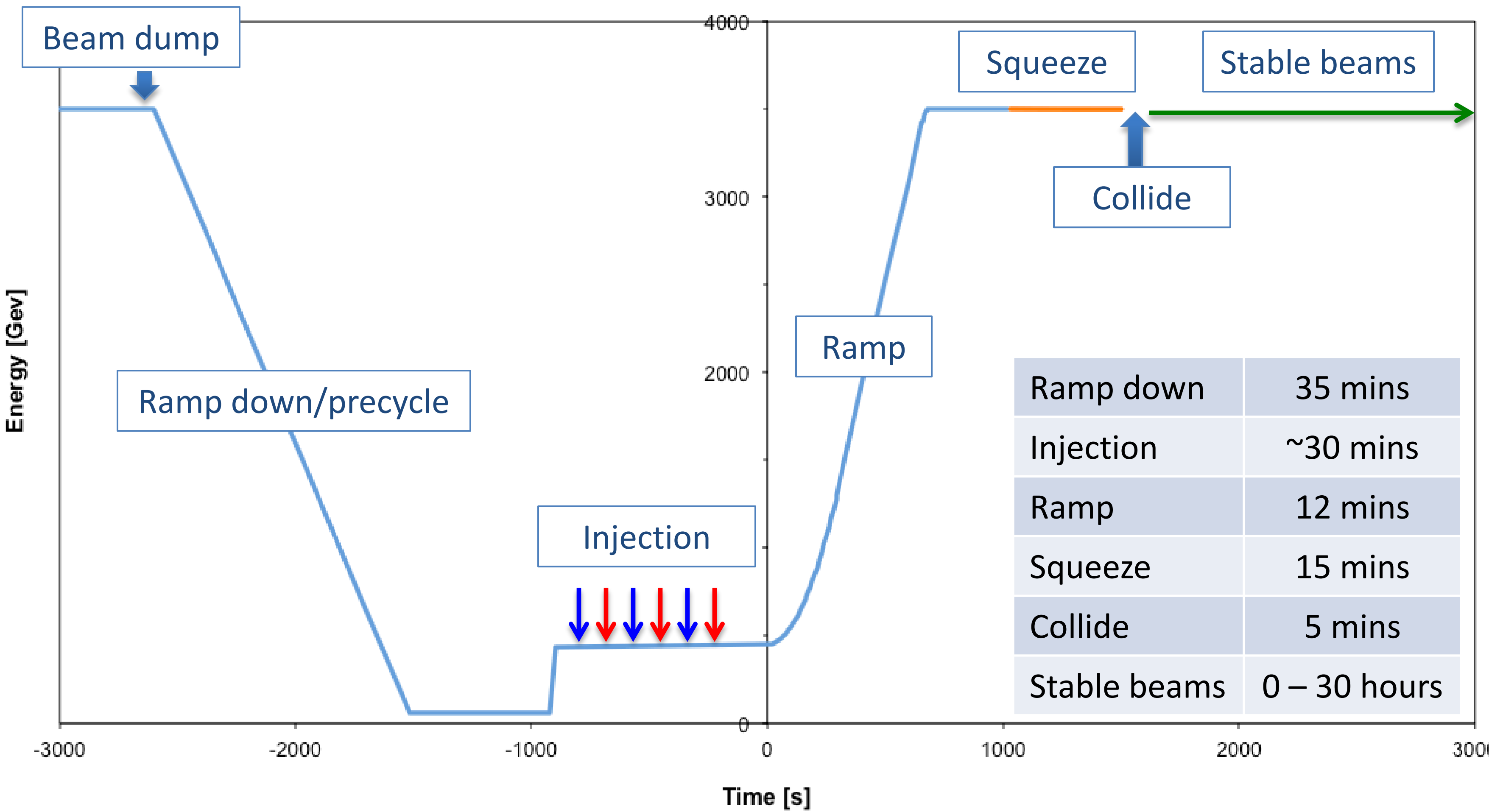
proton-lead

- beautiful result in early 2013
- final integrated luminosity above experiments' request of 30 nb^{-1}
- injectors: average number of ions per bunch was ~1.4×10^{8} at start of stable beams, i.e. around twice the nominal intensity



beam orbits at top energy with RF frequencies locked to Beam 1

operational cycle

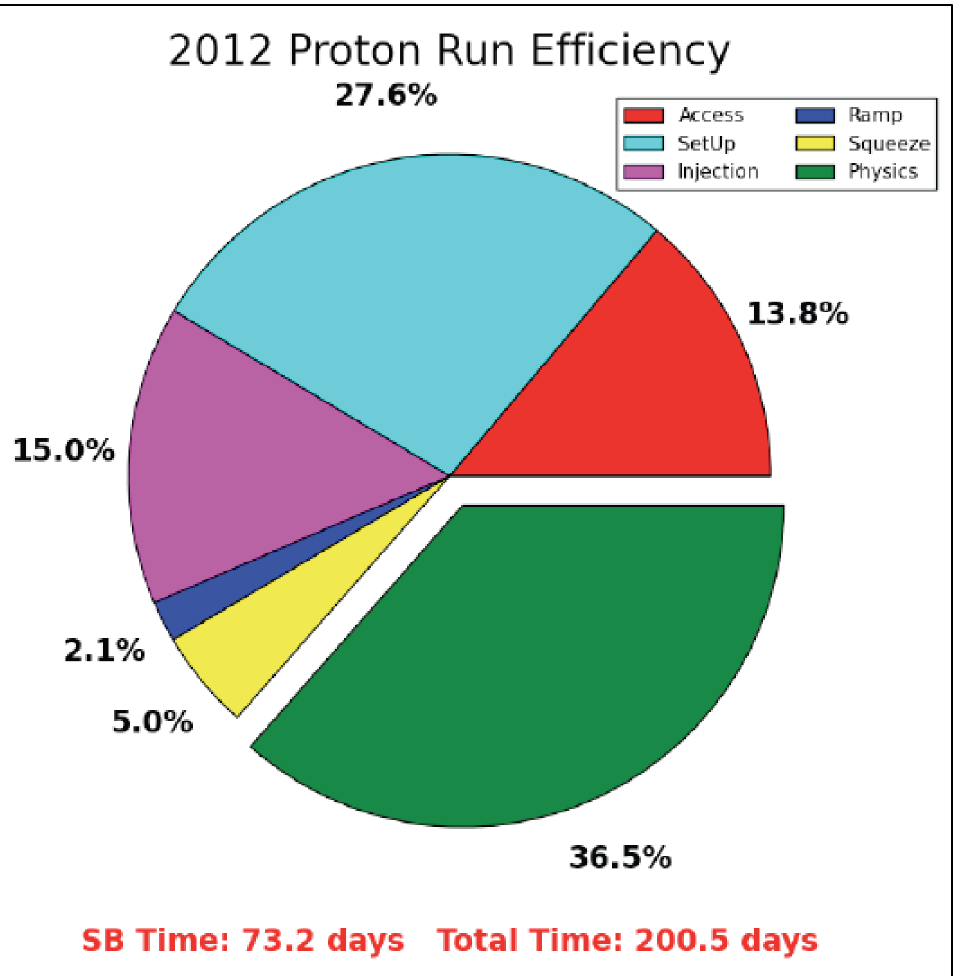


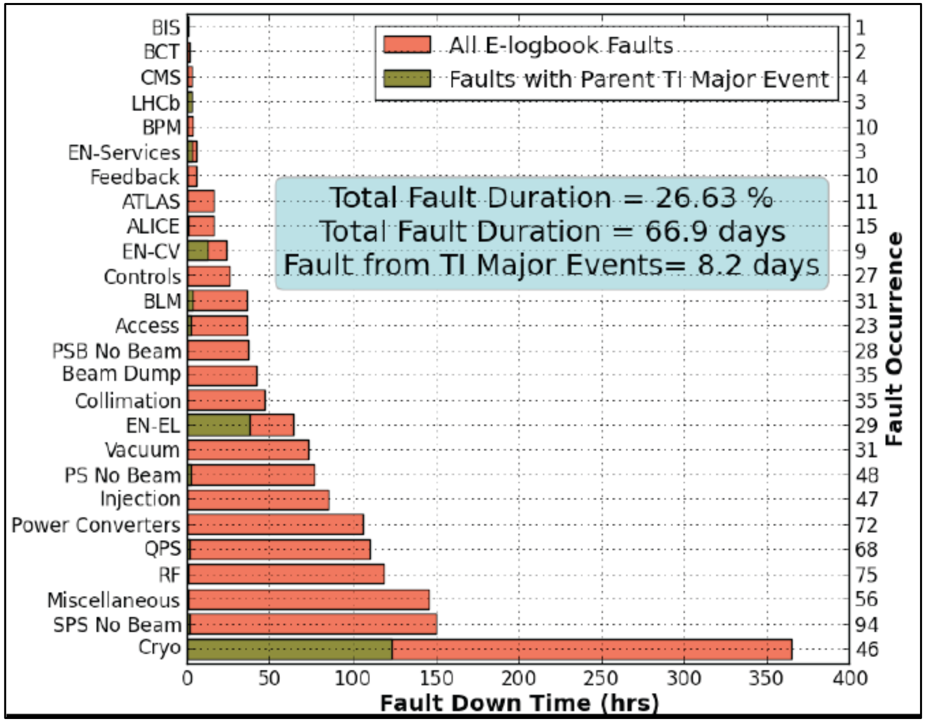
Ramp down	35 mins
Injection	~30 mins
Ramp	12 mins
Squeeze	15 mins
Collide	5 mins
Stable beams	0 – 30 hours

turn around 2 to 3 hours on a good day

availability

- “There are a lot of things that can go wrong – it’s always a battle”
- Pretty good availability considering the complexity and principles of operation





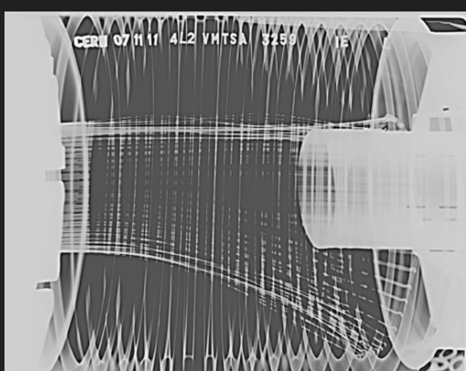
Cryogenics availability in 2012: 93.7%

M. Lamont, IPAC’13

some issues in 2011-12 operation

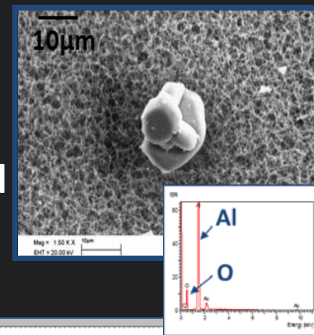
Beam induced heating

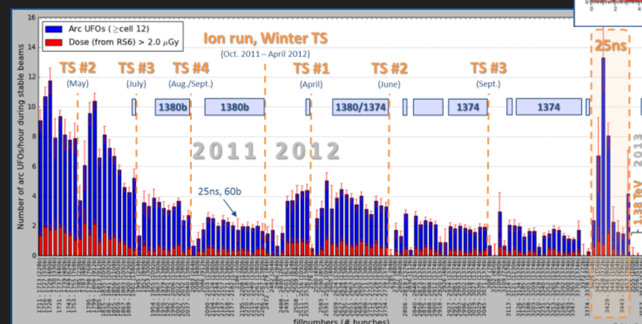
- Local non-conformities (design, installation)
  - injection protection devices
  - sync. Light mirrors
  - vacuum assemblies

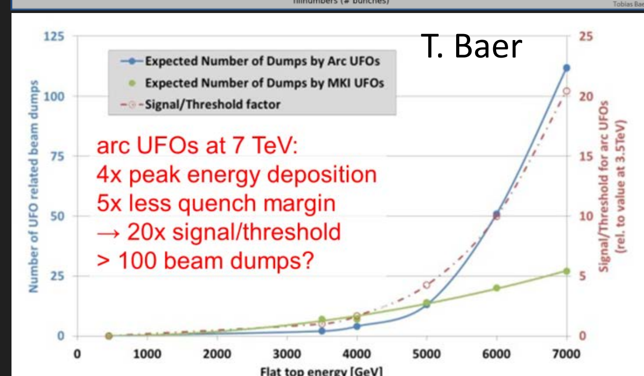


UFOs

- 20 dumps in 2012
- time scale 50-200 μs
- conditioning observed
- worry about 6.5 TeV and 25 ns spacing

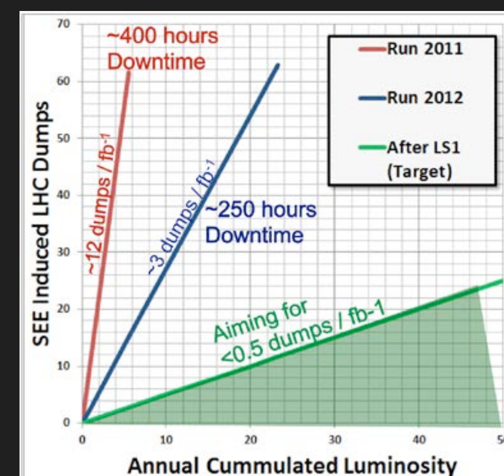






Radiation to electronics

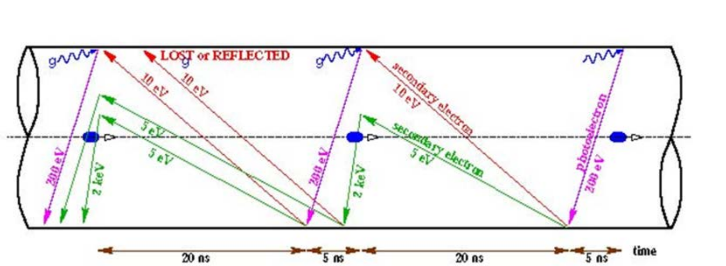
- concerted program of mitigation measures (shielding, relocation…)
- premature dump rate down from 12/fb^{-1} in 2011 to 3/fb^{-1} in 2012



another issue in 2011-12 operation

Electron cloud

- beam induced multipactoring process, depending on secondary emission yield
- LHC strategy based on surface conditioning (scrubbing runs)
- worry about 25 ns (more conditioning needed) and 6.5 TeV (photoelectrons)



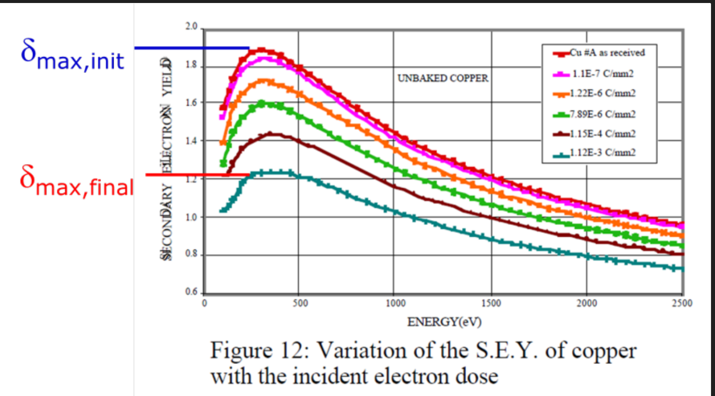
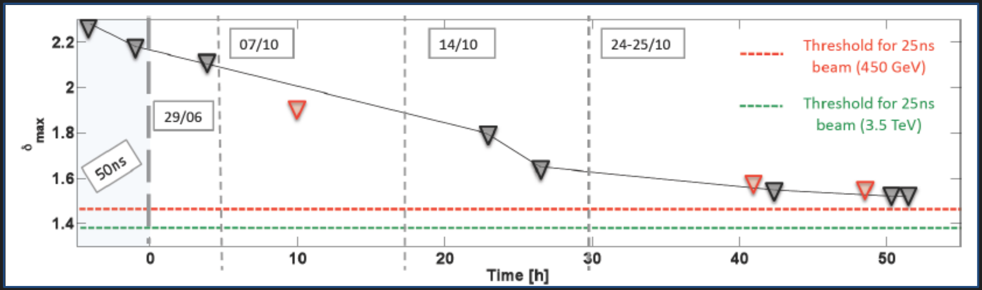
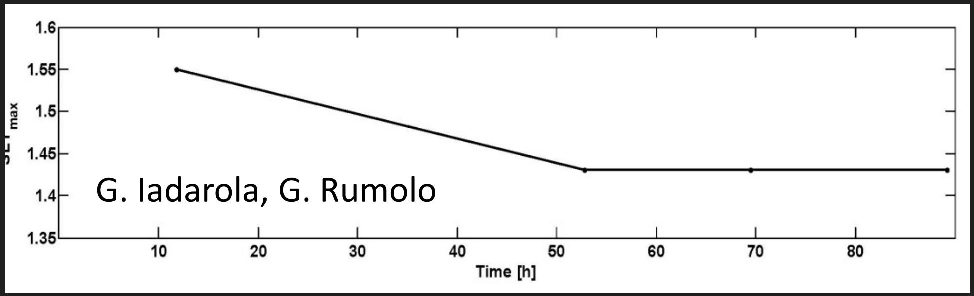


Figure 12: Variation of the S.E.Y. of copper with the incident electron dose

25-ns scrubbing in 2011 – decrease of SEY



25-ns scrubbing in 2012 – conditioning stop?



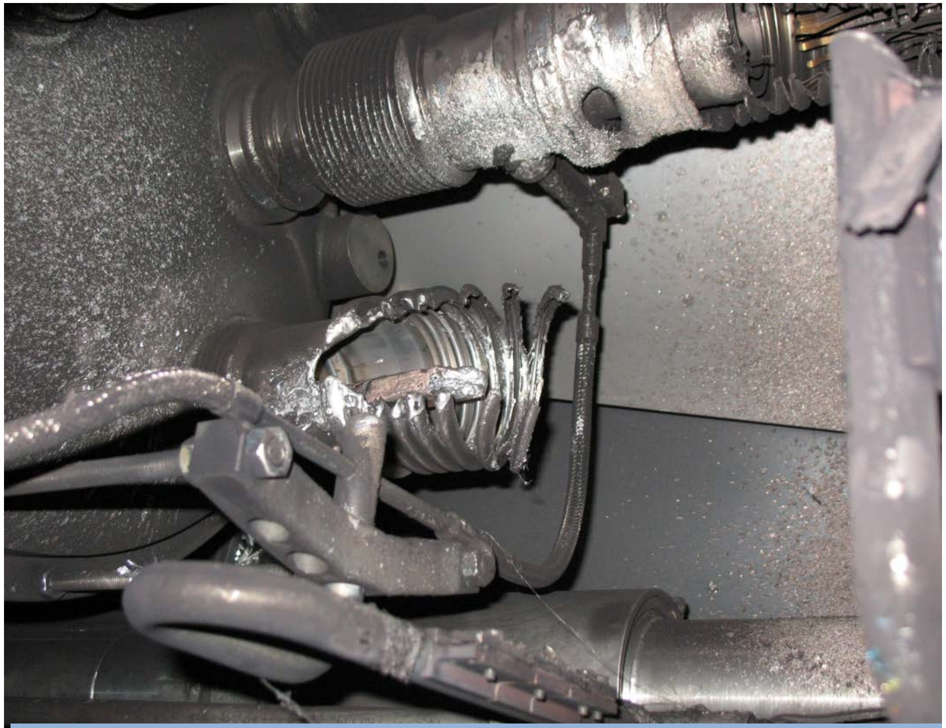
Long Shutdown 1 - motivation

after 2008 incident partial consolidation
& related problem of imperfect *Cu* stabilizer continuity discovered

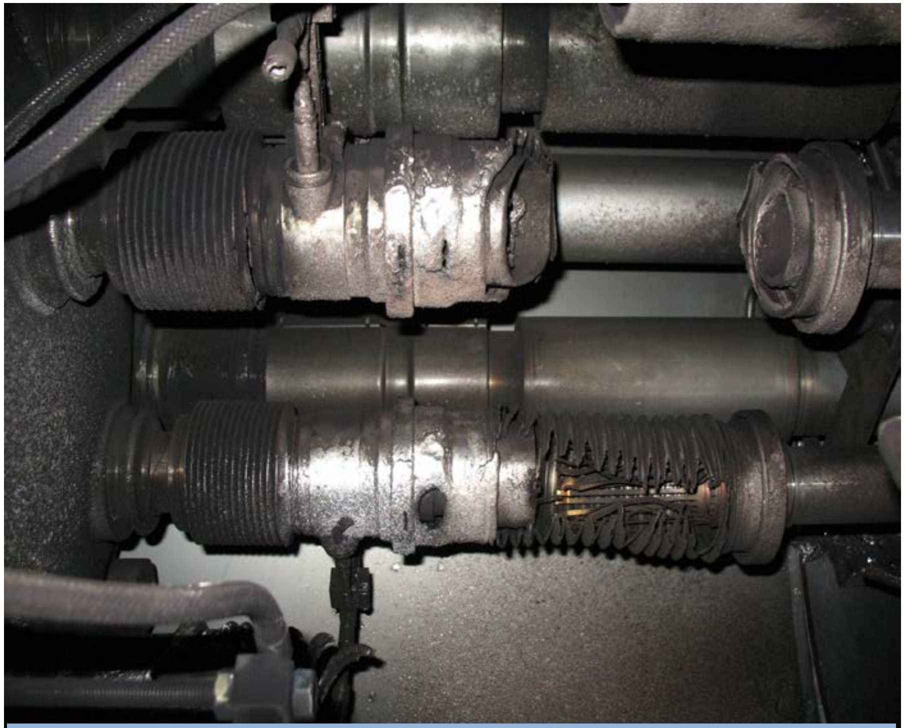
in 2010-12 LHC operated at 7 & 8 TeV c.m.
beam energy to avoid any risk

presently: Long Shutdown 1 (LS1) ~2 yr
to prepare LHC for 13-14 TeV c.m.,
detector upgrades in parallel

2008 "incident"

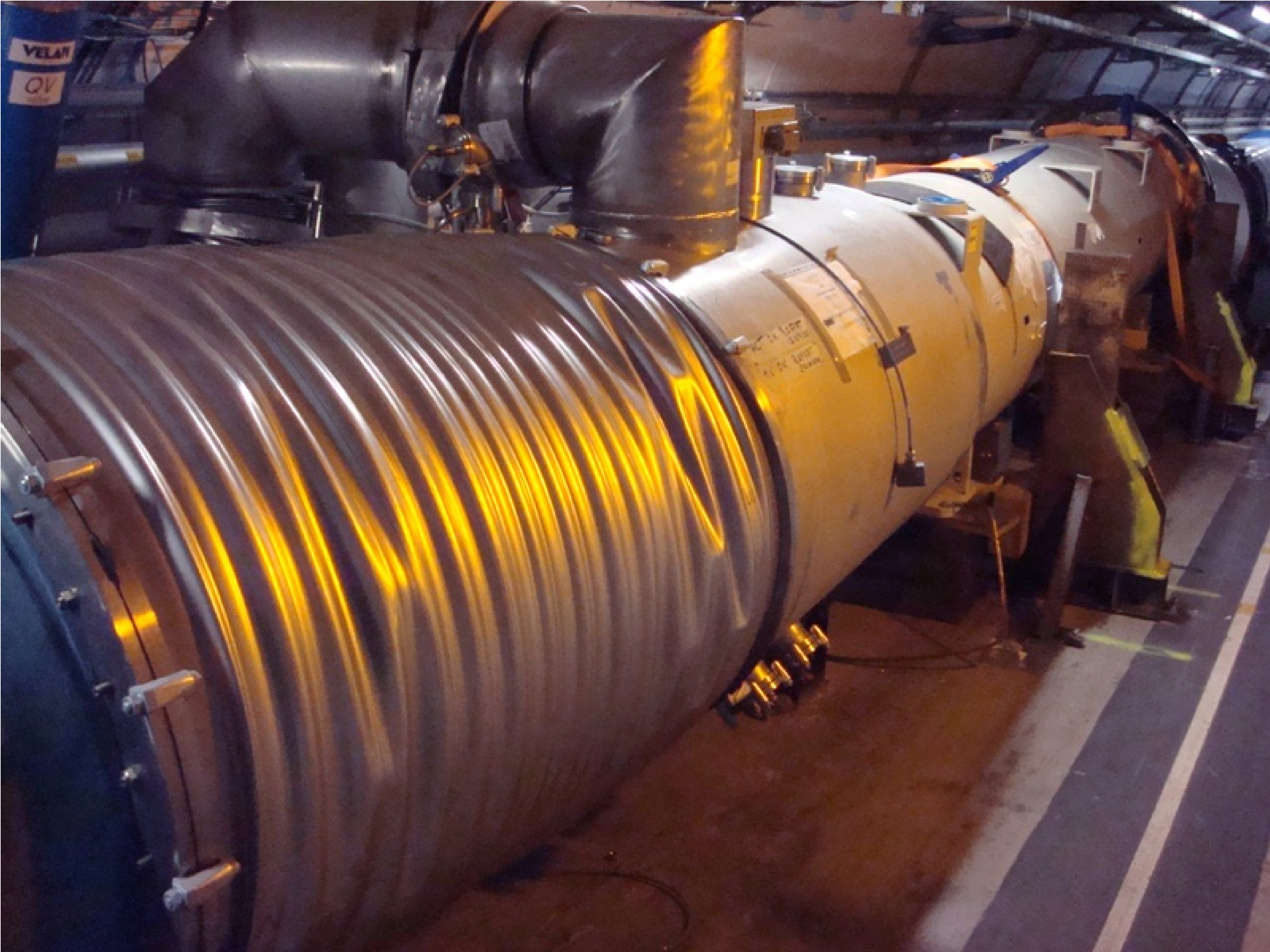


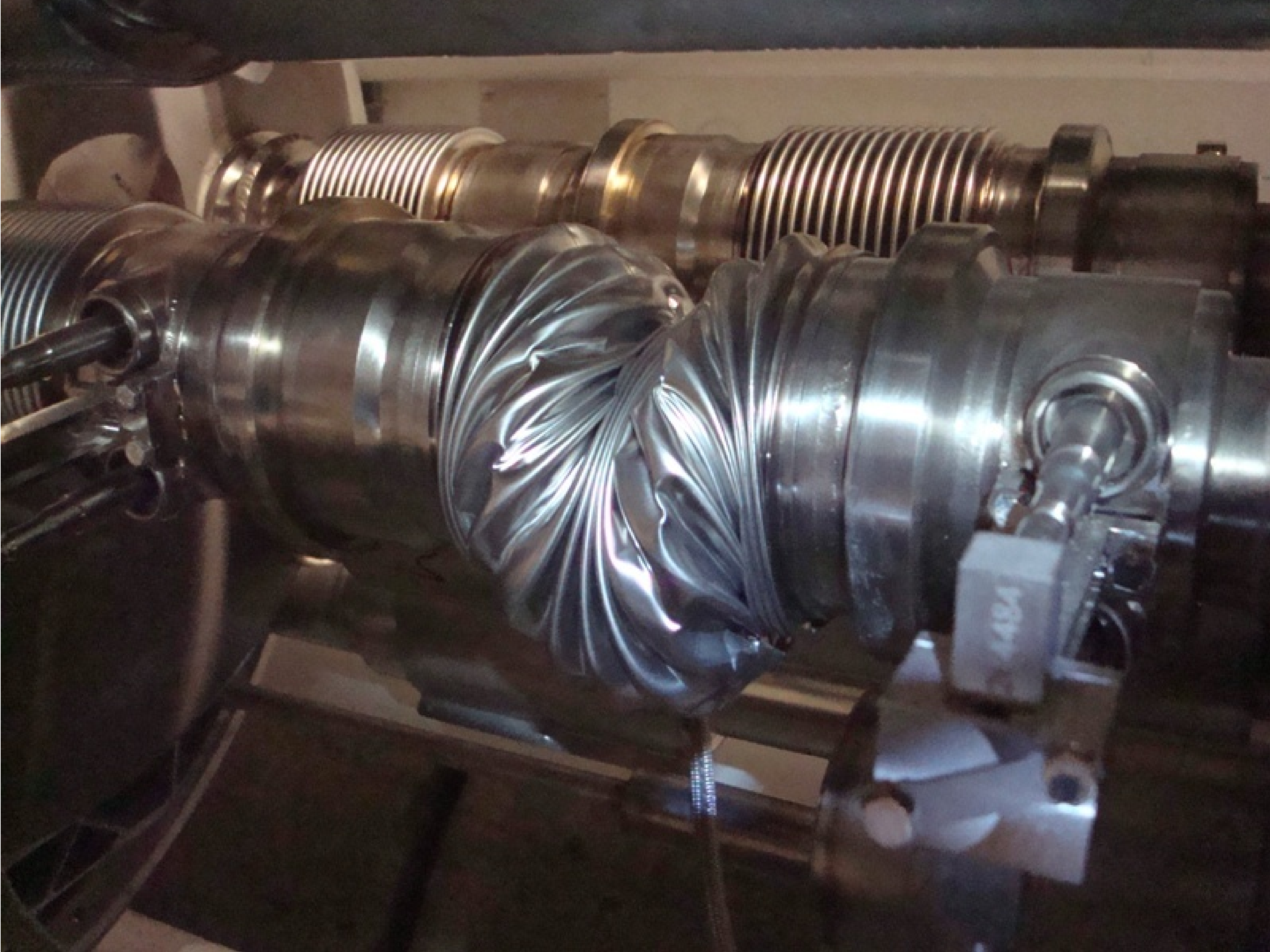
A faulty bus-bar (SC splice) in a magnet interconnect failed, leading to an electric arc which dissipated some 275 MJ



This burnt through beam vacuum and cryogenic lines, rapidly releasing ~2 tons of liquid helium into the vacuum enclosure

R. Veness


VELAN
QV



The main 2013-14 LHC consolidations

1695 Openings and final reclosures of the interconnections

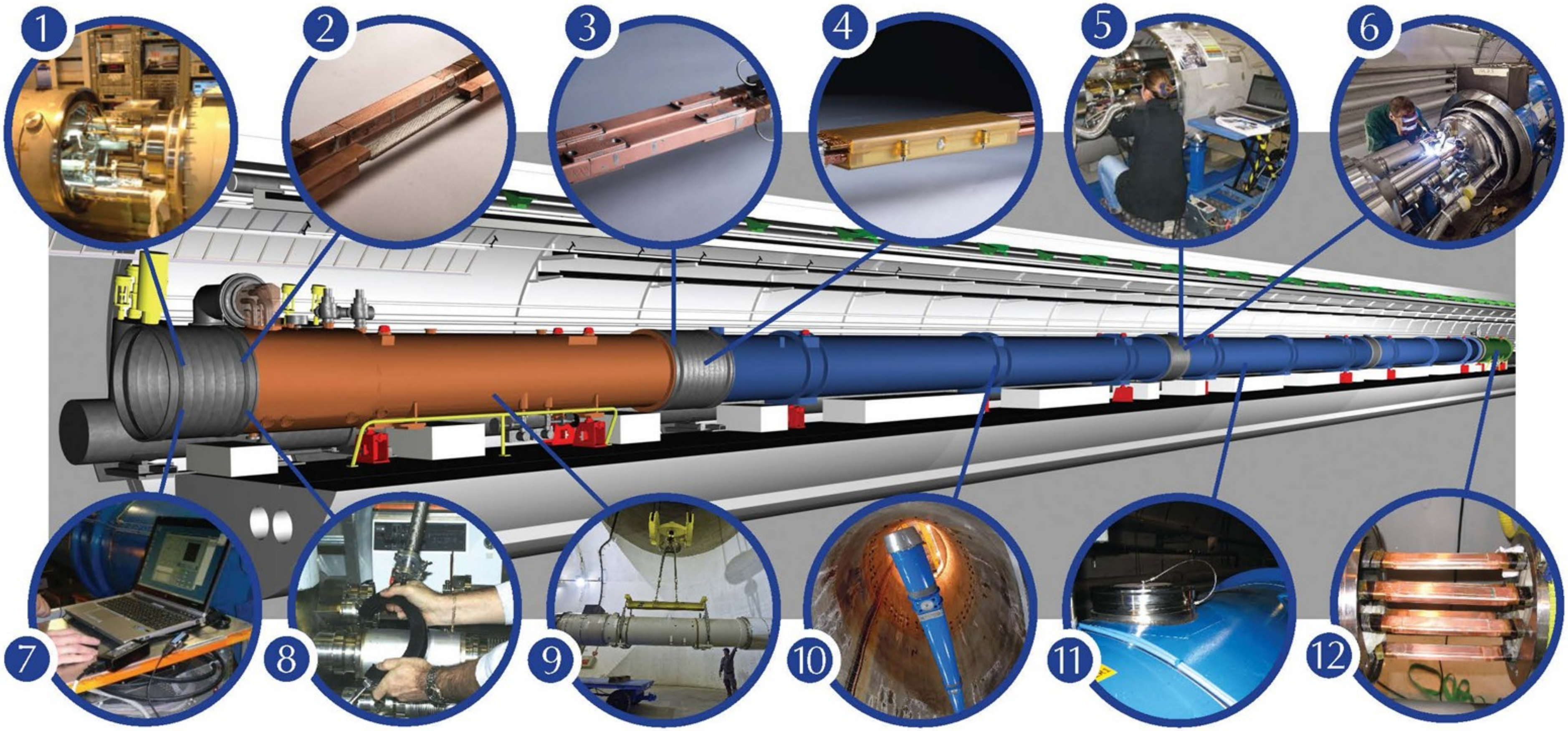
Complete reconstruction of 1500 of these splices

Consolidation of the 10170 13kA splices, installing 27 000 shunts

Installation of 5000 consolidated electrical insulation systems

300 000 electrical resistance measurements

10170 orbital welding of stainless steel lines



18 000 electrical Quality Assurance tests

10170 leak tightness tests

4 quadrupole magnets to be replaced

15 dipole magnets to be replaced

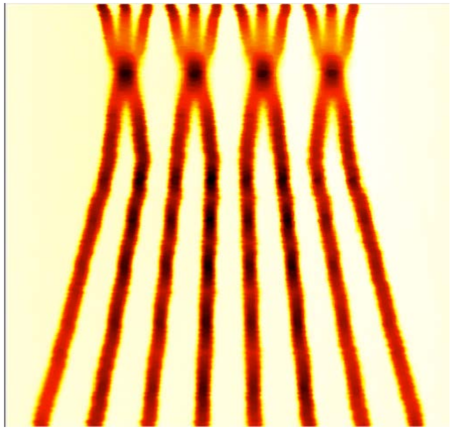
Installation of 612 pressure relief devices to bring the total to 1344

Consolidation of the 13 kA circuits in the 16 main electrical feedboxes

2015 – post LS1

- energy: 6.5 TeV (magnet retraining)
- bunch spacing: 25 ns
  - pile-up considerations
- injectors potentially able to offer nominal intensity with even lower emittance

BCMS = Batch Compression and Merging and Splitting



	Number of bunches	Ib LHC FT[1e11]	Emit LHC [um]	Peak Lumi [$cm^{-2}s^{-1}$]	~Pile-up	Int. Lumi per year [fb^{-1}]
25 ns low emit	2520	1.15	1.9	**1.7e34**	52	~45

expected maximum luminosity from inner triplet heat load (collisions debris) 1.7×10^{34} $cm^{-2}s^{-1}$ ±20%

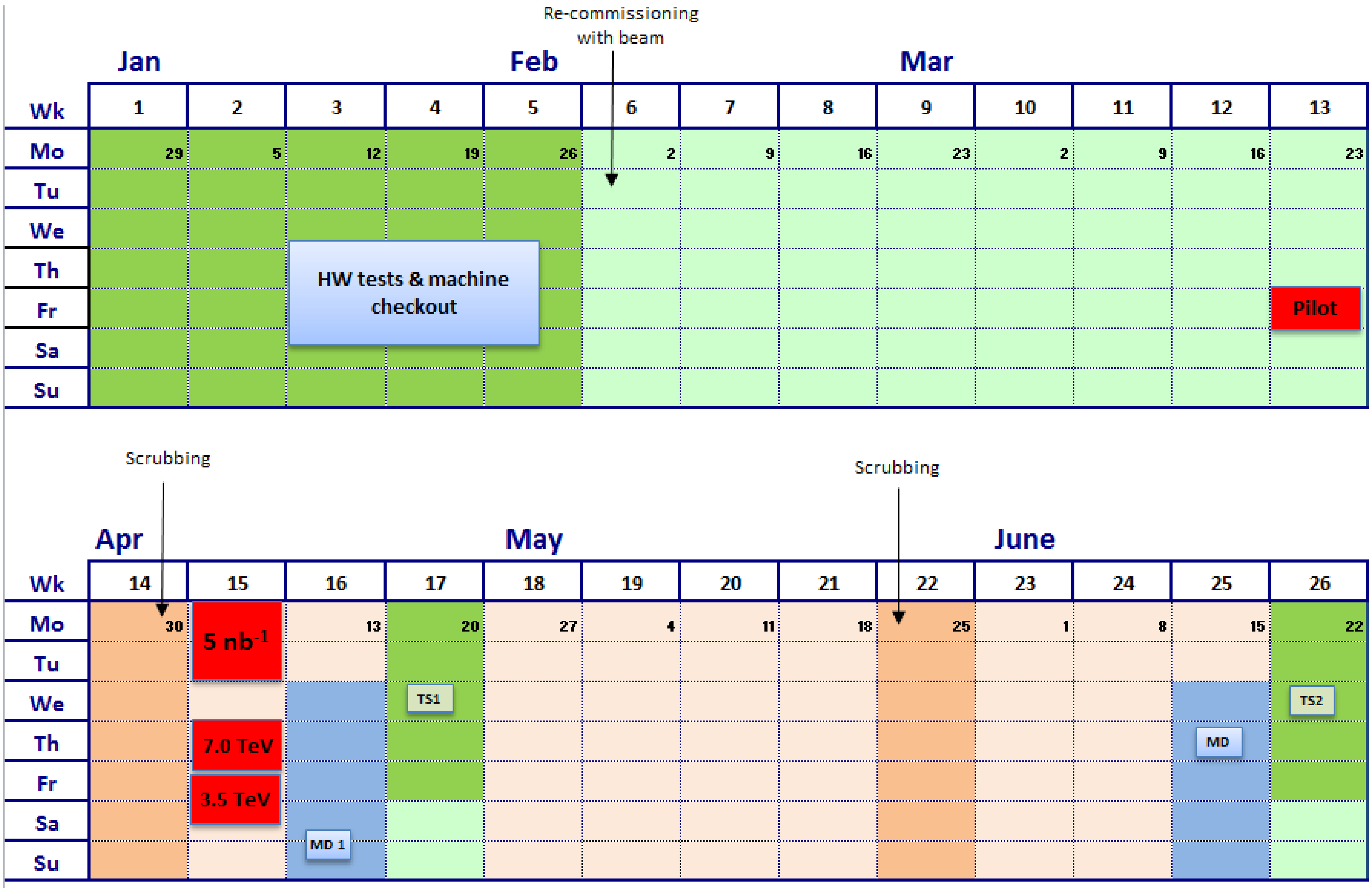
uncertainties for 2015:

- electron cloud
- UFOs

both get more difficult at 25 ns & at higher energy

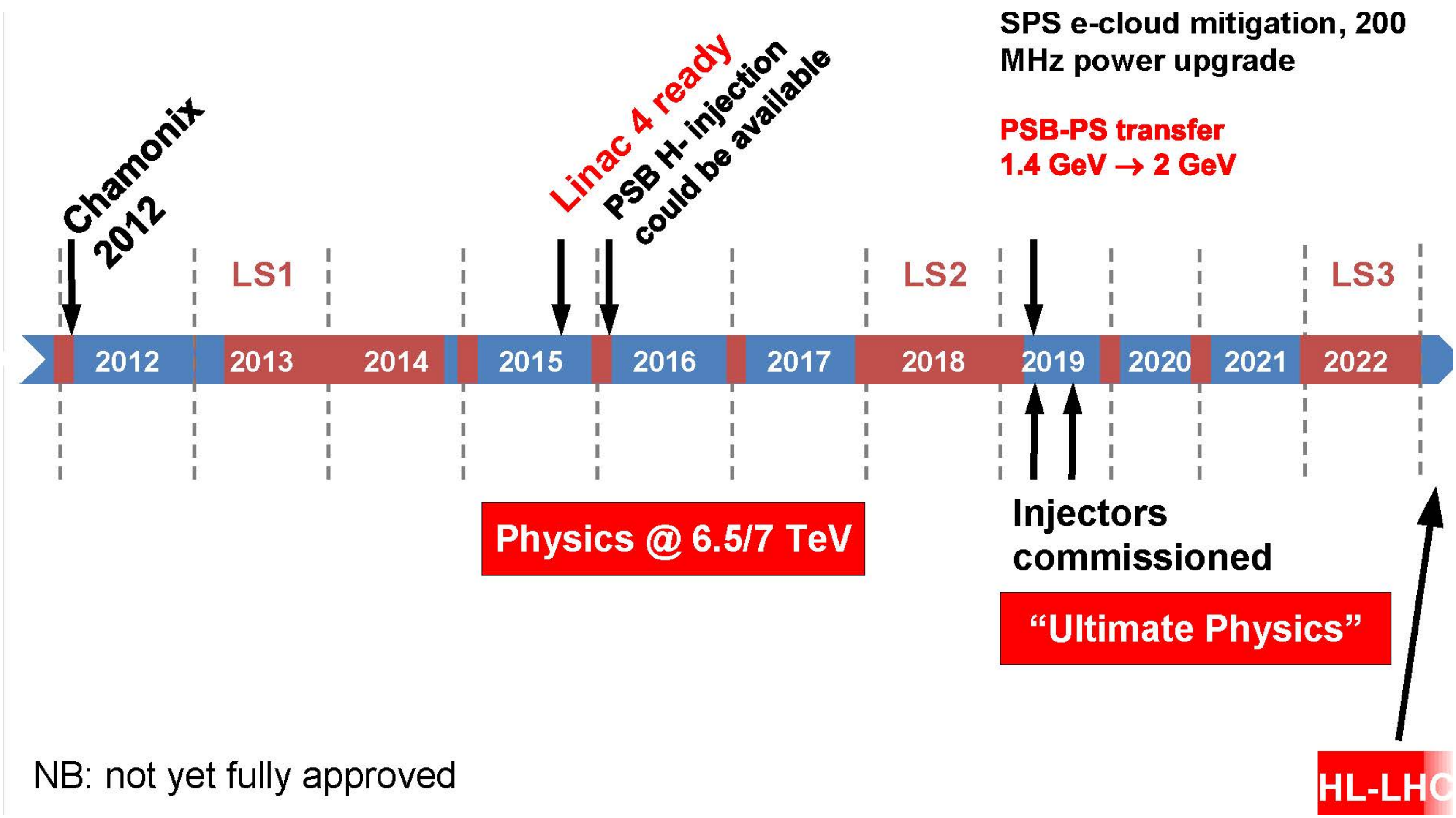
- energy (limited by retraining)

draft 2015 schedule



in red beam time requested by LHCf

example LHC time line – next ten years



Ralph Steinhagen, ICHEP2012

LHC luminosity forecast

~30/fb at 3.5 & 4 TeV **2012 DONE**

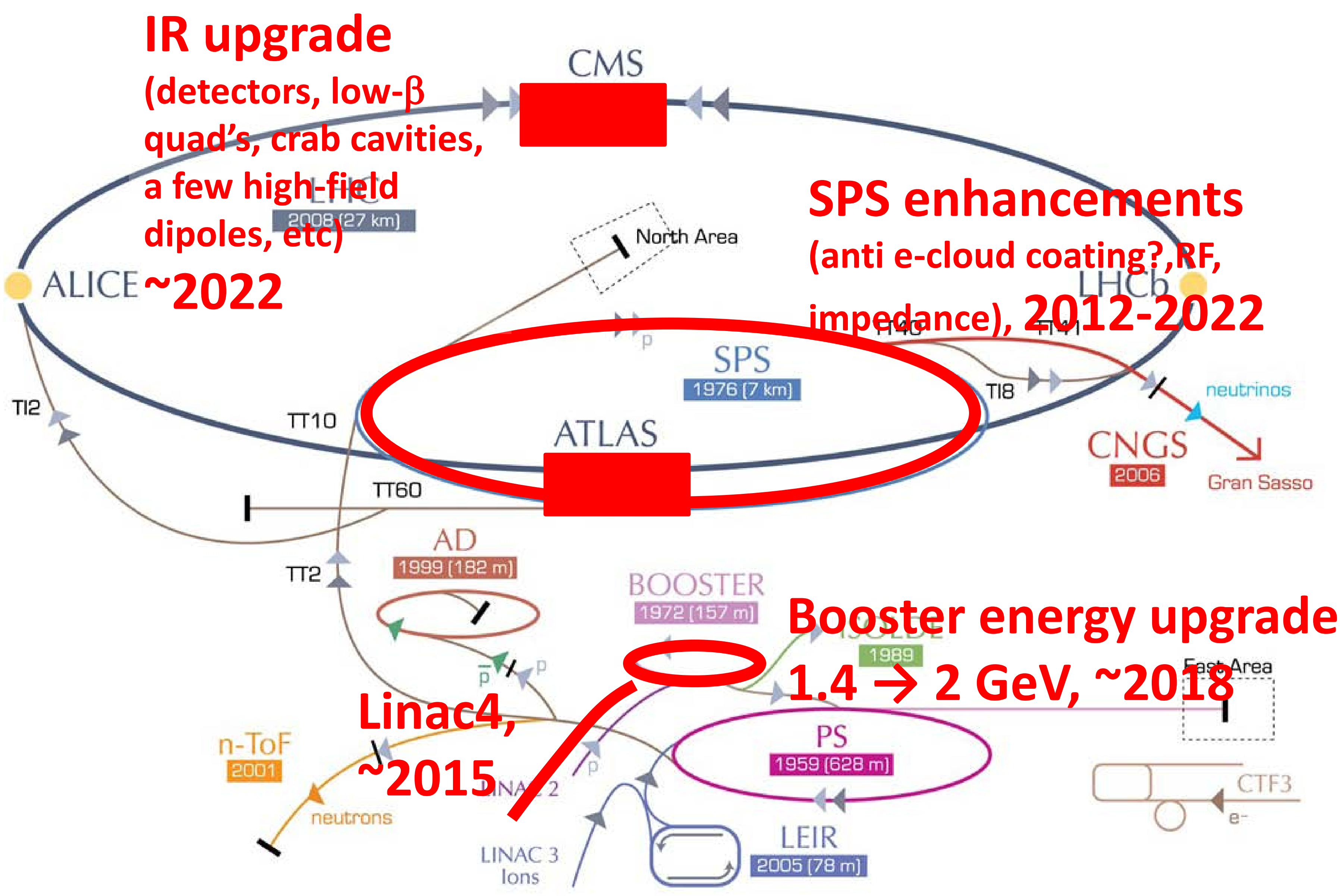
~400/fb at 6.5-7 TeV **2021 goal (?)**

~3000/fb at 7 TeV **2035 goal (??)**

*question: how do we get 3000/*fb *by 2035?*

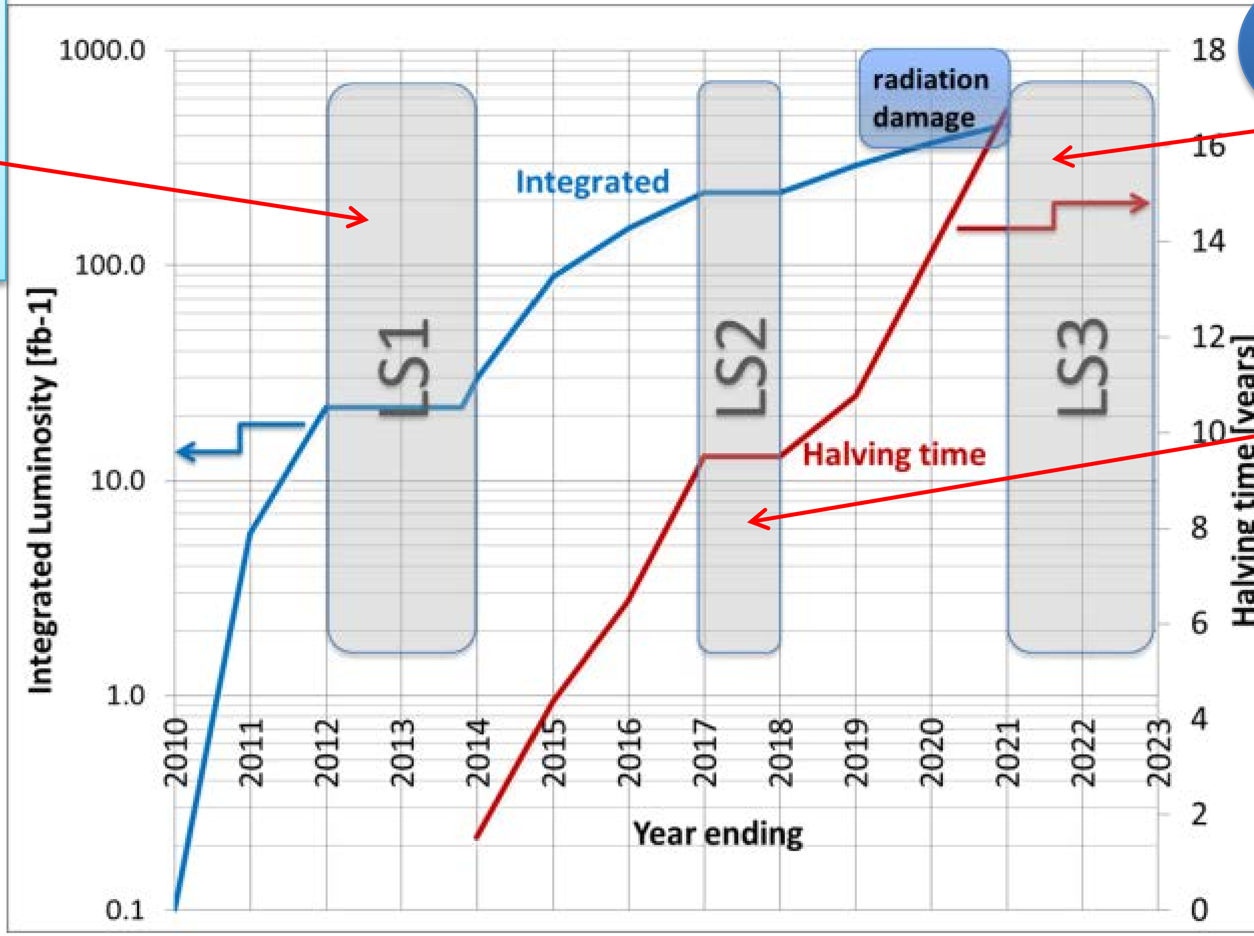
answer: with ***HL-LHC***

HL-LHC – modifications



(HL-)LHC Time Line

Shut down for interconnects to overcome energy limitation (LHC incident of Sept. 2008) and R2E

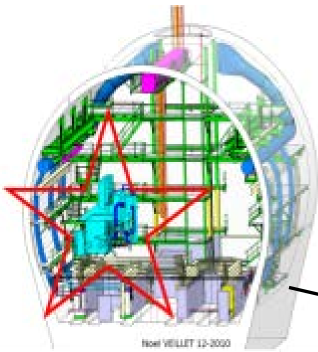


Full upgrade

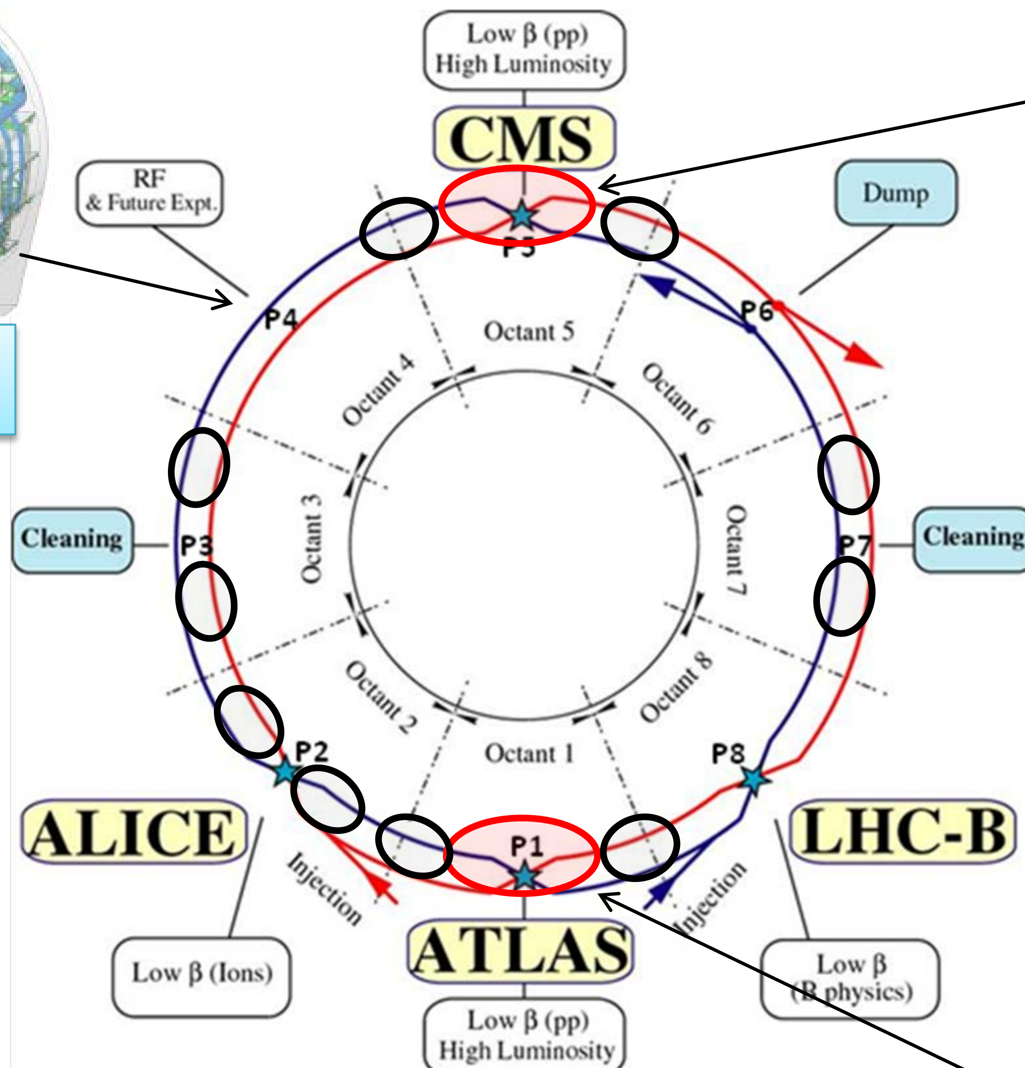
Shut down to overcome beam intensity limitation (Injectors, collimation and more…)

two reasons for HL-LHC: performance & consolidation

in LHC: 1.2 km of new equipment …



6.5 kW@4.5K cryoplant



2 x 18 kW @4.5K cryoplants for IRs

HL-LHC Official Beam Parameters

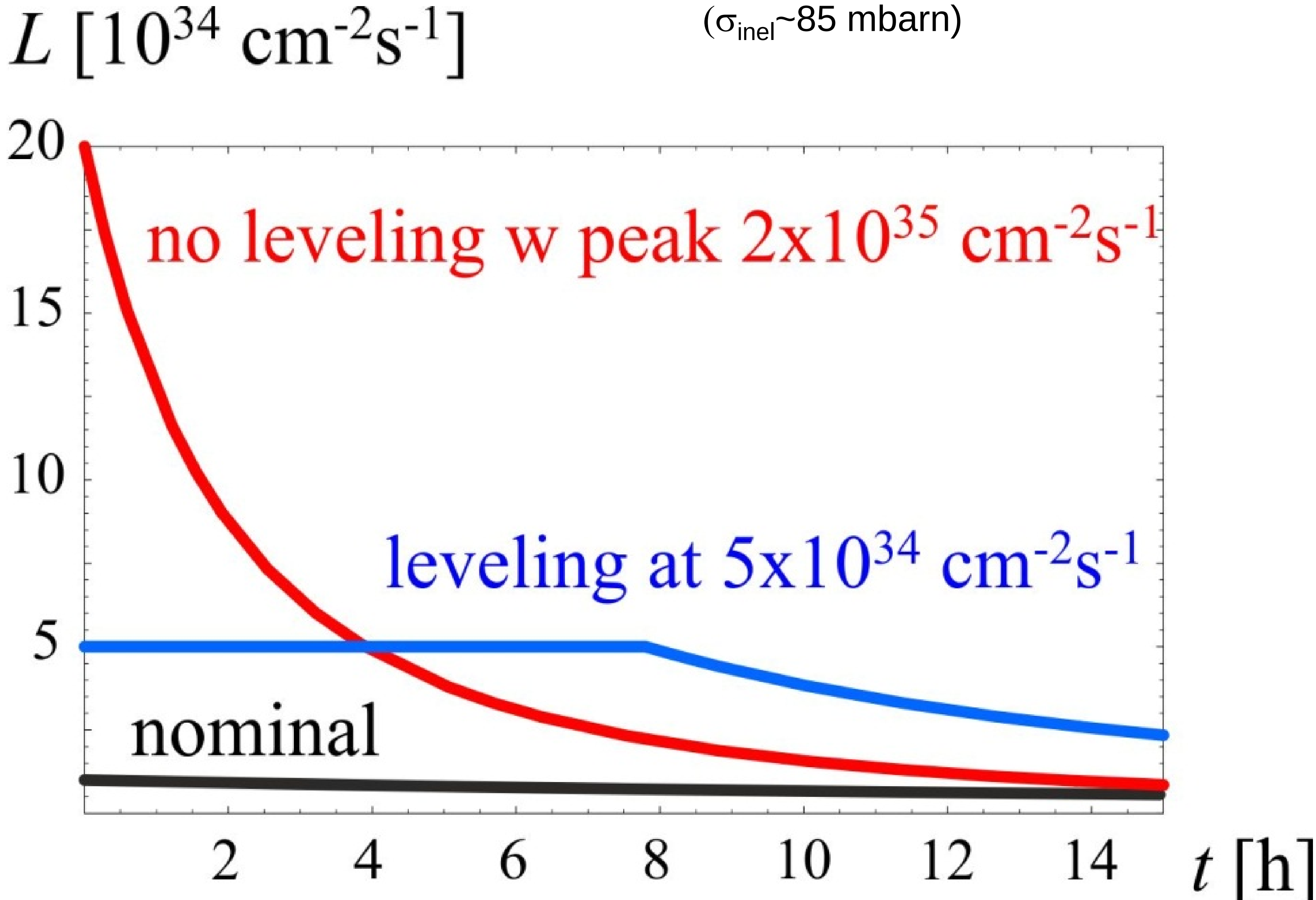
Parameter	nominal	25ns	50ns		
N	1.15E+11	**2.2E+11**	**3.5E+11**		
n_b	2808	2808	1404		
beam current [A]	0.58	**1.12**	**0.89**		
x-ing angle [μrad]	300	590	590		
beam separation [σ]	10	12.5	11.4		
β^* [m]	0.55	**0.15**	**0.15**		
ε_n [μm]	3.75	2.5	3.0		
ε_L [eVs]	2.51	2.5	2.5		
energy spread	1.20E-04	1.20E-04	1.20E-04		
bunch length [m]	7.50E-02	7.50E-02	7.50E-02		
IBS horizontal [h]	106	**20.0**	**20.7**		
IBS longitudinal [h]	60	**15.8**	**13.2**		
Piwinski parameter	0.68	**3.1**	**2.9**		
geom. reduction	0.83	**0.35**	**0.33**		
beam-beam / IP	3.10E-03	**3.9E-03**	**5.0E-03**		
Peak Luminosity	$1\ 10^{34}$	**$7.4\ 10^{34}$**	**$8.5\ 10^{34}$**		
Virtual Luminosity	$1.2\ 10^{34}$	**$21\ 10^{34}$**	**$26\ 10^{34}$**		
Events / crossing (peak & leveled L)	27	**210**	**475**	**140**	**140**

$6.2\ 10^{14}$ and $4.9\ 10^{14}$ p/beam

(Leveled to $5\ 10^{34}\ cm^{-2}\ s^{-1}$ and $2.5\ 10^{34}\ cm^{-2}\ s^{-1}$)

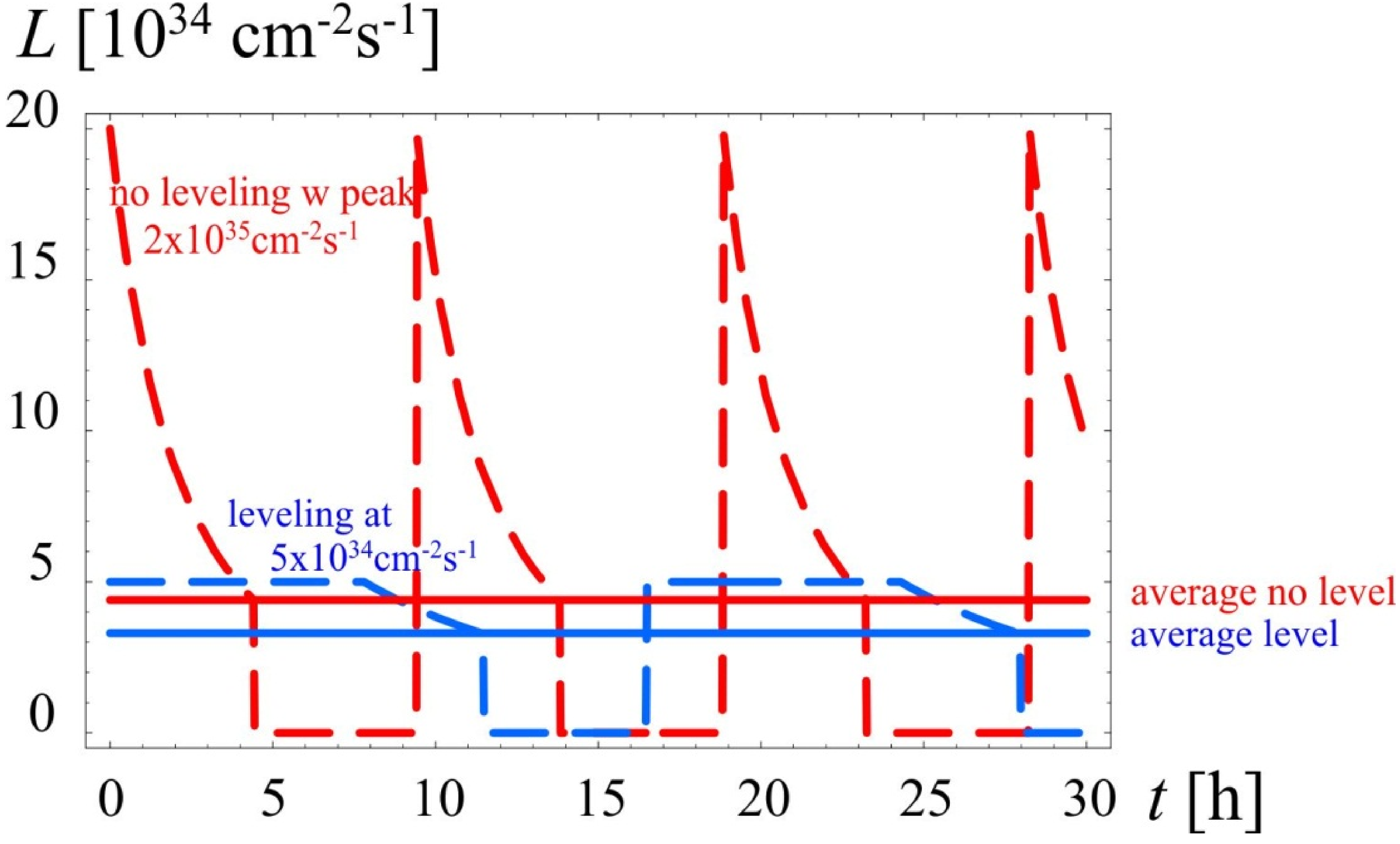
luminosity leveling at the HL-LHC

example: maximum pile up 140
(σ_{inel}~85 mbarn)



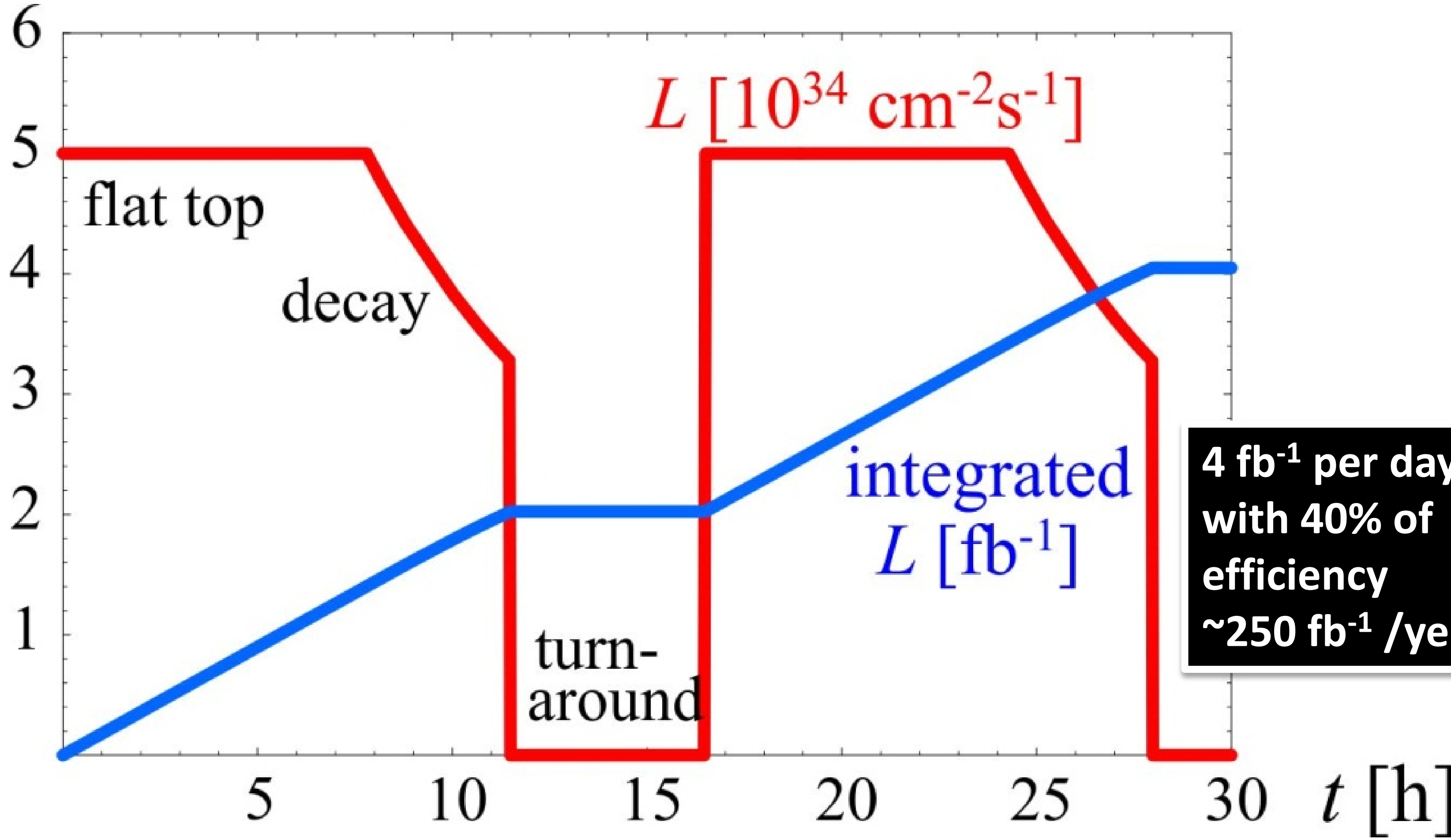
luminosity leveling at the HL-LHC

example: maximum pile up 140



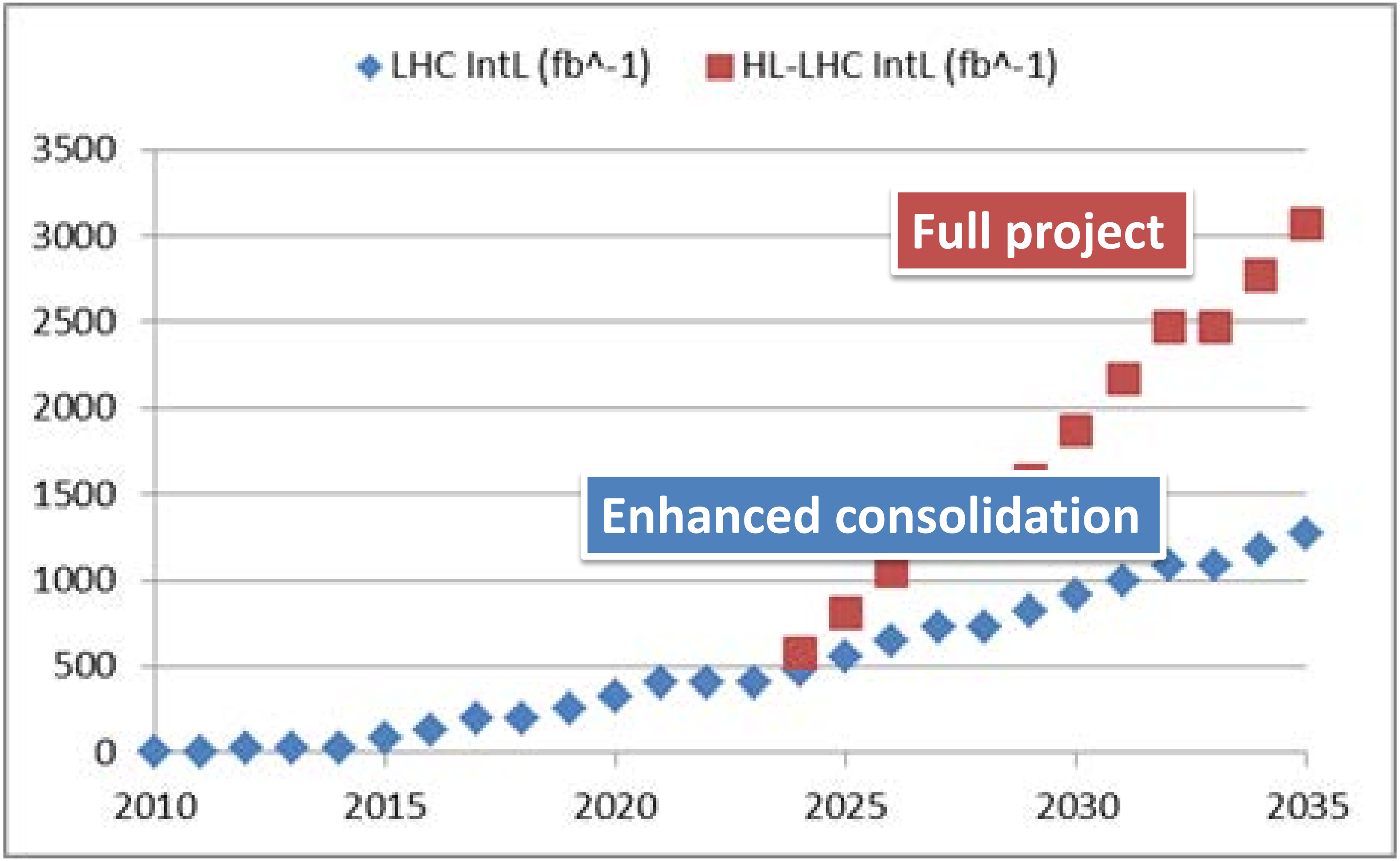
luminosity & integrated luminosity during 30 h at the HL-LHC

example: maximum pile up 140



4 fb^{-1} per day, with 40% of efficiency
~250 fb^{-1} /year

final goal : 3000 fb^{-1} by 2030's…

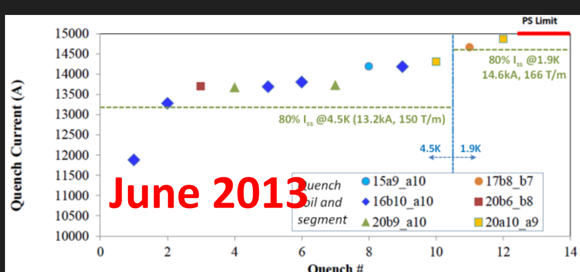


some HL-LHC ingredients

new final quadrupoles

- *Nb_3Sn* instead of *Nb-Ti*
- larger aperture allowing smaller β^*

LQS03 (90 mm ap., 3.7 m long): 208 T/m@4.6 K, **210 T/m**@1.9 K

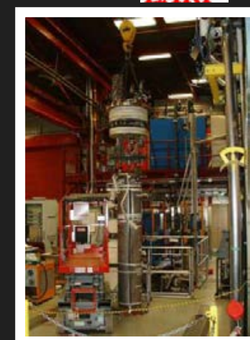


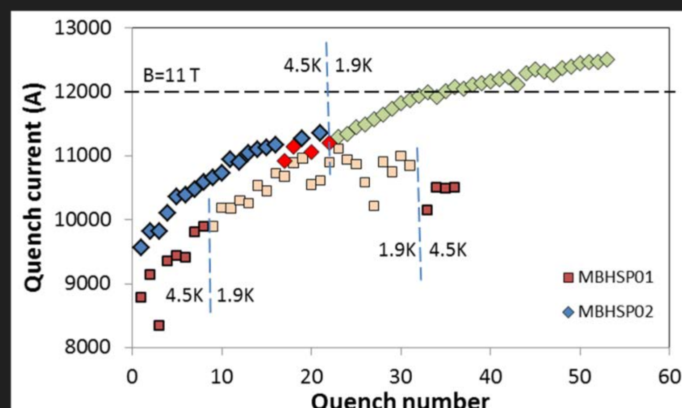
HQ02a (120 mm, 1.5 m long): 150 T/m@4.6 K, **170 T/m**@1.9 K

Goal: 150 mm ap, 140 T/m

11-T dipoles for dispersion suppressors

- *Nb_3Sn* instead of *Nb-Ti*
- provide space for extra collimators catching off -energy protons or ions at ALICE, collimator sections, ATLAS & CMS





1-m model tested in April 2014, B_{nom}=11 T achieved!

Next: 2-m single bore, then 2-in-1

SC link

- move radiation sensitive power converters away from machine
- first prototype, 20 m – 20 kA, under test at CERN!

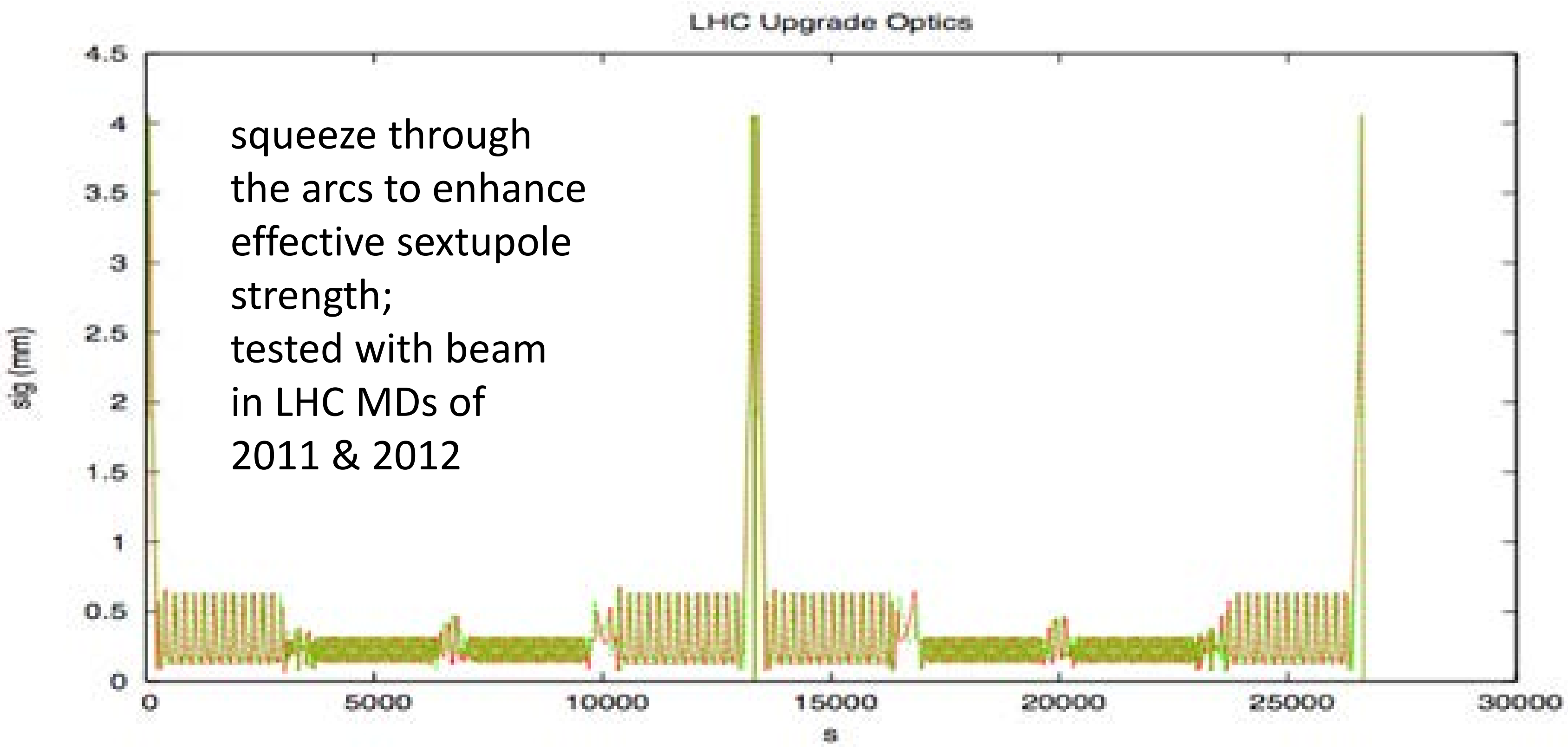
- also of interest for electrical power distribution

tests of novel *MgB_2* and *HTS* (YBCO and *BSCCO*) cables

HL-LHC optics

S. Fartoukh

Achromatic Telescopic Squeeze (ATS), «fully proven» MDs (β* = 15 cm «easy», room for β* ~ 10-12 cm)



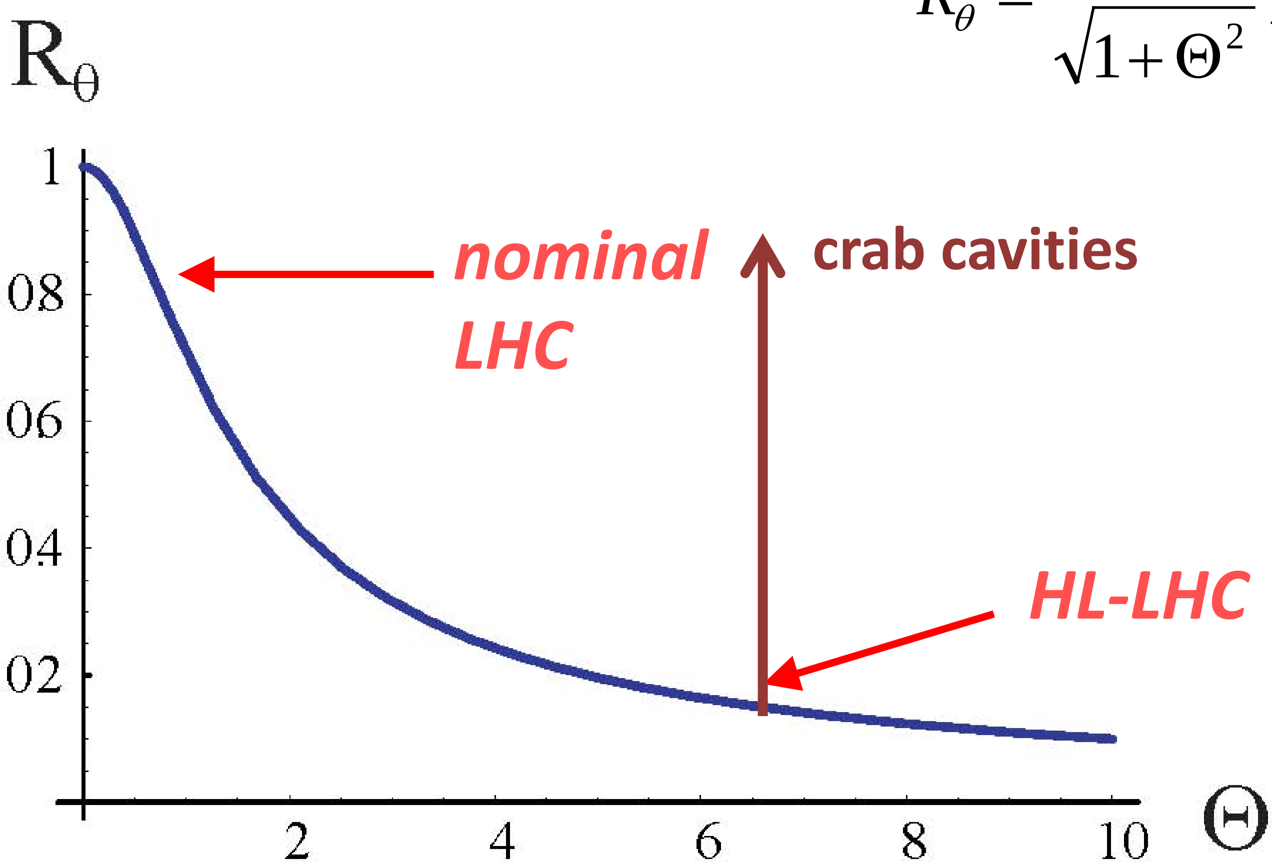
typical ATS collision optics with IR1 & IR5 squeezed down to β^*=10 cm

luminosity reduction due to crossing angle
is more pronounced at smaller β*

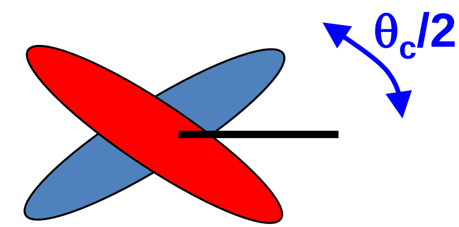
"Piwinski angle"

luminosity reduction factor

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



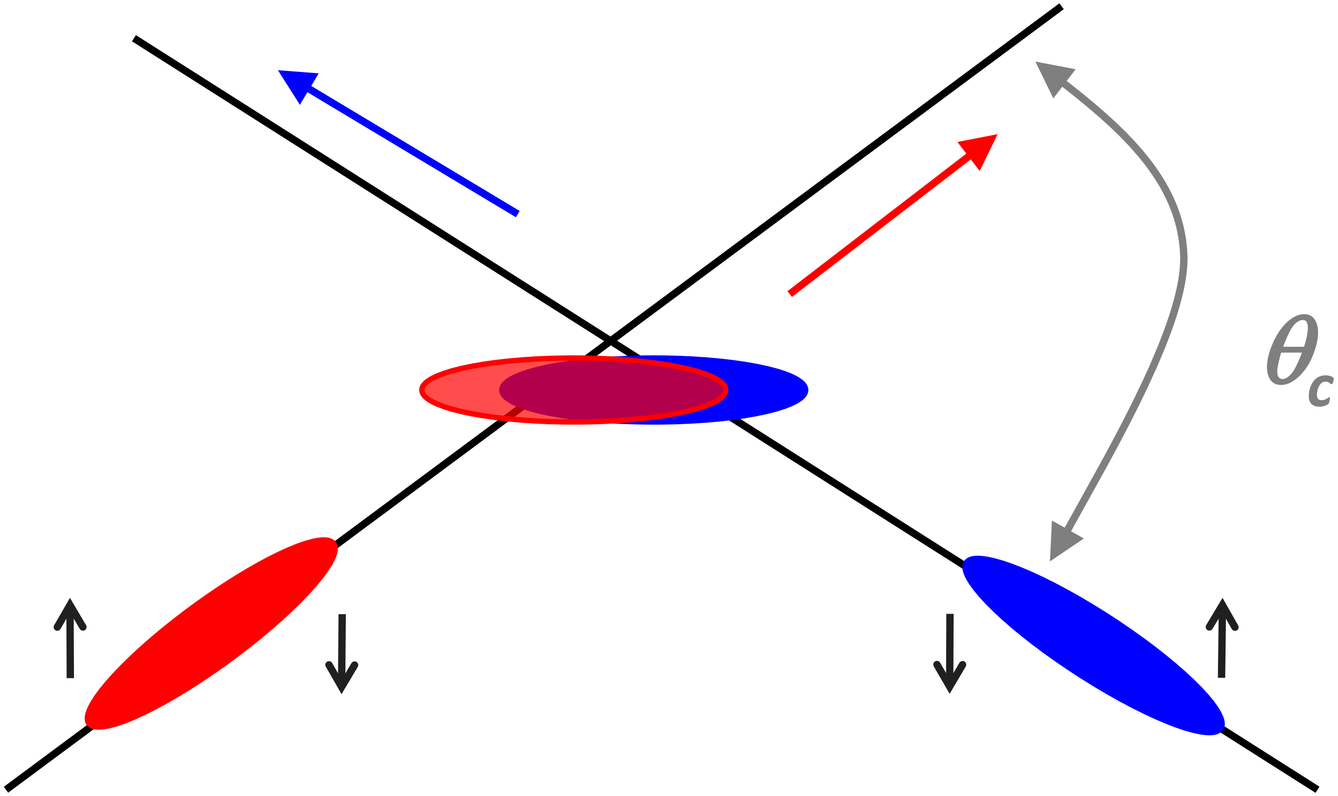
Θ ~1/β*



eff. beam size:

$$\sigma^*_{x,eff} \approx \sigma_x^*/R_\theta$$

schematic of crab crossing

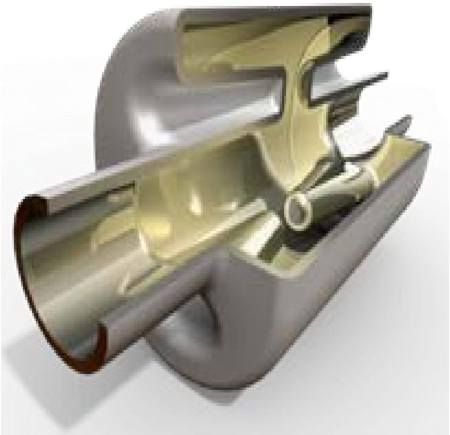
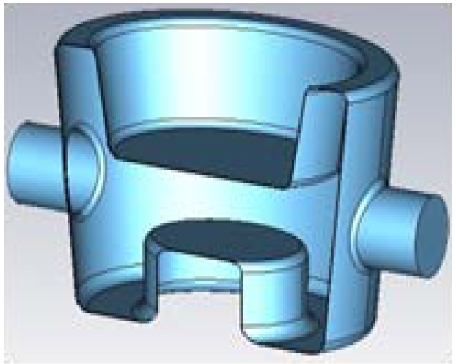
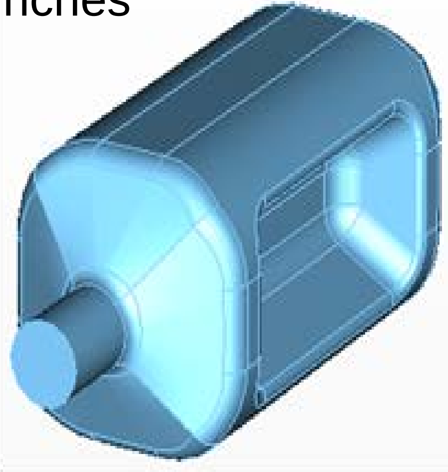


- RF crab cavity deflects head and tail in opposite direction so that collision is effectively "head on" for luminosity and tune shift
- bunch centroids still cross at an angle (easy separation)
- 1st proposed in 1988, used in operation at KEKB since 2007

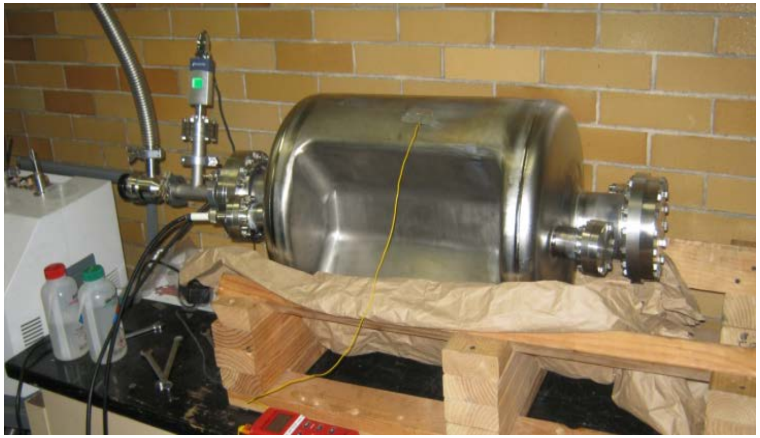
until recently plan was to vary crab cavity voltage for leveling, but this would change size of luminous region & is disliked by experiments (instead leveling by β^* or offset?)

HL-LHC needs compact crab cavities

only 19 cm beam separation, but long bunches

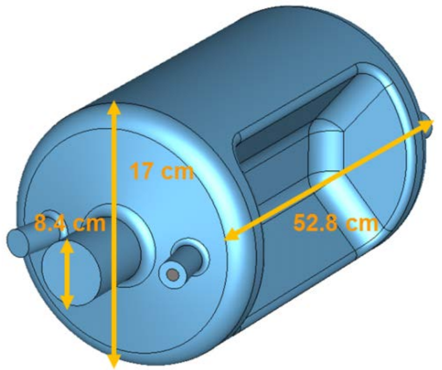




Final down-selected compact cavity designs for the LHC upgrade: 4-rod cavity design by Cockcroft I. & JLAB (left), $\lambda/4$ TEM cavity by BNL (centre), and double-ridge $\lambda/2$ TEM cavity by SLAC & ODU (right).

Prototype compact *Nb-Ti* crab cavities for the LHC: 4-rod cavity (left) and double-ridge cavity (right).

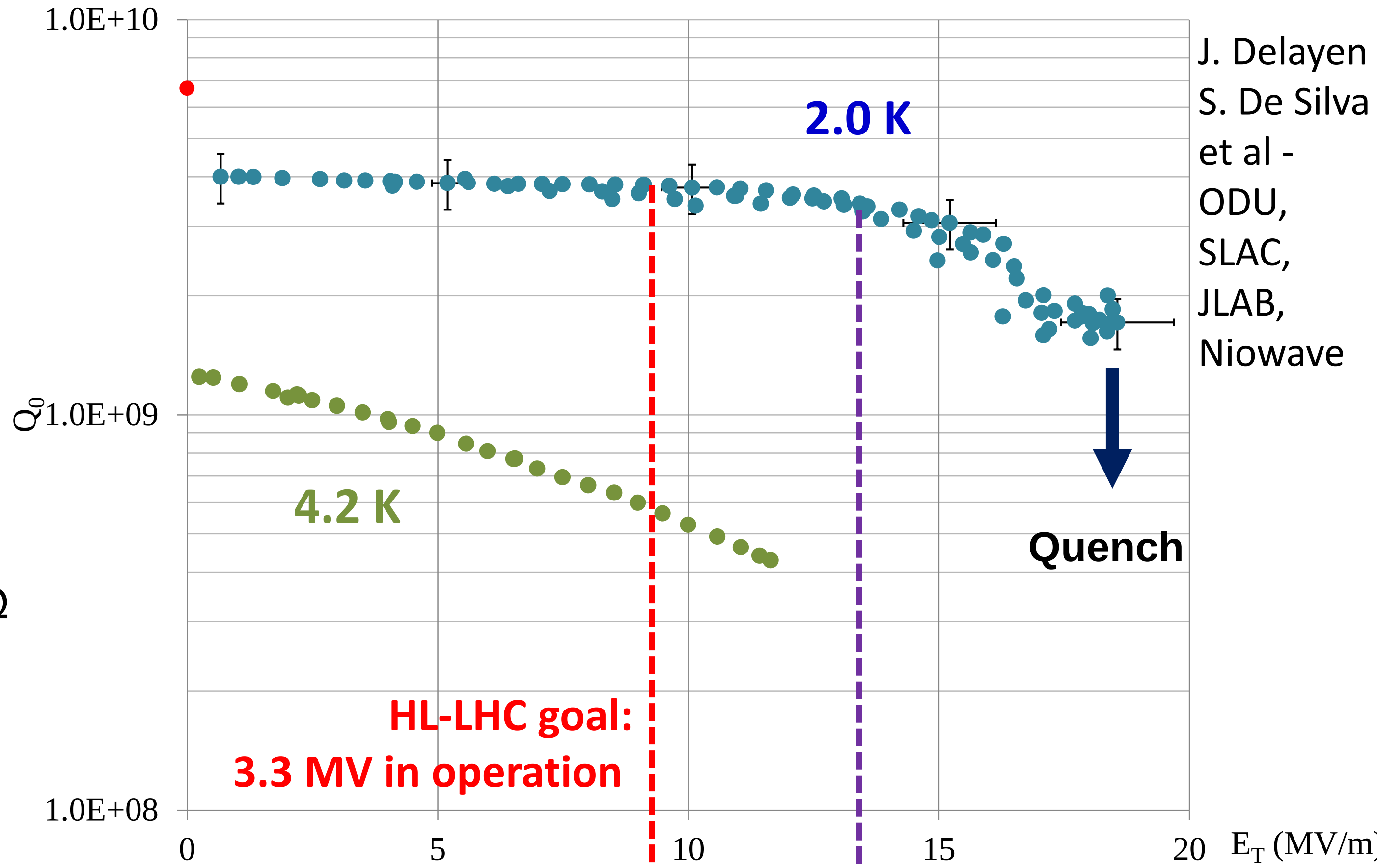
breaking news – PoP double-ridge cavity achieved 7 MV deflecting voltage cw



- Expected

  $Q_0 = 6.7\times10^9$
  - At R_S = 22 nΩ
  - And R_{res} = 20 nΩ
- Achieved

  $Q_0 = 4.0\times10^9$
- Achieved fields
  - E_T = 18.6 MV/m
  - V_T = 7.0 MV
  - E_P = 75 MV/m
  - B_P = 131 mT

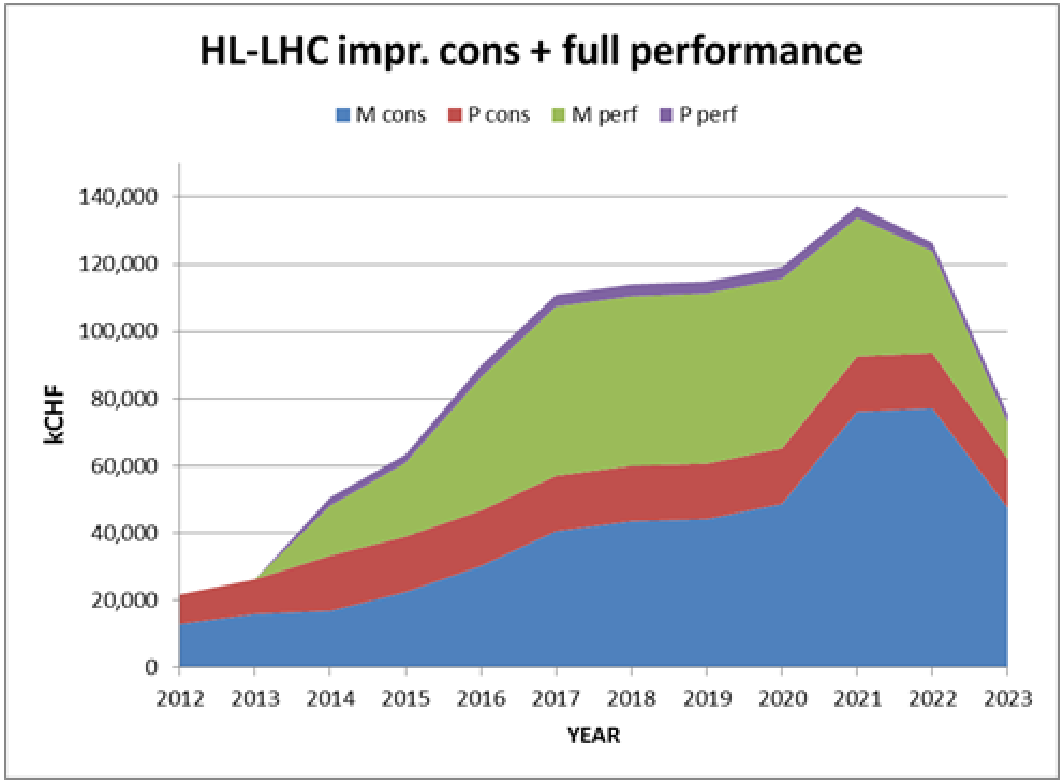


J. Delayen
S. De Silva
et al -
ODU,
SLAC,
JLAB,
Niowave

better than required!

J. Delayen, LARP CM20

HL-LHC preliminary budget estimate



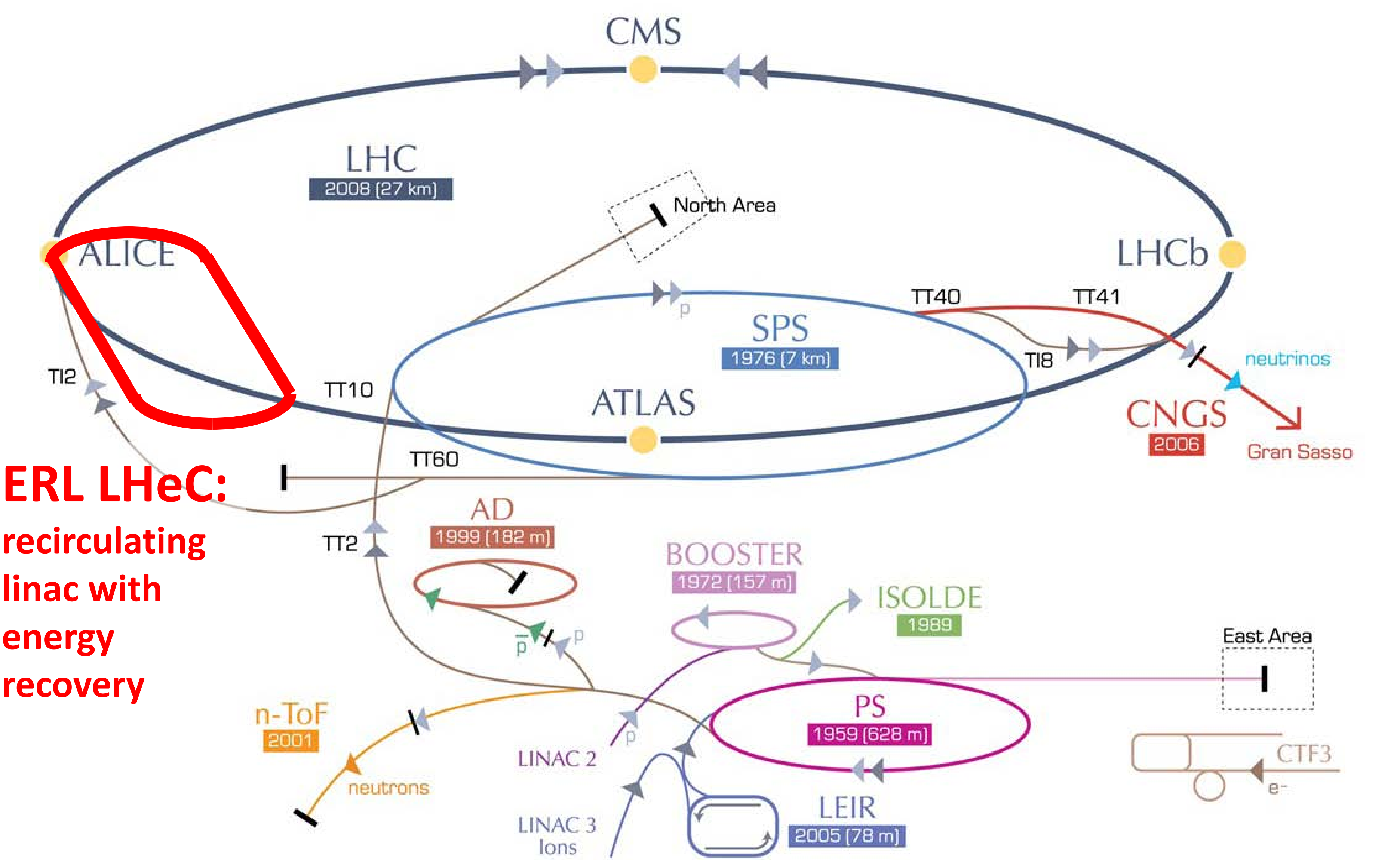
	Improving Consolidation	Full performance	Total HL-LHC
Mat. (MCHF)	476	360	836
Pers. (MCHF)	182	31	213
Pers. (FTE-y)	910	160	1070
TOT (MCHF)	658	391	1,049

RLIUP 2013
“Review of LHC and injector upgrade plans”
CERN, October 2013

3 scenarios	PICs Performance Improving Consolidations	US1 Upgrade Scenario 1	US2 Upgrade Scenario 2
		+HHRF?+DS collimators?	+crab cavities, e-lens,…
integrated luminosity by 2035	**1000-1200/fb**	**2000/fb**	**3000/fb**

physics needs & motivation?; also, reasons to go >3000/fb?

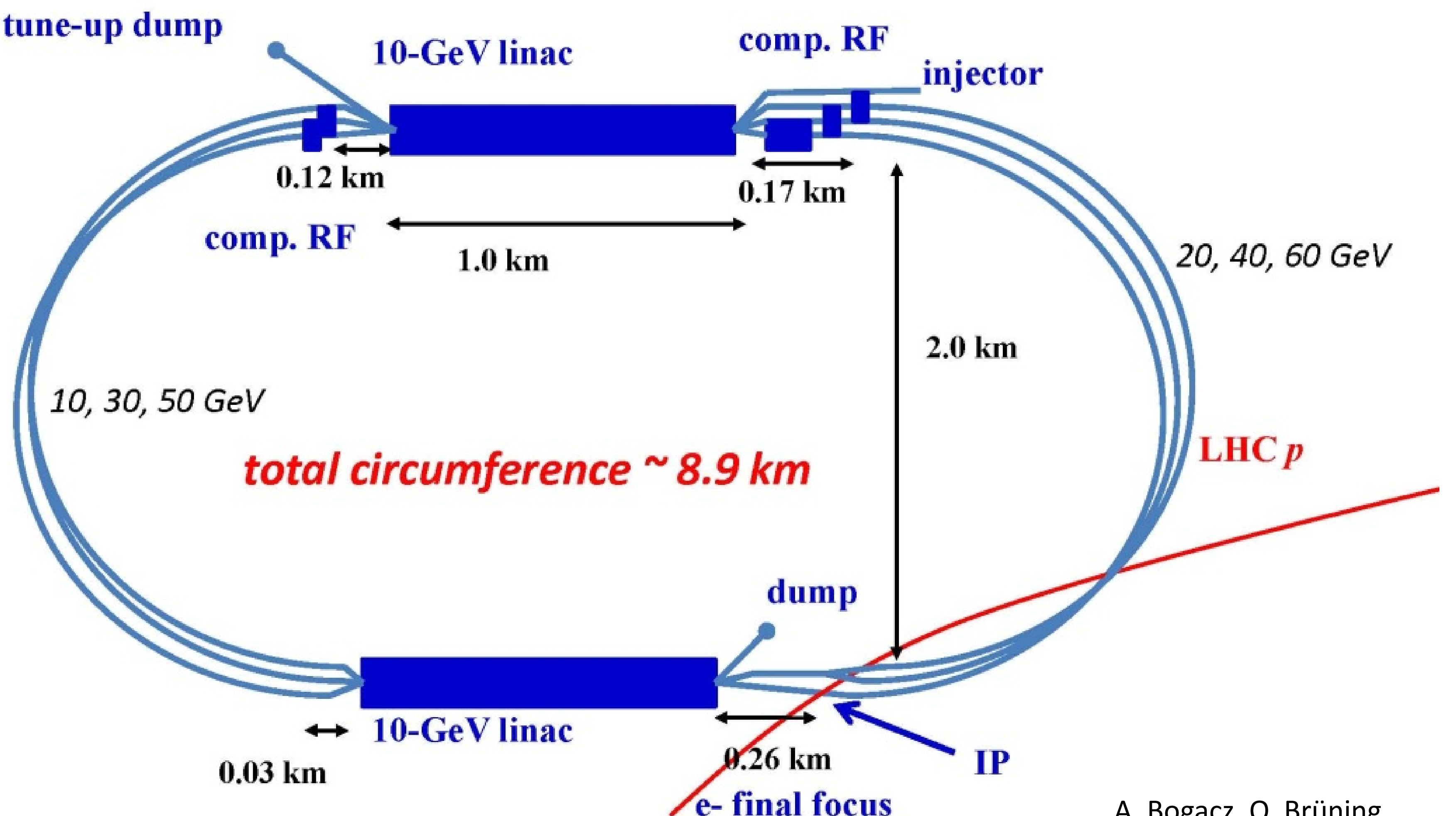
Large Hadron electron Collider (LHeC)



ERL LHeC:
recirculating linac with energy recovery

LHeC ERL layout

two SC linacs, 3-pass up, 3-pass down; 6.4-mA 60-GeV e^-'s collide w. LHC *p*/ions, e^- RF grad ~20 MV/m, 800 MHz



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

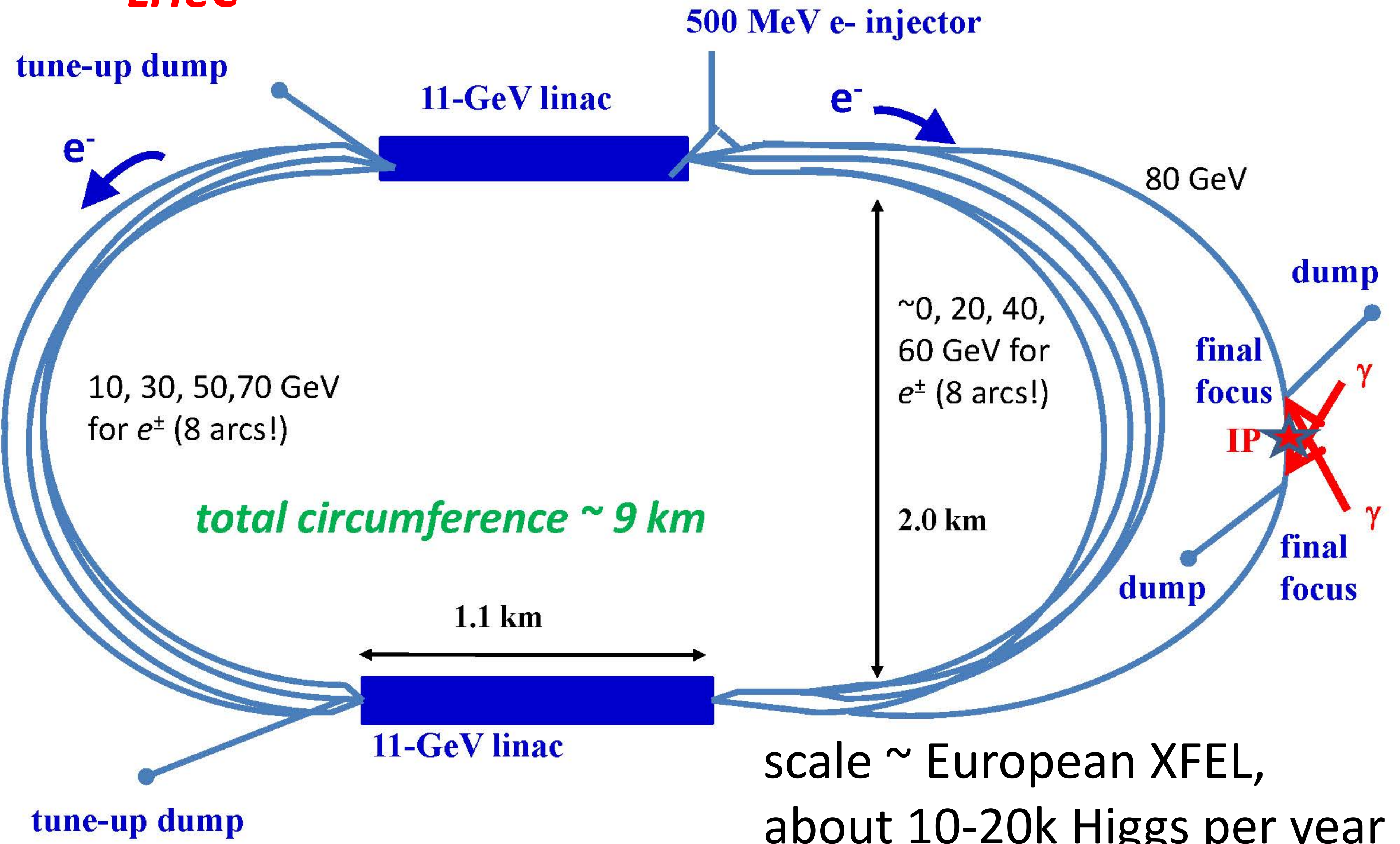
A. Bogacz, O. Brüning,
M. Klein, D. Schulte,
F. Zimmermann, et al

LHeC baseline & Higgs factory parameters

parameter [unit]	LHeC baseline		LHeC Higgs factory	
species	e^-	p	e^-	p
beam energy (/nucleon) [GeV]	60	7000	60	7000
bunch spacing [ns]	25 (50)	25 (50)	25 (50)	25 (50)
bunch intensity (nucleon) [10^{10}]	0.1 (0.2)	17	0.4 (0.8)	22 (35)
beam current [mA]	6.4	860	25.6	1110 (883)
rms bunch length [mm]	0.6	75.5	0.6	75.5
polarization [%]	90	none	90	none
normalized rms emittance [μm]	50	3.75	50	2.5 (3.0)
geometric rms emittance [nm]	0.43	0.50	0.43	0.34
IP beta function $\beta^*_{x,y}$ [m]	0.12	0.1	0.039	0.05
IP spot size [μm]	7.2	7.2	4.1	4.1
synchrotron tune Q_s	—	1.9×10^{-3}	—	1.9×10^{-3}
hadron beam-beam parameter	0.0001 (0.0002)		0.0004 (0.0008)	
lepton disruption parameter D	6		23 (31)	
crossing angle	0		0	
hourglass reduction factor H_{hg}	0.91		0.70 (0.73)	
pinch enhancement factor H_D	1.35		1.35	
c.m. energy [GeV]	1300		1300	
luminosity / nucleon [10^{33} cm^{-2}s^{-1}]	1.3		L_{ep} ~2 10^{34} cm^{-2}s^{-1}	

Reconfigured *LHeC*

SAPPHiRE γγ Higgs Factory



scale ~ European XFEL, about 10-20k Higgs per year

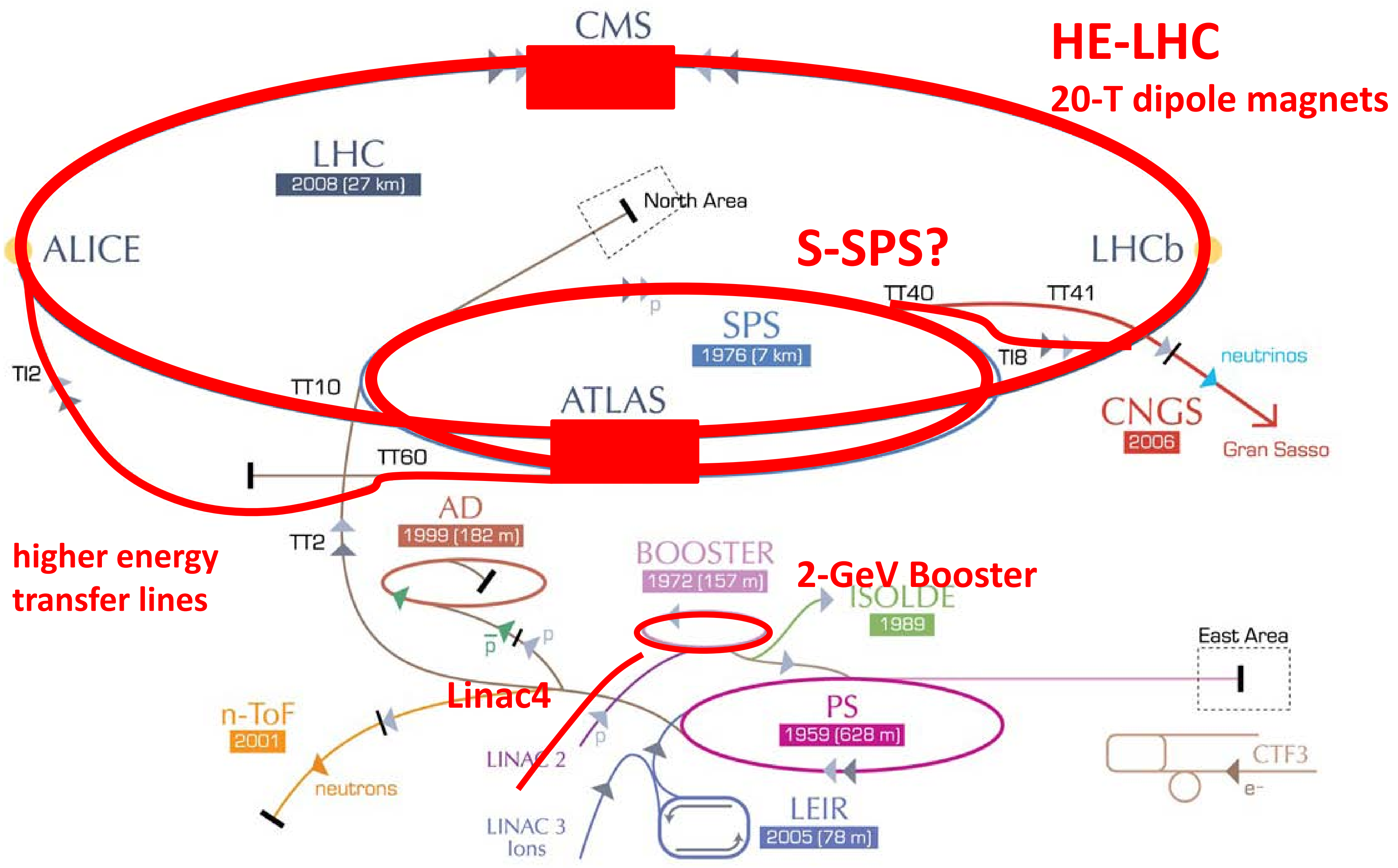
SAPPHiRE: Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons

LHeC Higgs factory comparison

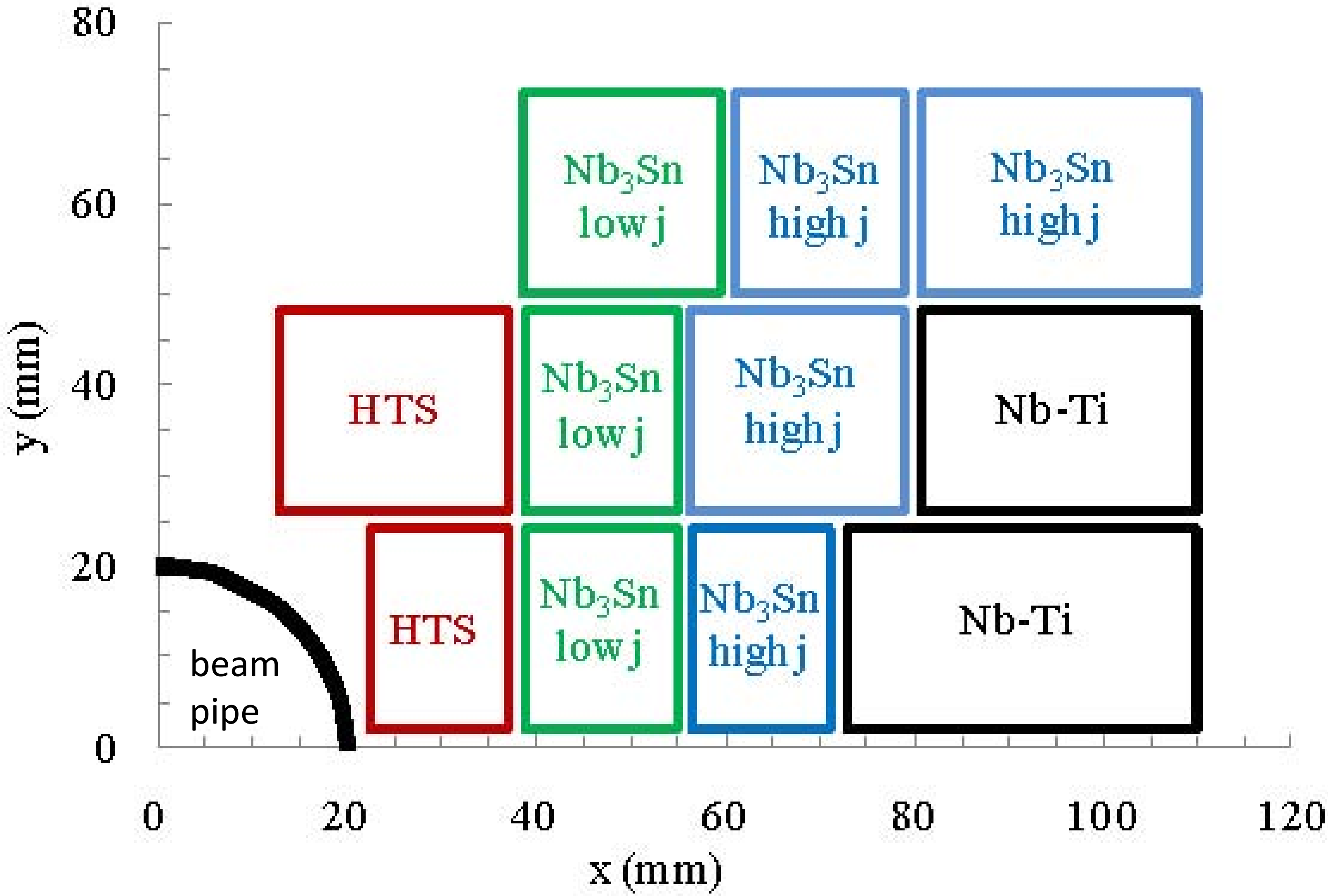
(1 year = 10^7 s at design luminosity).

machine	LHeC	LHeC-HF	SAPPHiRE
luminosity [10^{34} cm^{-2}s^{-1}]	0.1 (*ep*)	2 (*ep*)	0.06 ($\gamma\gamma$ >125 GeV)
cross section	~200 fb	~200 fb	>1.7 pb
no. Higgs/yr	2k	40k	>10k

High-Energy LHC

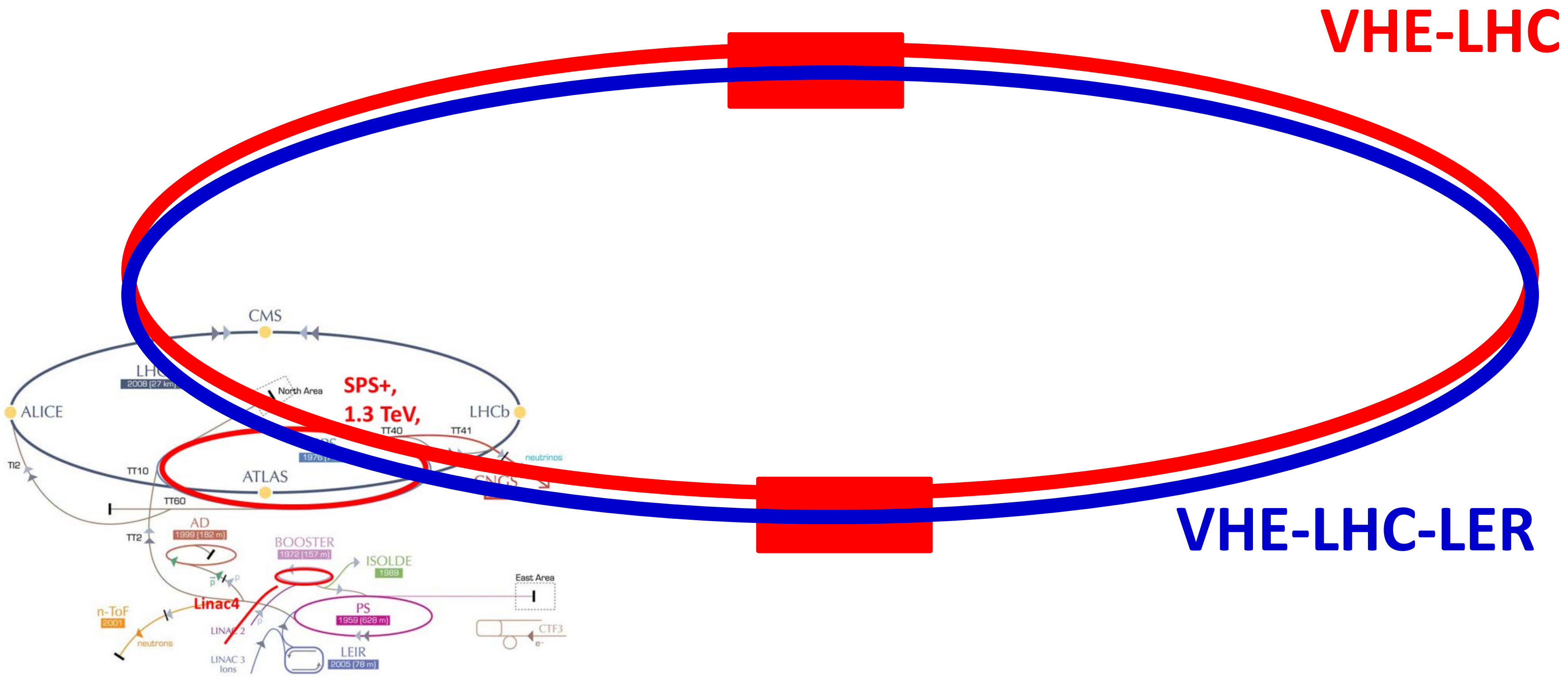


20-T dipole magnet



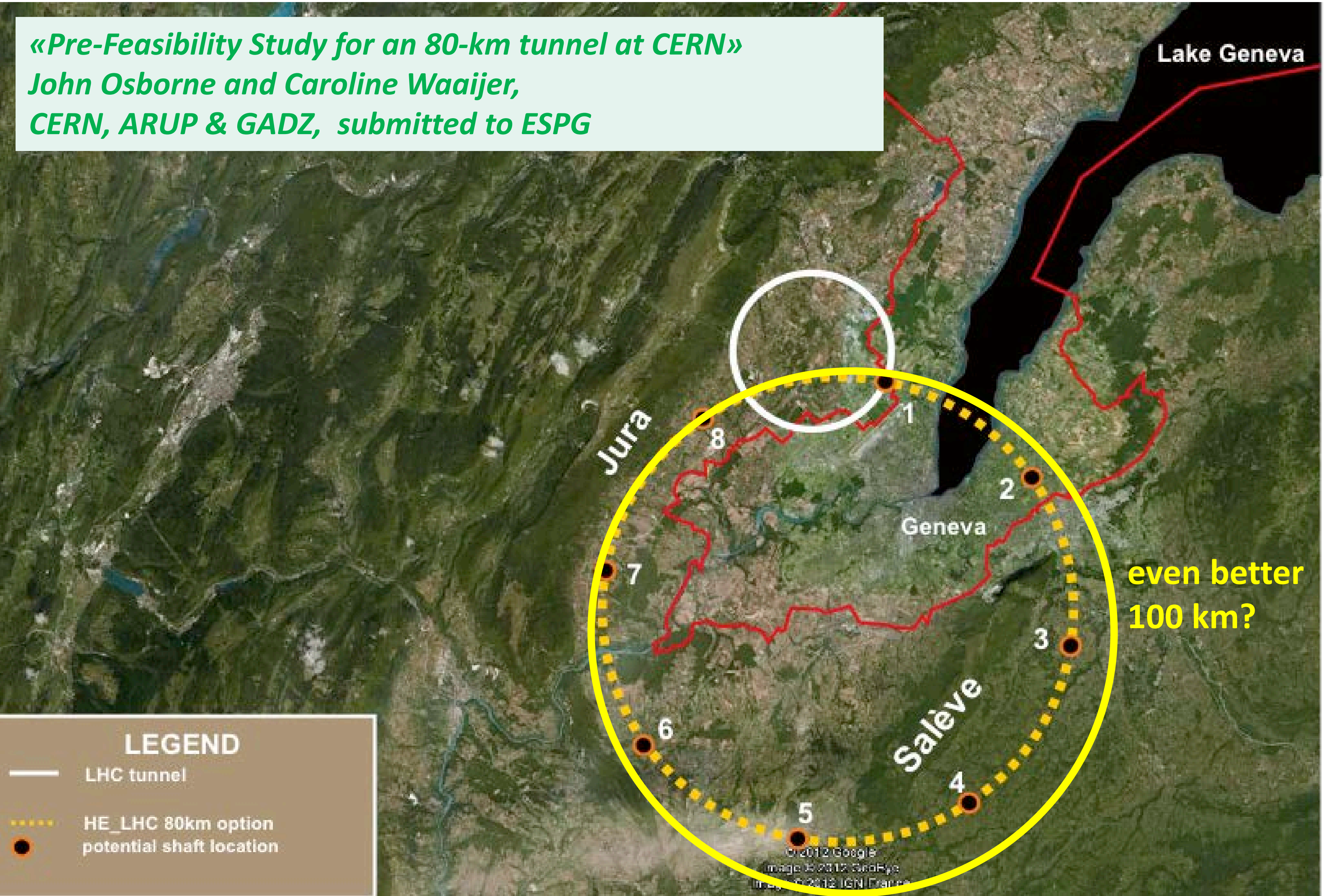
E. Todesco, L. Rossi, P.. McIntyre

VHE-LHC


VHE-LHC
VHE-LHC-LER
CMS
ALICE
LHCb
SPS+,
1.3 TeV,
North Area
TT40
TT41
TT10
ATLAS
TI2
TT60
neutrinos
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
Linac4
n-ToF
2001
neutrons
PS
1959 (628 m)
CTF3
LEIR
2005 (78 m)
LINAC 3
Ions

80-km tunnel for VHE-LHC – “best” option

«Pre-Feasibility Study for an 80-km tunnel at CERN»
John Osborne and Caroline Waaijer,
CERN, ARUP & GADZ, submitted to ESPG



HE-LHC & VHE-LHC parameters – 1

parameter	LHC	HL-LHC	HE-LHC	VHE-LHC
c.m. energy [TeV]	14	14	33	100
circumference C [km]	26.7	26.7	26.7	80
dipole field [T]	8.33	8.33	20	20
dipole coil aperture [mm]	56	56	40	≤ 40
beam half aperture [cm]	~ 2	~ 2	1.3	≤ 1.3
injection energy [TeV]	0.45	0.45	>1.0	>3.0
no. of bunches n_b	2808	2808	2808	8420
bunch population N_b [10^{11}]	1.15	2.2	0.94	0.97
init. transv. norm. emit. [μm]	3.75	2.5	1.38	2.15
initial longitudinal emit. [eVs]	2.5	2.5	3.8	13.5
no. IPs contributing to tune shift	3	2	2	2
max. total beam-beam tune shift	0.01	0.015	0.01	0.01
beam circulating current [A]	0.584	1.12	0.478	0.492
rms bunch length [cm]	7.55	7.55	7.55	7.55
IP beta function [m]	0.55	0.15 (min.)	0.35	1.1
rms IP spot size [μm]	16.7	7.1 (min.)	5.2	6.7
full crossing angle [μrad]	285	590	185	72
stored beam energy [MJ]	362	694	701	6610

O. Dominguez, L. Rossi, F.Z.

HE-LHC & VHE-LHC parameters – 2

parameter	LHC	HL-LHC	HE-LHC	VHE-LHC
SR power per ring [kW]	3.6	7.3	96.2	2900
arc SR heat load [W/m/aperture]	0.17	0.33	4.35	43.3
energy loss per turn [keV]	6.7	6.7	201	5857
critical photon energy [eV]	44	44	575	5474
photon flux [10^{17}/m/s]	1.0	2.0	1.9	2.0
longit. SR emit. damping time [h]	12.9	12.9	1.0	0.32
horiz. SR emit. damping time [h]	25.8	25.8	2.0	0.64
init. longit. IBS emit. rise time [h]	57	23.3	40	396
init. horiz. IBS emit. rise time [h]	103	10.4	20	157
peak events per crossing	27	135 (lev.)	147	171
total/inelastic cross section [mb]	111 / 85		129 / 93	153 / 108
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	5.0	5.0	5.0
beam lifetime due to burn off [h]	45	15.4	5.7	14.8
optimum run time [h]	15.2	10.2	5.8	10.7
opt. av. int. luminosity / day [fb^{-1}]	0.47	2.8	1.4	2.1

HE-LHC &VHE-LHC luminosities could greatly improve for bunch spacings < 25 ns, e.g. by factor 5 for 5 ns, and make better use of strong radiation damping!

are 5 ns spacing & 2.5x10^{35}cm^{-2}s^{-1} acceptable for detectors?

O. Dominguez, L. Rossi, F.Z.

pp Higgs factories

LHC is the 1st Higgs factory!
E_{CM}=8-14 TeV, $\widehat{L} \sim 10^{34} cm^{-2}s^{-1}$

1 M Higgs produced so far – more to come!
15 H bosons / min – and more to come

HL-LHC (~2022-2030):
E_{CM}=14 TeV, $L \sim 5x10^{34} cm^{-2}s^{-1}$ (leveled)

10x more Higgs

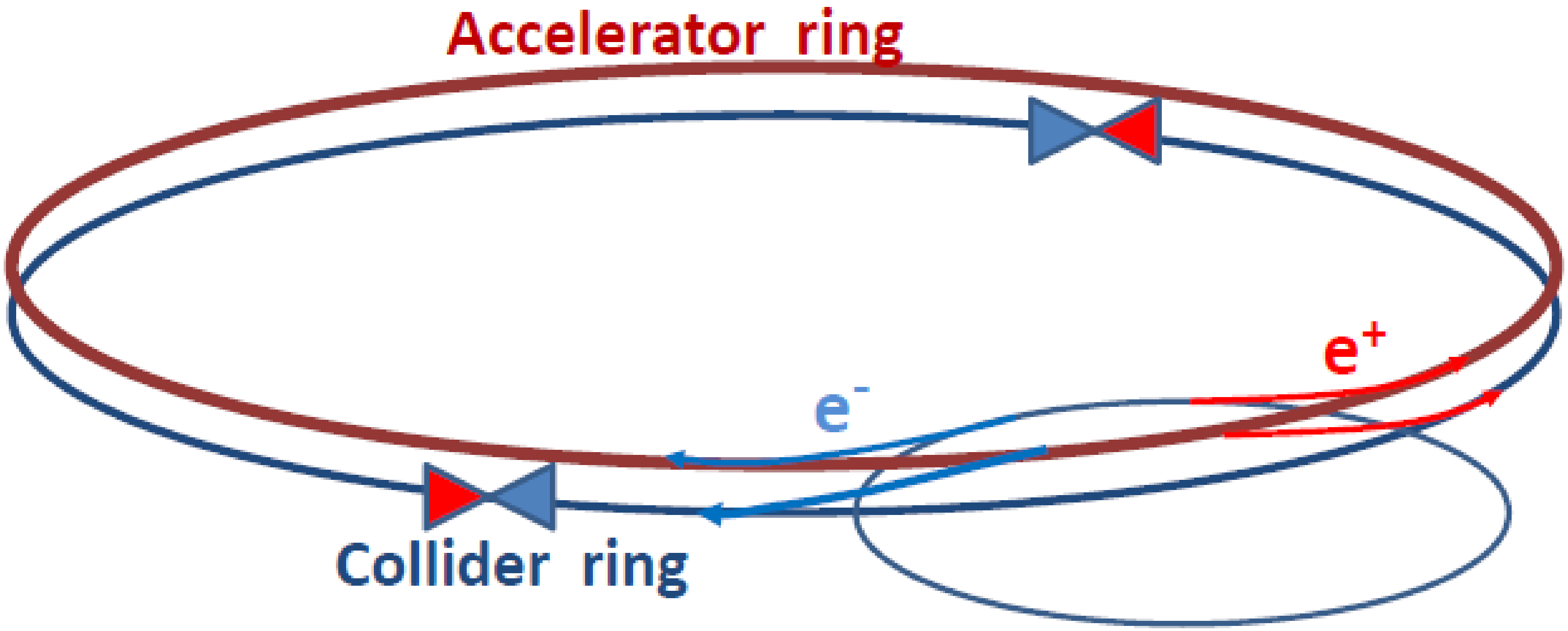
HE-LHC: in LHC tunnel (2035-?)
E_{CM}=33 TeV, $L = 5x10^{34} cm^{-2}s^{-1}$

6x higher cross section for *H* self coupling

VHE-LHC in new 80-100 km tunnel (2040?)
E_{CM}=84-104 TeV, $L = 5x10^{34} cm^{-2}s^{-1}$

42x higher cross section for *H* self coupling

circular e^+e^- colliders to study the «Higgs boson» X(126)

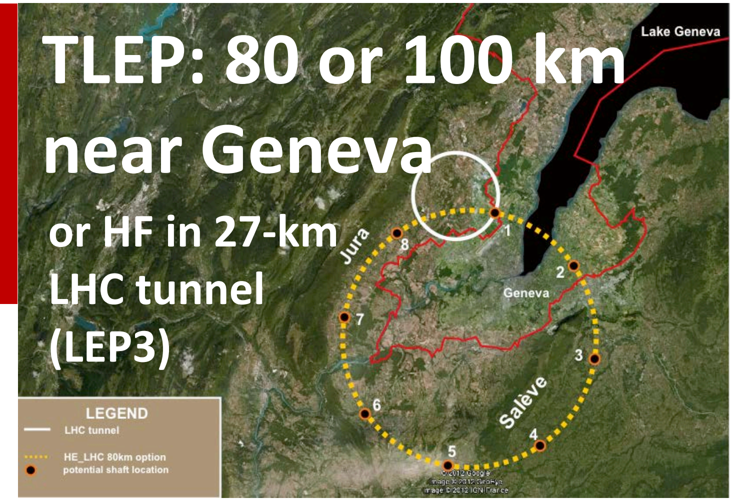


A. Blondel

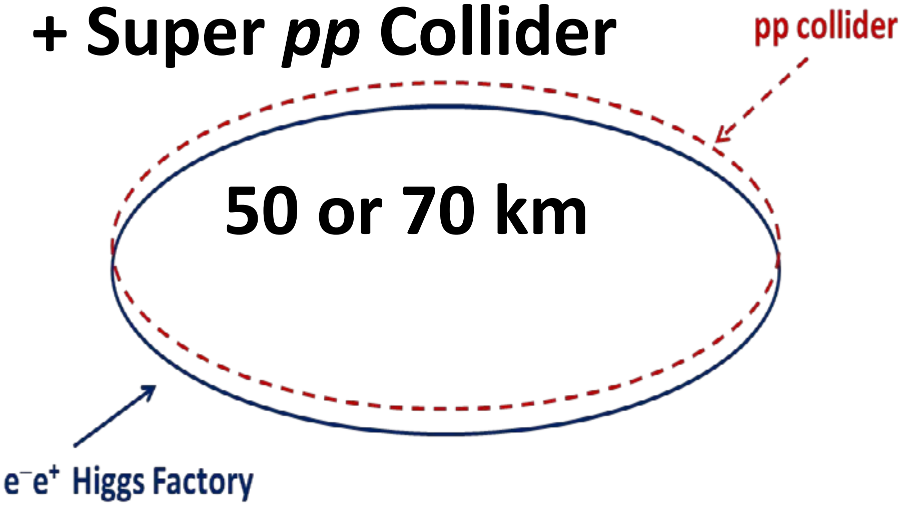
a relatively young concept (2011)

proposed circular e^+e^- Higgs factories

SLAC/LBNL design: 27 km



Chinese Higgs Factory
+ Super *pp* Collider



circular e^+e^- Higgs factories LEP3 & TLEP

option 1: installation in the LHC tunnel **"LEP3"**

+ inexpensive (only pay for new accelerator -- <~2B CHF)

+ tunnel exists

+ reusing ATLAS and CMS detectors

+ reusing LHC cryoplants

- interference with LHC and HL-LHC

option 2: in new 80 or 100-km tunnel **"TLEP"**

+ higher energy reach, 5-10x higher luminosity

+ decoupled from LHC/HL-LHC operation & construction

+ tunnel can later serve for VHE-LHC 100 TeV machine

long term vision

- more expensive because of tunnel

LEP3, TLEP

(e^+e^- -> ZH, $e^+e^- \rightarrow W^+W^-$, $e^+e^- \rightarrow Z$,[$e^+e^- \rightarrow t\bar{t}$])

key parameters

	LEP3	TLEP
circumference	26.7 km	80 km
max beam energy	120 GeV	175 GeV
max no. of IPs	4	4
Luminosity/IP at 350 GeV c.m.	-	1.3×10^{34} $cm^{-2}s^{-1}$
Luminosity/IP at 240 GeV c.m.	10^{34} $cm^{-2}s^{-1}$	4.8×10^{34} $cm^{-2}s^{-1}$
Luminosity/IP at 160 GeV c.m.	5×10^{34} $cm^{-2}s^{-1}$	1.6×10^{35} $cm^{-2}s^{-1}$
Luminosity/IP at 90 GeV c.m.	2×10^{35} $cm^{-2}s^{-1}$	$5.6\ 10^{35}$ $cm^{-2}s^{-1}$

at the *Z* pole repeat the LEP physics programme in a few minutes…

TLEP parameters – 1

	TLEP Z	TLEP W	TLEP H	TLEP t
E_{beam} [GeV]	**45**	80	120	**175**
circumf. [km]	80	80	80	80
beam current [mA]	**1180**	124	24.3	**5.4**
#bunches/beam	4400	600	80	12
#$e-$/beam [10^{12}]	1960	200	40.8	9.0
horiz. emit. [nm]	30.8	9.4	9.4	10
vert. emit. [nm]	0.07	0.02	0.02	0.01
bending rad. [km]	9.0	9.0	9.0	9.0
κ_ε	440	470	470	1000
mom. c. α_c [10^{-5}]	9.0	2.0	1.0	1.0
$P_{loss,SR}$/beam [MW]	50	50	50	50
β^*_x [m]	0.5	0.5	0.5	1
β^*_y [cm]	0.1	0.1	0.1	0.1
σ^*_x [μm]	124	78	68	100
σ^*_y [μm]	0.27	0.14	0.14	0.10

TLEP parameters – 2

	TLEP Z	**TLEP W**	**TLEP H**	**TLEP t**
hourglass F_{hg}	0.71	0.75	0.75	0.65
E^{SR}_{loss}/turn [GeV]	0.04	0.4	2.0	9.2
V_{RF},tot [GV]	2	2	6	12
$\delta_{max,RF}$ [%]	4.0	5.5	9.4	4.9
ξ_x/IP	0.07	0.10	0.10	0.10
ξ_y/IP	0.07	0.10	0.10	0.10
f_s [kHz]	1.29	0.45	0.44	0.43
E_{acc} [MV/m]	3	3	10	20
eff. RF length [m]	600	600	600	600
f_{RF} [MHz]	700	700	700	700
δ^{SR}_{rms} [%]	0.06	0.10	0.15	0.22
$\sigma^{SR}_{z,rms}$ [cm]	0.19	0.22	0.17	0.25
$\mathcal{L}$ /IP[10^{32}cm^{-2}s^{-1}]	5600	1600	480	130
number of IPs	4	4	4	4
beam lifet. [min]	**67**	**25**	**16**	**20**

circular HFs: synchroton-radiation heat load

	PEPII	SPEAR3	LEP3	TLEP-Z	TLEP-H	TLEP-t
E (GeV)	9	3	120	45.5	120	175
I (A)	3	0.5	0.0072	1.18	0.0243	0.0054
rho (m)	165	7.86	2625	9000	9000	9000
Linear Power (W/cm)	101.8	92.3	30.5	8.8	8.8	8.8

TLEP has >10 times less SR heat load per meter than PEP-II or SPEAR! (though higher photon energy)

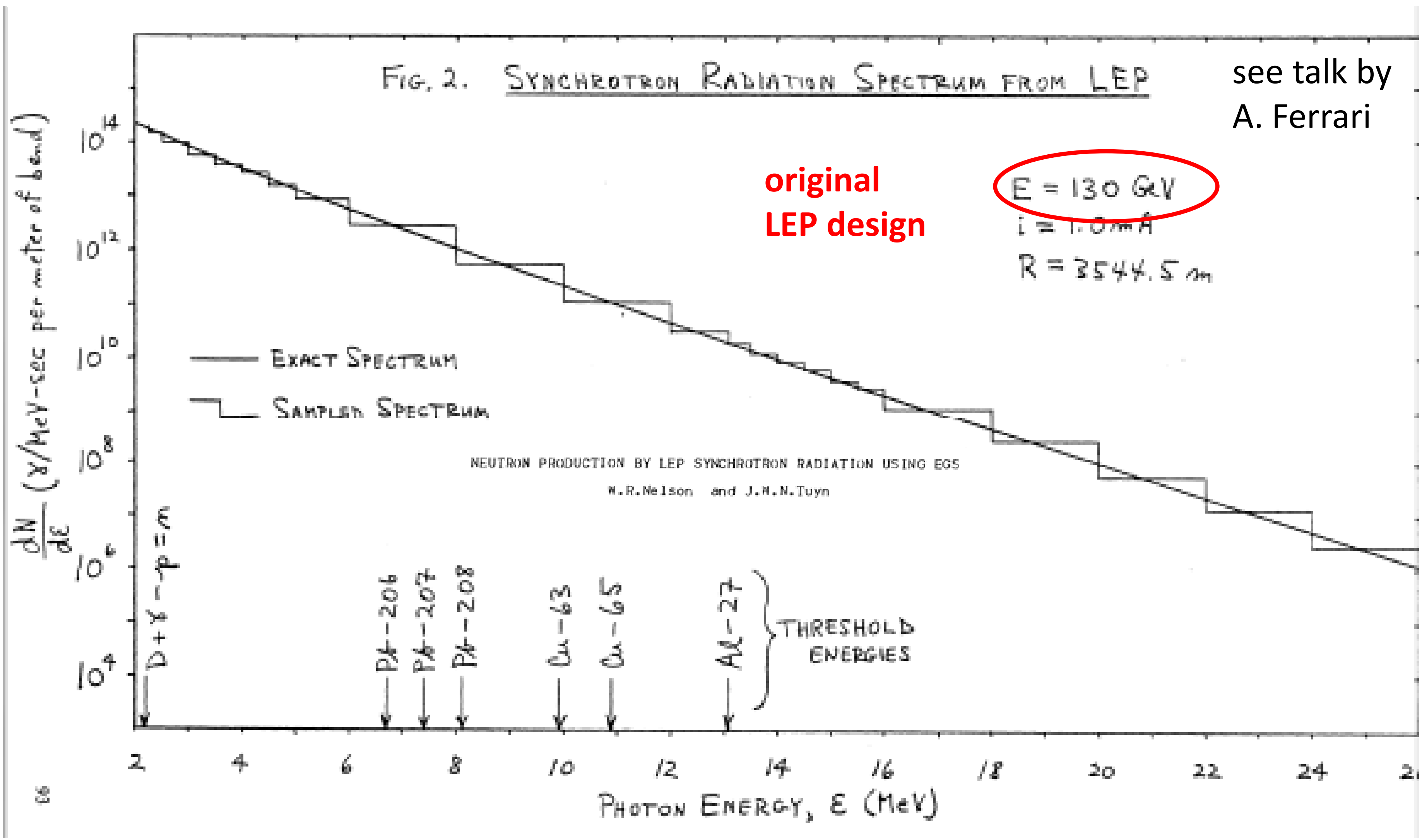
N. Kurita, U. Wienands, SLAC

synchrotron radiation - activation

NEUTRON PRODUCTION BY LEP SYNCHROTRON RADIATION USING EGS

W.R.Nelson and J.W.N.Tuyn

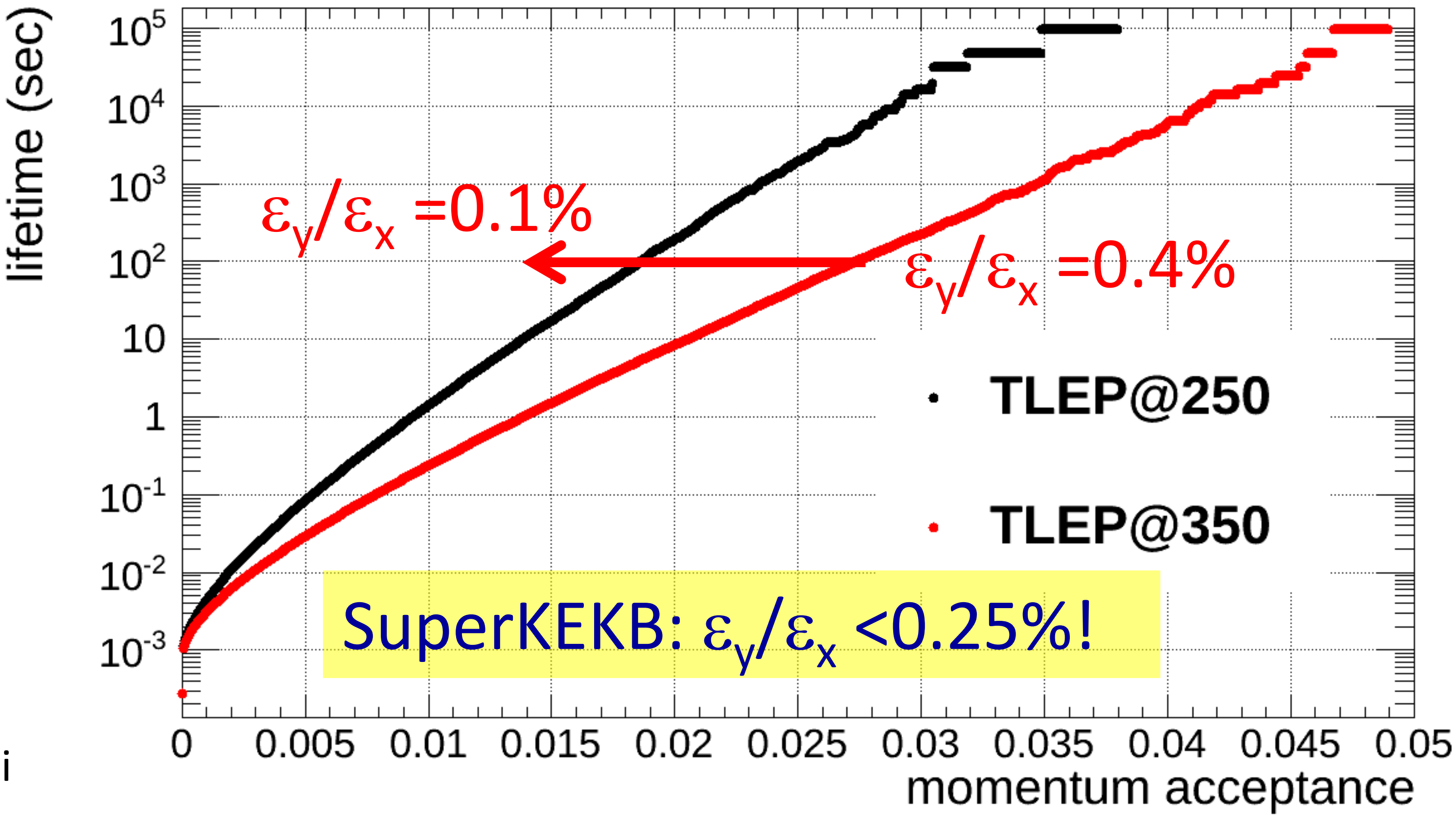
A. Fasso
3rd TLEP3 Day



beamstrahlung lifetime

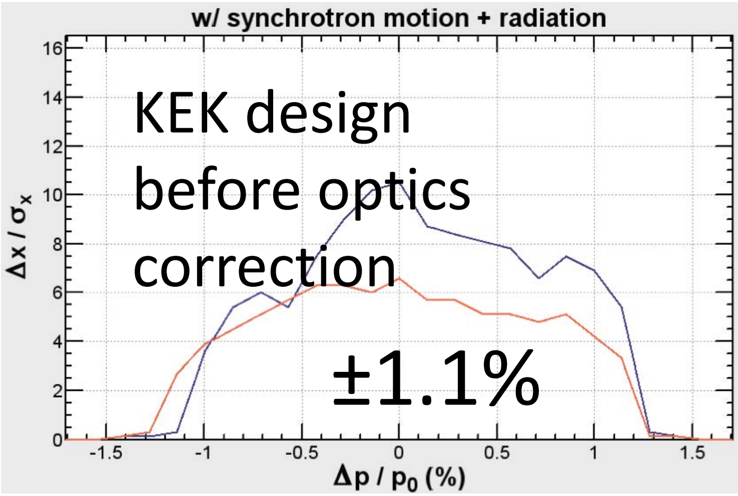
- simulation w 360M macroparticles
- τ varies exponentially w energy acceptance η
- post-collision E tail → lifetime τ

beam lifetime versus acceptance δ_{max} for 4 IPs:

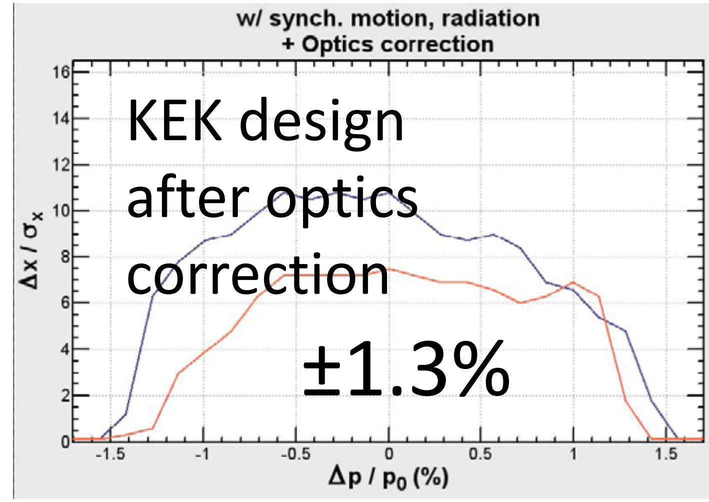


M. Zanetti

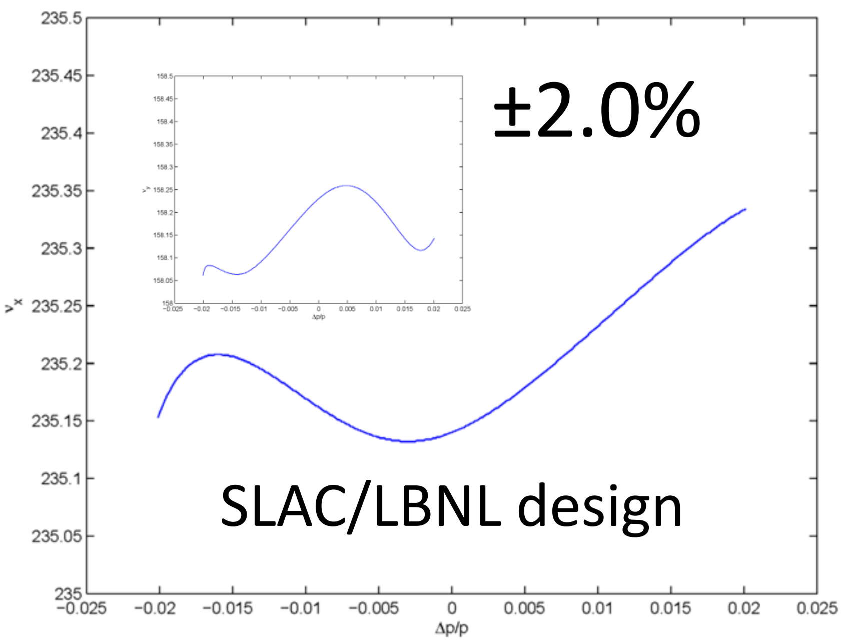
circular HFs - momentum acceptance

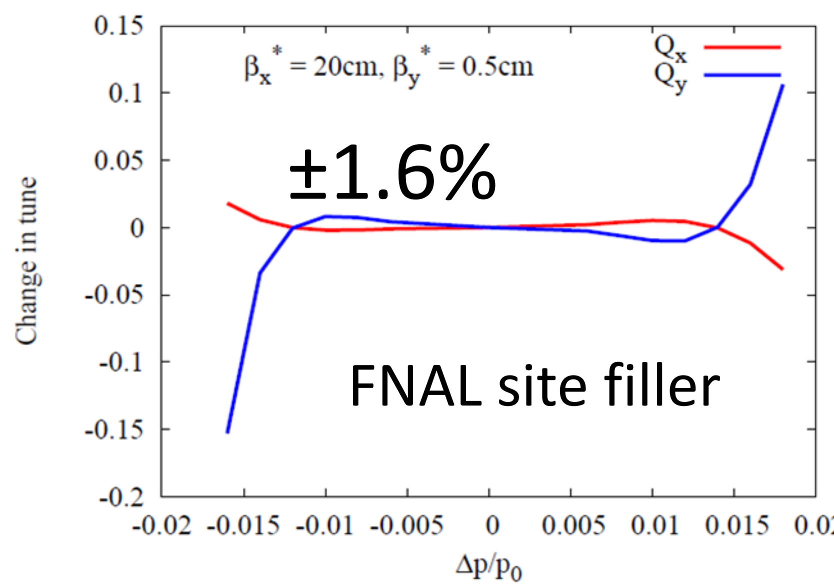


with synchrotron motion & radiation (sawtooth)



K. Oide

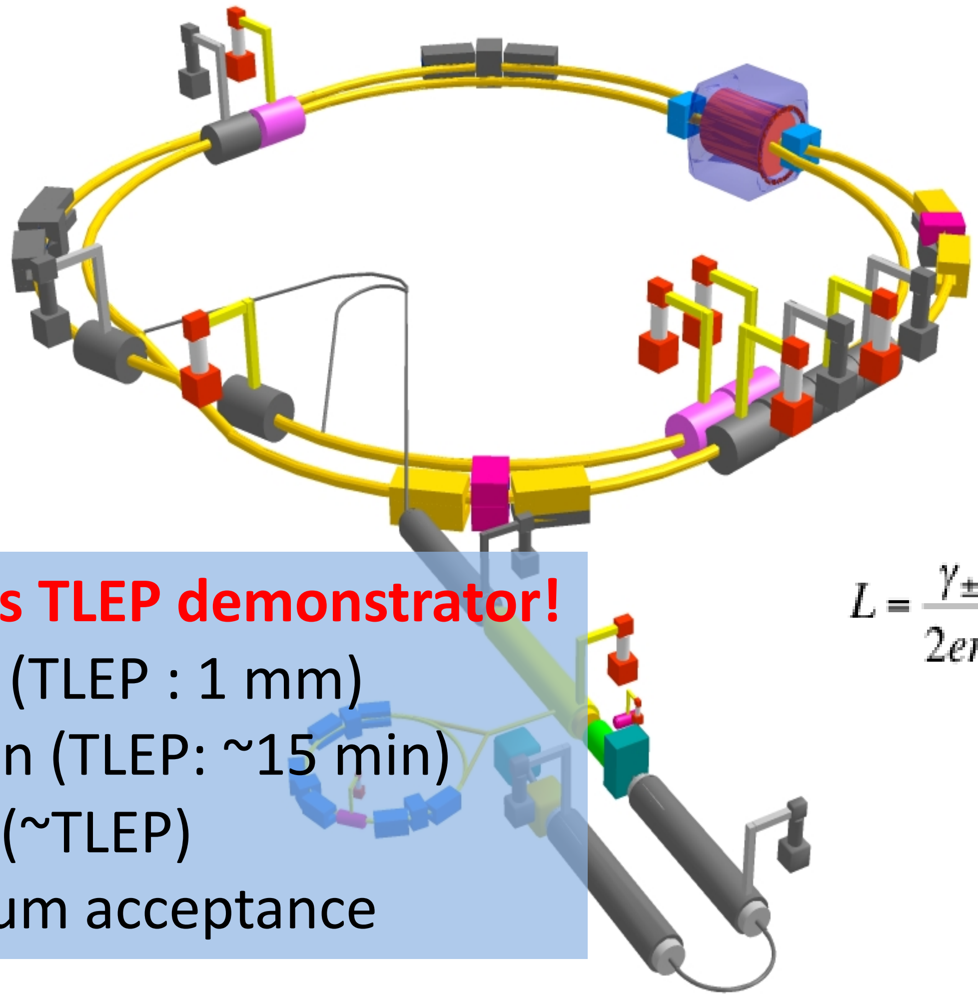




Y. Cai

T. Sen, E. Gianfelice-Wendt, Y. Alexahin

Next Collider: SuperKEKB



SuperKEKB is TLEP demonstrator!

β_y*=300 μm (TLEP : 1 mm)

lifetime 5 min (TLEP: ~15 min)

$\varepsilon_y/\varepsilon_x$=0.25% (~TLEP)

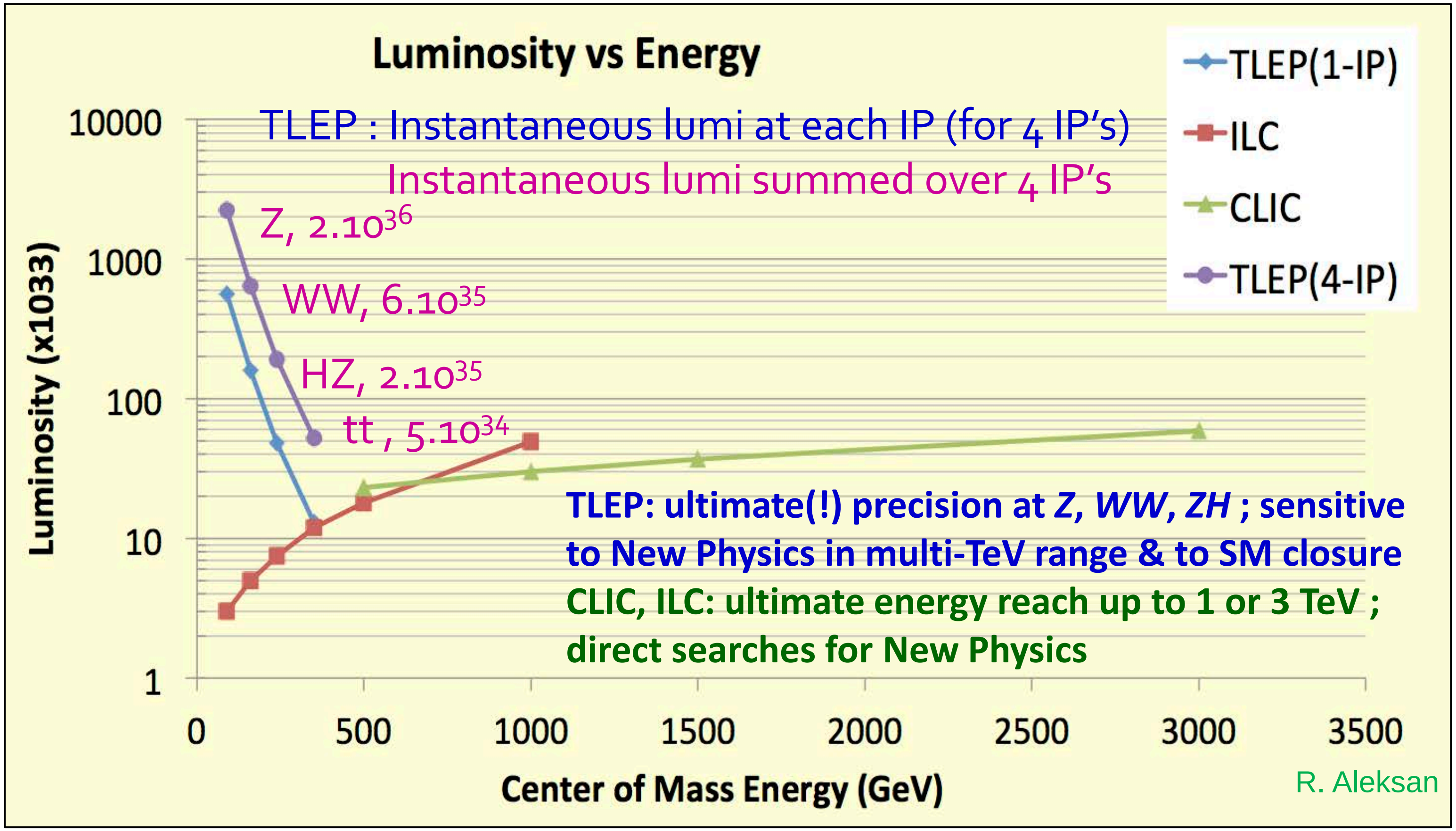
off momentum acceptance

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

beam commissioning will start early 2015

Luminosity Performance of e^+e^- colliders

Circular colliders have several IP's



- Lumi upgrade (×3) now envisioned at ILC : luminosity is key at low energy!
- Crossing point between circular and linear colliders ~ 400 GeV
- With fewer IP's expect total luminosity of facility to scale approx as $(N_{IP})^{0.5}$

Higgs factory performances

Precision on couplings, cross sections, mass, width, Summary of the ICFA HF2012 workshop (FNAL, Nov. 2012) arxiv1302:3318

Table 2.1: Expected performance on the Higgs boson couplings from the LHC and e^+e^- colliders, as compiled from the Higgs Factory 2012 workshop. Many studies are quite recent and still ongoing.

Accelerator → Physical Quantity ↓	**LHC** 300 fb^{-1} /expt	**HL-LHC** 3000 fb^{-1} /expt	**ILC** 250 GeV 250 fb^{-1} 5 yrs	**Full ILC** 250+350+ 1000 GeV 5yrs each	**CLIC** 350 GeV (500 fb^{-1}) 1.4 TeV (1.5 ab^{-1}) 5 yrs each	**LEP3, 4 IP** 240 GeV 2 ab^{-1} (*) 5 yrs	**TLEP, 4 IP** 240 GeV 10 ab^{-1} 5 yrs (*) 350 GeV 1.4 ab^{-1} 5 yrs (*)
N_H	1.7×10^7	1.7×10^8	6×10^4 ZH	10^5 ZH 1.4×10^5 Hνν	7.5×10^4 ZH 4.7×10^5 Hνν	4×10^5 ZH	2×10^6 ZH 3.5×10^4 Hνν
m_H (MeV)	100	50	35	35	100	26	7
$\Delta\Gamma_H / \Gamma_H$	--	--	10%	3%	ongoing	4%	1.3%
$\Delta\Gamma_{inv} / \Gamma_H$	Indirect (30%?)	Indirect (10% ?)	1.5%	1.0%	ongoing	0.35%	0.15%
$\Delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$	6.5 – 5.1%	5.4 – 1.5%	--	5%	ongoing	3.4%	1.4%
$\Delta g_{Hgg} / g_{Hgg}$	11 – 5.7%	7.5 – 2.7%	4.5%	2.5%	< 3%	2.2%	0.7%
$\Delta g_{Hww} / g_{Hww}$	5.7 – 2.7%	4.5 – 1.0%	4.3%	1%	~1%	1.5%	0.25%
$\Delta g_{HZZ} / g_{HZZ}$	5.7 – 2.7%	4.5 – 1.0%	1.3%	1.5%	~1%	0.65%	0.2%
$\Delta g_{HHH} / g_{HHH}$	--	< 30% (2 expts)	--	~30%	~22% (~11% at 3 TeV)	--	--
$\Delta g_{H\mu\mu} / g_{H\mu\mu}$	< 30%	< 10%	--	--	10%	14%	7%
$\Delta g_{H\tau\tau} / g_{H\tau\tau}$	8.5 – 5.1%	5.4 – 2.0%	3.5%	2.5%	≤ 3%	1.5%	0.4%
$\Delta g_{Hcc} / g_{Hcc}$	--	--	3.7%	2%	2%	2.0%	0.65%
$\Delta g_{Hbb} / g_{Hbb}$	15 – 6.9%	11 —2.7%	1.4%	1%	1%	0.7%	0.22%
$\Delta g_{Htt} / g_{Htt}$	14 – 8.7%	8.0 – 3.9%	--	5%	3%	--	30%

(*) The total luminosity is the sum of the integrated luminosity a

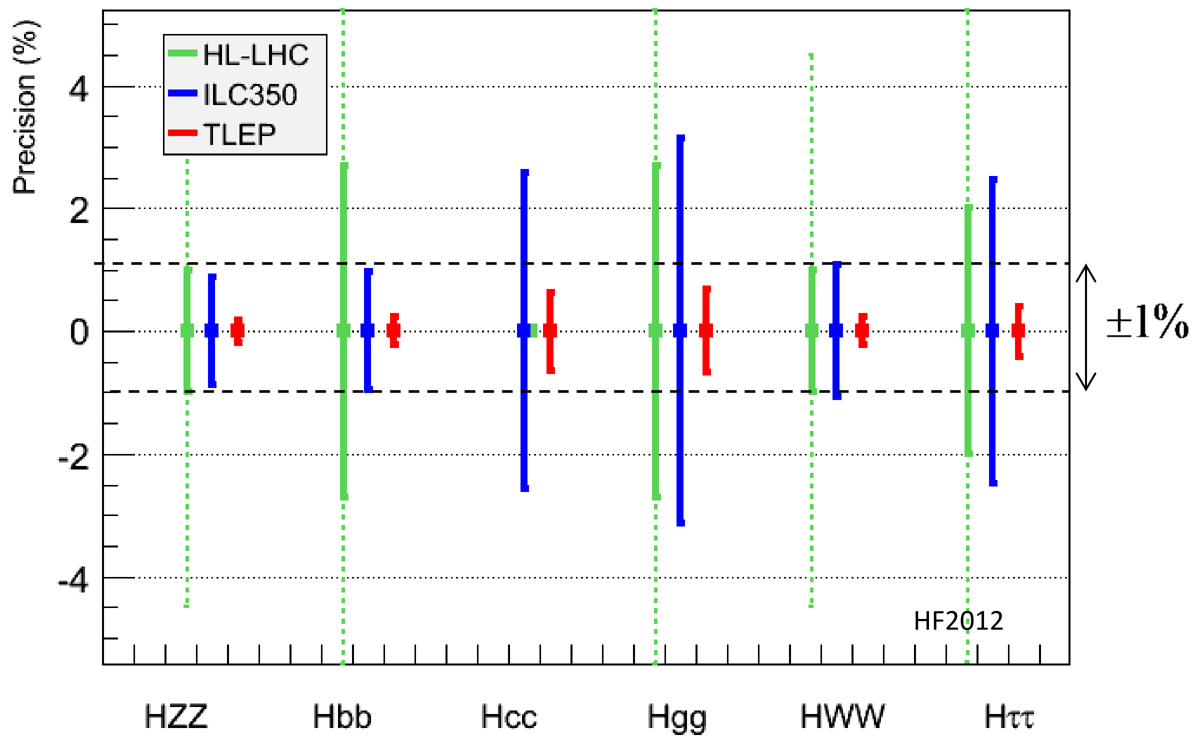
Circular Higgs Factory really goes to precision at few permil level.

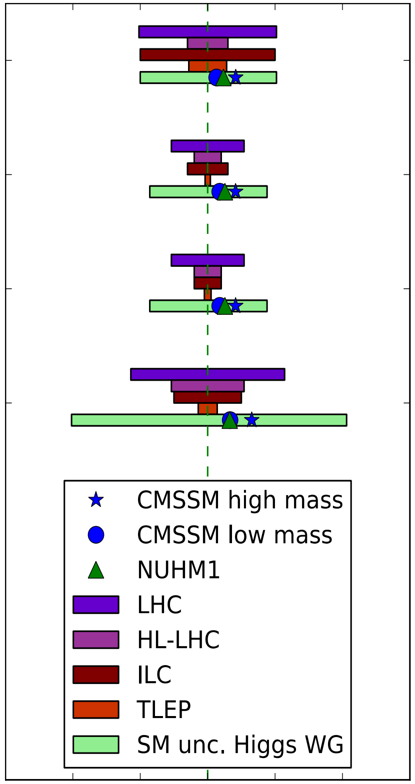
see talk by A. Blondel

Performance Comparison

Need sub-percent precision for sensitivity to multi-TeV New Physics

– Compare (LHC), HL-LHC, ILC, TLEP





J. Ellis et al.

- **TLEP reaches the needed sub-percent accuracy**
- **much theoretical work also needed**

P. Janot

see talk by A. Blondel

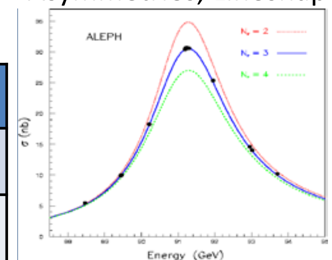
see talk by A. Blondel

TLEP TeraZ, Oku-W & Mega-Top

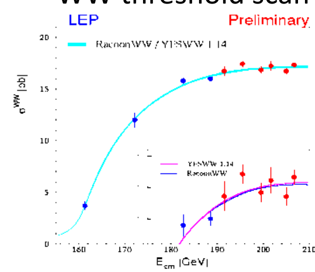
- Precision tests of EWSB

	LEP	ILC	TLEP
$\sqrt{s} \sim m_Z$	Mega-Z	Giga-Z	Tera-Z
#Z / year Polarization Precision vs LEP1 Error on m_Z, Γ_Z	2×10^7 Yes (T) 1 2 MeV	Few 10^9 Easy 1/5 to 1/10 –	10^{12} (>10^{11} b,c,τ) Yes (T,L) ~1/100 < 0.1 MeV
$\sqrt{s} \sim 2m_W$			
#W pairs / year Polarization Error on m_W	Few dozens No 220 MeV	2×10^5 Easy 7 MeV	2.5×10^7 Yes (T) 0.5 MeV
$\sqrt{s}$ = 240 GeV			Oku-W
# W pairs / 5 years Error on m_W	4×10^4 33 MeV	4×10^6 3 MeV	2×10^8 0.5 MeV
$\sqrt{s} \sim$ 350 GeV			Mega-Top
# top pairs / 5 years Error on m_{top} Error on λ_t	– – –	100,000 30 MeV 40%	500,000 13 MeV 15%

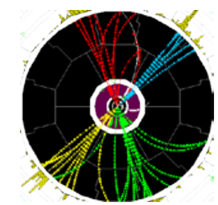
Asymmetries, Lineshape



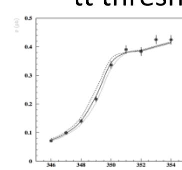
WW threshold scan

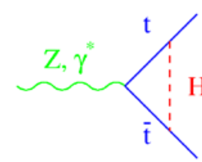


WW production



$t\bar{t}$ threshold scan





TLEP : Repeat the LEP1 physics programme every 15 min

Transverse polarization up to the WW threshold

➢ Exquisite beam energy determination (10 keV)\

Longitudinal polarization at the Z pole

➢ Measure $\sin^2\theta_W$ to 2.10^{-6} from A_{LR}

– measure m_Z, Γ_Z to < 0.1 MeV, m_W to < 1 MeV, $\sin^2\theta_W$ to 2.10^{-6} from A_{LR}

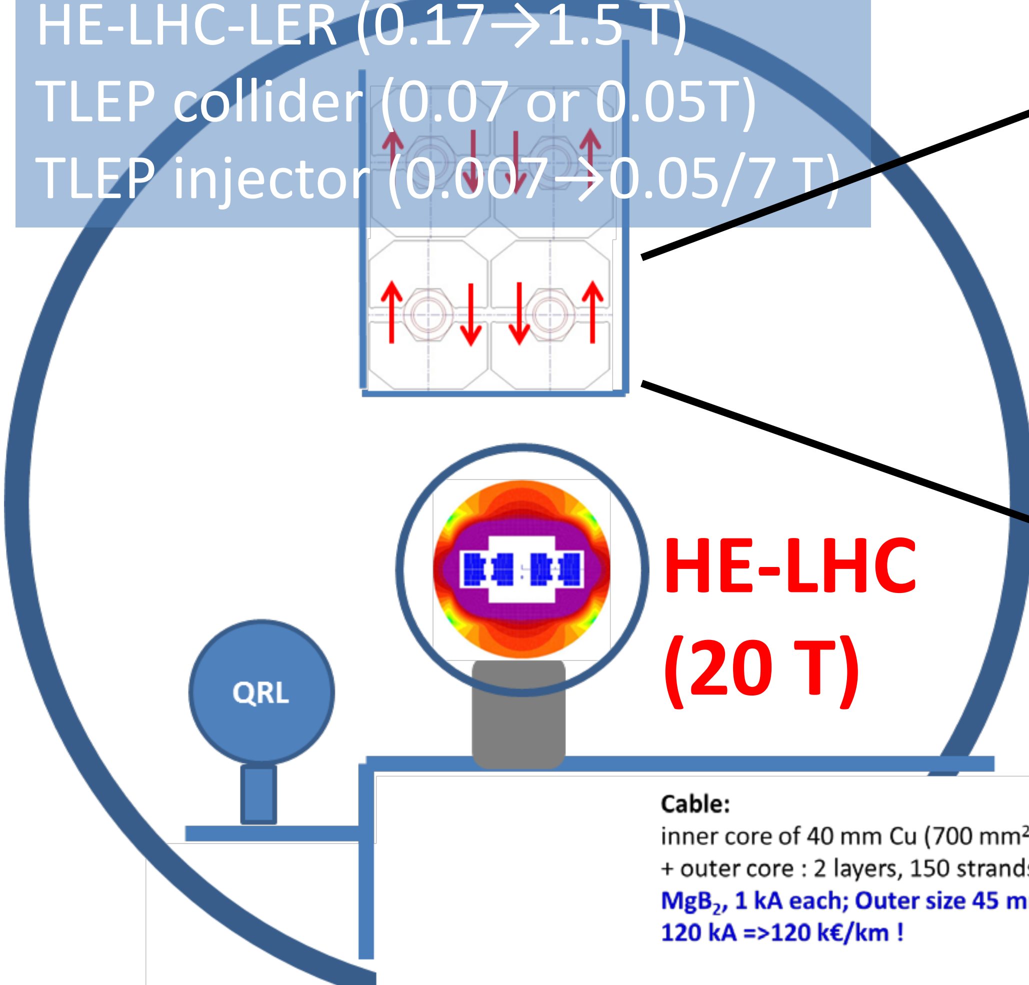
– TLEP beam polarization up to *W* threshold, for energy calibration

P. Janot

VHE-LHC + TLEP

L. Rossi

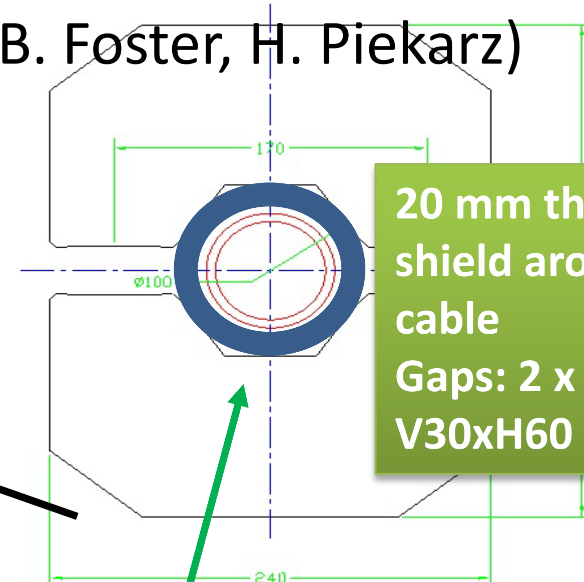
HE-LHC-LER (0.17→1.5 T)
TLEP collider (0.07 or 0.05T)
TLEP injector (0.007→0.05/7 T)



HE-LHC (20 T)

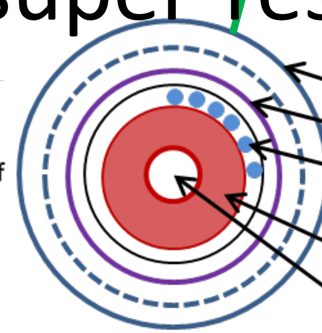
multipurpose tunnel

transmission line magnet (B. Foster, H. Piekarz)



20 mm thick shield around cable
Gaps: 2 x V30xH60 mm

super-resistive cable



Cryostat : 60 mm
He envelope : 50 mm
SC part: 2 layers MgB_2 (Bi2212)150x∅1mm
Cu inner core 40 mm
Cooling hole: 10 mm

Cable:
inner core of 40 mm Cu (700 mm²)
+ outer core : 2 layers, 150 strands of **MgB_2, 1 kA each; Outer size 45 mm.**
120 kA =>120 k€/km !

For electrons: Cu water cooled, J_{ov} 2.5 A/mm²

For protons: 800 A/strands
120 kA (for >2.1 T); central copper acts as stabilizer

based on *MgB_2* SC
only 12 MEuro/100 km!

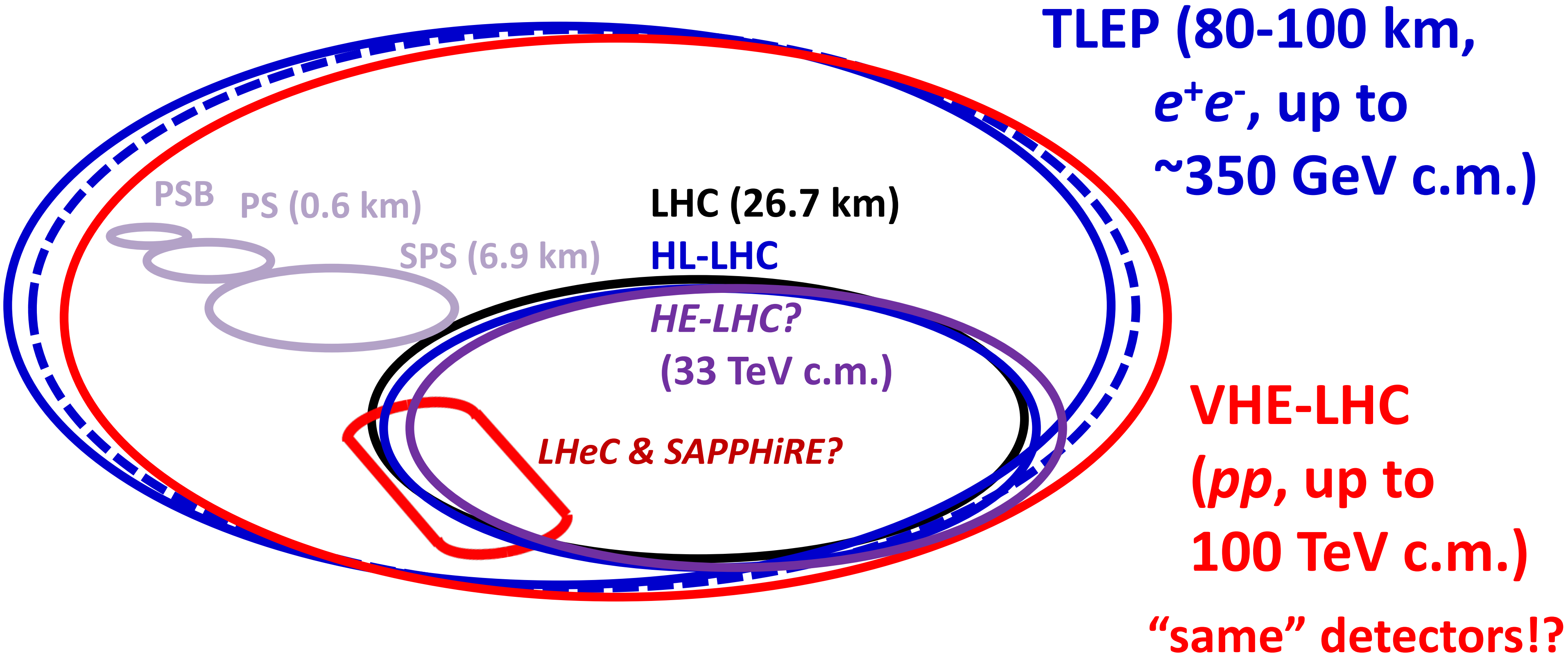
conclusions - LHC

- LHC **running well & predictably**; 2 years 3 months from 1st collisions to Higgs; foundations for run II
- **in 2015** LHC will operate **close to design energy** with peak **luminosity likely to exceed the design**
- **new performance limits** will be encountered (e.g. triplet cooling limit)
- **baseline for 2015 is 25 ns**, but uncertainties with regard to e-cloud and UFOs; **backup option: 50 ns** with leveling (pile up)
- **plans & schedules for injection upgrade and longer shutdowns** till~2022 to be **reviewed this fall**

conclusions – HL-LHC & beyond

- **well defined, key prototypes successfully tested**
- **plan & goals for HL-LHC under review**
  - budget considerations & LHC results
- HL-LHC develops the **technology** (Nb_3Sn magnets, 20-kA *HTS* cables) **for future higher energy *pp* colliders**: HE-LHC (33 TeV c.m.) and/or VHE-LHC (100 TeV c.m.)
- **TLEP**, in VHE-LHC tunnel, being studied as **highest-luminosity e^+e^- Higgs factory**
  - excellent energy resolution, & superb performance at *Z* pole , *W* & top threshold
- intermediate Higgs factories: **LHeC & SAPPHiRE**

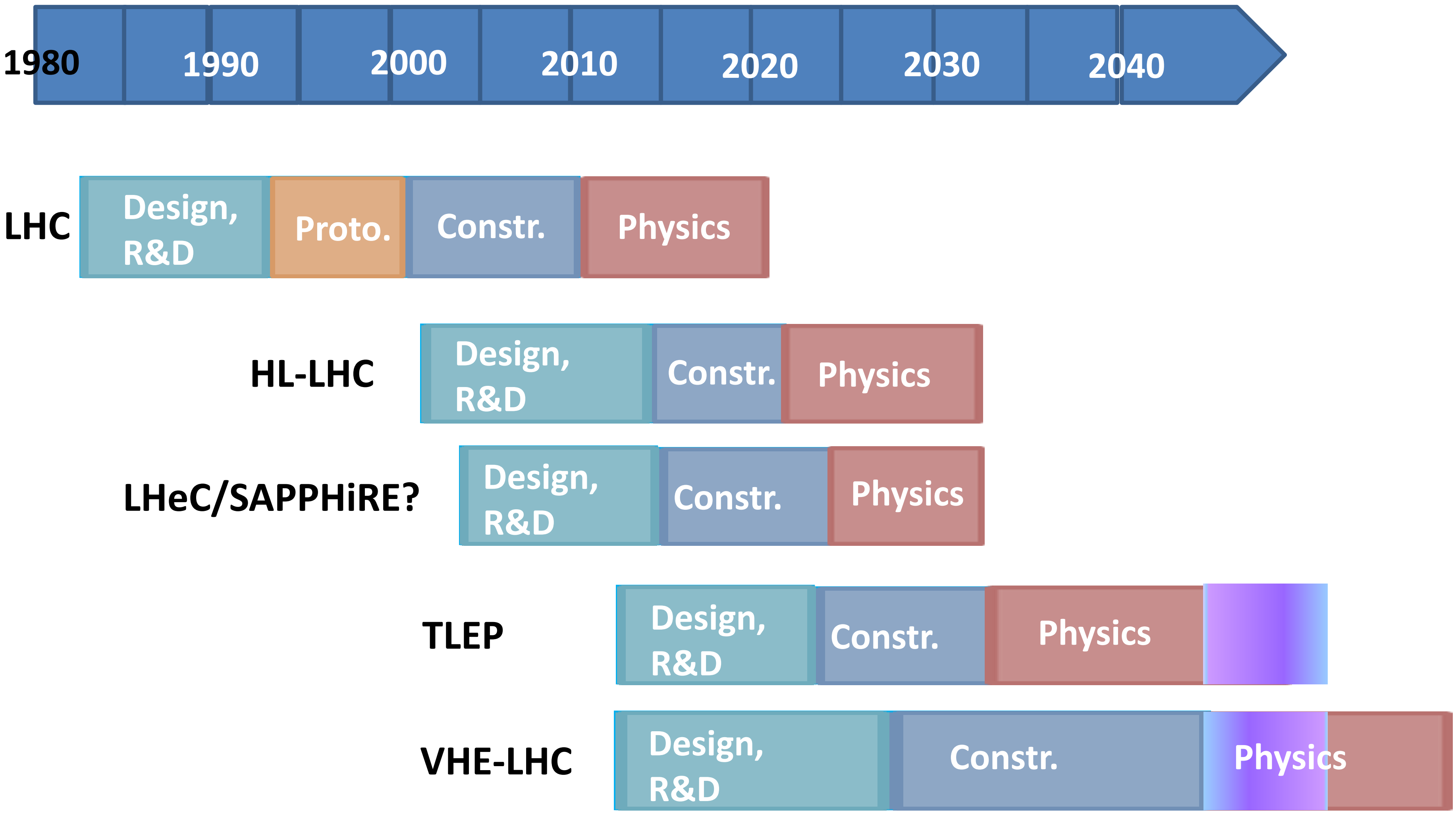
possible long-term strategy



& $e^{\pm}$ (120 GeV)–*p* (7, 16 & 50 TeV) collisions **([(V)HE-]TLHeC)**

≥50 years of e^+e^-, *pp*, *ep/A* physics at highest energies

possible long-term time line



(incidentally, the only appearance of a Roman in the history of mathematics)

"NOLI TURBARE CIRCULOS MEOS!"

Archimedes of Syracuse, 287 – 212 BC

thank you for listening!