HE-LHC parameters, constraints and key challenges

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for the FCC collaboration

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http://cern.ch/fcc

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HE-LHC design goals & basic choices

physics goals:

- 2x LHC collision energy with FCC-hh magnet technology
- c.m. energy = 27 TeV ~ 14 TeV x 16 T/8.33T
- target luminosity ≥ 10 ab^{-1} over 20 years

key technologies:

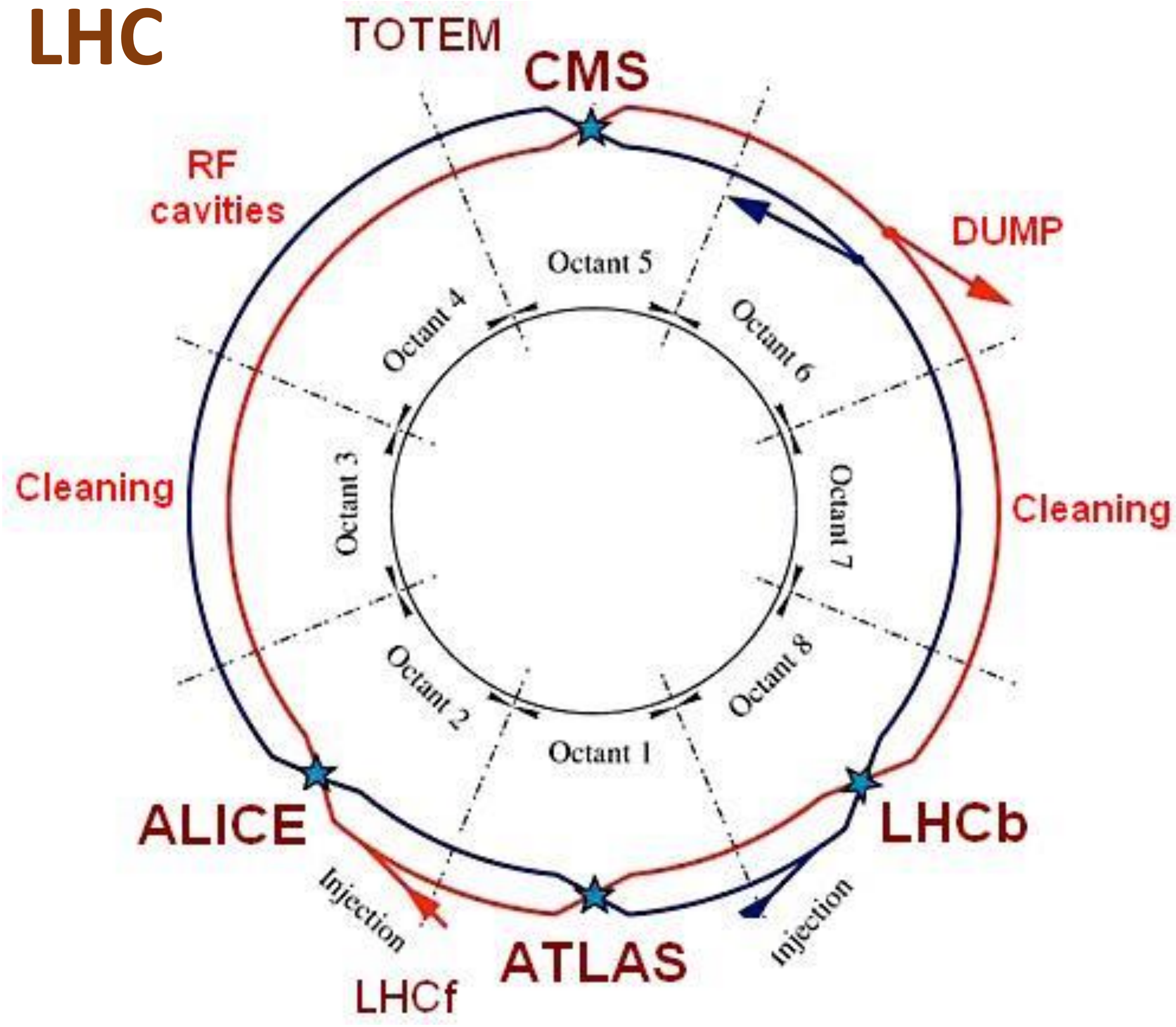
- FCC-hh magnets & FCC-hh vacuum system
- HL-LHC crab cavities & long-range wire compensation & leveling?

beam:

- HL-LHC/LIU parameters (25 ns baseline)

HE-LHC layout like LHC

LHC



8 interaction regions (IRs)

2 high-luminosity experiments in IR1 & 5

2 secondary experiments (perhaps including one e-p collision point) in IRs 2 & 8, shared with injection

IR3: momentum collimation

IR4: radiofrequency (RF) and diagnostics

IR6: beam extraction

IR7: betatron collimation

hadron collider parameters

parameter	FCC-hh		**HE-LHC**	HL-LHC	LHC
collision energy cms [TeV]	100		**27**	14	14
dipole field [T]	16		**16**	8.33	8.33
circumference [km]	97.75		**26.7**	26.7	26.7
beam current [A]	0.5		**1.1**	1.1	0.58
bunch intensity $[10^{11}]$	1	1	**2.2**	2.2	1.15
bunch spacing [ns]	25	25	**25**	25	25
synchr. rad. power / ring [kW]	2400		**101**	7.3	3.6
SR power / length [W/m/ap.]	28.4		**4.6**	0.33	0.17
long. emit. damping time [h]	0.54		**1.8**	12.9	12.9
beta* [m]	1.1	0.3	**0.25**	0.15 (min.)	0.55 (0.25)
normalized emittance [μm]	2.2		**2.5**	2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	**28**	5 (lev.)	1
events/bunch crossing	170	1000	**800**	132	27
stored energy/beam [GJ]	8.4		**1.3**	0.7	0.36

HE-LHC: topics requiring special attention

many aspects extrapolated/copied from HL-LHC or FCC-hh. most important exceptions:

tunnel integration and magnet technology

- push for **compact 16 T** magnets (magnetic cryostat, shielding) (LHC tunnel 3.8 m vs. FCC-hh 5.5 m)
- **HE-LHC Nb_3Sn magnets must be bent** - 9 mm horizontal orbit shift over 14 m (vs. 2 mm for FCC-hh)

arc optics

- high **dipole filling factor** to reach energy target, or strong focusing for lower energy injection
- acceptable **strength of quadrupoles and sextupoles**
- **dynamic aperture, beam size, apertures at injection**

straights

- low-beta insertions, **longer triplet than HL-LHC, β^* reach**
- collimation insertions, **LHC or FCC-hh optics scaling not applicable**, warm dipole length increase
- extraction straights – **length of kicker & septum sections**

injector and injection energy

- **physical & dynamic aperture, impedance and beam stability, swing of 16 T magnets…**

M. Benedikt

arc optics: two strategies

M. Hofer, J. Keintzel, R. Tomas,
Y. Nosochkov, T. Risselada, D. Zhou

highest energy reach = lowest dipole field (fewer longer cells)

lowest injection energy (more shorter cells, "LHC-like")

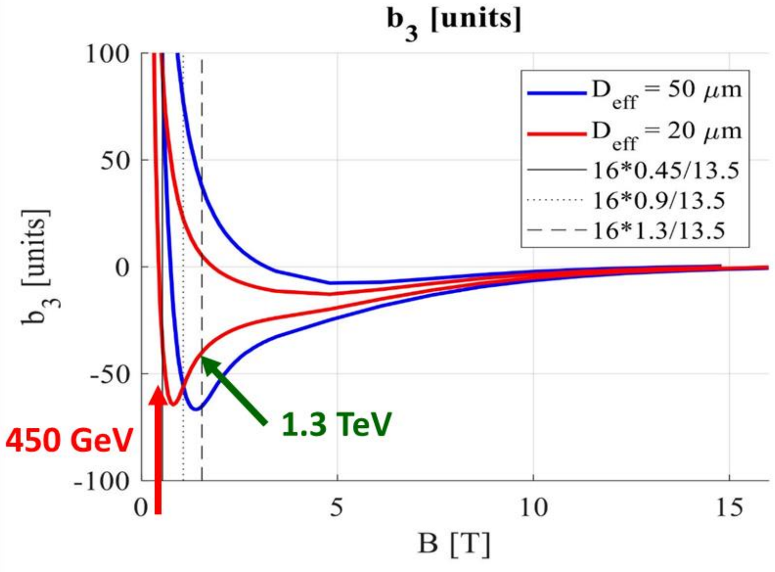
HE-LHC arc optics	18x90*	23x90**
arc cell length [m]	137.23	106.9
dipole length [m]	13.95 (x4/h-c)	13.83 (x3/h-c)
β_{max} [m]	**230**	**177**
D_{max} [m]	**3.6**	**2.2**
mom. comp. α_C [10^{-4}]	5.8	3.5
dipole filling factor	0.81	0.78
dipole field for 13.5 TeV [T]	**15.83**	**16.59**
c.o.m. energy for 16 T [TeV]	**27.28**	**26.01**

injector options & dynamic aperture

1. inject from present SPS at 450 GeV

concerns:

- **physical aperture** (~1/2-2/3 of LHC), machine protection,…
- energy swing (**field quality** at low energy)
- **instabilities**



alternatives:

2. new fast ramping SC SPS with single-layer SC dipole (scSPS), max. field 4 T → extract at 900 GeV

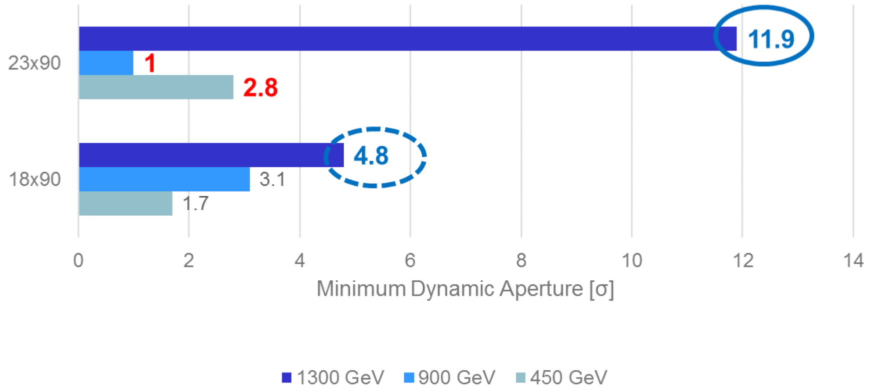
3. scSPS with double-layer SC dipole, max. field 6 T → extract at 1.3 TeV

downsides: large energy swing in scSPS,

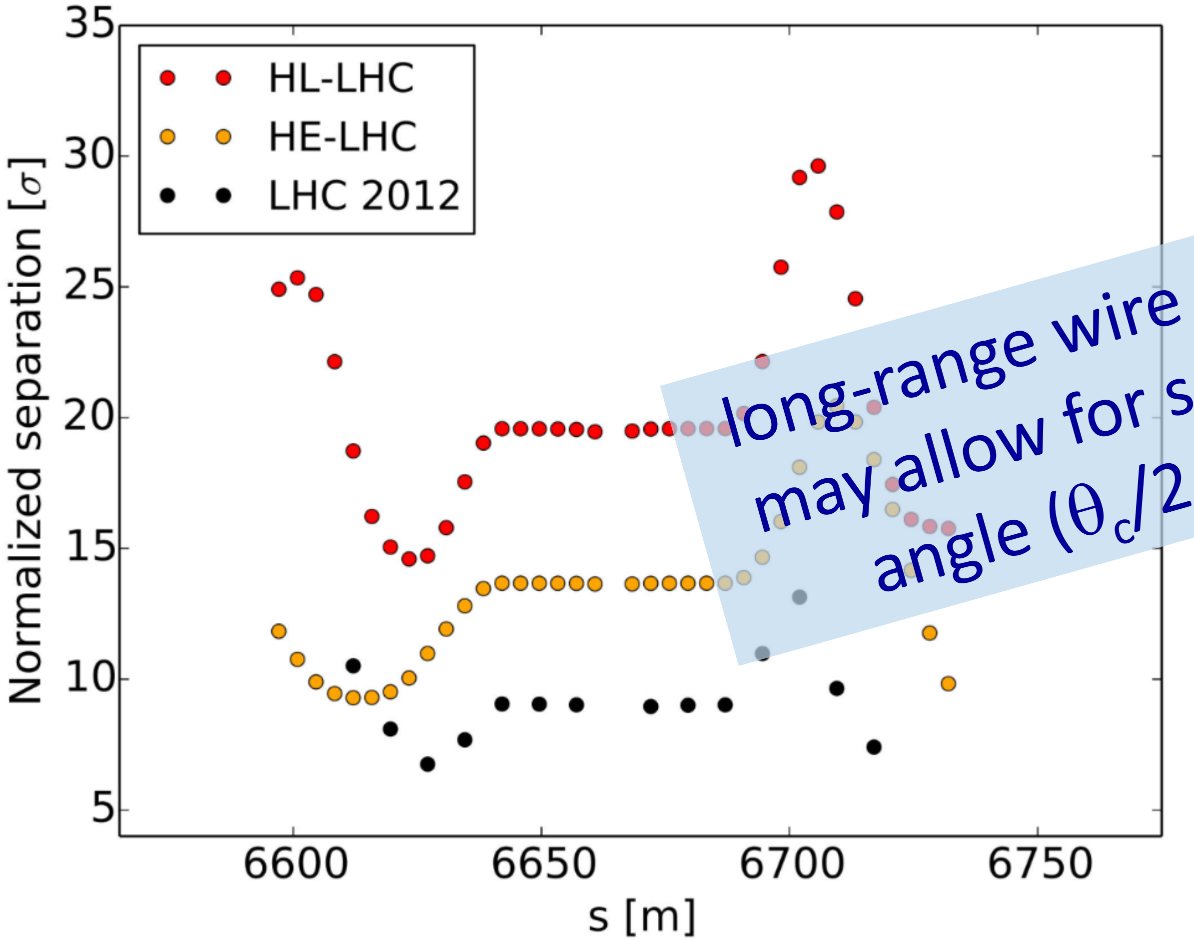
also new transfer-line magnets from scSPS to HE-LHC

dynamic aperture [σ]
w. corrected b3, b4, b5

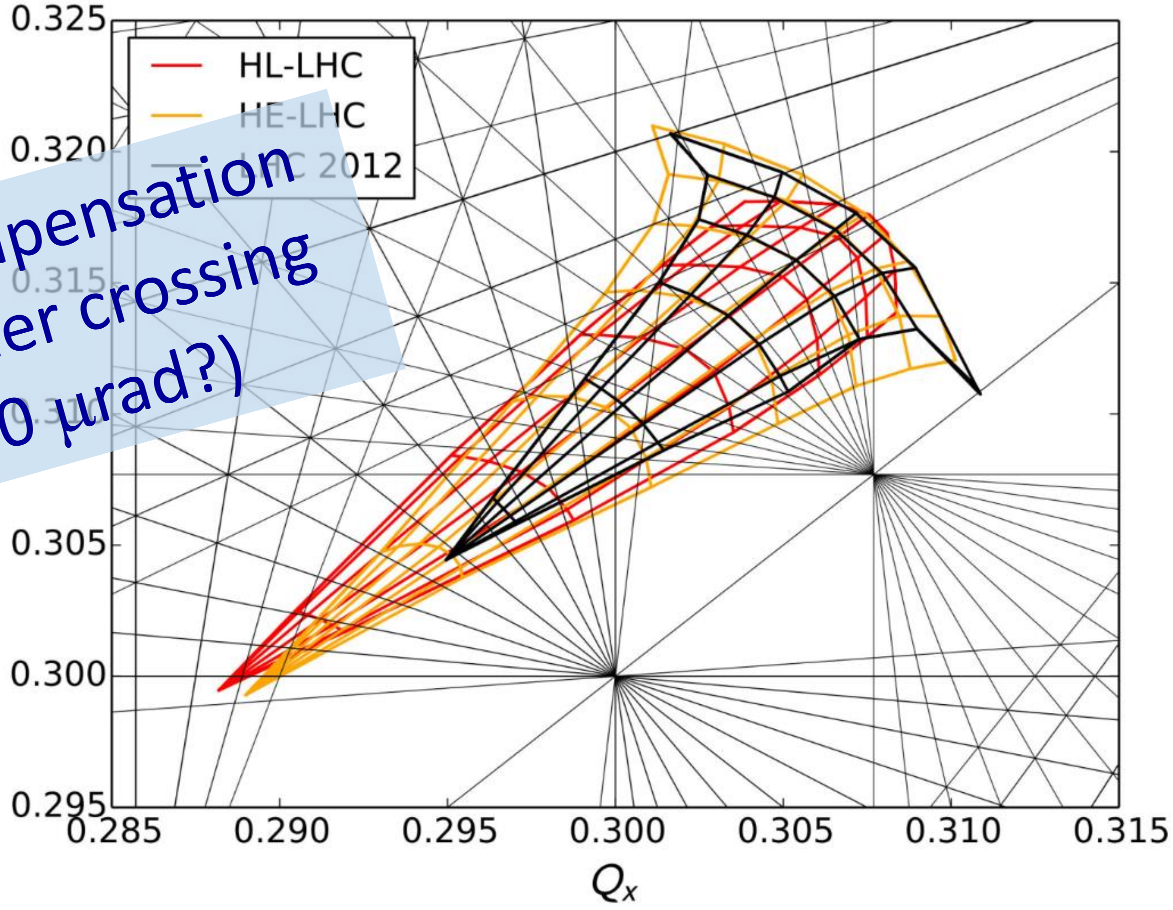
10^5 turns, 60 seeds,
$\Delta p/p=7.5\mathrm{x}10^{-4}$



long-range & head-on beam-beam



Separation at long-range encounters for the HE-LHC with 180 µrad half crossing angle, compared with the HL-LHC and the LHC configuration of 2012.

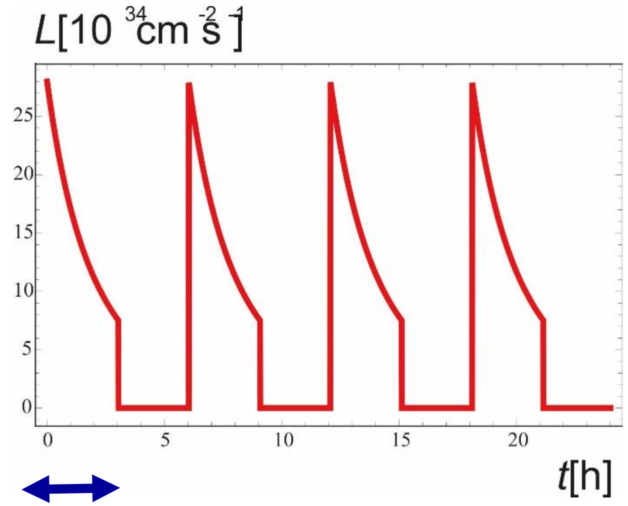


Beam-beam tune footprint up to 6σ in transverse amplitude for HE-LHC with 180 µrad half crossing angle, compared with HL-LHC and 2012 LHC configuration.

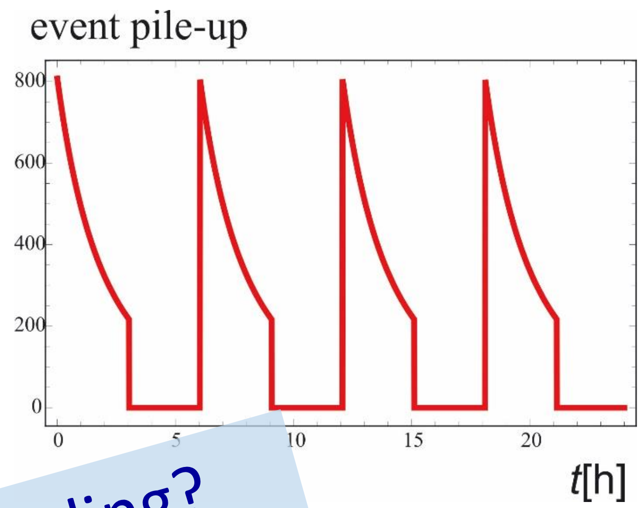
long-range wire compensation may allow for smaller crossing angle ($\theta_c/2 \sim 130$ µrad?)

T. Pieloni, C. Tambasco

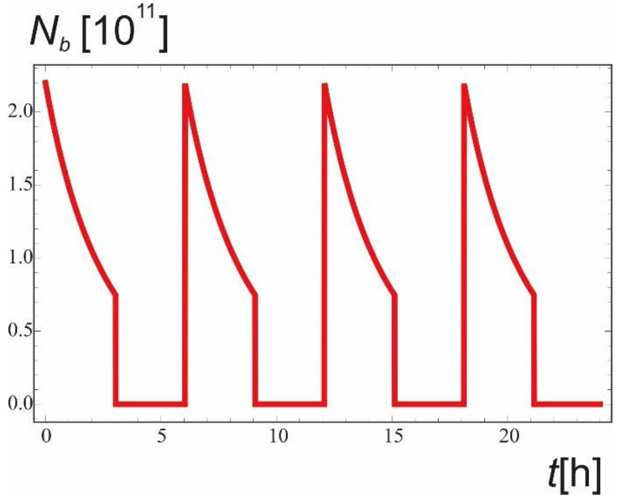
24 hours at the HE-LHC

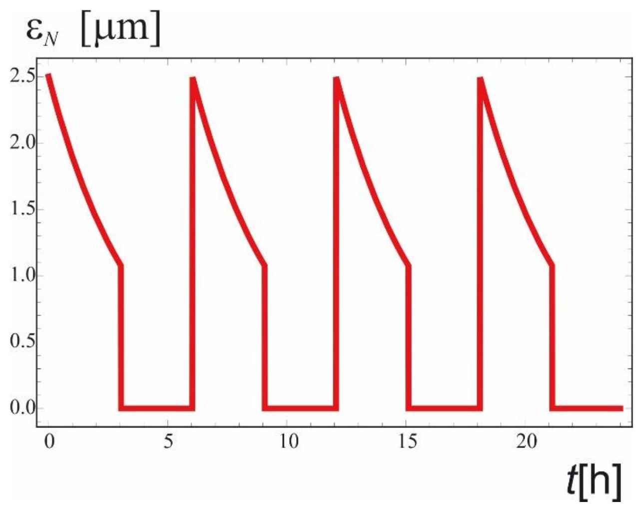


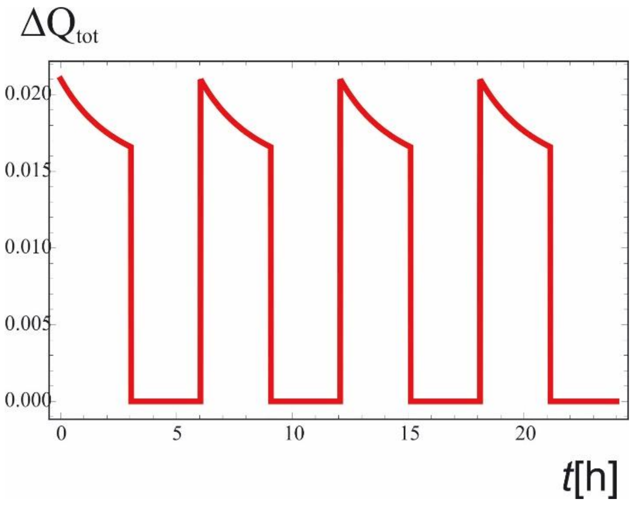
optimum fill length ∼3 h

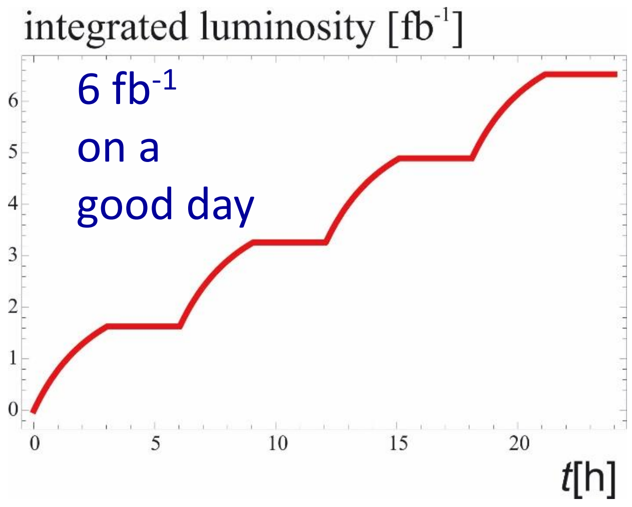


leveling?









6 fb^{-1}
on a
good day

luminosity / year vs turnaround time

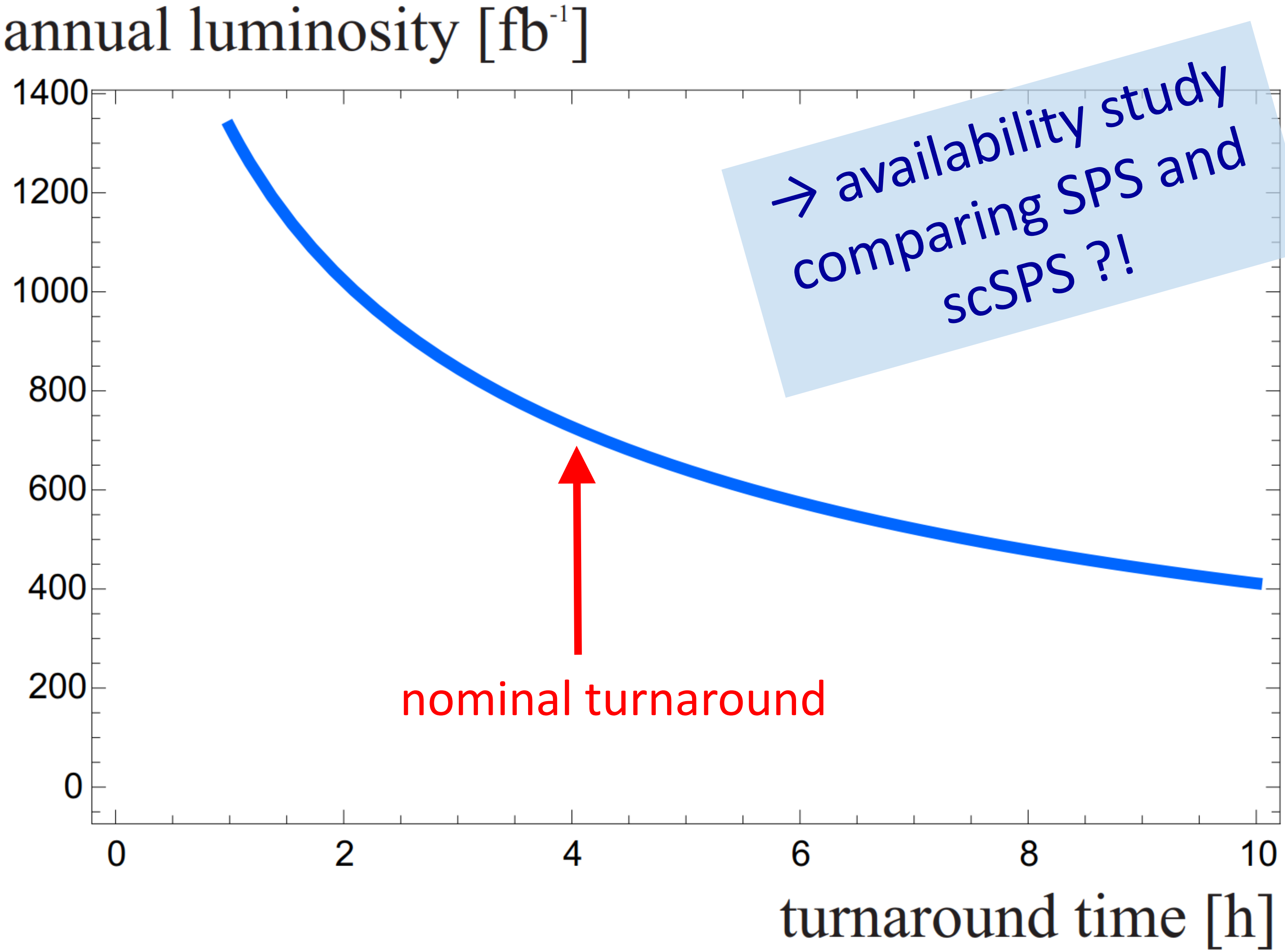
HE-LHC assumptions:

- 160 days scheduled for physics / year
- 70% availability

→ 30% of time in physics

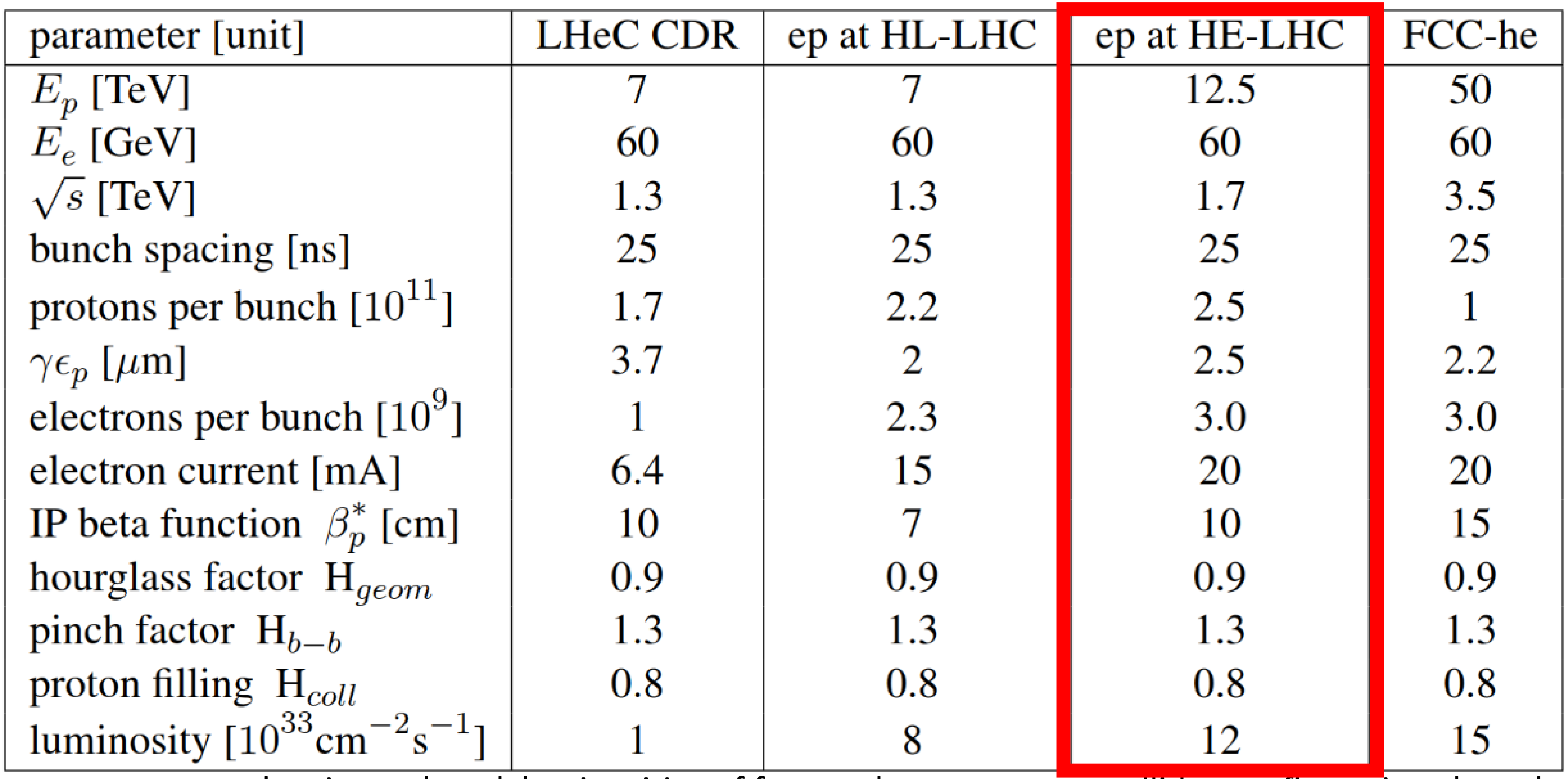
for comparison
LHC 2017:

82.9% availability
49% of time in physics



→ availability study comparing SPS and scSPS ?!

HE-LHeC parameters



parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8	0.8
luminosity [10^{33}cm^{-2}s^{-1}]	1	8	12	15

parameters and estimated peak luminosities of future electron-proton collider configurations based on an electron ERL, esp. HE-LHeC, when used in concurrent ep and pp operation mode

O. Brüning, J. Jowett, M. Klein, D. Pellegrini, D. Schulte, F.Z.

HE-LHC A-A and A-p operation

Pb-Pb

integrated luminosity ~ 10 nb^{-1} / month (2–3x HL-LHC)
peak luminosity > 2 × 10^{28} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

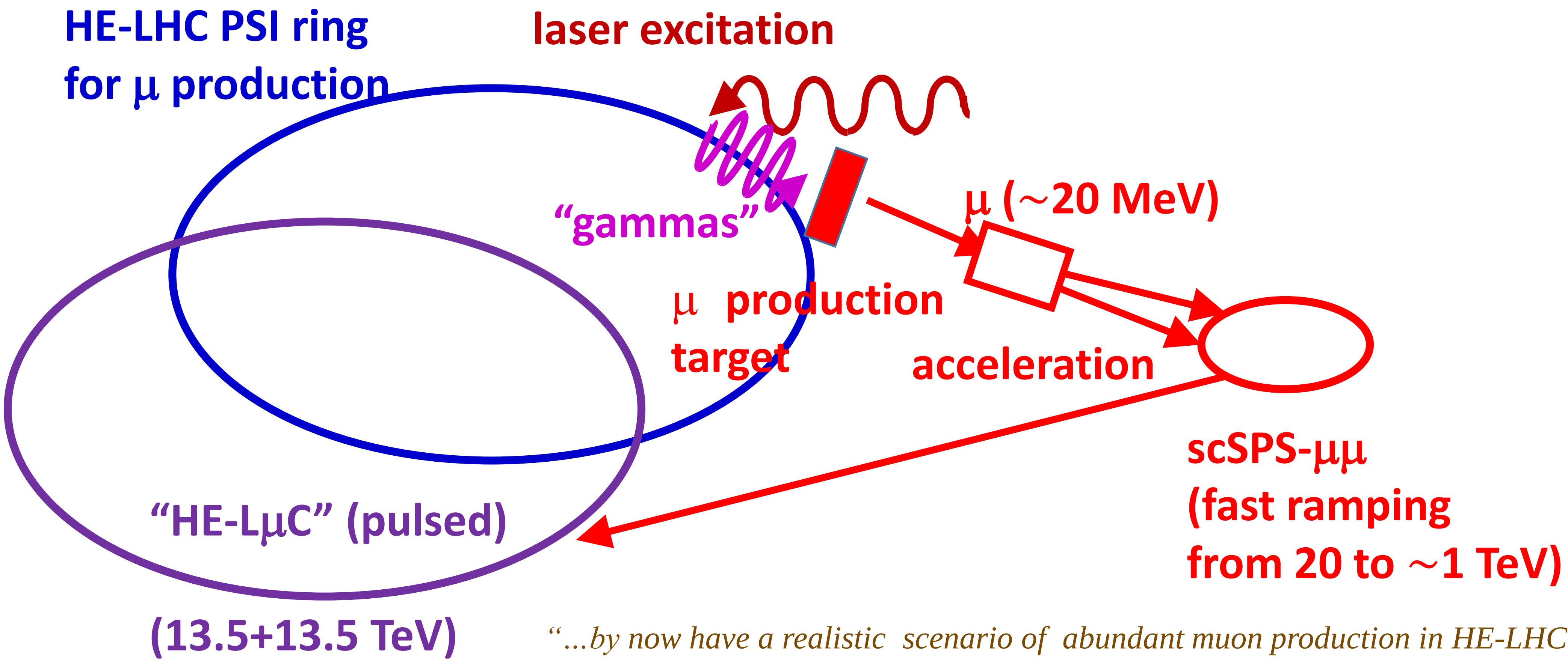
p-Pb

integrated luminosity ~ 2 pb^{-1} / month
peak luminosity > 2 × 10^{30} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

- higher energy and fast radiation damping
- more severe losses from bound-free pair production than for HL-LHC, and a more challenging collimation

see John Jowett’s talk from Tuesday

long-term prospect



"…by now have a realistic scenario of abundant muon production in HE-LHC, which .. could use ordinary laser + FP cavity technology, with significantly narrower spectrum of light frequency with respect to FEL. This could indeed be a breakthrough" W. Krasny 6 April 2018

27 TeV μ collider with HE-LHC Gamma-Factory μ production

some of the next steps

error table including APC’s

leveling scheme & wire compensation

availability and performance with SPS vs scSPS

improve collimation cleaning efficiency

…