

# HE-LHC Machine Overview

Frank Zimmermann, FCC Week 2018

Amsterdam, 9 April 2018

on behalf of the HE-LHC study group

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thanks to Oliver Brüning (CERN), Daniel Schulte (CERN), Vladimir Shiltsev (FNAL), Jörg Wenninger (CERN)



# HE-LHC design goals & basic choices

## physics goals:

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

## key technologies:

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

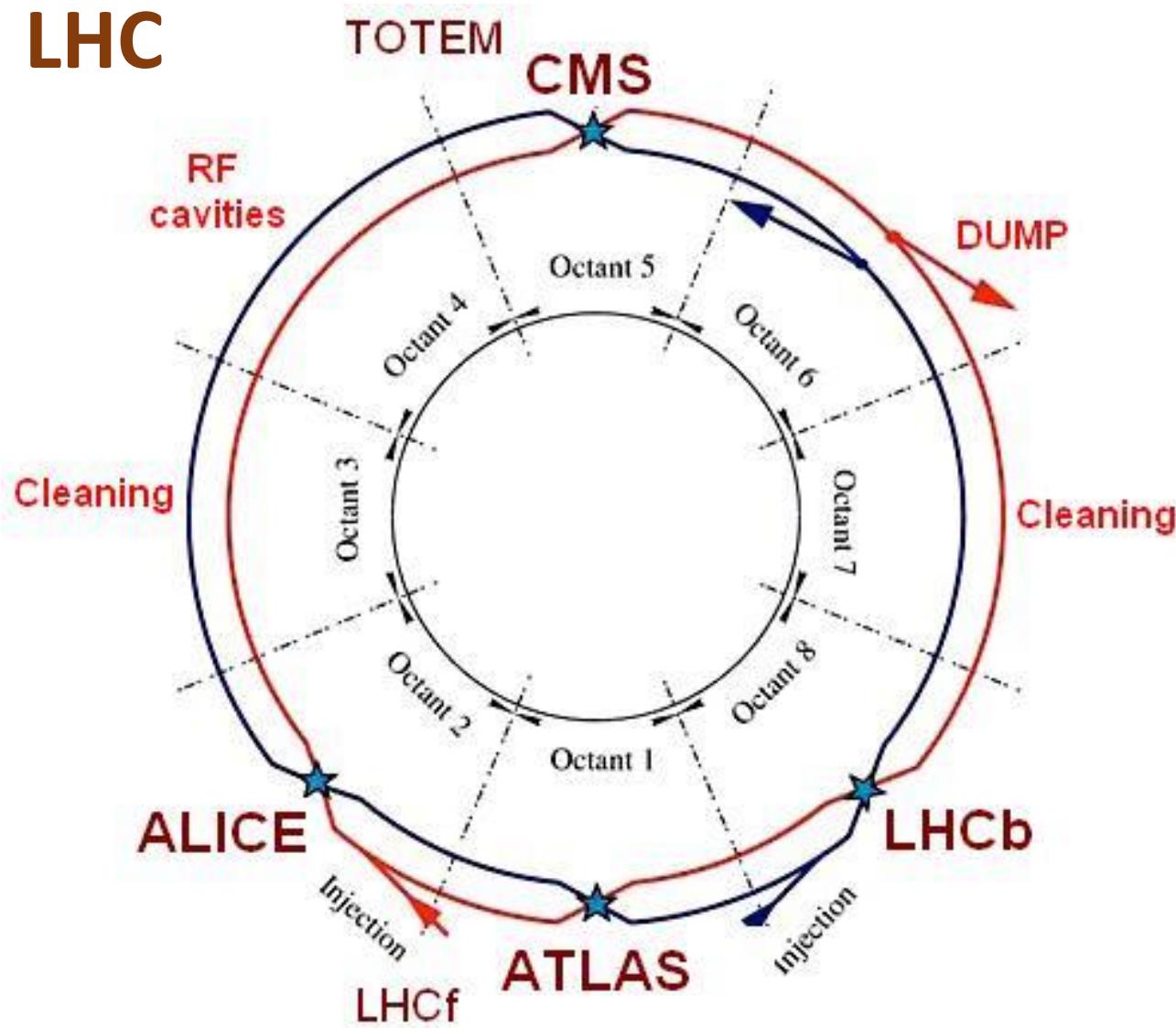
## beam:

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

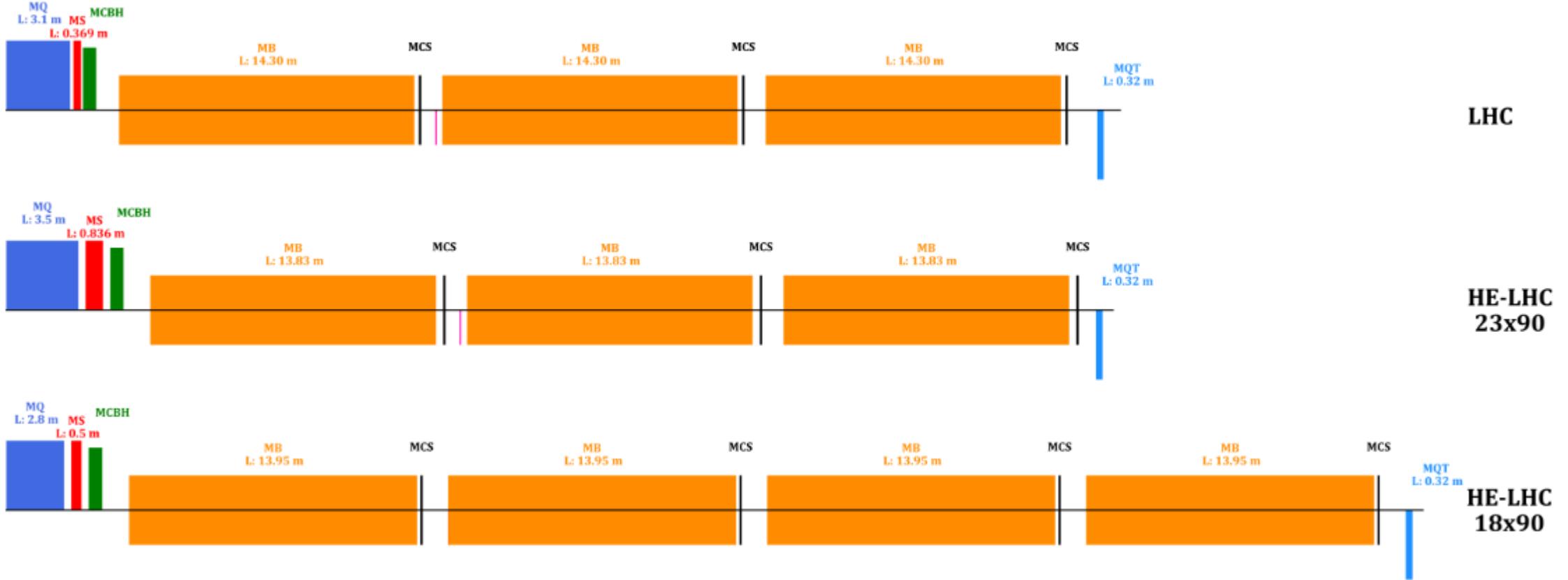
- low-beta insertions, **longer triplet than HL-LHC**,  $\beta^*$  reach
- collimation insertions, **LHC or FCC-hh optics scaling not applicable**, warm dipole length increase
- extraction straights – **length of kicker & septum sections**

## injector and injection energy

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



# arc half cells: LHC vs HE-LHC





# 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”)

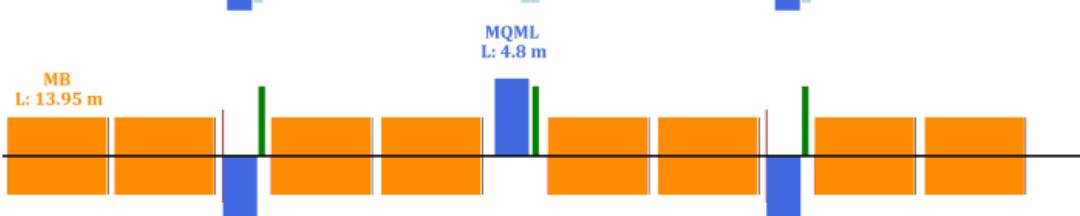
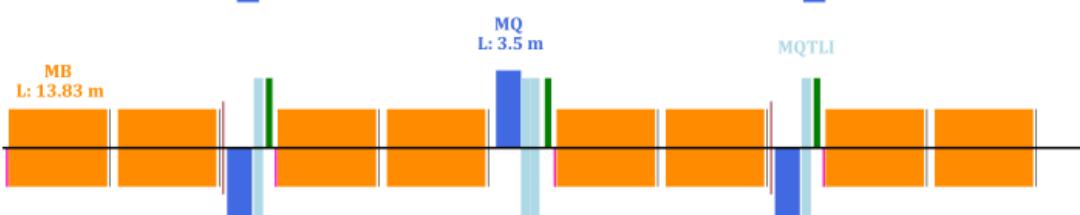
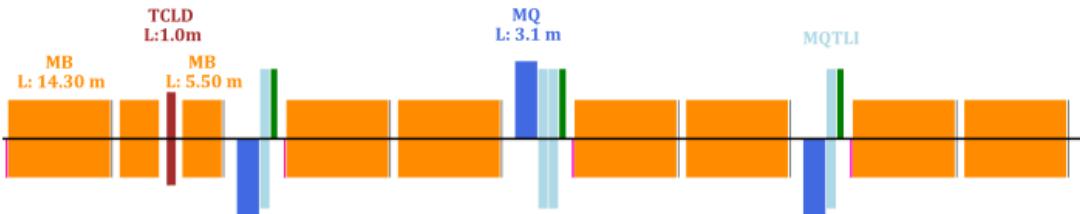
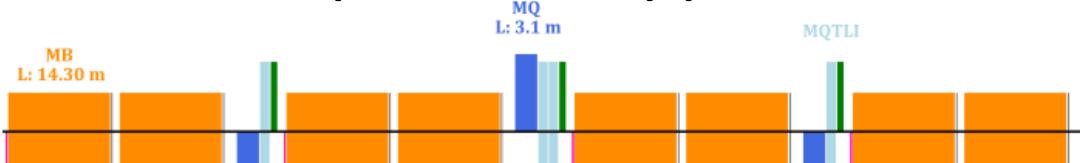
HE-LHC arc optics	18x90*	23x90**
arc cell length [m]	137.23	106.9
$\beta_{\max}$ [m]	230	177
$D_{\max}$ [m]	3.6	2.2
mom. comp. $\alpha_C$ [ $10^{-4}$ ]	5.8	3.5
dipole filling factor	0.81	0.78
<b>dipole field for 13.5 TeV [T]</b>	<b>15.83</b>	<b>16.59</b>
<b>c.o.m. energy for 16 T [TeV]</b>	<b>27.28</b>	<b>26.01</b>

\* 18 cells per arc, with 90 deg phase advance / cell

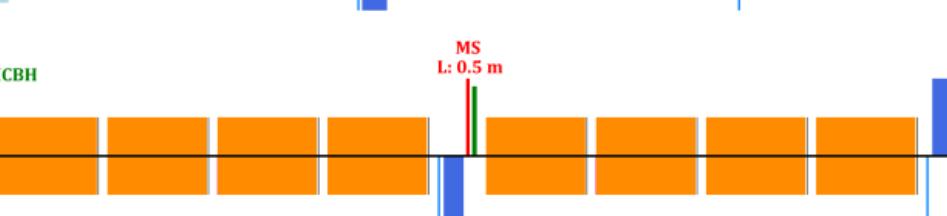
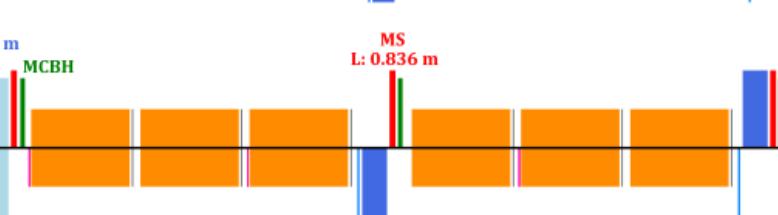
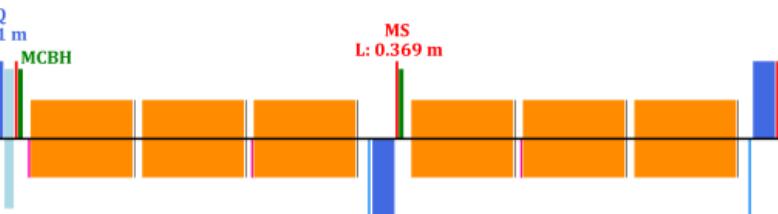
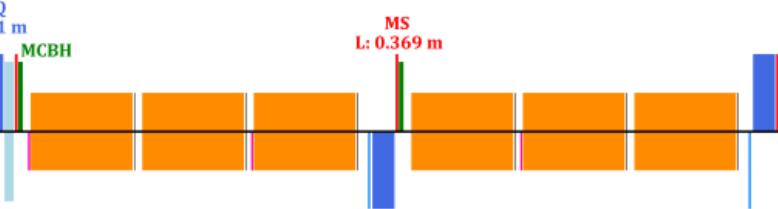
\*\* 23 cells per arc, with 90 deg phase advance / cell

# transition arc to straight

## dispersion suppressor



## 1<sup>st</sup> arc cell



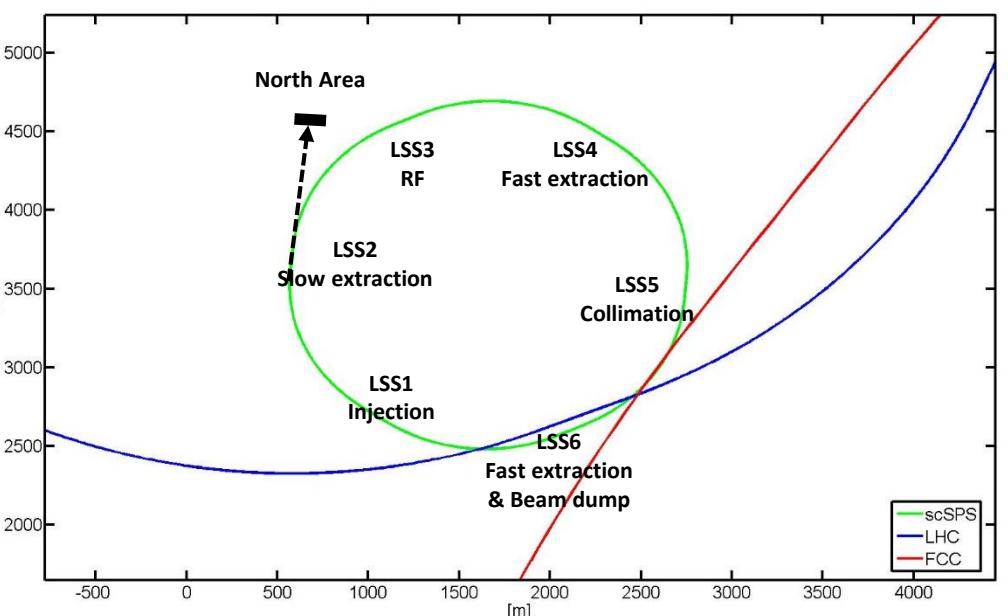
LHC

HL-LHC

HE-LHC  
23x90

HE-LHC  
18x90

# HE-LHC injector options



## 1. inject from present SPS at 450 GeV

concerns:

- physical aperture ( $\sim 1/2\text{--}2/3$  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 $\rightarrow$ extract at 900 GeV

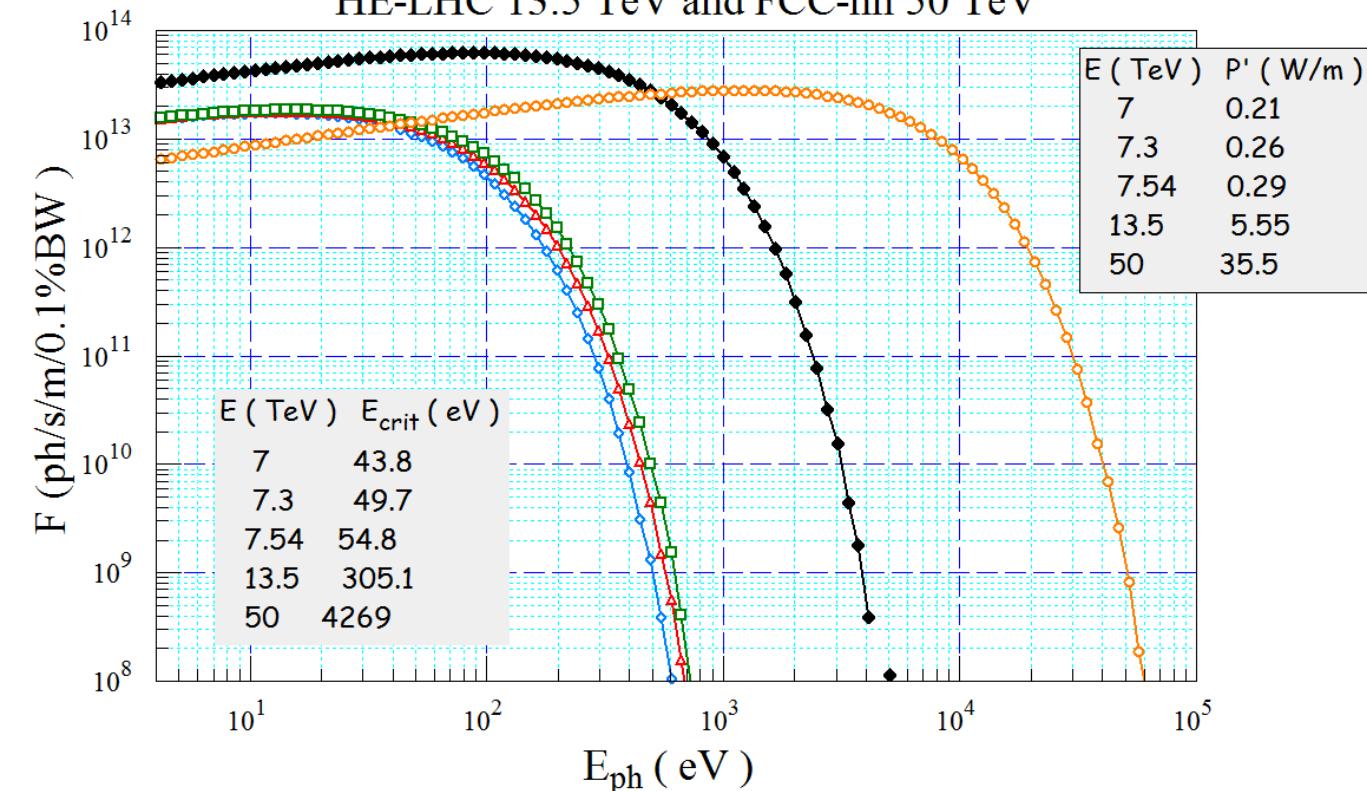
## 3. scSPS with double-layer SC dipole, max. field 6 T $\rightarrow$ extract at 1.3 TeV

downsides: large energy swing in scSPS,

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

# HE-LHC arc synchrotron radiation

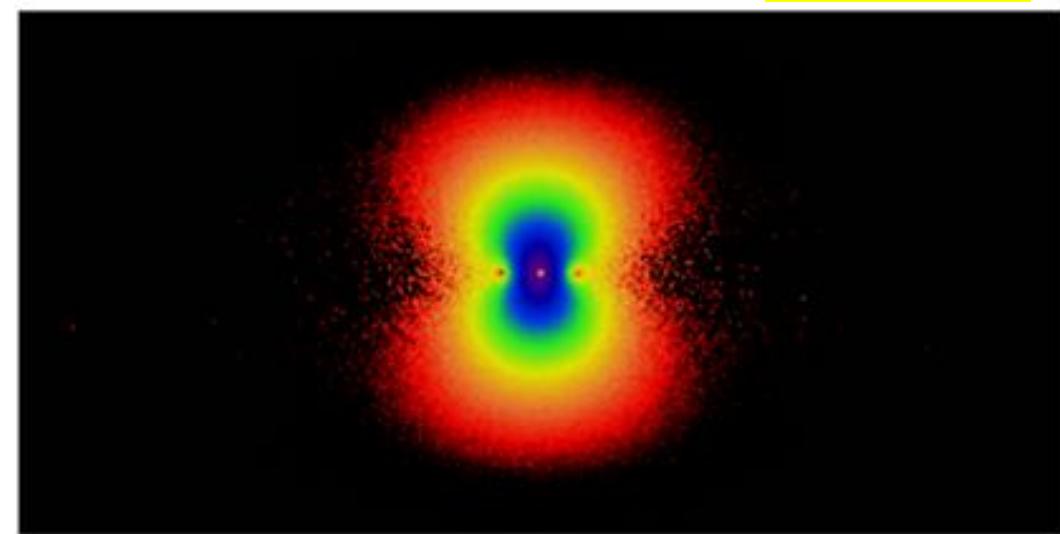
SR Photon Flux Spectra for LHC 7, 7.3, 7.54 TeV,  
HE-LHC 13.5 TeV and FCC-hh 50 TeV



Beam Currents: LHC:584 mA; HE-LHC: 1120 mA; FCC-hh: 500 mA

→ beam-screen to intercept synchrotron  
radiation at higher  $T$  and cryo-pumping

R. Kersevan



HE-LHC photon flux per meter = 5.4x LHC (7 TeV)  
and 1.8x FCC-hh (50 TeV)

parameter	LHC	HE-LHC	FCC-hh
linear SR power [W/m]	0.25	5.5	35
linear photon flux [ $10^{16}$ photons/m/s]	5	27	15
critical photon energy [eV]	44	320	4300

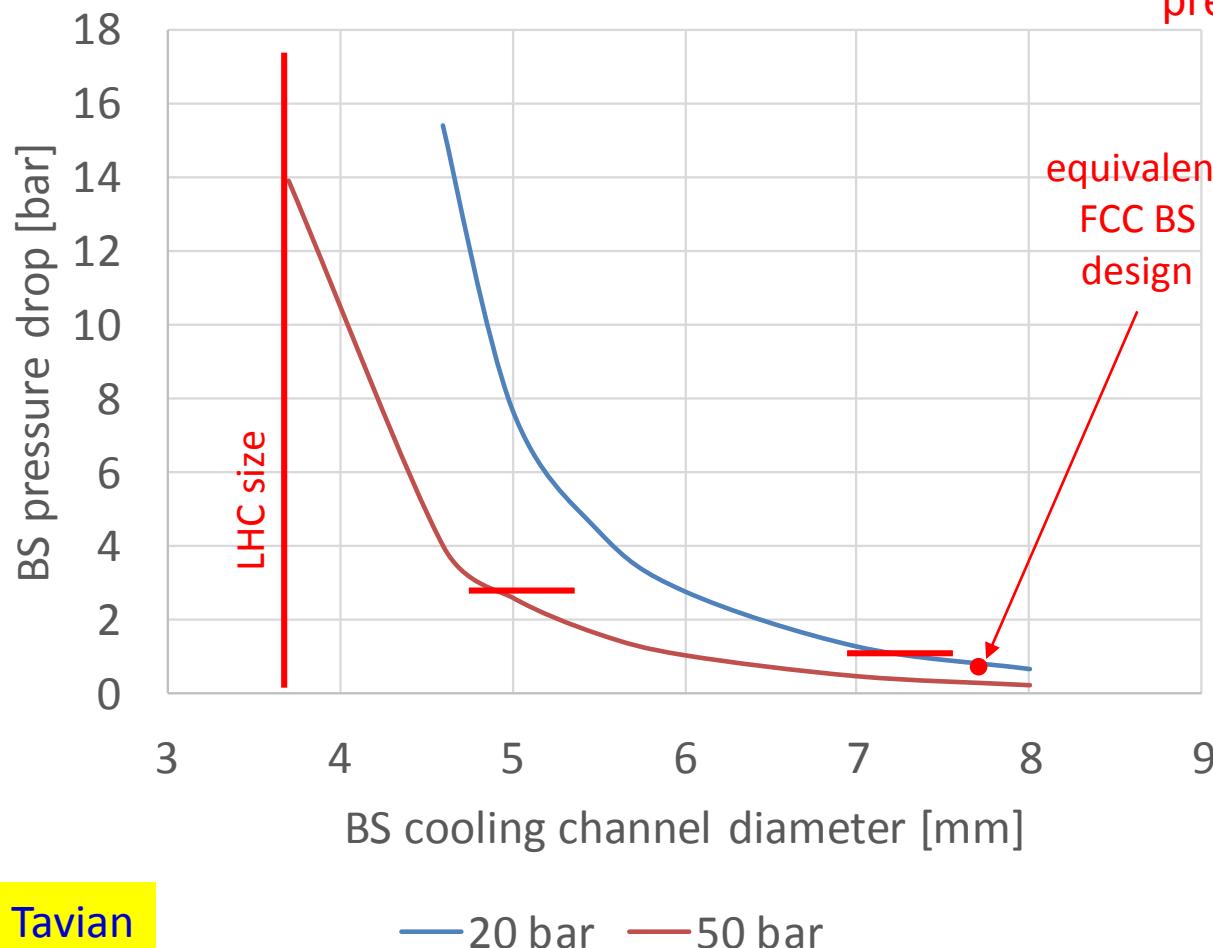
# arc beam-screen cooling channel

## HE-LHC beam-screen pressure drop

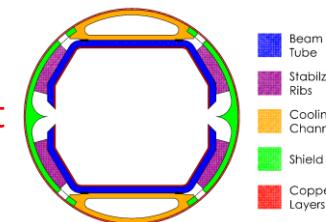
2 circular cooling channels per BS (LHC like)

mass flow per cooling channel:  $\sim 5 \text{ g/s}$

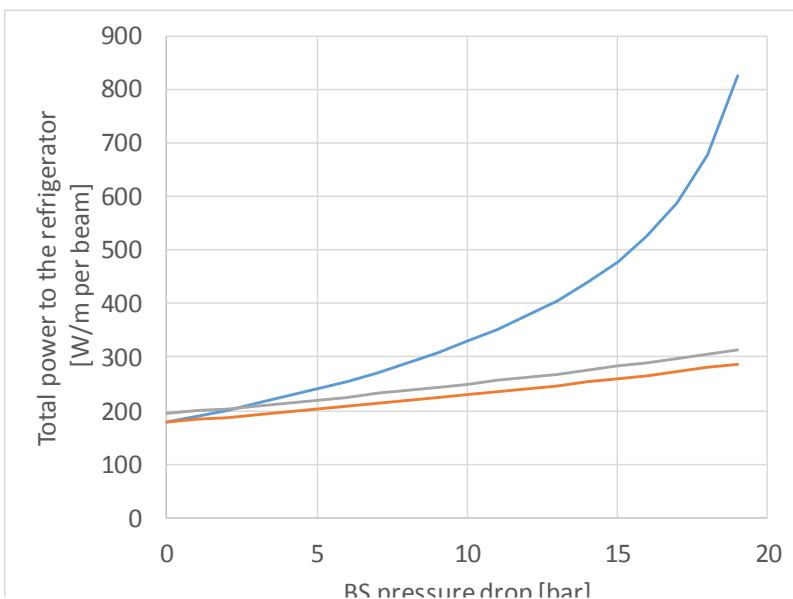
for exergetic efficiency:  $\Delta P < \sim 5\% \text{ of operating pressure}$



use the FCC-hh design  
which is compatible  
with a 20 bar operating  
pressure



## HE-LHC electrical power to refrigerator vs pressure drop



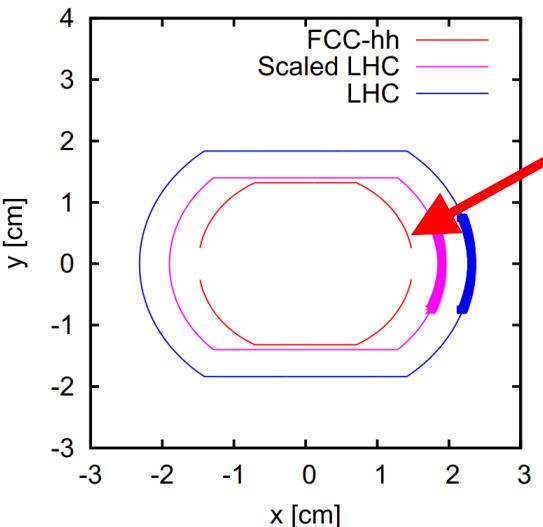
BS type	Operating Pressure [bar]	DP [bar] BS (+ CV)	Power to ref. [W/m/beam]	Operation cost (10 y) [MCHF]	Distribution cost
LHC-type beam screen	20	N/A	N/A	N/A	N/A
	50	14 (+3)	300	52	+
FCC-type beam screen	20	0.8 (+1)	200	35	-
	50	0.3 (+1)	184	32	+



# arc aperture & beam size at injection

HE-LHC  
vs LHC  
beam screen

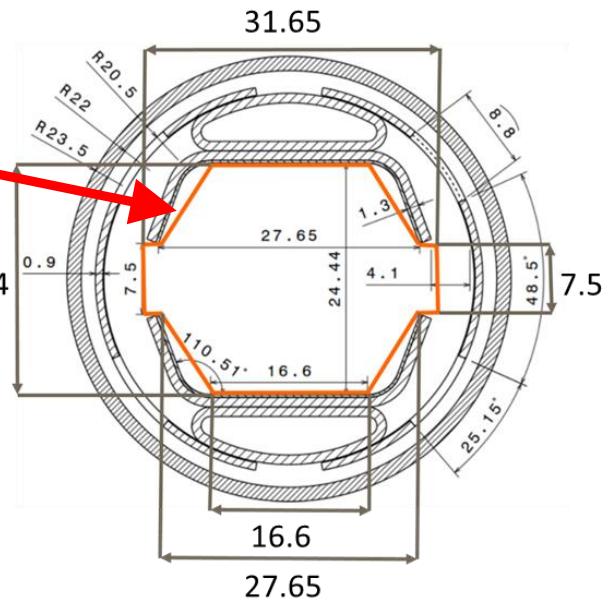
G. Guillermo



FCC-hh type beam screen:  
important for vacuum,  
cryogenics, and impedance

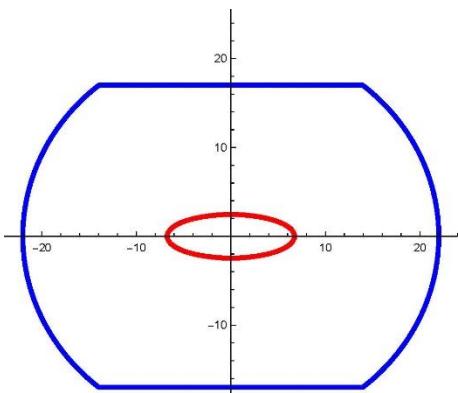
L. Tavian

R. Kersevan  
S. Arsenyev, D. Schulte

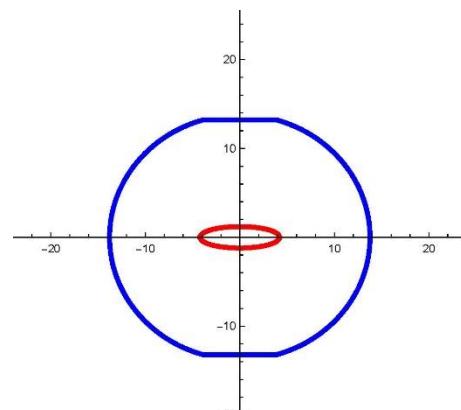


horizontal beam size ( $6\sigma$ ) in arcs (QF) at injection

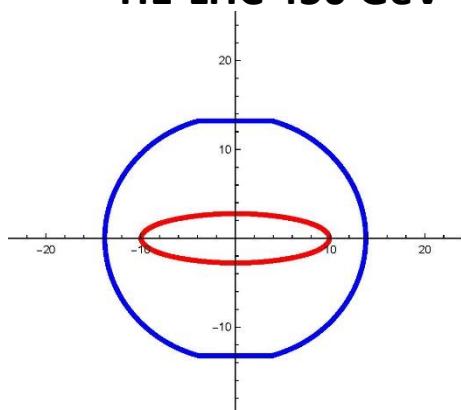
HL-LHC



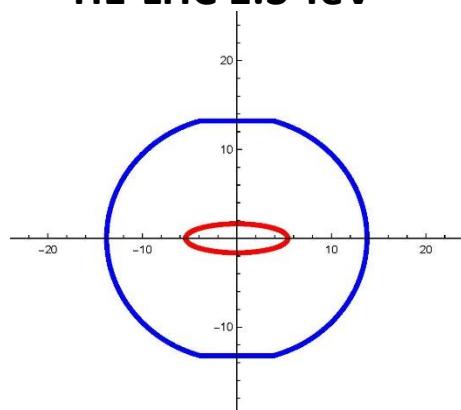
FCC-hh 3.3 TeV



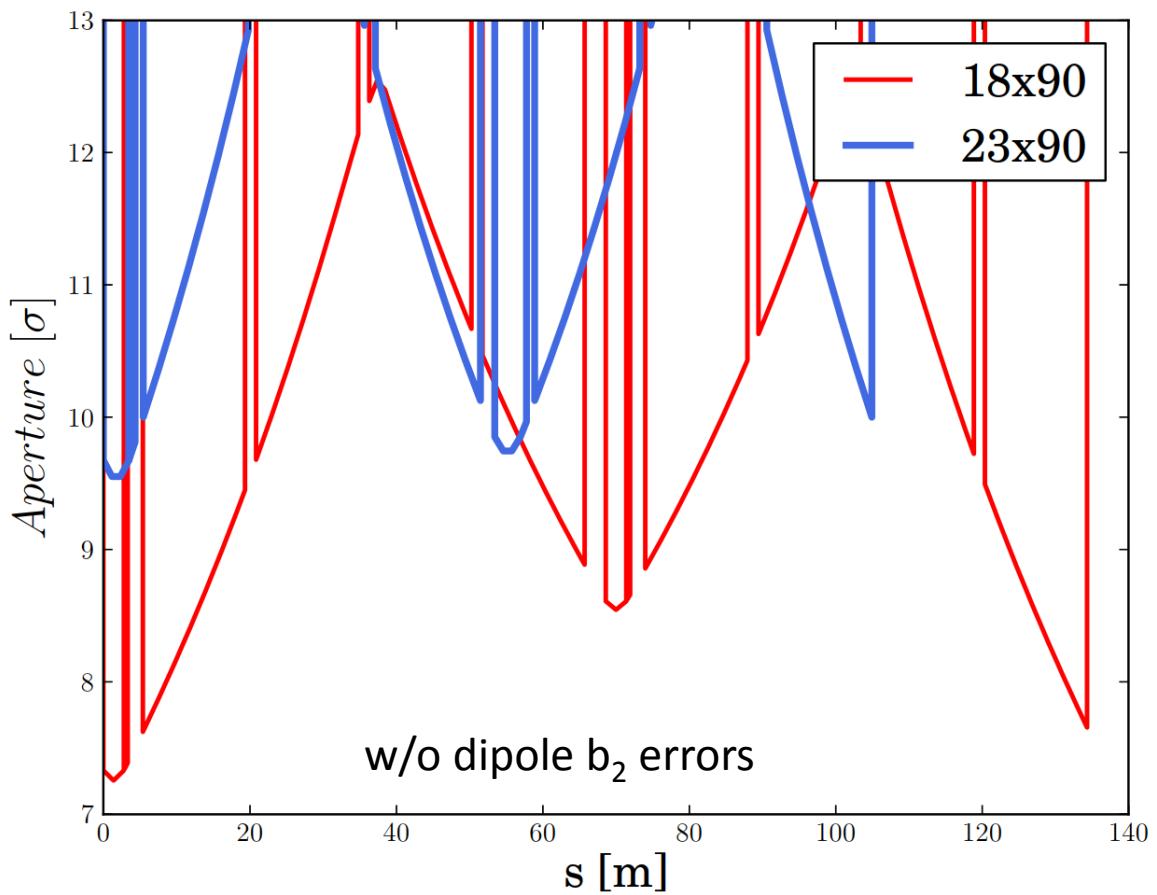
HE-LHC 450 GeV



HE-LHC 1.3 TeV



# normalized arc aperture at 450 GeV



aperture ( $\sigma$ )	450 GeV	900 GeV	1.3 TeV
18x90	7	10	12
23x90	9	12.5	15
setting ( $\sigma$ )	inj.prot.	TCP	apert.
LHC today	5.3	6.7	14.2
HE-LHC 23x90	<4?	5.0?	9
HE-LHC 18x90	<4?	4.5?	7

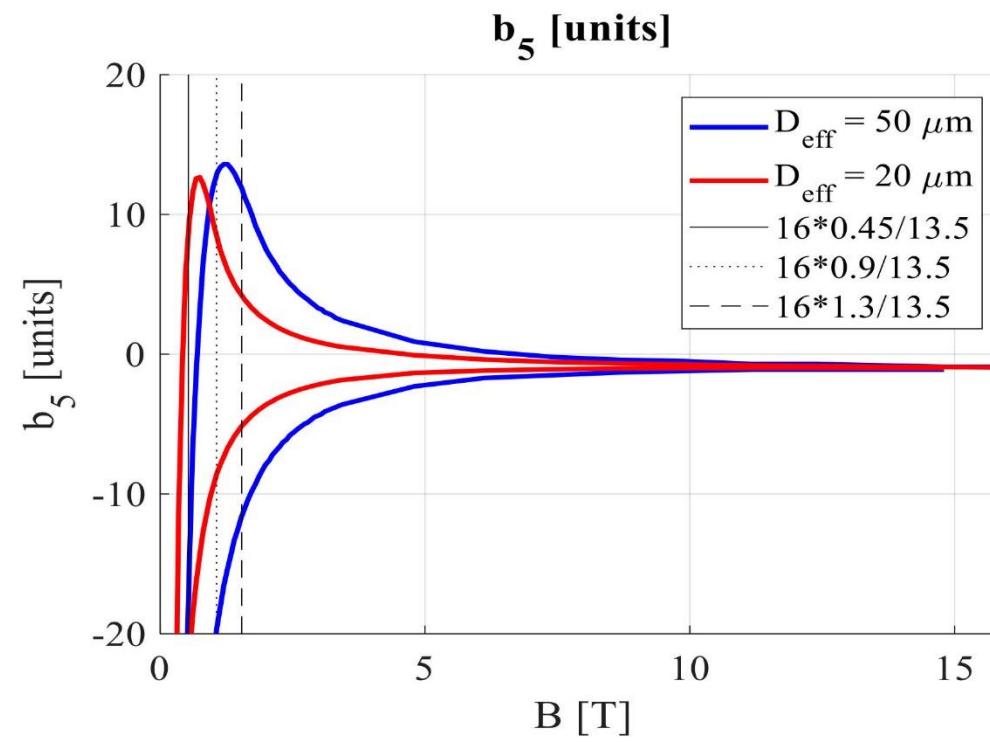
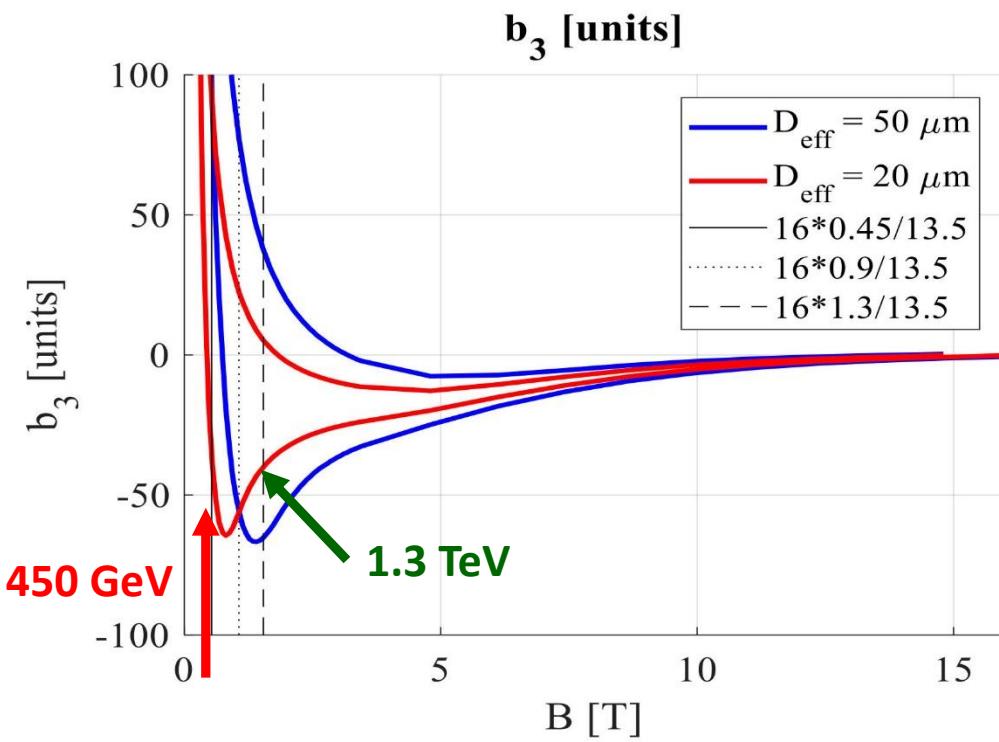
J. Keintzel

$\varepsilon_N = 2.5 \mu\text{m}$

hierarchy: secondary  
collimators,  
dump protection

R. Bruce, S. Redaelli

# field quality



sextupolar and decapolar multipole errors b3 and b5 for the 16 T dipole magnets as function of field strength for an effective Nb<sub>3</sub>Sn filament size of 50 μm (blue) or 20 μm (red).

sextupole component  
b<sub>3</sub> in the main arc  
dipoles, in units of 10<sup>-4</sup>  
at a radius of 16.7 mm

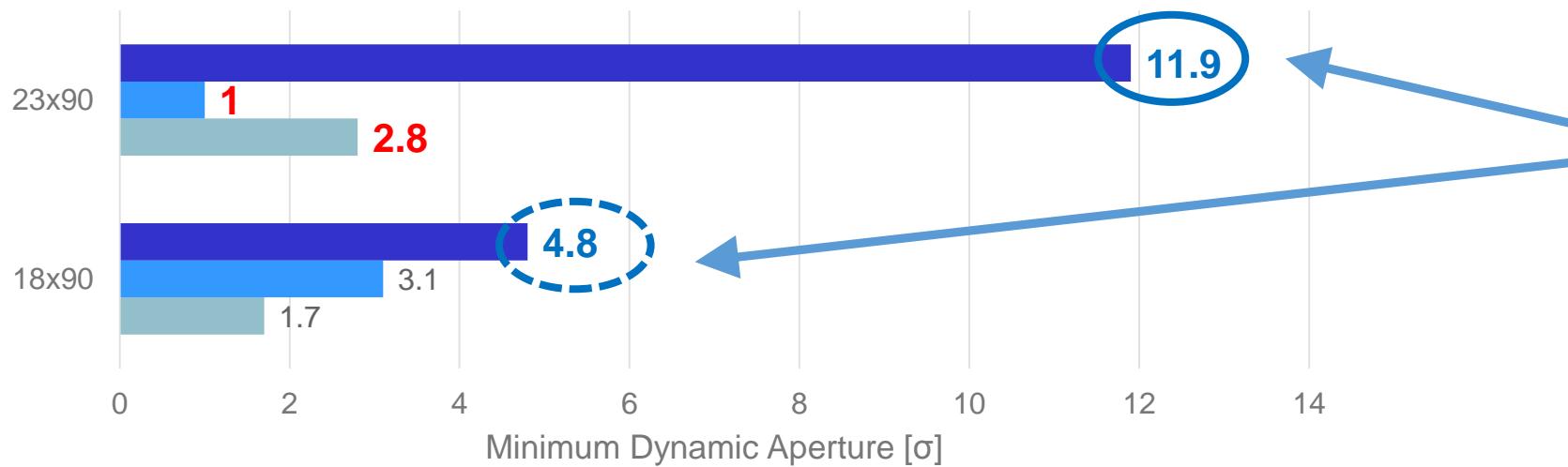
energy	syst.	uncertainty	random
450 GeV	-35	10	10
900 GeV	-55	4	4
1.3 TeV	-40	3	3

# dynamic aperture

M. Hofer,  
Y. Nosochkov

**dynamic aperture [ $\sigma$ ]**  
w. corrected b3, b4, b5

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



solution(s) found  
for 1.3 TeV  
injection

■ 1300 GeV ■ 900 GeV ■ 450 GeV

requirement/goals for 450 GeV injection:

- reduce systematic  $b_2$  by factor 3
- reduce random  $b_3$  to <10 units at all energies
- reduce random  $b_5$



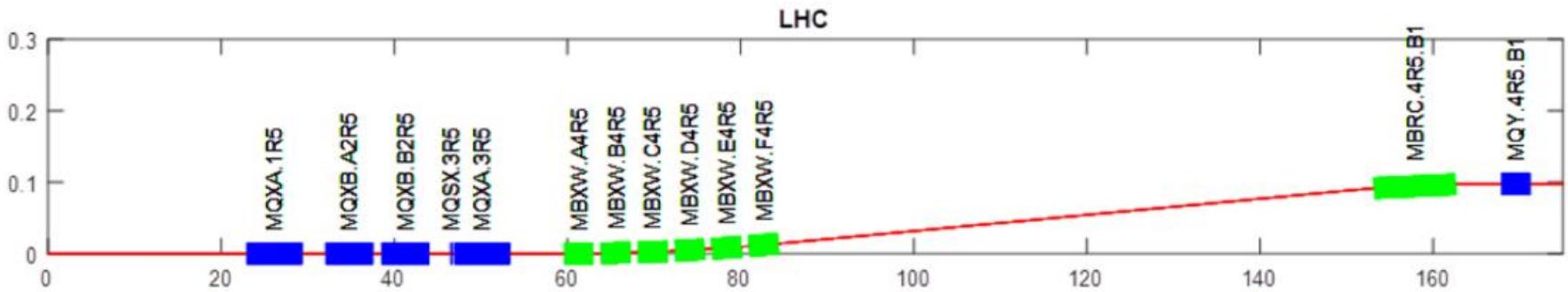
potential solutions:  
active pinning centres,  
iron shims, HTS shims, sorting,  
larger number of corrector families

D. Schoerling,  
R. Tomas,  
S. Fartoukh

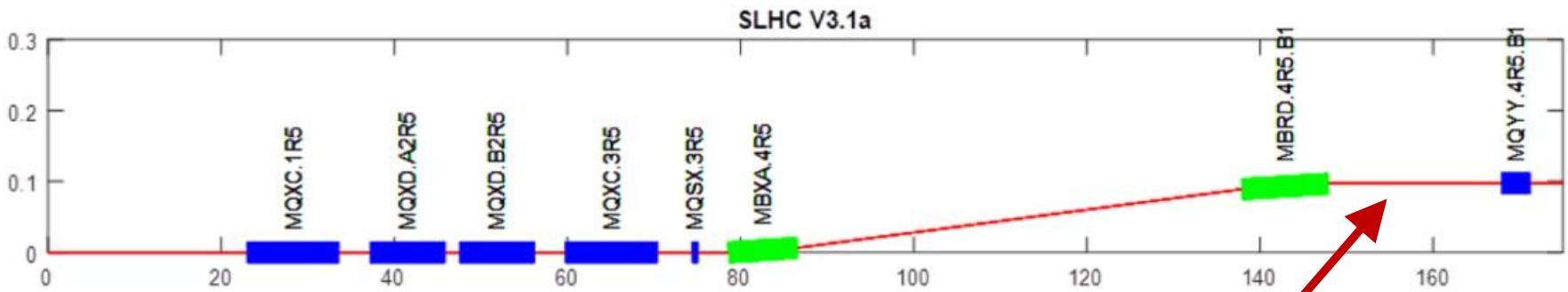


# HE-LHC final-focus layout (IR 1 & 5)

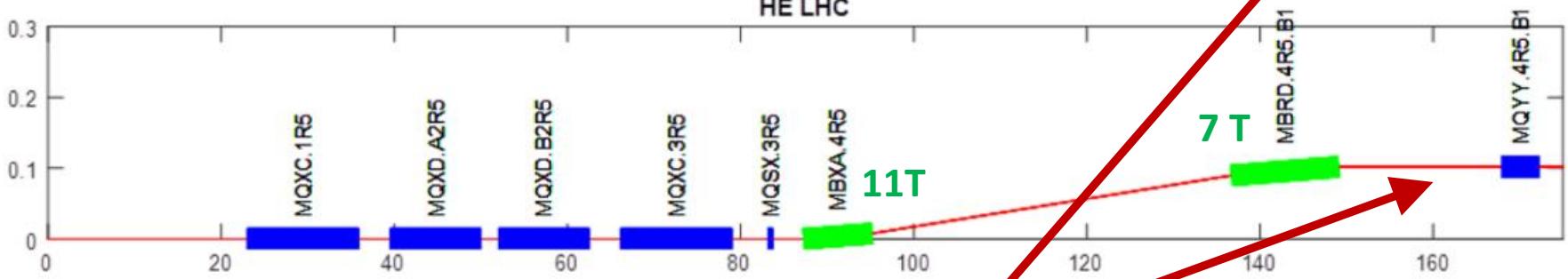
LHC



HL-LHC

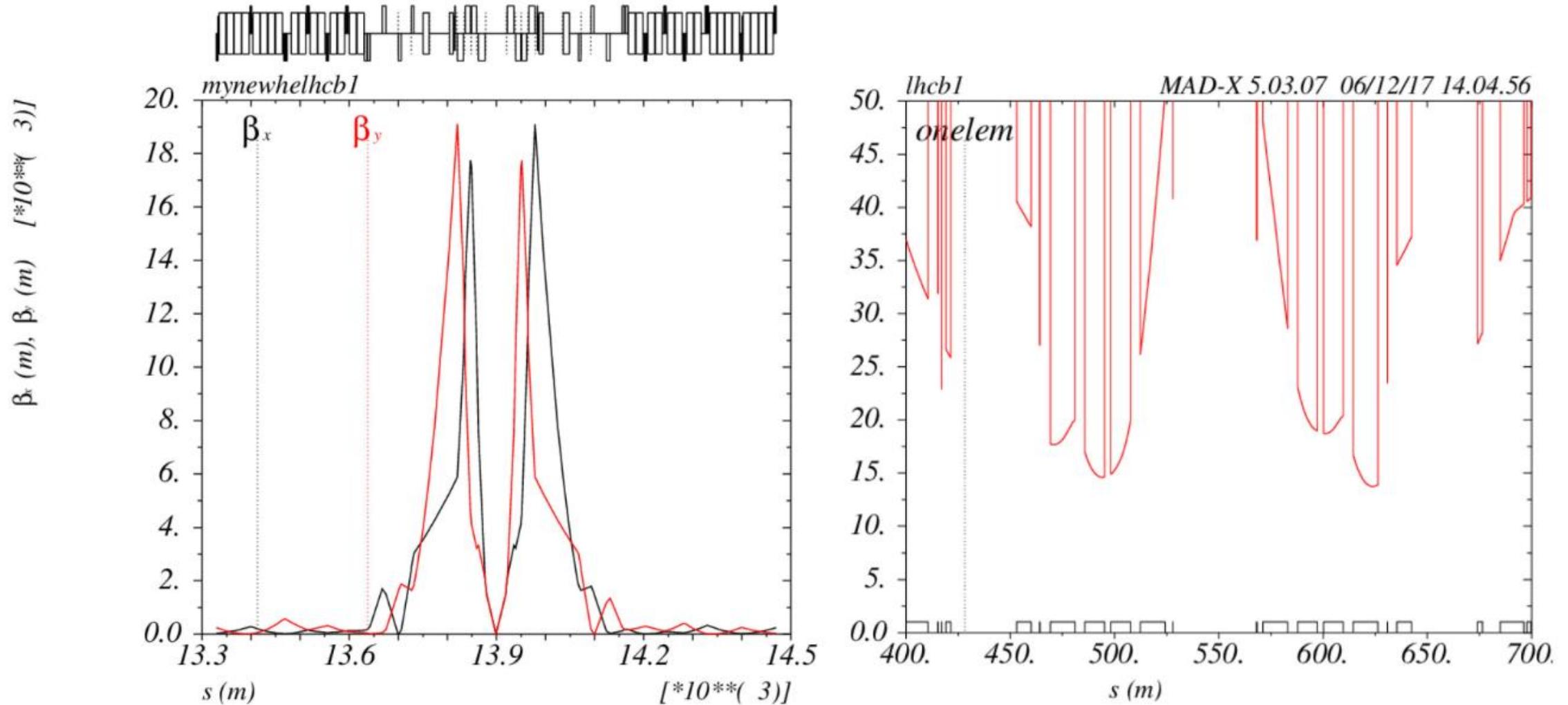


HE-LHC



space for crab cavities (~6 MV)

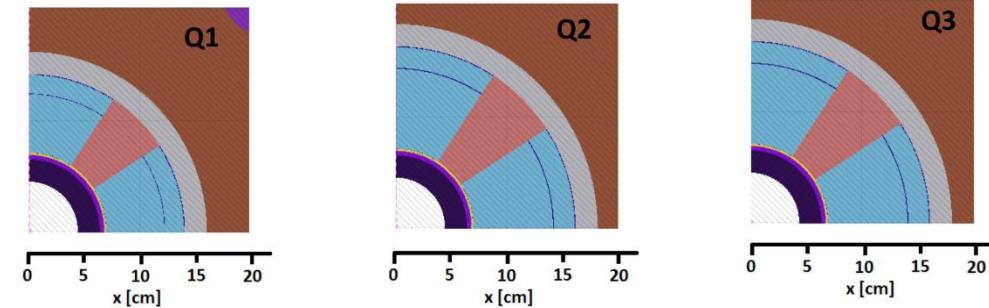
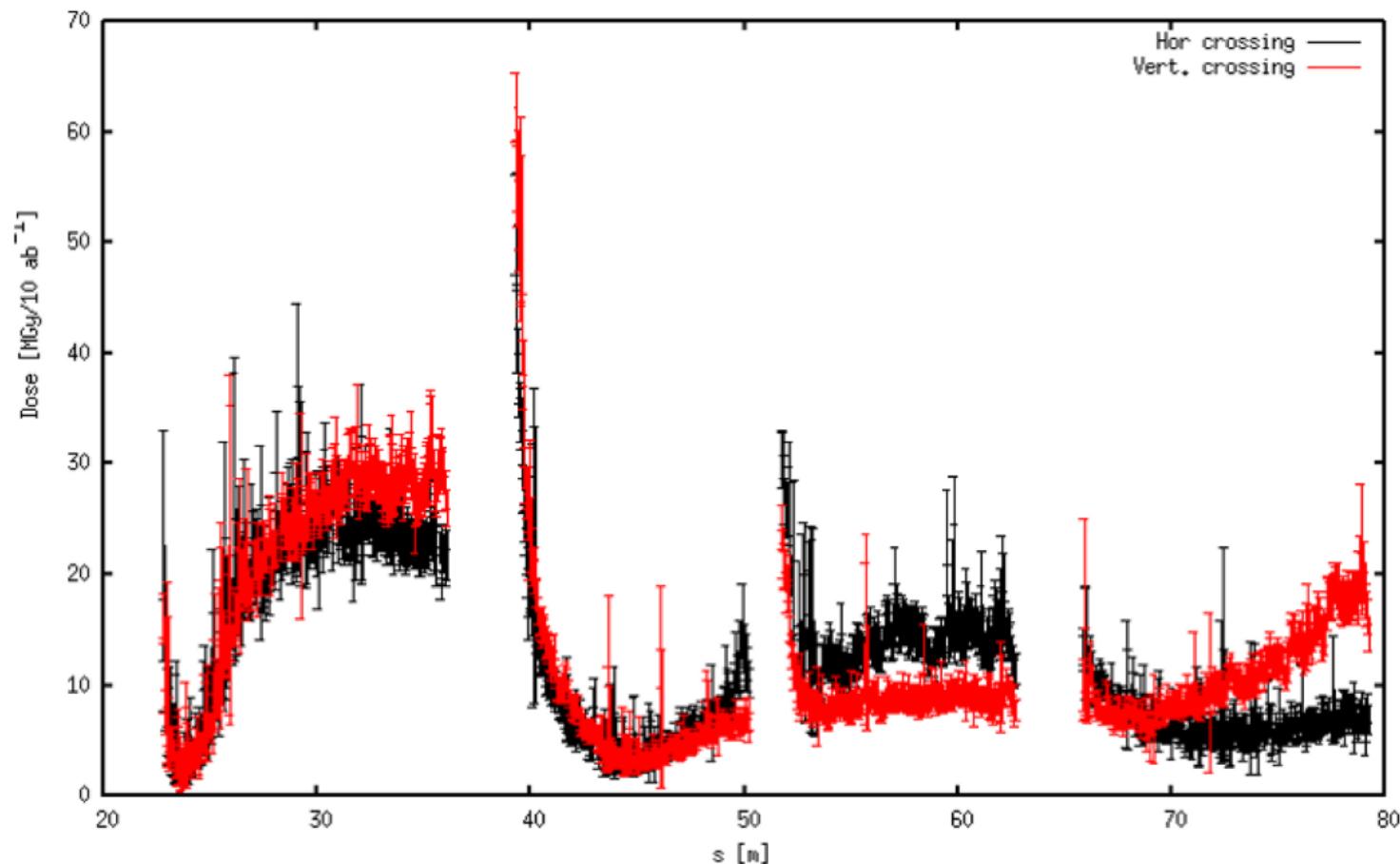
# squeezed IR optics & aperture



beta function and apertures for the squeezed optics at collision energy in the experimental IRs 1 and 5, for a half crossing angle of 131  $\mu$ rad, including a 2 mm closed-orbit uncertainty.

# triplet radiation, shielding & lifetime

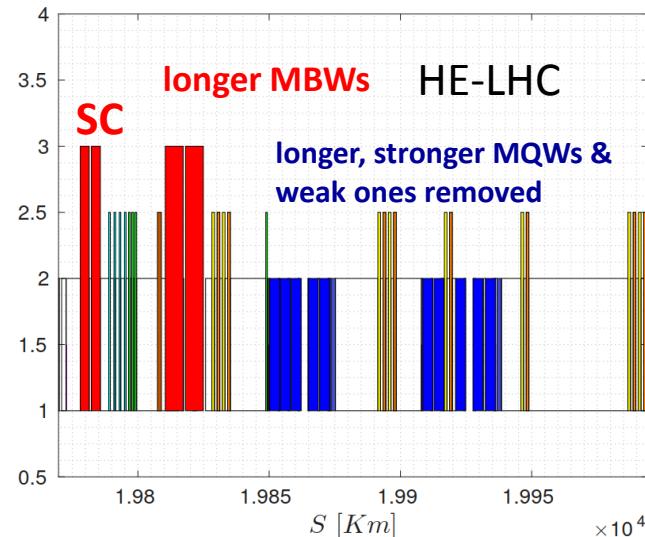
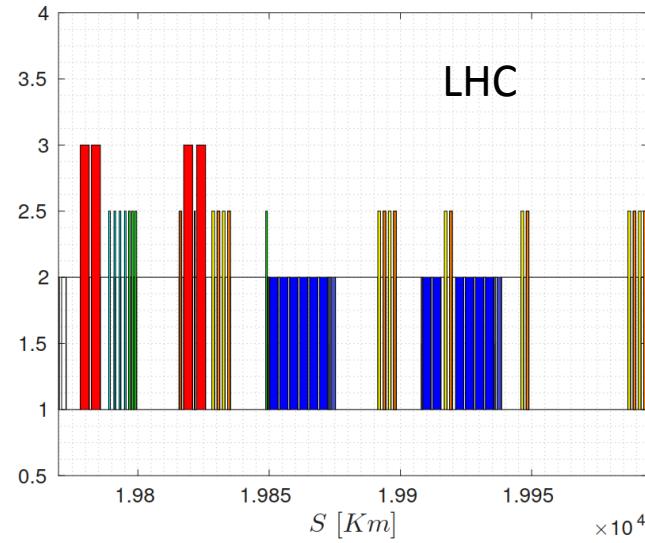
- triplet quadrupoles with 2 cm inside tungsten shielding
- for  $10 \text{ ab}^{-1}$  total luminosity: 30-40 MGy peak radiation  
(peak at interconnect can be reduced with shielding)



FLUKA model of the final triplet quadrupoles

peak dose along the final quadrupole triplet for  $10 \text{ ab}^{-1}$  and a half crossing angle of  $140 \mu\text{rad}$ , as simulated by FLUKA

# betatron collimation IR7

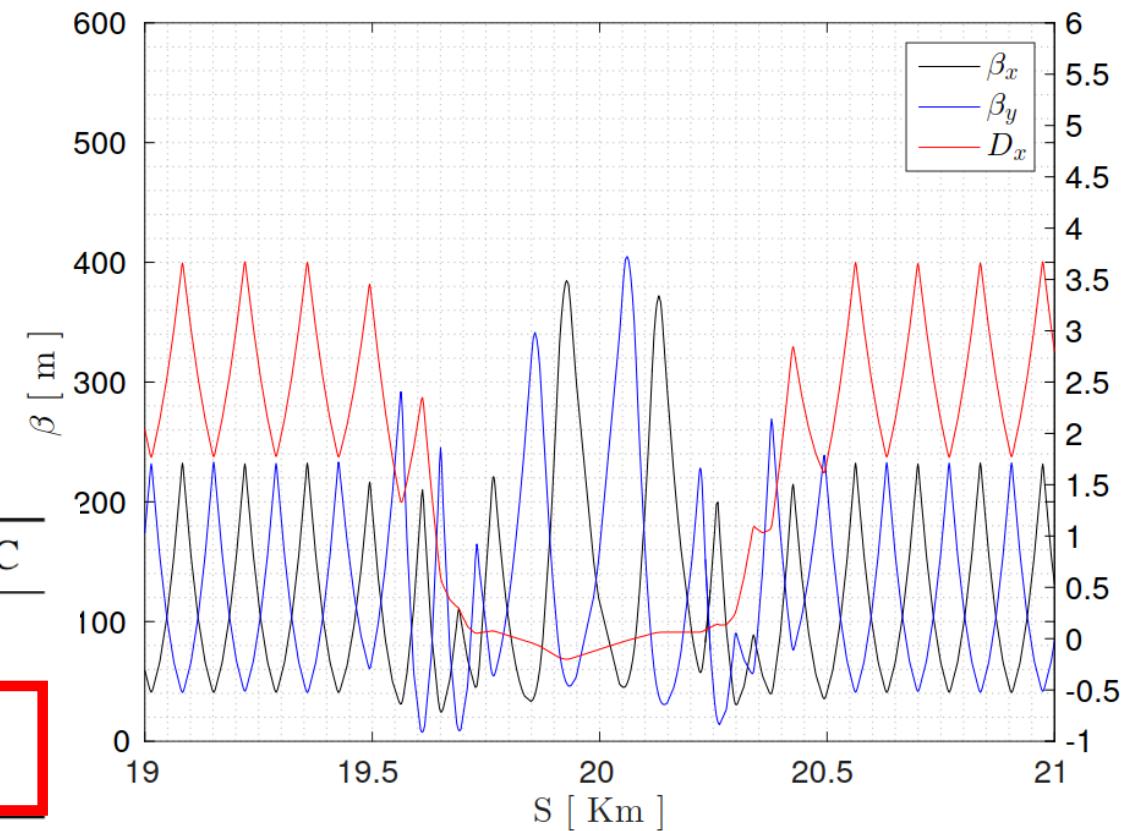


recipe:

- replace outer dogleg dipoles by SC ones
- push strength of and lengthen other dipoles and quads
- remove weak magnets
- use empty space

Parameter	LHC	HE-LHC
MB [T]	8.3	16.0
MQ [T/m]	200	360
MBW [T]	1.42	2.00
MQW [T/m]	35	50

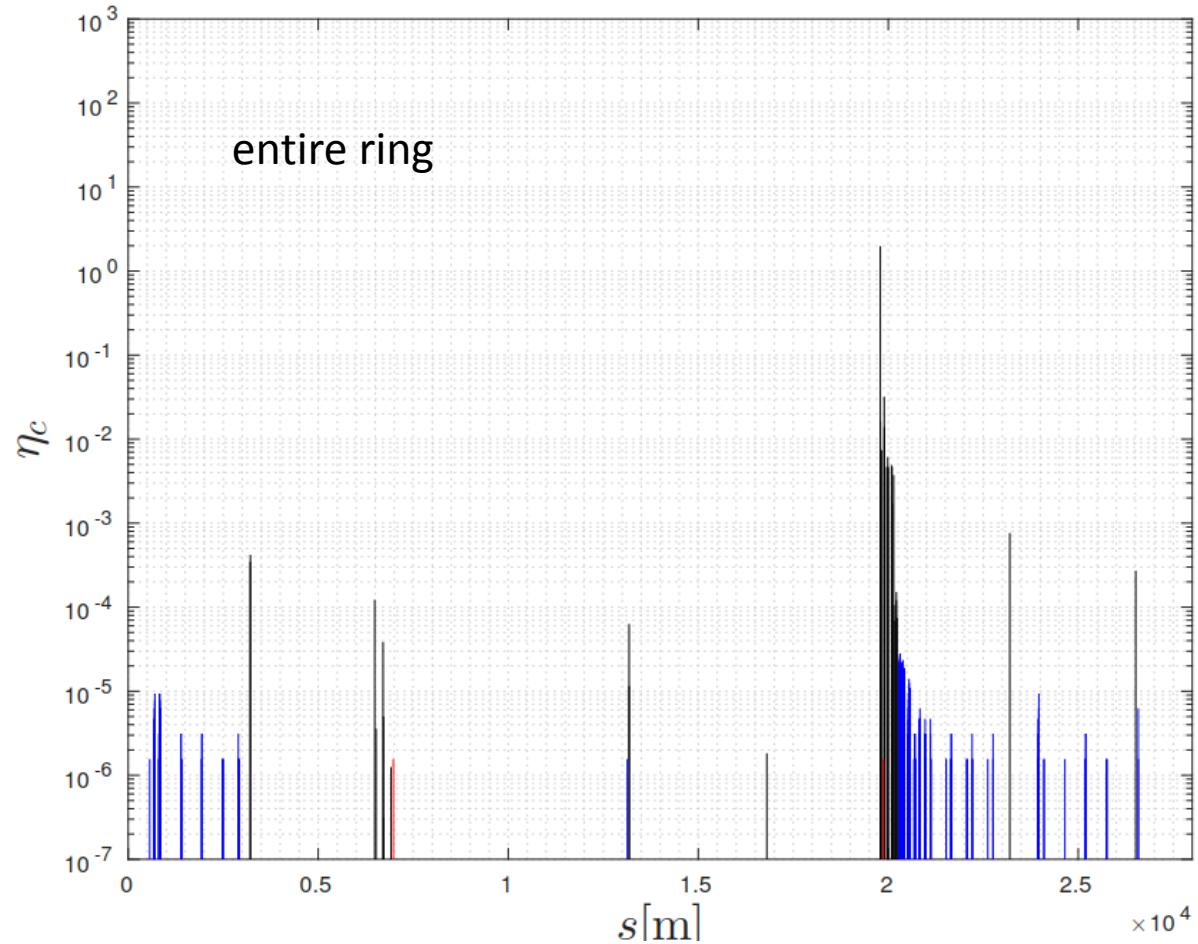
preliminary HE-LHC IR7 optics



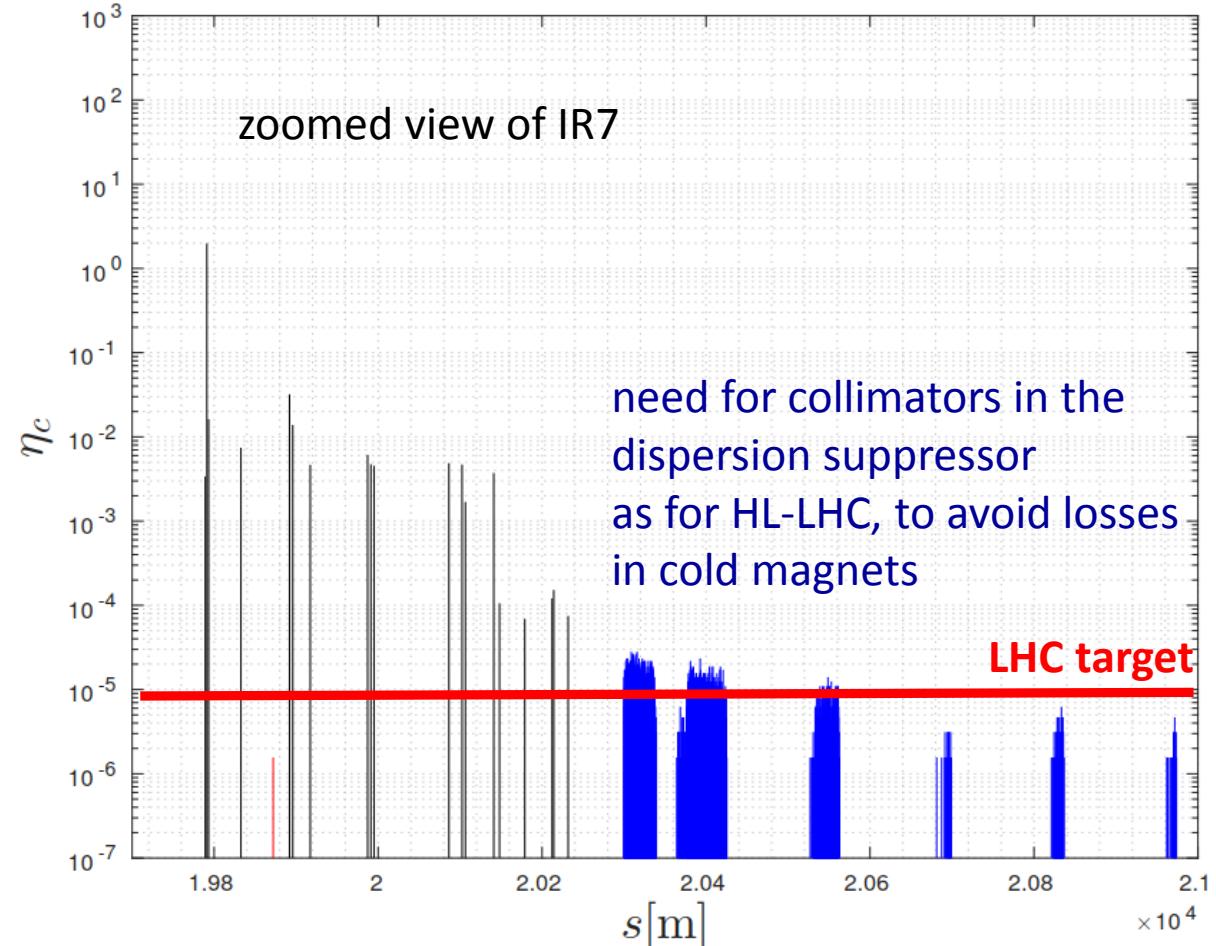
?

next steps: iteration with magnet designers, shielding model, and FLUKA simulations

# collimation cleaning efficiency



entire ring



zoomed view of IR7

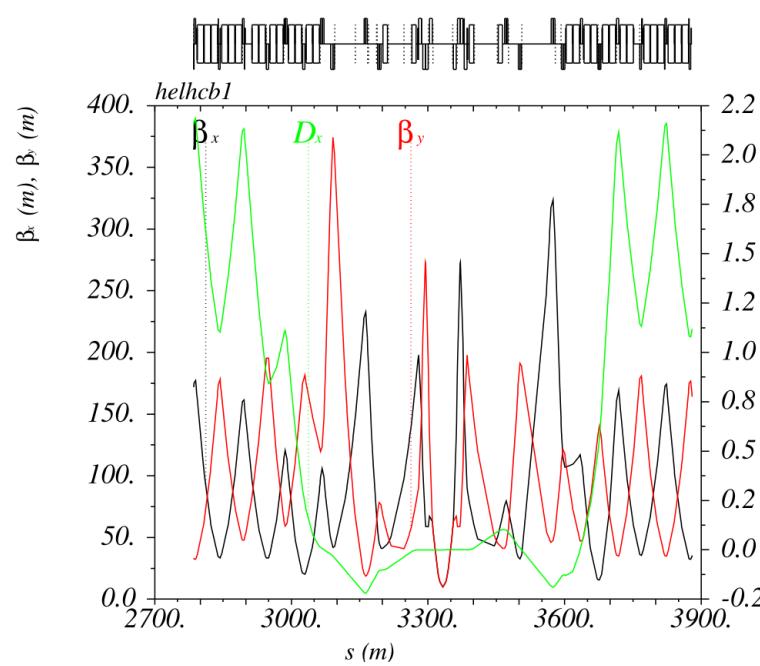
need for collimators in the dispersion suppressor as for HL-LHC, to avoid losses in cold magnets

LHC target

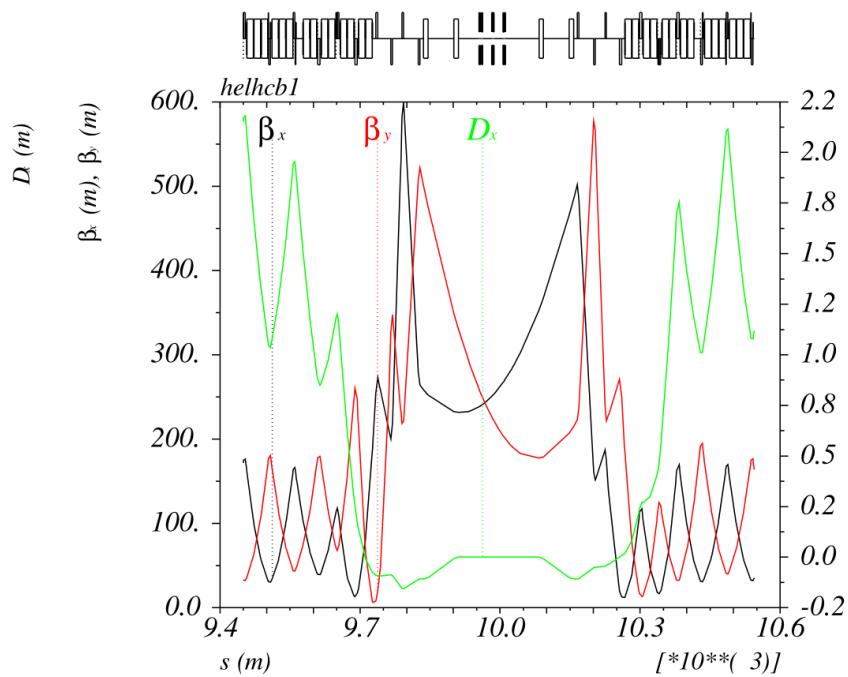
simulated particle losses around HE-LHC for a scaled “LHC” betatron cleaning insertion (scaled aperture and energy)

# optics for other IRs

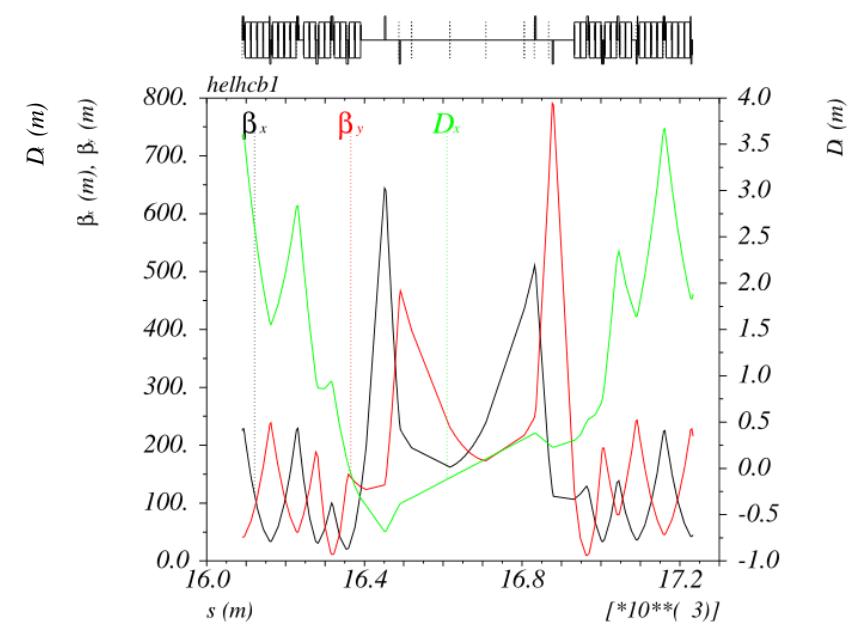
IR2 –  
injection &  
secondary exp.



IR4 –  
instrumentation &  
RF



IR6 –  
beam extraction





# extraction and injection kickers

parameter	unit	LHC now	HE-LHC inj. 1.3 TeV	HE-LHC inj. 0.9 TeV	HE-LHC inj. 450 GeV
rise time	$\mu\text{s}$	3	0.27	0.2	2
deflection angle	rad	0.27	0.27	0.27	0.27
magnet length	m	1.42	0.75	0.75	0.75
aperture height	m	0.072	0.054	0.062	0.072
gap field	T	0.323	0.49	0.49	0.49
$dI/dt$	kA/ $\mu\text{s}$	6.2	10.5	12.1	<b>14.0</b>
current	kA	18.5	21.1	24.2	<b>28.1</b>
voltage	kV	29.7	<b>35.7</b>	<b>35.7</b>	<b>35.7</b>
no. kicker modules	—	14	33	33	33
total installed length	m	25.6	32.6	32.6	32.6

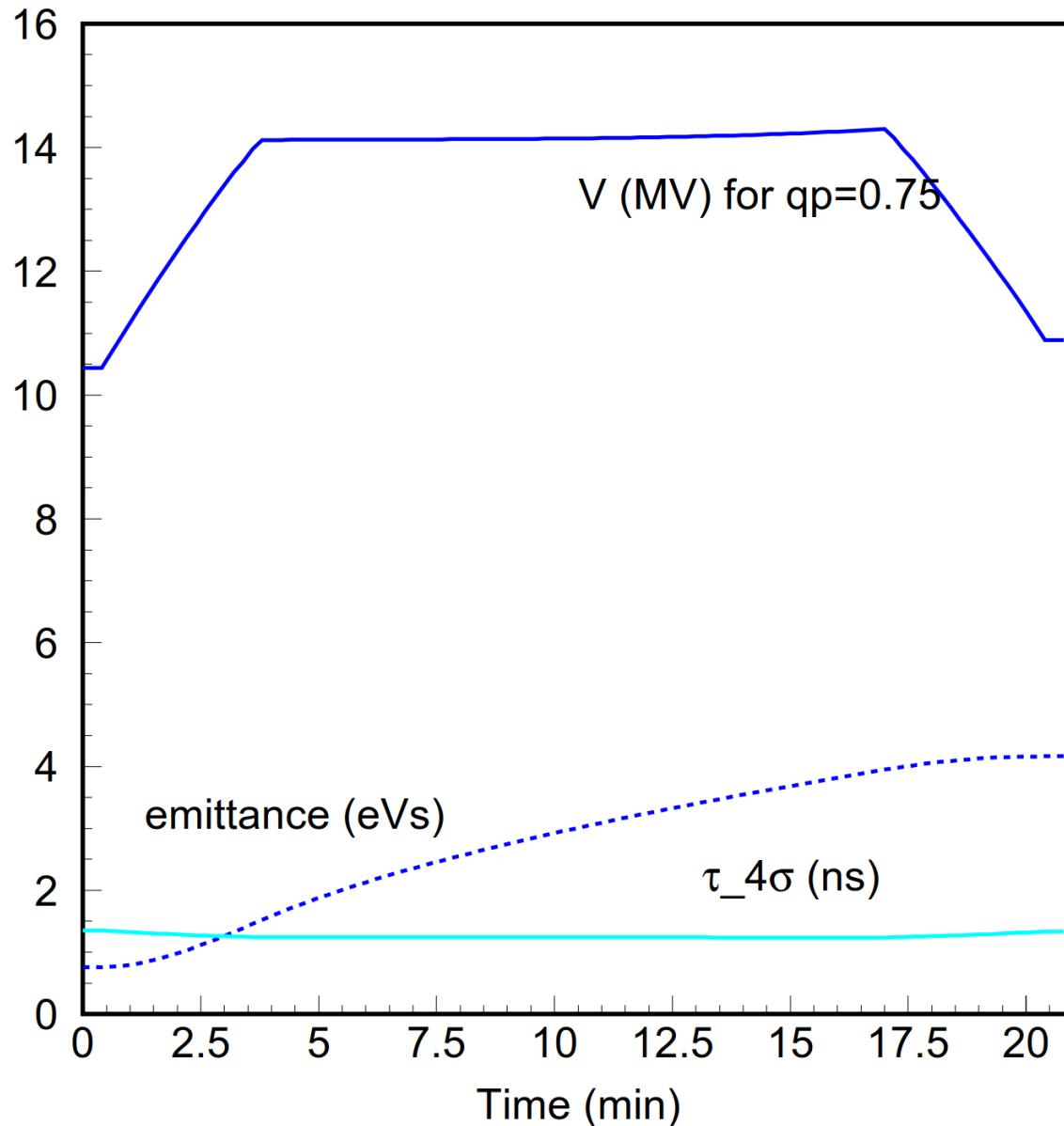
key parameters of  
LHC and HE-LHC  
injection kickers in  
IR2 and IR8

key parameters of LHC  
and HE-LHC extraction  
kickers in IR6

parameter	unit	LHC now	HE-LHC inj. 450 GeV	HE-LHC inj. 0.9 TeV	HE-LHC inj. 1.3 TeV
rise time	$\mu\text{s}$	1	1	1	1
deflection angle	rad	0.8	0.8	0.8	0.8
magnet length	m	2.72	2.7	2.7	2.7
aperture height	m	0.034	0.054	0.044	0.040
gap field	T	0.11	0.11	0.15	0.185
$dI/dt$	kA/ $\mu\text{s}$	4.7	4.7	5.3	5.9
voltage	kV	47.3	<b>47.2</b>	<b>52.6</b>	<b>58.9</b>
no. kicker modules	—	4	4	6	15
total installed length	m	15.3	15.3	22.4	56.9

injection kicker system longer  
for higher injection energy  
→ less space for secondary  
experiments?

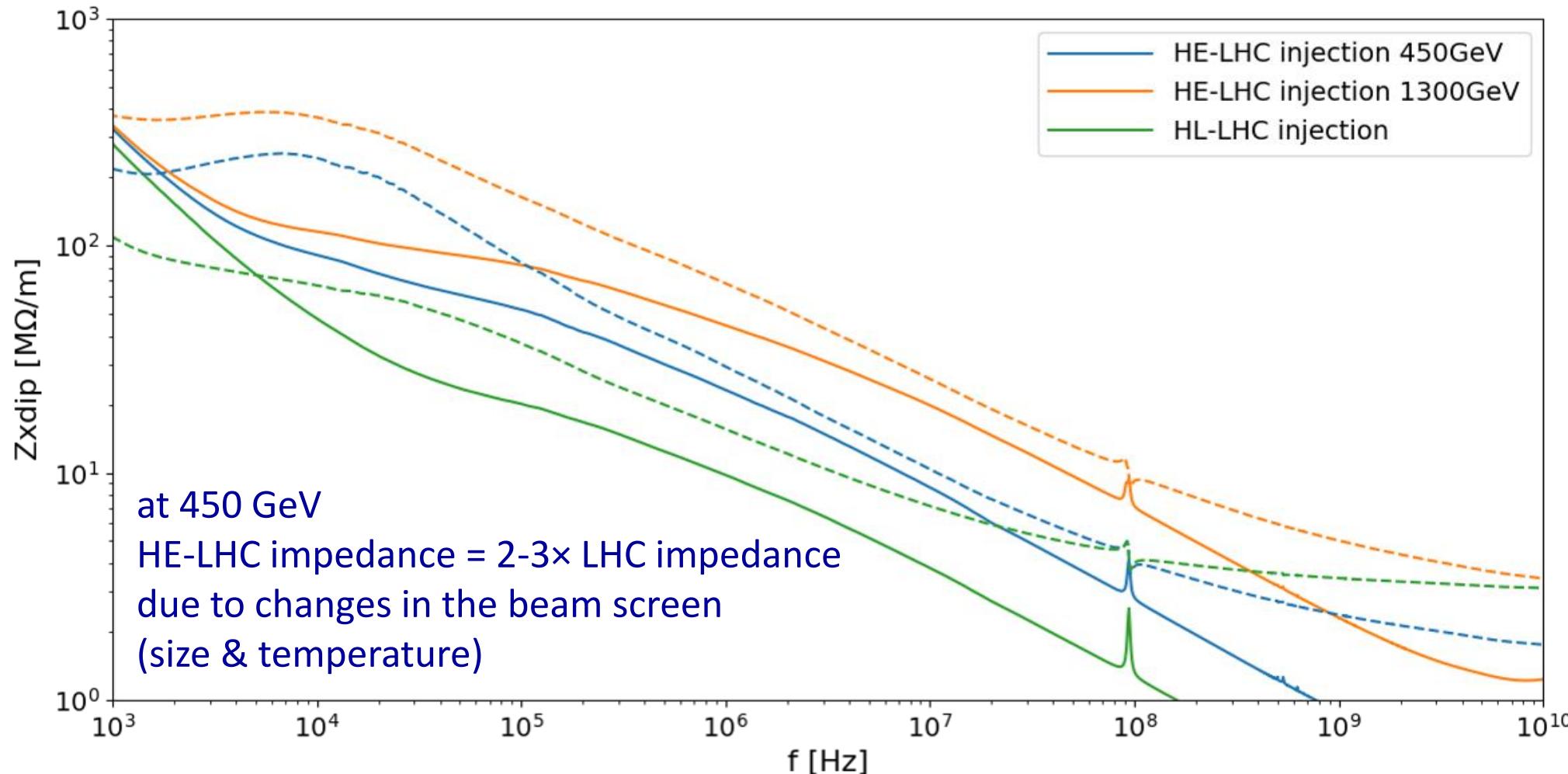
# longitudinal parameters



RF voltage (solid line) and emittance with controlled blow up (dashed line) during the 20-minute ramp from 450 GeV to 13.5 TeV. A transition energy  $\gamma_t$  of 53.8 is assumed.

RF power requirements do not exceed those of HL-LHC

# transverse impedance

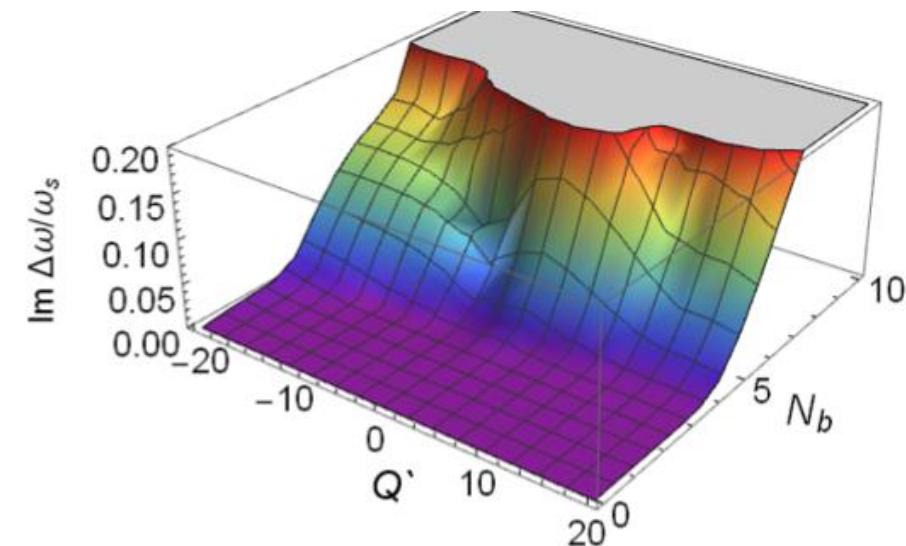
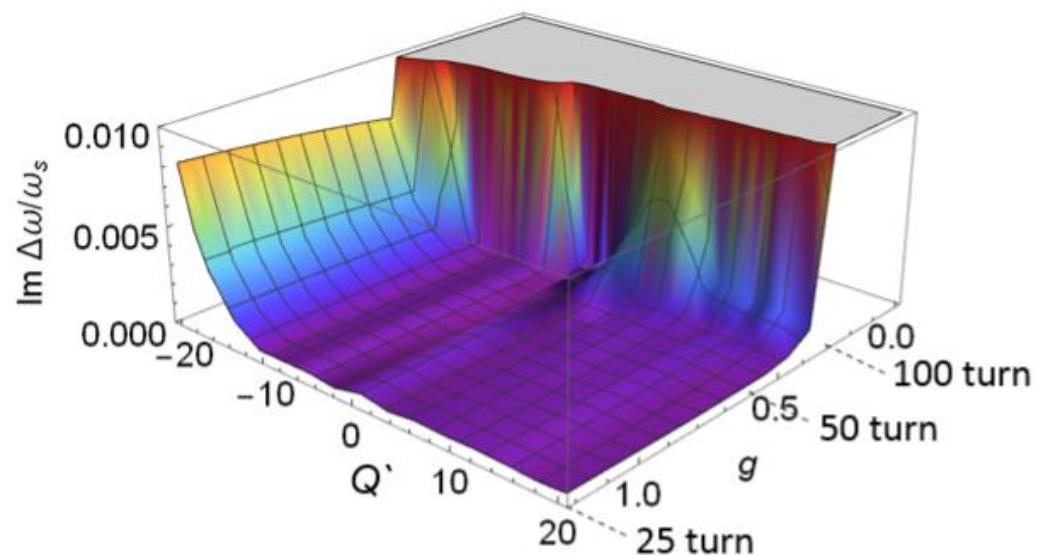


# conventional instabilities

Stability limits explored with Vlasov solvers (NHT and DELPHI):

At 450 GeV: feedback damping time < 50 turns needed

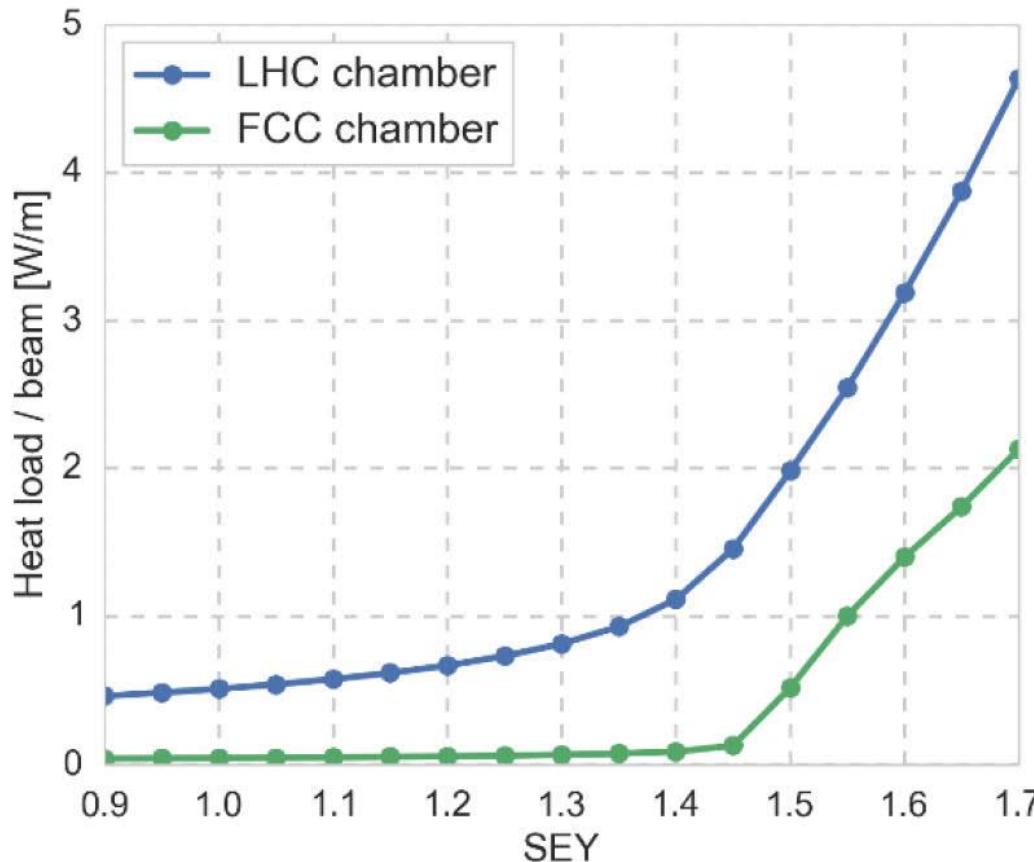
TMCI threshold  $\sim 7 \times 10^{11}$  ppb for single bunch,  $4 \times 10^{11}$  ppb for multi bunch, still 2x design



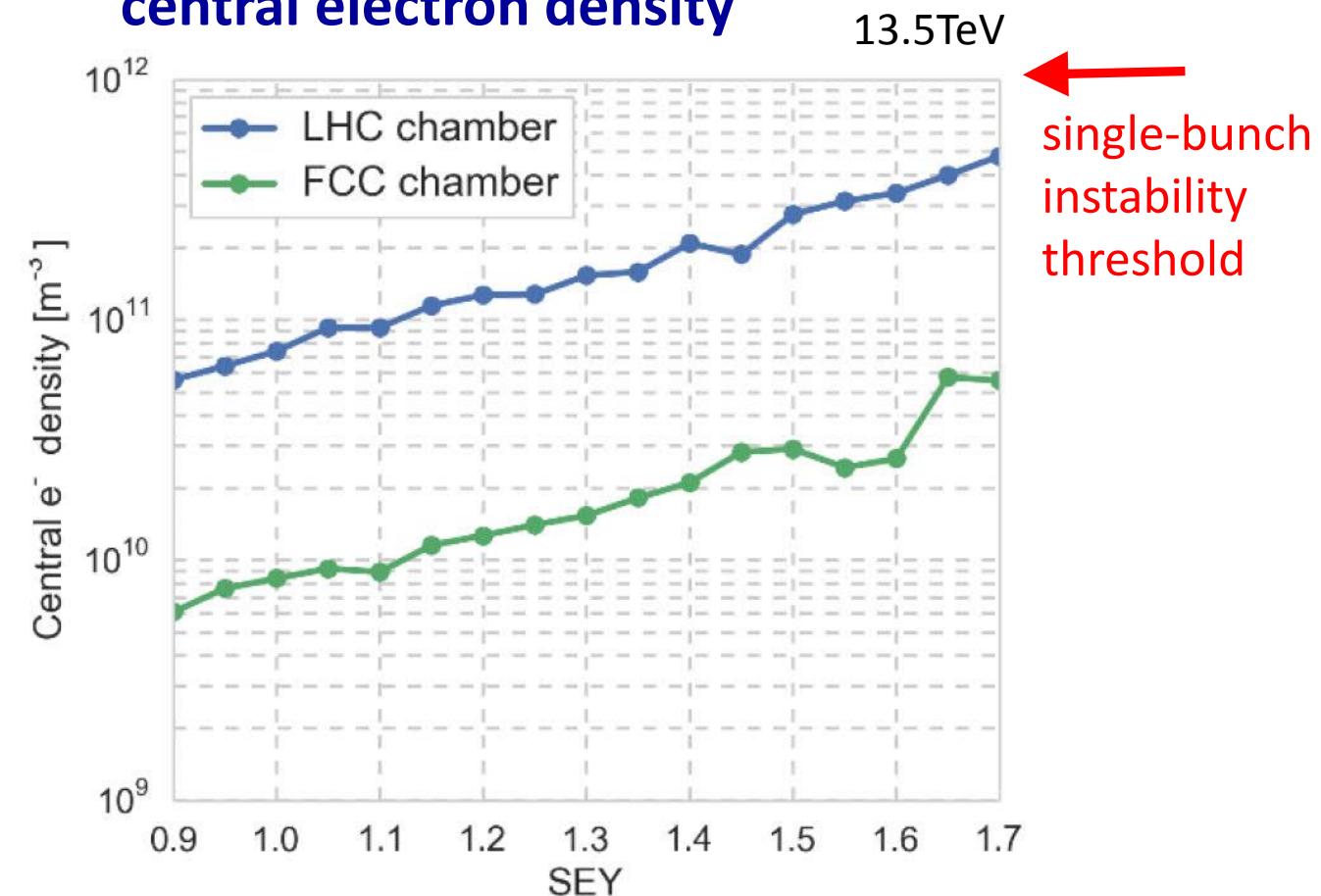
Growth rate of the most unstable mode  $\text{Im } \Delta\omega/\omega_s$  for  $N_b = 2.2 \times 10^{11}$  protons per bunch and 2748 bunches as a function of chromaticity  $Q'$  and damper gain  $g$  (left) and as a function  $Q'$  and  $N_b$  with a 50-turn damper (right) at 450 GeV.

# electron cloud

**heat load**

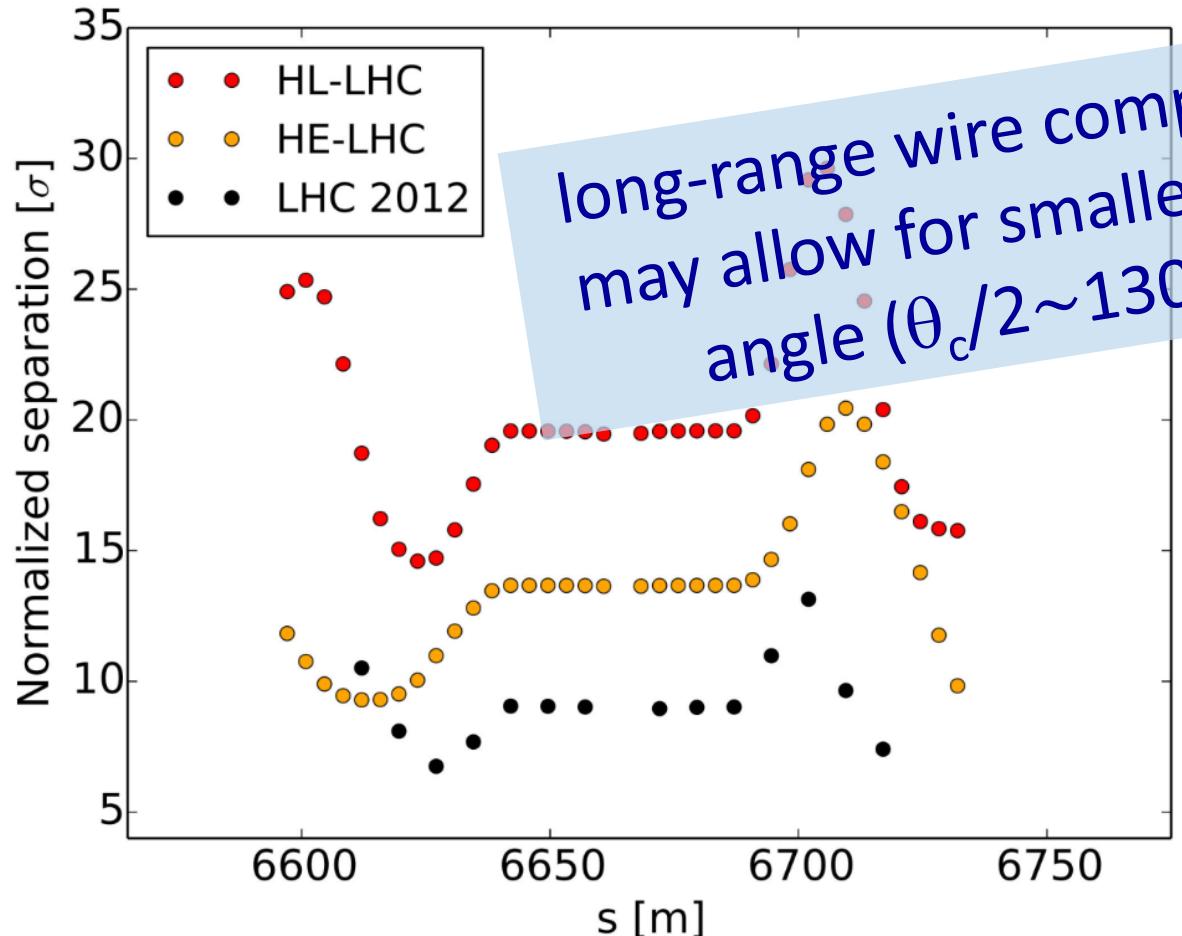


**central electron density**

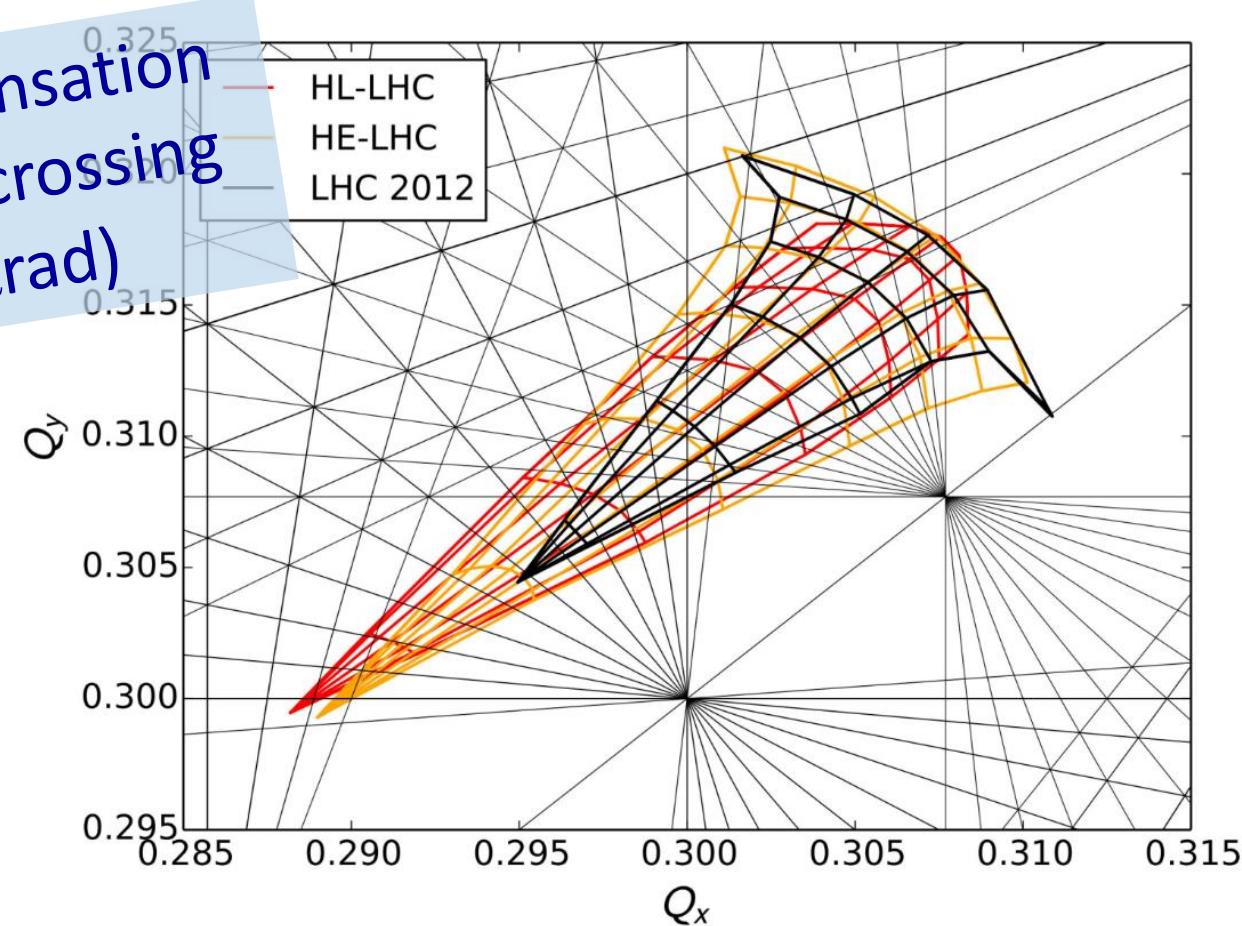


**maximum secondary emission yield**

# long-range & head-on beam-beam



long-range wire compensation  
may allow for smaller crossing  
angle ( $\theta_c/2 \sim 130 \mu\text{rad}$ )

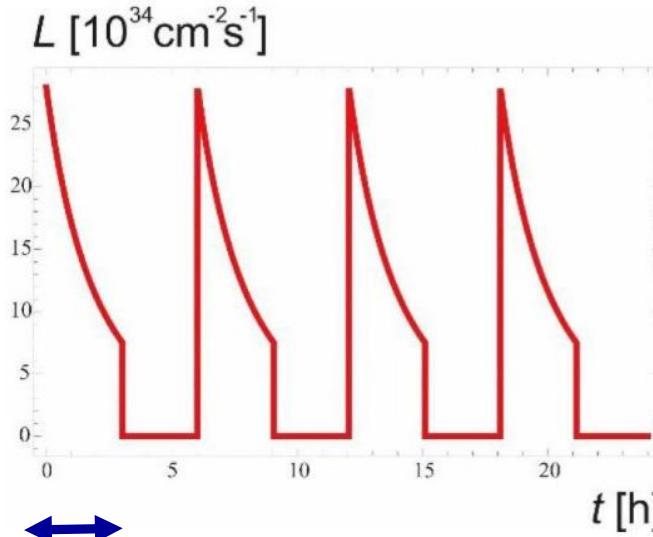


Separation at long-range encounters for the HE-LHC with  $180 \mu\text{rad}$  half crossing angle, compared with the HL-LHC and the LHC configuration of 2012.

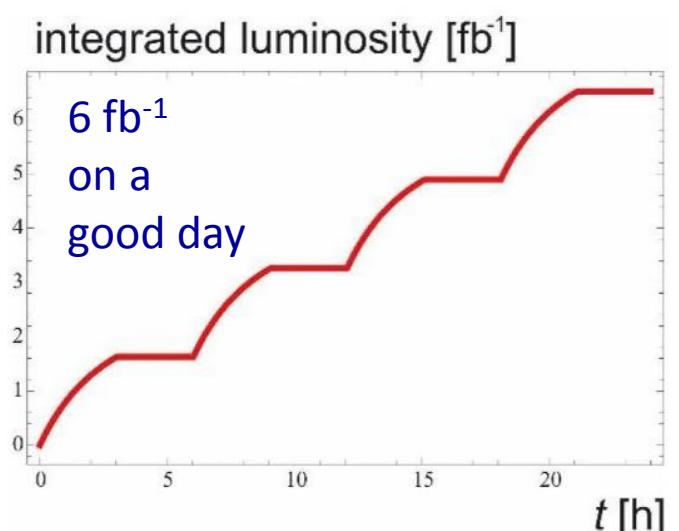
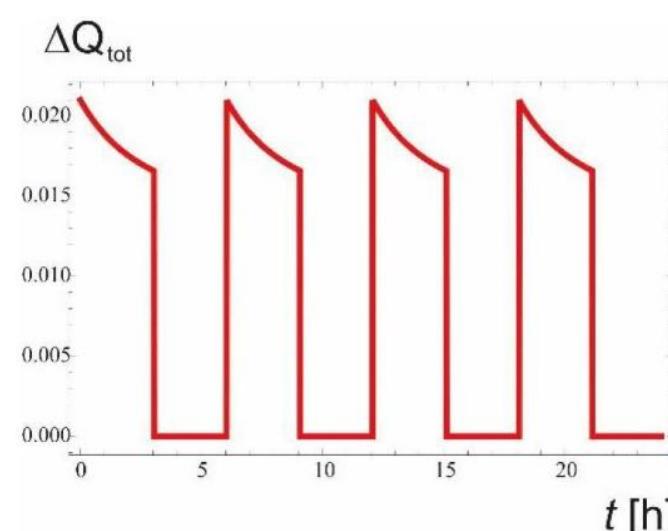
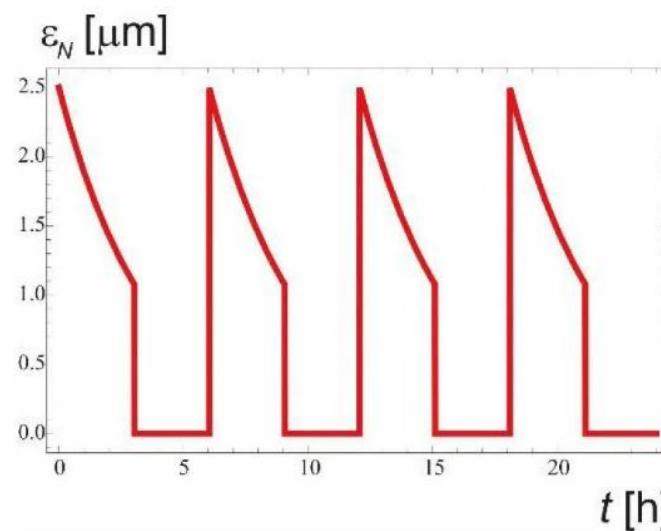
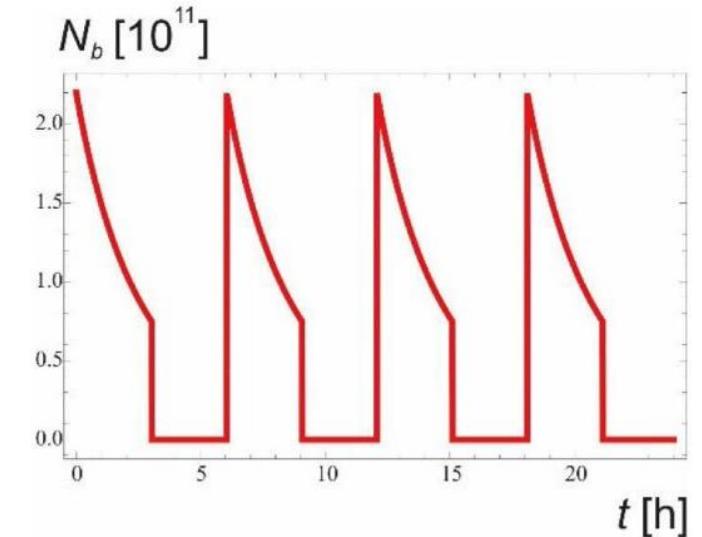
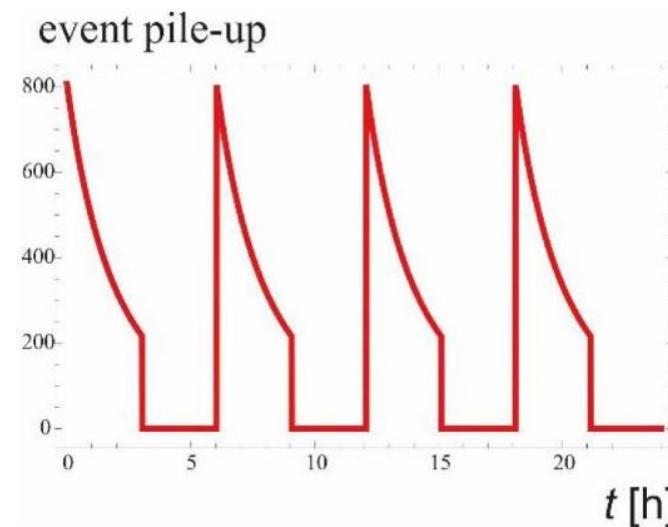
Beam-beam tune footprint up to  $6\sigma$  in transverse amplitude for HE-LHC with  $180 \mu\text{rad}$  half crossing angle, compared with HL-LHC and 2012 LHC configuration.



# 24 hours at the HE-LHC



optimum fill length  $\sim 3$  h



# luminosity / year vs turnaround time

HE-LHC assumptions:

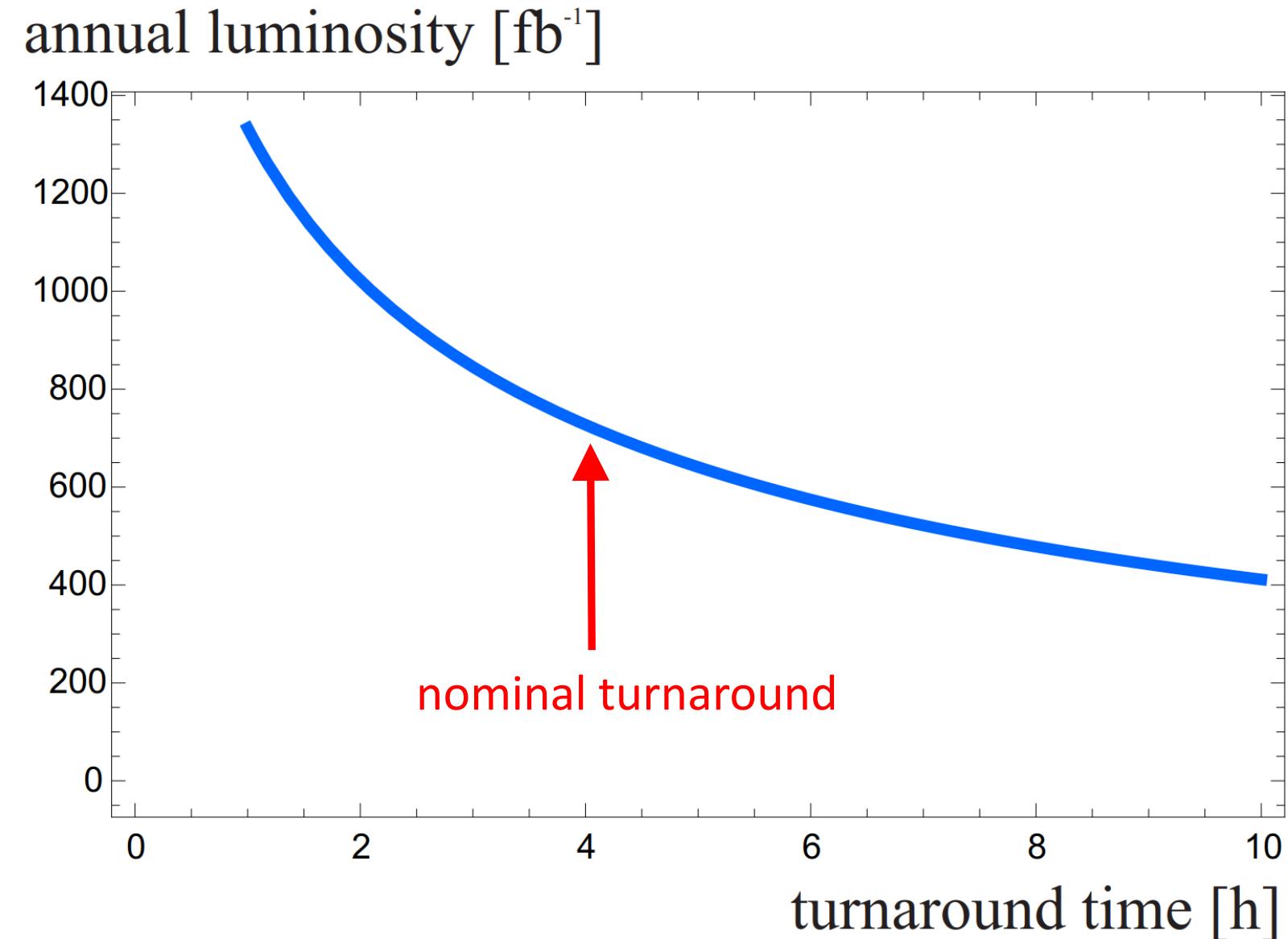
- 160 days scheduled for physics / year
- 70% availability

→ 30% of time in physics

for comparison  
LHC 2017:

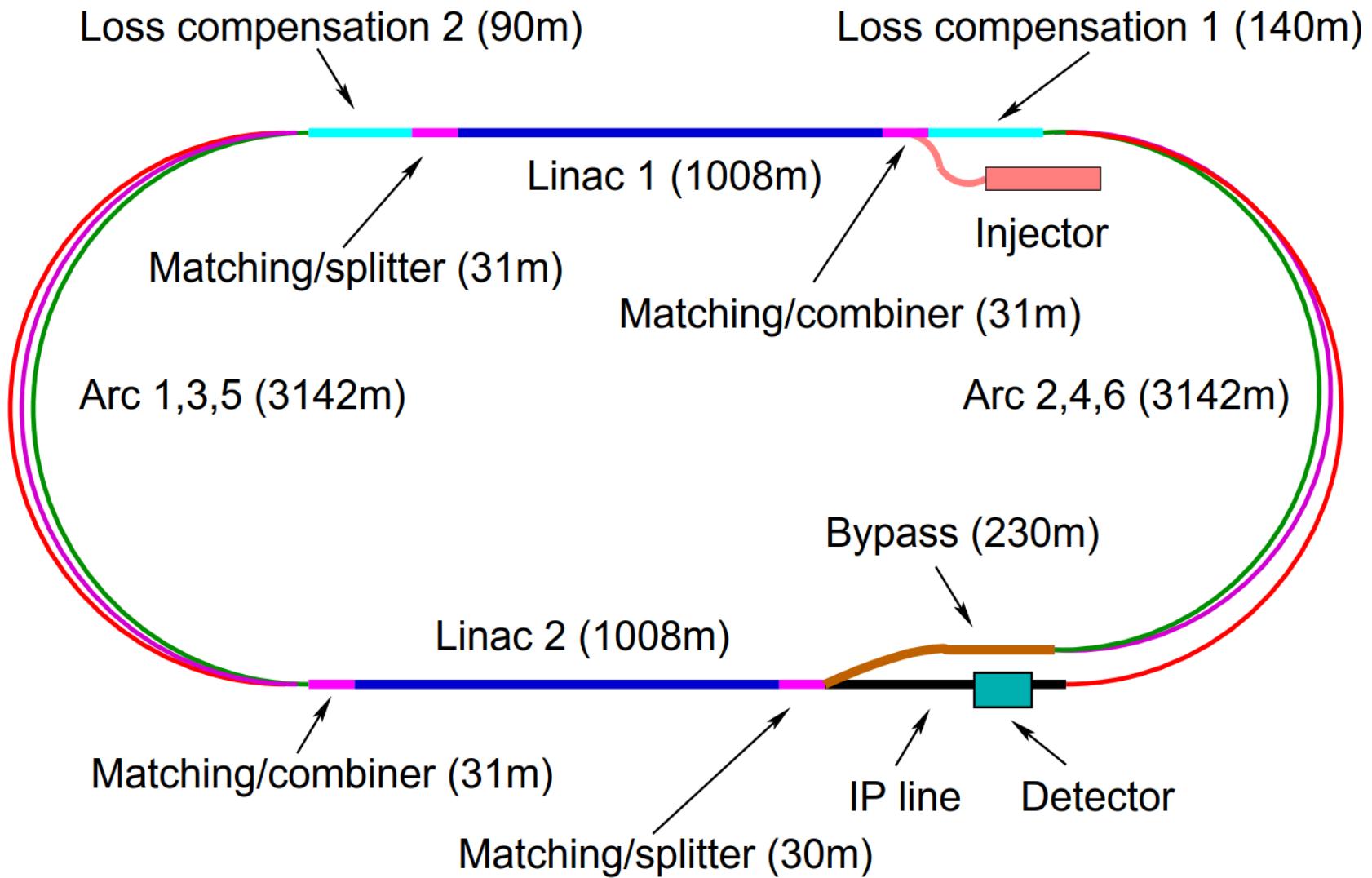
82.9% availability

49% of time in physics





# HE-LHeC: e<sup>-</sup> configuration like LHeC





# 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
$\gamma\epsilon_p$ [ $\mu\text{m}$ ]	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 $\beta_p^*$ [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 [ $10^{33}\text{cm}^{-2}\text{s}^{-1}$ ]	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



# HE-LHC conclusions

- optics solution with injection at 1.3 TeV & top energy 13.5 TeV (nearly) at hand; **would require sc SPS as injector**
- investigating alternative with injection at 450 GeV, maximum energy 13 TeV
- related magnet design improvements under study (APC's, shims,...)
- dynamic aperture, machine protection and collimation system challenging
- HE-LHC magnets, integration, and cryogenics not trivial
- collective effects mostly under control

*a great team and getting stronger*

# HE-LHC at FCC Week 2018

Tuesday 10 April	HE-LHC: Options and Beam-Beam, Chair: Angeles Faus-Golfe (IN2P3 LAL)	
13:30-13:50	Nuclear beams at HE-LHC	John Jowett (CERN)
13:50-14:10	Dynamic aperture at injection for different lattice options	Yuri Nosochkov (SLAC)
14:10-14:30	HE-LHC with flat beams	Jose Abelleira (JAI)
14:30-14:50	Beam-beam effects at HE-LHC	Tatiana Pieloni (EPFL)
Thursday 12 April	HE-LHC: Parameters & Optics, Chair: Andrei Seryi (JAI)	
13:30-13:48	Parameters, constraints, options	Frank Zimmermann (CERN)
13:48-14:06	HE-LHC optics overview	Rogelio Tomas (CERN)
14:06-14:24	Experimental Interaction Region Optics for the High Energy LHC	Leon van Riesen-Haupt (JAI)
14:24-14:42	Injection and extraction	Brennan Goddard (CERN)
14:42-15:00	Optics integration	Jacqueline Keintzel (TU Vienna)
Thursday 12 April	HE-LHC: Collimation and Beam Dynamics, Chair: Yunhai Cai (SLAC)	
15:30-15:48	IR1/5 radiation shielding	Jose Abelleira (JAI)
15:48-16:06	Collimation	Matthew Crouch (CERN)
16:06-16:24	Correction Circuits and Dynamic Aperture	Michael Hofer (TU Vienna)
16:24-16:42	First HE-LHC impedance model and aspects of single beam stability	David Amorim (U. Grenoble Alpes)
16:42-17:00	HE-LHC electron cloud	Lotta Mether (EPFL)

*thank you !*

*hartelijk dank !*

*spare slides*

# HE-LHC integration aspects

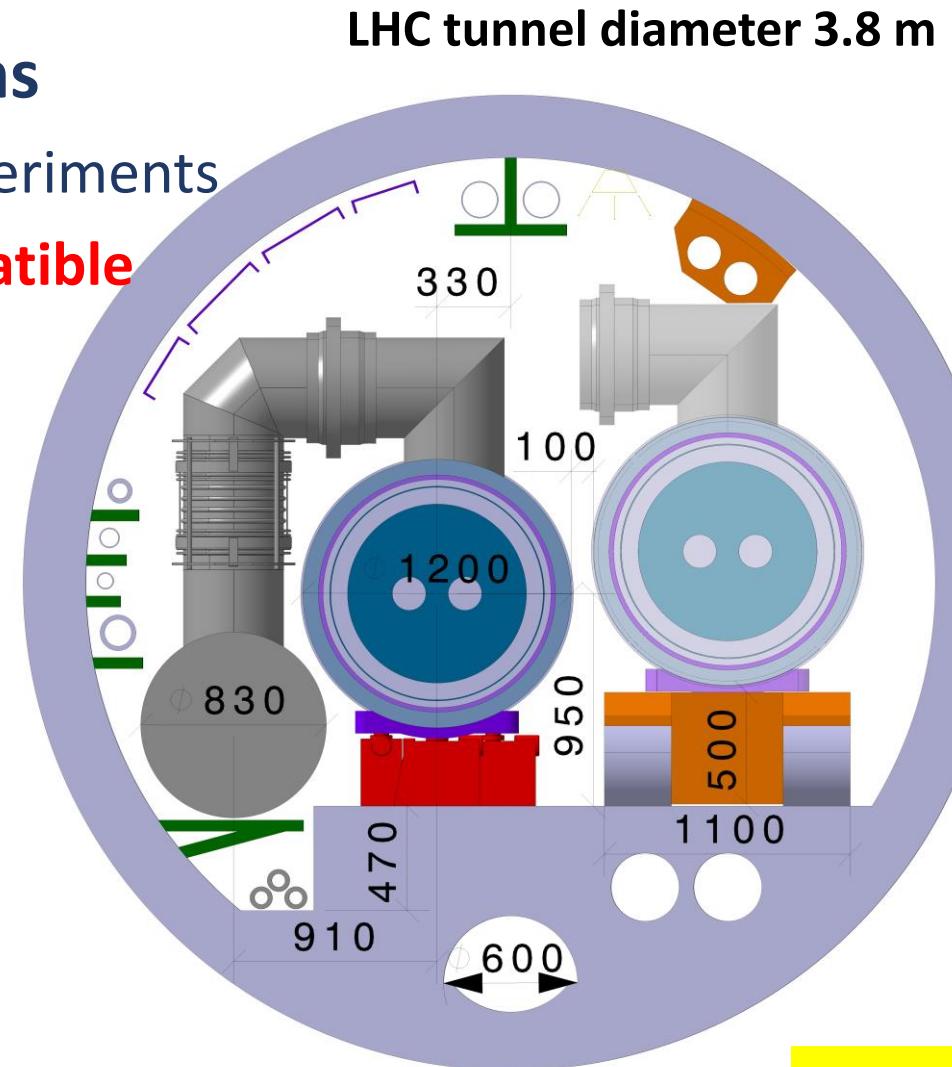
working hypothesis for HE LHC design:

no major CE modifications on tunnel and caverns

- similar geometry and layout as LHC machine and experiments
- **maximum magnet cryostat external diameter compatible with LHC tunnel  $\sim 1200$  mm**
- **classical cryostat design gives  $\sim 1500$  mm diameter!**

strategy: develop optimized 16 T magnet,  
compatible with both HE LHC and FCC-hh  
requirements:

- **allow stray-field and/or cryostat as return-yoke**
  - **optimization of inter-beam distance (compact)**
- smaller diameter also relevant for FCC-hh cost



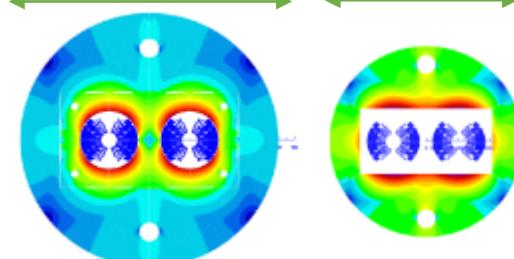
# 16 T cryo-dipole integration approach

## design evolution

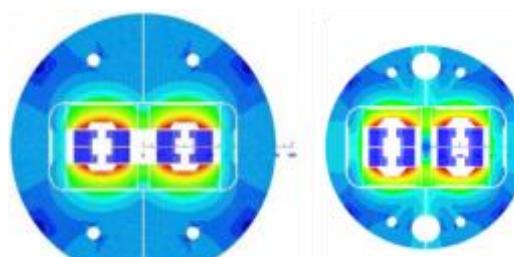
- coil optimization and margin 18 → 14%
- inter-beam distance 250 → 204 mm

stray-field < 0.1 T at cryostat

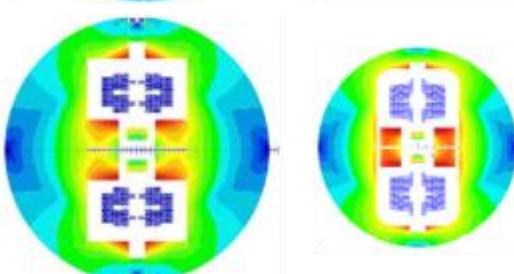
800 mm      600 mm



cosine-theta  
(baseline)



block-type coils

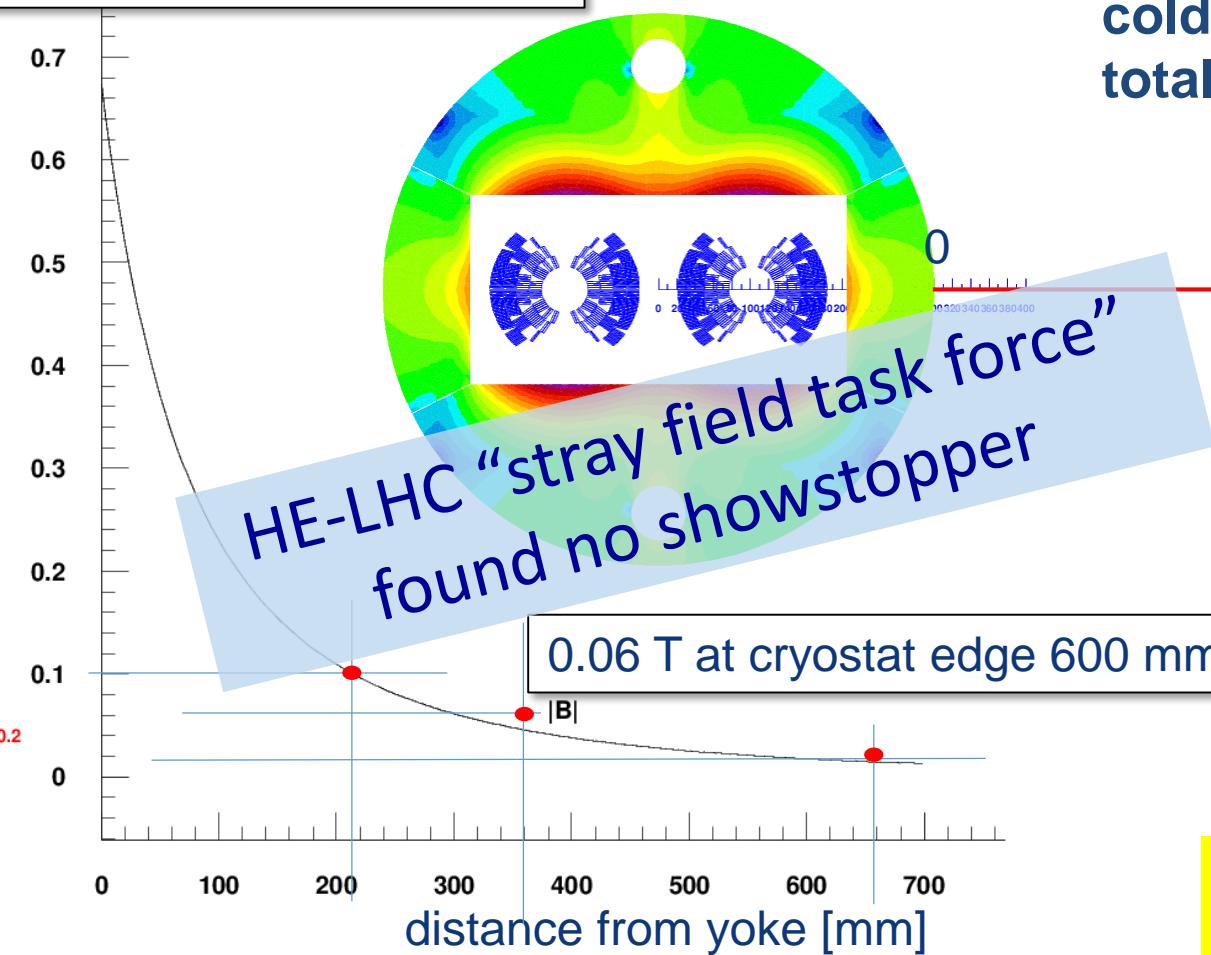


common-coils

2015

2017

fringe field – x axis [T]



cold mass 40t  
total mass 62t

700

# HE-LHC cryogenic layout

higher heat load and integration limitations  
(Cryo-line diameter) requires installation of

- **8 additional 1.8 K refrigeration units wrt. LHC**

- 2.3 kW @ 1.8 K (~ LHC size)
- P elect: ~500 kW per unit



- **8 new higher-power 4.5 K cryoplants**

- 28 kW @ 4.5 K (including 2.3 kW @ 1.8 K)
- P elect: ~6500 kW per cryopplant  
(cf. 4200 kW for LHC cryopplant)

half-sector cooling instead of full sector (as for LHC)  
to limit cross section of cryogenic distribution line

