Optics Integration

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Acknowledgements to
Michael Hofer, Rogelio Tomás Garcia,
Léon v. Riesen-Haupt, Thys Risselada,
Demin Zhou, Frank Zimmermann

Outline

- Overview of HE-LHC lattices generation and parameters
- Integrated IR optics
- b2-errors at collision energy
- Different beam screens and their effect on the aperture

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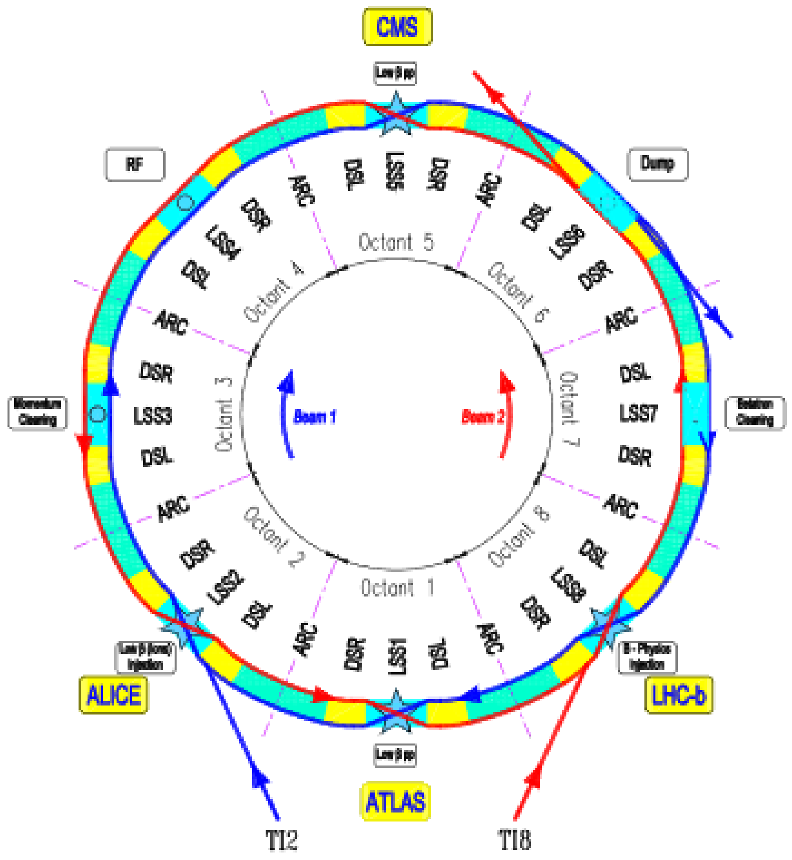
HE - Lattice Generation

- Scaling LHC is not enough
  - Strength, gradients would exceed limits
- New elements (FCC magnets), distances, …
- Explore various options
  - 23x90 (23 arc cells, 90° phase advance; LHC like)
  - 18x90 (18 arc cells, 90° phase advance)
  - …



LHC Design Report

HE - Lattice Generation

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- New elements (FCC magnets), distances, …
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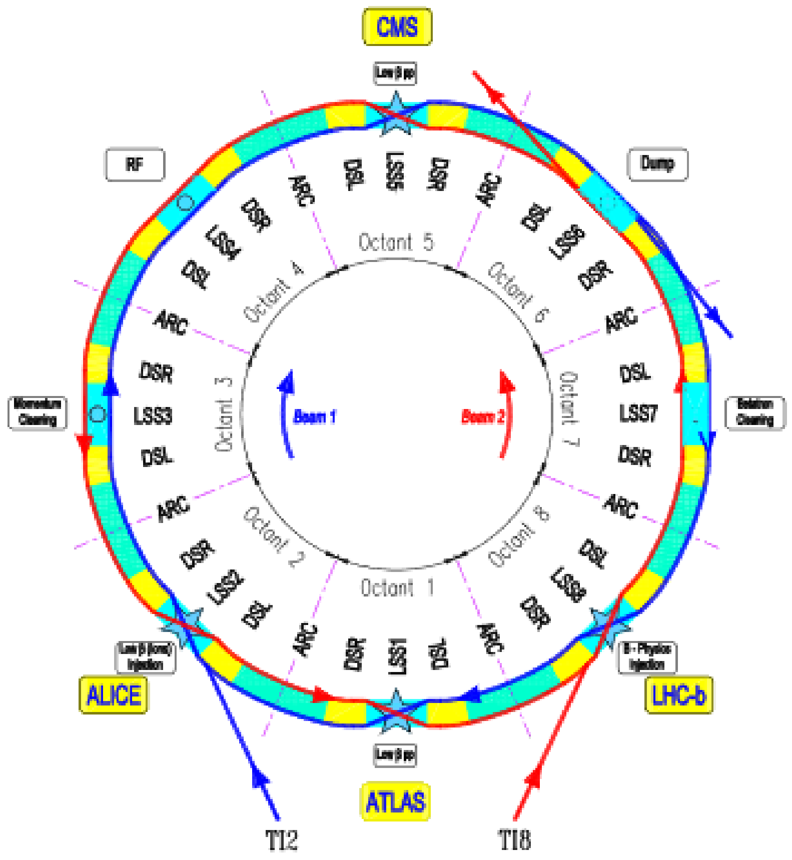
  - 23x90 (23 arc cells, 90° phase advance; LHC like)
  - 18x90 (18 arc cells, 90° phase advance)
  - …
- Generation by use of tool



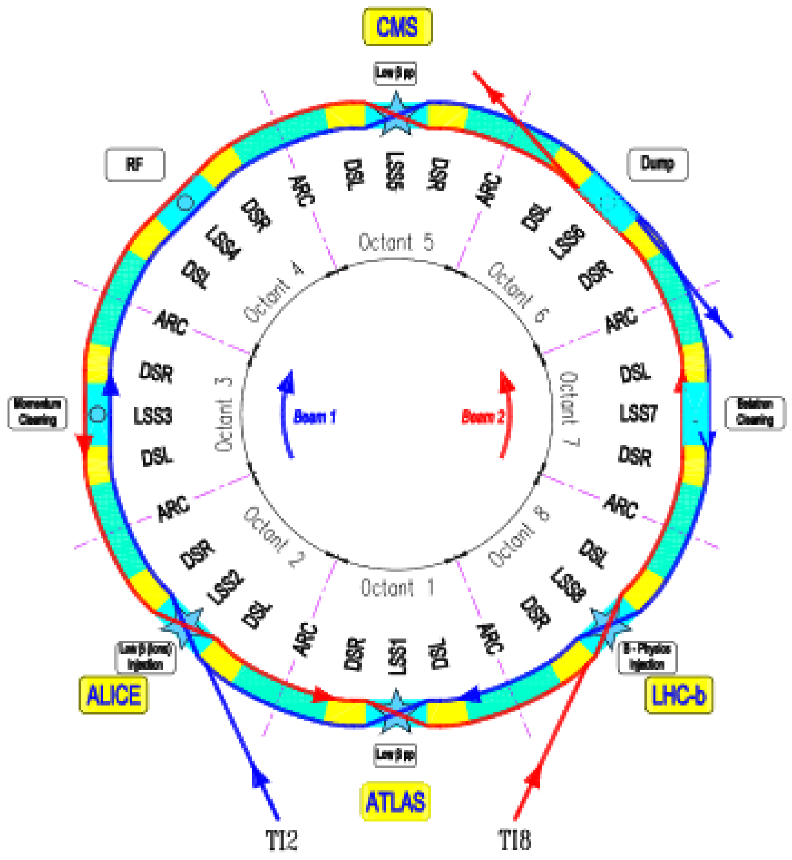
→ ALGEA (**A**utomatic **L**attice **GE**neration **A**pplication)

LHC Design Report

Lattice Generation with *ALGEA*

- Based on a few input parameters flexible generation of
  - Sequence
  - Powering
  - Naming convention
  - Dispersion Suppressor (DS)

- Constraints
  - Tunnel length (26658.8832 m)
  - 2 beams with beam separations
  - 4 crossing points
  - 8 long straight sections
  - Element distances (MB-MB, …)



LHC Design Report

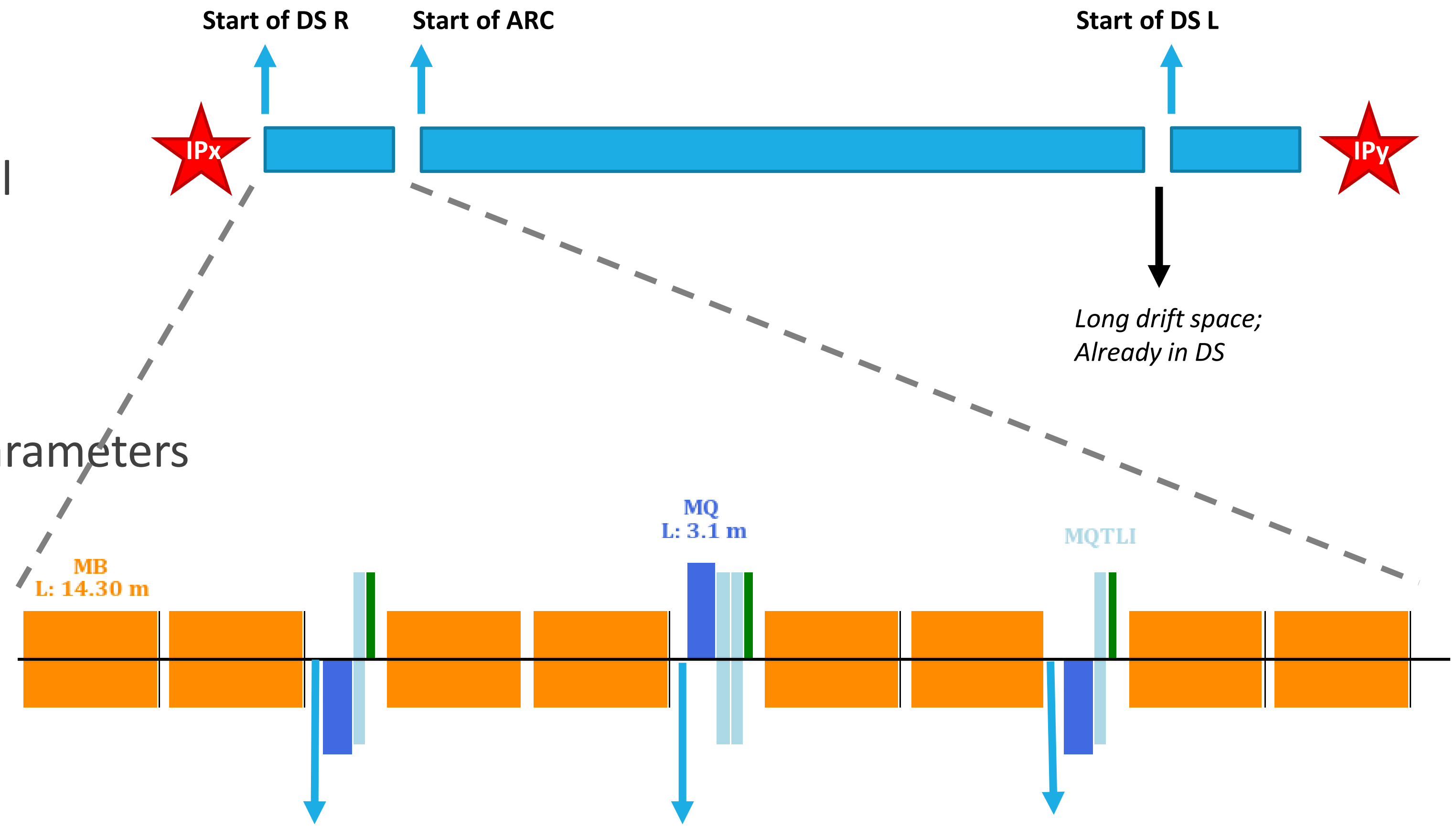
Survey fitting, DS optimisation with *ALGEA*

- Lattice generation still challenging

  → new machine has to fit in the tunnel

  → DS has to be optimised for lattice

- Automatic survey fitting by varying parameters
  - Minimizing offset to LEP tunnel
  - IP5 exactly opposite to IP1
  - Matchability, aperture, …



If varying the drift spaces is not enough:

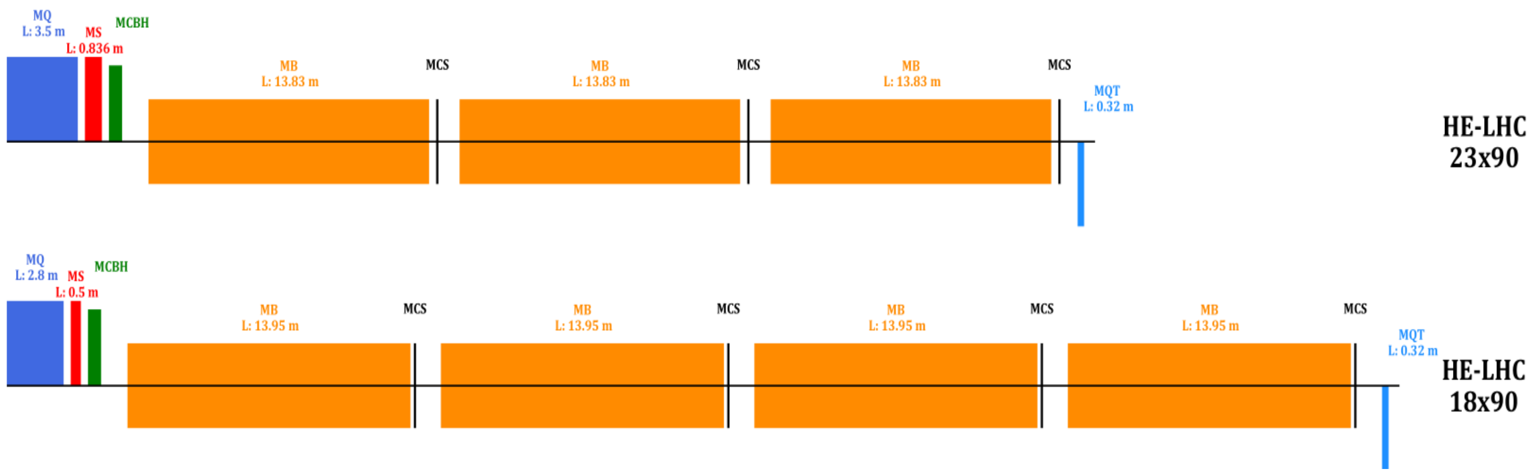
Cell length; MB length

Extra drift between MB and MQ in the DS

(LHC: + 1.0m (IP3, IP7); + 0.8m (other IPs), compared to an arc cell)

Arc Cells, Tuning, Correctors

- MQT:
  - Located next to MQ in the first 4 arc cells
  - Small changes compensated with IR4



- MS, MCS:
  - Chromaticity is corrected with two defocusing and two focusing sextupole families
  - b3, b4, b5 correction is required (see dynamic aperture studies by Yuri Nosochkov and Michael Hofer)

- MCBH, MCBV:
  - Spurious dispersion due to crossing angle is cancelled out due to orbit bumps

Lattices

- LHC cannot be directly scaled to 13.5 TeV (max. gradient and field strengths are exceeded) → new cell layout
- Focusing on two possible lattices (18x90, 23x90) due to previous studies
- V0.4 is under development

V0.3	18x90	23x90
Arc cell phase advance [°]	90	90
Arc cell length [m]	137.227	106.9
K_1 [m^{-2}]	0.00746	0.00773
Quadrupole strength at 13.5 TeV [T/m]	336	348
$\beta_{max, min}$ [m]	230 / 40	177 / 32
$D_{max, min}$ [m]	3.6 / 1.76	2.2 / 1.1
Momentum Compaction α_C [10^{-4}]	5.8	3.5
Quadrupole length	2.8	3.5
Dipole length [m]	13.95	13.83
Filling factor	0.81	0.78
Dipole filed for 13.5 TeV [m]	15.83	16.59
c.o.m. energy for 16 T [TeV]	27.28	26.01

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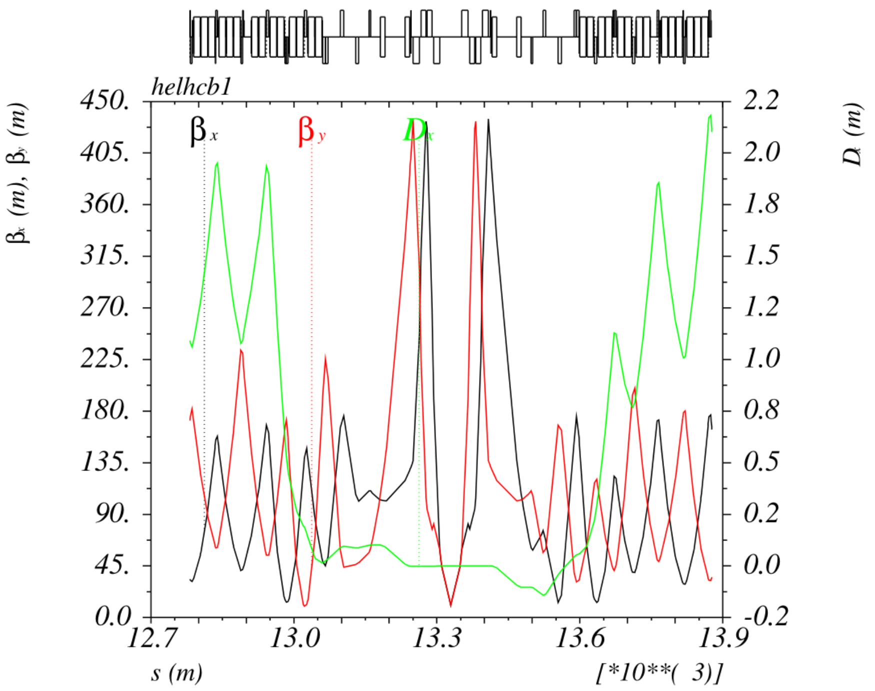
Insertions - Experiments and RF

IR1/5: Experiments



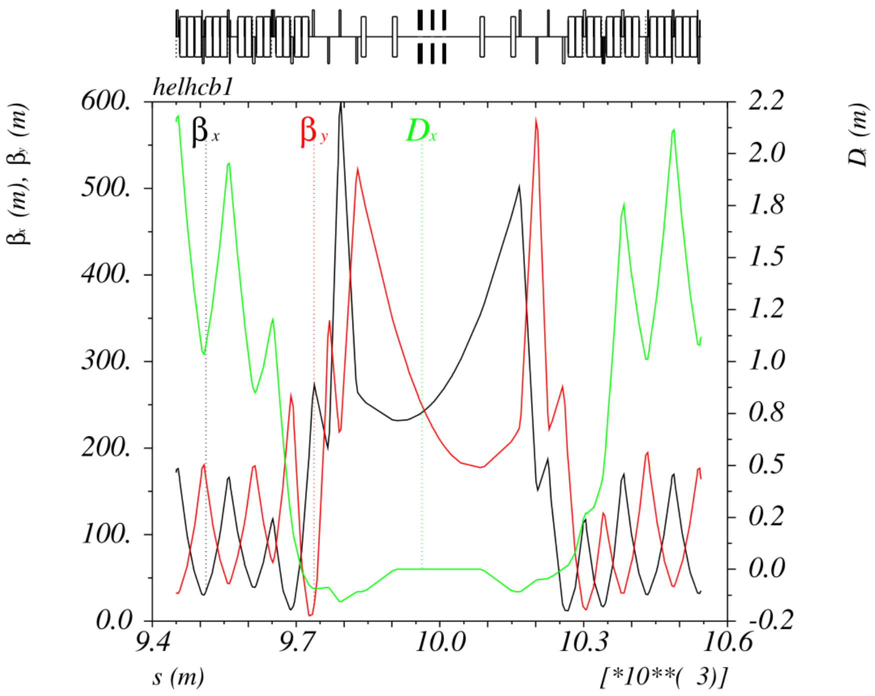
IR 1/5 by Léon van Riesen-Haupt is integrated at injection;

Issues with phase advance at collision energy

Injection β* = 11m

Optics taken from 23x90 lattice, for injection optics

IR4: Instrumentation and RF

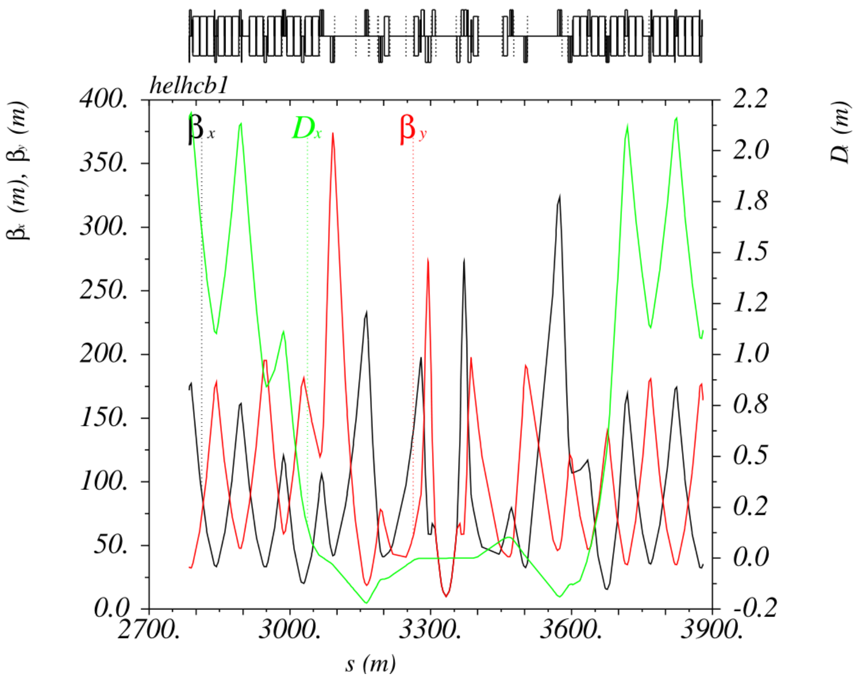


IR4 by Pablo Mirave and Léon van Riesen-Haupt is integrated

contains additional quadrupoles compared to LHC IR4; helps tuning the ring

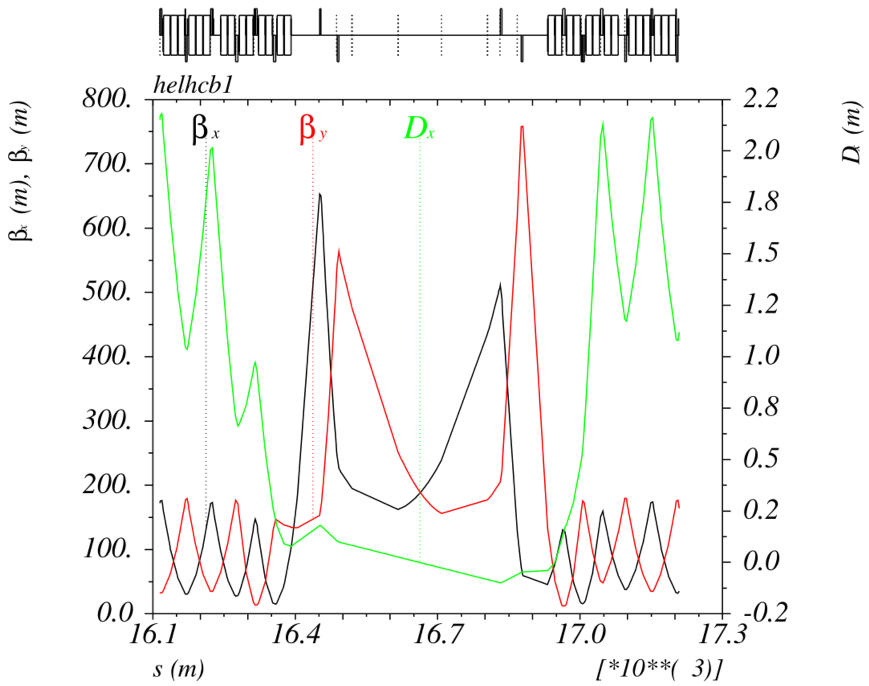
Insertions - Injection and Extraction

IR2: Injection and Experiment



IR2 from LHC is integrated

IR6: Extraction

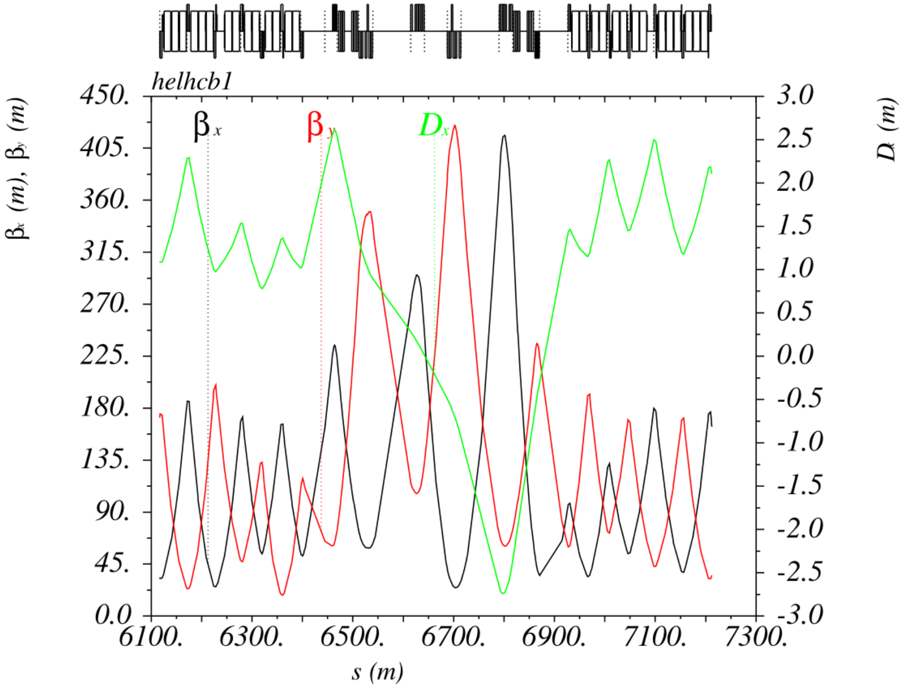


IR6 by Wolfgang Bartmann and Brennan Goddard is integrated (see Brennan's talk)

Optics taken from 23x90 lattice, for injection optics

Insertions - Collimation

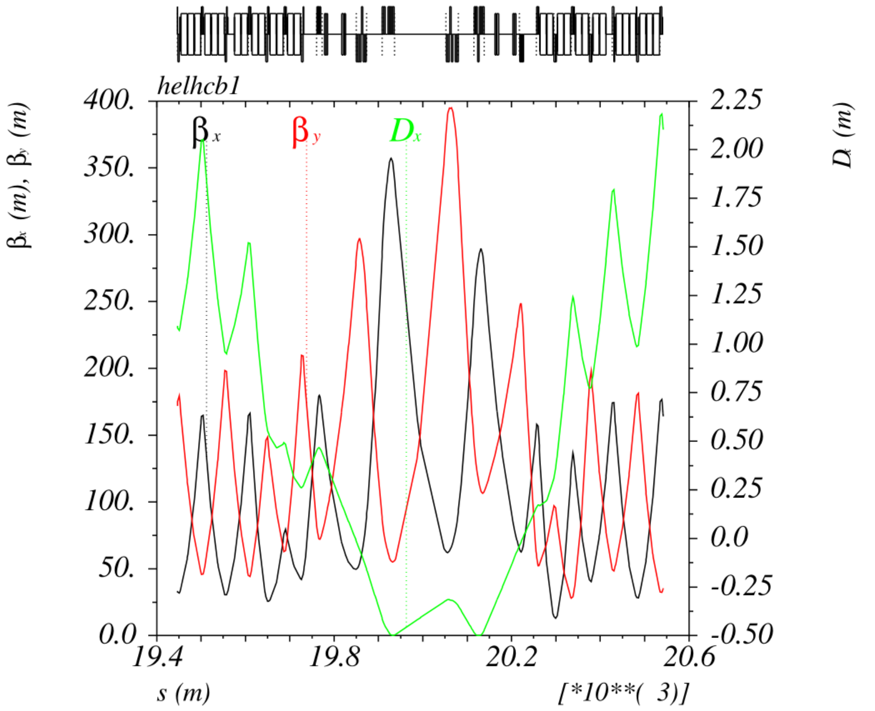
IR3: momentum collimation



IR3 from LHC is integrated

Thys Risselada works on new HE-LHC IR3

IR7: β- collimation



IR7 from LHC is integrated

Matthew Crouch works on new HE-LHC IR7 (see Matthew's talk)

Optics taken from 23x90 lattice, for injection optics

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Quadrupole errors in the dipoles

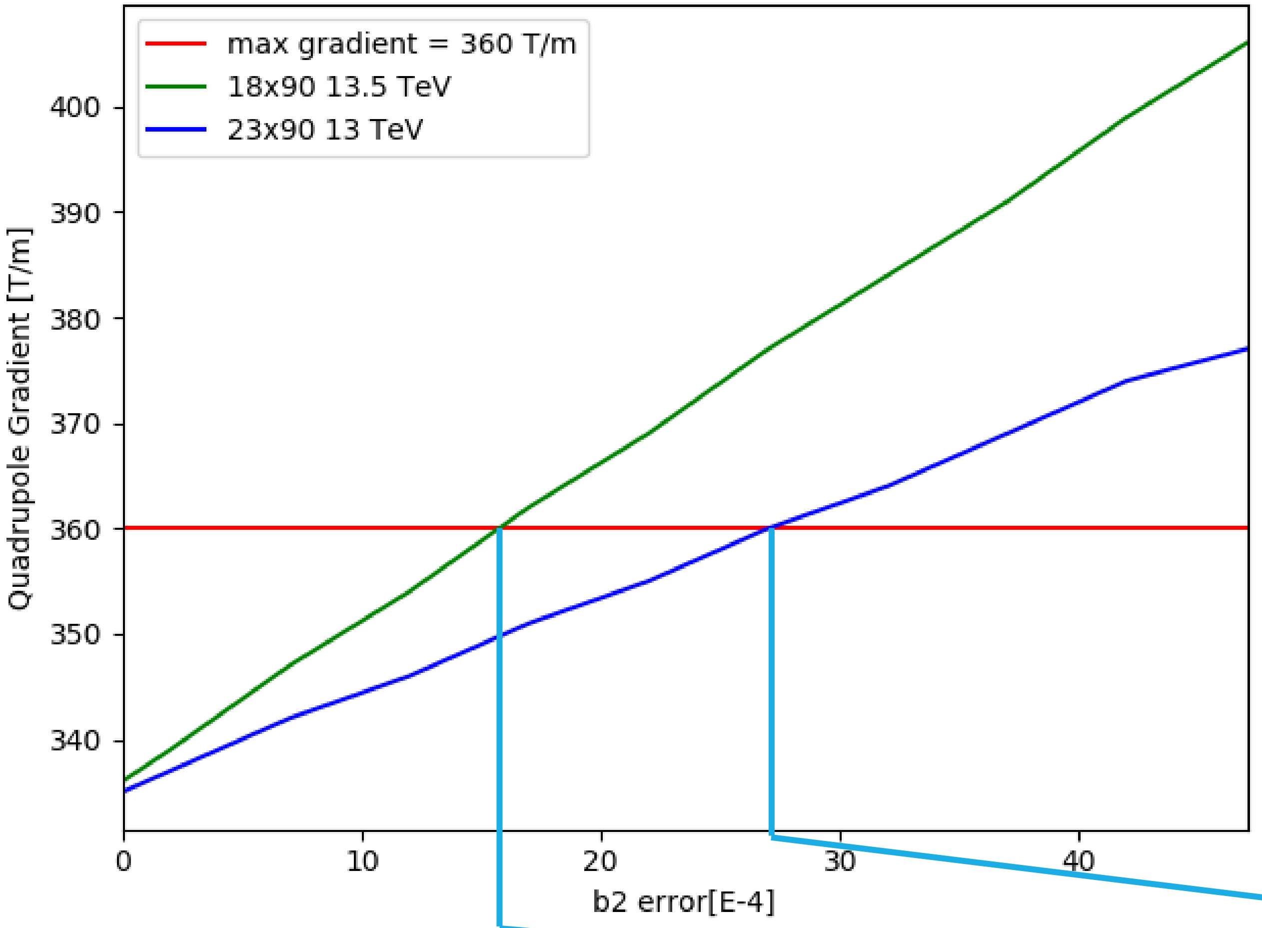
- Magnetic field of e.g. dipoles includes higher magnetic orders
- ***b2-component → quadrupole error***
- Sign depends on position of beam (inner or outer arc)
- Quadrupole errors are corrected with higher gradient in main quadrupoles; quadrupoles need to be larger and so dipoles become shorter (only in 23x90 lattice; no need to shorten dipoles in 18x90 due to spare space)

23x90, without b2-errors

23x90, with b2-errors = +/- 46.84 units *

* S.I. Bermudez, private communication, Jan 2018

Required quadrupole strength with b2-errors in dipoles



b2	18x90	23x90
	Max. grad	Max. grad
0	336 T/m	335 T/m
46.840	405 T/m	377 T/m

with b2 = +/- 46.84 units at collision energy maximal gradient of 360 T/m is exceeded (either for focusing or defosusing quadrupole)*

→ *quadrupole length needs to be increased*

Maximum b2 errors the lattices can bear:
→ ≈ 16 units for 18x90
→ ≈ 27 units for 23x90

** S.I. Bermudez, private communication, Jan 2018*

Quadrupole errors in the dipoles

- 18x90: longer quadrupole length has no impact on other cell parameters (spare space)

- 23x90: if quadrupole length increases, dipole length has to be decreased to fit in cell

→ effect on c.o.m. Energy

→ loss of 0.1 TeV c.o.m.

→ b2 – errors need to be decreased to ≈ **30 units**

18x90		23x90	
LMQ	**Energy**	**LMQ**	**Energy**
2.8 m	27.26 TeV	3.5 m	26.01 TeV
3.15 m	27.26 TeV	3.67 m	**25.90 TeV**

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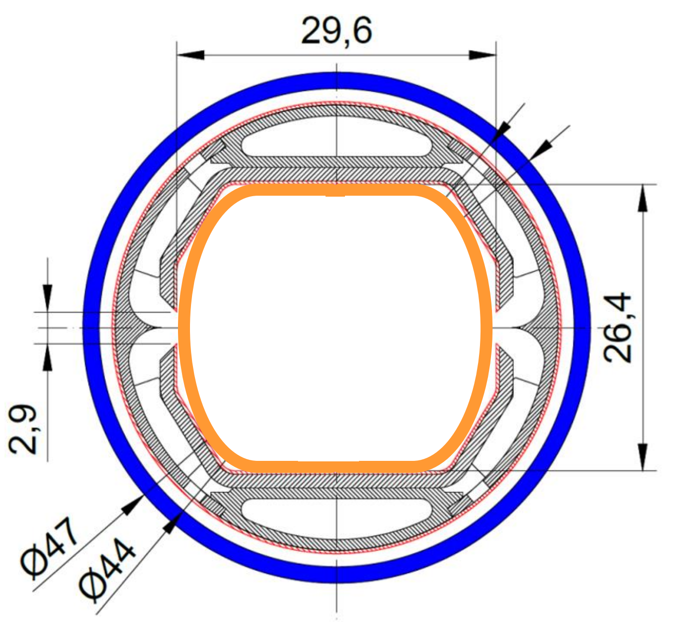
Different Beam Screens (BS)

taken from FCC-hh

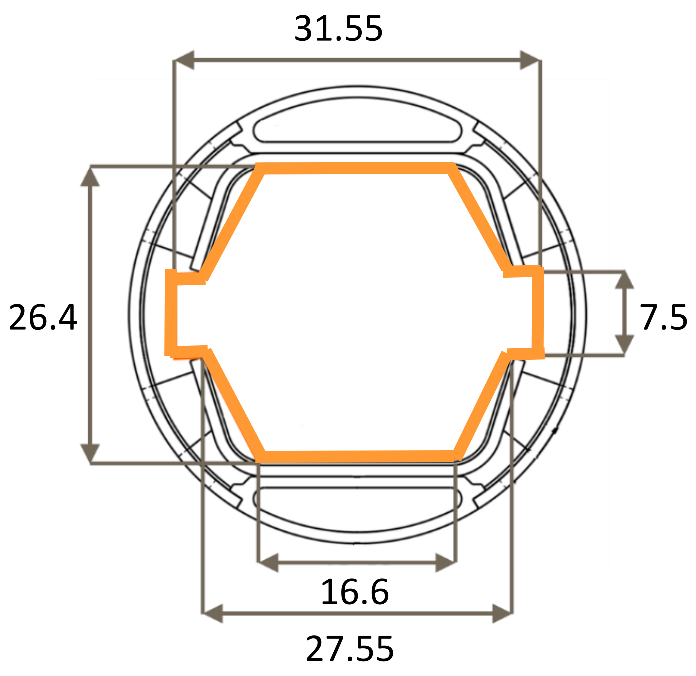
2016



APERTURE = {0.015, 0.0132, 0.015, 0.015}

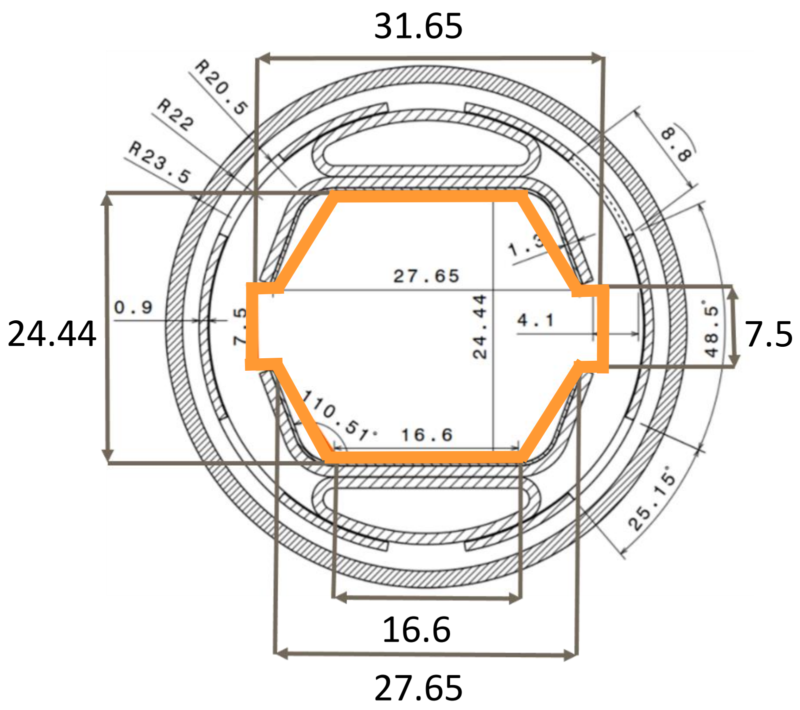
[C. Garion, FCC Week Apr. 2016](#)

2017



[I. Bellafont, EuroCirCol meeting Oct. 2017](#)

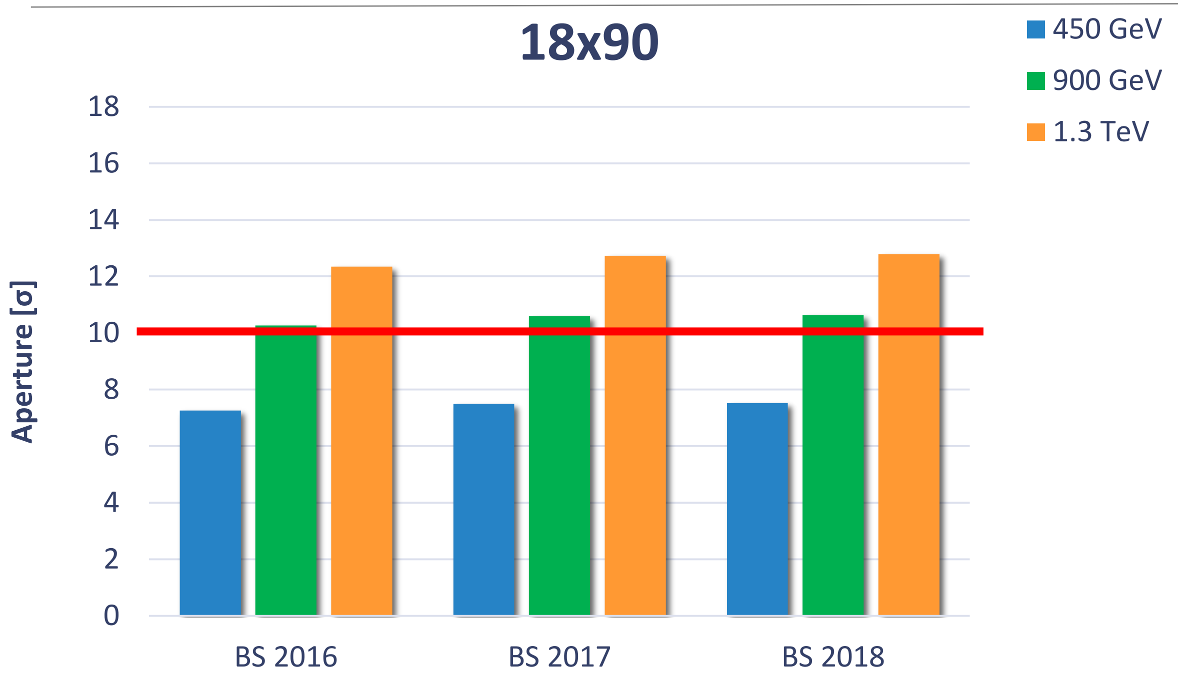
2018

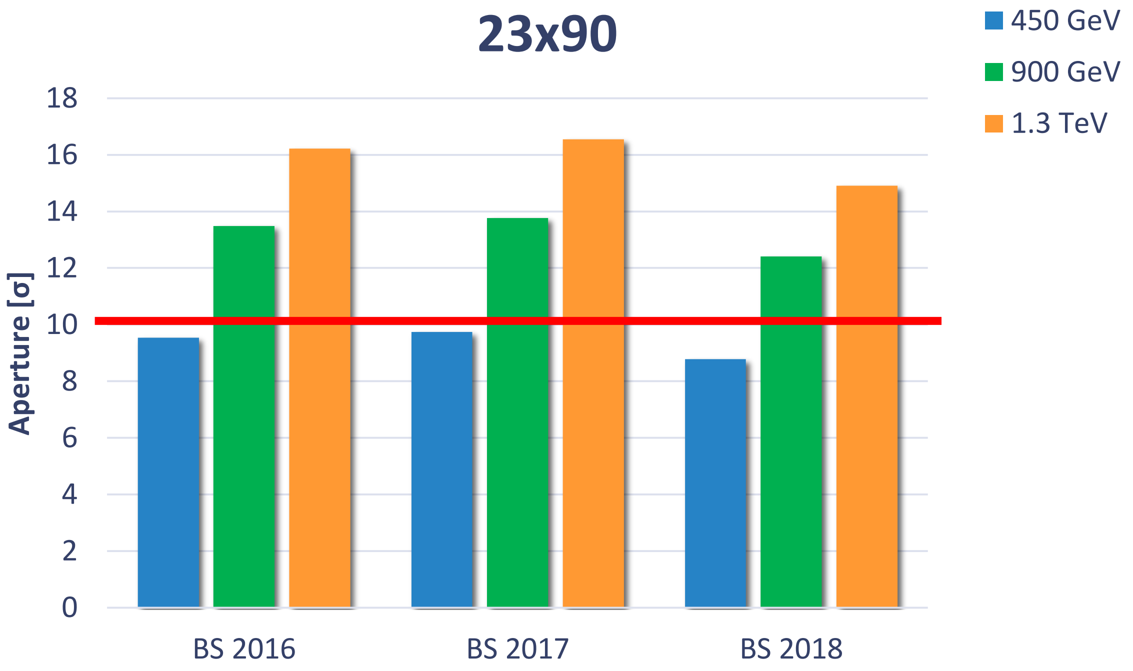


Note: values in mm

[R. Kersevan, FCC-hh design meeting Mar. 2018](#)

Aperture for different BS in the arcs





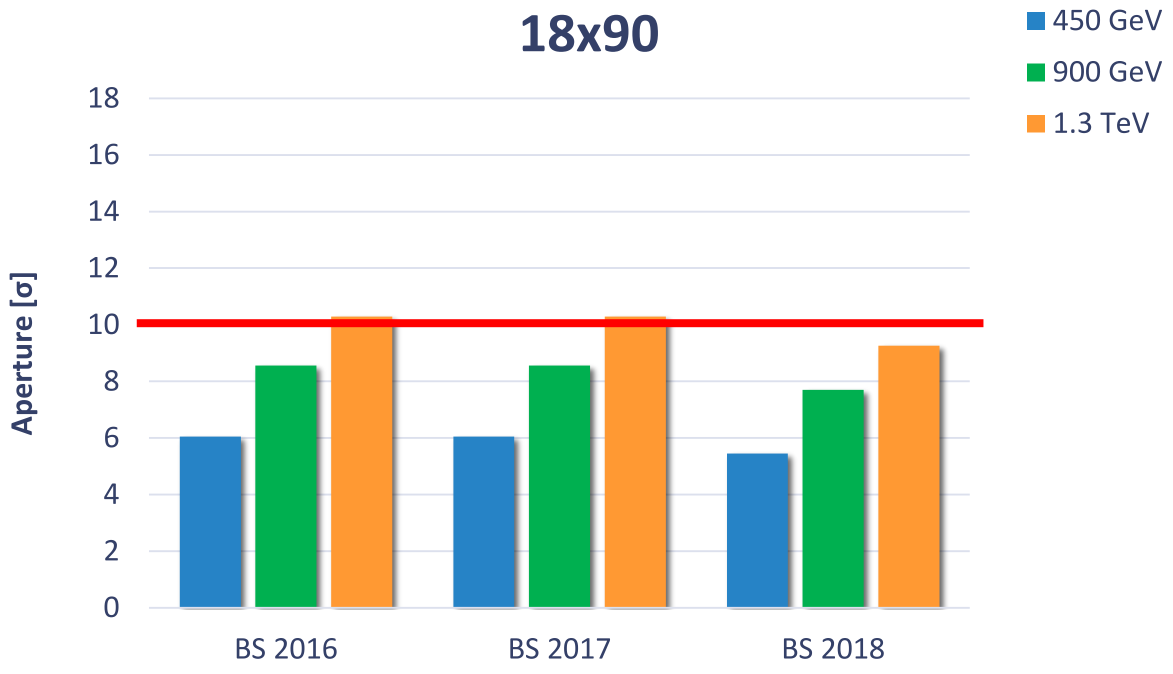
- BS 2017 improves the aperture in all cases, compared to BS 2016
- BS 2018 decreases aperture in 23x90

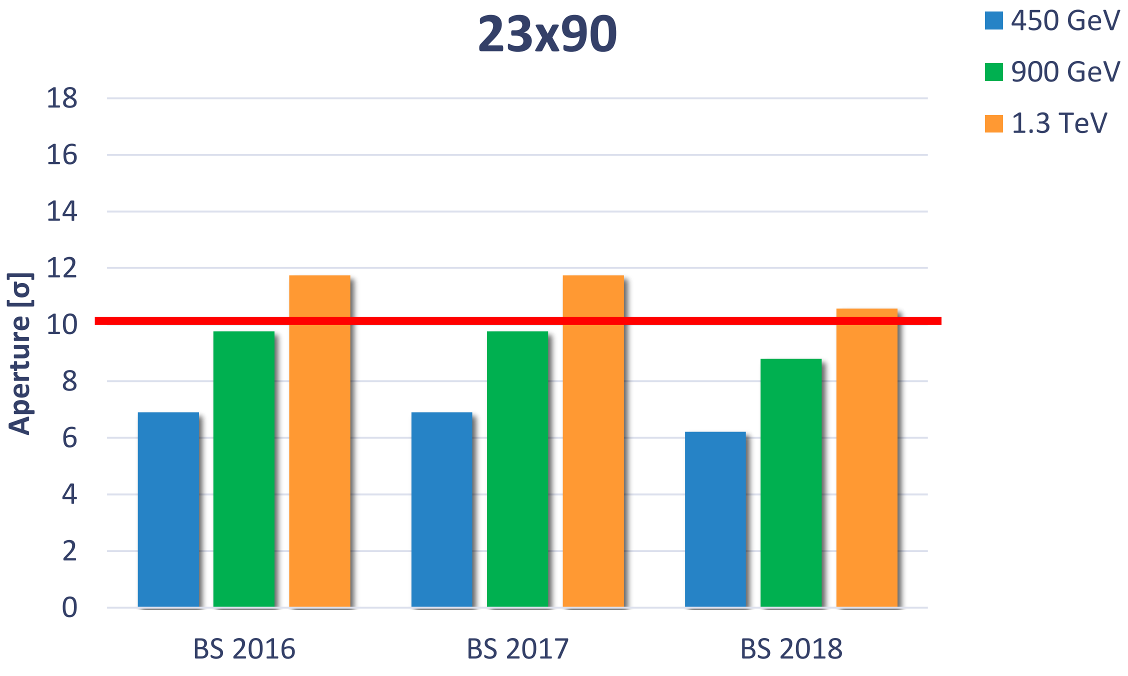
Plots summarize the results per arc cell; Studies performed with 90° phase advance

- 23x90:
  - 450 GeV more promising
- 18x90:
  - would probably require wider BS or higher injection energy

Used Parameters, see backup slides

Aperture for different BS in the DS





- Smallest aperture located in the DS left from IP1/5 (both lattices)
- Improvement with new design of the DS

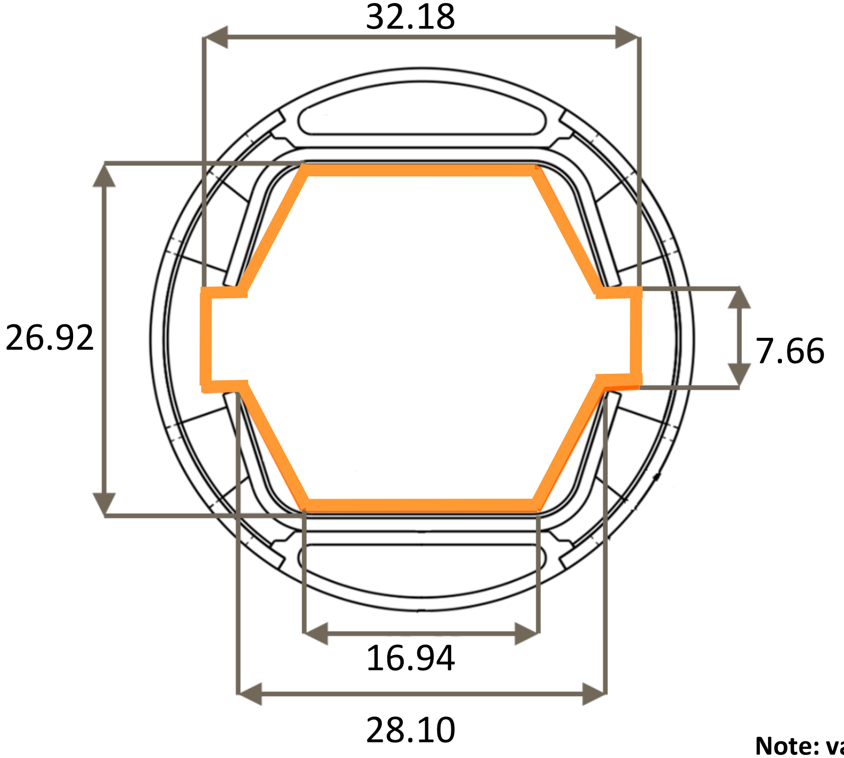
Plots summarize the minimum aperture in the DS

Used Parameters, see backup slides

Required Dimensions in the arcs (BS 2017)

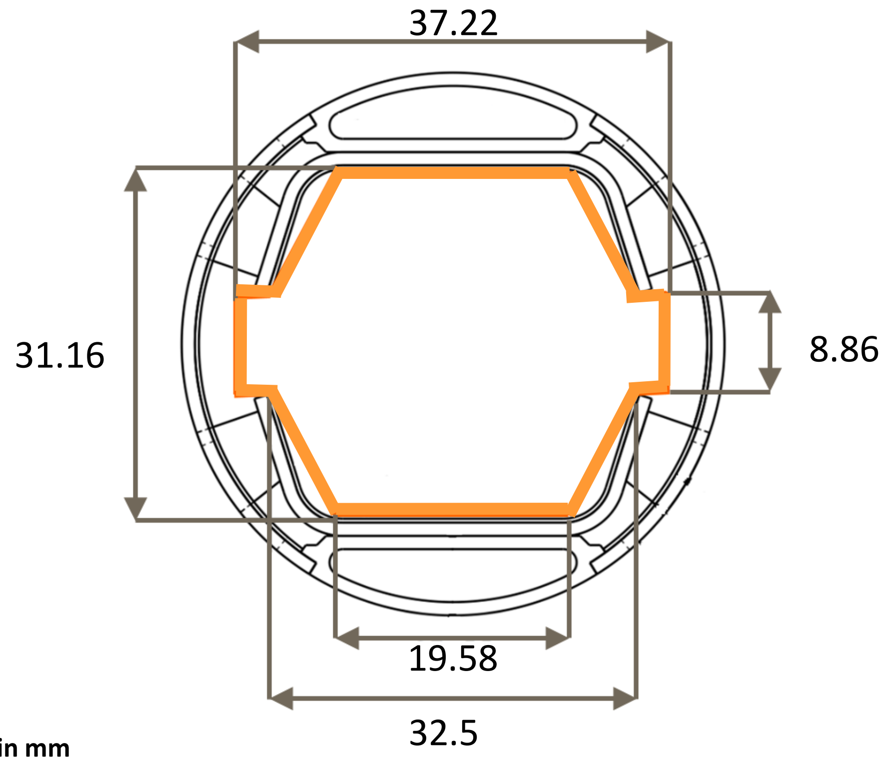
23x90   n1 = 10.00 σ

enlarged by 2 %



18x90   n1 = 10.01 σ

enlarged by 18 %



Note: values in mm

Required BS for 450 GeV is more challenging for 18x90 lattice;

aperture improves for higher injection energy

Conclusion and Outlook

- Two baseline lattices (23x90 and 18x90)

- Lattice change and generation can easily be performed with new tool (*ALGEA*)
  further step: add beam 2

- b2-errors of 46.84 units at collision energy → impact on energy
  - 18x90: no loss of c.o.m energy due to spare space in the cell
  - 23x90: loss of 0.1 TeV c.o.m energy; 30 units of b2 bearable

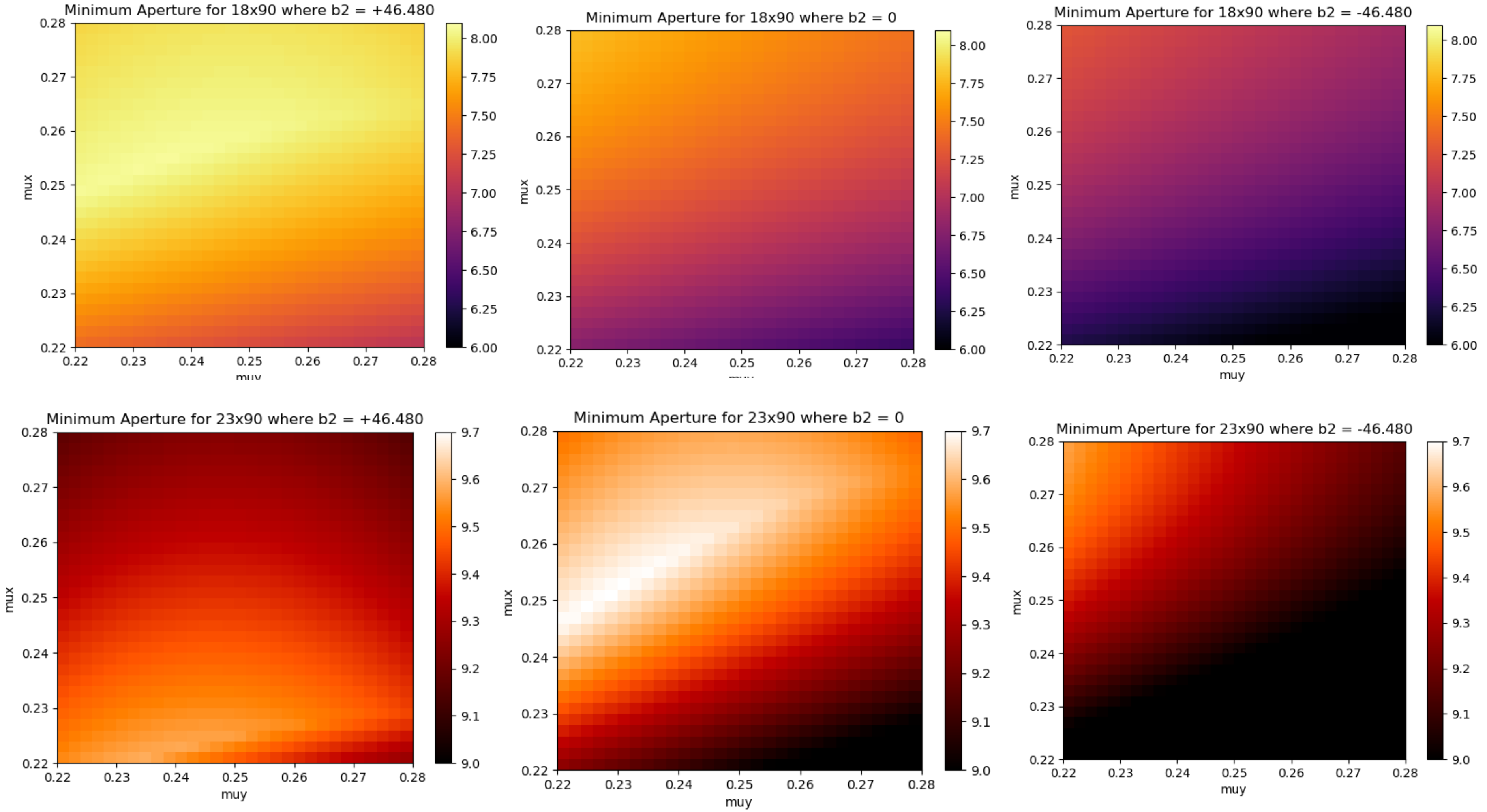
- Beam screen 2017 is most promising so far

- Limiting aperture located in the dispersion suppressor
  further step: work in DS needed

BACKUP SLIDES

Aperture for different μ_x , μ_y

Note: The lighter the color, the better the aperture.



Steps for improving the aperture by changing μ_x and μ_x

Assumption:
Dipoles with alternating b2 errors in the arcs;
in other words: if b2 = + 46.480 units in the inner arc,
b2 = - 46.480 units in the outer arc

Constraint:
The total phase advance needs to be constant. Therefore, when decreasing μ_x in one arc, it has to be increased in the other.

Result:
Finding two arc cells with parameter:
- Cell in arc one: b2 = + 46.480 units, μ_x = x, μ_y = y
- Cell in arc two: b2 = - 46.480 units, μ_x = 0.25 - x, μ_y = 0.25 – y

Aperture results

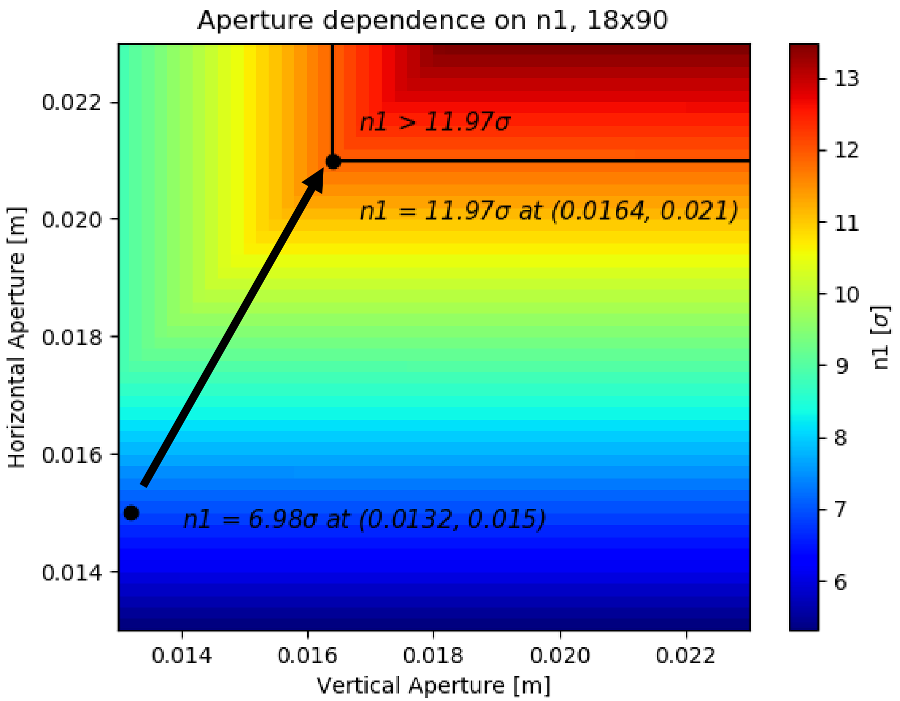
- Results of the beam stay clear are given in sigma for in the arcs with b2=0 / including aperture in the DS
- V0.3 was taken for calculations

Parameters, taken from HL-LHC			
normalized emittance	2.5 µm	relative parasitic dispersion	0.14
closed Orbit Uncertainty	2 mm	halo-parameters	(6,6,6,6)
β-beating coefficient	1.05	tolerances	1 mm
dp/p	8.6 e-4		

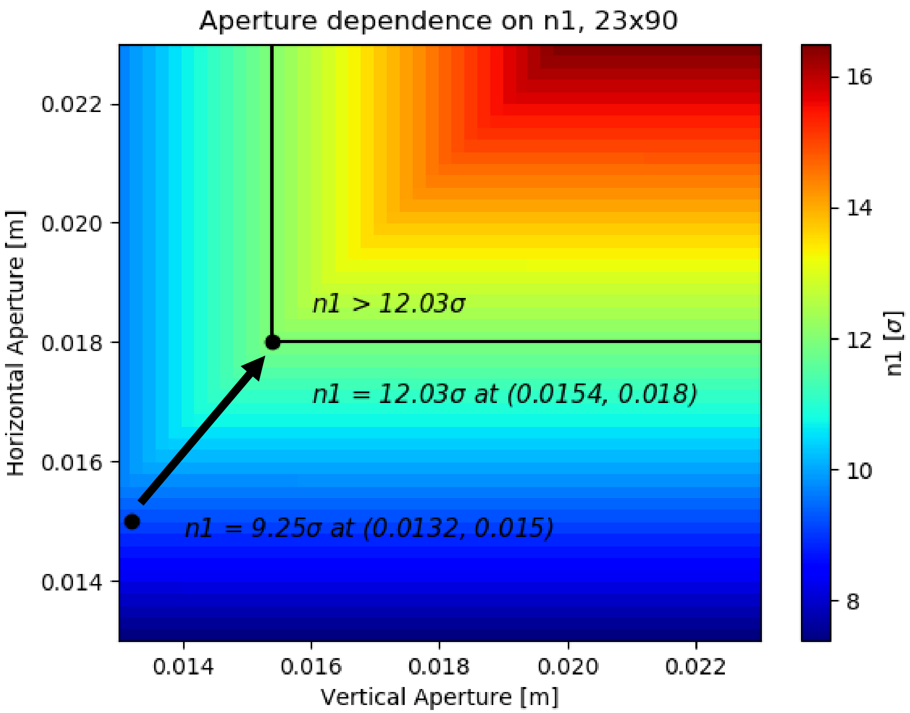
18x90	450 GeV	900 GeV	1.3 TeV
FCC-hh BS 2016	7.26 / 6.05	10.26 / 8.56	12.34 / 10.29
FCC-hh BS 2017	7.49 / 6.05	10.59 / 8.56	12.73 / 10.29
FCC-hh BS 2018	7.52 / 5.45	10.63 / 7.70	12.78 / 9.26

23x90	450 GeV	900 GeV	1.3 TeV
FCC-hh BS 2016	9.54 / 6.90	13.49 / 9.77	16.22 / 11.74
FCC-hh BS 2017	9.74 / 6.90	13.77 / 9.77	16.55 / 11.74
FCC-hh BS 2018	8.78 / 6.22	12.41 / 8.79	14.91 / 10.75

Required Dimensions (RECTELLIPSE)



- Horizontal aperture enlarged by **40%**
- Vertical aperture enlarged by ≈ **24%**



- Horizontal aperture enlarged by **20%**
- Vertical aperture enlarged by ≈ **17%**

For small gain in beam stay clear (n1) it is enough to increase only the horizontal aperture; however at some point the vertical aperture needs to be enlarged as well to improve n1 further.

→ ***It is not enough to increase only the horizontal dimensions of the beam pipe.***