Optics Options for the HE-LHC

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

Outline

- Requirements of the HE-LHC
- Lattice Generation and Geometry Fitting
- Baseline Options
- Effect of Quadrupole Errors in the Main Dipoles
- Integrated Insertion Region Optics
- Conclusion and Outlook

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HE-LHC Requirements

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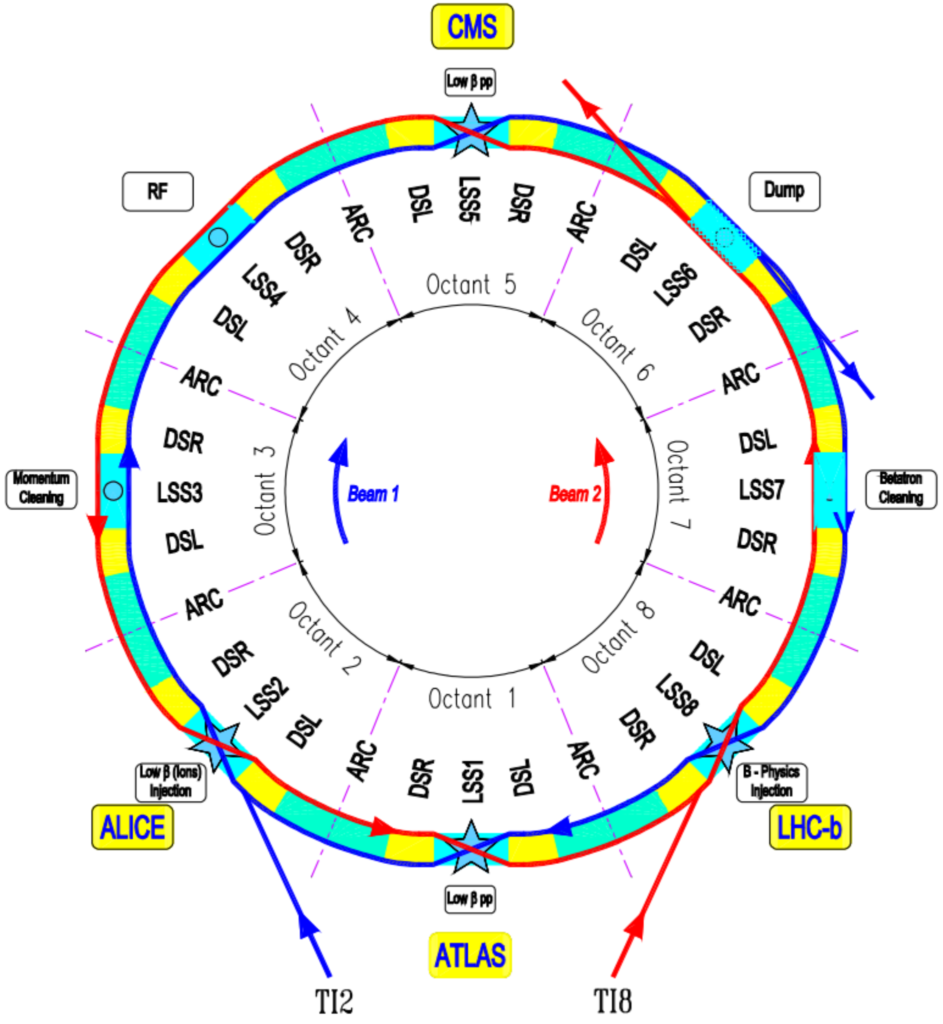
- Same tunnel as the LHC
- Injection energy: 450 GeV, 900 GeV or 1.3 TeV
- Similar Design
  - Two counter rotating proton beams
  - Eight arcs, IRs
  - Four beam crossings



LHC Design Report

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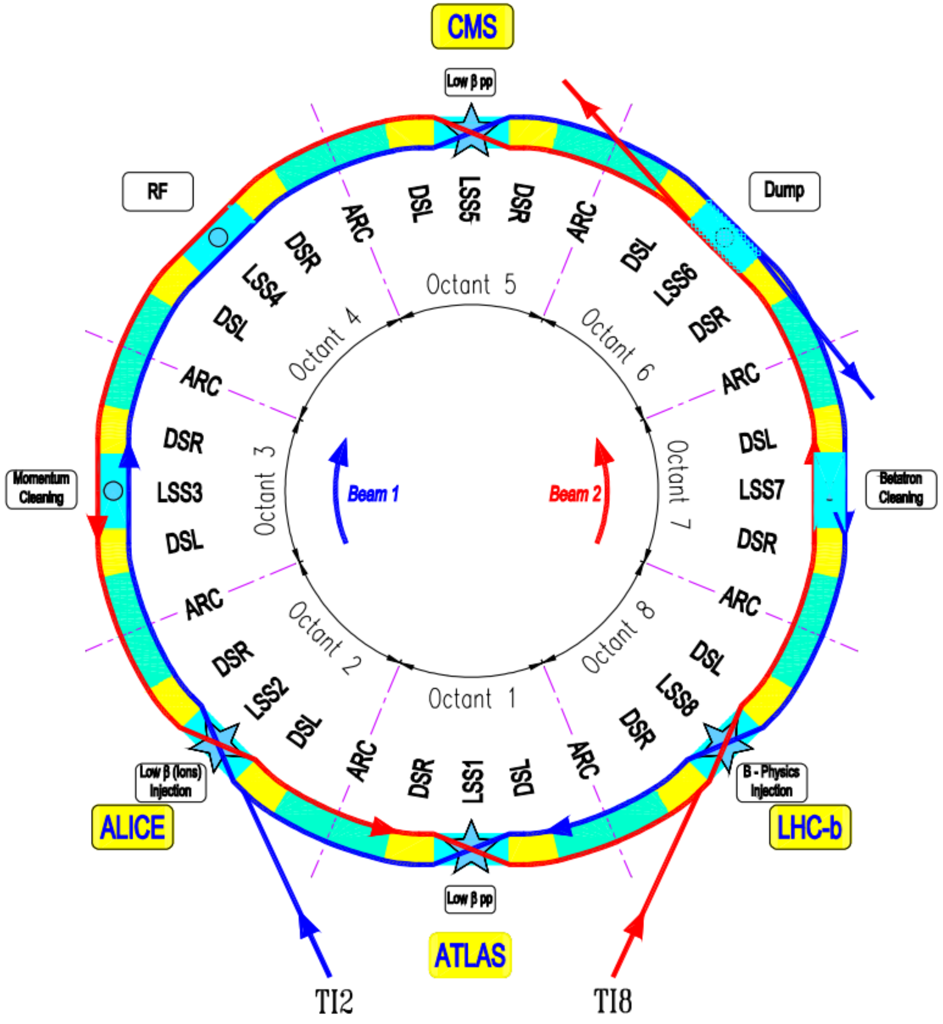
- Small geometry offset to the LHC (< 3 cm[1])
- Beam Stay Clear > 10 σ



LHC Design Report

[1] V. Mertens. Private communication.

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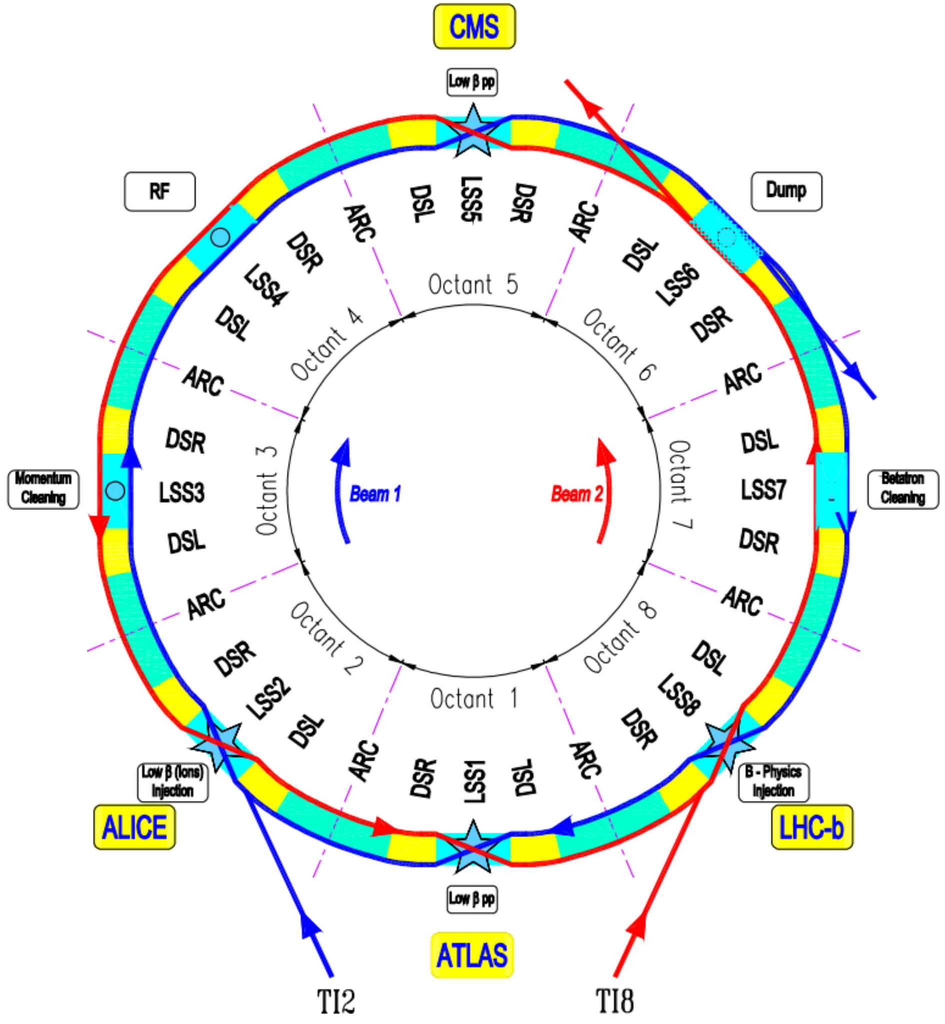

LHC Design Report

→ **Generate and test different arc cell and dispersion suppressor options**

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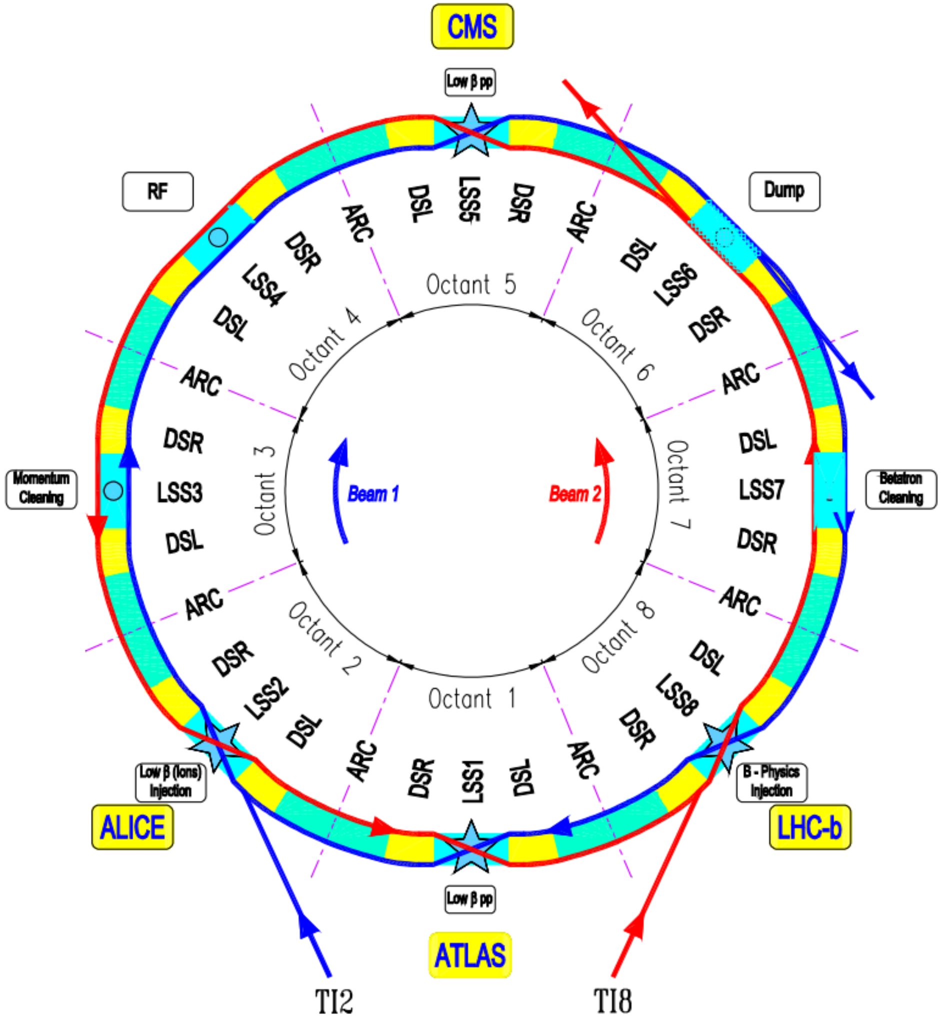

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→ **Tool: ALGEA (Automatic Lattice GEneration Application)**

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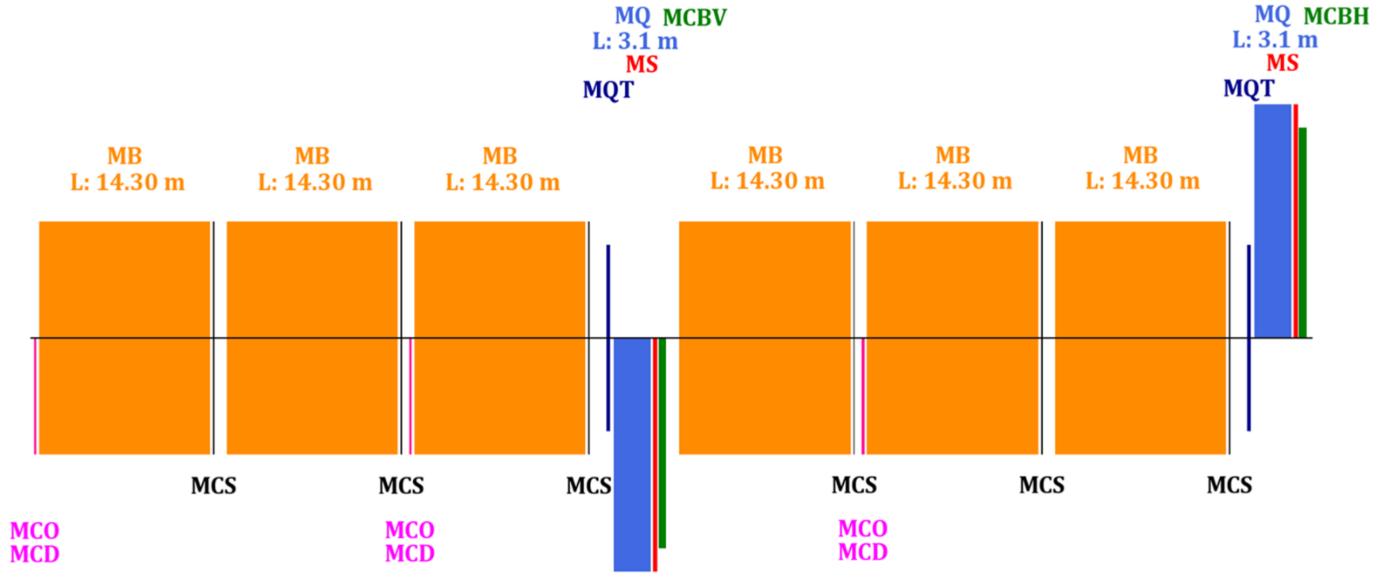
ALGEA

ALGEA

- Based on a few input parameters flexible generation of
  - Sequence
  - Powering
  - Naming convention
  - Arcs and Dispersion Suppressors
  - Beam 1 and beam 2

- Constraints
  - Similar FODO cell layout as in LHC
  - Tunnel length
  - IP positions



Geometry Optimisation in ALGEA

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- Lattice generation still challenging

→ new machine has to fit in the tunnel

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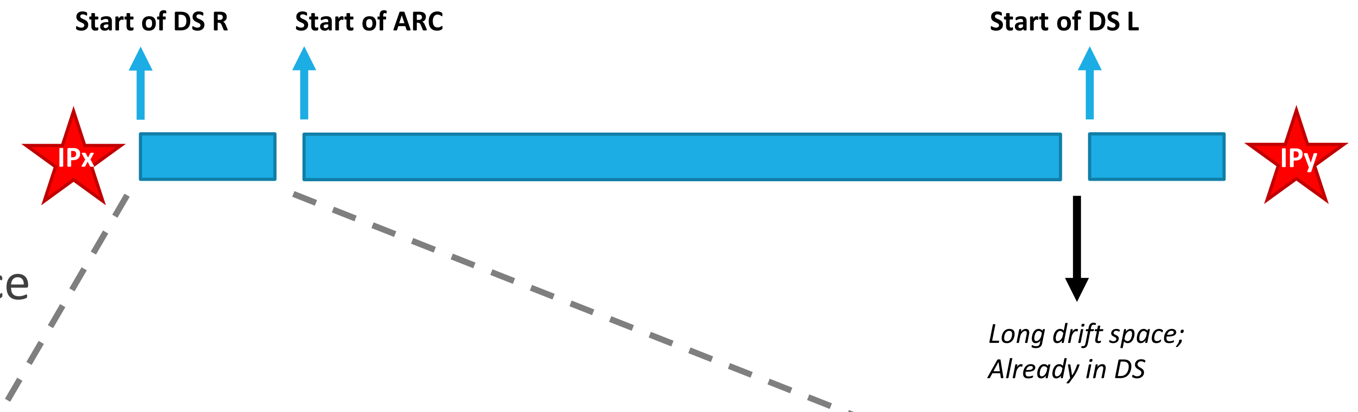
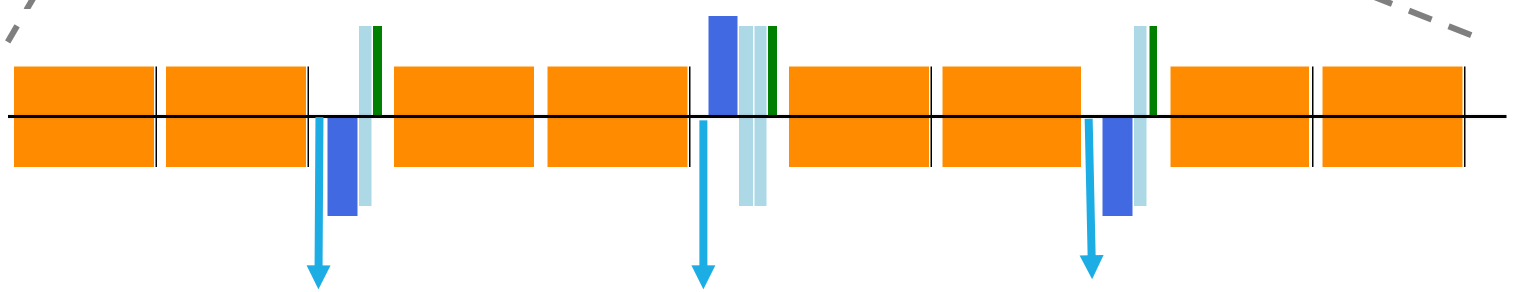


- Automatic survey fitting by varying parameters
  - Drift spaces in DS
  - Cell length
  - Dipole length



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)

Example of Geometry Fitting

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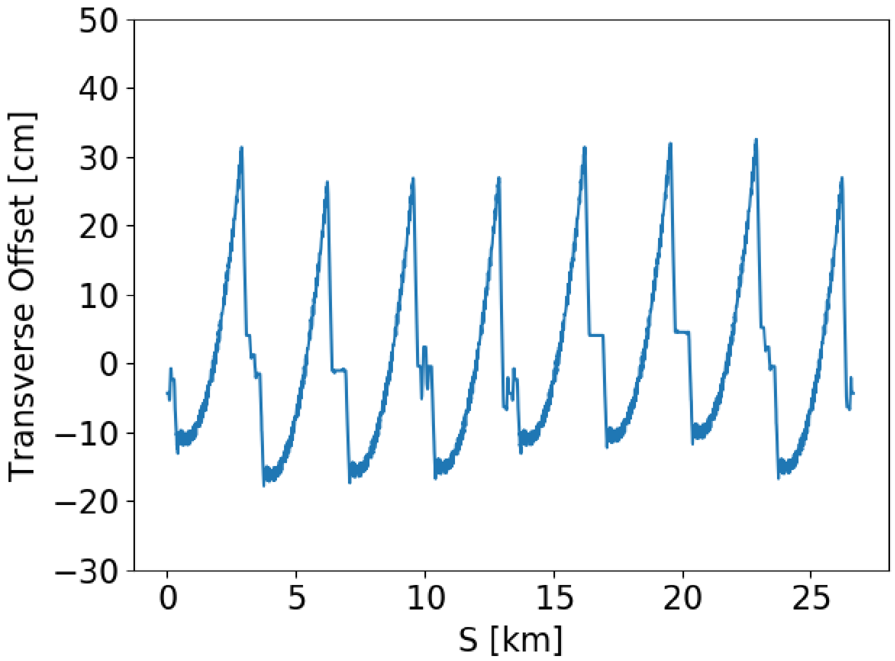
- Before
  - Maximal offset up to 35 cm
  - Offset distributed irregularly over arc



Example for an 18 cells per arc design

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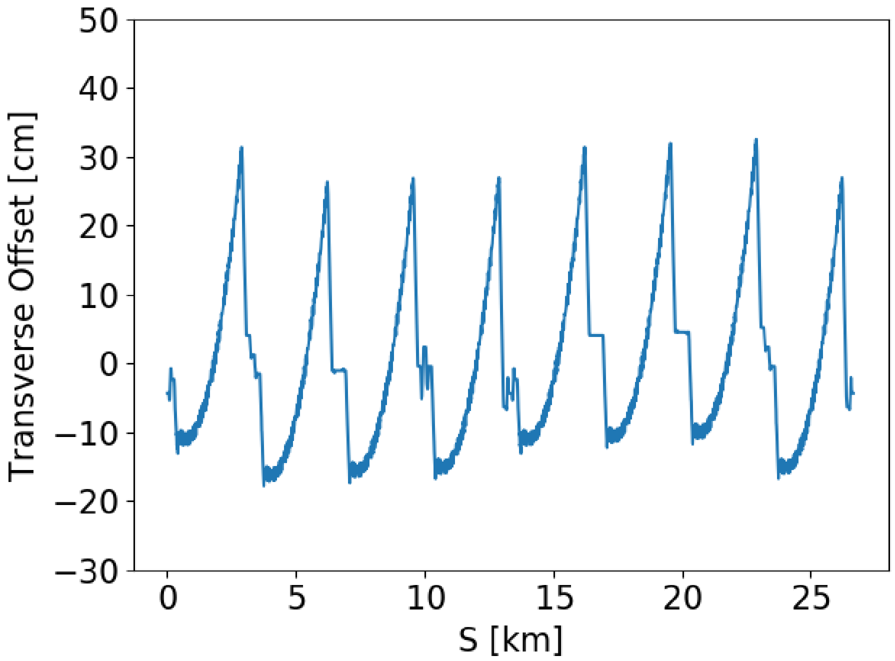
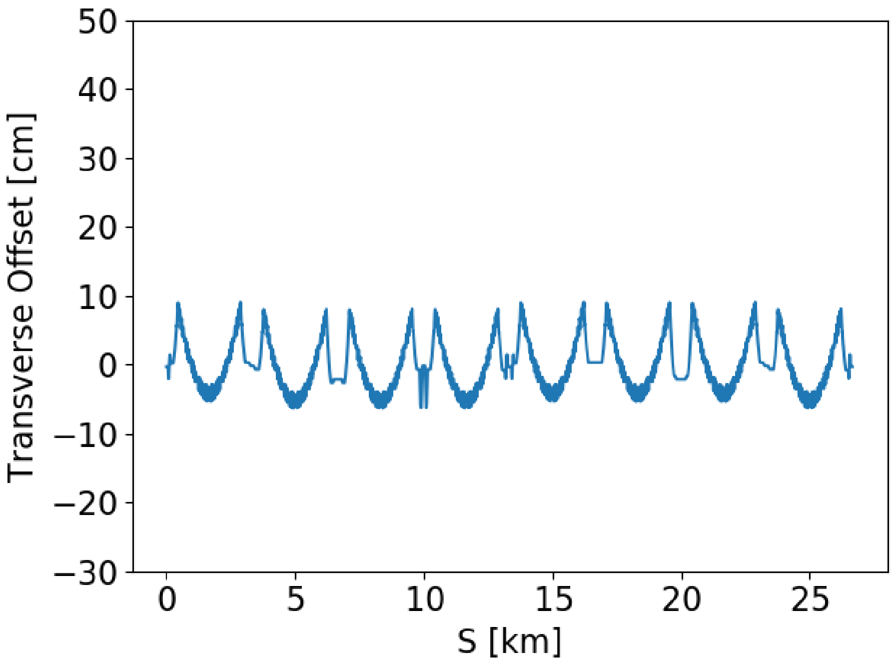


- After
  - Maximal offset decreased by factor 4
  - Offset distributed symmetrically over arc



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Baseline Options

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- Studying various arc cell options lead to conclude on two baseline options
  - 18x90: 18 cells per arc, 90° phase advance per cell
  - 23x90: 23 cells per arc, 90° phase advance per cell

Parameter	Unit	18x90	23x90
Phase Advance per Cell	°	90	90
Cell Length	m	137.33	106.9
Dipoles per Cell	-	8	6
Dipole Length	m	13.94	13.83
Bending Angle per Dipole	°	0.28	0.29
Filling Factor	-	0.81	0.78
Quadrupole Length	m	2.8	3.5
Quadrupole Strength	T/m	336	335
β_{max}/β_{min}	m	230/40	177/32
D_{max}/D_{min}	m	3.60/1.76	2.20/1.10
Momentum Compaction	10^{-4}	5.84	3.54
Required Field for 27 TeV c.o.m.	T	15.85	16.59
c.o.m. energy with 16 T Dipoles	TeV	27.24	26.01

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- Centre of mass energy: 27 TeV
  - 18x90: 27 TeV
  - 23x90: 26 TeV

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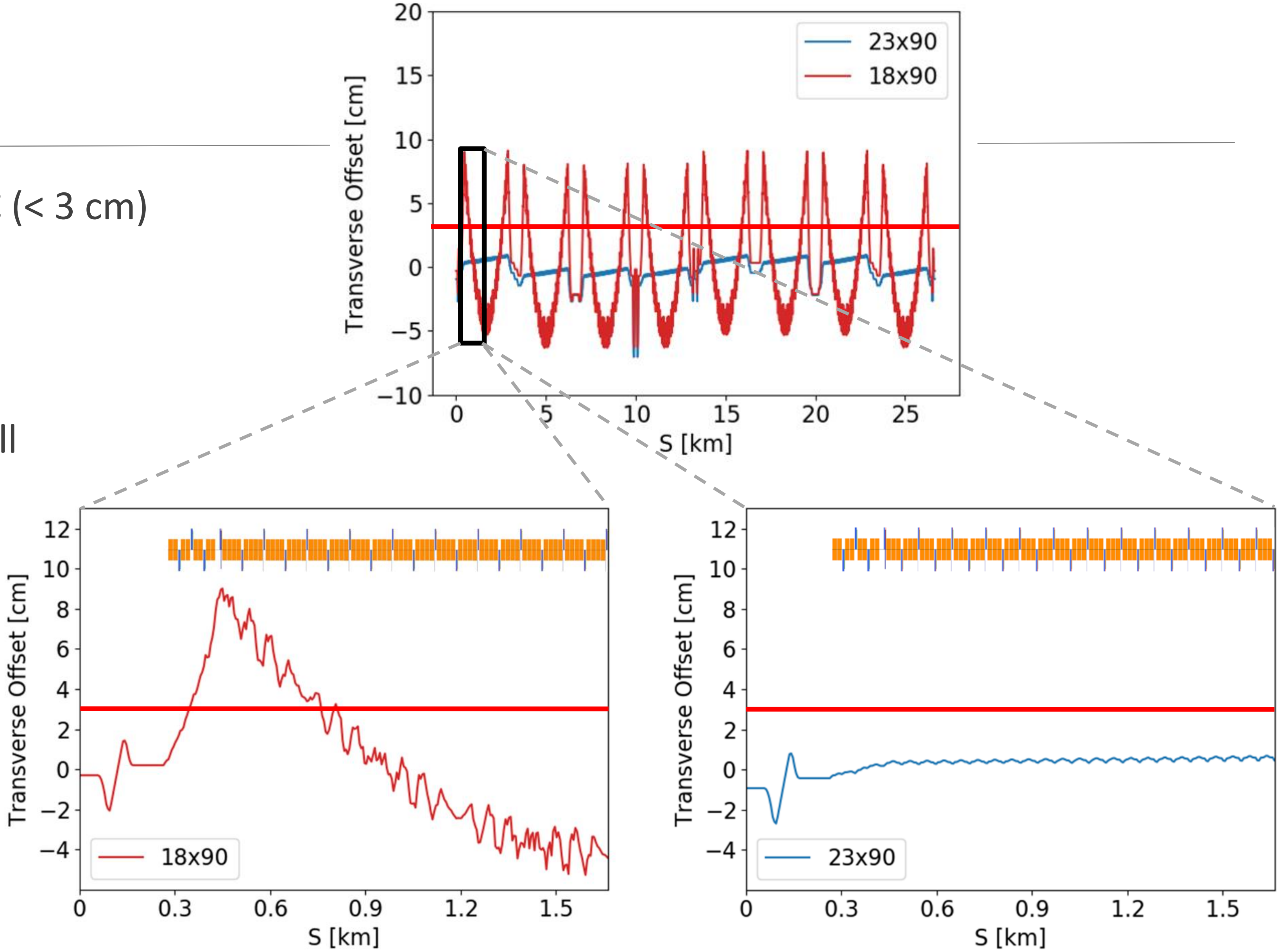
  - 18x90: ≈ 9 cm
  - 23x90: ≈ 1 cm

- Located in the first regular arc cell (part of dispersion suppressor)

- Result of different number and lengths of dipoles



Beam Stay Clear

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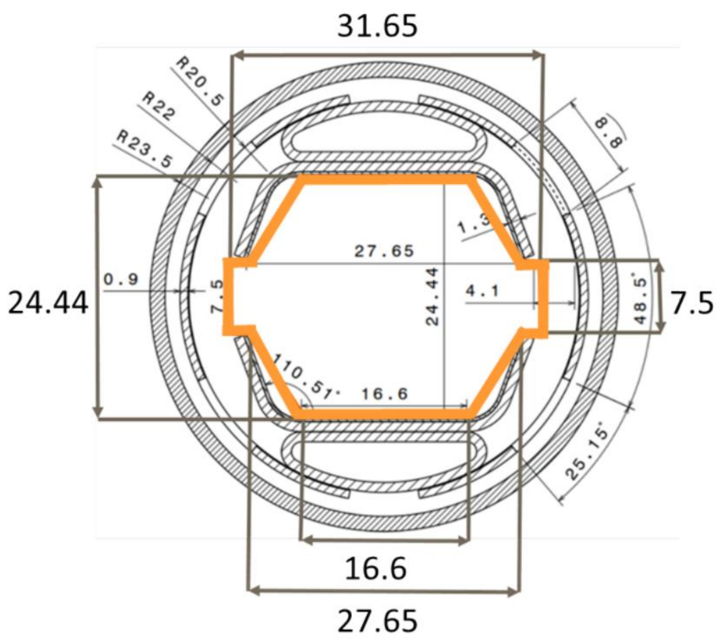
- Beam Stay Clear > 10 sigma



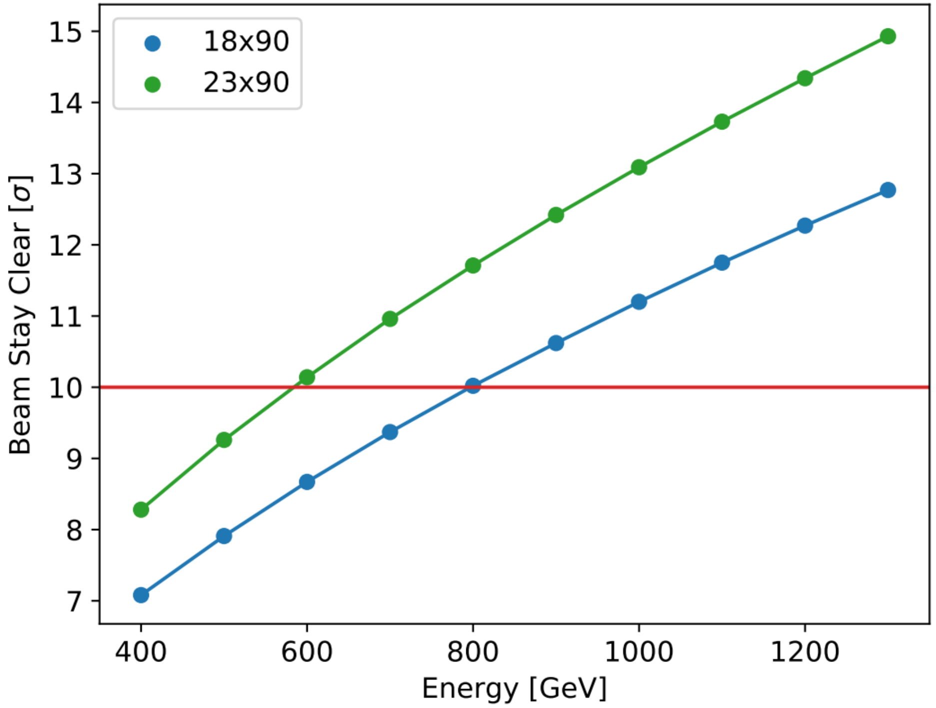
Note: Values in mm

R. Kersevan, FCC-hh design meeting Mar. 2018

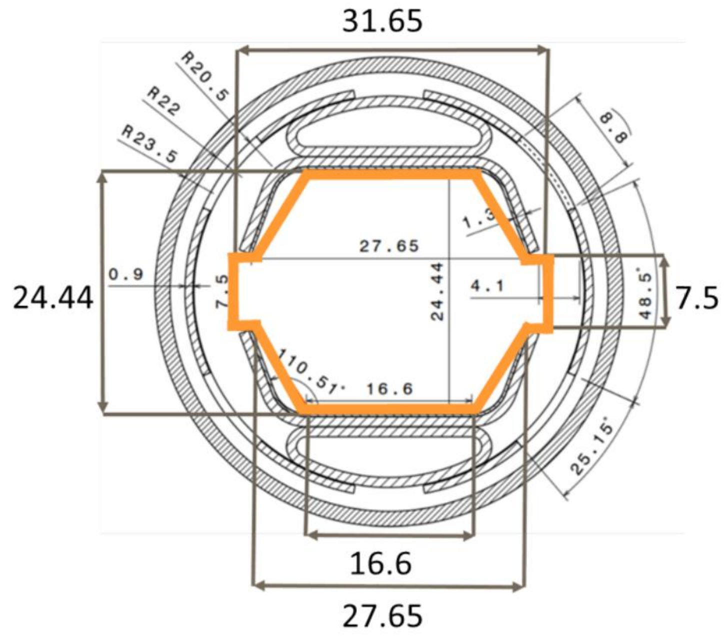
MAD-X Input	Description	Unit	Value
APERTOL	Aperture Tolerances	mm	1, 1, 1
HALO	Halo Parameters	σ	6, 6, 6, 6
BBEAT	Beam Size Beating	-	1.05
DPARX	Frac. Hor. Paras. Disp.	-	0.14
DPARY	Frac. Ver. Paras. Disp.	-	0.14
COR	Closed Orbit Uncertainty	m	0.002
DP	Rel. Momentum Offset	-	0.0086

Beam Stay Clear

- Beam Stay Clear > 10 sigma
- Larger for higher energy
  - 18x90: 800 GeV sufficient
  - 23x90: 600 GeV sufficient



Minimum beam stay clear in FODO cell



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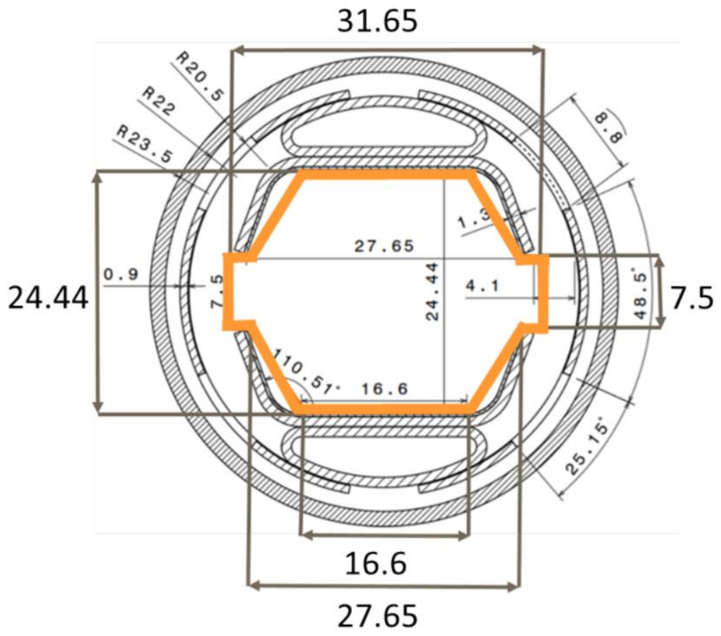
Replacing half of the magnets with superconducting ones about 600 GeV reachable with the SPS

(already proposed 1972)



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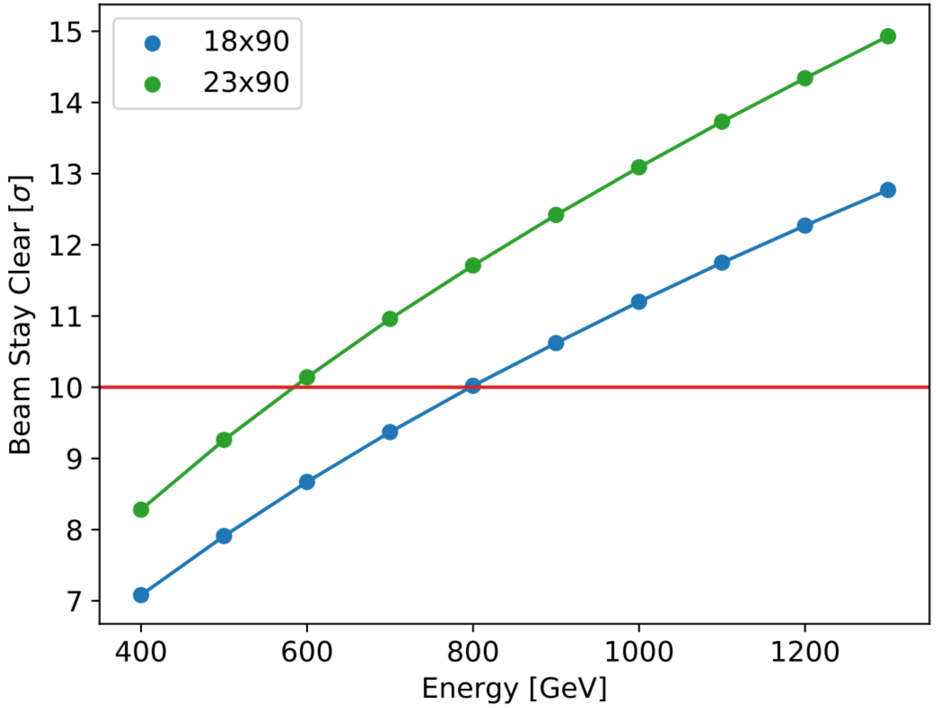

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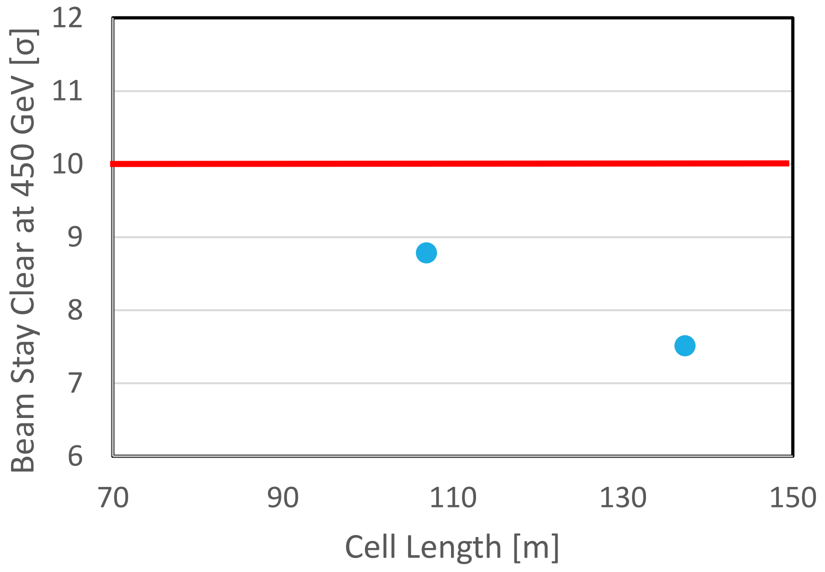
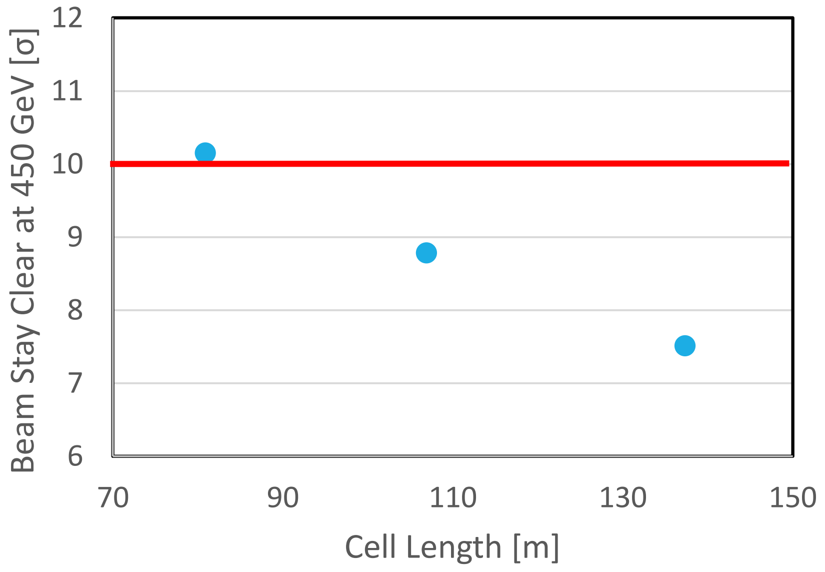


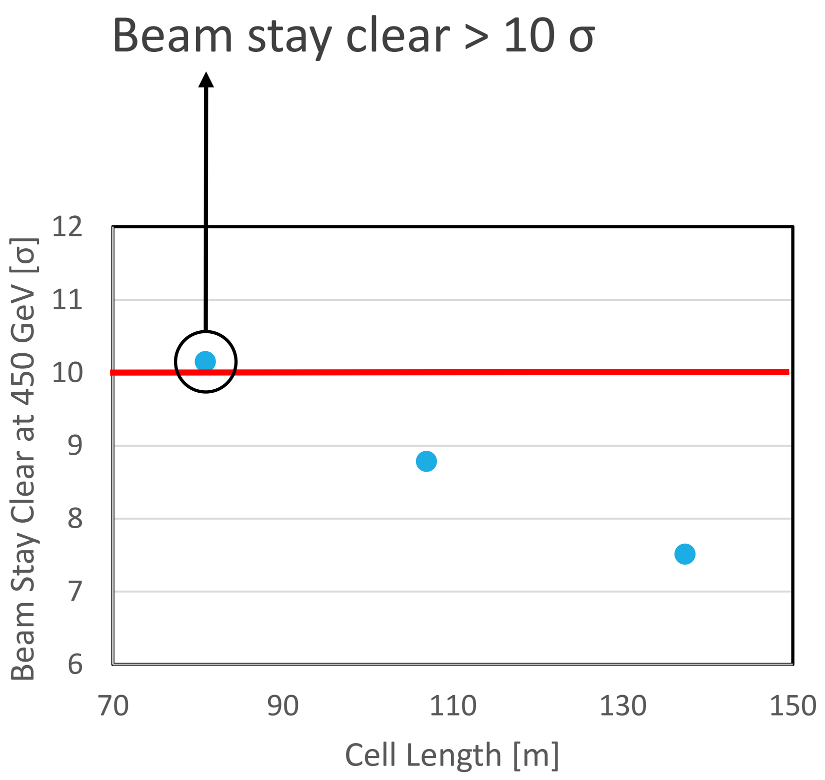
Beam Stay Clear – Different Design

- Choose design with smaller cells → more cells per arc



Beam Stay Clear – Different Design

- Choose design with smaller cells → more cells per arc → 32 cells per arc lead to



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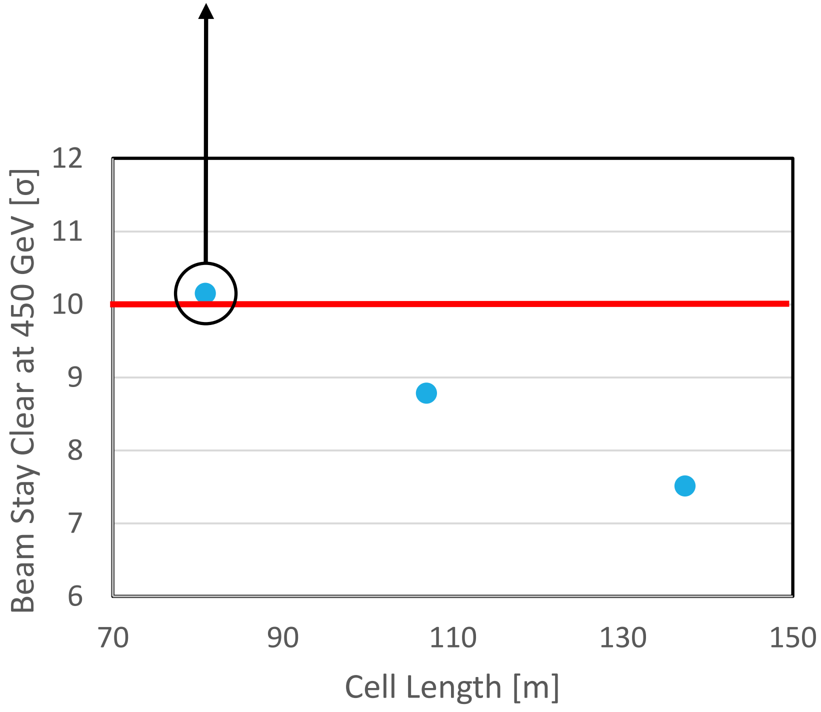
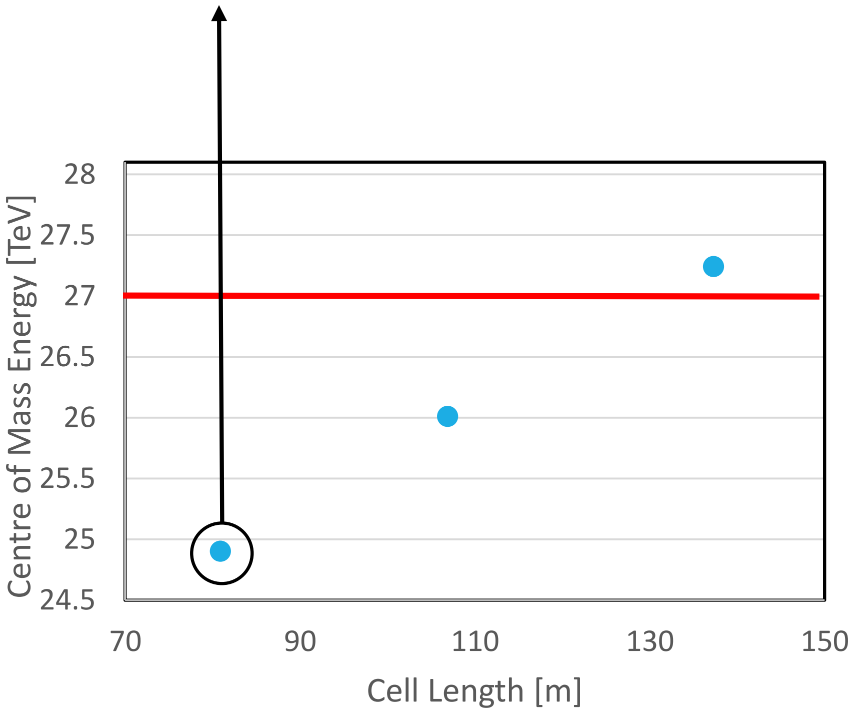


c.o.m. energy < 25 TeV



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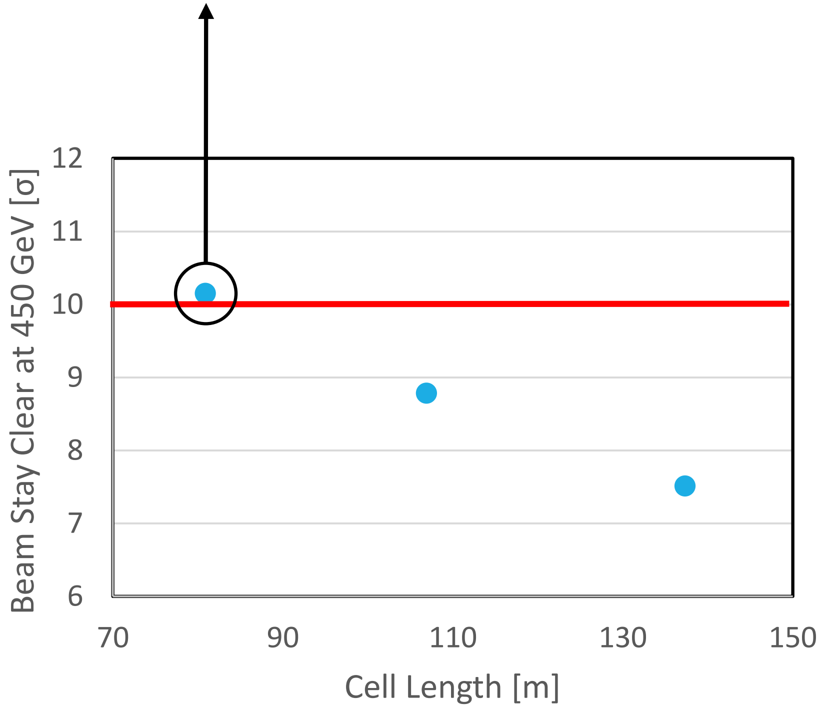

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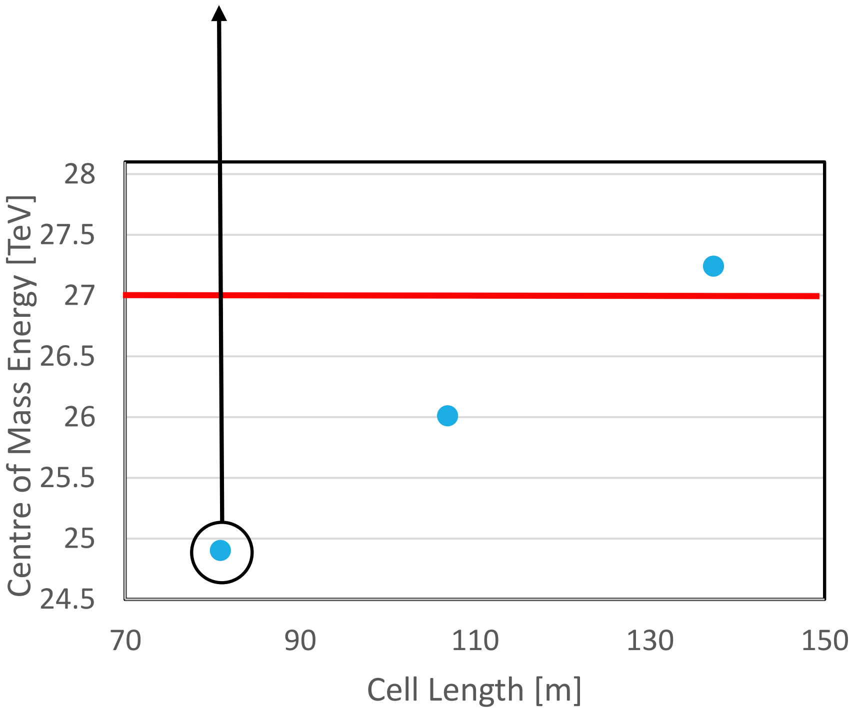
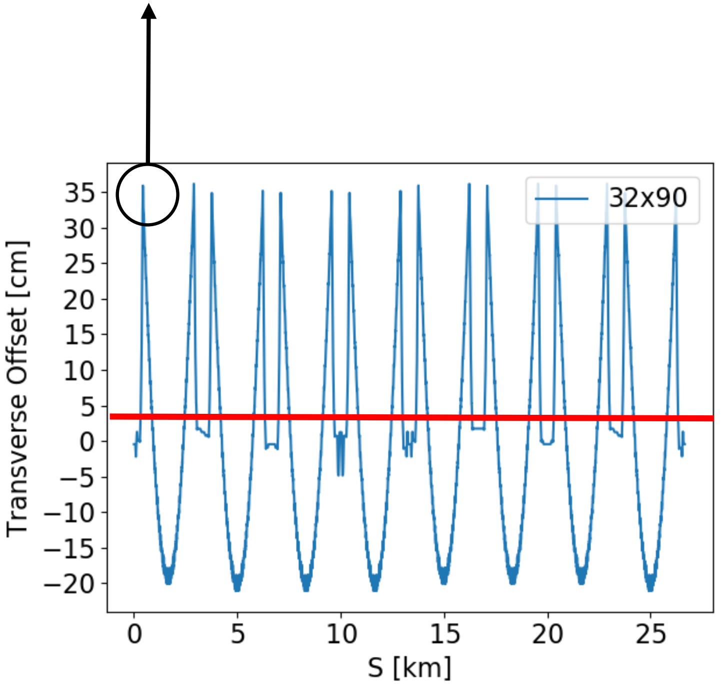


Geometry offset >> 3 cm



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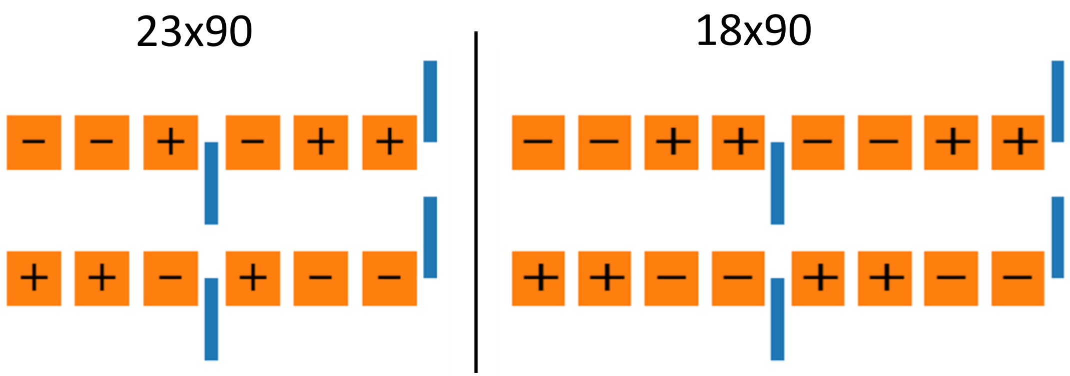
- Combined function dipoles
- Every dipole provides an additional quadrupole field → b_2 component
- Assumption: different sign of b_2 in inner and outer aperture



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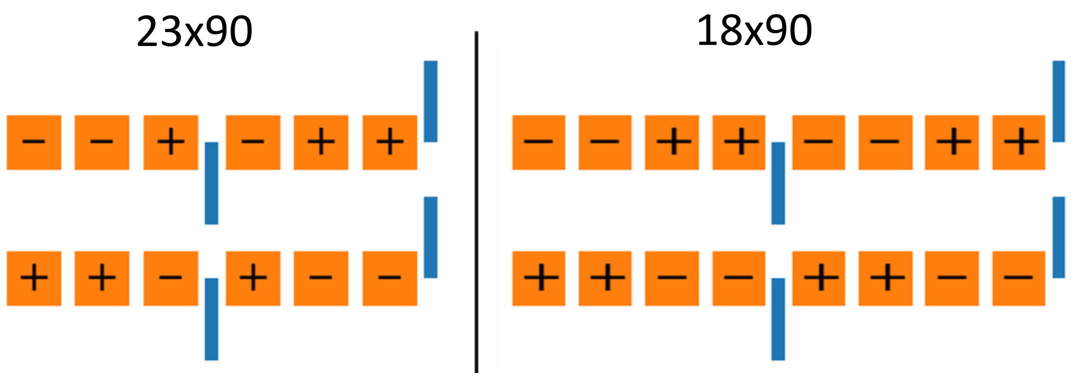
- Best combination for both cells is shown here
  → two different dipole types



- 23x90:
  - 450 units of b2
  - 9.89 σ
- 18x90:
  - 500 units of b2
  - 9.62 σ

Beam Stay Clear – Beam Screen Dimension

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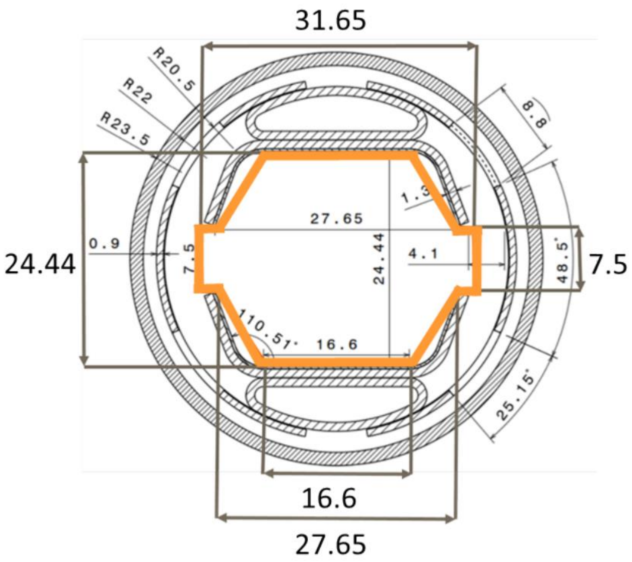
- Enlargement of the beam screen

Current beam screen design



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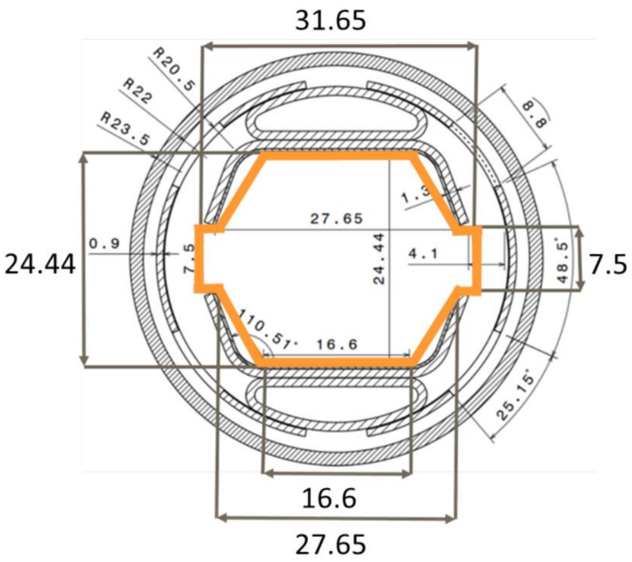

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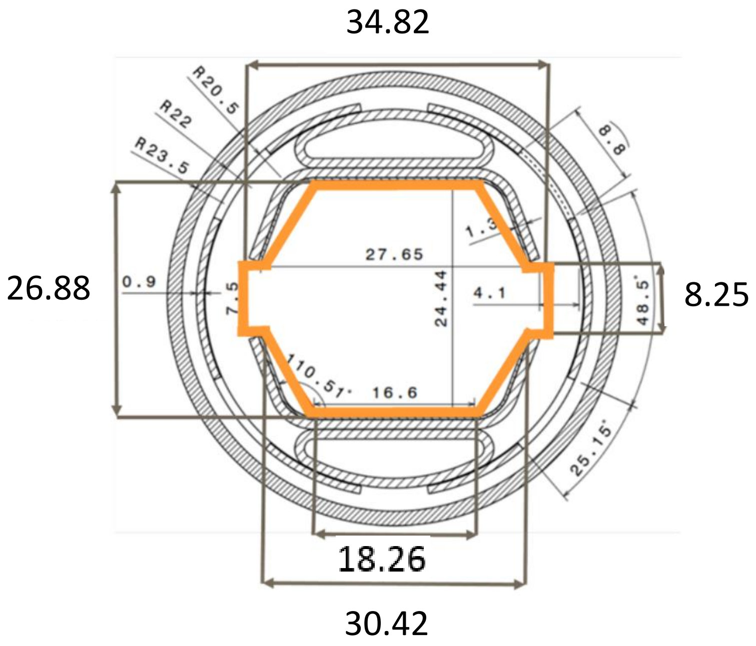
23x90: 10 % enlargement



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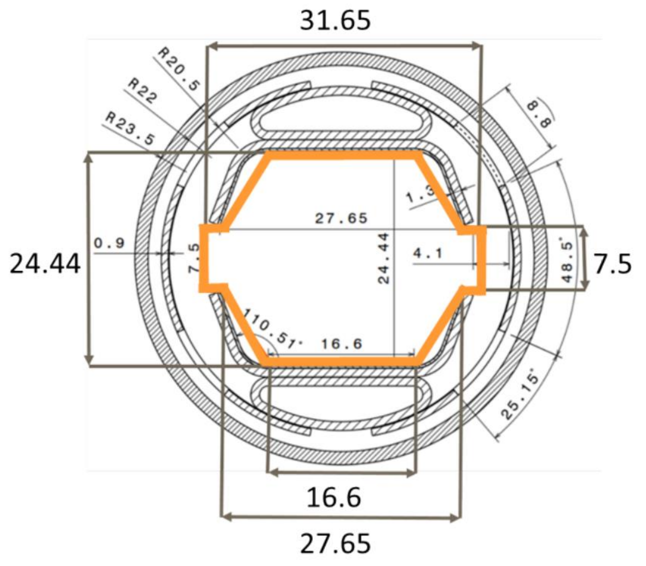

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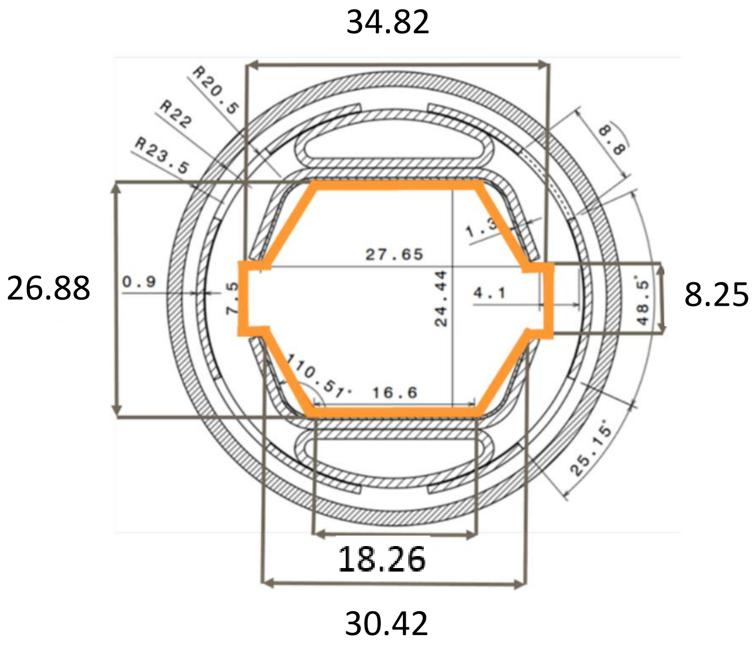

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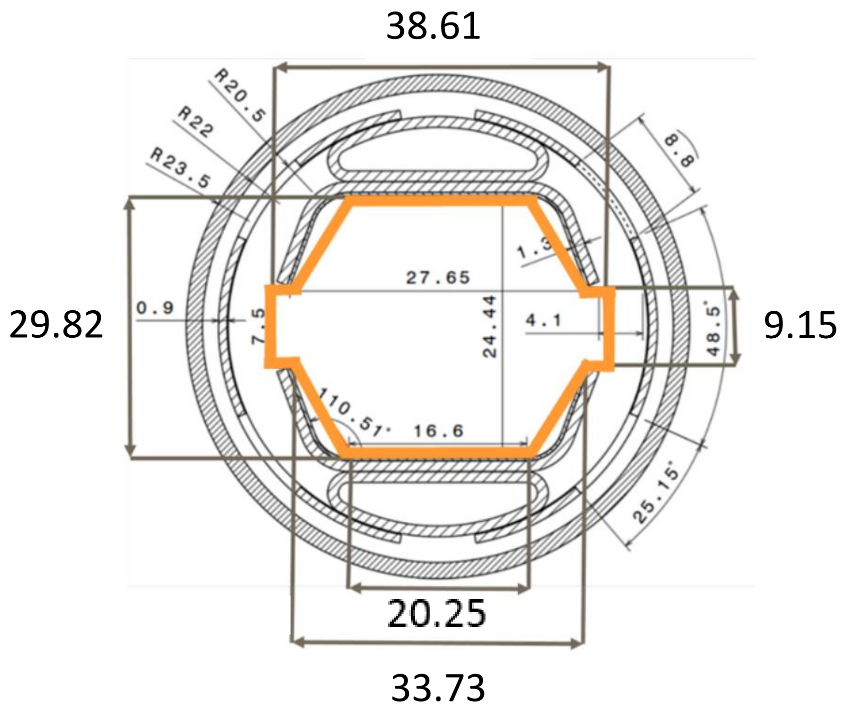
18x90: 22 % enlargement



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Beam Stay Clear – Bottlenecks

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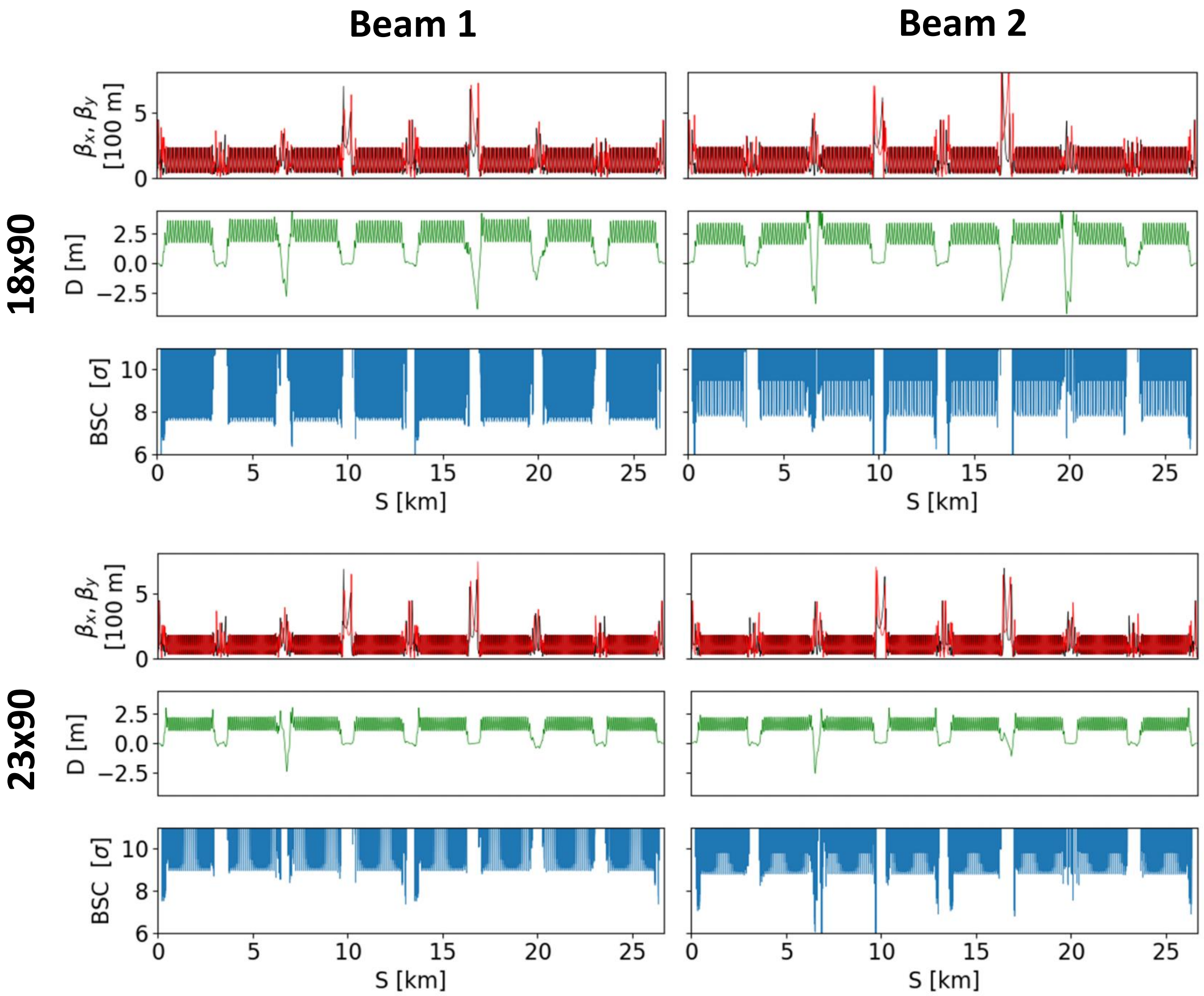

- Optics functions have peaks in the IRs and DS
- Beam stay clear smaller than in a FODO cell
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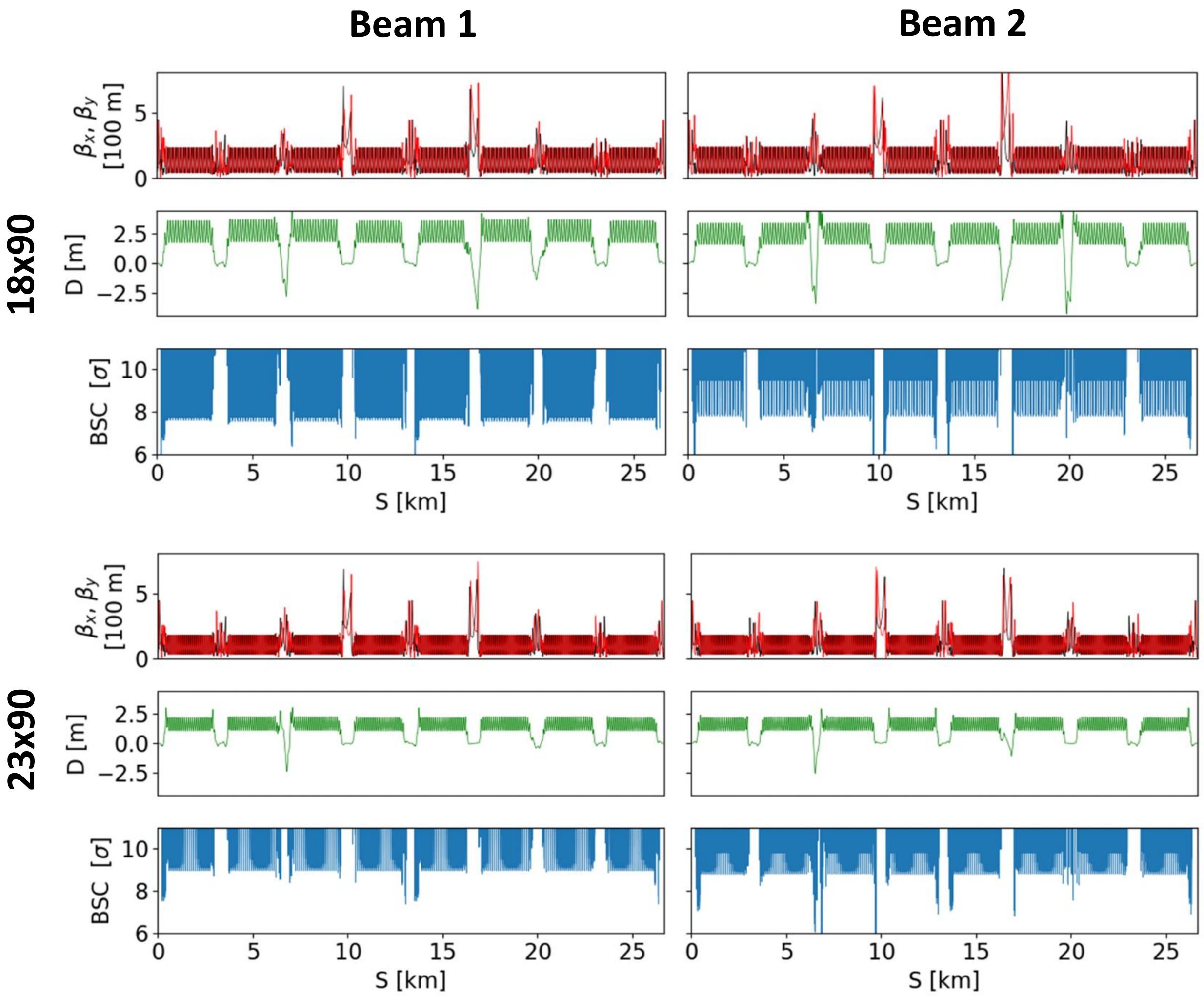

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- Local Problem
  - Small changes in dispersion suppressor
  - Improving optics

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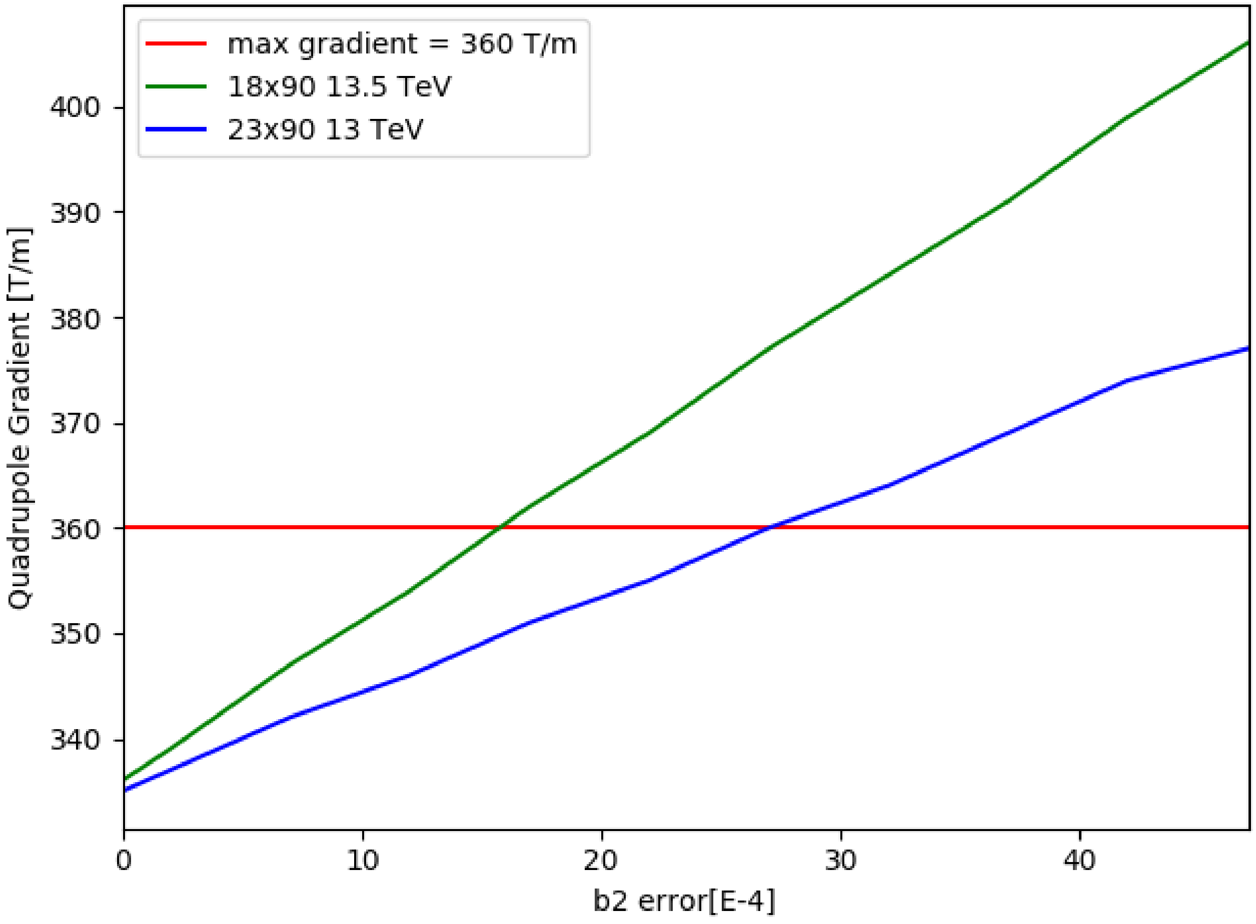

- Magnetic field of e.g. dipoles includes higher magnetic orders
- b_2 – component = quadrupole error

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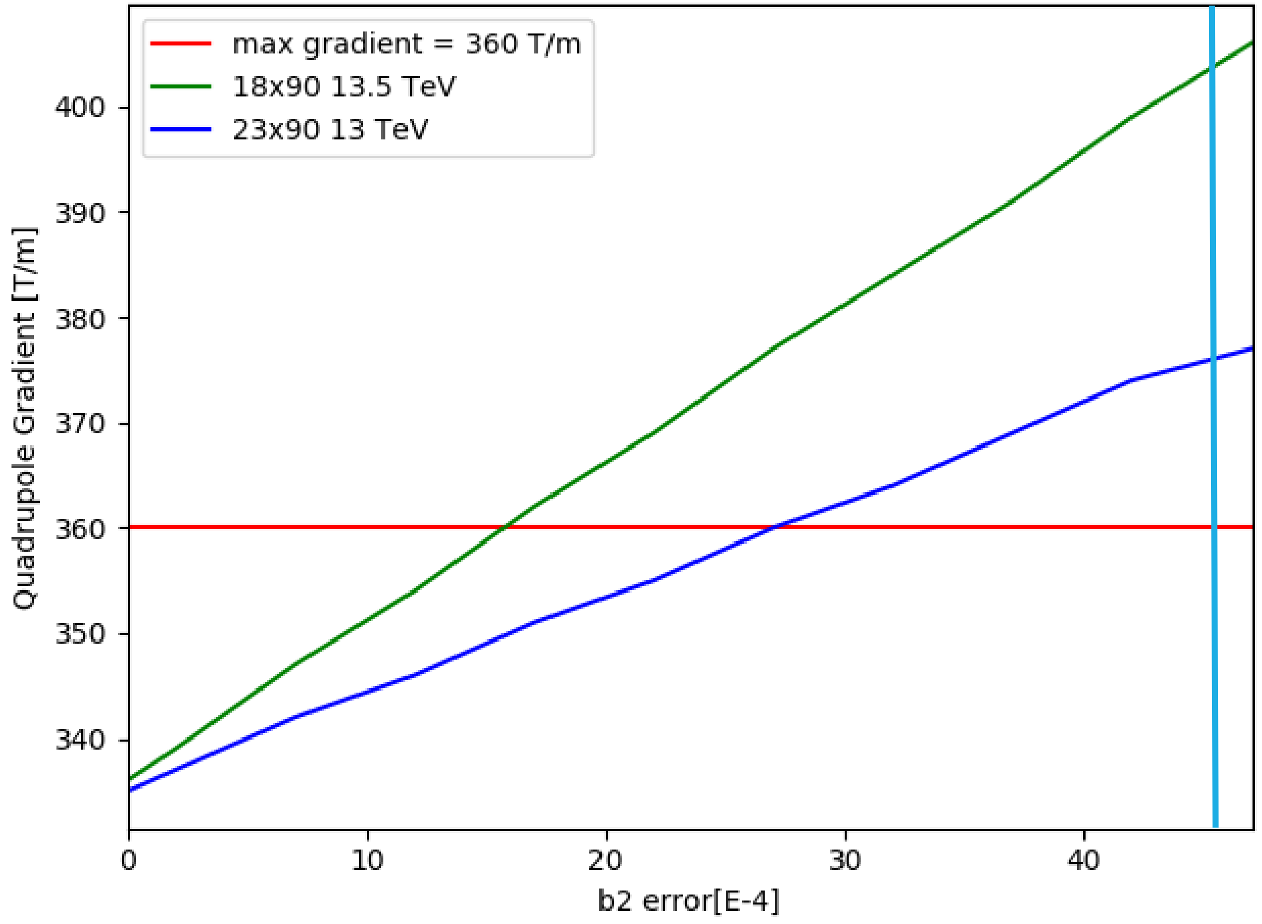

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- Jan 2018: at collision energy b_2 = 46.840 units[1]
  - Quadrupole exceeds limit of 360 T/m
  - Longer quadrupoles for correction
  - 23x90: Shorter dipoles, reduced c.o.m energy of 25.9 TeV
  - 18x90: no effect due to extra drift space in lattice

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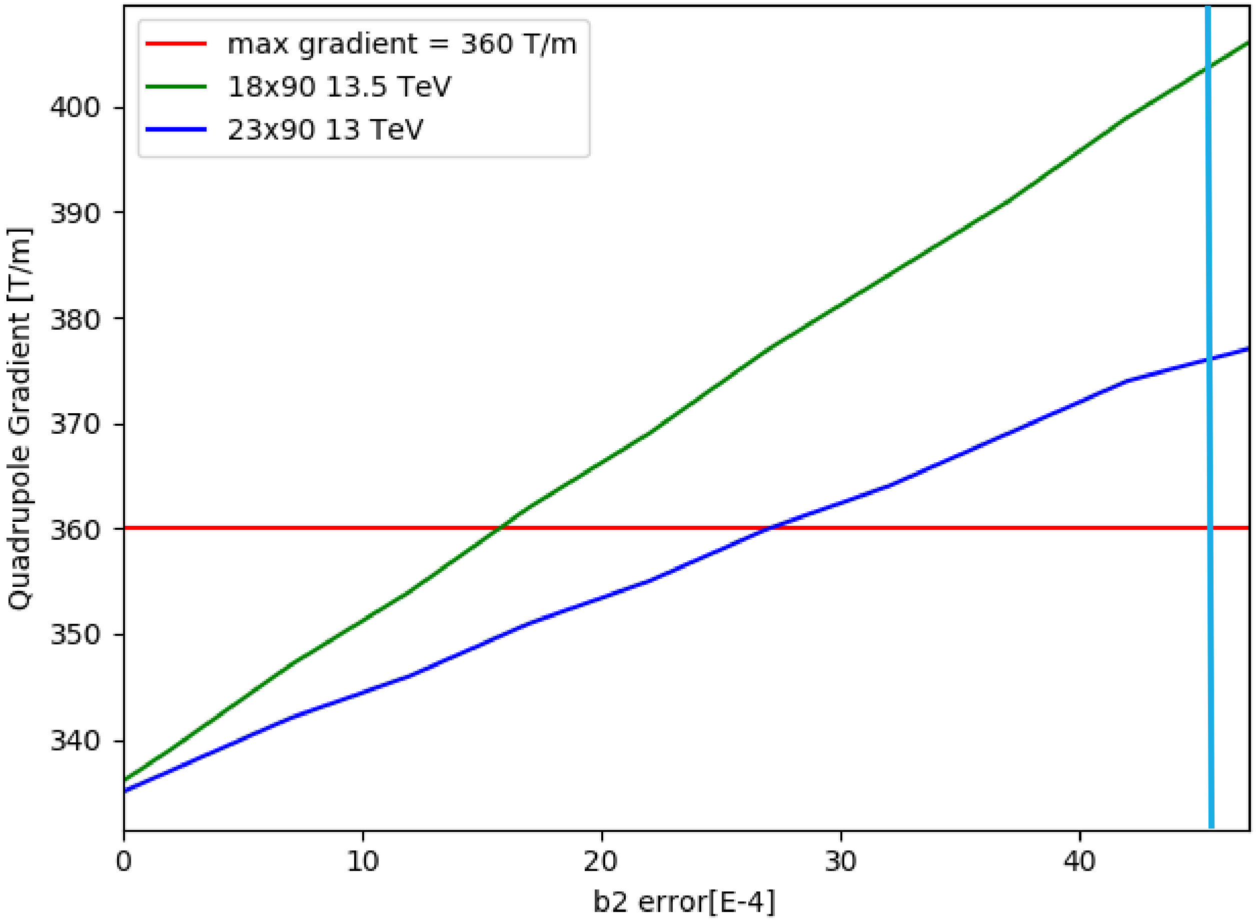

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  - 23x90: Shorter dipoles, reduced c.o.m energy of 25.9 TeV
  - 18x90: no effect due to extra drift space in lattice
- Oct 2018: at collision energy b_2 = 0.025 units[2]
  - No effect on lattice

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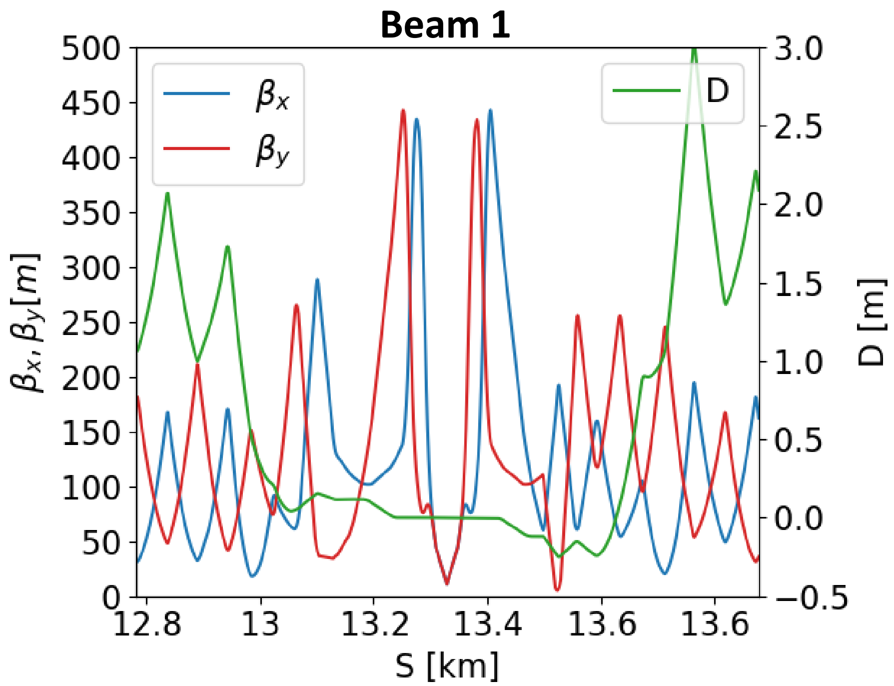
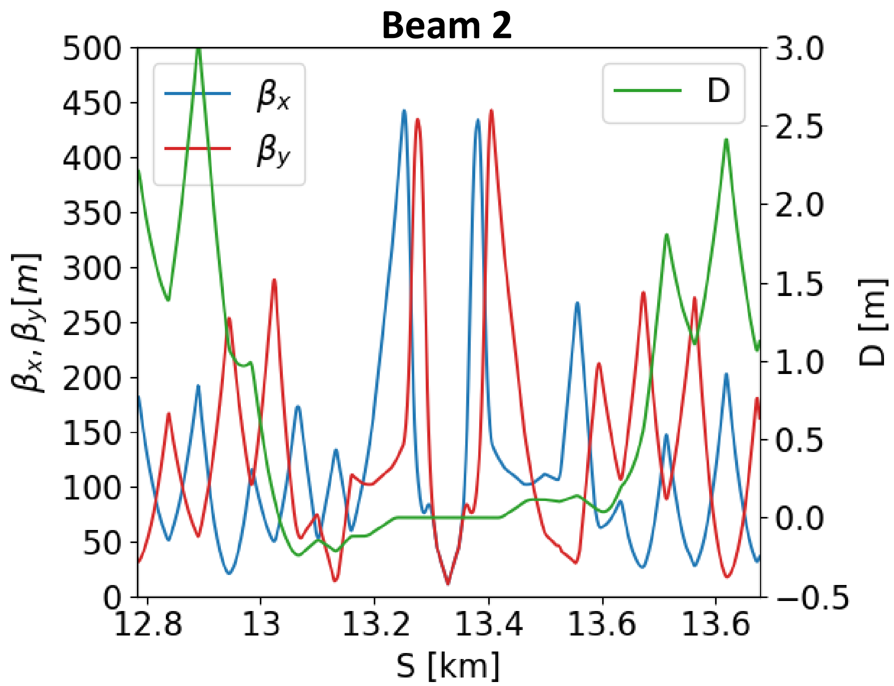
- Conclusion and Outlook

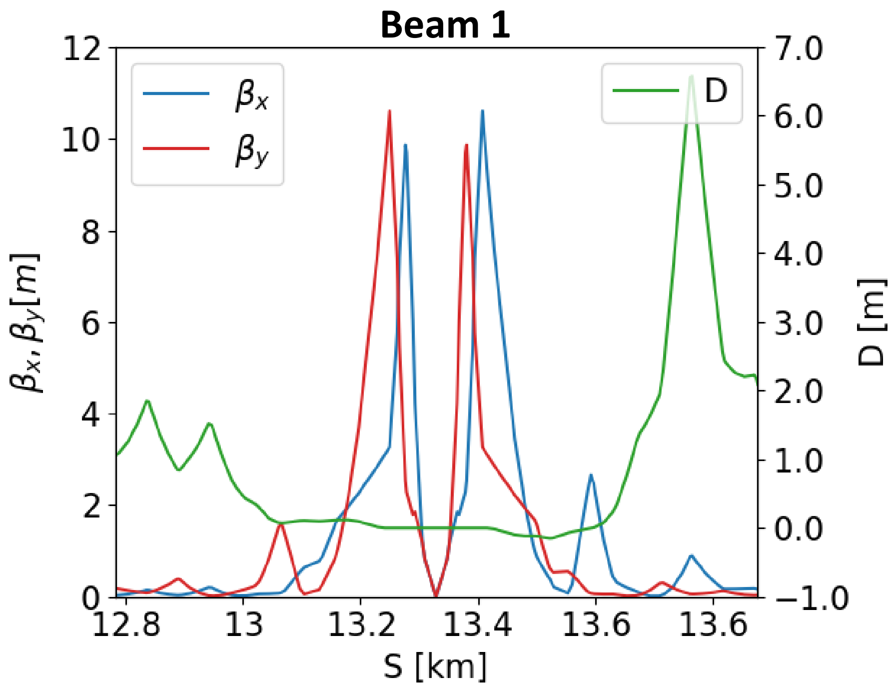
Experimental Insertion - Injection

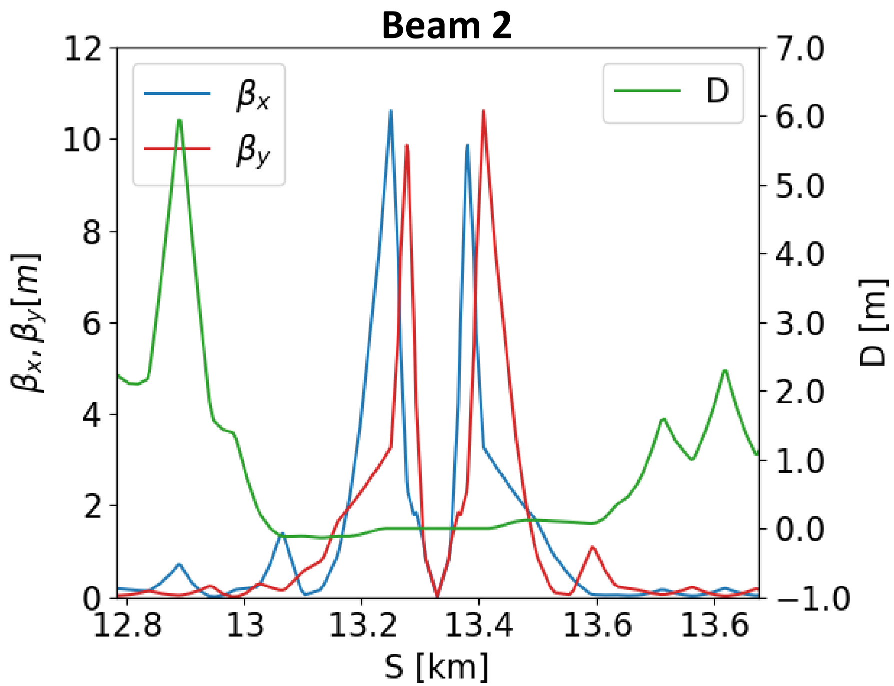




- IR 1/5 by Léon van Riesen-Haupt is integrated
- Injection: $\beta^* = 11$ m

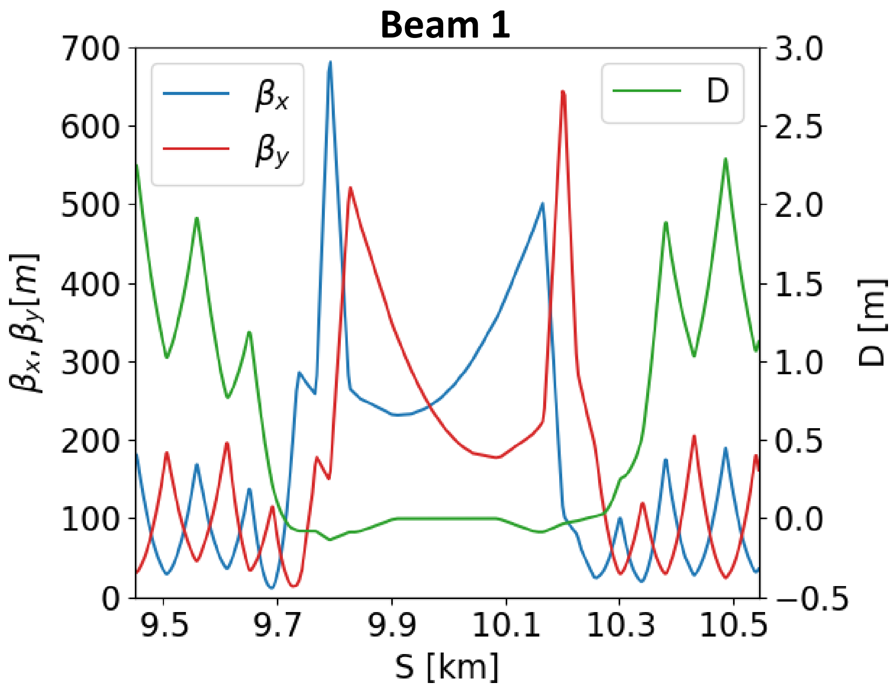
Experimental Insertion - Collision

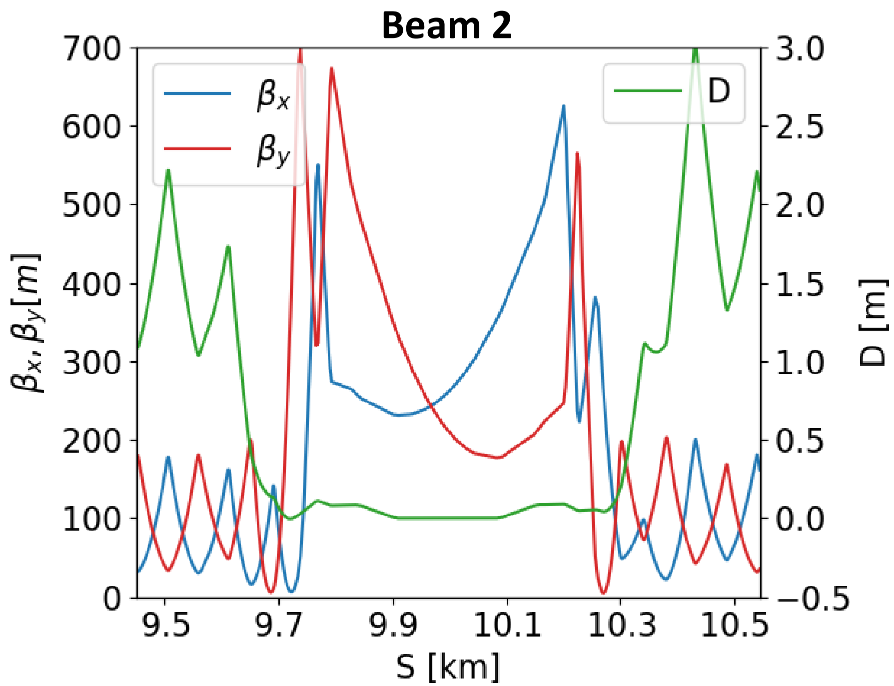




- IR 1/5 by Léon van Riesen-Haupt is integrated
- Collision: β* = 0.45 m
- Half crossing angle: 165 mrad

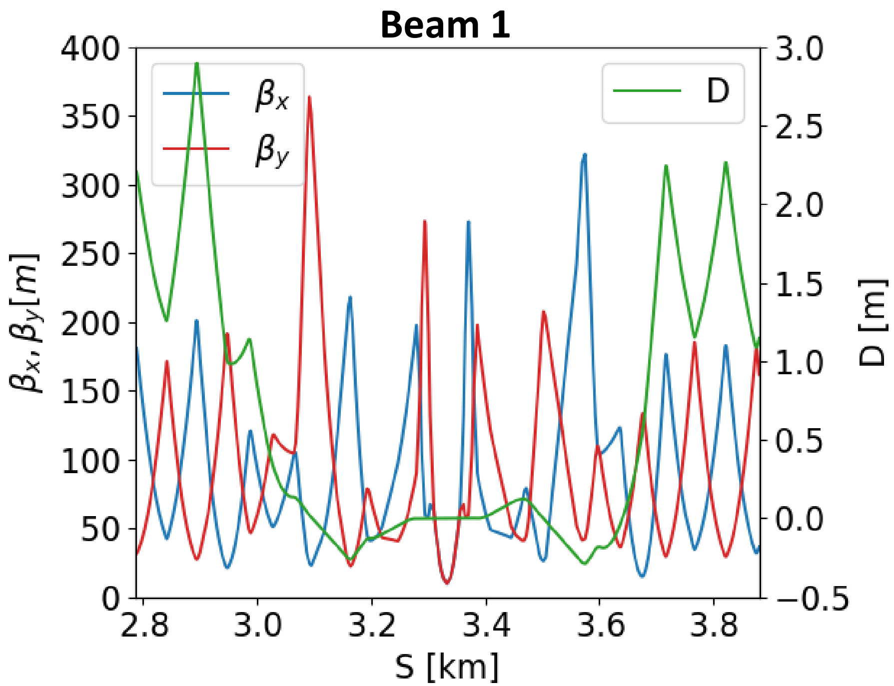
Radio Frequency

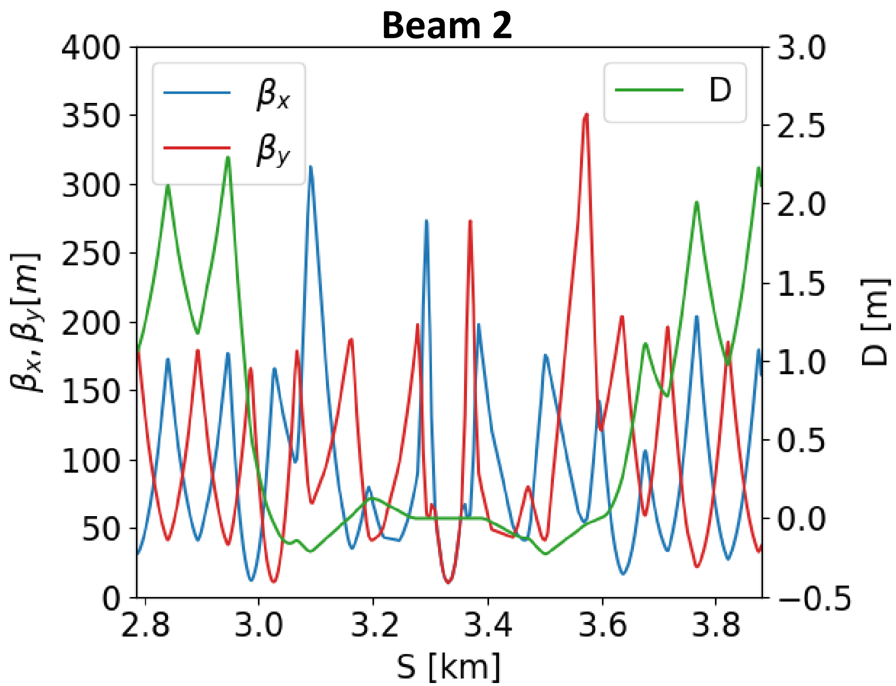




- IR4 by Pablo Mirave and Léon van Riesen-Haupt is integrated
- Contains additional quadrupoles compared to LHC IR4 helps tuning the ring

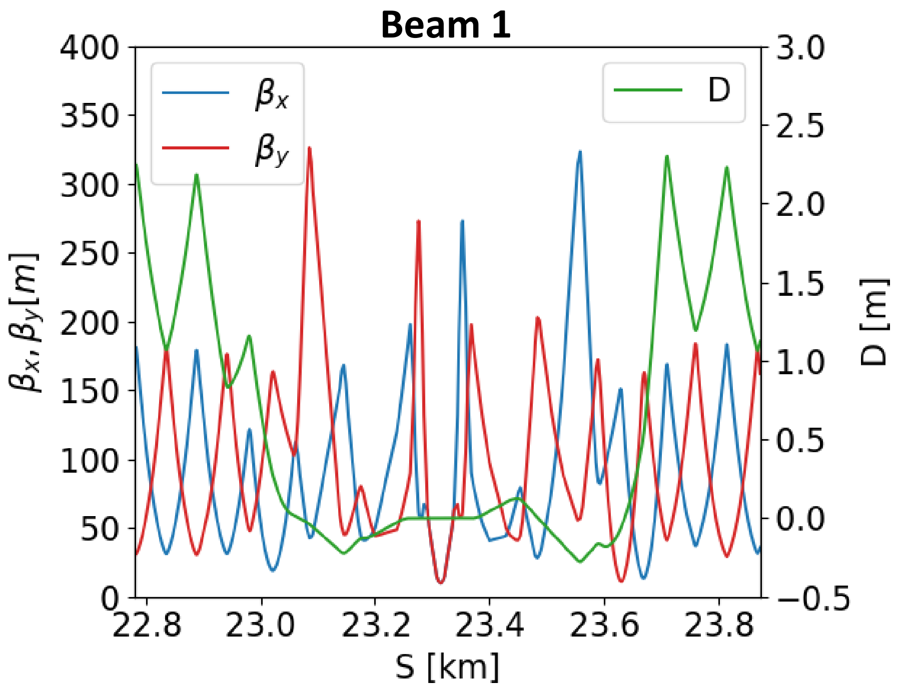
Injection Beam 1 and Experiment

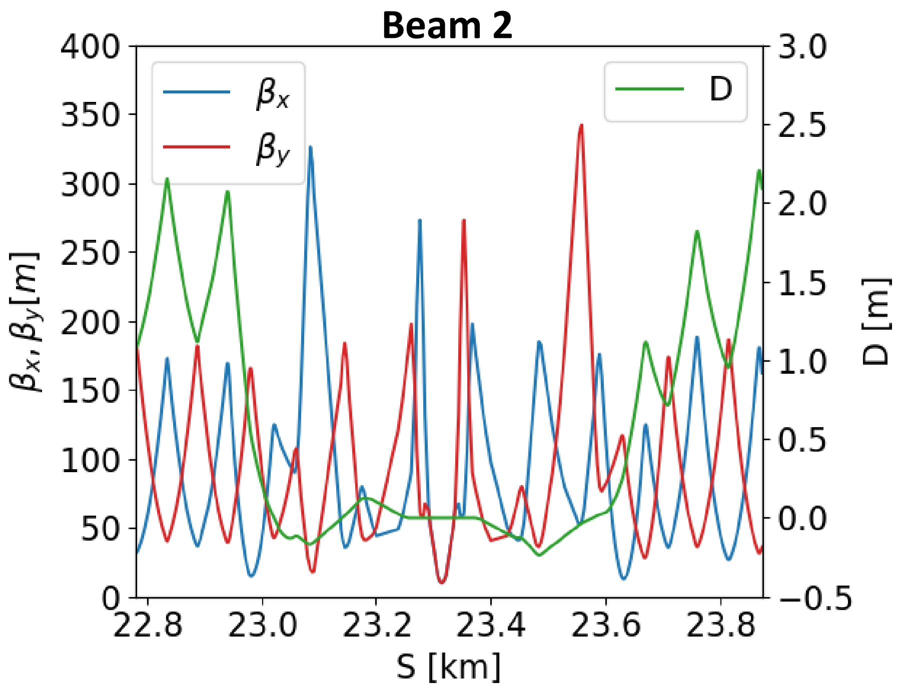




- Beam 1 is injected in IR2
- Taken from LHC

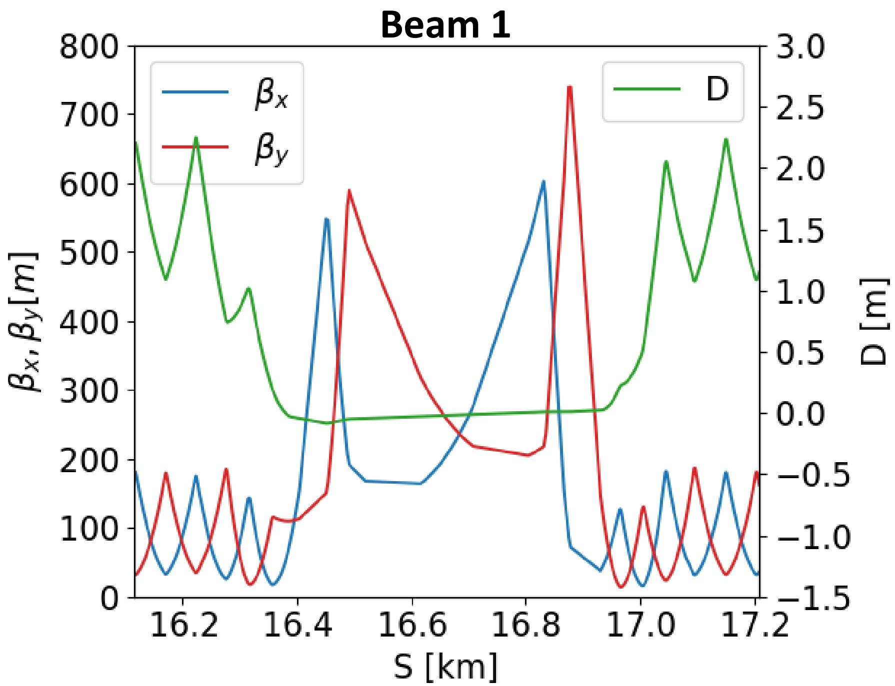
Injection Beam 2 and Experiment

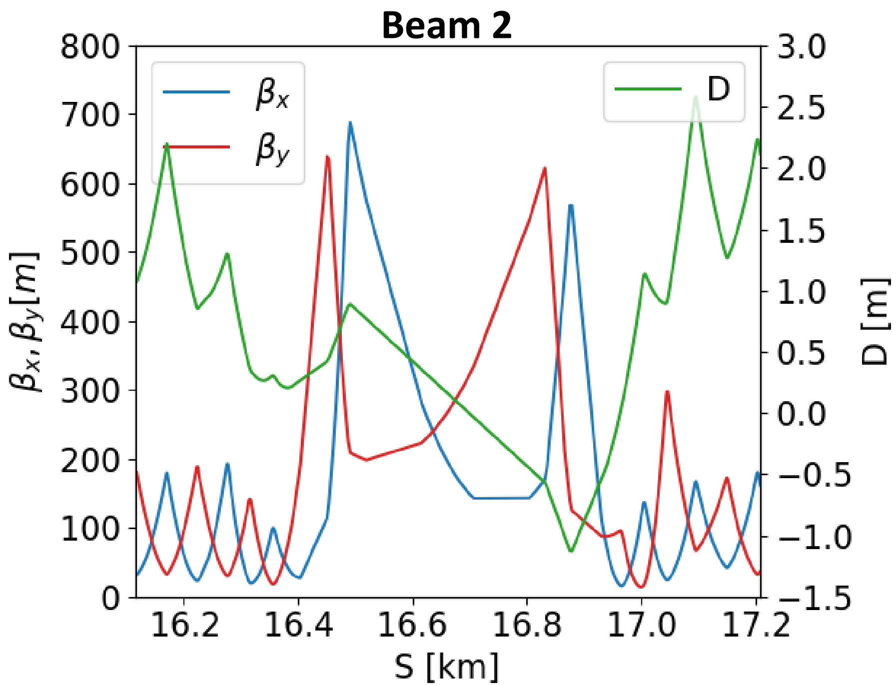




- Beam 2 is injected in IR8
- Taken from LHC

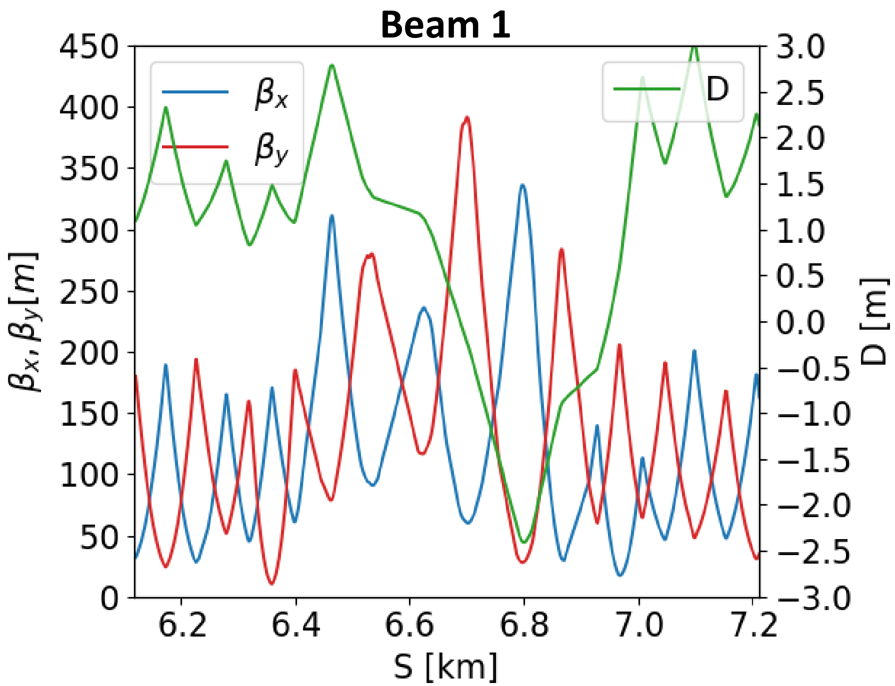
Extraction

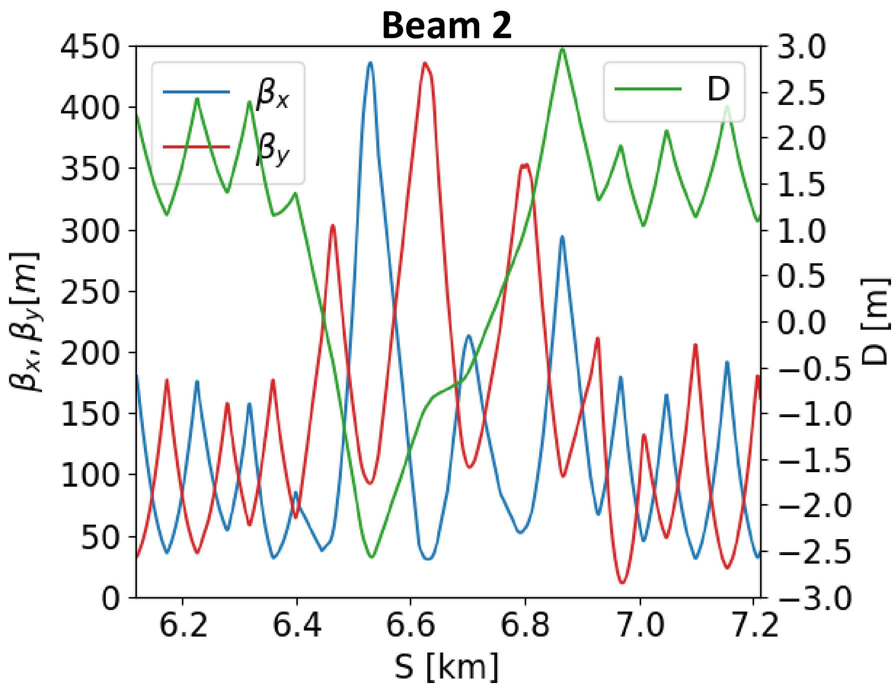




- IR6 design from Wolfgang Bartmann and Brennan Goddard

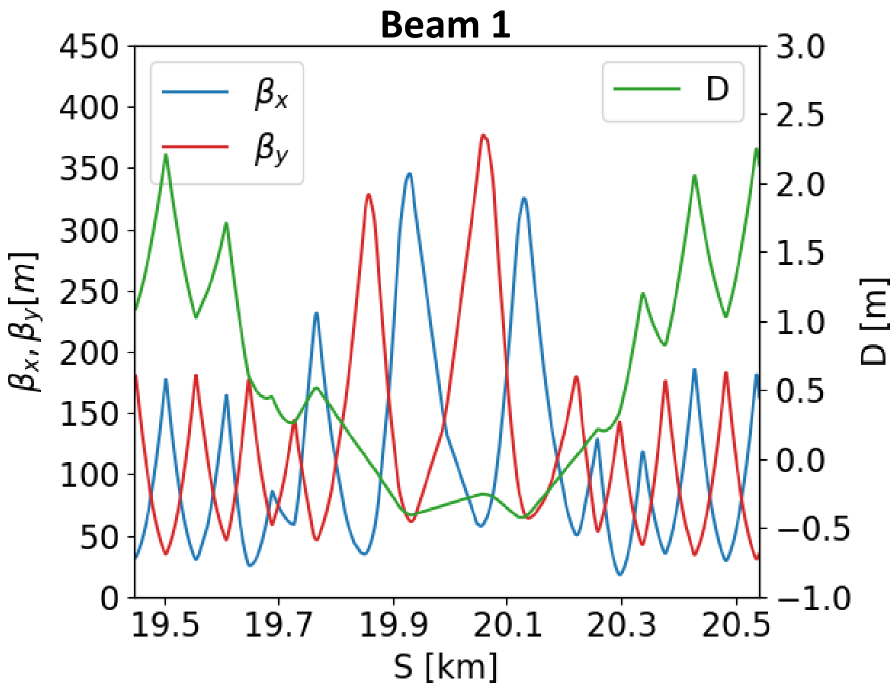
Momentum Collimation

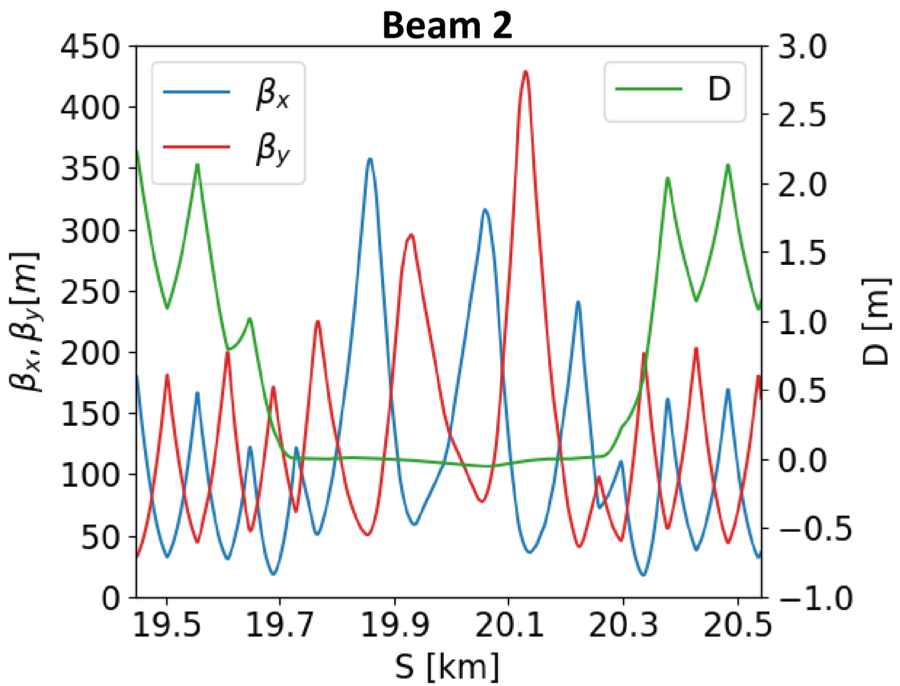




- IR3 from LHC is integrated
- Thys Risselada has already released a new IR
  → integration in the next version

β Collimation





- IR7 from LHC is integrated
- Matthew Crouch and Thys Risselada have already released a new IR → integration in the next version

Outline

- Requirements of the HE-LHC
- Lattice Generation and Geometry Fitting
- Baseline Options
- Effect of Quadrupole Errors in the Main Dipoles
- Integrated Insertion Region Optics
- Conclusion and Outlook

Conclusion and Outlook

- Two baseline designs
  - 23x90: Offset 1 cm, 26 TeV c.o.m. energy
  - 18x90: Offset 9 cm, 27 TeV c.o.m. energy
- Sufficient beam stay clear reached if
  - Injection energy of 800 GeV/600 GeV for the 18x90/23x90 design
  - Choosing a different design with 32 cells per arc
    → below 25 TeV c.o.m. energy, bad geometry
  - Using combined function dipoles with at least 500 units/450 units for the 18x90/23x90 design
  - Scaling the beam screen by 22%/10% for the 18x90/23x90 design
- Current b_2 errors negligible → no effect on designs

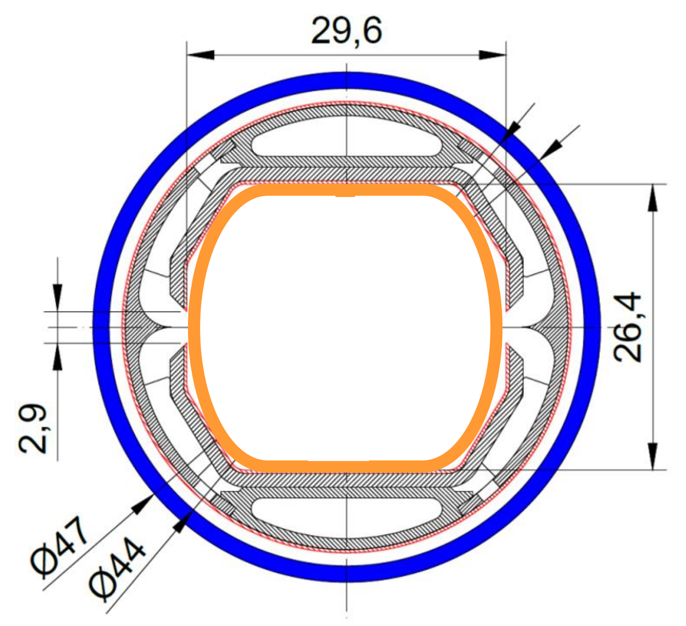
- V0.5 optics ready to release
  - 18x90 and 23x90 designs
  - Injection and collision
  - Beam 1 and beam 2
  - Thick and thin
- Mitigate geometry offset of 18x90
- V0.6 including new IR3 and IR7 designs ongoing

BACKUP SLIDES

Different Beam Screens (BS)

taken from FCC-hh

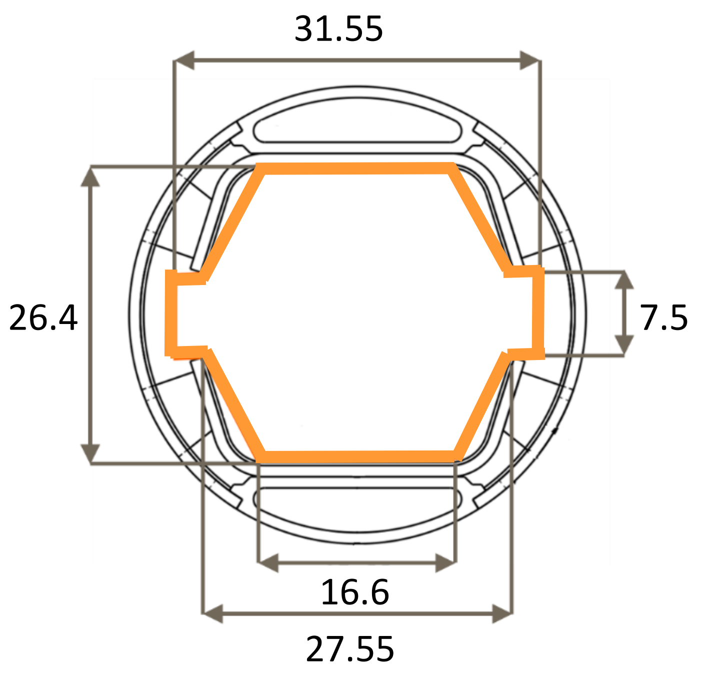
2016



APERTURE = {0.015, 0.0132, 0.015, 0.015}

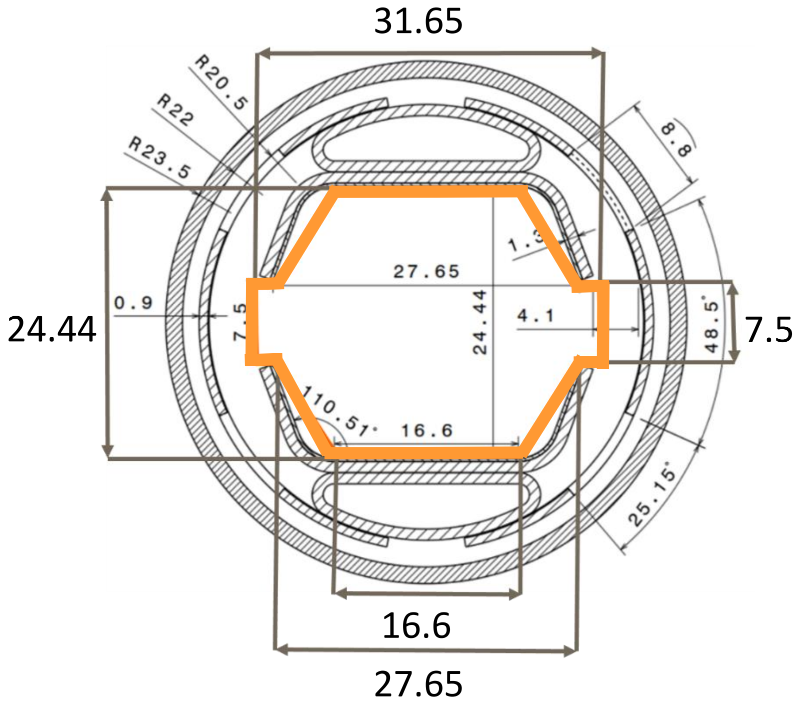
C. Garion, FCC Week Apr. 2016

2017



I. Bellafont, EuroCirCol meeting Oct. 2017

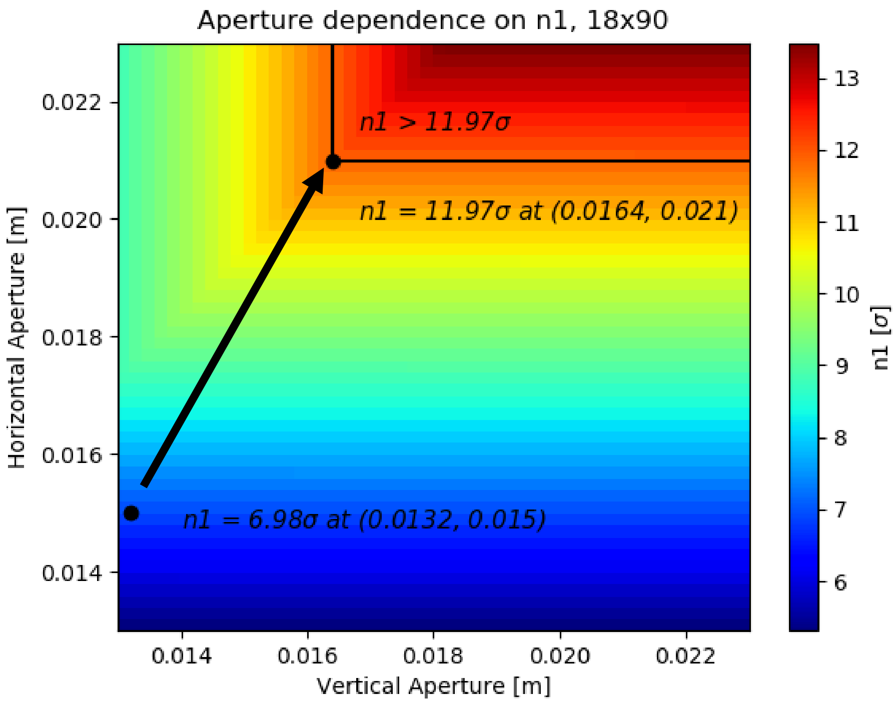
2018



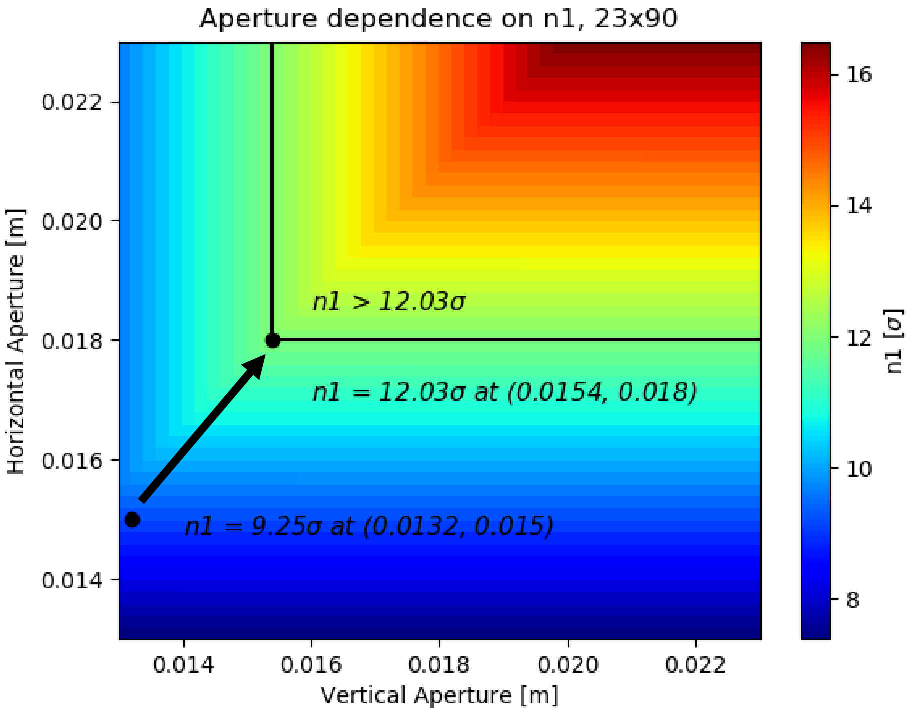
R. Kersevan, FCC-hh design meeting Mar. 2018

Note: values in mm

Required Dimensions (BS 2016)



- 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.***

Beam Stay Clear Values at Injection Energies

-

Energy [GeV]	Beam Stay Clear [σ]	
	18x90	23x90
450	7.51	8.78
900	10.62	12.42
1300	12.77	14.93