First Considerations on Beam Optics and Lattice Design for the Future Hadron-Hadron Collider FCC-hh

B. Dalena on behalf of the FCC-hh optics team

Motivations

- Higgs discovery
- The standard model seems confirmed
- Open questions still remain:
    - Neutrino mass
    - Asymmetry matter/antimatter
    - Dark matter
    - New physics: supersymmetry…

From European strategy for particle physics (to 2018):

To stay at the forefront of particle physics*, Europe needs to be in a position to* ***propose an ambitious post-LHC accelerator*** *project at CERN* ***by the time of the next Strategy update****, when physics results from the LHC running at 14 TeV will be available. CERN should* ***undertake design studies*** *for accelerator projects in a global context, with emphasis on proton-proton and electron- positron* ***high-energy frontier machines****. These design studies should be* ***coupled to a vigorous accelerator R&D program****, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.*

Parameters and Luminosity Target

Two high luminosity experiments
Baseline also two other lower luminosity experiments

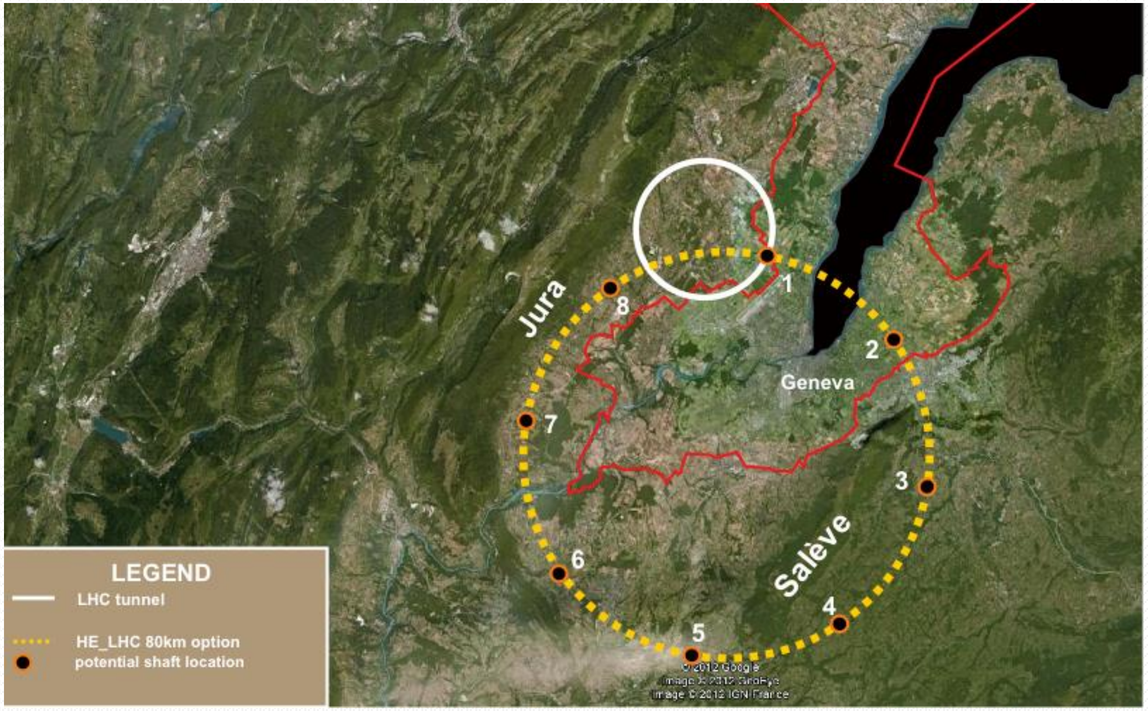
Baseline Promise
- Goal 250fb^{-1} per year
  - 2fb^{-1} per day
- focus on 25ns spacing

Ultimate reasonable hope
- goal 1000fb^{-1} per year
- more emphasis on 5ns

	Baseline	Ultimate
Luminosity [$10^{34}cm^{-2}s^{-1}$]	5	20
Bunch distance [ns]	25 (5)	
Background events/bx	170 (34)	680 (136)
Bunch charge [10^{11}]	1 (0.2)	
Norm. emitt. [μm]	2.2(0.44)	
RMS bunch length [cm]	8	
Synchrotron radiation power [MW]	5	
IP beta-function [m]	1.1	0.3
IP beam size [μm]	6.8 (3)	3.5 (1.6)
Max ξ for 2 IPs	0.01 (0.02)	0.03
Crossing angle [# σ]	12	Crab. Cav.
Turn-around time [h]	5	4

Geologic Layout considerations

- Detector cavern requirements,
- Dump caverns, shielding requirements
- Where & how to dig the tiny tunnel, e.g. shaft locations



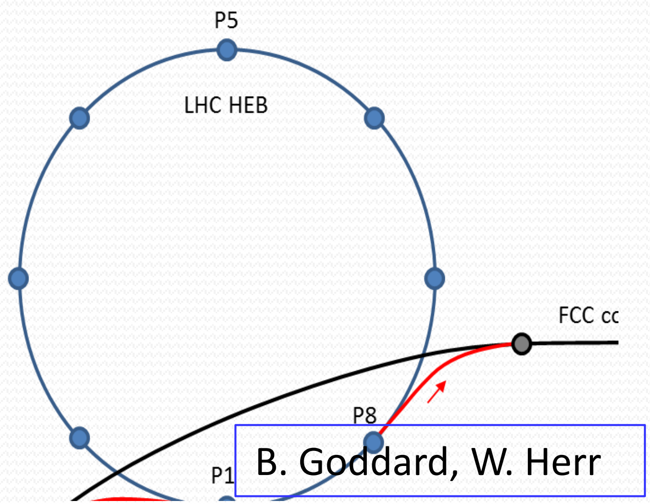
⇒ 93 km seems to fit the site really well, likely better than smaller ring

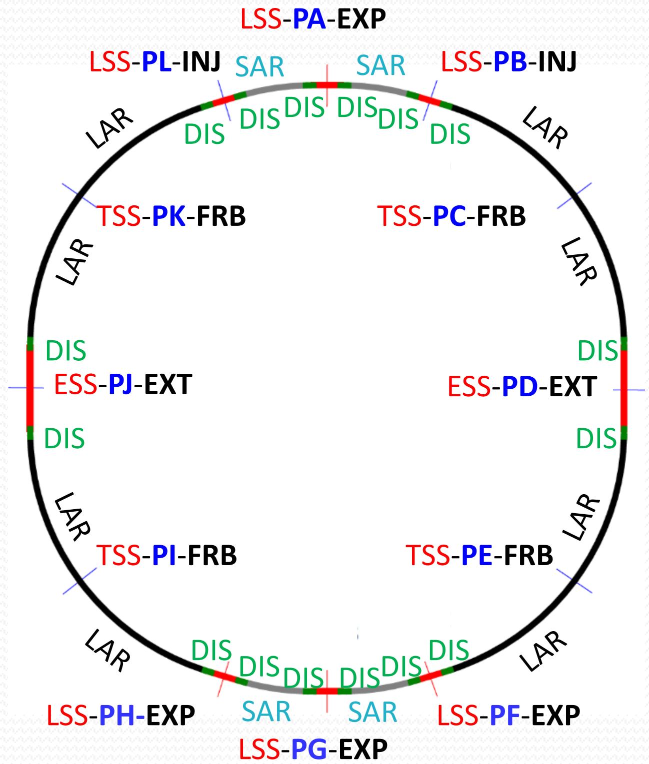
⇒ 100 km tunnel appears possible

Layout and functional sections

- Two high-luminosity experiments (PA and PG)
- Two other experiments (PF and PH)
- Two collimation lines
- Two injection and two extraction lines
- Insertion lengths are based on first order estimates, will be reviewed as optics designs are made

➢ It is consistent with the LHC used as an injector



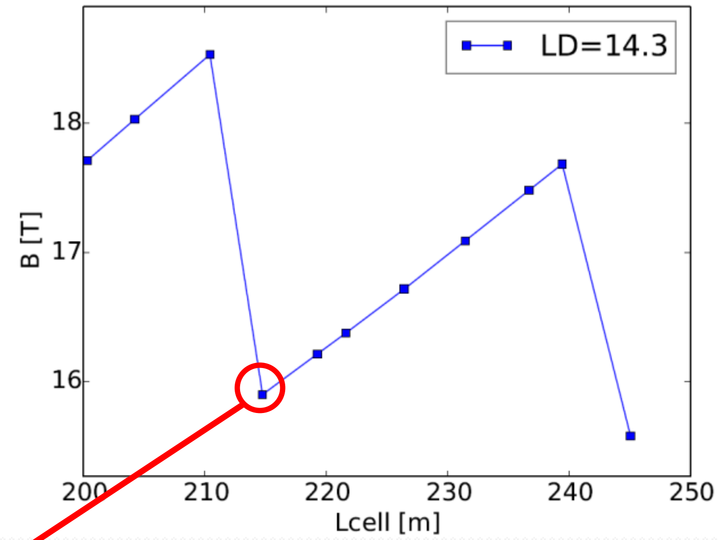


- **LAR** : long arc (L~16 km)
- **SAR** : short arc (L~3.2 km
- **DIS** : Dispersion Suppressor (L~0.4 km)
- **LSS/ESS** : Long/Extended Straight Sections

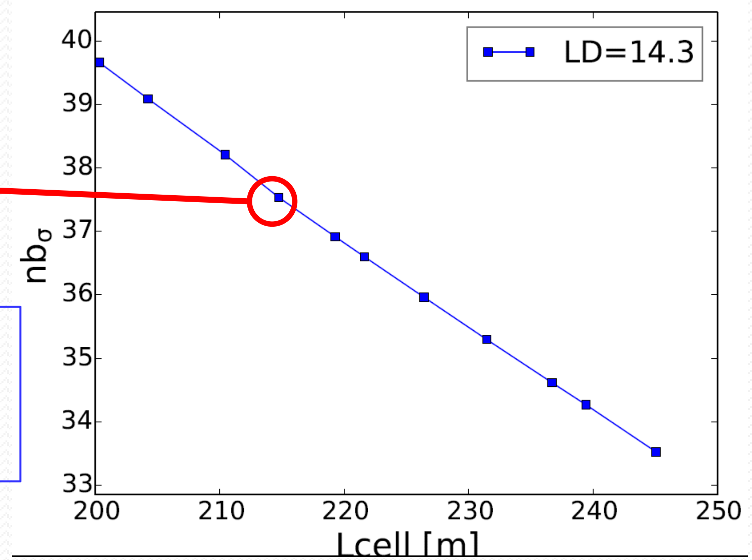
Cell Parameters

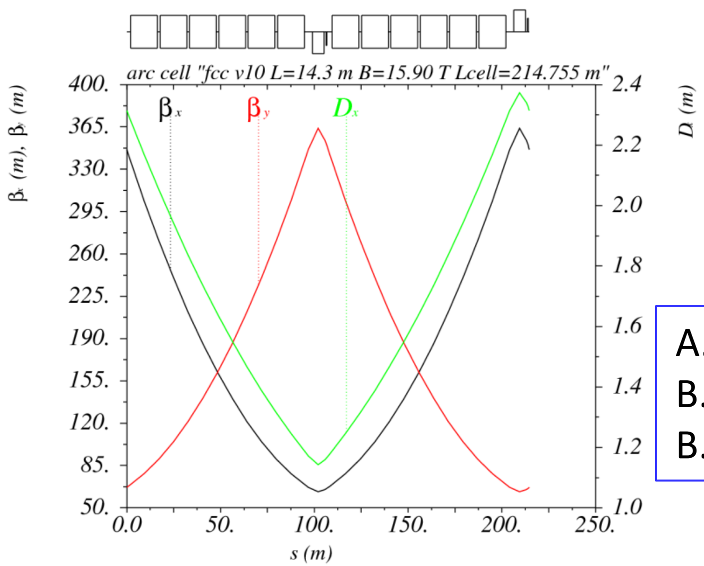
Input parameters:

- Dipole-dipole separation 1.36 m
- Dipole maximum field 16 T
- Dipole magnetic length 14.3 m
- Minimum quadrupole-dipole separation 3.67 m
- Maximum gradient of the quadrupole 370 T/m
- ∅ = 50 mm (beam screen radius 20 mm)
- Sextupole length 0.5 m
- Quadrupole-sextupole separation 1.0 m
- Cell Phase advance 90° x/y
- Circumference 3.75 × LHC ~ 100 km



# of sigma at E_{inj}=3. 3 TeV





A.Chance, J. Payet,
B. Holzer, R. Alemany,
B.D.

High Luminosity Interaction Region

Aim for largest reasonable L^*
- Explore range of L^*
- Currently study L^*=36 m and 61 m
- Experiments prefer $L^* \geq$ 40 m

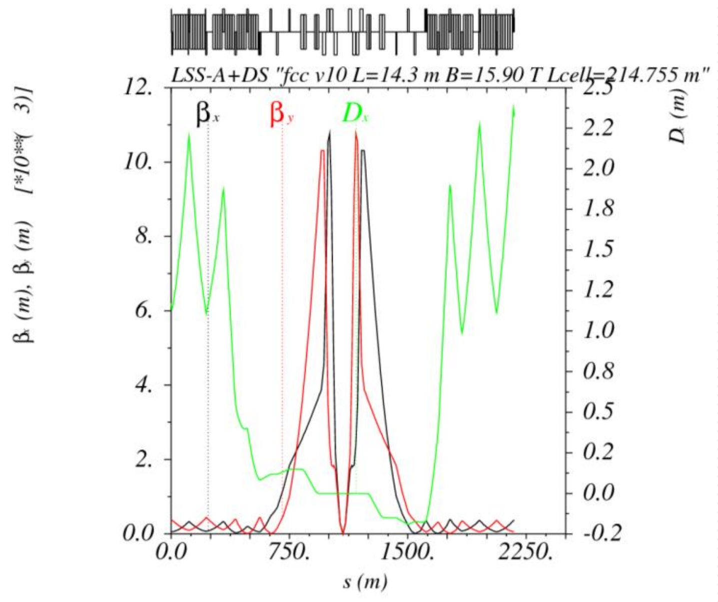
Quality of focusing
- Can achieve baseline of β^*=1.1 m and ultimate β^*=0.3 m with both L^*

Consider also flat beams option

Aperture and beam separation
- Aperture of the collimators, critical for the impedance
- Beam-beam effects, critical for beam stability

Concern: radiation from IP into final triplet
100 kW to 400 kW + collision debris produced in IP

Dispersion Suppressor LHC-like type



R. Martin, TUPTY001
R. Tomas
A. Seryi

⇒ **Large aperture quadrupoles like HL-LHC**

Betatron Collimation region

First betatron collimation system scaled from LHC

- Gaps as in HL-LHC
- But 2.7 km long

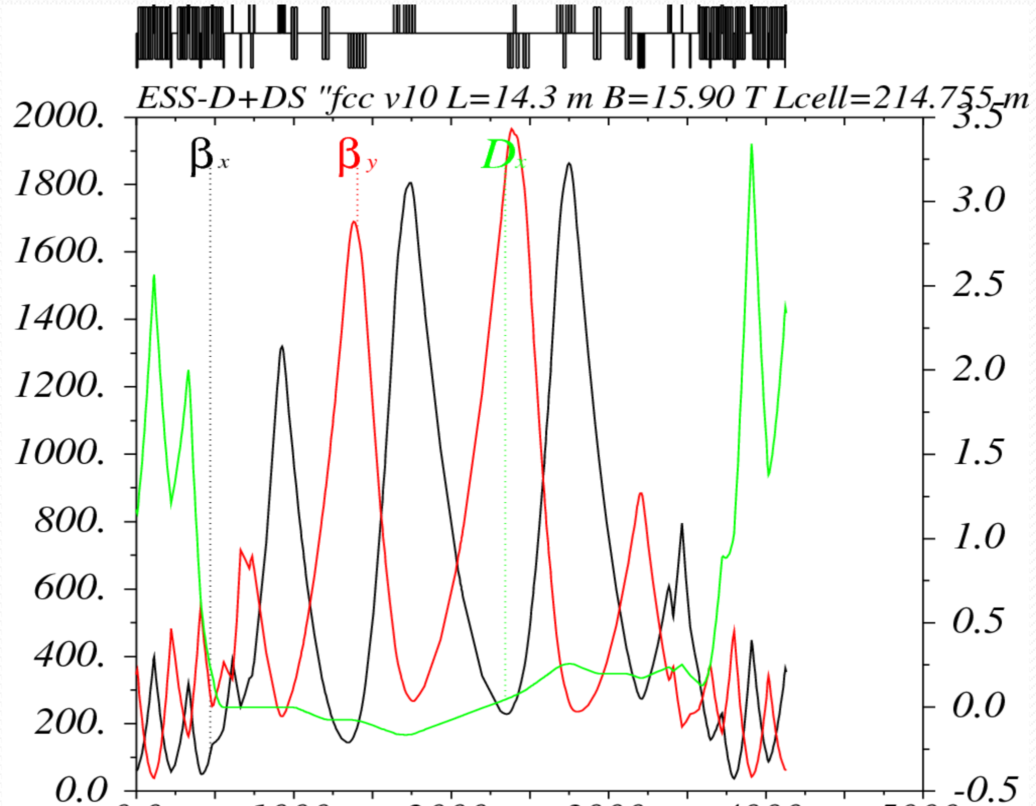
⇒ Starting point for exploration

- Additional matching section required to match to the arcs

⇒ Fix issues from LHC design

⇒ First results on performances are promising, similar to LHC

⇒ Other options under study



⇒ Integration with extraction still to be done

⇒ Energy collimation system challenging, still to come

R. Tomas
M. Fiascaris

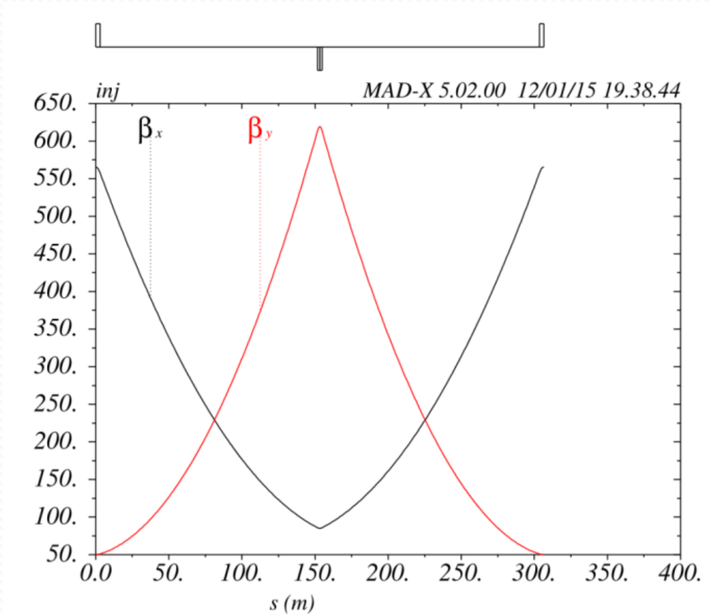
Injection/Extraction

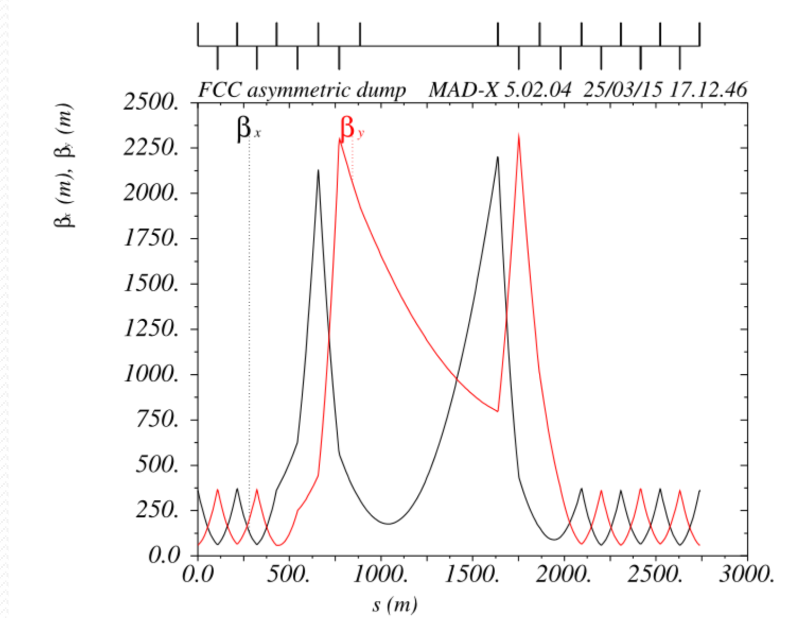
W. Bartmann, THPF089
T. Kramer, TUPTY050

- Increase regular half cell length from 100 m to 150 m in injection insertion
  - Relax magnet strengths, make space for instrumentation and protection devices
- Total injection insertion requires about **500 m** for septum, kicker and internal dump

Three options under study

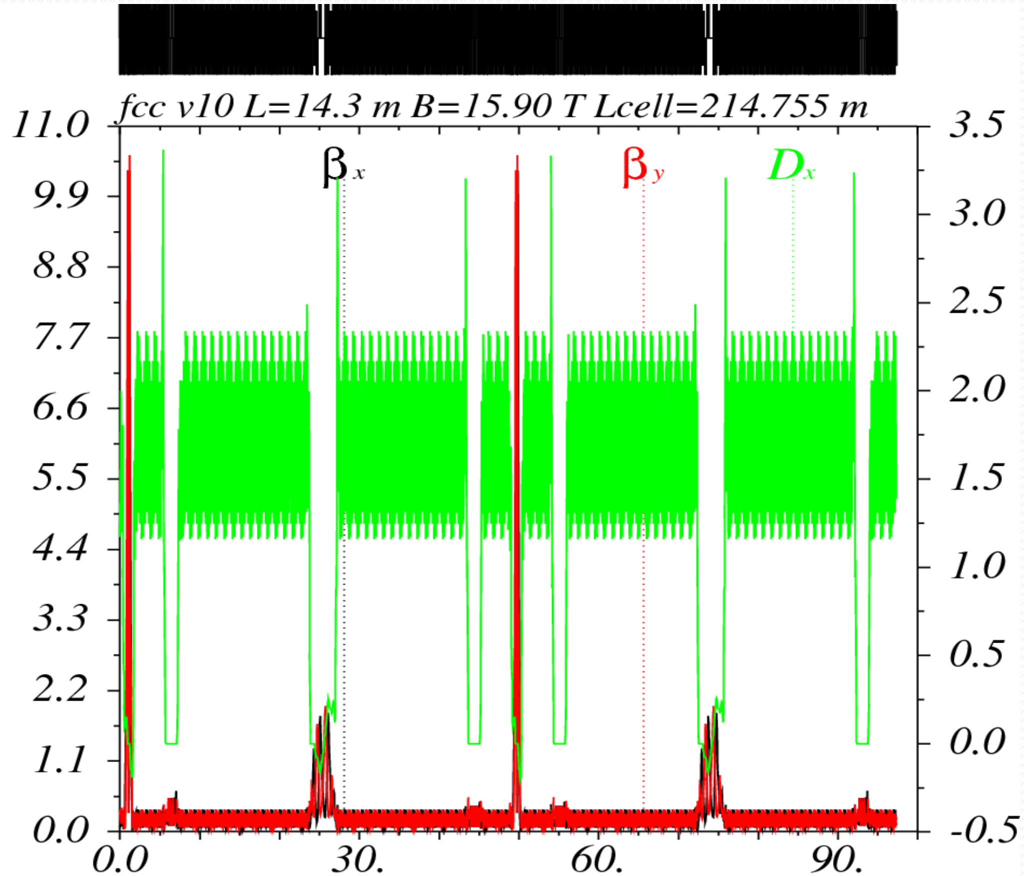
- LHC scaled dump insertion
- SSC –like
- Asymmetric dump insertion optics





Some Lattice parameters

Parameter	value
Bρ [T m]	166667
γ	53289
$\gamma_{transition}$	97
α	0.0001
β* [m]	1.1
Natural chromaticity x/y	-196./-197.
Equilibrium emittance* [m rad]	1e-12
$\varepsilon_{norm}/\beta\gamma$ [m rad]	4.1e-11
Transverse/Longitudinal Damping time** [h]	2/1



* $\varepsilon_{eq} = \frac{C_q \gamma^2 I_5}{\left(I_2\left(1 - \frac{I_4}{I_2}\right)\right)}$

** $\tau_t = \frac{2E_0T_0}{U_0}$ $\quad \tau_l = \frac{2E_0T_0}{U_0\left(2 + \frac{I_4}{I_2}\right)}$

Sensitivity to the parameters and layout choices

The present baseline layout and optics is based on:

- scaling laws from LHC
- possibility to re-use the know how and R&D developed for the LHC to handle the construction and maintenance of the different elements

↓

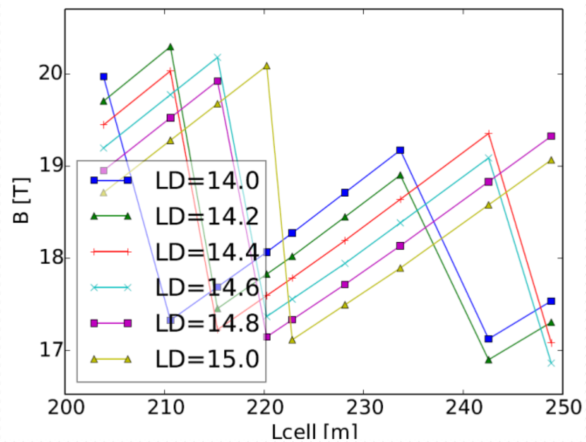
What we can gain or lose by changing some parameters ?

- circumference of the “quasi racetrack” : 3.5 , 3.75 and 4.0 times LHC
- dispersion suppressor types (DIS): Half Bend (twice weaker dipoles), LHC-like, Full Bend
- cell parameters

In the following:

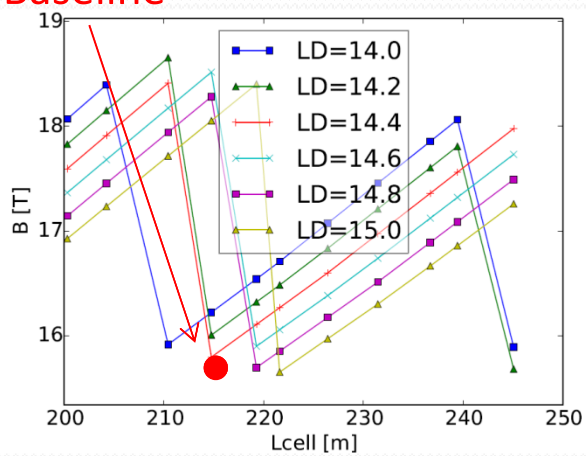
- reference energy for the protons is 50 TeV
- LD = dipole length
- Lcell = cell length
- nb_σ = number of RMS beam sizes (aperture) at injection energy

Circumference

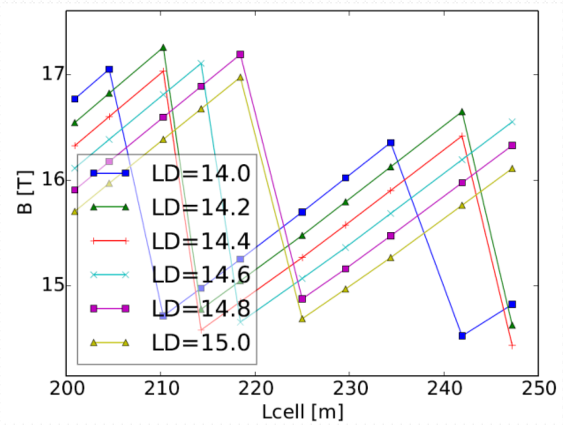


93.45 km

Baseline



100.12 km



106.80 km

For 100 TeV c.o.m. energy

$\Rightarrow$ 3.5 × LHC: no solution found with a dipole field below or equal to 16 T, minimum field 16.9 T

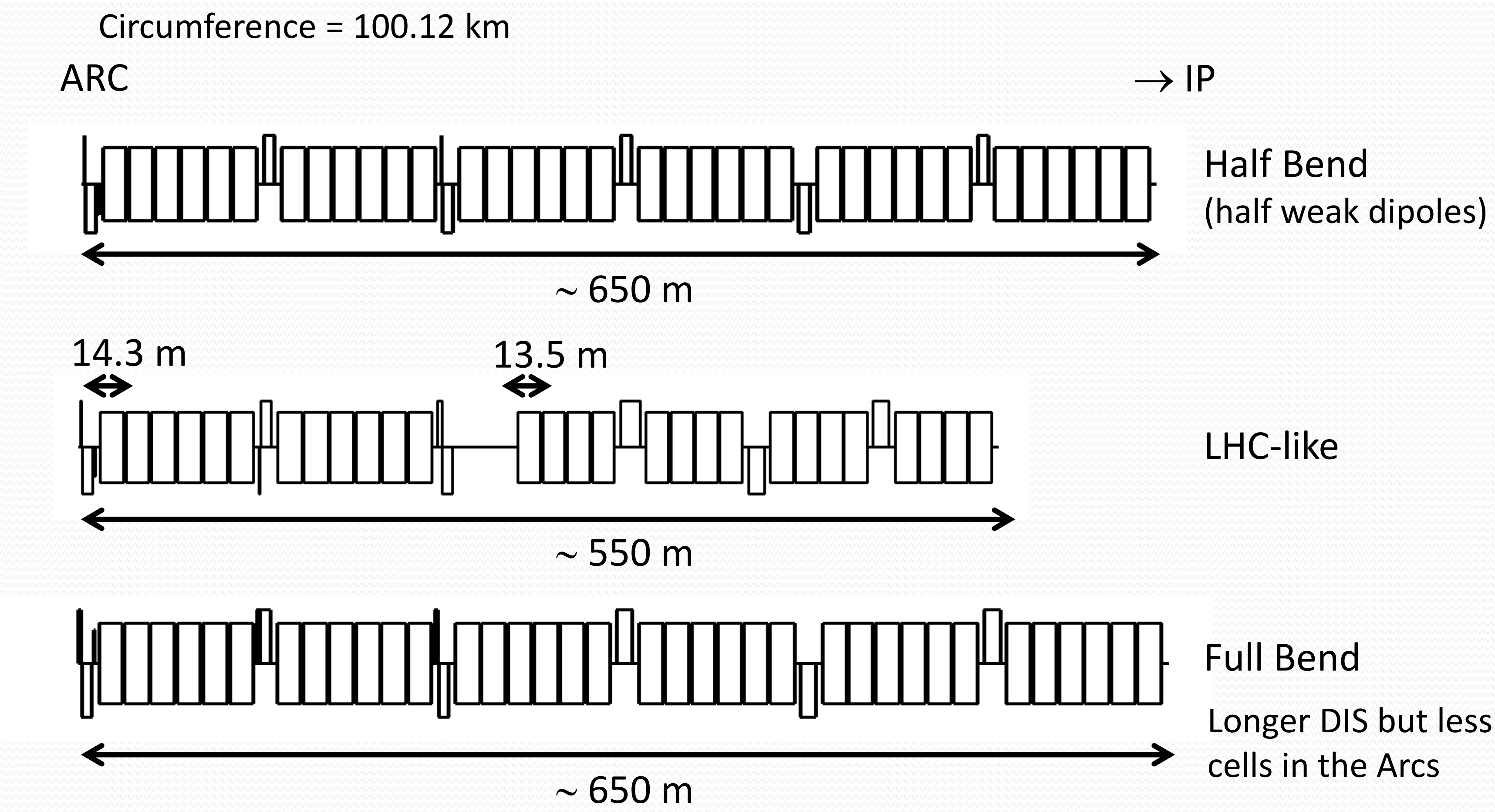
$\Rightarrow$ 4.0 × LHC: 9% lower dipole field (14.6 T) but 6% longer ring…

Proton energy reachable for a maximum field of 16 T

$\Rightarrow$ 3.5 × LHC: ~47 TeV

$\Rightarrow$ 4.0 × LHC: ~55 TeV

Dispersion Suppressor



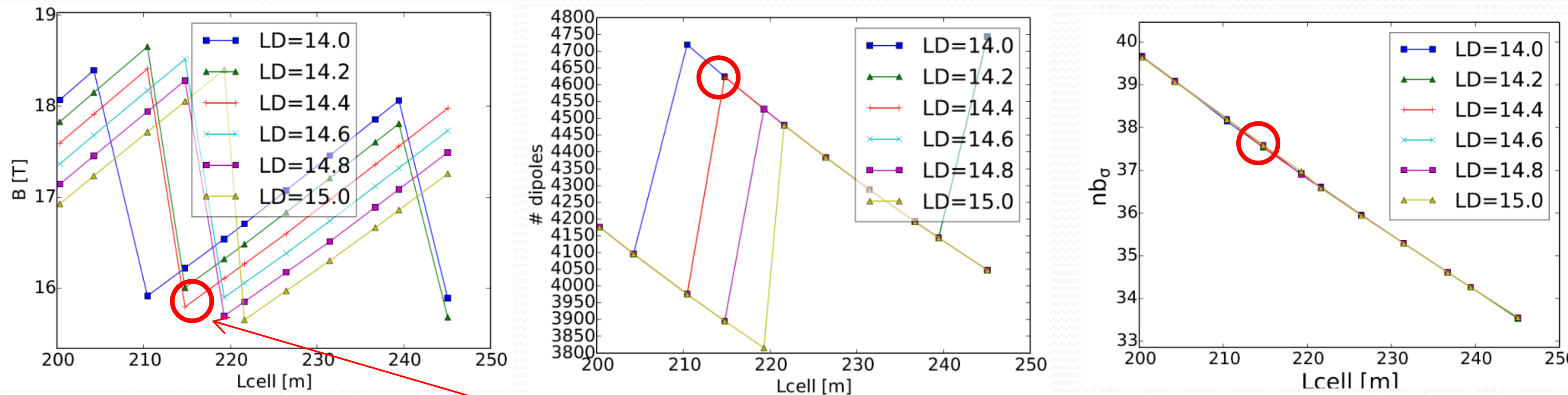
⇒ Half Bend DIS: minimum main dipole field required 16.3 T

⇒ LHC-like DIS: some space saved with respect to Full Bend DIS, dipole field 15.9 T

⇒ Full Bend DIS: lower dipole field 15.7 T and one type of dipole with respect to LHC-like DIS

Dipole and cell length

Circumference = 100.12 km, beam screen radius = 20 mm, LHC-like dispersion suppressor



Baseline (15.9 T)

For the best cases: fill factor 80-82%

⇒ LD =[14.0 : 14.3] m and Lcell=245 m: dipole field 15.6 T, losing ~15% of beam stay clear at injection and having 2.5-4% more dipoles

⇒ **LD =14.8 m** and **Lcell=219 m:** dipole field 15.7 T and ~3% less dipoles, losing ~3% of beam stay clear at injection

Conclusion

- FCC-hh baseline and ultimate parameters are defined
- **A preliminary layout exists, to be updated**
  -First integrated lattice exists **http://fccr.web.cern.ch/FCCr/hh/LATTICE_V4/Baseline**

  Arcs:
  -There is a bit of margin in the cell parameters choices (cell and dipoles lengths)
  -Type of dispersion suppressor: possible options LHC-like and Full Bend ?
  -In the case of 93.45 km ring and 16 T maximum dipole field the center-of-mass energy is likely to decrease

  Straight sections:
  -Baseline as well as options for injection, extraction, collimation and interaction region optics are under study

Outlook

Plenty of work to be done on the optics…

- Study options for the different insertions
- Complete integration of the straight insertions and reserve space for other systems
- Tune scan and working point study (including Beam-Beam)
- Chromaticity
- Dynamic aperture and magnet tolerance study
- Re-optimize the different systems design

…and R&D

- Magnets
- Beam screen design
- Final triplets (similar to HL-LHC)
- Beam dynamics, feedback
- Machine protection and availability
- …

You are welcome to join!

Work/meeting structures established based on INDICO, see:
-**FCC Study:** **https://indico.cern.ch/category/5153/**

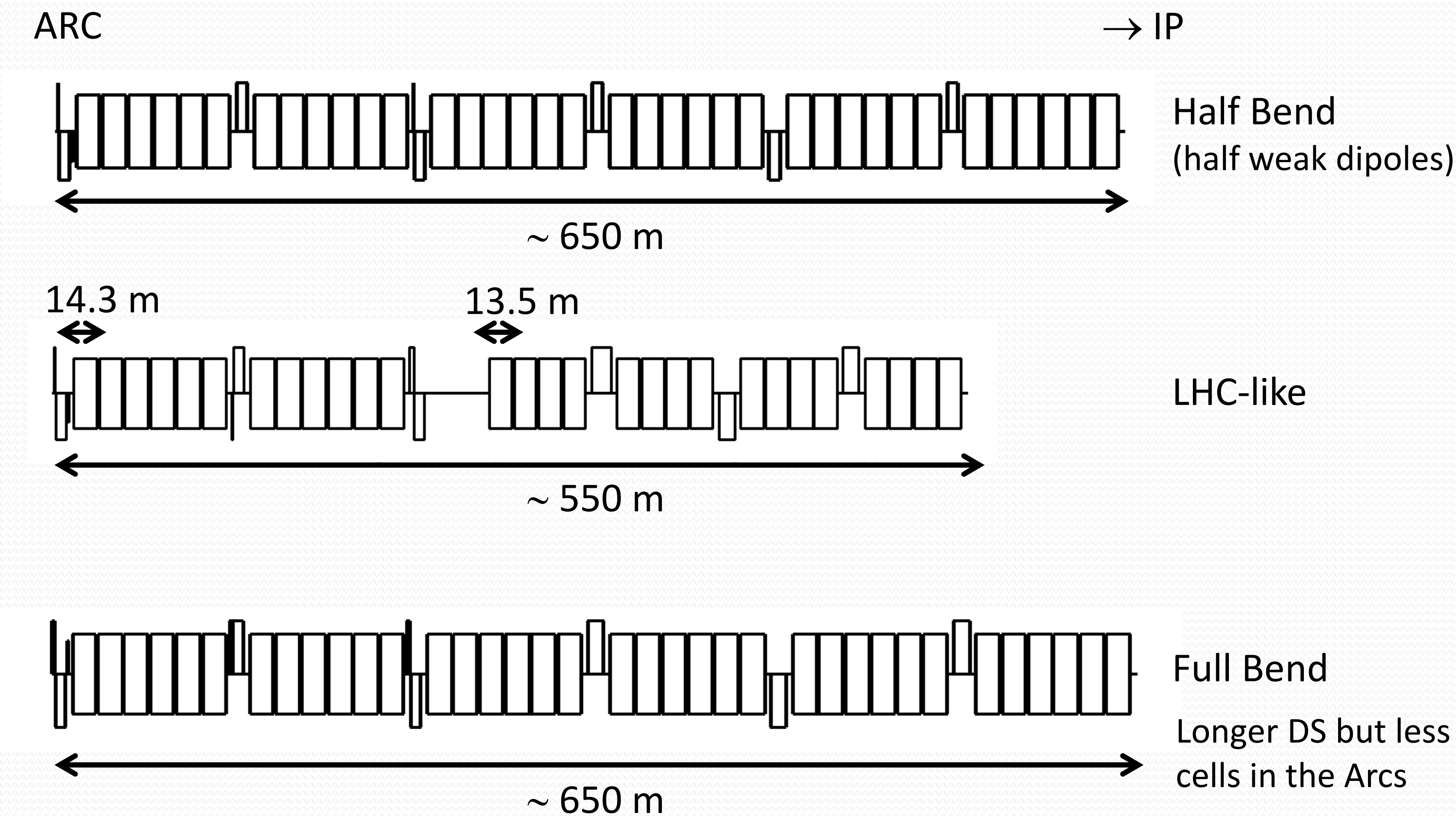
In particular:

-**FCC-hh Hadron Collider VIDYO meetings**
-**https://indico.cern.ch/category/5263/**
-**Contacts: daniel.schulte@cern.ch**

-**FCC-hadron injector meetings**
-**https://indico.cern.ch/category/5262/**
-**Contacts: brennan.goddard@cern.ch**

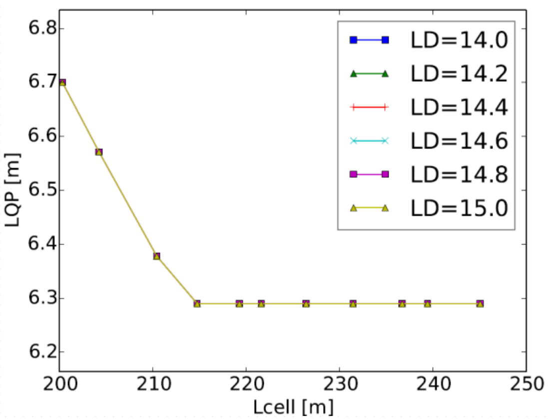
SPARES

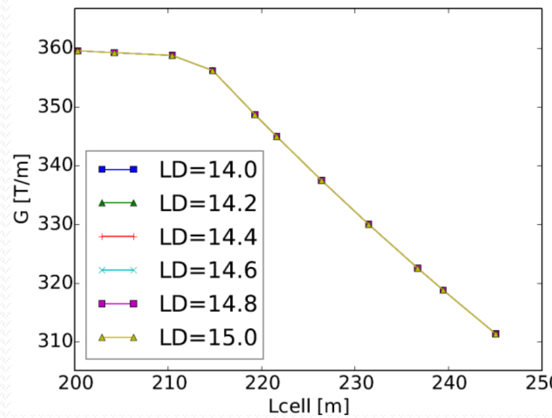
Dispersion Suppressor (DIS) types

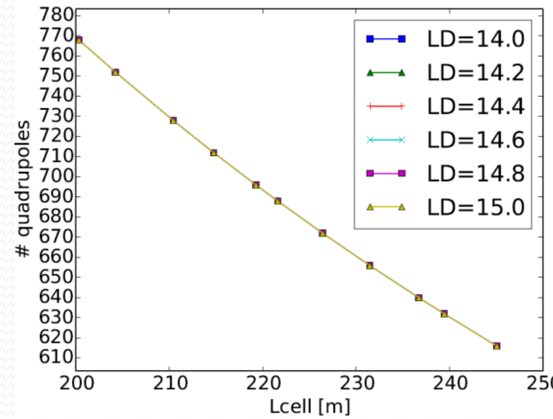


Quadrupoles and cell length

Circumference = 100.12 km, beam screen radius = 20 mm, LHC-like dispersion suppressor

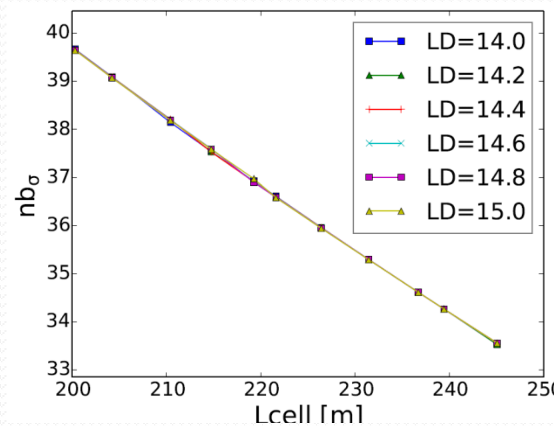






⇒ Lcell = 245 m: quads have same length as Lcell=215 m

⇒ Lcell = 245 m: 14% quadrupole gradient and 20% of quadrupoles can be saved, losing ~15% of beam sigma

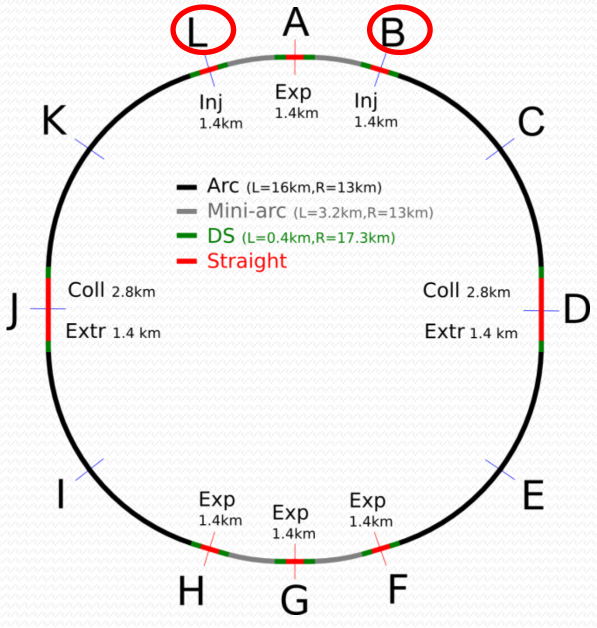


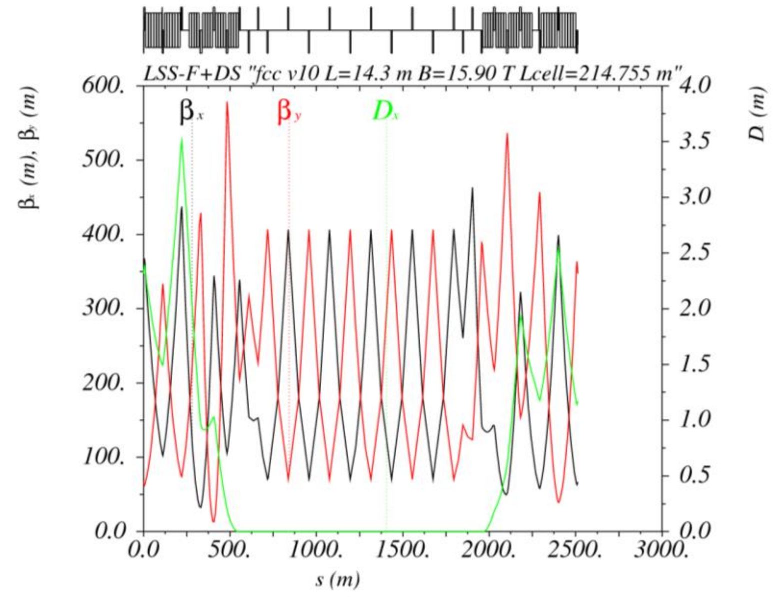
⇒ for a maximum field of 370 T/m, quadrupoles lengths > 6 m

⇒ higher quadrupoles gradients 420 T/m can reduce dipole field of few %

Other 2 Interaction Regions

- Simple FODO cells for the moment. The length of the FODO cells is adjusted to have a length of 1.4 km.

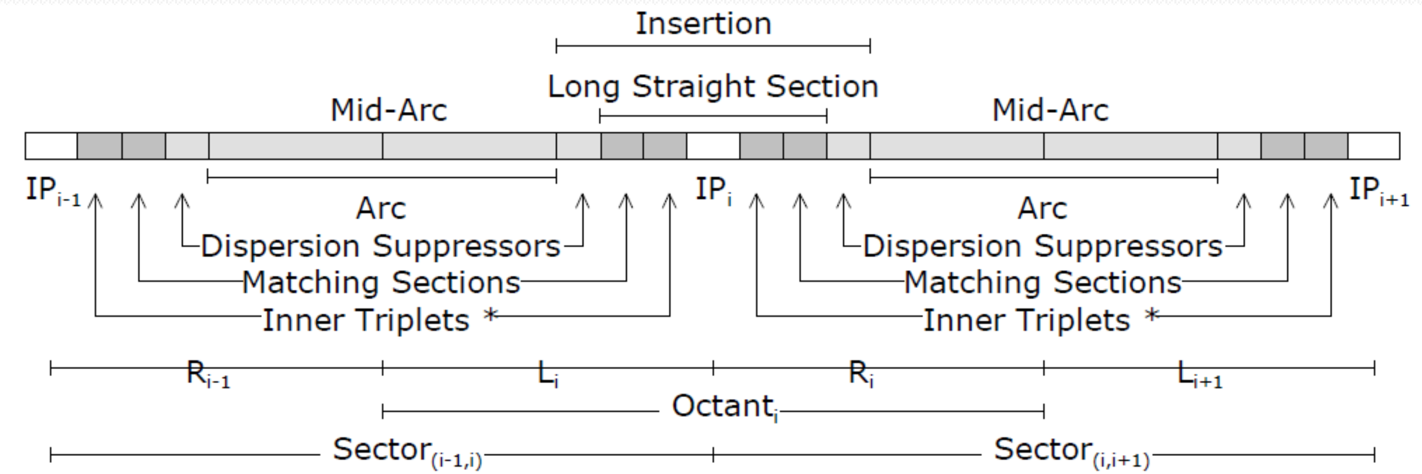




Sections and naming convention

Abbreviation	Generic name	Number	Length [km]
LSS	Long straight section	6	1.4
ESS	Extended straight section	2	4.2
TSS	Technical straight section	4	ε
DS	Dispersion suppressor	16	0.4
SARC	Short arc	4	3.2
LARC	Long arc	8	depends on total length

- A particular Functional Section has a name defined as:
  <generic abbreviation>-<Point or Sector identifier>(-<Order number>)
  Examples: LSS-A, ESS-D, DS-AB-1, DS-CD,…
- Numbering of the elements in the cells is the same of LHC:



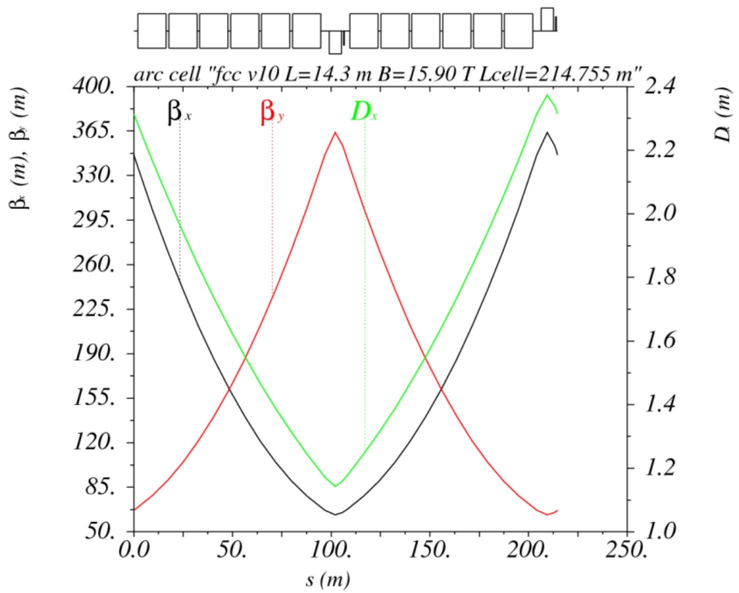
with i = A, i-1=L, i+1=B

ARC CELL

# dipoles	B max [T]	Length [m]
4368	15.90	14.3

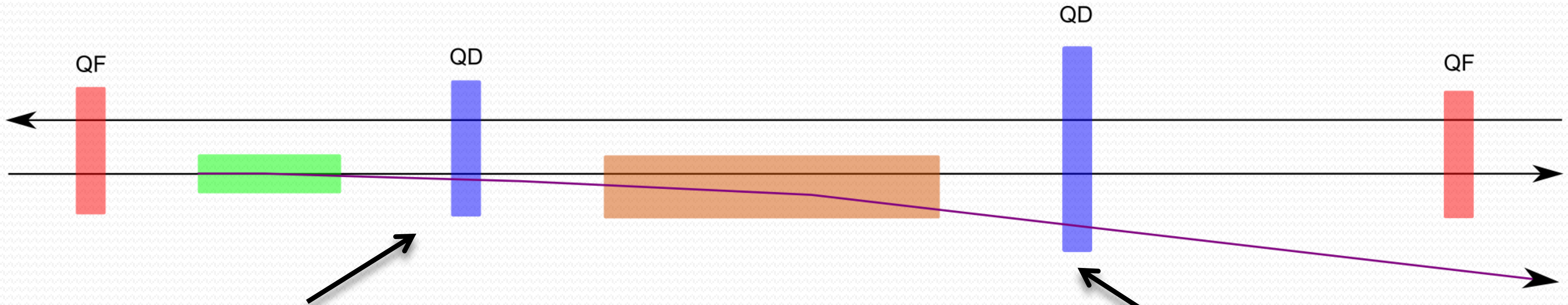
# quadrupoles	G max/min [T/m]	Length [m]
812*	356/-356.26	6.29

# sextupoles	G max/min [T/m²]	Length [m]
700	-7144.37/ 3551.32	0.5 (fixed)



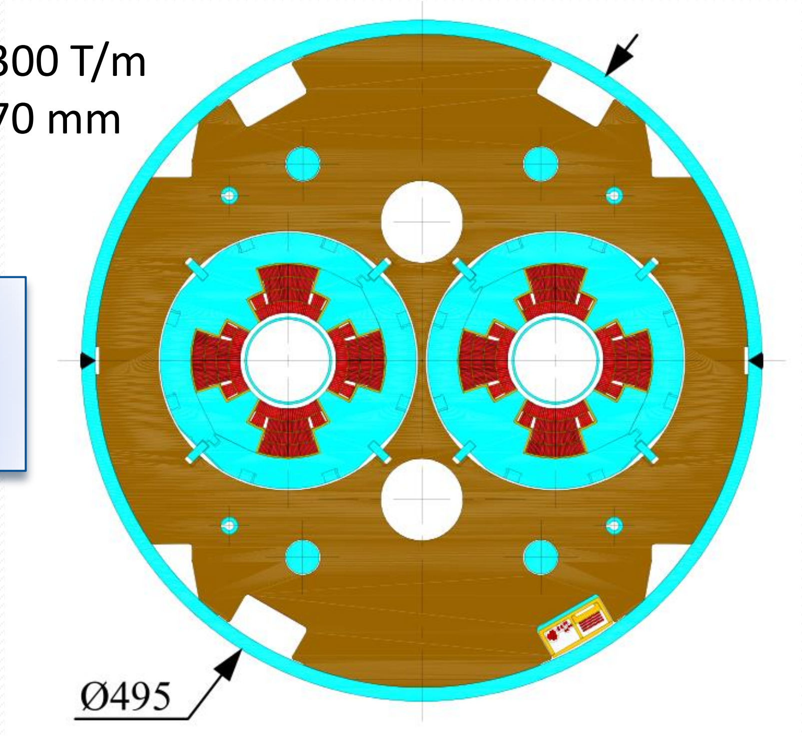
* the number of quadrupoles includes the quads in the dispersion suppressor

Requirements for special quadrupoles



Enlarged quadrupole

300 T/m
70 mm



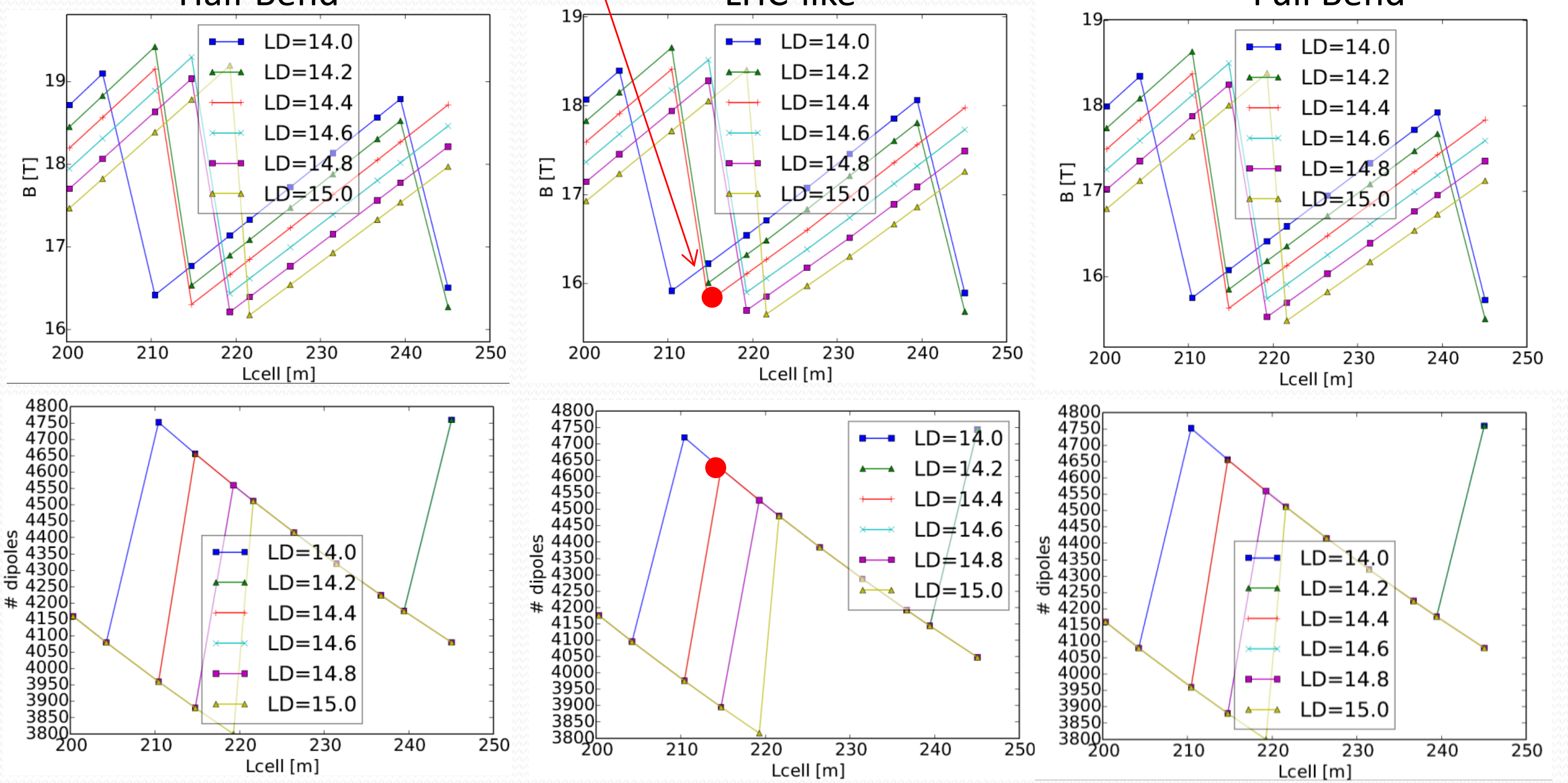
Triple chamber quadrupole?

Beam offset:
Injection up to 18 mm
Extraction up to 9 mm

Dispersion Suppressor types & dipoles

Circumference = 100.12 km

Half Bend | Baseline | LHC-like | Full Bend

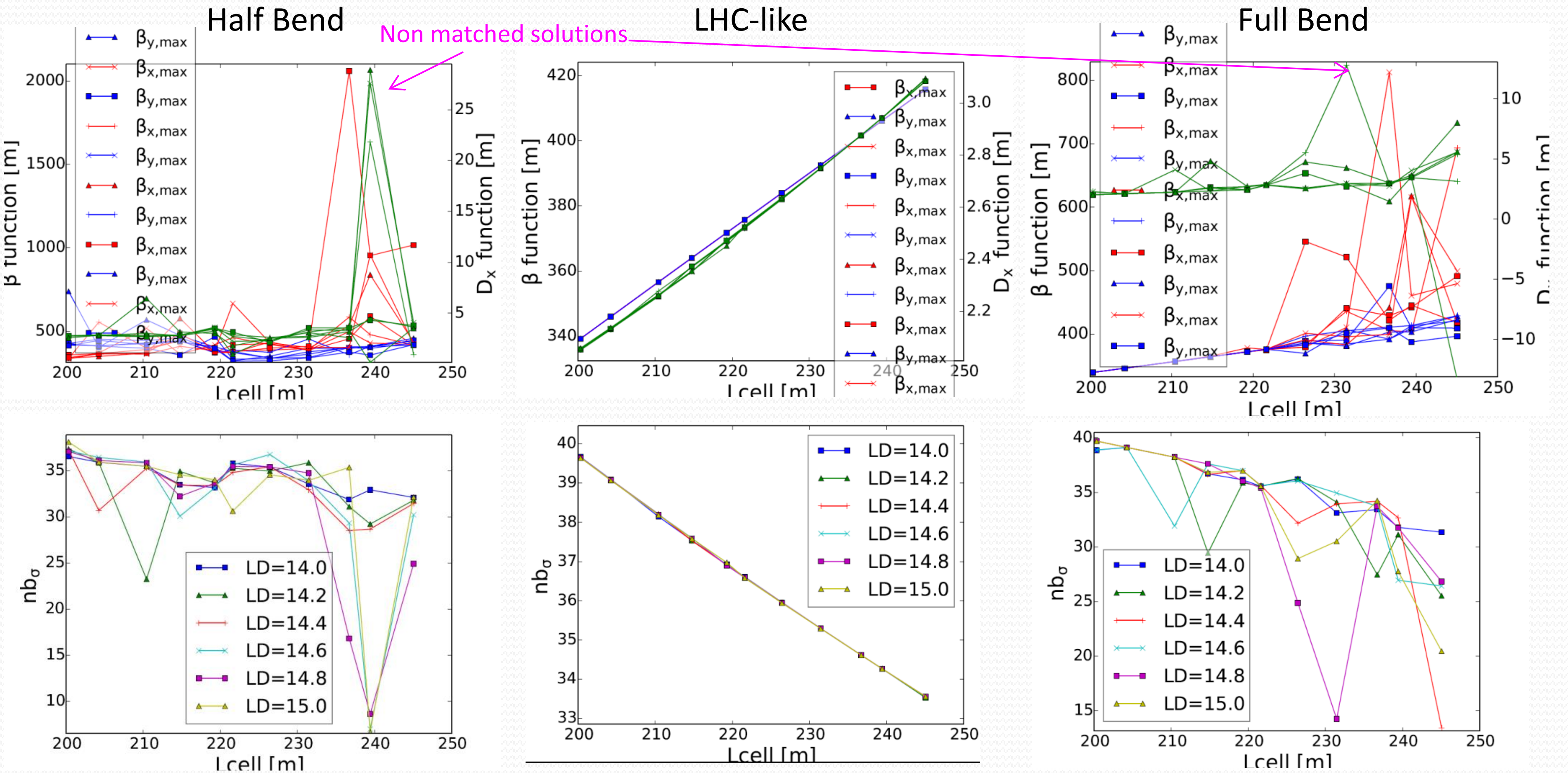


⇒ LHC-like DS has 32 less dipoles (and two different lengths) with respect to Full Bend DS

⇒ Full Bend DS has 1% lower dipole field with respect to LHC-like

Dispersion suppressor types & optics

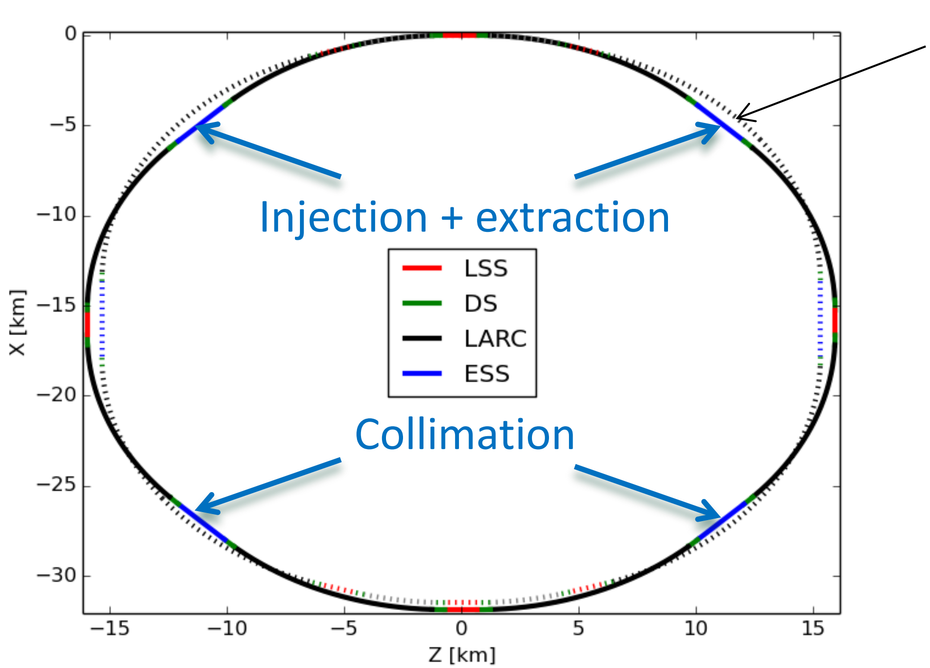
Circumference = 100.12 km, beam screen radius = 20 mm



⇒ Lcell ~215 m good for optics functions and number of sigma of the beam

⇒ LHC-like DS easiest to match to the insertions

Alternative to the baseline



- We have now 4 extended straight sections of 2.8 km (against 2 of 4.2 km in the baseline) and 4 long straight sections of 1.4 km (against 6 in the baseline)
- The extraction section is moved from the section where the collimation occurs to the section where the injection is located

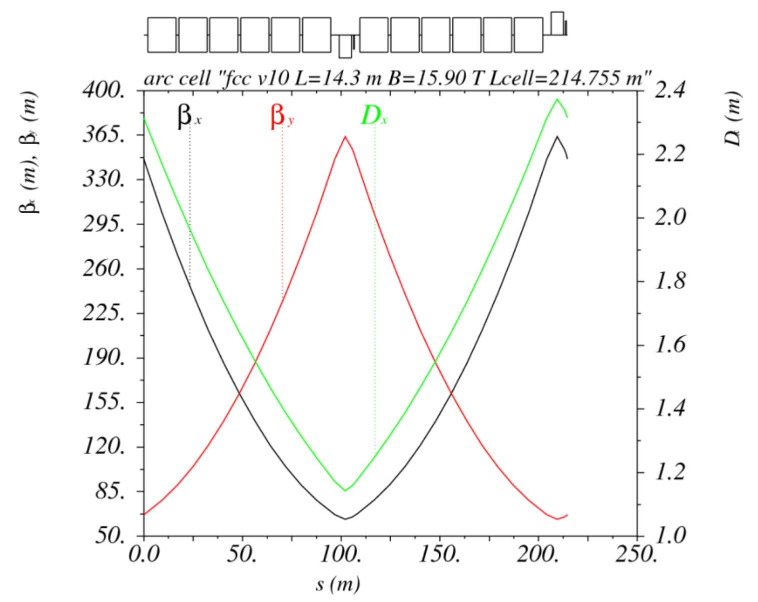
Pros	Cons
More regular layout.	Light modification of the layout.
The 2 additional IPs are separated by a diameter: good for synchronism.	Injection transfer lines might be longer.
Same number of DS as in the baseline.	More arcs but shorter (a pro if the TSS are not needed)

Optics of the Alternative

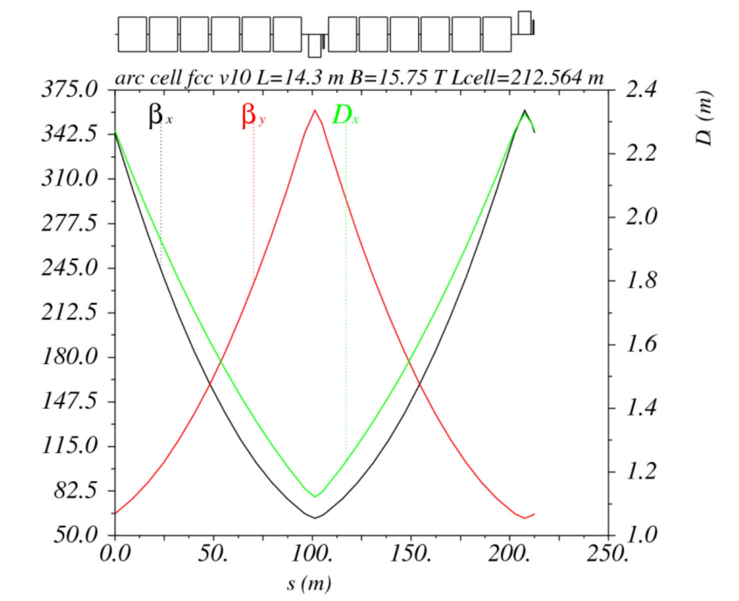
- The optical functions for this alternative are similar to the baseline optical functions.

Example in the case of a 100.12k-km-long ring:

Baseline



Alternative



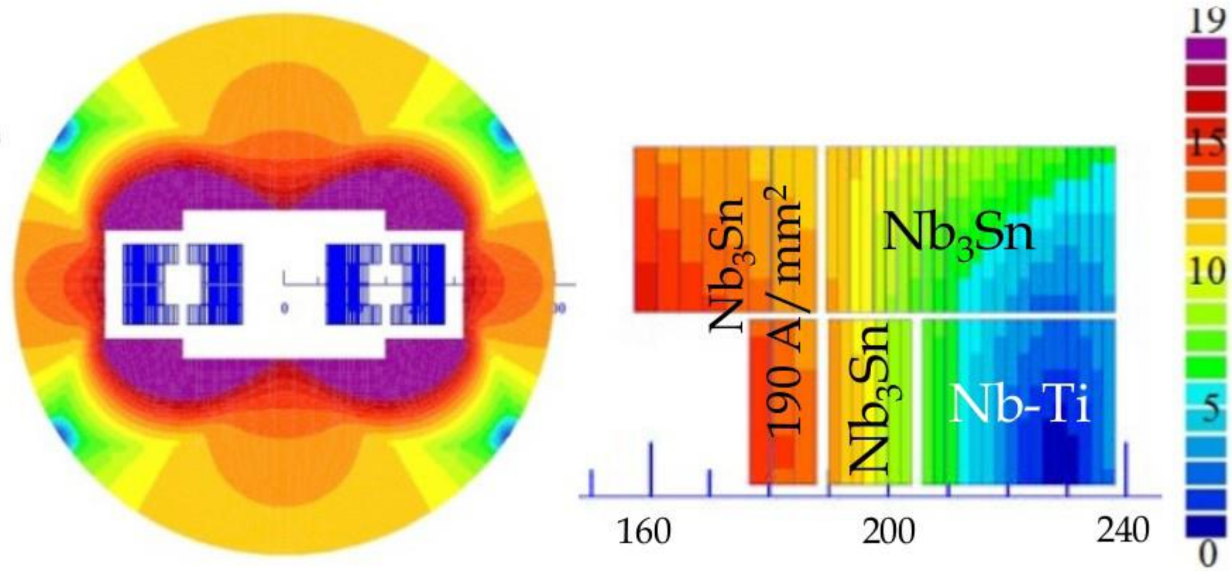
- The first order optics can be computed for the baseline and directly applied to this alternative thanks to the modularity of MAD-X.

FCC-hh Challenges: Magnets

Arc dipoles are the main cost and parameter driver

Baseline is Nb_3Sn at 16T

HTS at 20T also will be studied as alternative



Coil sketch of a 15 T magnet with grading, E. Todesco

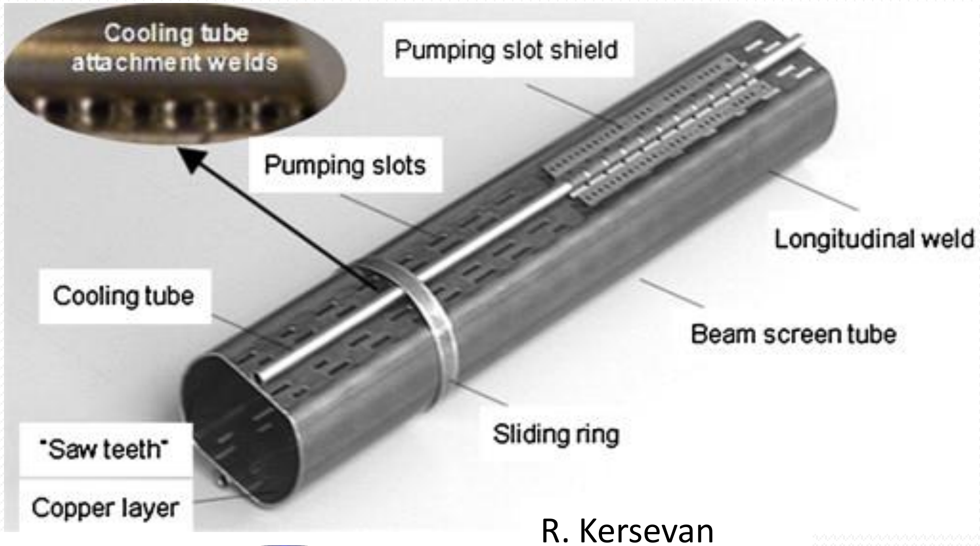
Field level is a challenge but many additional questions:

- Length, weight and cost
- Aperture
- Field quality
- Separation

Synchrotron Radiation and Beam Screen

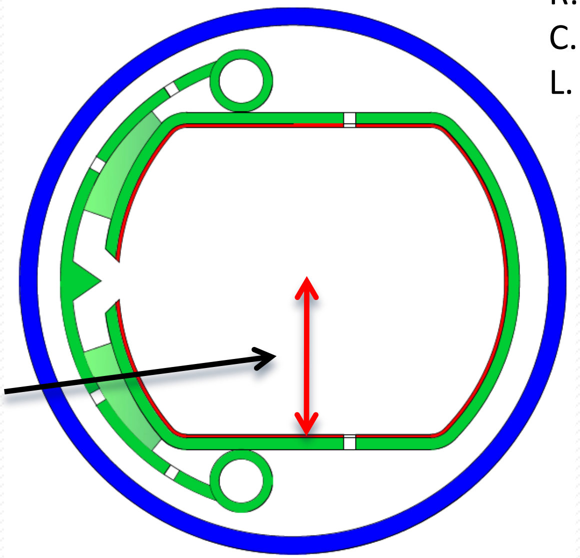
Synchrotron radiation power ~30W/m/beam in arcs (E_{crit}=4.3keV), total 5 MW (LHC 7kW)

- ⇒ Cooling challenge
- ⇒ Vacuum challenge
- ⇒ Impedance challenge
- ⇒ Mechanical challenge
- ⇒ Electron cloud
- ⇒ Cost challenge



R. Kersevan
C. Garion
L. Tavian, et al.

Choice of beam screen temperature is 50K
5MW synchrotron radiation => 100MW of cooling power
Good vacuum between 40-60K
Impedance still reasonable



Impedance: Minimum radius >13mm

Space for support: O(2mm)

Cooling: O(5mm) outer diameter

Impedance: 0.3mm copper coating

Stress in quench: 1.75mm steel

Cold bore and space for helium 1.5+1.5 mm

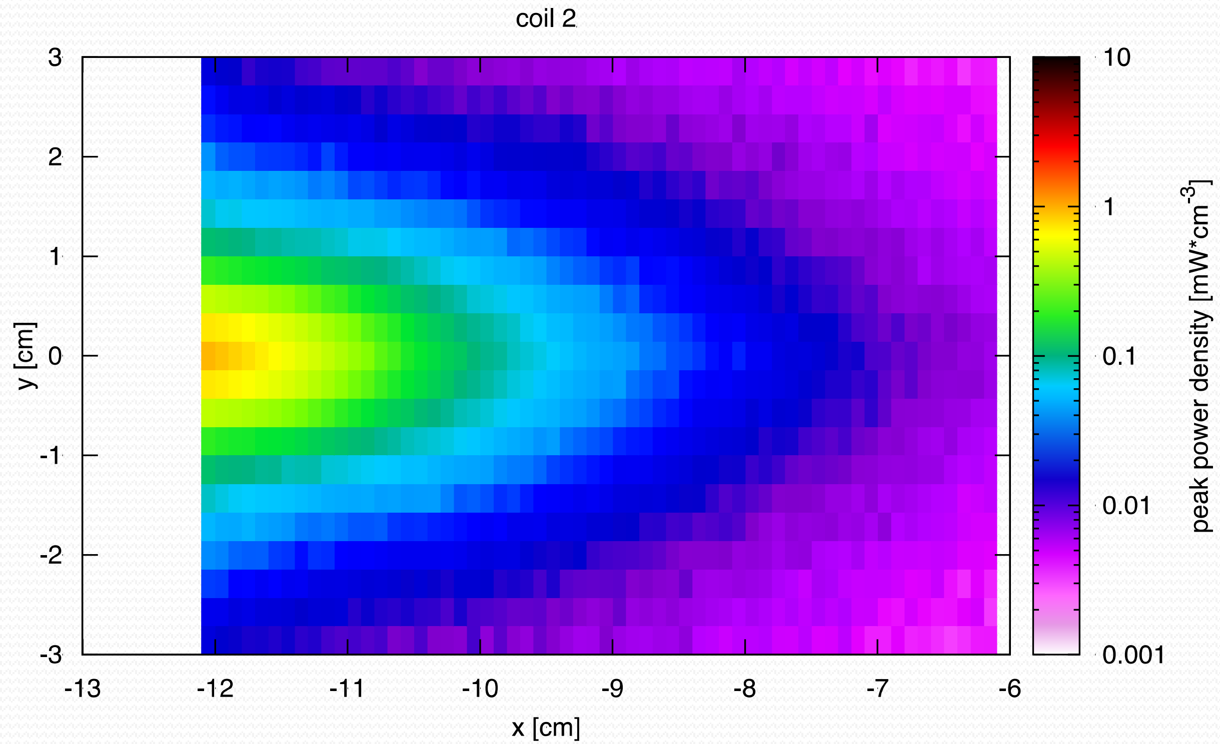
Total coil aperture 50mm

Vacuum and Losses

Beam-gas scattering goal
>100h beam lifetime

⇒ <O(10^{15} m^{-3}) H_2 (σ≈100mb)

⇒ 40kW proton losses
⇒ power for cooling @2K is <30MW, since elastic part is lost in collimation system



First studies indicate peak power density O(1mW/cm^{-3}) and 3.5W/beam/dipole in cold

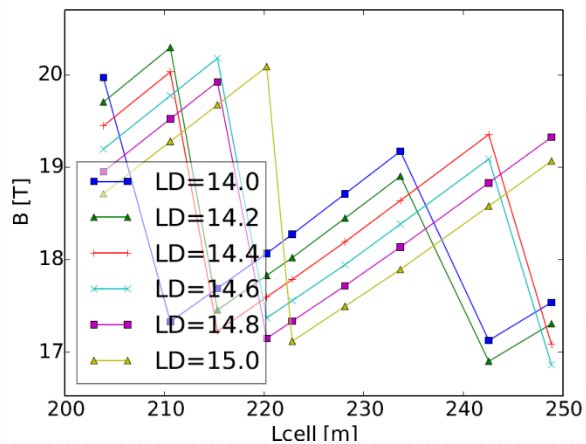
Seems very acceptable but need to define margin

Work in progress

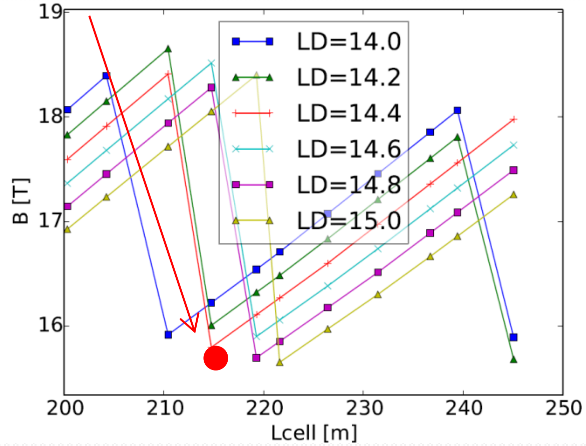
M. I. Besana, F. Cerutti, N. Mokhov

Circumference

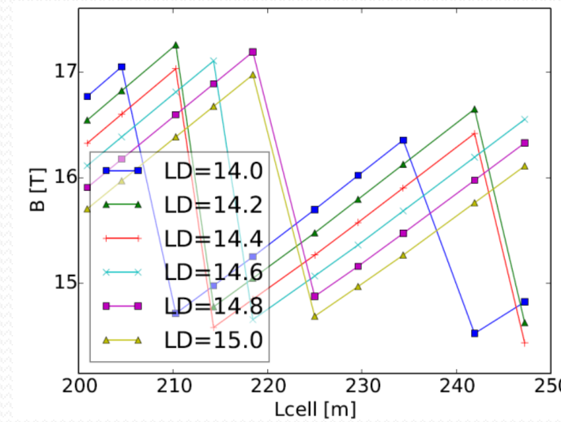
Baseline



93.45 km

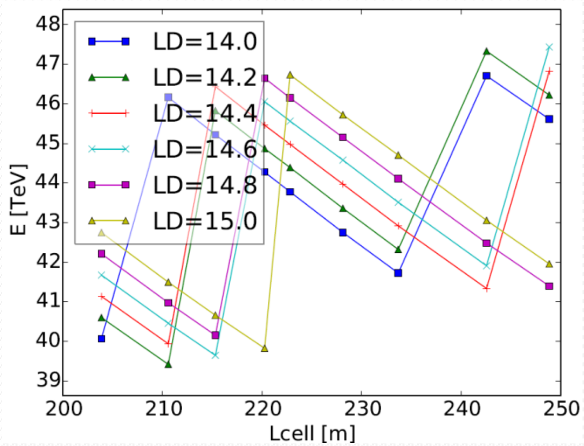


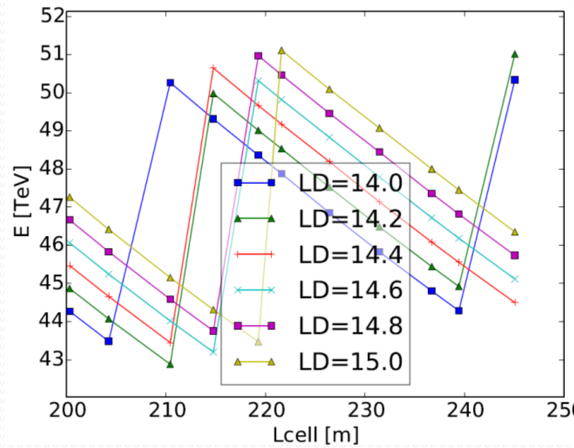
100.12 km

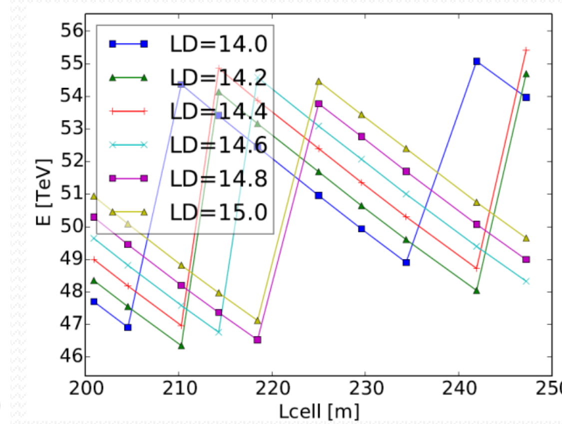


106.80 km

Proton energy reachable for a maximum field of 16 T







For 100 TeV c.o.m. energy

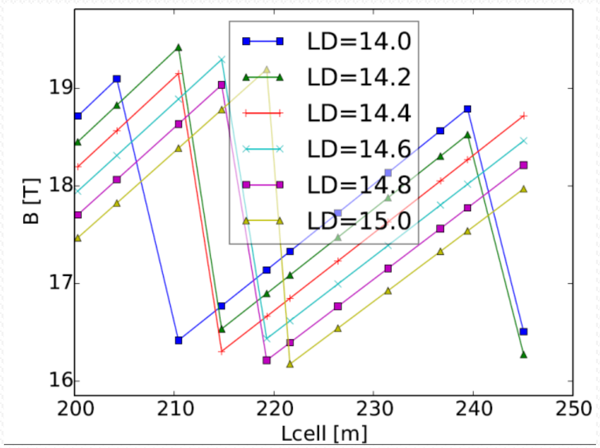
⇒ 3.5 × LHC: no solution found with a dipole field below or equal to 16 T, minimum field 16.9 T

⇒ 4.0 × LHC: 9% lower dipole field (14.6 T) but 6% longer ring…

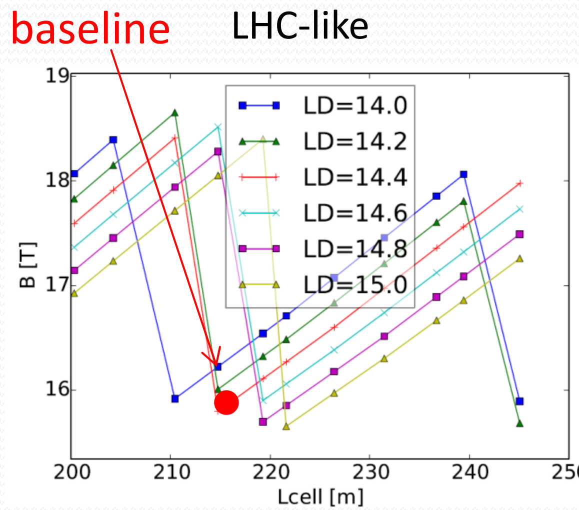
Dispersion Suppressor

Circumference = 100.12 km

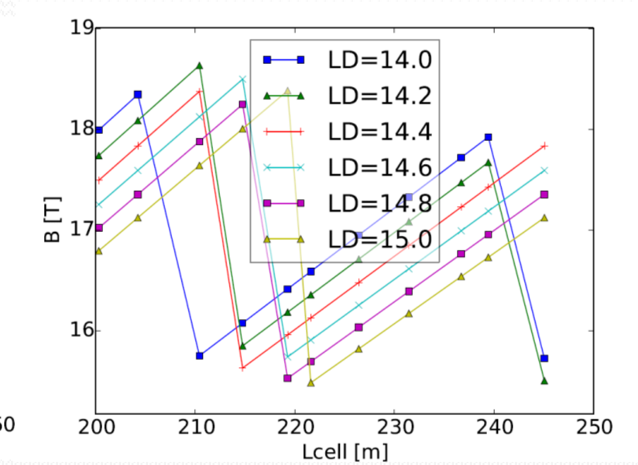
Half Bend



LHC-like



Full Bend



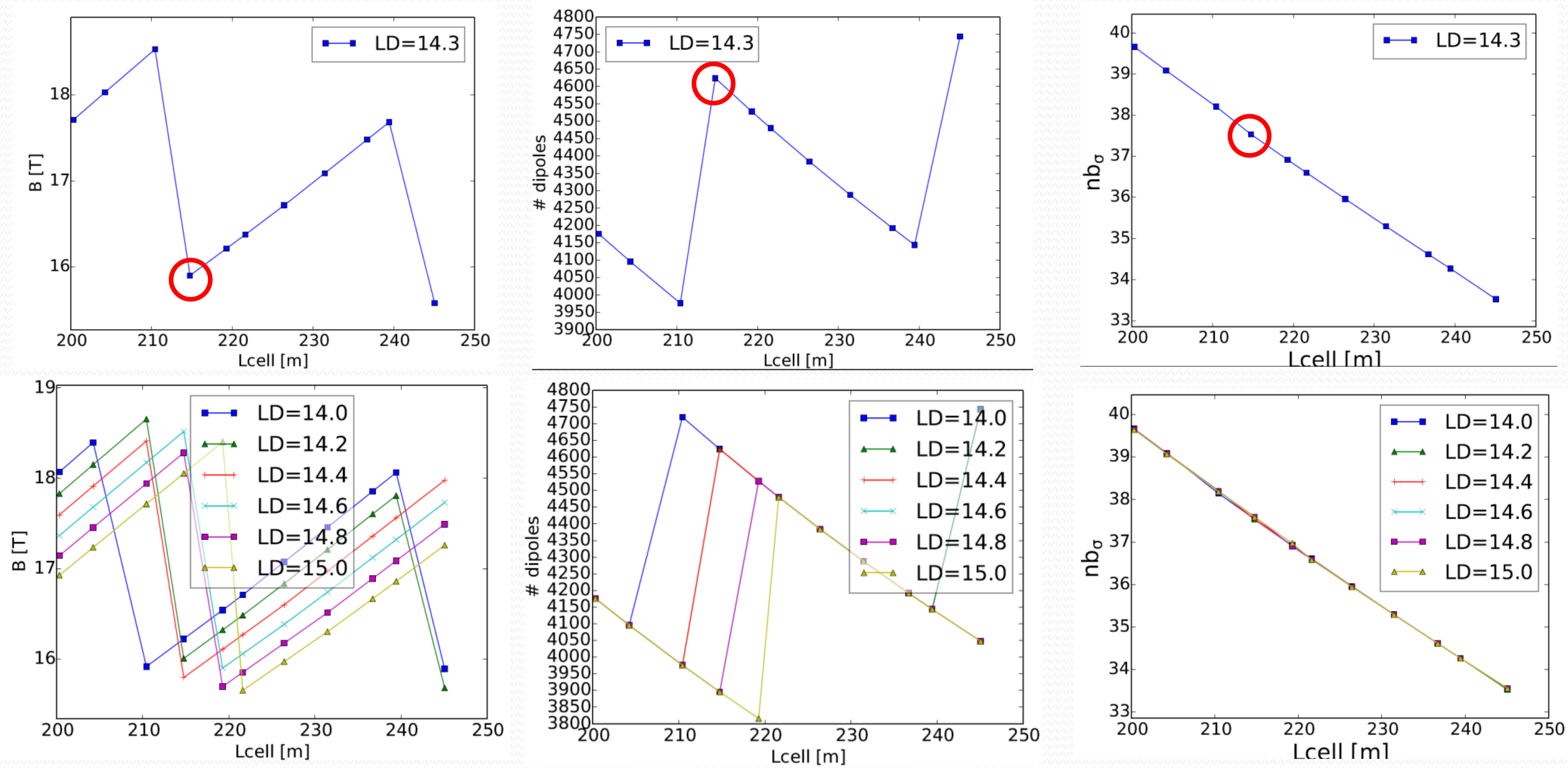
$\Rightarrow$ Half Bend DIS: no solution below 16 T, minimum field required 16.3 T

$\Rightarrow$ LHC-like DIS: 32 fewer dipoles (but two different lengths) with respect to Full Bend DIS

$\Rightarrow$ Full Bend DIS: 1% lower dipole field with respect to LHC-like DIS

Dipole and cell length

Circumference = 100.12 km, beam screen radius = 20 mm, LHC-like dispersion suppressor



⇒ LD =[14.0 : 14.3] m and Lcell=245 m: ~2% lower dipole field, losing ~15% of beam stay clear at injection and having 2.5-4% more dipoles

⇒ **LD =14.8 m** and **Lcell=219 m:** ~3% less dipoles and 1% lower dipole field, losing ~3% of beam stay clear at injection