Summary HE-LHC Machine Design

Leon van Riesen-Haupt, JAI Oxford

On behalf of the HE-LHC Team

HE-LHC Machine Design

- **3 sessions covering many areas**
- **Tuesday**
  - **Options and beam-beam**
    - **Flat optics, Nuclear Beams, Dynamic Aperture, Beam-Beam**
- **Thursday**
  - **Optics session**
    - **Overview, EIR, Injection, Dump and Integration**
  - **Collimation and beam dynamics**
    - **Collimation, Radiation, Dynamic Aperture, Impedence, Stability and Electron Cloud**

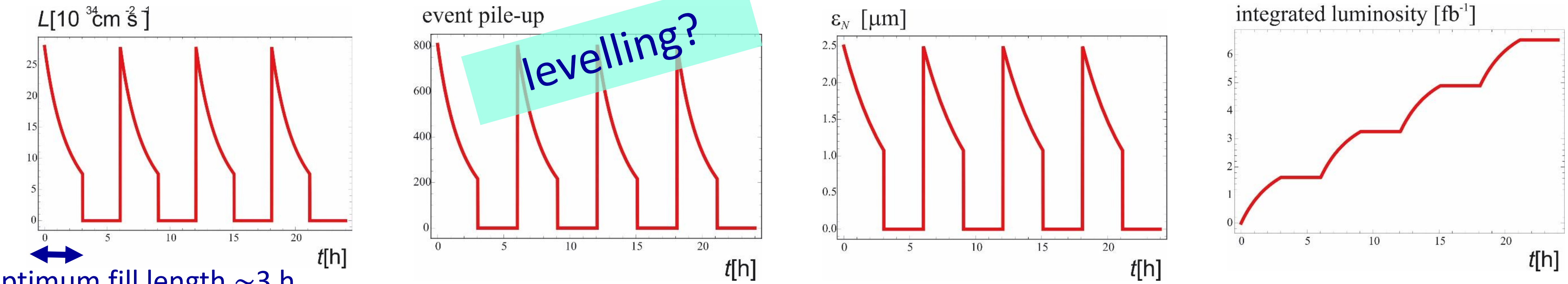
Parameters, Constraints, Options – F. Zimmerman

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**

availability and performance with different injectors?

24 hours at the HE-LHC:



optimum fill length ~3 h

Parameters, Constraints, Options – F. Zimmerman

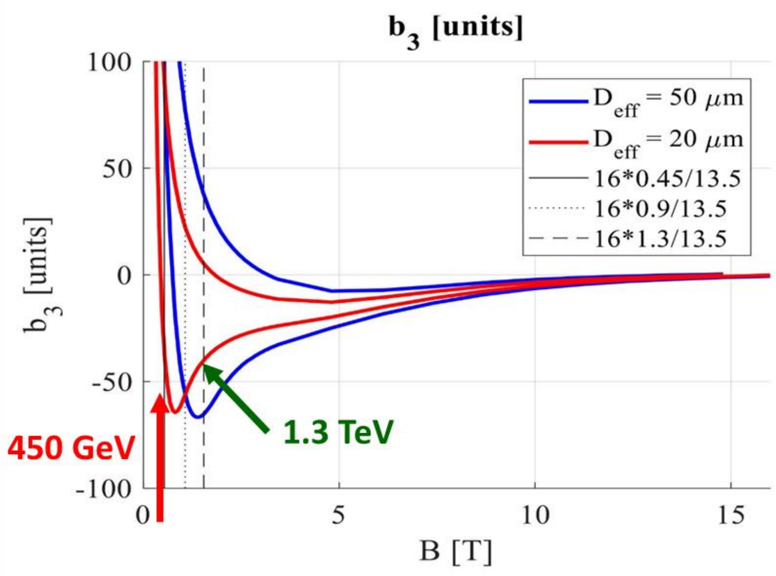
parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		**27**	14	14
dipole field [T]	16		**16**	8.33	8.33
circumference [km]	97.75		**26.7**	26.7	26.7
beam current [A]	0.5		**1.1**	1.1	0.58
bunch intensity [10^{11}]	1	1	**2.2**	2.2	1.15
bunch spacing [ns]	25	25	**25**	25	25
synchr. rad. 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

Parameters, Constraints, Options – F. Zimmerman

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**



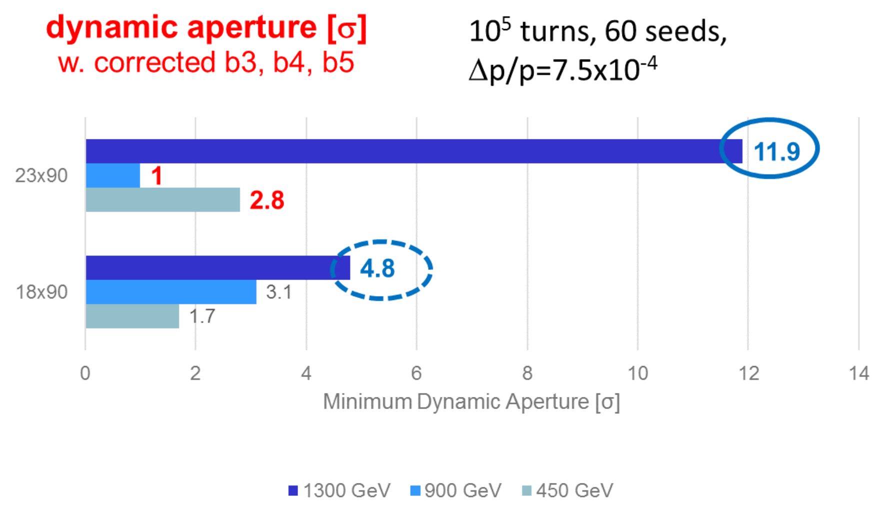
alternatives:

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



EuroCirCol A key to New Physics

Parameters, Constraints, Options – F. Zimmerman

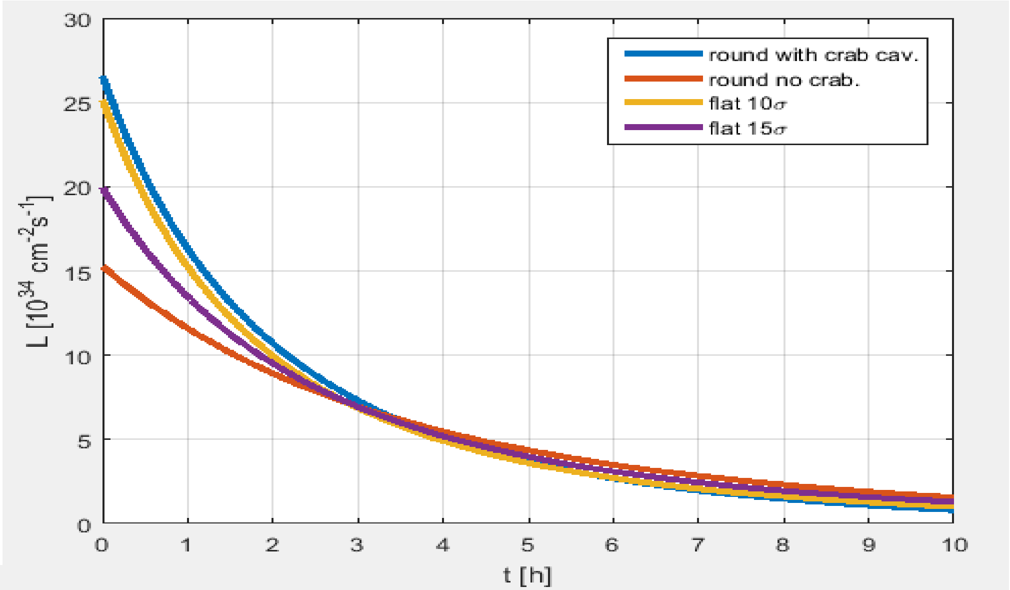
M. Hofer, J. Keintzel, R. Tomas,
Y. Nosochkov, T. Risselada, D. Zhou

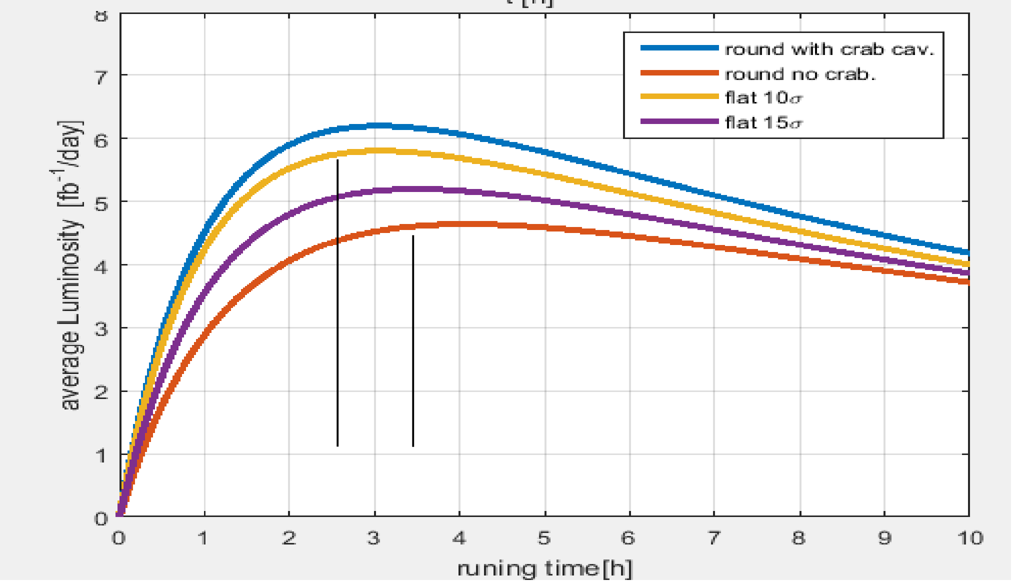
highest energy reach = lowest dipole field (fewer longer cells)

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**

Flat Beams – J. L. Abelleira





- **Flat beams** are an **alternative** to the use of **crab cavities** (β_x=0.4m, β_y=0.1m)

- We have come out with a set of flat IP parameters: $\boldsymbol{\beta_x}$**=0.4m,** $\boldsymbol{\beta_y}$**=0.1m**. We have designed the **triplet to be compatible** with this.

- The performance of the flat-beam optics depends heavily on the **beam-beam separation**, that must be **increased** from beam-beam studies experience

HE-LHC Optics Overview – R. Tomás

Challenges:

- **Physical aperture** at 450 GeV
- **Dynamic aperture** at 450 GeV
- **Layout** fitting existing tunnel
- IR **collision optics** at 13.5 TeV

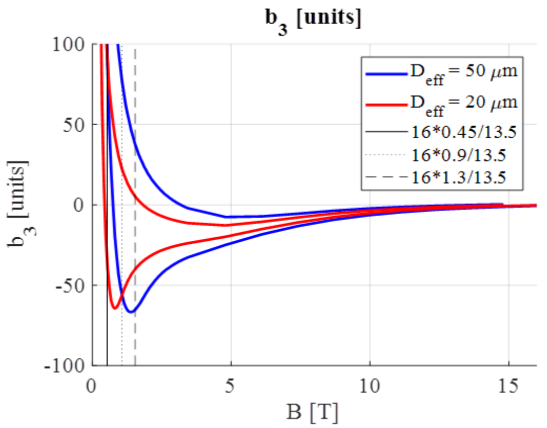
Things to look into:

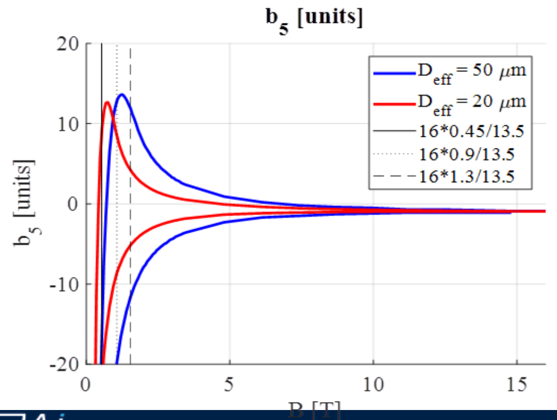
- Continue optimizing **dispersion suppressor** → ALGEA
- Beam stay-clear for collimation, is **10σ ok**? Even lower?
- Is the **beam screen** optimal for HE-LHC?
- If all fails, how much should we **increase magnet apertures**? Impact on Energy reach? Cost?
- **Combined function dipoles** to increase focusing and improve beam-stay clear at injection?
- **Longer dipoles**, e.g. 14→20m, for increased filling factor?
- **Shorter L*** to alleviate the collision optics challenge?

DA Injection – Y. Nosochkov

HE-LHC dipole field quality at 450, 900, 1300 GeV, version 24-JAN-2018

- Large non-linear field errors in **16 T dipole** at injection energy → concern for DA
- **b3s = -35 / -55 / -40 ; b3u/r = 10 / 4 / 3 ; b5s = 8 / 8 / 4 at 450 / 900 / 1300 GeV**





for wire filament size of **20 μm**

	450 GeV			900 GeV			1300 GeV		
Normal	Systematic	Uncertainty	Random	Systematic	Uncertainty	Random	Systematic	Uncertainty	Random
2	-2.230	0.922	0.922	-2.230	0.922	0.922	-2.230	0.922	0.922
3	-35.000	10.000	10.000	-55.000	4.000	4.000	-40.000	3.000	3.000
4	0.000	0.449	0.449	0.000	0.449	0.449	0.000	0.449	0.449
5	8.000	1.500	1.500	8.000	1.500	1.500	4.000	0.800	0.800
6	0.000	0.176	0.176	0.000	0.176	0.176	0.000	0.176	0.176
7	0.200	0.211	0.211	0.600	0.211	0.211	1.100	0.211	0.211
8	0.000	0.071	0.071	0.000	0.071	0.071	0.000	0.071	0.071
9	3.800	0.500	0.500	4.200	0.500	0.500	2.900	0.200	0.200
10	0.000	0.027	0.027	0.000	0.027	0.027	0.000	0.027	0.027
11	0.750	0.028	0.028	0.860	0.028	0.028	1.000	0.028	0.028
12	0.000	0.009	0.009	0.000	0.009	0.009	0.000	0.009	0.009
13	0.000	0.011	0.011	0.000	0.011	0.011	0.000	0.011	0.011
14	0.000	0.003	0.003	0.000	0.003	0.003	0.000	0.003	0.003
15	0.000	0.004	0.004	0.000	0.004	0.004	0.000	0.004	0.004
Skew									
2	0.000	1.040	1.040	0.000	1.040	1.040	0.000	1.040	1.040
3	0.000	0.678	0.678	0.000	0.678	0.678	0.000	0.678	0.678
4	0.000	0.450	0.450	0.000	0.450	0.450	0.000	0.450	0.450
5	0.000	0.317	0.317	0.000	0.317	0.317	0.000	0.317	0.317
6	0.000	0.205	0.205	0.000	0.205	0.205	0.000	0.205	0.205
7	0.000	0.116	0.116	0.000	0.116	0.116	0.000	0.116	0.116
8	0.000	0.071	0.071	0.000	0.071	0.071	0.000	0.071	0.071
9	0.000	0.041	0.041	0.000	0.041	0.041	0.000	0.041	0.041
10	0.000	0.025	0.025	0.000	0.025	0.025	0.000	0.025	0.025
11	0.000	0.016	0.016	0.000	0.016	0.016	0.000	0.016	0.016
12	0.000	0.000	0.009	0.000	0.000	0.009	0.000	0.000	0.009
13	0.000	0.000	0.005	0.000	0.000	0.005	0.000	0.000	0.005
14	0.000	0.000	0.003	0.000	0.000	0.003	0.000	0.000	0.003
15	0.000	0.000	0.002	0.000	0.000	0.002	0.000	0.000	0.002

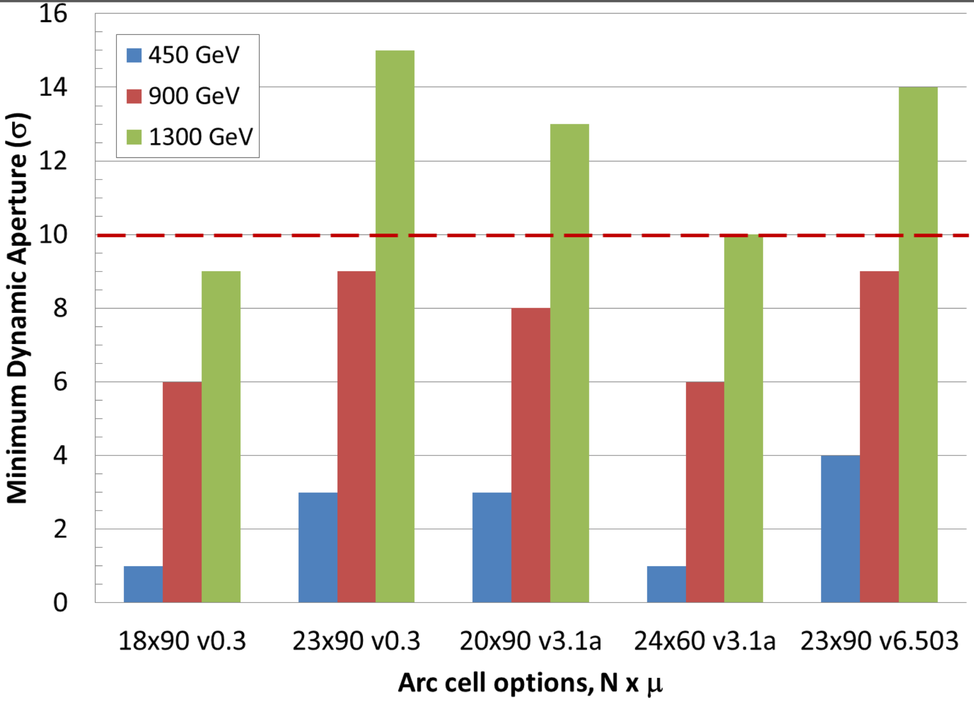
S.I. Bermudez, et al

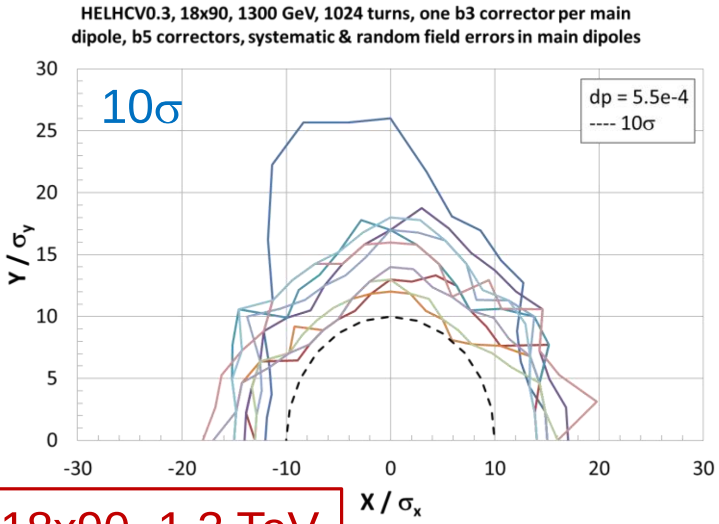
DA Injection – Y. Nosochkov

Dynamic aperture at injection for lattice options

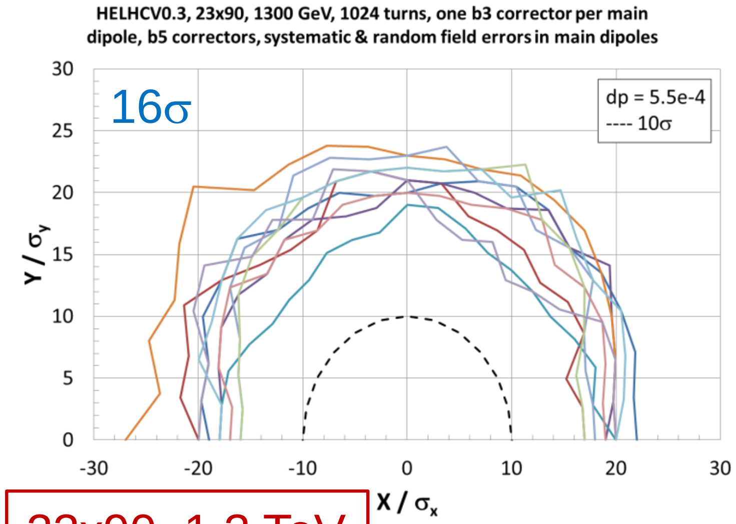
- HE-LHC lattice options: **24x60, 20x90, 18x90 v0.3, 23x90 v0.3** compared to **LHC lattice 23x90 v6.503**
- Main concern for injection dynamic aperture is **dipole field quality with large b3 and b5 errors**
- Short-term DA tracking study **(10^3 turns) for 450, 900, 1300 GeV** injection energy options
- **b3 and b5 corrections** studied

- **Insufficient DA at 450 and 900 energies (<10σ)**
- Best DA in 23x90 option at 1.3 TeV, **but strong dipole limits the CM energy reach to 26 TeV at 16 T**
- 18x90 option has the weakest dipole (27.25 GeV at 16 T), **but the DA may not be enough, especially in long-term tracking → better field quality is needed**
- 20x90 lattice provides an intermediate performance **between the 23x90 and 18x90 options**





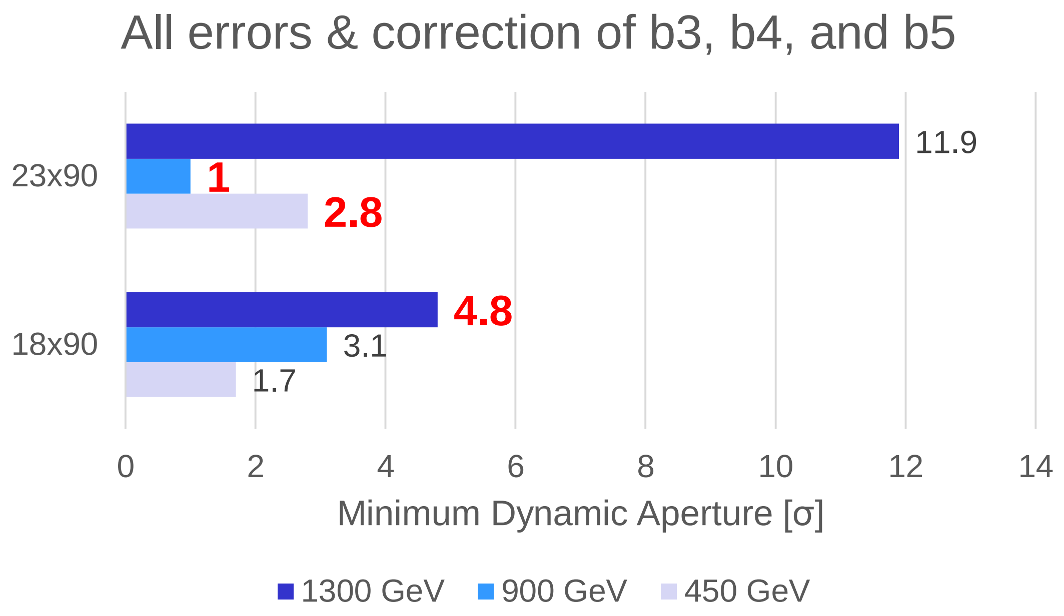
18x90, 1.3 TeV

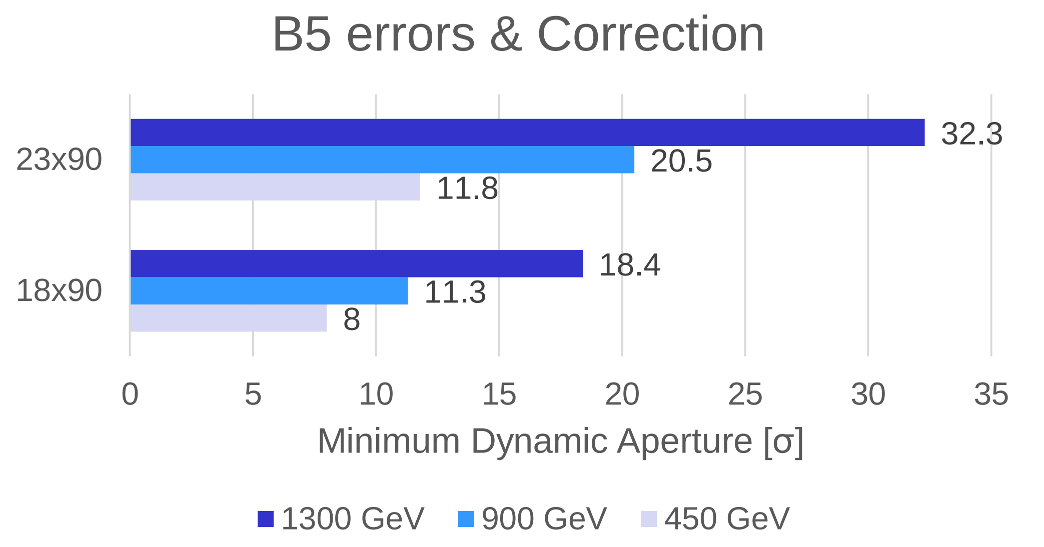


23x90, 1.3 TeV

Correction Circuits and DA – M. Hofer

- **The current status of the dynamic aperture in both lattices and for 3 different injections energies was presented using the latest field quality estimates**
- **With the current corrections, DA only in the case of the LHC-like lattice at the highest considered injection energy meets the target DA**
- **Sextupole component of the dipoles has the biggest impact on DA and requires better corrections**
- **To improve the DA, b_3 correction strategy will be refined and alternative ways such as sorting will be explored**

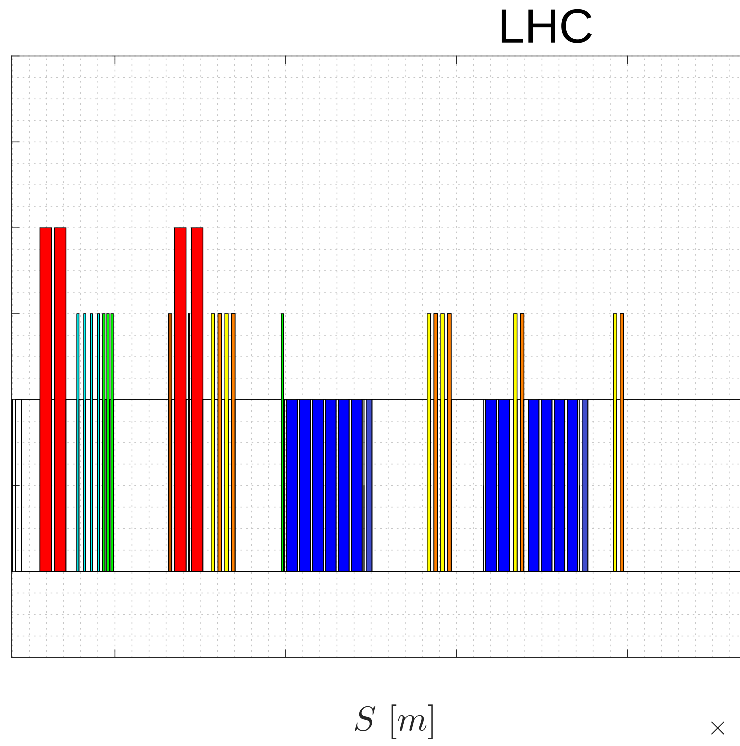


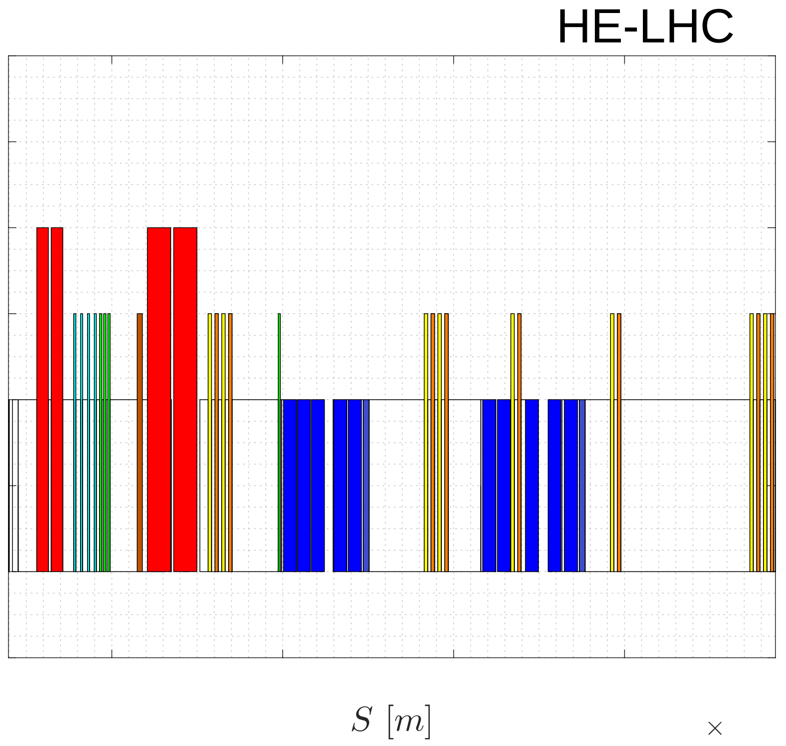


Injection and Extraction – B. Goddard

- **HE-LHC injection – strongly dependent on injection energy**
  - **At 1300 GeV there is impact on experiments' optics: β* has been matched down to 10 m**
- **Kicker and septum performance to push - SC septa to consider (depends on losses/quenches)**
- **Transfer lines to HE-LHC at 1300 GeV needs 6 T SC dipoles**
  - **Almost 50% as many dipoles again as scSPS, and 80% of quadrupoles**
  - **Integration, cryogenics, machine protection, collimation are all difficult**
- **Dump extraction is feasible**
  - **More space for extraction kickers, and advances in technology assumed**
  - **Need to work out solution for (protection) absorber limits/rise time**
  - **Trade-off between failure probability and consequences**
  - **Septa require SC technology and/or cryostat passage**
- **Dump dilution system most challenging**
  - **Failure scenarios also to consider in design**

Collimation – M. Crouch





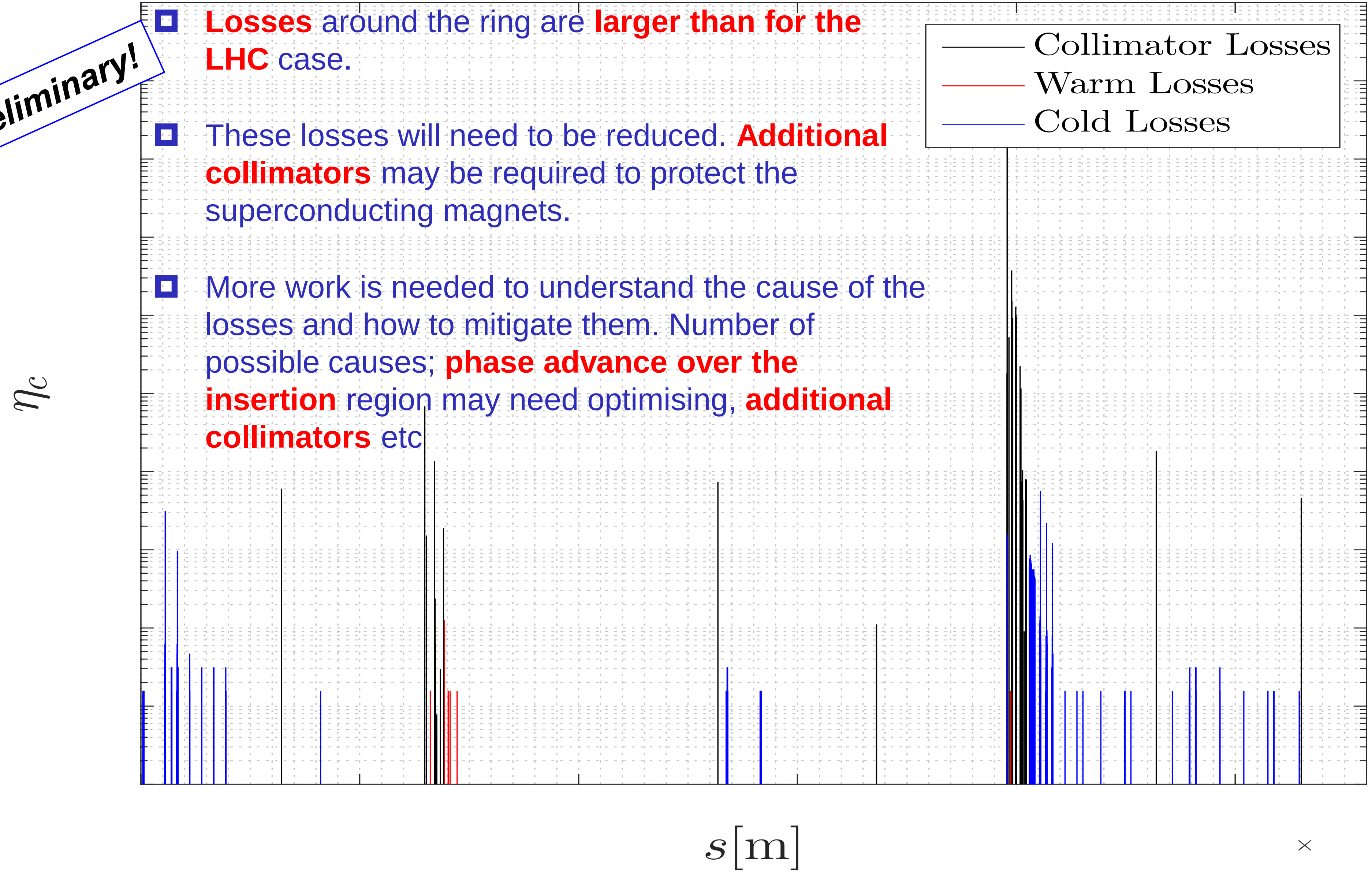
- **IR7 optics** modified to include some additional **magnet constraints**.
  - **Challenging** magnet parameters proposed with 2T field strength for the **normal conducting dipoles**
  - 1T field strength for the **warm quadrupoles** and a reduced aperture of 20mm

- **Outer dogleg dipoles made superconducting** and remain the same length, inner dogleg dipoles 6.8m and the passive absorber is shifted to protect the face. **One quadrupole is removed** in order to make the remaining quadrupoles 3.8m.

Collimation – M. Crouch

Preliminary!

- **Losses** around the ring are **larger than for the LHC** case.
- These losses will need to be reduced. **Additional collimators** may be required to protect the superconducting magnets.
- More work is needed to understand the cause of the losses and how to mitigate them. Number of possible causes; **phase advance over the insertion** region may need optimising, **additional collimators** etc

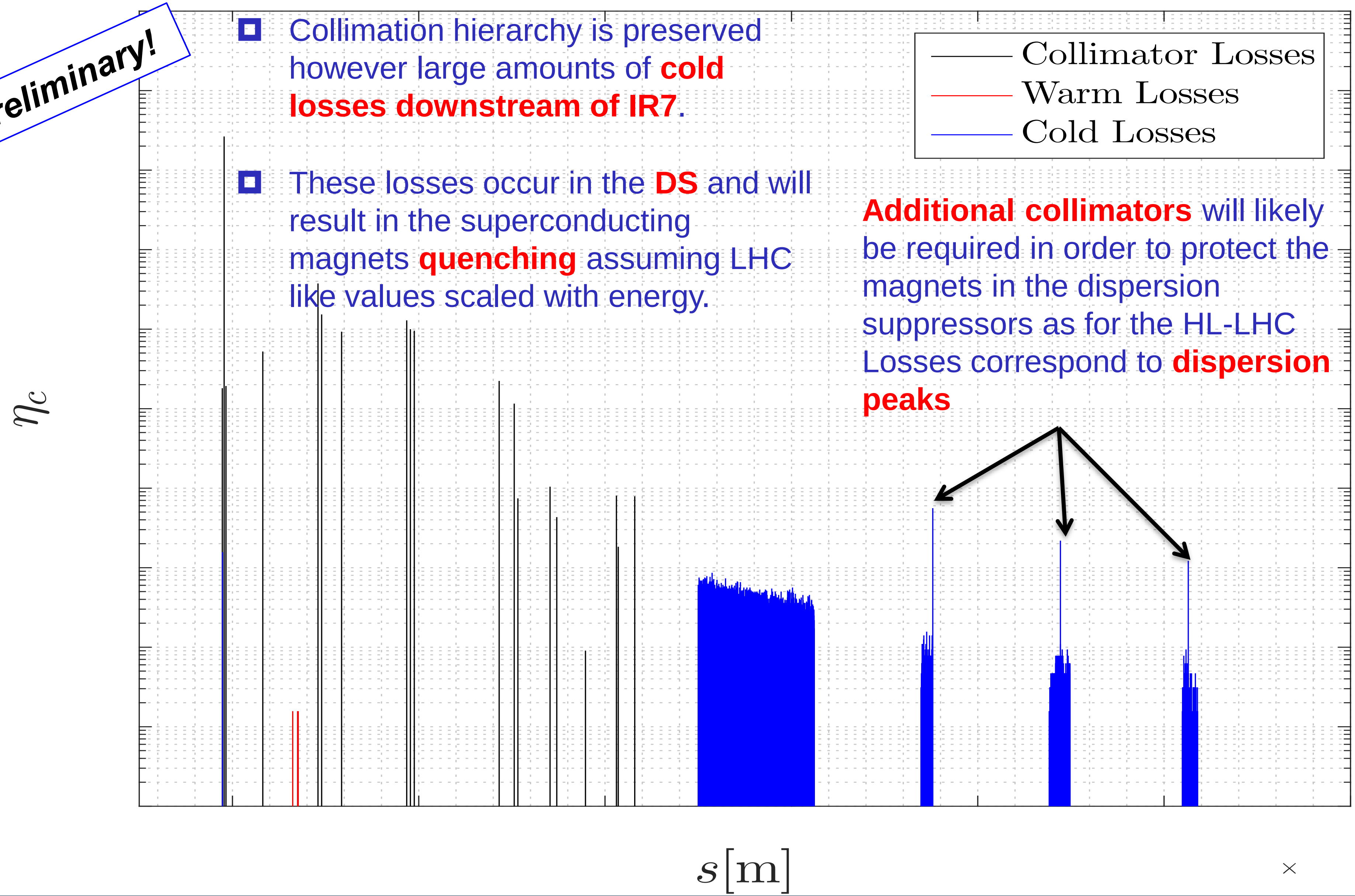


Collimation – M. Crouch

Preliminary!

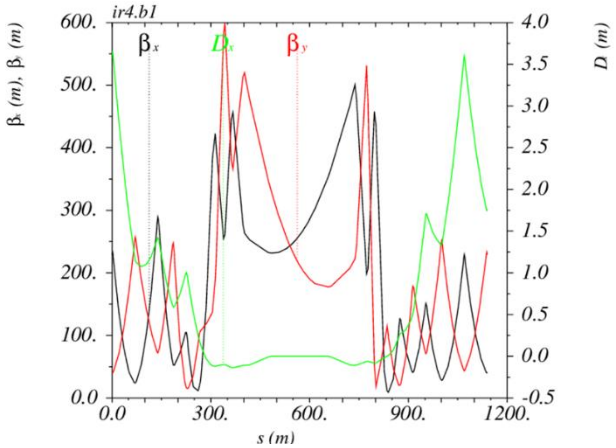
- Collimation hierarchy is preserved however large amounts of **cold losses downstream of IR7**.
- These losses occur in the **DS** and will result in the superconducting magnets **quenching** assuming LHC like values scaled with energy.

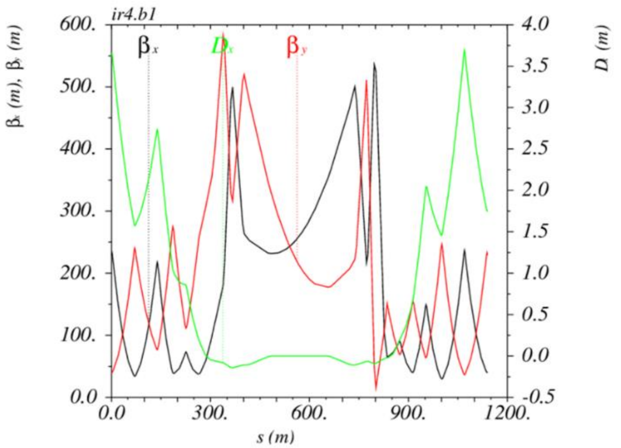
Additional collimators will likely be required in order to protect the magnets in the dispersion suppressors as for the HL-LHC Losses correspond to **dispersion peaks**

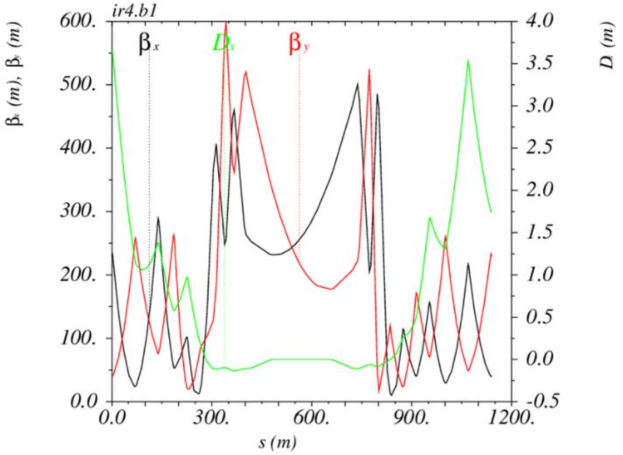


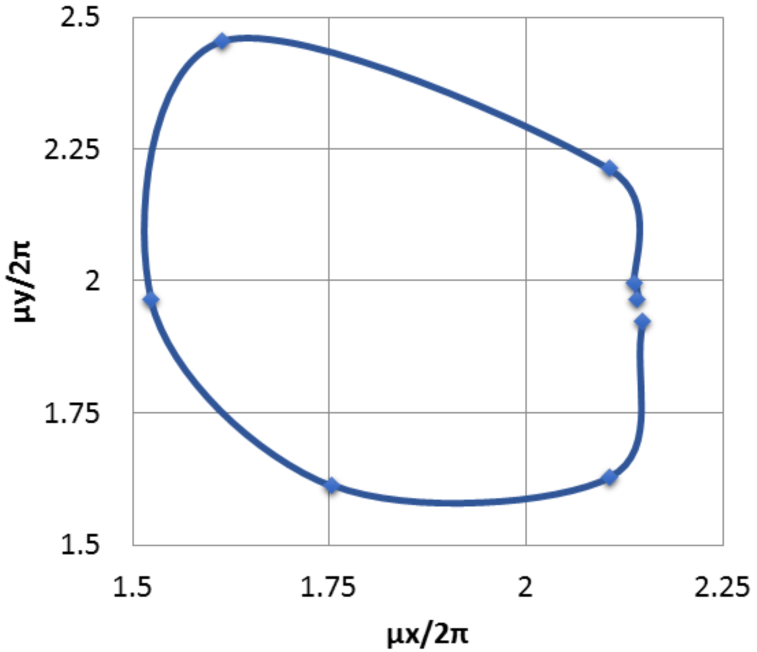
RF Insertion – L. van Riesen-Haupt

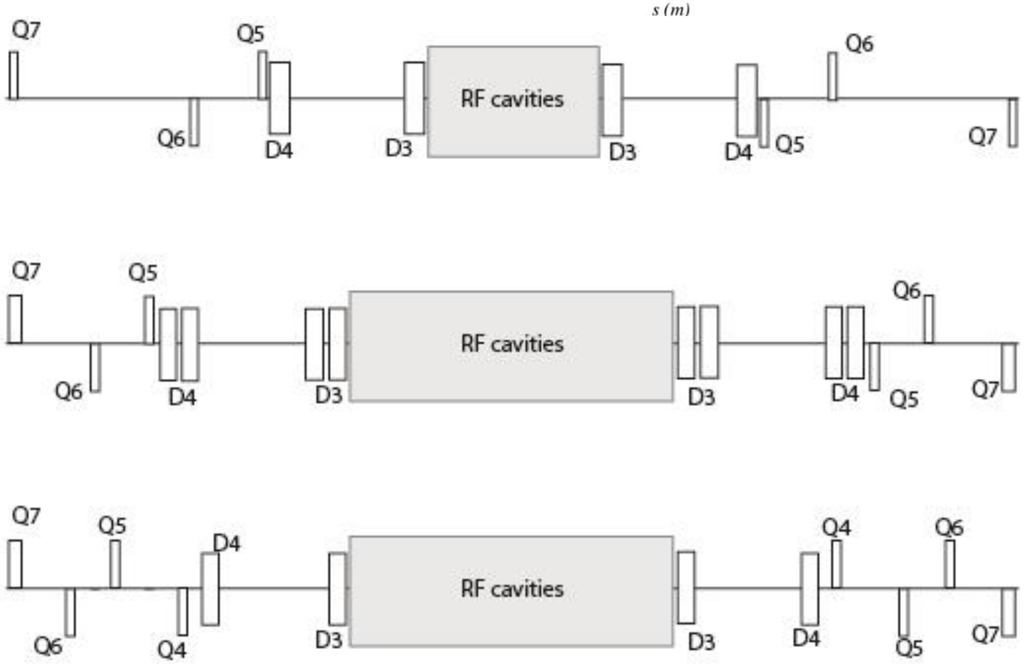
- **IR 4 re-optimised for HE-LHC**
  - **Increased space for RF cavities**
  - **Extra quadrupole for tuning**
  - **Adjust phase advance for DA**





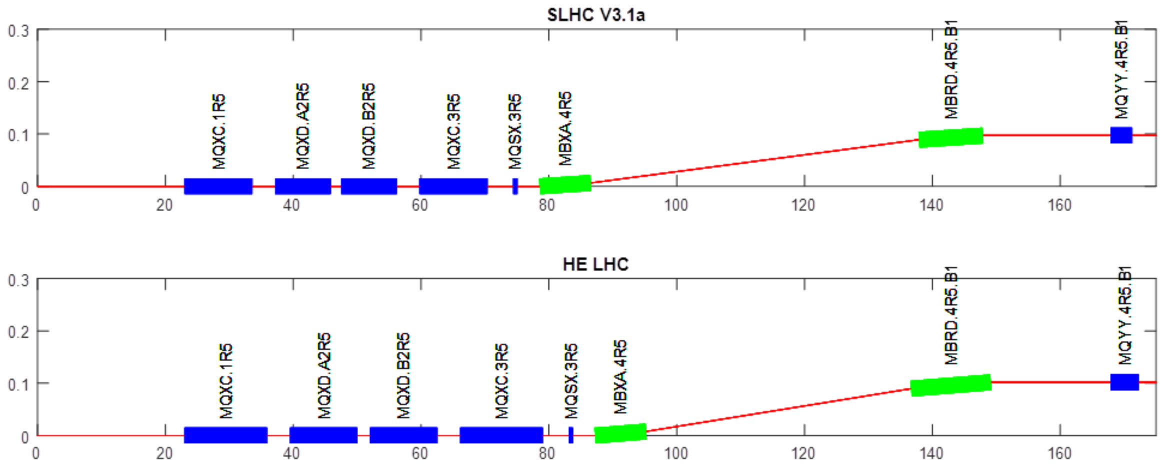


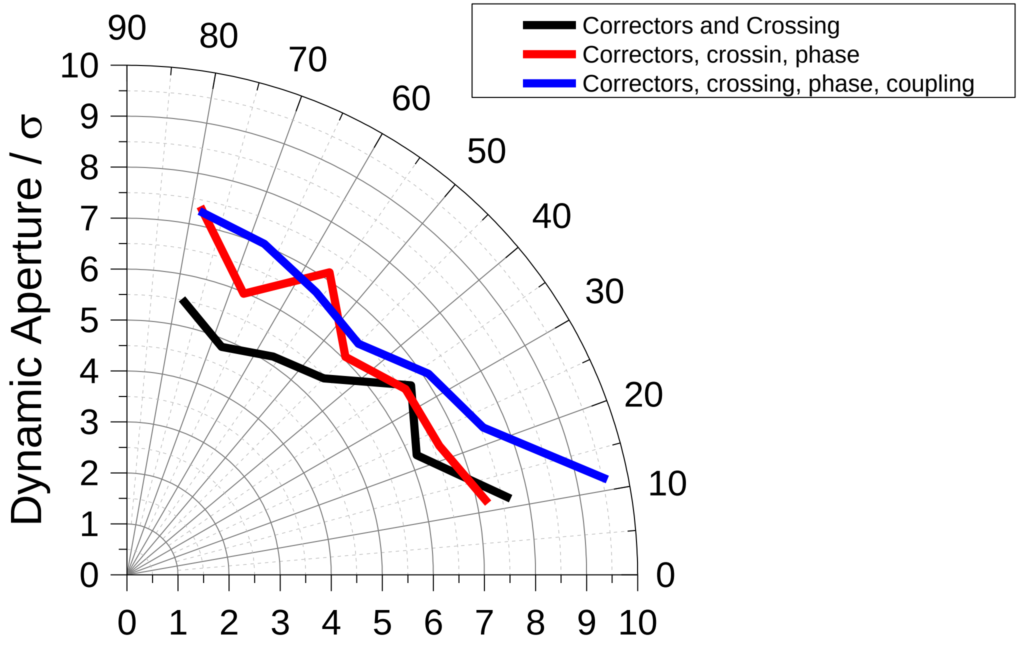


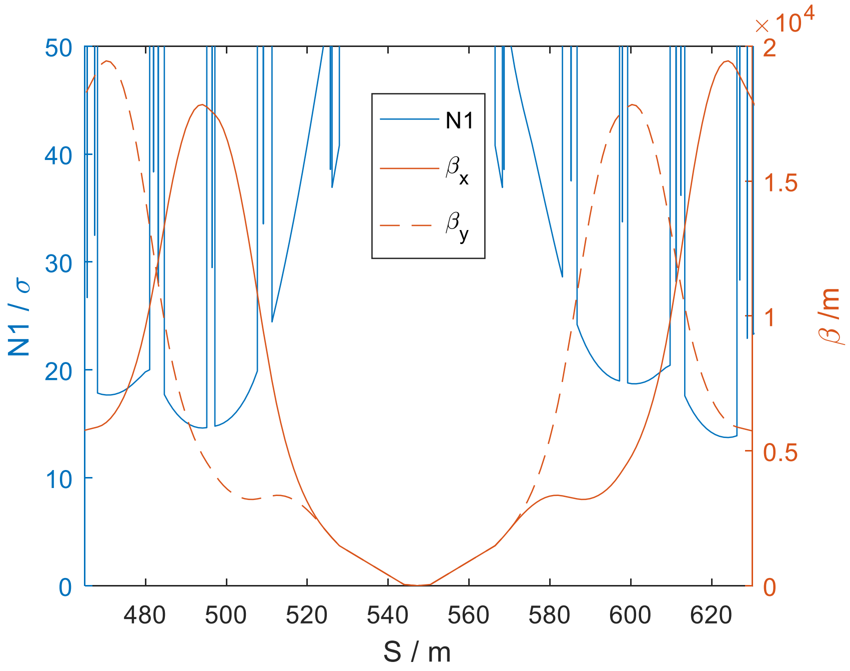


Experimental Interaction Regions – L. van Riesen-Haupt

- **Triplet optimised – 2 cm shielding**
- **Separation and crab cavities considered**
- **Matching dependant on DS**
  - **Work with integration**
- **DA studies with triplet errors at collision**
  - **6.4σ reached**

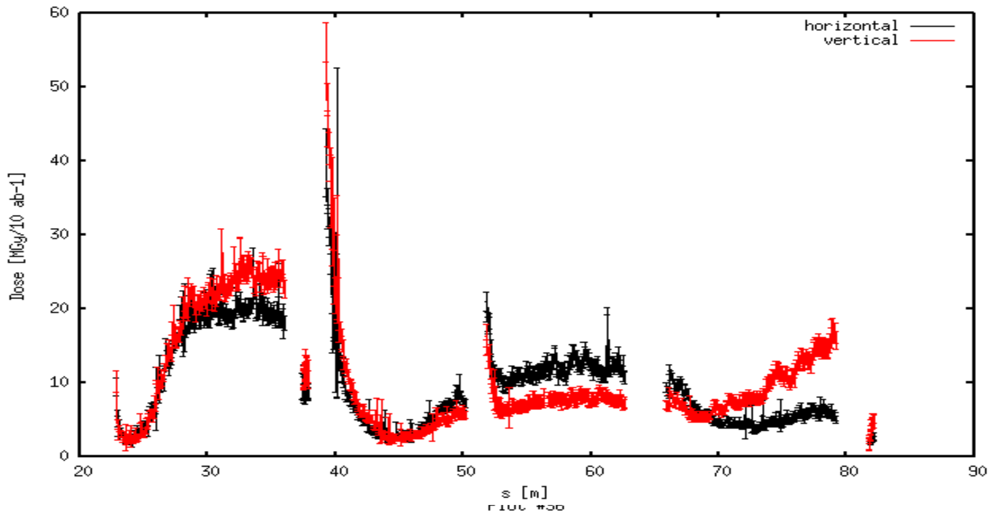


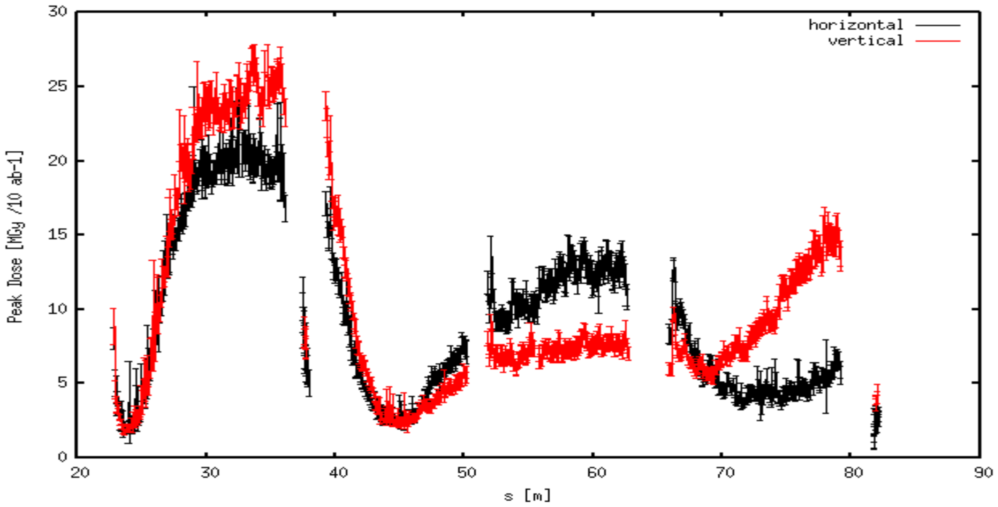


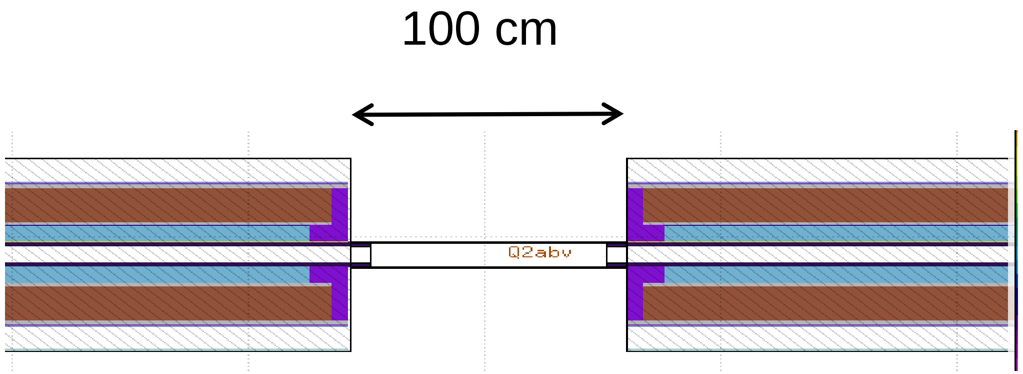


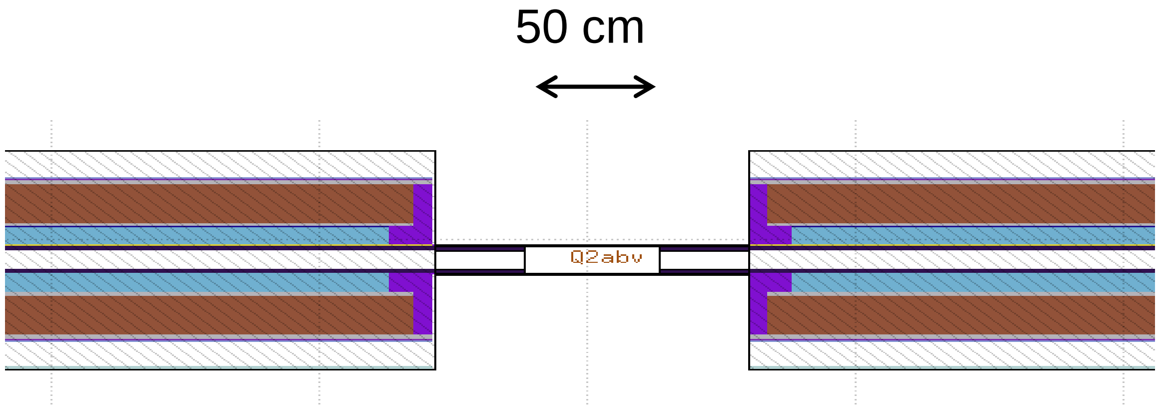
EIR Radiation – J. L. Abelleira

- Maximum dose profile. **peaks at the beginning** of each magnet are caused by **missing gaps** in the interconnects.









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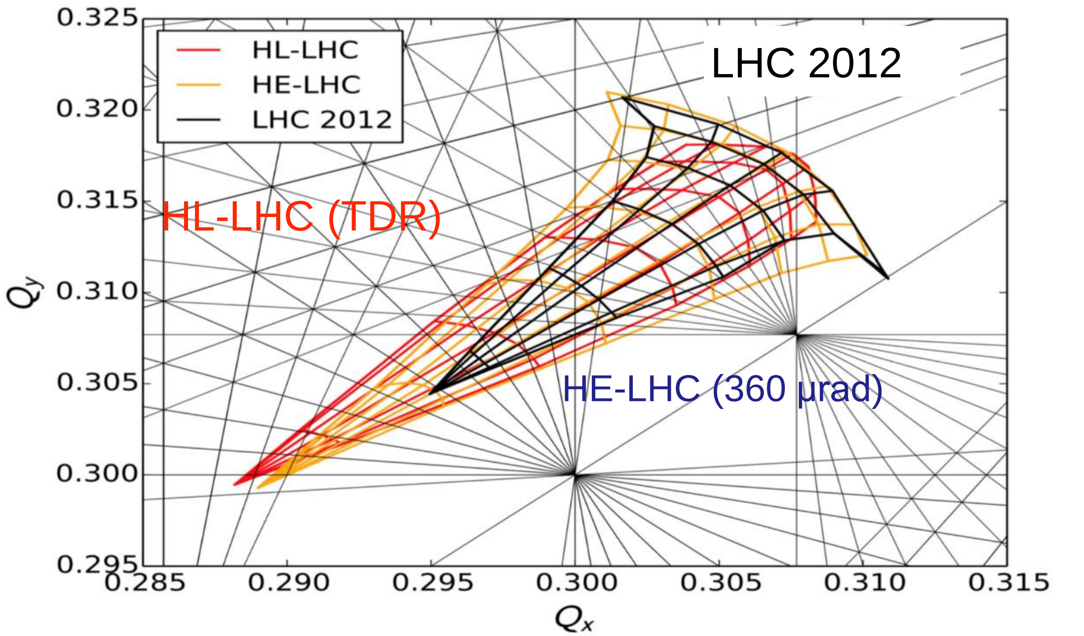
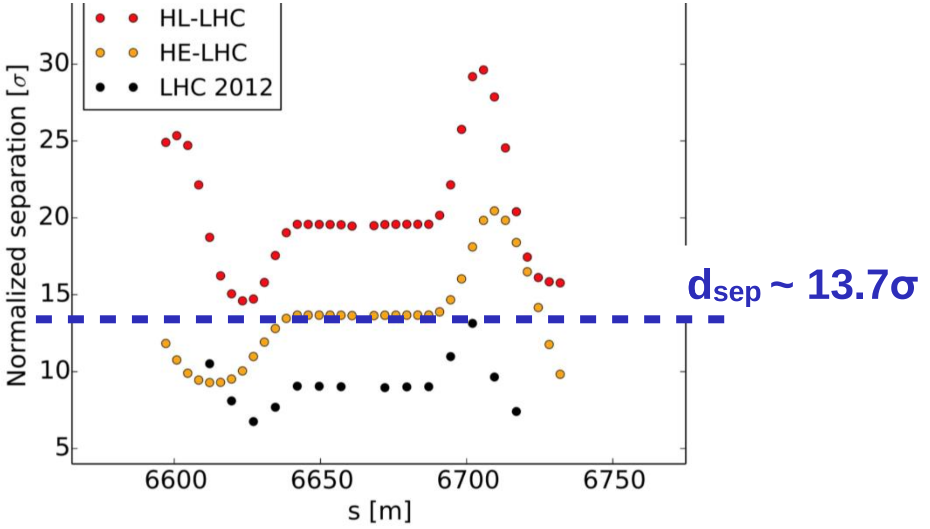
A key to New Physics

Beam-Beam – T. Pieloni

- **Scenario with H-V crossing and beam-beam separation of 13,5 σ (angle 360 μrad) is proposed rescaling from LHC, HL-LHC and FCC studies**
  - **Detailed DA** studies needed to address non-linearities impact (high Q' operations and magnets errors)
  - **Lattice optimization** in presence of beam-beam could improve further performances (reduced crossing angles)
- Relaxed scenario with β* from 25 cm to 40 cm (some loss in performances 15%)
- Separation can be reduced using **compensation schemes** → needed detailed study!
  - **Global compensation** with octupole magnets → seems robust from simulations for FCC and HL-LHC but needs optimized optics over the cycle to be kept in the presence of errors and optics changes.
  - **Local compensation** by using e-lenses (bunch to bunch differences for alternative crossing schemes)
- Two beam stability studies on-going
- **Alternative or rotatable x-angles are possible to dilute doses in IRs as for FCC-hh if needed.**
- Flat optics: work on-going to evaluate the effective gain vs round optics by DA simulations



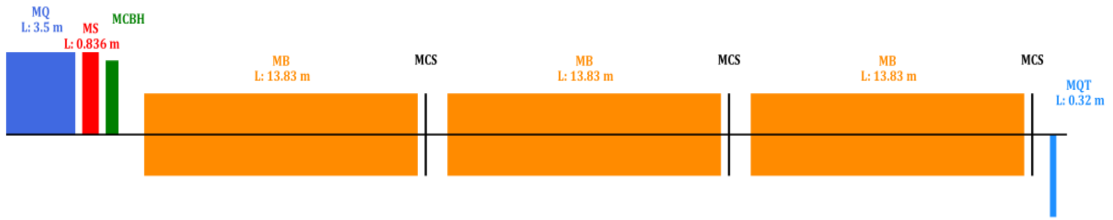


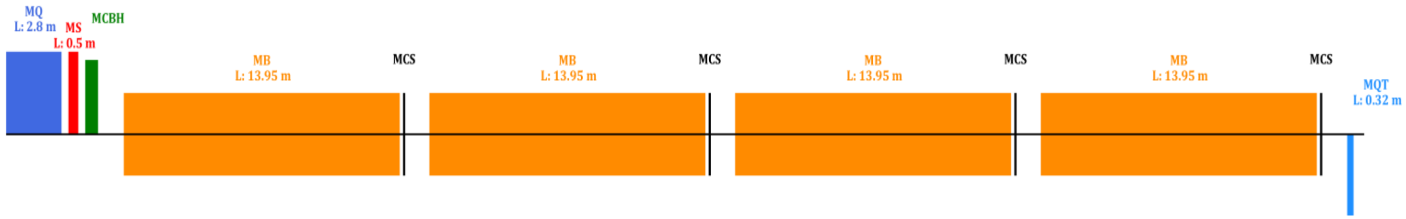
Optics Integration – J. Keintzel

ALGEA (Automatic Lattice GEneration Application);

- Based on a few input parameters **flexible generation** of Sequence, Powering, Naming convention, DS
- **Several constraints** are taken into account
- Automatic **survey fitting** by varying several parameters (drift spaces, LCELL, LMB)
- **V0.3** collision challenging, **V0.4 in progress**

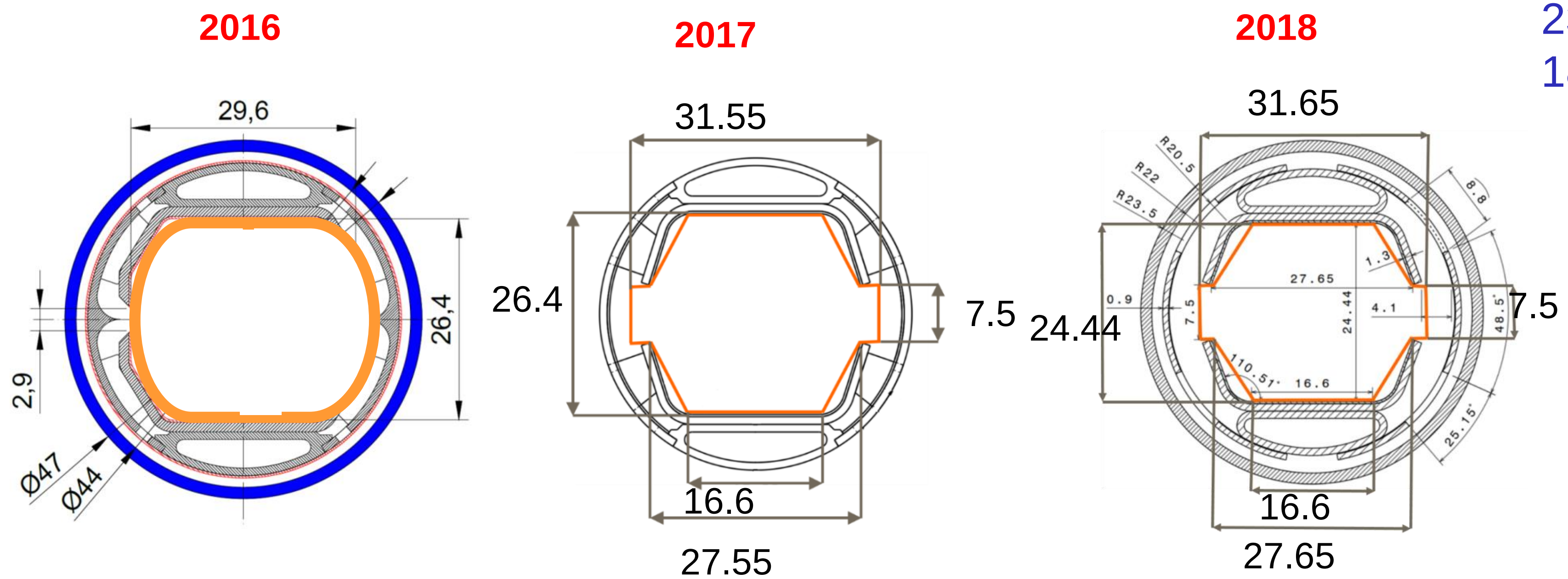
V0.3	18x90	23x90
Arc cell phase advance [°]	90	90
Arc cell length [m]	137.227	106.9
K_1 [m^{-2}]	0.00746	0.00773
Quadrupole strength at 13.5 TeV [T/m]	336	348
$\beta_{max, min}$ [m]	230 / 40	177 / 32
$D_{max, min}$ [m]	3.6 / 1.76	2.2 / 1.1
Momentum Compaction α_C [10^{-4}]	5.8	3.5
Quadrupole length	2.8	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





HE-LHC
18x90

Optics Integration – J. Keintzel



450 GeV injection energy
23x90: 9.5 σ aperture
18x90: 7.2 σ aperture

- **aperture better for higher injection energy**
- bottleneck in the DS
- worst case: 450 GeV injection energy
  - **23x90: 9.5 σ aperture**
  - **18x90: 7.2 σ aperture**

- BS 2017 most promising
- **18x90: collision energy**: longer quadrupole length has no impact on other cell parameters (**spare space**)
- **23x90: collision energy:** 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**

Impedance model

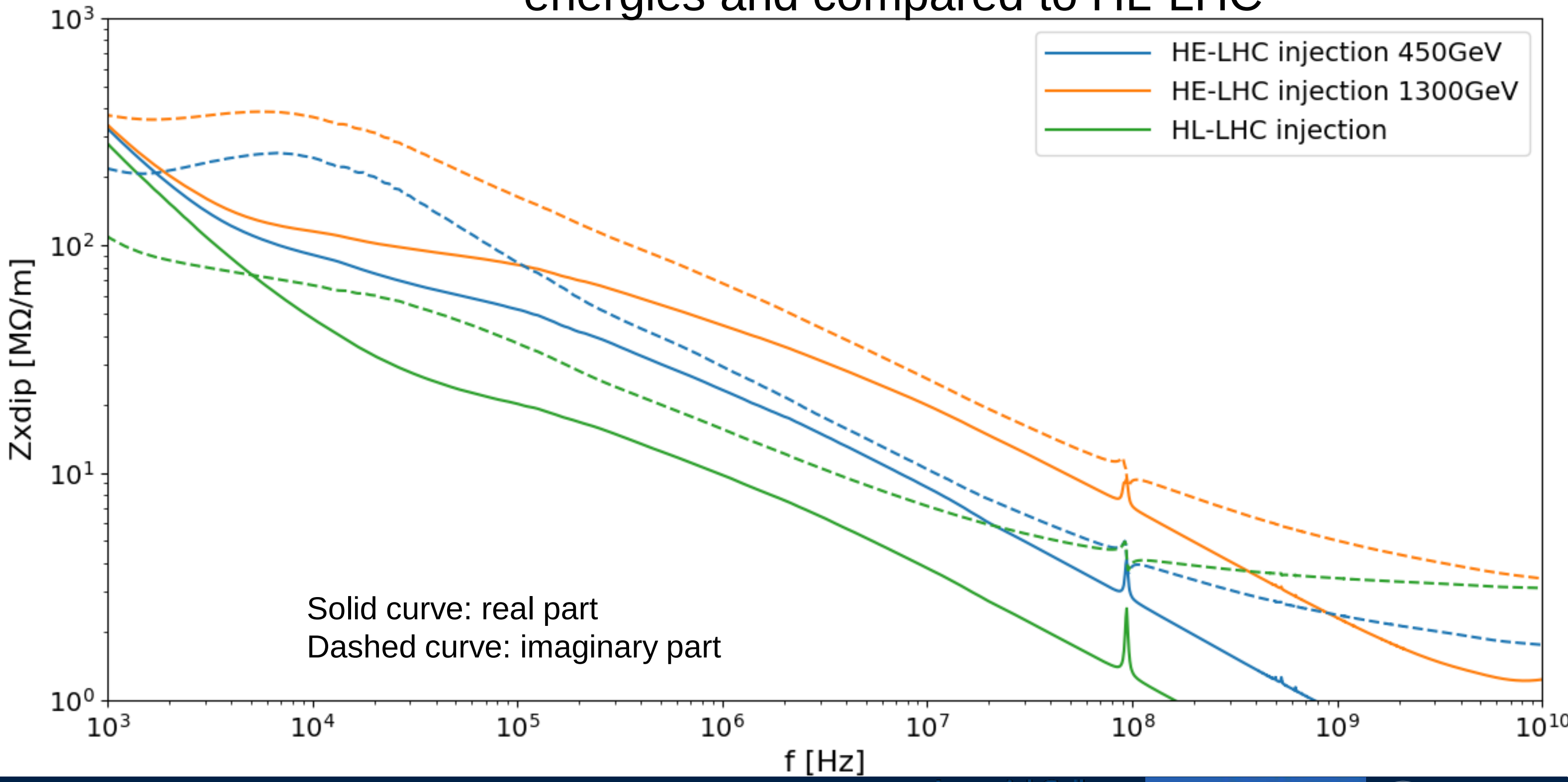
HE-LHC impedance model based on the **HL-LHC model**

- **All contributors** included, except for the **crab cavities**
- The **2017 FCC-hh beam screen** was used

Collimators and beam screen are the **main contributors** to the impedance

HL-LHC optics and collimators scaled to HE-LHC parameters were used, to be updated with HE-LHC design

Impedance as a function of frequency, for two injection energies and compared to HL-LHC



Single beam stability

At injection, the single beam instability threshold is at $\sim 3.5 \cdot 10^{11} ppb$

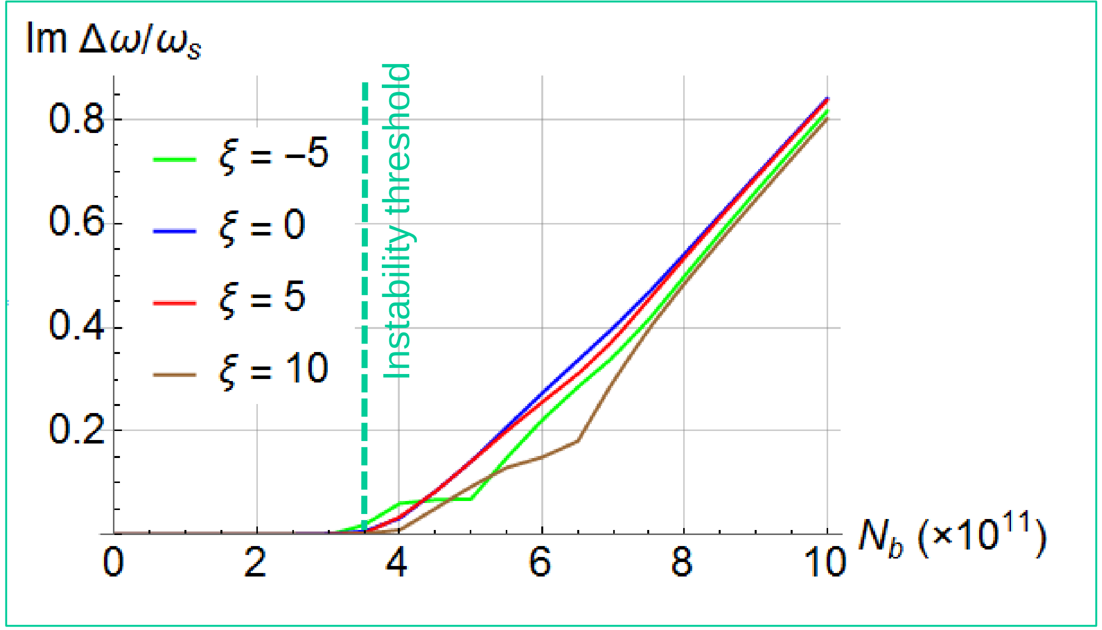
- **Octupoles** can efficiently stabilize the beam for these energies
- But **impact on dynamic aperture** could be important

Top energy is more challenging from the stability point of view

At **top energy**, the **octupoles are much less efficient** to stabilize the beam

- Assuming the LHC type octupoles and number, they would need $\sim 2000\ A$ (current limit: $550\ A$)
- Other solutions should be investigated such as electron lens or RF Quadrupole

Mode rise time vs bunch intensity for different chromaticities, 450 GeV injection energy, 2748 bunches



HE-LHC Electron Cloud – L. Mether

E-cloud build-up with the full FCC-hh beam screen geometry has been studied for 2017 and 2018 models

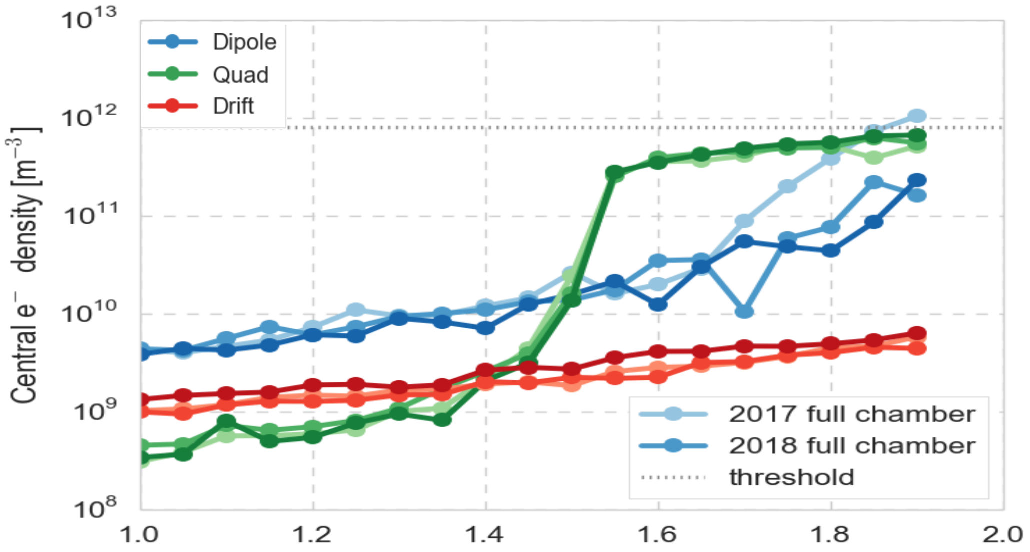
- **No significant difference between the two proposed models**
- **The slit effectively mitigates build-up in field free regions, at least for moderate photoelectron production at the saw-tooth surface**

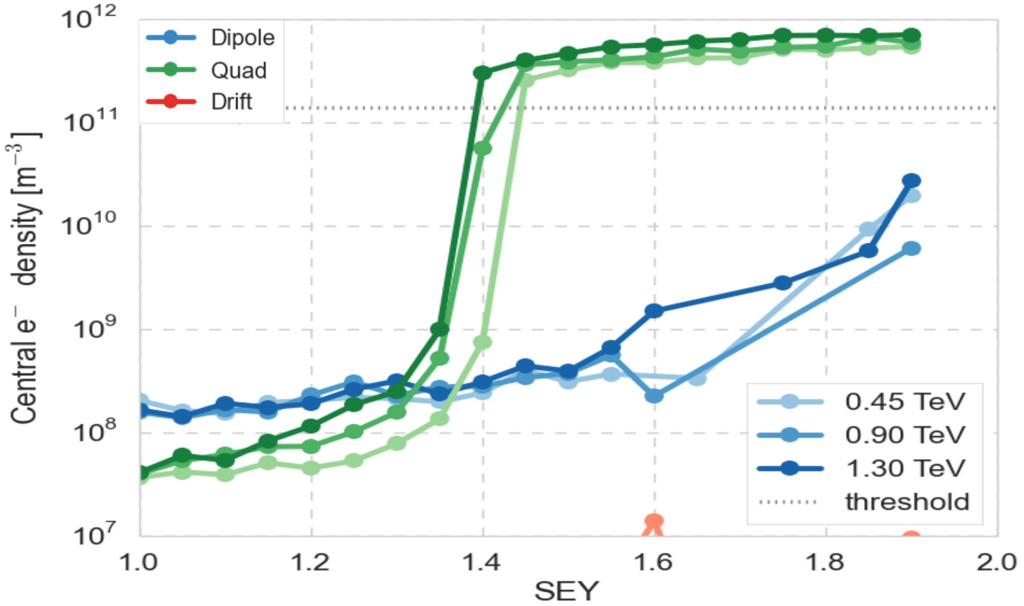
The effect of the injection energy on build up has been studied

- **No significant difference between injection energies was observed**

The SEY threshold for e-cloud build-up has been determined for different bunch spacing

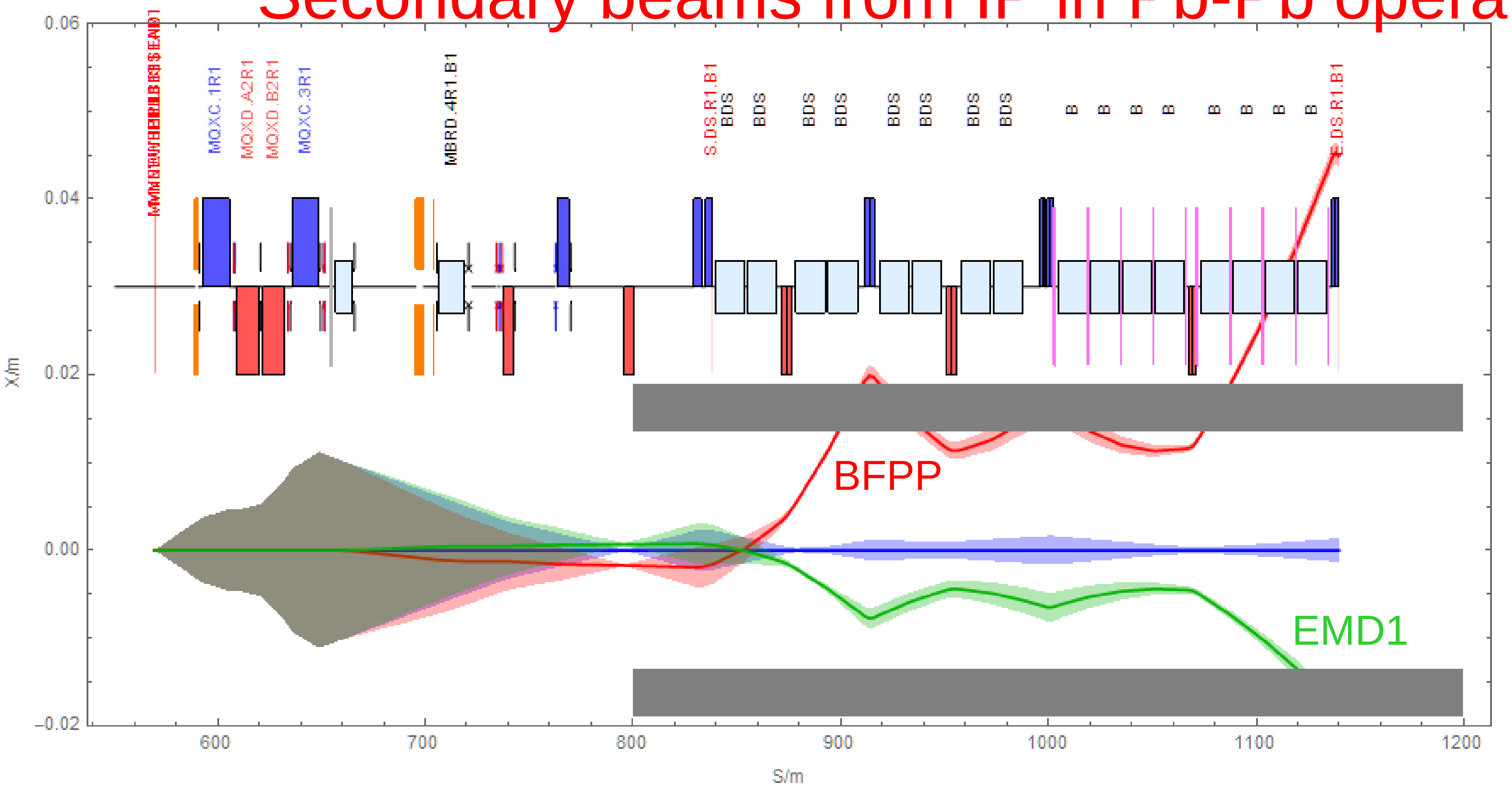
- **The 5 ns bunch spacing is an option only with a coating with SEY = 1.0 or less**
- **The 12.5 ns requires SEY ~ 1.0 – 1.1 in dipoles and quadrupoles**
- **The 25 ns bunch spacing has relatively high thresholds at nominal parameters, but build-up in the quadrupole is enhanced by intensity burn-off, requiring SEY ~ 1.1**





Nuclear Beams – J. Jowett

Secondary beams from IP in Pb-Pb operation of HE-LHC



Consequences of **small beam pipe** and weaker focussing:

Impact point of **bound-free pair production (BFPP)** beam is not near the **missing magnet** slot in the DS and the solutions adopted for LHC will not work.

May help with **EMD1** beam.

Can the **matching** be changed?

Secondary beam has **few 100 W power.**

Can the first 3 dipole magnets be moved closer to the IP to make a space for collimators?
Scheme used for earlier proposal for **DS collimators** in LHC – would not need >22 T dipoles … talk by JMJ at 2009 LHC Collimation Review https://indico.cern.ch/event/55195/

Another solution is to only collide nuclei with low enough Z. Acceptable for the physics programme ?

Nuclear Beams – J. Jowett

Conclusions for nuclear collisions at HE-LHC

- A first look at Pb-Pb collisions in HE-LHC suggests that **integrated luminosity** can be somewhat **more than at HL-LHC** (assuming similar injected beams)
  - Fills short, cycling and turn-around times are critical
- **BFPP and EMD losses** from IP may be unmanageable because of small beam pipe and weak focussing
  - Alternative layouts for the dispersion suppressors to install collimators ?
  - Limit colliding species to lighter nuclei, eg, Xe ?
- Heavy-ion operation of HE-LHC requires **serious study:**
  - BFPP and EMD losses from IPs, mitigations, solutions
  - Collimation and cleaning inefficiency
  - Best choice of colliding species for physics and machine ?
  - Injection, operational cycle
  - Hybrid proton-nucleus collisions, p-Pb, etc.

Conclusion

- Lots of topics covered in three sessions
- Large progress to complete integrated lattice
  - Dedicated IR designs
  - Integration
  - DA studies
- Many effects studied
  - Impedance
  - Electron cloud
  - Beam-beam
- Flat and nuclear beams explored
- Lots of progress but many things still open