



EuroCirCol WP2+3

FCC-hh design

Barbara Dalena for the FCC-hh team



The European Circular Energy-Frontier Collider Study (EuroCirCol) project has received funding from the European Union's Horizon 2020 research and innovation programme under grant No 654305. The information herein only reflects the views of its authors and the European Commission is not responsible for any use that may be made of the information.



The team



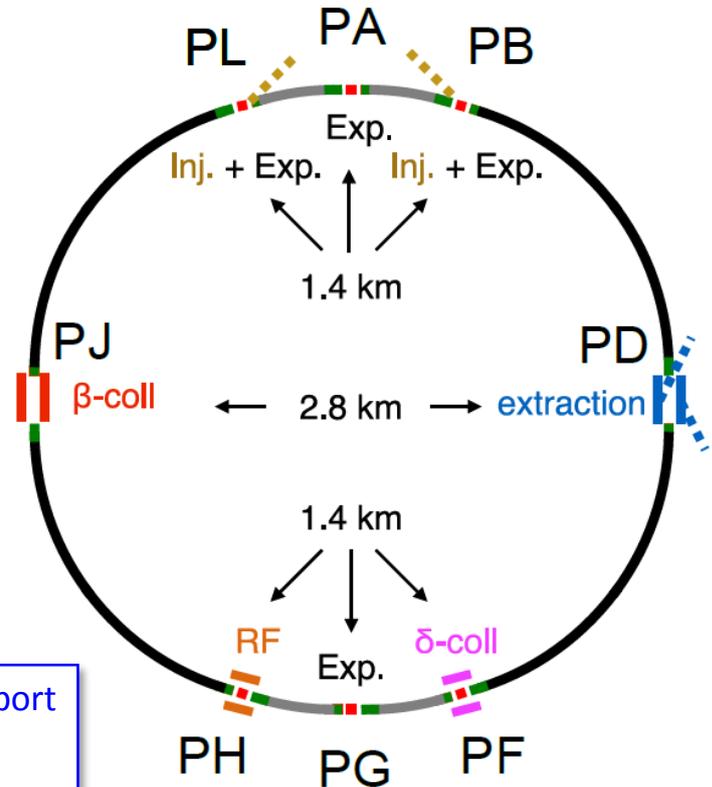
Layout

Circumference 97.75 km
Straight sections 6×1.4 km + 2×2.8 km
Geological constraints

Dipole Field < 16 T
Arc filling factor 80%

Separation of the various functions

Possibility to inject from LHC or SPS



Future Circular Collider Conceptual Design Report
Volume 3
<https://fcc-cdr.web.cern.ch>

Beam parameters

D. Schulte et al.

	LHC	HL-LHC	FCC-hh Initial	FCC-hh Nominal
C.M. Energy [TeV]	14		100	
Injection Energy [TeV]	0.45		3.3	
Peak Luminosity [$10^{34}\text{cm}^{-2}\text{s}^{-1}$]	1.0	5.0	5	<30
Integrated Luminosity/day [fb^{-1}]	0.47	2.8	2.2	8
Bunch distance Δt [ns]	25		25	
Bunch charge N [10^{11}]	1.15	2.2	1	
Number of bunches	2808		10400	
Norm. emitt. [mm]	3.75	2.5	2.2	
Max ξ for 2 IPs	0.01	0.015	0.01 (0.02)	0.03
IP beta-function β [m]	0.55	0.15	1.1	0.3
IP beam size σ [μm]	~ 16	~ 7	6.8	3.5
RMS bunch length σ_z [cm]	7.55		8	
Assumed Turn-around time [h]			5	4
Stored Energy per beam [GJ]	0.392	0.694	8.3	
SR power per ring [MW]	0.0036	0.0073	2.4	

Luminosity evolution

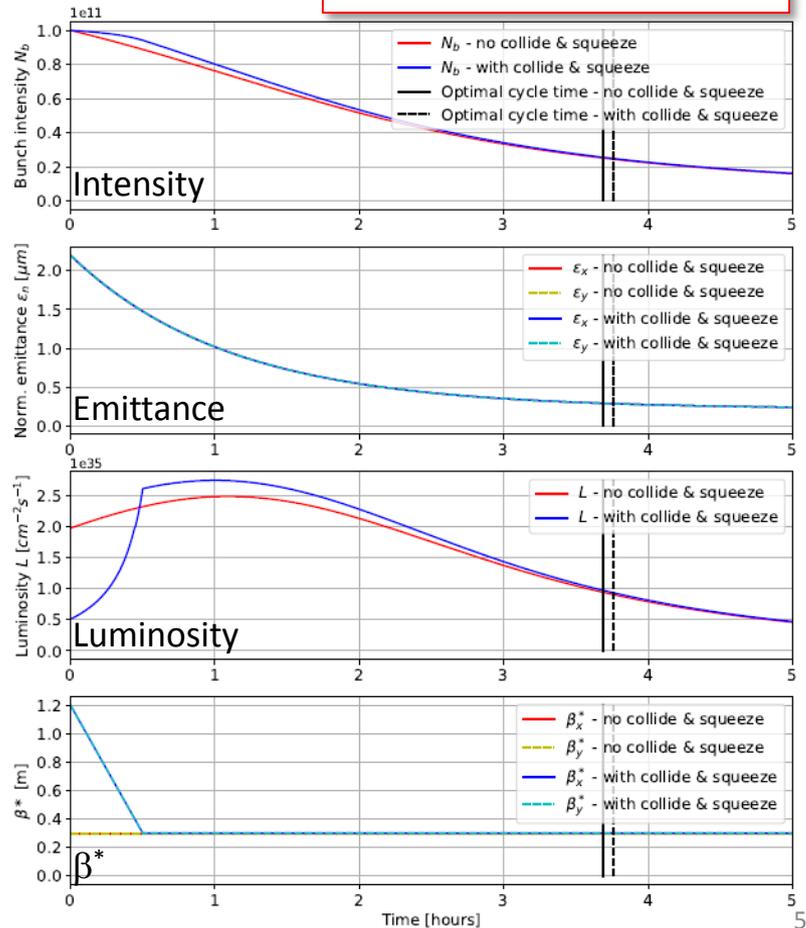
X. Buffat, , S. Arsenyev et al.

Integrated luminosity of 30 ab^{-1}
is required for physics

Optimum of 3.7 h in collision
4-5 h turn around time

Included:

- Intra-beam scattering
- Synchrotron radiation damping and excitation
- Burn-off
- Emittance-growth rate of $0.15 \mu\text{m}/\text{h}$
- Collide & Squeeze
- 70% availability



Machine Detector Interface

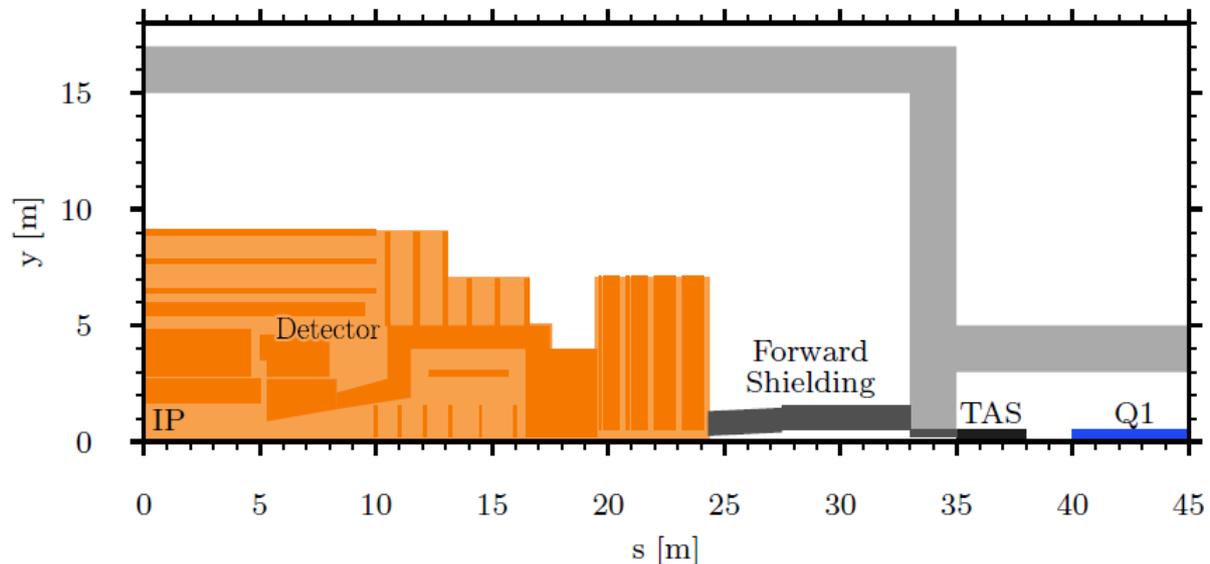
W. Riegler, R. Martin et al.

Detector total length ~ 50 m, cavern 66 m

Thick wall + copper absorber (TAS) + space for vacuum $\Rightarrow L^* \sim 40$ m

Beryllium beam pipe (radius 20 mm) with conical shape from 8 to 16 m

Aluminium beam pipe with 40 mm inner radius

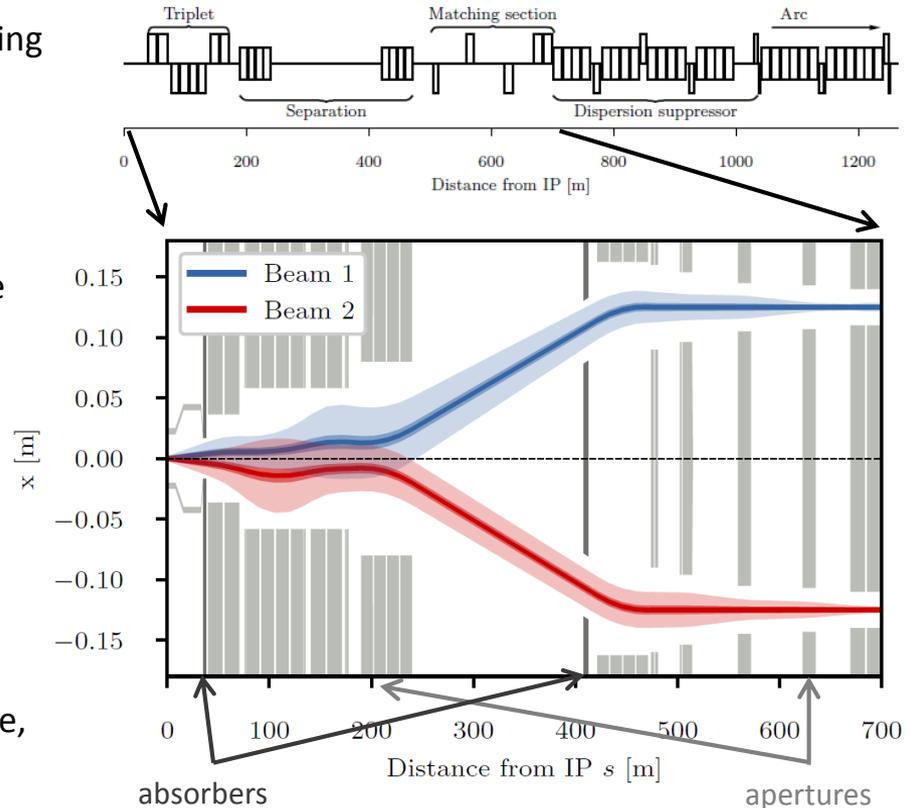


High Luminosity Insertions

R. Martin, E. Cruz, R. Tomas

Optimize triplet length and shielding according to the space available

- Sufficient aperture margins for nominal parameters
- Goal is $\beta^* = 0.3$ m, but 0.2 m can be achieved
- Space for Crab Cavity reserved
13.4 MV per beam per side (nominal)
- Dynamic Aperture above target:
 - Optimization of phase advance between IPs
 - Non-linear correctors (sextupole, octupole)



Alternatives

Systematic scan of design parameter space to find shortest possible triplet with sufficient beam stay clear and shielding.

Include Flat optics

For same DA, need larger separation according to β^* ratio, due to long range beam-beam interaction

Alternative Triplet specifications

Parameter	Quadrupole		
	Q1	Q2	Q3
Sub-Magnets	2	3	2
Sub-Magnet Length [m]	15	15	15
Coil Radius [mm]	96.5	96.5	96.5
Gradient [T/m]	106	112	99
Shielding [mm]	44.2	33.2	24.2

L. Van-Riesen Haupt, J. Abelleira

Parameter	Round	Flat
β_x^* [m]	0.3	1.2
β_y^* [m]	0.3	0.15
Full crossing angle [μ rad]	200	130
Beam-beam separation [σ]	17	22

T. Pieloni, J. Barranco

Low luminosity (Injection) Insertions

M. Hofer, F. Burkhard, E. Renner

No target luminosity: can achieve $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

No detector design: $L^* = 25 \text{ m}$ considered

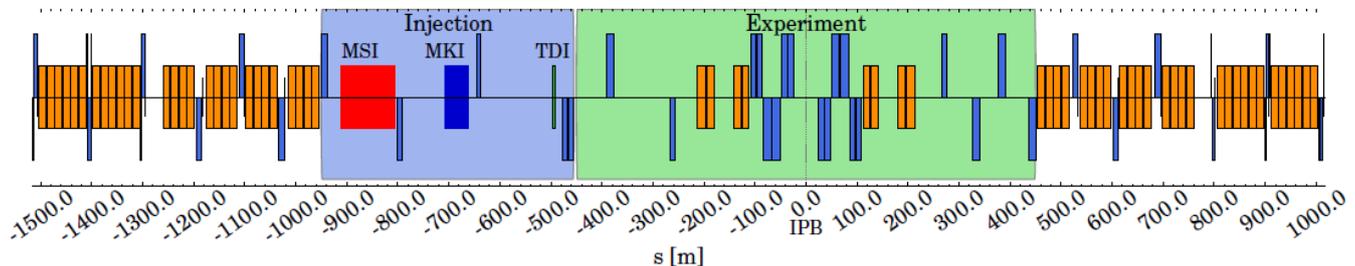
Triplet design similar to high luminosity insertion but less challenging

Superconducting separation dipoles: more compact design

Three half cells 150 m long for injection

Two additional half cells added between injection and experiment

(possibility to add more protection devices)



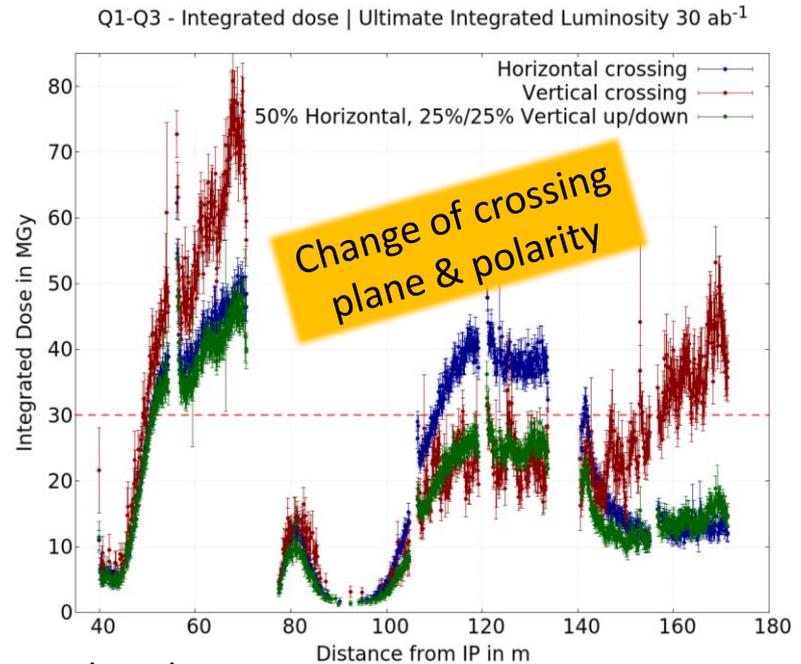
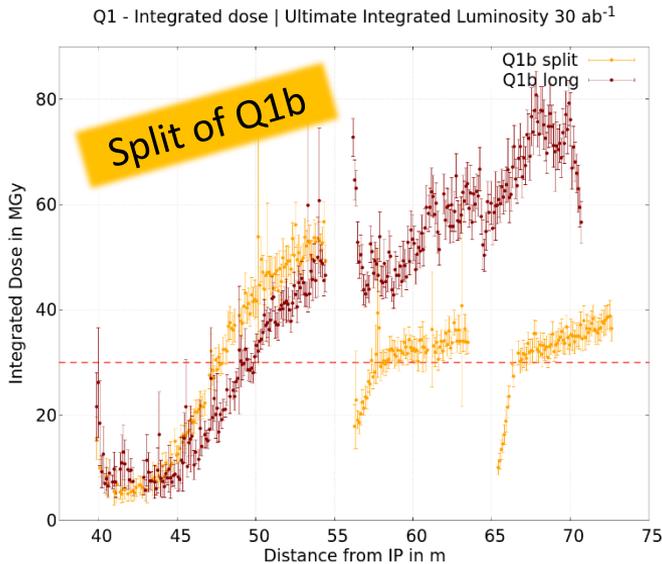
Collision debris

Comprehensive study of energy deposition due to the debris produced in p-p non-elastic collisions up to the end of the matching section.

Triplet: different mitigation strategies explored, based on:

- regular crossing plane and polarity alternation,
- splitting of magnets.

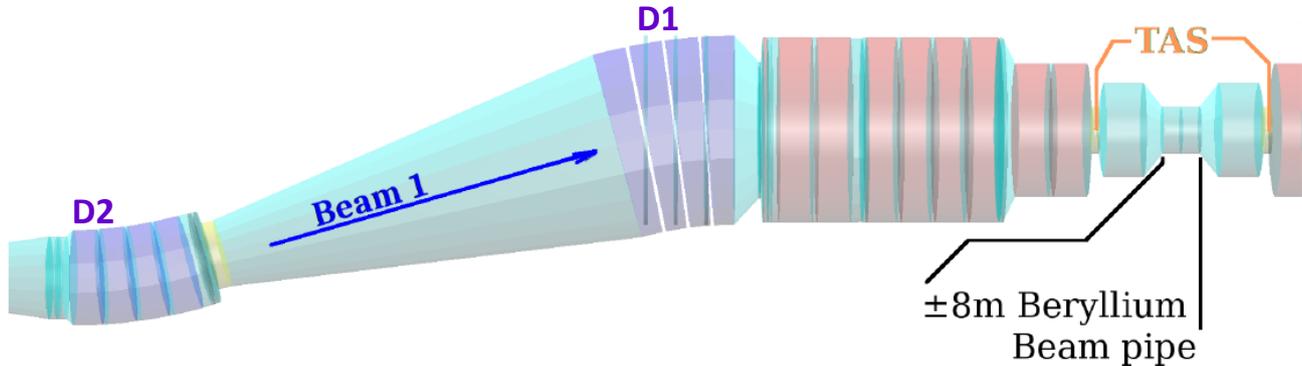
B. Humann, M.I. Besana et al.



Matching section: proposal of collimators and masks

Beam induced background

F. Collamati, H. Rafique et al.



- SR photons coming from separation dipoles D1 and D2 and entering the TAS are not an issue
- Muon cross talk between experimental regions is not a concern
- 50 cm long mask (INERMET180) required to protect first quadrupole in the Dispersion Suppression from inelastic protons losses in the DIS collimator

Extraction Insertion and Dump

(1) 150 Extraction Kicker

System length 120 m

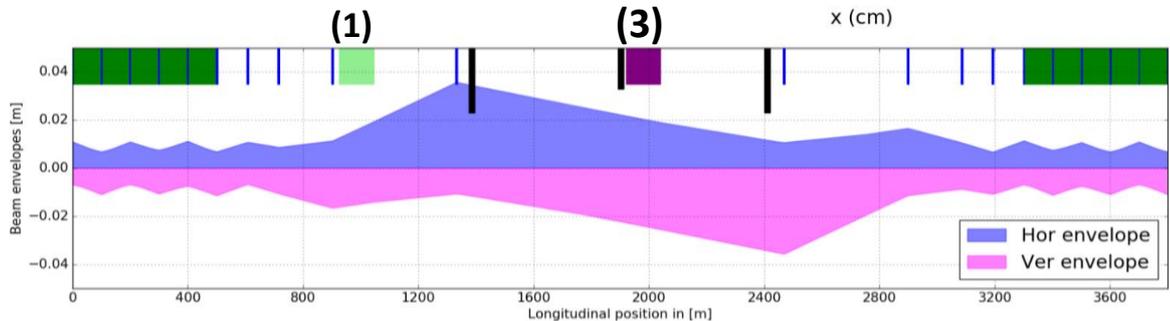
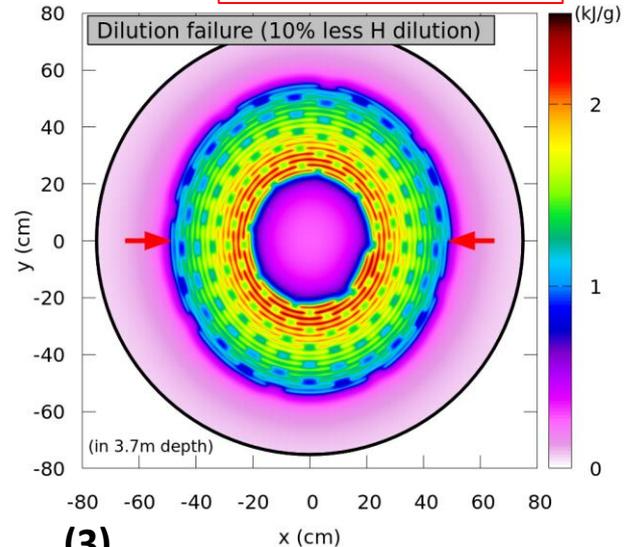
(2) Large beam size at protection absorber

(3) SuShi / Cos-Theta Septa instead of superferric Lambertson

single plane extraction (vertical)

- Sweep pattern reduces the load on the dump, but still challenging dilution kickers (could be improved with Carbon foams ?)
- Dump functionality not compromised in case of asynchronous dump

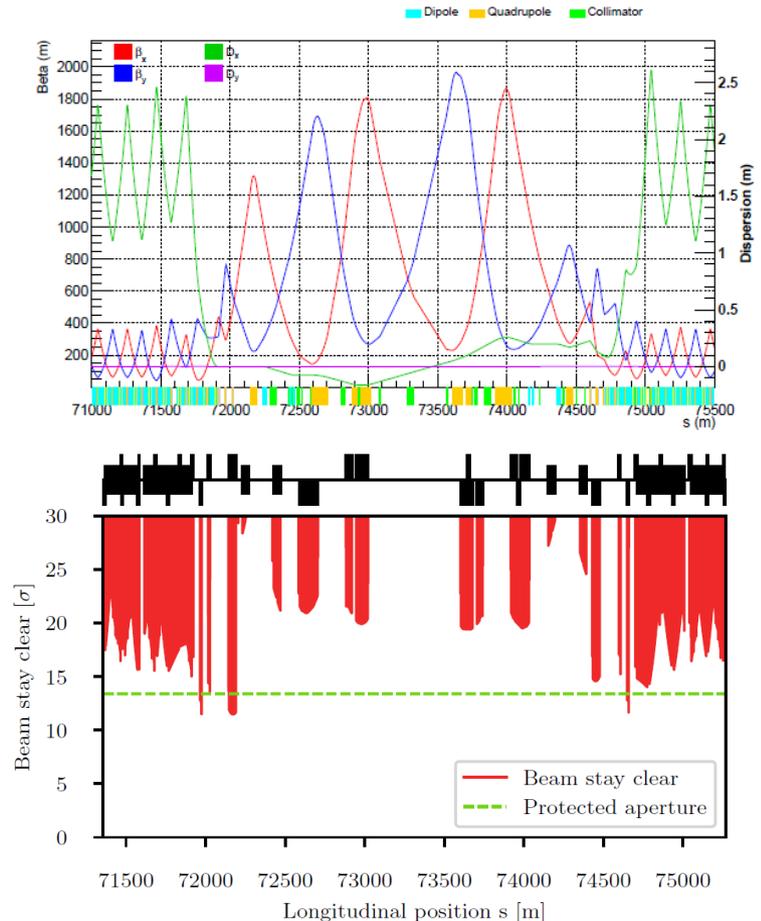
W. Bartmann et al.



Collimation

R. Bruce et al.

- LHC system scaled up in energy
multi stage cleaning
- Magnets length, separation and β functions scaled by a factor ~ 2.67 (momentum IRF and betatron IRJ)
- Horizontal and vertical primary collimators only
- Additional collimators in dispersion suppression regions, experimental and extraction insertions (59 movable collimators per beam installed, and in addition physics debris absorbers and fixed masks are required)
- Beam stay clear of the full ring important for collimation to work properly
 - Few elements below target can be cured by changing their design



Collimators

M. Varasteh, G. Gobbi et al.

Energy deposition

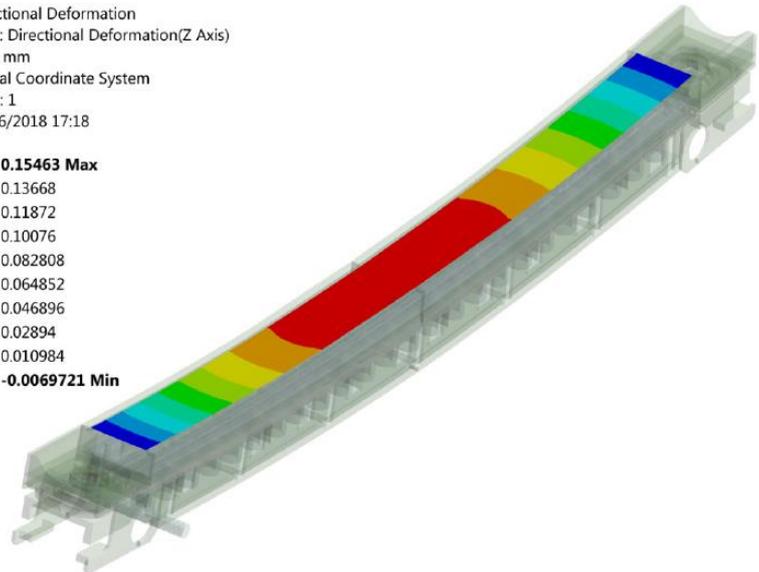
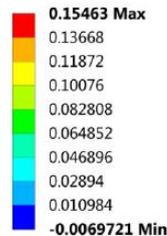
- Power on the primary collimator reduced from 260 kW to 80 kW by halving the primaries' active length and removing the skew primary
- Power on the first secondary collimator decreased by 60% making the Jaws thicker (3.5-4.5 cm)
- Re-design of dispersion suppression collimator and quadrupoles mask to withstand secondary shower (3 TLDs and 2 masks)

Robustness

- In general, collimators survive the very challenging losses without damage
- Some issues still to be solved, e.g. plasticity on cooling pipes

⇒ Novel materials might help
(CFC and MoGr chosen)

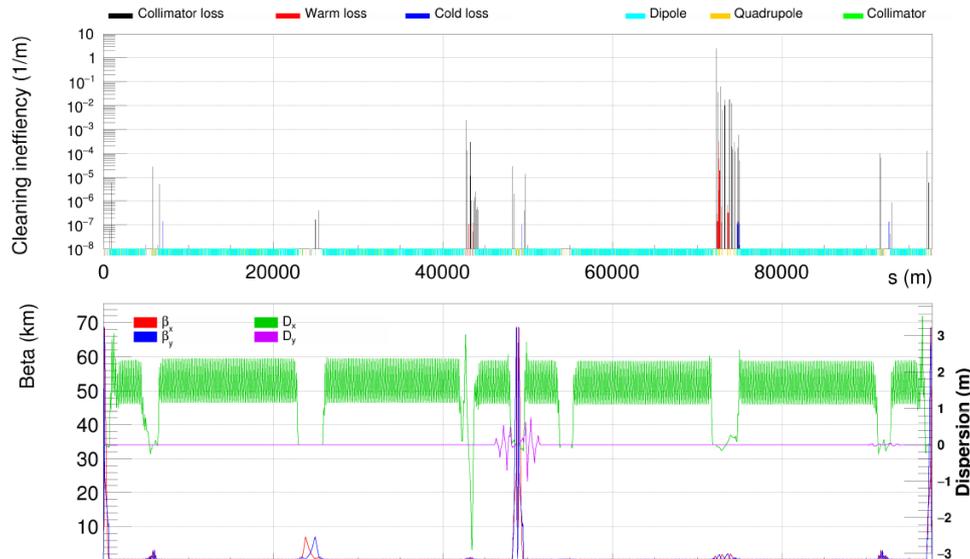
Directional Deformation
Type: Directional Deformation(Z Axis)
Unit: mm
Global Coordinate System
Time: 1
21/06/2018 17:18



Collimation performances

J. Molson, M. Serluca et al.

- Local cleaning inefficiency (at injection and collision):
Power load from horizontal and vertical losses (0.2 h lifetime) below the quench limits
- Inefficiency for off momentum halo beam at the start of acceleration ramp below the limit of $4 \times 10^{-5}/\text{m}$
- 3 extraction kickers can pre-fire safely before damaging the collimators (including alignment errors)
 - It might be reduced according to the phase advance between the extraction kickers and the primary collimators

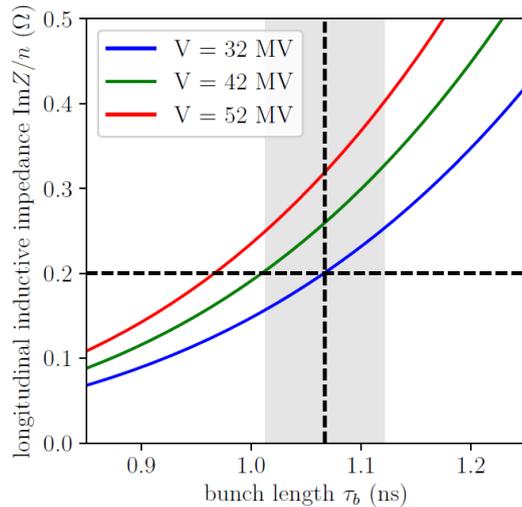


RF and RF Insertion

E. Shaposhnikova et al.

RF similar to LHC 400.8 MHz
 Installed voltage of 48 MV (collision)

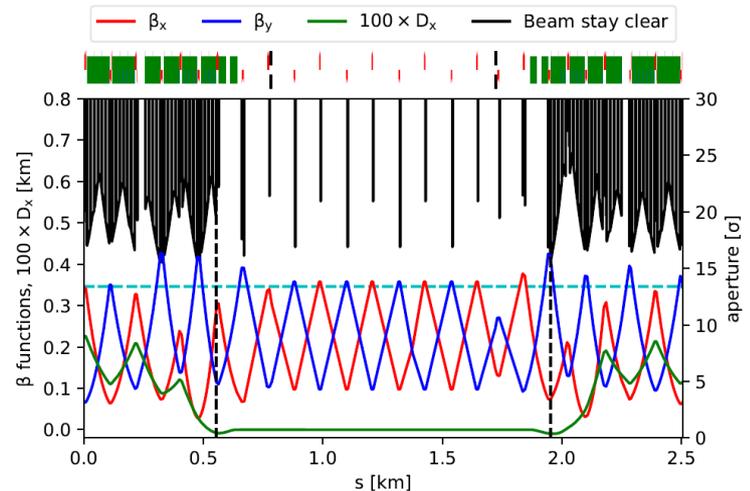
- 42 MV provides stability for $\pm 5\%$ energy spread bunches
- At injection 12 MV is chosen



Longitudinal beam stability is provided by controlled emittance blow-up

A. Chance

FODO cells of length 219.292 m
 72° phase advance: compromise between beam stay clear and maximum gradient of the quadrupoles
 Further optimization possible



Space for feedback, electron lens or RF quadrupoles foreseen

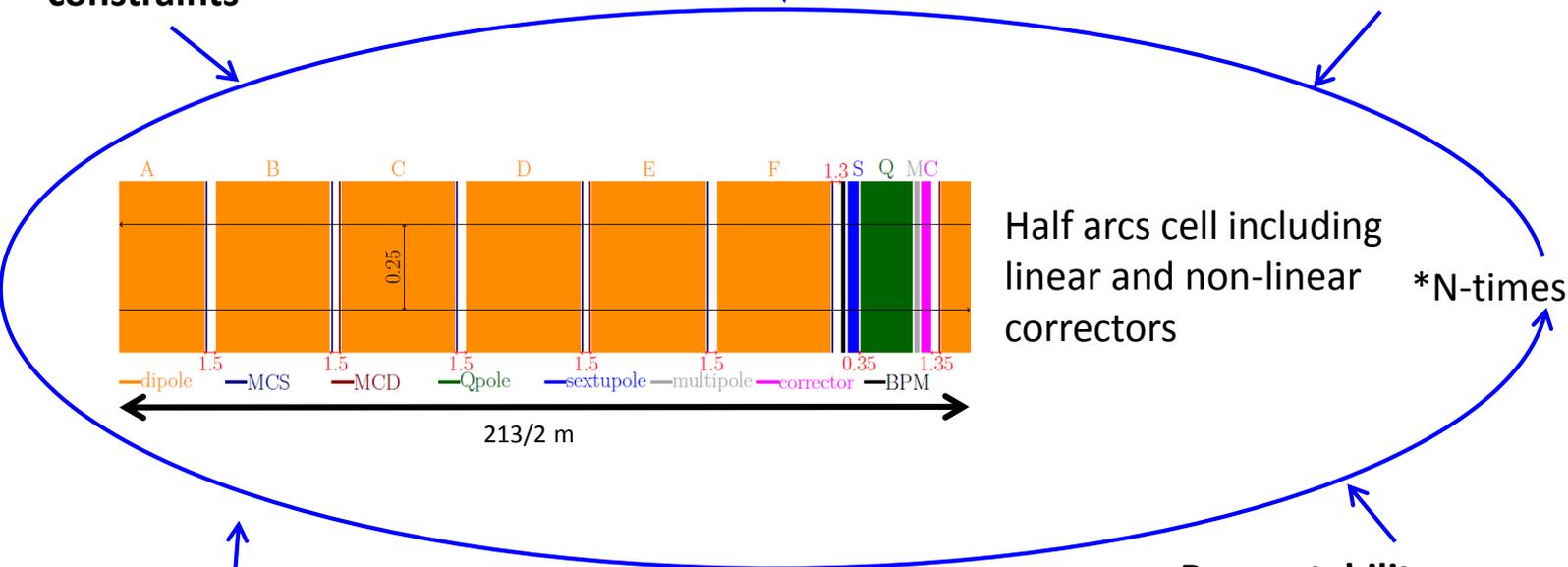
Arc concept

A. Chance et al.

Magnets max gradient and Field Quality

Civil engineer constraints

Beam-screen design



Half arcs cell including linear and non-linear correctors *N-times

Integrations of experimental IRs (correction schemes)

Collimation requirements

Beam-stability: Integration of Landau Damping octupoles

Alternative FODO cells at 60° under study

Integrated lattice and imperfections

Matching insertions and arcs

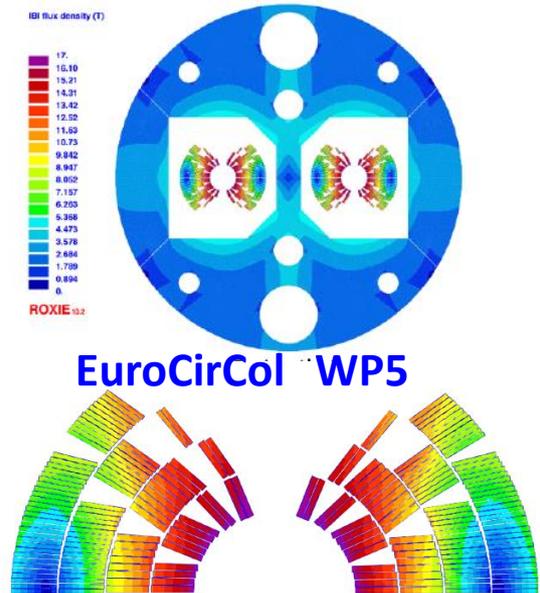
- constraints on beta-functions, dispersion, phase advances and maximum quadrupoles gradients
- space for collimators
- beam stay clear

Definition of linear and non linear correction schemes

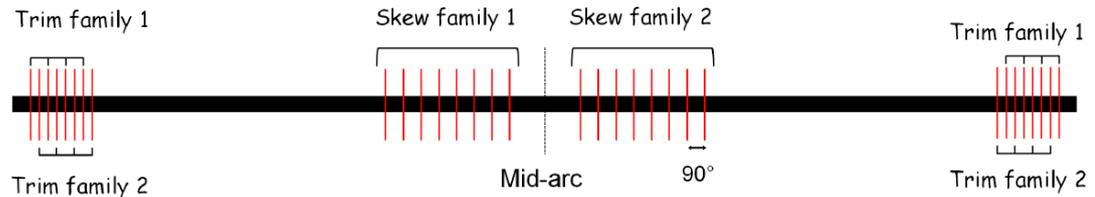
- reduced number of correctors in short arcs
- NbTi technology for correctors (long correctors)

Integrated lattice performances

- driven by field quality
- alignment of some specific elements



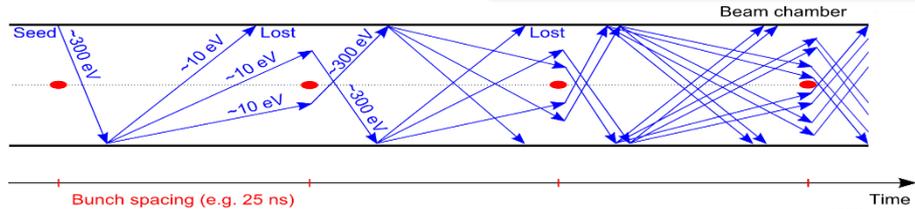
D. Boutin,
A. Chance et al.



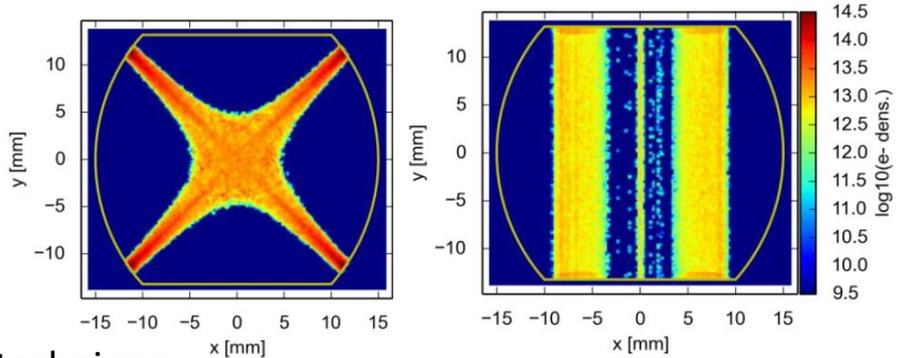
Electron Cloud

L. Mether, D. Astapovych

Secondary Emission Yield requirements (quadrupole):
 for 25 ns: below 1.2
 for 12.5 ns: around 1.0

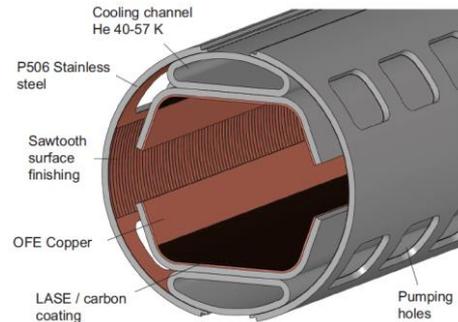


Baseline scenarios:
 Amorphous Carbon coating at top and bottom for the dipoles, at 45° for the quadrupole



LASE treated surfaces mitigation technique can be interesting for alternatives bunch spacing

Saw-tooth in the beam screen improves deflection of SR photons in the antechamber



**EuroCirCol
 WP4**

Impedances

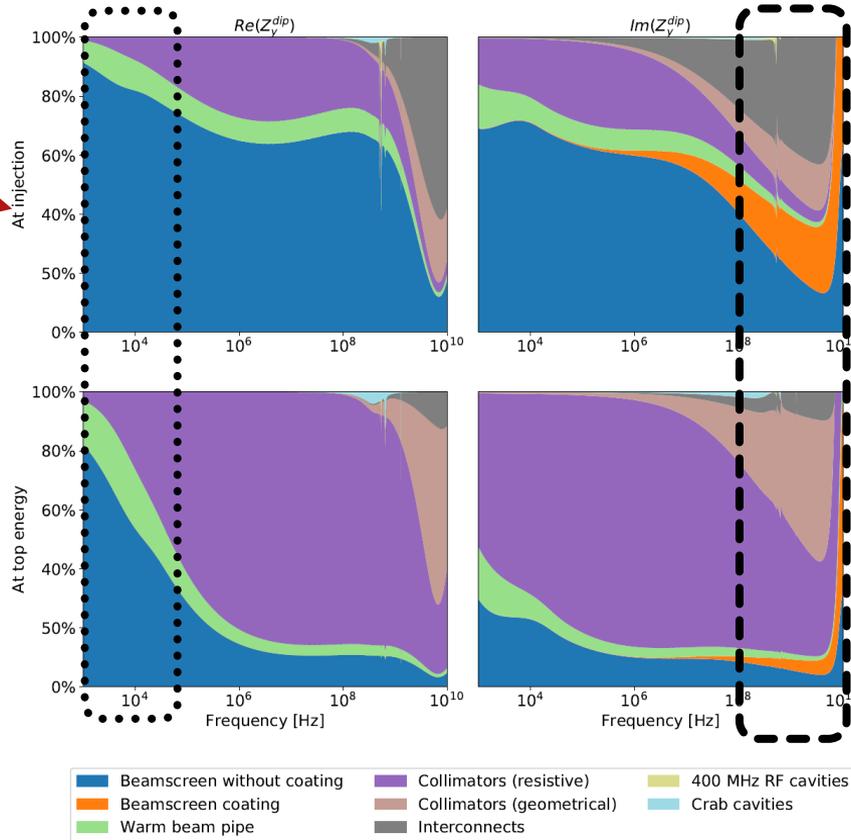
Weighted dipolar impedance

Coupled bunch instability is always dominated by the resistive wall impedance of the beamscreen BS

On-going work:

MKI transverse impedance

FRESCA experiment: measuring the impedance of beamscreen coatings (LASE, HTS, etc)



S. Arsenyev

Single bunch instabilities are dominated by

- Res wall BS, BS coating, collimators, interconnects (injection)
- Collimators (flat top)

Transverse beam stability

Injection and flat top

- Coupled bunch instability (k=0 mode) 3-4 times higher in FCC-hh compared to LHC
- Landau Octupole (LO) stability region comparable to LHC

⇒ Active stabilization by transverse feedback for k=0

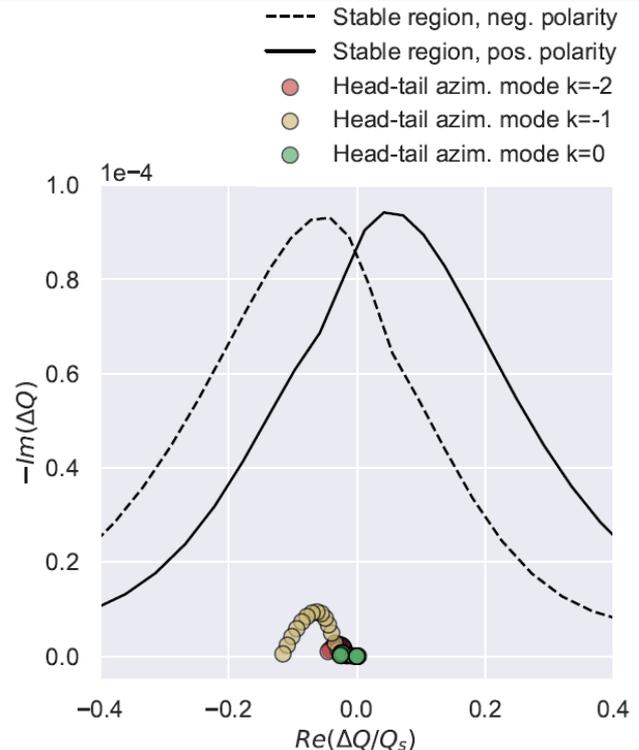
⇒ $|k| \geq 1$ modes stabilized by LO

Feedback

LHC ADT scaled to 2.35 MHz:

- Damping time of 20 turns at injection
- Damping rate of 460 turns at collision energy

S. Arsenyev, O. Boine-Frankenheim, J. Komppulla, V. Kornilov, C. Tambaco



Two beam stability and Alternatives

Collide&Squeeze

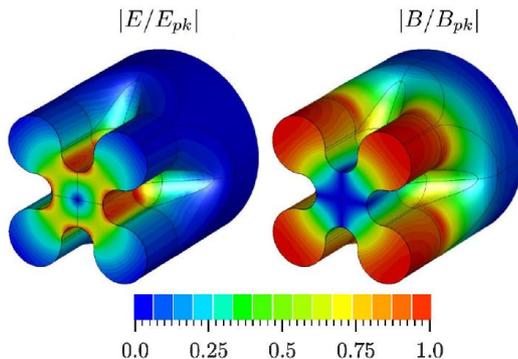
C. Tambasco, M. Schenk

- Beam beam interaction at the collapse of the separation bumps modify the transverse beam stability given by LO
- ⇒ Collapse at $1.1 \text{ m } \beta^*$ and collide during squeeze provide transverse stabilization

Alternatives

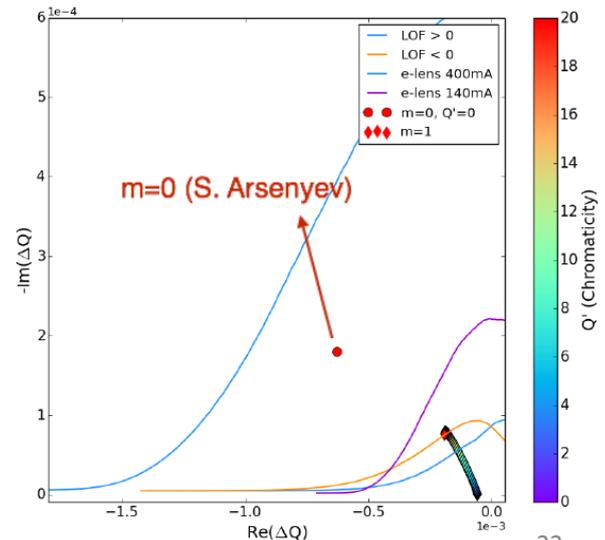
RF Quadrupole:

- Very challenging and many debates
- One RF Quadrupole can significantly decrease required octupole current
- 2-3 cavity can stabilize the beam alone



Electron lens:

140 mA provides enough Landau Damping for $m=1$ (flat top)



Beam-beam effects

S. Furuseth, X. Buffat, T. Pieloni, J. Barranco

Head-on beam-beam

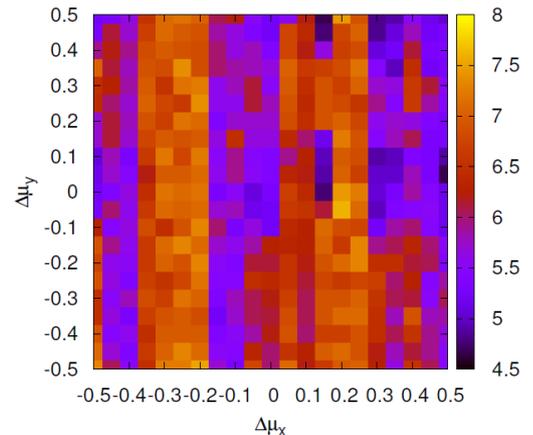
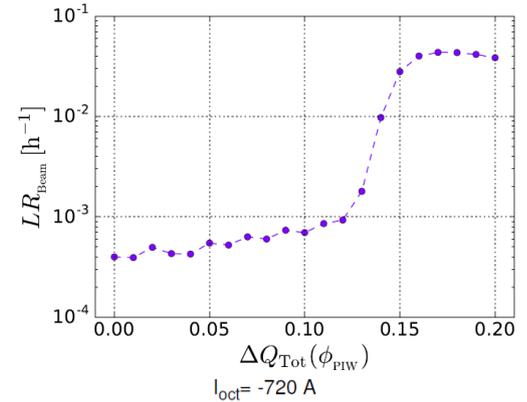
- 0.03 total tune shift is feasible having full cancellation of the crossing angle and a symmetric phase advance between IPs
- It generates β -beating to be considered in the beam stay clear and correction schemes

Long-range and head-on beam-beam

- Negative octupoles polarity provides larger single beam stability and more margins in terms of DA due to compensation of long-range beam-beam (further optimization of phases between IPs can help)

Alternatives

- Different crossing configurations for the two experimental insertions are feasible



FCC-hh as Ion(s) collider

Same optics as p-p collision

Parameters and luminosity estimates for lighter ion species

Performance driven by high quality of injectors (lower injection energy reduces performances)

Ion operation very challenging for collimators:

high flux of modified ions from the bound-free pair-production process impact DIS collimators and shower from fragmentation need to be absorbed

M. Schaumann, J. Jowett et al.

Initial:

Nominal:

Pb-Pb (p-Pb) Integrated Luminosity per 1 month

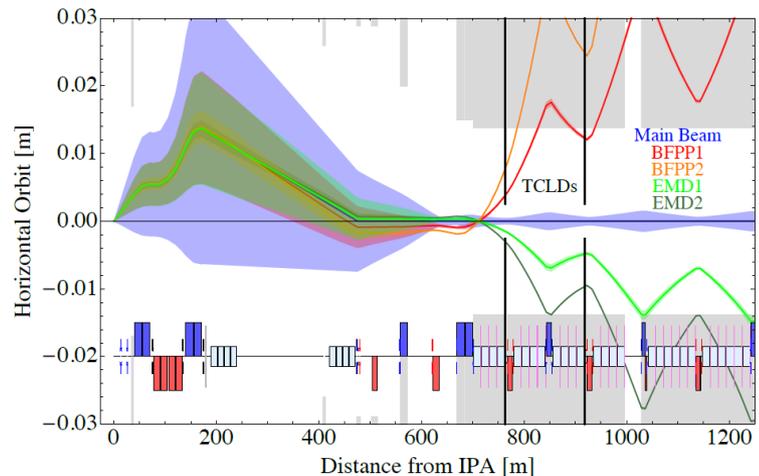
1 exp. $L_{\text{int}}/\text{run}$: **35 (2800)nb⁻¹** **105(29000)nb⁻¹**

2 exp. $L_{\text{int}}/\text{run}$: **23 (6000)nb⁻¹** **62(18000)nb⁻¹**

⁴⁰Ar¹⁸⁺ Integrated Luminosity per 1 month

2 exp. $L_{\text{int}}/\text{run}$: **28381nb⁻¹**

Including an overall **performance efficiency factor** of 50% for failures, start-up, etc.



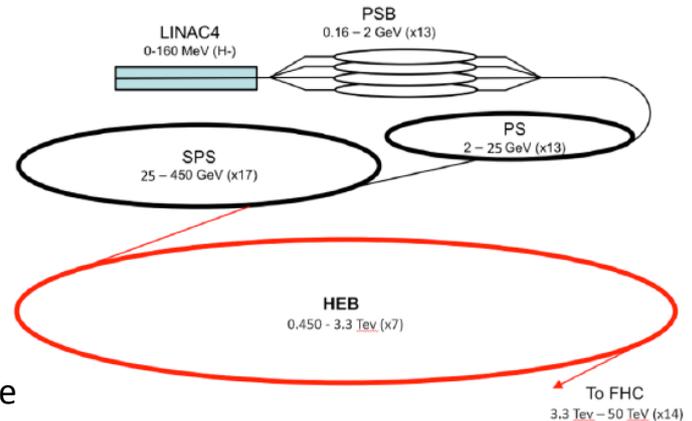
Injectors

For 3.3 TeV injection energy

- Reuse of existing LHC with 5x faster ramp remains FCC-hh baseline
- Two other alternative ‘simpler’ scenarios to keep as options

scSPS option only valid if 1.3 TeV FCC injection is possible

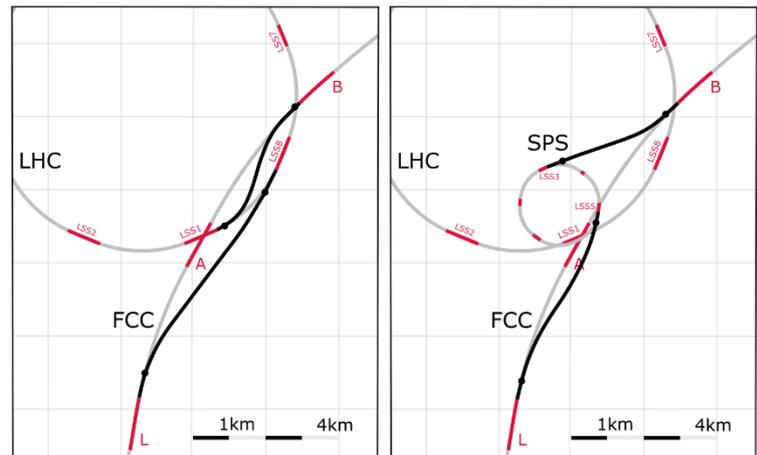
- presently excluded by collider dynamic aperture
- beam stability to be further studied



Transfer lines

⇒ Protection against machine failure is main issue

B. Goddard, W. Bartmann,
E. Renner, A. Milanese, M. Solfaroli



Conclusion

- A working conceptual design for the FCC-hh machine exists, it shows no showstoppers
- Several alternatives for the different functions of the machine have been investigated as well
- Challenges have been identified with possible R&D to be follow up
- Still room for further optimization possible

More to come...

Day	Sun. 23.6.	Monday 24 June	Tuesday 25 June				Wednesday 26 June					
Room		Plenary Ground floor Ballroom I+II	Parallel 1 Ground floor Ballroom I	Parallel 3 1st floor Crea/Explo	Parallel 4 1st floor Eva/Inno	Parallel 2 Ground floor Ballroom II	Parallel 1 Ground floor Ballroom I	Parallel 2 Ground floor Ballroom II	Parallel 3 1st floor Crea/Explo	Parallel 4 1st floor Eva/Inno		
Time												
08:30-09:00	Registration @ Palace Lobby (Ground floor)	Opening, study status and physics perspectives	Welcome	EuroCirCol machine design WP2	SRF cavities and technologies	Precision measurements, energy calibration and luminosity measurement	Sustainable research infrastructures - Challenges	FCC-ee machine design	EuroCirCol cryo-beam vacuum design WP4	Detector technology and proposals	FCC-hh kickers, septa, dumps and protection devices	
09:00-09:30		Keynote talk	Keynote talk	M. Giovannozzi (CERN)	A.-M. Valente (JLAB)	G. Wilkinson (Univ. of Oxford)	J. Gutleber (CERN)	J. Gao (IHEP)	R. Kersevan (CERN)			
09:30-10:00		Keynote talk	Keynote talk	M. Giovannozzi (CERN)	A.-M. Valente (JLAB)	G. Wilkinson (Univ. of Oxford)	J. Gutleber (CERN)	J. Gao (IHEP)	R. Kersevan (CERN)			
10:00-10:30		J. D'Hondt (VUB)	Overview of the Future Circular Collider study	Coffee Break Lobby Ballroom+Bar+Lobby Klimt (Ground floor) and 1st floor Atrium)				Coffee Break Lobby Ballroom+Bar+Lobby Klimt (Ground floor) and 1st floor Atrium)				
10:30-11:00		Coffee Break	Lobby Ballroom+ Bar+ Lobby Klimt (Ground floor)	EuroCirCol machine design WP2	SRF cavities and technologies	Precision measurements, energy calibration and luminosity measurement	Methods for impact assessment	FCC-ee machine design	EuroCirCol cryo-beam vacuum design WP4	Detector technology and proposals	Cryogenics	
11:00-11:30		EuroCirCol results	EuroCirCol WP2+3 FCC-hh design	EuroCirCol machine design WP2	SRF cavities and technologies	Precision measurements, energy calibration and luminosity measurement	Methods for impact assessment	FCC-ee machine design	EuroCirCol cryo-beam vacuum design WP4	Detector technology and proposals	Cryogenics	
11:30-12:00		EuroCirCol results	EuroCirCol WP4 - Vacuum system	EuroCirCol machine design WP2	SRF cavities and technologies	Precision measurements, energy calibration and luminosity measurement	Methods for impact assessment	FCC-ee machine design	EuroCirCol cryo-beam vacuum design WP4	Detector technology and proposals	Cryogenics	
11:30-12:00		EuroCirCol results	EuroCirCol WP4 - Vacuum system	B. Dalena (CEA)	C. Pira (INFN-LNL)	J. Alcaraz Maestre (CIEMAT)	S. Vignetti (CISL)		S. Casalbuoni (KIT)		L. Tavian (CERN)	
12:00-12:30		R. Alekan (CEA)	EuroCirCol WP5 - 16 T Magnets	2nd floor: Grace	Lunch				2nd floor: Grace	Lunch		
12:30-13:00		Lunch		Steering Committee (closed session)	Lobby Ballroom + Restaurant Galleries 1-2-3+Klimt Ground floor				International Advisory Committee (closed session)	Lobby Ballroom + Restaurant Galleries 1-2-3+Klimt Ground floor		
13:00-13:30	Lobby Ballroom + Restaurant Galleries 1-2-3+Klimt Ground floor		Steering Committee (closed session)	Lobby Ballroom + Restaurant Galleries 1-2-3+Klimt Ground floor				International Advisory Committee (closed session)	Lobby Ballroom + Restaurant Galleries 1-2-3+Klimt Ground floor			
13:30-14:00	Lobby Ballroom + Restaurant Galleries 1-2-3+Klimt Ground floor		EuroCirCol EIR design WP3	RF power sources	Standard model precision	Creating impact - bringing the local with the global	1st floor Eva/Inno	8th floor Vision	1st floor Crea/Explo	8th floor Clarity		
14:00-14:30	Status FCC-ee, technologies and infrastructure	FCC-ee design overview	EuroCirCol EIR design WP3	RF power sources	Standard model precision	Creating impact - bringing the local with the global	FCC-ee injector design	EuroCirCol 16 Tesla magnet WPS	Software and simulations	FCC-ee and HE-LHC beam dump...		
14:30-15:00	Status FCC-ee, technologies and infrastructure	SRF and power sources R&D overview	EuroCirCol EIR design WP3	RF power sources	Standard model precision	Creating impact - bringing the local with the global	FCC-ee injector design	EuroCirCol 16 Tesla magnet WPS	Software and simulations	FCC-ee and HE-LHC beam dump...		
15:00-15:30	P. Campana (INFN)	FCC infrastructures and implementation	EuroCirCol EIR design WP3	RF power sources	Standard model precision	Creating impact - bringing the local with the global	FCC-ee injector design	EuroCirCol 16 Tesla magnet WPS	Software and simulations	FCC-ee and HE-LHC beam dump...		
15:30-16:00	Coffee Break	Lobby Ballroom+ Bar+ Lobby Klimt (Ground floor)	Coffee Break	Poster session Klimt, Ground floor				Regional projects Ballroom I+II (Ground floor)				
16:00-16:30	Strategy, funding instruments	Horizon Europe and Europe's Strategy on R&I	EuroCirCol EIR design WP3	FCC-ee injector linacs	Standard model precision	Economics of Science WORKSHOP Reception (Klimt)	Cold refreshments Lobby Ground floor					
16:30-17:00	Strategy, funding instruments	Fundamental research as driver for Innovation	EuroCirCol EIR design WP3	FCC-ee injector linacs	Standard model precision	Economics of Science WORKSHOP Reception (Klimt)	Cold refreshments Lobby Ground floor					
17:00-17:30	Update on the European Strategy for Particle Physics	Update on the European Strategy for Particle Physics	EuroCirCol EIR design WP3	FCC-ee injector linacs	Standard model precision	Economics of Science WORKSHOP Reception (Klimt)	Cold refreshments Lobby Ground floor					
17:30-18:00			T. Pieloni (EPFL)	L. Rivkin (EPFL)	J. Erler	Economics of Science WORKSHOP Reception (Klimt)	2nd floor: Infinity 29p					

Additional slides