FCC-hh ring: overview of the new layout

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Outline

- Layout of the FCC-hh ring
- Alternative design of regular arcs and dispersion suppressors with combined-function magnets
- Considerations on transfer lines in the ring tunnel
- HTS coatings of beam screen

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CIRCULAR Layout of the FCC-hh ring as of CDR

The CDR layout

- Two high-luminosity experiments (A & G)
- Two other experiments combined with injection (L & B)
- Two collimation insertions
 - betatron cleaning (J)
 - momentum cleaning (F)
- Extraction insertion (D)
- Clean insertion with RF (H)
- Compatible with LHC or a superconducting SPS as injector



Circumference: 97.75 km



CIRCULAR Layout evolution of the FCC-hh ring

The main drivers

- Placement studies
- FCC-ee layout (the choice of having four symmetrical experimental IPs)
- RF harmonic number to optimize transfer from injector

The main choices

- Reduce the length of the ring circumference
- Reduce the length of technical insertions
- Displace radially the experimental IPs to match position of FCC-ee IPs
- Reduce the number of access shafts
- Four-fold symmetry
- Re-organize functionalities of insertions
- Locate transfer lines in ring tunnel



Current layout of the FCC-hh ring CIRCULAR

- IPA, IPD, IPG, IPJ: experimental insertions
- Two collimation insertions •

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- **IPF:** betatron cleaning •
- **IPH:** momentum cleaning •
- **IPB:** extraction (both beams) + injection (external) •
- IPL: RF (both beams) + injection (external)
- Last part of transfer lines in the ring tunnel
- Compatible with LHC or a superconducting SPS as injector

New beam energy (for 16 T dipoles): 48 TeV



Circumference: 90.66 km



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Fine tuning of the ring geometry in progress





Design of regular arcs and dispersion suppressors

The new layout has been used to optimise as much as possible the ring design

- 12-dipole FODO cells have been replaced with 16-dipole FODO cells
 - Increase dipole filling factor
 - Larger beam sizes can be compensated by a minor review of the beam screen geometry



R. Bruce for performance of collimation system





Alternative design of regular arcs and dispersion suppressors

A non-baseline, alternative design of arcs and dispersion suppressors based on combined-function (CF) magnets have been studied.

- Main advantages:
 - Increase the dipole filling factor
 - Simplify magnet production (no main quadrupoles)
- Possible disadvantage:
 - Dipole field limited by peak field in the coil
 - The quadrupole component limits the dipole one



Sketch of separated-function (top) and combined-function (bottom) cells



Alternative design of regular arcs and dispersion suppressors



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Other considerations

- Main advantages:
 - Smaller beta-functions and dispersion

(m)

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- Possible disadvantage:
 - Smaller optical functions imply stronger chromatic sertupoles

Further optimization: make longer cells

Improves dipole filling factor

 $D_x(m)$

- $12 dipole SF \rightarrow 0.80 \rightarrow 12 dipole CF \rightarrow 0.86 \rightarrow 16 dipole CF \rightarrow 0.9$
- Reduces quadrupole component
- Reduces strength of chromatic sextupoles



 $\beta_x(m), \beta_y(m)$



Alternative design of regular arcs and dispersion suppressors

An essential ingredient to make the combined-function solution realistic is the design of a dispersion suppressor.

• Several solutions found, which include combined-function magnets and quadrupoles



Decreasing length of dispersion suppressor

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Considerations on transfer lines

The new layout has impact on the design of the transfer lines

- Two scenarios at hand, the injector is:
 - LHC (baseline): injection energy is 3.3 TeV
 - A superconducting SPS (option): injection energy is 1.3 TeV
 - The injection points are
 - PB: clockwise beam
 - PL: counter-clockwise beam
 - To save tunnel length the transfer line tunnels join the ring tunnel close to PA.
 - The transfer lines then run in the ring tunnel until the injection point
- Optics

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- FODO cell equal to that of the FCC-hh ring
- Same transverse focusing used also for the part of transfer lines upstream of the ring tunnel





Considerations on transfer lines



Considerations on transfer lines magnets

Parameters of the transfer lines in ring tunnel

| Transfer line for FCC-hh, 3.3TeV injection [sections inside collider tunnel] | | | | |
|--|---|--------------|--|--|
| | Number of transfer lines | 2 | | |
| Transfer lines | Cells per transfer line | 37 | | |
| | Cell length | 276 m | | |
| | Total length* | 19.6 km | | |
| *26 regular cells and 11 shorter dispersion suppressor cells per line | | | | |
| Interconnections | Electromagnet longitudinal gap | 550 mm | | |
| | Permanent magnet longitudinal gap | 50 mm | | |
| Beam | Vacuum aperture height/diameter | 30 mm | | |
| | Good Field Region (GFR) diameter | 20 mm | | |
| | Field linearity in GFR | ±2 units | | |
| Dipoles | Integrated dipole field per cell | 235 Tm | | |
| | Dipole magnet field strength | 1.0 T | | |
| | Dipole magnetic length per cell | 230 m | | |
| | Total dipole length | 17.0 km | | |
| Quadrupoles | Integrated quadrupole gradient per cell | 118 T | | |
| | Quadrupole magnet gradient | 20 or 25 T/m | | |
| | Quadrupole magnetic length per cell | 6 or 4.8 m | | |
| | Total quadrupole length | 444 or 355 m | | |





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- These designs are conventional and well understood.
- The length and volume of magnets present significant challenges:
 - The dipole length is set at 5 m to minimize interconnection gaps.
 - The yokes must have adequate torsional rigidity.
- The key optimization focus is the coil cross-section.
- The goal is to minimize the total lifetime cost by carefully balancing:
 - Copper volume (capital investment)
 - Power usage (overhead cost)
 - Infrastructure requirements, i.e. cooling plant, cabling, power converters (capital investment)



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280mm x 500mm cross-section



Quadrupole concept

220mm x 220mm cross-section





Permanent Magnet Concepts

- Permanent Magnets (PMs) are highly suitable for transfer line specifications:
 - Single-pass beam requires less stringent field quality requirements
- PMs are already used in accelerators, although on a smaller scale.
- Temperature dependence of PMs is sufficiently small.
- The lifetime radiation dose is expected to be compatible with NdFeB or SmCo PMs.
 - The provisional designs use a high coercivity NdFeB grade (N42UH)
- Developing industrial-scale assembly processes will be a significant focus of future research.





Halbach dipole magnet for FASER experiment



Transverse radiation dose plots for FCC-hh collider

PM: Iron dominated Concept

- The iron yoke helps to smooth irregularities in permanent magnet blocks.
 - Field quality can be improved using pole shims
 - Magnet yoke can be manufactured with good accuracy
- Both designs offer field strength adjustment, allowing for a decrease in the field within the aperture.
 - Dipole: Shunts can be inserted to partially short-circuit the magnetic flux
 - Quadrupole: Shims can be radially adjusted to increase the magnetic reluctance of the flux circuit
- The volume of PM blocks must be minimised.
- We will iterate the magnet geometry to maximise utilisation of the PMs' maximum energy product (BH_{max})
- The combined PM mass is 950 tonnes (N42UH, unoptimised)



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PM: Shimmed Halbach Concept

- Halbach configurations are the most efficient arrangements of permanent magnet blocks.
- Similar to coil-dominated superconducting magnets, Halbach are susceptible to manufacturing tolerances.
 - Magnetisation errors: deviations in the magnitude and direction of magnetisation in PM blocks.
 - Assembly errors: variations in block positions.
- The CBETA team at BNL has achieved remarkable success in developing shimmed Halbach magnets:
 - After assembly, harmonic errors are measured and then mitigated by placing tuning iron rods around the bore.
 - Reduced quality assurance is required during manufacturing which decreases overall production costs.

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> Dipole Halbach configuration



Shimmed combined function Halbach (left) and CBETA return arc (right)





PM: Shimmed Halbach Concept

- Ideal Halbach magnets inherently achieve optimal field strength and field quality.
 - The combined PM mass is 625 tonnes (N42UH).
- However, real Halbach magnets fall short due to accumulated manufacturing errors.
- Our challenge is to determine the achievable field quality in manufactured magnets by:
 - Conducting a prototyping campaign
 - Utilising stochastic modelling tools
- From the experience of the CBETA production run, we extrapolate that the FCC-hh specifications can be met.
 - Provides valuable empirical data on field errors before and after shimming.



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Qualitative Costs Comparison

- Reliably estimating lifetime costs at this early stage is challenging due to high uncertainties.
 - However, permanent magnet concepts are anticipated to be the more cost-effective solution.
- The required volume of permanent magnets is realistic compared to industrial production:
 - Required PM volume: 625 to 950 tonnes
 - Global neodymium PM production by 2030: 200 k-tonnes per year

| Zero to low cost Significant cost Major cost driver | Iron dominated electromagnet | Iron dominated permenant magnet | Shimmed Halbach | | |
|---|---------------------------------|------------------------------------|--------------------|--|--|
| Captital investment costs | | | | | |
| Magnetic Iron | | | | | |
| Copper conductor | | | | | |
| Permanent magnet blocks | | | | | |
| Infrastructure | | | | | |
| (cooling, converters, cabling, etc.) | | | | | |
| Construction | | | | | |
| Ongoing costs | | | | | |
| Maintenance | | | | | |
| Electricity (inc. cooling plant) | | | | | |



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Design of transfer lines in the ring tunnel (for 3.3 TeV)

- Integration
 - Outcome of first studies is encouraging
 - Further studies are needed to consider detail, e.g.
 - Shielding
 - Machine protection



The size of the QRL should be reduced: drawings not updated, yet

FCC-hh n Massimo FCC Wee

The Hybrid REBCO – Cu Coating

EXCELENCIA SEVERO

- The FCC-hh beam screen (BS) has become a high-tech device and several activities are on going to study the novel configuration.
- The increased operating temperature imposes an HTS coating to reduce beam impedance.
- Full HTS coating generates a field distribution with poor properties.
- Alternated REBCO Cu longitudinal segments achieve
 - low overall surface impedance
 - decreased trapped field in the HTS, resulting in a better field quality than pure HTS



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The Hybrid REBCO – Cu Coating

Proposed geometry

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- HTS area ratio = 89% → low surface impedance
- Number of HTS segments = 4 → good field quality
- Widths of HTS segments = 2 and 4 mm, which are commercially available. This makes the coating production process cheaper, easier and faster.









The Hybrid REBCO – Cu Coating

Thermomechanical Behaviour

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- The currents induced by the ramping of the main dipole magnets, as well as the image currents produced by the beam are used to calculate the force and heat loads in the beam screen.
- FEM simulations show no significant temperature shift or induced mechanical stress during normal operation of the FCC-hh
 Beam-Induced Image Currents







FUTURE CIRCULAR The Hybrid REBCO – Cu Coating

• Behaviour during a dipole quench

- During a quench of main dipoles, significant mechanical stress is induced, although the maximum values are very local. The temperature shift cannot be neglected.
- The HTS coating would suffer stress levels below the irreversibility limit and heating below *T_c*. Therefore, it would withstand a magnet quench without degradation of electromagnetic properties.



CIRCULAR Magnetic measurements of FCC-hh BS

- The proposed REBCO-Cu coating deserves experimental verifications of the simulated properties.
- A series of magnetic measurements are planned for October 2023 at CERN (SM18 facility) to probe the impact of the BS on the field quality.
 - A rotating-coil device is being designed, with 6 sectors, 150 mm each.
 - HL-LHC magnet models will be used (11 T SP107 single-aperture, and a triplet quadrupole).
 - Test programme of about a couple of weeks









Conclusions and outlook

- Following the outcome of placement studies, a new FCC-hh layout has been designed.
- Several innovations have been introduced in the design.
- Reports about related studies will be given in the other talks of this session.
- Future activities include:
 - Fine tuning of the ring geometry to find a better matching with that of the FCC-ee rings.
 - Assess (and improve, if needed) performance of the betatron collimation insertion.
 - Further develop the alternative solution based on combined-function magnets.
 - Finalise studies about transfer line magnets, possibly selecting the solution to be further pursued.
 - Pursue the studies of the properties of the HTS coatings and the planned measurement programme.





Thank you for your attention!





Back up slides









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