A brief introduction to the Future Circular Collider (FCC) project

K. Oide (CERN)

Many thanks to M. Benedikt, A. Blondel, P. Janot, M. Koratzinos, D. Shatilov, F. Zimmermann, and all FCC-ee collaborators.
Limitation on proton (circular) collider

\[ \frac{E}{c} \approx p = eB\rho \]

\[ E \ [\text{GeV}] = 0.299792458 \times B\rho \ [\text{Tm}] \]

<table>
<thead>
<tr>
<th>Collider</th>
<th>LHC</th>
<th>FCC-hh</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E \ \text{(TeV)} )</td>
<td>7</td>
<td>50</td>
<td>7.1</td>
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<tr>
<td>Circumference ( C \ \text{(km)} )</td>
<td>26.6</td>
<td>97.8</td>
<td>3.7</td>
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<td>( \rho \ \text{(km)} )</td>
<td>2.8</td>
<td>10.4</td>
<td>3.7</td>
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<td>( B \ \text{(T)} )</td>
<td>8.3</td>
<td>16</td>
<td>1.9</td>
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</tbody>
</table>

most crucial subject

\( E \): beam energy
\( c \): speed of light
\( p \): momentum
\( e \): charge
\( B \): magnetic field
\( \rho \): bending radius
Limitation on electron circular collider

\[ P_{\text{SR}} = \frac{4\pi}{3} mc^2 r_e \frac{\gamma^4}{\rho} I \]

\[ P_{\text{SR}} = 88.5[\text{kW}] \times \frac{E[\text{GeV}]^4}{\rho[\text{m}]} I[\text{A}] \]

<table>
<thead>
<tr>
<th>Collider</th>
<th>LEP2</th>
<th>FCC-ee Z</th>
<th>FCC-ee tt</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E ) (GeV)</td>
<td>104.6</td>
<td>45.6</td>
<td>182.5</td>
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<tr>
<td>Circumference</td>
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<td>( C ) (km)</td>
<td>26.6</td>
<td>97.8</td>
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<td>( \rho ) (km)</td>
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<td>( I ) (mA)</td>
<td>3</td>
<td>1390</td>
<td>5.4</td>
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<td>( P_{\text{SR}} ) (MW)</td>
<td>12.2</td>
<td>50</td>
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</tbody>
</table>

\( m \): electron mass
\( c \): speed of light
\( r_e \): classical electron radius
\( \gamma \): Lorentz factor
\( \rho \): bending radius
\( I \): beam current

limits the luminosity
Limitation on luminosity

\[ \mathcal{L} \propto \frac{\xi I}{\beta^*} \]

\[ \mathcal{L} = \frac{N^2 f}{4\pi \sigma_x^* \sigma_y^*} \]

\[ \mathcal{L} \approx \frac{I}{2e} \left( \frac{0.1 \alpha \eta}{6\pi} \right)^{2/3} \left( \frac{\xi_y}{\gamma r_y^2 \epsilon_y} \right)^{1/3} \]

stored current \( I \)

beam dump

inators

pile up

Andy Haas, NYU

ATLAS Pileup and Overlay Simulation

ATLAS Pileup and Overlay Simulation

Andy Haas (NYU) on behalf of the ATLAS Collaboration

LHC Detector Simulations, CERN

March 18-19, 2014

https://indico.cern.ch/event/279530/

coherent

beam-beam parameter

3D flip-flop

beamstrahlung

crossing angle

crab-crossing

parasitic collision

crab-waist

dynamic aperture

interaction region

machine-detector interface

synchrotron radiation

superconducting RF acceleration

collimation

e-cloud

cryogenics

vacuum system

high field magnet

energy calibration

polarization

low-emittance tuning

diagnositics

interaction region

dynamic aperture

machine-detector interface

synchrotron radiation

superconducting RF acceleration

collimation

e-cloud

cryogenics

vacuum system

high field magnet

…and more!
Overview and status of the Future Circular Collider Study

M. Benedikt, F. Zimmermann

gratefully acknowledging input from FCC coordination group,
global FCC design study team and all other contributors

LHC
SPS
FCC
HE-LHC
International FCC collaboration with CERN as host lab to study:

- ~100 km tunnel infrastructure in Geneva area, linked to CERN
- $e^+e^-$ collider (FCC-ee), potential first step
- $pp$-collider (FCC-hh) long-term goal, defining infrastructure requirements
- HE-LHC with FCC-hh technology
- Ions and lepton-hadron options with hadron colliders

$\sim 16 \ T \Rightarrow 100 \ TeV \ pp \ in \ 100 \ km \ technology$
FCC-ee:
• ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass) ($m_Z$, $m_W$, $m_{\text{top}}$, $\sin^2 \theta_w^{\text{eff}}$, $R_b$, $\alpha_{\text{QED}}(m_Z)$, $\alpha_s(m_Z m_W m_{\tau})$, Higgs and top quark couplings)
• Exploring 10 - 100 TeV energy scale via couplings with precision measurements
  ➢ Machine design for highest luminosities at $Z$, $WW$, $ZH$ and $t\bar{t}$ working points

FCC-hh:
• Highest center of mass energy for direct production up to 20 - 30 TeV
• Huge rates for single and multiple production of SM bosons ($H, W, Z$) and quarks
  ➢ Machine design for ~100 TeV c.m. energy & int. luminosity ~20ab$^{-1}$ in 25 years

HE-LHC:
• Doubling LHC collision energy with FCC-hh 16 T magnet technology
• c.m. energy ~ 27 TeV = 14 TeV x 16 T/8.33T, target luminosity ≥ 4 x HL-LHC
**CDR Study Time Line (from 2014)**

<table>
<thead>
<tr>
<th>Year</th>
<th>Q1</th>
<th>Q2</th>
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<th>Q1</th>
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**2014**
- **Q4**: Study plan, scope definition
- **Q1**: Explore options

**2015**
- **Q4**: Conceptual study of baseline
- **Q1**: Develop baseline
- **Q2**: Detailed studies

**2016**
- **Q4**: FCC Week 2016
- **Q1**: Progress review

**2017**
- **Q4**: FCC Week 17 & Review
- **Q1**: Cost model, LHC results
- **Q2**: Study re-scoping?

**2018**
- **Q4**: FCC Week 2018
- **Q1**: Elaboration, consolidation
- **Q2**: Contents of CDR
- **Q3**: Report
- **Q4**: CDR ready
Status of global FCC Collaboration

136 Institutes
32 Companies
34 Countries

EC H2020
European Union Horizon 2020 program:

- 3 MEURO co-funding
- Started June 2015, ends in Dec 2019
- 15 European beneficiaries & KEK & associated FNAL, BNL, LBL, NHFML

Covers FCC-hh key work packages:

- Optics design (arc & IR)
- Cryogenic beam vacuum system design including beam tests at ANKA
- 16 T dipole design, construction folder for demonstrator magnets
Study Documentation:

4 CDR volumes submitted to EPJ in December 2018.

- FCC Physics Opportunities
- FCC-ee
- FCC-hh
- HE-LHC


CDR presentation during welcome event this evening.

Paper copies can be requested at [http://get-fcc-cdr.web.cern.ch](http://get-fcc-cdr.web.cern.ch)
More than 1350 contributors from 350 institutes, a truly global collaboration and effort as suggested by the EPPSU 2013.

Study Documentation:

- 4 CDR volumes submitted to EPJ in December 2018.
- FCC Physics Opportunities
- FCC-ee
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- Preprints available since 15 January 2019 [http://fcc-cdr.web.cern.ch/]

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Comprehensive cost-effective program maximizing physics opportunities

- **Stage 1:** FCC-ee (Z, W, H, tt) as first generation Higgs factory, EW and top factory at highest luminosities.
- **Stage 2:** FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options.
Comprehensive cost-effective program maximizing physics opportunities

- **Stage 1**: FCC-ee (Z, W, H, tt) as first generation Higgs factory, EW and top factory at highest luminosities.
- **Stage 2**: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options.

**Complementary physics**
- Integrating an ambitious high-field magnet R&D program
- Common civil engineering and technical infrastructures
- Building on and reusing CERN’s existing infrastructure.
- FCC integrated project plan is fully integrated with HL-LHC exploitation and provides for seamless continuation of HEP in Europe.
Implementation studies

• Total construction duration 7 years
• First sectors ready after 4.5 years

Additional 200 MW available for FCC at each of the three 400 kV sources from European grid


- Two main IPs in A, G for both machines.
- Common footprint except around IPs.
- FCC-ee asymmetric IR layout to limit synchrotron radiation.

![Diagram of FCC-ee and FCC-hh layouts](image)
Tunnel integration in arcs

FCC-ee

FCC-hh

5.5 m inner diameter
FCC-ee reaches highest luminosities & energies by combining ingredients and well-proven concepts of several recent colliders:

B-factories: KEKB & PEP-II: double-ring lepton colliders, high beam currents, top-up injection, positron source
DAFNE: crab waist, double ring
Super B-fact., S-KEKB: low $\beta_y$
LEP: high energy, SR effects
VEPP-4M, LEP: precision E calibration
KEKB: HERA, LEP, RHIC: spin gymnastics
In the case of FCC-ee, the luminosity scales by about $E^{-3.6}$, which is slightly better than the scaling by the SR power.
Aim at ~one order of magnitude performance increase in both energy and luminosity w.r.t LHC

100+ TeV cm collision energy (vs 14 TeV for LHC)

20 ab⁻¹ per experiment collected over 25 years of operation time (vs 3 ab⁻¹ for LHC).

Similar performance increase as from Tevatron to LHC.

Key technology: High-field magnets

From LHC technology
8.3 T NbTi

via HL-LHC technology
11 T Nb₃Sn

EuroCirCol, Chart, US MDP

to 16 T Nb₃Sn
FCC integrated project technical schedule

FCCW 2019, 24 June 2019, Brussels

Michael Benedikt

Future Circular Collider Study

[Diagram showing the schedule with phases such as project preparation & administrative processes, geological investigations, detector R&D and concept development, superconducting wire and high-field magnet R&D, etc., and timelines for 15 years operation and ~25 years operation.]
FCC integrated project plan is fully integrated with HL-LHC exploitation
• provides for seamless further continuation of HEP in Europe.
## Technical schedule

| year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 |
|------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| LHC  |   | Run 3 |   | Run 4 | Run 5 | Run 6 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Project management | Funding & governance strategy | premissions |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| tunnel & technical infrastructure | geological investigation technical design | construction |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| FCC-ee | accelerator technical design | detector R&D concept development | detector construction commissioning | detector construction commissioning | FCC-ee operation | Z | WW | Zh | tt |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| high field magnet | wire & magnet R&D | model magnets, prototypes, preserves | series production of dipoles |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| FCC-hh | accelerator technical design | detector R&D, technical design | accelerator construction commissioning | detector construction commissioning | FCC-hh operation |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |

*Notes:*
- FCC-ee: FCC-ee operation
- FCC-hh: FCC-hh operation
Construction cost phase1 (FCC-ee) is 11,6 BCHF
- 5,4 BCHF for civil engineering (47%)
- 2,2 BCHF for technical infrastructure (19%)
- 4,0 BCHF accelerator and injector (34%)
Construction cost phase 1 (FCC-ee) is 11,6 BCHF
- 5,4 BCHF for civil engineering (47%)
- 2,2 BCHF for technical infrastructure (19%)
- 4,0 BCHF accelerator and injector (34%)

Construction cost phase 2 (FCC-hh) is 17,0 BCHF.
- 13,6 BCHF accelerator and injector (57%)
  - Major part for 4,700 Nb$_3$Sn 16 T main dipole magnets, totalling 9,4 BCHF, targeting 2 MCHF/magnet.
- CE and TI from FCC-ee re-used, 0,6 BCHF for adaptation
- 2,8 BCHF for additional TI, driven by cryogenics
Construction cost **phase 1 (FCC-ee)** is 11,6 BCHF
- 5,4 BCHF for civil engineering (47%)
- 2,2 BCHF for technical infrastructure (19%)
- 4,0 BCHF accelerator and injector (34%)

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- CE and TI from FCC-ee re-used, 0,6 BCHF for adaptation
- 2,8 BCHF for additional TI, driven by cryogenics

(Cost FCC-hh stand alone would be 24,0 BCHF.)
Future Circular Collider Study
Michael Benedikt
FCCW 2019, 24 June 2019, Brussels

FCC work with host states

General secretariat of the region Auvergne-Rhône-Alpes and notified body “Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement”

Working group with representatives of federation, canton and state of Geneva and representation of Switzerland at the international organisations and consultancy companies
Administrative processes for project preparatory phase developed.

Working group with representatives of federation, canton and state of Geneva and representation of Switzerland at the international organisations and consultancy companies

General secretariat of the region Auvergne-Rhône-Alpes and notified body “Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement”
Administrative processes for project preparatory phase developed.

Requirements for urbanistic, environmental, economic impact, land acquisition and construction permit related processes defined.
Administrative processes for project preparatory phase developed.
Requirements for urbanistic, environmental, economic impact, land acquisition and construction permit related processes defined.
Common review of tunnel and surface site placement ongoing.

General secretariat of the region Auvergne-Rhône-Alpes and notified body “Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement”

Working group with representatives of federation, canton and state of Geneva and representation of Switzerland at the international organisations and consultancy companies.

FCC work with host states
Next steps 2019 - 2020

• Iteration of tunnel and surface structures layout and implementation with host states.

• Adaptation of CE, machine designs, etc. according to implementation optimisation.

• Following Integral Project proposal, presently focus on FCC-ee as potential first step (awaiting strategy recommendation).
  • Review and more detailed design for FCC-ee injector concept
  • Detailed design of technical infrastructure for FCC-ee

• Preparation of EU H2020 DS project (INFRADEV call November 2019), focused on preparations for infrastructure implementation.
backups
Conclusions from HE LHC studies

Performance
- 26 - 27 TeV cm collision energy
- ~10 ab⁻¹ per experiment collected over 20 years
- Key technology: high-field magnets FCC-hh

Very challenging option due to existing boundary conditions:
- Machine integration due to space limitations (tunnel cross section, straight section length, caverns) of existing underground infrastructures
- Compatibility with safety requirements
- Increased cryogenics requirements
- Injector requirements

LHC tunnel diameter 3.8 m

8 additional 1.8 K refrigeration units
8 new higher-power 4.5 K cryoplants
4 IP: layout with perfect period-4

- Equal spacing between IPs:
  - Otherwise more than 4 bunches couple together.
- Complete period 4 periodicity, including the RF (at least at ttbar):
  - For better beam-beam, dynamic aperture, etc.
- RF must be at the midpoint of 2 IPs:
  - For better dynamic aperture and beam cross over at the RF (ttbar).
- Thus the tunnel geometry deviates from the CDR and the current FCC-hh.
At least two issues (4 IP and final quads) have been addressed to go to the next step of FCC-ee beyond the CDR.

4 IP scheme looks acceptable so far: See D. Shatilov’s presentation on the expected beam-beam performance and the luminosity.

4 IP will have a huge impact on the layout, FCC-hh design, many components such as RF, injection, beam abort, polarimeter, etc.

Attention is necessary on the robustness of the final quads and solenoids against beam losses.

Detailed design studies on various components must be done, after the above issues are fixed. Some items which are not much affected by the number of IP’s can be started now.