Civil engineering, Infrastructure and Operation –
CDR status and plan

Volker Mertens, CERN

gratefully acknowledging the contributions of
the FCC Infrastructure and Operation WG,
all FCC study teams and
the collaborating partners (list in annex)

FCC Week 2017
Berlin, 29 May 2017
Infrastructure and Operation topics

- Geology & civil engineering
- Integration
- Electricity distribution
- Cryogenics
- Cooling & ventilation
- Transport & handling
- Installation
- Planning & coordination
- Survey & alignment
- Controls
- Computing
- Communications & networks

- General safety
- Access control
- Radiation protection
- Environmental protection
- Power/energy consumption
- Energy efficiency
- Operation & maintenance concepts
- Availability & reliability
- ...


Only presenting material with substantial evolution since Rome.
Infrastructure and Operation related programme

Overview (V. Mertens, 25’+5’)

Monday

Summary of IO related parallel sessions and posters (J. Osborne, 15’)

- civil engineering
- electricity
- ventilation
- logistics
- transport

Ch. Prasse/FIML

All sessions as input for review

D. Delikaris

- cryogenics

Ll. Miralles

- operation
- reliability
- safety

Poster list in annex.
Conceptual Design Report

1 - PHYSICS

2 Hadron Collider Summary

3 - Hadron Collider Comprehensive

- Accelerator
- Injectors
- Technologies
- Infrastructure
- Operation
- Experiment
- eh

4 Lepton Collider Summary

5 - Lepton Collider Comprehensive

- Accelerator
- Injectors
- Technologies
- Infrastructure
- Operation
- Experiment

6 High Energy LHC Summary

7 - High Energy LHC Comprehensive

- Accelerator
- Injectors
- Infrastructure

Refs to FCC-hh, HL-LHC, LHeC

Concise description of main concepts and key points

- Documents the performed studies
- Material to support the baseline concepts
- A basis for the next phase
- Highlights remaining work
- Lists alternatives
- ...

Physics opportunities across all scenarios
New features include:
Overall length 97.75 km
Injections upstream side experiments
Larger distances A-B, L-A (F-G, G-H) (altered footprint choices)

Taking this layout as fixed (for CDR preparation)

A. Langner, D. Schulte

J. Gutleber
New footprint baseline

Thursday 8:30: Civil engineering optimisation and design development (J. L. Stanyard)
Need ~ 1 km straight sections for collimation. Slope constraints for He flow and transport. Normal conducting magnets preferred.
## Main implementation characteristics

<table>
<thead>
<tr>
<th>FCC tunnel</th>
<th>2017 values</th>
<th>2016 values**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum of depths at all points [m]</td>
<td>2449*)</td>
<td>3211</td>
</tr>
<tr>
<td>Deepest shaft [m]</td>
<td>476 (F)</td>
<td>392 (F)</td>
</tr>
<tr>
<td>Limestone [%]</td>
<td>5.5</td>
<td>13.5</td>
</tr>
<tr>
<td>Moraine [%]</td>
<td>4.7</td>
<td>-</td>
</tr>
</tbody>
</table>

*) Based on a „shallow“ option, crossing Lake Geneva in moraine (positive indications on feasibility and cost efficiency; water exchange in layers surrounding the tunnel (radiation impact) yet to be studied.

**) Former 100 km intersecting version („option 2a“)

<table>
<thead>
<tr>
<th>Beam transfer [km]</th>
<th>SC part (6 T)</th>
<th>NC part (2 T)</th>
<th>Straight</th>
<th>Total length</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC_1 → FCC_B</td>
<td>2.4</td>
<td>1.4</td>
<td>0.9</td>
<td>4.7</td>
</tr>
<tr>
<td>LHC_8 → FCC_L</td>
<td>1.1</td>
<td>2.4</td>
<td>3.6</td>
<td>7.1</td>
</tr>
<tr>
<td>scSPS_3 → FCC_B</td>
<td>-</td>
<td>1.3</td>
<td>3.0</td>
<td>4.3</td>
</tr>
<tr>
<td>scSPS_5 → FCC_L</td>
<td>-</td>
<td>2.5</td>
<td>2.8</td>
<td>5.3</td>
</tr>
</tbody>
</table>
It conceptually works (limestone, shaft depths, surface locations, beam transfer).

Explore potential from inclined access tunnels, of displacing or suppressing specific shafts, or to use different techniques for lots to be delivered at different times.

Need to collect more information
- on geological conditions (extend data area, in-situ exploration);
- up-to-date status of areas (constructed, protected) and their evolution;
- legal requirements and constraints (proximity, noise, integration);
- cost of elements (tunnels, shafts, roads, ...).

Many constraints in a densely populated area, with interesting geology and topology.
Many design criteria (partly contradicting) – looking for „optimum“.
Geological design tool helps enormously – still time-intensive process.

Great interest to have more automated tool which optimises footprint to chosen criteria.

Still much work for civil engineering, to elaborate options and methods and check details.
"Generic layout", modelled after LHC (partly scaled). Detailed requirements to be elaborated.
Overall schematic 3D view

Single tunnel model updated with all main features known up to now (w/o FCC-ee enlargements)

Colour code:
- Machine tunnels + bypass galleries
- Detector caverns + shafts
- Service caverns + access shafts
- Electrical alcoves
- Connection tunnels

A. Navascues Cornago
Underground structures

Detector service cavern 100x20x15 m
Machine service cavern 60x20x15 m
Access shafts (here w magnet lowering) 18 m

Rock pillar between caverns 45 m
Technical + access galleries

Detector cavern 70x30(35)x35 m
Detector shafts 15, 10 m

First basic + very preliminary design using new dimensions from MDI WG (w/o detailed radioprotection treatment, access optimisation, detailed design over several floors)

red: part required for FCC-ee

F. Valchкова-Georgieva
Tunnel cross section, FCC-hh

Magnets OD 1480 m (all included)
QRL OD 1200 mm (all included)
Tunnel cross section, FCC-ee

F. Valchkova-Georgieva
Magnet model: A. Milanese
No civil engineering
Same beam height as LHC
→ Magnets OD ca. 1200 m (all included) – study in //
QRL (sector shorter than at FCC) OD ca. 850 mm (all included)
Re-routing of services above the cryogenics service module not yet studied
Magnet suspended during „handover“ from transport vehicle to installation transfer table
Shafts

Single access shaft per point
12 m diameter
double 3 t elevator
all requested service elements
Shafts (allowing magnet lowering)

18 m elliptical or round (whichever will be more cost-effective)

As many as indicated by logistics model, transport capabilities and installation schedule (1-4).
Arc ventilation
(working hypothesis for safety concept)

Abnormal conditions considered; redundant AHUs (also for smoke/He extraction)

Fresh air duct

Compartment with automated fire doors every 440 m

Smoke/He extraction

Air recycling

Longitudinal compartments with individual control of ventilation and smoke/He extraction

Ref to: Security and Workplace Safety Concept for the Construction, Installation and Operation of the XFEL Research Facility, STUVA e.V., Cologne
### General input data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section area</td>
<td>17.7 m²</td>
</tr>
<tr>
<td>Max. sector length</td>
<td>10.5 km</td>
</tr>
<tr>
<td>Maximum Temperature (running conditions)</td>
<td>32 °C (tbc)</td>
</tr>
<tr>
<td>Maximum dew point</td>
<td>12 °C (tbc)</td>
</tr>
</tbody>
</table>

### Compartment input data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of compartments</td>
<td>24</td>
</tr>
<tr>
<td>Compartment length</td>
<td>440 m</td>
</tr>
<tr>
<td>Volume Compartment</td>
<td>7788 m³</td>
</tr>
</tbody>
</table>

### Ventilation figures

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal air flow</td>
<td>2 x 25,000 m³/h</td>
</tr>
<tr>
<td>Flushing air flow</td>
<td>2 x 50,000 m³/h</td>
</tr>
<tr>
<td>Air supply points per compartment</td>
<td>4</td>
</tr>
<tr>
<td>Air flow per supply point (normal)</td>
<td>520 m³/h</td>
</tr>
<tr>
<td>Air flow per supply point (flushing)</td>
<td>1041 m³/h</td>
</tr>
<tr>
<td>Time for complete air renewal</td>
<td>1.8 h</td>
</tr>
<tr>
<td>Maximum air speed</td>
<td>0.78 m/s</td>
</tr>
<tr>
<td>Cooling capacity in normal operation, ΔT=15K</td>
<td>250 kW</td>
</tr>
<tr>
<td>Estimated head loss (supply in flushing)</td>
<td>3300 Pa</td>
</tr>
</tbody>
</table>

**Evolution of la température dans le sous-sol dans les conditions du Plateau suisse. Source S. Catin CREGE**

**Peak tunnel wall temperature (Pre-Alps)**

Estimated heat load to tunnel air (min. 101, ave 177., max. 239 kW/sector) can be cooled by air flow w/o additional cooling. Tunnel wall temperature needs further study (sector average < peak).
Safety accompanies development

- Conceptual Safety Study
  - Hazard Register
  - Standard best practice – directives, standards, guidelines
  - Identify cases for risk assessment
  - Proposal of conceptual approaches for risk-control

- Technical Safety Study
  - Specific Risk Assessments
    - Prescriptive solutions: strictly rule-based
    - Performance-based: tailor-made solutions to meet safety objectives
  - Proposal of detailed technical solutions for risk-control

Thursday, 16:15: FCC safety strategy for the CDR (Th. Otto)
Hazard register

Systematic, ordered collection
Technology
- SC magnets
- Cryogenics
- ...
- Location in the facility
  - Surface
  - Tunnel
  - Cavern
  - ...
- Project Phase
  - Installation
  - Operation
  - Shutdown
  - ...

Location
Technology
Phase
Item / Process
Activity
Equipment
Substance
Hazard
Hazard
Hazard
Other safety studies

Proposing performance-based analysis, following SFPE guideline - Society of Fire Protection Engineering (not only for fire risks)

Fire safety engineering collaboration

Active on:
WP1 – fire statistics
→ fire losses and cost
WP2 – fire detection and extinguishing
→ fire response (human and robotic)
WP3 – fire propagation and its limitation
→ cable fire test @Lund
→ modeling cable tray fires
WP4 – evacuation
→ mono-dimensional evacuation model
Radioprotection matters

Radiation hazards lists (prompt stray radiation, activated air, X-rays ...)

High-radiation areas

FCC-hh arc residual dose rate

FCC-hh detector residual dose rate

Ultimate, after 5 runs (17.5 ab⁻¹)
1 mSv/h after 1 wk
High levels in forward HC

Thursday, 16:40: Radioprotection matters (M. Widorski)
Radiation levels in FCC tunnel and alcoves (R2E)

**FCC FLUKA model:**
- **Full arc cell**: 12 dipoles + 2 quadrupoles
- Latest layout of **tunnel & alcove** infrastructure
- Up-to-date tentative **gas-density profile**
- Latest design of the **main dipole**
- Source: Beam-gas interactions @ 50 TeV/c
- Full particle transport

**Main achievements:**
- **Strong interaction** across many areas of expertise
- **Design**: FLUKA simulation used for finalising the design of the tunnel and alcove infrastructure.
- **R2E**: assessment of the radiation levels in **critical areas** for electronics:
  - **Dose** (long term effects): below the magnet (power converter) factor ~200 LHC
  - **High Energy Hadrons** (Single Event Effects):
    - Tunnel: below the magnet (power converter) factor ~500 LHC
    - **Alcove**: fluence factor ~3-4 LHC RE areas
- **Qualification requirements** already beyond current availability

Thursday, 11:10: FLUKA Monte-Carlo modelling of the FCC arc cell: radiation environment and energy deposition due to beam-gas interactions (A. Infantino)
Supply and distribution of electrical energy

- Power estimates are being updated and appear not to exceed the available power.
- "FCC service level" to be defined (full availability, degraded modes, redundancy).
- Local energy buffers could cover short (100 ms) network interruptions and increase availability.

Thursday, 8:50: Supply and distribution of electrical energy (D. Bozzini)
Supply and distribution of electrical energy

Nominal supply configuration

400 kV

- Outdoor
- Surface buildings
- Underground

- All networks supplied by transmission network.
- All points have at least two transmission sources.

Voltage drop along arcs and need for alcoves

Long arc electrical distribution scheme

Other design principles:
- Redundancy at all levels and on each equipment
- Limit underground installation of active components
Each 1.5 km, housing electrical MV/LV equipment, HVAC, machine equipment (PCs); dimensioned as LHC alcoves + 20 %
New collaboration with Fraunhofer Institute for material flow and logistics (FIML, Dortmund)

on several work packages:

1) Design and evaluation of global supply chains for large and heavy components.
2) Logistics concept for storage, assembly, testing and handling of cryomagnets.
3) Vehicle concept for underground transportation and handling of cryomagnets.

1) Supply chain – investigating and assessing ...
   • Transport options (seaship, barge/truck, ...)
   • Constraints (road size, maximum weight, road blockage)
   • Transport enclosures (non-standard containers, special handling equipment)
   • Maximum tolerable g-forces during transport and loading, maximum tilt angles

3) Vehicle
   • Rail vs wheel-based
   • Track guidance (optical/wire/marker) vs sensor based free navigation
   • Ideally covering/compatible with other transport needs (other equipment, personnel, remote reconnaissance/interventions)
2) Assembly concept

- Assess benefits and drawbacks of various scenarios

- Study required number of assembly and testing sites (amount of personnel, traffic, transport means, quality assurance, ...)

**SUPPLIER**

- Completely Built Up and Tested at CERN (ALTERNATIVE IV)

- Semi Knocked Down at Supplier Site (ALTERNATIVE IIa+b)

- Fully Built Up at Supplier Site (ALTERNATIVE IIa+b)

- Fully Built Up and Tested at Supplier Site (ALTERNATIVE I)

**CERN**

- Cold-mass
- Cryo-stat
- Cryo-Unit
- Cold-mass
- Cryo-Unit
- Cryo-Unit
- Cold-mass
- Cryo-Unit
- Cryo-Unit
- Cold-mass
- Cryo-Unit
- Cryo-Unit
Good progress across the board - globally well on track to conclude for CDR.
Timeline shown in Rome:

Baseline layout confirmed (FCC-hh: 10 plants, 6 sites).
Magnet operating temperature confirmed (1.9 K).
Refinement, simplications, dimensioning, ... (for FCC-hh and FCC-ee).

Thursday:
13:30: Towards a conceptual design for FCC cryogenics (L. Tavian)
14:00: Cryogenic refrigeration w neon-helium mixtures for the FCC-hh (S. Klöppel/TU Dresden)
14:20: Technical specifications for industry studies on the FCC cryogenic system (F. Millet/CEA Grenoble)
14:40: Cryogenic distribution for FCC-hh (P. Duda/Wroclaw UT)
Study of cool-down using the Ne-He turbo-Brayton refrigeration cycle (suppression of the LN$_2$ cool-down unit and associated huge storage and delivery logistics)

Cool-down time goes from 10 to 15 days-

Possibility to couple adjacent sectors
Cryogenics storage architecture

- GHe storage (250 m³, 20 bar)
- Quench buffer (250 m³, 20 bar)
- GHe storage (250 m³, 50 bar)
- Ne-He storage (250 m³, 50 bar)
- GNe cylinders (200 bar)
- LHe storage (120 m³)
- LHe boil-off liquefier (150 to 300 l/h)
- LN2 storage (50 m³)

He storage capacity:
- GHe: 190 t
- LHe: 650 t
- Total: 840 t
Study of the cold-mass cooling below 2 K. Definition of the cryogenic requirements (bayonet HX, free cross-section area, ...).
Update of the beam-screen cooling with SR absorbers at magnet interconnect.
Completion of the cryo-distribution study based on INVAR technology.
Main cryogenic transfer lines

Re-check/refinement of dimensioning; addition of pipes.
Completion of cryo-distribution study based on INVAR technology.
Initial operation schedule

- 5-yr cycles
- 18 m shutdown
- 1 m yearly stop
- 1 m commissioning
- 10 m operation

Total of 162 m of physics (p + ions)
6 x 1 wk MD + 1 wk stop per 5-yr cycle

Comparison of turn-around times

<table>
<thead>
<tr>
<th>Phase</th>
<th>FCC th.</th>
<th>LHC th.</th>
<th>LHC 2015</th>
<th>LHC 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setup</td>
<td>10</td>
<td>10</td>
<td>222.7</td>
<td>158.5</td>
</tr>
<tr>
<td>Injection</td>
<td>40°)</td>
<td>38</td>
<td>58.1</td>
<td>51.6</td>
</tr>
<tr>
<td>Pre-ramp</td>
<td>5</td>
<td>4</td>
<td>5.4</td>
<td>4.2</td>
</tr>
<tr>
<td>Ramp</td>
<td>20</td>
<td>20</td>
<td>20.4</td>
<td>20.4</td>
</tr>
<tr>
<td>Flattop</td>
<td>5</td>
<td>5</td>
<td>4.8</td>
<td>4.2</td>
</tr>
<tr>
<td>Squeeze</td>
<td>3</td>
<td>18</td>
<td>13.1</td>
<td>18.0</td>
</tr>
<tr>
<td>Adjust</td>
<td>5</td>
<td>10</td>
<td>12.5</td>
<td>14.1</td>
</tr>
<tr>
<td>Ramp down</td>
<td>20</td>
<td>31</td>
<td>41.0</td>
<td>41.0</td>
</tr>
<tr>
<td>Total</td>
<td>108 min (1.8 h)</td>
<td>132 min (2.2 h)</td>
<td>378 min (6.3 h)</td>
<td>312 min (5.2 h)</td>
</tr>
</tbody>
</table>

Stops need radiation cool-down and recommissioning \( \rightarrow \) reduce ?
Injector chain and detectors must sustain long maintenance-free periods and radiation levels.

Long setup times mainly due to system failures \( \rightarrow \) FCC to be designed for utmost availability (fault tolerance or quick repair between runs).
Injection time depends on injector chain availability and beam quality control.

Thursday 15:30: FCC-hh operation schedule and turnaround (A. Niemi/Tampere UT)
### Availability considerations

**Demonstrate that FCC luminosity goals are achievable**

**Approach:**
- Monte-Carlo model of accelerator operation (cycles, injections, luminosity production)
- Fault-tree model of system reliability (failures rates, repair times)

(benchmarked on LHC 2015 and 2016 results)

**Unavailability budget** [%]

If FCC will exhibit same overall LHC-like availability, production targets can be achieved. High availability essential; to be „designed in“ from early phases.

Redundance/fault tolerance, „maintenance-free“, limit radiation effects, advanced diagnostics/anticipate failures

**Sensitivity analysis**

**Effect of injector chain**

**Comparison of injector options**

Thursday 15:50: FCC availability studies (A. Apollonio)
„Infrastructure and operation“ team continues to be very active.

Major steps made towards CDR in key areas,
   with safety, performance, cost efficiency, impact, reliability aspects in mind.

Many topics to be elaborated further – iterative process.
Some of the assumptions need still to be validated/consolidated.
Certain „IO“ related matters need still to be addressed.

Will produce TO DO list of items to have for CDR after FCC Week.

FCC exiting in terms of size, logistics, system demands, reliability, ...
Advancement in methods and technologies is expected to help in many ways.

Maintaining the intensive effort will keep us well on track to round off in 2018.
THANK YOU FOR YOUR ATTENTION

LOOKING FORWARD TO
INTERESTING PRESENTATIONS
AND STIMULATING DISCUSSIONS
Annex
Cryogenics
• **TU Wroclaw** – Design pressure impact of the FCC-hh cryogenic distribution system and superconducting magnet cryostats on the heat inleaks at different temperature levels
• **CEA Grenoble** – New architectures and technologies for innovative helium refrigeration above 4.5 K and in superfluid helium at 1.8 K and 1.6 K including magnetic refrigeration
• **TU Dresden** – Ne-He cycle producing large refrigeration capacity above 40 K for the cooling of the FCC beam screens, thermal shields and HTS current leads

Safety (fire safety engineering, FCC-FSEC)
• **ESS** – Ignition probabilities of materials and equipment; intervention procedures for classified accelerator areas
• **FNAL** – Tunnel fire dynamics and egress studies based on a broad range of different US underground installations
• **DESY**
• **JRC Jülich Research Centre / University of Wuppertal** – Optimisation of Computational Fluid Dynamics tools for fire safety related calculations
• **Lund University** – Fire and egress scenarios typical for accelerator facilities and their special geometries, including fire testing and virtual reality
• **MAX IV** – Knowledge transfer on fire statistics for physics laboratories
Collaborations, II

Reliability, availability
- TU Tampere – RAMS design methods and tools to be applied to particle accelerators
- TU Delft – RAMS modeling of LHC cryogenic system
- Univ. Stuttgart – Reliability engineering training

Transport & Logistics
- FIML Dortmund – Transport and logistics modeling and consulting

Plus direct or indirect support from industrial and informal support from institutional partners (referenced in the respective presentations).
Integration:
• 3D study and integration of FCC-hh underground structures (F. Valchkova-Georgieva)

Survey, alignment:
• Application of the wire offset measurements technique in the FCC alignment (N. Ibarrola Subiza, D. Missiaen)

Electrical distribution:
• Power transmission network studies (M. Mylona, D. Bozzini)

Transport, handling:
• Lift layout (D. Lafarge, I. Rühl, Schindler SA)
• Optimisation of equipment design for handling and maintenance in radiation areas (K. Kershaw)
Cryogenics:
• Impact of large beam-induced heat loads on the transient operation of the beam screens and cryogenic plants of the Future Circular Collider (H. R. Correia Rodrigues, L. Tavian)
• Adaption of the LHC Cold Mass Cooling System to the requirements of the Future Circular Collider (C. Kotnig, G. Brenn / TU Graz, L. Tavian)

Reliability:
• Software for reliability modelling (Ramentor Oy)
• Kicker pulse generator anomaly detection for realiability improvements through advanced machine learning (P. van Trappen)

Safety:
• FCC Fire safety engineering collaboration (M. Plagge et al.)
• FCC performance-based safety design (S. La Mendola, S. Baird, A. Henriques)