LHC Upgrades and Future Circular Colliders

M. Benedikt

gratefully acknowledging input from HL-LHC project team, FCC coordination group global design study team and many other contributors.

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http://cern.ch/fcc

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Outline

• HL-LHC motivation and goals
• HL-LHC building blocks
• FCC motivation and scope
  • Parameters
  • Design Status
  • Technologies
Goal of High Luminosity LHC (HL-LHC)

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

Prepare machine for operation beyond 2025 and up to 2035

Devise beam parameters and operation scenarios for:

1. Enabling a total integrated luminosity of $3000 \text{ fb}^{-1}$
2. Imposing an integrated luminosity of $250 \text{ fb}^{-1}$ per year
3. Design operation for $\mu = 140$ ($\Rightarrow$ peak luminosity $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)

- Operation with levelled luminosity! ($\beta^*$, crossing angle & crab cavity)
- 10x the luminosity reach of first 10 years of LHC operation!!
Recap: Luminosity

colliding bunches:

\[ L = \frac{n_b \times N_1 \times N_2 \times f_{\text{rev}}}{A} \]

\[ A = 4 \times x \times y \]

with:

\[ = \sqrt{\times} \]

is determined by the magnet arrangement & powering

\[ = \frac{n}{\varepsilon_n} \]

\( \varepsilon_n \) is determined by the injector chain

goal:

\( L_{\text{peak}} > 2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1} \) high bunch intensity and many bunches

small \( \beta \) at IP and high collision energy
LHC upgrade goals: performance optimization

- Luminosity recipe (round beams):

\[ L = \frac{n_b \times N_1 \times N_2 \times f_{\text{rev}}}{4 \times \beta^* \times n} \times F(f, \beta^*, e, s) \]

- maximize bunch intensities \((1.1 \rightarrow 2.2 \times 10^{11})\) ⇒ Injector complex

- minimize the beam emittance \((3.75 \rightarrow 2.5 \, \mu m)\)  

- minimize beam size \((\beta^* 0.55 \rightarrow 0.15 \, m)\); ⇒ New triplets

- compensate for ‘F’ geometry crossing; ⇒ Crab Cavities

- improve machine ‘Efficiency’ ⇒ minimize number of unscheduled beam aborts
LHC Limitations and HL-LHC challenges

- **Insertion quadrupole magnets lifetime and aperture:**
  - New insertion magnets and low-β with increased aperture

- **Geometric Reduction Factor:**
  - SC Crab Cavities
  - New technology and first time for a hadron storage ring!

- **Performance Optimization: Pileup density:**
  - Lumi levelling
  - Requires virtual luminosity >> target levelled luminosity

- **Beam power & losses:**
  - Addt’l collimators in dispersion suppressors

- **Machine efficiency and availability:**
  - # R2E: removal of all electronics from tunnel region
  - # e-cloud: beam scrubbing (conditioning of surface), etc

- **Technical bottle necks (e.g. cryogenics)**

- **Civil Engineering (underground)**
LHC technical bottleneck: Radiation damage to triplet magnets at 300 fb⁻¹

Peak dose longitudinal profile

7+7 TeV proton interactions
IT quadrupoles
MCBX-1
MCBX-2
MQSX
MCTX nested in MCBX-3
MCSOX

Cold bore insulation ≈ 35 MGy

Q2 27 MGy

MCBX3 20 MGy
HL-LHC technical bottleneck: Radiation damage to triplet magnets

Need to replace existing triplet magnets with radiation hard system (shielding!) such that the new magnet coils receive a similar radiation dose @ 10 times higher integrated luminosity 3000 fb\(^{-1}\)! ➔ Shielding!

➔ Requires larger aperture!

➔ New magnet technology

➔ LHC: 70mm at 210 T/m ➔ HL@ 150mm diameter 140 T/m

➔ LHC: 8T peak field at coils ➔ HL> 12T field at coils (Nb\(_3\)Sn)!
HL-LHC Challenges: Crossing Angle

• **Insertion Layout:**

  Insertion Layout: ca. 130m → 150m

  ca. 50m

• **Parasitic bunch encounters:**

  Parasitic bunch encounters:
  Operation with ca. 2800 bunches @ 25ns spacing → approximately 30 unwanted collisions per Interaction Region (IR).

  Operation requires crossing angle prop. $1/\sqrt{\beta^*}$.
  → Factor 2 increase, 2 x 150 to 2 x 300 μrad)

• **Perturbations from long-range beam-beam interaction:**

  Perturbations from long-range beam-beam interaction:
  Efficient operation requires large beam separation at unwanted collision points.
  → Separation of 10 -12 σ → larger triplet apertures for HL-LHC!
HL-LHC Upgrade Ingredients: Crab Cavities

Geometric Luminosity Reduction Factor:
- Reduces the effect of geometrical reduction factor
- Independent for each IP

\[ F = \frac{1}{\sqrt{1 + \frac{c^2 z^2}{2 x^2}}} \]

- Challenging space constraints:
  \( \rightarrow \) requires novel compact cavity design
HL-LHC crab cavity designs

3 Advanced Design Studies with Different Coupler concepts

RF Dipole: Waveguide or waveguide-coax couplers

Double ¼-wave: Coaxial couplers with hook-type antenna

Present baseline: 4 cavity/cryomod

Successful tests in SPS
LHC Challenges: Beam Power

Unprecedented beam power:

- potential equipment damage in case of failures during operation
- In case of failure the beam must never reach sensitive equipment!

 Stored Beam power: HL-LHC > 500 MJ / beam
Collimation system upgrades

Completely new layouts
Novel materials.
IR1+IR5, per beam:
4 tertiary collimators
3 physics debris collimators
fixed masks

40 new collimators to be produced by LS3 in the present baseline!

Cleaning: DS coll. + 11T dipoles, 2 units per beam

Low-impedance, high robustness secondary collimators

Ion physics debris: DS collimation

S. Redaelli,
Chamonix 2016, 28-01-2016
Dispersion Suppressor collimators – 11 T Nb3Sn Dipole (LS2 -2018)

11 T Nb3Sn

6.18 m ($L_{CM}$)  5.3 m ($L_{mag}$)  2.27 m (collimator)  6.18 m ($L_{CM}$)
Implementation & Performance Projection:

- Peak luminosity
- Integrated luminosity

Run I
- Splices fixed
- Energy 6.5 TeV
- 25 fb\(^{-1}\)
- 0.75 \(10^{34}\) cm\(^{-2}\)s\(^{-1}\)
- 50 ns bunch high pile up \(\sim 40\)

Run II
- Injectors upgrade 11 T dipoles
- 50 ns bunch high pile up \(\sim 40\)

Run III
- New Low-\(\beta^*\) quads
- Crab Cavity Phase 1
- Detectors
- 300 fb\(^{-1}\)
- 5 \(10^{34}\) cm\(^{-2}\)s\(^{-1}\)
- levelled 25 ns bunch very high pile up \(\sim 140\)

Crab Cavity Phase 2
- Technical limits (in experiments, too)
- 1000 fb\(^{-1}\)
- 3000 fb\(^{-1}\)

Limit, Radiation & Damage of triplet magnets
The critical zones around IP1 and IP5

1. New triplet $\text{Nb}_3\text{Sn}$ required due to:
   - Radiation damage
   - Need for more aperture

2. We also need to modify a large part of the matching section e.g. Crab Cavities & D1, D2, Q4 & corrector

3. For collimation we also need to change the DS in the continuous cryostat:
   - 11T $\text{Nb}_3\text{Sn}$ dipole

More than 1.2 km of LHC!!

Plus technical infrastructure (e.g. Cryo and Powering)!!

Changing the triplet region is not enough for reaching the HL-LHC goal!
Luminosity profile: NOMINAL HL-LHC

After LS4, proton physics days increase from standard 160 days to 200 and after LS5 to 220
Energy frontier in the 21st century

- Very large circular hadron collider - only feasible approach to reach 100 TeV c.m. collision energy in coming decades
- Access to new particles (direct production) in few-TeV to 30 TeV mass range, far beyond LHC reach
- Much-increased rates for phenomena in sub-TeV mass range → much increased precision w.r.t. LHC

Hadron collider energy reach

\[ E \propto B_{dipole} \times \rho_{bending} \]

FCC-hh aims at O(10) higher performance (E, L) than LHC

LHC: factor ~4 in radius, factor ~2 in field → O(10) in \( E_{\text{cms}} \)
International FCC collaboration (CERN as host lab) to study:

- **pp-collider (FCC-hh)**
  - main emphasis, defining infrastructure requirements
  - \( \sim 16 \text{ T} \Rightarrow 100 \text{ TeV } pp \text{ in } 100 \text{ km} \)

- **80-100 km tunnel infrastructure** in Geneva area, site specific

- **\( e^+e^- \) collider (FCC-ee)**, as potential first step

- **\( p-e \) (FCC-he) option**, integration one IP, FCC-hh & ERL

- **HE-LHC** with FCC-hh technology
CepC/SppC study (CAS-IHEP) 100 km (new baseline!), $e^+e^-$ collisions $\sim$2028; $pp$ collisions $\sim$2042

Qinhuangdao (秦皇岛)

CepC, SppC

100 km

50 km

easy access
300 km east
from Beijing
3 h by car
1 h by train

Yifang Wang

"Chinese Toscana"
Must advance fast now to be ready for the period 2035 – 2040
Results phase 1: CDR published end 2018 for update European Strategy
Progress on site investigations

Alignment Profile

Geology Intersected by Shafts

Shaft Depths

Quaternary
Lake
Wiflysch
Molasse subalpine
Molasse
Limestone
Shaft
Alignment
• 90 – 100 km fits geological situation well
• LHC suitable as potential injector
• The 97.75 km version, intersecting LHC, is now being studied in more detail
FCC-hh injector studies

Injectors options:
- SPS $\rightarrow$ LHC $\rightarrow$ FCC
- SPS/SPS$_{\text{upgrade}}$ $\rightarrow$ FCC
- SPS $\rightarrow$ FCC booster $\rightarrow$ FCC

Current baseline:
- injection energy 3.3 TeV LHC

Alternative options:
- Injection around 1.3 – 1.4 TeV
- compatible with: SPS$_{\text{upgrade}}$, LHC, FCC booster
- SPS$_{\text{upgrade}}$ could be based on fast-cycling SC magnets, 6-7T, ~ 1T/s ramp
  - SC Magnet R&D program being launched (similar to SIS 300 parameters)
Common layouts for hh & ee

FCC-ee 1, FCC-ee 2, FCC-ee booster (FCC-hh footprint)

- 2 main IPs in A, G for both machines
- asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector

Lepton beams must cross over through the common RF to enter the IP from inside. Only a half of each ring is filled with bunches.

Max. separation of 3(4) rings is about 12 m: wider tunnel or two tunnels are necessary around the IPs, for ±1.2 km.
<table>
<thead>
<tr>
<th>parameter</th>
<th>FCC-hh</th>
<th>HE-LHC</th>
<th>(HL) LHC</th>
</tr>
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<tbody>
<tr>
<td>collision energy cms [TeV]</td>
<td>100</td>
<td>27</td>
<td>14</td>
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<tr>
<td>dipole field [T]</td>
<td>16</td>
<td>16</td>
<td>8.3</td>
</tr>
<tr>
<td>circumference [km]</td>
<td>100</td>
<td>27</td>
<td>27</td>
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<tr>
<td># IP</td>
<td>2 main &amp; 2</td>
<td>2 &amp; 2</td>
<td>2 &amp; 2</td>
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<tr>
<td>beam current [A]</td>
<td>0.5</td>
<td>1.27</td>
<td>(1.12) 0.58</td>
</tr>
<tr>
<td>bunch intensity [$10^{11}$]</td>
<td>1 (0.2)</td>
<td>1 (0.2)</td>
<td>2.5</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25 (5)</td>
<td>25 (5)</td>
<td>25 (5)</td>
</tr>
<tr>
<td>IP $\beta^*_x,y$ [m]</td>
<td>1.1</td>
<td>0.3</td>
<td>0.45</td>
</tr>
<tr>
<td>luminosity/IP [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>5</td>
<td>30</td>
<td>16</td>
</tr>
<tr>
<td>peak #events/bunch crossing</td>
<td>170</td>
<td>1020 (204)</td>
<td>460 (92)</td>
</tr>
<tr>
<td>stored energy/beam [GJ]</td>
<td>8.4</td>
<td>1.4</td>
<td>(0.7) 0.36</td>
</tr>
<tr>
<td>synchrotron rad. [W/m/beam]</td>
<td>30</td>
<td>4.1</td>
<td>(0.35) 0.18</td>
</tr>
</tbody>
</table>
pp/p-pbar in the \( L-E \) plane
phase 1: $\beta^*=1.1\,\text{m}$, $\xi_{\text{tot}}=0.01$, $t_{\text{ta}}=5\,\text{h}$, 250 fb$^{-1}$/year

phase 2: $\beta^*=0.3\,\text{m}$, $\xi_{\text{tot}}=0.03$, $t_{\text{ta}}=4\,\text{h}$, 1000 fb$^{-1}$/year

radiation damping: $\tau \sim 1\,\text{h}$

total synchrotron radiation power $\sim 5\,\text{MW}$.

for both phases:

beam current 0.5 A, unchanged!
Design of interaction region

- Distance from IP to first machine quadrupole \( L^* = 45 \) m.
- Allows integrated spectrometers and compensation dipoles (or fwd solenoids)
- Optics and magnet optimization for beam stay clear and collision debris.
  - Magnet (triplet) lifetime should be collider lifetime (from radiation damage).
Beam power & machine protection

Stored energy 8.4 GJ per beam
- Factor 25 higher than for LHC, equivalent to A380 (560 t) at nominal speed (850 km/h). Can melt 12t of copper.

- Collimation, control of beam losses and radiation effects (shielding) are of prime importance.
- Injection, beam transfer and beam dump all critical.

Machine protection issues to be addressed early on!

Damage of a beam with an energy of 2 MJ

Hydrodynamic tunneling: beam penetrates ~300 m in Cu
Huge energy to be extracted and dumped => need large dump section
Beam rigidity: 167 T.km => need long way to dilute beam ~2.5km!

- 1.4 km dump insertion
- 2.8 km collimation insertion
- 2.5 km dump line

Kicker Septum 10 mrad bend Dilution Absorber

Fluka studies:
- Bunch separation >1.8 mm
- Branch separation: 4 cm
- Keeps T<1500°C

Very reliable kickers, high segmentation, new methods for triggering (laser)

SC septum
R&D on Superconducting Septa

Need an extraction system for safely removing the beam from the collider hybrid system: short overall length with high robustness & availability

SuShi concept: SC shield creates field-free region inside strong dipole field

3 candidate technologies:
(1) NbTi/Nb/Cu multilayer sheet
(2) HTS tape/coating
(3) Bulk MgB$_2$
High synchrotron radiation load of proton beams @ 50 TeV:

- ~30 W/m/beam (@16 T) (LHC <0.2W/m)
- 5 MW total in arcs (@1.9 K!!!)

New Beam screen with ante-chamber

- absorption of synchrotron radiation at 50 K to reduce cryogenic power
- factor 50! reduction of cryo power

Simulation of quench behaviour

Photon distribution
Cryo power for cooling of SR heat

Overall optimisation of cryo-power, vacuum and impedance
Temperature ranges: <20, 40K-60K, 100K-120K

Multi-bunch instability growth time: 25 turns, 9 turns (ΔQ=0.5)
Main SC Magnet system
FCC (16 T) vs LHC (8.3 T)

FCC
Bore diameter: 50 mm
Dipoles: \textit{4578 units, 14.3 m long, 16 T} $\Leftrightarrow \int Bdl \sim 1 \text{ MTm}$
Stored energy $\sim 200 \text{ GJ (GigaJoule)} \sim 44 \text{ MJ/unit}$
Quads: \textit{762 magnets, 6.6 m long, 375 T/m}

LHC
Bore diameter: 56 mm
Dipoles: \textit{1232 units, 14.3 m long, 8.3 T} $\Leftrightarrow \int Bdl \sim 0.15 \text{ MTm}$
Stored energy $\sim 9 \text{ GJ (GigaJoule)} \sim 7 \text{ MJ/unit}$
Quads: \textit{392 units, 3.15 m long, 233 T/m}


**Nb\textsubscript{3}Sn conductor program**

**Nb\textsubscript{3}Sn** is one of the major cost & performance factors for FCC-hh and is given highest attention.

**Main development goals until 2020:**

- $J_c$ increase (16T, 4.2K) > 1500 A/mm\textsuperscript{2} i.e. 50% increase wrt HL-LHC wire
- Reference wire diameter 1 mm
- Potentials for large scale production and cost reduction

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**Diagram:**

- LHC
- High Luminosity
- FCC

**Curves:**

- $J_c$ at 4.2 K (A/mm\textsuperscript{2})

**Fields (T):**

- 10
- 12
- 14
- 16
- 18
- 20
- 22
- 24

**Curves at 1500 A/mm\textsuperscript{2}:**

- LHC
- High Luminosity
- FCC

**Curves at 1000 A/mm\textsuperscript{2}:**

- LHC
- High Luminosity
- FCC

**5400 mm\textsuperscript{2}:**

- ~1.7 times less SC

**3150 mm\textsuperscript{2}:**

- ~10% margin HL-LHC
- ~10% margin FCC ultimate

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**Footnote:**

HL-LHC and FCC
Michael Benedikt
CAS, Archamps, 10 October 2019
16 T dipole options and plans

- Model production 2018 – 2022,
- Prototype production 2023 - 2025
### lepton collider parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Z</th>
<th>WW</th>
<th>H (ZH)</th>
<th>ttbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy [GeV]</td>
<td>45</td>
<td>80</td>
<td>120</td>
<td>182.5</td>
</tr>
<tr>
<td>Beam current [mA]</td>
<td>1390</td>
<td>147</td>
<td>29</td>
<td>5.4</td>
</tr>
<tr>
<td>No. bunches/beam</td>
<td>16640</td>
<td>2000</td>
<td>393</td>
<td>48</td>
</tr>
<tr>
<td>Bunch intensity [$10^{11}$]</td>
<td>1.7</td>
<td>1.5</td>
<td>1.5</td>
<td>2.3</td>
</tr>
<tr>
<td>SR energy loss / turn [GeV]</td>
<td>0.036</td>
<td>0.34</td>
<td>1.72</td>
<td>9.21</td>
</tr>
<tr>
<td>Total RF voltage [GV]</td>
<td>0.1</td>
<td>0.44</td>
<td>2.0</td>
<td>10.9</td>
</tr>
<tr>
<td>Horizontal beta* [m]</td>
<td>0.15</td>
<td>0.2</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>Vertical beta* [mm]</td>
<td>0.8</td>
<td>1</td>
<td>1</td>
<td>1.6</td>
</tr>
<tr>
<td>Horiz. geometric emittance [nm]</td>
<td>0.27</td>
<td>0.28</td>
<td>0.63</td>
<td>1.46</td>
</tr>
<tr>
<td>Vert. geom. emittance [pm]</td>
<td>1.0</td>
<td>1.7</td>
<td>1.3</td>
<td>2.9</td>
</tr>
<tr>
<td>Luminosity per IP [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>$&gt;200$</td>
<td>$&gt;25$</td>
<td>$&gt;7$</td>
<td>$&gt;1.4$</td>
</tr>
</tbody>
</table>

**identical FCC-ee baseline optics for all energies**

FCC-ee: 2 separate rings, LEP: single beam pipe
FCC-ee exploits lessons & recipes from past $e^+e^-$ and $pp$ colliders

combining successful ingredients of recent colliders $\rightarrow$ extremely high luminosity at high energies

LEP: high energy SR effects

$B$-factories: KEKB & PEP-II: high beam currents top-up injection

DAFNE: crab waist

Super $B$-factories

S-KEKB: low $\beta_y^*$

KEKB: $e^+$ source

HERA, LEP, RHIC: spin gymnastics
FCC-ee optics design

Optics design for all working points achieving baseline performance
Interaction region: asymmetric optics design

- Synchrotron radiation from upstream dipoles <100 keV up to 450 m from IP
- Dynamic aperture & momentum acceptance requirements fulfilled at all WPs
FCC-ee MDI optimisation

MDI work focused on optimization of:

- $I^*$, IR quadrupole design
- Detector, compensation solenoid
- SR masking and chamber layout

- CERN model of CCT IR quadrupole
- BINP prototype IR quadrupole

"envelope" for the shielding solenoid (yellow):
- $z_{start} = 2.2$ m (front face)

Compensating solenoid (green):
- $z_{start} = 1.3$ m, $z_{end} = 2.2$ m
- $B = 4.9$ T

LumiCal:
- width = 20 cm i.e. $z_{start} \sim 1.1$ m
- Si/W calorimeter

VXD detector

20 cm long Tantalum masks (pink)
Efficient 2-in-1 FCC-ee arc magnets

Dipole:
- twin aperture yoke
- single busbars as coils

Quadrupole:
- twin 2-in-1 design

- Novel arrangements allow for considerable savings in Ampere-turns and power consumption
- Less units to manufacture, transport, install, align, remove,…
RF system requirements

Very large range of operation parameters

<table>
<thead>
<tr>
<th></th>
<th>$V_{\text{total}}$</th>
<th>$n_{\text{bunches}}$</th>
<th>$I_{\text{beam}}$</th>
<th>$\Delta E/$turn</th>
</tr>
</thead>
<tbody>
<tr>
<td>hh</td>
<td>0.032</td>
<td></td>
<td>500</td>
<td>0.034</td>
</tr>
<tr>
<td>Z</td>
<td>0.4/0.2</td>
<td>30000/90000</td>
<td>1450</td>
<td>0.33</td>
</tr>
<tr>
<td>W</td>
<td>0.8</td>
<td>5162</td>
<td>152</td>
<td>0.33</td>
</tr>
<tr>
<td>H</td>
<td>5.5</td>
<td>770</td>
<td>30</td>
<td>1.67</td>
</tr>
<tr>
<td>t</td>
<td>10</td>
<td>78</td>
<td>6.6</td>
<td>7.55</td>
</tr>
</tbody>
</table>

“Ampere-class” machines

“High gradient” machines

- Voltage and beam current ranges span more than factor $>10^2$
- No well-adapted single RF system solution satisfying requirements

Naive scale up from an hh system

≈ 16 x 1 cell 400MHz,
RF system R&D lines

400 MHz single-cell cavities preferred for hh and ee-Z (few MeV/m)
- Baseline Nb/Cu @4.5 K, development with synergies to HL-LHC, HE-LHC
- R&D: power coupling 1 MW/cell, HOM power handling (damper, cryomodule)

- hh: ≈ 16 cells per beam
- Z: ≈ 100 per beam (+ 100 for booster ring)
- W: ≈ 210 per beam (+ 210 for booster ring)

400 or 800 MHz multi-cell cavities preferred for ee-ZH, ee-tt and ee-WW
- Baseline options 400 MHz Nb/Cu @4.5 K, 800 MHz bulk Nb system @2K
- R&D: High Q₀ cavities, coating, long-term: Nb₃Sn like components

- W: ≈ 200 per beam (+ 200 for booster)
- H: ≈ 800 per beam (+ 800 for booster)
- t: ≈ common 2600 cells for both beams (+ 2600 for booster)
Summary

- The HL-LHC upgrade project is in full swing with first installations in LS2.
- The FCC study phase 1 is completed with Design Reports.
- Clearly HL-LHC is a necessary first step in the development of technologies for future HE accelerators, in particular the FCC.
- Superconductivity is the key enabling technology for LHC, HL-LHC, HE LHC and FCC.
- The Nb3Sn program for HL-LHC triplets and 11 T dipoles is of prime importance towards development fo 16 T model magnets.
- SC crab cavities are a major ingredient for HL-LHC and the development of high efficiency SRF systems is critical for FCC-ee.
- Both HL-LHC project and FCC study show the importance of international collaboration in our field, to advance on all challenging subjects and to assure a long-term future!
- **In this sense we rely on your future contributions!**