• Futures Circular Colliders Projects
  • HL-LHC
  • FCC-ee/FCC-hh
  • Novel techniques
A peak luminosity of \( L_{\text{peak}} = 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \) with **levelling**, allowing an integrated luminosity of 250 fb\(^{-1}\) **per year**, enabling the goal of \( L_{\text{int}} = 3000 \text{ fb}^{-1} \) twelve years after the upgrade.

This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

**Ultimate** performance established use of engineering margins:

\[ L_{\text{peak ult}} \equiv 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]  and  
\[ L_{\text{int ult}} \sim 4000 \text{ fb}^{-1} \]

LHC should not be the limit, would Physics programs require more...

---

**High Luminosity-LHC**

\[ L = \frac{kN^2 f \gamma}{4\pi \beta \varepsilon} \cdot F \]
COMPENSATION OF GEOMETRIC REDUCTION FACTOR

\[ L = \frac{kN^2 f \gamma}{4\pi \beta \varepsilon} \left( \frac{1}{\sqrt{1 + \left( \frac{\sigma_x}{\sigma_y} \right)^2}} \right) \]

- Crossing angle at HL-LHC must be larger than at LHC, due to higher intensity and higher beam divergence
  - Would cause very large loss in luminosity: \( F \approx 0.35 \)

- To compensate: use “crab cavities” that tilt the bunches longitudinally and ensure overlap at the collision point

- Prototypes tests in the SPS!

Schematic view of RFD (top) and DQW (bottom) crab cavity. Image credit: R Leuxe/CERN
LEVELLING MECHANISMS

• Levelling techniques will be a vital ingredient for HL-LHC operation and have been used successfully in operation:

- Separation: Will be used in ALICE and LHCb and for fine adjustments (separations < 1 σ) in ATLAS and CMS ➔ Operational since Run 1

- Crossing angle: Might be needed to optimize beam lifetime and as mean to reduce pile-up density given the reduced crabbing angle. Operational in 2017

- $\beta^*$: Main levelling mechanism during the fill. Operational in 2018

Reducing heat load on the IT triplet (quench and cooling limits) Limiting pile up in the detectors

Inst. luminosity [$10^{34}$ cm$^{-2}$ s$^{-1}$] vs. Time [h]
~1.2 KM OF NEW HARDWARE IN LHC

• New final focus quadrupoles around ATLAS and CMS:
  Ni$_3$Sn technology (See S. I. Bermudez’s lecture) for more aperture
  Radiation damage
• Matching section: separation dipoles, first double aperture magnet and correctors (See S. I. Bermudez’s Lecture)
• Crab Cavities
• Cryogenics plants
• SC links and rad. Mitigation
• 11 T Nb3Sn dipole for collimation
International **FCC** collaboration (CERN as host lab) to study:

- **pp-collider (FCC-hh)** → main emphasis, defining infrastructure requirements
- ~100 km tunnel infrastructure in Geneva area, site specific
- **e^+e^- collider (FCC-ee)**, as potential first step
- **HE-LHC** with FCC-hh technology
- **p-e (FCC-he) option**, IP integration, e^- from ERL

CDRs published in *European Physical Journal C* (Vol 1) and *ST* (Vol 2 – 4)

**Summary documents provided to EPPSU SG**

- FCC-integral, FCC-ee, FCC-hh, HE-LHC

Cost: ~28.6 BCHF
PREPARING FOR NEXT STRATEGY

Comprehensive long-term program maximizing physics opportunities

- stage 1: FCC-ee (Z, W, H, t̅t̅) as Higgs factory, electroweak & top factory at highest luminosities
- stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options
- complementary physics
- common civil engineering and technical infrastructures, reusing CERN’s existing infrastructure
- FCC integrated program allows continuation of HEP after completion of the HL-LHC program

M. Giovannozzi ICHEP 2022
FEASIBILITY STUDY GOALS AND ROADMAP

Highest priority goals:
Financial feasibility
Technical and administrative feasibility of tunnel: no show-stopper for ~100 km tunnel
Technologies of machine and experiments:
  - magnets; minimized environmental impact; energy efficiency & recovery
  - Establish a list of alternative technologies that could have significant impact on cost or performance

Gathering scientific, political, societal and other support

2012 Higgs discovery announced
2014 FCC study kickoff
2018 FCC CDR
2020 FCCIS kickoff
2020-25 FCC Feasibility Study
2025/26 Feasibility proof
2026/7 ESPPU
2025/26 Financing model Operation concept
>2028 approval
~2028 approval
>2030 start tunnel construction
>2030 - 37 element production
>2030 first ee collisions
>2038 machine installation
>2038 machine installation
>2038 machine installation
>2045 first ee collisions
>2026 - 30 full technical design
### FCC-ee PARAMETERS

<table>
<thead>
<tr>
<th>Running mode</th>
<th>Z</th>
<th>W</th>
<th>ZH</th>
<th>$t\bar{t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of IPs</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Beam energy (GeV)</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>182.5</td>
</tr>
<tr>
<td>Bunches/beam</td>
<td>11200</td>
<td>1780</td>
<td>440</td>
<td>60</td>
</tr>
<tr>
<td>Beam current [mA]</td>
<td>1270</td>
<td>137</td>
<td>26.7</td>
<td>4.9</td>
</tr>
<tr>
<td>Luminosity/IP [$10^{34}$ cm$^{-2}$ s$^{-1}$]</td>
<td>141</td>
<td>20</td>
<td>5.0</td>
<td>1.25</td>
</tr>
<tr>
<td>Energy loss / turn [GeV]</td>
<td>0.0394</td>
<td>0.374</td>
<td>1.89</td>
<td>10.42</td>
</tr>
<tr>
<td>Synchrotron Radiation Power [MW]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>RF Voltage 400/800 MHz [GV]</td>
<td>0.08/0</td>
<td>1.0/0</td>
<td>2.1/0</td>
<td>2.1/9.4</td>
</tr>
<tr>
<td>Rms bunch length (SR) [mm]</td>
<td>5.60</td>
<td>3.47</td>
<td>3.40</td>
<td>1.81</td>
</tr>
<tr>
<td>Rms bunch length (+BS) [mm]</td>
<td>15.5</td>
<td>5.41</td>
<td>4.70</td>
<td>2.17</td>
</tr>
<tr>
<td>Rms horizontal emittance $\varepsilon_{\parallel}$ [mm]</td>
<td>0.71</td>
<td>2.17</td>
<td>0.71</td>
<td>1.59</td>
</tr>
<tr>
<td>Rms vertical emittance $\varepsilon_{\perp}$ [pm]</td>
<td>1.9</td>
<td>2.2</td>
<td>1.4</td>
<td>1.6</td>
</tr>
<tr>
<td>Longitudinal damping time [turns]</td>
<td>1158</td>
<td>215</td>
<td>64</td>
<td>18</td>
</tr>
<tr>
<td>Horizontal IP beta $\beta_x^*$ [mm]</td>
<td>110</td>
<td>200</td>
<td>240</td>
<td>1000</td>
</tr>
<tr>
<td>Vertical IP beta $\beta_y^*$ [mm]</td>
<td>0.7</td>
<td>1.0</td>
<td>1.0</td>
<td>1.6</td>
</tr>
<tr>
<td>Beam lifetime (q+BS+lattice) [min.]</td>
<td>50</td>
<td>42</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Beam lifetime (lum.) [min.]</td>
<td>22</td>
<td>16</td>
<td>14</td>
<td>12</td>
</tr>
<tr>
<td>Int. annual luminosity / IP [ab$^{-1}$/yr]</td>
<td>17$^\dagger$</td>
<td>2.4$^\dagger$</td>
<td>0.6</td>
<td>0.15$^\dagger$</td>
</tr>
</tbody>
</table>

$\Rightarrow$ High efficient RF system, small emittance and short lifetime beam
BASIC DESIGN CHOICES

Double ring $e^+e^-$ collider

Two or four experiments

- Asymmetric Interaction Region layout and optics to limit synchrotron radiation towards the detector
- Horizontal crossing angle of 30 mrad and crab waist collision scheme

Perfect 4-fold superperiodicity allowing 2 or 4 IPs;

Synchrotron radiation power 50 MW/beam at all beam energies

Top-up injection scheme for high luminosity

Implies booster synchrotron in collider tunnel

M. Hofer ICHEP 2022
**FCC-ee KEY TECHNOLOGIES: ARCS**

Aim of the project

- **Arc half-cell**: most recurrent assembly of mechanical hardware in the accelerator (~1500 similar FODO cells in the FCC-ee)

- **Mock-up → Functional prototype(s) → Pre-series → Series**

- Building a mock-up allows optimizing and testing **fabrication, integration, installation, assembly, transport, maintenance**

- Working with demonstrators of the different equipment, and/or structures with equivalent volumes, weights, stiffness

  F. Carra et al

Arc perspective view, F. Valchko-Georgieva
OPTICS CORRECTIONS STRATEGY (FCC-EE BOOSTER)

Motivation

➢ Evaluate specifications of the main magnets misalignment of the High Energy Booster arcs cells and of magnets field error
➢ Definition of the orbit correction strategy and of correctors specifications for the booster

Orbit correction using beam position monitors reading

<table>
<thead>
<tr>
<th>errors</th>
<th>Case</th>
<th>Plane</th>
<th>3 x Analytical RMS</th>
<th>3 x Mean RMS/seeds</th>
</tr>
</thead>
<tbody>
<tr>
<td>MQ offset = 150 µm</td>
<td>Residual orbit [µm]</td>
<td>x</td>
<td>188</td>
<td>174</td>
</tr>
<tr>
<td>MB field err = 10^{-3}</td>
<td></td>
<td>y</td>
<td>192</td>
<td>188</td>
</tr>
<tr>
<td>MB roll = 300 µrad</td>
<td>Correctors stengths [mTm]</td>
<td>x</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>BPM offset = 150 µm</td>
<td></td>
<td>y</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>MS offset = 150 µm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BPM resolution = 50 µm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Improvements and related work to do:

➢ Other methods than SVD - AI ?
➢ Demonstrate full emittance tuning
➢ Study the impact of booster support vibrations on emittance (dynamic imperfections)
➢ Study the impact of energy ramp during the booster cycle

Images courtesy T. Charles
FCC-ee KEY TECHNOLOGIES: SRF-CAVITIES

We need to replenish energy loss by synchrotron radiation:
Superconductive RF most efficient way

- **SRF technology building on LHC studies and collaborative R&D** (F. Peauger et al.)
  - 5-cell 800 MHz cavity without damping built and tested at 2K by Jefferson lab with excellent results
  - 400 MHz cavities based on LHC studies of Cu-coated Nb cavities at 4.5K
  - Alternative slotted waveguide elliptical cavity with f=600 MHz

- **RF placement optimized for infrastructure requirements** (F. Valchкова-Georgieva et al)

see W. Venturini Lectures on RF superconductivity

---

SWELL 2-cell 600 MHz cavity for Z, W, H

Model for 2-cell 400 MHz for WW and ZH

---

Subtracting 0.5 mΩ due to NC RF losses in SS blank flanges

quench limit ~30 MV/m
FCC-ee KEY TECHNOLOGIES: INTERACTION REGION

- **Canted-Cosine-Theta magnets**
  - Elegant 2-layer design for inner quadrupoles
  - Working to fit within 100 mrad stay-clear cone
  - Prototype built and warm-tested
  - Complex integration of SC quadrupoles, LumiCal, shielding, diagnostics...
  - Mock-up under discussion

- **FCC-ee interaction region**
  - L* is 2.2 m.
  - The 10 mm central radius is for ± 9 cm from the IP.
  - The two symmetric beam pipes with radius of 15 mm are merged at 1.2 m from the IP
  - Low impedance vacuum chamber
  - Synchrotron Radiation Background and photon dumps

Integration within the detector
SuperKEKB as FCC-EE Test Facility

- 3 km double ring, top-up injection

- $\beta_y^{*} = 0.8$ mm demonstrated
- Collision with large crossing angle compensated by sextupoles schemes (as in DAFNE and as foreseen in FCC-ee)
- Design luminosity not reached so far due to intensity limitation (fast beam losses) in Super KEKB

Design parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LER</th>
<th>HER</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$</td>
<td>4.00</td>
<td>7.00</td>
<td>GeV</td>
</tr>
<tr>
<td>$I$</td>
<td>3.6</td>
<td>2.6</td>
<td>A</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2,500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch Current</td>
<td>1.44</td>
<td>1.04</td>
<td>mA</td>
</tr>
<tr>
<td>Circumference</td>
<td>3,016.315</td>
<td></td>
<td>m</td>
</tr>
<tr>
<td>$x_0/x_0$</td>
<td>3.2(1.9)/8.64(2.8)</td>
<td>4.6(4.4)/12.9(1.5)</td>
<td>mm/pm</td>
</tr>
<tr>
<td>Coupling</td>
<td>0.27</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>$\beta^{*}/\beta^{**}$</td>
<td>32/0.27</td>
<td>25/0.30</td>
<td>mm</td>
</tr>
<tr>
<td>Crossing angle</td>
<td>83</td>
<td></td>
<td>mrad</td>
</tr>
<tr>
<td>$\sigma_y$</td>
<td>3.20 x 10^{-4}</td>
<td>4.55 x 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>$\sigma_z$</td>
<td>7.92(7.53)x10^{-4}</td>
<td>6.37(6.30)x10^{-4}</td>
<td></td>
</tr>
<tr>
<td>$V_r$</td>
<td>9.4</td>
<td>15.0</td>
<td>MV</td>
</tr>
<tr>
<td>$\gamma_0$</td>
<td>6(4.7)</td>
<td>9(4.9)</td>
<td></td>
</tr>
<tr>
<td>$\gamma_0$</td>
<td>-0.0245</td>
<td>-0.0280</td>
<td></td>
</tr>
<tr>
<td>$\nu_{\mu}$</td>
<td>44.53/46.57</td>
<td>45.53/43.57</td>
<td></td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>1.76</td>
<td>2.48</td>
<td>MeV</td>
</tr>
<tr>
<td>$T_{\pi}/T_{\pi}$</td>
<td>45.7/22.8</td>
<td>58.0/29.0</td>
<td>m/sec</td>
</tr>
<tr>
<td>$\sigma_{\pi}/\sigma_{\pi}$</td>
<td>0.0026/0.0081</td>
<td>0.0012/0.0057</td>
<td></td>
</tr>
</tbody>
</table>

World's highest luminosity
$4.7 \times 10^{34}$ cm$^{-2}$s$^{-1}$ & lowest $\beta^{*}$
### FCC-hh parameters

<table>
<thead>
<tr>
<th>parameter</th>
<th>FCC-hh</th>
<th>HL-LHC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>collision energy cms [TeV]</td>
<td>96</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>dipole field [T]</td>
<td>16</td>
<td>8.33</td>
<td>8.33</td>
</tr>
<tr>
<td>circumference [km]</td>
<td>91</td>
<td>26.7</td>
<td>26.7</td>
</tr>
<tr>
<td>beam current [A]</td>
<td>0.5</td>
<td>1.1</td>
<td>0.58</td>
</tr>
<tr>
<td>bunch intensity (10^{11})</td>
<td>1</td>
<td>1</td>
<td>2.2</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>synchr. rad. power / ring [kW]</td>
<td>2400</td>
<td>7.3</td>
<td>3.6</td>
</tr>
<tr>
<td>SR power / length [W/m/ap.]</td>
<td>28.4</td>
<td>0.33</td>
<td>0.17</td>
</tr>
<tr>
<td>long. emit. damping time [h]</td>
<td>0.54</td>
<td>12.9</td>
<td>12.9</td>
</tr>
<tr>
<td>beta* [m]</td>
<td>1.1</td>
<td>0.3</td>
<td>0.15 (min.)</td>
</tr>
<tr>
<td>normalized emittance [mm]</td>
<td>2.2</td>
<td>2.5</td>
<td>3.75</td>
</tr>
<tr>
<td>peak luminosity (10^{34} \text{cm}^{-2}\cdot\text{s}^{-1})</td>
<td>5</td>
<td>30</td>
<td>5 (lev.)</td>
</tr>
<tr>
<td>events/bunch crossing</td>
<td>170</td>
<td>1000</td>
<td>132</td>
</tr>
<tr>
<td>stored energy/beam [GJ]</td>
<td>8.4</td>
<td>0.7</td>
<td>0.36</td>
</tr>
</tbody>
</table>

⇒ SR comparable to light sources, beam losses, high field magnets
BASIC DESIGN CHOICES

The main drivers
• Placement studies

• **Exact four-fold symmetry (FCC-ee layout)**
• Four experiments (A, D, G, & J)
• Two collimation insertions
  • betatron cleaning (F)
  • momentum cleaning (H)
• Extraction insertion + injection (B)
• RF insertion + injection (L)
• **Last part of transfer lines in the ring tunnel, using normal-conducting magnets**
• Compatible with LHC or SPS as injector
ARC CONCEPT (CDR)

Civil engineer constraints

Magnets max gradient and Field Quality

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

213/2 m

FODO cell

β*, β, D, δ
FCC-hh KEY TECHNOLOGIES: HIGH FIELD MAGNETS

Need 16 T to reach 48 TeV /beam
⇒ Move from NbTi (LHC technology) to Nb$_3$Sn 14.3 m long dipoles
⇒ HL-LHC experience is fundamental, but further step are needed to reduce the cost
⇒ Exploring HTS superconductors (See S. I. Bermudez Lecture)

Magnet is key cost driver
• Improve cable performance
• Reduce cable cost
• Improve fabrication of magnet
• Minimize amount of cables
• Push lattice filling factor
• Field Quality

Short models in 2018 – 2023
Prototypes 2026 – 2032
Synergies with other fields

11T First Nb$_3$Sn magnet, FRESCA2 dipole

15 T dipole demonstrator
60-mm aperture
4-layer graded coil
FCC-hh KEY TECHNOLOGY: MACHINE PROTECTION

- The loss of even a tiny fraction of the beam could cause a magnet quench or even damage

- Small to make magnet cheap (aperture 50 mm)
- Extract photons for good vacuum
- Strong to withstand quench
- Hide pumping holes from beam and REBCO-Cu longitudinal coating for low impedance
- Laser treatment / carbon coating against e-cloud

- ~30 W/M SYNCHROTRON RADIATION (LHC: 1 W/M)
  - Tests at KARA/KIT

- ~8 GJ kinetic energy per beam in FCC-hh O(20) times LHC
  - Boing 747 at cruising speed or 400 kg of chocolate (Run 25,000 km to spent calories)

- Designed shielding to cope with the 500 kW collision debris per experiment
  - Collimation system design
    - Designed system that can cope with the losses
    - Detailed studies and optimization of performance
  - Beam dump design
  - Machine protection (See F. Salvat Lecture)

- Use carbon-based materials for highest robustness
- Very challenging engineering task to design these collimators
“The particle physics community should ramp up its R&D effort focused on advanced accelerator technologies”

- High Field Magnets
- Super conductive cavities
- Plasma accelerations and other techniques
- Energy Recovery Linacs (ERL)
- Muons Colliders
PLASMA WAKE ACCELERATORS PRINCIPLE

\[ E_{cm} \approx L_{\text{linac}} G_{\text{acc}} \]

They have the potential to overcome the length and the accelerating gradient limitations of the linear colliders.

Wakefield due to space charge oscillation inside plasma \( \rightarrow 10 - 100 \text{ GV/m} \)

Laser or beam driver

Electron beam

\(~100 \mu\text{m}~\)

From Maxwell’s equations, the electric field in a (positively) charged sphere with uniform density \( n_i \) at location \( r \) is

\[ \vec{E}(r) = \frac{q_i n_i}{3 \varepsilon_0} r \]

The field is increasing inside the sphere.

Let’s put some numbers

\( n_i = 10^{14} \text{ cm}^{-3} \)

\( R = 0.5 \lambda_p = 150 \mu\text{m} \)

\( E \approx 10 \text{ GV/m} \)

M. Ferrario et al.
Specific topics to be addressed:

- Positron acceleration
- Technological issue (efficiency, cooling, polarization,...)
- The world wide R&D focus on beam quality, beam stability, staging and continuous operation
The concept become really viable with recent advances in SRF technology: reach high cavity quality factors \( Q_0 \geq 10^{10} \) enabling high average current operation.

Demonstration facilities around the world are pursuing to gain experimental experience of this technique.
Muons are heavier than electrons $\Rightarrow$ they lose less energy because of synchrotron radiation can reach $\sim 10$ TeV energy in the center of mass with leptons!

Would be easy if the muons did not decay: lifetime is $\tau = \gamma \times 2.2 \, \mu s$
CONCLUSIONS

• High Energy Accelerator Field is very active!
  • Plenty of different projects are under study to be ready to address different and complementary physics questions
  • Many beam dynamics challenges to be addressed
  • Key technology R&D roadmaps have been created:
    • A lot of synergies with other fields (energy, medicine, etc...)

• There is always room for new ideas!

You are very welcome to join us!
THANK YOU!
### EIC

#### Double-ring design based on existing RHIC complex

**Hadron Storage Ring: 40 - 275 GeV**
- RHIC Yellow+Blue Ring and Injector Complex
- Many Bunches, 1160 @ 1A Beam Current
- Bright Vertical Beam Emittance $\epsilon_{xp} = 1.5 \text{ nm}$
- Requires Strong Cooling (CeC)

**Electron Storage Ring: 2.5 - 18 GeV \(\text{(new)}\)**
- Many Bunches, Large Beam Current - 2.5 A
- 9 MW Synchrotron Radiation, SRF Cavities
- Needs injection of polarized bunches

**Electron Rapid Cycling Synchrotron: \(\text{(new)}\) 0.4-18 GeV**
- Spin Transparent Due to High Periodicity
- 1-2 Hz cycle for On-Energy Injection into ESR

**High Luminosity Interaction Region(s) \(\text{(new)}\)**
- 25 mrad Crossing Angle with Crab Cavities
- Superconducting Magnets
- Spin Rotators for Longitudinal Spin at IP
- Forward Hadron Instrumentation
COLLIMATORS AND ALIGNMENT

- Losses from the beam are inevitable, and could cause magnet quenches or even damage
- With higher intensity in the HL-LHC, need to enforce machine protection
- New collimators to be installed to better protect the machine. LS2 upgrade:
  - Dispersion suppressor cleaning for ALICE
  - Low-impedance primary and secondary (coated) collimators in IR7
  - Passive absorbers for IR7

Full remote alignment system (FRAS) will be deployed to keep the machine well aligned.

- All components equipped with alignment sensors and supported by motorized adjustment solutions
- Remote alignment of ±2.5 mm, to reposition the machine w.r.t. the IP, to correct ground motion.
FCC-ee KEY TECHNOLOGIES: VACUUM SYSTEM

- Specifying vacuum system
  - Consider discrete absorbers space every <6 m or continuous absorbers along chamber wall
  - NEG coated Cu vacuum chamber
  - Need shielding to minimize tunnel radiation levels
FCC-hh KEY TECHNOLOGIES: HIGH FIELD MAGNETS

Doubling the operating current density brings a reduction of the superconductor area to one third

\[ A_{\text{coil}} \propto SC \text{ mass} \]

Courtesy of A. Ballarino, CERN

The most promising route to fill the performance gap is the Internal Oxidation

Boutboul et al., IEEE TASC 19 (2009) 2564
Xu et al., APL 104 (2014) 082602

L. Rossi ICHEP 2022
High Field Magnet technology can always serve for a HE-LHC

To be changed

Insieme a quella di Prima
Replace CPU costly tracking simulations with fast surrogate model of the time evolution of Dynamic Aperture.
FCC-hh KEY TECHNOLOGY: MACHINE PROTECTION

HL-LHC: 680 MJ - kinetic energy of TGV train cruising at 215 km/h

FCC-hh: 8.3 GJ – kinetic energy of Airbus A380 (empty) cruising at 880 km/h
• The loss of even a tiny fraction of the beam could cause a magnet quench or even damage

• To safely intercept any losses and protect the machine: use collimation system (see lecture a. Lechner)
  • Should be the smallest aperture limitation in the ring

• 500 kw of continuous losses from collisions, downstream of experiments

• Design requirement: safely handle beam lifetime of 12-minute during ~10 s from instabilities, operational mistakes, orbit jitters….
  • Corresponds to power load of about 11.6 MW from the beam losses
  • Collimators must digest these losses without breaking, while protecting the superconducting magnets

Beam lifetime:
usually defined as time needed for reduction of intensity by factor $1/e$
assuming losses proportional to intensity (often true, but not always)

$$- \frac{dN}{dt} \propto N(t) \Rightarrow N(t) = N_0 e^{-t/T_0}$$
FCC-hh COLLIMATORS ROBUSTNESS

• Use carbon-based materials for highest robustness, with hardware design based on LHC but developed further
• Very important to study material response to the high loads
• Typically 3-stage simulations:
  • Generation of impact coordinates of lost particles
  • Energy deposition studies (e.g. FLUKA, see lecture A. Lechner)
  • Thermo-mechanical study using e.g. ANSYS of dynamic material response
    • Study peak temperatures, deformations, melting, detachment of material
• Very challenging engineering task to design these collimators
Planning demonstrator facility with muon production target and cooling stations
Suitable site on CERN land exists that can use PS proton beam
• could combine with NuStorm or other option
Other sites should be explored (FNAL?)
FCC-ee COLLIDER OPTICS AND BEAM-BEAM

- Novel ‘virtual’ crab waist combining local vertical chromaticity correction
  - Crab waist was demonstrated at DAFNE
  - Crab waist is also being used at SuperKEKB
- Optimized optics configurations for each of the 4 working points

Crab waist scheme https://arxiv.org/abs/physics/0702033

CDR optics, ttbar 182.5 GeV
BEAM-BEAM AND COLLECTIVE EFFECTS

- Beam-beam at high luminosity drives the ring parameters (limits Luminosity)
- Developing impedance model for the ring based on vacuum components
- Single bunch instabilities can be calculated based on impedance, beam-beam, and ring optics but there is complicated interplay
- Multibunch instabilities constrain bunch spacing
- Large ring circumference limits feedback gain
  - Developing integrated simulations for collective effects with feedback

Beamstrahlung $\rightarrow$ Dynamic aperture

$\sigma_0 = 1.3 \sigma_{00}$

F. Zimmermann, T. Raubenheimer FCC week 2022
**FCC-ee COLLIDER OPTICS AND COLLECTIVE EFFECTS**

- **Novel ‘virtual’ crab waist** combines local vertical chromaticity correction with crab waist of lepton factories

\[ \beta_y^* \approx \frac{2 \sigma_x}{\theta} \ll \sigma_z \quad (\theta = \text{half crossing angle}) \]

- **Sextupoles settings** are chosen to control vertical beam size chromatic aberrations at the IP
- **Two external sextupoles** control also the beam divergence at the IP (crab waist)

⇒ Luminosity is enhanced and beam beam resonances suppressed

- Crab waist was demonstrated at DAFNE
- Crab waist is also being used at SuperKEKB

- **Single bunch instabilities** can be calculated based on impedance, beam-beam, and ring optics but there is complicated interplay
- **Developing impedance model** for the ring based on vacuum components and integrated simulations for collective effects with feedback
Technically very similar project to FCC
The start with lepton collider followed then by Hadron Collider has been always the plan of China since 2013.

The choice for SC Magnet R&D is unique: IBS –iron based SC an HTS potentially much lower cost, but lower performance than REBCO.
Design of a ERL based 50 GeV electron beam in collision with the 7 TeV LHC protons.

Fully Modular Concept
- Imbedded in a LHC Interaction Region
- Influence on optics & orbit compensated
- Flexibility of the LHC rings checked
- Asymmetric beam optics for ultimate e-p luminosity
- Non-colliding p-beam well separated
- Negligible beam-beam force on both proton beams

Low energy test facility PERLE

<table>
<thead>
<tr>
<th></th>
<th>Electrons</th>
<th>Protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV)</td>
<td>50</td>
<td>7000</td>
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<tr>
<td>N /bunch</td>
<td>3.1 $10^9$</td>
<td>2.2 $10^{11}$</td>
</tr>
<tr>
<td>bunch distance (ns)</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>I (mA)</td>
<td>20</td>
<td>1100</td>
</tr>
<tr>
<td>Emittance (nm)</td>
<td>0.31</td>
<td>0.33</td>
</tr>
<tr>
<td>Beam size @ IP (μm)</td>
<td>6 / 6</td>
<td></td>
</tr>
<tr>
<td>Luminosity (cm$^{-2}$ s$^{-1}$)</td>
<td>$9 \times 10^{33}$</td>
<td></td>
</tr>
</tbody>
</table>

wall plug power: 100 MW

B. Holzer ICHEP 2022
ERL & IR can be imbedded at any straight section

60 GeV (electron) x 50 TeV (proton) → 1.5 TeV collider

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<tr>
<td>Luminosity (cm$^{-2}$ s$^{-1}$)</td>
<td>$1.5 \times 10^{34}$</td>
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</table>
ERL concept was proposed first in 1965 by Maury Tigner \(^1\) (Cornell University) for colliders...


- The concept was experimented first in 1986 at SCA/FEL in Stanford, accelerating beams at rather low power.
- The concept become really viable with recent advances in SRF technology in the last decades, quantified by reaching high cavity quality factors \((Q_0 \geq 10^{10})\) enabling high average current operation.
Muon Collider:
Acceleration and collision in multiple turns in rings promises

- **Power efficiency**
- **Compact tunnels**, 10 TeV similar to 3 TeV CLIC
- **Cost effectiveness**
- **Natural staging** is natural

Synergies exist (neutrino/higgs)
Unique opportunity for a **high-energy, high-luminosity lepton collider**

<table>
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<tr>
<th>$\sqrt{s}$</th>
<th>$\int L , dt$</th>
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<tbody>
<tr>
<td>3 TeV</td>
<td>1 ab$^{-1}$</td>
</tr>
<tr>
<td>10 TeV</td>
<td>10 ab$^{-1}$</td>
</tr>
<tr>
<td>14 TeV</td>
<td>20 ab$^{-1}$</td>
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MUON COLLIDERS

Previous studies in US (now very strong interest again), experimental programme in UK and alternatives studies by INFN

New strong interest:
- Focus on high energy
  - 10+ TeV
  - potential initial energy stage
- Technology and design advanced

New collaboration started

Initial integrated luminosity targets

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Discovery reach
14 TeV lepton collisions are comparable to 100-200 TeV proton collisions for production of heavy particle pairs

D. Schulte, Muon Collider, ICHEP, July 2022
Would be easy if the muons did not decay: lifetime is $\tau = \gamma \times 2.2 \, \mu s$

Protons produce pions which decay into muons. Muons are captured in the matter.

Ionisation cooling of muon in matter

Acceleration to collision energy
KEY CHALLENGES

1) Dense neutrino flux mitigated by mover system and site selection

2) Beam-induced background

3) Cost and power consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts beam quality

4) Drives the beam quality
MAP put much effort in design optimise as much as possible
Principle of ionization cooling with no RF has been demonstrated in MICE at RAL

Nature vol. 578, p. 53-59 (2020)

Planning **demonstrator facility** with muon production target and cooling stations

Suitable site on CERN land exists that can use PS proton beam

• could combine with NuStorm or other option

Other sites should be explored (FNAL?)