This work was performed under the auspices of and with support from the Swiss Accelerator Research and Technology (CHART) program (www.chart.ch).
Overview

• CHART and MagDev and the HFM Program
  • FCC-hh
    – LTS accelerator magnets
      – Main challenges
      – MagDev LTS technology program
    – HTS accelerator magnets
      – the promise
      – the difficulties
      – MagDev HTS technology program
  • FCC-ee
    – Technology coils and P3 experiment
    – HTS4
    – MDI
• Muon Collider magnets
• Synergies
  – Neutron scattering
  – RICS proposal
  – Muon target study
• “CHART, the Swiss Center for Accelerator Research and Technology, was founded to support the future oriented accelerator project Future Circular Collider (FCC) at CERN and the development of advanced accelerator concepts in Switzerland beyond the existing technology. [...] The high field magnet R&D has strong synergies with PSI projects [...]”

[Application for support of the Swiss Accelerator Research and Technology Initiative, 2018]

• ~50% of the effort directed to Applied Superconductivity for accelerators.

http://chart.ch
Vision of the HFM Programme

Create an innovative HFM research network that enables a future flagship HEP project in Europe.

• Fast-track pressing technology R&D.
• Invest in paradigm-shifting technologies.
• Provide timely feedback to ESPP via technology demonstrations and credible roadmaps.

https://cern.ch/hfm
1. **Demonstrate Nb3Sn magnet technology for large scale deployment**, pushing it to its limits in terms of maximum field and production scale.

   − The effort to quantify and demonstrate Nb3Sn ultimate field comprises the development of conductor and magnet technology **towards the ultimate Nb3Sn performance**.

   − Develop Nb3Sn magnet technology for collider-scale production, through robust design, industrial manufacturing and cost reduction.

2. **Demonstrate the suitability of HTS for accelerator magnets**, providing a proof-of-principle of HTS magnet technology beyond the reach of Nb3Sn.
HFM Programme Structure

**Governance**
- Collaboration Board
- HFM Steering Board
- Technical Advisory Committee
- Technical Coordination Board
- Project Office

**Executive**
- RD1 – Nb3Sn Conductors
- RD2 – HTS Conductor and HTS Magnet Technologies
- RD3 – Nb3Sn Magnets
- RD4 – Modeling Tools, Materials, Protection, and Cryogenics
- RD5 – Measurement Techniques and Infrastructures

**Institutions:**
- INFN
- CEA
- CIEMAT
- PSI
- KIT
- BAF
- ETH
- UniGE
- TE-MSC
- TE-CRG
- TE-MPE
- TE-VSC
- U-Twente
“The R&D programme must be holistic in nature: a compatible selection of electromagnetic, mechanical and thermal design approaches, conductors, materials, and manufacturing processes needs to be integrated seamlessly with instrumentation and protection into a magnet solution responding to the required specification.” Conversely, work across R&D lines must be closely integrated.
Overview

• CHART and MagDev and the HFM Program
• FCC-hh
  – LTS accelerator magnets
    – Main challenges
    – MagDev LTS technology program
  – HTS accelerator magnets
    – the promise
    – the difficulties
    – MagDev HTS technology program
• FCC-ee
  – Technology coils and P3 experiment
  – HTS4
  – MDI
• Muon Collider magnets
• Synergies
  – Neutron scattering
  – RICS proposal
  – Muon target study
Nb-Ti Accelerator Magnets

Tevatron
- 76 mm bore
- $B = 4.4 \, T$
- $T = 4.2 \, K$
- first beam 1983

HERA
- 75 mm bore
- $B = 5.0 \, T$
- $T = 4.5 \, K$
- first beam 1991

RHIC
- 80 mm bore
- $B = 3.5 \, T$
- $T = 4.3 - 4.6 \, K$
- first beam 2000

LHC
- 56 mm bore
- $B = 8.34 \, T$
- $T = 1.9 \, K$
- first beam 2008
Nb-Ti Technology Stack

- Filamented twisted wires
- Rutherford cable
- Kapton-wrap insulation
- Cos-theta coil geometry
- Full pre-stress (collars)
- HeI or HeII bath with heat exchanger
CERN with ELIN (AT)
Design field 10 T.
1989 reached 9.5 T at 4.3 K.
Technology was judged too immature to pursue for LHC.

S. Wenger, A. Asner, F. Zerobin,
IEEE Trans. Mag, 25(2) 1989

Twente, NE
1995 MSUT magnet reached 11.3 T.
Issues with conductor (filament size, cable eddy current).
First accelerator magnet above 10 T
Very little training.

A. den Ouden, H. H. J. ten Kate et al., in Proc. of 15th International Conference on Magnet Technology, Eds.
• The superconducting A15 phase is brittle and strain sensitive. Niobium and Tin are, therefore, co-extruded in the Rod-Restack Process into a strand.
• In wind-and-react processes, several 10s of strands form a Rutherford cable, that is insulated and used to wind a coil.
• The A15 phase is created during a heat treatment of 180 h at up to 660ºC.
Rod-Restack Process twisted wires.
Rutherford cable
S2 glass braid insulation
Cos-theta winding
Reaction
Epoxy Impregnation
Bladder&Key loading
HeI or HeII bath with heat exchanger
Full Pre-Stress Paradigm

- A lesson learned from the Nb-Ti era.
- Keep coils under compression at all stages of operation → avoid stick-slip motion.
  - Forces scale quadratically with field. For 16 T dipole, forces equivalent of 1.5 kt/m pull coil-halves apart.
  - 10 µm abrupt movement is enough to cause quench.
- However, need to limit stress on Nb$_3$Sn to 150-200 MPa.
- Axial forces and CTE mismatch are another major challenge.

Magnet Types

Cosine Theta Coil
Highest efficiency. Difficult stress management and coil end design.
Simple coil ends.
Higher stored energy.
Slightly lower efficiency.

Block Coil
On paper simpler end design.
Slightly lower efficiency.

Common Coil
Slightly lower efficiency.

Canted Cosine Theta (Tilted Helices)
Simple manufacturing, low coil stress.
Reduced efficiency.

Courtesy L. Brouwer, S. Caspi, M. Duharte, S. Farinon, C. Lorin, J. Munilla, M. Sorbi, F. Toral, Q. Xu
• For stress-managed coils, the winding mandrel acts as an endo-skeleton, intercepting forces, conferring rigid support, and protecting the conductor.
• Stress-managed coils see (nearly) no stress before powering.
• The mandrel acts as winding, reaction, and impregnation tooling.
• CCT is the extreme case with force interception at every single turn.
CHART joined the Nb3Sn HFM R&D during the Horizon2020 EuroCirCol effort.

PSI studied the Canted Cosine Theta option.
• EuroCirCol Design Goal: Shared specs and minimization of conductor volume.
• Stress Management adds mechanical margins and dilutes current density.
• CCT has 1/3 lower conductor stress (135 MPa) for 20% more conductor vol.
• Magnet design, lab refurbishment, equipment, and commissioning, as well as magnet construction from 02.2017 to 10.2019.
Canted Dipole 1 built at PSI

- Magnet design, lab refurbishment, equipment, and commissioning, as well as magnet construction from 02.2017 to 10.2019.


• CD1 main test was carried out in 2022/23.

• **It trained A LOT.**

• It reached **10.1 T in the bore** at 94% of Iss at 1.9 K; 9.9 T and 100% of Iss at 4.5 K.

• **But, it reached 100% of maximum field at 4.5 K.**

• These were the very first Nb$_3$Sn training coils at PSI:
  – No conductor degradation occurred from handling, assembly, powering, or thermal cycling.

• **Stress-management works, CD1 is a robust magnet.**

Courtesy F. Mangiarotti (CERN) and M. Daly (PSI).
Nb3Sn Dipoles History

Courtesy L. Bottura
• HFM R&D has suffered from slow turnaround and late feedback on technology.

  “We propose [...] a succession of meaningful fast-turnaround demonstrations [...]. In this way, new technologies can be tested under realistic conditions at the earliest possible stage, the smallest relevant scale and cost, and the fastest pace.”


---

<table>
<thead>
<tr>
<th>Year</th>
<th>Deliverables / year</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>100s</td>
</tr>
<tr>
<td>2020</td>
<td>10</td>
</tr>
<tr>
<td>2024</td>
<td>2-3</td>
</tr>
<tr>
<td>2025/26</td>
<td>0.5-1</td>
</tr>
</tbody>
</table>

First deliverable

- 2019
- 2020
- 2024

Materials and Composite Samples (not powered)

Powering Samples and Mechanical Models

Sub-scale Magnets (5 T)

Short Magnets
Ultimate Field (14...16T)

Long Magnets
Ultimate Field Magnets (14...16 T)

Long-magnet infrastructure available only at CERN.

2019
2020
2024
2025/26

2PoM01-01, D. Araujo

Courtesy D. Araujo

Courtesy M. Daly

Courtesy D. Araujo

ETH Zürich
Douglas Araujo
Engineer LTS

Jaap Kosse
Engineer ReBCO

Henrique Rodrigues
Process Engineer ReBCO

Dmitry Sotnikovs
Design Engineer ReBCO

André Brem
Material Scientist

Thomas Michlmayr
CAD, Technical Design
• Resin cracking.
• De-bonding from winding former or strand diameter.
• Voids due to processing → wire movement and/or crack initiation.
BOX Program

Pictures by M. Daly, S. Sidorov, S. Otten

SC Transformer

11-T solenoid
**BOX** (BOnding eXperiment) program with uTwente has shown a wide variety of results, from complete conductor **degradation (no impregnation)** to substantial **training (epoxy)** to **no-training (wax, Stycast, filled wax)**, with **20 BOX samples** successfully and tested to date.
Successful systems are characterized in U Twente’s transverse-compression setup.

CTD 101-K measurements reproduce previous results of Twente U-shaped samples.

Paraffin wax’s lower modulus and degradation.
Filled wax bumps wax up to CTD 101-K support.
PSI’s BigBOX: a 13-turn stress-managed racetrack.
- No training with 12.3 T coil field, 170 MPa coil stress at BNL’s DCC17 facility.

LBNL’s wax impregnated sub-scale (5 T) CCT.
- First Nb$_3$Sn CCT without training.
- Alumina-filled wax considered for CCT6.

Wigner Inst. / CERN collaboration on SuShi septum for FCC-hh
- Wax impregnated CCT required no training to nominal current.
• Goal, demonstrate robust and cost-efficient Nb3Sn technology for next ESPPU.
• **Novel concept: Stress-managed asymmetric common coils (SMACC).**
  Design by D. Araujo.

\[
\begin{align*}
B_0 \text{ target of } & 14 \text{ T} \\
T_{\text{op}} & : 4.2 \text{ K} \\
\text{Eng margin of } & 10\% \\
a_x, b_x & < 15 \text{ units (r = 16.67 mm)} \\
\text{from } 1.5 \text{ T (injection) to } & 14 \text{ T} \\
I_{\text{op}} & : 13.1 \text{ kA} \\
B_0 \text{ short sample @ } & 1.9 \text{ K: } 16 \text{ T}
\end{align*}
\]

Intra-beam distance: 300 mm
Clear aperture of 50 mm
Straight-section of 500 mm
Yoke dia: 720 mm
Shell thickness: 35 mm
Total number of coils: 10
Coil types: 3 (re-use of tooling)
Cable types: 3

Stainless steel shell
Iron yoke
Coil collar
Non-magnetic poles
\(\text{Nb}_3\text{Sn} \text{ conductor} \)
Subscale Technical Design Status

Technical design moving forward; construction for Q2’24.

Winding above SM former.

Reaction with axial split.

All handling and assembly ...

Novel clamp structure to react dipole forces.

... with thick support plates.

Courtesy T. Michlmayr, D. Araujo, C. Müller, H. Rodrigues

<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>80-116</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>dipole field [T]</td>
<td>14 (Nb₃Sn) – 20 (HTS/ Hybrid)</td>
<td>8.33</td>
<td>8.33</td>
</tr>
<tr>
<td>circumference [km]</td>
<td>90.7</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 [10¹¹]</td>
<td>1</td>
<td>2.2</td>
<td>1.15</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>1020-4250</td>
<td>7.3</td>
<td>3.6</td>
</tr>
<tr>
<td>SR power / length [W/m/ap.]</td>
<td>13-54</td>
<td>0.33</td>
<td>0.17</td>
</tr>
<tr>
<td>long. emit. damping time [h]</td>
<td>0.77-0.26</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 [μm]</td>
<td>2.2</td>
<td>2.5</td>
<td>3.75</td>
</tr>
<tr>
<td>peak luminosity [10³⁴ cm⁻²s⁻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></td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td>integrated luminosity [fb⁻¹]</td>
<td>20000</td>
<td>3000</td>
<td>300</td>
</tr>
</tbody>
</table>

Ongoing work examples: Prototype Nb$_3$Sn Wire Development at UniGE

### Internal Oxidation in prototype multifilamentary wires

**1.** Average grain size: 200 nm

**2.** Average grain size: ~47 nm

**3.** Average grain size: ~45 nm

---

**Pushing Nb$_3$Sn towards its ultimate performance**

1. Refinement of the grain size: 100 nm $\rightarrow$ 50 nm

2. Large increase of the layer $J_c$ $\rightarrow$ exceeding the FCC target

3. Enhancement of $B_{c2}$ by $>1$ T $\rightarrow$ improved in-field performance

---

FCC Seminar 02.05.2023

A. Siemko – HFM R&D Programme

---

**Reference**

- Pushing Nb$_3$Sn towards its ultimate performance
  - Refinement of the grain size: 100 nm $\rightarrow$ 50 nm
  - Enhancement of $B_{c2}$ by $>1$ T $\rightarrow$ improved in-field performance

**Larger billets under development**

**Courtesy of C. Senatore**
Development of a single aperture 12 T “robust dipole” in INFN, Genova

Main characteristics:
- 2 layers; 50 mm bore
- Rutherford 40 strands ($\varphi = 1$ mm $Jc$ (4.5 K, 16 T)=1200 A/mm$^2$)
- Nominal magnetic field: 12 T
- Ultimate (mechanical limit) field: 14 T
- Short sample limit: 15.7 T
- Mechanical structure: bladder & key
- Stress in conductors $\leq$150 MPa in all conditions
- Outer diameter: 640 mm (LASA test)

Development of twin 12 T “robust dipole” at CERN

Both the INFN and CERN 12 T short robust dipole models are expected to be ready in 2025
CEA R&D towards 16 T Nb$_3$Sn block coil

F2D2 Short model
Grading + Flared-ends + Aperture, 16 T
1.5 m, 50 mm bore with aperture

FD Demonstrator
Grading + flared-ends, 14 T
1.5 m, No bore with flared ends

CEA-CERN R2D2
Demonstrate grading ≥ 12 T
1.5 m, No bore with grading

CEA-CERN SMC-11T coil ✓ Done
Demonstrate Nb$_3$Sn tech. ≥ 12 T

CEA R&D towards 16 T Nb$_3$Sn block coil

- 16 T Demo
- 14 T Demo
- Subscale Demonstrators
- Powered samples
- Non-powered samples

A. Siemko – HFM R&D Programme

FCC Seminar 02.05.2023
Overview

• CHART and MagDev and the HFM Program

• FCC-hh
  – LTS accelerator magnets
  – Main challenges
  – MagDev LTS technology program

  – HTS accelerator magnets
  – the promise
  – the difficulties
  – MagDev HTS technology program

• FCC-ee
  – Technology coils and P3 experiment
  – HTS4
  – MDI

• Muon Collider magnets

• Synergies
  – Neutron scattering
  – RICS proposal
  – Muon target study
• LDG Roadmap on High-Field Magnets, p. 33
  – “Consideration of only engineering current density would suggest that magnetic fields in the range of 25 T could be generated by HTS”
  – “… performance of HTS in the range 10−20K has reached values of $J_e$ well in excess of 500 to 800A/mm², i.e., the level that is required for compact accelerator coils. [...] it would open a pathway towards a reduction of cryogenic power, [and] a reduction of helium inventory (e.g., dry magnets)”

Fig. 2.3: Engineering current density $J_e$ vs. magnetic field for several LTS and HTS conductors at 4.2 K. Latest results for REBCO tapes are reported both at 4.2 K as well as 20 K.

Main Challenges with ReBCO

**Ramp losses and field quality**
- LTS wires have filament sizes of few microns (Nb-Ti) to 50 µm (Nb$_3$Sn).
- ReBCO tapes are 2-12 mm wide. Screening currents and associated ramp losses are substantially increased.
- Tape orientation matters!

**High-current, low-loss cables with windability**
- Do we need full transposition (every tape in a cable “sees” the same field, inductive loops are shortened)?
- Can we pre-fabricate a cable, or do we need to assemble and insulate it “on the fly” during winding?
- Can the cable withstand pressure of 400+ MPa?


[Figure 1.7. Material composition of ReBCO coated conductor. For visual clearness the tape is cut in half along its length such that the inside becomes visible. In reality the copper and the silver layers fully surround the hastelloy substrate carrier.]

[Figure 1.10. Three different geometries for assembling a cable with ReBCO coated conductor. Also refer to Table 1.2.]

Main Challenges with ReBCO

**Protection:**
- HTS conductors are intrinsically more thermo-electrically stable than LTS conductors.
- The same margins make detection of quenches and protection from quench-induced damage more challenging.
- Disruptive innovation is required, if we are to account also for quadratic scaling of stored magnetic energy with field,
- and the fact that cost considerations push magnet engineers towards higher engineering current-densities with lower stabilizing copper fraction.

**Mechanics:**
- Due to the quadratic scaling with field, mechanics of 20 T magnets is expected to be a formidable challenge.
- The robust operation of novel conductors and cable sin high-stress/strain conditions is yet to be studied.
- New mechanical concepts and novel materials may need to be explored.
• **Cryogenics**
  – Improved Carnot factor can offset increased ramp losses.
  – Only if ramp losses can be reduced sufficiently will this lead to a net saving in cooling power!
  – FCC-hh has short turnaround time: 6h nominal, 2h for HL-FCC-hh.
  – Ramp losses must be extracted quickly from SC coils.
  – Increased temperatures (10-20 K) and reduced cryogen inventory will lead to increased temperature gradients within magnets and along cryogenic circuits.
  – Co-development of magnet and cryogenic technologies are essential.

*Main Challenges with ReBCO*

![The Carnot Factor](Diagram.png)

[Graph for $T_{\text{warm}} = 300$ K: $\frac{T_{\text{cold}}}{T_{\text{warm}}} - 1 \propto \frac{T_{\text{cold}}}{T_{\text{warm}}}$]

- Use of low temperatures if no alternative
- Better intercept heat at higher temperatures

[Serge Claudet, Introduction to Cryogenics for accelerators, CAS on Vacuum for Particle Accelerators Glumslöv-ESS, SE 7-15 June 2017]
• **Numerics**
  – Aspect-ratio of physically relevant layers in ReBCO tape make modeling and homogenization in all physical domains difficult.
  – Shielding current calculation
  – Thermal modeling
  – Mechanical behavior
  – The community lacks a commonly agreed design approach/tool for HTS magnets.

• **Conductor-Cost**
  – The prediction of ReBCO tape cost is chronically difficult.
  – The price slope of the past 10 years predicts that a 10x increase in demand leads to a 2x decrease in cost.
  – Compact fusion startups have increased demand towards 10’000 km year.
  – FCC may need 1’000’000 km over 10 years.
  – Will energy transport applications bring the next step?
Any future accelerator-magnet system will be strongly coupled to other accelerator subsystems such as cryogenics, beam optics, powering, etc.

Novel conductors and cryogenics concepts will mean that this coupling is far more consequential and bi-directional than in past accelerators, HL-LHC included.

New systems-engineering methods of cooperation and negotiation of specifications across subsystem boundaries will be required.

CHART is developing tools for Model-based systems engineering (MagNum/MagNum2).
Magnet Technology Readiness Gap

Technology Readiness Levels

1. Basic Observations
2. Technology Conceptualized
3. Proof-of-Concept Validation
4. Partial-Scale Prototype & Modeling
5. Full-Scale Prototype Field Demonstration
6. Full-Scale Prototype In Commercial Conditions
7. Final Commercial Product Certification
8. Final Commercial Product is Bank-Financiable

- Bi-2212
- ReBCO@14 T
- Nb₃Sn@12 T
- Nb-Ti@9 T

Rough estimates; bottom line is:

HTS technology must catch up to LTS over the coming 10 years in TRL to LTS.
HTS Innovation Funnel for HFM

First deliverable:
- 2023: Materials and Numerical Design Studies
- 2023: Powered Cable Samples
- 2024: Technology Racetrack Coils
- 2025: Short Hybrid HTS/LTS Sub-Scale and Ultimate-Field Magnets (7…17 T)

#Deliverables / year:
- 100s
- 10
- 2
- 1

Short All-HTS Magnets (16…20 T) (4.2…20 K)

Courtesy D. Araujo, T. Michlmayr

Courtesy D. Sotnikov
MI approach for high field dipole (CERN-CEA HTS collaboration)

Thibault Lécrevisse - HTS magnet at CEA and HTS Cable for I.FAST CCT - HiTAT workshop 09/03/2022
Overview

• CHART and MagDev and the HFM Program
• FCC-hh
  – LTS accelerator magnets
  – Main challenges
  – MagDev LTS technology program
  – HTS accelerator magnets
  – the promise
  – the difficulties
  – MagDev HTS technology program
• FCC-ee
  – Technology coils and P3 experiment
  – HTS4
  – MDI
• Muon Collider magnets
• Synergies
  – Neutron scattering
  – RICS proposal
  – Muon target study
Technology Solenoid Program in the Cryogen-free test station

• Successful test in cryogen-free test station of 4-pancake HTS NI solenoid, built in-house at PSI and using licensed Tokamak Energy Ltd technology.
• Coil reached 18.2 T in the center, 20.3 T on the conductor at the maximum current of the power converter of 2 kA and 12 K coil temperature.

Diameter: 100 mm
Aperture: 50 mm
SC type: ReBCO
# tapes: 2
# turns: 2 x 170
SC length: 2 x 49 m
Collaboration between PSI and CERN with external partners:
CNRS-IJCLab (Orsay); INFN-LNF (Frascati); SuperKEKB – as observer, also interested in the $\text{P}^3$ experiment; INFN-Ferrara – radiation from crystal

See: M. Schär, CHART Annual Meeting, https://indico.psi.ch/event/14732/
PSI Positron Production (P3) Experiment

See: M. Schär, CHART Annual Meeting, https://indico.psi.ch/event/14732/
State of the art of e+ sources

• High e+ yield at DR is enabled to great extent by:
  – High e- energy
  – Strong solenoid fields around target and along capture linac
  – Large aperture

<table>
<thead>
<tr>
<th></th>
<th>SLC (SLAC) 1989 - 1998</th>
<th>SuperKEKB (KEK) ca. 2014 -</th>
<th>P³ (PSI) ca. 2026</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary e- energy [GeV]</td>
<td>30 - 33</td>
<td>3.5</td>
<td>6</td>
</tr>
<tr>
<td>Max. sol. field at Target [T]</td>
<td>5.5</td>
<td>3.5</td>
<td>12.7</td>
</tr>
<tr>
<td>Avg. sol. field along linac [T]</td>
<td>0.5</td>
<td>0.4</td>
<td>0.45</td>
</tr>
<tr>
<td>Min. RF cavity aperture [mm]</td>
<td>18</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>e+ yield at target exit</td>
<td>~30</td>
<td>~8</td>
<td>13.77</td>
</tr>
<tr>
<td>Max. meas. e+ yield at DR</td>
<td>~2.5</td>
<td>~0.4</td>
<td>~5.64</td>
</tr>
</tbody>
</table>

*expected at Faraday Cups

See: N. Vallis, Swiss Physical Society Annual Meeting, https://indico.cern.ch/event/1252545/

- Chaikovska et al., Positron sources: from conventional to advanced accelerator concepts–based colliders, JINST, 17, P05015 (2022)
HTS NI target solenoid, to demonstrate high-yield positron source concept
- stable DC operation,
- high thermal conduction due to solder impregnation to extract heat deposited in coils,
- radiation robustness due to absence of insulators.
All components in procurement. Construction starting soon.
Experiment at PSI’s SwissFEL 2026

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil diameter</td>
<td>122 mm inner, 219 mm outer</td>
</tr>
<tr>
<td>Stored energy</td>
<td>331 kJ</td>
</tr>
<tr>
<td>Operating current</td>
<td>1.17 kA</td>
</tr>
<tr>
<td>Charging constant</td>
<td>11 hours</td>
</tr>
</tbody>
</table>

15 K conduction-cooling
5 coils from 12 mm ReBCO
Solid-state (Pb) thermal buffer
15 T in 72 mm warm bore
21 T on conductor

Solid-state (Pb) thermal buffer

Courtesy J. Kosse, T. Michlmayr, H. Rodrigues
FCC-ee NC Magnets

2900 magnets
Strength: 57 mT
Apert.: 130x84 mm
Power: 13.3 MW

4672 magnets
Strength: 807 T/m²
ID: 76 mm
Power: 20.5 MW

Table 3.1. Parameters of the main bending magnets.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength, 45.6 GeV-182.5 GeV</td>
<td>14.1-56.6</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>mT 21.94/23.94</td>
</tr>
<tr>
<td>Number of units per ring</td>
<td>2900</td>
</tr>
<tr>
<td>Aperture (horizontal x vertical)</td>
<td>130 x 84</td>
</tr>
<tr>
<td>Good field region (GFR) in horizontal plane</td>
<td>±10</td>
</tr>
<tr>
<td>Field quality in GFR (not counting quadrupole term)</td>
<td>10⁻⁴ ≈1</td>
</tr>
<tr>
<td>Central field</td>
<td>mT 57</td>
</tr>
<tr>
<td>Expected by at 10 mm</td>
<td>10⁻⁴ ≈3</td>
</tr>
<tr>
<td>Expected higher order harmonics at 10 mm</td>
<td>10⁻⁴ ≈1</td>
</tr>
<tr>
<td>Maximum operating current</td>
<td>kA 1.9</td>
</tr>
<tr>
<td>Maximum current density</td>
<td>A/mm² 0.79</td>
</tr>
<tr>
<td>Number of bushings per side</td>
<td>2</td>
</tr>
<tr>
<td>Resistance per unit length (twin magnet)</td>
<td>22.7 μΩ/m</td>
</tr>
<tr>
<td>Maximum power per unit length (twin magnet)</td>
<td>W/m 164</td>
</tr>
<tr>
<td>Maximum total power, 81.0 km (interconnections included)</td>
<td>MW 13.3</td>
</tr>
<tr>
<td>Inter-beam distance</td>
<td>mm 300</td>
</tr>
<tr>
<td>Iron mass per unit length</td>
<td>kg/m 219</td>
</tr>
<tr>
<td>Aluminium mass per unit length</td>
<td>kg/m 19.9</td>
</tr>
</tbody>
</table>

Table 3.2. Parameters of the main quadrupole magnets.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum gradient</td>
<td>T/m 10.0</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>m 3.1</td>
</tr>
<tr>
<td>Number of twin units per ring</td>
<td>2900</td>
</tr>
<tr>
<td>Aperture diameter</td>
<td>mm 84</td>
</tr>
<tr>
<td>Radius for good field region</td>
<td>mm 10</td>
</tr>
<tr>
<td>Field quality in GFR (not counting dip. term)</td>
<td>10⁻⁴ ≈1</td>
</tr>
<tr>
<td>Maximum operating current</td>
<td>A 474</td>
</tr>
<tr>
<td>Maximum current density</td>
<td>A/mm² 2.1</td>
</tr>
<tr>
<td>Number of turns</td>
<td>2 x 30</td>
</tr>
<tr>
<td>Resistance per twin magnet</td>
<td>kΩ 33.3</td>
</tr>
<tr>
<td>Inductance per twin magnet</td>
<td>H 81</td>
</tr>
<tr>
<td>Maximum power per twin magnet</td>
<td>kW 7.4</td>
</tr>
<tr>
<td>Maximum power, 2000 units (with 5% cable losses)</td>
<td>MW 22.6</td>
</tr>
<tr>
<td>Iron mass per magnet</td>
<td>kg 4400</td>
</tr>
<tr>
<td>Copper mass per magnet (two coils)</td>
<td>kg 820</td>
</tr>
</tbody>
</table>

Table 3.3. Parameters of the main sextupole magnets.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum strength, B²</td>
<td>T/m² 807.0</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>m 1.4</td>
</tr>
<tr>
<td>Number of units per ring</td>
<td>208 x 4  832 (Z, W)</td>
</tr>
<tr>
<td>Number of families per ring</td>
<td>206 (Z, W)</td>
</tr>
<tr>
<td>Number of families per ring</td>
<td>202 (II, II)</td>
</tr>
<tr>
<td>Aperture diameter</td>
<td>mm 76</td>
</tr>
<tr>
<td>Radius for good field region (GFR)</td>
<td>mm 10</td>
</tr>
<tr>
<td>Field quality in GFR</td>
<td>10⁻⁴ ≈1</td>
</tr>
<tr>
<td>Ampere turns</td>
<td>A 6270</td>
</tr>
<tr>
<td>Current density</td>
<td>A/mm² 7.8</td>
</tr>
<tr>
<td>Maximum power per single magnet at 182.5 GeV</td>
<td>kW 15.5</td>
</tr>
<tr>
<td>Average power per single magnet at 182.5 GeV</td>
<td>kW 4.4</td>
</tr>
<tr>
<td>Total power at 182.5 GeV (4672 units)</td>
<td>MW 20.5</td>
</tr>
</tbody>
</table>

FCC-ee Short Straight Section

By using **HTS sextupoles and quadrupoles** instead of the RT baseline, HTS4 aims to:

- **Reduce energy consumption** from up to 80 MW (43 MW in CDR) to ~10 MW
- Increase dipole filling factor – decrease SR
- Enhance optics flexibility

**Challenges:**

- **Accelerator-grade field quality** with HTS
- Balance **cooling** power with **conductor** volume
- **High-reliability** cryocooler-based operation
- **Low heat-load** powering
- Mitigation of **radiation** issues on electronics

**Sub-scale coils (start Q4’23)** and **1-m prototype module** to be constructed and tested at PSI.
• In support of FCCee HTS4, CPES develops a cryogenic power supply which, in its first iteration, may reduce heat load to the cryo-cooler by 50%.

• CPES development follows specifications provided by CERN power-supply specialists.

• The CPES unit may incorporate magnet protection functionality.

• Cold-testing and integration studies at PSI cryogen-free test station.

Courtesy J. Huber
• **22 superconducting magnets:**
  – 6 final focus (ID 40 mm, 100 T/m),
  – 12 correctors
  – 2 compensation solenoids (4.9 T, 118-195 mm tapered)
  – 2 screening solenoids (2 T, OD 390 mm)
• **Most located SC magnets in the heart of the detector.**
• **High complexity due to multiple strongly coupled systems:** IP, detector solenoid (forces and protection), mechanics and alignment, beam dynamics, etc.

[M. Boscolo, Pre-engineering design review and roadmap discussion for FCC-ee IR magnets, April 2022]
FCC-ee Final Focus Quadrupoles

- Current final focus design based on CCT concept.
- Room-temperature measurement of field quality < 0.15 units.
- May soon be impregnated with wax at PSI.
- To be tested at cold at CERN.

[M. Koratzinos, Pre-engineering design review and roadmap discussion for FCC-ee IR magnets, April 2022]
Overview

• CHART and MagDev and the HFM Program

• FCC-hh
  – LTS accelerator magnets
    – Main challenges
    – MagDev LTS technology program
  – HTS accelerator magnets
    – the promise
    – the difficulties
    – MagDev HTS technology program

• FCC-ee
  – Technology coils and P3 experiment
  – HTS4
  – MDI

• Muon Collider magnets

• Synergies
  – Neutron scattering
  – RICS proposal
  – Muon target study
Muon Collider magnets

**Muon Collider magnets**

HTS !

20 T, 200 mm
Radiation heat load ≈ 5…10 kW
Radiation dose: 80 MGy

<table>
<thead>
<tr>
<th>HTS ?</th>
<th>SC dipole</th>
<th>NC dipole</th>
<th>NC dipole</th>
<th>SC dipole</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>NC ±1.8 T, 400 Hz</th>
<th>100 mm x 30 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation heat load ≈ 5 W/m</td>
<td>Radiation dose ≈ 20…40 MGy</td>
</tr>
</tbody>
</table>

HTS !

Proton Driver
- SC Linac
- Accumulator
- Buncher
- Combiner

Front End
- MW-Class Target
- Capture Sol.
- Decay Channel
- Buncher
- Phase Rotator
- Initial 6D Cooling
- Charge Separator
- 6D Cooling
- Bunch
- Merge
- 6D Cooling
- Final Cooling

 Cooling
- Acceleration
  - RCS
  - Accelerators: Linacs, RLA or FFAG, RCS

Collider Ring
- $E_{\text{CoM}}$: Higgs Factory to ~10 TeV
- $\mu^+$
- $\mu^-$

Slides courtesy of L. Bottura for the for the Muon Magnets Working Group
Overview

• CHART and MagDev and the HFM Program

• FCC-hh
  – LTS accelerator magnets
    – Main challenges
    – MagDev LTS technology program
  – HTS accelerator magnets
    – the promise
    – the difficulties
    – MagDev HTS technology program

• FCC-ee
  – Technology coils and P3 experiment
  – HTS4
  – MDI

• Muon Collider magnets

• Synergies
  – Neutron scattering
  – RICS proposal
  – Muon target study
Split Solenoid for Neutron Scattering?

18 T NI HTS solenoid  Predict with simulation  10 mm split NI HTS solenoid

18 T at 2 kA, 12 K
4 coils

~18 T at max 2 kA
6 coils

Courtesy J. Kosse
• Proposed upgrade of the manipulator used in the RIXS beamline at SLS for soft X-ray scattering experiments.
• Supply a high magnetic field (up to 6 T) on the target.
Other Technology Development with Potential for Synergies

• HTS low-loss cables.
• Low-loss powering.
• Compact protection.
• Efficient thermal design.
• Compact magnets.

• Room-plug standalone magnet systems with cold or warm bore for lab research.
Conclusion

• An ambitious SC magnet R&D program has been set up within CHART at PSI and in other national labs (CEA, CIEMAT, INFN) and at CERN.

• These are exciting times to work on SC accelerator magnets.
  – LTS magnets will see innovative technological solutions in the coming years to reach performance, robustness, and cost targets.
  – The HTS revolution is becoming real.
    – We are researching the building blocks of HTS accelerator magnet technology.
    – Challenges are real and should not be underestimated.
    – Momentum is building and ideas abound.

• Collaboration, coordination, and communication will be the key to an innovative and ultimately successful European R&D network that creates technology to enables the HEP adventures of the future.