Concept of a hybrid (normal and superconducting) bending magnet based on iron magnetization for 80-100 km lepton / hadron colliders

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Tentative parameters for Future Circular Colliders (FCC) at CERN.

**FCC-hh**
- proton-proton collisions at a c.m. energy of 100 TeV
- 100 km (80 km) circumference
- dipole field 16 T (20 T)
- arc filling factor 0.79
- injection energy 3.3 TeV

**FCC-ee**
- electron-positron collisions at a c.m. energy from 91 GeV (Z-pole) up to 350 GeV (t-tbar threshold), passing through the Higgs resonance at 240 GeV
- 100 km circumference
- 100 MW synchrotron radiation power
A sizable addition to the CERN accelerator complex.
The accelerator chain needs to be re-thought to properly feed the large colliders, while delivering beams at intermediate energies for other unique physics.
The magnets for FCC-hh and FCC-ee colliders would be rather different. Focusing though on the injectors, there might be some synergies.

This is the focus of this talk.
Bending magnets
FCC-hh high energy injector
Options to inject into FCC-hh

Assumption: no dedicated new tunnel for a high energy injector.

- ... SPS ⇔ LHC ⇔ FCC-hh with LHC magnets ramped up to ≈ 4 T: an expensive injector to set up (≈ 3.3 TeV transfer lines), to operate and to maintain
- ... SPS ⇔ inj. in SPS tunnel ⇔ FCC-hh with fast ≈ 15 T (Nb₃Sn) magnets in SPS tunnel
- ... SPS ⇔ inj. in FCC tunnel ⇔ FCC-hh with 1.1 T superferric magnets

Here we focus on this option and on a concept for these magnets.
FCC-hh and its higher energy injector

These bending magnets shall be:

- double aperture, “up” and “down” field configuration, for counter rotating hadron beams
- compact, to leave tunnel space to the high field magnets
- as cheap as possible to manufacture, to operate and to maintain
- possibly enabling continuous operation for other physics in parallel to high energy frontier
  - ex.: from start of LHC operation, the SPS worked for LHC not even 5% of its time
  - ramped relatively fast
  - low power consumption
A conceptual cross-section for FCC-hh injector dipole

- "transmission line", superferric, 2-in-1 dipole
- apertures stacked vertically
  - magnetic reluctances of the 2 gaps not in series
  - field in 2nd gap comes for free with the return cable
  - C opening on the outside for both apertures, better for the emitted synchrotron radiation
  - same length for both rings, so no need for crossing to synchronize beams for simultaneous injection
  - increased mechanical stiffness
- tentative dimensions
  - vertical full gap 50 mm (each)
  - good field region of the order of ±20 mm (at ±5 \times 10^{-4})
  - overall diameter of cryostated cable 100 mm
  - 32 \times 60 \text{ cm} outer dimensions
- 50 kA for 1.1 T field (3.4 TeV)
- superconductor and cooling to be defined
  - depends on overall optimization
- 1-turn design: bus-bar coils, minimum inductive voltage for given dB/dt and volume
Resistive vs. superconducting

Resistive
- peak power (in magnets only) of **100 MW** with coil operating at low current density (1 A/mm²)
- overall size 54 x 108 cm
- 45 kA for 1.1 T in bore
- parallel physics?

Superconducting
- cryogenic power to be evaluated, function of cycle (ramp rate and frequency), superconducting material, operating temperature, cryostat design
- overall size 32 x 60 cm
- 50 kA for 1.1 T in bore
- peak power (in magnets only) of 100 MW with coil operating at low current density (1 A/mm²)
Bending magnets

FCC-ee high energy injector
Top energy booster for $e^+ / e^-$

- short lifetimes (some tens of minutes) in FCC-ee collider, so continuous top-up injection
- the baseline is a booster in FCC tunnel
  - used alternatively for $e^+$ and $e^-$ beams
  - beam currents $\ll$ than collider
  - maximum repetition rate around 0.1 Hz
- injection: 10-40 GeV (30 GeV $\Rightarrow$ $B = 0.010$ T)
- extraction: top energy, depends on excited resonance, for example
  - 120 GeV for Higgs, $B = 0.038$ T
  - 175 GeV for top quark, $B = 0.056$ T

Can we use the same magnets as in the high energy hadron injector?

- much lower fields, excitation current $\approx 2.5$ kA (instead of 50 kA)
- 2 apertures, but same polarity (counter rotating $e^+/e^-$): use the gaps one at a time with a bipolar power supply
A step in the past: LEP dipoles

A resistive transmission line magnet

- steel-concrete cores, 5.75 m long each
- injection: 20 GeV, 0.021 T
- top energy: 100 GeV, 0.110 T
- excitation current of 4.5 kA provided by 4 large water cooled aluminium bars (j = 0.8 A/mm²)
Hadrons and leptons: field range in FCC injector

450 GeV, $B = 0.14$ T

$\downarrow$

3.5 TeV, $B = 1.1$ T

$\downarrow$

30 GeV, $B = 0.010$ T

$\downarrow$

125 GeV (Higgs), $B = 0.040$ T

0.010 T too low?

1.1 T / 0.010 T = 110: too much?

17 Jun. 2014
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Minimum field in an iron dominated magnet

0.010 T too low? (is iron dilution needed?)

- LEP main dipoles: 0.021 T at injection in the gap, 0.27 filling factor in the cores
- Measurements on a prototype LEP dipole with an undiluted core showed satisfactory field quality down to ≈ 0.014 T

With (possibly) some forgiveness on field quality (for the lepton booster) and a core material with proper characteristics, the range around 0.010 T seems viable.

IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

IMPLICATIONS OF THE LOW FIELD LEVELS IN THE LEP MAGNETS

J.P. Gourber and L. Resegotti
Same magnets for p and e?

0.010 T too low? (is iron dilution needed?)
A factor of 110 too large for the yoke?

SPS at CERN

- LHC era: protons up to 450 GeV, 2.02 T
- LEP time: electrons / positrons injected at 3.5 GeV, so 0.016 T
- 2.02 T / 0.016 T = 129, so 110 seems viable
Options for the cable
Options for the cable

leptons $\approx 2.5 \text{kA}$  

hadrons $\approx 50 \text{kA}$

Option 1: change it

- standard resistive cable at first for electrons
- upgrade to 50 kA class superconducting cable for hadrons

Option 2: a “super-resistive” cable

- use the stabilizer in the superconducting cable itself for leptons
- then use the cable in a proper superconducting way for hadrons
- cooling compatibility between demineralized water and a cryogenic fluid to be properly handled
Options for superconductor

Choice depends on many factors and overall optimization

- large volume availability and form (wire, tape)
- operating temperature
- capital cost: material, cable manufacturing, cryogenic system
- running cost: for the cryogenic system, and for maintenance
- protection issues

**Nb-Ti:** cheapest and most available option, easy to handle, though needs a low operating temperature, possibly with supercritical He

**HTS, bismuth or rare earth based:** their cost will likely decrease in the future, higher operating temperature

**MgB$_2$:** promising in terms of cost, higher operating temperature than Nb-Ti, but still He based (40-m long cable developed at CERN, tested up to 20 kA at 24 K)
Conclusion
FCC-ee / FCC-hh in a 100 km tunnel at CERN will need an adapted injector chain

An option is a high energy injector synchrotron in the same tunnel

A first concept has been presented for the bending magnets of such high energy injectors, in the light of similar dipoles proposed for large synchrotrons (transmission line magnets)

The proposal is to use a compact iron dominated design

- double aperture
- a 50 kA class superconducting cable for hadron operation
- much lower excitation current (resistive) for lepton operation
- possibly combined function, to limit the number of quadrupoles in the arcs

Possible synergies between FCC-ee and FCC-hh magnet injector needs

Compatible to parallel physics with TeV range proton beams
Thank you.
- Extra slides –

Some past proposals and prototype magnets for large synchrotrons (colliders / injectors).
Superferric magnets for large synchrotrons

- Snowmass 1982, R. R. Wilson (referring to an older paper by Shelaev et al. of JINR, Dubna), the “Pipetron”
  Concept of 2.5 T superferric dipole, aperture 1 in. × 2 in., powered by four straight bars of Nb$_3$Sn.
  Artist’s conception of the 3-foot “tunnel” and the bending magnets.

- Superferric magnet options for SSC, with much work in Texas Accelerator Center:
  ≈ 25 models built and tested, including a 7-m and a 28-m 2-in-1 dipole.
  Superferric options laid to rest for SSC in 1986. SSC laid to rest in 1993.
  A cross-section of the 7-foot tunnel.
Superferric magnets for large synchrotrons

- **Snowmass 1996, low field option for a Really Large Hadron Collider (RLHC)**, G. W. Foster, E. Malamud (also Kovalenko, Baldin from JINR, Dubna, with Nuclotron-type cable)

  1.8 T, 646 km circumference for 100 TeV
  Double-C twin bore transmission line combined function dipole.

- **2001, Design Study for a Staged Very Large Hadron Collider (VLHC)**
  Stage 1: superferric magnets

  2.0 T, 233 km circumference for 40 TeV
  A cross-section of the 12-foot tunnel.

Cross-section of the transmission line magnet yoke

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Superferric magnets for large synchrotrons

- EPAC 2006, thoughts about VLHC Stage 1 kind magnets for a two-beam Low Energy Ring (LER) in the LHC tunnel

  450 GeV to 1.5 TeV, 1.6 T with 55 kA
  LER ring above the LHC magnets in the 3.8 m diameter tunnel

- 2010, HE-LHC Malta Workshop

  For an injector of High Energy LHC (33 TeV c.m. energy in LHC tunnel), H. Piekarz analysis of
  1) a S-SPS at 1 - 1.3 TeV, with superconducting fast ramping magnets, up to 4.5 - 5.9 T, and superconducting transfer lines to LHC (possibly with Tevatron magnets)
  2) a Low Energy Ring directly in LHC tunnel

  450 GeV to 1.65 TeV, 1.76 T with 83 kA
  2) cheaper than 1) for both installation and running costs

Arrangement of LER and HE-LHC magnets in the LHC tunnel
A built & tested transmission line magnet

A 2 T superconducting transmission line test magnet designed, built and tested at Fermilab.

- double C, 2 aperture side by side, combined function magnet
- prototype magnet 1.5 m long, 90 kA for 2 T in each gap
- 288 Nb-Ti 0.65 mm diameter strand, 80 mm outer diameter of cable cryostat
- designed for 100 kA up to 6.5 K, with a 2 K margin w.r.t. 4.5 K of liquid helium
- the cable performed as expected with the maximum observed current of 103.8 kA
- measured magnetic field properties in the range needed for the VLHC Stage 1

More recently also in HTS

A fast cycling 1.75 T superconducting transmission line test magnet, also at Fermilab.

- H design, single 40 mm aperture, single turn HTS cable, prototype magnet 1.2 m long
- cable capable to carry 80 kA current up to a temperature of 20 K
- proposed for fast cycling machines, like for example a muon collider