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

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Introduction: FCC

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

FCC-hh

EDMS NO.	REV.	VALIDITY
1342402	1.0	RELEASED

PROJECT DOCUMENT IDENTIFIER
FCC-ACC-SPC-0001

Date : 2014-02-11

Specification

Future Circular Collider Study
Hadron Collider Parameters

WBS PATH

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

EDMS NO.	REV.	VALIDITY
1346082	1.0	RELEASED

PROJECT DOCUMENT IDENTIFIER
FCC-ACC-SPC-0004

Date : 2014-02-10

Specification

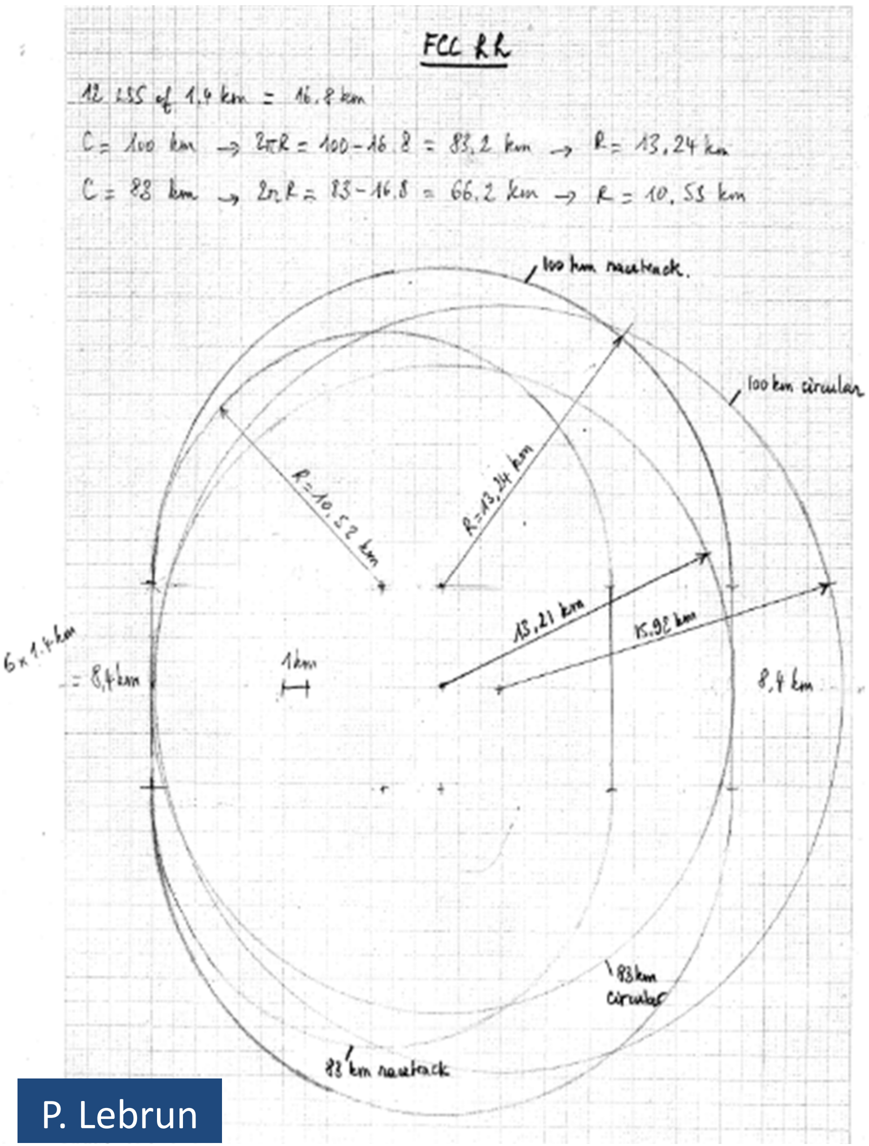
Future Circular Collider Study
Lepton Collider Parameters

WBS PATH
1.4.1.2

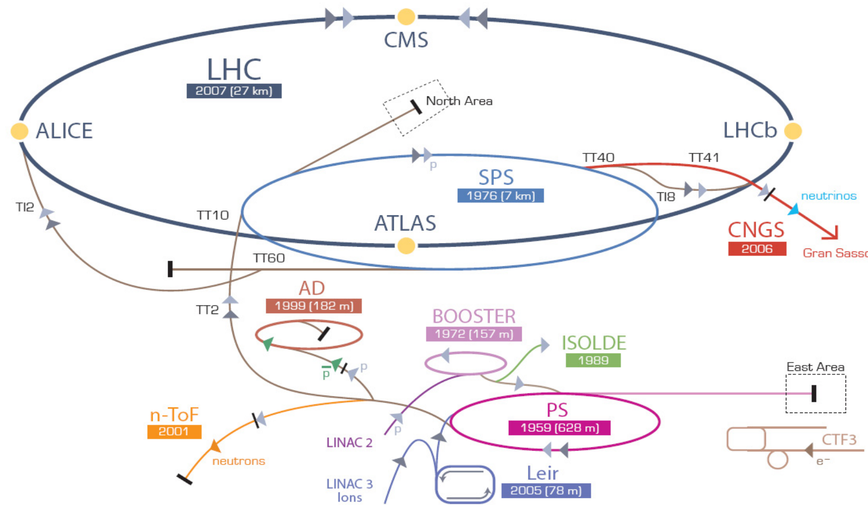
FCC-ee

- 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

Introduction: FCC



P. Lebrun



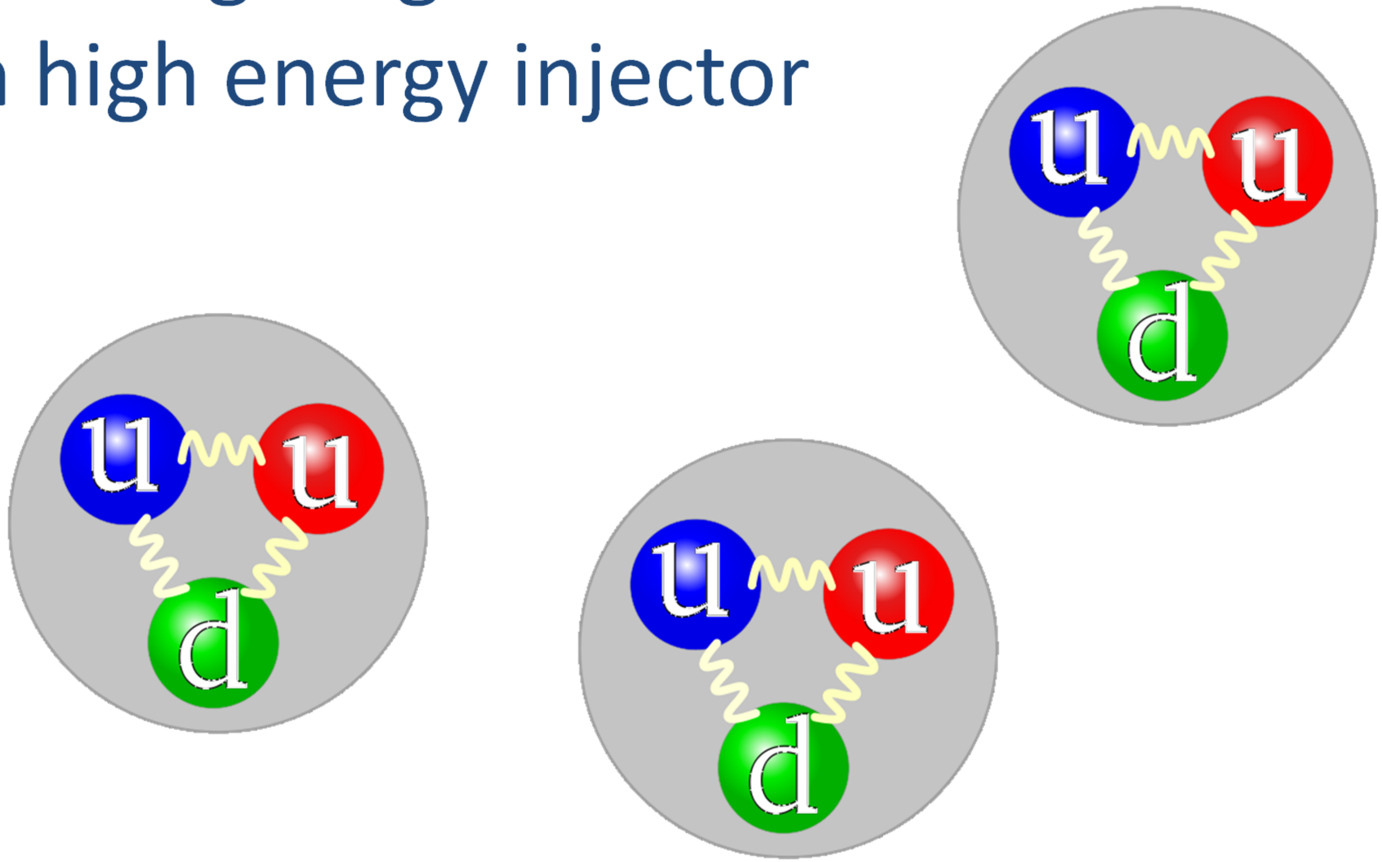
A sizable addition to the CERN accelerator complex.

The accelerator chain needs to be re-thought to properly feed the large colliders, while delivering beams at intermediate energies for other unique physics.

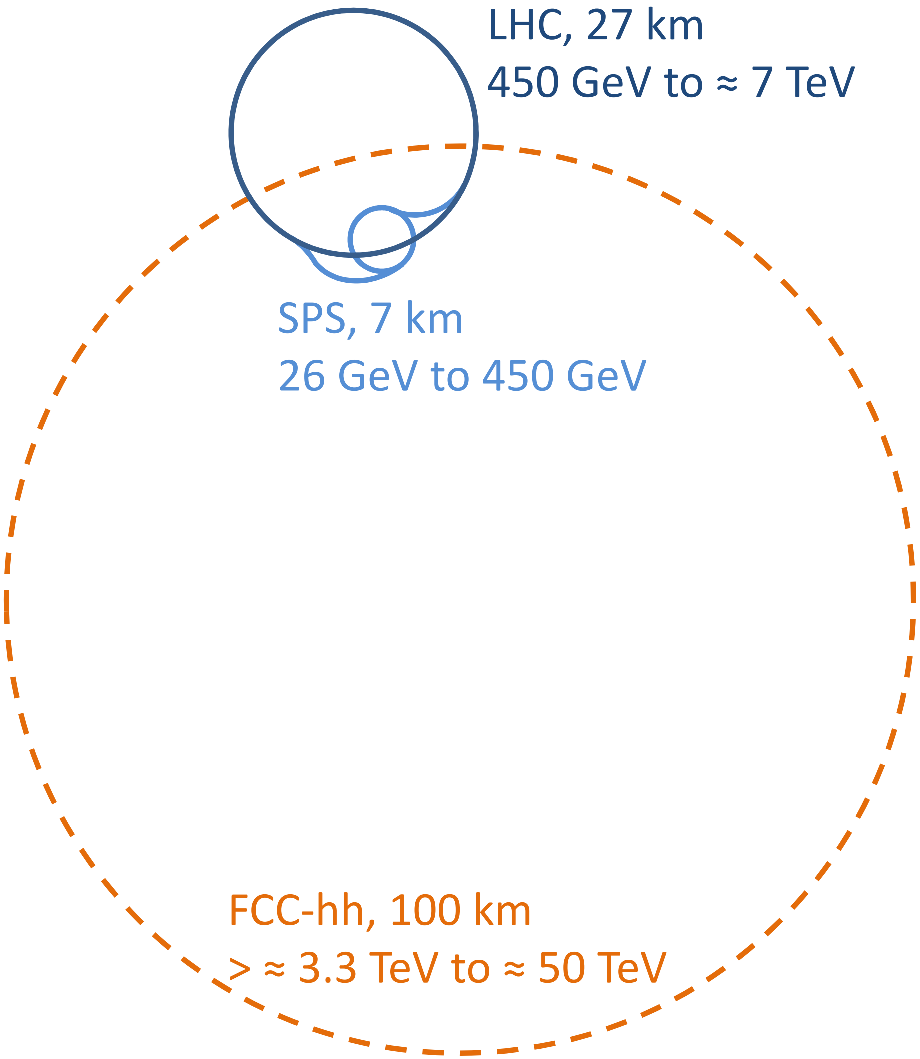
The magnets for FCC-hh and FCC-ee colliders would be rather different. Focusing though on the <u>injectors</u>, there might be some synergies.

This is the focus of this talk.

Bending magnets
FCC-**hh** high energy injector



Options to inject into FCC-hh

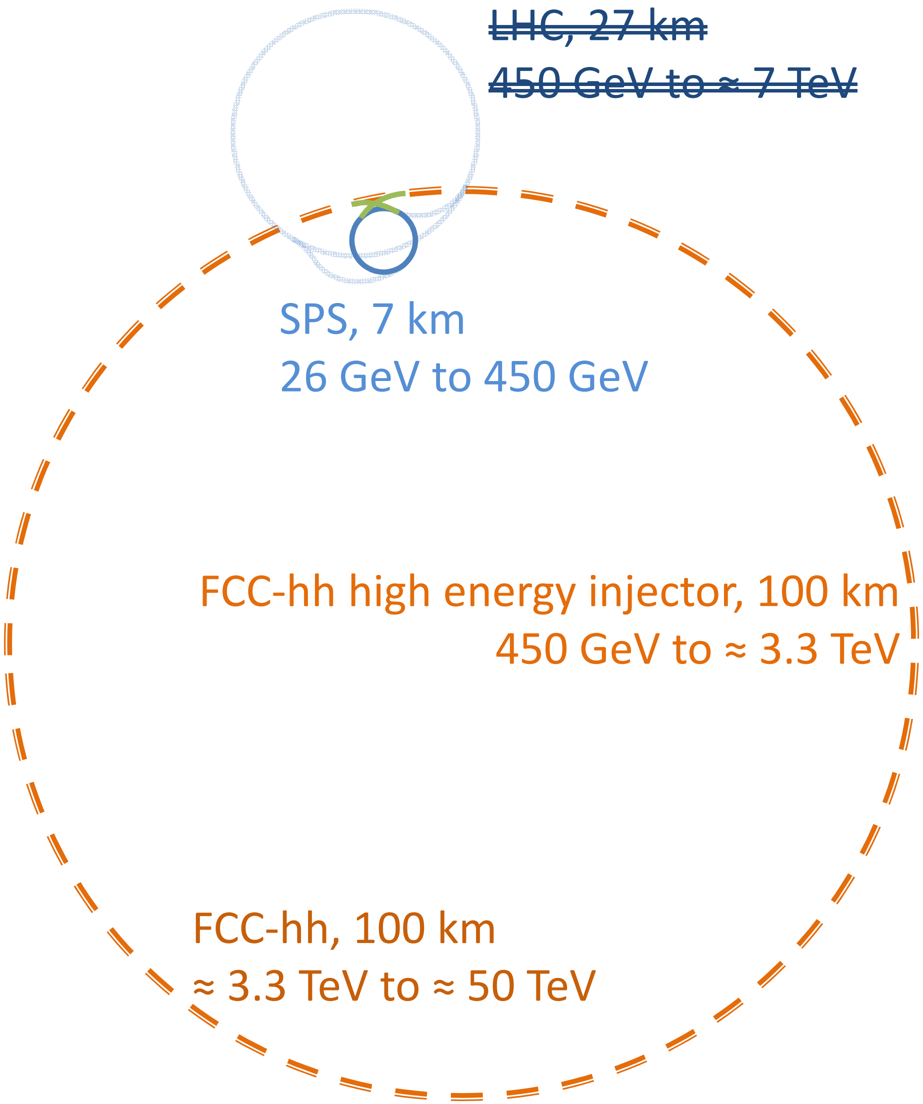


Assumption: no dedicated new tunnel for a high energy injector.

- … 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 (Nb_3Sn) 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

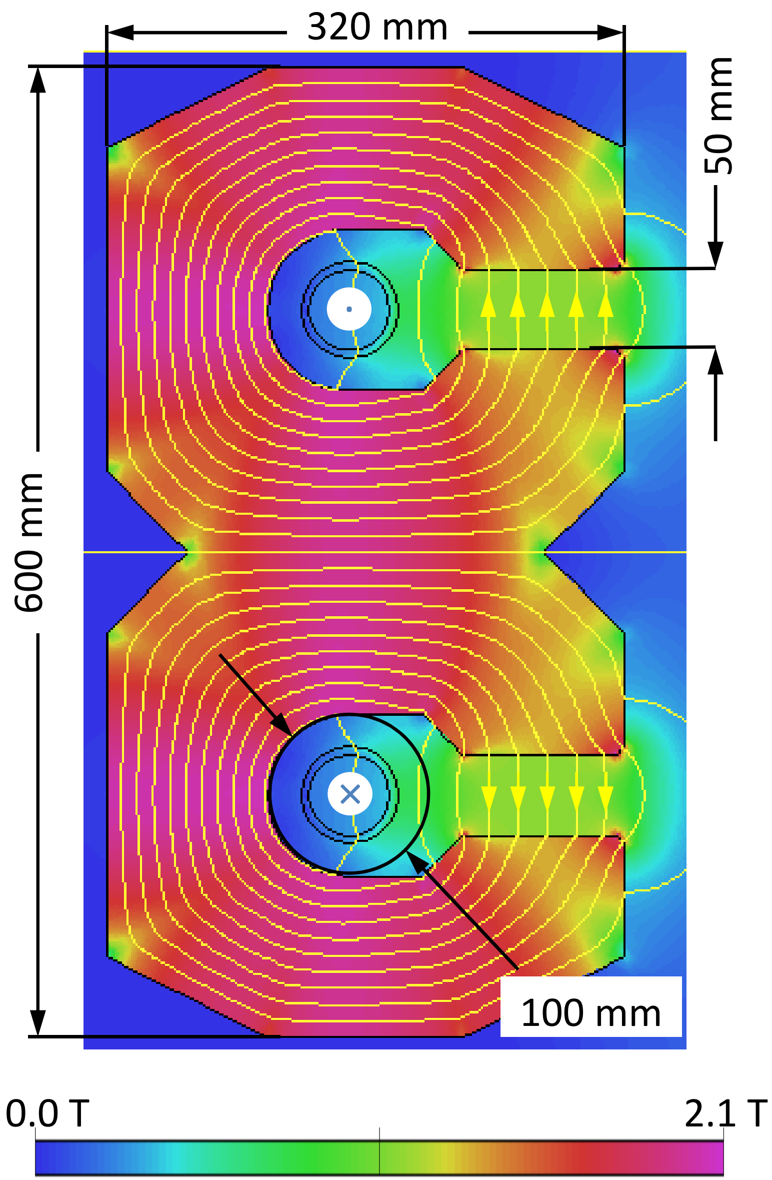


… SPS ⇨ inj. in FCC tunnel ⇨ FCC-hh

These bending magnets shall be:

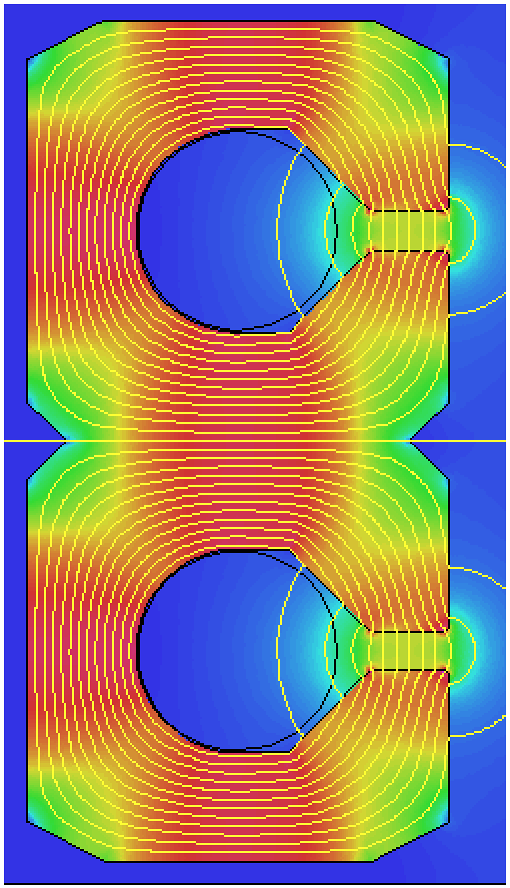
- double aperture, “up” and “down” field configuration, for counter rotating hadron beams
- compact, to leave tunnel space to the high field magnets
- as cheap as possible to manufacture, to operate and to maintain
- possibly enabling continuous operation for other physics in parallel to high energy 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



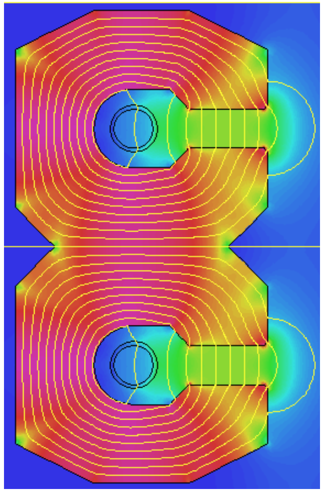
- "transmission line", superferric, 2-in-1 dipole
- apertures stacked vertically
  - magnetic reluctances of the 2 gaps not in series
  - field in 2nd gap comes for free with the return cable
  - C opening on the outside for both apertures, better for the emitted synchrotron radiation
  - same length 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 $\pm 5\cdot 10^{-4}$)
  - overall diameter of cryostated cable 100 mm
  - 32 × 60 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

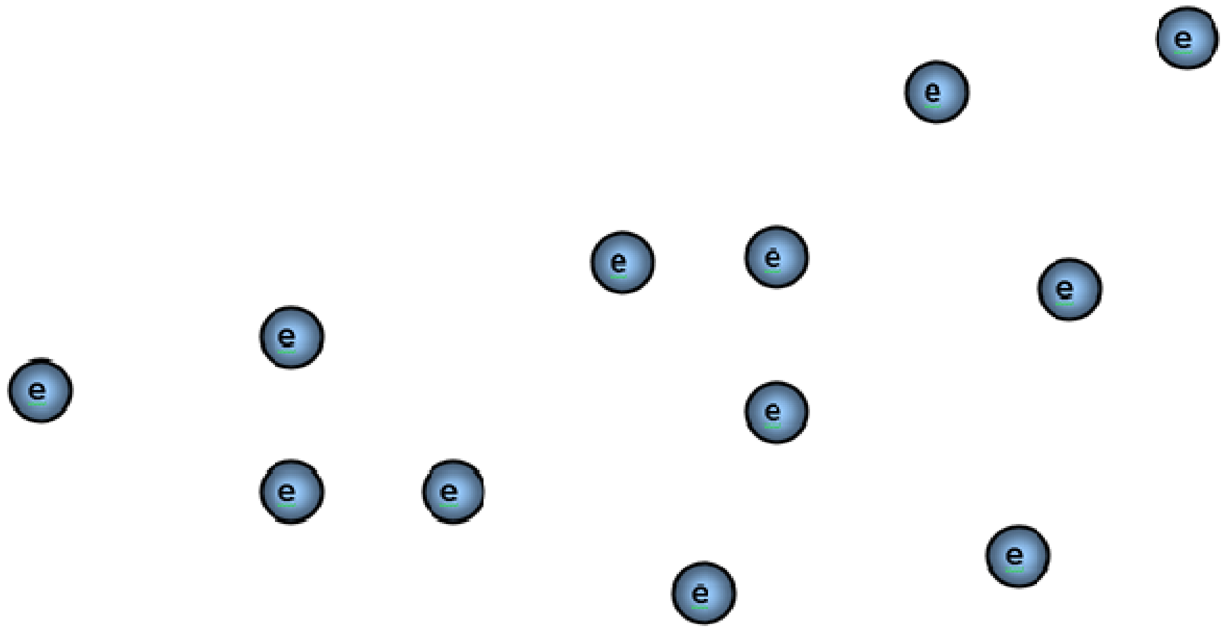
- peak power (in magnets only) of 100 MW with coil operating at low current density (1 A/mm^2)
- overall size 54 x 108 cm
- 45 kA for 1.1 T in bore
- parallel physics?



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/mm^2)

Bending magnets
FCC-**ee** high energy injector



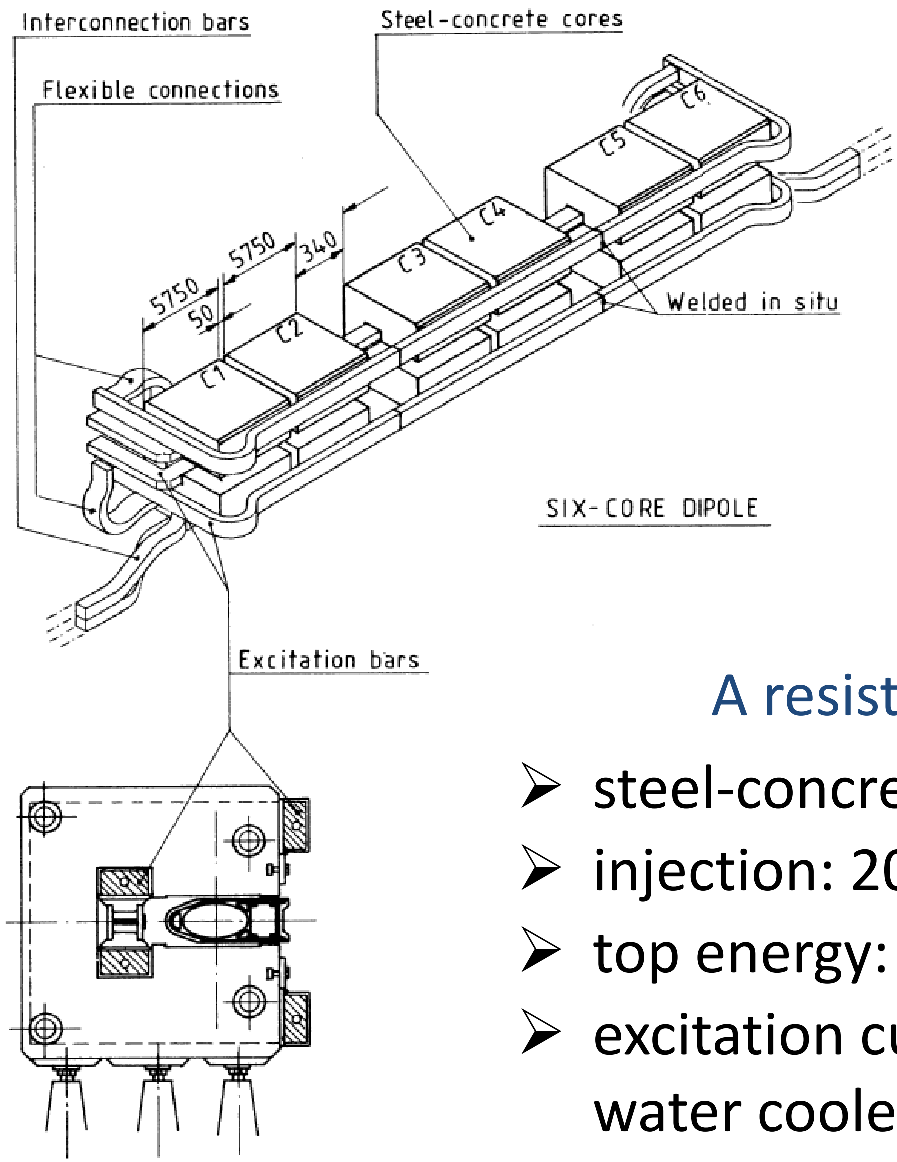
Top energy booster for e^+ / e^-

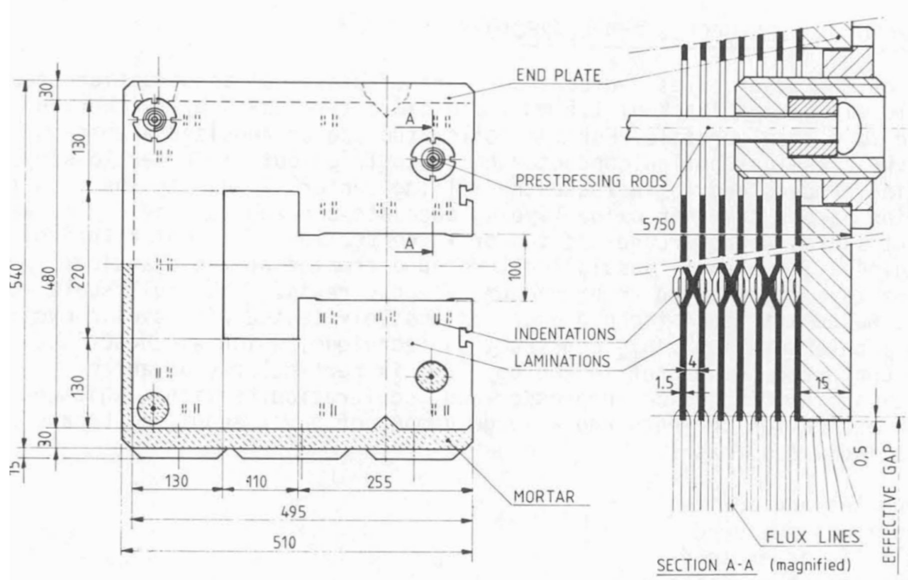
- short lifetimes (some tens of minutes) in FCC-ee collider, so continuous top-up injection
- the baseline is a booster in FCC tunnel
  - used alternatively for e^+ and e^- beams
  - beam currents ≪ than collider
  - maximum repetition rate around 0.1 H
- injection: 10-40 GeV (30 GeV ⇨ B = 0.010 T)
- 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 ≈ 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

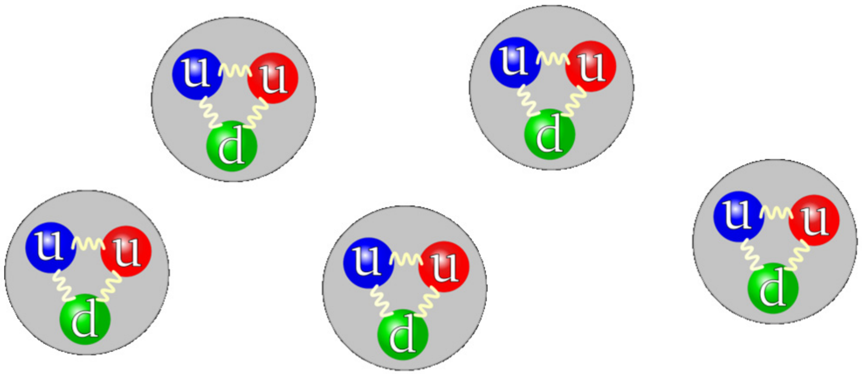




A resistive transmission line magnet

- 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/mm^2)

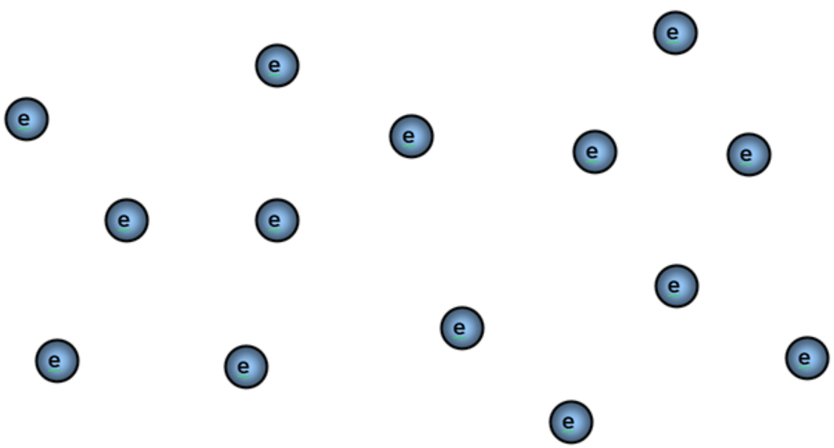
Hadrons and leptons: field range in FCC injector



450 GeV, B =0.14 T

⇩

3.5 TeV, B = 1.1 T



30 GeV, B = 0.010 T

⇩

125 GeV (Higgs), B = 0.040 T

0.010 T too low?

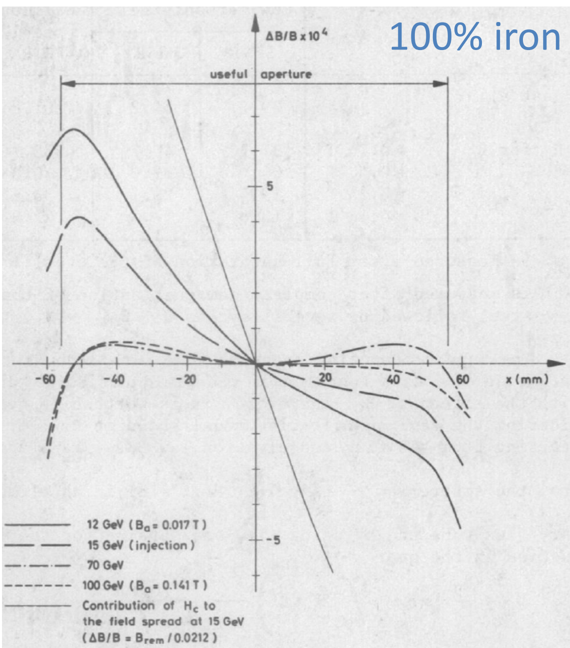
1.1 T / 0.010 T = 110: too much?

Minimum field in an iron dominated magnet

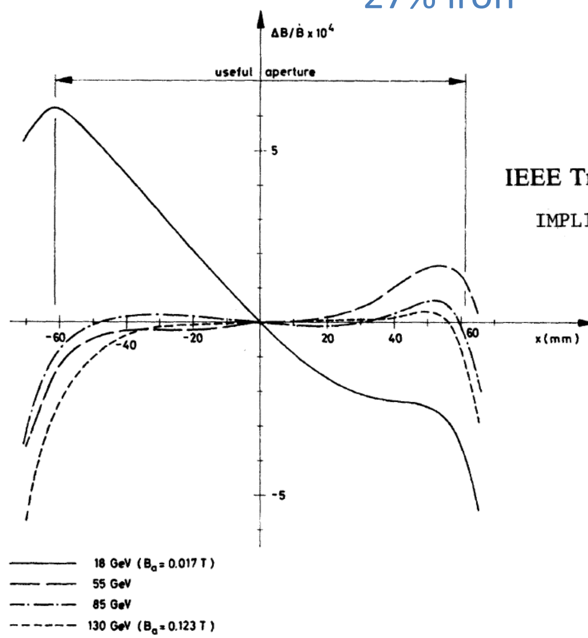
0.010 T too low? (is iron dilution needed?)

- 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

100% iron



27% iron



measured field uniformity

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

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.

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 ≈ 2.5 kA

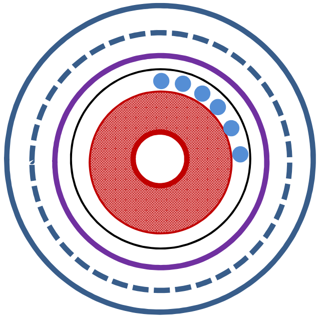
hadrons ≈ 50 kA

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

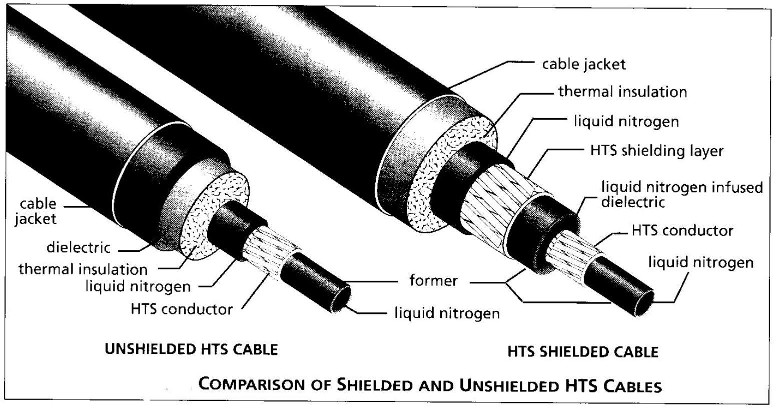
- use the stabilizer in the superconducting cable itself for leptons
- then use the cable in a proper superconducting way for hadrons
- cooling compatibility between demineralized water and a cryogenic fluid to be properly handled



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

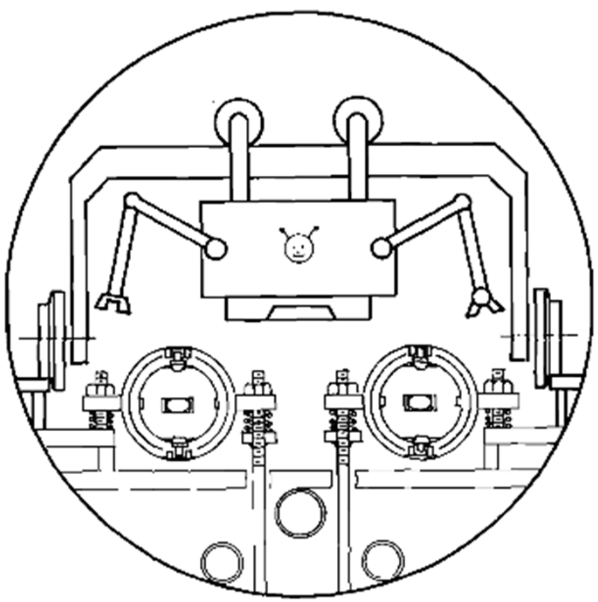
Conclusion

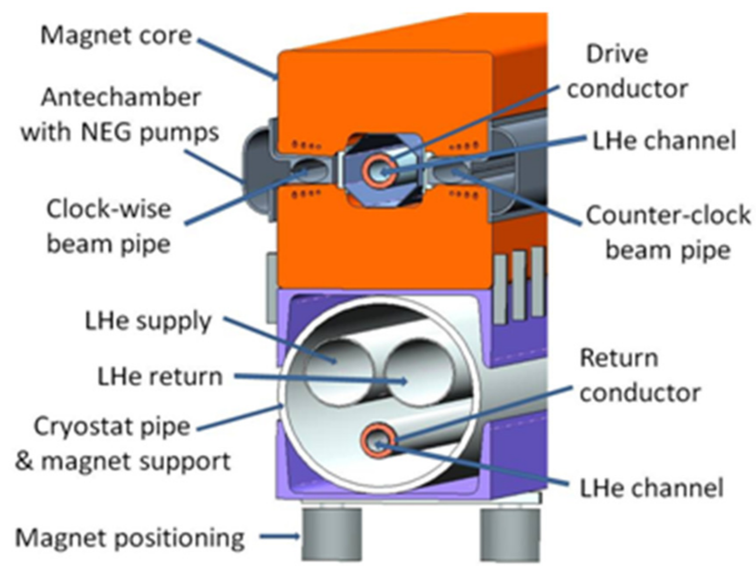
- FCC-ee / FCC-hh in a 100 km tunnel at CERN will need an adapted injector chain
- An option is a high energy injector synchrotron in the same tunnel
- A first concept has been presented for the bending magnets of such high energy injectors, in the light of similar dipoles proposed for large synchrotrons (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).



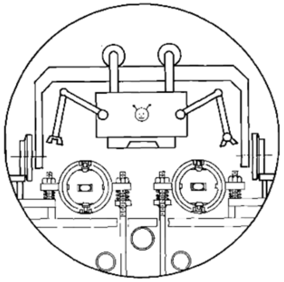


Superferric magnets for large synchrotrons

- 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_3Sn.

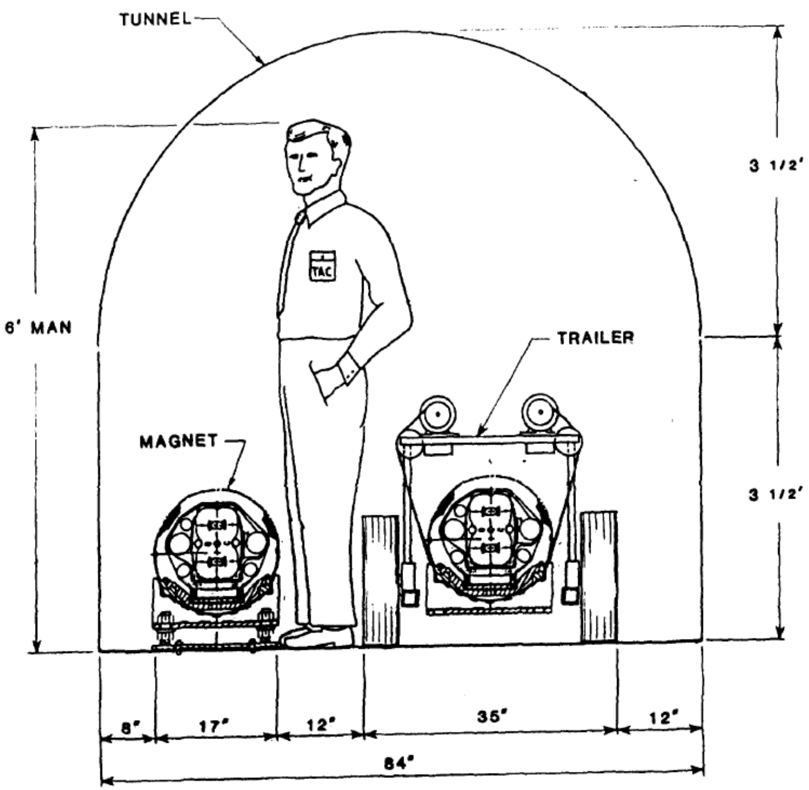
  Artist's conception of the 3-foot "tunnel" and the bending magnets.



- 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.

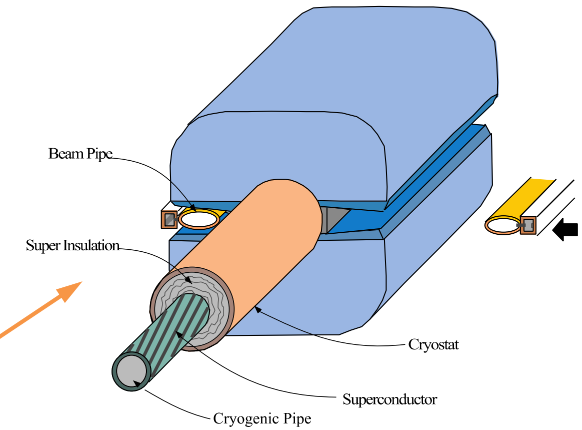


Superferric magnets for large synchrotrons

- 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

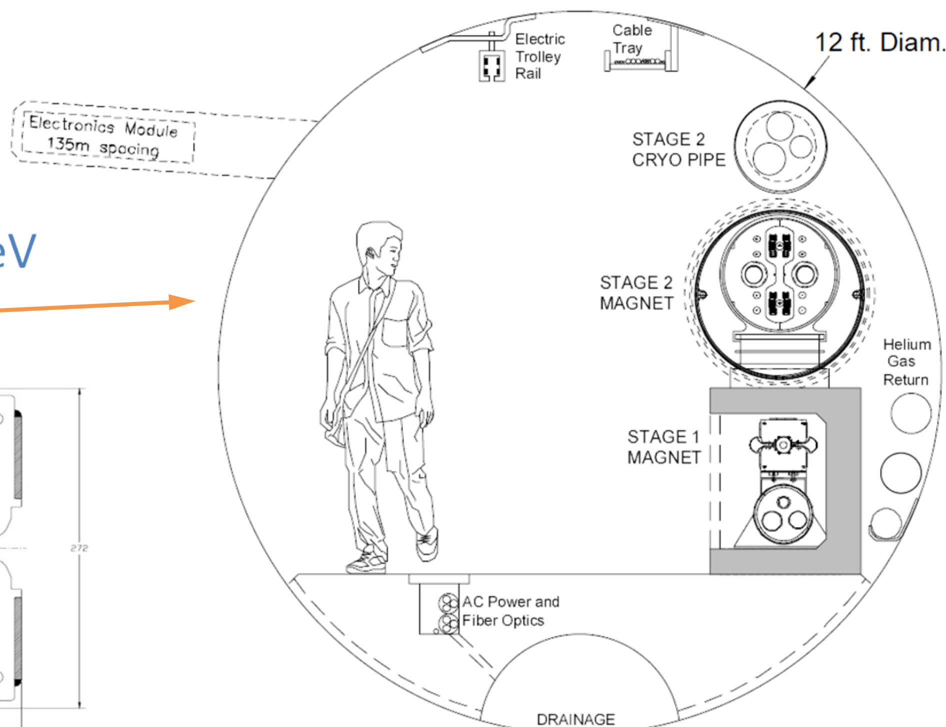
  Double-C twin bore transmission line combined function dipole.



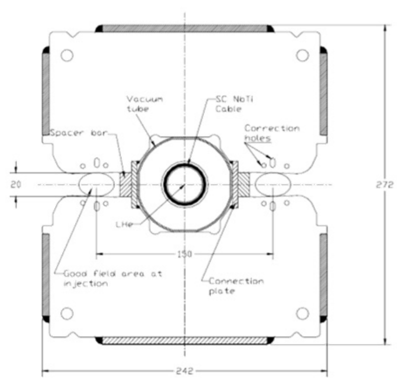
- 2001, Design Study for a Staged Very Large Hadron Collider (VLHC) Stage 1: superferric magnets

  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

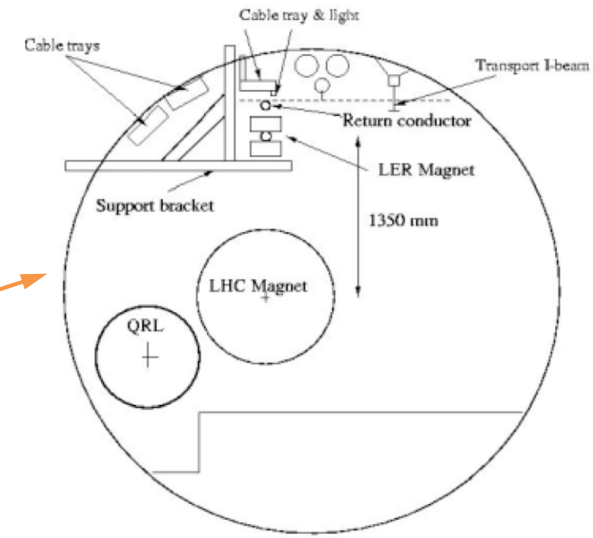


Superferric magnets for large synchrotrons

- 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



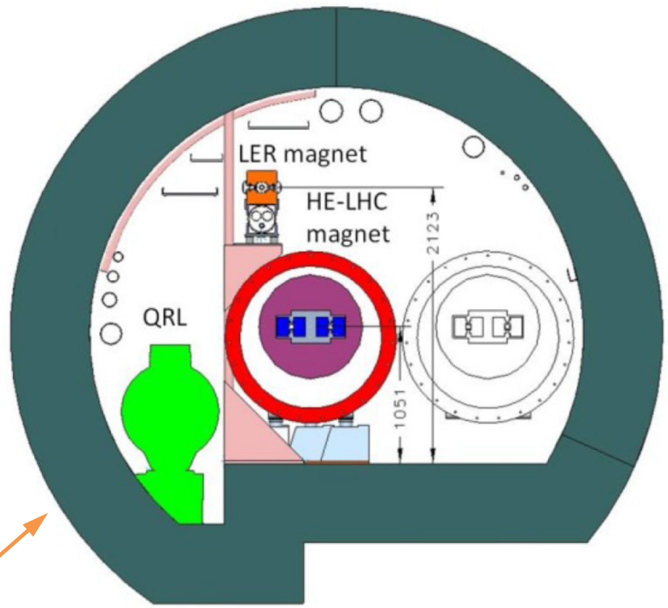
- 2010, HE-LHC Malta Workshop

  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

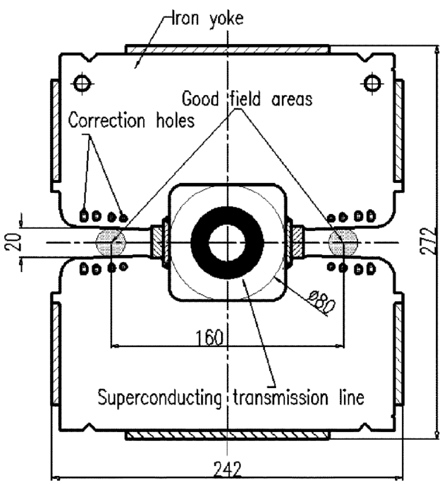
  2) cheaper than 1) for both installation and running costs

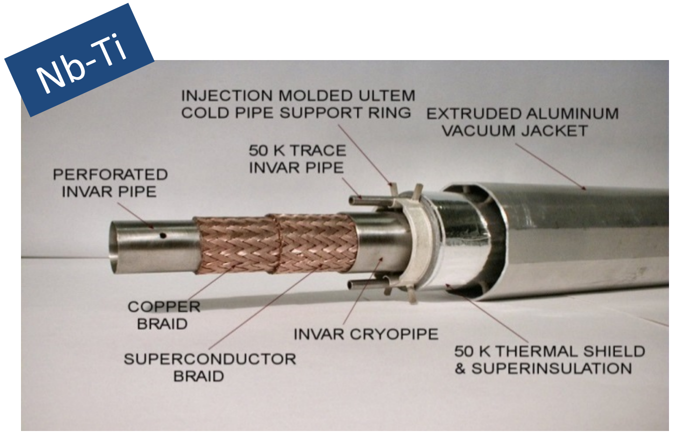
  Arrangement of LER and HE-LHC magnets in the LHC tunnel



A built & tested transmission line magnet

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



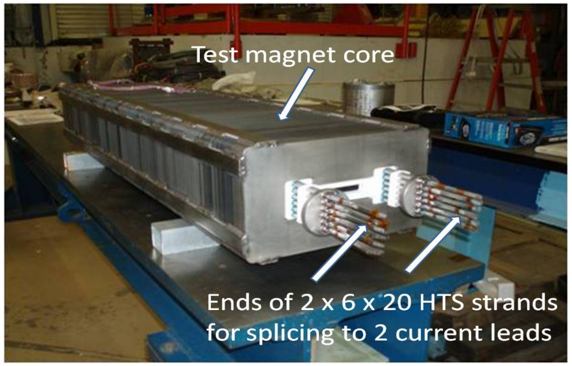


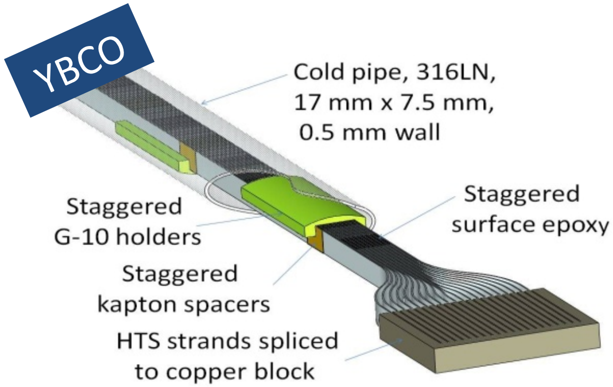
- double C, 2 aperture side by side, combined function magnet
- prototype magnet 1.5 m long, 90 kA for 2 T in each gap
- 288 Nb-Ti 0.65 mm diameter strand, 80 mm outer diameter of cable cryostat
- designed for 100 kA up to 6.5 K, with a 2 K margin w.r.t. 4.5 K of liquid helium
- the cable performed as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

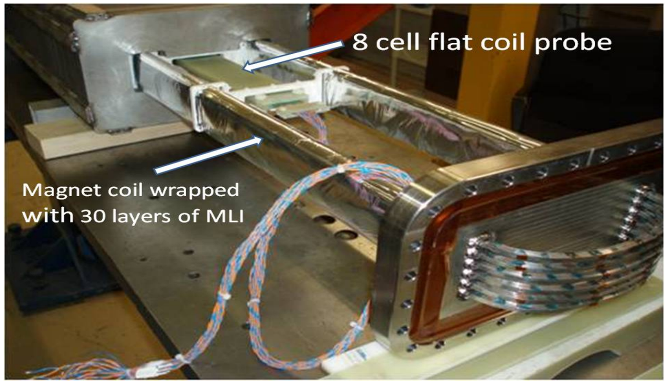
H. Piekarz *et al.*, "A Test of a 2 Tesla Superconducting Transmission Line Magnet System," MT19, 2005
G. Velev *et al.*, "Field Quality Measurements of a 2 Tesla Superconducting Transmission Line Magnet," MT19, 2005

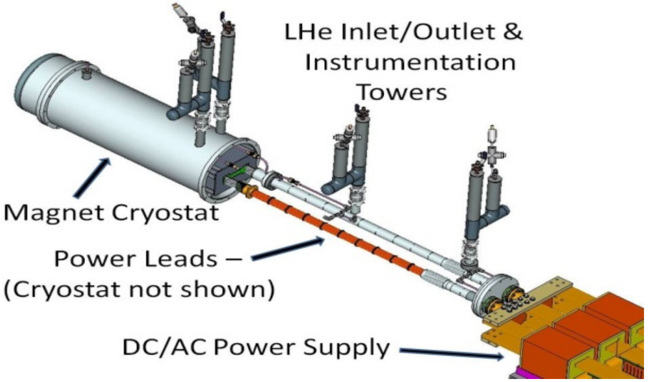
More recently also in HTS

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

H. Piekarz *et al.*, "Design, Construction and Test Arrangement of a Fast-Cycling HTS Accelerator Magnet," MT23, 2013