CERN

Summary of Session 3&4

Daniel Schoerling

Workshop on Compact and Energy Efficient Magnet Design

28/11/2014

CEA Saclay Experience, P. Védrine

ATLAS and CMS: largest magnets
- Design and follow-up manufacturing

LARGE magnets

Construction
- For physics GLAD (GSI)
- For neuroscience ISEULT

Testing
- For fusion W7X & JT60SA

R&D
- Nb_3Sn and HTS magnets
- Cryogenic systems
- Multi-scale simulations

LHC Upgrades
- Q4 NbTi Quadrupole for HL LHC
- 16 T Nb_3Sn Dipole for FCC

FCC detector magnet
- 6 T solenoid with 22 GJ stored energy, 24 m length, 10 m diameter
- 10 K operation under study with Mg_2B

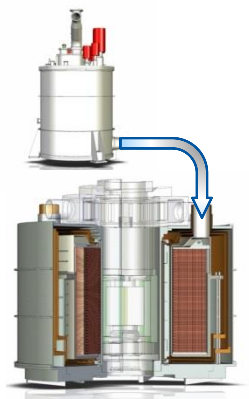
43 T LNCMI hybrid magnet
- Superconducting solenoid providing 8.5 T at 1.9 K
- Resistive solenoid: 25 T PolyHelix coil and 9T Bitter coil

30+ T All-superconducting magnet
- Large-bore 19 T NbTi-Nb_3Sn outer coil with an 11 T inner coil made from HTS conductors

ATLASsolenoid magnet

CMS solenoid magnet

LHC quadrupole magnets



43 T LNCMI hybride magnet

The DESY Experience, B. Krause

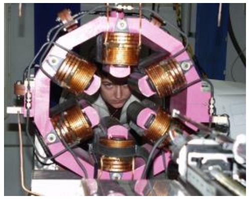
PETRA III in total ~ 750 warm magnets

- Combined function sextupoles

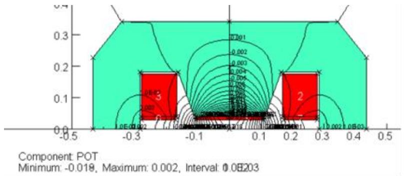
FLASH in total ~ 180 warm magnets

European XFEL accelerator in total ~ 850 magnets

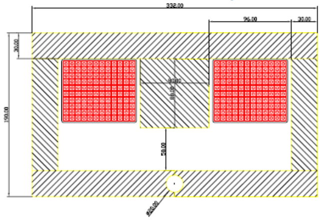
- Combined function magnet XBV (for XFEL); H-dipole with extra coil for creating a quadrupole
- Lambertson DC septum was chosen to reduce the electricity cost and have no active parts in beam path
- Hybrid quadrupole for the XFEL undulator intersection with external adjustment rings was investigated and disregarded due to limited experience with mechanical movement in radiation areas
- Normal-conducting magnet was designed and grain-oriented steel is used to obtain the required small change on the magnetic axis



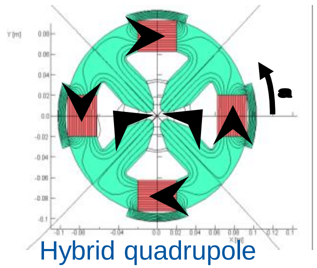
Cb. function sextupoles



Cb. dunction dipole



Lambertson DC septum



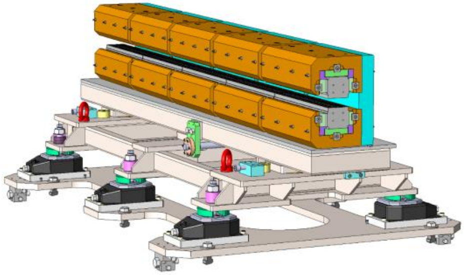
Hybrid quadrupole

Quadrupole with GO steel

Compact and Low Consumption Magnet Designs for Future Linear and Circular Colliders, G. le Bec

ESRF Upgrade Phase II

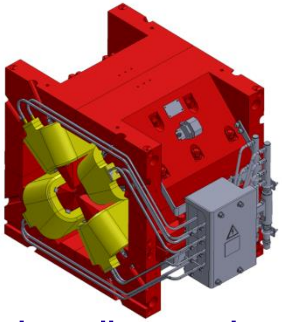
- Reduced horizontal emittance: 4000 to 147 pm.rad
- Same insertion devices source points
- New storage ring
- Increased number of magnets: 7-bend achromat
- Reduced longitudinal space
- Reduced power consumption



Dipoles with longitudinal gradient (DL)

Studies on Compactness

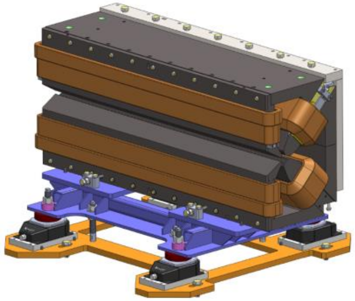
- Smaller apertures bring large energy savings
- Sensitivity to mechanical errors increases:
- Transverse vs. Longitudinal compactness; transverse size variation is much faster if the magnet is saturated
- Power consumption decreases rapidly for fixed gradient in quadrupoles with increasing length.



High gradient quadrupoles

Studies on normal vs. permanent magnets

- If gap < few cm PM dipoles are more compact
- Trimming up to a few % only because efficiency is poor.
- Mechanical trimming may lead to poor field quality, poor reliability, requires high accuracy and leads to comples mechanical systems.



Combined dipole-quadrupoles (DQ)

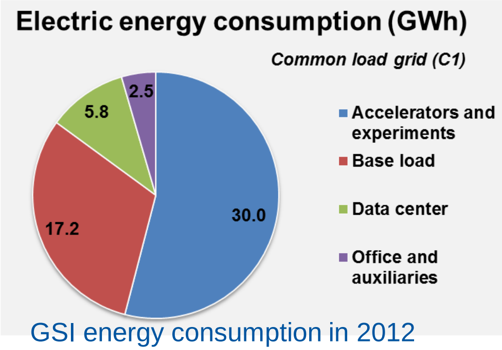
Compactness and power efficiency for the ESRF-SR2

- Dipoles with longitudinal gradient (DL)
- High gradient quadrupoles
- Combined dipole-quadrupoles (DQ)

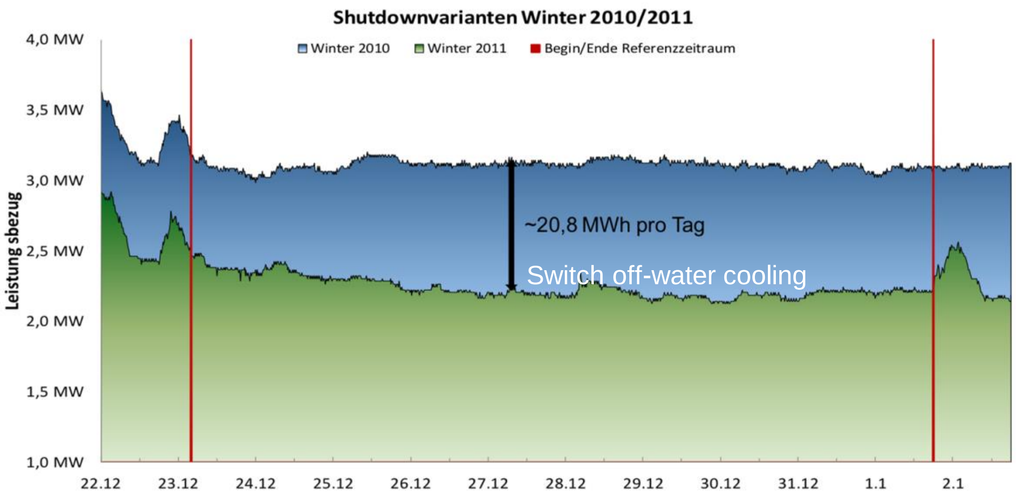
Energy management at GSI and FAIR, strategy on energy management, efficiency, sustainability strategy, P. Gardlowski

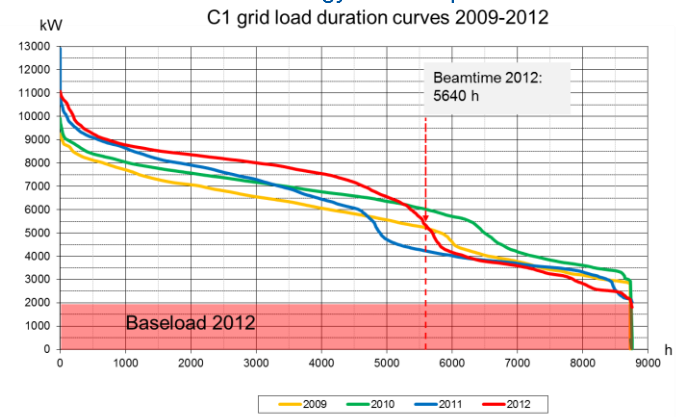
FAIR energy management

- Plan-Do-Check-Act principle will be implemented
- Green IT - currently highest MFLOPS/W supercomputer (H2O instead of air)
- Using emergency power aggregate as virtual power plant
- Switch off unused part of HEBT
- Pulsing beam lines with low repetition rate
- Switch off watercooling while Shutdown

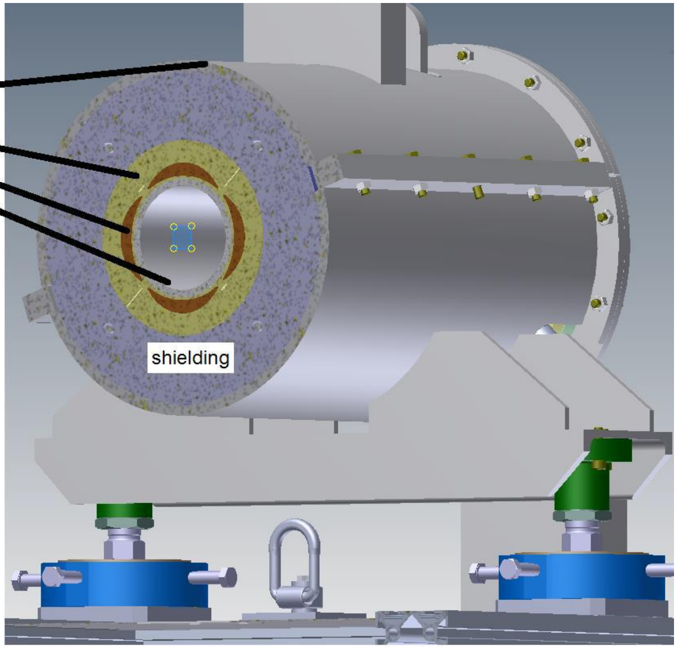


GSI energy consumption in 2012



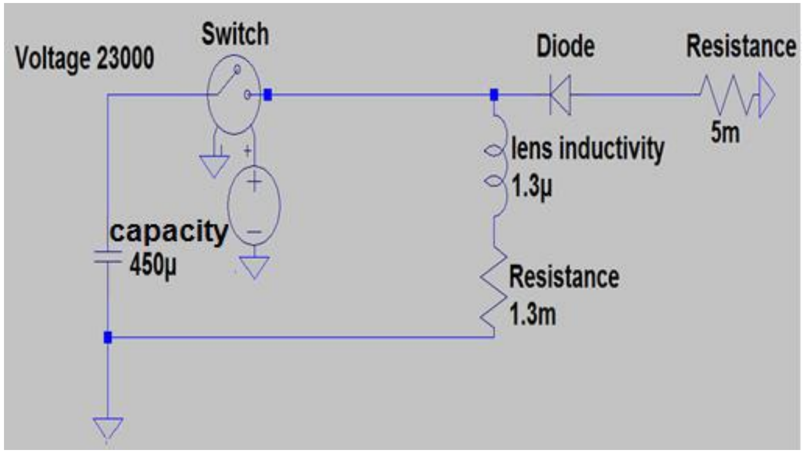


Energy efficient beam transport by means of high current pulsed magnets, C. Tenholt



Energy efficient beam transport

- Magnet with gradient of 80 T/m, length 0.65 m, pulse length of 170 μs, peak current 400 kA, peak voltage 23 kV, energy 119 kJ, inductance 1.3 μH, capacitor 450 μF, forces 200 kN
- Cos 2θ shaped conductor out of 600 Litz wires to reduce eddy current losses
- Energy recovery by using capacitor
- Factor of 22.2 times less energy consumption compared to a conventional magnet (if energy recovery is used)
- Prototype test is starting now



The PSI Experience: a Theory of Evolution, A. Gabard

Cost considerations at PSI in the 70ties

- Discussion of initial investment vs. operating costs
- Base: seven years, including a 50% factor for quads
- Stick to internal standards in terms of PS: 50 A, 200 A, 500 A
- Main constraint: space
- Large dipoles for 500 MeV cyclotron
- Large quadrupoles, main constraint space and beamline requirements

Proscan

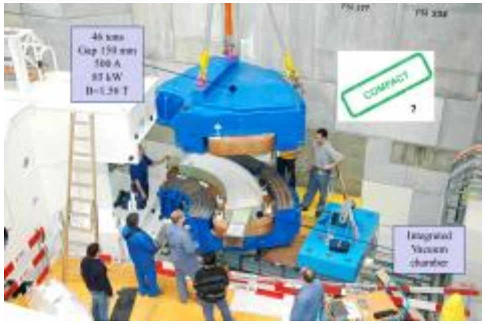
- Magnet parameters were mostly driven by physics requirements
- COMET 250 MeV cyclotron (SC: 3.9 T, 160 A, ∅ 4m, 90 t), compact
- Dipoles and quadrupoles not compact
- Gantry, 90 deg dipole: integrated vacuum chamber reduced magnet size

SLS, first light source at PSI

- Sextupoles with correctors, other magnets not compact

Laser-SwissFEL

- Reduce operating costs
- Reduce magnet size
- Reduce machine size and length with cb. function magnets
- Eliminate water cooling (and thus flow induced vibrations)
- Conclusion: low power, aircooled, combined magnets
- Compact magnets are harder to measure accurately



Gantry, 90 deg dipole w/ integrated vac chamber

Combined function quadrupole for SwissFEL

CERN experience on accelerator magnets based on permanent magnets, P.-A. Thonet

Reasons to use permanent magnets

- Reliability (no insulation failure and water leaks, no failure detection system)
- Cost efficiency (cheaper production, no power supply, no operating cost)
- Flexible design (compact, in-vacuum)

PM used

- Samarium Cobalt type Sm2Co17

LINAC4 permanent magnet quadrupole

- Iron free quadrupole based on a Halbach array
- A range of radial displacement of 6 mm of the permanent magnet blocks permits to adjust the integrated gradient from 1.1 to 1.6 Tesla

Permanent magnet sextupole for ASACUSA

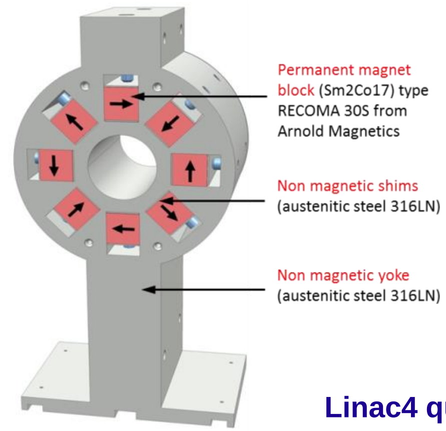
- Fe-Co poles with shimming possibility for adjusting the field
- In vacuum design
- Titanium yoke, vacuum brazed and annealed for 4h at 820°C to enhance the Highest magnetic characteristics of the Fe-Co grain size

N-Tof dipole magnet

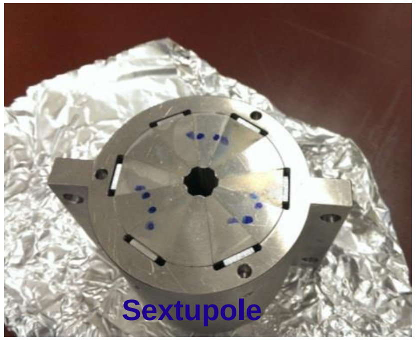
- Iron-dominated design
- The dipole is composed of 168 PM blocks
- More than twice lower total cost than a resistive magnet solution

Limits of permanent magnets

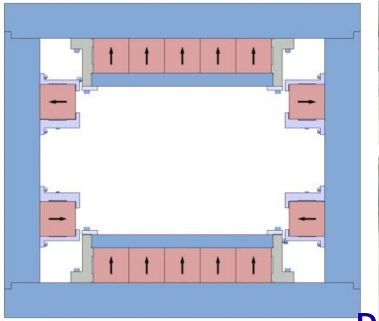
- Only for fixed energy machines/TL
- Limited fields, limited field quality due to inhomogeneities in the PM
- Field strength is temperature dependent

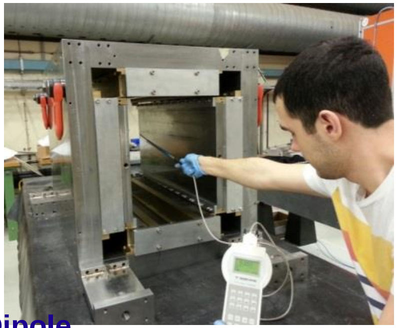


Linac4 quadrupole



Sextupole





Dipole

Compact Superconducting Magnets for Linear Accelerators, V. Kashikhin

ILC splittable quadrupole

- Full length ILC prototype, 4K bath tested, meets ILC requirements
- Split quad #2 and #3 constructed and successfully tested
- Successful thermal cycles

Conduction cooling test development at KEK

- Test stand was sent to FNAL
- Cryogen free system proposed

FNAL ASTA quadrupole design

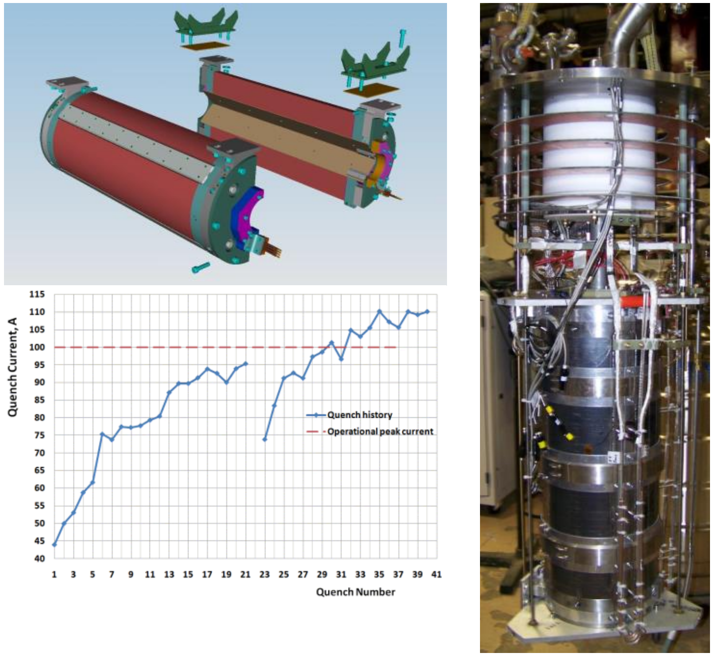
- Two magnets are built. One of them shipped to KEK and upgraded by Toshiba and installed in KEK-STF-cryomodule

Integrated magnet system scheme

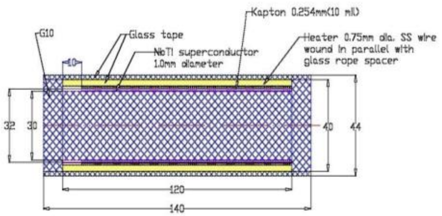
- Run magnets in persistent current mode and power them from a common busbar, connection to magnets with SC switches
- The main magnet system parameters should have:
  - large magnet inductances
  - very low splice resistances
  - high performance persistent current switches
  - long low inductive superconducting busses
  - efficient control system

Conclusions

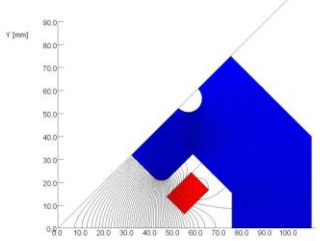
- Splittable design and conduction cooling is convenient
- Large residual magnetization observed
- Quadrupole shows acceptable center stability
- Degaussing could reduce iron core magnetization



ILC splittable quadrupole

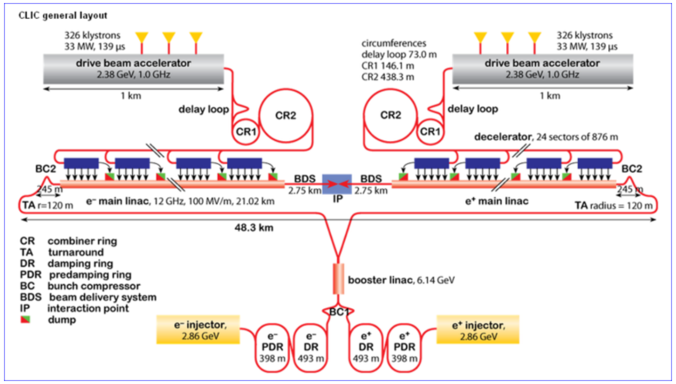


SC switch (1.8 s and 4.3 s switching times)



FNAL ASTA quadrupole design

Electromagnetic and hybrid design experience for CLIC magnets R&D, M. Modena



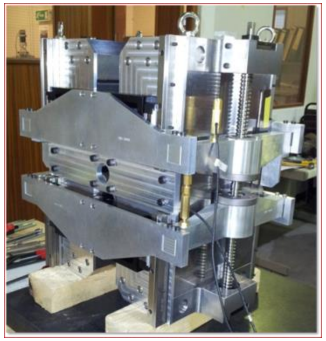
65000 magnets are required for CLIC

Magnets for the 2-beam modules

- Drive Beam Quadrupole (DBQ)
  - Big series
  - Very wide $\int Gdl$ variation required (for a constant physical space available on the Modules)
  - Extremely tight available space (considering the wide$\int$ $\int Gdl$ required)
  - Tight alignment tolerance (no active stabilization and beam feedback alignment for these magnets)
  - Minimize economic and logistic (total power, service requirement, cooling needs, etc.)
- Main Beam Quadrupole (MBQ)
- Beam Steering correctors
  - Not needed in latest design of CLIC, because nano-stabilization can be used to offset the quadrupoles

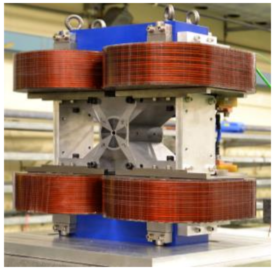
Magnets for the final focus system

- QD0 quadrupole
  - Hybrid magnet design to reach a gradient of around 500 T/m in an aperture of 8.1 mm
- SD0 sextupole

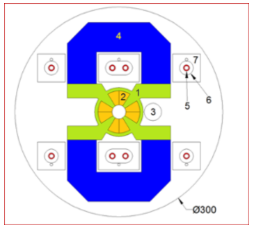


Drive Beam Quadrupole

Main Beam Quadrupole



QD0 Design



SC QD0 Design

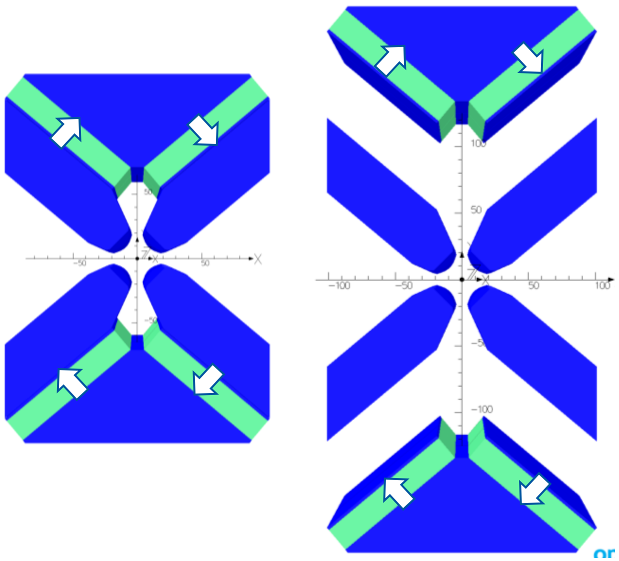
ZEPTO: Tunable Permanent Magnet Dipoles and Quadrupoles, B. Shepherd

Quadrupole Drive Beam Quadrupole

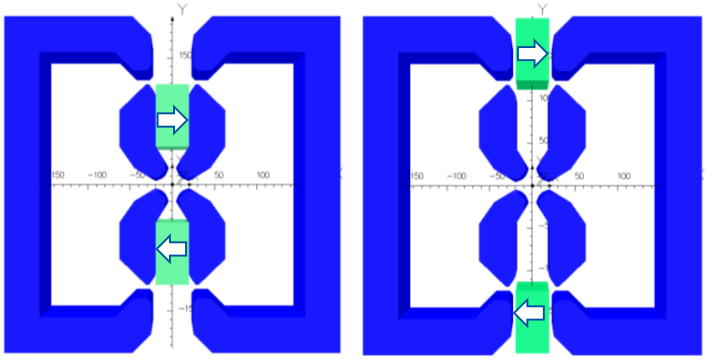
- High-energy end quadrupole: 12.2 T
- Low-energy end quadrupole: 1.22 T
- A PM quad would potentially have many advantages (reduced electrical power, very low operating costs, no cooling water needs, very low power to air)
- Many challenges (radiation damage, variation with temperature, variation from block to block)

Summary

- PM driven quads have many advantages in terms of operating costs, infrastructure requirements, and power load in the tunnel
- Only two PM designs are required to cover the entire range of gradients required for the CLIC Drive Beam
- Two prototypes have been built and measured, demonstrating the required gradient range
- The magnetic centre moves vertically as the gradient is adjusted
- Modelling of dipole concepts for the DB-TAL is in progress



High energy quad design

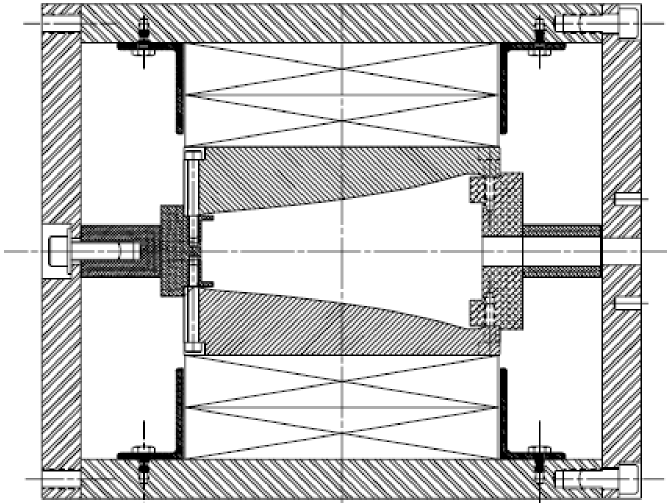


Low energy quad design

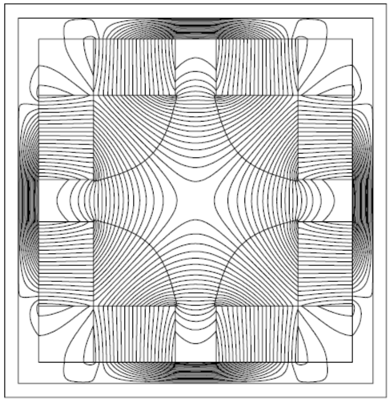
The experience at FERMILAB: recycler ring and beam lines based on PM technology, V. Kashikhin

Fermilab Recycler is a permanent magnet storage ring for the accumulation of antiprotons from the Antiproton Source, and the recovery and cooling of the antiprotons remaining at the end of a Tevatron store.

- Various permanent magnets were developed, installed, and are successfully working at Fermilab accelerator complex
- 6 various models of adjustable PM quadrupoles for the NLC project with gradients up to 100 T/m and an aperture 12.7 mm were built and tested
- A cost efficient approach was used for Recycler magnets based on ceramic strontium ferrite
- SmCo5 permanent magnets are more compact than the ferrite based, and provide better thermal stability
- Special attention must be paid on PM magnets assembly tooling, and safety for technicians
- Because PM magnets produce fixed and properly calibrated magnetic fields: large external fringe fields deviations, temperature variations, high radiation must be avoided



Recycler ring dipoles, with gradient

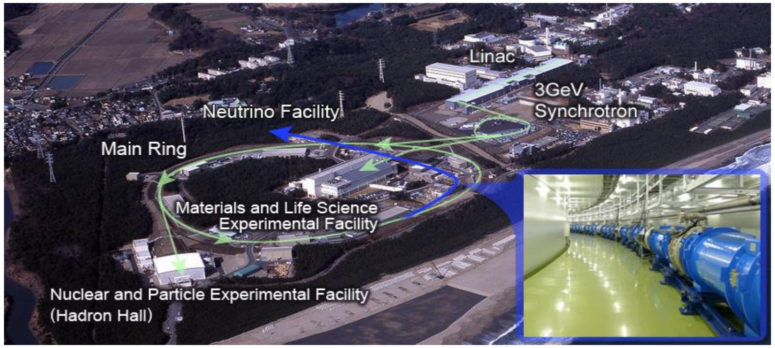


Recycler ring quadrupoles

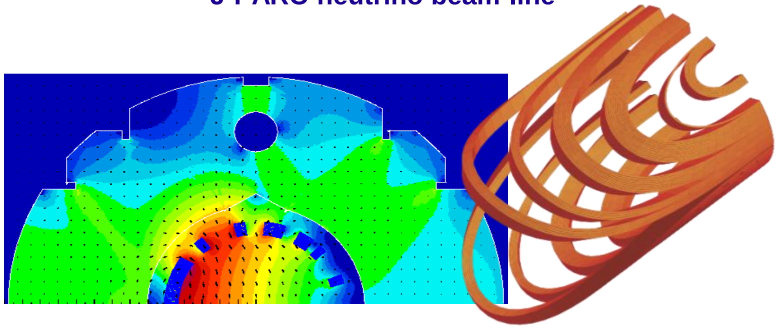
Development and Operation of a superconducting combined-function magnet system for J-PARC neutrino beam line , A.Yamamoto

SC combined function magnet.

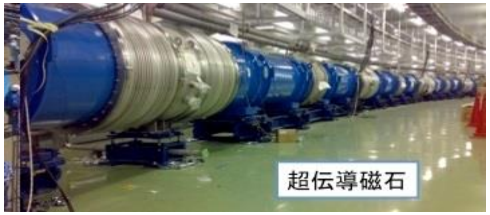
- Dipole field 2.59 T and quadrupole field 18.6 T/m
- Special coil design performed in Roxie for obtaining a current dominated magnet with a field quality better than 10^{-3}
- Prototype was fabricated and tested successfully.
- Mass production started in January 2006
- Reproducibility similar to MQXA.
- Common baseline, use of LHC cryostat
- Very successful operation until earthquake
- Tunnel was slightly damaged due to earthquake, re-alignment was required
- No beam stop due to SC trouble after summer 2012



J-PARC neutrino beam-line



SC combined function magnets



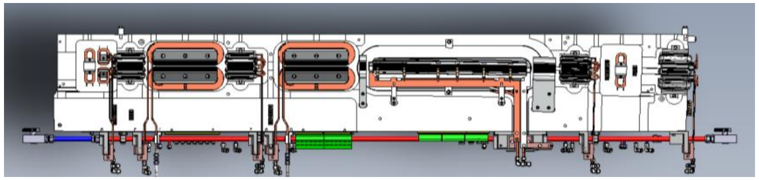
Integrated magnet block design and production, M. Johansson

3 GeV ring magnets key aspects

- Relatively small magnet aperture of Ø25 mm
- Magnet block concept → integrated unit containing several consecutive magnet elements

Ø25 mm aperture

- Required from the lattice design (pole aperture has a direct influence on lattice compactness, defining minimum distance between elements, and defining minimum lengths for quads, sextupoles, etc.)
- The aperture also has an indirect influence on lattice compactness through coil design, in that the required *NI* is proportional to *g* for dipoles, r^2 for quads, r^3 for sextupoles
- For the MAX IV 3 GeV ring design, the enabling factor for Ø25 mm magnet aperture is the choice of NEG-coated copper vacuum chambers throughout the achromats
- Production was build-to-print and close follow-up was required to ensure that the required quality was delivered in time
- In depth discussions were required for the mechanical and magnetic measurements but not for the manufacturing method
- Installation is ongoing



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