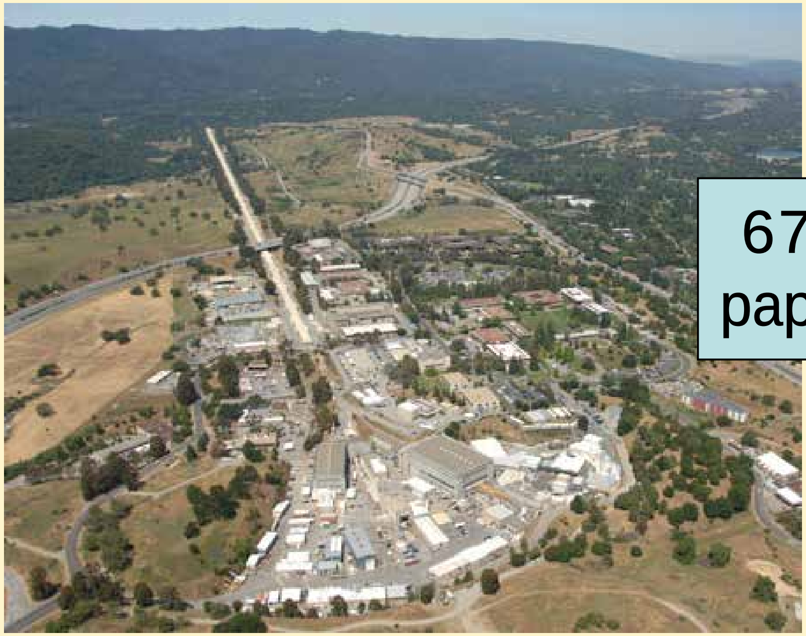
A Golden Anniversary:
50 Years of Superconductivity at MT

slides by Martin Wilson presented by David Hawksworth

MT-1 September 8-10, 1965
Stanford Linear Accelerator Laboratory USA
90 papers 319 participants



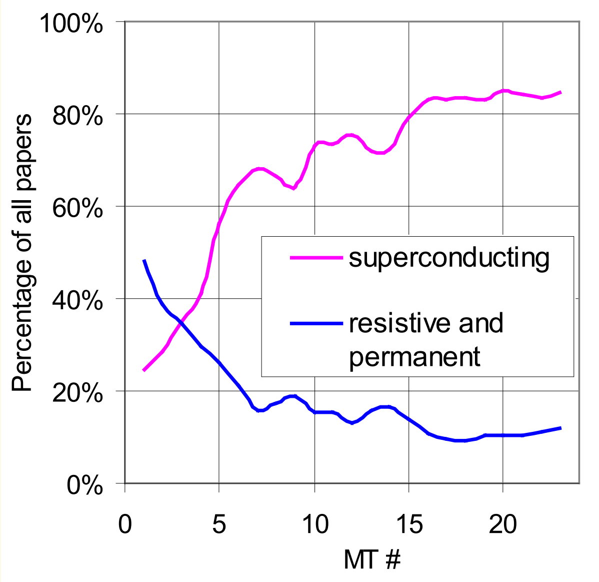
6750 papers

International Conference on
Magnet
Technology 24
October 18~23, 2015
COEX, Seoul, Korea

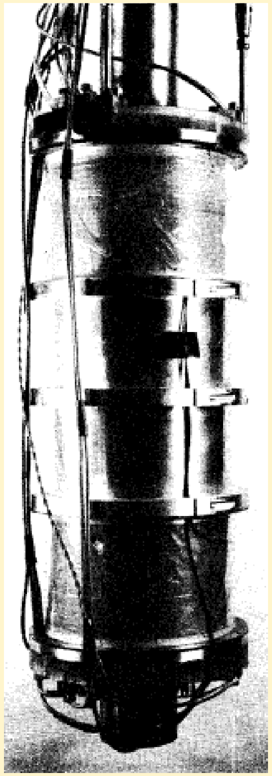
50 years of endeavour

1965	MT-1	Stanford USA
1967	MT-2	Oxford UK
1970	MT-3	Hamburg Germany
1972	MT-4	Upton USA
1975	MT-5	Rome Italy
1977	MT-6	Bratislava Czechoslovakia
1981	MT-7	Karlsruhe Germany
1983	MT-8	Grenoble France
1985	MT-9	Zurich Switzerland
1987	MT-10	Boston USA
1989	MT-11	Tsukuba Japan
1991	MT-12	Leningrad USSR
1993	MT-13	Victoria Canada
1995	MT-14	Tampere Finland
1997	MT-15	Beijing China
1999	MT-16	Ponta Vedra Beach USA
2001	MT-17	Geneva Switzerland
2003	MT-18	Morioka Japan
2005	MT-19	Genoa Italy
2007	MT-20	Philadelphia USA
2009	MT-21	Hefie China
2011	MT-22	Marseille France
2013	MT-23	Boston USA
2015	MT-24	Seoul Korea

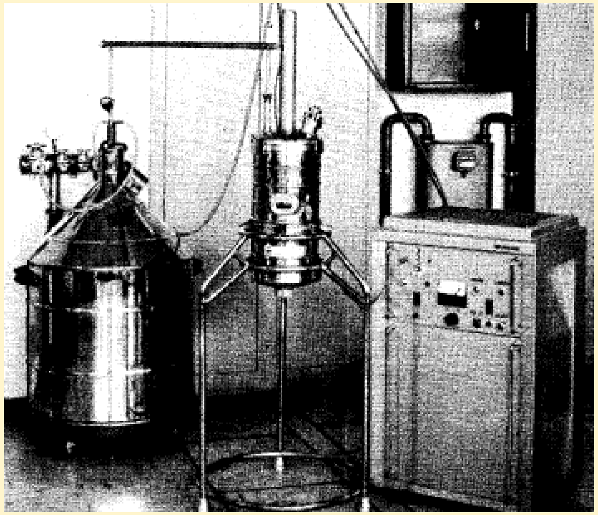
MAGNET TECHNOLOGY CONFERENCE
DIGITAL ARCHIVE
1965 - 2009



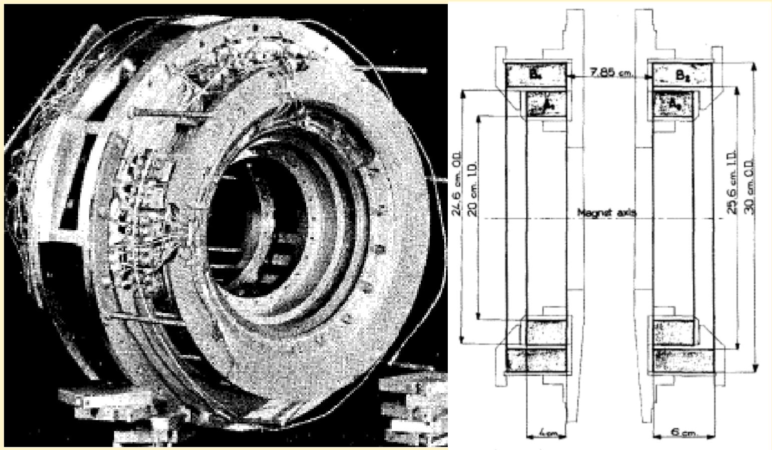
Superconducting magnets at MT-1



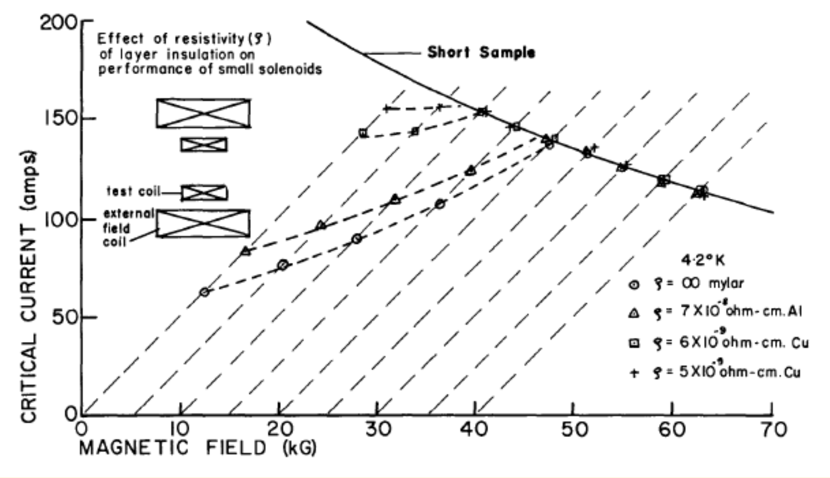
5.8T NMR solenoid (Grivet & Sauzade)



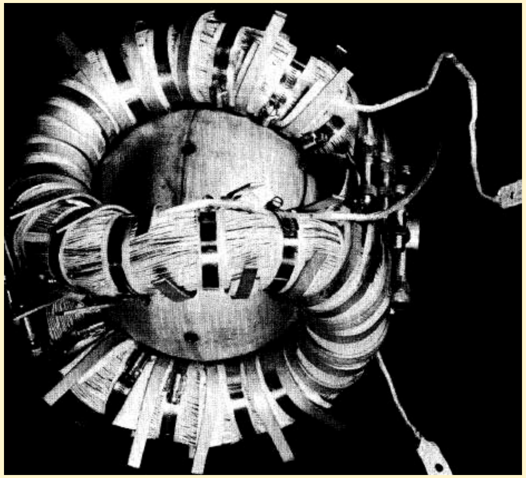
4.5T Split pair (Donadieu & Royet)



2.1T Polarized target magnet (Desportes & Tsai)



Nb_3Sn tape solenoid (Sampson)

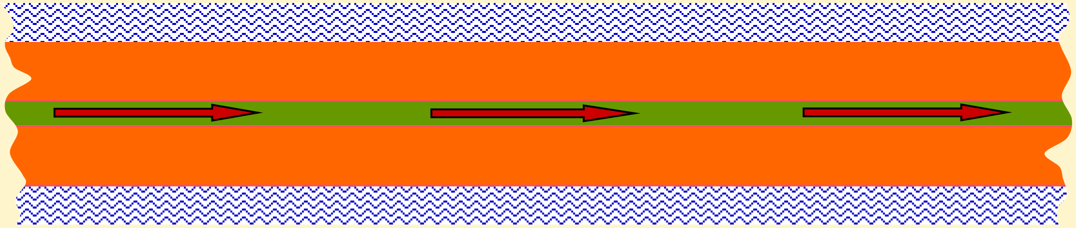


'Minimum B' (Taylor & Laverick)

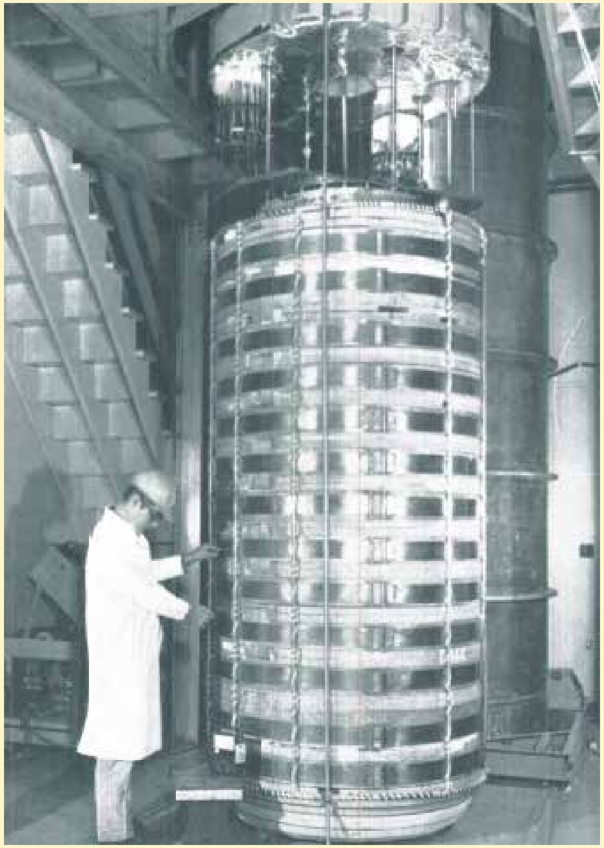
MT-1 Stanford, USA (1965)
Terminal Characteristics of Short Samples of Superconductors and their Effect on Coil Behaviour
ZJJ Stekly *Avco Everett USA*

Cryostabilization

- conductor with copper joined in parallel with superconductor
- well cooled by liquid helium



- current normally flows in superconductor
- if superconductor switches off, current diverts to copper
- Ohmic heating in copper
- heat transferred to helium, temperature falls
- current returns to superconductor



it works well
- Avco MHD generator

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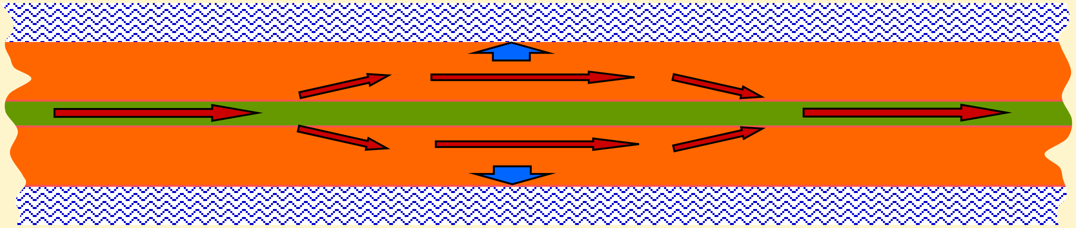

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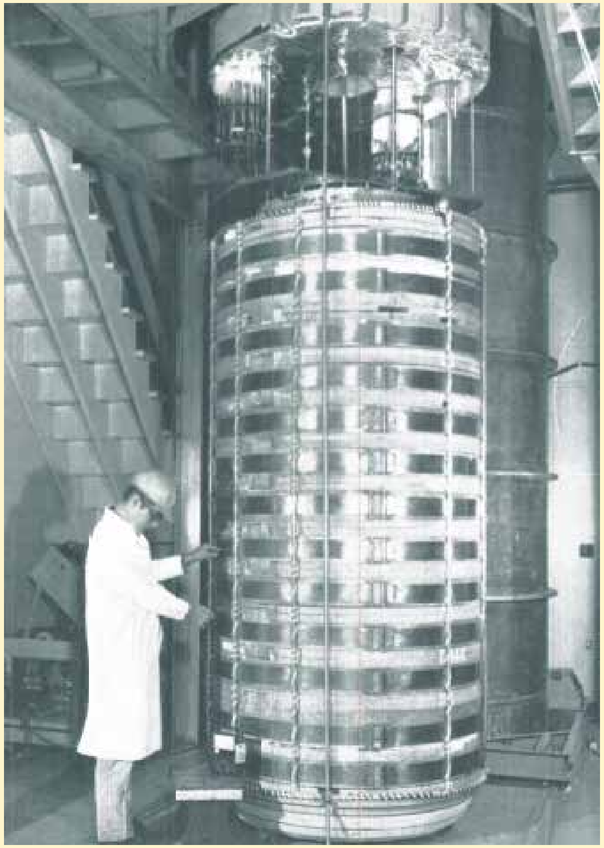

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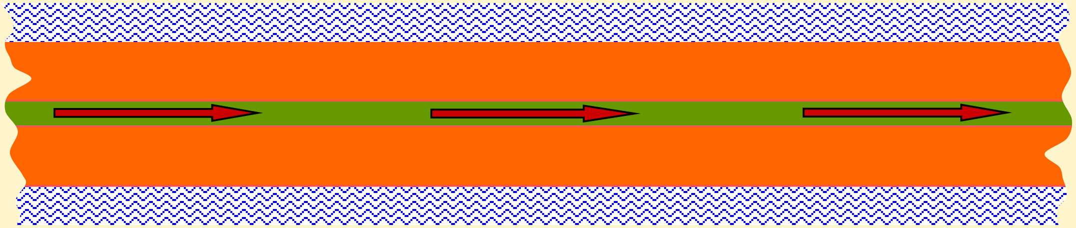

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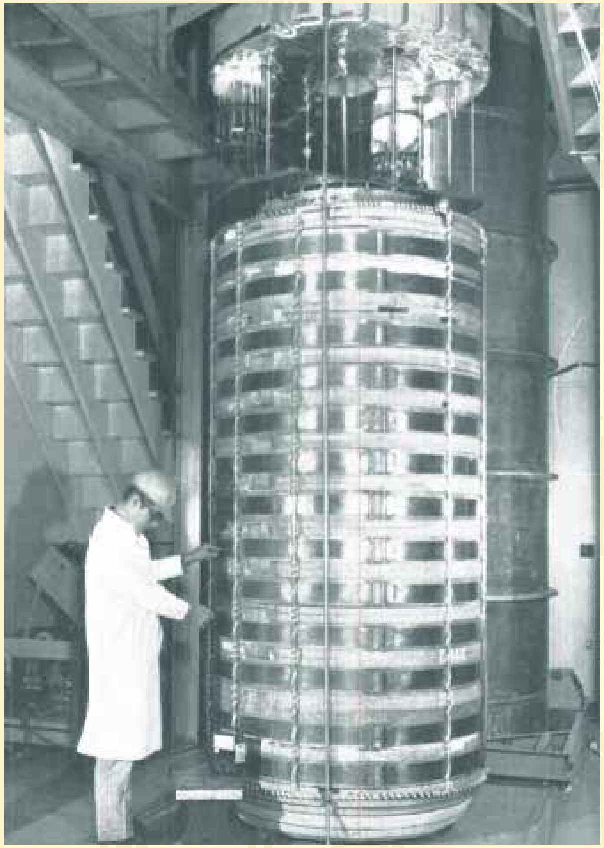

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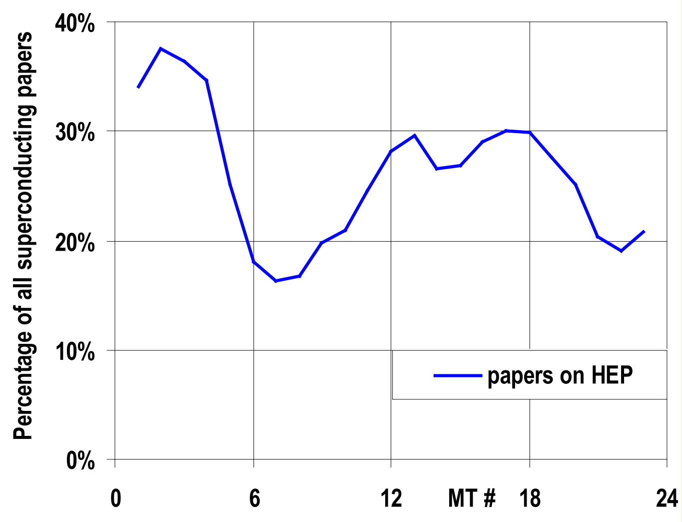
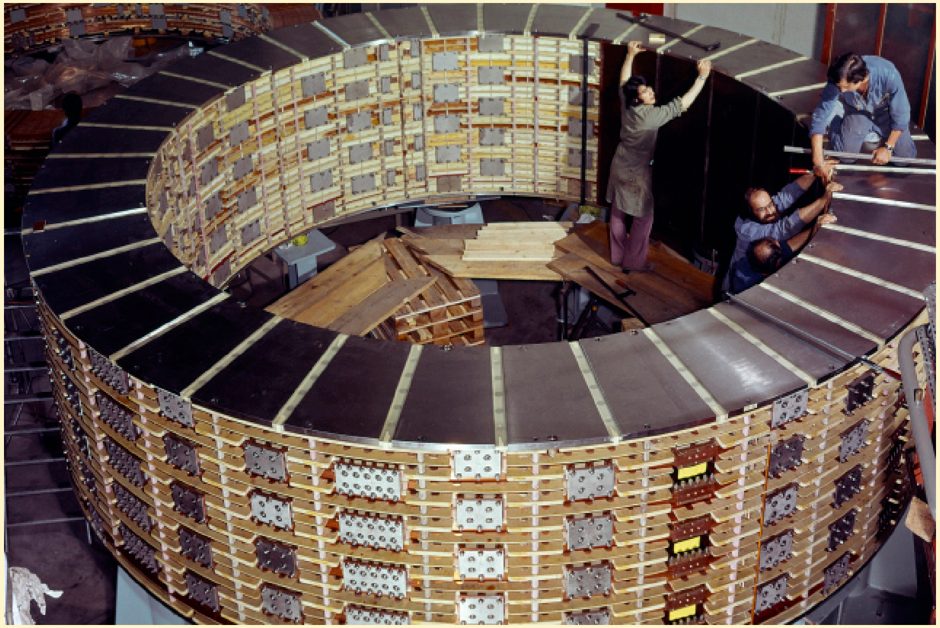
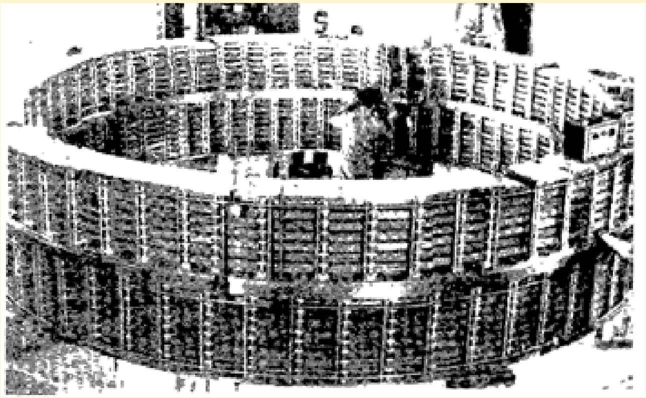
High energy physics: bubble chambers

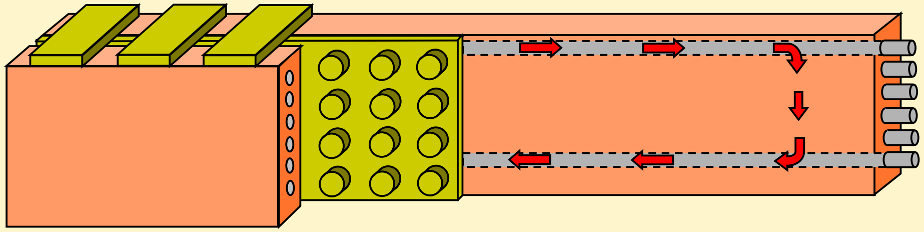




1973: Big European Bubble Chamber CERN: 4.7m dia 3.5T

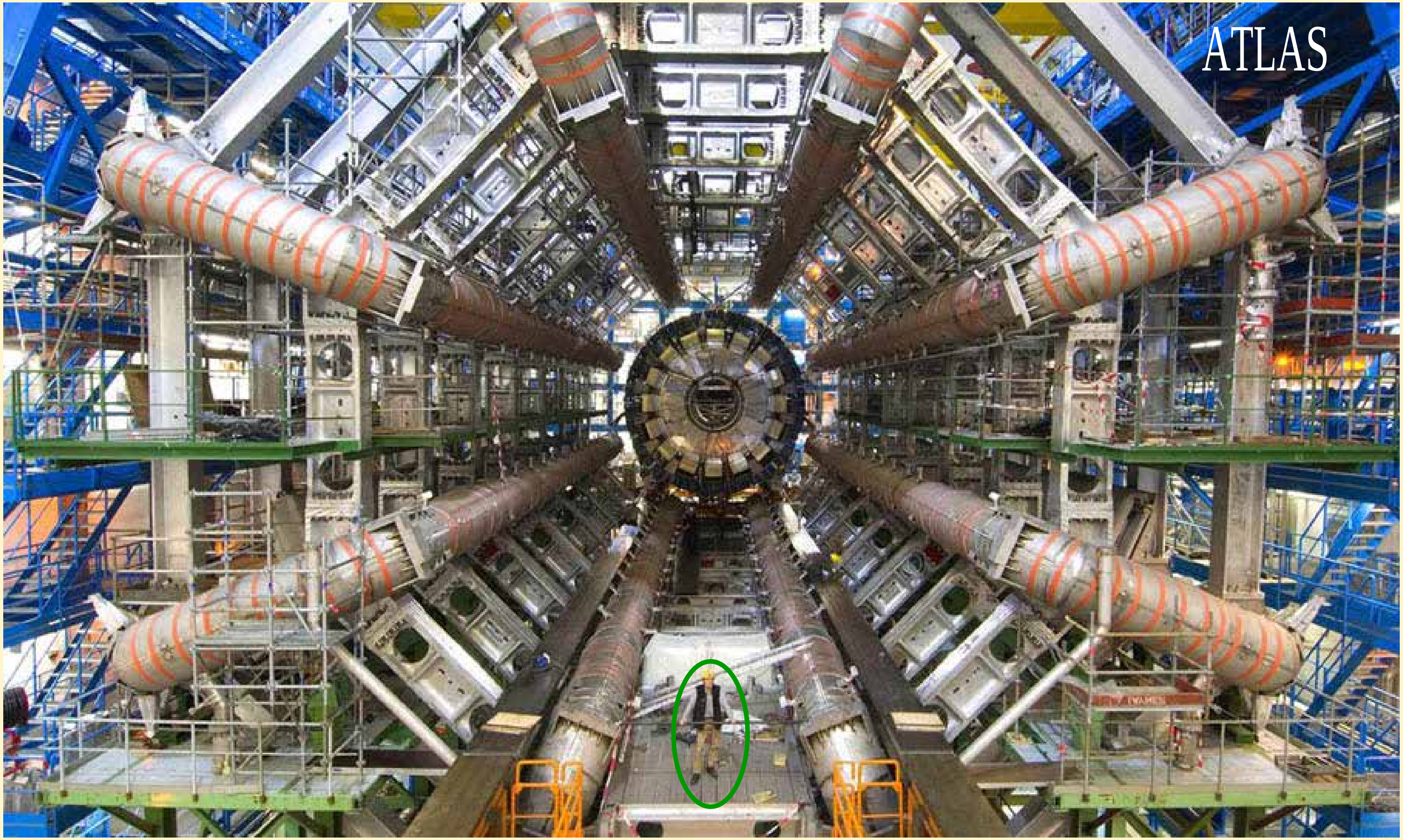


1969:Argonne Bubble Chamber:
4.8m dia 1.8T



cryostable conductor but untwisted filaments ð coupling currents

High energy physics detector magnets



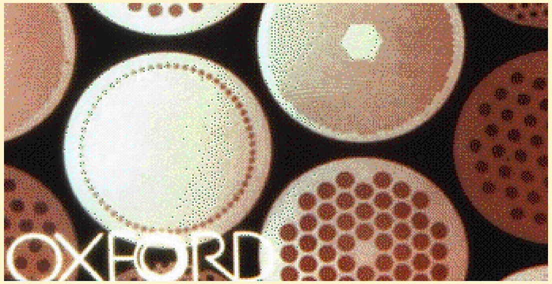
High energy physics: accelerators

MT-2 Oxford, UK (1967)
Pulsed Superconducting Magnets for Proton Synchrotrons
P.F. Smith *Rutherford Laboratory UK*
....replace the conventional magnets in a proton synchrotron. ..
.....reductions in the size and cost ....
..... or higher energies for the same cost..
… increase the energy of existing accelerators by a factor 5 …

Requirements for Superconducting Synchrotron Magnets to be Economic

- high engineering current density – too much dilution with cryostabilization – must fix the instability
- low ac losses during ramping
- good field quality at injection (low) field – small magnetization

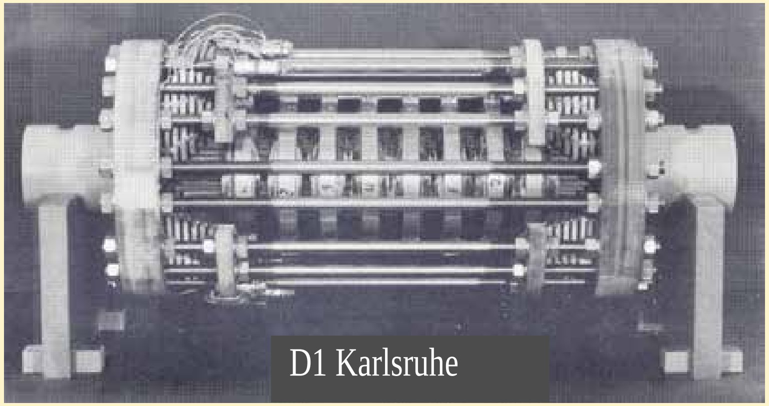
all three requirements demand fine filaments

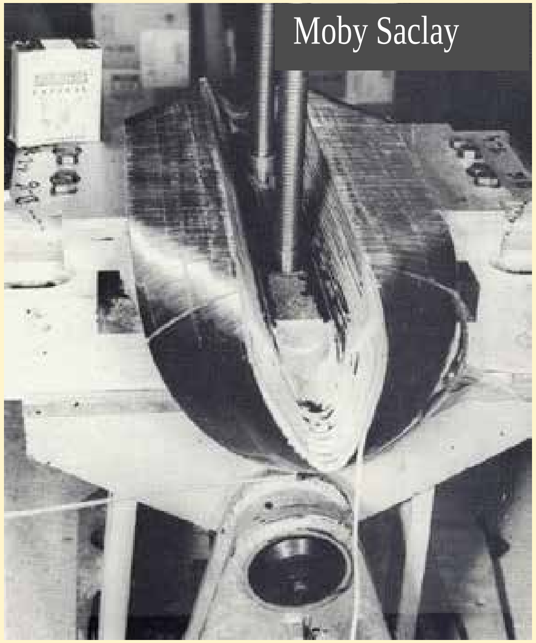


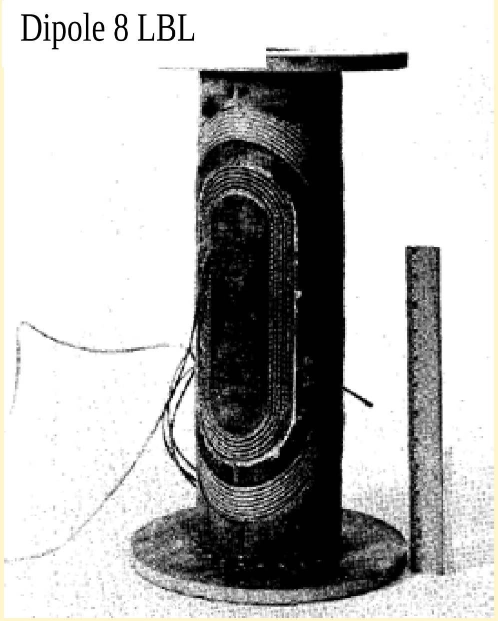
Prototype superconducting accelerator magnets

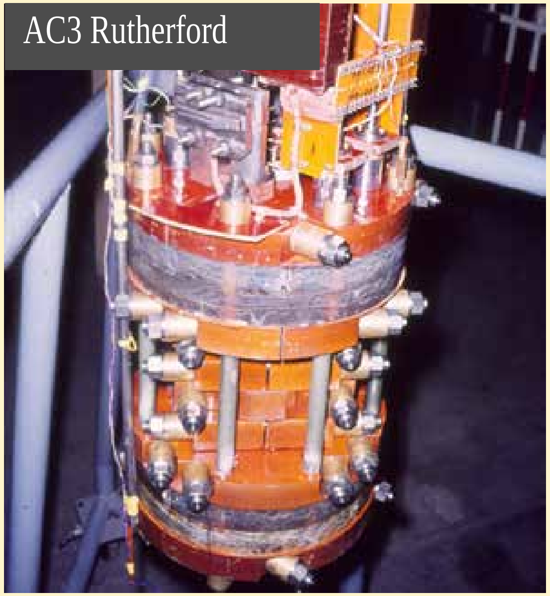
MT- 4 Brookhaven, USA (1972)
Pulsed Superconducting Magnets
G.Bronca P.Genevey F.Kircher JP.Pouillange G.Prost
CEA Saclay France

The possibility of using superconducting magnets to increase the energy of present accelerators or to get very high energy in new facilities has been studied in many laboratories all over the world....


D1 Karlsruhe


Moby Saclay

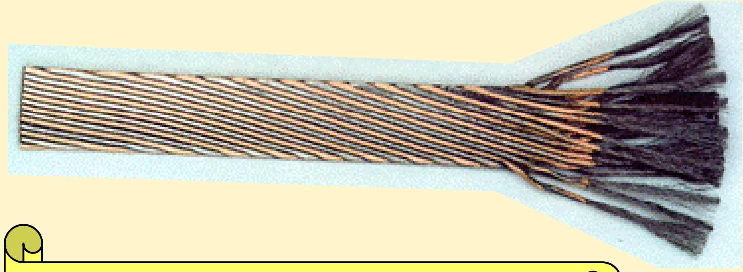

Dipole 8 LBL


AC3 Rutherford

Superconducting accelerator magnets

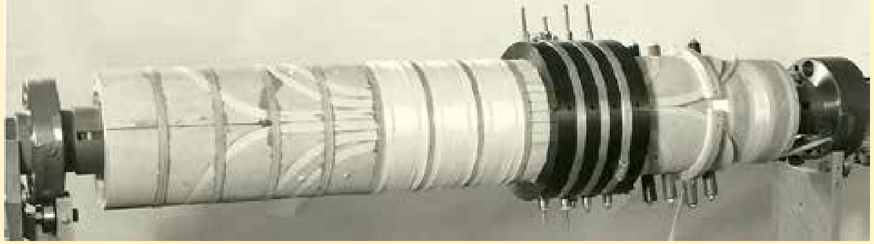
MT-5 Rome, Italy (1975)
The Pulsed Superconducting Magnet AC5
J.H. Coupland *Rutherford Laboratory UK*
………..maximum field B_o = 5.2T

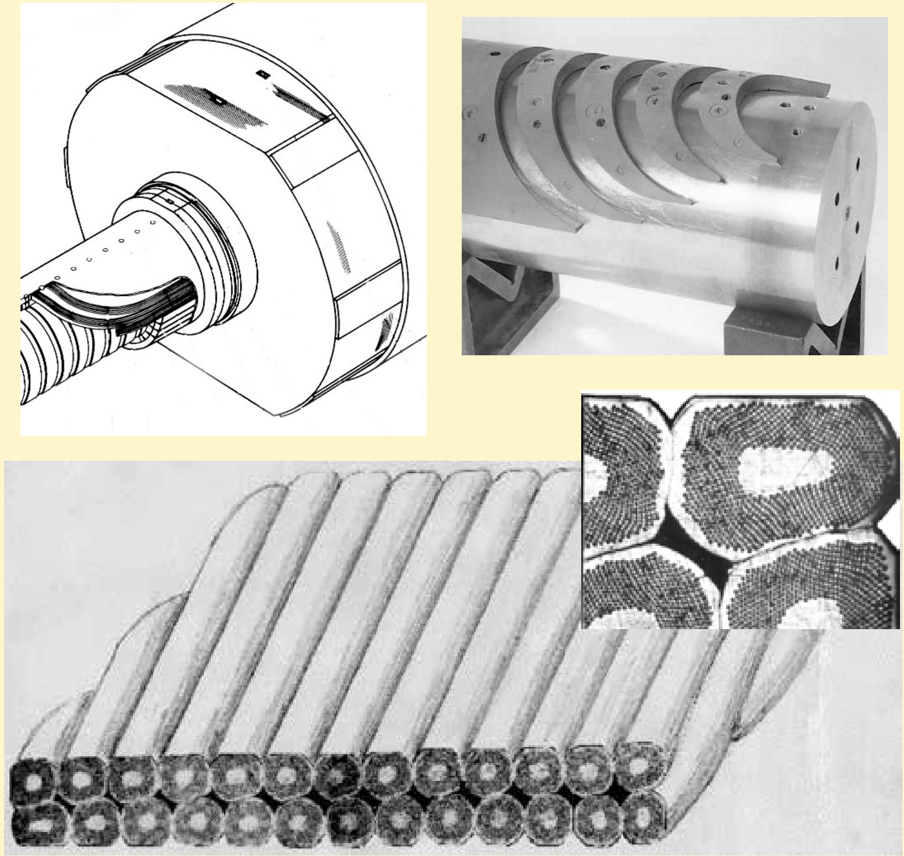
- smooth end turns
- iron close in
- **Rutherford cable**



used in all superconducting accelerators built to date

MT-5 Rome, Italy (1975)
The Work of the GESSS Collaboration
D.B. Thomas
Group for European Superconducting Synchrotron Studies
CEA France, KfZ Germany, RL UK

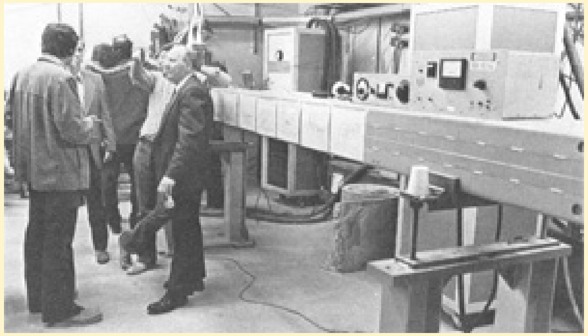




Fermilab: energy saver →Tevatron

March 1971: **Robert R. Wilson** testified before Joint Committee Atomic Energy U.S Congress "Fortune has smiled on us at NAL…costs have been low.. construction has been rapid … possibility of achieving a higher energy…by the use of super-conductivity… I like to call an '**energy doubler**.' …modest cost and should enable us to achieve higher energies -- as much as 1,000 BeV…operation above 200 BeV would cost less using the superconducting magnet...fraction of cost...might be recovered…by savings in operating costs…..

FermiNews April 1977 … milestone… string of four superconducting magnets …4,300 amperes…equivalent of 1,020 BeV

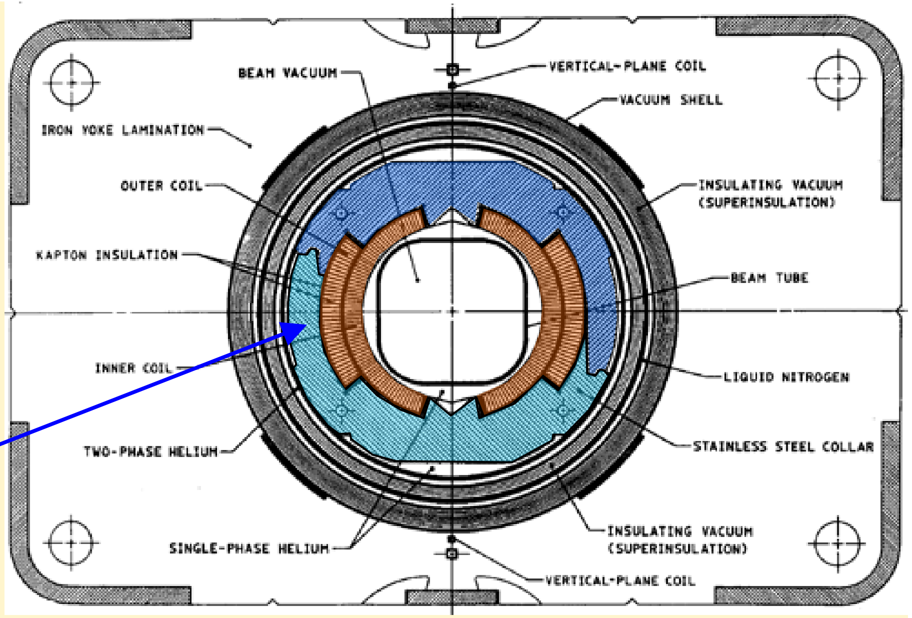


operational 1983 to 2011

proton energy 980GeV

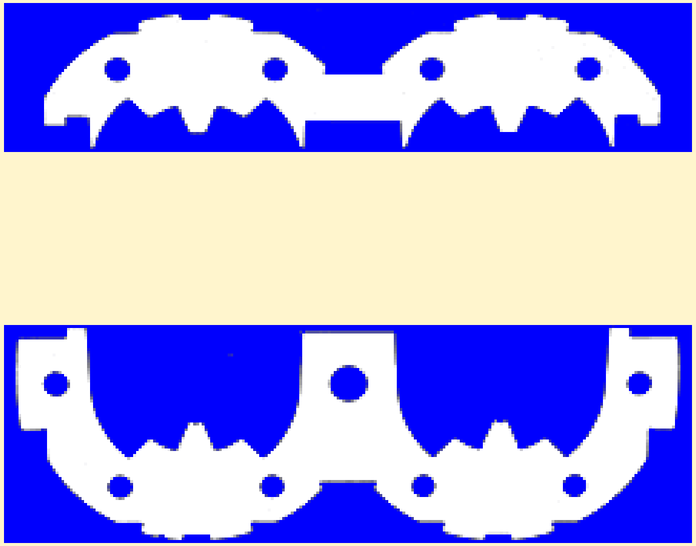
dipole field 4.2T

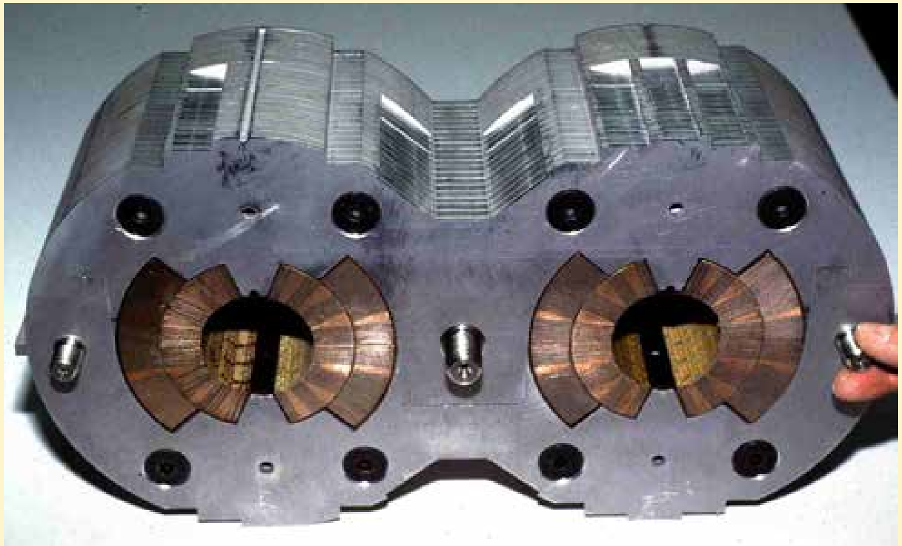
Mass production



Fermilab brought the methods of Henry Ford to superconducting accelerators

force supporting collars from precision stamped stainless steel laminations





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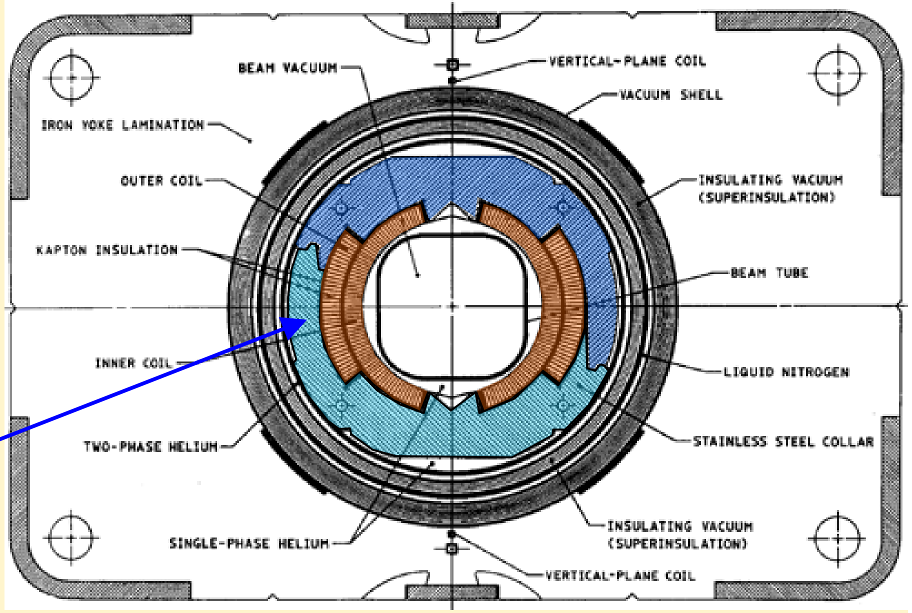

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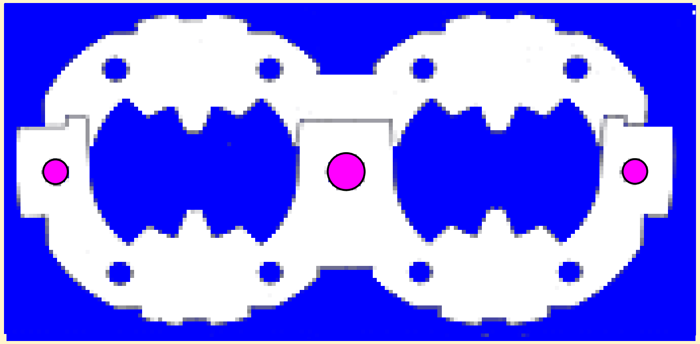


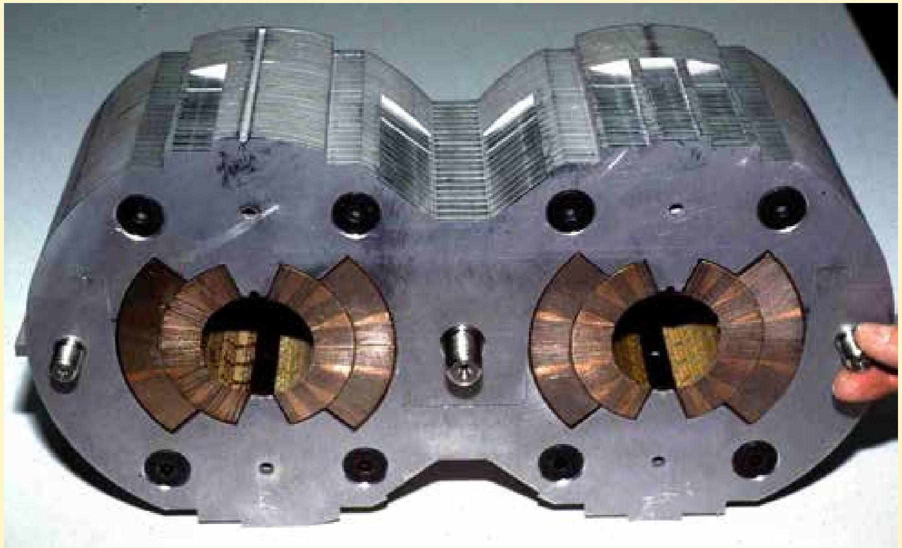
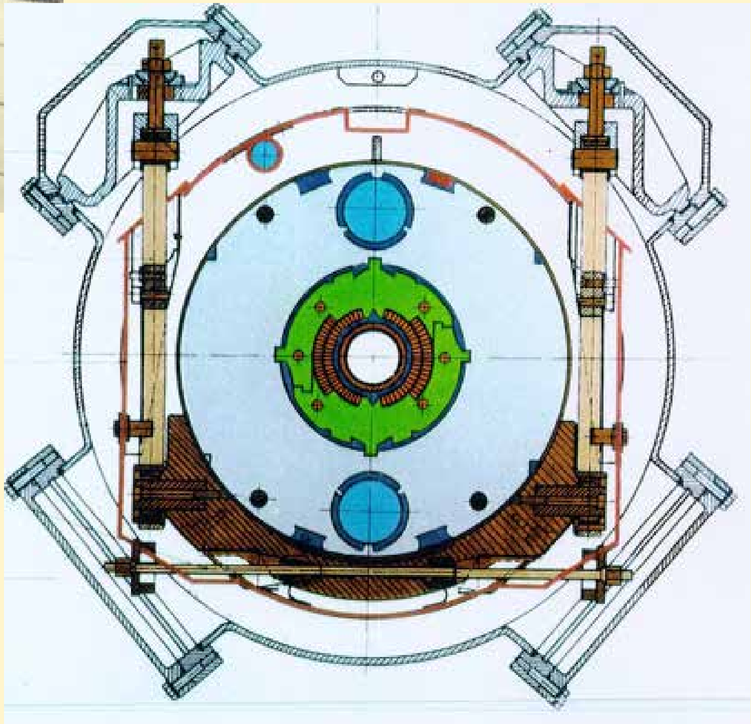


photo courtesy of DESY

DESY Hera

operational 1992 to 2007
proton energy 820GeV
dipole field 4.7T

MT-8 Grenoble France (1983)
Superconducting Prototype Dipole Coils for Hera
G.Horlitz H.Kaiser G.Knust K-H.Mess S.Wolf P.Schmuser BH.Wiik
The proposed electron-proton collider *HERA* consists of *a* 30 GeV electron storage ring and an 820 GeV proton ring, the latter equipped with superconducting dipole and quadruple magnets.



- **Rutherford cable**
- **force supporting collars**
- **cold iron**

ISABELLE

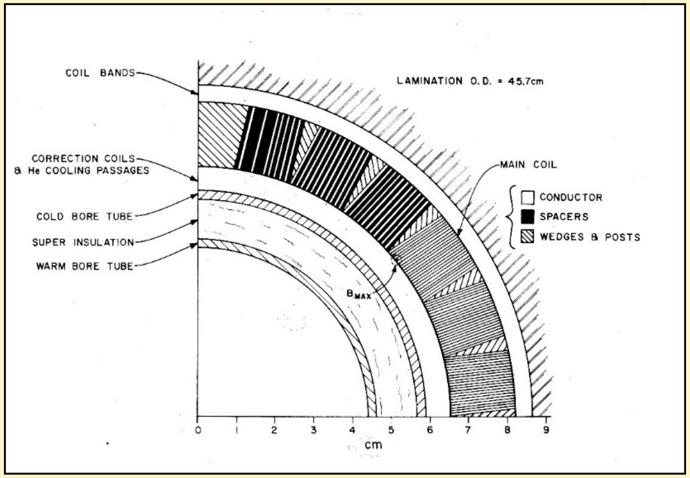
200-GeV Intersecting Storage Accelerators,
ISABELLE,
A Preliminary Design Study, 1972,
BNL Report 16716 USA.

MT-7 Karlruhe Germany (1981)
Upgraded Coil Configuration for Isabelle Magnets
H. Hahn, P.F. Dahl, J.E. Kaugerts, and A.G. Prodell
Brookhaven Laboratory USA

Achievement of the design field of 5 T in the ISABELLE dipole magnets is turning out to be more arduous than expected….

MT-10 Boston USA (1987)
Performance of Initial Full-length RHIC Dipoles
P.Dahl J.Cottingham M.Garber A.Ghosh C.Goodzeit A.Greene
Brookhaven Laboratory USA

The first four full-length (9.7 m) R&D dipoles for the proposed Relativistic Heavy Ion Collider (RHIC) have been successfully tested. The magnets reached a quench plateau of approximately 4.5 T with very reasonable training……



more arduous than expected……

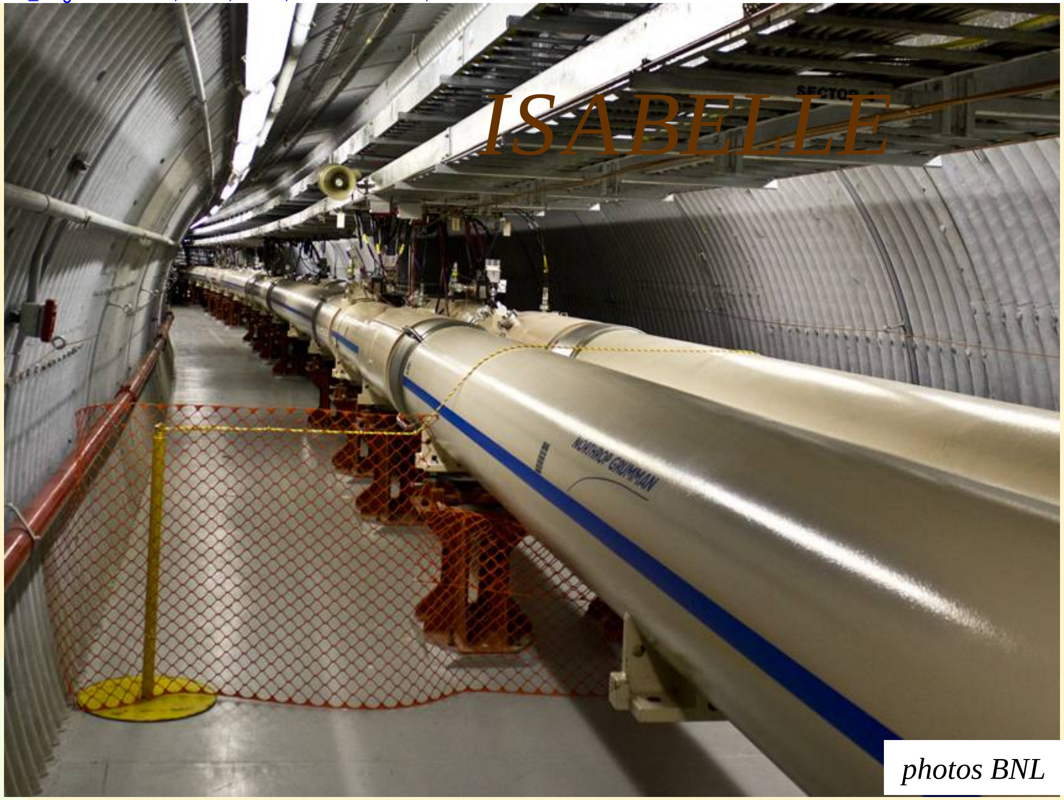
cancelled 1983

RHIC:
Relativistic Heavy Ion Collider

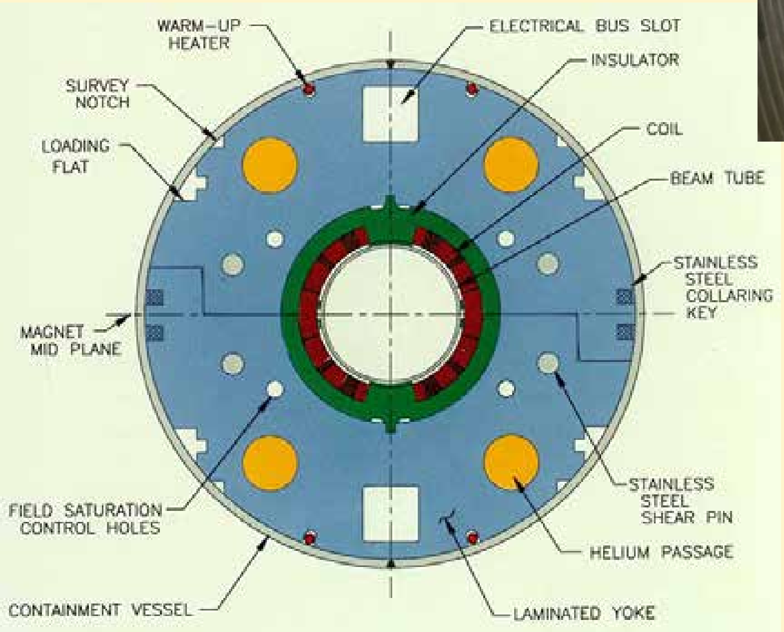
Operational from 2000

Ion energy ~ 200 GeV/nucleon

Dipole field 3.45T



photos BNL



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SSC

circumference 87km

proton energy 2 × 20 TeV (10^{12}ev)

dipole field 6.T

MT-9 Zurich (1985)

Performance of Three 4.5m Dipoles for SSC

P.Dahl J.Cottingham R.Fernow M.Garber A.Ghosh…

Brookhaven Laboratory USA

Three 4.5m long dipoles…… have been successfully tested…….reached 6.6T with little training

MT-10 Boston (1987)

SSC Magnet Technology

C Taylor

Lawrence Berkely Lab USA

To minimize cost... small-bore high field dipole magnets have been developed...

MT-11 Tsukuba (1989)

Investigation of Heater Induced Quenches in a Full Length SSC R&D Dipole

A.Devred M.Chapman J.Cortella A.Desportes…

Brookhaven Fermilab Lawrence Berkely USA

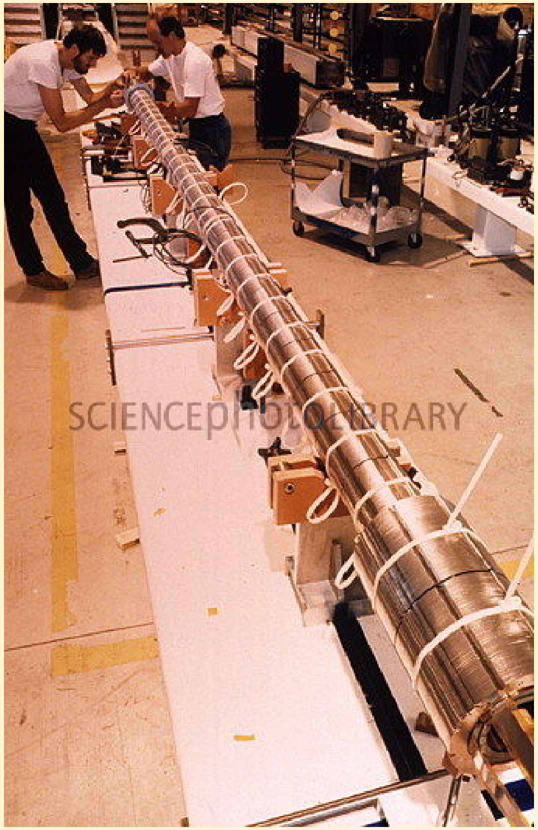
A 17m long SSC R&D dipole instrumented with quench heaters and numerous voltage taps…..

MT-12 Leningrad (1991) **Construction Experiences with SSC Dipole Magnets at Fermilab**

Fermilab & SSC Laboratory USA

RC.Bossert JS.Brandt JA.Carson K.Coulter ….

Full length and short model SSC 50mm bore dipoles are being built and tested at Fermilab



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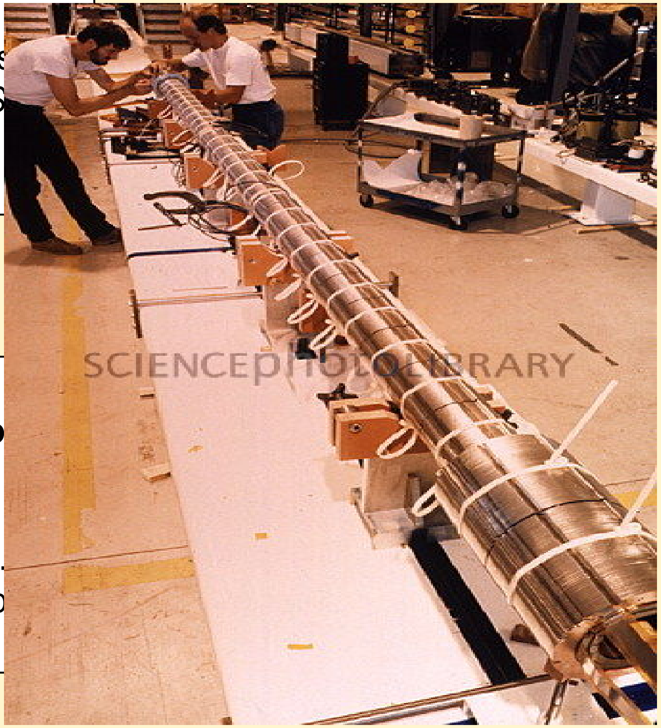

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Full length and short model SSC 50mm bore dip are being built and tested at Fermilab

SSC

circumference 87km

proton energy 2 × 20 TeV (10^{12}ev)

dipole field 6.T

LHC

circumference 27km

proton energy 2 × 6.5 TeV (10^{12}ev)

dipole field 7.8

Large Hadron Collider

photo CERN

LHC

MT-9 Zurich (1985)

Towards the Development of High Field Superconducting Magnets for a Hadron Collider in the LEP Tunnel

D.Hagedorn, D.Leroy and R.Perin

CERN Switzerland

…..a hadron collider in the LEP tunnel…. a natural …extension of the CERN accelerator facilities after the completion of LEP……

MT-11 Tsukuba (1989)

Design and Construction of a Twin-Aperture Prototype Magnet for the CERN LHC Project

D.Hagedorn Ph.Lebrun D.Leroy R.Perin J.Vlogaert

CERN Switzerland

A twin-aperture, 10 m long, prototype magnet was designed by CERN and built by industry……

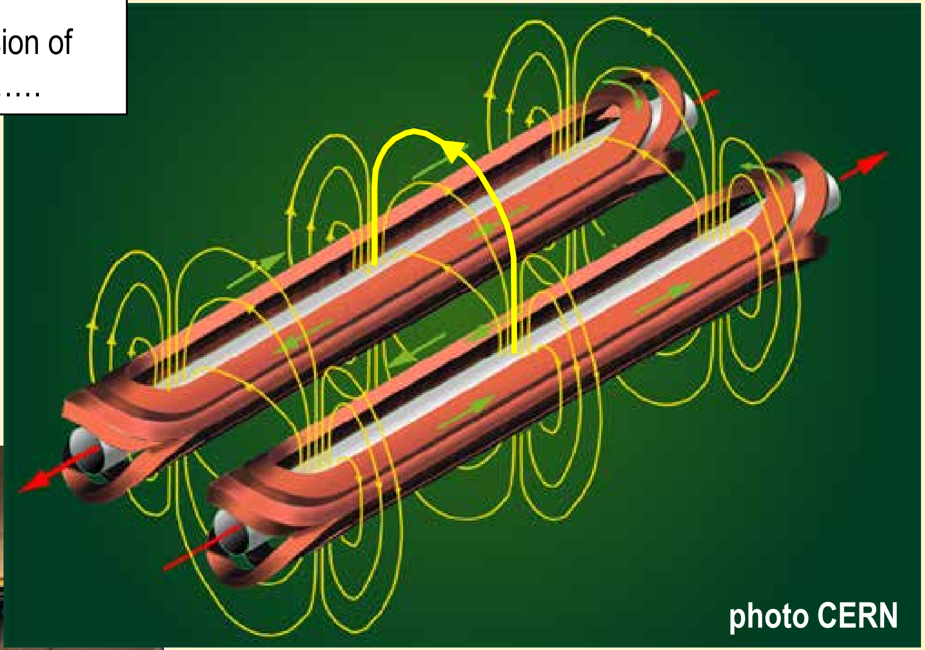


photo CERN

photo CERN

MT-16 Florida (1999)

Cryogenics for the LHC

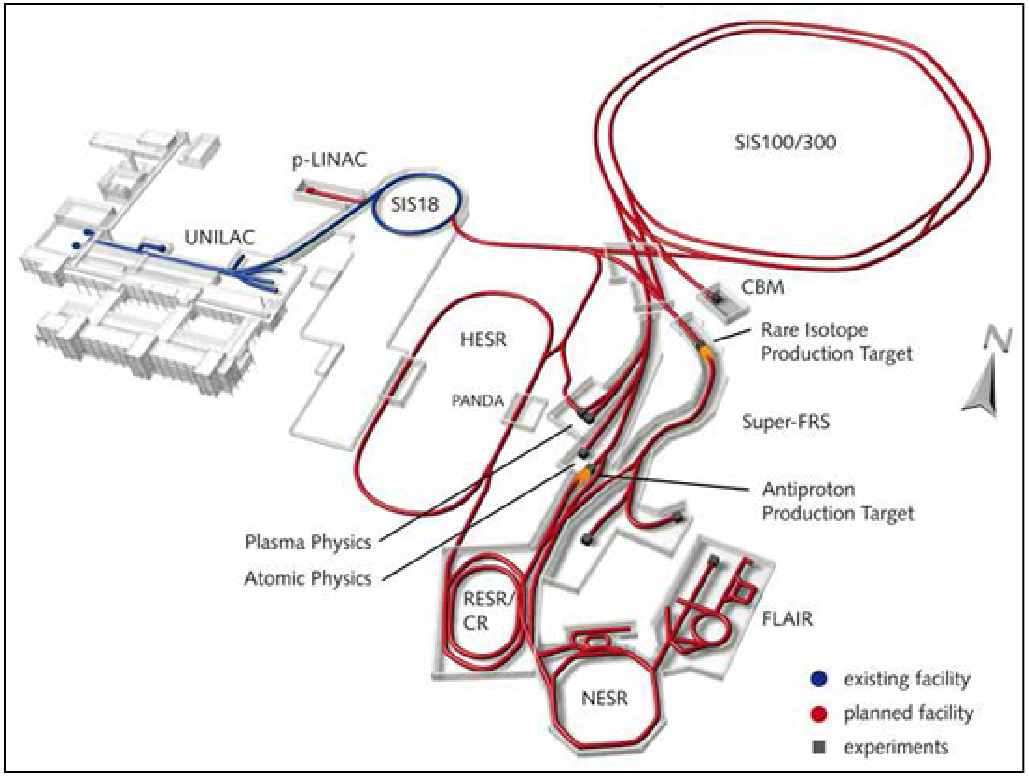
P.Lebrun

CERN Switzerland

….26.7 km circumference with… magnets operating in superfluid helium below 1.9 K…some 150 kW at 4.5 K and 20 kW at 1.9 K distributed around the ring

Martin Wilson slide22

FAIR: Facility for Antiproton and Ion Research



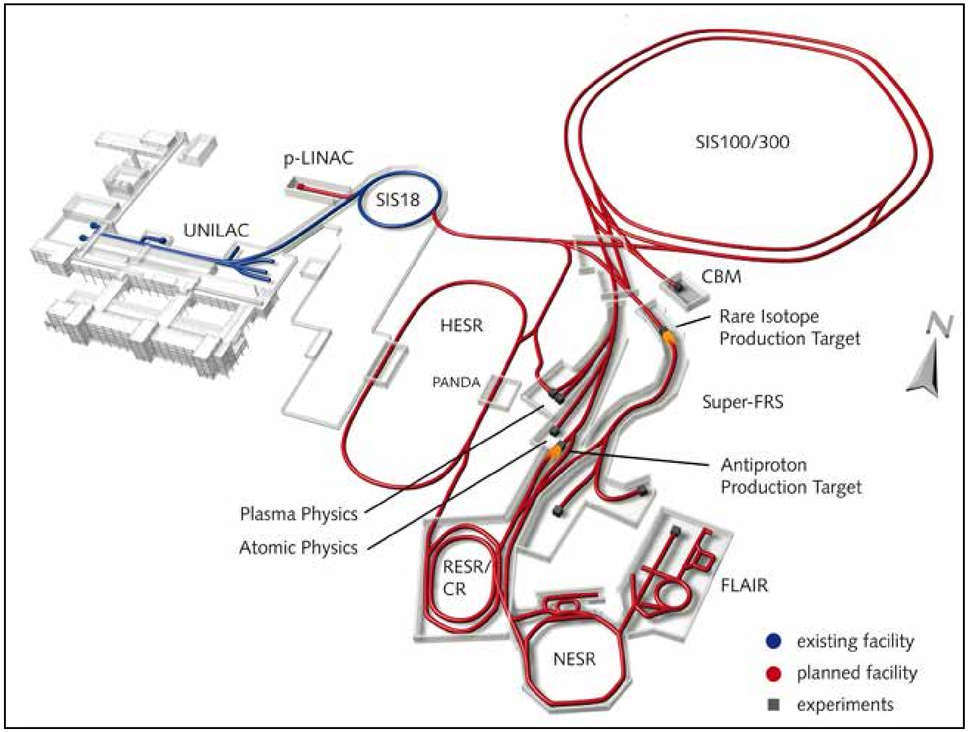
MT-20 Philadelphia USA (2007)
Development of a Curved Fast Ramped Dipole for FAIR SIS300
P.Fabbricatore F.Alessandria G.Bellomo S.Farinon U.Gambardella J.Kaugerts R.Marabotto R Musenich G Moritz M.Sorbi G.Volpini
GSI Germany INFN Italy

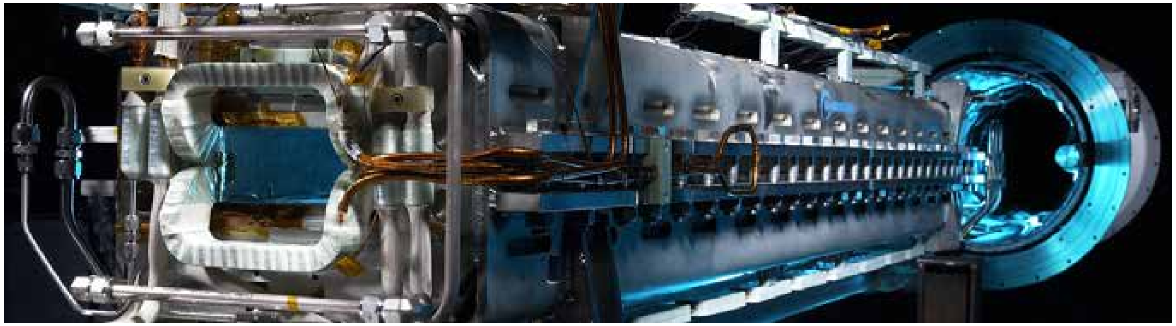
… options for dipoles of the SIS 300 synchrotron…. a single layer magnet 7.8 m long, 100 mm in bore diameter, generating 4.5 T. …two main features: it is curved, with radius of 66.67 m and ramped at 1 T/s….

MT-18 Morioka Japan (2003)
Progress in the Design and Study of a Superferric Dipole Magnet for the GSI Fast-Pulsed Synchrotron SIS100
A.Kovalenko N.Agapov V.Aksenov I.Karpunina H.Khodzhibagiyan G.Kuznetsov M.Voevodin G.Moritz E.Fischer G.Hess C.Muehle
GSI Germany JINR Dubna USSR

…. a superferric window frame dipole magnet with …. B = 2 T, dB dt = 4 T/s and pulse repetition rate f = 1Hz…. coil is made from a hollow multi-filamentary NbTi cable cooled with two phase helium flow …. minimization of AC power losses… 9 W/m ..obtained

FAIR: Facility for Antiproton and Ion Research





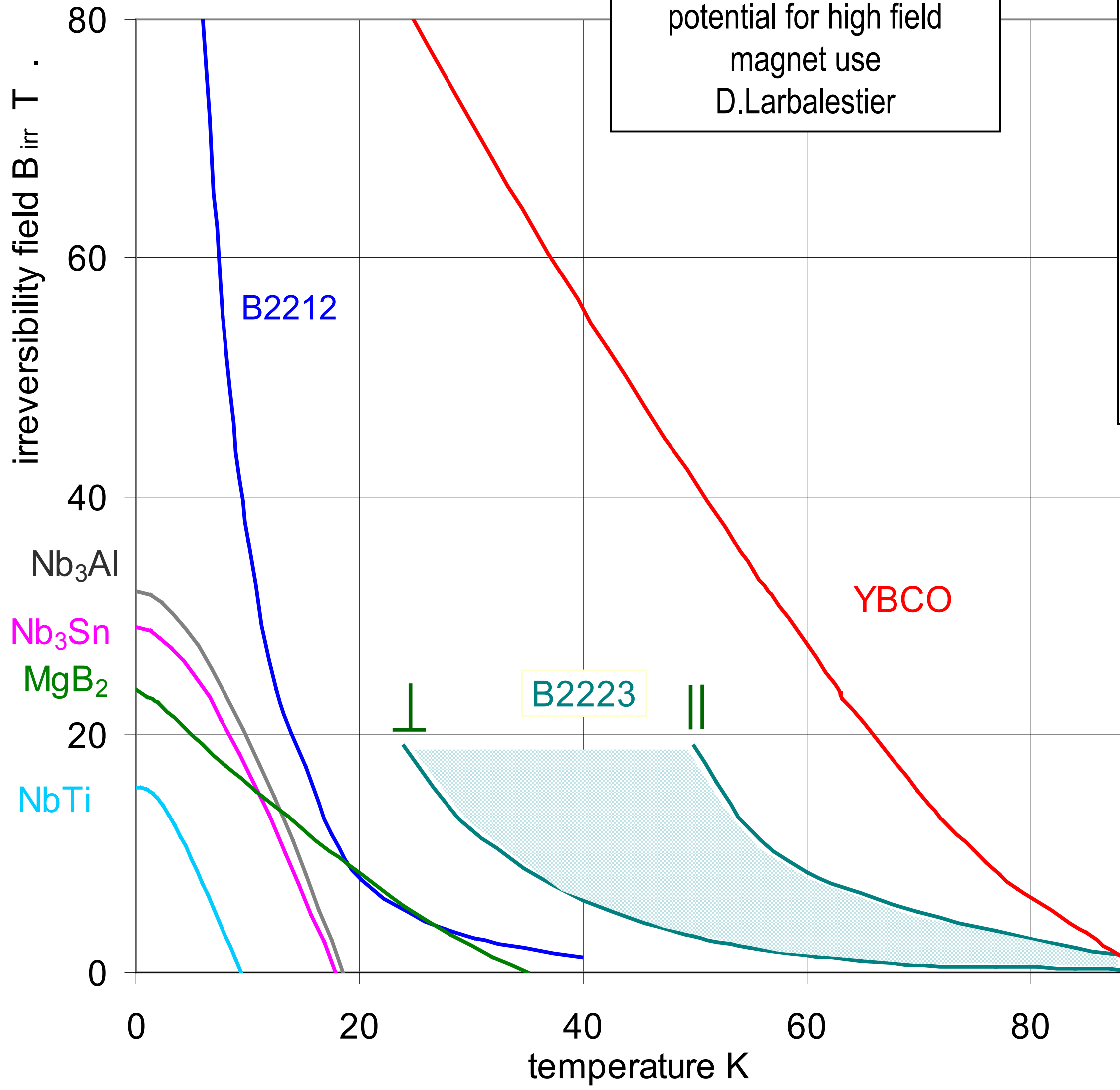
Helios: compact synchrotron X-ray source for microchip lithography

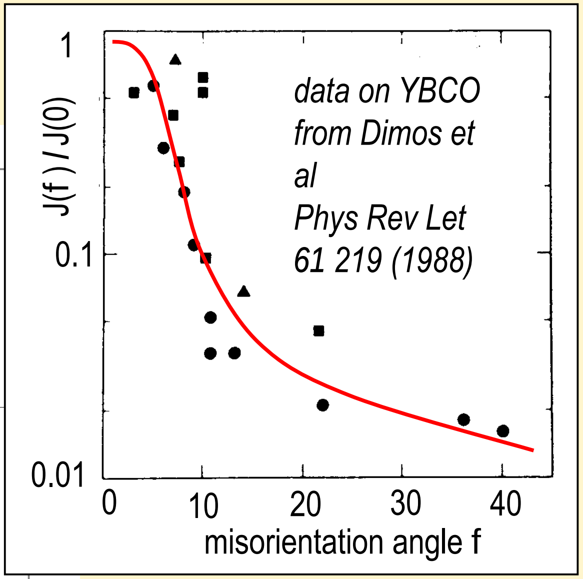
photos courtesy of

OXFORD INSTRUMENTS

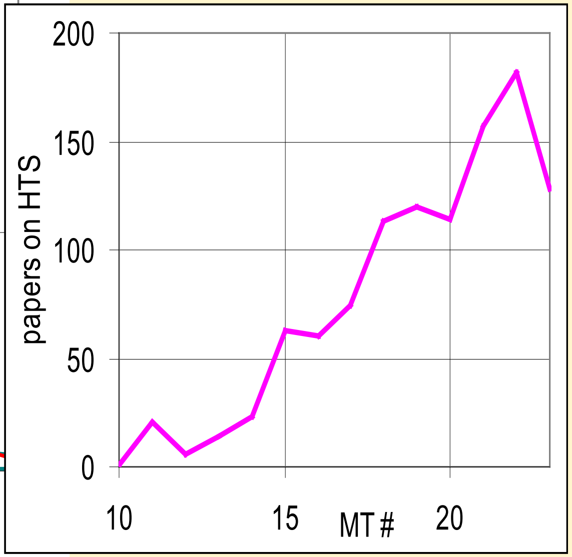
Materials

MT-10 Boston USA (1987)
High temperature oxide superconductors: their potential for high field magnet use
D.Larbalestier





data on YBCO from Dimos et al Phys Rev Let 61 219 (1988)

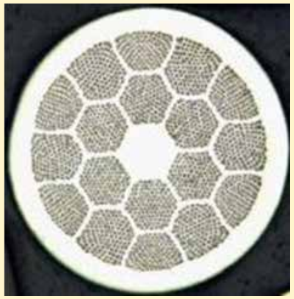


HTS magnet conductors

Wires

B2212

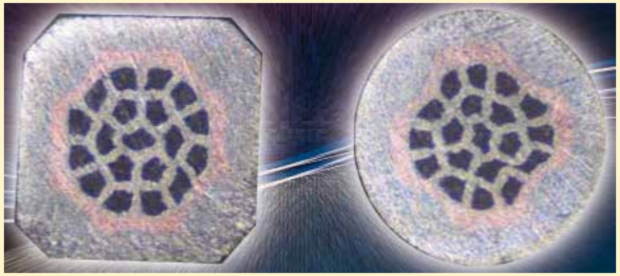
- filaments in silver matrix
- isotropic J_c
- leakage & bubbling ameliorated by gas pressure heat treatment



MT-23 Boston USA (2013)
B2212 round wire development for high field applications
Y.Huang H.Miao S.Hong J.Parrell
OST Carteret USA

MgB_2

- isotropic J_c
- filaments in monel matrix
- copper can be added

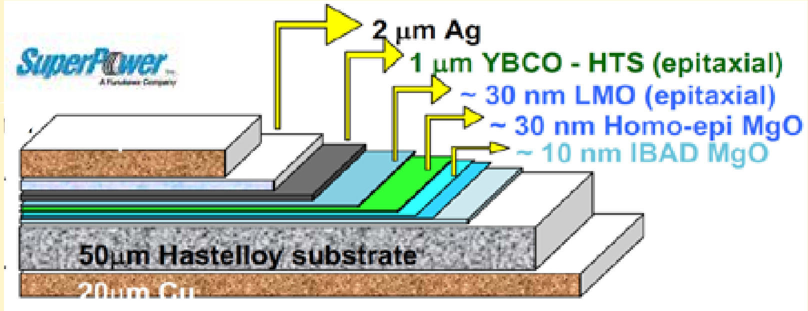


Tapes

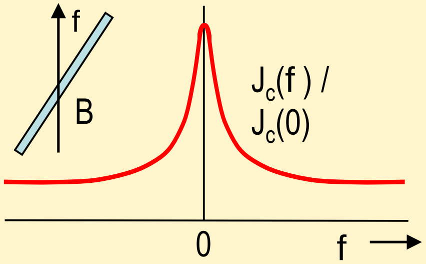
B2223

silver matrix, anisotropic critical current

YBCO



- high current density
- high field & temperature
- but anisotropic & expensive

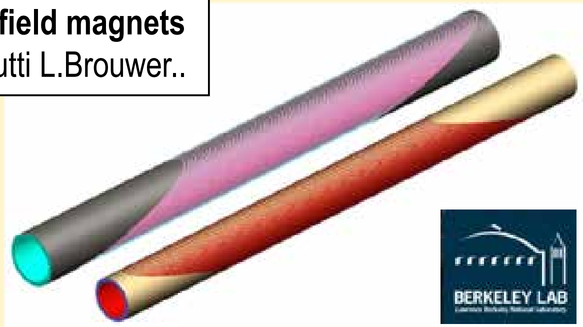


HTS accelerator magnets

LBL

- Rutherford cable made of B2212 wires

MT-23 Boston USA (2013)
Canted cosine theta CCT – a concept for high field magnets
S.Caspi F.Borgnolutti L.Brouwer..

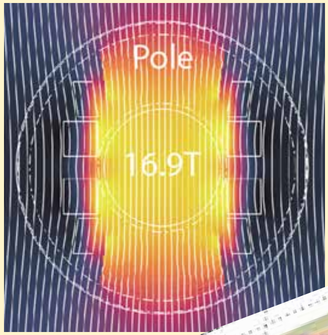


- react B2212 after winding

LBL pictures from S.Caspi & A.Godeke

CERN

- ReBCO coated tape in a Roebel cable

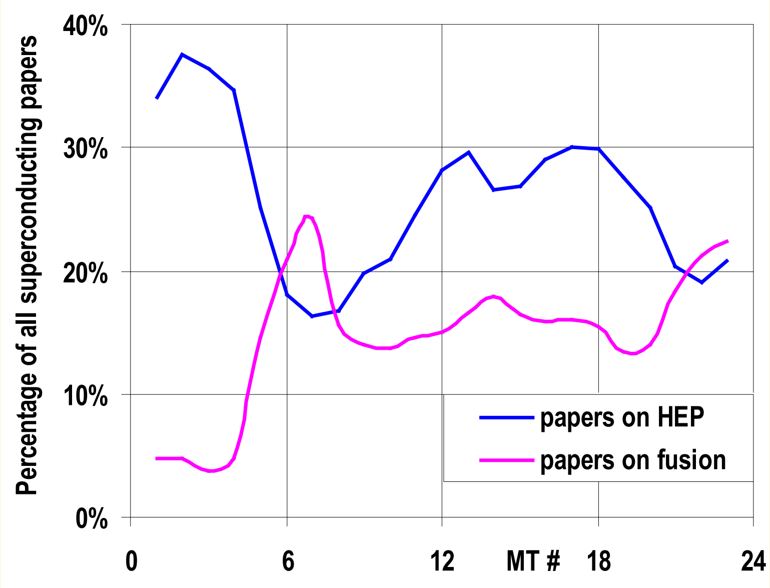


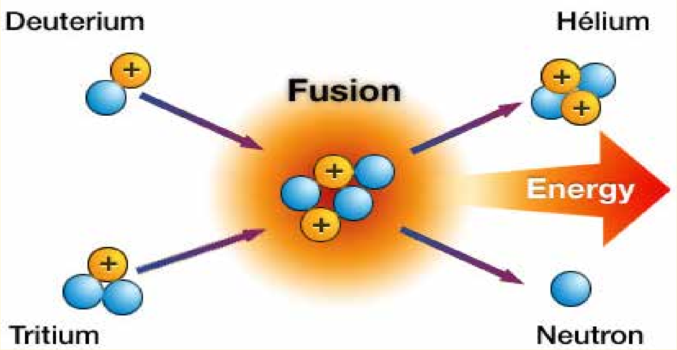
- winding blocks canted to align with field lines

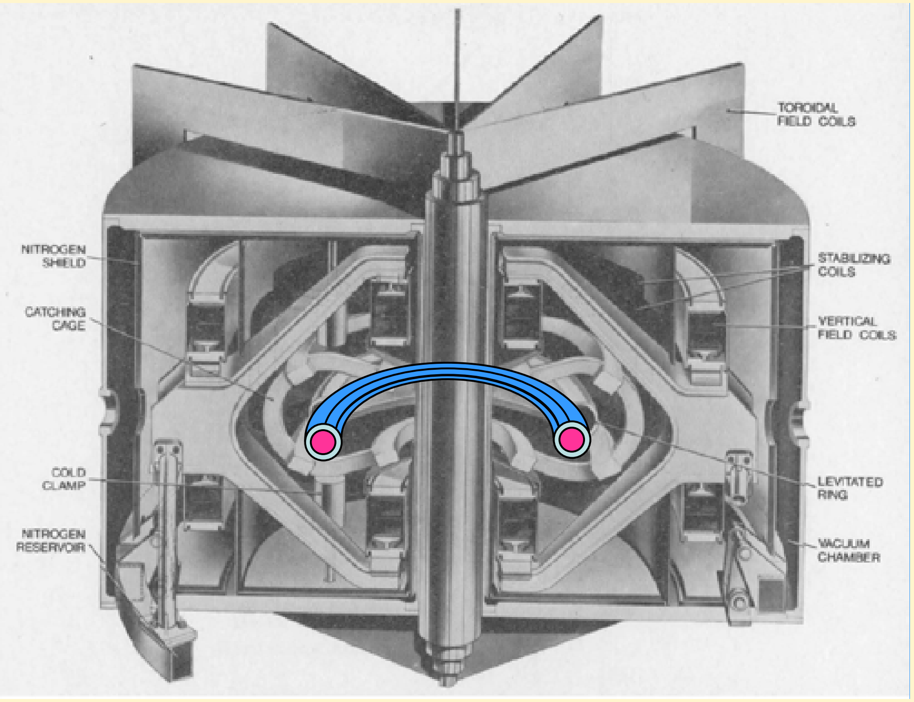
- copper loops for quench protection

CERN pictures from G Kirby

Magnetic confinement fusion







MT-3 Hamburg Germany (1970)

A Superconducting Levitron

DN.Cornish

Culham Laboratory UK

…In a Levitron the plasma is contained in the field surrounding a current-carrying ring which is supported by a magnetic field...

MFTF B mirror fusion test facility 1977-1986

MT-9 Zurich Switzerland (1985)

Design & Fabrication of the MFTF-B Magnet System

RE.Tatro and TA.Kozman

Lawrence Livermore NL and General Dynamics

… 40 NbTi magnets and two Nb_3Sn magnets. General Dynamics designed all magnets… fabricated 20 NbTi magnets..LLNL fabricated 20 NbTi magnets and two Nb_3Sn magnets.…

solenoids

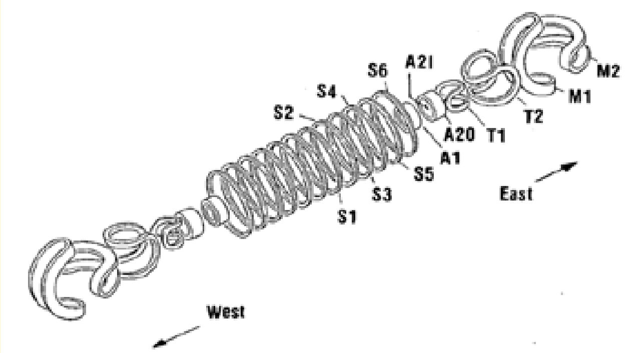
bore = 5.5m

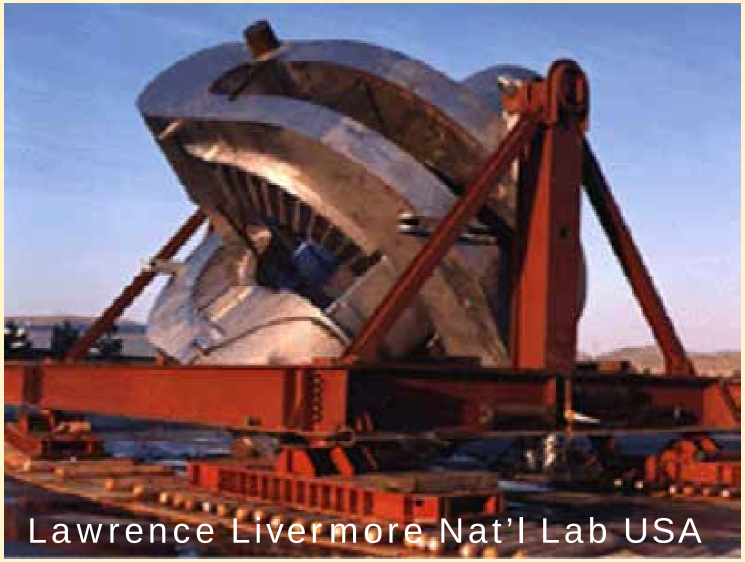
B_{max} = 3.2T

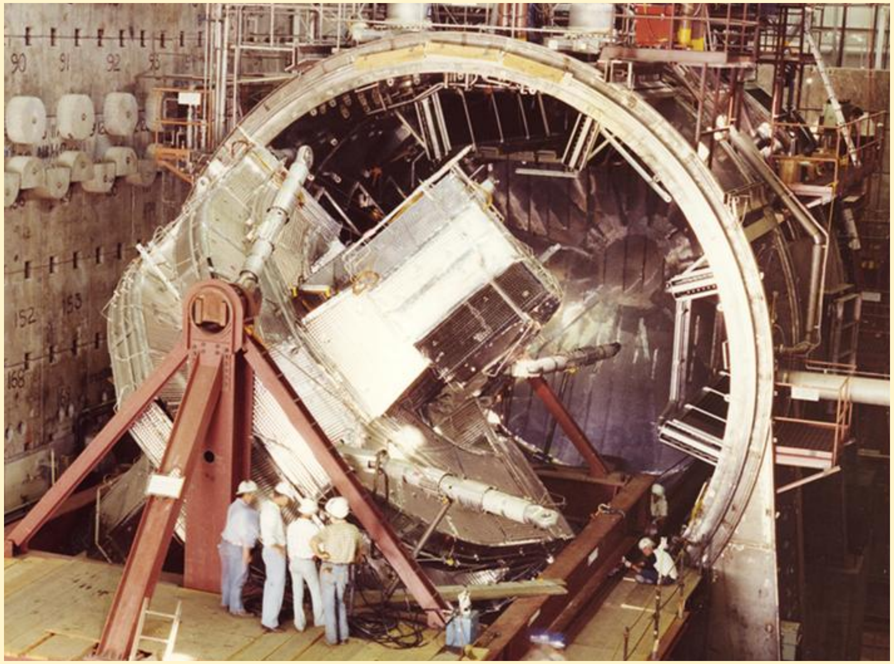
mirror

weight = 400t

B_{max} = 12.5T




Lawrence Livermore Nat'l Lab USA



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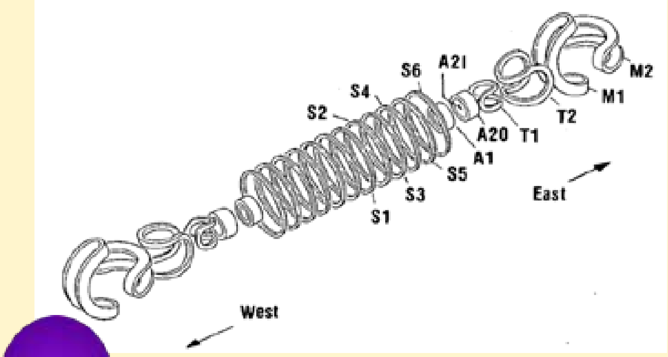

MFTFB dedicated on 21 Feb 1986

Lawrence Livermore Nat'l Lab USA

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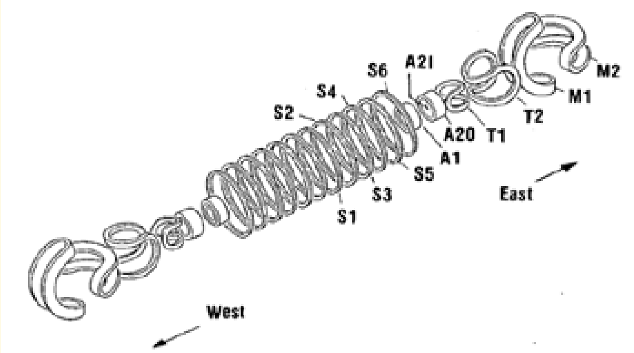
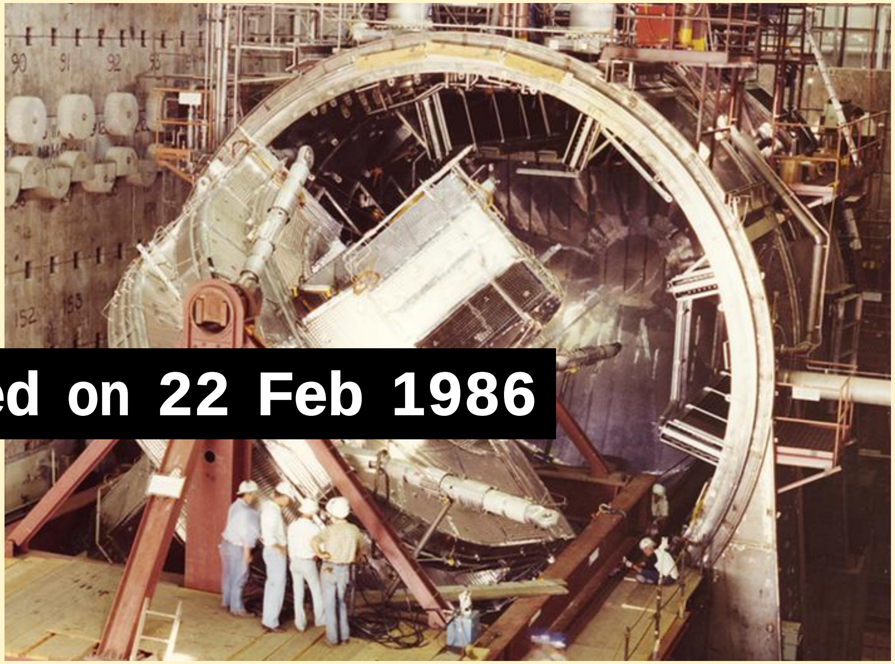



Lawrence Livermore Nat'l Lab USA



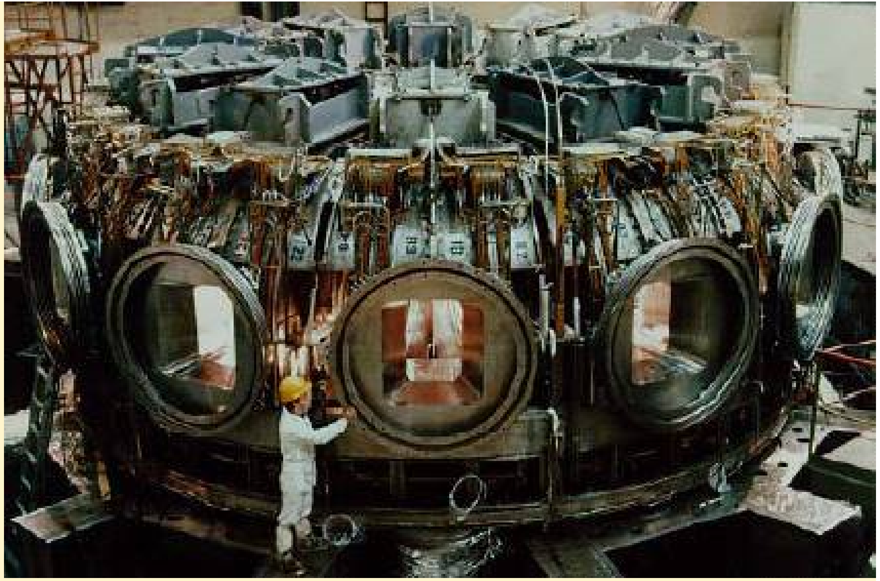
MTFB terminated on 22 Feb 1986

T-15 & Tore Supra

MT-11 Tsukuba Japan (1989)
First Tests of T-15 Toroidal Field System.
VA.Alhimovch IO.Anashkin AN.Vertiporokh AN.Volobuev..
Kurchatov Institute Moscow USSR
…physical start-up was realized in Dec 1988. TF system
…. superconducting state and first plasma produced.

T -15 Kurchov Institute Moscow Russia

operated 1985 – 95 *upgrade scheduled for 2018*
B_o = 3.6T B_{max} = 6.5T R_o = 2.4m
technology Nb_3Sn force flow cooling at 4.5K



MT-14 Tampere Finland (1995)
Six Years of Operating Experience with Tore Supra,
B.Turck
CEA Cadarache France
…largest Tokamak with superconducting coils.. behaviour
… under repetitive loadings.. time at 1.8 K of 14000 Hours

Tore supra: Cadarache France

1988 – present
B_o = 4.5T B_{max} = 9T R_o = 2.25m
technology NbTi at 1.9K atmos pressure
world record pulse 6 minutes
'West' project tungsten liner

Large coil task LCT

MT-7 Karlsruhe Germany (1981)

Large Coil Task of IEA in the Development of Superconducting Magnets for Fusion

K.Yasukochi

Japan Atomic Energy Research Institute

... development of large superconducting TF coils is urgently needed . Under the auspices of IEA, "The Large Coil Task, LCT"….. facility for testing six coils in a toroidal array is constructed at ORNL…

The Japanese LCT Coil

S Shimamoto

1986 App. Sup Conf

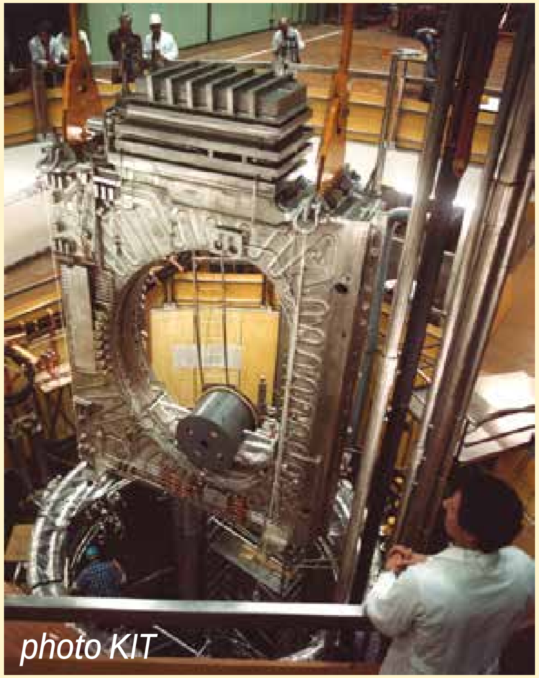


photo KIT

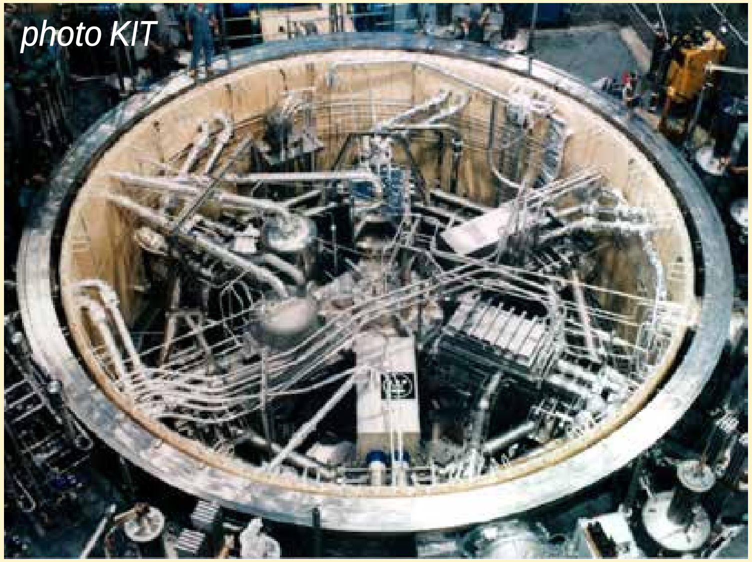


photo KIT

6 x D coils

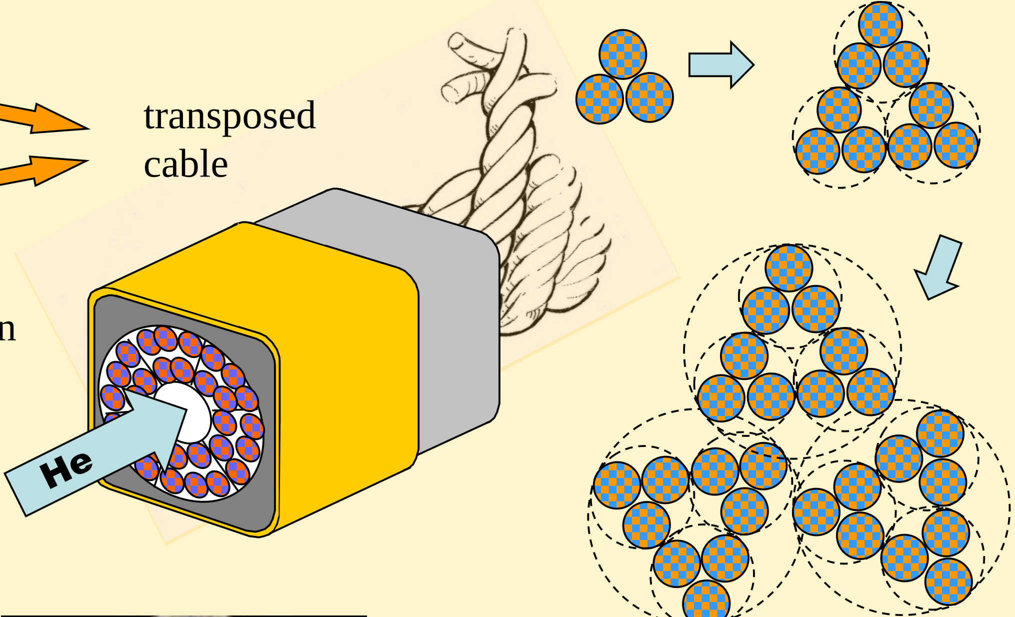
bore = 2.5m × 3m

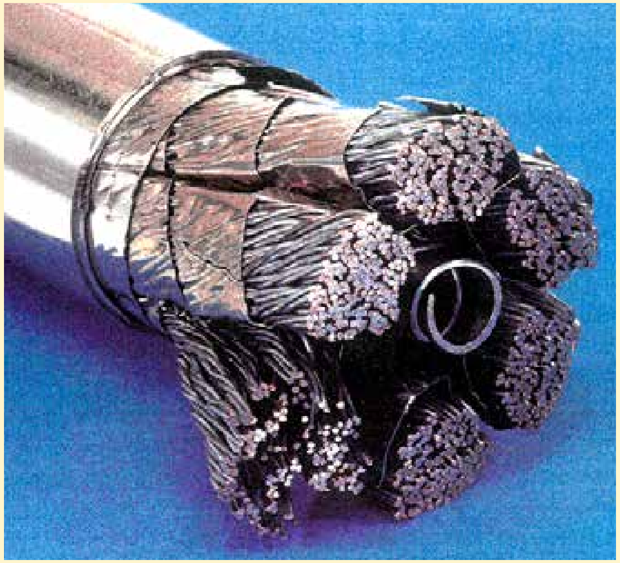
B_{max} ~ 9T

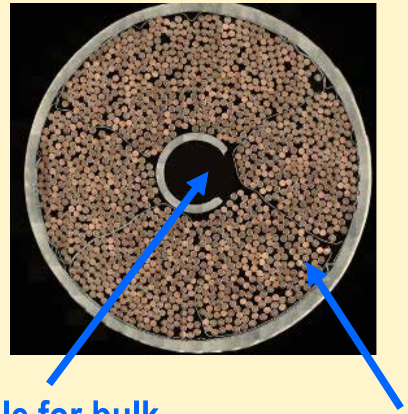
tested at Oak Ridge National Laboratory

Cable in conduit conductor CICC

- low ac losses ð fine filaments
- big magnets ð big conductors
- reliable performance ð cryostabilization







hole for bulk helium flow

porous array for local cooling

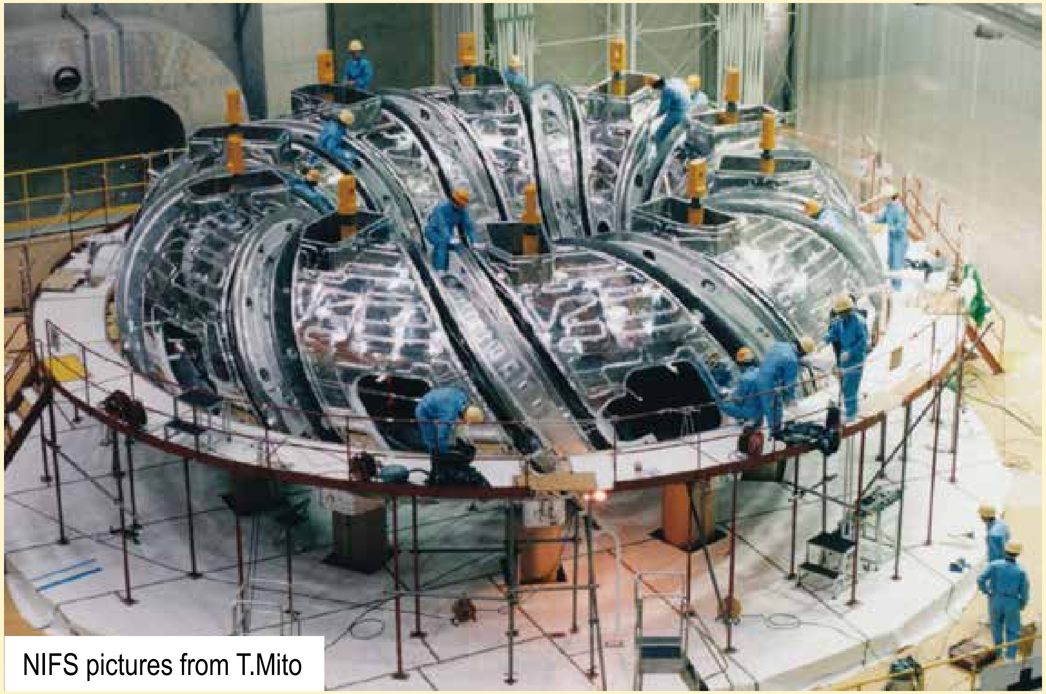
MT-6 Bratislava (1978)
Force cooled cable superconductors
M Hoenig, JW Lue, DB Montgomery
MIT Boston USA
..tests on cryo-stability of cabled superconductor enclosed in conduit and force cooled by pumped helium

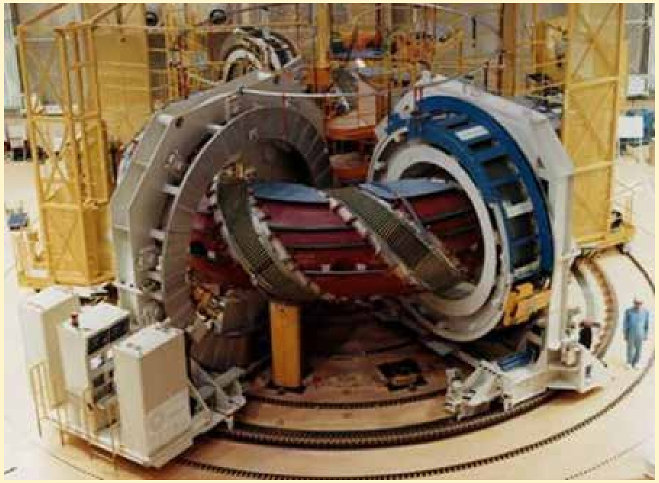
Stellarators: LHD Large Helical Device

LHD Toki Japan

operational 1998 – present
outer diameter = 13.5m
max field on coils = 6.6T

MT-15 Beijing China (1997)
Assembly of the Superconducting Coils & the Cryostat for the Large Helical Device
T.Satow S.Imagawa H.Tamura K.Takahata
N.Yanagi S.Yamada T.Mito A.Nishimura
NIFS Toki Japan
…two superconducting helical coils, 3 pairs of poloidal coils…a 13.5m dia. outside cylinder…..


NIFS pictures from T.Mito

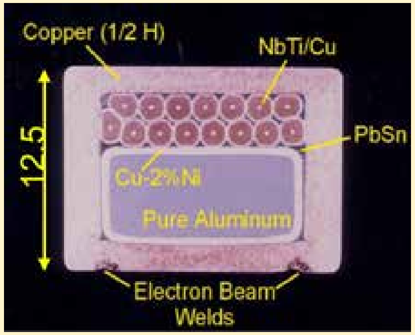


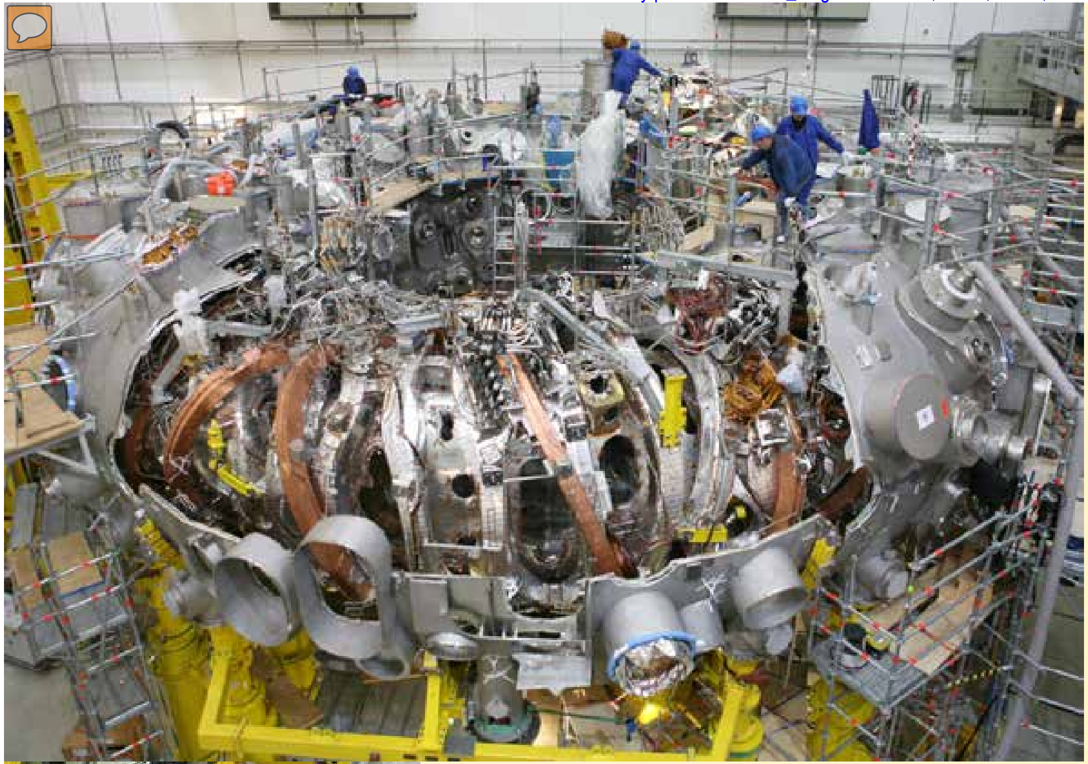
winding machine

conductor

poloidal ←

helical →





Wendlestein 7x

Greifswald Germany

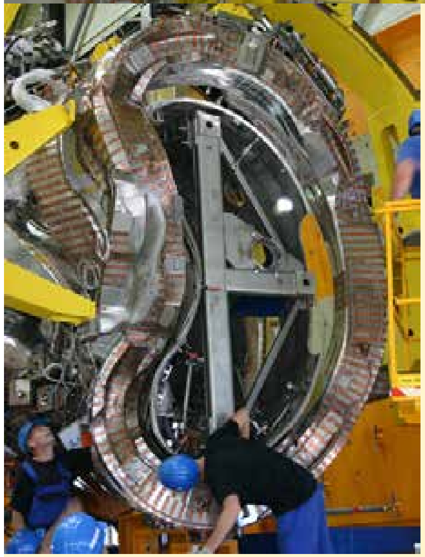
nearing completion

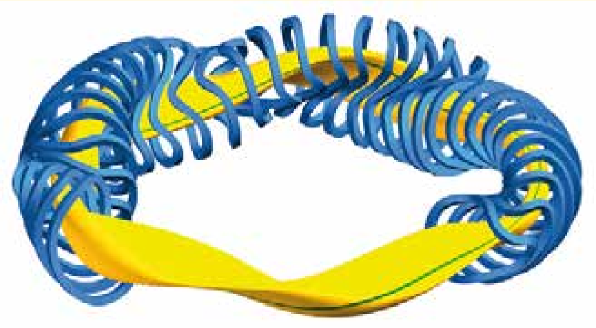
outer diameter = 16m

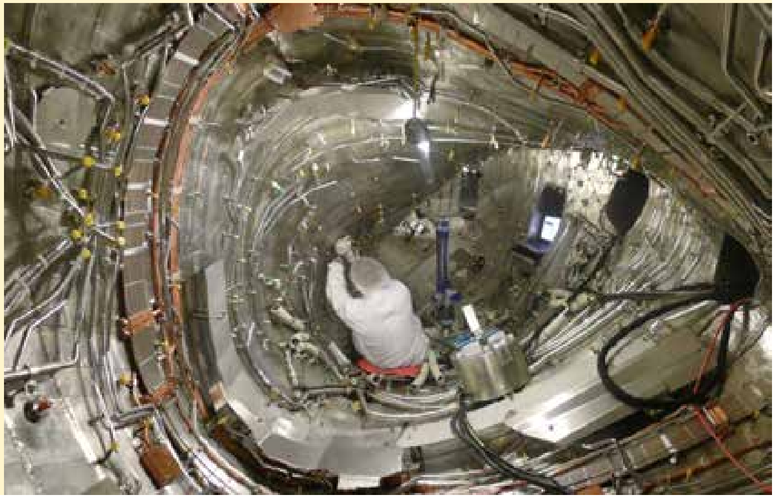
max field on coils = 6T

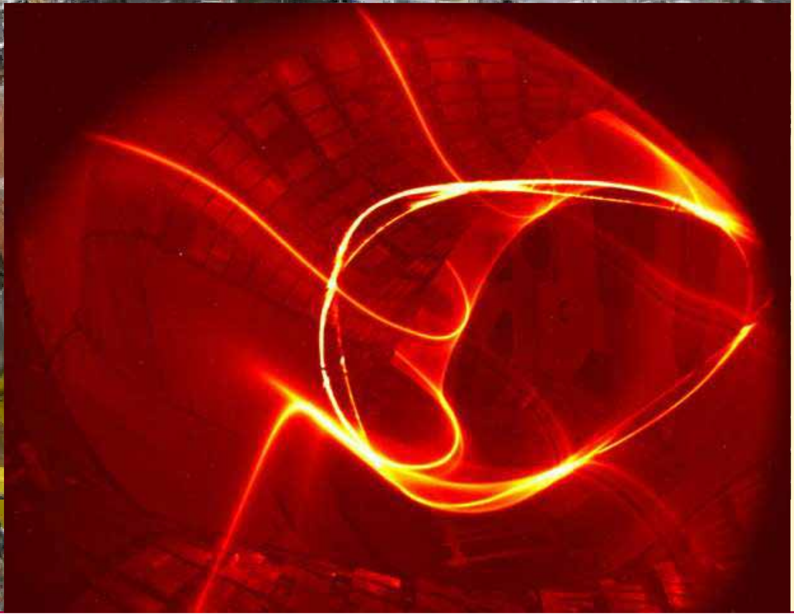
plasma pulse ~ 30 minutes

MT-19 Genoa Italy (2005)
Recent Results of the Cold Tests Performed on the Stellarator W7-X Coils
J.Baldzuhn H.Ehmler A.Hoelting C.Sborchia…
Max Planck Institute Greifswald Germany
..plasma .. 30 minutes… Superconducting coils mandatory … 50 nonplanar and 20 planar coils..









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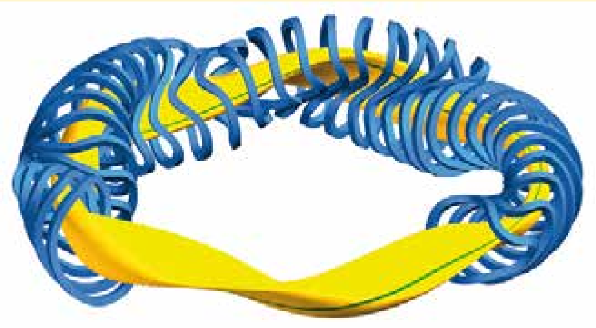
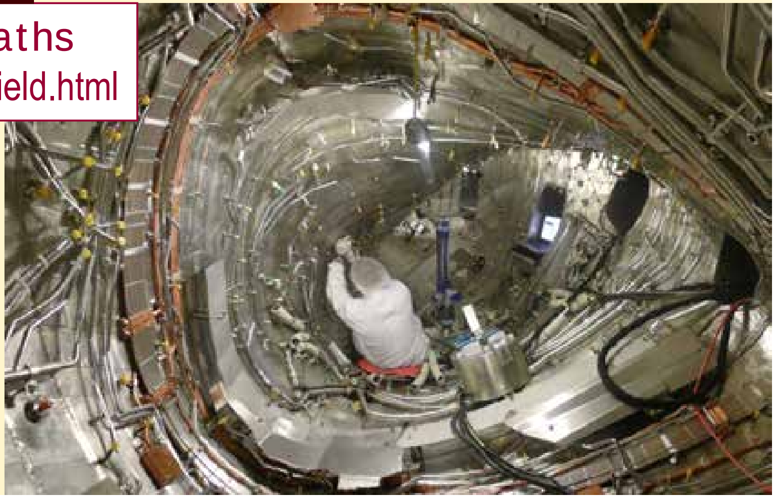
flux surface mapped by electron beam paths
http://phys.org/news/2015-07-wendelstein-x-magnetic-field.html





EAST & KStar

EAST: IPP Hefei China

2006 to present

$B_o = 3.5T \quad B_{max} = 5.8T \quad R_o = 1.7m$

technology CICC NbTi

lithium coating of plasma vessel

MT-19 Genoa (2005)

Fabrication of the Toroidal Field Superconducting Coils for the EAST Device

W.Chen Y.Pan S.Wu P.Weng D.Gao J.Wei J.Yu …

IPP Hefie China

KStar: NFRI Daejon S Korea

2008 to present

$B_o = 3.5T \quad B_{max} = 7.5T \quad R_o = 1.85m$

technology CICC NbTi and Nb_3Sn

MT-19 Genoa (2005)

Development of CICC for KSTAR Superconducting Magnet System

BS Lim JY Choi SI Lee Y Chu CS Kim

Korea Basis Science Institute Daejeon Korea

.. two different CICCs-Nb3Sn cable with Incoloy 908 conduit and NbTi cable with 316LN stainless steel

SST-1 and JT 60SA

SST: IPR Gujarat India

2012 to present
B_o = 3.0T (1.5T) B_{max} = 4.3T R_o = 1.0m
technology CICC NbTi 4.5K

MT-23 Boston USA (2013)
First Engineering Validation Results of SST-1 TF Magnets System
S Pradhan K Doshi A Sharma U Prasad Y Kristi..
Institute Plasma Research Gandhanagar India
….field of 1.5T… with two phase He flow in CICC

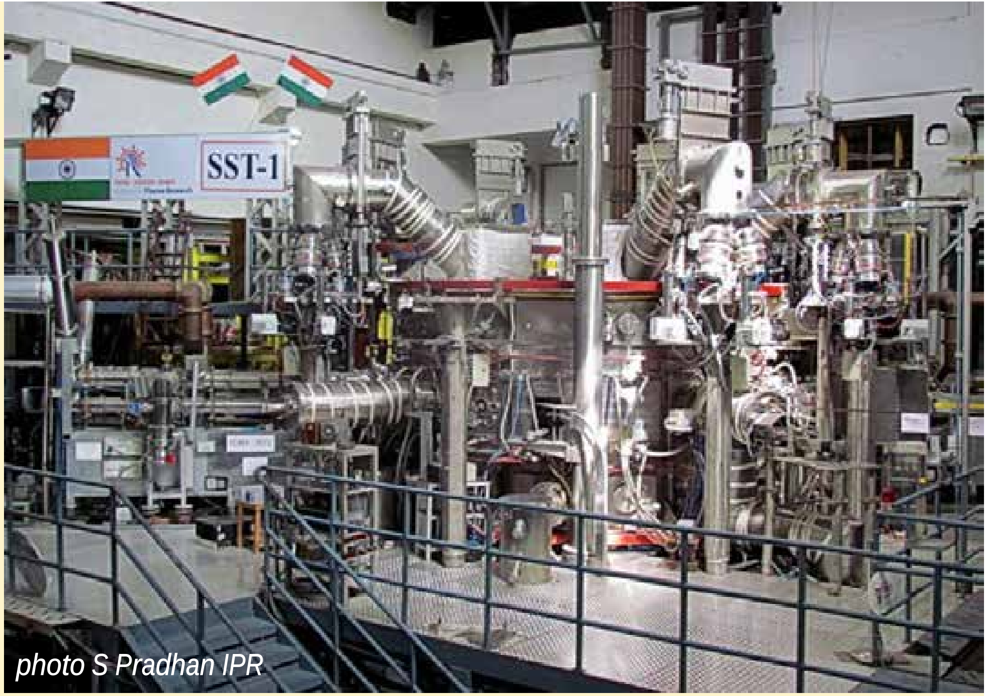


photo S Pradhan IPR

JT-60SA: JAERI Japan

operation planned 2019
B_o = 3.0T B_{max} = 4.3T R_o = 1.0m
technology CICC NbTi
joint project with Euratom

MT-23 Boston USA (2013)
Mass Production of superconducting Magnet components for JT-60SA
K Yoshida K Murakami K Kizu K Tsuchiya…
Japan AEA Naka Japan
JT60 satellite tokamak to ITER…upgrade to superconducting magnets CICC NbTi & Nb_3Sn

iter
china eu india japan korea russia usa

ITER

Cadarache France

first plasma 2020?

$B_o = 5.3T$ $B_{maxTF} = 11.8T$

$R_o = 6.2m$ $B_{maxCS} = 13T$

$E_{TF} = 41GJ$

output power 500MW

MT-11 Tsukuba (1989)

Japanese Design of ITER Superconducting Magnet System

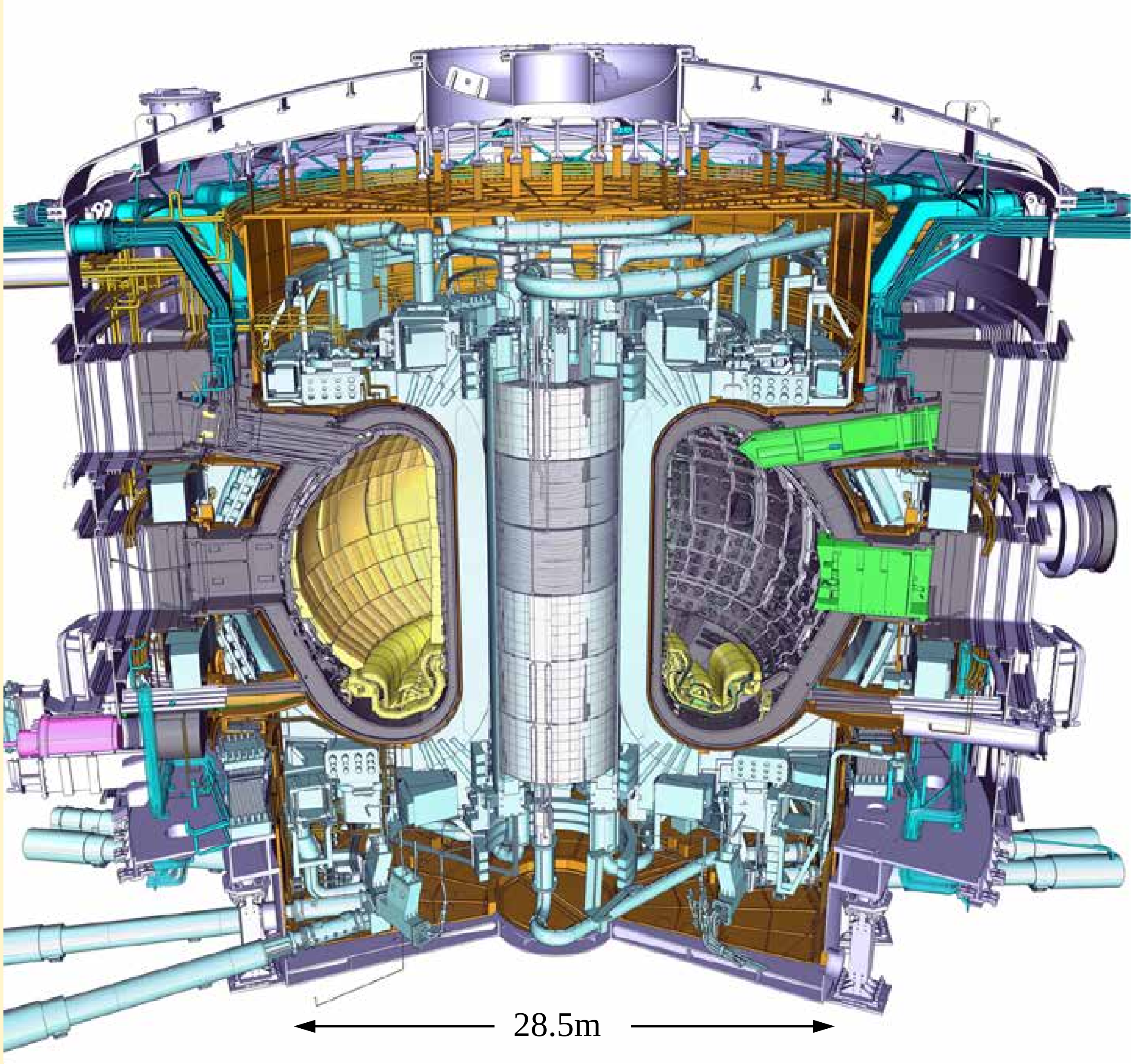
M.Hasegawa K.Yoshida…

JAERI Naka-machi Japan

key issues.. size..4 x LCT

neutron damage……

radio-activation…remote handling...



iter
china eu india japan korea russia usa

ITER

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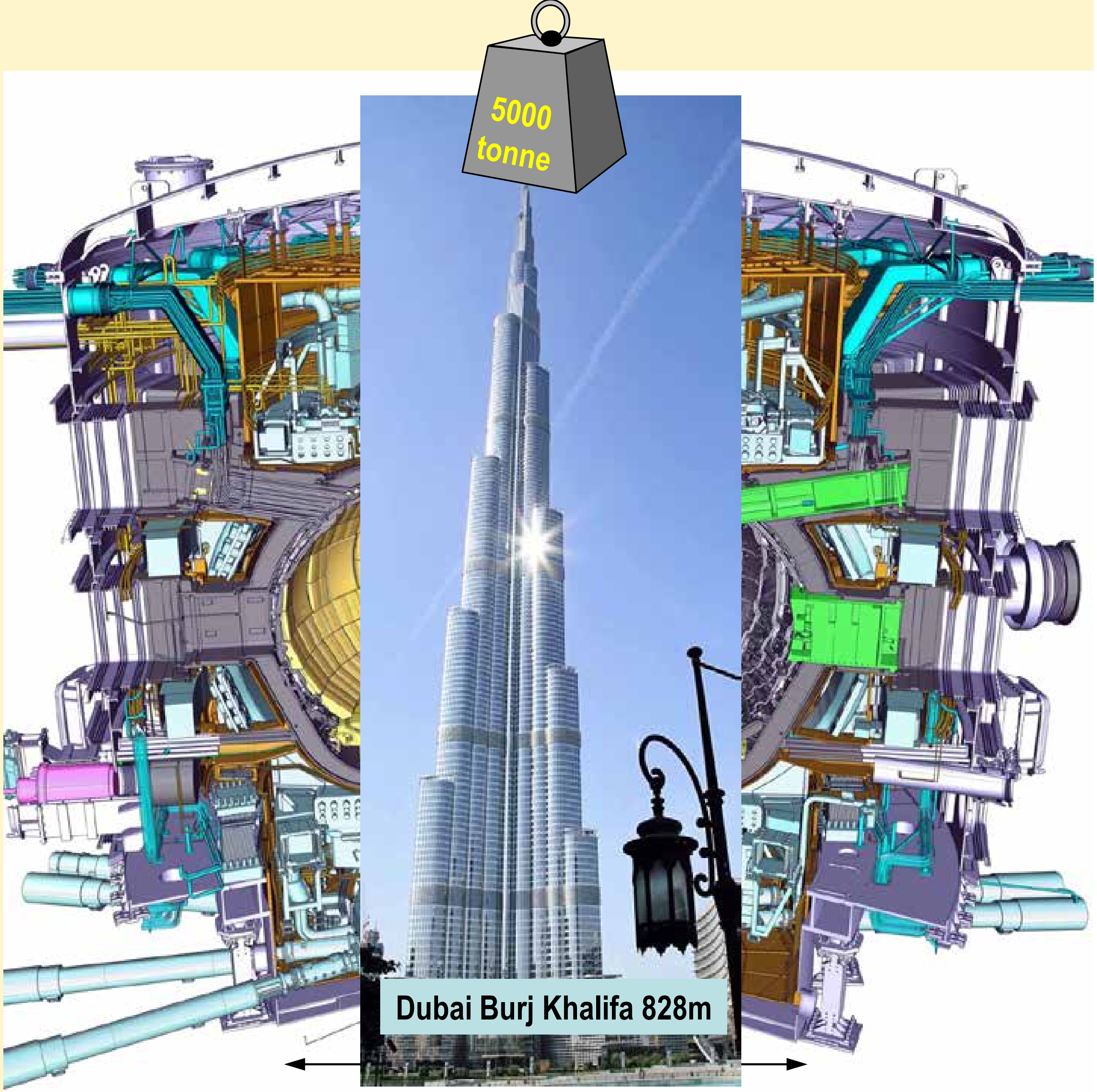

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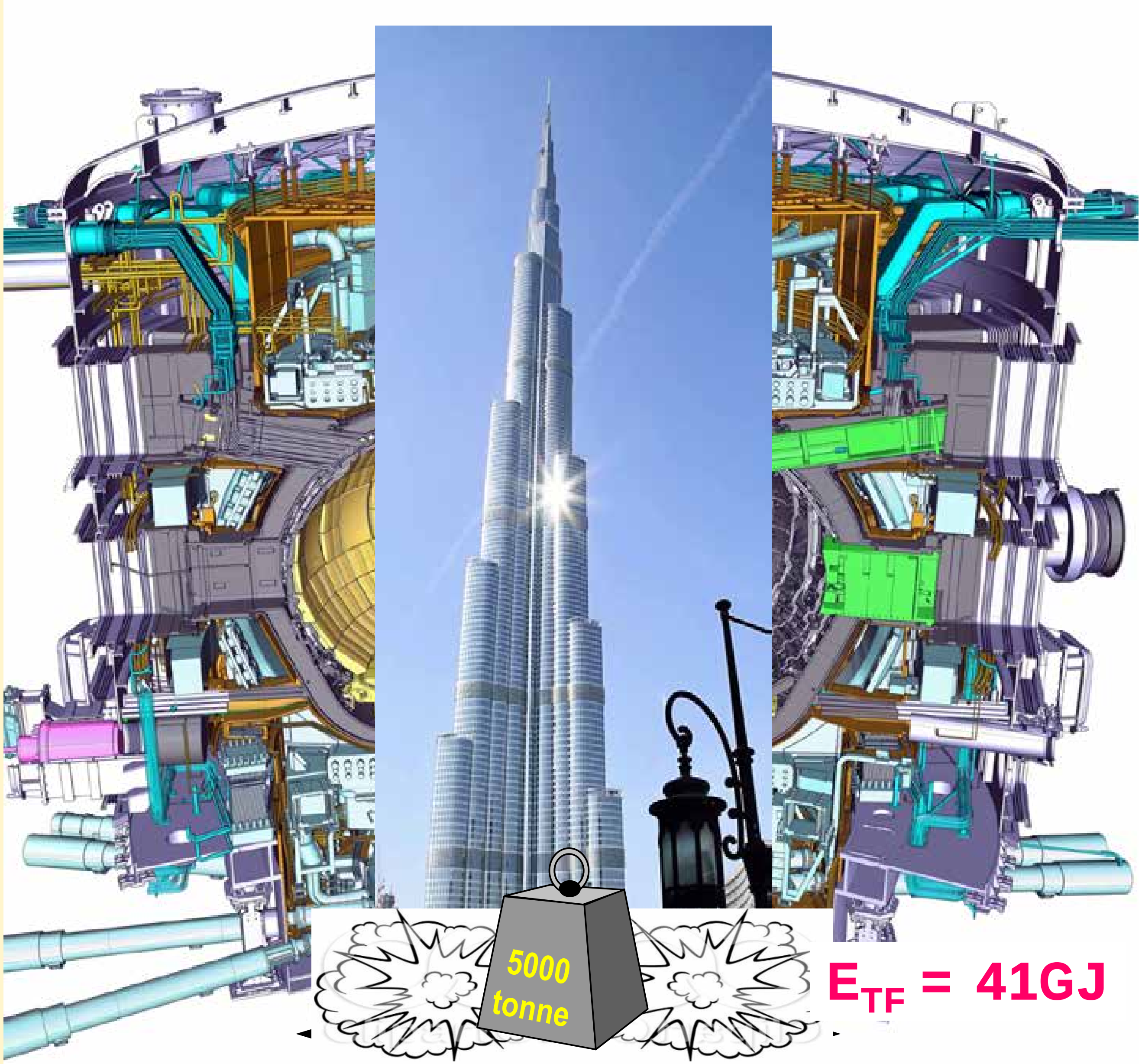
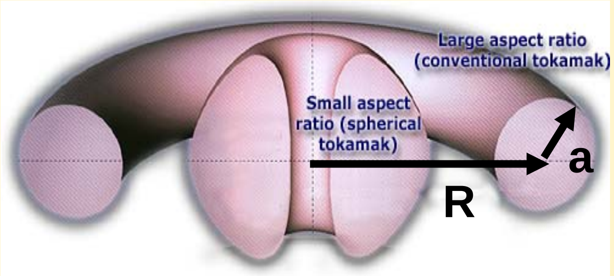
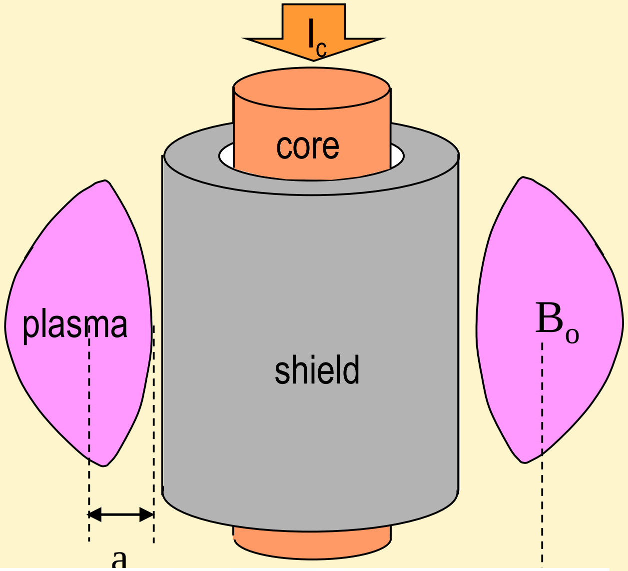


$E_{TF} = 41GJ$

Spherical tokamaks



minimum
aspect ratio
a = R_o / a

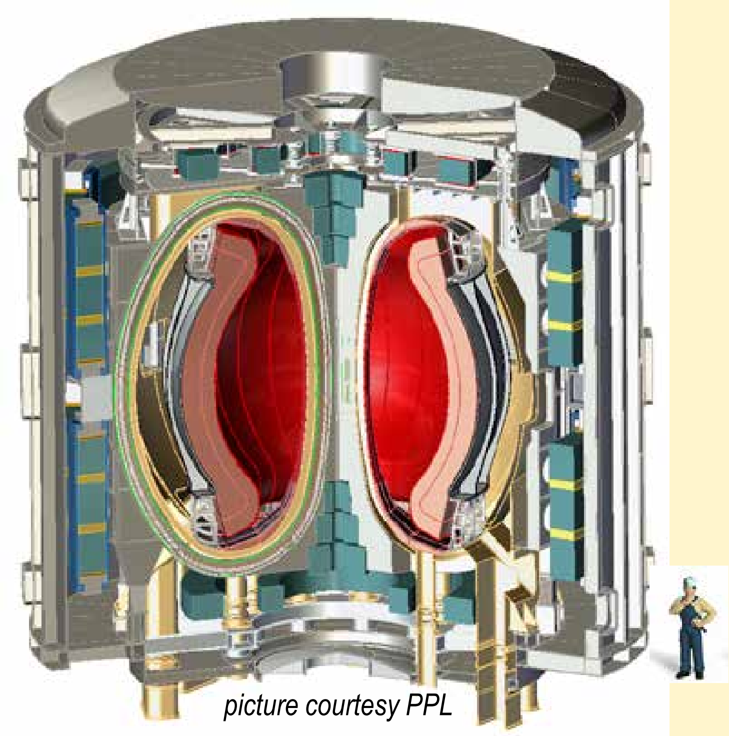


min core radius ð max peak field
ð max current density

min shield ð max core heating
ð max operating temperature

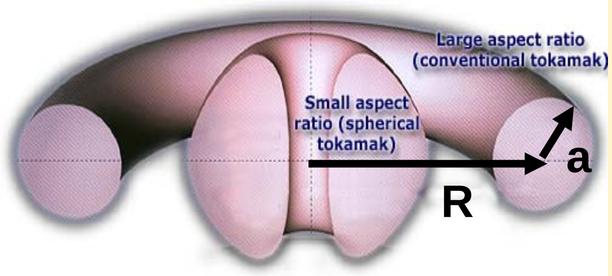
ð ReBCO

tokamak energy
a faster way to fusion



picture courtesy PPL

Spherical tokamaks



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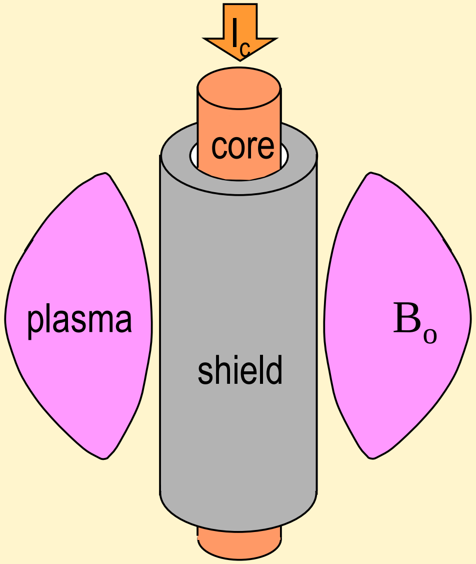

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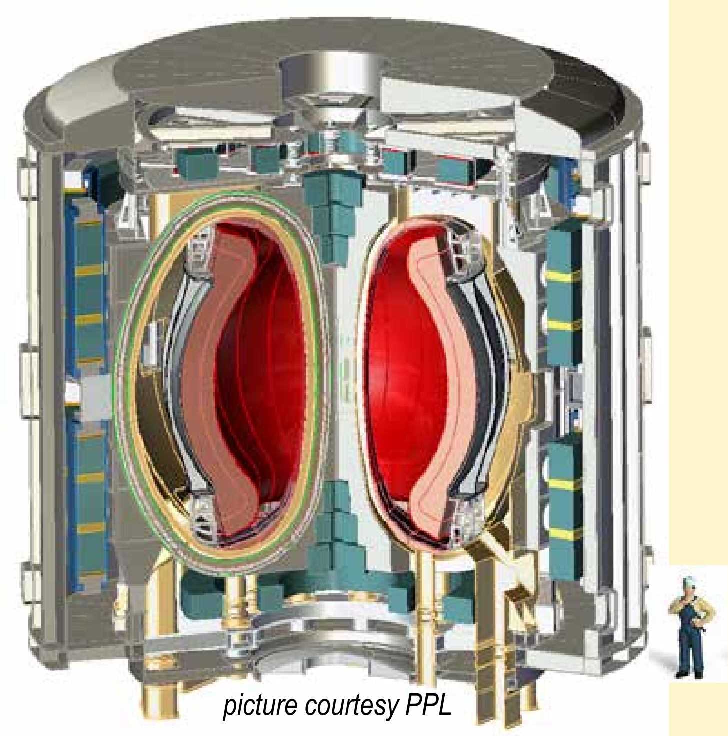
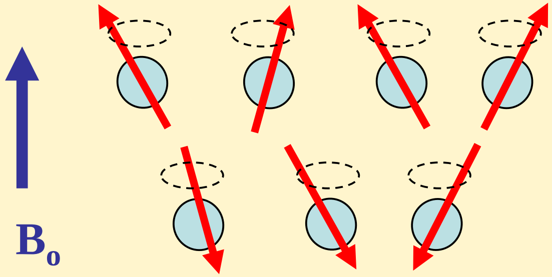
tokamak energy
a faster way to fusion



picture courtesy PPL

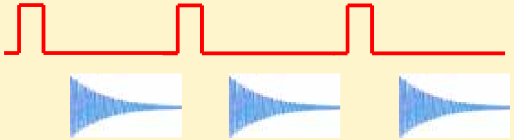
Nuclear magnetic resonance

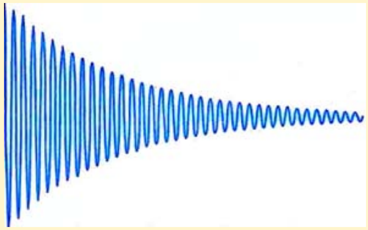


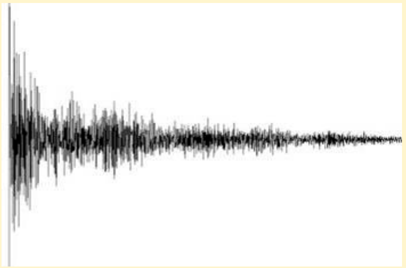
spinning nuclei in magnetic field precess at the *Larmor* frequency

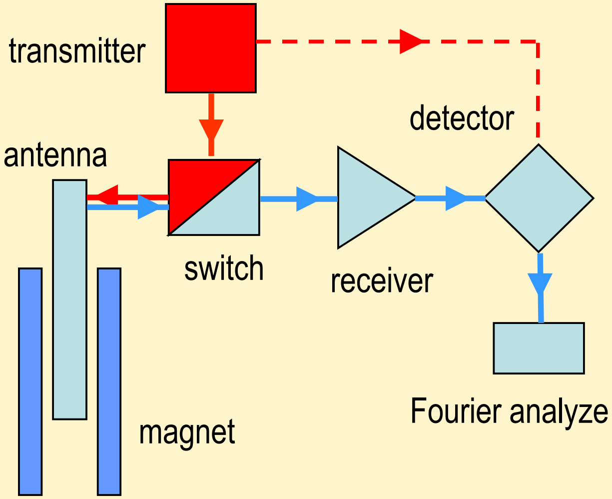
for B = 14.09T f = 600 MHz *(TV channel 37)*

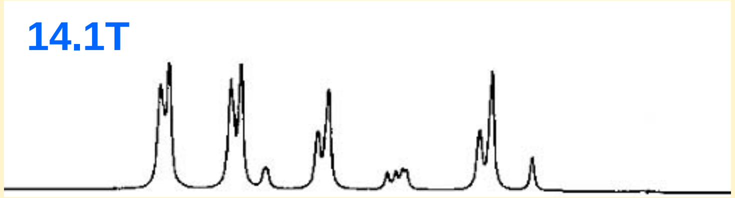
apply a resonant pulse then listen to the ‘ringing’





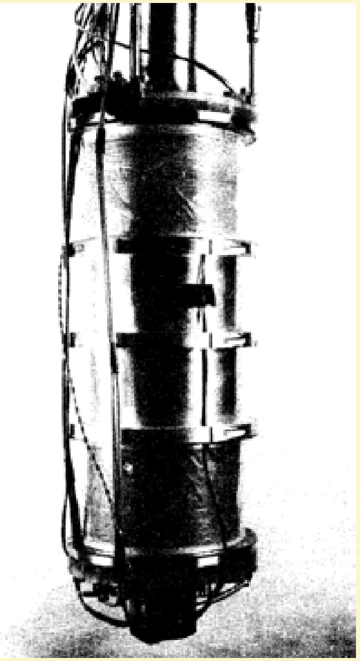






higher fields
ð higher resolution
ð more signal

Magnets for NMR Spectroscopy



Field Uniformities

natural resonance line width	~ 10^{-11}
magnet as made	~ 10^{-5}
magnet after shimming	~ 10^{-9}
power supply ripple	~ 10^{-5}
persistent decay per hour	~10^{-8}

photos courtesy of

OXFORD INSTRUMENTS

MT-1 Stanford USA (1965)

A High Homogeneity - High Field Superconducting Magnet for Nuclear Resonance

P.Grivet M.Sauzade.

Institut Electronique Orsay France

..magnetic field ..highly homogeneous highly stable.. 58 kG homogeneity 10^{-7} over 150 mm^3

A commercial product

Operational cryostat

- superinsulation
- gas cooled shields
- removable current leads (persistent mode)

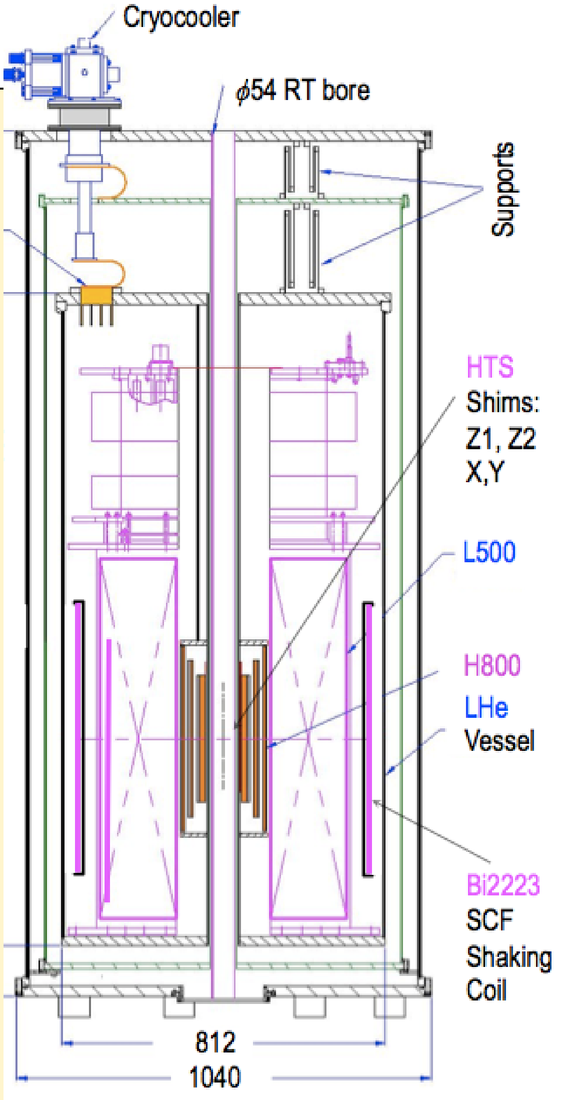
ð helium hold time > 1 year

900 MHz = 21.14T

1GHz (23.8T) and beyond

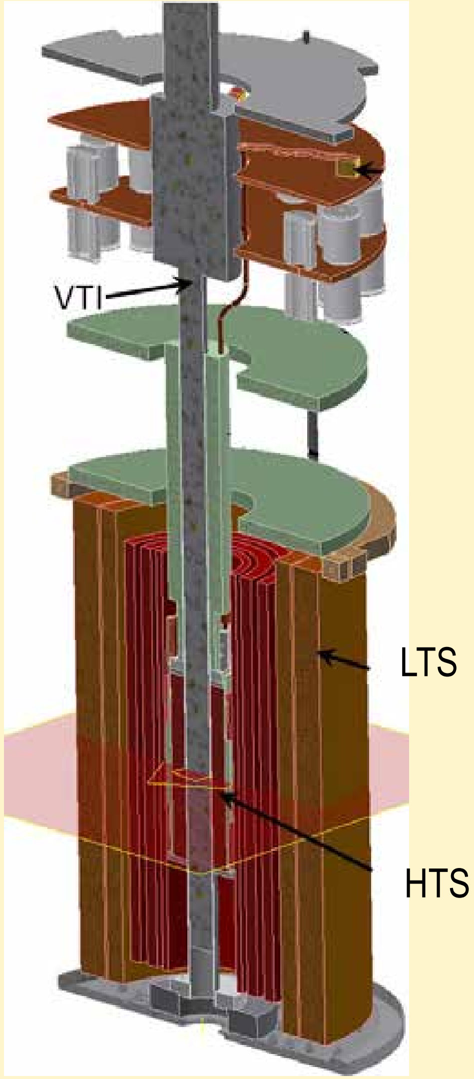
MT-23 Boston USA (2013)
90mm 18.8T all HTS insert magnet for 1.3 GHz NMR…
J.Bascunan S.Hahn Y.Kim
J.Song Y.Iwasa
MIT USA

YBCO tape
no inter turn insulation



Platypus
B2212 wire

NATIONAL HIGH MAGNETIC FIELD LABORATORY

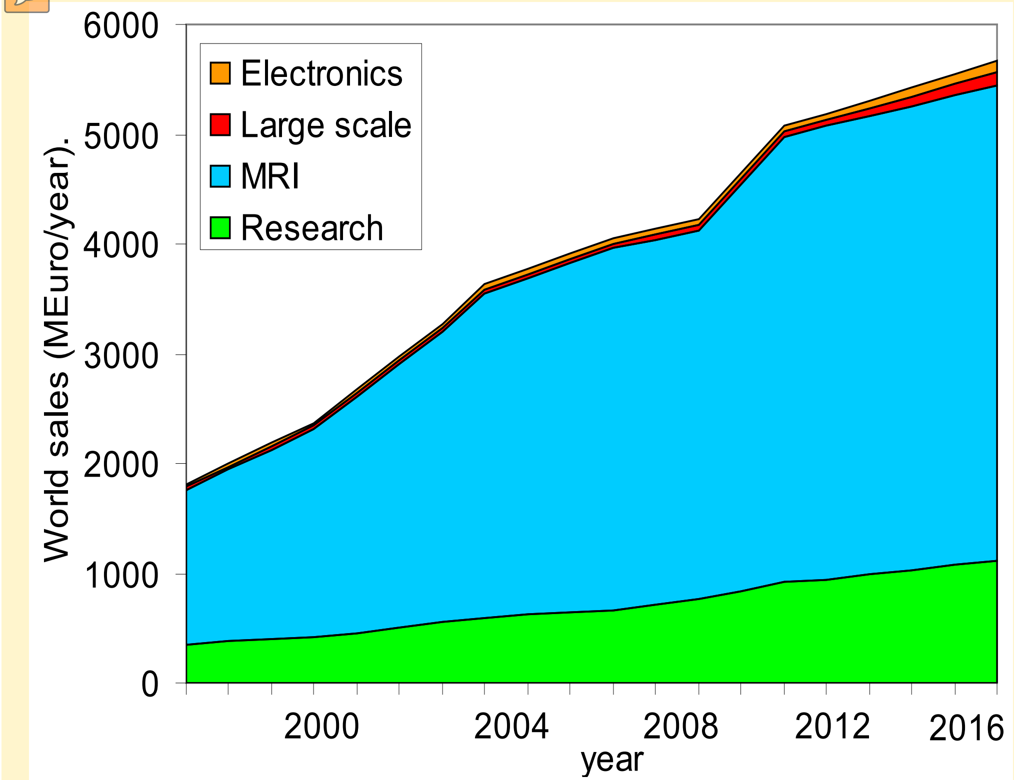


(nuclear) Magnetic resonance imaging MRI

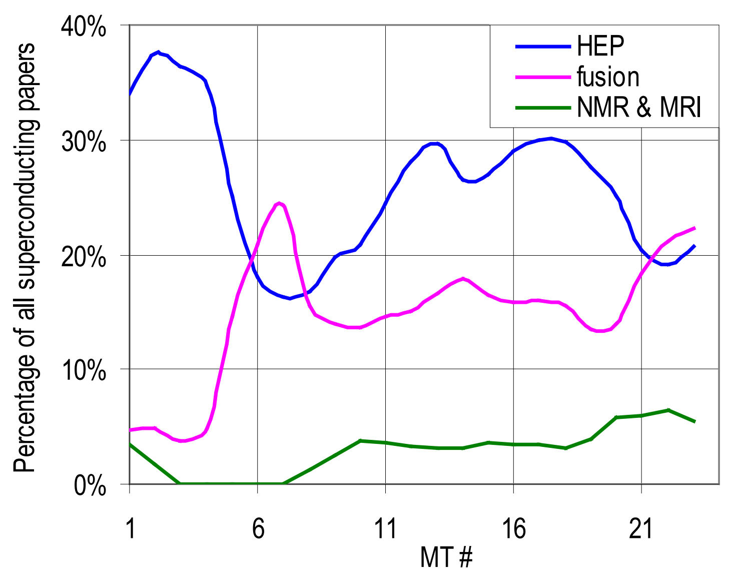
Photo courtesy of Oxford Instruments Ltd

1979 Oxford Instruments build world's first superconducting NMR imaging magnet

World's largest activity in superconductors



CONECTUS - CONsortium of **E**uropean **C**ompanies **T**o **U**se **S**uperconductivity



MT-9 Zurich Switzerland (1985)

Magnets for Magnetic Resonance in Medical Diagnostics from the Laboratory to a Product

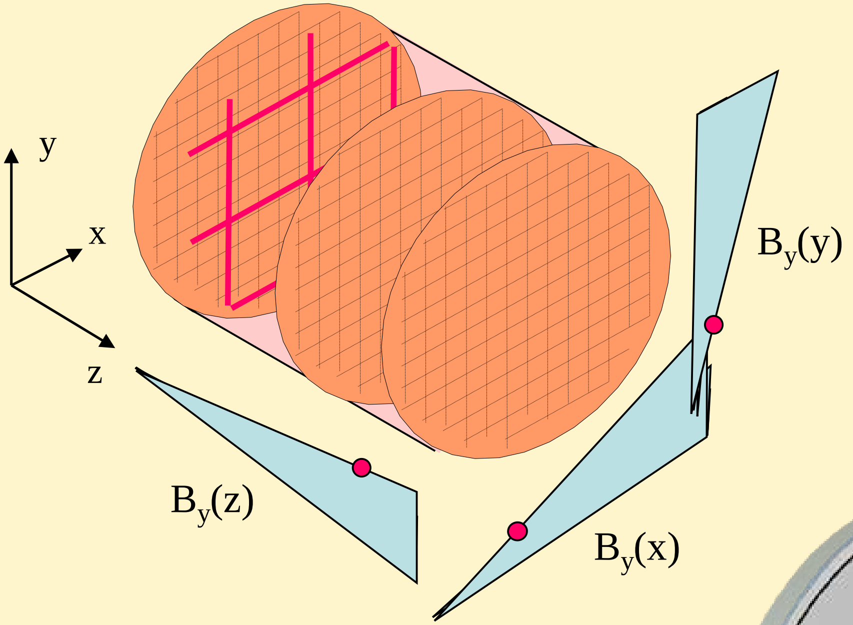
PA Rios ET Laskaris

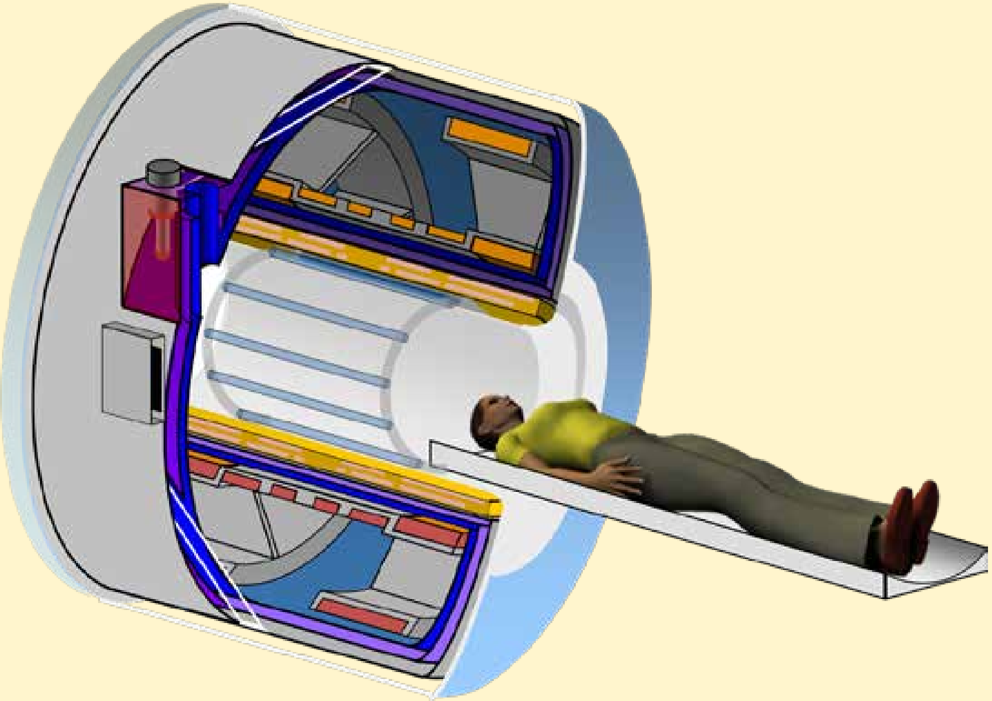
GE Schenectady USA

In the last three years…. moved from development to a product … transition of applied superconductivity technology from laboratory to industrial manufacturing

fraction of world activity = 80%
fraction of papers at MT = 5.6%
(averaged over last 10 years)

(nuclear) Magnetic resonance imaging MRI





Time varying field gradients move the resonance point

- along the x axis
  - along the y axis
    - along the z axis

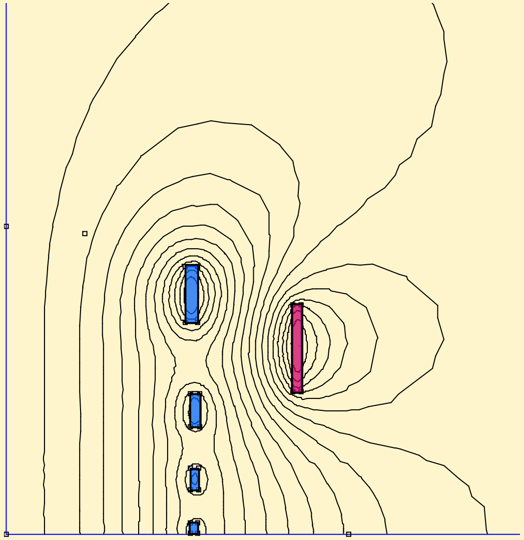
each pixel builds a map of proton density in the patients body

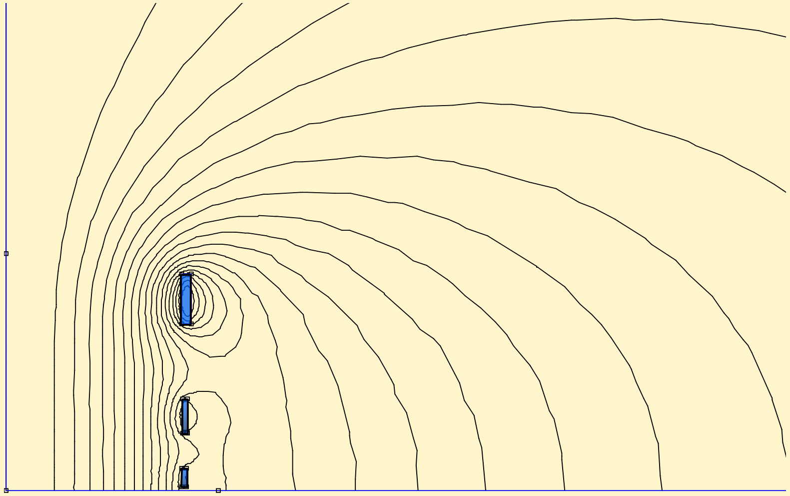
Martin Wilson slide53

MRI Magnet coils

Photo courtesy of GE Healthcare

shield coils reduce fringe field below the statutory limit of 0.5mT





A new industry

Photo courtesy of GE Healthcare

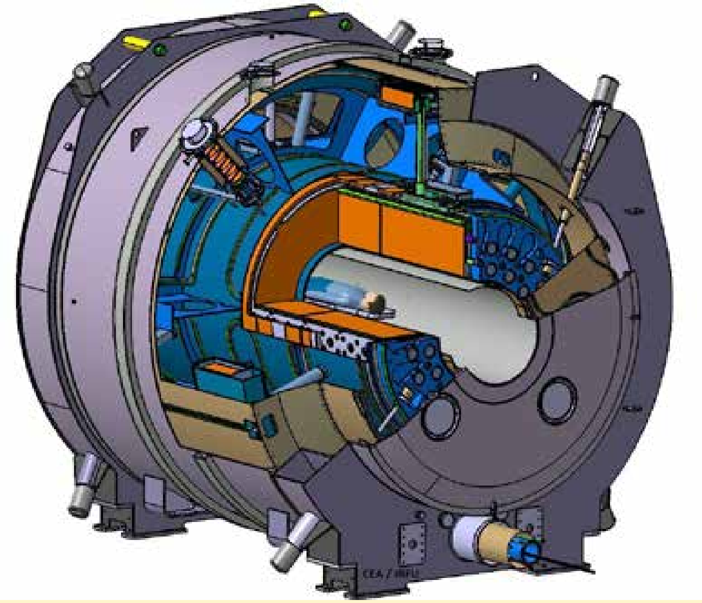
photos courtesy of Siemens AG © Siemens AG All rights reserved

MRI: where next?

higher field ð better resolution

higher temperature ð better access

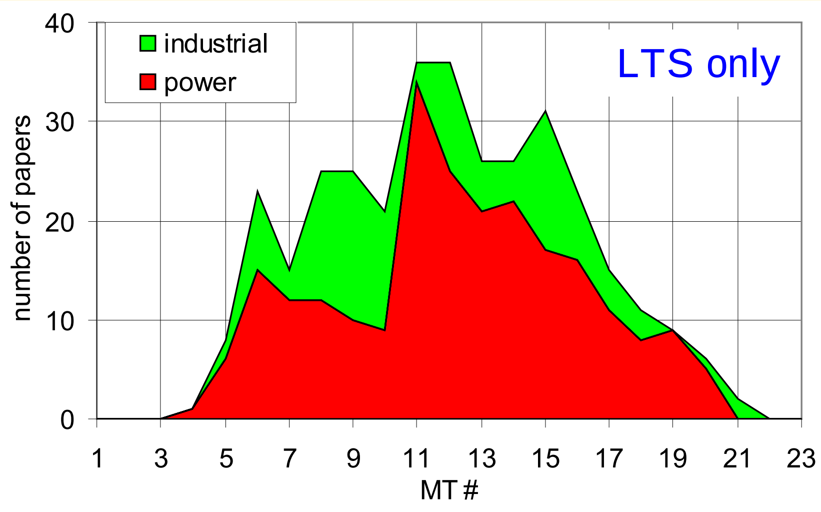
MT-23 Boston USA (2013)
Manufacture of the Iseult/
INUMAC whole body 11.7T
MRI magnet P.Vedrine
G.Aubert J.Belorgey….. *CEA*
Saclay & Alsthom
…Neurospine Centre…understanding
of the brain…improve images × 10…



'Open Sky' MRI with MgB2 magnet

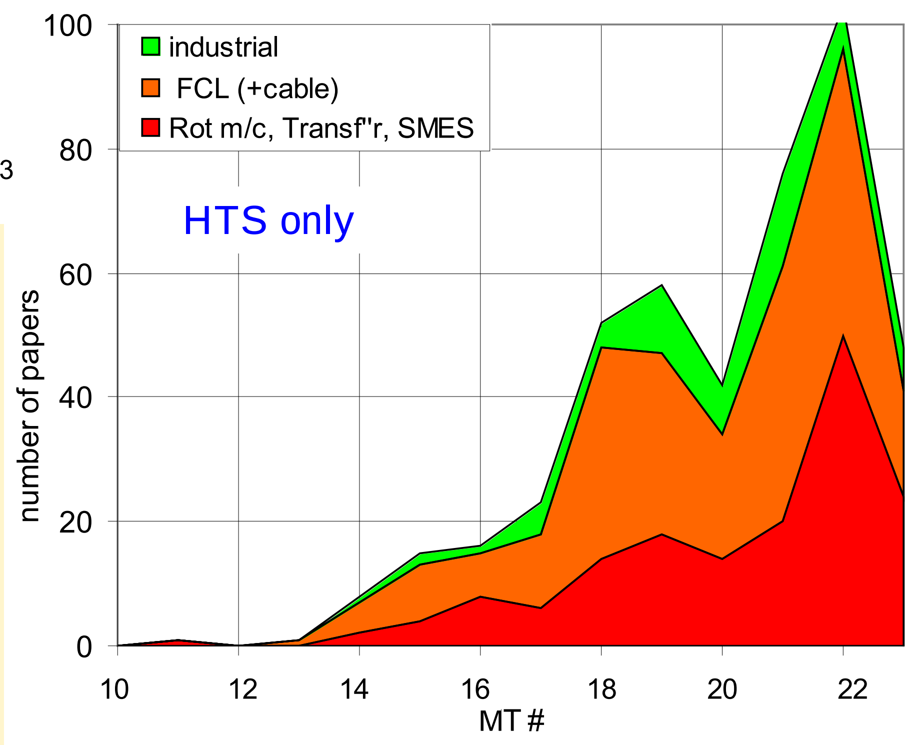
- patient can stand, sit or lie down
- less claustrophobic
- better diagnosis, eg spine

Engineering



Industrial

- transport
- magnetic separation
- magnetic bearings
- induction heating

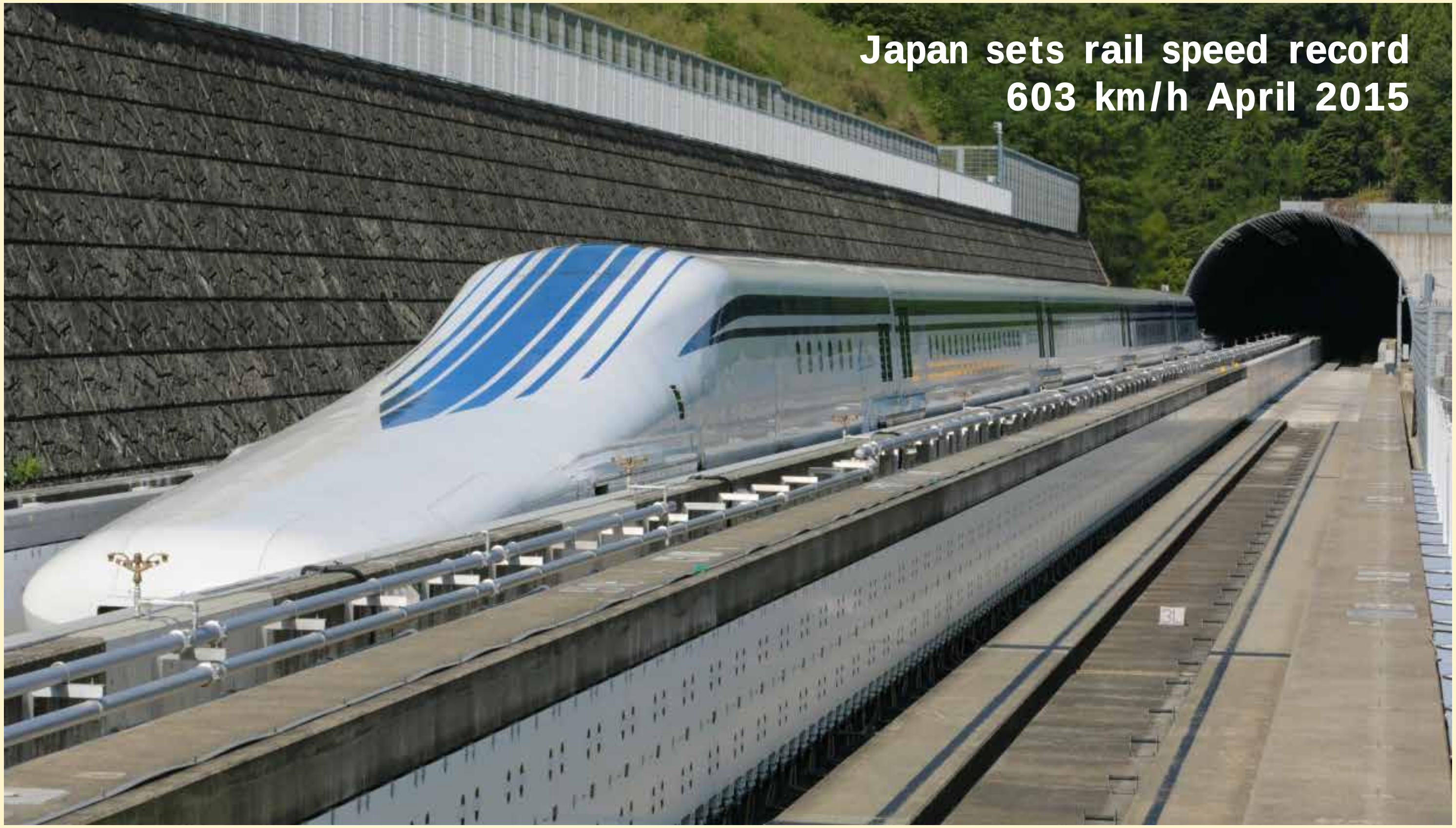


Power

- motors
- generators
- transformers
- magnetic energy storage SMES
- fault current limiters

MT-9 Zurich Switzerland (1985)
Magnetic Transport System Development in Japan
Yoshihiro Kyotani (invited)
Japan National Railways Marunouchi Japan
..superconducting magnetically levitated linear synchronous motor at JNR..1979 ML500, 13.5m long 517 km/h …. 1982 with men onboard MLUOOI

Maglev transport



Japan sets rail speed record
603 km/h April 2015

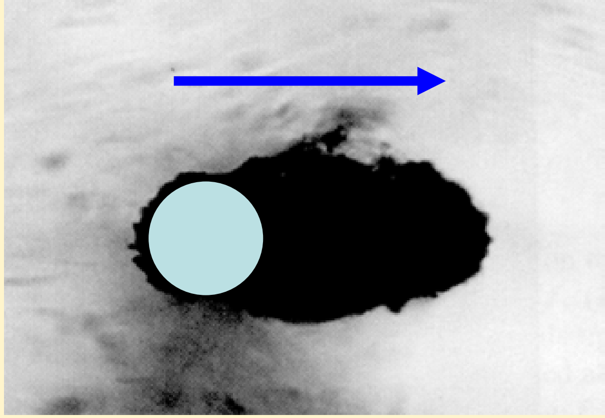
Magnetic Separation

MT-6 Bratislava (1975)	**5**
MT-8 Grenoble (1983)	**10**
MT-9 Zurich (1985)	**8**
MT-10 Boston (1987)	**9**

IEE Trans MAG-11, 5, p1597 (1975)
Theory of Capture of Particles in Magnetic High Intensity Filters
JHP.Watson
English China Clays Cornwall UK

High gradient magnetic separation

$$\frac{F}{vol} = \chi \frac{B_0}{\mu_o} grad\, B$$



fine mesh of magnetized ferromagnetic wires produces high local *gradB*

filter for magnetic particles

Research on application areas for HGMS

MT-21 Hefei China (2009)

Superconducting Magnetic Separation for:-

- *Purification of wastewater from Paper Factory*
- *Purification of Used Wash Water*
- *Powder Separation*
- *Trapping Immunoglobin in Serum*
- *Purification of Coolant for Hot Roller*
- *Separation of Aquatic Organisms*

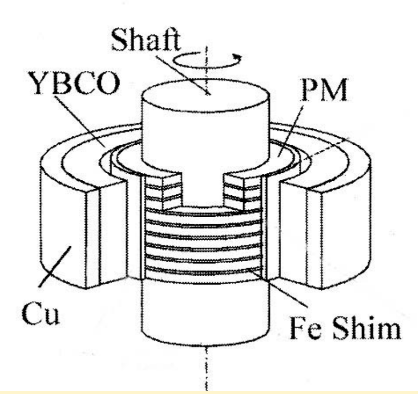
MT-23 Boston USA (2013)

Superconducting Magnetic Separation for:-

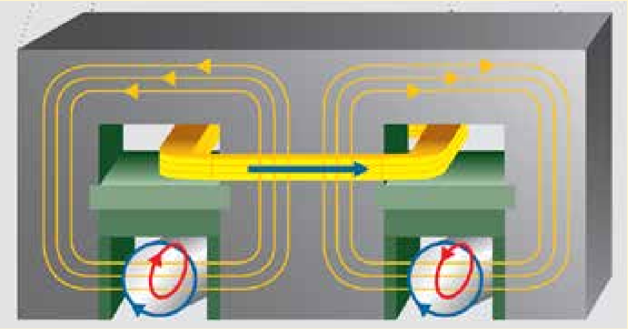
- *Decontamination of Contaminated Soils*
- *Medical Protein Separation*
- *Removal of Humic Substances and Ammonia Nitrogen in Water*
- *Separation of Powdered Activated Carbon from Aqueous Phase*
- *Plastic Separation*
- *Mercury Removal from Solution*

Magnetic bearings & induction heating

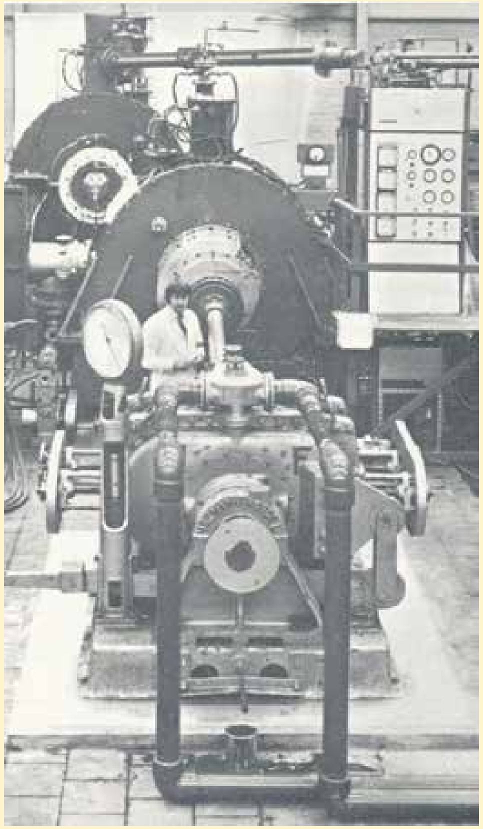
MT-21 Hefie China 2009
HTS Magnetic Bearings in Prototype Application
FN.Werfel U.Floegel-Delor T.Riedel
Adelwitz Technologiezentrum Germany
bulk melt textured YBCO with permanent magnet …tested in 5kWh (18MJ) flywheel, 400kW motor and a centrifuge



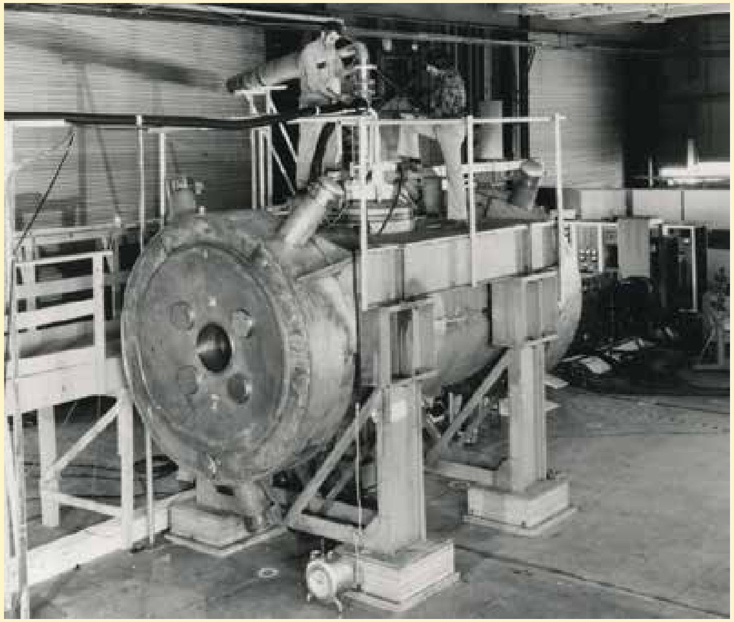
- rotate billet in dc field of HTS magnet
- double the efficiency from 45% to 90%



Power engineering: generators



MT-5 Rome (1975)
High Current DC Homopolar Generator using Carbon Fibre Brushes
AD.Appleton
IRD Ltd UK
carbon fibre brushes in 1MW superconducting generator + motor for marine propulsion

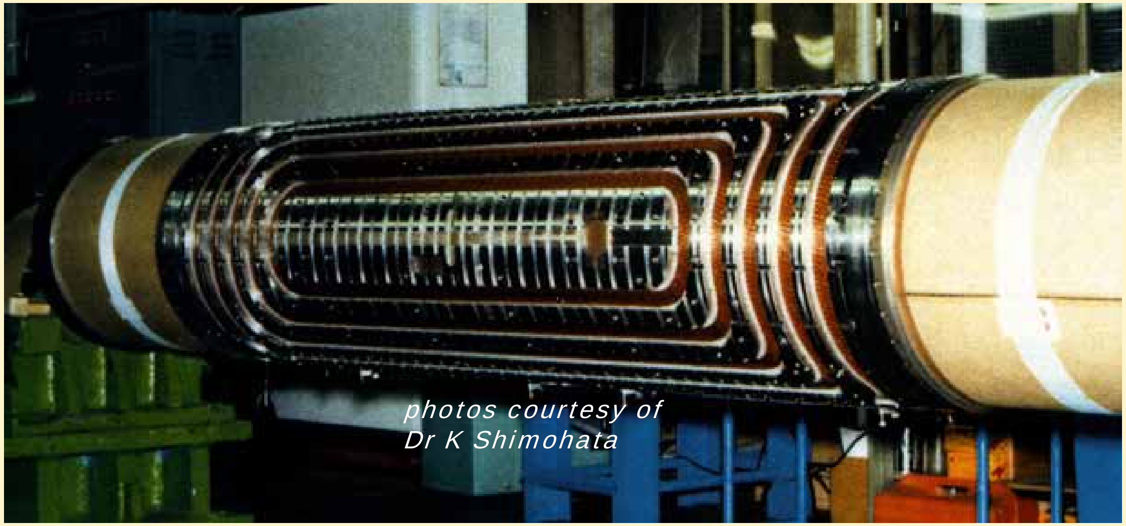


MT-6 Bratislava (1977)
The US SCMS Dipole Magnet System for the Byepass Loop of the U-25 MHD Facility
ST.Wang RC.Niemann..
Argonne NL USA
Large superconducting dipole built in US for use at the MHD facility in Moscow

Generators

Super GM 70 MW AC generator Japan

MT-12 Leningrad (1991)
Development of 70MW Class Superconducting Generators
S.Fuchino H.Fukuda T.Ogawa..
Hitachi Mitsubishi Toshiba Japan
..research on field winding, multi-cylindrical rotor, damper, rotating helium cooling …now manufacture



photos courtesy of Dr K Shimohata

- efficiency increased by ~ 0.5%
- large air gap

ð low synchronous reactance

ð enhanced grid stability

ð operation at low power factor

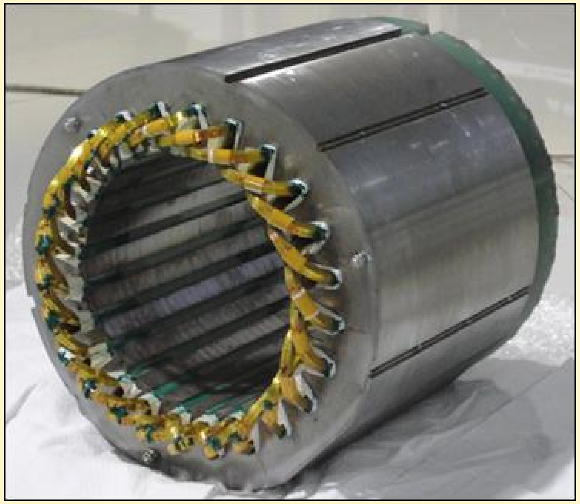
- but no clear economic benefit in moderate sizes

HTS Motors

36.5MW Motor for ship propulsion

- B2223 superconducting rotor
- 3 phase copper stator
- tested 2008 - 36.5MW power at 127rpm

MT-22 Marseille (2011)
Trial Test of Fully HTS Induction/ Synchronous Machine for Next Generation Electric Vehicle
D Sekiguchi T Nakamura
Kyoto University Japan
HTS rotor and stator…B2223 running at 77K…size similar to Prius.. max power ~ 8.8kW… max speed 1200rpm

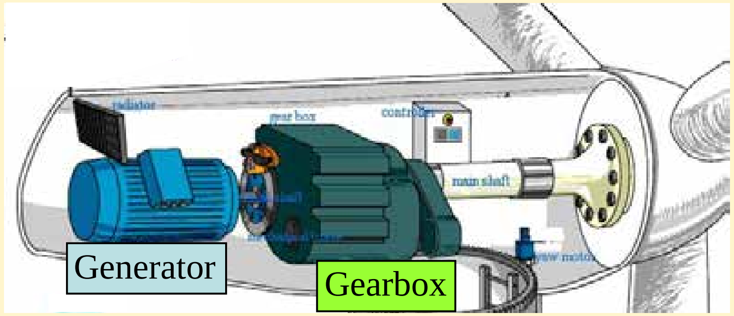


photos from N Amemya

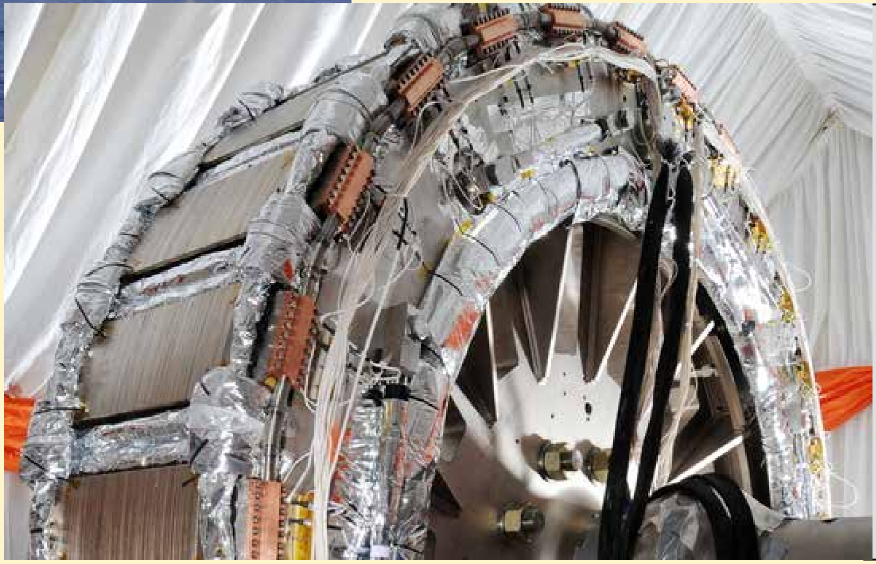
Slow speed generators: wind and water

rotation ~ 0.1 – 0.3Hz

output = 50 – 60Hz



MT-22 Marseille (2011)
Electromagnetic Design of 10MW Class Superconducting Wind Turbine Generators
Y.Terao M.Sekino H.Ohsaki.
Tokyo University Japan
…direct drive slow speed..fully superconducting ..ac losses



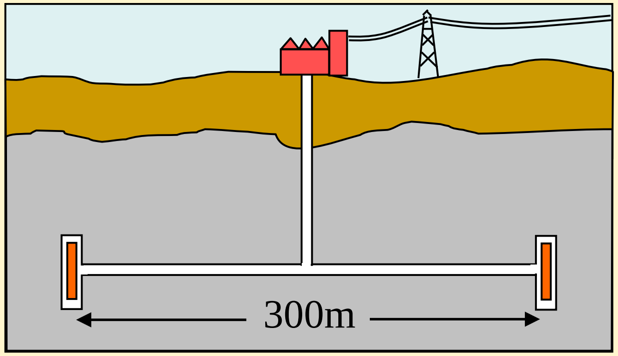
Hydrogenie

generator for hydro-power copper stator

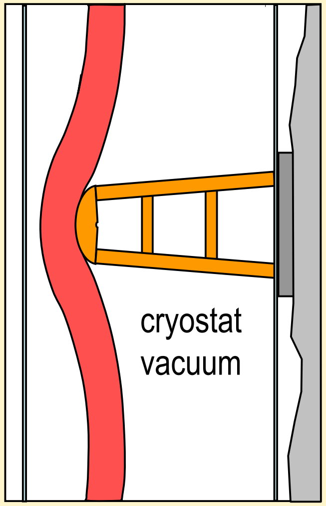
B2223 rotor at 40K
1.7MW at 214rpm

Converteam UK 2012

Superconducting Magnetic Energy Storage SMES



MT-5 Rome (1975)
Magnet Design for Superconducting Energy Storage for Power Systems
RW.Boom MA.Hilal RW.Moses…
University of Wisconsin USA
10,000MWh storage..solenoid 300m dia.. use bedrock for force support

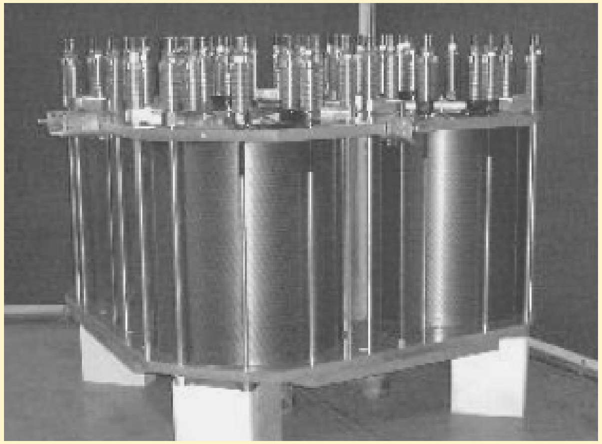


Virial theorem $V_{structure} > E/s$

MT-18 Morioka Japan (2003)
Development and Performance Results of 5MVA SMES for Bridging Instantaneous Voltage Dips
S.Nagaya N.Hirano M.Kondo…
Chuba and Toshiba Japan
..for protecting semiconductor plants against voltage dips.. 5MJ delivered as 5MVA for 1 sec… 6.6kV 3f 60Hz

$10{,}000\text{MWh} = 3.6\times10^{7}\text{MJ}$

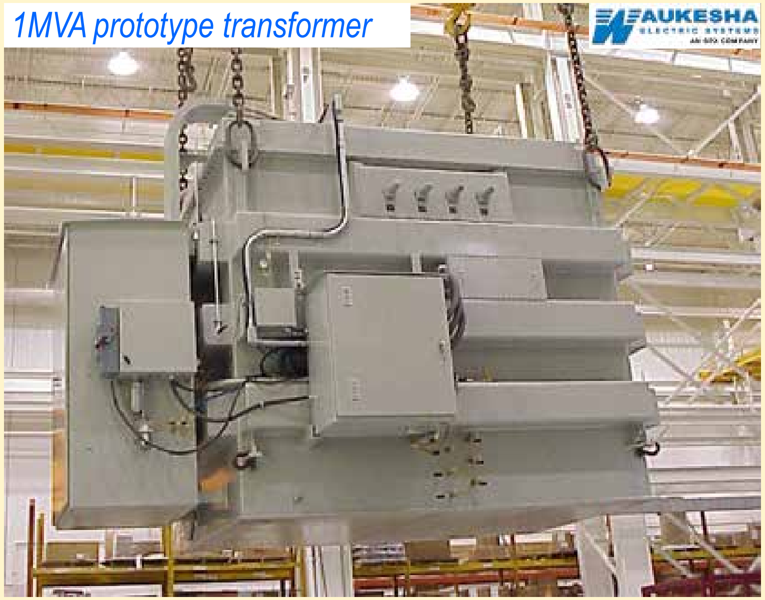
50 litres of gasoline = 1750MJ

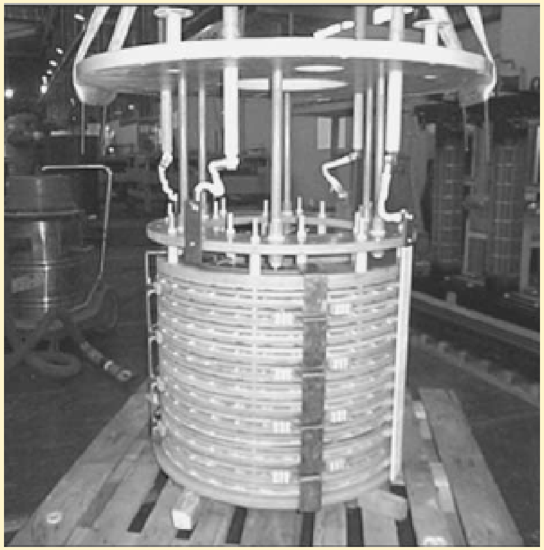


Transformers

MT-9 Zurich (1985)
Transient Characteristics Double-Coil Protection Device for Superconducting Transformer
F.van Overbeeke L.van de Klundert
Twente University Netherlands
..fine filament NbTi ..3kVA transformer..quench..

MT-18 Morioka Japan (2003)
Characteristic Test of a 1MVA Single Phase HTS Transformer with Pancake Windings
W-S.Kim J-H.Han S-H.Kim W.Gee T.Chang…
Centre for Applied Superconductivity Korea
B2223 windings…22.9kV primary 6.6kV secondary 77K temperature…60kV voltage test


1MVA prototype transformer

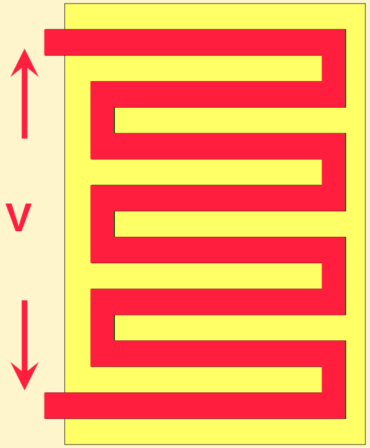



630kVA 3 phase transformer at Baiyin China

Fault current limiters – two types

Resistive

normal operation ð superconducting

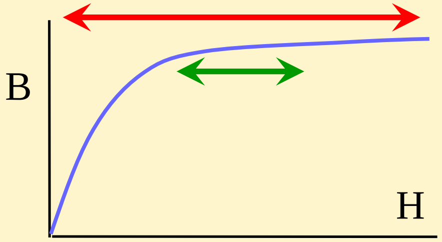


fault current
ð quenches superconductivity
ð resistance limits current

works ac or dc

Inductive

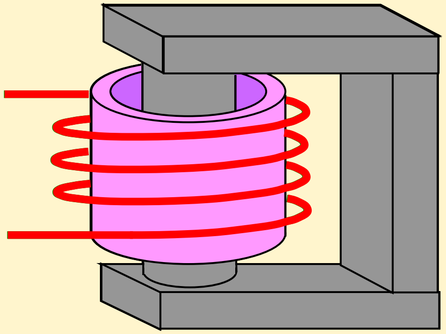
1 Inductor with dc bias



normal operation - dc bias field keeps iron saturated ð low inductance

fault current ð iron out of saturation for part of ac cycle ð high inductance

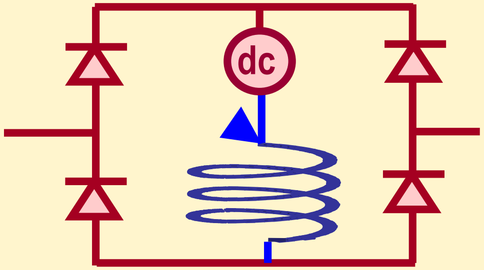
2 Screened Inductor



normal operation – superconductor screens iron ð low inductance

fault current ð superconductor quenches ð high inductance

3 Inductor with diode bridge



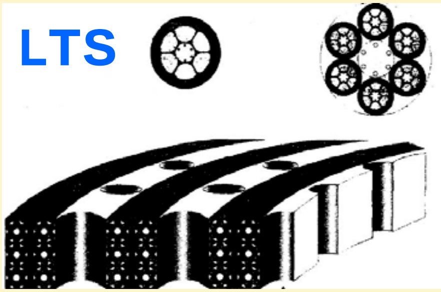
normal operation – constant dc current through superconducting coil

fault current ð increased dc current opposed by inductance of coil

only works with ac

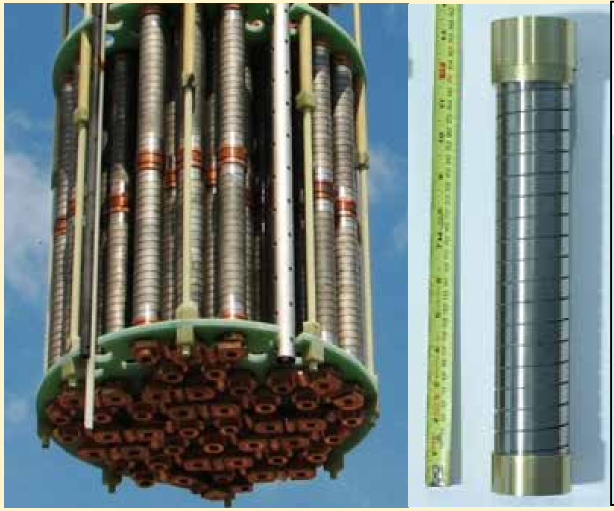
Resistive FCLs

MT-11 Tsukuba Japan (1989)
25 kV Superconducting Fault Current Limiter
T.Verhaege JP.Tavergnier .*GEC Alsthom France*
NbTi ulta fine filaments in CuNi matrix…25 kV at 200A



Siemens 2003
1 MVA FCL
100A 7.2kV
63 switching elements..
YBCO film on sapphire substrate
(Theva)

HTS



2009

bulk B2212 with spiral cut

MT-20 Philadelphia USA (2007)
Recovery of Superconducting Fault Current Limiters at Low Applied Voltages
HR.Kim SW.Yim SY.Oh OB.Hyun
KEPRI Daejon Korea
patterned 300nm thick YBCO films on sapphire substrates (THEVA)

Nexans
2014

Ampacity

ReBCO tape FCL 12kV 2.3kA protecting supercond-ucting cable in Essen city grid

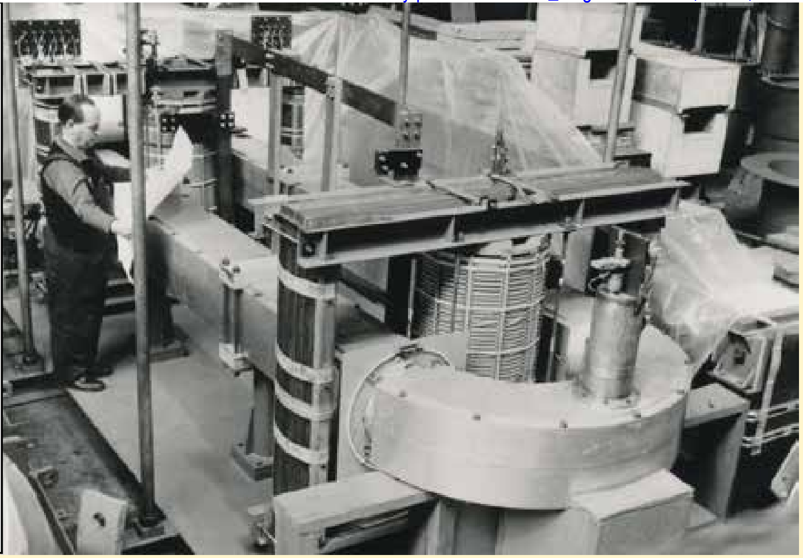
Inductor with dc bias

FCL 1978
NbTi dc coils at 4K

operating 500A rms

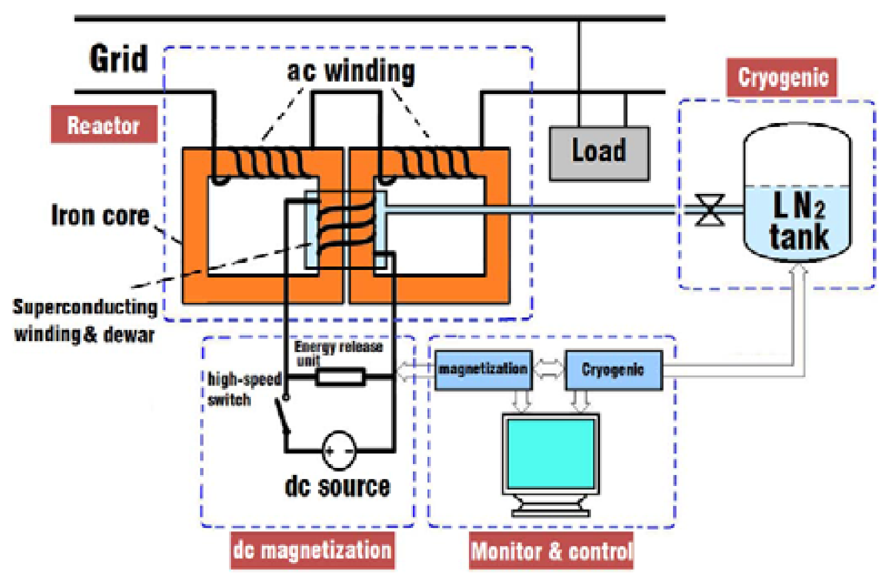
limiting 1600A rms

IRD Parsons Peebles UK



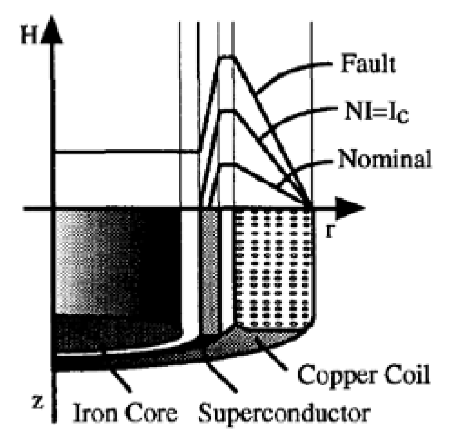
California 2009 Zenergy Power FCL
Normal operation: 800A rms at 12kV
prospective fault of 23kA rms limited to 18kA rms

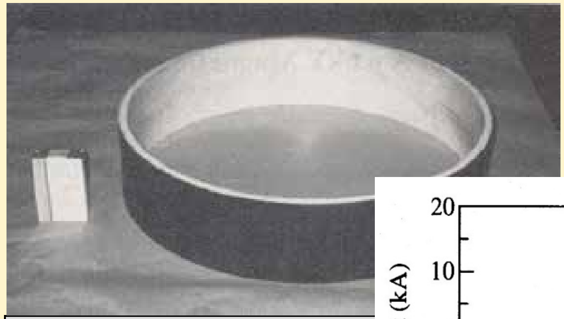
MT-23 Boston USA (2013)
Electrical Insulation of HTS Coils in Saturated Iron Core Superconducting Fault Current Limiter
H.Wang J.Zhang X.Niu B.Tian…
Innopower Cable Co Beijing
..dc magnetization by HTS tape coil
..switch off at fault....high voltages..



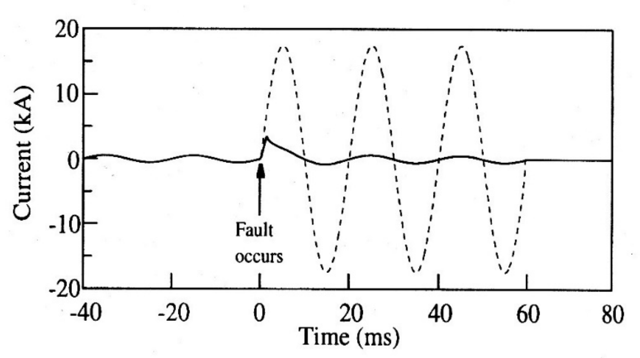
Screened inductor

MT-13 Victoria Canada (1993)
Test results for Laboratory Scale Inductive High -T_c Superconducting Fault Current Limiters
JR.Cave DWA.Willen Y.Brissette C.Richer
Hydro Quebec Canada
Copper coils..bulk B2212 shield..iron core





1996 CRIEPI Japan
400A rms at 6.6kV rms
12.5kA fault limited to
2.4kA B2212 rings



MT-17 Geneva Switzerland (2001)
Experimental Study on a Fast Self-Acting Magnetic Shield Type Superconducting Fault Current Limiter
T.Onishi M Kawasumi K.Sasaki R Akimoto
Hakaido University Japan
bulk B2212 shield ring with heaters

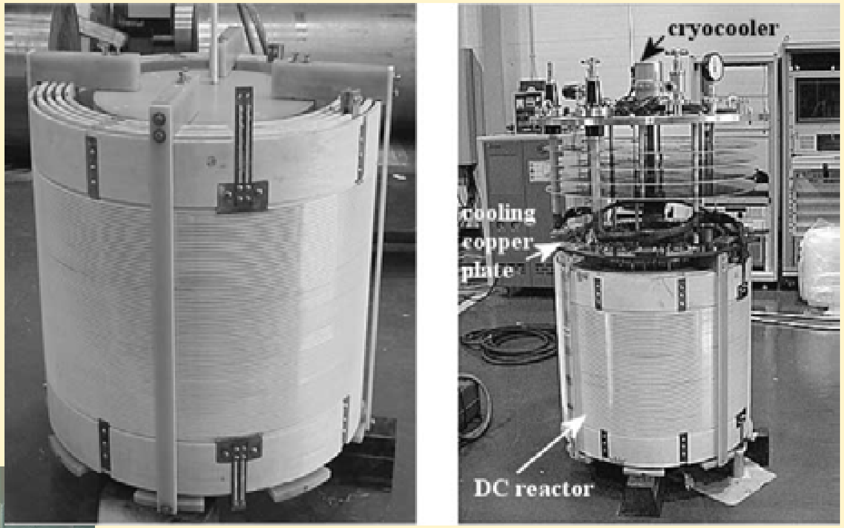
ABB 1998
First FCL on Power network

1.2MVA
3 phase

bulk B2212 at 77K

Inductor with diode bridge

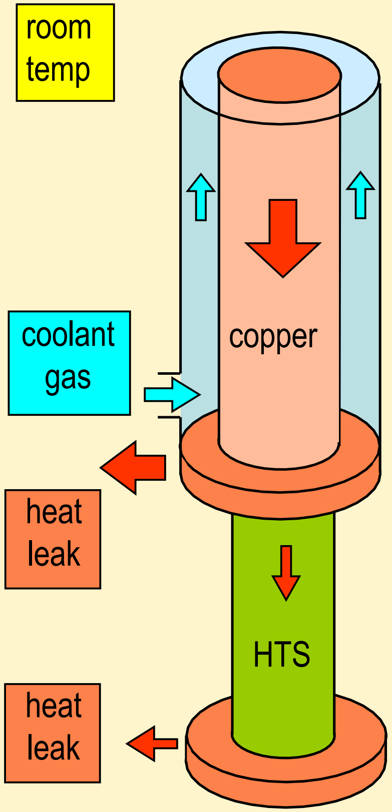
MT-18 Morioka Japan (2003)
Design Fabrication & Test of High-Tc Superconducting DC Reactor for Inductive Fault Current Limiter
MC.Ahn S.Lee H.Kang DK.Bae M.Joo HS.Kim ..
Yonsei University Seoul Korea
three phase bridge … single dc reactor coil wound from reinforced B2223 tape…



MT-21 Hefie China (2009)
Design Fabrication & Tests of Three HTS Coils for a Model Fault Current Limiter
J.Zhang S.Dai Z.Wang D. Zhang Z Zhang…
Chinese Academy of Sciences Beijing China
3 phase diode rectifier bridge…3 inductors with IGCTs and resistors in series….

HTS leads for high currents

MT-17 Geneva Switzerland (2001)
Current Leads for the LHC magnet system
A Ballarino
CERN Switzerland
.. procurement for about 3300 current leads
… rating 60A to 13kA … helium gas cooled…



room temp

coolant gas

heat leak

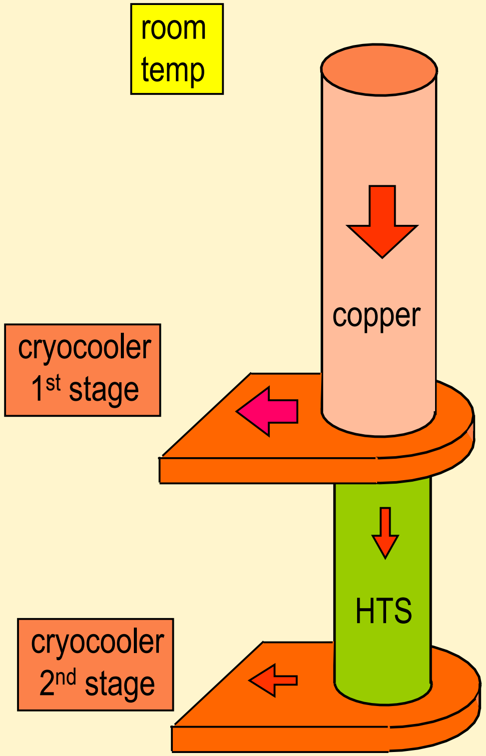
heat leak

copper

HTS

MT-17 Geneva Switzerland (2001)
Development of High Temperature Superconductor Current Leads for 70 kA
R.Heller G.Friesinger AM.Fuchs R.Wesche
ITP Germany CRPP Switzerland
..current leads for the TF coils of ITER…
B2223 tape with Ag/Au matrix..effect of self field.. heat exchange to He gas ..quench

Cryofree magnets



- current leads usually rely on upstreaming helium gas for cooling
- no upstreaming gas with cryocoolers
- dry leads have 40× the heat leak

- HTS leads can reduce 2nd stage heat leak to an acceptable level

HTS:
an essential enabling technology for cryofree magnets

To conclude…..

- MT-1: magnets for NMR, HEP and fusion + basic principles of cryostabilization
- MT-2: basic ideas for superconducting synchrotron ð fine filaments
- HEP & Accelerators: consistently the largest topic ~30% of papers
  ð future accelerators faster ramping (FAIR) and higher fields via HTS
- Fusion: ~20% of papers – mainly tokamaks ð future ITER, Wendelstein7 + ?
- NMR: first commercial superconducting product ð future higher fields for better resolution
- MRI: largest commercial superconducting product ð a new industry
  ð future higher fields for resolution and /or higher temperatures for better access
- Industrial Engineering: maglev, magnetic separation, induction heating
- Electrical Engineering: LTS for generators, motors, transformers, FCL ð not economic
  ð HTS for generators (slow speed), motors and FCL *(20 – 30 papers at last 5 MTs)*