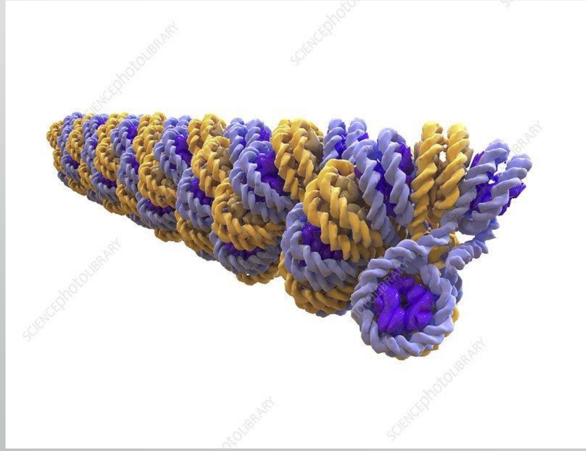
DNA of Superconducting magnets: Rutherford Cable

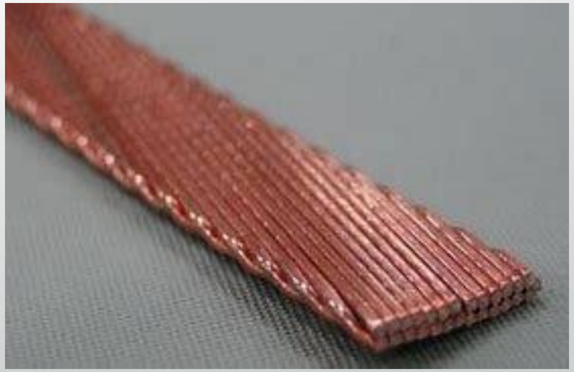
The development of superconducting filamentary composites, Rutherford Cable and their modern impact.

Introduction

- RAL has had a long history of scientific contribution and technological innovation.

- Superconducting filamentary composites and Rutherford Cable are an outstanding example
- Basis of all magnets in major accelerator thereafter. Through to the HL-LHC
- **Given my biology background, I think of them as the DNA of superconducting magnets.**
- **To first understand their origin and development, we require some context**



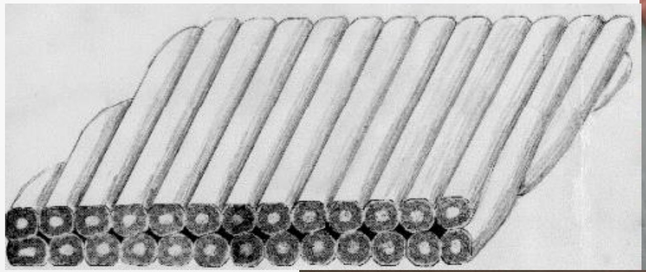


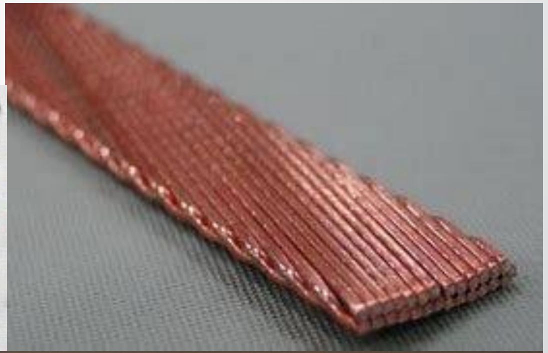
What is Rutherford Cable

Rutherford Cable are a compact collection of superconducting wires – they constitute up superconducting magnets used within synchrotrons.

They have a specific geometric orientation and various features, that mitigate sources of loss.

Can carry 30,000 Amps at 4k!





This presentation aims to inform you of

- **History and Context**
- **Rutherford cables development**
- **Cable manufacture**
- **Rutherford Cable HEP application**
    - Fermilab
    - RAL
- **Rutherford Cable application: Beyond HEP**
    - Fusion
    - Medicine

What is superconductivity?

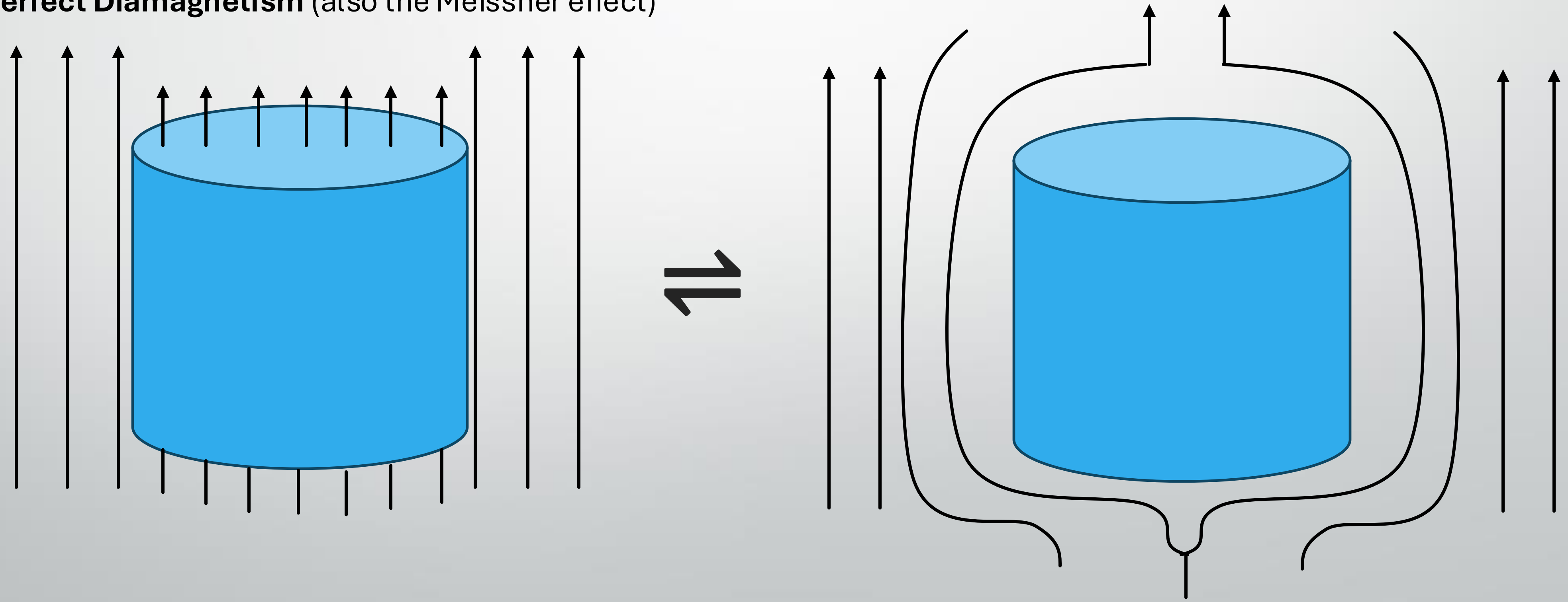
- Discovered by Heike Kamerlingh Onnes in 1911.
- He found that it would only occur below a specific temperature threshold.
    - **"Thus the mercury at 4.2K has entered a new state which, owing to its particular electrical properties, can be called the state of superconductivity"**
- Nobel Prize (1913)
- Physicists were excited to apply superconductivity to magnets:
    - **"Obtaining a field of 100,000 Gauss (equivalent to 10T) could then be obtained by a coil of say 30 cm in diameter... with relatively modest financial support."**

(Third International Congress on Refrigeration at Washington and Chicago, 1913)

However, superconductivity would only persist at very low fields.

Perfect Diamagnetism

- In the 1930s, theoretical understanding improved thanks to German physicists, Walther Meissner and Robert Oschenfeld.
- Measured the magnetic field from **superconducting tin crystals,** they observed a sudden expulsion of the field from the material at a certain magnetic field strength.
- They found this process was reversible as the field would re-enter the material above the critical temperature.
- Called **Perfect Diamagnetism** (also the Meissner effect)



London Penetration Depth

- Building on this concept, brothers F and L London found the magnetic field is a pivotal property of superconductivity.
- They measured the magnetic flux at the materials surface and defined the London Penetration depth
  - Distance from the surface where magnetic flux decreased by 1/e (37%) and decreases exponentially thereafter.
- London Penetration depth: several micrometres for most materials.
- Current yielded from this magnetic flux within the superconductor is known as "surface currents".
- Theory built upon by Ginzburg and Landau

Critical Field

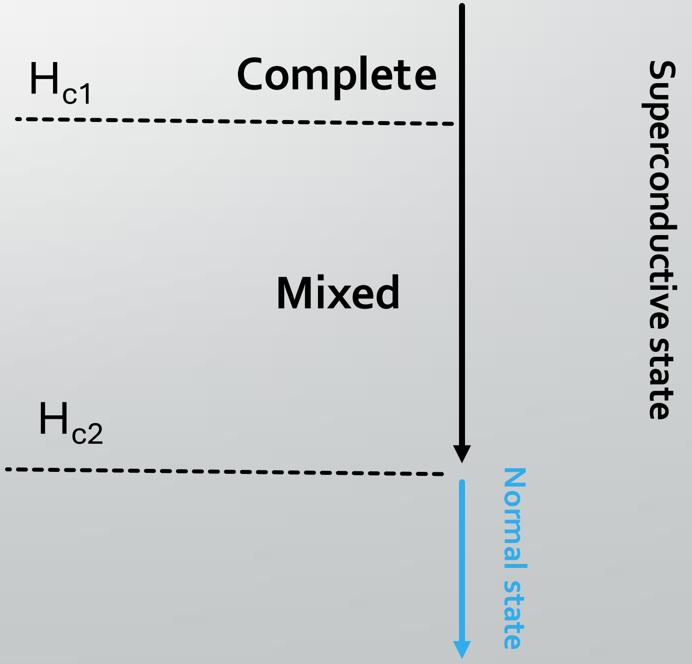
- L.V Shubnikov investigated superconductivity.
- Perfect diamagnetism was exhibited in pure Tin / lead but not metal alloys
- Observation of Meissner effect to a certain threshold.
- Above this threshold, observed a 'mixed' state.
- Mixed state held until reaching a higher magnetic field strength

- **This threshold is termed the upper critical field / critical field and is denoted as H_{c2}.**

L.V Shubnikov: Credited with the discovery of Type II superconductors, based on his observation of the mixed state (interval between two distinct critical fields)

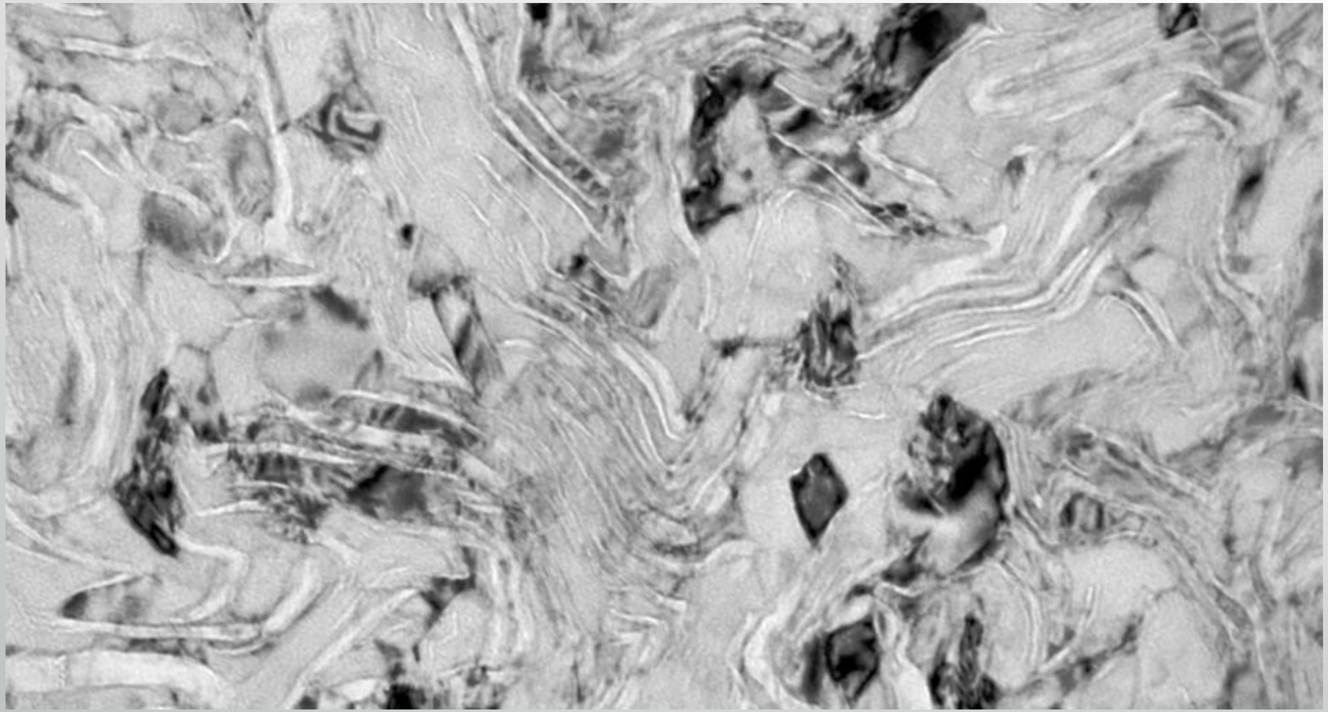
Work largely went unrecognised in the West following its publication.

Executed during the Great Purge.



Type I / Type II Superconductors

- L.V Shubnikov altered alloy composition to yield lower H_{c1} and greater H_{c2}
- These superconductors were later designated as **Type II superconductors**
- **Type II superconductors have preferable characteristics for magnets**

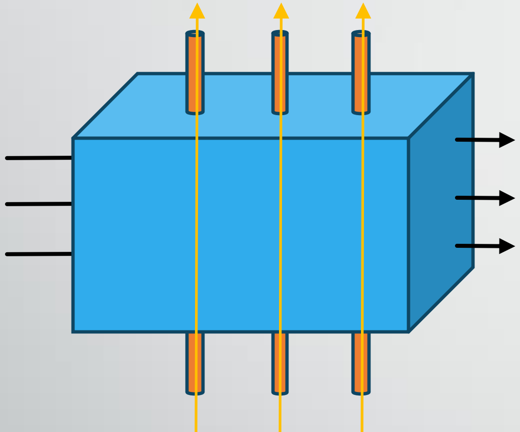


NbTi alloy: Transmission electron microscope image of a NbTi filament.

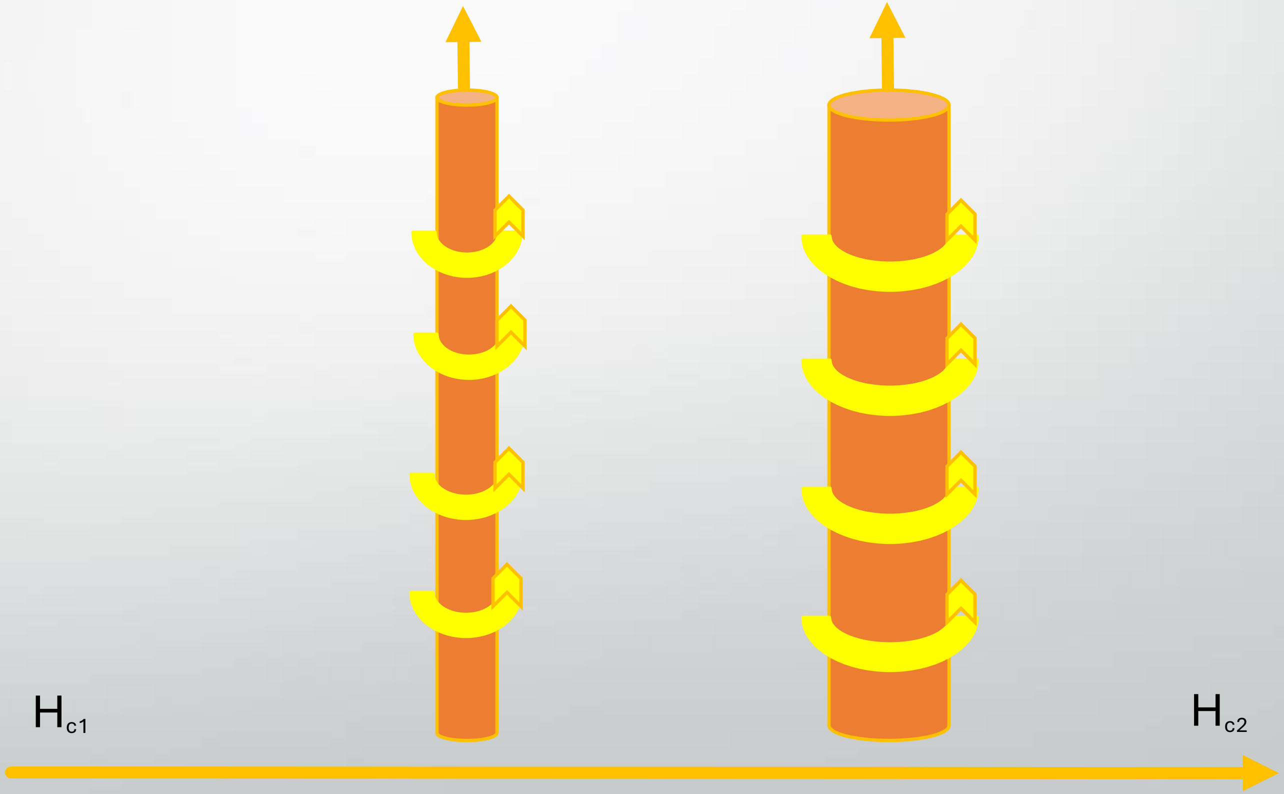
Areas of lighter contrast indicate the presence of precipitates of Titanium known as α-Ti.

Fluxoids

- Type II superconductors exist within **a mixed state** – whereby tiny normal 'cores' coexist the superconducting state.
- Fluxoids are tiny magnetic flux lines (2 x 10^{-5} Wb / 20μT) that penetrate Type II superconductors in their mixed state - $H_{c1} < H > H_{c2}$
- Generate their own circulating currents – termed screening currents. (they oppose bulk current flow within the superconductor)

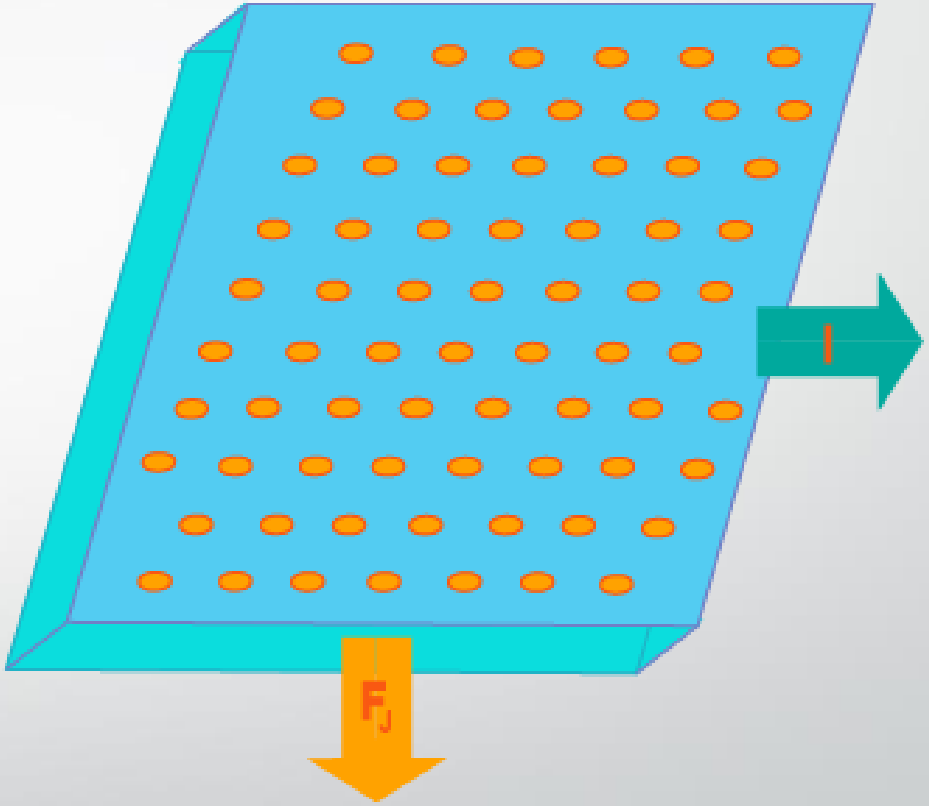


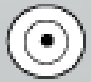
- Orange area represents normal core (area with resistivity)
- Blue area represents superconducting state
- Black arrows indicate external magnetic field.



Flux Flow and Pinning

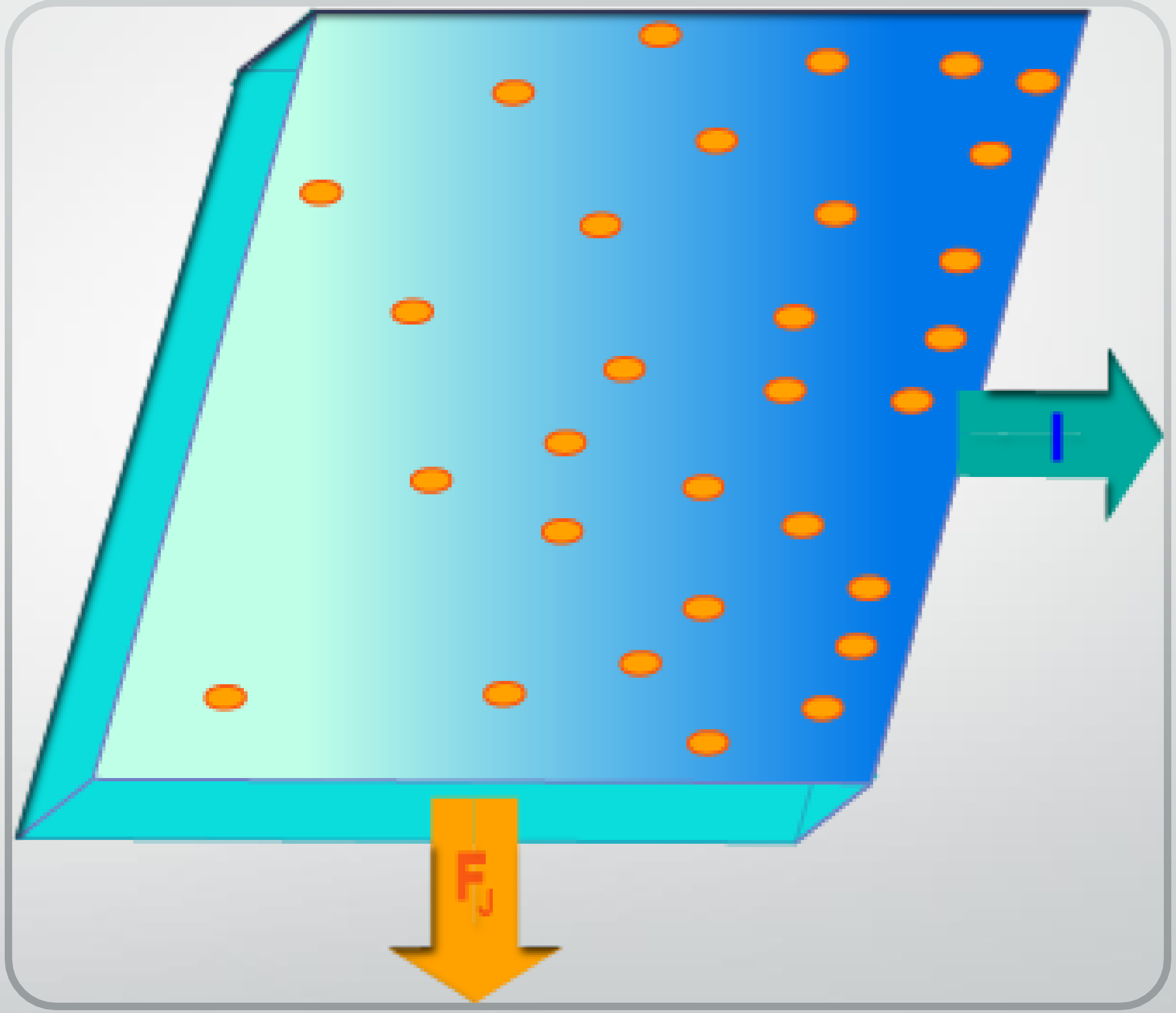
- Fluxoids are evenly distributed
- **Uniform magnetic flux density – Zero field gradient**
- Lorentz force applied within an external magnetic field
- This force causes the fluxoids to move freely - dissipative process called **Flux flow**





Flux Pinning

- Metal impurities / lattice imperfections serve as 'pinning centres.
- **Non uniform magnetic flux density = Field gradient**
- **This field gradient imposes bulk currents** (according to Faraday's law)
- Pinning centres impose a pinning force (Fp)



Critical Surface

Critical current density – Maximum current flow through a material

In values beyond: **Lorentz force** (incurred by current flow) EXCEEDS **Pinning force** (incurred by pinning centres)

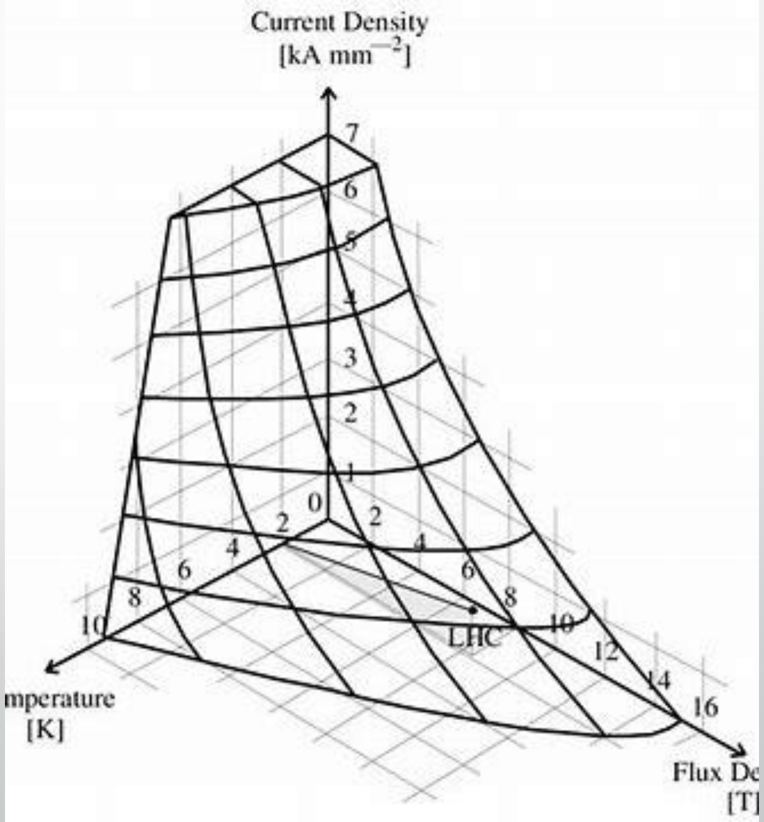
Dependence of Critical surface parameters –

3 Major thresholds that need to be maintained for superconductivity to remain.

Critical field (Hc), critical temperature (Tc) and critical current density (Jc).

3D threshold of Superconductivity and Resistivity.

Factors are dependent on one another



Electromagnetic instability

AC losses: Interaction between the pinning force and the magnetic flux allows for bulk current flow it also allows for AC loss.

Pinning force remains in a constant direction. Lorentz force is variable

Magnetization losses: Superconductors follow a magnetisation curve in changing magnetic fields – **persistent currents** are established.

Coupling losses: Coupling currents form large loops between wires and strands

Eddy currents

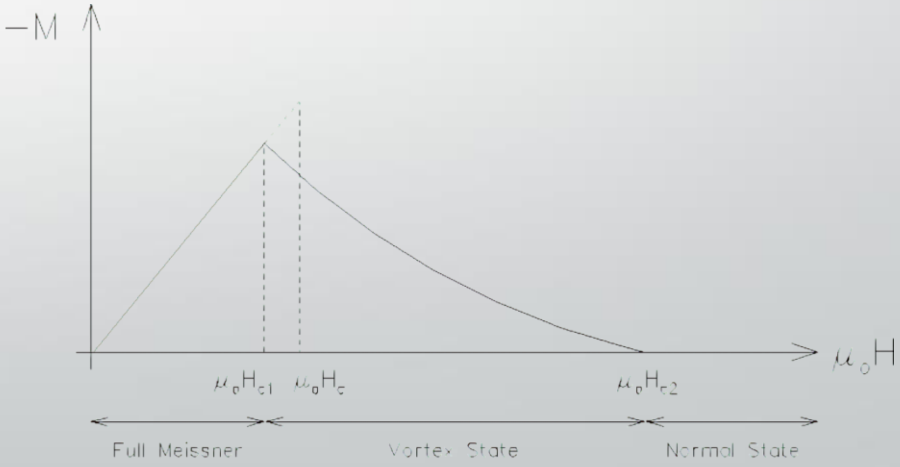


Figure 2.4: Magnetization curve for a type-II superconductor.

‘Woodstock’ of Superconductivity

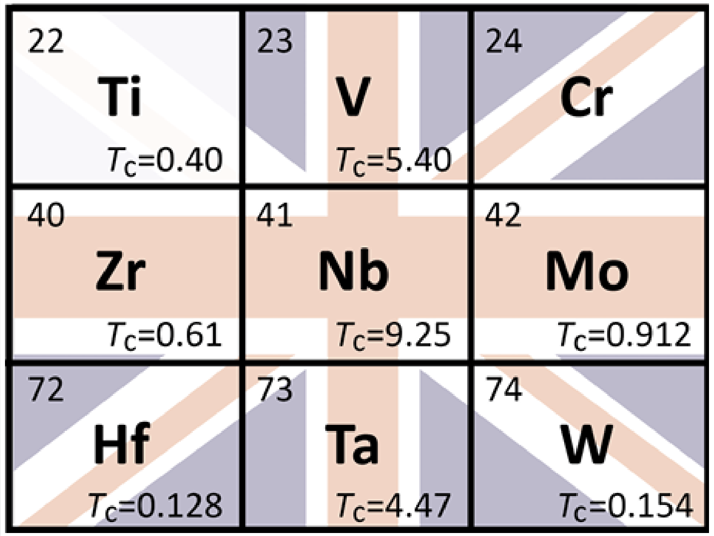
Revelatory announcements came in 1961 at the First International Conference on High Magnetic Fields at MIT.

Viable materials such as **NbZr** superconductors announced to have critical fields of up to 20T!

Coils were commercially available shortly following the conference.

Conference was attended by Audrey and Martin Wood, founders of **Oxford Instruments**

Used NbZr to build Europe's first superconducting magnet.



<u>God save the Queen</u>

Westinghouse Laboratory in Chicago was at the forefront of superconducting alloy R&D.

They had identified critical surface parameters of **V-Nb, Nb-Ta, V-Cr, V-Mo, Nb-Cr, Nb-Mo, Nb-W, Nb-Hf, and Nb-Zr**.

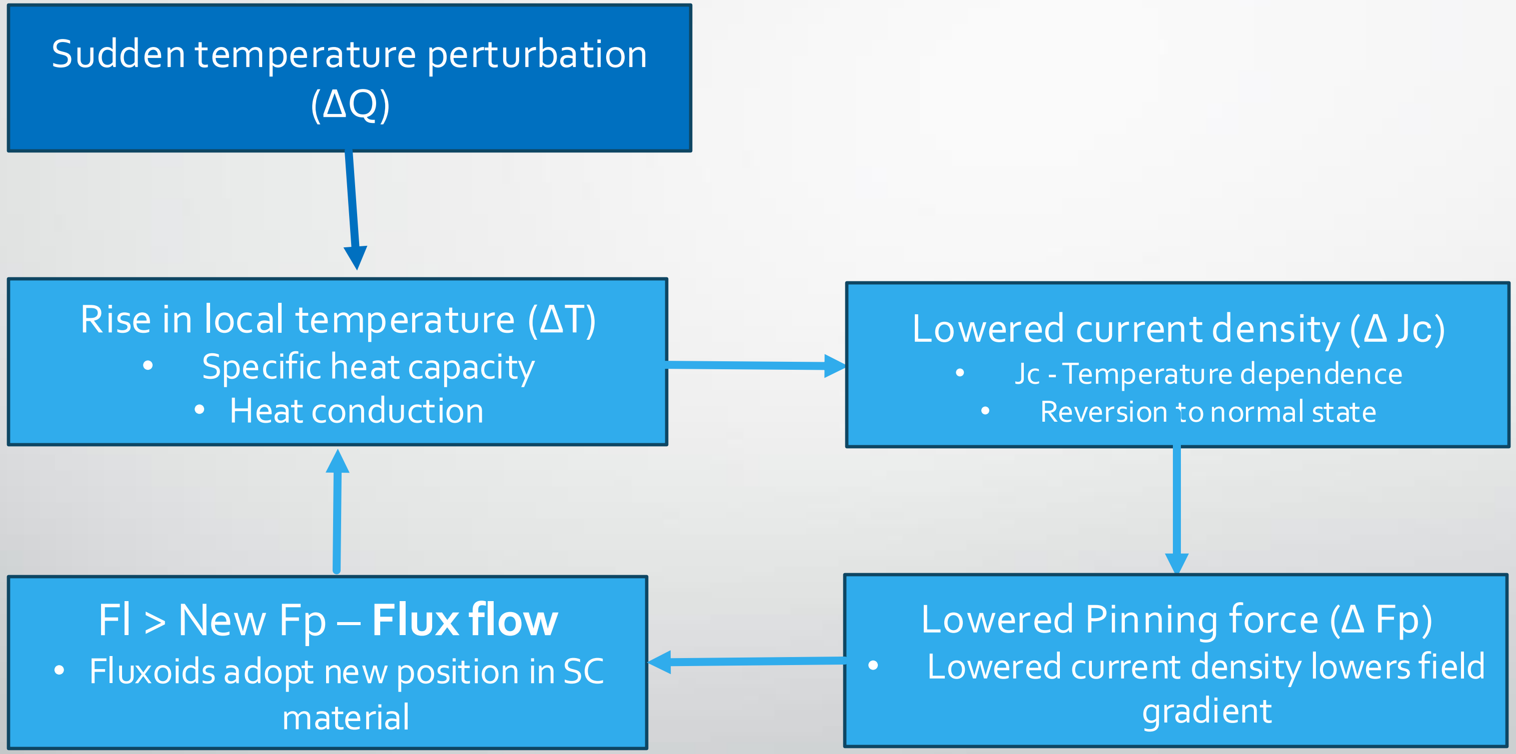
British Physicist, John Hulm, expressed a desire to investigate Nb-Ti as **‘God Save the Queen, we’ll have the union Jack’**

Flux jumps

- Optimism regarding this revelatory announcement quickly diminished as small coil prototypes would fall far below expectations.
- With the manufacturing methods used at the time, **NbZr superconductors would degrade over time** leading to a lower critical current density.
- Even after the magnet was trained, they would return to their normal state prematurely, before any thresholds exceeded the critical surface.
- This subpar performance was found to be caused by an instability called flux jumping
- R&D was directed at limiting this problem particularly at Fermilab, Argonne, Brookhaven and **RAL.**

Flux jumps

- Non uniform fluxoid distribution causes a screening current field gradient
- **This field gradient of screening currents contributes to the pinning force.**
- Positive feedback loop



Cryostabilisation

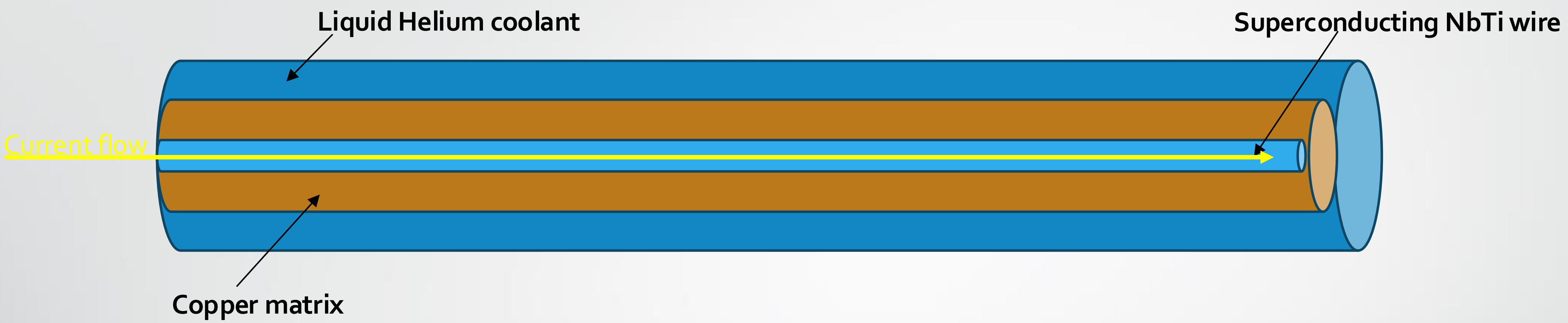
- Method of flux jump **tolerance** was developed in 1965 by Stekly and Zar working at Avco-Everett Research Laboratory in Boston.

- They conducted measurements of conductivity and resistivity in superconducting alloys (NbTi) and pure metals (Cu).
- **NORMAL STATE** NbTi alloy had higher **resisitivity** and lower **thermal conductivity** than Copper

A great example is the BEBC

Big European Bubble chamber : Use cryostabilised superconducting coils to generate magnetic fields of up to 3.5T. Largest at the time, boasting a 3m diameter

Cryostabilisation mechanism



Normal state: Liquid Helium coolant surrounds the copper conductor; the superconducting filament is kept below its critical temperature.

Fault state: Local normal state reversion

Current flow diversion. Ohmic generation becomes localised to the copper

Heat is transferred to surrounding coolant. Allowing NbTi to recovers and regains superconductivity.

Founding of the Superconductor Applications Group

- Cryostabilisation offered flux jump tolerance though had significant drawbacks
  - **Low current density**
  - **Susceptibility to AC losses and Eddy currents**
  - **High refrigeration losses**

Whilst not applicable for accelerators

- First use of reliable superconductive magnet (to critical current density)
- Copper annealing to NbTi
- Demonstrated use of effective cryogenic systems - refrigerant circulation

Superconducting applications group (SAG)

- Engineers at RALs Applied sciences division took notice.
- Peter Smith aimed to develop a coil design that **minimized flux jumps** and kept **refrigeration losses to acceptable limits**, within a 1 second rise time (time taken to reach design field).
- Alongside physicist, Martin Wilson, they would found the **superconducting applications group** in 1961.

Adiabatic Stability Criterion

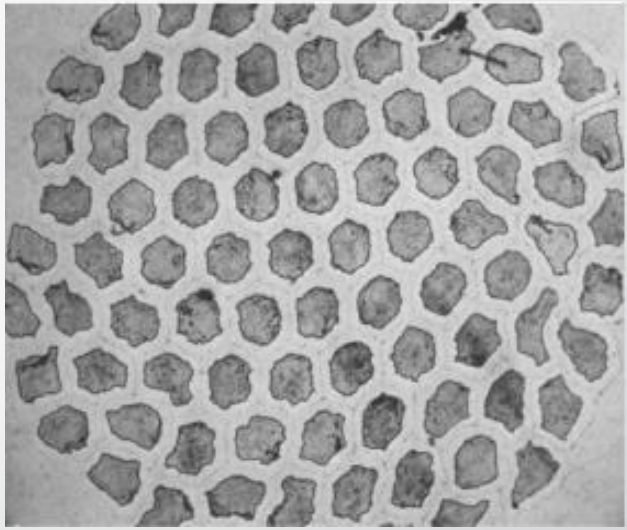
Adiabtic stability criterion is a set of equations – describing conditions required for flux jumps.

- SAG used this criteria during theoretical work from 1961 – 1965
- Thinner filaments – smaller cross section of the superconductor
- Smaller filaments confine fluxoid motion to a smaller volume **(provided filaments are uncoupled)**.

Used this criteria to establish flux jumps as tolerable at 50 micrometers

AC losses were tolerable at 5 micrometers.

RAL was not the first to identify this threshold…



100 Micrometer NbTi filaments embedded within a copper Matrix.

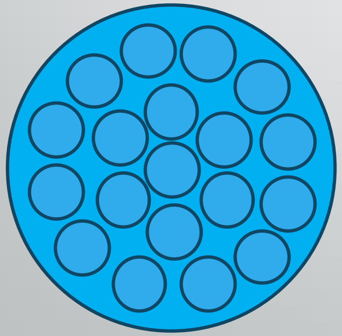
Manufacturing techniques were applied to NbTi within a copper matrix but to no success. Image courtesy of NASA 1964

Filament twisting

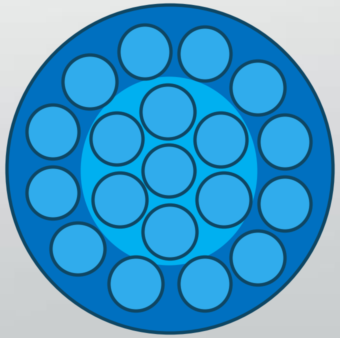
SAG pioneered wire twisting. Adjusting the **Twist pitch** to reduce self-field effects such as coupling losses

- Coupling current loops form between wires and within the conductors
- Coupling currents are dissipative – ohmic generation within copper matrix
- Twisting decouples inner and outer loops.

- Loops are still present within both layers.



Self-field effects are limited to the inner and outermost filaments when twisted



Superconducting filamentary composites

Peter Smith negotiated with Imperial Metal Industries (IMI) to produce a prototype coil of exacting specifications:

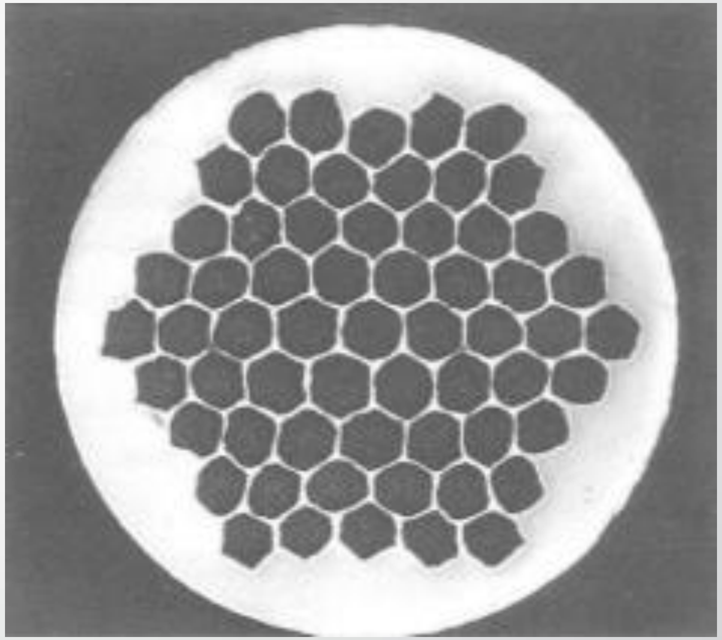
NbTi filaments with diameters of 50 Micrometres

Immersed within a fine copper conductive matrix.

- This **conductive matrix** follows the same principles as above with cryostabilisation. Redirecting current flow and conducting heat.

- SAG determined minimum volume of conductor to ensure stability
  - Less coating was needed
  - Superconductor to matrix ratio was close to **1:1** as opposed to **1: 1.4**.

Initially termed Smith-Wilson composites – now Superconducting filamentary composites



Prototype coil manufactured in 1967 by the IMI and RAL collaboration. This singular strand consisted of 61 50µm filaments (black polygons) within a conductive matrix (white surroundings).

This entire assembly is referred to as a strands. A series of strands constitutes a cable

Recap: History and Context

Theory

- Critical current density is a crucial metric of superconducting materials – **an extrinsic property to the material**
- Higher critical current density is desired.
- Electromagnetic criteria include Flux jumps, Magnetisation losses, Self field losses

Superconducting filamentary composites

RAL was not the only team researching this, with groups at **Fermilab and Brookhaven** dedicated to SC research

- RAL developed Superconducting filamentary composites.
- By 1970, AC losses are still far from 'tolerable' and coupling currents still persist.
- Reduce refrigeration losses within a 1 second rise time to tolerable levels.

Motivation for Rutherford Cable

What is the purpose of magnets within a synchrotron? (ARM)

Why is a cable needed?

Magnetic field homogeneity achieved by connecting magnets **in series**

Physicists desire a high magnetic inductance for **quench protection.**

For a high inductance and minimal voltage– magnets in series (kA) operate with high currents. $\mathbf{L \propto 1 / I^2}$

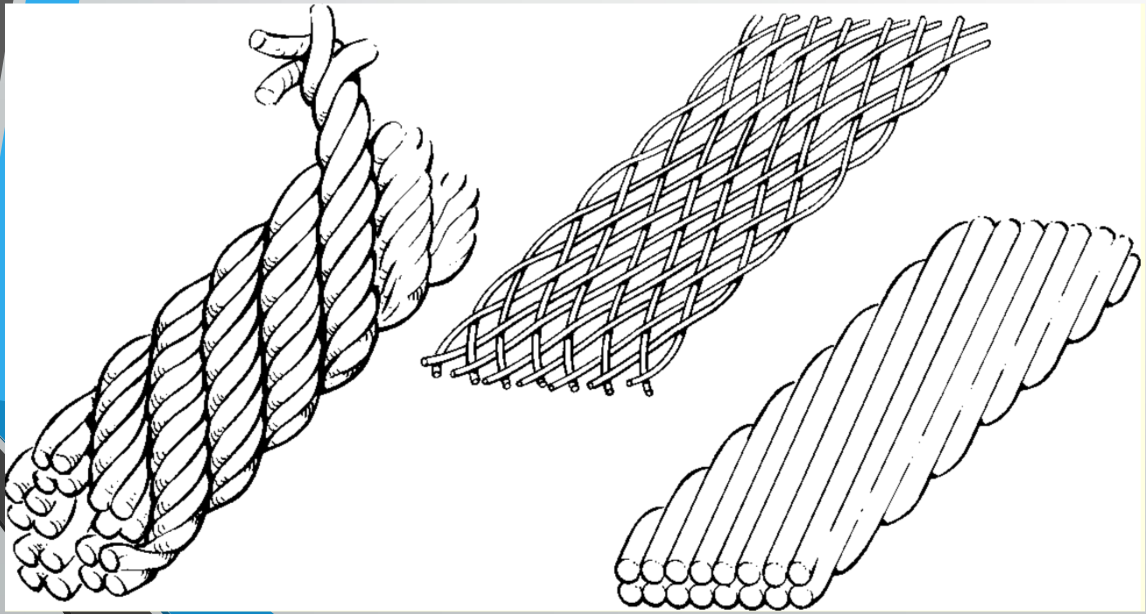
- High current single coils are not practical – sensitive to flux jumps
- Cables are also mechanically stable – Reducing frictional heating (more on this later)

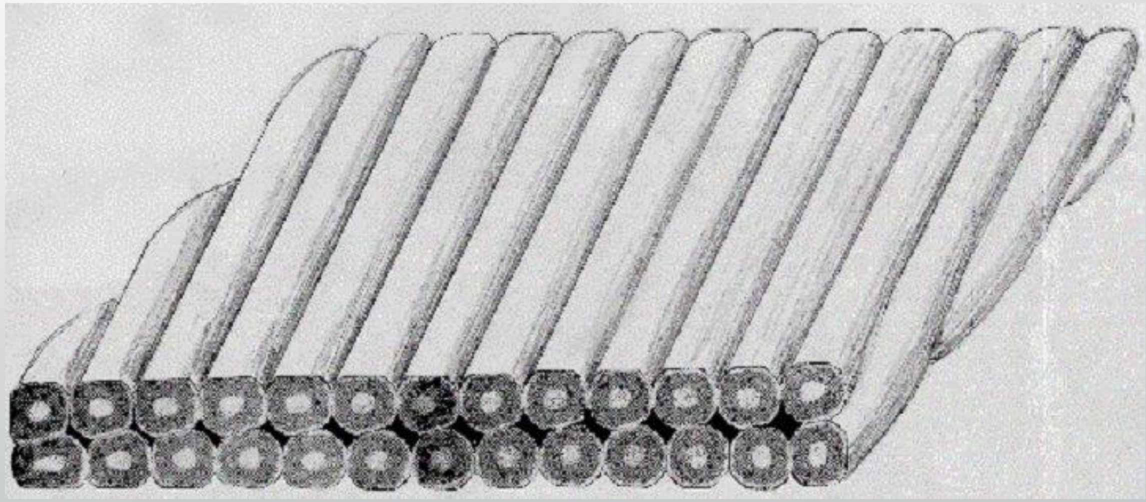
The solution is to compact 20 – 50 flattened strands of superconducting filamentary composites into cables.

Transposition

Reminder: Filaments generate self-fields and flux linkage occurs between the inner and outer filaments.

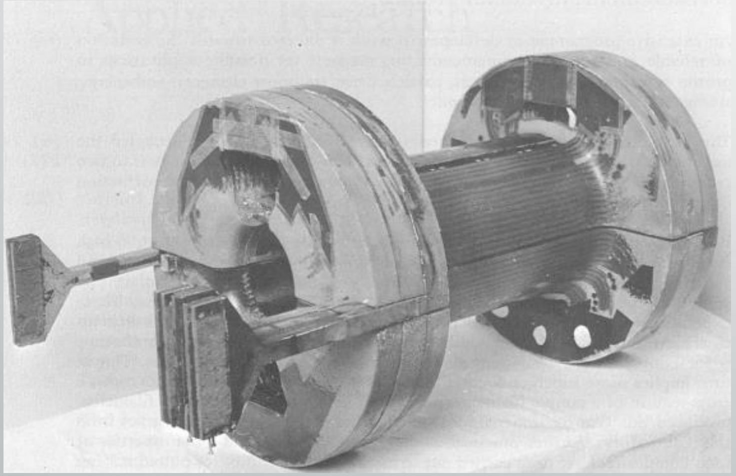
- To limit this change, physicists implemented wire **transposition.**
- This allows for equal current distribution and limits self-field losses during ramping.
- Rope, Braid and Rutherford (as it would later be known)
- **Maximum stable <u>packing factor</u> is desired for highest possible critical current density**



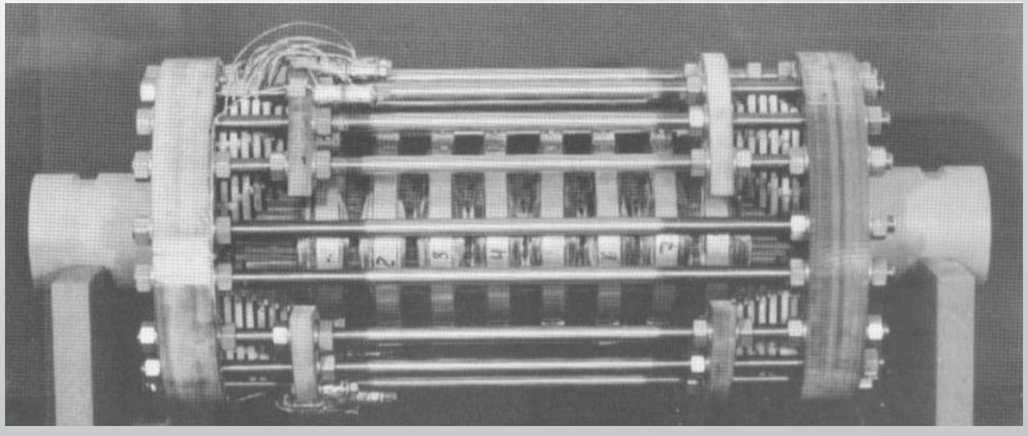


GESSS Collaboration

- Groups at RAL, Saclay and Karlsruhe formed the **Group for European Superconducting Synchrotron Studies (GESSS)**
- These laboratories each possessed their own cabling facilities.
- They sought to outfit CERN's proposed 300 GeV proton synchrotron (**later the SPS**) with superconducting magnets.
- GESSS design working group stated that if installed from the outset, they could increase beam acceleration to 800 GeV and then further to 1000 GeV
- GESSS aimed to demonstrate their feasibility.

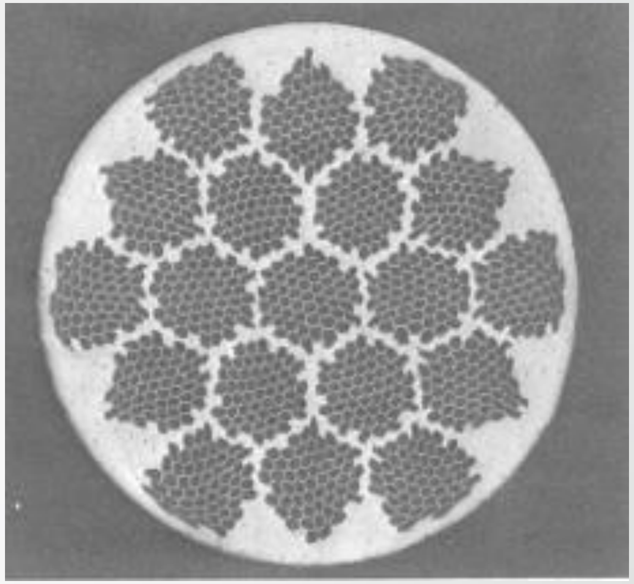


AC3 Magnet prototype produced by RAL (1971)

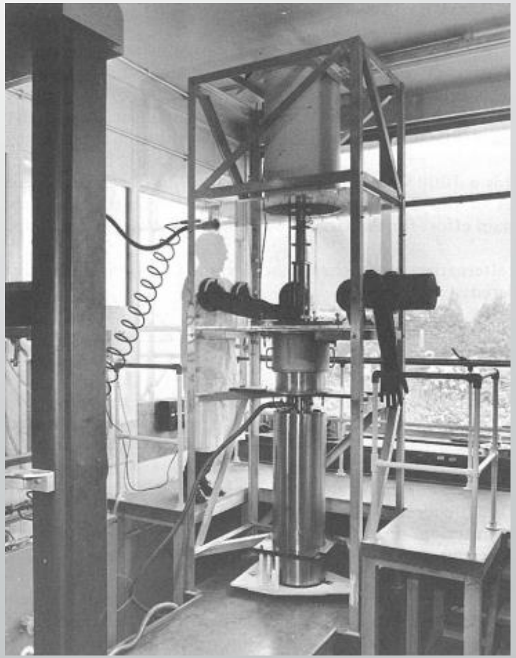


D1 magnet prototype produced by Karlsruhe Laboratory (1973)

Refining design



Strand produced by IMI and used by RAL in 1971



Coil Impregnation

- **Coil impregnation** – insert a small volume of material to resist mechanical movement.
- Specific properties were desired. At cryogenic temperatures it needed
  - High YM
  - Similar thermal contraction rate

RAL conducted a materials search campaign from a dedicated cryogenic facility in R52.

Culminated in selection of Epoxy Resin – still not ideal!

Addition of a copper oxide coating to strands

A copper oxide layer was deposited onto the strands to decrease interstrand coupling

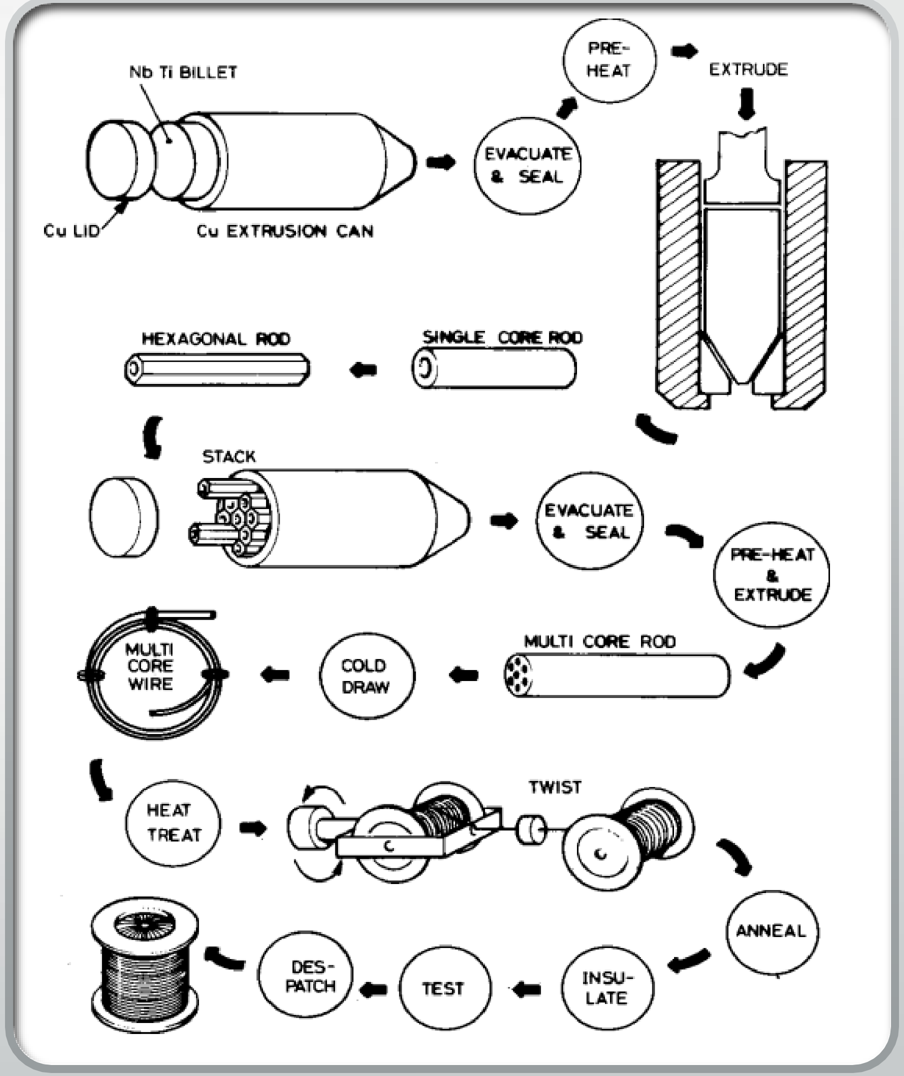
Cable manufacture

- Interplay between maximising the packing factor but ensuring mechanical stability of NbTi filaments

- Subject to several rounds of extrusion, drawing, twisting and compaction
  - – promote **degradation** (quantised by the degradation factor) or even **rupture!**

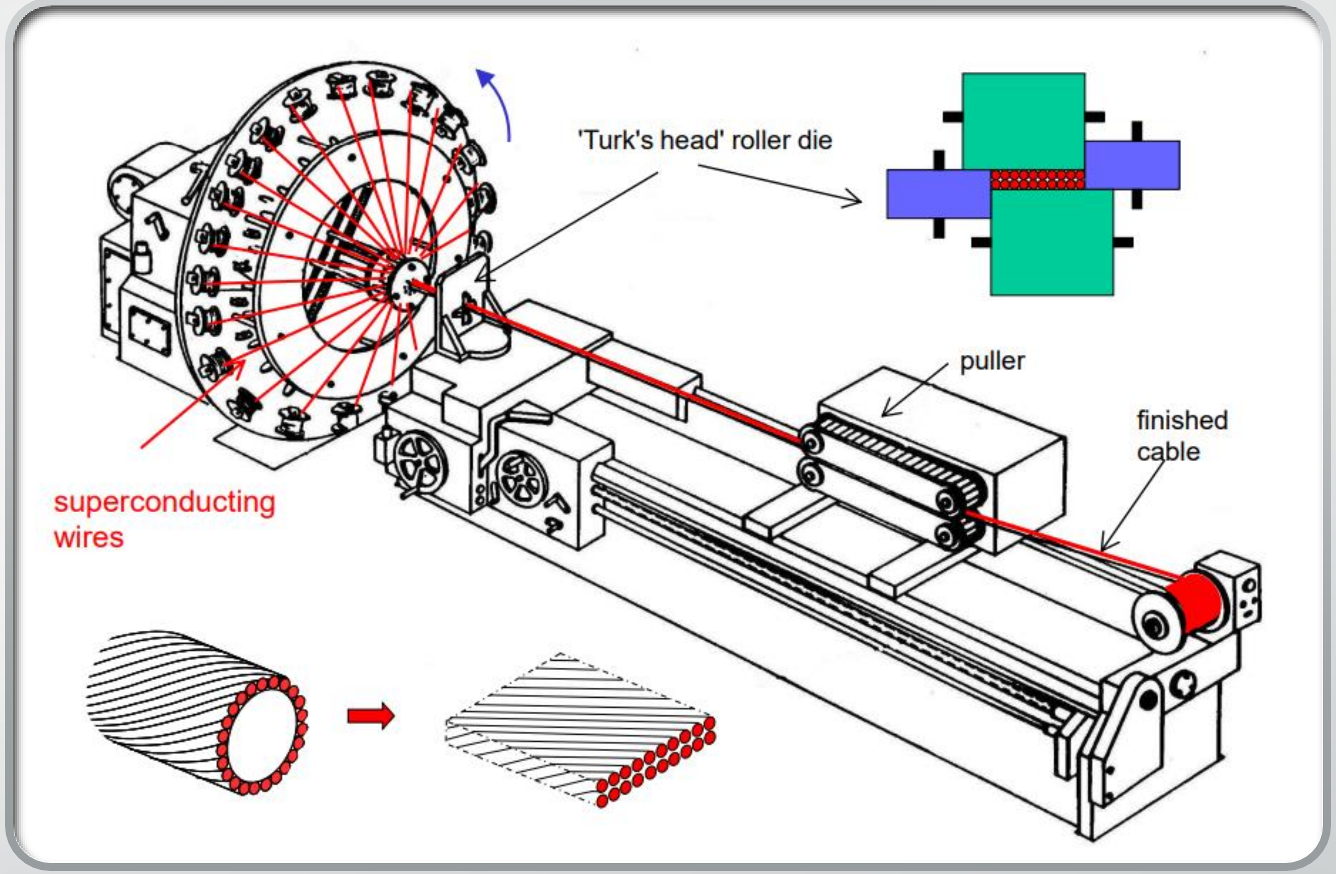
IMI enabled the monofilament and multifilament wire production.

Billet – Hexagonal rod – Multi-core rod – twisted filamentary composites



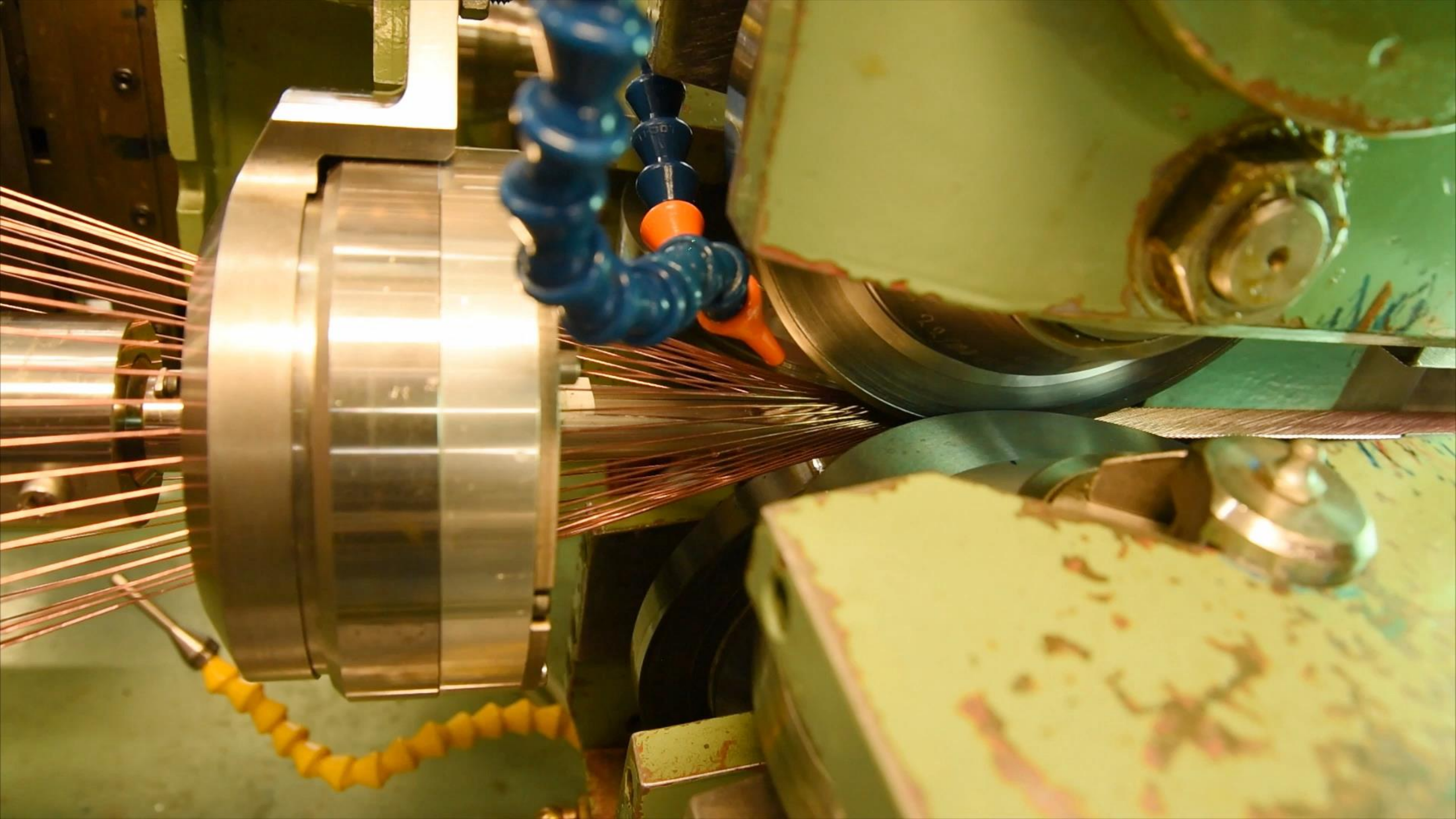
Cable manufacture

- Twisted wire was inserted into rotating spools
- Rotating mandrel induces wire transposition.
- **Turks Head Roller** compacts and flattens the strands into the desired shape.



RAL played an important role in coil layout

Main control parameters are
Twist pitch
Strand tension
Strand width
Window

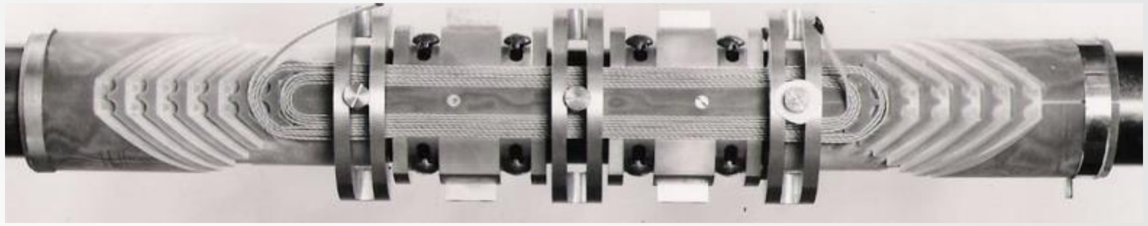


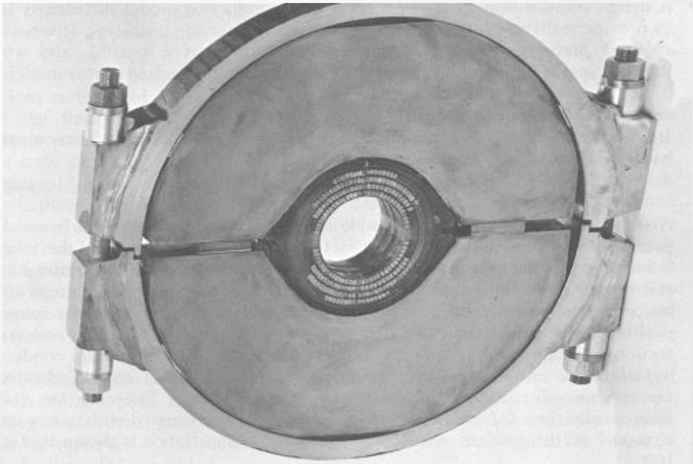
Rutherford Cable - AC4

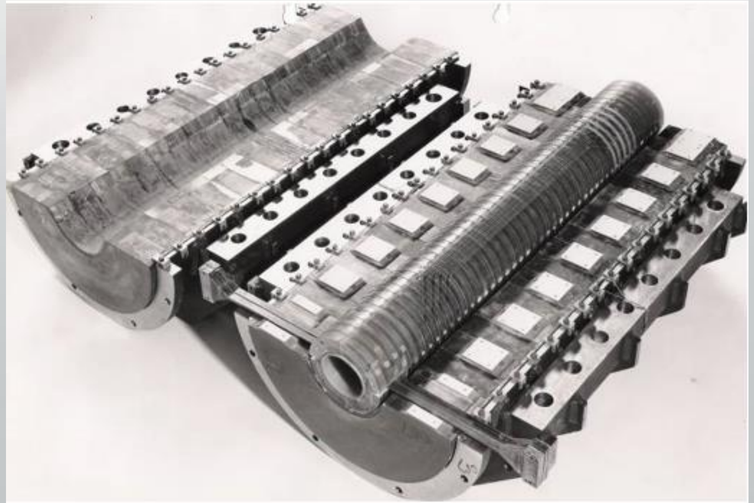
- Rutherford cable chosen above other configurations due to **<u>high packing factor</u> – providing greater current density.**

- Performed better than other prototypes, using rope transposition.
- AC4 developed in 1973 was the first magnet to use Rutherford cable within its magnetic windings.

After some training, it operated at its design current density!



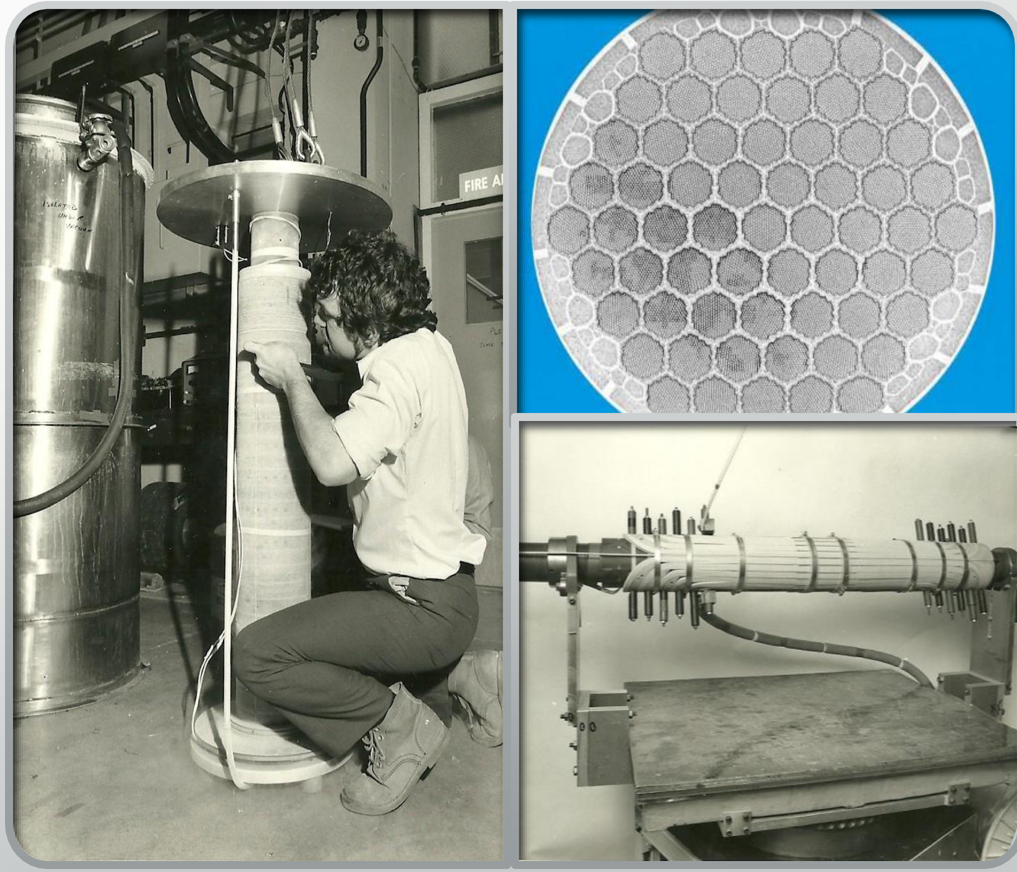




Rutherford Cable - AC5

- AC5 was the final prototype developed at RAL
- Increased packing density further by
  - Flattening the strands (P. G. Gallagher)
  - Adopting a rectangular window
- Fit the bill for the SPS – falling just short of ideal specs.
- Packed 10,000 – 20,000 filaments within each strand.
  - Each filament was only 5 micrometers.

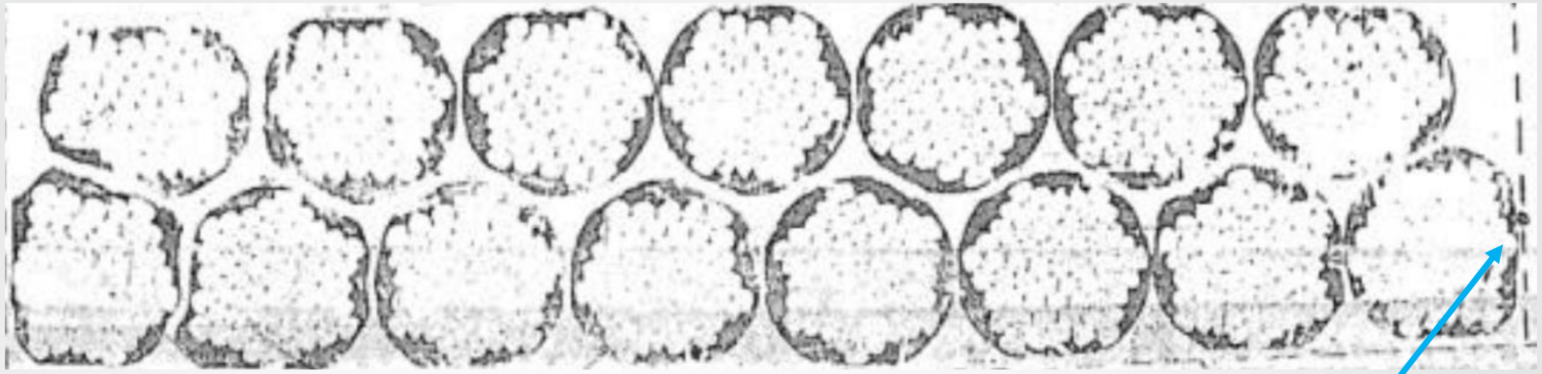
This 15 strand Rutherford Cable was named **'Flat 15'.**



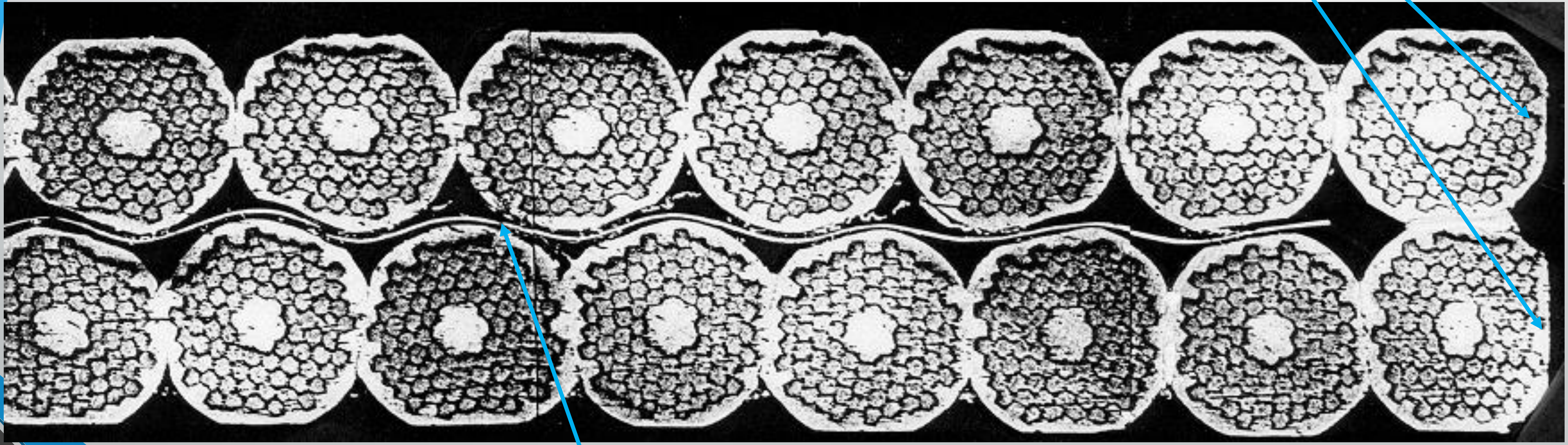
Flat 15

15 wires per cable

Rectangular window



Slight distortions at the edges



Oxide layer between wires

Over to the Tevatron

- CERN did not opt for Rutherford Cable for their magnets.

- Reinforced by RAL Metallurgist, David Larbaleister, commented that

  ‘Superconducting magnets were an exotic option'

- Robert Wilson, desired installation of superconducting synchrotron magnets to upgrade Fermilab's 400 GeV proton – proton synchrotron.

- Allowing for a significant increase to particle collision energy and effectively **HALVING** power consumption

RHIC (2011): The tunnel seen here was originally intended for the ISABELLE project. Although the team successfully developed prototype superconducting magnets, the project was ultimately hindered by persistent technical challenges. Image credit - BNL

Tevatron Dipole in storage (2013):
First particle accelerator to make use of Rutherford Cable within their superconducting magnets. Image credit – **Steve Krave Flickr**

Innovation at Fermilab

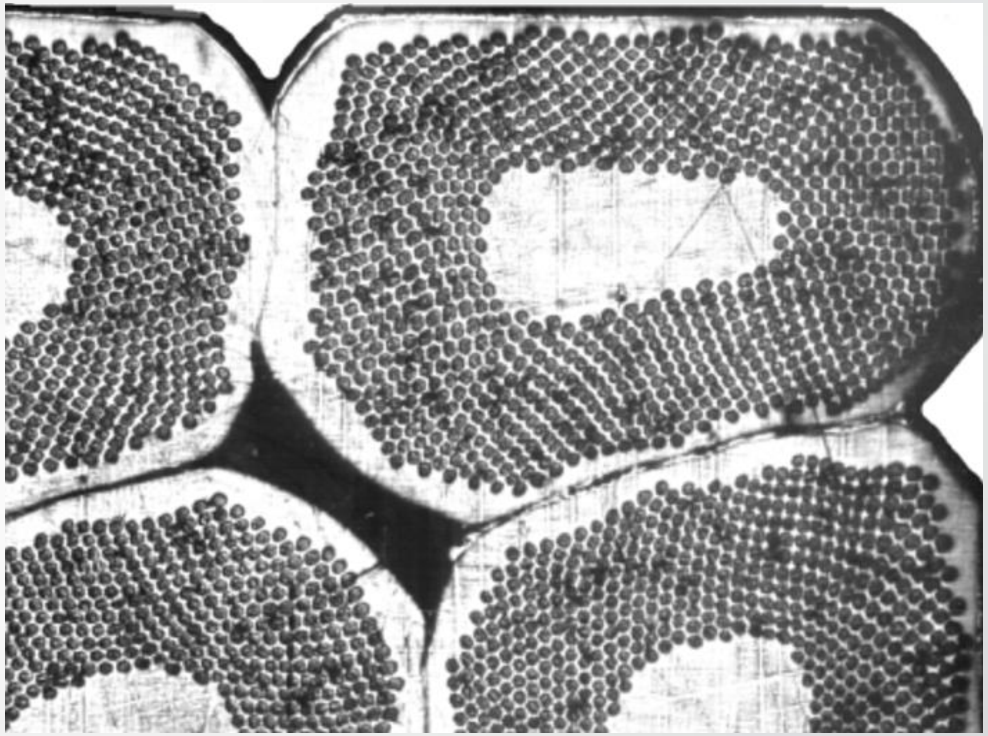
They selected a rectangular window, flat, twisted **23 strand Rutherford Cable.**

This was termed '**Zebra'** cable as the coated strands formed a stripy pattern.

Keystone angling

Kapton insulation

Effective cryogenics



Compaction to align with the magnet design

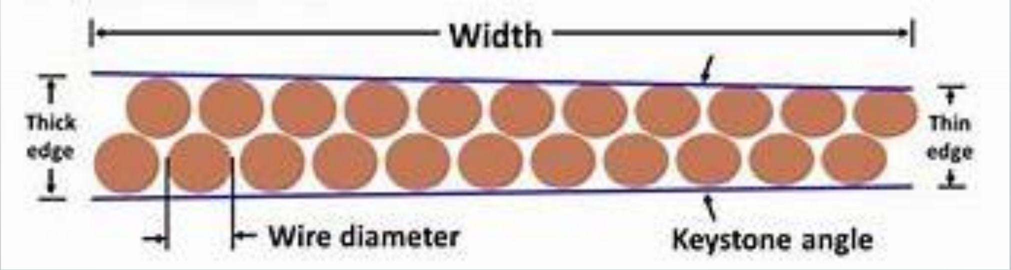


Image credit: [Charlie Sanabria]

Mass production

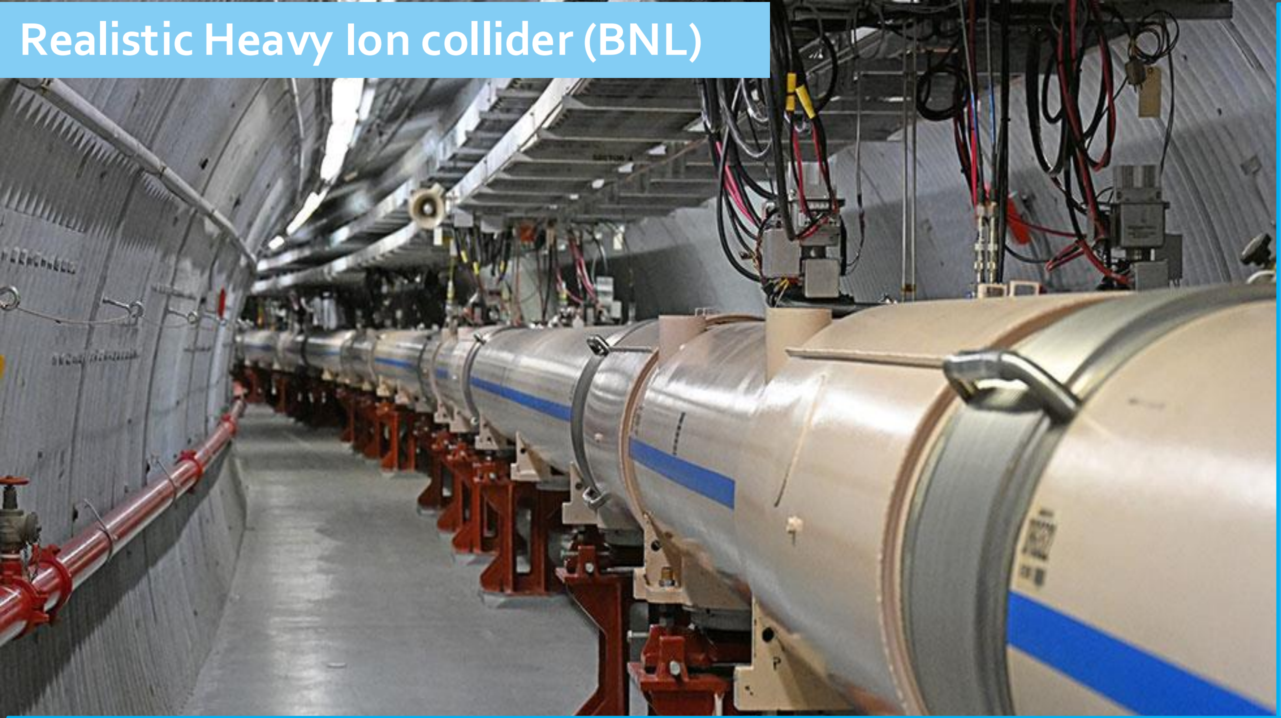
- Limited market and few sources
- Fermilab aided industrial partners
  - NbTi acquisition / Expertise / Equipment provision
- Wire is sent to Fermilab for Quality assurance and cabling
- **Close collaboration facilitated mass production**
- Contention between commerce and Fermilab
  - Being open with the scientific community

By 1974,

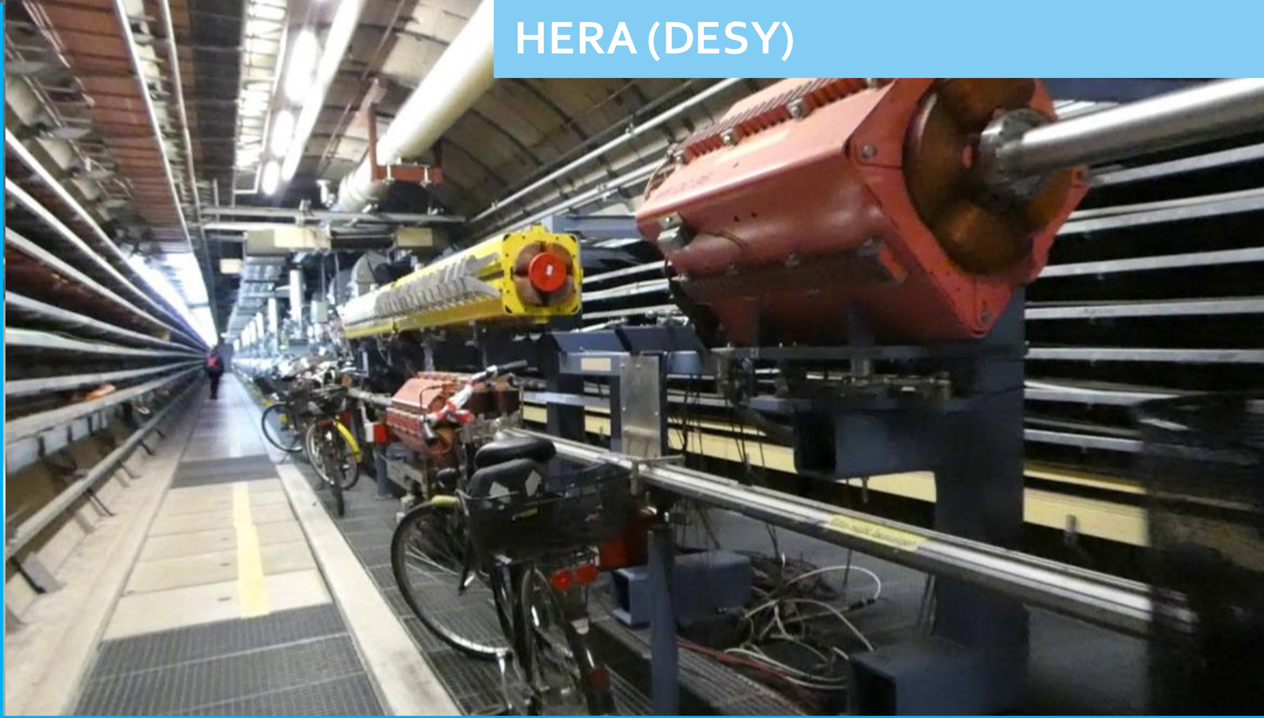
- Production lines were more efficient and capable of mass assembly of NbTi.
- Greater competition
- Consistent performance

NbTi rod insertion into copper billet at Intermagnetics General Corp Image credit: IGC

Realistic Heavy Ion collider (BNL)



HERA (DESY)

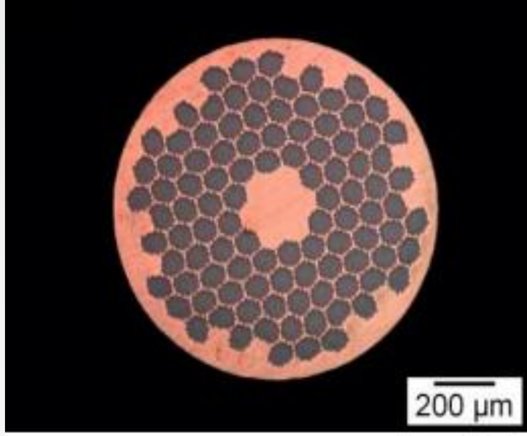


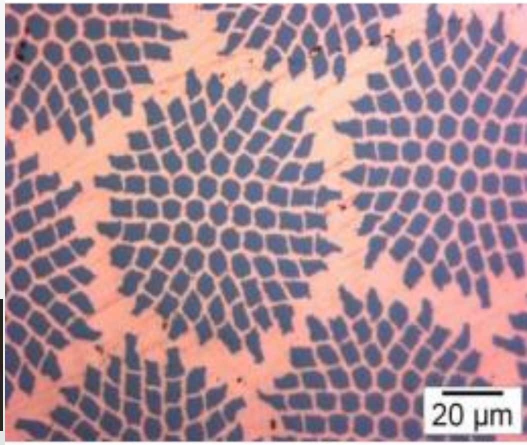
Large Hadron Collider (CERN)

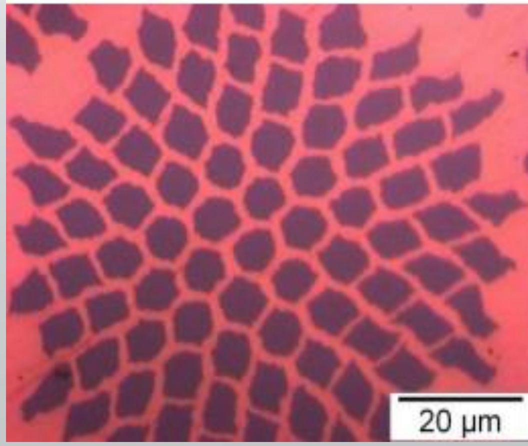
High Luminosity-LHC (CERN)

Rutherford Cable at the HL-LHC

- With the HL-LHC generating an unprecedented magnetic field strength of **12 Tesla**, the higher critical field of Nb_3Sn is required.
- 5 different types of Rutherford Cable are being produced for the HL-LHC.
    - 3 NbTi and 2 Nb_3Sn strands
- NbTi has been the dominant superconductor, but its reign may be coming to an end…
- First series of cable production has been complete!





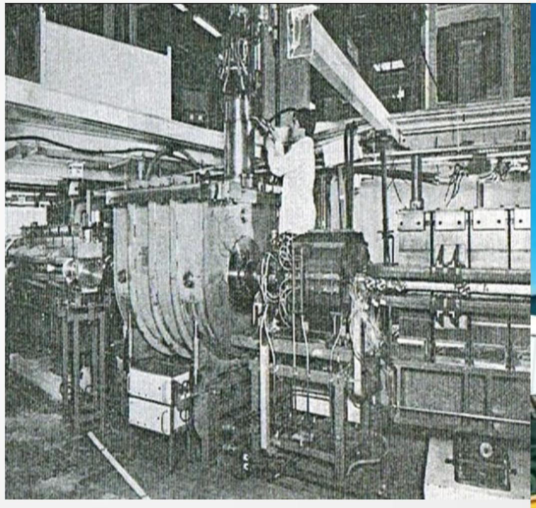


Rutherford Cable at RAL

Helical Undulator for polarised positron source **ILC prototype (2007)**

5T Wiggler magnet for the Daresbury Synchrotron Radiation Source (1978)

Superconducting coils for the DELPHI solenoid at LEP (1983)



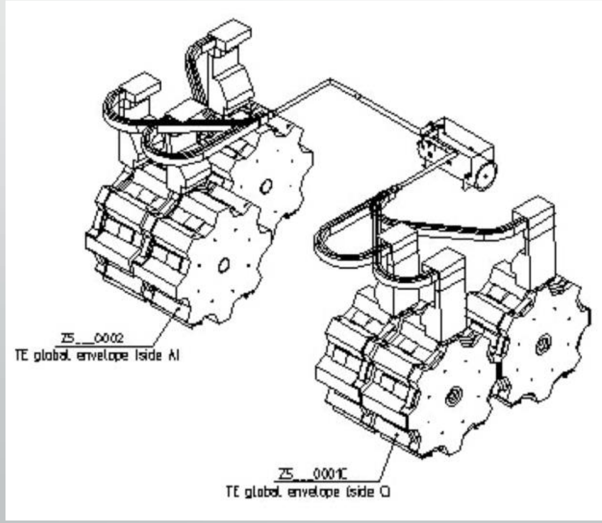
H1 coils at HERA

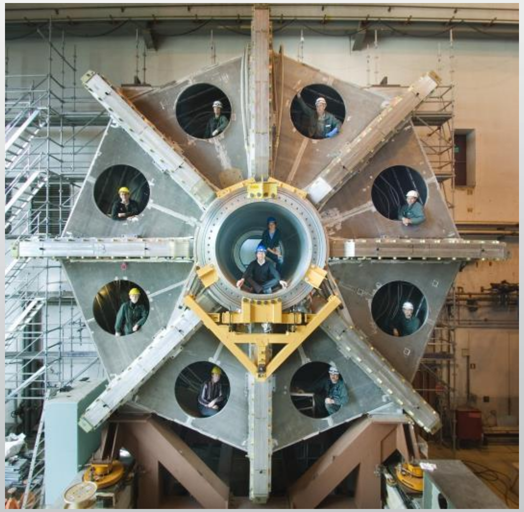
-

22km of Rutherford Cable
Internal Winding (Inside of Cylinder)
(1986)

ATLAS End cap toroid

- Engineering design and management for the ATLAS end cap toroid (1996 - 2007)
  - 10m in diameter
  - 120 tonnes of cold mass
  - Stores 250 MJ of energy
- Aluminium matrix
- Magnet heaters
- Dynamic lines





Beyond HEP applications

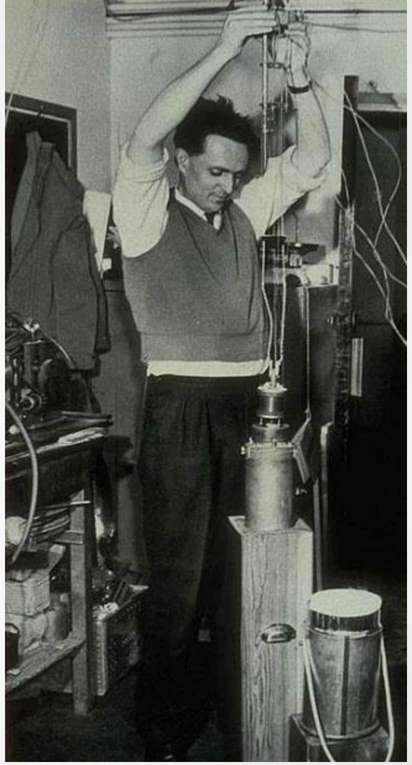
Oxford Instruments, in conjunction with Oxford University, developed superconducting joints, a pivotal part of NMR and MRI technology.

Oxford Instruments constructed magnets primarily for research purposes with their first product delivered in 1966.

First superconducting magnet for a NMR spectrometer

Nuclear Magnetic Resonance (NMR) is a technique very useful to biology and chemistry.

Superconducting magnets increased the precision and sensitivity



Martin Wood with prototype magnet in Clarendon Laboratory (1962)

Image courtesy of Oxford Instruments

NMR spectrometer (1979)

Image courtesy of Oxford Instruments

Beyond HEP applications: Medicine

Magnetic Resonance Imaging (MRI)

Used routinely in medical diagnostics.

Development of a superconducting joint

Decreasing power consumption and compact size.

First prototype was manufactured in 1979. Many MRI magnets now use Superconducting joints.

First superconducting joint prototype

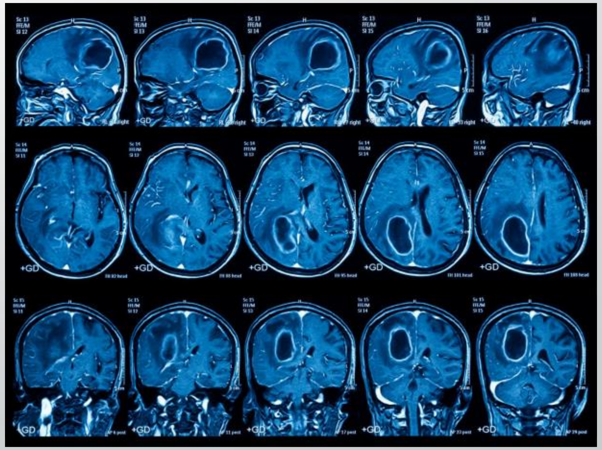
Accelerator based radiotherapy.

Accelerators accelerate the beam to specific energies and direct it at patients.

Targeting the tumour requires large costly infrastructure to attain correct energies and position the beam correctly.

Typical gantries are very large.

Superconducting magnets have been proposed for synchrotron gantries – involving Rutherford Cable.



MRI imaging – Routinely used in medicine

To summarise

Superconducting filamentary composites and Rutherford Cable were first manufactured at RAL.

20 – 50 strands were compacted and transposed to operate within high currents.

RAL developed first prototype and constructed the Rutherford Cable for detector solenoids.

Few other innovations have left such an enduring legacy, not only has this technology providing great strides in superconducting technology, but it has also been used within every large-scale collider since.

For the foreseeable future, Rutherford Cable will serve as the DNA of superconducting magnets.

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