Lecture 3: Quenching and a bit about hardware

Plan

- the quench process
- decay times and temperature rise
- quench protection schemes

- cryostats
- superconductor manufacture
- coil manufacture
- some superconducting accelerators

the most likely cause of death for a superconducting magnet

Magnetic stored energy

Magnetic energy density $E = \frac{B^2}{2\mu_o}$ at 5T $\boldsymbol{E}$ = 10^7 Joule.m^{-3} at 10T $\boldsymbol{E}$ = 4×10^7 Joule.m^{-3}

LHC dipole magnet (twin apertures) $\boldsymbol{E = \frac{1}{2} L I^2}$ $\boldsymbol{L}$ = 0.12H $\boldsymbol{I}$ = 11.5kA E = 7.8 x 10^6 Joules

the magnet weighs 26 tonnes

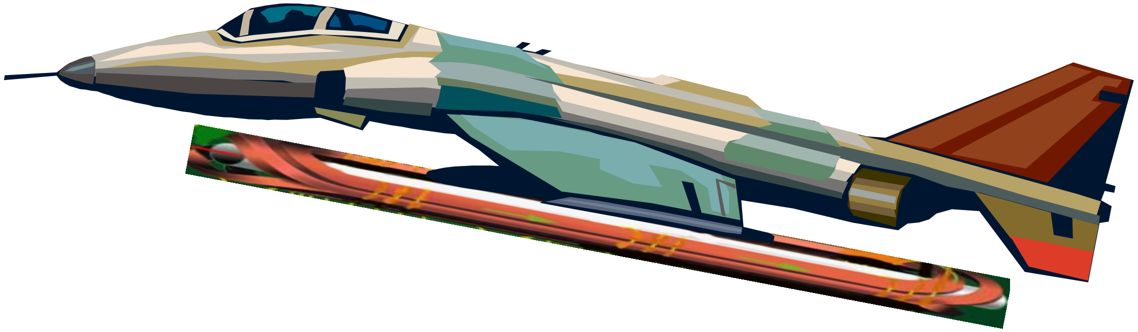
so the magnetic stored energy is equivalent to the kinetic energy of:-

26 tonnes travelling at 88km/hr

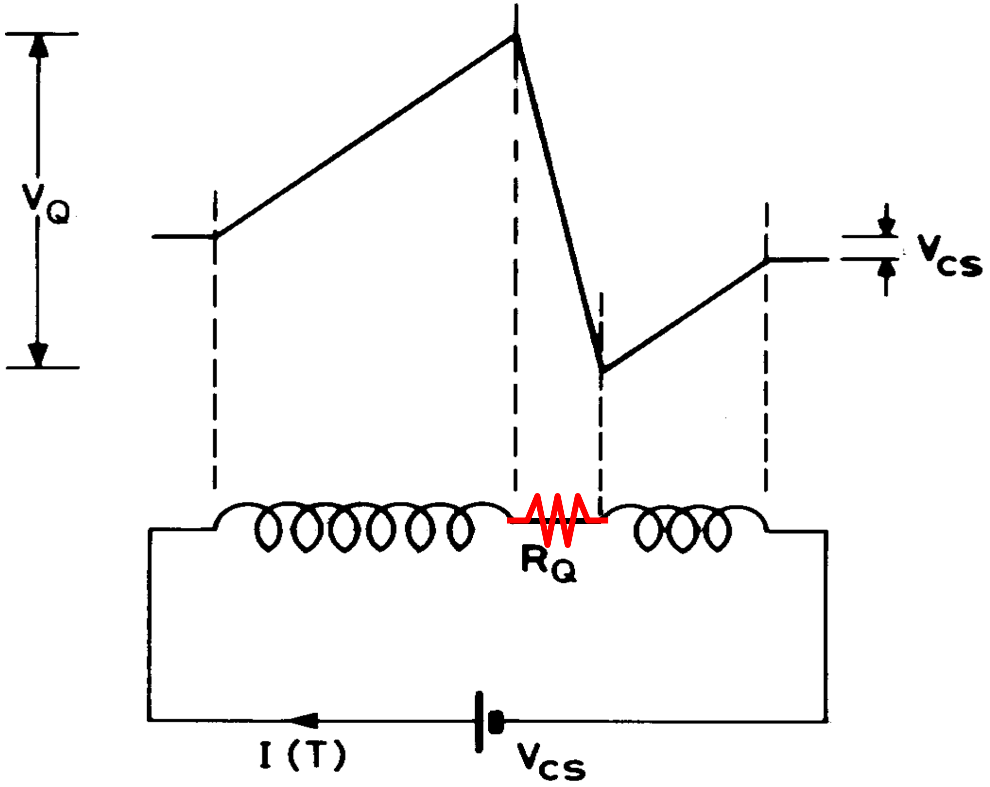
coils weigh 830 kg

equivalent to the kinetic energy of:-

830kg travelling at 495km/hr



The quench process



- resistive region starts somewhere in the winding

  at a **point - this is the problem!**
- it grows by thermal conduction
- stored energy $\frac{1}{2}LI^2$ of the magnet is dissipated as heat
- greatest integrated heat dissipation is at point where the quench starts
- internal voltages much greater than terminal voltage (= V_{cs} current supply)
- maximum temperature may be calculated from the current decay time via the $U(\theta)$ function (adiabatic approximation)

The temperature rise function $U(\theta)$

- Adiabatic approximation

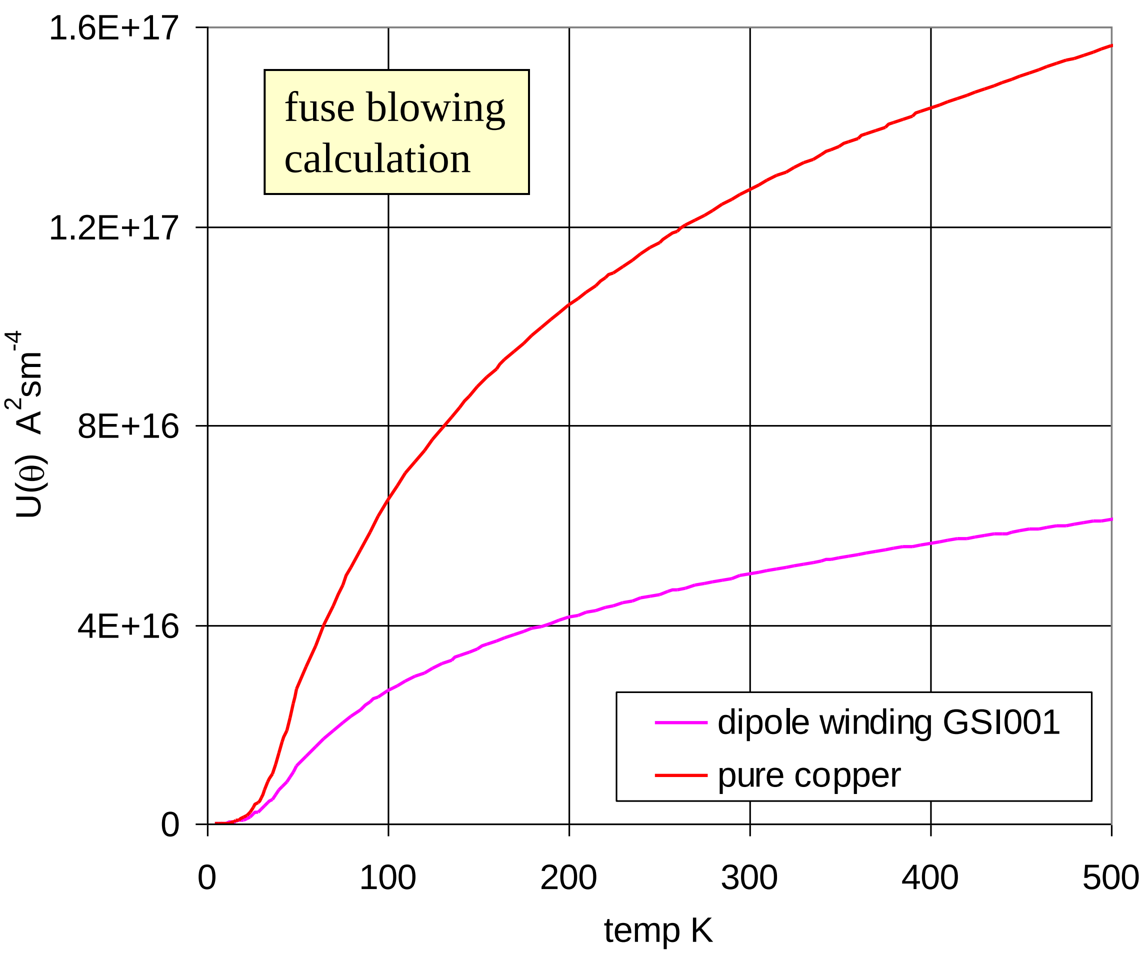
$$J^2(T)\rho(\theta)dT = \gamma C(\theta)d\theta$$

J(T) = overall current density,
T = time,
ρ(θ) = overall resistivity,
γ = density
θ = temperature,
C(θ) = specific heat,
T_Q = quench decay time.

$$\int_o^\infty J^2(T)\,dT = \int_{\theta o}^{\theta m}\frac{\gamma C(\theta)}{\rho(\theta)}\,d\theta$$

$$= U(\theta_m)$$

$$\boxed{J_o^2 T_Q = U(\theta_m)}$$



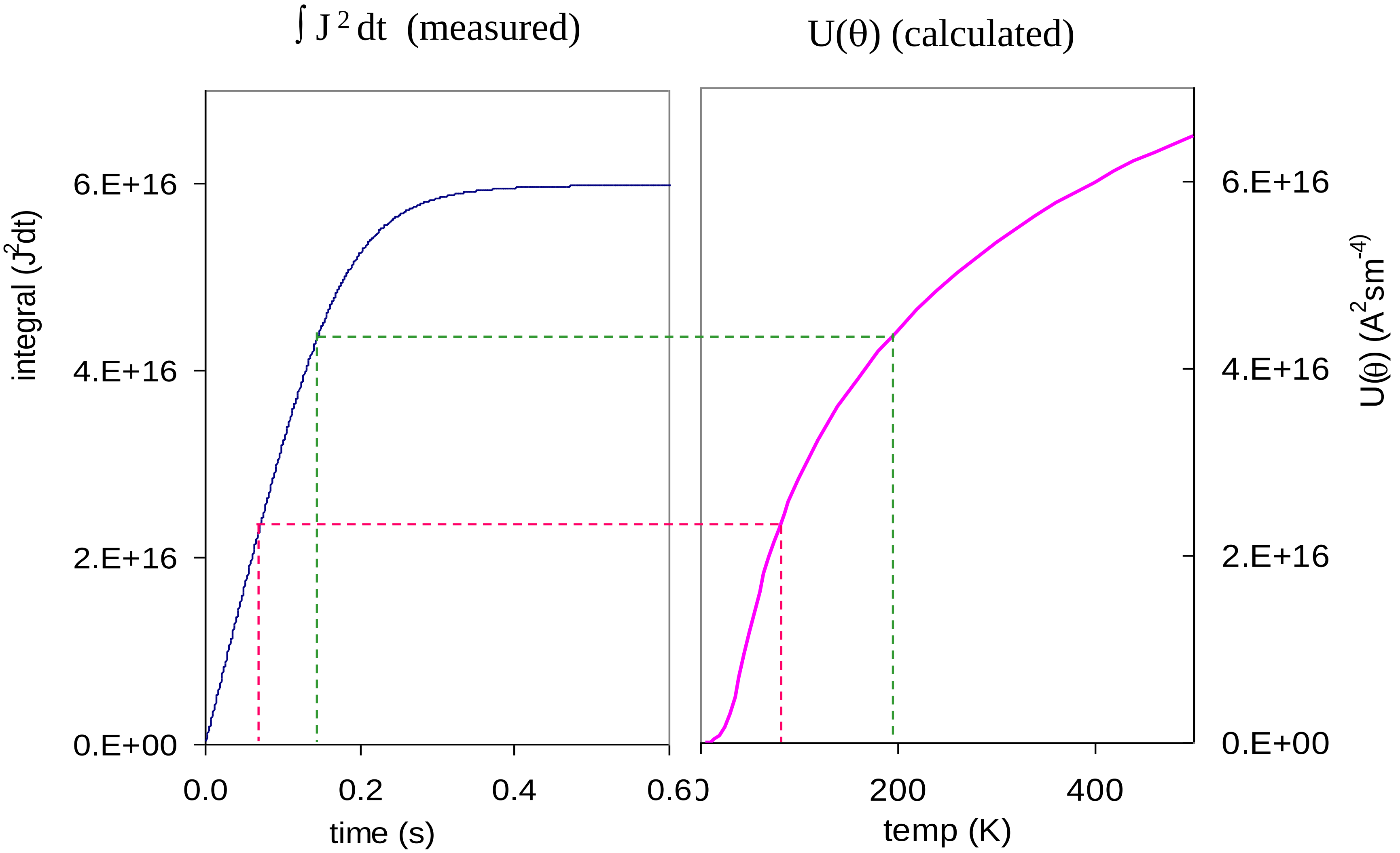
fuse blowing calculation

- GSI 001 dipole winding is 50% copper, 22% NbTi, 16% Kapton and 3% stainless steel

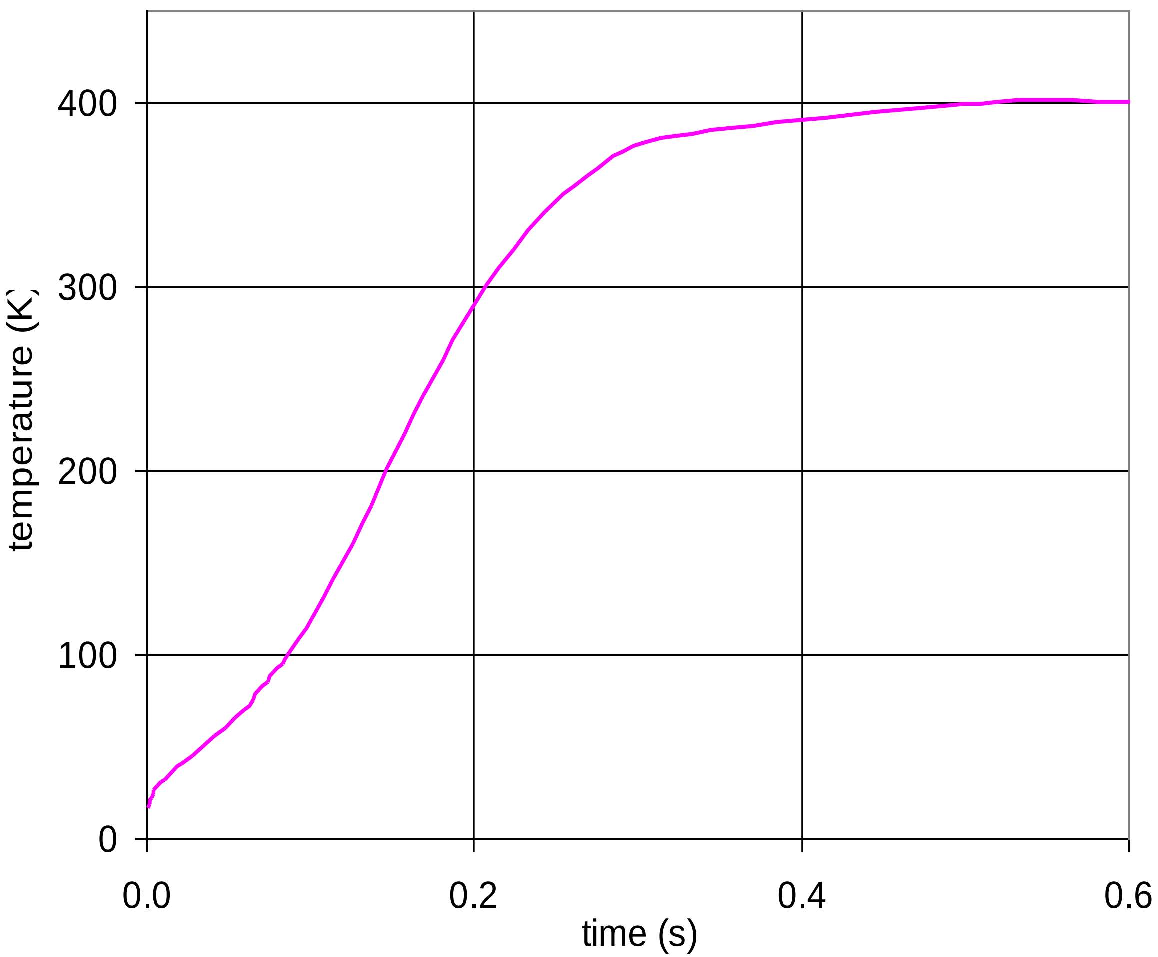
- NB always use **overall** current density

household fuse blows at 15A,
area = 0.15mm^2 J = 100Amm^{-2}
NbTi in 5T J_c = 2500Amm^{-2}

Calculating temperature rise from the current decay

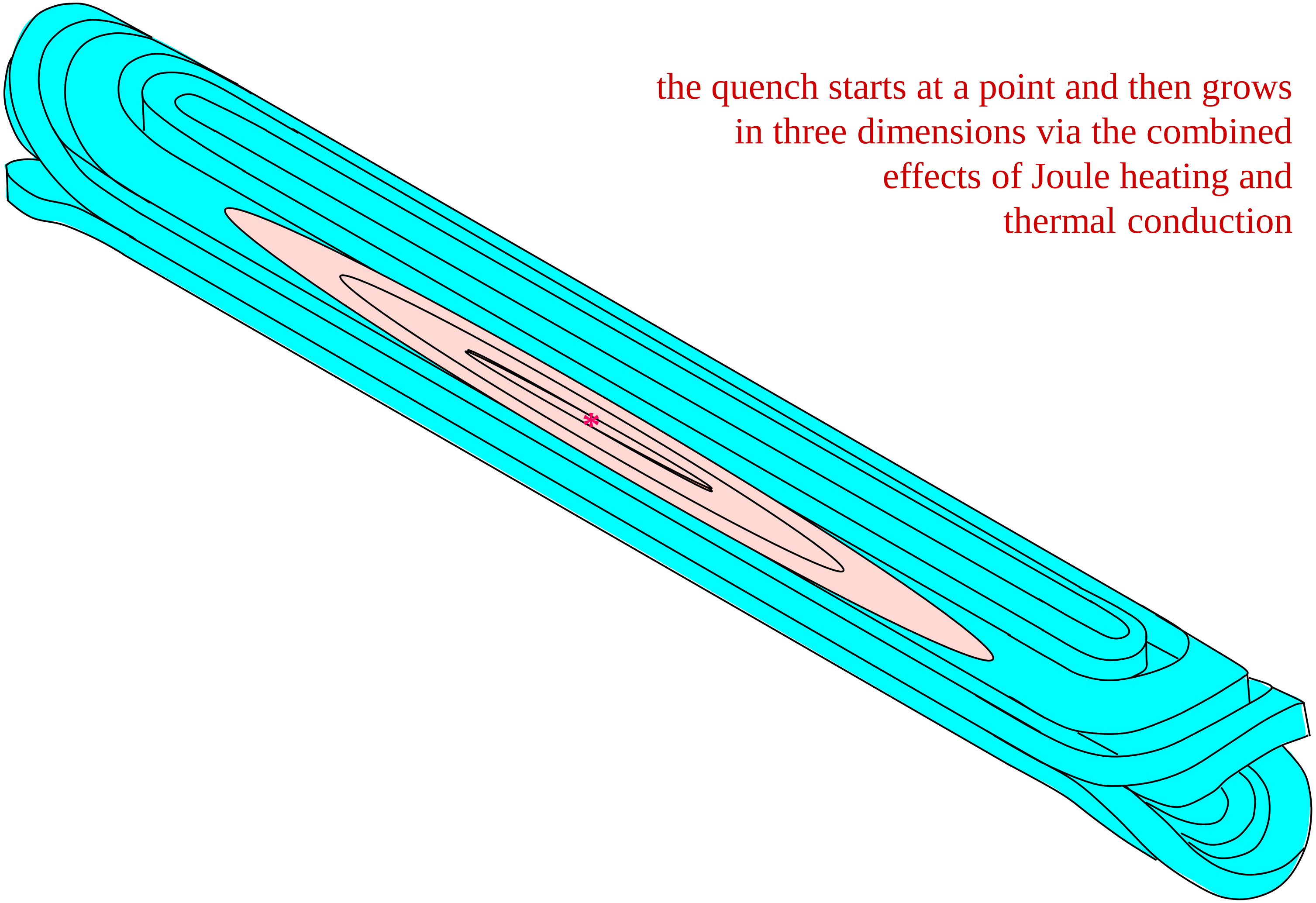


Calculated temperature



- calculate the U(θ) function from known materials properties
- measure the current decay profile
- calculate the maximum temperature rise at the point where quench starts
- we now know if the temperature rise is acceptable
  - but only after it has happened!
- need to calculate current decay curve before quenching

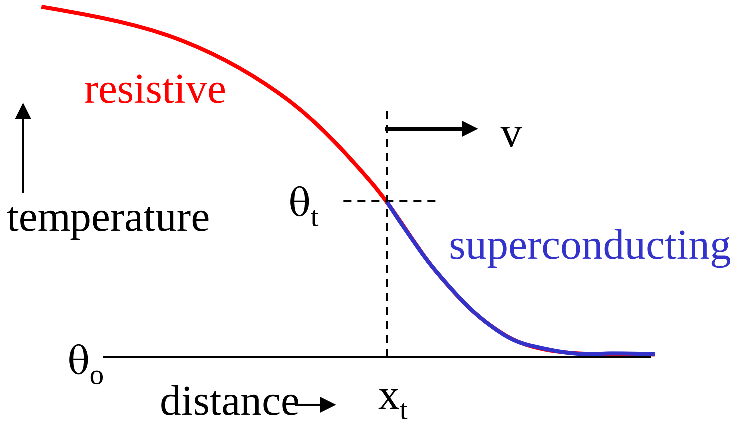
Growth of the resistive zone



the quench starts at a point and then grows in three dimensions via the combined effects of Joule heating and thermal conduction

Quench propagation velocity 1

- resistive zone starts at a point and spreads outwards
- the force driving it forward is the heat generation in the resistive zone, together with heat conduction along the wire
- write the heat conduction equations with resistive power generation $J^2\rho$ per unit volume in left hand region and $\rho = 0$ in right hand region.



$$\frac{\partial}{\partial x}\left(kA\frac{\partial\theta}{\partial x}\right)-\gamma CA\frac{\partial\theta}{\partial t}-hP(\theta-\theta_0)+J^2\rho A=0$$

where: k = thermal conductivity, A = area occupied by a single turn, γ = density, C = specific heat, h = heat transfer coefficient, P = cooled perimeter, ρ = resistivity, θ_o = base temperature

Note: all parameters are averaged over A the cross section occupied by one turn

assume x_t moves to the right at velocity v and take a new coordinate $\varepsilon = x - x_t = x - vt$

$$\frac{d^2\theta}{d\varepsilon^2}+\frac{v\gamma C}{k}\frac{d\theta}{d\varepsilon}-\frac{hP}{k\,A}(\theta-\theta_0)+\frac{J^2\rho}{k}=0$$

Quench propagation velocity 2

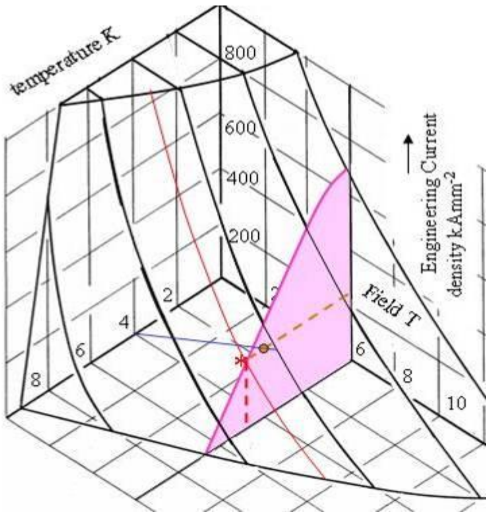
when $h = 0$, the solution for θ which gives a continuous join between left and right sides at θ_t gives the ***adiabatic propagation velocity***

$$v_{ad} = \frac{J}{\gamma C}\left\{\frac{\rho k}{\theta_t - \theta_0}\right\}^{\frac{1}{2}} = \frac{J}{\gamma C}\left\{\frac{L_o \theta_t}{\theta_t - \theta_0}\right\}^{\frac{1}{2}}$$

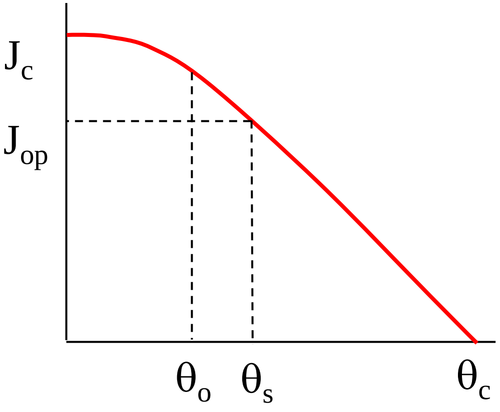
recap Wiedemann Franz Law $\rho(\theta).k(\theta) = L_o\theta$

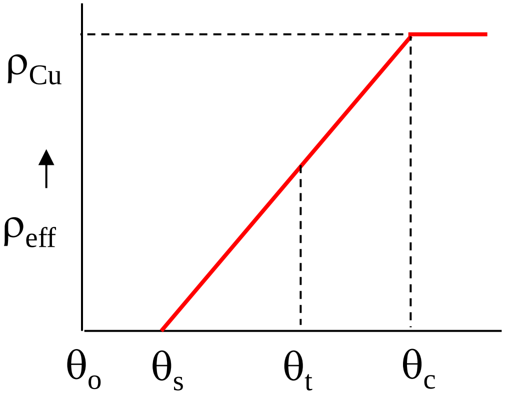
what to say about θ_t ?

- in a single superconductor it is just θ_c
- but in a practical filamentary composite wire the current transfers progressively to the copper



- current sharing temperature $\theta_s = \theta_o + margin$
- zero current in copper below θ_s all current in copper above θ_s
- take a mean transition temperature $\theta_s = (\theta_s + \theta_c)/2$





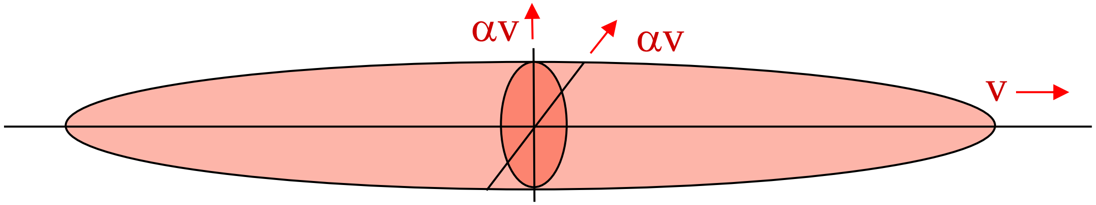
Quench propagation velocity 3

the resistive zone also propagates sideways through the inter-turn insulation (much more slowly) calculation is similar and the velocity ratio α is:

$$\alpha = \frac{v_{trans}}{v_{long}} = \left\{\frac{k_{trans}}{k_{long}}\right\}^{\frac{1}{2}}$$

Typical values $v_{ad} = 5 - 20\ \mathrm{ms}^{-1}$ $\alpha = 0.01 - 0.03$

so the resistive zone advances in the form of an ellipsoid, with its long dimension along the wire



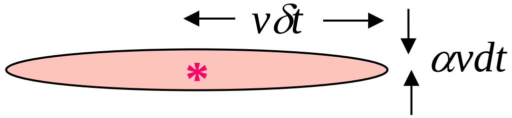
Some corrections for a better approximation

- because C varies so strongly with temperature, it is better to calculate an averaged C from the enthalpy change

$$C_{av}(\theta_g, \theta_c) = \frac{H(\theta_c) - H(\theta_g)}{(\theta_c - \theta_g)}$$

- heat diffuses slowly into the insulation, so its heat capacity should be excluded from the averaged heat capacity when calculating longitudinal velocity - but not transverse velocity
- if the winding is porous to liquid helium (usual in accelerator magnets) need to include a time dependent heat transfer term
- can approximate all the above, but for a really good answer must solve (numerically) the three dimensional heat diffusion equation or, even better, measure it!

Resistance growth and current decay - numerical



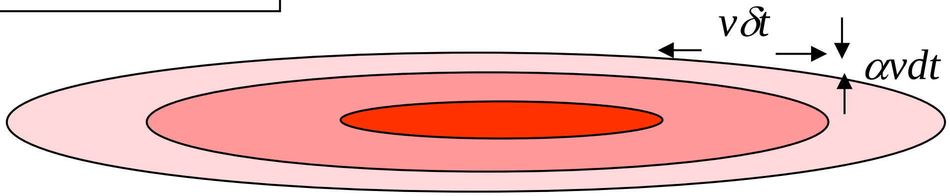
start resistive zone 1

in time δt zone 1 grows $v.dt$ longitudinally and $\alpha.v.dt$ transversely

temperature of zone grows by $\delta\theta_1 = J^2\rho(\theta_1)\delta\tau / \gamma C(\theta_1)$

resistivity of zone 1 is $\rho(\theta_1)$

calculate resistance and hence current decay $\delta I = R / L.\delta t$



in time δt add zone n:
$v.\delta t$ longitudinal and $\alpha.v.\delta t$ transverse

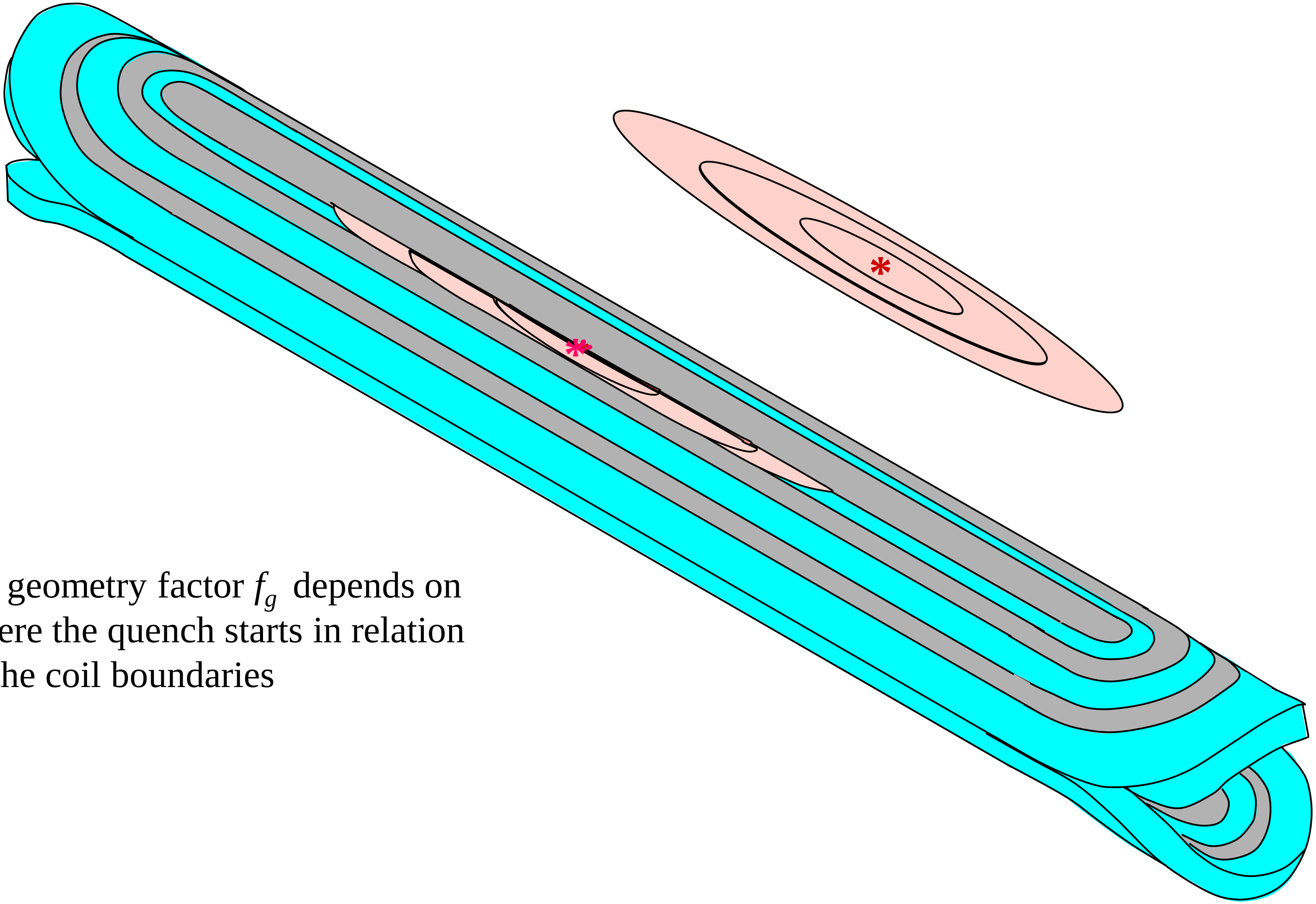
temperature of each zone grows by $\delta\theta_1 = J^2\rho(\theta_1)\delta t/\gamma C(\theta_1)$ $\delta\theta_2 = J^2\rho(\theta_2)\delta t/\gamma C(\theta_2)$ $\delta\theta_n = J^2\rho(\theta_1)\delta t/\gamma C(\theta_n)$

resistivity of each zone is $\rho(\theta_1)$ $\rho(\theta_2)$ $\rho(\theta_n)$ resistance $r_1 = \rho(\theta_1) * f_{g1}$ (geom factor) $r_2 = \rho(\theta_2) * f_{g2}$ $r_n = \rho(\theta_n) * f_{gn}$

calculate total resistance $R = \sum r_1 + r_2 + r_{n..}$ and hence current decay $\delta I = (I\,R/L)\delta t$

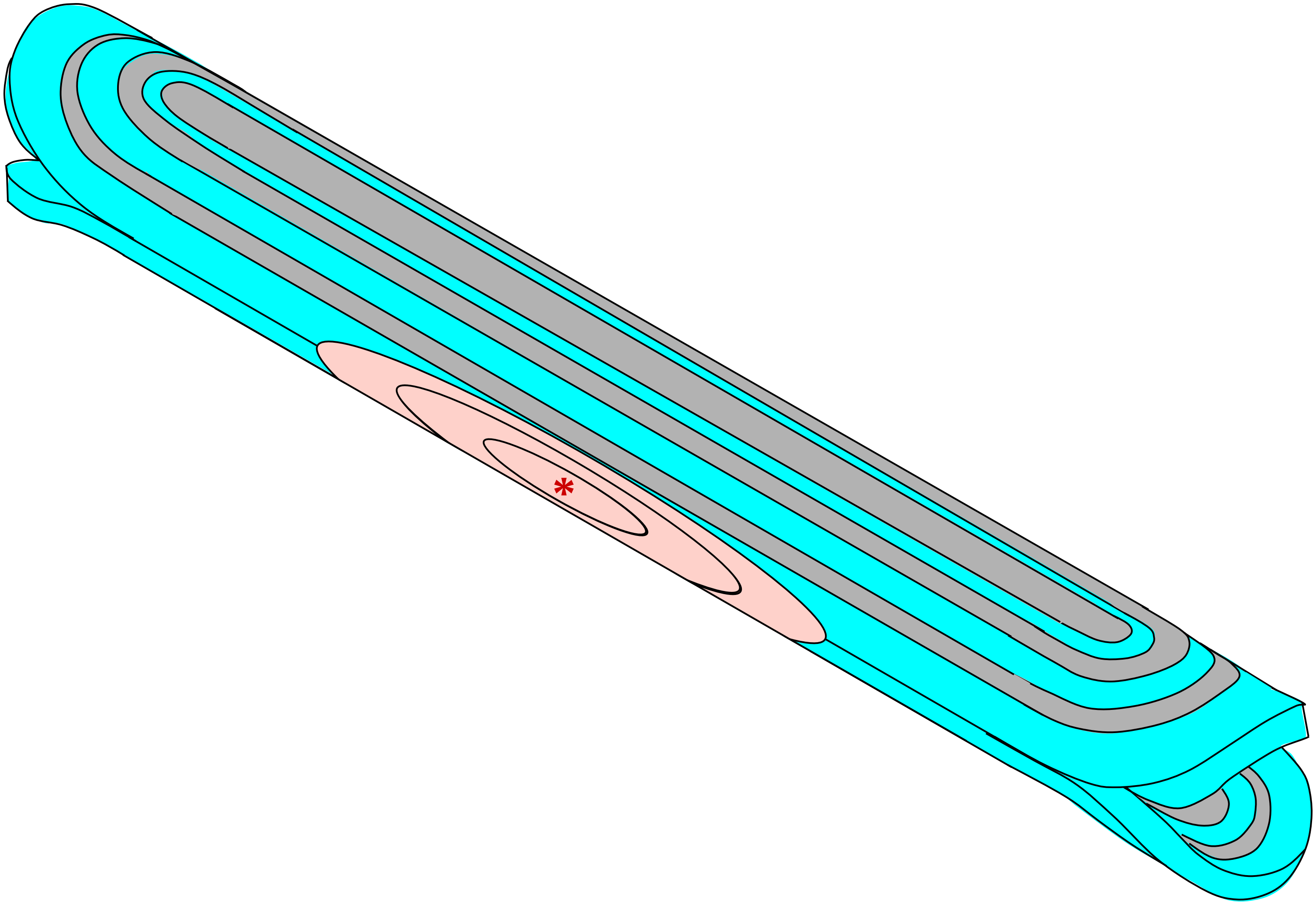
when $I \Rightarrow 0$ stop

Quench starts in the pole region

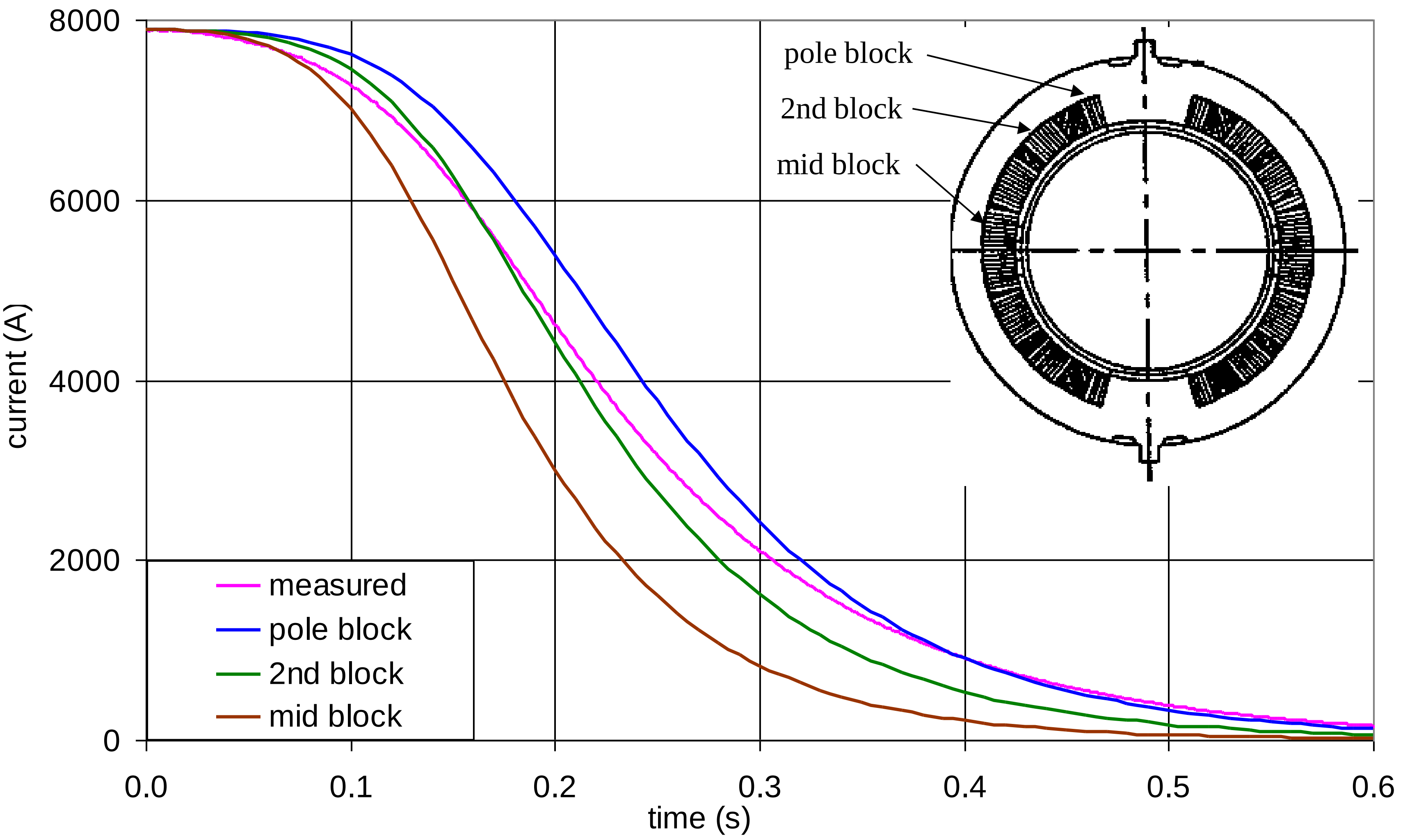


the geometry factor f_g depends on where the quench starts in relation to the coil boundaries

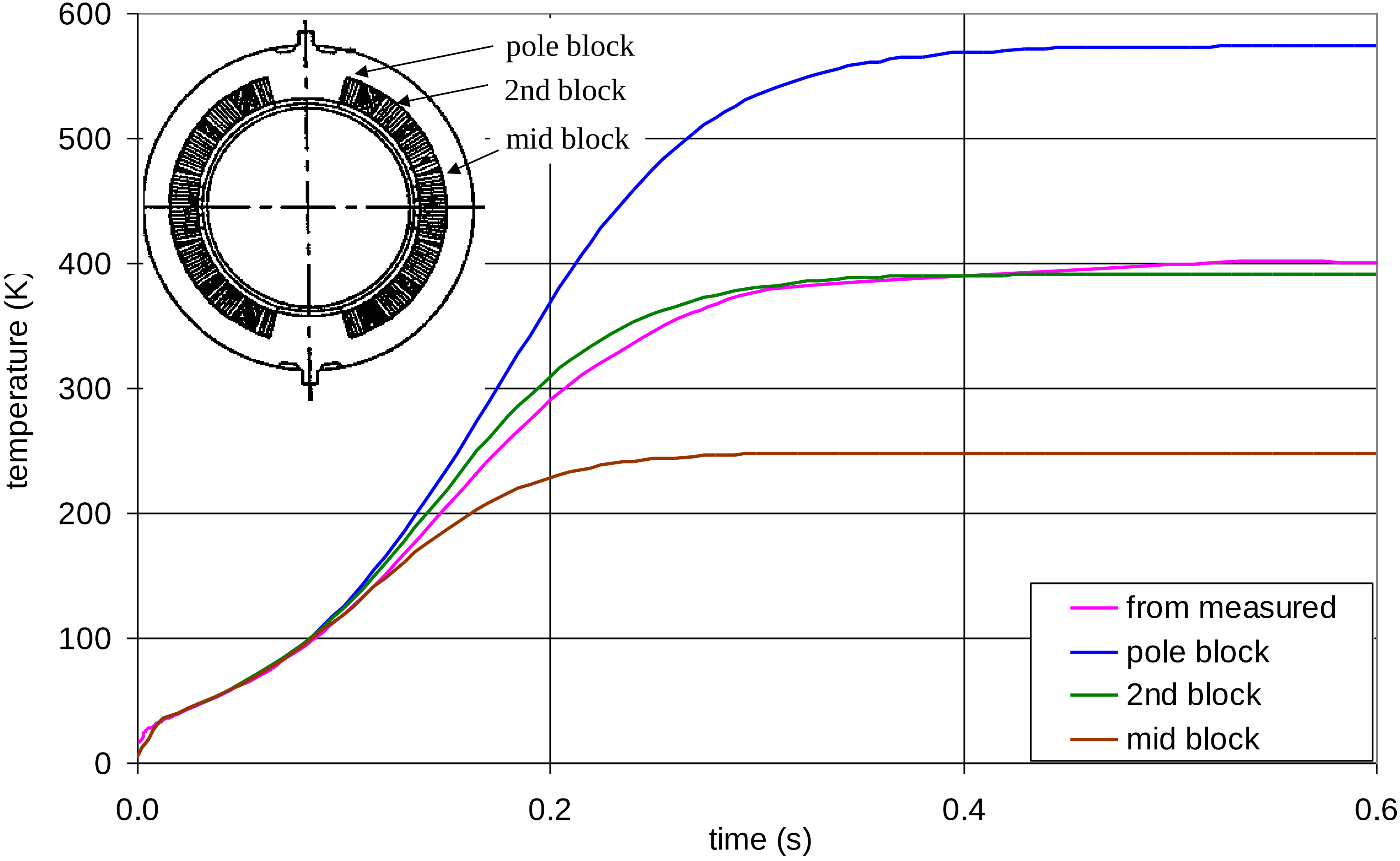
Quench starts in the mid plane



Computer simulation of quench (dipole GSI001)

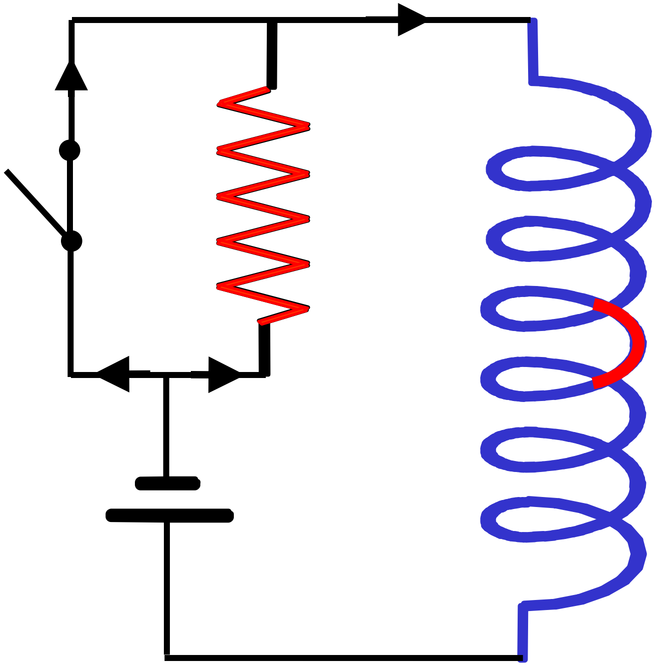


Computer simulation of quench temperature rise



Methods of quench protection:

1) external dump resistor



- detect the quench electronically
- open an external circuit breaker
- force the current to decay with a time constant

$$I = I_o e^{-\frac{t}{\tau}} \qquad \text{where} \qquad \tau = \frac{L}{R_p}$$

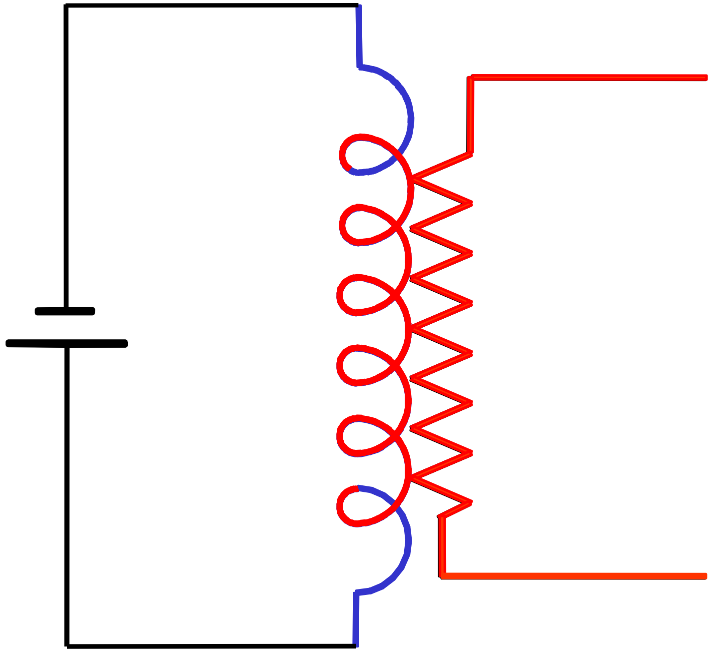
- calculate θ_{max} from

$$\int J^2 dt = J_o^2 \frac{\tau}{2} = U(\theta_m)$$

$$T_Q = \frac{\tau}{2}$$

Note: circuit breaker must be able to open at full current against a voltage $V = I.R_p$ (expensive)

Methods of quench protection:
2) quench back heater

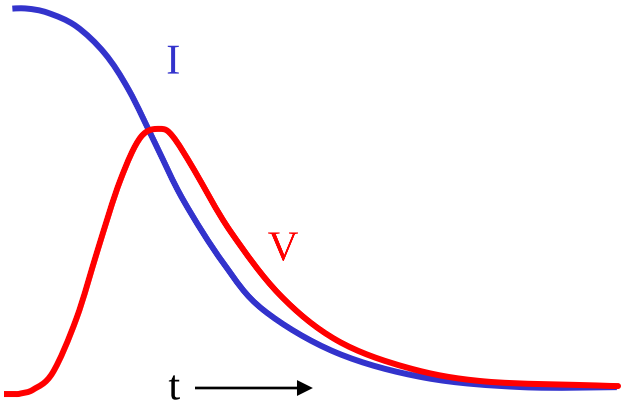


- detect the quench electronically
- power a heater in good thermal contact with the winding
- this quenches other regions of the magnet, effectively forcing the normal zone to grow more rapidly
  $\Rightarrow$ higher resistance
  $\Rightarrow$ shorter decay time
  $\Rightarrow$ lower temperature rise at the hot spot

Note: usually pulse the heater by a capacitor, the high voltages involved raise a conflict between:-
- ***good themal contact***
- ***good electrical insulation***

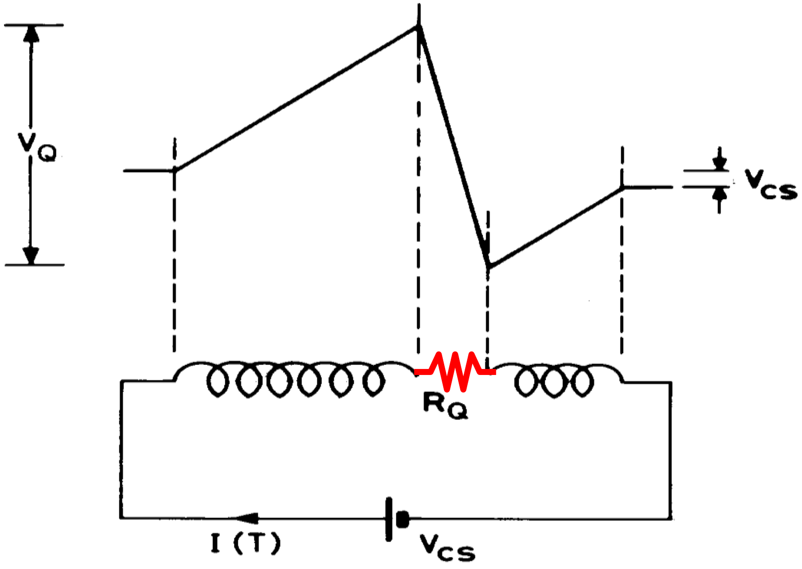
method most commonly used in accelerator magnets ✓

Methods of quench protection:
3) quench detection (a)



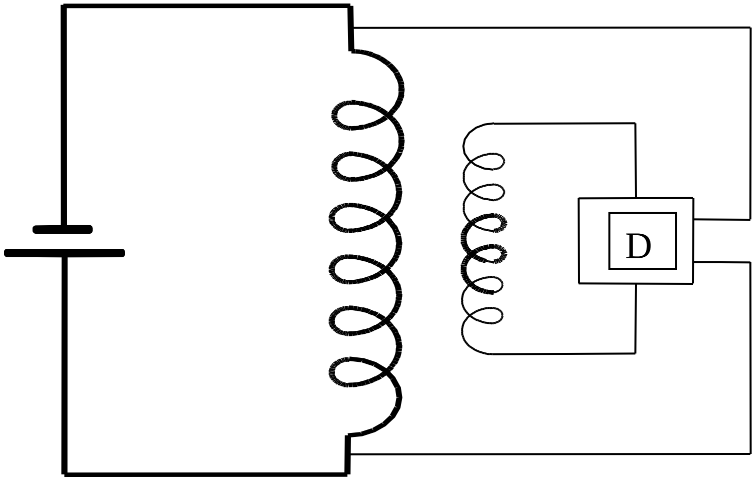
internal voltage after quench $V = IR_Q = -L\frac{dI}{dt} + V_{cs}$

- not much happens in the early stages - small $dI/dt \Rightarrow$ small V
- but important to act soon if we are to reduce T_Q significantly
- so must detect small voltage
- superconducting magnets have large inductance $\Rightarrow$ large voltages during charging
- detector must reject $V = L\,dI/dt$ and pick up $V = IR$
- detector must also withstand high voltage - **as must the insulation**



Methods of quench protection:
3) quench detection (6)

i) Mutual inductance



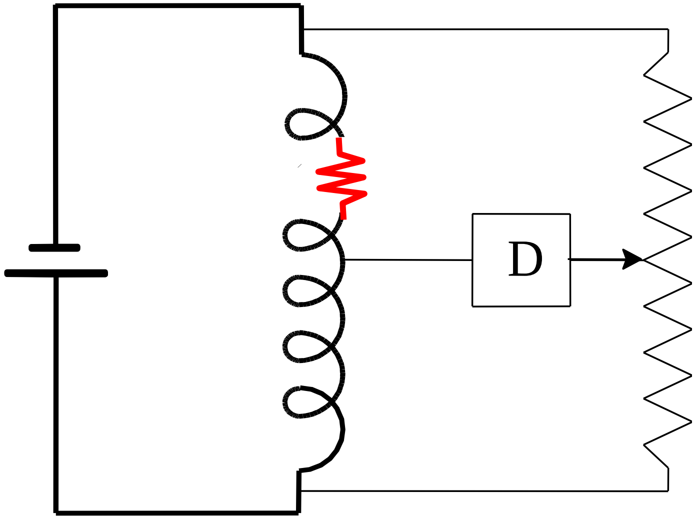
detector subtracts voltages to give

$$V = L\frac{di}{dt} + IR_Q - M\frac{di}{dt}$$

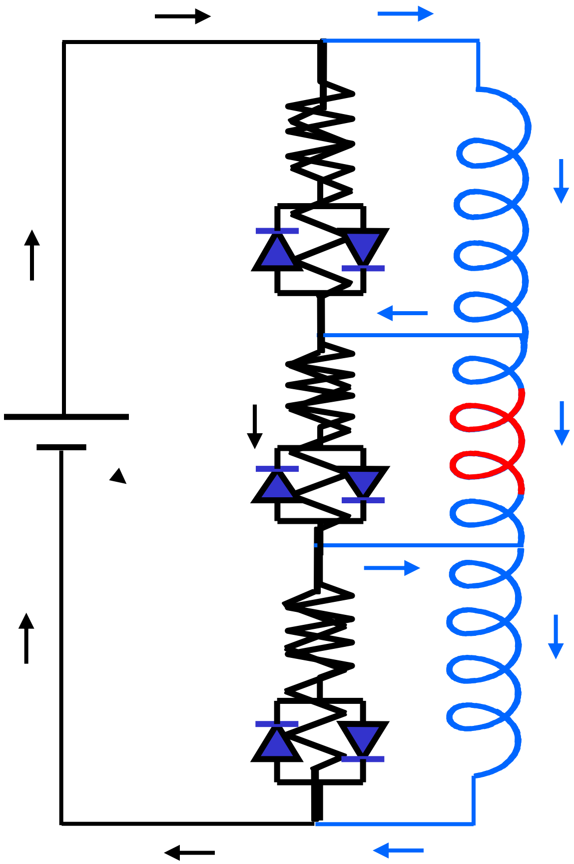
- adjust detector to effectively make $L = M$
- M can be a toroid linking the current supply bus, but must be linear - no iron!

ii) Balanced potentiometer

- adjust for balance when not quenched
- unbalance of resistive zone seen as voltage across detector D
- if you worry about symmetrical quenches connect a second detector at a different point



Methods of quench protection: 4) Subdivision



- resistor chain across magnet - cold in cryostat
- current from rest of magnet can by-pass the resistive section
- effective inductance of the quenched section is reduced

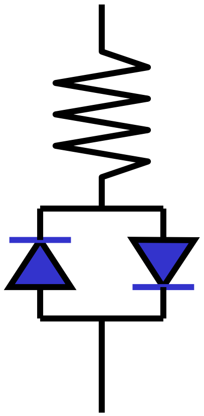
  ⇒ reduced decay time

  ⇒ reduced temperature rise

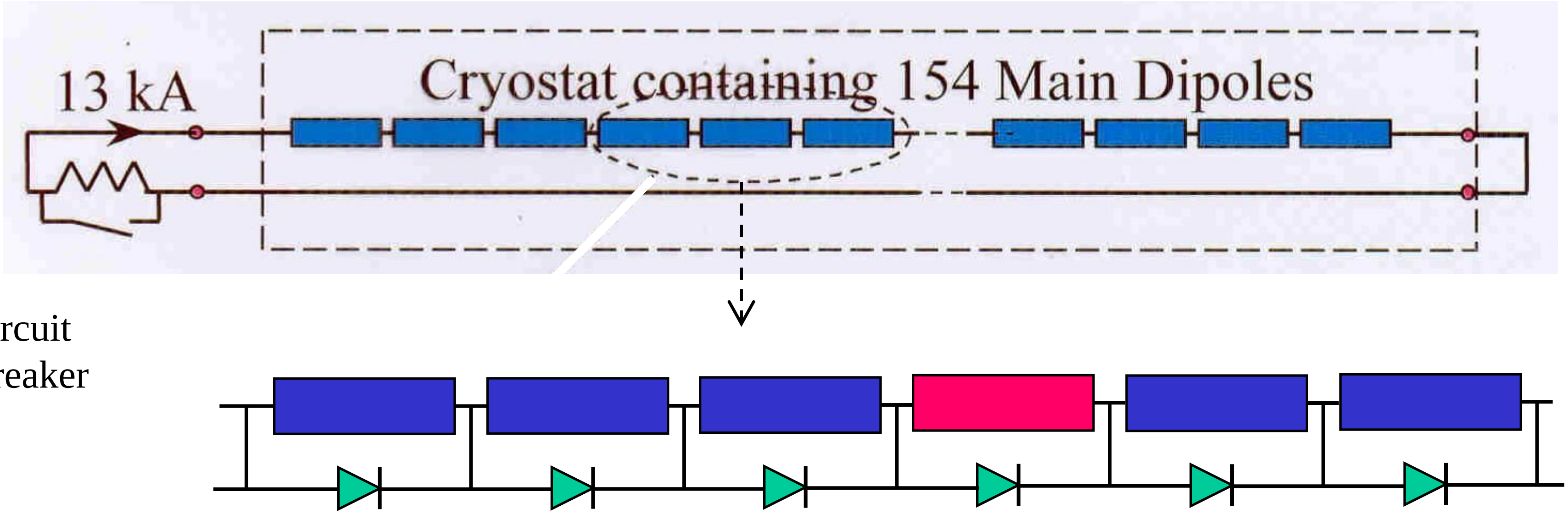
- current in rest of magnet increased by mutual inductance

  ⇒ quench initiation in other regions

- often use cold diodes to avoid shunting magnet when charging it
- diodes only conduct (forwards) when voltage rises to quench levels
- connect diodes 'back to back' so they can conduct (above threshold) in either direction



LHC power supply circuit for one octant

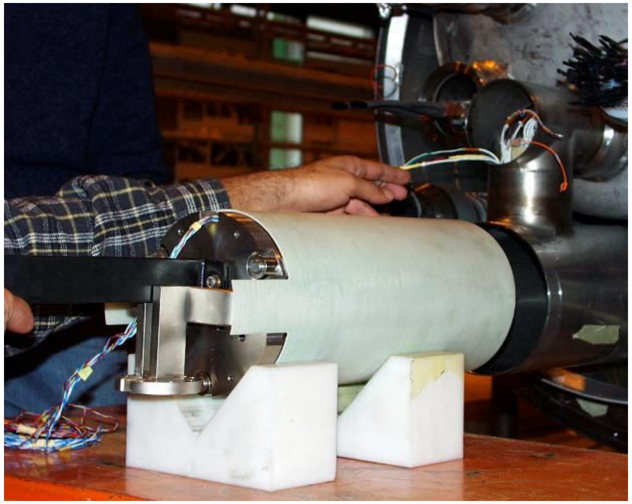


circuit
breaker

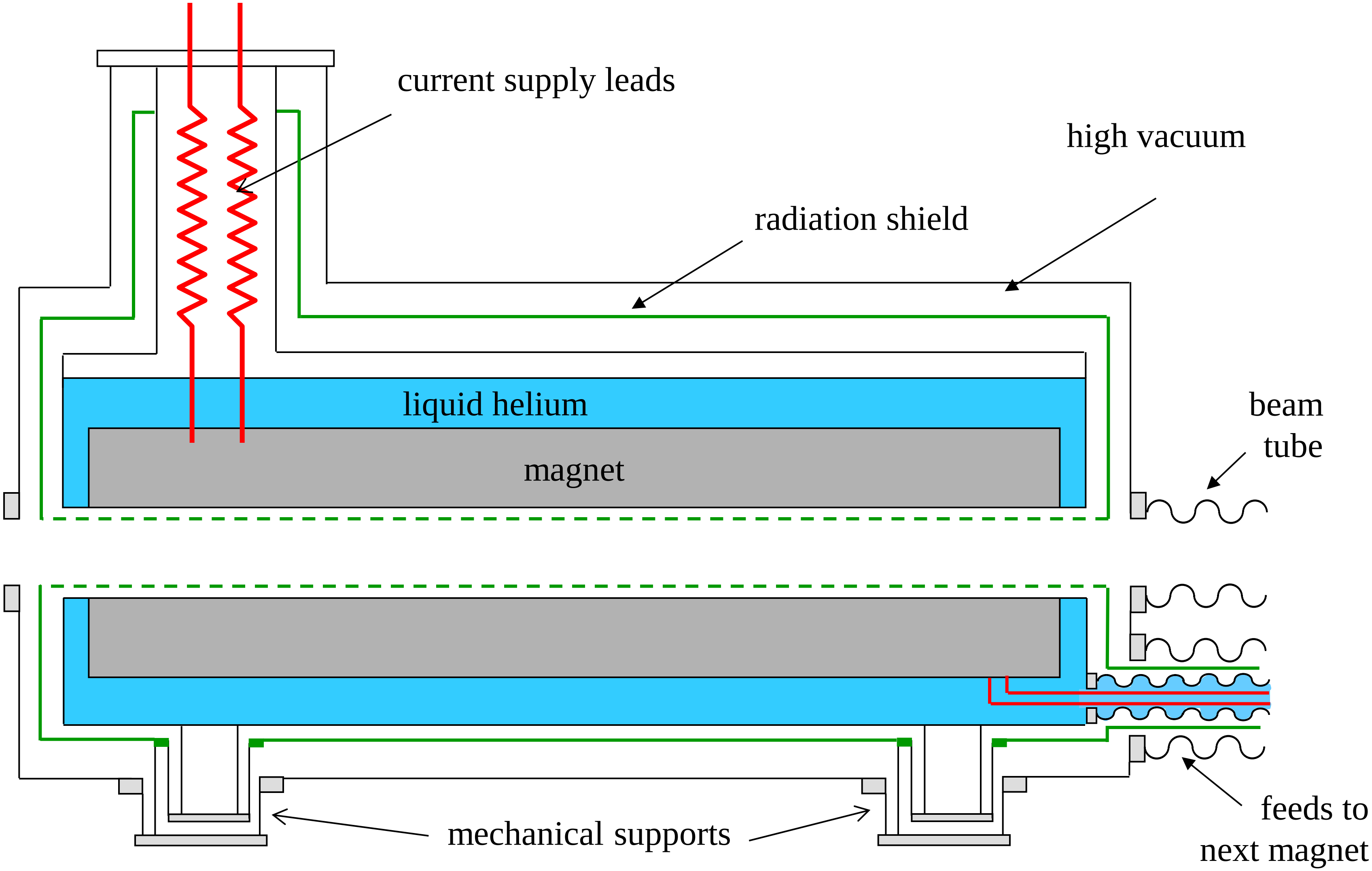
- diodes allow the octant current to by-pass the magnet which has quenched
- circuit breaker reduces to octant current to zero with a time constant of 100 sec
- initial voltage across breaker = 2000V
- stored energy of the octant = 1.33GJ

Diodes to by-pass the main ring current

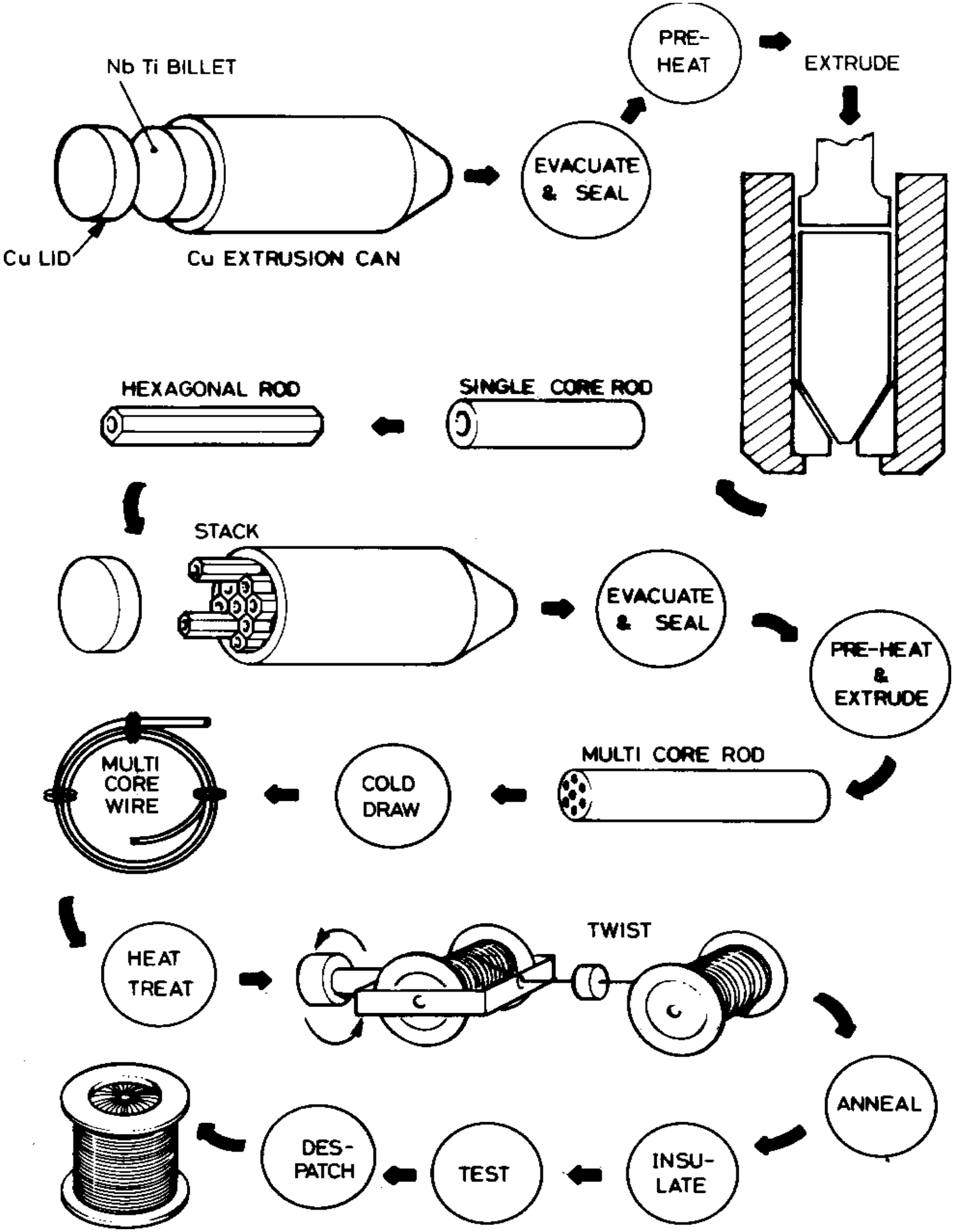
Installing the cold diode package on the end of an LHC dipole



Cryostat essentials



Manufacture of NbTi

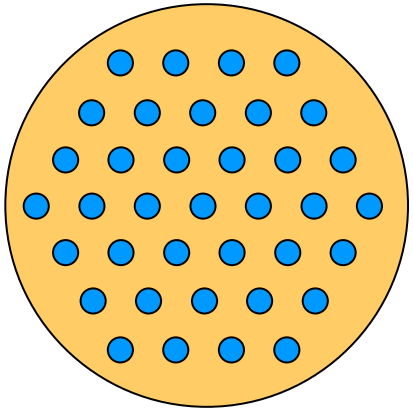


- vacuum melting of NbTi billets
- hot extrusion of copper NbTi composite
- sequence of cold drawing and intermediate heat treatments to precipitate αTi phases as flux pinning centres
- for very fine filaments, must avoid the formation of brittle CuTi intermetallic compounds during heat treatment
  - usually done by enclosing the NbTi in a thin Nb shell
- twisting to avoid coupling - recap lecture 2

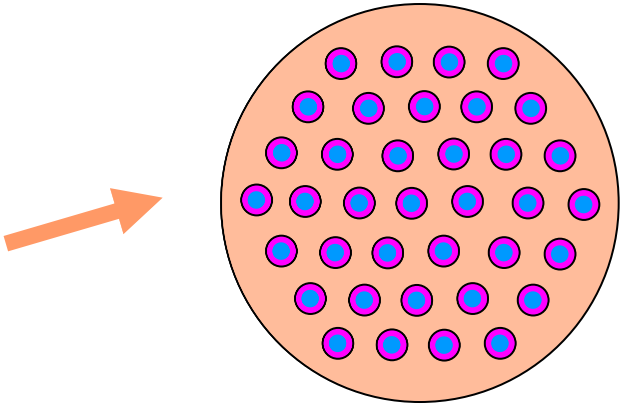
Manufacture of filamentary Nb_3Sn wire

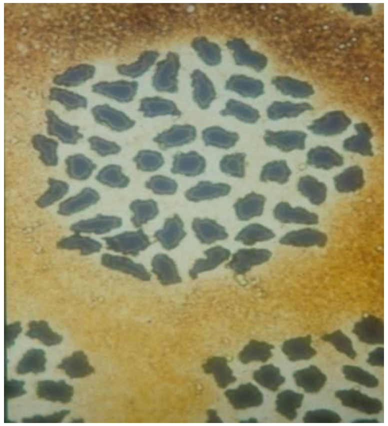
Because Nb_3Sn is a brittle material, it cannot be drawn down in final form.

Instead we must draw down pure niobium in a matrix of bronze (copper tin)

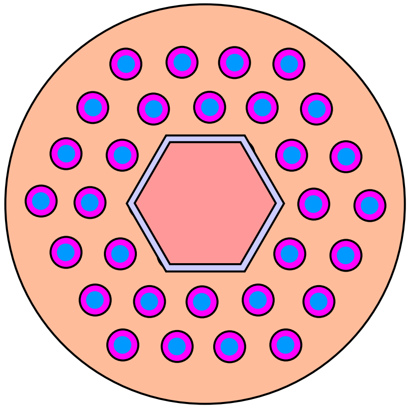


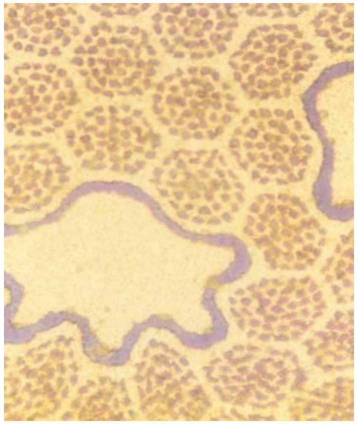
At final size the wire is heated (~700C for some days) tin diffuses through the Cu and reacts with the Nb to form Nb_3Sn





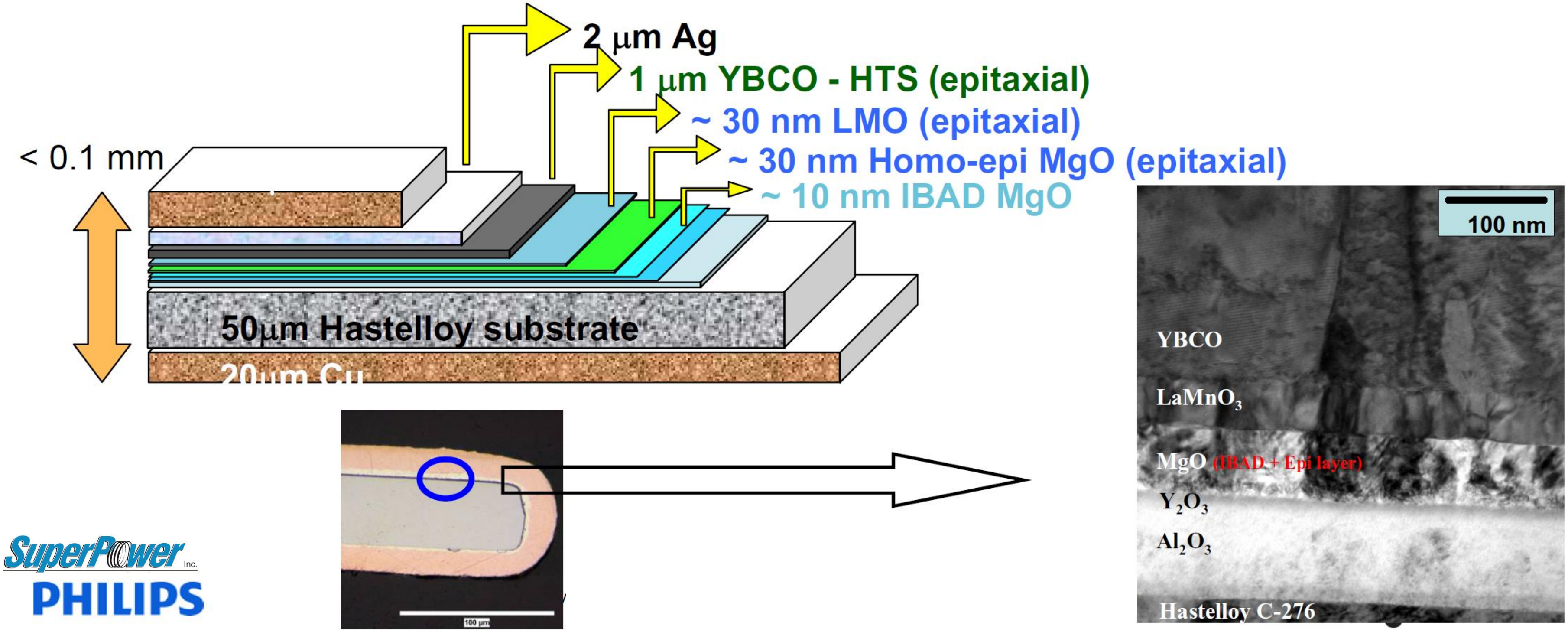
Unfortunately the remaining copper still contains some tin and has a high resistivity. We therefore include 'islands' of pure copper surrounded by a diffusion barrier





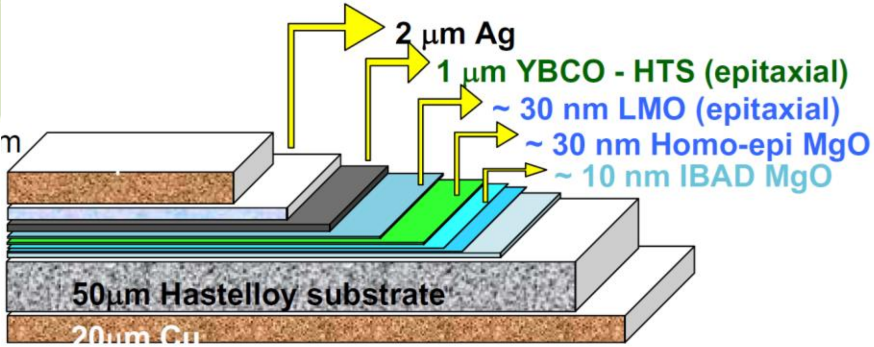
Coated YBCO tape

- YBCO has the best irreversibility field, but it is very sensitive to grain boundary misalignment
- the grains do not line up naturally - they must be persuaded
- deposit YBCO on a substrate where the grains are aligned and the lattice roughly matches YBCO



SuperPower Inc.
PHILIPS

YBCO coated tape at SuperPower Inc.



2 μm Ag

1 μm YBCO - HTS (epitaxial)

~ 30 nm LMO (epitaxial)

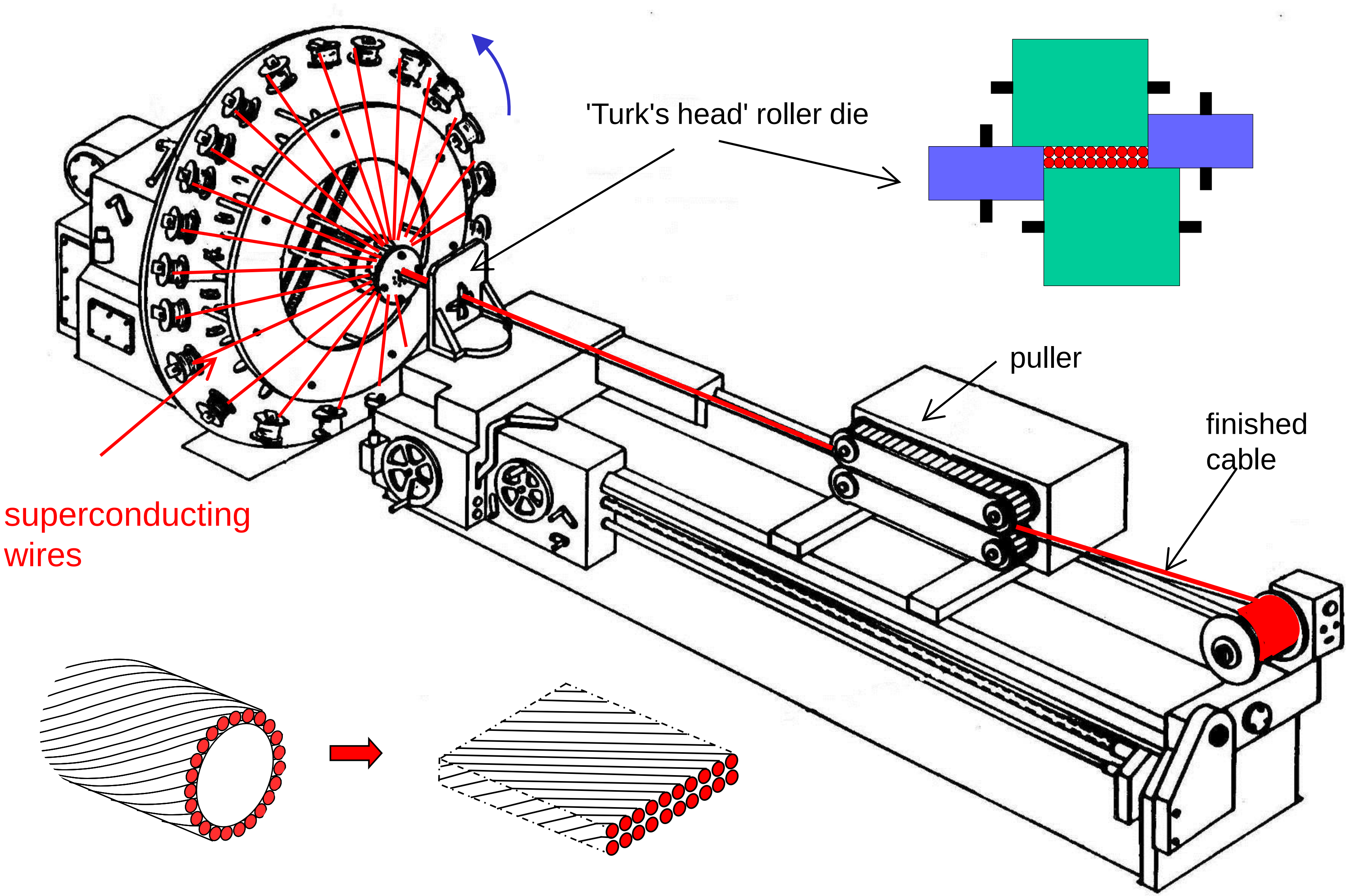
~ 30 nm Homo-epi MgO

~ 10 nm IBAD MgO

50μm Hastelloy substrate

20μm Cu

Manufacture of Rutherford cable



Winding the LHC dipoles

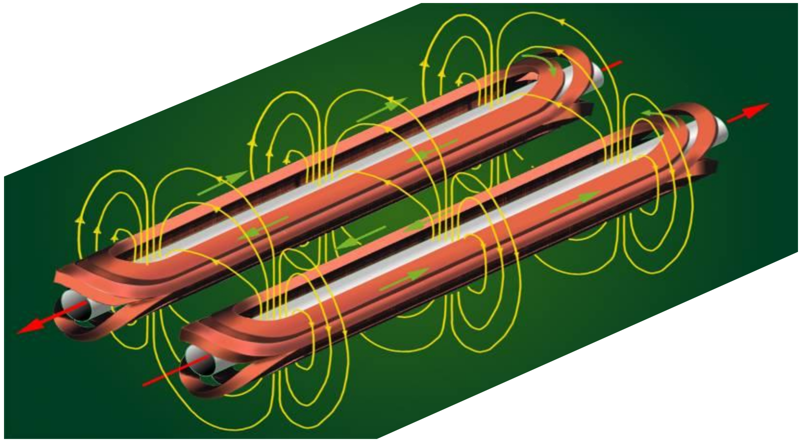
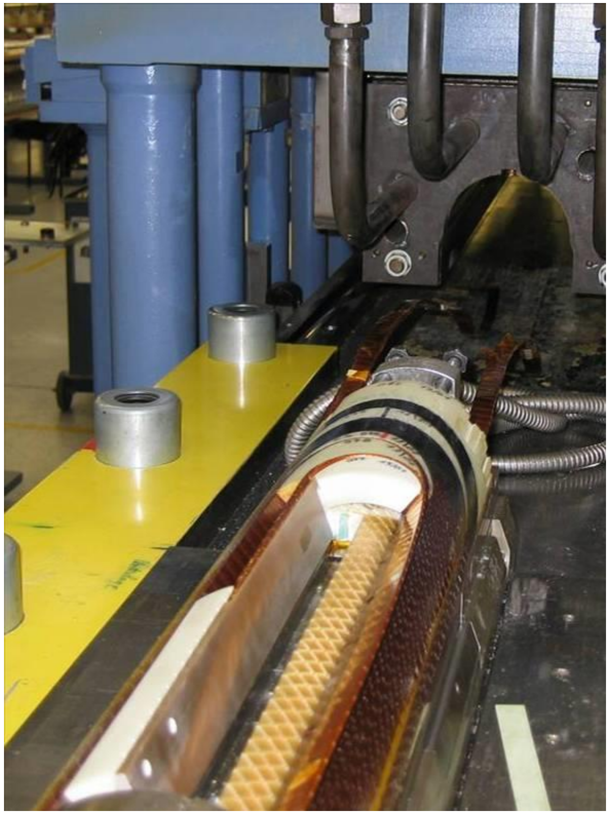
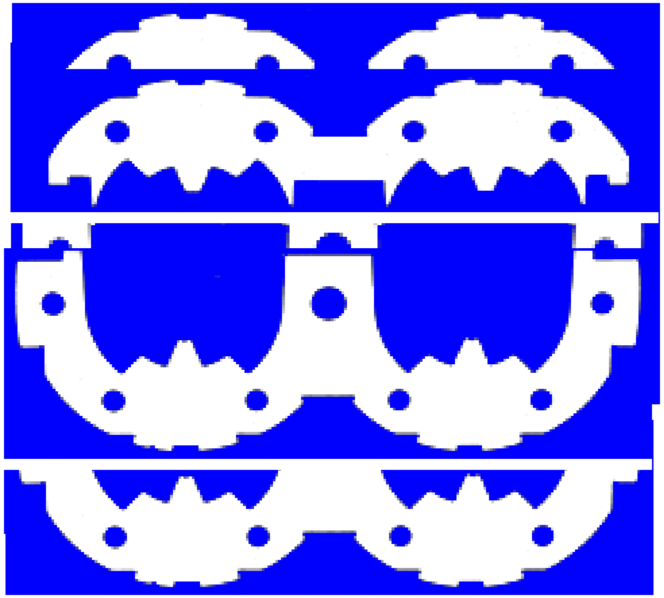


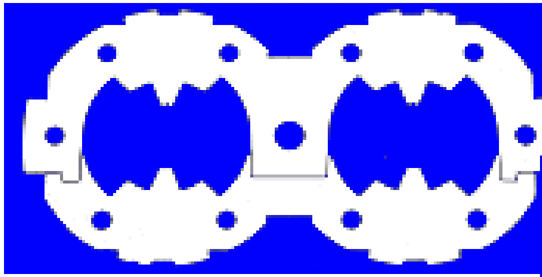
photo courtesy of Babcock Noell

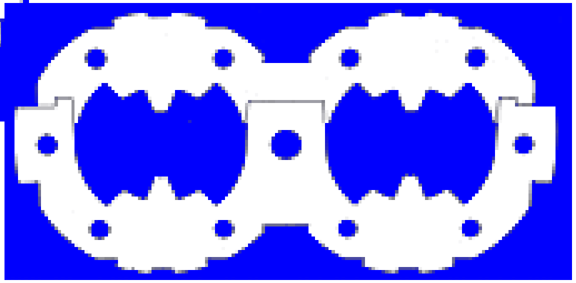


Collars to support magnetic forces

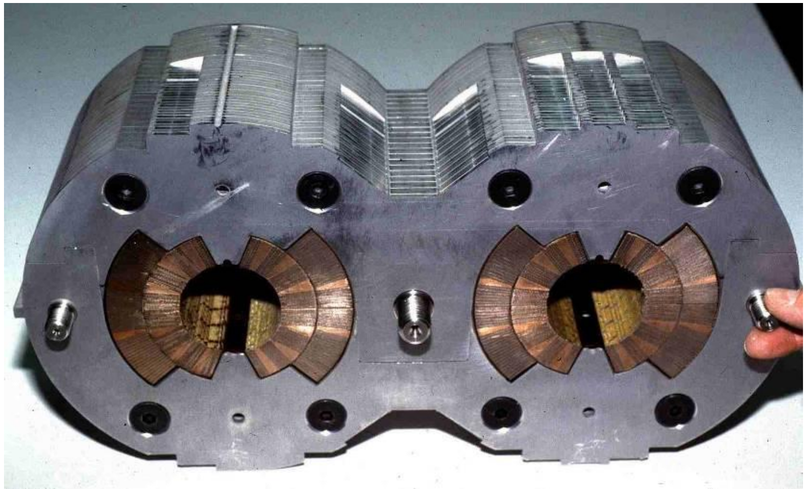


- field quality depends on coil shape - define accurately
- collars stamped from stainless steel plate a few mm thick



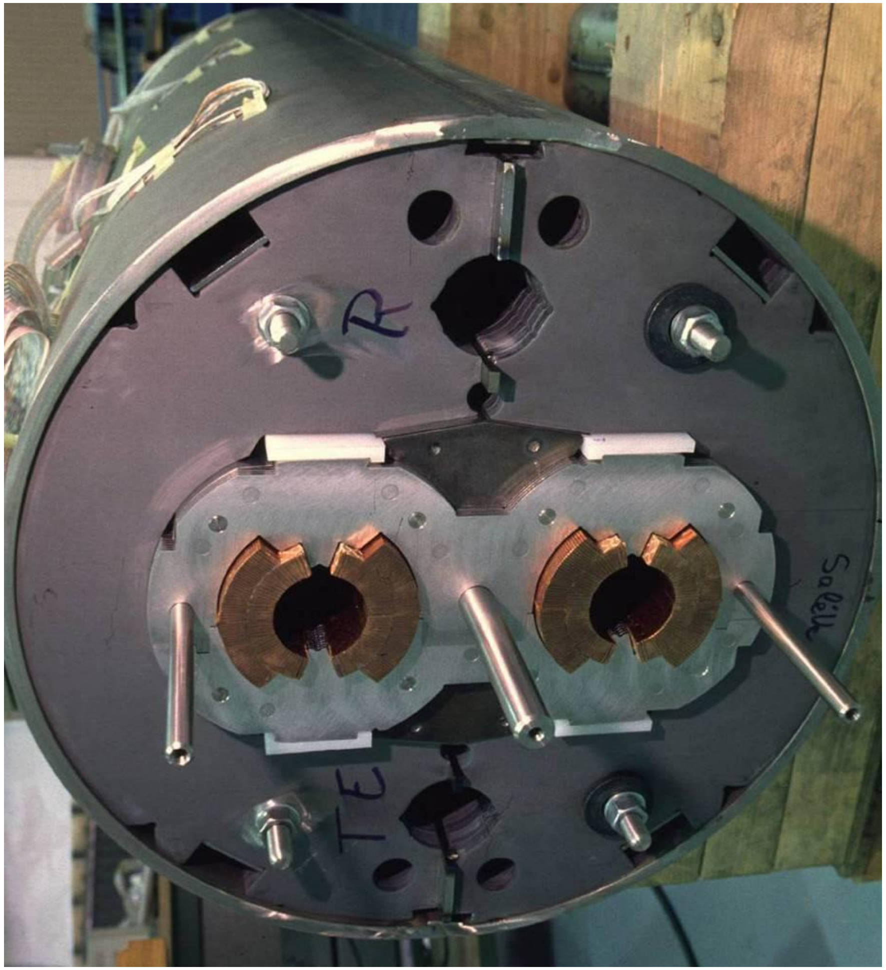


- alternate up/down and push in locking pins



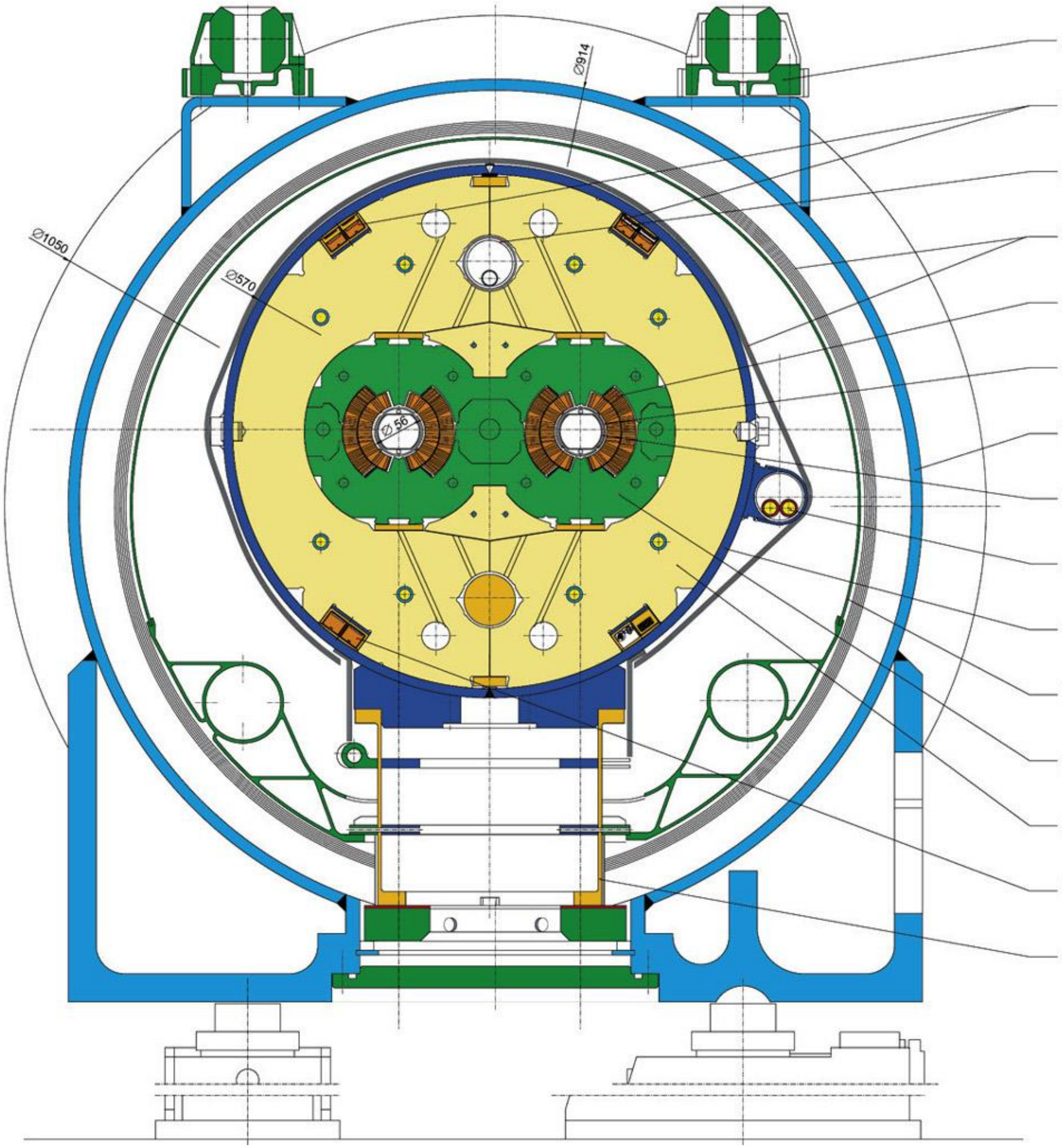
Adding the iron

enclosed and compressed by the stainless steel helium vessel



LHC DIPOLE : STANDARD CROSS-SECTION

CERN AC/DI/MM - HE107 - 30 04 1999



ALIGNMENT TARGET

MAIN QUADRIPOLE BUS-BARS

HEAT EXCHANGER PIPE

SUPERINSULATION

SUPERCONDUCTING COILS

BEAM PIPE

VACUUM VESSEL

BEAM SCREEN

AUXILIARY BUS-BARS

SHRINKING CYLINDER / HE I-VESSEL

THERMAL SHIELD (55 to 75K)

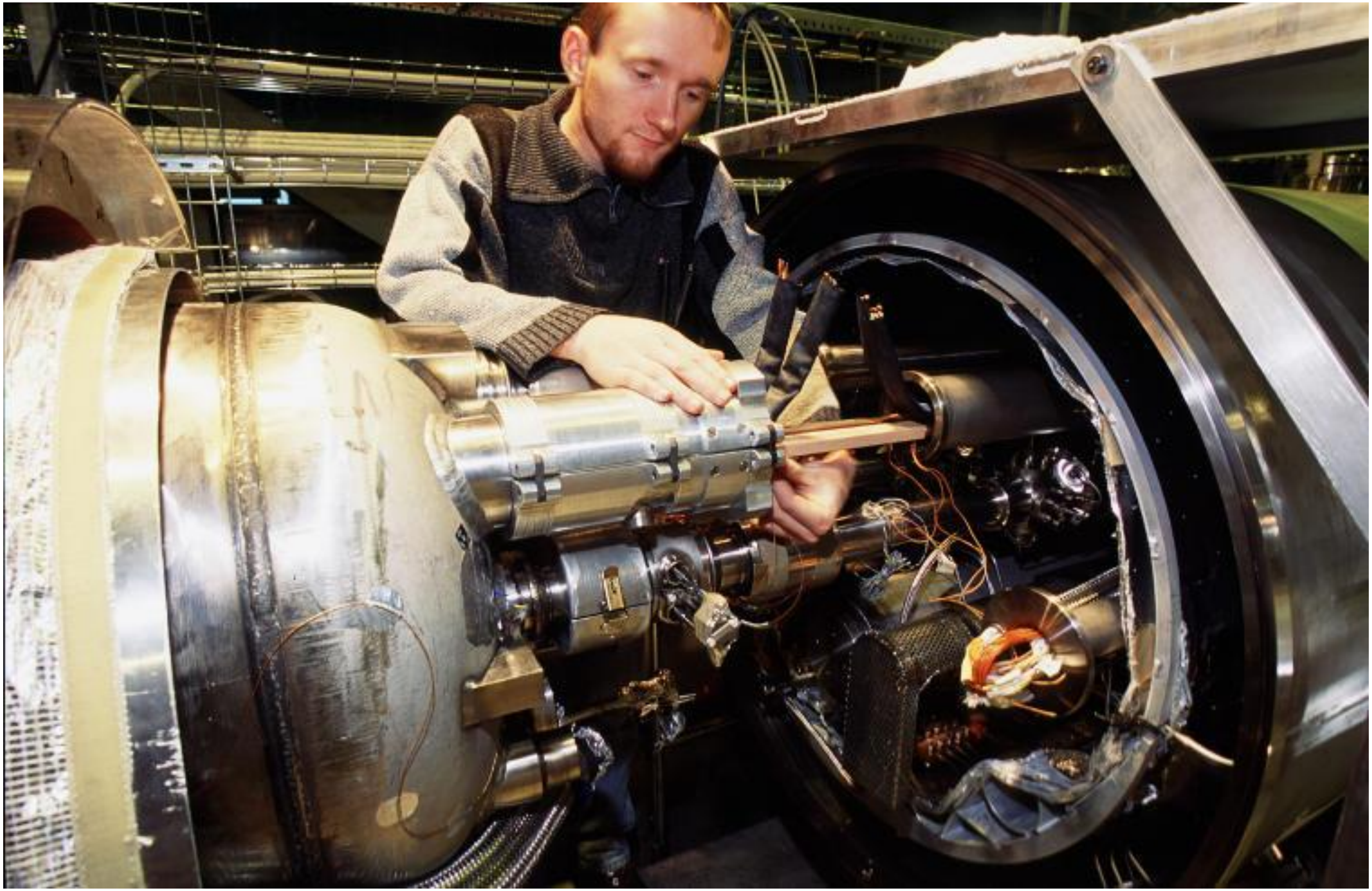
NON-MAGNETIC COLLARS

IRON YOKE (COLD MASS, 1.9K)

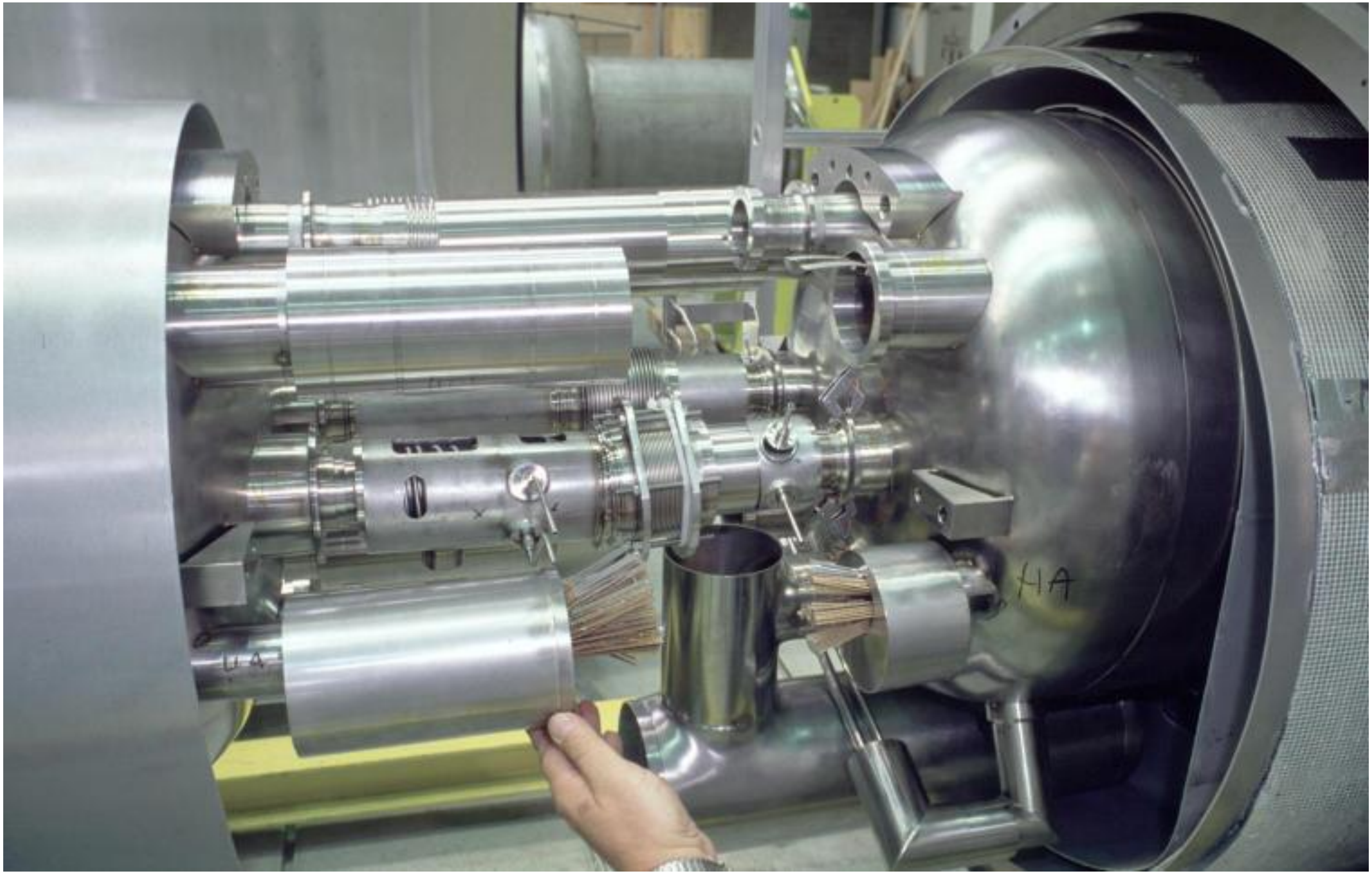
DIPOLE BUS-BARS

SUPPORT POST

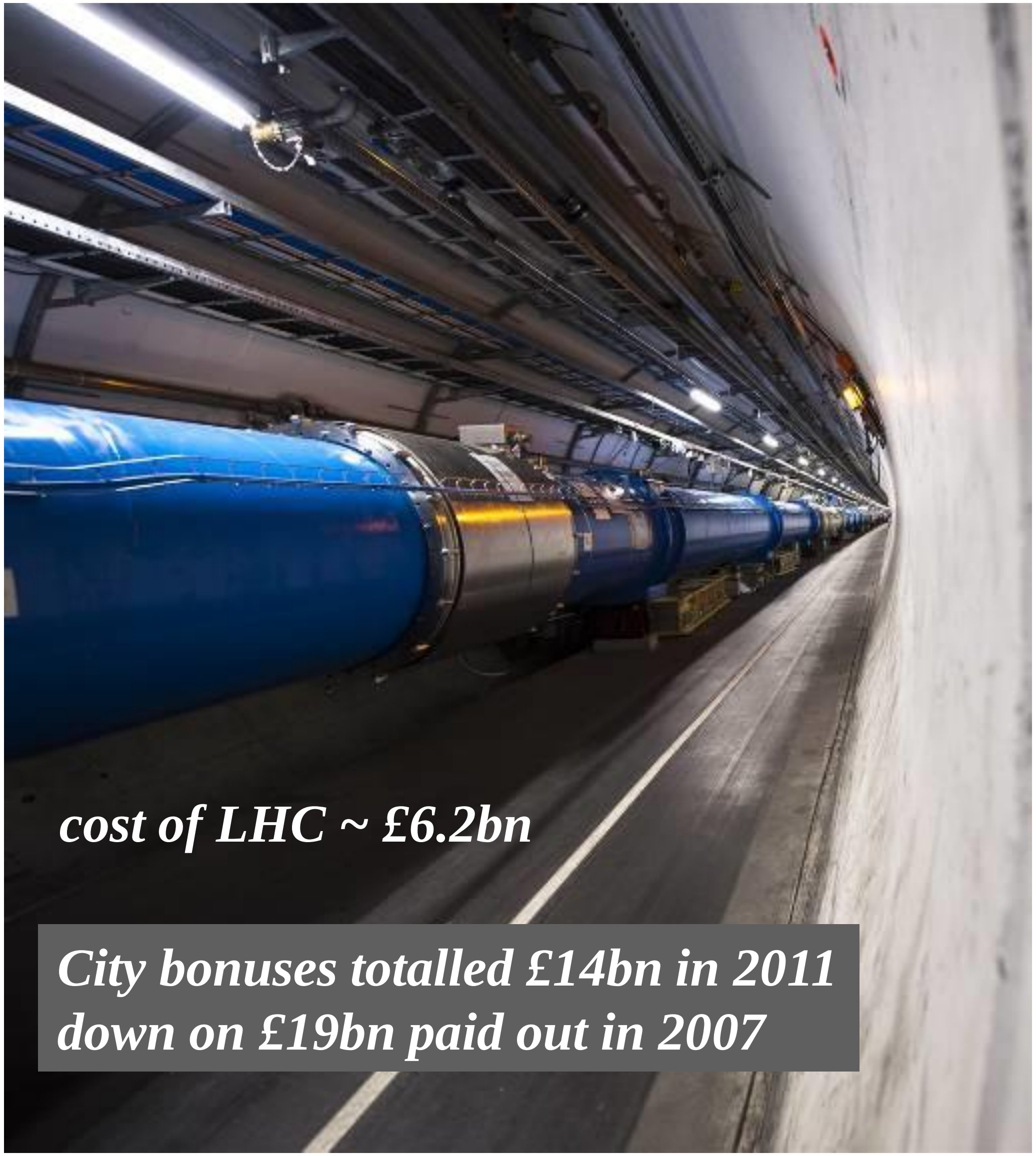
Make the interconnections - electrical



Make interconnections - cryogenic



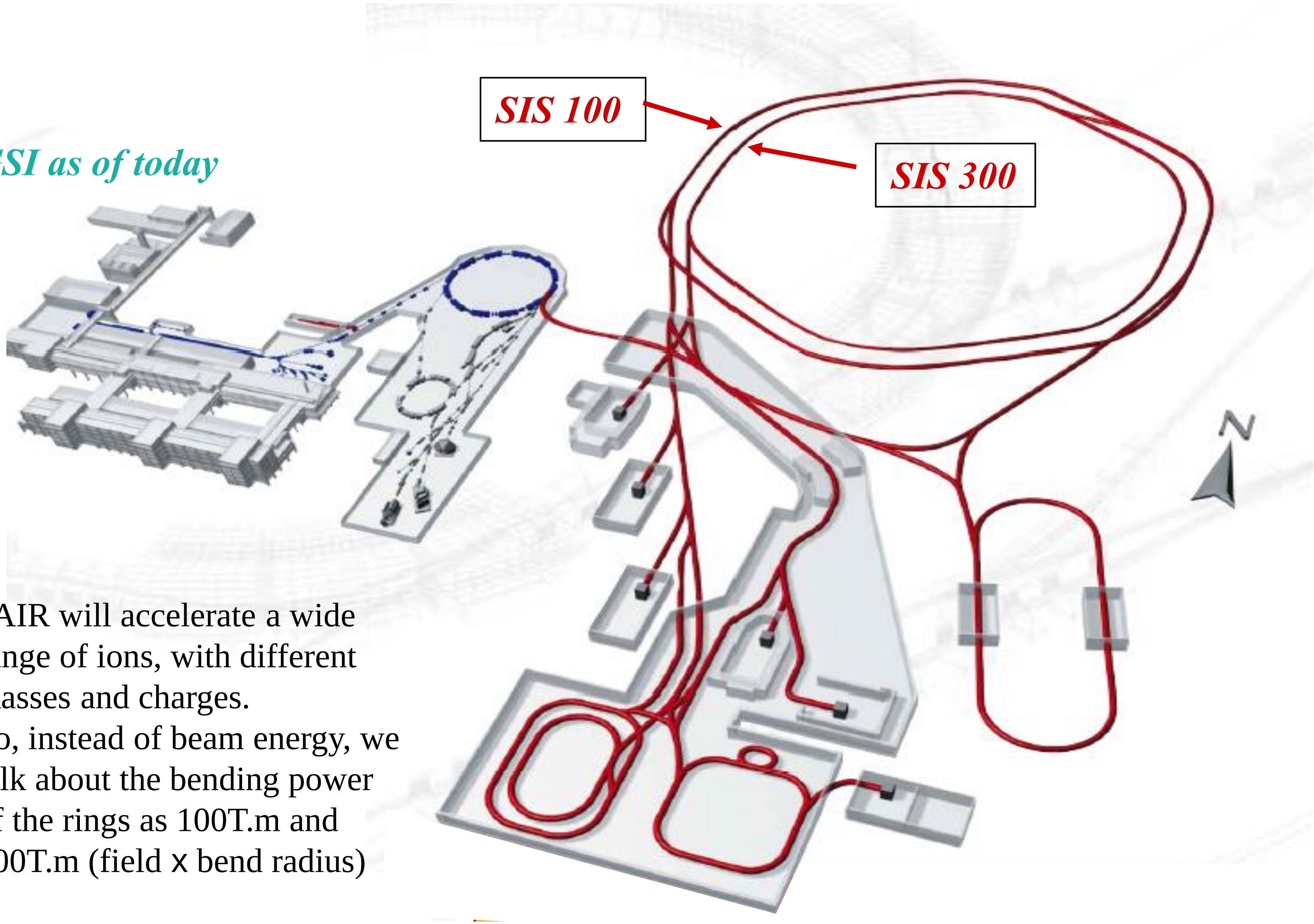
The Large Hadron Collider



cost of LHC ~ £6.2bn

City bonuses totalled £14bn in 2011 down on £19bn paid out in 2007

Facility for Antiproton and Ion Research FAIR

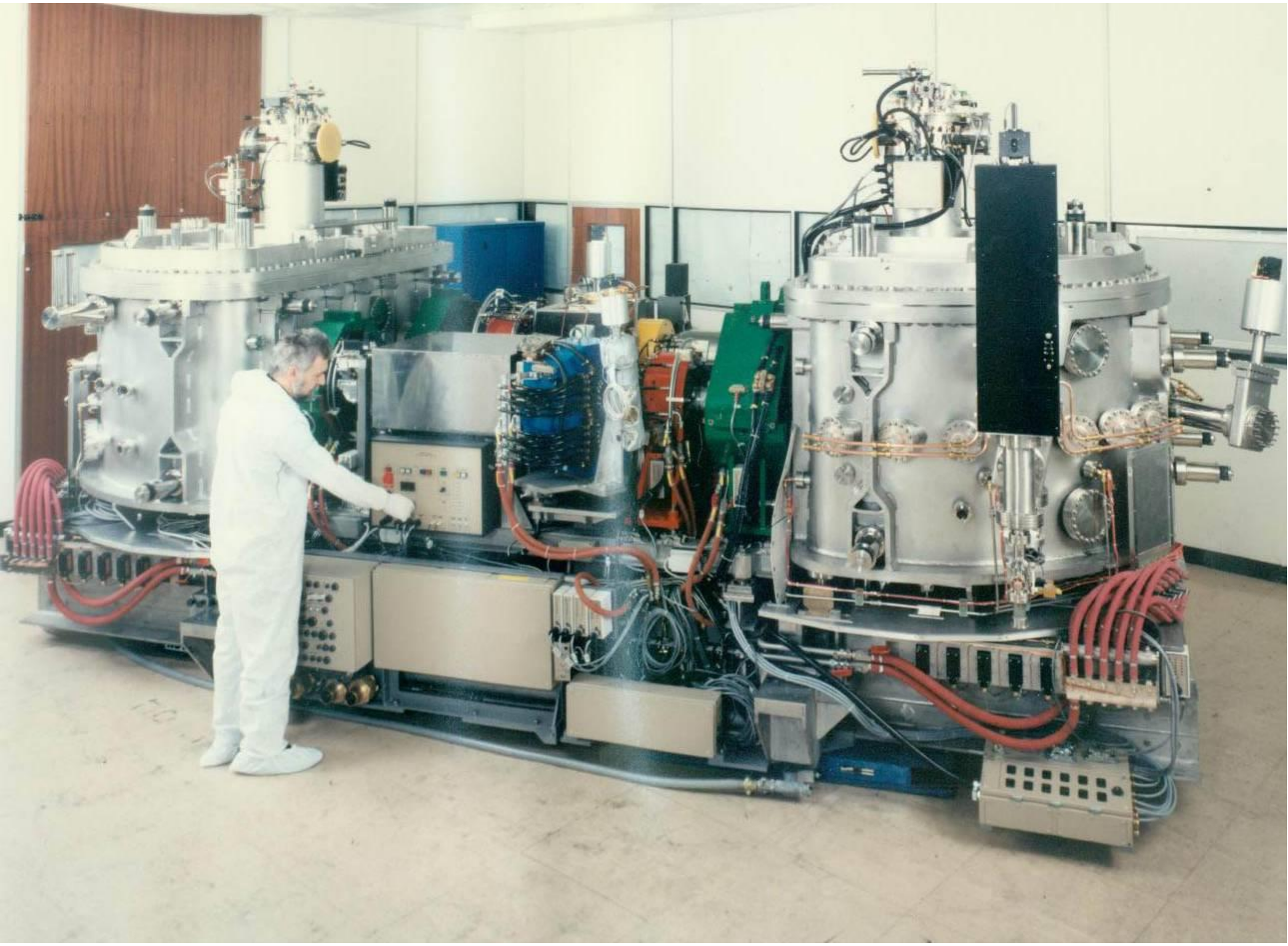


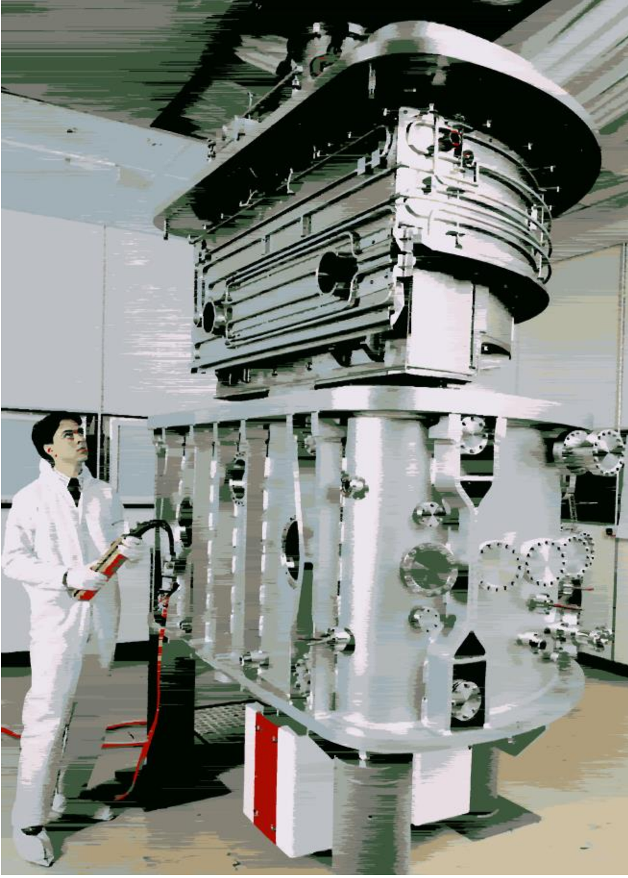
FAIR will accelerate a wide range of ions, with different masses and charges.
So, instead of beam energy, we talk about the bending power of the rings as 100T.m and 300T.m (field x bend radius)

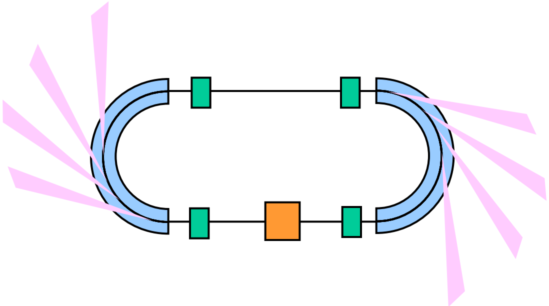
Winding curved dipoles for FAIR

Helios

compact electron synchrotron X-ray source for microchip lithography

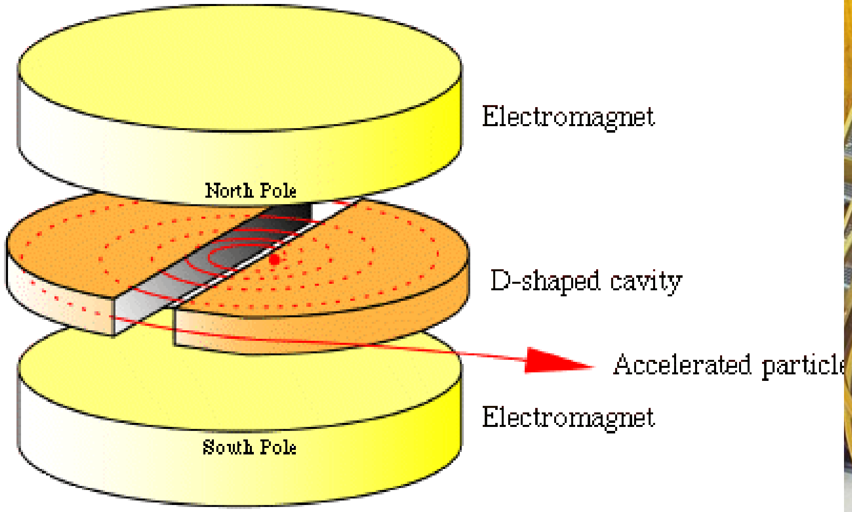




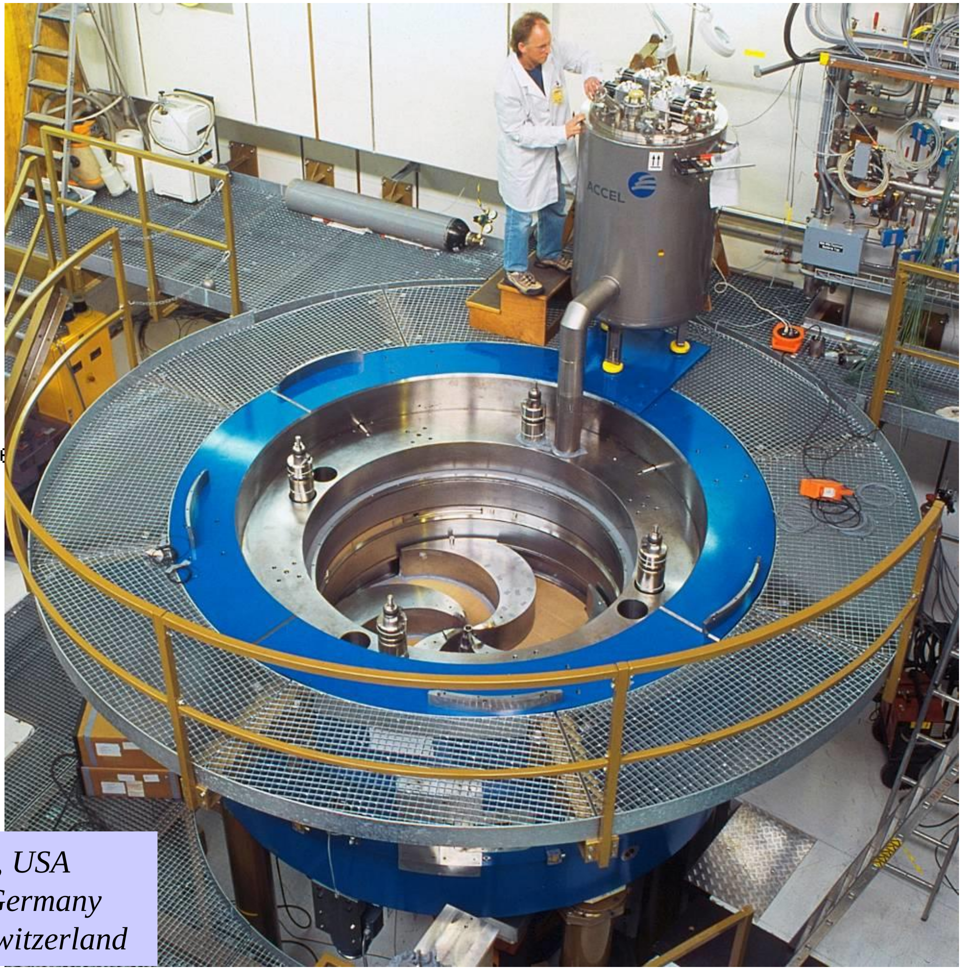


Cyclotrons

- constant magnetic field so particles spiral out as their energy increases
- cw operation ⇒ high beam current
- large magnet but no ac loss



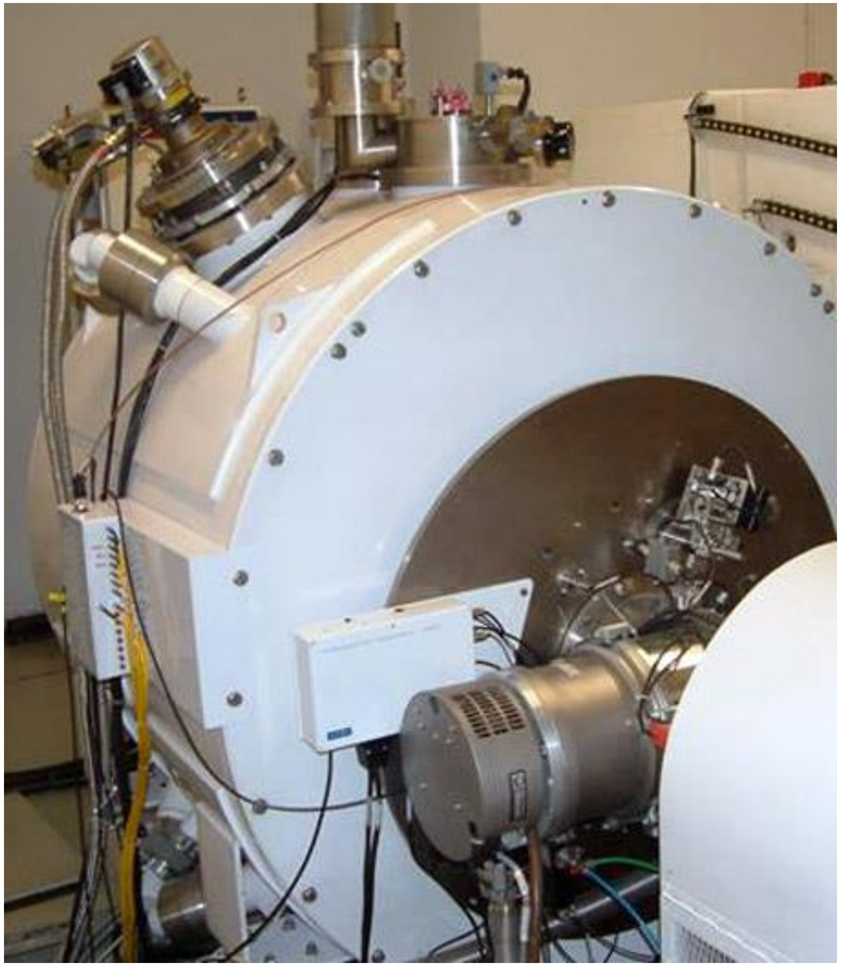
- cyclotrons are increasingly being used for cancer therapy

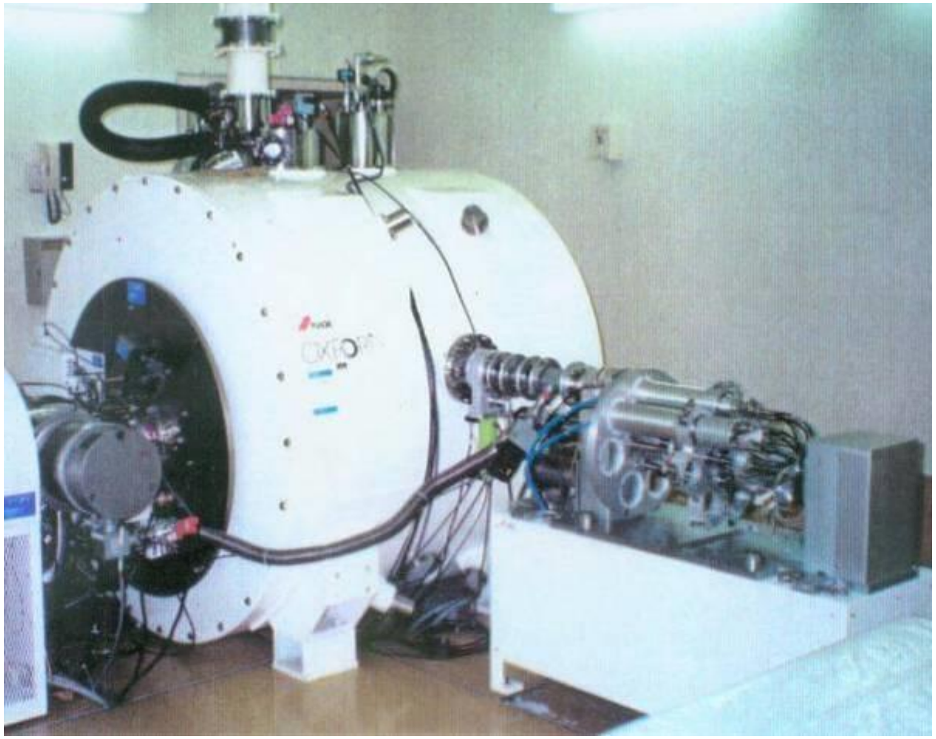


design by Michigan State University, USA
manufactured by ACCEL (Varian), Germany
installed at Paul Scherrer Institut, Switzerland

Oscar ⇒ Isotrace

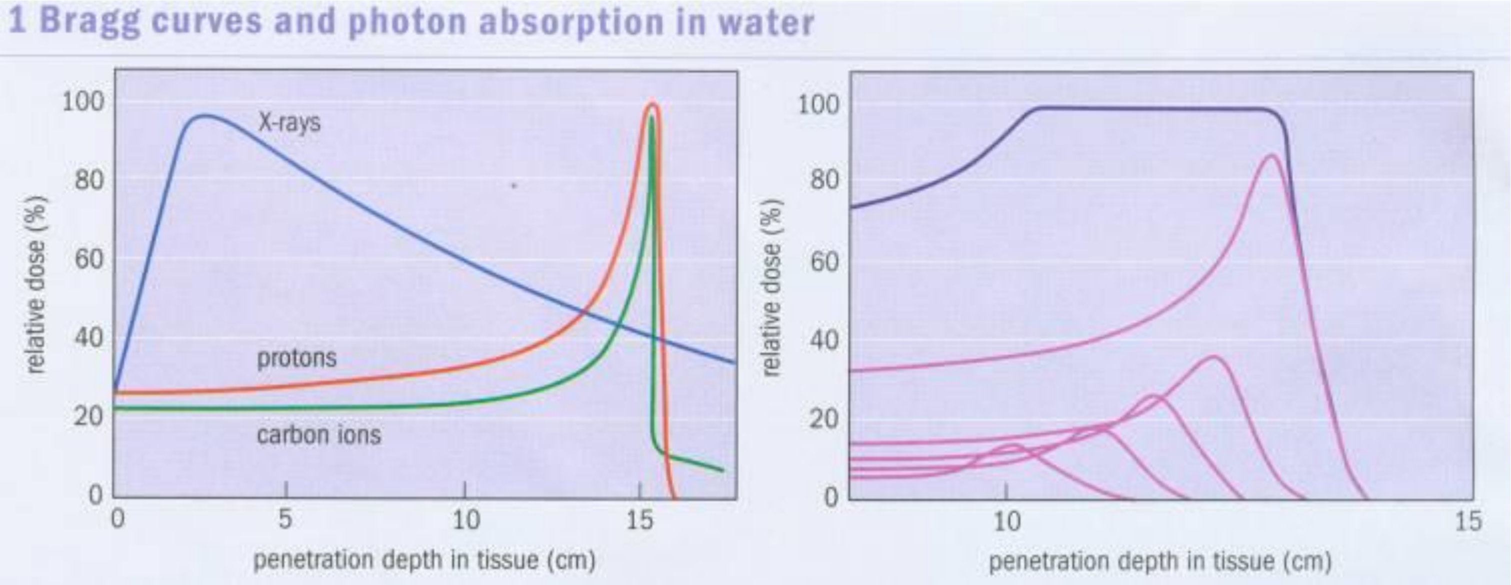
- 11 MeV superconducting cyclotron developed by Oxford Instruments
- proton beam used to produce short lived isotopes for use in positron emission tomography PET imaging



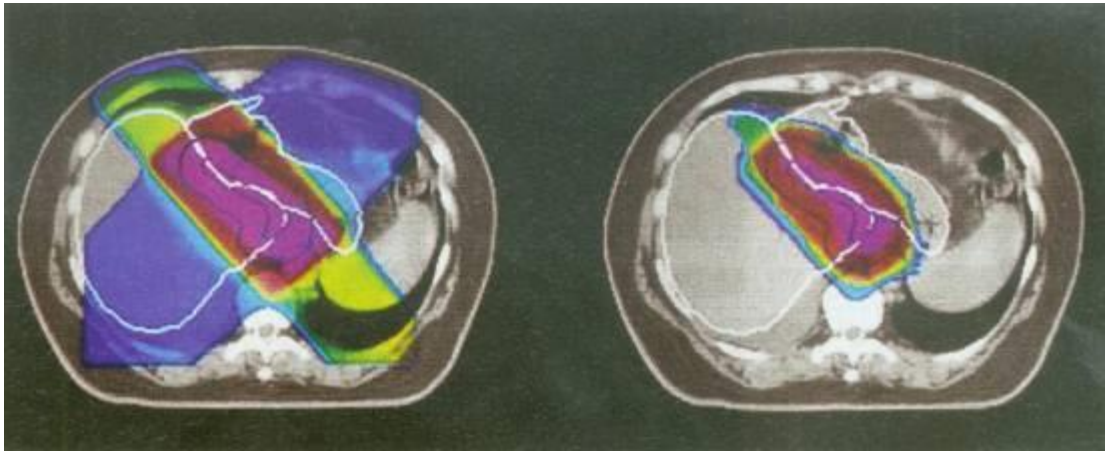


- design acquired by Alcen and marketed as the Isotrace cyclotron

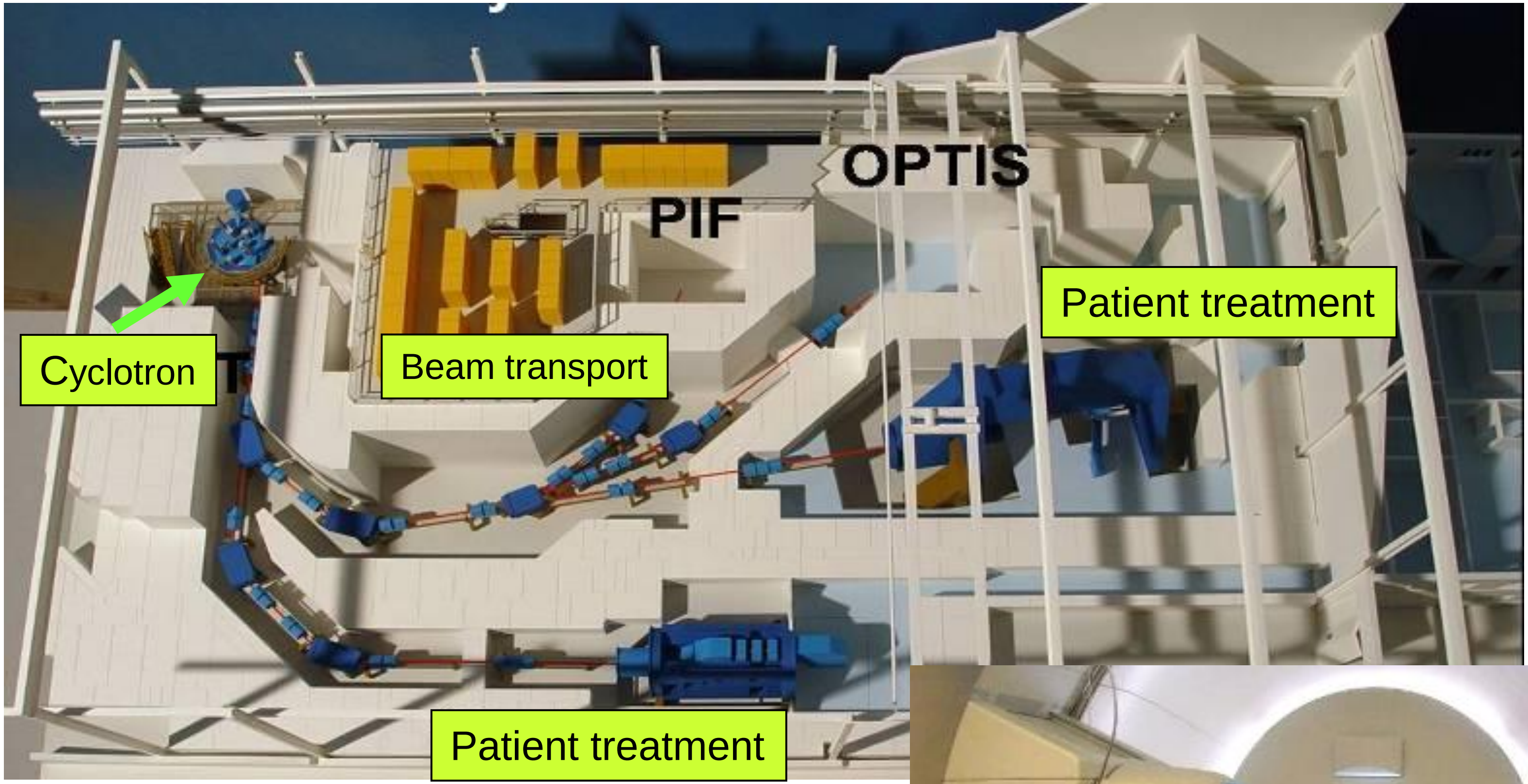
Cancer therapy by charged particle beams


1 Bragg curves and photon absorption in water

- photons (X-rays) deposit most energy at surface (skin)
- protons deposit most energy at depth
- adjust energy to make depth = tumour
- carbon ions are even better



Layout of a Proton therapy Facility



- Cyclotron: produces 250MeV protons
- Beam transport: selects the right energy and guides proton beam to patient
- Patient treatment gantry: scans the beam over the patient

Concluding remarks

Quenching

- magnets store large amounts of energy - during a quench this energy gets dumped in the winding
  ⇒ intense heating (*J* ~ fuse blowing) ⇒ possible death of magnet
- temperature rise and internal voltage can be calculated from the current decay time
- computer modelling of the quench process gives an estimate of decay time
  – but must first decide where the quench starts
- if temperature rise is too much, must use a protection scheme - active or passive
- protection of accelerator magnets is made much more difficult by their series connection

always do the quench calculations before testing the magnet ✓

Hardware

- helium doesn't want to be a liquid - a lot of technology needed to keep it so - cryogenics
- manufacture of NbTi and Nb3Sn filamentary wires is a routine industrial process ~ 10^{5} km per year
- BSCCO wires and textured YBCO tapes are a ‘semi industrial’ process ~ 10^{2} km per year
- Rutherford cable used in all superconducting accelerators to date
- in recent years the largest accelerators have all been superconducting – industrial scale of manufacture

thank you for your attention