Manufacturing and calibration of search coil

Part I – Manufacturing

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Contents

Introduction

Scope of the lectures

- Lectures on “manufacturing and calibration of instrumentation” focused essentially on **search coils**:

  - if one needs field integral for accelerator magnets this is the “best” sensor type:
    wide range of applicability, **high accuracy**, **cost-effective**
  - commercial options limited ⇒ users must often build and calibrate their own equipment
  - other important sensor category: Hall probes, treated in the lecture by S. Sanfilippo
  - specialized sensors (e.g. NMR, see lecture by L. Bottura) usually made and calibrated commercially

- Material drawn extensively (but not exclusively) from CERN experience

  - generations of specialists working on a very wide range of accelerators and magnets
  - hardware and know-how accumulated over more than 50 years

- Aim of the lectures:

  - share the experience …
  - give a broad overview of the subject + references
  - emphasis on practical aspects – skilled manual work involved

Acknowledgement

The lecture is based upon the work of a great many people, whose contributions are gratefully acknowledged:

- The team (at least, those I've personally met in the last 12 years …):

  R. Beltron Mercadillo, G. Busetta, R. Camus, R. Chritin, D. Cote, G. Deferne, O. Dunkel, J. Dutour, L. Gaborit, P. Galbraith, D. Giloteaux, F. Fischer, A. Musso, A. Ozturk, P. Leclere, S. Pauletta, S. Sanfilippo, N. Smirnov, L. Vuffray

- Former and current magnetic measurement team leaders:

  J. Billan , L. Bottura, D Cornuet, J. Garcia Perez, P. Sievers, L Walckiers

  J. Billan, "Search Coils for LHC Magnet Measurements", IMMW11, 1999, Brookhaven, NY

- Our colleagues from US: A. Jain (BNL) and J. Di Marco (Fermilab) for their contributions and useful discussions

- All the authors of the bibliography referenced and in particular the authors of lectures on the same topic at earlier CAS (M. Green, A. Jain, L. Walckiers)

  CAS - CERN Accelerator School : Magnet Measurements (1992)

  CAS - CERN Accelerator School: Measurement and alignment of accelerator and detector magnets (1997)

Requirements for search coils in accelerator magnets

- Detect magnetic field $B \propto \int V_{coil} dt$, *use directly*:
  - ✓ **Integral field** as an input for beam optics: strength, quality (homogeneity or harmonics), direction, axis, as $f(I, t, dI/dt, I(\tau \leq t))$

    or indirectly:
  - ✓ **Local harmonics as a QA tool** (e.g. individuation of winding defects in SC magnets)
  - ✓ **Quench Localization**: in SC magnets, localize longitudinal and transversal spot where a quench originates

- Main constraints:
  - ✓ Long and slender magnet gaps: up to 15 m long, Ø20~100 mm *(today …)*
  - ✓ Wide main field ranges, e.g. from few mT to 10 T *(SC magnets at room and nominal temperature)*
  - ✓ Typical accuracy: 10^{-4} (main field), 10^{-6} (field errors)

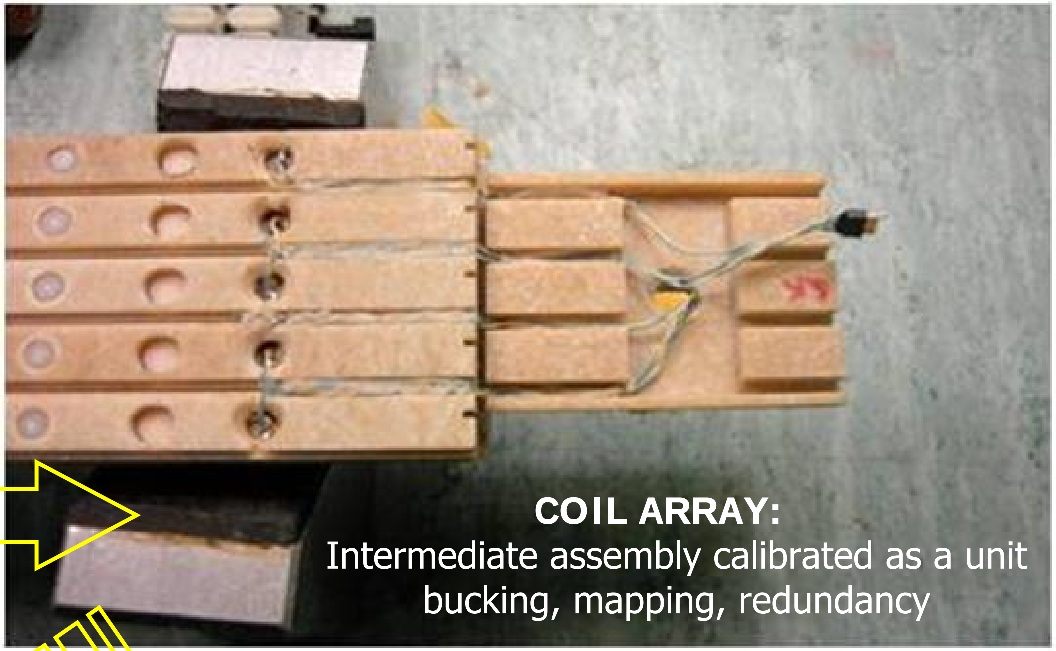
Long and slender line-integral coils are the natural choice

Harmonic coils give directly integral field in the format required by the beam $\{C_n = B_n + iA_n\}$

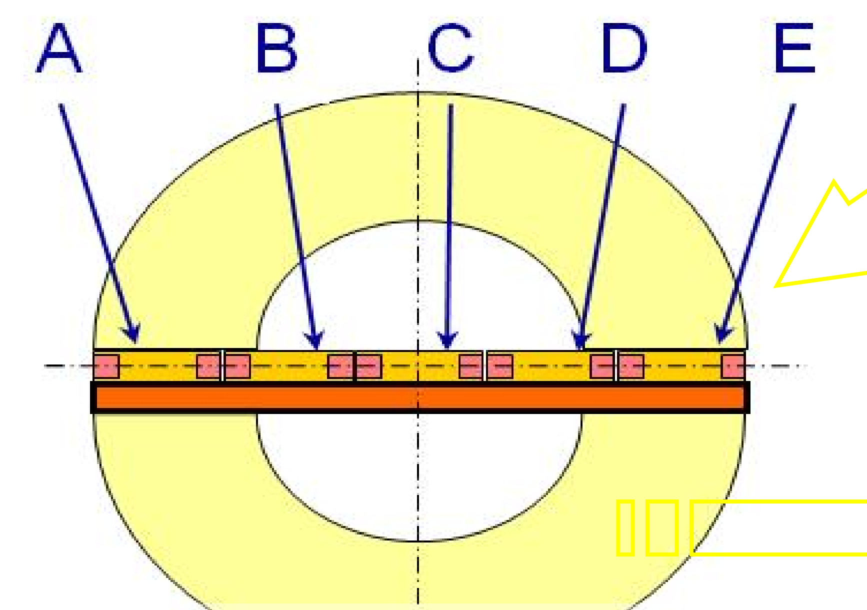
General introduction: S. Tumanski "Induction coil sensors—a review" - Meas. Sci. Technol. 18 (2007) (http://stacks.iop.org/MST/18/R31)

Components of a fluxmeter

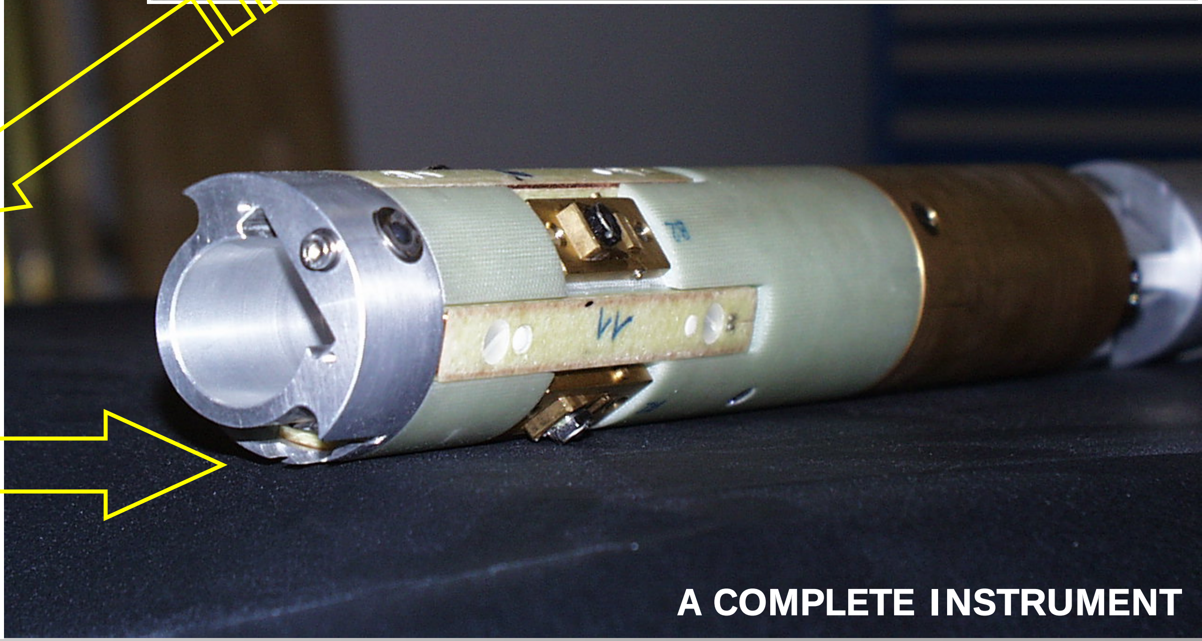
SEARCH COIL: the sensor



COIL ARRAY:
Intermediate assembly calibrated as a unit
bucking, mapping, redundancy



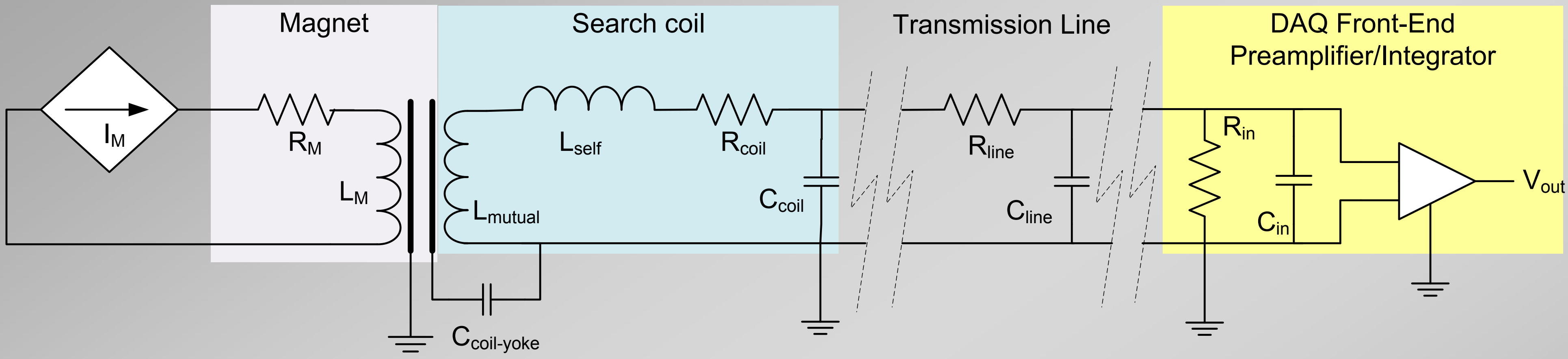
MEASUREMENT HEAD: coils mounted and cabled on a rigid support for handling, rotation/translation



A COMPLETE INSTRUMENT

Coil design

Equivalent coil circuit



Equivalent coil circuit

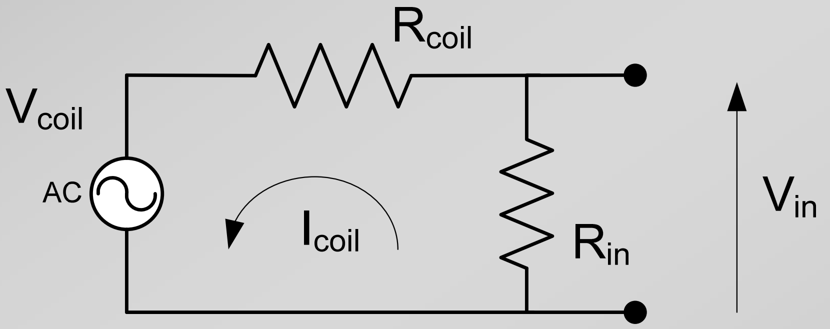
- A search coil is characterized primarily by its own resistance and the mutual inductance corresponding to the linked flux to be measured
- Coil self-inductance and capacitance become important only at high frequencies (10~100 kHz or more, to be compared to $(LC)^{-1/2}$). Impedance matching across the transmission line may be necessary.

Side remark: it is good practice to connect magnet, cable screen, DAQ electronics etc. to a a common ground even in case of differential-mode measurement (reduce unwanted common-mode voltages – beware of ground loops though ! ground potentials of different wall sockets in the same building may differ up to several ~100 mV or more in case of distribution faults)

Simplified equivalent circuit

Quasi-DC approximation

- The mutual inductance to the magnet is replaced by an e.m.f. source
- The only relevant coil parameter is its resistance, which must be as small as possible if standard acquisition techniques are used (ADC, voltage integrator)
- The voltage at the input of the acquisition system will be equal to the coil e.m.f. only if Rcoil << Rin (typically 1 MΩ to 1 GΩ)
- In the general case, an appropriate correction factor k_R must be measured an applied.
- Coil current I_{coil} typically in the μA range can be safely ignored (actual value dominated by R_{in}).
  Potential issues:
  - perturbation of Vin (consider behaviour full coil circuit)
  - wire heating (with diminution of Rc): e.g. a Ø32 μm wire can carry adiabatically ~5 mA.



$$V_{in} = \underbrace{\frac{1}{1+\frac{R_{coil}}{R_{in}}}}_{k_R} V_{coil}$$

$$I_{coil} = \frac{V_{coil}}{R_{coil} + R_{in}}$$

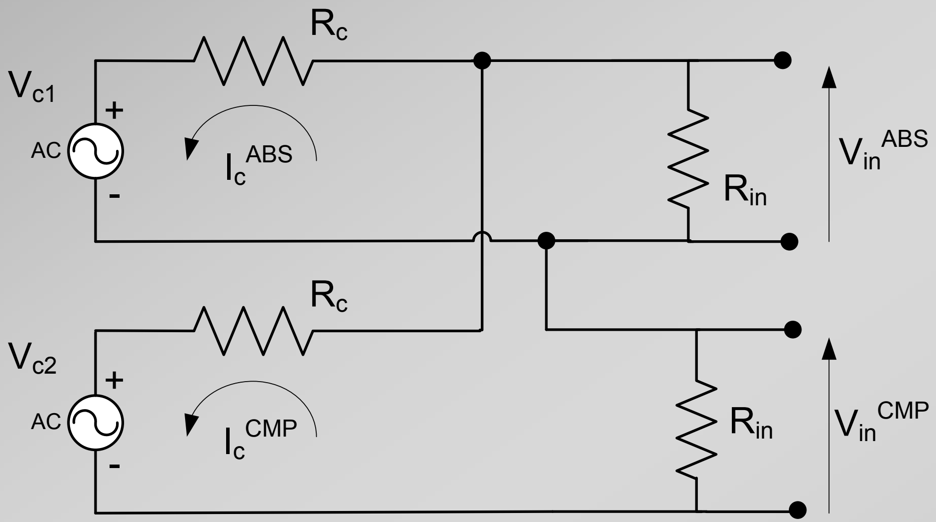
Warning

Correction coefficient $\mathbf{k_R}$: take into account variations with temperature (Cu resistivity drops by >300 below 20K) and compensation scheme. Efficient calibration should be done in real time (Rin depends on the input amplifier gain, which may change dynamically …)

Simplified equivalent circuit – bucked coils

Example: dipole compensation (2 bucked coils in series opposition)

- Assume equal coil and input resistances
- Even in case of perfect bucking, the compensated signal contains a fraction of the absolute signal

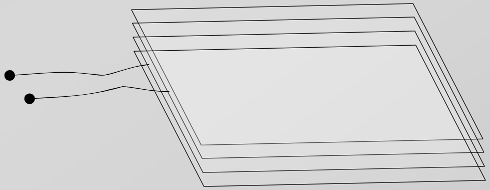


$$\begin{cases} V_{in}^{ABS} \cong \dfrac{1}{1+2\dfrac{R_C}{R_{in}}} V_{C1} + \dfrac{R_C}{R_{in}} V_{C2} \\ V_{in}^{CMP} \cong \dfrac{1}{1+3\dfrac{R_C}{R_{in}}} \left(V_{C1} - V_{C2}\right) - \dfrac{R_C}{R_{in}} V_{C2} \end{cases}$$

Coil design

Ideal rectangular coil

- 4 geometrical parameters: N_T turns, length ℓ_C, width w_C, wire diameter $\varnothing_W$
- Main parameter: total area exposed to flux change **Ac**, which determines the peak induced voltage (limited by electronics, typically ±5 or ±10 V)



$$-V_c = \frac{\partial \Phi}{\partial t} = \begin{cases} A_c \dot{B} & \text{Fixed coil in a time-varying field} \\ A_c B \omega & \text{Coil rotating at angular speed } \omega \text{ in stationary, homogeneous field} \\ A_c \nabla B v & \text{Coil translating at speed } v \text{ in stationary field with gradient } \nabla B \end{cases}$$

- Neglecting capacitive effects (important only at very high frequencies), we get 7 variables + 3 equations:

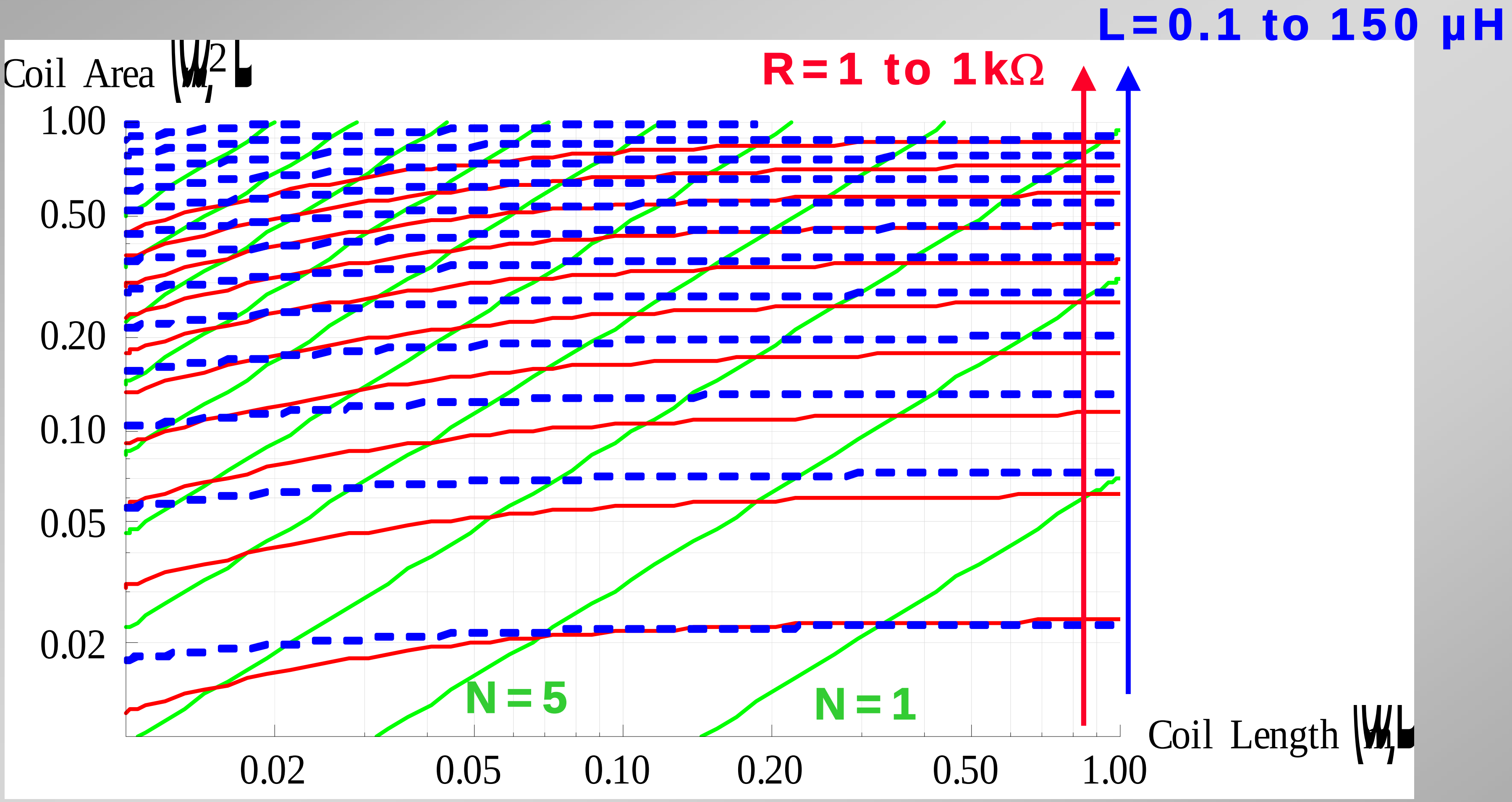
$$\begin{cases} A_c = N_T \ell_c w_c \\ R_c = \dfrac{8}{\pi} N_T \rho \dfrac{\ell_c + w_c}{\varnothing_w^2} \\ L_c = \dfrac{\mu_0}{\pi} N_T^2 \left(\ell_c \ln \dfrac{\ell_c}{\varnothing_w} + w_c \ln \dfrac{w_c}{\varnothing_w} + 2\sqrt{\ell_c^2 + w_c^2} - \ell_c \sinh^{-1} \dfrac{\ell_c}{w_c} - w_c \sinh^{-1} \dfrac{w_c}{\ell_c} - \dfrac{7}{4}\left(\ell_c + w_c\right) \right) \end{cases}$$

NB: choice of width: attention to zero sensitivity to certain harmonics in case of tangential coil

Summary of coil design criteria

N_C	- Increase for high sensitivity - Balance with R_C
ℓ_C	- Dictated by the geometry of the magnet to be measured (local or integral measurement)
w_C	- Dictated by the geometry of the magnet to be measured (gap size): coil must rotate, or translate, or stay fixed - Case of tangential coils: choose appropriately the blind harmonic (n: $\sin\frac{1}{2}n\alpha=0$)
Ø_w	- Reduce to wind more turns, get small cross-section (improve harmonic accuracy), solder more easily - Increase to improve mechanical strength, reduce R_C
A_C	- Aim at having $\lvert V_C \rvert \max \leq$ 5 or 10 V in normal use (depending on electronics specs)
R_C	- Lower for higher measurement accuracy (also reduces thermal voltage noise $\sqrt{4k_b RT\Delta f}$)
C_C, L_C	- In case of high-frequency measurements: resonant frequency >> bandwidth

An example of parameterization



- Fixed variables: w_C=10 mm, $Ø_W$ = 0.06mm
- Independent variables: ℓ_C, A_C
- Determined by equation: N_T, R_C, L_C

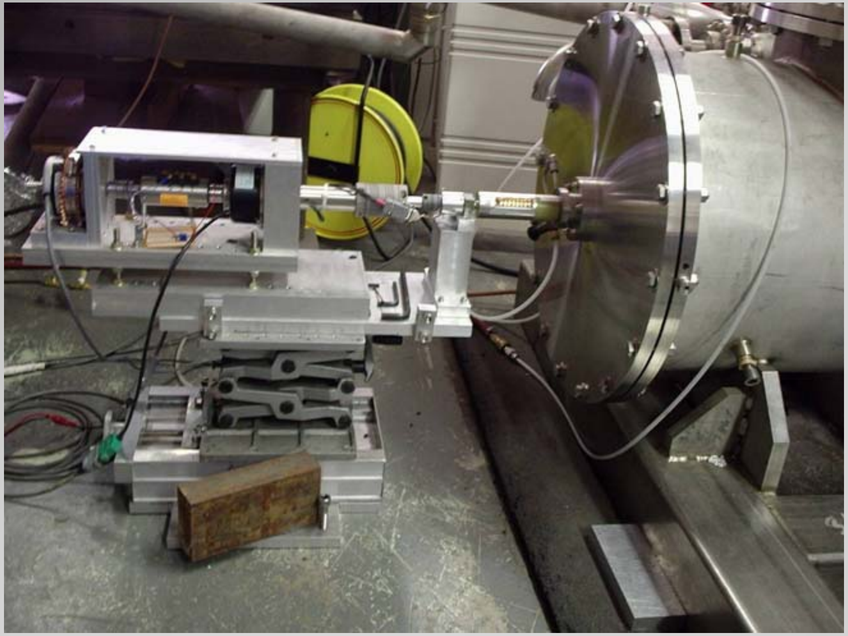
Winding Forms

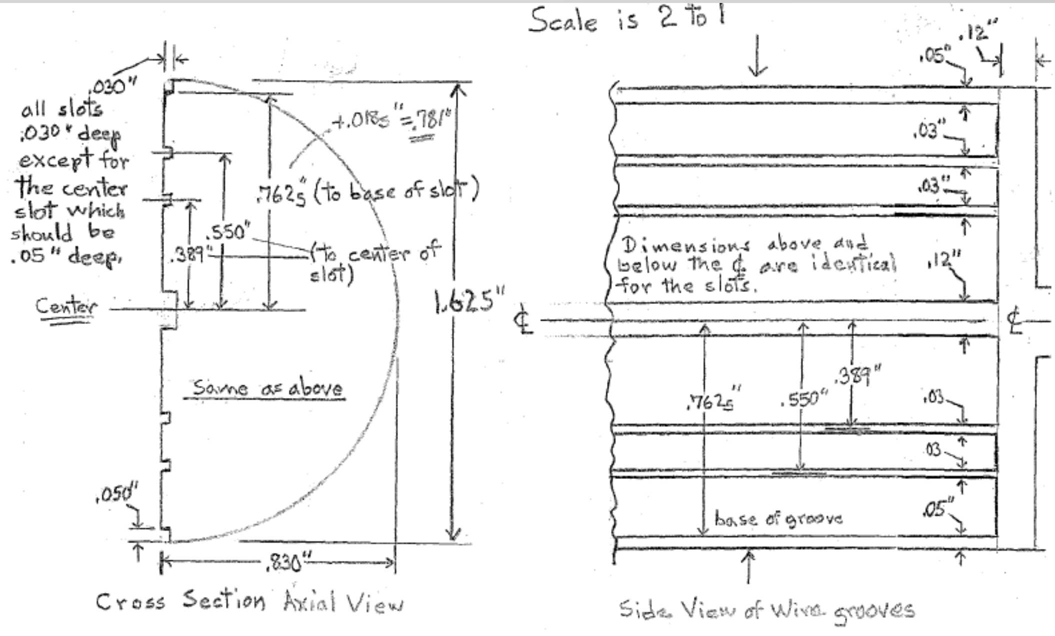
Winding forms

Type	☺	☹
Individual cores	• relatively easy to machine, handle and wind accurately • large series production feasible • allows sorting for bucking • easy maintenance	• need rigid support • long-term stability problems
Monolithic assemblies (forms machined tangentially in a thick tube)	• monolithic construction • very accurate and stable	• difficult winding many turns
Printed Circuit Boards	• very high accuracy possible • high compensation order • practical in large series	• limited size • results must be corrected for geometric fx (ends, x-section) • cost, availability
Air cores	• coil is self-supported by the bonding between the turns • production facilitated by thermally activated covering • OK only for point-like measurements	• small size only possible, bad stability

Machined Coil Shaft (SLAC)

- Alternative to separate coils: the winding form is machined directly on the rotating shaft
- Coils hand-wound from AWG 36 Litz wire in machined grooves in G10 form, 19 turns each set
- 7 precisely positioned grooves
- winding and eventual repairs more difficult, however there may be more accuracy and stability of the instrument as a whole





Materials for forms and supports

Material selection criteria:

- low magnetic susceptibility to minimize perturbations,
- non conducting to avoid eddy currents (a $d\Phi/dt$ is always necessary for the measurement to work!)
- mechanically rigid, hard and stable (low moisture absorption)
- machinable to required precision (of the order of a few 0.01 mm)
- thermal expansion minimal or matched to wire/support – isotropy is important
- low dielectric constant to minimize parasitic capacitance effects
- in some cases: compatible with insulation vacuum (not UHV) and/or operation in LHe at $T \geq 2K$

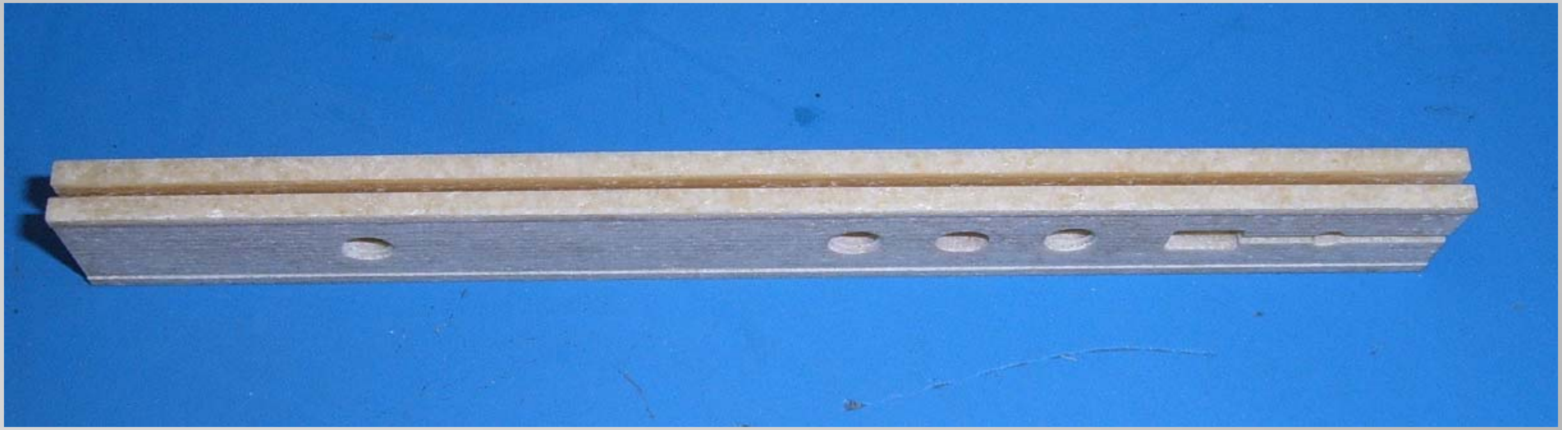
	Density	Young	Thermal exp.	Resistivity	Dielectric constant	Susceptibility
	ρ	E	α 300K	ρ	ε_r	χ_m
	$[kg/m^3]$	[GPa]	[ppm/K]	$[\Omega m]$	[-]	[-]
Macor™	2520	64	0.9	$>10^{14}$	6.0	$<10^{-5}$
Vycor™ (96% Si)	2180	66	0.8	$>10^{14}$	3.8	$<10^{-5}$
Quartz (fused Si)	2200	72	0.6	$>10^{14}$	3.8	$<2 \cdot 10^{-7}$
Carbon Fiber	1600	250	6.5	10^{-5}	-	$-1.6 \cdot 10^{-5}$
Al2O3	3980	380	6.5	$>10^{14}$	9.1	$<10^{-5}$
G10	1820	25	10.0	$>10^{14}$	5.2	$<10^{-5}$

optimal material classes: ceramic / glasses

other materials (e.g. aluminum, polymers, foam board) ok only in very special cases

NEMA G10 Glass-Reinforced Epoxy Laminate

- Standardized by National Electrical Manufacturer's Association (NEMA)
- Very good electromagnetic properties
- good mechanical properties: easy to machine to ~0.05 mm, can be threaded BUT: attention, depending on reinforcementgs used can be anisotropic (e.g. precision surface should not be machined // weave)
  <u>quality grade very important (impregnation, type of fibers .. .can make a lot of difference)</u>
- More stable than corresponding fire-retardant grade (FR4), ok up to 180 C.
- Among the similar NEMA grades (G7, G9, G11) it is the one with highest hardness and lowest thermal expansion coefficients
- 0.1% water absorption in 24 h
- relatively inexpensive



default choice for not-too-stringent requirements

Alumina Al_2O_3

- ground/sintered ceramic material with extremely good mechanical properties (10× as stiff, 2× as thermally stable than G10) ⇒ necessary for very demanding tasks such as 15 m long LHC cryodipole coil shafts
- machinable to ~0.01 mm or better with appropriate tooling (diamond-coated grinding)
- routinely used as an insulator
- base material is cheap but very expensive to fabricate and machine in the required shapes, very few suppliers in Europe, limited size for rectified parts (eg. 7500 Euro/sector)
- fragile – handle with care !
- Other uses: aluminium production, refractory, abrasive, insulator

MACOR™ Glass Ceramic

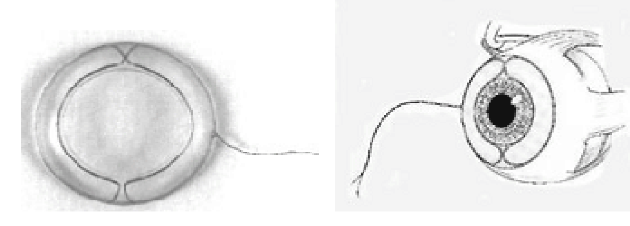
- (or MCG,TM by Corning)
- Boro-silicate glass-ceramic loaded with mica to inhibit crack propagation
- intermediate rigidity, extremely low thermal expansion (~matches metals)
- Machinable with standard steel tools to ~1 μm tolerance (can be polished to 0.5 μm finish)
- Non-conducting, non-magnetic, refractory up to 800 C, BUT: does not tolerate thermal shocks
- limited size of monolithic pieces (500 m) -> to be assembled

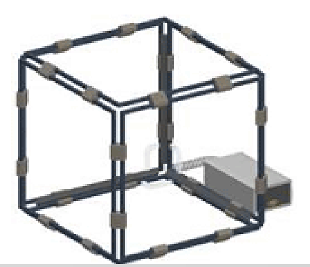
Other materials

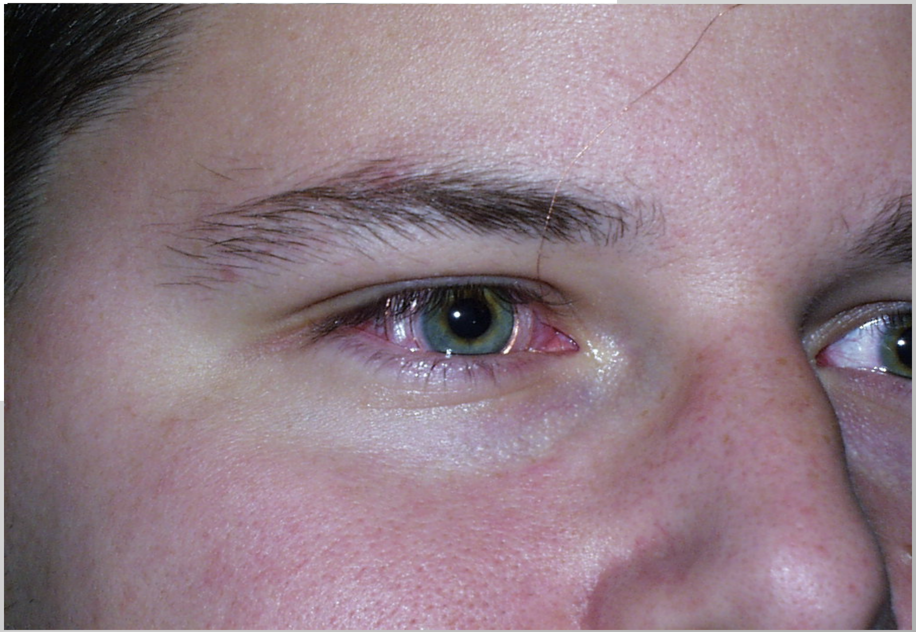
- Aluminium: good conductor, cheap and easy to machine ⇒ interesting only for very large coils (transversal area of support << area exposed to dΦ/dt)
- Carbon fiber composite: very good strength-to-weigh ratio, however it is conductive and has markedly anisotropic properties (e.g. a tube shall twist due to thermal expansion)
- Silicon Nitride ceramic (Si_3N_4): extremely hard and stable, ideal for non-magnetic ball bearings. Highest strength-to-weight, lowest dielectrical constant of all ceramics
- Quartz: attention – piezoelectric !
- Metals for bodies: bronze, steel (attention to magnetic grades !!)

An unusual coil substrate ...

- **Scleral search coil method:** the gold standard in eye movement recordings, i.e. saccades, smooth pursuit, tremor, drift … (rotational degrees of freedom)
- Subject immersed in the superposition of three mutually perpendicular homogeneous field components with AC modulation at different frequencies (created by Helmoltz-like large size coils).
- 2 single-turn coils embedded in silicone rubber, AC signals detected synchronously with lock-in amplifier. At least one coil almost perpendicular to any field component (linear response range)
- Very high accuracy and bandwidth







Single-strand wire coils

Selection of a wire

- **Material criteria**:
  - electrical conductor (insulated)
  - ductile to achieve small diameters
  - sufficiently strong to withstand pulling and bending
  - easy to solder contacts
  - min. diff. thermal expansion w.r.t. core
  - commercially available

⇒ Cu is the obvious choice

- **Cross-section**
  - Diameter optimized for R_C, N_T: choose among standard American Wire Gauges
  - Rectangular wire x-sections exist, but difficult to find in small gauges (0.1~0.2 mm). Could allow in theory higher packing factor, BUT tends to get twisted during winding (not a problem with round x-section)
  - Uniformity of winding geometry important for accuracy (see L Walckiers' lecture)

- **Electrical Insulation**
  Thickness = f(Vmax): while the coil is dimensioned to get total output voltage in the 5-10 V range, insulation need dictated by off-normal conditions = thermal trip for resistive magnet or quench for SC ⇒ dB/dt in the 10-100 T/s possible, max. voltages in the hundreds of volts.
  For single-filament, Polyurethane insulation (3.5 – 9 µm soldex insulation according to IEC 60317)

- **Thermal class**
  Wires classified normally according to high-T compatibility (not an issue for a search coil, *except* for possible material testing of materials destined to UVH and therefore operating at baking temperatures).

Mono-filament coil winding machine

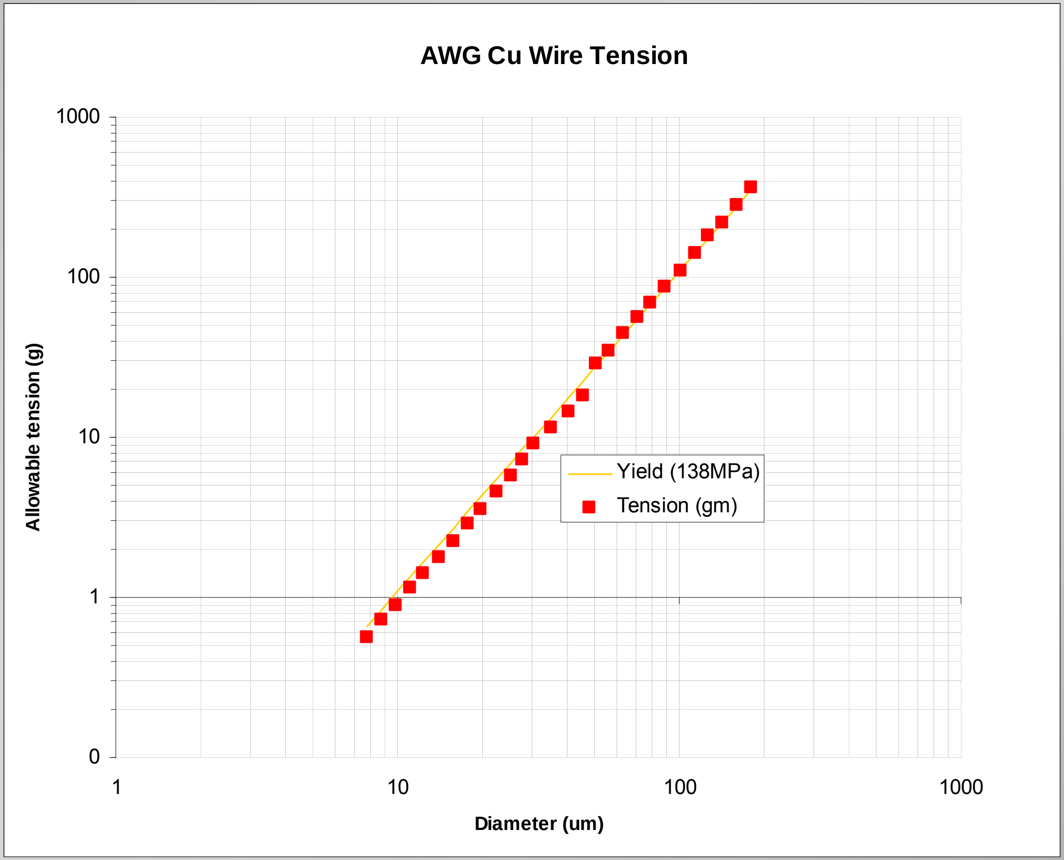
Wire winding tension

Wire Tension

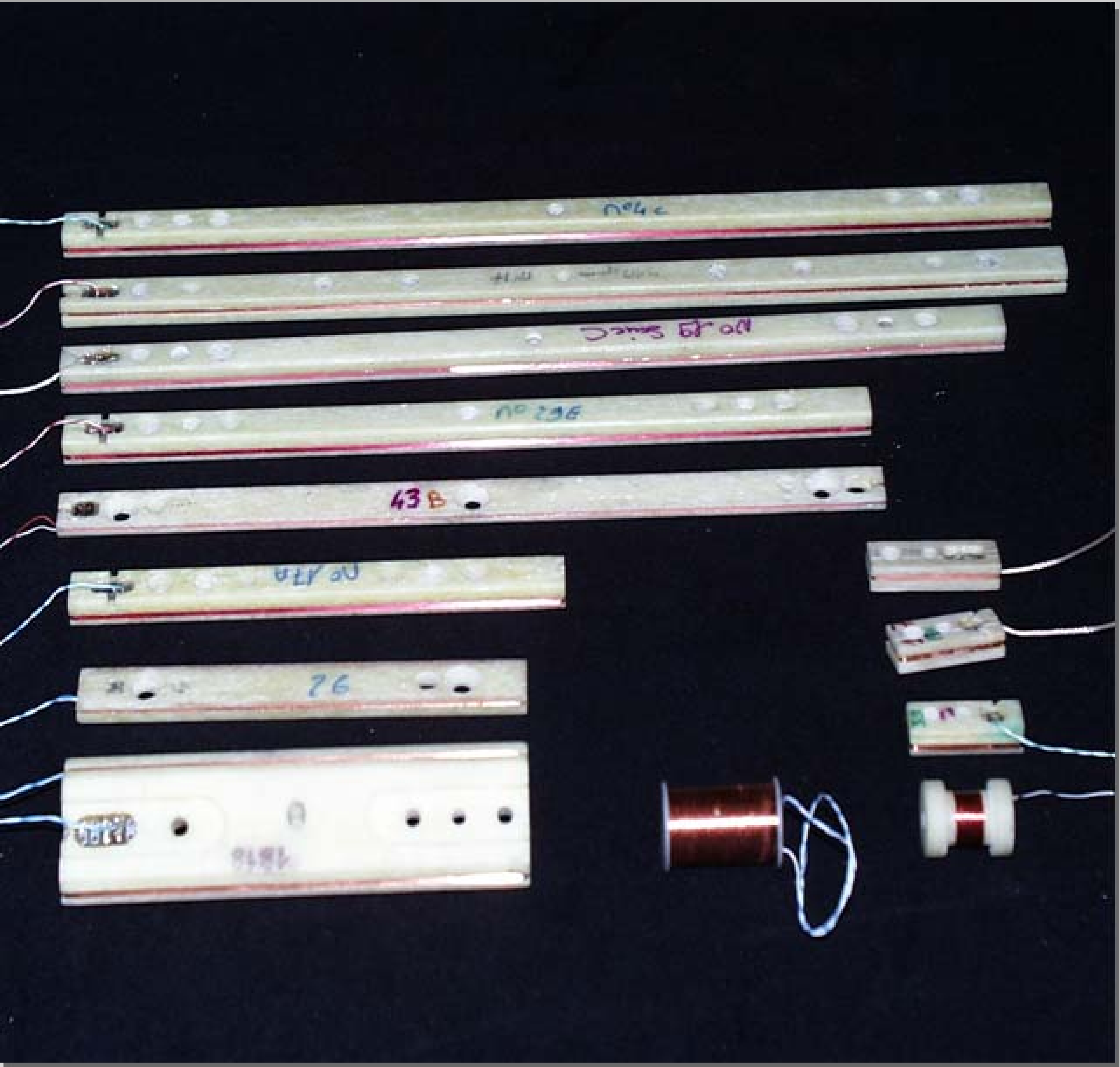
The wire should be pulled constantly *just* below yield throughout the winding in order to:

a) ensure adherence to substrate
b) ensure uniform cross-section (it will "neck" dramatically at yield)

… hovever: tension can be modulated during winding to partially recover winding core size defects



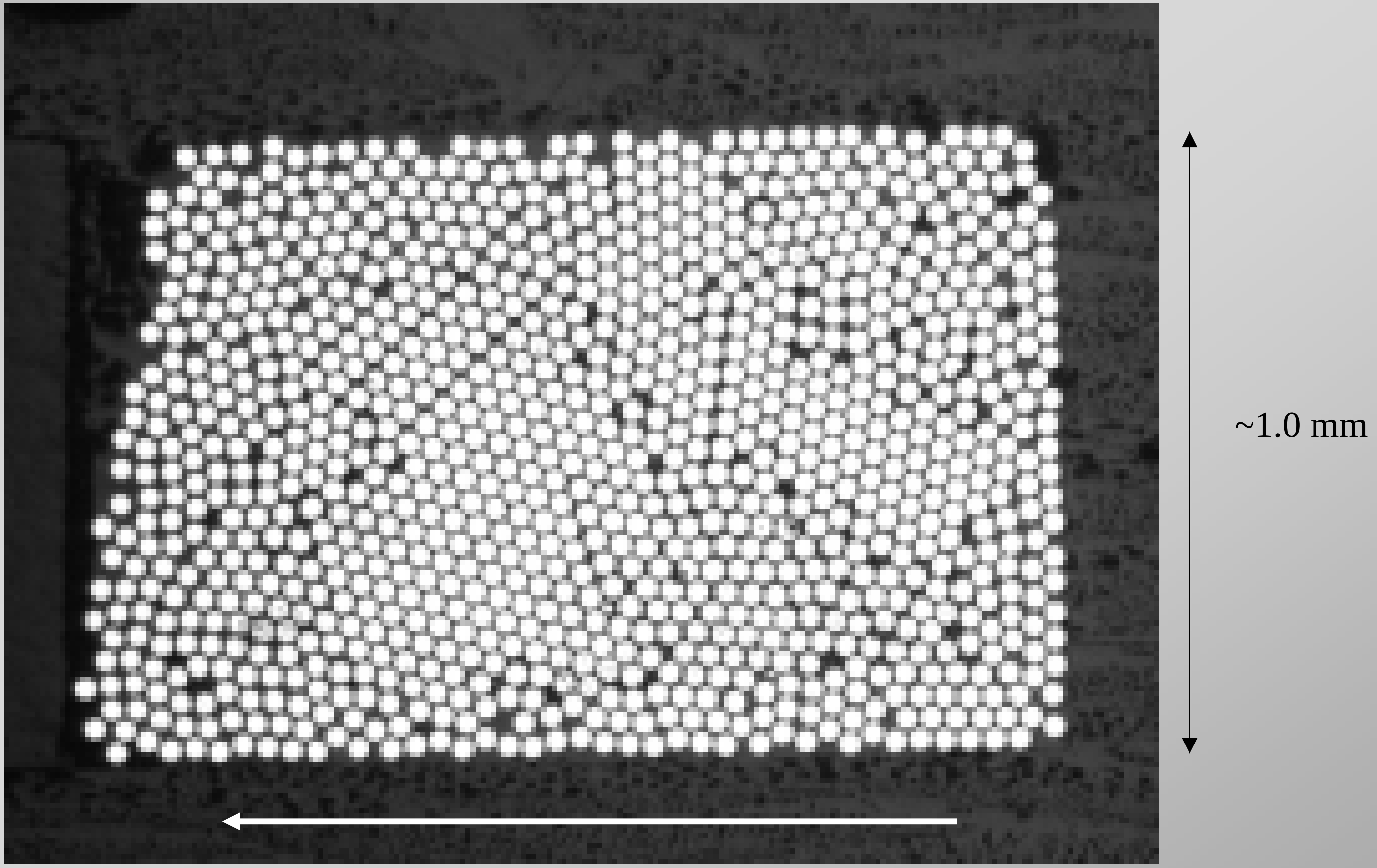
CERN-made single-strand coils



- At CERN: two commercial machines for rectangular coils and solenoids
  - Meteor M101 B, pitch can be varied manually during the measurement to adapt to out-of-spec wire size
  - Bobifil ER33, fully digital, high precision
- Coil length 18 mm to 260mm, winding stroke ~300mm
  Up to 3.000 turns routinely
  (many more possible)
- Weak point: wire tensioning (many breakages)
- After winding: glued with Cementit™ Universal (methylacetate) diluted with acetone and brushed upon the external layer only (this can be easily removed if necessary with T>100 C or acetone – stronger bonding usually not required)

Single-strand cross section

- many possible options, can be wound on semi-automatic machines, large turn count and total area in small geometry (at CERN: 32 to 200 um Von Roll wire).
- Geometrical quality deteriorates as the turn count increases (outer layers build up chaotically)
- OK for large series to be done quickly with relatively low accuracy requirements (e.g. quench antenna)

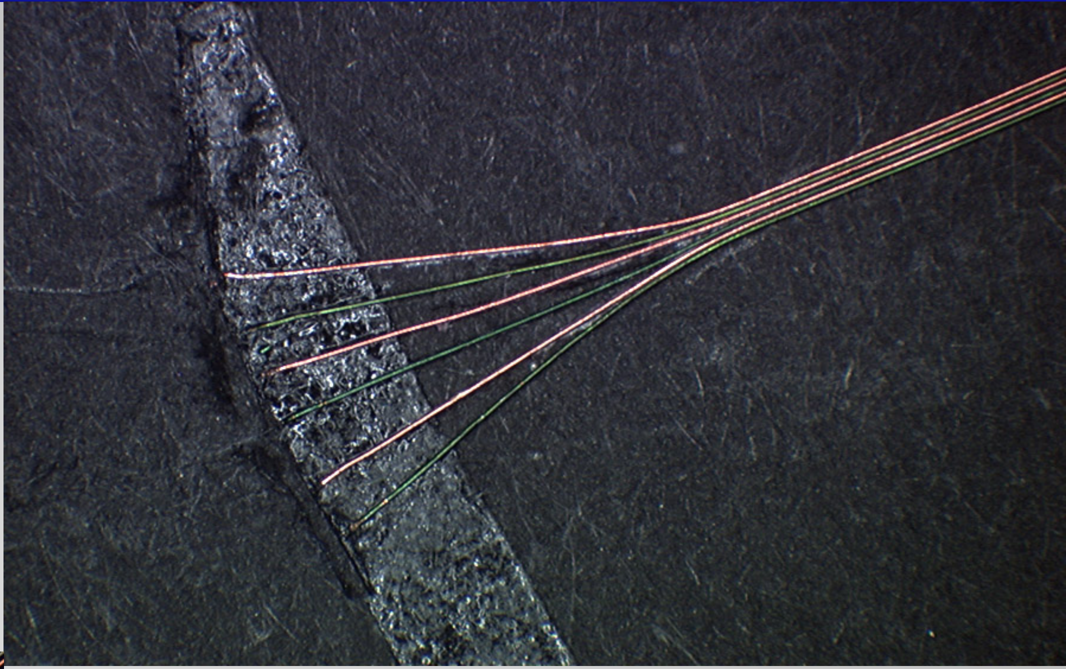


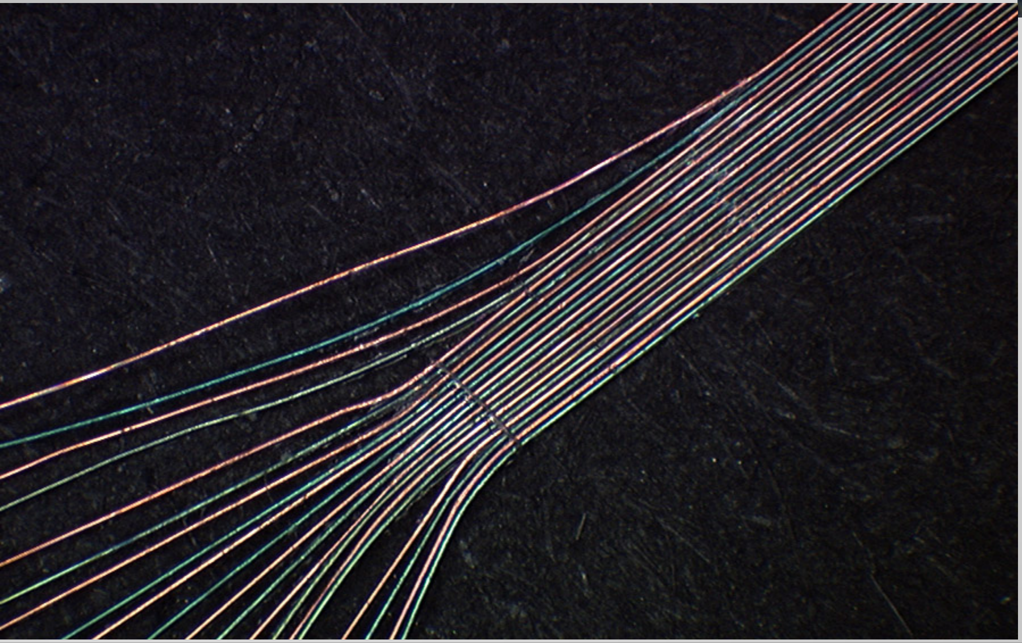
winding direction

Multi-strand wire coils

Multi-strand wire

- Parallel cable made with polyurethane-insulated wires bonded with PVB (polyvinyl butyral, easily dissolved in alcohol prior to soldering).
- Difficult to find (MWS, US), some gauges made to order (3 wires)
- Wound and soldered manually
- Excellent geometric regularity of rectangular or square ($n_{layers}=n_{filaments}$) cross-section.



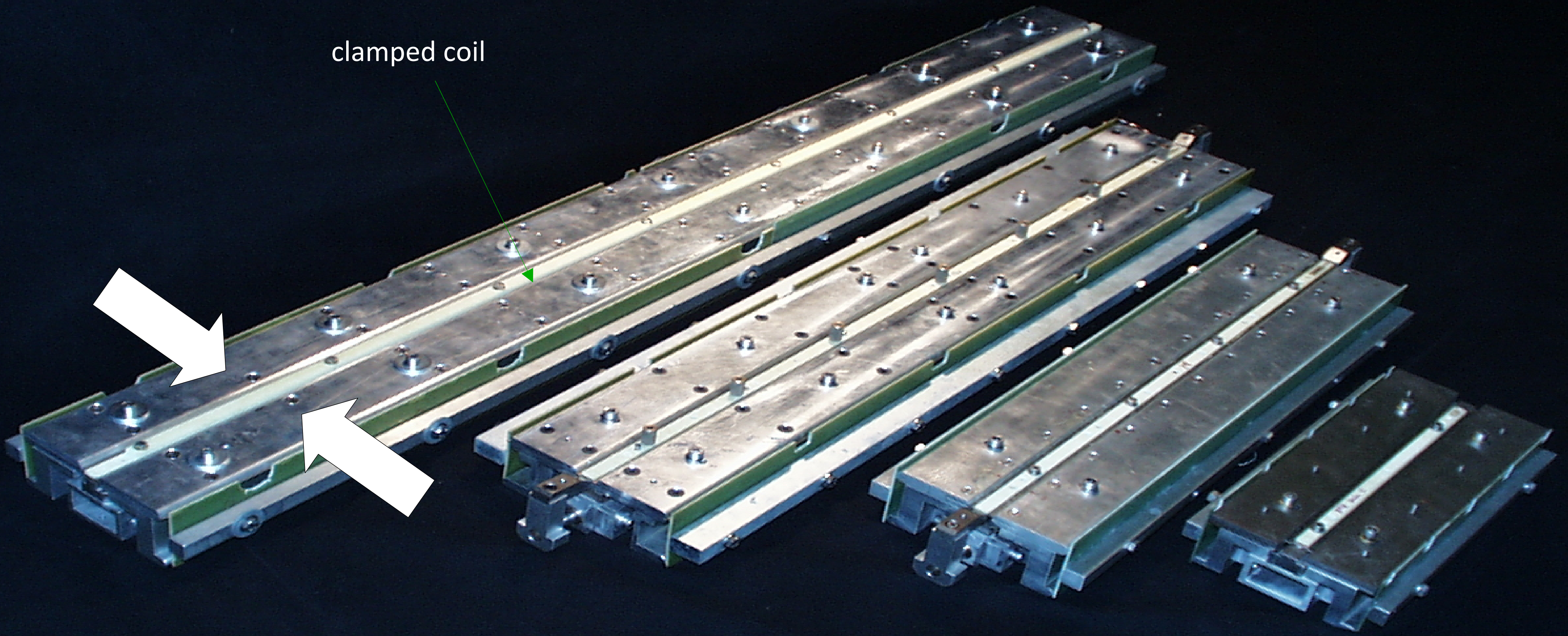


Filaments	Ø [µm]
3	170
6	90
8	82
10	80
16	70
20	60

Multi-filament coil winding rig

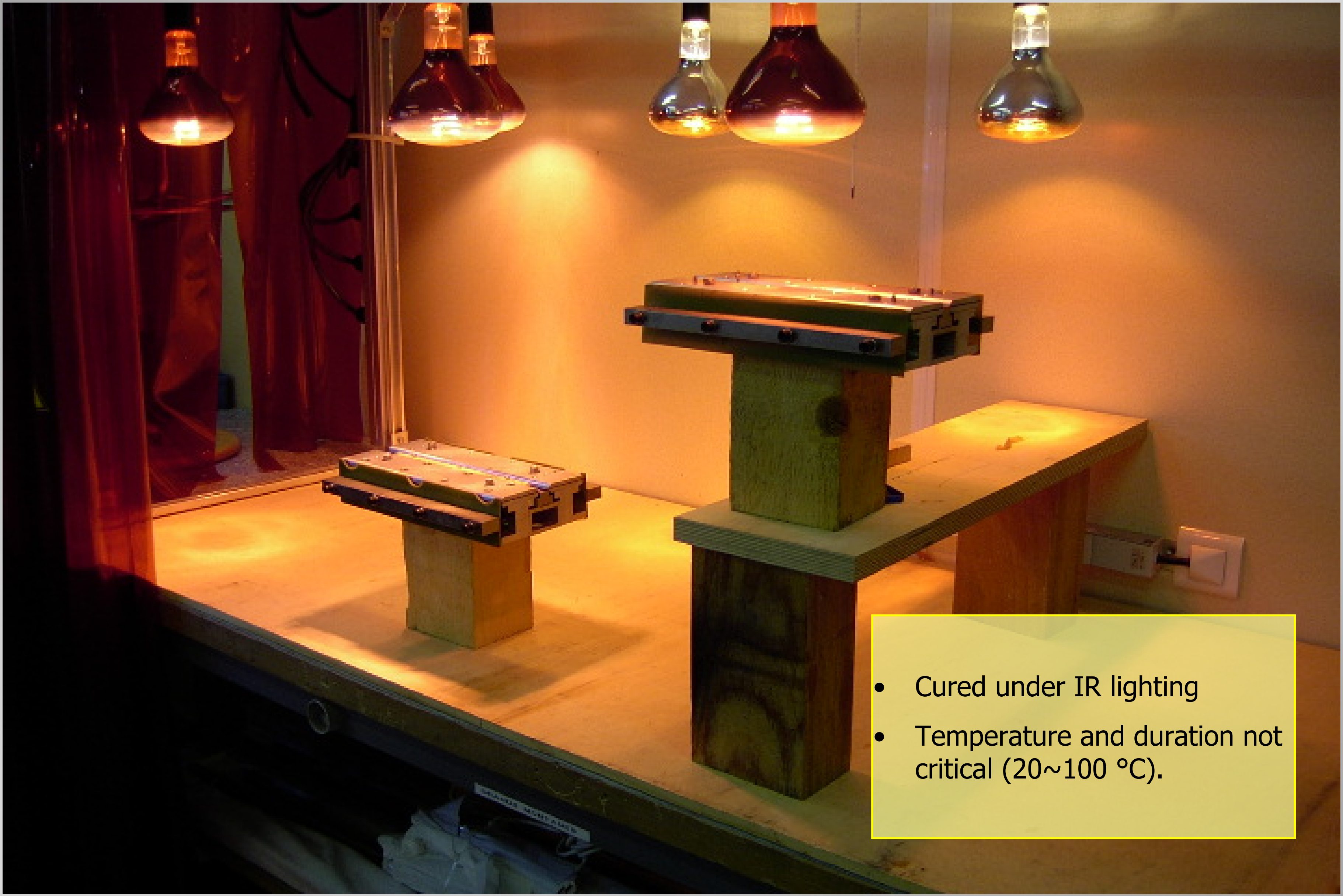
- Wound by hand on a rotating support able to accommodate cores up to 2 m long (no need for helical motion)
- Bonded with Araldite AY103 + hardener HY991 (transparent, low viscosity general-purpose epoxy adhesive).
- Tension applied manually throrughout the winding process

Polymerization clamp



- Polymerization should be carried out under a certain amount of pressure to make sure that air bubbles do not form in the epoxy and to ensure a regular shape (e.g. no bulging at ends, where bonfing may be less effective).
- At CERN we use several rigs, adpated to different coil lengths up to 2000 m.
- Release agent/teflon spray should be used to avoid sticking.
- Exact pressure not very influential.
- Some springback unavoidable.

Epoxy Polymerization

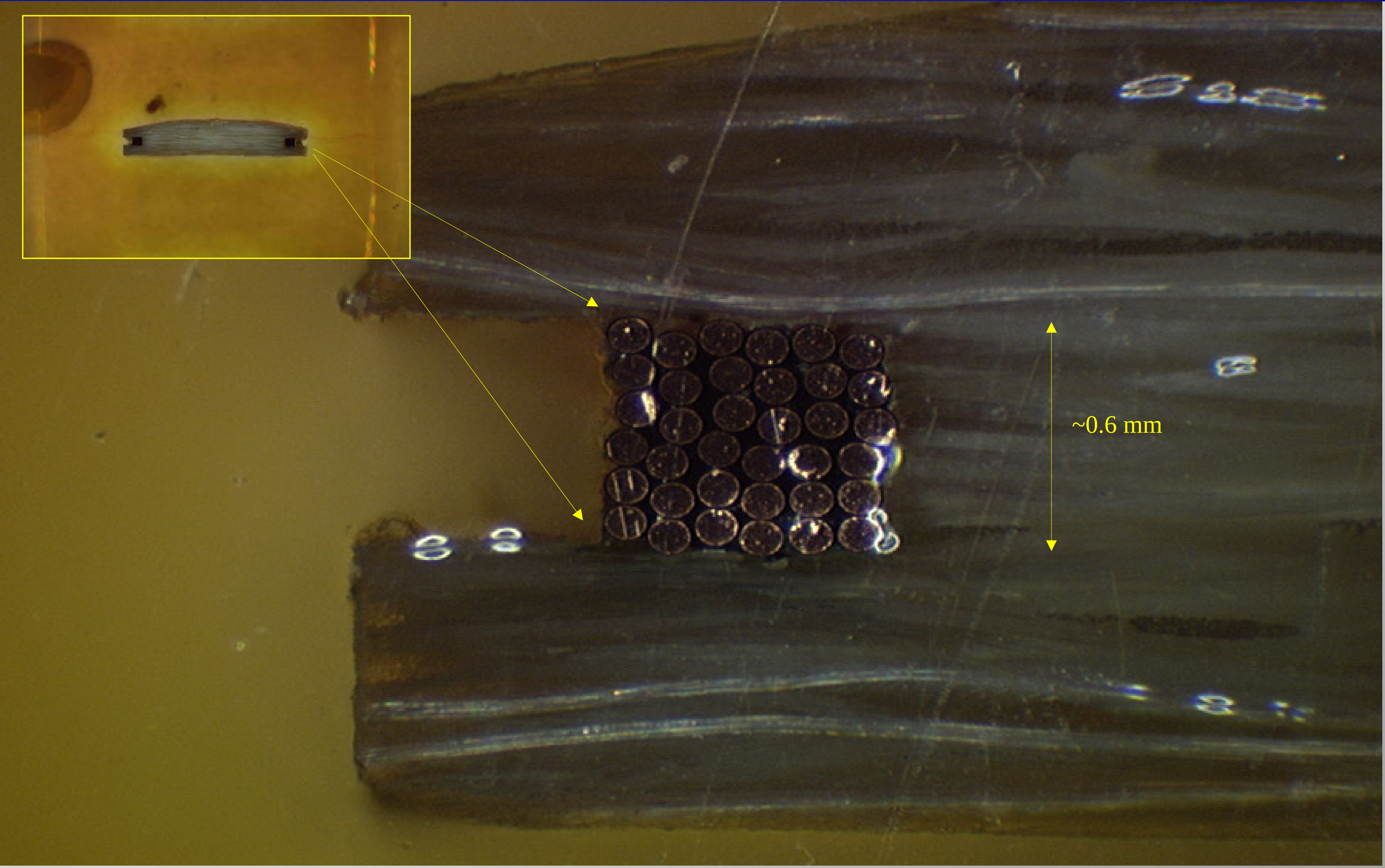


- Cured under IR lighting
- Temperature and duration not critical (20~100 °C).

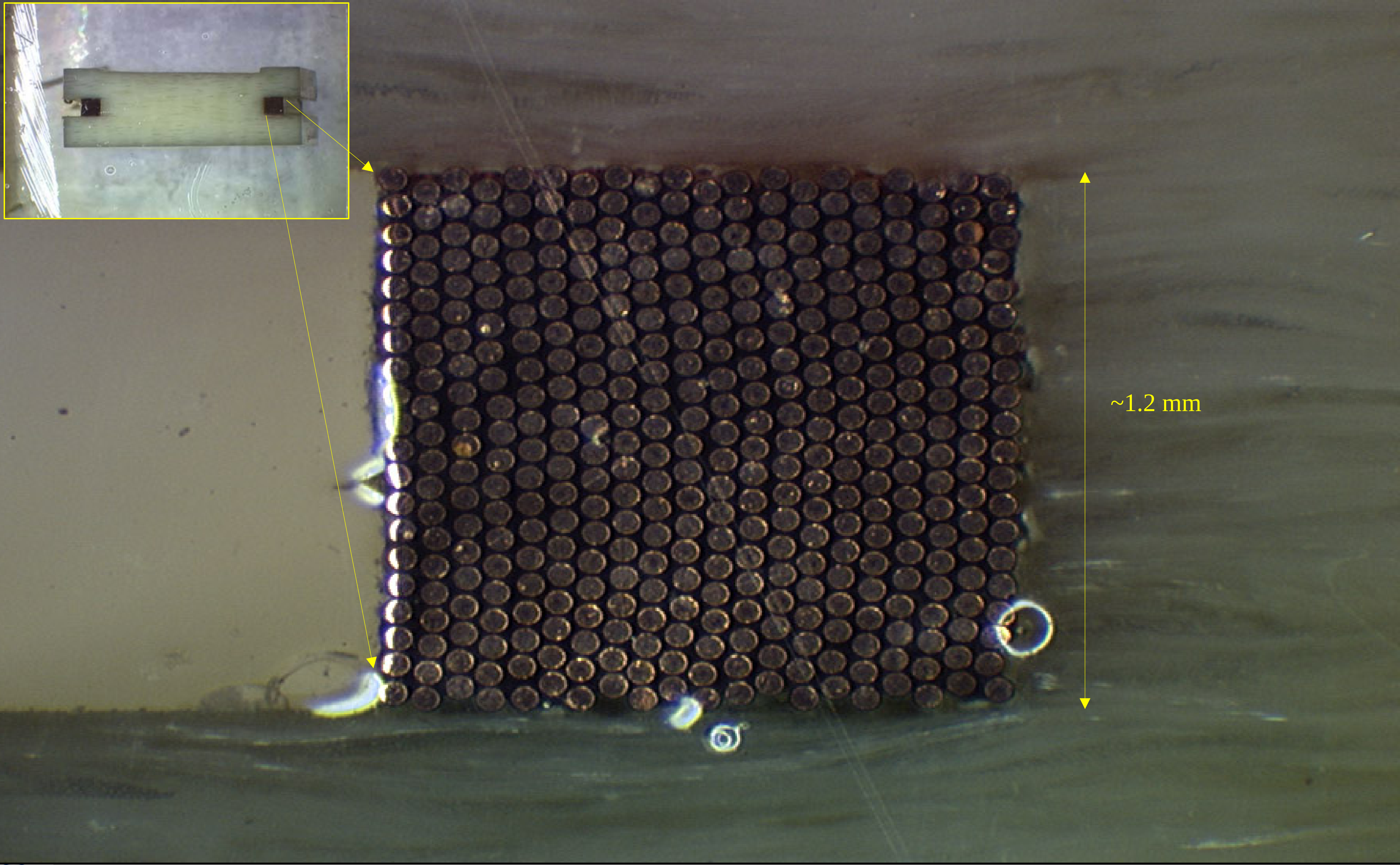
Multi-strand coils

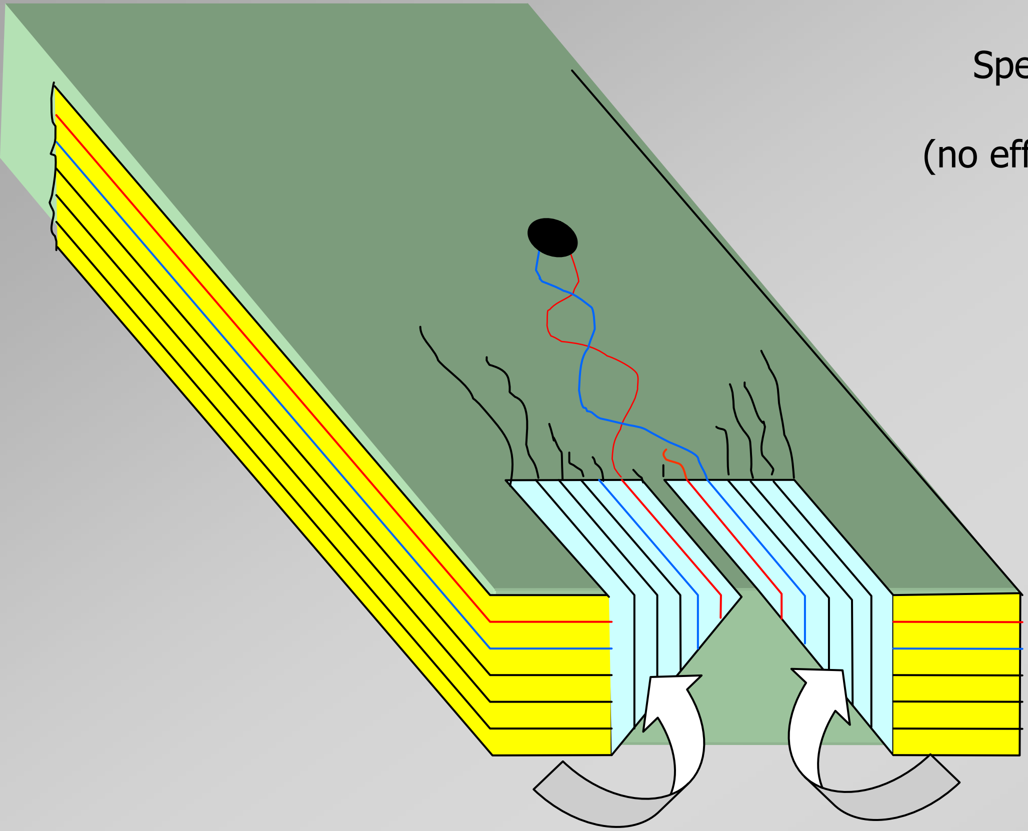
- Up to ~2 m length coils routinely done with up to 16x16 turns
- 20x20 turns coils very difficult to achieve: insulation tears, wire breaks easily during winding or under clamp pressure.

6-filaments × 6-layers

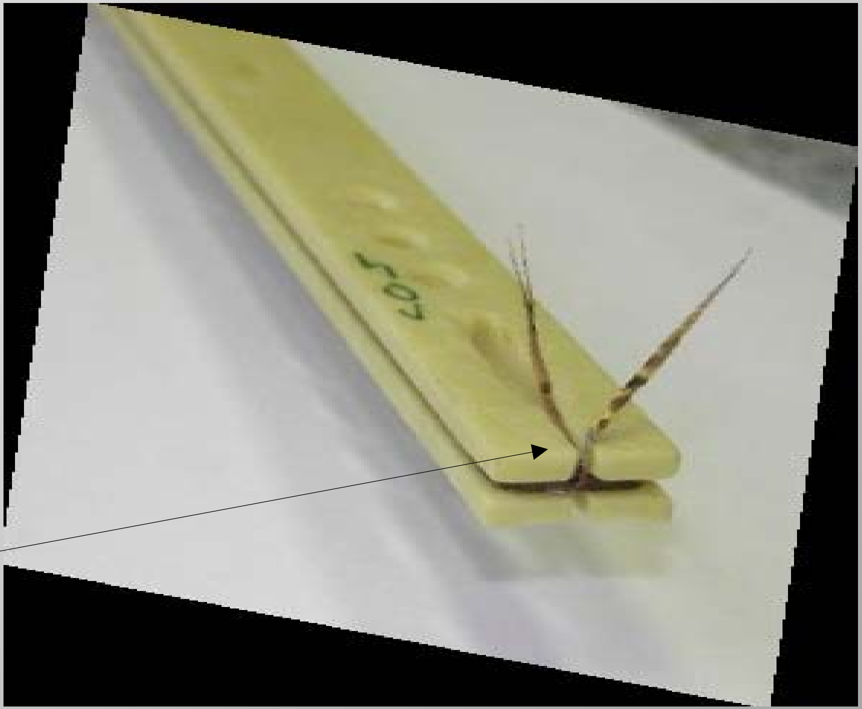


20 filaments × 20 layers





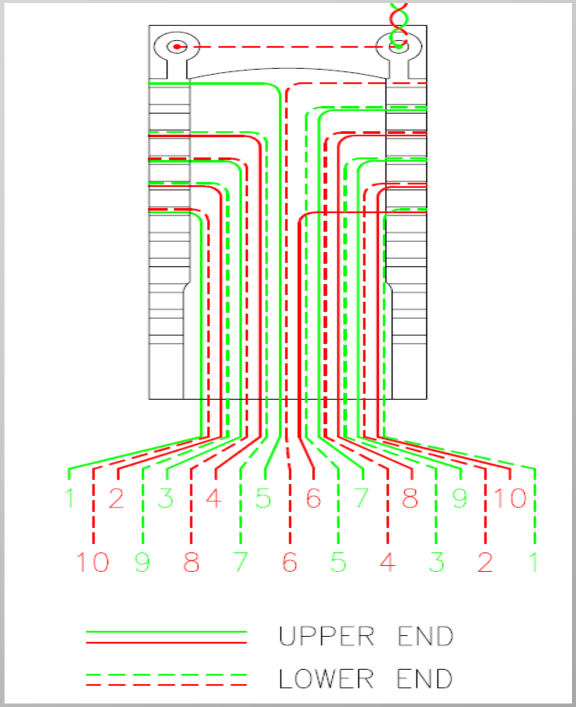
Special arrangement at cable ends to minimize linked flux
(horizontal plane + twisted pair)
(no effect if termination outside the field – not always the case)



the two folded ends are fully overlapped
(not shown in the drawing above)

Micro-connectors for multi-filament wires

http://www.resarm.com/



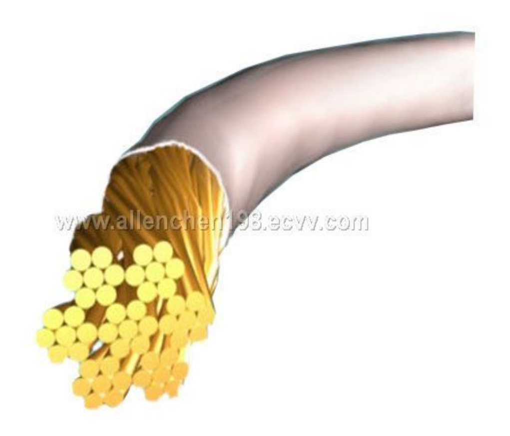
- CERN standard (Resarm-made) PCB plaquettes. Spot-glued or built-in the core (must be demountable for repairs).
  Machined, aluminized, etched with micro glass balls + cementite + acetone (glass abrasive for deburring)
- Width currently limits the min. coil width achievable -> must be practical !
  Highest-count type can work or other cases (minimize stock)
- Axon multi-conductor 6- or 12-pair micro-cables with connectors
- connection realized under the microscope
- main issues: reliability, shorts, twisting the cable so that the area cutting the flux be minimized
- Stress relief provided by thermoretractable sleeve

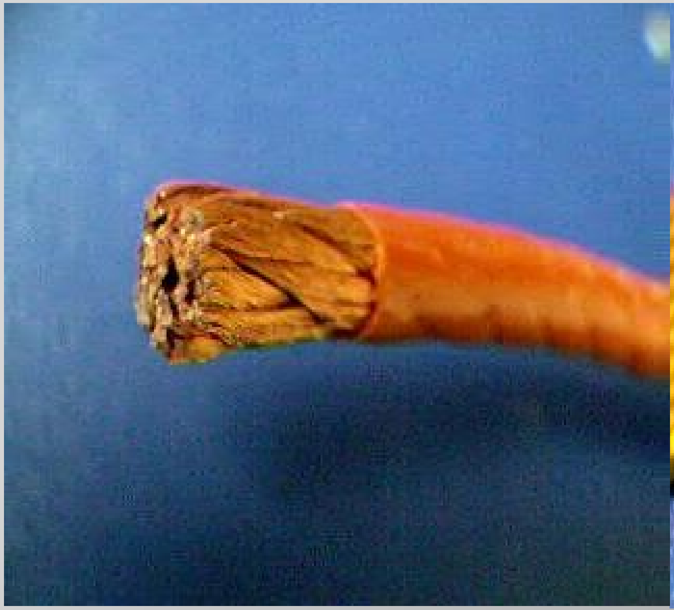
Litz-wire coils

Litz wire

- Litz wire is derived from the German word litzendraht (woven wire).
  Made of individual film insulated wires (counts into the thousands in commerce!) bunched or braided together in a uniform pattern of twists.
- Main interest: RF applications (spread the current over many small conductors, reduce skin-depth effects)
- Pros: no winding required – just lay the cable in the groove. Ideal for difficult geometries (e.g. coil impossible to turn)
- Cons: assuming that the geometry of each strand is given by the average value over a twist pitch (typically 10 mm), harmonic errors of the order of the % are made (not important for long magnets); connection nightmare
- Beware: the standard specifies that a certain % of wires may be broken in commercial products – test them all !
- Not used for CERN coils since a long time (but currently employed with good results elsewhere)

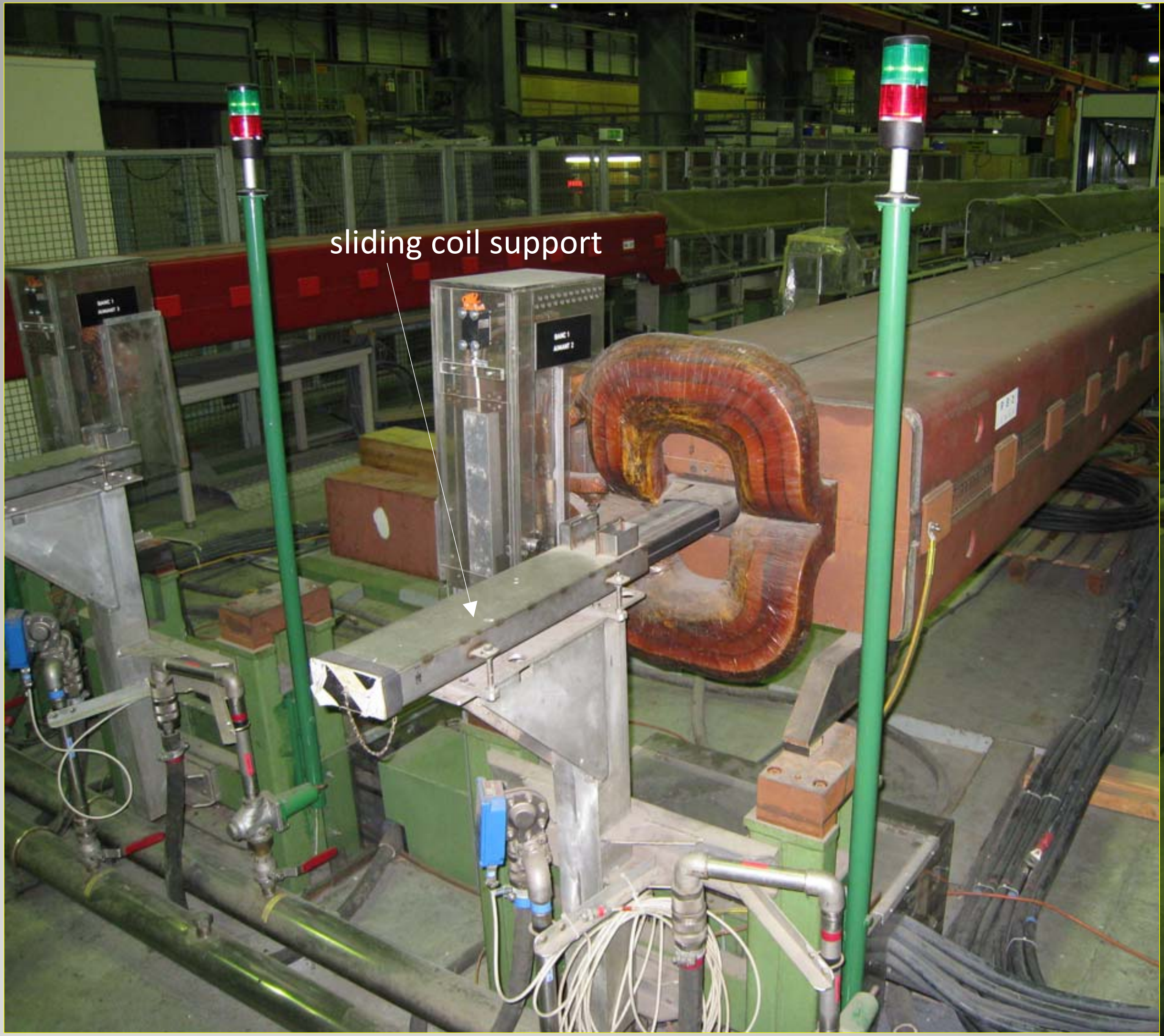
http://www.litz-wire.com/





Application example: CERN SPS coils

- 7 m long bucked coil systems for the measurement of main SPS dipoles and quads
- fixed coils working in pulsed mode
- differential measurements w.r.t. reference magnets – shimmed to ensure equal integrated lengths



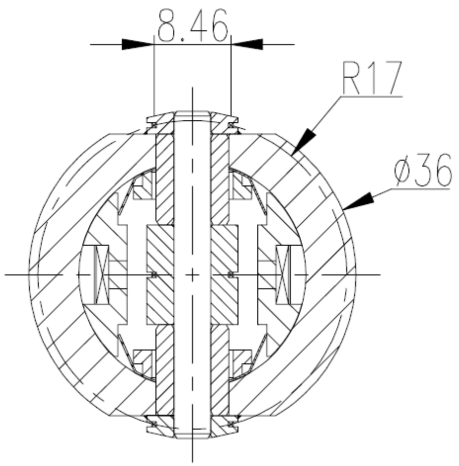
Application example: SPS coils

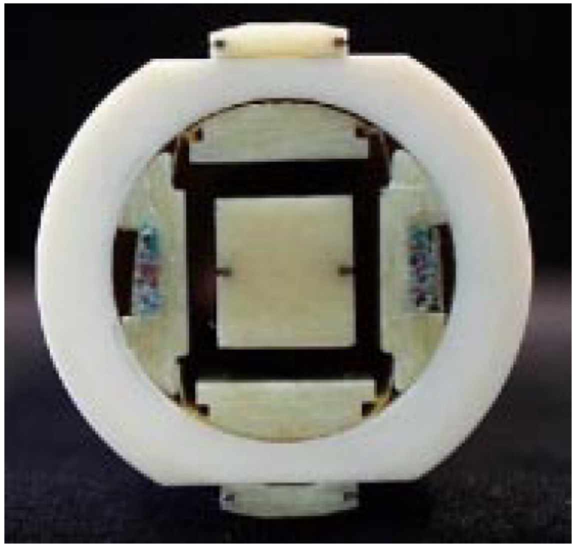
- Coil based on 10 strand Litz wire
- Winding form (very floppy!) supported by a rigid aluminium fixture
- Litz wire wound manually (12 turns on one layer). Tension kept by a weight. During winding, wire brushed with Cementit™ + acetone to keep it in place (also, this glue allows for real-time adjustments).
- After winding, coil inserted in a form and bonded permanently with Araldite (allow manipulation), one side at a time.
- Bubbles created during polymerization were bursted with a toothpick
- Silicon elastomer to keep wires in place at the connection (stress relief)
- Turns soldered on a standard PCB (well outside the field fringe)
- Coils in stable operation since 1980 …

Assembly example: the 15m coil shafts for LHC cryomagnets

Ceramic sectors

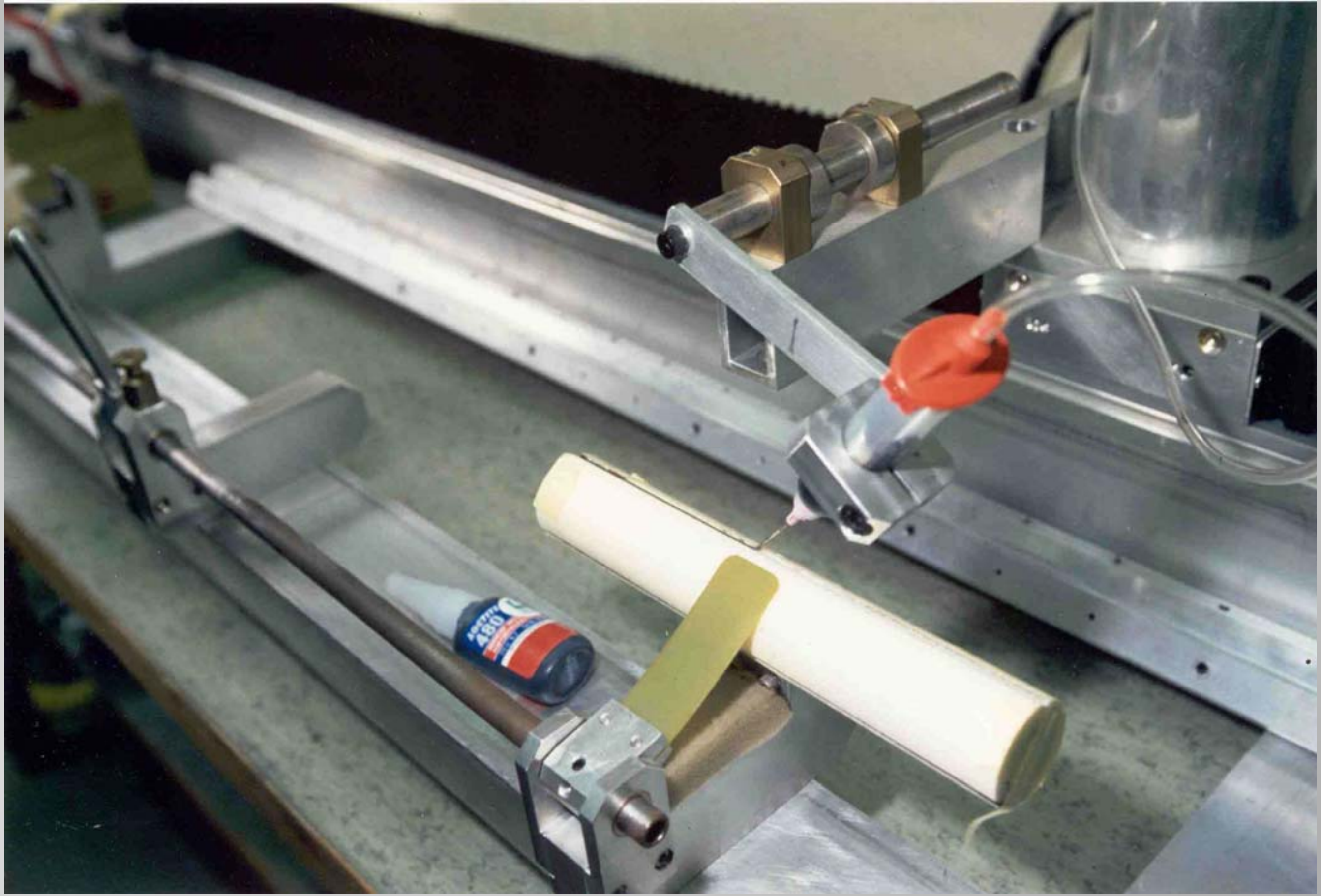
- Al_2O_3 tubular supports for compensated 3× or 5× coil arrays.
- Very difficult to machine long pieces (~1.3 m) at the required tolerance of 0.02 mm; work subcontracted on a R&D basis.
- Partners: Instiyut Problemow Jadrowych, Swierk (PL); Cerobear, Herzogenrath (DE); Energieonderzoek Centrum Nederland (ECN), Petten (NL); Institute for Nuclear Research of the Russian Academy of Sciences, Moscow
- Several manufacturing steps necessary (sintering, grinding, glueing subcomponents with Araldite – Loctite initially tried without success). ~2 years development time to optimize the procedures
- Standard subminiature connectors to pass signal cables throughout
- All elements must be absolutely identical for interchangeability
- Relative twist angle not controlled during assembly





Coil assembly

- Coils aligned with precise ceramic pins and fastened with nylon screws + secured with UV Loctite™ 322 glue to avoid "flapping ends" effect
- Low viscosity, flexible bond, can be scratched off if needed
- UV must be applied immediately to avoid penetration between coil and support → swelling during polymerization, loss of parallelism
- Glue tends to crumble with time and thermal shocks – attention to the residue !
- Surface roughened/etched locally to facilitate bonding (acid treatment proved ineffective)



Bearings

requirements: minimize friction coefficient at low speeds, mechanical stability (0.01 mm), moderate loads (< 100 N)

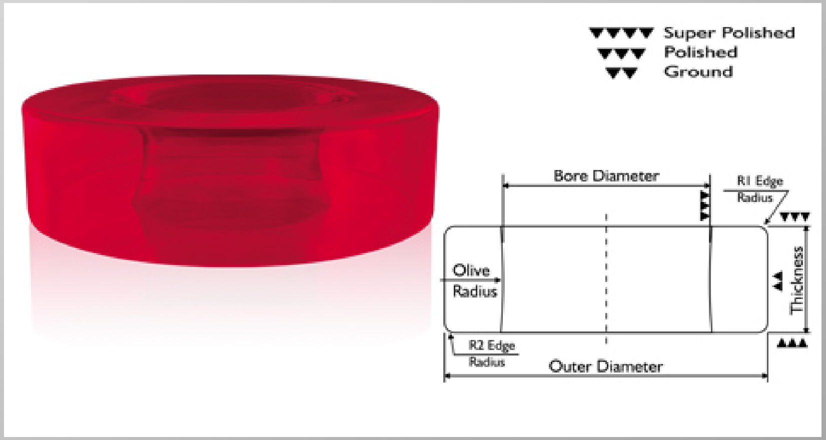
Si3N4 ceramic ball bearings

- low friction and vibrations, durability, cryogenic compatibility
- can be mounted permanently around the coil shaft to provide a stable reference
- available in custom sizes only from Cerobear (DE), other producers in USA/Japan can supply standard sizes
- very expensive

… but also consider:

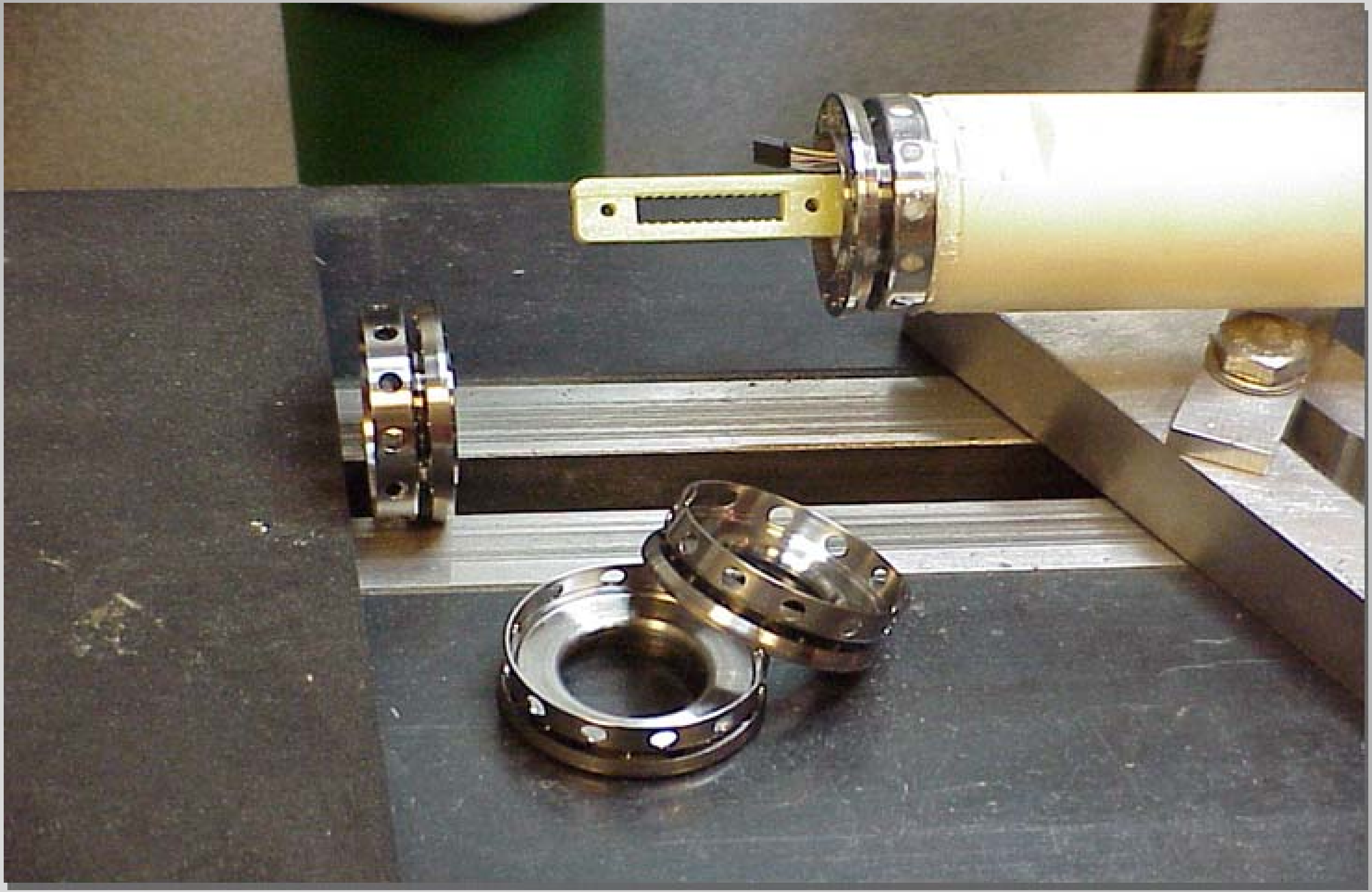
Olive Hole Ring Jewel bearing

- artificial sapphire (monocristalline Al_2O_3), extremely low static friction coefficient (0.15), very cheap.
- Used at SLAC for ILC quad testing
- Main drawback: zero axial load, cannot be fixed to a shaft.



Ti bellows

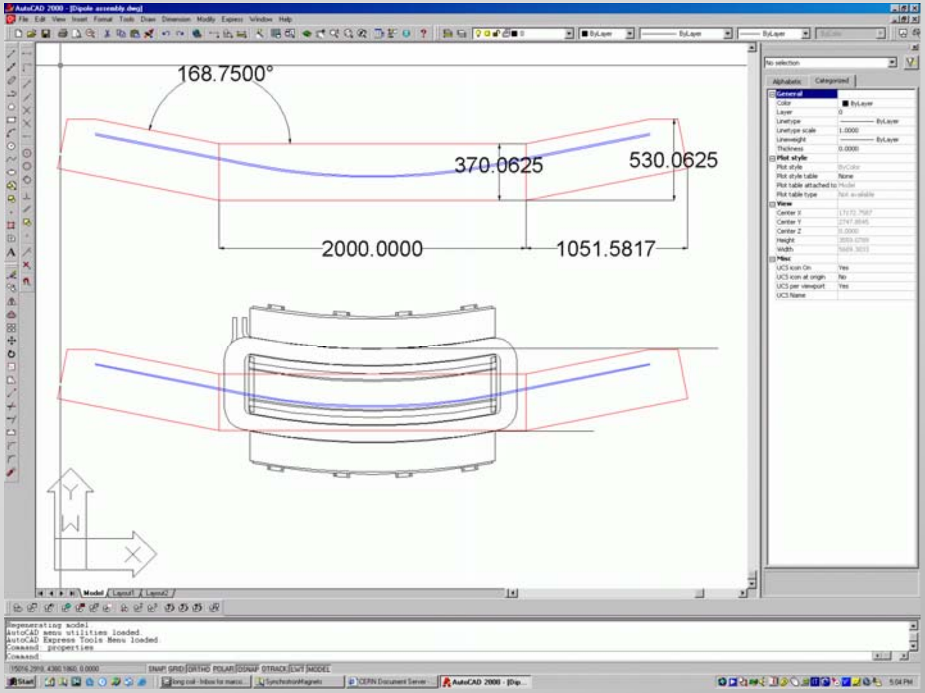
- High resistivity, non-magnetic
- High elastic range, allow up to 1~2 mrad bending between sectors
- Glued with Araldite (surface must be etched mechanically for the bond to be strong)



Special applications

Curved coils

- **Requirement:** measure BdL exactly along the curved beam path in a dipole (but ask yourself: is it really worth the trouble ? random non-homogeneity effect may well be estimated by measuring along straight lines)
- **Method:** forming long straight coils on a rigid substrate (strong back) with pins.
  Problems: difficult handling, mechanical stability leading to the necessity of frequent recalibrations
  Winding directly on a curved form: also possible, with LOTS of care …
- **Differential bending stress:** major risk = detaching the coil from the support
- **Coupling between bending/torsion:** in case of non-symmetric cross-section

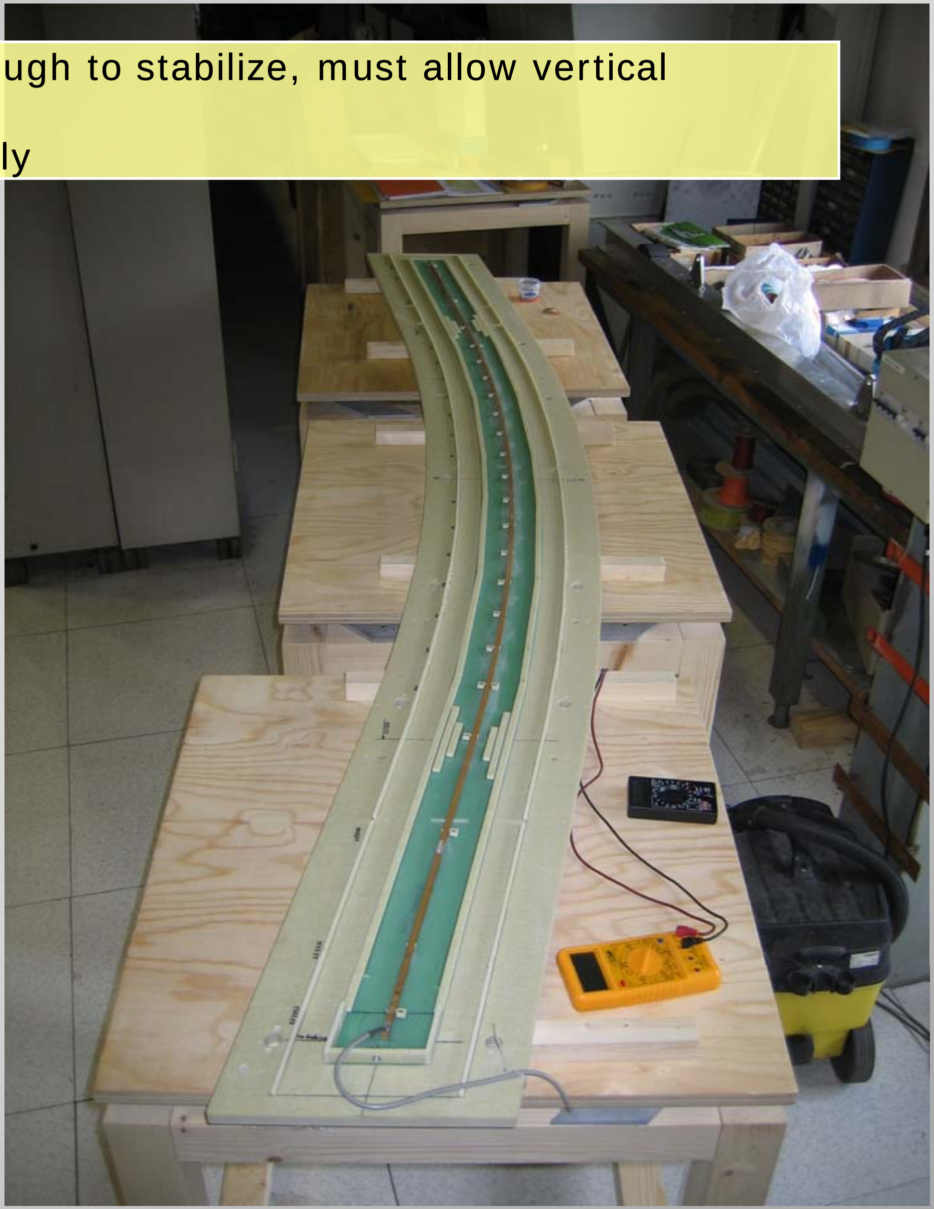


```
Regenerating model.
AutoCAD menu utilities loaded.
AutoCAD Express Tools Menu loaded.
Command: _properties
Command:
```

CNAO Fluxmeter

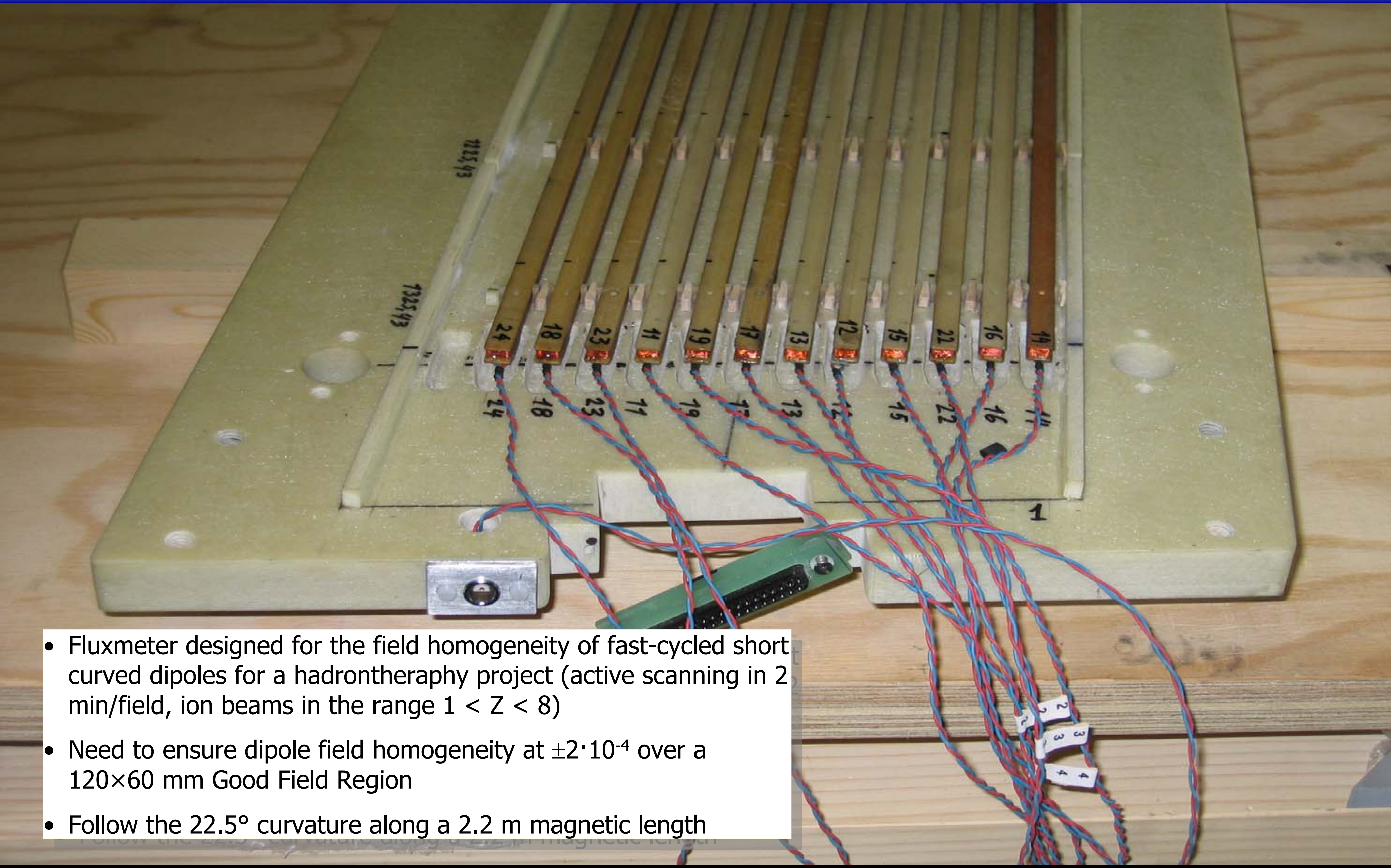
- 50 kg - G10 support (stiff enough to stabilize, must allow vertical scanning of the aperture)
- G10 pins to fix the coils radially

12-coil fluxmeter



reference coil for calibration and tracking

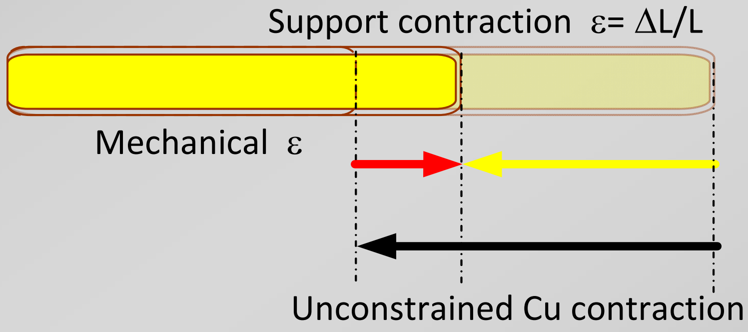
CNAO Fluxmeter



- Fluxmeter designed for the field homogeneity of fast-cycled short curved dipoles for a hadrontheraphy project (active scanning in 2 min/field, ion beams in the range 1 < Z < 8)
- Need to ensure dipole field homogeneity at ±$2 \cdot 10^{-4}$ over a 120×60 mm Good Field Region
- Follow the 22.5° curvature along a 2.2 m magnetic length

Coils for cryogenic tests

- main purpose: harmonic measurements/quench detection in short superconducting models/prototypes (vertical cryostat) when no anticryostat is available
- G10, G11, Cu (OFHC, ETP & phosporous deoxidized): all OK at cryogenic temperatures
- Grade 3 wire (thermal shock resistant) [NB: all wire specified for high T – difficult to find certification for cryogenic temperatures]
- Adhesive: Araldite GY285 (very low viscosity) + Jeffamine hardener. This brings elasticity to the epoxy and the specific capacity to withstand differential expansion and thermal shocks without delamination.
  12 h @ 45 C + 6 h @ 80 C curing.
- Thermal shocks: need to recalibrate, unglue …
- Tensile stress in the copper due to differential contraction between 300K and 4.2K. Also: solder may crack …
  Almost linear until 70K, then contraction stops.
  Wire - Support = 0.37% - 0.33%=4.4E-4 (integrated between 300 and 4 K), (normally << 1 MPa, Yield ~138 MPa). Shear stress in the bonding is usually more critical.



$$\sigma_{Cu} = \frac{\int_{4.2}^{300} (\alpha_{Cu} - \alpha_{Support})dt}{\frac{\pi}{2} \frac{\varnothing_{Cu}^{2}}{A_{Support}} N_T \frac{E_{Cu}}{E_{Support}} - 1} E_{Cu}$$

Coils for radiation environment

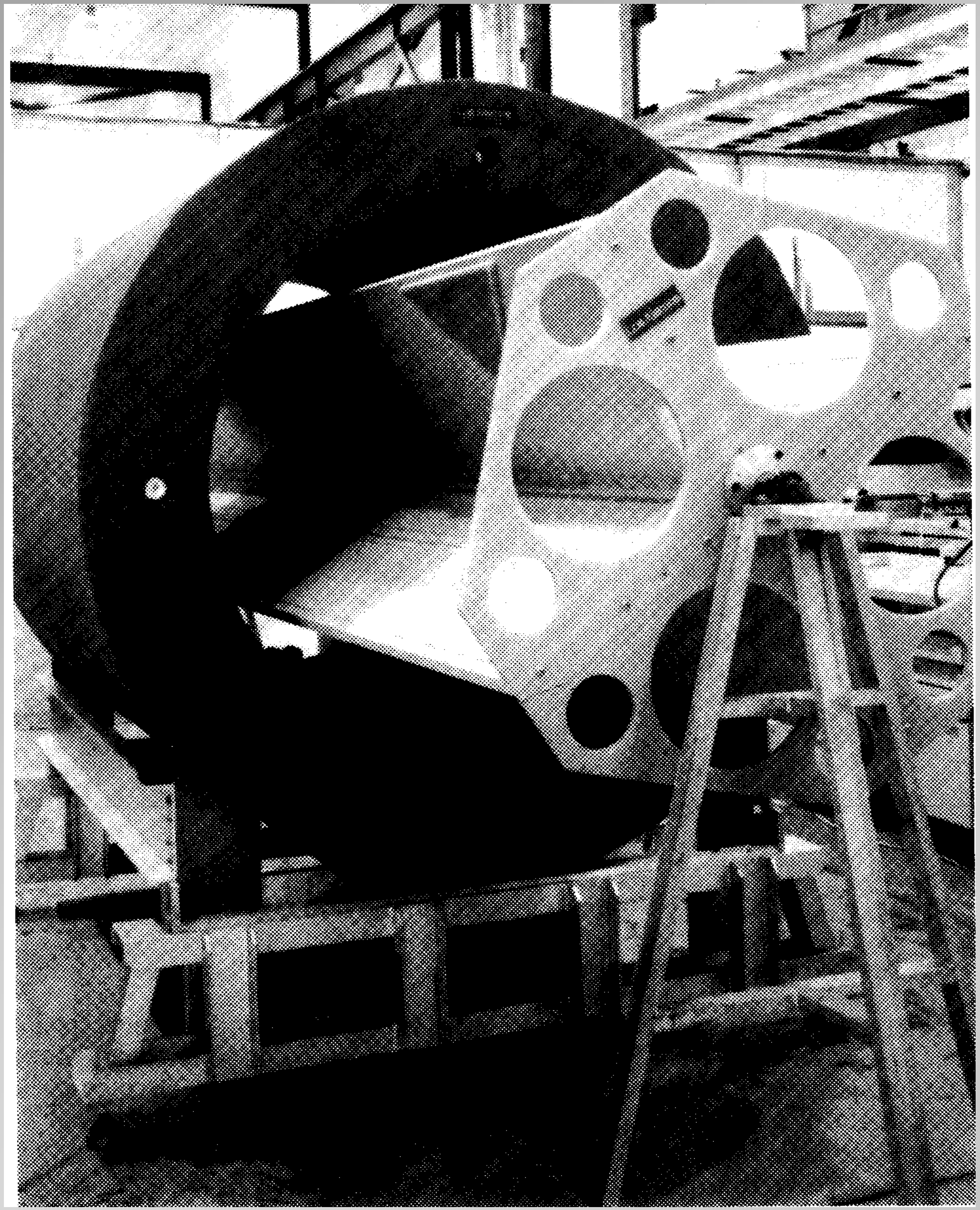
- **Issue:** long-term installation of fluxmeters inside operating accelerator magnets (e.g. real-time field measurement system or “B-train” in the CERN PS Booster Ring)
- **Sources of ionizing radiation:**
  - synchrotron radiation
  - beam losses: can directly affect the structure and/or activate materials → local dose in Gray/year must be established
- **Material effects**:

  - Copper windings: can be activated, especially if trace impurities are present (small wires use ETP Cu at 99.90% purity with up to 0.04% Oxygen to improve ductility)
  - ceramic materials, glasses: very low activation
  - organic components (bonding, insulators): can be (moderately) activated, certain polymers (eg polyethylene) disintegrate completely

Long-term effects normally negligible

(e.g. CERN’s Antiproton Decelerator B-train coils in working order since decades)

Extreme size



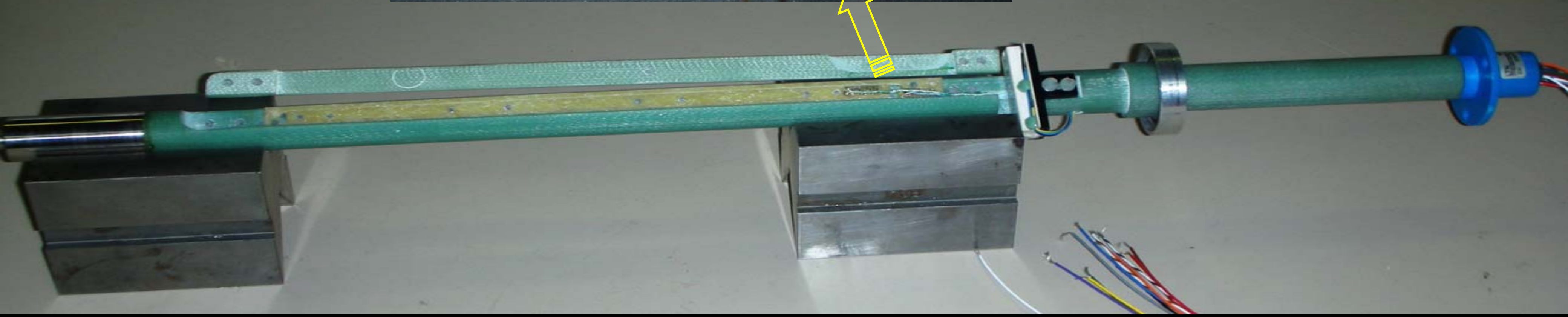
- **LANL:** coil for 1.25 m bore quadrupole
- G10 structure
- Difficult to rotate due to inertia
- **new class of problems:** stiffness/weight ratio of materials becomes an issue.
  Some systematic deformation will be unavoidable ⇒ good bucking is absolutely essential
- **on the plus side**: standard machine tolerances will give much higher relative accuracy

Courtesy B. Kraus, LANL

Small diameter coils for Permanent Magnet Quadrupoles

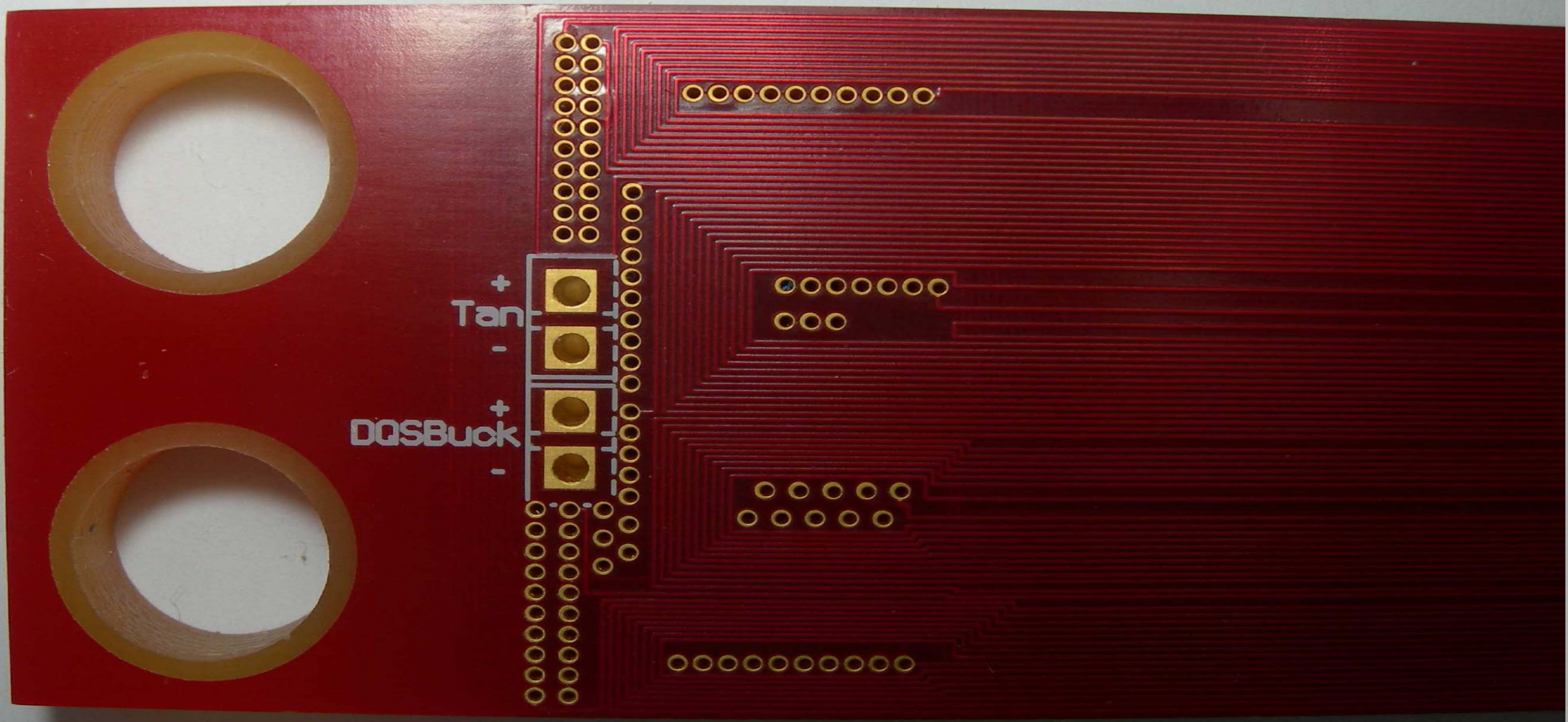
- Ø10 mm harmonic coil shaft for use at 20K (LANL)
- Coil printed on PCB then glued on a quartz substrate

- Ø20 mm harmonic coil shaft for Linac4 PMQs (CERN)
- Two concentric coils with 1:2 width and 2:1 turns for B1 and B2 compensation
- G10 shaft prototype (final piece in MACOR)



Printed-circuit coils

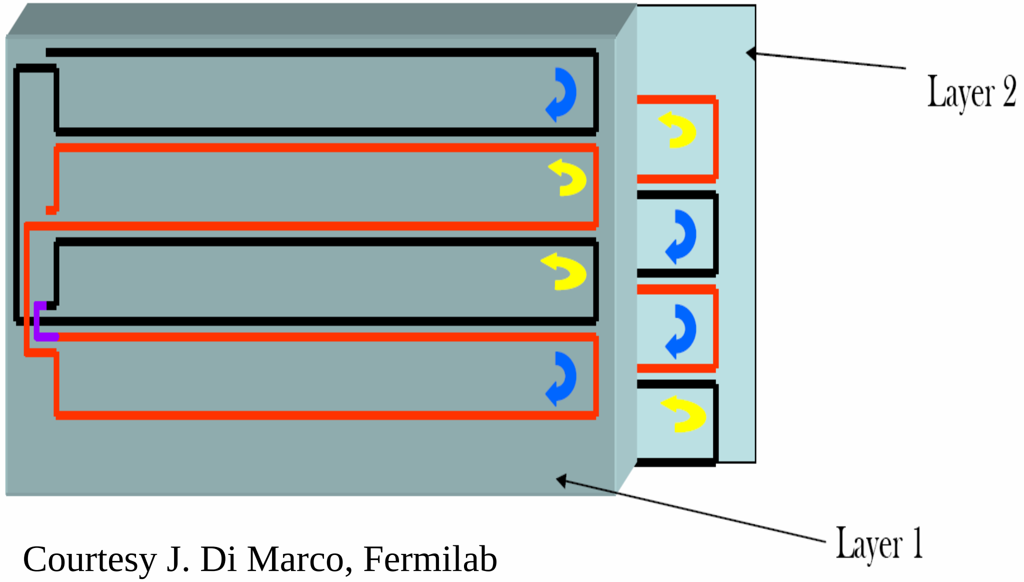
Coils on PCB



Courtesy J. Di Marco, Fermilab

Coils on Printed Circuit Board

☺	☹
• Precise trace positioning (<10 µm) • Sensitivity comparable to traditional designs (with 32 or more layers) • Manufacture large series quickly, reproducibly, cheaply • Makes practical high-order compensation schemes (B1=B2=B3=B4=B5=0)	• Novel R&D and optimization techniques to explore with willing industrial partners • Coil length above ~1 m not easy feasible • High coil resistance (in the kΩ range), must use high Z_{in} electronics • Short prototype runs, multi-layer difficult to get (unless one is prepared to pay) • High aspect ratio winding cross-section – must be corrected well ! • End effects must be taken into account (comparatively long end regions)

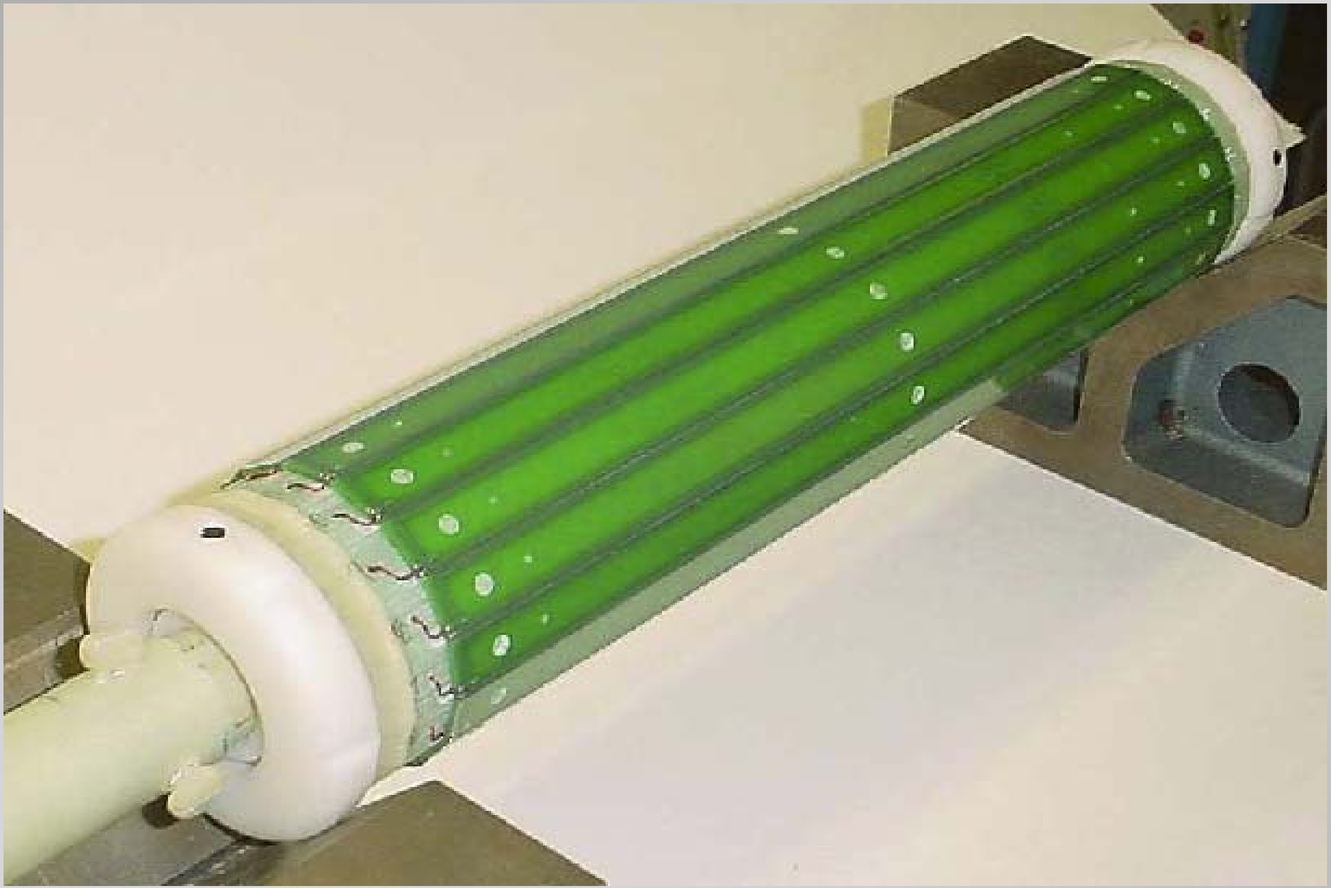


Courtesy J. Di Marco, Fermilab

Coils on PCB

BNL system of fixed / rotating coils

- 16×10-layer × 6 turns/layer, 300 mm long rectangular tangential PCB coils
- overproduction + sorting for optimal bucking
- on each channel: custom-made Programmable Gain Amplifier + 16-bit ADC (50 Hz – 10 kHz)
- digital bucking/numerical integration – flexible and convenient; sensitive to inaccuracy of gains, common modes

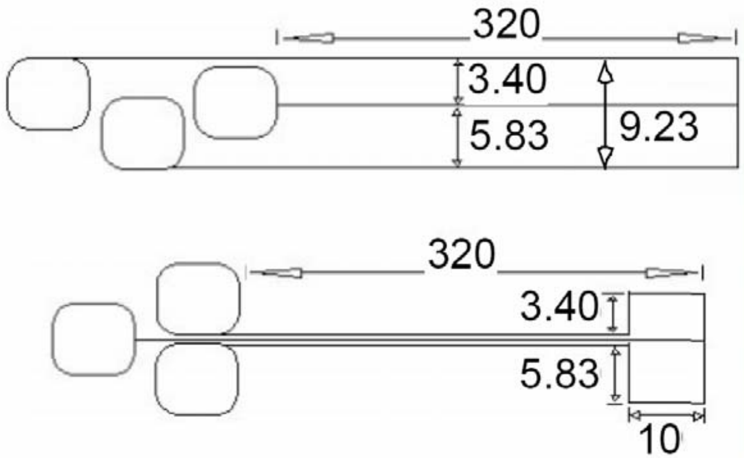


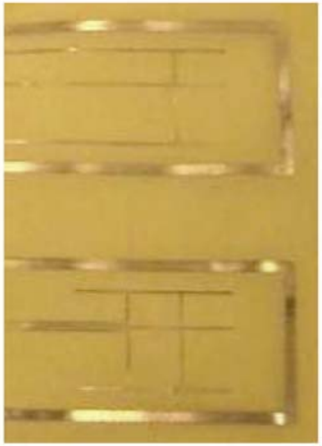
[A. Jain, « Measurements of the Field Quality in Superconducting Dipoles at High Ramp Rates », IEEE Trans. Appl. Supercond. 2006]

Coils on flexible supports

Kyoto university rotating coil system

- Measurement of small PMQs with Ø20 and Ø15 mm bore
- printed circuit coil: 1 Cu turn (100 µm wide × 35 µm thick) on 25 µm thick polymide sheet, glued onto a quartz rod (very small thermal expansion)
- two diametrically opposed coils with two parallel windings each – several series and opposition combination possible for bucking and harmonic measurement up to n=10 (integral and local coils available)
- 10 Hz rotation necessary to get reasonable signal





Y. Iwashita MODIFICATION AND MEASUREMENT OF THE ADJUSTABLE PERMANENT MAGNET QUADRUPOLE FOR THE FINAL FOCUS IN A LINEAR COLLIDER, PAC 2007

Final Remarks

Final Remarks

Search coils are an essential tool for the measurements of accelerator magnets

- **enabling technology** for certain applications (e.g. efficient series measurements of long LHC dipoles)
- **multi-filament wires** provide the best accuracy for high precision harmonic measurements
- **skilled and careful** manual work is necessary

areas for future development

- **Coils on PCB**: allow automatic, very high precision winding. Desirable improvements: larger size (length), lower width, denser stacks for higher sensitivities, lower costs

- **Winding techniques:** better control of manufacturing procedures (tensioning and impregnation of multi-filar cables, materials for higher reliability at cryogenic temperatures)

- **Scalable technologies:** going efficiently towards very small or large diameters, long and possibly curved coils

Final Remarks

Winding a coil *looks* easy ....

... it is not ! Be careful and enjoy