LESSONS FROM THE 3-POLE SC WIGGLER TEST

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Three-pole wiggler model tested in Dewar demonstrated ~2.7T field in series of runs. Results are discussed here under the scope of comparison of reached and calculated parameters and review of technology.

1. Introduction

In a framework of a CESR upgrade to Charm-Factory [1], there was proposed to install wigglers for obtaining the damping required. Such a wiggler unit supposed to be short enough allowing modular filling of the ring's free space [2]. As the full-scale wiggler model is a long-time enterprise, it was suggested, that 3-pole model can be manufactured quickly and all nuances of technology and engineering can be evaluated a prior to the full-scale prototype [2]. This suggestion was based on existing 12" Dewar with all necessary current feedthrough and service elements specially designed for the SC magnet tests [3].
Despite the wiggler period initially suggested was 28 cm [2], those days concerns about irradiation of the walls of CESR's vacuum chamber moved it to 20 cm. Latest considerations show however that problems with beam dynamics require longer period, hence problems with wall irradiation recognized as less important. So the wiggler period was finally settled as 40 cm. So mostly for historical reasons the wiggler model for the test described here has period of 20 cm.
The latest calculations indicated that wiggler will have five poles with equal field and two end poles with ~ a half field each [4]. The operational field is supposed to be up to 3.5 T. Each of the end poles also carries additional multi-turn trim coil. These additional coils are connected in series and will trim integral of magnetic field over the wiggler.

The main point of concern in a job acquired was technology for winding. We tested a few wire sizes and technologies. Finally we came out with technology and procedures of the coils and poles fixation in place.
Composition of the wiggler magnet as individual poles carrying a coil and bolted as a whole unit to the single yoke plate was under test also.

As this job was successfully finished here we are representing some main results obtained on the way. These results might be interesting in future.

2. Model

So the wiggler model has three pairs of poles with SC coils. End poles have two coils: main one and trim one. Main one connected in series with central coils.

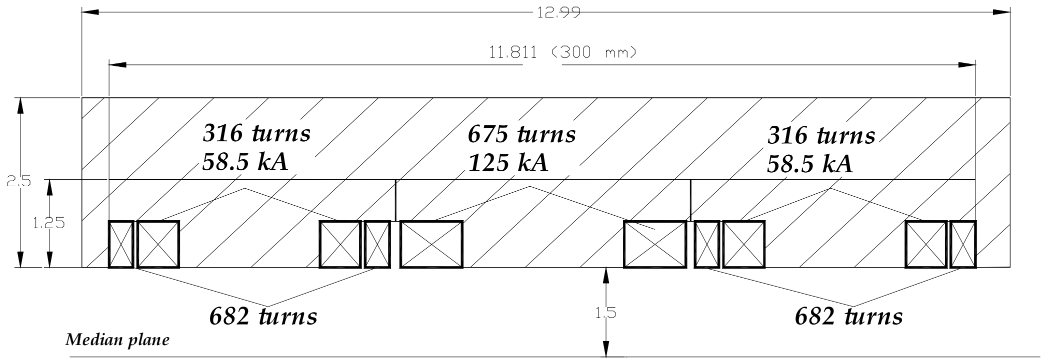

FIGURE 2.1: Distribution of turns in 3-pole model. Upper half of the wiggler is shown. Design currents are shown also. Lines in iron show schematically the poles and assembling plate divisions. Dimensions are given in inches.

Coil shape was a subject of intensive optimization using 3D code MERMAID, coming out with the shape shown in Figs.2.3 and 2.4.

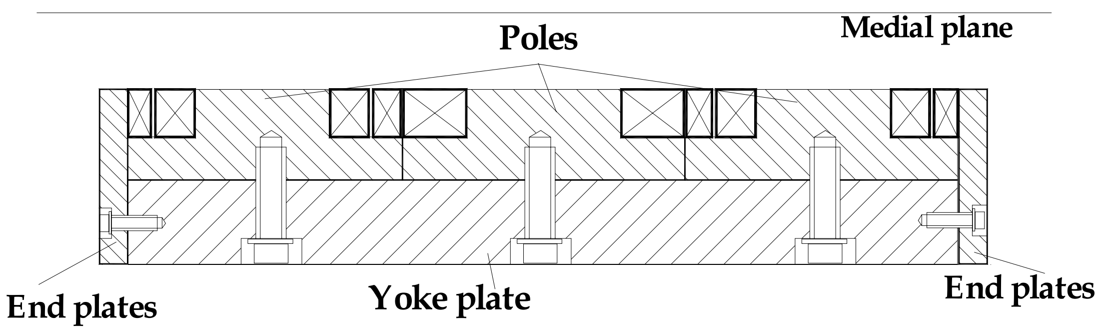

FIGURE 2.2: Mechanical scheme of the wiggler.

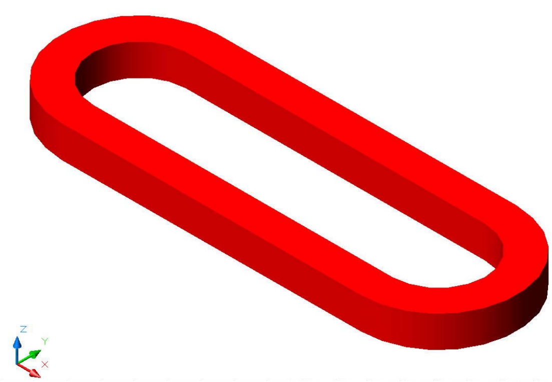

FIGURE 2.3: Isometric view of the race track type coil.

The poles bolted to the assembling plate, carrying three poles each and representing upper and lower pole assembly respectively.

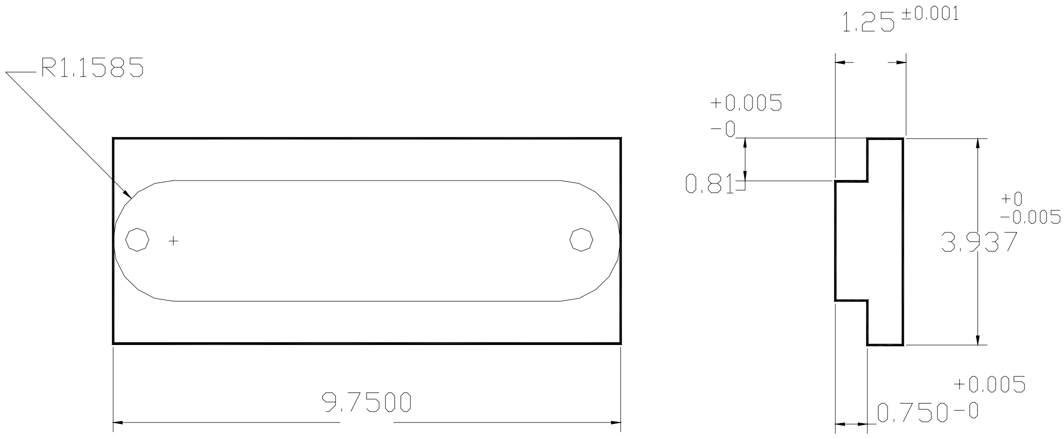

FIGURE 2.4: The individual Pole iron of the wiggler.

End poles have lowering in the middle of 0.5 mm deep and ± 5.5 cm wide.

3. Technology

The very first coil was wounded on the dummy pole, made on aluminum directly with 10*mils* Teflon tape and two Capton 3*mils* layers between the wires and core. Later we used glass tape instead of Teflon. This allows stronger fixation of the coil on pole. Wounding form is pretty much in the same manner as we used before [7].
This first probe coil has the designed number of turns and geometry. The wire used for this test was Otocumpu 0.6-mm SC wire. This wire contains 54 filaments of NbTi alloy in Copper matrix. The wire is covered with Formvar enamel. For impregnation the Epo-Tek T905 Epoxy was used. The paper NOMEX was used for interlayer insulation. After every four layers of windings, the coil restrained for curing during ~1.5 hours with the side pressure applied up to ~ 30 *atm* on it. During the winding the tension applied to the wire was at the level ~9 lb. per wire diameter *d=0.6 mm*. Teflon spray allowed us to avoid sticking between the parts.

The coils wound on iron demonstrated good properties. We used this technology found for winding of all poles.

We have experience in using ECCOPOUND (Stycast) also, which we used in coil winding of dual bore quad [7]. However we didn't use this epoxy in 3 pole wiggler model.
During winding and after the resistance readings of all wire in action were taken.

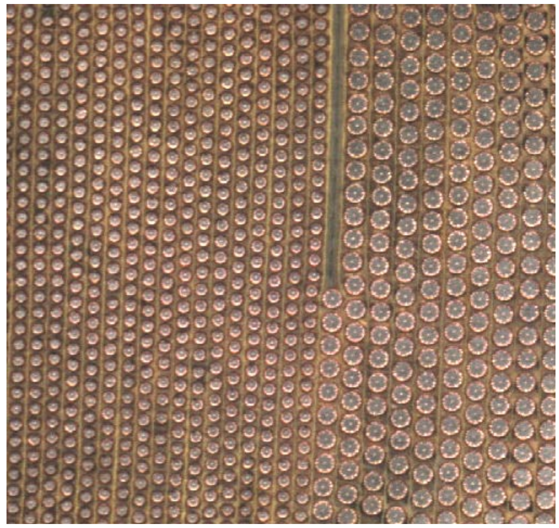

FIGURE 3.1: View to the cut of the end coil. This is one of the latest in series. Wire with larger diameter is the main one. Trim coil wound with wire having smaller diameter.

4. Calculations

As it was mentioned, all calculations were done with 3D code MERMAID.

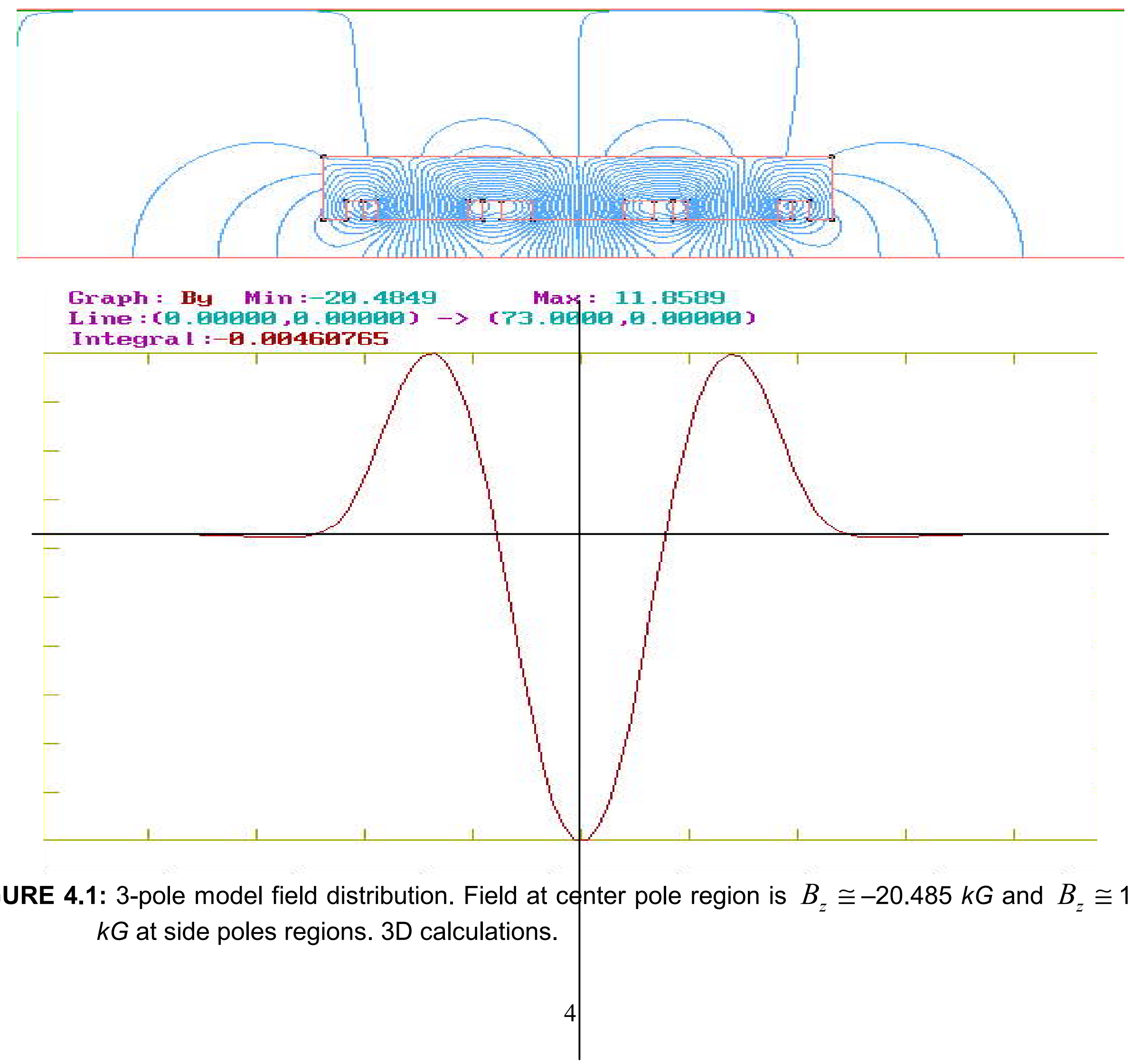

FIGURE 4.1: 3-pole model field distribution. Field at center pole region is $B_z \cong -20.485$ *kG* and $B_z \cong 11.86$ *kG* at side poles regions. 3D calculations.

The forces acting to the each *cm* of the coil length in central area right to the midpoint in Fig. 4.2 are the following:

	F_x, *kg/cm*	F_y, *kg/cm*
Central coil	129.855	106.687
Trim coil, center side	-35.304	53.127
Trim coil, out side	16.681	61.762

For estimation of the pressure one needs to divide these numbers by the height of the coil, which is 0.75 *in*=1.905 *cm*, i.e. roughly by two. The pressure acting at the curved part of the coil is little bit more complicated, 3D-computer code allowed to calculate local force at every point of the coil, however.

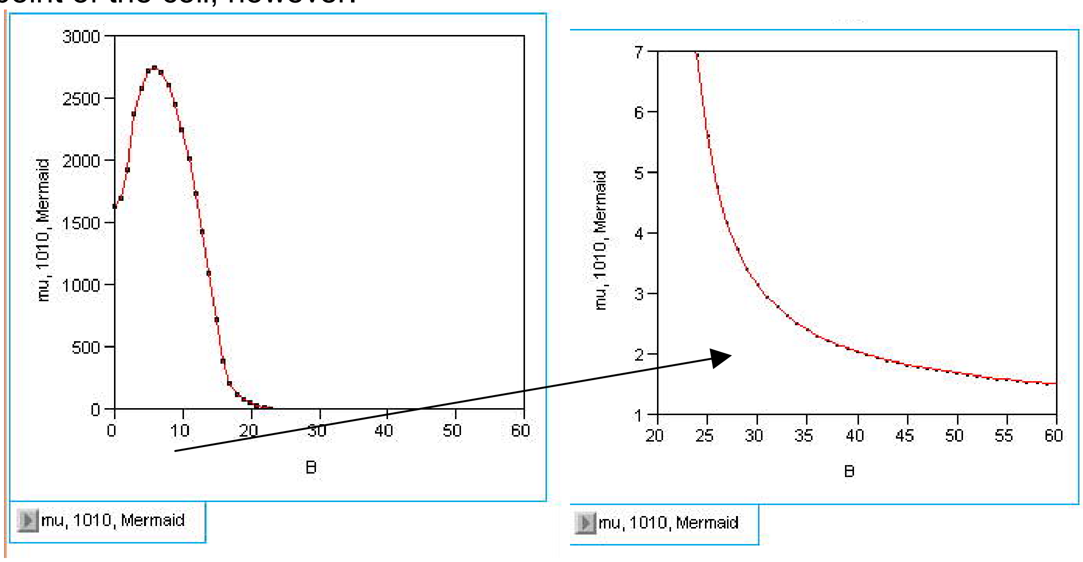

FIGURE 4.2: Magnetic permeability functionally generated by MERMAID. At the right the scaled view of the curve at high field values is represented.

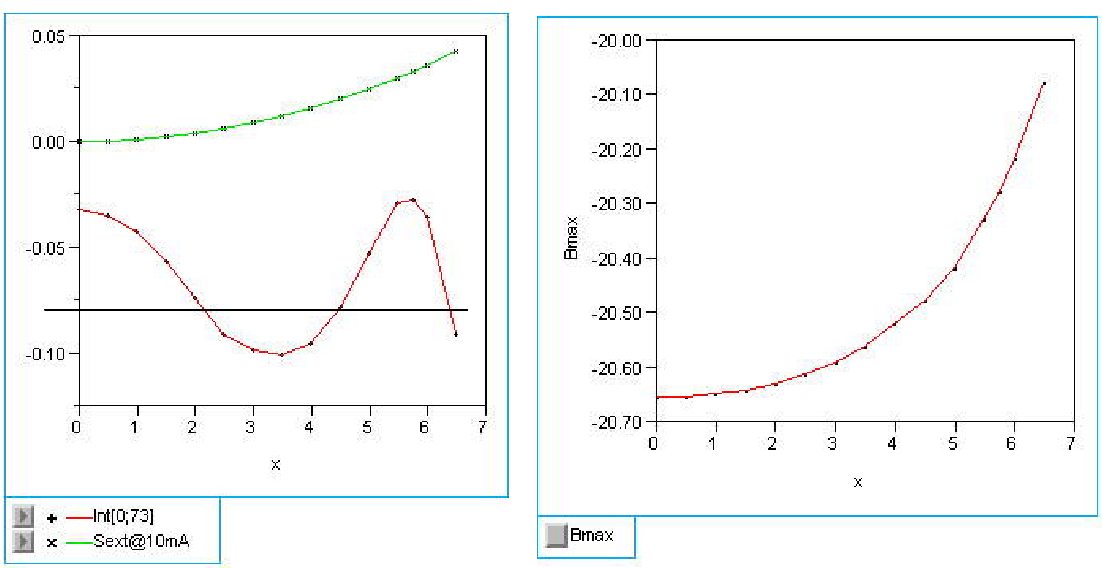

FIGURE 4.3: Integral *kG* $\times$*cm* (left) and field at maximum *kG* (right) as functions of transverse coordinate. Integral for CESR sextupole running at 10 mA is represented at the left for the reference.

5.Installation in Dewar

As it was mentioned we used existing 12in Dewar. Top flange caries all feedthrough holes with flanges, feeding tubes and so on. Multi wire connectors were used to deliver signals from the liquid Helium level monitor. Two coaxial tubes with vacuum and superinsulation in between was used for positioned Hall probe into magnetic field of wiggler. So the probe remained at about room temperature [3].

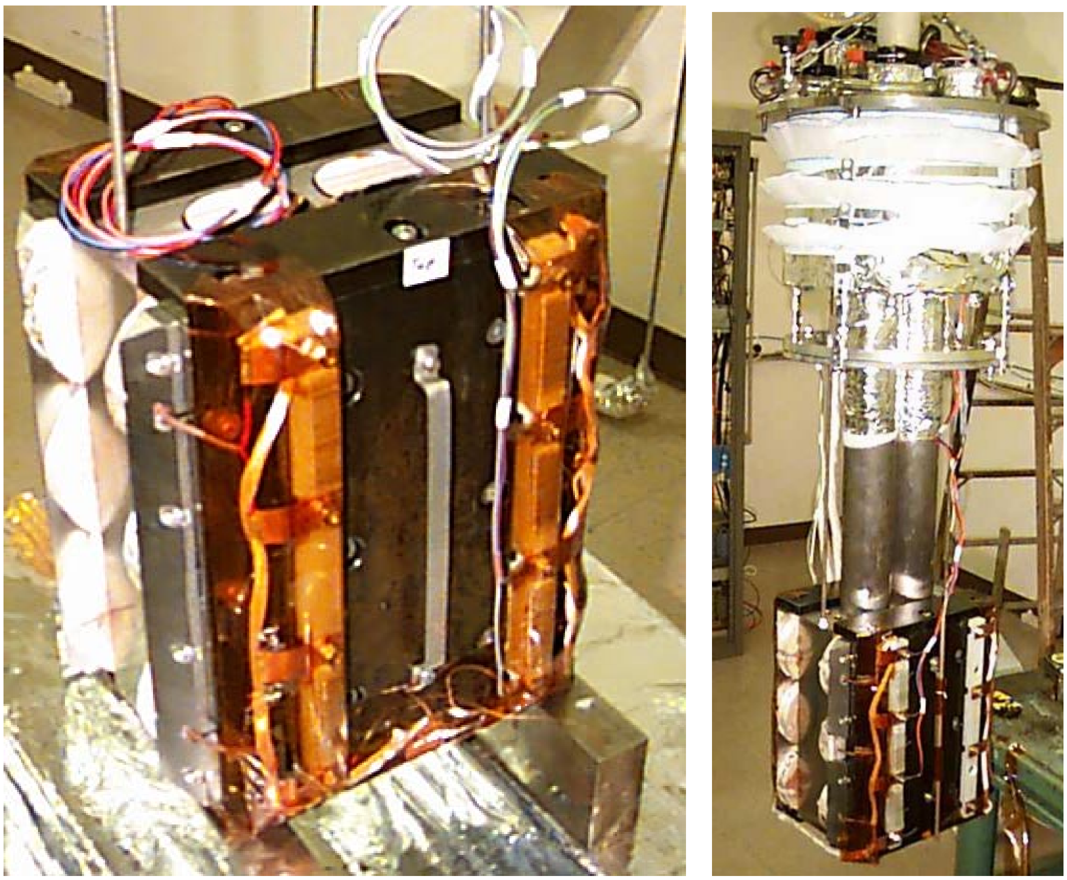

FIGURE 5.1: 3-pole model. At the right- prepared for testing in existing Dewar.

We made the filling of Dewar in such a way, that the Helium flow not touching the magnet yoke. This helps in avoiding deformations of the magnet during cool down. Also additional copper plates for preliminary Nitrogen cooling was installed and used here.

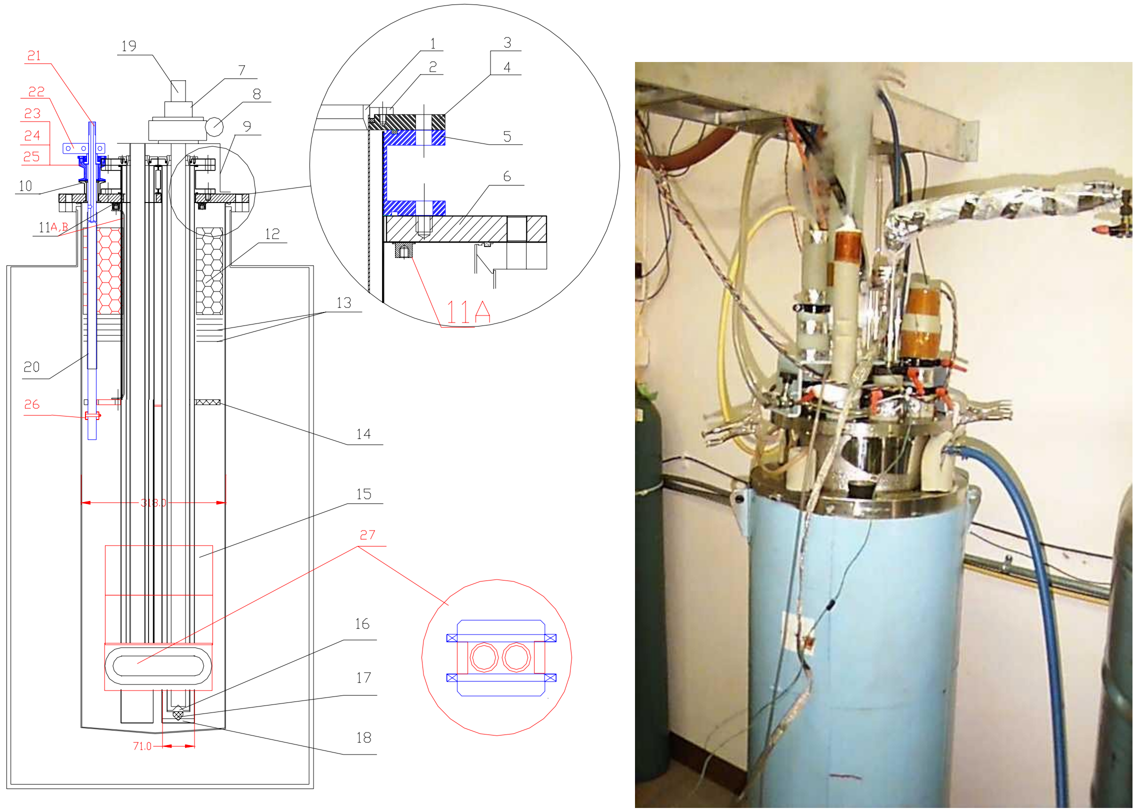

FIGURE 5.2: Dewar assembly during the test.

6. Measurements

For measurements we fabricate special mechanism allowing motion of a Hall probe inside tubing. So despite the probe remains in room atmosphere, also it becomes cold, however. That is why the Hall probes with thermal sensitivity ~10^{-4}%/K was used here.

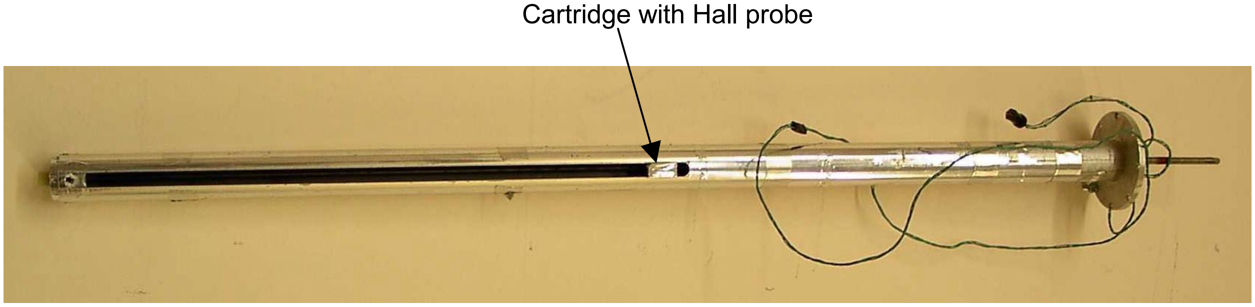

FIGURE 6.1: Device with Hall probe for the field measurements inside coaxial tubes.

Threaded shaft with threads 1/24 per inch rotated by stepping motor carries a cartridge with Hall probe.

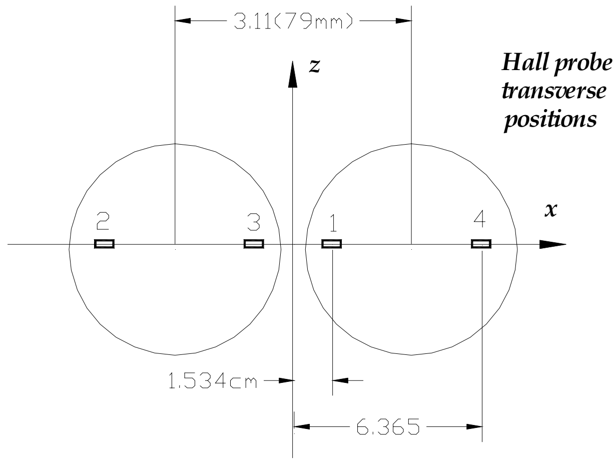

FIGURE 6.2: Integrals along the longitudinal coordinate *s* are taken at the transverse displacements of the Hall probe as indicated here. Distributions in Figs. 6.5 and 6.6 are taken for points 1 and 2 respectively.

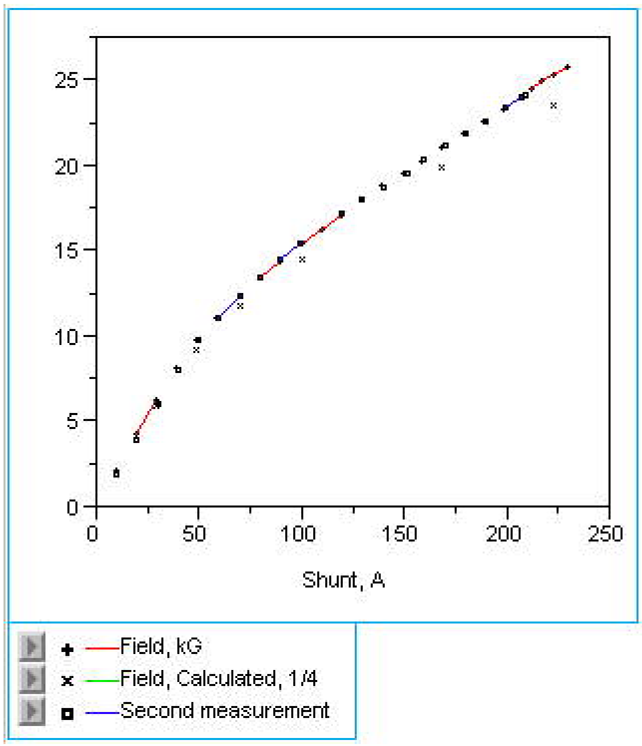

FIGURE 6.3: Measured saturation curve versus calculated. Measurements had done in two different runs. Measured field is ~6% **higher**, than calculated with 1010 iron room temperature table[1].

Field at central point measured also with F.W. Bell model 5080, having guaranteed accuracy $\pm 1\%$. Re-calibration confirmed this.

[1] That was explained by the presence of iron wrap around Dewar. The Dewar was acquired from RF group working with SC cavities, where screening from the Earth field is important.

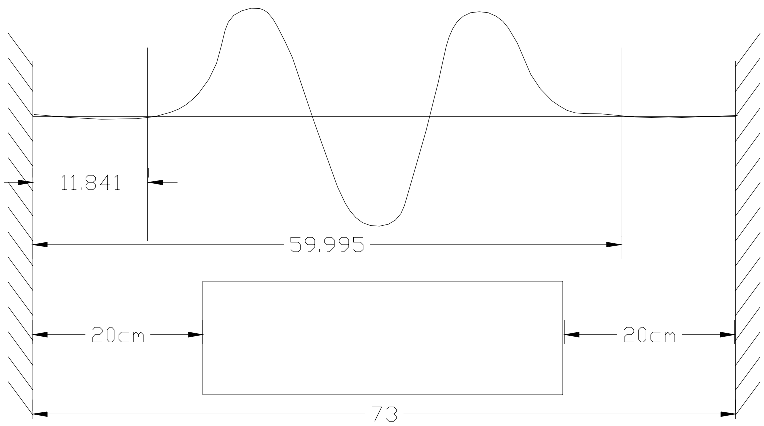

FIGURE 6.4: Measurements in longitudinal direction with Hall probe vs. model margins.

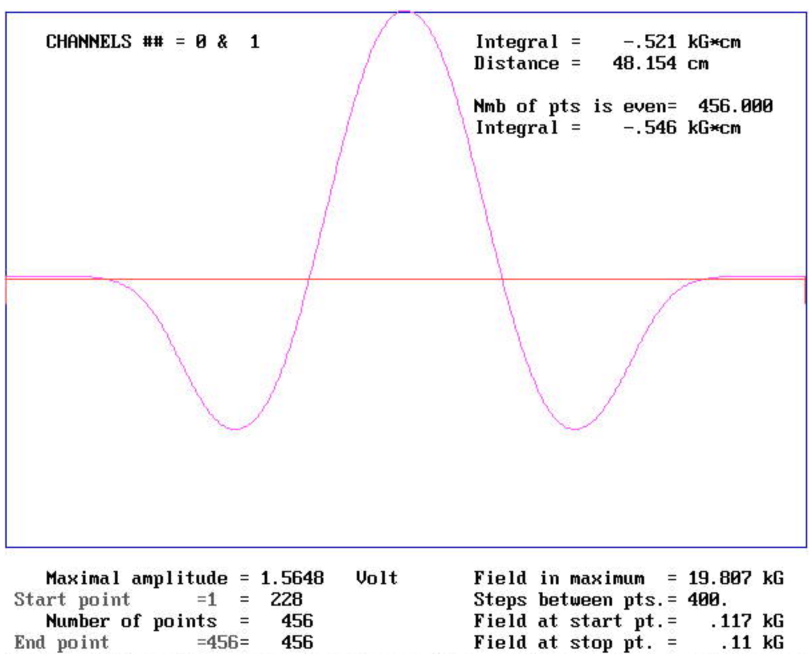

FIGURE 6.5: The field profile for feeding current 170A and trim coil current 2.1 A. Inner position, *x*=1.53 cm. For Hall-probe calibration used the factory specifications (1988). Hall probe has temperature dependence as low as 0.004%/degK. Magnetic field in maximum is 21.16 kG. File: mov3.

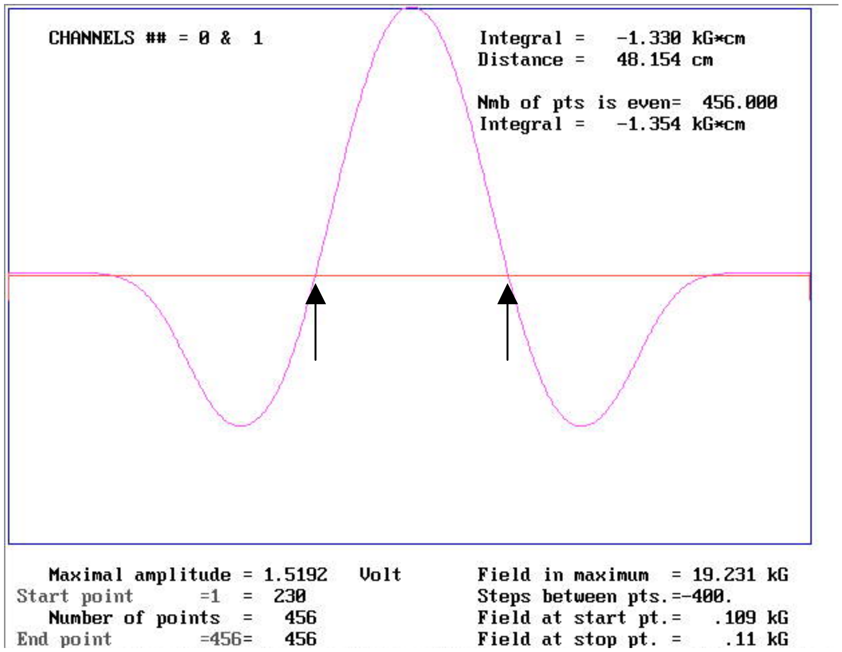

FIGURE 6.6: The field profile for feeding current 170A and trim coil current 2.1 A. Inner position, *x*=6.37 cm. For Hall-probe calibration used the factory specifications (1988). File: mov4. Distance between zeros of field is 11.536 cm in good agreement with calculated by MERMAID: 11.534.

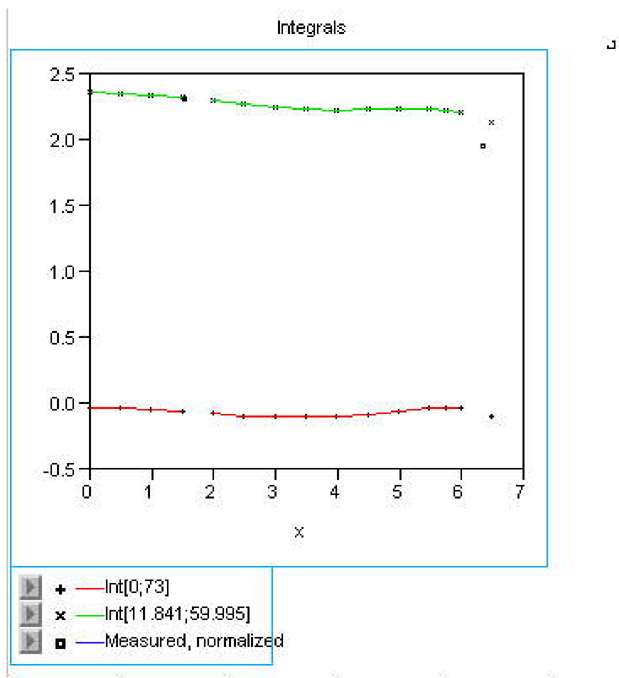

FIGURE 6.7: Calculated difference in integrals. Upper integral calculated for the real run distance of the Hall probe. Lower curve is the same as shown in Fig.7. In calculations main pole has negative value. This means, that for comparison with measurements, the integral value must be multiplied by the factor –1. Two points represent measured values.

Latest measurement showed that the integrals along straight line are:
Integral over x=1.534 *cm* is I= -0.52 *kGcm*
Integral over x=6.365 *cm* is I= -1.33 *kGcm*

Difference is $\Delta I \cong -0.81$ *kGcm* in a favor of end poles (they are stronger, than necessary). This coincides with better iron properties.
The difference between integrals can be explained by improper profiling the end pole and clamping the end coil in attempt to reach maximal strain. The lowering right now is ~0.5*mm* only. (In 40 *cm* wiggler it will be ~3.5 *mm*). Will be adjusted if necessary. This requires less lowering, however.

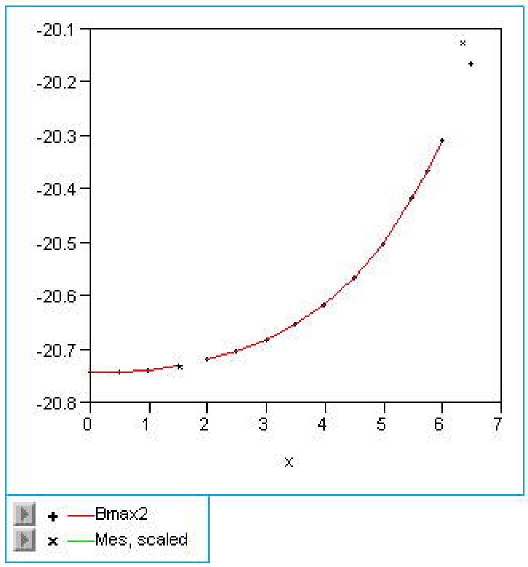

FIGURE 6.8: Field at maximum *kG* from Fig **4.4,** with measured points added.

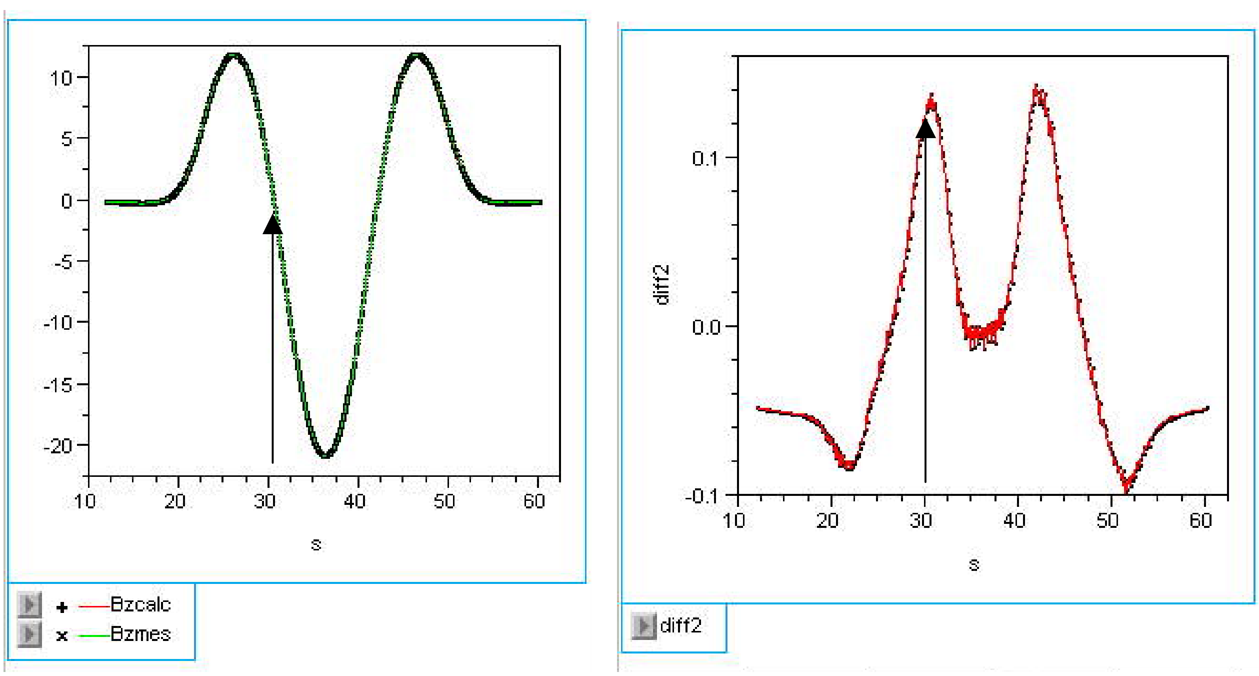

FIGURE 6.9: At the left measured and calculated field (in *kG*) in full scale is represented as functions of longitudinal coordinate, *cm*. At the right–the difference. Maximal difference takes place around zero field regions. File Lev8, x=1.53*cm*.

General output from measurements done in Dewar is that they are in good agreement with calculations.

7. Quench history

is represented for few runs with strained and free coils as follows:
1) 4 layers of paper : 119, 158, 204, 221, 223 A
2) Released longitud. coil : 140, 201, 202, 205, 212, 227 A
3) Strained ~ 1Mpa, G10 : 125, 141, 196, 234, ~4 hrs of measurements(170*A*), 242 (not quenching).
4) Strained ~20MPa, G10 : 134, 202, 226, ~1.5 hrs of measurements (170*A*), 202, 207
5) Cooled with new pipe : 120, 223, 245.
6) Strained ~20MPa, G10, pins: 108, 237, 218, 230, 244, 224
7) Str.~20Mpa, G-10,pins, Vert. free: 108, 221, 218, 226, 233
8) Free vert., longitud. free : 93, 152, 166, 174, 184, 185, 191, 193, 204, 207, 215, 215, 223, 230, 222, 220, 218
9) Repeat, previous : 88, 202, 232, 211, 229, 231
10) Strained 35 Mpa, G10, epoxy :230, 252, 253
The same is represented in the graphs below.

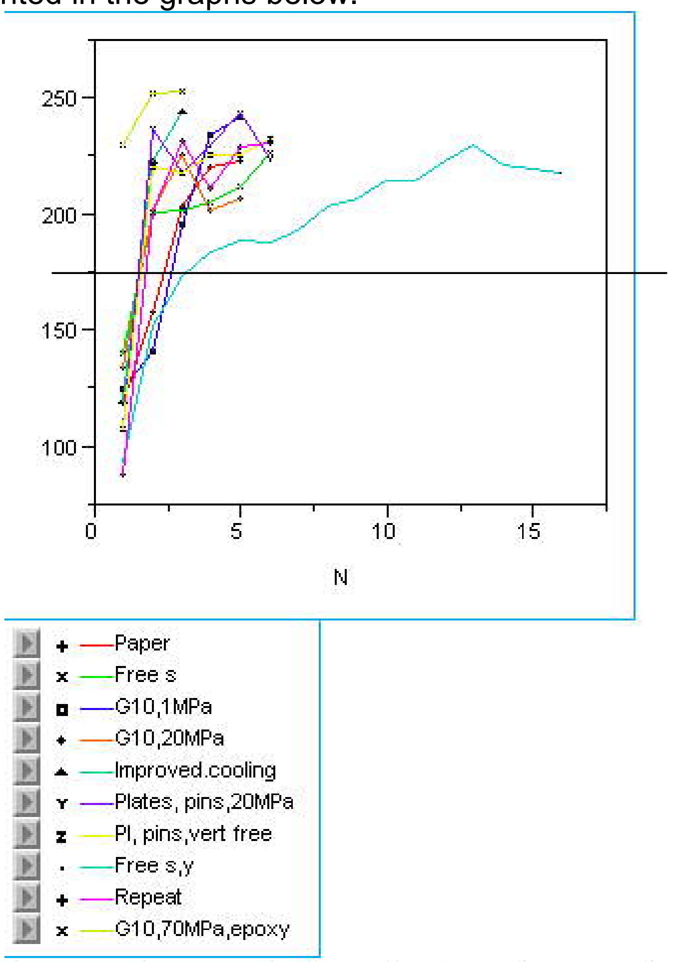

FIGURE 7.1: Quench history for four different strains and cooling procedures. Line corresponds to design current. Pressure at lower title must be read G10,35 Mpa.

Partly restrained coil demonstrated current~242A and was limited by power supply for the time of measurements. Latest test showed first quenches on 230A. This technology supposed to be used for 40-cm period wiggler.

For estimation torque *T*-load *P* relation the formula was used for 60 *deg* threads and angle of threads 30 *deg* [5]

$$T \cong P \times [0.159 \times l + 1.156 d \times \mu] = P \times d[0.159 \times l / d + 1.156 \times \mu]\ ,$$

where μ –are the friction coefficient, the same between threads and bearing surfaces, *d* –is the bolt diameter, *l* –is a height of the thread (so the angle of the thread α defined as $tg\alpha = l/\pi d$). For $\mu \cong 0.15$ could be taken. Torque applied to the six bolts clamping the end coil is 10*lbft*.

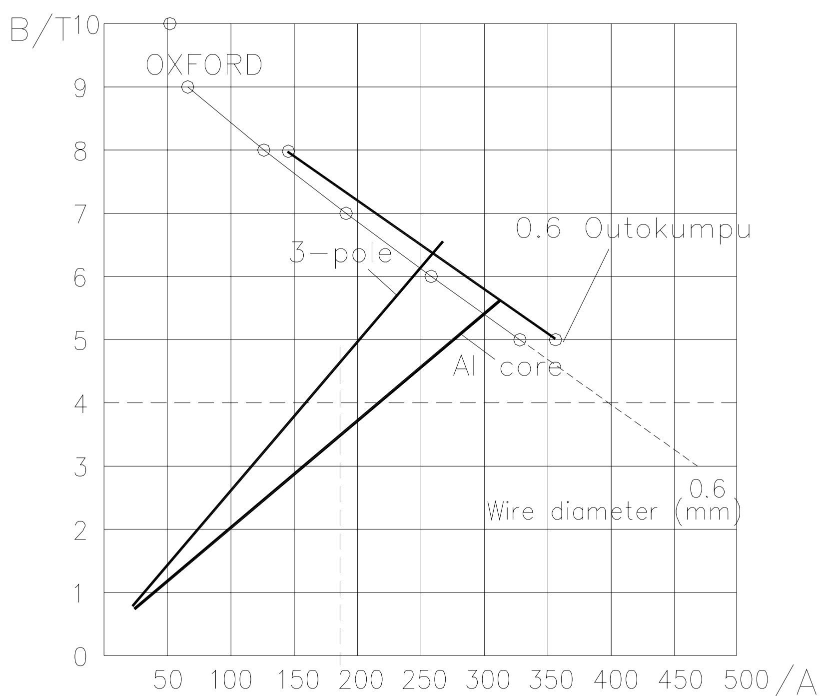

FIGURE 7.2: Loading curves for three-pole wiggler. Copper to NbTi ratio in wire is 1.35.

8. Procedure for installation of poles

Finally we tested a new procedure for the poles installation. This procedure allowed elimination of forces acting to the iron yoke at the stage of squeezing coils. This allows the end plate to function as required by magnetic properties only.

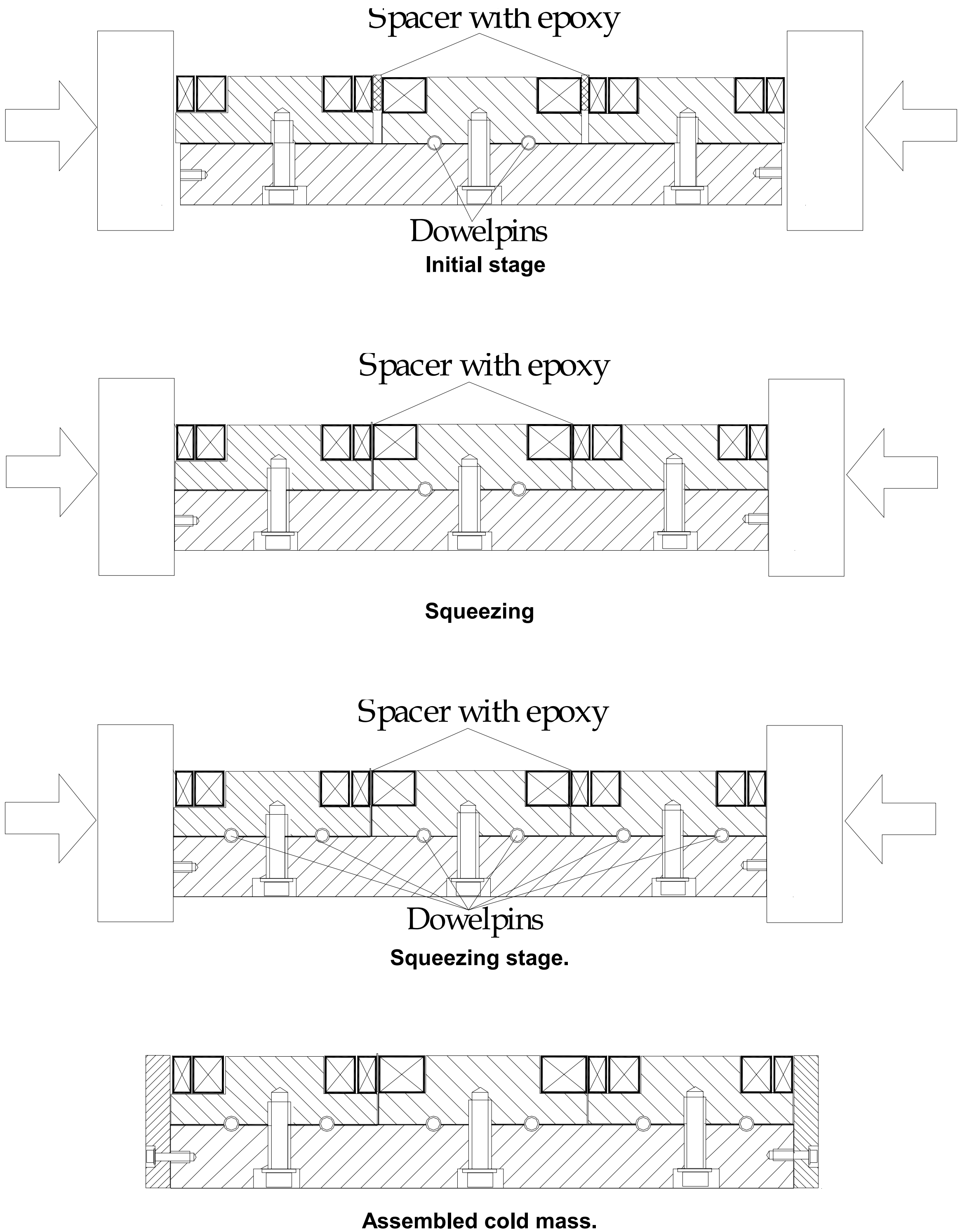

FIGURE 8.1: The sequence of assembling.

Squeezing arranged with help of hydraulic system. In a piston having 10 cm in diameter the pressure was build about 5000 psi. Area of the coil surface is about 40 cmxcm.

9. Discussion

1) Different types of the coil strain indicate, that the first quench happens at lower that current than final one does not matter what strain (up to ~40 Mpa) applied.

2) Maximal current achieved indicates some dependence on the strain force, but not drastic, always remaining above designed current. Meanwhile deformation of the coil under ponderomotiv forces will be macroscopic, so that the coils will touch each other, despite of ~100 micrometer initial gap, what is the case if the coil is free, see Fig. 9.1. Coil still not quenching during this trip.

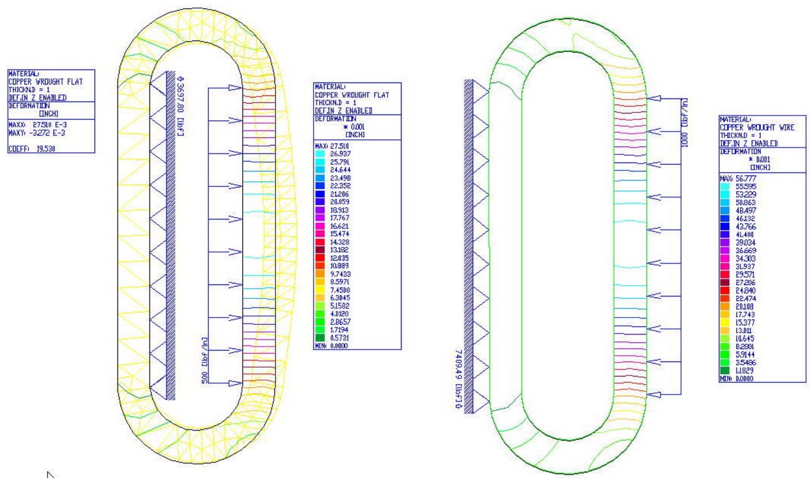

FIGURE 9.1: Modeling of deformations. Force applied ~500lb/in. Coil will be deformed definitely so the neighboring coils are touched.

3) One definite result is that the coil has no memory on training: each new runtime, after the wiggler was warmed up, the first quench occurs at lower current for the first time. This means, that the quench occurs due to reversible motion of the coil(s). According to statistics of quenches [6] one of the central coils quenches in ~41% of cases. Normalized pressure about 40 Mpa is enough for holding coils in place after cool down.

4) Procedure for the pole fixation on the yoke plate tested and recommended for future utilization.

5) MERMAID gives the field in good agreement with measurements.

Latest test done with 3-pole wiggler in Dewar was done with rewound end coil. First quench happened at ~162 A, while a run immediately after this first quench the wiggler was not quenched at 200 A feeding current.

In this stage the wiggler was transferred to the installation into horizontal cryostat[2].

[2] For 40 cm period 7 pole wiggler more tuns allowed for the coil, so the first quench in coils tested occurs at ~330 A, while designed current is ~161A.

10. References

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