USAGE OF FERROFLUID FOR IMPROVEMENT PARAMETERS OF MICRO-MAGNET

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Abstract. It is shown here, that if the media surrounding wires in helical undulator acquires magnetic permeability $\mu \sim 10$, this ~doubles magnetic field at the axis. We concluded, that suspension of ferrite powder in oil based liquid –ferro/ferrifluid– can serve for this purposes and for cooling purposes at the same time as well. We investigated self-made fluid with micrometer size ferrite particles and factory made fluids with nanometer size ones.

INTRODUCTION

Utilization of helical undulator with minimal period is a key moment in polarized positron/electron production scheme [1]. Conversion system with undulator having ~10^4 periods can provide one to one pulsed conversion of primary 150 GeV electron/positron beam into polarized one. In [2] some tested constructions of undulators having period 6 and 10 mm described. The core of pulsed undulator is so-called double helix, introduced in [3] for spin manipulation. One can see, that shortening period of undulator allows cut of total length of undulator and/or widens safety margins for conversion efficiency. With decreasing period, axis magnetic field drops exponentially, so period shortage inevitably forces decrease of radius of helix and, hence, shrinkage of aperture allowed for the beam. So the aperture reduction becomes limited by the beam emittance only. Wiring becomes adequately small, which in its turn yields high current density and high volume density of energy dissipation. Magnetic yoke improves the situation as always, however, in case of mm and especially sub mm-period undulator, this creates significant technological difficulties. One can consider cementing of conductors in ferrite powder. Cooling possibilities becomes reduced, however. Although we have shown here that this method is working well in some extend; however other, more elegant solution described here for the first time.

Namely, for pulsed helical undulator we are proposing to use a liquid magnetic substance for cooling and magnetic field enhancement at the same time. In case if liquid kept in intense motion for the purposes of cooling, the turbulence itself can keep the substance homogeneous as well. We have found that utilization of *ferrite* powder of micrometer size in turbulent flow makes this kind of fluid working well and makes this substance cheap and hence more attractive for magnet design. We called this type of fluid as *ferrifluid* (FF).

After this work began and bring some hopeful results, we found that this type of liquid substance –ferrofluid was well-described about twenty years ago, [4]. Initially ferrofluid considered as colloidal suspension of nanometer-size ferrous material. The oil or water serves as a caring substance for ferro/ferri particles. So the typical magnetic particle in ferrofluid is a single-domain object. Brownian motion keeps ferrofluid substance homogeneous. Ferrofluid fabrication is rather developed business now. Ferrofluid of good quality is rather expensive[1], however.

So, usage of magnetic liquids together with improvement of magnetic properties of micro-magnet opens a new possibility for efficient cooling and insulation of wires, as the ferrite practically does not conduct electricity. In its turn this allows either reaching higher fields at the axis and/or increasing an aperture allowable for the beam paying reasonable cost.

This publication makes strong support for design of 1-m long helical undulator with 2.4 mm period, supposing to be used in E-166 experiment for test of polarized positron production scheme [5].

BASIC ELEMENTS OF HELICAL UNDULATOR DESIGN

As it was pointed out in [3], helical magnetic field can be provided by pair of shifted on half period in longitudinal direction helical conductors, caring opposite currents. This type of helical undulator suggested for E-166 experiment [6]-[8]; see Fig. 1. Here we use a wire with square cross section as it delivers ~15% more axis field.

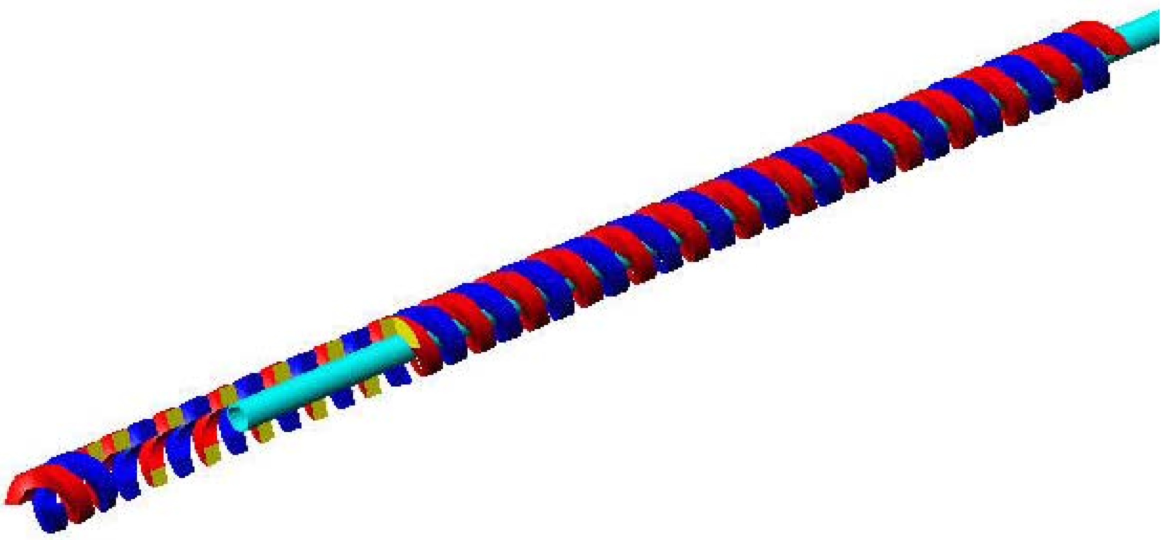

FIGURE 1: Bi-helix with rectangular wires. The cut made for better visibility of details.

One peculiarity, associated with this design is that magnetic field at the axis is a strong function of helix's radius if period is fixed (or period of helix if this time radius is fixed). In Fig. 2 this dependence represented graphically. Saturation in this curve indicates that the field can be calculated as for two parallel infinitely long wires. One wants to have maximal axis field, while aperture kept as big as possible, so this yields some compromise. The current running in the wire comes close to thermal break down even with intense cooling.

One can see in Fig.1 that there is a space between the wire conductors of the order of the wire size itself. One can consider filling this space by ferrite in attempt to improve the field/current ratio. Technologically this is rather easy thing to do.

[1] Reaching ~$10/ml for the best; typically it is $1/ml.

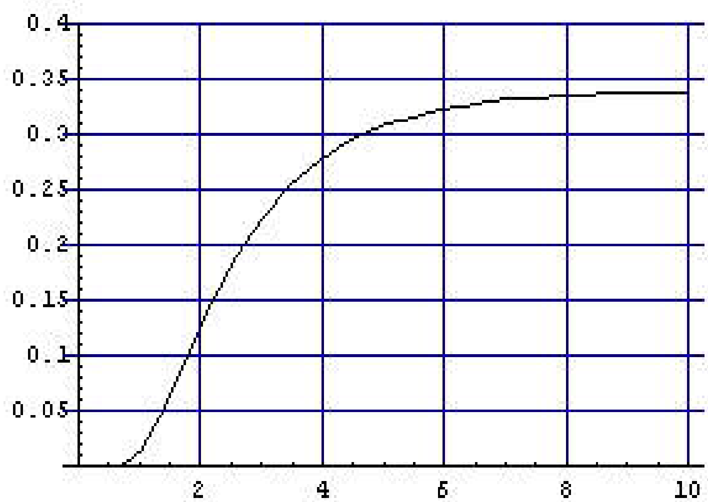

FIGURE 2: Field at the axis, *G*, for radius *a*=1cm as a function of λ_u/a for current *I*=1 A. In our case of interest λ_u/a=4.3, as period of undulator is λ_u=2.4 mm, *a*=0.56 mm.

The field distribution for three cases represented in Fig.3 and the field value as a function of effective magnetic permeability is represented in Fig. 4. In first case in Fig. 3 there is no magnetic substance at all. This gives the reference point for the axis field, Fig.4. In second case the substance is present only between wires. In final case the substance filled all free space around wires, except vacuum chamber, naturally.

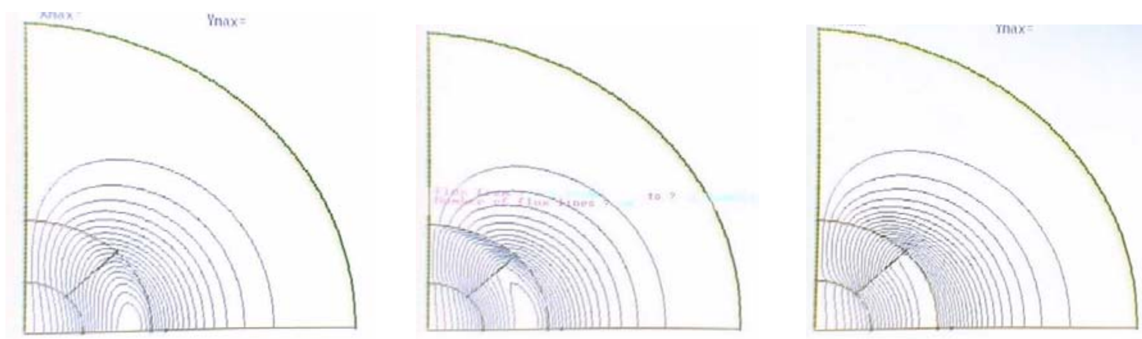

FIGURE 3: Field lines in helical geometry. Quarter of transverse cross-section is shown. Left picture corresponds to μ=1. Center: the only space between wires is filled with magnetic material. Right: all free space occupied by magnetic material.

One can see, that filling the space between wires increases the field at the axis ~2 times compared with non-magnetic surroundings. Moreover, usage of magnetic substance filling *all free space* increases the field at the axis even more, up to ~3 times. This allows either having bigger K-factor in undulator in the same proportion, or increase in aperture, if K-factor kept fixed. According to Fig. 2, the aperture can be doubled, however. K-factor defined as usual,

$$K = \frac{eH\lambda_u}{2\pi mc^2} \cong 93.4 \times \mathrm{B[T]} \times \lambda_u\,\mathrm{[m]}.$$

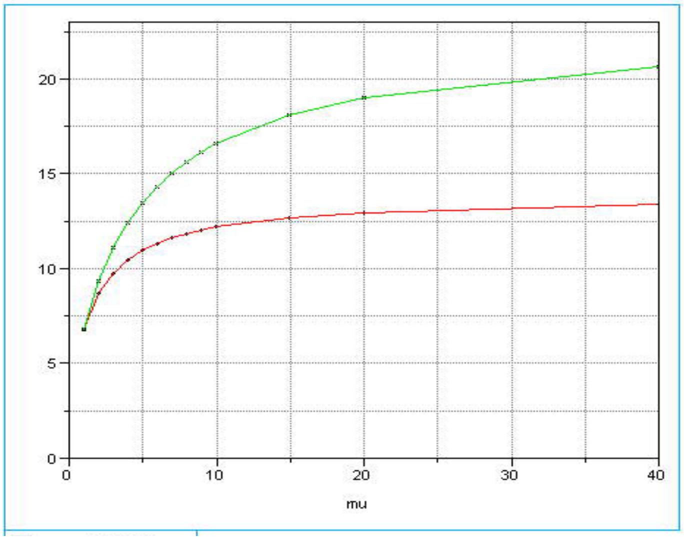

FIGURE 4: Maximal field at the axis, kG, as a function of effective permeability of substance, surrounding wires.

Lower curve in Fig. 4 corresponds to the case, when the only space between wires is filled; upper curve corresponds to the case when all free space filled with FF. Maximal field for μ=1 is 6.83 kG. One can see from here, that μ~ 15 saturate magnetic field growths, i.e. this value is enough for practical purposes.

SELF MADE FERRIFLUID

We used ferrite powder of ~15 μm chips suspended into pure transformer oil. Ferrite powder obtained free from manufacturer. Powder is a mixture of Nickel-Zink Ferrite belonging to Spinel-Ferrite family. In the case interesting for us, the cooling properties of fluid is mostly important item. This means that liquid is in intensive motion, caring heat to a cooler. Usage of ferrite chips instead of pure iron ones also allows easy insulation, as Ferrite manifests very low electrical conductivity. The last is important as the undulator operates under pulsed voltage ~500V in a fraction-of-mm gap. This relatively high voltage required for excitation of current in wiring. Basically current running in wires of $0.6\times 0.6\,\mathrm{mm}^2$ goes to be ~2200A in 25 μsec pulse at 30 Hz. Average power deposition in wires goes to be ~0.5 kW. As the liquid is in motion, requested by cooling, *the turbulence* is responsible for the substance's homogenization (in ferrofluid, due to small size of particles, Brownian motion serves for this purpose).

We investigated magnetic properties by measuring inductance of coil in fixed geometry and comparison variation of inductance with calculations. Results of calculations represented in Table below. The coil was immersed inside the bottle filled with fluid. Manufacturer did not indicate effective permeability of Ferrite powder so we measured it. Normalization of inductance done by measurements of inductance of coil in air and for the coil placed inside the glass, filled with dry Ferrite powder. In this last case coil remains inside the powder. Effective magnetic permeability found with this method is ~ 5. Calculations show that this number is sensitive to the details of coil carcass caring the wire. For liquid an accurate estimation of volume important also density together with exact value of initial magnetic permeability. The Ferrite powder mixed with oil in proportion ~15% by volume and measurements of inductance carried in the same manner. We are planning to make soon more direct measurements of field enhancement in geometry of magnet. So the summary for self made fluid looks as following.

Self made fluid. Saturation field unknown, Viscosity ~50 cp. Transformer Oil based carrier. Inductance, after immersion in bottle, rumps from ~11 μH initial one to ~13 μH. The last gives effective permeability μ~1.5 for ~15% volume filling. Even so, this magnetic permeability measured, according to Fig.4, ~ increases the axis field ~20%.

In Table bellow there is represented the inductance change as function of effective magnetic permeability.

μ	$E_{stored} \times 10^6$ /kA/kJ	Increase, times	Inductance, μH
1	5.68	1	10.7
2	8.72	1.53	16.4
3	11.5	2.02	21.7
4	14.3	2.52	26.93
5	16.9	2.97	31.83
10	29.6	5.21	55.7
100	220	38.7	414.4
1000	1250	220	2354

The only one ferrite powder was tested so far. We also are planning to test the limit for volume filling with powder. Probably 15% filling is not a limiting number.

HEATING LIMIT

Time required for powder to fall down under gravity force, measured to be ~50 min, what is more than enough. Simple loop which includes the oil pump, reservoir and flow meter was assembled, see Fig. 5.

FIGURE 5: Pump, flow meter and reservoir make the loop for investigating FF flow. Sample coil made with wire $0.6 \times 0.6\,\text{mm}^2$ and immersed in flow feed by power supply, right, up to 70 A.

The fluid filamented in cooling system after the pump shuts down, quickly becomes homogeneous after start of pump, not creating problem in a pump start. An abrasive property of this fluid is not manifested also so far. Some mentionable problem here is accumulation of ferri-particles in flow-meter magnet.

Equivalent DC current I which heats the wire in the same amounts as the pulsed current with amplitude $\hat{I}$ which lasts τ seconds with repetition rate f, can be found from balancing energy as the following

$$I \cong \hat{I} \times \sqrt{\tau \cdot f} \ .$$

In our case for repetition rate 30 Hz and 30 μs half sin-wave this goes to be ~47A. With the same equipment, see Fig.5, the capability to carry DC current, equivalent in heating to the pulsed one was measured here too. Although the current required is ~47A, we run higher current. So square wire $0.6 \times 0.6\,\text{mm}^2$ was able to carry 70 A of DC current under cooling by ferrifluid. Hence, current density was demonstrated is ~194.4 A/mm^2. This is close to a limit, however.

By adding ferrite material into liquid one increases the volume density. The last is also useful as the volume heat capacity increases by this action.

FACTORY MADE FERROFLUID

After we learn about ferrofluid, we acquired samples of ferrofluid for estimation of theirs properties. Usually ferrofluid available on the market composed by nano-size magnetic chips of ferro- or ferri-materials, covered by soap-like instance (surfactants) to avoid sticking the particles into big clusters. So basically this is a colloidal suspension. Technology of fabrication is rather expensive for the moment; we mentioned this in introduction. We ordered few bottles by 30 ml each from FerroTech. Liquids #2-#5 below are coming in evaluation kit. So the liquids are the following:

1. **EMG 900**. Saturation field ~900 Gauss, Viscosity ~60 cp. Oil based liquid. Volume particle concentration is 17% giving density 1.74 g/ml. It has flash point 89^{o}C and Pour point -80 ^{o}C. Inductance after immersion in bottle rumps from ~11 μH initial one to ~54 μH.
2. **APG O87**. Saturation field ~250 Gauss, Viscosity ~750 cp. Oil based liquid Inductance after immersion in bottle rumps from ~11 μH initial one to ~20.4 μH.
3. **APG S51**. Saturation field ~350 Gauss, Viscosity ~500 cp. Oil based liquid Inductance after immersion in bottle rumps from ~11 μH initial one to ~25.3 μH.
4. **APG O27n**. Saturation field ~325 Gauss, Viscosity ~175 cp. Oil based liquid Inductance after immersion in bottle rumps from ~11 μH initial one to ~23.4 μH.
5. **APG O17**. Saturation field ~300 Gauss, Viscosity ~350 cp. Oil based liquid Inductance after immersion in bottle rumps from ~11 μH initial one to ~20.1 μH.

So liquid EMG 900 according to the Table demonstrates effective permeability ~10, the rest ones ~2-3. Average size of particles in these liquids is 100 Å.

Resistance of these fluids was measured by immersing needle-type electrodes into sample liquid and applying high voltage (AVO MEGGER BM403/2). With distance between needles ~1 mm meter shoved GOhm at 1kV.

REQUIREMENTS AND BENEFITS FOR E-166 UNDULATOR

The price of EMG 900 is $10/ml what is ~ten times higher, than the others. Company offers a 30% discount for volume ≥ 2 liters however. After 5 l order this discount negotiable.

Amount required for undulator cooling system estimated as ~3 l. About 66% of this amount located outside of undulator–in the pump, oil filter, reservoir and tubing. Probably this volume can be cut, but not much. One way is to use EMG 900 liquid in dissolved condition. Usage of factory made fluid EMG 900 will increase the axis field ~2.4 times i.e. 240%. Solvating will decrease this number proportionally to the volume density of magnetic material. One can see that the media with permeability even ~5 will increase axis field ~1.5 times.

Tube of 50 mils OD and 4 mils wall thickness becomes preferable for the vacuum chamber instead of initial tube with 42 OD. The change of size can be demonstrated by the fact that the tube with 42 mils can be inserted inside the tube with 50 mils OD.

Amount of 2.0 liters costs ~20k$ minus 30% discount what comes to 14 k$. Solvent costs ~1.5$/ml and will be required in quantities ~1 liter what brings its cost to 1.5$. So the total cost goes to be 15.5k$. Self made liquid with ~15% filling can give ~20% of axis field gain. It is free however.

CONCLUSION

In this publication we proposed to use ferro/ferri-fluid for improvement of field/current parameter and for cooling in pulsed undulator for E-166 experiment. It is clear, however, that usage of this type of suspensions can help in many other cases, where improvement of magnetic properties together with cooling and insulating capabilities allow elegant design of micro-magnets (magnets) for wide applications.

We think that even high power RF elements can use ferrifluid for improvement of its parameters. For example RF power absorbers can use ferrifluid (RF loads). One can imagine usage of ferrifluid for variation of inductance, as magnetic particles can be easily separated from carrying liquid by (electro) magnet.

We also hope that the cost of ferrofluid may go down as request for this liquid grows.

So for conversion system of NLC/JLC/CLIC type collider the pulsed undulator cooled by ferrofluid, might be preferable option now if compared with SC undulator. For this particular case optimization of volume can be done more carefully.

As far as the pulsed undulator for E-166, ferro/ferrifluid allows usage of tubes with diameter 50 mils instead of present 42 mils. One of two undulators fabricated can be with 42 mils tube and extended K~0.45 and the second one having designed K=0.17 but extended aperture. The price rise ~15k$ still reasonable for experiment, which costs ~1.2M$. This question becomes open for E-166 Collaboration.

Without knowing situation with ferrofluid, we introduced the term *ferrifluid*. Now it reflects that ferrite powder has thousands times bigger grain, than in ferrofluid and keeping in mind that turbulent flow of this fluid is important item. Turbulent flow helps to support homogeneity in ferrifluid while it is running. With the other words, namely the running liquid makes possible to use the ferri-chips of much bigger size, than in traditional ferrofluid. This allowance drastically reduces the cost of magnetic substance.

I began this work in full assurance that I invented this type of fluid by myself. Thanks to Maury Tigner, I became released from this delusion now.

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