OPERATIONAL EXPERIENCE WITH UNDULATOR FOR E-166

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Abstract

We represent results of operation with 1-m long, 2.54 mm period, K=0.2, 20 Hz undulator used in E-166 experiment of polarized positron production. One peculiarity is in usage of Ferrofluid for cooling.

INTRODUCTION

E-166 experiment carried out at SLAC dedicated to test polarized positron production with the help of circularly polarized gammas radiated by high-energy (~50 GeV) beam in helical undulator [1]. Description of undulators for E-166 experiment done in detail in [2].

Some undulator designed parameters are represented in Table 1. Two pulsed undulators with slightly different aperture were fabricated, the only one with smallest aperture was in use, however (first column). In this publication we represent results of operation with this undulator during experiment. This undulator works with average pulsed current density ~6.39 kA/mm^2 in pulse duration ~12 *µsec* pulsed up to 30 Hz. During experiment, maximal repetition rate used was 20 Hz due to the problems with synchronization with SLAC beam pattern.

Table 1. Parameters of undulator

Energy, GeV	50	50
Length, m	1	1
Period, mm	2.54	2.38
Apert. dia, mm	0.889	1.067
K	~0.17	~0.12
Curr., kA	2.3	2.3
Conductor	0.6$\times$0.6 mm^2	0.6$\times$0.6 mm^2
Pulse dur., µs	12	13
Press. drop, psi	~11	~11
Oil flow, gal/min	3.5	3.5

Initially we planned to use the Hall probe and Bi wire technique for measurement of magnetic field in aperture (0.8mm in dia). The Hall probe having appropriate dimensions was obtained, however the probe was supplied without wires attached. Attachment required some efforts (mostly in time) and taking into account extremely tight time schedule and limited men-power, this procedure was not fulfilled. We also measure the field in aperture with Bi wire. Bismuth wire of 0.1 mm in dia and ~1 m long was fabricated and calibrated in static field. Peculiarity with helical field is that absolute value of field is constant along the longitudinal coordinate. DC current ~45 *A* used here for the measurements. DC current density reached ~125A/mm^2. Calibration coefficient obtained indiated, that for 2.3 kA undulatority factor comes to K~0.4 what was declined as not possible. Explanation to this was found in assumption, that internal volume was warmed up and tolerating to the read-out. While the the current is ramped the heating following the current, which provides significant systematic error. So the measurements with Bi wire did not give convincing number.

So the only way to deal with undulator parameters remained just trust the calculations. However, although period and current can be measured pretty accurate, the exact dimensions, especially at inner radius are hardly measurable due to the limited access. In addition the square conductor having cross-section 0.6$\times$0.6 *mm*^{2} demonstrated tendency to manifest a keystone effect.

Fabrication of such undulators was an engineering challenge. Experiment confirmed that principles put in grounds were correct.

CALCULATED FIELDS

One nuance enhances the field in aperture, however. It is in the following. As we described [2], the undulator wound with rectangular 0.6 ×0.6 *mm*^{2} wire tightly to the vacuum chamber. Oxygen free Copper wire (conductor) used here. StSt Tube has diameter 42 mils (=1.0668 mm) outer diameter and 30 mils inner diameter served as a vacuum chmber. Tube wrapped by two layers of Kapton insulation having thickness 0.5 mils (so addition to the diameter is 2×0.5=1mils=0.0254 mm i.e.~25 micrometers). While winding is going, the insulation becomes squeezed, so the conductor (wire) comes closer to the tube surface.

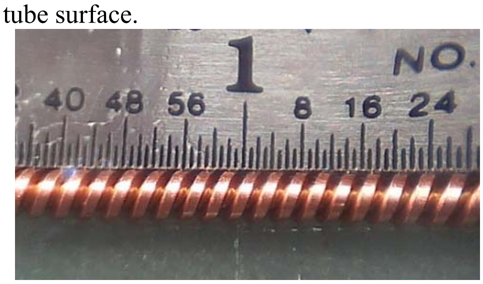

Figure 1: Scaled view on the undulator windings [2]. Wire with rectangular cross-section has dimensions 0.6$\times$0.6 mm^2, period $\cong$ 2.54 mm.

Peculiarity here is that the current density is different across the conductor in such a way, that current is running preferably through inner part of conductor. This is natural as the distance inside conductor is the shortest there. This gives significant enhancement, compared with homogeneous current density.

The current density in *kA/cm*^{2} represented in Fig.3 calculated with MERMAID. This code calculates the current solving electrostatic potential in a conductor. So it takes into account real geometry of thick conductor. As the dimensions of conductor comparable with the bending radius, the current has a tendency to run in layers closer to the center. And this is good, as it yields the field enhancement at the axis. In addition as the conductor dimensions also comparable with period, the current also runs with pitch angle bigger than the winding one. So as one can see, the current concentrated in the lower corner from the side following the direction of the twist. The difference in pulsed current density is 1200/300~ 4 times. This is also gives some field enhancement.

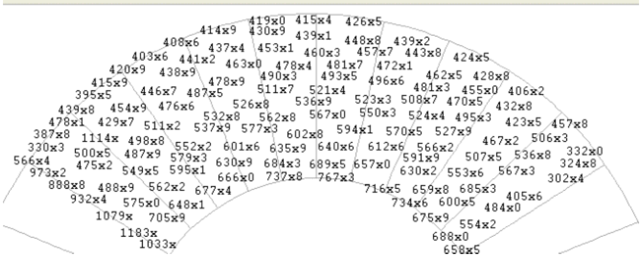

Figure 2. Current density in cross-section of conductor, kA/cm^2. The conductor is twisted counterclockwise. x used as decimal separator.

Anyway the calculated field at the axis comes to be $H_{\perp} \cong 7.16$ kG at I=2.3 kA. As the period measured is $\lambda_u \cong 2.54$ mm, the undulatority factor according to these calculations comes to $K \cong 0.17$.

At last, another peculiarity here is that the pulse is ~12μs at half height, what formally yields a skin-depth ~0.3mm. That means the current has a tendency to be expelled from conductor body. This effect might give an additional enhancement, but it is difficult to calculate it.

So the only trusted method is the direct measurement of Gamma-flux. In some sense this is mostly important parameters verification as namely the gamma-flux is a final product here.

FLUX AS FUNCTION OF CURRENT IN THE UNDULATOR

For registration of gammas, numerous gamma counters located on gamma-table used here [1]. This table located ~33 meters from undulator down to the beam direction.

In Fig. 5 there is represented a signal from counter #22 as function of *current* in undulator, obtained in owl run on September 17, 2005. Conversional target moved out. Reading of current was carried from the shunt at the moment of bunch passage.

According to the table of attenuations at the moment of measurements, the counter #22 has 60 dB. Calibration coefficient for the Si counter #22 according to the latest information represented in [4] is 4600 gammas/cout. Hence the number of quants going to be $N_\gamma \cong 175 \cdot 10^{60/20} \cdot 4600 \cong 8 \cdot 10^8$, where 175 –is the signal value, see the graph in Fig.5 for 2300 A.

From the other hand, the *total* number of quants can be *calculated* as

$$N_{\gamma tot}^{theory} \cong N_e \cdot \frac{4\pi\alpha}{3} \frac{L}{\lambda_u} \frac{K^2}{1+K^2}, \quad (1)$$

where $K = \frac{eH\lambda_u}{2\pi mc^2} \propto I$ and I stands for the current running

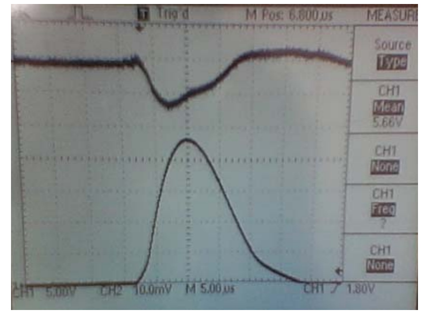

Figure 3: Shunt signal, low curve. Voltage-upper curve. Shunt calibration -100A/V.

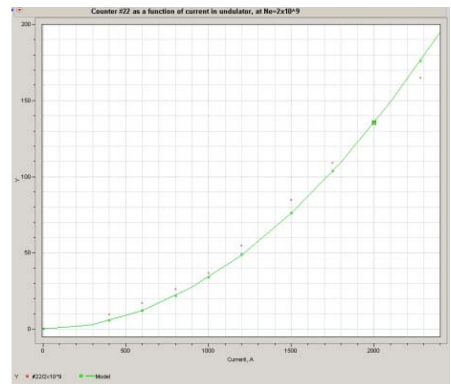

Figure 4: Flux measured together with parabola.

in undulator. Our undulator has the length $L \cong 1000$ mm, period $\lambda_u \cong 2.54$; the number of electrons in this measurements was $N_e \cong 2.2 \cdot 10^9$, so K-factor corresponding to the number of photons N_γ according to the formula (1) is $K \cong 0.177$. This value defined by accuracy in knowing N_e, N_γ as ~square root of these.

BEAM STEERING

The 6070 unit at FFTB is a set of magnets for vertical and radial corrections installed in series close to the undulator entrance. The sensitivity of these correctors was found to be $\alpha \cong 27.5\ \mu rad / A$. Meanwhile during fine tuning, the signal in e^+ calorimeter feels even mA scale change in these correctors. So we are dealing with fine tuning. This also means that the gamma-line must be kept with the same accuracy.

It was found, that undulator kicks the electron beam. Deflection of electron beam provided by undulator along the way down is shown in Fig. 7 below. This is basically displacement in X-direction. The kick angle was found to be $\sim \vartheta \cong 25.5 \mu rad$, which corresponds to the integral of magnetic field as big as $\int Bds = \vartheta \cdot (HR) \cong 4.66\ kG \cdot cm$.

That was explained by non accurate design of end jumper, Fig. 6. This jumper located at the end of helixes downstream the beam direction, so formally this does not affect the gamma beam. This kick can be easily taken into account. In ILC undulator special measures accepted to make the kick of undulator controllable. The last might be useful for enlargement of the gamma spot size on the target.

Scrapping the collimator by gamma-beam might be responsible for the reduction of counts from #22 right after the filling. So extensive steering with 6070 unit was done.

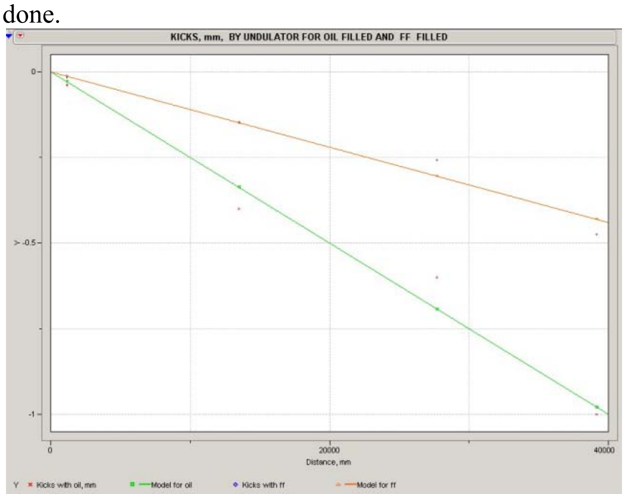

Figure 5: Transverse displacement of the beam along longitudinal distance. Lower curve corresponds to undulator filled with oil –the upper –to the undulator filled with ferrofluid.

Figure 6: End jumper.

If absolute calibration of #22 done with 10% accuracy, then one can say that namely this is the accuracy of measured *K* value. Absolute number of electrons measured with the same accuracy, probably, although relative sensibility defined by resolution of ADC and by the number of digits in presentation and can be estimated as 3%.

OPERATION WITH FERROFLUID

For cooling, mostly of operational time the pure transformer oil was used. Undulator was connected to the cooling device by the oil resistant flexible tubes. It was found that the system has a ~one milliliter/week leak in one of joints. As the leak was small the decision was made just to leave it as it is. As the liquid is not compressible this required an access once a day to add the tiny fraction of the oil to the system. This access was used for visual control of system also. The power supply was located is the same rack with the pulser in the FFTB tunnel. So this was practically the only inconsistence. At the end of run, the coolant (oil) was replaced with Ferrofluid EMG 900. The reason for this is in specifics of undulator design. Here conductor is sitting tightly on the vacuum chamber and outer to the conductor space could serve as a yoke. *Calculations* show, that with Ferrofluid instead of oil enhancement is ~20%. So one can expect here K~0.2. *This number was confirmed experimentally by measuring the gamma flux.*

Ferrofluid has viscosity~ the same as oil, so there were no any problems found. The Ferrofluid found to be a radioactive, however its isotopes are found to be a short lived with lifetime ~24 hours. Oil demonstrates much lower radioactivity (but longer lived).

So according to Fig. 5, undulator filled with ferrofluid kicks electron beam ~twice weaker (less), than if the one filled with oil. This is clear: presence of magnetic material reduces axial field here, see Fig. 6.

CONCLUSION

Undulator during all runs pulsed ~3.5 $\times 10^7$ times at 2.3 kA. General conclusion is that basic elements of cooling, settlement of windings and alignment of vacuum chamber were chosen correctly. Parameters are pretty close to designed ones. Ferrofluid used here in significant quantities (~2 Liters) for the first time demonstrated predicted field enhancement. End fields can be improved, if necessary. K factor at maximum was reached ~0.2. In Laboratory this undulator tested at 30Hz repetition rate. Maximal rate in E-166 experiment was used 20 Hz defined by timing of registering electronics with SLAC beam pattern.

Successful run of E-166 experiment is the best verification of undulator parameters and confirmation of engineering principles put in grounds.

Work supported by NSF.

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