April 10 2003 CBN 03-5

PULSED UNDULATOR FOR TEST AT SLAC THE POLARIZED POSITRON PRODUCTION[1]

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Abstract

We represent technical details and results of testing pulsed undulator with ~2-mm period, K~0.1, manufactured by Cornell LEPP for test of polarized positron production at SLAC.

1 INTRODUCTION

Conversion system for polarized positron production [1] contains ~130 m-long helical undulator followed by thin target. Helical gammas radiated by primary high-energy beam in undulator transfer theirs polarization to the positrons and electrons at the high edge of energy spectrum. Selecting secondary positrons/electrons by energy, one can at the same time select theirs polarization (higher energy–higher polarization). Right now there is a proposal for E-166 experiment at SLAC [2] to test this idea, initiated by publication [3].

Experiment requires, that two sections of undulator with opposite helicities, ~0.5m-long each, must be installed in FFTB channel. Here ~50 GeV SLAC beam will generate ~10 MeV gammas in controllable sequence of left/right polarized gammas [2]. General descriptions of ~2 mm –period undulators suitable for these purposes were done in [4], [5], and model with period 2.4mm was manufactured, Fig.1. This model was tested for 1 kV of static voltage. In this publication we describe more engineering details of undulator design.

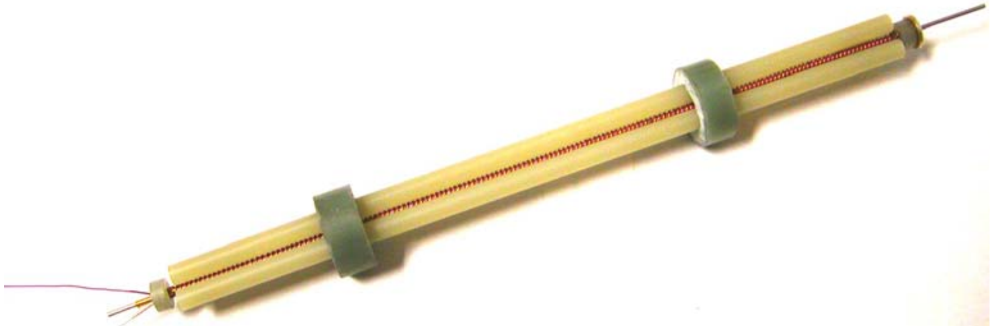

FIGURE 1: Model of pulsed undulator with period of 2.42 mm and 231.5 mm long [4]. Three G-10 rods squeezed with help of short rings having cylindrical grooves. This arrangement serves as a positioning system

One meter long pulsed undulator having 6 mm period and the axis field ~6*kG* ($K \cong 0.35^{2}$) was successfully tested many years ago [6]. The feeding current in a wire with 1×1 mm^2 cross section was ~10 kA. Pulse duration was ~50 μsec, feeding voltage ~ 1.19 kV required by inductance ~1.3 μH allowed operation with repetition rate of 25*Hz*[3]. Such high current (and

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[1] Electronic version is available at http://www.lns.cornell.edu/public/CBN/2003/CBN03-5/CBN03_5.pdf

[2] This value is optimal for 150 GeV primary beams.

[3] Required by VLEPP parameters at that time.

inductance) was forced by the aperture clearance of 4mm in diameter required. Intensive cooling of this device was a main engineering achievement.
Namely this technology was used for short period undulator suitable for test at SLAC.

2 GENERAL DESCRIPTIONS

Undulator has two helixes shifted in longitudinal direction by half-period [7], Fig.2. Technology for manufacturing of double helix with period 2.4 mm was tested successfully [4]. There was not found any limitation to make the windings with period 2 mm. Small period required for generation of gammas with appropriate energy ~10 MeV, forcing shrinkage of aperture. Fortunately this drastically reduces inductance of undulator. In its turn this yields proportional reduction of voltage required for excitation of necessary current ~1.6 kA. The helixes immersed in coolant liquid avoiding overheating.

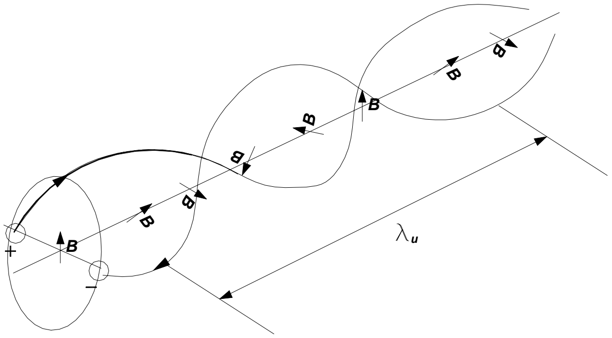

FIGURE 2: Helical undulator is a bifilar helix with opposed currents.

Direction of helix twist (left/right handed) defines helicity of radiation in undulator. In high-energy physics (in contrast to optics) the observer is looking *towards* direction of propagation. By requirements of experiment planned [2], undulator consists of two sections with opposed helicities, which can be feed independently.

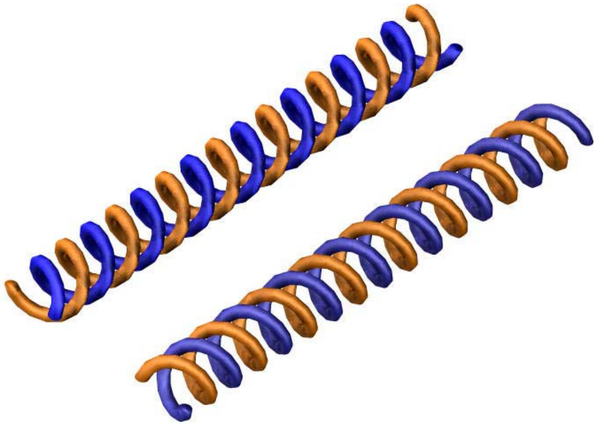

FIGURE 3: (Color) Bifilar helixes having opposite helicities.

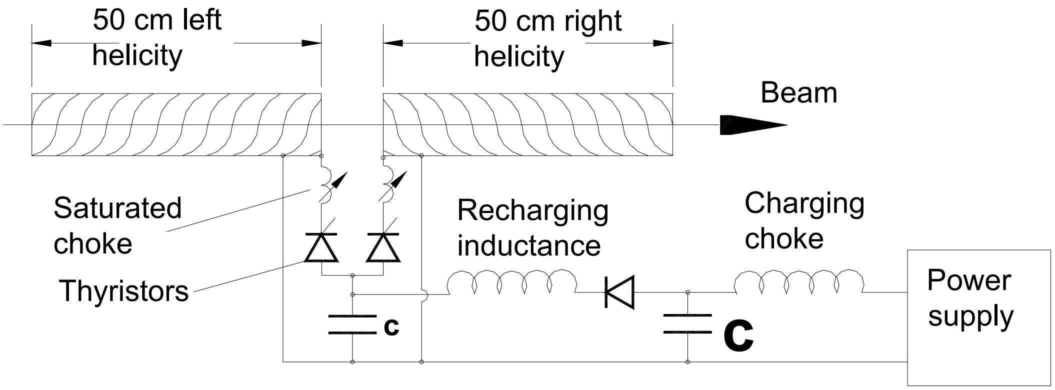

FIGURE 4: General pulsed-undulator concept [5].

For experiment at SLAC, two undulators having opposite helicities will be installed in series, Fig.4. Basically the helixes will be wound on the StSt tube of gage size 19 with nominal OD 0.042” (1.0668 mm). Kapton insulation 0.003″ - thick will serve for electrical insulation. This tube has the wall thickness of 0.0035” (0.0889mm)[4]. This tube allows the ID diameter 0.889 mm available for the beam.

Power supply will charge capacity **C** (Fig.4) which has much bigger value than **c.** Thyristors have independent triggering electronics so it is possible to feed each of these helixes in any time pattern exclusively. Operation of this scheme is quite transparent. We tested and are using such scheme for new CESR positron source [5].

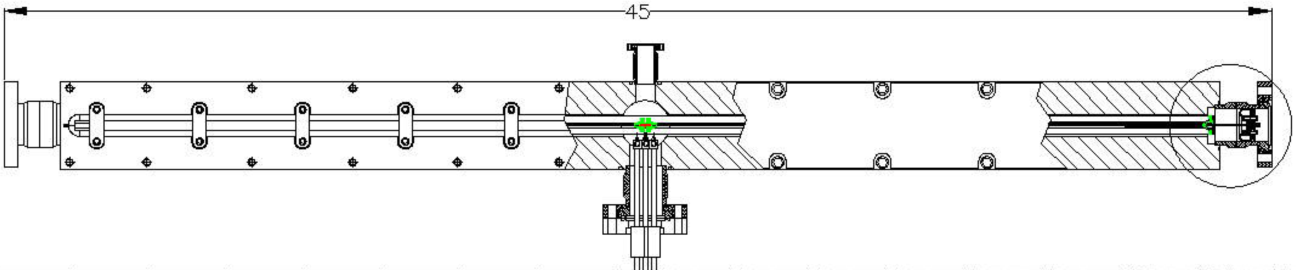

FIGURE 5: General view of undulator. Length is shown in inches. The current feed-throughs (four in total) located at the central part. Circled region scaled in Fig.6. StSteel flanges are the parts of transitions welded to Al corps.

General view of undulator represented in Fig. 5. Total length of undulator is $45''(\cong 114)$ cm allowing pure helical winding occupy 2×50 cm of each helicity. Corps made from Aluminum alloy. We used here the same scheme for fixation core with helixes as in [6]. StSteel flanges are welded to the corps using commercially made transitions[5]. Cross section of undulator in regular part is represented in Fig. 6. Basically the body of undulator is an $3''\times 3''\times 41''$ Aluminum block with groove in the middle. Inside this groove two roads 5 located in corners, giving the basis by theirs surfaces. These roads made from G10 cylindrical rods of $0.375''$ in diameter. After making cut with 60° upper surfaces of these roads coincide with axes of undulator. This axis located $\cong 1.5''$ from the bottom surface. The third road presses the helical windings to the

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[4] New England Small Tube Catalog, tube GS#19, XTW.

[5] Thermionics Northwest, Inc.

basement lodgment arranged by other two by springing bars seeing if Fig.4, and marked as 4 in Fig.6.

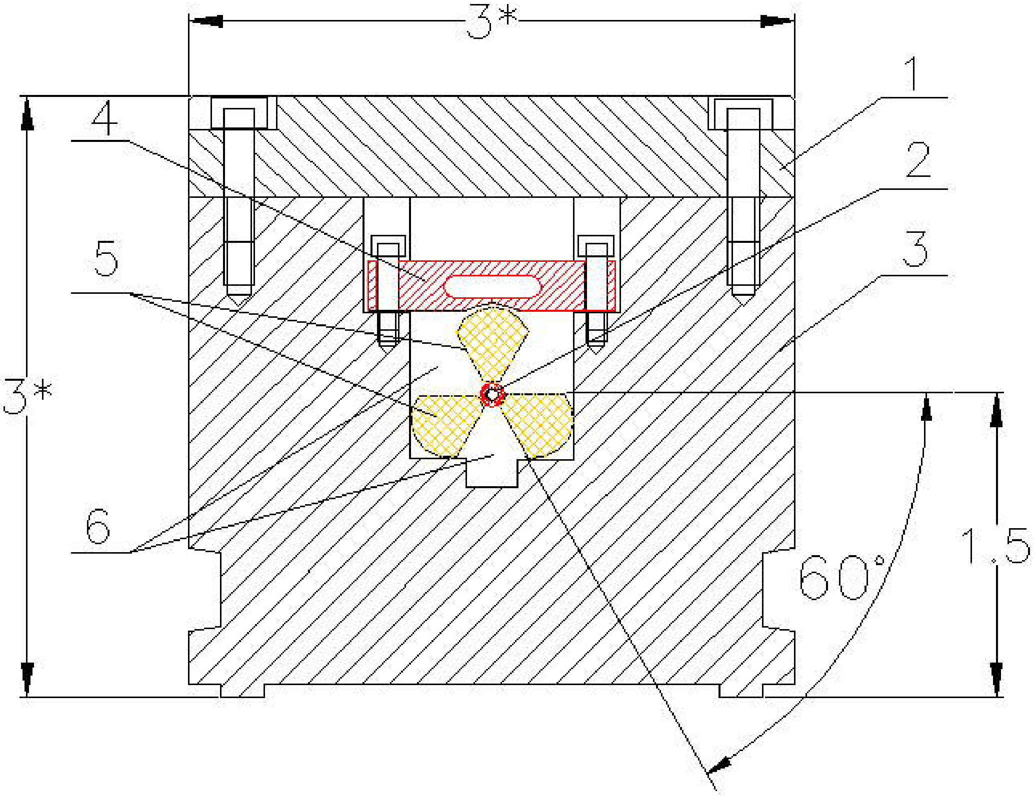

FIGURE 6: Cross-section of undulator, Fig.5. Two G10 rods are based in corners of long groove. Third rod with help of springing bars 4 compresses the windings to the other two ones. 1 –is a cover, 2 –is bi-helix. 3 –is a corps, 5 –are G10 rods, 6 –is filled with coolant. Parts 1, 3 made from Aluminum.

Supposed, that the corps will be attached to the support frame using grooves at the sides of corps. Inner volume sealed by cover 1 with the help if Indium gasket running around groove. The cover 1 also has welded inputs/output flanges for running coolant.

The final dimensioning of the groove will be done after welding all flanges. This will help to keep the axes of undulator straight.

End part of undulator circled in Fig. 5 is shown scaled in Fig.7. Here helixes 1 with tube based on the surface of two rods. It is clearly seen the end commutation 9 made with ring. Conically expanded helixes can be seen here too. Conical expansion made for proper adjustment of integrals along edge region. For the same purposes the conducting cylinders (See Fig.10) serve too. For high-energy particles the radius of space helix of trajectory is very small, $\rho \cong \lambda_u K / 2\pi\gamma$, where K–is undulatority factor, For 50GeV beam $\gamma \cong 10^5$ and for our parameters $\rho \cong 3 \cdot 10^{-7}\, mm$ allows to treat trajectory as a straight line when calculating integrals along trajectory.

Intermediate cap 6 made from St Steel welded to the transition. In this design standard transition Al/StSteel with rotatable flange used at both ends. StSteel tube (vacuum chamber) caring the helixes brazed to the cap 6 with end cap 5. This end cap 5 allows small transverse movements, accommodating the transverse position of the end cap on the orifice of intermediate cap 6. With the help of threads 10 and washer 11 the vacuum tube can be stretched in longitudinal direction. That is why the intermediate cap 6 made with developed surface. Copper cylinder 12 serves as trimming flux attenuator, see Fig.11.

In principle this technical solution allows disassembling construction with minimal efforts.

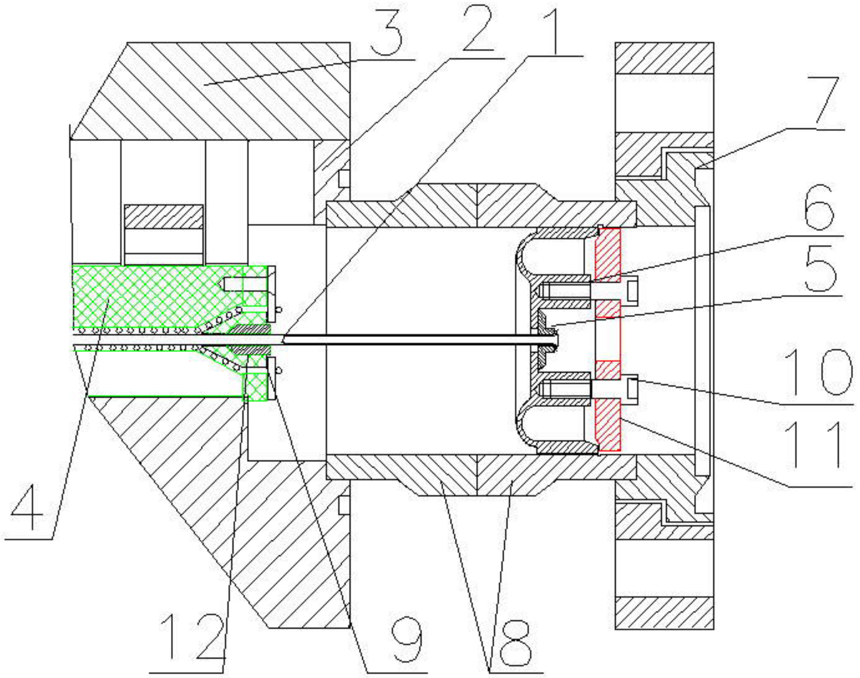

FIGURE 7: Scaled view of circled parts in Fig.3. 1 –is the helixes, wounded on StSteel tube. 2–is the corps, 3–is a cover, 4 –is the upper rod, 5–is end cup, 6–is intermediate cup, 7–is a standard 2¾ flange, 8–is a StSteel-Aluminum transition, 9–is the end commutation, 10 –are screws, 11–is a springing washer, 12–is a trimming conducting cylinder (flux attenuator). Inner volume filled by coolant.

Upper rod has grooves with period of helix, fixing longitudinal positions of the wires.

2 FIELDS IN UNDULATOR

Fields in undulator calculated analytically and numerically with 3D code MERMAID. We used both ways for the fields evaluation. Both gave the same result [4]. We suggested that the feeding current is steady, as the time of the beam passage through the undulator is much less, than suggested duty time (30 μs). Field attenuation defined by skin-depth in StSteel, what is of the order ~3.6mm for such duty times. So attenuation is going to be $1-exp(-0.0889/3.6)\cong 2.4\%$.

For our case the only first longitudinal harmonic is important. This defined by how much the particle is shifted from the central axis (ρ value) and by a/λ_u ratio. For the first harmonic the field dependence on coordinates has a form [10]

$$H_{\varphi}(\rho,\varphi,z)=-\frac{I}{\pi\rho}\cdot\left(\frac{2\pi a}{\lambda_u}\right)\cdot\frac{sin(\alpha)}{\alpha}cos\left(\varphi-\varphi_0-\frac{2\pi z}{\lambda_u}\right)\times I_1\left(\frac{2\pi\rho}{\lambda_u}\right)\left[K_0\left(\frac{2\pi a}{\lambda_u}\right)+K_2\left(\frac{2\pi a}{\lambda_u}\right)\right], \qquad (1)$$

where α is angle under which the conductor seeing from center.
For the axis field of undulator with thin wires, $\alpha \to 0$, $\rho = 0$, one can obtain expression as

$$H_{\varphi}(0,0,z)=-\frac{I}{\pi a}\times\left(\frac{2\pi a}{\lambda_u}\right)\times cos\left(\frac{2\pi z}{\lambda_u}\right)\times\left[\left(\frac{2\pi a}{\lambda_u}\right)K_0\left(\frac{2\pi a}{\lambda_u}\right)+K_1\left(\frac{2\pi a}{\lambda_u}\right)\right]=$$

$$=\frac{I}{\pi a}\times\left(\frac{2\pi a}{\lambda_u}\right)^2\times cos\left(\frac{2\pi z}{\lambda_u}\right)\times K_1'\left(\frac{2\pi a}{\lambda_u}\right). \qquad (2)$$

This formula is illustrated in Fig.8. One can see from there, that for $\lambda_u \cong 2a$ the field is only ~17% less, than asymptotical value for infinitely long two-wire line.

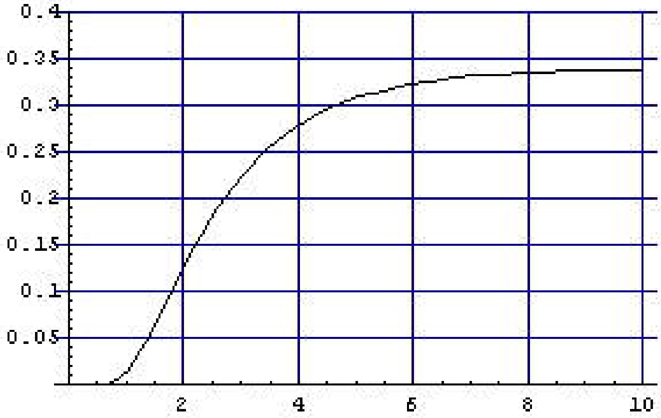

FIGURE 8: Field at the axis, *G*, for radius *a*=1 as a function of λ_u, Current *I*=1 A, formula (4). Saturation indicates that the field can be calculated as for two parallel infinitely long wires.

The terms in rectangular brackets in (2) are the constants depending on ratio of diameter to the period, which is about $2\pi a/\lambda_u \equiv \pi(2a)/\lambda_u \cong \pi/2$ in our case, so $K_0(\pi/2)+K_2(\pi/2)\cong 0.71$. For a thin conductor also $sin\alpha/\alpha \cong 1$, so expanding Bessel functions one can obtain from (1) dependence of magnetic field on transverse coordinate, $x = 2\pi\rho/\lambda_u \cong \rho/\bar{\lambda}_u$

$$H_{\varphi}(\rho,\varphi,z)=-\frac{0.71}{2}\frac{I}{\bar{\lambda}_u}\cdot cos\left(\varphi-\varphi_0-\frac{2\pi z}{\lambda_u}\right)\times I_1\left(\frac{2\pi\rho}{\lambda_u}\right)\Big/\left(\frac{2\pi\rho}{\lambda_u}\right)\cong$$

$$\cong-\frac{0.71}{4}\frac{I}{\bar{\lambda}_u}\cdot cos\left(\varphi-\varphi_0-\frac{2\pi z}{\lambda_u}\right)\times\left[1+\frac{1}{8}\left(\frac{\rho}{\bar{\lambda}_u}\right)^2+\frac{1}{768}\left(\frac{\rho}{\bar{\lambda}_u}\right)^4+...\right] \qquad (3)$$

The terms in rectangular brackets describe the dipole, sextupole, decapole, … fields responsible for the perturbation of emittance of a primary beam as a result of motion in nonlinear fields. What is important here is that the measure of these effects is the ratio of the beam size to the period of undulator $(\rho/\bar{\lambda}_u)^2/8 \cong (\sigma/\bar{\lambda}_u)^2/8 \cong \gamma\varepsilon\beta/\bar{\lambda}_u^2/8\gamma$, where $\gamma\varepsilon$ is invariant emittance of the beam and β is envelope function. For SLAC emittance $\gamma\varepsilon \cong 3\times10^{\ 3}$ cm×rad in a crossover of envelope function having value there $\beta_0 \cong 300$cm sigma of the beam goes to $\sigma \cong \sqrt{(\gamma\varepsilon)\beta_0/\gamma} \cong 3\times10^{-3} cm$. At 0.3 mm, what is ten sigma, the field deviation from constant is ~10%. First nonlinear term is going to be $\frac{1}{8}(\sigma/ƛ_u)^2 \cong 10^{-3}$. One other circumstance important here is that due to extremely small wiggling amplitude of particle in undulator, $\sim 3\cdot10^{-7} mm$, the trajectory can be treated as a straight line. In this case the nonlinearities are canceling each other in regular part of undulator field leaving only edge fields responsible for angular kicks.

In Fig. 9 there are represented transverse field distributions obtained analytically and numerically. In Fig. 10 extended field profile is represented. Here the field distribution is shown starting from the center and going between wires.

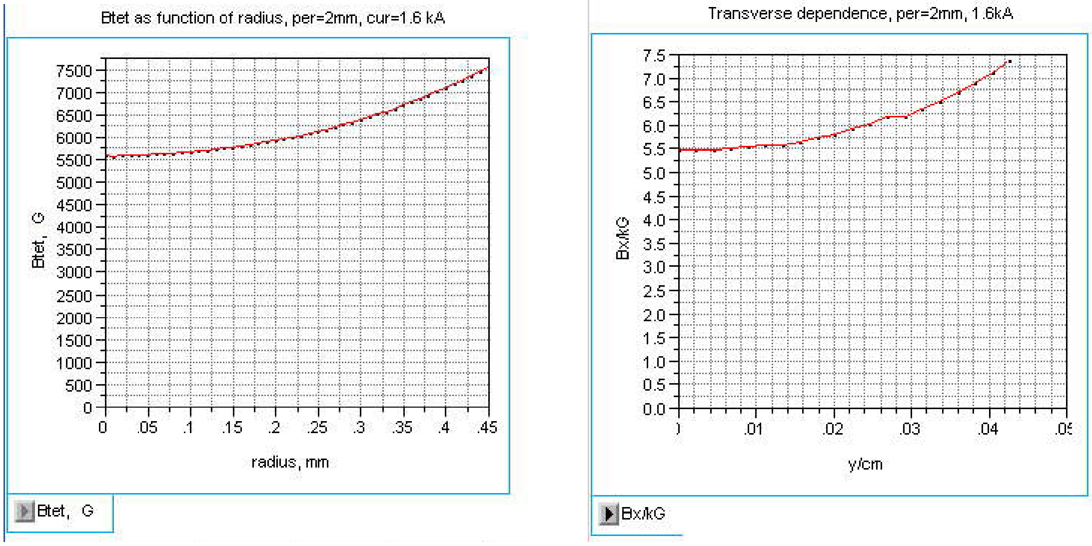

FIGURE 9: Transverse distribution of the field across the line connecting the centers of conductors. Analytical calculation, Gauss, left, and numerical one, kG-right.

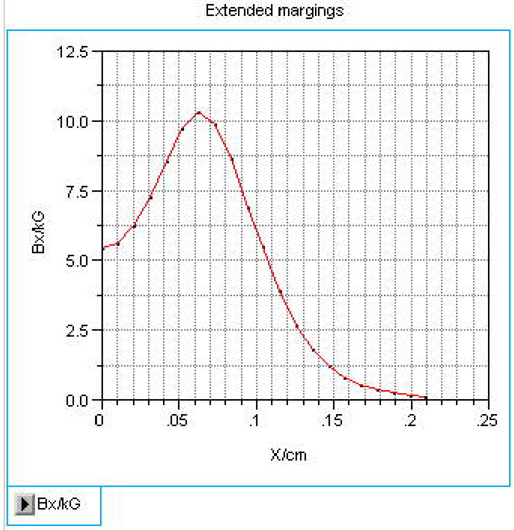

FIGURE 10: Field profile across undulator aperture starting from the center. Feeding current 1.6 kA. Calculations have done with MERMAID.

Longitudinal profile at the end of helixes is represented in Fig.11, Fig.12. This type of field mapping used for modeling end field effects.

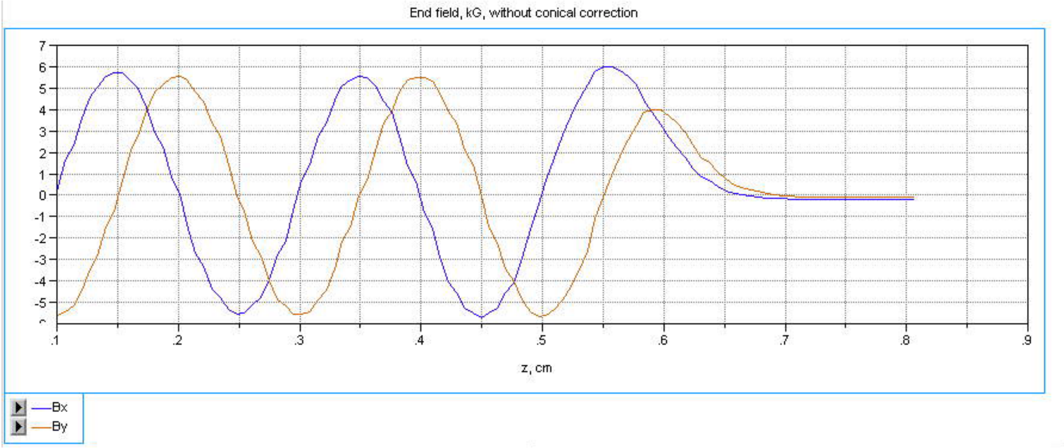

FIGURE 11: (Color) Longitudinal field profile, kG along undulator aperture near the end, cm. There is no end correction. Feeding current =1.6kA.

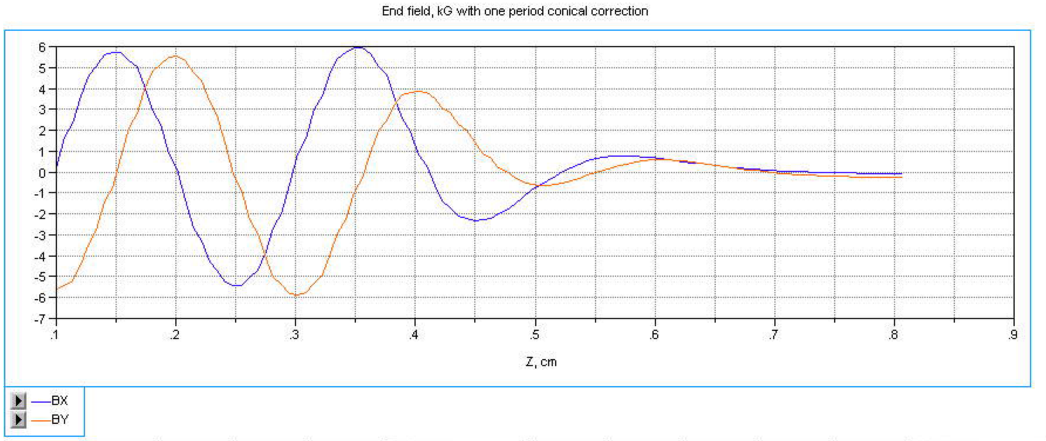

FIGURE 12: (Color) Longitudinal field profile, kG along undulator aperture near the end, cm. End correction. Feeding current =1.6kA.

Fig. 13 explains what type of corrections used to trim end fields.

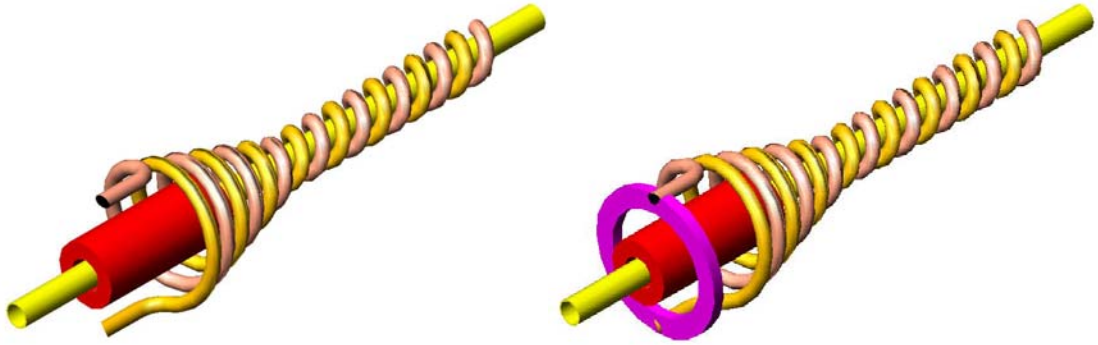

FIGURE 13: (Color) End correction made for input, left and conductor jumper, right. Cupper cylinder serves as a flux attenuator.

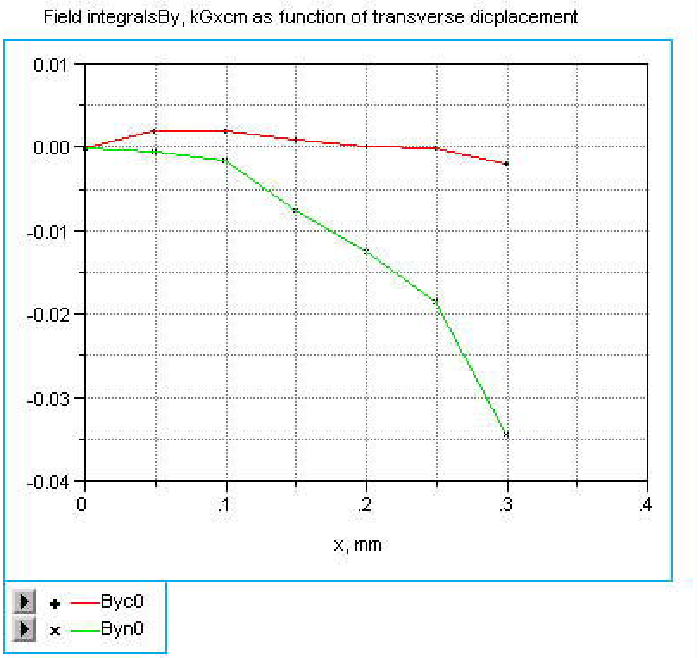

FIGURE 14: (Color) Integrals $\int_{s0}^{\infty} B_y(s)ds$ for conical end, upper curve, and regular one, without conical transition, lower curve.

In Fig.14 the integrals $\int_{s0}^{\infty} B_y(s)ds$ for conical helix end and just regular one are represented. Integrals calculated from fixed point inside the undulator to the point far out from the end and the integral for central (axes) line subtracted from every one, calculated for off-axis position. One can see from Fig.14, that even not corrected end commutation gives integral deviation ~$0.035\,kG \cdot cm$, what yields the angular kick $x' \cong \int Bds/(HR) \cong .035/1.67 \cdot 10^5 \cong 2 \cdot 10^{-7} rad$ only for 50GeV beam. Nevertheless this commutation correction is a useful tool.

PARAMETERS

Parameters of undulator are represented in Table 1 below. Voltage required based on the calculation of inductance done at the same time with field calculations. Number of quants radiated, radiation losses and polarization value are taken from [4] and [9].

Factor undulatority $K = eH\lambda_u / 2\pi mc^2 \cong 93.4 \cdot H(T) \cdot \lambda_u(m)$ for designed feeding current value ~1.6kA goes to $K = 0.1$. Heating per pulse with 30 μsec duty time goes to ~$3\,^oC$/pulse. Voltage required to support the current 1.6kA goes to ~7.25V/cm or ~360V at input of undulator. We expect, that stray inductance might ~double the voltage required from the pulser. Power supply described in detail in [5]. It is pretty much the same type used in [8]. As we mentioned the model of undulator tested in static 1kV applied to the wires. Right now preparation for test this model with power supply is under way.

TABLE 1.

Parameter	Value
Length	2×50cm
Period	2mm
Axis field	5.6kG
K	~0.1
$\hbar\omega$	11.72MeV(50GeV); 9.94MeV(46GeV)
Losses/particle	0.1518×10^{-12} J/m
Losses	0.948 MeV/m
Number of quants/particle	0.16/m
Feeding current	1.6 kA
Feeding pulse duration	30 μs
Heating/pulse	~3 degC
Inductance	~$9.9\text{x}10^{-9}$ H/cm
Resistance	~0.0035Ohm/cm
Inductive Voltage/length	~1.65V/cm
Resistive Voltage/length	~5.6V/cm
Average polarization	~90%

Radiation in the undulator is typical for quantum regime: the amount of energy radiated by particle in less, than energy of quanta. This brings the radiation process in statistical regime.

So, a 50 cm long device will have total inductance ~0.5 μH. Power supply needs to be design for a higher voltage, due to the losses in transmission line. Discharge will be with aperiodic component, significant amount of energy will be dissipated. The temperature gain per pulse calculated to be ~3deg. Full resistance of 50 cm long unit goes to 0.175 Ohm, so impulse active power goes to 0.45 MW. For 30 μs duty pulse averaged per single pulse per second power goes to 6.7 W, which comes to 67 W for 10 HZ repetition rate. Transformer oil will be used as a coolant liquid. Cooling of this oil will be done either in special heat exchanger and/or by cooling the walls of corps by water, so convection will be responsible for transferring heat from wires to the walls and further to the water.

CONCLUSIONS

Pulsed undulator developed for E-166 experiment at SLAC itself despite its unique parameters looks also a pretty guaranteed from the engineering point of view. Real test with designed pulsed current is under preparation with existing (old) pulser removed from positron converter. Static test of insulation done at the Air for 1 kV DC voltage applied to the chamber and wires.

We believe however, that for future linear collider a SC undulator with large (~6mm in dia) aperture and ~8mm period is more suitable from the exploitation point of view.

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