FINAL REPORT
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There were two major objectives of the work supported by this grant: 1) tests of a high voltage pulser for the ILC damping ring kickers; 2) ILC undulator based positron source tests and simulations.

Damping Ring Kicker Pulser (04-05, 05-06)
The ILC damping rings require kickers able to inject and extract bunches of approximately 3 ns spacing without disturbing neighboring bunches. In addition, the kickers must be able to operate in 3.25 MHz bursts with an average pulse rate of 14.1 kHz, driven by 10 kV pulsers. The work reported here focused on the pulser itself. Bench and beam tests of a commercial pulser built by FID Technology were carried out. The pulser, model FPG2-3000-MC2 has a nominal output of + and – 1 kV with advertised rise and fall times and rep rate capability close to that needed by the ILC. Details of the specification derivation and the pulser tests can be found in the appended paper (THPCH148) which was published in the proceedings of EPAC2006,

Figure 1 shows waveforms of the positive and negative 1.08 kV outputs measured with an oscilloscope

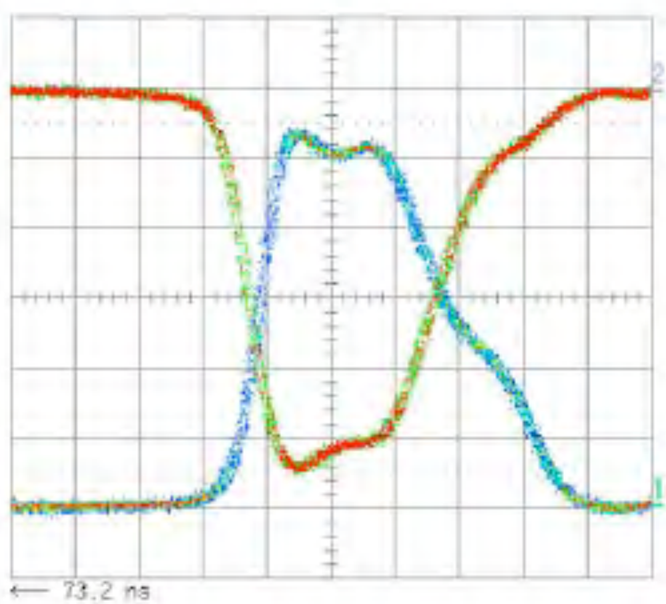

Fig. 1 Waveform obtained from the FPG2-3000-MC2 pulser with 46 db attenuation. The waveform shown is for the first pulse in a burst and is the accumulation of several hundred sweeps, 1 ns per horizontal square.

If we define the full width of the pulse to be the period between the 10% points we see that the pulse is about 5 ns, somewhat wider than desirable for use with bunch spacing of 3 ns and 1 ns long stripline kicker. A large portion of this width is due to the approximately 2.4 ns fall-time of the pulse. Since this will only impact the trailing "hot" bunch, it may be acceptable. A variation of 2% in amplitude over the pulses measured was recorded.

As a further test of the performance of the pulser under accelerator operating conditions, it was used to drive an existing 2.1 ns long stripline kicker on the A0 photo-injector beamline at Fermilab. The kick delivered to a nominal 15 MeV beam was measured and simulated using a digitized recording of the waveforms above. The measured result is shown in Fig. 2 and agrees well with the simulation.

While the measured parameters of the pulser approach that required by the ILC, issues remain: a unit operating at 10 kV must be demonstrated; amplitude stability must be improved by a factor of 2; a detailed characterization of the pulses throughout the train is required.

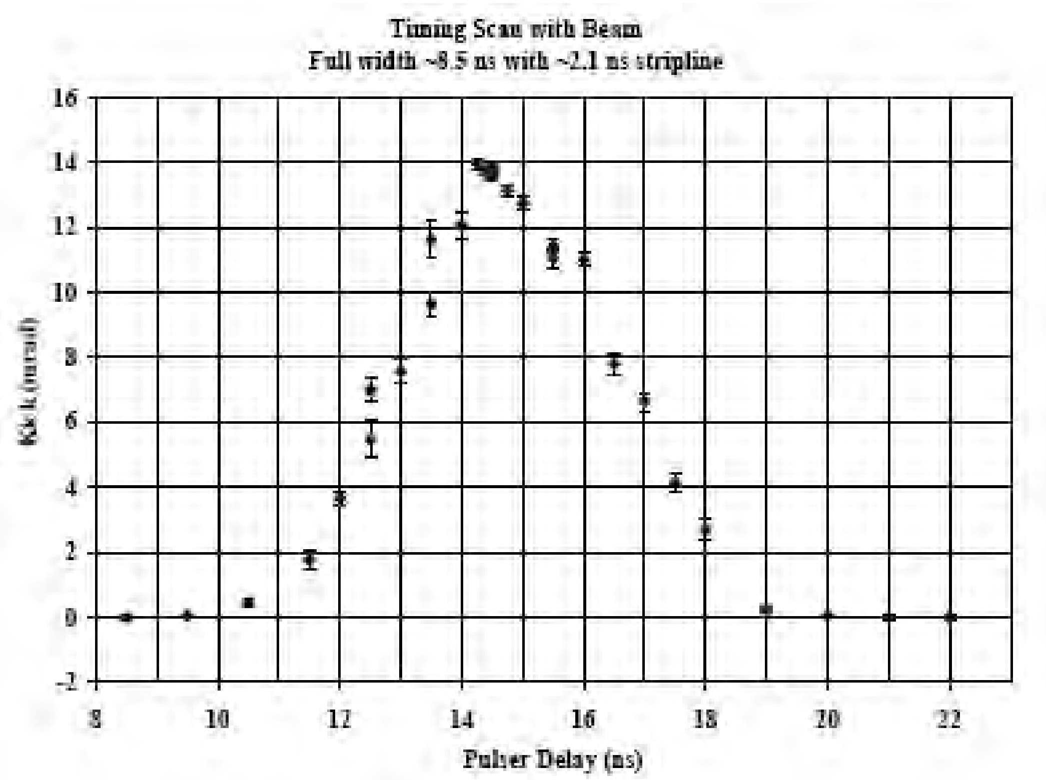

Fig. 2 Beam kick obtained by scanning the pulser trigger relative to the beam arrival time taken at the A0 photo-injector.

After due consideration of positron sources based on electrons on a heavy metal target, inverse Compton effect, and high energy gamma rays on a relatively thin heavy metal target, the ILC Reference Design selected the undulator source as the baseline. Considerations of efficiency, and the possibility of creating polarized positrons, led to the choice of a superconducting, helical undulator approach.

In the work supported by this grant, a design for modules comprising the full scale undulator has been made and short lengths of the undulator cold mass have been produced and tested. The accomplishments up to June of 2007 have been presented in a 2007 Particle Accelerator Conference paper (WEZAB01, appended)

Fig. 3 shows schematically how the undulator is assembled at the end. Fig. 4 is a photo of the tapered end section of the undulator. Fig. 5 is a typical, measured field plot along the two perpendicular axes for this design of undulator. Fig. 6 shows the excitation curve for the model of Fig. 5.

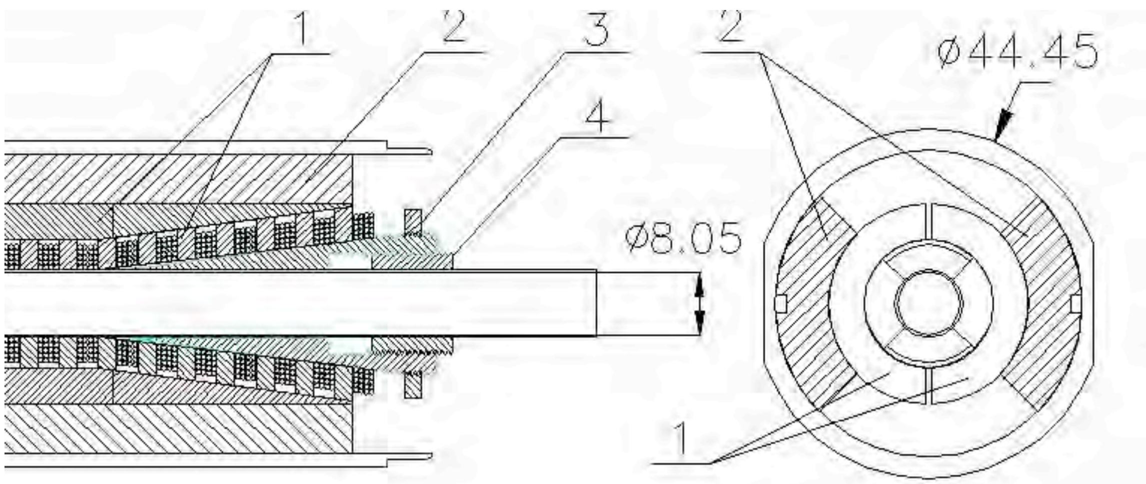

Fig. 3 Details of cold mass design at the fringe with conical tapering. 1–Iron yoke, 2–Copper collar, 3, 4–trimming Iron nuts. Inner diameter of Copper vacuum chamber is 8.05mm clear.

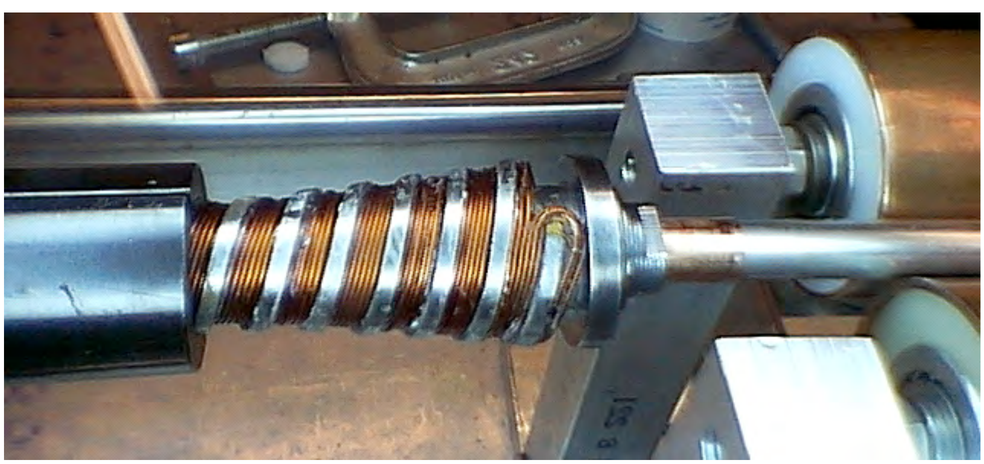

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Fig. 4 Conical coil end during fabrication

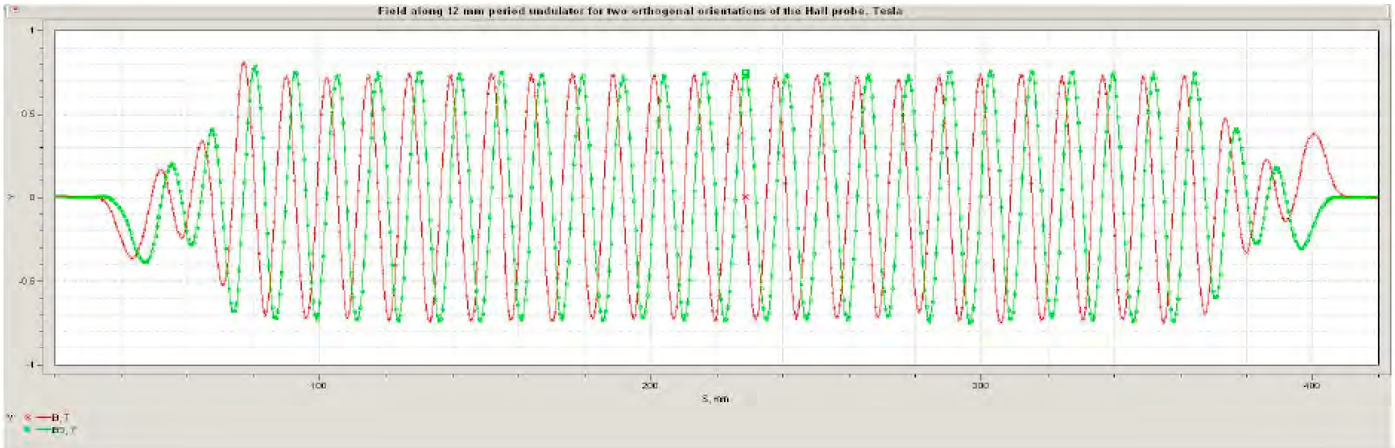

Fig. 5 Field profile – conical ends. 6 layer, 12 mm period – orthogonal hall probes. 1 Tesla full scale.

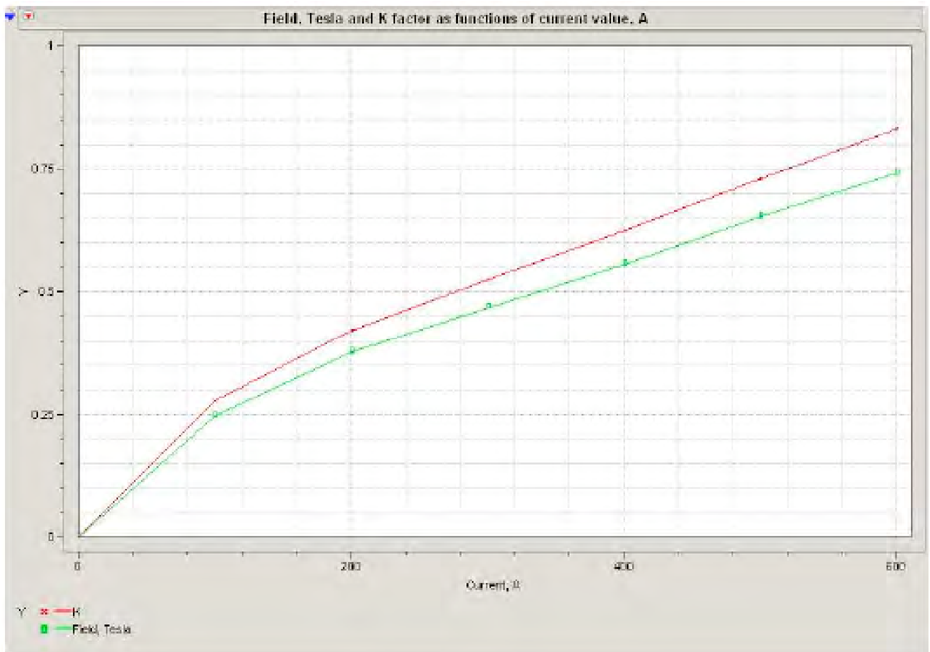

Fig. 6 Excitation curve for 6 layer,, 12 mm period model – *K* value in red, field in green

Parameter trade-off flexibility is shown by three examples of models built with this style of construction

K achieved	Period [mm]	Beam aperture[mm]
0.467	10	8
0.83	12	8
1.48	13.5	6.35

A 3D concept design for an extensible undulator module for the ILC is shown in Fig. 7 while a scale model for use with the 40 cm models discussed above is shown in Fig. 8.

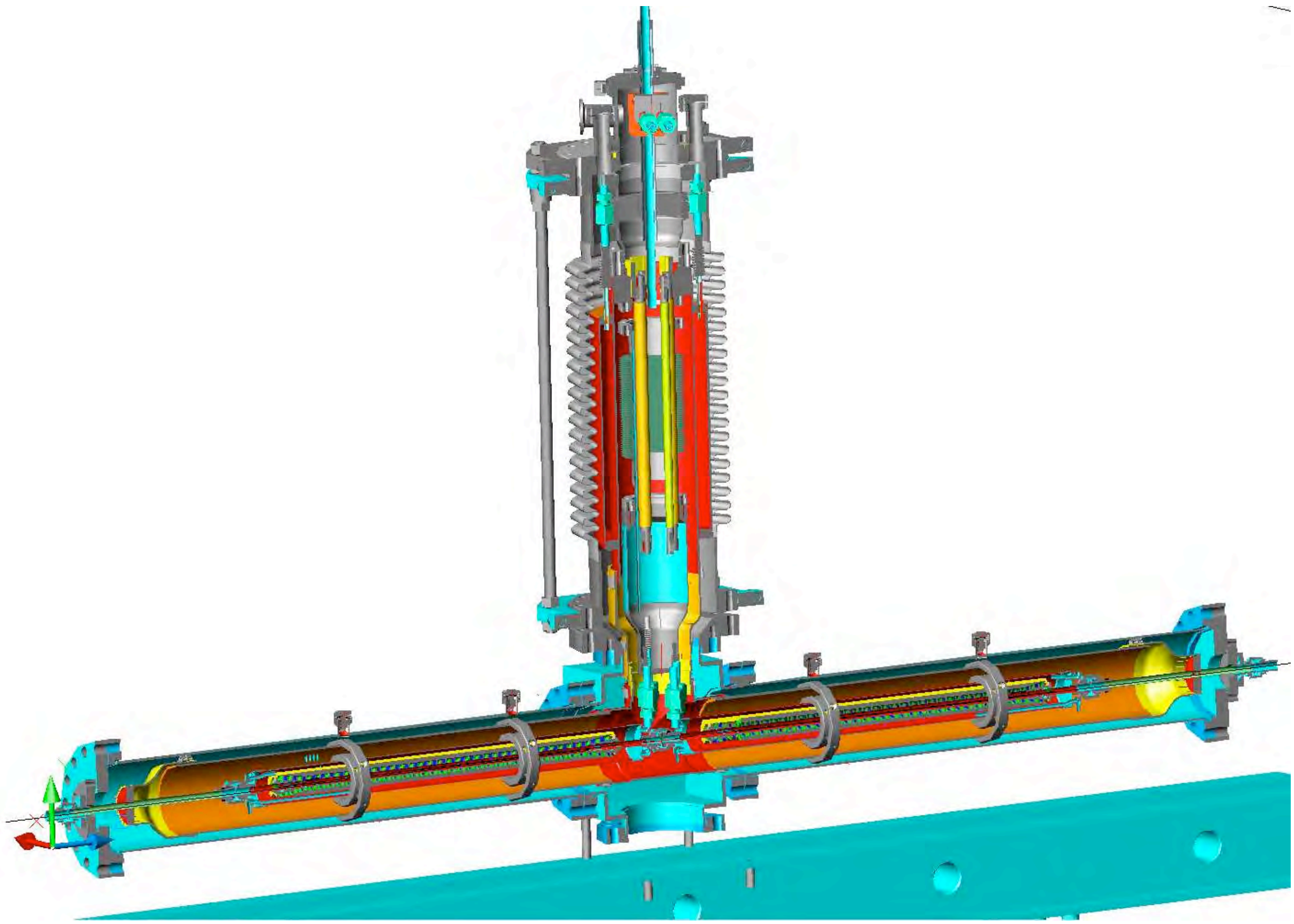

Fig. 7 Extensible prototype concept for ILC positron undulator

Fig. 8. 1m long model of an undulator cryostat for testing with 40 cm model cores waiting for assembly

Extensive references will be found in the appended PAC 2007 paper WEZAB01.

TESTS OF A HIGH VOLTAGE PULSER FOR ILC DAMPING RING KICKERS*

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Abstract

The baseline configuration for the International Linear Collider (ILC) damping rings specifies a single 6.6 km damping ring for electrons and two 6.6 km rings for positrons. Kicker requirements are determined by the damping ring circumference and the train structure in the main linac. The nominal bunch train parameters in the ILC main linac are trains of 2820 bunches with 308 ns spacing and a train repetition rate of 5 Hz. The pulsers for the damping ring kickers must have rise and fall times suitable for bunch spacings of ~ 3 ns, must be able to operate with 3.25 MHz bursts, and must support an average pulse rate of 14.1 kHz. We describe bench and beam tests of a pulser from FID Technology whose specifications roughly meet these requirements. We then discuss the implications of our results for the ILC damping ring kickers.

INTRODUCTION

The large number of bunches per train (2820) and the relatively large main linac inter-bunch spacing (308 ns) in the International Linear Collider baseline design [1] result in a bunch train that is more than 200 km long. A damping ring of this size would be very costly so the bunch train is damped in compressed form. In the 6.6 km electron damping ring of the ILC baseline, mini-trains spaced at 308 ns intervals with an inter-bunch spacing of 3.08 ns are specified. An alternate mode of operation for the main linac has been proposed which would roughly double the number of bunches, while halving both the bunch charge and the inter-bunch spacing. This would require that the damping ring mini-trains be spaced at 154 ns intervals. The damping ring injection and extraction systems are expected to be able to handle either operating scenario.

A system of stripline kickers has been chosen as the default technology for injection into and extraction from the damping rings. Very fast pulsers with a few nanosecond pulse width and operating in the multi-kV regime are required in order to inject and extract the beams with a reasonable total number of kickers.

PULSER REQUIREMENTS

In order to maintain constant beam loading in each damping ring, the injection and extraction cycles will be synchronized. Extraction will proceed from the tail to the head of a train, with each damped bunch that is extracted being replaced by a "hot" injected bunch. In order not to perturb the neighboring bunches in the train, in particular the damped bunch just in front of a bunch undergoing injection or extraction, this means that the energy in the kicker structure must be zero when the preceding bunch exits the structure and must return to zero before the trailing bunch enters the structure. If we treat the bunch as a δ-function, this requirement can be expressed as:

$$t_p \leq 2t_b - 2t_k \tag{1}$$

where t_p is the duration of the pulse driving the kicker, t_b is the bunch spacing, and t_k is the length of the kicker structure. Thus, for a 30 cm stripline kicker, and the specified ILC damping ring bunch spacing, this means that the total width of the pulse must be ≤ 4.16 ns. Note that, for a flat-top pulse with negligible rise and fall times, we would ideally want the pulse width to be twice the kicker length for the kicker to be fully efficient. Furthermore, in this limit, we would want to make the kicker length be one-half of the bunch spacing in order to maximize the available kick to each bunch.

Extraction (and injection) of the bunches from (into) the damping ring takes place in a burst with a repetition period given by the bunch spacing in the main linac. Thus, the driver for the kicker structure must be able to sustain a peak repetition rate of roughly 3.25 MHz for short periods of time (≤ 1 ms). Trains in the ILC main linac are injected in a 5 Hz cycle. This means that the driver must be able to handle the power requirements of an average repetition rate of approximately 14 kHz. If we also consider the possibility of main linac bunch spacings as short as 154 ns and longer bunch trains, up to 5640, we must double the peak and average repetition rate requirements for pulsers.

The overall requirement for the system of fast kickers is to deliver a kick of 0.6 mrad to a 5 GeV electron beam. The kick angle is related to the kicker parameters by:

$$\theta = \frac{2eV_0 l}{Eh} \tanh\left(\frac{\pi w}{2h}\right) \tag{2}$$

where V_0 is the kicker voltage (per electrode), l is the kicker length, h is the kicker half-gap, w is the half-width of the electrodes, and E is the beam energy. As can be seen from Eqn. 1, the length of a single kicker module is constrained due to the requirement for a rapid rise time. For plausible pulser voltages, this implies that large arrays of stripline kickers are required for injection and extraction. The baseline damping ring lattice specifies an array of 22 10 kV extraction kickers and 42 equivalent injection kickers. The pulse stability requirement for the array of extraction kickers is determined by the necessary kick angle repeatability

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Table 1: FID Technology Pulser Specifications[2]

Pulser	FPG2-3000-MC2	FPG1-3000	FPG3-3000	FPG10-3000
Output impedance [Ω]	50	100	100	100
Maximum output per channel [kV]	±1	1	3	10
Number of channels	2	1	1	1
Rise time 10-90% of amplitude [ns]	0.6-0.7	0.6-0.7	0.6-0.7	0.6-0.7
Pulse duration at 90% of maximum [ns]	2-2.5	2.5-3	2.5-3	2.5-3
Fall time 90-10% of amplitude [ns]	1-1.5	1-1.5	1-1.5	1.2-1.7
Maximum PRF in burst mode [MHz]	3	3	3	3
Maximum PRF in continuous mode [kHz]	15	15	15	15
Triggering - internal, external 5-10 v [ns]	20	20	100	100
Amplitude stability in burst mode [%]	0.5-0.7			
Pre- and after-pulses [%]	1.5			
Timing jitter, relative to trigger [ps]	20			

of 7×10^{-4}. For an array of kickers, this means that the tolerance on the voltage fluctuations in individual kickers is given by

$$\sigma_V \leq \sqrt{N_k} \times 7 \times 10^{-4} \tag{3}$$

where N_k is the number of kickers. For the case of 22 extraction kickers this becomes $\sigma_V \leq 0.33\%$.

We have investigated the availability of a commercial device, suitable for driving a stripline kicker, that can meet the baseline requirements. FID Technology, Ltd., a manufacturer of pulse generators, provided several sets of pulser specifications that they feel they can meet. These are presented in Table 1. Note that one possibility for the increased pulse rates required in the case of 5640 bunches would be to allow for alternating pairs of units to be fired. We have purchased an FPG2-3000-MC2 unit for our initial testing on the bench and with a linac beam.

PULSER TESTS

We have carried out tests on two versions of the FPG2-3000-MC2 pulser. Experience with our first unit was somewhat disappointing. Initial tests at low duty cycle showed reasonable output from the unit. However, we soon encountered serious degradation in the output of all but the first pulse when operating the pulser in burst mode at high duty cycle. The problem first appeared in the negative channel with the positive channel quickly following. The failure was traced to a bad resistor in the charging circuit of each channel and the unit was repaired by FID. In order to validate the fix, we set the repaired unit up to run at high duty cycle for several weeks. After just under a month, the unit began to show the same symptoms as in the original failure. Shortly thereafter, FID Technology provided us with a second unit that had significantly improved cooling. The results in the remainder of this paper describe tests carried out with the second unit which has performed without significant problems.

Figure 1 shows the waveforms of the two channels of the FPG2-3000-MC2 as obtained with a LeCroy LC574AL oscilloscope (1 GHz input bandwidth) using 46 dB of attenuation. From these waveforms we infer the peak voltage at the outputs of the pulser to be approximately 1.08 kV. Fea-

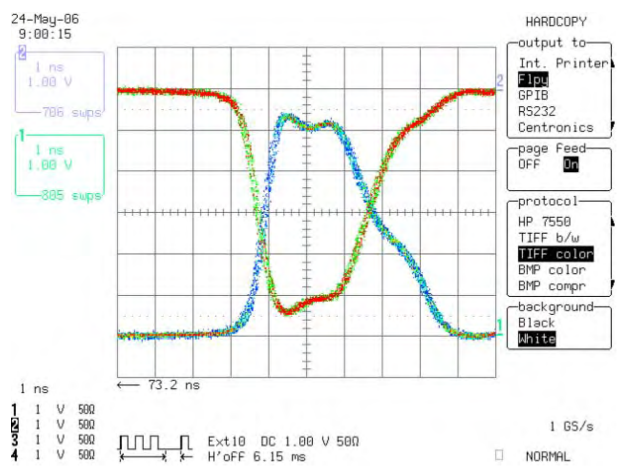

Figure 1: Waveform obtained from the FPG2-3000-MC2 pulser with 46 dB attenuation. The waveform shown is for the first pulse in a burst and is the accumulation of several hundred sweeps.

tures of the scope traces to note are: a small voltage, associated with the charging of the device, is discernible prior to the main pulse; the rise-time and top of the pulse appear consistent with the specifications given in Table 1; and the fall-time of the pulse is somewhat longer than the specifications given in Table 1. If we define the full width of the pulse to be the period between the 10% points of the waveform, we see that the pulse is ~ 5 ns in duration, which is somewhat wider than desirable for use with bunch spacings of 3.08 ns and a 1 ns long stripline. A large portion of this width is due to the approximately 2.4 ns fall-time of the pulse. Since this will only impact the trailing “hot” bunch, it may be acceptable. The voltage induced in the kicker due to device charging prior to the main pulse will be seen by the damped bunch which precedes the bunch being extracted or injected. As has been suggested elsewhere, this feature can potentially be dealt with by a suitable feed forward system using an extra kicker.

Although not shown, we have also investigated variations in amplitude from pulse to pulse within bursts of pulses. Comparisons of the oscilloscope waveforms for the different pulses show equivalent pulse heights to within approximately 2% for all of the pulses examined.

Digitized output from the pulser has been used to simulate the response of a stripline kicker to the pulser. Figure 2 shows the expected kicks to the beam for a 1 ns stripline (red) corresponding to the ILC baseline and a 2.1 ns stripline (black) corresponding to the test kicker at the A0 Photoinjector (A0PI) at Fermilab. For the nominal 15 MeV A0 beam and a 1.05 kV kicker, this implies a kick of roughly 14 mrad to the beam.

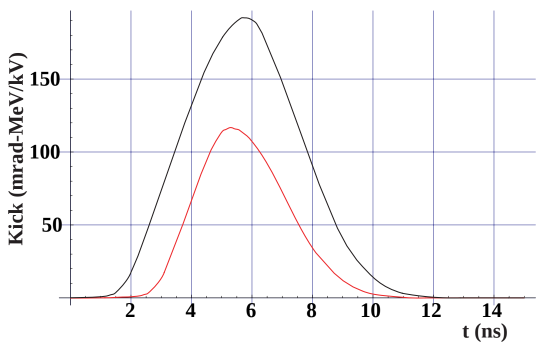

Figure 2: Simulation of the expected kick from a 1 ns stripline (red) and a 2.1 ns stripline (black) based on scope data taken with the FPG2-3000-MC2 pulser.

The kicker diagnostic line at the A0PI provides a pair of BPMs, with 1.46 m moment arm, upstream of the 2.1 ns kicker. A dipole corrector is located 0.79 m after the center of the kicker and allows approximate nulling of the beam trajectory before it passes through a pair of downstream BPMs spaced by 1.39 m. Figure 3 shows data that was obtained by scanning the trigger time of the pulser relative to the arrival time of the bunch in the A0 kicker. The points are determined by measuring the difference in angles between the two sets of BPMs and subtracting the contribution of the nulling corrector. The maximum kick amplitude recorded in Figure 3 is just under 14 mrad and the width of the pulse at the 10% points is slightly under 8.0 ns, both in good agreement with our simulation prediction. The error bars on the points represent the sigma of the angle distribution as obtained over many pulses in the accelerator. When the pulser is triggered out of time with the bunch, the scatter is approximately 0.06 mrad and represents our resolution limit using the A0PI as presently configured. On the top of the peak, the scatter is approximately 0.12 mrad. If we subtract the measurement resolution in quadrature from this value, we obtain a measure of the short term stability which includes the effects of both timing jitter and pulser amplitude stability. This value is 0.75% of the kick and is reasonably consistent with the pulser amplitude stability specification shown in Table 1. It is approximately twice as

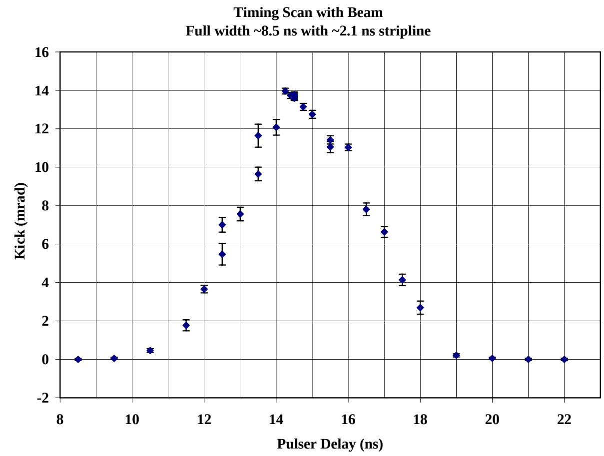

Figure 3: Beam kick obtained by scanning the pulser trigger relative to the beam arrival time taken at the A0 Photoinjector.

large as the value desired for the damping ring extraction kickers.

CONCLUSION

The measured parameters of the FPG2-3000-MC2 pulser approach the timing specifications desired for the ILC damping ring kickers. If it is found acceptable to have some perturbation of the "hot" bunch trailing the extracted/injected, it is possible that the a pulser with the observed time structure would be acceptable for damping ring applications. At the same time, there are several issues that require further research: first and foremost, the performance of a unit operating at 10 kV must be demonstrated; we also need to verify that the amplitude stability can be improved by roughly a factor of 2 in comparison to the present unit; a more detailed characterization of the performance of pulses throughout the pulse train is required; and, for the option of 154 ns spaced bunches it must be demonstrated that a unit can be built and operated with 6.5 MHz bursts and 28 kHz average pulse rate.

ACKNOWLEDGMENTS

We would like to thank Helen Edwards, Ray Fliller, Jamie Santucci and all the Fermilab staff who helped make the A0 photoinjector available for these tests. We would especially like to thank George Gollin and Michael Davidsaver of the University of Illinois for all their work on the data acquisition system and kicker diagnostic line.

REFERENCES

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[2] V. M. Efanaov, B. O'Meara, private communication.

ILC UNDULATOR BASED POSITRON SOURCE, TESTS AND SIMULATIONS

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Abstract. An undulator based positron source allows generation of polarized positrons in quantities required by ILC. Here we describe the results of modeling and testing of elements for such a system.

Classification 3: Linear Colliders, Lepton Accelerators and New Acceleration Techniques, A03.
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INTRODUCTION

The scheme for polarized positron production was proposed a long time ago in a framework of VLEPP project [1]. The basis of the method is a two stage process, where at first stage the circularly polarized photons generated in helical electromagnetic field and then, at second stage, these photons converted into positrons and/or electrons in a thin (~half radiation length) target. Secondary particles carry longitudinal polarization transferred from the primary photon beam in accordance with theirs energy. In this first publication [1] the gammas considered to be generated by energetic particle in the following substances: in a field of electromagnetic wave, in static magnetic helical field of undulator and in crystals with helical dislocations (helical crystals). In [2] the laser radiation was considered as a specific example of an electromagnetic wave. With application of selection of energetic positrons only, the final polarization increased and defined by the length of undulator (as one needs to compensate partial collection of secondary positrons). For typical length of undulator~175 m, the degree of polarization reaches ~60% and it could reach ~80% with 300 m long undulator. One peculiarity associated with helical undulator scheme is that this system is able to generate *polarized* positrons with degree of polarization ~30% if no energy selection mechanism applied to the positrons at all.

The undulator scheme of positron production has been chosen as a baseline for ILC [3] accommodated from TESLA design [4]. One peculiarity here is that the beam, like in original VLEPP scheme is going through the undulator on its way to IP. One positive moment of this is that the beam can be made having small transverse dimensions as the emittance is small. This allows small aperture in undulator and hence makes engineering problem less severe. From the other hand nonlinear field of undulator could disturb this tiny emittance and polarization of this primary beam while it is going to IP. Considerations show that this is not a problem here however as the beam trajectory remains line-type with accuracy ~1/γ so the nonlinearities cancel each other. So the ILC scheme looks as it is represented in Fig.1

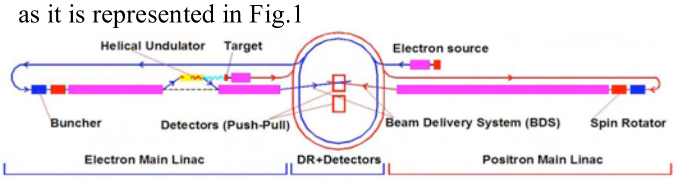

Figure 1: The basic scheme of ILC.

Undulator located at the 150 GeV mark in a chicane, as the energy of quanta radiated on harmonic number n=1 for the undulator with period λ_u comes to ~20 MeV there

$$E_{\gamma n} \cong \frac{n \cdot 2.48 \cdot (\gamma/10^5)^2}{\lambda_u[cm](1+K^2+\gamma^2\vartheta^2)}[MeV], \quad (1)$$

where the factor $K = eH\lambda_u/2\pi mc^2 \cong 93.4 \cdot H[T] \cdot \lambda_u[m]$, ϑ stands for the angle in direction to observer. Efficiency of conversion could reach such level, that two initial electrons generate in average three secondary positrons captured (1:1.5 conversion).

Minimal offset in chicane helps in reduction of radiated power (and power density, as the beam size is small) and makes possible emittance perturbation to be smaller also. This chicane could be arranged is the same tunnel without any additional extensions at all, se below.

So one can see that positron source is a complex system which includes a lot of different components and each of these components can be a subject of a separate talk.

GENERATION OF POSITRONS

As the only gamma-quanta can create an electron-positron pair, by all means the positron source must generate the gammas in necessary amounts, able to cover limited acceptance of collection optics. There are few possibilities on how to get gammas, Fig.2.

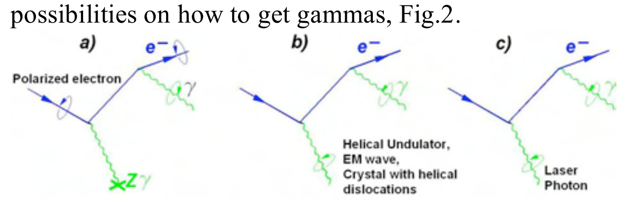

Figure 2: The way to obtain the (polarized) gamma-quanta. a)-the incoming electron is polarized [5], b)-the electron radiates in a helical electromagnetic field of broad nature [1], c)-the laser radiation appointed as a specific example of helical electromagnetic wave [2].

In ordinary conversion system the gammas created as a result of a cascade (shower), developed by the primary non polarized electron (Fig.2, a) with non polarized electron). This is so called generation of gammas by bremstrahlung. Shaking of electron here is going by the field of nuclei. This process is characterized by X_0– radiation length

$$X_0^{-1} \cong 4r_0^2\alpha\frac{N_0}{A}Z(Z+1)\ln(\frac{183}{Z^{1/3}})[cm^2/gramm], \quad (2)$$

where A –is atomic weight of target substance, $N_0 \cong 6.022 \cdot 10^{23}$ is the Avogadro number, Z is the charge of nuclei, factor $Z(Z+1)$ takes into account atom electrons, $\alpha = e^2/\hbar c = 1/137$, r_0 is a classic electron radius.

Despite the thickness of target is significant in this type of conversion, the only outer layers are serving as the source of positrons, which energies in maximum are of the order of the critical, one, ~10MeV. The effective RMS depth l of positron creation is

$$l \cong \langle xx' \rangle / \langle x'^2 \rangle \quad , \tag{3}$$

where x and x' stand for the transverse coordinate and its derivative, brackets mean average over all phase space. The last expression comes to ~0.8mm for 10-*MeV* positrons. Knowing last number is important for description of target immersed in magnetic field, showing the principal depth, which magnetic field penetration tolerates the process.

In the scheme of positron production with gammas obtained by shaking primary electron (or positron) either in a field of static undulator, EM wave or in a laser field, Fig.3 b), c), the gammas represented by a *separate source*. So here the heating the target by primary electron component is absent and all target can be used for positron creation. Thus the target becomes having thickness of the order of latest layer in previous method.

The number of the quants radiated by electron in the presence of the photons (real or virtual from wiggler) can be described in terms of effective length as the following

$$N_\gamma \cong L\sigma_\gamma n_\gamma \,, \tag{4}$$

where $\sigma_\gamma \cong \frac{8\pi}{3} r_0^2$, $n_\gamma \cong \dfrac{H^2}{8\pi\hbar c/\lambdabar_u}$ is the photon density, H is magnetic field value, $\omega = 2\pi c/\lambda$ is the frequency of the photon. So the length of interaction goes to $l_\gamma \cong 1/\sigma_\gamma n_\gamma$. For the undulator having the length L

$$N_\gamma \cong L r_0^2 \frac{H^2}{\hbar c/\lambdabar} \propto 4\pi\alpha \frac{L}{\lambda_u} \frac{K^2}{1+K^2} \,. \tag{5}$$

As the length of formation for undulator $\sim \lambda_u$ then this formula reflects the simple fact that the number of radiated photons is equal to the number of radiation lengths, L/λ_u. It is known, that particle radiates α photons on its passage through this distance.

Positron ring can be filled from electron linac also, Fig.3. This magnet system can be made compact; with high-field bending magnets as there are no obstacles from emittance dilution, while the beam irradiates the target.

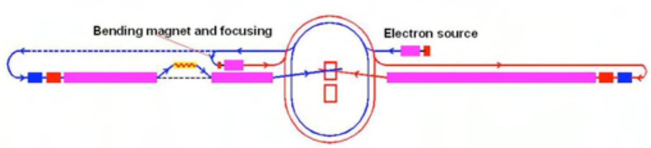

Figure 3: Possible operational scheme for filling positron ring by usage of electron source linac. With stacking and polarized electron source this scheme allows accumulation of polarized positrons.

One additional comment can be made here. In [5] the method for *polarized positron* production was proposed implementing the usage of polarized electrons as a primary source (Fig. 3-a). During bremstrahlung, the longitudinally polarized electron radiates circularly polarized gamma at high edge of spectra. Further on, these polarized gammas become converted into electron-positron pairs in (the same) heavy target, similarly to conversion of undulator gamma-radiation. Polarized electrons obtained from the photocathode, in the same manner, as required for polarized electron source for ILC. Efficiency of this method could reach ~1.5% [5] i.e. each primary electron generates positron with probability 0.015 with polarization up to ~80% of polarization of primary electron beam (which could be~90%, so coming to ~72% total). So to satisfy the requirements of ILC, the positron beam must be stacked in a damping (cooling) ring. But this is the same yield as for the mechanism for polarized gamma production by usage of Compton back scattering process [6]. By other words the efficiencies of processes shown in Fig.3 a) and c) are the same. For implementation of method [5], one needs to use polarized electron source and insert a target in electron injection line; *no lasers required at all*, as in Fig.3. But still, the method with helical undulator is much more effective way to go. This comment can be considered as a serious argument against the Compton source of positrons for ILC.

Parallel shift in chicane arranged with the help of two bending magnets at each side. Two radially focused quadrupoles at each side accomplish this bend. Total distance occupied by chicane comes to ~350 m minimum; at this distance the RF structures more likely need to be removed. Minimal offset defined by the size of RF modules shadow further on of gamma-ray way as the target located at the distance ≥ 180 m from the end of undulator. According to this minimal offset distance might be ~450mm. Bending magnets have active length ~20m each with bending radius ~2km. Calculation of this chicane is rather challenging procedure as the tiny beam emittance makes SR radiation so severe, that without special measures this radiation can damage opposing wall of vacuum chamber [21].

MODELING OF CONVERSION

Diagram on Fig.2 needs to be considered with polarization of secondary positron (electron) as function of its energy E_+ [7], [8]. Main characteristics of Undulator Radiation (UR) are the energy of quants (1), spectral photon density dN_γ/dE_γ and it polarization as this parameter appears as a factor in final polarization of positron. Expression for spectral density of radiation for undulator having length L has a form [18] [14],

$$\frac{dN_\gamma}{dE_\gamma} = \sum_n \frac{dN_{\gamma n}}{dE_\gamma} = \frac{\alpha K^2 L}{\hbar c 2\gamma^2} \sum_{n=1}^{\infty} F_n(K,s) \,, \tag{6}$$

where $s = E_{\gamma n}/E_{\gamma n \max}$, $E_{\gamma \max}$ defined by (1) for $\vartheta = 0$,

$$F_n(K,s) = J_n'^2(n\kappa) + \frac{1+K^2}{4K^2}\frac{(2s-1)^2}{s(1-s)}J_n^2(n\kappa), \qquad (7)$$

$\kappa = 2K\sqrt{s(1-s)/(1+K^2)}$, J_n stands for the Bessel function of the first kind. Differential cross section referred to the radiation length unit can be represented as the following $d\sigma(E_\gamma, E_+) \cong \sigma_0 dE_+ / dE_\gamma$, where [22]

$$\sigma_0 \cong A/(N_0 X_0) G(E_+, E_\gamma) \qquad (8)$$

stands for total cross-section of photon absorption at the radiation length growing up to 7/9 at high energy,

$$G(x) = x^2 + (1-x)^2 + \frac{2}{3}x(1-x) - x(1-x)/(9\ln(183Z^{-1/3}) \cdot$$

Variation of σ_0 is equivalent of slow variation with energy of the interaction length and requires appropriate correction of target thickness for better efficiency.

The number of positrons generated by a single photon in the target becomes [16]

$$\frac{dN_+}{dE_+ d\tau} \cong 0.4\frac{\alpha K^2 L}{\gamma^2 \hbar c}\frac{7}{9}(1 - E/E_{\gamma 1})(1 - e^{-7\tau/9}) \qquad (9)$$

For E_0=150 *GeV*, *L*=150 *m*, K^2=0.1, $\tau \cong 0.5$ (rad units)

$$\frac{1}{N_{tot}}\frac{dN_+}{dE_+} \cong 0.2\,[1/MeV] \cdot \qquad (10)$$

More detailed analytical formula for efficiency of conversion per each initial electron taking into account finite length of undulator stands [18]

$$\Delta N_{+1} \cong 2 \cdot 10^{-2}\chi^2 M\delta\frac{K^2}{1+K^2}\frac{z_f}{z_i}(1 - \zeta_{cap}), \qquad (11)$$

where χ is a is a fraction of what is the target radius in respect to the size of the gamma spot at the target distance, $z_{i,f}$ are the coordinates of undulator end and beginning calculated from the target position, ζ_{cap} is efficiency of geometric capture of positrons, $M = L/\lambda_u$ is total amount of undulator periods, □ is thickness of target in radiation length. For

χ = ½ , M=10^4, $\delta = 0.2$, K=1, $\zeta_{cap} = 0.7$, $z_f = M\lambda_u = 2z_i$, total amount of positrons per electron in undulator comes to $\Delta N_{+1} \cong 3$.

Although analytical calculations found to be accurate, from the very beginning, numerical calculations were thought as a supplemental way to go.

One general question is: how low K-factor could be? One can see from (5) that the number of photons is extremely sensitive to the *K* factor value. From the other hand with increasing the K value the content of higher harmonics also increased. At *K*≈0.7, the power radiated at the first harmonic comes to 50% of total one. Radiation at harmonics has proportionally higher photon energy, what makes collection of particles more difficult.

To answer these questions few numerical code were used such as KONN [21], CONVER [23], OBRA [26], [27], In particular KONN is start to end computer code realizing Monte-Carlo simulation of radiation in undulator, conversion in target, collection by Li lens and further acceleration.

Argonne Laboratory also began modeling of positron conversion with undulator using EGS4, Geant4 and Fluka [19]. Same type of calculations carried at SLAC [28]

Answer to this question obtained is that K<0.4, λ_u =1cm, L~175 is enough for 1:1.5 conversion in positrons with ~60% polarization. Bigger K~0.9 allows having *L*~30m with polarization ~40%.

TARGET

Power dissipated in a target with traditional method by direct electron/positron conversion becomes so big, that it is not practical for ILC. That is why positron production scheme with undulator was chosen as a baseline for ILC. Even so the target problem remains serious.

The base line for now, is the Titanium rim-target having diameter ~1m spinning at 500 rpm [20]. Thickness of this rim comes to ~1.42cm, close to X_0 /2 for Ti. Such a big thickness introduces additional difficulty for collection optics, which now needs to have the focal depth of the order of the thickness of target.

On possible solution of this could be a *sandwich* type target [21], Fig.4.

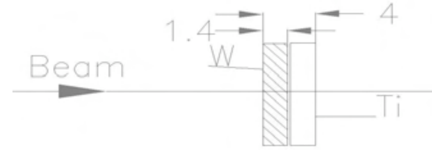

Figure 4: Two-layer target with W as the first one. Dimensions are given in mm

Other possibility is a liquid metal target, Pb/Bi or Hg [24]. In this type of target the metal confined in a profiled duct having Be window at the exit side of this duct. Some results of this modeling show that temperature rise could be kept at the level of 125°C then the thermal pressure at the first moment comes to ~1*kbar* level. By introduction of focusing and/or some steering of beam in undulator, one can artificially increase the gamma-spot size on the target.

COLLECTION OPTICS

Usage of collection optics has a peculiarity here as the spinning target rim perturbs magnetic field as result of eddy currents in moving metal [25]. So collection optics must be field free in region of target. Description of Li lens and solenoidal lens on can find in [30]

Accelerating structure is important component of positron conversion system. Structure immersed in solenoidal field having maximal value up to 40kG, so the room temperature structure with big aperture must be used here. Such structures with appropriate parameters are under development [10], [20]. Structure developed in [20] has one input located close to the target side, indeed the RF power input in [10] made in a symmetric way by usage of two waveguides. What is important here is to locate RF input at the far end of the structure counted from the target.

TEST OF UNDULATORS

Undulators satisfying requirements of positron conversion system very fabricated and tested in Novosibirsk in 1986 as a part of VLEPP program [11]. Pulsed undulator tested had aperture 4mm, period 6mm and could reach K=0.35 with feeding current ~10kA. SC undulator had period 10 mm, aperture ~6mm and could reach K~0.6. Basically these designs served as prototypes for design of undulator for E-166 experiment (see below) and for SC undulators developed at Cornell.

Few undulators were tested at Cornell. Basically they can be grouped in two categories as having 10mm and 12mm periods. Helical iron yoke of appropriate period used in all undulators designs so far. All undulators tested have clear aperture 8mm. Maximum K factor reached for 10mm period undulator is K=0.467 and K=0.83 for 12 mm period. According to our calculation any of these undulators can satisfy 1:1.5 efficiency of conversion. However we considering the reduction of aperture down to 6.25mm which allows having K=0.7 for 10mm period and K=1.2 for 12 mm period. This might be useful for initial period of tuning the ILC. And low K factor helping in obtaining higher degree of polarization could be installed later on by lowering the feeding current.

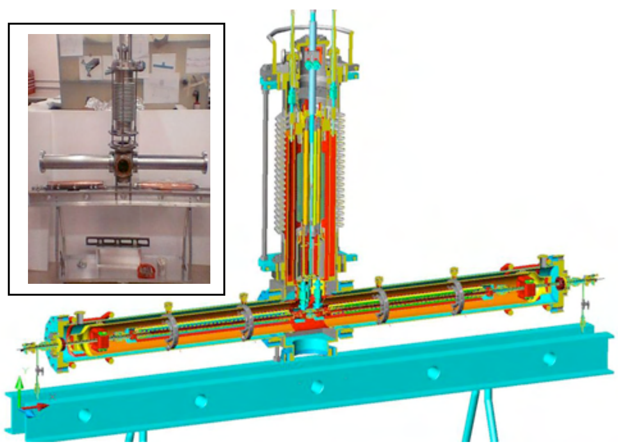

Figure 5: The cross-section of undulator module under assembling in Cornell LEPP. This 1.5 m long prototype model has all elements carried by full 4-m long prototype.

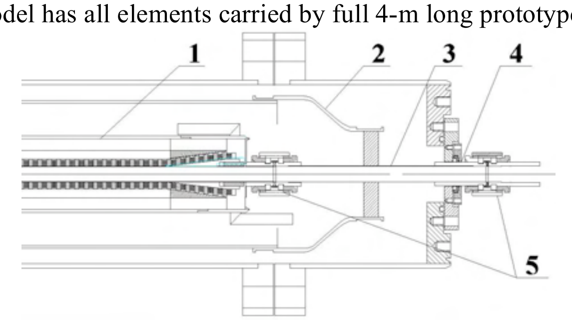

Figure 6: Schematics of transition region between cold mass and the room temperature flange in Cornell undulator. 1—cold mass, 70 °K shield, 3—StSteel thin wall tube, 4—Wilson type sealant, 5—Conflat® joints.

Much attention paid for smooth transition between modules. One can see from Fig.6, that the Copper vacuum chamber in region of cold mass with a help of metal gasket joint to the stainless steel tube covered by thin Copper layer inside. At some distance between LHe cold mass and room temperature flange, there is c thermal contact with 70 °K Copper shields. Diameters of copper tube in cold mass and the stainless steel transition one are the same so the perturbation due to wake fields is minimal. This transition required only between long segments as for mostly length, the cold mass of one section joint directly to another one with metallic gaskets. Indeed, in design [9] the transition is rather long and has significant variations in diameter. Mode detailed description about development of undulators in UK on can find in [29].

TEST OF CONVERSION SYSTEM

Recently the test of polarized positron production in experiment E-166 [17] was done successfully. Polarization of positrons ~85% measured in good agreement with calculations. We expect detailed publication soon. Polarization measured by usage of spin dependence in cross section of circularly polarized gammas, propagating in magnetized Iron.

Targets were installed on remotely movable device having few slots for installation of targets of different materials and thickness. It was found, that W target gives~45% higher yield than the Ti target of the same thickness ($0.5X_0$).

CONCLUSIONS

Conversion system using undulator as a source of circularly polarized photons delivers polarized positrons at the exit in the amounts >1.5 per each initial electron/positron at the entrance. This efficiency can be obtained with relatively low K factor <0.4. Main beam of electrons after reaching 150 GeV directed in undulator installed in chicane line with minimal deflection from the linac axis. Aperture of undulator due to small dimensions of the driving (primary) beam could be 6-8mm only. Period of undulator might be 10-12 mm and this well supported by models developed and tested at Cornell and at Daresbury.

Polarization in both beams is extremely powerful tool for High energy physics as it delivers a possibility to prepare more cleanly initial condition and suppress mostly backgrounds. Perturbation of polarization is minimal [12], [13]. We are concluding that *if* Linear Collider will be built in some time at all, it must be able colliding both positrons and electrons polarized. Undulator needs to be made with sections ~4m each with total length ~200m. Longer undulator-higher polarization can be achieved. With 300 m-long undulator polarization can reach 80%. Polarized electrons could be obtained by the same way also.

Experiment E-166, which completed at SLAC, eliminated any doubts about polarized positron production possibilities**.**

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