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ZERO-TH ORDER DESIGN OF FLUX CONCENTRATOR
FOR ILC CONVENTIONAL POSITRON SOURCE

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Abstract

A peak energy deposited density in a target material for ILC positron source is so high that electron beam spot on a converter should be about 8 mm in diameter to provide target surviving during long operation time. In this case, the matching device also should have enough enlarged face aperture to steer through the positron beam. Several types of matching devices based on a Flux Concentrator technics are considered in the report.

Численное моделирование концентратора потока для позитронного источника ILC

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Аннотация

Максимальная плотность энерговыделения в материале мишени позитронного источника ILC достигает большой величины, поэтому для обеспечения надежности её эксплуатации в течение долгого времени размер сфокусированного электронного пучка должен быть не менее 8 mm в диаметре. Согласно фокусирующее устройство, расположенное после мишени также должно иметь увеличенную апертуру. В работе представлено численное моделирование нескольких типов согласующего устройства на основе концентратора потока.

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ZERO-TH ORDER DESIGN OF FLUX CONCENTRATOR FOR ILC CONVENTIONAL POSITRON SOURCE

The International Linear Collider (ILC) is a next generation of electron positron accelerator for high-energy physics in TeV energy range. Positron production rate for ILC is very high in comparison with already existed electron positron complexes. There are two methods of positron production. The first modern way is gamma positron conversion. Follow to this way gammas generated by undulator irradiation of electron beam with energy higher 130 GeV produce positrons in the target of non-high-Z material. A titanium (Ti) disk of 1000 mm in diameter with thickness about $0.4\div 0.5$ radiation length is one from discussable target design. The second method is used in conventional positron source based on electron positron conversion in heavy material target. In this scheme positron beam is generated by multi-GeV electron beam colliding with high Z-material target with a thickness several radiation lengths (r.l.). Usually, tungsten rhenium alloy (W75Re25) is applied as a target material. A peak energy deposited density in a target material is so high that electron beam spot on a converter should be about 8 mm in diameter to provide target surviving during long operation time. In this case, the matching device also should have enough enlarged face aperture to steer through the positron beam. Several types of matching devices based on a Flux Concentrator (FC) technics are considered in the report.

INTRODUCTION

A very high ILC luminosity forces a large number of particles in electron and positron beams. Main superconducting ILC linac operates with 5 pulses per second rate (5pps) and electron beam train as well as positron beam train contain 2625 bunches in 0.96 ms train's length. Each bunch has intensity of 3.2 nc (2×10^{10} particles in bunch). In the ILC technical design report the gamma positron generation scheme was taken as the baseline [1]. The enough gamma's number should be generated by electron beam with an extremely high energy steering through undulator units. Gamma rays are converted to positrons by a practically one cascade pair creation processes in thin titanium alloy target. This scheme of

positron production overcomes significant trouble of extremely high energy deposition inside of the target material and looks attractive from this point of view. On the other hand, undulator unit should have length about 200 m to produce enough gamma's number. Such a long undulator has not been fabricated in the past and undulator positron generation has not been applied at actual accelerators. Taking into account a technical risk to use units not well tested in the long operation time, a conventional scheme of a positron production also is considered as a technical backup.

The conventional positron source scheme applies a multi-GeV electron beam, which impinges into a high-Z material target. Electron beam generates several cascades electro-magnetic shower the into target material. The target should be thick enough for the electro-magnetic shower to reach a maximum positron number. Computer simulation of electron positron conversion in a heavy metal such as W75Re25 alloy shows the peak production rate a little less than $15 e^+/e^-$ with target length 5 r.l. and impinging electron beam energy about 6 GeV. The one radiation length of W75Re25 alloy is approximately 3.4 mm. The same material target of 4 r.l. thick generates $13.2 e^+/e^-$. But the total energy deposition in target material becomes lower 15% of the impinging electron beam energy with 4 r.l. thick target instead of 23% with 5 r.l.. The total energy of one electron beam is about 50.5 kJ. Thus the total mean power deposition into a target material of ILC conventional positron source is estimated as 38 or 58 kW (in case of 15% and 23% of energy deposition, respectively). SLC target had a mean power deposition in target about 4 kW. Another very important parameter, which defines surviving and reliable target operation in long time, is a peak energy deposition density (PEDD). A many years' experience of SLC operation indicates PEDD value in W75Re25 target material should be not higher than 35 J/g to avoid of any target damage.

Taking into account all the target characteristics mentioned above, following time structure of the electron beam was suggested [2]. One electron beam train of 63 ms in length includes 21 mini-trains with a time gap between mini-trains of 3.3 ms and the length of mini-train is 1 μ s. This length is comparable with RF pulse length of accelerating structure. Each mini-train contains 3×44 bunches as triplet structure. To provide the surviving PEDD limit the W75Re25 target of 4 r.l. thickness and 500 mm in diameter has been chosen, and the electron beam spot size on target is 4mm (one sigma). To avoid overlapping of the spots of adjacent mini-trains, the distance between mini-trains should be longer than 4σ or 16 mm. Tangential speed of the target in this case about 5 m/s is required.

Numerical simulation of positron capture efficiency shows the Adiabatic Matching Device (AMD) with moderate field of 5 Tesla and enlarged face aperture up to 20 mm in diameter and 200 mm in length is preferable. The distance between positron production target and front face of AMD was optimized to 5 mm.

FLUX CONCENTRATOR AS ADIABATIC MATCHING DEVICE

Flux concentrator (FC) is one of existing devices, which can be considered as AMD. FC is a well and long-time known device for generating high longitudinal magnetic field. Making a conical profile of inside FC cavity for example, a magnetic field also should vary along longitudinal axis from a peak field value. Well-known classical FC consists of two parts: firstly a relatively big and massive FC body fabricated from well-conducting metal and, secondly, winding placed around the FC body. The FC body has a transverse slit from inside cavity to FC a side. The typical width of this slit is about $0.2\div 0.4$ mm and is determined by technical reasons. In practice the annealed copper is used for FC fabrication.

Unfortunately, the design of a classical FC is not free from technical disadvantages. The open slit makes the FC body insufficiently strong mechanically against the magnetic field force. The second disadvantage is a primary winding holding around FC body and a primary winding insulation. The insulation should be enough reliable as between winding turns well as between winding and FC body and should have very long lifetime under a huge irradiation flux. Due to this reason nonorganic or vacuum insulation only can be used for FC, for example any vacuum ceramics. Ceramics insulator should be installed only in key point of the device where a vacuum insulation can't be used from the mechanic point of view. The epoxy is another material, which used to be applied previously as insulator and holder of primary winding. The primary is impregnated by epoxy compound and baked in special mould. This technology of coil fabrication is applied until now for any DC current accelerator components. As an experience of classical FC exploitation at positron source has shown, classical FC does not have a long lifetime even with a moderate magnetic field. The typical FC winding lifetime with magnetic field about 3.5 Tesla is less than $7\times 10^8 \div 8\times 10^8$ pulses.

FC is not an axisymmetric device from eddy current point of view. The narrow slit of the FC body forms such asymmetry and generates a transverse component of magnetic field on the geometrical axis of device. The transverse component has a clearly defined set of odd field harmonics with a strong domination of dipole component. The typical peak value of dipole harmonic averages $3\div 4\%$ of a peak longitudinal field. So, high transverse magnetic field component makes the trajectories of positron strongly distorted and as the result, a beam line are not centered with accelerator line well. The classical FC is not optimized well from the ohmic losses point of view. It becomes clear, taking into consideration a current path length of classical FC winding and eddy current path length generated around of FC body. Thus, the classical FC is not well suited to install to a positron source as a matching devise, but a classical FC may be taken as a baseline to develop an improvement design of the same principle, which should not have the disadvantages mentioned above.

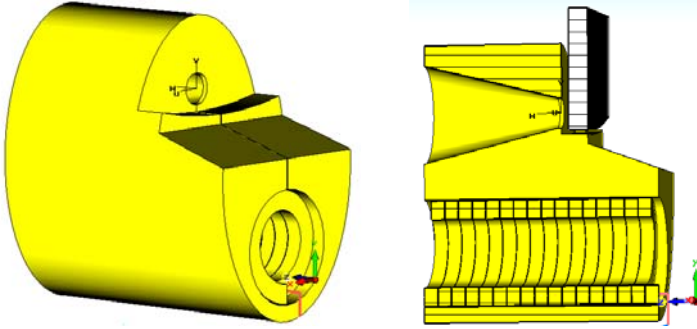


Fig. 1. Single-turn modification of FC computer model (left) cross-section with a target (right).

Single-Turn Magnet

The single-turn version of the magnet is distinguished by the simplicity of the design of conical part, which is connected to the cylindrical cavity with the help of a flat slit, the primary winding of the pulsed transformer being located in the cylindrical cavity[3]. The computer model of single-turn modification of FC without target is shown in fig. 1. Specific for such a load made as a cone is a very low inductance value. Therefore, this low-impedance load required a minimum distance before the pulsed transformer, which is easily achievable in this design and makes its main merit. The ohmic losses have been expected to be 3÷5 times less in comparison of a classical FC design with the same size, because the current path length is significantly shorter. Mechanical properties of a single-turn version of the magnet obviously are better, because a magnet body is fabricated from a solid piece copper without a slit. A winding holder design also should be simple from technical design of view due to a well centering of one inside of a conical cavity. The magnetic force unbalance along the winding turns is minimized. Radial component of magnetic field force is significantly reduced, because the winding is placed inside of a practically geometry symmetrical cylindrical cavity. A special grooving for the positron production target suppresses a transverse component of magnetic field on the beam line between the target and front face of FC. Main geometrical parameters of single-turn FC are presented in the table 1.

The cone angle parameter was varied to form smooth and pseudo adiabatic changing of longitudinal magnetic field profile along the geometrical axis. The gap between the grooving part of FC body and positron production target defines a quality of magnetic field. Variation of gap parameter can compensate transverse component of magnetic field on FC axis or significantly minimize its value.

Table 1. Main parameters of Single-turn FC.

Shape of FC body	Elliptical cylinder
FC size	120x180 mm
Total FC length	170 mm
Conical cavity length	100 mm
Front aperture diameter	20 mm
Rear aperture diameter	64 mm
Cone angle	24 degrees
Cylindrical hole diameter	70 mm
Number of winding turns	16
Turns size	9.6x12 mm
Grooving gap	3 mm

The half-sine shape of current with a pulse length of $25 \mu\text{s}$ was taken for numerical simulation of the single turn FC. A peak current value about 34 kA is required to generate a peak magnetic field of 5 Tesla. Profiles of magnetic field components are presented in fig. 2.

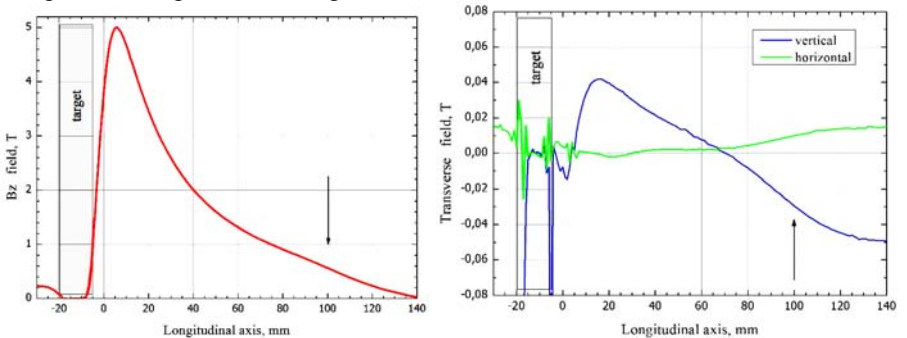


Fig. 2. Longitudinal field profile (left) and vertical and horizontal field profiles (right). The origin of the position is the front face the conical part of FC body.

As one can see in fig. 2 the vertical component of magnetic field generally defines the offset of magnetic axis from geometrical. Magnetic axis is not a straight line but has a complicated 3D-curve in space. The vertical field varies from 40 mT to -40 mT through a whole length of FC cone. A very fast oscillation of field horizontal component can be explained by insufficient computation accuracy in the target and in region close to the target. Another very interested and important computation parameter is ohmic losses of eddy current generated in material of

positron production target. Ohmic losses in target was computed to be about 24 J/pulse. This value of ohmic losses is not so high compared with the electron beam energy deposition in target material. The sum of the ohmic losses in the FC body and winding was estimated to be about 245 J/pulse. Taking in account a time gap between mini-trains and electron beam time structure the mean power deposited in production target was calculated as 2.3 kW and 25 kW in FC components.

Two-Hole Symmetric Magnet

The single-turn version of a magnet is an asymmetrical device from eddy current topology point of view. Magnetic flux generated into narrow slit flows to the conical cavity and generates additional transverse field component on the geometrical axis of a conical cavity. By using different shims and making a grooving it is possible of course to make transverse field component smaller, but making it negligible small, for example 5 mT or even less, is not possible. The reason is a current topology asymmetry.

Let us consider some of possible symmetric device. The simple way to make the previous FC type symmetrical is to add a second cylindrical hole with second winding opposite of a first. The second cylindrical hole should be also coupled with conical cavity by a narrow slit. First and second windings should be connected in serial. This device is from perspective point of view a compensation of a transverse magnetic field component on the axis, because magnetic fluxes in first and second slits are mutually antithetic. However, such a symmetrical devise is not appropriate to use together with a big size conversion target. The target partially overlaps geometrically with the cylindrical holes of windings, and as a result the target also overlaps with magnetic flux of windings. Another weak point of this devise also is the result of overlapping. There is not enough free room between device face and target to place winding's holders and spacers. To avoid the trouble described above let us transform symmetrical device as one can see in fig. 3. The table 2 contains main parameters of 2-hole FC.

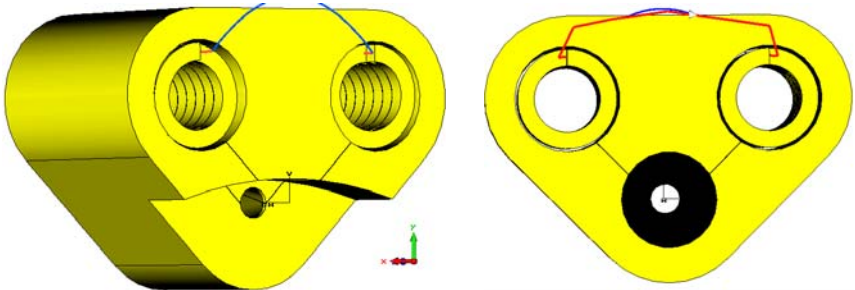


Fig. 3. Two-hole flux concentrator model front view (left) rear view (right).

Table 2. Main parameters of two-hole FC.

FC size	190x122 mm (w x h)
Total FC length	140 mm
Conical cavity length	100 mm
Front aperture diameter	20 mm
Rear aperture diameter	64 mm
Cone angle	25 degrees
Cylindrical hole diameter	70 mm
Number of winding turns	13 x 2
Turns size	9.6x12 mm
Grooving gap	3 mm

To make the magnetic flux between FC and conversion target symmetrical and to compensate a vertical component of a magnetic field a front of FC body was shaved for a target.

The current shape is a half-sine and current pulse length is 25 μ s. The peak current value of 39 kA is required to generate a peak magnetic field 5 Tesla. Profiles of magnetic field components are shown in fig. 4. The longitudinal profile is very close to that of the single turn FC.

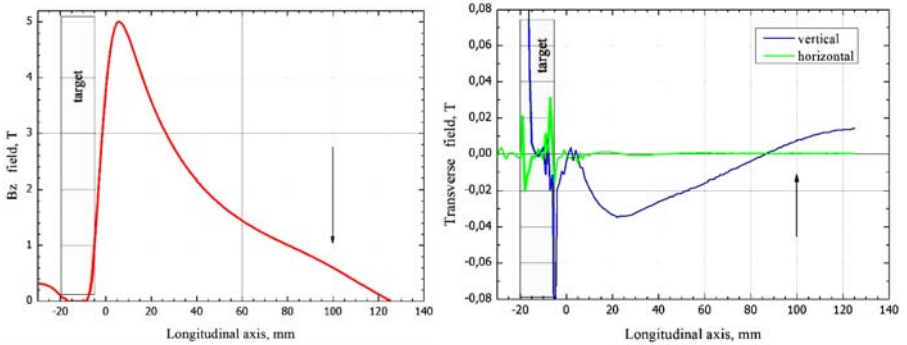


Fig. 4. Longitudinal (left) and transverse (right) magnetic field profiles of two-holes FC.

Horizontal field component is negligibly small along the whole axis except the target area only. Thus, this component should be taken as zero on the axis everywhere. The vertical component is varied from -35 mT to 15 mT that practically is in the same range as for single-turn FC. The ohmic loss is 27 J/pulse in target and 530 J/pulse in FC parts (FC body and 2 windings together).

Comparison of the ohmic losses in the two types of FC shows practically equal values in a target, and more than twice higher in two-hole FC device. The mean power dissipation is 2.7 kW in target material and about 52 kW in all FC parts.

Spiral Flux Concentrator

The spiral flux concentrator (SFC) is a well-known type of manyturn coil. For example at SLAC, this coil was made of a copper block with a narrow spiral slit [4]. No other design providing with the mechanical strength (stability) of this spiral is envisaged – the strength (stability) is attained due to the inertia of massive turns, which is quite acceptable for a short pulse duration of about 10 μ s and a moderate value of the pulsed magnetic field under 5 Tesla. Fig. 5 demonstrates a spiral flux concentrator model with a small front modification for a big sized target at close location. The grooving for the target allows to compensate a vertical magnetic field component on the geometrical axis between target and SFC front face. A half-sine shape with pulse length of 25 μ s was taken as a current profile for a computer simulation of a modified SFC. Main parameters of SFC model are listed in the table 3. Results of magnetic field computation are presented in fig. 6. The peak current value of 49 kA is required to generate a peak magnetic field 5 Tesla.

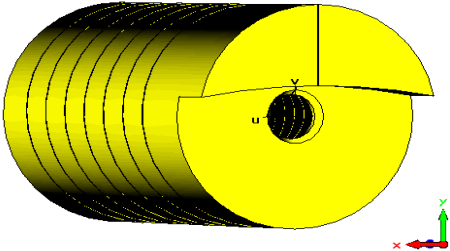


Fig. 6. Spiral flux concentrator.

Table 3. Main parameters of a Spiral Flux Concentrator.

SFC diameter	100 mm
Total SFC length	136 mm
Conical cavity length	100 mm
Front aperture diameter	20 mm
Rear aperture diameter	72 mm
Cone angle	30 degrees
Turns number	8
Turn width	9.6 mm
Gap between turns	0.3 mm
Grooving gap	3 mm

This value is approximately 1.4 times higher than that of the single-turn FC current and 1.25 times higher than two-hole FC current. Since the target is close to the SFC, the magnetic flux extends to the target through the front aperture. In result, a significant a side leakage of magnetic field flux is observed through a narrow gap between SFC turns. Thus, a big target in front of SFC becomes a semi-transparent body for a magnetic field flux. A side flux leakage is well observed in fig. 6 (see vertical and horizontal components), which shows magnetic field component profiles. Transverse components of field (vertical and horizontal) approximately are 2.5 times higher or even more than the same field component of any previous FC computed models. So high transverse field component values make SFC absolutely not suitable to install one as a matching device for a positron source. Ohmic losses 24 J/pulse in target and 395 J/pulse in FC.

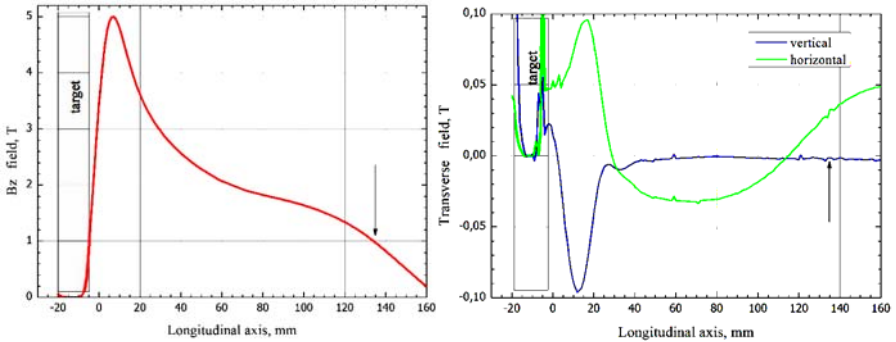


Fig. 7. Longitudinal (left) and transverse (right) magnetic field profiles of SFC.

SUMMARY

Any type of FC with enlarged size of front aperture and high repetition rate has two important parameters, which defines the technical difficulty of fabrication and longtime operation reliability. These parameters are FC peak current value and ohmic losses in all FC parts. Peak current value and voltage finally define the technical opportunity of FC power supply development, cost and reliability. Mean ohmic losses power of 60 kW and higher for example make FC technical realization very hard or impossible practically. Two previous limits have electro technical nature. The transverse field component value is another very important FC parameter from positron yield point of view. The FC with high transverse component of magnetic field on the axis should not be used as a matching device and cannot be installed at a positron source. Results of different FC types magnetic field simulation, peak current and ohmic losses are compiled a table 4.

Taking into account all mentioned above FC parameters, a single turn FC looks mostly attractive device for ILC positron source. The peak current value

about 35 kA is considered, rather as a high for the development of a fast cycled power supply unit. For this reason, FC with a smaller front aperture was also discussed. The front face aperture was resized from 20 mm down to 16 mm. Other geometrical parameters of FC are unchangeable. As one can see in table 4, a peak current of 25 kA is required to generate the same value (5 Tesla) of magnetic field. Transverse field components are a bit higher against of FC with 20 mm aperture, but it is not so significant. Mean ohmic losses power in all FC component became regular (13.7 kW) and do not make any trouble of FC components cooling designing. FC inductance is estimated about 1 μ H.

Table 4. Parameters of different FC types.

	Single turn FC D20 mm	Two-holes FC	Spiral FC	Single turn FC D16 mm
Peak field	5 Tesla	5 Tesla	5 Tesla	5 Tesla
Peak current	34 kA	39 kA	49 kA	25 kA
Peak transverse field	40–50 mTesla	31 mTesla	100 mTesla X,Y component	50–60 mTesla
Current shape	half of sine	half of sine	half of sine	half of sine
Current pulse length	25 μ s	25 μ s	25 μ s	25 μs
Target ohmic loss	24 J/pulse	27 J/pulse	24 J/pulse	10 J/pulse
FC ohmic loss	245 J/pulse	530 J/pulse	395 J/pulse	140 J/pulse
Target mean power	2.3 kW	2.7 kW	2.3 kW	1.1 kW
FC mean power	25 kW	52 kW	40 kW	13.7 kW

In case the voltage of power supply is not critical, the current pulse length of FC may be shorter, for example 20 μ s or even 15 μ s. Positive effect of a short pulse length is reduced FC ohmic losses.

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