



**ARES PHI-FACTORY INJECTION: ELECTRON AND POSITRON  
GENERATION**

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**1 - Introduction**

Recently at LNF Frascati a project of a superconducting linac of energy about 500 MeV has been proposed<sup>[1]</sup>. The aim is to create the high quality beams of electrons and positrons which can be used :

- i ) To build a short wavelength FEL and to study the techniques of production and acceleration of high peak current pulses which are of interest for very high energy linear colliders.
- ii ) To inject into a Phi - Factory composed of two  $e^-e^+$  rings and possibly to realize a high luminosity Phi-Factory of the type Linac against storage ring. The energy of the  $e^-e^+$  beams should be close to 510 MeV for which the Phi Meson resonance occurs , and the luminosity at least  $10^{32} \text{ cm}^{-2}\text{sec}^{-1}$ .

The general layout of a multipurpose injection system including a superconducting RF linac is shown in Fig. 1. The SC linac allows the realization of the high charge high repetition rate or quasi continuous beams for the above applications.

Below we will describe the injection system of the ARES Phi - Factory. The requirements for the generation and acceleration of electrons and positrons before injection in the rings of the Phi - Factory connected with ARES have been discussed in Memos ARES 9,12,19 [2-4].

The main results of these discussions are given in Tab. I and the detailed layout of the Front - End of the linac injector is presented in Fig. 2. These data will be taken as the basis for our considerations.

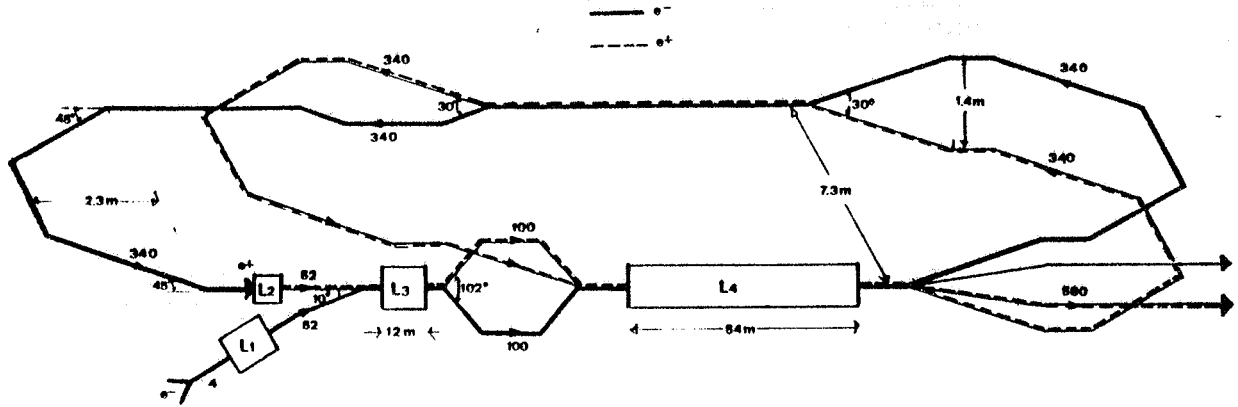


FIG. 1 - ARES Phi - Factory Injection System. L1, L3, L4 - Superconducting Linacs, L2 - Normal Conducting Linac.

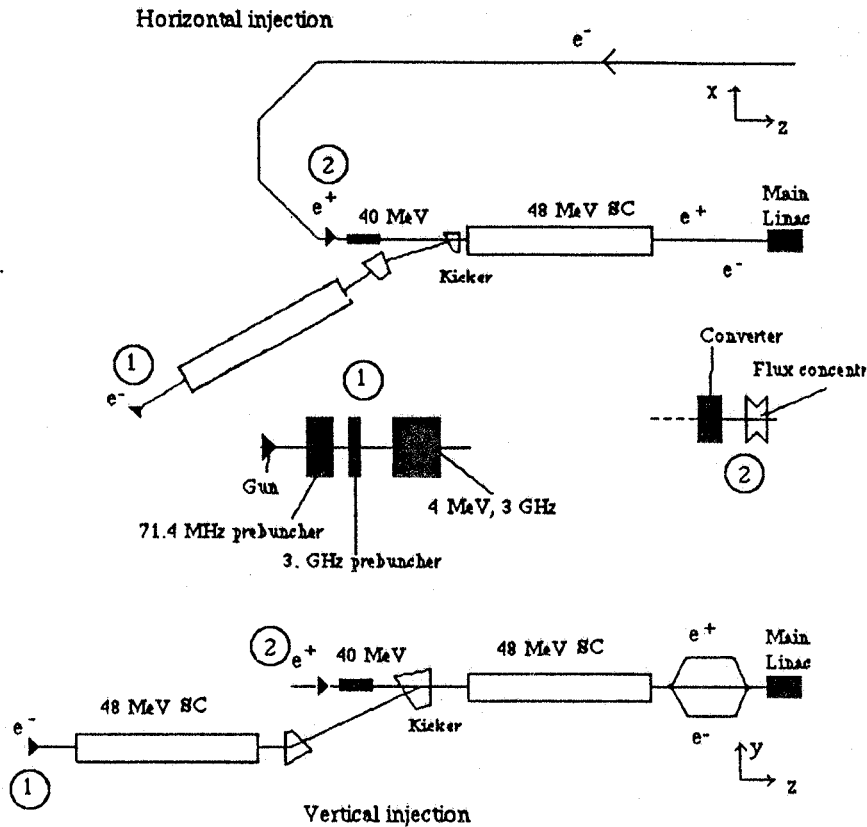


FIG. 2 - Detailed Layout of the Front - End of the Linac Injector.

According to Fig. 2. the main components of the Front - End of the linac injector are :

- Electron Source.
- Positron Source.
- Transport Channel.
- Radiofrequency System.

The details of the different elements of the system are given below.

*Table I - Linac as Phi - Factory injector.*

		e-,e+	e- (for conv.)
Beam energy	[MeV]	510	300
Total injection efficiency		0.05	
Conversion efficiency		0.012	
Average current	[ $\mu$ A]	0.07	5.8
Average beam power [kW]	.036	1.7	
Avg. macropulse current	[mA]	2	166.7
Avg. macropulse power	[MW]	1.02	50
Macropulse duration [ns]	350	350	
Macropulse charge	[nC]	.7	58
Macrop. repetition rate	[Hz]	100	100
Microbunch rep. freq.	[MHz]	71.4	71.4
N. microbunches/pulse		25	25
Charge/microbunch	[nC]	.028	2.3
Gun Invariant emittance	[ $\pi$ m rad]		$2 \times 10^{-6}$
Positron tran. emitt.(inv.)	[ $\pi$ m rad ]		$5 \times 10^{-3}$
Energy dispersion	[ $10^{-3}$ ]		$\pm 5$

## 2 - Electron source

The main parts of this system are the gun with a 4 MeV buncher and a 48 MeV SC preaccelerator.

The first part can be either a classical solution composed of a thermionic gun followed by a subharmonic prebuncher and a normal conducting buncher system similar to that of LISA<sup>[5]</sup>, or an RF gun. Below we will describe the classical solution.

### 2.1 - The gun

The main requirement for positron production is on the current. We assume reasonable values for the following efficiencies:

- transport of e<sup>-</sup> from gun to buncher exit  $\eta_t = 0.3$
- e<sup>-</sup> to e<sup>+</sup> conversion  $\eta_c = 4\%/GeV$ .

The gun current that results from the above values is:

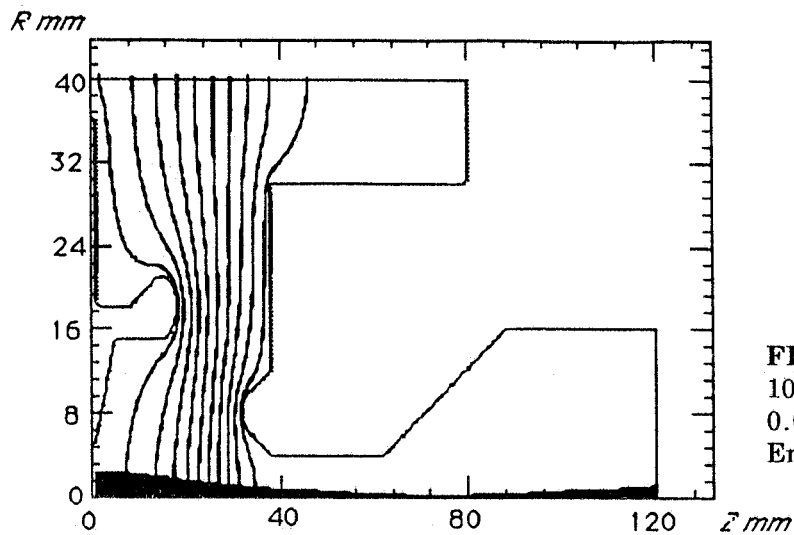
$$I_g = 0.56 \text{ A}$$

The LISA gun can generate such a current<sup>[6]</sup>. The main parameters of this gun are given in Tab. II:

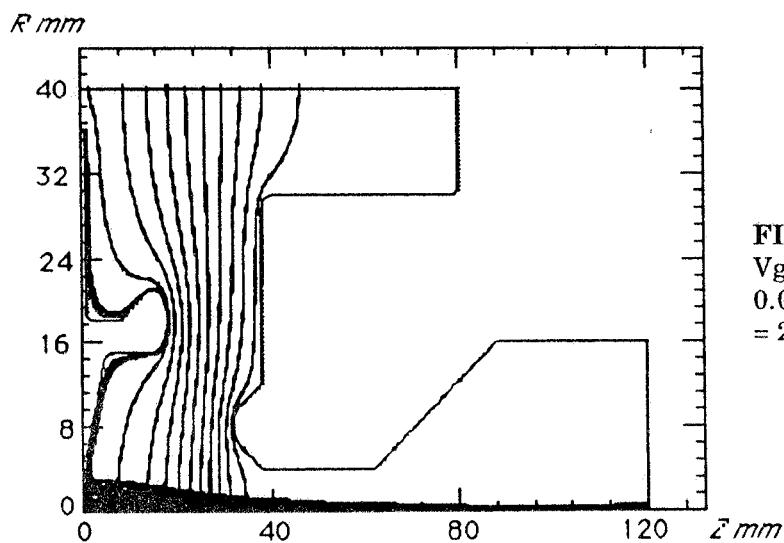
**Table II - Gun parameters**

Spherical radius of the cathode	$R_k = 40$ mm
Cathode diameter (height)	$D_k = 6.4$ mm
Anode potential	$U_a = 100$ kV
Current (@ grid pot. = 450 V)	$I_g = 0.7$ A
Emittance (invariant)	$\epsilon_n = 2.3\pi \times 10^{-6}$ m.rad.
Macrobunch length	$t = 350$ ns

The geometry of the gun together with electron trajectories and equipotential lines is shown in Fig. 3 and 4 for two values of grid potential. The correlation between the gun current and the emittance is evident from these figures.



**FIG. 3** - A Gun for LISA.  $V_a = 100$  kV,  $V_g = 0$ ,  $I = 0.3$  A, Perveance = 0.009 micro perv., Normalized Emittance =  $5.8 \pi 10^{-7}$  mrad.



**FIG. 4** - A Gun for LISA.  $V_a = 100$  kV,  $V_g = 445$  V,  $I = 0.7$  A, Perveance = 0.022 microperv., Norm. Emittance =  $2.9 \pi 10^{-6}$  mrad.

## 2.2 - The bunching system

As mentioned above, this system will be similar to that of LISA. The main components of it will be: subharmonic and harmonic prebunchers, buncher, magnetic focusing lenses and solenoids. The main task of this system is to transform the 350 ns long pulse of electrons leaving the gun into the train of short bunches which can be accepted both by the 3000 MHz and the 500 MHz accelerating structures.

Taking into account that the proposed RF frequency for the storage rings is  $500/7=71.43$  MHz, we have chosen this as the frequency of the first subharmonic prebuncher, which will serve also as a kind of chopper. In fact preliminary calculations have shown that such a prebuncher followed by a 3000 MHz, 4 MeV buncher will accelerate at least 30% of the gun current with an energy spread of approximately  $\pm 5\%$  and phase spread smaller than  $60^\circ$  at 3 GHz. After an additional 48 MeV energy increase in the SC linac the energy spread will shrink to  $\pm 5 \times 10^{-3}$  and the phase spread will be less than  $\pm 5^\circ$  at 500 MHz. This should allow the injection of such a beam into the line of the main SC linac by a pulsed deflector without particular concerns for achromaticity and isochronism.

On the other hand, assuming that the transport channel to the converter, after acceleration up to 300 MeV in the main linac, will be both isochronous and achromatic, the phase spread of the electrons will be conserved, so also the phase of the produced positrons will be comprised in  $60^\circ$  at the entrance of the 3 GHz positron capture section.

## 2.3 - 48 MeV Preaccelerator

It is composed of 4 standard superconducting cavities giving energy increase of 48 MeV. The resulting 52 MeV electrons are further accelerated to 100 MeV by another 4 SC cavities and then injected into the main SC linac and recirculation system. For positron production the electrons after one passage through the main linac will have the energy of 300 MeV and will be bent back to the  $e^-e^+$  converter.

Since for the electron operation the required current is much lower it is obvious that the same system will be used for this purpose.

## **3 - Positron source**

The main components of the positron production line are:

- converter
- magnetic focusing
- high gradient capture accelerating section
- SC pre-accelerator

### 3.1 - Converter and magnetic focusing

The average power of the 300 MeV electron beam passing through the converter will be :

$$EI_g\eta-\tau f \approx 2.5 \text{ kW}$$

where  $\tau = 350 \text{ ns}$  is the pulse duration and  $f = 100 \text{ Hz}$  is the repetition frequency.

The power dissipated in the converter is a fraction of that of the striking beam. For high energy electrons the energy loss is almost entirely due to Bremsstrahlung. For instance for heavy elements such as W, Au or Pb this is already valid for energies higher than about  $20 m_0c^2$  [7]. The average energy loss per cm is given by

$$(-dE/dx)_{\text{rad}} = NEF_{\text{rad}}$$

where  $N$  is the number of atoms per  $\text{cm}^3$ ,  $E$  is the energy of striking electrons and  $F_{\text{rad}}$  represents a cross section for Bremsstrahlung. Again for sufficiently high energies  $E \gg E_0 = 137 m_0c^2 Z^{-1/3}$ , where  $Z$  is the atomic number of the target material, corresponding to  $E_0 \approx 32 m_0c^2$  for gold,  $F_{\text{rad}}$  practically does not depend on the energy of incident electrons. [7] In agreement with this according to Amman [8] for  $E > 100 \text{ MeV}$  the power deposited divided by the primary beam energy is practically constant and equal to about 16% of incident power. For our case it will be

$$W \approx 0.16 * 2.5 = .4 \text{ kW}$$

This is less than the power dissipation for which the ADONE converter was designed (about 3 kW). Considering the good performance of the ADONE converter, we propose to adopt a similar solution for ARES. A sketch of this target is shown in Fig. 5 Taking into account a higher energy of striking electrons (300 MeV instead of about 100 MeV in the case of ADONE) the thickness of the converter target should be perhaps a little larger, e.g. 1.5-2 radiation length instead of about one in ADONE.

For a good positron production efficiency the diameter of the electron spot on the converter should be of the order of 1 mm, which can be obtained with a special focusing system, usually consisting of a quadrupole triplet. However one must also take care that the spot diameter is not less than 1 mm, otherwise the power density could cause excessive thermal stress and eventually damage the target itself.

To optimize the efficiency of positron capture the converter should be closely followed by a very intense tapered solenoidal magnetic field of the order of 5 to 6 Tesla. This can be generated by a so called flux concentrator similar to that employed at SLAC.

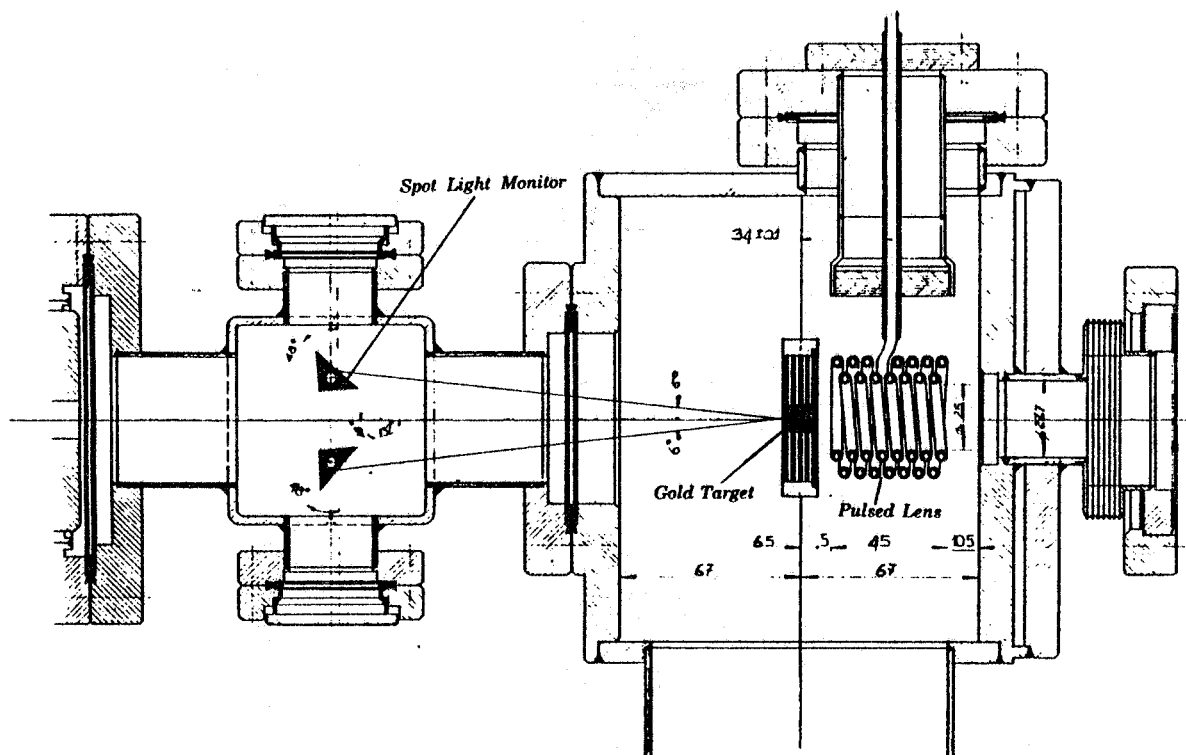


FIG. 5 - A Sketch of the ADONE Converter.

A scheme of the converter - flux concentrator - capture section configuration is shown in Fig. 6. The magnetic field of the flux concentrator must be matched to that of the solenoidal field of the capture section according to the following table.

*Table III*

Flux concentrator field	5.8 T
Tapered solenoid field	1.2 T
Uniform solenoid field	0.5 T

To optimize the positron capture efficiency, the flux concentrator must be followed by a short accelerating capture section with a very high accelerating field. The high gradient ( $> 30$  MV/m) required for this section excludes the use of the same frequency as the SC linac since klystrons able to deliver a few tens of MW at this frequency do not exist. We therefore choose a frequency of 3000 MHz, which is very close to the European standard (2998 MHz) at which 30 MW klystrons are available. It is to be remarked that in our case SLED pulse compression cannot be used because the long pulse (350 ns) and the low peak positron current (a few mA) would give a high energy dispersion ( $> 20\%$ )<sup>[4]</sup>.



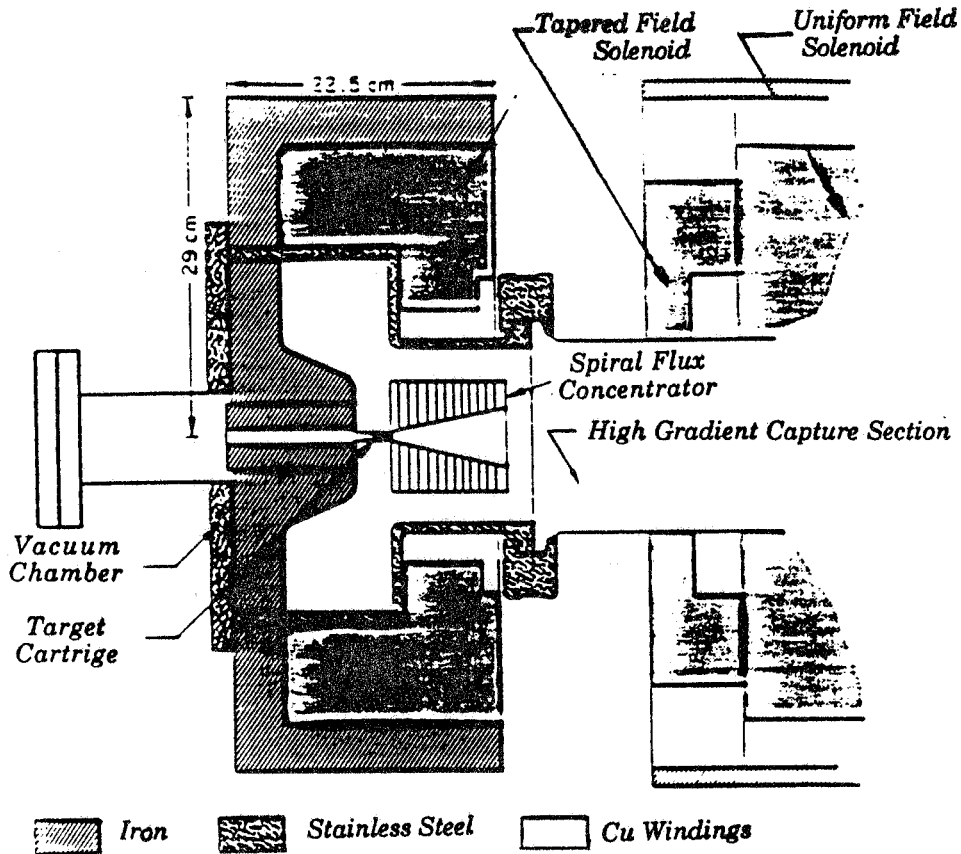


FIG. 6 - A Scheme of the Converter Flux Concentrator Matched to the High Gradient Capture Section.

### 3.2 High gradient capture section.

The main requirements of the capture section are:

1. High field gradient:  $E > 25-30 \text{ MV/m}$
2. Short length:  $L < 2 \text{ m}$
3. No SLED. RF power supply by one klystron:  $P_{\text{max}} = 35 \text{ MW}$  (cavity input power  $P \approx 30 \text{ MW}$ ).

Different types of accelerating structures can be chosen to fulfil the above requirements, e.g. travelling wave (TW) constant gradient (CG) or constant impedance (CI) or standing wave (SW) structures. A preliminary discussion on the choice of the accelerating structure is given in [4]. According to the results obtained there choosing the length  $L = 1.5 \text{ m}$  and  $P = 30 \text{ MW}$  of input power we get:

$E=27 \text{ MV/m}$ ,  $W=40 \text{ MeV}$  for CG travelling wave section and  
 $E=37 \text{ MV/m}$ ,  $W=56 \text{ MeV}$  for SW  $\pi/2$  biperiodic section.

Taking into account that the mean energy of positrons accepted for acceleration will be about 10 MeV, for both structure types we can have the

centre energy of positrons close to 50 MeV, i.e. the value which also the electrons will have at this point.

The energy spread at the end of the capture section will be of the order of 20%. Since it would be difficult to transport the beam with such large energy spread along the curved path without dispersion, a straight line injection is proposed.

Another difficult point is the recirculation of the positron beam. Assuming that the maximum energy spread which can be tolerated in the positron recirculation arcs is at most 4%<sup>[9]</sup> we should find the constraints which this condition imposes on phase and energy dispersion in the electron and positron accelerating lines. This problem was also analysed in<sup>[4]</sup>. The main requirements will concern the bunch length of electrons striking the converter since it will define the micropulse duration of the created positrons i.e. their phase length. According to the results obtained in<sup>[4]</sup> the phase length of the positrons accepted for the acceleration in the S-Band linac can be  $\pm 30^\circ$  around the optimum phase, corresponding to  $\pm 5^\circ$  in the SC 500 MHz linacs. Such phase length must be assured by the electron injection system. As already mentioned the proposed injector will fulfil this requirement.

#### 4- Transport channel and pulsed deflector

##### 4.1 Pulsed deflector

The proper functioning of the layout scheme (Fig. 1) requires for the 52 Mev electron beam a transport channel of which the last magnet is pulsed. The pulse duration must be larger than the beam pulse (350 ns) and less than the time it takes a particle to go through the main linac and back, through the converter, to the deflecting magnet itself. The kick that the deflector must impart is given by:

$$Bl \approx P\Theta / 0.3$$

where B is the magnetic field in Tesla,  $\Theta$  is the deflection angle in radians, l is the magnet length in meters and P is the momentum in GeV/c.

For  $\Theta=0.175$  rad ( $10^\circ$ ) this gives a kick of 0.03 Tm; therefore for a 0.6 m long magnet it is required a peak field B=500 Gauss.

For a pulse flat top of 350 ns and rise and fall times of the order of 50 ns a delay line structure with ferrite core is necessary. A similar design has been developed for the ELETTRA machine<sup>[10]</sup>. In Fig. 7 we show a scheme of the cross section, taken from the quoted reference. As the magnet is subdivided in 15 cm sections driven in parallel to allow fast rise time, a curvature of the structure can be easily obtained.



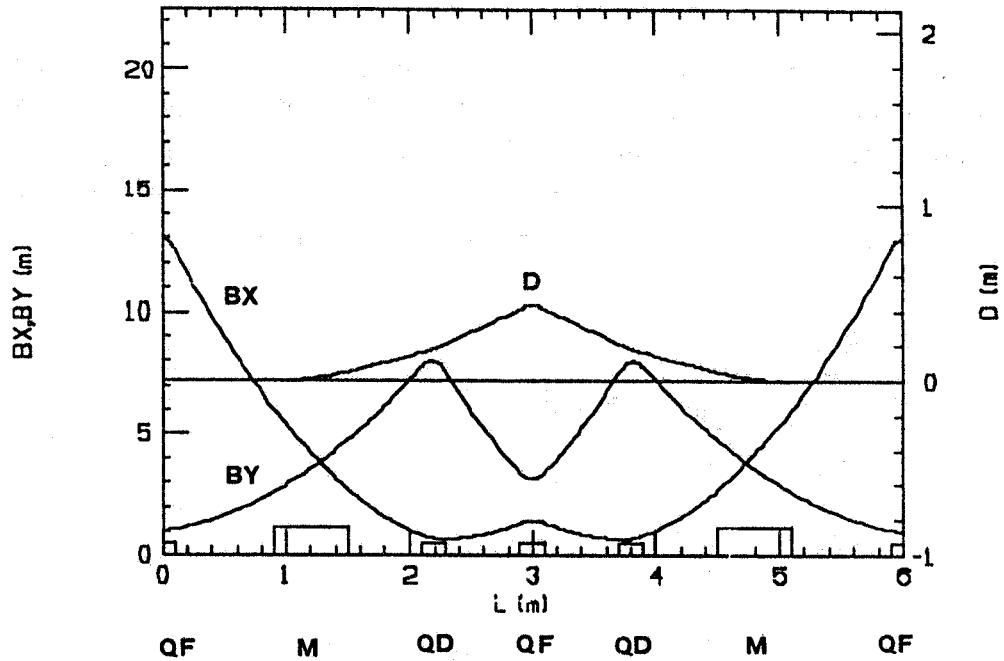


FIG. 8 - Optical functions in the horizontal solution for the 52 e<sup>-</sup> beam transport line.

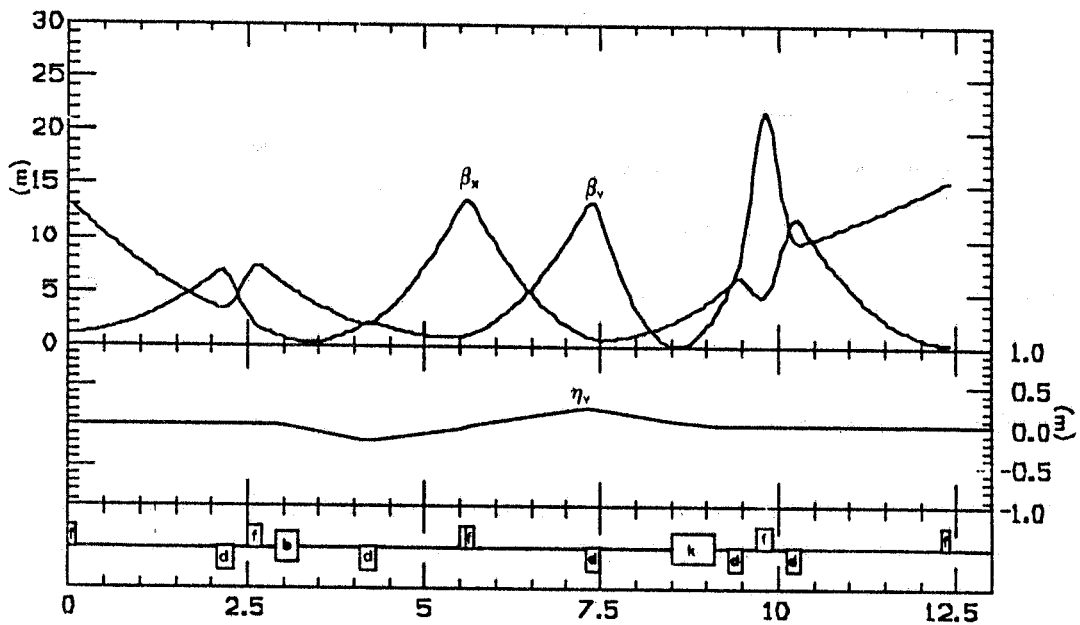


FIG. 9 - Optical functions in the vertical solution for the 52 e<sup>-</sup> beam transport line.

## 5 - Radiofrequency System

### 5.1 - The RF System of the Electron injector

The RF system of the electron injector consists of a set of three resonators each fed by its power source: a Sub-Harmonic (SH) buncher cavity at the frequency of the storage ring radiofrequency (i.e. 71.4 MHz), a microwave

prebuncher at 3 GHz, followed by a high energy (4 MeV) graded- $\beta$  accelerating capture section also working at 3 GHz and by four 500 MHz niobium SC cavities raising the total energy to about 50 MeV. The warm section of the system will operate at 1  $\mu$ sec pulses at a repetition rate of 100 Hz. Schematic layout of the RF system of electron and positron ARES injector is presented in Fig. 10.

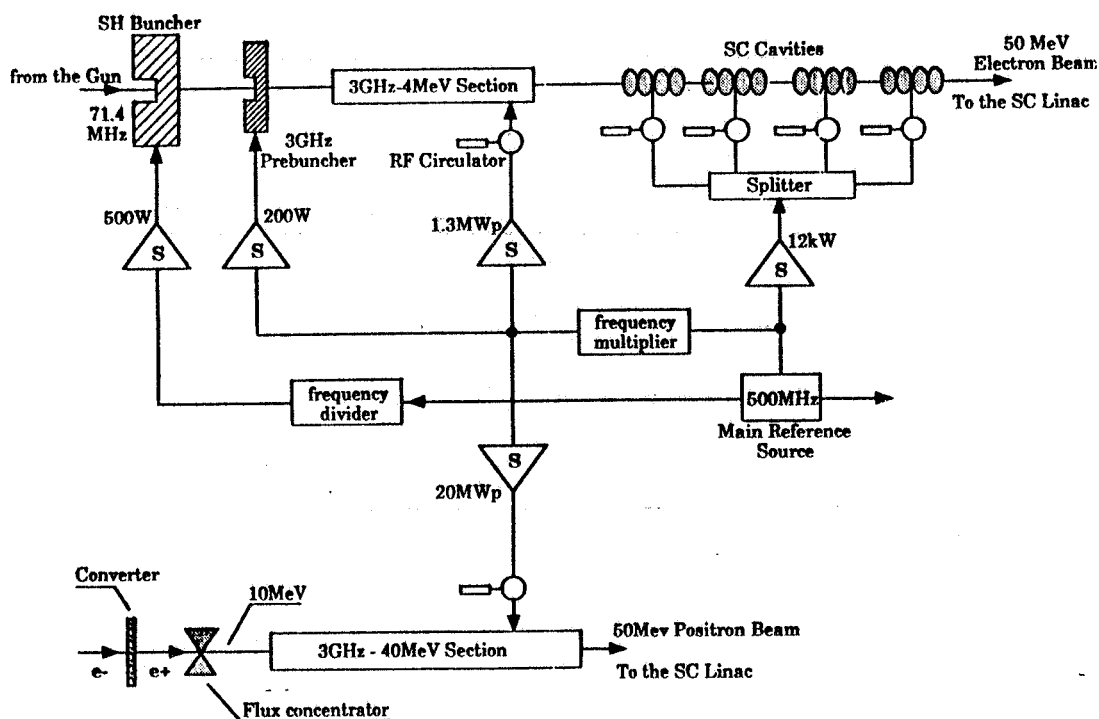


FIG. 10 - Schematic layout of the RF system of electron and positron ARES injector.

### 5.1.1 - SH Bunching System

It acts on the electron beam with a longitudinal RF electric field at a frequency of 71.4 MHz. The RF voltage required to bunch the gun beam is estimated to be 20 kV peak. A  $TM_{010}$ -like resonator must then be used. The cavity can be an aluminium quarter-wave resonator of coaxial type.

With the following main parameters :

$$R/Q \approx 200 \Omega$$

$$Q_0 \approx 5000$$

an RF power of about 500 W must be dissipated on the cavity walls for the required RF voltage. No average power is required for bunching the beam.

The RF source is a solid state amplifier driven by a low level signal prescaled from the 500 MHz main reference source of the superconducting linac. Amplitude and phase controls of the cavity signal are foreseen and also a cavity tuning system to keep the resonant frequency constant with the temperature variations.

### 5.1.2 - 3 GHz Prebuncher System

It provides an additional bunching to the beam before the acceleration in the capture section. A reentrant copper pill-box cavity working in the fundamental  $TM_{010}$  mode can be used. At 3 GHz such a cavity could have the following parameters:

$$Z_{\text{eff}} \approx 1.5 \text{ M}\Omega$$

$$Q_0 \approx 10,000$$

For a gap RF voltage of 10 - 15 kV peak, the feeding power to dissipate in the cavity would be less than 200 W obtainable either with a solid state amplifier or deriving it from the capture section feeding line. An equivalent system to that of SH buncher will control the most significant parameters. In this case, the cavity tuning system is probably unnecessary due to the large resonator bandwidth.

### 5.1.3 - The Capture Section System

It provides to the electron beam an energy of 4 MeV and consists of a graded- $\beta$  standing wave (SW) biperiodic structure of the same type used in LISA injector. It is approximately 50 cm long and with an average effective shunt impedance of about 70  $M\Omega/m$  can provide the necessary energy gain with a RF power:

$$P_D = (V_A)^2 / (Z_{\text{eff}} \cdot L) \approx 0.5 \text{ MW}$$

Moreover, for an average beam current of 200 mA per macrobunch of 350 ns, an additional power:

$$P_B = V_A \cdot \langle I_b \rangle = 0.7 \text{ MW}$$

must be considered giving a total RF power  $P = 1.2 \text{ MW}$  during 1  $\mu\text{sec}$ .

The coupling factor between source and capture section is in this case:  $\beta = 1 + P_B/P_D = 2.4$  which corresponds to the standing wave ratio (SWR) in the waveguide when the section does not accelerate the particles.

The average needed power is only 120 W due to the very low duty factor. In this field of frequencies (S-band), a large choice of klystron or magnetron sources of this output power is available on the market. The klystron will be connected to the capture section through waveguides and protected against the SWR with a RF isolator.

Standard RF feedbacks like amplitude and phase controls have to be provided to keep the beam parameters in accordance with the design values.

## 5.2 - The RF System of the Positron Injector

Travelling waves (TW) or Standing Waves (SW) structures can be used to accelerate the positron beam up to the design energy. The needed energy gain is about 40 MeV because the particles are extracted from the converter at about 10 MeV.

The average effective impedance of TW or SW accelerating structures is normally in the range of 70 M $\Omega$ /m. Hence, for an accelerating gradient of 40 MeV and a structure length of 1.5 m the dissipated power is:

$$P_D = V_A^2 / (Z_{\text{eff}} \cdot L) \approx 15.2 \text{ MW}$$

which becomes 15.3 MW considering the power transferred to the positron beam ( $\langle I_b \rangle = 2 \text{ mA}$ ).

High peak power klystron generators are nowadays available like the source developed for LIL injector of LEP (CERN) which can supply up to 30 MW peak. The power for the electron capture section could then be derived from the positron high power RF source by means of a 10-12 dB directional coupler.

Computer control of the parameters of electronic circuitry and power feeders is foreseen.

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