Positron source considerations for TESLA

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Introduction

Among all linear collider projects currently under investigation TESLA requires the highest number of positrons per bunch train. Since the bunch spacing is large for TESLA (1 μs) compared to other designs, it was suggested to investigate a wiggler based source with a fast rotating target, in order to seperate the hot-spots induced by each bunch in the target and thus to avoid a mechanical failure of the target [1].
After a short discussion of 'conventional' sources, a wiggler based source will be applied for TESLA and general design criteria of the rotating target will be considered. In the second part of the paper the preacceleration of the positrons will be discussed.

Conventional approach

The bunch charge of TESLA ($5.6 * 10^{10}$ particles per bunch) is the same as the one used in the SLC. Hence one can easily scale the SLC-source for TESLA. At the SLC a 33 GeV electron beam strikes a 6 radiation length thick target of a tungsten-rhenium-alloy. Per incident electron ~60 positrons are produced, of which ~4.5% = 2.7 e^+ are captured and accelerated to the damping ring. During the beam transfer, the injection into the damping ring etc. another factor of two of the positrons gets lost, so that the overall yield is ~1 e^+/e^-. The maximum temperature rise in the target during a shot is ~720 K and the mean power deposited in the target with 120 Hz rep. rate is 8 kW.
Since the maximum allowable mechanical stress in the target is reached within one shot at SLC [2], one can allow no overlap of adjacent bunches for an SLC like source.
The diameter of the electromagnetic shower at the exit of the target is ~2-3 mm. We find for the velocity of rotation of the target:

$$v = \frac{2\text{-}3 * 10^{-3}}{1 * 10^{-6}} = 2000 - 3000 \text{ m/s}$$

With 10 Hz rep. rate the mean power deposited in the target would be ~530 kW.

Using the 250 GeV electron beam instead of the 33 GeV beam, one can reduce the target thickness to ~3 radiation length. The mean power deposited in the target would be reduced to ~100 kW, in this case, while the rotational speed of the target would be the same.

A wiggler based source

The schematic layout of the scheme is shown in fig. 1. The 250 GeV electron beam is used after the collision as a primary beam. After travelling through a special matching optics [3, 4], the beam emittance is still small enough to pass the subsequent wiggler section of about 34 m length. Here photons of 0 - 70 MeV are emitted into a narrow cone. The minimum attainable spot size on the target is $\sigma_{min} \simeq 0.5$ mm. The photons will be converted into electron positron pairs inside a thin target of titanium-alloy, while the primary electrons are deflected by a dipole magnet.
Since a very thin target (compared to the radiation length) can be used, thermal load problems are reduced due to two effects:

- one is able to use a low Z material with high heat capacity
- the divergence of the positron beam is small, hence one gets a higher capture efficiency.

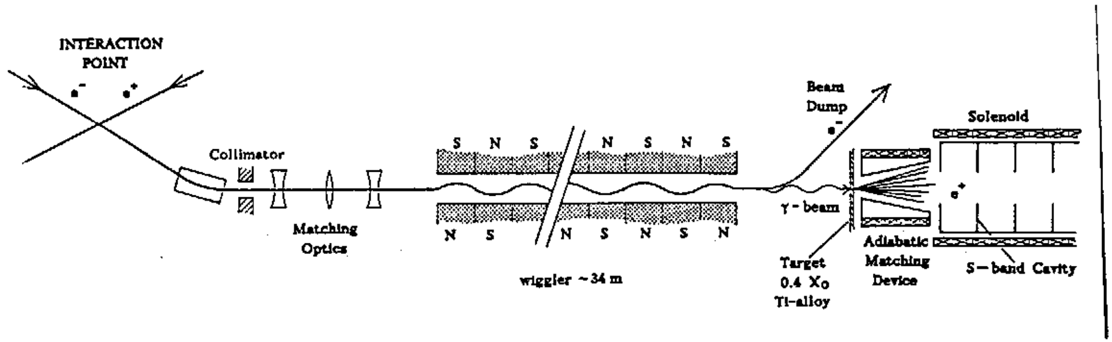

Fig. 1 Layout of the proposed positron source

Choice of material

A conventional target requires many radiation lengths for full development of the electromagnetic shower. Positrons which are produced in the first steps of the cascade will not emerge from the target, due to the ionisation losses inside the material. The ionisation loss per radiation length depends on the material and is lower for high Z materials. Thus, in order to achieve a high yield, one *has* to use high Z materials in conventional sources.
In thin targets, however, the conversion efficiency is to first order independent of the material, hence it is possible to use a low Z material, which has in general a higher heat capacity (Dulong-Petit-rule). In fig. 2, the positron yield for a 1 m long wiggler is plotted for different materials. From the yield point of view, titanium is only about 16% worse than tungsten, if a target of 0.4 radiation length (X_0) is considered. The maximum allowable particle density inside the target, however, is up to an order of magnitude larger for a titanium-alloy target as compared to a target made of tungsten-alloy, mainly due to the higher heat capacity.

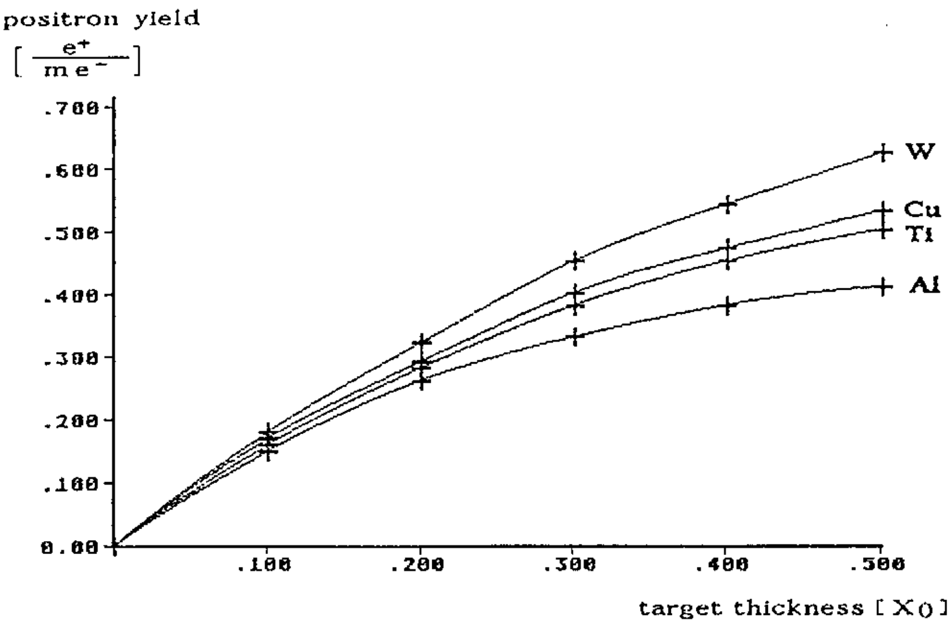

Fig. 2 Positron yield for different materials obtained with wiggler photons (B = 1.7 T) versus target thickness in units of radiation length X_0

Emmittance considerations

The second advantage of a thin target is the reduction of multiple scattering inside the target. Fig. 3 shows a comparison of the transverse momenta of a SLC-like source and a wiggler based source (0.4 X_0 titanium target). The results were calculated by means of the Monte-Carlo programm EGS4 [5]. As a consequence of the smaller transverse momenta, the particle density in the transverse phase-space is higher in the case of the thin target.

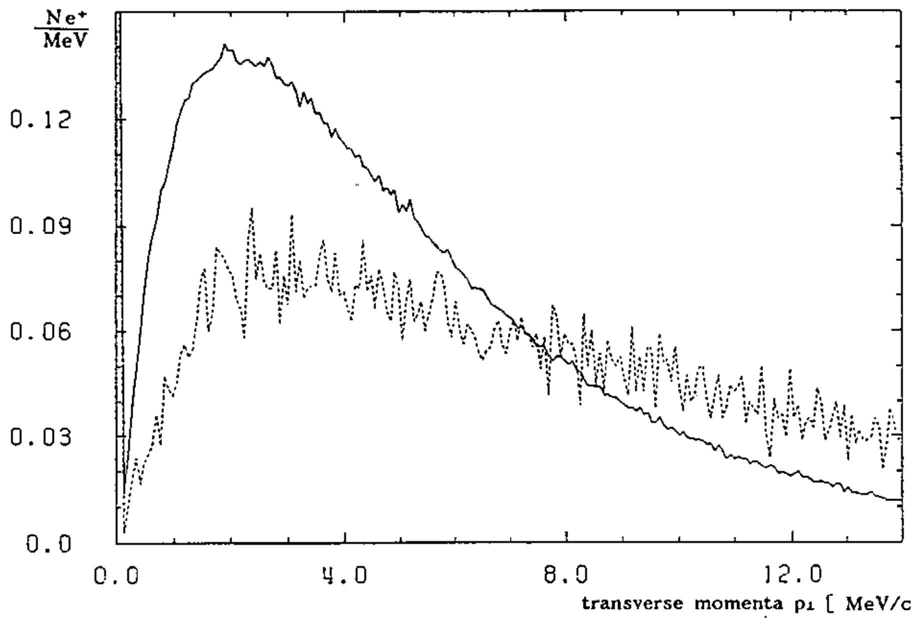

Fig. 3 Comparison of the transverse momenta of a SLC like source (dotted line) and a thin target driven by wiggler photons

Layout of the target

If we choose the velocity of the outer part of the rotating target disk to be 50 m/s no more than 60 bunches will overlap on the target, leading to a maximum temperature rise of ~ 700 K. The mean power deposited in the target with 10 Hz rep. rate will be 14 kW.

In order to load all parts of the target disk with thermal stress, successive shots should be placed beside each other on the target as sketched in fig. 4. Within one bunch train (0.8 ms) the advance of the target on the disk Δs will be 0.04 m. In order to place the next shot after n revolutions beside the foregoing shot the condition

$$\tau_{rep} = \tau_{bunch\ train}\,(N * n \pm 1)$$

has to be fullfilled.

N denotes the number of shotes, which can be placed on the circumference of the target. Thus the diameter of the target has to be $d = N * 0.04/\pi$ and the time for cooling, i.e. the time between two shots on the same place, is $\tau_{cool} = N * \tau_{rep}$. Tab. 1 compares parameters for different numbers of revolutions between successive shots.

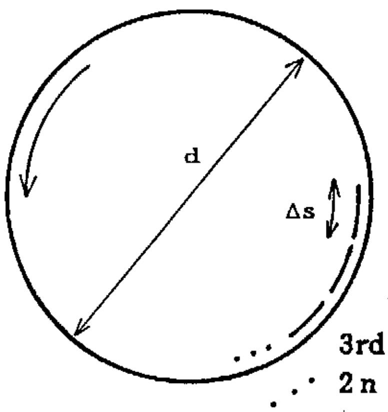

Fig. 4 The rotating target disk

n	N	d [m]	τ_{cool} [s]	revolutions per minute
1	124	1.58	12.4	605
2	62	0.79	6.2	1210
3	41.3	0.53	4.1	1815
4	31	0.39	3.1	2419

Tab. 1 Comparison of target parameters.

Target cooling

The basic component of a water cooled target is the rotating vacuum feed-through for the water supply. Organic materials as they are used for example in 0-rings can not be used in the highly radiative enviroment of the positron target and commercially available feed-throughs with bellows can not be used at the revolution frequency which is necessary for TESLA.
A possible solution has been worked out by P. Sievers and M. Höfert from CERN for a positron target, able to withstand a mean power deposition of 800 kW [6]. Fig. 5 shows the feed-through, based on differential pumping of a series of stationary chambers around the axis.

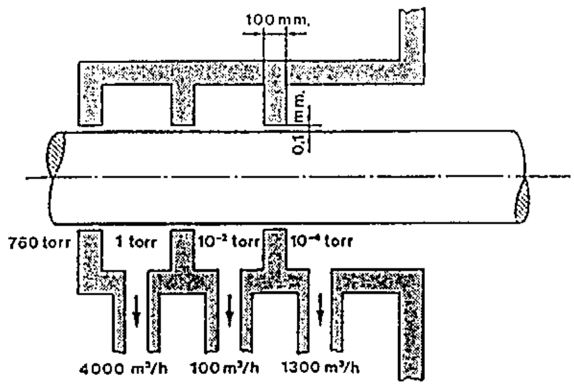

Fig. 5 Feed-through for the rotating axis of the target wheel into vacuum, achieved by differential pumping of a series of stationary chambers around the axis [6].

For TESLA, however, the mean power deposition is only small compared to the large volume of the target.
Hence one might as well consider radiation cooling supported by cooling of the rest gas in the camber. A radiation cooled target offers the additional advantage that problems like the radiolysis of the cooling water and the transport of radioactivity with the cooling water are reduced. The rotation can in this case be transfered to the target by means of a magnetic coupling.

The radiation flux Φ from a hot body (surface area A, temperature T) to the environment (temperature T') is given by the Stefan-Boltzmann-law :

$$\Phi = \varepsilon \sigma A (T^4 - T'^4)$$

ε = emission coefficient ≤ 1
σ = Stefan-Boltzmann-constant = $5.67 * 10^{-8} \dfrac{W}{m^2\ K^4}$

If we embed the target in a material with hight heat conductivity, the energy has to be transfered to the material and then radiated at a low temperature level from a large surface area A.

Assuming a mean temperature of the target disk of 500 K, while the environment stays on 300 K, we find for the surface area of the disk $A = 4.5\,m^2$, if the power of 14 kW has to be radiated from this area. Since the circumference of the wheel is in the order of some meters, this area can be provided by means of large cooling fins.
In order to achieve a substantial cooling of the rest gas in the vacuum chamber, it would be necessary to allow the pressure to be in the order of 10^{-2}– 10^{-1} mbar for a large part of the target surface. The pressure near the beam area could nevertheless reach the operational requirements by means of differential pumping.

Preacceleration of the positrons

Behind the positron target there will be a large background of positrons, electrons, photons, neutrons and muons which will deposit energy in the first cavities behind the target. In addition solenoid fields are required for the focusing of the positrons. Hence it seems to be impossible to preaccelerate the positrons by means of superconducting cavities.
The preacceleration has to be done with normal conducting cavities up to an energy of 100-200 MeV, where the positrons can be seperated from the background and be injected into the standard TESLA cavities.
Since the standard klystrons for TESLA (4.5 MW) may not be sufficient to reach the required gradients in the normal conducting cavities and hence special klystrons are needed anyway, one may also think of using a different rf-frequency for this section.
Due to the long rf-pulse of TESLA (> 0.8 ms) a normal conducting acceleration section is by no means a simple task, hence it would be an advantage not to be fixed in the rf- frequency from the beginning.
Long rf-pulses seem to favour lower frequencies. However, klystrons with higher power are available for S-band frequencies. In addition a given power leads to somewhat increased gradients for the higher frequency.
We will compare a preacceleration with normal conducting L-band structures and with S-band structures in the following.
The target will be followed by an adiabatic matching device. It consists of a solenoidial magnetic field, which decreases adiabatically from a high initial field to a constant end field.
In order to get a high initial field (up to $\sim$10 T), a pulsed field from a flux concentrator is added to a strong DC-field in the matching device [7]. At SLC the flux concentrator is driven by a half-sinusodial wave with 5 μs bottom width. The pluse width is a compromise between insulating considerations, calling for low voltages and hence a long pulse and mechanical

considerations calling for a short pulse in order to reduce the motion of the windings under Lorentz forces [8].
An extension to the long pulse required for TESLA would therefore need a new design concept.
The condition for an adiabatic field is given by [9]:

$$\left| \frac{dB(z)}{dz} * \frac{1}{B(z)^2} \right| \ll \frac{e}{p}$$

p = particle momentum

It can be shown that this condition is independent of the longitudinal coordinate z for the following field distribution:

$$B(z) = \frac{Bi}{1 + g * z}$$

Bi = initial field
g = taper parameter

The matching device matches the emittance of the source to the acceptance of the solenoid. The source is characterized by a small spot size and a large divergence, whereas the acceptance of the solenoid is characterized by a large spot size and a small divergence. The bandwidth of this system is limited by two effects:

- The low energy particles travel with velocities below the speed of light on long spiral trajectories. Hence, the bunch length increases in the matching device. This results in an intolerably large energy spread at the end of the linac.
- The adiabatic condition breaks down for high energy particles. Hence, the emittance of these particles may be increased intolerably.

Both the dephasing of the low energy particles and the emittance increase of the high energy particles scale with the transverse momenta of the positrons. Therefore these effects are reduced in case of a thin target.
The normalized acceptance of the preacceleration section is in the best case as high as the normalized acceptance of the damping ring, which might be large for TESLA compared to other linear collider designs. However, it seems to be impossible to increase the acceptance of the preacceleration section beyond 2-3 times the one obtained at SLC ($\gamma\varepsilon$ = 0.012) with conventional technology. (For larger acceptances the L-band approach seems to be advantageous.) On the other hand the target parameters are not very critical, and hence the requirements for the capture efficiency can be somewhat relaxed.
Therefore we have choosen moderate parameters for our comparison ($\gamma\varepsilon$ = 0.015, Bi = 7 T equivalent to SLC). The results will to first order scale linearly with the normalized acceptance.
The acceptance of a solenoid is proportional to $B * r^2$, hence, by scaling the iris radius r with the wave length, we end up with a lower solenoid field and

increased length of the matching device in the L-band case.
For our calculation 50 000 particles as generated by EGS4 have been numerically tracked through the matching device by a Runge-Kutta integration including the numerical integration of the path length.
In the cavities the transverse momenta keep constant and the variation of the longitudinal velocity can be analytically calculated. We found for the path length difference of a particle with respect to a particle traveling with velocity of light:

$$\Delta s = c\left(T - \frac{1}{a}\left[\sqrt{(aT+b)^2+1} - \sqrt{b^2+1}\,\right]\right)$$

$$T \equiv \text{time of flight} = E/(\Delta E * c)$$

$$a = \frac{e * \Delta E}{m_e c * K} \quad ; \qquad b = \frac{p_{oll}}{m_e c * K}$$

$$K = \left[\left(\frac{p_t}{m_e c}\right)^2 + 1\right]^{1/2}$$

p_t ≡ transverse momentum
poll ≡ longitudinal momentum at the beginning of the section
E ≡ total voltage of the section (100 MV)
ΔE ≡ gradient in the section

Since not all particles of a long bunch are on the crest of the accelerating rf-wave, a coherent energy spread of the particles in the bunch is maintained during acceleration to the damping ring.
Assuming an energy acceptance of ±1% in the damping ring, we accept only particles within ±7.5° rf-phase with respect to an optimized phase in our calculation. (In the S-band case ±15° rf-phase corresponding to ±7.5° of an L-band cavity have been accepted.)
Fig. 6 shows the capture efficiency as a function of the gradient in the pre-acceleration section.

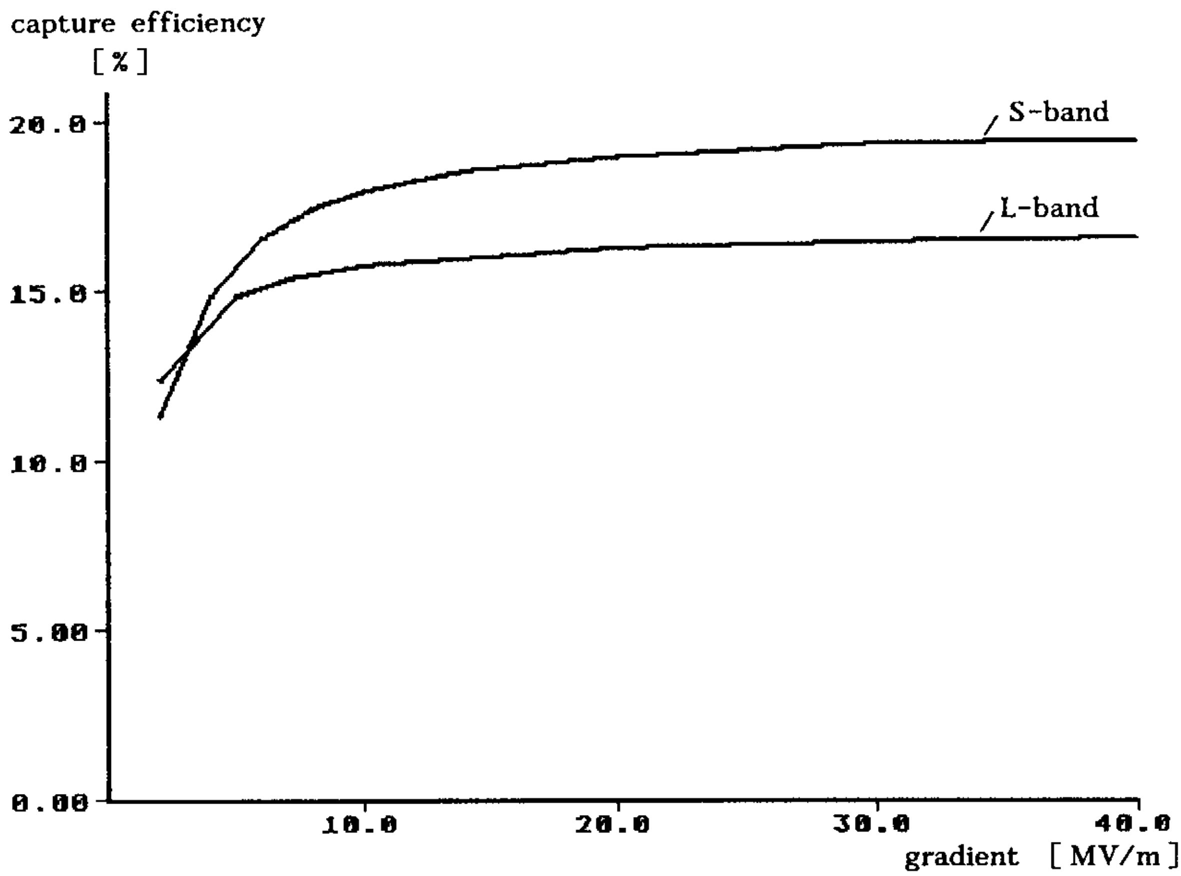

Fig. 6 Positron yield as function of the gradient in the preacceleration section

Due to the shorter matching device the efficiency is somewhat higher in the S-band case. Only at extreme low gradients the capture efficiency of the L-band section becomes higher than the S-band approach. Here the variation of the longitudinal velocity due to the matching device exceeds that of the acceleration section.
The capture efficiency may be improved in both cases by more refined optimization. Nevertheless we can conclude that a sufficient yield can be obtained with both approaches by means of moderatë gradients. Therefore the decision for the rf-frequency can be done on the basis of rf considerations only.

Rf-system

Two problems arise for the acceleration of the long TESLA bunch train in a normal conducting cavity:

- klystrons, able to deliver high power for such a long pulse, are not available yet.
- the energy deposition of a long rf-pulse in the cavity walls would be much too high in case of a high power, i.e. high gradient cavity.

To overcome these problems we consider a special SLED system with short accelerating stuctures.

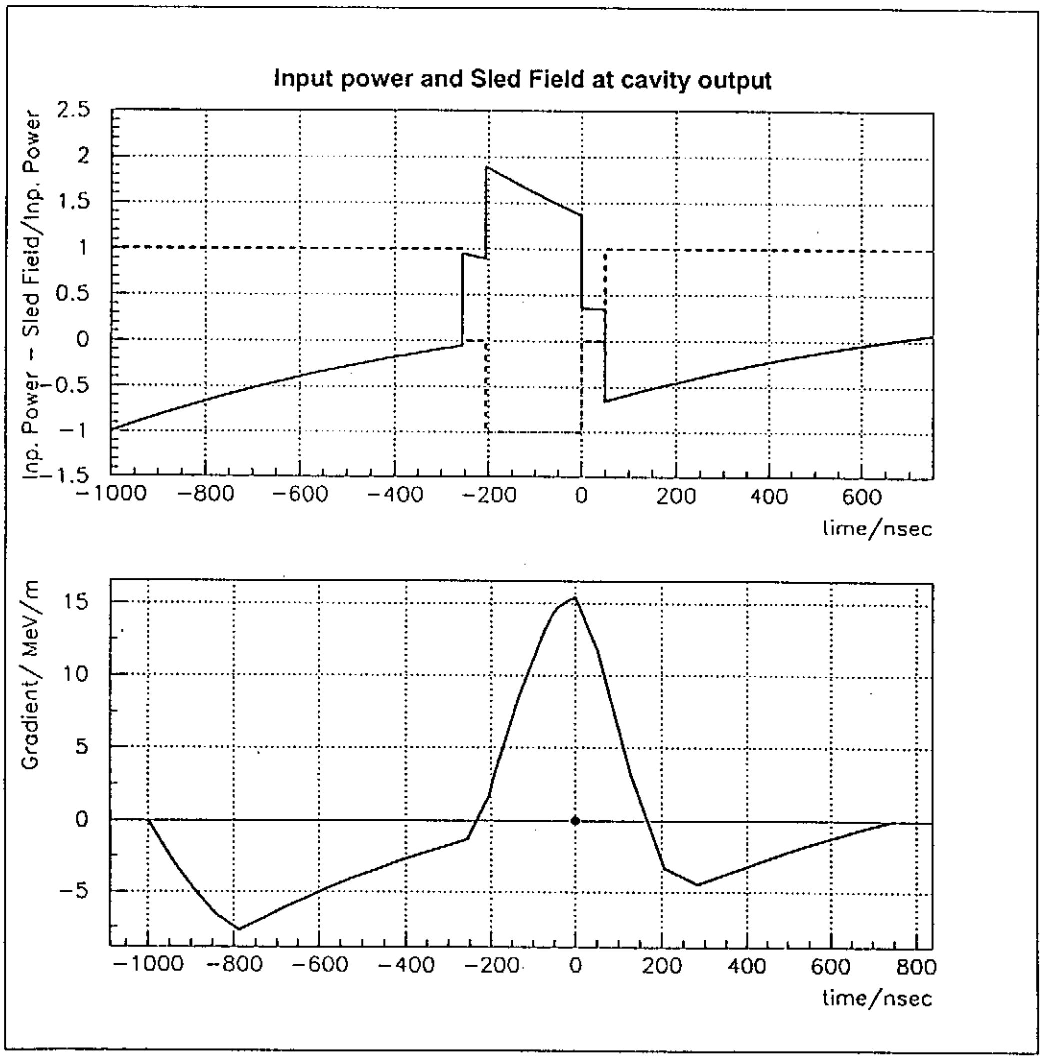

Fig. 7 Rf output pulse from klystron, SLED pulse and accelerating voltage as function of time.

Klystron	
frequency	2.998 GHz
peak power	7.5 MW
pulse length	800 µs
accel. cavity	
length	1 m
filling time	205 ns
attenuation (τ)	0.15 neper
Q	12 900
shunt impedance	50 MΩ/m

SLED cavity	
external Q	10 000
unloaded Q	50 000
filling time	885 ns
SLED gain	
- field	1.61
- power	2.58
max. gradient	15.4 MV/m

Tab. 2 Parameters of the rf-system

While the klystron delivers power on a low level over the whole pulse length of 800 µs, the travelling wave structure is filled with 1 MHz rep. rate for every single bunch. Between the bunches the power is used to fill the SLED cavities again.
The whole cycle looks as follows: After loading the SLED cavity for ~800 ns the phase of the klystron drive is reversed, the power, radiating out of the storage cavity, is added to the klystron power and fed into the short accelerating structure within 200 ns. (The time for phase reversal is ~55 ns.) After another phase reversal the SLED cavity is filled again, for the next bunch to be accelerated.
Fig. 7 shows in the upper part the normalized klystron field amplitude (broken line) and the resulting SLED pulse. The lower plot shows the gradient in the accelerating sturcture which can be achieved with 7.5 MW peak klystron power. The SLED gain is 1.61, corresponding to a power gain of 2.58, and the maximum gradient achieved is 15.4 MV/m.
From the yield point of view the system is on the safe side with a 7.5 MW klystron. (The capture efficiency is improved by only 2% in this case.) Hence the klystron power might even be reduced, then the effect of the SLED gain on the capture efficiency would be larger (see fig. 6). However, with the higher gradient also the expenditure for focusing is reduced.
Since the cavity is filled only for a short pulse, the heat load of the section is still low, roughly 13 kW/m; another 10 kW are deposited in the SLED cavity and approximately 35 kW are dumped into the load. The heat load scales with the power gain, hence we gain a factor of 2.58 with the SLED system.
Parameters of the proposed rf-system are summarized in tab. 2.
The large number of particles per bunch with a bunch length of ~1 mm induces a strong longitudinal wake-field, which leads to an energy spread of approximately 10%. For compensation the bunch has to be accelerated off the crest, which leads to an effective gradient of ~13 MV/m.

Acknowledgement

We are indepted to M. Bieler and D. Trines for stimulating discussions.

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