NEW METHOD [illegible] POSITRON PRODUCTION AT SLAC *

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Introduction

[illegible] adiabatically tapered solenoid [illegible] energy [illegible] distribution in energy of the [illegible] estimate that approximately [illegible] total number [illegible] lies within the energy band from [illegible] MeV [illegible] the debunching effect [illegible] drift [illegible] following the target [illegible] [illegible] emittance [illegible] MeV within approximately [illegible] giving an increase [illegible] factor of two in the [illegible] current.

Description

Focusing System

The focusing system has been described.[1] It consists of a 2-meter long solenoid (up to an energy of 55 MeV) and of quadrupole triplets and doublets. The emittance matching between the plane of the target and the solenoid uses an adiabatically tapered solenoid. Recent computations made by M.B. James et al.[2] showed that the transverse momentum accepted by the system remains high ($p_t \simeq 0.6$ MeV/c) over a very broad energy band (2.5 MeV $\lesssim$ E $\lesssim$ 30 MeV). In addition they computed the distribution in energy of the accepted positrons from which one can estimate that approximately one-half of the total number of accepted positrons lies within the energy band from 2 - 4 MeV. To maximize the current of positrons it is then necessary to accelerate the broadest energy band possible, starting from the lowest energy possible. The limitation in that process is the debunching effect in the drift space following the target and in the first few cm of the acceleration, leading to a broadening of the energy spectrum.

RF System

The distance between the target and the first accelerating section had been set rather large (93 cm) mainly to provide space for collimators. It was decided last year to insert in that space a special short section, Fig. 1. This section is a 5λ long (52.5 cm) constant impedance structure: the group velocity is vg/c = 0.0204, the accelerating field is related to the input power by E (MeV/m) = 3.55 $\sqrt{P}$ (MW).

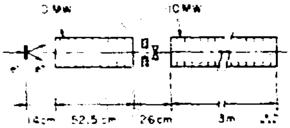

Fig. 1. Positron source accelerator structure.

The distance between the target and the first section is then reduced to 14.2 cm. The section is followed [illegible]

[illegible]

[illegible]

In the drift space from the target [illegible] the beam is debunched because [illegible] different velocities [illegible] of positrons with different transverse momenta.

[illegible] D be the length of the drift [illegible] slippage, with respect to a wave [illegible] of light, is given by:

$$[illegible]$$

where v_z is the axial velocity [illegible] rf wavelength. The axial momentum is [illegible]

$$p_z^2 = [illegible] - p_t^2$$

where p_t is the transverse momentum [illegible] γ = E/mc². The axial velocity [illegible] p_z [illegible] tapered field region the transverse momentum varies according to:[1]

$$p_t(z) = p_{to}\left(\frac{B(z)}{B_o}\right)^{\frac{1}{2}}$$

where p_{to} and B_o are the transverse momentum [illegible] netic field on the target. The phase slippage [illegible]

$$\Delta\phi(\gamma_{o1}, p_{to}) = \int_0^D \frac{2\pi}{\lambda}\left(1 - [illegible]\right)$$

with $p_t(z)$ given by Eq. (2), which can be approximated [illegible]

$$\Delta\phi = [illegible] \frac{1}{\gamma_o^2} p_{to}^2 \frac{1}{B_o}\int_0^D B(z)dz - [illegible]$$

The total longitudinal phase space can be calculated for a distance D and a range of energy and transverse momentum, for a given law of magnetic field $B_{(z)}$. Fig. 2

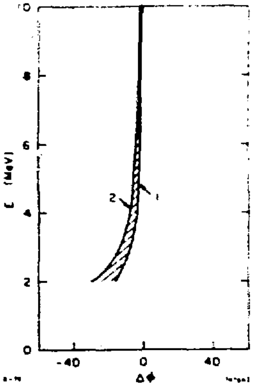

Fig. 2. Longitudinal phase space after a 14.2 cm drift: Curve 1 for p_{to} = 0; Curve 2 for p_{to} = 0.6 MeV/c.

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[illegible] energies [illegible] MeV [illegible] maximum transverse momentum in the target [illegible] MeV [illegible]. The total [illegible] is about [illegible] [illegible] MeV [illegible] [illegible] [illegible] [illegible] [illegible] acceptable energy spectrum.

[illegible]

[illegible]

[illegible] for the [illegible]

$$[illegible] \qquad (4)$$

where [illegible] energy gain per wavelength in the [illegible] the asymptotic phase. (The [illegible] that the electric field is [illegible]

[illegible] there exists a relation between phase and energy as the beam enters the accelerator, which can be written, using Eq. (2):

$$\phi_{[illegible]} = \phi_o + [illegible] \left(1 - \frac{[illegible]}{(\gamma_o^2 - 1)^{\frac{1}{2}}} \right) \qquad (5)$$

ϕ_o being a parameter which represents the input phase of the field for γ = 1 positron.

By using Eqs. (4) and (5) one can compute optimum values for the parameters α, D and ϕ_o in order to obtain a minimum dispersion in asymptotic phase for a given range of γ_o. The asymptotic phase ϕ_∞ must be chosen near -90° in order to obtain the maximum acceleration. The orbits (γ, ϕ) resulting from Eq. (4) are symmetric with respect to ϕ = 0. The positive values of ϕ_o (decelerating field) give a positive slope $d\gamma_o/d\phi_o$. Eq. (5) gives a positive slope $d\gamma_o/d\phi_o$. The best fitting between relations (4) and (5) will then be obtained when the beam enters the accelerator in a decelerating field. (The optimum value of ϕ_o will be near 90° for ϕ_∞ = -90°). This fact can be easily understood by looking at Fig. 2 and comparing it with the general shape of the phase space orbits in Fig. 3.

As an illustration of this bunching process, Fig. 4 shows the phase space resulting from the drift space of 14.2 cm for energies from 2 MeV to 10 MeV, (solid curve) together with the orbits ϕ_∞ = -85°, -90° and -95° for an accelerating field of 12 MeV/m (dotted curves) and ϕ_o = 86° (decelerating field). It is seen that the

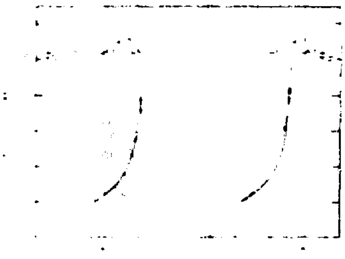

Fig. 4. [illegible] phase [illegible] [illegible] field

[illegible] orbit is achieved within less than [illegible] expect a dispersion [illegible] asymptotic phase [illegible] less than [illegible]. On the other [illegible] the same phase space for the beam together with the orbits -[illegible]°, -80°, -9[illegible]° and -100° in [illegible] accelerating field). It is evident that the dispersion in asymptotic phase will be greater than [illegible]. The integration of the equations of motion [illegible] a distance [illegible] gives a total bunch length of 3[illegible]°, the input energy varies from [illegible] MeV to [illegible] MeV.

It appears that this bunching process is very efficient for an initially bunched beam, which contains particles within a large energy band extending down to a very low energy, and which has been debunched under the action of different velocities over a drift space.

2. Positrons With Transverse Momentum - If we assume that there exists no other transverse force than the focusing effect of the dc magnetic field, then the transverse momentum remains constant in a constant focusing field, or varies according to Eq. (2) if the magnetic field varies slowly. The equations of longitudinal motion can be written in that case.

$$\begin{cases} d\gamma = \alpha \sin\phi \, dz \\ d\phi = 2\pi\left(1 - \dfrac{\gamma}{(\gamma^2 - 1 - p_t^2(z))^{\frac{1}{2}}}\right) dz \end{cases} \quad z \text{ in units of } \lambda$$

For constant p_t these equations can be combined and integrated, giving

$$\cos\phi_o - \cos\phi_\infty = \frac{2\pi}{\alpha} \left[\gamma_o - (\gamma_o^2 - 1 - p_t^2)^{\frac{1}{2}}\right] \qquad (6)$$

which defines new orbits in the phase space E, ϕ. Let us consider two positrons of the same energy γ_o, one moving on the axis and one leaving the target with a transverse momentum p_{to}. Let ϕ_{o1} be the entrance phase for first one and $\phi_1 = \phi_{o1} - \delta\phi$ the phase for the second one, where

$$\delta\phi = \Delta\phi\ (\gamma_o,\ 0) - \Delta\phi\ (\gamma_o,\ p_{to}),$$

where $\Delta\phi$ is given by Eq. (3). In the approximation of small angle of emission one can write

$$\delta\phi = \frac{\pi}{\lambda}\ \frac{p_{to}^2}{\gamma_o^2}\ \frac{1}{B_o} \int_o^D B\, dz$$

which can also be written

$$\delta\phi = \frac{\pi}{\lambda}\ \frac{p_t^2}{\gamma_o^2} \cdot K$$

where p_t is the transverse momentum in the section and

$$K = \frac{1}{B_z}\int_0^D B_{(z)}\,dz,$$

B_z being the magnetic field in the section, which is supposed to be constant. Eq. (6) can be approximated by:

$$\cos\phi_o - \cos\phi_\infty = \frac{2\pi}{\lambda}\,[illegible] \qquad (6b)$$

Using Eqs. (4) and (6b) together with the expression for [illegible], the dispersion in asymptotic phase is given by:

$$\Delta\phi_\infty \sin\phi_\infty = [illegible] \qquad (7)$$

It is seen that one can choose the accelerating field and input phase, for a given energy, to make the asymptotic phase independent of the transverse momentum.

It is evident from Eq. (7) that ϕ_{c1} must be positive, i.e., the beam must be decelerated. The accelerating field E' and input phase are simply related to the energy E_o by:

$$E'\sin\phi_{c1} \approx \frac{E_o}{K}$$

In the case of SLAC, K is of the order of 0.45 m. For E_o = 2 MeV, we must choose $E'\sin\phi_{c1} \approx$ 4.4 MeV/m. The equations of motion have been integrated over a distance of 3 m for E_o = 2 MeV, E' = 10 MeV/m, p_{to} = 0 to 0.6 MeV/c, and ϕ_{c1} = 25° (ϕ_o in Eq. (5) = 40°). The resulting phase dispersion is less than 1°, for an input dispersion of 15°.

This bunching process could be very useful in the case of a high transverse acceptance over a narrow energy band centered on a low energy (use of a quarter wave transformer).

We can conclude that, by first decelerating the positron beam, one can take advantage of using very low energy and high acceptance (in our case the angular acceptance at 2 MeV is 18°) together with large energy band, leading to a maximum current of positrons within a narrow energy spectrum. The limitation may be the initial energy dispersion in the case of a low final energy.

Results of Calculations in the Case of SLAC

The first section is a very short one, followed by a drift space (Fig. 1). With an accelerating field of the order of 10 MeV/m it is evident that one cannot take full advantage of the bunching process described above, mainly because the minimum energy at the end of the first section must be high enough to avoid a debunching effect over the second drift space. We have computed the longitudinal motion for several values of the parameter ϕ_o (see Eq. (5)) and of the accelerating field. Fig. 5 shows the resulting phase space at the entrance of the second section in the cases ϕ_o = 70° and 30° (beam initially decelerated) and ϕ_o = −70° (beam accelerated), and a field of 10 MeV/m. (For each case, the two solid curves with cross hatching between them represent the phase space for *positrons with initial transverse momenta* between 0 and 0.6 MeV/c.) The effect of the second drift space is clearly seen in the case ϕ_o = 70°: the minimum energy is about 1 MeV and the phase space is completely distorted. In the case ϕ_o = 30° the minimum energy is 2.5 MeV and the distortion of the phase space is much less important. The orbits for ϕ_∞ = −40° and ϕ_∞ = −50° are shown on the same scale for an accelerating field of 10 MeV/m (the second section is long enough to consider at a first approximation the asymptotic behavior). The fitting between these orbits and the phase space of the

Fig. 5. Longitudinal phase [illegible] to second section [illegible] entering short section [illegible] ϕ_o = +70° and [illegible]

beam is reasonably good and one can expect a final bunch length of less than 10°. In addition it can be seen that the bunching of low energy positrons with transverse momentum from 0 to 0.6 MeV/c has been achieved in the short section.

In the case ϕ_o = −70° (beam accelerated) no bunching effect has occured, the total bunch length is [illegible] and no further bunching can occur in the second section. The phase space at the end of the second section has been computed for various values of the accelerating field, input phase and different phase space configurations resulting from the first section. Fig. 6 shows on the left the result in the case of the phase space shown in Fig. 5 for ϕ_p = 30°. The input phase for the second section is ϕ_o = 50° (phase of the field for a p = 1 particle). The average output phase is −45°, giving a total phase slippage for the beam of about 95°. The bunch length is 6° and the energy dispersion 0.5 MeV. Shorter bunches can be obtained at the expense of final energy and energy dispersion. The transition between the solenoid and the quadrupole must take place at an energy of at least 55 MeV in order to keep an admittance of 0.15 π MeV/c.cm[1]. With the phase space of Fig. 4, adding a 3 m-long section with the same field gives an energy from 44 MeV to 54 MeV. We have investigated two

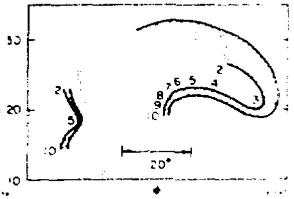

Fig. 6. Phase space at output of second section;
Left: New section in use.
Right: Without new section.

ways of increasing the energy without perturbing the bunching process, for the same accelerating field:

- [illegible] of three [illegible] of the long section at [illegible] from the [illegible] having a phase shift of [illegible] increases the output energy by about [illegible] MeV, giving a bunch length [illegible]
- [illegible] the temperature of [illegible] section by [illegible], to increase [illegible] giving [illegible]

[illegible]

[illegible]

[illegible] field [illegible] we have integrated [illegible] for a SLA [illegible] for an amplitude [illegible] in phase and [illegible] within the [illegible]

[illegible] Influence of the E_r and B_φ components of the field

[illegible] during their motion [illegible] wave, in a region where [illegible]. The [illegible] will experience a defocusing force due [illegible] components of the field. The radial [illegible] written[6]:

$$[illegible] \frac{dr}{dz} [illegible] = r [illegible] \cos\varphi - \frac{B_{ext}^2}{4\gamma}] \quad (8)$$

where r = distance from the axis, [illegible] = accelerating field in units of [illegible] MeV/m, and B_{ext} is the dc magnetic field in units of [illegible] gauss). The first term, which is due to the rf fields, can have a magnitude about 1/4 the magnitude of the second term for distances of a few centimeters when a low energy positron passes through zero phase.

[illegible] Longitudinal Motion - When we studied the bunching of positrons of the same energy and different transverse momentum, the effect of the axial force resulting from the interaction of radial velocity and azimuthal magnetic field was neglected. The complete equation of motion can be written in the case of the fundamental above[7]:

$$d\varphi = -\alpha [\sin\varphi - \frac{2e}{[illegible]} [illegible] \cos\varphi] dz \quad (9)$$

This equation has been integrated in the case mentioned before (E_0 = 2 MeV, [illegible] = 10 MeV/m, φ_0 = 25°, p_{to} = 0 to 0.6 MeV/c) for various values of the initial azimuth angle. It was found that the maximum output phase variation is about 2°.

Comparison with the Present Mode of Operation

In the present mode of operation, the short section is not used. The rf phases of the linac are not changed from electron to positron acceleration. The positron beam is then decelerated in the 3 m long section. The phase space at the end of the section was computed for different values of the input phase and field which give a total phase slippage for the beam of about 180°. Fig. 6 shows the resulting phase space for a field of 10 MeV/m and an input phase of φ_0 = 80°. Positrons with energies from 4.5 MeV to 10 MeV are bunched within approximately 10°. Positrons from 2 to 4 MeV are far away in phase and will not contribute to the useful beam (within 1% energy bin).

Results of Experiment

The short section was used in June 1979 for an experiment with positron beams of final energy 1.6 GeV and [illegible] GeV. The analyzed current within 1% was increased in both cases by at least a factor of two with respect to the usual current. The optimum shift for the rf downstream of the target, versus electron operation was found to be about 60°, giving a phase slippage for the beam of about 160°. These results are in good agreement with the calculated values. The short section will be put into normal operation next October with [illegible] pulsed phase shifters for the klystrons upstream the converter.

References

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