

Single Electron Operation Mode in DAΦNE BTF

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Abstract

The DAΦNE Beam Test Facility (BTF) [1] will use the LINAC-beam parasitically injection into the collider. It is a beam transfer line which has been designed in order to optimize the operation mode in which single electrons are stochastically produced for detector calibration purposes. The system consists of a metallic target intercepting the LINAC beam followed by an 'Energy Selector System' (ESS). The target strongly increases the beam energy spread, while the ESS selects the beam reducing the number of electrons in the bunches. Fine tuning is achieved by trimming focusing elements in the line. The facility is now under construction and the final design is presented.

1. INTRODUCTION

The injector of the DAΦNE accelerator complex [2] is a LINAC delivering electron and positron beams with a maximum energy of 800 MeV and 550 MeV respectively. Between two consecutive injections these beams can be switched on a special transfer line, the BTF, for the production of single particle pulses. Such beams are useful for the calibration of particle detectors used in high energy physics experiments. It is worth remarking that pulses of single electrons have already been obtained at Orsay with a system similar to the one described here [3] and also at CERN with a different approach [4].

2. BASIC PRINCIPLES

2.1. Beam-target Interaction

A relativistic electron (or positron) passing through matter loses energy mainly through two processes: ionization and radiation loss. The ratio between these two different losses is a function of the electron energy and of the material and can be roughly expressed by [5]:

$$\frac{\left(\frac{\partial E}{\partial x}\right)_{RAD}}{\left(\frac{\partial E}{\partial x}\right)_{ION}} \approx \frac{ZE_0}{800} \quad (1)$$

where E is the electron energy in MeV, x the material thickness, Z the atomic number of the material and E_0 the initial electron energy in MeV. For copper ($Z=29$), and a 500 MeV electron the ratio is ≈ 18 , indicating that the radiation loss dominates. In this situation it is reasonable to neglect the ionization term, assuming that the electron loses energy only through radiation.

The energy distribution w of an electron (positron) of initial energy E_0 after passing through a target of α radiation lengths thickness, is given, with good approximation, by [6]:

$$w(E_0, \alpha, E) = \frac{1}{E_0} \frac{\left[\ln \left(\frac{E_0}{E} \right) \right]^{\frac{\alpha}{2} - 1}}{\Gamma \left(\frac{\alpha}{2} \right)} \quad (2)$$

where $\Gamma(x)$ is the gamma function. The probability P to find the electron with energy in the interval $[E_0 - \Delta E, E_0]$, with $\Delta E \ll E_0$, is given by:

$$P = \frac{1}{2 \Gamma \left(\frac{\alpha}{2} \right)} \left[\ln \left(\frac{1}{1 - \frac{\Delta E}{E_0}} \right) \right]^{\frac{\alpha}{2} - 1} \frac{\Delta E}{E_0} \quad (3)$$

where the factor $1/2$ comes from the arithmetic average between the values of (2) in $E_0 - \Delta E$ and E_0 . Furthermore, since again $\Delta E \ll E_0$, it is possible to write, with good approximation, that:

$$P = \frac{1}{2 \Gamma \left(\frac{\alpha}{2} \right)} \left(\frac{\Delta E}{E_0} \right)^{\frac{\alpha}{2}} \quad (4)$$

As a conclusion, for a bunch of N electrons or positrons with energy E_0 passing through a target of α radiation lengths, the average number of outgoing particles with energy in the range $[E_0 - \Delta E, E_0]$ will be:

$$N_{\Delta E} = N P \quad (5)$$

2.2. Energy Selection

The Energy Selector System (ESS) is the device which selects, from the whole bunch, only the particles satisfying condition (5).

As shown in Figure 1, the system consists of a 45° DC sector bending magnet (DHSTB01) with a vertical slit in its focus (SLTTB01) and with a second slit upstream the magnet (SLTTM01). The energy acceptance of the ESS can then be easily derived:

$$\left| \frac{\Delta E}{E} \right| = \frac{h_F}{2\rho} + \sqrt{2} \left| x_0 \right|_{MAX} \quad (6)$$

where ρ is the bending magnet radius, h_F the total aperture of the slit in the magnet focus and $\left| x_0 \right|_{MAX}$ the maximum horizontal divergence the particle can have at the magnet entrance.

The latter can be limited by the slit upstream the magnet:

$$|x_0'|_{MAX} = \frac{\sigma_x^T + h_U / 2}{l} \quad (7)$$

where h_U is the total slit aperture, l is the target-slit distance and σ_x^T the beam radius at the target output. This cut on maximum divergence is necessary because the beam-target interaction dramatically increases the beam emittance.

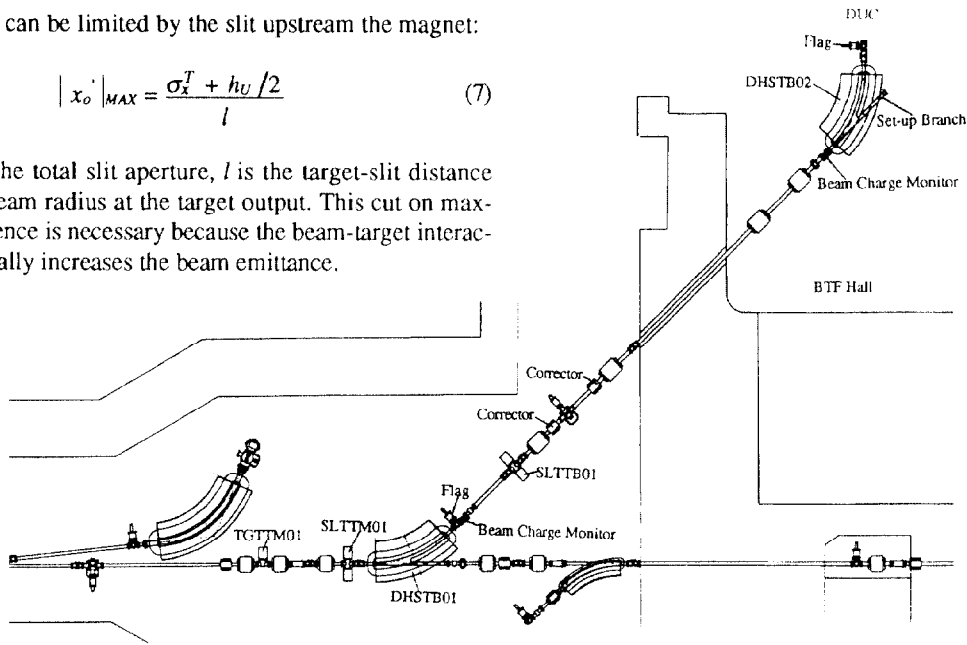


Figure 1. BTF General Lay-Out.

To give an idea of the magnitude of the selection factors involved in the production of a single electron pulse, we describe here the case of the BTF at 500 MeV.

First we set the LINAC to deliver a 500 MeV electron beam with the minimum current diagnostic system is able to detect (≈ 1 mA averaged over the 10 ns FWHM macrobunch), corresponding to:

$$N = 6.2 \times 10^7 \text{ particles} \quad (8)$$

ρ and l are 1.722 m 1.499 m respectively, and the expected beam radius at the target input face is 1.2 mm. The passage through the $\alpha = 2$ radiation lengths target enlarges the beam by a factor ≈ 3 (a more detailed estimate can be given by the EGS code [7]) and thus $\sigma_x^T \approx 4$ mm. Setting $h_U = 8$ mm, $h_F = 8.5$ mm and using expressions (6) and (7), we obtain an ESS energy acceptance:

$$\left| \frac{\Delta E}{E} \right| = 1 \% \quad (9)$$

and from (4):

$$P = 4.7 \times 10^{-7} \quad (10)$$

Finally, using (5) and (8), we get:

$$N_{\Delta E} \approx 30 \quad (11)$$

2.3. Fine Tuning

Expression (11) indicates that, in order to achieve $N_{\Delta E} = 1$ for the average number of electrons with energy $E = (500 \pm 3)$ MeV, fine tuning is necessary. In practice an adjustment of this kind is always necessary and can be performed following several methods.

The simplest are:

- Trimming of the LINAC gun current.
- Proper setting of the LINAC focusing system.

2.4. Statistical Considerations and Error Analysis

The number of particles within the selected energy range follows the Poisson distribution:

$$P_m(k) = e^{-m} \frac{m^k}{k!} \quad (12)$$

where $m = N_{\Delta E}$. This means that when the BTF is properly set ($m=1$), it delivers $\approx 37\%$ of the pulses with a single electron, $\approx 37\%$ with no electrons, $\approx 18\%$ with two electrons and $\approx 8\%$ with more than two electrons.

From another point of view $\approx 59\%$ of the non empty pulses carry a single electron. It is worth remarking that, setting $m < 1$, the number of empty pulses increases but the ratio of single electron pulses over the non empty ones increases as well. For example, if $m = 0.5$, then $\approx 80\%$ of the non empty pulses carry a single electron.

In order to estimate the sensitivity of m to the variation of the system parameters it is necessary to differentiate expression (5), taking (4) into account. After some algebra, it can be found that:

$$\frac{\Delta m}{m} = \frac{\Delta N}{N} + \frac{\alpha}{\ln 2} \left[\frac{\Delta E_o}{E_o} + \frac{\Delta(\Delta E)}{(\Delta E)} \right] + \left| \ln \left(\frac{\Delta E}{E_o} \right) \right| \cdot \psi \left(\frac{\alpha}{\ln 2} \right) \left| \frac{\Delta \alpha}{\alpha} \right| \quad (13)$$

where $\psi(x)$ is the digamma function. Let us now consider the meaning of each error contribution.

$\Delta N / N$: fluctuation of the number of particles per pulse. This is determined mainly by the gun stability.

$\Delta E_o / E_o$: LINAC beam central energy fluctuation: RF and trigger systems stability.

$\Delta \alpha / \alpha$: target thickness error. The dependence of (13) on this term is quite strong. The target surfaces must be carefully machined to minimize this error. It is worth pointing out that, for a given surface finishing, the use of a larger radiation length material decreases this error contribution.

$\Delta(\Delta E) / (\Delta E)$ describes the fluctuations of the range selected by the ESS. It can be expressed, using (6), as:

$$\frac{\Delta(\Delta E)}{(\Delta E)} = \frac{\Delta E_o}{E_o} + \frac{1}{1 + \frac{2\sqrt{2}\rho|x_0|_{MAX}}{h_F}} \left(\frac{\Delta h_F}{h_F} + \frac{\Delta \rho}{\rho} \right) + \frac{1}{1 + \frac{h_F}{2\sqrt{2}\rho|x_0|_{MAX}}} \frac{\Delta|x_0|_{MAX}}{|x_0|_{MAX}} \quad (14)$$

with:

$$\frac{\Delta|x_0|_{MAX}}{|x_0|_{MAX}} = \frac{\Delta l}{l} + \frac{1}{1 + \frac{2\sigma_x^T}{h_U}} \frac{\Delta h_U}{h_U} + \frac{1}{1 + \frac{h_U}{2\sigma_x^T}} \frac{\Delta \sigma_x^T}{\sigma_x^T} \quad (15)$$

where:

$\Delta h_F / h_F$: variations of h_F due to slit inner faces parallelism and finishing errors.

$\Delta \rho / \rho$: bending radius variations mainly due to the power supply current fluctuations.

$\Delta l / l$: this error appears when the output face of the target is not parallel to the input face of the slit upstream the dipole magnet.

$\Delta \sigma_x^T / \sigma_x^T$: the beam spot variation comes mainly from the fluctuations of the focusing magnets power supply current.

$\Delta h_U / h_U$: variations of h_U due to slit inner faces parallelism and finishing errors.

The dependence of the Poisson distribution (12) on m is:

$$\frac{\Delta P_m(k)}{P_m(k)} = e^{-\Delta m} \left(1 + \frac{\Delta m}{m} \right)^k - 1 \quad (16)$$

and, in particular, if $k=1$, $m \approx 1$ and $\Delta m / m < 15\%$ then:

$$\frac{\Delta P_m(1)}{P_m(1)} = \frac{1}{2} \left(\frac{\Delta m}{m} \right)^2 \quad (17)$$

These expressions allow to estimate the effects of the tolerances (mechanical, electrical, etc.) on the system stability. The BTF has been designed to yield $\Delta m / m < 10\%$ and therefore the overall system stability (17) is better than 1%.

3. THE BTF TRANSFER LINE AND DIAGNOSTICS

The BTF lay-out is shown in Figure 1. The LINAC beam comes from the left side and strikes the removable copper target (TGTTMO1). Three different thicknesses can be selected: 1.7, 2.0 and 2.3 radiation lengths.

A change of one order of magnitude per thickness step in the value of P given by expression (4) is therefore possible. Downstream the target, the beam goes into the ESS (see §2.2) and after energy selection the remaining particles are driven into a room outside the LINAC vault where the detector under calibration (DUC) can be placed. This choice allows to isolate the DUC from the strong noise coming from the LINAC vault.

The dipole magnet DHSTB02, identical to DHSTB01, can send the beam on the DUC (magnet ON) or in a special small branch (magnet OFF) where a single particle detector, probably a lead glass, is used to set the BTF without damaging the DUC.

The BTF transfer line focusing system consists of four quadrupoles and a complete diagnostic set including 2 beam charge monitors, 2 fluorescent flags and 2 horizontal and vertical correctors, which will be useful in setting the line before the insertion of the target.

4. REFERENCES

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