Beam Instrumentation for the Single Electron DAΦNE Beam Test Facility

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Abstract

The DAΦNE Beam Test Facility (BTF) has been successfully commissioned in February 2002, and started operation in November of the same year. Although the BTF is a beam transfer line optimized for single particle production, mainly for high energy detectors calibration, it can provide electrons and positrons in a wide range of multiplicity: between $1 \div 10^{10}$, with energies from a few tens of MeV up to 800 MeV. The large multiplicity range requires many different diagnostic devices, from high-energy calorimeters and ionization/fluorescence chambers in the few particles range, to standard beam diagnostics systems. The schemes of operation, the commissioning results, as well as the beam diagnostics are presented.

DESCRIPTION OF THE DAΦNE BTF

The Beam Test Facility (BTF) is a beam line optimized for the production of a pre-determined number of electrons or positrons, in a wide range of energies (up to 800 MeV) and multiplicity. The facility is particulary suitable for particle detector testing purposes, such as energy calibration and efficiency measurements, in single electron mode; while beam diagnostics devices and detector aging can be studied at higher intensities.

The BTF is part of the DAΦNE accelerator complex, consisting of a double ring electron-positron collider, a high current linear accelerator (LINAC), an intermediate damping ring (Accumulator) and a system of 180 m transfer lines connecting the four machines. The LINAC delivers electrons with energy up to 800 MeV, with a typical current of 500 mA/pulse, or positrons with energy up to 550 MeV, with a typical current of 100 mA/pulse; the pulse duration can be adjusted in the range $1 \div 20$ ns with a maximum repetition rate of 50 Hz. When injecting for operation of the main rings at the ϕ resonance, the beam energy is 510 MeV.

Since the minimum LINAC beam current that can be conveniently measured by the DAΦNE current monitors is $I \approx 1$ mA, the corresponding number of electrons (positrons) is $\approx 10^8$/pulse. It is thus necessary to strongly reduce the number of particles to reach the few particles range. The reduction of the particle multiplicity can be achieved with different methods, the one chosen for the BTF operation is the following[1]: first the LINAC beam is intercepted by a (variable depth) target in order to strongly increase the energy spread of the primary beam; then the out-coming particles are energy selected by means of a bending magnet and slit system. The energy selector only accepts a small fraction of the resulting energy distribution, thus reducing of the number of electrons by a large and tunable factor. The target is shaped in such a way that three different values of radiation length can be selected ($1.7, 2.0, 2.3\ X_0$) by inserting it at different depths into the beam-pipe. The attenuated beam is transported by a ≈ 12 m transfer line to the BTF hall, where the experimental set-ups can be installed. The dipole magnet, together with a downstream collimator, selects the momentum of the particles. At the end of the BTF line a second bending magnet allows to use two separate test lines: one directly from the straight section, the other from the magnet at 45°.

Due to the momentum dispersion introduced by the bending magnet, the relative energy spread $\Delta E/E$ is essentially determined by the magnet/collimators configuration[2]; in the standard BTF operation for a wide range of slit apertures a resolution better than 1% can be obtained.

The number of transported electrons (or positrons) can be adjusted in a wide range, down to single particle, and is well below the sensitivity of any standard beam diagnostics device, so that many different particle detectors have been used to monitor the beam characteristics.

BEAM COMMISSIONING AND DIAGNOSTICS

During 2002 the BTF has been successfully commissioned and started operation, delivering beam to the first user experiments, from Nov. 2002 to May 2003[3]. The facility has been operating both in the single electron production scheme and the high multiplicity operation mode, according to the different user requirements.

At low multiplicity a calorimeter has been used as main diagnostic device. The detector is a lead/scintillating fibers calorimeter of the KLOE type[4], with single side photomultiplier readout. The main features are a sampling fraction of $\approx 15\%$, a good energy resolution, $\sigma_E/E = 4.7\%/\sqrt{E(\text{GeV})}$, and excellent timing resolution, $\sigma_{\text{t}}/\text{t} = 54\text{ps}/\sqrt{E(\text{GeV})}$.

The LINAC setting has been optimized to provide a 510 MeV energy, $4 \div 5$ mA intensity beam. The repetition rate of the LINAC was 24 Hz (+1 shot to the spectrometer line

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for LINAC energy measurement), and the pulse duration was the same as for injection in the accumulator, ≈ 10 ns. The typical collimator settings were 2 mm of total aperture, both for the upstream and downstream slits: with the attenuator depth set to $1.7\ X_0$ only a few electrons reach the diagnostic detectors.

Due to the good energy resolution of the calorimeter, $\approx 7\%$ at 500 MeV, the number of produced electrons can be counted simply by measuring the total deposited energy E: $n = E/E_1$, where E_1 is the energy deposited by a single electron. An example of ADC spectrum (pedestal subtracted) is shown in Fig. 1, for a selected energy of $E_{\rm sel} = 471$ MeV: the individual peaks corresponding to $0, 1, \ldots, n$ electrons can be easily identified. The total number of events in each peak should represent the probability of producing n particles: by fitting the distribution of the number of events in each peak with the Poisson function, the average number of particles can be determined (see the inset of the figure).

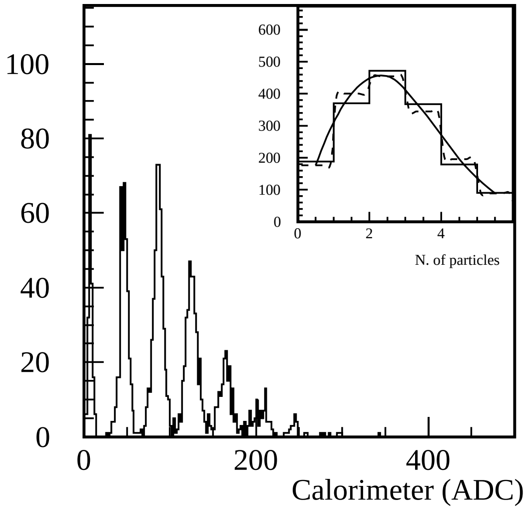

Figure 1: *Counting electrons in the calorimeter: charge spectrum for $E_{\rm sel} = 471$ MeV (in the inset: the number of particles in each peak is fitted with the Poisson function, mean value $\overline{n} = 2.3$).*

The most effective way to change the average number of particles in the beam is to change the selected energy $E_{\rm sel}$; in particular, at the **same** LINAC energy and intensity and with the **same** collimator settings, the multiplicity increases by decreasing the chosen $E_{\rm sel}$. In addition, the multiplicity can be tuned by changing the aperture of the upstream and/or downstream collimators. In this case the energy resolution of the selector will be also affected, but by a relatively small amount, in any case well below the intrinsic resolution of our calorimeters. In particular, the measured multiplicity increases by increasing the slits aperture until the intrinsic beam spot size is exceeded.

There are two intrinsic limitations to the particle counting with calorimeters. Since the absolute width of the peaks increases as $\sqrt{n}$, increasing the average multiplicity the peaked structure in the energy distribution gradually disappears, approaching a Gaussian shape. In this case the number of particles in the beam cannot be measured *event by event*, but only the average multiplicity $\overline{n}$ can be statistically estimated. Another intrinsic limitation to the particle counting performed by means of the total energy measurement in a calorimeter is the detector saturation, *i.e.* when the signal begins to be no longer proportional to the number of particles. This is in general due to one or more of the following factors: saturation of the ADC scale, of the photomultiplier gain or the scintillation light yield.

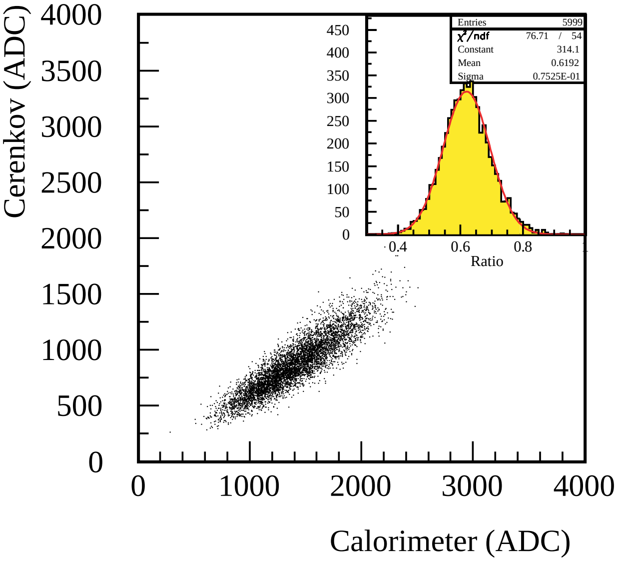

Figure 2: *The signal in the Cerenkov counter as a function of the total energy in the calorimeter (in the inset the ratio between the two measurements is fitted with a Gaussian).*

Above ≈ 20 particles the calorimeters are no longer effective due to saturation effects. In order to have a diagnostic device in the $\overline{n} = 100$-1000 range (and higher), a different detector has been developed and tested in collaboration with the AIRFLY group [5]. It is essentially a counter based on the Cerenkov light emission in a PLEXIGLAS radiator when crossed by relativistic electrons (which in the BTF energy range is always the case). The light is then extracted by properly shaping the end part of the radiator itself and collected by a photomultiplier, without optical connection: this gives the possibility of interposing a calibrated optical filter between the radiator and the PMT, in order to attenuate the Cerenkov light by a known factor, thus extending the dynamical range of the counter. The Cerenkov light yield, and in turn the phototube analog signal, should be proportional to the number of electrons crossing the radiator; this phenomenon should be linear up to a very high number of electrons. The Cerenkov counter signal shows a good correlation with the energy deposited in the calorimeter, as shown in Fig. 2, with a suitably low multiplicity beam; using the cross-calibration between the two detectors, the Cerenkov counter has been used to monitor the beam multiplicity up to ≈ 1000.

The above described devices are fully remotely controlled by the DAΦNE control system. The Data Acquisition System is based on VME bus, equipped with a VMIC 7740 controller CPU, running Red Hat 7.3 Linux and National Instruments LabView. The splitted analog signals are properly delayed and fed to CAEN V792 ADCs, and discriminated and fed to CAEN V775 TDCs. The DAQ trigger and gate signals are driven by the digital pulse of the LINAC gun provided by the DAΦNE timing system.

Another important parameter is the beam energy, that can be chosen by changing the current of the energy selector dipole magnet. The average measured energy of the single electron signal in the calorimeter is proportional to the incoming beam energy $E_{\rm sel}$ as shown in Fig. 3.

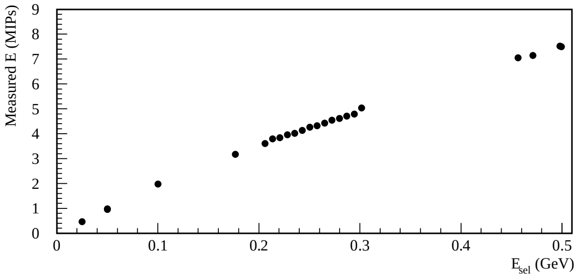

Figure 3: *Total energy deposited in the calorimeter by a single electron as a function of the selected beam energy* $E_{\rm sel}$.

Many user experiments were carried out since Nov. 2002 in the two main different operation modes of the BTF facility:

- high multiplicity in a wide range of energies: the AIRFLY experiment measuring the air fluorescence yield, in the widest accessible energy range for the BTF beam, with the air fluorescence detector chamber in a fixed position; and the DIAMANTE2 beam intensity monitor;

- single electron for a number of energy points, full coverage of the detectors (moving them across the beam): LCCAL electromagnetic calorimeter calibration, CAPIRE collaboration RPC efficiency tests, LHCb gas detectors efficiency tests, AGILE silicon tracker tests.

Profiting of the high spatial resolution of the silicon micro-strip detector, a beam profiling chamber has been installed in collaboration with the AGILE group[6], in order to monitor the beam spot size (at low multiplicities). An example of the beam spot measured by the silicon microstrip monitor is shown in Fig. 4. The device is a single-sided, AC-coupled, 410 μm thick, 9.5 cm side square silicon strip detector with a readout pitch of 242 μm and one floating strip with polysilicon bias voltage resistors. Three 128-channel analog-digital, low noise, self-triggering ASICs, with multiplexed analog readout are used.

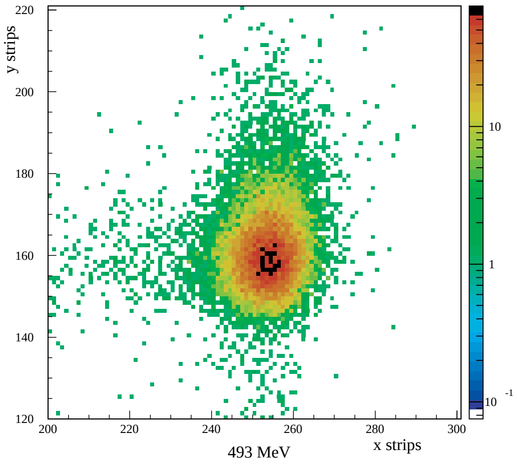

Figure 4: *Beam spot measured by the AGILE silicon tracker (242 μm strip pitch): $\sigma_x \approx \sigma_y \approx$ 2 mm.*

CONCLUSIONS

Since the beginning of operation, the BTF has demonstrated to be easily tunable both from the point of view of the desired particle multiplicity (from single electron mode to ≈ 1000) and energy setting. In order to overcome the present limitations imposed by the DAΦNE collider experiments operation and to largely improve the duty-cycle, we plan to upgrade the facility [7]; a complete separation between the DAΦNE transfer lines to the Main Rings and the BTF channel will allow to operate in the BTF mode with the only limitations of the LINAC switching time and the time spent for filling the Main Rings.

More diagnostic systems, especially devoted to high multiplicity measurement and beam energy resolution, are under development in order to improve the characterization of the beam quality.

Finally, an upgrade of allowed radio-protection dose up to 10^{10} particles/s, will permit to use the BTF also for testing of standard beam diagnostics devices.

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