PROPOSAL OF AN EXPERIMENTAL TEST AT DAΦNE FOR THE LOW EMITTANCE MUON BEAM PRODUCTION FROM POSITRONS ON TARGET

M. Boscolo*, M. Antonelli, O.R. Blanco-García, S. Guiducci, A. Stella,
INFN-LNF, Via Fermi 40, 00044 Frascati, Italy
F. Collamati, INFN-Rome, Piazzale A. Moro 2, 00185 Rome, Italy
S. Liuzzo, P. Raimondi, ESRF, CS 40220, 38043 Grenoble Cedex 9, France
R. Li Voti, Sapienza Univ., of Rome Dep. SBAI, Via A. Scarpa 16 , Rome, Italy

Abstract

We present in this paper the proposal of an experimental test at DAΦNE of the positron-ring-plus-target scheme foreseen in the Low EMittance Muon Accelerator. This test would be a validation of the on-going studies for LEMMA and it would be synergic with other proposals at DAΦNE after the SIDDHARTA run. We discuss the beam dynamics studies for different targets inserted in a proper location through the ring, i.e. where the beam is focused and dispersion-free. The development of the existent diagnostic needed to test the behaviour of the circulating beam is described together with the turn-by-turn measurement systems of charge, lifetime and transverse size. Measurements on the temperature and thermo-mechanical stress on the target are also under study.

INTRODUCTION

The possibility of a muon collider in the future of accelerator physics has been studied by the Muon Accelerator Program (MAP) [1, 2], where muons are obtained from the decay of $\pi^{\pm}$ particles that have been produced from protons impinging on target. Muon beams are produced with a large emittance, requiring a cooling phase in the accelerator chain.

The Low EMittance Muon Accelerator (LEMMA) project [3, 4] studies the possibility of a muon collider scheme where the cooling phase is not required. Muon generation comes from electron-positron annihilation [5], that could be achieved by several techniques, each with different challenges. Among those techniques, positrons at 45 GeV impinging on a target seems the most feasible in order to produce similar luminosities to the ones stated by the MAP program.

MOTIVATION AND SCOPE

LEMMA requires a demanding positron source and a high momentum acceptance positron ring, where positrons interact turn-by-turn with a target for producing muons. The positron beam has been tracked through the ring-plus-target scheme to check for emittance degradation and perform beam dynamics studies [6]. Results are encouraging, but the requirements on the target are demanding. The target thermo-mechanical stress together with beam dynamics of the beam

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* manuela.boscolo@lnf.infn.it

interacting on the target is a key point of the LEMMA proposal, so it needs to be deeply studied not only by simulation but possibly also validated by measurements. In addition, an experimental test would validate also beam dynamics studies for the positron beam behaviour. Thin solid targets are used to strip partially ionized beams [7]. Low density gas-jet or pellet targets are used or planned to be used in future facilities [8]. Beam degradation due to the interaction with the target has been tested for only one pass (stripping case) or with low density targets. Insertion of high density targets in a ring intercepting the entire beam causing strong beam perturbation has never been tested. We propose to perform this experimental test at DAΦNE [9] after the run for SIDDHARTA-2 [10] in the end of 2019. SIDDHARTA-2 is a small experiment with no solenoid. The first SIDDHARTA run has allowed the crab-waist collision scheme to be tested for the first time [11].

With the end of this run DAΦNE will end its collider operation and there is a proposal to transform it into an international test facility. For the test we are proposing here only one beam is needed, either electron or positron. We could measure the beam lifetime and beam size evolution comparing results with numerical predictions obtained with the same tools used for the LEMMA design study.

Although the beam energy is as low as 0.51 GeV and large differences in many important parameters are present, the measurements of the beam size dependence on the optical parameters and target can be performed, together with experimental studies on the target issues related to heat load and thermo-mechanical stress. Different thicknesses and materials of the target could be tested. Given the limited energy acceptance of the ring, we plan to test Be or C targets with thicknesses in the range of 10-100 μm. Also crystals can be tested as target and channeling effects can be envisaged, with a measurement of emittance growth reduction due to multiple scattering.

To minimize the cost of this experiment we propose to use the existing configuration with only minimal modifications needed to insert the target and the proper diagnostics.

DAΦNE OPTICS AND BEAM DYNAMICS SIMULATIONS

We present here beam dynamics studies performed with the optics used for the SIDDHARTA 2008-2009 run, as it is

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the closest configuration expected for the machine when the test could take place, given the optics available now.

The optics functions are shown in Fig. 1, while the main parameters needed for this test are summarised in Table 1. The target is placed at the SIDDHARTA Interaction Point (IP), where the low-β functions and zero dispersion allow the suppression of multiple scattering and Bremsstrahlung effects. The IP is at s = 25.607 m in the plot. Here the beam spot size is σ_x = 0.27 mm and σ_y = 4.4 µm, resulting from β-functions at IP of β_x^*=26 cm and β_y^*=0.9 cm and a horizontal emittance of 0.28×10^{-6} m. The LEMMA ring is in a completely different energy range and the parameter table is in Ref. [6].
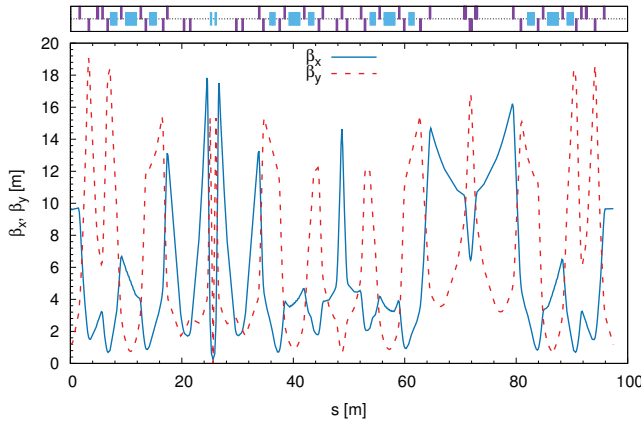

Figure 1: (Color online) β functions of the DAΦNE ring, the thin target is placed at the IP at s = 25.607 m; magnets are shown on the top.

Table 1: DAΦNE Parameter Table

Parameter	Units	
Energy/beam	GeV	0.51
Circumference	m	97.4
Emittance x,y	nm	280, 2.1
Bunch length	mm	10
Beam current	mA	5
Number of bunches	#	1
RF frequency	MHz	368.366
RF voltage	MV	0.15
particles/bunch	#	1×10^{10}
Revolution time	µs	0.033
τ_x (Transv. Damping)	ms	42
	turns	1.2×10^5
τ_y (Transv. Damping)	ms	37
	turns	1.1×10^5
Longitudinal Damping τ_s	ms	17.5
	turns	5.7×10^4
Energy loss/turn	keV	9
Momentum Compaction		1.9×10^{-2}
RF acceptance	%	± 1

Particle tracking in the ring–plus–target scheme is performed using PTC MAD-X [12] and GEANT4 [13], as for

the 45 GeV LEMMA ring, showing an energy acceptance of 1% with this optics configuration. We believe that this value can be improved by optics modifications and by increasing the vacuum chamber at the target (IP). Once this experiment will be approved in the preparatory phase dedicated studies on the optics and machine configuration are foreseen to optimize the configuration. We discuss here the principle idea with the feasibility scheme of this test.
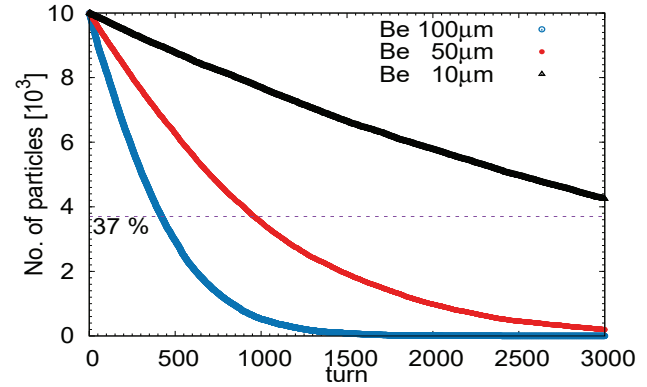

Figure 2: (Color online) Number of e$^+$ vs number of machine turns with a 10, 50 and 100 µm Be target at the IP.
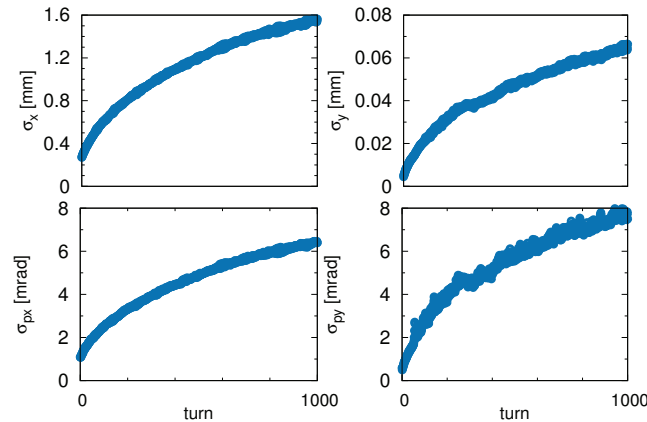

Figure 3: (Color online) Evolution of horizontal and vertical beam size and divergence at the IP for a Be target of 50 µm.

Figure 2 shows the number of particles as a function of machine turns for a Be target of different thicknesses: 10, 50 and 100 µm. The 37% line indicates the resulting beam lifetime in terms of turns. Lifetime larger than 3000 turns is found for 10 µm thick Be target, about 1000 turns for 50 µm and 500 turns for 100 µm. The evolution of the transverse beam size and divergence at the IP with the number of turns for 50-µm Be target is shown in Figure 3.

BEAM DIAGNOSTICS

Some modifications to the existing storage ring beam diagnostics systems will be required to provide measurements of charge, lifetime and transverse size at each turn after beam interaction with the target (which will not allow a stored beam regime). Measurements of the average stored beam

current is available, during the usual collider operation, with resolution better than 0.1% through acquisition of toroidal current monitors. The bandwidth of this specific pickup can provide accurate average beam current measurements for a beam lifetime as short as 100 s.

In addition to this test, turn-by-turn beam charge measurements (with resolution of ~1%) can be available through sampling of sum signals from beam position monitors installed along the rings. By using a pre-existing hardware included in the DAΦNE orbit system, after proper reconfiguration of timing and development of software acquisition tools, it will be possible to sample up to 64 kTurns (~20 ms) after each bunch injection. A beam transverse size measurement system at different turns in the ring, can be implemented with an upgrade of the existing optic equipment and instrumentation. A dedicated synchrotron radiation line, collecting synchrotron radiation in the visible wavelength range emitted from the beam passing in one of the dipole magnets, is routinely used during DAΦNE collider operation to measure, by imaging, the transverse and longitudinal size of the stored beam. Given the radiation source in a zone with vanishing value of the dispersion function, the beam transverse emittances can be directly evaluated from horizontal and vertical dimension measurements.

In order to follow the evolution of the beam transverse size (Fig. 3), the synchrotron radiation beam image can be focused in a CCD camera sensor at selected time intervals (in the order of the revolution period) and averaged over multiple injections (to increase signal to noise ratio) by using the gating capabilities of a CCD gated camera with image intensifier already available in the DAΦNE instrumentation. The beam size enlargement (Fig. 3) and the beam charge foreseen for this test (Table 1) appears to be compatible with the actual system aperture and sensitivity.

TEMPERATURE MEASUREMENT IN SITU ON THE TARGET

A robust experimental setup should be designed for measuring contactless the temperature of the target surface at the microsecond scale and with a high spatial resolution (10 μm). Several technical solutions can be adopted by using different measurement techniques.

Passive infrared thermography It is a remote sensing technique. The infrared camera works outside the vacuum chamber and can detect the IR emission of the hot target through a transparent IR window (for example CaF window). Since the maximum temperature of the target is expected in the range 500°C–1000°C the InSb cameras working in the MIR spectral band 3-5 μm can give optimal performances. For example, in Fig. 4 it is reported the thermal image of the cross section of three layered polyamide films [14]. The InSb camera has 256×256 pixels showing a very good spatial resolution 7.5 μm (3 μm/pixel). The frame rate can vary from 60 Hz to 5000 Hz, corresponding to the pixel size

$256 \times 256 \sim 64 \times 64$. This means that the time resolution can be obtained by loosing the spatial resolution.
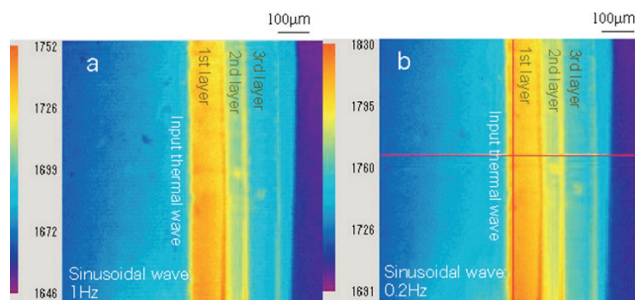

Figure 4: Example of spatial resolution obtainable with an InSb infrared camera on 3 thin layers [14].

One disadvantage is that the IR camera is not fast enough to follow the dynamic range of the temperature in the microsecond range. Nevertheless the cooling dynamic after the pulse can be clearly measured so that the maximum temperature during the pulse can be extrapolated according to the known geometry (see some examples on the extrapolation [15, 16]).

Infrared radiometry This is also a remote sensing technique. The infrared detection system works outside the vacuum chamber and, after calibration, can monitor the temperature in one point (the hottest region i.e. the center of the pulse) from the IR emitted by the target. Even in this case the HgZnCdTe infrared detector should have the best performances in the spectral band 2-5 μm. The advantage in this case is that the detector can be pretty fast following the temperature dynamics in the microsecond range. The disadvantage is that one can monitor the temperature in one point only (see ref [17]).

Measurement of surface deformation of the target and temperature determination A contactless measurement of the surface deformation can be performed with laser technique as shown in Fig. 5. The target is subject to a surface thermoelastic deformation induced by the heat deposition. The maximum deformation is expected at the centre of the pulse. The probe laser beam enters the vacuum chamber and is reflected back by the target surface. When the target surface is subjected to a thermoelastic deformation the probe beam changes its direction of reflection. This change is measured by a position sensor. This technique is very sensitive and can detect very weak deformation of the order of some picometer corresponding to less than 1°C. After a proper calibration it can be used to follow the ultrafast dynamic of the temperature of the target (see ref. [18, 19]).

CONCLUSIONS

We discussed an experimental test of the ring–plus–target scheme that we propose at DAΦNE. Even if the beam energy and parameters are very different from the LEMMA case, we believe that interesting validation studies on the
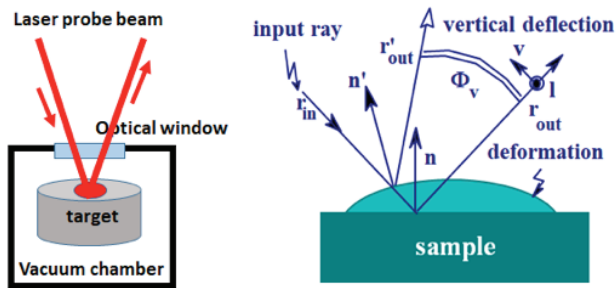
Figure 5: Surface deformation measurements.

beam dynamics level and on the thermo-mechanical stress can be performed, contributing to the demonstration of the feasibility of the LEMMA proposal.

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