DAΦNE Beam-Test Facility (BTF)

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Introduction

The LNF's beam-test facility (BTF) is a research infrastructure hosting about 200 users per year, over about 30 shifts per week, from Monday to Monday, over all 24 hours. Access by the scientific community involves participation in a call published twice a year and is subject to the scrutiny of a User Committee. This corresponds to approximately 200 days of beam per year, delivered almost exclusively opportunistically, i.e. profiting of LINAC pulses not used for injection into the DAΦNE rings, during the normal operation of the complex for fundamental physical experiments.

Electrons or positrons can be extracted before the injection into the damping ring, on a bunch-by-bunch basis, by means of a pulsed dipole; then the beam is driven to the BTF dedicated transfer line, where a system composed by a target plus a 42° dipole and collimating slits, can attenuate and select the momentum of secondary particles in narrow ($< 1\%$) band. The secondary beam is then driven to the experimental hall and focussed by means of two FODO quadrupole doublets. The final bending is performed by a 45° dipole, while horizontal and vertical correctors provide fine adjustment of the trajectory.

Working in parallel with the collider operation involves some limitations, mainly due to the alternate acceleration and injection of electron and positron beams, and in particular:

- the maximum energy is fixed to 510 MeV;
- the LINAC pulse duration is fixed around 10 ns, in order to fit with the damping ring 73.6 MHz radio-frequency;
- the duty-cycle is limited to a weekly average of $\approx$20 Hz, mainly because of two factors:
  - the number of pulses available, ranging from about 18 in the positron phase to about 38 electrons, out of the total 50 pulses available per second from the LINAC;
  - the dead-time due to the switching between the two phases (electrons and positrons), which causes the LINAC to be switched off for about 90 seconds (every 5-8 minutes) during the ramping of magnets.
- the intensity, linked to that of the primary beam, reflecting the alternate electron and positron injections in DAΦNE rings, with a complete cycle of 6-8 minutes duration. In addition, the secondary beam intensity depends on the energy selected and the collimators configuration, due to the energy and angular distribution of the particle shower emerging from the BTF target.

Alternatively, to use the beam without the restrictions associated with the injection into the rings, the collider must not be operational. This usually happens only for very short periods of the year, mostly dedicated to the ordinary and extraordinary maintenance of all the facilities, including the

LINAC and the infrastructure required for its operation (cooling tower, electric systems, control, etc.).

In order to increase the growing need of experimental users, and for keeping the possibility of performing test-beam activities also during long-term experiments like PADME (planned for 2018 and possibly 2019 on the BTF line), an important upgrade program for the facility has been approved and funded, under the supervision of the INFN Machine Advisory Committee. The upgrade is aimed at two main objectives:

- consolidating the LINAC infrastructure, in order to allow running efficiently and in a reliable way the electron and positron beams for at least another decade;
- doubling the existing user beam-line, using the space formerly used as BTF control room as a second experimental area [1].

The upgrade program thus required to stop the user activities at the summer shutdown, so that no shift has been allocated since September 2017.

1 The BTF running with users

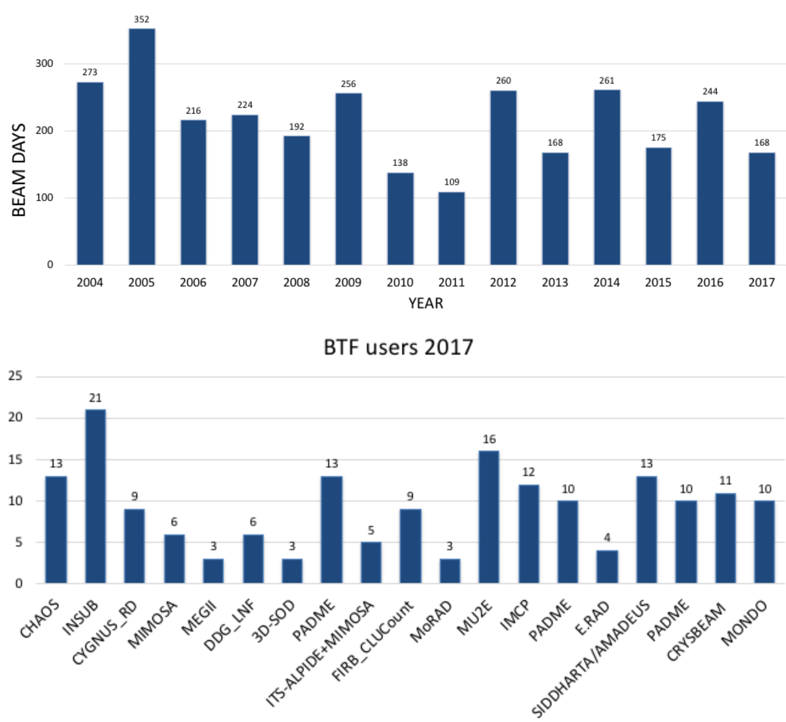

Figure 1: *Summary of BTF beam-days and external users in year 2017.*

In Fig. 1 the summary of external users access to BTF is shown: the number of beam-days available to users in 2017 was limited to 168, in order to allow starting the upgrade activities and working on the BTF infrastructure (see Sec. 3).

The regular beam-time for user groups in 2017 was limited to the period from January to July: beam was assigned mainly to high-energy detector testing, in particular with various shifts dedicated to the PADME experiment, with only four weeks dedicated to BTF upgrade related activities before the long BTF shutdown. The remaining part was dedicated for the preparation of irradiation runs, related to the ASIF program, a project of INFN, ENEA and the Italian Space Agency for establishing a network of irradiation facilities for space applications. Finally, science outreach and dissemination activities were also organized, but mostly in the shutdown period. In some weeks, more than one experiment were running in parallel: grouping not conflicting activities has been necessary for optimizing the shorter running period in the 2017. Therefore, in the following we briefly describe activities divided as follows: users beam time, control system development, upgrade and maintenance, irradiation, and outreach.

1.1 Users Beam Time

A good portion of these experiments was in the area of gaseous detectors for 3D tracking, aimed at the identification of secondaries and primaries with online reconstruction, using different techniques such as: GEM-based TPC (Cygnus R&D) or an innovative optical readout GEM, employing a CCD camera (ORANGE). The LNF detector development group tested a new micro-pattern detector, the μ-RWELL, while an experiment funded by the FIRB grant used the BTF beam for cluster counting and timing using a drift chamber.

Some beam-time was allocated to solid-state detectors testing, in particular for the readout monolithic active pixel sensors (MAPS) for the ALICE Inner Tracker System upgrade (ITS) with the ALPIDE chip, and for the development of a tracking system based on the MIMOSA family.

PADME shifts were mainly dedicated to the calibration and commissioning of the fast calorimeter used for vetoing the Bremsstrahlung background (see Sec.**??**). The final prototype of the MU2E un-doped cesium iodide crystal calorimeter was calibrated with the BTF electron beam, especially in the low energy regime (<100MeV), also validating the technological layout of the vacuum setup and related subsystem. The IMCP collaboration tested a new geometry of the their Micro Channeled Plate detector, operated in i-MCP mode, reaching excellent timing resolution results.

1.2 Control system development

BTF is strongly involved in the !CHAOS project, an open source software system, being developed by several INFN and private partners. Originally born within the context of High Energy Physics (HEP) as candidate of distributed detector control system (DCS) and data acquisition (DAQ), it has evolved to a prototype of a national cloud infrastructure that offers monitoring and control services also to the society and industries. The dedicated beam-time was dedicated to the development of HEP hardware DCS and some back-end subsystem (live and historical engine), where the cloud infrastructure has been intensively tested. Using the already engineered part of the !CHAOS system, the BTF staff has developed the new information technology and networked diagnostics and monitoring systems of the facility [2].

1.3 *Irradiation*

Some shifts were dedicated to the improvement of our experience in the irradiation field, in particular taking into account at the European Space Agency recommendations (ESCC guidelines) (see Sec.4), in the case of low energy electrons, as in the case of BTF secondary beam. The beam-time allowed to improve our calorimeter-based flux measurement, as well as the measurement of the transverse beam profile by using our FitPIX silicon pixel detector: our setup now allows to have a real-time monitor of both the transverse beam parameters, and particle counting from the FitPIX readout. A prototype of the cross-calibration of the calorimeter and FitPIX-based flux measurement was tested in a dedicated irradiation run for the MEG-2 collaboration, aimed at the full characterization of the I-V load curve on silicon photomultiplier sensor, which was positively performed. Subsequently, we optimized the procedure for irradiation tests for space qualification, working with a team of CERN, ESA and TRAD company, with several dedicated irradiation runs with a 100 MeV secondary electron beam. During the run the electronics device under test was irradiated with a grand-total of 4×10^{11} particles, and a number of single event upset on the DUT in good agreement with expectations was recorded.

From the point of view of primary beam irradiation, we have also used the high-intensity beam from LINAC for a radiation-hardness test of the PADME calorimeter BGO crystals. The test was aimed at detecting the creation and relaxation of color centers, a useful information for understanding the BGO crystals energy response under a very pessimistic dose, corresponding to extremely long running times of the experiment. The primary beam was also used for a short irradiation test, performed in order to test the production of ^{99m}Tc from natural Molybdenum: in particular the test was intended for validating the Monte Carlo simulation predictions for ^{99}Mo (a precursor of ^{99m}Tc) photo-production by a 510 MeV electron beam.

1.4 BTF upgrade and maintenance

The BTF scheduled maintenance lasted one week, in particular the LNF services have been working on the BTF scrapers and on the power supplies of the dipoles DHPTB101 and DHSTB001, relevant for the beam energy-selection, in order to improve field stability. In addition we performed the scheduled maintenance of the gas distribution system and its related detectors, mandatory due the high number of beam time requests for gaseous detectors. Two weeks were scheduled for BTF devices characterization and testing and irradiation detector developing, in particular dedicated to the setup of the fast-setup tracker made by FitPIX sensors, implementing a new a mirror system for the laser alignment of user devices, and for the activities related to the revamping of the Silicon strip detector of the photon-tagging facility, formerly developed for the AGILE satellite commissioning. Finally, a new version of the BTF users and public site has been developed:

http://w3.lnf.infn.it/acceleratori/btf/

http://da.lnf.infn.it/projects/btf/

1.5 Outreach

The BTF is generally fully involved in the scientific outreach program of the LNF, in 2017 we have moved this kind of activity in the shutdown period, except one week in January, assigned to a group of undergraduate students coming from Insubria National University (CO). They developed a homogeneous calorimeter, from the construction to the calibration in energy and multiplicity.

As a follow-up of the BTF education activities, in 2017 a group of high school students from the Fermo (FM) “Liceo Calzecchi Onesti” institute won the CERN “Beam Line 4 School” international competition, after a period of beam-testing and preparation, using the BTF beam (in 2016):

https://tinyurl.com/y75482lk.

BTF staff member held a public lecture to the school students on Accelerator technology and related HEP particle detector, immediately before the CERN shift:

https://tinyurl.com/ya98fsl8.

A similar lecture was given at the Insubria University, during the OFIS 2017 workshop days for High school guidance:

http://www.officinadellafisica.dsat.uninsubria.it/programma/.

For public dissemination, in synergy with the LNF SIDS service, we have prepared a 12-minutes video about LNF LINAC and BTF, aimed at a general-public explanation of our facility infrastructure and activities.

$$\texttt{https://www.youtube.com/watch?v=-x363gxjAfE}$$

In addition, during the SIDDHARTA experiment beam time at BTF, the national movie studio "Istituto Luce" produced some parts of the feature film "Conversazioni Atomiche" by director Felice Farina, with the counseling and scientific advice of BTF staff. The movie was presented in the context of the "Gravity" exhibit in Rome, a INFN and National Geographics Science Festival production:

$$\texttt{http://www.maxxi.art/en/events/conversazioni-atomiche/}$$

From the technology transfer point of view, the BTF staff contributed to the LNF open day and workshop dedicated to Industries, in particular on the topic of electron irradiation for space-qualification tests on passive and active material

$$\texttt{https://agenda.infn.it/conferenceTimeTable.py?confId=13362\#20170615}$$

2 The BTF diagnostics, monitoring and controls improvements

Proficient running at the BTF is possible thanks to a variety of services made available to the users: power supply, networking, gas system, DAQ and beam diagnostics, vacuum and cryogenics, alignment, and magnetic fields.

3 The BTF upgrades

An important upgrade program of the facility is under way, along different lines:

- consolidation of the LINAC infrastructure, in order to guarantee a stable operation in the longer term;
- optimization of the operational parameters for irradiation and high-intensity test. For this purpose an improvement of the BTF hall shielding has also been performed;
- increase of the beam pulse lenght (limited to 10 ns during DAΦNE injection and to 40 ns by the existing gun-pulsing system) in order to get higher beam intensity while keeping constant particle density;
- doubling of the BTF beam-lines, in order to cope with the significant increase of users due to the growing range of applications.

An energy upgrade of the LINAC, in order to increase the facility capability (especially for the almost unique extracted positron beam), has also been proposed: by adding four more accelerating sections in the last 15 m of drift space at the end of the LINAC should allow reaching 1 GeV with a relatively low cost.

In order to reach an energy as high as 750 MeV in 60 m of the S-band LINAC, the accelerating field is increased thanks to the compression of the radio-frequency (RF) field produced by the four klystrons by the SLED devices: their coupled resonant cavities accumulate the RF power (over an interval of 4.5 μs), until a 180° phase inversion of the input from the klystron produces an amplified transient peak of power in SLED output, leading a peak acceleration more than twice (that without SLED) in the accelerating section. The peak accelerating gradient in section could be up to 17 MV/m in the standard sections and 26 MV/m in the capture section. This is generally not an issue when producing 10 ns pulses for injection into the DAΦNE rings, but in order to accelerate much longer trains of 2856 MHz micro-bunches the overall beam loading effect from the tail of the pulse to the head should be compensated.

3.1 LINAC consolidation and beam pulse extension

An extensive maintenance program has been performed on all the LINAC components, in particular on the four RF power stations. Several components such as filter capacitors, thyratrons and high power pulse discrete elements have been replaced, and a newly designed RF driver system has been installed, in order to achieve a better stability of the delivered power. In critical parts, like waveguides downstream the SLEDs, additional pumps with higher pumping speed have been added, in order to reduce discharge occurrences. All the ceramic windows, placed downstream the klystron ones to decouple the LINAC vacuum, have been substituted. The LINAC control system has been revised in order to be compatible with the new network infrastructure. Also the control of the cooling has been upgraded to a new PLC-based system, together with a revision of the water ducts, flux-meters and water pumping system of the primary cooling system (at 30° C).

A new electron gun system has been also developed and put into operation, with the main purpose of accelerating longer electron and positron macro-bunches: the existing power supply could deliver HV pulses in the range 1.5–40 ns, while the requirement for some applications, like for instance the PADME dark photon experiment, is of low-density longer beam pulses (up to several hundreds of ns).

3.2 Beam line splitting

The present BTF configuration practically makes available only a useful beam exit (parallel to the long side of the BTF experimental hall). The useful experimental area, downstream of the DHSTB02 45° dipole, is presently used for the beam-tests, and is equipped with the remotely controlled trolley, FitPIX and GEM diagnostics, scintillator hodoscope, and so on. The exit at the end of the straight beam line (receiving beam when DHSTB02 is off), which points towards the lateral wall of the hall, is currently used for high-intensity electron runs, typically with the neutron production target, and as photon exit with the tagged photon source

The idea for the new layout is schematically shown in Fig. 2: a beam-splitting magnet (the 15° dipole DP01), wrapped around a double-exit pipe, can drive beam pulses from the upstream BTF beam-line alternatively to the two new lines. This dipole can be connected to a pulsed power supply for a fast switch between the two lines.

In order to have sufficient space and to allow bending the beam towards the former control room, it has to be placed as close as possible to the entry point of the BTF vacuum-pipe in the present experimental hall. One line will be turned by 45° using the existing DHSTB02, in a configuration very similar to the existing BTF line. The available space will be only slightly reduced in the transverse direction with respect to the beam to a useful surface of about 3×6 m^2.

The second, new line, will be further bent (by two additional 45° dipoles) in order to enter the former control room close to the intersection of the two perpendicular walls of the control room. A hole in the wall separating the two rooms should be realized. Since the entire area has a kind of L-shape, an additional angle will be needed in order to complete the 90° turn, thus directing the beam parallel to the long side of the second hall, by means of a last dipole (DC01).

In order to preserve the beam quality, to this basic configuration quadrupoles and correctors have been added, after a careful optimization of the optics of the two lines with MAD-X and with G4beamline codes.

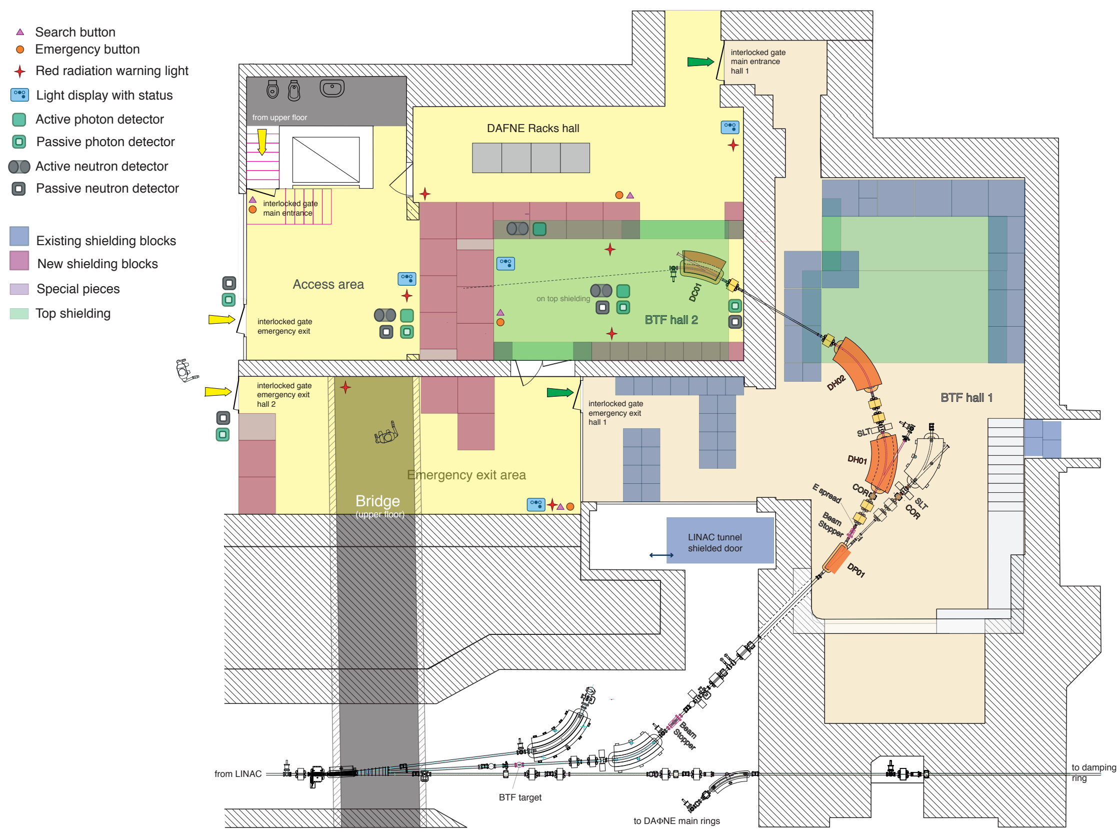

Figure 2: *The new BTF layout with two beam-lines and two experimental areas.*

In order to use the new experimental area, the present control room should has to be dismantled and moved in some other place, and an adequate shielding should be foreseen. Taking into account that the new room has to be shielded with concrete blocks as the existing one, and considering a depth of 1 m, the useful surface in this new hall will be of about 3×5 m^2. Preliminary calculations show that this kind of shielding, covered by a concrete beam roof, will allow keeping the dose outside of the restricted area below the required level of 0.6 mSv/year (0.1 μSv/h for 6000 hours of operation).

4 Irradiation

The main requirements for running the BTF as an electron irradiation facility are the following:

- High fluence of electrons of well defined energy (10%) over a wide range: down to few tens of MeV and up to the GeV range;
- Uniformity of irradiation over a $\mathcal{O}(\mathrm{cm}^2)$ surface within 10%;
- Determination of the dose with an uncertainty better than 10%.

The present BTF beam quality is adequate, provided that a better and calibrated fluence and uniformity diagnostics is provided to the irradiation users, as required, for instance, by ESA ESCC (European Space Component Coordination) guidelines. Preliminary studies of the defocussed beam, in order to control the uniformity at the required level, demonstrate that BTF can be qualified quickly as an irradiation facility, suitable for space qualification. Preliminary contacts with the Italian Space Agency (ASI) have been established, in order to both qualify the BTF as a facility recognized by ESA, and to include it in a network of Italian irradiation facilities for space (ASIF). With similar purposes, BTF is also included in the NASA-SSERVI solar system exploration program, in collaboration with the American space agency and the Frascati spatial qualification laboratory (SCF-LAB).

5 AIDA-2020

The BTF is part of the Horizon 2020 project AIDA-2020, GA no. 654168, in particular in the Work-Package 15 the task 15.4 is aimed at achieving “Improvements of the test beam infrastructure at INFN-LNF”.

6 List of papers by BTF users in 2017

1. B. Panico *et al.*, “The HEPD apparatus for the CSES mission,” PoS EPS-HEP2017 (2017) 509.

2. D. Pinci *et al.*, “Cygnus: development of a high resolution TPC for rare events,” PoS EPS-HEP2017 (2017) 077.

3. S. M. Hughes, “Fast timing hodoscope for CLAS12 and the first measurement of the $\gamma p \to \omega\pi\pi p$ decay channel,” Ph.D. Thesis U. Edinburgh (2017).

4. A. Anastasi, “The Calibration System of the E989 Experiment at Fermilab,” Ph. D. Thesis Univ. Messina (2017).

5. V. Kozhuharov *et al.*, “PADME: Searching for dark mediator at the Frascati BTF,” Il Nuovo Cimento 40 C (2017) 192.

6. V. Scherini *et al.*, "Search for the Dark Photon with the PADME Experiment at LNF," arXiv:1712.01936 [hep-ex].

7. R. de Sangro *et al.*, "Experimental result on the propagation of Coulomb fields," J. Phys. Conf. Ser. 845 (2017) 012015.

8. V. C. Antoci *et al.*, "Carbon nanotubes as target for directional detection of light WIMP," arXiv:1707.02549 [physics.ins-det].

9. M. Raggi *et al.*, "Performance of the PADME Calorimeter prototype at the DAΦNE BTF," Nucl. Instrum. Meth. A 862 (2017) 31.

10. M. Marafini *et al.*, "ORANGE: A high sensitivity particle tracker based on optically read out GEM," Nucl. Instrum. Meth. A 845 (2017) 285.

11. A. Besson *et al.*, "From vertex detectors to inner trackers with CMOS pixel sensors," Nucl. Instrum. Meth. A 845 (2017) 33.

12. A. Anastasi *et al.*, "Electron beam test of key elements of the laser-based calibration system for the muon $g-2$ experiment," Nucl. Instrum. Meth. A 842 (2017) 86.

13. E. Baracchini *et al.*, "Negative ion Time Projection Chamber operation with SF6 at nearly atmospheric pressure," arXiv:1710.01994 [physics.ins-det]

14. R. Assiro *et al.*, "Performance of the diamond active target prototype for the PADME experiment at the DAΦNE BTF," arXiv:1709.07081 [physics.ins-det].

15. M. Bonesini *et al.*, "The construction of the Fiber-SiPM beam monitor system of the R484 and R582 experiments at the RIKEN-RAL," JINST 12 (2017) C03035.

16. O. Atanova *et al.*, "Measurement of the energy and time resolution of a undoped CsI + MPPC array for the Mu2e experiment," JINST 12 (2017) P05007.

17. A. Yu. Barnyakov *et al.*, "Micro-channel plates in ionization mode as a fast timing device for future hadron colliders," JINST 12 (2017) C08014.

18. V. Puill *et al.*, "The CpFM, an in-vacuum Cherenkov beam monitor for UA9 at SPS," JINST 12 (2017) P04029.

7 List of papers by BTF authors in 2017

1. P. Valente *et al.*, "DAΦNE BTF Improvements of the Transverse Beam Diagnostics," JACoW-IPAC2017-MOPAB061.

2. P. Valente *et al.*, "Long beam pulses with SLED compression in DAΦNE LINAC," J. Phys. Conf. Ser. 874 (2017) no.1, 012017.

3. P. Valente, "Status of positron beams for dark photons experiments ," EPJ Web Conf. 142 (2017) 01028.

References

1. Paolo Valente et al. Linear Accelerator Test Facility at LNF. 2016.

2. B. Buonomo, D.G.C. Di Giulio, L.G. Foggetta, and P. Valente. A hardware and software overview on the new btf transverse profile monitor. In *Proc. of International Beam Instrumentation Conference (IBIC'16), Barcelona, Spain, Sept. 13-18, 2016*, number 5 in International Beam Instrumentation Conference, pages 819–822, Geneva, Switzerland, Feb. 2017. JACoW. doi:10.18429/JACoW-IBIC2016-WEPG73.