DIAGNOSTICS FOR HIGH POWER TARGETS AND DUMPS

E. Gschwendtner, CERN, Geneva, Switzerland

Abstract

High power targets are generally used for neutrino, antiproton, neutron and secondary beam production whereas dumps are needed in beam waste management. In order to guarantee an optimized and safe use of these targets and dumps, reliable instrumentation is needed; the diagnostics in high power beams around targets and dumps is reviewed. The suite of beam diagnostics devices used in such extreme environments is discussed, including their role in commissioning and operation. The handling and maintenance of the instrumentation components in high radiation areas is also addressed.

INTRODUCTION

Beam diagnostics around high power targets and dumps is a crucial tool to secure safe operation of these facilities, and thus to assure an important part of the scientific program at accelerators worldwide. Therefore, beam diagnostics is an important part of the beam safety and interlock system.

Beam diagnostics in this harsh environment must be designed to withstand the high radiation for the predicted lifetime of the targets and dumps in these facilities. Repair and exchange of the equipment is usually not possible in the traditional way using direct interventions and the design of the instrumentation has to include remote handling instead.

High Power Target Facilities Requirements

The requirements on the stability and lifetime of today's high power targets are extremely demanding as the design of these targets approaches their mechanical limit. Therefore the objectives for the beam diagnostics of high power targets is firstly to protect the targets from any beam-induced damage to the target system, and secondly to make sure that the quality of the secondary particle production is assured. Table 1 shows beam facilities where targets are used to produce secondary beams: T2K, NuMI/Nova and CNGS are neutrino beam facilities, SINQ, ISIS, SNS and ESS are neutron spallation sources and CEBAF is a high-power electron beam facility.

Table 1: Examples for Facilities with Strong Requirements on the Diagnostic System for the Target

Facility	**Beam**	**Beam Energy**	**Beam power**	**Energy/ pulse**
T2K	p	30 (50) GeV	750 kW (4MW)	0.4 MJ / -
NuMI/ Nova	p	120 GeV	320/700 kW	0.7/0.9 MJ
CNGS	p	400GeV	510 kW	3.1 MJ
SINQ (PSI)	p	0.59 GeV	1.2 MW	DC (50 MHz)
ISIS (RAL)	p	0.8 GeV	160 kW	3 kJ (50 Hz)
SNS	p	1 GeV	1.4 MW	23 kJ (60 Hz)
ESS	p	2.2.5 GeV	5 MW	360 kJ (14 Hz)
CEBAF	e^-	6 GeV	1 MW	DC

High Power Dump Facilities Requirements

Beam dumps are needed for the safe disposal of used beams. They are crucial to ensure safe machine operation and to protect the machine in case of any failure: unstable beams must be safely dumped before they can damage any equipment in the accelerator. Table 2 shows examples of accelerator facilities with dumps where high power beams are deposited. PEPII, ILC/CLIC and LHC are colliders; FLASH and XFEL are high brilliance X-ray facilities.

Beam diagnostics for dumps are needed to make sure that the beam dump is well protected and also to check the quality of the entire beam dump system. The beam diagnostics in dump areas also have strict requirements in terms of radiation hardness.

Table 2: Examples of Facilities with Strong Requirements on the Diagnostic System for Dumps

Facility	**Beam**	**Beam Energy**	**Beam power**	**Energy/ pulse**
PEPII	e^-	9(e^-)/ 3.1(e^+) GeV	n.a.	-
ILC/ CLIC	e^-	0.5/1.5 TeV	18/14 MW	3.6/0.28 MJ
LHC	p	7 TeV	n.a.	360 MJ
FLASH	e^-	1.25 GeV	50 kW	20kJ (5 Hz)
XFEL	e^-	20 GeV	2x300 kW	60 kJ (10 Hz)

DIAGNOSTICS FOR HIGH POWER TARGET FACILITIES

The beam diagnostics for targets is usually comprised of beam position monitors to make sure that the beam hits the target in the correct place (usually the center), as well as beam profile and intensity detectors to ensure that the beam density on the target is smoothly distributed and safely below the failure limit of the target. Secondary beam instrumentation depends on the type of particles required in the secondary beam line.

Some examples of beam diagnostics in the vicinity of high power targets such as in the CNGS and SNS facilities will be presented in the following sections, while an example of a remote exchange of beam monitors is illustrated through an example in the T2K facility.

CNGS – Primary Beam Line

The CNGS target (graphite target rods of 5mm and 4mm diameter) must be hit very accurately in order to prevent any excessive mechanical stress, which could result in breaking the rods. The allowed tolerance on the target beam positioning is +/-0.5mm [1]. In the proton beam delivery line there are eight beam profile monitors, 23 beam position monitors and 22 beam loss monitors installed. While the profile monitors are mainly used for setting up the line, the BPM and BLM systems form an integral part of the beam interlock system. Either system can inhibit further extraction if the losses or position are out of tolerance.

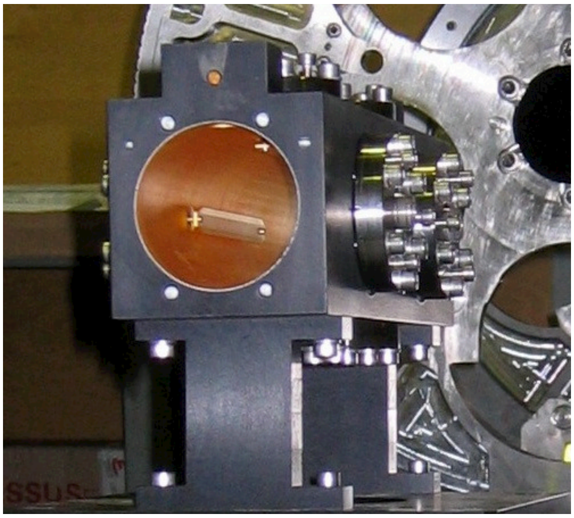


Figure 1: CNGS strip-line pick-up beam position monitor operated in air and installed directly in front of the CNGS target on the target table.

The last beam position monitor in the CNGS proton beam line is installed just upstream of the CNGS target, on the target table itself. The radiation level at this location exceeds 5E6 Gy/yr, requiring a robust monitor. As the proton beam has already exited the main delivery line through a beryllium window by this point, it was decided to use an electromagnetic strip-line pick-up monitor operated in air [2], rather than a monitor under vacuum, which would have required additional vacuum pumps and diagnostics. An electromagnetic pick-up was chosen rather than an electrostatic pick-up due to its insensitivity to signals produced through ionization of the air. Special care was taken to use radiation hard materials including ceramic-insulated cables (LHC BPM technology) and materials that minimized levels of induced activation and corrosion. The achieved resolution of this monitor is better than 0.1mm and the absolute precision is about 0.2mm. This complies well with the requirement on the trajectory tolerance of +/-0.5mm for the last monitors upstream of the target. After 4 years of physics running and delivery of more than 2/3 of the approved protons on target, this monitor still performs well.

CNGS - Secondary Beam Line

A new ultra-fast diagnostic tool was installed in the CNGS facility in 2011 following the initial “faster than light neutrino” results. Several pCVD diamond detectors with typical dimensions of 0.3x8x8mm^3 were placed in the secondary beam line ~1200m downstream of the CNGS target in order to measure the time structure of the muons which are produced together with the muon neutrinos. This allowed an accurate measurement of the GPS timing of individual secondary particle bunches crossing these detectors, and provided an independent timing measurement at CERN, which has previously been based solely on the fast beam current transformers installed in the primary proton beam line upstream of the CNGS target. The measurements revealed that the GPS timing measurement performed at CERN is consistent between these two types of monitors.

SNS

The liquid mercury target at the Spallation Neutron Source SNS was initially designed to be operational for an integrated power of 2500MWh, or 2500hrs of 1MW operation [3]. At one Megawatt beam power, one of the main critical points for this type of target is the pitting damage due to the collapse of cavitation bubbles in the mercury. The damage of the target scales much faster than linear with the beam power density and it is therefore critical to measure and control the proton beam intensity, and more particularly the beam distribution on the target, in a region of extremely high radiation and very limited accessibility.

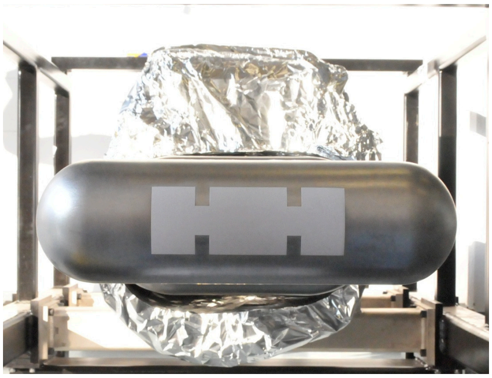


Figure 2: SNS Target Imaging System: luminescent Al_20_3:Cr coating on the water shroud of the liquid mercury target. Pattern size is 0.25x70x200mm^3 [5].

The beam on target imaging system has a flame-sprayed coat of Al_20_3:Cr luminescent material on the water shroud of the target (see Fig. 2). The footprint of the beam on target is nominally, for safe operation, 70x200mm^2. The photon yield is 20 photons/protons/steradian [4].

The photons are reflected upward from a convex mirror mounted close to the proton beam window through a viewport to a turning mirror and lens mounted on the top of a 1m thick the proton beam window shielding plug. From there a fiber bundle consisting of 20000 [6] radiation hard optical fibers transfers the image over 11.5m to a CCD camera.

Fig. 3 shows the display of the target imaging system [7] in the control room. The tolerance on the beam centroid under normal conditions is +/-4mm and using the target imaging system, it is usually controlled to within approximately +/-1mm [8]. Operational experience shows that the mirror optics survives beyond the lifetime of the beam window assembly and that the coating lasts for the lifetime of the target. The accuracy on the peak intensity measurement is of the order of 20% with work ongoing to improve it.

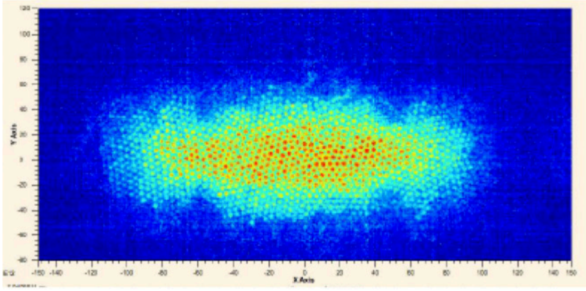


Figure 3: SNS target-imaging system with the display in the control room [6].

T2K

Due to the high radiation levels in the T2K target area, the facility was designed with remote handling capacities in mind, in close collaboration with TRIUMF and RAL for maintenance, repair and exchange of equipment. The T2K target area includes the target and three horns and is embedded in a Helium-vessel with iron and concrete shielding above the equipment [9]. The remote exchange system of the final focus section beam monitors is in vacuum and includes the proton beam window [10]. This section is located only 1m upstream of the Helium vessel (see Fig 4).

Two segmented secondary emission foils (SSEMs) and one electrostatic beam position monitor are installed on the monitor stack on a 4.2m iron-shielding plug.

Any manipulation on the monitors can only be performed after an appropriate beam cool-down and using a remotely controlled crane, which hoists the shield plug with the beam monitors and transfers it to a nearby hot-cell. The monitor replacements are actuated from top of the shield plug with a mechanical clamp and screw draw-bolt engagement. The replacement alignment accuracy of the diagnostic monitors after a full exchange procedure is +/– 0.1mm.

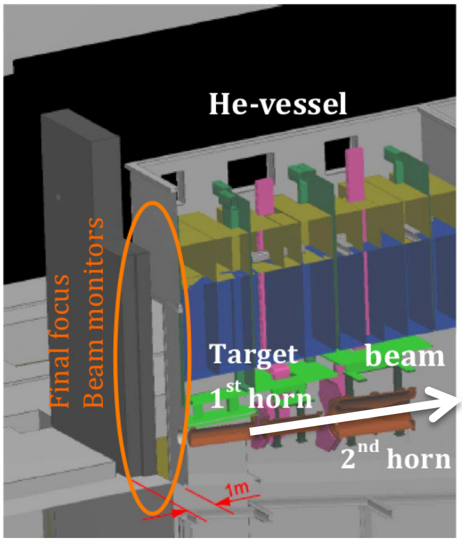


Figure 4: T2K final focus section where two SSEMs and one static BPM are installed.

DIAGNOSTICS FOR HIGH POWER DUMP FACILITIES

Beam diagnostics instrumentation for high power dumps often have to cover unusually large areas as the beams are often blown-up to a big size in order to reduce the deposited energy density on the dump. Typical beam detectors include screens to measure the beam profile on the dump, e.g. when the beam is painted across the dump, and beam loss monitors, beam position monitors and beam halo monitors to ensure the quality of the dumping system.

Examples of interesting beam diagnostic monitors in the beam dumping system near the LHC and FLASH beam dumps will be discussed in later sections.

LHC

The LHC beam dump system is a critical component of the machine protection system and is designed to safely extract the beam with proton energies ranging from 450 GeV to 7 TeV and a total beam energy up to 360 MJ. After every dump the *eXternal Operational Checks (XPOC)* system automatically analyzes the different signals of the beam dump system including associated beam instrumentation measurements [11]. This includes verification of:

- the extraction and dilution kicker waveforms
- the beam position monitors in the dump line which also give the total number of bunches extracted
- the beam intensities in the dump line
- the beam loss monitors in the extraction region, in the dump line and at collimators distributed over the machine
- the beam population in the 3µs abort gap required to accomodate the extraction kicker rise-time

- the vacuum pressure in the dump line and the nitrogen (over)pressure in dump itself
- the beam image on the scintillation screen just in front of the dump.

This analysis ascertains that the beam dumping system performed as expected and is 'as good as new' before any new proton beam injection [12]. If the XPOC analysis fails, or has a negative result, the next injection is disabled and an expert is required to re-enable the system.

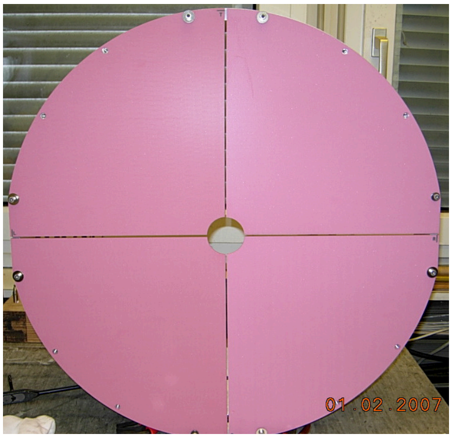
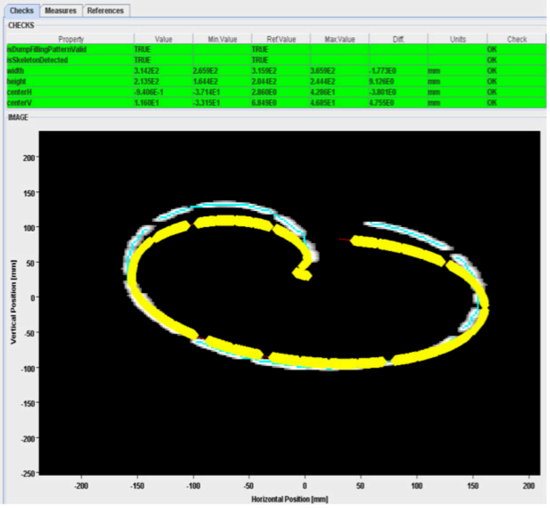


Figure 5: LHC large luminescence screen installed 30m upstream of the dump vacuum window. The 600mm diameter big screen is made of $Al_2O_3:Cr^{3+}$ and produced in four quadrants.

The beam observation screen closest to the beam dump is a high sensitivity, thermally resistant 3mm thick chromium doped aluminum ($Al_20_3:Cr$) radiation hard screen with a diameter of 600mm, a hole of 50mm in the middle and made of four quadrants (see Fig.5) [13]. As the central part could be damaged in case of total dilution kicker failure, the central portion of the detector behind the hole is designed in such a way that it can be replaced. The screen together with a radiation hard CCD camera is installed 30m upstream of the exit vacuum window.



Property	Value	Min.Value	Ref.Value	Max.Value	Diff.	Units	Check
isDumpFillingPatternValid	TRUE		TRUE				OK
isSkeletonDetected	TRUE		TRUE				OK
width	3.142E2	2.659E2	3.159E2	3.659E2	-1.773E0	mm	OK
height	2.135E2	1.644E2	2.044E2	2.444E2	9.126E0	mm	OK
centerH	-9.406E-1	-3.714E1	2.860E0	4.286E1	-3.801E0	mm	OK
centerV	1.160E1	-3.315E1	6.849E0	4.685E1	4.755E0	mm	OK

Figure 6: Beam dilution measurements (white) of a 4 TeV LHC beam as measured with the beam screen in the dump line. The yellow curve shows the simulated curve.

The dilution kickers provide a sweeping deflection spreading the extracted beam over a 400mm diameter area on the face of the beam dump. This reduces the beam density from ~10^{15} p/mm^2 to ~10^{11} p/mm^2. Fig. 6 shows a typical profile of a well-painted 4 TeV LHC beam as measured with the beam screen on19 April 2012. The white curve is the measured and the yellow curve is the expected beam profile.

This beam observation screen is a crucial tool to perform an immediate 'on-line' diagnosis of the quality of the beam dump system.

Experience to date shows that the best measurement results are achieved when the images are taken up one second after the beam passage, to avoid radiation effects of the camera at the moment of the beam passage.

FLASH

FLASH, *A Free electron LASer in Hamburg*, delivers intense ultra-short femtosecond coherent radiation in the wavelength range between 44nm and 4.1nm to user and test facilities. The facility is also used for beam tests, for XFEL and ILC, which require long bunch trains (~800µs). All these beams need to be safely dumped. In 2008 the incorrect positioning of these long, high-current electron beam pulses on the beam dump led to damage and a subsequent vacuum leak.

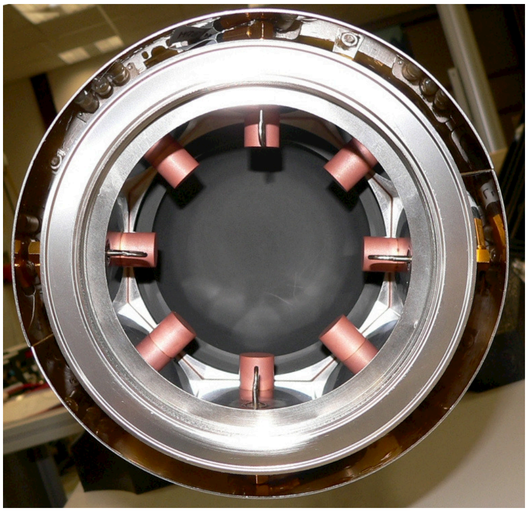


Figure 7: The eight beam halo monitors in the FLASH facility installed inside caps and placed alternately around the beam pipe downstream the beam dump window.

Additional beam position monitors have therefore been installed to better monitor the position and prevent such damage re-occuring. Beam halo monitors (BHMs) were also installed and commissioned in 2009 to ensure that even the beam halo is minimised and stays inside the beam pipe close to the beam dump [14]. The BHM system consists of four 500µm thick artificial mono-crystalline sapphire sensors and four 300µm thick pCVD diamond sensors, all with an area of 12x12mm^2 [15]. They are placed inside caps mounted inside the beam pipe, in an alternating fashion as shown in Fig. 7.

The detectors see clear signals as soon as even a small fraction of the beam approaches the sensors. The diamond sensors are more sensitive than the sapphire detectors, but quickly saturate, while the sapphire still show good signals for higher intensities, enhancing the overall dynamic range of the system.

The BHM system is also designed for FLASHII and XFEL, where it will be installed outside the beam vacuum pipe.

SUMMARY

Using a few examples, the particularities of beam diagnostic equipment near high intensity target and dumps have been described. The common feature of all the facilities considered is the high radiation environment and a very close link between the beam diagnostics and the interlock systems used to guarantee the safety of the target and dumps. The solutions adopted for beam monitoring very much depend on the characteristics of each facility. In specific cases, redundancy by installing a large number of monitors is required. In other examples, remote handling and repair or replacement of monitors in hot cells – with minimal exposure to staff - is the only acceptable solution. In all scenarios, developments towards more radiation hard materials (e.g. diamonds) or towards optical signal transmission to monitors (cameras) in well shielded areas are very valuable contributions. The accumulated experience in remote handling from existing facilities is crucial to ensure the fail-safe design of shielding/transport solutions for future target and dump region designs.

ACKNOWLEDGMENT

Very special thanks go to all colleagues who helped in preparing this paper: Oliver Aberle, Marco Calviani, Konrad Elsener, Alexandr Ignatenko, Rhodri Jones, Thibaut Lefevre, Thomas McManamy, Etam Noah Messomo, Hermann Schmickler, Thomas Shea, Jan Uythoven.

REFERENCES

[1] E. Gschwendtner et al., “Performance and operational experience of the CNGS facility”, IPAC2010, Kyoto, Japan, 2010, THPEC046, CERN-ATS-2010-153.

[2] T.Bogey, R. Jones, “Beam Position System of the CERN Neutrino to Gran Sasso proton beam line”, CERN-AB-2007-024 BI, 2007.

[3] P. Ferguson, “Status of the SNS,” presentation at the International Collaboration on Advanced Neutron Sources (ICANS-XX), Bariloche, Rio Negro, Argentina, March 2012.

[4] T.J. Shea et al., “Status of beam imaging developments for the SNS target,” DIPAC2009, Basel, Switzerland, 2009, MOOC04, p. 38 (2009); http://www.JACoW.org.

[5] T.J. McManamy, “SNS target systems operational experience and upgrade plans”, presentation at the Workshop on Applications of High Intensity Proton Accelerators, Oct 2009, FNAL, Batavia, IL, USA, 2009.

[6] T.J. McManamy et al., “Spallation Neutron Source Target Imaging System Operation”, Proc. AccApp ’11, Knoxville, April 3-7 2011.

[7] T.J. Shea et al., “Accelerator to target diagnostics”, presentation at the workshop on non linear beam expander systems in high-power accelerator facilities, ISA, Aarhus, Denmark, March 2012, http://www.isa.au.dk/meetings/beamExpander2012.

[8] T.J. Shea et al., “Installation and initial operation of an on-line target imaging system for SNS”, Proceedings of 19th meeting on International Collaboration of Advanced Neutron Sources (ICANS XIX), Grindelwald, Switzerland, PSI-Proceedings 10-01/ISSN-Nr 1019-6447, March 2010.

[9] K. Abe et al., “The T2K experiment”, arXiv:1106.1238v2 [physics.ins-det] 8 Jun 2011.

[10] Neutrino Beams and Instrumentation Workshop, NBI2010, J-PARC, Tokai, Japan, 2010, http://www-conf.kek.jp/NBI2010.

[11] N. Magnin et al., “External Post-operational Checks for the LHC Beam Dumping System,” 13th International Conference on Accelerator and Large Experimental Physics Control System, ICALEPCS 2011, Grenoble, France, Oct. 2011, CERN-ATS-2012-11.

[12] J. Uythoven et al., “Experience with the LHC beam dump post-operational checks system,” PAC09, Vancouver, Canada, TU6RFP029, p. 159 (2009).

[13] T. Lefevre et al., “A large scintillating screen for the LHC dump line,” DIPAC07, Venice, Italy, TUPB28, p. 132 (2007).

[14] N. Baboi et al., “New Electron beam diagnostics in the beam FLASH dump line,” BIW10, Santa Fe, New Mexico, USA, 2010, TUPSM093, p. 420 (2010); http://www.JACoW.org.

[15] A. Ignatenko et al., “The beam halo monitor for FLASH,” DIPAC2011, Hamburg, Germany, 2011, TUPD41, p. 395 (2011); http://www.JACoW.org.