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OVERVIEW AND STATUS OF DIAGNOSTICS FOR THE ESS PROJECT

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Abstract

The European Spallation Source, now under construction in Lund, Sweden, aims to be the world's most powerful pulsed neutron scattering facility. Driving the neutron source is a 5 MW superconducting proton linear accelerator operating at 4 percent beam duty factor and 14 Hz repetition rate. Nineteen partner institutions from across Europe are working with the Accelerator Division in Lund to design and construct the accelerator. The suite of accelerator instrumentation consists of over 20 unique system types developed by over 20 partners and collaborators. Although the organizational complexity presents challenges, it also provides the vast capabilities required to achieve the technical goals. At this time, the beam instrumentation team is in transition, completing the design phase while scaling up to the deployment phase. Commissioning of the ion source has commenced in Catania, preparations for installation on the Lund site are ramping up, and basic R&D on target instrumentation continues. Beam commissioning results from the systems immediately following the ion source will be presented, along with technical highlights and status of the many remaining instrumentation systems.

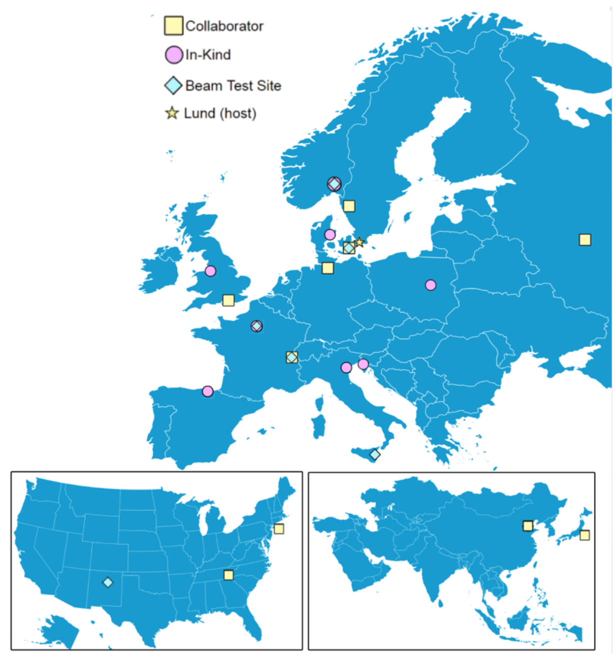

Figure 1: Map of In-kind partners, collaborators, and test sites.

OVERVIEW

The Project Organization

Like the ESS project itself, the beam diagnostics project is executed by an international partnership. Figure 1 illustrates the breadth of this organization, consisting of in-kind contributors from partner countries, collaborators that participate via memorandum or contract, and finally, several institutes that provide beam test facilities. From this partnership of over 20 institutions, all designs, components and completed systems are eventually delivered to the host facility, ESS in Lund, Sweden.

The Diagnostic Suite

As itemized in Table 1, the beam diagnostics team will deliver a comprehensive suite of instrumentation that supports commissioning and operations of the ESS accelerator. Reading from left to right in the table, the devices are deployed in the 75 keV transport line (LEBT) following the ion source, in the normal-conducting section ending with the drift tube linac (DTL), in the superconducting section ending with the high beta linac (HBL), and finally in the transport lines to the tuning dump and the target.

MEASUREMENT CAPABILITIES

The diagnostic systems provide three categories of measurement, the first being beam accounting. Throughout the machine, various diagnostic devices measure the beam current and where it is lost, starting from constituents of beam extracted from the ion source, then the proton current and losses throughout the accelerator, and finally the beam leaving aperture in the region of the tuning dump and the target.

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Table 1: Inventory of Diagnostics Throughout the ESS Machine

System	LEBT	RFQ	MEBT	DTL	Spk	MBL	HBL	HEBT	A2T	DumpL	TOTAL
Position	0	0	7	15	14	9	21	16	12	4	98
Ionization profile	0	0	0	0	1	3	1	0	0	0	5
Fluorescence profile	1	0	2	0	0	0	0	0	1	0	4
Ionization chamber	0	0	0	5	52	36	84	49	37	6	269
Neutron detector	0	0	5	11	14	4	0	1	0	0	35
Wire scanner	0	0	3	0	3	3	1	3	1	0	14
Bunch Shape	0	0	1	0	1	1	0	0	0	0	3
Faraday cup	1	0	1	2	0	0	0	0	0	0	4
Current monitor	1	1	4	5	0	1	1	2	3	2	20
Emittance	1	0	1	0	0	0	0	0	0	0	2
Aperture monitor	0	0	0	0	0	0	0	0	3	1	4
Doppler	1	0	0	0	0	0	0	0	0	0	1
Multi-wire grid	0	0	0	0	0	0	0	0	1	0	1

With beam accounted for, instrumentation from the other two categories, centroid measurements and distribution measurements provide a more detailed characterization of the beam properties.

Beam Accounting

Doppler System The Doppler system measures the species fraction with a non-intercepting technique based on neutralization of ion beam particles passing through the residual gas [1–3]. It was used for the characterization of the high intensity beams at ATP and LEDA [4], on the LEBT lines at SILHI, IFMIF and ESS [5], and also for the characterization of neutral beams in tokamaks [6]. The instrument is composed of a high sensitivity and high resolution spectrometer[1], a 25 m long fiber bundle in a round end to linear end configuration, and an optimized lens coupling assembly matching the geometry imposed by the viewport of the vacuum tank. Through the viewport, the spectrometer acquires a spectrum of the beam luminescence at 14 Hz, triggered by the machine timing system. Each spectrum is analyzed to deliver a species fraction measurement.

The instrument has been delivered and commissioned on the ESS source at INFN in Catania. It met the design performance, and by adjusting the spectrometer exposure and the trigger delay, it performs not only single shot measurements, but also intra-pulse measurements. The details of the measurement performance have been published elsewhere [7], and a typical spectrum is presented in Figure 2.

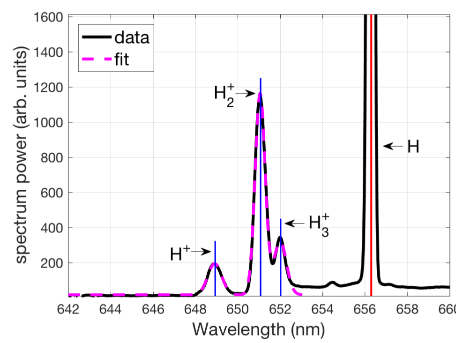

Figure 2: Typical spectrum from the Doppler system showing the Balmer α ray and Doppler shifted rays of H, H_2 and H_3. The vertical lines are positioned using the Doppler shift equation, the mass and energy of the species, and the geometrical angle of observation.

Beam Current Monitors The Beam Current Monitor (BCM) system in total consists of 20 sensors: 18 AC Current Transformers and 1 Fast Current Transformer all from Bergoz, as well as one specially instrumented position monitor electrode that is planned for bunched beam current measurements downstream of the MEBT chopper. Most of the sensors will be provided by the ESS in-kind partners as integral parts of the different linac sections. As with most other diagnostic systems, the BCM electronics is based on the MicroTCA.4 platform, and in this case will include a Struck SIS8300-KU as the digitizer. An external, custom front-end unit provides a calibrator, a remote sanity check, signal conditioning and a redundant power module [8]. Signal processing functions, implemented on a Field Programmable Gate Array (FPGA), provide machine protection and beam monitoring functions and has been developed together with DESY and Cosylab. It is currently being tested and verified at ESS. An AC Current Transformer and an early version of the MTCA-based electronics were deployed in Catania to measure the current of the 75 kV ion source power supply. Although not a direct measurement of extracted proton beam current, the results in Figure 3 demonstrate that the system can meet performance requirements in an accelerator environment.

Like the other systems responsible for machine protection, the BCM system must provide low latency. To keep latency

[1] Shamrock500i with a cooled CCD camera Newton 920, from ANDOR

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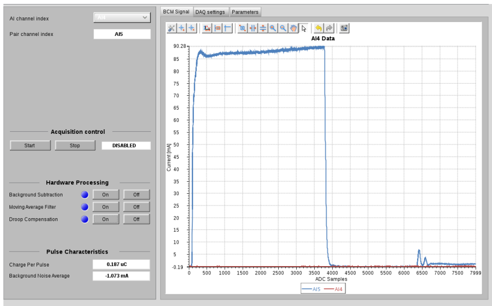

Figure 3: Current of the power supply extracting a beam pulse from the ESS ion source.

below 2 µs, the system uses fast ADCs running at 88 MSa/s, FPGA-based processing, short cables and fast analog electronics. The ADC data is low-pass filtered and decimated in the FPGA, thus resulting in a sample rate of 11 MSa/s with the advantage of reducing noise and data traffic on the network, and without compromising the useful bandwidth of 1 MHz. Also, data at the full sample rate is buffered in local memory for test and data-on-demand purposes. Future improvements include an optical link for differential current measurement over large distances, automatic setting of the machine protection parameters based on the machine state, and automatic calibration.

Faraday Cups The Faraday cups primarily provide destinations for the beam in the normal conducting linac during start up and tuning operations. Particularly at low energies, they also measure the current with reasonable accuracy. The LEBT Faraday cup was fully commissioned in late 2016, and this Faraday cup is the only one able to handle the full ESS beam duty factor. PANTECHNIK designed and constructed this Faraday cup based on ESS specifications. The other Faraday cups are able to withstand a small fraction of the beam power and will be used more as beam stops. ESS-Bilbao has designed the MEBT Faraday cup and began the fabrication process in mid-2017. At the time that this paper was written, the two other Faraday cups located in the DTL are still under design at ESS.

Beam Loss Monitors Loss of even a small fraction of the intense ESS beam could result in significant radiation and destruction of accelerator equipment. The Beam Loss Monitor (BLM) systems are the only diagnostics capable of detecting the smallest fraction of beam loss, approaching parts per million, that could activate machine components and prevent hands-on maintenance. Two types of detectors will be deployed, each providing unique capabilities. The first type is an ionization chamber (ICBLM) that provides a simple and proven detector, but lacks the ability to discriminate against background from the accelerating structures. The second type is a neutron detector (nBLM) of higher complexity, but with the ability to discriminate between neutrons produced by loss of even low energy protons, and photons produced by field emission in the cavities. Monte Carlo simulations are used to optimize the locations of the detectors, such that coverage and redundancy are provided for machine protection purposes, and spatial resolution is provided for diagnostic purposes [9].

The ICBLM detectors are parallel-plate gas ionization chambers developed by CERN for LHC and manufactured and tested at the Institute for High Energy Physics, Protvino, Russia. They are chosen for the ESS linear accelerator due to their fast response, stable gain, robustness against aging, large dynamic range (about 8 decades), and the low required maintenance. The ICBLM detector is very sturdy, its radiation resistance is very good.

As shown in Table 1, ICBLM detectors are located throughout the accelerator, and the total quantity is high enough to afford some redundancy. Adjustable mounts will allow refinement of the layout based upon initial operational experience. 285 detectors were received at ESS in July 2017 and are now under reception and calibration tests [10].

The baseline for the ICBLM readout electronics is an 8-channel, 20-bit commercial-off-the-shelf picoammeter in MTCA format. Its full-scale ranges of 500 µA and 10 mA, together with a 300 kHz input bandwidth ensure it fulfills ESS requirements. A complete evaluation of this readout solution is being performed by the Beam Diagnostics team in Lund and Figure 4 depicts an example of the test results. An alternative solution involving a custom acquisition crate equipped with the latest CERN BLEDP prototype is being evaluated. Two BLEDP acquisition cards have been received at ESS, featuring an advanced current-to-frequency converter covering the 10 pA to 30 mA range. To support testing in the ESS controls environment, a readout has been implemented with an FPGA-based platform in MTCA. A double width AMC HV power supply in MTCA format is being evaluated as well, giving a complete ICBLM system prototype. The final ICBLM system layout will be fixed in early 2018, and at the same time, the corresponding selection of the electronics will be made based on the evaluation results.

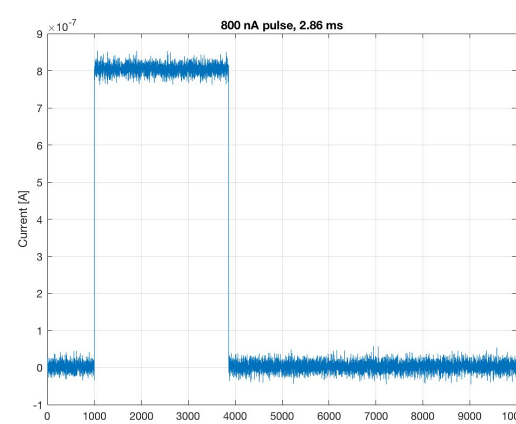

Figure 4: A test pulse corresponding to the smallest beam loss rate that the ICBLM system must measure. The signal was acquired by prototype current readout electronics.

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The nBLM detectors are based on Micromegas devices specially designed to be sensitive to fast neutrons and insensitive to low energy photons. In addition, the detectors will be as insensitive as possible to thermal neutrons. The nBLM system will complement the ICBLM systems, being optimized to operate in the low energy region of the accelerator, where almost none of the charged particles escape the vacuum envelope. The Micromegas detectors will be equipped with appropriate neutron-to-charge converters and absorbers to fulfill these requirements. Two detection techniques will be implemented: the fast detector relies on proton recoils produced by the elastic scattering of a neutron in a hydrogen-rich converter, and the slow detector uses a Boron-10 converter that moderates the neutrons first to increase the efficiency. A 3D model of the detector package is shown in Figure 5.

A total of 42 fast detectors and 42 slow detectors will be delivered from CEA-Saclay to Lund by April 2019. The layout is still being refined, with a focus on providing complete coverage in the low energy end of the linac, plus several additional channels for development purposes in the high energy end. Using ESS loss scenarios as input [9,11], Monte Carlo simulations performed with GEANT4 show that the detectors give a multiple counts within 1 μs when low energy protons are lost at a low level of 0.01 W/m. At high loss levels, the system will experience pileup and eventually transition from event mode to current mode readout. The CEA-Saclay team has commenced laboratory testing of the first prototypes and in Fall 2017, they will begin testing at different radiation facilities to study response in high radiation environments with different source particles. The final design of the detectors, the electronics and the control system will be completed by May 2018 and the foreseen installation and commissioning will start by the end of 2018.

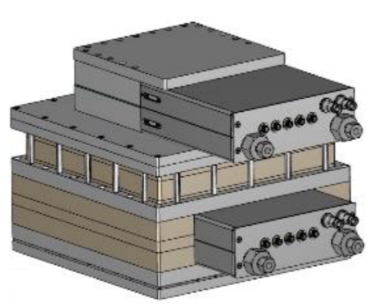

Figure 5: The neutron detector package, showing the fast detector on top and the slow detector surrounded by its polyethylene moderator below.

Aperture Monitors The Aperture Monitors measure the portion of the beam current that exits the physical aperture. They are used for tuning as well as for machine protection. The instrument detects the prompt current induced by the proton beam as it passes through metallic plates, and the slower temperature rise of low-mass temperature sensors that surround the aperture. There are 4 Aperture Monitors in the accelerator: one in front of the tuning Dump, two in the target station, and one at the final beam waist located about 20 meters upstream of the target. The first 3 are fixed in transverse position and consist of 16 Nickel plates and 12 thermal sensors surrounding the aperture. The 4th one consists of 4 movable plates and thermal sensors that can be adjusted to intercept only the halo of the focussed beam. The current induced in the plates is measured with a 300 kHz bandwidth, while the signal from the thermal sensors is constrained by thermal mass to much lower bandwidth.

Centroid Measurements

Once beam current is accounted for, the single particle understanding of the machine is verified and refined through 3D measurements of the bunch centroid, including phase and transverse position. The primary system for these measurements, and the only one distributed throughout the accelerator is the Beam Position Monitor (BPM) system. In addition, a few additional systems provide centroid measurements at locations that lack BPMs.

Beam Position Monitors The ESS linac will be instrumented with 98 BPMs, the majority of which are designed to have their peak spectral response at the beam bunching frequency. In the sections of the linac where the accelerating RF is also at the bunching frequency, the BPM receivers are tuned to the 2nd harmonic. The MEBT and the DTL BPM electrodes are shorted striplines, with those in the DTL tanks being embedded inside drift tubes. Throughout the remainder of the linac, the electrodes are buttons.

The electronics design is based on the same commercial MicroTCA.4 digitizer that is used in the BCM system, complemented by a commercial transition module and also a custom RF Front-End chassis for RF filtering, calibration and gain adjustment. The electronics can be tuned to 352 MHz or 704 MHz by selecting the proper bandpass filters and analog down-conversion local oscillator frequency.

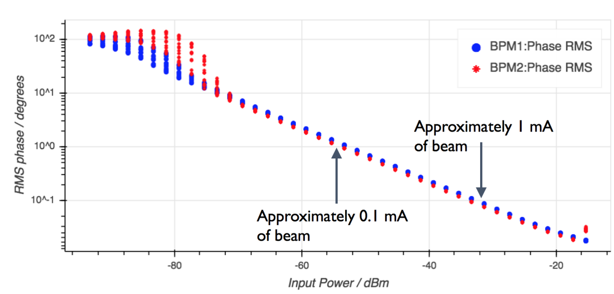

Figure 6: BPM electronics prototype results showing measured RMS phase over a range of input power.

Figure 6 shows the most recent results from a test of the prototype electronics. Performance is characterized over the range of input power expected for the ESS linac. The input power was swept over this very wide range, and the RMS of phase and other parameters for a 2 MHz readout signal bandwidth were recorded. This demonstrates that the performance meets requirements for measuring beam phase

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with respect to the Phase Reference Line (0.1 degrees RMS at nominal beam parameters).

Additional centroid measurements All of the of the systems described in the next section also provide centroid measurements, but a few merit special attention because of their unique capability or location. In the LEBT, there is no RF structure that provides a signal to the BPM system, so the Non-invasive Profile Monitors measure the transverse position. In the target station, the Grid and the Imaging systems support centering of the beam footprint.

Distribution Measurements

Beyond the centroid measurements, distribution measurements deliver the next level of detail about proton beam properties. In most cases, the cost of obtaining this detail is the need to perform invasive measurements, typically during special modes of operation that limit beam duty factor. Some systems allow measurements during full duty factor operation by employing inherently non-invasive techniques (Non-invasive Profile Monitor), by employing invasive techniques for brief periods of time (fast wire scanners), or by operating on or in a structure designed to receive the full beam current (Grid and Imaging systems).

Emittance Measurement Units Two Emittance Measurement Units (EMU) will be installed in the ESS linac. The first one is an Allison scanner in the LEBT, and is already installed and commissioned at the ion source test stand located at INFN-LNS in Catania. This EMU is able to measure the full beam power at the exit of the ion source with a time resolution of 1 µs. A time-resolved measurement result is shown in Figure 7. The second EMU will be installed in the MEBT, and it is based on slit and grid system built at ESS-Bilbao. A design concept has been analyzed and performance of the device has been predicted [12].

Bunch Shape Monitors The bunch length will be measured in the MEBT, at the transition between the warm and cold linac, and within the cold linac by utilizing 3 Bunch Shape Monitors designed and constructed by INR. The resolution of the instrument is 0.5 degrees.

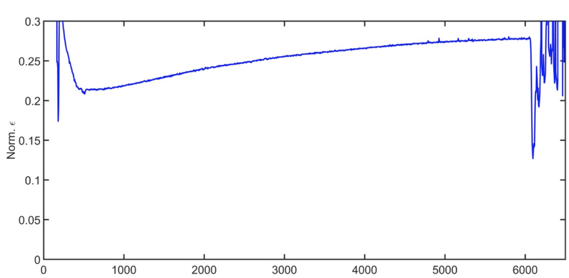

Figure 7: Time-resolved emittance of 75 keV beam measured directly after the ion source in Catania.

Invasive Profile Monitors: Wire Scanners and Grid In normal-conducting and superconducting sections of the ESS linac, 11 wire scanner systems will be installed, and for all of them, the profiles will be reconstructed by measuring the secondary emission signal from the wire. In addition, the wire scanners installed in the elliptical sections and downstream will be equipped with a scintillator in order to measure the shower created by the interaction of the beam with the wire [13, 14]. The operation of the wire scanner is limited by the thermal load on the wire, so the beam duty cycle must be reduced to preserve the wire integrity. Measurement at full beam power will be possible by using 3 fast wire scanner stations in the transport line that follows the linac. The simulation results shown in Figure 8 demonstrate that peak wire temperature stays below the melting point of carbon throughout a scan of the proton beams expected in this section of the machine. The design and fabrication of these fast wire scanners is done at CERN and the readout system will be similar to that of the other wire scanners.

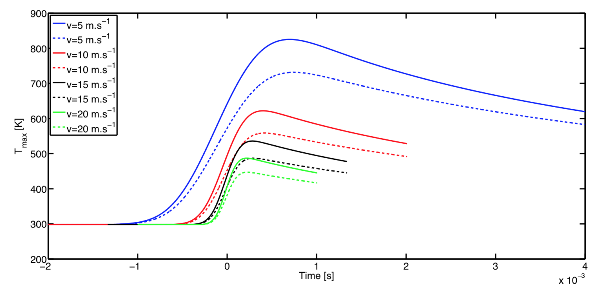

Figure 8: Simulation of wire peak temperature during a scan at 560 MeV (solid line) and 2000 MeV (dashed line) for different wire velocities.

In the target station, a multi-wire grid system is being designed at ESS, with support of collaborators from cADS, J-Parc, and SNS. The main function of the Grid is to provide two 1D profiles of the beam on target. The grid is fixed in position within the diagnostics plug in the the target monolith. Unlike the wire scanners upstream, this device only intercepts a reduced-density beam that has been prepared for delivery to the target by expansion and/or rastering. With the wire temperature moderated by the low beam current density and the resulting radiation shielded by the target monoilith, this device can measure full duty-factor beam.

Non-invasive Profile Monitors Non-invasive Profile Monitors (NPM) are designed to measure beam profiles of long pulses when the wire scanners cannot be used. For pulses at full peak current, this includes pulse lengths from 50 µs to 3 ms. There are two types of NPMs designed for the ESS. One is the Beam Induced Fluorescence (BIF) monitor based on imaging the beam-induced fluorescence of the residual gas, and the other is an Ionization Profile Monitor (IPM) based on collecting charge from beam induced ionization of the residual gas. The BIF is designed and constructed at ESS, whereas the IPM is designed and constructed by CEA-Saclay as an in-kind contribution. The first

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BIF system has been delivered for the LEBT, and is waiting for commissioning with beam [15], and the IPM prototypes are being prepared for testing in Saclay.

Imaging Imaging systems produce a 2D map of the beam's transverse current distribution on the Target and the Tuning Dump [16] and are a key component of the beam-on-target instrumentation suite [17]. They are the only instruments capable of directly measuring with the required precision the beam current footprint on Target during production. They are also sensitive enough to detect unrastered short pulses for system calibration and beam tuning purposes. There are two imaging systems in the target area, one looking at the target wheel, and one looking at the Proton Beam Window. They are redundant, but also can be used to measure the beam divergence. Fiducials at the object plane allow geometric calibration of the beam measurement, and also allow measurement of the target wheel position with respect to the neutron moderator position. An additional imaging system measures beam as it approaches the tuning dump.

Many challenges have to be overcome to deliver these imaging systems, primarily due to the radiation environment. The source for imaging the protons is a luminescent material, coated on beam-intercepting components. This material must be luminescent at the high temperature induced by the primary beam and secondary particles from the target, and it has to remain luminescent for the lifetime of the device, i.e. 5 years for the target wheel and 2 years for the proton beam window. In addition, and particularly for the moving target wheel, the luminescence decay time should be shorter than 10 μs in order to provide a still image of the beam [18]. Studies are being carried out in order to downselect the best candidate materials. These studies include long irradiation campaigns. This first one that has started recently, is an irradiation of 2 kinds of materials, chromium alumina and yttria, at Brookhaven National Laboratory's BLIP facility, under the RaDIATE collaboration [19]. After a series of post irradiation examinations, these materials will be qualified in proton beams at DTU and at higher energy facilities available at LANL and J-PARC.

Optics design is also affected by the target environment. The radiation shielding requirements mandate a small numerical aperture for the optical system, limiting not only the transmission, but also placing severe constraints on position and size of the optical elements. In addition, the radiation from the target will heat the first optical elements, potentially disrupting the image quality. It may also induce chemical reactions that can affect the reflectance of the mirror. For instance, a water and air leak, common in high power target stations, can lead to formation of acids that will rapidly attack and damage the surface of the mirrors. Downselection of optical component material and coating is proceeding with a goal of mitigating these issues. An optical design has already been simulated and prototyped at University of Olso as shown in Figure 9.

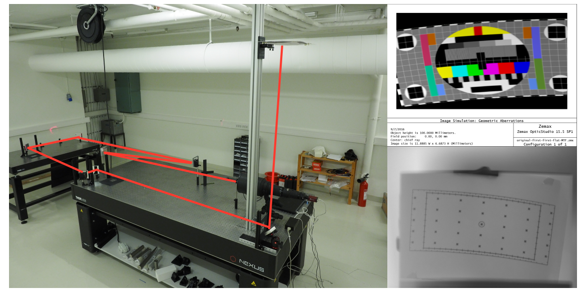

Figure 9: Prototype of the optical system at the University of Oslo. The image target is shown on the bottom right, and the Zemax simulation on the top right. The agreement shows that the performance in design and in reality are matched.

PROTECTION STRATEGY

Several beam diagnostic systems provide input to the beam interlock system, reporting potentially damaging beam conditions before damage occurs. With a processing latency on the order of microseconds, these diagnostic systems calculate the response of machine components to primary protons and secondary particles, producing a scaler value called damage potential. When this value exceeds a predetermined threshold, the beam interlock system can suppress beam production within microseconds to tens of microseconds. To achieve this performance and the required availability, these protection functions are implemented in field programmable gate arrays. Two general classes of damaging conditions are detected by the appropriate diagnostic devices: beam loss in the linac, and errant beam properties at destinations.

Beam Loss in the Linac

The BCM, nBLM, and ICBLM systems measure beam loss in the linac. All three are capable of detecting peak current losses that exceed 2% of the nominal 62.5 mA peak current. Below this level, errors could dominate the current difference reported by the BCM system, yet some accelerator components can still be damaged by an integrated loss exceeding about one μC within the diffusion time constant. Therefore, the nBLM and ICBLM provide exclusive coverage for low level losses over a pulse or even multiple pulses.

Over much longer time scales, an average loss limit of 1 W/m should lead to acceptable activation levels in the accelerator tunnel and acceptable lifetime of radiation sensitive components. Temporarily, machine studies and other activities could produce elevated losses, and these would be managed by an activation plan and monitored by the nBLM and ICBLM systems.

Utilization of multiple signals communicated over low-latency links will provide additional robustness and protection capability. Protection functions that combine signals from multiple beam loss detectors can increase immunity to anomalous single-channel errors like sparks, and reduce sensitivity to the spatial distribution of the lost beam. Time-of-flight measurements by the BPM system can detect beam

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energy deviations before they exceed the acceptance of the accelerator. For some failures, like RF faults that occur during a beam pulse, the beam production could be suppressed *prior* to beam loss.

Beam Properties at Destinations

Properly tuned, the ESS accelerator transports beam with low loss to one of several intended destinations, from insertable Faraday cups, to the fixed tuning dump and finally, to the target station. These destinations vary in their beam handling capabilities, and a suite of diverse and redundant instrumentation systems assure that beam properties do not exceed specified limits [20]. A combination of the two imaging systems and multiwire Grid protect the target station from high current density that could overheat the beam windows or the target elements. Just upstream of the tuning dump, an imaging system provides similar protection. At both of these locations, aperture monitors protect against energy deposition in the vacuum envelope and shielding just upstream of the target and dump.

When beam enters a section of accelerator that has not been verified, the destination must be assumed to be anywhere in this section, including the most sensitive components. Even after tuning and verification of a section, the ultimate destination might only be configured to absorb a limited charge per pulse and average beam current. From start up with initial test pulses through operations with fully verified beam transport, the BCM system in the low energy end of the linac will verify that beam pulse parameters are consistent with intentions.

OUTLOOK

During 2017, beam measurements at CEA-Saclay and ion source commissioning in Catania provided valuable experience and demonstrated that the initial BCM, Doppler, Emittance, and Faraday cup systems achieved their performance requirements. In early 2018, these same systems will be deployed in Lund, Sweden to measure the first proton beam at the ESS site. In 2019, most types of diagnostic systems will be deployed and commissioning of bunched beam will commence.

ACKNOWLEDGMENTS

The ESS beam diagnostics team gratefully acknowledges INFN colleagues in Catania for designing and commissioning the ion source and LEBT, which provided beam for the commissioning of the initial diagnostic systems. Every diagnostic system depends on technology and service provided by the ESS Integrated Control System division, is integrated into the accelerator with the help of the ESS Linac Group, and benefits from the clear requirements provided by the ESS Beam Physics section.

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