PIP-II Beam Instrumentation Physics Requirement Document

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Document Approval

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Revision History

Revision	Date of Release	Description of Change
-	1-10-2020	Initial Release
A	8-10-2021	(cadornaa)Modified for LEBT& MEBT Invasive BCMs as well as to update bias voltage based on internal conversations
B	May 2023	(cadornaa)Updated verbiage to match downstream Invasive BProM documents; Added physics requirement for TWS in diagnostic cart; Removed option to use adjustable scrapers for beam profiles based on PIP2IT experience; Removed short description of diamond detector because device is not in BI WBS; Added verbiage regarding diagnostic and commissioning modes
C	July 2023	(cadornaa) Updated for BCM/BLM/BPM FDR
D	Feb 2024	(cadornaa) Updated per discussions with Accel. Physics; Updated Approval List

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1. Purpose

Physics Requirement Documents (PRDs) contain the summary parameters and configuration definitions for systems, sub-systems, and devices that impact higher-level requirements established in the PIP-II Global Requirements Document (GRD) [1]. PRDs establish a traceable link to lower-level requirements (FRSs, TRSs) that affect the PIP-II beam or machine performance. In the aggregate, the PRDs for the PIP-II Project contain the essential parameters and configuration developed through the preliminary design phase to enable completion of the PIP-II accelerator and complex design.

2. Acronyms

ACCT	AC Current Transformer
BI	Beam Instrumentation
BLM	Beam Loss Monitor
BM	Beam Mode
BPM	Beam Position Monitor
BTL	Beam Transfer Line
DCCT	DC Current Transformer
EID	Electrically Isolated Diaphragm
FRS	Functional Requirements Specification
GRD	Global Requirements Document
L2	WBS Level 2 System
L3	WBS Level 3 System
LEBT	Low Energy Beam Transport
MEBT	Medium Energy Beam Transport
MM	Machine Mode
MPS	Machine Protection System
PIP2IT	PIP-II Injector Test
PIP-II	Proton Improvement Plan II Project
PMT	Photomultiplier Tube
PRD	Physics Requirements Document
RF	Radio Frequency
RT	Room Temperature
RWCM	Resistive Wall Current Monitor
SCL	Superconducting Linac
SSR	Single Spoke Resonator
TC	TeamCenter
TRS	Technical Requirements Specification
WBS	Work Breakdown Structure
WFE	Warm Front End

3. Scope

The document describes requirements for the diagnostics and instrumentation for the PIP-II WFE, SCL and BTL into the Booster ring.

4. Assumptions

Key cost, schedule, technical and programmatic assumptions are provided in PIP-II Project Assumptions [2].

5. Definitions

Resolution, or *precision*, is associated with the standard deviation of many measurements. Examples are:

- Quantization error of signal digitization and data acquisition
- Errors associated with reproducibility of positioning moving mechanical components
- Measurement errors caused by random noise.

Accuracy refers to a systematic offset from the ideal condition or set point, often when averaged over many measurements. Examples are:

- Scale and calibration errors
- Systematic offsets and positioning errors are not considered.

In addition, PIP-II 'machine modes' and 'beam modes' are defined in the PIP-II Accelerator Commissioning and Start-Up Plan [9] as follows:

- A *Machine Mode* (MM) defines a portion of the accelerator that can be operated with beam and is associated with a specific final beam destination (beam stop/dump/absorber). Beam operations in the downstream of that destination are not allowed.

- A *Beam Mode* (BM) defines the pulse length and repetition rate, or a range of repetition rates, of beam pulses, thus defining the maximum average beam power.

Table 5-1 provides a summary of the beam modes, copied here from the plan for reference.

Table 5-1 - Summary of Beam Modes taken from PIP-II Beam and Machine Modes [9]

Beam Mode	Description	Pulse length (µs)	Pulse rep. rate (Hz)	Intended Usage
BM 1	Short pulse, low rep. rate	10	1	Low-power mode safe for use with insertable instrumentation. Initial commissioning to establish beam through the machine
BM 2	Short pulse, 20 Hz rep. rate	10	1 – 20	Commissioning to measure beam parameters and tune the machine
BM 3	Long pulse, low rep. rate	550	1	Commissioning with long pulses
BM 4	LBNF Booster	550	1 – 20	Booster Operation for LBNF
BM 5	Front End High Power	Up to 50000	1 – 20	Front End (through MEBT) high power operations up to CW

6. Overview

Lattice simulations are performed to form and optimize an optics file for the PIP-II project to achieve the physics requirements within the given constraints. The lattice configuration output files [3] are under revision control in order to manage and record lattice releases [4]. Based on the lattice configuration, identified beam diagnostics and instrumentation are summarized in Table 6-1.

Table 6-1. PIP-II Diagnostics by System and PIP-II Beamline Section

	WFE	SCL	BTL
Beam transverse position and energy in dispersion area. Beam phase relatively to RF.			
Warm BPM	X	X	X
Cold BPM		X	
Beam transverse profiles			
Laser profiler	X	X	
Beam scrapers	X		
Transverse Wire Scanner	X		X
Beam transverse emittance			
Allison Emittance Scanner	X		
Laser Wire			X
Beam longitudinal profiles			
Laser Wire	X		
Bunch Shape Monitor			X
Beam current and intensity			
ACCT	X	X	X
DCCT	X	X	
RWCM	X	X	
Scrapers	X		
Electrical isolated pickups	X		
Beam loss			
PMT loss monitor		X	
Neutron loss monitor	X	X	
Ionization loss monitor		X	X

In addition, exact quantities and locations of BI systems are reflected in the PIP-II Parameters PRD [7].

7. General Requirements

7.1. Vacuum Requirements

Beamline components for BI systems will comply with PIP-II Vacuum PRD [5].
Additional requirements will be elaborated in the FRS and TRS for individual BI systems.

7.2. Alignment Requirement

Beamline components for BI systems will comply with PIP-II Misalignment Tolerances PRD [6].
Additional requirements will be elaborated in the FRS and TRS for individual BI systems.

7.3. Space requirements

BI systems, such as laser wires, beam intensity diagnostics, and BPMs in the SCL, are placed between cryomodules. The drift space between cryomodules available is very limited due to beam dynamics limitations and space occupied by other systems, such as focusing magnets and vacuum components. Due to these limitations and based on estimates of geometrical dimensions of instrumentation, the distance allocated for the instrumentation between cryomodules (any) is 250 mm. The lattice files [3] and PIP-II Parameters PRD [7] document the distance between specific cryomodules.

8. Physics Requirements

Table 8-1 through Table 8-19 provide physics requirements for each BI system, based on the beam parameters, provided in the PIP-II Parameters PRD [7]. These physics requirements are used to define each system's performance under commissioning as well as nominal diagnostic and operating conditions. Invasive devices will only be operated during diagnostic modes; failure to do will trip the MPS to inhibit beam.

The nominal average beam current over the pulse is 2mA for all machine modes for the SCL (33, 177, and 800 MeV) and 5 mA for the WFE (2.1 MeV). The requirements in this document are specified for the currents indicated above and the pulse length of 10 µs (Diagnostics Modes BM 1, BM 2 in [9]) unless explicitly stated otherwise. The full tuning range of the beam upstream of the MEBT absorber is up to 10 mA and, correspondingly, bunch charge up to 60 pC. Preferably, all BI system should be capable of measuring in this entire range.

8.1. Beam Position Monitors

Beam position/orbit monitoring is the most fundamental measurement and powerful diagnostics tool in an accelerator. PIP-II requires a significant number of warm and cold BPM for the SCL and 800 MeV BTL, in addition to those in the WFE. The beam line design, for the MEBT and warm BPMs, includes a single four-button BPM located near each beam focusing element (solenoid, quad, doublet, triplet). The geometry of all BPMs will be similar with their aperture scaled in size as required. Cold BPMs are not covered under BI WBS but requirements are covered in this PRD.

The general functional requirements for BPMs, except for wideband system of BPMs in the MEBT chopper section, are the following:

- Measure coordinates of the beam transverse position/orbit.
- Measure the relative beam phase, relative to the RF.
- Measure the relative beam intensity.

BPMs in the MEBT chopper section have, in addition to the standard readings, a wideband bunch-by-bunch system. This wideband system measures ONLY the beam positions; it will NOT measure either beam phase or 1st harmonic intensity.

The BPM requirements are specified for the pulse length of 10 µs. The BPM system is expected to operate in WFE (excluding the Wideband system) up to CW (High Power Mode, BM5) and with the pulse length up to 0.55 ms (BM 3, BM 4) in other sections of PIP-II with resolution not worse than indicated in the corresponding Tables below.

8.1.1. Standard MEBT BPMs

Location: MEBT, next to MEBT quadrupoles.

Table 8-1. MEBT BPM Parameters, non-chopper section

Parameter	Nominal Beam
Position resolution	10 µm
Position accuracy (rms)	0.1 mm
1st Harmonic Intensity resolution	1 %
Phase resolution	0.3° @ 162.5 MHz
Beam aperture	30 mm
Operational temperature	+15 to +30 ºC

8.1.2. Wideband MEBT BPM system

Location: MEBT, next to MEBT quadrupoles, in chopper section, high-bandwidth system.

The wideband BPM system in the MEBT chopper section is used to measure individual orbits of the chopped and un-chopped beam going through simultaneously. This requires an additional chopper BPM system with a bandwidth able to measure individual bunch positions. Consequently, it will ONLY measure beam position; it will NOT measure either beam phase or 1st harmonic intensity. This wideband BPM system will operate in parallel with the standard BPM system in the chopper section of the MEBT.

Table 8-2. MEBT BPM Parameters, chopper section, high-bandwidth bunch-by-bunch system

Parameter	Nominal Beam
Position resolution	100 µm

8.1.3. HWR, SSR1 and SSR2 BPMs

Location: Internal to HWR, SSR1 and SSR2 cryomodules, next to each focusing solenoids.

Table 8-3. HWR, SSR1 and SSR2 Cryomodule BPM Parameters

Parameter	Nominal Beam
Position resolution	10 µm
Position accuracy (rms)	0.1 mm
1st Harmonic Intensity resolution	1%
Phase resolution	0.3° @ 162.5 MHz
Beam aperture (HWR / SSR1 / SSR2)	32 mm / 30 mm / 40 mm
Operational temperature	2 to 45 K

8.1.4. BPMs in RT sections of LB650, HB650 and in the Beam Transfer Line (BTL)

Location: RT sections of SCL, BTL, next to RT quadrupoles, Diagnostic Cart

Table 8-4. RT Sections of SCL and BTL BPM Parameters

Parameter	Nominal beam
Position resolution	10 µm
Position accuracy (rms)	0.1 mm
1st Harmonic Intensity resolution	1%
Phase resolution	0.3° @ 162.5 MHz
Beam aperture	50 mm
Operational temperature	+15 to +30 ºC

8.1.5. Large aperture BPMs

Location: In front of the Lambertson septum magnet in BTL

Table 8-5. Large Aperture BPM Parameters

Parameter	Nominal Beam
Position resolution	50 µm
Position accuracy (rms)	0.2 mm
1st Harmonic intensity resolution	2% @ 162.5 MHz
Phase resolution	1° @ 162.5 MHz
Beam aperture	160mm x 40mm elliptical
Operational temperature	+15 to +30 ºC

8.2. Beam Profile and Beam Emittance

Two types of transverse wire profiling methods for PIP-II are implemented. The first method uses photo-disassociation of H− by laser radiation. Because of the minimal interaction with the beam, the laser-based profile monitor is the only profiling method allowed near the superconducting cryomodules. The second method is a traditional wire scanner. Because of their proven technology, wire scanners are the primary choice in the 800 MeV transfer line.

In addition, PIP-II utilizes two methods for longitudinal bunch shape profiles: (1) a picosecond laserwire in the WFE MEBT to make longitudinal measurements and (2) a Feschenko-style wire-based bunch shape monitor [14] at the end of the SCL.

Transverse emittance measurements are a highly useful and versatile tool for the tuning and operation of an accelerator. There are various techniques that can be used to determine the transverse emittance. PIP-II will employ two types of emittance measurements for transverse phase-space: (1) Allison-type emittance scanners and (2) a laser-based emittance scanner. The Allison-type emittance scanner are used in the LEBT [12] and MEBT [13]. The laser-based emittance scanner is utilized in the end of the SCL.

8.2.1. Transverse Wire Scanner

Location: MEBT, BTL, Diagnostic Cart
General functional requirements:

- Measure transverse distribution, including its shape and coordinates, process the data

Table 8-6. Transverse Wire Scanner Parameters

Parameter	Nominal Beam
Beam energy	2.1, 800 MeV (Diagnostic Cart: 32, 177 MeV)
Beam transverse size (rms)	1 to 4 mm
Transverse resolution	100 µm
Transverse accuracy	0.5 mm
Size of measurable region	±20 mm
Desirable typical scan time	<3 min
Min Beam aperture (WFE / SCL / BTL)	30 mm / 50 mm / 50 mm
Operational temperature	+15 to +30 ºC

TWS, which is an interceptive device, will only be operated during diagnostic beam modes BM1, BM2 [9]. To protect from beam-induced damage, each TWS shall provide to the MPS information on whether they are fully retracted.

8.2.2. Allison Emittance Scanner

Location: LEBT and MEBT
General functional requirements:

- Measure and output the transverse phase space distribution [12][13].

Table 8-7. Allison Emittance Scanner Parameters

Parameter	LEBT	MEBT
Beam energy	30 KeV	2.1 MeV
Average Maximum Beam Power	300 W	60 W
Positioning reproducibility	50 mm	50 mm
Positioning accuracy	1 mm	1 mm
Positioning step	25 mm	25 mm
Angular resolution	0.5 mrad	0.2 mrad
Angular accuracy	3 mrad	1 mrad
Intensity resolution	1 %	1 %
Intensity accuracy	5 %	5 %
Scanning stroke	±30 mm	±15 mm
Angular sweep	±80 mrad	±10 mrad
Desirable typical scan time	<3 min	<3 min
Operational temperature	+15 to +30 ºC	

The MEBT AES, which is an interceptive device, will only be operated during diagnostic beam modes BM1, BM2 [9]. The LEBT AES can operate up to CW. To protect from beam-induced damage, each of the AES shall provide to the MPS information on whether they are fully retracted.

8.2.3. Laser Wire

Location: MEBT, SCL, end of SCL, BTL
General functional requirements:

- Measure transverse distribution, including its shape and coordinates, process the data.
- Measure average longitudinal bunch distribution, including its shape and coordinates, process the data.

Table 8-8. Laser Wire Parameters for Transverse Profiles

Parameter	Nominal Beam
Beam energy	2.1, 800 MeV
Beam pulse length	10 ms
Bunch Intensity	30 pC
Bunch Intensity (particles)	1.9e8
Beam transverse size (rms)	2 mm
Transverse resolution	100 µm
Transverse accuracy (rms)	0.25 mm
Size of measurable region	±15 mm
Desirable typical scan time	<3 min
Min Beam aperture (WFE / SCL / BTL)	30 mm / 50 mm / 50 mm
Operational temperature	+15 to +30 ºC

Table 8-9. Laser Wire Parameters for Longitudinal Profiles

Parameter	Nominal Beam
Longitudinal resolution	20 psec
Size of measurable region (degrees of phase @ 162.5 MHz)	360º
Desirable typical scan time	<5 min
Min Beam aperture (WFE / SCL / BTL)	30 mm / 50 mm / 50 mm
Operational temperature	+15 to +30 ºC

Laser Wire Profile Monitors will not be able to resolve the nominal longitudinal bunch profile in the SCL downstream of the WFE. However, Laser Wire Monitors at the end of the SCL still can be used to measure the longitudinal profile of bunches that are allowed to drift and elongate without acceleration and longitudinal focusing. This technique will be used to measure the longitudinal emittance of the beam.

8.2.4. Bunch Shape Monitor

Location: end of SCL

General functional requirements:

- Measure average longitudinal bunch distribution, including its shape and coordinates, process the data [14].

Table 8-10. Bunch Shape Monitor Parameters for Longitudinal Profiles

Parameter	Nominal Beam
Longitudinal resolution	8 psec
Size of measurable region (degrees of phase @ 162.5 MHz)	90º
Desirable typical scan time	<5 min
Min Beam aperture	350 mm
Operational temperature	+15 to +30 ºC

8.3. Beam and Bunch Intensity Monitors

A combination of invasive and non-invasive beam current instruments will be used to adequately cover the proposed range of beam timing structures.

Non-invasive pickups include the DCCT, ACCT, and RWCM. Instrumentation for both ACCT and DCCT pickups will provide instantaneous or average beam current measurements, as well as the capability to request and display waveforms. RWCM will be employed to measure the bunch-by-bunch chopping pattern and the chopping efficiency.

The invasive pickups include electrically isolated pickups, which consist of EIDs, beam absorbers/dumps, kicker protection electrodes, insertable scrapers, and an electrically isolated beam pipe aperture restriction.

Calibration of these beam current pickups is critical to maintain accurate measurements. The PIP-II beam current monitoring system will employ a semi-automated calibration system allowing for nominal calibration times of minutes or less.

In addition, an accurate measure of beam current loss computed from the difference of beam currents at different locations along the beamline is required for the MPS. ACCT provide primary inputs to the MPS system and will comply with PIP-II MPS PRD [8].

Also, several dedicated ring pickups, which behave like single button BPMs, will be employed in the WFE to give an independent measure of the relative beam current for the MPS. Requirements and specifications for the ring pickups are NOT covered within the scope of BI WBS.

DCCT measurements will be provided for safety systems, but not for MPS.

8.3.1. DCCT

Location: WFE, end of SCL
General functional requirements:

- Measure DC current component to control total beam current out of ion source and into SRF cryomodules.

Table 8-11. DCCT Parameters

Parameter	Value
Intensity resolution (rms)	<1 µA / sqrt(Hz)
Intensity accuracy	±0.1%
Time response	DC to 10 kHz
Min Beam aperture (WFE / SCL / BTL)	30 mm / 50 mm / 50 mm
Approx. slot length	120 mm
Maximum operational temperature	100 ºC
Temperature coefficient	<0.5 µA/ºC typical

8.3.2. ACCT

Location: WFE, SCL, end of SCL, Diagnostic Cart, BTL
General functional requirements:

- Measure current of pulsed beam, intensity measurements for SCL tuning, operations, and MPS.
- Provide waveform displays, upon request.

Table 8-12. ACCT Parameters

Parameter	Value
Intensity resolution (rms)	3 µA
Intensity accuracy	±1%
Bandwidth	3 Hz to 1 MHz
Min Beam aperture (WFE / SCL / BTL)	30 mm / 50 mm / 50 mm
Approx. slot length	40 mm
Maximum operational temperature	100 ºC

8.3.3. RWCM

Location: MEBT, end of SCL, Diagnostic Cart
General functional requirements:

- Manual readout of digitized waveform by stand-alone scope
- Measurement of bunch-by-bunch chopper efficiency

Table 8-13. RWCM Parameters

Parameter	Value
Bandwidth (MHz)	0.01 to 4000 MHz
Min Beam aperture (WFE / SCL / BTL)	30 mm / 50 mm / 50 mm
Approximate slot length (mm)	50 mm
Operational temperature	+15 to +30 ºC

8.3.4. MEBT Adjustable Beam Scrapers

Location: MEBT
General functional requirements:

- Scrape and collimate the beam
- Read collimated current from the scraper jaws to measure halo
- The scraper reading system should be capable of detecting an increase of the current above a user-specified level (accident detection) and sending a corresponding signal to the MPS. Additional requirements are provided in the LEBT and MEBT Scraper Functional Requirements FRS [10][11].

Table 8-14. Adjustable Beam Scraper Parameters

Parameter	Value
Beam energy	2.1 MeV
Beam diameter, rms., typ.	1 to 4 mm
Average Maximum Beam Power	75 W per plate / 200 W total
Transverse positioning resolution	100 µm
Transverse positioning accuracy	1 mm
Stroke size for each jaw	±15 mm
Current read out from each jaw	Yes
Bias	0 to +100 V
Maximum readout current	10mA =
Resolution of beam current readout	1 mA
Desirable typical scan time	<5 min

8.3.5. LEBT Invasive Pickups

Location: LEBT
General functional requirements:

- Measure instantaneous current of pulsed beam, sampled and held relative to a beam event, for SCL tuning, operations, and MPS

Table 8-15. LEBT Invasive Pickups Parameters

Parameter	Value
Beam energy	30 KeV
Beam pulse length	10 µs to DC
Intensity resolution	±1 %
Intensity accuracy	NA

8.3.6. MEBT Invasive Pickups

Location: MEBT
General functional requirements:

- Measure instantaneous current of pulsed beam, sampled and held relative to a beam event, for SCL tuning, operations, and MPS

Table 8-16. MEBT Invasive Pickups Parameters

Parameter	Value
Beam energy	2.1 MeV
Beam pulse length	10 ms to CW
Intensity resolution	±1 %
Intensity accuracy	NA
Beam aperture	50 mm

8.4. Beam Loss Monitors

Beam loss monitoring is an important tool for beam tuning as well as a critical part of machine protection to prevent excessive activation of materials. Beam loss monitors will be located in places of likely losses to ensure their sensitivity to beam losses. Such places are focusing elements between LB650 and HB650 cryomodules and along the BTL beam transport tile line and drifts between SSR cryomodules. Maps of radiation dose induced by beam losses will be simulated using the MARS Monte-Carlo code. Based on these simulations, parameters of beam loss monitors, and their exact location will be selected.

In general, the current acceptable beam loss limit for SCL is 1 W/m. PIP-II will utilize three types of BLM devices through the SCL and the SCL-to-BTL. The primary BLM devices will be ionization chambers. Ionization chambers have a relatively good response time (few µs), are simple in design and are resistant to radiation damage. The other two BLM devices will be fast PMT based detectors and neutron detectors. These devices generally have a much faster response (~10 to 100 ns).

To protect the accelerator from damage in a case of catastrophic accidental beam loss the response of the MPS system, including loss monitors, should be < 10 µs. The MPS beam inhibit time are further elaborated in the PIP-II MPS PRD [8].

The BLM should be capable of reporting at 20 Hz on every beam pulse.

8.4.1. Ionization Chambers

Location: SCL, BTL

General functional requirements:

- Detect loss
- Provide signal to the control system
- Provide input to MPS

Table 8-17. Ionization Chamber Parameters

Parameter	Nominal beam
Detection time	<5 µs
Detection threshold	10^5 particles/cm^2/s
Input to MPS	Yes

8.4.2. Photomultiplier Tube (PMT) Loss Monitors

Location: WFE, SCL

General functional requirements:

- Detect loss
- Provide signal to the control system
- Provide input to MPS

Table 8-18. PMT Parameters

Parameter	Nominal beam
Detection time	<100 ns
Detection threshold	10^3 particles/cm^2/s
Input to MPS	Yes

8.4.3. Neutron Detectors

Location: WFE, SCL

General functional requirements:

- Detect loss
- Provide signal to the control system
- Provide input to MPS

Table 8-19. Neutron Detector Parameters

Parameter	Nominal Beam
Detection time	100 ns
Detection threshold	100 neutrons/cm^2/s
Input to MPS	Yes

9. Reference Documents

#	Reference	Document #
1.	PIP-II Global Requirements Document (GRD)	TC# ED0001222
2.	PIP-II Project Assumptions	PIP-II docDB #144
3.	PIP-II Lattice Files	TC# ED0011224
4.	PIP-II Lattice Management and CAD Integration Guidelines	PIP-II docDB #2952
5.	PIP-II Vacuum Physics Requirements Document (PRD)	TC# ED0010228
6.	PIP-II Misalignment Tolerances PRD	TC# ED0010231
7.	PIP-II Parameters Physics PRD	TC# ED0010216
8.	PIP-II Machine Protection System PRD	TC# ED0010232
9.	PIP-II Accelerator Commissioning and Start-Up Plan	PIP-II docDB #5420
10.	LEBT Scraper Functional Requirement Specification (FRS)	TC# ED0001290
11.	MEBT Scraper Functional Requirement Specification (FRS)	TC# ED0001306
12.	D′Arcy, R., et al. "Characterization of the PXIE Allison-Type Emittance Scanner." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 815, Apr. 2016, pp. 7–17, https://doi.org/10.1016/j.nima.2016.01.039.	
13.	Richard, C., et al. "Measurements of a 2.1 MeV H− Beam with an Allison Scanner." Review of Scientific Instruments, vol. 91, no. 7, July 2020, p. 073301, https://doi.org/10.1063/5.0004502.	
14.	Gavrilov, S., et al. "Bunch Shape Monitors for Modern Ion Linacs." Journal of Instrumentation, vol. 12, no. 12, Dec. 2017, p. P12014, https://doi.org/10.1088/1748-0221/12/12/P12014.	