Document Number:	ESS-0039088
Date:	March 31, 2016
Revision:	5
State:	Released

Scope of Work for the In-Kind Collaboration with CEA SACLAY on the Non-invasive Profile Monitors for the ESS Cold Linac

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Abstract

This document describes the Scope of Work (SoW) required to complete the delivery of Non-invasive Profile Monitors to the ESS Cold Linac by CEA SACLAY. It is an integral part of the In-Kind Contribution Agreement and is agreed upon by all undersigning Parties. The SoW contains an appropriate level of detail so all parties clearly understand what work is required, the duration of the work involved, the deliverables and the conditions of acceptance.

1 Scope of the Cold Linac NPM project

One of the proton beam diagnostics to be operating at ESS is the Non-invasive Profile Monitor (NPM). This diagnostics provides a measurement of the beam profile in both horizontal and vertical plan, all along the ESS Linac. The ESS Linac can be divided in two main sections, the Warm Linac, which has usual conducting RF cavities, and the Cold Linac, which has superconducting RF cavities. In this technical document, we address the scope of work (SoW) for the design and delivery of NPM in the Cold Linac by CEA Saclay as in-kind collaborator to the ESS.

The scope of work covers the 3 main phases of the project, which are a Design Study, articulated in a Preliminary Design, already started at ESS, and a Detailed Design, and the Production Phase. The Design Study phase ends by achievement of reports which statue on the feasibility and performance of the system to be installed and operated at ESS. These milestones are marked by two reviews, the Preliminary Design Review and the Critical Design Review. The PDR sanctions the end of the Preliminary Design phase, and CDR the Critical Detailed Design one. Once the CDR milestone is reached, the production can start. The Production phase includes production of the NPM units planned for the Cold Linac sections, installation of the units in the ESS linac, integration of the NPM units, and commissioning of the NPM with beam. The work and delivery by the in-kind partner will be supported at various level by ESS Lund as collaborator and receiver of the NPM units for the cold linac.

2 Design Studies

Each of the studies will be described in a technical report, building the case for the Reviews and marking milestones achievements.

2.1 Preliminary studies

Objective of the Preliminary studies is to establish the possible instruments that can be developed to make an NPM for the Cold Linac, and to define the technology to be used.

The existing baseline is to develop an Ionisation Profile Monitor (IPM). This choice is based on initial studies performed at ESS in which an estimation of the signal intensity from such an instrument, taking into account the residual gas pressure of 10^{-9} mbar and protons from 90 MeV to 2 GeV. In this range, the signal from a modeled IPM is expected to be 3 orders of magnitude larger than from a beam induced fluorescence monitor [1]. The NPM for the Cold Linac consists of an assembly of two IPMs, providing the beam profile in the horizontal and vertical plans. Each of the two IPMs consists of a High Voltage cages, a readout unit systems and an in situ calibration systems.

The SoW for the Conceptual Design to be delivered by CEA as an in-kind collaborator consists in delivering a set of documents showing the feasibility of the IPM and ability to fulfill the ESS requirements for the transverse profile measurements of the proton beam in the Cold Linac sections. These requirements shall be found in DOORS. The SoW is enumerated bellow. The conceptual design has been already started at ESS, and therefore this work is available for the achievement of each of the requested studies and technical report before reaching the Preliminary Design Review level.

1. **Selection of the readout signal system**

[1] The IPM modeled here assumes a screen scintillator and optical imaging system for the profile measurement, and the BIF is based on the optical imaging of the Balmer Alpha ray of hydrogen.

Several possible detectors, namely crystal, conductive strips, MCP, scintillator, and others proposed by CEA, will have to be evaluated in terms of performance in the ESS Linac environment. Sensitivity, lifetime, signal intensity and signal to noise ratio, perturbation from beam loss, will be based criteria to perform the selection of the readout signal system.

Report: technical report, based on available data, shall derive numbers for the smallest detectable and measurable beam profile, lifetime of the device in the ESS linac environment, performance of the system under beam loss perturbation. The results shall be used for the selection of the readout signal system.

2. **Influence of Space Charge on the profile measurement**

   Initial studies from the ESS BI group tend to show that the space charge may affect the IPM profile measurement. It has been also observed experimentally [1] that the beam profile can be distorted for the case of longitudinal uniformly distributed charged beams. However, the scaling from these measurements seems to be not applicable to the ESS pulsed beam. To investigate this, ESS has developed a model of the dynamic interaction between the created ions and the proton bunches. This Matlab model, debugged and partially tested (CHESS technical document ESS-0039075), is available to complete study on the perturbation of the space charge to the beam profile measurement. The model and the results from the studies shall be used to select the operating voltage of the HV cage of the IPM

   Report: case study of the beam profile distortion as function of the bunch charge, beam size, and external electric field strength and for all energies, beam sizes and bunch lengths along the Cold Linac. The conclusion of the report selects the HV intensity for the IPM operation.

3. **Influence of beam loss on measured beam profile**

   Beam loss will cause additional signal in the NPM. This signal might be homogeneous or distributed, or sparse, or characteristic of a particular pattern. Studies of the perturbation to the measured profile shall be carried on. The results of the studies shall give a confidence in the operation of the NPM.

   Report: impact of the radiation environment on the performance of the system; studies shall consider all mentioned detection systems all along the Cold Linac.

4. **High Voltage Cage Preliminary Design**

   - Geometry optimization: several sketches of the possible design have been done, but ultimately the field homogeneity and sparks potential must be done with the final Linac Warm Unit (LWU[2]) design provided by ESS.
     - The NPM delivers horizontal and vertical profiles at the same location; therefore, the study of the electric field includes the whole assembly with the two HV cages. The studies should always take into account the two adjacent and orthogonal assemblies to be place in the available volume and the potential interference between them.

   Report: Based on the mechanical design of the LWU and the electrodes cages, max intensity and uniformity volume will be given, probably out of numerical simulation, using CST studio or any other suitable software.

[2] LWU is girder assembly connecting two adjacent superconducting RF cavities, on which are the vacuum vessel, the proton beam instrumentation and the quadrupole and steerer magnets.

5. **In situ calibration conceptual design**

    - The projected ions toward the readout system may induce degradation of its signal response. The degradation, as for instance the MCP decaying signal from ions, or the yield intensity decrease for scintillator crystals shall be investigated. The consequent lifetime of the read-out system shall be estimated. A calibration system shall be proposed. This shall provide an in-situ scaling and an intensity linear scaling for the profile measurement. In addition, the calibration shall permit the follow up of the aging of the readout system

    Report: technical document describing the concept and performance of the in-situ calibration system for the NPM Cold Linac.

6. **Interfaces of the NPM** with its environment have to be identified and explicitly defined in the interfaces and requirements documentation. Several ESS tools have been developed supporting the interfaces. This will address numerous issues, from performance, maintenance and operation requirements of the instrument to more detailed requirement on HV, mechanical support, cabling and connectors, vacuum requirements, etc. The documentation for the interfaces is done in DOORS. Among them, the interfaces already identified listed are:

    - Vacuum: type of flange, qualified vacuum compatible materials of the NPM, bakeable materials.
    - Mechanical interface, volume envelop of the NPM, length of the NPM in the vessel, dimension inside and outside of the vessel.
    - Residual gas composition, gas pressure, gas injection.
    - EMC: electromagnetic perturbation to the applied uniform electric field, and perturbation to the beam.
    - Maintenance aspects for replacement of out or in vacuum parts.

    Report: document describing the interface requirements for the Cold Linac NPM

2.2 Risks and Hazards Analysis

It is essential to evaluate the risks that an NPM cannot reach the targeted performance. The risk analysis shall be conducted by CEA in full collaboration with ESS. The initial list of identified risks can be found below:

- Feasibility: it is essential to demonstrate at any stage of the project that the performance of the NPM can be reached.
- Perturbation of the signal from beam loss, noise from ground, EMC perturbation, etc. is a non-exhaustive list of risks to evaluate.

Also essential is the analysis of the potential hazards linked with the operation and maintenance of the NPM, and the actions to take for their removal or their mitigation. For instance, IPM presents potential of HV electrocution. This is a well understood potential hazard, which can be removed with well established safety measures.

Report: the list of risks and hazards shall be drawn with analysis showing how risks can be managed and hazards removed or mitigated.

2.3 Alternative NPM

In addition to the above list of reports for the conceptual design of the Cold Linac NPM, studies conducted by ESS shall focus on possible methods to enhance the signal for either a BIF or IPM based NPM, and to study new alternative methods for a NPM. The studies will focus on the possibility to locally increase the gas pressure, and on alternative concepts based on electron probes and laser pulses interactions between the residual gas, in competition or perturbed by the proton beam. The results of the studies shall be part of the NPM preliminary design.

2.4 PDR

The Preliminary studies conclude with the Preliminary Design Review (PDR) in which a compendium of the above reports, interfaces documentation and risk analysis will be presented. The technical choices and the performance of the instrument against the ESS requirements will be assessed. The conclusion of the report shall draw the detailed studies to conduct and give details of the Cold Linac NPM prototype to be developed in view of the Critical Design Review. The PDR sanctions the results from the preliminary studies, and as such authorises the project to continue with the detailed design.

3 Cold Linac NPM Detailed Design

Once the PDR has approved the concepts for the NPM, the phase of the detailed design shall start, following the technical choices issued by the preliminary design conclusion.

Depending on the conclusion and the recommendation of the PDR, the detailed studies may lead to the development of a prototype, demonstrating the operation of an NPM with simultaneous horizontal and vertical profile measurements, for a beam with characteristics identical or comparable to the ESS proton beam. The level of detail required for the prototype will be defined by the PDR, and which details of the design will be required for the Critical Design Review.

A Cold Linac NPM prototype might be required to be build as a first instrument of the production. It is also anticipated that not only a prototype will help to establish the right process for the production, but also it will demonstrate expected performance in measuring beam profiles for the ESS proton beam. The validation of an NPM prototype for the Cold Linac may be expected to be part of the Critical Design Review (CDR). The validation of the prototype by the CDR will launch the production phase.

CEA shall deliver the detailed design of the NPM, following the recommendation and the conclusion of the PDR.

The vertical integration and in particular the EPICS control integration of the system is essential to the finalisation and smooth integration of the NPM into ESS linac. Integration will be supported by ESS ICS group, and CEA control group.

Report: the technical drawings for the manufacturing and assembling the NPMs, the technical documentation for the operation and maintenance of the NPM, and the documentation for the EPICS control integration. All documents mentioned shall be delivered for the CDR. The CDR sanctions the start of the production phase.

4 NPM Manufacturing, System Acceptance Review

This phase starts only when the CDR has approved the NPM systems to be built. The number of NPM to be built is not fixed at this point in time. The baseline shows that 5 NPMs may be installed in the Cold Linac sections (1 in the Spoke, 3 in the MB, and 1 in the HB). However, the final number of NPM to be built will be decided by the Accelerator Physics Group responsible for the commissioning of the ESS Linac. So this number will be updated at a later stage, when commissioning preparation studies are published.

During the production phase, system acceptance test shall be performed for quality assurance. The NPM produced for each section of the Cold Linac shall be delivered, installed, integrated in the ESS control system, and commissioned with the ESS proton beam. The participation from CEA in-kind partners at various degrees to this final phase up to the commissioning is strongly encouraged and has been taken into account in the in-kind budget. The final system acceptance review (SAR) shall occur after the NPM commissioning with the ESS proton beam.

5 ESS Cost Book

In initial evaluation of the NPM for the Cold Linac has been done by ESS Beam Instrumentation Group. This evaluation, based on cost comparison with existing recent developments, has been used to establish the budget which is shown in the ESS Cost Book. The WBS numbers and total budgeted cost is shown in the table 1 for reference.

Table 1: ESS Cost Book for the In-Kind NPM Cold Linac SoW

WBS	Activity number	Name	Budgeted Total Cost (kEuro)
11.7.9.2	A147610	NPM: Preliminary Design Cold Units	209
		NPM: Detailed Design Cold Units	586
11.7.9.3.6 11.7.9.3.7 11.7.9.3.8		Spoke: NPM (×1 NPM) MB: NPM (×3 NPM) HB: NPM (×1 NPM)	751
		Budget Total for NPM in-kind project	1546.4

The time schedule as given by the ESS planning (Primavera 6 or P6) has been established so that delivery of the IPM systems occurs with the delivery of the Linac Warm Units (LWU). The NPM systems shall be delivered at the same time as LWU delivery, in order to be conditioned for the high vacuum, prior to the commissioning of the Linac.

5.1 Milestones

The main milestones of the project are the PDR, the CDR, and the system ready for commissioning. These dates are planned to be at the beginning of 2017 for the PDR, at the at the beginning of 2018 for the CDR, and for the delivery and ready for commissioning the date are January 2019 for the Spoke, for the MB, and for the HB. These dates might be revised with the evolution of the ESS and NPM Cold Linac plannings. The milestones for the NPM Cold Linac are summarised in the table 2

Table 2: Milstones for the NPM Cold Linac as Shown in P6

Milestone		Date
Kick-Off Meeting		Apr. 2016
Delivery of the conceptual design, feasibility and expected NPM performance		Jan. 2017
NPM Cold Linac PDR: Preliminary Design delivered and Review Closed Out		Mar. 2017
Experimental performance for the NPM Cold Linac Ready to be started		Jul. 2017
NPM performance demonstration validated		Jan. 2018
CDR		Mar. 2018
QA production		May 2018
NPM SAR 1,2,3	Spoke	Jan. 2019
	MB	Jan. 2019
	HB	Jan. 2019
NPM Delivery	Spoke	Jan. 2019
	MB	Jan. 2019
	HB	Jan. 2019
SAR 4: Handover to ESS		Jun. 2019

6 Glossary

The table 3 shows the main acronyms in used at ESS.

7 Annex

7.1 NPM Cold Linac Conceptual Drawing

In the figure 1, the NPM for the Cold Linac can be seen. The figure shows a representation of the LWU, holding the magnets, the vacuum vessel and the beam instrumentation. The beam instrumentation of the LWU presented here is composed of transverse beam profile instrumentation, and beam position monitors. Some other LWU have beam current monitor and other bunch longitudinal profiles measurements. For the transverse profile, two instruments are developed: 2 wire scanners measure the beam profile both horizontal and vertical axis, measuring beam profile of low beam power, and 2 IPMs measure the beam profile of high beam power in the same both axis. One may note that the figure shows two optical systems on the NPM ports, which are NPM developed for the Warm Linac.

7.2 ESS Beam Parameters

At the NPM positions in the Cold Linac, the nominal beam size to be measured is of the order of 2 mm in both transverse axis. The longitudinal beam size is of the order of 1.5 mm. The charge per bunch at full power is of the order of 20pC, making a total

Table 3: Table of the ESS acronyms

NPM	Non-invasive Profile Monitor	Proton Beam instrument measuring the beam transverse profile in Horizontal and Vertical planes
IPM	Ionisation Profile Monitor	Proton Beam instrument measuring the beam transverse profile in one plane, based on ionisation of the residual gas by the beam of particles
PDR	Preliminary Design Review	Milestone: concludes conceptual and preliminary design
CDR	Critical Design Review	Milestone: concludes detailed design and authorises production to start
SAR	System Acceptance Review	Milestone: concludes the project
SoW	Scope of Work	Defines the deliverable for the project
LWU	Linac Warm Unit	Vacuum vessel supporting the beam instrumentation between Cold RF cavities

charge per pulse of the order of 20μC. The number of pulses per second is 14, and the average current is 62.5mA.

The beam size in the transverse plane at the LWU can vary from 0.5 mm to 10 mm, depending on beam physics studies or lattice errors.

7.3 CEA Evaluation Cost for the NPM Cold Linac Project

Cost evaluation from the CEA is also reported for information in the following table 4:

Table 4: CEA anticipated budget for the In-Kind NPM Cold Linac SoW

WBS	Activity number	Name	Budgeted Total Cost (kEuro)
11.7.9.2	A147610	NPM: Preliminary Design Cold Units	256
		NPM: Detailed Design Cold Units	577
11.7.9.3.6		Spoke: NPM (×1 NPM)	173
1.7.9.3.7		MB: NPM (×3 NPM)	522
11.7.9.3.8		HB: NPM (×1 NPM)	173
		Budget Total for NPM in-kind project	1700

This table is based on CEA previous experience and estimate, with contingency. Detail of the table is available.

7.4 Summary for the Scope of Work

The table 5 summarises the scope of work activities for the NPM Cold Linac project.

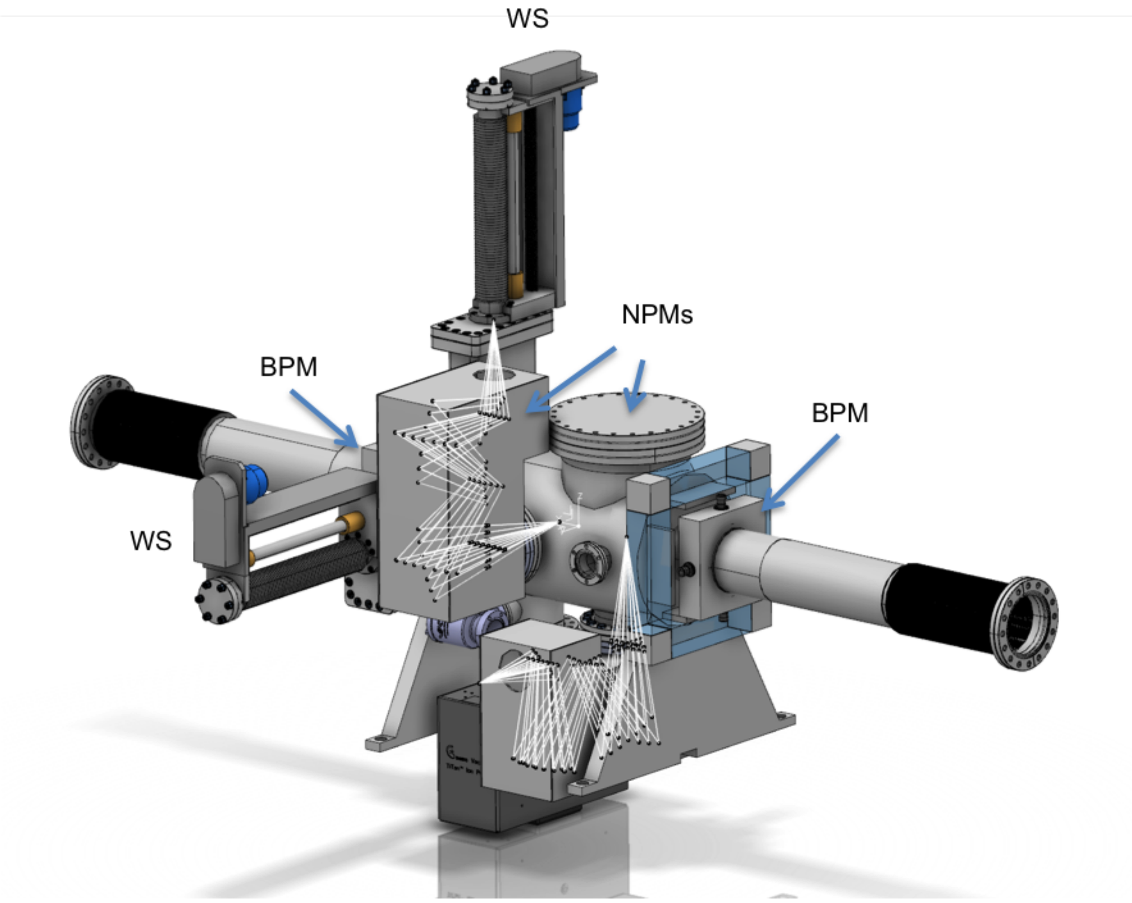

Figure 1: LWU conceptual design drawing. The magnets and the girder are not shown in this drawing: Beam Position Monitors (BPM), some of the RF connectors are visible; Wire scanner (WS), the wire is inside, and what can be seen outside the vessel is its actuator, and the scintillator detecting the secondary emissions, near the second BPM; Non-invasive profile monitors (NPM), showing here an optical system for a beam induced fluorescence monitor on the vertical and horizontal viewports. The distance between two BPMs is 460 mm.

References

[1] Jan Egberts. *IFMIF-LIPAc Beam Diagnostics: Profiling and Loss Monitoring Systems put*. PhD thesis, Paris Sud, 2012.

Table 5: Summary of the scope of Work for the NPM Cold Linac and timeline of the project phases. The dates estimated here are dependent on the P6 installation schedule

Project Phase	Document	Responsible	Start date	End date
Preliminary Design	Selection of the readout signal system	CEA	Q2 2016	Q1 2017
	Influence of Space Charge on the profile measurement	CEA		
	Influence of beam loss on measured beam profile	CEA		
	High Voltage Cage Preliminary Design	CEA		
	In situ calibration conceptual design	CEA		
	Interfaces for the Cold Linac NPM	CEA		
	Risk and Hazards Analysis	CEA		
	Alternatives NPM	ESS	Q2 2016	Q1 2017
PDR		CEA / ESS	Mar. 2017	
Detailed Design	Prototype design	CEA	Q2 2017	Q1 2018
	Prototype construction	CEA		
	Prototype tests and validation	CEA		
CDR		CEA / ESS	Mar. 2018	
Production	Production of all cold Linac NPMs	CEA	Q2 2018	Q1 2019
	Installation and Integration	CEA		
	Commissioning	CEA		
SAR	Handover to ESS	CEA / ESS	end of Q1 2019	