

# THE LINAC4 PROJECT

A. M. Lombardi for the LINAC4 team , CERN, Geneva, Switzerland

## Abstract

Linac4 is a normal conducting, 160 MeV H<sup>-</sup> ion accelerator that is being constructed within the scope of the LHC injectors upgrade project. Linac4 will be connected to the Proton Synchrotron Booster (PSB) during the next long LHC shut-down and it will replace the current 50 MeV hadron linac, Linac2. Linac4 is presently being commissioned, with the aim of achieving the final energy at the end of the year. A test of the injection chicane and a reliability run will follow. The beam commissioning, in steps of increasing energy, has been prepared by an extended series of studies and interlaced with phases of installation. In this paper we will detail the beam dynamics challenges and we will report on the commissioning results.

ject. A sketch of Linac4 and a detailed description of the layout and beam dynamics can be found in [1,2].

The pre-injector includes a source followed by a Low Energy Beam Transport at 45 keV, a Radio Frequency Quadrupole which accelerates the beam to 3MeV and a Medium Energy Beam Transport line (MEBT). The MEBT, 3.6 m in length, houses a fast chopper with the purpose of removing selected micro-bunches in the 352 MHz sequence and therefore avoid losses at capture in the CERN PSB (1MHz). Presently the preferred scheme envisages to chop out 133 bunches over 352 with a resulting average current reduced by 40%. The beam is then further accelerated to 50 MeV by a conventional Drift Tube Linac (DTL) equipped with Permanent Magnet Quadrupoles (PMQ), to 100 MeV by a Cell-Coupled Drift Tube Linac (CCDTL) and to 160 MeV by a  $\pi$ -mode structure (PIMS). The focusing after 100 MeV is provided by Electromagnetic Quadrupoles (EMQ) whereas between 50 and 100 MeV by a combination of PMQs and EMQs. The nominal beam delivered by Linac4 consist of an H-pulse 400 $\mu$ sec in duration and with peak current during

## INTRODUCTION

Linac4 is a 160 MeV H<sup>-</sup> linear accelerator presently under construction at CERN. It will replace the present 50 MeV proton Linac2 as injector of the CERN PS Booster, as a first step of the LHC Injector Upgrade pro-

LINAC4 machine layout- 352MHz					
Pre-injector (9m)		DTL (19m)		CCDTL (25m)	II-mode (23m)
3MeV		50 MeV		100 MeV	160 MeV
SOURCE	RFQ	3 Tanks		<u>7 Modules</u>	12 Modules
Plasma Generator	CHOPPER LINE	3 Klystrons : 5 MW		7 Klystrons : 7 MW	8 Klystrons: 12MW
Extraction	11 EMQ	1 EMQ		7 EMQ + 14 PMQ	12 EMQ
e-Dump	3 Cavities	114 PMQ		7 EMQ + 14 PMQ	12 steerers
LEBT	2 Chopper units	2 steerers		7 steerers	
2 solenoids	In-line dump				
Pre chopper					
Beam Commissioning stages					
45 keV	3 MeV	12 MeV	50 MeV	105 MeV	160 MeV
Not yet the final source	Octobre2013	August 2014	November 2015	June 2016	Octobre 2016 (foreseen)

Figure 1: Layout of Linac4 and key stages of the beam commissioning.

the pulse of 40 mA. As a fall back, a beam of 600 $\mu$ sec and 30mA would give the same performance in the PSB for the LHC type beams [3].

The machine layout and the key stages of the beam commissioning are shown in Figure 1

Linac4 is equipped with 7 beam transformers, 7 wire scanners, 7 profile harps, 7 beam position monitors and phase probes.

At the time of writing a beam of 25 mA peak current (vs 50 mA nominal) and 100 MeV has been observed on the measurement bench at the end of the first PIMS structure. The normalised transverse emittance of the beam is estimated at 0.3  $\pi$  mm mrad rms, corresponding to expectations.

### *RF Cavities*

The pre-injector of Linac4 [4] [5] [6] has been described in many references and it is working reliably since 2014. The status and challenges of the remaining RF cavities is detailed in the following.

The DTL [7] has been designed for reliable operation with up to 10% duty cycle, it is composed of rigid self-supporting steel tanks assembled from segments less than 2 m in length. The tank design is almost without welds, heat-treated after rough machining. The Permanent Magnet Quadrupoles are in vacuum for streamlined drift tube assembly. The philosophy of the design is “adjust & assemble”: tightly-toleranced Al girders w/o adjustment mechanism once assembled.

The tank mounting mechanism (easy to use) has been patented. To guarantee reliability of operation, the first cells of tank1 (shorter) present an increased gap spacing to reduce the chance of breakdown which could be enhanced by the PMQ fields.

All the above choices have paid off, with a smooth conditioning and an excellent availability during the commissioning phase.

The CCDTL [8] has been constructed by the Russian Scientific Research Institute for Technical Physics (VNIITF) and the Budker Institute of Nuclear Physics. The quadrupoles are located outside of the RF structure. The structures are made of copper plated stainless steel, and because of high number of C-shaped metal seals, the assembly process is rather time consuming.

Each cavity needed around 1 month of conditioning to clean surfaces, after which the full gradient was established without problems. All drift tube centres are aligned within  $\pm 0.1$  mm, for increased acceptance. The Linac4 CCDTL is first-ever CCDTL in a working machine! Its performance so far have been up to specification..

The last of the Linac4 RF structure, the PIMS [9], is made out of bulk copper, it doesn't present RF seals, and discs and rings that constitute the cells are tuned and electron-beam welded at CERN

The PIMS were constructed within a CERN-NCBJ-FZ Jülich collaboration and assembled and tuned at CERN. Series production could start only after a qualification period of almost 3 years. The critical point was the required precision machining on large pieces of copper (10

- 20  $\mu$ m on 500 mm diameter pieces). The conditioning of the prototype was extremely swift, it took only 24 hours. The PIMS will be the first low-beta  $\pi$ -mode structure to go into an operational machine. Beam commissioning through the PIMS is foreseen for fall 2016

## COMMISSIONING

The commissioning of Linac4 has been staged in 6 phases of increasing energy with the aim of matching the schedule of the RF cavities delivery and to be able to assess the beam qualities after each structure with the help of extra diagnostics located on a movable bench. This approach has allowed to progress in beam commissioning before complete installation of the hardware and to optimise the beam throughput at each stage. Most important it has also allowed to cross check the information from the permanent diagnostics against more detailed information coming from the temporary diagnostics and therefore validate a strategy to set-up and diagnose possible faults when the Linac4 will be operational as the sole proton injector to the CERN Proton Synchrotron Booster [3], currently scheduled for the LHC Long Shutdown 2 in 2019.

The 6 phases of commissioning include dedicated beam measurements at the energy of 45keV, 3 MeV, 12 MeV, 50 MeV, 100 MeV and finally 160 MeV. The 100 MeV stage has recently been completed. The 160 MeV stage will begin after the summer.

Two benches have been used during the Linac4 commissioning. A “low-energy” bench, used at 3 and 12 MeV which allows direct measurement of the transverse emittance with a slit and grid (or laser and diamond detector) [10] and direct measurement of the energy spread with a 28 degrees bending magnet followed by a profile harp[4]. A “high-energy” bench has been employed for the measurements at 50 and 100 MeV, it contains a) three profile harps and 3 wire scanners at the appropriate phase advance (about 60degrees) for an indirect emittance measurement b) a Bunch Shape Monitor and a lasing station (which allows transverse profile measurement via stripping) and c) two monitors for Time-of-Flight and beam centre position.

### *Direct Measurements*

Some of these measurements have been already reported in [6] [11] [12] and are repeated here for sake of completeness. The important results of the campaign at 3 and 12 MeV is that the direct method of slit-and-grid (or laser-diamond) and the indirect method based on emittance reconstruction from profiles give the same overall value for the emittance. Even more important, both the direct and indirect emittance measurements give the same orientation of the emittance within a range of 10% which is a very important information for the matching of the beam to the structures downstream. With this result we have validated the model of the machine on which emittance reconstruction techniques rely and the correspondence between direct and indirect methods. The success of this campaign is due as well to the method applied for the

reconstruction which are more sophisticated than the standard matrix inversion. In particular in the framework of Linac4 we have developed the “forward-method” [13] which extends the accuracy of the classic emittance reconstruction techniques to space charge dominated regimes, and the tomographic method which allows phase space density information to be calculated from the profile [14]. These two methods combined allow for a full knowledge of the beam parameters without relying on direct emittance measurements. Example of a direct emittance measurement compared with a reconstructed emittance is given in Figure 2.

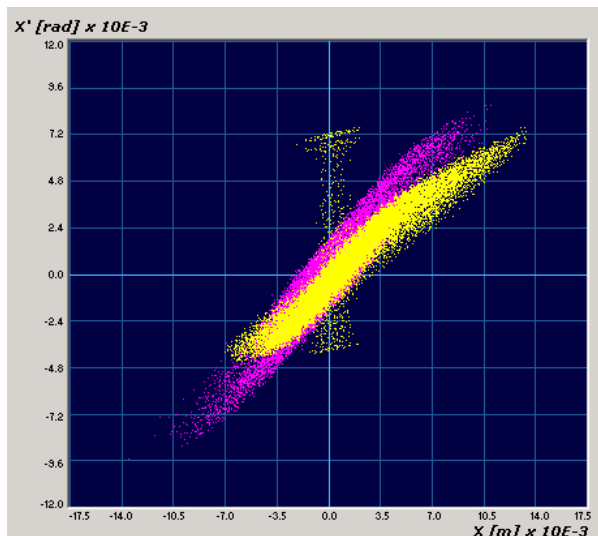


Figure 2: Transverse emittance measured with slit-and-grid (yellow) compared to expectation (pink) at 12 MeV.

*Indirect Measurements*

Following the measurements performed after the first DTL tank at 12 MeV [6], a period of installation of about 10 months has brought to the second type of measurement campaign. After the installation of the remaining DTL structures, the beam energy of 50MeV no longer allows direct emittance and energy spread measurements. Several RF structure are installed in one period and the beam is passed through unpowered RF structure to measure its quality at each energy step. This part of the commissioning has been accompanied by very accurate simulation as the beam in certain cases would travel 20 meters without any acceleration before being measured in the bench. Backtracking techniques have also been employed and a combination of backtracking/forward tracing has been employed to verify the consistency of the measurement. As of today we had two such campaigns, after the DTL from October to December 2015) and after the CCDTL from May 2016 to present. In the first case we were able to transport the 12 MeV DTL beam for 12 meters to the bench and measure its characteristics, as well as a 30 MeV beam. Emittance measured on the high energy bench is deduced from three (or more) profile measurements, a typical example shown in Figure 3. An optimal phase advance between the profiles, located at 0.7 and 0.9 m from each other allows for a very accurate reconstruc-

tion. Emittance measured at 50 and 80 MeV are shown in Figure 4 and 5 respectively.

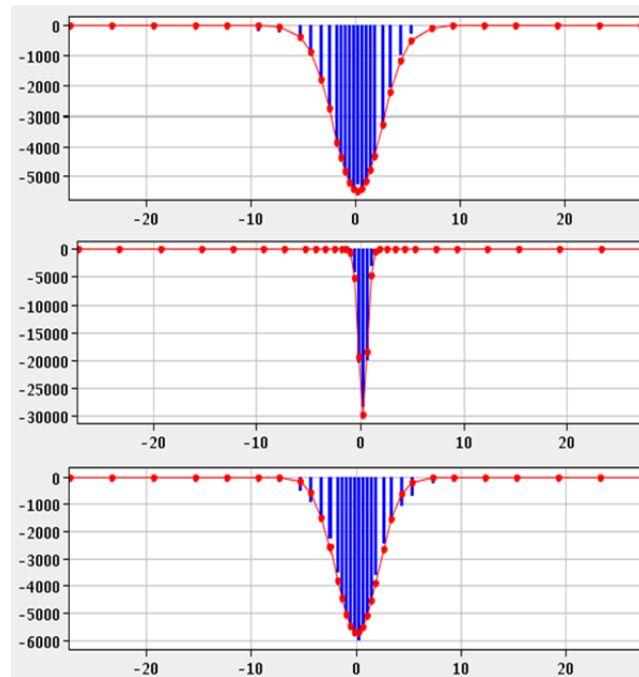


Figure 3: Typical transverse profiles (units of mm) obtained on the profile harps located on the high-energy measurement bench. The distance between the three profile-harp is 0.7 m and 0.9 m and the corresponding phase advance is suitable for emittance reconstruction.

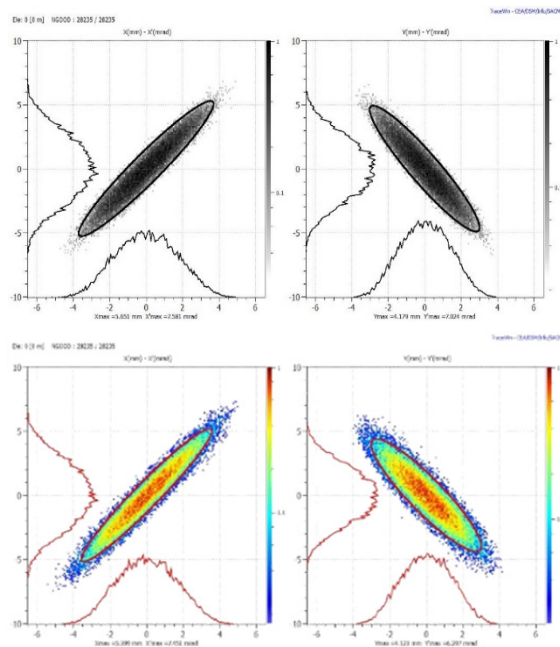


Figure 4: Transverse emittance measured at 50 MeV (bottom), compared to expectation (top).

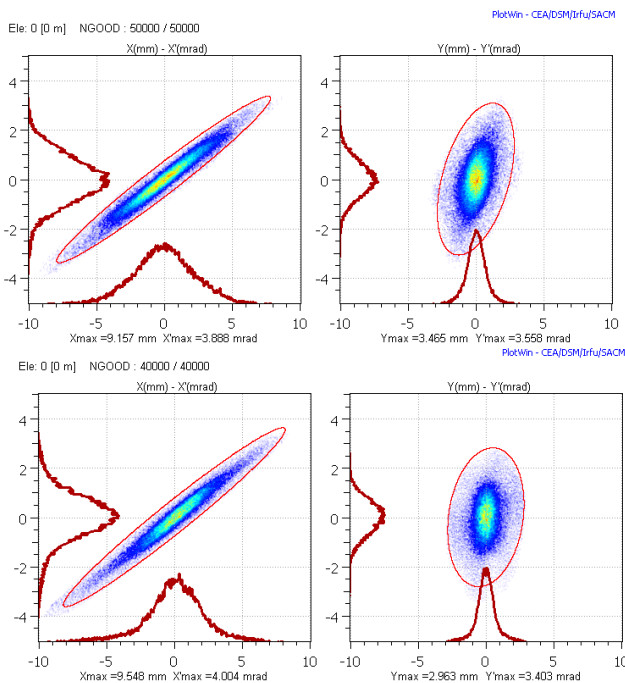


Figure 5: Transverse emittance measured at 80 MeV (bottom), compared to expectation (top).

In general the agreement between the transverse measurement be it emittance profile or steering is very good which is a key for a swift and successful commission and for being able to plan efficiently the beam time and the necessary ancillary services. In the author's opinion this is due to several factors including an accurate model of the machine, a fruitful exchange of essential information with the equipment responsible, a direct participation of RF and Beam Instrumentation experts to the commissioning and most important of all a thorough description of the input beam at the low energy end (after the source and the matching line to the RFQ) which has been gained by back tracing to the source a number of measurements taken under different condition therefore creating a beam representative of what is generated from the source, not only in term of distribution but also in terms of source variability.

### Setting of RF Cavities' Phase and Amplitudes

One of the challenges of Linac4 during operation is to be able to set 22 phases and 23 amplitudes of the RF cavities without dedicated longitudinal beam diagnostics. To address this issue a dedicated campaign of finding beam-based signatures (indirect measurements of beam longitudinal parameters) has been put in place after each structure. For the RFQ, amplitude a characteristics curves based on the transmission as a function of the RF voltage is sufficient to find the nominal amplitude. For the bunchers a combination of beam loading observations, (to find the two RF zero crossings) and transverse beam sizes on a wire scanners allows to identify the correct phase. Transmission through the DTL RF bucket [6] is a good indication of the buncher amplitude and phase. For the DTL,CCDTL and in the future for the PIMS a system based on measuring the average beam energy as a func-

tion of the cavity phase has been validated as an accurate method to complement RF pick-up calibrations. In particular a simple yet surprisingly precise method of measuring the beam energy gain through a cavity is the measurement of the beam loading. As the cavity is regulated such to have a constant voltage, the low level RF systems responds to the presence of the beam depending on the phase between the cavity and the beam. The LLRF system will increase/decrease the power in the cavity (Power forward) depending whether the beam is accelerated and therefore takes power from the cavity or is decelerated and therefore gives power to the cavity. Figure 6 shows the power to the cavity as the beam passes through at the accelerating phase or at the decelerating phase. By measuring the difference in power ( $\Delta P$ ) and the beam current ( $I$ ) at a downstream transformer the energy gain  $\Delta E$  can be calculated via the formula

$$\Delta E = \frac{\Delta P}{I}$$

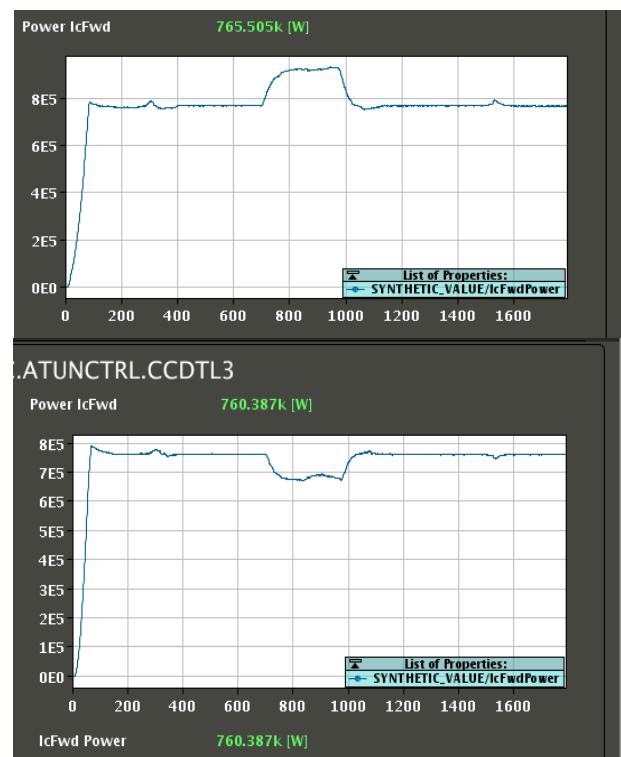


Figure 6: Forward power in CCDTL cavity number 3 when the beam is at the accelerating phase (top) or at the decelerating one (bottom).

Applying the above technique to the Linac4 CCDTL, has allowed to cross calibrate phase and amplitudes of the seven cavities. An example is shown in Figure 7.

For increased precision the same measurement has been repeated with a pair of pick-ups which allow the measurement of the time of flight. Some pick up are located in between cavities and some are located on the bench. During the measurements all the cavities downstream the one being measured have been switched off and detuned. The results are shown in Figure 8.

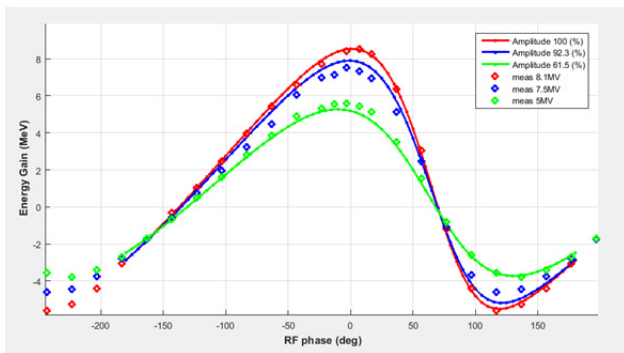


Figure 7: Energy gain in CCDTL cavity number 3 for three different amplitude as a function of phase. Solid lines are simulation and dots are energy measurements deduced from beam loading observations.

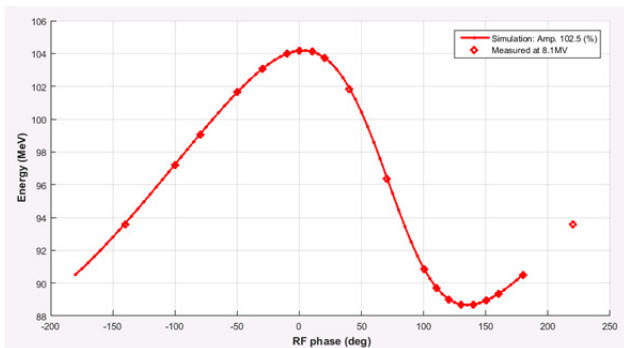


Figure 8: Energy gain in CCDTL cavity number 7 for three different amplitude and varying phase. Solid lines are simulation and dots are energy measurements deduced from Time-of-Flight measurements.

### HIGHLIGHTS

During the last six months a very useful tool has been deployed at Linac4. It is a system which will regulate the source parameters ( e.g. the gas injection and the RF power) while watching some given observables like the electron/H- ratio with the aim of delivering a constant flat pulse of current of the desired intensity and duration. It is important to stress that this system is not a random optimiser but rather an intelligent Autopilot which contains the knowledge and expertise of beam source expert developed during years. This autopilot is used also to guide the monthly caesiation needed for the correct functioning of the source.

### OUTLOOK AND POTENTIAL

The next steps are the commissioning to the final energy of 160MeV followed by a reliability run. From October part of the 160 MeV beam will be deviated towards the half-sector test (HST,[15]) which aims at testing half of the injection chicane into the PSB. The reason for this test is to gain experience on H- injection, and in general to mitigate the risks for future PSB H- injection, namely to study in time to steer the design of some critical components like the H- stripping foil unit, the H0/H- monitor and dump for unstripped/partially stripped particles and the relative instrumentation.

Linac4 is a machine with an enormous potential for upgrade: the peak current limit for beam stability is 80mA – 3 times what we run today, the beam duty cycle limit is 5% - 10 times what we run today and the chopping pattern (sequence of 352MHz micro-bunches) is extremely flexible and can be repeated at frequency up to 20MHz. The potential will be fully exploitable only if the beam formation, extraction and transport through the pre-injector are studied in more details and solution to the present limitation and bottlenecks are found.

### ACKNOWLEDGMENT

I wish to thank the member of the commissioning team from BE/ABP. Members of the RF, BI, VAC, CO, RP and EPC groups were always there when needed, to all of them goes my thanks.

### REFERENCES

- [1] F. Gerigk, M. Vretenar (eds.), Linac4 Technical Design Report, CERN-AB-2006-084.
- [2] A.M. Lombardi, *et al.*, “Beam Dynamics in Linac4 at CERN”, in *proc. HB’08*, Nashville, Tennessee, Aug. 2008, paper WGB14.
- [3] E. Benedetto, “Space Charge effects and Mitigation in the CERN PS Booster, in view of the upgrade”, presented at HB2016, Malmö, Sweden, July 2016, paper THPM6X01
- [4] G Bellodi *et al.*, “3 MeV Test Stand commissioning report”, CERN-ACC-2013-0259.
- [5] M. Paoluzzi *et al.*, CERN-AB-Note-2008-040 (2008) F.Caspers *et al.*, “The CERN-SPL Chopper Concept and Final Layout”, EPAC’04, Luzern, Switzerland (2004)
- [6] A.M. lombardi., “Commissioning Of The Low-Energy Part Of Linac4”, in *Proc. Linac’14*, Geneva, Switzerland, Sept. 2014, paper MOIOA02.
- [7] S. Ramberger , “CERN Linac4 Drift Tube Linac Manufacturing and Assembly”, in *Proc. Linac’14*, Geneva, Switzerland, Sept. 2014, paper THPP036.
- [8] A. Tribendis , “Construction and RF Conditioning of the Cell-Coupled Drift Tube Linac (CCDTL) for Linac4 at CERN” in *Proc. Linac’14*, Geneva, Switzerland, Sept. 2014, paper WEIOA01.
- [9] F. Gerigk, “The Hot Prototype of the PI-Mode Structure for Linac4”, in *Proc. Linac’10*, Tsukuba, Japan, Sep. 2010, paper MOP071.
- [10] S. M. Gibson, *et al.*, “A Fibre Coupled, Low Power Laserwire Emittance Scanner at CERN Linac4”, IPAC’14, Dresden, Germany, May 2014, paper THPME190.
- [11] V. Dimov *et al.*, “Beam commissioning of Linac4 up to 12MeV”, in *Proc. IPAC’15*, Richmond, VA, USA, May 2015, pp. 3886-3889.
- [12] G. Bellodi *et al.*, “Longitudinal beam profile measurements in Linac4 commissioning”, in *Proc. Linac’14*, Geneva, Switzerland, Sept. 2014, 108-110.
- [13] J.B. Lallement *et al.*, “Linac4 transverse and longitudinal emittance reconstruction in the presence of space charge”, in *Proc. Linac’14*, Geneva, Switzerland, Sept. 2014, 913-915.
- [14] V. Dimov, “Emittance Reconstruction Techniques in Presence of Space Charge Applied during Linac4”, presented at HB2016, Malmö, Sweden, July 2016, paper WEPMIY01.
- [15] W. Bartmann *et al.*, New PSB H- Injection and 2 GeV Transfer to the CERN, in *Proc. HB 2014*, East-Lansing, USA, Nov. 2014, paper WEO4AB02.