Linac4 PIMS CONSTRUCTION AND FIRST OPERATION

R. Wegner, G. Favre, P. Françon, J-M. Geisser, F. Gerigk, J-M. Giguet, J. Hansen,
J-B. Lallement, A. Lombardi, S. Papadopoulos, M. Polini, M. Redondas Monteserin,
T. Tardy, N. Thaus, M. Vretenar, CERN, Geneva, Switzerland
G. Brzezinski, P. Krawczyk, L. Kujawinski, M. Marczenko, NCBJ*, Swierk, Poland
W. Behr, M. Pap, FZJ GmbH†, Jülich, Germany

Abstract

Linac4, CERN's new H^- injector Linac uses PI–Mode Structures (PIMS) for the energy range between 103 and 160 MeV. 180 copper elements for 12 PIMS cavities have been fabricated in a collaboration between CERN, NCBJ and FZJ from 2011 to 2016. The cavities have been assembled, RF tuned and validated at CERN. This paper reports on the results as well as the experience with construction, installation, RF conditioning and first operation with beam.

INTRODUCTION

12 PIMS modules are employed in Linac4, CERN's new H^- injector, for accelerating the beam from 103 to 160 MeV (β 0.43 to 0.52) at a frequency of 352.2 MHz. It is the first time a π–mode structure is used for a medium energy range in a high intensity proton Linac. This choice has been made because (a) all other Linac4 components are normal–conducting — superconducting cavities (e.g. spoke cavities) would require a cryogenic installation, (b) the same frequency as for all other accelerating structures can be used at the same peak power level of about 1 MW and (c) the PIMS cavities are mechanically robust and comparably simple to design, construct and RF tune.

The PIMS design, its electromagnetic and its thermal behaviour are described in [1, 2]. The Linac4 PIMS cavity parameters are listed in [3, 4]. A construction concept and a full scale prototype have been developed at CERN during 2009–2010 [5, 6]. Main choices were to align the 15 cavity elements from the outside and to electron–beam (EB) weld them together using specially designed tooling for alignment. By EB welding, the material properties of the 3D forged OFE copper are preserved. The prototype cavity was successfully tested at high power [7]. It fulfils all requirements for Linac4 and future upgrade options, so that it became the first Linac4 PIMS cavity.

A collaboration agreement was signed in 2011 between the National Centre for Nuclear Research (NCBJ) in Poland and CERN for the fabrication of 96 discs and 84 rings for 12 PIMS cavities (more precisely, 11 PIMS cavities and a PIMS like debuncher cavity with a larger beam aperture). NCBJ subcontracted the EB welding of ports to rings to Forschungszentrum Jülich (FZJ) in Germany. In March 2016 the last PIMS elements were delivered to CERN. The cavities were assembled until June and installed in September 2016. Figure 1 shows a photo of PIMS cavities in the Linac4 tunnel.

* National Centre for Nuclear Research, Andrzeja Soltana 7, 05-400 Otwock–Swierk, Poland
† Forschungszentrum Jülich GmbH, Central Institute of Engineering, Electronics and Analytics - Engineering and Technology (ZEA-1), 52425 Jülich, Germany

Figure 1: PIMS cavities installed in the Linac4 tunnel.

PRODUCTION AND QUALITY CONTROL OF PIMS ELEMENTS AT NCBJ AND FZJ

Every PIMS cavity is made of 8 discs and 7 rings of different subtypes (2 end discs, 2 central discs with asymmetric nose cones, 4 standard discs, 2 pick–up rings with ports for piston tuners and RF antennas, 4 standard rings with tuner ports and 1 waveguide ring with ports for tuner, RF antenna and waveguide connection). The geometry of every cavity is adapted to the average energy of the seven gaps, so that rings of different cavities vary in length while discs of different cavities possess different nose cone shapes. Discs and rings were machined in several rough–machining and final–machining steps. Milling and boring was mainly used for discs (Fig. 2) and turning for rings and end discs. The production at NCBJ has been a mixture between a series production of one element type and a cavity–by–cavity production as preferred by CERN for the final assembly where only complete cavities (made of all 15 elements) could be treated. Jointly the priorities were optimised and several times the cavity order has been re–adjusted to machining advances and difficulties.

While the tolerances for the inside RF geometry were comparably straight forward to reach, a lot of effort was needed to achieve the tolerances for alignment (outside diameter, coaxiality, planarity). The interlocking system which was implemented to pre–align discs and rings turned out to be particularly challenging. The gap of 0.05 to 0.10 mm required machining of grooves at a diameter of 525 mm to

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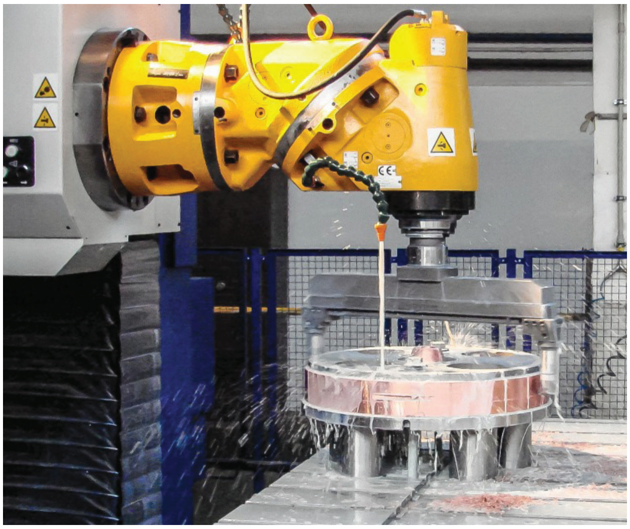

Figure 2: Machining the outer surface of a disc.

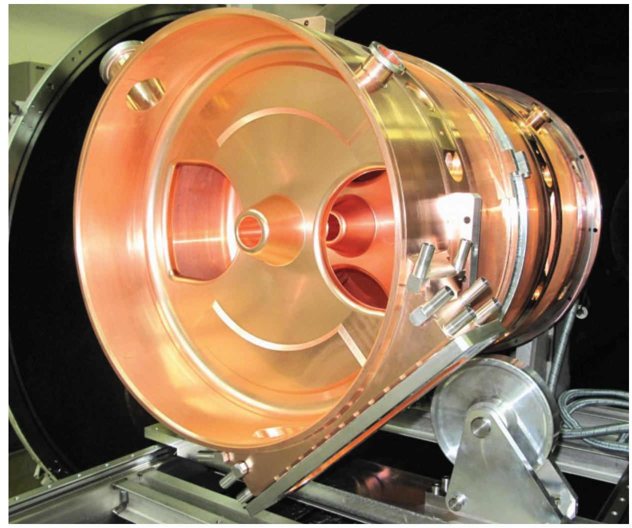

Figure 3: EB welding of a PIMS cavity at CERN.

a tolerance of ±0.012 mm. Whenever the gap of adjacent elements was below 0.05 mm, one of the elements would be individually re–machined. In total 336 of those shapes were machined and carefully checked so that not a single assembly issue occurred.

All 180 elements were fully measured in the metrology laboratory at NCBJ. All 16 cooling channels of the discs were measured in 3D to evaluate the remaining wall thickness to vacuum and the distance between cooling channels. In total about 16 000 metrology values are reported for the 180 PIMS elements, among them 7 500 for cooling channels.

In FZJ, 8 ports were EB welded to 6 rings per cavity – giving a total seam length of 25 m. The joining zones were locally pickled and cleaned immediately before welding to guarantee a reproducible weld surface. All welding joints were helium leak tested in Jülich and checked by stringent X–ray tests in NCBJ.

All 180 PIMS elements were vacuum leak tested at NCBJ. A special tooling made of two stainless steel covers was used to close a vacuum volume with the PIMS element under test. Cooling channels of discs were connected and pressured up to 16 bar with helium while the volume was pumped down and the helium content inside was steadily measured. All elements have been leak tested at a rate below $2 \cdot 10^{-10}$ mbar l s^{-1}.

Waveguide rings are the only PIMS elements where the ports (and cooling channel connections) have been vacuum–brazed due to the complex shape of the waveguide port. The copper ring was heat treated twice during the machining process and the stainless steel waveguide flange once to avoid deformation during brazing. However, for a few rings the waveguide flange had to be carefully re–machined after brazing to reach the required planarity of 0.1 mm.

CAVITY ASSEMBLY AT CERN

Arriving at CERN, the elements were inspected, surface treated where needed, vertically assembled and RF bead–pull measured. The results were used to determine the amount of re–machining to be applied to the tuning rings of the discs. A high repeatability from cavity to cavity has been noticed, underlining the machining quality achieved at NCBJ. After the validation RF measurement, the 15 cavity elements were cleaned and EB welded (see Fig. 3). Prior to welding, all contact surfaces of adjacent elements were scraped by hand to fully remove the oxide layer and contaminants. In total about 600 m have been treated millimetre by millimetre across a wall thickness of 10 mm. This time consuming process proved to be the key in producing homogeneous and 100% leak tight weld seams over a length of nearly 300 m.

The final steps in the assembly process were the cavity survey, vacuum leak testing and residual gas analysis (RGA), the final RF tuning by cutting piston tuners, the preparation of ports for metallic gaskets, the connection of cooling channels and the cooling water pressure test. For Linac4, each PIMS cavity has 2 parallel cooling circuits which connect the individual channels of the discs in series. For high duty cycle operation (10% and above), up to 112 channels per cavity can be connected in parallel.

RESULTS

All 12 PIMS cavities and the debuncher were tuned to the nominal resonant frequency of 352.2 MHz at 22°C with an electric field flatness of better than ±0.9% (acceptable are up to ±5.0% [8]). The tuning range of ±110 kHz is rather comfortable and can compensate temperature variations of up to ±12 K. The Q-values of the cavities and the effective shunt impedances are about 8% higher than foreseen (Fig. 4) due to a very smooth surface ($R_a \approx 0.3$ μm) and less penetration of the piston tuners — gained by a slightly increased height of the tuning rings.

Another important parameter is the cavity straightness $\triangle R$ (the maximum deviation of the cavity axis from a straight line). The requirement is $\triangle R \leq 0.3$ mm. The machining

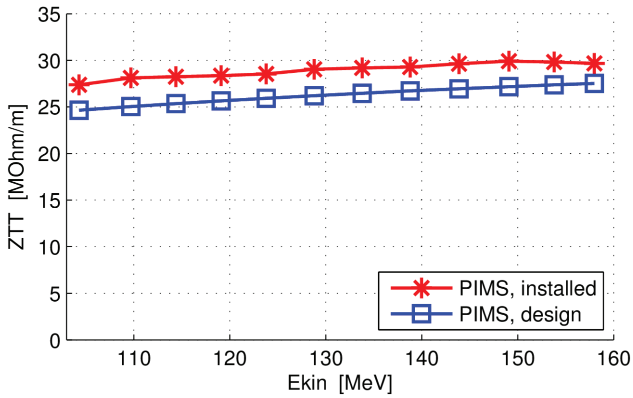

Figure 4: The effective shunt impedance per length as a function of the particle energy for the design (blue squares) and the constructed PIMS cavities (red stars).

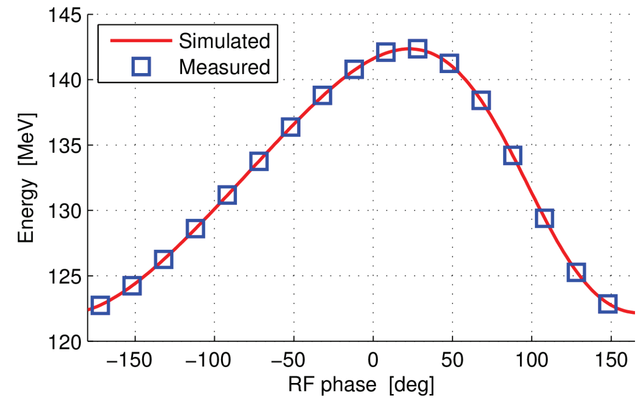

Figure 5: Simulated (red curve) and measured (blue squares) beam energy when sweeping the RF phase of PIMS cavities 7 and 8 (which are jointly powered by the same klystron).

precision, the alignment accuracy during welding and the welding procedure influence the cavity straightness. All 13 PIMS cavities were measured to be within $\triangle R \leq 0.1$ mm — a factor 3 better than required. The best cavity even reaches $\triangle R < 0.04$ mm. The cavity length is less important because it can be compensated by bellows up to ±6 mm. Still all cavities deviate from the theoretical length (1.4 to 1.6 m) by less than ±0.15 mm (≤ ±0.03 mm for the 6 best cavities).

All 13 PIMS cavities successfully passed the final vacuum leak and RGA tests at CERN.

CONSTRUCTION EXPERIENCE

The field distribution in an unstabilised π-mode structure is rather sensitive to frequency changes. It proved to be a good choice to use a comparably strong cell–to–cell coupling of about 5% to reduce this sensitivity.

Due to the relatively big coupling slots between cells and the wide waveguide port opening (303 x 50 mm cross section) it is possible to pump PIMS cavities through the waveguide, avoiding pumping ports on the cavity itself.

The tight machining tolerances of PIMS elements required a longer learning period (clamping procedure, development of tooling, adaptation of technological choices, usage/exchange of cutting tools etc.). A relaxation of the alignment tolerances could be investigated for another cavity construction — the straightness requirement ($\triangle R \leq 0.3$ mm) could for example be relaxed by opening the cavity's beam aperture (40 mm for Linac4 PIMS) slightly. However, reliable numbers for the production time and cost as functions of design parameters are usually difficult to obtain during the development process and also the assembly concept might change depending on the requirements for alignment.

The tuning rings of the discs were initially designed to increase the frequency by 1.5 MHz, corresponding to 9 mm in height. Since the material for the discs was sufficiently thick and since 3D RF simulations could predict the amount of re–machining with a precision of 0.01 mm, it was decided to double the tuning ring height. This extra margin allowed to recover two problematic parts.

The tuner-adjustable waveguide coupler (TaCo) [9] proved to be a robust coupler and handy in matching cavities to the desired coupling. A movable tuner in the TaCo of the debuncher cavity can vary the coupling factor between 1.0 and 8.5, which is advantageous for off–resonant swings.

EXPERIENCE IN OPERATION

The PIMS cavities conditioned rapidly under high power. 110% of the nominal field level could typically be reached within 650 000 pulses, including a comprehensive conditioning across the multipactor regime between 0.1 and 10 kW of input power [10].

A 15 mA H^- beam was successfully accelerated from 103 to 107 MeV in the first PIMS cavity in July 2016. After the final installation phase, the remaining 11 PIMS cavities were progressively commissioned with beam, reaching the final energy in October 2016. The nominal phase and power level for each cavity were determined by beam based measurements. The beam energy was measured by the Time of Flight (ToF) for a varying cavity phase and compared to the expected energy variation calculated from the integrated field map. This precise method relies on average beam properties and is independent of space charge and beam distribution. Figure 5 shows the evaluation for a sweep of PIMS cavities 7 and 8, which are jointly connected to the same klystron. The very good agreement between simulation and calculation confirms both, the simulation model and the field distribution inside the PIMS cavities.

Linac4 was restarted in February 2017 after a two–month shutdown. Since then the PIMS cavities reliably accelerate the beam to 160 MeV.

SUMMARY

The 12 PIMS cavities constructed in a collaboration between CERN, NCBJ and FZJ were completed and installed in the Linac4 tunnel in 2016. They comfortably exceed the requirements for RF, straightness and vacuum and have been routinely operated for 3 months, accelerating the H^- beam from 103 to 160 MeV.

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