CAVITY PROCUREMENT AND QUALIFICATION PLAN FOR LCLS-II*

F. Marhauser#, E.F. Daly, J.A. Fitzpatrick
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

Abstract

LCLS-II will incorporate a new 4 GeV superconducting linear accelerator. This paper describes the plans for the industrial procurement of the dressed accelerating cavities and the prerequisites for vendor qualification, which aims to transfer the technology of cavity Nitrogen-doping, developed at US laboratories, to the commercial partners in its initial phase.

INTRODUCTION

The Linac Coherent Light Source (LCLS)-II project at the SLAC National Accelerator Laboratory (SLAC) requires a 4 GeV continuous-wave (CW) superconducting radio frequency (SRF) linear accelerator in the first kilometer of the SLAC tunnel. The aim is to operate a high repetition rate X-ray free-electron laser, i.e. with electron pulses at rates approaching 1 MHz delivered to two new undulators covering the spectral ranges of 0.2-1.2 keV and 1-5 keV, respectively. The collaborative project brings together six US institutions, which in alphabetical order are Argonne National Laboratory (ANL), Cornell University, Fermi National Accelerator Laboratory (FNAL), Thomas Jefferson National Accelerator Facility (JLab), Lawrence Berkeley National Laboratory (LBNL), and SLAC [1].

As part of their responsibilities FNAL and JLab will build the 1.3 GHz accelerating cavity cryomodules (CMs) concurrently at two assembly lines. The procurement of CM components are distributed among FNAL and JLab, with the exception of SLAC acquiring the main RF power couplers [2]. In preparation of the CM assembly, FNAL has been leading the LCLS-II CM and cavity design efforts, while JLab is directing the procurement of the production cavities. Engineering designs heavily borrow from the mature TESLA technology utilized at the European XFEL at DESY to leverage the vast experience. Similarly to the EU-XFEL strategy, LCLS-II relies on 'build-to-print' SRF cavity manufacturing. This implies that vendors have to follow precise technical specifications and procedures. Each cavity will be delivered welded into a helium vessel and shipped under vacuum assembled with RF qualification hardware ready for high power acceptance testing in a vertical dewar. The project bears the risk of cavity performance. Qualifying cavities proceed immediately to CM string assembly.

Currently, activities concentrate on building two prototype CMs, one at each laboratory. This consumes 16 project-owned ILC-type nine-cell cavities that were built by AES, Inc. [3]. The near-future cavity large-scale fabrication comprises 266 production LCLS-II cavities for the assembly of additional 33 CMs (16 at FNAL, 17 at JLab) leaving two cavities as spares. This will complete the required 35 CMs for the envisioned 4 GeV energy gain, which can be achieved at an accelerating field (E_{acc}) of 16 MV/m in average accounting for 18 (~6%) unpowered cavities with ~1 % reserved for energy feedback systems, while two third-harmonic (3.9 GHz) decelerating CMs are employed for phase-space linearization housing 16 nine-cell cavities.

The procurement of the dressed accelerating LCLS-II cavities is divided into three phases:

Phase I: Vendor Qualification (VQ)
Phase II: First Article Production (16 cavities)
Phase III: Full Production (250 cavities).

The project reserves the option for a Phase IV to acquire additional cavities depending on upgrade needs.

COMMERCIAL VENDORS FOR SERIES FABRICATION

Following the public request for proposals of LCLS-II production cavities announced early October 2014, bidders' proposals were collected in December. Technical evaluations were conducted in compliance with JLab's standard 'Best Value' source selection process, which has been approved by the US Department of Energy (DOE). The Buy American Act applied to non-domestic vendors. Members of the source selection team, comprising technical experts from both FNAL and JLab, evaluated the proposals independently based on experience, past performance, resources, understanding of requirements and quality assurance. The findings were comprised in a final technical evaluation report for procurement recommendation. The DOE followed the teams' recommendation for a dual award. Subcontract awards were executed by end of May 2015. The awardees are RI Research Instruments, GmbH (Germany) [4] and Ettore Zanon, S.p.A. (Italy) [5] with each vendor producing half of the required quantity of cavities (8+125) in Phases II and III.

* Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177 with supplemental funding from the LCLS-II Project U.S. DOE Contract No. DE-AC02-76SF00515. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.
# marhause@jlab.org

ISBN 978-3-95450-178-6

PHASE I – VENDOR QUALIFICATION

The LCLS-II SRF linac is designated for CW operation. In comparison to the pulsed EU-XFEL facility, this would increase the dynamic heat load about ten-fold at the same field levels. Consequently with start of the project, it has been envisioned to utilize high-Q_0 N-doped cavities as pioneered at FNAL [6] to significantly reduce the cryogenic load to the helium refrigeration system saving capital and operation costs. The project objective is to achieve a $Q_0 = 2.7e10$ at 2 K and $E_{acc} = 16$ MV/m with cavities installed in CMs. To allow for a performance degradation from vertical tests to the fully dressed stage in a CM, a vertical acceptance criteria has been enforced requiring cavities to meet a Q_0-value of 3e10 at 2 K and at $E_{acc} = 18$ MV/m. LCLS-II has therefore implemented Phase I prior to cavity production, which is specifically dedicated to the transfer of the cavity Nitrogen-doping process for vendor qualification in a timeframe of six months.

Nitrogen-Doping and Electropolishing Process

During 2014, a concerted R&D activity took place at Cornell University, FNAL and JLab to scrutinize the impact of N-doping process parameters (temperature, time, and N-pressure) on performance at 1.3 GHz (for single and multi-cell cavities) in conjunction with refining the removal amount by Electropolishing (EP). The process can be briefly summarized as an injection of high purity grade Nitrogen gas at low pressure into the furnace following a UHV high-temperature cavity bake-out at 800°C for three hours (H degassing), such that the nitrogen can thermally diffuse into the surface (few ten microns) within a short period of time (few minutes). Once the nitrogen supply is stopped, the cavity may anneal at 800°C (few minutes). Afterwards all heater elements are turned off for an unconstrained cool-down maintaining active pumping. The process parameters and allowable ranges are summarized in Table 1.

Table 1: Furnace Process Parameters and Allowable Control Ranges as Part of the High Temperature Furnace Run for LCLS-II Cavity Nitrogen-Doping

Step	Temperature (°C)	Duration	N-Pressure (mTorr)
H degassing	800 ± 10	180 ± 5 min	0
N-Doping	800 ± 10	2 min ± 6 sec	26 ± 4
Annealing	800 ± 10	6 min ± 6 sec	0

The N-doping is succeeded by a well-controlled light EP removing a layer of a few microns from the interior. The EP process does usually result in a differential removal between cavity equators and irises along the cavity and thus can either refer to the removal at cell equators or the average removal derived from integrating the process current over time [7]. The latter can be readily assessed given the internal cavity surface area and the bulk removal rate (cm^3 Nb/Cb) based on the chemical processes of the surface with the HF:H_2SO_4 electrolyte, which yields five electrons per one Nb atom removed. Hereby, the EP process at the Nb surface can be described as a balance of the growth of Nb_2O_5 via anodization by sulfate ions and the dissolution of the niobium oxide by fluorine ions.

A nomenclature describing the post-processing treatment according to 'N(min)A(min) EP(microns)' has been accepted among the laboratories [8]. The prescribed recipe for vendors is thus dubbed N2A6 EP5.

Facility Upgrade Efforts at Vendor Sites

The N2A6 EP5 recipe is a trade-off between the preservation of the high Q_0-value - around 3e10 at 2 K and $E_{acc} = 16$ MV/m - and the experimentally observed reduction of the quench-field limit when compared to cavities in an undoped stage, i.e. after conventional treatment methods. The recipe provided relatively consistent results among the nine-cell cavities tested at the three partner laboratories. This implies rather low risks for the technology transfer to industry. The argument is substantiated insofar as laboratories employed differing hardware and controls for both the furnace and the EP facilities to meet the process requirements. Similarly, vendors are flexible to adapt specific hardware and controls best suitable for existing facilities as long as being compliant with the specifications. For instance, N-doping may be carried out without active pumping if the pumping speed cannot keep up with the gas load. The injection of nitrogen then can occur intermittently in more frequent time periods. In this respect, the N-absorption decaying as a function of time and depending on the total Nb surface must be well compensated for, particularly since vendors aim to load their furnaces with up to four cavities during each furnace run to maximize the production throughput. The aim is to well control the average pressure during injection. The process is required to be automated by software control using a programmable logic controller that is linked to the mass flow controller. All process parameters including mass spectra from a residual gas analyzer will be continuously monitored and recorded for quality assurance and documentation.

Presently, both vendors are upgrading their furnaces. The first step is to verify proper control of the pressure during the N-injection period utilizing a 'dummy' Nb nine-cell cavity, which provides a similar surface as an LCLS-II cavity (interior plus exterior). The dummy cavity is not foreseen for RF testing and thus may have blemishes. Upon completion of these control runs, the vendors may commence with N-doping of VQ cavities, preparation of which have been estimated to take about one month at each site. All VQ cavities are supplied by the project in an undoped state, but not before passing RF vertical 'baseline' tests at JLab. Hereby, the criteria is to guarantee a $Q_0 > 1e10$ at 2 K and at $E_{acc} = 16$ MV/m with a quench field beyond $E_{acc} = 25$ MV/m. Figure 1 for instance comprises acceptable test results of two VQ cavities and four prototype CM cavities after conventional post-processing treatments. Additionally, it shows the performance of a cavity following the N2A6 EP5 recipe.

This exemplifies the characteristic rise of the Q_0 at lower field levels that may result in Q_0 values as high as 4e10 at 2 K. It is this Q_0-rise, which is an indication of a successful N-doping process.

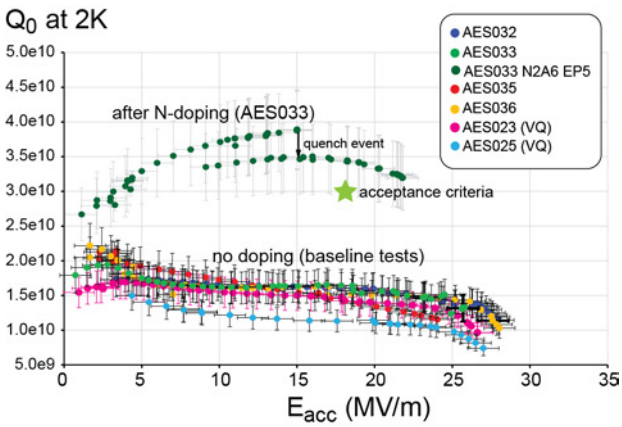

Figure 1: Vertical tests of nine-cell cavities at JLab.

The N2A6 EP5 recipe will be strictly adhered to by the vendors. Alterations at future production stages are conceivable if substantial evidence of improvements can be asserted justifying an adjustment to the recipe. E.g., the cause of the quench-field reduction experienced after N-doping (few MV/m) is not fully understood and under scrutiny (see for instance ref. [8]).

In parallel to the furnace upgrade activities, test runs in vendor's EP facilities are currently conducted to assure a well-controlled EP removal with focus on lowering the cavity wall temperatures (< 25°C). Chilling the incoming acid and minimizing temperature variations by fine-tuning of process parameters is one objective to minimize differential removal rates in the cavity interior. One directive is to minimize the cathode masking as best as practicable given the individual facility constraints. This not only will be more consistent with the configurations used at ANL (EP for FNAL) and JLab during the project's R&D phase, but maximizes the cathode surface area as a benefit. As a consequence, the required current flow is achieved with minimum polarization of the cathode, which reduces the reaction rate of parasitic electrochemical processes, e.g. responsible for the precipitation of solid sulfur [9]. The objective is therefore to lower the applied voltage between the cathode and the cavity (anode), while operating at the lower end of the "plateau" on the I-V curve, i.e. when the entire Nb surface is anodized. An increase in voltage in this regime does not increase the steady-state current flow. Hence, the power dissipated is given by the locally dependent oxide layer thickness presenting a resistive impedance for the current flow ($R \cdot I^2$). Temperature control is paramount to minimize the variations of the dissipated power in order to result in more uniformity of the interior removal along the cavity, which otherwise would lead to increased reaction rates and local current excursions. Outside water spray cooling of the cavity as routinely carried out at JLab has been found to be beneficial to keep cavity wall temperatures well controlled. This also fully eliminated the sulfur contamination such that ethanol rinsing of the cavity and the facility plumbing system has not been a requirement. As of writing, the first two VQ cavities have been delivered to vendor sites in preparation of the N-doping, while the two remaining two cavities are awaiting baseline tests at JLab before shipment. Upon completion of the N-doping and light EP, vendors will send the cavities back under vacuum and with vertical test hardware installed ready for cryogenic acceptance testing. Note that completion of Phase I mandates that each company demonstrates a successful N2A6 EP5 process of two VQ cavities consecutively. This rationale enforces that the technical prerequisites are met for the application of a reliable N-doping process viable for the series fabrication of high-Q_0 cavities at industries. The completion of Phase I is projected for early 2016. In the unlikely event that a cavity would not satisfy the requirements – and since the cavity supply is limited - it would need to be 'reset' removing ~50 µm by EP, which restores the Nitrogen concentration to its original level [10]. The cavity would then need to repeat the VQ cycle, but not without understanding the cause of rejection by the collaboration partners.

PHASE II, III, IV – DRESSED CAVITY PRODUCTION

Dressed cavity production phases do not differ from each other with respect to the production flow, only the throughput. While Phases II and III are scheduled to meet the baseline needs, Phase IV is optional. The contracts grant seven months for the delivery of the first eight cavities after receipt of the offer in Phase II for each vendor. Full production in Phase III mandates a more aggressive delivery of 125 cavities per vendor in 15 months overall. This time line has to tie in with the assembly of one cryomodule per month each at FNAL and JLab.

The production requires vendors to follow strict regulations outlined in a series of technical specifications covering the complete production flow. Figure 2 illustrated the primary fabrication steps by means of the cavity process flow chart. It is divided into the mechanical fabrication (top), the main chemical post-processing including a bulk EP and the N-doping (middle), and the final light EP, helium vessel welding, vertical test hardware assembly and preparation for shipment (bottom). Note that the usual low-temperature bake-out around 120°C at the end of the post-processing cycle is omitted. The procurement foresees three hold points (red hexagons) during the fabrication cycle, which occur

1. after the mechanical fabrication of bare cavity,
2. after N-doping, and
3. before shipment.

The hold points enforce the review of recorded quality assurance documents of individual cavities. Upon

ISBN 978-3-95450-178-6

approval the cavity may proceed according to the flow chart. At hold point 1, the shape and mechanical dimensions, visual inspections data, and successful leak tests are verified. At hold point 2, the N-doping doping parameters are reviewed. At hold point 3 the successful pressure test on the helium circuity and leak test of the helium vessel is verified. Furthermore, the RF measurements are reviewed at each hold point. In fact, the cavity will be placed on the tuning machine four times throughout the production cycle to be compliant with tuning and field flatness specifications.

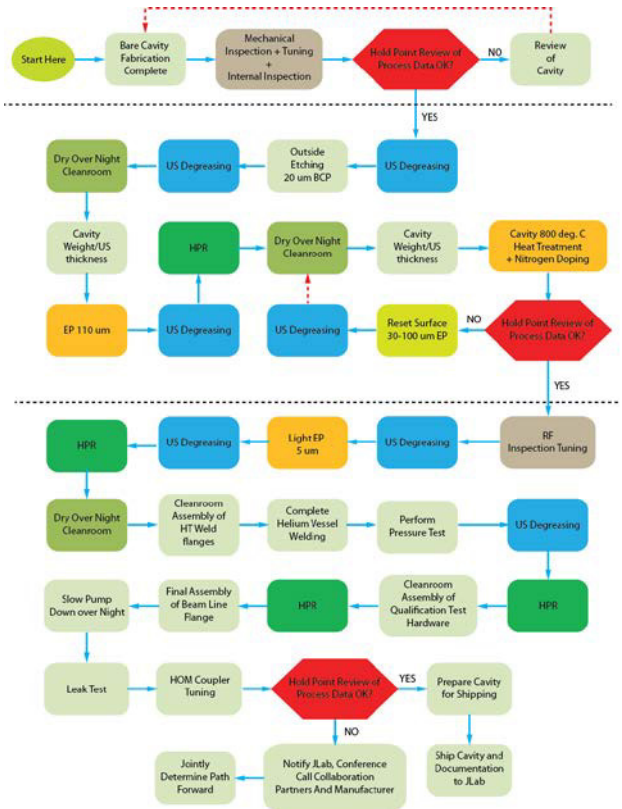

Figure 2: LCLS-II cavity process flow chart (US = Ultrasonic, HPR = High Pressure Rinsing).

It must be noted that DESY has granted permission to use technical documents employed for the series fabrication of the dressed 1.3 GHz Tesla-type nine-cell cavity for XFEL, which after appropriate modifications also form the basis for the LCLS-II production cavities. The modified documents as listed in Table 2 have been released with the request for purchase in October 2014. The aim was to minimize alteration as best as practicable in order to follow the 'build-to-print' approach successfully applied by industry. Deviations however were required since design changes were mandatory for the CM and its cavities as a consequence of CW operation as well as the aim to preserve the high Q_0-values of the cavities, which implied the need of fast cryogenic cool-down with rapid magnetic flux expulsion. The geometrical changes for the cavities are reflected in manufacturing drawings provided by FNAL, which mainly impacts the helium vessel (cf. Fig. 3). Compared to the XFEL design, the helium vessel features a larger chimney diameter, and shifted to the inside of the cavity, while two lateral helium fill lines are employed, which aims to improve magnetic flux expulsion from the inside out to the beam tubes.

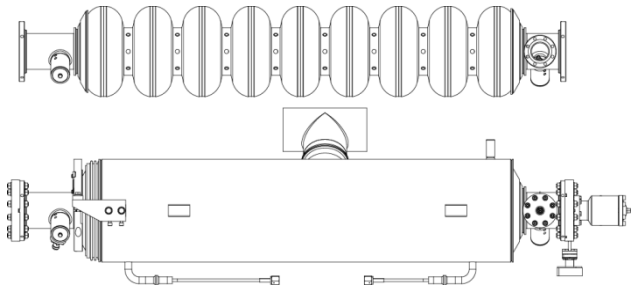

Figure 3: Sketch of the LCLS-II 1.3 GHz nine-cell cavity with view facing the main coupler port to the right. Top: Bare cavity, Bottom: Dressed cavity after helium vessel welding with vertical qualification hardware.

Table 2: Modified XFEL Documents as Applied to LCLS-II Production Cavities

Document	Modified XFEL Document Description
XFEL/002	Technical Specifications for the Series Mechanical Fabrication Superconducting 1.3 GHz Cavities for the LCLS-II Project
XFEL/003	Quality Assurance and Quality Control Specifications
XFEL/004	Descriptions, Abbreviations, Drawing and Cavity Production Traveler Numbers
XFEL/005	Helium Leak Tests
XFEL/006	Special Tools and Equipment
XFEL/009	Flow Chart Dumb-Bell Production
XFEL/010	Recommendations for the Machining of Niobium and Niobium-Titanium
XFEL/011	Recommendation for the Treatment of Niobium Parts (Handling, Cleaning, Etching, Welding)
XFEL/012	Overview List and Detailed Inspection List of Tests and Demonstrations
XFEL/014	Frequency Measurement on Dumb-Bell, Half Cell, End Group and Cavity
XFEL/015	Technical Specifications for the Series Production of Helium Tanks
XFEL/016	Specifications for Welding the Helium Tank to the Cavity
XFEL/017	Helium Tank Welding
XFEL/A-D	Series Surface and Acceptance Test Preparation of Superconducting Cavities for the LCLS-II Project

As a consequence of the modified helium vessel, changes were made to the titanium transition rings welded to the NbTi conical end discs and the bellows design when compared to the XFEL design. The bellows are located on the tuner side, and enable the end lever tuner to keep the cavity under compression. The changes to the helium vessel together with subtle differences of cavity features - as a consequence of using earlier DESY drawings - has triggered concerns with the use of existing

vendor tuning machines. The issues were addressed by DESY in collaboration with JLab and resolutions elaborated successively, which has led FNAL to revise the drawings according to the recommendations. Upon release of the finalized drawing package, vendors will prepare their own manufacturing drawings to be sent to JLab for final review and approval in collaboration with FNAL. After approval, the cavity production may begin.

Note that design and safety analyses will be performed by FNAL and documented in accordance with FNAL guidelines. Key specifications include weld joint designs, safety factor for designs, maximum allowable working pressure, size and type of pressure relief devices, material testing requirements and non-destructive examination. A Third Party Inspector (TPI) may be hired to ensure that the fabrication is performed to ASME standards and documented at vendor locations. This is consistent with XFEL cavity production, i.e. XFEL was required to use a TPI to satisfy Pressure Equipment Directive (PED). LCLS-II has an option to use TPI or project staff based on a cost and benefit analysis. The design will be compliant with the federal worker safety and health program 10CFR851 as opposed to PED/TÜV requirements.

A proposal has been made recently to accelerate the production by avoiding idle times for fabrication machines between the Phases II and III, which rather can be used to expedite the manufacturing of cavity subassemblies until completion of bare cavities up to hold point 1, which also would not interfere with Phase I activities. This will improve the production throughput, while creating a buffer of cavities awaiting chemical post-processing. The accelerated schedule has been discussed in agreement with vendors and is awaiting approval. With the accelerated schedule, the last LCLS-II cavity could be completed by March 2017 compared to September 2017 when following the present scheduling. Both end dates do not account for unforeseen delays.

NB AND NBTI MATERIALS

The material procurement is an important part impacting the cavity production schedule directly. The LCLS-II is dedicated to provide all Nb and NbTi material to vendors for the cavity fabrication with quality assurance and control following XFEL experience (100% inspection). FNAL is in charge to procure the material as listed in Table 3 with support from SLAC and JLab. To date over 75% of the total quantities has been delivered. Several material lots are ready to be shipped to vendor sites after approval of custom declarations. For instance, DESY is supporting LCLS-II by inspecting all Nb sheets for the half cells via Eddy-current scans. Over half of the sheets are already packed in crates ready for shipment in equal parts to both vendors. Both vendors in principle have the capacity to store the all material on site already.

Note that the project ordered more material than necessary for Phase II-IV considering exercising the option of building cavity spares. The receipt of the remainder of the material is foreseen by early 2016. Except for material issues experienced with one vendor related to the procurement of the short end tubes and connecting tubes - with resolutions already addressed by FNAL [11] - no negative impact is expected on the fabrication schedule due to the material supply.

Table 3: List of Nb and NbTi Material Procured by LCLS-II for Cavity Fabrication

Item	Material	Quantity
1	Half Cells (RRR300 Nb Sheet)	5720
2	Short End Tubes (RRR 300 Nb Tube)	313
3	Long End Tubes (RRR300 Nb Tube)	313
4	MC Tubes (RRR300 Nb Tube)	313
5	Connection Tubes (RRR300 Nb Tube)	624
6	Field Probe Tubes HOM Antenna (RRR300 Nb Rod)	28
7	HOM Housings (RRR300 Nb)	624
8	F-parts (RRR300 Nb sheet)	24
9	Connecting Flanges (RRR40 Nb)	624
10	Conical Disks (Nb55Ti)	624
11	Stiffening Rings (RRR40 Nb sheet)	58
12	Flanges (Nb55Ti Rod)	16

ACKNOWLEDGMENTS

We like to thank the team at FNAL that continuously contribute to the procurement effort and provide a fruitful collaboration atmosphere. Likewise, we thank Marc Ross from SLAC for his ongoing support and participation in this endeavour. We express our gratitude to our DESY colleagues for their generosity providing permission to a vast pool of technical specifications and data related to the XFEL cavity production. In particular we like to thank Jens Iversen and Jan-Hendrik Thie for the ongoing technical discussions to assure that the DESY-owned automated cavity tuning machine and half-cell measurement devices as used at vendor sites are compatible with the LCLS-II cavity.

REFERENCES

[1] J.N. Galayda representing the LCLS-II Collaboration, TUIOA04, Proc. LINAC2014, http://jacow.org/
[2] 1.3 GHz Cryomodule Components Procurement, LCLS-II Document LCLSII-4.1-PM-0229-R0.
[3] http://www.aesys.net/
[4] http://research-instruments.de/
[5] http://www.zanon.com/
[6] A. Grassellino et al., Superconductor Science and Technology **26**(10), 102001 (2013).
[7] F. Marhauser et al., WEPWI016, Proc. IPAC2015, http://jacow.org/
[8] A.D. Palczewski et al., WEPWI019, Proc. IPAC2015, http://jacow.org/
[9] C. Reece et al., *these proceedings*, MOPB110, Proc. SRF2015, Whistler, BC, Canada (2015).
[10] H. Tian et al., WEPWI026, Proc. IPAC2015, http://jacow.org/
[11] C. Ginsburg, private conversation.

ISBN 978-3-95450-178-6