OVERVIEW OF RECENT SRF DEVELOPMENTS FOR ERLS*

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Abstract

This presentation reviews SRF technology for Energy Recovery Linacs (ERLs). In particular, recent developments and results reported at the ERL2015 Workshop are highlighted. The paper covers facilities under construction, commissioning or operation, such as cERL at KEK, b*ERL*inPro at HZB and R&D ERL at BNL, as well as facilities in the development phase. Future perspectives will be discussed.

INTRODUCTION

Energy recovery linacs still generate a lot of interest in the accelerator and user communities as the recent Workshop on Energy Recovery Linacs [1] has demonstrated, attracting more than one hundred participants. Along with "traditional" applications of ERLs for X-ray light sources and FELs [2, 3], electron-ion colliders [4], and electron coolers [5, 6], several new proposals and ideas were presented at the workshop as reported in [7]. Among those are: a compact ultra-high flux X-ray and THz source at John Adams Institute [8], ERLs for nuclear physics research MESA at Mainz University [9] and particle physics experiments at the jointly proposed BNL/Cornell demonstration multi-pass FFAG machine [10], γ-ray sources [11, 12], an ERL facility at CERN for applications [13] and even a concept of lepton ERL scalable to TeV energies [14]. However, only a few big proposals are actually funded. The field is very active, but is still in the development/demonstration stage. Tigner in his talk [15] outlined challenges to realization of ERLs. Some R&D needs related to SRF are:

- CW operation of large-scale SRF installations: high Q_0 at relevant accelerating gradients.
- Unprecedented beam currents and number of spatially superimposed high charge bunches in the SRF linacs: beam break up, halo, other beam dynamics issues.
- Photoinjectors producing high-brightness beams.
- Precise phase and amplitude control of narrow-bandwidth SRF cavities required over large spatial extent with varying ground vibration conditions.

As SRF linacs are essential to realize full benefits of the ERL approach, a significant portion of the ERL'2015 was devoted to the SRF technology, which was discussed in several working groups [16-18]. ERLs operate in CW mode and as a result, an optimal accelerating gradient for their SRF structures lie in a range between 15 and 20 MV/m (see [19] for example). Cryogenic power in such installations is dominated by the dynamic heat loads and hence achieving high quality factors in CW SRF cavities is very important. There was a lot of progress in this area recently, started with pioneering work on nitrogen doping at Fermilab [20], which was adopted for LCLS-II [21]. Other laboratories around the world joined the efforts trying to shed a light on the physics behind this effect, which is not fully understood yet. This is a very "hot topic" that will be widely discussed at this conference and warrants a separate review paper as many new and exciting results will be presented. As this topic will be outside the scope of present paper, I concentrate on such aspects as SRF injectors, HOM-damped SRF structures and cryomodules for ERLs. I review recent developments of the SRF technology for ERL projects around the world reported at the ERL'2015 workshop as well as some results obtained after the workshop.

RECENT RESULTS FROM SRF INJECTORS FOR ERLS

Significant progress was made since the last SRF conference in developing superconducting RF electron guns. As this will be covered in two other reviews talks [22, 23], here I highlight only some results relevant for ERLs. While we see more SRF guns generating first beams, there are still issues to be resolved. The photocathode materials survive well in the SRF guns when installed properly. However, contamination of the gun cavities photoemission materials often causes multipacting and field emission. Particulate-free installation of the cathodes is not always successful either and sometimes results in performance degradation.

SRF Gun II at ELBE

A new SRF gun for ELBE (SRF Gun II), shown in Figure 1, was developed, installed and commissioned at HZDR [24, 25]. This gun has an improved 3.5-cell niobium cavity with a better accelerating filed distribution: peak field ratio of 0.8:1 between the half-cell and TESLA cells. A superconducting solenoid is integrated into the gun cryomodule. There were also several smaller modifications.

An accelerating gradient of 10 MV/m was achieved in the first RF test of the gun without a cathode [24], which is a significant improvement as compared with SRF Gun I as one can see from Figure 2. Beam dynamics simulations showed that higher gradient should result in reduced emittance and bunch length. The first beam test has been carried out with a copper photocathode with gradients up to 9 MV/m. Installation of a Cs_2Te photocathode was not successful as it resulted in very low quantum efficiency

* Work is supported by Brookhaven Science Associates, LLC under contract No. DE-AC02-98CH10886 with the US DOE
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(QE) and contamination of the gun cavity. Thus in the following the accelerating gradient was restricted to 7 MV/m, it should still potentially allow generating a bunch charge up to 500 pC, improving user operation. Transverse emittance and longitudinal phase space measurements were performed, and agreed well with expectations from Astra simulations [25]. The critical issue at present is the quality and cleanliness of photocathodes. More details are reported in [26-28].

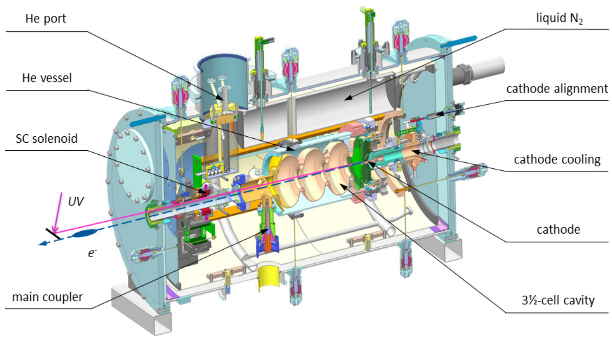

Figure 1: SRF Gun II cryomodule.

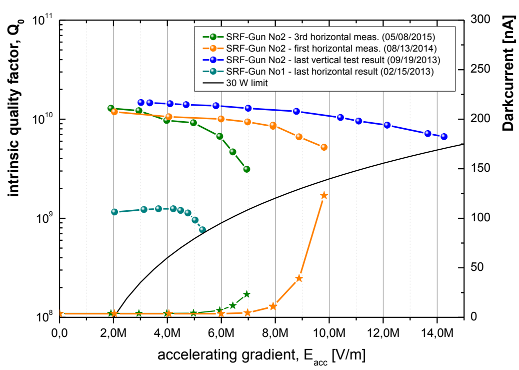

Figure 2: Measured cavity performance of the ELBE SRF Gun II (intrinsic quality factor versus acceleration gradient) and comparison with the SRF Gun I.

Pioneering work on SRF guns at HZDR is extremely valuable for the ERL community as many technical solutions from HZDR guns are adopted at other laboratories.

Recent Results on SRF Gun for bERLinPro

b*ERL*inPro, a demonstration ERL at HZB [29], plans to utilize an SRF photoinjector with CsK_2Sb cathode. The SRF gun is based in part on HZDR's design. Its 1.4-cell cavity operates at 1.3 GHz. The first cavity was fabricated and tested in a vertical cryostat at JLab. Vertical test results were then confirmed in horizontal testing of jacketed cavity at HoBiCaT. Strong multipacting (MP) activity has been observed initially, but was processed away. Simulations showed that MP should be expected between 16 and 18 MV/m. This is due to the fact that the half-cell was fabricated 5 mm shorter. After modification of the helium vessel, another series of tests was performed. The cavity has reached 34.5 MV/m, where it quenched. Its performance was recovered after thermal cycling and it now routinely achieves design field with the *Q* factor above design specification (Figure 3) [30]. The plan is to use this cavity in the first gun cryomodule.

In parallel with the SRF gun cavity and cryomodule design, efforts are underway on the photocathode development front [31]. Recently a cathode with QE of 5% at 515 nm was made inside a preparation and analysis system. The next step is to build a system for transferring cathodes from the preparation chamber to the gun.

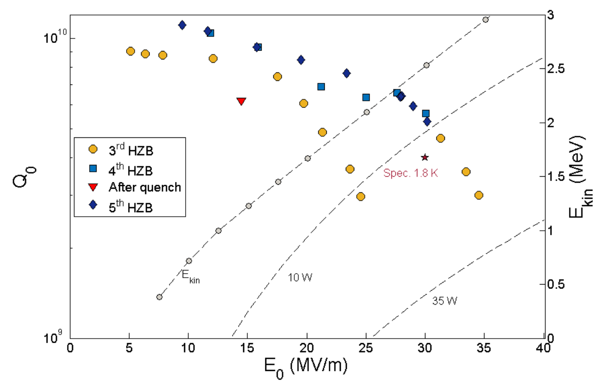

Figure 3: Horizontal test results of the b*ERL*inPro SRF gun cavity.

First Beams from SRF Guns at BNL

Two SRF electron guns are under commissioning at BNL: a 704 MHz half-cell gun installed in the R&D ERL facility [23] and a 112 MHz quarter wave resonator (QWR) type gun for the Coherent electron Cooling Proof-of-Principle experiment [33]. Both gun have recently generated their first beams from CsK_2Sb photocathodes.

The 704 MHz gun cryomodule was designed and built by AES, Inc. In this gun the photoemission layer is deposited on the tip of a large cathode stalk cooled with liquid nitrogen. Cylindrical protrusions on the outside of the gun cavity's back wall and on the cathode stalk form a folded RF choke joint with four gaps as shown in Figure 4. Grooved surfaces of the protrusions are meant to suppress multipacting.

The gun cavity performs well without the cathode stalk, reaching an accelerating voltage of 2 MV in CW mode. However, when the original cathode stalk was inserted, MP zones in the 3rd and 4th gaps (unexpected) prevented the gun from operating in CW mode in the desired voltage range. Also, the copper tip of the stalk was not suitable for high QE photocathodes. The cathode stalk was redesigned: i) the RF choke geometry was improved to eliminated MP; ii) the tip of the stalk was coated with tantalum to increase QE of the photoemission layer. With the new stalk the gun cavity could be quickly conditioned for CW operation. However, after deposition of CsK_2Sb, the gun can still operate only in pulsed mode due to contamination of the sides of the tip with the photoemission layer. To date, the 704 MHz SRF gun generated electron bunches with a charge up to 0.55 nC [32].

ISBN 978-3-95450-178-6

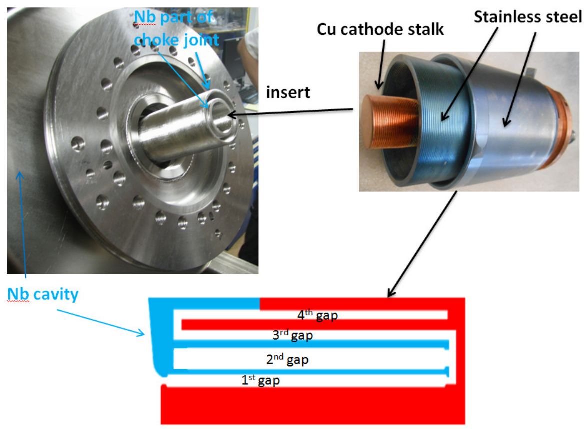

Figure 4: Back wall of the 704 MHz gun cavity (left) and the cathode stalk insertion (right). The cathode stalk is depicted in red and the Nb cavity is in blue on the RF choke layout [23].

The 112 MHz QWR SRF gun was installed in the RHIC tunnel at BNL in fall of 2014. This gun was developed by BNL in collaboration with Niowave Inc. After initial RF conditioning the gun cavity was limited to 1.3 MV CW. Helium processing improved the cavity performance with its accelerating voltage reaching up to 1.7 MV in CW mode and 2 MV in pulsed mode. While still limited by field emission at its highest voltage, the gun was able to generate a record-high bunch charge of 3 nC from a CsK_2Sb photocathode. At a repetition rate of 5 kHz, the beam current was about 15 μA [33]. Figure 5 shows an example of oscilloscope traces obtained from an integrating current transformer (ICT) corresponding to bunch charge of 2.4 nC. Commissioning of this gun will resume in early 2016.

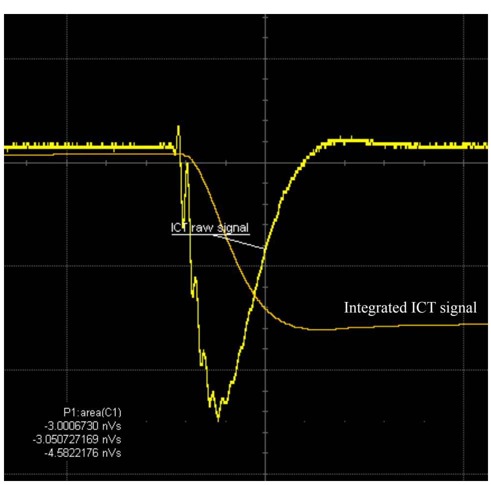

Figure 5: Oscilloscope trace of a raw signal from ICT , located downstream of the 112 MHz QWR gun, and its integral. The integrated signal corresponds to bunch charge of 2.4 nC [34].

NEW SRF CAVITIES UNDER DEVELOPMENT

HOM damping remains one of the most critical issues in ERL designs. Providing strong damping in a wide frequency range in combination with high average power is very challenging. Below we review several SRF cavities under development, which are designed to meet this challenge.

Development of the High Current Superconducting Cavity at IHEP

A slotted SRF cavity for ampere-class ERLs was proposed by Liu and Nassiri [35]. The cavity is made of three equal parts as shown in Figure 6a. The parts are slotted from a conventional elliptical cavity longitudinally along three lines separated by 120°. Each slot is then extended to form a wide-open waveguide. This waveguide is not coupled to fundamental mode while offering strong HOM damping. The three pieces are then electron beam welded together.

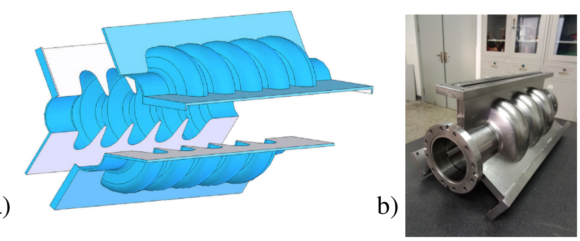

Figure 6: a) Three parts of the slotted cavity [35]; b) Fabricated cavity [36].

The cavity development has begun in 2012 at IHEP. It was fabricated in 2014. At room temperature HOM properties were measured up to 2.5 GHz confirming predicted low HOM impedance. Following that the cavity went through standard SRF treatment (BCP, 650°C bake, light BCP, HPR, 120°C bake) and vertically tested at 4.2 K. It reached Q_0 1.4×10^8 at an accelerating gradient of 2.4 MV/m, limited by available RF power. Several hard multipacting barriers have been encountered along the way. A test at 2 K will be done soon [36]. While this geometry shows some potential for future applications, serious studies will have to be performed on fabrication tolerances.

SRF Cavities for bERLinPro

Along with designing an SRF gun, HZB is developing two accelerating cavity geometries: one for the booster and one for the main linac [29, 30]. The booster cavity is of the Cornell ERL injector type [37] with modified fundamental power coupler (FPC) section to accommodate modified (with a golf tee antenna tip) KEK cERL coupler [38]. Four cavities were manufactured at JLab, all of them met the b*ERL*inPro specifications and far beyond after the first vertical test, with only one treatment (bulk 120 μm BCP, 600°C bake, light 25 μm BCP). Three cavities had helium vessels welded and tested again with very good results (Figure 7), the fourth cavity will remain as spare with helium vessel separate.

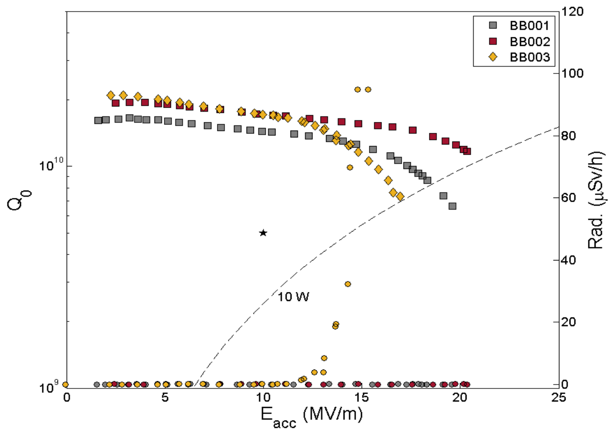

Figure 7: Vertical test results for 4 dressed booster cavities [30]. The star represents the b*ERL*inPro specification.

The main linac cavity is a 7-cell structure with mid-cells of a Cornell geometry [39] and end-cells optimized for waveguide (WG) based HOM damping (similar to those developed at Jlab [40]) and one TTF coupler [41]. The cavity's RF design is finished. WG tapering helped to reduce coupler kicks. The helium vessel design is in progress. Figure 8 shows possible integration of endgroups and blade tuner in the helium vessel.

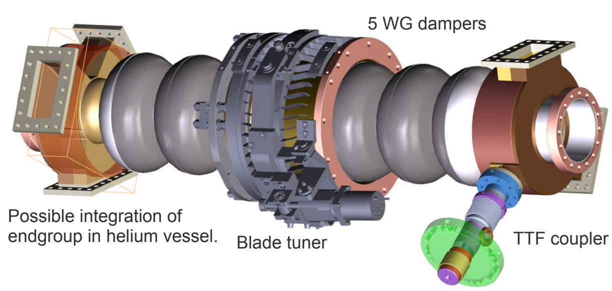

Figure 8: Possible integration of the b*ERL*inPro main linac cavity's endgroups and blade tuner into the helium vessel [30].

422 MHz Cavity for eRHIC at BNL

An electron-ion collider eRHIC will collide high-intensity hadron beams from RHIC with an electron beam delivered by a multi-pass ERL. An FFAG-based ERL will accelerate an electron beam to 15.9 GeV (50 mA) after 12 passes through an SRF linac or to 21.2 GeV (18.5 mA) after 16 passes. In both cases, the linac energy is 1.322 GeV. With up to 16 passes, the requirements to the HOM impedance become very stringent. To mitigate various beam dynamics effects, it was proposed to lower the RF frequency to 422 MHz [42]. The new cavity, BNL4, is designed to operate at 18.5 MV/m at $Q_0 = 5\times10^{10}$. It is a 5-cell cavity with HOM damping provided by coaxial and waveguide couplers [43]. A 3-cell prototype is ordered to demonstrate the cavity performance and study HOM damping schemes. Figure 9 illustrates one of the HOM damping schemes under consideration.

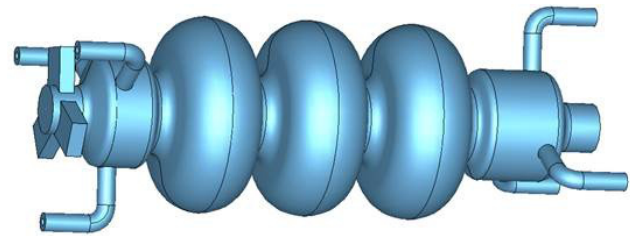

Figure 9: One of the HOM damping schemes under consideration for the BNL4 cavity [43].

SRF Cavity for UH-FLUX, an Asymmetric ERL

UH-FLUX is a compact ultra-high flux X-ray and THz source based on asymmetric dual axis ERL under development at John Adams Institute [8]. Its conceptual layout is shown in Figure 10. As one can see from the figure, its accelerating/decelerating structure consists of two cavities coupled via a special coupling cell. One of the cavities is accelerating electrons while the other one is decelerating them. All modes in two cavities other than the accelerating mode are decoupled. Thus the BBU threshold beam current in such layout is significantly higher that in conventional ERL. Potentially this concept might be useful for compact high-current ERLs.

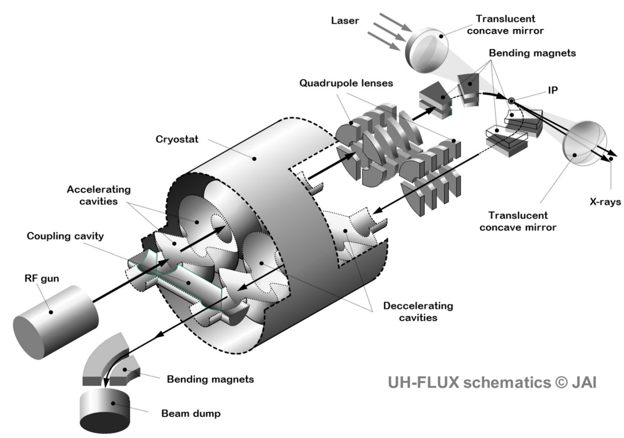

Figure 10: Conceptual layout of UH-FLUX [8].

DEVELOPMENT OF ERL INJECTOR AND MAIN LINACS INCLUDING PRECISE FIELD CONTROL

Several ERL cryomodules are under commissioning or have been successfully commissioned recently. One of the challenges here is preservation of high Q_0 during cryomodule assembly and long-term operation. As ERL main linac cavities operate under zero beam loading, they are designed with high external Q factors (narrow bandwidth). Thus, another challenge is precise phase and amplitude control of narrow-bandwidth SRF cavities required over large spatial extent with varying ground vibration conditions.

ISBN 978-3-95450-178-6

Operational Experience of CW SRF Injector and Main-linac Cryomodules at the Compact ERL

Operation of the CW injector and main linac cryomodules of compact ERL (cERL) project has started with 20 MeV beam in Dec. 2013 [44]. After precise beam tuning, energy recovery operation was achieved with more than 90 μA. *Q*-values of the main linac cavities were measured several times, see results shown in Figure 11. Over time the *Q*-values degraded, but then the degradation stopped after May of 2014. The reason for such behaviour is still unknown [45].

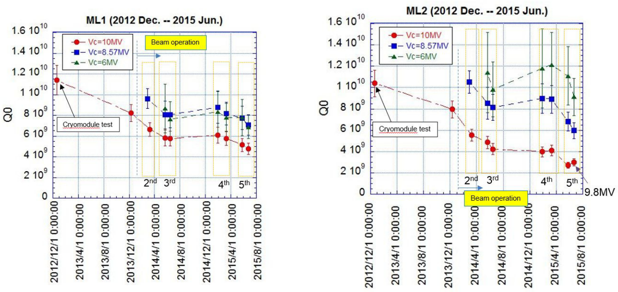

Figure 11: Measurement of the cavity performance at 6, 8.57 and 10 MV cavity voltage, which almost equals with MV/m, during long-term beam operation including high power test of Main linac 1(left) and 2 (right) [45].

Completion of the Cornell High Q Main Linac Cryomodule

The Cornell's ERL main linac cryomodule houses six 7-cell SRF cavities. All six 1.3 GHz cavities were tested vertically with results presented in Figure 12. All six cavities exceeded the design quality factor, averaging to 2.9×10^{10} at 1.8 K. Currently the cryomodule is being cooled down in preparation for testing [46].

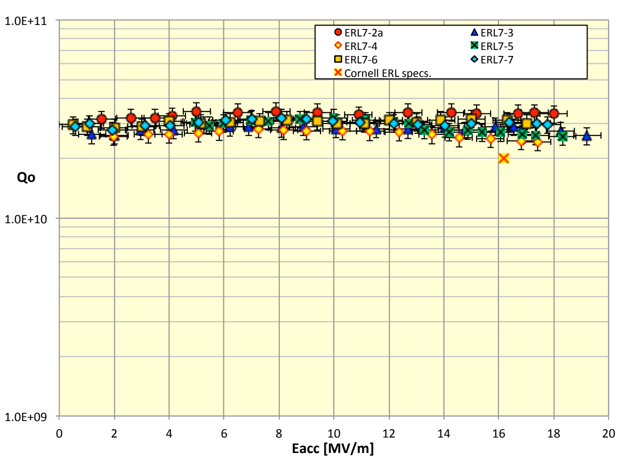

Figure 12: Vertical test results for all six Cornell ERL cavities. All cavities exceeded the design specifications for the ERL ($Q_0 = 2\times10^{10}$ at 1.8 K). The reproducibility of the results, gained without any reprocessing of cavities, is remarkable [47].

Cryomodule for SETF at Peking University

The main linac cryomodule of the Superconducting ERL Test Facility (SETF) at Peking University comprises two 9-cell cavities. The cryomodule assembly is complete, it is installed in the 25 MeV beam line and is being cooled down in preparation for a beam test [48].

ARIEL

The ARIEL e-Linac has an injector cryomodule (ICM) with one 9-cell cavity and two accelerating cryomodules (ACM1 and ACM2) with two 9-cell cavities each. Phase I includes ICM and ACM1. Currently, both cryomodules are installed with only one cavity in ACM1. Each cavity reached on-line performance as demonstrated by electron acceleration with $Q > 10^{10}$, and $E_{acc} > 10$ MV/m as illustrated in Figure 13 [49].

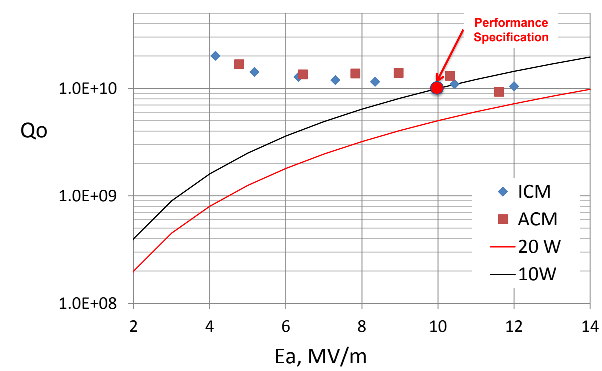

Figure 13: Installed accelerating cavities meet specification: 10MV/m at $Q_0 = 10^{10}$.

Resonance Control for Narrow-Bandwidth, Superconducting RF Applications

New results are obtained recently at Fermilab for LCLS-II project (in collaboration with Cornell University) and PIP-II project [50]. For LCLS-II, feedforward Lorentz force detuning compensation (piezo driven with stimulus pulse proportional to accelerating gradient square) and feedback to detuning to compensate 45 Hz external noise compensation were applied to a 1.3 GHz cavity in CW mode. Results are close to the LCLS-II requirements (peak detuning of 10 Hz).

For PIP-II, a similar algorithm was applied to a 325 MHz single spoke cavity (SSR1) in CW and pulsed modes. In CW, a remarkable suppression was achieved, with a residual rms detuning of 11 mHz (Figure 14). In pulsed mode, the rms detuning of ~10 Hz is still worse that requires 1.5 Hz. Further development is in progress.

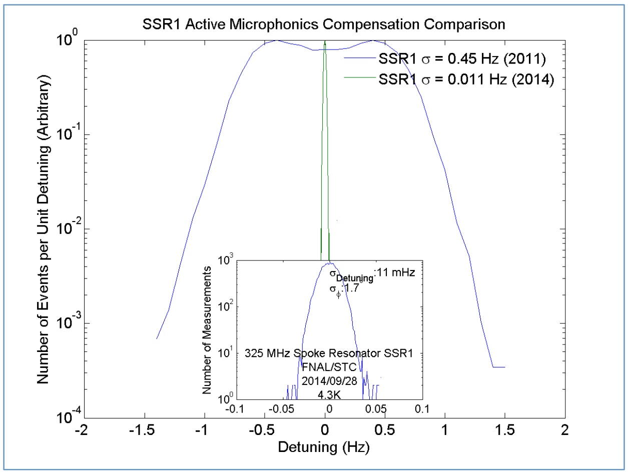

Figure 14: Active resonance stabilization of the PIP-II SSR1 SRF cavity in CW mode [50].

SUMMARY

The ERL field is very active, but is still in the development/demonstration stage: a lot of need and opportunities for R&D. In this paper I reviewed:

- Recent results from SRF photoinjectors for ERLs. First beams were obtained from several SRF guns. The main issues here are related to operation with high QE photocathode materials: multipacting and field emission, cavity contamination.
- New SRF cavities for ERLs. There are still opportunities for new cavity designs. Issues are related to HOM damping: handling high average power in a wide frequency range.
- Development of ERL linacs including precise field control. The main issues are: maintaining high Q0 during cryomodule assembly and long-term; resonance control of narrow-band cavities, robustness of control algorithms.

ACKNOWLEDGMENT

I would like to thank my colleagues A. Arnold (HZDR), R. Eichhorn (Cornell University), T. Kamps (HZB), R. Laxdal (TRIUMF), K. Liu (Peking University), A. Neumann (HZB), Y. Pishchalnikov (Fermilab) and H. Sakai (KEK) for sending me updates on their projects at the last minute. I also grateful to H. Sakai (KEK) and E. Jensen (CERN) for their efforts on organizing a working group on SRF at the ERL'2015 Workshop and writing an excellent summary report [15], which helped me in preparing this paper.

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