HIGH Q CAVITIES FOR THE CORNELL ERL MAIN LINAC

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Abstract

While SRF research for linear colliders was focused on achieving high gradients, Cornell's proposal for an energy recovery linac (ERL) demanded for low cw losses. Starting several years ago, a high-Q R&D phase was launched that led to remarkable results recently: A fully dressed cavity (7 cells, 1.3 GHz) with side-mounted input coupler and beamline HOM absorbers achieved a Q of $6*10^{10}$ ((16 MV/m, 1.8 K). This talk will review the staged approach we have chosen in testing a single cavity in a horizontal short cryomodule (HTC) report results on each step and conclude on our findings about preserving high Q from vertical testing. We also discuss the production of six additional cavities as we progress toward constructing a full 6-cavity cryomodule as a prototype for Cornell's main linac module.

INTRODUCTION

Energy-Recovery Linacs (ERLs) are proposed as drivers for hard x-ray sources because of their ability to produce electron bunches with small, flexible cross sections and short lengths at high repetition rates. Cornell University has pioneered the design and hardware for such an ERL light-sources [1].

But before a large-scale light source could be built, several important milestones needed to be achieved. The National Science Foundation therefore has been funding Cornell University since 2005 to verify that the required beam. On all these fronts, major milestones have been achieved: 75 mA beam currents [2] have surpassed the previous world record by a factor of two; the 90% x/y-emittance has become so small that an acceleration to5 GeV would lead to 51/29 pm for 77 pC bunches and 23/14 pm for 19 pC [3]. With 1.3 GHz bunch repetition, this 5 GeV beam could drive a hard-x-ray source with a brightness that is about 20 times larger than the brightest beam today (at PETRA-III). A potential layout of such an ERL at Cornell is shown in Fig. 1.

Furthermore, it was important to show that the proposed operations cost of an ERL can be achieved, much of which is for cooling the SRF cryo-system. This paper will focus on this topic as it describes our effort to achieve high quality factors of the superconducting cavities reliably.

THE HIGH Q PROGRAM

The SRF properties of a 7-cell main Linac cavity were characterized at several stages before completing the assembly of a fully equipped horizontal test cryomodule (HTC). The purpose of measuring the cavity properties at intermediate stages was to both qualify the assembly pro-

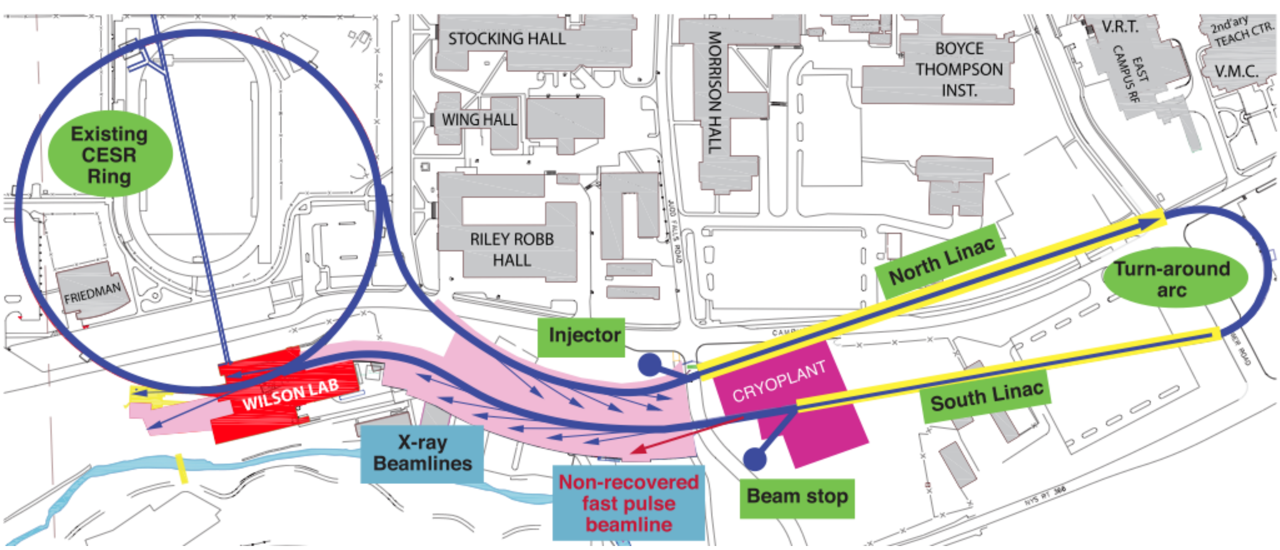

Figure 1: The proposed Cornell ERL, transforming the existing CESR storage ring into a high brightness coherent X-ray source.

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cess as well as understand the contribution of each stage to the overall quality factor Q and higher-order mode properties. Qualification proceeded in four stages:

1) Vertical testing of the cavity;
2) horizontal test with axial RF input coupler (HTC-1);
3) horizontal test with side mounted high power RF input coupler (HTC-2); and
4) test with high power RF input coupler and beam line HOM loads (HTC-3).

More details about these tests are available in other papers [4, 5], with the results quoted here. The cavity Q was measured by standard RF methods in a vertical dewar at 1.6, 1.8 and 2.0 K. The cavity reached 26 MV/m (limited by available RF power), and met the Q specification of $2*10^{10}$ (16 MV/m, 1.8 K).

Following the successful vertical test, while maintaining a clean RF surface, the cavity was outfitted with a helium jacket, and installed in a horizontal test cryomodule in the HTC-1 experiment. For this run, the same axial RF coupler used in the vertical test was left on the cavity, and used to measure the Q of the cavity via RF methods. Additionally, the Q was measured via cryogenic methods. After thermal cycling, gradient and quality factor measurements exceeded design specifications, reaching $3.0*10^{10}$ at 1.8 K, and a record $6*10^{10}$ at 1.6 K and 5.0 MV/m.

HTC-2 incorporated the side mounted high power RF input coupler to the HTC-1 assembly. The Q at design gradient and temperature were met the $2*10^{10}$ but strong field emission and high radiation levels were observed.

For the HTC-3 run, the cavity was reprocessed (light BCP) before reinstallation into the module and beamline higher order mode absorbers.

Initial measurements show quality factors consistent with the pre-thermal cycled values from the previous HTC experiments, and suggest successful broadband

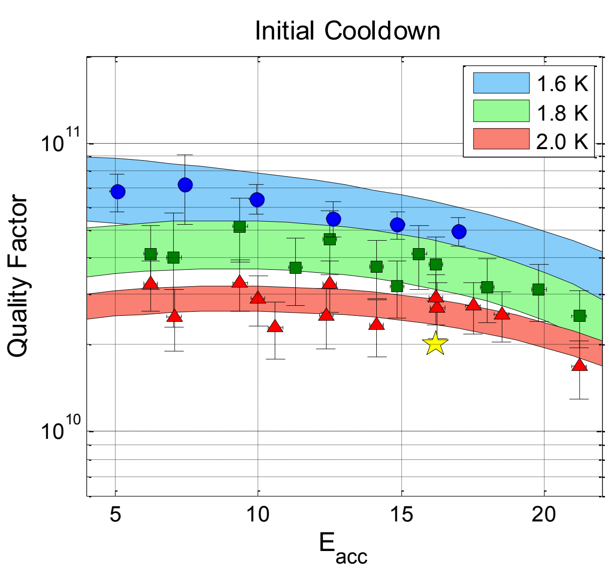

Figure 2: Q versus E of the first ERL cavity, mounted inside the HTC cryomodule, fully equipped with power coupler and HOM absorber.

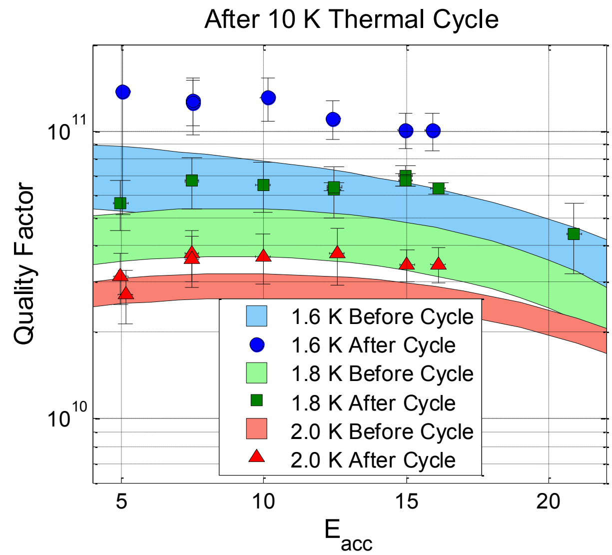

Figure 3: Q versus E for the same cavity after going through a 10 K thermal cycle. A significant Q increase could be measured.

damping of higher order modes [6]. The measured Q versus E curve is shown in Fig 2.

After a 10 K thermal cycle which warmed up the cavity slightly above the critical temperature and cooling it down slowly again, we saw a significant increase in the Q (see Fig. 3). Remarkably, this leads to a Q of $6*10^{10}$ at our design operation parameters being three times higher than targeted.

Achieving such a high Q horizontally for a fully dressed cavity certainly triggers a necessary discussion:

- can this high Q be reached reliably for many cavities
- what Q should be base-lined for future CW accelerator projects

The effect of seen increased quality factors is consistent with what we have seen in prior HTC testing's and relates to the findings at HZB [7]. The reason for this finding is still under investigation.

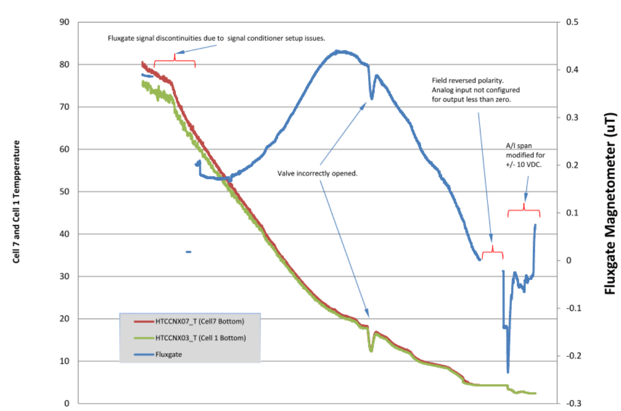

Figure 4: Magnetic field measurement during initial cooldown of the HTC-3. The flux gate sensor was mounted outside the helium tank but inside the second layer of magnetic shielding.

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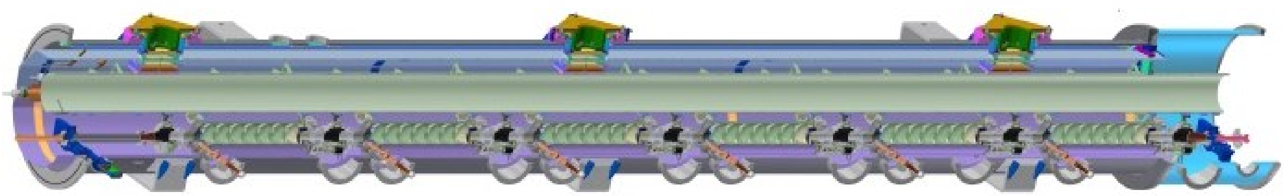

Figure 5: CAD model of the cryomodule prototype (MLC). It will house 6 ERL type cavities. More details are given in the text.

Recent measurements however, suggest that it might be related to magnetic fields: We mounted a flux gate magnetic probe between the helium vessel and the inner magnetic shielding of the cavity and saw during the initial cool-down a drastic change in the residual magnetic field-leading even to a reversal of the flux direction. The measured curves are given in Fig. 4. In contrast to the findings in Berlin, these curves suggest a dependency from the absolute temperature and not the gradient.

BUILDING THE MAIN LINAC CRYOMODULE

In preparation for constructing the ERL, a full prototype linac module (MLC) is currently under fabrication [8].

Module Design

The general layout of the cryomodule prototype is shown in Fig. 5. In principle, it is based on the ILC design but incorporates the necessary changes to allow for CW operation plus improving the design by simplification (which for example lead to changes in the alignment concept of our module).

The almost 10 m long module houses 6 superconducting cavities, operated in CW mode at 1.8 K. These 7-cells, 1.3 GHz cavities with an envisaged Q of $2x10^{10}$ will provide an energy gain of 16 MV/m. Each cavity is fed by a 5 kW RF power input coupler described below.

Due to the high beam current combined with the short bunch operation a careful control and efficient damping of the HOMs is essential, leading to the installation of dampers next to each cavity [6]. The series linac module will have a quadrupole/ steerer superconducting magnet section behind the 6 cavity string, making the transition to the adjacent module. This magnet section will be omitted in the prototype as it, in contrast to the other components, technically does not represent a challenge.

The design was guided by several principles:

- Achieving good alignment of all components
- Providing excellent magnetic shielding to get highest Qs of the cavity
- Careful control of all natural frequencies to achieve low microphonics
- Ensure CW operation of all cavities even if the Q is lower than designed
- Allow clean installation and minimize contamination risks

Currently, all components are procured or under fabrication and completion is planned in 2014. More details on the MLC are described in [9].

Cavity Fabrication

All cavities for the MLC are or will be produced in-house. The process begins with half cells formed by a deep drawing process in which sheet metal of 3 mm RRR niobium is radially drawn into a forming die by a first press at 3 tons, then a second forming press (100 tons). The dies for the centre cells were carefully designed to deal with the spring back effect.

The equators of each cup have an additional straight length on them (approx. 1.5 mm). The purpose of this extra length is to allow for trimming later on to meet the target frequency and length. We will focus on that below when we discuss the dumbbell trimming. Those dumbbells are built in an intermediate step by welding two cups together on their irises.

Ultimately six dumbbells will be welded together by electron beam welding to form the centre-cells of the seven cell cavity and end-cells with end-groups are added.

Figure 6: Three ERL cavities built at Cornell to be installed into the prototype Main Linac Cryomodule (MLC).

After welding, the assemblies are cleaned by both chemical etching and a high purity water rinse to rid them of any surface impurities that may have accumulated during the production process.

For the MLC, we decided to build 3 unstiffened cavities as show in Fig. 6 as well as 3 cavities with stiffening rings. The reason for doing so as well as the optimization of the stiffening ring position is described in [10].

Cavity Preparation

For the preparation of the cavity, a simple recipe – being modified with experience- based on BCP has been chosen. Starting after fabrication, the damage layer is removed by bulk buffered chemical polishing (BCP, 140 µm). While we started to measure the removal rate with a witness sample first we learned that an on-line ultrasonic head measurement is more appropriate. The hydrogen degassing is done at 650 °C for 4 days while we monitor the hydrogen residual gas inside the furnace. Studies showed that a higher temperature (800 °C) seams to remove more hydrogen but would slightly soften the cavity which would still be acceptable. However, as the Qs are above our specifications we limited our self and did not yet risk softening the material.

The degasing is followed by a frequency and flatness tuning and an optical inspection. As final preparation steps we do a light BCP (10 µm), a low temperature baking (120 °C, 48hrs), and more recently an HF rinse. Each chemistry step is followed by ultra-sonic cleaning and high pressure rinsing. Table 1 gives an overview of the slightly different procedures applied to the so-far build 4 cavities.

After final assembly, cavity is slowly pumped down with mass flow control system, confirmed leak tightness, and then installed on vertical test insert and the Q is measured. Figure 7 shows a recent result on the 4th ERL cavity.

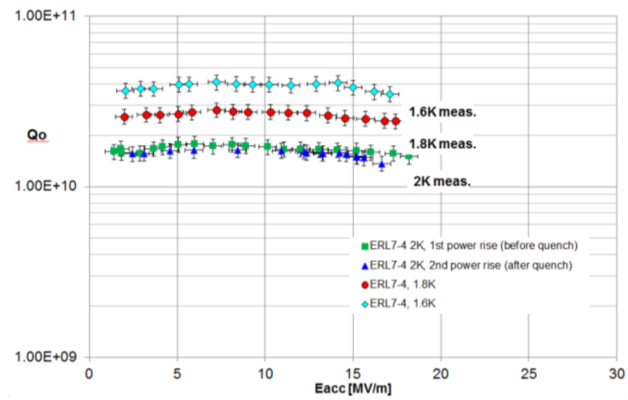

Figure 7: Q-curves for the latest produced ERL cavity (ERL7-4), achieving $2.5*10^{10}$ at 16 MV/m and 1.8 K.

Table 1: Parameters of the Cavity Preparation and its Slight Changed During our Learning Experience.

	ERL7-1 (HTC)	**ERL7-2**	**ERL7-3**	**ERL7-4**
Bulk BCP	140um (witness sample)	135±10 um (cavity equator)	138±5 um (cavity equator)	132±7 um (cavity equator)
Degassing	Jlab, 650C*10hrs	TM-furnace 650C*4days	TM-furnace 650C*4days	TM-furnace 650C*4days
tuning	88%	94%	91%	92%
Final BCP	10 um	10 um	10 um	10 um
120C bake	On insert	TM-furnace	On insert	TM-furnace
HF rinse	No	Yes	Yes	Yes
VT 1st (1.8K)	17MV/m, 1.6e10 (No T-map , old insert)	17MV/m, 1.53e10 w/ T-map	Limited by FE w/ T-map	17.4MV/m, 2.4e10 w/ T-map
Re-process	- BCP (10µm) - 120 C bake(in clean room, old set-up) - HF rinse		- BCP (10µm) - 120 C bake(TM-furnace) - HF rinse	

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Cavity Testing

As mentioned in Tab. 1, every ERL 7-cell cavity was tested with the full temperature-mapping system. This T-map consists of 1848 Allen-Bradley resistors and is able to offer 1mK temperature resolution. Figure 8 shows the T-map result of ERL 7-4 cavity at 17MV/m in 2 K helium bath. Each blue square represents the resistor array covered on one cell. The sequence of the T-map is identical to the cavity orientation during the vertical test, and the main coupler port is on the bottom. The tiny hot-spots were detected on each cell, and the maximum temperature increase which is about 20 mK was found in the cell 3.

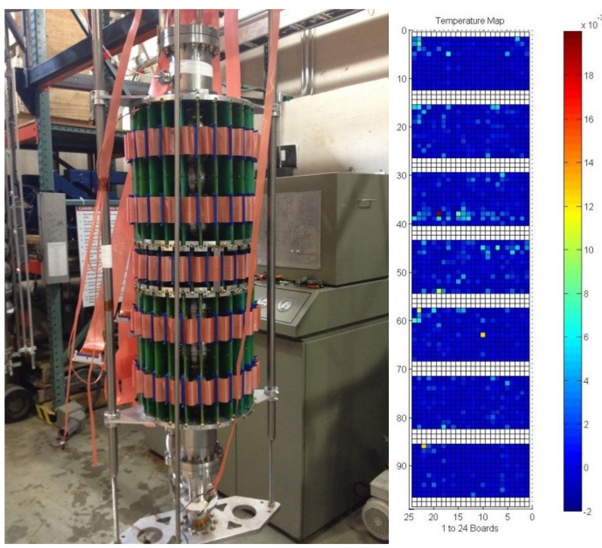

Figure 8: The Cornell T-map system as it is installed around an ERL cavity (left) and the heating map we got on ERL7-4 (17 MV/m, 2K).

Over the course of the testing we found this system being an essential tool in understand our Q findings and analysing the sources. Some cavities, even meeting the specifications were reprocessed as we saw very located hot spots. Needless to say that by this reprocessing the Q became even higher.

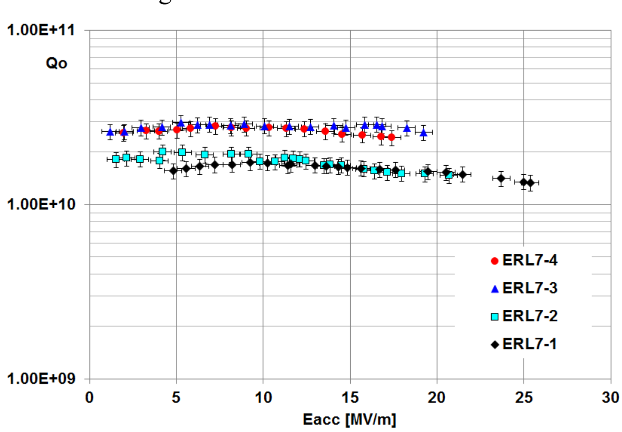

Figure 9: Q curves for the 4 ERL cavities tested so far. All data were taken at 1.8 K.

The results we got for the 4 cavity we have produced so far are summarized in Fig. 9. All measurements were done at 1.8 K. While ERL7-1 and 7-2 were slightly below the targeted value of $2*10^{10}$, the later cavities 7-3 and 7-4 exceeded that goal by almost 50 %. It should be noted that the cavity ERL 7-1 became the cavity to be tested in the various HTC assemblies, now having a Q of $6*10^{10}$! This results in the statement that we currently achieve higher Qs in horizontal measurements with fully dressed cavities than in vertical test which seems to contradict discussions a decade ago.

RF Input Coupler and Source

The ERL main linac input couplers must deliver up to 5 kW CW RF power to the cavities. At this CW power level, active cooling of the inner conductor is required. The design of the ERL main linac coupler is based on the TTF-III and Cornell ERL injector couplers (see Fig. 10). To simplify the input coupler, it has fixed coupling with a nominal external Q of $6.5*10^7$. Coupling adjustability can be achieved using three-stub tuners in the feed-transmission line to have a coupling range of $2*10^7$ to $1*10^8$. Two sets of bellows are placed on the warm portion of the coupler, on both the inner and outer conductor, to allow for significant lateral motion of the cavities during cool down while keeping the cold antenna fixed relative to the cavity coupler port.

All couplers have been ordered at CPI and meanwhile delivered. So far, we have tested 4 up to 5 kW CW RF power under full reflection without seeing any vacuum action [11]. Essentially, no conditioning was required to reach this power level leading to our believe that this coupler could operate reliably even at a doubled power level.

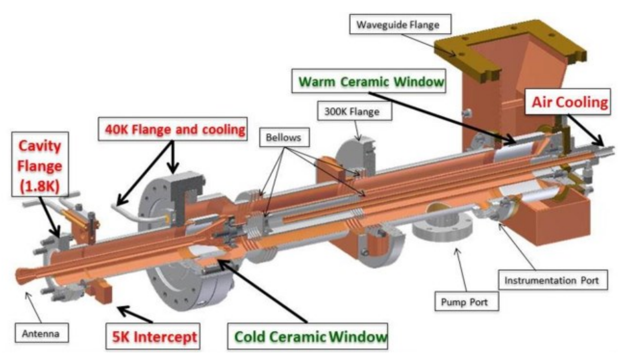

Figure10: RF Power coupler. The coaxial transmission line has two bellows which allow for lateral movement during cool-down.

SUMARY AND OUTLOOK

Cornell University has achieved important milestones for the construction of ERL light sources: world-record currents from a photoinjector; ultra-small emittances; long-lived photocathodes and SRF cavities with extremely high Quality factors which had been the focus of this article. The design goal of $2*10^{10}$ at 16 MV/m and 1.8 K, set a decade ago seems unrealistic at that time but is being achieved and outperformed regularly, today.

We have measured a Q as high as $6*10^{10}$ for a cavity being fully dressed with a power coupler and two adjacent HOM absorbers in our Horizontal Test Cryostat (HTC). As we progress along building a full linac cryomodule we fabricated 6 additional cavities, four of which are finished and tested so far. All of them outperformed our expectations.

Cornell is currently building a prototype for the full linac cryomodule. String assembly inside the clean room will start by the end of 2013, the whole module is expected to be finished in late 2014. In preparation for ERL construction, this allows us to verify the cost model of this cost-driving part of the full ERL. It allows high Q performance studies with significant statistics (6 cavities) as well as quantifying microphonics impacting operation. Using this module, the study of HOMs in a multi-cavity structure with imperfect cavities can be performed, which is the basis for the proposed small loop demonstrator. The fabrication is seen as a preparation step for future industry collaboration, defining key procedures and quality standards. We believe that these technologies have sufficiently progressed years to allow the construction of an ERL-based lightsource.

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