Superconducting RF R&D for Energy Recovery Linacs

J. Knobloch
Helmholtz-Zentrum Berlin, Hahn Meitner Platz 1, 14109, Germany

INTRODUCTION

Several projects worldwide are now considering ERL-drivers to take advantage of the extraordinary beam properties that can be achieved by linear accelerators while providing an energy efficiency close to that of conventional storage rings. Presently, the main drivers fall into three categories: Next-generation x-ray light sources, electron coolers, and electron accelerators for electron-hadron colliders.

Proponents for ERL light sources include Cornell University[1], KEK/JAEA[2], Jefferson Laboratory[3] and, in the longer term, Helmholtz-Zentrum Berlin (HZB). In all cases, the proposals call for GeV-class ERLs. Brookhaven National Laboratory is advocating ERLs for high-energy colliders, either as an electron cooler for RHIC or for electron-hadron collisions (eRHIC)[4, 5].

These ERLs have many commonalities, the most obvious being the use of superconducting RF. However, the required beam parameters may differ significantly. X-ray light sources, for instance, require beam emittances below 1 π mm mrad (norm.) and sub-ps pulse lengths. Here, space charge effects limit the maximum bunch charge. For L-Band linacs 100-mA currents are typically envisaged with every RF bucket filled. Electron coolers require longer bunches with moderate emittances ($< 10\ \pi$ mm mrad) but ampere-level currents and much higher bunch charge. Consequently, the SRF hardware solutions will differ as well.

While the Jefferson Laboratory ERL has impressively demonstrated the applicability of ERL technology to drive an IR FEL, the technology is not sufficiently advanced for realization of the future proposals. Often the beam parameters must be improved by more than a factor of 10. Hence several prototypes are under construction. The most ambitious are the BNL ERL[6], the Cornell ERL Test Facility, the KEK cERL[2] and the recently funded B*ERL*inPro at HZB[7]. Their parameters (Table 1) reflect those of future full-scale ERL applications, albeit with a significantly lower beam energy.

SRF-systems play an important part in three areas of ERLs. **SRF photoinjectors** are a promising alternative to DC injectors or normal-conducting RF photoinjectors as a source of low-emittance beams. A 2008 workshop held at HZB came to the conclusion that SRF systems bear the greatest future potential for ERLs. While first experimental results[8] fall short of their potential, in theory SRF systems provide both a high beam voltage *and* a high accelerating field to rapidly boost the beam energy out of the space-charge-dominated regime. Furthermore, the cold environment provides ideal vacuum conditions—a prerequisite for cathode longevity. However, significant challenges for SRF sources remain. They include the integration of a normal-conducting cathode into the SRF environment, limiting the dark current which might otherwise be transported down the ERL, the coupling of high power into the cavity without disturbing the beam and extracting HOM power that can otherwise cause BBU[9].

In the **SRF booster**, the beam is accelerated to around 5–10 MeV. A lower limit is set by the requirement that the beam has to be sufficiently stiff to prevent emittance dilution in the merger section. The upper limit is dictated by beam dump and RF power considerations, since the booster energy is not recovered. Similar to the injector, heavy beam loading is a design driver. Careful attention also has to be paid to the impact of the input coupler on the beam, as coupler kicks can lead to rapid beam deterioration.

Since the energy is recovered in the **main linac**, the focus shifts away from beam loading and other considerations come to the fore. GeV-class machines must operate at high gradients (15–20 MV/m range) and be designed for acceptable filling factors. The cryogenic load is another essential consideration as the multi-kW cryoplant can account for as much as 20%–30% of the total linac cost.

Paradoxically, the low effective beam loading presents another challenge. In principle, the cavities can be operated with a few-hundred watts of RF power. In practice, significant overhead has to be installed to enable precise field regulation of the narrow-bandwidth cavities in light of microphonic detuning[10]. Perhaps as much as 20 kW/m are required and the RF system can be another significant cost driver. Hence low-microphonic designs and compensation schemes take on a high priority.

In the main linac the total beam current is at least twice as high as that in the injector (single-turn operation). At 200 mA, the HOM power will be in excess of 100 W/m and clearly this power must be removed from the LHe environment. However, equally important is the fact that HOMs can drive beam instabilities (BBU). The SRF design must thus (a) limit the HOM excitation, (b) facilitate the HOM extraction, and (c) provide heavy HOM damping. In fact, for the highest-current applications, kW HOM management becomes the overarching design consideration.

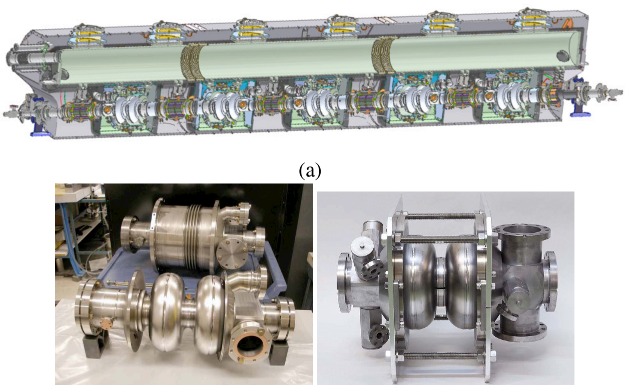
While many groups are working on new ERL designs, the most advanced development is currently underway at BNL, Cornell University and in the KEK/JAEA collaboration. What follows is a (non-exhaustive) overview of some of the international efforts.

SRF BOOSTER DEVELOPMENT

Figure 1(a) depicts the booster module developed by Cornell[11] that went into operation in June 2008. While it is nominally based on the 1.3-GHz TESLA module

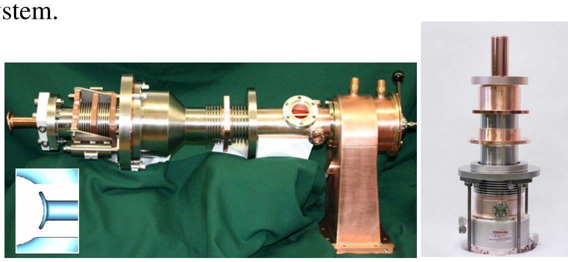
Table 1: Parameters of ERL Demonstration Facilities under Construction

Parameter	BNL ERL	Cornell ERL	KEK ERL	B*ERL*inPro
Beam energy (MeV)	20	n/a	100	100
Injection Energy (MeV)	2.5	5–10	5–10	5–10
Beam current (mA)	500	100	100	100
Bunch charge (pC)	10,000	77	77	77
Bunch length (ps)	few 10	2	2	2
Emittance (π mm mrad)	few	< 1	< 1	< 1



(a) (b) (c)

Figure 1: (a) Cross-section of the cornell booster module in operation since 2008. (b) Five, two-cell 1.3-GHz cavities are employed. (c) Prototype KEK 1.3 GHz two-cell system.

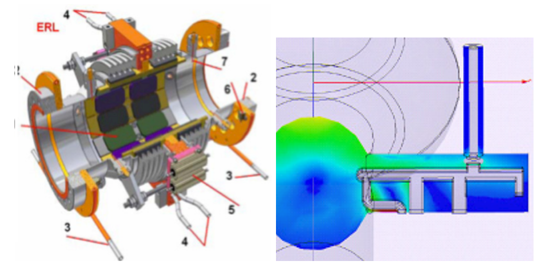


(a) (b)

Figure 2: (a) RF input coupler on the Cornell booster module showing the "pringle tip" in the inset. (b) Cold part of the KEK coupler.

"philosophy", significant changes have been incorporated. More than 100 kW of beam loading per cavity dictates that each cavity can only supply 1–2 MeV and only 2-cell cavities as shown in Fig. 1(b) are employed. Following refurbishment of the module in 2009, reasonable Q-factors have been achieved, in the order of $(6 \times 10^9 - 10^{10})$[11]. While lower than expected, given that a triple magnetic shield is employed, the impact on booster operation is not severe.

RF coupling is provided by coaxial couplers on the beam-tube (see Fig. 2(a)). These are based on the TTF-III design, modified to improve the CW-power capability[12]. Modifications include the reduction of the cold-part's impedance and forced-air cooling of the warm inner conductor. Nominally designed for 75 kW TW, the system has been tested off-line and on the module up to 53 kW SW. An important feature of the coupler is the antenna's curved "pringle-tip" (see inset)[13]. It reduces the penetration into the beam tube for a strong coupling (external Q in the 10^5 range), thus reducing coupler kicks. Similarly, each cavity is equipped with opposing couplers for symmetry, with the added benefit that the RF load per coupler is reduced to 50 kW.



(a) (b)

Figure 3: (a) Cross section of the HOM beam pipe absorber employed in the Cornell booster module. (b) Design of the KEK loop coupler.

HOM-power extraction (approx. 45 W) is facilitated by a large diameter beam pipe that permits dipole modes to propagate. Beam-pipe absorbers at either end, as shown in Fig. 3(a), dissipate the intercepted power at 80 K[14]. The absorber design is based on the well-established room-temperature 500-MHz B-cell system for CESR. However, in the ERL the loads must operate at cryogenic temperatures because transitions to room temperature waste valuable real estate. Cold gaseous helium cools lossy "tiles" soldered to both sides of elkonite carriers. For ps bunch lengths the HOM spectrum extends out to over 45 GHz. Numerous materials were tested at 80 K, and three types (two ferrites, one ceramic) were employed in the load to provide broad-band absorption. Surprisingly, module tests in 2008 revealed beam steering in the loads. Subsequent investigations came to the conclusion that all three materials lost their DC conductivity at 80 K, thereby collecting stray charge[15]. In the short term, the tiles facing the beam were removed, HOM damping now being performed only by the tiles on the backside of the elkonite. While this solution is sufficient for booster operation, new approaches (described below) are being investigated for the main linac modules.

KEK's booster module is also designed around 2-cell 1.3-GHz cavities as shown in Fig. 1(c). The current module design[16] includes only three units, placing a larger strain on the input couplers, which have to handle up to 333 kW per cavity. Opposing couplers once again symmetrize the system. Much success with coaxial couplers has been achieved with the KEK-B design, which handles over 800 kW at 508 MHz. This system has been scaled

Figure 4: Prototype of BNL's photoinjector cavity that will go into operation in 2011.

(a) (b)

Figure 5: (a) The first of three generations of SRF injector cavities for B*ERL*inPro. (b) The Pb cathode coated on the back plane at Soltan Institute of Nuclear Studies.

to 1.3 GHz, as shown in Fig. 2(b)[17]. Unlike the Cornell unit, the KEK system employs fixed coupling at 3.3×10^5 and cools the inner conductor with water. So far, room-temperature coupler tests have been performed to 100 kW CW TW[16] limited by the doorknob transition.

An important difference between the Cornell and the KEK booster units lies in the HOM damping, the latter system using five loop couplers (see Fig. 3(b)). While successful with HERA and TESLA cavities, it is well known that the outcoupling antenna of the dampers is not completely insulated from the accelerating mode. It must thus consist of niobium, which has been shown to quench at CW fields above about 10 MV/m on account of poor cooling[18]. To circumvent the problem, KEK added an additional filter loop to reduce the field of the TM_{010} mode at the tip by 50%. The max. CW field should thus increase to about 15 MV/m, sufficient for booster module operation. This has indeed been verified by vertical tests[16].

SRF PHOTOINJECTOR

DC photoinjectors are commonly planned as ERL sources. However, given the potential of SRF systems mentioned earlier, both BNL and HZB are proposing SRF injectors. Figure 4(a) depicts BNL's prototype injector cavities. At 2-MeV, 500-mA operation the 1-MW beam loading limits the cavity to a half cell. Still, two 500-kW couplers with pringle tips are required to handle the power and to symmetrize the system. A cathode system can be introduced through the back plane of the cavity where a choke filter prevents RF from propagating along the stalk. Even with high-quantum-efficiency cathodes, such as CsK_2Sb, the laser system for 500-mA operation is exceedingly challenging. Hence BNL plans on implementing a diamond amplified system, whereby the cathode is located in a separate vacuum sealed from the cavity by a diamond window. A DC potential of a few kV is applied between the cathode and the diamond window. Electrons emitted from the back-illuminated cathode are accelerated and strike the diamond, where secondaries are created. The amplified current is then injected into the cavity[19].

The SRF injector for HZB's B*ERL*inPro is less challenging in terms of beam current, but must supply shorter bunches and lower emittances. HZB is planning on tackling the challenges mentioned earlier in three steps[20]: First study the beam dynamics at low currents generated with a superconducting (Pb) cathode, secondly incorporate a normal-conducting cathode in the system and finally develop a system for high-power operation with appropriate input coupling and HOM damping.

Currently, the first stage is being pursued in collaboration with DESY, Jefferson Laboratory, Soltan Institute of Nuclear Studies (SINS) and Max-Born Institute (MBI)[20]. The $1\frac{1}{2}$-cell cavity, as shown in Fig. 5(a) represents a good compromise between the peak field (of order 30 MV/m) and total beam energy (of order 1.5 MeV), limited by beam loading once high-current operation begins. A thin Pb film of a few 100 nm in thickness was vacuum-arc deposited on the back plane by SINS (see Fig. 5(b)). This will act as the cathode to be illuminated by a 30 kHz UV laser. Superconducting Pb was found to have negligible impact on the cavity performance[21] while the quantum efficiency is about one order of magnitude greater than that of Nb. With the laser specifications, nearly a microamp of current can be generated, which is sufficient for the first-stage beam dynamics studies. Tests with this injector will be carried out in the HZB's HoBiCaT facility, modified to accommodate a simple beamline. For the first time, a superconducting solenoid in the immediate vicinity of the cavity will be used for emittance compensation. Vertical acceptance tests were performed and first beam tests are expected in early 2011.

SRF MAIN LINAC DEVELOPMENT

As discussed, the challenges for the main linac differ from those in the booster system. Beam loading can essentially be ignored, but design considerations focus on HOM damping and BBU issues. Attention must be paid to microphonics and RF control and, for large machines, cryogenic losses and SRF-hardware cost will be important issues.

Cavity design Given the BBU issues, significant attention has been paid to the optimization of the cavity shape. Generally, the shape can be parameterized in terms of ellipses and beam-tube/iris diameter. To handle the large number of free parameters, Cornell adopted an automated optimization routine. To identify an appropriate figure of merit for any particular design, BBU simulations of a 5-GeV ERL as a function of parameters such as R/Q, Q and mode frequency were performed with BMAD. The results demonstrated that the BBU threshold is generally maximized when the empirical "BBU parameter" $\zeta = \frac{R}{Q}\sqrt{Q}f^{-1}$ is minimized[22]. Here, f, R and Q are the mode frequency, shunt impedance and quality factor, respectively. ζ was then used to control the shape optimization routine. Figure 6(a) depicts the final 7-cell cavity design. It was found that the BBU threshold depends significantly on the frequency spread of HOMs from one cavity to the next. For a 400 mA threshold, this needs to be about 3×10^{-3}. However, simulations demonstrated that it is insufficient to simply relax the manufacturing tolerances, because then a large scatter of Q factors results. Rather, several "families" of cavities with slightly different mode spectra must be designed. First prototype cavities will be tested in 2012[23].

KEK's cavities[24] are already being prototyped. The design, as shown in Fig. 6(b), features three important differences: (1) Two more cells have been added to improve the filling factor. (2) To ease HOM extraction, the iris and beam tube have been enlarged for easier propagation, with the penalty of raising the ratio E_{pk} to E_{acc} from about two to three. (3) KEK simulations suggest that quadrupole HOMs can also cause BBU instabilities. As these do not propagate for the chosen beam-tube diameter (120 mm), off axis "flutes" as in Fig. 6(c) were added to one beam tube. This "converts" quadrupole modes to propagating dipole modes. Measurements with copper models suggest that significant damping of these can then be achieved[25]. This cavity design has now undergone vertical testing. Following identification and removal of several defects, accelerating fields up to 25 MV/m have been achieved, albeit at a rather low Q factor of about 7×10^9[24].

The cavity for BNL's ampere-class electron cooler requires even more attention to HOM management. Figure 6(d) depicts the prototype about to go into operation[26]. The frequency is reduced to 704 MHz to limit the HOM excitation. HOM extraction is improved by (a) reducing the number of cells to five to limit the chance of trapped modes, and (b) increasing the iris and beam tube diameters to 170 mm and 240 mm, respectively. Scaled to 1.3 GHz, these values are 20 mm larger than those of the Cornell cavity! As a result, the ratio of $H_{\text{pk}}/E_{\text{acc}}$ increases to 60 mT/(MV/m).

HOM damping Efficient damping of more than 100 W HOM power at 100 mA operation and > 1 kW at 1 A beam current is vital to limit the cryogenic load and to prevent BBU instabilities. The dampers must fulfill several important conditions:

- Heavy damping of monopole and dipole modes to Qs of order 10^4 or even less.
- Broad-band damping up to several 10 GHz.
- No room-temperature transition between cavities for high-energy ERLs.
- Compatibility with the SRF environment and low cost.

The currently favored systems are all based on beam-line absorbers, similar in concept to the Cornell booster system. However, this system is costly and complex with a significant risk of cavity dust contamination, and the chosen materials lack sufficient DC conductivity. More recent efforts have concentrated on simplified designs. Figure7(a) depicts the system planned for the KEK main linac[27]. It is based on ferrite HIPped to a copper shell anchored to 80 K and thermally isolated from the cavity beamline via 4-K heat intercepts and bellows. HIPped ferrite was originally developed for the KEK-B 500-MHz system, which has handled up to 15 kW[28]. As this system is operated at room temperature it remains to be seen whether HIPping is suitable for cryogenic loads. So far cryogenic tests have only been performed without ferrite to determine the thermal properties and expected heat load to the cavity[27].

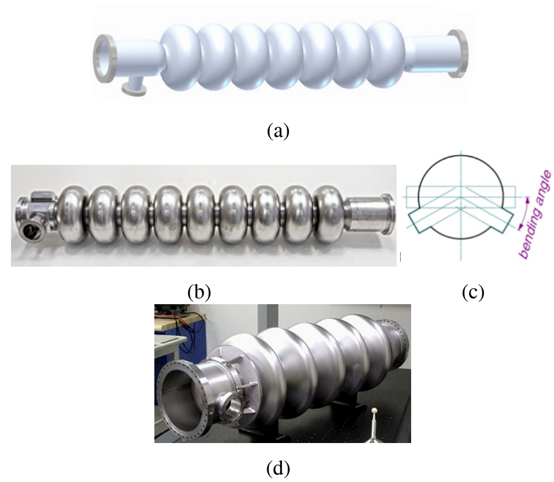


Figure 6: (a) Cornell's 7-cell main-linac cavity. (b) Prototype cavity for the KEK ERL main linac . (c) Flutes added to one beam tube propagate quadrupole modes. (d) BNL's ERL cavity.

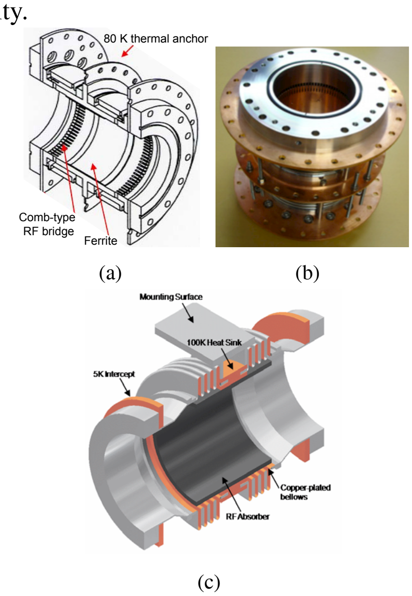


Figure 7: (a) Concept of the KEK's HIPped HOM absorber. (b) Prototype without ferrite. (c) Cornell's beam-line absorber based on carbon nanotubes.

New absorber materials are being investigated by a collaboration between UC Davis and Cornell, with a focus on carbon nanotubes (CNT)[29]. These can be embedded in ceramics commonly used in the accelerator environment. Measurements up to 40 GHz have shown that composites with about 1–2 wt% CNT provide constant absorption with reasonable permittivity to limit reflections. Importantly, at these concentrations overlap between nanotubes is sufficient to establish adequate DC conductivity at 80 K. Plans

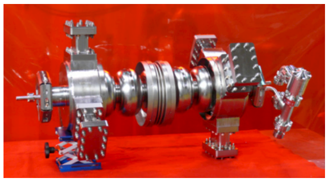


Figure 8: 1.5-GHz ERL cavity with waveguide HOM dampers developed at Jefferson Laboratory.

call for the production of a complete cylinder that can be integrated into a low-cost design as shown in Fig. 7(c).

An alternative to beamline absorbers has been pursued at Jefferson Laboratory for highest current applications[30]. It is based on six waveguide dampers that extract the HOM power to room temperature (see Fig. 8). Several potential advantages exist:

- The waveguide naturally rejects the fundamental.
- High power handling
- The input coupler can be combined with a waveguide.
- Symmetrization avoids coupler kicks

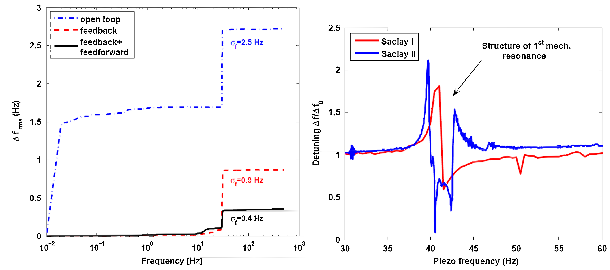
On the other hand, management of the thermal load to liquid helium may require a space consuming design.

Two systems have been prototyped, one at 1.5 GHz and one at 750 MHz for 100-mA and Ampere-class operation, repectively. Similar to the BNL design, only five cells are employed to facilitate HOM extraction. Initial room-temperature bead pulls and simulations suggest that the 750-MHz unit is capable of supporting beam currents in excess of 1 A. Designs for a two-cavity cryomodule were under way, but unfortunately Jefferson Laboratory recently terminated the high-power program.

Operational aspects In light of the small cavity bandwidth, microphonics-driven detuning is an important operational consideration. Attention is being paid to adequate RF control, microphonics characterization and their active compensation. If microphonics can be reliably reduced to a peak detuning on the order of 20 Hz (at L-Band), then a 5-kW/m RF installation should suffice and solid-state amplifiers become an attractive option.

Such studies require the characterization of a complete cavity unit, including helium tank and tuner. Extensive CW studies have been performed at HZB with TESLA systems in the HoBiCaT facility[18]. Long-term measurements[10] demonstrated RMS detuning on the order of 6 Hz and less. About 50% of the microphonics were due to helium pressure fluctuations with the other 50% being contributed by one or two mechanical resonances (see Fig. 9(a)). But peak events of up to 16 σ were observed several times daily! These govern the necessary capacity of the RF-power installation. Mitigation by passive and active means is thus an important field of R&D for ERLs.

Several tuner systems that included piezo-electric elements for rapid tuning (Saclay I, Saclay II and "Blade") have been characterized[31]. The general features of the transfer function from the piezo stack to the cavity frequency apply to all systems—apparently these are determined primarily by the cavity-helium tank combination.



(a) (b)

Figure 9: (a) Compensation of microphonics using feedback and adaptive feedforward. (b) Measured piezo-to-detuning transfer function near a mechanical resonance.

However, the details of the resonances are governed by the tuner and can be quite complex (see Fig. 9(a)).

The characteristics of the microphonics and the details of the transfer function were incorporated in a scheme for active noise compensation. It uses a combination of feedback for sub-Hz helium pressure fluctuations and adaptive feedforward for noise at the mechanical resonances. In total a reduction by a factor of seven was demonstrated (see Fig. 9(b)). At this point it still remains to be demonstrated that the system can be automated and operate robustly over a long period of time.

REFERENCES

[1] C. E. Mayes and G. H. Hoffstaetter, these proceedings.
[2] S. Sakanaka et al., *Proc. IPAC 2010*.
[3] `www.jlab.org/FEL/jlamp/JLAMP_Proposal.pdf`
[4] I. Ben-Zvi, *Proc. EPAC 2006*.
[5] V. N. Litvinenko et. al, *Proc. PAC 2005*.
[6] D. Kayran et al., *Proc. LINAC 2008*.
[7] A. Jankowiak et al., these proceedings.
[8] A. Arnold and J. Teichert, *Proc. SRF 2009*.
[9] V. Volkov, *PRST-AB* **12**, 011301 (2009)
[10] A. Neumann, W. Anders, O. Kugeler, and J. Knobloch, *PRST-AB* **13**, 082001 (2010).
[11] M. Liepe et al., *Proc. IPAC 2010*.
[12] V. Vesherevich et al., *Proc. PAC 2007*.
[13] H. Padamsee et al., *Proc. SRF 2003*.
[14] V. Shemelin et al., , *Proc. EPAC 2006*.
[15] E. Chojnacki et al., *Proc. SRF 2009*.
[16] S. Noguchi et al., *Proc. IPAC 2010*.
[17] E. Kako et al., *Proc. SRF 2009*.
[18] O. Kugeler, W. Anders, A. Neumann and J. Knobloch, *Rev. Sci. Instrum.* **81**, 074701 (2010)
[19] X. Chang et al., *Proc. PAC 2007*.
[20] A. Neumann et al., these proceedings.
[21] J. Sekutowicz, *Proc. PAC 2009*.
[22] N. Valles and M. Liepe, *Proc. IPAC 2010*.
[23] M. Liepe, Cornell University, private communication.
[24] K. Umemori, *Proc. IPAC 2010*.
[25] M. Sawamura, *PRST-AB* **13**, 022003 (2010)
[26] A. Burrill et al., *Proc. PAC 2007*.
[27] M. Sawamura et al., *Proc. IPAC 2010*.
[28] A. Akai et al., NIM **A** 499 (2003) 45–65.
[29] Q. Huang et al., *Proc. SRF 2009*.
[30] R. Rimmer et al., *Proc. IPAC 2010*.
[31] O. Kugeler et al., *Proc. SRF 2007*.