HIGHER ORDER MODE ABSORBERS FOR HIGH CURRENT ERL APPLICATIONS

R. Eichhorn[#], J. Conway, Y. He, Y. Li, G. Hoffstaetter, M. Liepe, T. Gruber, M. Tigner,
T. O' Connell, P. Quigley, J. Sears, E. Smith, V.D. Shemelin,
Cornell Laboratory for Accelerator Based Sciences and Education

Abstract

Efficient damping of the higher-order modes (HOMs) of the superconducting cavities is essential for any high current operation. The talk will provide an overview on the latest advances of HOM absorber development for high intensity SRF applications. As the ideal absorber does not exist, the different conceptual approaches will be presented and the associated issues are outlined. Design examples from various labs will be given that help explain the issues and resolutions. Some focus will be given to the Cornell HOM beamline absorber that was designed for high current, short bunch operation with up to 400 W heating. The design will be reviewed and testing results will be reported.

INTRODUCTION

The acceleration of particle inside an accelerator is usually provided by RF cavities and many machines today rely on superconducting cavities. Usually, the accelerating mode inside that cavity is chosen to be the fundamental mode (even so exceptions exists). In this mode, which corresponds to a certain (operation) frequency, power is forwarded to the cavity and eventually transferred to the particle beam. However, cavities have (theoretically) an infinite number of resonant frequencies. They are denoted higher order modes and these frequencies may be excited by the beam, which leads then to a reverse power flow: from the beam to the cavity. Not only exists the drawback of the beam loosing energy via this mechanism, the excited higher order modes correspond to field configurations inside the cavity which can seriously affect the beam. For example, if a higher order mode frequency corresponds to a dipole mode, any excitation of that mode results in a deflection of the beam. For circular machines this can be a limiting factor.

Several strategies to minimize higher order mode effects exists, starting from a carefully designed accelerating cavity to control mode frequencies, to having dedicated coupler antennas or waveguides to extract higher order mode power to absorbing the power directly at the beam pipe using ferrites or lossy ceramics. This paper focusses on the absorbing materials. Widely used materials to absorb RF frequencies are ferrites and (electrically) lossy ceramics, and a variety of materials exist. They differ in their loss tangent (a figure of merit for the absorption) and the frequency range in which they display adequate absorption. Being common to all ferrites, the losses in the material are of magnetic type and display a resonant-like behaviour, which usually leads to absorption characteristics with limited bandwidth (which still can be in the GHz region). Typically, one can find good ferrites for frequencies below 5-10 GHz.
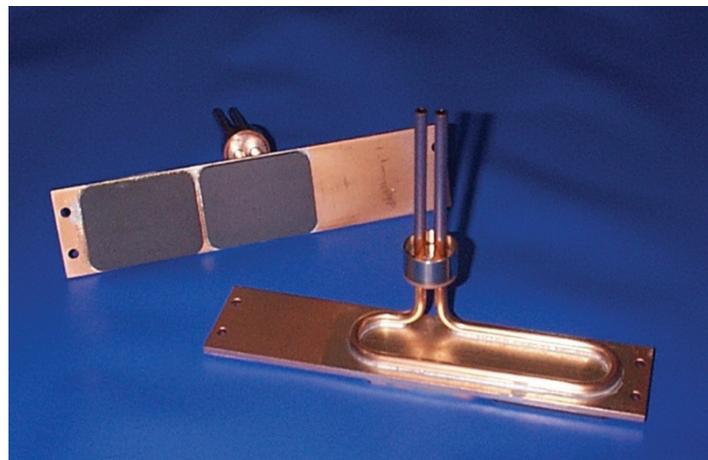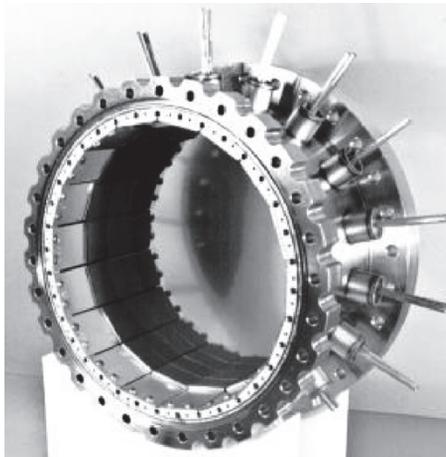
Figure 1: Absorbing tiles of the CESR B-Cell HOM absorber. Three layers are sputtered onto the ferrite (titanium, a mixture of titanium/copper, and a copper layer: total thickness: 1 μm). The ferrite tiles are soldered to a copper plated Elkonite (copper-tungsten sinter metal that fits the thermal expansion of the ferrites) plate. Water cooling tubes are soldered on the backside of the Elkonite. Each HOM panel is designed to absorb up to 600 W RF power. For the delicate soldering of the ferrites to the Elkonite plate inductive brazing under an argon atmosphere is used.

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[#] r.eichhorn@cornell.edu

FERRITE ABSORBER

CESR HOM Absorber

In high current storage rings with superconducting cavities (like CESR at Cornell) strong broadband HOM damping has been achieved by using beam line absorbers. The CESR-B Cell absorber (Fig. 1) uses ferrite absorbers [1,2]. Great effort was put into selecting appropriate ferrites [3,4], to measure their absorption as a function of frequency [4] and to braze them to the copper support [5]. The design is rather complicated, limited to room temperature operation and long beam bunch lengths (due to the rather low frequency band covered by the ferrites).

Like with most beam line absorbers, the risk of contaminating the cavity, charge-up of the material and techniques of how to bond the absorbing material to a support structure have found to be demanding fields. However, many of these units are operated worldwide and no operational issues were reported.

BNL ERL HOM Absorber

The HOM absorber design for the ECX cavity at Brookhaven, shown in Fig. 2, follows a similar design approach [6]. Again, ferrites are used, but the absorbing material is separated from the beam by a ceramic break that could protect the beam vacuum in case of a water leak and help preventing ferrite chips or dust to enter the superconducting cavity [7]. This ceramic is sputter coated with a 1 nm thick layer of stainless steel. Currently, there are indications that this coating is insufficient or has become insufficient during operation.

Figure 2: HOM absorber for the ECX cavity at BNL. The absorption of the microwaves is provided by ferrites. To shield them from the beam (which could charge-up the tiles) and to prevent contamination of the cavity (by ferrite particles and chips) a ceramic break is inserted.

KEK CERL HOM Absorber

A slightly different approach has been chosen for the compact energy recovery linac project (cERL) at KEK. Targeting at beam currents of 2 * 100 mA and a bunch length of 3 ps, they expect a total of 150 W of HOM
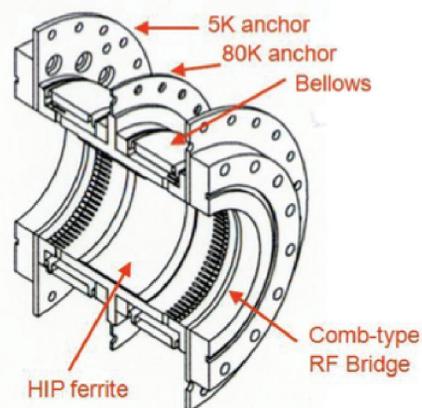
Figure 3: HOM absorber of the compact ERL (cERL) at KEK. As absorbing material, HIP ferrites (IB004) have been chosen. The ferrite cylinder has been bonded to a copper support and successfully operated at 80 K.

power per cavity. Frequency-wise, they found an HIP ferrite (IB004) to provide sufficient damping. This ferrite is bonded to a copper pipe and eventually operated at 80 K [8]. Figure 3 shows the absorber.

ALUMINUM NITRIDE ABSORBER

A HOM absorber currently produced in series for the European X-FEL accelerator is shown in Fig. 4. It uses a cylinder of a dielectrically lossy material, brazed to a copper stem. This stem is slotted in order to "give" during thermal cycling, as there is a big mismatch in the thermal expansion coefficient of the ceramic and the copper [9].

Initially, two different materials (CA137 from Ceradyne and STL-150D from Sienna Technologies) were considered. Sample testing initially favoured CA137, as the material provided a tg δ > 0.1 for frequencies between 5 GHz and 40 GHz while maintaining an ϵ < 30 (compared to STL-150D with tg δ > 0.4 for 5 GHz to
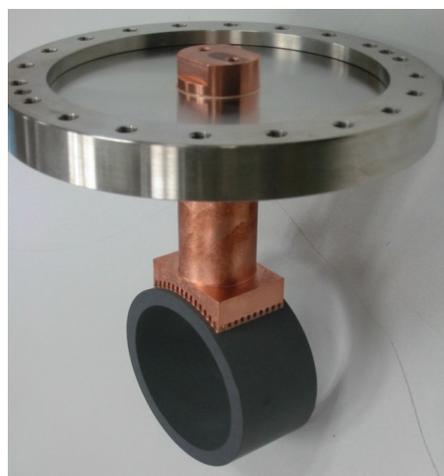
Figure 4: Higher order mode absorber for the X-FEL machine currently under construction at DESY. An AlN based lossy ceramics (STL-150D from Sienna Technologies) was chosen. The transition to the copper stem is made by brazing using a slotted finger design. The ceramic is at 80 K
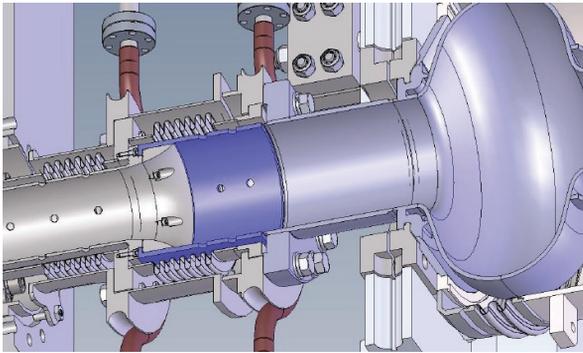
Figure 5: SiC beam line absorber of the ARIEL linac at TRIUMF. The absorbing cylinder is clamped to a flange, avoiding issues in matching the thermal expansion coefficient. Cooling is provided by liquid Nitrogen.

12 GHz). In addition, a sufficiently low DC resistivity across the cylinder of less than 200 MΩ at 70 K to avoid charge-up was measured. However, it was found that for the CA137 these parameters were not reliable and dependant on the production batch [10].

SILICON CARBIDE BASED ABSORBER

Ariel HOM Absorber

The ARIEL project is a Linac project at TRIUMF, aiming to provide a 50 MeV, 10 mA electron beam to drive production of radioactive ion beam. It was designed to be upgradeable for energy recovery operation.

Under the operation parameters the BBU shunt-impedance limit was calculated to be 10 MΩ, the design itself was targeting 1 MΩ at max. In order to reduce the loaded Q resistive beam line absorbers are used on the pick-up side of the cavity. A carbon-fiber reinforced
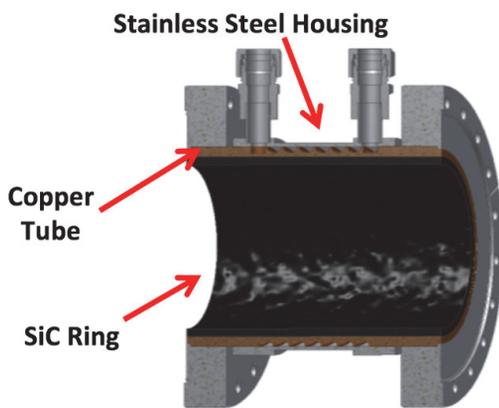
Figure 6: Higher order mode absorber for the APS upgrade. The HOM consists of two SiC cylinders matched to both beam pipes. The absorbing material is Coorstek SC-35, shrink-fitted into copper. Both absorbers are located at a certain distance to the cavity at room temperature operation. The calculated HOM power is ~1.7 kW.

silicon carbide (CESIC®) was chosen. The material is cylindrically shaped and clamped by copper rings to a flange, also shielding the bellow. Cooling is provided by liquid nitrogen. Details of the arrangement can be found in Fig. 5 and in Ref. 11.

APS Upgrade HOM Absorber

The Advanced Photon Source (APS) operated at Argonne National Lab is currently preparing for an upgrade, targeting beam currents of 200 mA and bunch repetition rates of 13 or 88 MHz. Bunch charges are 15.3 and 2.2 nC and bunch lengths are in the order of 50 ps, achieved by harmonic cavities [12]. These cavities will have two SiC cylinders matched to both beam pipes (Fig. 6). As material, Coorstek SC-35 was chosen. The absorbing cylinders are shrink-fitted into a copper shelve (with a nominal 0.1 mm diameter interference). The material is operated at room temperature, cooled by water. The Calculated HOM power is ~1.7 kW per cavity.

Waveguide HOM Absorber at JLab

As a continuous effort Jefferson Lab is improving the design of the waveguide based HOM absorbers. They also use a graphite loaded SiC from Coorstek but in contrast to others this absorber is operated at 2 K which is acceptable as the HOM power is less than 10 W per cavity for a C50 cryomodule. Current efforts go into optimizing the shape, improving the brazing to reduce stress and enhancing thermal conduction. They also found that one simple load wedge provides sufficient damping for lower powers [13].

bERLinPro HOM Absorbers

bERLinPro in an energy recovery linac demonstration facility currently under construction in Germany [14,15]. For the SRF gun (Fig. 7), an HOM absorber was built in a collaboration with Cornell which is a copy of the absorber described in more details below.

For the linac cryomodule, wave guide absorbers similar to the JLab design will be used, except that the absorbing material will be operated at 80 K.
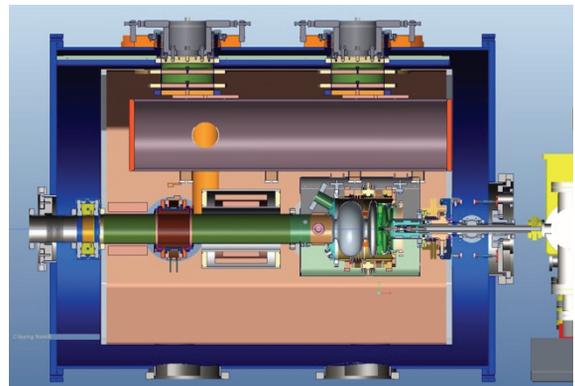
Figure 7: Higher order mode absorber of the bERLinPro SRF gun. The absorber is placed behind a solenoid following the 1.5 cell SRF gun. The absorber is of the Cornell MLC style (described in more details below) with slightly adjusted parameters.
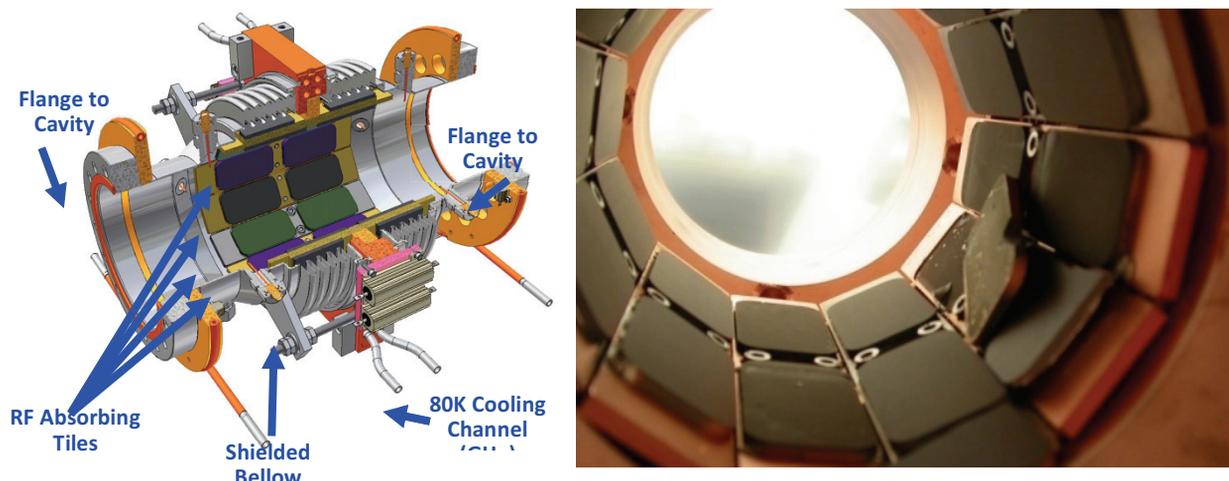
Figure 8: Higher Order Mode absorber in the Cornell injector cryo-module. It is based on three absorbing materials ensure broad band absorption up to high frequencies. Delamination was observed after thermal cycling due to mismatch the CTE. In addition, serious beam deflection occurred, indicating the charging up of the low conductivity materi Eventually, the dielectric lossy ceramic (137ZR10) had to be removed.

CORNELL INJECTOR HOM ABSORBER

In the framework of the Cornell ERL project [16], a higher order mode absorber was developed for the injector cryo-module that allowed absorption of frequencies well beyond the range of ferrites[17]. As the targeted bunch length is much shorter than in storage rings, significant HOM power at higher frequencies is expected. As a consequence, a selection of three different materials to absorb the RF was made. The design is shown in Fig. 8.

During operation we observed a serious charge-up of the (single) dielectric lossy material [18]. As a result, the whole cryo-module had to be rebuilt and the highly resistive material facing the beam was removed. In addition, the thermal stresses in the tile assembly coming from the cool-down to the 80 K operation temperature lead eventually to catastrophic delamination of one tile [19]. With some modifications the HOM absorber is back in usage but the lesson we learned is that charge-up and potential contamination of the cavity is a real risk. As a consequence, the design was improved for the absorbers in the main linac cryo-module, as described below.

CORNELL LINAC HOM ABSORBER

Design Concept

The guiding concept for the HOM absorbers in the main linac cryo-module (MLC) was to have a broad band absorbing material covering the whole range from 1 to 40 GHz in the shape of a cylinder with the beam passing through the centre. After several iterations we came up with the final design as depicted in Fig. 9.

The centre assembly consists of a SiC cylinder from coorsteck (CS-35) which is shrink fit into a titanium cooling jacket and flange. The cooling jacket and flange locate, support, and provide cooling at 80 K to the absorbing cylinder using a cooling channel inside the titanium to ensure 400 W of HOM power can be extracted. The end pieces of the assemblies contain a 3 convolution bellows, a 5 K cooling plate, and taper seal flange to mate with the cavities. The bellows allows for small length variations in the string, small angular misalignments of cavity flanges, as well as adds a long thermal path from 80 K to 5 K. There are positive stops that prevent the bellows from compressing and closing the gap between the 5 K cooling jacket and the absorbing cylinder to less than 1 mm. This prevents any rubbing of metal to ceramic that could create particles. The beam tubes have a copper plating about 10 micron thick to prevent beam induced heating. More details on the design can be found in [20,21].
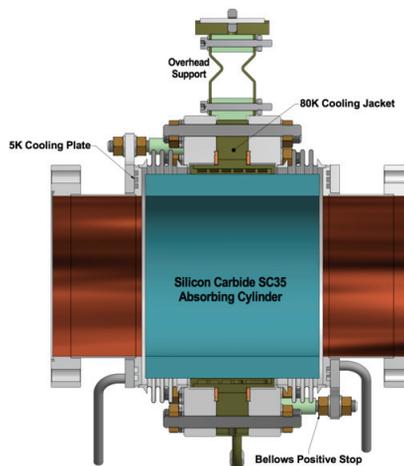
Figure 9: Cornell's HOM absorber used in the main linac cryo-module (MLC). The absorbing material is SC-35 from coorsteck, shrink-fitted into a Ti cylinder.

RF Absorbing Material

The RF absorbing characteristics, measured on a SC-35 samples are reported in Fig. 10 for reference. However, one should be aware that we found batch-to-batch variations in the material. It was also found that even small geometrical tolerances in the sample size tested with our waveguide set-up can have a significant impact in the measured parameters which requires correction of the data [22].

In addition to that the material has a borderline DC conductivity at 80 K [21]. To mitigate the risk of charge-up during beam operation, coating the cylinders with TiN was considered and tried. Even so the results were promising we built the HOM absorbers for the Main Linac Cryomodule without coating for time reasons.
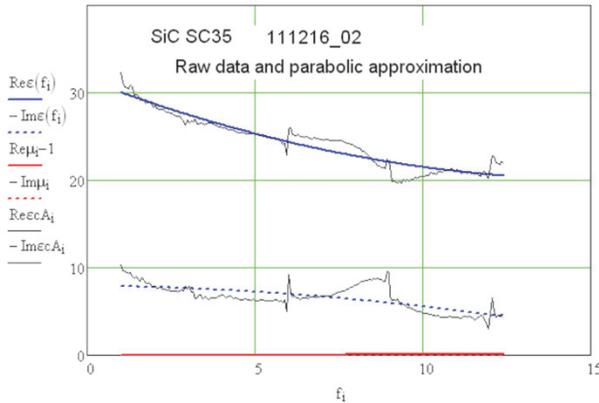
Figure 10: RF absorbing characteristics measured on a SC-35 sample.

Test Results from the Prototype

Two prototype HOM absorbers where build with a slightly mechanically different design: the absorbing ceramic was identical, but it was brazed into a tungsten cylinder. As part of designing and verifying parameters for the main linac cryo-module (MLC)[23] they were tested in a horizontal test-cryostat (HTC).

In one test, a 7-cell ERL cavity was placed between the two HOM absorbers and operated. Excellent higher order mode damping was observed with no mode having an external Q higher than 10^4 while the Q of the fundamental mode was unaffected ($6*10^{10}$ at 1.8 K). Figure 11 shows the quality factors of the cavity with and without the absorber. More details are published in Ref. 24.
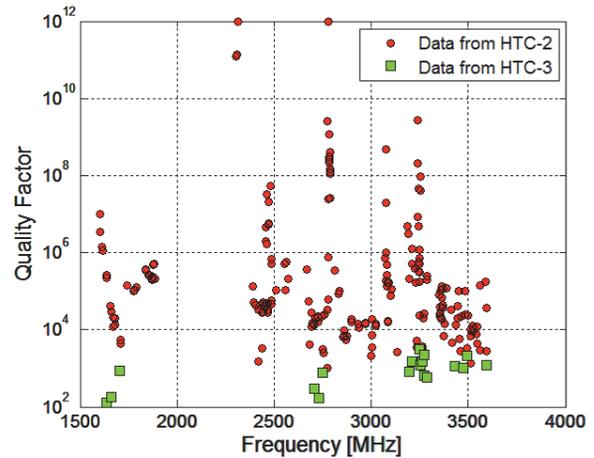
Figure 11: External Quality factor of the Cornell 7-cell ERL cavity without (red) and with (green) HOM absorbers installed. No Q higher than 10^4 was found with the absorbers installed.

Beam Test

To quantify the HOM power extracted and measure the heating effects, tests with beam were conducted on the prototype absorbers. For that, the HTC was moved to the photo-injector and located directly behind the injector cryo-module. The layout of the beamline is show in Fig. 12.

One of the HOM absorber had copper plated end tubes while the other HOM absorber remained uncoated stainless. This allowed us to balance the pros and cons of a CU-plating, as CU-plating reduces the losses of the higher order modes on the beam pipe while propagating to the absorber, meanwhile increasing the head transfer from the 5 K cooling of the HOM absorber towards the 2 K cavity end group.

For the beam test, we ran different beams through the HTC and measured the heating in various locations. The results of the runs are summarized in Table 1. As expected, the heating scaled with beam current, shorter bunches lead to higher heating and the copper coated end groups of the HOMs see less heating. We also learned that the copper coating does not give a significant heating on the cavity end-group. The overall HOM power we saw was about 7 W which we calibrated by electrical heater runs. Scaled to the envisaged 2*100 mA beam at 2 ps bunch length this would lead to 90 W of HOM power.

HTC (7-cell cavity with HOM absorbers)   ICM (5 2-cell cavities)   DC photo gun
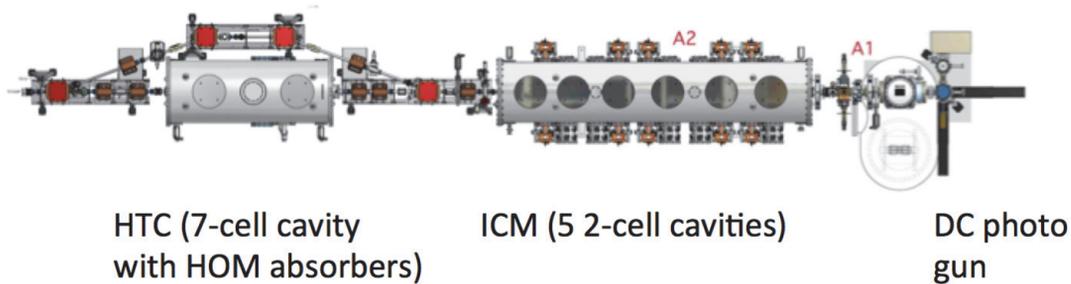
Figure 12: The horizontal test cryostat (HTC) placed behind the photo injector for testing of the 7-cell cavity equipped with HOM absorbers with beam. A beam current of up to 40 mA was run through the set-up.

Table 1: Results of the HOM absorber beam test. Temperature increase is given in K

Current, bunch length	ΔT (beam pipe behind Abs.) coated/uncoated	ΔT (80K gas temp) coated/uncoated	ΔT (80K absorber temp) coated/uncoated	ΔT (5K flange next to cavity) coated	ΔT, beam pipe to cavity coated/uncoated
25 mA, 3.0 ps	0.075/0.075	1.14/0.82	1.02/0.975	0.007	0.076/-.005
40 mA, 3.4 ps	0.2475/0.335	2.95/2.16	2.72/2.53	0.021	0.179/0.009
40 mA, 2.7 ps	0.2975/0.425	3.00/2.22	2.772/2.63	0.027	0.203/0.014

ALTERNATIVE MATERIALS

Experience from different labs as described above reveals that there are several problems with HOM dampers as they exist:

- obtaining the desired electromagnetic absorption properties across the HOM frequency band
- maintaining mechanical integrity of the HOM damper structure across a large thermal gradient (cryogenic to room temperature)
- high-vacuum compatibility (low degas rate)
- and achieving a finite electrical conductivity at low temperature to dissipate static charge

are the most prominent issues.

For some complex doped materials (SC-35, CA-137) a lack of reproducibility in the material properties has been reported.

Unfortunately, the use of these materials as HOM absorbers in the field of accelerator physics is not a big market for none of the vendors. An additional factor is the unwillingness of ceramic manufacturers to develop a custom product for this application or to disclose details of their sintering process.

This triggered our R&D on basic ceramic research, conducted within an DOE SBIR phase I grant together with colleagues from Alfred University. The underlying idea was to have a good conductor (like graphene) interlaid in the lossy material matrix (like SiC or AlN).

The constituents were initially combined in the form of powders. The powder particles are bonded and the composite densified by means of sintering in a high temperature thermal process. After synthesis, the goal was to have the individual matrix and filler materials on a micro-scale be distinct and unreacted, but in combined bulk form to behave as a composite material with the desired HOM absorber properties. The matrix is to provide the thermal and mechanical properties, and the filler material establishes the electrical and magnetic properties. In whole or aggregate, the composite material will behave as a new and unique lossy material.

It proved extremely difficult to obtain a dense pressed pellet even at 5% graphene– some samples would not press to a green density greater than 1.5 g/cm^3 (specific gravity of dense AlN is 3.26, SiC has 3.20). We found that densification also depends on the vendor of the incoming graphene. SEM analysis showed that the graphene from one vendor had hollow imprints while the other graphene was lamellar. The graphene in the form of shells behaved like springs and the pressed disks rebound considerably as pressure is released, sometimes destroying the pressed pellet.

We found that graphite-containing samples densified much more predictably. However, many process iterations and modifications had to be made to finally come up with samples that densified enough to be mechanical integrant (see Fig. 13). We produced about 50 samples with different recipes. In summary we were able to get samples with good RF damping properties (ε'~12, ε''~5 around 10 GHz) but poor DC conductivity (100 kΩ at room temperature, which becomes GΩ at 80 K). By adjusting the amount of graphene or graphite, we were able to lower the DC resistivity while maintaining the RF loss characteristics but loosing more and more the mechanical integrity of the material. At a level of 5% graphene the samples started to become unmachineable and fractured. More details can be found in Ref. 26.

We learned that many products in the ceramic industry are not standardized with a general lack of quality assurance processes. Pressureless sintering of graphene-containing compositions using conventional ceramic processing technology, even using compositions
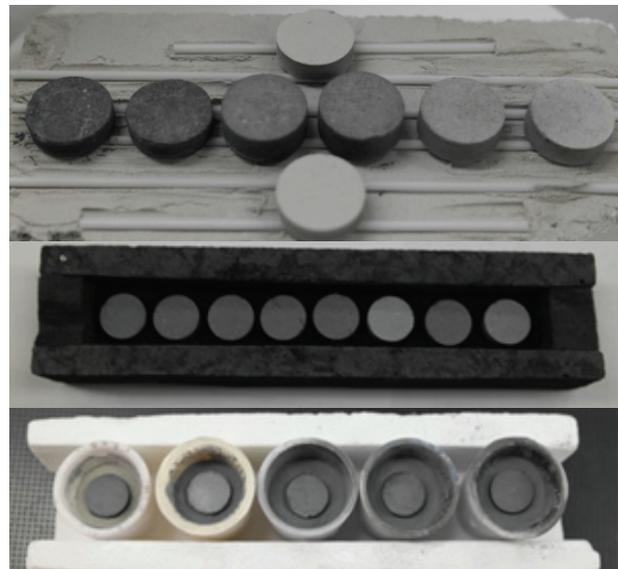
Figure 13: Sample arrangement from the HOM absorbing material R&D at Cornell and Alfred Universities.

recommended by the literature, proved to be very problematic. This might well explain why the vendors of the commercial absorbing materials are unable to guarantee or even control their material parameters.

ACKNOWLEDGMENTS

REFERENCES

[1] D. Moffat, et al., "Design and Fabrication of a Ferrite-lined HOM Load for CESR-B", Proceedings of the 1993 Particle Accelerators Conference, Washington, DC (1993) 977.

[2] S. Belomestnykh, et. al. , "Comparison of the Predicted and Measured Loss Factor of the Superconducting Cavity Assembly for the CESR Upgrade", Proceedings of the 1999 Workshop on RF Superconductivity, Santa Fee, NM (1999) 24.

[3] W. Hartung, P. Barnes, S. Belomestnykh, M. Billing, R. Chiang, E. Chojnacki, J. Kirchgessner, D. Moffat, H. Padamsee, M. Pisharody, D. Rubin, M. Tigner "Measurement of the Interaction Between a Beam and a Beam Line Higher-Order Mode Absorber in a Storage Ring" PAC95

[4] W. Hartung, "The Interaction Between a Beam and a Layer of Microwave-Absorbing Material", Ph.D. Thesis, Cornell University (1996)

[5] E. Chojnacki and W. J. Alton, "Beamline RF Load Development at Cornell", Proc. of the PAC'99, (1999) 845.

[6] H. Hahn, E. M. Choi, and L. Hammons, "Ferrite-damped higher-order mode study in the Brookhaven energy-recovery linac cavity", Phys. Rev. ST Accel. Beams 12, 021002 (2009).

[7] H. Hahn et. al. "Higher-order-mode absorbers for energy recovery linac cryomodules at Brookhaven National Laboratory", Phys. Rev. ST Accel. Beams 13, 121002 (2010).

[8] M. Sawamura, T. Furuya, K. Umemori, H. Sakai, K. Shinoe, "KEK ERL HOM Absorber Development" Presentation ERL workshop 2009, http://accelconf.web.cern.ch/AccelConf/ERL2009/talks/wg316_talk.pdf

[9] J. Sekutowicz et al., "A Beam Line HOM Absorber for the European XFEL Linac", Proceedings SRF05, July 10-15, 2005, Ithaca, NY, USA (2005)

[10] J. Sekutowicz, A. Go□ssel, N. Mildner, M. Dohlus, "BEAM TESTS OF HOM ABSORBER AT FLASH", Proceedings of IPAC'10, Kyoto, Japan (2010) 4092.

[11] P. Kolb, R.E. Laxdal, Y. Ma, Z. Yao, V. Zvyagintsev, "HOM Measurements on the ARIEL eLINAC cryomodules", Proc of the 2015 Conf on SRF, Whistler, BC, (2015).

[12] S. Henderson, "Status of the APS Upgrade Project", Proceedings of IPAC2015, Richmond, VA, USA (2015) 1791.

[13] F. Marhauser, T. Elliot, A.T. Wu, JLab, E. Savrun, E. Chojnacki, "Absorber Materials at Room and Cryogenic Temperatures", Proceedings of IPAC2011, San Sebastián, Spain (2011) 1792.

[14] M. Abo-Bakr et. al. "Progress Report of the Berlin Energy Recovery Project BERLinPro", Proceedings of IPAC2015, Richmond, VA, USA (2015) 1438.

[15] A. Neumann et. al. "Towards a 100mA Superconducting RF Photoinjector for BERLinPro", Proceedings of SRF2013, Paris, France (2013) 42.

[16] G. H. Hoffstaetter, S. Gruner, M. Tigner, eds., Cornell ERL Project Definition Design Report (2013) http://erl. chess.cornell.edu/PDDR/PDDR.pdf

[17] H. Padamsee et. al., "Status of the Cornell ERL Injector Cryomodule," Proc. of the SRF 2007 (2007) 9.

[18] B. Dunham et. al. "Performance of the Cornell High-Brightness, High-Power Electron Injector", Proceedings of IPAC2012, New Orleans, Louisiana, USA (2012) 20.

[19] M. Liepe, et. al., "Latest Test Results and Test Plans from the 100 mA Cornell ERL Injector SCRF Cryomodule", Proceedings of IPAC'10, Kyoto, Japan (2010) 3043.

[20] R. Eichhorn, et. al. "Cornell's HOM Beamline Absorbers", Proc. of the 2013 Intern. Part. Acc. Conf., Shanghai, China (2013) 2441.

[21] R. Eichhorn, J. Conway, Y. He, Y. Li, T. O'Connel, P. Quigley, J. Sears, V. Shemelin, "Higher Order Mode Absorbers for High Current ERL Applications", Proc. of the 2014 Intern. Part. Acc. Conf., Dresden, Germany (2014) 4037.

[22] V. Shemelin, N. Valles, "Improved accuracy of measurements of complex permittivity and permeability using transmission lines.", Nucl. Instr. and Meth. in Phys. Research A 767 (2014) 385.

[23] R. Eichhorn et.al. ,"The CW Linac Cryomodule for Cornell's ERL," Proc. of the IPAC 2013 (2013).

[24] N. Valles et. al., "HOM studies of the Cornell ERL Main Linac Cavity in the Horizontal Test Cryomodule", Proc. of the 2013 Int. Conf. on RF Supercond., Paris, France (2013) 1090.

[25] D.L. Hall, A. Bartnik, M.G. Billing, R. Eichhorn, G.H. Hoffstaetter, M. Liepe C. Mayes, P. Quigley, V. Veshcherevich, "Beam-based HOM Studies of the Cornell Energy Recovery Linac 7-cell SRF Cavity", Proc. of the 2014 Intern. Conf. on Lin. Acc., Geneva, Switzerland (2014) 869.

[26] R. Eichhorn, P. Quigley, V. Shemelin, W. Carty, J. Matteson, A. Rae, " Basic Research on RF Absorbing Ceramics for Beam Line HOM Absorbers", Proc. of the 2014 Intern. Part. Acc. Conf., Dresden, Germany (2014) 4040.