THE JLAB AMPERE-CLASS CRYOMODULE*

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Abstract

We report on the design of a new cryomodule capable of accelerating high-current beams for future ERL based high power compact FEL's. We discuss the factors influencing the design choices, including BBU threshold, frequency, HOM power, real-estate gradient, peak surface fields, and operating efficiency. We present a conceptual design that meets the requirements of compact MW-class FEL, however this module design could be useful for a wide range of applications such as electron cooling, electron-ion colliders, industrial processing etc. The concepts developed for this design could also be useful for larger ERL-based light sources, XFELs and even linear colliders.

INTRODUCTION

For the next generation compact FEL being developed at JLab a new cryomodule is required that is capable of accelerating up to Ampere levels of beam current. Table 1 gives a summary of the proposed specifications for the new module. To achieve these goals we propose to use a compact waveguide-damped multi-cell cavity packaged in an SNS-style cryomodule. Challenges include strong HOM damping, high HOM power and high fundamental-mode power (in operating scenarios where energy recovery is designed to be less than 100%).

Table 1: JLab Ampere-class module draft specifications.

Voltage	100-120 MV
Length	~10m
Frequency	750 MHz
Beam Aperture	>3" (76.2mm)
BBU Threshold	>1A
HOM Q's	$<10^4$
Beam power	0-1MW

GENERAL LAYOUT

The module will use six five-cell cavities with waveguide end groups, figure 1, mounted in a modified version of the JLab space-frame design, as used for the SNS project and the CEBAF 12 GeV upgrade. Five-cell cavities are chosen as a good compromise allowing strong HOM damping and good packing factor. The voltage requirement can be achieved with an average cavity gradient of 16.7-20 MV/m (real-estate gradient of 10-12 MV/m). This cavity performance is typical of that achieved during SNS cavity production. HOM power will be taken out to water-cooled room temperature loads.

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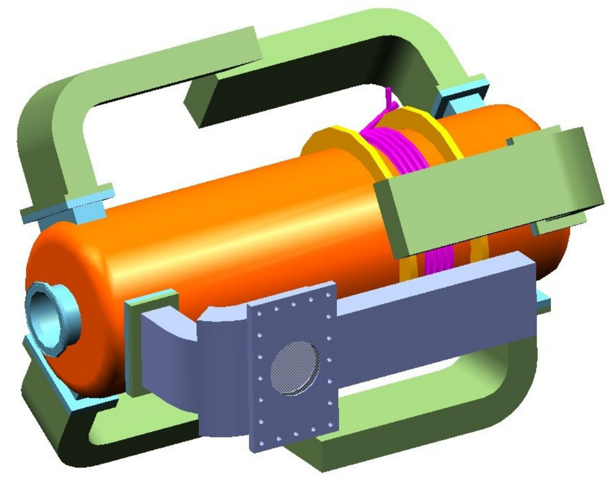

Figure 1: JLab Ampere class cavity with HOM loads and waveguide fundamental power coupler.

CAVITY SHAPE

The cavity shape needs to satisfy multiple and often conflicting requirements. A large bore is preferred for good HOM damping and minimal interception of beam halo, while strong fundamental-mode impedance is desirable for high real-estate gradient and operating efficiency with moderate peak fields. A short cavity provides good HOM damping while a longer cavity typically yields a better packing factor. We also seek a cell shape that places strong HOM frequencies safely between dangerous harmonics of the beam. A five-cell cavity with a rounded pillbox cell shape, figure 2, with either circular or elliptical profile at the equator is a good fit to these requirements [1]. Compact waveguide end groups, figure 3, carry HOM power away and fundamental-mode power to the cavity with minimal loss of active length.

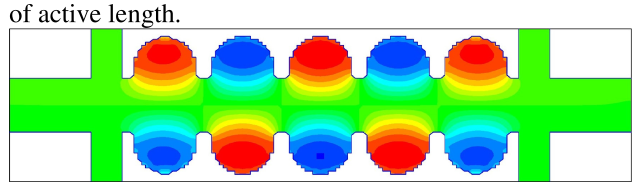

Figure 2: Five cell cavity with rounded pillbox profile.

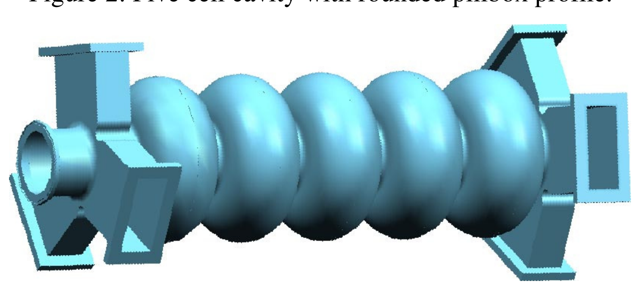

Figure 3: Five cell cavity with waveguide end groups.

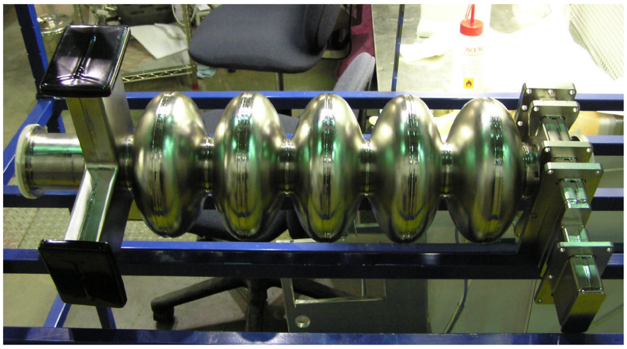

Figure 4: JLab original CEBAF five-cell 1500 MHz cavity with elliptical cells and waveguide end groups.

HOM DAMPING

Waveguide HOM dampers and fundamental power couplers have been used for many years, most notably in CEBAF, fig 4. With modern simulation tools these concepts can be optimized to eliminate coupler kicks and trapped modes and allow BBU thresholds in the Ampere class, while still preserving good operating efficiency. Careful optimization can give HOM loaded Q's two or more orders of magnitude lower than the loop-coupled designs in use today in the JLab 10 kW FEL [2]. Waveguide HOM dampers are natural high pass filters and work over a very broad band. They can handle very high HOM power, are simple to make and require no tuning. The three-port end groups we have developed couple to any orientation of dipole and quadrupole modes and all monopole modes even if the field profile is tilted after tuning. Inside each end group between the waveguides are small vanes. These tune the lowest mode in the end group volume above the cut-off frequency of the waveguides, preventing it from being trapped. We propose to stagger the end groups in azimuth to capture sextupole and higher modes, which has the added benefit of allowing a straight run for the helium header.

The HOM loads will be at ambient temperature and will use wedges of absorbing ceramic material as used on the B-Factory cavities [3], figure 5. Such loads have been shown to handle kW levels of power, are broad-band and employ simple fabrication steps and commercially available materials.

The calculated broad-band impedance spectra for such a design are shown in figure 6 (monopole), and 7 (dipole). Loaded Q's of the strong modes are within specification.

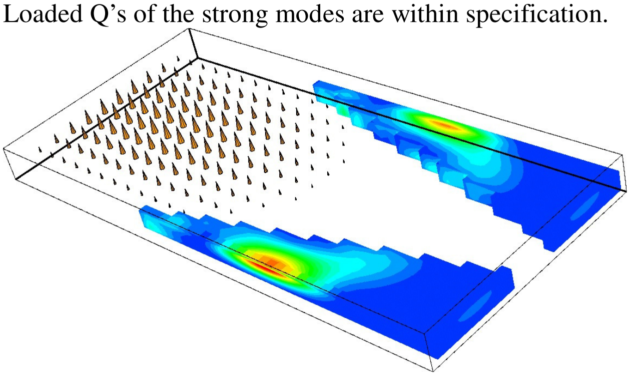

Figure 5: MAFIA model of B-Factory type HOM load.

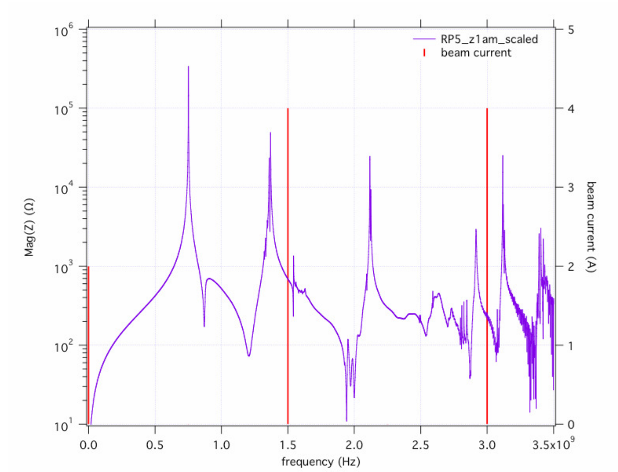

Figure 6: Monopole spectrum of rounded-pillbox 5-cell cavity with strong beam harmonics at 1 Ampere current.

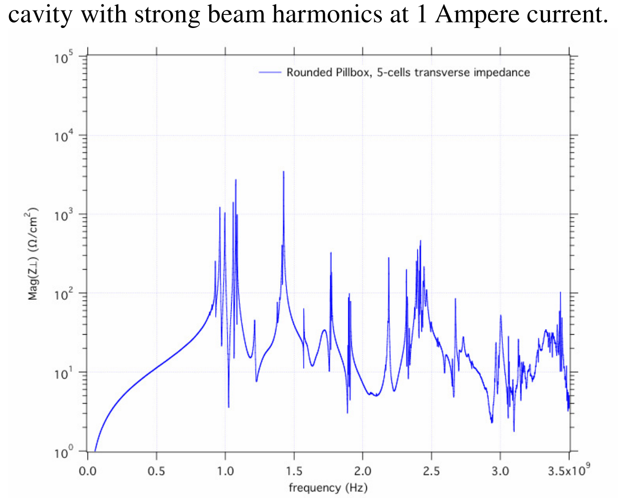

Figure 7: Transverse impedance spectrum of rounded-pillbox 5-cell cavity.

FUNDAMENTAL POWER COUPLER

Future high-power FEL's may produce up to 1 MW of optical power and under some scenarios this may need to be provided by the linac RF system. For a single six-cavity cryomodule this would require up to 167 kW per cavity/coupler. While this is considerably higher than existing ERL/FEL machines it is well within capacity of B-Factory style windows/couplers, figure 8, [4].

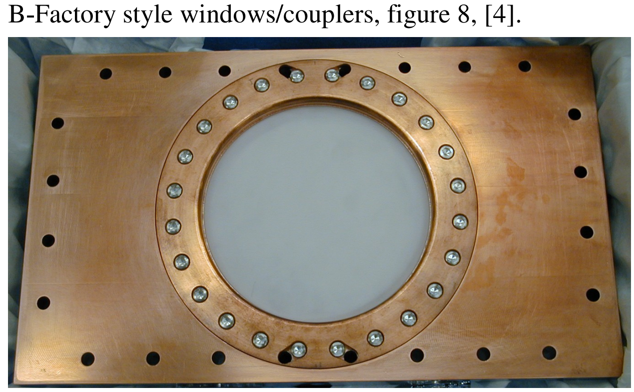

Figure 8: 700 MHz MW-class waveguide window.

While a coaxial fundamental power coupler could surely be made to work, a waveguide window and fundamental power coupler is a better fit with the HOM damping scheme proposed. Indeed one arm of the waveguide end group can do double-duty as HOM damper and fundamental power coupler. Figure 1 shows a full height waveguide window attached to one of the HOM waveguides.

TUNER

A modified version of the12 GeV upgrade or SNS-style tuner would work in this application. Other alternatives are being investigated. It is desirable to have the motor and drive mechanism accessible for maintenance either inside the module, through access ports, or externally.

COPPER MODEL FIRST RESULTS

We have recently completed the first half-scale copper model of a waveguide-damped single-cell cavity using the original 1.5 GHz CEBAF cell shape to take advantage of existing hardware. A new waveguide end group was made and attached to one side of the cavity, figures 9 and 10. Low-power dummy loads were made from carbon-loaded foam in straight waveguide extensions, figure 11.

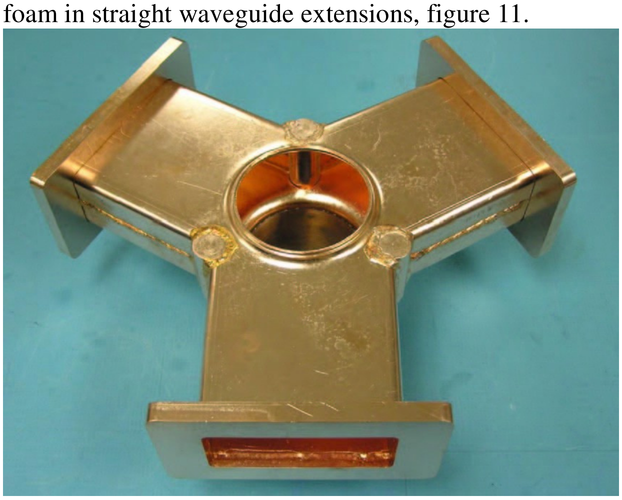

Figure 9. Copper model of waveguide end group.

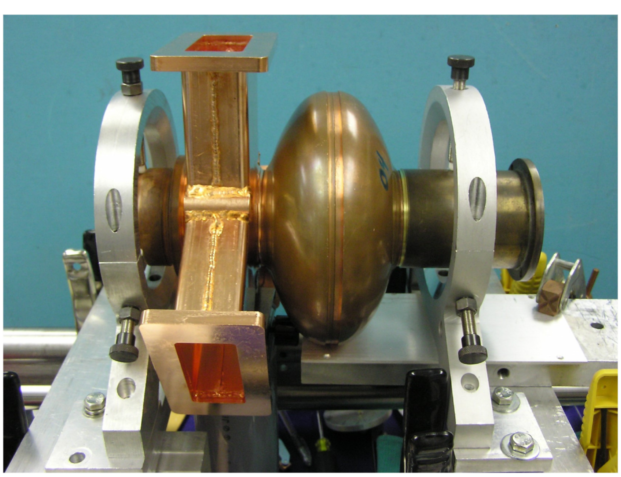

Figure 10. Copper model with CEBAF cell shape and one end group.

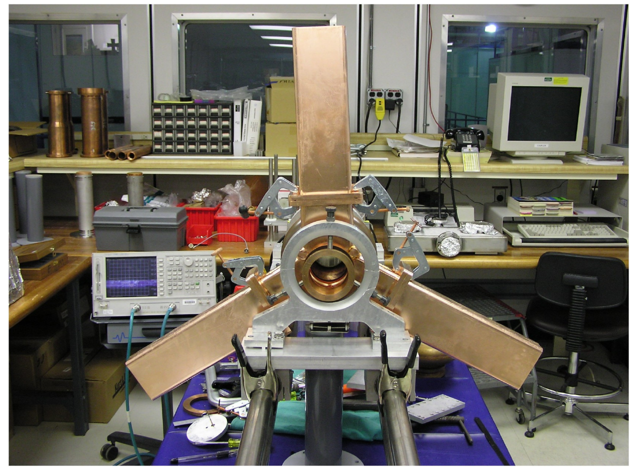

Figure 11: Copper model with CEBAF cell shape, one end group and three waveguide HOM loads.

Preliminary measurements, figure 12, agree well with simulations, with all HOM Q's being in the range of 10^4 or less. A detailed analysis along with results for a five-cell model with two end groups will be reported in a future publication.

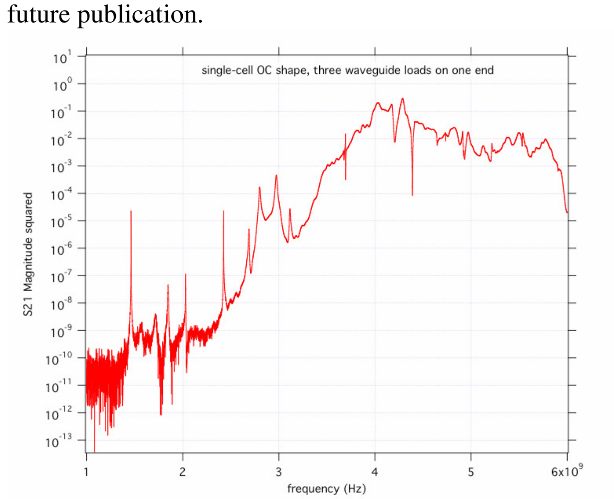

Figure 12: Measured spectrum of single-cell copper model.

INTEGRATION

The cavities, HOM loads, FPC's tuners etc. will be integrated into a modified version of the JLab space frame design, see figure 13. This allows the maximum re-use of existing tooling and facilities. Existing cryogenic end can designs can be used with modifications to increase the mass flow rate to accommodate the increased heat load of this module. The present concept uses bellows between cavities to accommodate longitudinal motion during cool-down and tuning. This simplifies the connection to the fundamental power couplers. Table 2 lists some of the major parameters of a six-cavity module based on this concept. Similar concepts could be useful for other projects, even those not requiring Ampere level currents per se, such as proposed ERL based light sources, XFELs or ILC, figure 14.

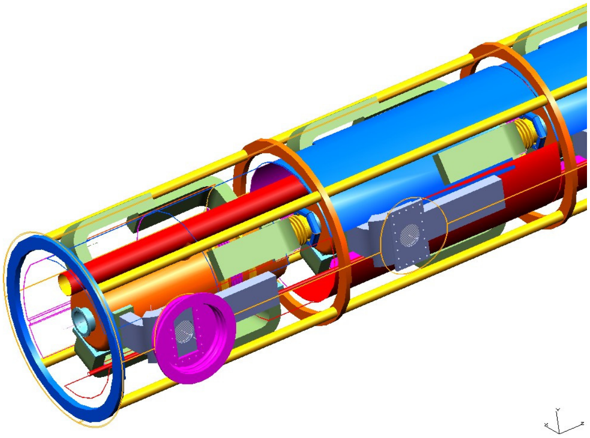

Figure 13: JLab integrated cryomodule concept.

Table 2. 750 MHz cryomodule with six five-cell cavities.

Frequency	750 MHz
# cells	5
Damping Type	Waveguide
Cavity Length	1.4m
Iris Diameter	14 cm (5.5”)
# Cavities	6
Min. Module Length	10.4m
Nominal Module Voltage	100 MV (120 MV peak)
Cavity Gradient (Eacc)	16.7 MV/m (20 MV/m max)
Real Estate Gradient	~10 MV/m
TE_{111} freq, Q_{ext}	947 MHz, 9.5e2 (calc.)
TM_{110} freq, Q_{ext}	1052 MHz, 3.3e3 (calc.)
TM_{011} freq, Q_{ext}	1436 MHz, 7.1e2 (calc.)
HOM Power/Cavity	~20 kW(est.)
BBU Threshold	>1A

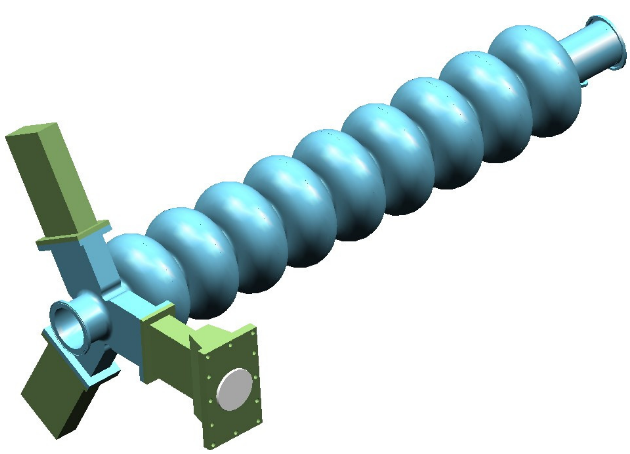

Figure 14: ILC version with simple compact end group and high-power waveguide FPC.

FUTURE ACTIVITIES

We are ready to move forward with many of the designs from the concept phase to more detailed engineering and prototypes. Multipacting analysis of the new cell shapes is under way to check for troublesome barriers that might spoil the Q or hamper processing and operation [5]. Detailed thermal modeling of the cavity and particularly the waveguide end groups has yet to be done. We propose to actively cool the end groups to handle the losses from the high HOM and fundamental power in the waveguides. Microphonic measurements and modal analysis will be performed as for a cavity of this size there is more likelihood of mechanical resonances falling at low and possibly harmful frequencies. For high average currents such as these all beamline components must be designed for low impedance or be shielded. A low-impedance cold bellows or a particulate free bellows shield must be developed for use between cavities. Niobium models of the cavity and end groups will be tested, starting at 1.5 GHz to take advantage of existing JLab infrastructure, then moving to 750 MHz as tooling becomes available.

Detailed design and prototyping of all main components must be done before starting the full prototype cryomodule assembly.

CONCLUSIONS

We have developed concepts for the key components of an Ampere-class cryomodule suitable for a compact high-power FEL. We conclude that strong HOM damping can be achieved in a multi-cell cavity while preserving good fundamental mode efficiency and real-estate gradient. Concepts for the module layout and ancillary components are closely based on existing proven designs and production methods and processes in use at JLab and elsewhere.

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