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ON THE WAY TO A 10 MeV, CONDUCTION-COOLED COMPACT SRF ACCELERATOR

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Abstract

After the success of designing a compact 1 MeV, 1 MW accelerator based on conduction-cooled SRF, Jefferson Lab is now pursuing a concept to provide a tenfold increase of the beam energy. The obvious challenge for SRF is to move from a single-cell to a multicell cavity while maintaining high efficiency and the ability to operate the machine without a complex cryogenic plant. This paper summarizes the current state of this effort with respect to the design of a Nb_3Sn coated five-cell cavity and the corresponding RF components, especially the fundamental power coupler (FPC), as well as first thermal analysis of the cryocooler-based cooling setup.

MOTIVATION

The combination of Nb_3Sn coated SRF cavities and commercially available cryocoolers allows to envision accelerator designs which do not required a costly and complex cryogenic plant. Especially in the US, a variety of R&D efforts targeted at this technology transfer have been started [1–3]. As of now, these developments mostly aim at compact, single cavity systems yielding a beam energy of 1 to 10 MeV. Potential applications for such machines can be found in compact irradiation facilities for medical device sterilization, chemical industrial processes, as well as for many environmental applications, such as flue gas or wastewater treatment [4, 5]. The significant advantage of SRF compared to normal conducting (NC) technology in this field is the much higher efficiency of RF to beam power conversion. While existing NC solutions are therefore typically limited to few tens of kW in continuous wave mode (CW), the SRF design concepts mentioned above target the MW regime. Independent of the actual application, this allows for either much higher throughput or much larger dose application.

Recent studies at Jefferson Lab have successfully demonstrated the operation of multi-metallic, single-cell SRF cavity by conduction cooling in a horizontal test cryostat [6]. Together with this hardware demonstration, a concept design for a 1 MeV compact accelerator has been developed. In parallel, a new research effort aiming at a compact 10 MeV accelerator design has been initiated. A key element of the latter is advancing from a single to a multicell cavity.

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915 MHz FIVE-CELL CAVITY

The first step for designing a multicell cavity is to pick the resonant frequency and the geometry with respect to the relative particle speed, i.e. $\beta = v/v_c$, with v_c the vacuum speed of light. As the operational cost of a compact SRF machine is dominated by the RF source, compare [1], the technology chosen here has a significant impact on the overall economical appeal of any derived application. Analyzing the available technology landscape, magnetrons stand out with an efficiency beyond 85%. Although there are certain disadvantages when compared to other available sources, namely phase stability and lifetime, significant progress has been made tackling these issues in dedicated research for compact machines [7]. The underlying technology is based upon industrial magnetrons used for heating processes. Their operation frequency is also within an acceptable range for SRF cavity design, i.e. 915 MHz, and was hence chosen for the multicell concept of this project. Table 1 gives the corresponding design parameters while Fig. 1 shows a 3D model of a 915 MHz five-cell cavity. A $\beta = 1$ has been chosen to reduce manufacturing and treatment complexity compared to a graded-β design while the actual geometry has been optimized to increase the accelerating field while minimizing the surface field.

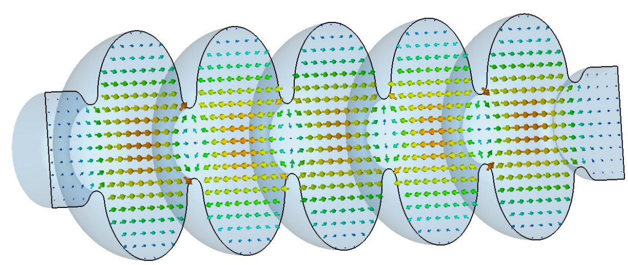

Figure 1: CST model of the 915 MHz five-cell cavity design, the arrows indicated the electrical field in π mode.

Multipacting Analysis

To analyze the generated resonator design for potential multipacting barriers, the code FishPact was utilized [8] with the secondary emission parameters for Nb_3Sn from [9]. The analysis is conducted by taking a field file computed with SuperFish [10] and examining the trajectories of electrons and secondary electrons emitted from the cavity surface. Fig-

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Table 1: Design Parameters for the 915 MHz Five-Cell Cavity

parameter	value
f	915.032 MHz
l	81.9 cm
R/Q	607.1 Ω
G	275.3 Ω
E_p/E_{acc}	2.145
H_p/E_{acc}	4.235 $\frac{\text{mT}}{\text{MV/m}}$

ure 2 shows the results of such a study conducted for the first and second cell i.e. an endcell and a standard midcell of the five-cell geometry for varying gradients. Only multipacting electrons which survived 20 impacts were considered.

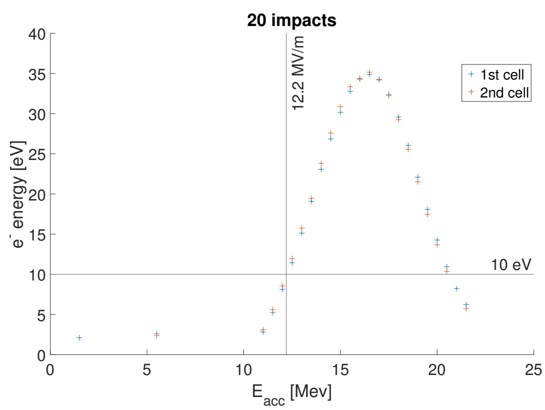

Figure 2: Result for the FishPact analysis: Final impact energy of stable electron trajectories from the equator region of the first and second cell.

Neglecting any injection energy the required gradient to generate a 10 MeV beam is about 12.2 MV/m . As Fig. 2 shows, the expected multipacting electron energy is still below 10 eV at this gradient, hence, no complication with regard to multipacting for the chosen resonator geometry is expected.

Thermal Analysis

To evaluate the thermal behavior of the conduction-cooled cavity, a 3D model has been setup in the finite element analysis software Ansys. The model is based on multiple input parameters:

1. The surface magnetic field, which was calculated with a corresponding CST model, compare Fig. 1,
2. different assumed behaviors of the surface resistance of the cavity itself, varying for field and temperature; three different cases for different thermal gradients and external magnetic fields during transitioning to the superconducting state as well as different values for the intrinsic residual resistance have been studied, see Table 2,
3. the thermal conductance of the heat sink connection from the cavity to the cryocooler(s) taken from measurements conducted for the single cell experiments [6],
4. the known heat capacity for different temperatures of the second stage of a Sumitomo RDE-418D4 cryocooler, currently the highest capacity GM-type coolers on the market with about 2 W cooling capacity at 4.2 K,
5. and different total number as well as orientation of such cryocoolers around the five-cell cavity.

Table 2: Different Input Parameters for the Three Studied Surface Resistance Models for the Thermal Analysis

	temp. grad. [K/m]	magn. field [µT]	intr. R_{res} [nΩ]
R_s "good"	0.1	0.2	2
R_s "medium"	1	0.5	3
R_s "bad"	3	1	5

During the development of conduction-cooled single-cells Jefferson Lab has so far pursued an approach of coating a Nb cavity, which serves as substrate for the Nb_3Sn coating, with a thick (≥ 5 mm) copper layer. This has proven to yield a great thermal stability of the entire system. However, this benefit also comes with some downsides as observed during the most recent study [6]. The difference in thermal contraction of the two materials results in an additional strain on the coating which can cause a significant deterioration of its superconducting characteristics. Furthermore, thermoelectric currents between Cu and Nb generate local magnetic fields which also impact the quality factor. Motivated by the success of similar attempts for conduction-cooled cavities at Fermilab [11], a study on adding Nb rings to the equator region of the cells has been initiated. This approach is also examined in the thermal analysis where it is easy to vary thickness and position of these rings. Future comparisons with partial copper coating/plating are foreseen.

Promising results for the targeted performance have been generated with a total number of seven coolers placed above and below the cavity[1], compare Fig. 3. Considering the different input parameters for the surface resistance listed in Table 2, different results for a stable gradient can be achieved. Table 3 compares such results for a varying thickness of the heat sinks i.e. equator rings. The cavity walls themselves are 4 mm thick Nb. The last numerical analysis includes a copper layer of 2 mm on each side of the equator ring, compare Fig. 4, yielding a significant improvement of the heat reduction in the cavity and, hence, a larger achievable gradient sufficient for a 10 MeV design.

FUNDAMENTAL POWER COUPLER

An essential part of every SRF cryomodule is the FPC which links the outside RF source, typically operating at

[1] There is a slight reduction in cooling capacity of a GM-type cooler when operated upside down. This was taken into account for the simulation.

Table 3: Results for the Thermal Analysis of the 915 MHz Five-Cell with Different Input Parameters and a Cooling Concept of Seven 2 W RDE-418D4 Cryocoolers, Compare Fig. 3 and Table 2

	R_s "bad"			R_s "good"		
heat sink design	max E_{acc} [MV/m]	av. cavity temp. [K]	heat/cooler [W]	max E_{acc} [MV/m]	av. cavity temp. [K]	heat/cooler [W]
4 mm Nb ring	9.2	6.1	2.1	12.5	5.2	1.2
6 mm Nb ring	9.8	5.9	2.2	13.1	5.0	1.3
8 mm Nb ring	10.1	5.9	2.3	13.5	5.1	1.5
4 mm Nb 2 x 2 mm Cu ring	11.5	5.5	2.6	15	4.9	1.9

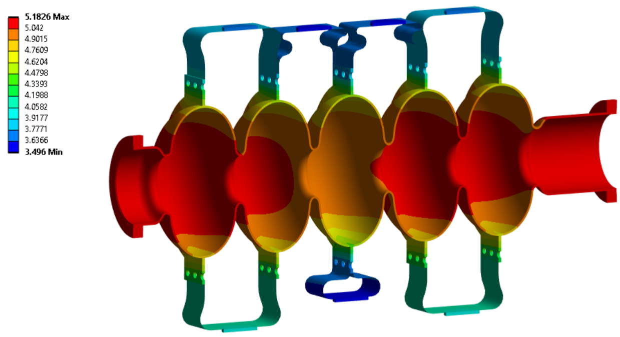

Figure 3: Stable result of the thermal analysis of the five-cell cavity with equator rings of 6 mm thickness and seven RDE-418D4 cryocoolers at 13.1 MV/m, compare Table 3.

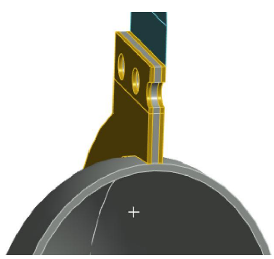

Figure 4: A variation of the heat sink equator ring with a layer of 2 mm copper on each side, corresponding to the results in the last row of Table 3.

room temperature, to the cryogenic cavity at the core of the module. In regular SRF modules there are usually multiple stages of heat shielding facilitating that transition over about 300 K. In the case of a cryocooler driven module, a similar approach can be pursued utilizing the higher capacity first stage(s) of a single or multiple coolers. Hence, existing FPC designs offer a good starting point for a first concept. Nevertheless, the characteristics of conduction cooling itself impact certain requirements.

Coupler Port FPC

A classic FPC design is to add a coaxial line to an additional port at one of the beampipes of the cavity. Given that the 10 MeV accelerator concept is targeting a total beam power of up to 1 MW, a twin FPC concept with two identical couplers is favorable, see Fig. 5. For this study, an adapted version of an SNS-type FPC was used [12]. Characteristics of this design are a single, circular, warm RF window and two heat sinks. For the purpose of the conduction cooling design the inner anchor – copper/orange disc in Fig. 5 – is connected to the first stage of a two-stage cryocooler, while the second – steel/grey disc in Fig, 5 – is connected to the vacuum vessel itself – for simulation purposes fixed at 300 K. An adaptation to the design itself are so called "pringle tips" of the inner conductors, following the radius of the beampipe. Furthermore, the addition of RF shields in the cold section of the FPC has been investigated. These shields consist of a copper cylinder inside the outer conductor of the cold section of the FPC which is connected to the cold/first stage heat anchor but not the cavity cold flange. Hence, it shields the outer mechanical steel tube which is connected to the Nb port of the cavity from the heating induced by the RF field. Consequently, such a shield helps to further reduce the heat load to the cavity and therefore the second stage system. Results for the total heat loads are summarized in Table 4. The loads are given for one RDE-418D4 cryocooler per FPC applying an RF power of 500 kW, i.e. 1 MW for the twin system. Similar to the situation in SRF cryomodules cooled with liquid cryogens, the main heat load is successfully intercepted at the intermediate cooling stage.

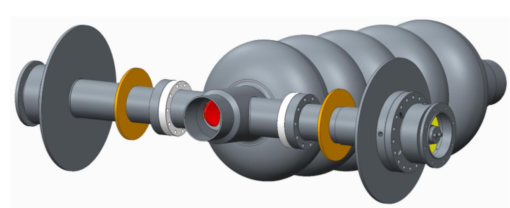

Figure 5: 3D model of the 915 MHz cavity with two Coupler Port Coax type FPCs.

Beamline Coax FPC

An alternative design approach for the conduction-cooled cavity is to use an in-beamline coaxial FPC. Here, the beam tube itself is used as an outer conductor in combination with a tube-shaped inner conductor to introduce the RF power into the resonator. One advantage of this concept is that the waveguides which feed the coupler can be placed outside the module itself, compare Fig. 6. While this reduces the heat load to the cryogenic system, it also comes at the cost of

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Table 4: Thermal Input by Different FPC Solutions 500 kW Each

	port w/o RF shield		port w/ RF shield		beamline w/o RF shield		beamline w/ RF shield	
	heat [W]	temp. [K]	heat [W]	temp. [K]	heat [W]	temp. [K]	heat [W]	temp. [K]
2nd stage	4.1	4.7	2.6	3.9	4.2	7.5	2.4	4.5
1st stage	26.5	35.6	27.0	34.6	20.0	34.3	24.4	33.9

additional real estate on the beamline, i.e. an increase in the distance between cavity and injector section. In the case of the two presented concepts, the coax beamline design adds about 5”. Another advantage is that the inner conductor shields the beam from the warm-cold transition bellows of the beamline, the latter being placed between first stage heat shield and outer tank. In case of a 100 mA beam current, this is a significant advantage.

The heat input to the first and second stage of – again – two RDE 418D4 cryocoolers has been studied by an Ansys simulation for a total RF input power of 1 MW. Similar to the dedicated port coax FPC case an RF shield in form of a copper tube inside the cold part of the coax volume – up until the cavity flange – has been added in thermally connected to the first stage heat sink, copper/orange disc in Fig. 6. The corresponding heat load results are given in Table 4. In both cases the RF shield yields a noteworthy (≥ 40%) reduction of the heat load on the 4.2 K system.

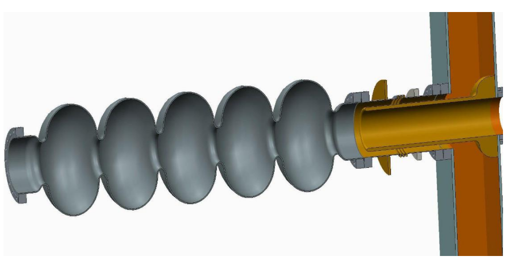

Figure 6: Cross section of the 915 MHz five-cell with a Beamline Coax FPC with two input waveguides; warm RF windows inside the waveguides are not shown.

BEAM DYNAMICS

Based on the field attributes of the 915 MHz five-cell cavity, first beam dynamics studies have been conducted. They target the combination with an injector section capable to deliver the required beam current to generate a 1 MW electron beam at 10 MeV. The preliminary design presumes that the electron beam is delivered from a robust, gridded, thermionic source. The electron gun, with a commercially available 2 cm diameter gridded cathode, is modulated at 915 MHz to produce a 100 mA bunched beam at 45 keV. This low energy beam cannot be directly captured efficiently into the SRF cavity due to the long transit time and phase-slippage in the first cells. The simplest and most cost effective solution is to use a booster cavity to increase the energy to about 500 keV. In the proposed design a normal conducting two-cell, 915 MHz, beta-matched copper cavity is invoked to accelerate the beam. Finally, typical magnets are used to manipulate the transverse properties of the beam prior to the SC cavity.

First simulations of this system have been performed using the General Particle Tracer code [13]. The 100 pC electron bunch from the gun initially expands both longitudinally and transversely due to space charge forces. A solenoid is used to focus this beam into the booster cavity located at 40 cm from the cathode face. The phasing of the copper booster cavity is set to provide some longitudinal bunching in addition to acceleration, which results in lower energy spread at the beamline exit. This is followed by a second solenoid to focus the beam into the superconducting cavity.

Although the transverse emittance is not a critical parameter for this application, the thermal emittance from the cathode has been included in the simulation, and beam tracking takes account of space charge effects. The resulting electron beam is well within typical beamline apertures, with a final transverse rms emittance of 12 µm. A total energy spread of the beam at the end of the beamline of about 700 keV peak-to-peak has been achieved. Figure 7 shows the evolution of the energy along the proposed beamline.

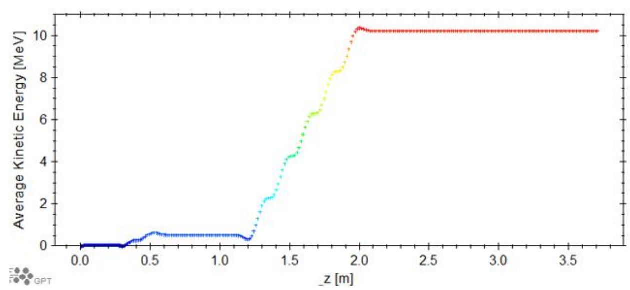

Figure 7: Average energy gain along the beamline for the compact accelerator design.

OUTLOOK – 9 W CRYOCOOLER

In parallel to the design and computational analysis work described here, a hardware study on conduction cooling of multicell cavities is conducted. This effort focuses on the conduction-cooled operation of a three-cell cavity in a horizontal test cryostat. One interesting addition to the scope of this proof-of-principle experiment has recently been triggered by the release of a new cryocooler type by Sumitomo Heavy Industries. The RJT-100 [14] combines a GM-type, two-stage cooler with a Joule Thomson valve, offering a total cooling power capacity of up to 9 W at 4.2 K. This poses an interesting alternative to contemporary coolers for the design of a compact machine. For example, looking at the design concept of a compact 10 MeV machine driven by

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915 MHz five-cell cavity as described above, the operational consumption of the cooling section could be reduced by more than one third as an estimate calculation based on preliminary results in Table 5 shows. Currently, Jefferson Lab is in negotiations with Sumitomo to potentially include a prototype of this new cooler in the test setup of the three-cell cavity. Figure 8 gives a first impression of what such a setup could look like.

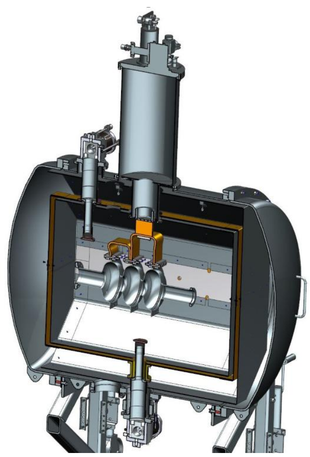

Figure 8: Draft of the Sumitomo RJT-100 on top of the horizontal test cryostat foreseen for the conduction-cooled test of a three-cell cavity, two RDE-418D4s are used as additional shield coolers.

Table 5: Cost and consumption estimates for the cooling concept of a 10 MeV compact SRF accelerator, the estimate is based on 7-8 2 W GM type coolers for the cavity and 2 for the FPC. In the GMJT case an additional shield cooler is included.

	power cons. [kW]	cooling @ 4.2 K [W]
10 GM type	**70**	20
2 GMJT & 1 GM	**42**	20

CONCLUSION

Targeting the design of a compact, SRF-based accelerator that can reach beam energies up to 10 MeV, multiple design efforts and simulation studies have been conducted at Jefferson Lab. Motivated by magnetrons as the most efficient RF sources, a 915 MHz five-cell cavity has been designed. As a next step, conduction cooling concepts based on the application of cryocoolers for this cavity have been examined, yielding successful solutions. Further studies of alternative, novel standalone coolers are foreseen. Two FPC concepts were adapted to the cavity and studied in their thermal behavior. As a next step the full integration of cavity and FPC(s) in a cryomodule will be examined. A thorough analysis of the cavity higher-order modes (HOM) will be done as well to determine the need for HOM dampers.

The result of the beam dynamics studies suggests that 1 MW can readily be delivered with the proposed system. Further work will be performed to optimize the layout and further develop the design of the additional beamline components.

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