Minutes of μ-cool RF system workshop

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The meeting was held at Lawrence Berkeley National Laboratory, February 17 and 18 1998.

Attendees:

Perry Wilson, Roger Miller, Artem Kulikov (SLAC)

Al Moretti, Zubao Qian (FNAL)

Harold Kirk, Yongxiang Zhao, Bob Palmer (BNL)

Don Summers (University of Mississippi - Oxford)

Bob Rimmer, Walter Barry, Derun Li, Glen Lambertson, Bill Turner, John Corlett, Alan Lyon, Ron Scanlan (LBNL)

Speakers:

Palmer	Cooling experiment and simulations
Zhao	$2\pi/3$ mode RF structure
Moretti	$\pi/2$ mode RF structure
Li	RF structure options
Zhao	Be materials properties
Summers	Low Temperature Resistivity of Beryllium, Copper, and Aluminum
Kirk	Be thickness variation
Moretti	Be window design
Wilson	Wakefields
Lyon	Coating surfaces with Be, Al, TiN etc.
Rimmer	Multipactor issues
Kulikov	RF in extreme environments
Corlett	Experimental program

Day 1

Palmer gave an overview of the cooling experiment and transverse cooling simulations. The requirement for low Z material and low $\beta_\perp$ to provide a small acceptance angle was highlighted (0.35 rad for hydrogen vs. 0.6 for beryllium). Low $\beta_\perp$ is achieved by use of alternating solenoids, with high fields (15 T at the H target), matching between them is the problem. The RF structure is in a solenoidal field of up to approximately 8 T at the ends, and a field reversal in the center. The overall 6-dimensional emittance is reduced by exchange of longitudinal and transverse emittance in bent solenoids at the ends of the transverse cooling sections. A 6-D emittance reduction of 6 orders of magnitude is required; with a reduction per stage of 2 and typical length 20m requires 500 m total length cooling channel. The 800 MHz RF structures require 24 MeV/m average acceleration at peak phase (for the $\pi/2$ mode interleaved structure with a transit time of 0.9, this equates to 27 MV/m peak field), FNAL already achieve 38 MeV/m. Operating at liquid nitrogen temperatures increases Q and shunt impedance of the RF structures, we are assuming a factor of 2 until otherwise shown. Each linac structure is approximately 1.3 m in length, 15 cm radius. Parameters are being optimized.

Zhao described a design for a $2\pi/3$ structure, using three sets of cavities, each set linked by one of three waveguides running along the structure at the outer radius. In the time that the beam traverses an RF cell, the phase shifts by one third of a period, and each cell is approximately 10.4 cm long. Shunt impedance at room temperature (ZT^2) is 46 MΩ/m, Q 26,000, group velocity 4.6% of c. The three sets of coupled cavities are interleaved, leading to a high shunt impedance as the beam experiences a high accelerating field in each cell it traverses, with a phase shift of $2\pi/3$ per cell as seen by the beam.

Moretti described interlaced $2\pi/4$, and interlaced $\pi/2$ structures, coupled by resonant coaxial structures between the groups of cavities. The $2\pi/4$ structure has four sets of cells and coupling structures, and little room for diagnostics. The $\pi/2$ mode interleaved structure has a shunt impedance at room temperature (ZT^2) of 46 MΩ/m, and Q is 22,000. The beam sees a phase shift of $\pi/2$ per cell. A preliminary design including liquid nitrogen cooling channels was presented.

Li presented a review of structure options, including the $\pi/2$ side coupled structure. Traveling wave structures have been rejected due to their difficulty in tuning, and tight tolerance requirements. Standing wave structures with higher group velocity (stronger coupling) and higher shunt impedance are preferred. Comparison of major parameters for each structure (1.4 m section):

	ZT^2 ($M\Omega$/m)	Q	Power for average acceleration 24 MeV/m (MW)	# windows	Fill time (μs)	Power per cell @ 24 MeV/m (MW)
$2\pi/4$ interleaved	46	22000	18	19	4.4	1
$\pi/2$ interleaved	46	22000	18	19	4.4	1
$2\pi/3$ interleaved	46	26600	18	14	5	1.4
$\pi/2$ side coupled	37	31000	22	10	6	2.4

Calculations of heating of a beryllium window by RF currents was presented, both from analytical models and MAFIA calculations, for different window thickness and tapered windows. The window temperature rise is maximum in the center, and for a 20 μs pulse at 15 Hz, accelerating field 24 MV/m and shunt impedance 35 $M\Omega$/m, thermal conductivity of Be 200 W/(m.K), then the power deposited in the Be window is approximately 62 W. This is a conservative calculation, and using more realistic parameters we expect the power loss to decrease. For these parameters the maximum temperature rise for a 0.001 inch window is approximately 330 degrees, and for a 0.005 inch window approximately 70 degrees.

Zhao presented a survey of beryllium materials properties. Electrical conductivity of Be is very good at liquid nitrogen temperatures (resistivity approximately 0.075×10^{-5} Ωm at 80 K), but the variation in data is about two orders of magnitude, depending on sample types. Thermal conductivity is approximately 8 times that of copper, but data varies between material batches. To obtain characteristics relevant to the materials to be used in the muon cooling RF structures, a resonant structures are being made to measure the electrical properties of beryllium coatings and strips at low temperatures. A resonant cylindrical cavity (TM_{100} mode), with Be coating, is being designed. The Q of the mode will be measured as a function of temperature, giving the electrical conductivity of the Be surface. In addition, a two-strip $\lambda/2$ resonator is also being designed; again, the Q of the resonator will allow measurement of electrical conductivity as a function of temperature, for different samples of Be used in making the strips. Both cavity and strips will be mounted in a vacuum tank for thermal insulation, and coolant piped along the outside of the cavity. The strips will be mounted inside the cavity.

Summers reviewed the low temperature properties of Be, Cu, and Al. At liquid nitrogen temperatures, Be is the better conductor of these metals. At 20 K, Al is the best conductor, which may be advantageous if an RF system operating at 20K were to be considered. One problem with the choice of aluminum is that it suffers from being especially prone to multipacting, and surface treatments will be necessary to reduce the secondary emission yield in an Al cavity. The crossover temperature in electrical conductivity between Be and Al is about 50 K. LANL have some experience with low temperature Al and Be RF cavities, and contact should be made with them. Annealing is useful in removing lattice defects, radiation damage at liquid nitrogen temperatures does not appear to be a problem for Be. Transverse magnetoresistivity of each metal appears to be not a problem, however the magnetic field strengths in the cooling channel need to be re-assessed. Anomalous skin effect (charge carrier mean free path > penetration depth of RF field) has not yet been quantified. Evaporative coating of Be and Al is possible, expertise exists particularly for Al, but Be is poisonous and ES&H issues become more severe. LBNL and LLNL are known to have Be coating capabilities. Measurements of the DC resistivity of Be wire are being made using a four-terminal resistor.

Kirk presented cooling studies using PARMELA and ICOOL, using different thicknesses of Be windows between RF cells in the alternating solenoid cooling channel. The conclusions are that for emittances down to approximately 800 π mm-rad, Be window thicknesses of up to 0.015 inch are acceptable. For lower emittances, however, the effects of scattering in the windows is more pronounced and a thickness of the order of 0.005 inch is required. This more stringent requirement is to be taken as our baseline in RF cavity and window designs. The smaller transverse beam size at lower emittance may help in that smaller windows can be used.

Moretti described work on the Be window work, including ANSYS studies of stresses from atmospheric loading. In this case a 6 inch diameter, 0.015 inch thick window deflects by 0.087 inch at the center. Pre-forming a concave surface reduces the deflection, manufacturers suggest a 30 inch radius of curvature for a 0.01 to 0.046 inch thick window of 6 inch diameter. Thermal expansion properties of the window and support materials were discussed, niobium or titanium being the closest to beryllium in thermal expansion coefficient. It may be advantageous to remove the window edges from the high field region of the cavity to avoid RF breakdown. Several designs for allowing differential expansion were discussed, including sliding fingers (allowing change of windows in the cavity, which would be slotted to accept the window between cells), and a "bridge" design which will absorb the few thousandths of an inch differential contraction between materials.

Wilson described the physics of wakefields for simple pillbox structures. Fields generated by the beam are reflected from the cavity outer walls, and then catch up again with the slower-moving beam. Further reflection of these fields from the opposite wall of the cavity causes spikes in the energy transfer in the beam/cavity/beam system. Calculations for relativistic beams are well known, but the situation for non-relativistic particles is more complicated and not developed analytically yet. Computer codes can be used to calculate wakefields in pillbox cavities. The time between the first and second bunches (of the order of several ns) should be determined with these wakefield affects borne in mind.

Lyon described Be sputtering and evaporation techniques. The process is possible using a "boat" introduced into the cavity after assembly, but is simplified and better controlled if components can be coated before final assembly. This is particularly true for the coupling structures, which would otherwise be hard to access with a coating device. Aluminum or stainless steel are easier to coat than copper, but copper is also possible. Migration into the copper surface may be a problem. A chromium bonding layer is sometimes used. Annealing at a temperature approximately 2/3 melting point helps to reduce "crazing" in the coating, and improves electrical and thermal characteristics. LLNL have experience of Be coatings and may also have information on materials properties as a function of purity.

<u>Day 2</u>

Rimmer presented a review of multipactor issues. The process is a resonant RF electron discharge, dependent on secondary emission coefficient, which is itself a function of primary electron energy, angle of incidence, surface roughness, and surface cleanliness. RF processing and a low secondary emission coating (e.g. TiN) can cure multipacting, which otherwise may deposit large amounts of energy in the metal surface, causing significant heating and damage. The RF voltage at which multipactoring (two-surface) occurs is a function of frequency of applied field and spacing between surfaces. For the muon collider cooling channel RF structures, we do not expect the windows of the cells to operate in a multipacting zone, since the field strength at the windows will be high enough that emitted electrons are not trapped by and become resonant with the field. Some parts of the cavity, however, may be subject to multipactor, and the whole structure will have to pass through multipacting regions to achieve high fields. The influence of external magnetic fields was discussed, and it is clear that the location of multipacting can be moved by applying a magnetic field to deflect the electrons. Construction of the PEP-II B-factory cavities was discussed, which involved electron beam welding of several sections. Weld shrinkage is approximately 0.01 inch for 1 inch thickness of material. Conditioning of these cavities takes a few days.

Kulikov described the SLAC positron production source, as an example of an RF system in strong radiation and magnetic field environments. The s-band structures have been conditioned to 30 -35 MeV/m, in a 0.5 T solenoidal field. Conditioning with the solenoidal field on was critical, the multipacting pattern is very sensitive to magnetic environment and conditioning with the magnets off did not allow high-power operation with the field on. Radiation damage to components is considerable, and electrical insulation is presumed to be turned to dust for all components near the target. Radiation damage did not, however, affect the operation of the RF cavities. Tungsten rhenium alloy is used as a target material, it is machineable, maintains mechanical properties at high temperatures, and has a high density.

Corlett presented RF structure experimental program options. A low power test cavity designed to allow window changes and minor modifications to the structure is desirable. Coordination with the window designers is essential, and will influence the choice of cavity body material (to allow for differential contraction). A cavity consisting of two half-cells with coupling between is proposed. The cavity will be placed in a vacuum enclosure and cooled with liquid nitrogen piped around the structure (the original proposal to immerse the cavity in a bath of liquid nitrogen was rejected as not allowing precise temperature control). Feedthroughs to measure cavity frequency, Q, and field strengths in each cell, as a function of temperature will be installed, in addition to thermocouples to measure cavity and window temperatures, and viewports to monitor window condition. Tuning will be accomplished by deformation of the cavity. Sensitivity of the resonant frequency to vibration and deformation of the Be window will be measured. The low power cavity allows tests of the structure before beginning the more expensive and involved high power cavity design, manufacture, and testing. The high power cavity must be vacuum and high-power RF compatible, with good weld or braze joints rather than bolt-in windows etc. High power cavity measurements will be conducted at FNAL, using an existing 805 MHz klystron and modulator. There is considerable work to be done in building the high power test stand; in shielding, floor loading, RF power routing, and location choice. The requirement of having a solenoidal magnetic field to allow measurements of multipactor effects in different magnetic environments was noted, this further complicates the high-power cavity testing. The possibility of exciting a TE_{111} mode to continuously monitor the cavity at a frequency other than the 805 MHz fundamental mode was discussed.

<u>Discussions and action items:</u>

Structure choice and operating temperature:

Four structure options were considered, as outlined above. Based on power requirements, simplicity of construction, peak field, and power per cell, the $\pi/2$ interleaved structure is favored. The $\pi/2$ interleaved structure, with copper body and Be window in frame designed to accommodate differential contraction, was chosen as the design of choice at the moment. R&D will continue on this structure, and in parallel we will continue to consider an all-aluminum cavity (including windows) operating at 20 K. A gain of approximately 8 in Q may be obtained by using Al at 20 K, and thermal contraction problems are avoided. Kirk will compute emittance in the cooling channel with Al windows of various thicknesses. Al coating on Be windows is another possibility. Summers will investigate anomalous skin depth effects and magnetoresistivity. Zhao will measure Al samples at 20 K as well as Be at 77 K in his test rig.

Pulse compression:

SLED pulse compression to increase peak power from existing long-pulse klystrons may be beneficial, Perry Wilson will investigate. The experiment requires a pulse of the order 30 μs, and we have available at FNAL 125 μs, 13 MW, 15 Hz 805 MHz klystrons. The pulse length ratio ≈ 4:1 is good for SLED application.

Be window:

Materials properties at low temperature are uncertain - literature shows two to three orders of magnitude variation in conductivity depending on sample type etc. Zhao will proceed with measurements at BNL.

Temperature calculations of Be windows look conservative, Li will repeat with more realistic materials properties when these become known. Calculations for the aluminum windows will also be made.

Be window thickness 0.015” is acceptable at higher-emittance, but 0.005” desirable for later stages of cooling. We will work on 0.005” designs. Air to vacuum windows will be 0.010” Ti.

R&D on three window mount types will be pursued: deflecting bridge mount, demountable window with spring contacts, and all-aluminum window. Moretti will lead this work, primarily with the “bridge” design to support a Be foil in Cu cavity. Al at 20 Kelvin remains a possible choice for cavity and window (with TiN coating). Kirk will compute emittance in the cooling channel with Al windows of various thicknesses.

Wakefields:

Corlett will calculate longitudinal and transverse wakefields for the pillbox cavity (using ABCI and MAFIA). Long time-records are required to obtain the fields at the time of passage of the second bunch (several ns behind the first) and for relativistic β=0.84.

Multipacting:

Rimmer and Kulikov pointed out that RF conditioning must be done in a realistic electromagnetic environment, and behavior will be different without the 5T field. A pair of superconducting coils will be required for the high-power cavity tests. The coils will need independent power supplies to allow a continuous field or a field reversal in the high power test cavity, simulating conditions through the accelerating structure in the cooling channel.

Superconducting magnet coils:

Ron Scanlan will look into details of the S.C. coils required for the high-power RF cavity tests. Warm bore magnets with approximately 40 cm free aperture are required.

Superinsulation will allow operation of the cavity at room temperature. LBNL will design and build the cavity / cryostat / S.C. magnet assembly, ship to FNAL for testing.

Experimental program:

The low power cavity design is to proceed, using the $\pi/2$ interleaved structure with one full cell and coupling structures appropriately terminated. The aim is to test window designs. The cavity will be designed, manufactured and tested at LBNL. A vacuum cryo system will be used to allow temperature control (rather than a liquid nitrogen bath).

The high power cavity will follow, design to begin in about 1 year from now. High power cavity tests will be complicated, we have identified several areas that need attention:

> Multipacting studies require magnetic fields similar to those in the cooling channel - S.C. solenoids (Scanlan)
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> Location / shielding / 805 MHz RF power etc. issues at FNAL (Moretti)
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> Test cavity design will be staged to test different aspects - start with one cell, then add other cells and RF feeds to test coupling between cells and input power coupling