EXTERNAL REVIEW OF THE SUPERCONDUCTING 56 MHz STORAGE CAVITY FOR RHIC

Brookhaven, 8-9 January 2009

COMMITTEE :

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CHARGE

The committee is requested to go over the plans as described in the project reports, presentations made to the committee and discussions with the team. The committee is requested to look for errors or weak points in the design and inform the team. The committee is requested to provide advice on how to proceed with the project and recommend changes as necessary.

GENERAL REMARKS

The 56 MHz superconducting quarter-wave cavity was presented to the review Committee on 8 and 9 January 2009 by members of the BNL project group. The motivation for the installation of the cavity in RHIC is a significant increase of the luminosity.

The committee was impressed by the technical quality of the work and the clarity of the presentations. Many technical issues were addressed and the general concept of the project is sound.

The committee has not identified any fundamental issue of serious concern and feels that this was the appropriate time for a review. The project is advanced enough for evaluation but there is still time to incorporate changes while maintaining schedule.

COMMENTS ON THE PRESENTATIONS

Introduction (Ilan Ben-Zvi)

Findings:

The motivation for the 56 MHz cavity is to increase the luminosity by providing a larger bucket. This is part of an C-AD Accelerator Improvement Project (AIP).

The cavity is of a well-known geometry, the quarter-wave resonator, but used in an unusual configuration for superconducting cavities. Additionally the cavity must be designed to satisfy the requirements of the ASME pressure vessel code, which has not been the case for previous superconducting cavities. The cavity is also designed to be multipacting-free and to provide a voltage of 2.5 MV at which the peak surface electric field is 44 MV/m and the peak surface magnetic field is 105 mT. High degree of HOM damping and fundamental mode damping (the latter only during beam injection and acceleration) is required to avoid beam instabilities.

The goal is to install the 56 MHz system in the beam line late 2010; otherwise installation would be delayed by one year due to RHIC run schedule.

Comments and recommendations:

The surface fields at design voltage are not unrealistic but are still somewhat ambitious. Since the cavity would perform almost as well at 2 MV (where the surface fields are still challenging) and still be useful at 1.5 MV, it might be unnecessary to set such a high goal which, if not achieved, would make the Project run the risk of being perceived as having failed.

Beam Stability (Mike Blaskiewicz)

Findings:

Part of the presentation was based on the work performed by N. Towne. The new cavity is to operate only during a store. During the injecting/accelerating phase, the fundamental mode is to be detuned and well damped. During either phase, the HOMs must be damped.

There seems to be a comfort level associated with the fact that the new 56 MHz cavity, when damped, will have less installed impedance at HOMs than the existing normal 197 MHz cavities have. According to the presented result, the 56 MHz cavity will cause negligible beam instabilities when HOMs are damped to the assumed level or better. In that case, the cavity plays a minor role in that issue as compared to 197 MHz system. Furthermore, the instability thresholds are sensitive to bunch length. All calculations so far have been done with an incorrect set of HOM parameters calculated for a preliminary cavity and HOM damper configuration. The major concerns are longitudinal emittance growth during transition crossing and instabilities during store.

Transition crossing simulations by Towne indicate that if Q's are damped down to around 2000 or so, the longitudinal emittance growth for 10^9 ions per bunch is less than 5%. By contrast, the same calculations for the existing 197 MHz system predict growth of about 50%. Qualitatively, this seems to be in agreement with observed behavior.

The well-established RHIC broad band impedance Z/n = -3j Ω causes loss of Landau damping of longitudinal coupled bunch modes during store. Analytic calculations indicate that for 2 ns rms bunch length, the most dangerous HOM (168 MHz, R/Q = 11 Ω) will not destabilize the longitudinal motion compared with the current rf system, even if the Q is 3800. This is understandable: the existing 197 MHz system has a mode at 308 MHz that has R/Q = 12 Ω, Q = 4400. Damping the Q further would allow stable operation with bunches shorter than 2ns rms. According to measurements by Choi, Q < 2000 is achievable with the inductively-coupled damper at the shorted end of the cavity.

The impedances of the other HOMs used by Blaskiewicz are quite different from those measured by Choi. In particular, Choi shows an important HOM at 280 MHz. As well, Choi's measurements find a transverse mode of undetermined azimuthal impedance near 579 MHz that is not damped.

Comments and Recommendatons:

We recommend redoing the calculations for the HOM spectrum and quality factors of the final HOM damper design. R/Q's can be taken from computer simulations with Omega 3P or MWS and Q's from measurements on the copper model of the 56 MHz cavity. A caveat is that measured Q's around and higher than 10,000 may be much higher yet in the superconducting case. Ideally, measurements and final design of the damper should be done on a superconducting prototype.

It is thought that dipole HOMs are not an issue. This should be confirmed. In particular, the 579 MHz labelled by Choi as "quadrupole?" should be investigated, as it apparently does not couple well to the damper.

The calculations indicate that on transition crossing, if the existing 197 MHz cavities are removed, the 56 MHz system will lead to improved beam quality. It would be good to establish quantitative agreement between the emittance growth observed, and the simulations for the existing cavities.

Cavity Electromagnetic Design (Xiangyun Chang)

Findings:

The resulted presented are from cavity geometry optimization with a 2D code. At an assumed design gap voltage of 2.5 MV the peak magnetic flux and electric field on the cavity wall are B=105 mT and E=44 MV/m respectively. This is for a bare cavity with rotational symmetry without penetrations for the various couplers. Additional enhancement of the magnetic field at small curvatures of all openings, ports, loops, etc, which are located in the high maximum field region are expected.

A detailed analysis of all the steps in the manufacturing and assembly steps that would affect the frequency of the cavity was performed. As a result it was decided that a tuning range of ± 9kHz would be sufficient to achieve the design frequency when the cavity is installed on the beam line.

Comments and Recommendatons:

Local enhancement of the magnetic field caused by the penetrations in the high magnetic field region may cause uncontrolled heating of the auxiliaries leading to a quench. The committee recommends a very careful electromagnetic and thermal modeling with a 3D software to address that problem. While 3D codes are quite good at predicting the frequency of complex geometries they can often be inaccurate in determining peak surface fields so using a range of mesh sizes and several 3D codes is recommended.

The most likely site for field emission is between the high voltage end of the quarter-wave line and the end plate. Even a few µA's of dark current, when accelerated by substantial fraction of the gap voltage, could deposit several watts of heat over a small area of the end plate. The Committee is concerned that, in such an event, the cooling of the end plate may be inadequate leading to a thermal quench of the cavity.

The Committee suggests evaluation of using the fundamental mode damper as a variable coupler for the RF conditioning process.

Fundamental Mode Damper (Eunmi Choi)

Findings:

The fundamental mode damper (FD) is required since, during beam energy ramp-up, a harmonic of the beam revolution frequency will cross the cavity resonance. At store, the FD will be withdrawn. During the withdrawing of the damper the cavity resonant frequency shifts and must not cross the harmonic of the beam revolution frequency. The cavity resonance should remain below the beam frequency to satisfy the Robinson stability.

FD electromagnetic design was done with CST MWS. Measurements on a prototype copper cavity model were performed to verify the computer simulations. This provided the basis for choosing the final location of the FD at 20 cm from the shorted end of the cavity.

Total mechanical motion, from fully inserted during injection/acceleration to completely withdrawn for beam store, of the FD mechanism is 18 cm. The cavity loaded quality factor changes from 300 to 10^{11}. The power transmitted by FD to an external RF load varies during the change of the damper position and reaches maximum of about 16 kW when the cavity is detuned by 10 kHz. Estimated power dissipation in the FD components is 2 W at this transmitted power level.

FD is a normal conducting structure with the coupling loop fabricated of copper and operated at room temperature. A mirror-like polished surface of the coupling loop will be used to lower emissivity. Thus there will be no issue with heat radiation. A 3 mm clearance is provided between the FD coupling loop and the walls of the Nb cavity port.

Comments and Recommendatons:

As any mechanical contact between the FD structure and Nb cavity can destroy cavity performance, the needed clearance during motion and assembly should be confirmed, and assembly procedure and hardware designed accolrdingly.

The Committee recommends to carefully study multipacting in this highly complicated 3D structure.

HOM damper design (Eunmi Choi)

Findings:

Specifications and design of the HOM dampers were obtained as a combination of simulations and study of the prototype cavity.

The HOM damping scheme is based on magnetic coupling loops which are equipped with high-pass filters and terminated with thermal loads. As expected an effective location of the HOM dampers is close to the shorting plate where the magnetic field is maximum for the most important modes.

Comments and Recommendations:

The Committee recommends investigation of active cooling of all superconducting loops located in or close to the maximum magnetic flux, unless the RF and thermal modeling, including normal-conducting spots on the surface, demonstrates that couplers will stay in the superconducting state (T< 9K). Preferably the modeling should be verified experimentally.

Thermal analysis should include the cryogenic feedthroughs which need to be selected carefully.

The impact of the HOM dampers on the fundamental mode should be assessed to assure that its external Q is sufficiently high ($>>Q_0$).

Cavity Structural Design (Chien Pai)
Cavity Tuner Design (Chien Pai)
Cavity/ Helium Vessel Fabrication Procedures (Chien Pai)

Findings:

ASME pressure vessel code compliance is now mandatory for superconducting cavities used at DOE laboratories.

The presentation of the structural designs for the resonating cavity and its tuner were generally very complete. Consistent with the maturity of the project at present, the thought that has gone into the design, choice of materials, and fabrication was obvious.

The structural design of the cavity is particularly challenging since the cavity must be in compliance with the ASME code.

The stiffening ribs on the outside of the cavity within the helium vessel are used to prevent longitudinal vessel collapse; they are under compression. Each rib is stated as being .375 inches thick. This seems adequate for their length, but no bucking calculations were supplied.

Comments and Recommendations:

Stresses in the tuning plate, while not overly large, could be troublesome in the area close to the weld joining the tuner cover to the convoluted shell. Although this is not the region of highest stress under elastic deflection, the stress in that region under plastic motion appears to be around 7000-7500 psi. This is roughly equal to the quoted yield strength of the material used (Niobium). Since the material properties in the heat-affected zone of the weld will be altered negatively, the weld joint should be located father away from the bending "knuckle" of the tuner plate to reduce the possibility of fatigue cracking. Another possibly beneficial change to consider is to add a local convolution(s) in the knuckle to decrease the stress. Alternatives to deflecting the tuner plate, such as moving the inner or outer conductors relative to a stationary flat end, might also warrant consideration.

The Committee was concerned generally about adequate cooling of the tuner plate and the heat deposited from field emission. One possible solution to the problem is to increase the thickness of the cylindrical beam tube, thus allowing better heat transfer. Other solutions should also be brainstormed. If any of the assumptions made in the analysis are in error, cooling could become a major problem.

A rudimentary calculation of the actually buckling load on the stiffening ribs, and resulting safety factor of this design against buckling failure, should be documented before the next review of the vessel.

The construction of the tuner mechanism and integration into the cavity has resulted in a screw being used inside the UHV space. Because of possible complications with particles generated when tightening the screw, the design should be altered so that this screw is either eliminated, relocated outside the UHV area, or a cleaning step should be introduced to remove potential particles before this sub-assembly is installed.

Good steps have been taken to try to eliminate backlash and hysteresis from the tuner mechanism. However, being a mechanical linkage system, the Committee is concerned about any remaining effects that will make it difficult or impossible to tune within the required accuracy, or a "stick-slip" condition that will cause the tuner to overshoot the desired frequency correction. One particular area that might be weak in this regard is the Acme power screw. It would be helpful therefore to advance the schedule on the construction of the entire tuner mechanism so that the final design can be tested in a fixture that simulates the actual forces and is able to resolve nanometer motion vs. time, to either confirm proper operation or allow time to re-engineer a solution. It is suggested that the test parts be the final parts, assembled such that they can be reused. If the test shows inadequate function, a prototype will have been made that can be modified and retested.

An estimate of the number of cycles to be imposed on the mechanism during the lifetime of the cavity should be made. This should be compared to the mean time to failure rating of components making up the system, such as motors, actuators and bearings, as well as to the elastic-plastic stress analysis of the tuner plate itself.

A check on the radiation hardness of the piezo motor to be used in the fast adjustment section of the tuner mechanism should be compared to the expected radiation dose at its location. Shielding or a component change may be warranted. If the motor will need to be changed out regularly, the design should readily accommodate this.

The sensitivity of the frequency on He pressure can be difficult to calculate accurately since the displacements are small. The Committee suggests that the calculated values be confirmed with other codes or by the Slater method by calculating the work done by the radiation pressure.

Multipacting Supperssion by Ripple Structure (Damayanti Naik)

Findings:

Detailed and very time consuming simulations of the multipacting phenomenon in the 56 MHz cavity using the 2D `multipac 2.1` code were presented. The barriers that were found show one- and two-side type multipacting. The latter one has trajectories of electrons moving towards the end-plate of the cavity.

To break the resonant conditions for the phenomenon 20 mm deep and 20 mm wide grooves were made in the outer conductor of the cavity. The work was performed with a 2D code and secondary electron yield for clean Nb.

Comments and Recommendations:

Grooving of the outer conductor in coaxial geometries looks like a promising way to eliminate or reduce multipacting. However, since it substantially increases the mechanical complexity of the cavity it is recommended to explore its range of usefulness, for example by assessing its effectiveness with less optimistic assumptions on the secondary emission yield.

[Note: Simulations performed subsequently to the review seem to indicate that the grooving is effective over a wide range of assumptions.]

3D Multipacting (Jorg Kewisch et al)

Findings:

First results of 3D multipacting calculations were presented. While no multipacting was observed in the first run, finer steps in field levels and higher particle density is necessary. Calculations must be repeated for all FD positions at fixed field level.

Comments and Recommendations:

HOM couplers are notorious candidates for sources of multipacting barriers. The Committee recommends performing 3D simulations for the areas of auxiliaries' penetrations. These can be difficult and time consuming to simulate but should nevertheless be attempted.

Cryogenic system (Roberto Than)

Findings:

The cryogenic system was designed to provide ample cooling capacity to the 56 MHz system while assuring pressure stability in order to minimize fluctuation of the cavity frequency.

Comments and Recommendations:

A load leveling heater might improve the system stability and may warrant investigation.

Several issues associated with thermal stability and cooling are identified in other sections of this report and need to be addressed in a holistic manner.

Chemistry and testing (Andrew Burrill)
Cryomodule Assembly and Beamline IntegrationCleanliness (Andrew Burrill)

Findings:

A complete infrastructure required for the processing and testing of the cavity was identified and presented. Cavity cleaning, chemistry, high-pressure water rinsing and clean-room assembly will be performed at the BNL-owned facility located on the premises of AES. UHV 600°C cavity bake and RF tests in a vertical cryostat will be done at BNL.

Comments and Recommendations:

As presented, all the chemistry would be performed on the cavity after its completion. The Committee recommends evaluation of performing most of the chemistry on parts before closure of the cavity. This would allow performing EP on all the parts, with only a light BCP after the final weld.

The most sensitive area for field emission is the high-voltage region at the end of the quarter-wave line. The high pressure rinsing should be done in the appropriate sequence and configuration to minimize the probability of contamination in that area.

If the schedule permits, a full test of the completed cryomodule should be performed before installation in RHIC.

Microphonics, LLRF (Ilan Ben-Zvi)

Findings:

A brief overview of requiements to microphonic noise and implementation of LLRF controls was given at the request of the Committee. The requirement for the amplitude stabilization is 10^{-4} at twice the synchrotron frequency, where the noise content is expected to be less that 0.5 Hz. A digital LLRF, similar to the one used in other C-AD RF systems, will be used. The system is capable of 2×10^{-7} with 4 kHz sampling or 10^{-4} direct (with averaging).

GENERAL COMMENTS

Production

The stated completion date for installation is late 2010. Given the status of the project it seems to be a fairly tight schedule. The Committee recommends preparing a detailed plan for acceptance and commissioning consistent with that schedule.

Off normal events, trips

The Committee recommends a thorough analysis and evaluation of the impact and consequences of so called "off normal events" such as: quenches, bursts of electron emission, vacuum breaks, *etc.* As an example for a cavity quench, if Q_0 drops to or below $5 \cdot 10^4$, an enormous amount of power could be deposited by the beam since the detuning of the cavity with respect to the nearest spectral line is small compared to the resonance width, and impedance is still very high ($80 \times 5 \cdot 10^4\ \Omega$). In such a case the beam must be dumped immediately.

A concept of the Machine Protection System and Interlock to prevent damage to the hardware or significant impact on the physics should be proposed.

Tuning plate region

A number of significant interrelated issues were identified around the end/tuning plate region: field emission, cooling, mechanical stresses. A thorough integrated review of all the issues of this part of the cavity involving all the relevant expertise is recommended.

Further reviews

At this stage of the project, the Committee has not identified any fundamental issue or potential showstopper and the project is in good shape. Nevertheless there are still many options to consider and details to finalize. Furthermore the schedule is tight. The Committee recommends an additional review later this year to assess progress.

Since ponderomotive instabilities, microphonics, and LLRF control are not expected to present insurmountable problems and be showstoppers, it was agreed between the Project and the Committee that they would not be subjects of presentations during this review. Nevertheless, if not addressed correctly they could degrade performance and availability. It is recommended that a careful analysis and design be pursued and that the status and results be presented at the next review.