PHYSICS OF THE SNS SRF CAVITY

Sang-ho Kim, Dong-o Jeon, Daniel Stout, Isidoro Campisi
SNS/ORNL, Oak Ridge, TN 37830, USA
Marc Doleans, NSCL/MSU, East Lansing, MI 48824, USA

Abstract

The superconducting linac of the Spallation Neutron Source (SNS) is designed to accelerate H- ion beam in the energy range from 186 MeV to 1000 MeV. Two types of superconducting radio-frequency (SRF) cavities are developed and successfully tested. Presently cryomodules and SRF cavities are under production along with a series of performance tests at JLab. Physics related issues on the SNS SRF cavities have been studied and some are introduced in this paper, which includes optimization procedure in determining the cell shape at a given set of design criteria, fundamental power coupling in the relation with end cell and end group design, multipacting, higher-order-mode (HOM), cavity vibration dynamics for control and operation, longitudinal beam dynamics taking into account a velocity changes in the multicell cavities, dynamics of the SRF thermal stability, etc.

INTRODUCTION

The SRF linac of SNS has two beta sections (medium beta section β=0.61 and high beta section β=0.81) and will accelerate H- beam from 186 MeV to 1 GeV operating at 805 MHz. Spaces for 9 more high beta cryomodules are reserved for the future upgrade up to 1.4 GeV or higher [1],[2]. The physics studies justified the parameter selections on the SRF cavities and linac, and also the benefits in choosing SRF cavities such as allowable operation with one or two failed cavity, easiness in beam transport, etc. Key parameters of SNS SRF linac and cavity are summarized in Table 1. Design and analysis efforts have been put to have optimum parameters from the view points of cavity performances, reliability, cost, and schedule, along with the beam physics study in the SRF linac such as cavity fault, time of flight while acceleration, misalignment/off-axis field effect, field flatness, etc. The SNS is a pulsed machine at a repetition rate of 60 Hz, which addresses additional concerns related with cavity dynamic detuning, HOM from the multiple beam time-structure, thermal stability, etc. Some highlights are summarized in the followings.

RF GEOMETRY

Many RF parameters are determined by the cell geometry, which includes peak fields versus accelerating gradient, shunt impedances, inter-cell couplings, static mechanical stiffness at a given wall thickness, etc. An elliptical cavity is usually defined with five geometry dimensions. A systematic scanning method in these geometry spaces is developed, from which the optimization of the cavity shape is done by visualizing dependencies of cavity parameters on geometry [3].

Table 1: Key parameters of the SNS SRF linac and cavity

No. of cryomodules (medium/high)	11/12
No. of cavities (medium/high)	33/48
Peak surface E field (medium/high)	27.5/35 MV/m
Acc. Gradient at βp=βg (medium/high)	10.1/15.6 MV/m
Peak surface B field (medium/high)	58/76 mT
Number of cells per cavity	6
Inter-cell coupling coefficient	1.6 %
Q_{ex} (medium/high) x 10^5	7.3/7.0

βp=particle velocity (v/c), βg=cavity geometric beta

End-cell is designed separately with beam pipes where stray field exists to provide good field flatness and not to have bigger Ep/Eacc nad Bp/Eacc than those in the cell. Also end-cell is designed to meet the required *Qex*'s. *Qex* variation including error study of alignment is predicted with 3-D simulation, which shows good agreement with experimental results [4].

HIGHER-ORDER-MODE (HOM)

The HOM's are also determined by the cavity geometry. In linacs for intense pulsed proton accelerators, the beam has a multiple time-structure, and each beam time-structure generates resonance. When a HOM is near these resonance frequencies, the induced voltage could be harmful to the beam and/or generate large HOM powers. To address these two main concerns related with HOM, systematic studies are carried out [5]-[8]. In the case of SNS, bunch tracking simulations for both transverse and longitudinal direction show that beam instabilities are not a main concern if the external quality factor Q_{ex} for each HOM is less than 108, the loaded cavity Q for each non-Pi fundamental mode has the expected value, and the expected cavity-to-cavity frequency variation is present. Concerning the HOM power issue, general analytic expressions of beam-induced voltages and the HOM power from the multiple beam time-structures are developed, from which the effect of the beam time-structure on the beam-induced voltage and the HOM power development are fully understood by exploring the parameter space of the HOM properties. The damping requirement of each mode is set up in terms of Q_{ex} by taking into account the actual HOM frequency behavior of elliptical SC cavities. To satisfy the damping requirement, the SNS cavity has two TESLA type HOM couplers on each side of beam pipe [9].

MULTIPACTING

A multipacting condition is primarily determined by the cell geometry. It is known that lower β_g structure would have more severe multipacting problem and a larger circular dome seems to be helpful to avoid multipacting [10], though there's, so far, no clear comprehensive explanation to eliminate multipacting while designing a cavity geometry especially in reduced-beta structures. Another determining factor for the multipacting condition is the secondary electron yield versus electron landing energy on surfaces. Simulations predicted that developments of multipacting in the SNS cavities are difficult when surfaces of cavities are cleaned properly [11]. The prototype and production cavities that followed proper cleaning processes, so far, show no evidences of multipacting.

DYNAMIC DETUNING

The SNS SRF cavities will suffer from the Lorentz force detuning (LFD), since they are intrinsically weak in mechanical stiffness. Microphonics is a minor issue because the bandwidth of the cavity is much larger than detuning due to the microphonics. To keep the cavity field flat during RF pulses, more RF power is needed in presence of dynamic detuning.

Each SNS cavity has the piezoelectric fast tuner, which was firstly proposed and tested at TTF (Tesla Test Facility), to compensate the dynamic detuning and to allow more stable and higher beam power operations in a future upgrade [12].

For the further understanding of the cavity dynamic detuning and its effect on the cavity fields, a series of comprehensive studies are carried out. The full descriptions can be found in [13]. The goal is to model that combine the calculation of the RF voltage when the cavity is under a dynamic detuning and the calculation of this detuning, mainly created mechanically by the Lorentz forces and by the piezoelectric tuner action. Such understanding has for example been beneficial 1) for the extraction of the cavity mechanical parameters from measurements or for identifying possible parasitic signals in these measurements, 2) for having very practical insights on the RF filling of a cavity under dynamic detuning, 3) for a simple and useful scaling of the required additional RF power when the cavities parameters, Q_{ex} and detuning, are varied from their optimum values. 4) for a method to monitor the cavity resonant frequency when some RF signal is available in the cavity, etc.

This study makes it clear that the static LFD coefficient is the sum of all the coupling coefficients of all mechanical modes and is the figure of merit just for a CW case. More meaningful parameters in a pulsed operation are the position of the mechanical modes frequencies with respect to the harmonics of the repetition rate and the damping coefficients of mechanical modes. The most important thing is to figure out couplings between rf field behaviors and mechanical vibrations from sources. It is explained that the LFD is very special case where the coupling coefficients have same sign for the all mechanical modes, while those from the piezoelectric tuner could have both sign. This understanding is confirmed by the reconstruction of the mechanical parameters associated to the Lorentz force action using measured data.

Finally a virtual cavity is built and provides many useful and practical tools to deal with the SNS cavity. This virtual cavity is based on the analytic formalism, so provides very fast calculation and very general pictures. For example, it is shown that compensation could be done by using one or a few harmonics of the repetition rate, which does not require information on the mechanical modes. This method makes the optimization more straightforward and simpler than the compensation using a trapezoidal signal profile to the piezoelectric tuner. This virtual cavity could handle some further studies like microphonics compensation study in a CW and/or high Qex cavity, and dynamic analysis for the ponderomotive oscillation from the view point of RF control.

THERMAL STABILITY

Because of highly non-linear thermomagnetic properties of niobium at the cryogenic temperature, the resulting thermal behaviors of SRF cavities are also quite non-linear. Considerable efforts have been made to better understand this topic [14] both theoretically and experimentally especially for the CW condition. In pulsed mode SRF cavities like those of the SNS, the time scales to build a thermal instability are an important factor in connection with a repetition rate and a pulse length in pulsed machines. There are regions like an end-group of SRF cavities that have more complex thermal conditions such as thermal radiations from the inner conductor of the power coupler, an indirect conduction cooling condition, a lower niobium quality than main cavity part, and etc. As the interests for SRF technology in pulsed machines increase, there is need to have more understanding of the dynamics of thermal stability in connection with all thermomagnetic parameters, which include 3D structure, varying material properties, non-linearity of material properties, transient behaviors, realistic thermal loads and boundary conditions along with the RF surface dissipations, etc. It will be very useful for choosing materials, setting the operating conditions, and understating the cavity system in terms of thermal stability. To address the thermal stability concerns in a pulsed mode SRF cavity with complex thermal boundaries and geometry, an algorithm and calculation procedure is set, which can handle all the concerns mentioned above. In cell region where fields are relatively high, a pulsed operation does not have differences with concerns in CW operation, since a quench development is much faster than usual RF pulse lengths. In the low field region like the end group, there are some noticeable features in terms of external thermal loads, sizes of material defects, niobium quality for the end group, field levels, etc [15].

LONGITUDINAL DYNAMICS

As an accelerating field is getting higher in the SRF cavities, there's a need of a re-evaluation in the longitudinal phase law while acceleration especially when the beta varies significantly within a cavity. To deal with this concern, an analytic formalism is made, which uses a real accelerating field profile and includes beta changing effects [13],[16]. This method could be used for comparisons of phase advances between two physical locations while beam commissioning.

Instead of fractioning the accelerating element into smaller pieces, an alternative method taking into account the non linearity of the phase law is developed. This method shows that the usual set of Panofsky equations is a simplification of a more general formulation for the longitudinal dynamics of accelerated particles. The method based on a solution of the problem by analytical iterations was developed. Fully analytical calculations are made up to three iterations, which is sufficient to cover cases where the non linearity of the phase law is below few tens of degrees. The analytical form of the solutions after three iterations suggests a general form for the solution after n iterations applicable to cases with stronger non linearity of the phase law.

OTHER ISSUES

Effects of cavity misalignment and off-axis field on transverse beam dynamics are investigated. For the random distributions of cavity misalignment within +/-1 mm off-set and +/-1mrad tilts, of quadrupoles, some beam centroid displacement is expected, which is easily correctable with steering magnets. An also the analysis shows that the transverse kick effect mainly due to the asymmetric fields from the fundamental power coupler on beam centroid movement is about same level with that from the cavity misalignment. In both cases emittance growths are negligible [17].

Keeping good field flatness is necessary for mainly two concerns. One is the achieving a higher accelerating gradient or having more safety margin. The other is the beam dynamics issue. Up to certain amount of field tilt between cells, for example 10 % field tilt, no major issues are expected in the SNS. Unfortunately field flatness is difficult to check in the cryomodule and after cool down. Very careful preparations and procedures are needed after room temperature tuning of cavities.

CONCLUDING REMARKS

Many physics aspects for the SRF cavity and linac have been studied and some of them are introduced in this paper. The prototyping efforts and tests for the medium beta cryomodule was successfully finished [9],[12]. The production cavities and cryomodules are under production at Jlab and some are delivered to Oak Ridge. Installation is under process for the re-test of cryomodules, and beam commissioning in the SNS linac tunnel.

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