COMPUTATIONAL NEEDS FOR RF DESIGN OF SUPERCONDUCTING CAVITIES*

A. Lunin#, T. Khabiboulline, S. Yakovlev, Fermilab, Batavia, IL 60510, USA

Abstract

The computational approaches assure essential guidance and order for the design of superconducting cavities and cryomodules. The nature of superconductivity requires the precise computation of surface electromagnetic fields in order to design the cavity shape with a maximum accelerating gradient. At the same time, the thickness of the cavity shell is limited by the ability to cool it down to the temperature of liquid He, which makes the mechanical stability of a cavity and a liquid He vessel assembly extremely important. Hence, a self-consistent electro-mechanical optimization is required in order to minimize microphonics and/or Lorentz force detuning phenomena. Some specific challenges are estimation of the amount of RF losses caused by the interaction of the passing beam with SC cavity and a multipactor analysis in the SC cavity and RF coupler. Finally, the irregular time structure of a beam train with its own dense spectra may stochastically induce High Order Mode (HOM) fields in a cavity which results in beam emittance dilution.

The study of these effects leads to specification of the SC cavity and cryomodule and can significantly impact the efficiency and reliability of superconducting linac operation.

INTRODUCTION

SRF cavities are widely used today for various applications in high energy physics, nuclear physics and material science requiring an acceleration of charged particles [1][2][3]. New projects such as Accelerator Driven Subcritical systems (ADS), high intensity proton accelerator (Project X), Facility for Rare Isotope Beams (FRIB) and Next Generation Light Source Facility (NGLS) are under development [4][5][6][7]. Because of such diversity, designs of SRF cavities cover wide range of particles velocities (beta ~ 0.05 - 1), operating frequencies (0.072 - 4 GHz), beam currents (1mA - 100mA) and suitability for pulsed and continuous operation regimes. Besides, the SRF cavity is a complicated electro-mechanical assembly and consists of: bare cavity shell with power and HOM couplers, stiffening elements (ring, bars), welded LHe vessel, slow and fast frequency tuners and vacuum and coupler ports. A mechanical design of SRF cavity is illustrated in Figure 1 [8]. Therefore, the development of SRF cavity requires a complex, self-consistent electro-mechanical analysis in order to minimize microphonics and/or Lorentz force detuning phenomena and preserve good cavity tenability simultaneously.

* Operated by Fermi Research Alliance, LLC under Contract No.DE-AC02-07CH11359 with the U.S. Department of Energy.
#lunin@fnal.gov

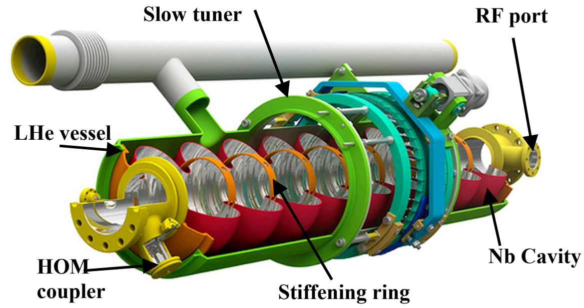

Figure 1: ILC 1.3 GHz 9-cell cavity.

The following aspects need to be taken into account during the design process:

- Cavity acceleration efficiency, including minimization of surface field enhancement factors (both electric and magnetic) and choosing optimum beta value for multiple cavities in the linac section.
- High gradient pulsed operation and minimizing of Lorentz force detuning coefficient.
- Operation with small beam current and narrow cavity bandwidth, particularly suppressing microphonics and preserving good cavity tenability simultaneously.
- HOM dumping in order to minimize cryogenic losses, preserving good beam emittance and excluding any transverse or longitudinal beam instabilities.
- Analyzing field emission effects including multipactor and dark current simulations.

We discuss all these issues and possible solutions below

SRF CAVITY EM ANALYSIS

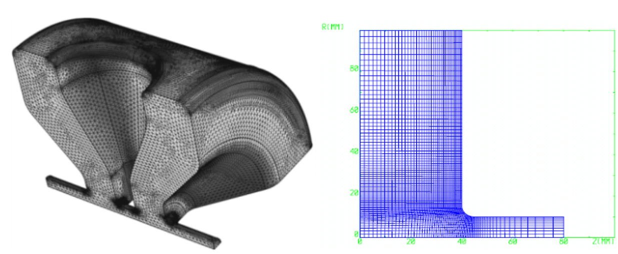

Figure 2: Meshing approaches in 3D (left) and 2D (right) domains.

Superconducting resonators suffer from both high magnetic field, which causes a thermal quench if it goes above critical value, and high electrical field, because it initiates surface field emission which produces additional cryolosses and may result in strong x-rays as well. Thus, the SRF cavity EM design requires precise surface

Copyright © 2012 by the respective authors — cc Creative Commons Attribution 3.0 (CC BY 3.0)

ISBN 978-3-95450-116-8

electromagnetic fields computation in order to optimize the cavity shape and achieve a maximum accelerating gradient.

Despite the fact that modern software for eigenmode EM analysis (ANSYS, COMSOL, CST, OMEGA3P [9,10,11,12]) provide very good accuracy in eigen frequencies, the precise calculation of surface fields is still a challenge. It requires a high quality surface mesh, which results in either the dense tetrahedral mesh with curved boundary elements in 3D domain or running the simulation in 2D space for axisymmetric structures (see Figure 2). The simulations with dense mesh require extra CPU time, while solving a problem in 2D has an obvious limitation in representing all the details of complex cavity geometry. The remedy is creating artificial mesh structure with high density area near the cavity outer surface only. The result of precise surface fields' simulation with less than 1% error is presented in Figure 3 for HFSS eigenmode solver [13].

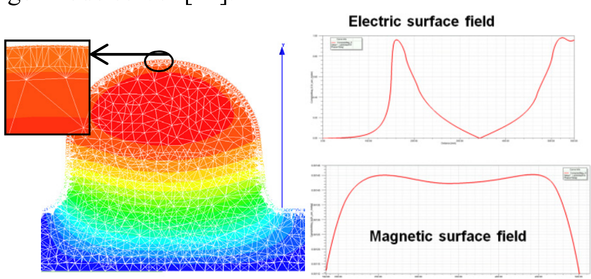

Figure 3: HFSS artificial surface mesh a) and calculated fields b).

The goal of the cavity shape optimization is to minimize both surface electric E_s and magnetic H_s fields. Hence, the result is not just a single point but the series of limiting curves in the E_s versus H_s coordinates. The idea is illustrated in Figure 4. The recent results of a cavity shape optimization for Project X linac are presented in [14], [15], [16] for low beta half-wave, medium beta spoke and high beta elliptical cavities respectively. The final choice of the cavity geometry is a trade-off between the requirements on cavity mechanical stability and surface processing issues.

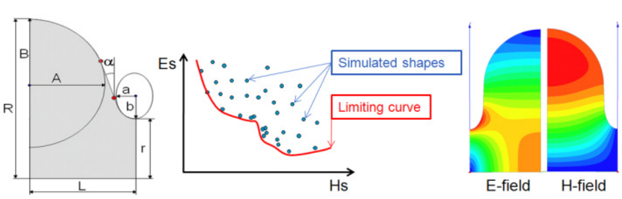

Figure 4: The conception of a cavity shape optimization.

LOSS FACTOR SIMULATION

Incoherent losses introduced by radiated wakefields might be an essential part of the total cryolosses in the SC accelerating structure. The effect of beam velocity on generated wakes can be demonstrated using the following consideration (see Fig. 5). The spectrum of wakefields excited by a beam bunch, passing an SRF structure, depends on σ_{field}, the characteristic size of the EM field distribution on the wall of the beam pipe at the cavity entrance. In linacs with relativistic beams, such as ILC or NGLS, field distribution is essentially disk-like and $\sigma_{field} = \sigma_{bunch}$, frequency spectrum up to $f_{max} \sim c/\sigma_{bunch}$. For the bunch size of 50 µm frequencies up to 6 THz can be excited. In a case of non-relativistic beam, field lines diverged much more, $\sigma_{field} \sim a$ and $f_{max} \sim c/a$. If the beam pipe radius is 50 mm, only HOMs below 6 GHz are exited. Thus, the cavity loss factor depends strongly on beam velocity.

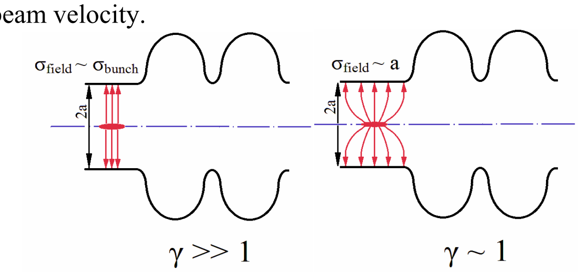

Figure 5: Effect of beam velocity on wakes excitation.

There are two approaches on how to calculate cavity loss factors, the integration of a wake potential over the bunch profile and the addition of loss factors for individual cavity modes. The time-domain computation of beam energy loss factors is very common and well developed for relativistic beams. It can be done by a variety of codes like ACE3P, GdfidL, CST or ABCI [17, 18, 11, 19]. Nevertheless, the wake calculation for a periodic system with the short bunch presents serious difficulties because the mesh size should be small enough in order to provide calculation stability and accuracy. There are several methods (e. g. indirect wake potential calculation and moving mesh technique) which allow overcoming the problem and calculating loss factors for the relativistic beam with sub-micron bunch size.

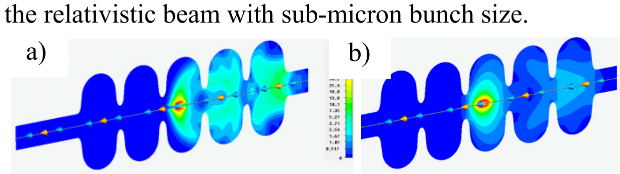

Figure 6: Time domain simulations of wakefields in 5-cell elliptical cavity for Project X in a case of ultra-relativistic beam (a) and high-relativistic beam (b).

For non-relativistic beams passing through a cavity one needs to take into account the static Coulomb forces, and indirect methods and moving mesh technique are not applicable. The direct method requires a meshing of the full structure volume, and the beam pipe length needs to be longer than a wake's catch-up distance. The alternative is a simulation in the frequency domain and finding the loss factor of individual cavity modes. This method is preferable when the beam is low-relativistic, its spectrum is limited and the number of modes is not too large. The example of a time domain loss factor simulation in 5-cell elliptical cavity made by CST Studio is presented in Figure 6 for both ultra-relativistic and high-relativistic beams [20].

ISBN 978-3-95450-116-8

Copyright © 2012 by the respective authors — cc Creative Commons Attribution 3.0 (CC BY 3.0)

MULTIPACTOR AND DARK CURRENT SIMULATIONS

Secondary electron emission, RF discharge or multipactor (MP) might be a serious obstacle for normal operation of SC cavities and couplers. When the electron trajectories oscillate in a resonance with the RF field, it causes exponential growth in the number of electrons by secondary emission.

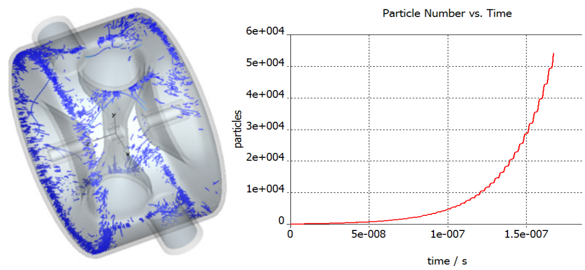

Figure 7: Multipactor simulation in the SSR1 cavity for Project X.

The main challenges in reliable multipactor prediction are accurately applying a probabilistic mechanism of secondary emission model given in [21], adjusting the tracking mesh with precise surface representation and obtaining a smooth distribution of electromagnetic fields in the cavity. Most codes for multipactor simulation tend to simplify secondary emission model and to use so-called counter function or impact function to predict a multipactor instead of a straightforward stochastic analysis [22, 23, 24]. Such assumptions usually give good results but predict a multipactor only within relatively narrow separated bands of field levels. The most advanced model of secondary emission [21] is implemented in CST PS solver, which makes it possible to detect the multipactor within a wider range of field levels and see the overlapped (merged) multipactor zones. The recent multipactor simulations made with CST PS are shown in Figures 7 and 8 and demonstrate the close agreement with experimental observations [25, 26].

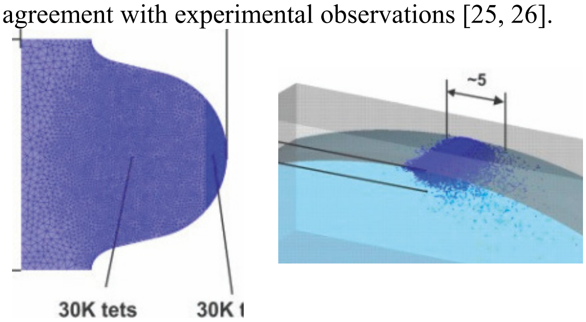

Figure 8: Multipactor simulation on the equator of the 9-cell ILC cavity.

Operation of SC cavity at high gradient may initiate the electron emission or dark current from the cavity surface; electrons can be captured by RF fields and accelerated along the linac to hundreds of MeV before being kicked out by quadrupoles. The goal of dark current simulation is to estimate the amount of additional losses in the cavity due to high field emission and the percentage of electrons that might be accelerated along the cryomodule. Because the surface distribution of electric field is highly non-uniform, the field emission cannot occur in an arbitrary location, and realistic model of emission is very important in the simulation. There are two codes, ACE3P and CST PS, which realize the advanced Fowler-Nordheim field electron emission model.

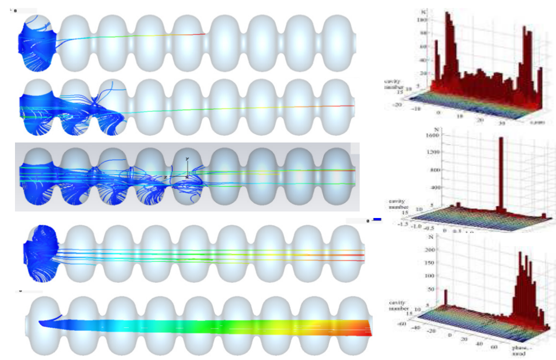

Figure 9: Dark current simulation in the ILC 1.3 GHz, 9-cell cavity and captured particle distributions: a) radial, b) angular and c) phase.

In order to calculate the effects of dark current, heat and RF loading of the cavity, influence of secondary emission and the properties of accelerated particles, the program has to provide the detailed statistics on lost and captured electrons, the number of impacts and their locations across the cavity surface. The example of dark current simulation with CST PS is shown in Figure 9 for the ILC, 1.3 GHz 9-cell elliptical cavity [27].

HOM STATISTICAL ANALYSIS

Excitation of High Order Modes (HOM) in SRF cavities is always a concern. Heating caused by beam power lost to HOMs adds to the cryogenic losses and increases the operational cost of the linac. The interaction of the beam with excited HOMs deteriorates the quality of the beam. In order to accurately estimate the probability of resonance HOM excitation in the Project X linac by the beam, one has to do statistical analysis, which requires data for HOM frequency, impedance and quality factor spreads.

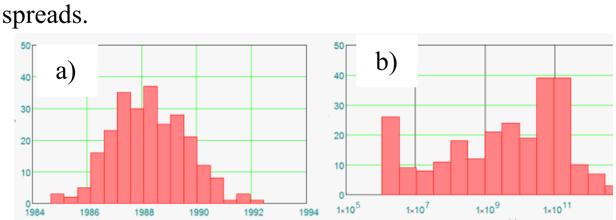

Figure 10: The frequency (a) and Q_{ext} (b) spreads of monopole HOMs for the 650 MHz, β_{geom}=0.9 Project X structure.

Because of the fabrication tolerances and further surface processing the actual cavity shape never matches with the theoretical shape. Thus, there is a natural spread of the HOM parameters from cavity to cavity. The simulation of HOM parameter spreads is a challenging problem because it requires eigenmode analysis of many random structures and HOM spectrums. Nevertheless, the

Copyright © 2012 by the respective authors — cc Creative Commons Attribution 3.0 (CC BY 3.0)

ISBN 978-3-95450-116-8

use of scripts or macros allows easy running of such statistical analysis together with modern eigenmode solvers. The result of HOM statistical analysis is presented in Figure 10 for high-beta elliptical cavity for Project X [28].

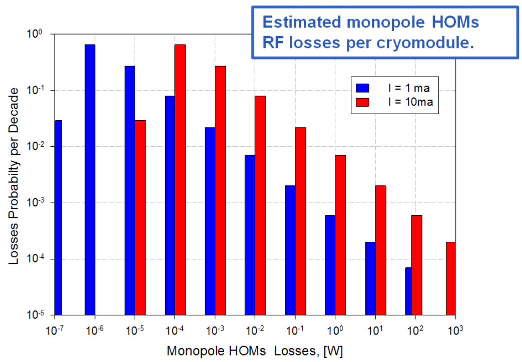

Figure 11: Probability of monopole HOMs RF losses per cryomodule in Project X linac for 1 mA and 10 mA beam currents.

Based on the predicted deviations in monopole HOM frequencies, R/Q and Q_{ext} it is possible to estimate the probability of RF losses per cryomodule as well as the probability of the beam longitudinal emittance growth. The outcome of HOMs influence on RF losses and beam emittance for the high energy part of Project X CW linac is summarized in Figures 11 and 12 respectively.

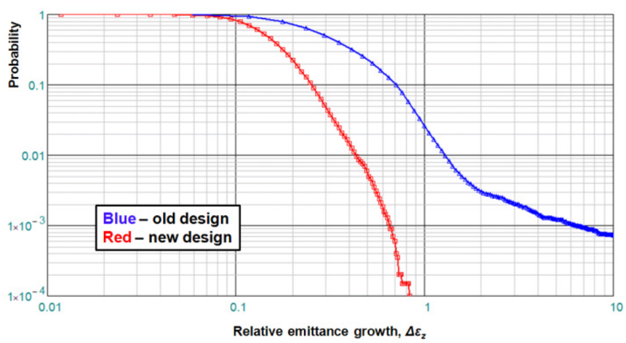

Figure 12: The probability of longitudinal emittance growth in the Project X linac for the 10mA beam current for two different designs of the same cavity.

The HOMs statistical analysis is a powerful tool to predict the SRF cavity behavior in the presence of a beam with complex time structure, especially for high current operations and CW regimes.

MULTIPHYSICS ANALYSIS

The study of coupled multiphysics problems is extremely important during the SRF cavity design, because it defines the technical feasibility to build, assemble and run the cavity under the operating parameters. Among the common problems which needed to be solved, are the microphonics effect, Lorentz Force Detuning (LFD) and coupled RF-thermal analysis.

Microphonics is a cavity mechanical deformation driven by external forces such as the pressure fluctuations in a He-vessel and results in unfavourable RF phase errors. In order to calculate the frequency dependence on external pressure fluctuation, named *df/dp* coefficient, we have to run eigenmode simulation to find the nominal frequency f_0 , find the cavity deformation under the given pressure load and repeat the eigenmode analysis again to find the resonant frequency, f_p, after the deformation. Thus, microphonics study requires self-consistent electro-mechanical simulations. The main difficulty here is transferring the deformed cavity model back to the EM solver, because it requires re-meshing of the cavity volume and, thus, introduces undesirable mesh errors, which cannot be neglected for small deformations. The clever solution was proposed and realized in COMSOL multiphysics environment. The idea is to use a common mesh for all solvers and transfer only the boundary deformation. Therefore, the conception of moving mesh allows to exclude the mesh errors and to achieve excellent accuracy (~1Hz/Torr) in *df/dp* analysis. Examples of required mesh for microphonics simulation are presented in Figure 13, a) and b) for COMSOL and ANSYS programs respectively [29, 14].

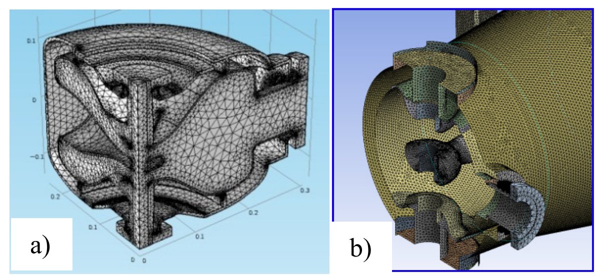

Figure 13: The concept of common mesh in COMSOL (a) and independent mesh in ANSYS (b) multiphysics simulations.

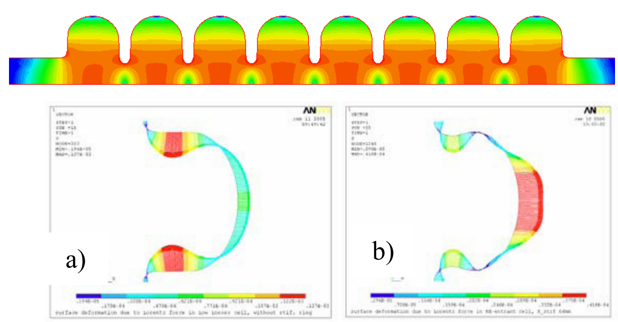

Figure 14: Lorentz force detuning simulation of SRF β=0.81 elliptical cavity and cavity walls deformation with no ring (a) and with stiffening ring (b).

Lorentz Force Detuning (LFD) is the cavity mechanical deformations caused by a pressure load of the Lorentz forces from EM-fields in the cavity. It significantly distorts the pulsed operation of SC cavity at high accelerating gradient. The LFD analysis requires transferring the solution for EM-fields to mechanical solver, finding the cavity wall deformation and then transferring it back to EM solver. Thus, LFD simulation suffers the same difficulties as microphonics, and introduces additional ones because it requires the consideration of the complete cavity mechanical model

Copyright © 2012 by the respective authors — cc Creative Commons Attribution 3.0 (CC BY 3.0)

including He-vessel and slow tuner. The example of LFD analysis, made in ANSYS, is shown in Figure 14 for SRF β=0.81 elliptical cavity [30]. The simulations show that stiffening rings allow the compensation of deformations due to electric and magnetic fields and, thus, the reduction of the LFD coefficient.

CONCLUSION

The design of SRF cavity has to satisfy a complex relationship between accelerator requirements, cryogenic effects and cryomodule structure. Modern state-of-the-art software for multiphysics analysis allows the simulation of various problems related to the design of SRF cavity and the attainment of reliable engineering solutions.

The study of these effects leads to specification of SC cavity and cryomodule and can significantly impact the efficiency and reliability of the superconducting linac.

REFERENCES

[1] D. Boussard, et al., "The LHC superconducting cavities", Proceeding. of PAC1999, New York, USA

[2] K. Shepard, at al., "Superconducting RF Development at ATLAS", Proceedings of the 6th Workshop on RF Superconductivity, 1993, VA, USA

[3] http://www.xfel.eu/

[4] P. Singh, "SRF accelerator for Indian ADS Program: Present & future prospects", Proceeding. of SRF2011, Chicago, IL, USA

[5] Project X: Accelerator Overview, http://projectx.fnal.gov/.

[6] The Facility for Rare Isotope Beams (FRIB) http://www.frib.msu.edu/

[7] J. Corlett, "A Next Generation Light Source Facility at LBNL", Proc. of PAC 2011, New York, NY, USA

[8] http://newsline.linearcollider.org/

[9] http://www.ansys.com

[10] http://www.comsol.com

[11] http://www.cst.com

[12] Lie-Quan Lee, et al, Omega3P: A Parallel Finite-Element Eigenmode Analysis Code for Accelerator Cavities, SLAC-PUB-13529, 2009.

[13] A. Lunin, "Design of alternative β=0.92 cavity for Project X", Project X Document 926-v1

[14] P. Ostroumov, et al., "Development of a Half-Wave Resonator for Project X", WEPPC039, IPAC'12, New Orleans, USA

[15] L. Ristori, et al., "Design of SSR1 Single Spoke Resonators for PXIE", WEPPC057, IPAC'12, New Orleans, USA

[16] A. Lunin, et al., "Alternative Cavity for H E Part of the Project X linac", WEPPR029, IPAC'12, New Orleans, USA

[17] Cho Ng, et al, Design and optimization of large accelerator systems through high-fidelity electromagnetic simulations, Journal of Physics: Conference Series 125, 2008

[18] http://www.gdfidl.de/

[19] Y. Chin, "User Guide for ABCI", LBL-35258

[20] A. Lunin, et al., "Cavity Loss Factors of Non-relativistic Beams for Project X", TUP075, PAC'11, NY, USA

[21] M.A. Furman, M.T.F. Pivi, "Probabilistic model for the simulation of secondary electron emission", PRSTAB, 5, 124404, (2002)

[22] S. Molloy, et al., "Multipacting Analysis for the Superconducting RF Cavity HOM Couplers in ESS", ESS Docs Document 115-v1

[23] J. DeFord, et al., "Improved Algorithms for Multipacting Simulation in the Analyst Code", WEP159, PAC'11, NY, USA

[24] P. Ylä-Oijala,et al., "MultiPac 2.1 - Multipacting simulation toolbox with 2D FEM field solver", User's manual, Rolf Nevanlinna Institute, Helsinki (2001).

[25] G. Romanov, "Simulation of Multipacting in HINS Accelerating Structures with CST Particle Studio", MOP043, LINAC'08, British Columbia, Canada

[26] S. Kazakov, et al., "Multipactor Simulation in SC Elliptical Shape Cavities", WEPPC051, IPAC'12, New Orleans, USA

[27] S. Solyak, et al., "Dark Current Model for ILC Main Linac", MOPP036, EPAC'08, Genoa, Italy

[28] S. Yakovlev, et al., "Higher Order Modes in the Project-X Linac", International Workshop on Higher-Order-Mode Diagnostics and Suppression in Superconducting Cavities, HOMSC12, UK

[29] L. Ristori, et al., "Design of Single Spoke Resonators for Project X", MOPO024, SRF2011, Chicago, USA

[30] I. Gonin, et al., "Development of the SCRF ß=0.81 Cavity for Proton Driver", TUP35, SRF2005, NY, USA

Copyright © 2012 by the respective authors — cc Creative Commons Attribution 3.0 (CC BY 3.0)

ISBN 978-3-95450-116-8