ALTERNATIVE CAVITY FOR HE PART OF THE PROJECT X LINAC*

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Abstract

A new superconducting elliptical cavity is suggested for the High Energy (HE) part of the Project X linac. The cavity is suitable to operate in CW regime with high beam current (10 mA), which makes the synergy possible with proposed Accelerator Driven Subcritical systems (ADS) [1]. We present the algorithm of the cavity shape optimization, comprehensive tolerances analysis and the solution for monopole High Order Modes (HOM) damping. Based on these results we estimated the probabilities of cryogenic losses per cryomodule and spread of the longitudinal emittance due to the resonance excitation of monopole HOMs in the HE linac for Project X.

INTRODUCTION

Project X is a future high intensity proton accelerator to be built in Fermi National Accelerator Laboratory targeting the intensity frontier with focus on the study of rare subatomic processes and supporting neutrino experiments. Project X would provide, by a large margin, better neutrino, kaon and muon beams compared with existing facilities. At the same time the proposed facility would not only allow for numerous experiments at the intensity frontier, but Project X technique may be used directly in Accelerator-Driven Subcritical systems (ADS) for energy generation and the transmutation of a nuclear waste. The ADS applications require a continuous wave (CW) multi-megawatt proton beam with high average current. Thus, the Project X capability for a future upgrade is critical.

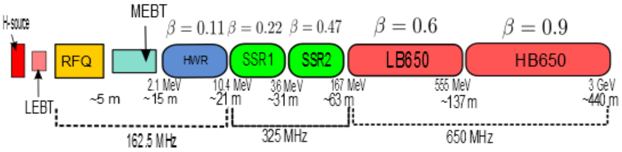

Figure 1: Project X linac layout.

The Project X frontend consists of a room temperature injector section and a superconducting linear accelerator working in CW regime and accelerating the beam from 2.1 MeV to 3 GeV [2]. The machine layout is shown in Figure 1. The 650 MHz 5-cell elliptical cavities are used for the high energy part of the linac. One of the great concerns is the stable operation in CW regime which can be limited by an additional cryogenic loss due to a synchronous excitation of the high order monopole modes. It has been shown that monopole HOMs are not a problem for the current Project X parameters, CW and 1 mA average beam current. Nevertheless, the cryogenic losses in the SC cavity are proportional to square of the average beam current - $P_{cryo} \sim I_{beam}^2$, and the potential problem of the present HE structure with the trapped 5th monopole passband could rise up P_{cryo} to hundred watt for the 10mA average beam current. The estimated monopole HOMs RF losses per cryomodule is presented in Figure 2. Therefore, we consider the alternative design of the accelerating structure for the HE section of Project X, suitable for the future upgrade to high current operations and, thus, for the ADS applications.

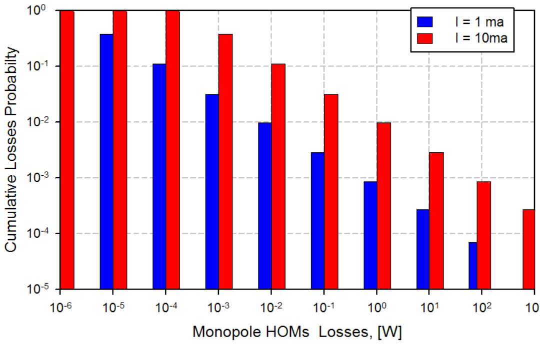

Figure 2: Estimated monopole HOMs RF losses per cryomodule for the present HE section of Project X linac.

CAVITY SHAPE OPTIMIZATION

The initial design of the $\beta_{geom}=0.9$ elliptical cavity for Project X was optimized for CW operation with 1 mA average beam current and has a conservative 5° walls angle [3]. Moderate sloping walls guarantee a good surface processing, make the cavity stiffer and, thus, reduce the microphonics effect. At the same time, it is known, that the smaller degree of the cavity wall slope (even negative) allows to reduce the surface electric and magnetic fields. Fortunately, the recent JLAB experiment with $\beta_{geom}=0.61$, 650 MHz single cavity has shown a very good result even the cavity has a flat (0°) walls [4]. Also the detailed mechanical analysis has proved that the proper position of the stiffening ring can provide the good mechanical stability for such a cavity [5]. Therefore, we decided to limit the cavity shape only by the negative wall slope.

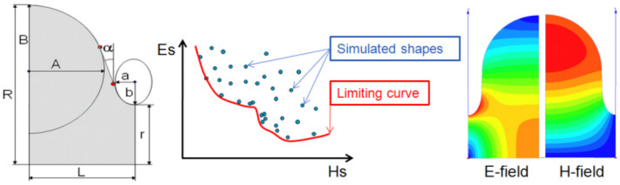

Figure 3: The conception of a cell shape optimization.

There is a well developed strategy how to optimize the shape of the elliptical cavity for $\beta_{geom}=1$ [6]. Similar algorithm can be adopted for the design of the cavity $\beta<1$, but the optimization becomes more challenging because of additional degree of freedom – the cell period ($b_{geom}\lambda$). Nevertheless, modern computers are able to simulate a

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single variant of the 2D cell geometry for less than a minute with a high accuracy of eigenfrequency and surface fields. Therefore, it is possible to perform a full multi-dimensional optimization of the $\beta<1$ cavity within a reasonable amount of time.

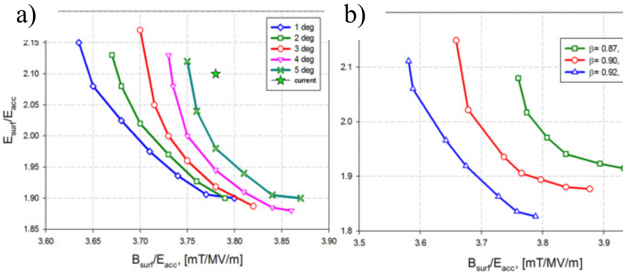
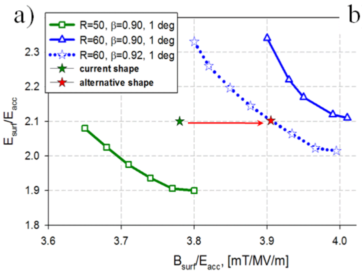


Figure 4: Normalized surface fields versus cavity wall slope (a) and cell period (b) (green star is the current cell).

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 3. Since there are only four independent parameters "A", "B", "a", "b" – the radii of two conjugated ellipses, then, by a proper choice of each parameter range, one can limit the total number of the examined cavity shapes. The dependences of optimal surface fields on cavity wall slope and cell period are shown in Figure 4. One can see, that a simple changing the wall slope from five degrees to one allows reducing the surface electric by 10% or the surface magnetic field by 4%. At last we broaden out the scope of the optimization and included the radius of the iris. A large cell aperture has following evident advantages: a) higher cell to cell coupling and a better field flatness; b) lower possible beam losses for a high beam current operation; c) provide better coupling with operating mode and make the antenna penetration less; d) lower the HOMs quality factors and, thus, reduce potential cryogenic losses. The simulations predict only ~2.5% surface magnetic field enhancement if we would increase both the cell aperture to 120mm and the cell period to $\beta_{geom}=0.92$. Thus, we decided to propose these parameters as the alternative for the Project X high beta cavity (see Figure 5).



b)

Quantity	Old	New
Aperture, mm	100	120
G, Ω	256	261
R_{sh}/Q_0, Ω	607	563
$G*R_{sh}/Q_0$, $Ω^2$	1.55E6	1.47E6
E_{surf}/E_{acc}	2.1	2.1
B_{surf}/E_{acc}, mT/MV/m	3.79	3.92
K_{couple}, %	0.75	1.42

Figure 5: Optimization of the surface fields (a) and parameters of the regular cell for $\beta_{geom}=0.92$ (b) for the alternative high beta structure for Project X.

Optimization of the end cell is the most challenging part of the cavity design, because it has to fulfill to the different criteria: a) the surface fields must not exceed the ones in the regular cell; b) the shape of the end cell has to be tuned in order to dump the Q_{ext} of the most dangerous HOMs; c) the length of the cell needs to provide the optimal beta value for the multi-cell structure. The consequence of such analysis is the optimum profile of the end cell, which is illustrated in Figure 6 (a). One can see that the excess of the surface magnetic field defines the minimum possible R_x radius, while the pair of r_x and R_y radiuses allows to find the geometry with a good coupling of the high order TM-modes with a beam pipe.

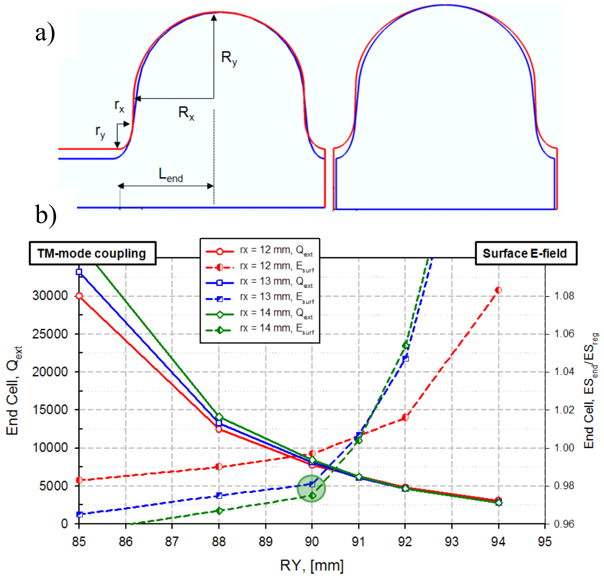


Figure 6: Old (blue) and new (red) cell shapes (a) and results of the end cell optimization (b).

Finally we analyzed the full geometry of the 5-cell accelerating structure and compared it with the present design. The results of the comparison are shown in Figure 7. The major advantage of the proposed cavity is that the quality factors Q_{ext} of the monopole HOMs are suppressed below 10^6. At the same time both structures have similar RF losses and acceleration efficiency and, thus, it is possible to keep the same layout of the HE part of the linac.

Quantity	Old	New
G, Ω	256	260
R_{sh}/Q_0 max, Ω	638	602
β_{opt}	0.95	0.97
E_{surf}/E_{acc}	2.08	1.98
B_{surf}/E_{acc}	3.68	3.69
K_{couple}, %	0.75	1.29
Monopole HOM Q_{ext}	10^{10}	10^6

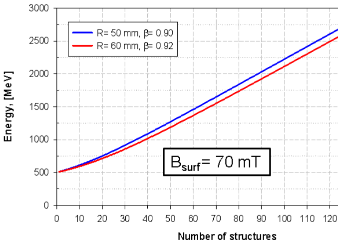


Figure 7: Parameters of old (blue) and new (red) 5-cell accelerating structures (left table) and particles acceleration along the Project X linac.

HOM STATISTICAL ANALISYS

Because of the fabricating tolerances and further surface processing the actual cavity shape never matches with the theoretical shape. Thus, there is a natural spread of the HOMs parameters from cavity to cavity. The HOM in the accelerating cavity is characterized by its frequency, shunt impedance and quality factor. We can reproduce the statistical deviations of these parameters with the following procedure. First, set the actual mechanical tolerances to the cell dimensions (±0.2mm). Secondly, tune the individual cell frequency by changing its period and preserving the field flatness along the cavity. Then, finally calculate a HOM spectrum of the derived 5-cell structure. It is possible to accumulate the data for further statistical analysis generating many random structures. The typical result for the Q_{ext} variation of monopole HOMs is illustrated in Figure 8 for the present 650 MHz, β_{geom}=0.9 Project X structure.

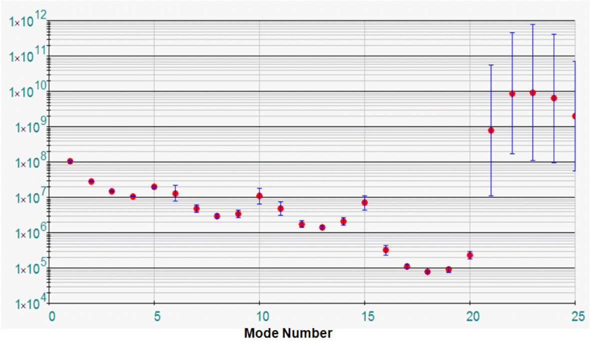


Figure 8: The Q_{ext} variation of monopole HOMs for the 650 MHz, β_{geom}=0.9 Project X structure.

Based on the predicted deviations of monopole HOMs frequencies and Q_{ext} we generated 10^5 random structures in order to estimate the probability of RF losses per cryomodule for Project X operation. The computing results are presented in Figure 9 for the old and new cavity designs respectively. One can see that the chance to get large cryolosses due to resonant monopole HOM excitation is significant for the present structure. The new cavity shape allows to suppress high Q monopole HOMs completely and, thus, to mitigate the large cryolosses problem.

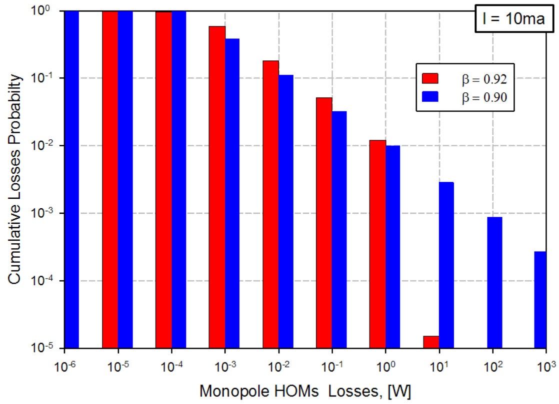


Figure 9: Probability of monopole HOMs RF losses per cryomodule in Project X linac for the 10 mA beam.

Baseline Project X design has a complicate beam structure consisted of three sub-components (1MHz, 10MHz and 20MHz). Because the HOM and beam components frequencies are not multiple in general, the resonance HOM excitation by one of the beam component will cause that other will see its voltage at different phases. Hence, a HOM with high Q may introduce a significant energy variation along the beam train. The influence of an individual HOM is proportional to the amplitude of the beam spectrum line closest to the HOM frequency and the effect is accumulated along the linac. We performed the statistical analysis in order to calculate the probability of the beam longitudinal emittance growth. The result is summarized in Figure 10.

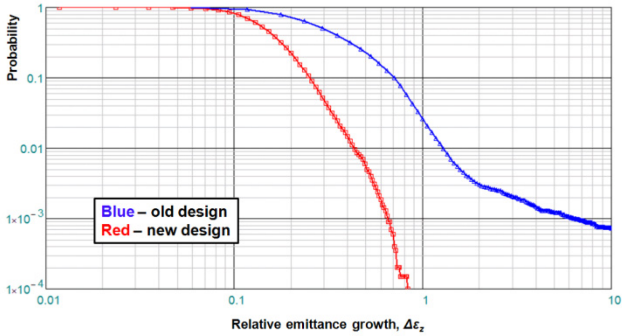


Figure 10: The probability of a longitudinal emittance growth in the Project X linac for the 10mA beam current.

The beam longitudinal emittance growth could be a significant problem for the high current operation of the present baseline of Project X CW linac. The proposed alternative design of the high beta cavity allows to limit the emittance growth by factor of two maximum.

CONCLUSION

An alternative version of the cavity for the HE section of the Project X linac is suggested. The cavity has larger 120 mm aperture and higher beta value of β_{geom}=0.92. Nevertheless, it demonstrates about the same field enhancement factors and acceleration efficiency. The proposed high beta cavity provides good monopole HOM damping and, thus, assure the reliable operation at high beam current. The cavity may be used for future ADS applications.

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