SHAPE OPTIMIZATION OF A SRF INJECTOR CAVITY

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Abstract

In this paper we present studies on the shape optimization of 1.6-cell cavity with solenoid for a 1-mA class photo injector, meant as an electron source for FEL facilities. The main criterion for the optimization was the lowest slice emittance. The inclination angle of the cavity back wall, solenoid magnetic field and amplitude of the accelerating field and other parameters were varied in these studies in order to find the minimum of slice emittance, ca. at 1m distance from the Pb photocathode, located in center of the cavity back wall.

INTRODUCTION

The aim of presented studies was optimization of the Tesla–type 1.6-cell cavity in terms of the emittance reduction for slices in the middle part of a bunch, taking into account that mainly electrons in these slices contribute to the lasing process. Considered injector is shown schematically in Figure 1.

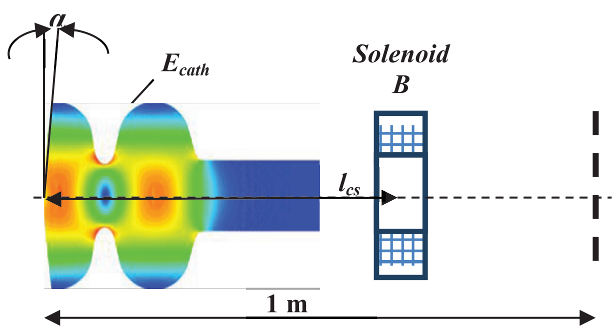

Figure 1: (Color) Layout of the SRF injector with the Tesla-type 1.6-cell cavity and solenoid.

SEARCH OF PARAMETERS

In the studies, we used ASTRA [1] tracing code for the beam parameter modeling and FEM code for the electro-magnetic field calculation in the SRF gun cavities [2]. The studies were performed in 2D, primarily for 1 nC bunches, emission time $\boldsymbol{\tau}$ = 20 ps and the thermal emittance ε_t of 1 mm·mrad, a value expected for a 2 mm diameter lead cathode irradiated with 213 nm light. The relatively long emission time, chosen to diminish the space charge force, was equal to 2.6 % of the RF period for 1.3 GHz, the frequency of accelerating mode of the TESLA cavities. The duration of irradiation causes intra bunch electron energy spread, which can be partially compensated with 3-rd harmonic cavities located downstream in a linac. Position of the solenoid was primary chosen to $\boldsymbol{l_{cs}}$ =0.41 m, accordingly to a proposed cryostat design and the space required for an input coupler, HOM couplers and a cold tuner. At the end of presented studies we investigated influence of the solenoid position on the slice emittance.

Slice Emittance vs. $\boldsymbol{\alpha}$

At first, we investigated the slice emittance vs. both the distribution and amplitude of the electric filed in the half-cell of the injector cavity. The field pattern, radial and longitudinal component of the electric field close to the emitting spot, depends on an inclination angle $\boldsymbol{\alpha}$ of the cavity rear wall (see Figure 1). Therefore, it influences emittance of the generated beam. In our studies, $\boldsymbol{\alpha}$ was changed in the range from 0 to 12 degree. For each $\boldsymbol{\alpha}$, half-cell was "re-tuned" to balance the peak electric field on axis in either cell. Additionally, for each $\boldsymbol{\alpha}$ electron emission time (phase) was chosen to ensure the maximum kinetic energy of the electrons. Other parameters for this investigation are listed in Table 1.

The electron bunches were split in 10 slices. The dependence of the horizontal slice emittance $\boldsymbol{\varepsilon}_x$ on the rear wall tilt is shown in Figure 2.

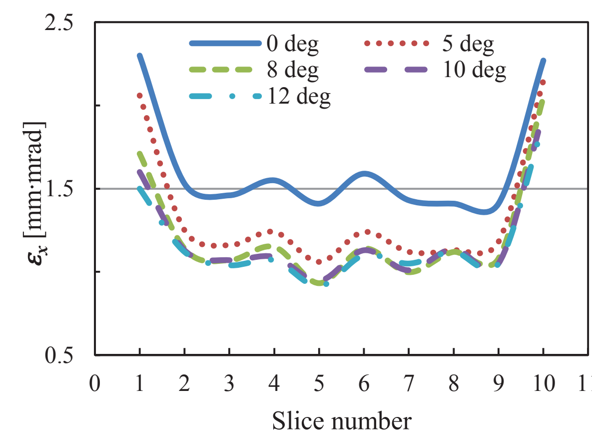

Figure 2: (Color) Slice emittance ε_x for different $\boldsymbol{\alpha}$.

Table 1: Fixed Parameters for Investigation ε_x vs. $\boldsymbol{\alpha}$

Parameter	Unit	Value
Bunch charge, $\boldsymbol{Q}$	nC	1
$\boldsymbol{\tau}$	ps	20
Electric field on the cathode, $\boldsymbol{E_{cath}}$	MV/m	60
$\boldsymbol{B}$	T	0.25
Cathode-to-solenoid distance, $\boldsymbol{l_{cs}}$	m	0.41

Very similar dependence was found for the vertical emittance ε_y. The result shows that ε_x and ε_y of six middle slices decrease while $\boldsymbol{\alpha}$ rises from 0° to 8° and then remain close to the minimal value of ca. 1 mm·mrad for the angles ranged up to 12°. We chose $\boldsymbol{\alpha}$ = 8°as an optimal for the cavity design and used that shape for all following studies.

Slice Emittance vs. Electric Field on the Cathode

In the second step of our analysis, ε_x and ε_y were calculated as functions of electric field amplitude $\boldsymbol{E}_{cath}$, which was varied in the range from 40 to 60 MV/m. The result for ε_x is shown in Figure 3. The fixed parameters are listed in Table 2. The result for ε_y is very similar.

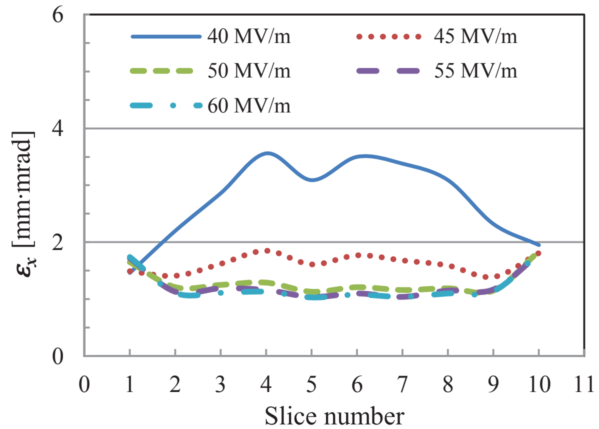

Figure 3: (Color) Slice emittance ε_x vs. $\boldsymbol{E}_{cath}$.

Table 2: Fixed Parameters for Investigation ε_x vs. $\boldsymbol{E}_{cath}$

Parameter	Unit	Value
Bunch charge, $\boldsymbol{Q}$	nC	1
$\boldsymbol{\tau}$	ps	20
$\boldsymbol{\alpha}$	[deg]	8
$\boldsymbol{B}$	T	0.25
$\boldsymbol{l}_{cs}$	m	0.41

The lowest ε_x and ε_y of 1 mm·mrad for inner slices are achievable for gradients $\boldsymbol{E}_{cath} \geq 55$ MV/m. On the other hand the emittance is only by 10% higher for $\boldsymbol{E}_{cath}$ of 50 MV/m. That enables to get a reasonable slice emittance also in the case of a moderate performance of the cavity.

Slice Emittance vs. *B*

The solenoid magnetic field $\boldsymbol{B}$ reduces transvers size of the emitted bunch and thus it is inevitable component of an injector. In the third step, we conducted the calculations of ε_x and ε_y as a function of the magnetic field. $\boldsymbol{B}$ amplitude was varied in the range from 0 to 0.4 T. Other parameters were kept constant. They are displayed in Table 3. The emission phase was set for the highest average kinetic energy. The result is shown in Figure 4. The slice emittance increases slowly with $\boldsymbol{B}$ and one needs to choose possible low $\boldsymbol{B}$ ensuring specified transvers bunch dimensions.

Table 3: Fixed Parameters for Investigation ε_x vs. $\boldsymbol{B}$

Parameter	Unit	Value
Bunch charge, $\boldsymbol{Q}$	nC	1
$\boldsymbol{\tau}$	ps	20
$\boldsymbol{\alpha}$	[deg]	8
Electric field on the cathode, $\boldsymbol{E}_{cath}$	MV/m	60
$\boldsymbol{l}_{cs}$	m	0.41

Dependence of all three bunch sizes $\boldsymbol{\sigma}_x$, $\boldsymbol{\sigma}_y$ and $\boldsymbol{\sigma}_z$ is displayed in Figure 5. The longitudinal length $\boldsymbol{\sigma}_z$ practically does not depend on $\boldsymbol{B}$, while the transvers sizes $\boldsymbol{\sigma}_x$ and $\boldsymbol{\sigma}_y$ do. For our studies we chose $\boldsymbol{B}$ = 0.25 T, which keeps $\boldsymbol{\sigma}_x$ and $\boldsymbol{\sigma}_y$ below 3 mm.

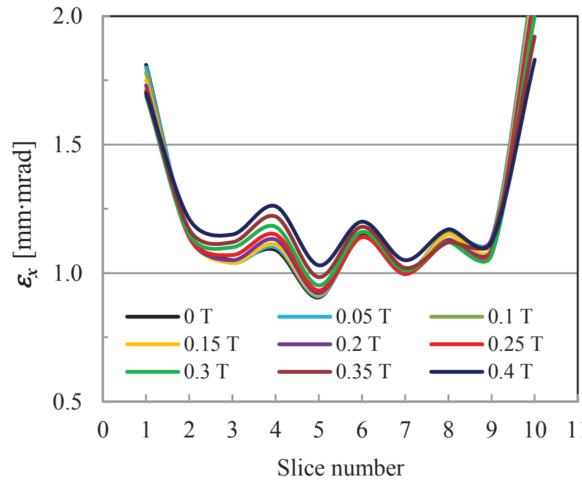

Figure 4: (Color) Slice emittance ε_x vs. $\boldsymbol{B}$.

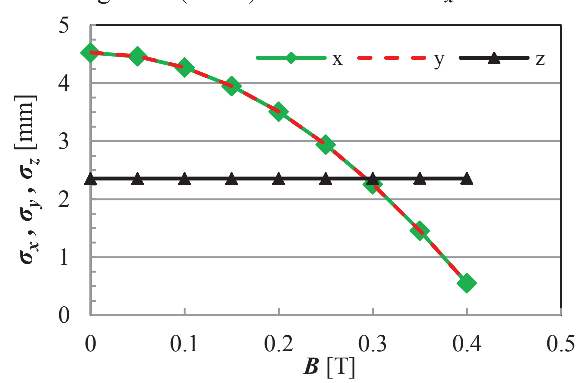

Figure 5: (Color) Bunch size for different $\boldsymbol{B}$ values. Note the overlapping of $\boldsymbol{\sigma}_x$ and $\boldsymbol{\sigma}_y$.

Slice Emittance and Kinetic Energy vs. Phase

The next goal was to find out if lower emittance can be achieved by changing the phase even though the particles will gain less kinetic energy. The Auto Phase function in ASTRA sets the optimal phase with respect to the highest average kinetic energy. For this investigation, the phases were set manually. Other parameters were fixed as listed in Table 3. Additionally to these listed in the table, the solenoid magnetic field was set to 0.25 T. At first, phases from 190˚ to 270˚ were investigated with step of 10˚. With this simulation we could narrow the phase range for further investigation from 200˚ to 220˚, in which emittance of inner slices was low. Then, the narrowed range was investigated with 2° increment. The result presented in Figure 6 shows that phases from 216° to 220° give the lowest slice emittance, however there is a minor change in the slice emittance for the whole investigated range of 20°. Figure 7 displays average kinetic energy for the investigated phase range, which proves to be rather slow changing function in that range. The conclusion is that however the Auto Phase function

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of ASTRA gives for maximum kinetic energy slightly different optimum phase of 210°, the difference in slice emittance for both phases is marginal.

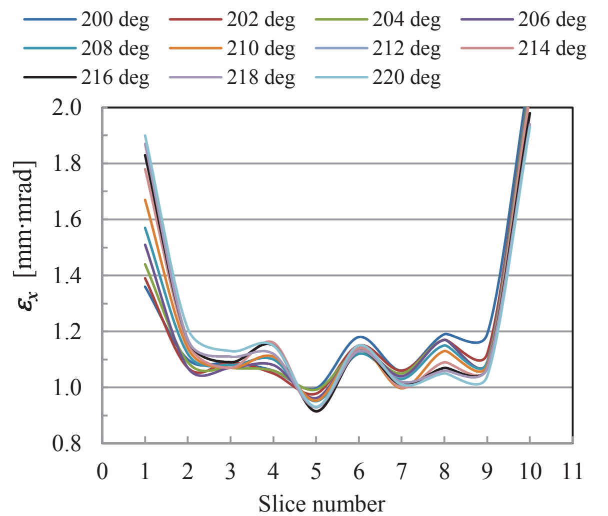

Figure 6: (Color) Slice emittance ε_x for different irradiation phase. Result for ε_y was very similar.

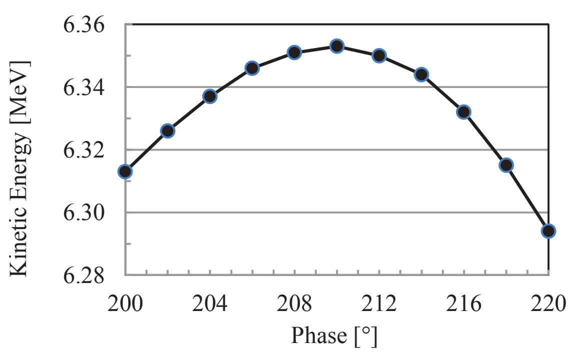

Figure 7: (Color) Kinetic energy vs. phase.

Slice Emittance vs. Location of Solenoid

As already mentioned finally we investigated dependence of the slice emittance on the location of solenoid. The cathode-to-solenoid distance was change in the range from 0.35 m to 0.7 m.

Table 4: Parameters for Investigation of ε_x vs. l_{cs}

Parameter	Unit	Value
Bunch charge, Q	nC	1
τ	ps	20
α	[deg]	8
Electric field on the cathode, E_{cath}	MV/m	60
B	T	0.25

Table 4 displays all fixed parameters. The result, summarized in Figure 8 for ε_x, indicates that shorter l_{cs} makes slice emittance lower. The chosen primary distance of 0.41 m seems to be a good compromise for mechanical design of cryostat, and it is very close to the distance proposed for high brightness injector discussed by M. Ferrario et al. in [3].

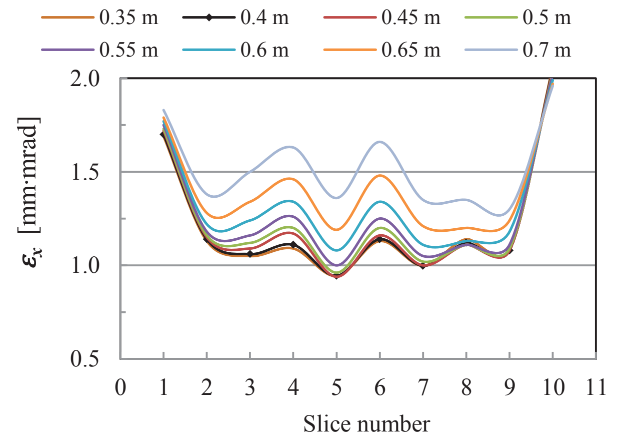

Figure 8: (Color) Slice emittance ε_x for different position of solenoid.

SUMMARY

The studies showed that 1.6-cell cavity having conical back wall with tilt of 8° can generate lower transvers emittance bunches than a flat back wall cavity. This conclusion reassembles result by R. Calaga for 704 MHz half-cell injector cavity, which has optimal tilt of 6° [4]. The assumed E_{cat} = 60 MV/m has not been demonstrated yet on the cathode in the superconducting injector cavity but it was achieved many times on properly cleaned Nb wall of the TESLA single-cell and 9-cell structures in vertical tests. Very recently, 54 MV/m at the cathode location was achieved in the 1.6-cell prototype Nb injector cavity [5] built at TJNAF for DESY.

We will continue these studies with 3D codes, to calculate slice emittance in injector cavities, which have broken cylindrical symmetry by FM and HOM couplers.

ACKNOWLEDGEMENTS

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