CATHODE INSERT DESIGN FOR SC RF GUNS*

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Abstract

The cathode inserts in superconducting (SC) RF guns are normal conducting devices attached to a SC RF gun cavity. They enable the photocathode replacement and, at the same time, preserve high quality factor and high fields in the RF guns. However, the insert may also limit the gun performance because of multipacting etc. The experience gathered in early designs at Wuppertal [1], and, more recently at BNL [2] and HZDR [3] is taken into account. We consider the design structure of the cathode insert worked out by BINP for 1 cell prototype of SC HZDR RF gun [4]. The detailed electric, mechanic, and thermal calculations of the initial [4] and the upgraded design are presented in this paper.

INTRODUCTION

The Berlin Energy Recovery Linac Project that was proposed by the Helmholtz-Zentrum Berlin requires a continuous wave (CW) superconducting photoinjector to supply the 100 mA average current beam. The normalconducting (NC) photocathode insert is the crucial part of the injector which allows changing the cathode.

We consider the upgrade of the cathode insert that was designed for SC RF gun prototype by BINP and then tested by HZDR [4]. With some modifications it has been applied further in HZDR 3+1/2 cell SC RF gun [3] to supply 1 mA average current beam.

This cathode insert [5] is unique due to the design of SC notch cell (See Fig.1, pos.22) joined to the cathode SC cell (11) of the RF gun through niobium (Nb) pipe. The pipe and the notch cell are the outside conductor of coax lines in which the inner conductor is the copper (Cu) photo cathode stem (23).

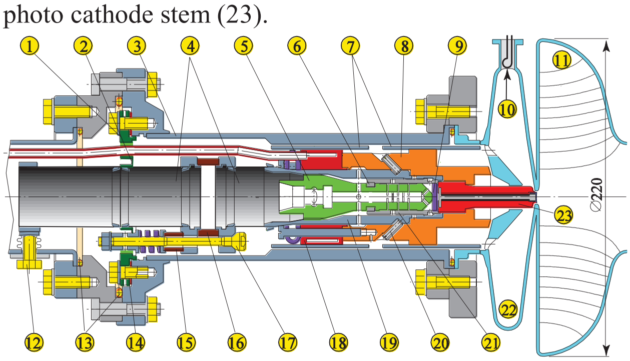

Figure 1: The sketch of the upgraded cathode insert.

The NC coaxial filter is positioned behind notch cell. The filter is designed to reflect the residual wave behind the notch in case the notch is detuned due to cathode position adjusting. The inner conductor of the coaxial filter is designed also as the thermal conductor (8) between the cooler (18) with liquid nitrogen and the photocathode stem (23). All these parts are electrically and thermally isolated from the cavity and the insert frame (3) by the 1 mm gap and ceramic insulators (16).

The photo-cathode stem is inserted into the RF gun through the vacuum preparation chamber by the manipulator and positioned on a thread (5). The modification made by HZDR is the spring contact applied instead of the BINP supposed thermal self-contraction effect. The other modification is the Molybdenum plug at the end of the stem. The plug is positioned on a thread.

The main parameters of the SC injector are following: rms normalized emittance is less 1 μm, bunch charge is 77 pC, laser thermal dissipated power is about 10 W. The 40 MV/m of maximum on-axis electric field corresponds to the accelerating gradient of 20 MeV/m that is considered for CW SC RF gun operation [7]. The total thermal dissipated power must be no greater than 30 W because the cooling potential of liquid nitrogen is limited.

MULTIPACTOR SUPPRESSION

Multipactor simulation is made with ASTRA. In the initial geometry the multipacting was in the 1 mm gap between the Cu stem and Nb pipe joining the notch SC cell and the cathode cell of the RF gun cavity (see Fig.2). Also the geometry with 2 mm gap was considered to compare its multipactor conditions. The calculations show that the multipacting are in the both geometries if the enhancement factor of the secondary electrons is more than 2 and the field in the gap is less than some boundary value corresponding to maximum on-axis field of the cavity named here as multipactor zones: 7 MV/m for the 1 mm gap, and 12 MV/m for the 2 mm gap.

We see from table 2 (variants 1/0 and 2/0) that the larger gap gives a wider multipactor zone, large dissipated power, and higher edge peak fields.

The multipactor suppression in these geometries by the static voltage and by the HOM with 2652 MHz frequency was also simulated by ASTRA code. HOM is controlled by mechanical cathode adjustment that is described below.

It is shown that the suppression of the multipacting by this HOM in the 1 mm gap of the initial geometry is impossible. But the static voltage of about half of RF amplitude in the gap is enough to suppress the multipacting. In the upgraded geometry (Fig.3) the multipactor discharge is non-excitant even without these suppression techniques.

RF Power and Fields

In the initial geometry, the incident RF wave with the power of about *415* kW is propagated along the cathode

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stem in the 1 mm gap of the coax line. A wave with approximately the same power is reflected back from the notch cell. Due to the notch superconductivity, the difference between the incident and reflected power is dissipated only on the Cu cathode stem in the coax line connecting the notch cell and the cathode cell. This power is not large because the combination of the notch cell with the coax line has no resonance at the frequency of 1.3 GHz and the coax line is relatively short (10 mm). Nonresonant RF field amplitude in the notch cell is 2 orders less than in the accelerating cell.

The estimation of the incident power can be made with the electric equivalent circuit in which the coax line with *1* mm gap is connected to a current source with $I = \varepsilon_o \omega E s \approx 275A$, where $E=40$ *MV/m* is cathode electric field, ω is $2\pi \cdot 1.3 \cdot 10^9$ Hz, s is the area of the cathode stem tip plus half of the gap area. In total it has the equivalent diameter of *11* mm. The characteristic impedance of the coax line with *1* mm gap is $\rho=60\ln(12/10)\approx 11$ Ohm. Then the incident RF power in the coax line is $\rho I^2/2=415$ *kW*.

The way to decrease this power is decreasing of the cathode field and the cathode stem tip area. The cathode field will be decreased if the cathode is deeper in the back cavity wall (see Fig.2 dotted line). In such a design the focusing electric field close to the cathode is formed. A cathode depth of about 2 mm is considered because it is optimally compatible with the beam emittance compensation by the focusing RF field [8]. In column 2 of Table 1, parameters for the 2 mm deep cathode are given. If cathode surface field is decreased to 25 MV/m and RF dissipated power is decreased by a factor of 6.

Table 1: Upgradeable Parameters of the Initial Cathode Insert Geometry

The variant: gap/depth[mm]	1/0	1/2	2/0
Dissipated RF power, [W]	48	8.2	61
Cathode field, [MV/m]	40	25.2	39.3
Av. gap E field, [MV/m]	8.8	4.38	8.5
Edge E_{peak}, [MV/m]	59.5	72.2	65
Multipactor zone, [MV/m]	≤7	≤7	≤12

GEOMETRY UPGRADE

The upgraded geometry is presented in Fig.3. The diameter of the cathode stem is increased up to 14 mm to improve the cooling. The geometry of the notch cell with the coax filter working at a frequency of 1.3 GHz was adapted to this diameter. The diameter of the stem tip is decreased down to 7 mm. The coax line between the notch and cathode cells is redesigned to have a grooved surface and a shorter length. Due to the grooved surface the multipacting is absent in the 1 mm gap as shown by simulations. Such a multipactor suppression method by another grooved surface is described in [2].

The stem tip cathode surface has a spherical form with the curvature radius of 16 mm. Due to this; the nonlinearity of the radial focusing field close to the cathode is negligible [8]. The particle dynamics calculation shows that bunch transversal emittance is reduced to 0.6 μm. In the calculation the bunch image charge in the spherical surface of the stem tip, in the 1 mm gap, and in both edges of the gap was taking into account.

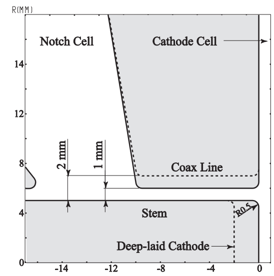

Figure 2: Initial cathode insert geometry [3, 4, 5].

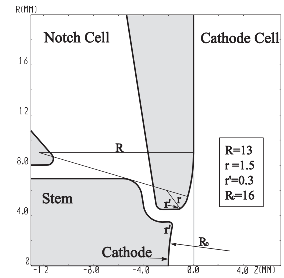

Fig. 3: Upgraded geometry of the cathode insert.

The geometry of the outer edge of the 1 mm gap consists of three conjugated arcs. Due to this the peak surface field is decreased here from 72 MV/m (see column 2 of Table 2) down to 45 MV/m. Therefore enhancement factors of all dark current emitters disposed on the edge becomes less by 72/45= 1.6 times. This allows us to work with higher field gradients without dark currents.

The dissipated RF power on the cathode stem is less than 2.8 W. The sum with the laser dissipated power (10 W) gives the total thermal power propagating through the stem of about 13 W.

PLUG

The plug is the replaceable molybdenum head of the cathode stem (see Fig.4). There must be a good thermal and electric contact between the plug and the stem. The contact place is a ring with the diameter of 7 mm. The good contact is provided by the contact force of more than 300 N [9]. This force is ensured by the thermal contraction effect applied between aluminum and copper parts of the cathode stem assembly. The aluminum rod with the thread at its end is attached inside the copper cathode stem and the plug is turned on the rod by the thread. After the cooling from 300K down to the 80K, the contraction difference between the copper (α_{Cu}=0.0033/K) and aluminum (α_{Al}=0.005/K) both having 60 mm length is 0.1 mm. This elastic deformation of the aluminum rod with 2.2 mm in diameter causes a force of about F=320 N acting between the plug coated by cooper at the contact and the cathode stem. The temperature drop at the contact is [9]

$$\Delta T = \frac{3\sigma_{Cu} 10^{-4}}{2.1F\lambda} P = 2.8K \tag{1}$$

where $\sigma_{Cu}=2.1\cdot 10^8$ N/m^2 is tensile strength of the stem copper material, $\lambda=\lambda_{Cu}=389$ W/m·K is thermal conductivity of the cathode copper material, P=13W is thermal power propagating through the contact. The force F=320 N is the maximum one can apply before damaging

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the thread of 5 mm in diameter on the aluminum rod [9] that is used to support the plug.

The molybdenum plug has to be coated by cooper or argentum layer in order to increase the surface electric and thermal conductivity, otherwise the dissipated power will be increased up to 3.6 W and the contact temperature drop will be increased up to 6 K [9].

A note concerning the contact between the cathode stem and the cooler: it can be made using the thermal contraction effect by the force of about 500 N with the temperature drop at the contact of about 2K as described in Ref.[5]. If this force is made by the spring as it is in HZRD modified cathodes insert then there is a risk to damage the thin parts of the insert and damage the mechanical setting of the cathode. To exclude these damage risks the thermal contraction effect must be used.

We have not taken into account the RF power dissipated on the contact. This power can be estimated experimentally by the formula $P_c=\omega U/Q_{ex}$, where $U=9.67J$ is the stored RF energy at $E_{acc}=20\ MV/m$, Q_{ex} is the external quality factor of the contact measured in the experiment. Without this power, the temperature estimation gives the stem tip temperature of about 94K.

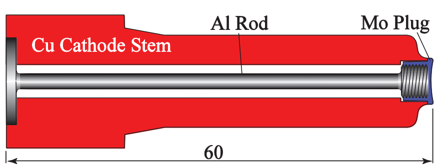

Figure 4: The cathode stem (mm scale).

LONGITUDINAL CATHODE ADJUSTING

The cathode longitudinal position in the cell is adjusted by the longitudinal deformation of the notch cell. This deformation causes the RF detuning of the notch cell that can increase the dissipated RF power in the coaxial filter. We consider the range of the deformation corresponding to the quality factor drop down to $5.6{\cdot}10^8$ (lowest quality factor). This quality corresponds to the RF power dissipated in the cathode insert of about 20 W. Together with the 10 W laser dissipated power, it gives 30 W which is the limit for the liquid nitrogen cooling potential.

The coaxial filter is useful to decrease the dissipated RF power in the cathode insert at the detuned notch cell and to extend boundaries of the notch cell longitudinal deformation [6]. We consider here two types of coaxial filters. One of them consists of 5 coaxial segments each with λ/4 length and different impedances as described in Ref. [5]. The other ("cylinder") has smooth inner and outer cylinders with the 5 mm gap between them. Their length (127 mm) is adjusted to the resonance of 1.3 GHz when an electrical short-circuit is set at its end.

The maximal range of the deformation corresponding to the lowest quality factor depends on the load impedance at the end of the coaxial filter. The largest range (>3 mm) is for the unloaded coaxial filter and the lower range (2 mm) corresponds to the short-circuit one. Figs. 5, 6 demonstrate the dependency of the cavity quality factor on the notch longitudinal deformation.

The HOM in the notch cell is used to control the longitudinal cathode position and 1 mm gap value. The HOM resonance frequency of about 2527 MHz depends on the notch cell longitudinal deformation with the sensitivity of ±73 MHz/mm. This HOM has quality factor of $1.5{\cdot}10^5$ and it has the same electric field distribution in the 1mm gap as the accelerating mode but the HOM field in the cavity cells and in the coax filter is negligible.

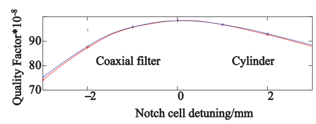

Figure 5: Quality factor of the cavity with unloaded coaxial filter.

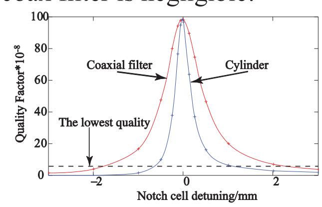

Figure 6: Quality factor of the cavity with the shortcut at the coaxial filter end

Pick up couplers could be made at the notch cell equator (see Fig 1, pos.10). The coupler would not limit the cavity accelerating gradient and quality factor due to low RF fields in the notch cell. This coupler is useful for the main frequency control and as the HOM input and output port.

TRANSVERSAL CATHODE ADJUSTING

The cathode is precisely adjusted on the cavity axis using three cross-feed screws (see Fig.1, pos. 12) azimuthally positioned around the axis. The assembly of the cathode stem (4-9, 15-21, 23) is attached to the flange (1) through the thin ring membrane (2). The deformation of the membrane using the screws (12) can incline the assembly by a small angle and adjusts the cathode transversally by ± 1 mm. The thickness of the stainless steel membrane is 0.2 mm. A force of about 16 N is sufficient to make this deformation.

SUMMARY

Our upgrade proves that the multipactor discharge can be suppressed, dark current reduced, dissipated RF power and electric fields in the 1 mm gap decreased. Furthermore, the upgrade design proves the trouble free thermal and electric contacts in the chain of the plug, the cathode stem, and the thermal conductor. Also it proves the realization of accuracy requirements for the mechanical adjustment of the cathode in the RF gun.

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