Power coupler kick of the TRIUMF ICM capture cavities

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Abstract: The TRIUMF Injector CryoModule (ICM) adapted two superconducting single cavities as the capture section for the low injecting energy of 100 keV electrons. Coupler kick induced beam deflection and projected emittance growth are one of the prime concerns of the beam stability, especially at low energies. In low energy applications, the electron velocity changes rapidly inside the cavity, which makes the numerical analysis much more complicated. The commonly used theoretical formulas of the direct integral or the Panofsky-Wenzel theorem is not suitable for the kick calculation of $\beta<1$ electrons. Despite that, the above mentioned kick calculation method doesn't consider injecting electron energy, the beam offset due to the coupler kick may not be negligible because of the low injection energy even if the kick is optimized. Thus the beam dynamics code TRACK is used here for the simulation of the power coupler kick perturbation. The coupler kick can be compensated for by a judicious choice of the coupler position in successive cavities from upstream to downstream. The simulation shows that because of the adiabatic damping by the following superconducting 9-cell cavity, even for the worst orbit distortion case after two capture cavities, the kick is still acceptable at the exit of the ICM after reaching 10 MeV. This paper presents the analysis of the transverse kick and the projected emittance growth induced by the coupler for $\beta<1$ electrons. The simulated results of the TRIUMF ICM capture cavities are described and presented.

Key words: coupler RF kick, capture cavities, $\beta<1$ electron

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1 Introduction

The TRIUMF Injector Crymodule (ICM) is proposed to accelerate electrons from the 100 keV source potential to 10 MeV at 10 mA. Two 1.3 GHz superconducting β=0.7 elliptical single cell cavities are designed to capture the β=0.54 electrons right after the normal temperature (NT) buncher. A superconducting 9-cell cavity sitting in the same cryomodule with the capture cavities is used to boost the energy up to 10 MeV. The co-axial TTF-III power coupler is chosen for the power coupling into each capture cavity. Variable coupling strength can be obtained by varying the penetration depth of the inner conductor. The existence of the power coupler destroys the cavity symmetric geometry and leads to non-zero transverse fields at the axis. Thus the accelerating mode will not be a pure mode at the axis but have small multipole components located at the coupler position in addition to the TM_{010} mode. The dominant multipole fields induced by the coupler are the dipole, quadrupole and skew quadrupole fields. The quadrupole and skew quadrupole moments mainly cause transverse focusing effects and x-y coupling to the beam. These can be adjusted by the transverse focusing devices [1]. The dipole moment produces a transverse kick to the bunch and causes a projected emittance growth because of the time dependent kick of the head relative to the tail of the bunch. The coupler kick can be cancelled by situating a symmetric coupler on the other side of the beam pipe or to position a short stub instead of the second coupler [2]. These approaches are effective, but solutions that don't include additional devices are preferable. In this paper, we examine ways to compensate the coupler kicks by varying the positions of the two couplers corresponding to the capture cavities. The RF kick is optimized and the on-axis electron divergence

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can be minimized to be 24 μrad after the capture section. Furthermore, simulations show that for the ICM injector design, the phases of the capture cavities are matched with the following 9-cell RF waveform, so that the maximum divergence moment of the beam encounters zero degree (maximum acceleration) of each cell. The divergence of the beam could be damped gradually, so even for the worst RF kick after the capture, the orbit distortion and transverse emittance growth of the beam will still be acceptable after the ICM.

2 The coupler RF kick

The coupler kick at the final operation current (10 mA) is investigated in this paper and the inner conductor of the coupler is kept flush with the cavity beam pipe to give a smaller kick. According to the specification, $Q_{\rm ext}$ at 10 mA for the two capture cavities are 1×10^6 and 2.6×10^6, respectively. The $Q_{\rm ext}$ specification determines the coupler position. The position of the coupler and the penetration depth of the inner conductor determine the multipole field strengths, which the coupler could induce. The $Q_{\rm ext}$ is inversely proportional to the power leaking back out of the power coupler when the RF generator is switched off, so the closer the coupler is to the cavity and the deeper the penetration depth of the inner conductor in the cavity, the smaller $Q_{\rm ext}$ will be.

The cavity and the coupler model are simulated with CST [3]. The waveguide transmits a traveling wave through the coupler and forms a standing wave inside the cavity. In older versions of CST (version 2007 or lower), there are no options for a travelling wave boundary, so the wave travelling through the coupler is derived from combining two standing waves with different boundary conditions (Perfect Electric Wall or Perfect Magnetic Wall) together. The new "port" boundary condition in CST provides the user with the capability of simulating infinitely long waveguide connections. Perfect matching is assumed, so there are only pure incoming fields from the coupler.

Figure 1(left) shows the TTF-III coupler together with the capture cavity model. (The beam pipe radius is 35 mm.) As shown in the left figure, the z axis is in the direction of the beam propagation with the positive y axis pointing up and the positive x axis pointing into the paper. Fig. 1 (right) shows the variation in $Q_{\rm ext}$ with the coupler position and the inner conductor penetration depth. From the plot, we can conclude that the deeper the penetration depth inside the cavity, the smaller is $Q_{\rm ext}$. ("L_port" is the distance between the coupler antenna and the beam axis.) Also, by moving the coupler position from 100 mm to 80 mm with respect to the cavity center, the coupling is stronger and $Q_{\rm ext}$ is smaller. The coupler position of the first capture cavity is chosen to be 83 mm away from the cavity center and the coupler of the second cavity is located at 90.3 mm while keeping the inner conductor flush with the beam pipe.

The coupler induced mutipole fields are mostly quadruple fields that are symmetric along the beam axis, as shown in Fig. 2 (left). The solid line and the dash dot line are the coupler induced longitudinal multipole fields of the first capture cavity, off axis with $y=\pm1$ mm. The square dot curve is the longitudinal field of the dipole component at y=1 mm. The coupler is located downstream of the capture cavity

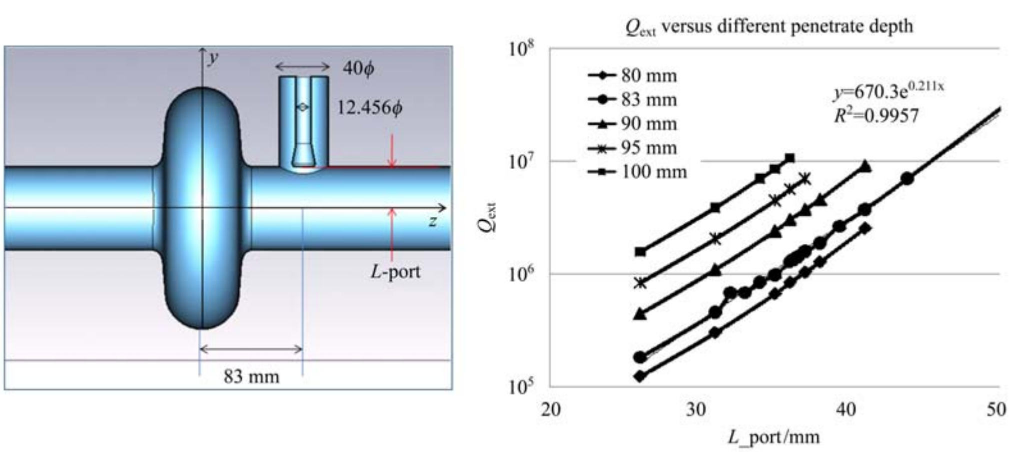

Fig. 1. The model of the capture cavity and the first power coupler (left). Variation of the capture cavity $Q_{\rm ext}$ with the inner conductor penetration depth and the distance between the cavity and the coupler from 100 mm to 80 mm (right).

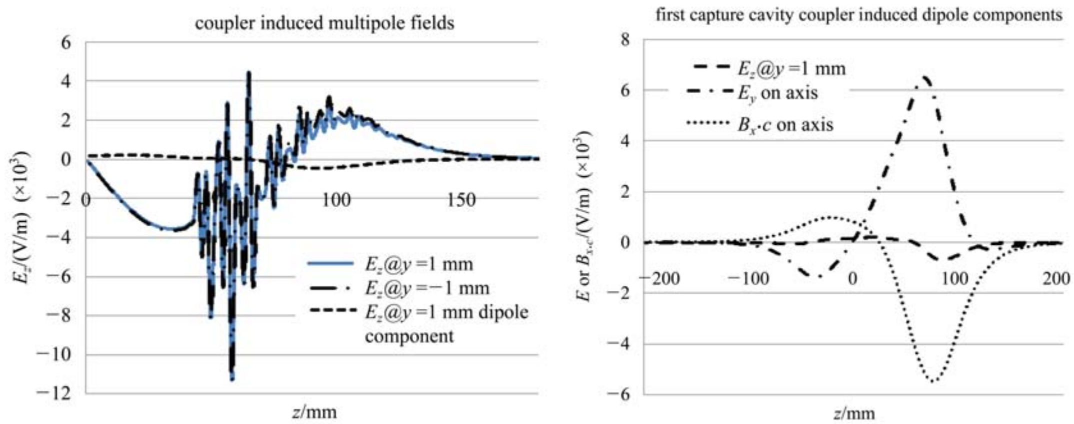

Fig. 2. The multipole fields at the coupler position (left). The coupler induced on-axis fields and the longitudinal field off axis at y=1 mm (dipole moments only; right).

and below the beam pipe. The field oscillation is due to an insufficient number of mesh points in CST for such small coupler perturbation fields as compared with the fundamental mode. The existence of the coupler induces non-zero transverse fields at the beam axis: the dipole components, as shown by the dash dot and the round dot curves in Fig. 2 (right). The non zero dipole transverse components result in electron deflection and projected emittance growth. The commonly used numerical formulas for the coupler kick calculation is the direct integral of the transverse on-axis fields. The calculated results can be checked by the Panofsky-Wenzel theorem using the off-axis longitudinal components of the dipole moment. The dash line in Fig. 2 (right) is the longitudinal dipole moment off axis by y=1 mm.

2.1 The direct integral and the Panofsky-Wenzel theorem

The coupler kick is defined as the ratio between the complex transverse impulse to the complex longitudinal accelerating impulse [4, 5],

$$K_{x/y}=\Delta P_{x/y}/\Delta P_z=|\Delta P_{x/y}/\Delta P_z|\mathrm{e}^{\mathrm{i}\phi}, \quad (1)$$

where ϕ is the phase of the coupler kick. The transverse impulse comes from the coupler kick and the longitudinal impulse comes from the fundamental mode according to

$$\Delta P=\int F\mathrm{d}t=\int F\mathrm{d}z/v=qV/v=qV/\beta c.$$

The effective kick can also be described as the ratio between the effective transverse voltage and the effective longitudinal voltage on the axis,

$$K_{x/y}=V_{x/y}/V_{\mathrm{acc}}. \quad (2)$$

The transverse Lorenz force for the RF cavity is described as

$$F_{\perp}=\int q[E_{\perp}+(v_z\times B)_{\perp}]\mathrm{d}z.$$

Thus, if we define an $\mathrm{e}^{\mathrm{i}(\omega)t}$ time dependence of the electric field and the RF operating phase to be φ, the transverse voltage can be derived by the direct integral of the transverse fields (dipole components) on the axis,

$$V_x=\int_{-z_{\mathrm{end}}}^{z_{\mathrm{end}}}[(E_x(z)-v\times\mu_0H_y(z)]\cdot\exp[\mathrm{i}\cdot(w_0t+\varphi)]\mathrm{d}z, \quad (3)$$

$$V_y=\int_{-z_{\mathrm{end}}}^{z_{\mathrm{end}}}[(E_y(z)+v\times\mu_0H_x(z)]\cdot\exp[\mathrm{i}\cdot(w_0t+\varphi)]\mathrm{d}z, \quad (4)$$

$$V_{\mathrm{acc}}=\int_{-z_{\mathrm{end}}}^{z_{\mathrm{end}}}E_z(z)\cdot\exp[\mathrm{i}\cdot(w_0t+\varphi)]\mathrm{d}z. \quad (5)$$

Because of the perpendicular relationship between electric and magnetic field for the resonant frequencies, both the electric and magnetic fields are complex numbers with the imaginary part of the electric field and the real part of the magnetic field being zero. If the cavity has ends perpendicular to its axis (zero transverse electric fields at both ends), which is suitable for the cavity with a beam pipe, the Panofsky-Wenzel theorems tell us that the transverse deflecting effect is related only to the longitudinal field gradient in the form of [6]

$$\Delta P_{\perp}=\left(\frac{\mathrm{ie}}{w_0}\right)\int_0^{\mathrm{d}}\nabla_{\perp}E_z\mathrm{d}z. \quad (6)$$

For the deflection of dipole fields to $\beta<1$ electrons, if we can neglect the variation in the charge's transverse coordinate during its transit through the cavity, we then have

$$V_{\perp}=\left(\frac{iv}{w_0}\right)\int_0^{d}E_z(\rho=a)\mathrm{e}^{\mathrm{i}(w_0z/v+\varphi_0)}\mathrm{d}z/a, \quad (7)$$

where a is the beam pipe radius, ρ is the off-axis distance and v is the beam velocity. Because of the multipole fields at the coupler position, the off axis longitudinal dipole fields can be derived by the following formula in order to get rid of the quadruple components. In our case, the coupler is parallel to the y axis, as shown in Fig. 1(left), then the horizontal component of the kick vanishes ($y_1=1$ mm),

$$V_y=\left(\frac{iv}{w_0}\right)\int_0^{d}[E_z(y_1)-E_z(-y_1)]\mathrm{e}^{\mathrm{i}(w_0z/v+\varphi_0)}\mathrm{d}z/2y_1. \quad (8)$$

Applying Eqs. (8) and (5) to (2) yields the coupler kick. The coupler kick has both real and imaginary components. The real component corresponds to a momentum imparted to each bunch. The corresponding imaginary component imparts a time varied kick to the bunch and this causes the projected emittance growth of the beam. In our case, the on axis electron has no initial transverse momentum at the entrance of the first capture cavity. Then the divergence of the on axis electron after the first capture cavity is

$$\begin{aligned} y' &= \frac{\mathrm{Re}(P_y)}{\mathrm{Re}(P_{\mathrm{acc}})}\approx\frac{\mathrm{Re}(\Delta P_y)}{\mathrm{Re}(\Delta P_{\mathrm{acc}})+P_{z0}} \\ &= \frac{\mathrm{Re}(\Delta V_y)/v}{\mathrm{Re}(V_{\mathrm{acc}})/v+P_{z0}/(e)} \\ &= \frac{\mathrm{Re}(\Delta V_y)/\beta}{\mathrm{Re}(V_{\mathrm{acc}})/\beta+\sqrt{\varepsilon_1^2-\varepsilon_0^2}/e}, \end{aligned} \quad (9)$$

where ε_1 and ε_0 are the total energy and the rest mass energy of the electron, respectively. As there is no corrector in the cryomodule, for the second capture cavity, the initial transverse momentum ($P_{\mathrm{cav1}y}$) due to the coupler kick from the first cavity is not zero, then the divergence at the exit of the second capture cavity is

$$\begin{aligned} y' &= \frac{\mathrm{Re}(P_y)}{\mathrm{Re}(P_{\mathrm{acc}})}\approx\frac{\mathrm{Re}[P_{\mathrm{cav1}y}/e+(\Delta V_y)/(\beta c)]}{\mathrm{Re}(V_{\mathrm{acc}})/(\beta c)+P_{z0}/e} \\ &= \frac{\mathrm{Re}[P_{\mathrm{cav1}y}c/e+(\Delta V_y)/\beta]}{\mathrm{Re}(V_{\mathrm{acc}})/\beta+\sqrt{\varepsilon_1^2-\varepsilon_0^2}/e}. \end{aligned} \quad (10)$$

For the high energy application, the velocity of the electrons can be treated as constant. If the cavities have a periodical distribution and identical accelerating conditions (the absolute kick is the same for all cavities), the kick can be compensated for by different orientations of the coupler directions. In this way, the orbit distortion or the emittance growth of the beam can be cancelled. In our case, the electron energy injecting into the capture is 100 keV and it changes rapidly inside the cavity while it is accelerated. Furthermore, the operational phase, accelerating gradient and Q_{ext} of each cavity are not identical, so the kick can only be cancelled partly by varying different positions of the couplers and the offset of the electrons may not be negligible after the two capture cavities. The beam dynamics code TRACK [7] is used here for the precise simulation of the coupler kick effect because the unique feature of TRACK allows the user to use asymmetric 3D fields. The equations (9) and (10) will later be used to crosscheck the TRACK simulation results using the average velocity of the electron traveling through the cavity.

2.2 The TRACK simulation

A single on-axis electron with initial energy of 100 keV is tracked through the two capture cavities. The first β=0.7 capture cavity operates at 1.12° with an accelerating gradient of E_{acc}=5.7 MV/m. The second capture cavity operates at −113° with E_{acc}=6.75 MV/m. All of the phases in this paper have the same definition that zero degrees corresponds to a maximum energy gain while minus ninety degrees corresponds to a longitudinal focusing phase. After acceleration, the energy coming out of each cavity is 546 keV and 517.6 keV, respectively. The coordinate system is the same as shown in Fig. 1 (left). The simulations show that the first coupler located downstream (define as "d" for further reference) of the first cavity gives less deflection to the beam than if it is positioned upstream (define as "u"). For this discussion, we define "a" to be the case of mounting the coupler above the beam pipe and "b" to be below the beam pipe. Fig. 3 shows the coupler steering a single on-axis electron in four different cases while keeping the coupler downstream of the first capture cavity. Four possible coupler positions are upstream of the cavity above or below the beam pipe and downstream of the cavity, above or below the beam pipe. As shown in Fig. 3, the solid line ("$d(b)+u(b)$") has a minimum kick but it is not mechanically feasible because of limited space between the two capture cavities. The dash line (case 1: "$d(b)+d(b)$") is a better solution with a divergence of −0.198 mrad and an offset of −0.1 mm obtained by TRACK simulation. However, the dash dot line case (case 2: "$d(b)+u(a)$") is the mechanical preferred configuration with a divergence of −0.784 mrad and an offset of −0.189 mm. Further investigation of the projected emittance growth and the crosschecking by the theoretical formulas will be done for these two particular cases.

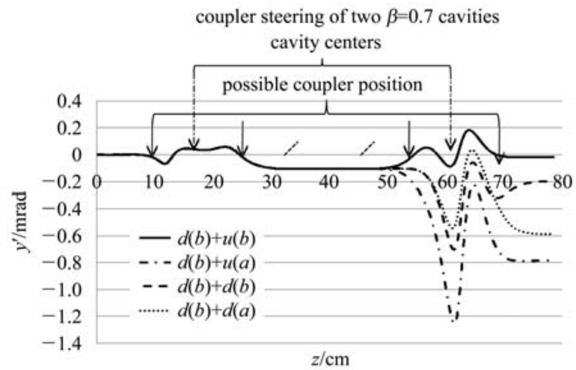

Fig. 3. The coupler steering a single on-axis electron: the "u", "d" in the graph stand for the coupler located upstream or downstream of the cavity, respectively, and "a", "b" stand for the coupler positioned above or below the beam pipe of the cavity.

2.3 The cross-checking

Table 1 shows the results according to Eqs. (9) and (10). The average velocity of the beam in the cavity is used with β=0.7 for the first cavity and β=0.87 for the second one. The TRACK simulation yields a much bigger perturbation when the second coupler is located upstream of the cavity (case 2). For the second capture cavity, the operating RF phase is −113° and the cavity off-axis field has a big defocusing effect once the electron is steered away from the axis. The further it is steered, the stronger the defocusing effect gets. As shown in Fig. 4, the off-axis 0.5 cm electron receives a big defocusing force when the operating phase is negative. From the TRACK simulations, the electrons are steered off axis by 0.1 mm at the exit of the capture cavities in case 1 and by 0.2 mm in case 2. But in these formulas, only on axis fields are considered. In case 1, both of the couplers are located downstream of the capture cavity so the kick is partly cancelled because of the different operating phases of the two capture cavities.

Table 1. The crosschecking of TRACK simulations for case 1 and case 2 using the direct integral and the Panofsky-Wenzel theorem.

	direct integral/ mrad	P-W theorem/ mrad	track/ mrad
Case 1 : y'	−0.149	−0.148	−0.198
Case 2: y'	−0.195	−0.196	−0.784

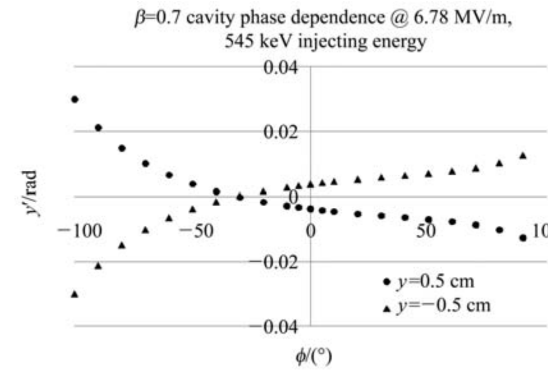

Fig. 4. The cavity field focusing effect on the off axis 0.5 cm electron at different RF phases.

2.4 Emittance growth

The projected emittance growth is analyzed for the whole injector with the optimized solution and the initial beam distribution simulated after the gun. The bunched beam ensemble is traced (using TRACK) in the injector with the optimized kick (case 1) position and the worst kick position (both couplers upstream of the cavities and on the same side of the beam pipe). The results are compared with the cavity models without couplers. The transverse emittance growths for the optimized case are $\Delta\varepsilon_x$(RMS)=1.87%, $\Delta\varepsilon_y$(RMS)=0.76% and for the worst kick are $\Delta\varepsilon_x$(RMS)=6%, $\Delta\varepsilon_y$(RMS)=1.6%. The results shows that even for the worst kick, the transverse emittance growth is still acceptable at the end of the whole injector. For the optimized solution, the phases of the capture cavities are designed to match the downstream superconduting 9-cell cavity. The phase shift acceptance is then studied and the results are shown in Fig. 5. "C1" and "C2" are the phases (default phases) of the two capture cavities, respectively, for the optimized solution and they are shifted 10 degrees up or down. The simulations show that the kicks from the capture cavity couplers can be damped by the following 9-cell cavity. This is the case only if the capture cavity phases are matched with the following 9-cell RF waveform. When the capture cavities are properly phased, the arrival time of the biggest divergence moment of the beam encounters zero degrees for each cell, and then the match occurs. The unmatched situation is when the arrival time is behind zero degrees and correspondingly the anti-damped situation occurs when the arrival time has a 90° difference with part or all of the cells of the 9-cell cavity. The plot in Fig. 5 (left) shows the y' of a well-damped orbit (from properly phased captures) superimposed on the E_z field seen by the electron in

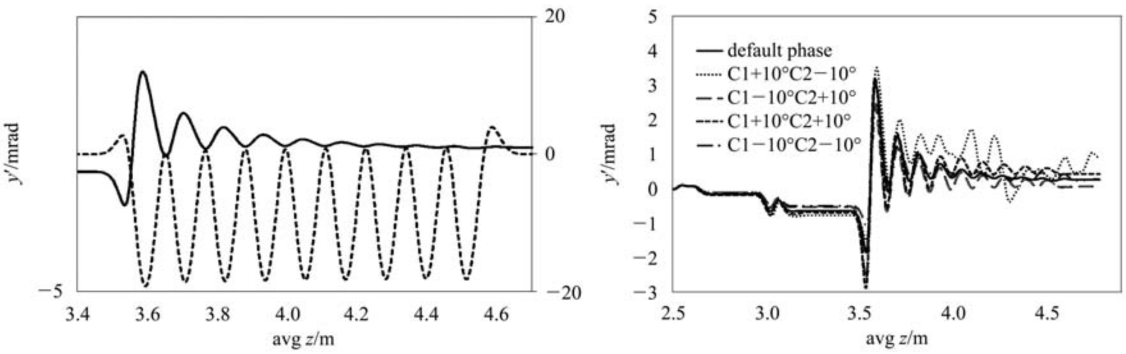

Fig. 5. Coupler induced orbit being well damped by the following 9-cell RF field (left). The comparison of electron orbits being damped by following 9-cell or not sufficiently damped (the round dot line; right).

the 9-cell cavity. The coupler kick can generate a large deflection by insufficient damping or even anti-damping in the 9-cell cavity due to non-ideal capture cavity phases, as shown in Fig. 5 (right; the round dot curve). The antidumping happenes in the middle cells.

3 Conclusion

The coupler kicks of the TRIUMF ICM injector capture cavities are investigated in this paper. The analysis method for coupler kicks of $\beta <1$ electrons is presented. The minimized coupler kick is derived by alternating the locations of the two power couplers. The simulations show that because of adiabatic damping of the following superconducting 9-cell cavity, the transverse emittance growth even for the worst kick case is acceptable. Therefore, the mechanically favorable configuration of the coupler positions can be chosen. The beam offset is smaller than 0.1 mm and the divergence is smaller than 0.5 mrad at the end of the 9-cell, which can be corrected by steering at the exit of the ICM.

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