UPGRADING THE RHIC BEAM DUMP FOR HIGHER INTENSITY*

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Abstract

Mechanical analysis of the RHIC beam dump window has shown that present heavy ion beam intensities are close to the tolerable limit, and will likely exceed that limit in future runs. Two approaches to upgrade the abort system for those projected higher intensities have been studied, namely replacing the existing window, and adding a vertical kicker that distributes the individual bunches more evenly across the window, thus reducing the heat load. We present the results of these studies and the present status of the upgrade project.

INTRODUCTION

The RHIC beam is aborted by a set of five kickers that deflect it horizontally into the dump. The dumped beam first passes through a 50 cm long C-C carbon block that dilutes its emittance before it exits the RHIC vacuum enclosure through a pair of 17-7 PH steel windows. Outside the beam vacuum, the aborted beam is diluted further by a second carbon block before it is absorbed by a massive steel block.

The RHIC beam dump system was originally designed for a 100 GeV/nucleon gold bunch intensity of $1 \cdot 10^9$ Au ions/bunch in 56 bunches. During the 13 years of RHIC operation, the actual beam intensity has been increased by more than a factor 2, to $1.3 \cdot 10^9$ Au bunches in 111 bunches. In addition, stochastic cooling [1] now results in much smaller emittances than originally envisioned during the RHIC design phase [2]. These developments led to a re-evaluation of the integrity of the vacuum window.

NUCLEAR INTERACTION AND MULTIPLE SCATTERING IN THE C-C CARBON BLOCK

Due to stochastic cooling the Au beam emittance in RHIC depends strongly on the bunch intensity. A simple scaling law can be derived from the fact that cooling rate and intrabeam scattering (IBS) growth rate counterbalance each other in the equilibrium.

With the cooling rate scaling with the bunch intensity as

$$\tau_{\rm cool}^{-1} \propto \frac{1}{N} \tag{1}$$

and the IBS emittance growth rate scaling as

$$\tau_{\rm IBS}^{-1} \propto \frac{N}{\epsilon_\perp^2 \epsilon_{\rm L}}, \tag{2}$$

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Table 1: Double-Gaussian Fit Parameters for the Energy Deposition for Two Different Beam Emittances

emittance [πmm mrad]	4	8
bunch intensity 10^9	0.7	1.6
A_1 [MeV/cm^3]	$43.0 \cdot 10^{13}$	$66.8 \cdot 10^{13}$
σ_1 [mm]	0.51	0.62
A_2 [MeV/cm^3]	$0.77 \cdot 10^{13}$	$1.74 \cdot 10^{13}$
σ_2 [mm]	5.25	5.26

where $\epsilon_\perp$ and $\epsilon_{\rm L}$ are the transverse and longitudinal emittances, respectively, the transverse emittance is therefore proportional to the bunch intensity [3]

$$\epsilon_\perp \propto N \tag{3}$$

for a constant longitudinal emittance $\epsilon_{\rm L}$. This scaling rule agrees well with simulation results that show a transverse equilibrium normalized 95 percent emittance of 4πmm mrad for $0.7 \cdot 10^9$ Au ions/bunch, and 8πmm mrad for $1.6 \cdot 10^9$ Au ions/bunch [3].

The interaction of a single incoming bunch with the C-C carbon block and the resulting energy deposition is simulated using the code MCNPX [4]. Nuclear interaction and multiple scattering in the C-C carbon block widens the distribution and reduces the peak intensity of the round Gaussian beam, while at the same time producing significant non-Gaussian tails. The resulting distribution is described by a double-Gaussian fit as

$$\rho(r) = A_1 \exp\left(-\frac{r^2}{2\sigma_1^2}\right) + A_2 \exp\left(-\frac{r^2}{2\sigma_2^2}\right), \tag{4}$$

where r is the radial particle coordinate, and A_1, A_2 and σ_1, σ_2 are the normalized amplitudes and RMS widths of the double-Gaussian distribution. Table 1 lists the double-Gaussian fit parameters for two different emittances. Together with the abort kicker pulse shape, the spatial energy distribution on the abort kicker window for the entire 111 bunches can then be calculated.

MECHANICAL AND THERMAL STRESS IN THE WINDOW

The RHIC beam dump system aborts the beam by applying a horizontal kick. The pulse shape of these abort kickers is designed such that after an initial fast rise that kicks the first bunch across the septum, the remaining bunches are spread out in a straight line by an oscillatory behavior of the kick, as shown in Figure 1.

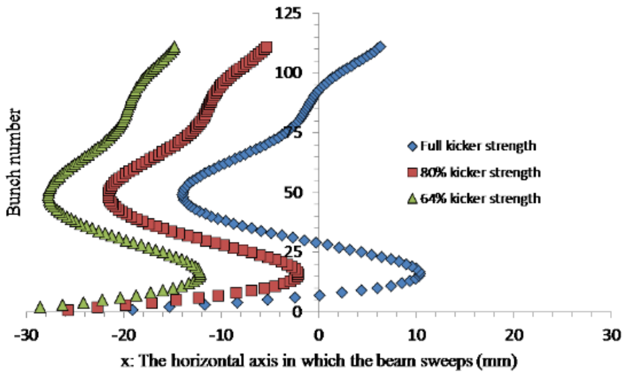

Figure 1: Kicker pulses for full kicker strength, and reduced strengths of 80 and 64 percent.

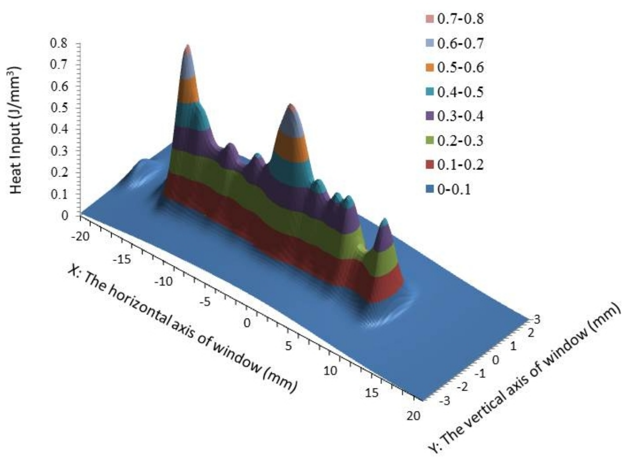

Figure 2: Heat input of 111 bunches of $0.7 \cdot 10^9$ Au ions on the beam dump window, assuming a 95 percent normalized emittance of 4π mm mrad.

This oscillating kick results in several distinct hot spots on the window surface where bunches are dumped in close vicinity due to the near-zero slope of the kicker pulse at its minima and maxima. Figure 2 shows the heat input for 111 gold bunches with a bunch intensity of $0.7 \cdot 10^9$ Au ions/bunch and a 95 percent normalized emittance of 4π mm mrad on the existing steel dump window. Table 2 lists the material properties for the 17-7 PH steel used for the RHIC abort window.

In the numerical analysis of the mechanical and thermal stress in the window we require a safety factor of two. An analysis of the heat deposition in the window reveals that at a 95 percent normalized emittance of 4π mm mrad a maximum bunch intensity of $0.7 \cdot 10^9$ gold ions per bunch is allowable. In this case, the maximum stress reaches half the yield stress of the present 17-7 PH steel window [5]. The success of the stochastic cooling effort results in emittances of 8π mm mrad at bunch intensities of $1.6 \cdot 10^9$. This will shrink the safety margin for the window below an acceptable level, so the beam dump system needs to be upgraded in the near future.

Table 2: Material Properties of 17-7 PH Stainless Steel and of Titanium 6242 Alloy

	steel 17-7 PH	Ti 6242
elastic modulus [GPa]	197	115
Poisson's ratio	0.29	0.32
yield stress [MPa]	940	960
ultimate stress [MPa]	1289	1016
therm. cond. $[\mathrm{W/m \cdot K}]$ (100°C)	16.4	7.1
therm. cond. $[\mathrm{W/m \cdot K}]$ (500°C)	21.8	
therm. exp. coeff. $[\mu\mathrm{m/(m \cdot K)}]$	12	8.1
specific heat $[\mathrm{J/(kg \cdot K)}]$	460	460
melting point [°C]	1400	1700
density $\mathrm{kg/m^3}$	7800	4540

UPGRADE SCENARIOS

To increase the allowable beam intensity at the reduced emittances, two possible upgrade scenarios are being considered. The first scenario involves replacing the 17-7 PH steel window with a different material, while in the second scenario a vertical kicker would be added to increase the spacing between individual bunches in the hot spots on the window surface. Both scenarios have been evaluated for two consistent combinations of intensities and emittances, namely $0.7 \cdot 10^9$ Au ions/bunch at a normalized 95 percent emittance of 4π mm mrad, and $1.6 \cdot 10^9$ Au ions/bunch at 8π mm mrad.

Window Replacement

Replacing the existing window with a high strength titanium 6242 alloy (see Table 2) raises the safety factor from 1.35 to 2.65 for a bunch intensity of $1.6 \cdot 10^9$ Au ions/bunch and the associated normalized emittance of 8π mm mrad, while at a low intensity of $0.7 \cdot 10^9$ Au ions/bunch and an emittance of 4π mm mrad the safety factor of two is exceeded even with the existing window, as listed in Table 3. Based on these results, the safety factor is expected to remain greater than two for intensities up to $2.1 \cdot 10^9$ Au ions/bunch with a corresponding normalized emittance of 10π mm mrad,

Vertical Kicker

To dilute the hot spots on the window, a vertical kicker may be added. The pulse waveform of this kicker needs to be chosen such that the vertical kicker pulse has its greatest slope at times when the slope of the horizontal kickers is near zero. A larger vertical kick amplitude results in a greater spread of the individual bunches on the window and therefore a lower heat load, which increases the safety factor for a given intensity and emittance. However, bunches that experience kicks near the minima and maxima of the sinusoidal vertical kicker pulse hit the window at a different vertical position, but their distance relative to each other is unchanged. The dependence of the resulting safety factor on the amplitude of the vertical kicker pulse is therefore

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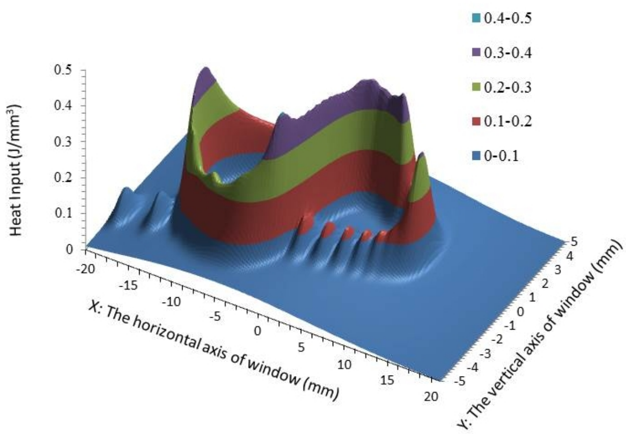

Figure 3: Heat input of 111 bunches of $0.7 \cdot 10^9$ Au ions with an emittance of 4π mm mrad on the beam dump window, with an additional vertical kicker.

Table 3: Safety Factor for the Various Abort System Configurations, for Two Different Beam Intensities. A minimum safety factor of 2 is required for safe operation of the RHIC abort system.

emittance [πmm mrad]	intensity [10^9]	steel 17-7 PH	Ti 6242	steel 17-7 PH and vertical kicker
8	1.6	1.35	2.65	2.47
4	0.7	2.80	5.11	4.88

nonlinear, and the gain increase is reduced at larger amplitudes. At the same time, achieving large kicker amplitudes is costly due to the required high kicker currents and voltages. For these reasons, the maximum vertical kick angle is chosen as 164 μrad, which corresponds to an orbit amplitude of 3 mm at the window. Table 4 shows lists the design paramters of such a kicker.

Simulations show that the lowest peak heat deposition is achieved by adding a vertical kicker with a cosine-like pulse shape of 8 μsec period, delayed by 2.64 μsec w.r.t. the horizontal kicker pulse. Figure 3 shows the resulting heat input distribution for a $4\,\pi$ mm mrad beam with $0.7 \cdot 10^9$ Au ions per bunch in 111 bunches. In this case, the safety factor for the 17-7 PH steel window is significantly raised, Table 3, and a bunch intensity of $2.0 \cdot 10^9$ Au ions/bunch in 111 bunches at a corresponding emittance of $10\,\pi$ mm mrad becomes feasible.

Table 4: Parameters of the Vertical Kicker Assembly

Total length [m]	1.83
Number of modules	3
Deflection angle peak-to-peak [mrad]	0.328
Au beam energy [GeV/n]	100
Integrated field [Tm]	0.28
Magnetic field strength [T]	0.152
Magnet current peak-to-peak [A]	6161
Voltage [kV]	5
Sine wave period [μsec]	8.0
Beam duration [μsec]	11.7

SUMMARY

We have investigated two scenarios to upgrade the RHIC beam dump system for higher heavy ion beam intensities, which is currently limited by mechanical and thermal stress in the stainless steel exit window. Replacing the existing window with a titanium alloy window would allow maximum bunch intensities of $2.1 \cdot 10^9$ Au ions per bunch in 111 bunches.

Alternatively, additional abort kickers could be installed that spread the aborted beam in the vertical direction, thus reducing the peak energy deposition in the window. A preliminary design of this kicker has been developed, which would allow for a maximum bunch intensity of $2.0 \cdot 10^9$ Au ions per bunch in 111 bunches.

While both scenarios result in very similar improvements of the RHIC beam dump system, replacing the exit window is significantly cheaper than adding a vertical kicker, though also very labor intensive. As an additional advantage, a window upgrade is inherently more fail-safe than an additonal vertical kicker since it is a passive system.

Based on these studies and considerations it has therefore been decided to replace the exit window with a titanium alloy one. A vertical kicker can then still be added in the future should the need arise.

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