



BNL-101943-2014-TECH

AD/RHIC/31;BNL-101943-2013-IR

RHIC Performance Limitations Due to Beam Heating of Vacuum Chamber

H. Hahn

December 1987

Collider Accelerator Department
Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

Notice: This technical note has been authored by employees of Brookhaven Science Associates, LLC under Contract No. DE-AC02-76CH00016 with the U.S. Department of Energy. The publisher by accepting the technical note for publication acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this technical note, or allow others to do so, for United States Government purposes.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Accelerator Development Department
BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.
Upton, New York 11973

AD/RHIC-31

RHIC TECHNICAL NOTE No. 31

RHIC PERFORMANCE LIMITATIONS DUE TO BEAM HEATING
OF VACUUM CHAMBER

H. Hahn

December 31, 1987

RHIC Performance Limitations Due to Beam Heating
of Vacuum Chamber

H. Hahn

Introduction

Beam heating due to the wall resistance has been the reason for requiring copper-plated cold-bore vacuum chambers in the SSC and HERA magnets. The Conceptual Design Report of RHIC, in contrast, assumes a stainless steel vacuum chamber. Estimates of the resistive wall heating indicated that stainless steel beam tubes are adequate, with considerable margin, for the nominal RHIC design numbers. However, the desire to provide room for future performance upgrades, in particular higher luminosities and shorter bunches, requires a review of the choice regarding stainless/copper-plated beam tubes. Whereas most other technical components allow modification without great financial penalties, the beam tube of a superconducting magnet system is quasi-permanent. In this note, an estimate of the limitations on beam intensity (and consequently luminosity) due to beam heating of stainless steel vacuum chambers are presented.

Wall Heating Estimates

Estimates of the resistive wall heating are obtained from the expression given in Appendix I. The power per unit length of the beam tube depends on beam and beam tube parameters according to the scaling law^{1,2,3}

$$P' \propto \frac{M (N_B Q)^2}{b R \sigma_\ell^{3/2} \sigma^{1/2}}$$

¹A. Piwinski, DESY Report DESY 72/72 (1972).

²Report SSC-SR-2020, p. 177 (1986).

³A. G. Ruggiero, BNL Report AD/RHIC-AP-48 (1987).

where

$$\begin{aligned} R &= \text{machine radius} \\ b &= \text{vacuum chamber radius} \\ M &= \text{number of bunches/ring} \\ N_B &= \text{number of ions/bunch} \\ \sigma_\ell &= \text{rms bunch length} \\ \sigma &= \text{wall conductivity} \\ Q &= \text{charge of ion} \\ Z_0 &= c \mu_0 \end{aligned}$$

The rms bunch length is related to the bunch area in longitudinal phase space and the rf parameters as shown in Appendix II. The bunch area is determined by the injector ($S = 0.3 \text{ eV}\cdot\text{sec}/u$ for Au and $1 \text{ eV}\cdot\text{sec}$ for p beams). The desire to operate with smallest diamond length makes it imperative to retain the injector bunch area during the injection and acceleration phases and avoid manipulations which would lengthen the bunch and reduce wall heating.

Estimates of the coil temperature increase in dipole magnets due to resistive wall heating have been made by Shutt and Wu.⁴ The estimated steady-state temperature rise of the coil end where the helium exits is about 0.04 K/W and the resulting reduction of the quench field is about 0.9 T/W .⁵ Heat generated in the beam tube is assumed to be removed mostly by the helium flowing in the coil passages with only negligible heat being conducted through the iron yoke into the helium bypass. A further approximation is made by neglecting the heat capacity of the coil compared to the helium in the coil. Ignoring the axial extent of the coil, the temperature rise of the coil is then given by

$$\frac{d\theta}{dt} + \frac{\dot{m}}{m} \theta = \frac{P_d}{C m}$$

where

$$\begin{aligned} P_d &= \text{wall heating/dipole} \\ m &= \text{stored helium mass in coil } (\sim 400 \text{ g}) \\ \dot{m} &= \text{helium flow in coil } (7\text{-}8 \text{ g/sec}) \\ C &= \text{specific heat of supercritical He at } 4.5 \text{ K and } 5 \text{ atm } (3.5 \text{ Jg}^{-1}\text{K}^{-1}) \end{aligned}$$

⁴K. C. Wu, private communication (1987).

⁵G. H. Morgan, private communication (1987).

The time constant with which the steady state temperature is reached follows from

$$\tau_{\theta} = m/\dot{m}$$

to be about 1 min. Heating of the coil is a relatively fast process when compared to the total beam storage time but it must be compared to bunch length growth by beam diffusion, in particular due to intrabeam scattering, in order to determine if these temperatures are actually reached.

The diffusion rates due to intrabeam scattering are above the transition energy given by the approximate formulae⁶

$$\tau_E^{-1} = \frac{1}{\delta_E} \frac{d\delta_E}{dt} = \left[\frac{\langle \sigma_H \rangle}{\langle X_P \rangle \delta_E} \right]^2 \tau_H^{-1}$$

with

$$\tau_H^{-1} = \frac{27\pi}{2} L_g r_p^2 E_o \frac{N_B}{S \epsilon_H \epsilon_v} \frac{\langle X_P \rangle}{\langle \beta \rangle} \frac{1}{\left[1 + \left[\frac{\langle \sigma_H \rangle}{\langle X_P \rangle \delta_E} \right]^2 \right]^{1/2}} \left[\frac{Q^2}{A} \right]^2$$

where

$$L_g \approx 20$$

$$r_p = \frac{\mu_o e^2 c^2}{4\pi E_o}$$

$$\langle \sigma_H \rangle = \left[\frac{\epsilon_H}{6\pi} \frac{\langle \beta \rangle}{\gamma} \right]^{1/2}$$

S = bunch area

$\epsilon_{H,v}$ = normalized transverse emittance

$\langle X_P \rangle$ = averaged dispersion

$\langle \beta \rangle$ = averaged betatron function

⁶G. Parzen, Nucl. Instr. Methods, A256, p. 231 (1987).

The initial diffusion times are at top energy $\tau_E > 160$ min for protons ($\epsilon = 20\pi \times 10^{-6}$ m) and $\tau_E > 1$ min for gold ($\epsilon = 10\pi \times 10^{-6}$ m). It follows that in the case of proton beams, the temperature increases at a faster rate than the resistive heating decreases due to bunch lengthening from intrabeam scattering. In the case of high-intensity gold beams ($2-3 \times$ CDR values), heating and bunch lengthening have comparable time constants, and the temperature rise of the coil is likely to be smaller than calculated. However, if intrabeam scattering is counteracted by stochastic cooling, full heating of the dipole coil is to be expected.

Intensity and Luminosity Limitations

The wall heating estimates for various gold and proton operation conditions are given in Tables I and II. Also shown is the maximum number of ions per bunch assuming a 2W/dipole wall heating limit. Although no hard limit on the tolerable wall heating exists, it would seem that this value is acceptable. A wall heating of 2 W/dipole has to be compared with the total 3.5 W/dipole heat load allowance due to other sources. It is to be noted that heating of the beam tube (as well as beam radiation) is likely to increase the coil temperature directly whereas all other heat loads have only a broad impact on the cryogenic system.

The nominal design beam intensities are initially, i.e., without diffusion due to intrabeam scattering, at the beam-beam limit given by a tuneshift of $\nu_{BB} \approx 3 \times 10^{-3}$. At higher intensities, the luminosity in the beam-beam limit is given by

$$L_{BB} = \frac{c}{2\pi r_p} \frac{\gamma M N_B}{R} \frac{A}{Q^2} \frac{\Delta\nu_{BB}}{\beta^*}$$

The estimated limits on luminosity due to resistive wall heating are given in Tables I and II.

Resistive heating of a copper-plated beam tube is reduced by a factor of about 30 ($\sigma_{Cu} = 1.8 \times 10^9 / \Omega m$ versus $\sigma_{ss} = 2 \times 10^6 / \Omega m$) and thus for all practical considerations negligible. The skin depth at the bunch frequency ($M = 57$)

$$f_B = \frac{c M}{2\pi R} = 4.46 \text{ MHz}$$

follows to be

$$\delta = (\mu_0 \pi f_B \sigma)^{-1/2} = 5.6 \mu\text{m}$$

A 12-24 μm (0.5-1 mil) thick copperplating would thus seem sufficient to eliminate wall heating. Stresses and deflections during quenches in RHIC dipoles were calculated by Shutt⁷ who concluded that 1 mil plating is acceptable.

In summary, copperplating of the beam tube is recommended in order not to limit future RHIC performance improvements. The possibility of copperplating requires additional R&D efforts and it will increase construction cost. An acceptable compromise to minimize cost would be to copperplate dipole beam tubes only. Quadrupoles without copperplating may also be advantageous for the fast gamma-transition jump.

⁷R. P. Shutt, BNL Report RHIC-MD-63 (1987)

TABLE I. Wall Heating in RHIC (Gold operation)

	Nominal Design		Wall Heat Limits			
Energy, E	11.6	100	100	100	100	GeV/u
# ions/bunch, N_B	1.2	1.1	4	2.4	2.2	$\times 10^9$
Harmonic, h	342	342	342	342	684	
rf voltage, V	0.21	1.2	1.2	2.4	2.4	MV
Bunch area, S	0.3	0.3	0.3	0.3	0.3	eV \cdot sec/u
rms bunch length, σ_ℓ	0.99	0.27	0.27	0.22	0.19	m
Peak current, I_p	1.68	6.18	22.4	15.7	17.5	A
# bunches, M	57	57	57	114	114	
Wallheat/dipole @ ss	0.02	0.15	2.0	2.0	2.0	W
Wallheat/dipole @ Cu	0.7	0.5	67	66	69	mW
Intrabeam scattering τ_E		2.1	0.5	1.1	1.5	min
Maximum Luminosity, L_{BB}		1.1	3.9	4.7	4.3×10^{27}	$\text{cm}^{-2} \text{sec}^{-1}$

TABLE II. Wall Heating in RHIC (proton operation)

	Nominal Design		Wall Heat Limits		
Energy, E	29.5	250	250	250	250 GeV
# ions/bunch, N_B	1.0	1.0	3.5	2.2	2.0×10^{11}
Harmonic, h	342	342	342	342	684
rf voltage, V	0.0165	1.2	1.2	2.4	2.4 MV
Bunch area, S	1.0	1.0	1.0	1.0	1.0 eV·sec
rms bunch length, σ_ℓ	1.32	0.31	0.31	0.26	0.23 m
Peak current, I_p	1.45	6.18	21.6	16.2	16.7 A
# bunches, M	57	57	57	114	114
Wallheat/dipole @ ss	0.02	0.16	2	2	2 W
Wallheat/dipole @ Cu	0.6	5.4	67	68	68 mW
Intrabeam scattering τ_E		410	110	220	290 min
Maximum Luminosity, L_{BB}		0.8	2.7	3.4	$3.1 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$

APPENDIX I. RESISTIVE WALL HEATING

RESISTIVE WALL HEATING PER RING

$$P = \frac{\Gamma(3/4)}{2\pi} \frac{M}{b} I_p^2 \left[\frac{Z_o \sigma_\ell}{2\sigma} \right]^{1/2}$$

WALL HEATING PER UNIT LENGTH

$$P' = \frac{\Gamma(3/4)}{2\pi} \left[\frac{M \sigma_\ell}{R} \right]^{1/2} R_M I_p^2$$

WITH PEAK CURRENT

$$I_p = \frac{ec}{(2\pi)^{1/2}} \frac{Q N_B}{\sigma_\ell}$$

WALL RESISTANCE PER UNIT LENGTH

$$R_M = \frac{1}{2\pi b} \left[\frac{Z_o M}{2 \sigma R} \right]^{1/2}$$

AND

- R = machine radius
- b = vacuum chamber radius
- M = number of bunches/ring
- N_B = number of ions/bunch
- σ_ℓ = rms bunch length
- σ = wall conductivity
- Q = charge of ion.
- Z_o = $c\mu_o$

APPENDIX II. RF BUCKET AND LONGITUDINAL BUNCH PARAMETERS

BUCKET HALF HEIGHT $\Delta_B = \left[\frac{2 e V}{\pi h |\eta| \gamma E_o} \frac{Q}{A} \right]^{1/2}$

BUCKET AREA/AMU $A_B = 8 \Delta_B \frac{\gamma E_o}{h \omega_o}$

BUNCH PHASE HALF WIDTH $0 < \phi < \pi$

COLE-MORTON: $N = \sin^2 \phi/2$

RMS BUNCH LENGTH $\sigma_l = \frac{1}{\sqrt{6}} \frac{R}{h} \phi$

RMS BUNCH HEIGHT $\delta_E = \frac{1}{\sqrt{6}} \Delta_B \sin \phi/2$

BUNCH AREA/AMU $S = A_B \left\{ (N-1) K(N) + E(N) \right\}$

$$\approx 6 \pi \sigma_l \delta_E \gamma E_o / c$$