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Collider Vacuum Requirements

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COLLIDER VACUUM REQUIREMENTS

1. Atomic charge Exchange
2. Nuclear Reaction (Beam-Gas) Background

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(BNL, December 5, 1983)

RHIC-BG-

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Vacuum Requirements in Collider Rings Resulting from Atomic Charge Exchange

We want to know the fractional loss in beam intensity

$$\eta = \frac{I}{I_0} = e^{-\sigma_T l n_0 P}$$

where σ_T = total charge exchange cross section for the ion of interest
l = path length = $\beta c t$, t the storage time
n_0 = atoms / cm^3 at 1 torr and the temperature of the vacuum (cold $\equiv 4°K$, warm $\equiv 295°K$)
P = residual gas pressure in torr

(As the cross sections available are given per atom, we will need to convert the usual molecular number densities to atomic number densities. This involves no change for He, but a change $\times 2$ for H_2, O_2, CO, N_2 and $\times 3$ for CO_2, H_2O. The cross sections also depend on Z of the gas, so we do the necessary weighting.)

From $PV = nkT$, we have

$$n_0 = \frac{6.02 \times 10^{23}}{22.4 \times 10^3 \text{ cm}^3} \times \frac{273}{295} \times \frac{1}{760} = 3.27 \times 10^{16} \frac{\text{molecules}}{\text{cm}^3 \cdot \text{torr}} \quad (\underline{\text{warm}})$$

$$n_0 = \frac{6.02 \times 10^{23}}{22.4 \times 10^3 \text{ cm}^3} \times \frac{273}{4} \frac{1}{760} = 2.41 \times 10^{18} \frac{\text{molecules}}{\text{cm}^3 \cdot \text{torr}} \quad (\underline{\text{cold}})$$

We tabulate $\tau_B = (\sigma_T \beta c n_0 P)^{-1}$, the time for the beam to decay to $e^{-1} = 0.368$ of it's intensity at injection, or the time for luminosity to decay to $e^{-2} = 0.135$ of its original value.

Since no relativistic heavy ion accelerators exist, with the exception of the LBL Bevalac and the JINR Synchrophasotron, cross sections for charge exchange for relativistic heavy ions are scarce. The Synchrophasotron has no injector for very heavy ions, so the only results come from LBL's Bevalac.

There is one recent result for single electron capture by U^{92+} and U^{91+} and single electron loss for U^{90+} and U^{91+} ~~by~~, at energies of 437 MeV/A and 962 MeV/A, by LBL staff (H. Gould, D. Greiner, P. Lindstrom, TJM Symons and H. Crawford, LBL-16467 (preprint)) Targets of Mylar ($C_5H_4O_2$, $Z_T \sim 6.6$) Copper ($Z_T = 29$) and tantalum ($Z = 73$) were used to check the Z_{Target} dependence of the cross sections.

As the collider only will contain fully stripped heavy ions, we only need the cross section for electron capture. We must allow K, L, M, ... shell capture of one or multiple electrons. Multiple electron capture cross sections get to be as large as 15% - 30% for heavy ions of high charge state and low velocity ($\beta \lesssim 0.15$), but this cross section decreases more rapidly with β than does the single capture cross section (See H. D. Betz, Reviews of Modern Physics, 44, 465 (1972), and, J. Alonso and H. Gould, Phys Rev A 26, 1134 (1982))

It is possible to relate the radiative capture process of a single electron to the ionization process of photoelectric absorption via the principle of detailed balance, as

$$h\nu + \text{ion} \rightleftharpoons e^- + \text{ion} .$$

The process of non radiative capture (non radiative charge exchange) is not included in this, but present calculations from hydrogenlike targets find a strong dependence on Z_{target}. For small Z_T, these values are much smaller than the radiative electron capture cross sections; in high Z_T material they are somewhat larger. As residual gas in the collider will be (eg) H_2, He, CO, H_2O etc, this process can be neglected. (See R. Shakeshaft, Phys Rev A 20, 779 (1979); BL Moiseiwitsch and SG Stockman J Phys B 13, 2975 (1980) and B13, 4031 (1980); DH Jakubaßa-Amundsen and PA Amundsen, Z Physick A 298, 13 (1980).)

For photons from $100\,\text{keV} < h\nu < 5\,\text{MeV}$, the photoelectric cross section for a nucleus of charge Z is well approximated by

$$\sigma_{pe} \sim 1.2 \times 10^{-32}\, f\, Z^{4.4}\, \frac{(h\nu + 2m_ec^2)^2\, m_ec^2}{(h\nu)^3} \quad \text{cm}^2$$

where f is the fraction of the K shell that is filled. The coefficient 1.2 accounts for L, M, ... shell ionization in addition to K shell ionization. Since the photon energy is related to the electron mass by

$$h\nu = (\gamma - 1)\, m_ec^2 + B_K \qquad B_K \text{ the K shell binding energy},$$

$\gamma = (1-\beta^2)^{-1/2}$, this approximation works at least to 10 GeV/A heavy ions; this gives an upper limit for the rest of the collider range, as σ_{pe} will continue to drop with increasing γ.

Detailed balance gives $\sigma_{capture} = \dfrac{(h\nu)^2}{(h\nu - B_K + m_ec^2)^2 - (m_ec^2)^2} \times \sigma_\phi \quad \text{cm}^2$

where X is the ratio of statistical weights. Thus using

$$\gamma = \frac{h\nu - B_K + m_e c^2}{m_e c^2},$$ we have

$$\sigma_{capture} \sim 1.2 \times 10^{-32} \; Xf \; Z^{4.4} \frac{(\gamma + 1 + B_K/m_e c^2)^2}{(\gamma^2 - 1)(\gamma - 1 + B_K/m_e c^2)} \; cm^2$$

where $Xf = 1$ for capture into an empty K shell ie capture by a bare heavy ion. (See P H Fowler et al, Proc Roy. Soc London A318, 1–43 (1970))

The values for B_K are, for our six standard nuclei, plus U, (AIP handbook, 3rd edition pp 7-158 to 7-166)

ion	B_K (keV)
$_1H$	0.013598
$_6C$	0.2838
$_{16}S$	2.472
$_{29}Cu$	8.9789
$_{53}I$	33.1694
$_{79}Au$	80.7249
$_{92}U$	115.6061

The cross section in a material of nuclear charge Z_T is then

$$\sigma_{capture, Z_T} = Z_T \, \sigma_{capture} .$$

In the first figure, we calculate values for 437 MeV/A and 962 MeV/A U^{92+} and compare to the results of Gould et al from the Bevalac. (We read values from their graph)

Z_T	E/A (MeV/A)	γ	$h\nu$ (keV)	calculated $\sigma_{capture}$ (barns)	measured $\sigma_{capture}$ (barns)
6.6	437	1.469	355	312.4	132^{+118}_{-65}
29	"	"	"	1372.8	2737^{+2700}_{-1300}
73	"	"	"	3455.7	—
6.6	962	2.033	643	93.2	57^{+57}_{-28}
29	"	"	"	409.6	474^{+400}_{-250}
73	"	"	"	1031.2	1654^{+1400}_{-880}

The errors on the measured cross sections are worse than normal; however, 'normal' for such measurements is ~25% fitting error to measured charge state distributions, and ~20% systematic (usually due to gas target thickness).

In the following we list values of $\sigma_{capture}$ for our standard nuclei, for kinetic energies of 5, 10, 20, 50 and 100 GeV/A, for targets of H, He, C, N and O. (Z_T= 1, 2, 6, 7, 8)

$\boxed{\sigma_{capture}}$ vs γ

Carbon, $Z=6$; $B_K = 0.2838$ keV

T/A	γ	$\sigma_{capture}$ (barns) H	He	C	N	O
5	6.37	8.1×10^{-6}	$1.6\ 10^{-5}$	$4.8\ 10^{-5}$	$5.7\ 10^{-5}$	$6.5\ 10^{-5}$
10	11.74	$3.5\ 10^{-6}$	$7\ 10^{-6}$	$2.1\ 10^{-5}$	$2.5\ 10^{-6}$	$2.8\ 10^{-5}$
20	22.47	$1.6\ 10^{-6}$	$3.2\ 10^{-6}$	$9.7\ 10^{-6}$	$1.1\ 10^{-5}$	$1.3\ 10^{-5}$
50	54.68	$6.2\ 10^{-7}$	$1.2\ 10^{-6}$	$3.7\ 10^{-6}$	$4.3\ 10^{-6}$	$4.9\ 10^{-6}$
100	108.4	$3.0\ 10^{-7}$	$6\ 10^{-7}$	$1.8\ 10^{-6}$	$2.1\ 10^{-6}$	$2.4\ 10^{-6}$
1	2.074	$8.5\ 10^{-5}$	$1.7\ 10^{-4}$	$5.1\ 10^{-4}$	$5.9\ 10^{-4}$	$6.8\ 10^{-4}$

Negligible compared to nuclear scattering from the gas

Sulfur, $Z=16$; $B_K = 2.472$ keV

T/A	γ	$\sigma_{capture}$ (barns) H	He	C	N	O
5	6.37	$6.1\ 10^{-4}$	$1.2\ 10^{-3}$	$3.6\ 10^{-3}$	$4.3\ 10^{-3}$	$4.9\ 10^{-3}$
10	11.74	$2.6\ 10^{-4}$	$5.2\ 10^{-4}$	$1.6\ 10^{-3}$	$1.8\ 10^{-3}$	$2.1\ 10^{-3}$
20	22.47	$1.2\ 10^{-4}$	$2.4\ 10^{-4}$	$7.2\ 10^{-4}$	$8.4\ 10^{-4}$	$9.6\ 10^{-4}$
50	54.68	$4.6\ 10^{-5}$	$9.2\ 10^{-5}$	$2.8\ 10^{-4}$	$3.2\ 10^{-4}$	$3.7\ 10^{-4}$
100	108.4	$2.2\ 10^{-5}$	$4.4\ 10^{-5}$	$1.3\ 10^{-4}$	$1.5\ 10^{-4}$	$1.8\ 10^{-4}$
1	2.074	$6.3\ 10^{-3}$	$1.3\ 10^{-2}$	$3.8\ 10^{-2}$	$4.4\ 10^{-2}$	$5.1\ 10^{-2}$

Negligible compared to nuclear scattering from the gas

Copper, $Z=29$; $B_K = 8.9789$ keV

T/A	γ	$\sigma_{capture}$ (barns) H	He	C	N	O
5	6.37	$8.3\ 10^{-3}$	$1.6\ 10^{-2}$	$4.8\ 10^{-2}$	$5.8\ 10^{-2}$	$6.6\ 10^{-2}$
10	11.74	$3.6\ 10^{-3}$	$7.2\ 10^{-3}$	$2.1\ 10^{-2}$	$2.5\ 10^{-2}$	$2.9\ 10^{-2}$
20	22.47	$1.6\ 10^{-3}$	$3.2\ 10^{-3}$	$9.6\ 10^{-3}$	$1.1\ 10^{-2}$	$1.3\ 10^{-2}$
50	54.68	$6.4\ 10^{-4}$	$1.2\ 10^{-4}$	$3.6\ 10^{-3}$	$4.5\ 10^{-3}$	$5.1\ 10^{-3}$
100	108.4	$3.1\ 10^{-4}$	$6.2\ 10^{-4}$	$1.8\ 10^{-3}$	$2.2\ 10^{-3}$	$2.5\ 10^{-3}$
1	2.074	$8.7\ 10^{-2}$	0.17	0.52	0.60	0.69

Negligible compared to nuclear scattering from the gas

$\boxed{\sigma_{capture}}$ vs γ

Iodine, $Z = 53$ $B_K = 33.1694$ keV

T/A	γ	H	He	C	N	O
		$\sigma_{capture}$ (barns)				
5	6.37	0.12	0.24	0.72	0.84	0.96
10	11.74	0.051	0.10	0.30	0.35	0.41
20	22.47	0.024	0.048	0.144	0.17	0.19
50	54.68	0.0090	0.018	0.054	0.063	0.072
100	108.4	0.0044	0.0088	0.026	0.031	0.035
1	2.074	1.2	2.4	7.2	8.4	9.6

Gold, $Z = 79$ $B_K = 80.7249$ keV

T/A	γ	H	He	C	N	O
		$\sigma_{capture}$ (barns)				
5	6.37	0.70	1.4	4.2	4.9	5.6
10	11.74	0.30	0.6	1.8	2.1	2.4
20	22.47	0.14	0.27	0.82	0.96	1.1
50	54.68	0.052	0.10	0.31	0.36	0.42
100	108.4	0.025	0.05	0.15	0.175	0.20
1	2.074	6.9	13.8	41.4	48.2	55.1

Uranium, $Z = 92$ $B_K = 115.6061$ keV

T/A	γ	H	He	C	N	O
		$\sigma_{capture}$ (barns)				
5	6.37	1.37	2.7	8.2	9.6	10.9
10	11.74	0.59	1.2	3.5	4.1	4.7
20	22.47	0.27	0.54	1.6	1.9	2.2
50	54.68	0.10	0.20	0.61	0.71	0.81
100	108.4	0.05	0.10	0.30	0.35	0.4
1	2.074	13.3	26.6	79.9	93.2	106.5

As expected, gold (and uranium) are the worst cases; the cross section drops as 1/8 at high energy. These cross sections are so small we should consider adding the nuclear cross section to them. This will be roughly the geometric cross section, which can be found from

$$\sigma_{geom} = \pi (R_1 + R_2)^2 \text{ fm}^2 \sim \pi (1.25)^2 (A_1^{1/3} + A_2^{1/3})^2 \text{ fm}^2$$
$$= \frac{\pi}{100} (1.25)^2 (A_1^{1/3} + A_2^{1/3})^2 \text{ barns}$$
$$= 0.049 (A_1^{1/3} + A_2^{1/3})^2 \text{ barns}$$

For:

$^{12}C + H$	σ_{geom} = 0.53 barns		
$^{12}C + O$	1.14	C + C	1.03
$^{32}S + H$	0.86		
$^{32}S + O$	1.59	S + S	1.98
$^{63}Cu + H$	1.22		
$^{63}Cu + O$	2.07	Cu + Cu	3.11
$^{127}I + H$	1.78		
$^{127}I + O$	2.80	I + I	4.96
$^{197}Au + H$	2.28		
$^{197}Au + O$	3.41	Au + Au	6.65
$^{238}U + H$	2.54		
$^{238}U + O$	3.73	U + U	7.54

Below we tabulate $\tau_B = (\sigma_{capture} \cdot \beta \cdot c \cdot n_0 \cdot P)^{-1}$ in hours for C, S, Cu, I and Au at 1 and 5 GeV/amu. For warm vacuums we take 40% H_2 and 60% CO_2 (change this as you wish) and $P = 10^{-8}, 10^{-9}, 10^{-10}$ torr. For cold vacuum, use 50% H_2 + 50% He and $P = 10^{-9}, 10^{-10}$ and 10^{-12}. We calculate τ_B for ($\sigma_{capture}$) and ($\sigma_{capture} + \sigma_{geometrical}$) i.e. include nuclear cross section.

Warm ($n_0 = 3.27 \times 10^{16}$ $\frac{\text{molecules}}{\text{cm}^2 \cdot \text{torr}}$) $\boxed{\tau_B \text{ (hours)}}$

		$\sigma_{capture}$			$\sigma_{capture} + \sigma_{geometrical}$		
Ion	T/A	10^{-8} torr	10^{-9}	10^{-10}	10^{-8}	10^{-9}	10^{-10}
C	1	2.4×10^4	2.4×10^5	2.4×10^6	11.8	118	1175
	5	2.5×10^5	2.5×10^6	2.5×10^7	11.8	118	1175
S	1	$3.2\ 10^2$	$3.2\ 10^3$	$3.2\ 10^4$	8.2	82	815
	5	$3.3\ 10^3$	$3.3\ 10^4$	$3.3\ 10^5$	8.2	82	815
Cu	1	23.4	234	2343	4.9	49	486
	5	$2.5\ 10^2$	$2.5\ 10^3$	$2.5\ 10^4$	6.0	60	599
I	1	1.68	16.9	169	1.22	12.2	122
	5	16.9	169	1687	3.52	35.2	352
Au	1	0.29	2.9	29.4	0.27	2.7	27.2
	5	2.9	28.9	289	1.61	16.1	160.5

For an all CO_2 residual gas, the Au values are:

Au	1	0.19	1.9	18.7	0.18	1.75	17.5
	5	1.84	18.4	184	1.1	11.1	111

For a mixture 90% H_2, 10% CO_2, the Au values are

Au	1	1.03	10.3	103	0.8[illegible]	8.7	86.7
	5	10.1	101	1012	3.58	35.8	358

Cold ($n_0 = 2.41 \times 10^{18}$ $\frac{\text{molecules}}{\text{cm}^3\ \text{torr}}$) $\boxed{\tau_B \text{ (hours)}}$

Ion	T/A	$\sigma_{capture}$ 10^{-9}	10^{-10}	10^{-11}	$\sigma_{capture} + \sigma_{geometrical}$ 10^{-9}	10^{-10}	10^{-11}
C	1	$2.26\ 10^4$	$2.26\ 10^5$	$2.26\ 10^6$	4.27	42.7	427
	5	$2.4\ 10^5$	$2.4\ 10^6$	$2.4\ 10^7$	4.27	42.7	427
S	1	$3.05\ 10^2$	$3.05\ 10^3$	$3.05\ 10^4$	2.72	27.2	272
	5	$3.2\ 10^3$	$3.2\ 10^4$	$3.2\ 10^5$	2.72	27.2	272
Cu	1	22.1	221	2210	1.78	17.8	178
	5	$2.32\ 10^2$	$2.32\ 10^3$	$2.32\ 10^4$	1.93	19.3	192.6
I	1	1.6	16.0	160	0.732	7.32	73.2
	5	16.0	160	1600	1.24	12.4	124
Au	1	0.28	2.79	27.9	0.221	2.21	22.1
	5	2.75	27.5	275	0.765	7.65	76.5

Apparently, if it is technically as easy to make 10^{-10} torr cold as it is to make 10^{-8} torr warm, then 10^{-10} torr cold is preferred. 10^{-9} torr warm would be better.

If we ask for $\tau_L = 1$ hour, so $\tau_B = 2$ hour, then for 5 GeV Au we need

warm	40% H_2 + 60% CO_2	$8.1\ 10^{-9}$ torr
	all CO_2	$5.5\ 10^{-9}$ torr
	90% H_2 + 10% CO_2	$1.8\ 10^{-8}$ torr
cold	50% H_2 + 50% He	$3.8\ 10^{-10}$ torr

Beam-Gas Background

A related vacuum problem is the beam-gas interaction in the crossing region. If the detector at a crossing is sensitive to all of a 20 meter length, and to all of the ~ 80 meters "upstream" of it along each beam (as the gas is a target in a 5-100 GeV fixed target experiment), then a (large in transverse size) detector sees most of the secondaries from this 20 m + 2 x 80 meter length. This is an effective target of $n_0 P l$ molecules/cm^2 areal density. For 6×10^8 particles per bunch, 57 bunches and a revolution frequency 78.1973 kHz we have a beam current 2.67×10^{15}/second. Using the nuclear geometrical cross sections, we find for gold: (use the $\tau_B = 2$ hr pressures)

Warm a) 40% H_2 + 60% CO_2, $8.1\ 10^{-9}$ torr $\langle \sigma_{geom} \rangle = 7.8$ barns/molecule

$$\text{Rate} = (n_0 P l)(I)\,\sigma$$
$$= (3.27 \times 10^{16}\ 8.1 \times 10^{-9}\ 1.8\ 10^4\,\text{cm})(2.67 \times 10^{15}/\text{s})(7.8\ 10^{-24}\,\text{cm}^2)$$
$$= 9.93 \times 10^4/\text{second}$$

b) all CO_2 $\langle \sigma_{geom} \rangle = 10.05$ barn $5.5\ 10^{-9}$ torr

$$\text{Rate} = 8.69 \times 10^4/\text{second}$$

c) 90% H_2, 10% CO_2 $\langle \sigma_{geom} \rangle = 5.11$ barn $1.8\ 10^{-8}$ torr

$$\text{Rate} = 1.45 \times 10^5/\text{second}$$

Cold 50% H_2, 50% He $\langle \sigma_{geom} \rangle = 3.63$ barn $3.8\ 10^{-10}$ torr

$n_0 = 2.41 \times 10^{18}$

$$\text{Rate} = 1.60 \times 10^5/\text{second}$$

These are to be compared to Au + Au, $\sigma = 6.7$ barns, $L = 10^{27}/\text{cm}^2\cdot\text{s}$

"Good" Rate $= L\sigma = 6.65 \times 10^3$/second

Thus, we must reduce all above pressures by ~50-100 so that the beam-gas rate is $< \frac{1}{4}$ the beam-beam rate!

If we work out the same numbers for carbon beams, we find

Warm a) 40% H_2 + 60% CO_2 $\langle\sigma_{geom}\rangle$ = 2.41 barn 8.1 10^{-9} torr
Rate = 3.07×10^4 /second

b) all CO_2 $\langle\sigma_{geom}\rangle$ = 3.31 5.5 10^{-9} torr
Rate = 2.86×10^4 /second

c) 90% H_2, 10% CO_2 $\langle\sigma_{geom}\rangle$ = 1.29 barn 1.8×10^{-8} torr
Rate = 3.65×10^4 /second

Cold 50% H_2, 50% He $\langle\sigma_{geom}\rangle$ = 0.9 3.8 10^{-10} torr
Rate = 3.96×10^4 /second

C+C σ_{geom} = 1.03 barns, so the true rate at $L = 10^{27}$ is
"Good" Rate = 1000 /second

So we need to decrease these pressures by $\sim \times 100 - 150$.
For carbon, we will likely have more current (particles/bunch) which helps, as (good rate / background rate) $\propto$ N/bunch.

If we require a beam-gas rate that is 10% of the beam beam rate, we need pressures

Warm (90% H_2, 10% CO_2) 40% H_2, 60% CO_2	C+C	4.9×10^{-11} torr 2.6×10^{-11} torr	Au+Au	8.2×10^{-11} torr 5.4×10^{-11} torr
Cold (50% H_2, 50% He)	C+C	9.6×10^{-13} torr	Au+Au	1.6×10^{-12} torr

These requirements can be relaxed if we can shield the detectors from the beam pipe away from the crossing point, or if this length could be reduced. Also, if experimenters feel they can allow a larger beam-gas background rate than ~10% of the true rate, these requirements can also be relaxed.

We note these vacuum requirements apply only to the crossing regions, and perhaps the last one or two cells of the arcs. The vacuum requirements in the arcs could still be the less stringent values given on page 10.

Stacking more beam current without increasing luminosity will aggravate this problem. Though it presently appears that lighter ions require lower pressures (an odd situation), the parameter used of 6×10^8 ions/bunch is probably too low for carbon, where both ion source performance at the tandem and space charge limits in the booster are increased.