

Collider Vacuum Requirements

G. R. Young

December 1983

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.

COLLIDER VACUUM REQUIREMENTS

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

G. R. YOUNG

(BNL, December 5, 1983)

Collider Vacuum Requirements

1) Atomic Charge Exchange

2) Nuclear Reaction (Beam-Gas)
Background

G. R. Young

(BNL, December 5, 1983)

12/5/83

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/cm³ at 1 torr and the temperature of the vacuum (cold $\equiv 4^\circ K$, warm $\equiv 295^\circ K$)
- 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 H₂, O₂, CO, N₂ and $\times 3$ for CO₂, H₂O. The cross sections also depend on Z of the gas, so we do the necessary weighting.)

From $PV = n k T$, we have

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

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

We tabulate $\tau_B = (\sigma_T \beta c n_0 P)^{-1}$, the time for the beam to

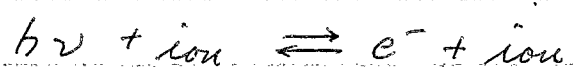
decay to $e^{-1} = 0.368$ of its intensity at injection, or the time for luminosity to decay to $e^{-2} = 0.135$ of its original value.

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, T. J. M. 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 ($\beta \leq 0.15$), 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 A26, 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



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); B L Moiseiwitsch and S G Stockman J Phys B 13, 2975 (1980) and B13, 4031 (1980); D H Jakuboba - Amundsen and P A Amundsen, Z Physik 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

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

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

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

$\gamma = (1 - \beta^2)^{-1/2}$, 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 .

$$\text{Detailed balance gives } \sigma_{\text{capture}} = \frac{(h\nu)^2}{(h\nu - B_K + m_e c^2)^2 - (m_e c^2)^2} \times \sigma_{\phi} \text{ cm}^2$$

where X is the ratio of statistical weights. Thus using

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

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

where $Xf = 1$ for capture into an empty K shell i.e. 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)
${}^1_1\text{H}$	0.013598
${}^6_6\text{C}$	0.2838
${}^{16}_{16}\text{S}$	2.472
${}^{29}_{29}\text{Cu}$	8.9789
${}^{53}_{53}\text{I}$	33.1694
${}^{79}_{79}\text{Au}$	80.7249
${}^{92}_{92}\text{U}$	115.6061

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

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

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 σ_{capture} (barns)	measured σ_{capture} (barns)
6.6	437	1.469	355	312.4	132 $\begin{matrix} +118 \\ -65 \end{matrix}$
29	"	"	"	1372.8	2737 $\begin{matrix} +2700 \\ -1300 \end{matrix}$
73	"	"	"	3455.7	—
6.6	962	2.033	643	93.2	57 $\begin{matrix} +57 \\ -28 \end{matrix}$
29	"	"	"	409.6	474 $\begin{matrix} +400 \\ -250 \end{matrix}$
73	"	"	"	1031.2	1654 $\begin{matrix} +1400 \\ -880 \end{matrix}$

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

In the following we list values of σ_{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. ($Z_T = 1, 2, 6, 7, 8$)

σ_{capture} vs γ

Carbon, $Z=6$; $B_K = 0.2838 \text{ keV}$

T/A	γ	σ _{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, $Z=16$; $B_K = 2.472 \text{ keV}$

T/A	γ	σ _{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, $Z=29$; $B_K = 8.9789 \text{ keV}$

T/A	γ	σ _{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

σ_{capture} vs γ

Iodine, $Z=53$ $B_K = 33,1694 \text{ keV}$

T/A	γ	σ_{capture} (barns)				
		H	He	C	N	O
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, $Z=79$ $B_K = 80.7249 \text{ keV}$

T/A	γ	σ_{capture} (barns)				
		H	He	C	N	O
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	6.4	13.8	41.4	48.2	55.1

Uranium, $Z=92$ $B_K = 115.6061 \text{ keV}$

T/A	γ	σ_{capture} (barns)				
		H	He	C	N	O
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

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

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

Below we tabulate $\tau_B = (\sigma_{\text{capture}} \cdot \beta \cdot c \cdot n_0 \cdot P)^{-1}$ in hours for C, S, Cu, I and Au at 1.5 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% $\text{H}_2 + 50\% \text{He}$ and $P = 10^{-9}, 10^{-10}$ and 10^{-12} . We calculate τ_B for $(\sigma_{\text{capture}})$ and $(\sigma_{\text{capture}} + \sigma_{\text{geometrical}})$ i.e. include nuclear cross section.

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

Ion	T/A	σ_{capture}			$\sigma_{\text{capture}} + \sigma_{\text{geometrical}}$		
		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	$3.2 \cdot 10^2$	$3.2 \cdot 10^3$	$3.2 \cdot 10^4$	8.2	82	815
	5	$3.3 \cdot 10^3$	$3.3 \cdot 10^4$	$3.3 \cdot 10^5$	8.2	82	815
Cu	1	23.4	234	2343	4.9	49	486
	5	$2.5 \cdot 10^2$	$2.5 \cdot 10^3$	$2.5 \cdot 10^4$	6.0	60	599
I	1	1.69	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	0.87	8.7	86.7
	5	10.1	101	1012	3.58	35.8	358

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/cm² 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 $T_B = 2$ hr pressures)

Warm a) 40% H₂, 60% CO₂, 8.1×10^{-9} torr $\langle \sigma_{geom} \rangle = 7.8$ barns/molecule

$$\begin{aligned} \text{Rate} &= (n_0 P l) (I) \sigma \\ &= (3.27 \times 10^{16} \text{ } 81 \times 10^{-9} \text{ } 1.8 \times 10^4 \text{ cm}) (2.67 \times 10^{15} / \text{s}) (7.8 \times 10^{-24} \text{ cm}^2) \\ &= 9.93 \times 10^4 / \text{second} \end{aligned}$$

b) all CO₂ $\langle \sigma_{geom} \rangle = 10.05$ barn 5.5×10^{-9} torr

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

c) 90% H₂, 10% CO₂ $\langle \sigma_{geom} \rangle = 5.11$ barn 1.8×10^{-8} torr

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

Cold 50% H₂, 50% He $\langle \sigma_{geom} \rangle = 3.63$ barn 3.8×10^{-10} torr

$$n_0 = 2.41 \times 10^{16}$$

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

These are to be compared to Au+Au, $\sigma = 6.7$ barns, $L = 10^{27} / \text{cm}^2 \cdot \text{s}$
 "Good" Rate = $L\sigma = 6.65 \times 10^3 / \text{second}$

Thus, we must reduce all above pressures by $\sim 50-100$ so that

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 $\sim 10\%$ 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.