VACUUM STUDIES FOR THE EIC HADRON RING

Time Dependent Residual Gas Density

Beam Lifetime and Emittance Growth due to Interactions with Residual Gas

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U.S. DEPARTMENT OF ENERGY | Office of Science

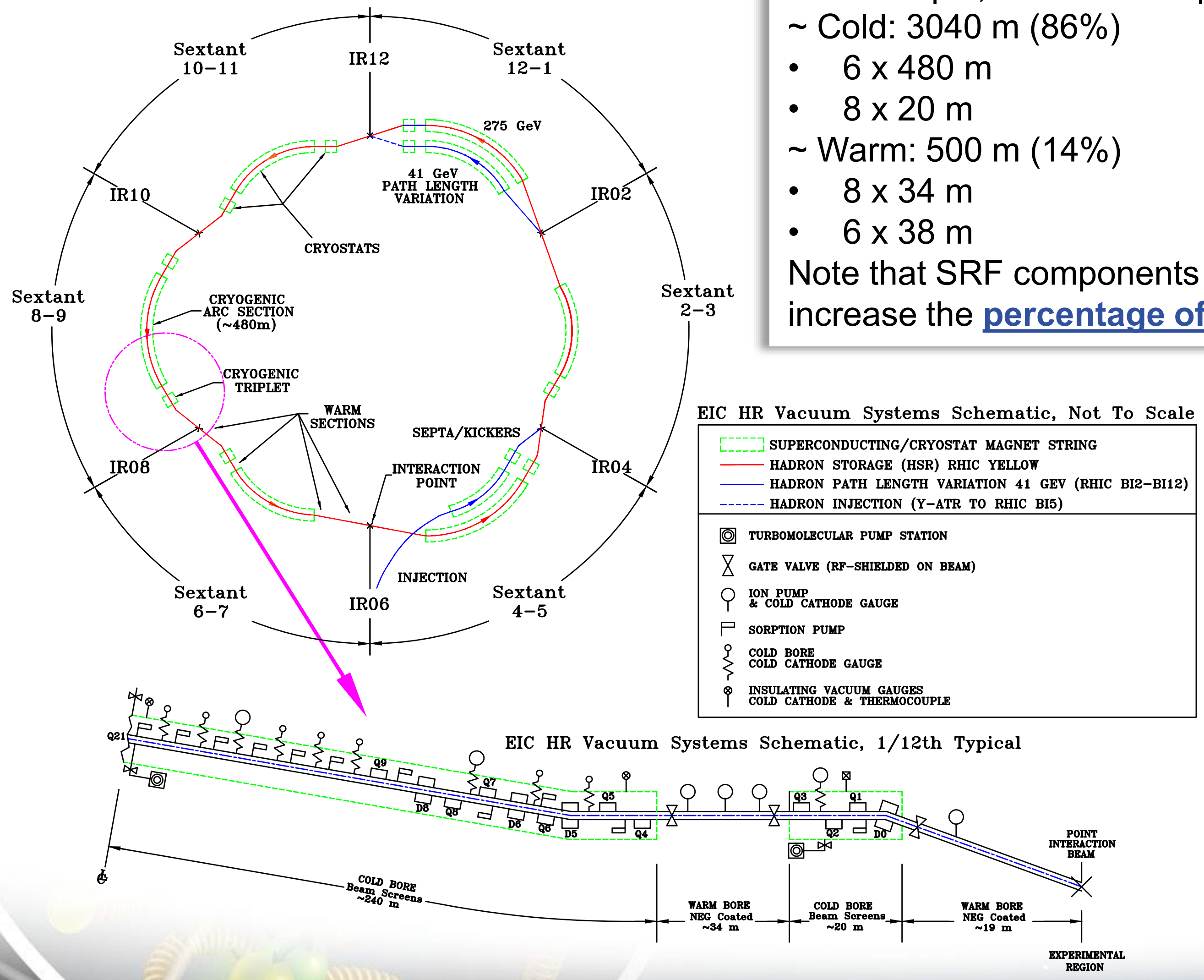
EIC Hadron Ring (HR) cold and warm sections

For example, the 275 GeV path:

~ Cold: 3040 m (86%)
- 6 x 480 m
- 8 x 20 m

~ Warm: 500 m (14%)
- 8 x 34 m
- 6 x 38 m

Note that SRF components and cold magnets in the IR will increase the **percentage of cold sections** to **almost 90%.**



(I) Beamline vacuum level and beam quality

- What is the **highest allowable vacuum level** above which **beam quality is compromised**?
- Which **beam parameter** (emittance, intensity, etc.) **sets this threshold**?

Work these questions in parallel to evaluation of the expected residual gas composition and pressure in the warm and cold sections of the EIC hadron rings vacuum chamber.

⇒ Goal of this work: prepare, debug calculation file to evaluate beam lifetime, emittance growth due to residual gas when we know expected residual gas composition and pressure

Beam loss due to interaction with residual gas

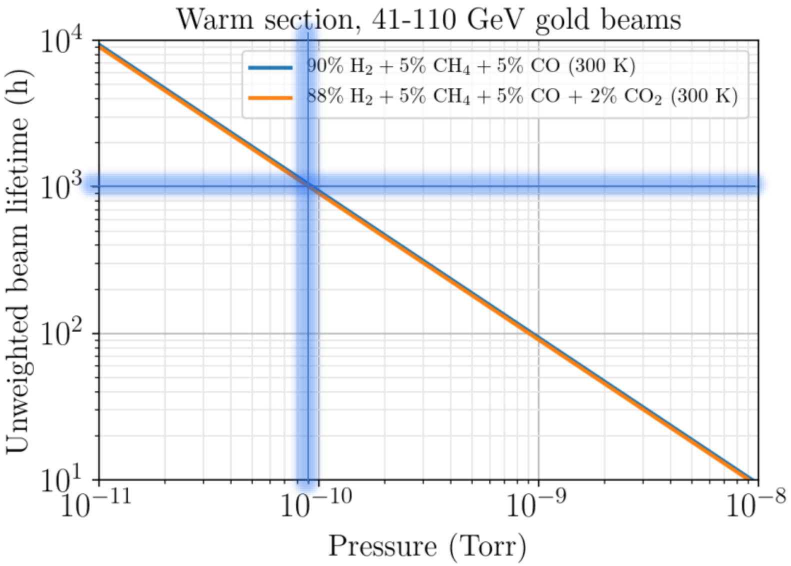
41 – 110 GeV/u $^{197}Au^{79+}$ beams

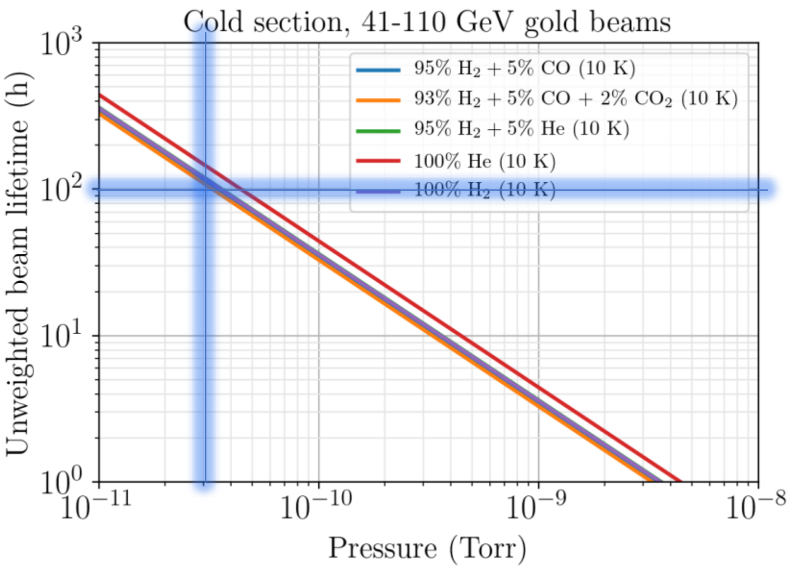
GOAL Aim for hundreds of hours of beam lifetime ($\tau_{gas}\sim$ 100 h)

ASSUMPTIONS $W^{(w)} \sim$ 0.1; $W^{(c)} \sim$ 0.9 (EIC hadron lattice)

RESULTS $\boldsymbol{p^{(w)} \leq}$ **9e-11 Torr;** $\boldsymbol{p^{(c)} \leq}$ **3e-11 Torr**

$\Rightarrow$ $\boldsymbol{\tau_{gas} \geq}$ **110 h for EIC 41-110 GeV $^{197}Au^{79+}$ beams and studied gas compositions**


Warm section, 41-110 GeV gold beams


Cold section, 41-110 GeV gold beams

MOST RESTRICTIVE SCENARIO DUE TO LARGER CROSS-SECTION OF GOLD NUCLEUS

Emittance growth due to residual gas

41 GeV proton beams, vertical emittance

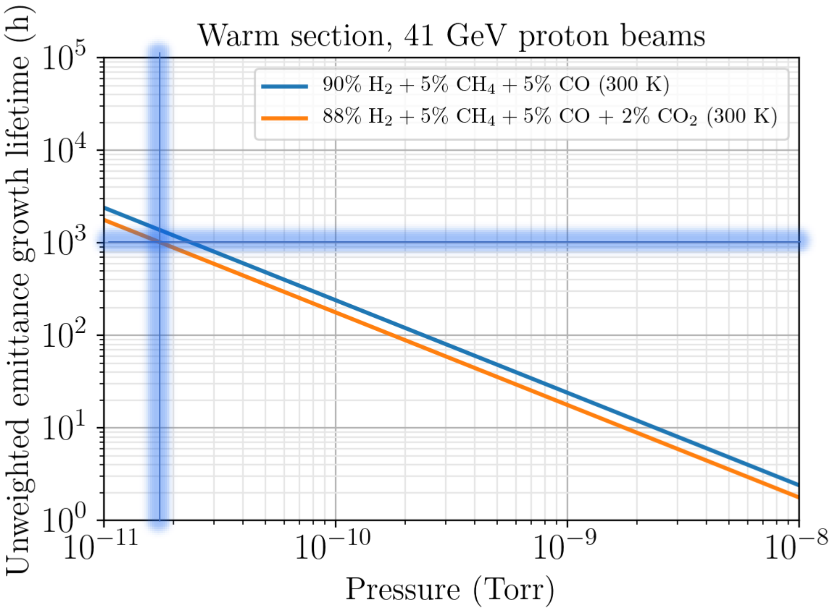
Using Rhoades-Brown

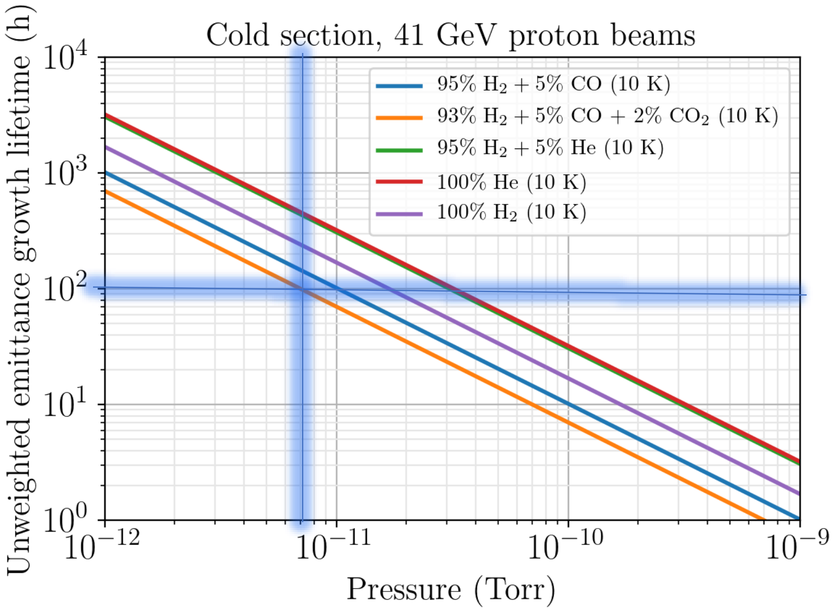
GOAL Analogously to beam lifetime case, aim for hundreds of hours

ASSUMPTIONS $W^{(w)} \sim$ 0.1; $W^{(c)} \sim$ 0.9 (EIC hadron lattice)

$\boldsymbol{p^{(w)}} \leq$ **1.5e-11 Torr;** $\boldsymbol{p^{(c)}} \leq$ **7e-12 Torr**

$\Rightarrow \boldsymbol{\tau_{gas}} \geq$ **110 h for EIC 41 GeV proton beams and studied gas compositions**





Lower energy beams suffer faster emittance growth.

Outlook (I)

VACUUM LEVEL REQUIREMENT FOR THE EIC HADRON RING

Taking most stringent residual gas composition (with presence of C, O):

							Beam loss		Emittance growth☆	
Species	Z	A	E (GeV)	$\bar{\beta}$ (m)	$\beta\gamma$	$\varepsilon_{n,x}, \varepsilon_{n,y}$ (mm mrad)	$p^{(w)}$ (Torr)	$p^{(c)}$ (Torr)	$p^{(w)}$ (Torr)	$p^{(c)}$ (Torr)
proton	1	1	275	20.34	294	5.2 / 0.47	3e-9	9e-10	6e-11	4.5e-11
			41		45	1.9/ 0.45			1.5e-11	7e-12
gold	79	197	110		118	5.1/0.7	9e-11	3e-11	*5e-10	*1.5e-10
			41		45	3.0/0.3			*	*

*Stochastic cooling available.
☆Computed for vertical plane.

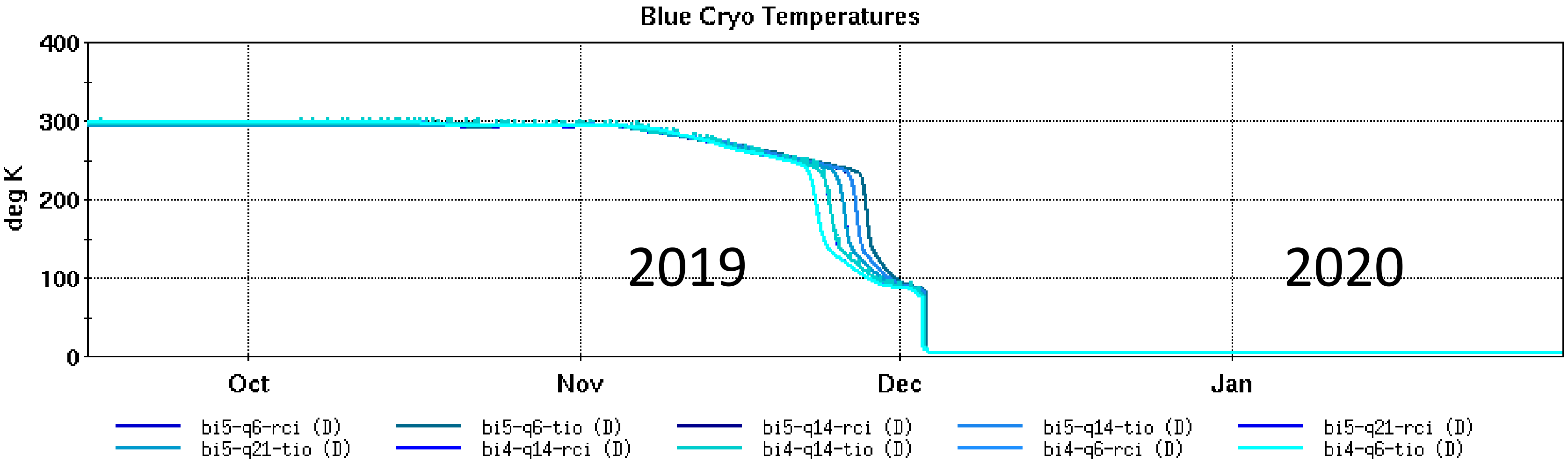
- Beam lifetime is almost independent on beam energy but does greatly decrease with the atomic weight A of the beam species. The most demanding vacuum level conditions are found for gold beams.
- Emittance growth is more severe for low energy beams. The EIC will be equipped with stochastic cooling and thus, we focus on proton beams that, independently of stochastic cooling or not, set the most demanding vacuum level to mitigate emittance growth.

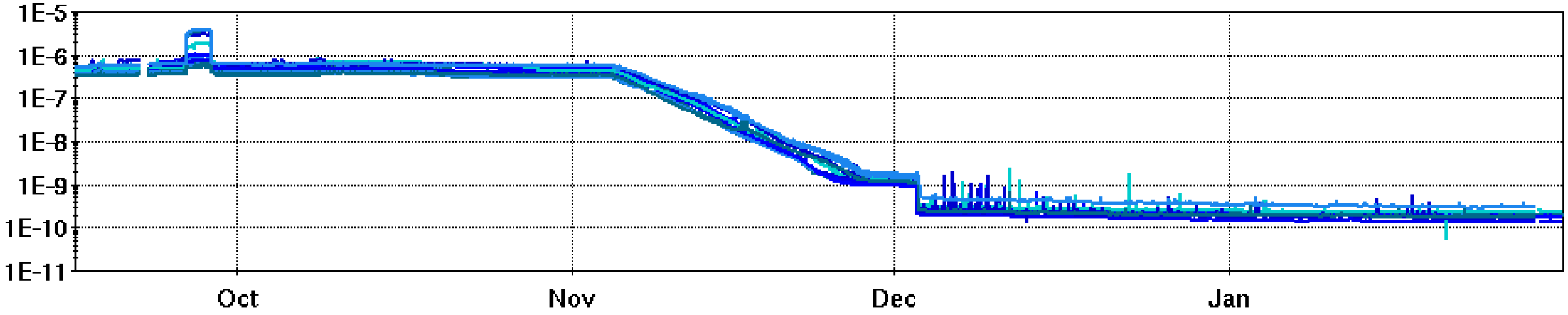
(II) EIC HSR Cryogenic Beam Screen
Vacuum Assessment

- (1) Initial conditions Ideal gas law and bulk gas thermodynamics suggest cold bore arcs with a-C coating will have very low initial monolayer H2 coverage
- (2) Time Dependence: pressure (gas density) will increase over time IAW the adsorption isotherm & magnitude of gas sources as gas evolves and propagates along the length of the beamtube (sources, interconnect thermal desorption, warm-to-cold, leaks etc.)
  - a-C Carbon in limited experiments exhibits high capacity (~100x sSST/Cu) and high thermal desorption temperature
  - So far only need to consider H2. The following may require adding CO partial pressure to vacuum analysis
    - Interconnect Bellows thermal (analysis performed for range of conditions)
    - Beam stimulated desorption
    - Beam screen thermal contact (higher temperature >10K)

(1) Initial Conditions at Cooldown

Recent RHIC performance



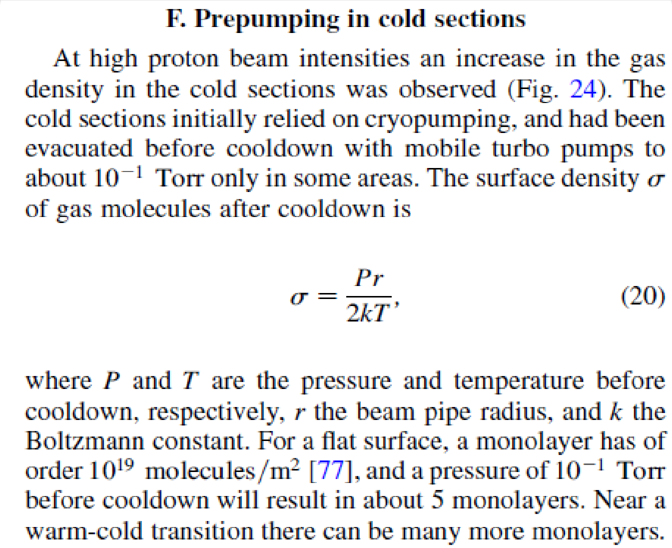


P(RT) ~1e-6 torr -> gas density start cooldown -> surface coverage -> all condensed at cooldown -> θ after cooldown

(1) Initial Conditions: Adsorbed Gas

RHIC & EIC HR Coldbore

With existing ion pumps: pre-pumping << 1 monolayer, sorption dominant



F. Prepumping in cold sections

At high proton beam intensities an increase in the gas density in the cold sections was observed (Fig. 24). The cold sections initially relied on cryopumping, and had been evacuated before cooldown with mobile turbo pumps to about 10^{-1} Torr only in some areas. The surface density σ of gas molecules after cooldown is

$$\sigma = \frac{Pr}{2kT}, \tag{20}$$

where P and T are the pressure and temperature before cooldown, respectively, r the beam pipe radius, and k the Boltzmann constant. For a flat surface, a monolayer has of order 10^{19} molecules/m^2 [77], and a pressure of 10^{-1} Torr before cooldown will result in about 5 monolayers. Near a warm-cold transition there can be many more monolayers.

Adsorption + Condensation

Apply more rigorous 1-D wave propagation method for more accurate prediction of cold bore gas density versus time.

Smooth SST Surface some EIC SST BS T>4.2K & aC Surface… $PV=Nk_BT$

Pressure before cool down to form one monolayer & σ/σm for			**1.E-04**	**torr warm**
	RHIC ARC	**HSR ARC**		
A (cm^2/cm)	**22**	**32**	**RHIC + screen flats**	
V (cm^3/cm)	**37**	**37**		
One monolayer				
molecule/cm^2	**5.E+14**	**5.E+16**	**aC σ~100x > SST (CERN ColdEx Ref)**	
molecule/cm	**1.E+16**	**2.E+18**		
Torr-cm^3 (PV)	**4.E-01**	**5.E+01**		
Torr (one mono)	**9.7E-03**	**1.4E+00**		
σ/σm=	**1.0E-02**	**7.1E-05**		
θ(molecule/cm^2)=	**5.E+12**	**4.E+12**	CERN COLDEX >10x	

H2 migration from warm beamline to coldbore… $Q=CP$

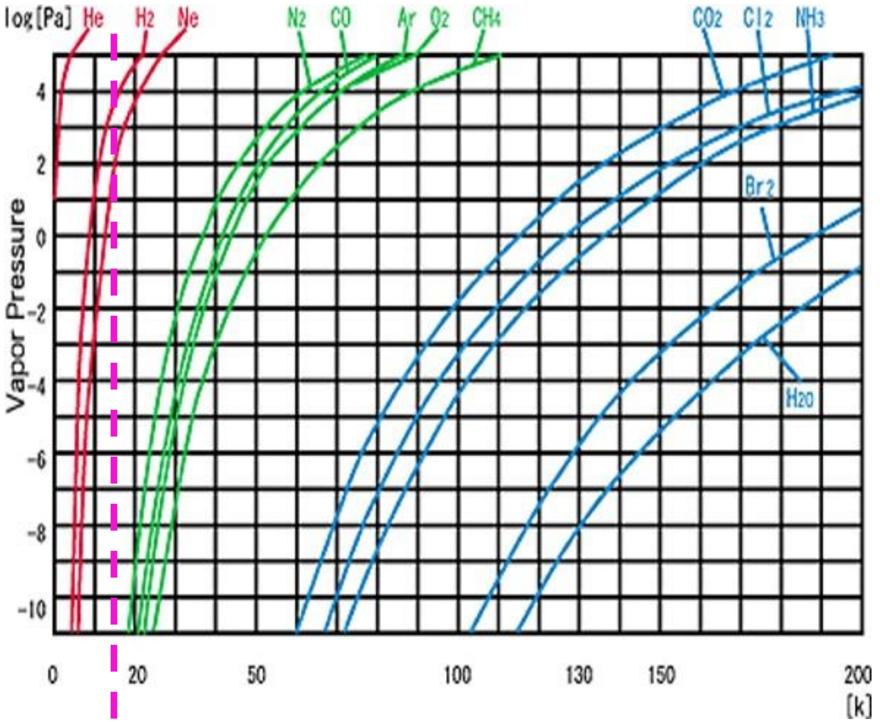
H2 diffusion from warm bore to form one monolayer			
	RHIC ARC	**HSR ARC**	
P (Torr)	**1.E-10**	**1.E-10**	
C (l/s)	**500**	**500**	
Q (Torr.l/s)	**5.E-08**	**5.E-08**	
Q (Torr.l / 7 mos)	**9.E-01**	**9.E-01**	
Q (molecules/yr)	**3.E+19**	**3.E+19**	
A (cm^2) each end	**5.E+04**	**5.E+02**	**σm 1 year**
L (m) - Arcs each end	**23.93**	**0.16**	**σm 1 year**
Assuming no sorption pump and no RW beam heating			

(1) Initial Conditions: Adsorbed Gas

RHIC & EIC HR Coldbore

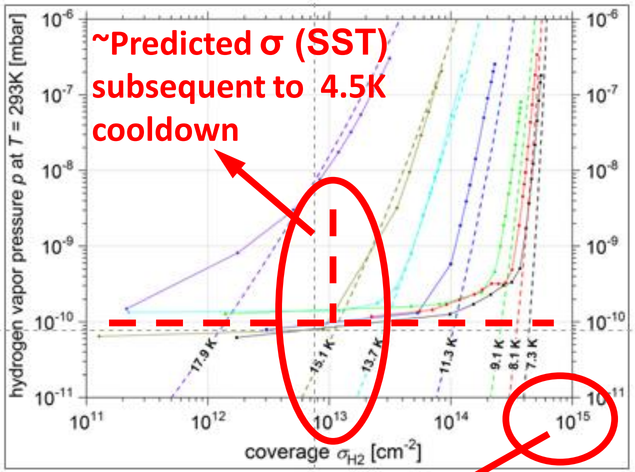
Vapor Pressure: Temperature and Surface Coverage Dependence

Saturated Vapor capacity ~ monolayer



T~15K => Psat H2 ~100 mbar

Sorption (capacity << monolayer)



~Predicted σ (SST) subsequent to 4.5K cooldown

Fig. 3. Adsorption isotherms of H_2 on an electropolished stainless steel surface in the temperature range between 7.3 and 17.9 K. The dashed curves are the theoretical isotherms calculated according to the DRK [Eq. (2)] with the experimentally determined constants, $B = 3076\ eV^{-2}$ and $\sigma_{mono} = 6.46 \cdot 10^{14}$ cm^{-2}.

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DOI: 10.1116/1.5086164

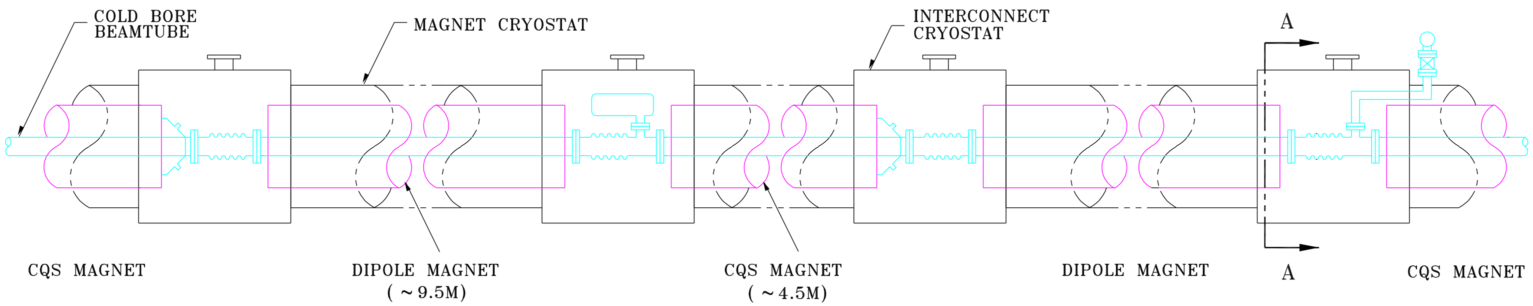
= ~1 monolayer

Vapor pressure reduces at surface coverage << 1 monolayer:
e.g., Psat ~E-10mbar @ T~15K and θ~ .01 (~E13 H2/cm^2) SST,
Assume θ 100X lower for a-C for same initial conditions

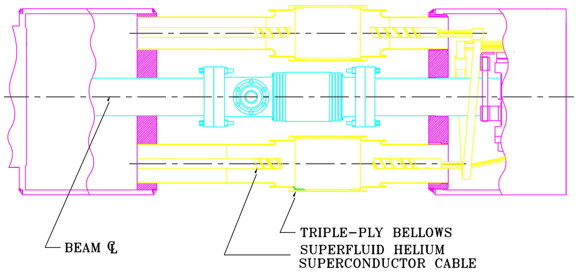
Must maintain << 1 monolayer H2 coverage

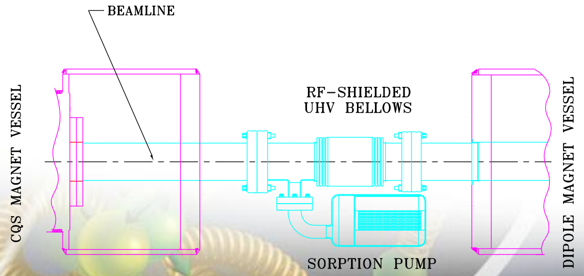
(2) 1-D Time Dependent Pressure Profile
RHIC Basis Arc Interconnect

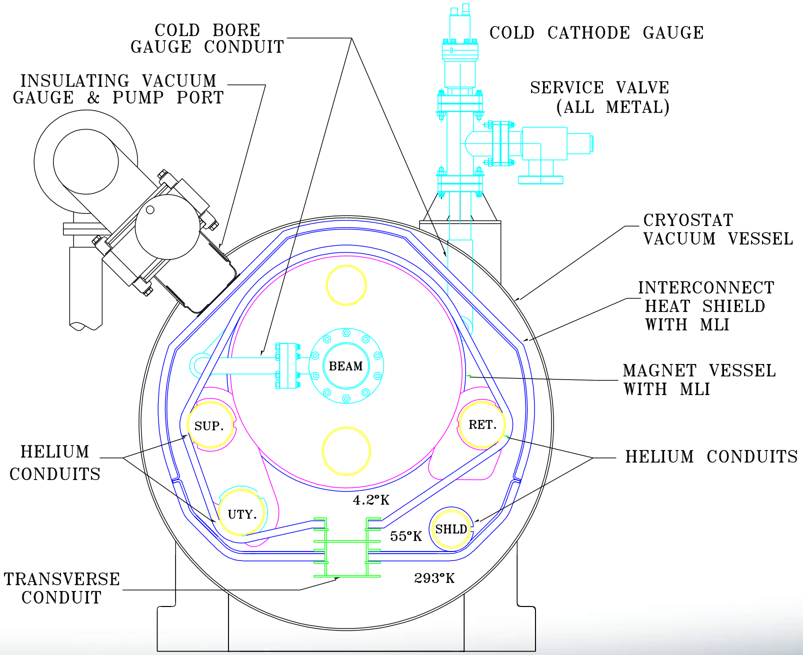
RHIC ARC SECTION LAYOUT



INTERCONNECT







SECTION A – A

(2) General 1-D Solution Method

- Calculate Steady State Pressure Profile from the gas source (interconnect X=0) to the leading edge of the propagating wave front (X_f) based on the interconnect outgassing rate and cold bore conductance at X_f (Independent of adsorption)

- Using a modified adsorption Isotherm equation, and knowing the pressure at all X from X=0 to Xf, calculate the quantity of adsorbed gas from X= 0 to Xf

- The time to reach this pressure profile condition is the total adsorbed gas divided by the outgassing rate

- The cold bore gas density is taken as the average for the pressure profile, corrected for temperature.

- Analysis performed for
  - Various outgassing rates (Interconnect design and temperature)
  - Various Adsorption Isotherm conditions (a-C temperature)

(2) 1-D Solution Method Development

$$Qt = k_2 \int_0^{xf} \theta(x)dx$$

The total gas pumped by the magnet cold bore from the source (x=0) to the gas wave front (Xf) via integration of the Adsorption Isotherm Relation

$$Q_t = k_2 \int_0^{x_f} e^{-B(RT\ln(P/P_0))^2} dx$$

Applying the well tested analytic expression; P. A. Redhead, J. P. Hobson, & E. Y. Kornelsen, The Physical Basis of Ultrahigh Vacuum (Chapman and Hall, London, I 968).

$$k_2 = \pi\sigma_m DrT/N_o$$

σ_m = monolayer coverage at Temperature T, r surface roughness factor, N_o is Avogadro's Number

$$\Theta = k_1 P^m$$

The adsorption isotherm relation, power law approximation for integration purposes

$$Qt = k_1 k_2 \int_0^{xf} [P(x)]^{\prime\prime\prime} dx$$

$$P(x) = (Q/Ca) \cdot [1+.75(X_F - X)D]$$

Cold bore pressure as a function of gas load and beam tube diameter

$$Qt = k_1 k_2 \int_0^{xf} (Q/Ca)^{\prime\prime\prime} \cdot [1+.75(X_F - X)D]^{\prime\prime\prime} dx$$

Substituting for P(X)

$$Qt = -k_1 k_2 (Q/C_a)^m \frac{D}{.75(m+1)} \left[1 - (1+.75X_f/D)^{m+1}\right]$$

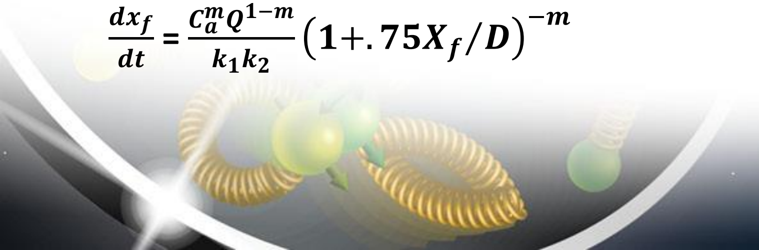
The total gas pumped by the magnet cold bore from the source (0) to the gas wave front (Xf)

$$t = Qt/q$$

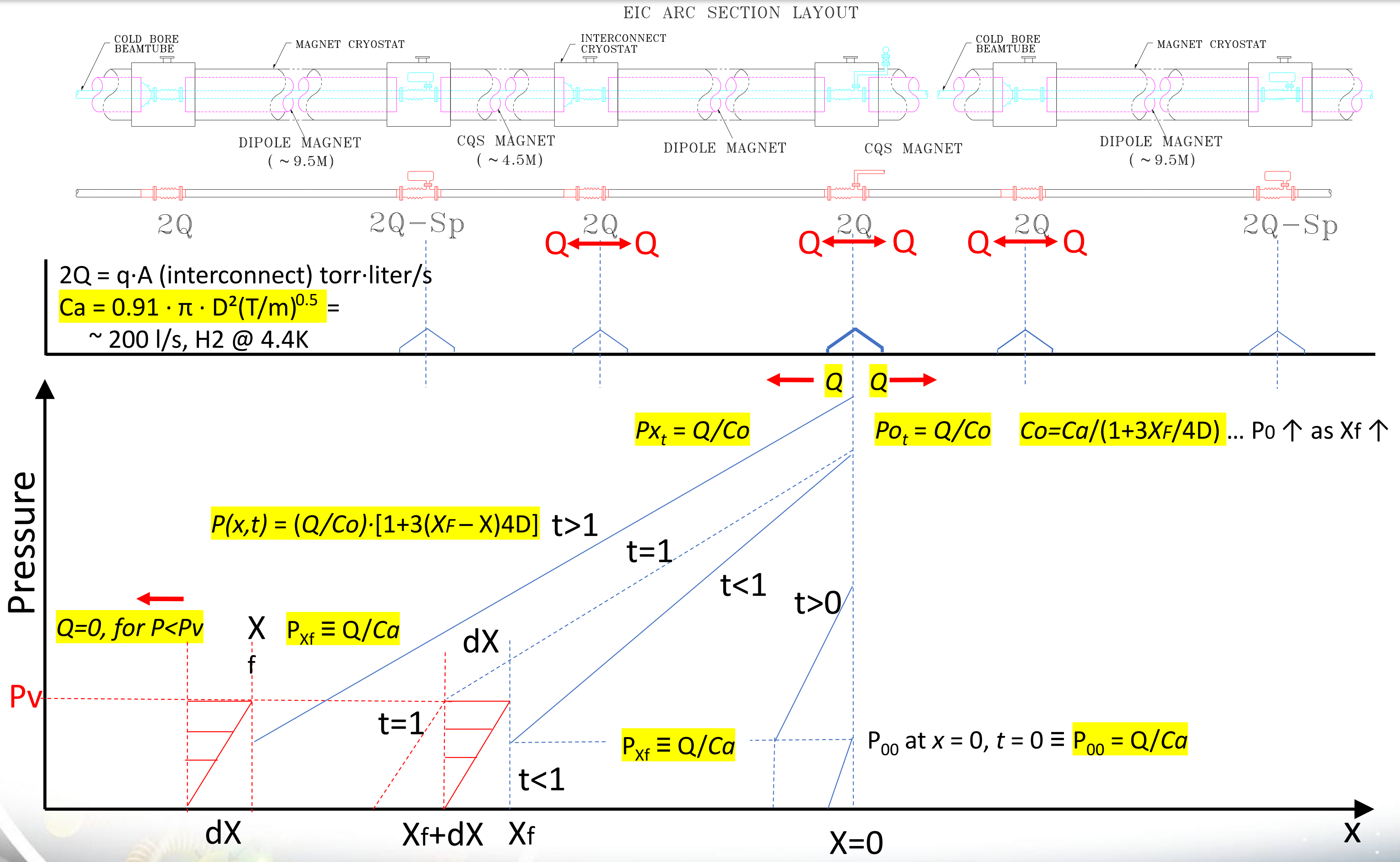
The time for the wave to propagate a distance Xf is the total adsorbed gas (Qt) divided by the outgassing rate (q)

$$\frac{dx_f}{dt} = \frac{C_a^m Q^{1-m}}{k_1 k_2} (1+.75X_f/D)^{-m}$$

Differentiated and manipulated to yield wave front propagation velocity



(2) EIC Time Dependent Pressure Profile



2Q = q·A (interconnect) torr·liter/s

$Ca = 0.91 \cdot \pi \cdot D^2(T/m)^{0.5}$ = ~ 200 l/s, H_2 @ 4.4K

$Px_t = Q/Co$

$Po_t = Q/Co$

$Co = Ca/(1+3X_F/4D)$ … Po ↑ as Xf ↑

$P(x,t) = (Q/Co)\cdot[1+3(X_F - X)4D]$ t>1

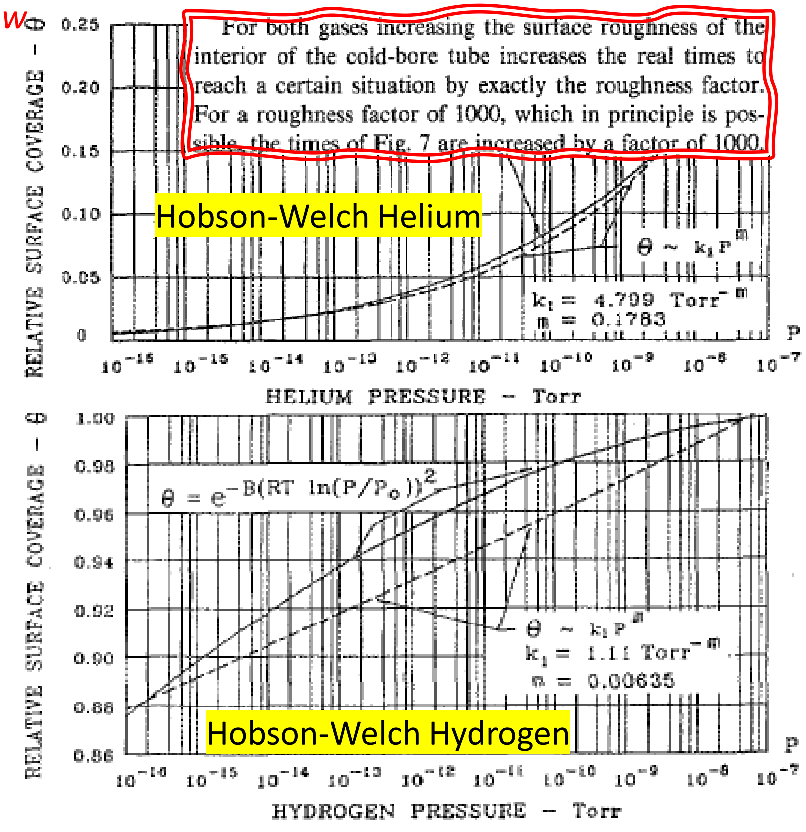
Q=0, for P<Pv

$P_{Xf} \equiv Q/Ca$

P_{00} at $x = 0$, $t = 0 \equiv P_{00} = Q/Ca$

(2) Adsorption Isotherm Development

The relation between the amount of gas adsorbed at a point x i.e., a(x) in molecules/cm^2 and the pressure P(x) at that point is given by the adsorption isotherm. Adapting the well tested analytic expression[1]*:* $\mathbf{\ln\Theta = -B(RT \ln P/P_0)^2}$ *where* $\Theta = \sigma/\sigma_m$ *is the ratio of surface coverage to full monolayer coverage in molecules/cm^2 and P_0 being the vapor pressure of the adsorbed species at the pipe temperature T. The values for H2 on smooth bare SST and those estimated for a-C coated SST are given below*



For both gases increasing the surface roughness of the interior of the cold-bore tube increases the real times to reach a certain situation by exactly the roughness factor. For a roughness factor of 1000, which in principle is possible, the times of Fig. 7 are increased by a factor of 1000.

FIG. 4. Hydrogen adsorption isotherm at 4.2 K.

Modeling an appropriate adsorption isotherm equation

shown in Fig. 2. Signs of surface saturation were recorded with a coverage of > $4\cdot10^{17}$ H_2/cm^2 and > $2\cdot10^{17}$ H_2/cm^2 respectively, *i.e.* two orders of magnitude higher than the monolayer capacity of metallic surfaces like Cu or SS. This result points to a porous surface morphology of a-C.

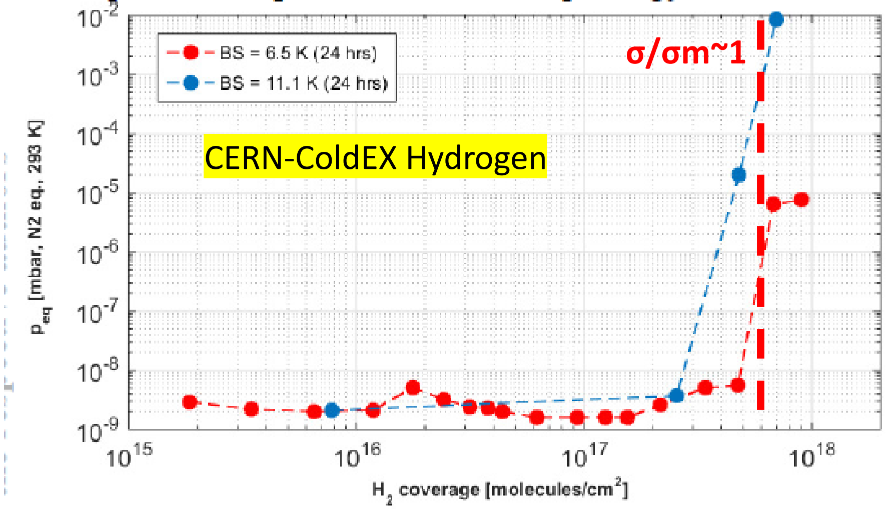


Figure 2: a-C H_2 adsorption isotherms at 6.5 K and 11.1 K.

(2) 1-D Solution Results

INTERCONNECT THERMAL					
T	(K)	50	20	10	5
q(H2)	(torr-l/(s-cm^2))	1E-11	1E-12	1E-13	1E-14
Q = q(Interconnect Surface Area)	(torr-l/s)	5.18E-09	5.18E-10	5.18E-11	5.18E-12

Pressure Profile function of outgassing rate and beam tube conductance

PRESSURE PROFILE $P(x) = (Q/Ca)\cdot[1+.75(XF - X)D]$		Results when H2 wave has propagated to dipole midpoint			
Pf at X=Xf=5m	(torr)	2.11E-11	2.11E-12	2.11E-13	2.11E-14
P0 at X=0 when Xf=5m	(torr)	5.47E-08	5.47E-09	5.47E-10	5.47E-11
Pavg = (Pf+P0)/2	(torr)	2.74E-08	2.74E-09	2.74E-10	2.74E-11
Pavg => target	(torr)	1.82E-10	1.82E-10	1.82E-10	1.82E-10
ρavg => target	(H2/cm^3)	2.00E+06	2.00E+06	2.00E+06	2.00E+06
ρavg => PV=NkBT => (N/V)=P/kB*T (Xf=5m)	(H2/cm^3)	3.01E+08	3.01E+07	3.01E+06	3.01E+05
Xf at target ρ (Q dependent only)	**(cm)**	**40.0**	**128.2**	**407.0**	**500.0**
ISOTHERM PARAMETERS		**H-W (base)**	**H-W (a-C)**	**11K**	**6.5K**
r		1	100	1	1
σm	(H2/cm^2)	2E+15	2E+15	2E+17	5E+17

Propagation time a function of the adsorption Isotherm

WAVE PROPAGATION $Qt = k_1 k_2 \left({}^{Q}/_{C_a}\right)^m \frac{D}{.75(m+1)}\left[1-\left(1+.75X_f/D\right)^{m+1}\right]$ $k_2 = \pi\sigma m D r R T/N_o$ $t = Qad/Q$

Qad (H-W, RHIC baseline, r=1)	(torr-l)	2.73E-04	2.69E-04	2.65E-04	2.61E-04
Time (t) for Xf=5m	(yr)	0.002	0.016	0.162	1.598
time when Xf at target ρ	**(yr)**	**0.0001**	**0.004**	**0.13**	**1.60**
Qad (H-W: r=100)	(torr-l)	2.05E-02	2.02E-02	1.99E-02	1.96E-02
Time (t) for Xf=5m	(yr)	0.13	1.23	12.16	119.86
time when Xf at target ρ	**(yr)**	**0.01**	**0.31**	**9.89**	**119.86**
Qad (σCOLDEX: 11K, r=1)	(torr-l)	2.73E-02	2.69E-02	2.65E-02	2.61E-02
Time (t) for Xf=5m	(yr)	0.17	1.65	16.22	159.82
time when Xf at target ρ	**(yr)**	**0.01**	**0.42**	**13.18**	**159.82**
Qad (σCOLDEX, 6.5K, r=1)	(torr-l)	6.82E-02	6.73E-02	6.63E-02	6.53E-02
Time (t) for Xf=5m	(yr)	0.42	4.11	40.54	399.55
time when Xf at target ρ	**(yr)**	**0.03**	**1.05**	**32.96**	**399.55**

(2) 1-D Method Parameter Assumptions

- **Interconnect:**
  - Temperature: Unknown pending final thermal analysis, Assumed range between 4 and 50K
  - Outgassing rate: estimated as a function of interconnect temperature, validation needed as there is no available rates at the cryogenic temperature range considered. Dependent on specific material treatment and conditions

- **Beam tube/Beam screen**
  - Temperature: 6.5 and 11K based on available COLDEX adsorption isotherm data
  - Cryogenic Outgassing rate: assumed 0 as in the case of RHIC model at 4K. A value may be needed if screen is higher temperature. Needs validation
  - Adsorption Capacity: Range of values applied. Developed EIC a-C coating needs validation
    - Assumed COLDEX values at 6.5K and 11K
    - Initial condition θ very small ~ 0 for wave propagation analysis. Room temperature a-C coating characteristics required to validate.

Outlook II

- **H2 Propagation magnitude, time and avg gas density analyzed for various interconnect and beam screen conditions**
  - Pressure Profile approaches the pressure profile absent any adsorption over time.
  - Surface and adsorption isotherm properties only serve to adjust the time to establish that profile.

- **a-C cryogenic vacuum properties in published literature are promising**
  - High H2 adsorption capacity (~100x SST)
  - Higher thermal desorption temperatures compared to SST
  - EIC a-C film cryogenic vacuum properties require validation
  - Carbon Fiber Cryosorber (& screen cross-section design) and perforations remain a consideration in beam screen design

- **Initial a-C adsorption coverage depends on pressure before cooldown**
  - Assumed ~0 for 1-D analysis
  - EIC a-C film ambient temperature vacuum properties require validation
  - more ion pumps and longer pumpdown prior to cooldown remain considerations

- **Higher Confidence if conditions below are also achieved**
  - Beam screen thermal analysis (thermal contact => BS Temperature ~5K)
  - Interconnect thermal analysis (Temperature <10K)
  - Beam stimulated desorption analysis: ion and e- dose rates

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