USPAS - Fundamentals of Ion Sources
15. Vacuum Technology for Ion Sources

Daniela Leitner (LBNL, MSU),
Damon Todd (LBNL),
Daniel Winklehner (MIT)

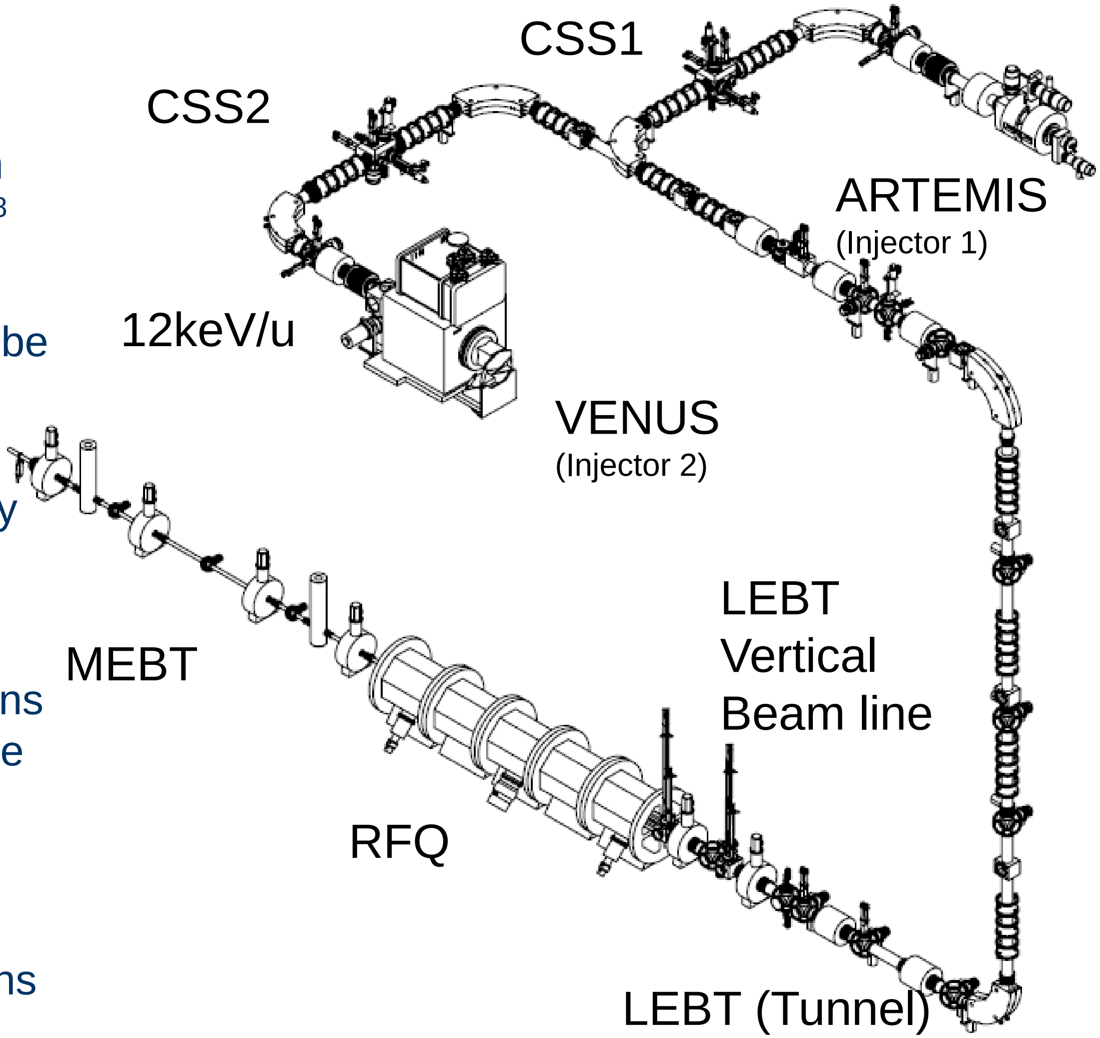
Outline

- Why is vacuum important for ion sources
  - Some examples
- Vacuum Systems – definitions
- Key Concepts
- Pumping systems
- Limitations on final pressure
- Estimating average beamline vacuum
- Analytic Example
- Available programs

Beam Transport

Why is vacuum important for injector systems

- Ion Source plasma requires gas for the discharge (depending on the ion source pressures can be 10^{-2} to 10^{-8} mbar) in the plasma chamber
- The beam is slow in the low energy be transport section (a few keV/u):
  - HCI: Charge exchange cross sections are highest for low energy
  - H-: Charge stripping with residual gas
- Beam losses in the analyzing sections and slits will create additional particle loads
- Space charge compensation is directly dependent on the neutral pressure and can vary with conditions of the beam line/ pulsed beams



Vacuum considerations for the beam transport of high charge state Ions

$X^{q+} + X \rightarrow X^{(q-1)+} + X^{+}$ neutral-ion charge exchange

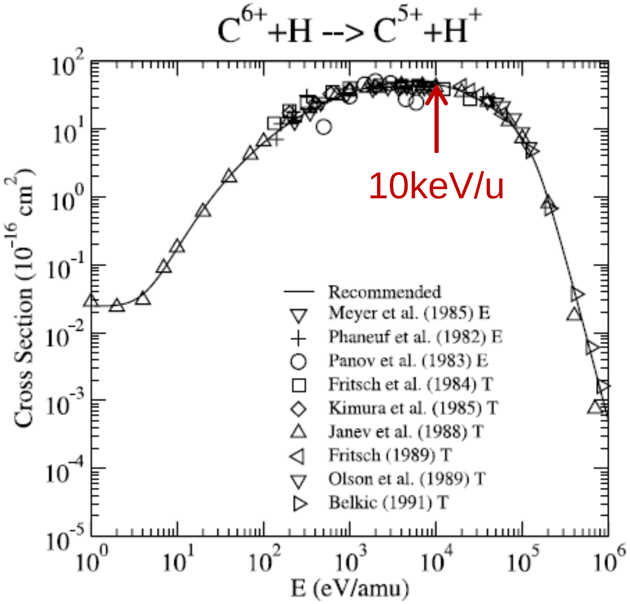
$$\sigma^{CX} = 1.43 \cdot 10^{-12} \cdot q^{1.17} \cdot E_i^{-2.76}$$

$E_i \ldots Ionization\ potential\ of\ the\ neutral\ atom$

$q \ldots Charge\ State$

For example Xe^{44+}, $p = 2 \cdot 10^{-7} Torr$,
Losses are 5% per m !

Homework:
Calculate losses for a given pressure
Calculate maximum pressure along a beamline to maintain 90 % transmission



Graph 158: Cross section for charge exchange.

Formula is valid for lower energy region, charge exchange cross section reduces at higher energy (see for example CX cross section for C^{6+} + H)

Vacuum considerations for the beam transport of H^-

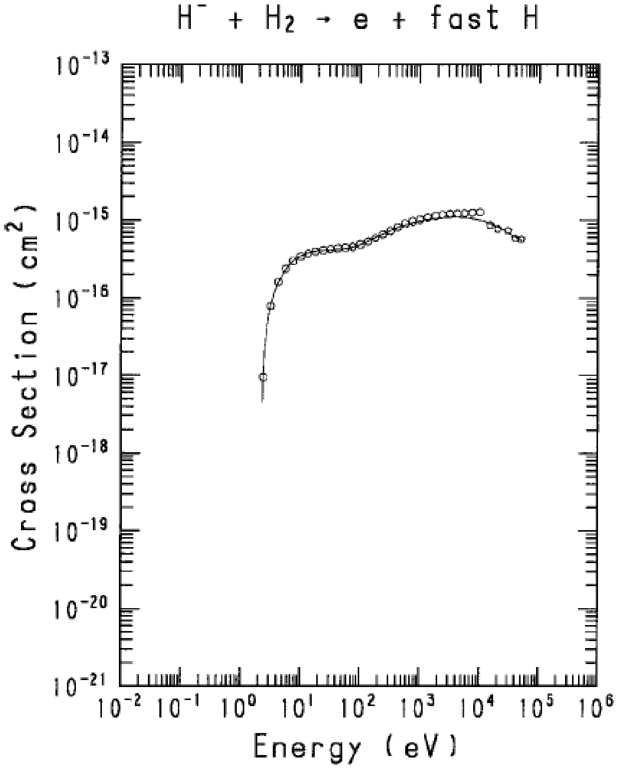
- H^- ionization potential is only 0.75eV – very fragile ion !
- Dominant process of loss in the beam line: Electron striping of H− ion by molecular hydrogen (e.g. extraction region)

$$H^- + H_2 \rightarrow e + fast\, H$$

For example

$p = 2 \cdot 10^{-5} Torr,$ Losses are 7% per m

$p = 2 \cdot 10^{-4} Torr,$ Losses are 48% per m !



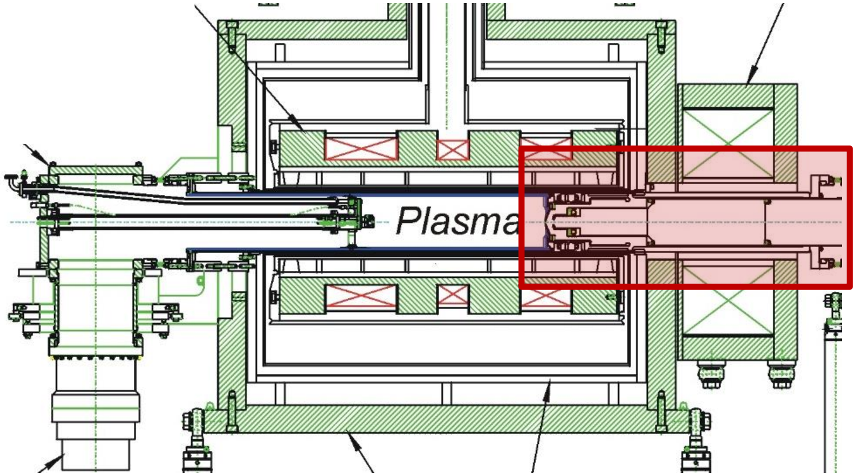
Draganic, I.N., *Electron stripping processes of H− ion beam in the 80 kV high voltage extraction column and low energy beam transport line at LANSCE.* Review of Scientific Instruments, 2016. **87**(2): p. 02B111.

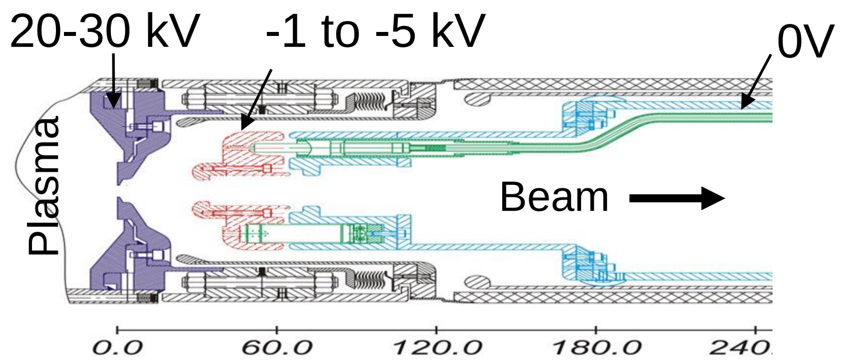
Tabata, T. and T. Shirai, *ANALYTIC CROSS SECTIONS FOR COLLISIONS OF H+, H2+, H3+, H, H2, AND H− WITH HYDROGEN MOLECULES.* Atomic Data and Nuclear Data Tables, 2000. **76**(1): p. 1-25.

Extraction Region of Ion Sources

Vacuum in the extraction region

- Neutrals escaping from the plasma will enter the extraction chamber and raise the pressure
- Can cause sparking issues – discharge issues in the extraction region





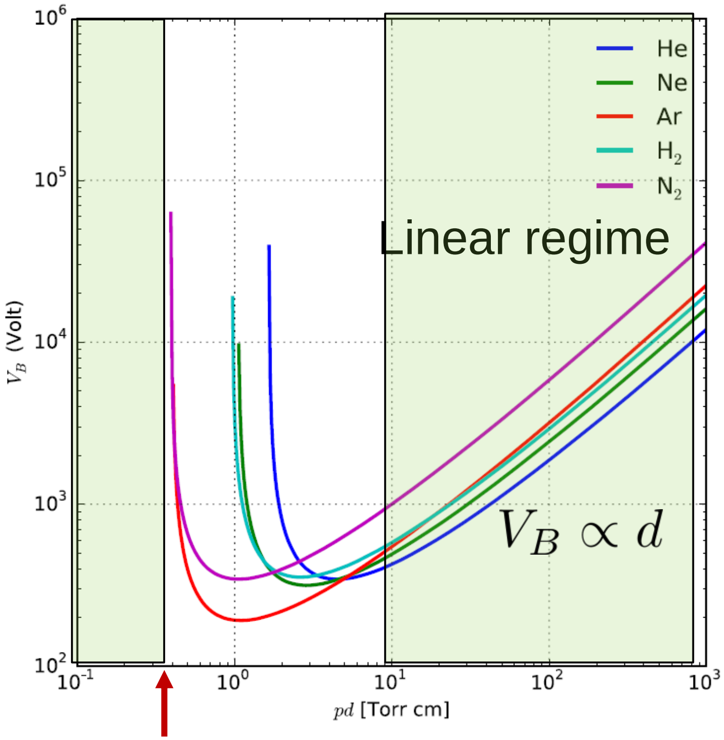
Beam extraction

The Breakdown Voltage (Paschen's Law)

- 1889 Friedrich Paschen described a breakdown voltage function V(p,d) with pressure *p*, electrode gap *d*, and experimental determined coefficients :*A* & *B, which* depend on the gas and the electrodes
- γ_{se} is the secondary electron coefficient

$$V_B = \frac{Bpd}{\ln(Apd) - ln[ln(1 + \frac{1}{\gamma_{se}})]}$$

- Decreasing the pressure increases the mean path between collisions (λ_i), which is compensated by proportionally increasing d
- The minimum represents the minimum energy spent on producing enough ions for one secondary electron from the cathode.
- At high *p·d*, the voltage increases linearly with the gap between the electrodes



Energy gained by the electrons between collisions is too small

Vacuum in the extraction region

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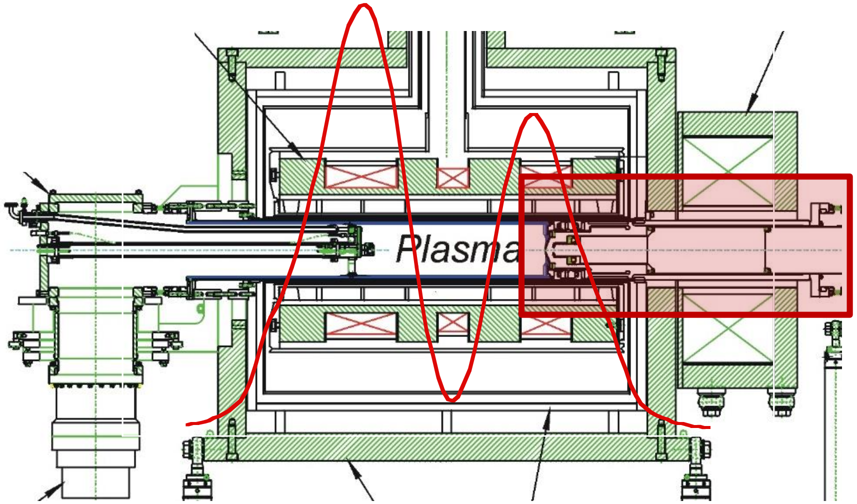
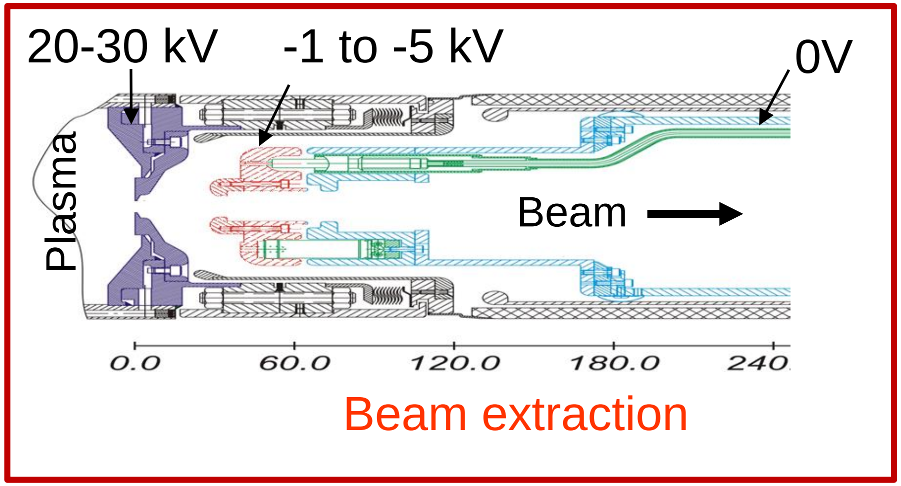




Beam extraction

- Strong axial magnet field
  - enhanced electron confinement
  - perfect penning discharge condition (vacuum must be low enough to prevent run away discharge)

Pressure should be better than 10^{-7} mbar !

- Difficult to engineer (max. conductance): No confined electrical feedthrough! Avoid einzel lenses!

Beam Impurities

Residual Gas/Outgassing/Surface influence the Condition in the Ion Source

- The final gas pressure and composition of the residual gas in the plasma chamber of the ion source determines the composition of the beam

- Impurities are usually not a problem for sources running at pressures above 10^{-5} Torr, but get very important for high charge state ion sources (< 10^{-8} Torr)

  - Ion sources are very sensitive RGAs!
  - EBIT ion sources – residual gas can limit the maximum confinement time (see Thursday)

Residual Gas/Outgassing/Surface influence the Condition in the Ion Source

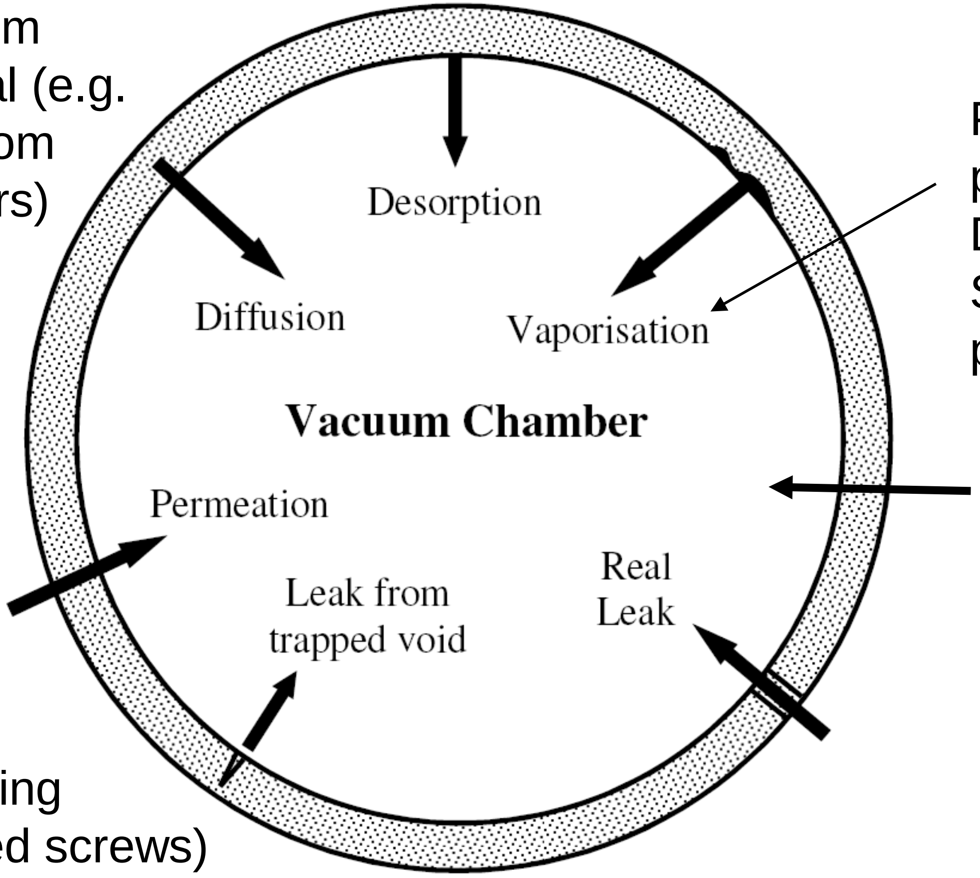
- Wall coating/deposition during run-time can influence the performance of the ions sources (ECR see lecture later)

- Impurities in the beam from residual ions can be problematic for the experiment (particular important for linacs)

- Gas composition due to leaks can influence the performance ($H_{2,}$ N_2)

- Performance loss through filament poisoning, Surface poisoning…

Limitations on final pressure



Gases frozen on the surface

Diffusion from bulk material (e.g. hydrogen from SS chambers)

Particles previously Deposited Sputtering of the plasma

Back streaming from vacuum pumps (or material diffusion from vacuum pump components)

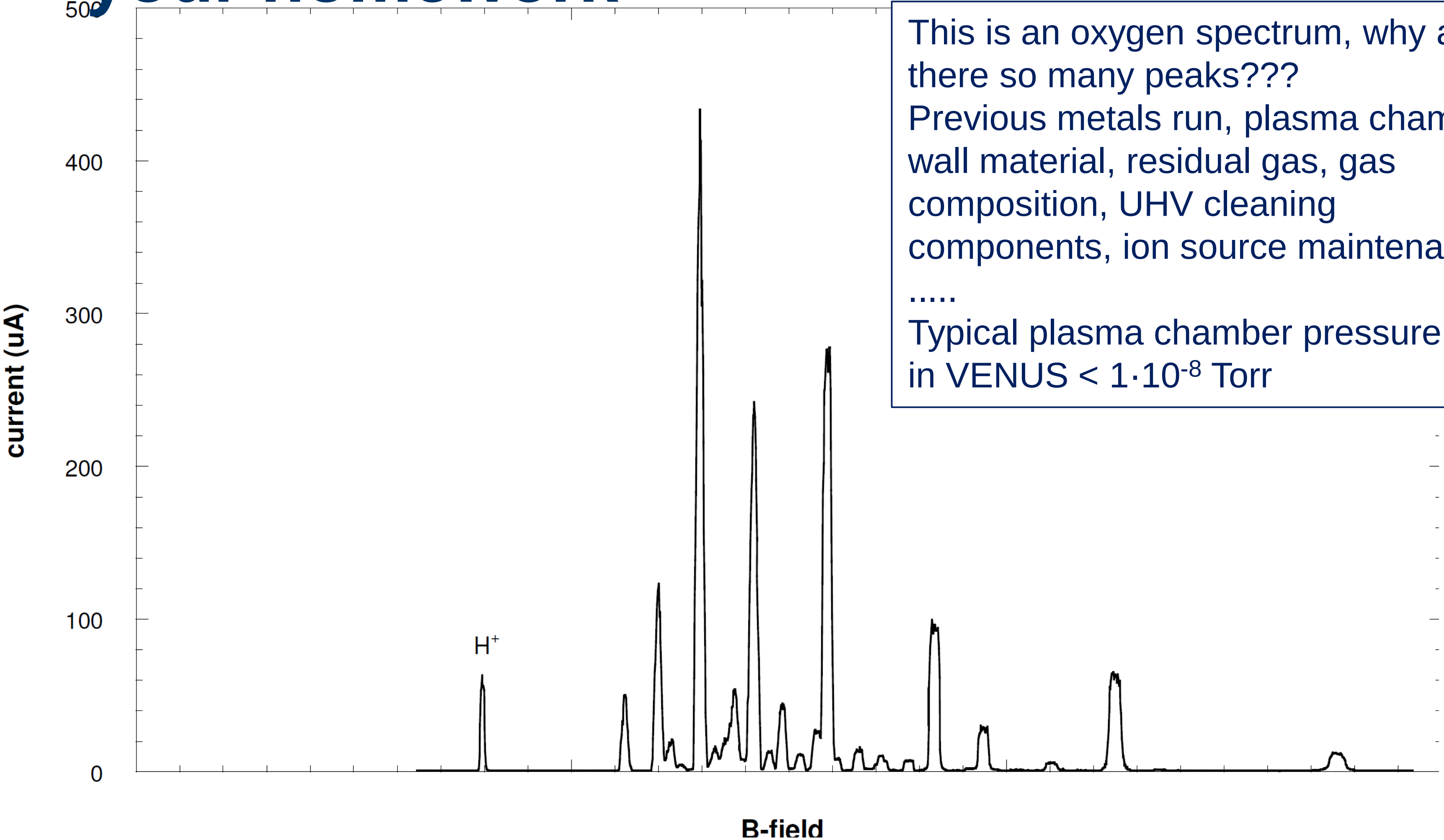
O-rings

Poor engineering (e.g non vented screws)

Fig 8. Unwanted gas source wheel

Garton, D., *Vacuum Technology and Vacuum Design Handbook for Accelerator Technicians* 2011, http://apo.ansto.gov.au/dspace/handle/10238/4126

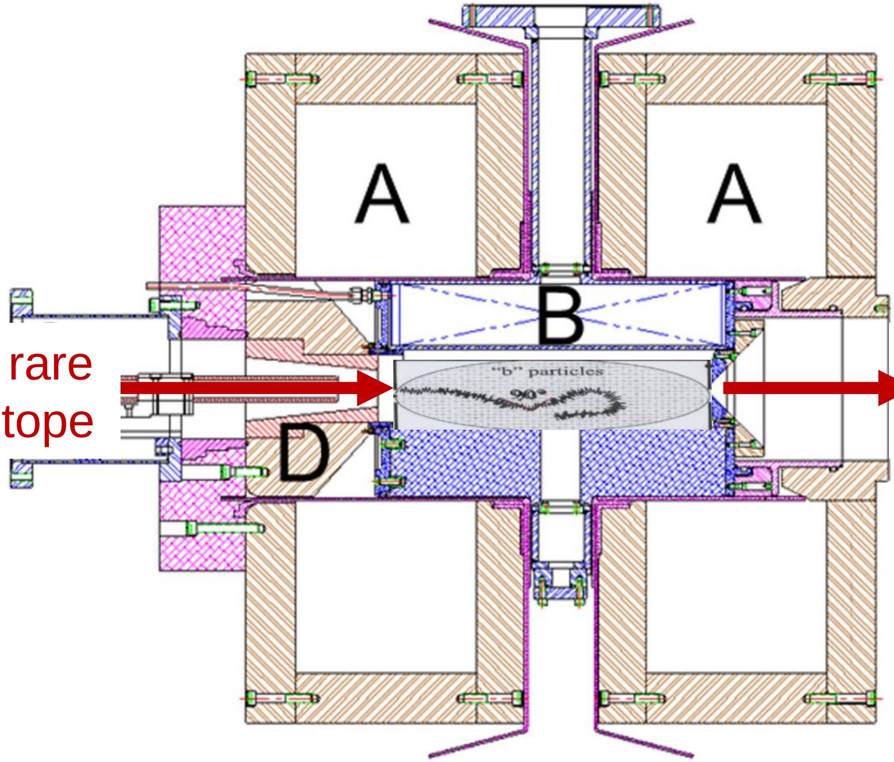
VENUS Spectrum you will analyze in your homework



This is an oxygen spectrum, why are there so many peaks???
Previous metals run, plasma chamber wall material, residual gas, gas composition, UHV cleaning components, ion source maintenance .....
Typical plasma chamber pressure in VENUS < $1 \cdot 10^{-8}$ Torr

Take a closer look for an ECR spectrum from one of the best ECR charge breeders!

Example: CARIBU-ANL; Charge Breeder, typical M/Q region: 4.667 (N^{3+}) to 6 (C^{2+})



1+ rare isotope

n+ rare isotope

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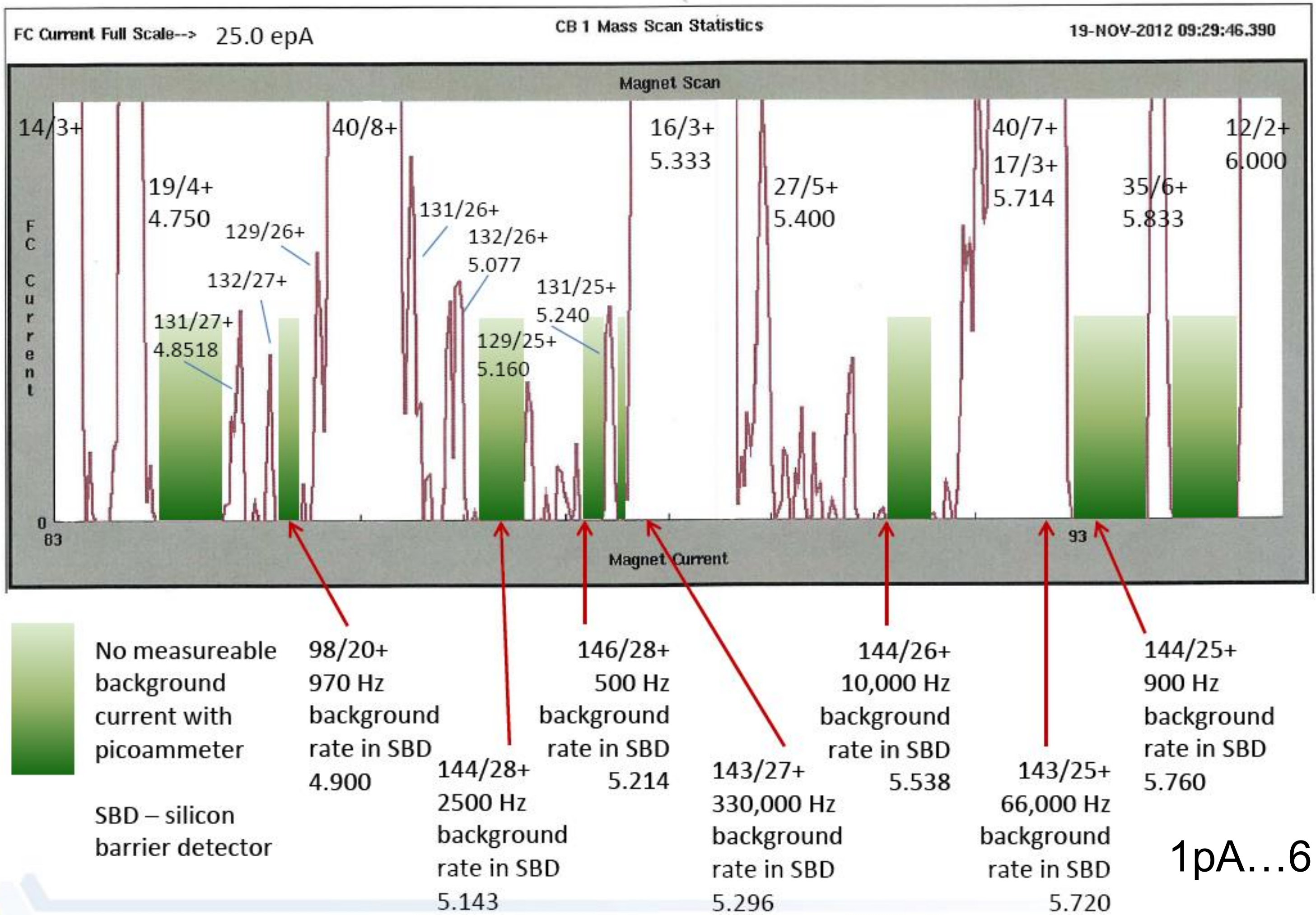

🟩 No measureable background current with picoammeter

SBD – silicon barrier detector

98/20+
970 Hz
background
rate in SBD
4.900

144/28+
2500 Hz
background
rate in SBD
5.143

146/28+
500 Hz
background
rate in SBD
5.214

143/27+
330,000 Hz
background
rate in SBD
5.296

144/26+
10,000 Hz
background
rate in SBD
5.538

143/25+
66,000 Hz
background
rate in SBD
5.720

144/25+
900 Hz
background
rate in SBD
5.760

Sources of Contaminations

O-Ring permeation Chamber walls

Rare isotope rate 1Hz to 10kHz!

1pA…$6.2 \cdot 10^6$ particles/sec

R. Vondrasek
ICIS Brightness Award Lecture 2015

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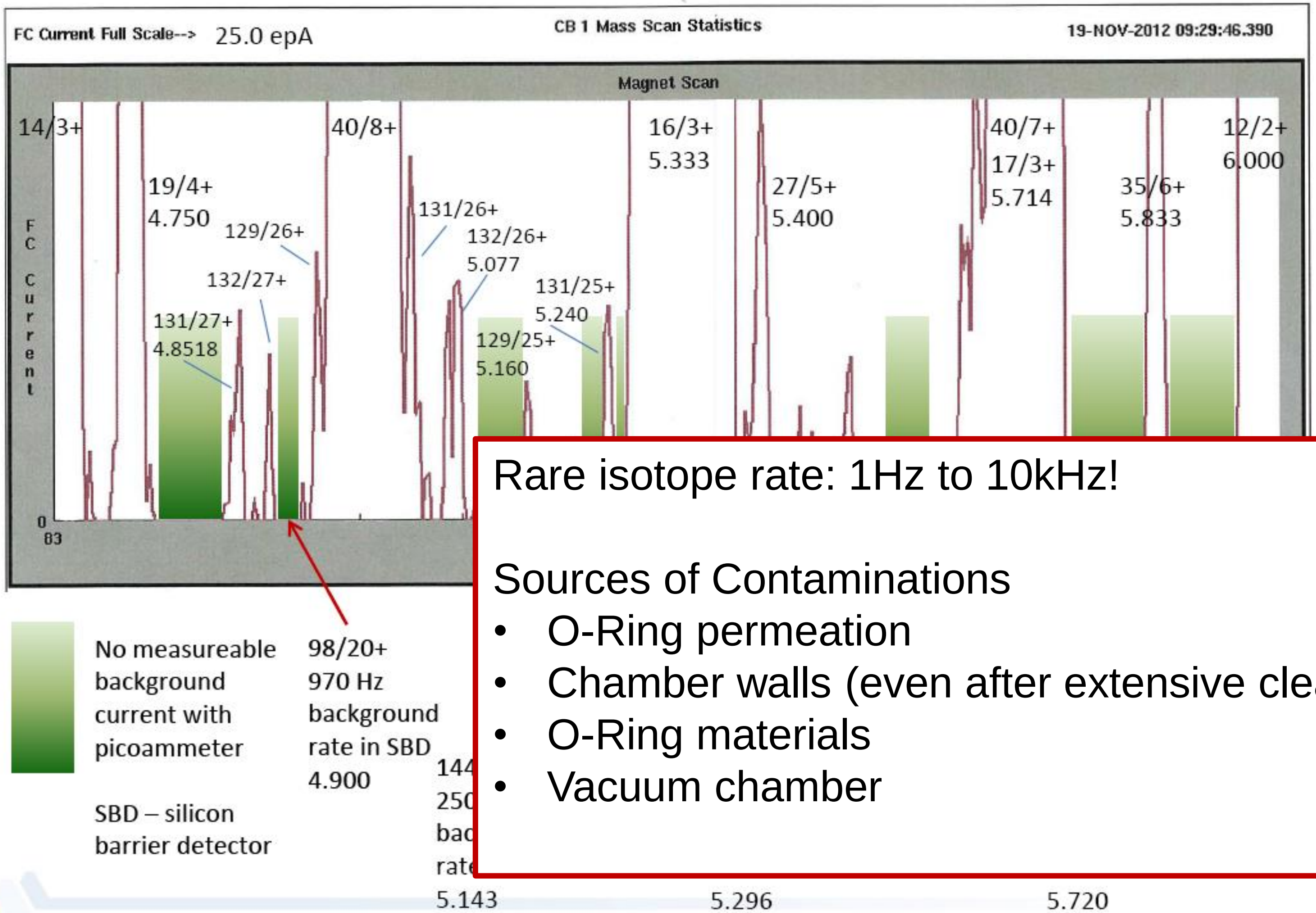
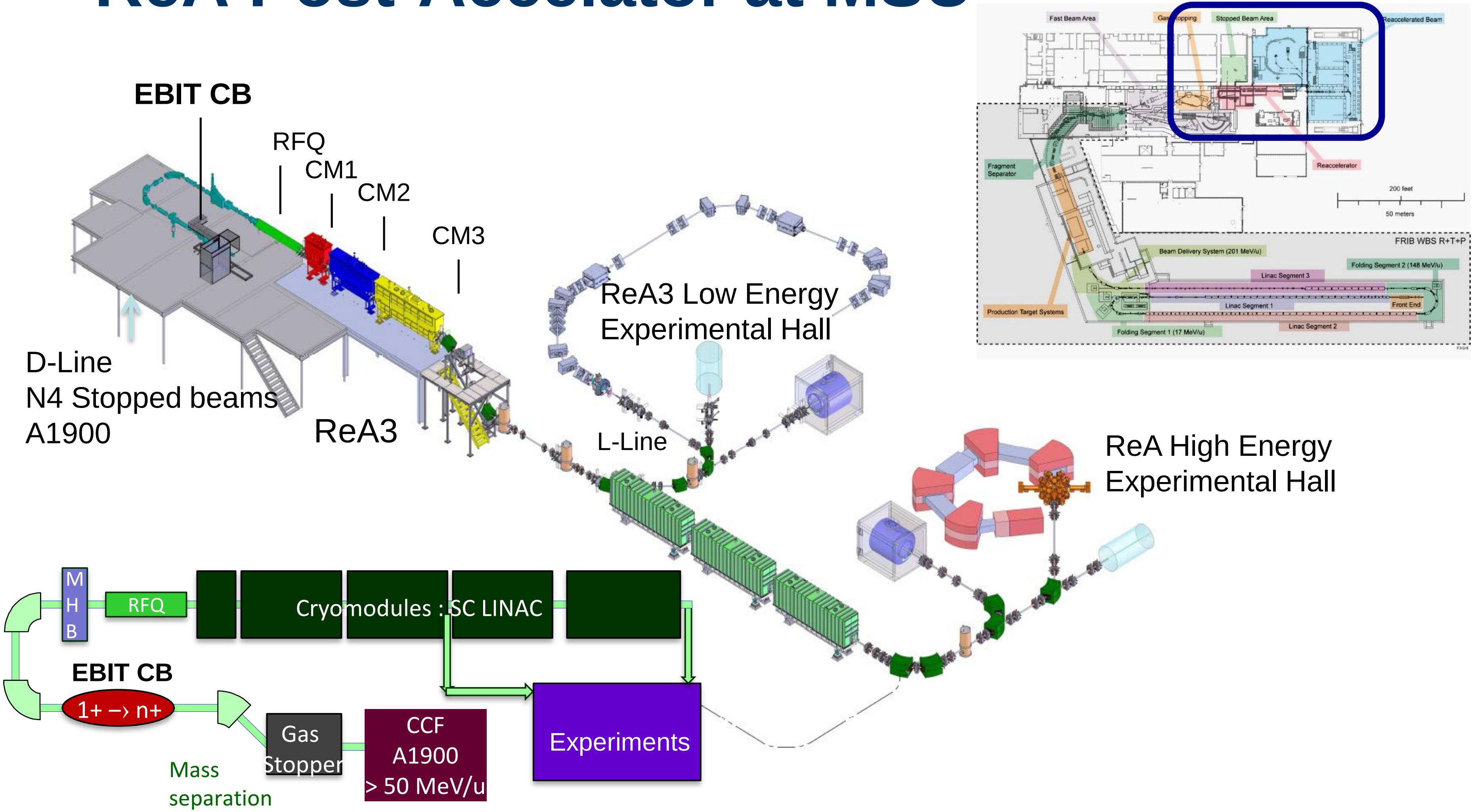


Rare isotope rate: 1Hz to 10kHz!

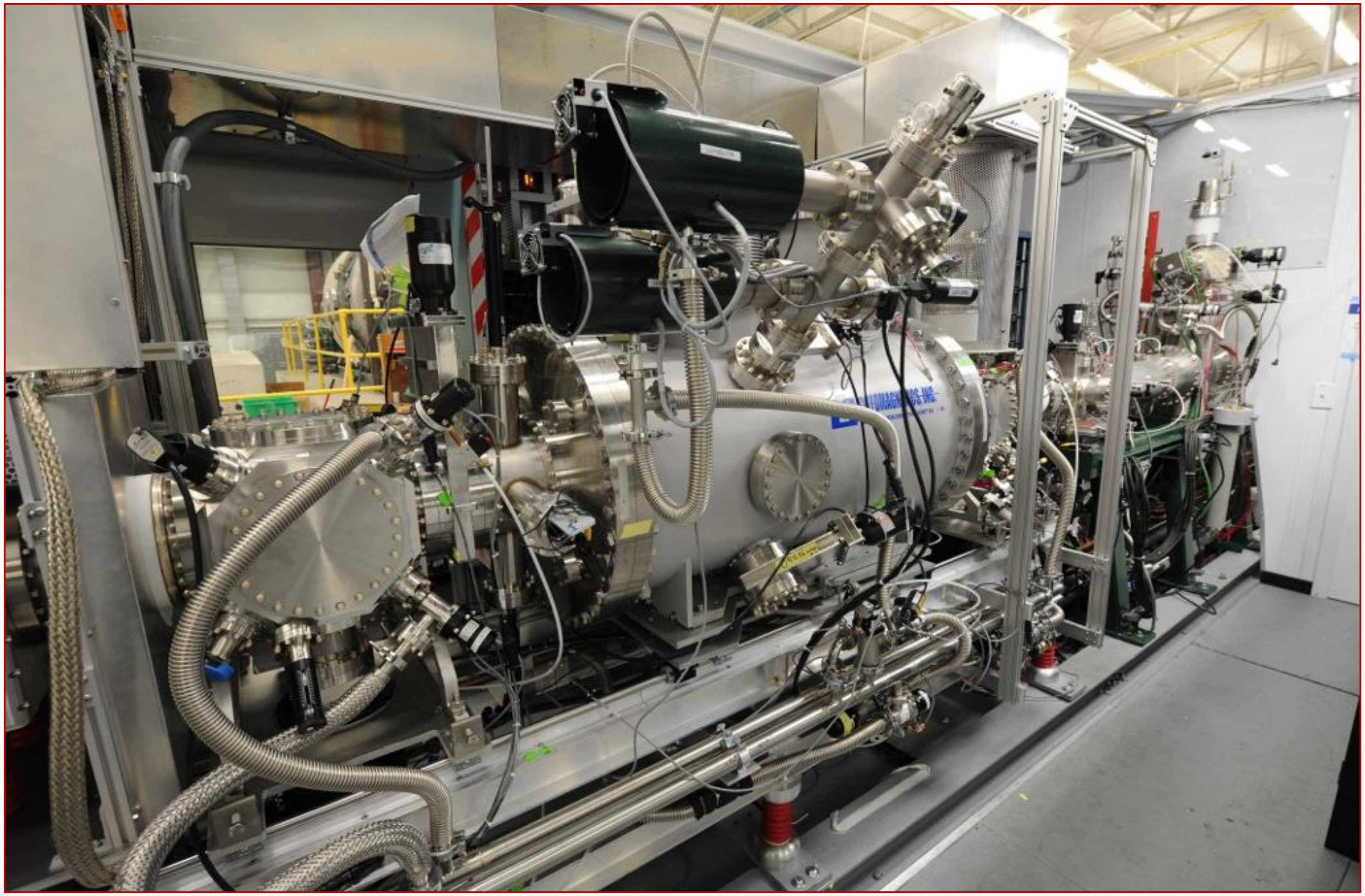
Sources of Contaminations

- O-Ring permeation
- Chamber walls (even after extensive cleaning!)
- O-Ring materials
- Vacuum chamber

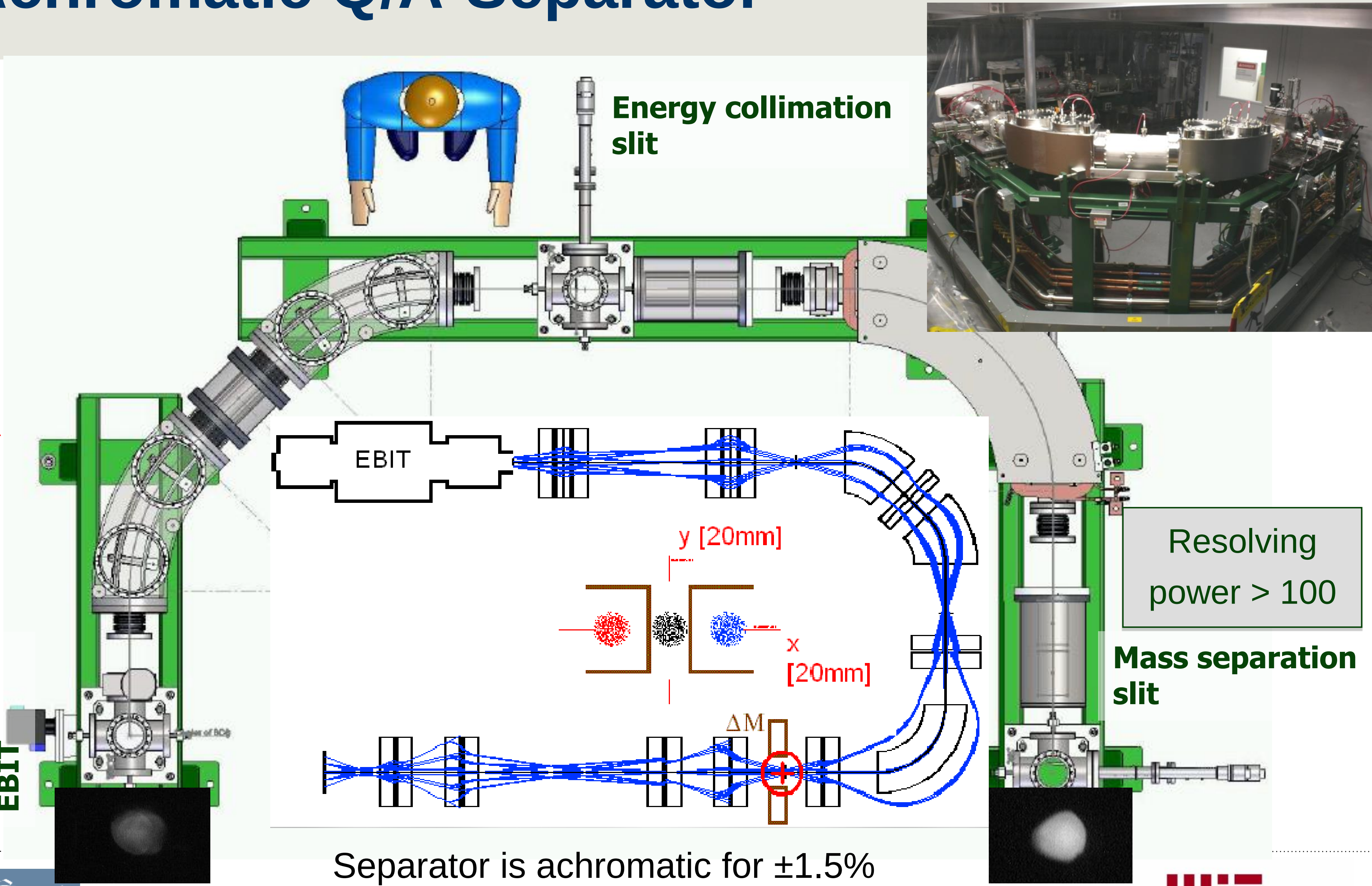
ReA Post-Accelerator at MSU



ReA EBIT: Cryogenic Vacuum System with base pressure $<10^{-11}$Torr!



Achromatic Q/A-Separator



Energy collimation slit

Resolving power > 100

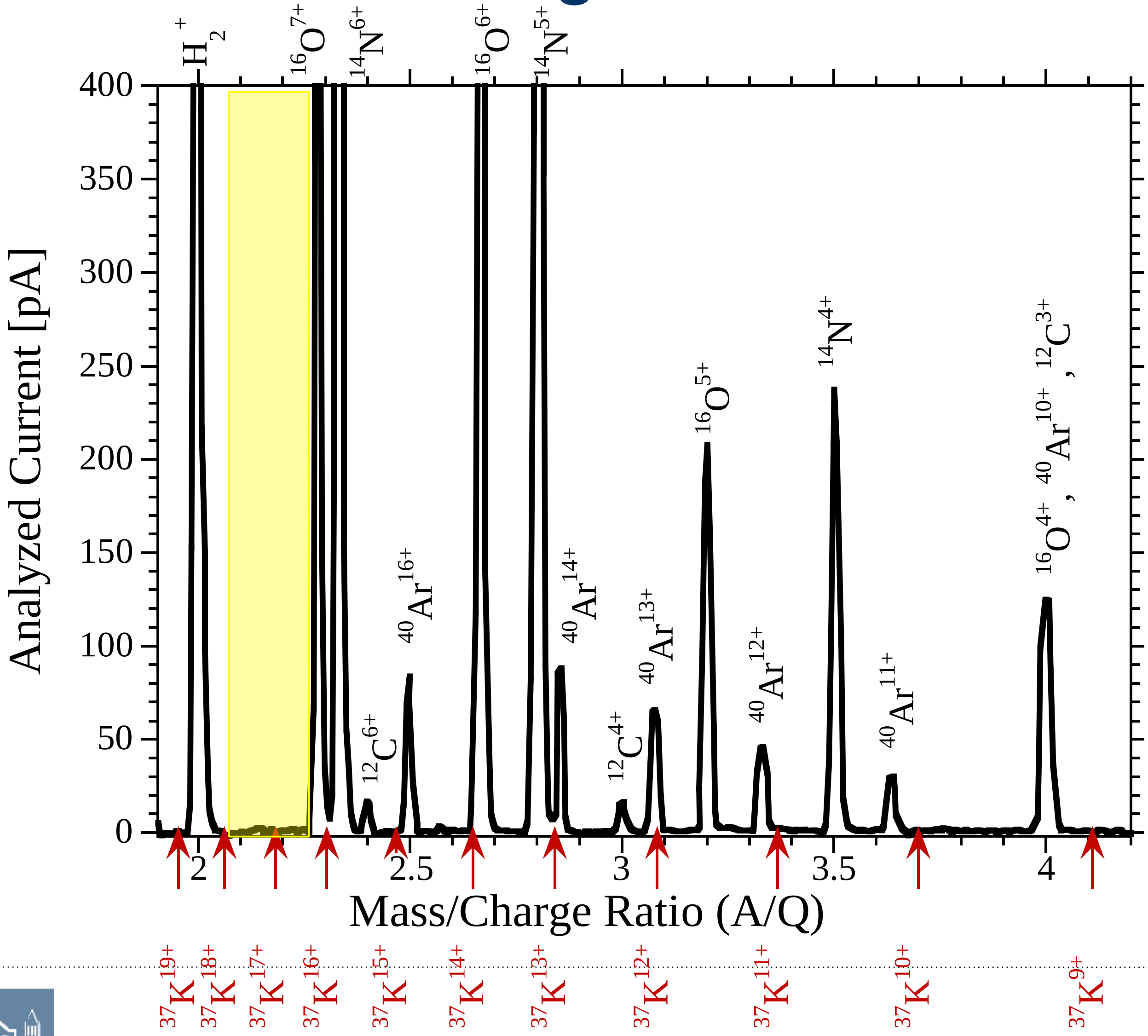
Mass separation slit

Beam from EBIT

Separator is achromatic for ±1.5% beam energy deviation

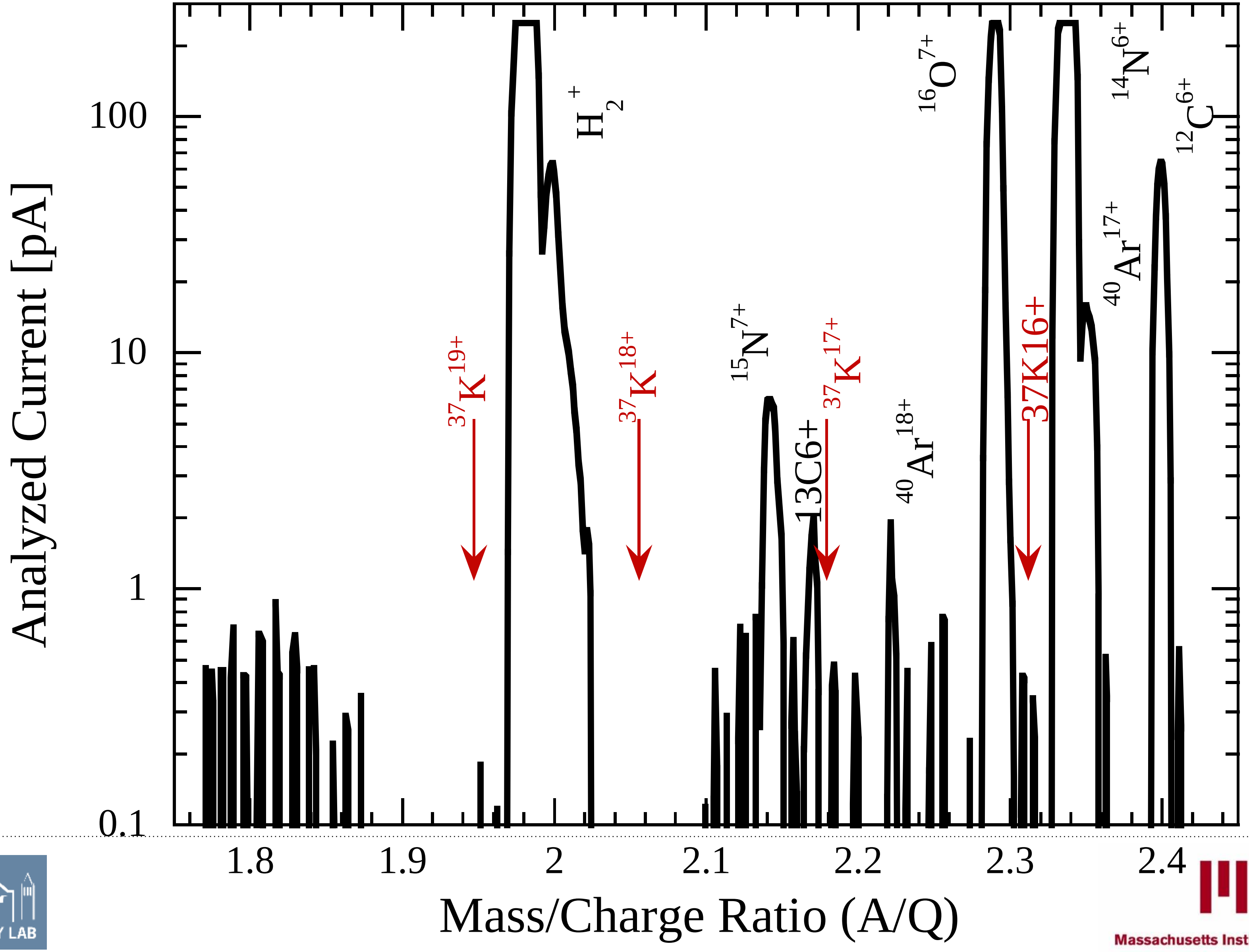
Courtesy of M. Pordilla, M. Doleans

EBIT spectrum zoom in for ReA EBIT after the achromatic charge state selection section



Preparation for a $^{37}K^{17+}$ beam
Selected charge state for the experiment was 17+ to achieve the energy required by the experiment

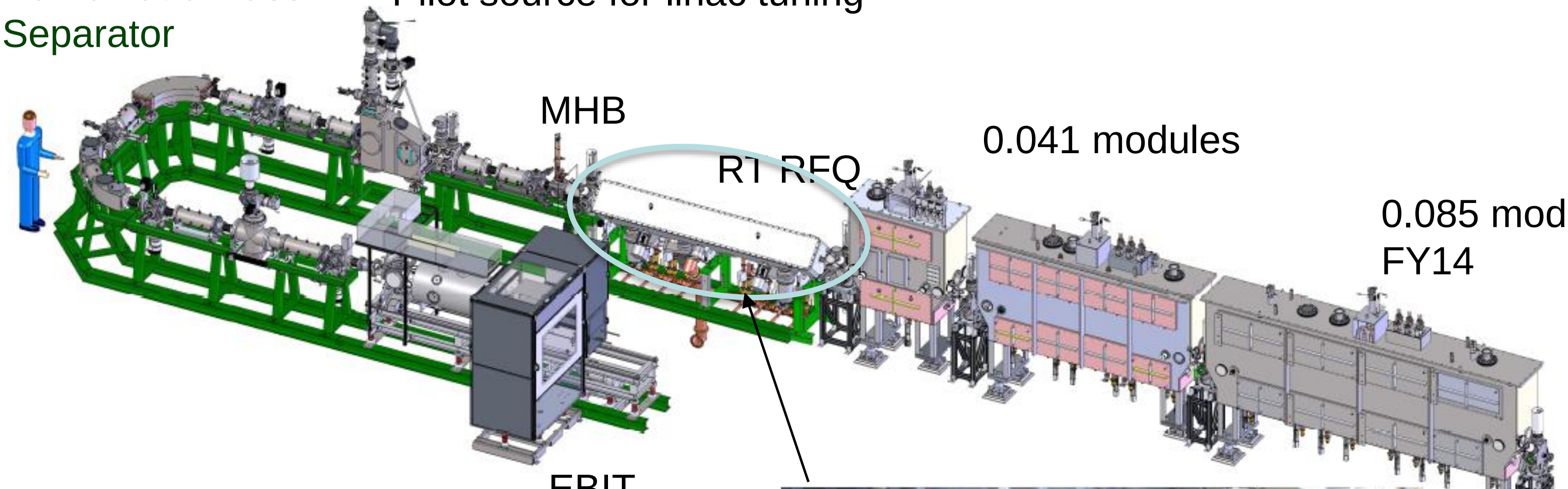
Zoom into the spectrum in the region of interest
Vacuum in the EBIT (cryogenic chamber walls): < 10^{-11}Torr



BERKELEY LAB

Massachusetts Institute of Technology

After mass selection ions get injected into the Radiofrequency Quadrupole and accelerated to 600keV/u



Achromatic Mass Separator

Pilot source for linac tuning

MHB

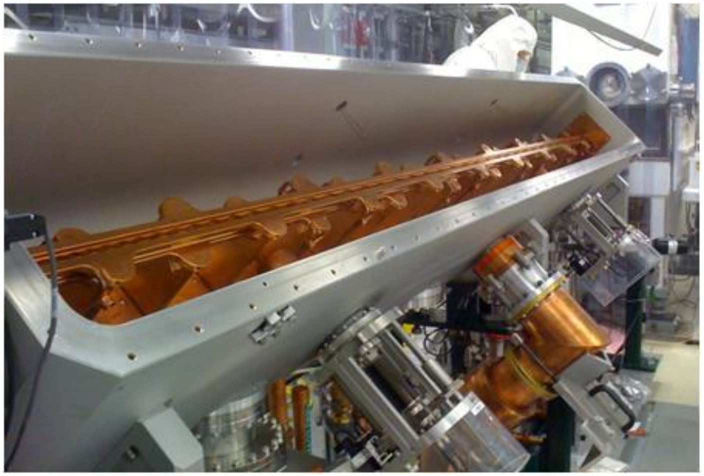
RT RFQ

0.041 modules

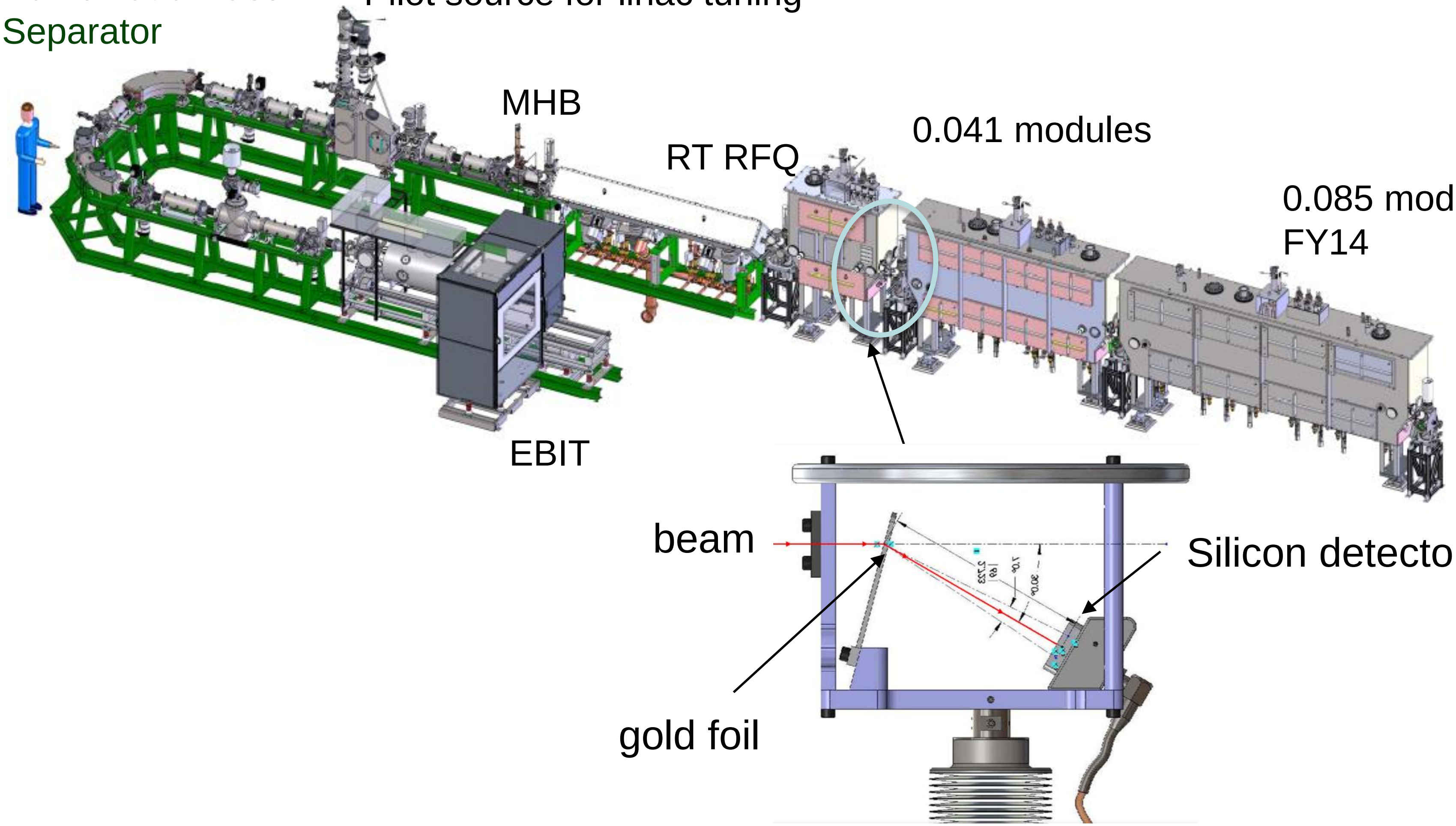
0.085 module FY14

EBIT

- RFQ is large acceptance in terms of Q/A (at least 10%)
- Any impurity after the analyzing section will be accelerated and captured by the linac



At this energy the beam is energetic enough to measure the beam composition using an scattering detector



Achromatic Mass Separator

Pilot source for linac tuning

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0.041 modules

0.085 module FY14

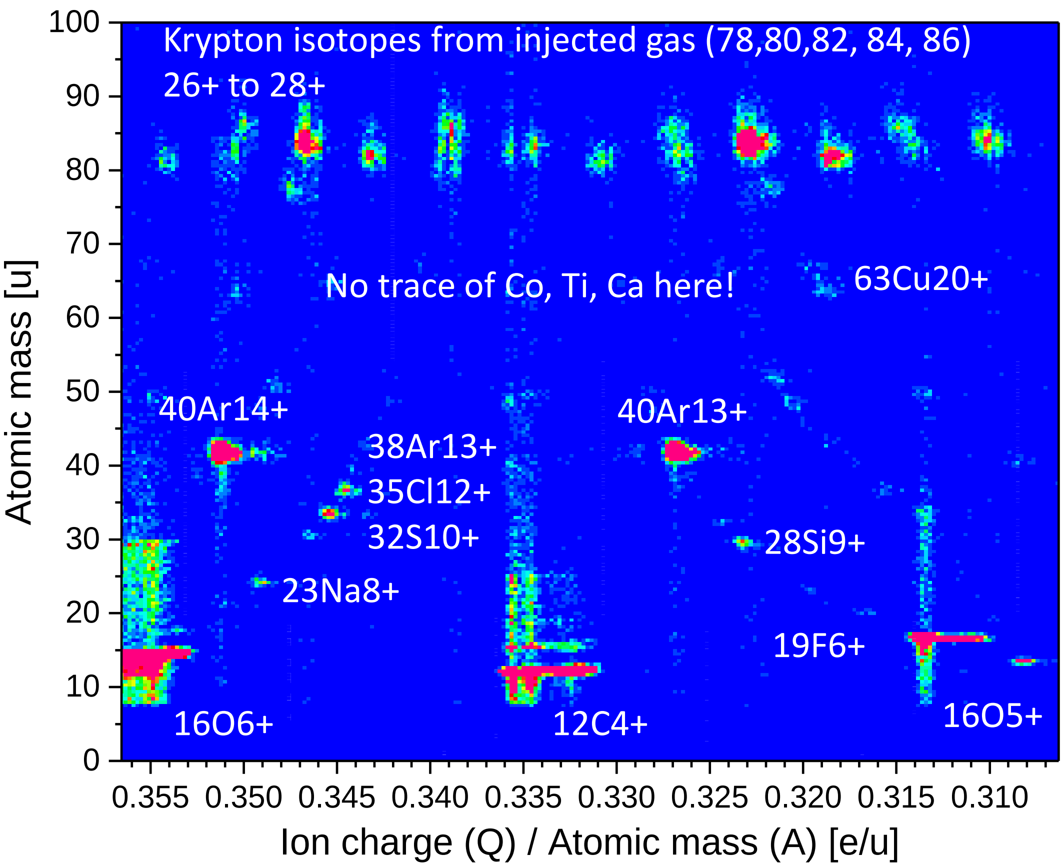
EBIT

beam

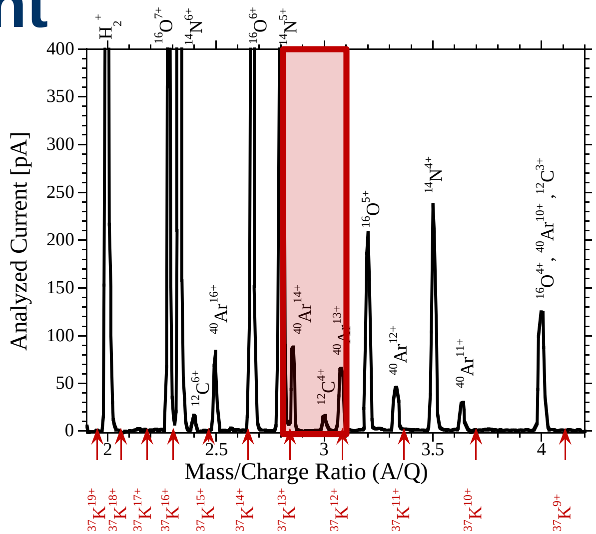
Silicon detector

gold foil

Contamination ‘Map’ for the ReA EBIT on the silicon detector after acceleration in a very small region in preparation for a Kr-77 experiment



Adjust ReA beam dipole magnet



Contaminants:

Na, Cl → NaCl (fingerprint?)

Si → Aluminized mylar tape adhesive

F → Scroll-pumps:
Bearing lubricant & tip seal (Teflon)

S → Dichronite UHV bearing lubricant (WS$_2$

Ba, W → Dispenser cathode

All C, N, O, Ar stable isotopes → from residual gas.

So you better understand the vacuum in the beam line along your accelerator column !

Key Concepts

- Ideal Gas Equation
- Maxwell-Boltzmann Statistics to describe the dynamics of the gas
- Molecular incident rate – flow rate
- Mean Free Path
- Flow regimes for vacuum systems – Knudsen Number
- Calculations of Vacuum Systems
  - Conductance and Pumping Speed
  - Outgassing and surface treatments

Chiggiato, P., *Vacuum Technology for Ion Sources*, in *CAS - CERN Accelerator School, Ion Sources*. 2013, CERN-2013-007.
Garton, D., *Vacuum Technology and Vacuum Design Handbook for Accelerator Technicians* 2011, http://apo.ansto.gov.au/dspace/handle/10238/4126

Ideal Gas Equation

$$PV = Nk_BT \text{ with } k_B = 1.38 \cdot 10^{-23} JK^{-1}$$
$$P = nk_BT$$

Describes particle balance

P, T and V are the gas pressure, temperature and volume
Given P, T one can calculate the gas density
for example
$P = 2 \cdot 10^{-5} Torr,\ n_0 = 6.4 \cdot 10^{12} \frac{1}{cm^3}$

Units

SI: Pa
$1Pa = 1 \cdot 10^{-5} bar, = 1 \cdot 10^{-5} atm \ = 7.5 \cdot 10^{-3} Torr,$
within the measuring accuracy of the ion gauges
$Torr \approx mbar$

- Gas quantities are often expressed at P*V for ion sources @ standard temp (e.g. 1 liter standard conditions: 1 atm, 293K)
- With the ideal gas equation one can calculate the number of atoms in the bottle
- If the efficiency of the IS or the gas flow requirement is known, one can estimate the consumption: Important for rare (expensive) gases and materials

Gas Dynamics

$$< v >= \sqrt{\frac{8k_bT}{\pi m_{molecule}}} = 145.51 \cdot \sqrt{\frac{T}{M}}$$

Boltzmann statistics

T in Kelvin

M is the Molecule Mass Number

Mean speed of gases at room temperature and cryogenic temperatures

	H_2	He	CH_4	N_2	Ar
$\langle v \rangle$ at 293 K ($m\,s^{-1}$)	1761	1244	622	470	394
$\langle v \rangle$ at 4.3 K ($m\,s^{-1}$)	213	151	75	57	48

Application:

- Pumping speed calculations, diffusion times…..
- Wave of gas will move with the speed above, typical fast valve closure time are in the ms range, to protect your vacuum system you will need several meters of beam line to protect equipment

Molecular Incident Rate

$$\varphi = \frac{1}{4} n \langle v \rangle,$$

Molecular impingement rate onto a surface

⇩

$$\varphi\,[\mathrm{cm}^{-2}\,\mathrm{s}^{-1}] = 2.635 \times 10^{22} \frac{P\,[\mathrm{mbar}]}{\sqrt{M[\mathrm{g}]\,T[\mathrm{K}]}}.$$

→ Maximum pump out speed for your vacuum system!

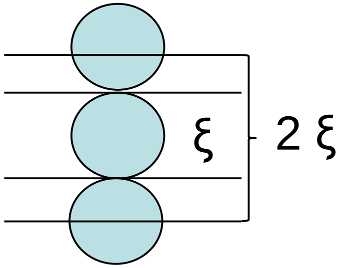
(example: for air the pump out speed is 11.6l/sec x area to pump out your vacuum system)

→ Surface coverage for UHV systems

Rule of thumb: at 10^{-6} mbar it takes 1 sec to cover a surface with one monolayer of residual gas

Mean Free Path

- Definition: Distance of travel between collisions of 2 molecules



$$\Delta V = \pi\xi^2 v \Delta t \ \ldots \ \text{Volume displacement}$$

$$\Delta V = \frac{1}{n} \ \ldots \ \text{volume that contains 1 particle}$$

$$\frac{1}{n} = \pi\xi^2 v\tau = \pi\xi^2\lambda$$

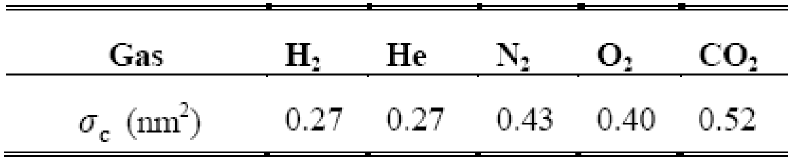
$$\lambda = \frac{1}{n\pi\xi^2}$$

$$\overline{\lambda} = \frac{1}{\sqrt{2}}\frac{1}{n\pi\xi^2} \quad \overline{\lambda} = \frac{1}{\sqrt{2}}\frac{1}{n\sigma_c}$$

σ_c …. collision cross section

n …. residual gas density

$$\boxed{\overline{\lambda} = \frac{1}{\sqrt{2}}\frac{1}{n\sigma_c}}$$



Gas	H_2	He	N_2	O_2	CO_2
σ_c (nm^2)	0.27	0.27	0.43	0.40	0.52

for $1 \cdot 10^{-5} torr$ λ is 5m for air

Chiggiato, P., *Vacuum Technology for Ion Sources*, in *CAS - CERN Accelerator School, Ion Sources*. 2013, CERN-2013-007.

Knudsen Number $K = \frac{\lambda}{D}$

- Compare λ to the dimension of the vacuum chamber determines the flow regime – determines how particles are transported in the vacuum system
- Knudsen Number: Ratio of the mean free path to a characteristic lengths of the vacuum system (D)

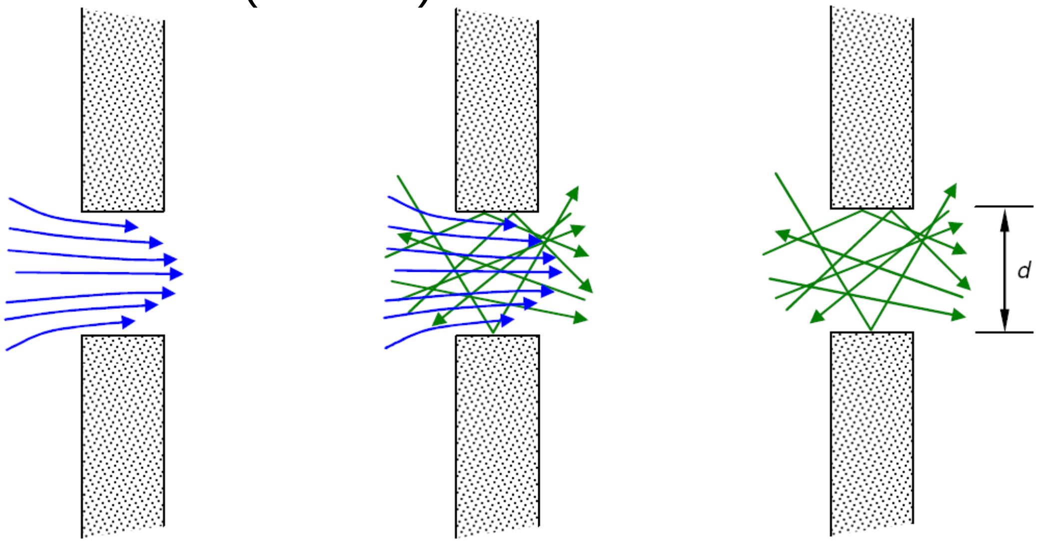
$$\begin{array}{ll} \mathrm{K} > 0.5 & \rightarrow \text{free molecular flow} \\ \mathrm{K} < 0.01 & \rightarrow \text{continous flow} \\ 0.5 < \mathrm{K} < 0.01 & \rightarrow \text{transitional flow} \end{array}$$

- Equilibrium vacuum codes calculate in the molecular flow regime, K > 0.5, molecular collisions with the wall are dominant
- For K < 0.01 molecular- molecular collisions are dominant –viscous flow
- Important for **particulate free vacuum system** (cryomodules), **pump down must be done very slowly,** once the vacuum level reaches **10^{-5} Torr** particulates follow gravity (accumulate on the bottom of the vacuum chamber)

Flow regimes

Transport through molecular-molecular collisions (viscous)

Transport through collisions with the wall



(Viscous Flow)
Laminar Re<2320, Kn<0.01
Turbulent Re>2320, Kn< 0.01
Low Vacuum

Knudsen Flow
$0.01 < Kn < 1.0$
Medium Vacuum

Molecular Flow
$Kn > 1.0$
High/Ultra High Vacuum

Fig 5. Molecular paths during different flow phases

Garton, D., *Vacuum Technology and Vacuum Design Handbook for Accelerator Technicians* 2011, http://apo.ansto.gov.au/dspace/handle/10238/4126

Conductance in free molecular flow

- Gas flow Q is defined as

$$Q = \frac{dPV}{dt} \quad [\text{liters mbar/sec}]$$

Gasflow/throughput

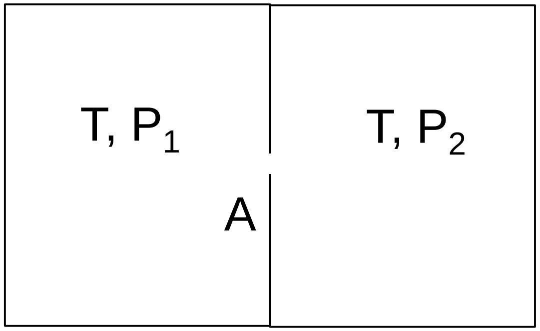
- The gas flow **Q** between two point of a vacuum system is **proportional to the pressure difference**
- The proportionality constant is called **Conductance**

$$Q_{1\rightarrow 2} = C(P_1 - P_2)$$

- Conductance is reported as volume per unit time, e.g. liters/sec
- For K>0.5, the conductance is independent from pressure and is only dependent on mean molecular speed and geometry

Practical Application

Simplest Geometry



$$\phi_{1\to 2} = \frac{1}{4} A n_1 < v >$$

$$\phi_{2\to 1} = \frac{1}{4} A n_2 < v >$$

Molecular incident rate on the aperture A

$$\phi_{1\to 2} - \phi_{2\to 1} = \frac{1}{4} A \frac{<v>}{kT} (P_1 - P_2)$$

$$Q = \boxed{\frac{1}{4} A < v >} (P_1 - P_2)$$

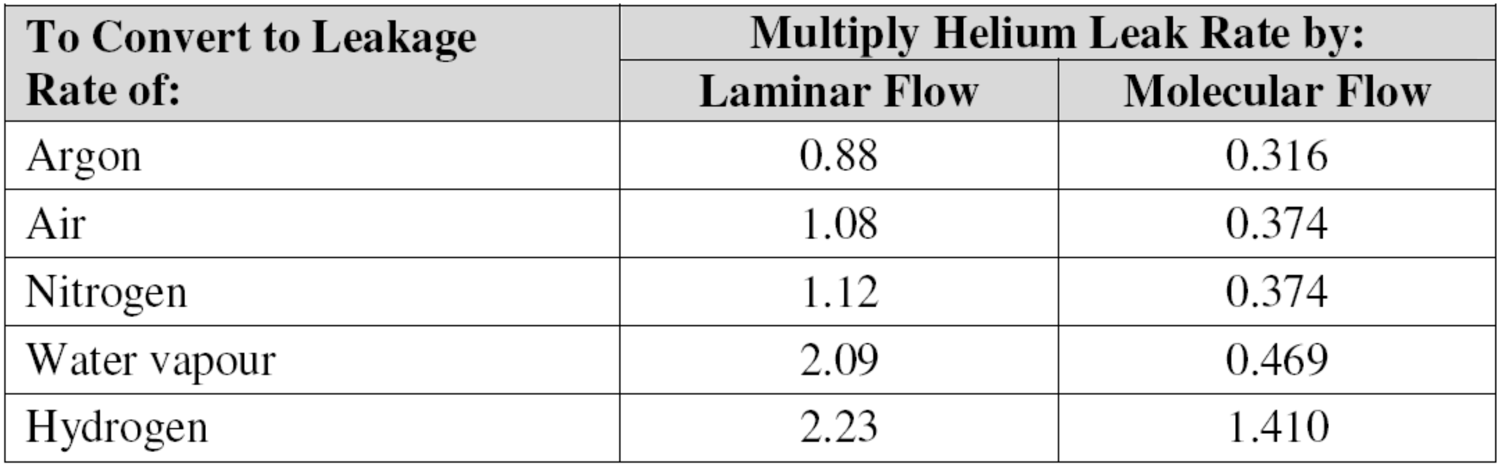
$$\nwarrow \; C \propto \sqrt{\frac{T}{m}}$$

- Conductance is proportional to T/m and to the area of the opening
- Used for differential pumping apertures
- For two gases proportional to

$$\frac{C_1}{C_2} = \sqrt{\frac{m_1}{m_2}}$$

To translate measured leak rates to other gases one must consider the mass difference !

- For a gas passing through small holes in a thin wall, the number of molecules that pass through a hole is proportional to the pressure of the gas and inversely proportional to its molecular weight.



To Convert to Leakage Rate of:	Multiply Helium Leak Rate by:	
	Laminar Flow	Molecular Flow
Argon	0.88	0.316
Air	1.08	0.374
Nitrogen	1.12	0.374
Water vapour	2.09	0.469
Hydrogen	2.23	1.410

Table 9. Conversation table for leak rates

Garton, D., *Vacuum Technology and Vacuum Design Handbook for Accelerator Technicians* 2011, http://apo.ansto.gov.au/dspace/handle/10238/4126

Complexer Geometries

- For more complex arrangements: calculate transmission probabilities

$$\phi_{1\rightarrow 2} = \tfrac{1}{4} A_1 n_1 < v > \tau_{1\rightarrow 2}$$
$$\phi_{2\rightarrow 1} = \tfrac{1}{4} A_2 n_2 < v > \tau_{2\rightarrow 1}$$

τ . . . transmission probability through the connecting pipe

$A_2 \tau_{2\rightarrow 1} = A_1 \tau_{1\rightarrow 2}$ for $n_1 = n_2$ and $\phi_1 = \phi_2$

for $n_1 \neq n_2$ a net flow develops

$\phi_{1\rightarrow 2} - \phi_{2\rightarrow 1} = \frac{1}{4} A_1 \frac{<v>}{kT} \tau_{1\rightarrow 2}(P_1 - P_2)$ multiply by kT

$Q = C_{A1} \cdot \tau_{1\rightarrow 2}(P_1 - P_2)$

Chiggiato, P., *Vacuum Technology for Ion Sources*, in *CAS - CERN Accelerator School, Ion Sources*. 2013, CERN-2013-007.

Complexer Geometries

- For more complex arrangements: calculate transmission probabilities

$$\phi_{1\rightarrow 2} - \phi_{2\rightarrow 1} = \frac{1}{4} A_1 \frac{<v>}{kT} \tau_{1\rightarrow 2}(P_1 - P_2) \text{ multiply by } kT$$

$$Q = C_{A1} \cdot \tau_{1\rightarrow 2}(P_1 - P_2)$$

- The conductance of the connecting duct is equal to the conductance of the duct entrance in vessel 1, considered as a wall slot, multiplied by the molecular transmission probability from vessel 1 to vessel 2.
- The transmission probability depends on the geometry of the system – many analytical approximations
- Simulation programs calculate the probability through the Monte Carlo algorithm (e.g. MolFlow)

Chiggiato, P., *Vacuum Technology for Ion Sources*, in *CAS - CERN Accelerator School, Ion Sources*. 2013, CERN-2013-007.

Uniform circular cross-section of length *L* and radius *R*

Santeler (1986)

$$\tau = \tau_{1\rightarrow 2} = \tau_{2\rightarrow 1} = \frac{1}{1+\frac{3L}{8R}(1+\frac{1}{3(1+\frac{L}{7R})}} \longrightarrow \frac{L}{R} >> 1$$

Approximation for long tubes

$$\tau \approx \frac{1}{1+\frac{3L}{8R}} \approx \frac{8}{3}\frac{R}{L}.$$

$$C = \tau \cdot R^2 \cdot \pi \frac{<v>}{4}$$

$$< v > = \sqrt{8k\frac{T}{\pi M}} = 470\frac{m}{sec}$$

for N_2

Easy applicable estimate tool:

$$C \approx 11.75 \times \frac{\pi D^2}{4} \times \frac{4D}{3L} = 12.3\frac{D^3}{L}\,[\mathrm{l\,s^{-1}}]\ \ ([D]\ \text{and}\ [L] = \text{cm}).$$

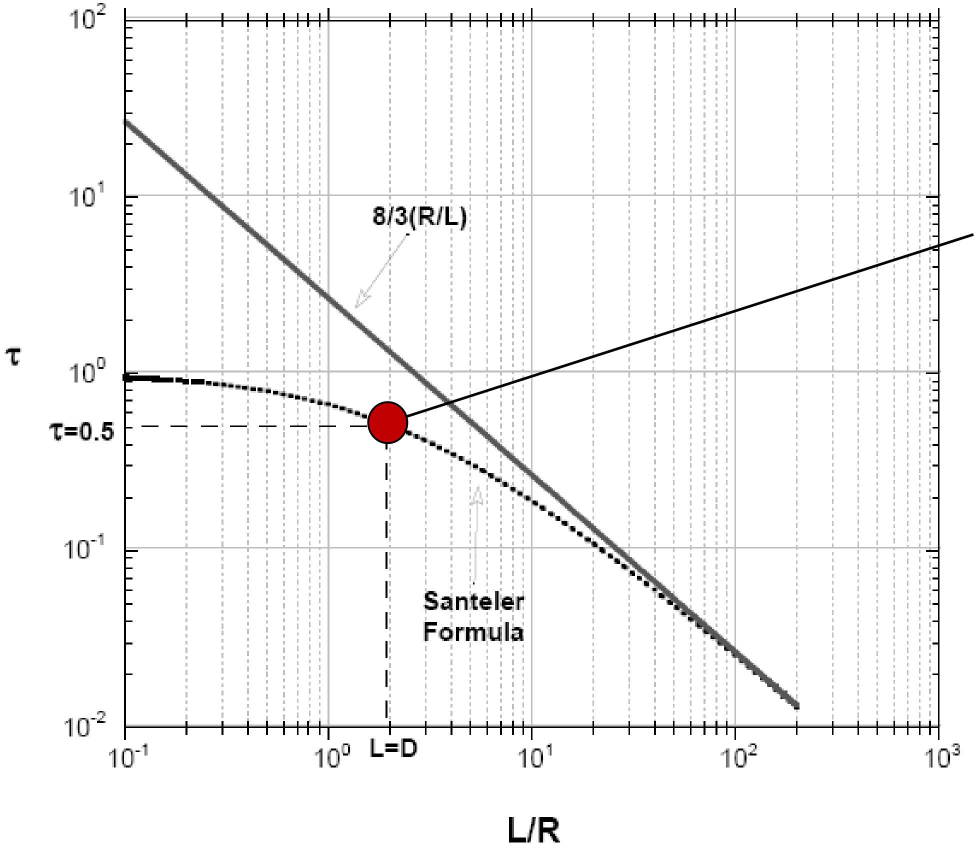
Conductance is strongly dependent on D !!

Long tube approximation has an error of less than 10% for L/R>>20, below the Santeler approximation should be used which has less than 0.7% error

Santeler, D.J., *Exit loss in viscous tube flow.* Journal of Vacuum Science & Technology A, 1986. **4**(3): p. 348-352.

Chiggiato, P., *Vacuum Technology for Ion Sources*, in *CAS - CERN Accelerator School, Ion Sources*. 2013, CERN-2013-007.

Transmission probability of tubes of uniform circular cross-section calculated by the Santeler equation and its approximation for high L/R.

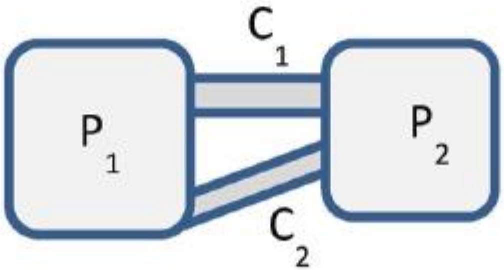


The transmission probability is about 0.5 for circular tubes for which the diameter is equal to their length.
The conductance of such tubes is half that of their entrance surface.

Chiggiato, P., *Vacuum Technology for Ion Sources*, in *CAS - CERN Accelerator School, Ion Sources*. 2013, CERN-2013-007.

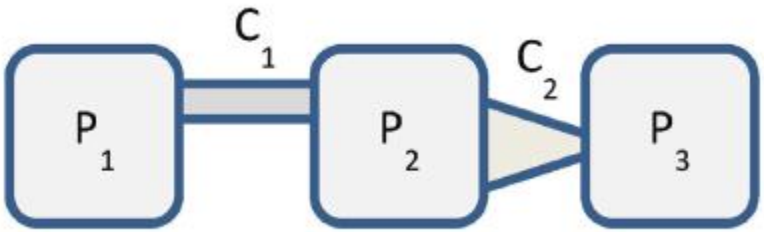
Combining Conductances

Parallel flow



$$Q = (C_1 + C_2)(P_1 - P_2)$$
$$Q = (C_{TOT})(P_1 - P_2)$$

Series flow



$$Q = C_1(P_1 - P_2)$$
$$Q = C_2(P_2 - P_3)$$

$$Q = C_{TOT}(P_1 - P_3) \;\rightarrow\; \frac{1}{C_{TOT}} = \frac{1}{C_1} + \frac{1}{C_2}$$

Or in general

$$C_{TOT} = \sum_{i=1}^{i=N} C_i$$

$$\frac{1}{C_{TOT}} = \sum_{i=1}^{i=N} \frac{1}{C_i}$$

Chiggiato, P., *Vacuum Technology for Ion Sources*, in *CAS - CERN Accelerator School, Ion Sources*. 2013, CERN-2013-007.

Pumping Speed

- Vacuum pumps removes gas molecules
- The pumping speed S can be defined as the ratio between the pumped gas flow and the pump inlet pressure [V/time, liters/sec]

$$S = \frac{Q_p}{P} \longrightarrow S = \frac{dQ_p}{dP}$$

$$Q_p = \frac{<v>}{4} A n \sigma = \frac{\sqrt{\frac{8 k_b T}{\pi m_{mol}}}}{4} A \frac{P}{kT} \sigma \propto \boxed{\sqrt{\frac{1}{M}}}$$

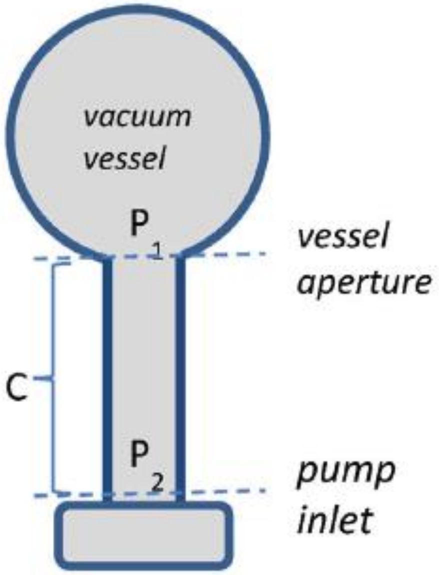
- σ…. probability for a molecule that enters the pump to be removed
- Hydrogen has the highest pumping speed – pumps typically are quoted for nitrogen
- Nominal pumping speed is only valid at the pump inlet!

BERKELEY LAB

Chiggiato, P., *Vacuum Technology for Ion Sources*, in *CAS - CERN Accelerator School, Ion Sources*. 2013, CERN-2013-007.

Massachusetts Institute of Technology

Effective Pumping Speed



- Pump is connected via a pipe to the vacuum system $P_1 > P_2$

$$Q = C_1(P_1 - P_2) = SP_2 = S_{eff}P_1$$

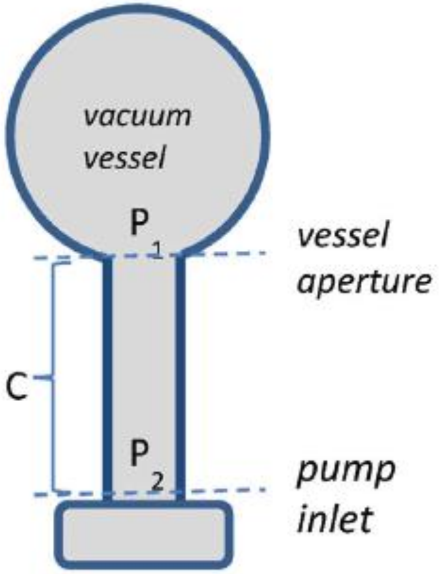
$$\frac{Q}{S} = P_2, \ \frac{Q}{S_{eff}} = P_1$$

$$\frac{Q}{S_{eff}} - \frac{Q}{S} = (P_1 - P_2) = \frac{Q}{C1}$$

$$\boxed{\frac{1}{S_{eff}} = \frac{1}{S} + \frac{1}{C1}}$$

Chiggiato, P., *Vacuum Technology for Ion Sources*, in *CAS - CERN Accelerator School, Ion Sources*. 2013, CERN-2013-007.

Effective Pumping Speed



- Effective pumping speed is the pumping speed at the vacuum vessel

$$\frac{1}{S_{eff}} = \frac{1}{S} + \frac{1}{C1}$$

For C<<S: $Seff \approx C$

- If the conductance is very low the pumping speed of the pump has little effect on the final pressure, but it is dominated by the conductance of the pipe!
- Example: If a turbo pump is mounted with a standard nipple R=2", L=10" S_{eff} is reduced by 30% for S=100 l/sec, but by 70% for S=1000l/sec

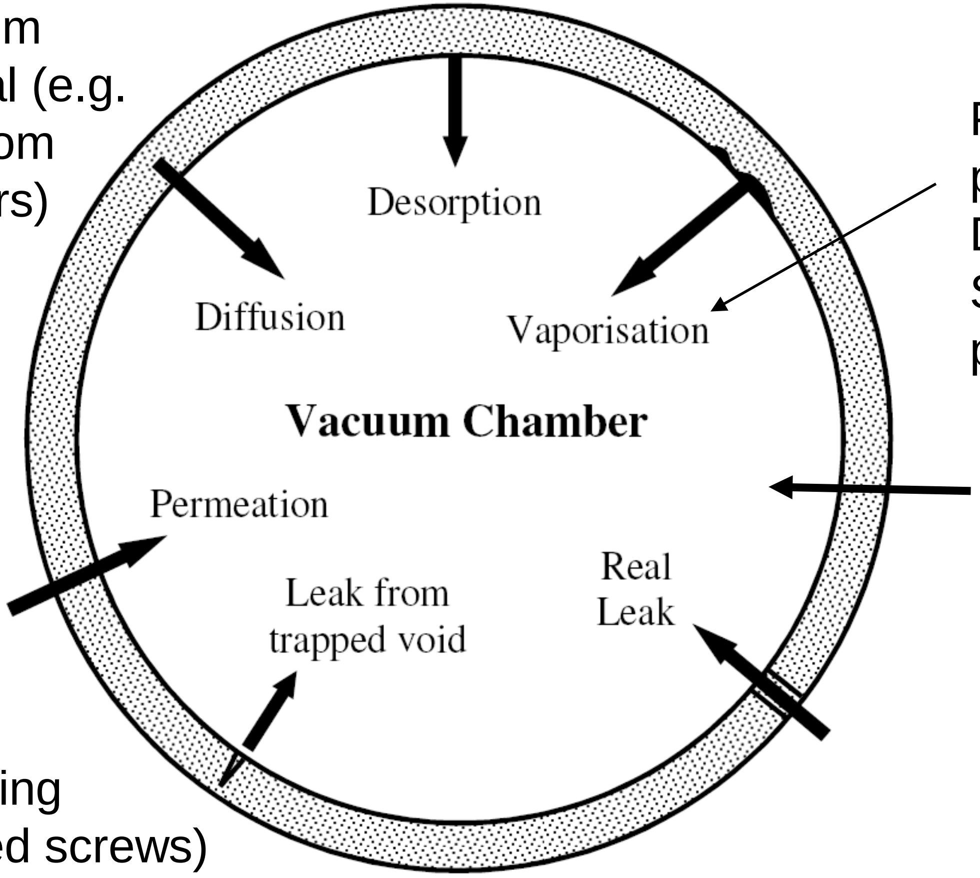
Chiggiato, P., *Vacuum Technology for Ion Sources*, in *CAS - CERN Accelerator School, Ion Sources*. 2013, CERN-2013-007.

Vacuum loads to the system

Gases frozen on the surface

Diffusion from bulk material (e.g. hydrogen from SS chambers)

Particles previously Deposited Sputtering of the plasma



Back streaming from vacuum pumps (or material diffusion from vacuum pump components)

O-rings

Poor engineering (e.g non vented screws)

Fig 8. Unwanted gas source wheel

Garton, D., *Vacuum Technology and Vacuum Design Handbook for Accelerator Technicians* 2011, http://apo.ansto.gov.au/dspace/handle/10238/4126

Outgassing and sources of gas into the vacuum system q

Denotes as small q :Gas Flow/Surface Area [(Volume*Pressure)/(time*area)]

- Intentional gas injection
- Material released from the surfaces
- Leaks

Depending on how the surface has been processed (choosing q for vacuum calculations is tricky!)

- polishing and final machining, etching…
- vacuum cleaning
- the smoother the surface area the lower the outgassing rate

Outgassing and sources of gas into the vacuum system

- After UHV cleaning, the outgassing is dominated by water

Organics

$$q_{H_2O} \approx \frac{1}{\sqrt{t[h]}} \frac{mbarl}{scm^2}$$

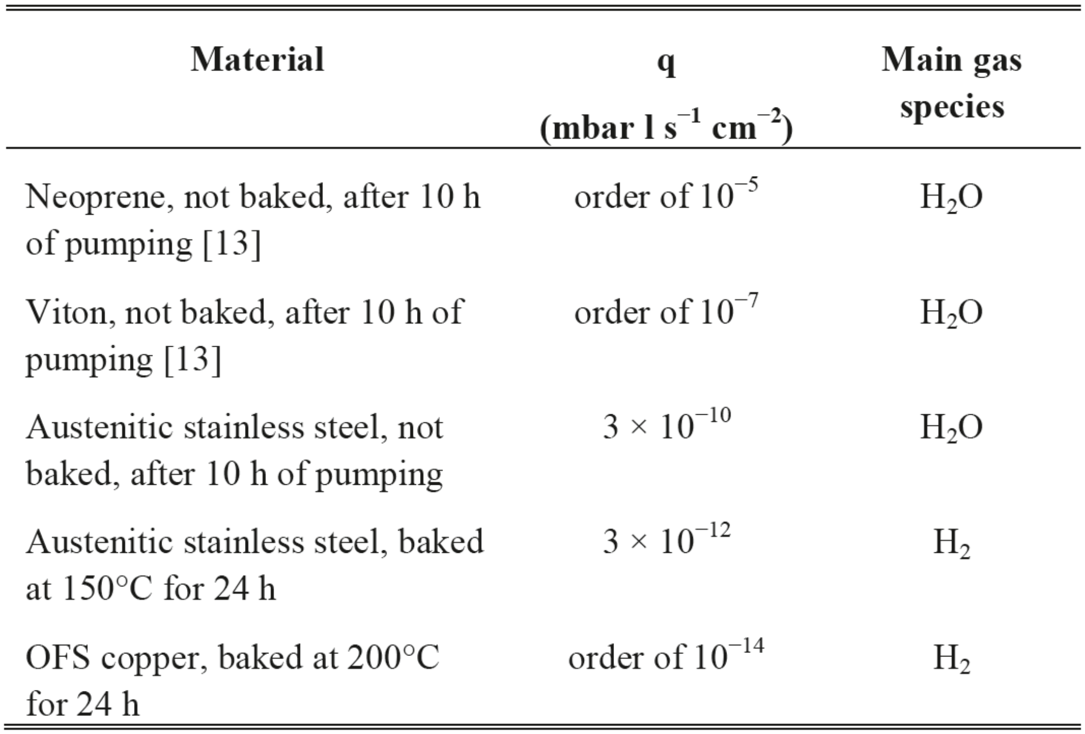
Metals

$$q_{H_2O} \approx \frac{3 \cdot 10^{-9}}{t[h]} \frac{mbarl}{scm^2}$$

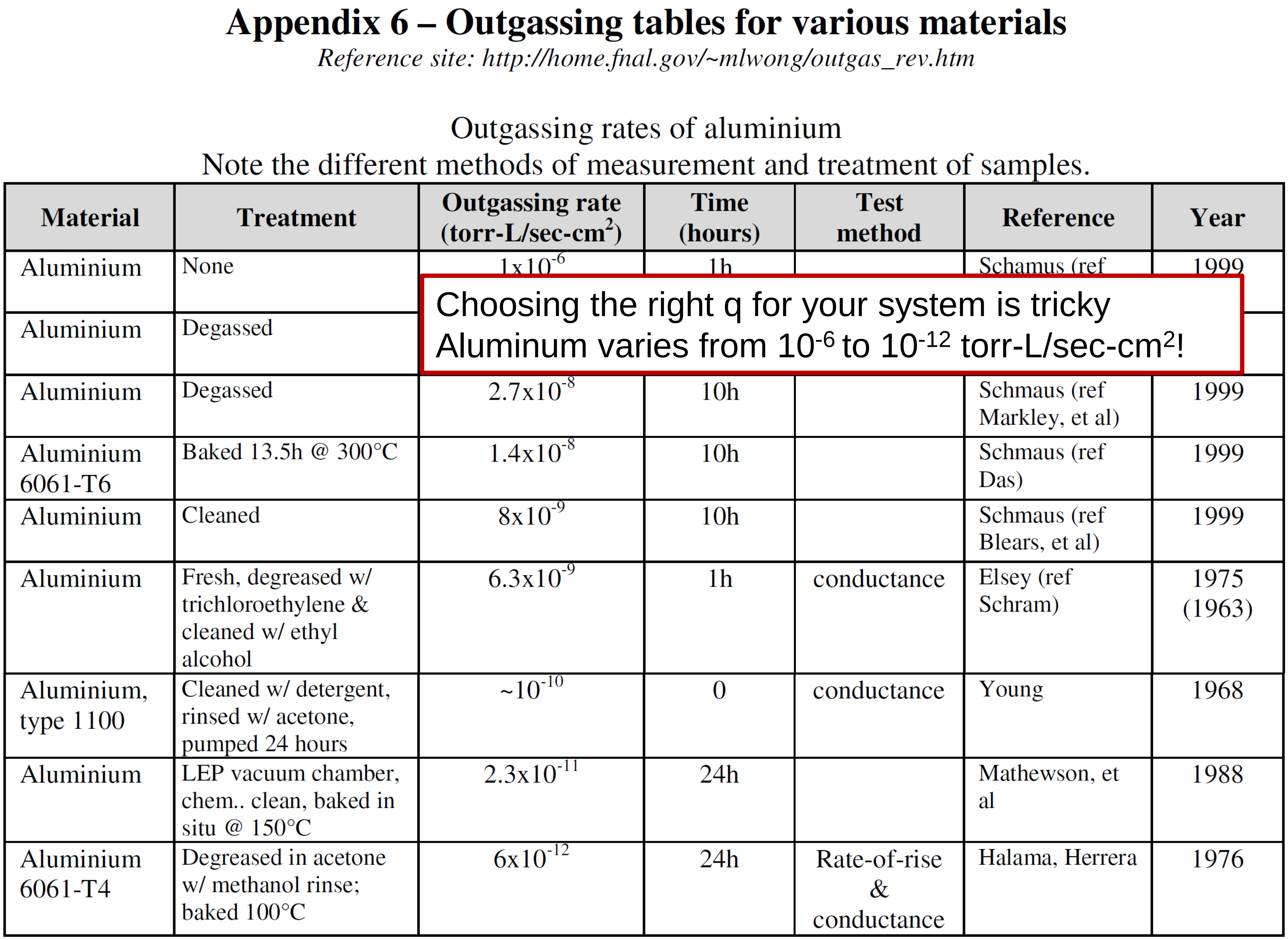
  - bake out (12h, 120 degrees)
  - after baking that the spectrum is dominated by H_2 diffusion, bake out at higher temperature

Outgassing rates for various materials

- Appendix: Garton, D., Vacuum Technology and Vacuum Design Handbook for Accelerator Technicians 2011, http://apo.ansto.gov.au/dspace/handle/10238/4126



Material	**q** (mbar l s^{-1} cm^{-2})	**Main gas species**
Neoprene, not baked, after 10 h of pumping [13]	order of 10^{-5}	H_2O
Viton, not baked, after 10 h of pumping [13]	order of 10^{-7}	H_2O
Austenitic stainless steel, not baked, after 10 h of pumping	3×10^{-10}	H_2O
Austenitic stainless steel, baked at 150°C for 24 h	3×10^{-12}	H_2
OFS copper, baked at 200°C for 24 h	order of 10^{-14}	H_2



Appendix 6 – Outgassing tables for various materials

Reference site: http://home.fnal.gov/~mlwong/outgas_rev.htm

Outgassing rates of aluminium

Note the different methods of measurement and treatment of samples.

Material	Treatment	Outgassing rate (torr-L/sec-cm^2)	Time (hours)	Test method	Reference	Year
Aluminium	None	1×10^{-6}	1h		Schamus (ref	1999
Aluminium	Degassed					
Aluminium	Degassed	2.7×10^{-8}	10h		Schmaus (ref Markley, et al)	1999
Aluminium 6061-T6	Baked 13.5h @ 300°C	1.4×10^{-8}	10h		Schmaus (ref Das)	1999
Aluminium	Cleaned	8×10^{-9}	10h		Schmaus (ref Blears, et al)	1999
Aluminium	Fresh, degreased w/ trichloroethylene & cleaned w/ ethyl alcohol	6.3×10^{-9}	1h	conductance	Elsey (ref Schram)	1975 (1963)
Aluminium, type 1100	Cleaned w/ detergent, rinsed w/ acetone, pumped 24 hours	$\sim 10^{-10}$	0	conductance	Young	1968
Aluminium	LEP vacuum chamber, chem.. clean, baked in situ @ 150°C	2.3×10^{-11}	24h		Mathewson, et al	1988
Aluminium 6061-T4	Degreased in acetone w/ methanol rinse; baked 100°C	6×10^{-12}	24h	Rate-of-rise & conductance	Halama, Herrera	1976

Choosing the right q for your system is tricky

Aluminum varies from 10^{-6} to 10^{-12} torr-L/sec-cm^2!

Calculation of pressure profiles

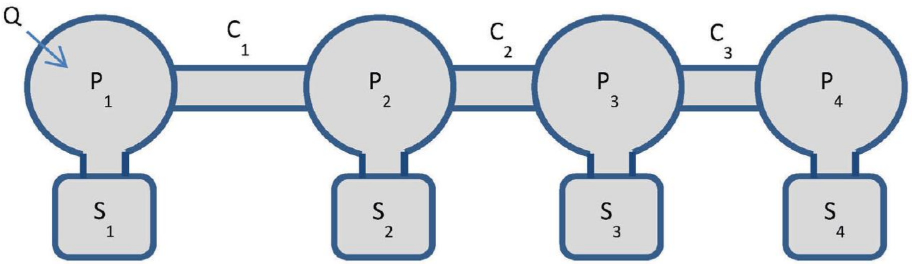
- In simplest form the pressure is the combination of the base pressure + the gas load/pumping speed
- Simple vacuum vessel

$$P = \frac{Q}{S} + P_0$$

$$P = \frac{Q}{S_{eff}} + P_0,$$

$$\frac{1}{S_{eff}} = \frac{1}{S} + \frac{1}{C}$$

- The vacuum can be calculated by considering each vessel and carry the gas load to the next vessel



New Q

$$Q = P_1 S_1 + \boxed{C_1(P_1 - P_2)}$$

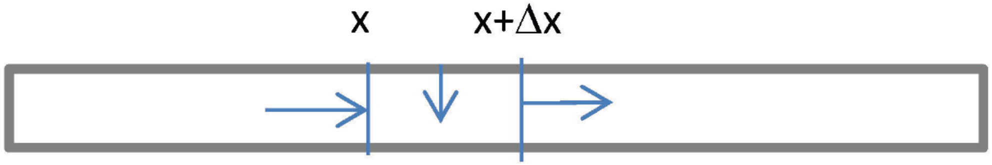
$$\boxed{C_1(P_1 - P_2)} = P_2 S_2 + \boxed{C_2(P_2 - P_3)}$$

$$\boxed{C_2(P_2 - P_3)} = P_3 S_3 + C_3(P_3 - P_4)$$

$$C_3(P_3 - P_4) = P_4 S_4$$

Chiggiato, P., *Vacuum Technology for Ion Sources*, in *CAS - CERN Accelerator School, Ion Sources*. 2013, CERN-2013-007.

Pressure profiles generated by distributed gas sources

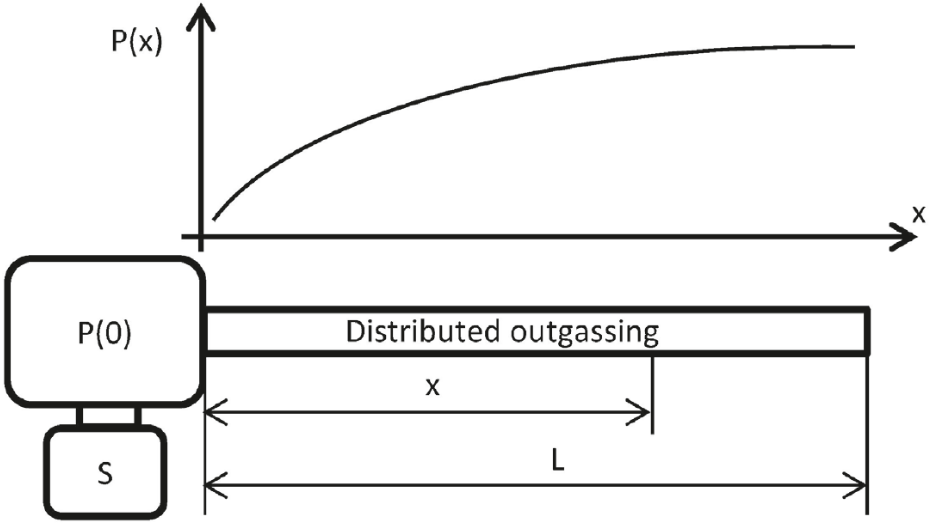


$$Q(x+\Delta x)-Q(x)=2\pi R\Delta x\, q \quad \Rightarrow \quad \frac{\mathrm{d}Q}{\mathrm{d}x}=2\pi R\, q,$$

$$Q(x+\Delta x)=-C\frac{L}{\Delta x}\left(P\left(x+\Delta x\right)-P(x)\right)=-CL\frac{\Delta P}{\Delta x} \quad \Rightarrow \quad Q(x)=-CL\frac{\mathrm{d}P}{\mathrm{d}x},$$

$$\Rightarrow \quad CL\frac{\mathrm{d}^2 P}{\mathrm{d}^2 x}=-2\pi R\, q,$$

Pressure profiles generated by distributed gas sources



Boundary Conditions

$$P(0)=\frac{Q_{TOT}}{S}=\frac{2\pi RLq}{S},$$

$$\left(\frac{dP}{dx}\right)_{x=L}=0.$$

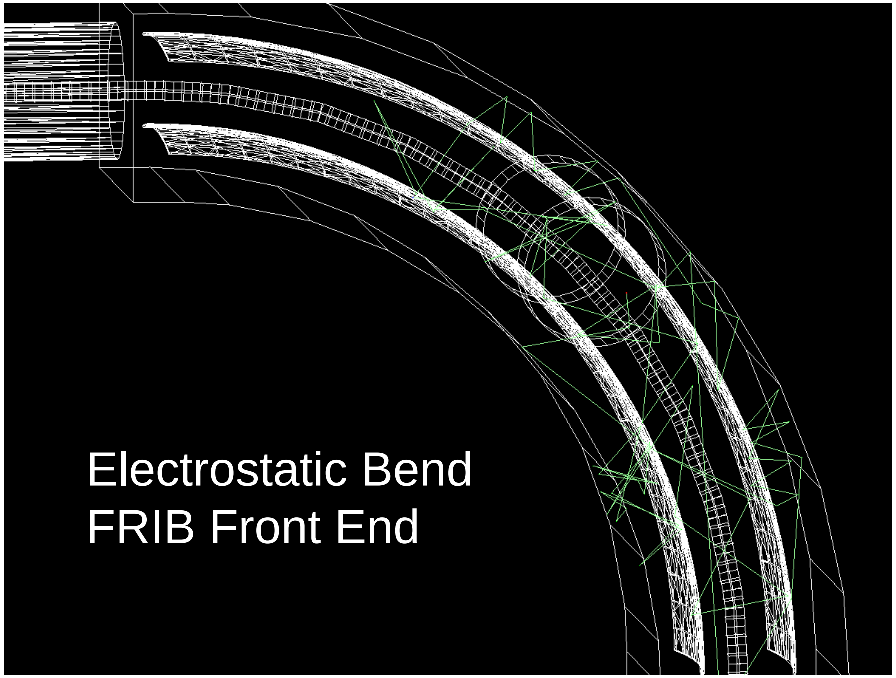
$$P(x)-P(0)=-\frac{Q_{TOT}}{C}\left[\left(\frac{x}{L}\right)-\frac{1}{2}\left(\frac{x}{L}\right)^2\right],$$

$$P(L)-P(0)=-\frac{Q_{TOT}}{2C}.$$

- Pressure is lowest at the pump and then increases parabolically to the end of the pipe
- The average pressure can be calculated by integrating the pressure over the pipe and divide it by the lengths of the pipe.

Simulation tools: Standard code is MolFlow developed by Roberto Kersevan (CERN)

- Particles bounce off walls in random direction
- No memory of momentum before the interaction
- Outgoing probability distribution governed by Lambert's Cosine Law
- Pressure obtained from particle hit counts over a given surface
- Provides stationary-state pressure profiles



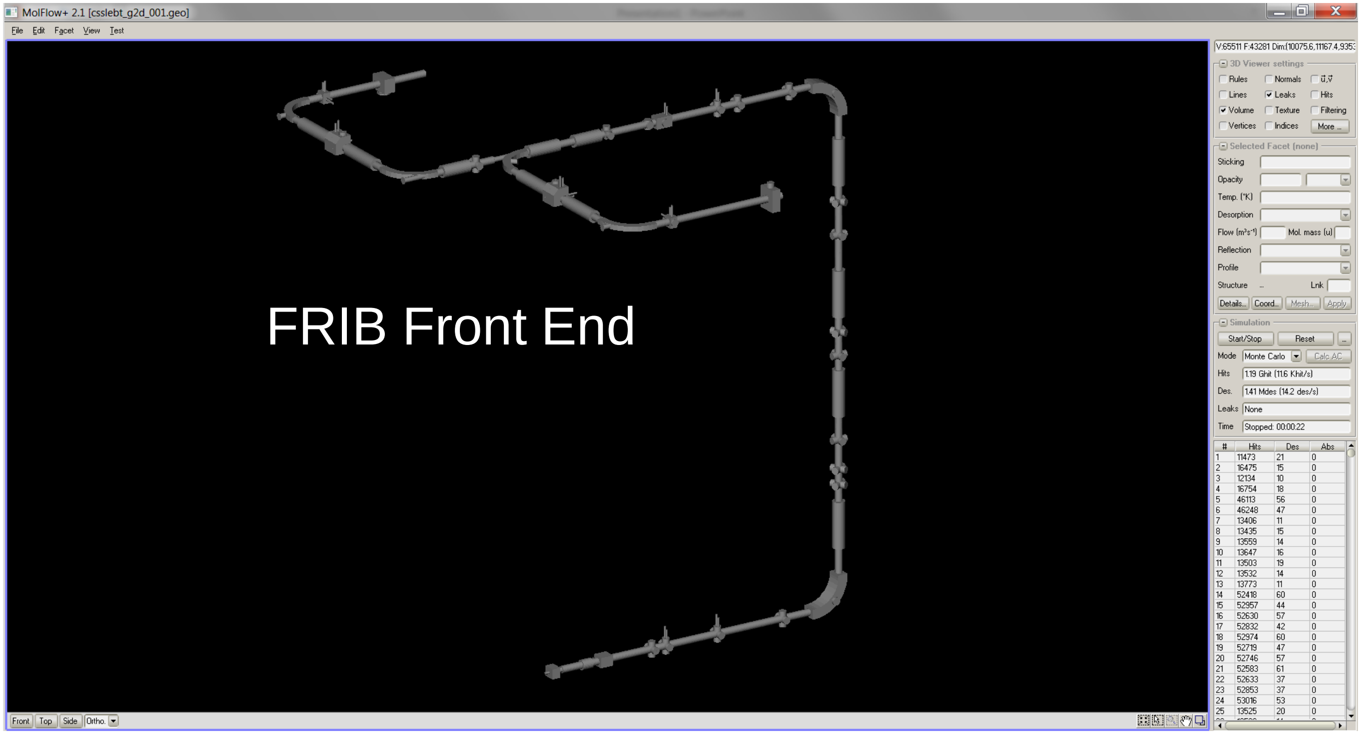
Particles bouncing off the dipole electrodes and chamber walls
in the vertical drop dipole in FRIB Front End

R. Kersevan and J.-L. Pons, J. Vac. Sci. Technol. , 2009. **A27**: p. 1017.
Molflow+ is available at http://test-molflow.web.cern.ch/.

Courtesy of Bojan Durikovic, FRIB project, MSU

Simulation tools: Standard code is MolFlow developed by Roberto Kersevan (CERN)

Molflow+ interface with a model of the FRIB Front End
(from the two ECR sources to the RFQ entrance down in the tunnel)



V:65511 F:43281 Dim:(10075.6,11167.4,9353

☐ Rules ☐ Normals ☐ u,v
☐ Lines ☑ Leaks ☐ Hits
☑ Volume ☐ Texture ☐ Filtering
☐ Vertices ☐ Indices

Sticking
Opacity
Temp. (°K)
Desorption
Flow (m^3s^{-1}) Mol. mass (u)
Reflection
Profile
Structure ... Lnk

Mode: Monte Carlo
Hits: 1.19 Ghit (11.6 Khit/s)
Des.: 1.41 Mdes (14.2 des/s)
Leaks: None
Time: Stopped: 00:00:22

#	Hits	Des	Abs
1	11473	21	0
2	16475	15	0
3	12134	10	0
4	16754	18	0
5	46113	56	0
6	46248	47	0
7	13406	11	0
8	13435	15	0
9	13559	14	0
10	13647	16	0
11	13503	19	0
12	13532	14	0
13	13773	11	0
14	52418	60	0
15	52957	44	0
16	52630	57	0
17	52832	42	0
18	52974	60	0
19	52719	47	0
20	52746	57	0
21	52583	61	0
22	52633	37	0
23	52853	37	0
24	53016	53	0
25	13525	20	0

R. Kersevan and J.-L. Pons, J. Vac. Sci. Technol. , 2009. **A27**: p. 1017.
Molflow+ is available at http://test-molflow.web.cern.ch/.

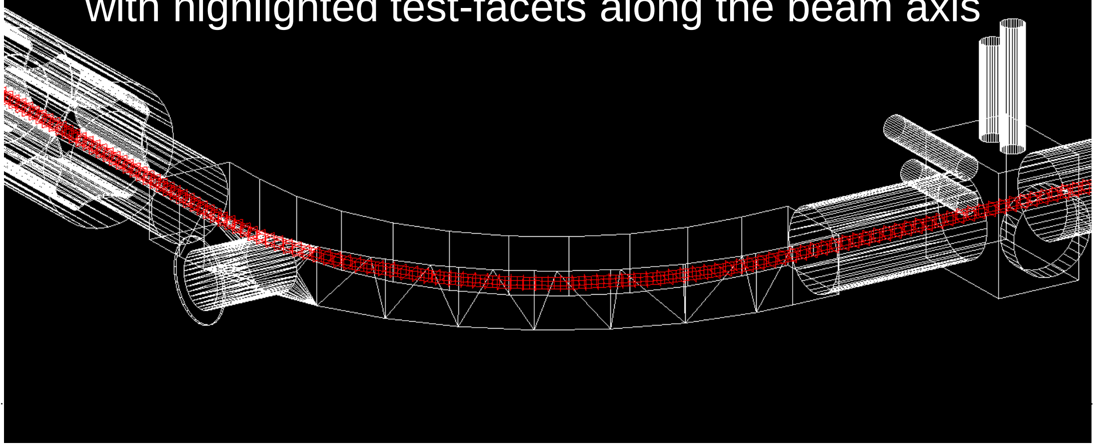
Courtesy of Bojan Durikovic, FRIB project, MSU

FRIB Front End Simulations in MolFlow+

- Pressure requirements for the average pressure over FE sections:
  - Extraction Region: 1E-7 Torr
  - Charge Selection Section: 3E-8 Torr
  - Low Energy Beam Transport: 5E-9 Torr
- Requirements established based on the uranium beam scenario

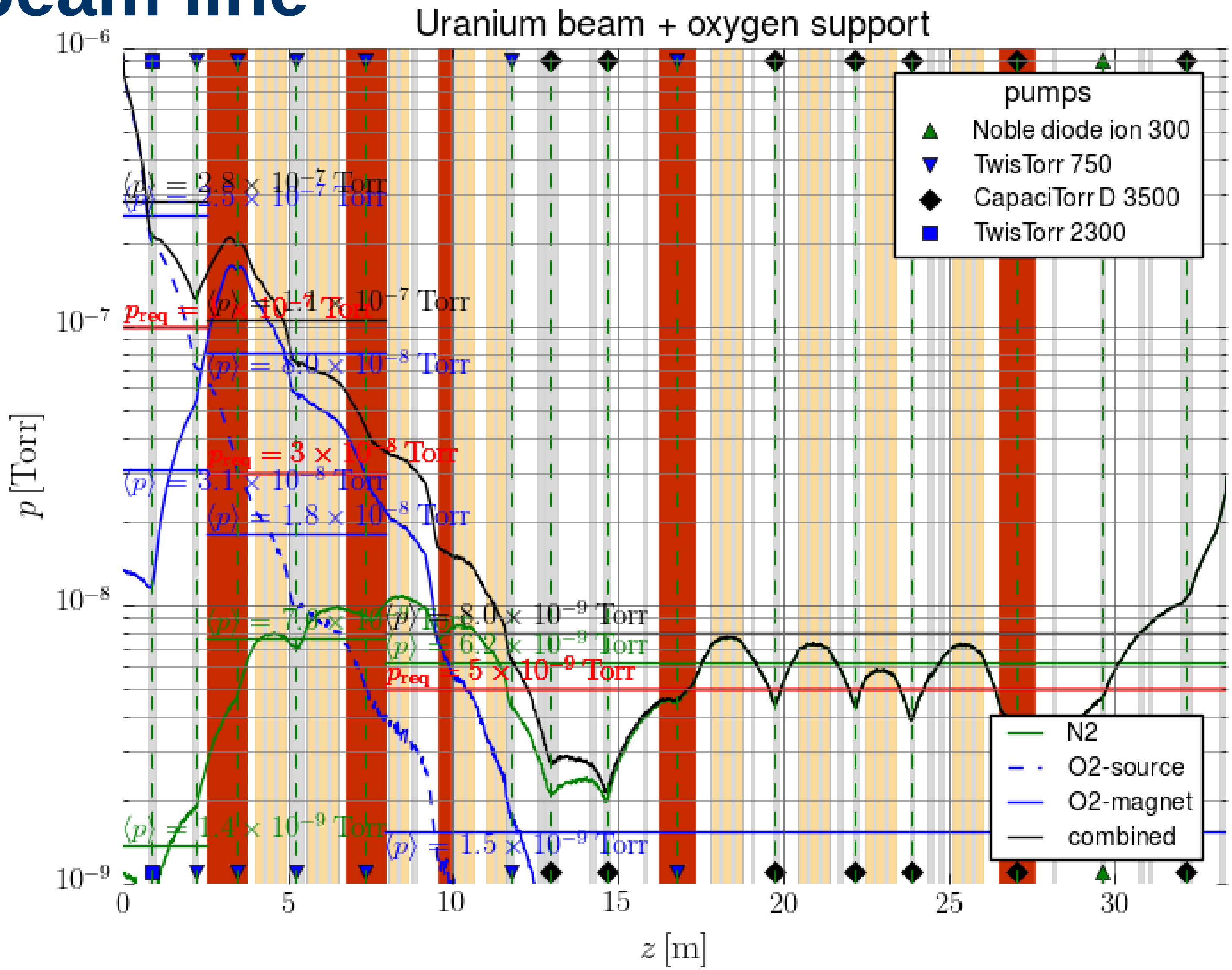
– Based on beam transmission requirement of $\geq 90\%$ transmission

Analyzing magnet in the model of the FRIB Front End with highlighted test-facets along the beam axis



Courtesy of Bojan Durikovic, FRIB project, MSU

Results are pressure profiles along the beam line



Courtesy of Bojan Durikovic, FRIB project, MSU

Homework

- Estimate beam loss/ required average vacuum for transporting high charge state beams
- Calculate minimum distance for a fast acting valve in a vacuum system for two different gases
- Estimate the beamline vacuum for an injector system: What spacing of the pumps/pumping size do you need to achieve the desired vacuum?