Ultra and Extreme High Vacuum

Marcy Stutzman, Ph.D. Jefferson Lab Center for Injectors and Sources

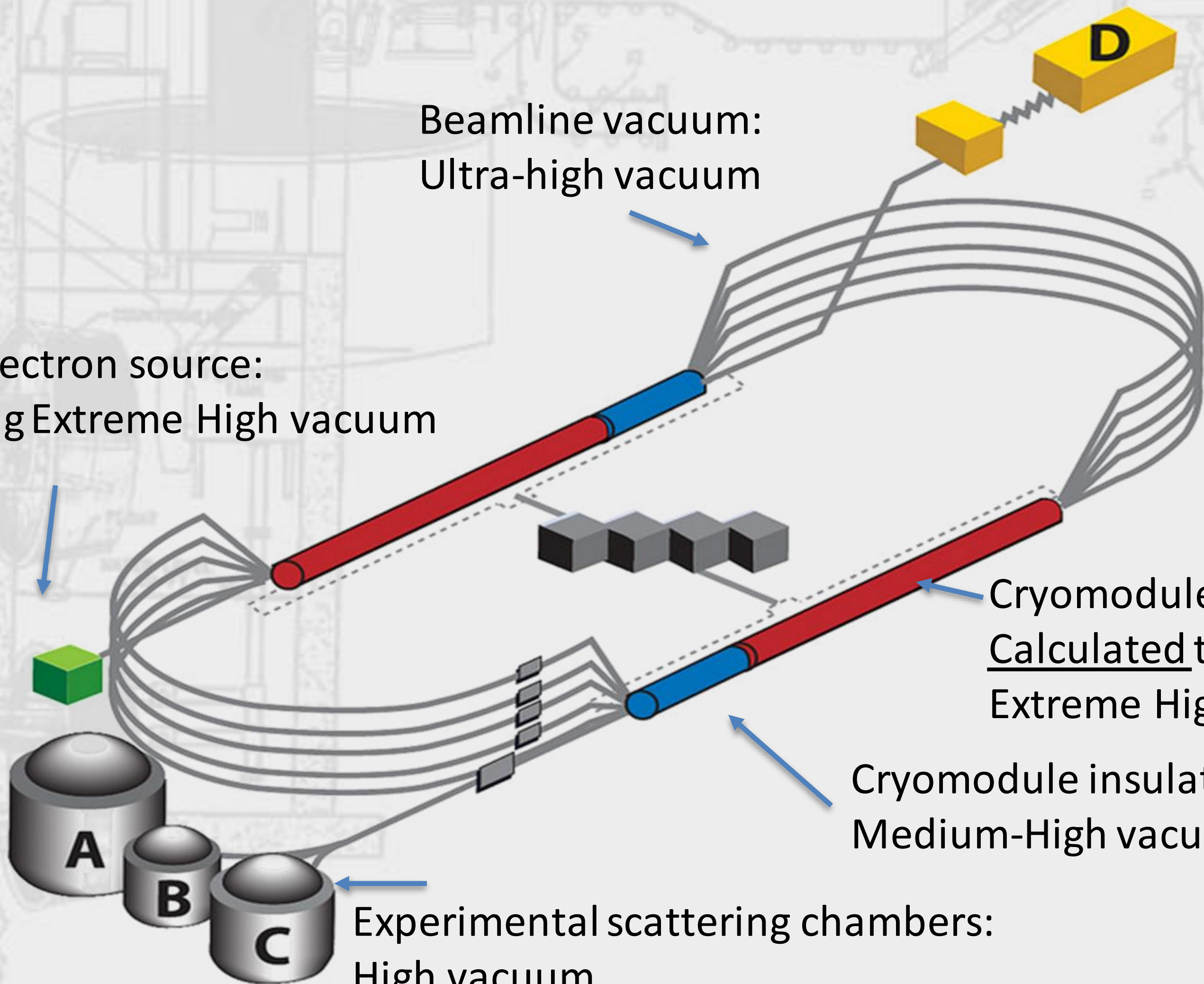
Outline

- JLab and my background
- Outgassing
  - Materials selection, treatment
  - Design considerations
- Pumping
  - Pump speed,
  - NEG coatings
    - Morphology
  - Lifetime, Pd overlayer
- Modeling
  - Pressure gradients
  - Synchrotron radiation desorption

Jefferson Lab

DOE office of science labs
Oldest - LBNL: 1931, 3800 people
Newest - JLab: 1984, 750 people

Jefferson Lab vacuum



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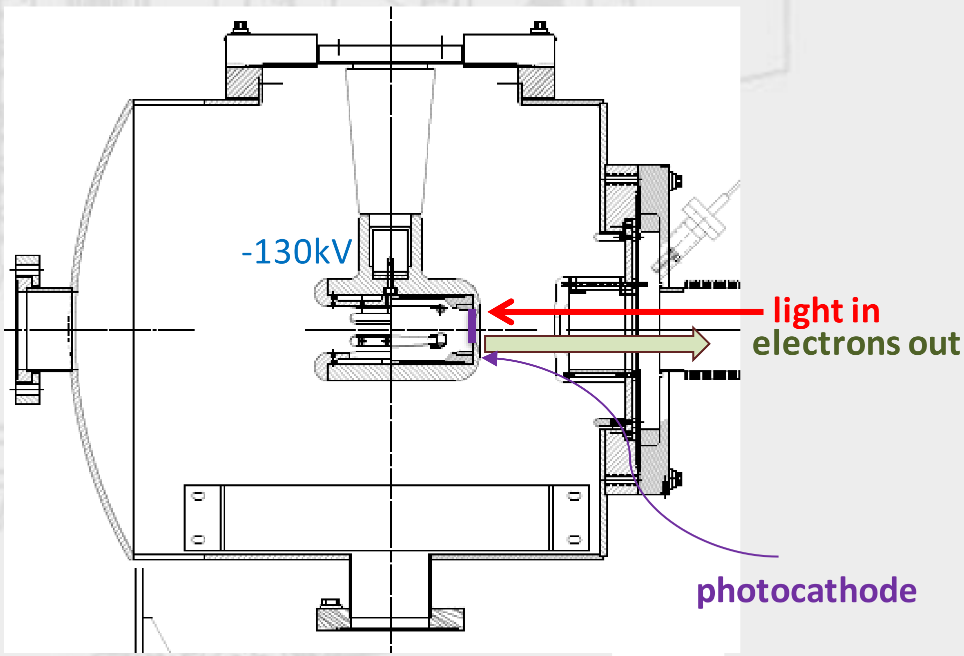
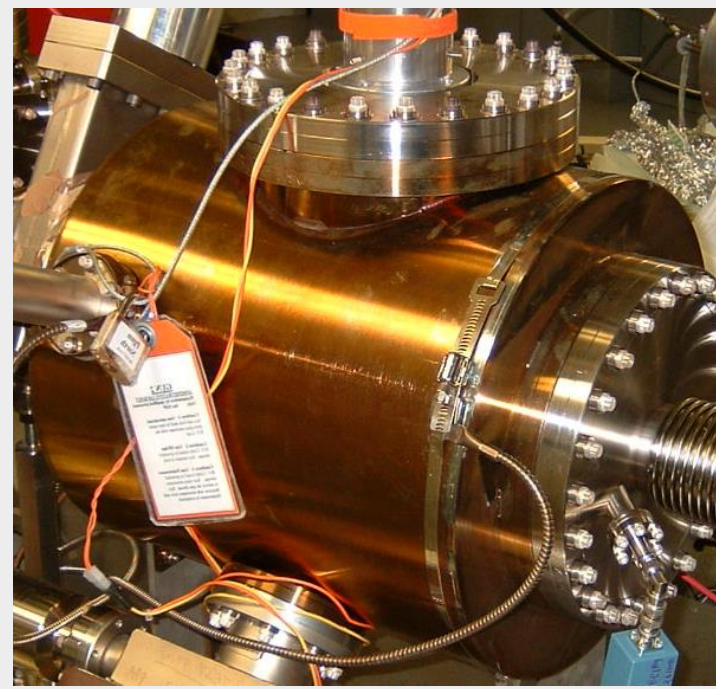
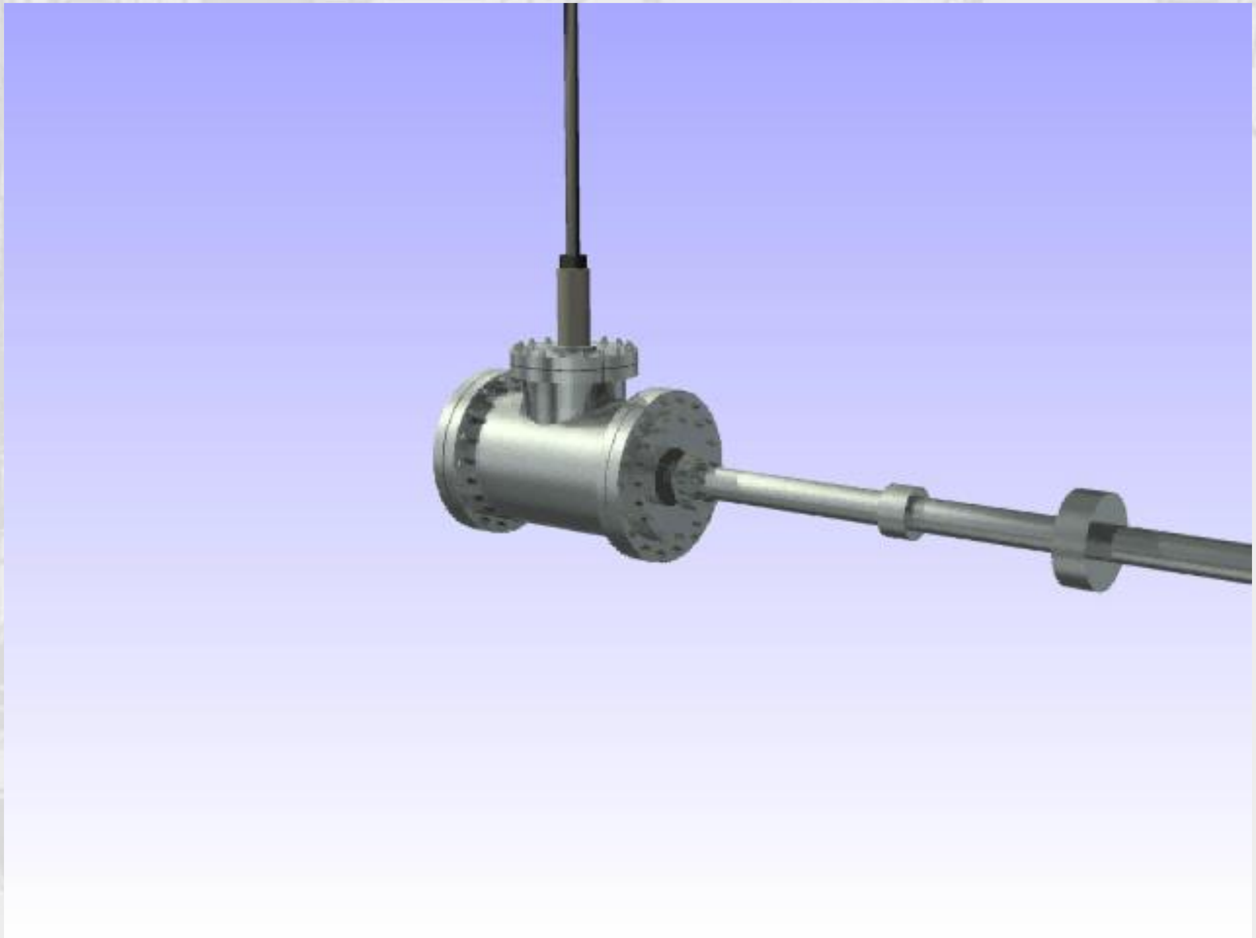
Photoemission Source

- -130 kV DC (*vs.* RF) electrode bias
- x-ray standard "inverted" insulator
- Pumps with NEG modules and ion pump
- Base pressure approaching XHV ≡ $P < 1\text{x}10^{-12}$ Torr



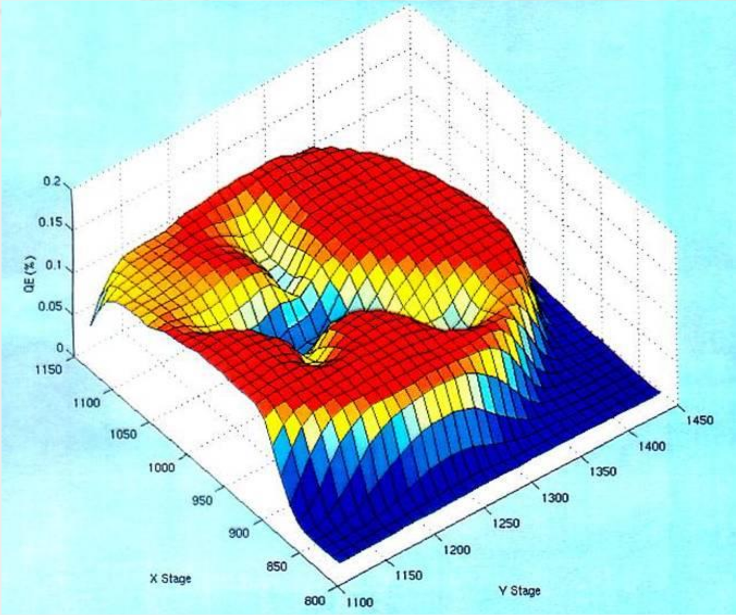


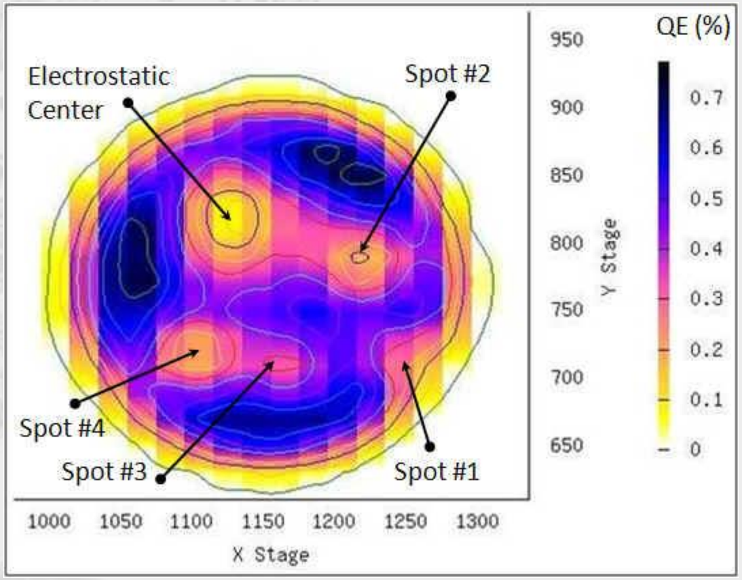
Any gas in chamber can be ionized by electron beam, accelerated back toward the photocathode and limit photocathode operational lifetime



Photocathode Lifetime

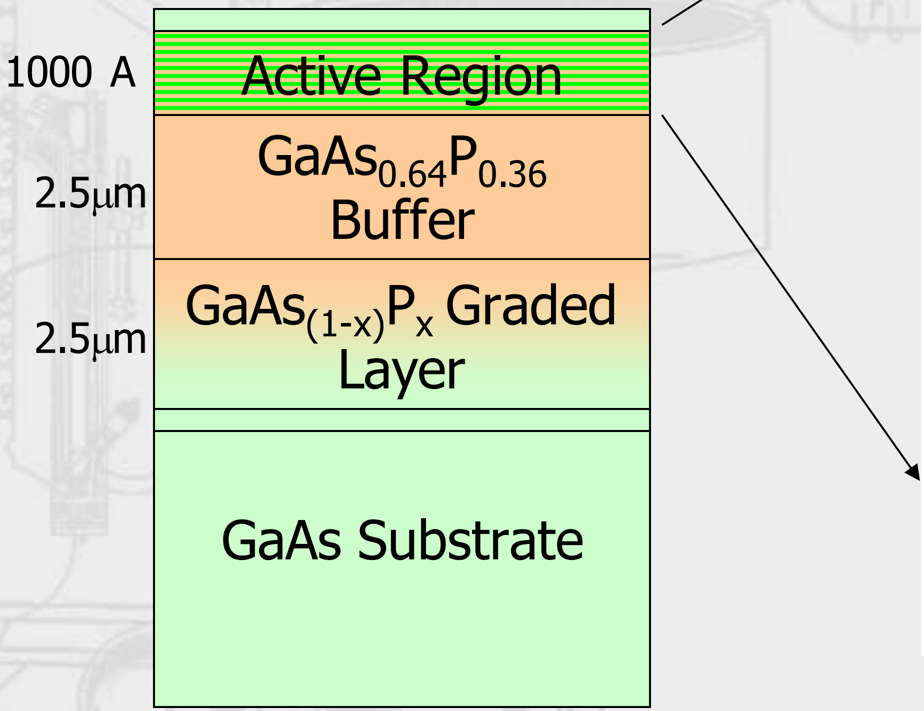
- Ion bombardment – with characteristic QE "trench" from laser spot to electrostatic center of photocathode – **damages NEA** of GaAs
- High energy ions are focused to electrostatic center: create QE "hole"
  Don't run beam from electrostatic center.
- QE can be restored, but takes about 8 hours to heat and reactivate

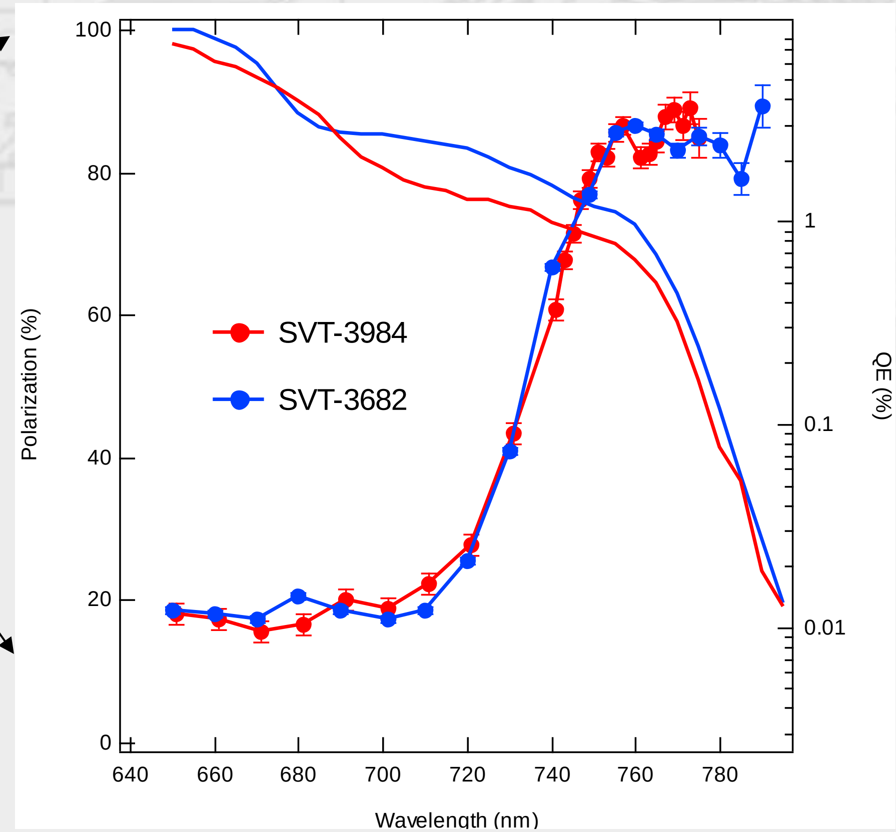




Strained-Superlattice GaAs/GaAsP

QE 1% and Polarization 85%





D. Luh et al, SLAC, PESP2002

SVT ASSOCIATES

From Aaron Moy, SVT Assoc and SLAC, PESP2002

Vacuum levels

	Example	Pressure (Torr)	atoms/cm^3
Atmosphere	Atmosphere at sea level	760	27,000,000,000, 000,000,000 or 2.7x10^{19}
Low vacuum (1-300 Torr)	Atmosphere on Mount Everest	252	1x10^{19}
	Pressure in bell jar experiment, Mars	1-10	1-3 x 10^{17}
Medium vacuum (1 Torr-1mTorr)	Insulating vacuum, atmosphere on Pluto	10^{-3}	10 quadrillion
High vacuum (1 mTorr- 1x10^{-7})	Scattering chambers	10^{-5}	100 trillion
Ultra high vacuum (UHV, 1x10^{-7} – 1x10^{-12})	Vacuum tubes, Cathode Ray tubes, beamline vacuum	10^{-8}	100 million
	Pressure outside Space Station (400 km)	10^{-10}	1 million
	JLab Electron Gun	10^{-12}	10,000
Extreme high vacuum (XHV <1x10^{-12})	Interstellar space estimate ~ 1 atom / cm^3	10^{-17}	1

Voyager space probe

Requirements for UHV/XHV

$$P = \frac{QA}{S}$$

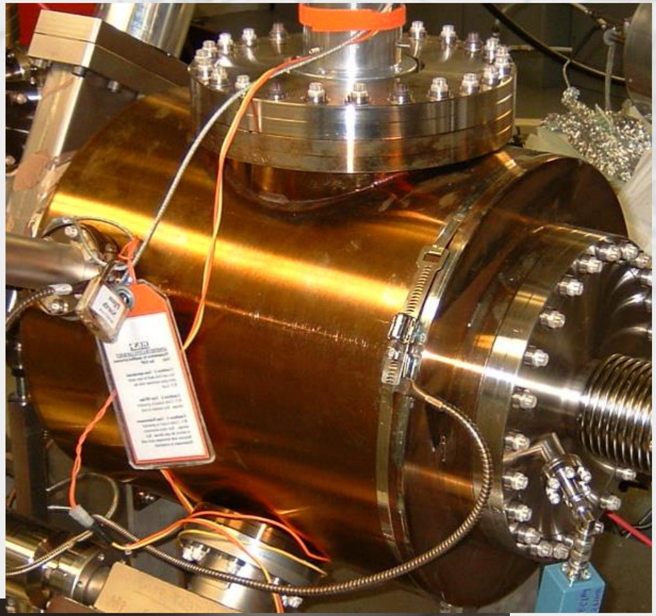
Q: Outgassing rate – minimize

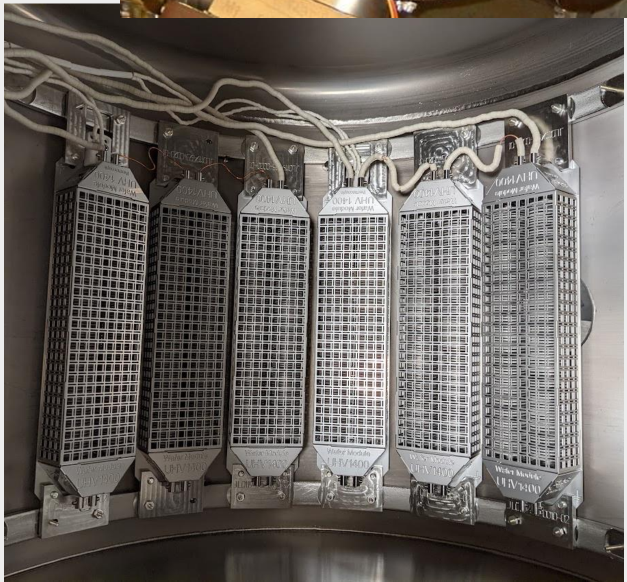
A: surface area – minimize

S: Pump Speed – maximize

Steps to minimize outgassing

- All metal seals – leak free (Conflat flanges)
- Heat treated stainless steel
  - 316LN: 900°C, 2 hours
  - 304L: 400°C, 100-240 hours
- Leak check with RGA on pump cart
- Dry Pump carts, N_2 venting
  - Turbo or drag pump
- Vent blind holes
  - Slot vented screws for long screws
- Internal components:
  - Steel, copper, ceramic, Mo, Ta
  - No Kapton, Teflon, etc



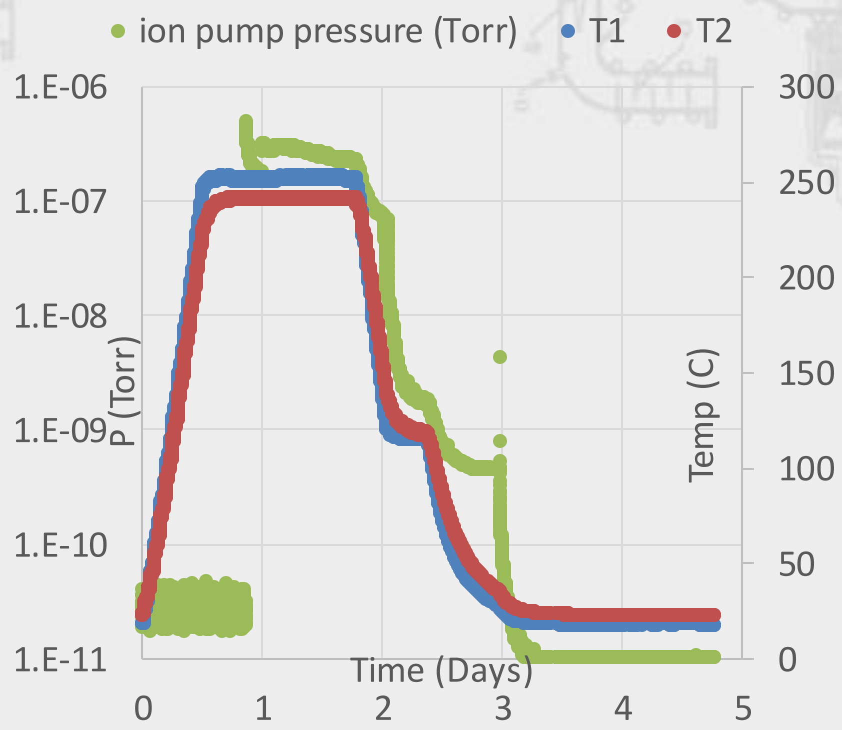


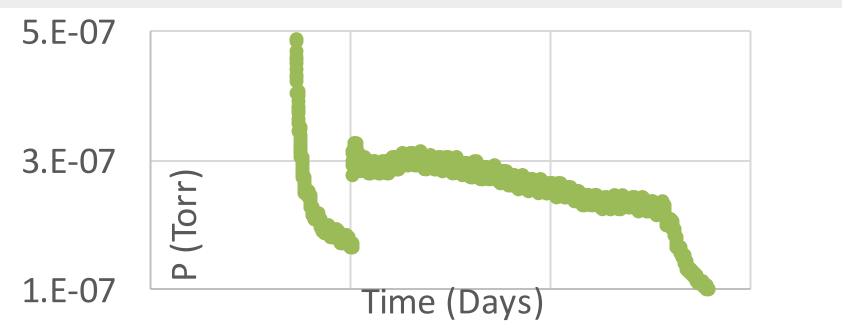
Center vented

Slot vented
(UC Components image)

Bake all systems in-situ

- Hot air ovens
- Overboard pumping – turbo and ion pump
- Hardware appropriate for baking 250°C
  - Silver plated hardware
  - Belleville spring washers
- Bake until pressure stops falling 10% in 24 hours – usually 36-48 hours at 250°C
- Reduce temperature to 120-150°C and activate NEG pumps
  - Close valve to pump cart after activation to avoid backstreaming

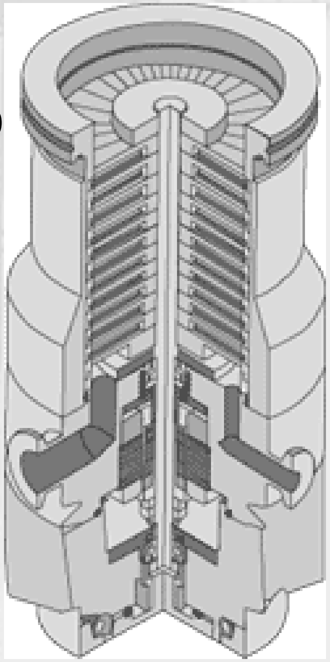




Modern Vacuum Pumps

Gas Transfer Pumps

- Rotary vane pump
- Roots pumps
- Turbo pumps



Compress rarified gas
Move gas to higher pressure exhaust

Capture Pumps

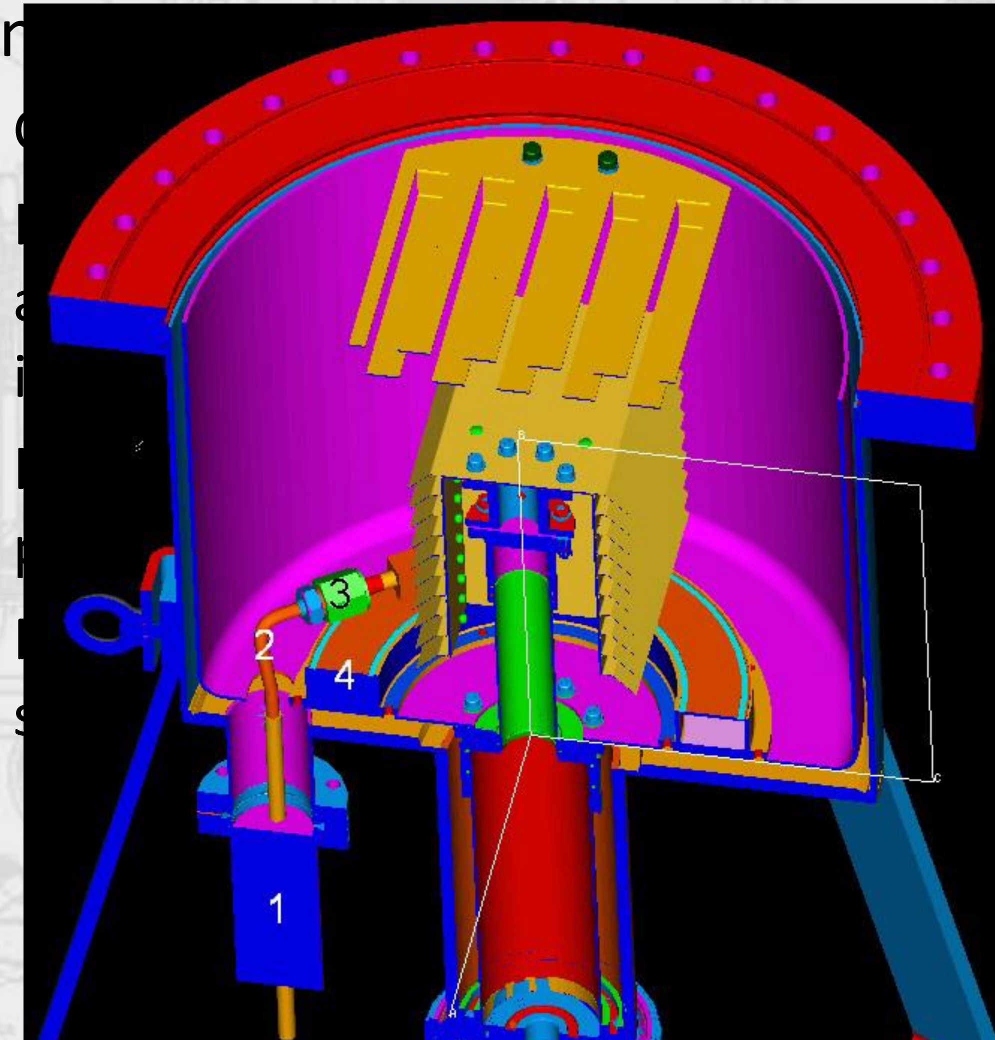
- Ion pumps
- Getter pumps
- Cryopumps

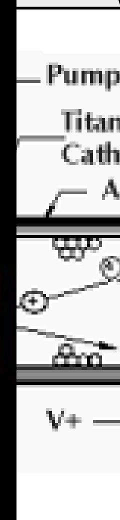
Remove molecules from *gas phase*

Jefferson Lab

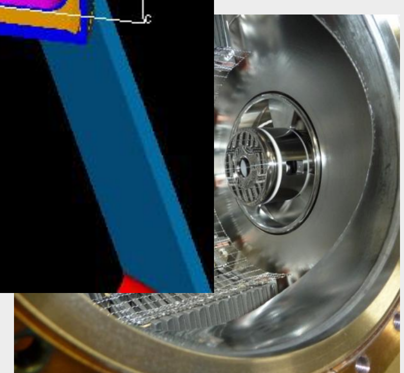
Capture Pumping

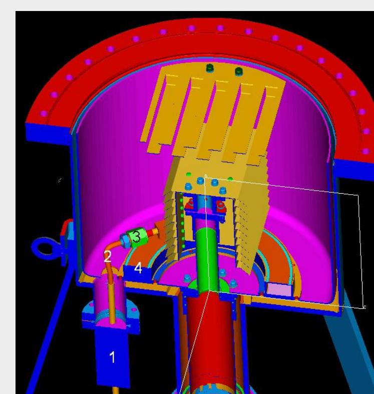
Ion



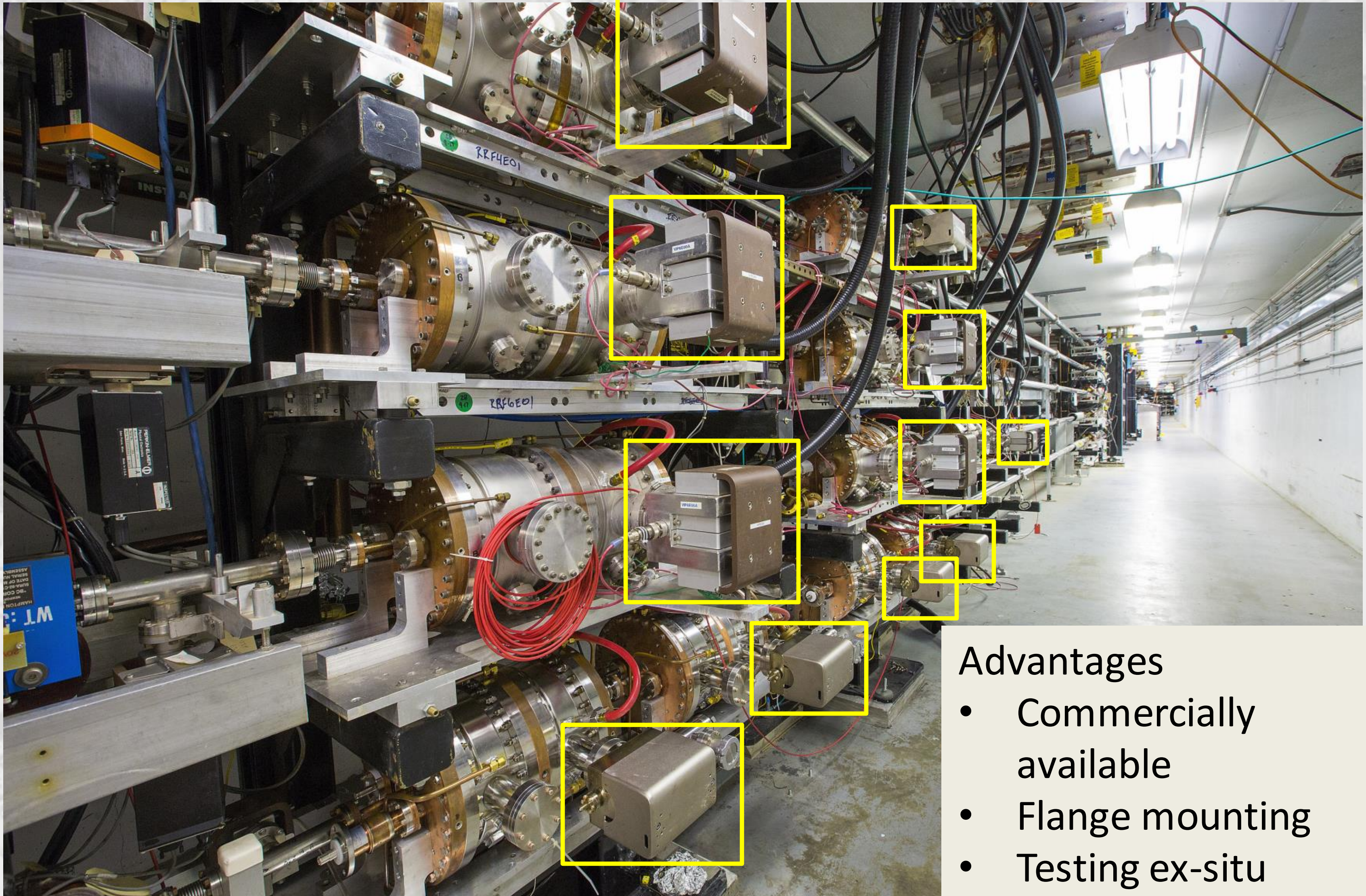


- Gas incident on cold surface sticks



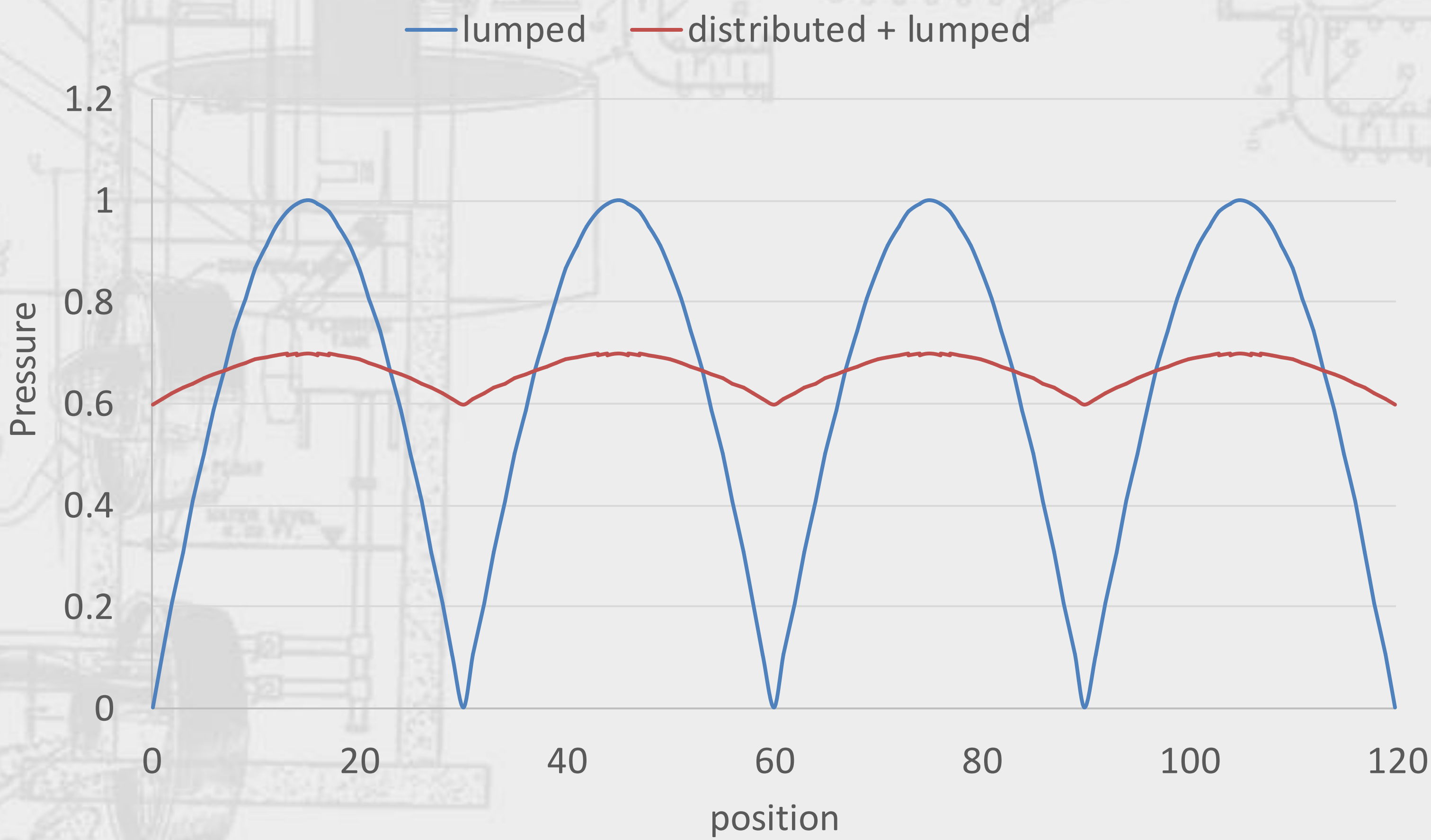


Discrete (lumped) pumping



Advantages
- Commercially available
- Flange mounting
- Testing ex-situ

Pressure profiles: lumped & distributed

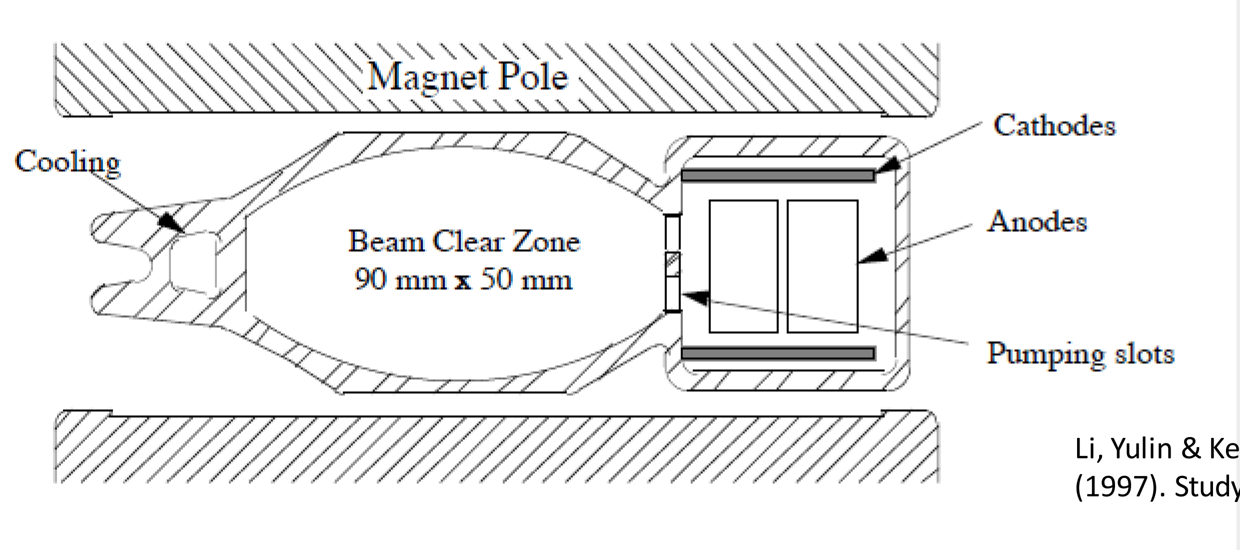


Disadvantages to discrete pumps

- No pumping between ports
- Conductance limitations due to pump drops

Distributed pumping

Storage rings: Lots of vacuum due to synchrotron radiation
Difficult to get pumps in with the magnets
➢ Use the magnetic fields to make distributed ion pumps!



Li, Yulin & Kersevan, Roberto & Mistry, Nariman. (1997). Study of Distributed Ion-Pumps in CESR.

Distributed NEG pumps

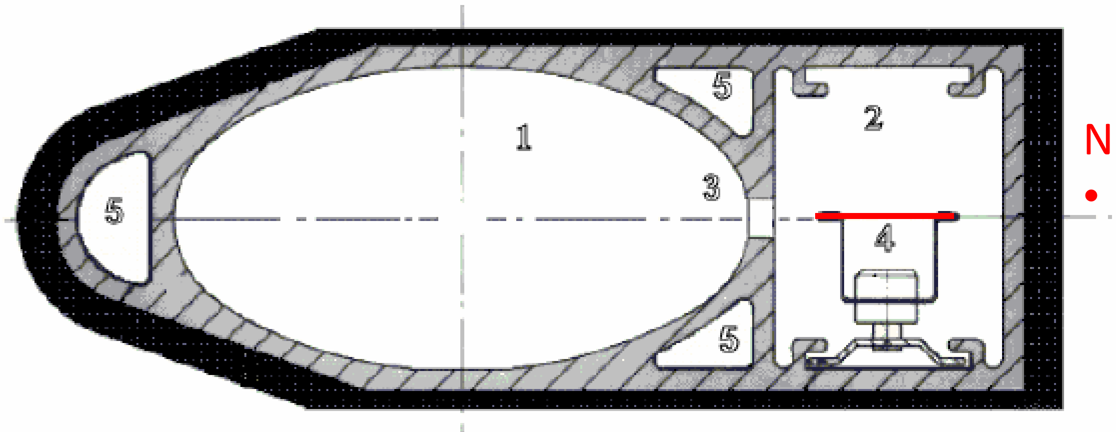


Fig. 5: Cross-section of the LEP dipole vacuum chamber: 1) chamber, 2) antechamber, 3) slot, 4) NEG strip and its support, 5) cooling channels

NEG strip in ante-chamber
- Resistive heating through substrate

F. Mazzolini, CERN Accelerator School, vacuum in accelerators, Platja d'Aro, Spain, 16-24 May 2006, 341-349

Ante-chamber limitations
- Requires horizontal space – won't work for tight magnets
- Conductance limitation between beampipe and ante-chamber

NEG coated beampipe

- CERN developed NEG coatings for beampipes
- ESRF installed Al beampipe with NEG coatings 2000
- Used at many labs
- JLab has used in-house NEG coatings for gun exit pipe since ~2001
- JLab polarized source chamber NEG coated

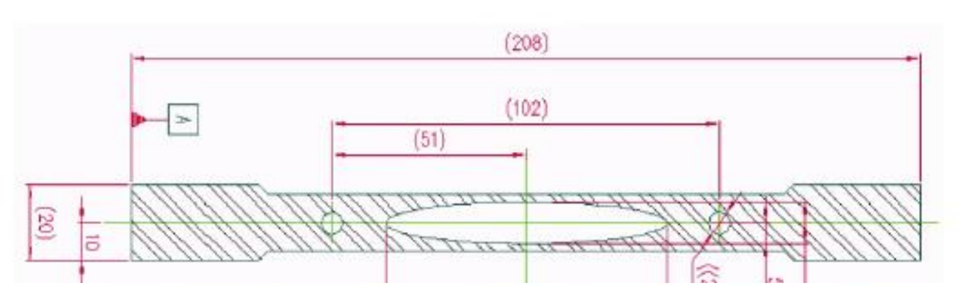
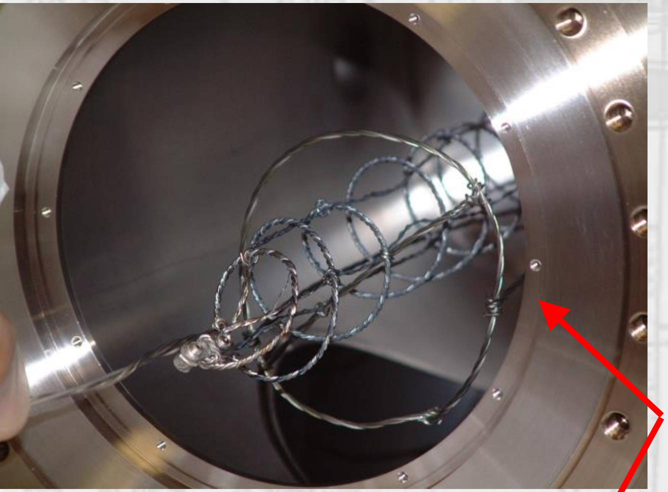


FIGURE 1.7: A stock of NEG coated vacuum chamber ready to be installed in the LHC tunnel.

Chiara Barcellini masters thesis, Poltecnico di Milano 2015

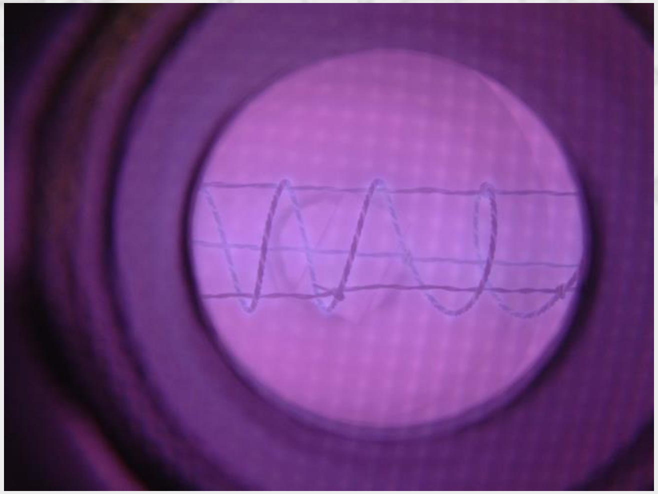
JLab NEG coatings



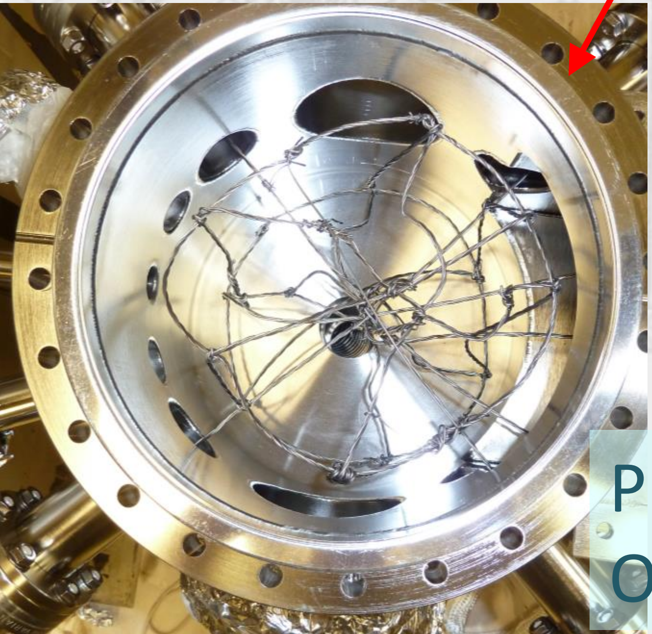
DC sputtering,

- no magnetron

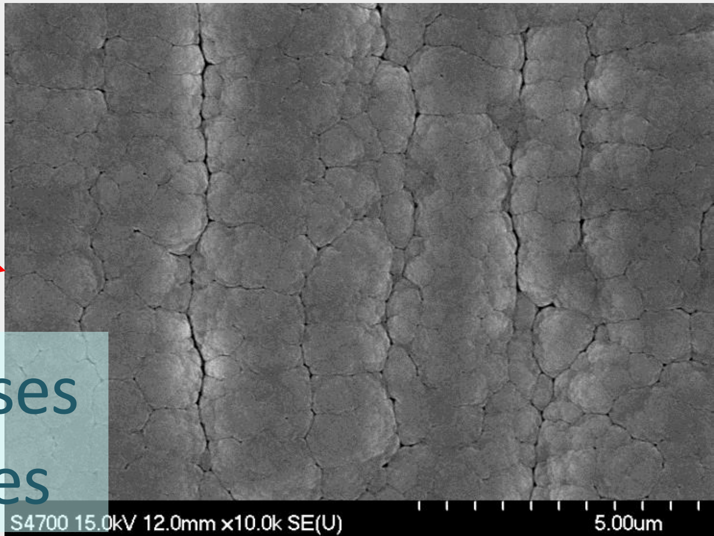
Kr or Ar gas



Non-uniform twisted wire



Dense columnar structure



Pump Speed increases
Outgassing decreases

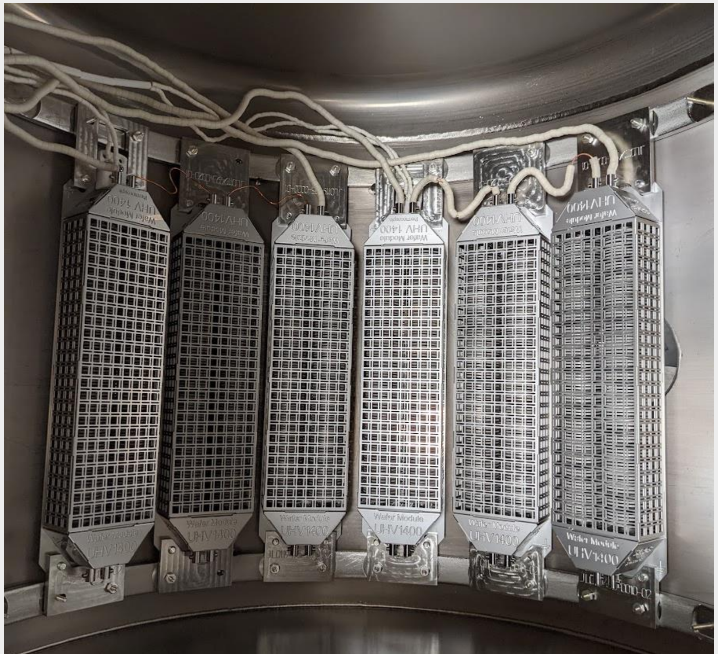
Operational experience

Chamber	NEG modules	Ion pump	Bake Time/Temp	Pressure (Torr)
NEG coated	None	45 L/s	48 hours/250C	1.5×10^{-12}
NEG coated	8x WP1250	45 L/s	53 hours/230C	6×10^{-13}
No coating	NEG strips	45 L/s	48 hours/250C	2.3×10^{-11}

Stutzman, JVSTA **36** 031603 (2018)

JLab has been using NEG coated vacuum chambers for DC high voltage electron guns since ~2008

Currently building next generation gun for 200kV using next generation NEG modules



Pressure system Modeling

Desirable to know what pressure to expect before building systems

- Calculations are tedious
- Test particle Monte Carlo simulation software available

C=*lW*=*qpV*Δ*p*

*C*ges=*C*1+*C*2+⋯+*Cn*

1*C*ges=1*C*1+1*C*2+⋯+1*Cn*

qpV=*A*·*c*¯4·(*p*1−*p*2)

Formula 1-23: Orifice flow

*C*or,mol=*A*·*c*¯4=*A*·*kT*2*πm*0−−−−−√

*C*or,mol=11.6·*A*

Formula 1-25: Orifice conductivity for air

*C*pipe,lam=*π*·*d*4256·*η*·*l*·(*p*1+*p*2)=*π*·*d*4128·*η*·*l*·*p*¯

*C*pipe,lam=1.35·*d*4*l*·*p*¯

*C*pipe,mol=*C*orifice,mol·*P*pipe,mol

*P*pipe,mol=43·*dl*l

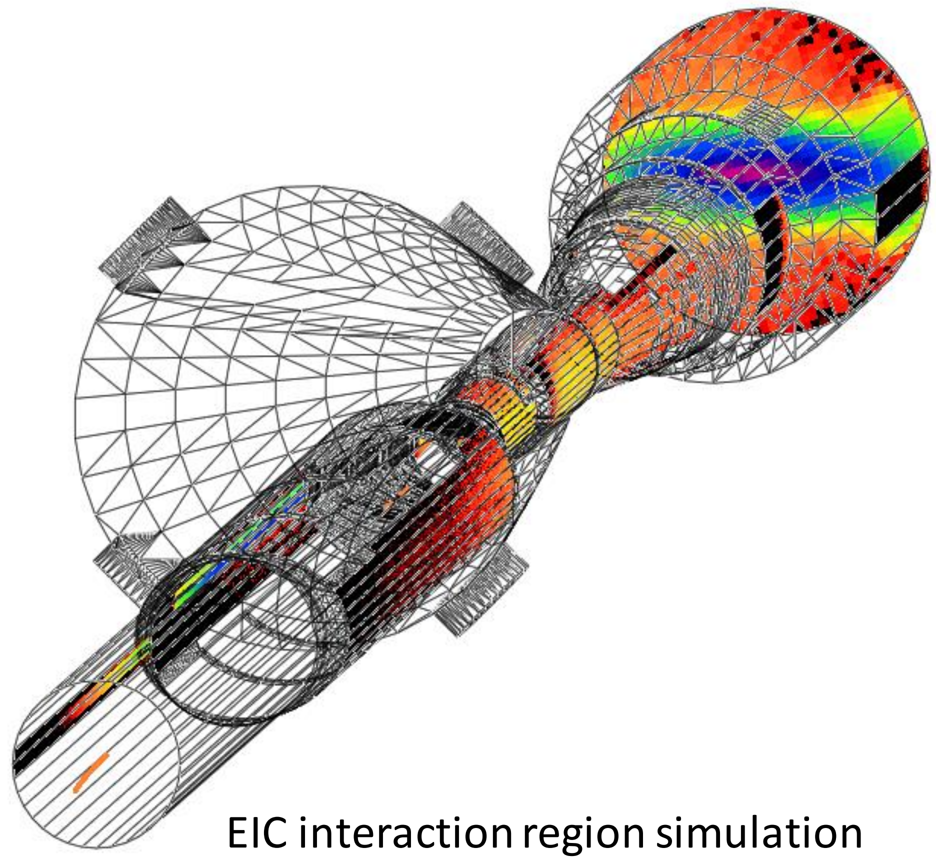
*C*pipe,mol=*c*¯·*π*·*d*312·*l*

*C*pipe,mol=12.1·*d*3*l*

SynRad+ modeling software

Input
- 3D model of beampipe
- Beam emittance, current
- Magnet locations and fields

Output
- Synchrotron Radiation
  - Position
  - Flux
  - Energy
  - Direction
- Input for Molflow+ dynamic vacuum modeling

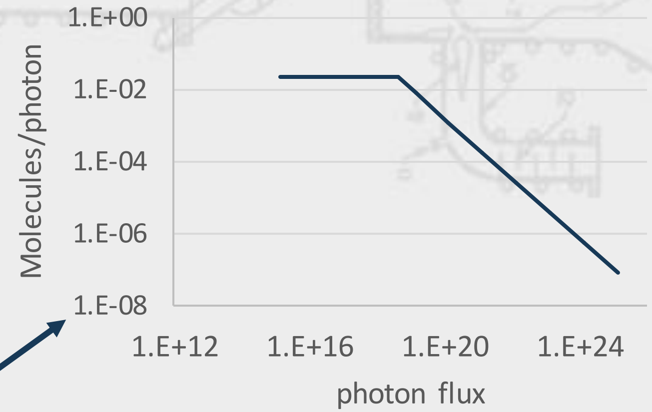


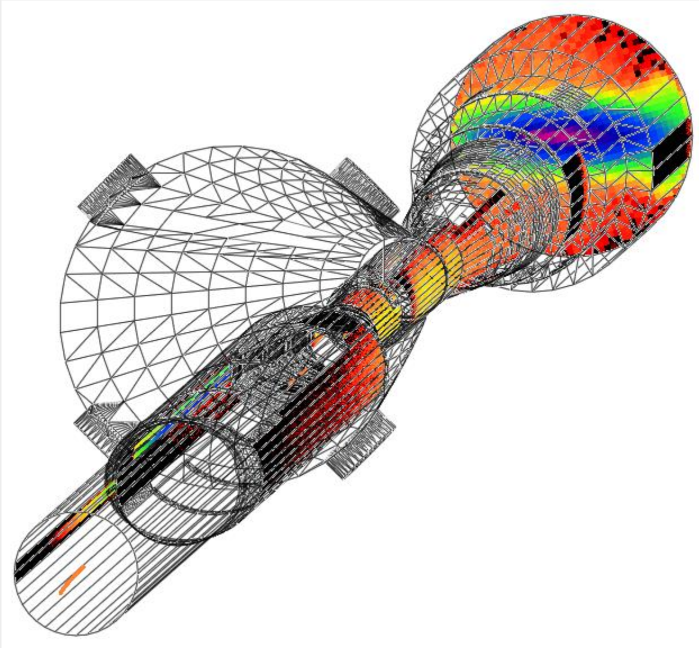
EIC interaction region simulation

SynRad+ & Molflow+ for Dynamic Vacuum

Input

- 3D model of beampipe
- Pump locations
- Materials & Outgassing Rates
- SynRad+ flux per facet
  - Photon Stimulated Desorption Rate
  - Depends on material and gas species

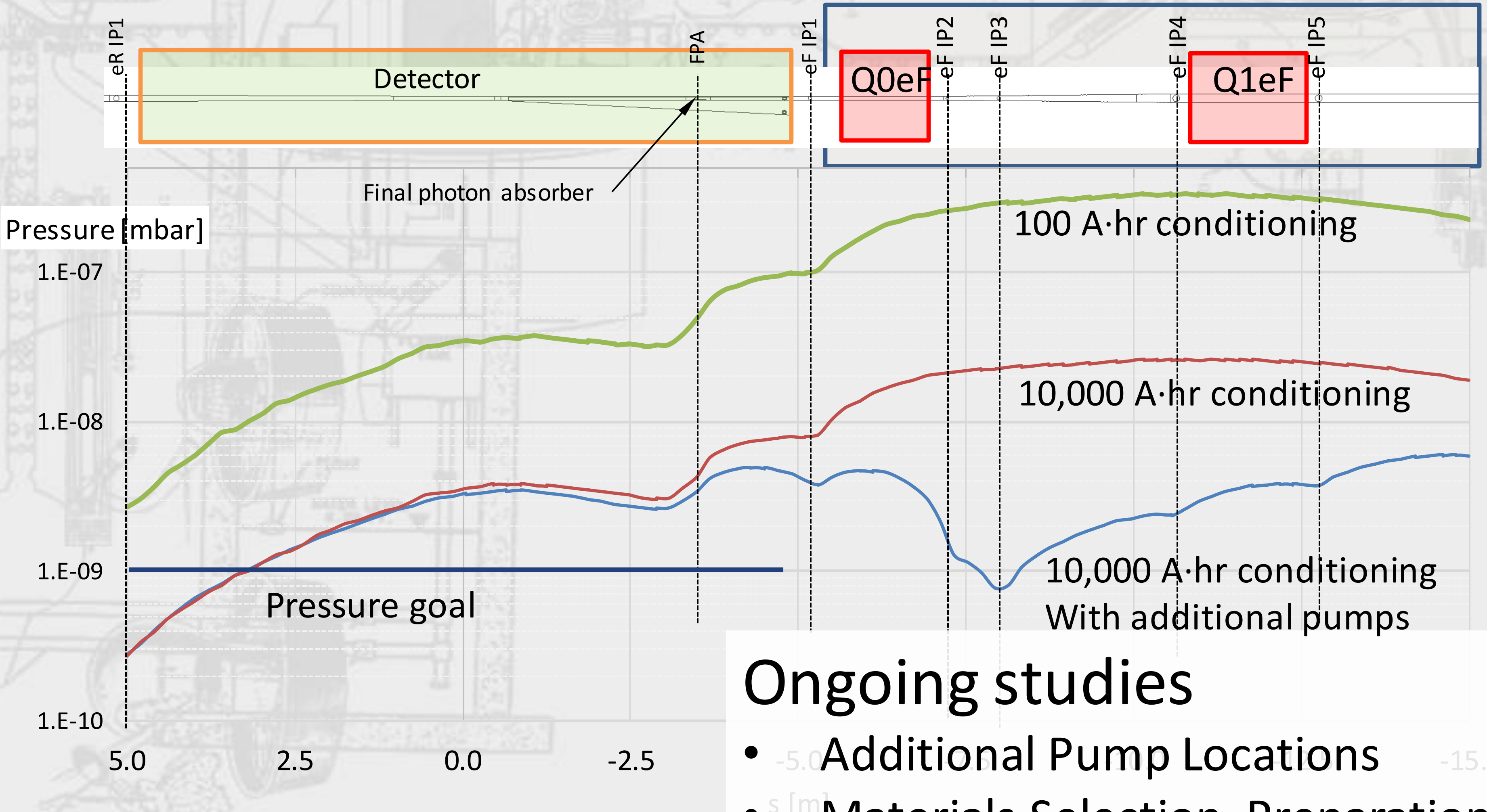




Output

- Base Pressure distribution
- Outgassing rate of each facet with synchrotron radiation
  - Pressure vs. Amp-hours during commissioning

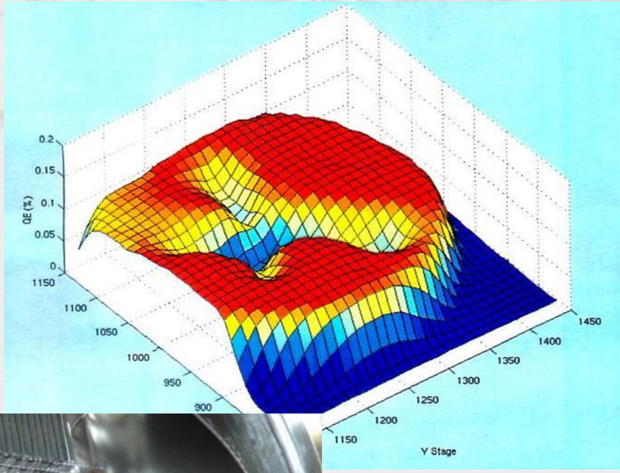
Dynamic Vacuum



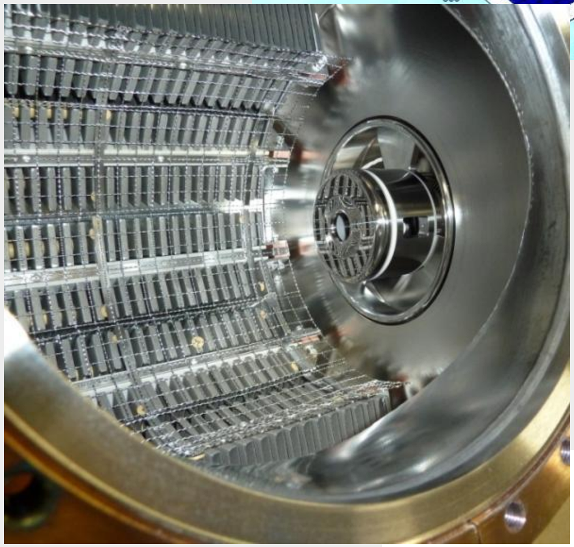
Ongoing studies

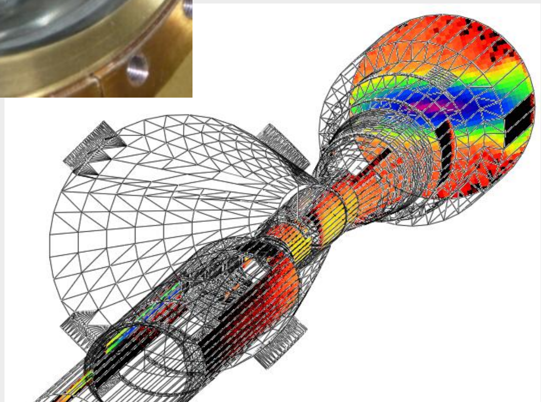
- Additional Pump Locations
- Materials Selection, Preparation
- Synchrotron Radiation Mitigation
- Recovery after maintenance

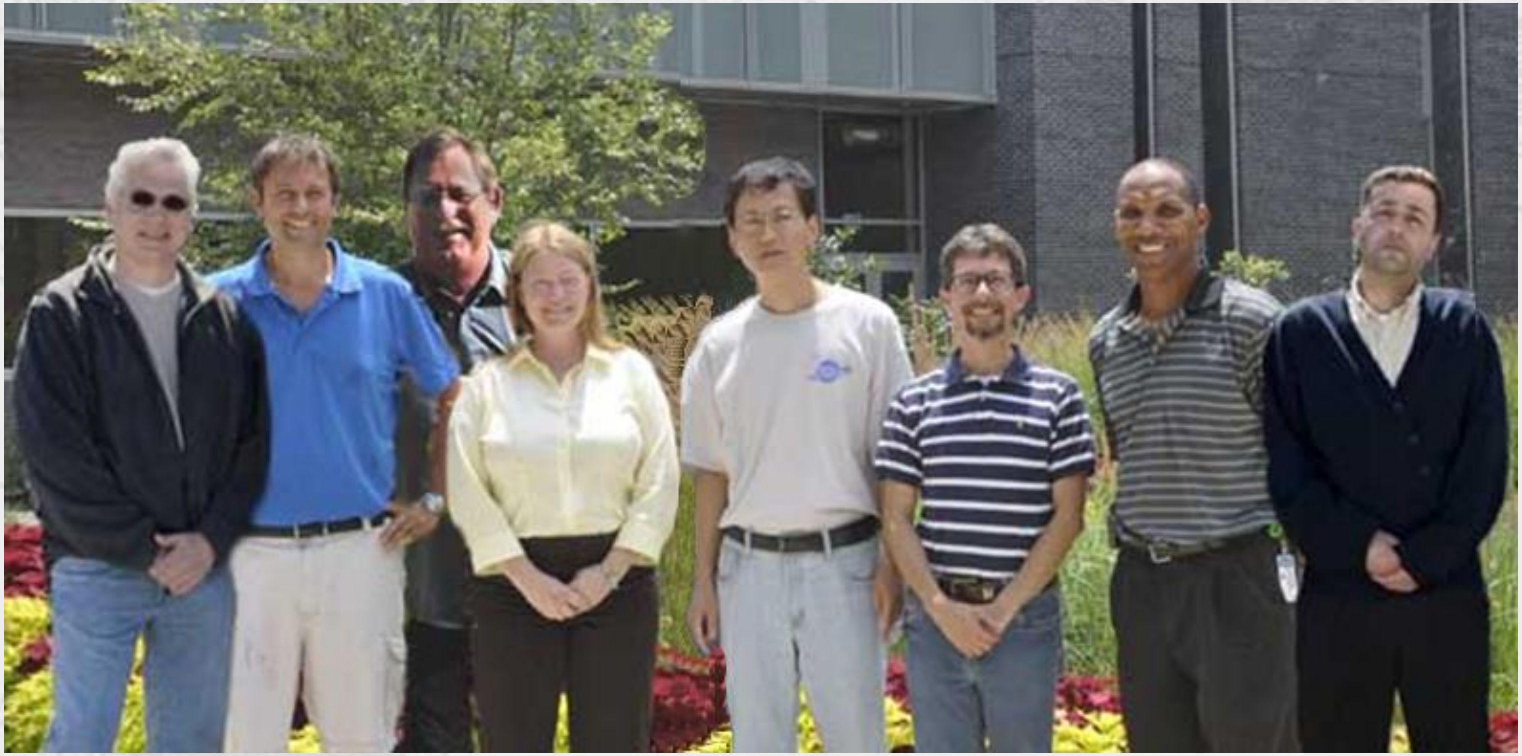
Summary



- High polarization photocathodes require vacuum near or at XHV for long lifetime
- Reduce outgassing
  - Heat treatment
  - In-situ bakeout
  - Good design practices
- Pump optimization
  - UHV ion pumps
  - NEG pumps
  - NEG coating
- Modeling required for new machine designs







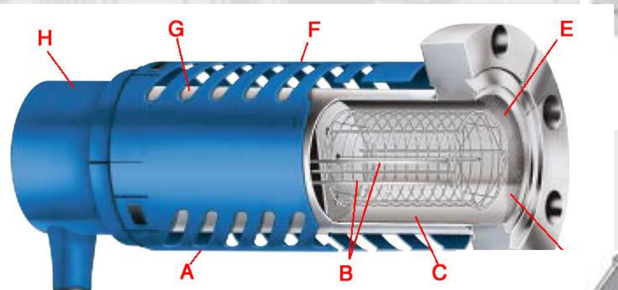
Questions?

Jefferson Lab Center for Injectors and Sources

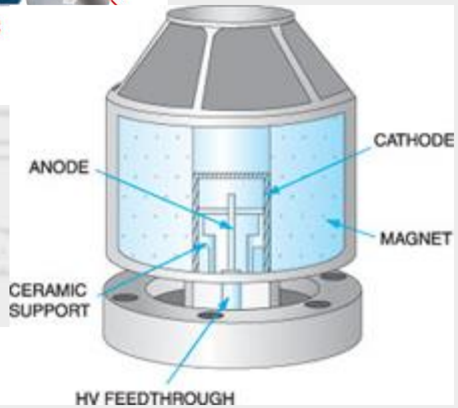
Matt Poelker, Joe Grames, Bubba Bullard
Marcy Stutzman, Shukui Zhang
Carlos Hernandez Garcia, Phil Adderley, Riad Suleiman

High/Ultra High Gauges

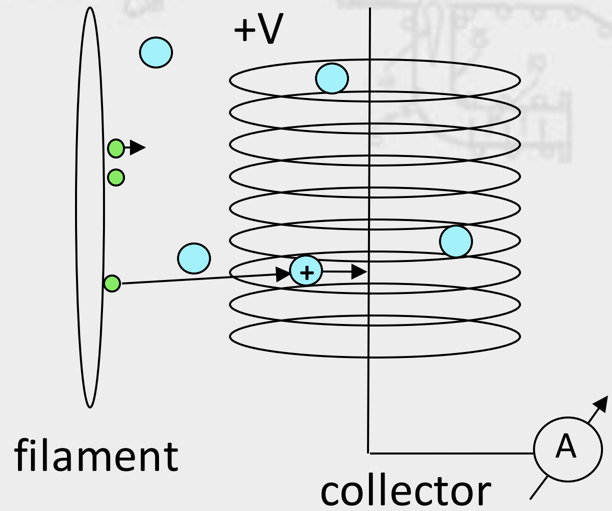
Bayard-Alpert Gauges



Stabil-Ion gauge



Cold Cathode gauge



- Lowest pressures:

  10^{-8} Torr – 10^{-11} Torr

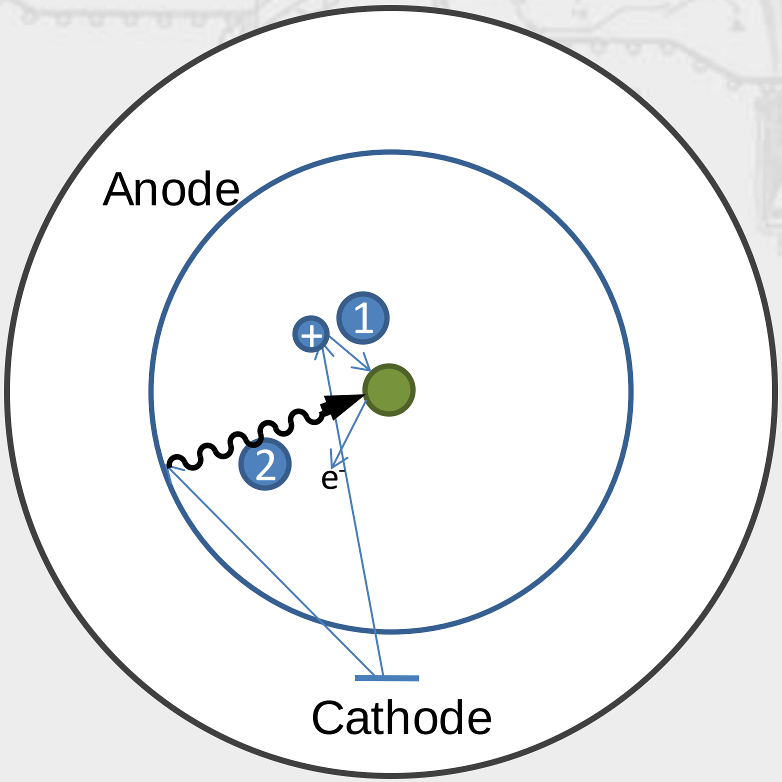
  up to $4,000

Measure Pressure:
Hot cathode gauge operation and errors

1. True gas ionization
   - Positive current
2. X-ray effect
   - e- on anode -> photons emitted
   - Photons on collector -> electrons emitted
   - Extra positive current

Additional effects:

3. Inverse X-ray effect
4. Electron Stimulated Desorption



$$I^{+} = I_{real} + I^{-}_{x-ray} - I^{-}_{inv.x-ray} + I_{ESD}$$

Ionization gauge pressure calibration

- Chamber evacuated
- Gauge energized
- Current measured
- Calibration factor to translate measured current to pressure

$$P = \frac{\textit{ion current}}{\textit{Sensitivity} \ast \textit{emission current}}$$

- x-ray limit determines lowest pressure that can be measured

XHV gauges: reduce x-ray limit

Hot filament

- Extractor gauge
  - available commercially for decades
  - x-ray limit reduced through geometry
  - x-ray limit quote: **7.5x10^{-13} Torr**
  - $4,300
- Axtran gauge
  - Bessel box energy discrimination
  - electron multiplier to assist in low current measurements
  - Quoted limit: **3.75x10^{-13} Torr**
  - $7,500
- Watanabe BBB (Bent Belt Beam) gauge
  - Uses Leybold IE540 controller
  - 230° deflector BeCu housing
  - JVSTA **28**, 486 (2010)
  - Quoted limit: **4x10^{-14} Torr**
  - $13,000 + Ext. controller ($2,600)