USPAS Course on Photocathode Physics

John Smedley, BNL and Matt Poelker, TJNAF

Lecture 8
Practical Matters
Lecture 8:
• Ion Bombardment
• High Voltage: avoiding breakdown and field emission
• A clean photocathode
• Vacuum Hot Filament Gauges
Imperfect Vacuum = Finite Lifetime

- What about while you run beam?
- Ion bombardment – notice characteristic “trench” from laser spot to electrostatic center of photocathode

Ionization cross section for H$_2$

Most ions created at low energy

100kV

Active area = 5mm
Laser spot = 0.5mm dia.
Compare NEW and OLD load locked guns

Better Vacuum in New Gun ➔ better Lifetime!

“Further Measurements of Photocathode Operational Lifetime at Beam Current > 1mA using an Improved 100 kV DC High Voltage GaAs Photogun,”
J. Grames, et al., Proceedings Polarized Electron Source Workshop, SPIN06, Tokyo, Japan
But Sometimes Lifetime is Still Not Good!!

<table>
<thead>
<tr>
<th>✓ OK, good vacuum. What else matters?</th>
</tr>
</thead>
<tbody>
<tr>
<td>✜ Clean laser beam, no stray light</td>
</tr>
<tr>
<td>✜ Good orbit, proper electron beam optics</td>
</tr>
<tr>
<td>✜ No field emission from cathode</td>
</tr>
</tbody>
</table>

| ➢ Reduce the active area of photocathode |
| ➢ Move the laser away from the electrostatic center |
| ➢ Increase the size of the laser beam |
| ➢ Apply bias to the anode             |
| ➢ Operate at Higher Bias Voltage?    |
Good beam versus Bad Beam

The beam that doesn’t make it to the experiment only serves to degrade vacuum. This leads to ion-bombardment and QE decay

- Eliminate stray light
- Generate only electrons you can transport away from the gun
- Use large diameter beampipes
- NEG coated chambers to limit ESD
- Proper electrode geometry, proper lens configuration: don’t over focus
- No field emission from cathode!!!

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“Free” beam loss monitoring

Designed and constructed by J. Hansknecht

UHV Ion Pump Power Supplies

Ion Pumps detect bad orbit and beam loss

Extractor Gauge Pressure vs. UHV Ion Pump Current

Pressure (Torr) vs. current (nA)

Graph showing pressure vs. current for UHV Ion Pump Current.
How much field emission is acceptable? Unfortunately, it seems if you can measure it, it’s too much.
Anode won’t always capture all FE.... Better to look for x-rays....

Built an inexpensive radiation monitoring system: lots of GM tubes, powered by one HV supply and data stream to computer via RS232
HV “Conditioning”: sometimes it works

Floating Anode connected to Pico-ammeter

Macor glass-ceramic spacer

100 MΩ Conditioning Resistor

Oil Tank

A Short for Beam Delivery

Fowler-Nordheim: \( I = a_0 V^2 e^{-a_1/V} \)
\( a_0 = 4.7e+04, \quad a_1 = 3.0e+03 \)
Lifetime Experiments at the Injector Test Cave
Imperfect Vacuum and Ion Bombardment

Electron beam makes ions, that are attracted to the EC of the photocathode

I mentioned other factors can limit lifetime: Field emission, photocathode material, laser wavelength, laser radial position on photocathode, beam optics, gun voltage
Avoid the Electrostatic Center (EC)

- characteristic QE “trench” from laser spot to EC. Ion are attracted to EC
- Laser spot size ~0.5 mm and can be moved to different locations on the photocathode.
- QE can be restored, but takes about 8 hours to heat and reactivate

We don’t run beam from electrostatic center

Ions create QE trough to electrostatic center

laser light IN
electron beam OUT
Lifetime vs. Laser Position and Active Area

I. Activate with different Masks: 5 mm, 7 mm, and No Mask (12.8 mm)

II. Measure Lifetime from different spots on Bulk GaAs with 532 nm green laser

\[
\text{QE} = \text{QE}_0 e^{-\text{Charge} / \text{It}}
\]

\[
\text{It} = 595.9 \pm 27.2 \text{ C}
\]
Lifetime vs. Laser Position and Active Area

After Activation

After Lifetime Measurements

Spot

Electrostatic Center
# Lifetime vs. Laser Position and Active Area

Stray light, Spontaneous Emission from GaAs photocathode, and x-ray induced photoemission might be generating this “extra” beam

<table>
<thead>
<tr>
<th></th>
<th>I=0 (HV = 0, 100 kV)</th>
<th>I = 2 mA (Bulk GaAs, 532 nm, 350 μm Laser Spot)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 mm Active Area</td>
<td>7 mm Active Area</td>
</tr>
<tr>
<td></td>
<td>12.8 mm Active Area</td>
<td></td>
</tr>
<tr>
<td>Anode Current (pA)</td>
<td>0.0 ± 0.3</td>
<td>0.0 ± 0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.0 ± 0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-100 – -1000</td>
</tr>
<tr>
<td>X-ray Detector (E-2 mR/h)</td>
<td>0.6 ± 0.3</td>
<td>1.5 ± 0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.8 ± 0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 – 7</td>
</tr>
<tr>
<td>Gun Vacuum (pA)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 – 30</td>
</tr>
<tr>
<td>Y-Chamber Vacuum (nA)</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 – 20</td>
</tr>
</tbody>
</table>
Lesson: electrons from the edge of the photocathode strike the anode and vacuum chamber walls, degrading vacuum and limiting lifetime. 

Don’t make beam from the edge of the photocathode!!!

Also, don’t expect to run beam from the EC
Improve Lifetime with Larger Laser Spot?

(Best Solution – Improve Vacuum, but not easy)

Bigger laser spot, same # electrons, same # ions

Ionized residual gas strikes photocathode

Ion damage distributed over larger area
Lifetime with Large/Small Laser Spots

Tough to measure large Coulomb lifetimes with only 100-200 C runs!

Factor of 5 to 10 improvement with larger laser spot size

$\left( \frac{1500}{350} \right)^2 \approx 18$

Expectation:

“Further Measurements of Photocathode Operational Lifetime at Beam Current > 1mA using an Improved 100 kV DC High Voltage GaAs Photogun,” J. Grames, et al., Proceedings Polarized Electron Source Workshop, SPIN06, Tokyo, Japan
Ionization cross section for $H_2$

\[ \Omega_{\text{tot}} = \int \sigma(E) \cdot dE \sim 4 \cdot 10^{-18} \text{ cm}^2 \]
\[ L_{\text{gap}} \sim 5 \text{ cm} \]
\[ P_{\text{gun}} \sim 5 \cdot 10^{-12} \text{ Torr} \]
\[ Y_{\text{gun}} \sim 1.5 \cdot 10^7 \text{ ions/C} \]

$\Omega(100\text{keV}) = 4 \cdot 10^{-19} \text{ cm}^2$
\[ L_{\text{beamline}} \sim 100 \cdot L_{\text{gap}} \]
\[ P_{\text{beamline}} \sim 20 \cdot P_{\text{gun}} \]
\[ Y_{\text{beamline}} \sim 200 \cdot Y_{\text{gun}} \]

What about Ions Created Downstream of Anode?
Modifying the HV Chamber Anode Structure
Limiting Ionized Gas from HV Chamber

E. Pozdeyev,
Unbiased vs. Biased Running at 5mA

laser light IN

electron beam
OUT

Ions create QE through to electrostatic center

Anode = 0 V

Anode = 2 kV
Photocathode Lifetime at "EC" at 2mA

![Graph showing the lifetime of a photocathode under biased and grounded anodes, with data points indicating longer lifetimes for grounded anodes.](image-url)
Hypothesis: Double the gun voltage, halve the # of “bad” ions, improve lifetime by 2
Prolong Photocathode Charge Lifetime

At 200 kV, only 60% of ions are created compared to 100 kV, longer lifetime

Beam Current: 2.0 mA
Vacuum: 8.0 × 10^{-12} Torr
Field Emission – A Very Important Issue

- Previous measurements with flat electrodes, small gaps and low voltage - not very useful
- Want to keep gun dimensions about the same – suggests our 200kV gun needs “quiet” electrodes to 10MV/m

Stainless Steel and Diamond-Paste Polishing Good to ~ 5MV/m and 100kV.

Work of Ken Surles-Law, Jefferson Lab
Single Crystal Niobium:
- Capable of operation at higher voltage and gradient?
- Buffer chemical polish (BCP) much easier than diamond-paste-polish

Conventional geometry: cathode electrode mounted on metal support structure

Replace conventional ceramic insulator with “Inverted” insulator: no SF6 and no HV breakdown outside chamber

![Graph showing BCP Niobium vs Stainless Steel](image)

Field Emission Current (pA) vs Voltage (kV) for:
- Niobium
- 304 SS
- 304 SS #2
Single Crystal Nb: Good Cathode Electrode Material

~ No field emission at 225kV bias and 50mm gap

Anode Current (i.e. FE current)

2.5nA FS

Voltage induced gas desorption
No field emission at 225kV bias and 20mm gap

Voltage induced gas desorption

- But Niobium can be pushed too far, producing (many?) field emission sites. Avoid small gaps.
- These field emission sites can be difficult to process out
- Krypton processing works
- Sometimes, electrode needs to be re-BCP-ed.
Why a Niobium Cathode Electrode?

DPP 304 SS

Single Crystal Nb

Fine Grain Nb

Large Grain Nb
Krypton Processing to Eliminate FE

Large Grain Nb1 & 2 before Kr

Anode Current (pA) vs. High Voltage (kV)

Large Grain Nb after Kr

Anode Current (pA) vs. High Voltage (kV)

Large Grain Nb1&2 before Kr

Anode Current (pA) vs. Gradient (MV/m)

Large Grain Nb1&2 after Kr

Anode Current (pA) vs. Gradient (MV/m)
Our design has one region of “unintended” high gradient – could be problematic.....exploring new designs via electrostatic modeling.
Limiting the Active Area via Anodization

Normal photocathode; “out of box”

Anodized photocathode

- Electrons emitted from edge of wafer hit vacuum chamber walls. This is bad for vacuum.
- Anodization eliminates inadvertent photoemission from locations not intentionally illuminated with laser light
- Anodizing process dirties the photocathode surface, bad for QE
Atomic Hydrogen Cleaning

Photocathode sits here, inside vacuum chamber

Molecular hydrogen dissociated with RF inductive discharge
“Portable-H”
Atomic Hydrogen Cleaning

- Extremely high QE from bulk GaAs
- Reliable cleaning method
- No wet chemicals
- *In situ* cleaning an option (i.e., put it on the gun or in prep chamber)
But not for High Polarization Photocathodes

Wavelength

Polarization (%)

Polarization w/o Hydrogen cleaning

Polarization w/ Hydrogen cleaning

Solution: Arsenic Capping and Masking
Deep UHV gauges
Theory and Practice

Marcy Stutzman

Bruce Kendall  Elvac Laboratories
Pressure ranges

- Deep ultra high vacuum: below $1 \times 10^{-10}$ Torr
  - Commercially available gauges exist
  - Care must be taken in using gauges properly
- Extreme high vacuum: below $1 \times 10^{-12}$ Torr
  - Few room temperature systems obtain XHV
    - Electron sources for accelerators would benefit
    - Particle collider interaction regions
    - Reactive surface science applications
    - Nano-electronics
- Ionization gauges required to measure deep UHV
  - Hot filament gauges
  - Cold cathode gauges
HOT FILAMENT GAUGES

Bayard-Alpert
Modulated Bayard-Alpert
Extractor
Bessel Box
Bent Beam
Hot filament gauges

- Electrons produced by hot filament
- Electrons accelerated toward biased grid
- Gas molecules ionized by electron impact
- Ionized molecules collected on wire
- Collector current proportional to gas density

\[ P = nkT \]
HOT FILAMENT GAUGE ERRORS

X-ray limit
Inverse X-ray effect
Electron Stimulated Desorption
Outgassing from heated surfaces
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

3. Inverse X-ray effect
   - e- on anode -> photons
   - Photons on walls -> electrons
   - Electrons to collector
   - Extra negative current

4. Electron stimulated desorption
   - e- strike gas molecules on anode
   - Gas ionized and reaches collector
     - can be distinguished with energy analysis
   - Neutral atom desorbed
     - Ionized within grid
     - Indistinguishable from real gas
     - Must eliminate source

\[
I^+ = I_{\text{real}} + I_{x\text{-ray}} - I_{\text{inv.x-ray}} + I_{\text{ESD}}
\]
Reduction of x-ray and ESD errors

- Modulation
  - Extends BA gauge below $10^{-9}$ Torr
  - Redhead modulated gauges 1960s
    - ETI / Teledyne sold commercial version
  - Modulator varied between potentials near grid and collector voltages
    - Careful selection of potentials required to avoid changing ESD and x-ray currents
    - Real signal modulates, background constant
    - High pressure ($10^{-8}$ Torr) determination of modulation constant
- Geometry
  - MBAG benefits
    - Retrofit existing BAG with external modulation unit
    - Unaffected by electrometer drift
    - Read pressure near/better? extractor gauge
Reduction of x-ray and ESD errors

- CERN style commercial MBAG coming from Volotek
  - CERN vendor for MBAG controllers
  - Finishing prototyping
  - Commercial manufacturing run soon
  - Hope to exceed extractor capabilities
- XHV vacuum work
  - Heat treat flanges
  - Ceramic feedthroughs (previously glass)
  - 4.5” flange – less wall interference
  - CERN working on qualification
- Televac/ETI have produced metal MBAG as special order – Kendall, custom electronics
Reduction of x-ray and ESD errors

- **Geometry**
  - Reduce collector solid angle (thin wire BA)
  - Shield the collector from line of sight to the grid
    - Extractor
    - Bent Beam
      - Helmer
      - Ion Spectroscopy
    - Bessel Box
      - AxTran
  - Energy discrimination
    - Repeller in extractor
    - Bent beam gauges
X-ray limit measurements

Determine x-ray limit for certain setup
Current at reflector > grid
Current with voltages off


<table>
<thead>
<tr>
<th>Gauge</th>
<th>X-ray Limit (Torr)</th>
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<tbody>
<tr>
<td>Watanabe A</td>
<td>2.1 x 10^{-12}</td>
</tr>
<tr>
<td>Watanabe B</td>
<td>1.6 x 10^{-12}</td>
</tr>
<tr>
<td>Watanabe C</td>
<td>1.9 x 10^{-12}</td>
</tr>
<tr>
<td>JLab A</td>
<td>0.63 x 10^{-12}</td>
</tr>
<tr>
<td>JLab Gun 2</td>
<td>&gt;2 x 10^{-12}</td>
</tr>
<tr>
<td>JLab Gun 3</td>
<td>&gt;2 x 10^{-12}</td>
</tr>
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</table>
Modulated extractor gauge

- Cornell vacuum group with Charlie Sinclair (retired)
  - Modulate reflector potential with AC voltage
  - Read signal using Lock-in amplifier system
  - Measure field-off current (often negative) and account for this
  - Real time measurement with compensation for x-ray limit

- Student project that requires follow-up

- Redhead 1966 modulated extractor with filament in grid – revisit?
Extractor gauge long-term stability data

- Excellent stability with near continuous operation for more than a decade
- Venting 3-4 times per year
- Largest sensitivity changes follow system bakeouts
- Factors affecting stability
  - Excessive heating - deformation
  - Contamination
  - Mechanical damage
  - Nude gauge mounting geometry
  - Degas protocol
Energy analysis for ESD ions

- Bent Beam Gauges
  - Helmer/Improved Helmer
    - 90° bend
    - Distinguish against ions at grid potential
    - <10^{-13} Torr measured CERN ISR interaction region
    - Volotek: available next year?

- Watanabe Ion Spectroscopy Gauge
  - 180° bend – hemispherical energy analyzer
  - Spherical Grid - more uniform ion energy
  - Not commercially available

- Bessel Box
  - Bend ions
  - High energy ESD ions blocked
  - Sold as AxTran by ULVAC
  - Good agreement with extractor
  - Electron multiplier

Redhead: For scientists energy analyzer gauges ideally have tunable energy for analysis

Axtran (Torr)

Extractor (Torr)
Application notes

- Hot filament gauges will heat walls
  - Reduce heat of gauge (1 mA instead of 10 mA)
    - Outgassing from walls reduced
    - More gas adsorbed on grid, walls -> ESD increased
  - Use better wall materials
    - BeCu – Watanabe
    - Silco-steel™ – Kendall
  - Heat walls until molecules don’t stick
    - Kendall: operation 700-800K eliminates adsorbed molecules on walls and grid
      - Eliminates ESD neutrals
    - Watanabe: heated grid / cold cathode gauge

- Electronics issues
  - Cable leakage
    - Replace coax cables with twin-ax or tri-ax
  - Electrometer stability
    - Always use same head/control unit combination
  - Calibrate each gauge (vs. spinning rotor gauge) regularly for optimal performance
COLD CATHODE GAUGES

Magnetron
Inverted Magnetron
Double Inverted Magnetron
Ion pump?
Cold Cathode Gauge Operation

- Electron cloud trapped in crossed electric and magnetic fields
  - Spontaneously starts in presence of electric field at HV pressures
  - Electron cloud density limited by space charge effects
- Ionized gas collected at cathode
  - UHV starting element
    - Radioactive
    - Thermal
    - UV

Image from Peacock et al. JVSTA 9 1977 (1991)
Modern Cold Cathode Gauge

- No gauge heating
- Very rugged, low power consumption
  - Lunar missions, space applications
- Change in power law behavior at “magnetron knee” \( \approx 10^{-9} \) Torr
- Stray magnetic fields minimized in modern designs
- Accuracy for ELVAC modification of Televac CCG
  - Stronger magnets
  - Smaller volume
  - Precision alignment mounting jig
  - Controller improvements

\[ I \propto p^x \]

Televac Double Inverted design
Kendall JVSTA 18 1724 (2000).

Edwards low field magnet design

Long term stability Televac UHV CCG
CCG vs. Extractor at 2\( \times 10^{-10} \) Torr

\begin{align*}
\text{CCG Accuracy} \\
\text{Pressure x } 10^{-10} \text{ Torr} \\
\text{Months}
\end{align*}
Ion pump as a pressure gauge

- Current linear vs. extractor gauge
- Minimum voltage to sustain discharge
- Does not work with all ion pump designs (Noble ion configuration)

- PE sputter DI pumps
- Penning cell
- Power supply with Electrometer

- Current linear vs. extractor gauge
- Minimum voltage to sustain discharge
- Does not work with all ion pump designs (Noble ion configuration)
Conclusions

Hot filament gauges

- X-ray limit, ESD ions
  - Geometry
  - Modulation
- ESD neutrals
  - Heated grid gauges
  - Novel materials
- Sensitive to abuse, contamination
- Lowest pressure measured with Helmer gauge

Cold cathode gauges

- Rugged, low energy consumption
  - Lunar, space applications
- Compensation for “knee” in electronics
- Ion pumps with sensitive current monitor shown to work as a relative pressure gauge
- Extension of conventional gauges toward XHV requires more work

Small market – few commercially available gauges
Careful selection, utilization essential for accurate readings
Deep UHV gauges essential for improvements toward XHV
Deep UHV/XHV gauges

- **Extractor gauge**
  - available for decades
  - x-ray limit reduced through geometry
  - x-ray limit quote: $7.5 \times 10^{-13}$ Torr

- **Axtran gauge**
  - Bessel box energy discrimination
  - electron multiplier to assist in low current measurements
  - Purchased, not yet installed
  - Measurement limit quote: $<7.5 \times 10^{-15}$ Torr

- **Watanabe BBB (Bent Belt Beam) gauge**
  - Operates with Leybold IE540 controller
  - 230° degree deflector (similar to Helmer)
  - BeCu housing to reduce $I_{heating}$
  - Manufacturer’s lower limit: $4 \times 10^{-14}$ Torr
Pressure Measurement = Current Measurement

**Ionization gauge current contributions**

\[ I_{\text{measured}} = I_{\text{real}} + I_{\text{x-ray}} + I_{\text{heating}} + I_{\text{ESD}} + \left( I_{\text{inv.x-ray}} + I_{\text{ESD neut}} \right) \]

- \( I_{\text{real}} \): pressure dependent gas phase ions – species sensitive
- \( I_{\text{x-ray}} \): x-ray induced electron desorption from collector
  - reduce by geometry
- \( I_{\text{ESD}} \): ions arriving at collector from electron stimulated desorption (ESD) of molecules on the grid
  - reduce by degassing grid
- \( I_{\text{heating}} \): pressure rise due to filament heating – species sensitive
  - reduce by material selection, geometry, long duration
Gauge characterization chamber

- Heat treated twice
  - 400°C 10 days
- Outgassing (Q)
  - $3 \times 10^{-14}$ Torr·L/s·cm²
- Q following 250°C bake
  - $6.3 \times 10^{-14}$ Torr·L/s·cm²
- 3800 cm², 12L
- Pumping
  - 4 WP1250 NEGs, 60% 1300 L/s
  - 40 L/s ion pump (behind right angle valve)

**Predicted pressure**

$2 \times 10^{-13}$ Torr

- Extractor Gauge
- BBB Gauge
- 2 Leybold IE540 controllers
- 2 Keithley electrometers
- UHV ion pump power supply
- Diagnostic cross with RGA and ion pump
- NEG activation flange
Gauge responses linear response over decades, possible deviation at lowest pressures
Sensitivity

\[ S = \frac{I_i}{P \times I_e} \]

Sensitivity (1/Torr)

- BBB and Extractor
  - 120V electron energy
  - 1.6 mA emission current
  - geometry, collection efficiency vary

BBB vs. SRG data from previous setup
BBB sensitivity calculated using extractor

SRG Data: pressure $10^5$ higher than our area of concern
Calculate BBB sensitivity from Extractor gauge pressure?

Calculated Extractor pressure relies on sensitivity of extractor gauge.

$$P = \frac{I_i}{S \times I_e}$$

Gauge sensitivity depends on
- Ionization energy
- Gas species
- Geometry
- Collection efficiency

same
constant
relative sensitivity

Define sensitivity ratio
- should be constant

\[ \frac{S_{BBB}}{S_{EXT}} = \frac{I_{BBB}}{I_{EXT}} \]

Can the deviation from constant behavior be explained by gauge backgrounds?
Background current measurements

Extractor x-ray current accounts for 3/5 of total measured signal

BBB signal of 35 fA with background of -1 fA

Gauge backgrounds measured at different times, different pressures
Sensitivity ratio: x-ray limit correction

- Subtraction of x-ray background for extractor gauge overcorrects
- What else?
  - ESD limits
  - Load due to gauges
  - Small current measurement errors
  - Nonlinearity in gauge response?
Electron stimulated desorption

\[ I_{\text{measured}} = I_{\text{real}} + I_{x\text{-ray}} + I_{\text{heating}} + I_{\text{ESD}} + \ldots \]

- Electrons can liberate elements adsorbed on the grid
- If grid-filament potential equal to electron energy, ESD difficult to separate
- Methods to reduce ESD
  - high energy electron bombardment (degas mode)
  - operate grid at elevated temperature
  - grid material optimization (BBB)
  - stabilize for months
  - Axtran: energy analysis since electron energy ≠ grid-filament potential
Current due to heating by filaments

\[ I_{\text{measured}} = I_{\text{real}} + I_{x\text{-}ray} + I_{\text{heating}} + I_{\text{ESD}} + \ldots \]

Use one gauge to measure the additional current generated by other hot filament

\[ \Delta I (\text{BBB}) = 4.8 \text{ fA} \]
\[ \Delta I (\text{Extractor}) = 5.6 \text{ fA} \]

*BeCu BBB housing should reduce effect*

*Difference minimized after 6 months?*
So what is our pressure?

\[ I_{\text{measured}} = I_{\text{real}} + I_{x\text{-ray}} + I_{\text{heating}} + I_{\text{ESD}} + \ldots \]
Conclusions

• Pressure in our systems (nitrogen equivalent) corrected for gauge effects is near $1 \times 10^{-12}$ Torr
• BBB signal to noise good: Noise < 10% signal
• Extractor gauge: measurements at lowest pressures dominated by background
• BBB and extractor agree very well above $1 \times 10^{-11}$ Torr, diverge at lowest pressures
• The BBB gauge should be able to quantify pressure improvements in the bakable cryopump system.
Back up slides
Emittance and Brightness

- Normalized Emittance from GaAs:
  \[ \varepsilon_{n,x,y} = \sqrt{\frac{q}{4\pi\varepsilon_0 E_s \frac{k_B T_{eff}}{m_e c^2}}} \]

- Bunch Charge (= 0.4 pC, 200 μA and 499 MHz)
- Electric Field at GaAs surface
- Effective Temperature of GaAs (= 300 – 400 K, 780 nm)
- Thermal Energy (= 34 meV)

<table>
<thead>
<tr>
<th>Gun HV (kV)</th>
<th>( E_s ) (MV/m)</th>
<th>( \varepsilon_n ) (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>2.0</td>
<td>0.011</td>
</tr>
<tr>
<td>140</td>
<td>2.8</td>
<td>0.009</td>
</tr>
<tr>
<td>200</td>
<td>4.0</td>
<td>0.008</td>
</tr>
</tbody>
</table>

- Normalized Brightness:
  \[ B_n \propto \frac{1}{\varepsilon^2} \propto E_s \]

Brightness is proportional to Gun HV
DC beam from bulk GaAs, green light and 350µm spot.

Similar (good) results as with older guns, at 100kV

Finite lifetime due to ion back-bombardment