Deep UHV gauges
Theory and Practice

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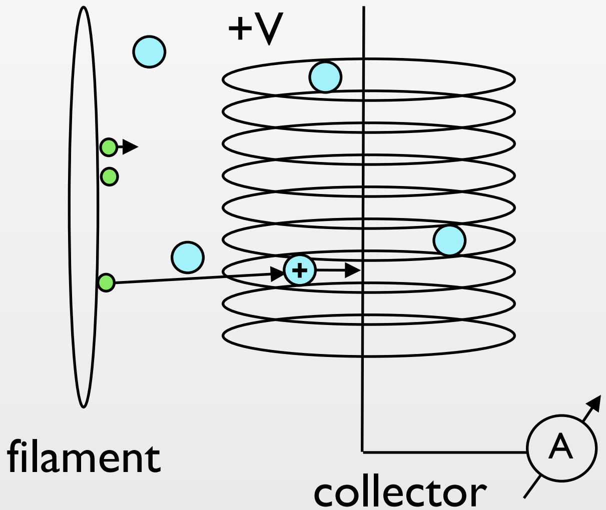
Pressure ranges

- Deep ultra high vacuum: below $1x10^{-10}$ Torr
  - Commercially available gauges exist
  - Care must be taken in using gauges properly
- Extreme high vacuum: below $1x10^{-12}$ 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



$$P = nkT$$

- 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

Hot filament gauge errors

X-ray limit

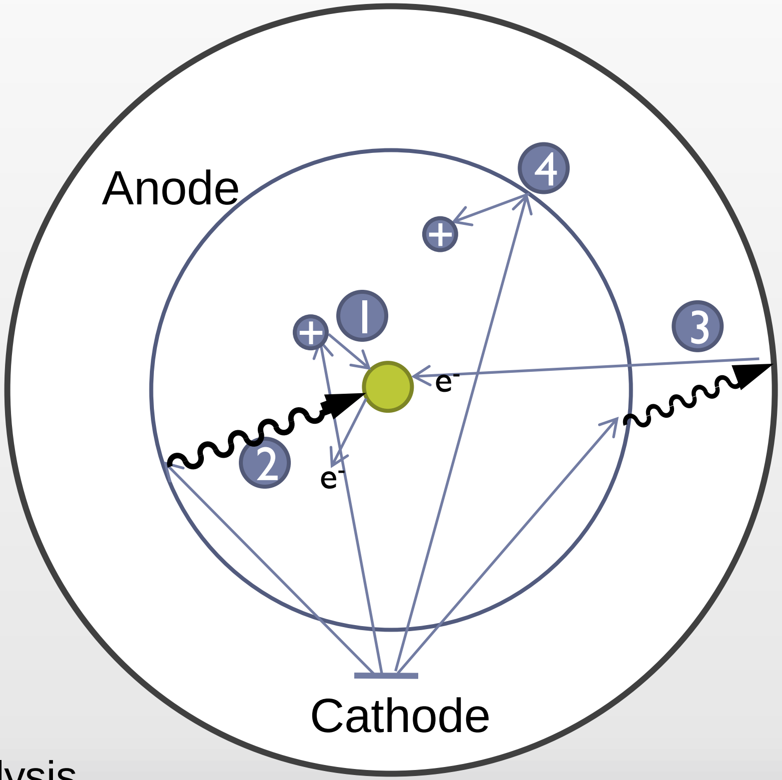
Inverse X-ray effect

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 souce

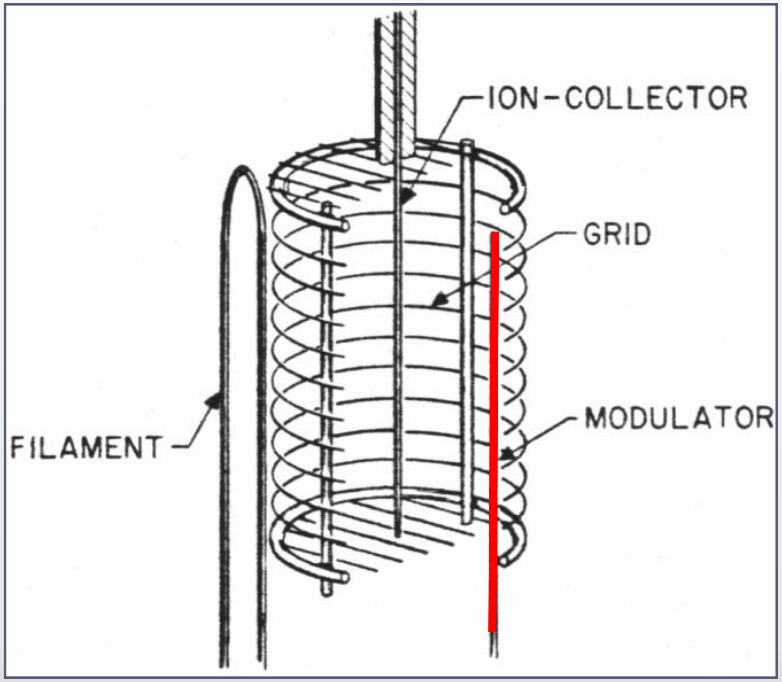


$$I^+ = I_{real} + I^-_{x-ray} - I^-_{inv.x-ray} + I_{ESD}$$

Reduction of x-ray and ESD errors

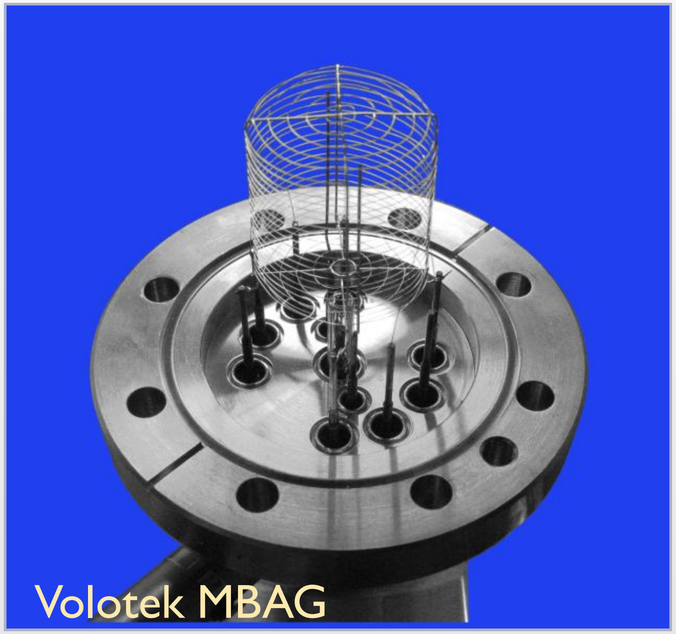
- Modulation
- Geometry

- 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
- MBAG benefits
  - Retrofit existing BAG with external modulation unit
  - Unaffected by electrometer drift
  - Read pressure near/better? extractor gauge



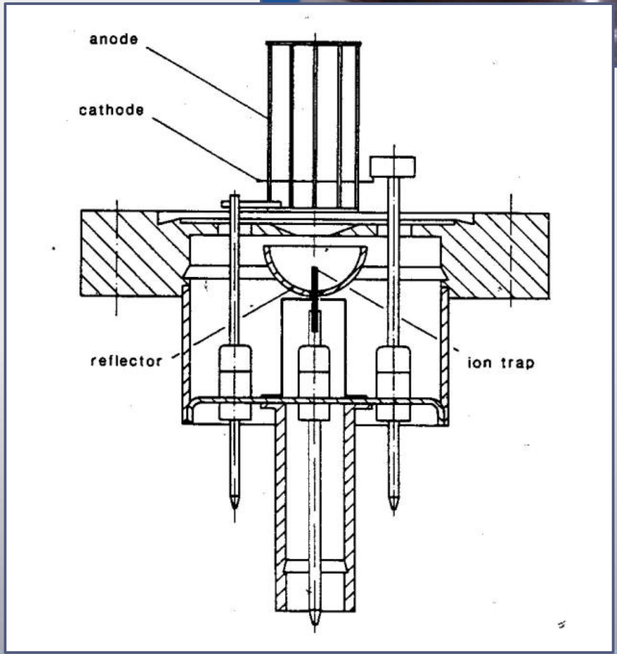
Reduction of x-ray and ESD errors

- CERN style commerical 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



Oerlikon Leybold Extractor gauge

X-ray limit measurements

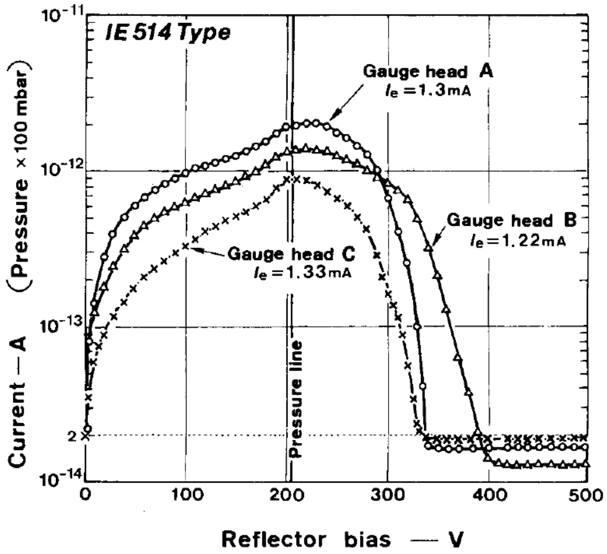
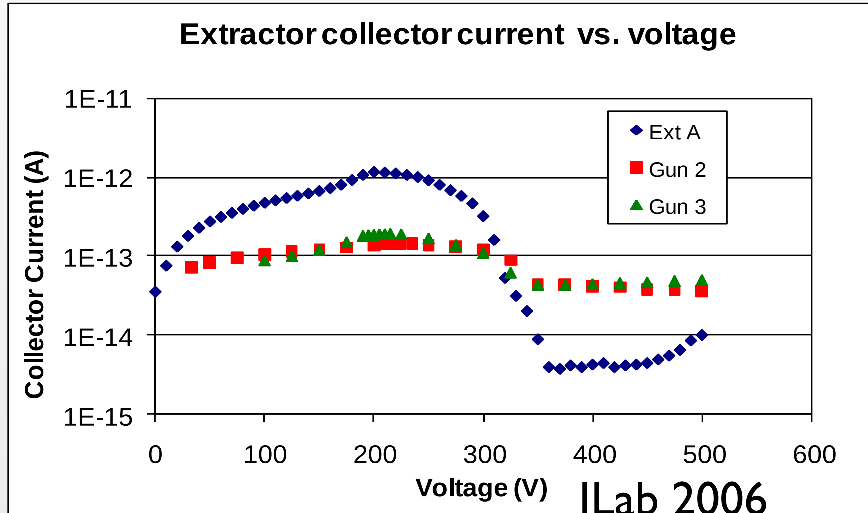


FIG. 3. Reflector bias effect for various IE514 gauge heads.



Fumio Watanabe JVSTA 9 (1991).

Determines x-ray limit for certain setup

- Current at reflector > grid
- Current with voltages off

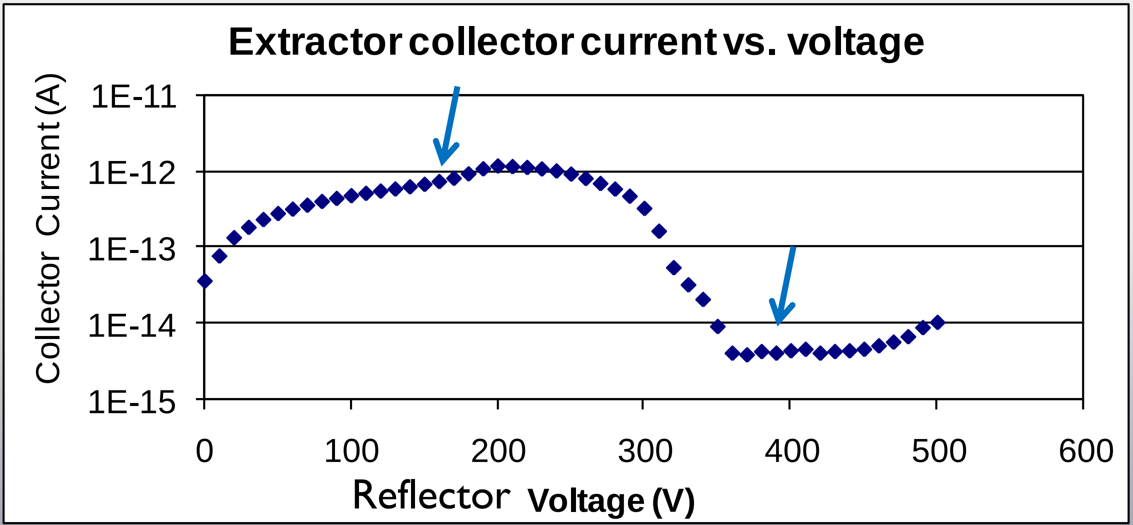
Gauge	X-ray Limit (Torr)
Watanabe A	2.1×10^{-12}
Watanabe B	1.6×10^{-12}
Watanabe C	1.9×10^{-12}
JLab A	0.63×10^{-12}
JLab Gun 2	$>2 \times 10^{-12}$
JLab Gun 3	$>2 \times 10^{-12}$

Modulated extractor gauge

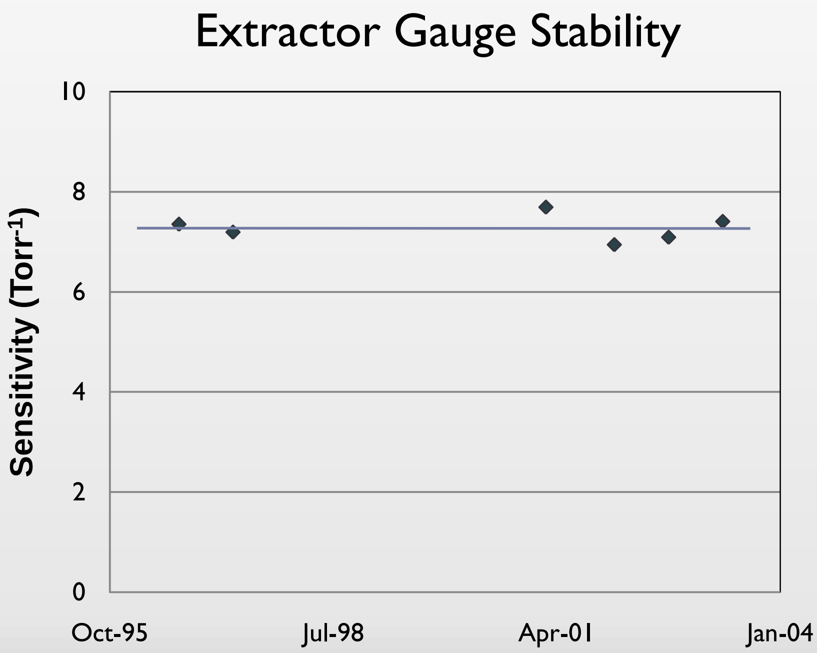
- Cornell vacuum group with Charlie Sinclair (retired)
  - Modulate reflector potential with AC voltage
  - Read signal using Lock-in amplifier system
  - Measure field-off current (often negative) and account for this
  - Real time measurement with compensation for x-ray limit

- Student project that requires follow-up

- Redhead 1966 modulated extractor with filament in grid – revisit?



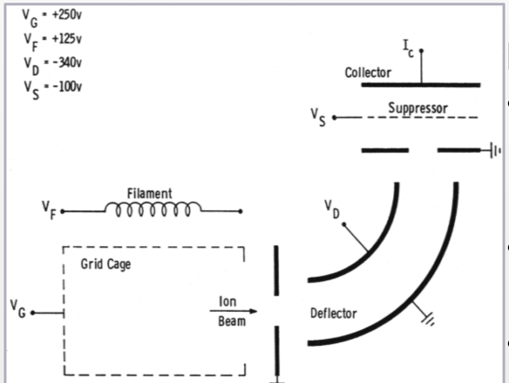
Extractor gauge long-term stability data



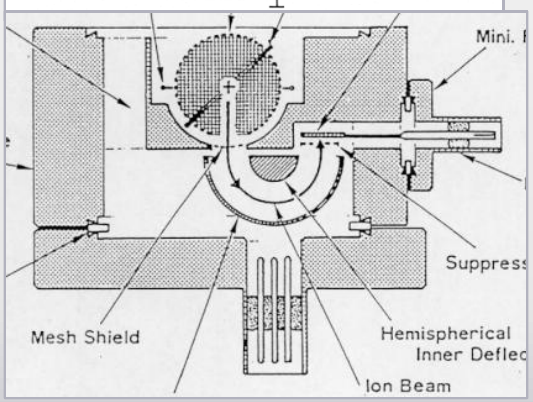
- Excellent stability with near continuous operation for more than a decade
- Venting 3-4 times per year
- Largest sensitivity changes follow system bakeouts
- Factors affecting stability
  - Excessive heating - deformation
  - Contamination
  - Mechanical damage
  - Nude gauge mounting geometry
  -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

Energy analysis for ESD ions

Bent Beam Gauges



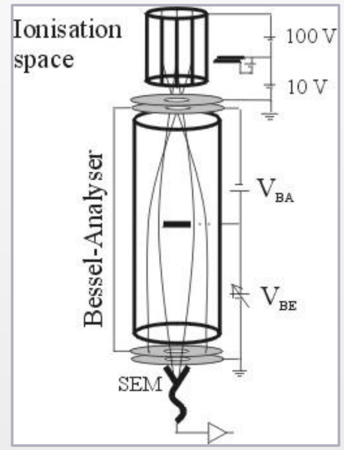
Helmer/Improved Helmer
- 90 bend
  - Distinguish against ions at grid potential
- $<10^{-13}$ Torr measured CERN ISR interaction region
- Volotek: available next year?



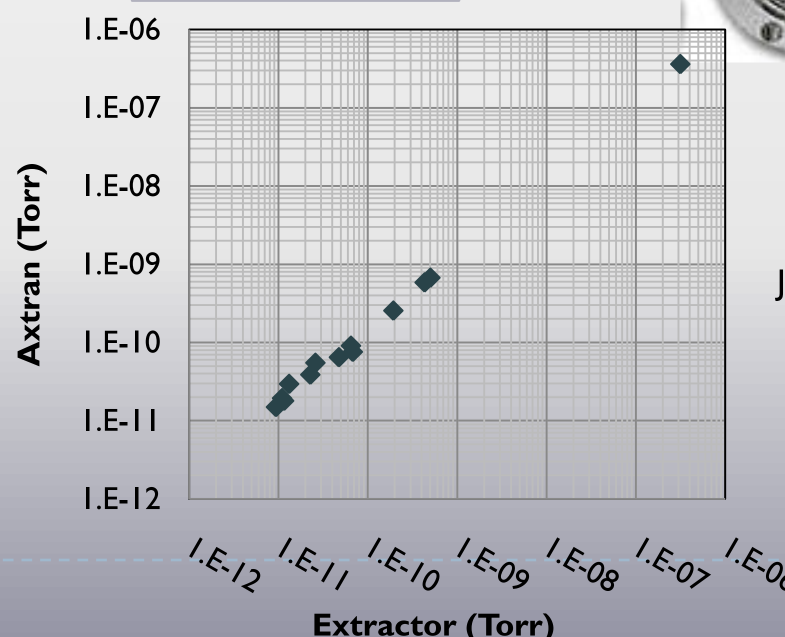
Redhead:
For scientists energy analyzer gauges ideally have tunable energy for analysis

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



JLab 2004

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

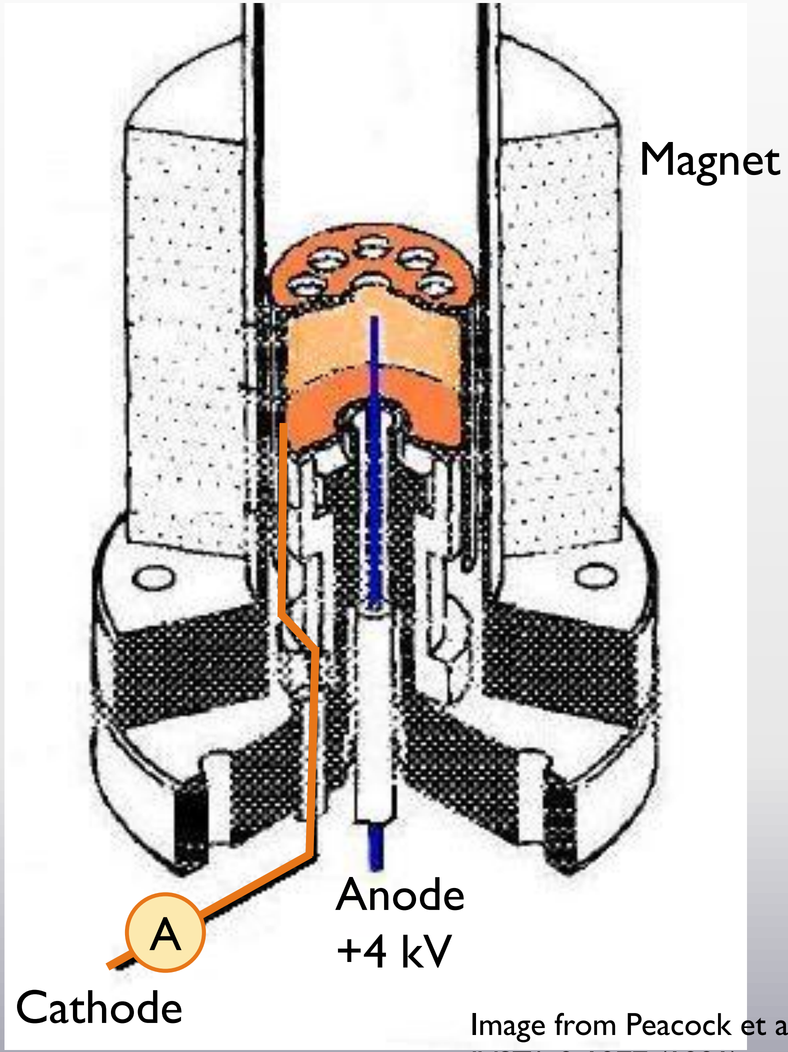
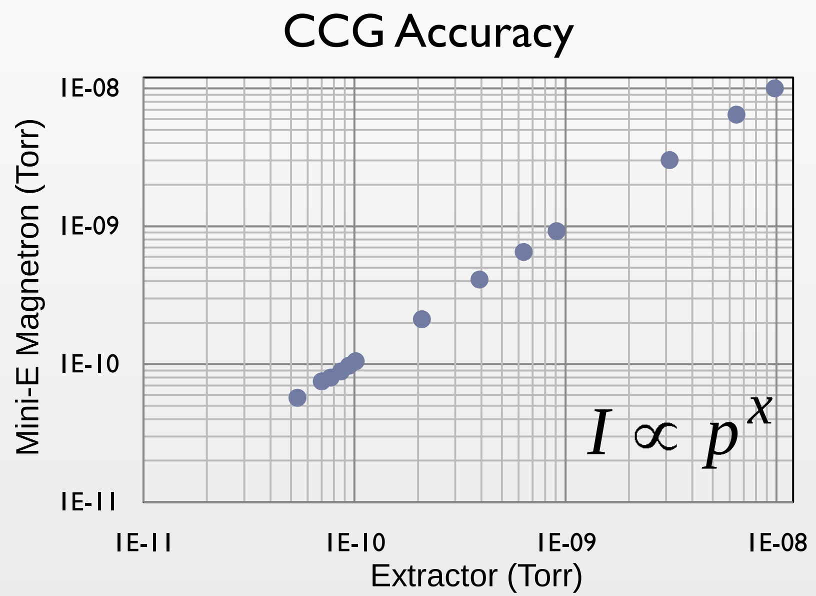


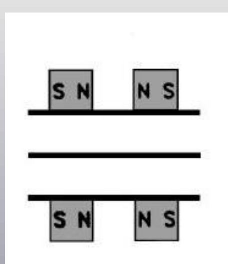
Image from Peacock et al. JVSTA 9 1977 (1991)

- 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

Modern Cold Cathode Gauge

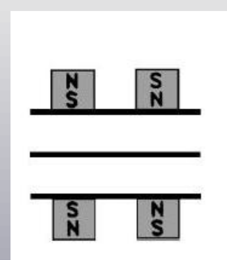
- No gauge heating
- Very rugged, low power consumption
  - Lunar missions, space applications
- Change in power law behavior at "magnetron knee" ~10^{-9} Torr
- Stray magnetic fields minimized in modern designs
- Accuracy for ELVAC modification of Televac CCG
  - Stronger magnets
  - Smaller volume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



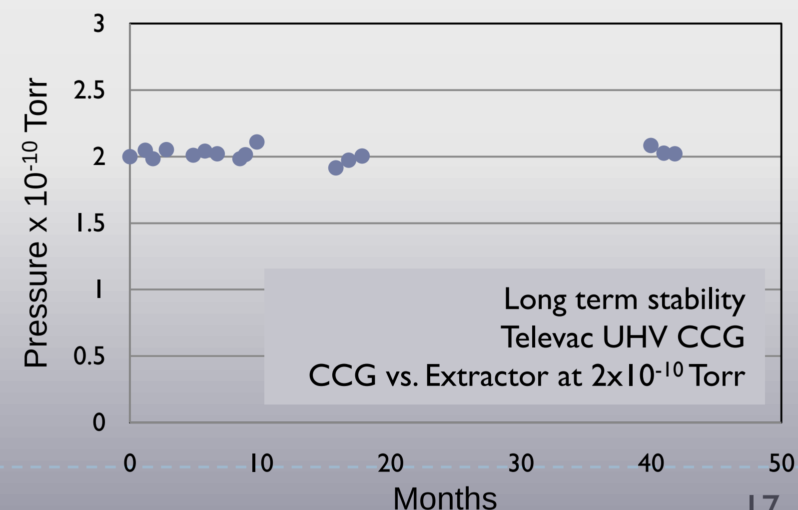


Televac Double Inverted design

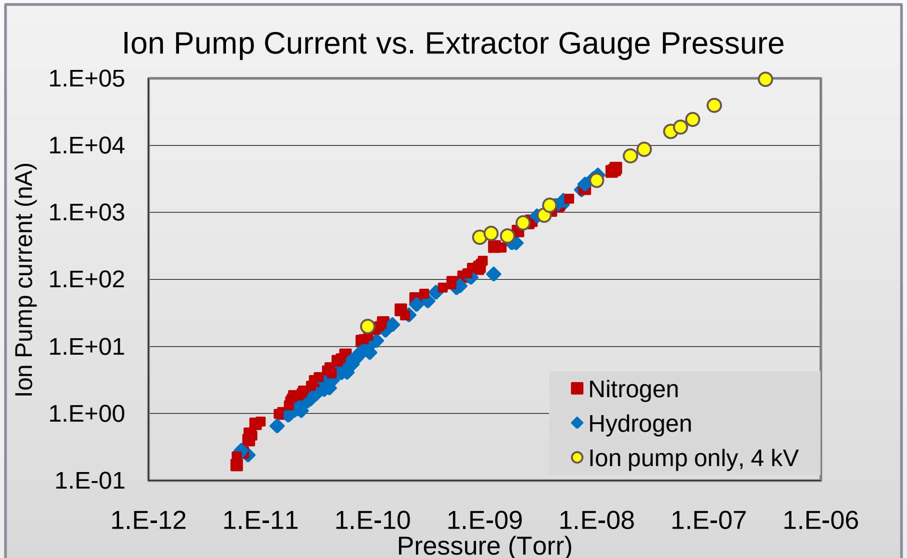
Kendall JVSTA **18** 1724 (2000).

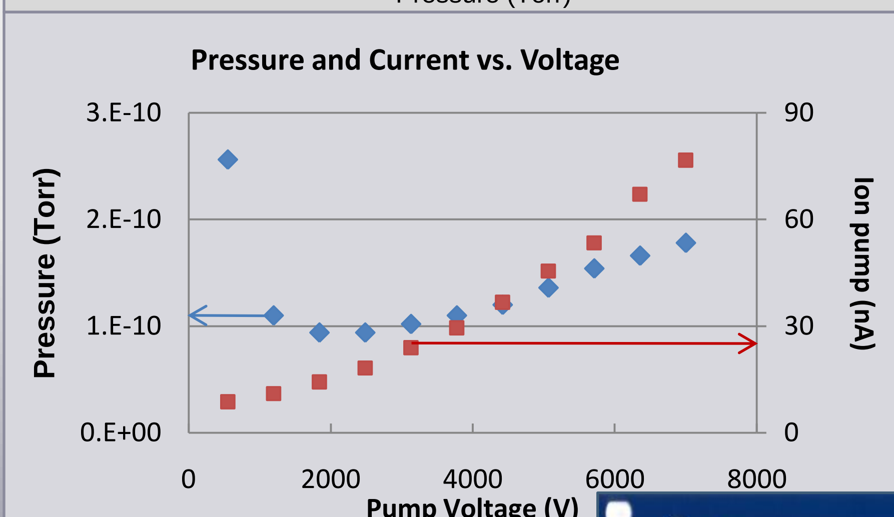


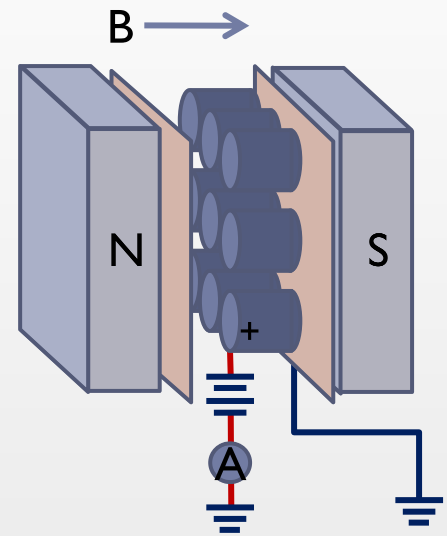
Edwards low field magnet design



Ion pump as a pressure gauge







- 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