16.522 Space Propulsion

Characterization of Space Propulsion Devices

Vacuum Systems and Practice

Contents

- Vacuum Systems:
  - Vacuum requirements for space propulsion testing
- Vacuum pumps:
  - Mechanical (roughing), Diffusion, Turbomolecular, Cryos
- Vacuum practice (good habits around the lab)
- Vacuum capabilities at SPL

Why do we need vacuum?

- Simulate conditions in which thrusters will operate (back-pressure)
- Plasmas can be created under any pressure condition (Saha's)
- Low pressures mostly used given the power level available
- In testing, important to avoid "chamber effects":
  - Avoid spurious elastic and inelastic collisions, i.e., charge exchange, background ionization, scattering, etc...
- Allow for more realistic operational issues, i.e., heat transfer

What is considered vacuum?

- In interstellar space there is one H atom per cm^3

$$n = 1\times10^{6}\ \mathrm{m}^{-3} \qquad T \approx 10{,}000\ \mathrm{K}$$

$$p = nkT = 1.4\times10^{-13}\ \mathrm{Pa} = 1\times10^{-15}\ \mathrm{Torr}$$

- In LEO at 600 km:

$$n = 1\times10^{13}\ \mathrm{m}^{-3} \qquad T \approx 1300\ \mathrm{K}$$

$$p = nkT = 2\times10^{-7}\ \mathrm{Pa} = 1.5\times10^{-9}\ \mathrm{Torr}$$

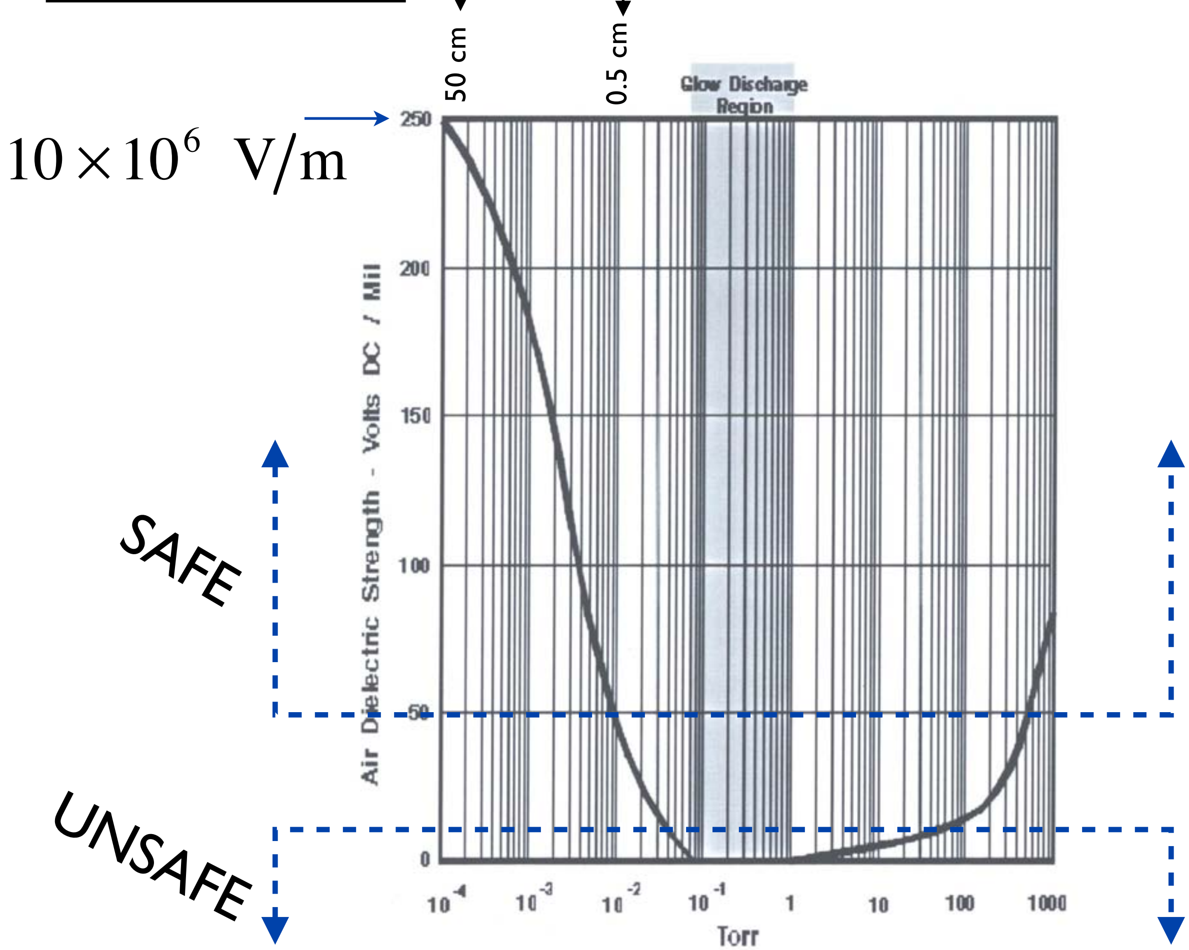
Pressure Units

Table removed due to copyright restrictions. Please see conversion factors on page 205 of Brown, Charles D. Spacecraft propulsion. AIAA Education Series, AIAA, 1996.

Glow Discharges

Mean free path

$$\lambda_{mfp} = \frac{1}{nQ_{c.s.}}$$

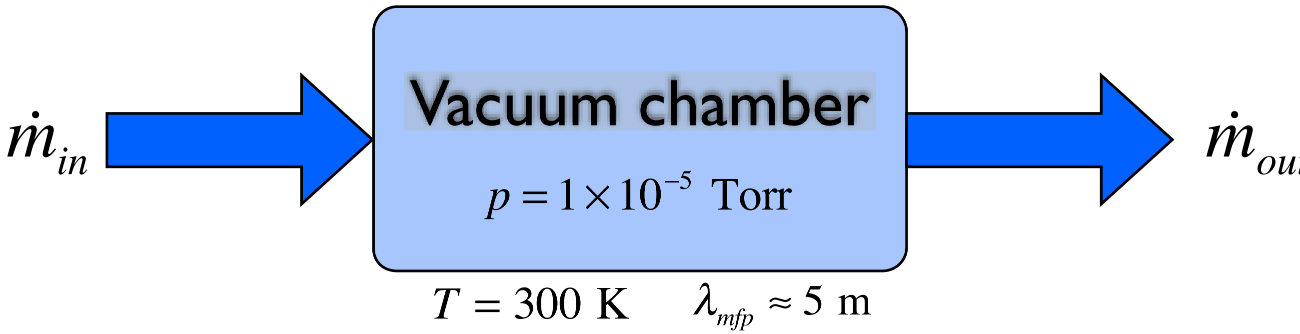


2×10^6 V/m

- At poor vacuum levels, a significant amount of current can flow through a glow discharge.
- Equipment damage possible (likely).
- Extra-care when pumping down, or venting vacuum equipment.

Pumping Speed for Required Vacuum

Say we want to test a Xe electric propulsion engine with a specific impulse of 1500 sec and efficiency of 60% at 200 W:



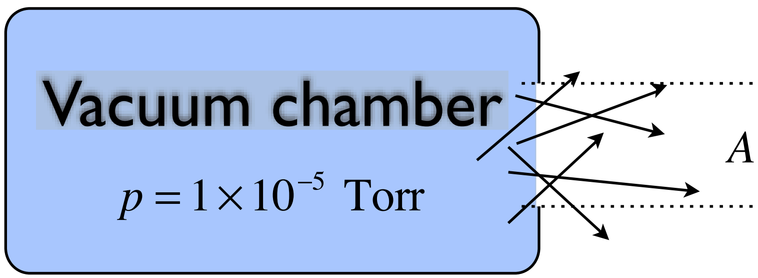
$$\dot{m} = \frac{2\eta P}{c^2} = \frac{2(0.6)(200)}{(1500 \cdot 9.8)^2} = 1.11 \times 10^{-6} \text{ kg/s}$$

volumetric flow rate at standard conditions

$$Q_s = \frac{\dot{m}}{\rho_s} = \frac{\dot{m}}{p_s} RT_s = \frac{1.11 \times 10^{-6}}{101325} \left(\frac{8314}{131} \right) (300) \left(6 \times 10^7 \right) = 12.5 \text{ sccm}$$

Pumping Speed for Required Vacuum

Say we want to test a Xe electric propulsion engine with a specific impulse of 1500 sec and efficiency of 60% at 200 W:



$T = 300$ K $\quad \lambda_{mfp} \approx 5$ m

An ideal vacuum pump can be represented as an opening with area A on the chamber. Gas particles flow out of the chamber through this opening. The volumetric flow rate at which particles leave is given by:

$$Q_{out}^{ideal} = \frac{\Gamma A}{n} = \frac{\bar{c}A}{4} = \frac{A}{4}\sqrt{\frac{8kT}{\pi m}}$$

If conditions in the chamber are to be preserved, this flow rate must be equal to the injected flow rate:

$$Q_{out} = Q_{in} = \frac{\dot{m}}{\rho} = \frac{\dot{m}}{p}RT \longrightarrow p = \frac{4\dot{m}RT}{\bar{c}A}$$

In our example, we solve for the opening area:

$$\bar{c} = \sqrt{\frac{8kT}{\pi m}} = 224 \text{ m/s} \qquad A = \frac{4\dot{m}RT}{\bar{c}p} = 0.283 \text{ m}^2$$

Pump specification:

$$D = \sqrt{\frac{4A}{\pi}} = 0.6 \text{ m} \qquad Q_{out}^{ideal} = 15{,}800 \text{ liter/s}$$

Real Vacuum Pumps

In real systems, there are components which "slow down" gas flow in the desired direction. In addition, backflow is always present to some extent. These effects are characterized through an effective *conductance* (C) of the vacuum system. The real pumping speed is then:

$$Q_{out} = \frac{C Q_{out}^{ideal}}{Q_{out}^{ideal} + C}$$

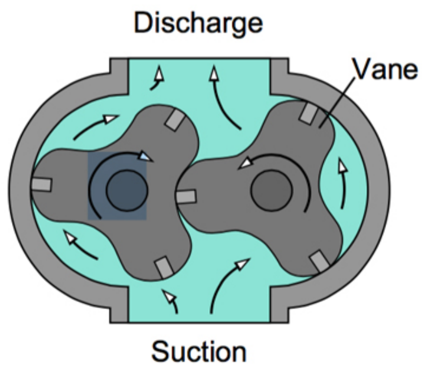
High performance pumping systems are able to:

- Capture, compress and expel the gas molecules (positive displacement pump), e.g. mechanical pump
- Give the gas molecule a preferential direction (momentum transfer pump), e.g. diffusion pump, turbomolecular pump, aspiration pump, vacuum cleaner
- Capture and keep the gas molecules (adsorption pump, absorption or reaction pump), e.g. cryopump, sorption pump, ion pump, evaporative getter pump, absorption pump, getter pump

Mechanical (Roughing) Pumps

Mechanical pumps are positive displacement pumps that take a large volume of gas at low pressure and compress it into a smaller volume at higher pressure.

Mechanical pumps are often used to "back" high vacuum pumps and the pump capacity should not be restricted by the conductance between it and the high vacuum pump or by the conductance of the exhaust system. Many of the mechanical pumps can exhaust to ambient pressure whereas most high vacuum pumps cannot.



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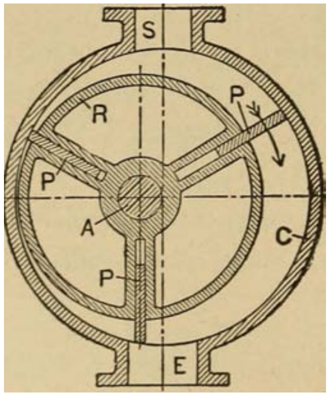

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Schematic of a claw pump removed due to copyright restrictions.

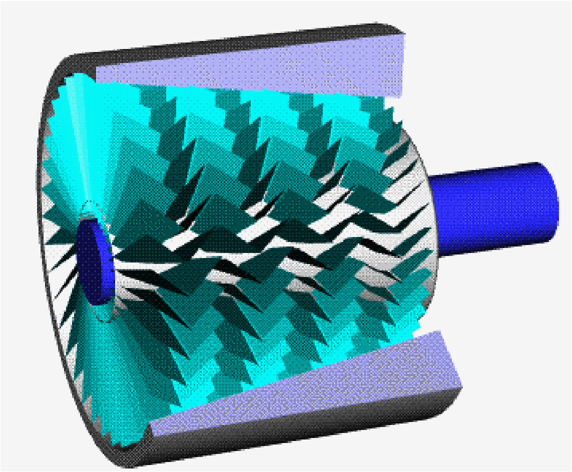
Diffusion Pumps

The diffusion pump (DP) or vapor jet pump is a momentum transfer pump that uses a jet of heavy molecular weight vapors to impart velocity (direction) to the gases by collision in the vapor phase. DP's are probably the most widely used high vacuum pumps in most industrial applications, with a wide range of pumping speeds up to 30,000 liters/s and ultimate pressures (no load) of 10^{-8} Torr.

Figure removed due to copyright restrictions. Please see the schematic of a diffusion pump on Wikipedia.

Turbomolecular Pumps

The turbomolecular pump or "turbopump" is a mechanical type momentum transfer pump in which very high speed vanes impart momentum to the gas molecules. This type of pump operates with speeds up to 100,000 rpm. Pumping speeds range from a few liters/s to over 10,000 liters/s. Turbopumps require very close tolerances in the mechanical parts and cannot tolerate abrasive particles or large objects. Turbomolecular pumps are expensive, but clean and able to reach ultimate pressures down to 10^{-11} Torr.



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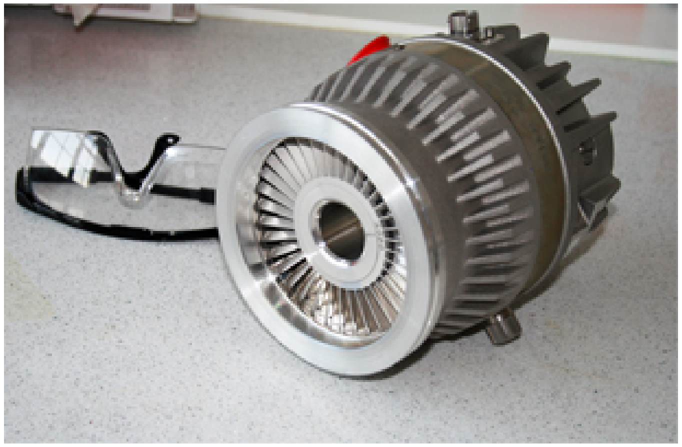

Photo available on Wikipedia from Karelj. Photo is in public domain.

Cryopumps

Cryopumps operate by condensing and/or trapping gases and vapors on surfaces cooled by helium to a temperature of 10-20 K, which solidifies gases such as N_2, and O_2. Gases which do not condense (Ne, H_2), are trapped by *cryosorption* in activated charcoal panels bonded to the cold elements. Other surfaces are near liquid nitrogen temperature (77 K) which solidify water and CO_2. The pumping speed is very high in comparison with other pumps of comparable size and is proportional to the surface area and the amount of previously pumped gas on the surface, reaching values up to 200,000 liters/s. Ultimate vacuum is about 10^{-9} Torr.

Figure removed due to copyright restrictions. Please see figure 6 of Day, C. "Basics and Applications of Cryopumps. CERN Accelerator School." *Vacuum in Accelerators* (2007): 241.

Flow Control and Pressure Gauges

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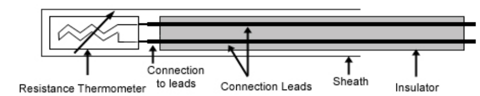
Schematic of a thermocouple gauge removed due to copyright restrictions.



Courtesy of JohnnyMrNinja on Wikipedia.
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Schematic of a thermocouple gauge removed due to copyright restrictions.

Schematic of a capacitance manometer removed due to copyright restrictions.

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	Capacitance diaphragm gauge	**Viscosity gauge/spinning rotor**	**Thermal conductivity/Piriani gauge**	**Hot cathode ionization gauge**
Pressure (Torr)	Atmosphere to 10^{-6}	1 to 10^{-8}	Atmosphere to 10^{-4}	10^{-1} to 10^{-9}
Accuracy (%)	±0.02 to 0.2	±1 to 10	±5	±1

Vacuum Practice

- Very small flow rates require very large pumping capacity
- Important to avoid leaks and outgassing
- Materials and operation are crucial to reach desired low pressures.
- Use low vapor-pressure materials only:
  - Clean, polished metals (stainless steel is best choice)
  - Reduce use of polymers, plastics or organic materials. If strictly required (no non-porous substitute) use teflon or UHMW PE.
- Machined assemblies must be clean, no virtual leaks (gas traps)
- Access doors/flanges need to be wiped before closing
- Never touch the inside of a chamber without powder-free gloves.
  - If required use shoe covers, lab coats, hair covers, goggles, etc...
- Always use clean tools (free of oil, dirt, or any other type of contaminant)

Vacuum Practice

- Make sure pump access is free from obstructions or objects
- Check for specified ratings of electrical feedthroughs
- Always follow operating instructions (use checklists)
- Verify system operates nominally before and during startup
- No electric/electronic equipment should be on during pump startup or system venting (including high vacuum pressure gauges, they use high voltage)
- Do not use liquids inside the vacuum system (especially water)
- Use low outgassing electrical cables inside vacuum chambers
- Keep a clean environment in the lab room

Vacuum Systems at MIT's SPL

ASTROVAC

1.6 x 1.5 m cylindrical chamber

Two Cryopumps (~7500 ls^{-1}, Xe)

Bakeable with included heaters and controller

Pumps all gases (except He)

MINIVAC

50 cm long, 20 cm DIA cylindrical chamber

Two turbomolecular pumps (140 ls^{-1}, N_2)

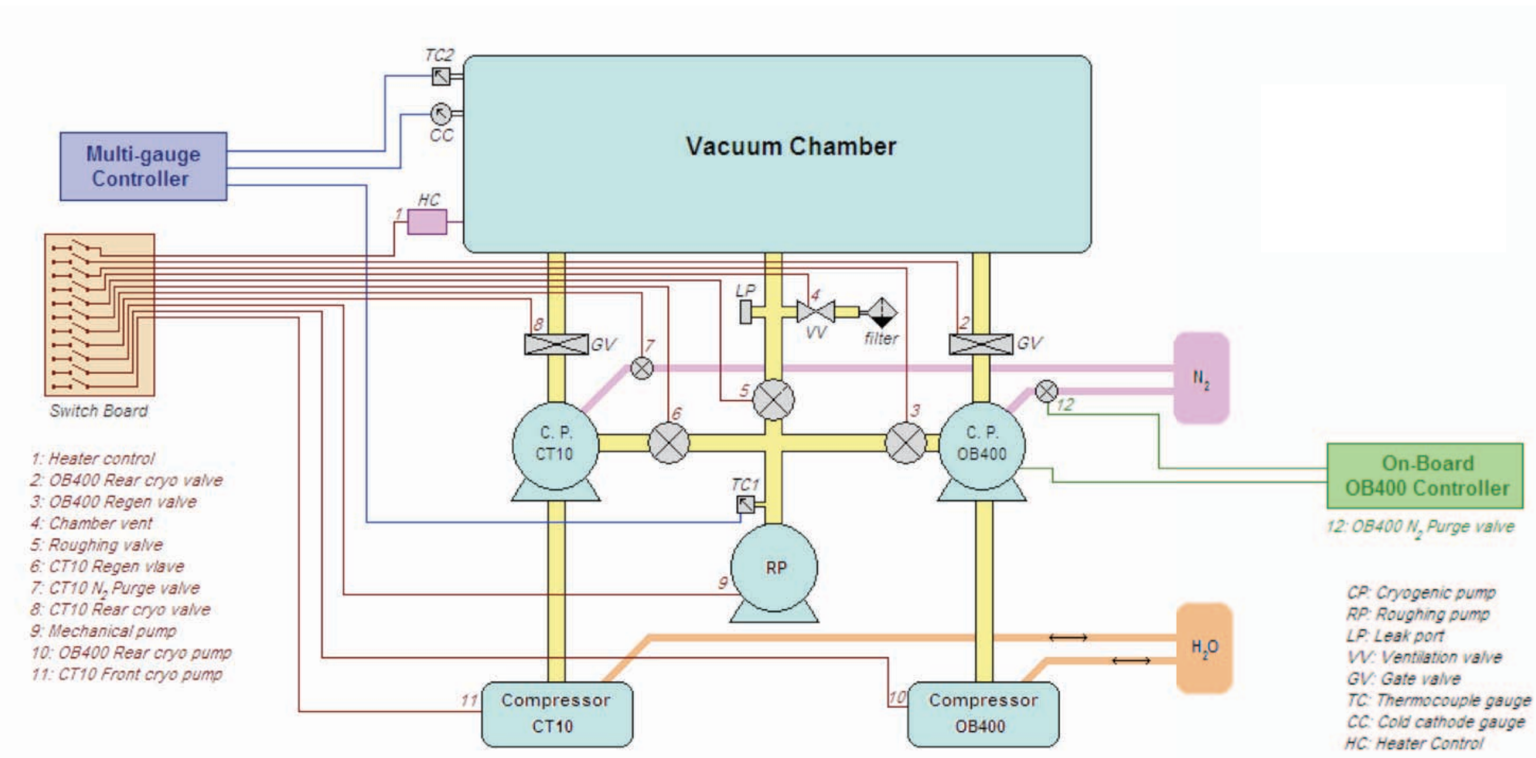
SPUTNIK

30 cm spherical chamber

One high compression ratio turbomolecular pump (70 ls^{-1}, N_2)

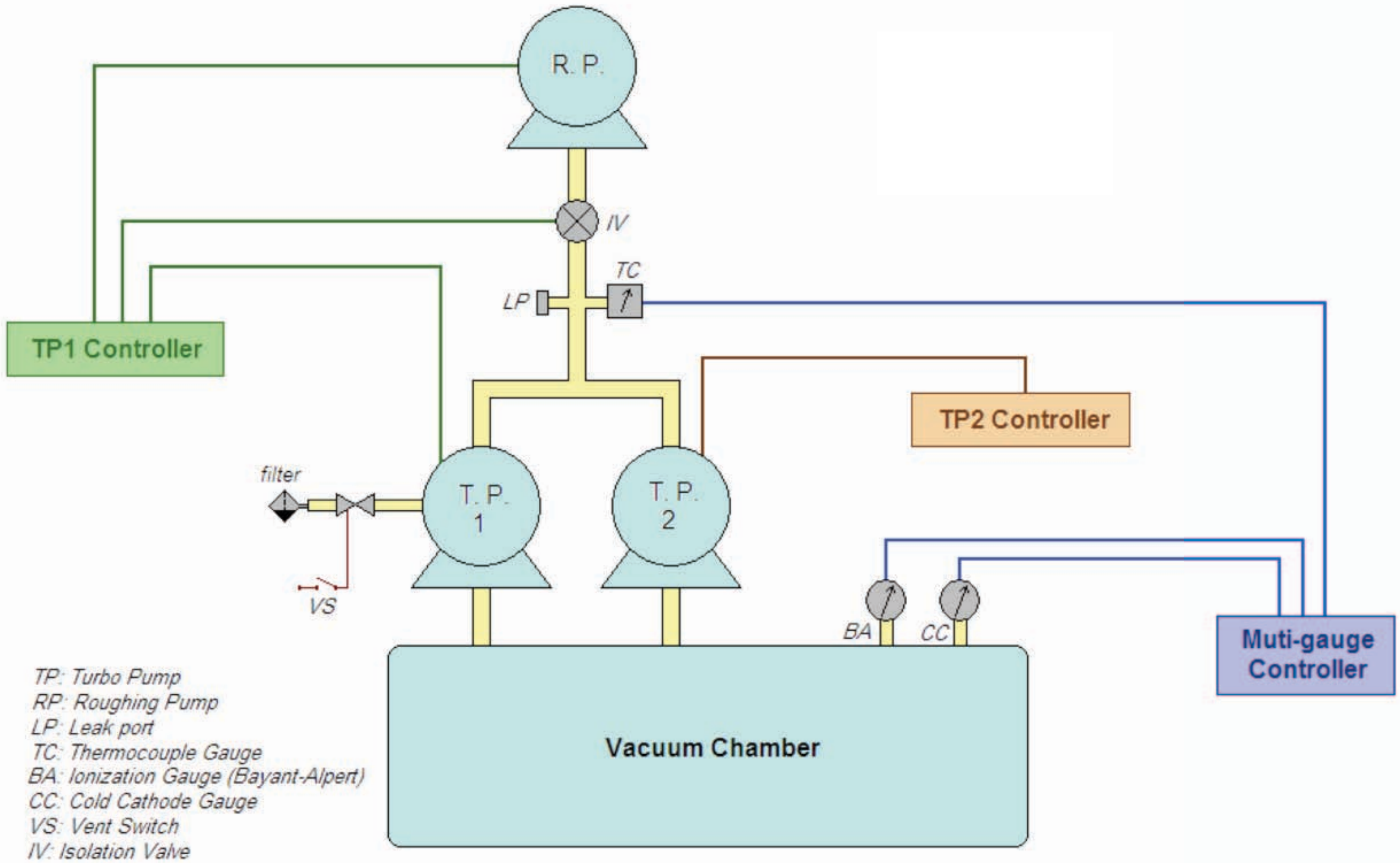
Gate isolation valve to ASTROVAC for enhanced pumping

ASTROVAC

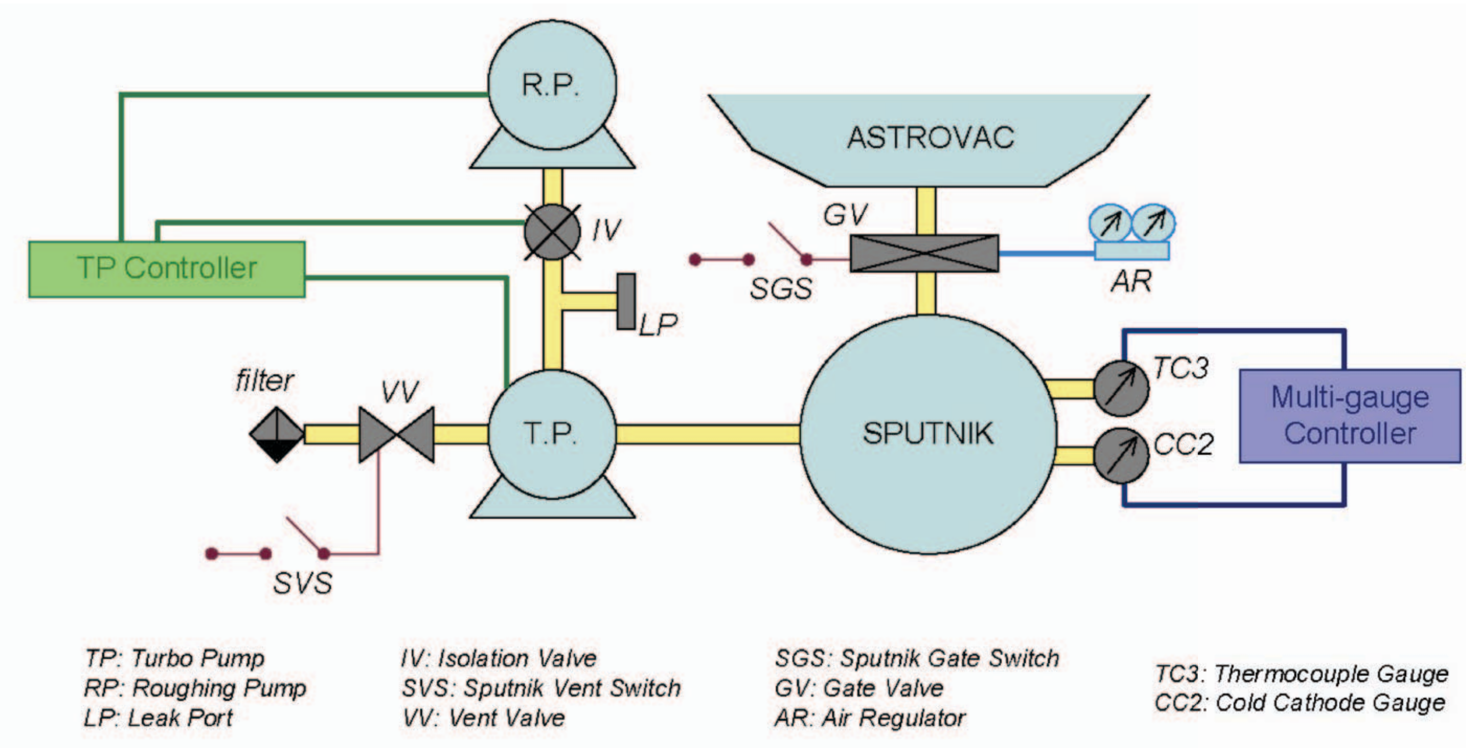


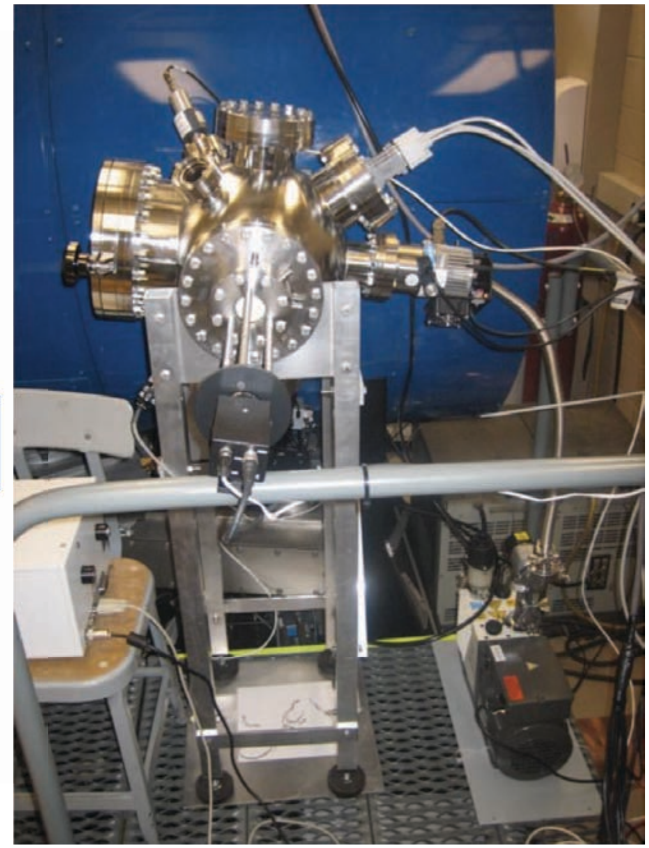
Vacuum Chamber
Multi-gauge Controller
TC2
CC
HC
Switch Board
LP
VV
filter
GV
GV
C. P. CT10
C. P. OB400
TC1
RP
N_2
H_2O
On-Board OB400 Controller
12: OB400 N_2 Purge valve
Compressor CT10
Compressor OB400
1: Heater control
2: OB400 Rear cryo valve
3: OB400 Regen valve
4: Chamber vent
5: Roughing valve
6: CT10 Regen vlave
7: CT10 N_2 Purge valve
8: CT10 Rear cryo valve
9: Mechanical pump
10: OB400 Rear cryo pump
11: CT10 Front cryo pump
CP: Cryogenic pump
RP: Roughing pump
LP: Leak port
VV: Ventilation valve
GV: Gate valve
TC: Thermocouple gauge
CC: Cold cathode gauge
HC: Heater Control

MINIVAC


R. P.
IV
TC
LP
TP1 Controller
TP2 Controller
filter
T. P. 1
T. P. 2
VS
BA
CC
Muti-gauge Controller
Vacuum Chamber
TP: Turbo Pump
RP: Roughing Pump
LP: Leak port
TC: Thermocouple Gauge
BA: Ionization Gauge (Bayant-Alpert)
CC: Cold Cathode Gauge
VS: Vent Switch
IV: Isolation Valve

SPUTNIK


R.P.
ASTROVAC
IV
GV
TP Controller
SGS
AR
LP
TC3
filter
VV
T.P.
SPUTNIK
Multi-gauge Controller
CC2
SVS
TP: Turbo Pump
RP: Roughing Pump
LP: Leak Port
IV: Isolation Valve
SVS: Sputnik Vent Switch
VV: Vent Valve
SGS: Sputnik Gate Switch
GV: Gate Valve
AR: Air Regulator
TC3: Thermocouple Gauge
CC2: Cold Cathode Gauge



Overview of Experimental Techniques

Contents

- Performance characterization:
  - Measure mass flow rate
  - Measure thrust
- Characterization tools:
  - The Faraday cup (beam fluxes)
  - Electrostatic probes (plasma properties)
  - Line of sight measurements (densities)
  - Time-of-flight spectrometry (beam composition)
  - Retarding potential analyzer (beam energies)

Measuring Performance

- What do mission planers and spacecraft designers need to know from the propulsion engineer?
  - Efficiency
  - Specific impulse

$\longrightarrow$ $$F = \dot{m}c \qquad P_{in} = \frac{Fc}{2\eta}$$

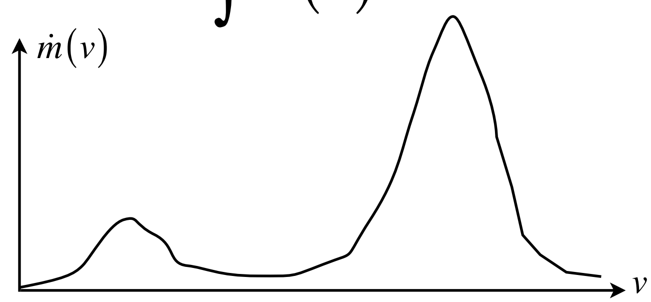
Order of magnitude

$$F = \dot{m}_i v_i + \dot{m}_n v_n \approx \dot{m}_i v_i$$

$$\dot{m}_i = I\frac{m_i}{Ze} \qquad v_i = \sqrt{\frac{2Ze}{m_i}V_{NET}}$$

More realistic values

$$F = \int \dot{m}(v)\,dv$$



Best accuracy

Directly measure:

Mass flow rate

Thrust

$$c = \frac{F}{\dot{m}} \qquad \eta = \frac{Fc}{2P_{in}}$$

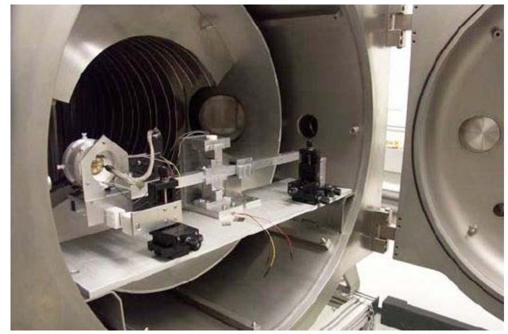
Mass flow rate

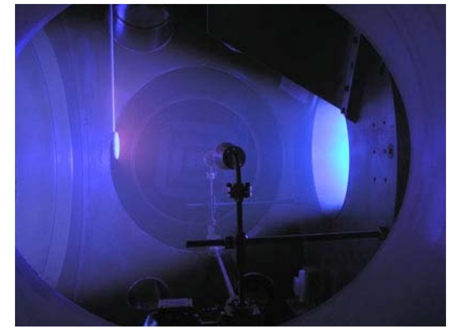
- Piezoelectric valve
- Heater
- Temperature monitoring
- Feedback control

Photo removed due to copyright restrictions. Please see the DFC digital mass flow controller on AALBORG's website.

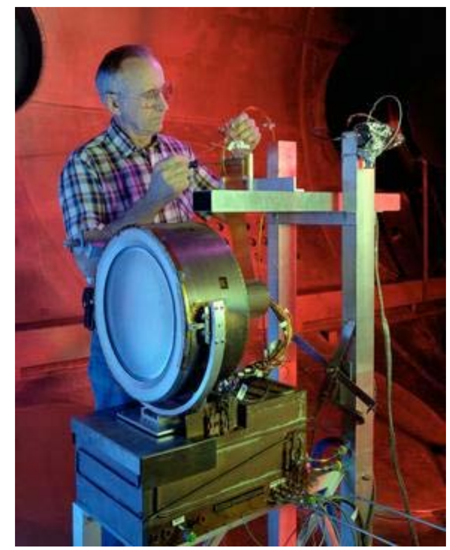
Schematic of a mass flow rate controlled by a piezoelectric valve removed due to copyright restrictions. Please see the AALBORG website.

Thrust


Torsional


Paddle

- Measure:
  - Displacement
  - Nulling power
- Issues:
  - Sensitivity
  - Thermal drifts
  - Heavy loads


Axial

Courtesy: Dr. Yassir Azziz

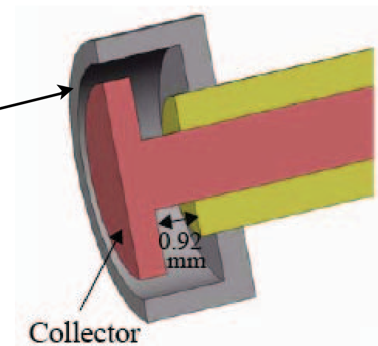
Faraday Cup

- Faraday cups are used to measure current density in plasma and ion beams.
- In electrosprays, Faraday cups are typically used to collect total current.

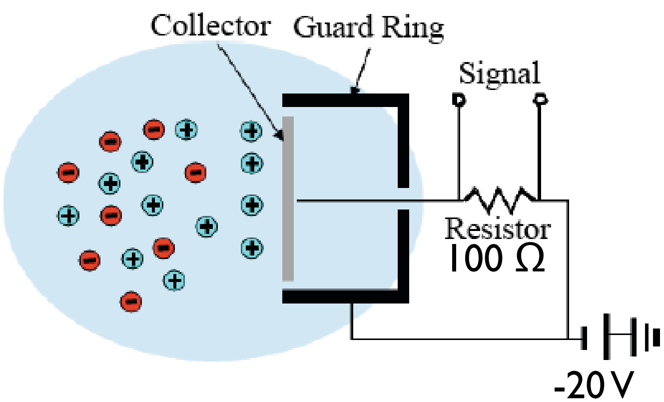
spacing near:

$$\lambda_d = \sqrt{\frac{\varepsilon_0 k T_e}{n_e e^2}}$$

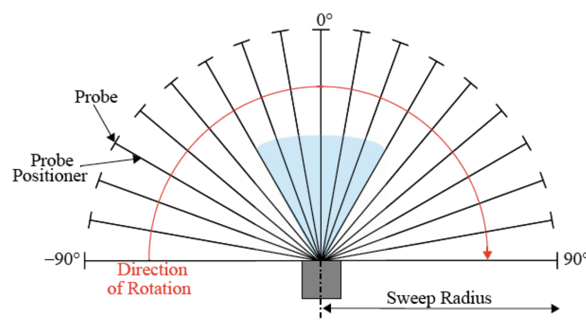
to avoid edge effects

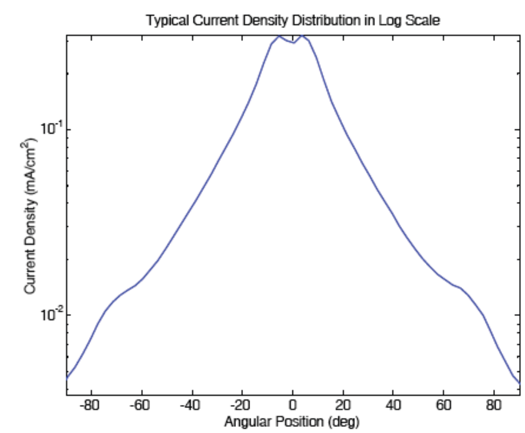


small probe to minimize plasma perturbations



- Collector is typically biased to some negative voltage:
  - To repel electrons and collect only ions (plasma thrusters)
  - To suppress secondary electron emission (electrosprays)

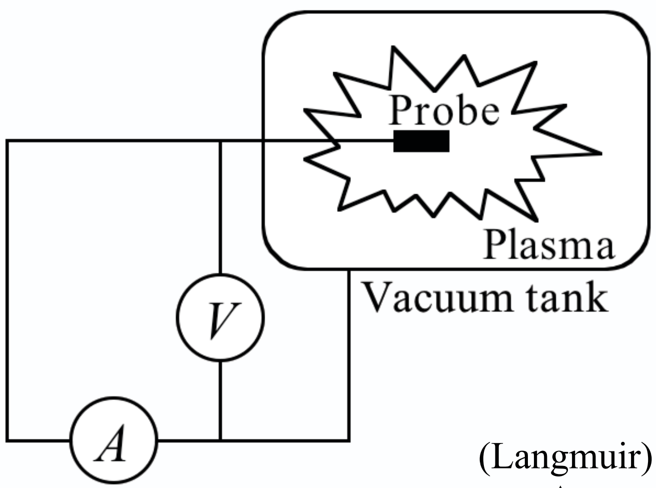




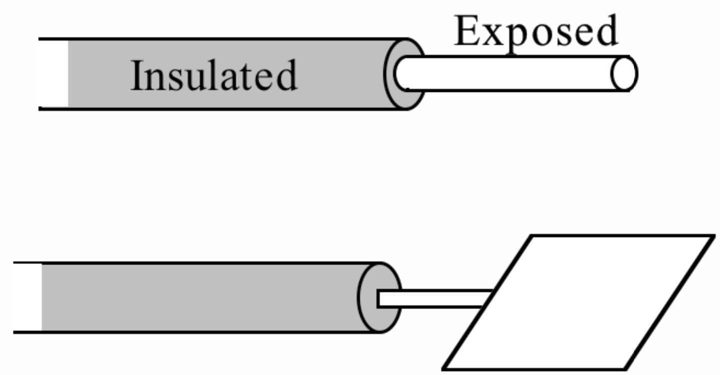
typical angular distributions

Electrostatic Probes

- Electrostatic probes are extensively used in plasma devices to measure plasma potentials, temperature and (to a much lower precision) density.
- These properties are essential to describe the state of the plasma and characterize all physical processes (characteristics speeds, plasma sheaths, ion and electron fluxes, energy fluxes and losses, etc)



(Langmuir)
Typical connection for a single ↑ probe

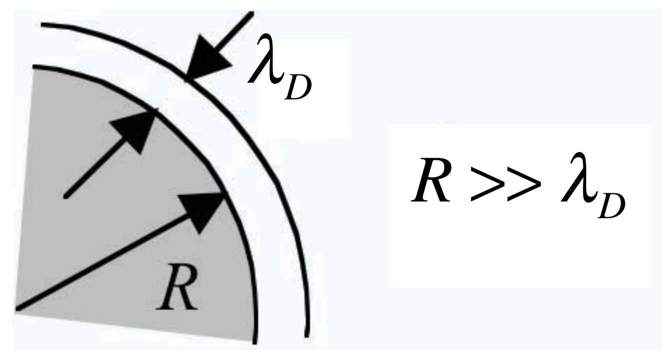


Two types of probes

Electrostatic Probes

- By far, the most widely used type of probe is the Langmuir Probe.
- Getting data is "easy" - Interpreting data is challenging.
- For the simplest cases, Langmuir theory can be used, provided:

1. The geometry of the probe must be planar, i.e., the physical dimensions are much larger than the local Debye length.



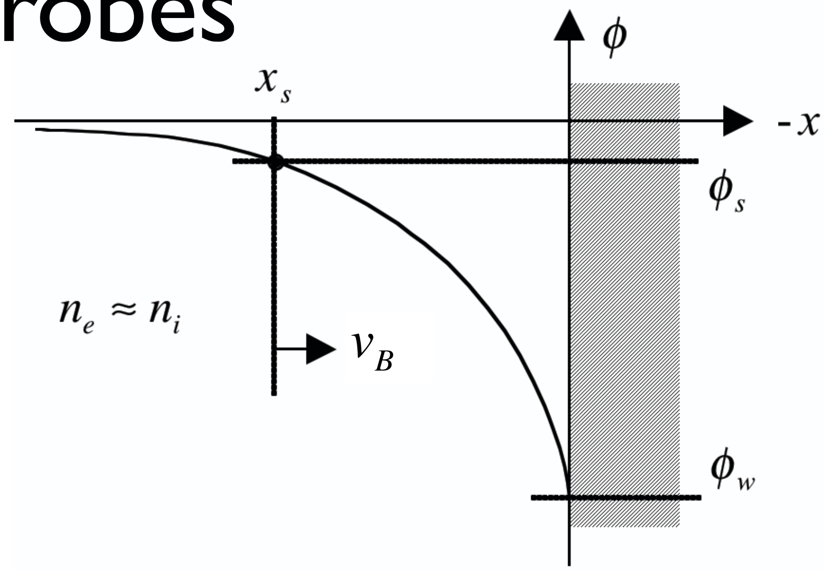
2. The plasma is collisionless.

$$\lambda_{mfp} >> \lambda_D$$

4. Quiescent plasma

Electrostatic Probes

- We can make use of kinetic theory results of charged particle collection on a biased wall:

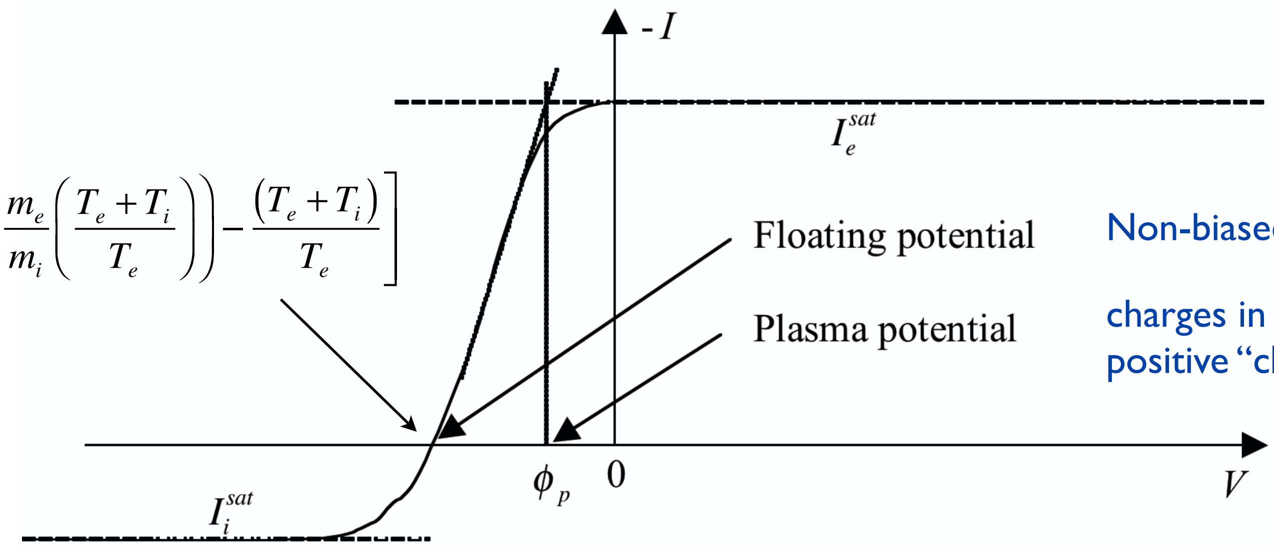


$$I = en_e A_p \left(\frac{\bar{c}_i}{4} e^{-\frac{e\phi}{kT_i}} - e^{-\left(\frac{T_e+T_i}{2T_e}\right)} \sqrt{\frac{k(T_e+T_i)}{m_e}} \right) \qquad \phi > 0$$

$$I = en_e A_p \left(e^{-\left(\frac{T_e+T_i}{2T_e}\right)} \sqrt{\frac{k(T_e+T_i)}{m_i}} - \frac{\bar{c}_e}{4} e^{\frac{e\phi}{kT_e}} \right) \qquad \phi < 0$$

Electrostatic Probes

$$\phi_{fp} = \phi_{I=0} = \frac{kT_e}{2e}\left[\ln\left(2\pi\frac{m_e}{m_i}\left(\frac{T_e+T_i}{T_e}\right)\right) - \frac{(T_e+T_i)}{T_e}\right]$$



Non-biased probe in plasma

charges in sheath change from positive “cloud” to negative “cloud”

Saturation Currents:

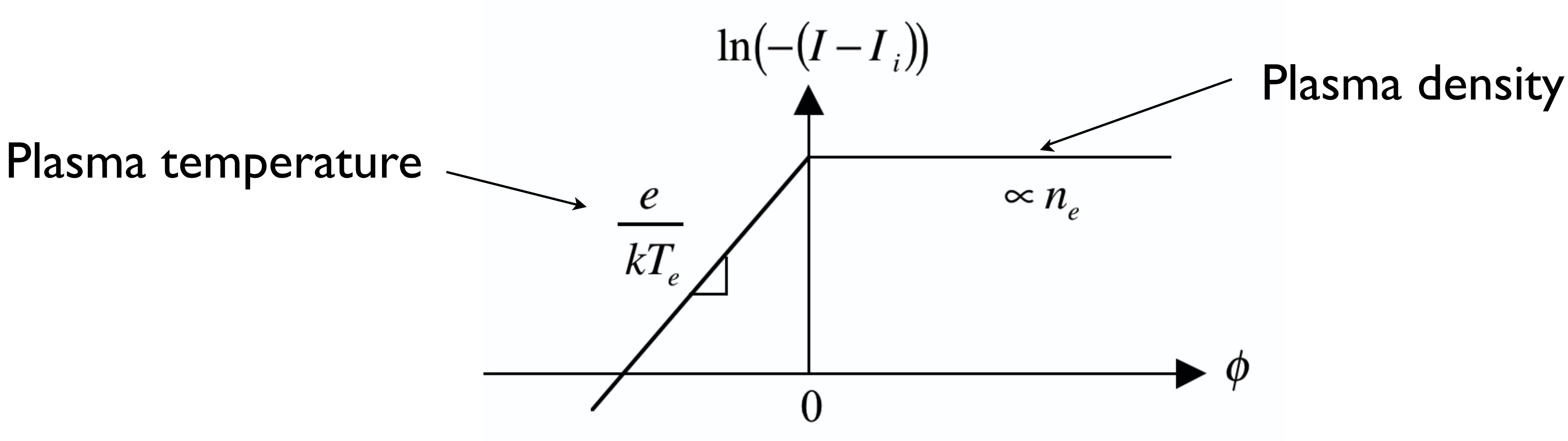
$$I_e^{sat} = -en_eA_pe^{-\left(\frac{T_e+T_i}{2T_e}\right)}\sqrt{\frac{k(T_e+T_i)}{m_e}}$$

$$I_i^{sat} = en_eA_pe^{-\left(\frac{T_e+T_i}{2T_e}\right)}\sqrt{\frac{k(T_e+T_i)}{m_i}}$$

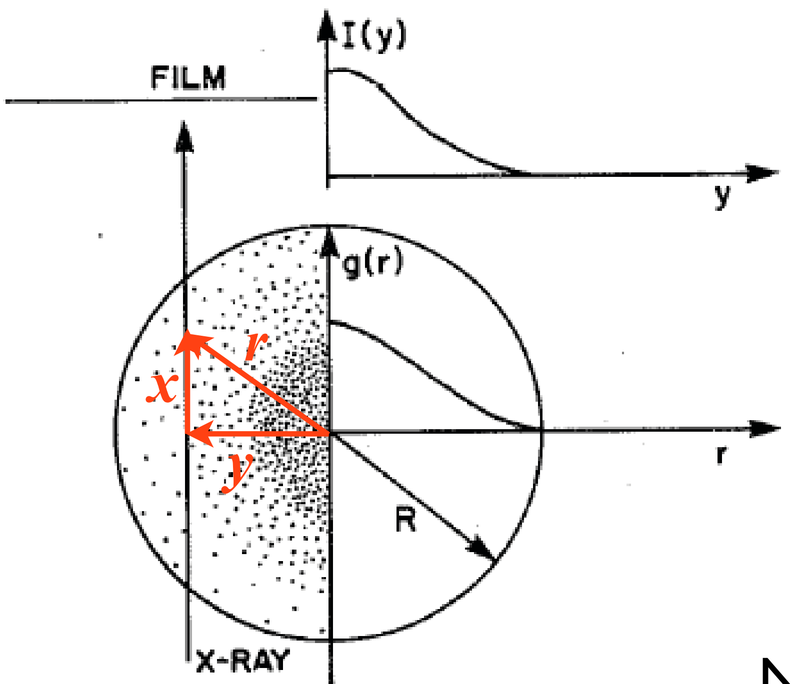
Electrostatic Probes

$$\ln\left(-\left(I - I_i\right)\right) = \ln\left(en_e A_p \sqrt{\frac{k\left(T_e + T_i\right)}{m_e}}\right) - \left(\frac{T_e + T_i}{2T_e}\right) \qquad \phi > 0$$

$$\ln\left(-\left(I - I_i\right)\right) = \ln\left(A_p \frac{en_e \bar{c}_e}{4}\right) + \frac{e}{kT_e}\phi \qquad \phi < 0$$



Line of Sight Probes



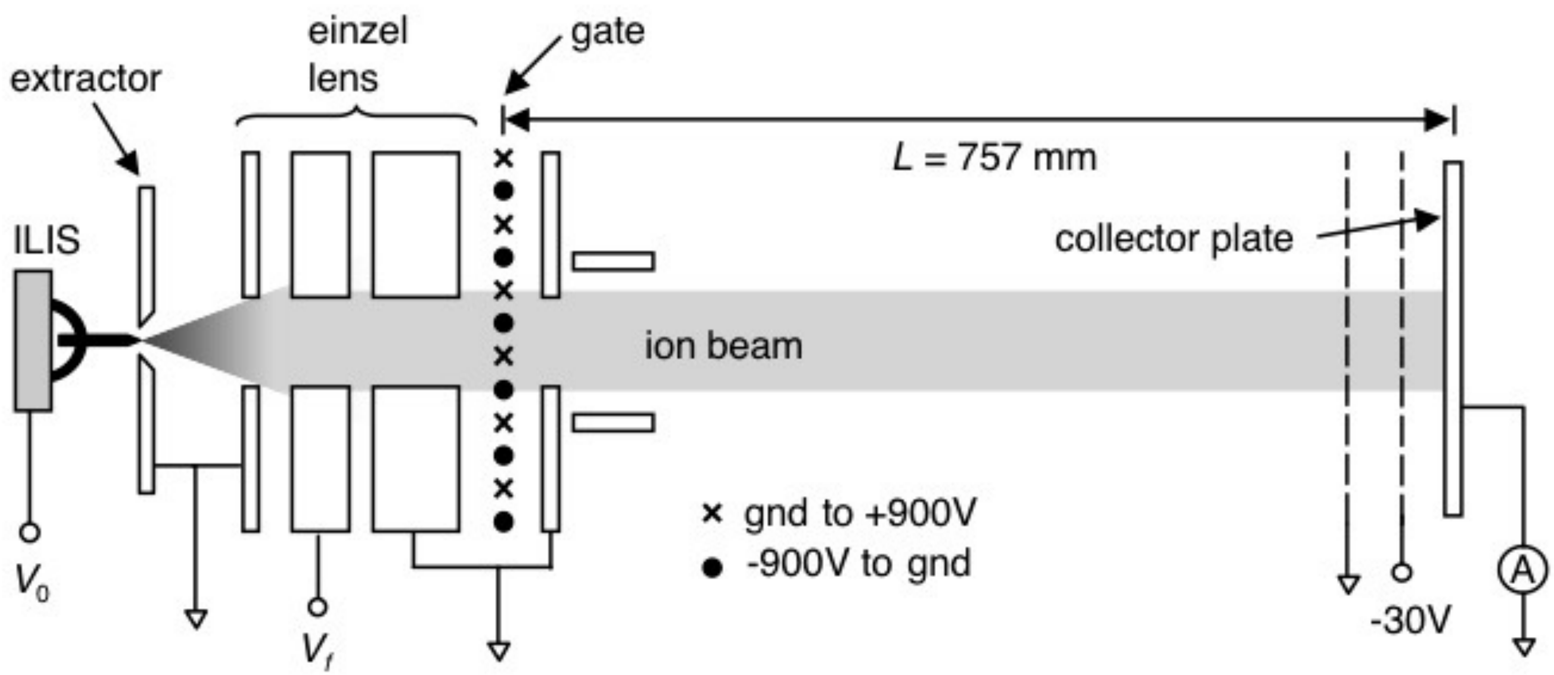
$$I(y) = 2\int_0^x g(r)dx$$

$$x = \sqrt{r^2 - y^2} \longrightarrow dx = \frac{rdr}{\sqrt{r^2 - y^2}}$$

$$I(y) = 2\int_y^R g(r)\left(r^2 - y^2\right)^{-1/2} rdr$$

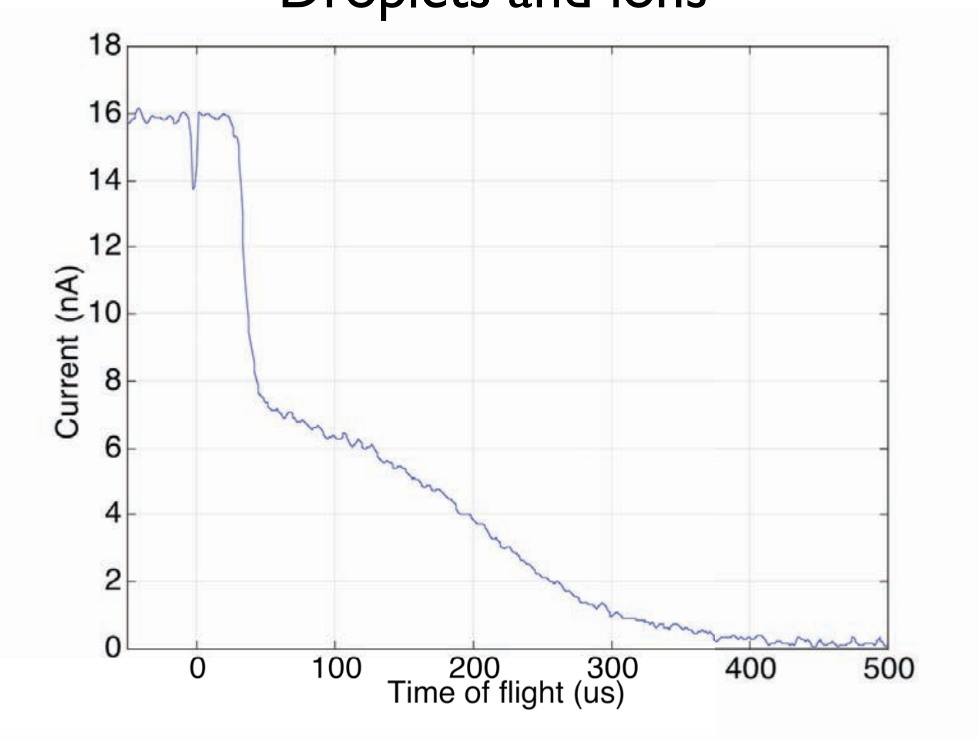
Need to perform Abel Inversion to obtain *g(r)*

Time of Flight (TOF) Spectrometry

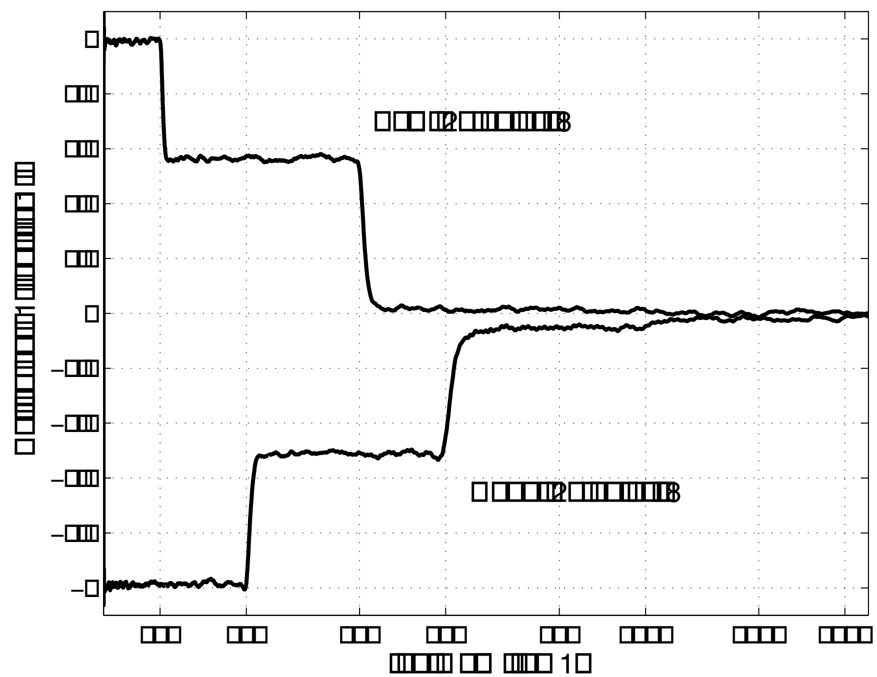


Time of Flight (TOF) Spectrometry

Droplets and ions



Pure ion emission



Time of Flight (TOF) Spectrometry

$$\bar{c} = \frac{L}{\bar{t}}$$

$$\bar{m} = \frac{2Ze\phi}{\bar{c}^2}$$ for ions only

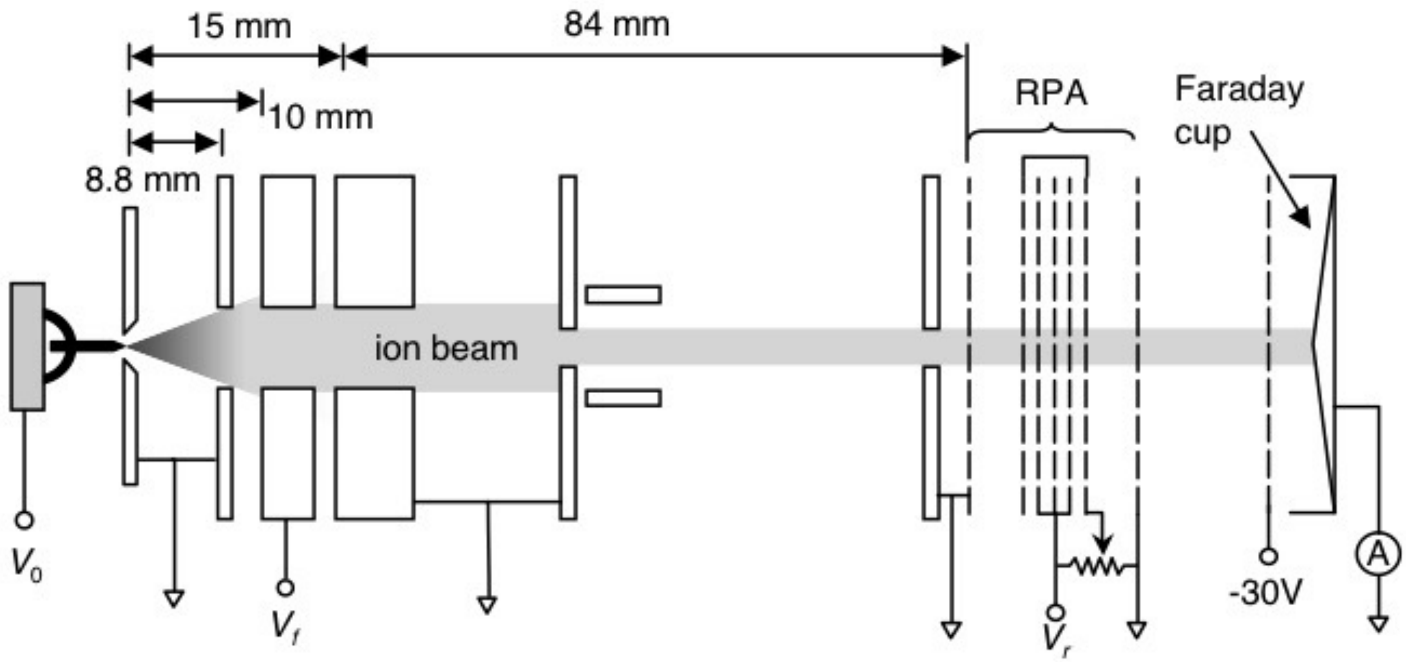
$$\overline{\frac{q}{m}} = \frac{\bar{c}^2}{2\phi}$$ in general

$$\bar{F} = I\sqrt{\frac{2\phi}{q/m}}$$

Given the TOF spectrum in the form: $I = I(t)$

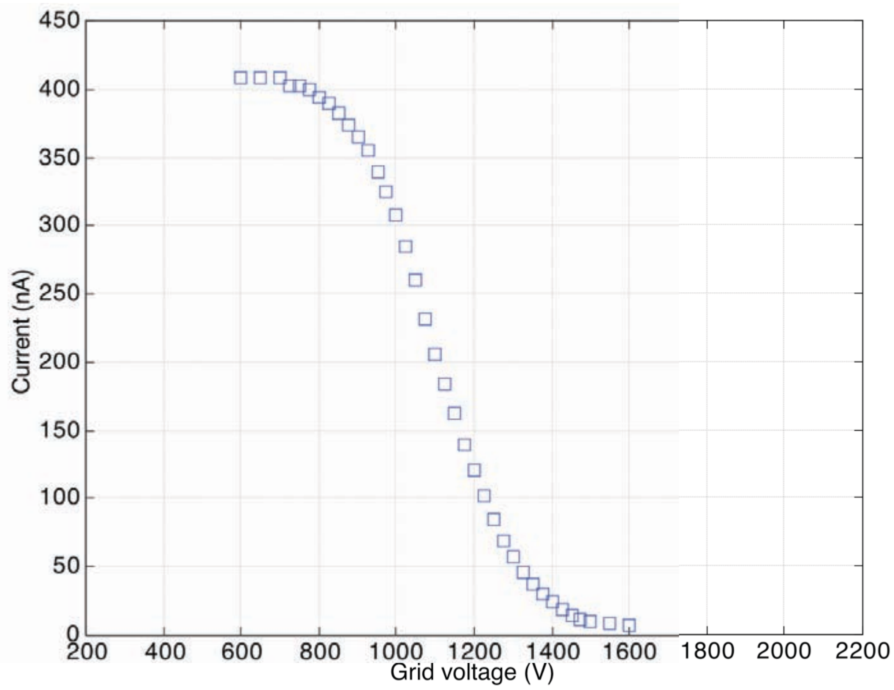
$$\dot{m} = \frac{4\phi}{L^2}\int_0^\infty I(t)\,t\,dt \qquad F = \frac{2\phi}{L}\int_0^\infty I(t)\,dt$$

Retarding Potential Analyzer

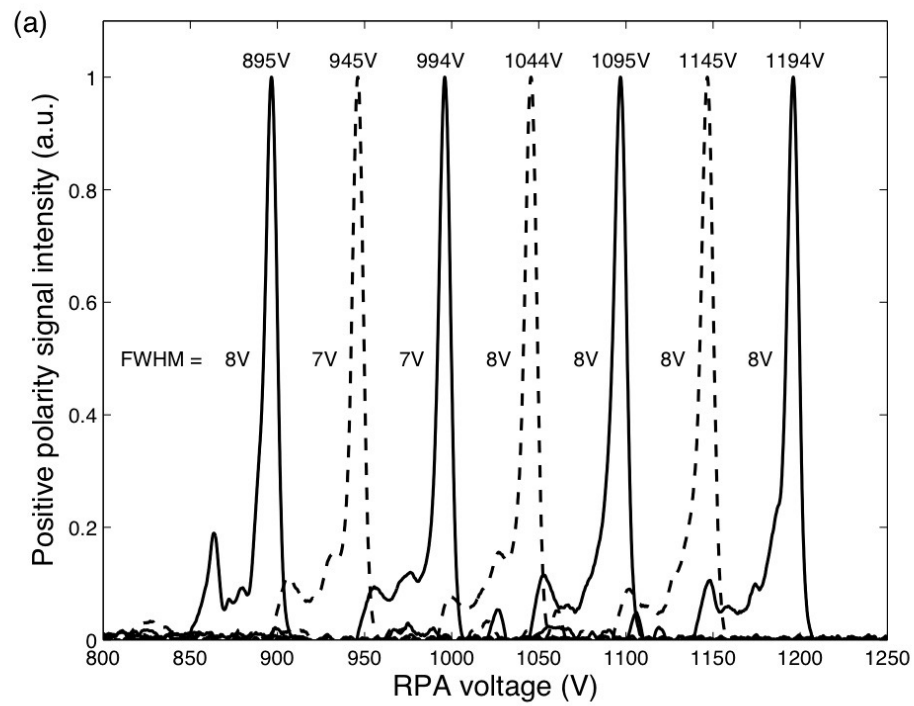


Retarding Potential Analyzer

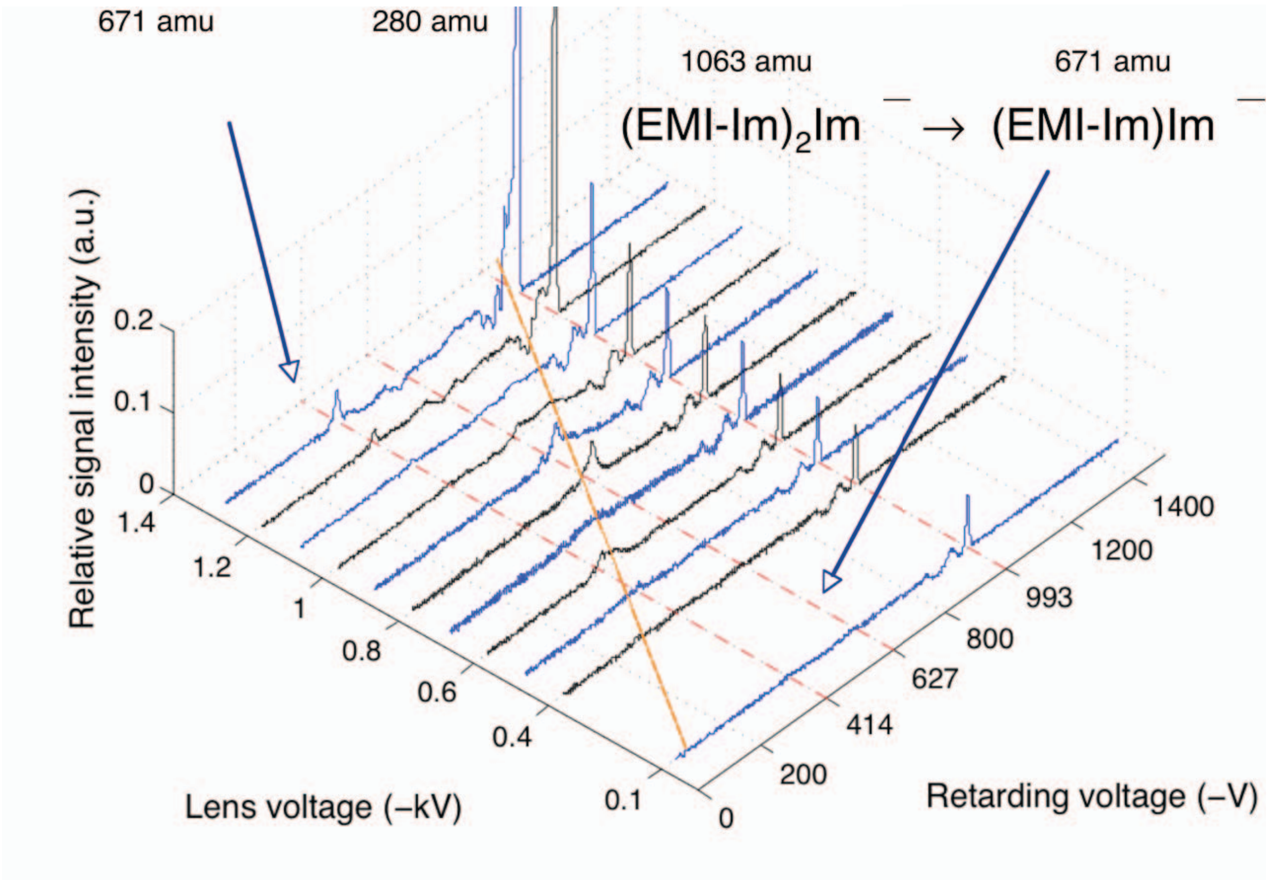
Droplets and ions



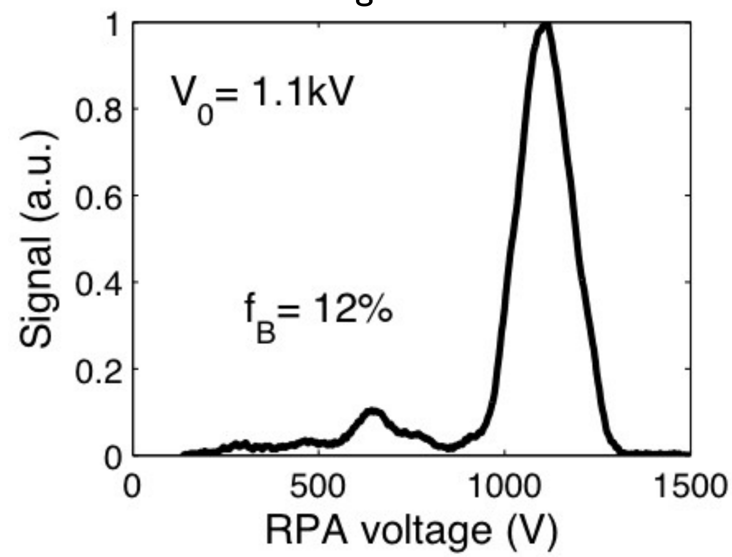
Pure ion emission



Retarding Potential Analyzer



full divergent beam RPA



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Spring 2015