The US Particle Accelerator School
Vacuum System Design Calculations

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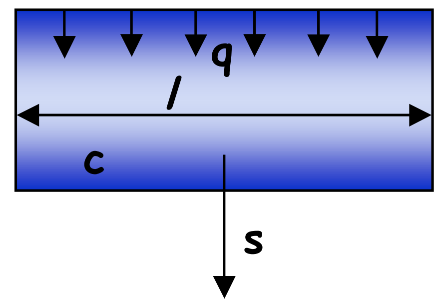
Calculating Steady-State Pressure Profiles using VACCALC

$$\frac{d}{dz}\left(c\frac{dP}{dz}\right) - sP + q = 0$$



where z = axial beamline length (m)

c = conductance m(liters/sec)

s = pumping speed (liters/sec)/m

q = gasload (nTorr - liters/sec)/m

Ref. "A Method for Calculating Pressure Profiles in Vacuum Pipes", Sullivan, SLAC, 1993

VACCALC Input

- Each beampipe element is described by the following characteristics:
  - Lumped or distributed values.
  - Length (m)
  - Axial conductance (liters/sec)
  - Outgassing rate (nTorr-liters/sec)
  - Pumping speed (liters/sec)

- Segment length (Δz) is specified for all elements

- (10,000 segments max. per pipe).

Sample VACCALC Input File

Segment Length

Length

Outgassing load

Pumping Speed

Conductance

```
Model of LCLS Undulator Beam Pipe

0.005
2              Segments
First Segment
   0.00    0.00    1    2    LIN    20
Pump           L              0.1         0.15537     0.00785     1.00
Undulator      L              4.9         0.00317     0.39781     0.00
Pump           L              0.1         0.15537     0.00838     1.00
Undulator      L              4.9         0.00317     0.39781     0.00
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Undulator      L              4.9         0.00317     0.39781     0.00
Pump           L              0.1         0.15537     0.00838     1.00
ENDPIPE
Second Segment
   0.00    0.00    2    3    LIN    20
Pump           L              0.1         0.15537     0.00785     2.00
Undulator      L              4.9         0.00317     0.39781     0.00
Pump           L              0.1         0.15537     0.00838     3.00
Undulator      L              4.9         0.00317     0.39781     0.00
Pump           L              0.1         0.15537     0.00838     4.00
Undulator      L              4.9         0.00317     0.39781     0.00
Pump           L              0.1         0.15537     0.00838     5.00
Undulator      L              4.9         0.00317     0.39781     0.00
Pump           L              0.1         0.15537     0.00838     1.00
ENDPIPE
```

System Design: Motivation

- The goal is to develop a numerical model of the vacuum sys tem whether simple or complex.
- This effort is undertaken to provide an understanding of the critical issues (e.g. conductance limiting components, surface outgassing and leak rates) in order to design the most cost-effective pumping system.
- Simple pumping calculations can lead to over-designing the pumping system which can escalate the costs for a large accelerator system.

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Designing a system using a numerical model

- In the mid-1990's, we at LLNL started using numerical modeling to design the vacuum systems for the APT RFQ and linac.

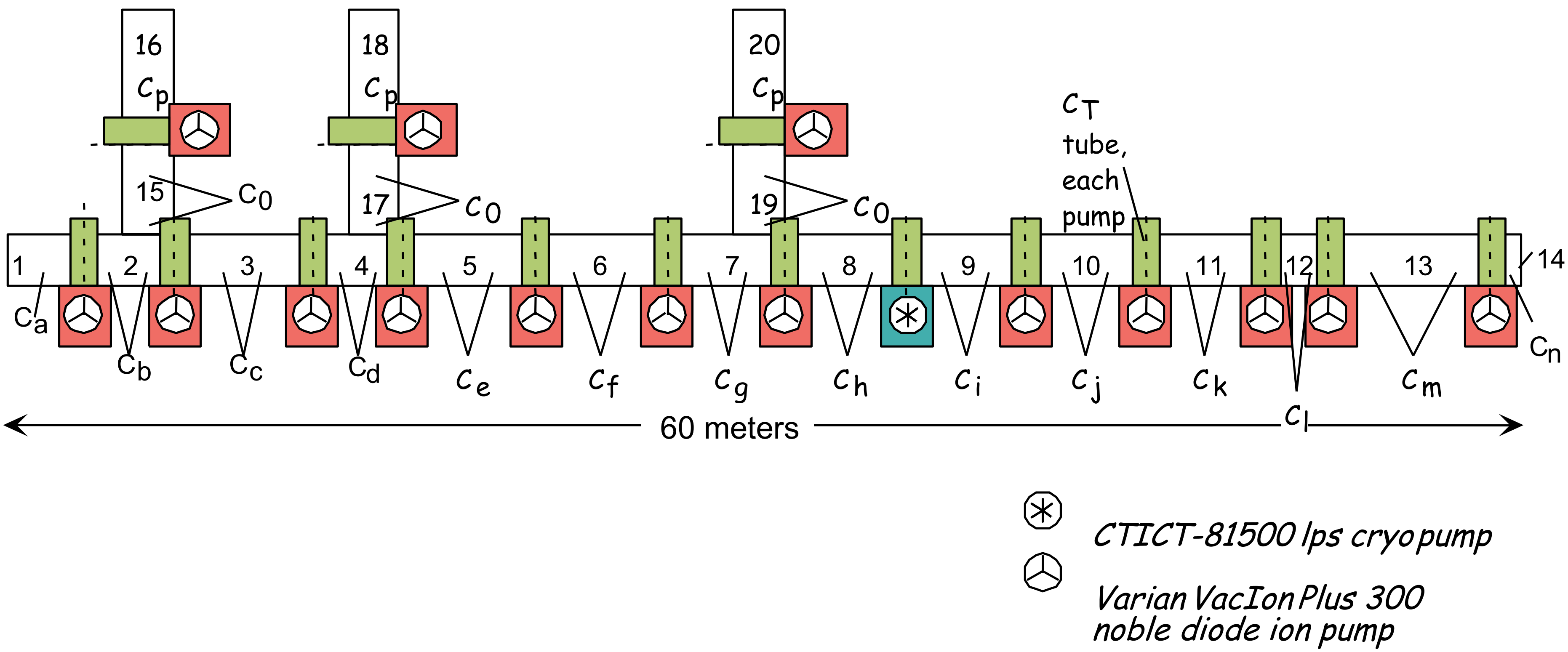
- Later we used it to design the vacuum systems for the Spallation Neutron Source linac.

Typical features of a numerical model

- Pressure histories are solved for each sub-volume.
- We save the pumpdown history for specific sub-volumes of interest.
- We can employ separate time-dependent outgassing rates for pre- and post-conditioned surfaces.
- We can employ pressure-dependent pump speeds.
- We can do parametric studies of pump speeds and pump distribution,
- We can even run partial-pressure cases.

Simple example: distributed pumping along a beam tube

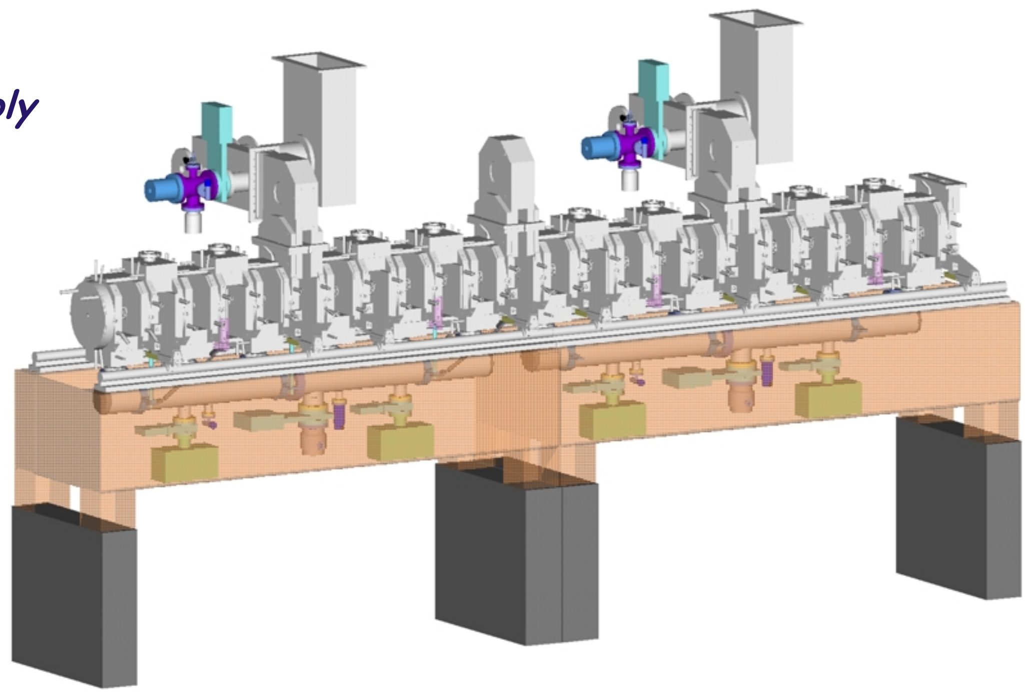
20 sub-volumes interconnected with 16 conductances $C_a - C_p$
and pumped with 15 ion pumps and 1 cryo pump



Complex example: Pumping using a manifold along an rf linac

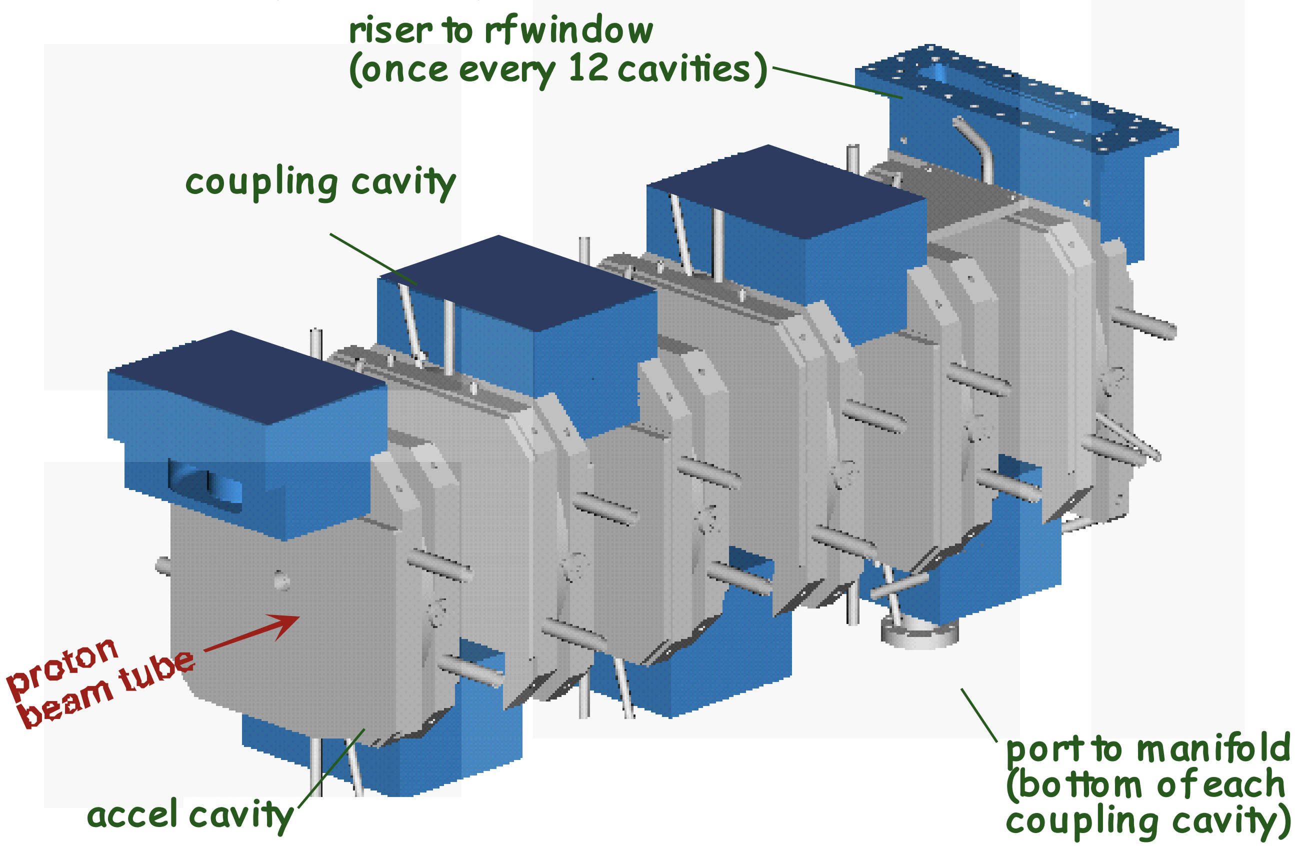
Model the first twelve cavities with a length of 2.5 meters (per manifold) and extrapolate results to the full length (10's to 100's of meters)

rf window assembly with separate pumping system

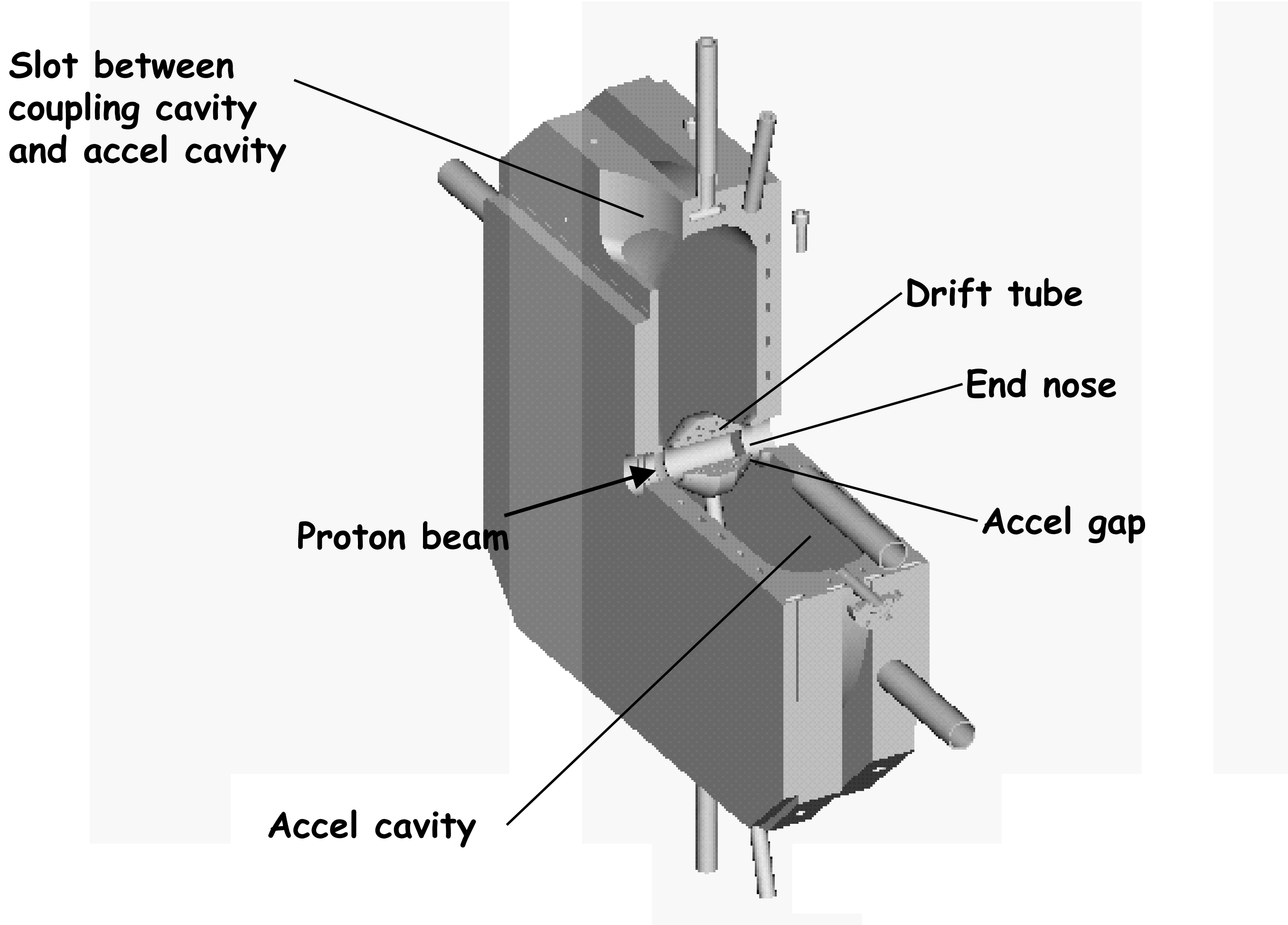


Detail of the first six cavities of an rf linac

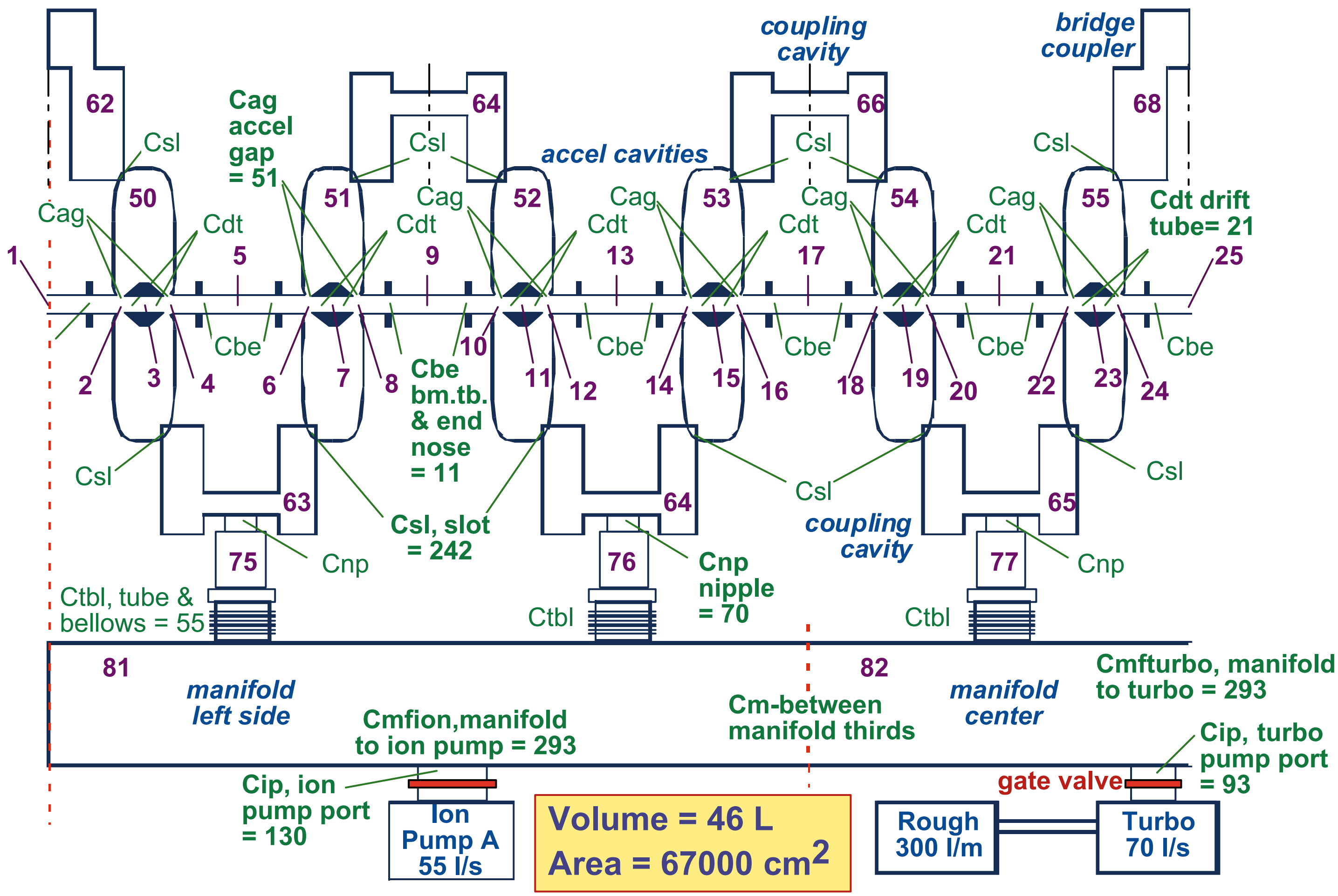
Goal: Pump through the coupling cavities and accel cavities to maintain the operating pressure of 10^{-6} Torr within the beam tube



Internal cavity detail included in the model



For twelve cavities, conductances interconnect 83 sub-volumes (half-symmetry)



N ordinary differential equations must be solved simultaneously for each time where N = the number of sub-volumes

Gasload balance is the hearty of the numerical model.

$$V_n \frac{dP_n}{dt} = \sum Q_{in} - \sum Q_{out}$$

where V_n = volume of the nth sub-volume (liters)

P_n = pressure of the nth sub-volume (Torr)

there are N pressures to solve for at each time t (sec)

Q_{in} = leakage or outgassing into volume n (Torr-liters/sec)

Q_{out} = $C_{nm}(P_n - P_m)$ where m is the adjacent sub-volume

C_{nm} = your favorite conducatance formula for the resistive component between sub-volumes n and m (liters/sec)

or Q_{out} = $S_p P_n$ where S_p is pressure-dependent pump speed

Pressure history for each pump phase is found for each of the N sub-volumes.

- Modol solve sfor pressure with N coupled differential equations (for each N sub-volumes) during each time for each pumping phase:
  - Roughing phase from atmospheric pressure down to 50 mTorr
  - Turbopumping phase from 50 mTorr to 10^{-6} Torr
  - Ion pumping phase down to base pressure

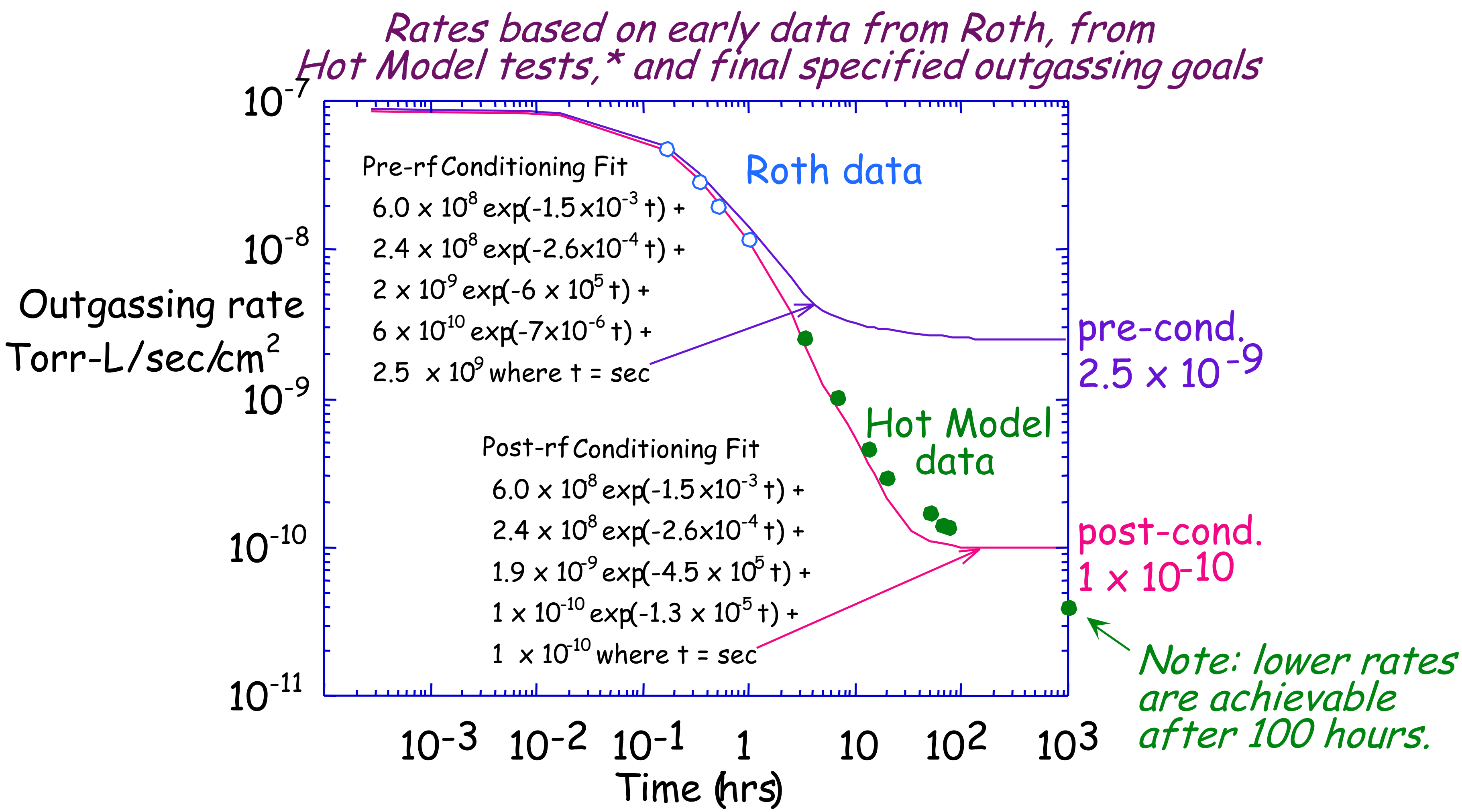
- Note that the choice of pump type depends on the design and operational requirements.

- Note that the final time for the pumpdown history should be chosen based on characteristics of outgassing data and operational requirements.

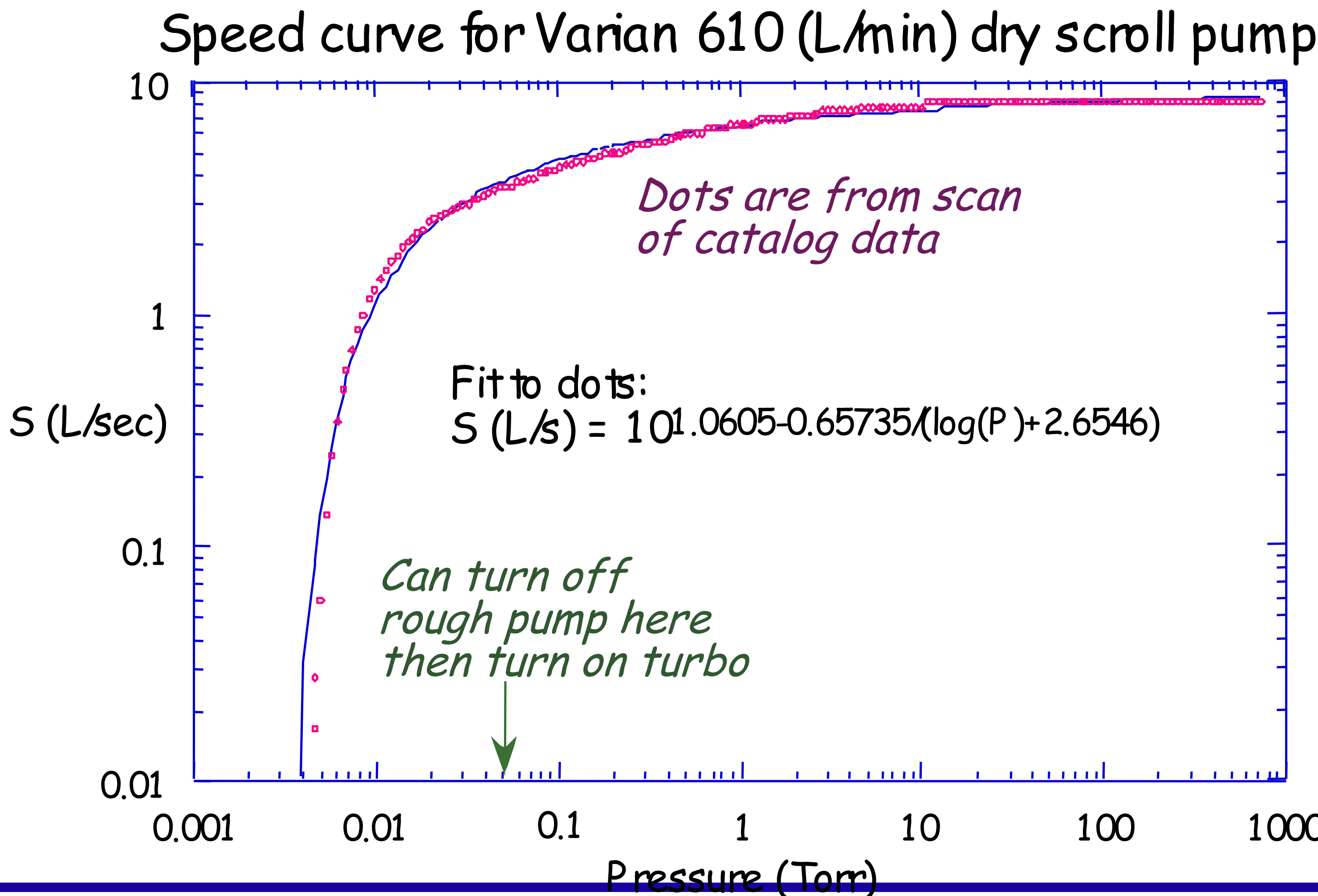
The software tool to solve the model depends on the number of sub-volumes and the speed of your computer.

- You can build your own solver routine using your favorite language and computer.
- You can use a routine like rkfixed from MathCad.
- You can use a routine like NDSolve from Mathmatica.
- We have solved small problems (N<10 sub-volumes) using MathCad on a PC in less than one hour.
- For larger problems, it is worth learning Mathmatica.
  - Example: N = 83 sub-volumes with tress separate pumping phases, the computer processing time was 4.5 min on a 266 MHz G3 PowerMac.
  - With MathCad, the problem would have taken days due to the overhead needed to MathCad more user friendly with a cleaner output.

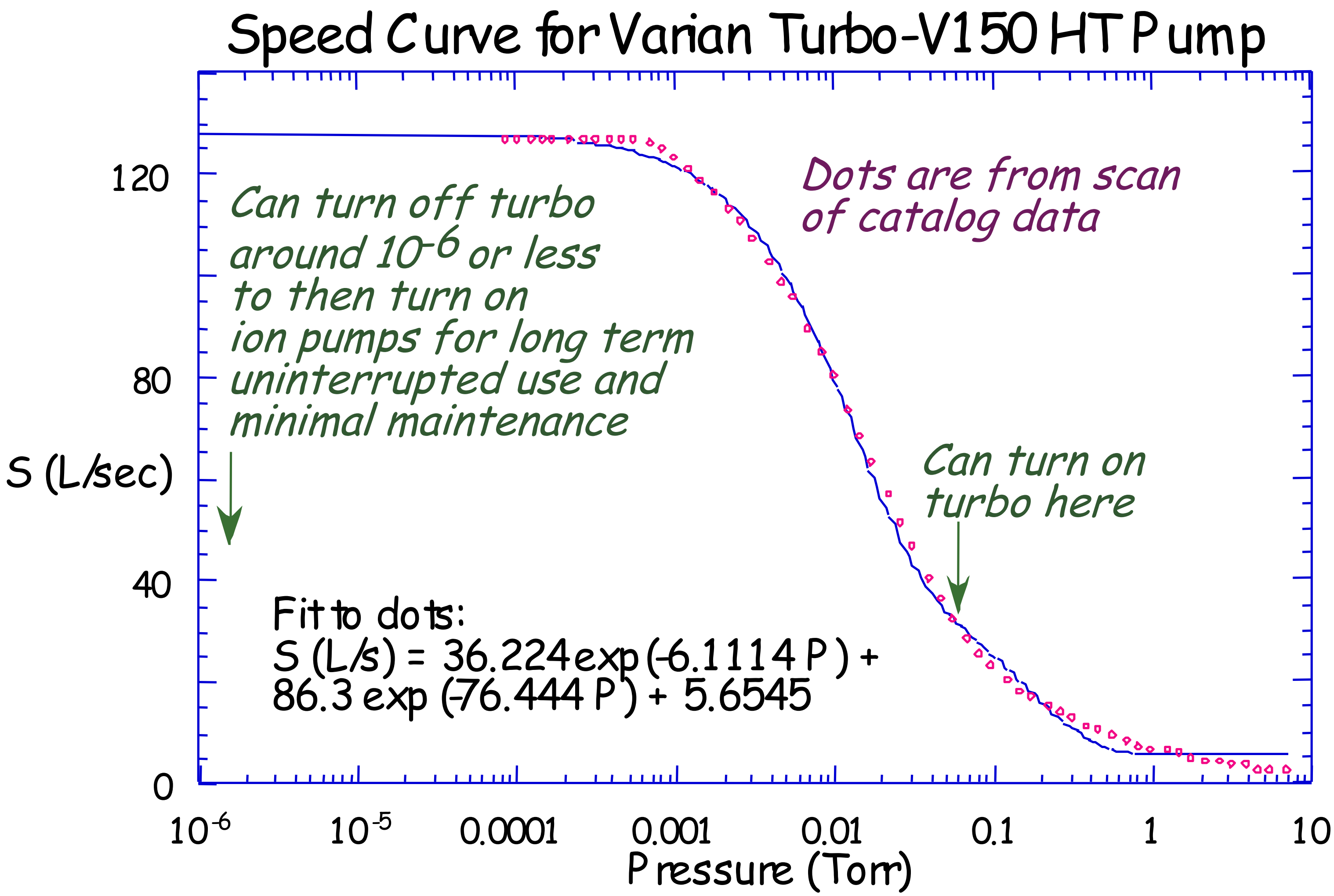
Model can include multiple time-dependent outgassing rates for pre-and post-conditioned surfaces.



Pressure dependence of speed for a Varian dry scroll pump

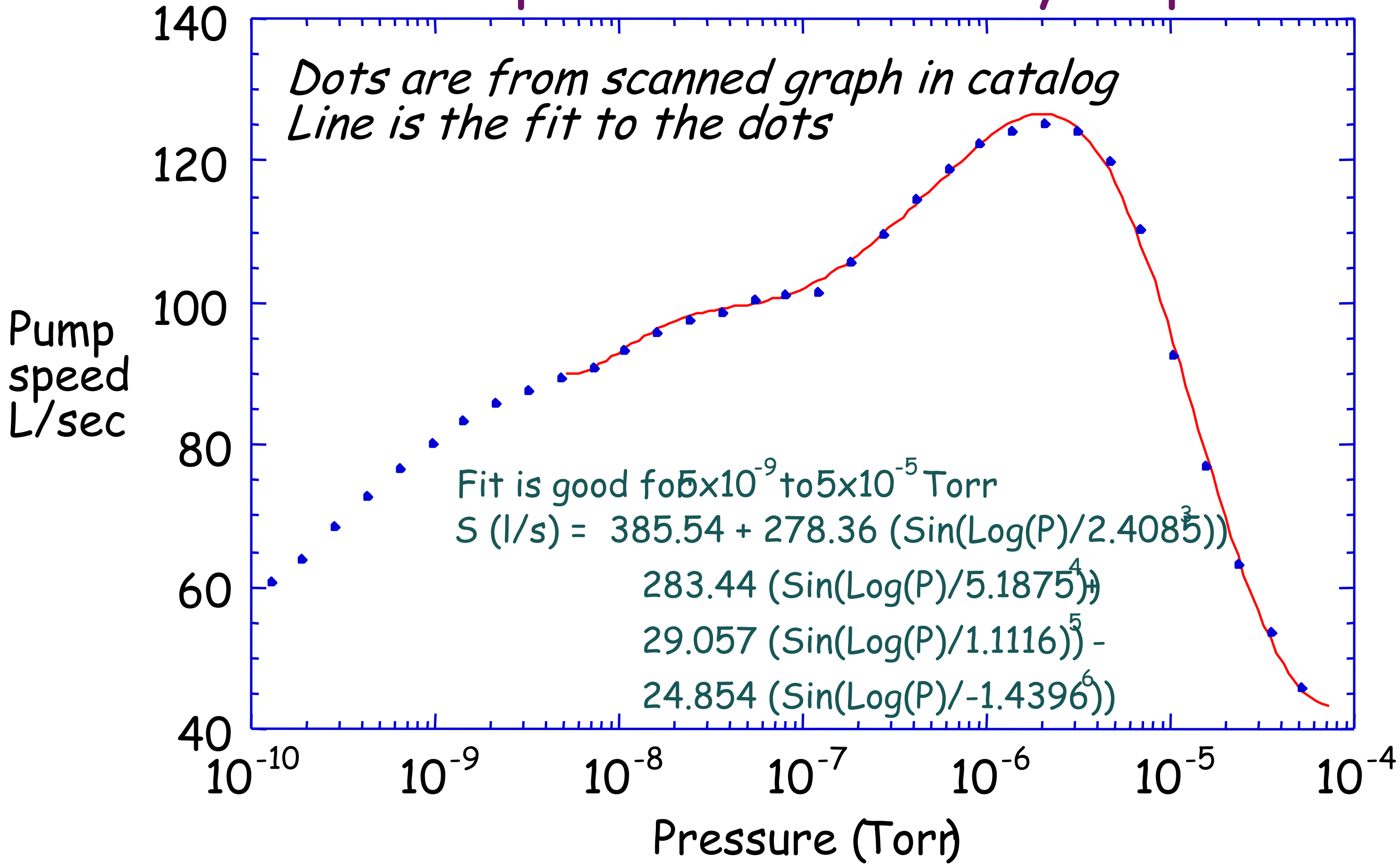


Pressure dependence of a speed for a Varian turbomolecular pump



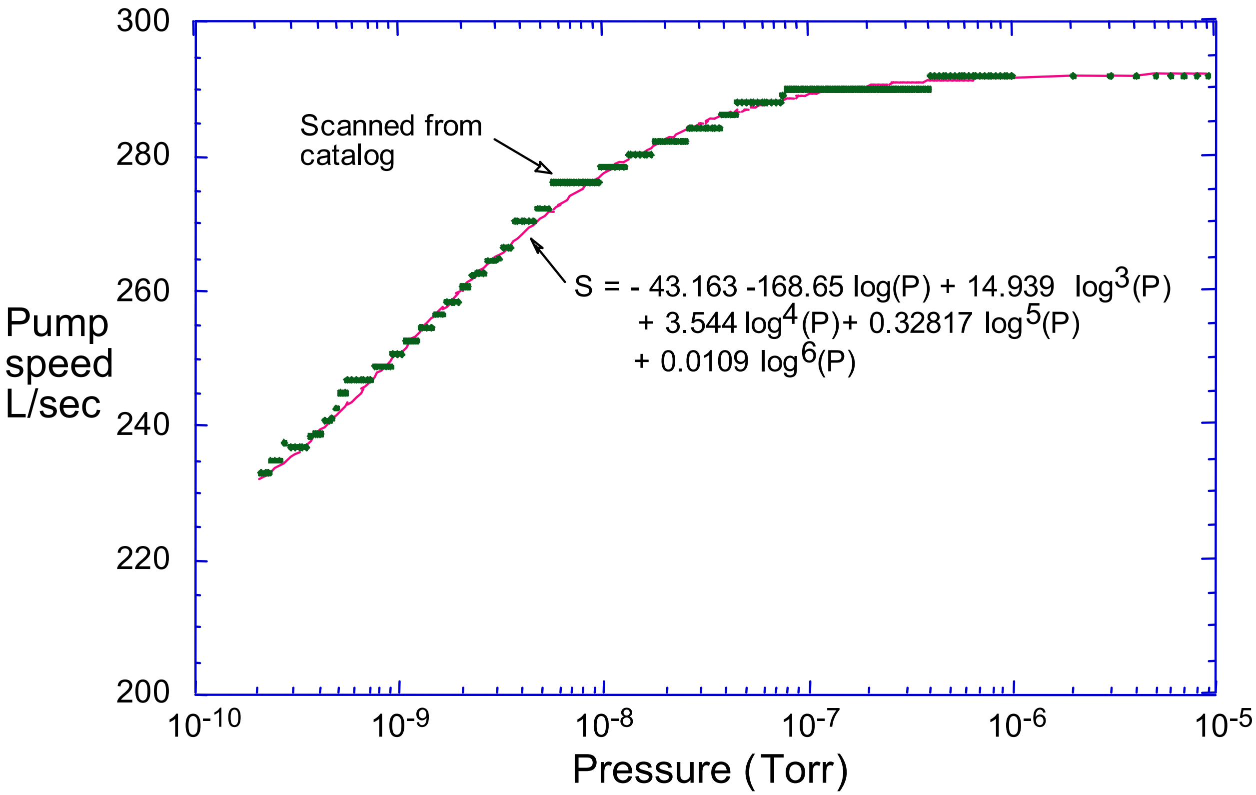
Pressure dependence of a speed for a Varian Starcell ion pump

An input of constant nominal speed of 150 L/sec would have predicted an erroneously low pressure

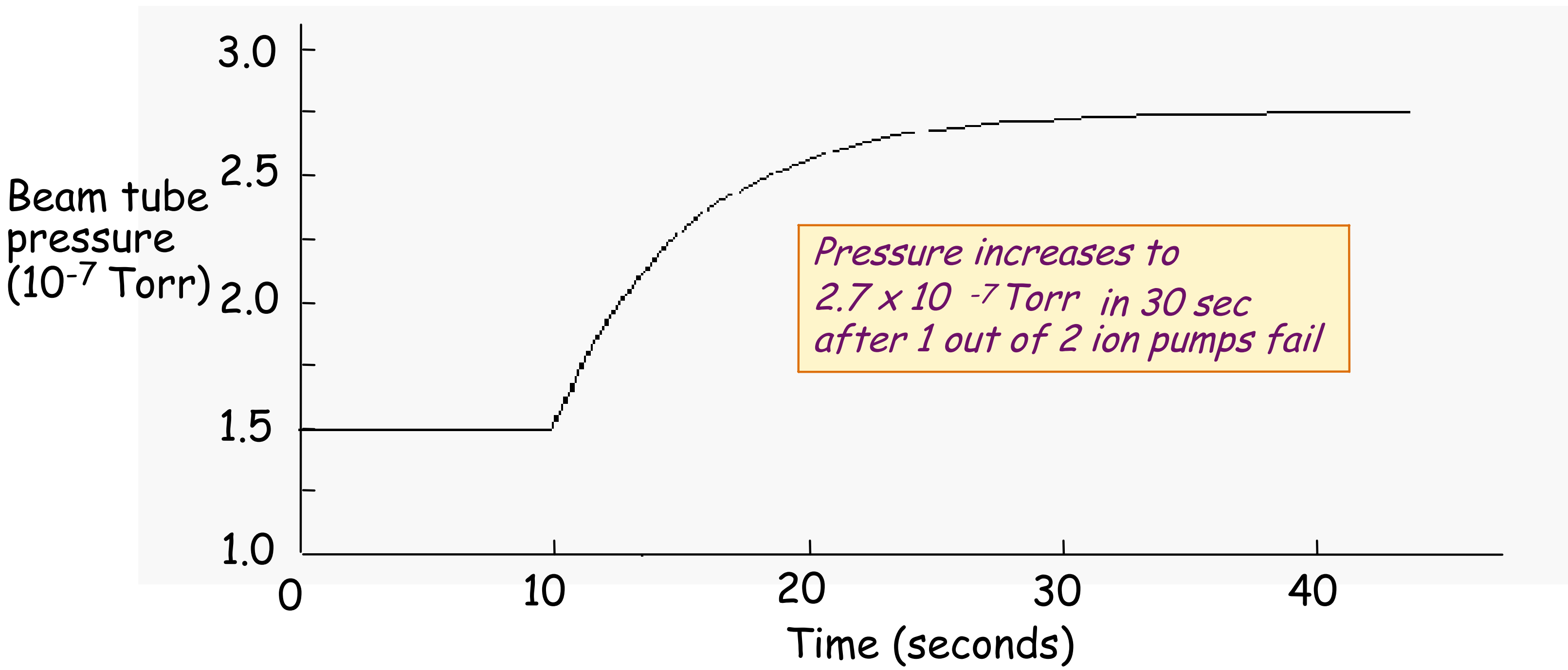


All ion pumps are not alike

Pump characteristics with nitrogen for 300 L/s conventional PHI ion pump



System response to a perturbation can be studied such as a failed pump.



After the optimal system is chosen, then plot the entire pressure history.