Plasma Diagnostics for Nanoscale Fabrication

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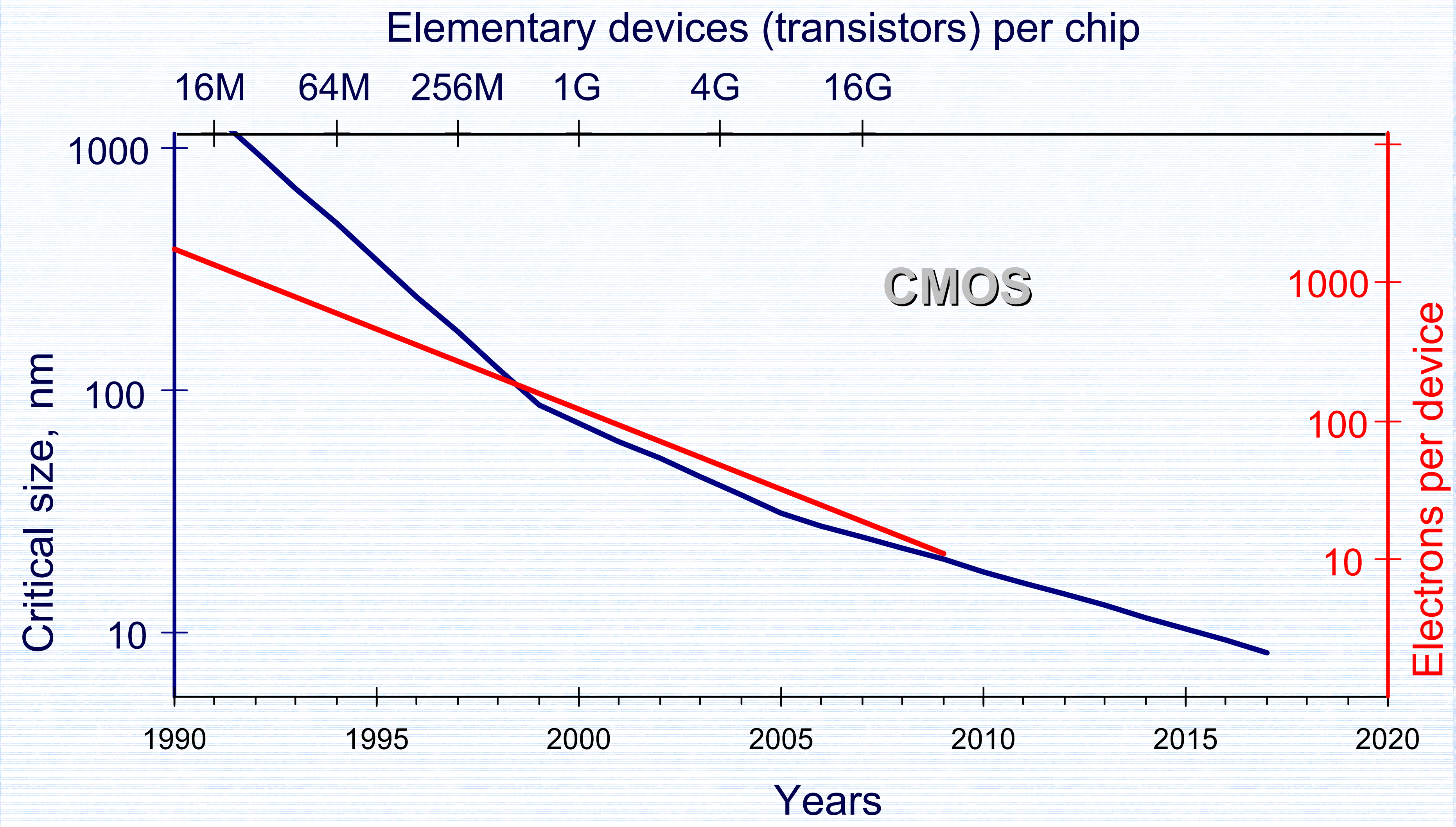
Presentation outline

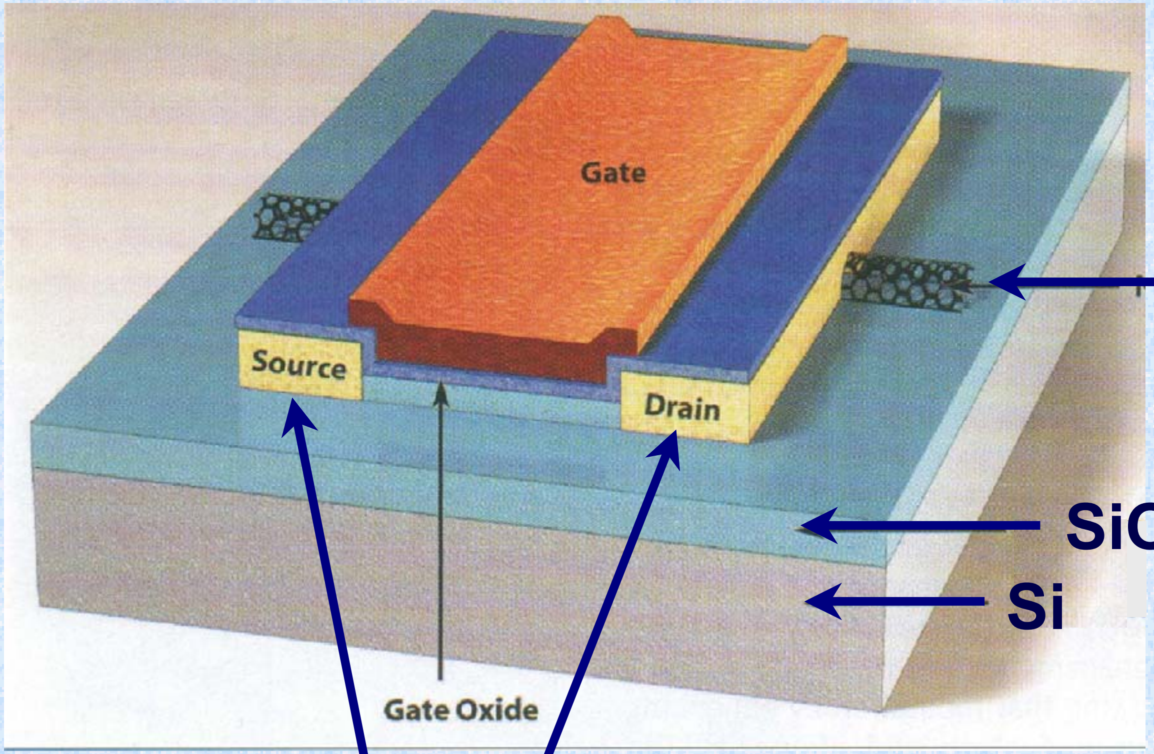
- Introduction:
  - micro/nano-electronics roadmap
  - diode lasers
- Experimental setup
- Temperature determination
- Simulation of plasma mechanisms
- Estimation of densities of species
- Conclusions

ITRS functional dimensions



* *International Technology Roadmap for Semiconductors*

Nanotube-based transistor



Carbon nanotube

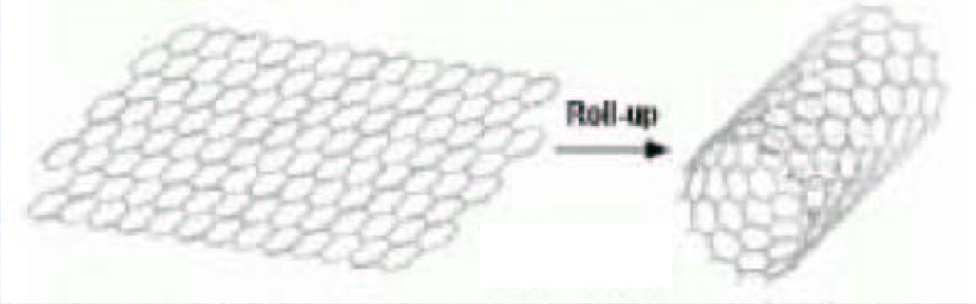
SiO_2

Si

Electrodes (Au)

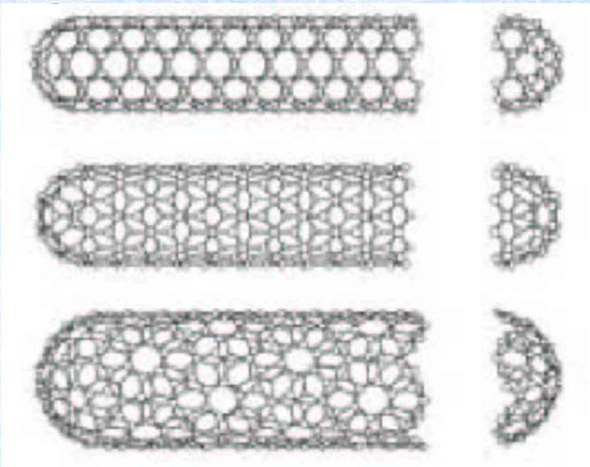
* S.J. Wind, J. Appenzeller, R. Martel, V. Derycke, P. Avouris, *J. Vac. Sci. Technol. B*

Carbon nanotubes



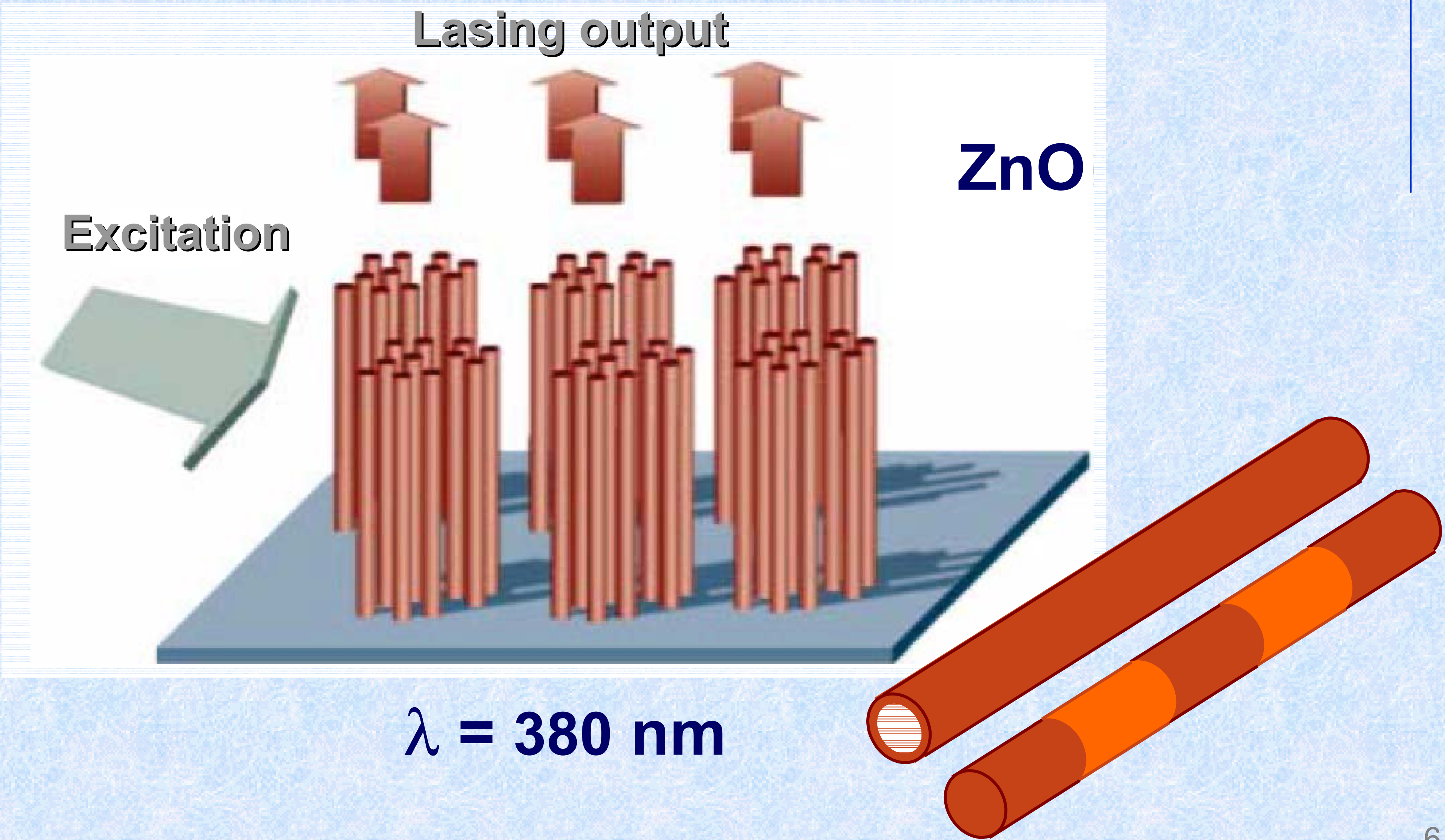
Graphen layer

Nanotubes



- ~20 atoms in circumference, ~2 nm in diam.
- Semiconducting or metallic
- Useful as transistors or interconnect

Nanorods/wires – nanolasers



ZnO

λ = 380 nm

* M.H. Huang, S. Mao, H. Feick, H. Yan, Y. Wu, H. Kind, E. Weber, R. Russo, P. Yang, *Science*.

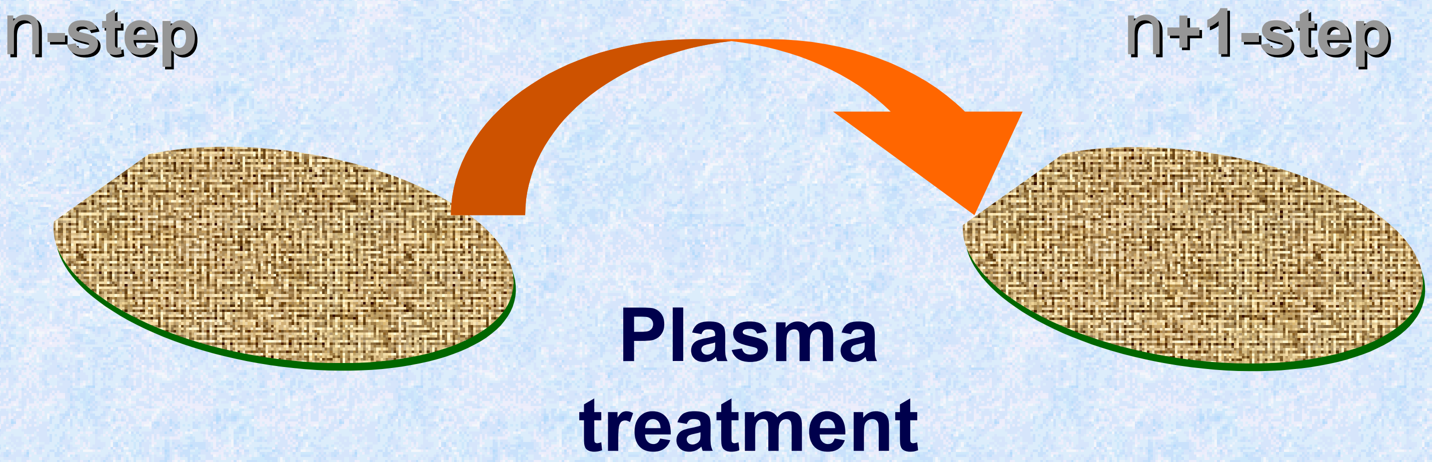
Current and future needs

- Advanced process control required
- Must be non-intrusive, compact, and simple
- Monitoring of chemical species:
  - end-point detection
  - process optimization and control
  - contamination “management”
- Local temperature monitoring:
  - plasma uniformity
  - intentionally non-uniform (!?)

Semiconductor process gases

Inert	(e.g., Ar, He, N_2)
Corrosive	(e.g., HCl, HBr, SF_6, NF_3, CF_4)
Highly Toxic	(e.g., AsH_3, PH_3)
Pyrophoric	(e.g., SiH_4)
Reactive	(e.g., NH_3, N_2O, WF_6, CO_2, O_2)

Impurity transfer



n-step

n+1-step

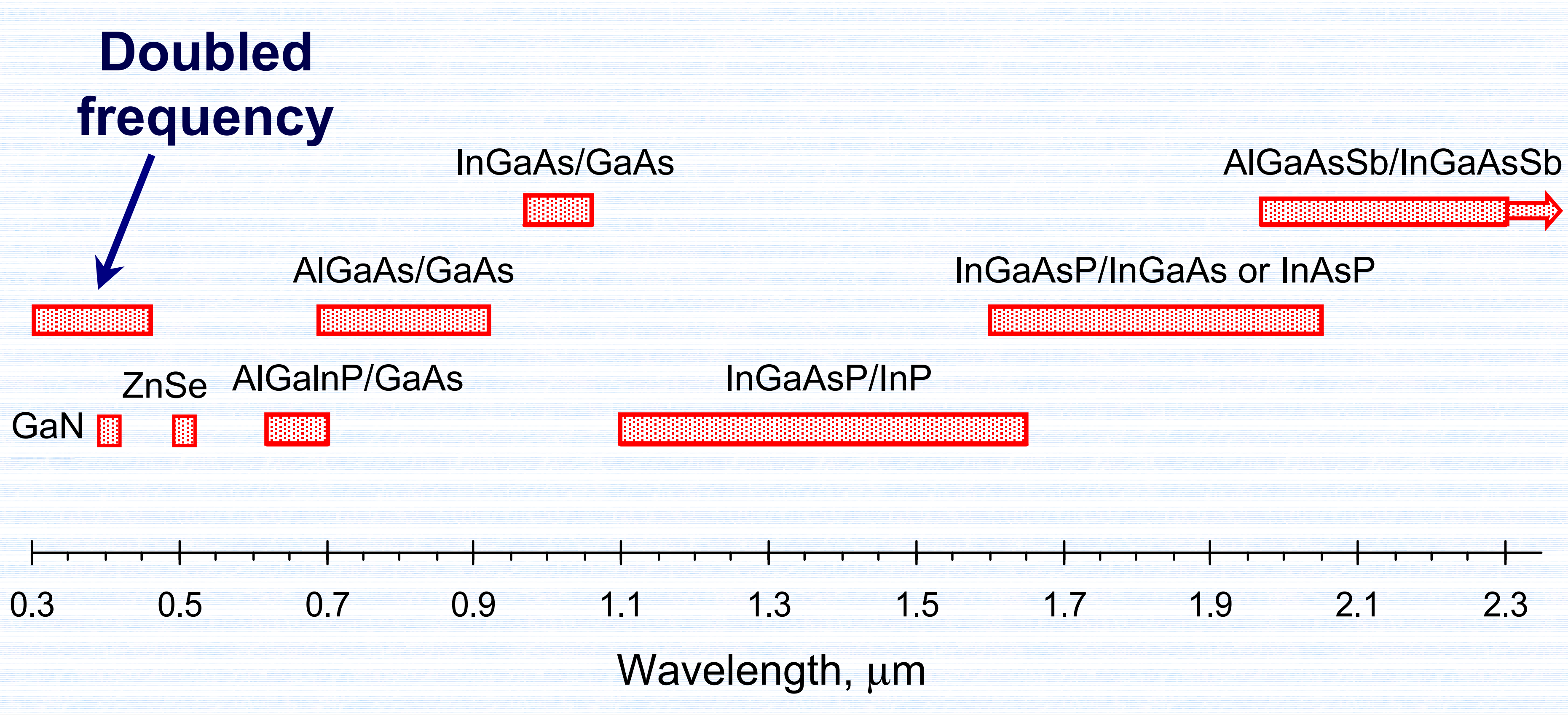
Plasma treatment

- More than 300 technology steps for one chip
- High variety of materials in use

How to monitor processes?

Emission:	low resolution only emitting species
Absorption:	limited if FTIR or UV diode lasers - ideal
Fluorescence:	requires powerful lasers
Mass spectrometry:	intrusive, cumbersome
Electrical:	non-selective

Commercial diode lasers



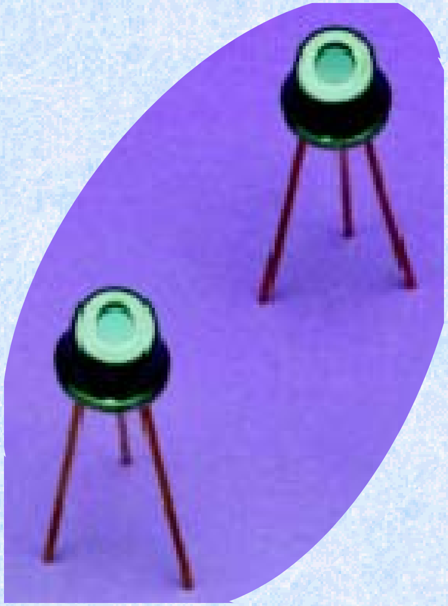
- Room temperature operation

Accessible elements

Probed already	Possible	Excited only
Al, Ba, Ca, Cr, Cs, Cu, Hg, I, In, K, La, Li, Mn, Pb, Rb, Sm, Sr, U, Y, Zr	Ag, Co, Eu, Fe, Ga, Gd, Hf, Ho, Lu, Mo, Nb, Nd, Ni, Os, Re, Rh, Ru, Sc, Tb, Th, Ti, Tl, Tm, V, W	Ar, As, B, Br, Cl, F, H, Kr, N, Ne, O, P, S, Si, Xe, Zn & *etc.*
H_2O, OH, O_2, CH, CO, CO_2, CH_4, NH_3, HCl, HBr		N_2, Cl_2, F_2, CF, CN, SiF, AlCl and *etc.*

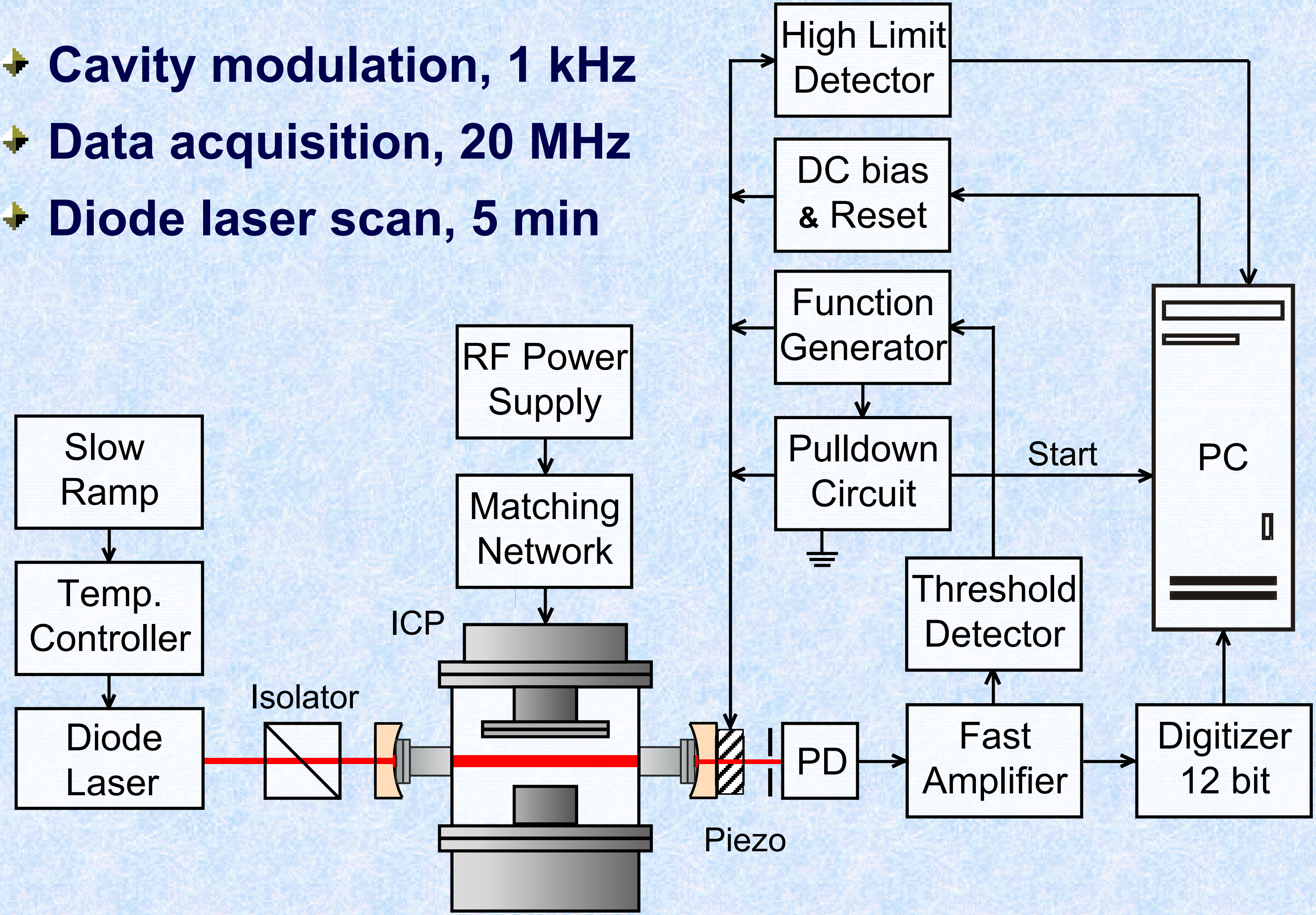
Diode laser characteristics

- Tunable over absorption features
- Provide spectrally narrow linewidths
- Compact and simple to use
- Can be multiplexed
- Commercially available
- Relatively inexpensive



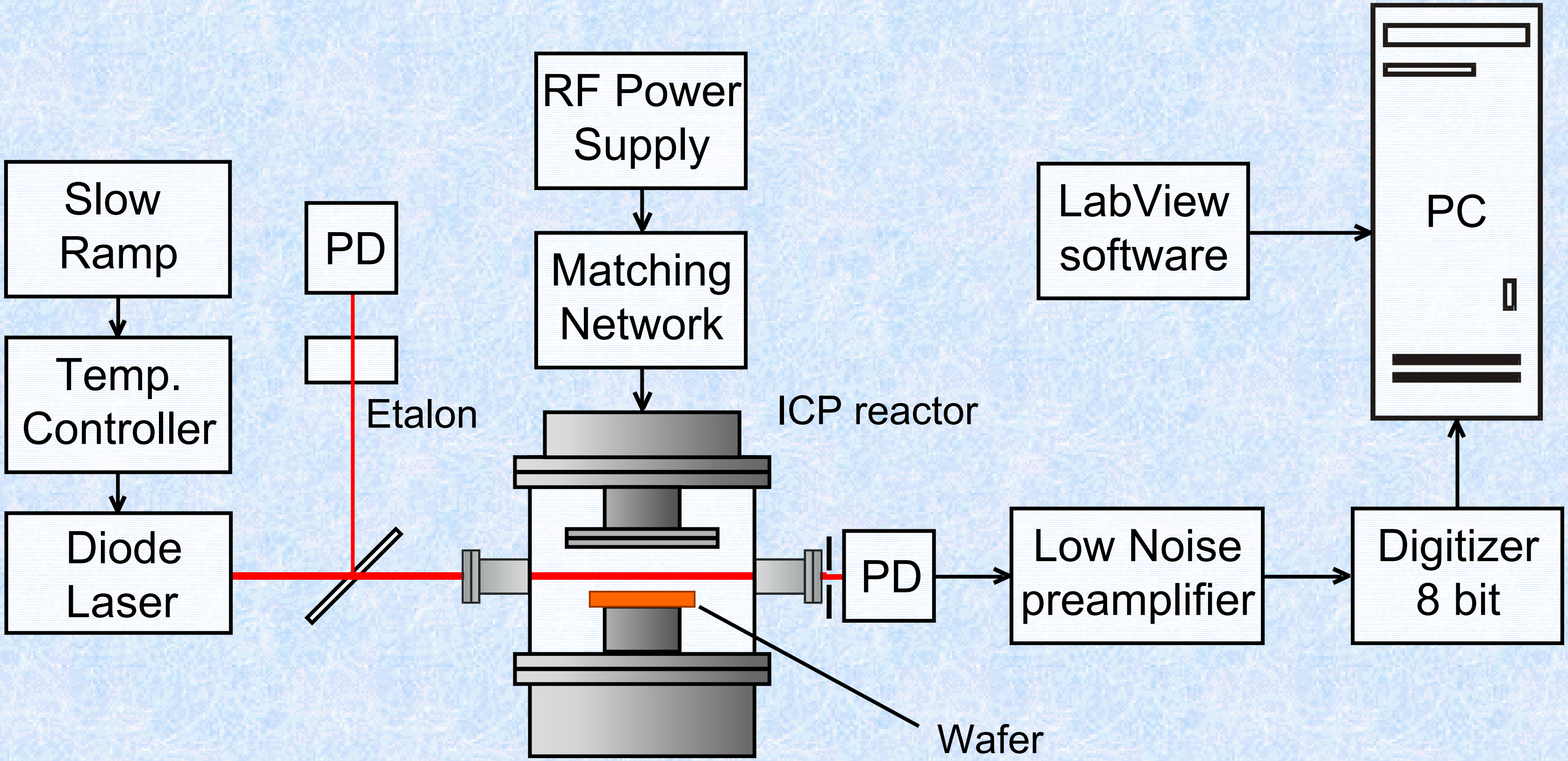
Experimental Setup

- **Cavity modulation, 1 kHz**
- **Data acquisition, 20 MHz**
- **Diode laser scan, 5 min**



Simplified Setup

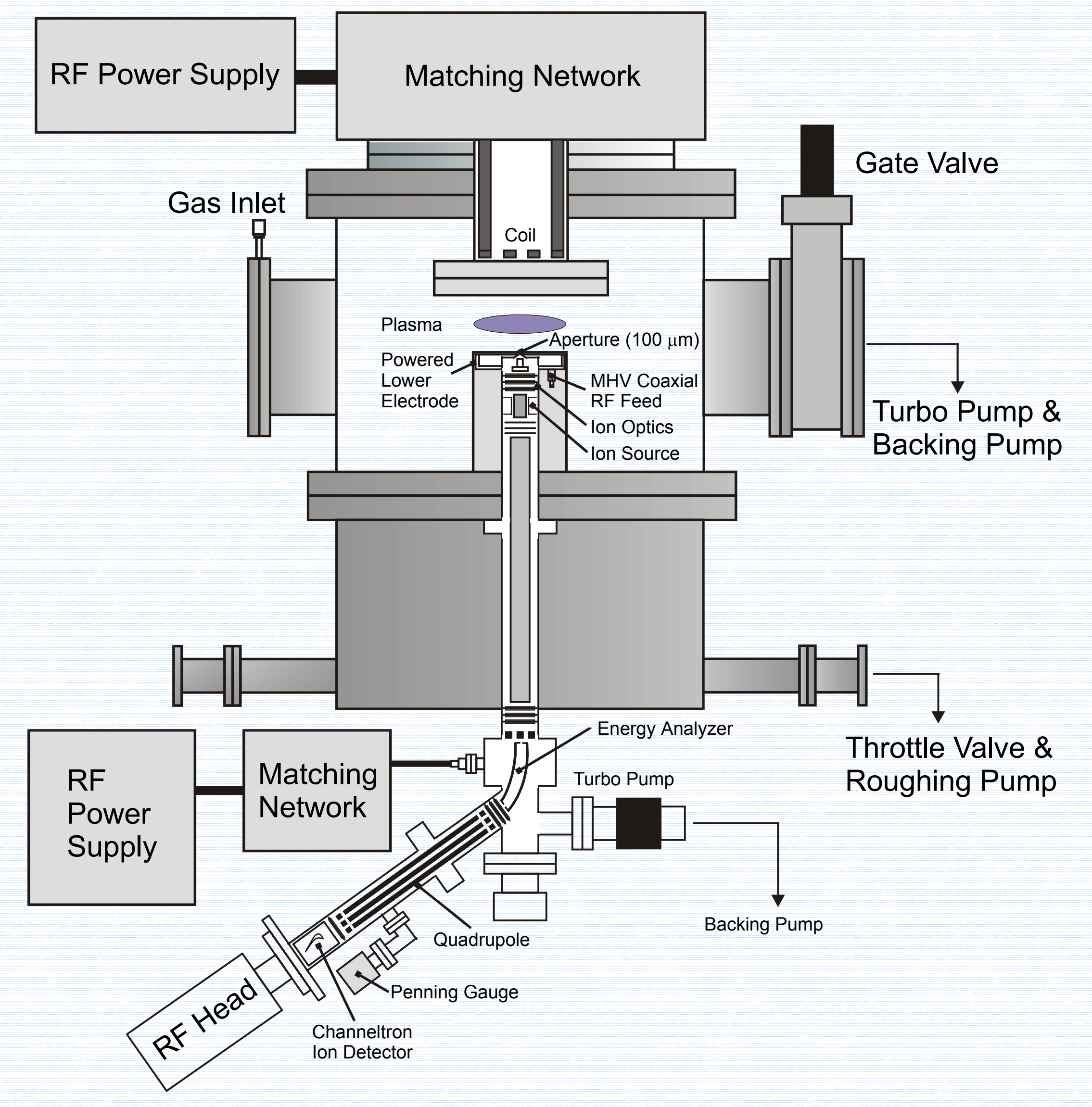
- **Data acquisition, 0.1 kHz**



Rate of energy loss from cavity

Reflectance	L=50 cm τ (μs)	L=100 cm τ (μs)	Number of passes
96	0.04	0.08	25
99	0.17	0.33	100
99.9	1.67	3.33	1000
99.99	16.67	33.33	10000
99.999	166.67	333.33	100000

Etching ICP Reactor



13.56 MHz

RF Power Supply

Matching Network

Gas Inlet

Coil

Gate Valve

Plasma

Aperture (100 μm)

Powered Lower Electrode

MHV Coaxial RF Feed

Ion Optics

Ion Source

Turbo Pump & Backing Pump

Throttle Valve & Roughing Pump

100 kHz

RF Power Supply

Matching Network

Energy Analyzer

Turbo Pump

Backing Pump

Quadrupole

Penning Gauge

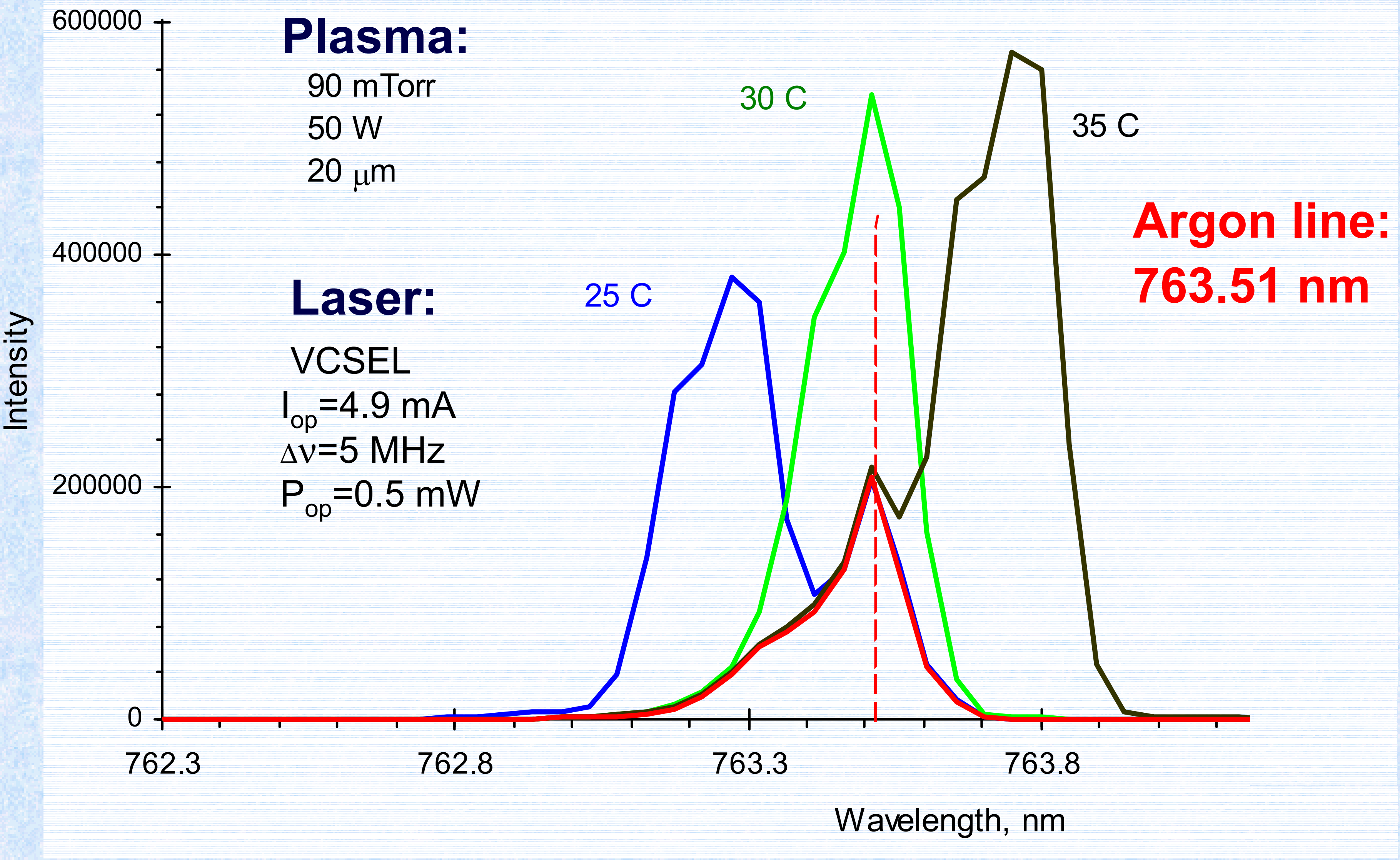
Channeltron Ion Detector

RF Head

Diagnostics objectives

- Determination of plasma parameters:
    - gas temperature
    - electron temperature
    - degree of ionization
- Identification of species in etching plasmas
- Measurement of concentrations of species
- Simulation of plasma etching mechanisms based on acquired experimental data

Laser Scan over Argon Line



Plasma:

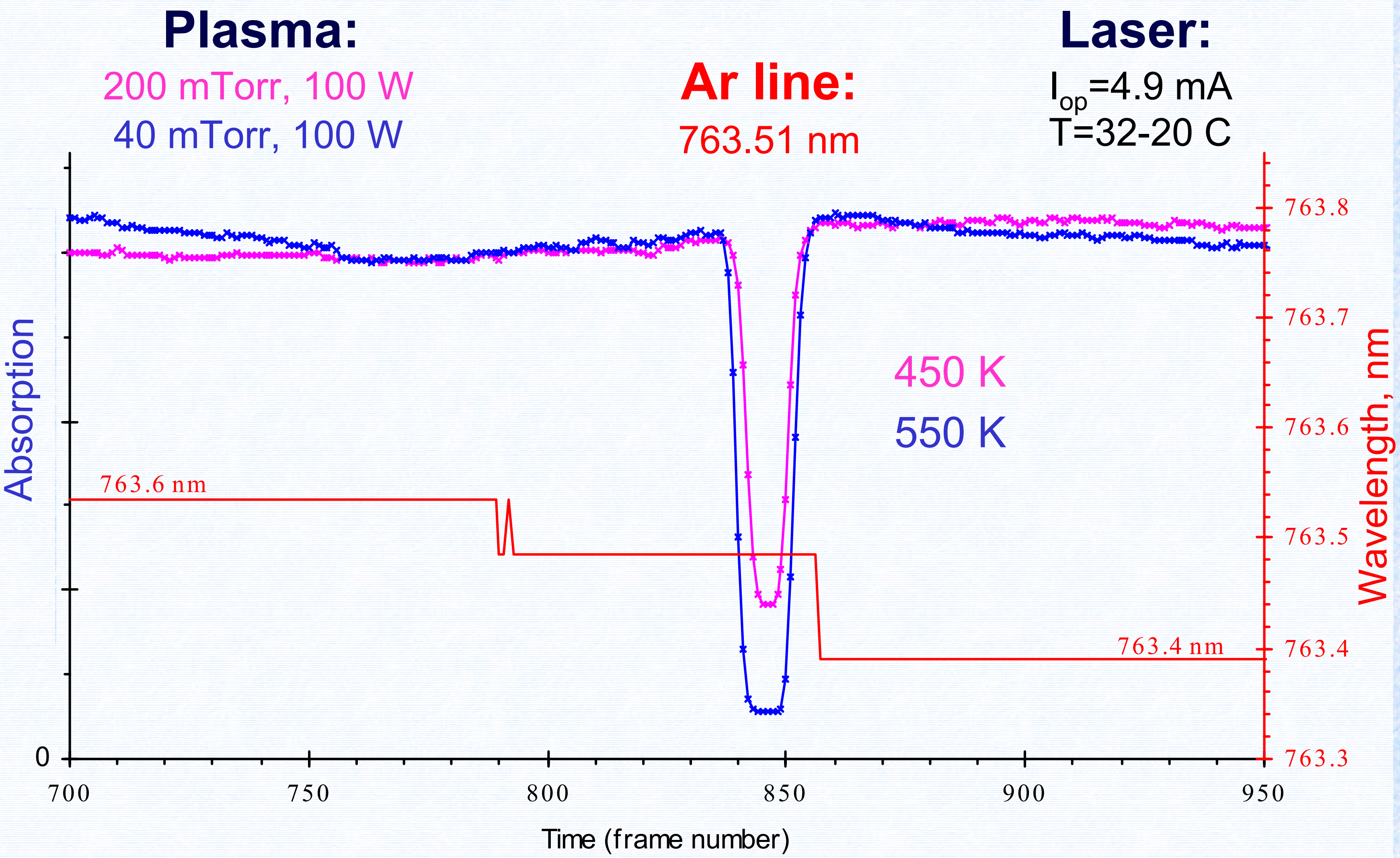
90 mTorr
50 W
20 μm

Laser:

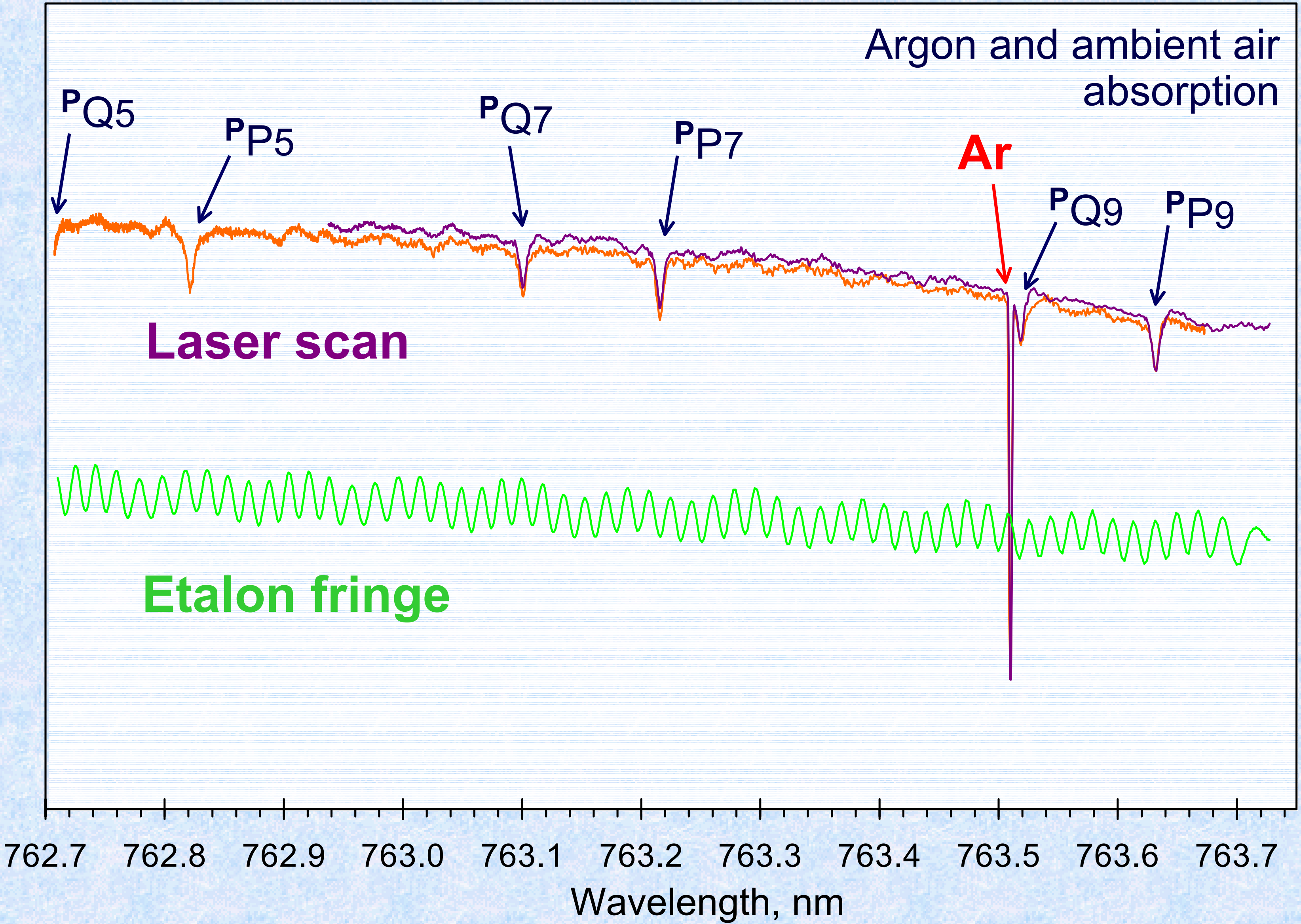
VCSEL
I_{op}=4.9 mA
$\Delta\nu$=5 MHz
P_{op}=0.5 mW

Argon line:
763.51 nm

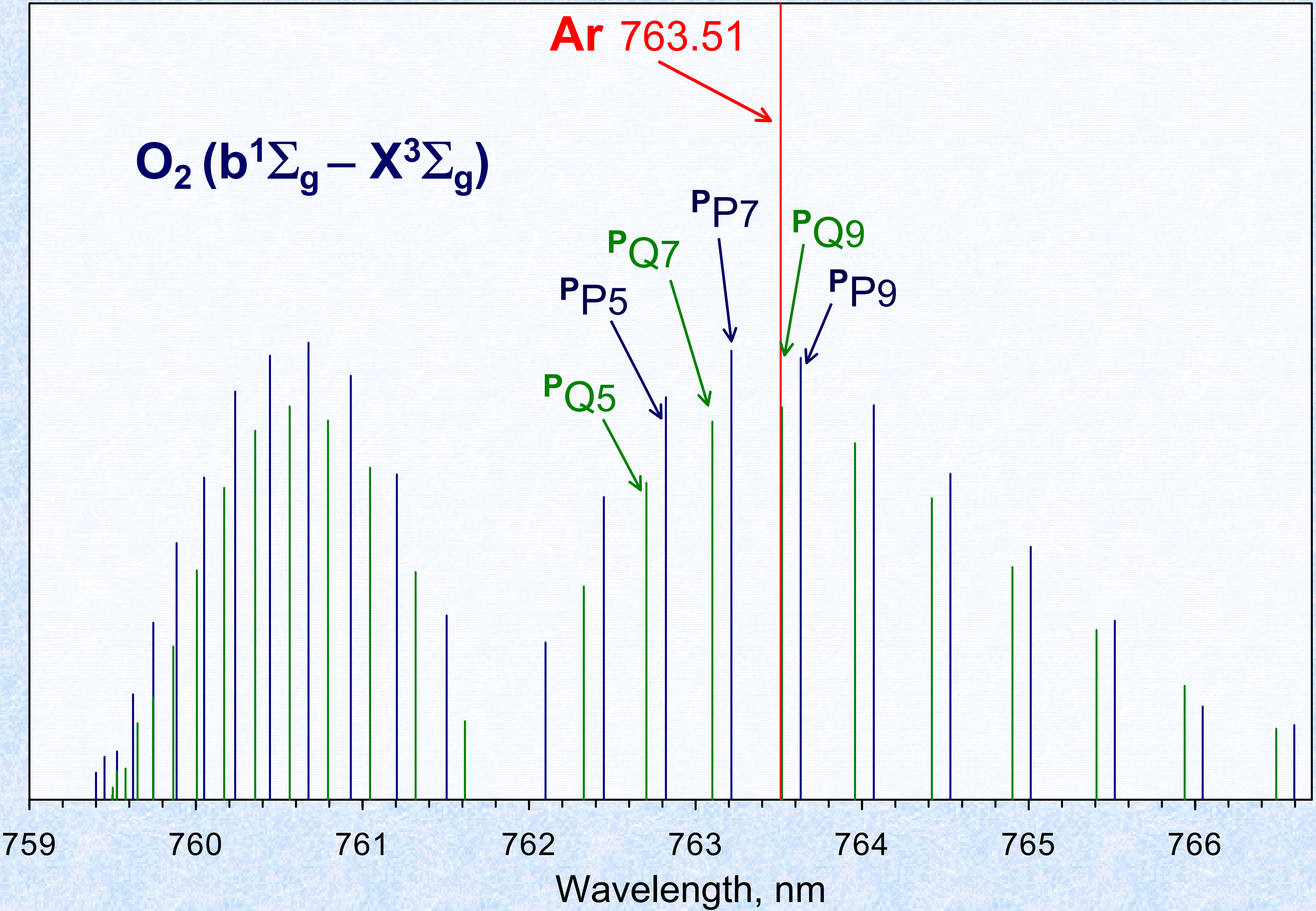
Absorption by Argon Plasma



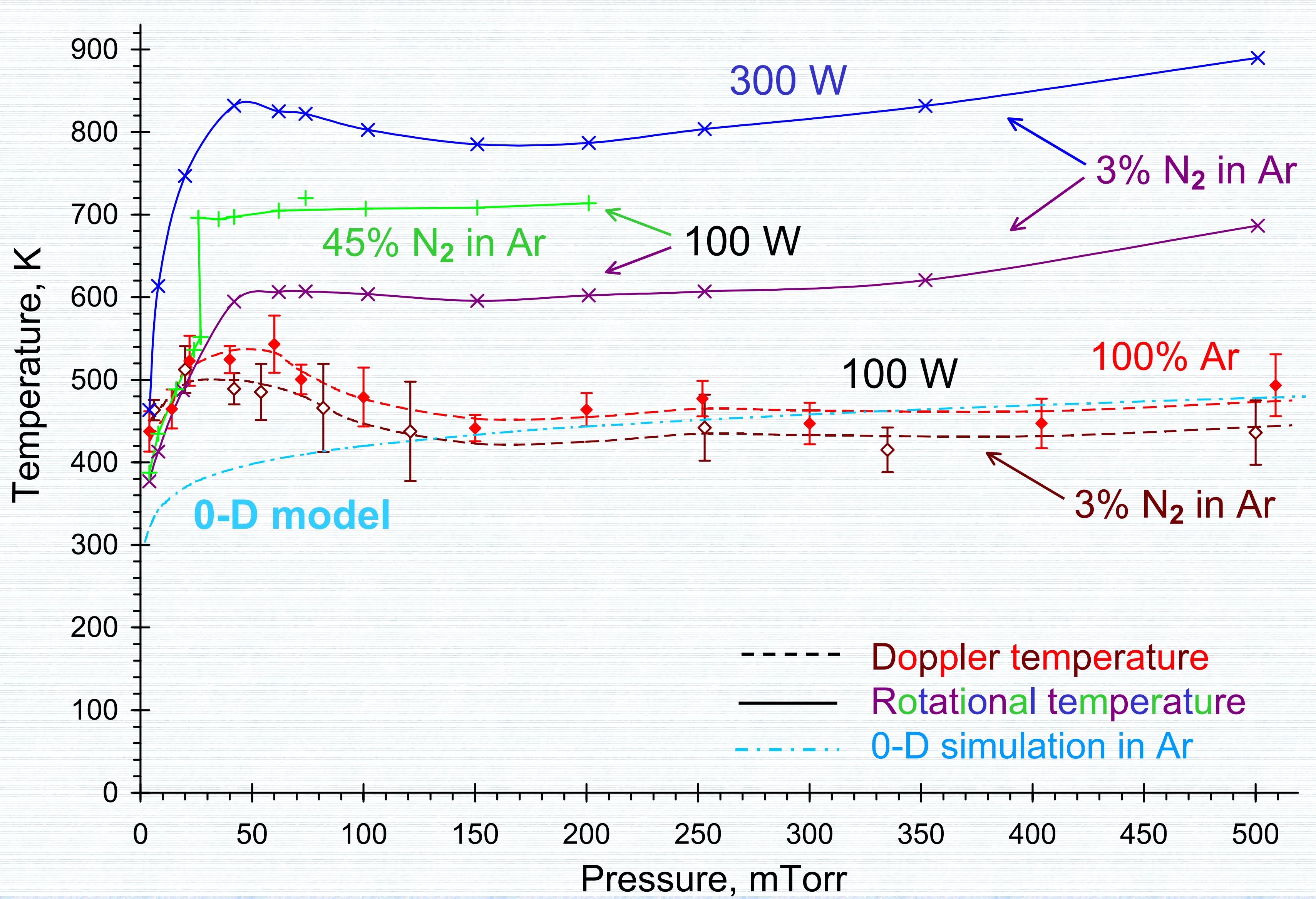
Laser wavelength calibration



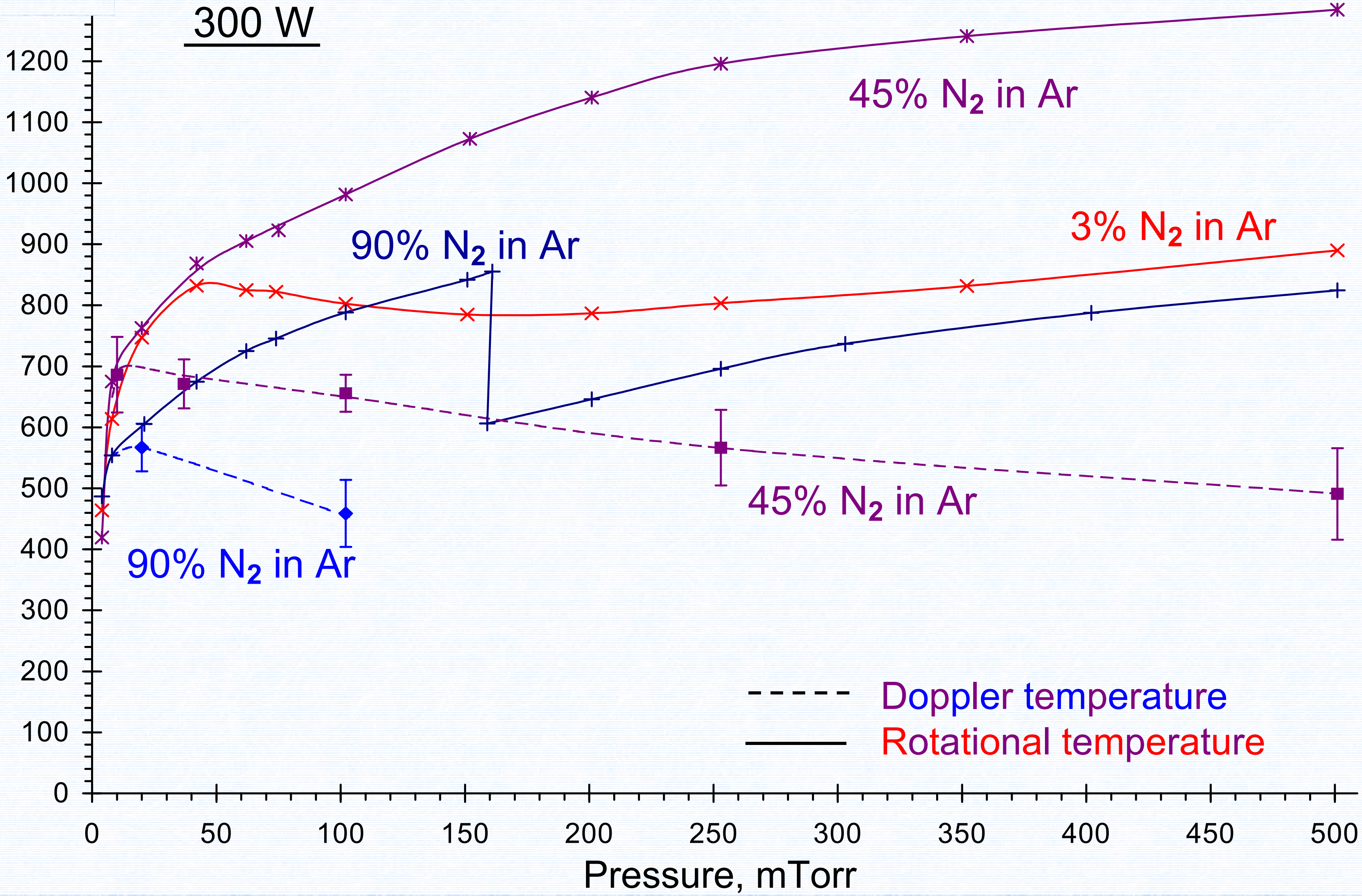
Ambient oxygen absorption



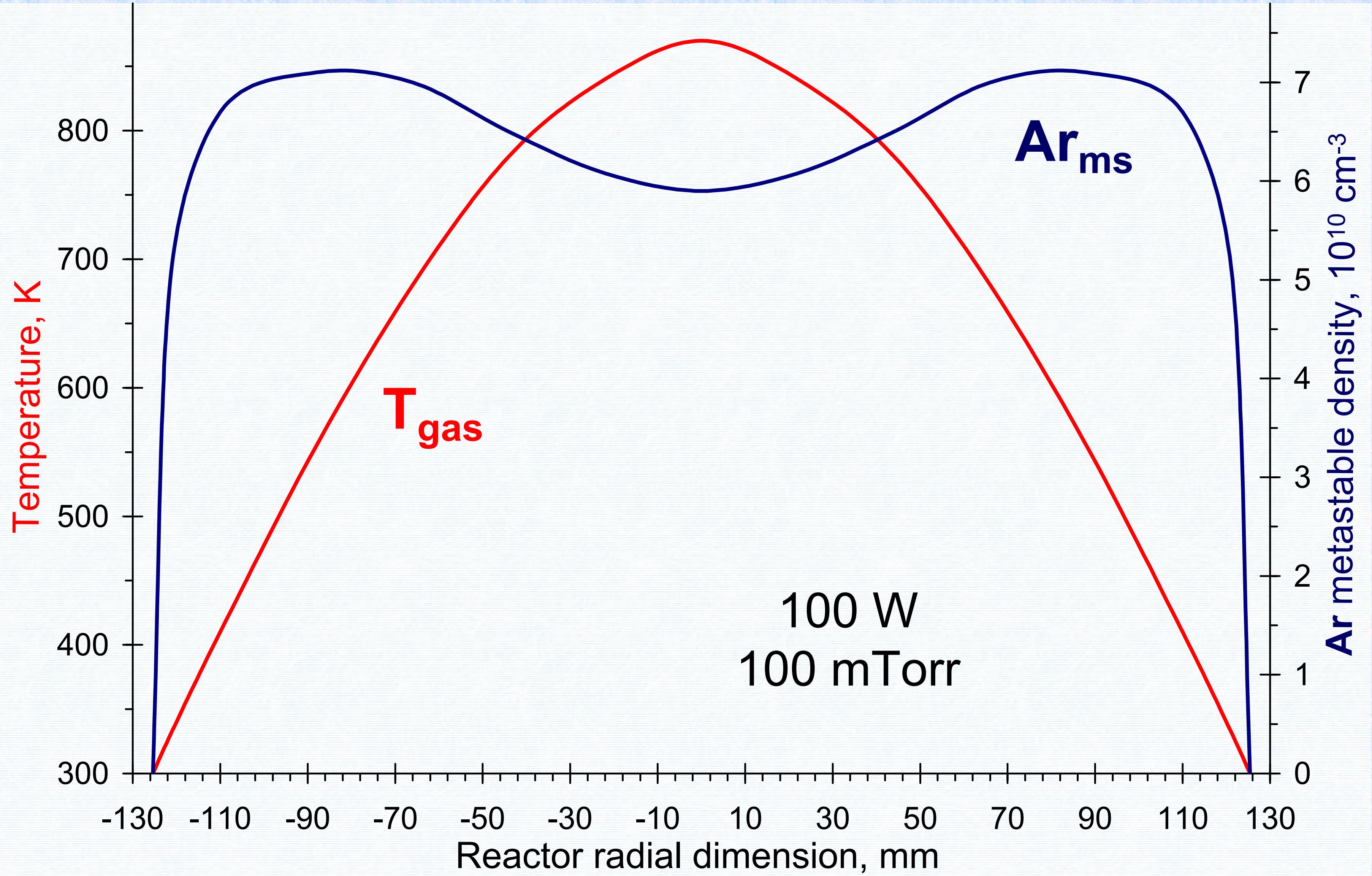
Temperature in Ar/N_2 plasma



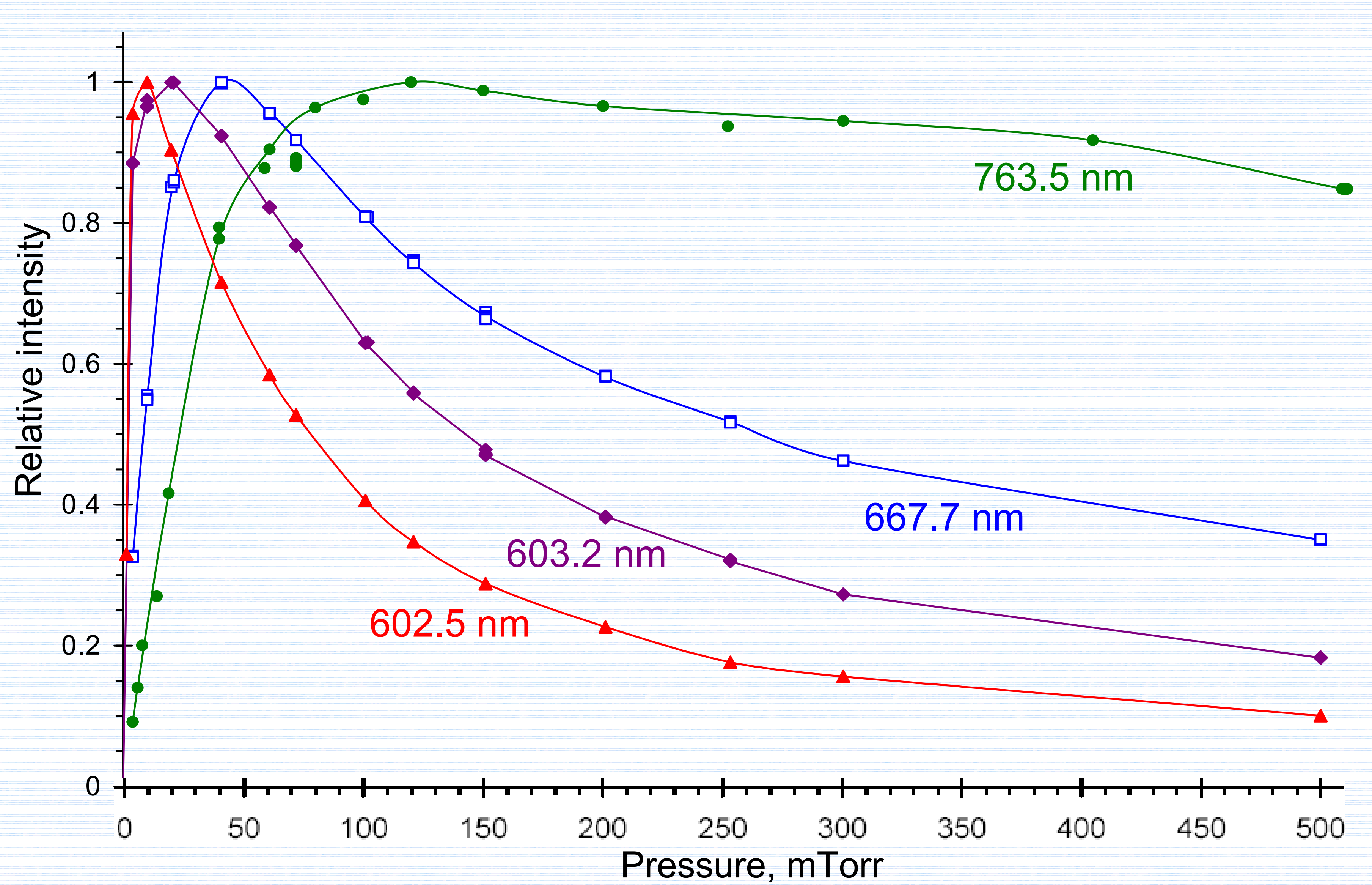
Temperature in Ar/N_2 plasma



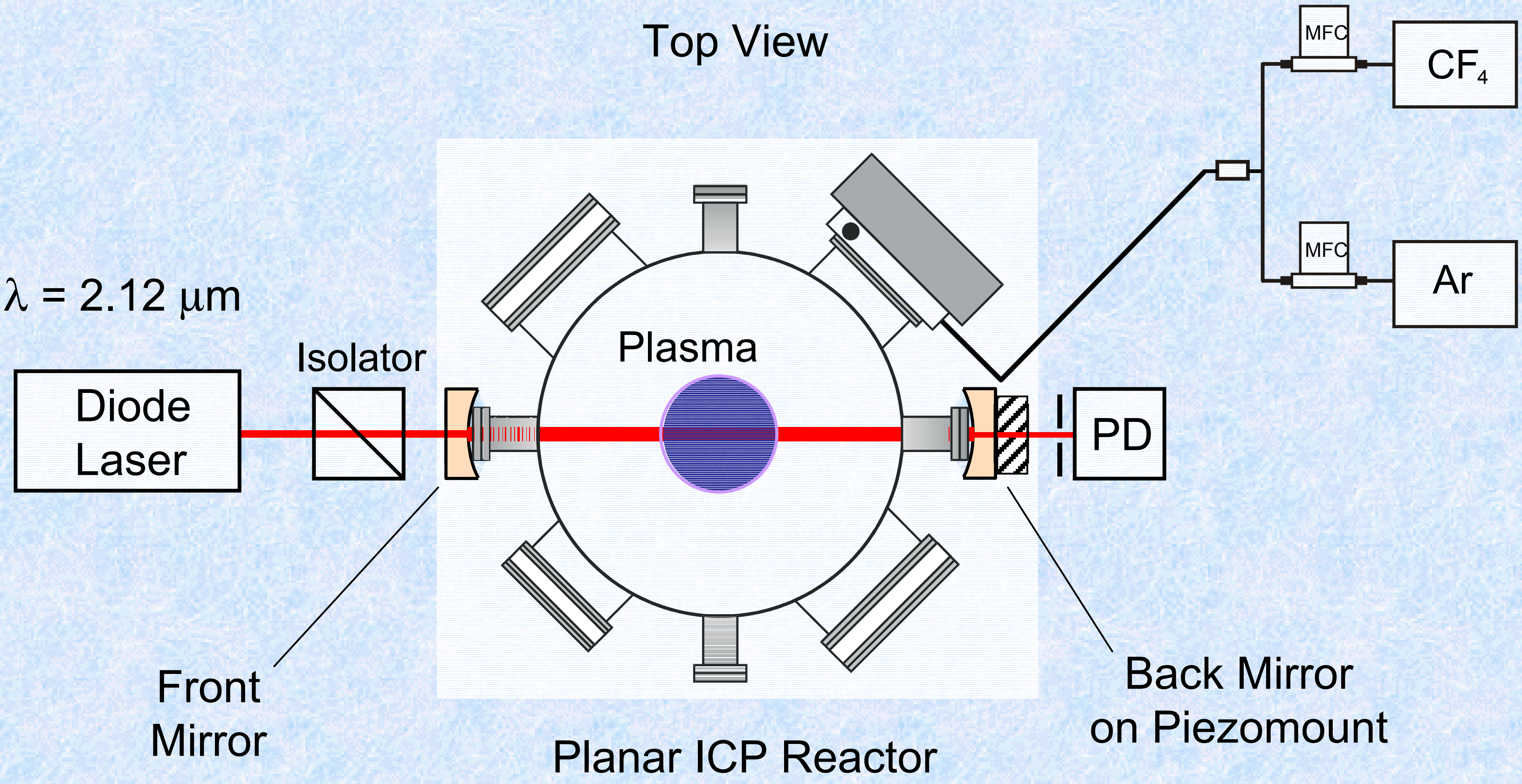
Argon plasma simulation



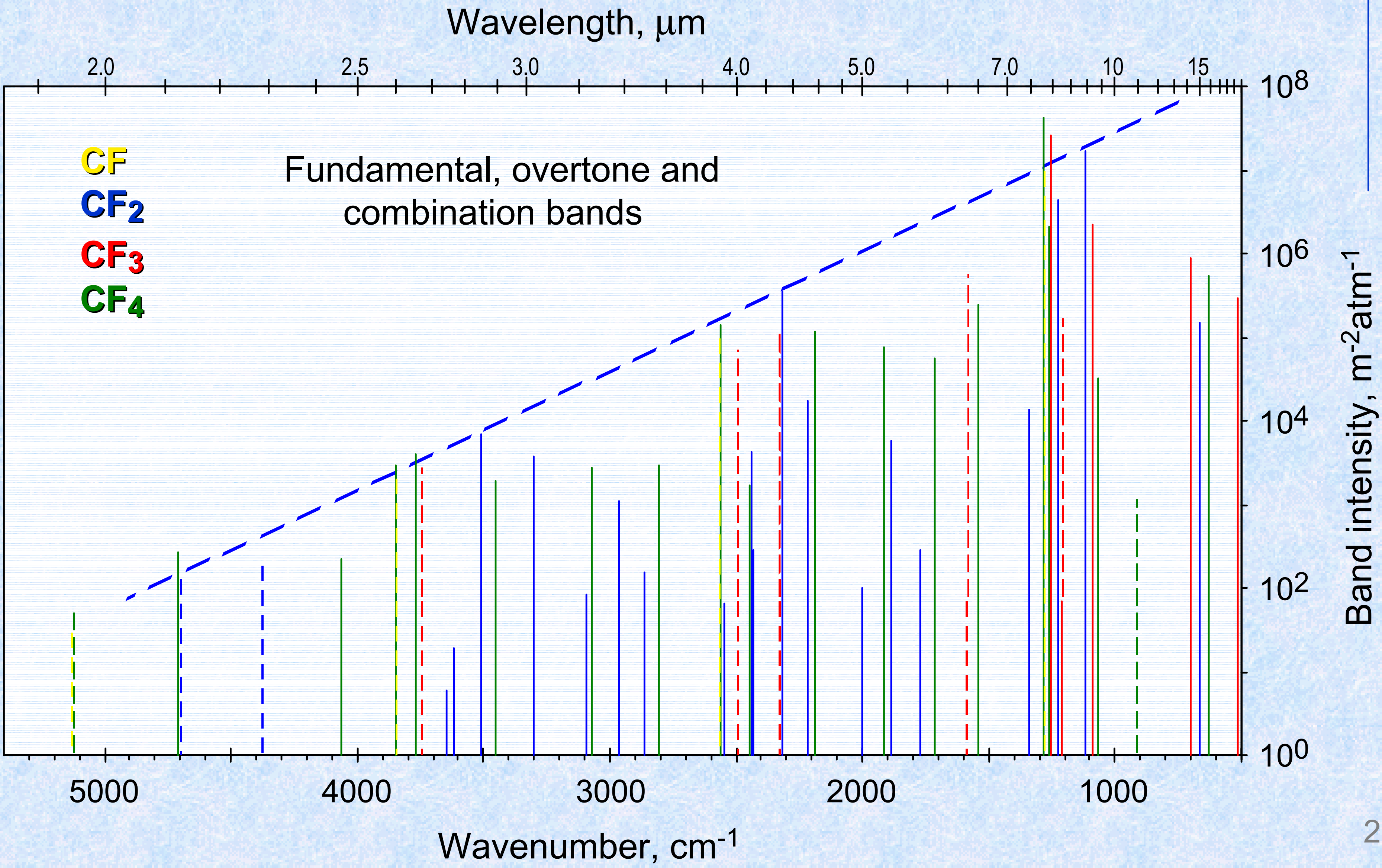
Emission from Ar plasma



Passive Optical Cavity

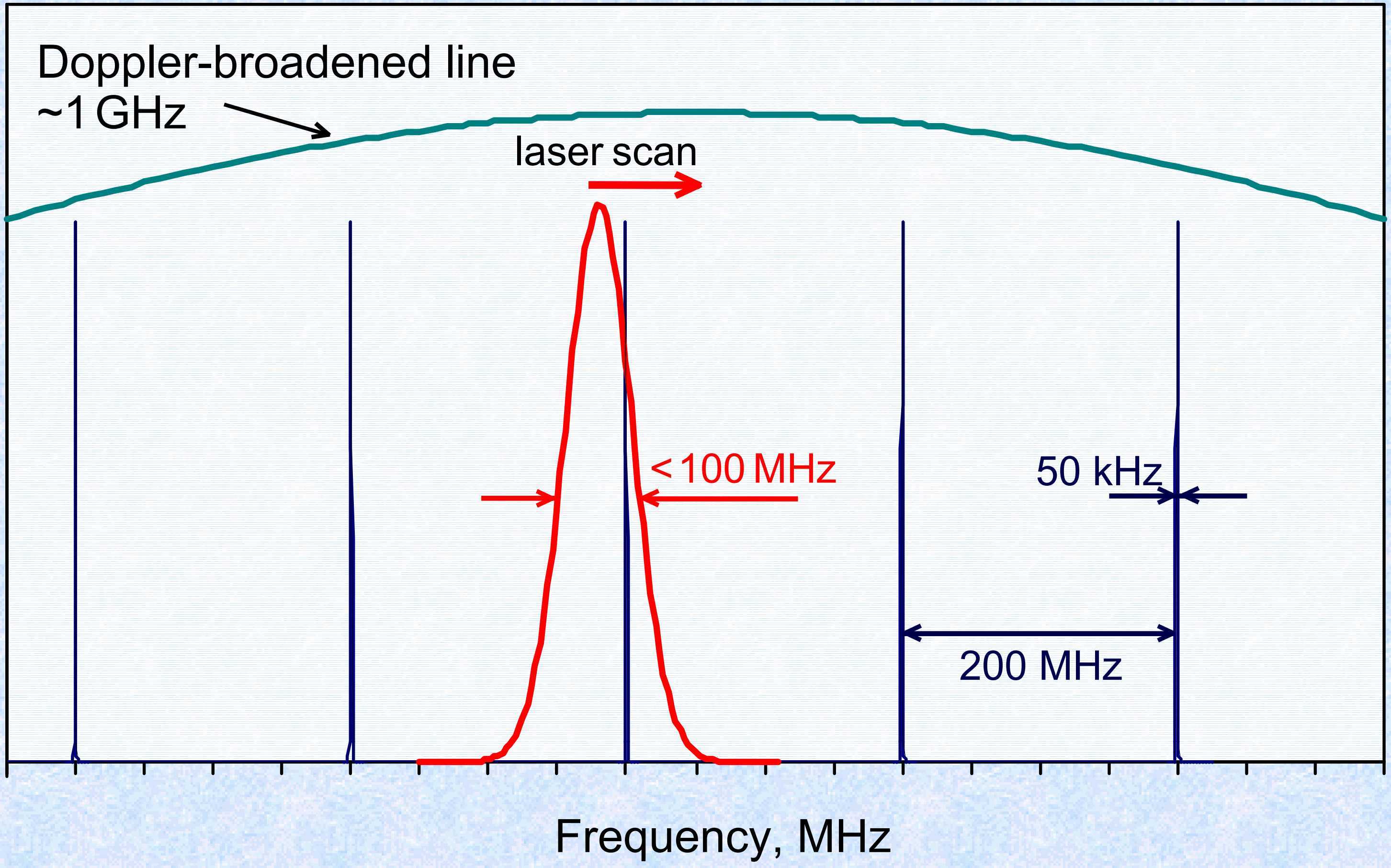


Composite Spectrum of CF_x



Cavity Modes and Laser Line

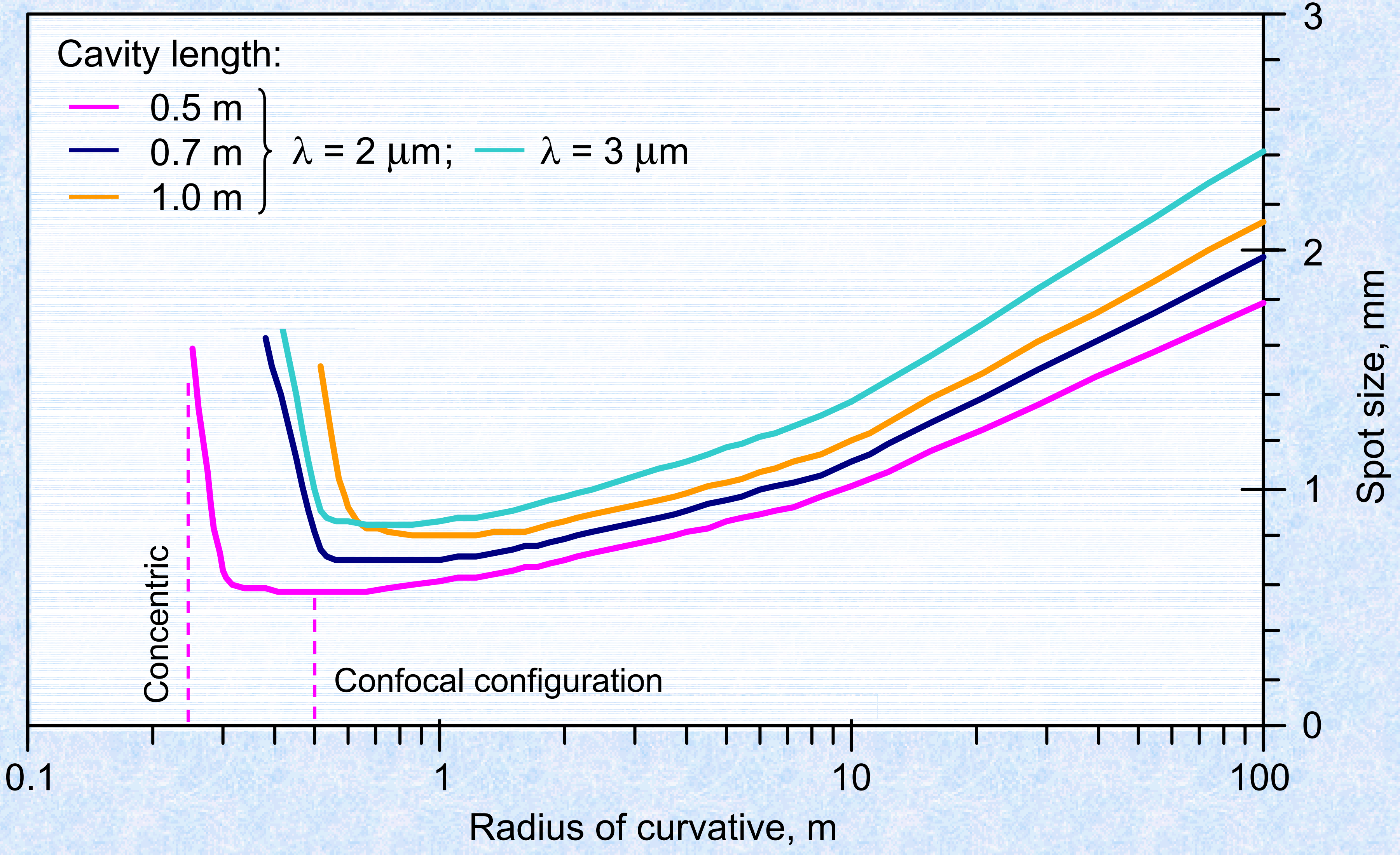
- Laser is slowly scanned throughout ~400 GHz
- Cavity length is fast modulated within ±100 MHz



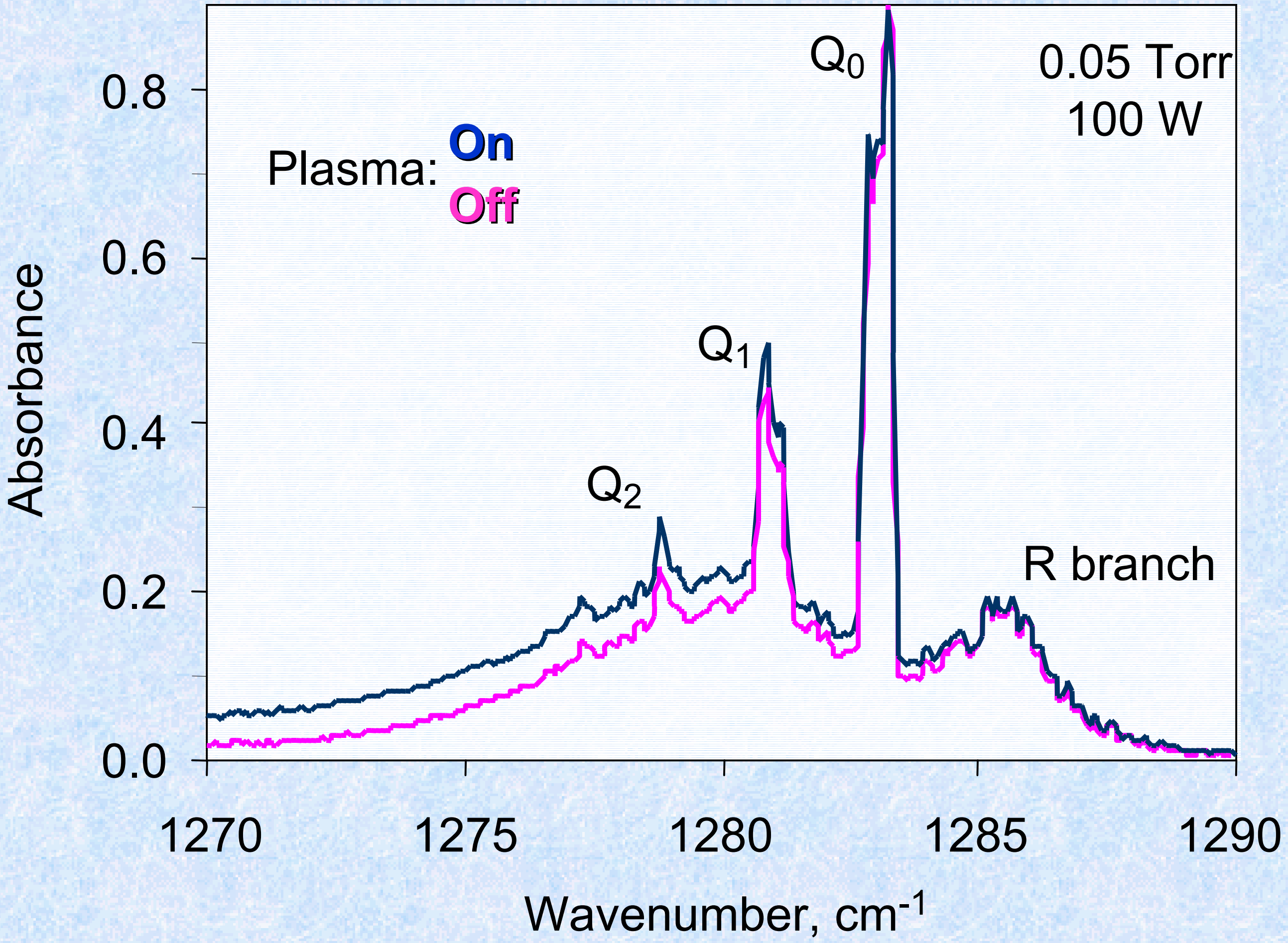
Detection of plasma species

- High anisotropy & selectivity in etching of Si over SiO_2 or SiN_3 is necessary; research in CF_x radicals plasmachemistry is needed
- Absolute densities of C_xH_y, CF_x radicals and kinetics in plasma can be measured by cavity absorption spectroscopy at ~1 km of the equivalent optical pathlength
- Useful for diagnostics, analysis, monitoring and control of both nano- and microelectronic fabrication processes and development of micro- and nanodevice-based sensors

Spot Size at Mirrors

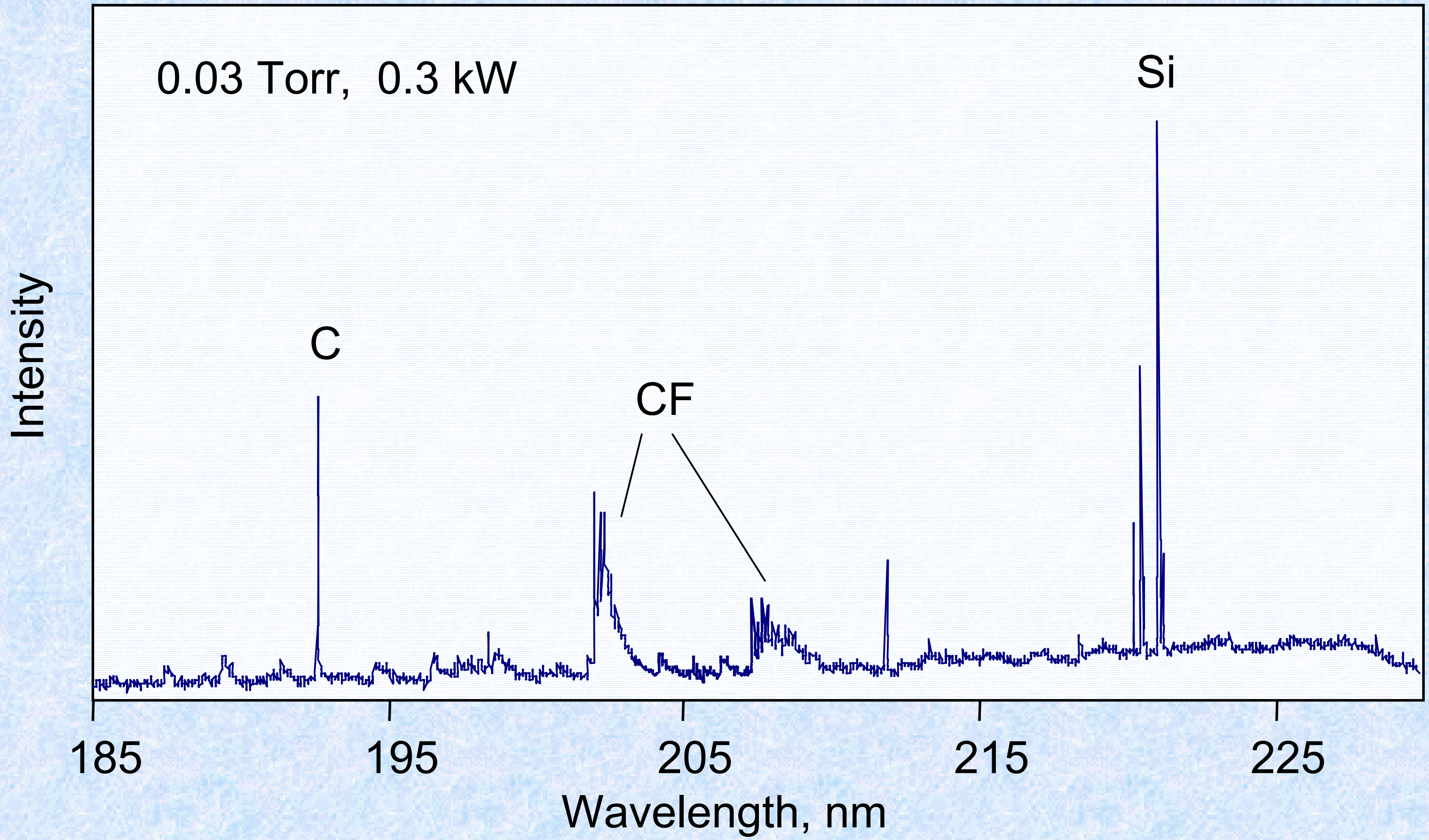


ν_3 Fundamental Band of CF_4



* B.A.Cruden, M.V.V.S.Rao, S.P.Sharma, M.Meyyappan, *Plasma Sci. Source Technol.*

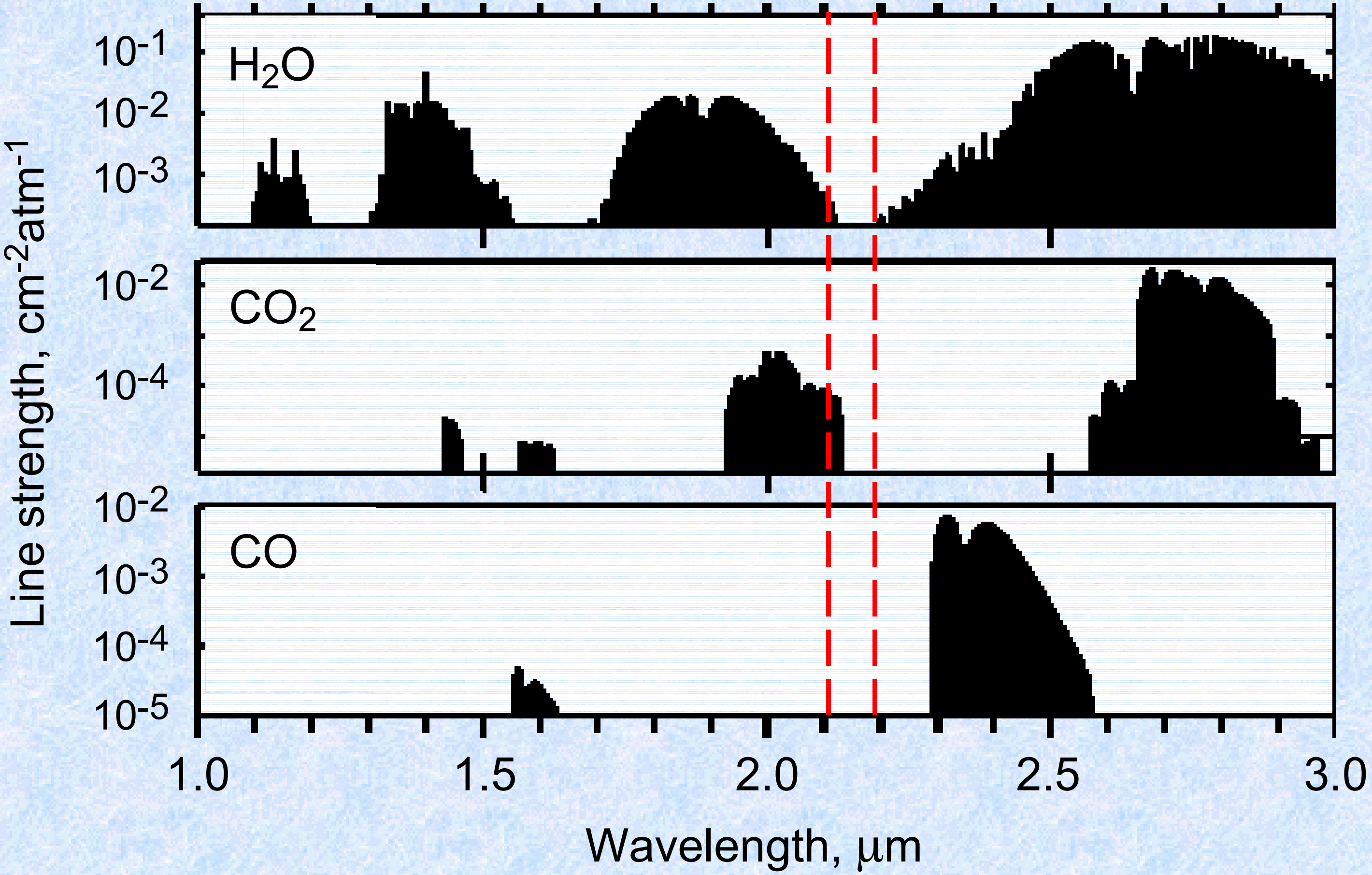
Emission from CF_4 Plasma



- Species detected include C, C_2, F, CF, Si, O, CO

* B.A.Cruden, M.V.V.S.Rao, S.P.Sharma, M.Meyyappan, *J. Vac. Sci. Technol. B*

Impurity Absorption



- Interference-free window between 2.1 – 2.2 μm

* M.E.Webber, J.Wang, S.T.Sanders, D.S.Baer, R.K.Hanson, *Proc. 28 Int. Symp.Combustion*

Sensitivity Estimates

- Minimum absorption coeff. ~10^{-10} cm^{-1}Hz$^{-½}$
- CF$_x$ radicals detection limit ~10^{11} cm^{-3}

(λ = 2.12 μm; Cavity leakout time =100 μs)

- Single molecule absorption can in principle be detected at strong fundamental bands

(α ~10^{-15} cm^{-1}Hz$^{-½}$; λ = 8 μm)

Conclusions

- Diode lasers operating in the 0.3 - 2.3 μm region are convenient, compact, inexpensive, tunable, of spectrally narrow bandwidth, and require no cryogenic cooling
- Local and averaged temperature can be determined with different thermometric species
- Absolute densities of atoms, radicals and molecules can be monitored
- Multi-parametric measurements possible

Conclusions

- Checking overall chamber health in real time
- Chamber clean-up/fast start-up optimization
- End-point for small features, cost-effectively
- Dopant species detection for end-pointing
- Monitoring atomic metal species in ALD
- Replacing the slow techniques (TXRF, SIMS)
- B and P implants detection in gate etch
- Aerosol detection in photoresist processing

Acknowledgements

- Alexander Bol'shakov held NRC senior research associateship award at NASA Ames Research Center while performing this work
- Brett Cruden's work was contracted through Eloret Corporation