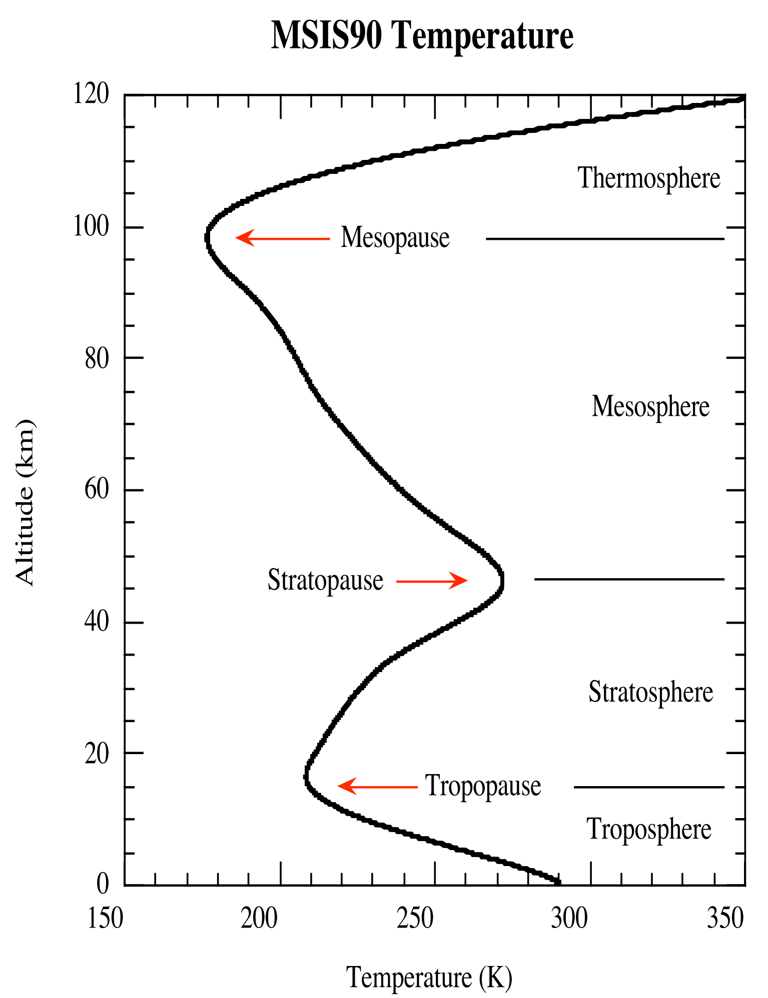
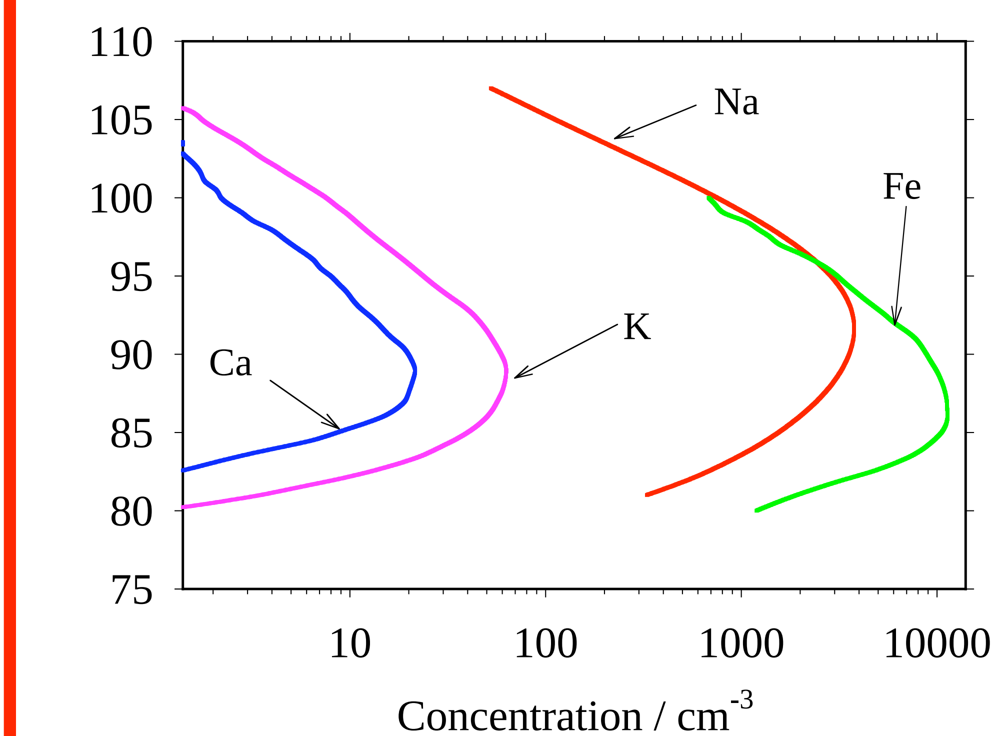
Lecture 15. Temperature Lidar (4)
Comparison of Doppler Lidars

- Introduction
- Metal species in MLT region
- K Doppler lidar
- Fe Doppler lidar
- Comparisons
- Summary

Introduction: More Resonance Fluorescence Doppler Lidar



- Besides Na, there are more metal species (K, Fe, Ca, Ca^+, Mg, Li, …) from meteor ablation. They can be used as tracers for Doppler lidar measurements in MLT region.

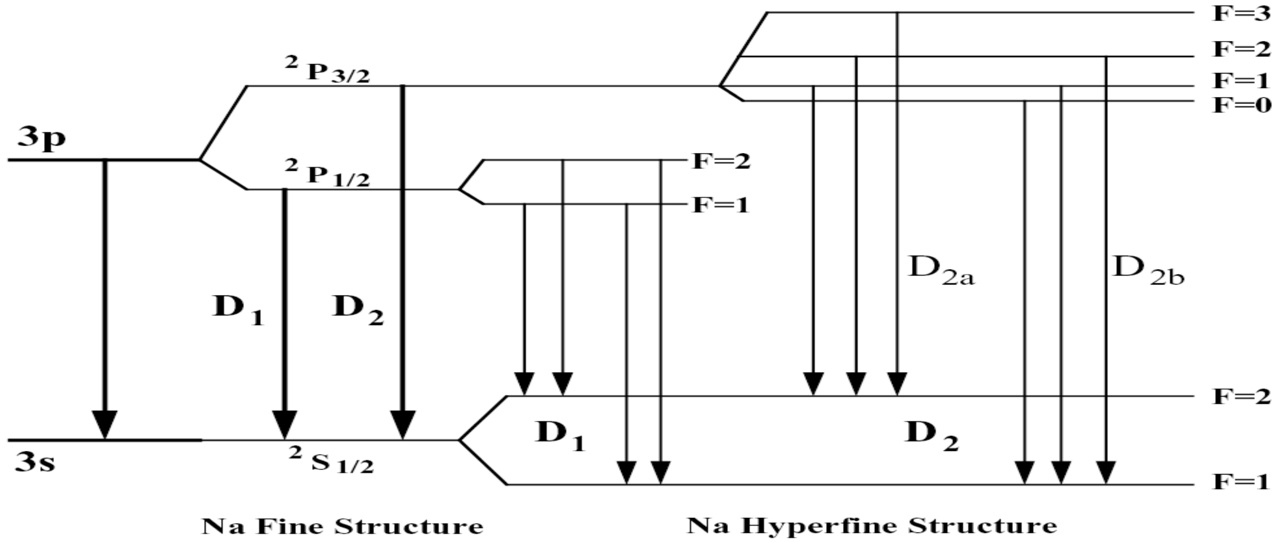


Metal Species in MLT Region

Species	Central wavelength (nm)	A_{ki} ($\times 10^8$ s^{-1})	Degeneracy g_k / g_i	Atomic Weight	Isotopes	Doppler rms Width (MHz)	σ_0 ($\times 10^{-12}$ cm^2)	Abundance ($\times 10^9$ cm^{-2})	Centroid Altitude (km)	Layer rms Width (km)
Na (D_2)	589.1583	0.616	4 / 2	22.98977	23	456.54	14.87	4.0	91.5	4.6
Fe	372.0993	0.163	11 / 9	55.845	54, 56, 57, 58	463.79	0.944	10.2	88.3	4.5
K (D_1)	770.1088	0.382	2 / 2	39.0983	39, 40, 41	267.90	13.42	4.5×10^{-2}	91.0	4.7
Ca	422.793	2.18	3 / 1	40.078	40, 42, 43, 44, 46, 48	481.96	38.48	3.4×10^{-2}	90.5	3.5
Ca^+	393.777	1.47	4 / 2	40.078	Same as Ca	517.87	13.94	7.2×10^{-2}	95.0	3.6

- In principle, all these species can be used as tracer atoms for resonance fluorescence Doppler lidar measurements.
- Whether a Doppler lidar can be developed and used mainly depends on whether the laser and electro-optic technologies are available and ready.

Na Atomic Energy Levels



Energy Level Diagram of Atomic Na

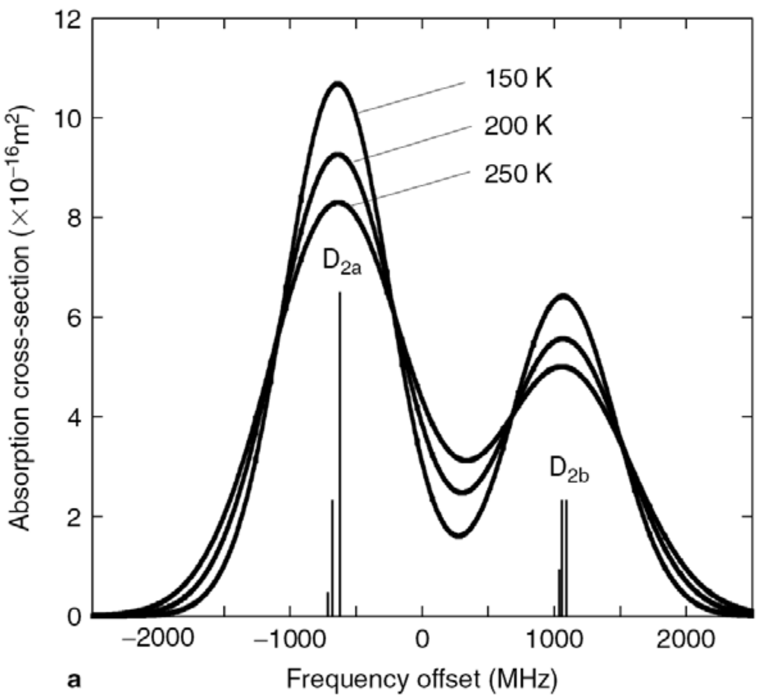


Table 5.1 Parameters of the Na D_1 and D_2 Transition Lines

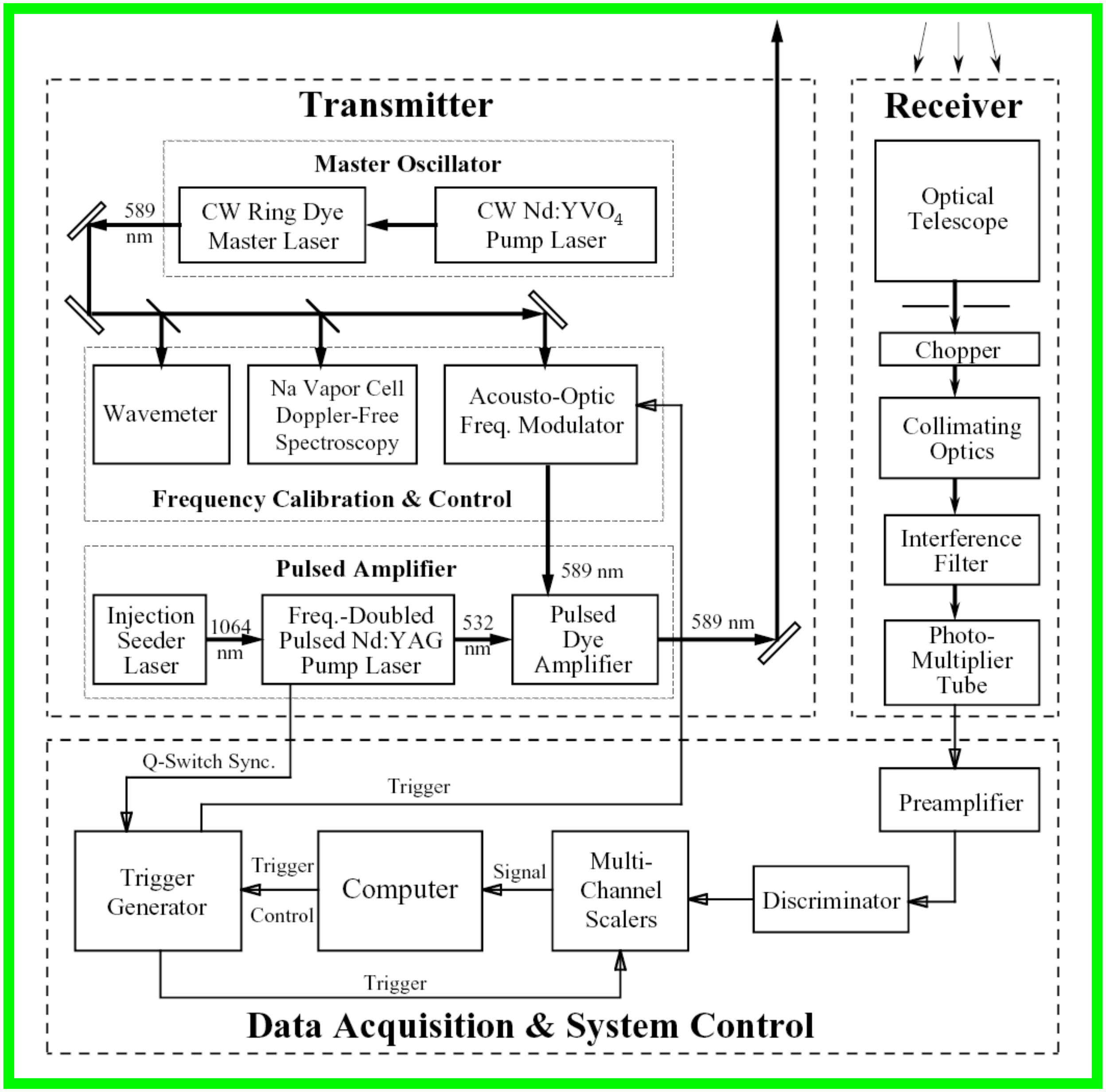
Transition Line	Central Wavelength (nm)	Transition Probability ($10^8\ s^{-1}$)	Radiative Lifetime (nsec)	Oscillator Strength f_{ik}
D_1 ($^2P_{1/2} \rightarrow {^2S_{1/2}}$)	589.7558	0.614	16.29	0.320
D_2 ($^2P_{3/2} \rightarrow {^2S_{1/2}}$)	589.1583	0.616	16.23	0.641

Group	$^2S_{1/2}$	$^2P_{3/2}$	Offset (GHz)	Relative Line Strength[a]
D_{2b}	$F=1$	$F=2$	1.0911	5/32
		$F=1$	1.0566	5/32
		$F=0$	1.0408	2/32
D_{2a}	$F=2$	$F=3$	−0.6216	14/32
		$F=2$	−0.6806	5/32
		$F=1$	−0.7150	1/32

Doppler-Free Saturation–Absorption Features of the Na D_2 Line

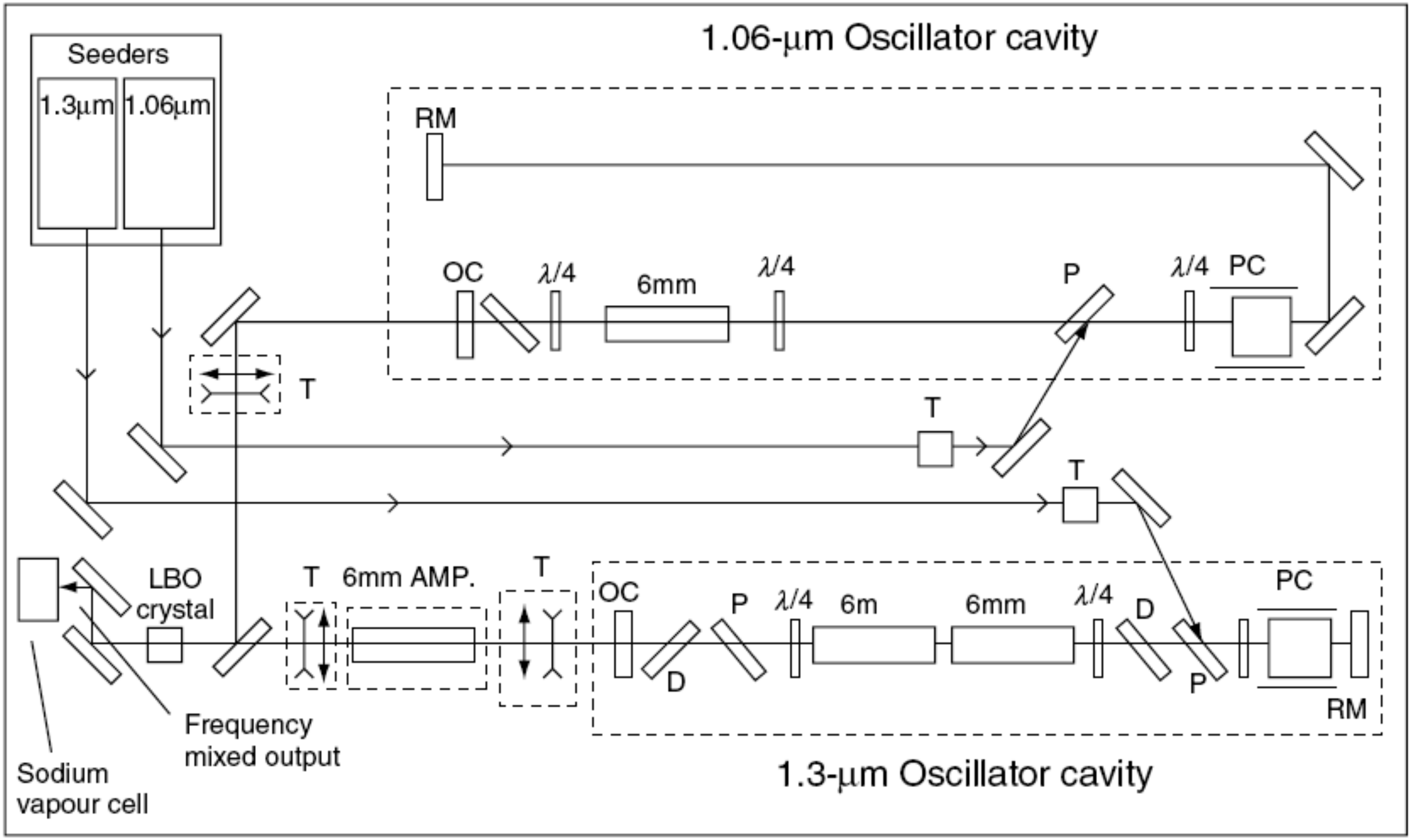
f_a (MHz)	f_c (MHz)	f_b (MHz)	f_+ (MHz)	f_- (MHz)
−651.4	187.8	1067.8	−21.4	−1281.4

Na Doppler Lidar: Conventional



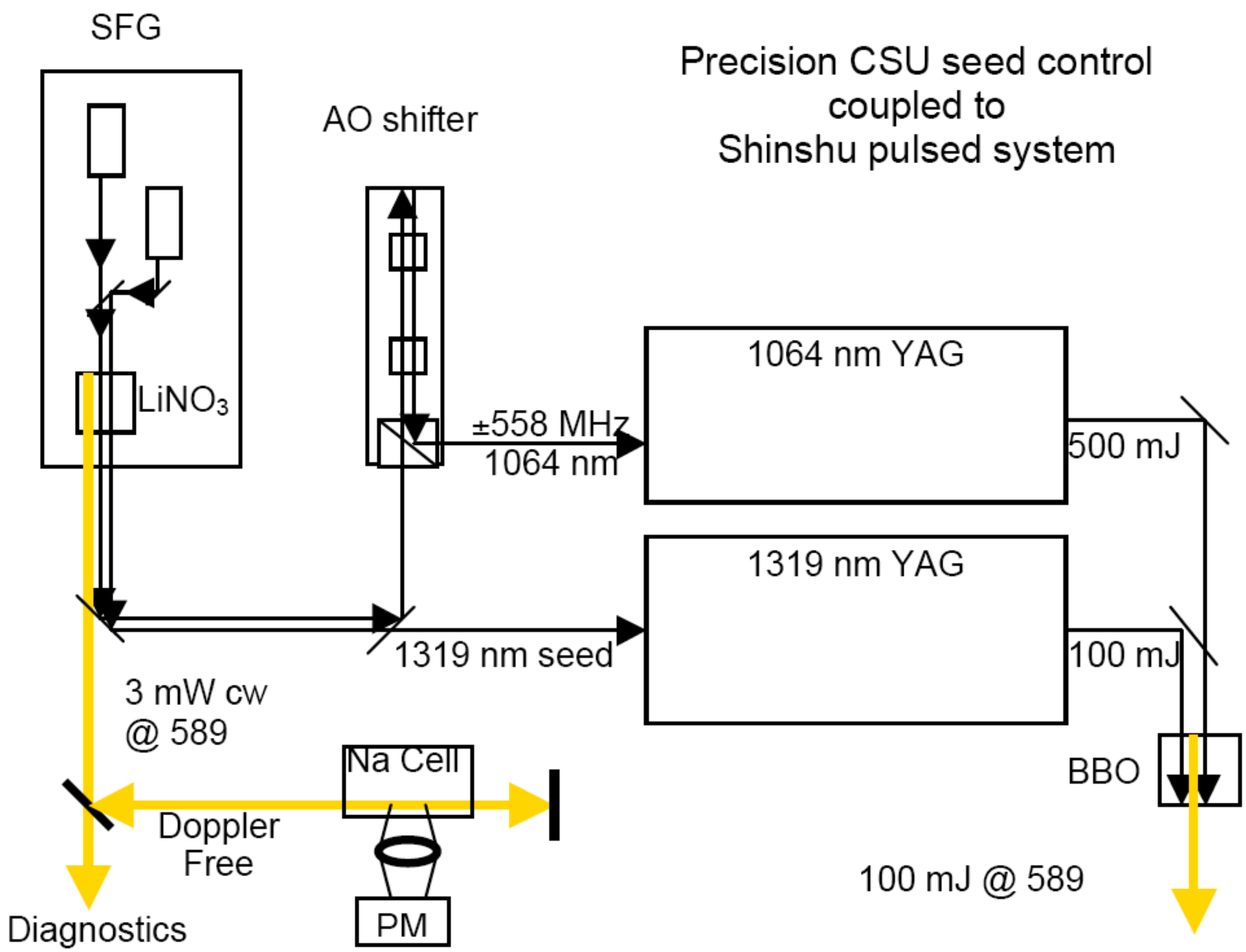
Na Doppler Lidar: Solid-State

- Japanese Shinshu system

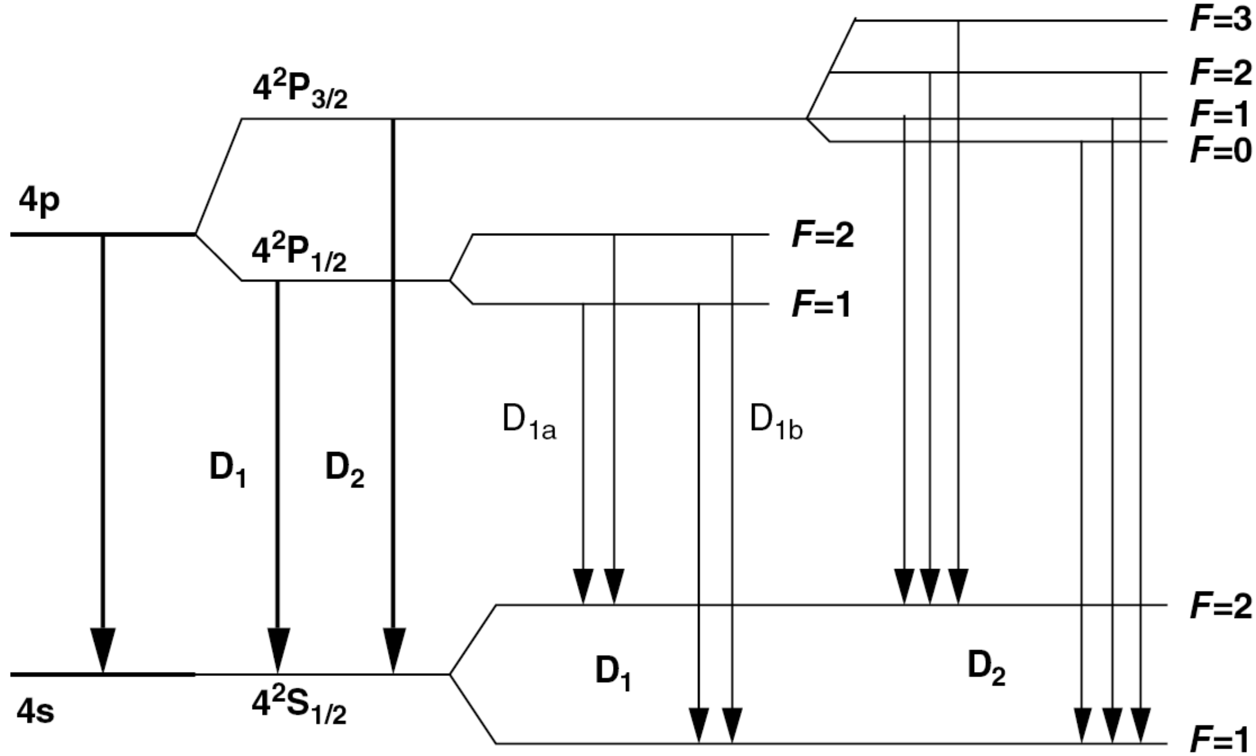


Na Doppler Lidar: Solid-State

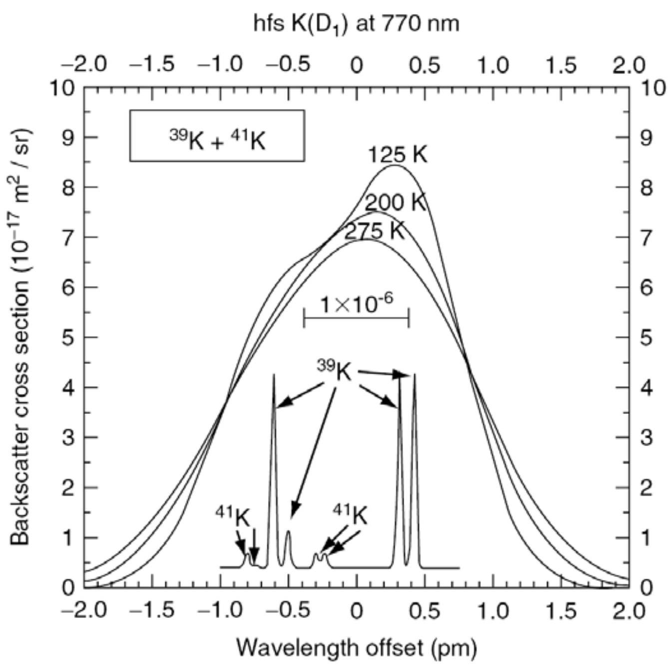
- CSU proposed system



K Atomic Energy Levels



K fine structure **K hyperfine structure**



Transition	$K(D_1)$	$K(D_2)$
Wavelength air [nm]	769.8974	766.4911
Wavelength vacuum [nm]	770.1093	766.7021
Rel. intensity	24	25
A_{ik} $[10^8 s^{-1}]$	0.382 (±10%)	0.387 (±10%)
f-value	0.340	0.682
Terms $^{2S+1}L_J$	$^2S_{1/2} - ^2P^o_{1/2}$	$^2S_{1/2} - ^2P^o_{3/2}$
$g_i - g_k$	2-2	2-4

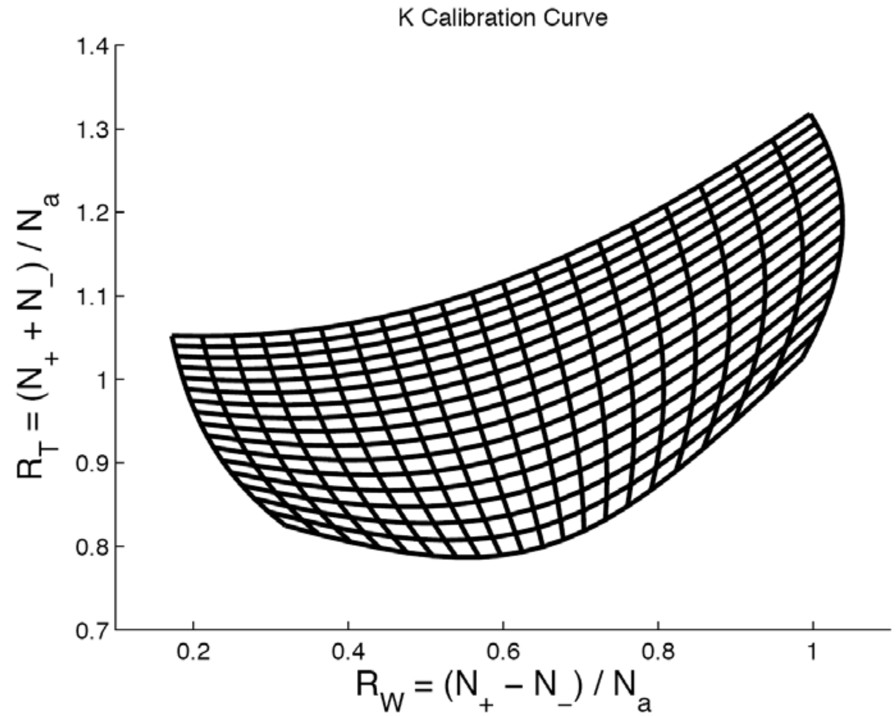
K Atomic Parameters

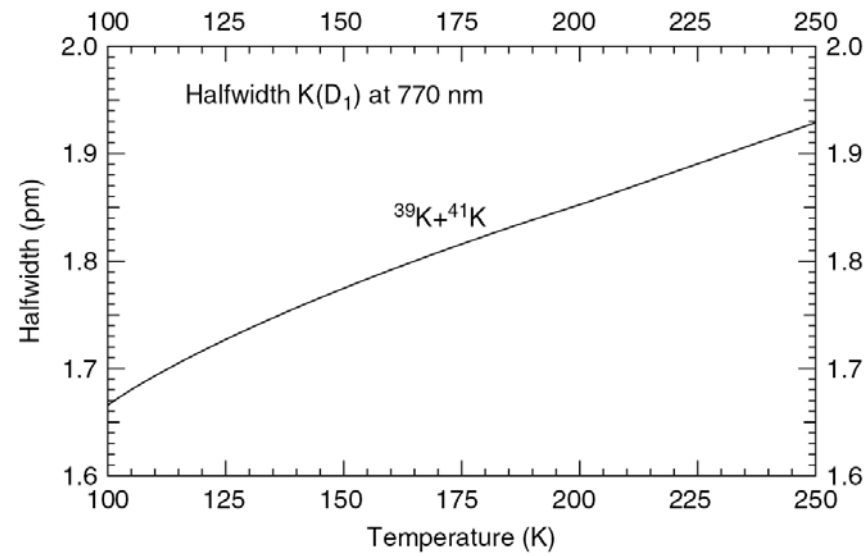
Isotope	Atomic mass	Abundance	Nuclear spin	$K(D_1)$ line shift
39	38.963 706 9(3)	0.932 581(44)	$I = 3/2$	0
40	39.963 998 67(29)	0.000 117(1)	$I = 4$	125.58 MHz
41	40.961 825 97(28)	0.067 302(44)	$I = 3/2$	235.28 MHz

Table 5.8 Quantum Numbers, Frequency Offsets, and Relative Line Strength for K (D_1) Hyperfine Structure Lines

$^2S_{1/2}$	$^2P_{1/2}$	^{39}K (MHz)	^{41}K (MHz)	Relative Line Strength
$F = 1$	$F = 2$	310	405	5/16
	$F = 1$	254	375	1/16
$F = 2$	$F = 2$	−152	151	5/16
	$F = 1$	−208	121	5/16

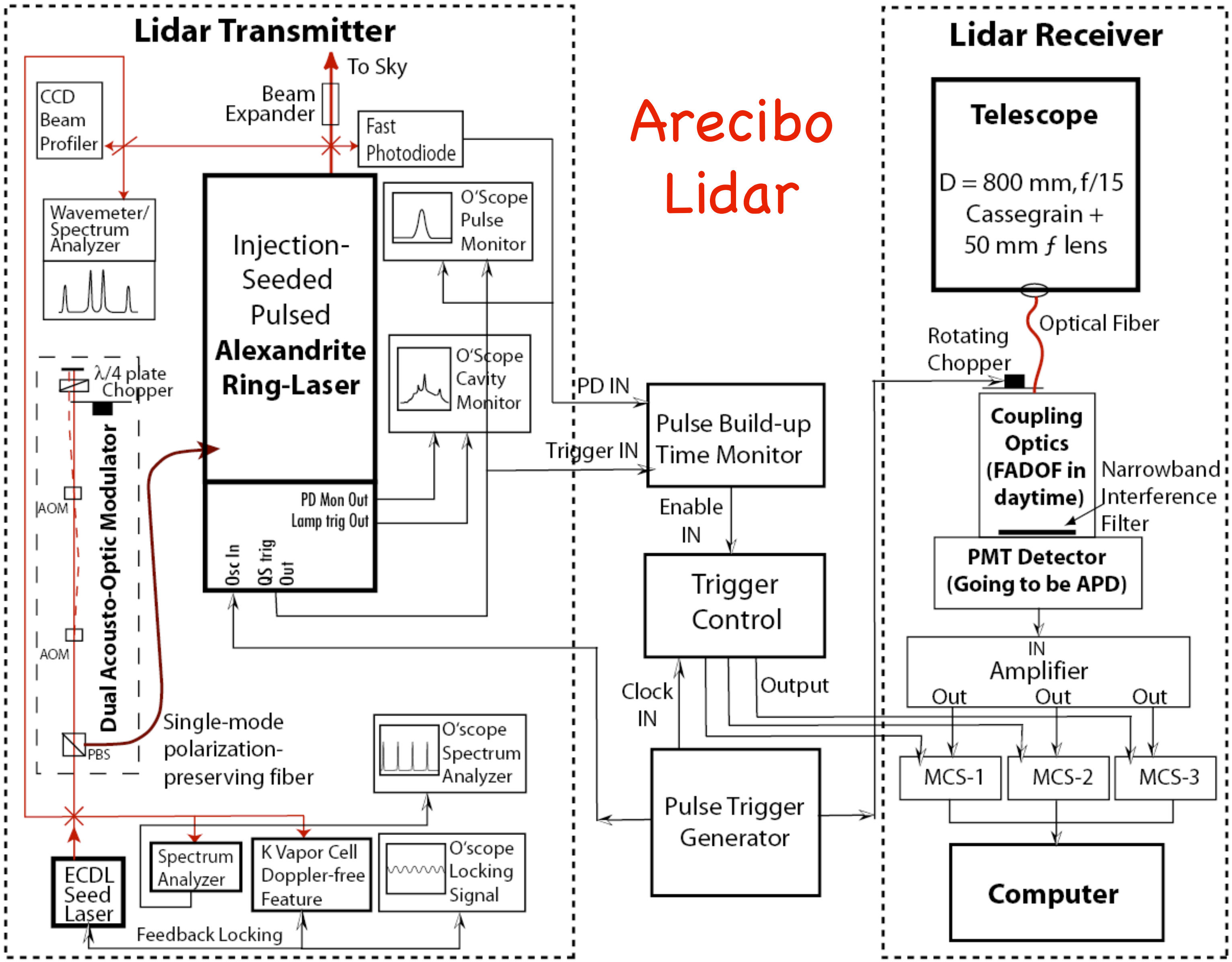
K Doppler Lidar Principle & Metrics





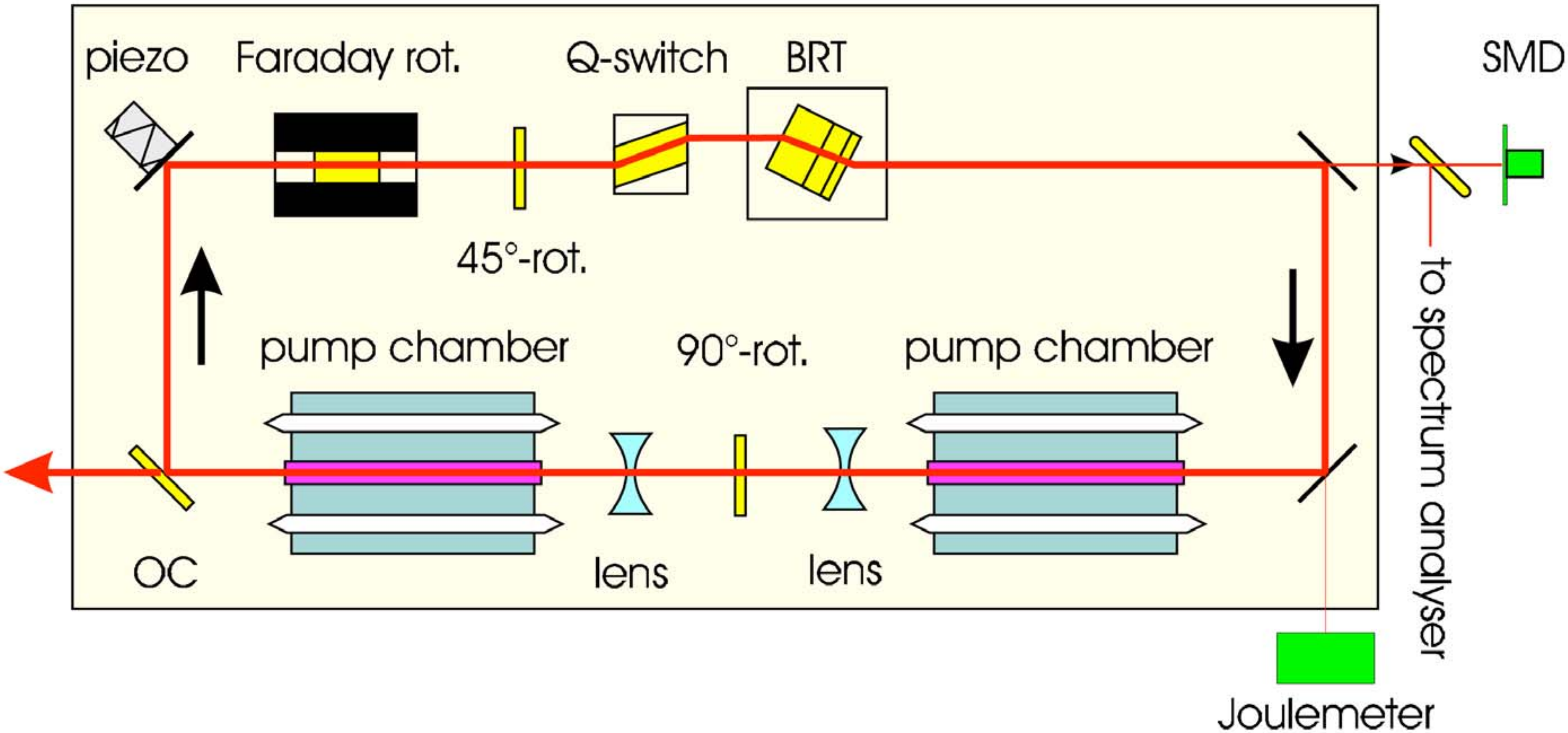
- ❑ Ratio technique versus scanning technique
- ❑ Scanning technique actually has its advantages on several aspects, depending on the laser system used – whether there is pedestal, background problems, etc.
- ❑ Ratio technique usually gives higher resolution.

K Doppler Lidar Instrumentation



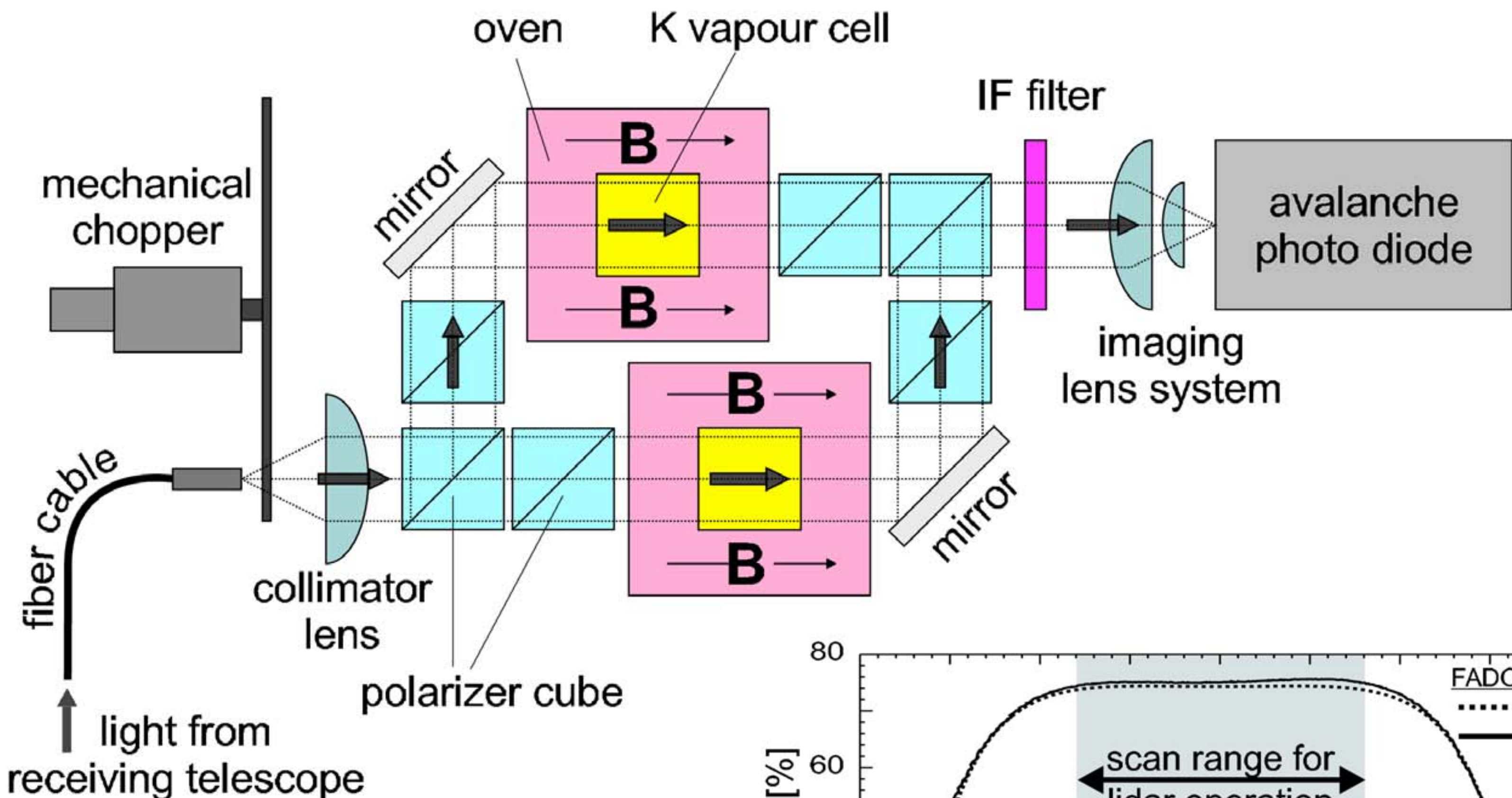
Arecibo Lidar

Alexandrite Ring Laser

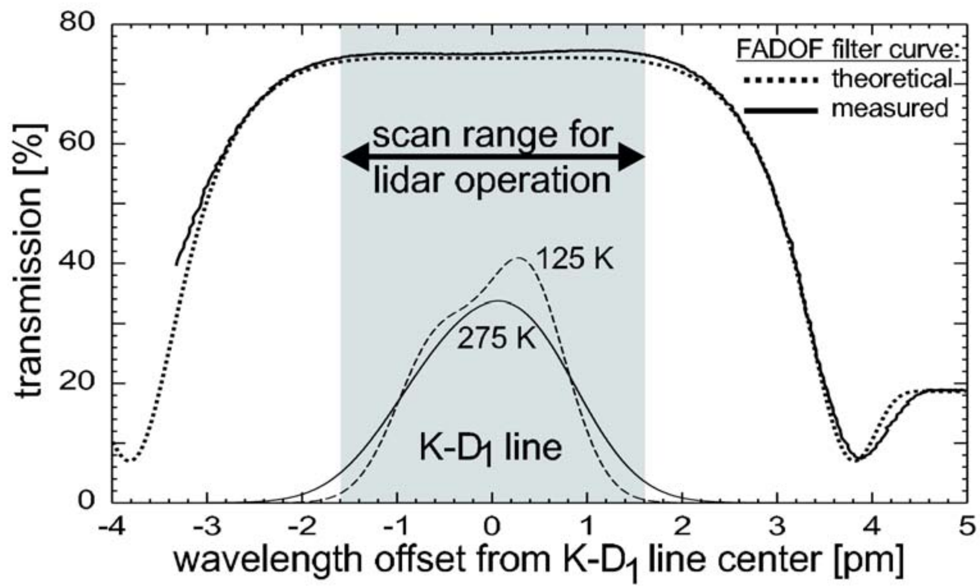


- The long pulse duration (>200 ns) allows the pulsed laser Doppler-free spectroscopy and frequency locking.
- This will enable us to achieve chirp-free / bias-free lidar.

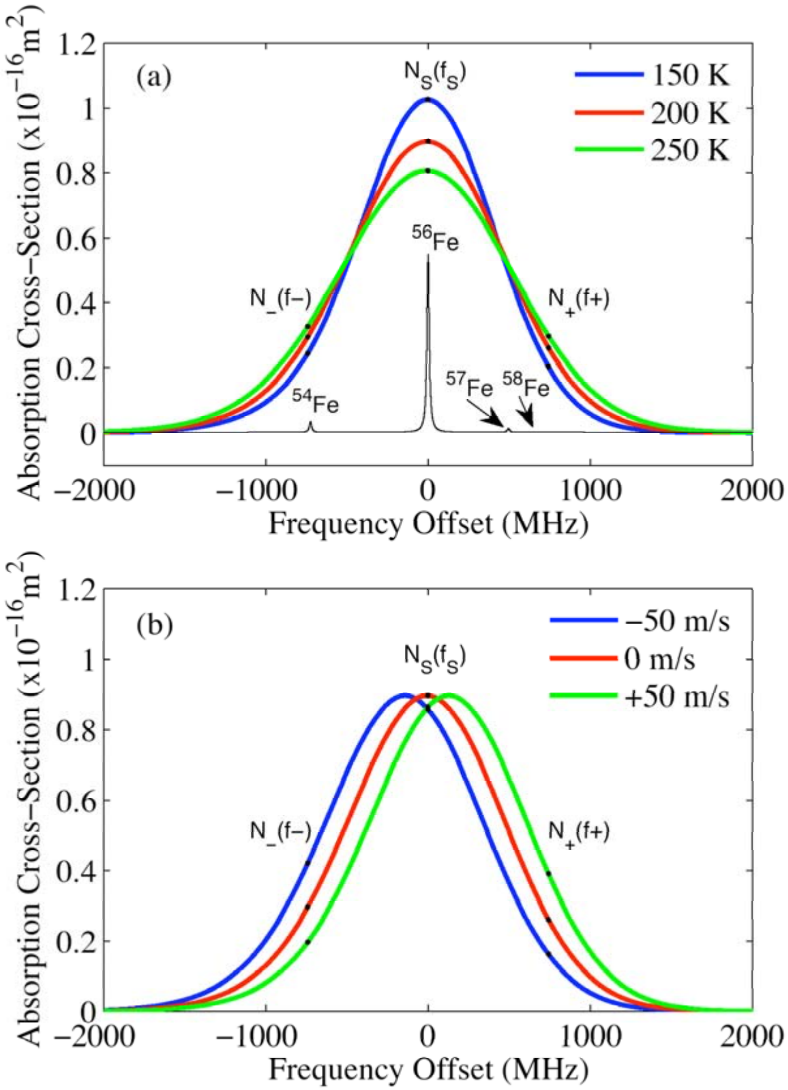
Dual K-Faraday Filter

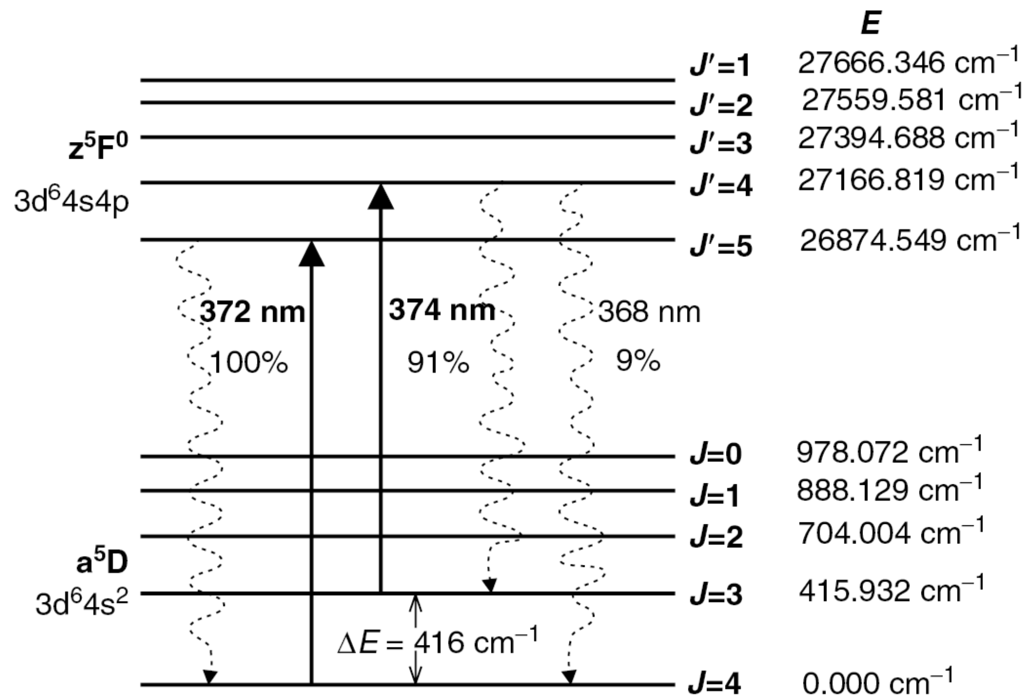


- Due to closer spacing of D_{1a} and D_{1b}, the K Faraday filter can be made nearly flat in the range we care.



Fe Atomic Energy Levels





Fe Atomic Parameters

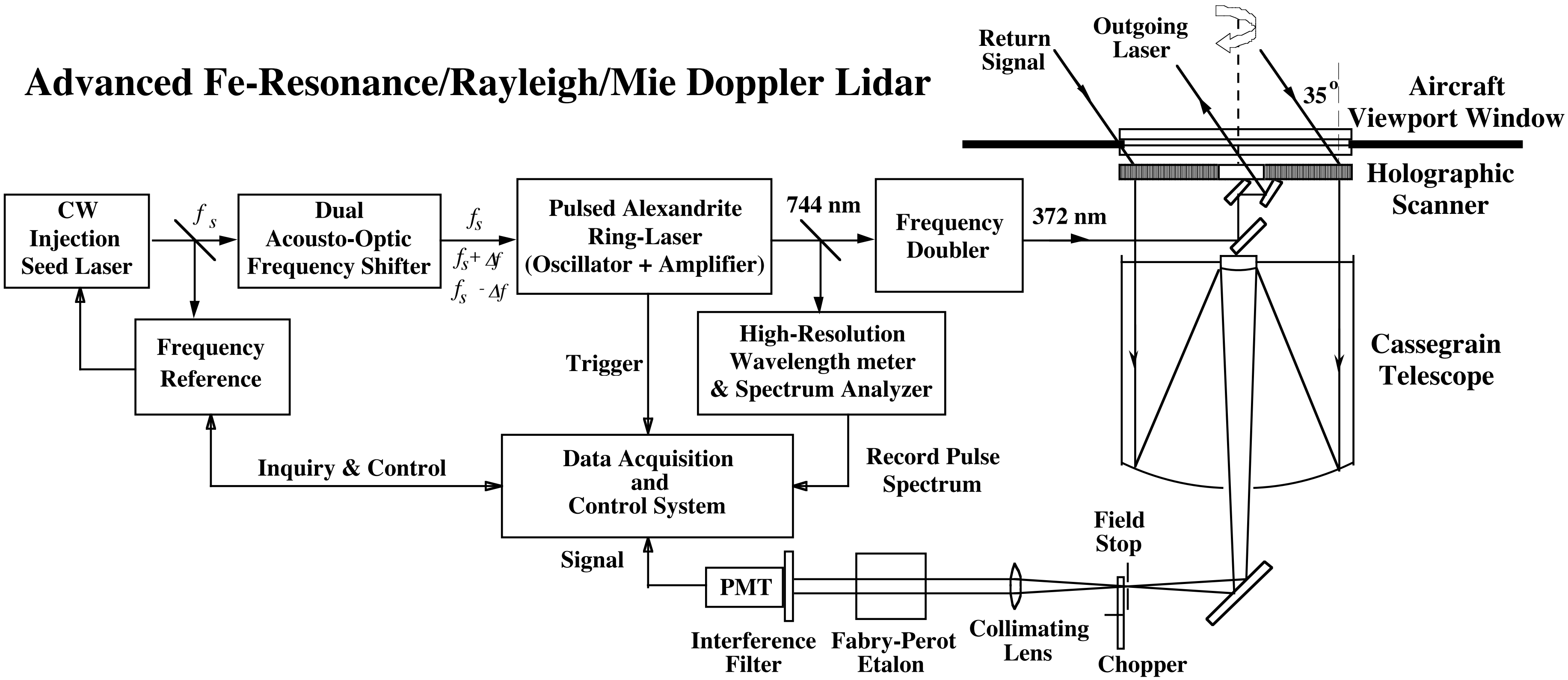
Table 5.3 Isotopic Data of Fe Atoms

	^{54}Fe	^{56}Fe	^{57}Fe	^{58}Fe
Z	26	26	26	26
A	54	56	57	58
Nuclear spin	0	0	1/2	0
Natural abundance	5.845%	91.754%	2.119%	0.282%

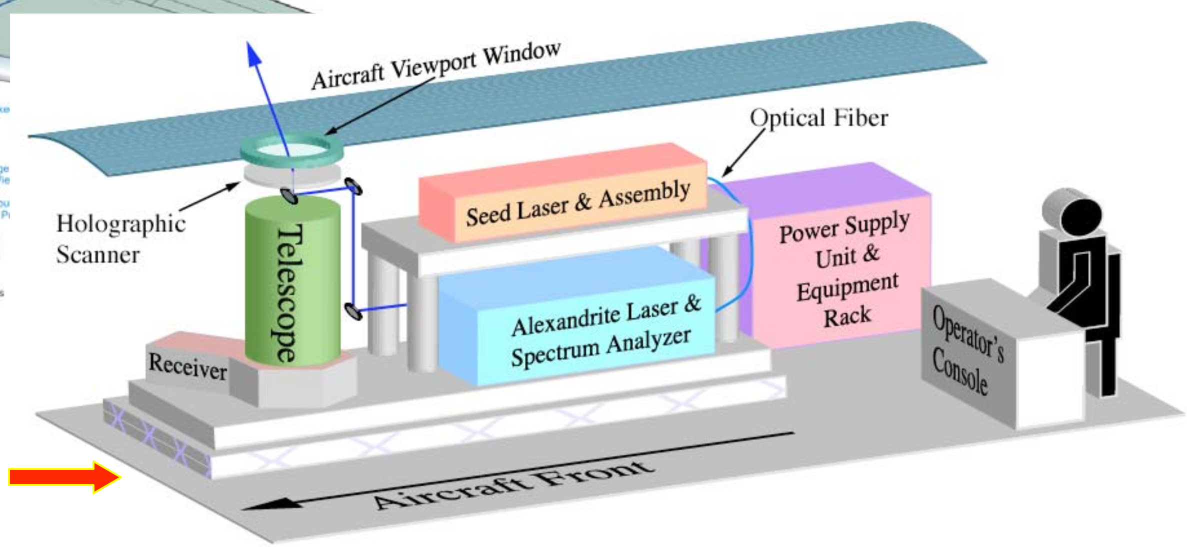
Table 5.4 Fe Resonance Line Parameters

Transition wavelength λ	372.0993 nm	373.8194 nm
Degeneracy for ground state	$g_1 = 9$	$g_2 = 7$
Degeneracy for excited state	$g_1' = 11$	$g_2' = 9$
Radiative lifetime of excited state (ns)	61.0	63.6
Einstein coefficient A_{ki} (10^8 s^{-1})	0.163	0.142
Oscillator strength f_{ik}	0.0413	0.0382
Branching ratio R_B	0.9959	0.9079
σ_0 (10^{-17} m^2)	9.4	8.7

Fe Doppler Lidar: Airborne

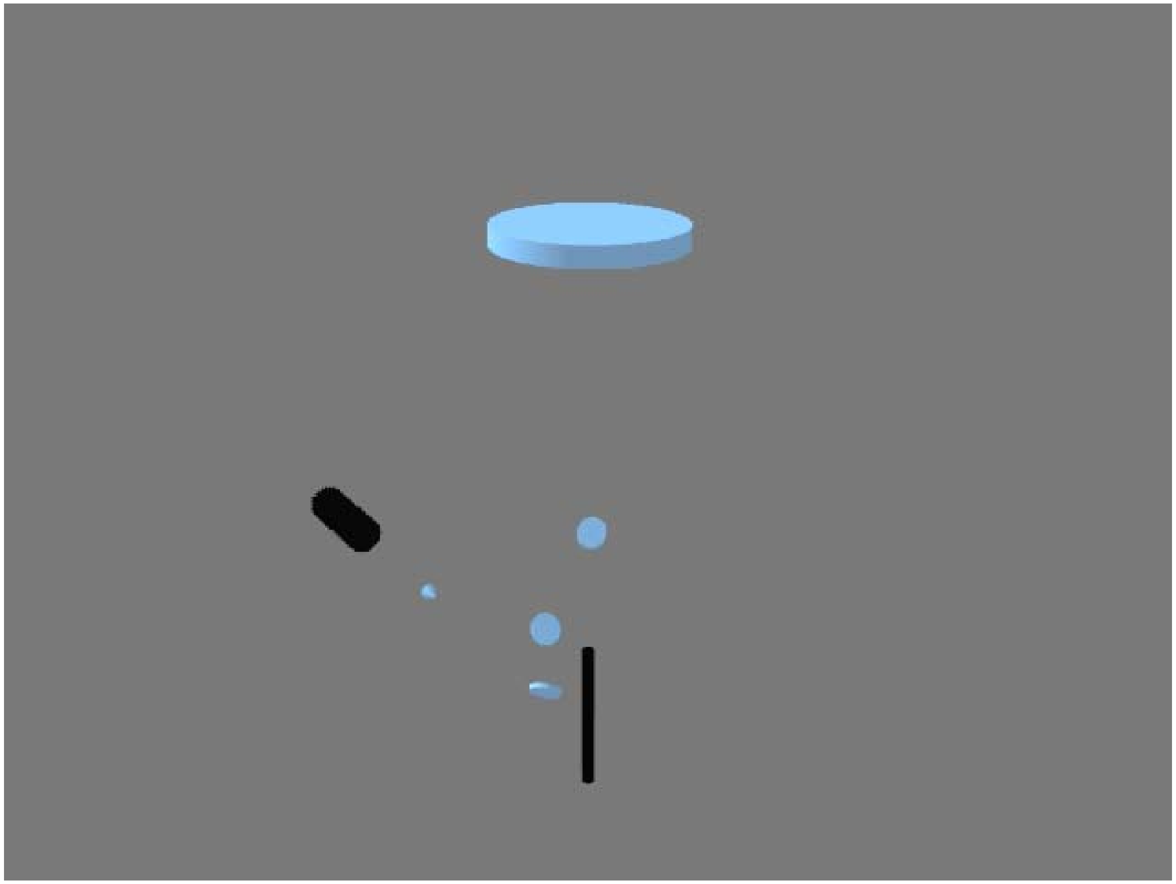


Fe Doppler Lidar: Airborne

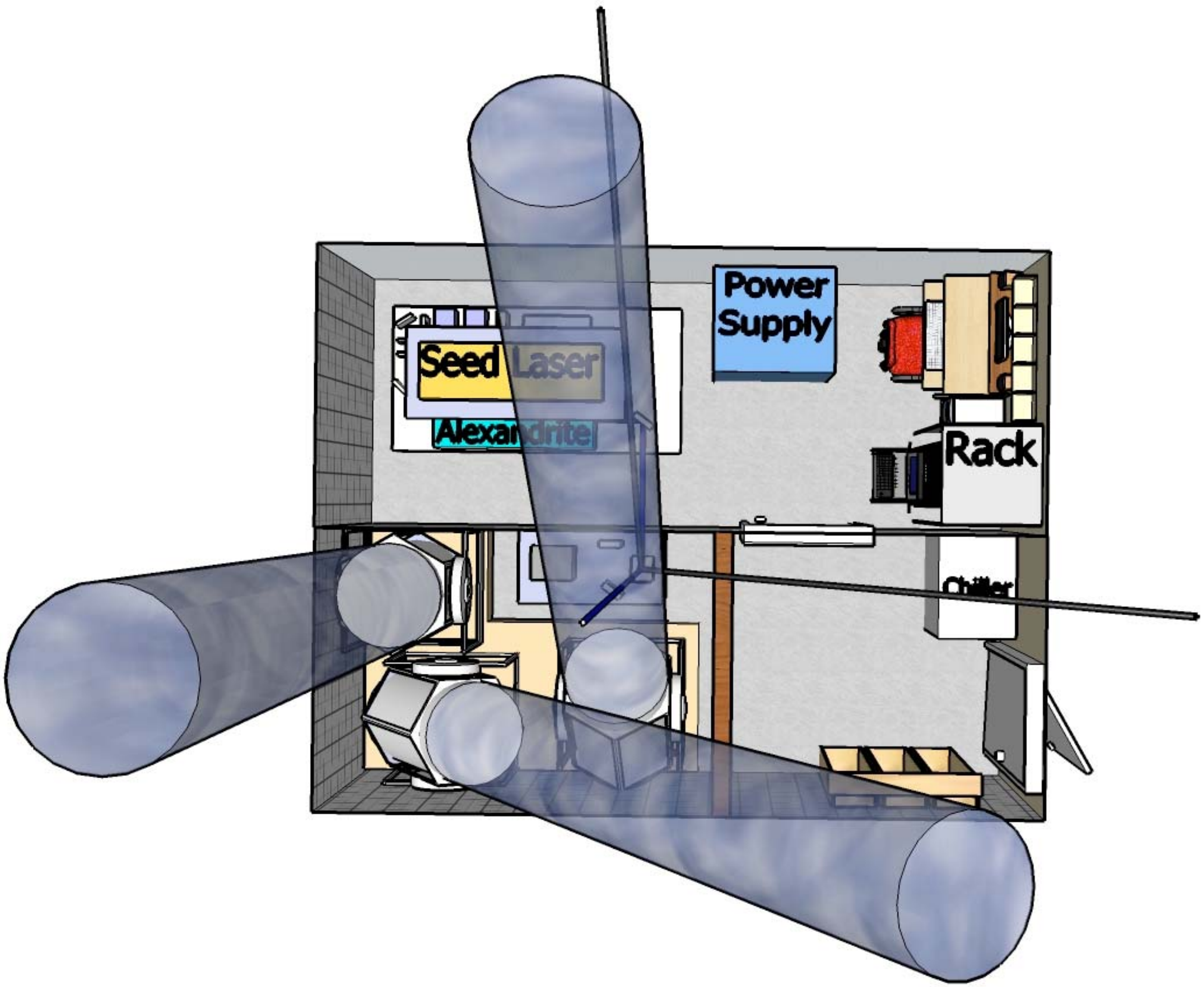


Proposed Doppler Lidar →

Holographic Scanning Telescope

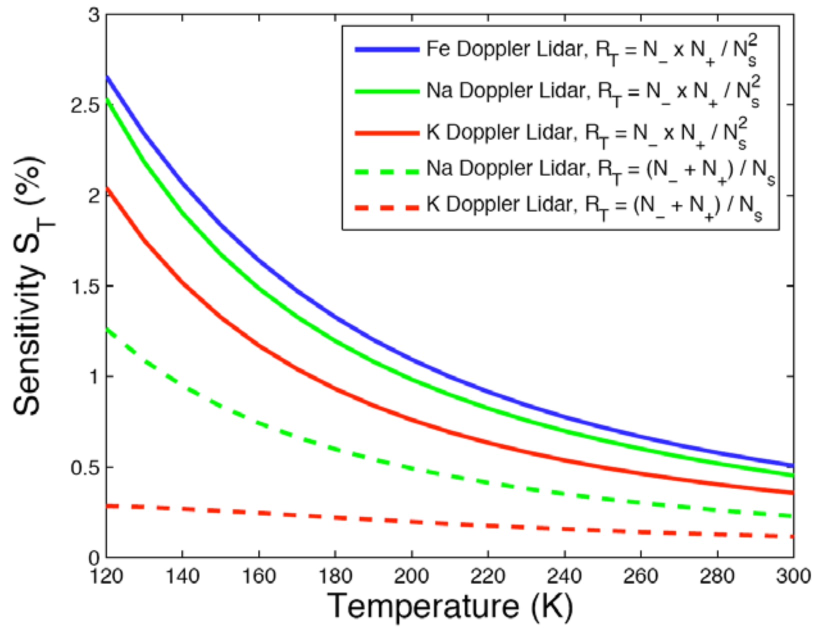


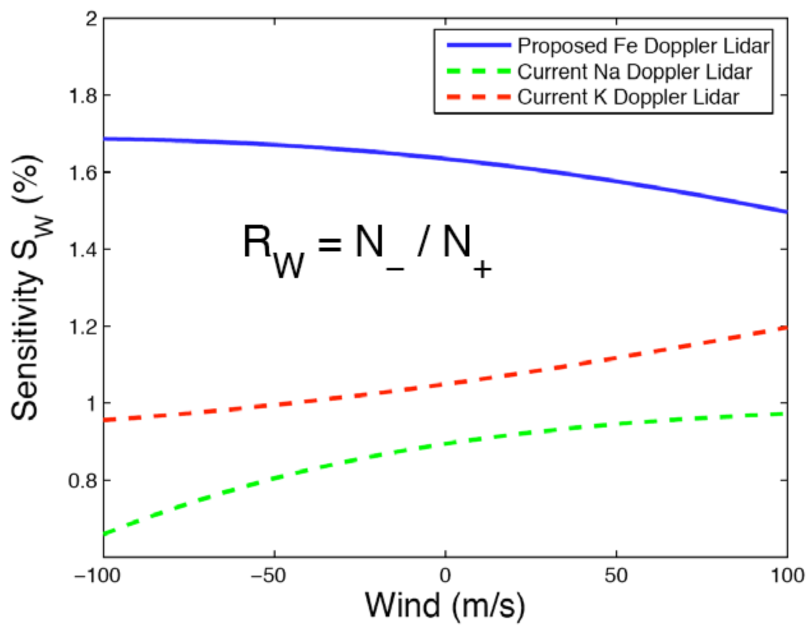
Fe Doppler Lidar: Containerized



Comparison of Na, K, Fe Doppler Lidars

- Sensitivity
- Signal-to-Noise Ratio (SNR) depends on atomic properties, geophysical parameters, and lidar system parameters.
- [Gardner et al., 2004] would be a good reference.





Summary

- There are several different atomic species originating from meteor ablation in the mesosphere and lower thermosphere (MLT) region. They all have the potentials to be tracers for resonance fluorescence Doppler lidars to measure the temperature and wind in MLT region.
- Na and K Doppler lidars are currently near mature status and making great contributions to MLT science.
- Fe Doppler lidar has very high future potential due to the high Fe abundance, advanced alexandrite laser technology, and potential pulsed laser Doppler-free spectroscopy, etc.
- Solid-state Doppler lidars are demanded for science advancement, although dye-laser-based Na Doppler lidar is still the golden standard for now.