Deuterium Lamp Calibrations at SURF III

CORM/CIE US & Canada National Committee 2021 Joint Conference

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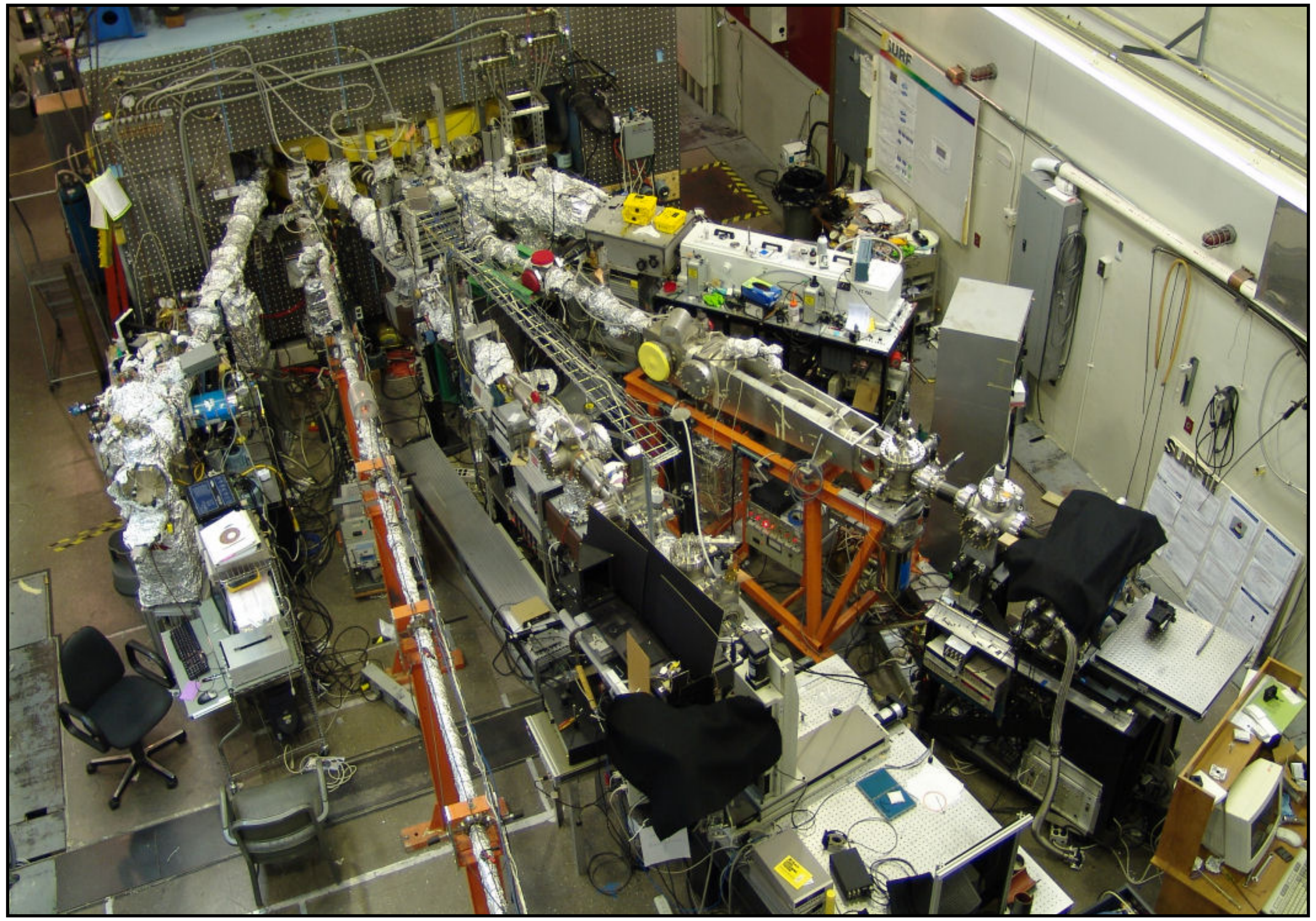
Special thanks to: Eric Shirley and Alex Farrell

What is a Deuterium Lamp?

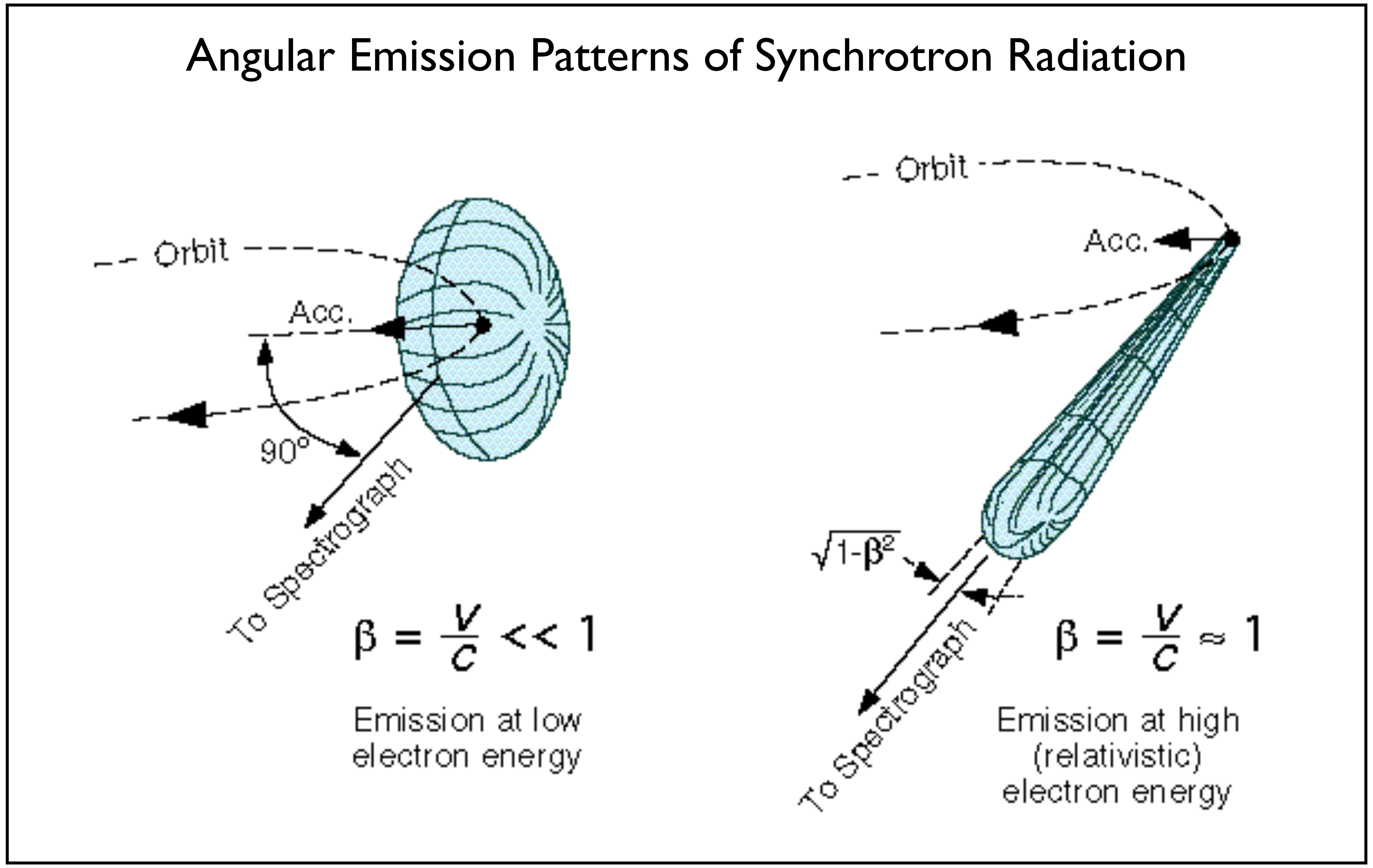
- It's just a typical arc discharge lamp.
- Emitting gas is deuterium, D_2, or “heavy hydrogen”
- Hydrogen and deuterium arcs have high UV (and VUV) emission with little infrared, making them excellent sources for UV systems.
- The UV emission is a molecular continuum with a few lines superimposed, but none of those fall into our 200 nm to 400 nm calibration range.
- D_2 arcs are more intense than H_2 arcs, so commercial lamps use D_2.

The Standard: Synchrotron Radiation

The SURF III synchrotron produces calculable radiation by storing a beam of electrons in a circular orbit. Emitted energy is replaced in an rf accelerating cavity.



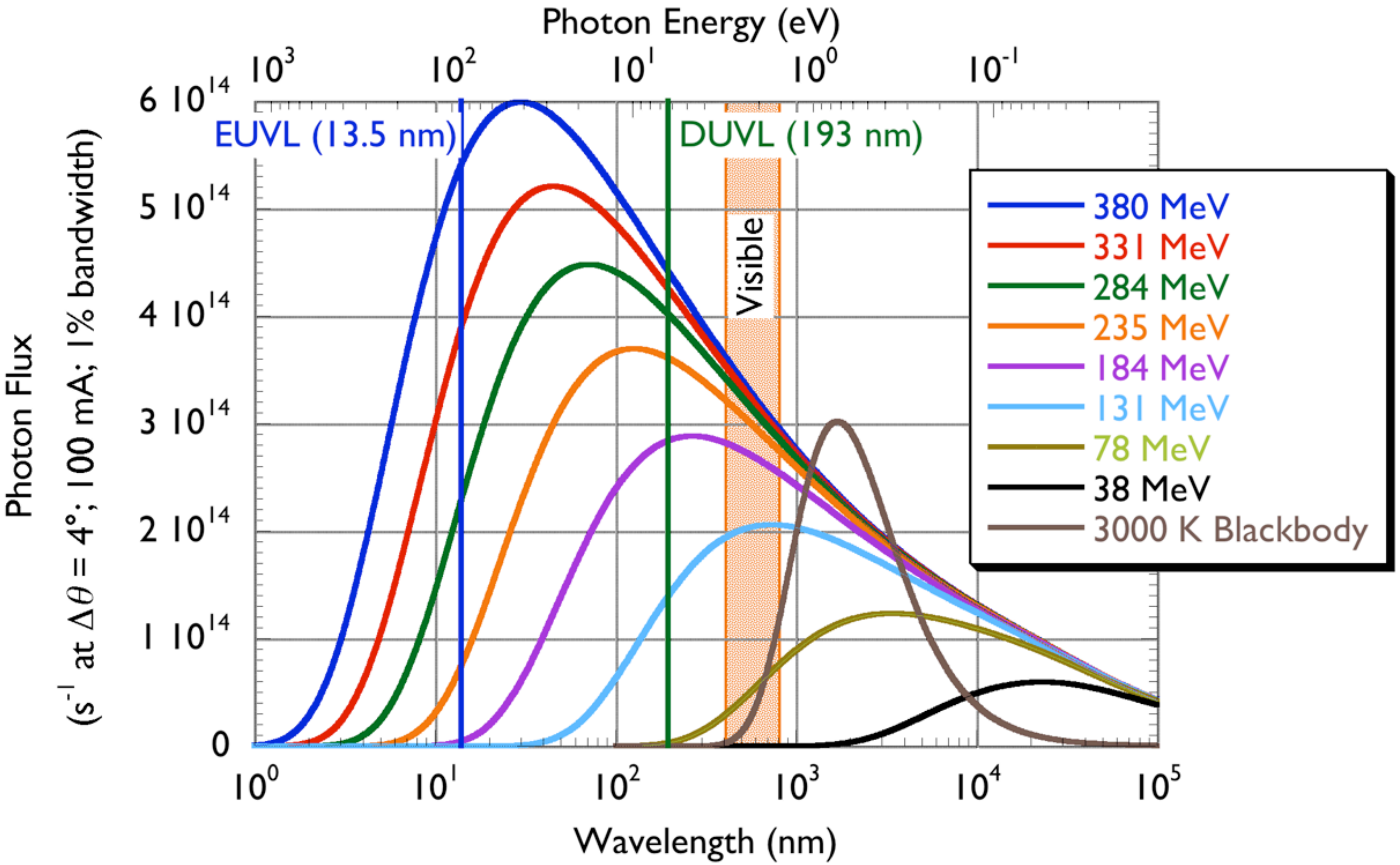
An orbiting electron undergoes acceleration and radiates according to Maxwell's equations. The emission must be corrected for relativistic effects.



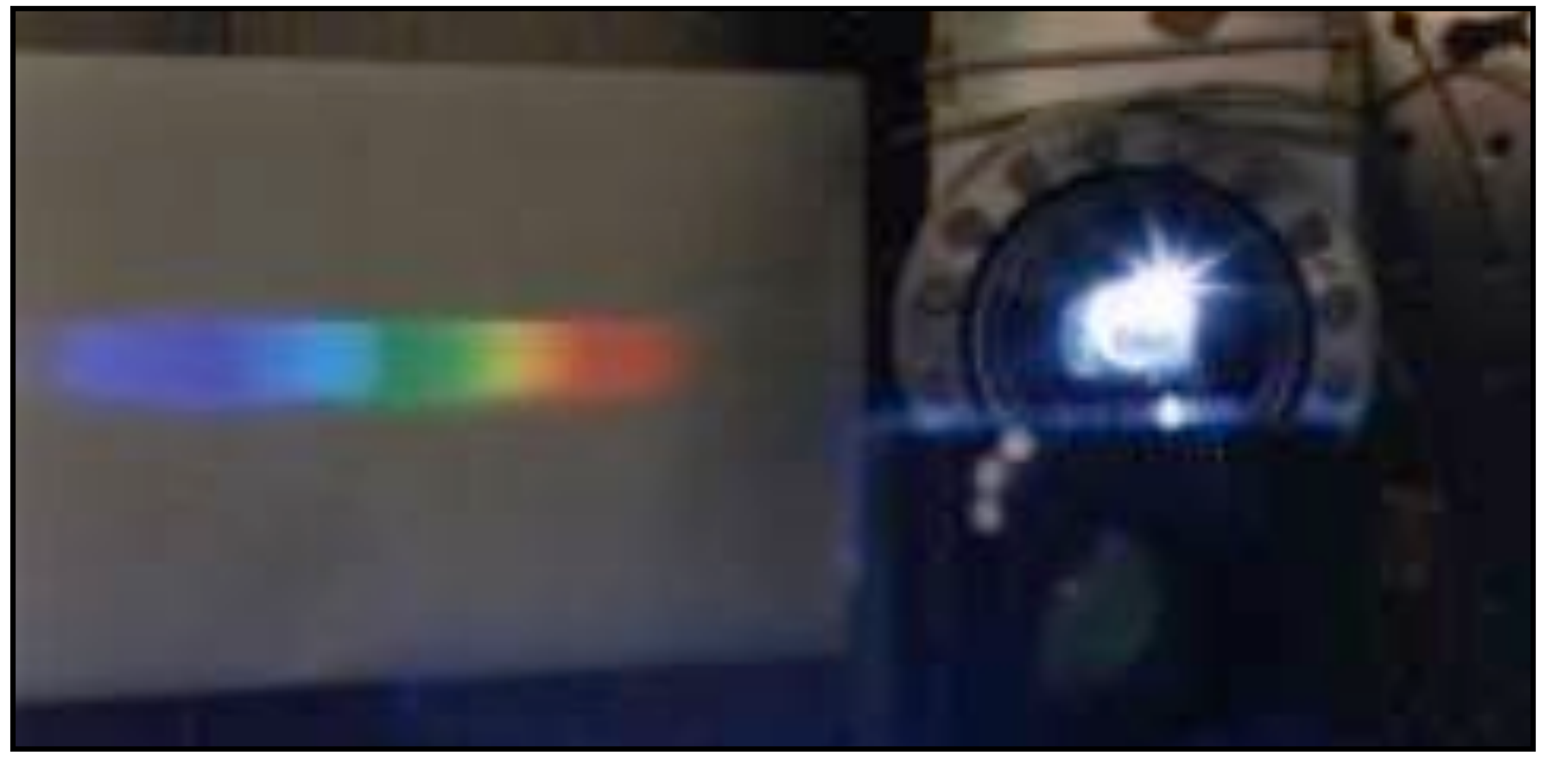
Properties of Synchrotron Radiation

- Spectral distribution of absolute irradiance on a known aperture can be calculated from first principles
  - Need to know:
    - any two of:
      a) electron energy
      b) bending radius
      c) magnetic field strength
    - Beam current (number of electrons)
  - Only other absolute source is blackbody radiator.
- Continuum source
- Linearly polarized in orbital plane
- Peak wavelength can be tuned by selecting the electron energy
- Essentially a cw source

Spectrum of Synchrotron Radiation



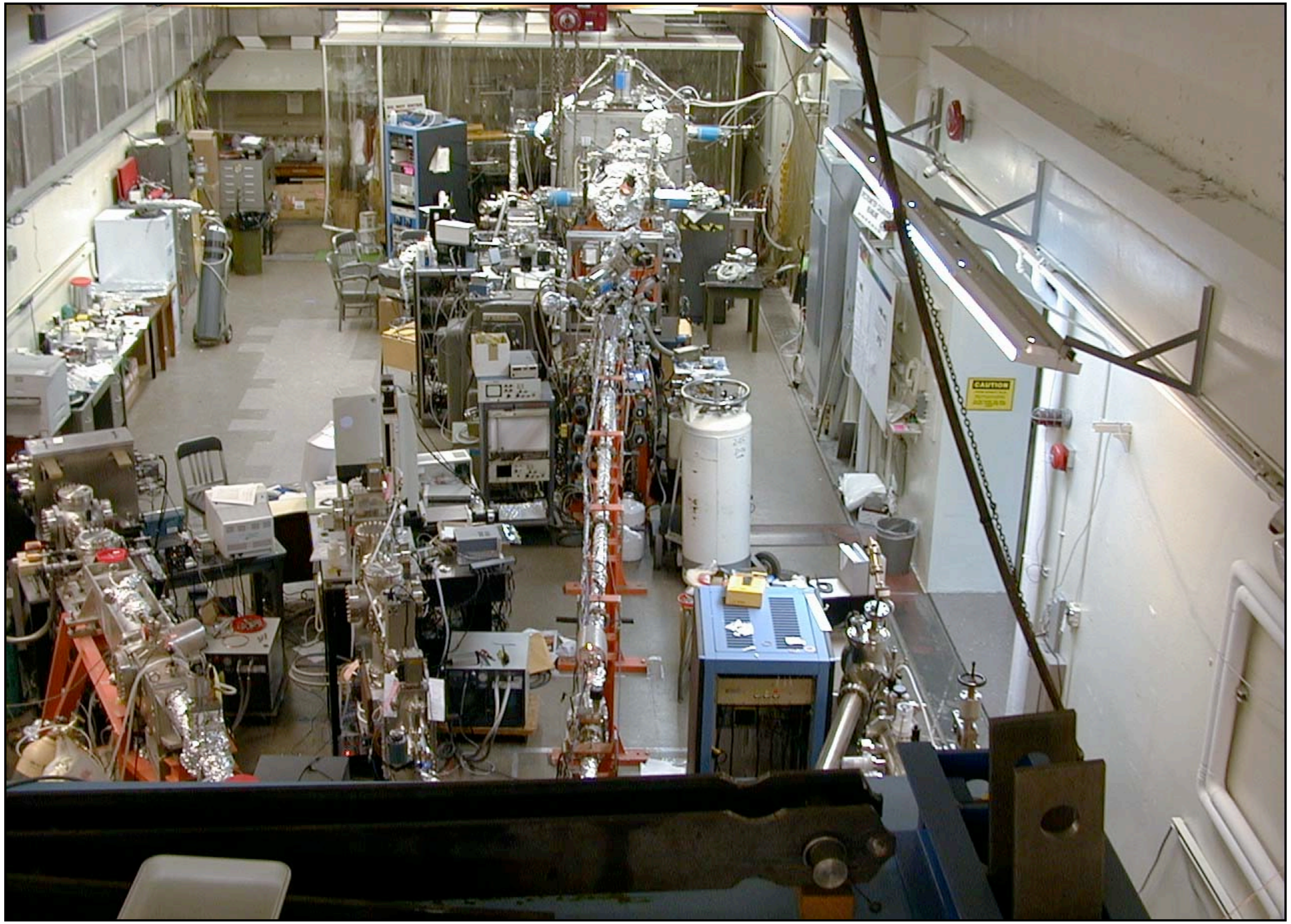
- Continuum source
- Broad-Band
- Peak wavelength is controlled by selecting electron energy
- Only practical, calculable source in the ultraviolet



Spectrometer Calibration Beamline: BL-2

BL-2 provides:

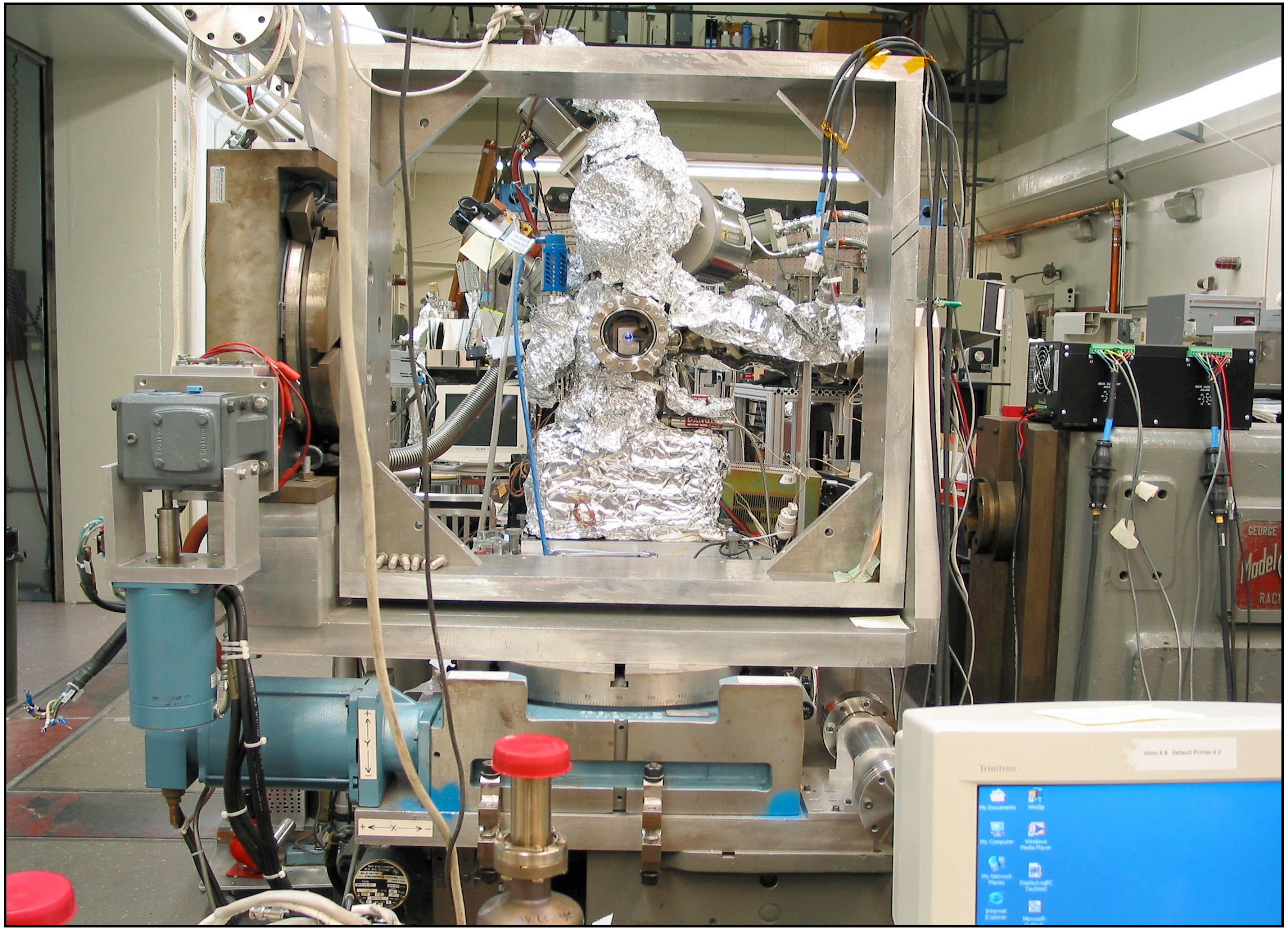
- undispersed synchrotron radiation
- calculable radiance and irradiance field
- linearly polarized (horizontal)



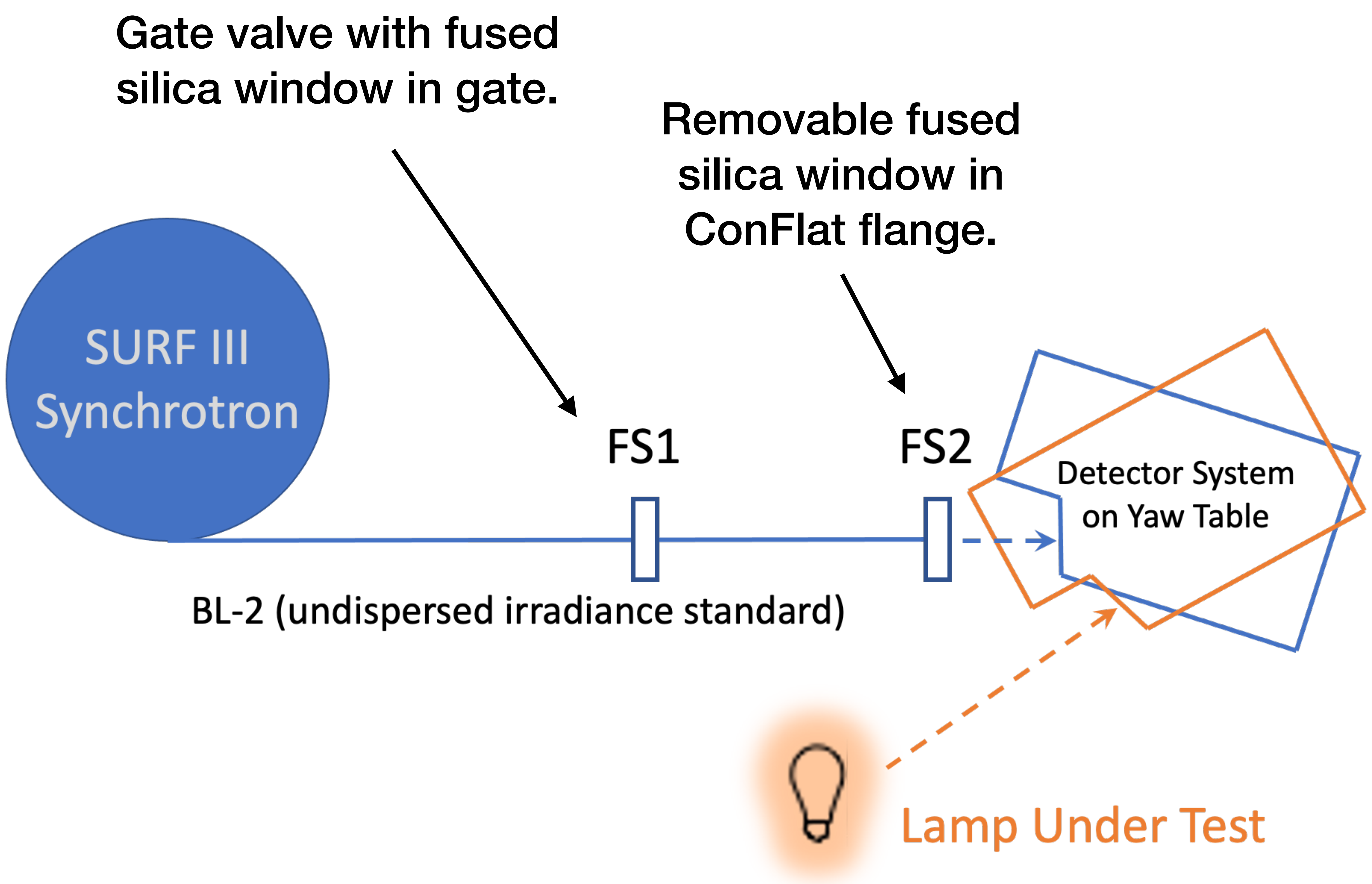
Spectrometer Calibration Beamline: BL-2

Milling Table:

- 4-axis motion stage
- Detector system mounts in the gimbals
- Milling table and gimbals allow alignment to synchrotron beam and selection of SURF or D_2 sample.



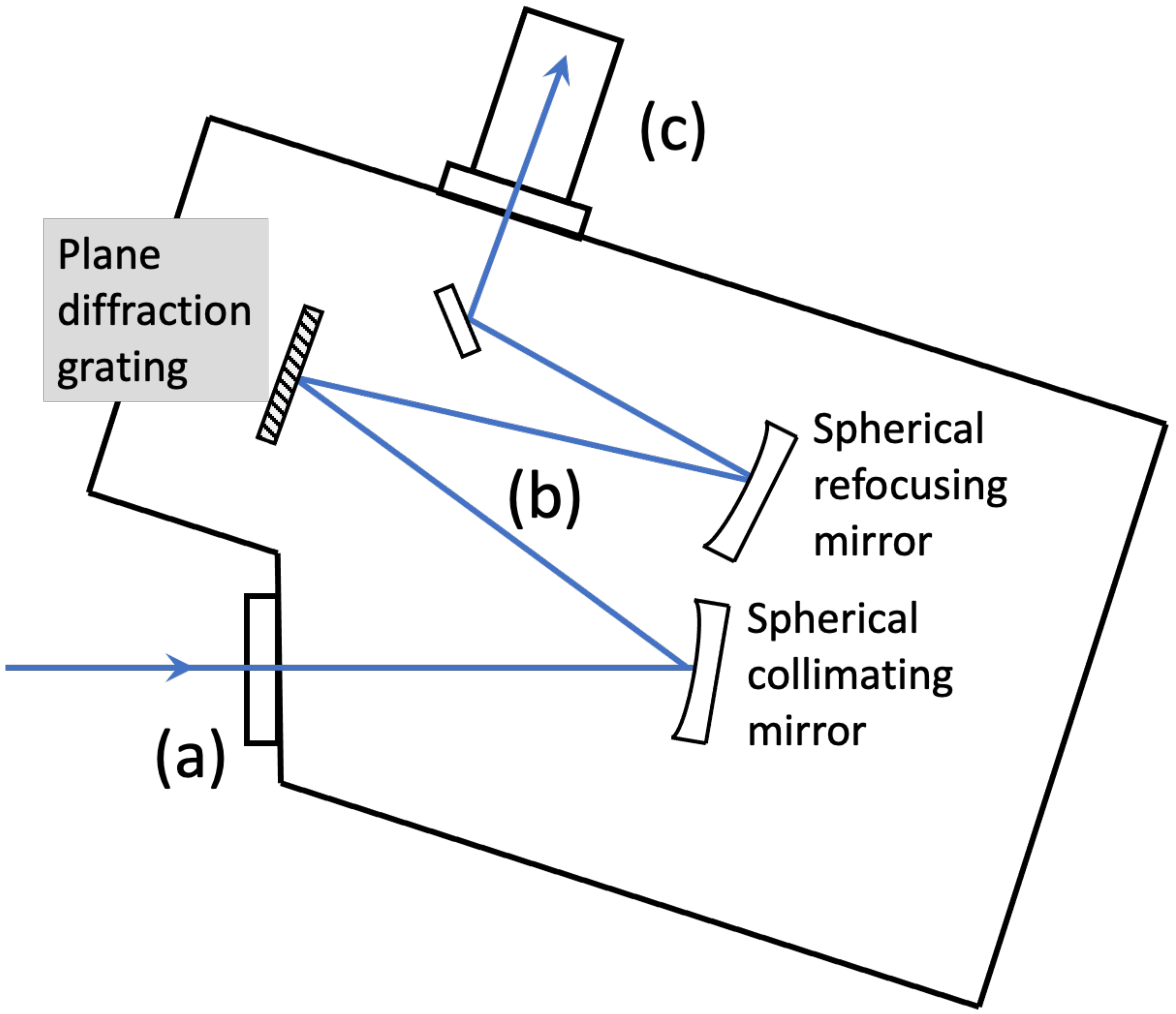
Calibration Concept: A Closer View



- Detector system is mounted to the gimbals on the milling table.
- Direct comparison is impossible without breaching the synchrotron vacuum system.
- Calibrate the detector responsivity by a multi-step process against the SURF BL-2 irradiance.
- Use that responsivity to determine the irradiance from the sample.

The "Detector”

- The “detector” is very complicated system with many pieces:
  - calibrated entrance aperture;
  - transmissive diffuser to depolarize the synchrotron radiation;
  - monochromator for wavelength selection;
  - Si photodiode for light detection; and
  - fixed-gain transimpedance amplifier 3×10^{10} V / A to generate voltage signal.



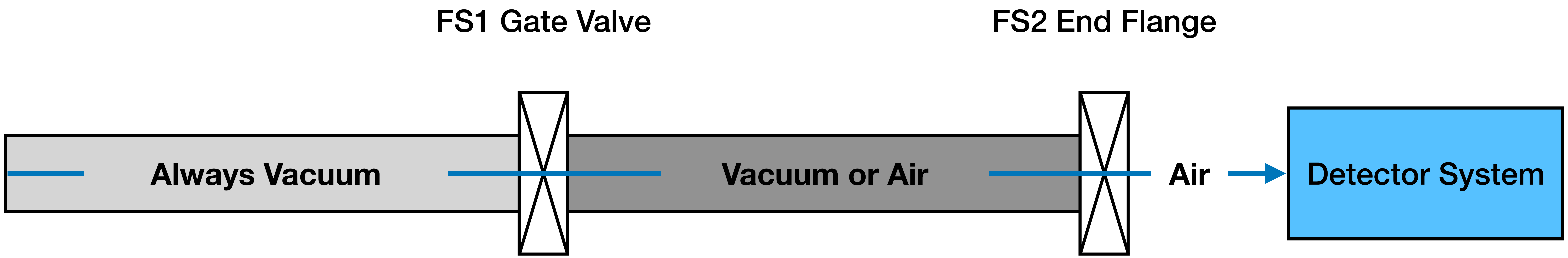
Detector Stability

- The detector must be stable over about a day to make this calibration work.

- It is nice if it is stable for longer, so you do not have to recalibrate it every day.

- It took a lot of work to stabilize our detector:
  - custom-built, low-noise amplifier runs on a battery instead of a switching power supply;
  - added a 2.54-cm thick Al plate to the base of the monochromator to reduce thermal gradients across the instrument, increase thermal mass, and improve thermal coupling to the room;
  - removed heat sources (*i.e.* power supplies) from the interior of the monochromator;
  - added building around the SURF experimental floor – the new D-wing addition to Bldg. 245 means the thin roll-up door is no longer the boundary between BL-2 and the unconditioned world outside.

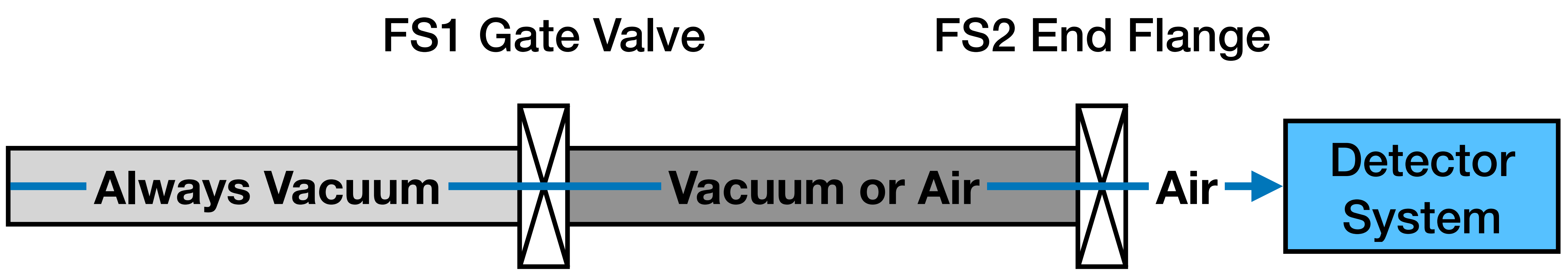
Calibration of Detector

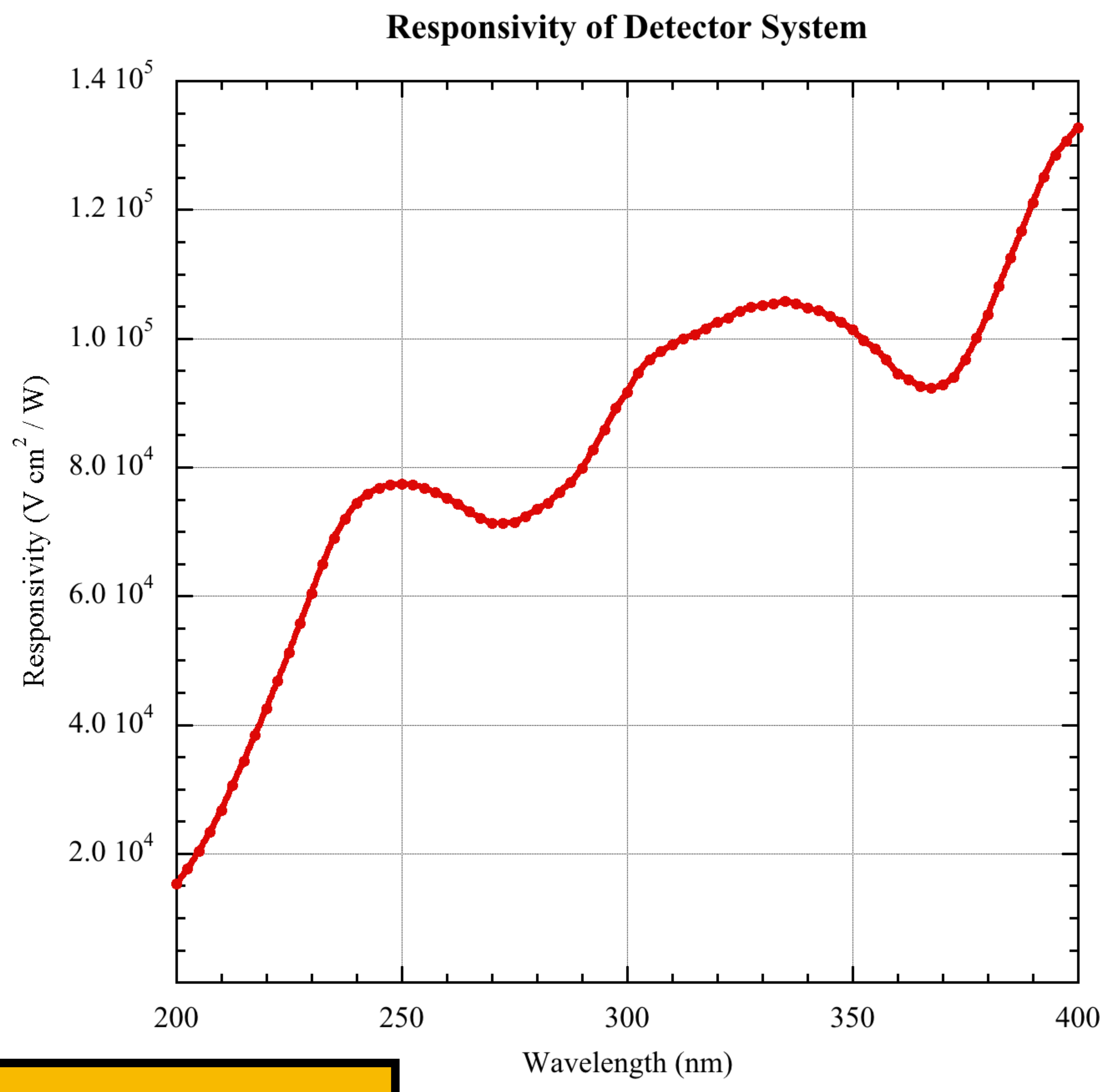


Calibrate the detector under four different conditions:

- η_2: FS1 open; FS2 on (beamline section must be under vacuum)
- $\eta_{1,2}^{vac}$: FS1 closed; FS2 on; Beamline section under vacuum
- $\eta_{1,2}^{air}$: FS1 closed; FS2 on; Beamline section vented
- η_1: FS1 closed; FS2 off (beamline section must be vented)

Calibration of Detector





What we really want, though, is none of these: the responsivity with both FS1 open and FS2 off, but that breaches the SURF vacuum!

- $\eta_2 = T_2 \times \eta_0$
- $\eta_{1,2}^{vac} = \left(T_1\ T_2\right) \times \eta_0$
- $\eta_{1,2}^{air} = \left(T_1\ T_2\ T_{air}\right) \times \eta_0$
- $\eta_1 = \left(T_1\ T_{air}\right) \times \eta_0$

$$\frac{\eta_1\ \eta_2}{\eta_{1,2}^{air}} = \frac{\left(T_1\ T_{air}\right)\eta_0\ \left(T_2\right)\eta_0}{\left(T_1\ T_2\ T_{air}\right)\eta_0} = \eta_0$$

Valuable System Characteristics

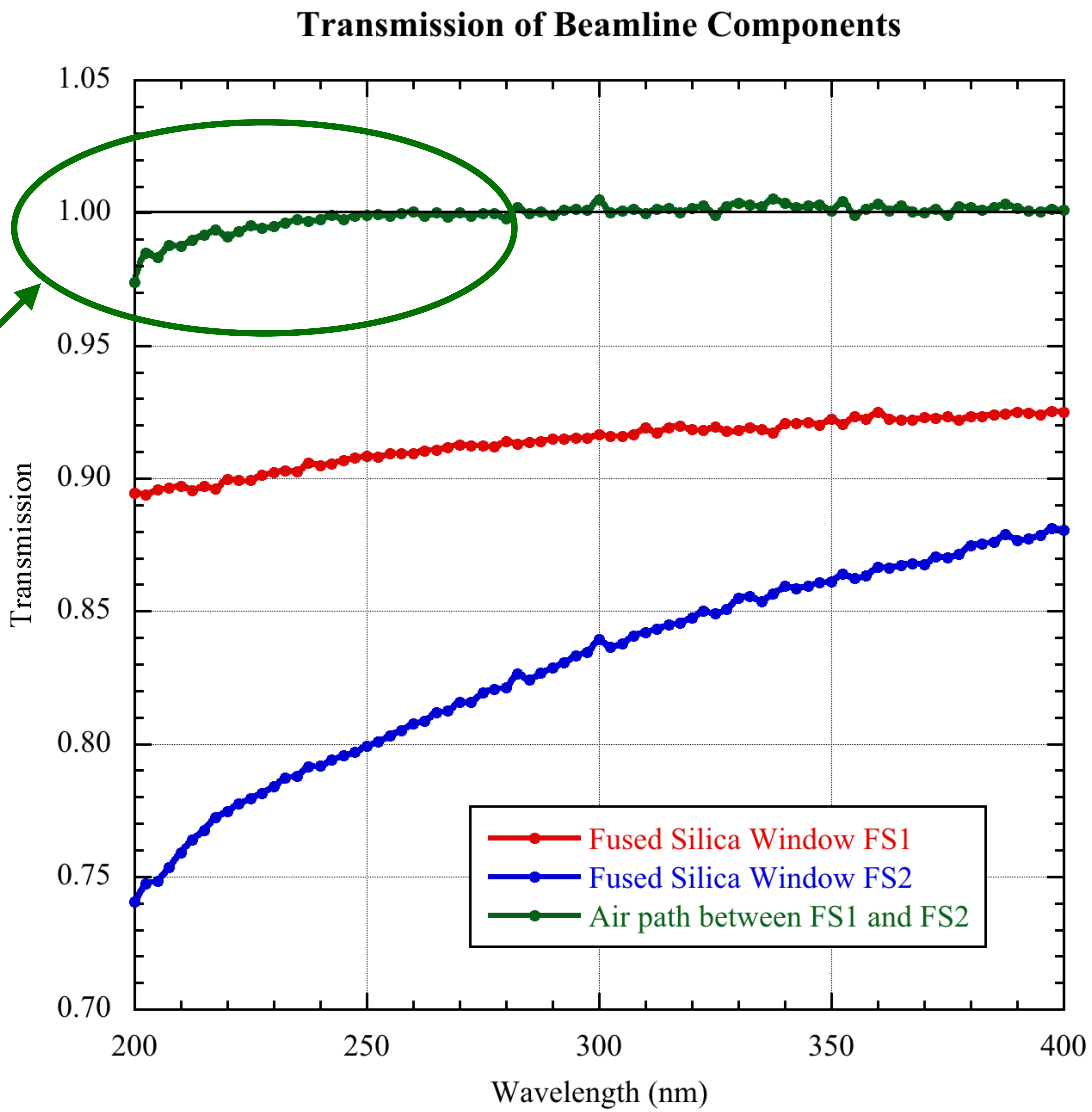
Transmission of components:

$$T_{FS1} = \frac{\eta_{1,2}^{vac}}{\eta_2}$$

$$T_{FS2} = \frac{\eta_{1,2}^{air}}{\eta_1}$$

$$T_{air} = \frac{\eta_{1,2}^{air}}{\eta_{1,2}^{vac}}$$

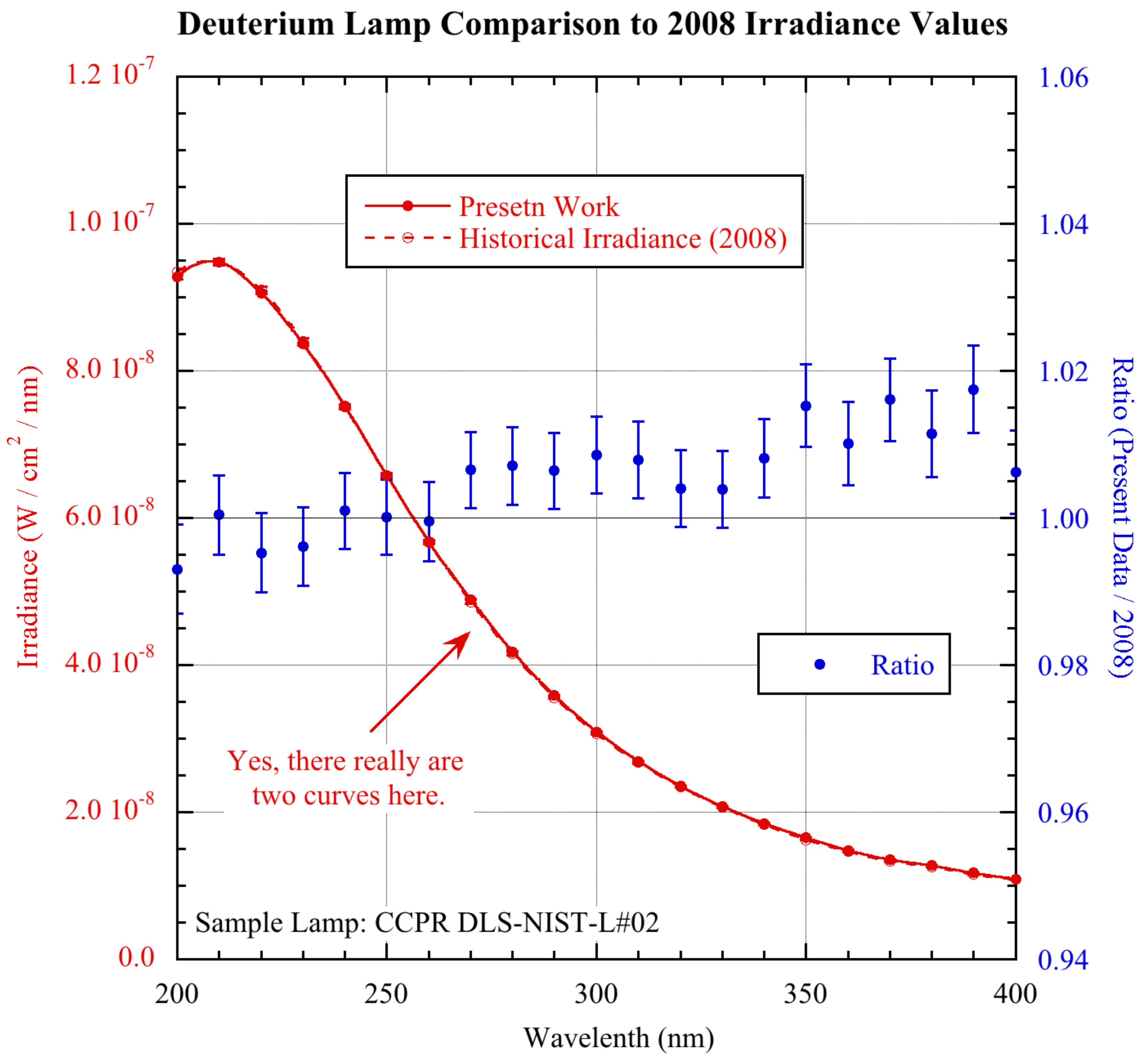
Air absorption cannot be ignored in the detector calibration!

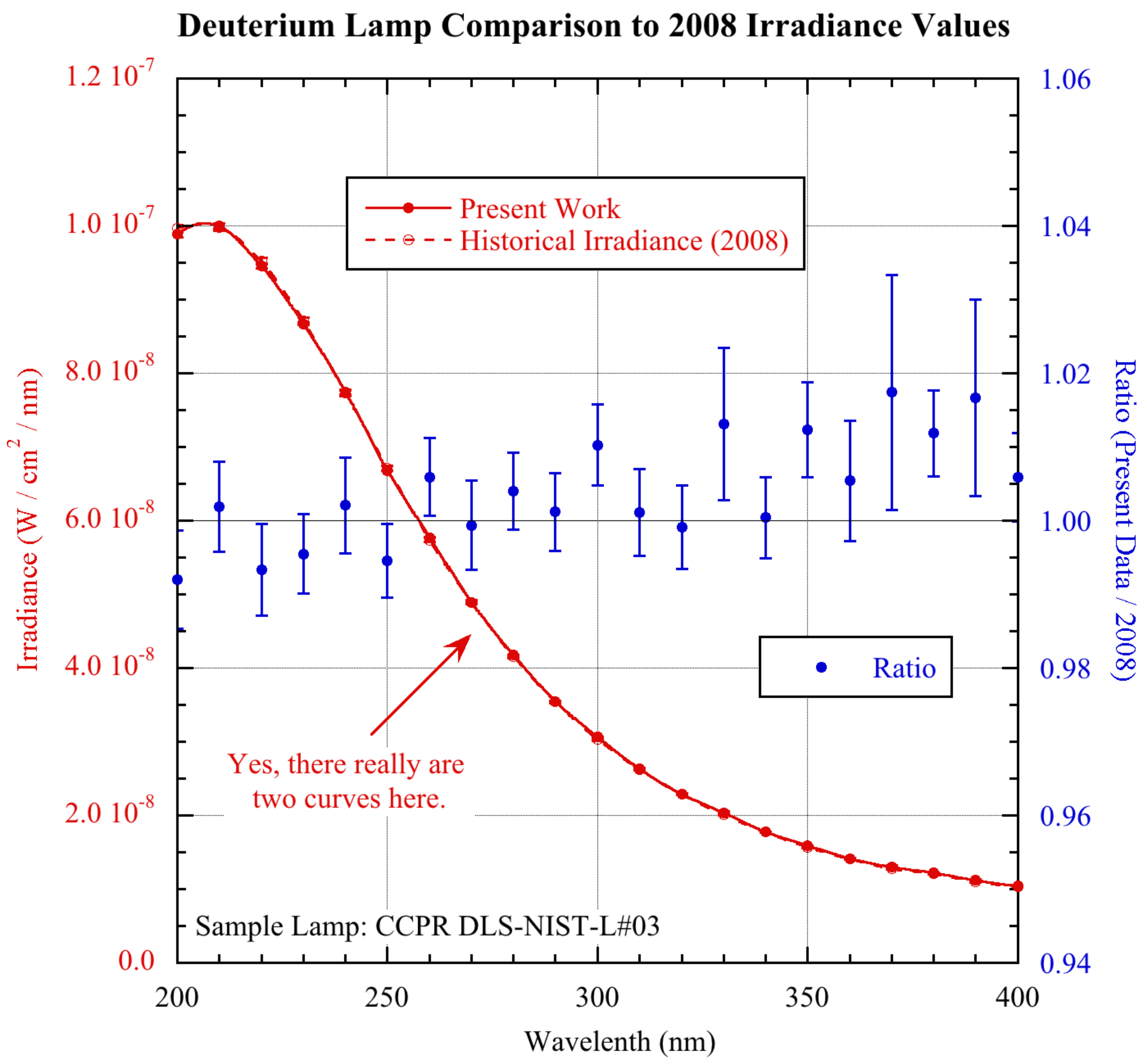


Lamp Calibration

With the detector responsivity known, all that remains is to measure the sample lamp irradiance with the calibrated detector:

$$E_{lamp} = \frac{V_{lamp}}{\eta_0}$$



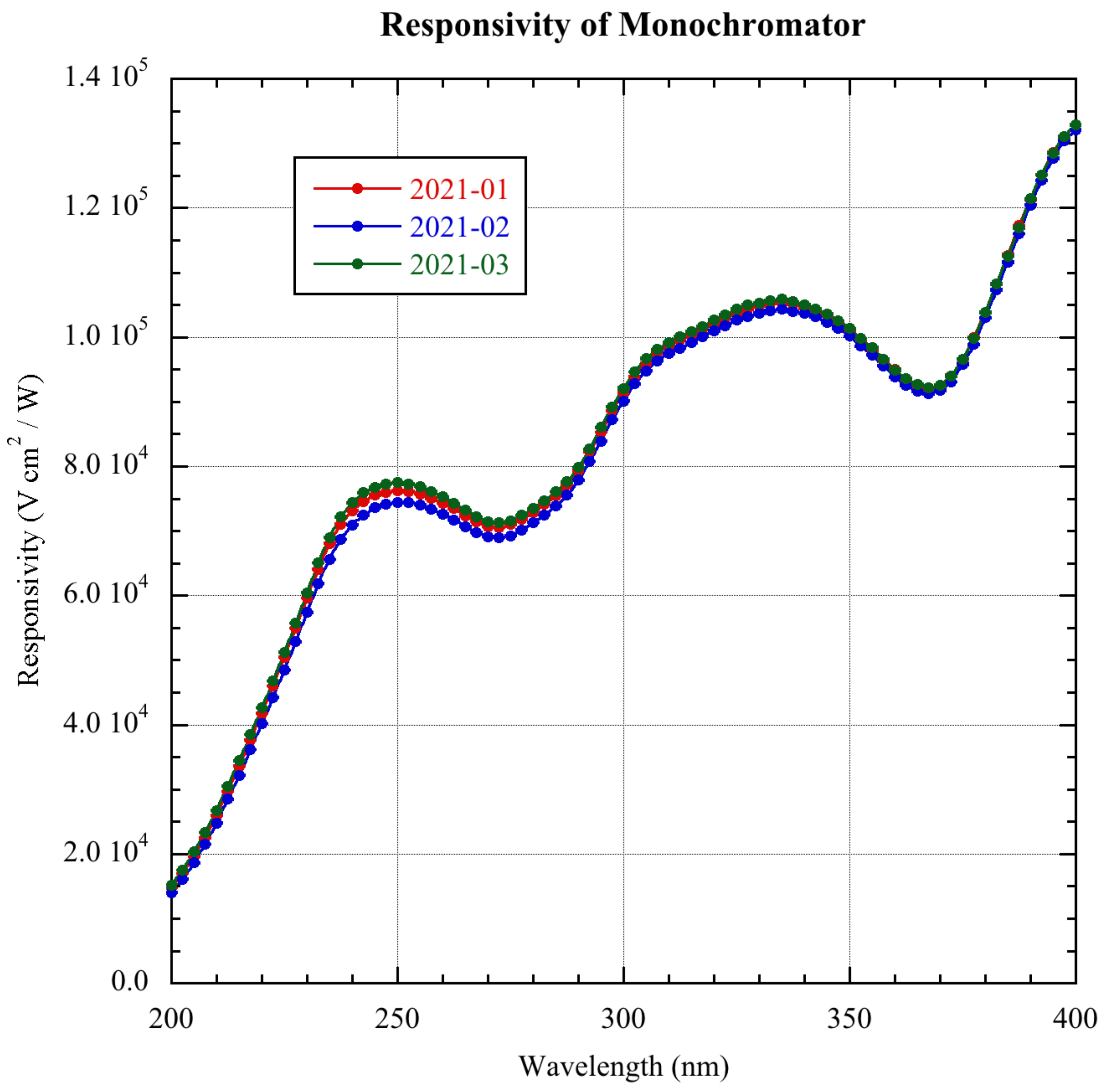


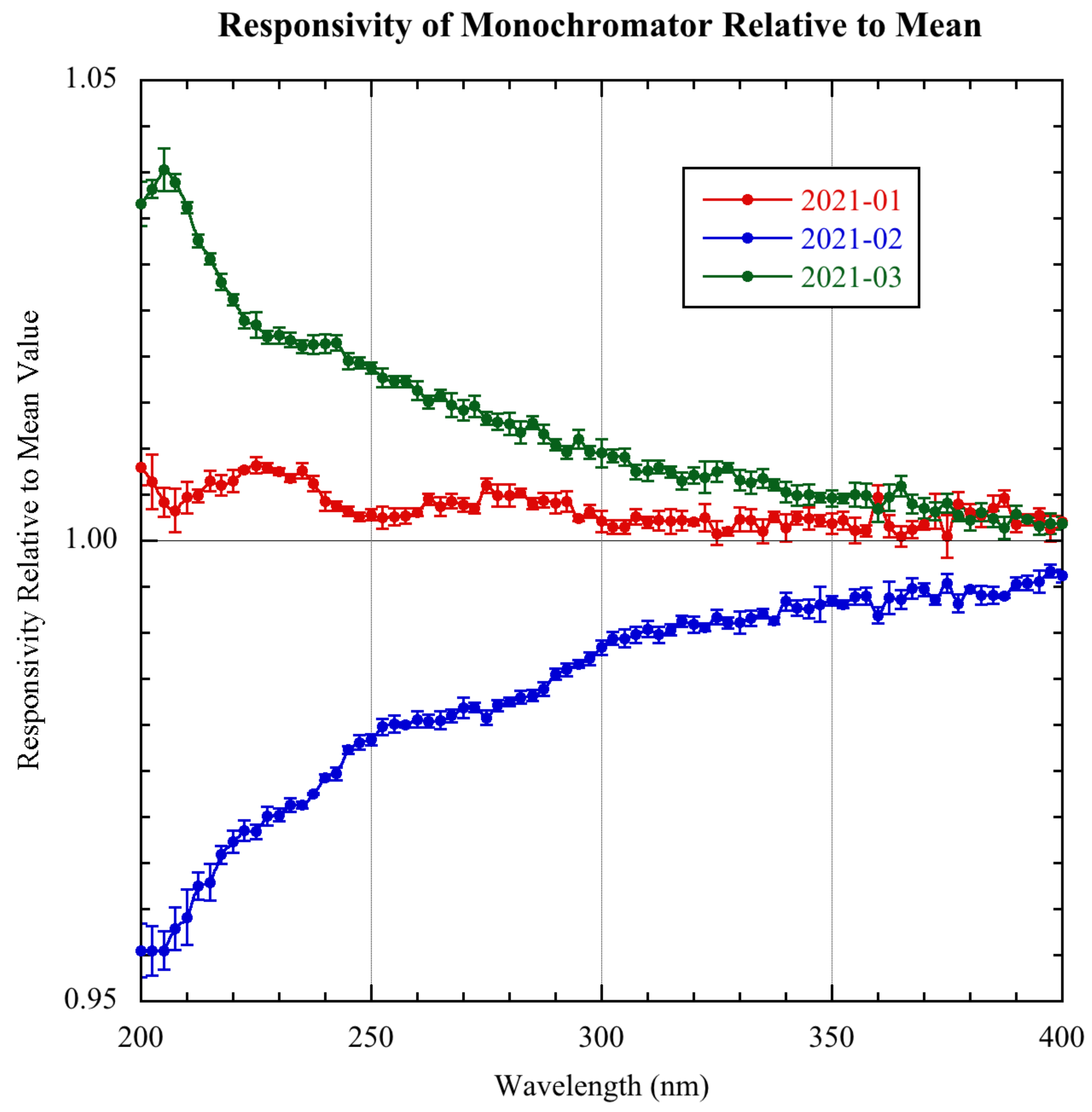
Recent results from BL-2 are compared to historic data from 2008 (13 years ago) and found agreement to within about 1%.

Detector Stability

We conducted three measurement campaigns on a family of four D2 lamps:

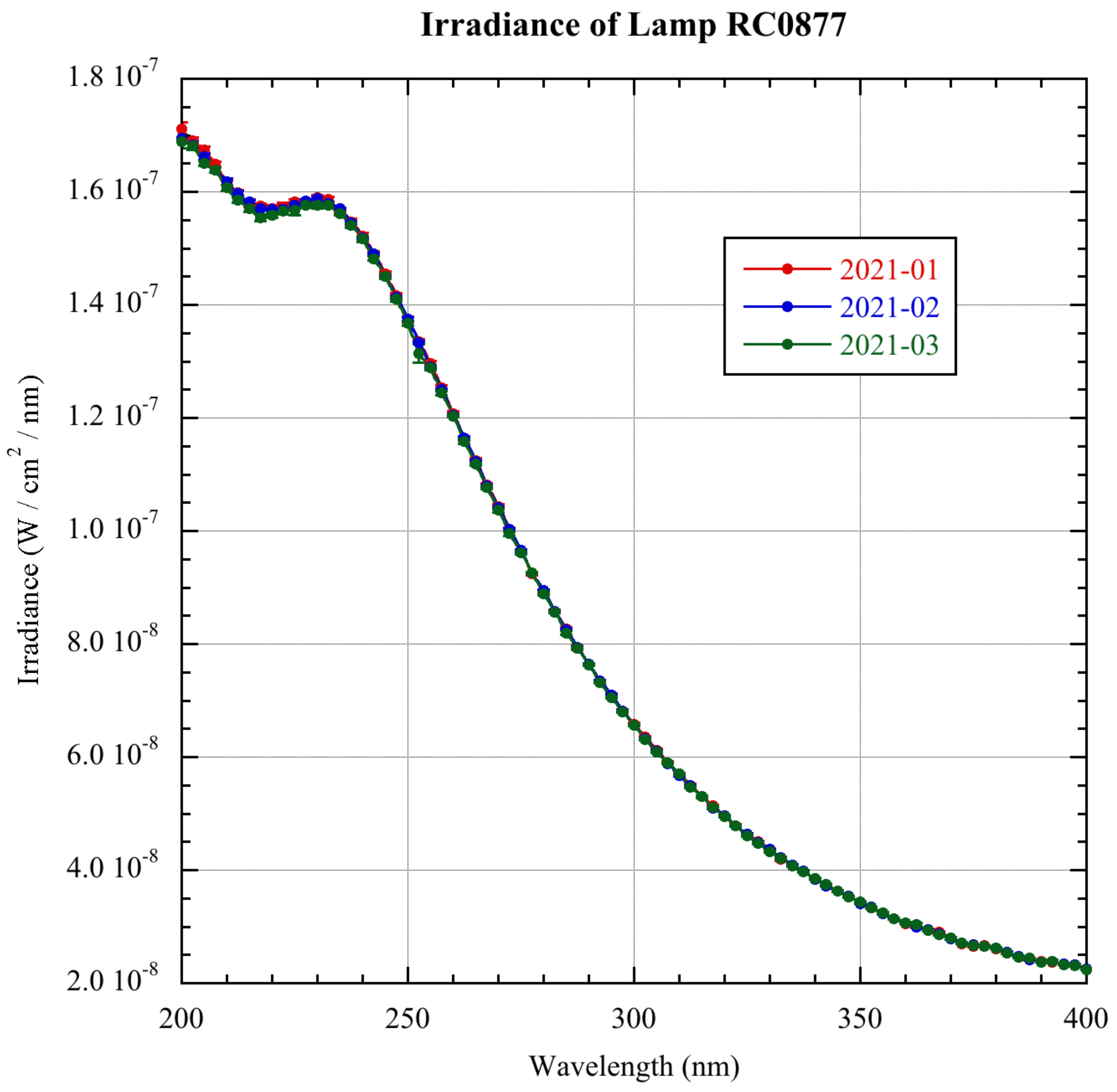
- Jan 2021: Initial campaign
- Took the top off (and reinstalled it), adjusted baffles, removed and reinstalled the diffuser.
- Feb 2021: significantly degraded
- Removed, cleaned, and reinstalled the diffuser.
- Mar 2021: better than original.

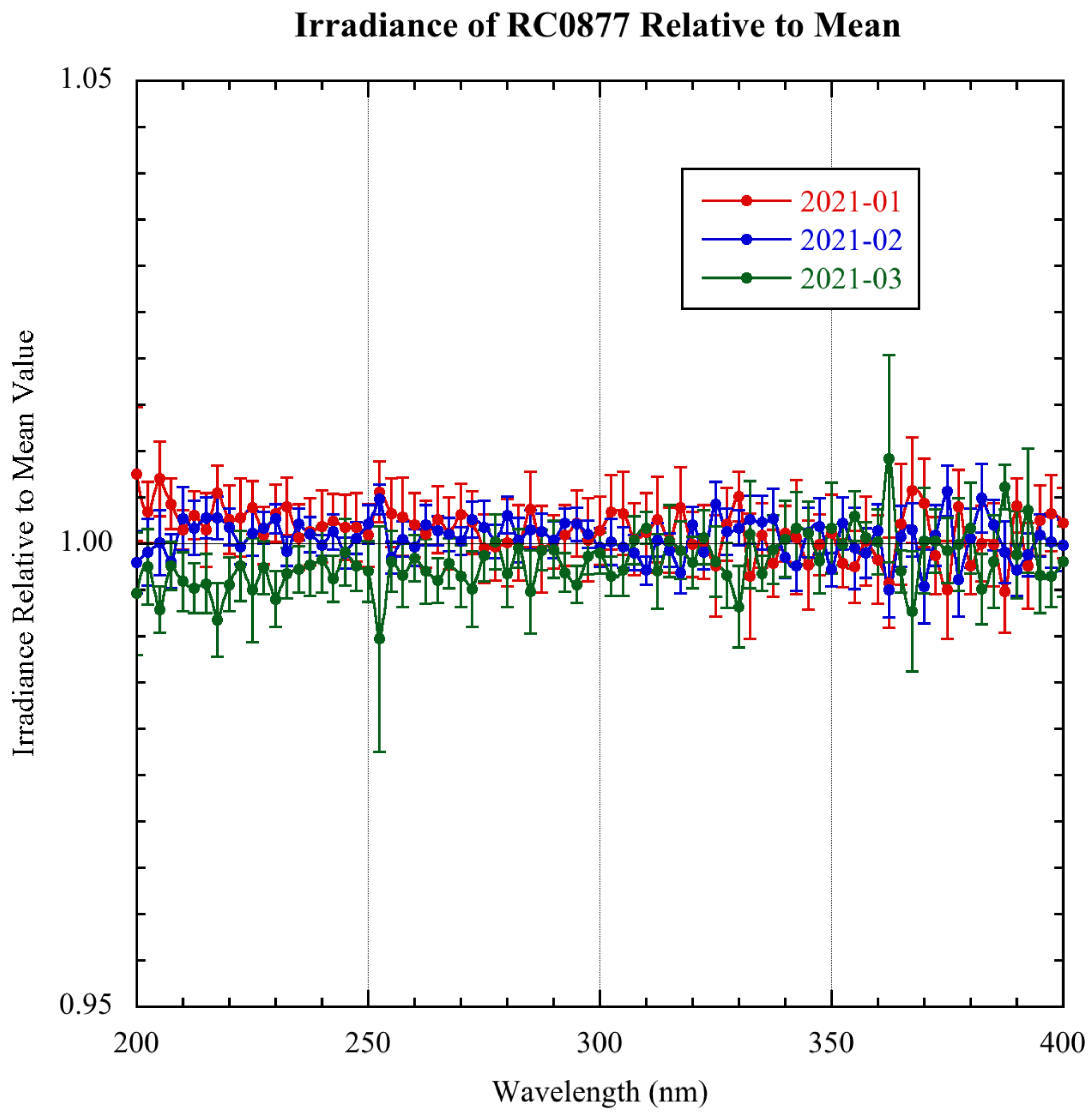




The detector system was very stable within a campaign (note the small error bars), but showed large changes (±5%) between the campaigns when we did things to it.

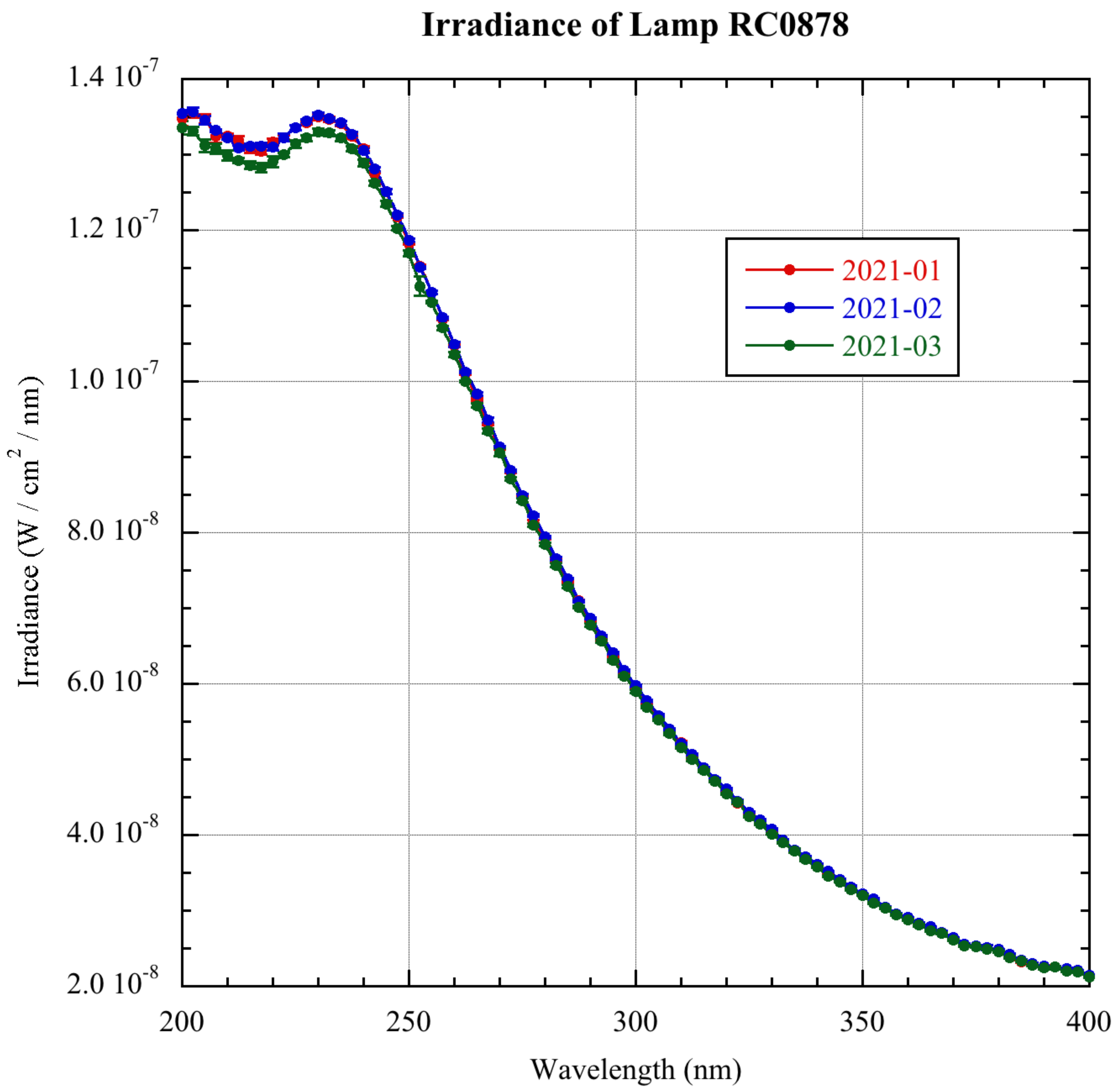
Lamp RC0877

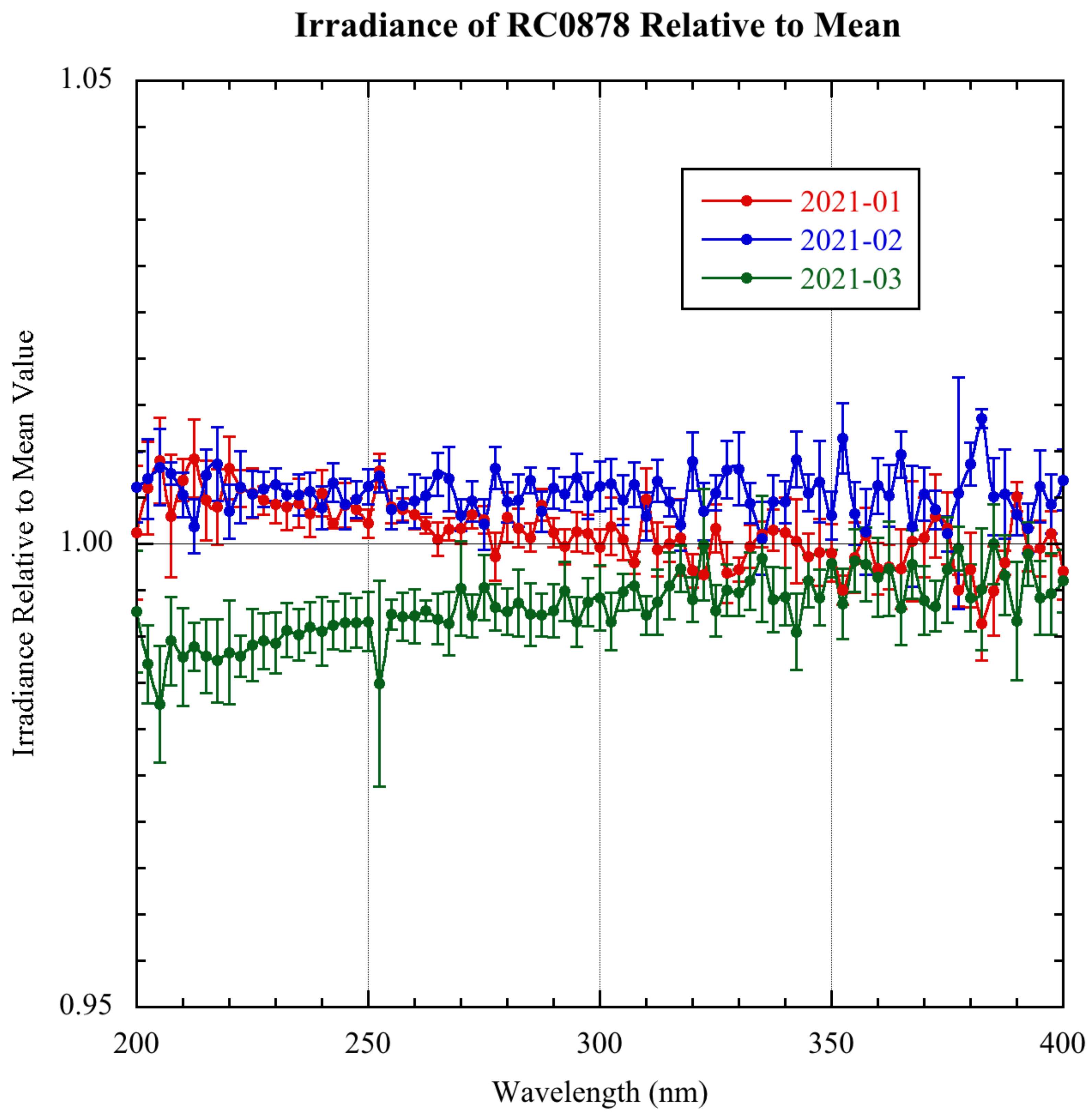




Lamp RC0877 was measured in all three campaigns. It was stable to about ±0.5%.

Lamp RC0878





Lamp RC0878 was measured in all three campaigns. It was stable to about ±1%, but the 2021-03 campaign is a notable outlier. Maybe it's a fluke that the other two are such good repeats, since the overall stability of ±1% is comparable to other lamps?

Uncertainty in SURF Irradiance

Components of relative combined standard uncertainty (k = 1) in the SURF III irradiance primary standard.

	Wavelength (nm)				
Component of Uncertainty	**200**	**250**	**300**	**350**	**400**
Electron energy (0.3% at 229 MeV)	0.11%	0.08%	0.07%	0.06%	0.05%
Orbital Plane Location (0.58 mm)	0.01%	0.01%	0.01%	0.01%	0.01%
Stored electron beam current	0.20%	0.20%	0.20%	0.20%	0.20%
Fuzz - no fuzz ratio	0.04%	0.04%	0.04%	0.04%	0.04%
Distance to tangent point (2.0 mm)	0.05%	0.05%	0.05%	0.05%	0.05%
Diffraction (10% of correction factor)	0.02%	0.02%	0.03%	0.03%	0.04%
SURF III Irradiance Uncertainty	***0.24%***	***0.23%***	***0.22%***	***0.22%***	***0.22%***

Uncertainty in Lamp Irradiance

Components of relative combined standard uncertainty (k = 1) in the irradiance calibration of a lamp.

	Wavelength (nm)				
Component of Uncertainty	**200**	**250**	**300**	**350**	**400**
SURF III Irradiance Uncertainty	*0.24%*	*0.23%*	*0.22%*	*0.22%*	*0.22%*
Wavelength (0.05 nm)	0.41%	0.10%	0.05%	0.11%	0.05%
Detector stability	0.20%	0.20%	0.20%	0.20%	0.20%
Type B Uncertainty	*0.51%*	*0.32%*	*0.30%*	*0.32%*	*0.30%*
Detector calibration (typical)	0.40%	0.25%	0.23%	0.33%	0.39%
Lamp calibration (typical)	0.22%	0.14%	0.19%	0.26%	0.32%
Type A Uncertainty	*0.46%*	*0.29%*	*0.30%*	*0.42%*	*0.50%*
Uncertainty in lamp irradiance	**0.69%**	**0.43%**	**0.43%**	**0.53%**	**0.59%**

The 0.5% (*k* = 1) uncertainty of a lamp calibration compares well to the observed repeatability after 13 years of abut 1%.