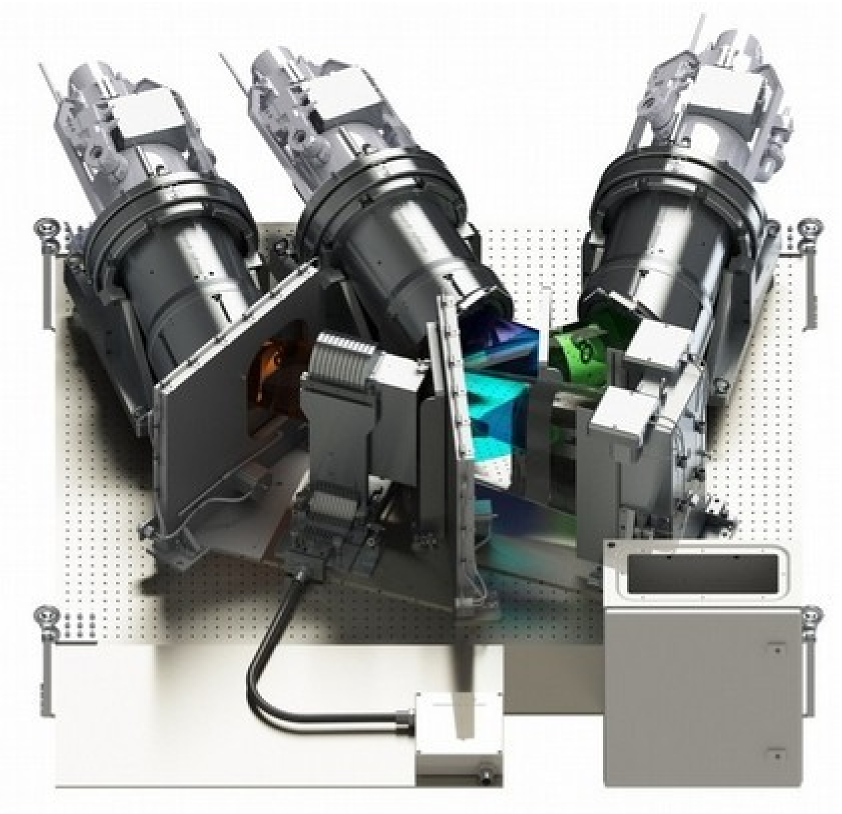

DESI EM#1/SM#1 First Spectrograph: Throughput Measurement

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DESI Workshop
Tucson, 2018-05-23

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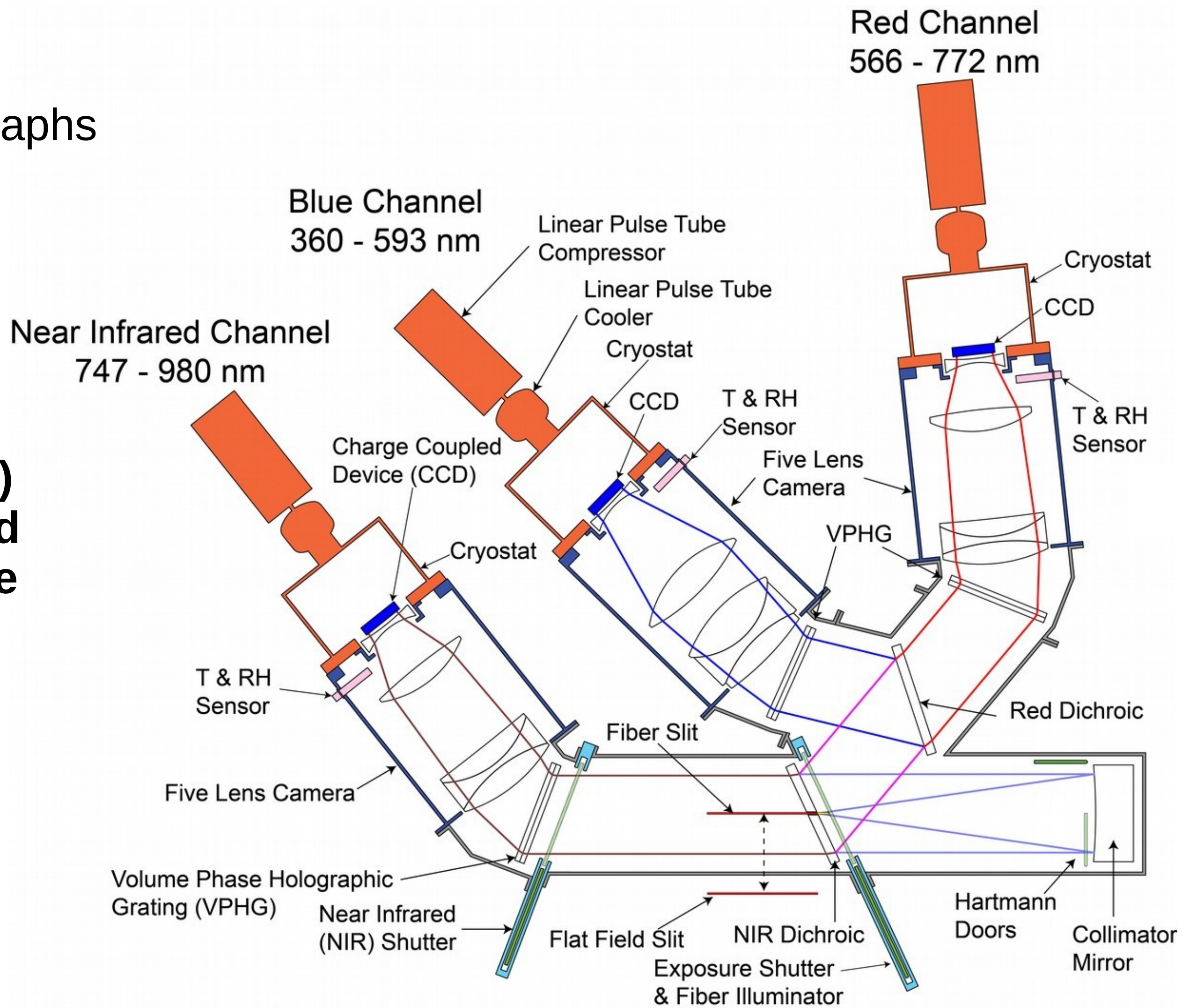
AMU : Pierre-Eric Blanc, Sandrine Perruchot, Xavier Regal, Samuel Ronayette
CEA : C. Magneville

Talk outline

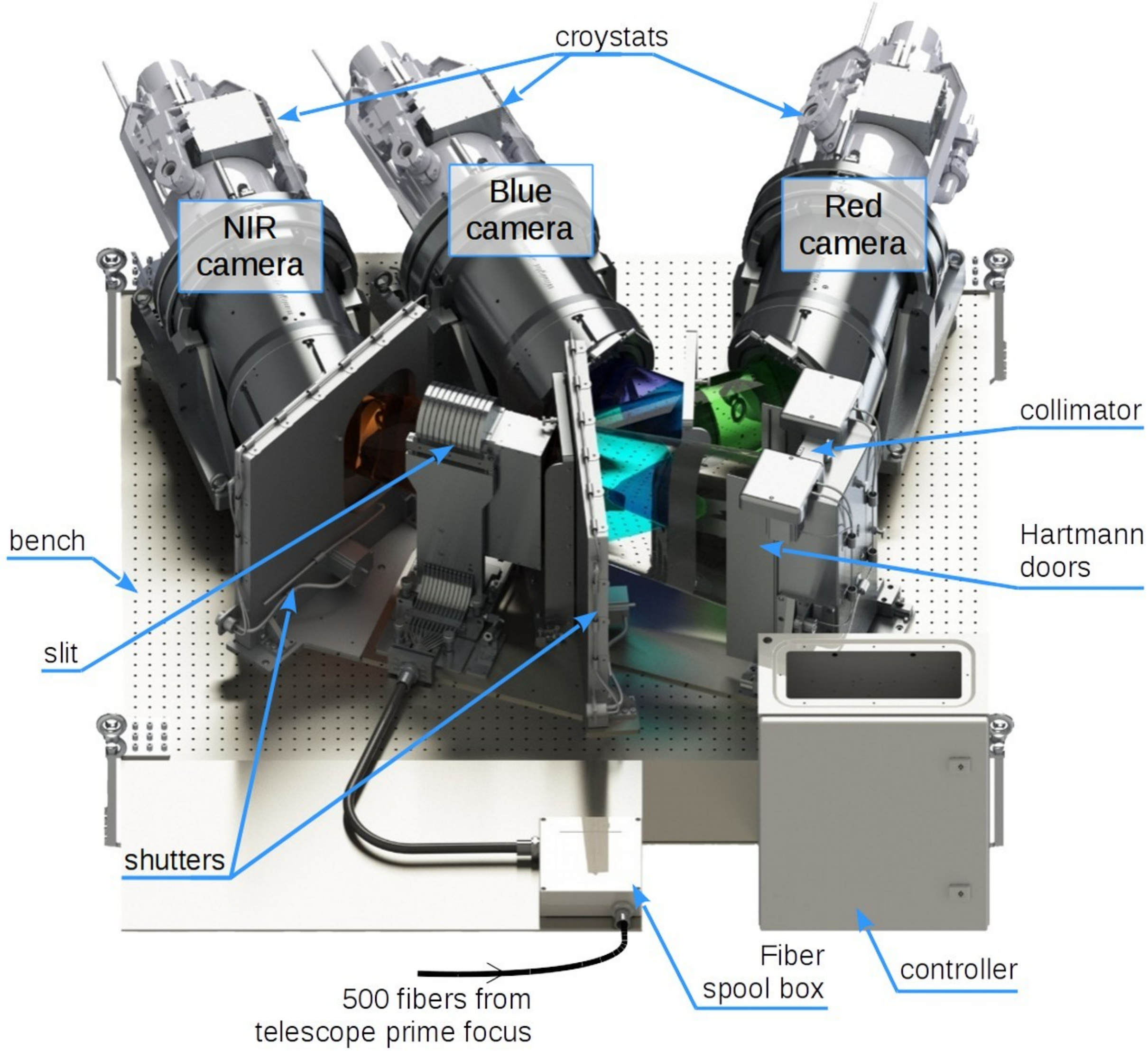
- **Throughput Measurement: Proposal & Method**
- **Flux Calibration Device for the Sparse Fiber Slit**
- **Measurement Campaigns for EM#1 & SM#1**
- **Data Analysis**
  - Absolute flux measurements with the photodiode (calib. DKD)
  - LED spectra with the DESI spectrograph: reduction, extraction
  - Exposure time: shutter time correction
  - Gain correction: Gain determination for the CCD amplifiers
  - Direct throughput estimate (without model) for EM#1 & SM#1
  - Combining with Tungsten lamp exposures and bench throughput data
- **Focal Ratio Degradation (FRD) estimates**

The DESI spectrograph

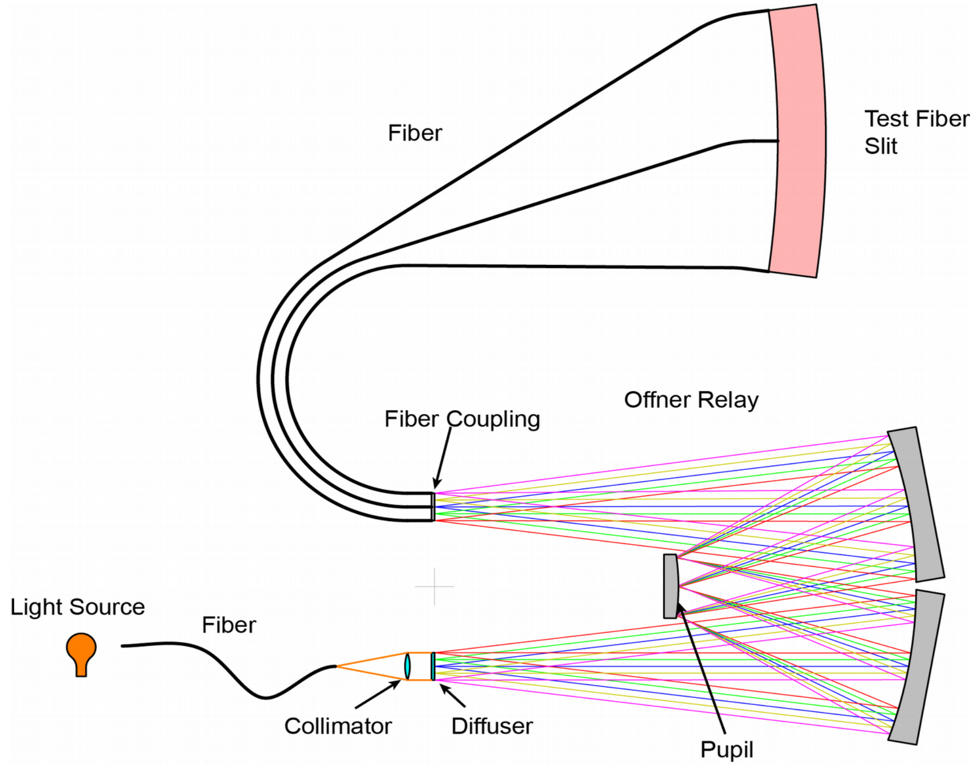
- 10 identical spectrographs
- 10 x 500 fibers
- 3 arms :
  NIR, Red, Blue
- **Fiber slit (500 fibers) may be removed and replaced by a sparse fiber slit for tests.**

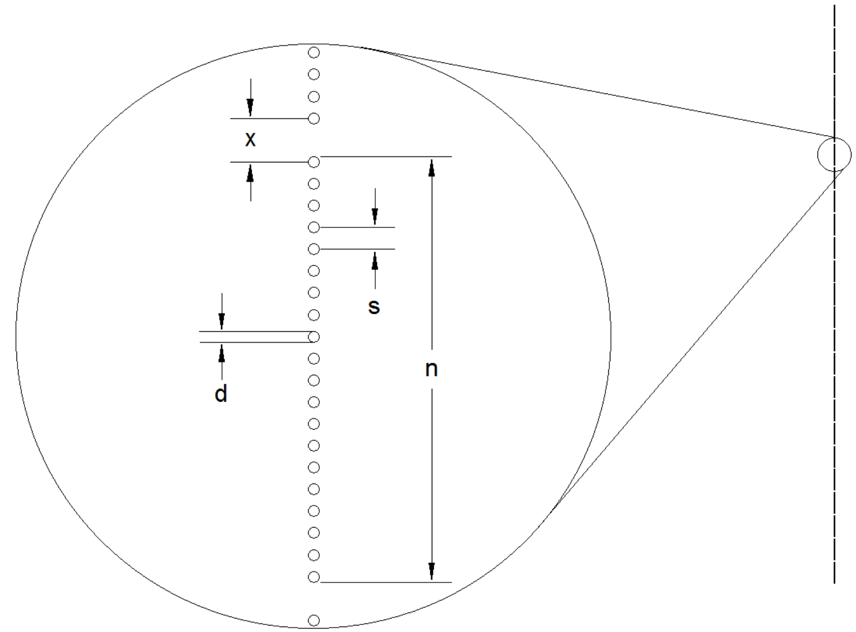


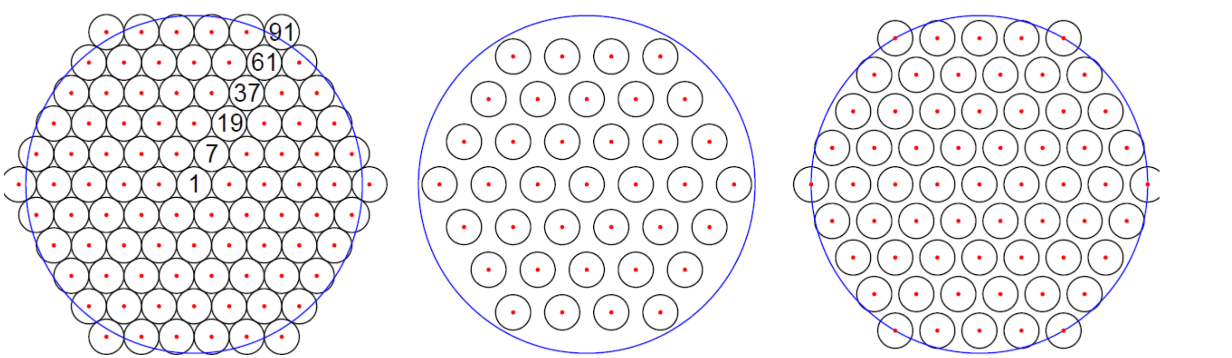
The DESI spectrograph



Sparse fiber slit(s): allows single fiber illumination



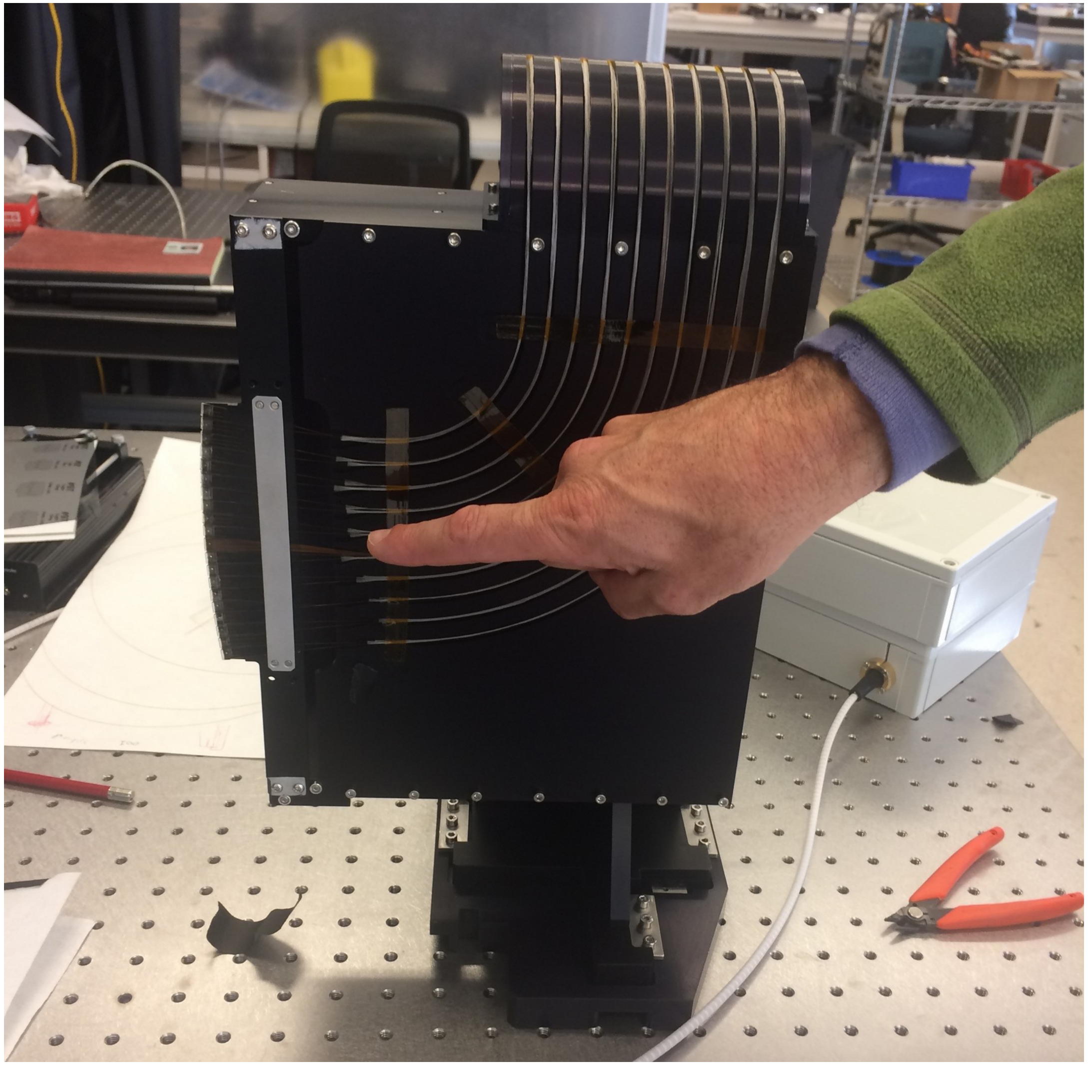


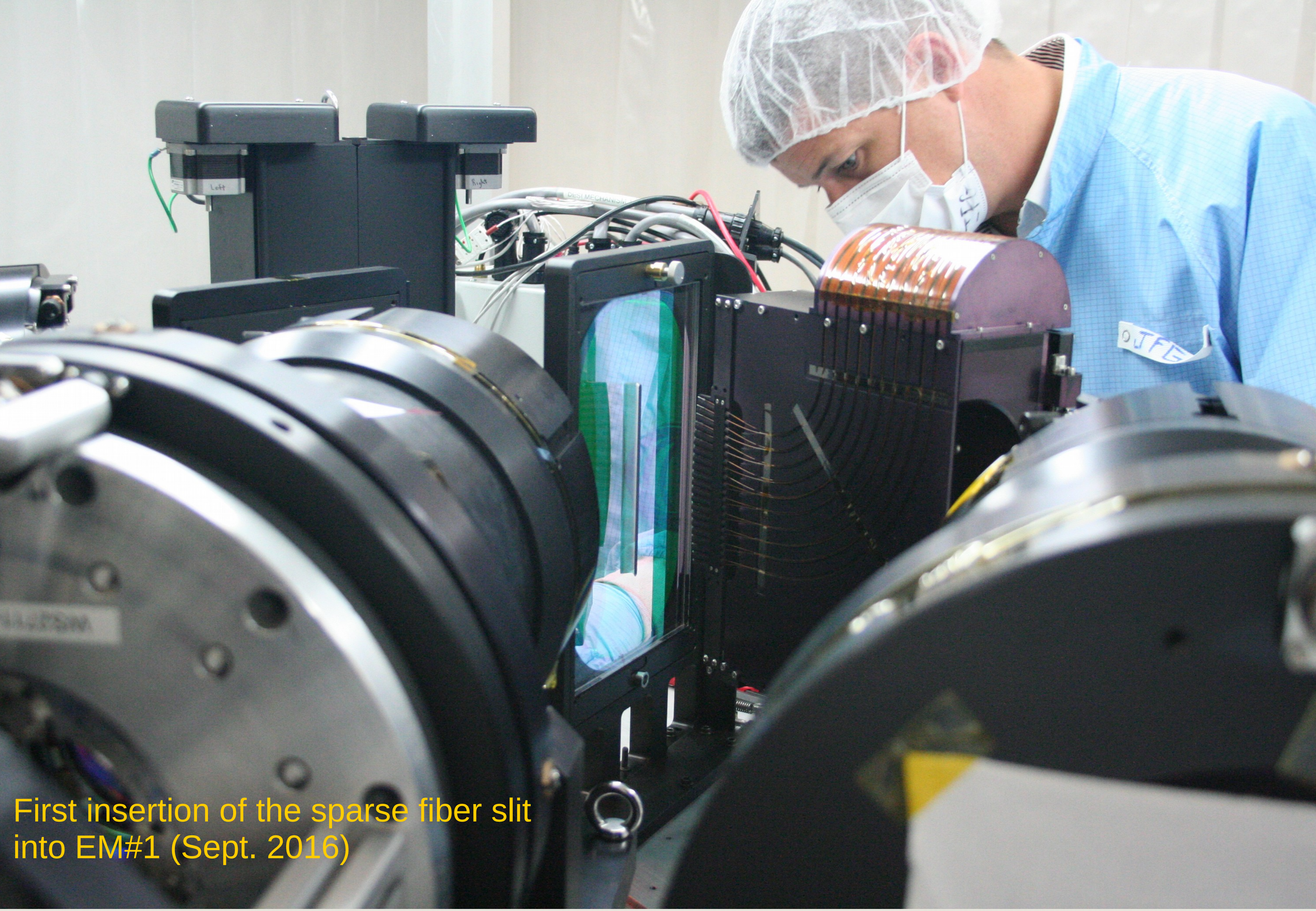


Fiber slit(s): “sparse fiber slit”

- 21 well separated fibers
- May be illuminated individually (AMU bench)

Fiber : f/3.57
Angle θ ~ 8°



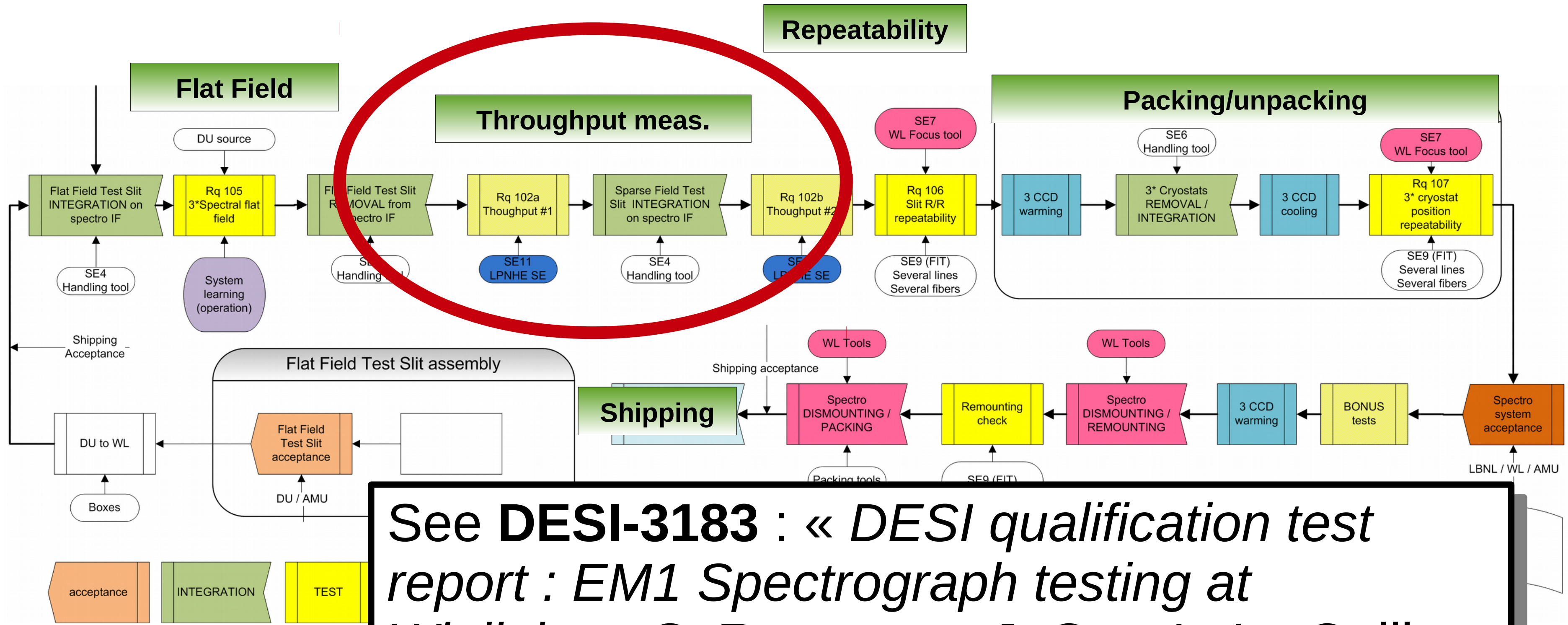


First insertion of the sparse fiber slit into EM#1 (Sept. 2016)

Throughput measurement: proposal & method

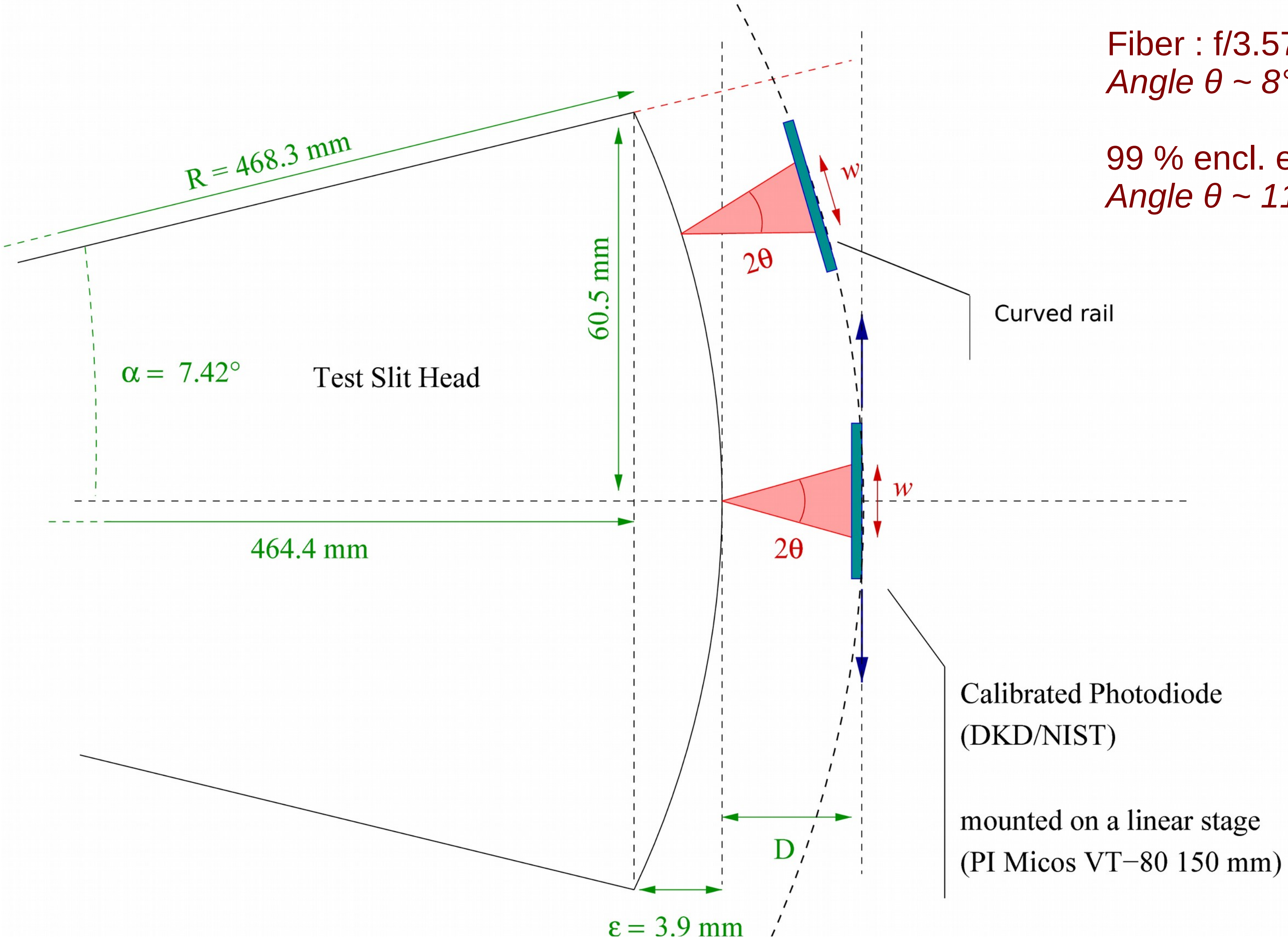
- Measurement to be done during **slit removal/reinstall** repeatability test (limited overhead)
- **Calibration of the total flux** at the exit of each fiber of the sparse fiber slit
- **Proposed Procedure** : for the same illumination setups (LEDs)
  - **(1) Sparse Test Slit outside of the spectrograph, in front of our device** : flux (in the same illumination conditions) measured by our calibrated photodiode, for each LED / fiber ;
  - **(2) Sparse Test Slit inside the spectrograph** : integrated flux measured on the CCD for the 3 arms of the spectrograph for each LED / fiber ;
  - **Ratio (1)/(2)** gives **throughput** (from fiber exit to the CCD included)

Incl. in Spectro. Qualification Tests (AMU)



See **DESI-3183** : « *DESI qualification test report : EM1 Spectrograph testing at Winlight* », S. Ronayette, J. Guy, L. Le Guillou, Sept. 2017.

Mechanical design

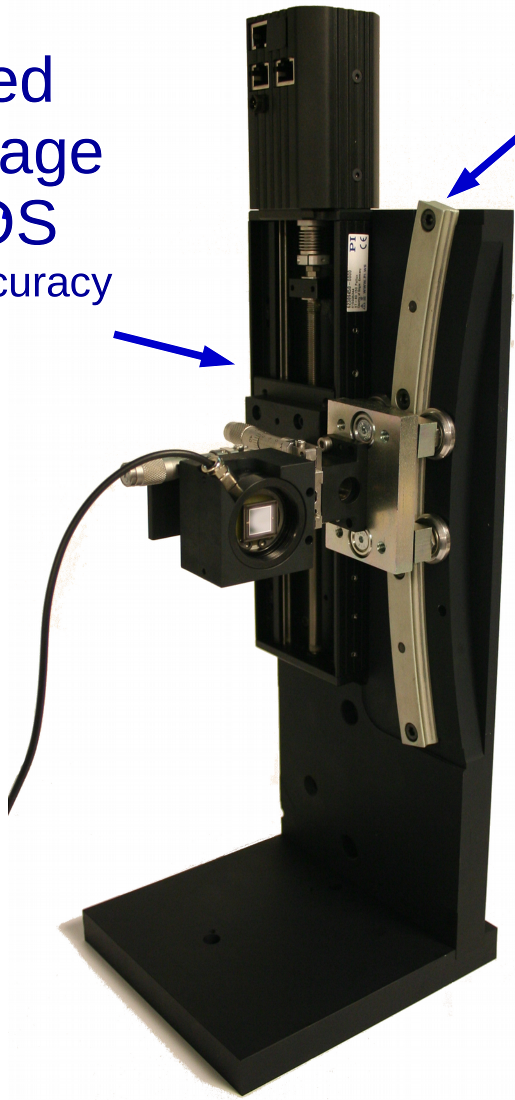


Fiber : f/3.57
Angle θ ~ 8°

99 % encl. energy : f/2.5
Angle θ ~ 11.3°

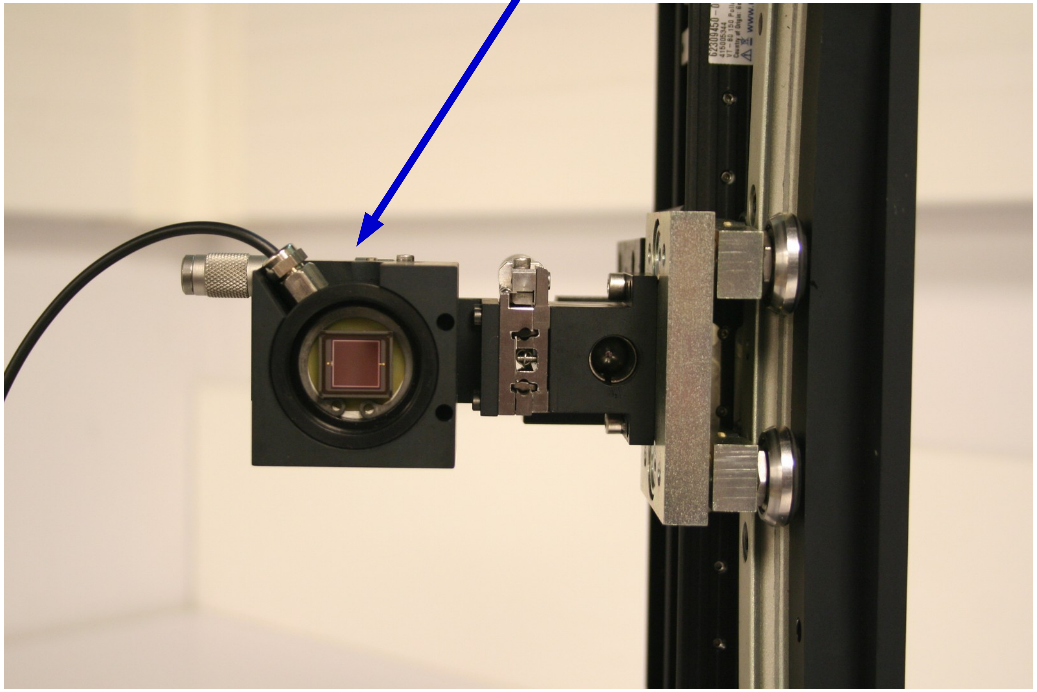
Throughput measurement device

Motorized linear stage Pi/MICOS
<0.4 µm accuracy

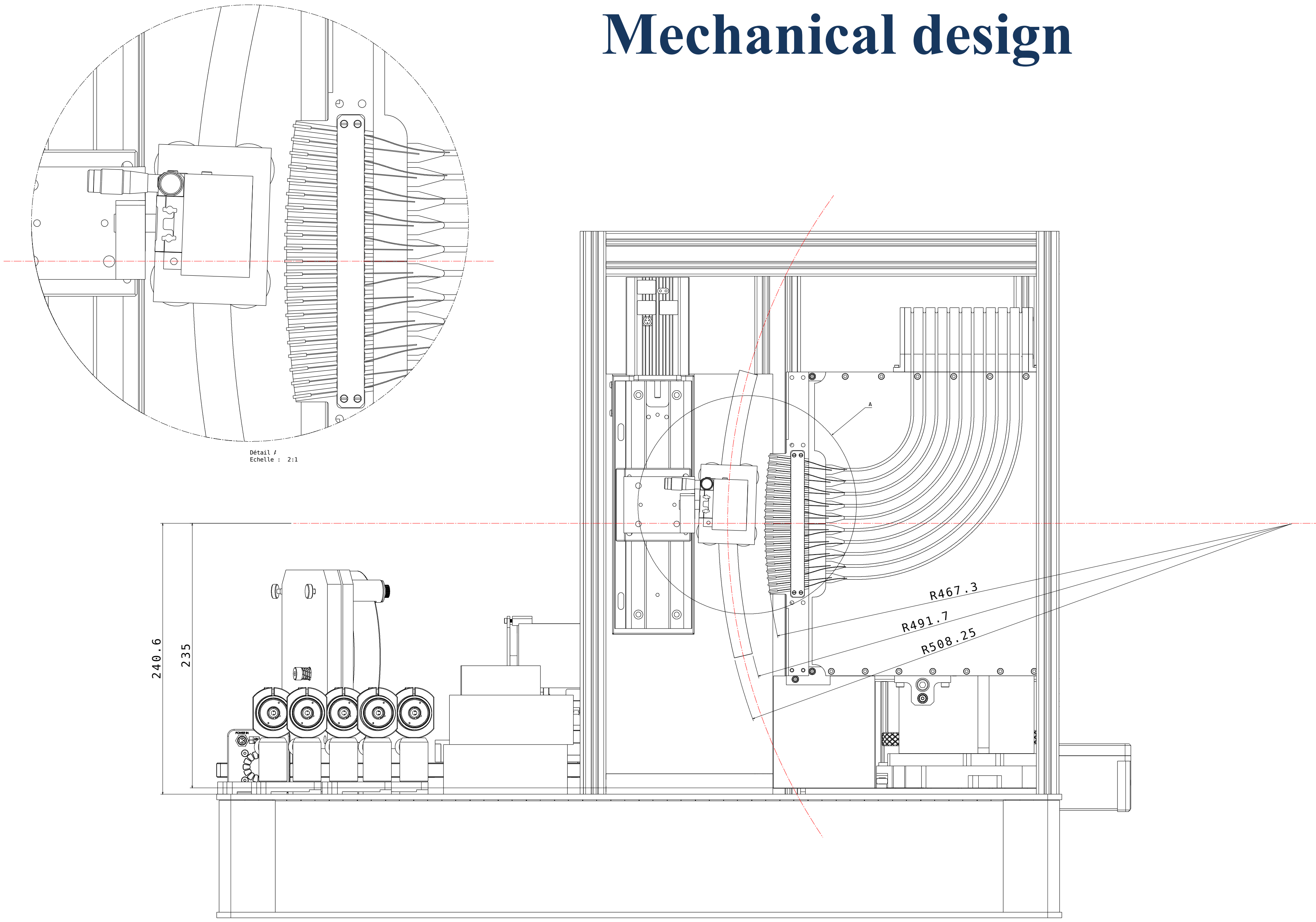


Curved rail
(radius 500 mm)

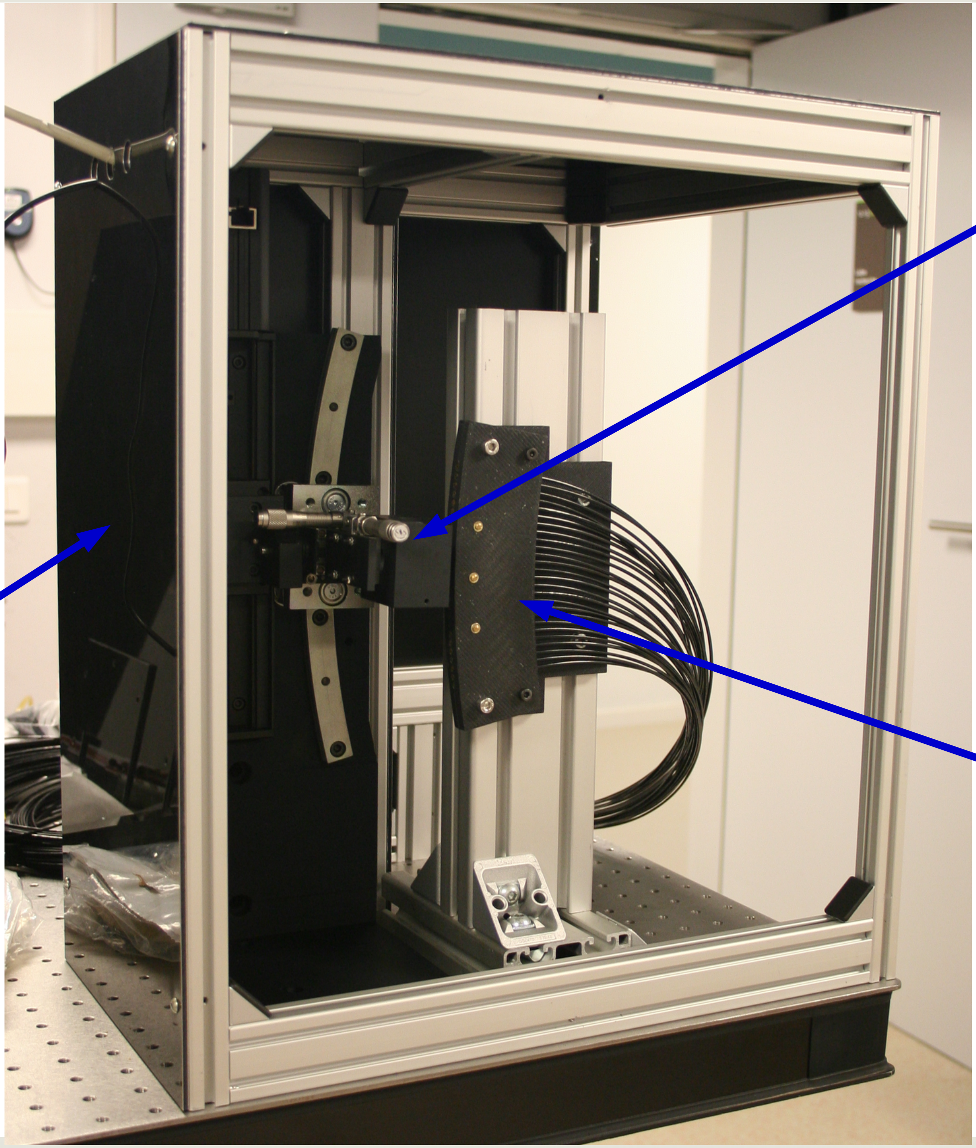
Calibrated Photodiode
10x10 mm²



Mechanical design



Throughput measurement device



Calibrated Photodiode

Dedicated Dark Box

Mock test slit
3D printed
Old fiber bundle
(DESY, H1)

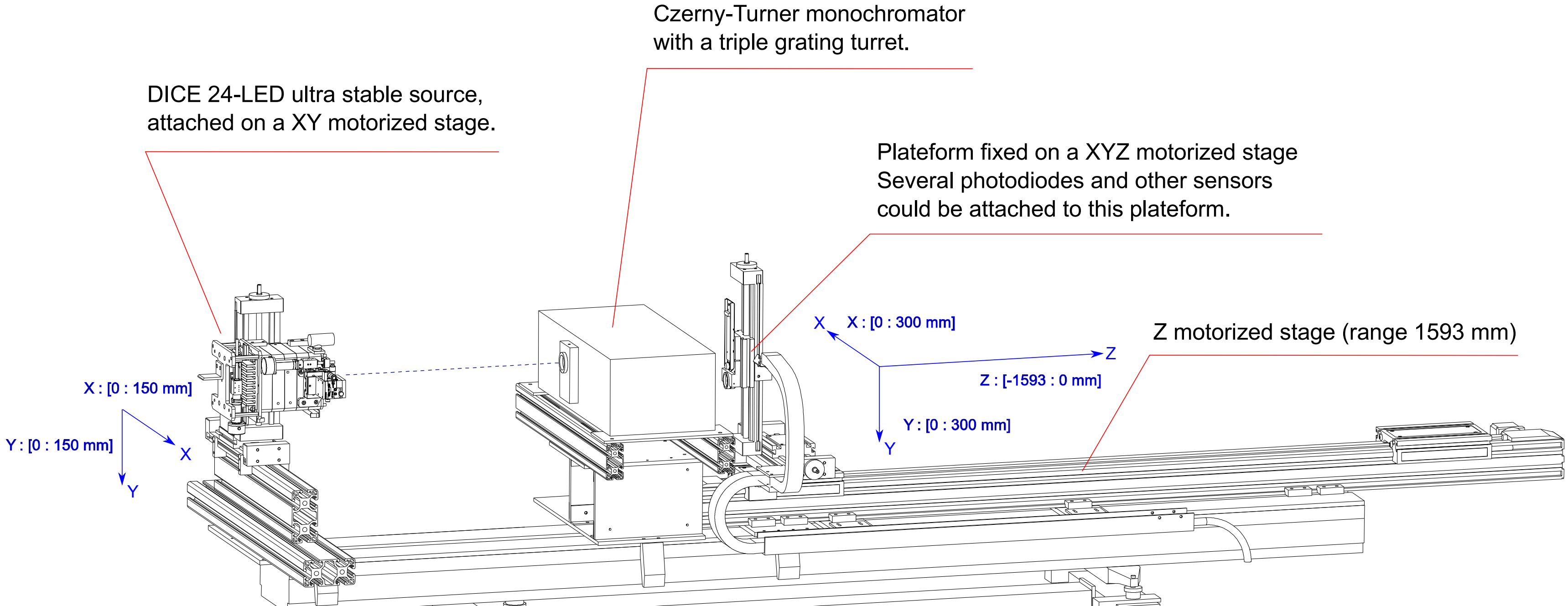
Calibrated Photodiode

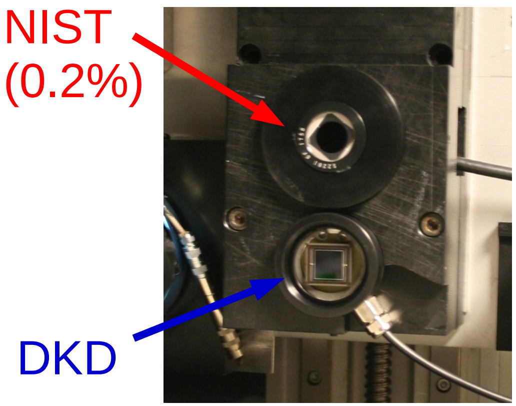
- MD-37-SU100 **calibrated** (**spectral responsivity** [A/W])
  - **DKD** (DE) **certified absolute calibration**
  - 2 % on 250 – 1100 nm.
- Size : 10x10 = 100 mm²
- Photodiode current readout : picoammeter

  Keithley 6514, or better **6482** (2 channels), (fA)
- **Simultaneous monitoring** of :
  - Light flux in the integrating sphere
  - Light flux exiting the fiber

  → Control of the **illumination stability**

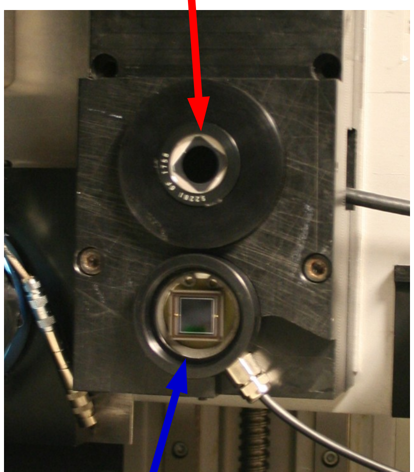
Intercalib. : LPNHE spectrophotometric bench





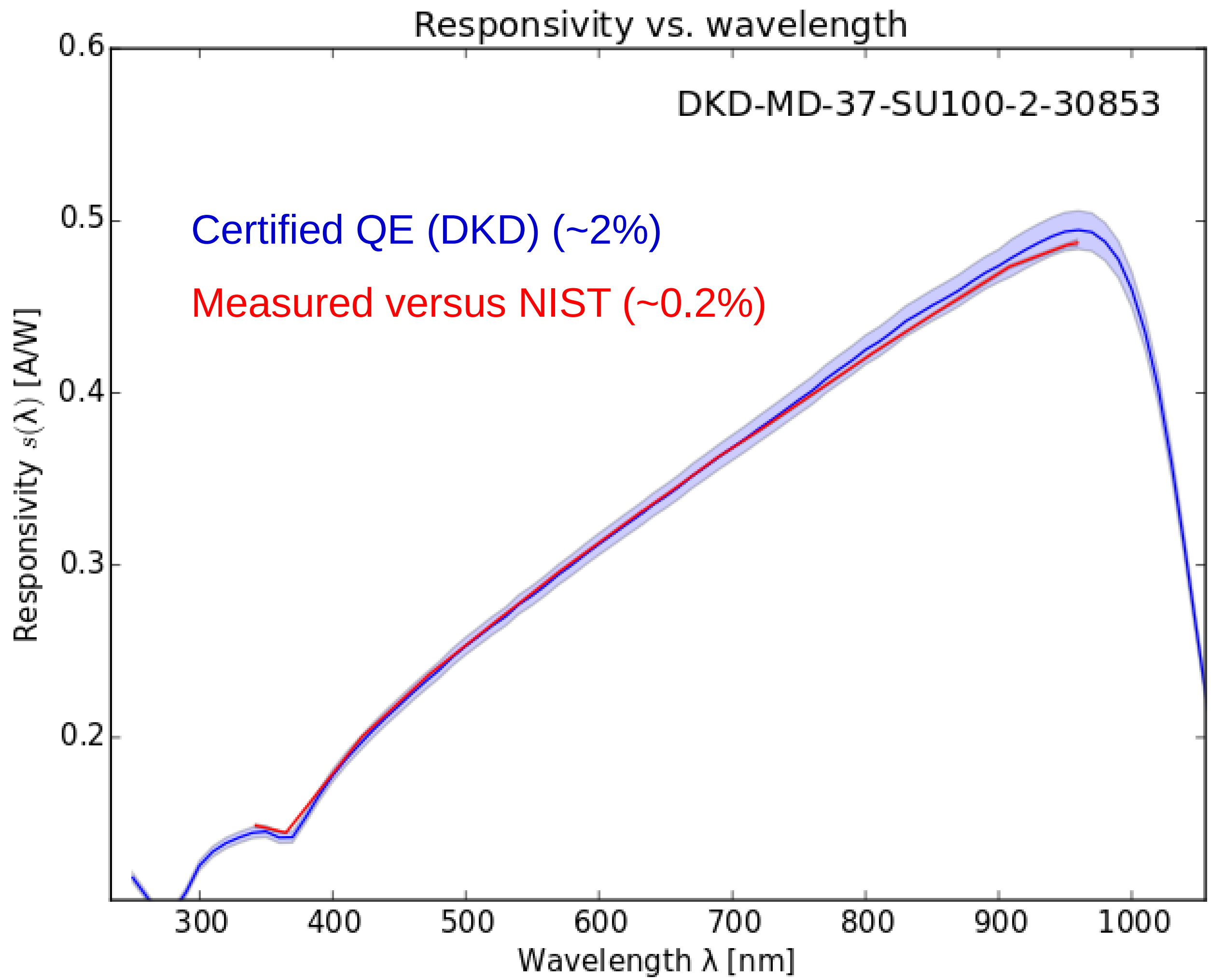
Photodiode Calibration & checks at LPNHE

NIST (0.2%)

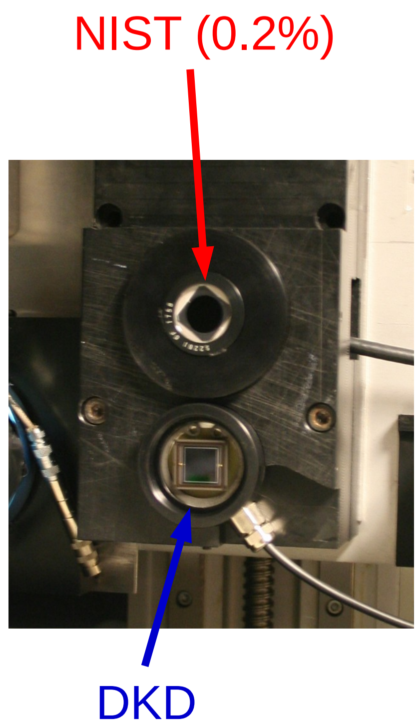


DKD

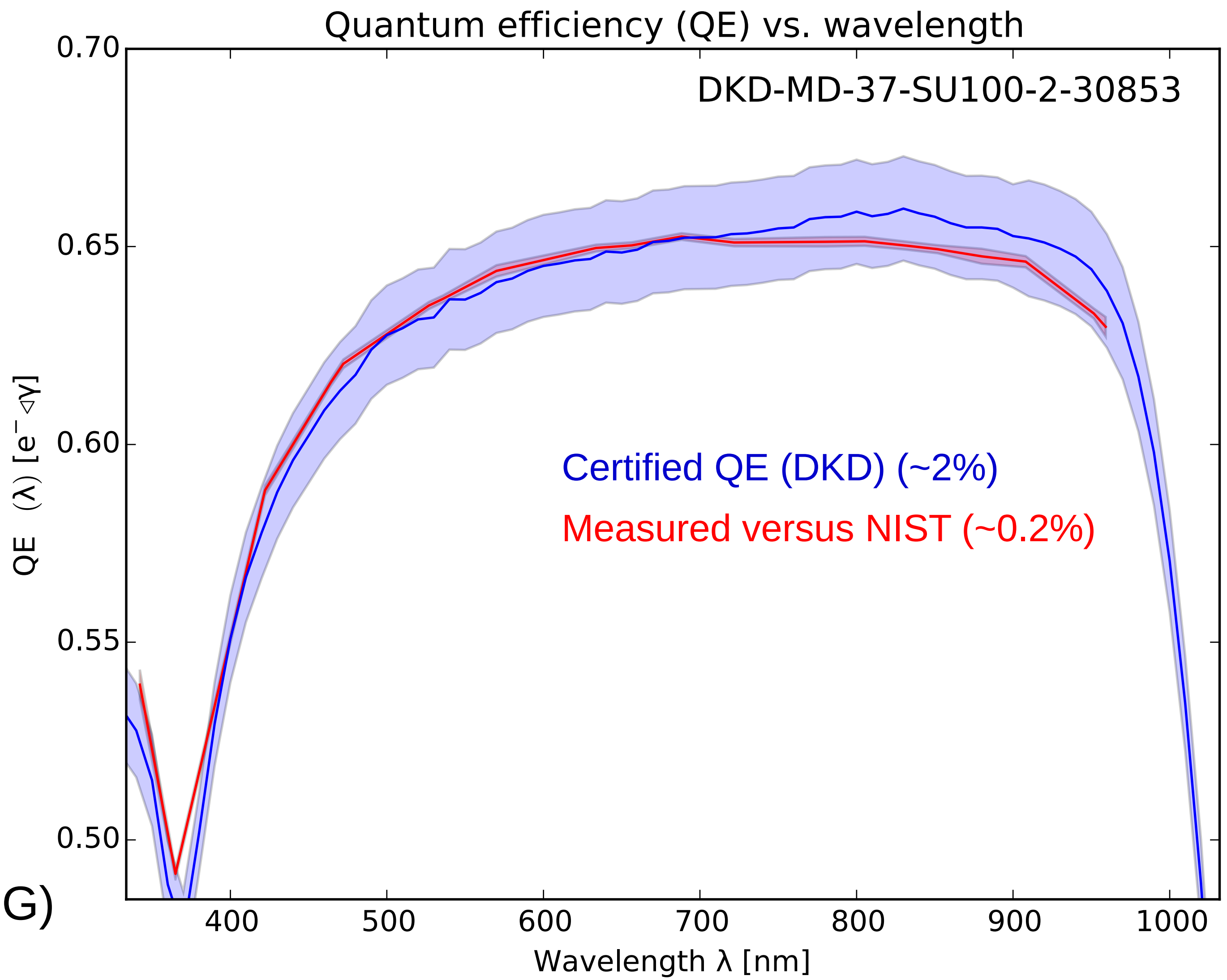
See DESI-2635 (LLG)



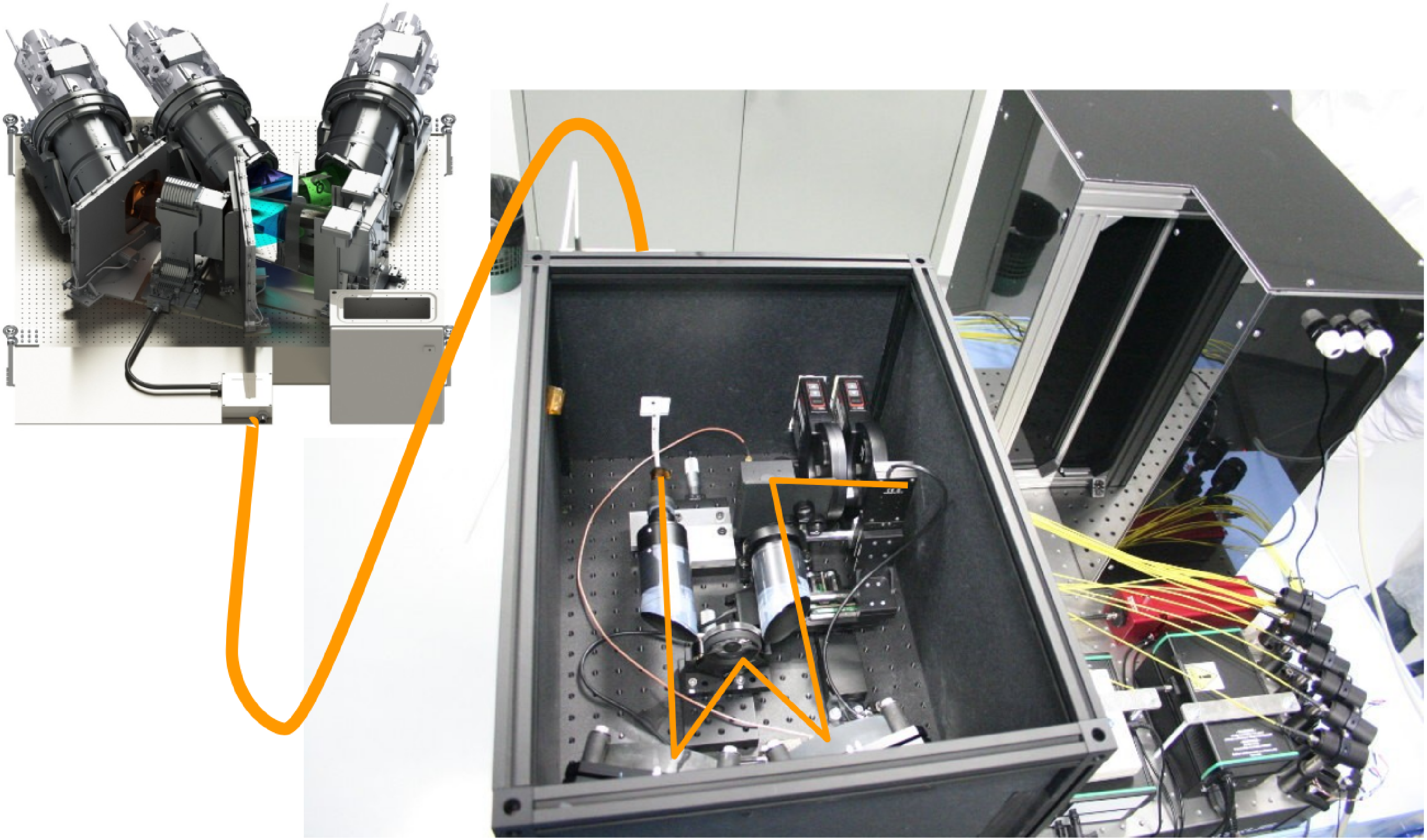
Photodiode Calibration & checks at LPNHE



See DESI-2635 (LLG)

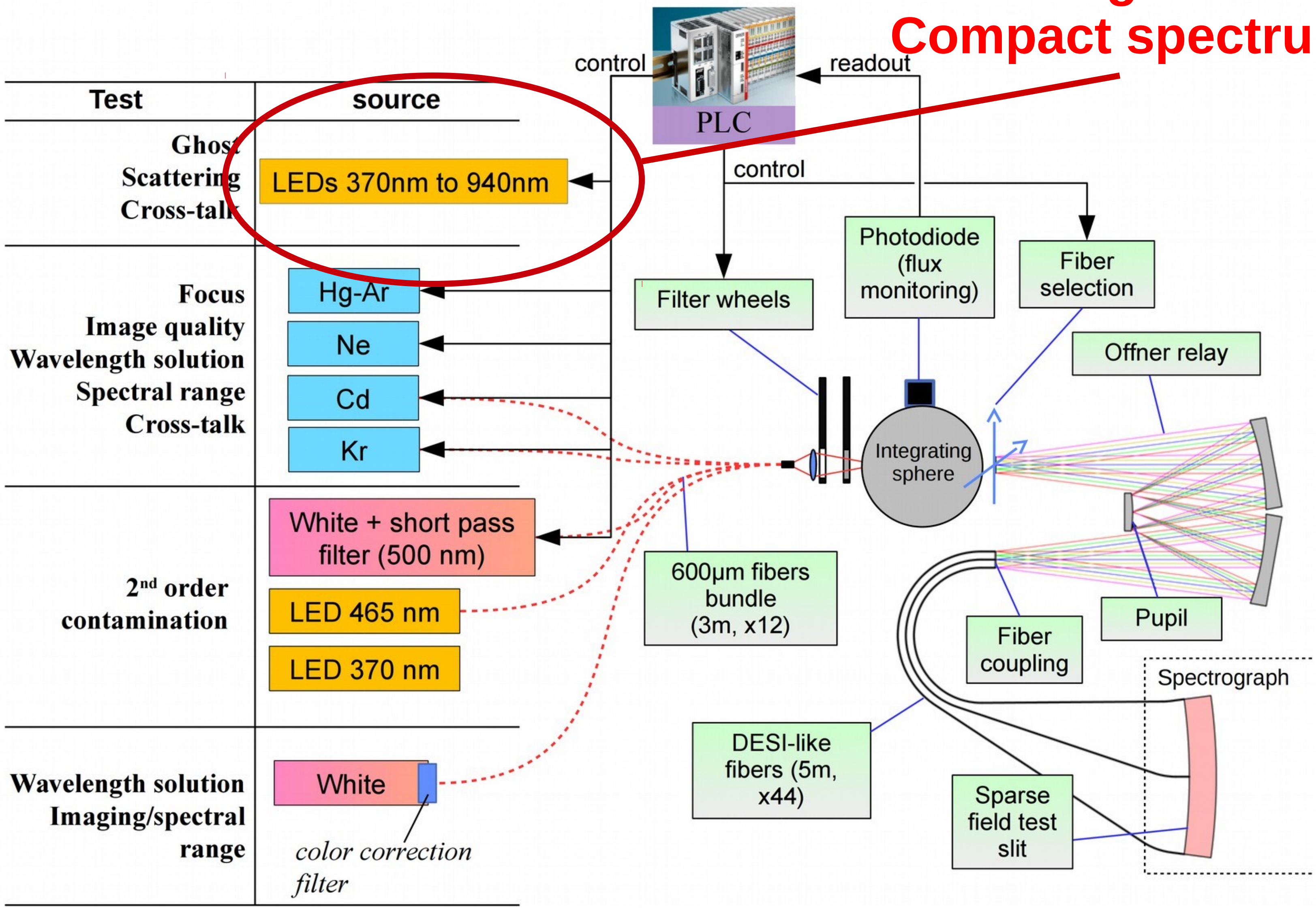


Illumination Testbench

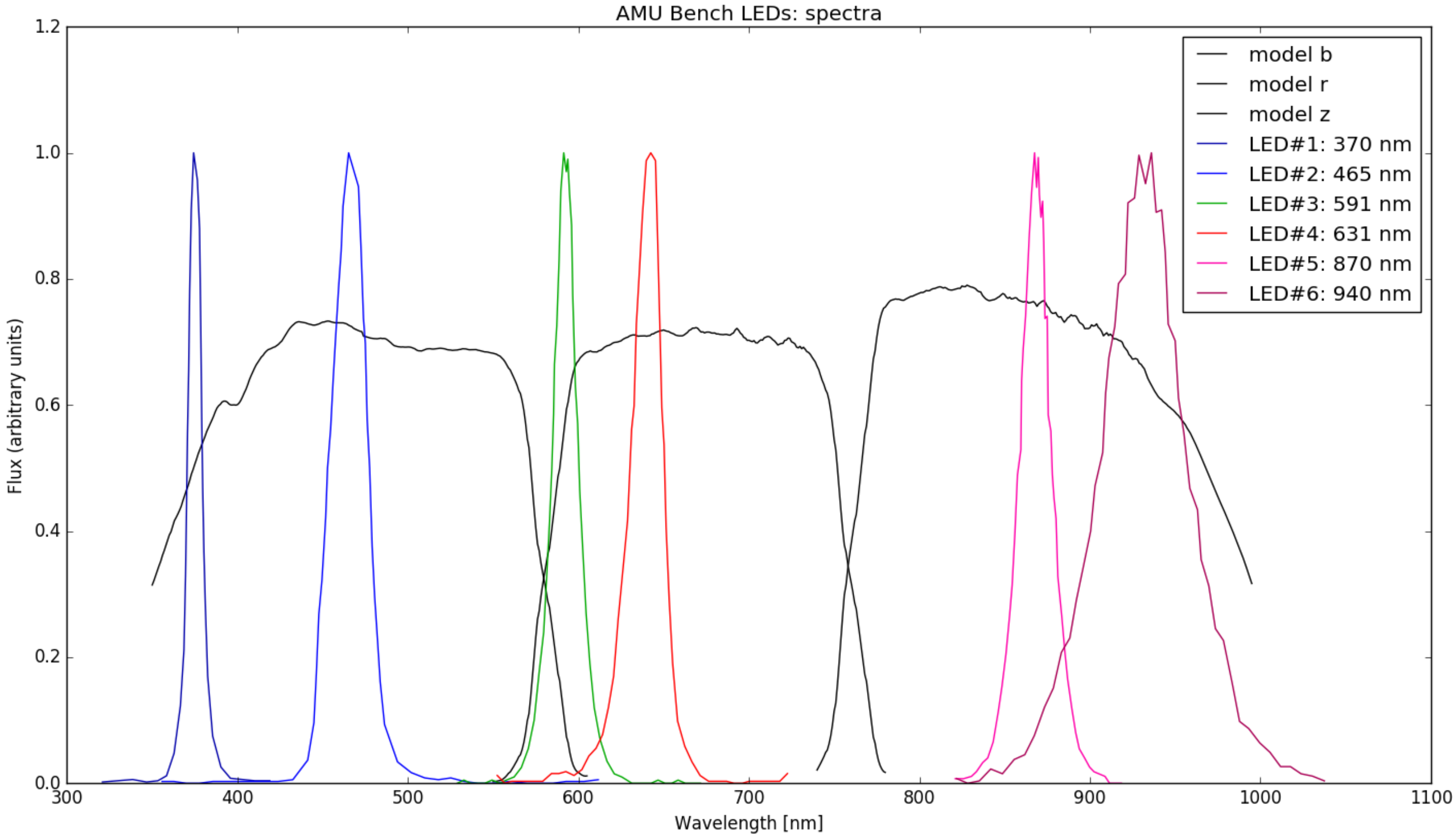


Illumination Testbench (AMU)

LED : bright enough
Compact spectrum !

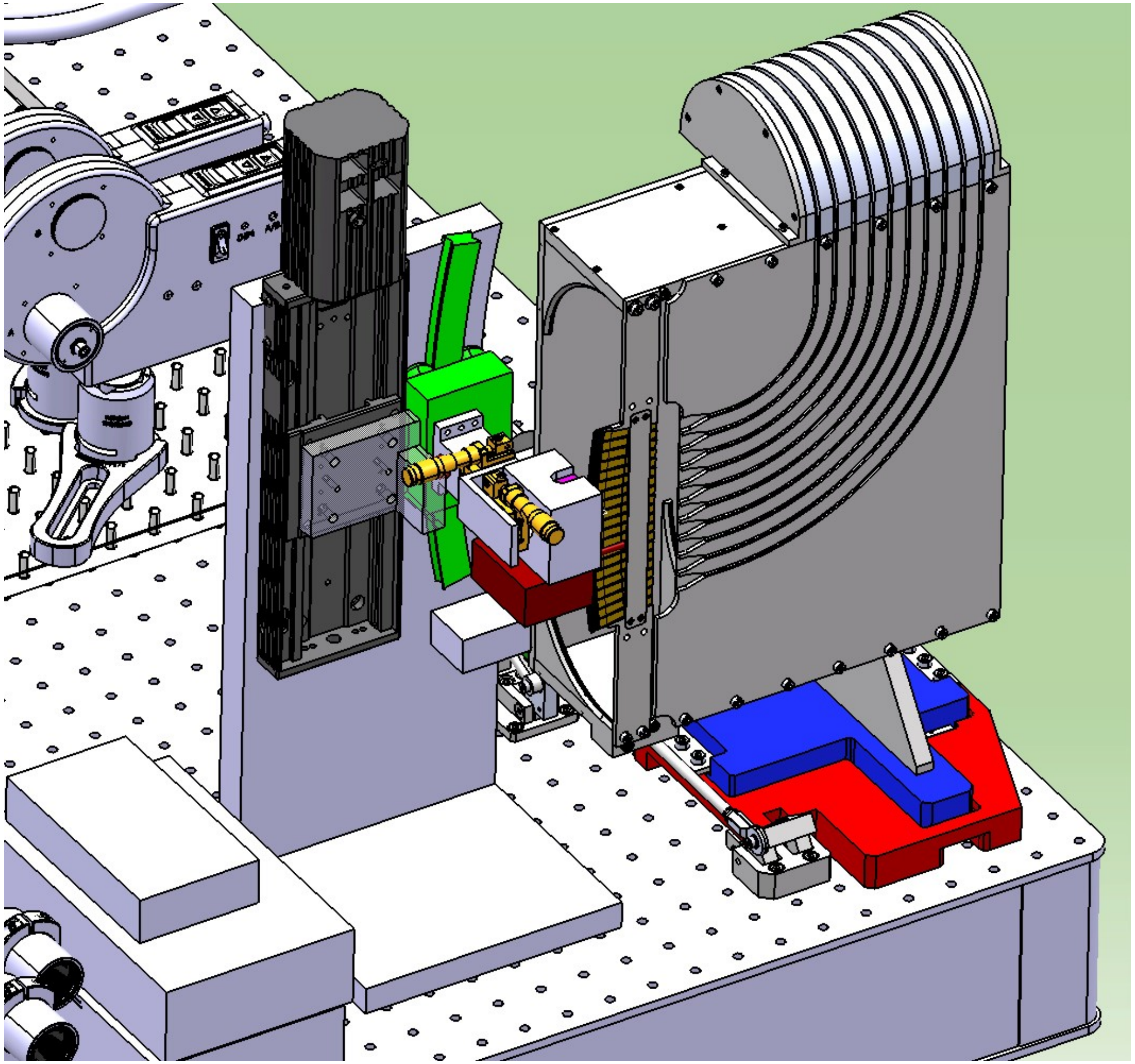


LED spectra: compact spectra

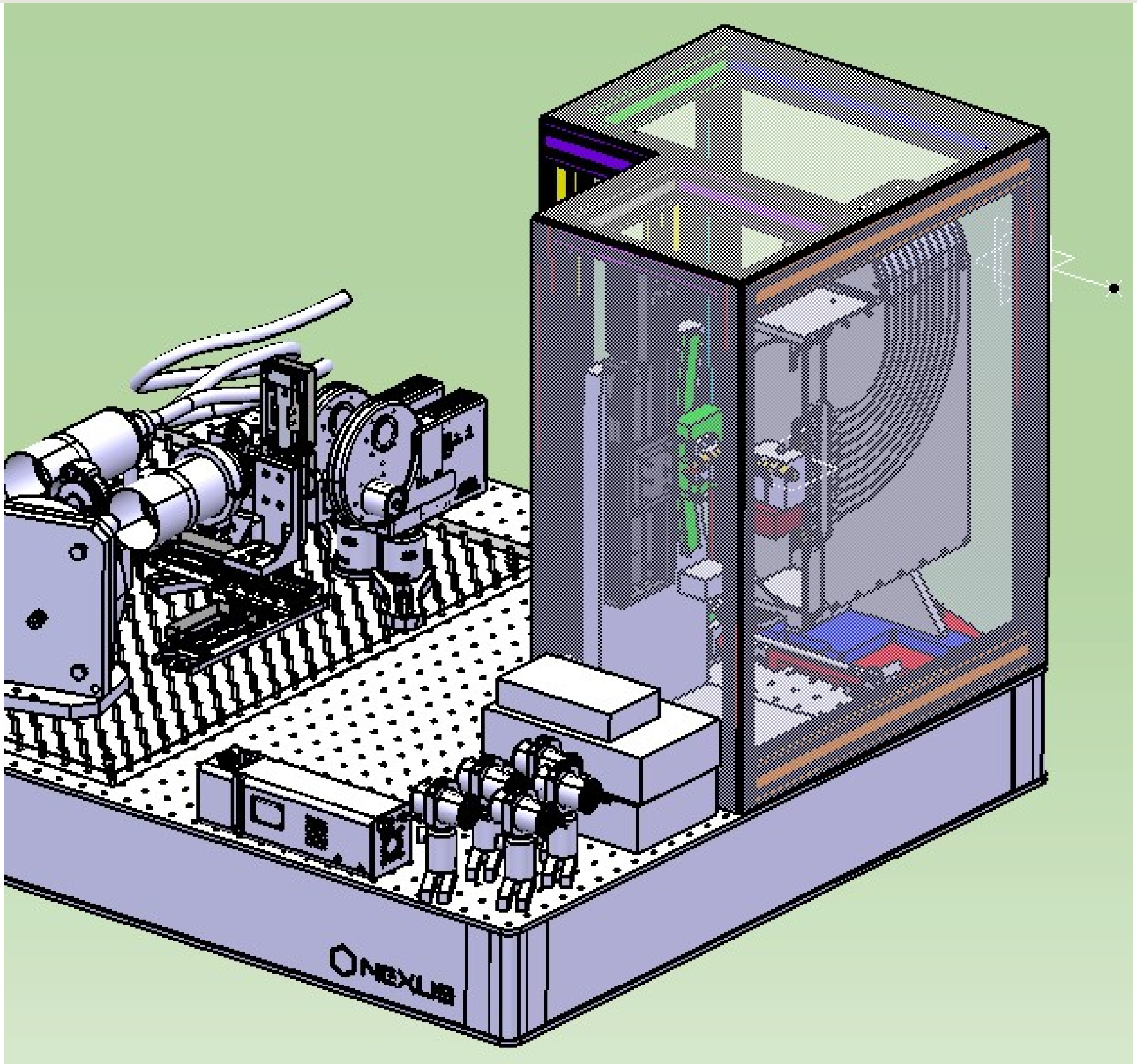


Integration on the AMU Testbench

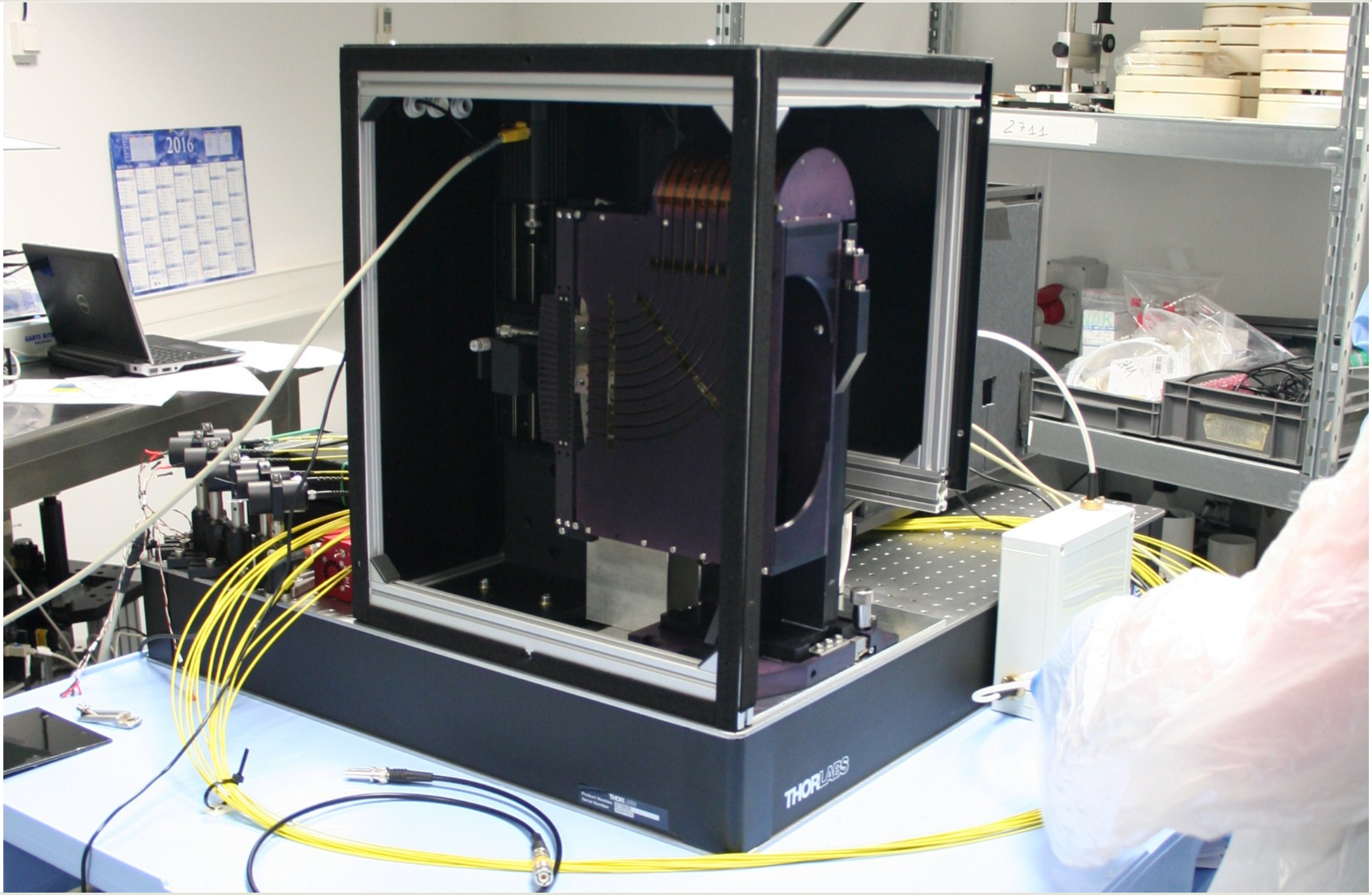
- **Challenging mechanical interface** between the fiber slit and our device (collision with fiber ends should be avoided at all cost!!)
- **Integration within the AMU testbench software** and the **ICS** (Xavier Regal, AMU)



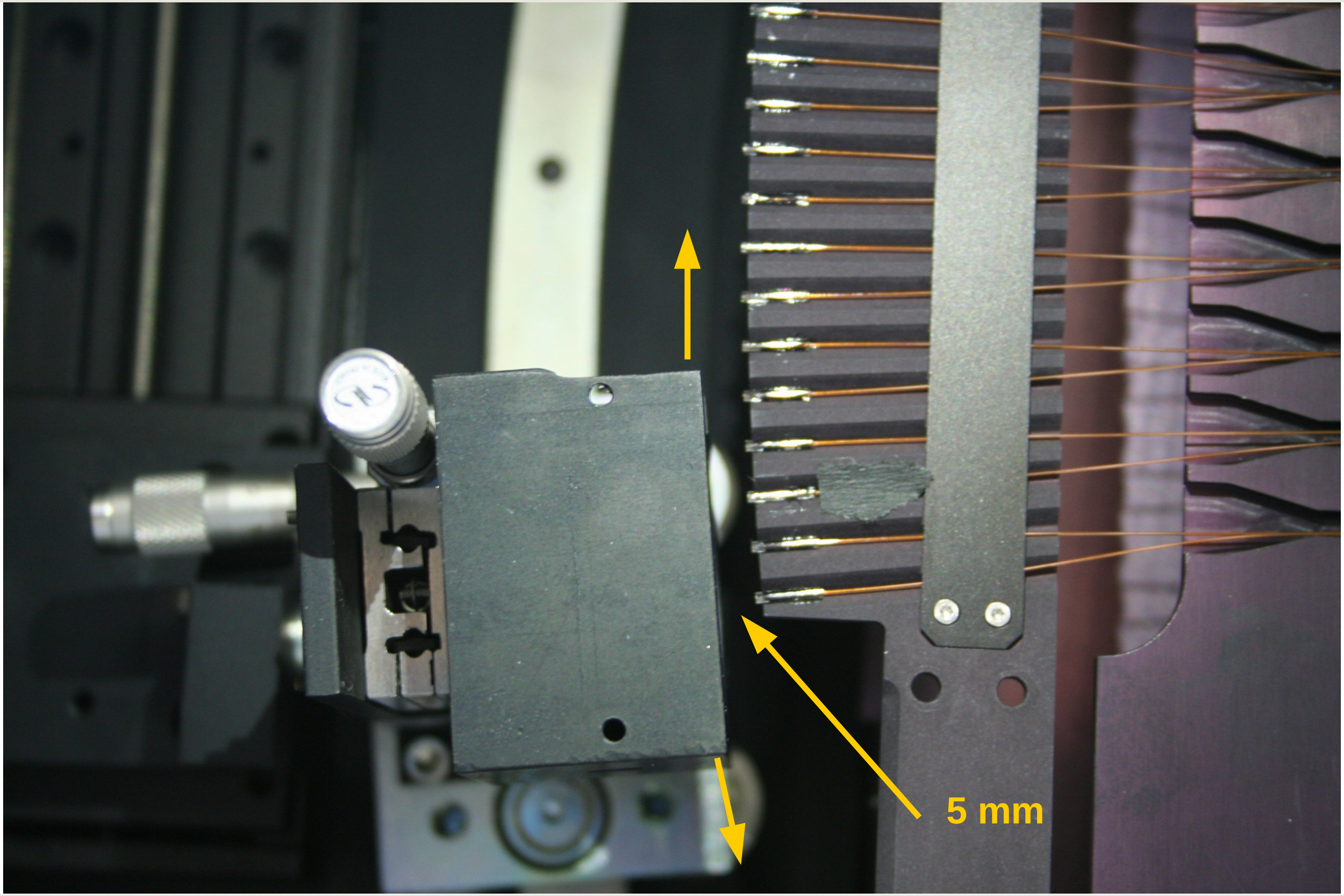
Integration on the AMU Testbench (dark box)



Installation at Winlight (sept. 2016)



Installation of our device at Winlight



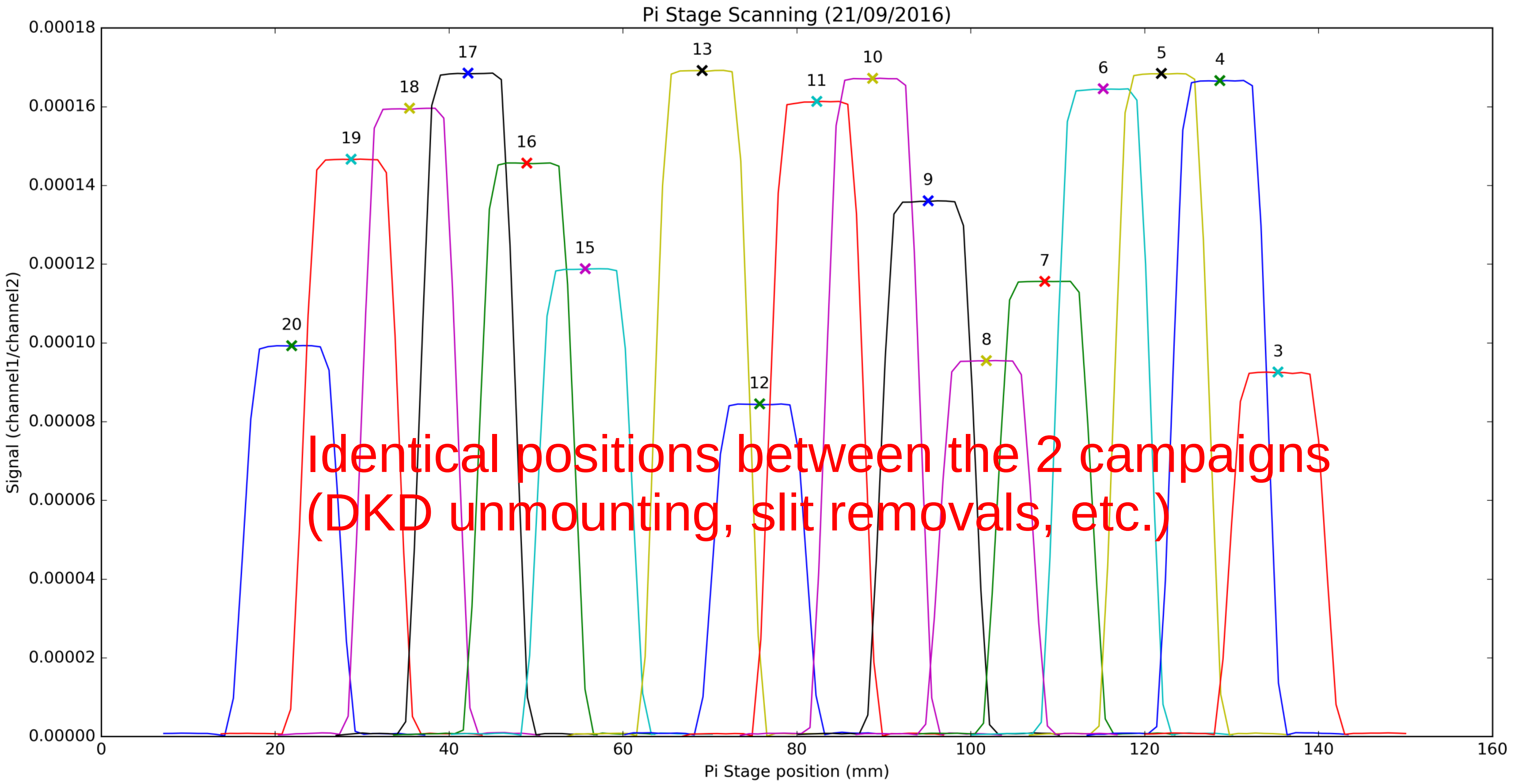
Meas. campaigns: EM#01 (2017) & SM#01 (2018)

- **1st campaign: Jan 31 to Feb 2, 2017 (LLG, JG, PEB, SR) & 2nd campaign: March 14 – 17, 2017 (LLG, PEB, SR)**
  - **Absolute flux measurements** (sparse slit in the box)
  - **Separate spectra of all LEDs / individual fibers** (slit in spectro)
  - Scanning the fiber beam with the entire 10x10 photodiode
  - ***Scanning the fiber output beam with a 100 µm slit*** *in front of the photodiode (to model the beam and estimate the FRD) [2nd campaign]*
  - CCD frames (W) to estimate **true shutter time** and **the amplifier gains**
  - ***Flat slit*** *available: for* ***better ampli. gain measurements*** *[2nd camp.]*
- **3rd campaign: July 3 – 5, 2017 (LLG, PEB) :** shutter problems
- **4th campaign: April 7th-12th, 2018 (LLG, PEB) : SM#01.**

Throughput measurement principles

- Measurement to be done during **slit removal/reinstall** repeatability test (limited overhead)
- **Calibration of the total flux** at the exit of each fiber of the sparse fiber slit
- **Proposed Procedure** : for the same illumination setups (LEDs)
  - **(1) Sparse Test Slit outside of the spectrograph, in front of our device** : flux (in the same illumination conditions) measured by our calibrated photodiode for each LED / fiber ;
  - **(2) Sparse Test Slit inside the spectrograph** : integrated flux measured on the CCD for the 3 arms of the spectrograph for each LED / fiber ;
  - **Ratio (1)/(2)** gives **throughput** (from fiber exit to the CCD included)

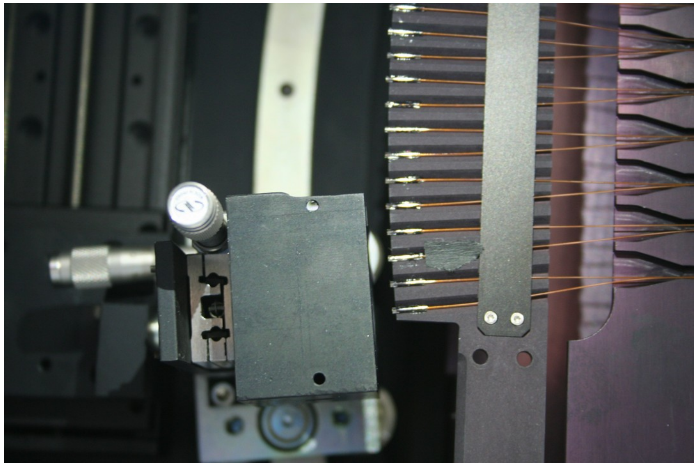
Scan of all the sparse slit fibers (centering)

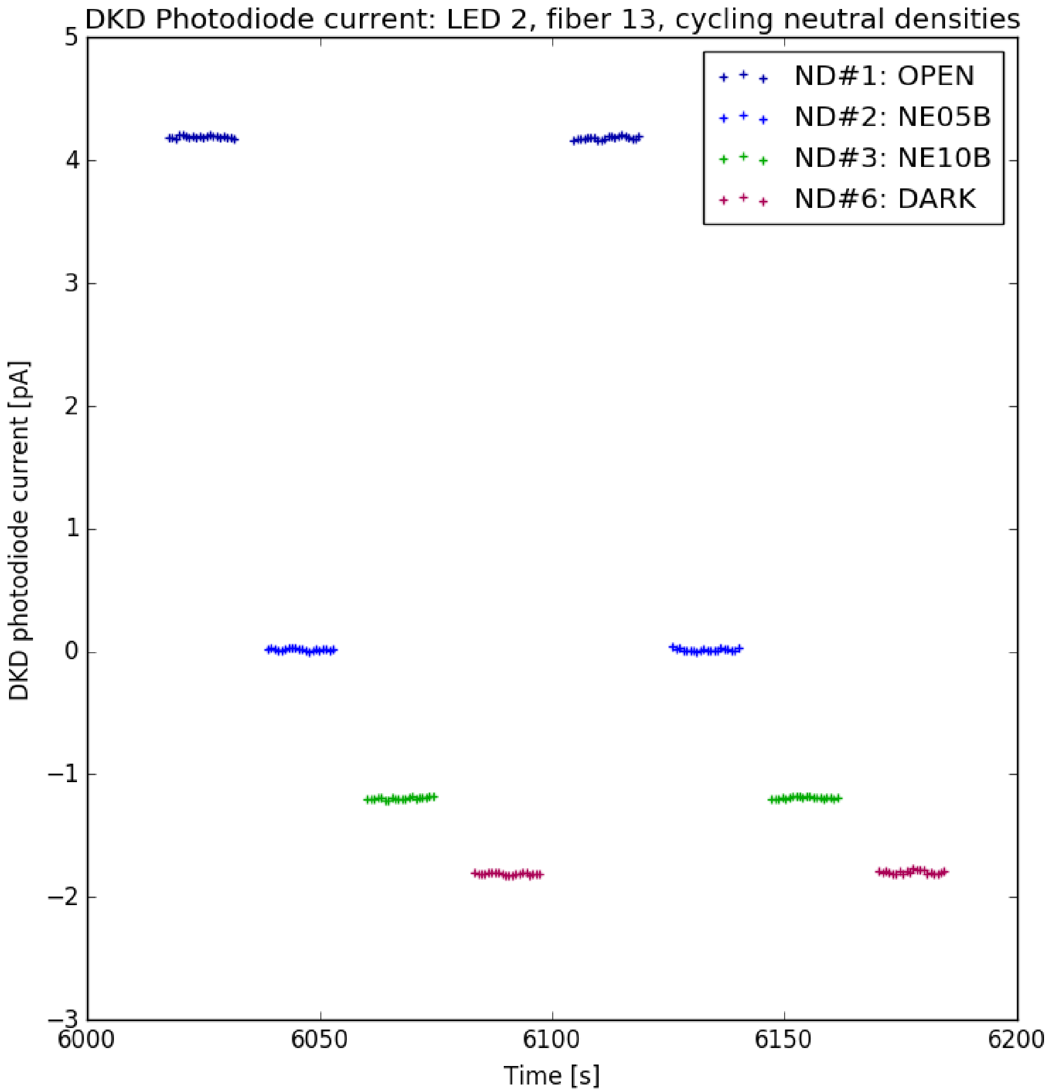


1 broken fiber; last one unreachable (mechanical limit)

Absolute flux measurements (DKD photocurrent)

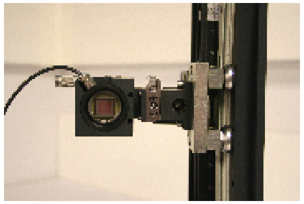
- **For each fiber, for each LED :**
  - centering the DK photodiode to catch the whole beam
  - measuring the photocurrent
- **Cycling over OPEN, DARK, and other neutral densities filters**
- **Subtracting dark current**
- **Photocurrents RMS < 0.01 pA**



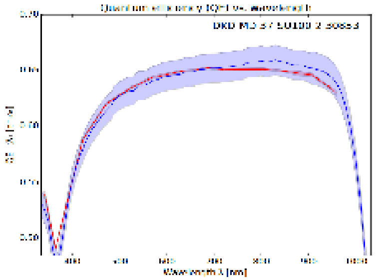


DKD photocurrents analysis

I(t) [pA] ; [e−/s]

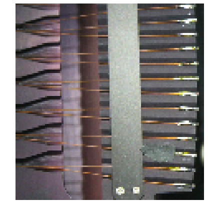


DKD Photodiode + Keithley 6514



/ QE [e−/photon]

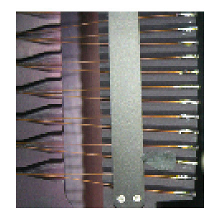
ϕ_{total} **Total fiber flux [photon/s]**



Total LED flux from 1 fiber

FRD correction

$\phi_{injected}$ **Injected flux [photon/s]**



Injected LED flux from 1 fiber

$$\phi_{\mathrm{injected}} = \frac{I - I_{\mathrm{dark}}}{QE_{\mathrm{DKD,\ LED}}} \times \mathrm{FRD}_{\mathrm{fiber}}$$

$$QE_{\mathrm{DKD,\ LED}} = \frac{\int \phi_{\mathrm{LED}}(\lambda) QE_{\mathrm{DKD}}(\lambda)\, d\lambda}{\int \phi_{\mathrm{LED}}(\lambda)\, d\lambda}$$

Throughput measurement principles

- Measurement to be done during **slit removal/reinstall** repeatability test (limited overhead)
- **Calibration of the total flux** at the exit of each fiber of the sparse fiber slit
- **Proposed Procedure** : for the same illumination setups (LEDs)
  - **(1) Sparse Test Slit outside of the spectrograph, in front of our device** : flux (in the same illumination conditions) measured by our calibrated photodiode for each LED / fiber ;
  - **(2) Sparse Test Slit inside the spectrograph** : integrated flux measured on the CCD for the 3 arms of the spectrograph for each LED / fiber ;
  - **Ratio (1)/(2)** gives **throughput** (from fiber exit to the CCD included)

Integrated LED flux [e-/s] on the 3 CCDs

- For **each LED**, for **each fiber** 11 – 20, a **separate exposure**
- Frames are reduced (DESI pipeline), spectrum region is integrated
- CCD amplifier gains [ADU → e-] are applied
- Resulting CCD flux [e-] is then **divided by the effective exposure time**
- The resulting spectrum is **integrated on the whole arm wavelength range**

$$\phi^{\mathrm{CCD}}_{[\mathrm{e\text{-}/s}]} = \frac{\mathrm{gain}^{\mathrm{ampli}}_{[\mathrm{e\text{-}/ADU}]} \times \sum\limits_{\mathrm{ill.\ pixels}}^{\mathrm{spectrum}} \phi^{\mathrm{CCD}}_{[\mathrm{ADU}]}(\mathrm{pixel})}{\Delta t^{\mathrm{exposure}}_{[\mathrm{s}]}}$$

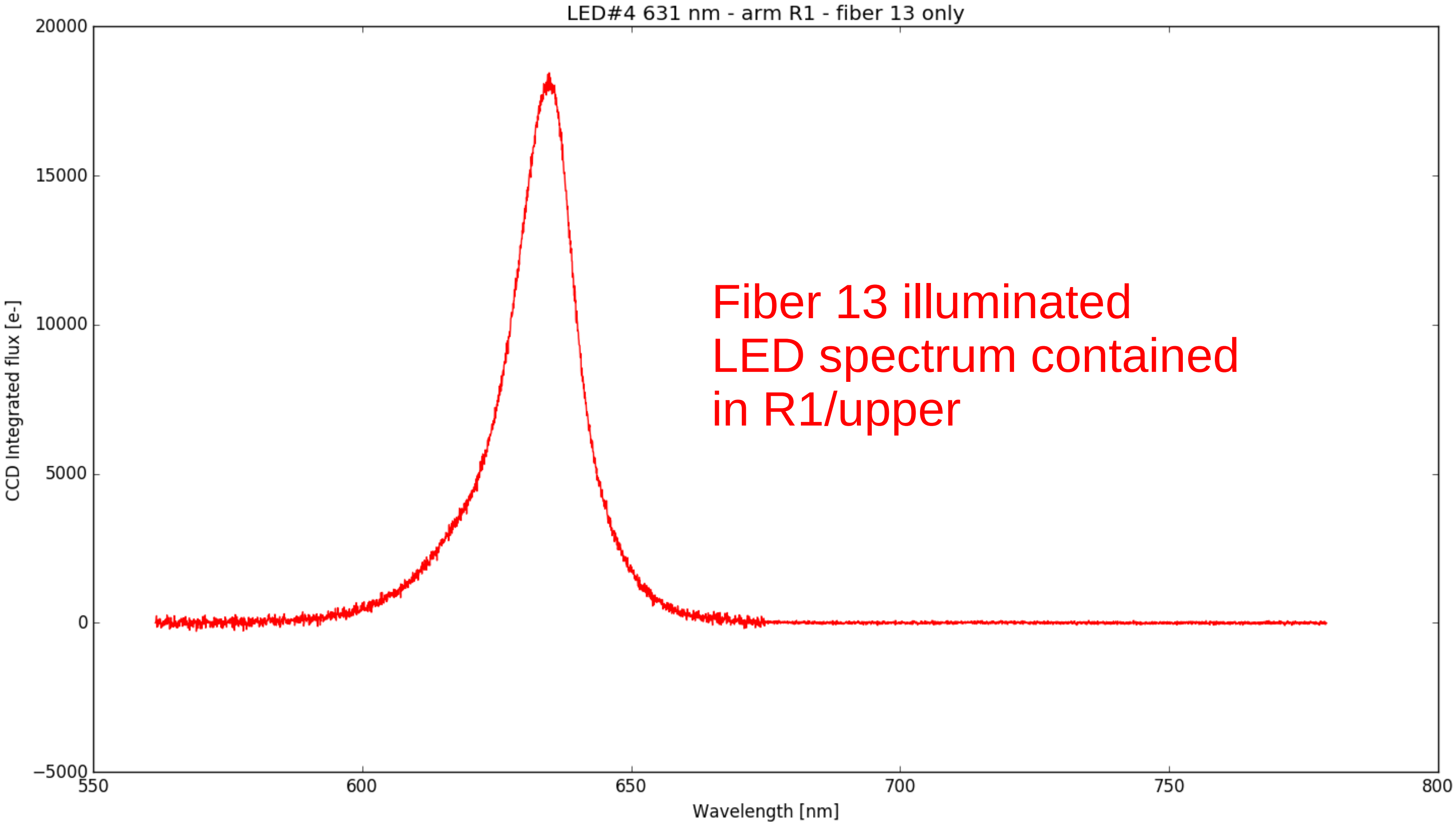
- **We need to calibrate the exposure time and the CCDs amplifiers gains**

LED spectrum extraction (pipeline JG)

- **Removing Bias / Dark current** (dark model)
- **Automatic extraction of all fiber spectra**
- **« Boxcar » : sum on 9 CCD pixel wide**
- Wavelength calibration from lamps and PSF model
  - Wavelength calibration better than 0.1 nm

    (no temperature correction)
- We verify that the **background is consistent with zero**
- We assume gain = 1 and the **gain correction is applied later**

Ex: spectrum in DESI arm R1: LED#4: 631 nm



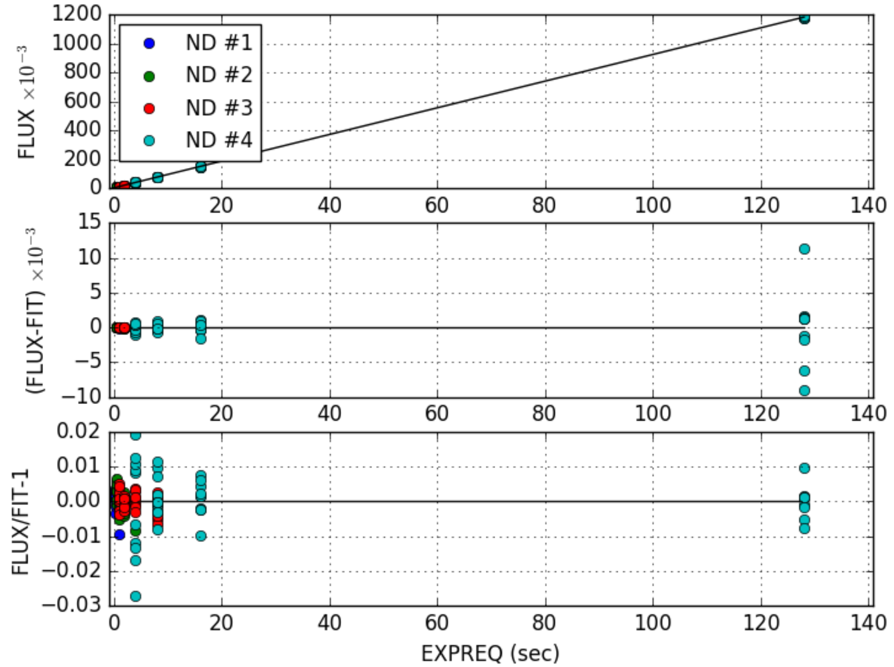
Exposure time : shutter time correction

- Series of exposures with **increasing exposure time** and **different neutral densities** filters have been taken (all campaigns).

- Non-linearity corrections were needed for EM#01.

- Shutter control system has been changed due to shutter problems in July 2017.

- Assuming at least linearity for low fluxes, we were able to estimate an effective exposure time correction (**same result on the 3 arms**) :



$$\Delta t^{\mathrm{EM\#1}}_{\mathrm{effective}} = [\mathrm{EXPREQ}] + 0.36\,\mathrm{s} \pm 0.01\,\mathrm{s}$$

$$\Delta t^{\mathrm{SM\#1}}_{\mathrm{effective}} = [\mathrm{EXPREQ}] + 0.662\,\mathrm{s} \pm 0.003\,\mathrm{s}$$

Amplifier gain determination (DESI-2657)

- We measured the amplifier gains **with a PTC (Pixel Transfer Curve)** (variance versus mean flux curve)

- Amplifier gains were estimated in two ways :

  - **Tungsten lamp spectra** (DESI-2657),
    → ramp of exposure time, exposure pairs

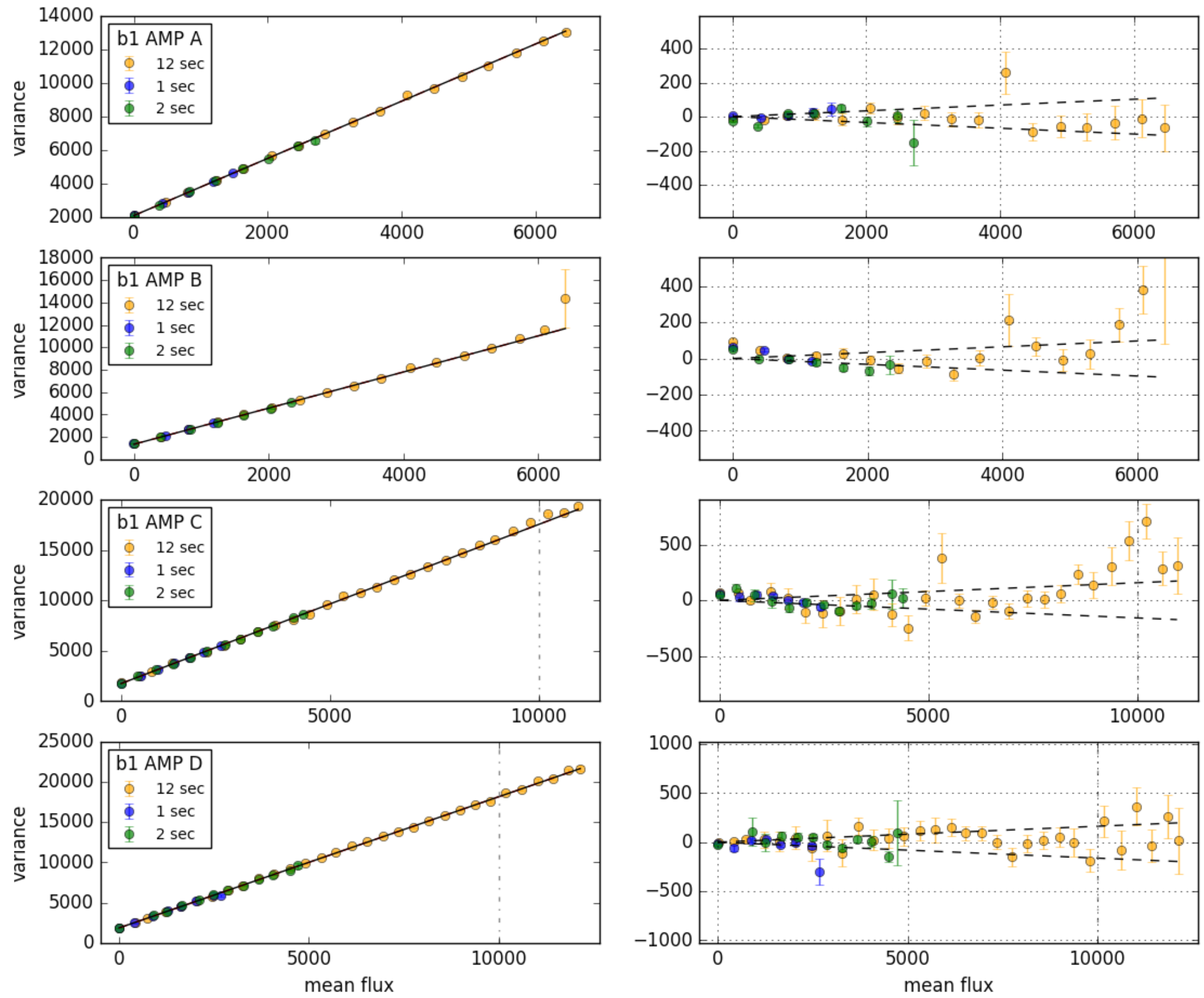
  - **Flat with flat slit**, **tungsten**, (2017-03-29),
    → ramp of exposure time, exposure pairs

EM#1: Amp. gain determination : PTC (arm B)

- **Building PTC** (photon transfer curve) **for each CCD amplifier**
- **b amplifiers** are reasonably **linear**
- **Using tungsten spectra**

Amplifier	gain
B1-A	0.587
B1-B	0.614
B1-C	0.630
B1-D	0.615

- **See DESI-2657 (JG)**

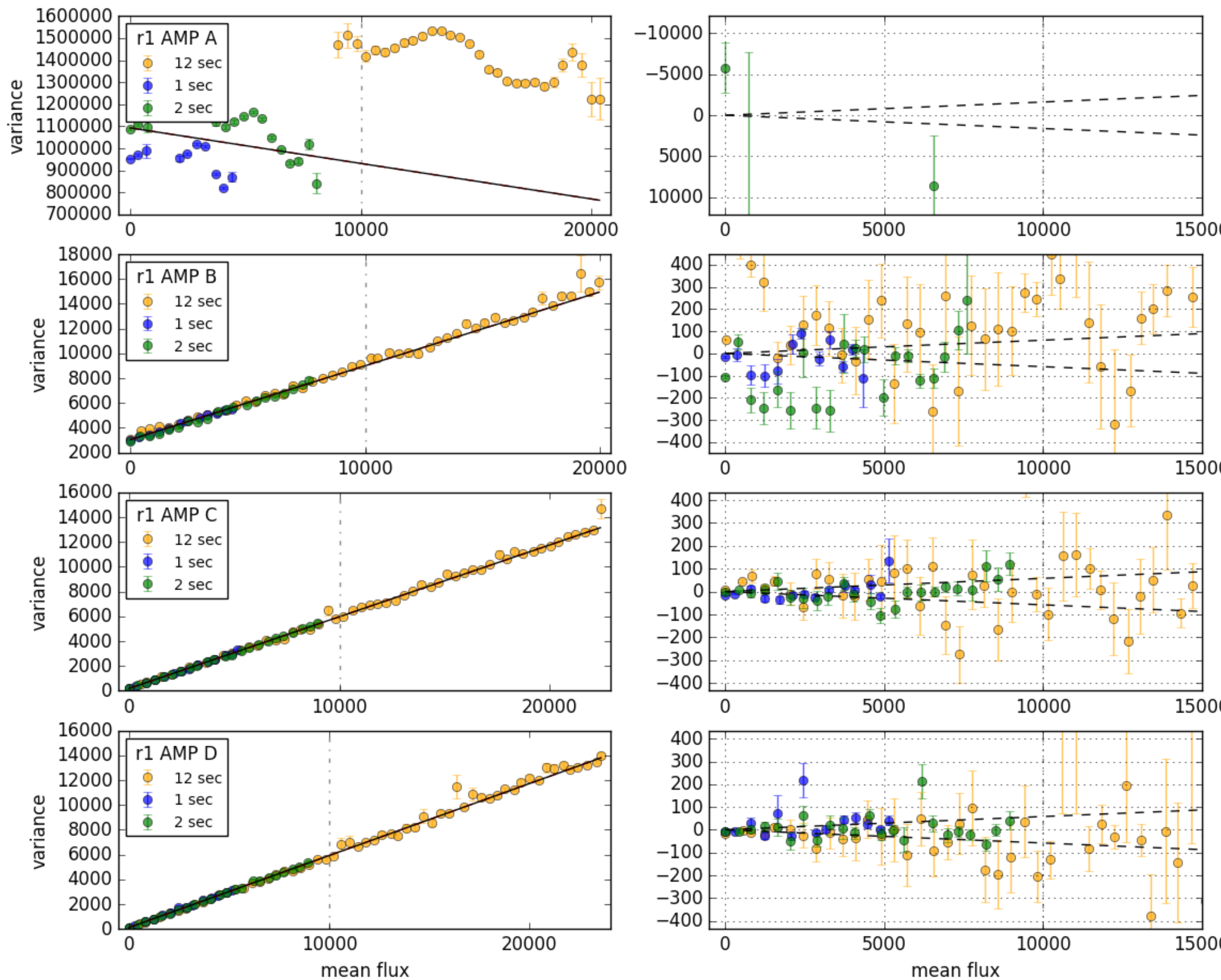


EM#1: Amp. gain determination : PTC (arm R)

- Amplifier r1-A **unusable**
- **Other r amplifiers** are reasonably **linear**
- **Using tungsten spectra**

Amplifier	gain
R1-A	unusable
R1-B	1.658
R1-C	1.726
R1-D	1.723

- **See DESI-2657 (JG)**

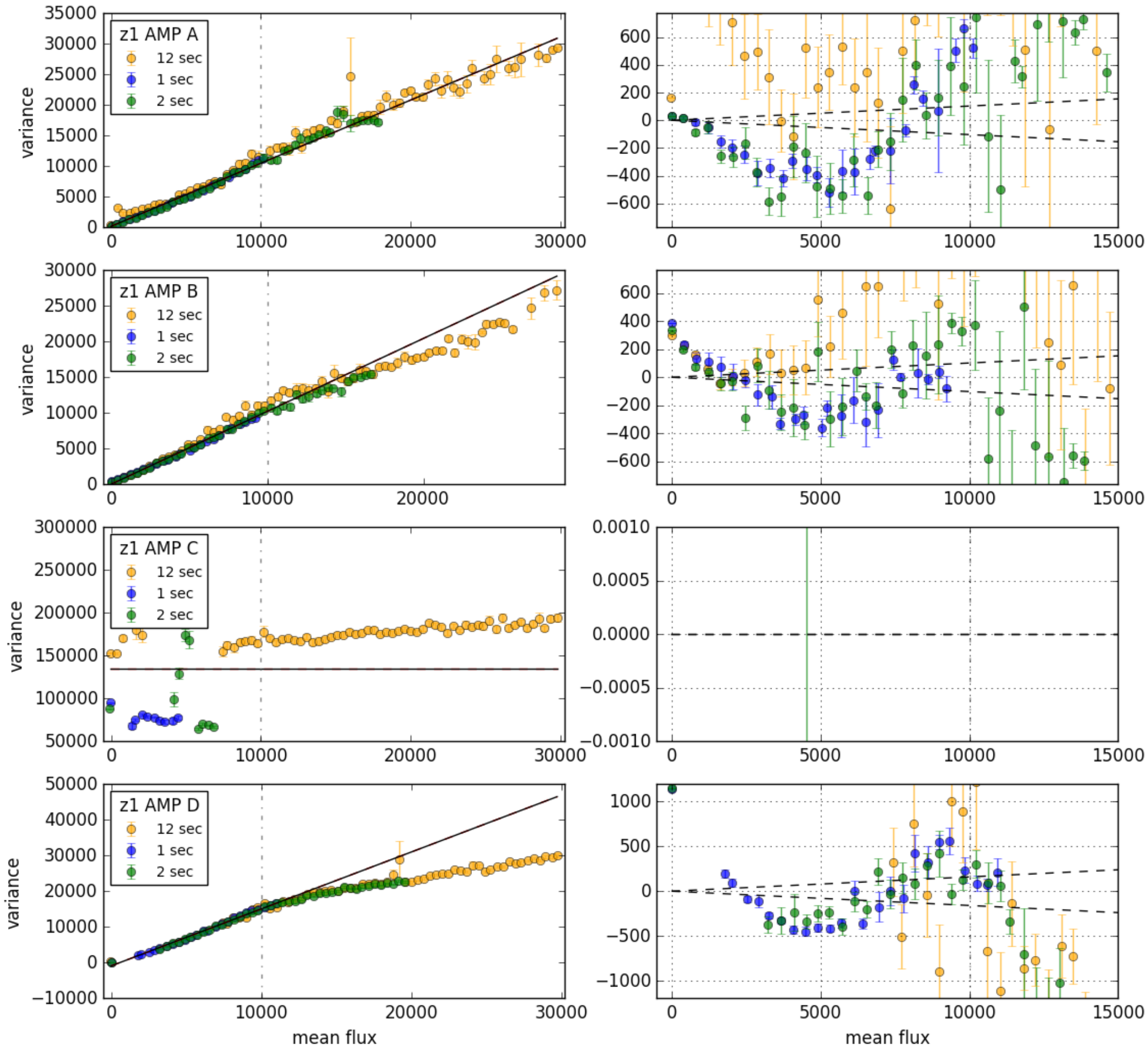


EM#1: Amp. gain determination : PTC (arm Z)

- Highly **non-linear** amplis
- Z1-C **unusable**
- **Using tungsten spectra**

Amplifier	Gain (< 5000)
Z1-A	1.072
Z1-B	1.135
Z1-C	Unusable
Z1-D	0.774

- **See DESI-2657 (JG)**



EM#1: Amp. gain (flat slit, tungsten)

- Gains obtained with a PTC with **flat slit exposure, tungsten lamp** :

Amplifier	gain
B1-A	0.546
B1-B	0.619
B1-C	0.624
B1-D	0.602

Amplifier	gain
R1-A	unusable
R1-B	1.681
R1-C	1.666
R1-D	1.677

Amplifier	Gain (< 5000)
Z1-A	–
Z1-B	1.047
Z1-C	???
Z1-D	0.687

- For this analysis, we used the gains **obtained from the flat slit exposures** (seem more reliable)

- **For b1 & r1, gain systematics around 3 %**

- **For z1, huge uncertainties due to the important non-linearity**

SM#1: Gains measured at CEA/Saclay (CM, JG)

- Much better CCDs, readout system
- Gains obtained with a PTC with **true flats on the CEA/Saclay testbench** after CCD integration into the cryostats (CM & colleagues).
- Gains were **double checked and slightly corrected** (JG).

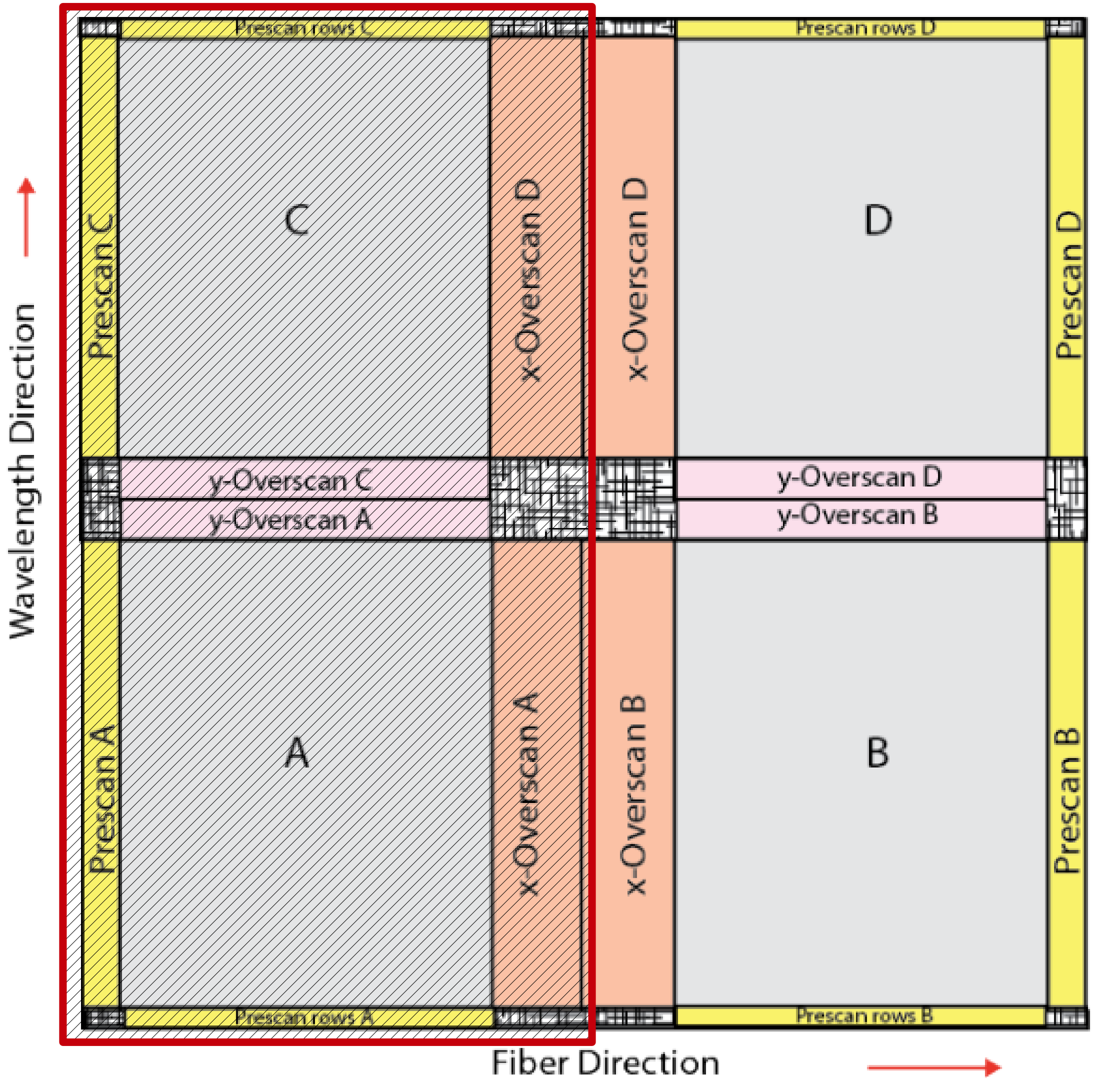
Amplifier	gain
B1-A	1.21 ± 0.04
B1-B	1.24 ± 0.03
B1-C	1.22 ± 0.05
B1-D	1.23 ± 0.03

Amplifier	gain
R1-A	1.76 ± 0.06
R1-B	1.69 ± 0.06
R1-C	1.63 ± 0.06
R1-D	1.55 ± 0.06

Amplifier	Gain
Z1-A	1.77 ± 0.11
Z1-B	1.75 ± 0.09
Z1-C	1.77 ± 0.05
Z1-D	1.66 ± 0.10

Measurement strategy: using fibers 11 – 20

- **For EM#1 :**
  - r1-A **unusable**
  - z1-C **unusable**
  - **We choose to take LED spectra only with amplifiers B and D → fibers 11 to 20**
  - **Limiting the flux in all spectra (< 5000 ADU in all pixels) to avoid amplifiers non-linearity**
- **For SM#1 : much better CCDs, but same strategy.**



Direct throughput estimate (without a model)

- We first estimate the spectrograph throughput by **dividing** the **integrated flux in each CCD** (for each LED and each fiber 11-20) by the **injected flux (DKD)** :

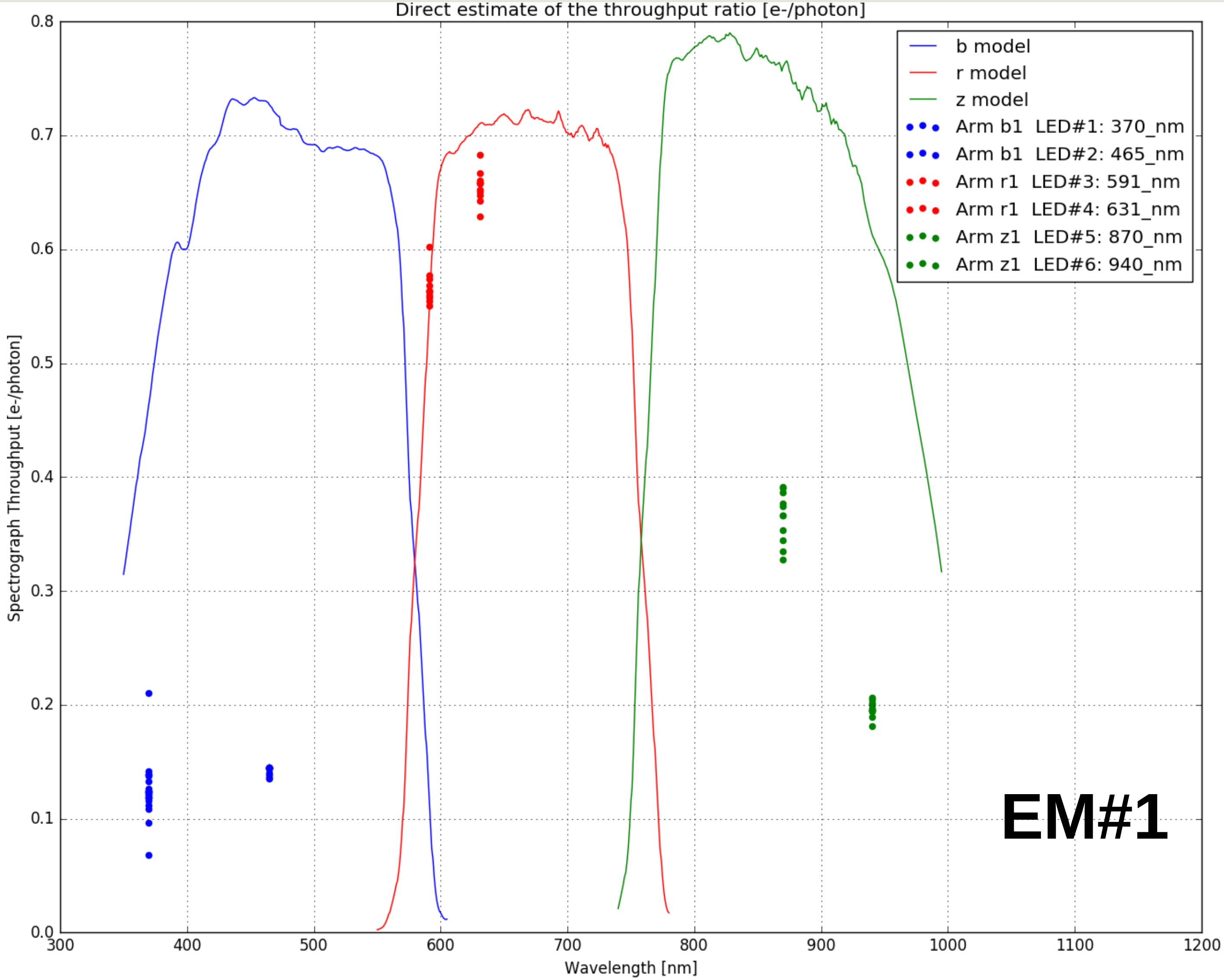
$$\eta_{[\text{e-}/\gamma]}(\lambda_{\text{LED}}) = (QE_{\text{CCD}} \times T_{\text{optics}}(\lambda_{\text{LED}})) = \frac{\phi^{\text{CCD}}_{[\text{e-}/\text{s}]}(\text{LED})}{\phi^{\text{injected}}_{[\gamma/\text{s}]}(\text{LED})}$$

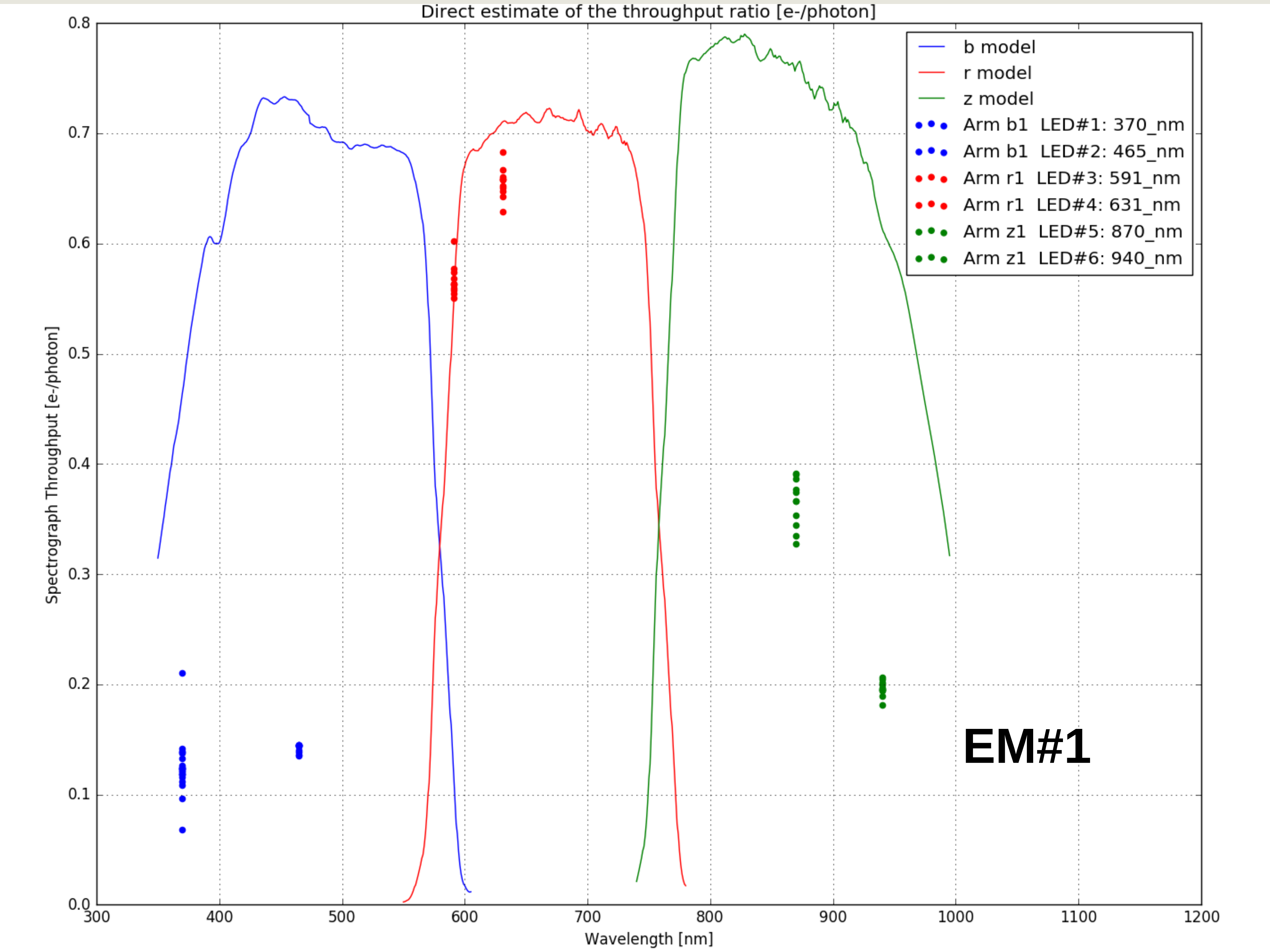
- A this step, no FRD correction (see below).

- What we got that way is an **estimate of the spectrograph throughput** at the LED wavelength (weighted by the LED spectrum)

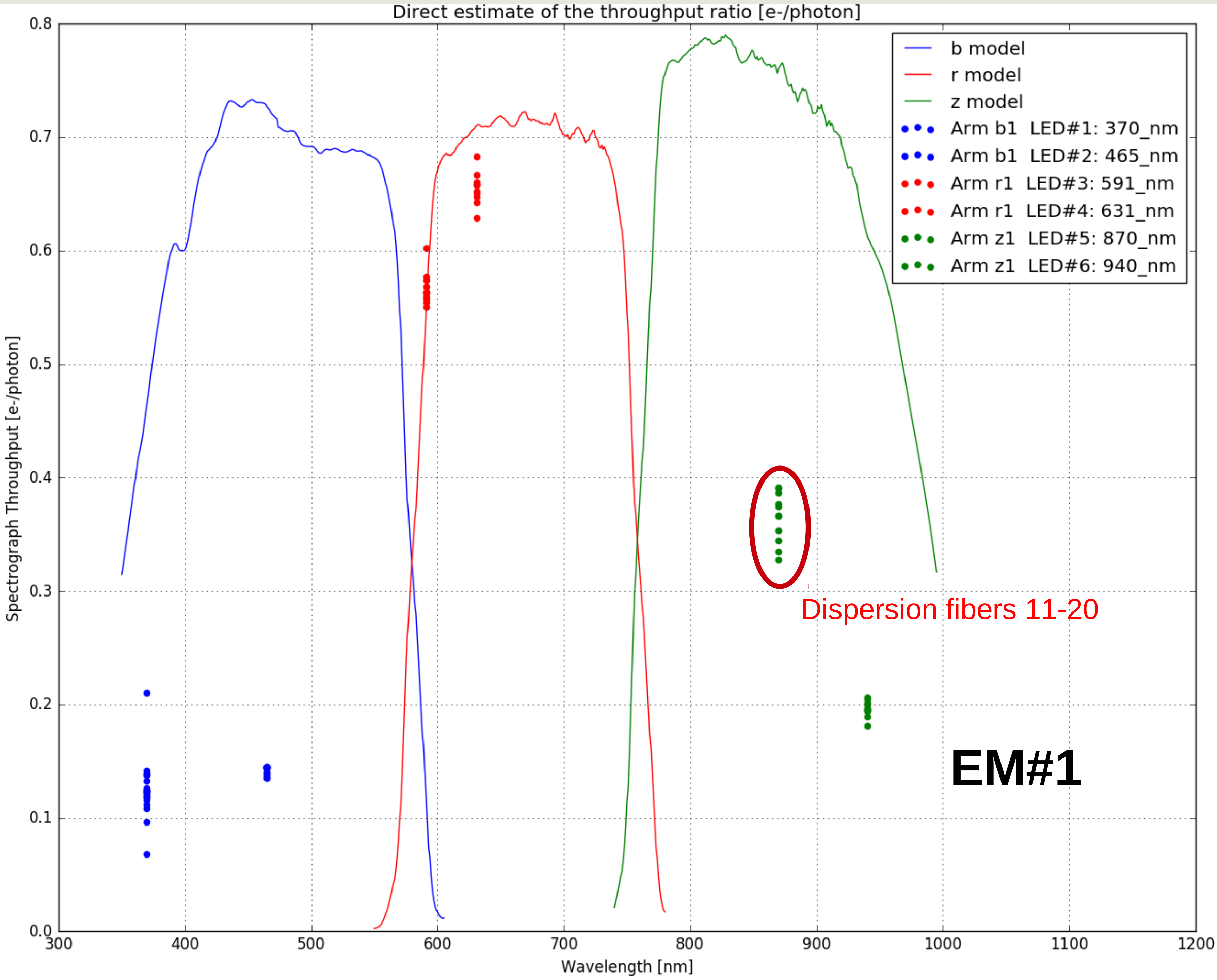
- Comparison with the **DESI optical model** (**without fibers**)

EM#1 : direct throughput estimate (no model)

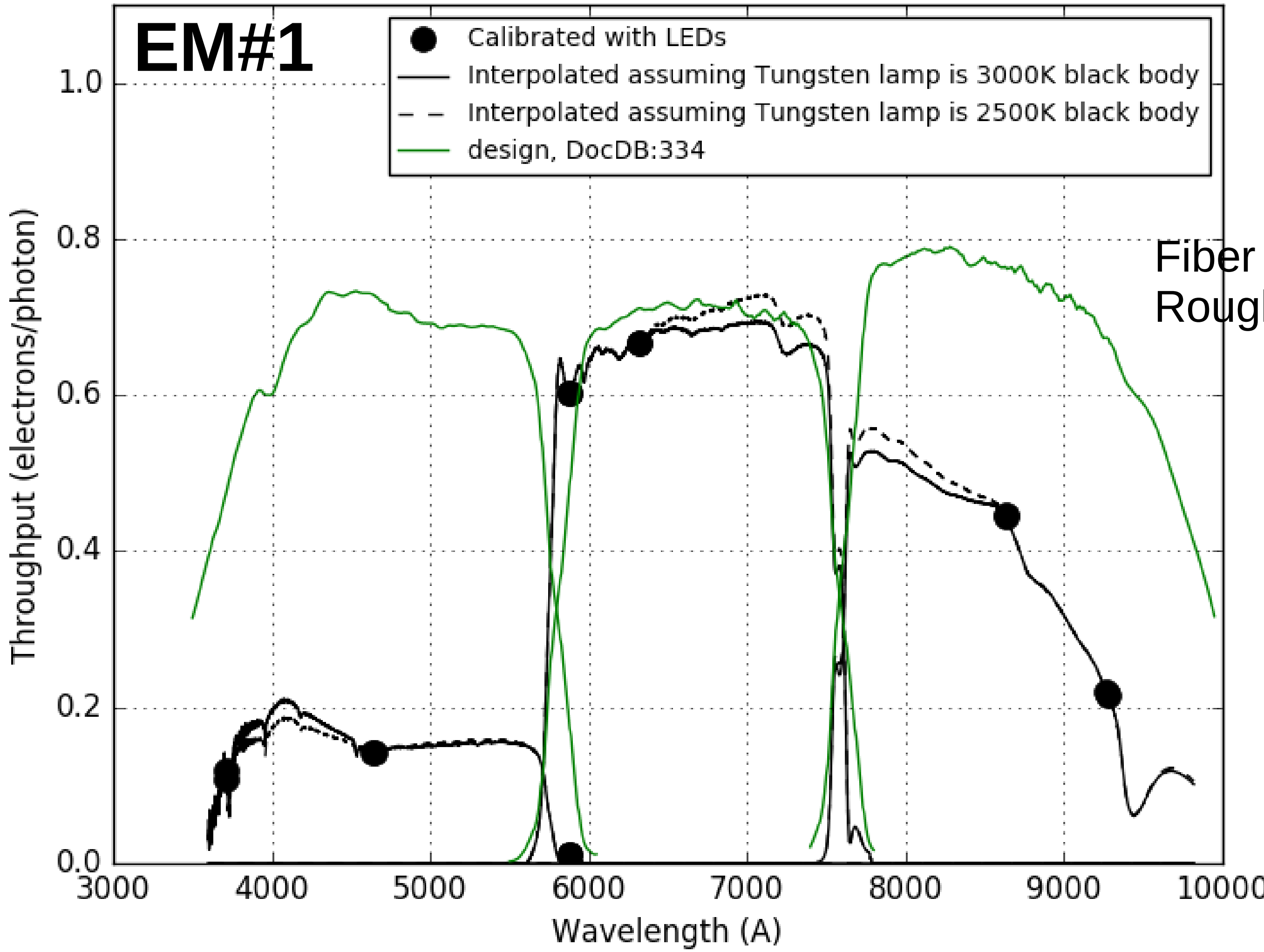




Direct estimate of the throughput ratio [e-/photon]
Spectrograph Throughput [e-/photon]
Wavelength [nm]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
300
400
500
600
700
800
900
1000
1100
1200
b model
r model
z model
Arm b1 LED#1: 370_nm
Arm b1 LED#2: 465_nm
Arm r1 LED#3: 591_nm
Arm r1 LED#4: 631_nm
Arm z1 LED#5: 870_nm
Arm z1 LED#6: 940_nm
EM#1

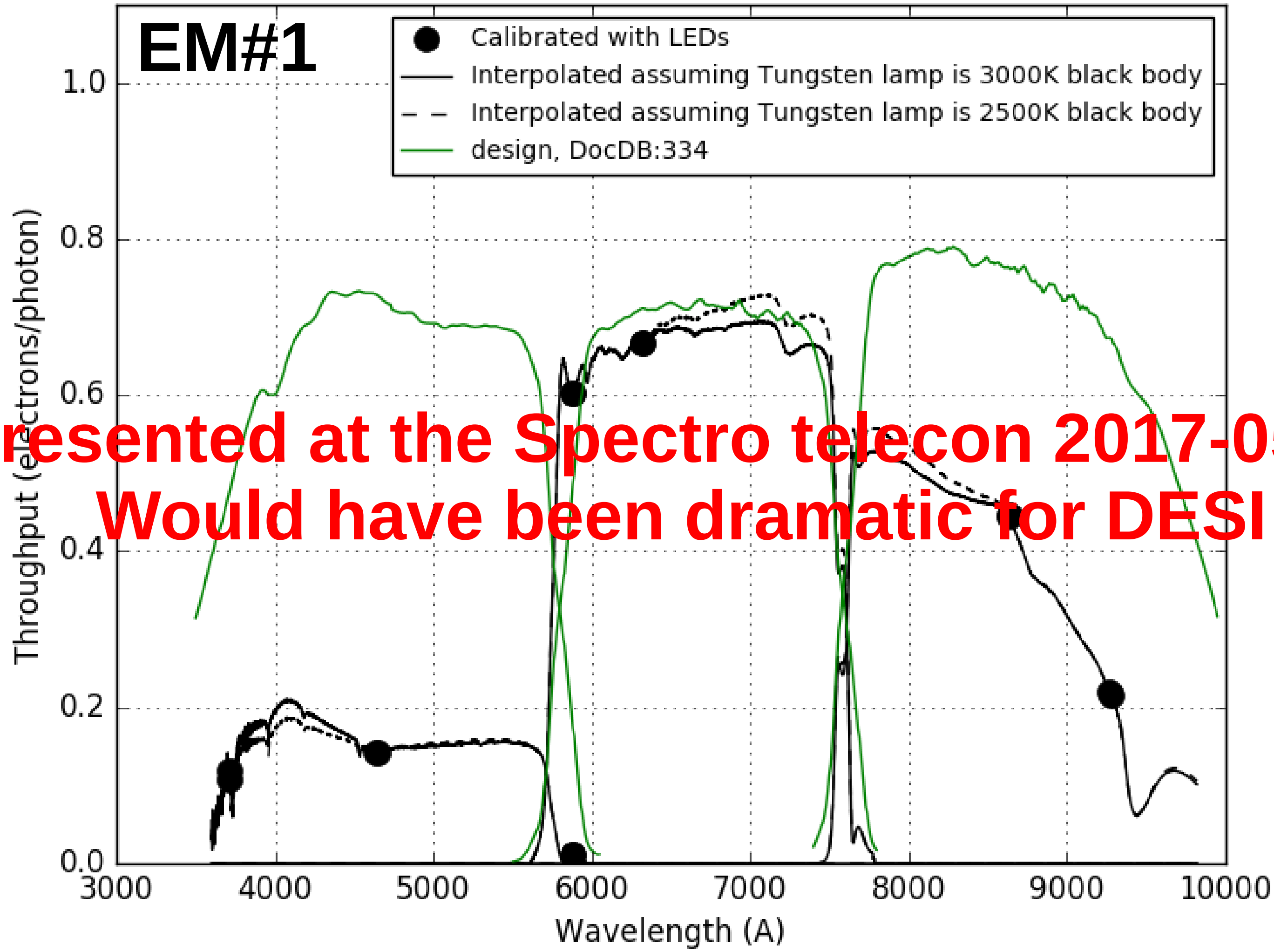

Direct estimate of the throughput ratio [e-/photon]
b model
r model
z model
Arm b1 LED#1: 370_nm
Arm b1 LED#2: 465_nm
Arm r1 LED#3: 591_nm
Arm r1 LED#4: 631_nm
Arm z1 LED#5: 870_nm
Arm z1 LED#6: 940_nm
Dispersion fibers 11-20
EM#1
Spectrograph Throughput [e-/photon]
Wavelength [nm]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
300
400
500
600
700
800
900
1000
1100
1200

With a model of the tungsten lamp spectrum



Fiber 13 only
Rough estimate

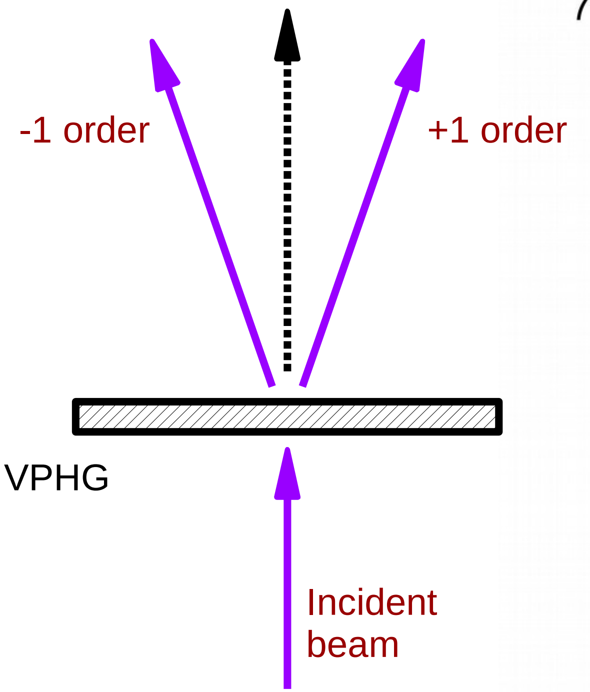
Result: Very Low Throughput in B & Z(NIR) arms

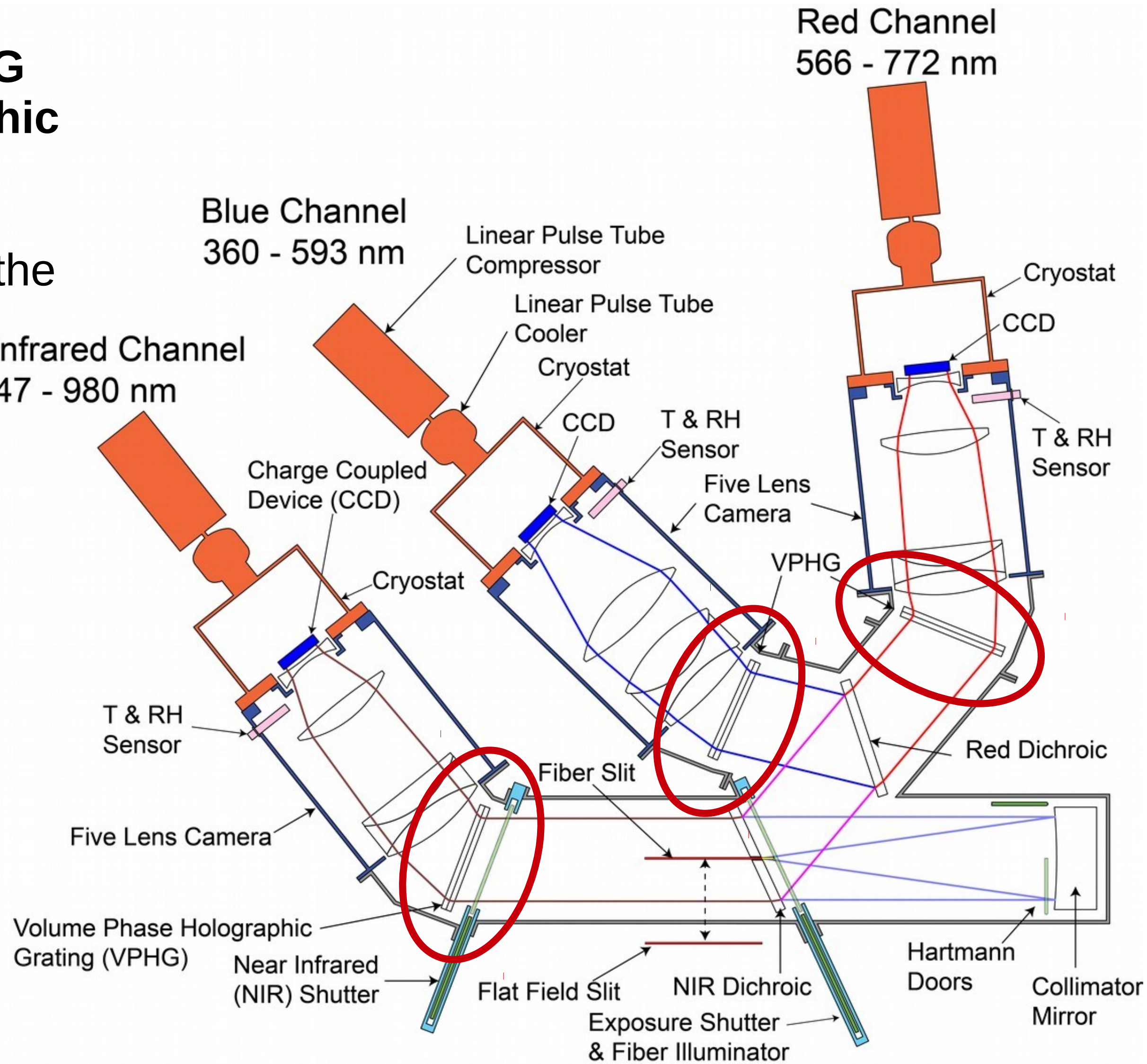


Presented at the Spectro telecon 2017-05-23
Would have been dramatic for DESI

Very Low Throughput in B and Z arms: why ?

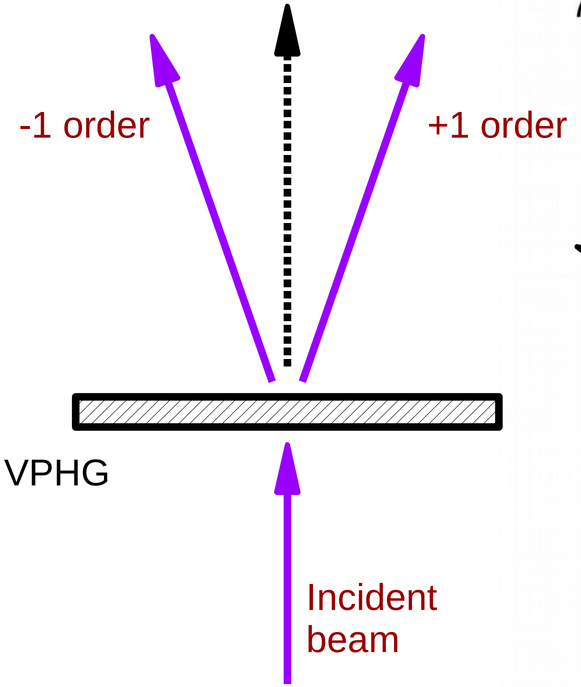
- **Possible culprit : the VPHG « Volume Phase Holographic gratings »**
- **Optimized** to send most of the flux **in order +1**

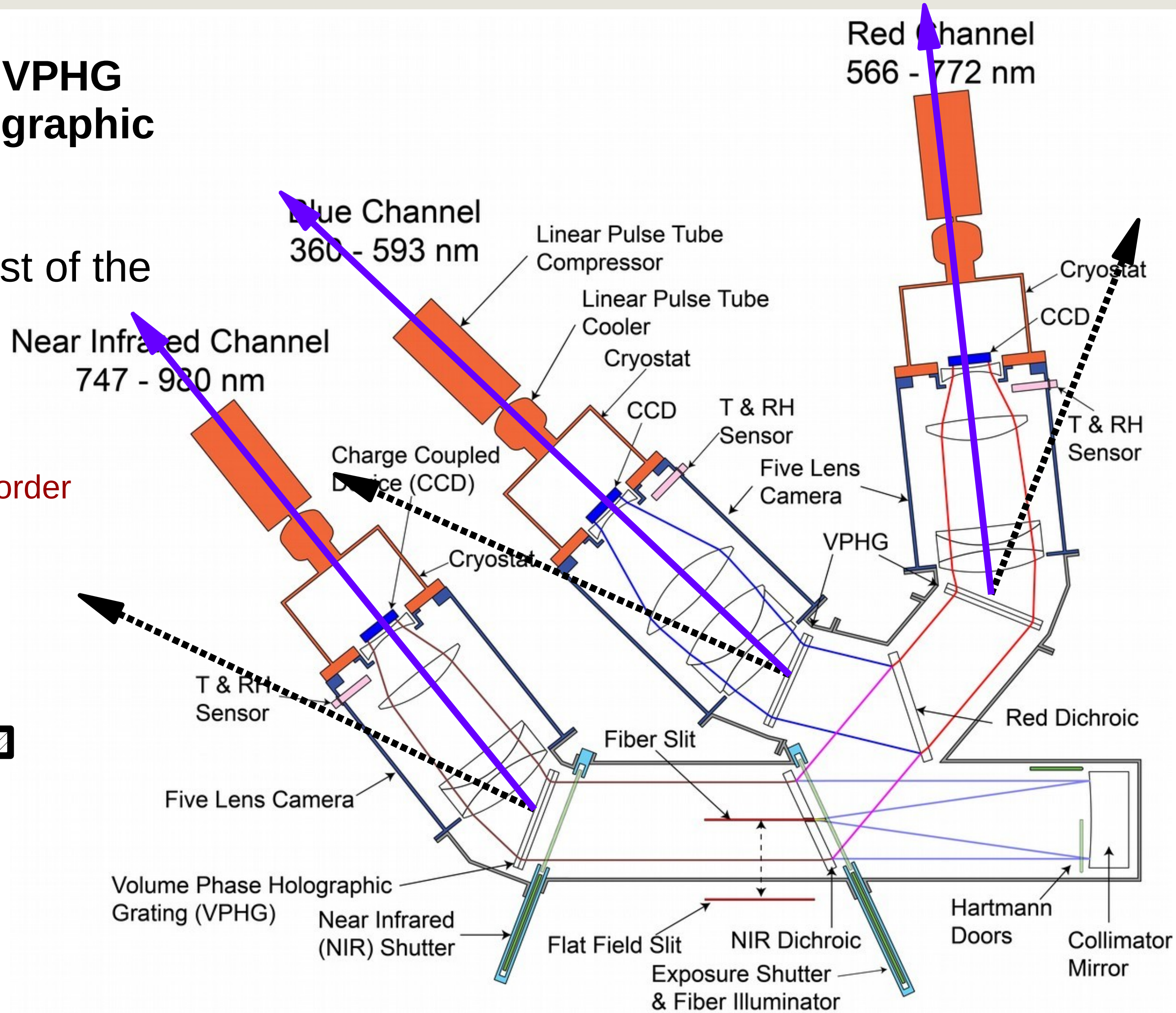




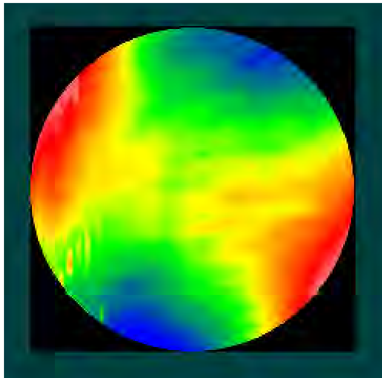
Hypothesis: are some VPHG upside-down ?

- **Possible culprit : the VPHG « Volume Phase Holographic gratings »**
- **Optimized** to send most of the flux **in order +1**

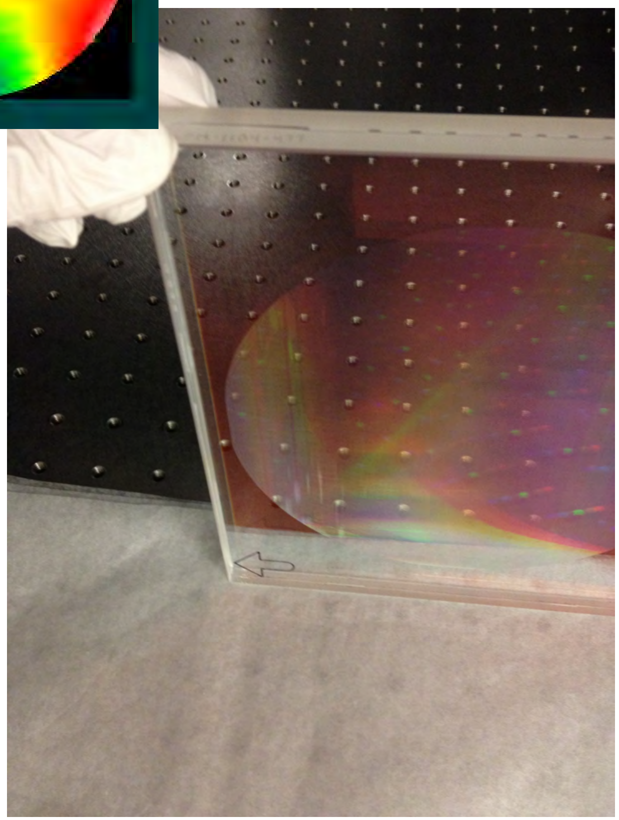


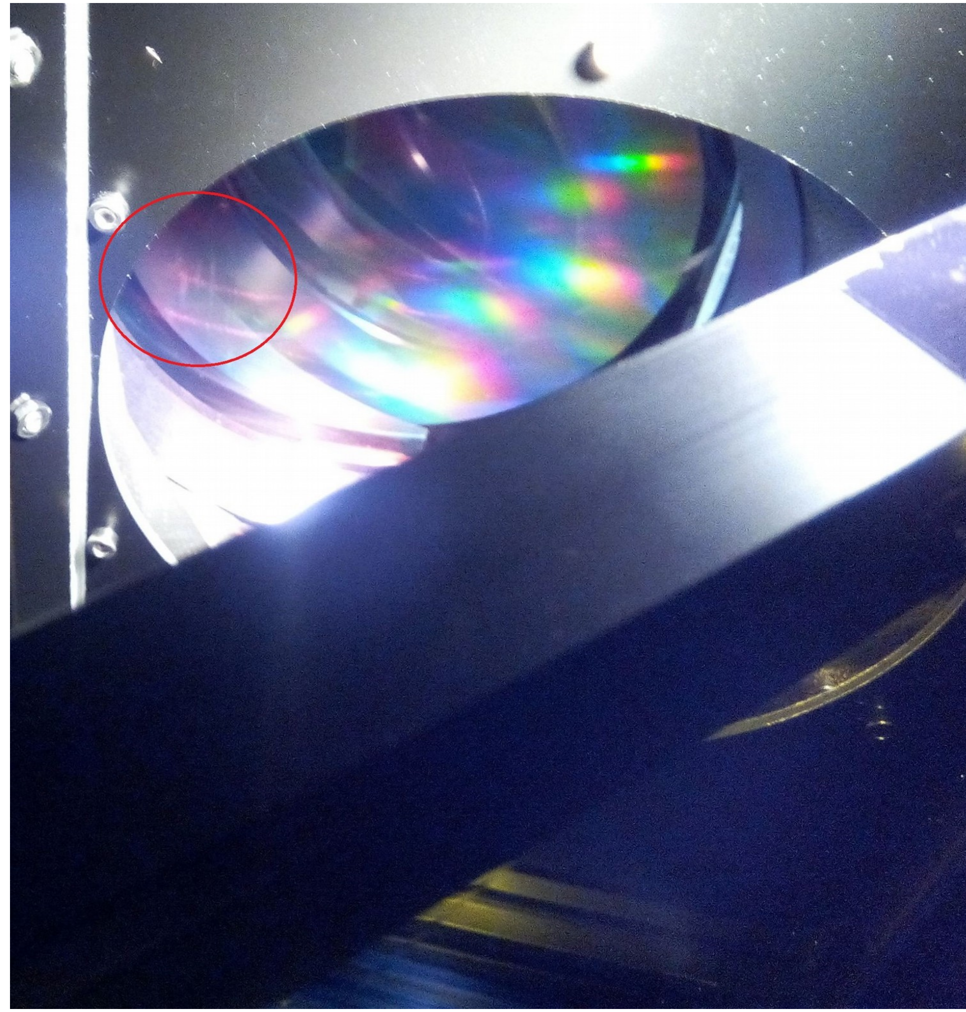


VPHG were mounted upside-down in B & Z arms

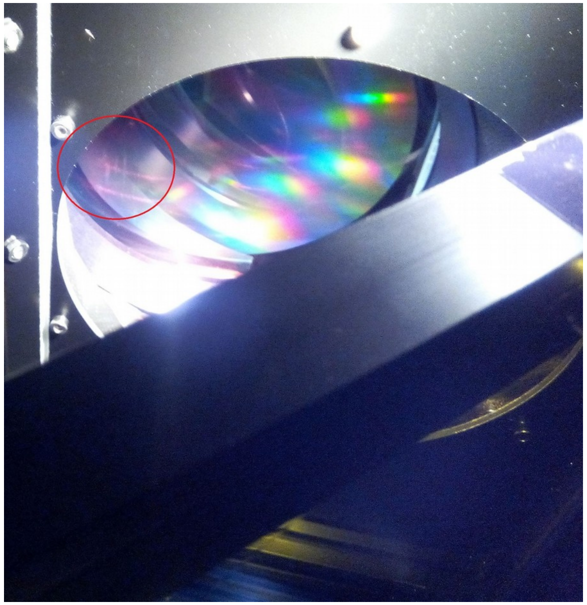


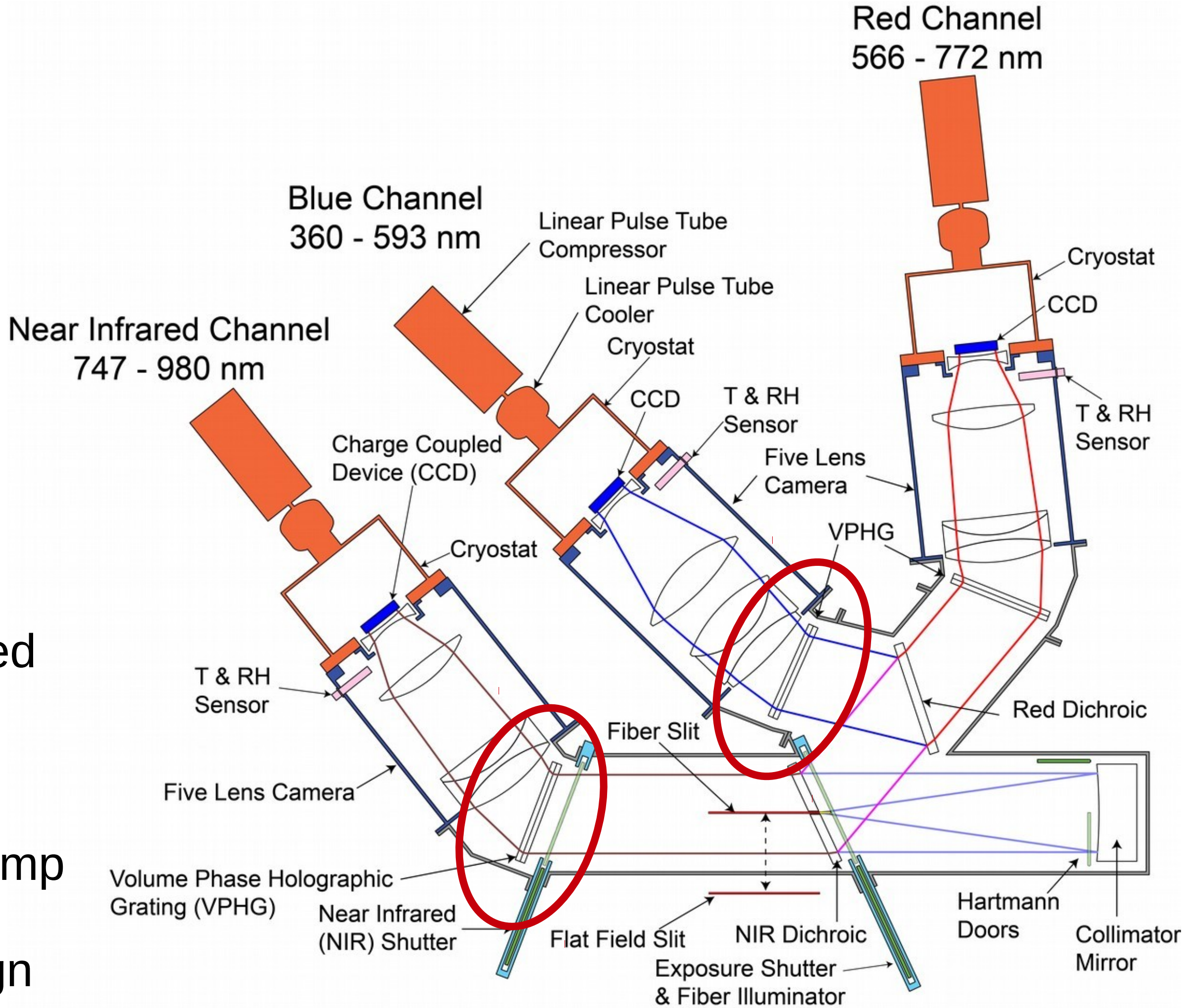
Blue arm VPHG
(photos Eric T.)





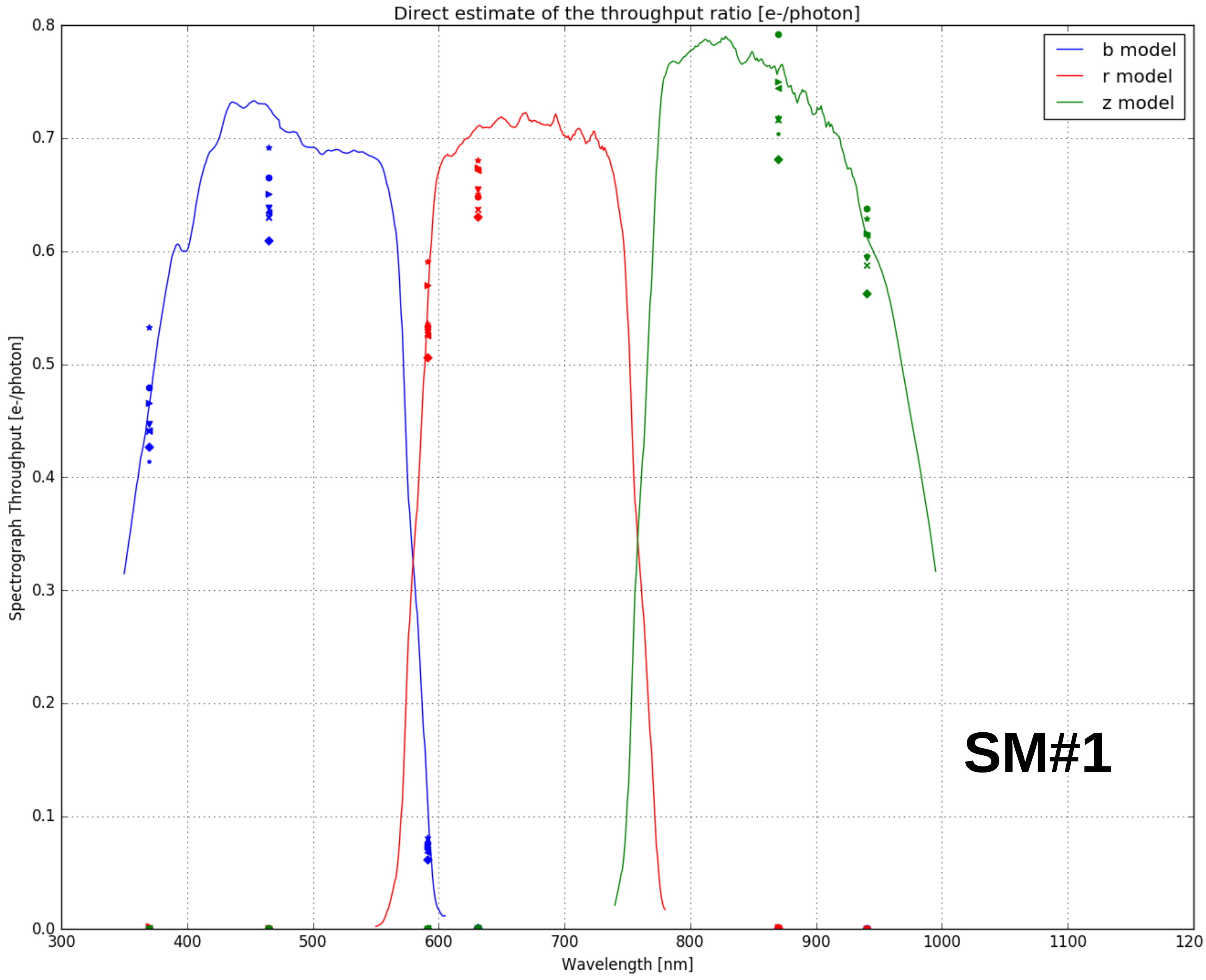
VPHG were mounted upside-down in B & Z arms



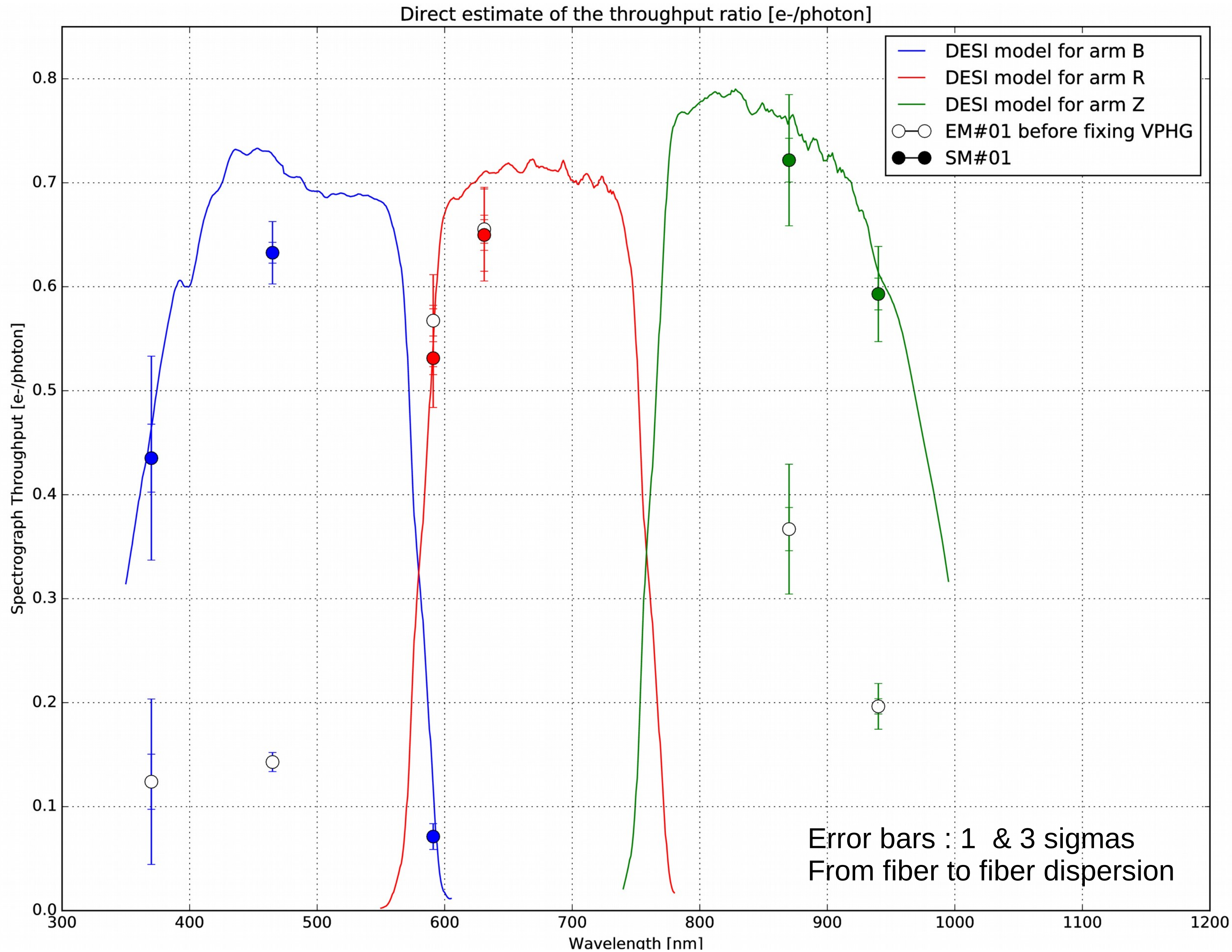


- **B & Z VPHG** were dismounted and **remounted in the right orientation** (June 2017).
- First checks with Tungsten lamp show that the throughput has been improved. July campaign cancelled (shutter problems)

SM#1: Direct throughput estimate (2018-04-09)

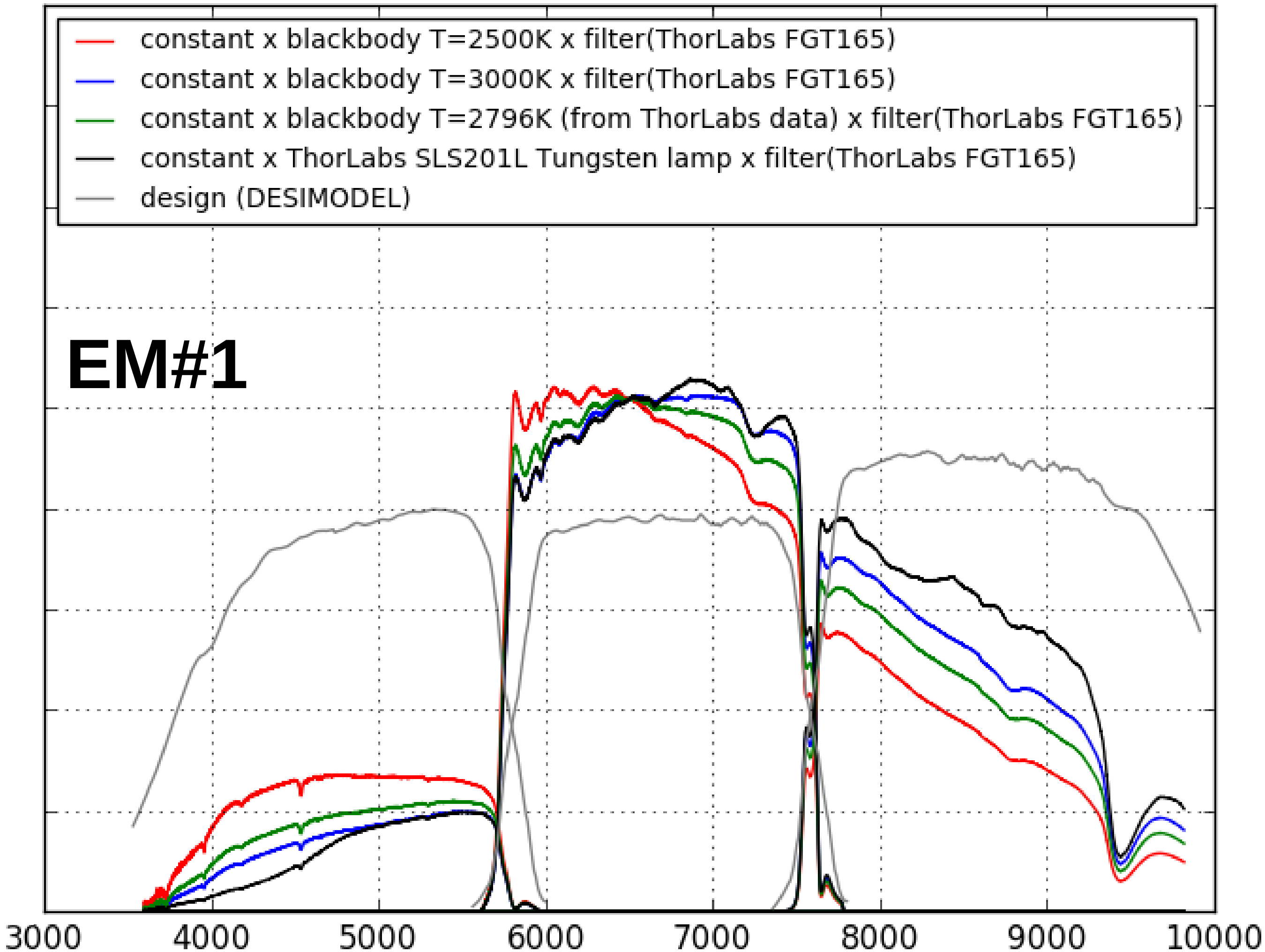


Direct throughput estimate: EM#1 & SM#1

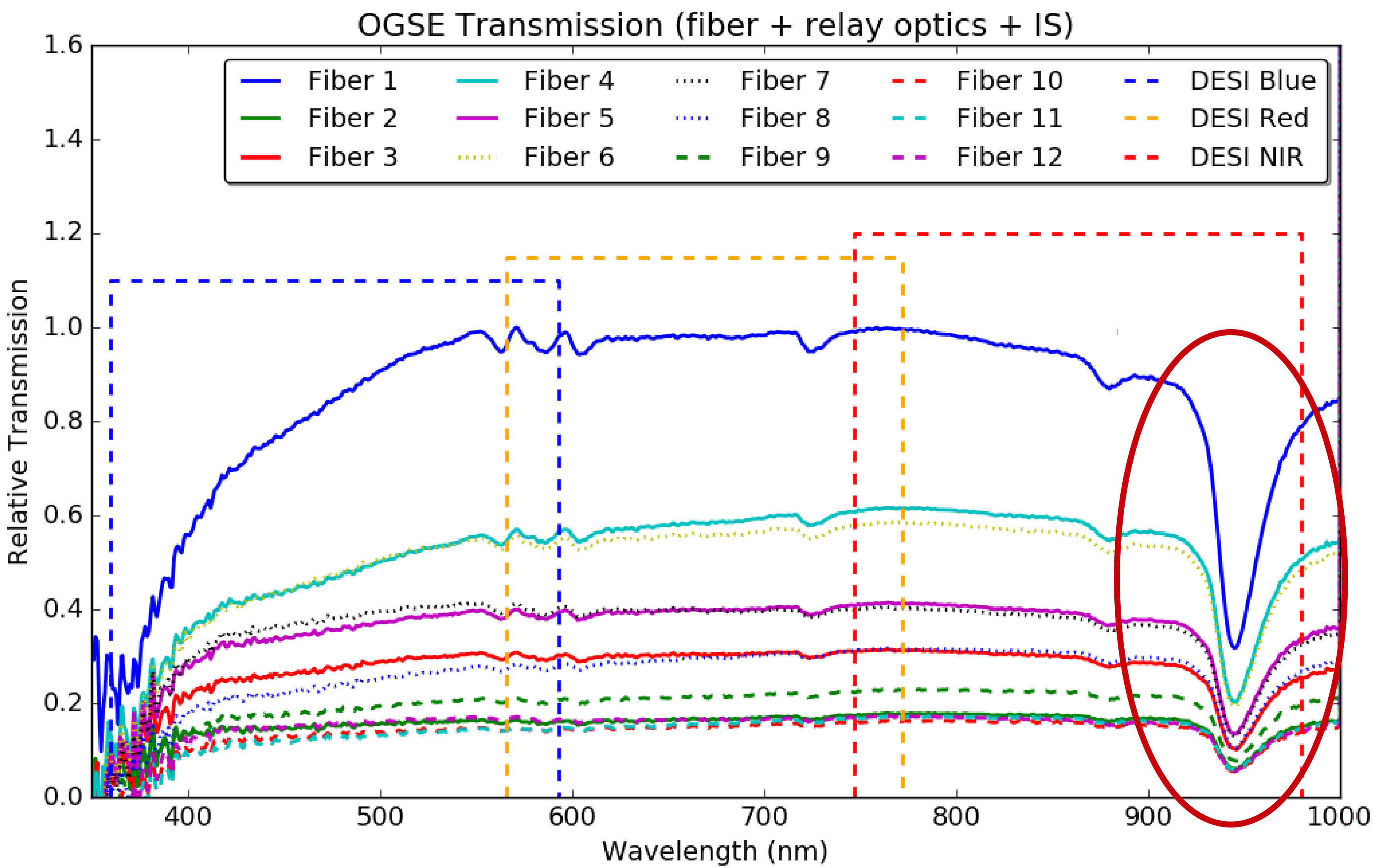


Throughput shape from Tungsten lamp exposures

- **Derived from Tungsten lamp exposures (JG)**
- **Hypotheses on Tungsten spectrum** (blackbody, Thorlabs specs)
- **Normalisation to be determined ! Gives the shape of the throughput function**
- **« Absorption » features : some are real** and also seen in **LED spectra**.

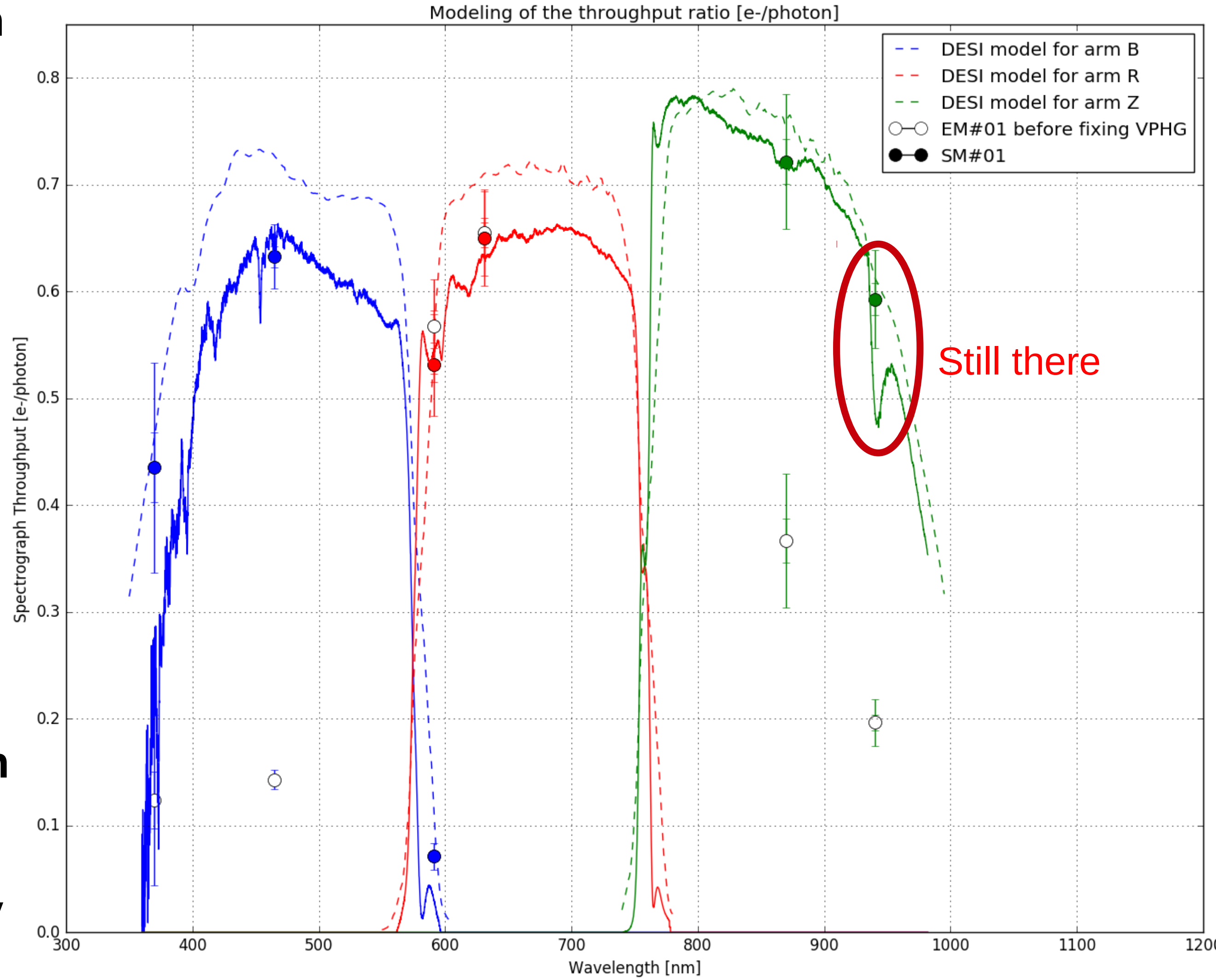


Absorption at 950 nm (partly) due to testbench

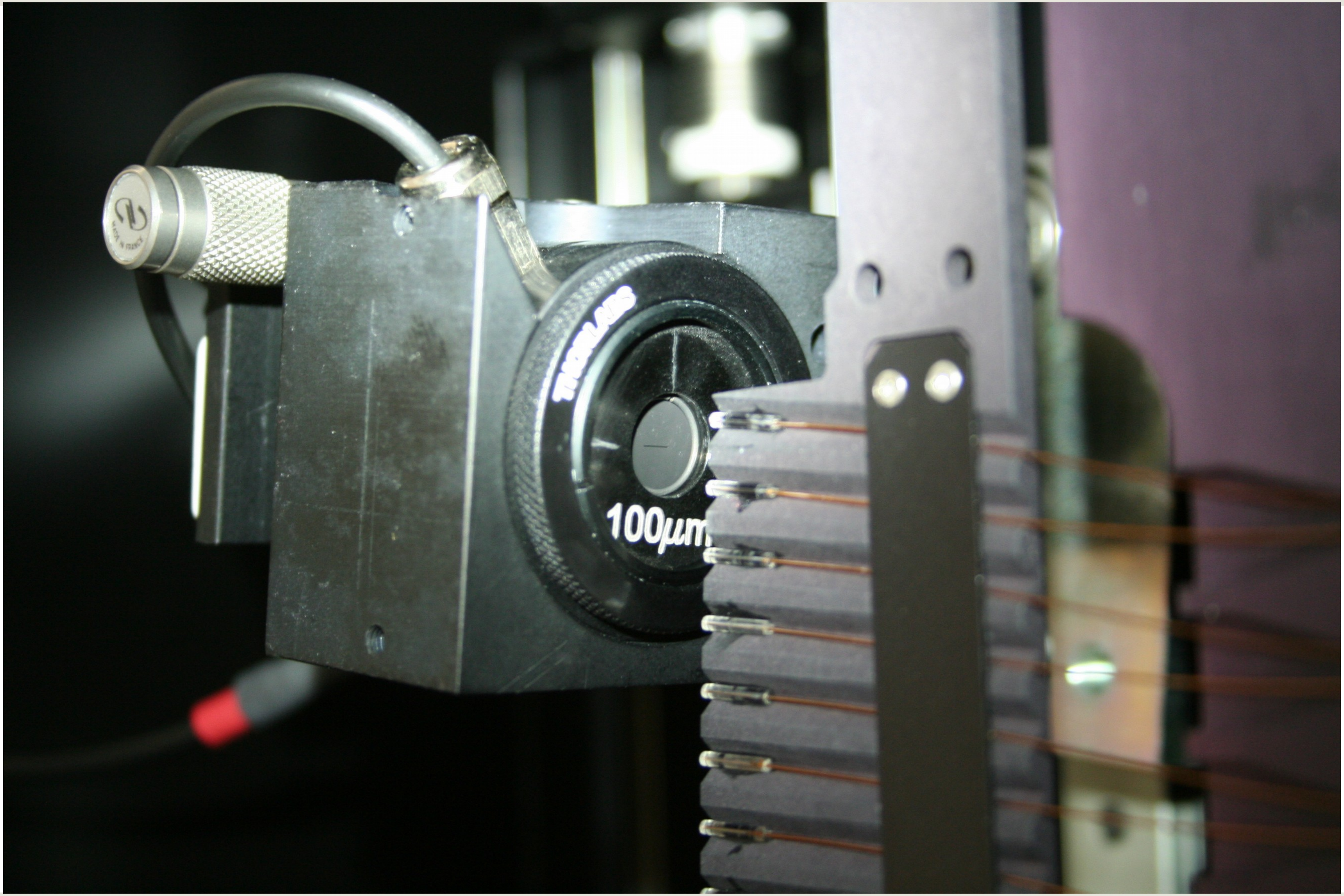


Throughput shape from Tungsten lamp exposures

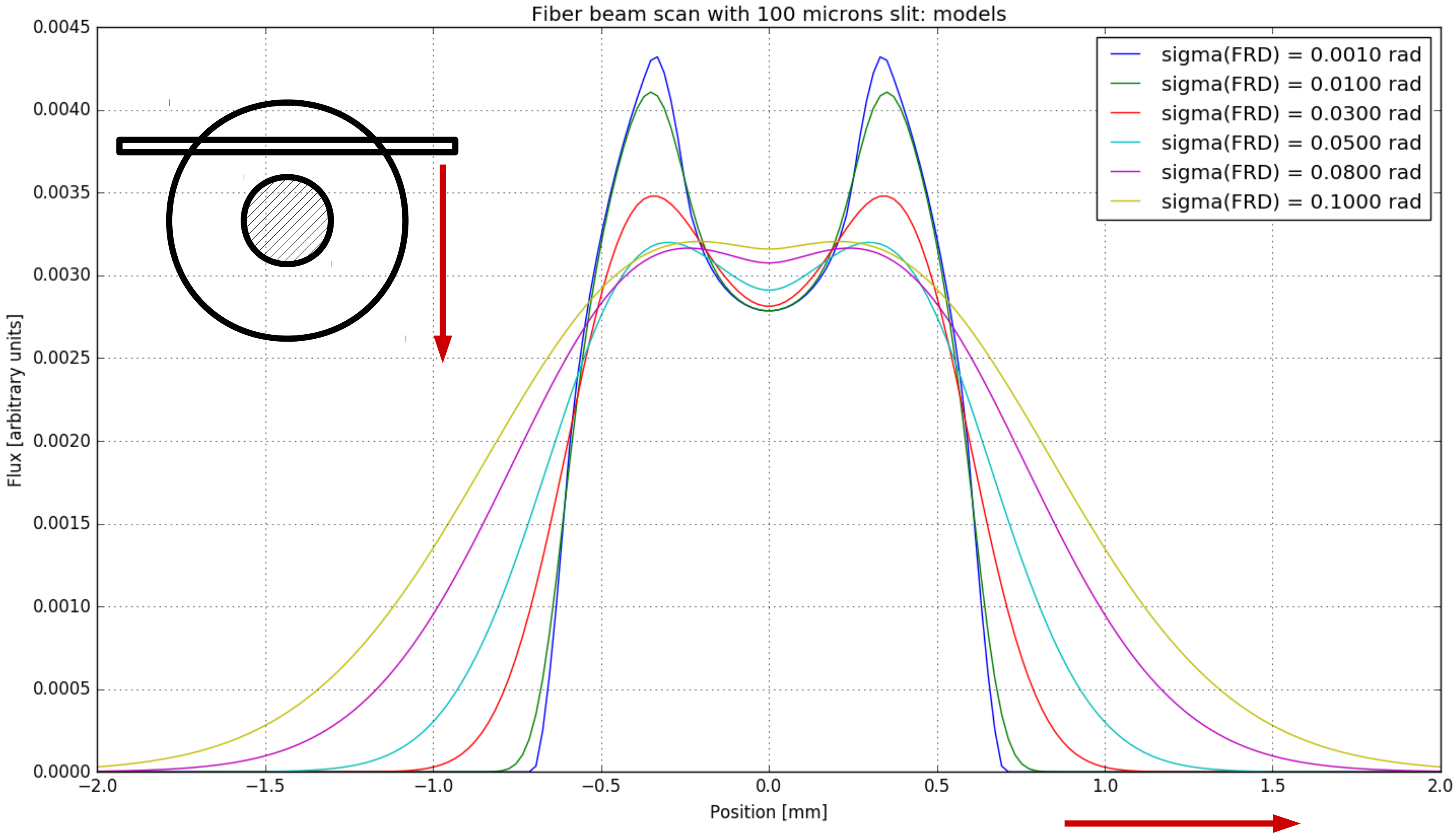
- **Derived from Tungsten lamp exposures (JG)**
- **Hypotheses on Tungsten spectrum** (blackbody, Thorlabs specs, filter) : **many unknowns**
- **Dividing by the testbench fiber throughput (not very well known)**
- **Linear « modeling » (scale + slope) on each arm (empirical)...**
- **Do not use this for any serious science...**



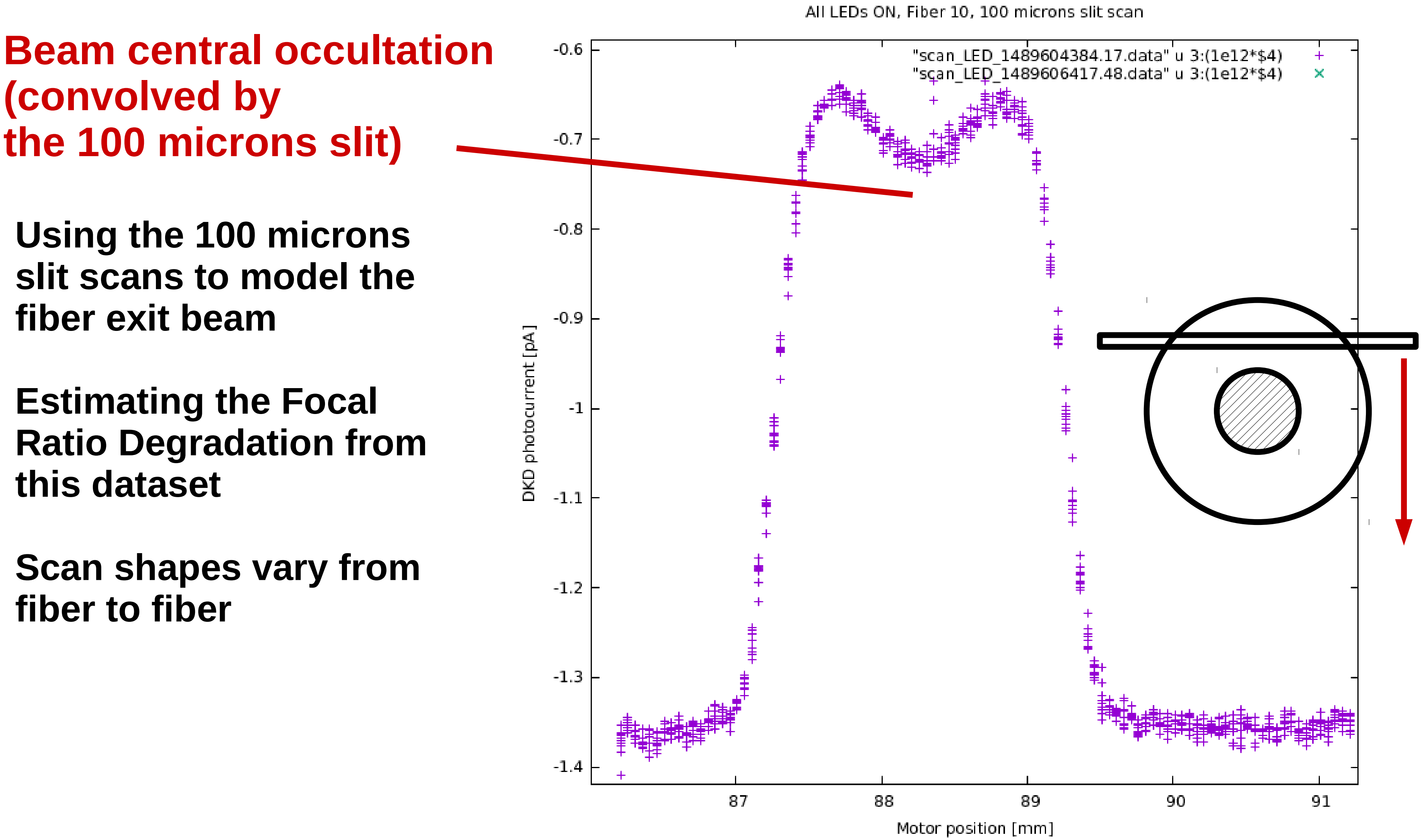
Estimating the FRD from fiber beam scans



Modeling the FRD from fiber beam scans

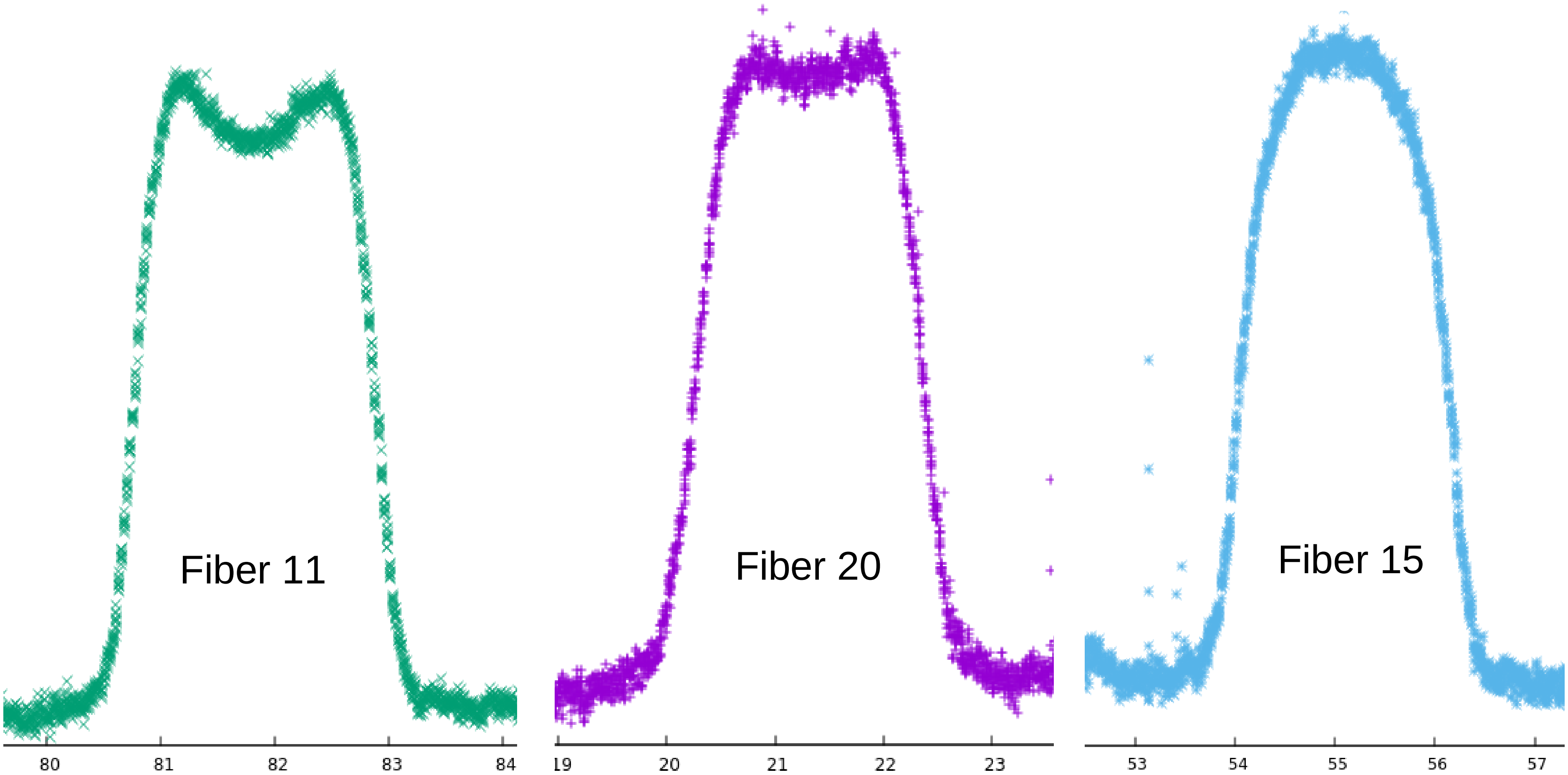


Estimating the FRD from fiber beam scans



- **Using the 100 microns slit scans to model the fiber exit beam**
- **Estimating the Focal Ratio Degradation from this dataset**
- **Scan shapes vary from fiber to fiber**

Estimating the FRD from fiber beam scans



Analysis still ongoing. The occultation dip is visible in most fiber scans.

Conclusions

◆ Throughput measurement device **designed**, **built, tested and installed by LPNHE on the AMU testbench** at Winlight**.**

◆ **Measurement campaigns in 2017-2018 for EM#1 & SM#1.**

◆ **EM#1**: **Low throughput in arms B1 and Z1**: VPHG wrongly mounted, problem detected and fixed.

◆ **SM#1: Much better throughput**, compatible with design.

◆ **Direct throughput measurement is a valuable test for the DESI spectrographs**: will be performed on all of them.