Laboratory tests for MIR light detection and transport with specialty optical fibers

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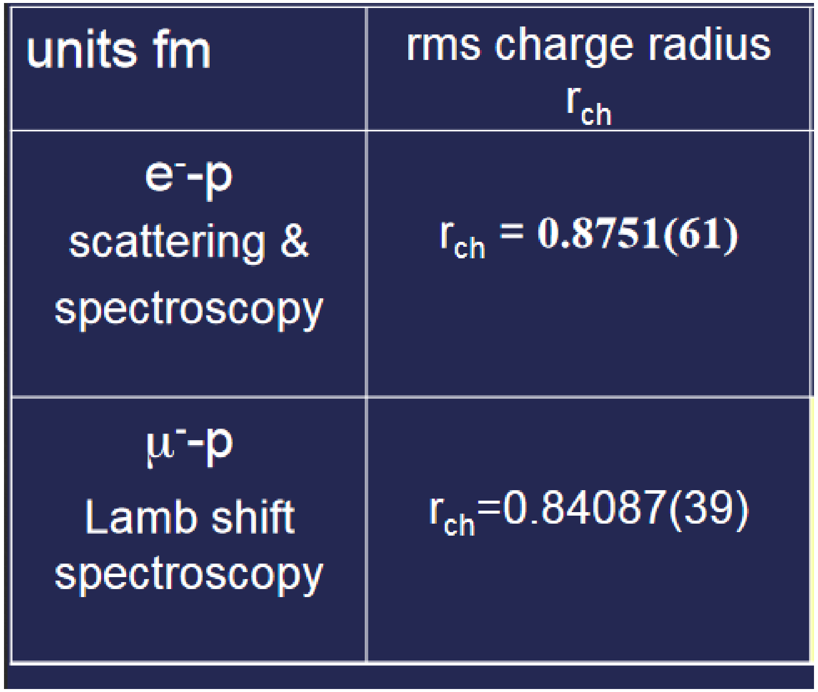
Outline

- General Motivation
- The FAMU experiment
- Test on MIR fiber optics for laser beam delivery
  - IR spectroscopy
  - Chemical sensing
  - Scientific and medical diagnostics IR-imaging system
- MIR Detectors
- Conclusions

Proton charge radius

- The proton charge radius can be extracted for each lepton probe from two independent methods

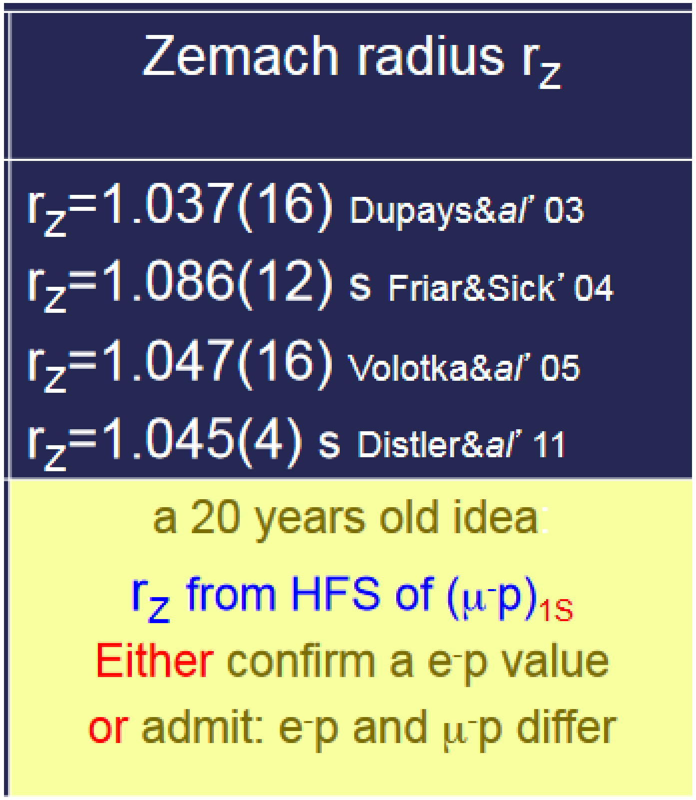


units fm	rms charge radius r_{ch}
e^--p scattering & spectroscopy	$r_{ch} = \mathbf{0.8751(61)}$
μ^--p Lamb shift spectroscopy	r_{ch}=0.84087(39)

- The CODATA value of the proton charge radius as obtained from a combination of 24 transition frequency measurements in H and deuterium and several results from elastic electron scattering is 0.88 fm . However, the muonic hydrogen Lamb Shift measurements yield a radius of 0.84 fm. Discrepancy due to a violation of the electron-muon universality or simply to not well understood experimental problems

Proton Zemach radius

The Zemach radius r_Z and the r.m.s. charge radius r_{ch} are the only values, related to the proton shape, that can be directly extracted from experimental data. The Zemach radius is the only that carries information about the proton's magnetic dipole moment distribution and therefore may help solve the riddle.



Zemach radius r_Z

r_Z=1.037(16) Dupays&*al'* 03

r_Z=1.086(12) s Friar&Sick' 04

r_Z=1.047(16) Volotka&*al'* 05

r_Z=1.045(4) s Distler&*al'* 11

a 20 years old idea

r_Z from HFS of $(\mu^- p)_{1S}$

Either confirm a $e^- p$ value

or admit: $e^- p$ and $\mu^- p$ differ

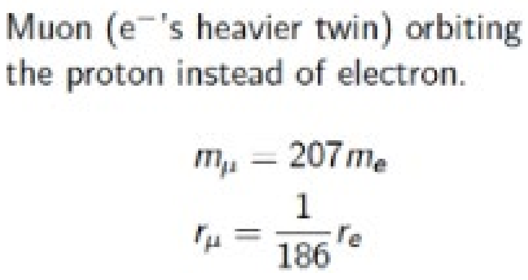
The Zemach radius can be determined from the hyperfine splitting energy of a hydrogen-like atom (muonic hydrogen atom)

Recently : from HFS of $(\mu^- p)_{2S}$ r_Z = 1.082(37)fm [PSI'12]

FAMU aims:

- Measure the Hyperfine Splitting (HFS) of μ-p **ground level** with accuracy 10^{-5}
- Extract the Zemach radius of the proton with an accuracy of better than 1%

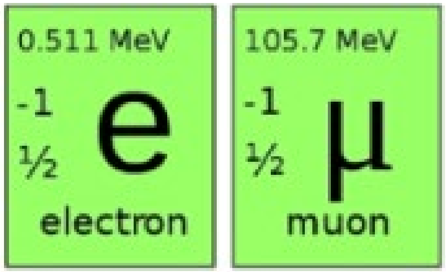
Why Muons?



Muon (e^-'s heavier twin) orbiting the proton instead of electron.

$$m_\mu = 207 m_e$$

$$r_\mu = \frac{1}{186} r_e$$

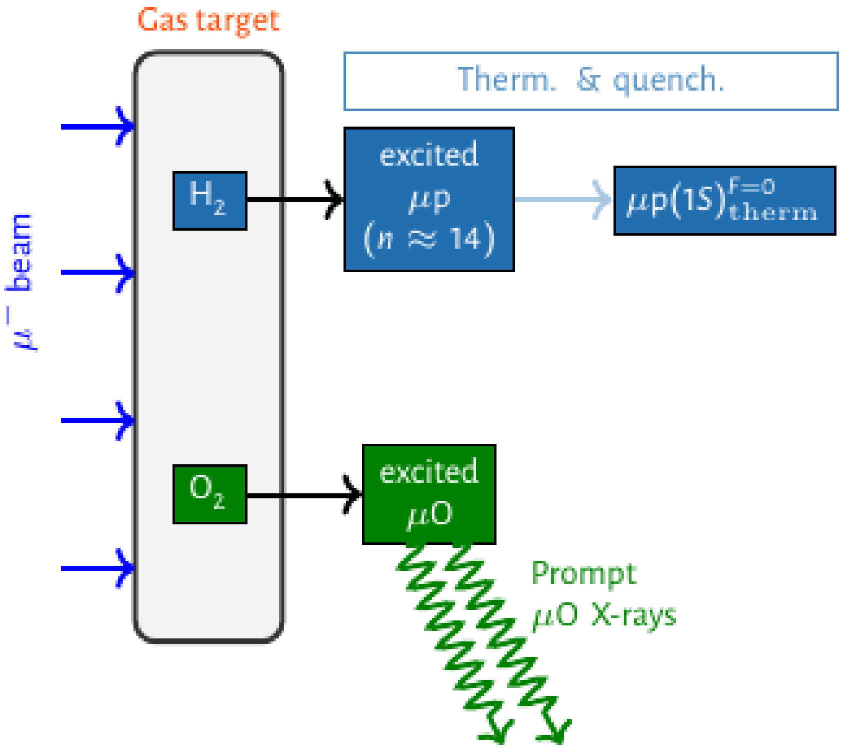


$m_\mu/m_e \approx 2\text{x}10^2$

- The radius of the muon orbit is $\sim a_0/200$ so that the energy levels of muonic hydrogen are orders of magnitude more “sensitive” to the details of the proton structure than the levels of normal hydrogen.

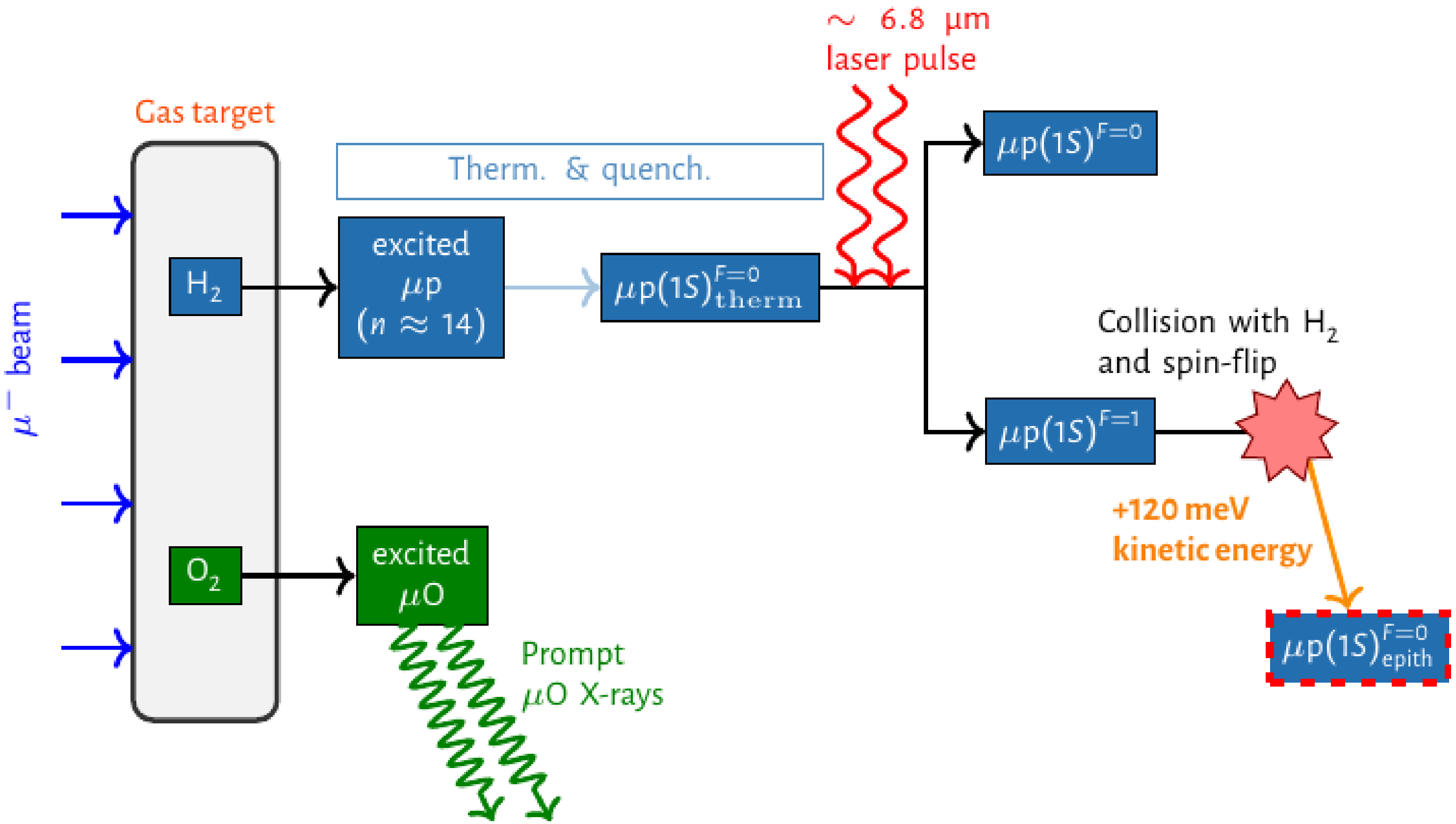
- The binding energy of the ground state of muonic hydrogen is of the order of 200 Ry

FAMU method and workflow (I)



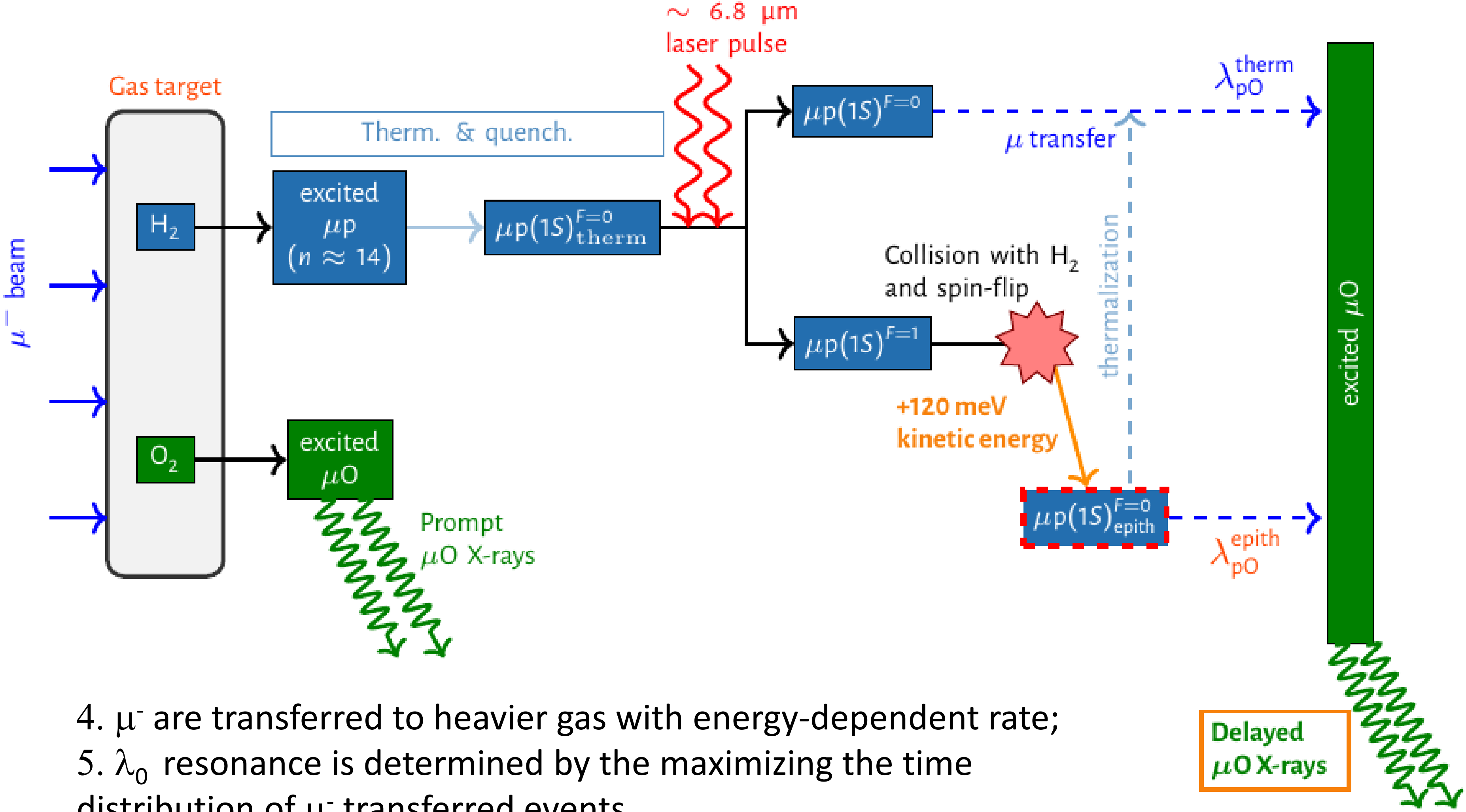
1. Create muonic hydrogen and wait for thermalization;

FAMU method and workflow (I)



1. Create muonic hydrogen and wait for its thermalization;
2. Shoot laser at resonance (λ_0 ~6.8μ) spin state of $\mu^- p$ from 1^1S_0 to 1^3S_1 ,
   spin is flipped: $\mu^- p(\uparrow\downarrow) \rightarrow \mu^- p(\uparrow\uparrow)$;
3. De-excitation and acceleration: $\mu^- p(\uparrow\uparrow)$ hits a H atom
   It is depolarized back to $\mu^- p(\uparrow\downarrow)$ and is accelerated by ~120 meV ;

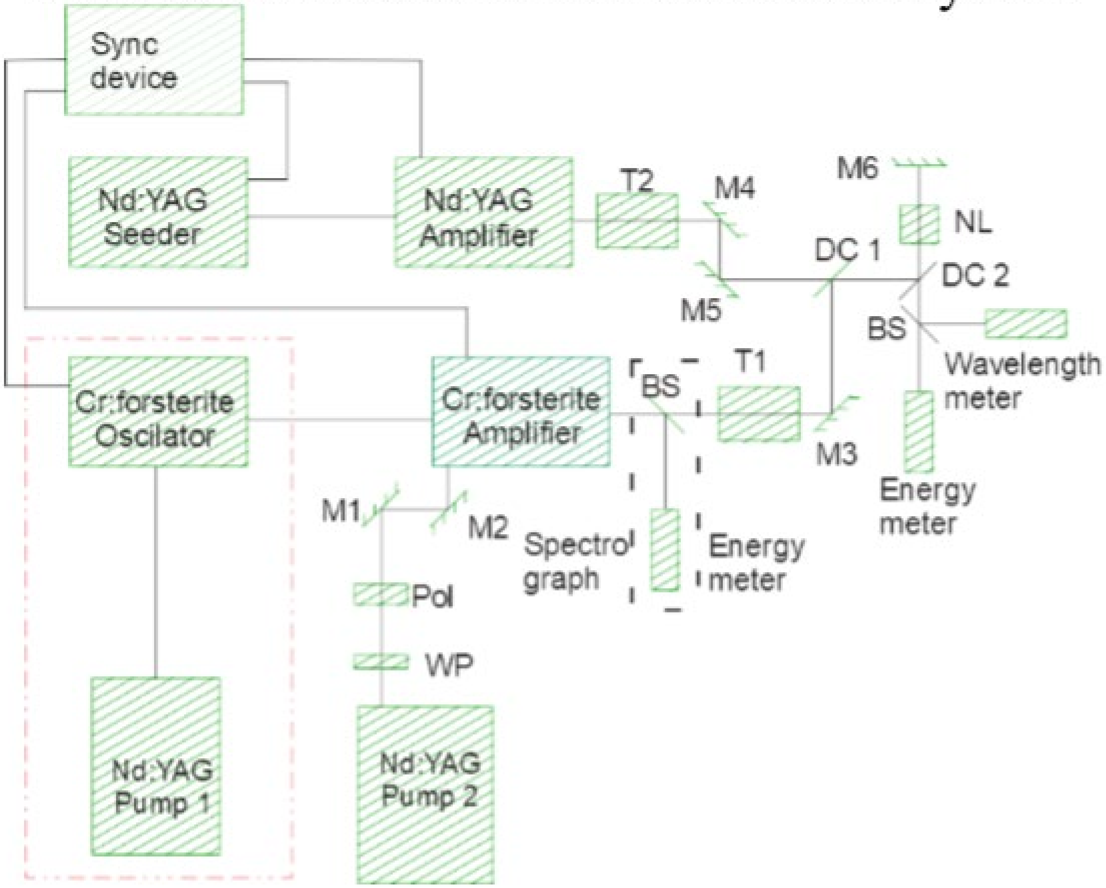
FAMU method and workflow (I)



4. μ^- are transferred to heavier gas with energy-dependent rate;
5. λ_0 resonance is determined by the maximizing the time distribution of μ^- transferred events.

Excitation Laser

Final scheme of the DFG based laser system



WP - waveplate, Po - polarizer, M1-M5 - mirrors, T1 and T2 - telescopes, BS - beamsplitters,DC1 - dichroic mirror (reflecting 1.26μm, transmitting1.06μm), DC2 - dichroic mirror(reflecting 1.06 and 1.26 μm, transmitting 6.76μm)

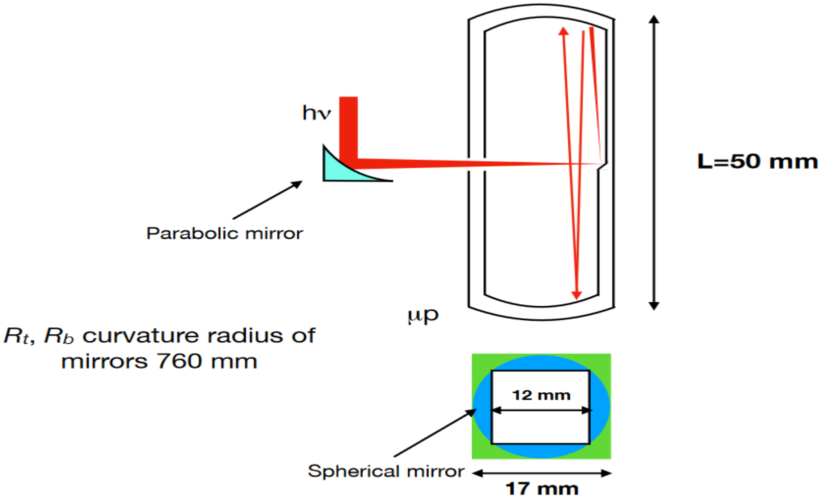
Excitation Laser

Tunable MIR emission in the 6785 nm range

Pulse energy:	> 1 mJ	(5 mJ)
Wavelength:	λ =6785 nm	
Line width:	$\Delta\lambda$ = 0.070 nm (450 MHz)	
Tunability range:	6785 ± 3 nm required (± 50 nm)	
Tunability step:	0.030 nm	(200 MHz)
Repetition rate:	25 Hz	

Available NL crystals at 6760 – 6790 nm
Expected energies:

LiInS2& LiInSe2: 1 – 1.5 mJ
BGSe ~ 5 mJ



Direct injection vs. Fiber transport

Direct injection

Pros	Cons
No transport losses (in vacuum)	Alignment difficulty
Spatial mode preserved	Vacuum transport required
	Vibration sensitive due to decoupling

Fiber transport

Pros	Cons
Easy positioning	Additional losses (injection, attenuation, collimation)
Integral with the target	Remote position control
No need of vacuum transport	Possible growth of undesired spatial modes in multimode fibers
Easy injection in multimode fibers	

Selected fibers for tests on pulsed QCL laser at ICTP Trieste and Milano Bicocca

Selected fibers for tests on pulsed QCL laser

- Hollow Fiber HF500MWLW-SMA-1m ID = 500 µm; MWLW Silver Iodide coating for λ = 5 – 12 µm; SMA connectors; green jacket;
  Opto-Knowledge Systems
- **RF-Se-300** multimode LW mid-infrared Chalcogenide glass fiber has transmission range from 1.5 to 9.7µm, with minimum optical loss of 0.21dB/m at 2.59µm.
  IRFLEX
- PIR AgCl:AgBr Polycrystalline fiber, core 410 µm and 860 µm

  ArtPhotonics

Laser Characteristics at ICTP Trieste

QCL Alpes Lasers Technology

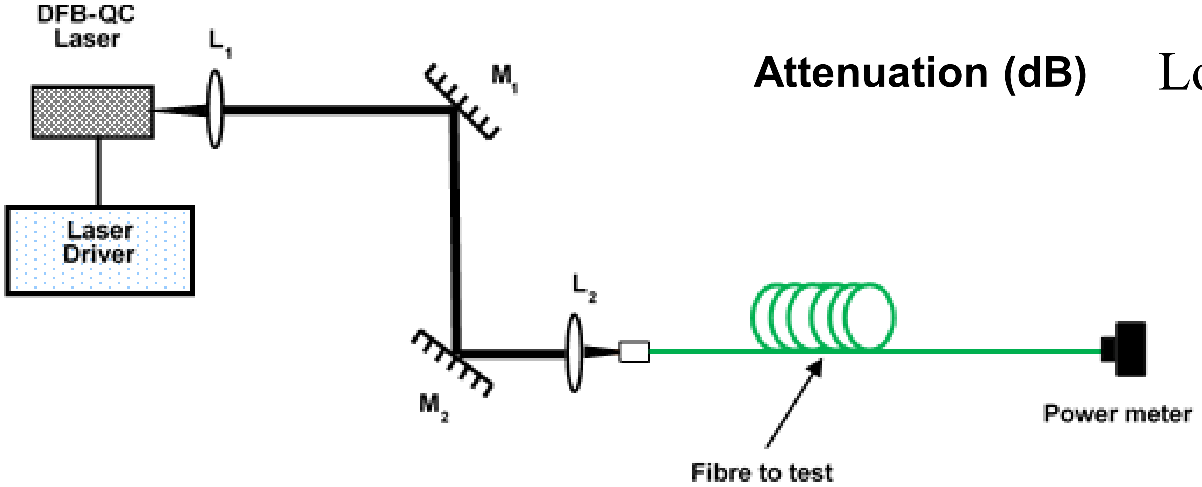
pulse duration 100 ns and repetition rate 200 kHz (5 µs)

single mode with linewidth of 2 nm

wavelength between 6780 to 6825 nm

Duty cycle (2%) with average power up to 12 mW (Energy of 60 nJ i.e. 12mW x 5 µs)

1st experimental campaign: P_{ref} output power of SMA/FC adapter and compared with the output power of the fiber under test, in order to test both the coupling and the transmission/attenuation factor.

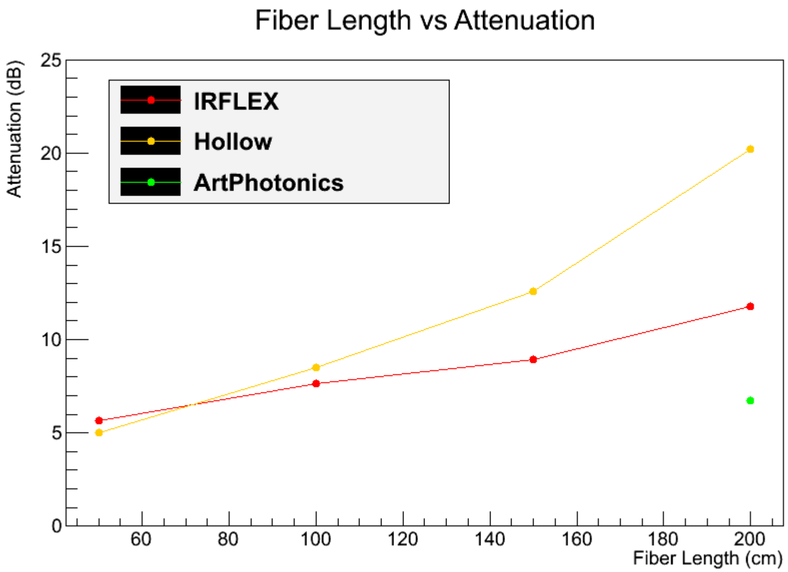


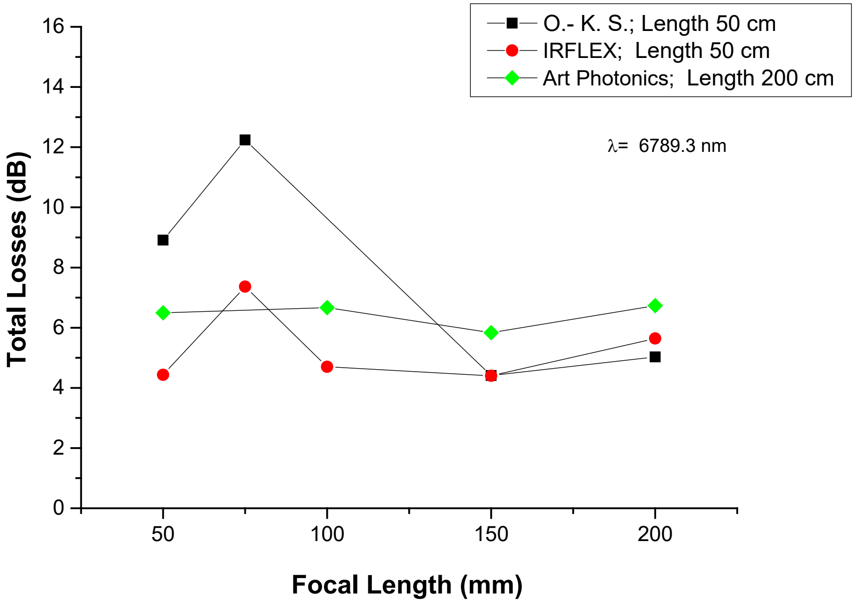
Attenuation (dB)

$$\mathrm{Loss}_{\mathrm{dB}} = 10\log\left(\frac{P_{ref}}{P_{out}}\right)$$

(3A-SH, Ophir)

Results

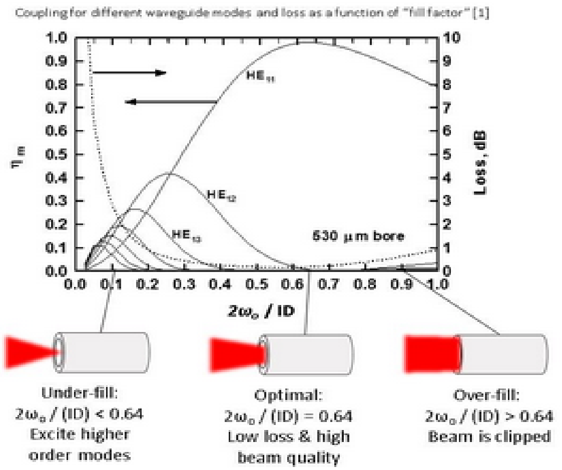

Fiber Length vs Attenuation
Attenuation (dB)
25
20
15
10
5
0
IRFLEX
Hollow
ArtPhotonics
60
80
100
120
140
160
180
200
Fiber Length (cm)


O.- K. S.; Length 50 cm
IRFLEX; Length 50 cm
Art Photonics; Length 200 cm
λ= 6789.3 nm
Total Losses (dB)
16
14
12
10
8
6
4
2
0
50
100
150
200
Focal Length (mm)

Focal length

In general, coupling light into hollow core fibers is relatively simple, given the relatively large core. However, both transmission and beam quality can be adversely affected if the proper focal length optic is not used. In general, the beam should enter straight into the fiber with a relatively gradual focus. Optimal coupling into the lowest order mode occurs when the ratio of the focused spot size to the fiber ID, $2\omega_0$ / (ID) = 0.64.

Coupling for different waveguide modes and loss as a function of "fill factor" [1]



Under-fill:
$2\omega_o$ / (ID) < 0.64
Excite higher order modes

Optimal:
$2\omega_o$ / (ID) = 0.64
Low loss & high beam quality

Over-fill:
$2\omega_o$ / (ID) > 0.64
Beam is clipped

It exists an optimal coupling in order to minimize high order modes growth

Focused beam waist ($1/e^2$ radius):

$$\omega_o = \frac{2\lambda}{\pi}\left(\frac{f}{D}\right)$$

Lens focal length

Laser beam $1/e^2$ diameter

Optimal focus:

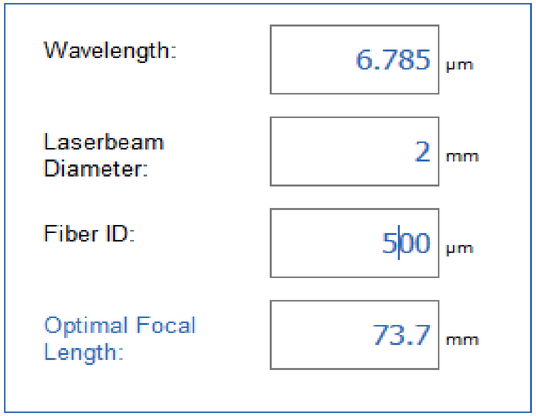
$$f_{opt} = 0.16\,\pi(ID)\left(\frac{D}{\lambda}\right)$$

The calculation for optimal focus assumes an ideal collimated Gaussian input beam, a non-ideal beam will have a larger focused spot. For this reason, we recommend selecting a focal length that is either equal to or less than the optimal focal length. Example recommendations are provided in the table for the case where the input laser beam has a diameter (D = 4 mm) and the fiber internal diameter is (ID = 300 µm).

Example with D = 4 mm; ID = 300 µm

λ	f_{opt}	Recommend focal length
3 µm	201 mm	150 mm
5 µm	121 mm	100 mm
7 µm	86 mm	75 mm
9 µm	67 mm	50 mm

Focal Length Calculator



Wavelength: 6.785 µm

Laserbeam Diameter: 2 mm

Fiber ID: 500 µm

Optimal Focal Length: 73.7 mm

Laser Characteristics at Milano Bicocca

- ☐ **Pulsed Pigtailed HHL-696 Alpes Lasers QCL**
- ☐ **QCL module + pulser + TEC cooler**
- ☐ **Needs to implement H_2O cooling of QCL base (10-15 C to have QCL working @ -40 C or lower)**

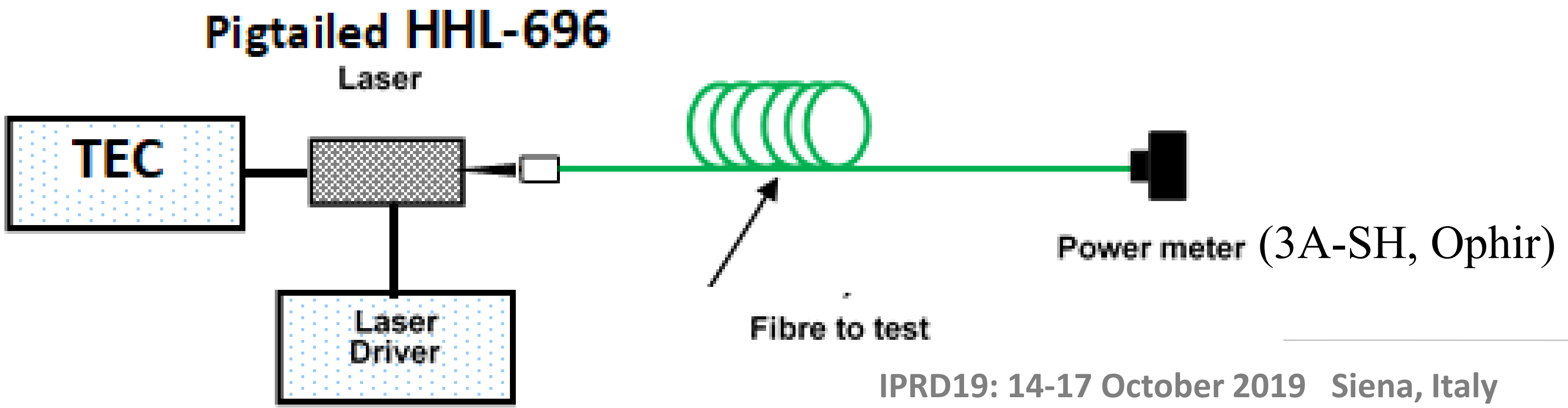
pulse duration 20 ns with repetition rate 1MHz (duty cycle of 2%)

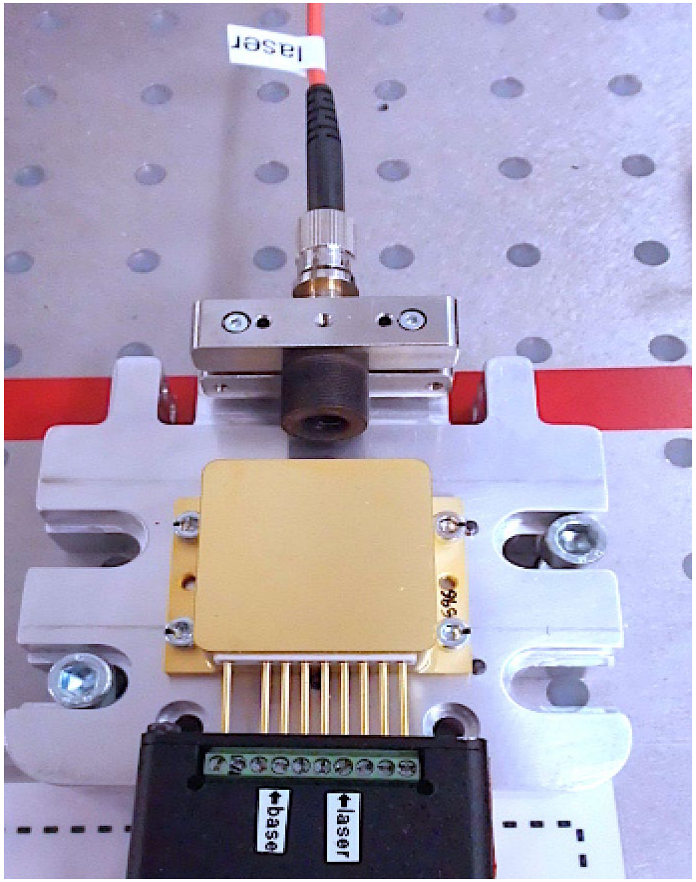
single mode with linewidth <1.3 nm

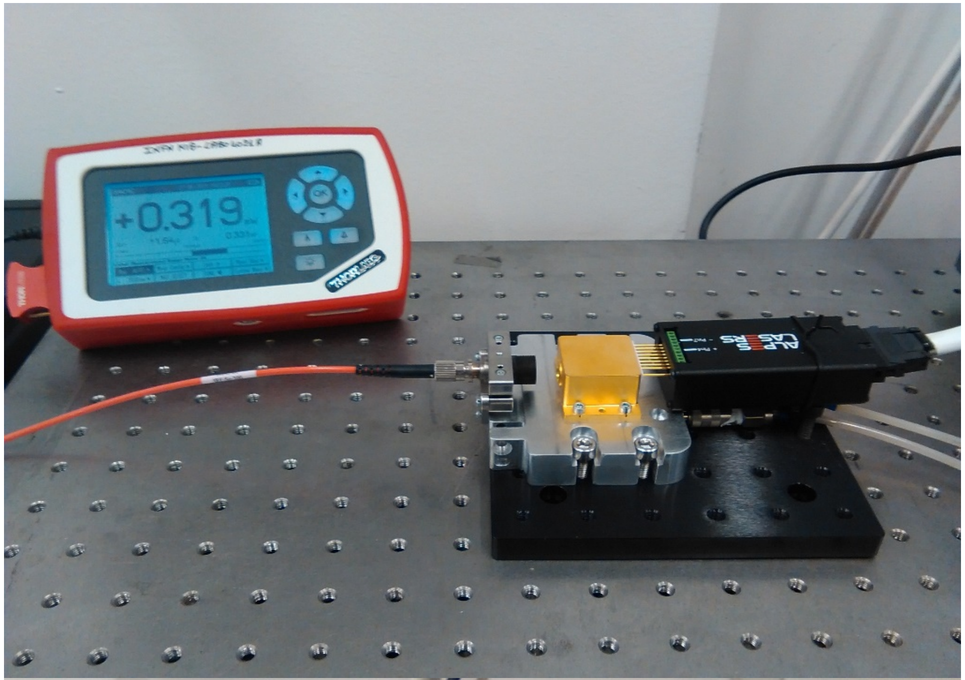
wavelength between 6780 to 6816 nm

Average power up to 3.5 mW (Energy of 3.5 nJ i.e. 3.5mW x 1 µs)

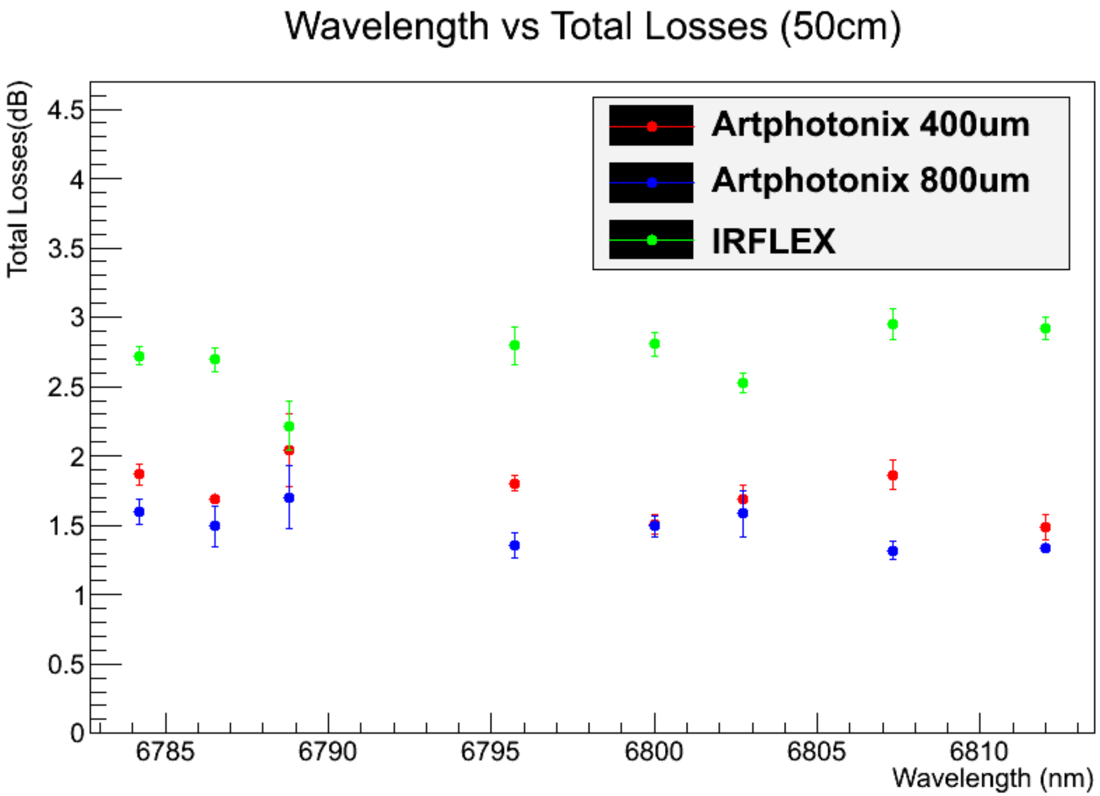
2nd experimental campaign: P_{ref} output power of a 50 cm long fiber and compared with the output of a 1m long fiber in order to measure just the transmission/attenuation factor.



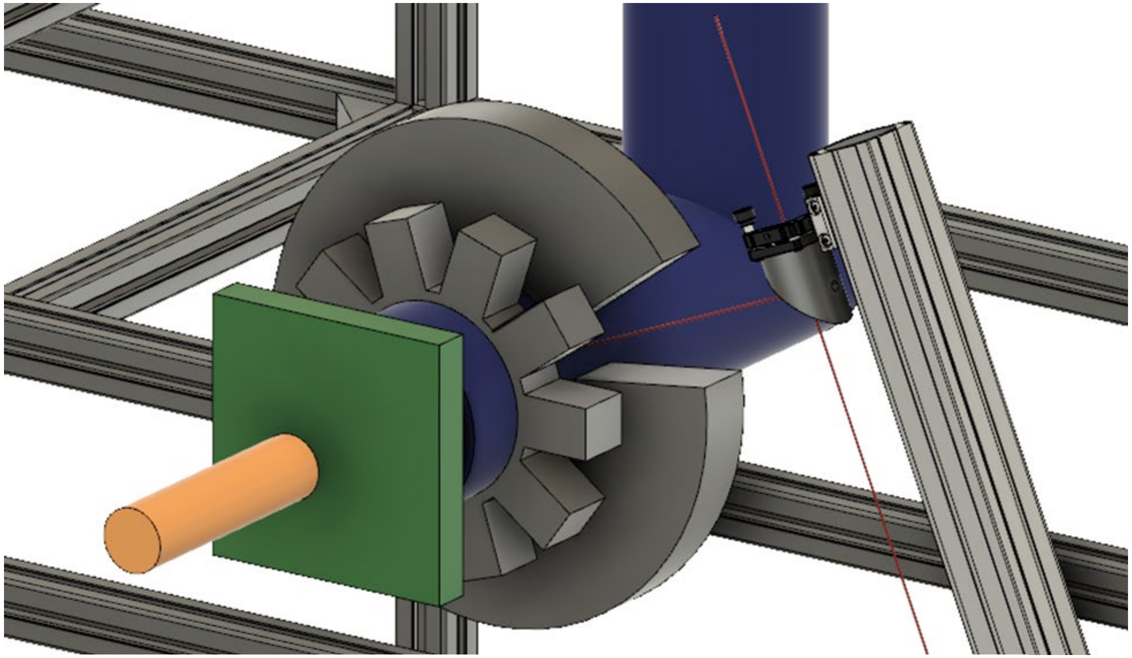

laser
596
base
laser

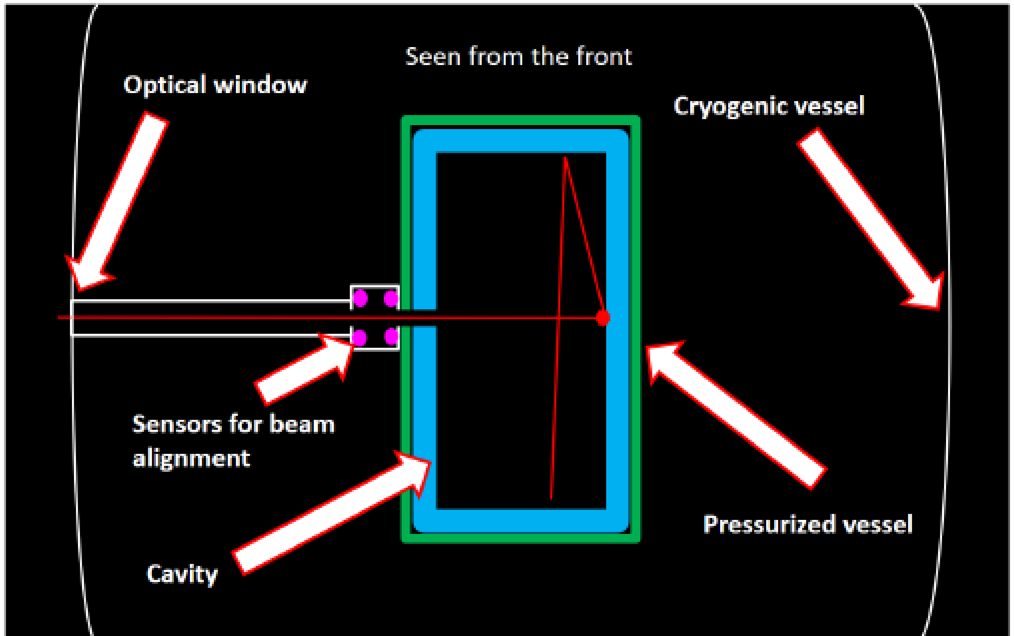

+0.319
THORLABS
ALPES LASERS


ALPES LASERS
Error
Remote
Output
Menu
Tset= 18.00°C V= 0.27V
T= 21.50°C I= 0.02A
TC-3
High Power TEC Controller
Power

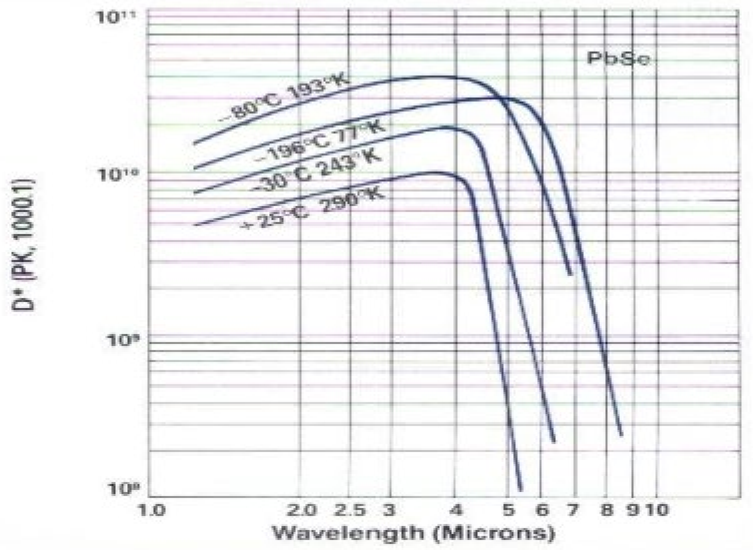

Wavelength vs Total Losses (50cm)
Total Losses(dB)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
6785
6790
6795
6800
6805
6810
Wavelength (nm)
Artphotonix 400um
Artphotonix 800um
IRFLEX

MIR Detectors



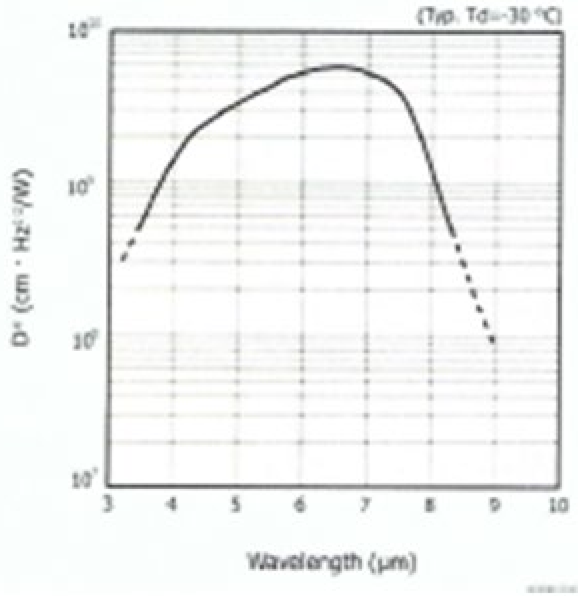


PbSe Photoconductive detector



InAsSb photovoltaic detector

Spectral response (D*)



Conclusions

- The results showed Ag-Halide Fibers perform better

- Attenuation decreases significantly with the core diameter: $\alpha < 1$ dB/m
- Total losses : 1.5 dB (50 cm)

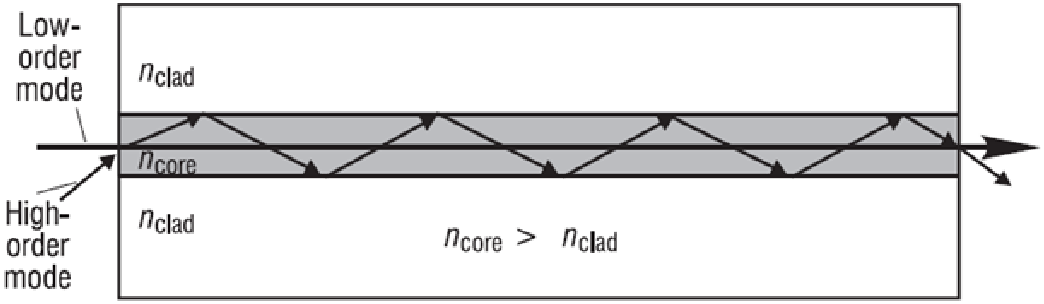
- Tests for damage threshold

- Soon test on MIR detectors

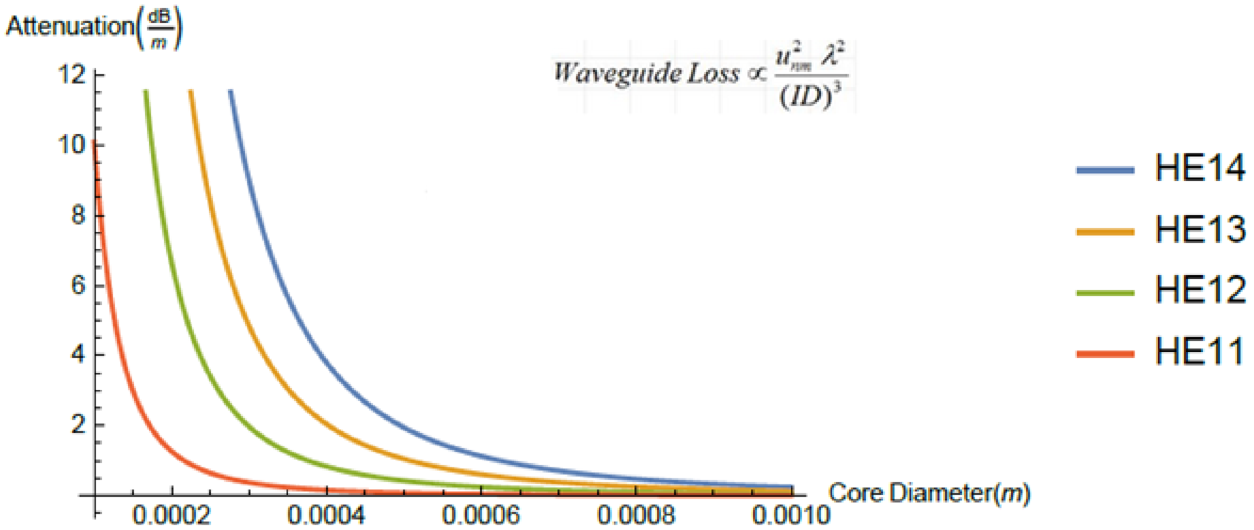
Thank you for your attention

High-order modes generation

Modal dispersion: pulse spreading due to time delay between lower and higher-order modes



With strong guidance hybrid modes of HE, having a non-zero longitudinal components of both electric and magnetic field.



$$Waveguide\ Loss \propto \frac{u_{nm}^2\ \lambda^2}{(ID)^3}$$