Study of periodic “Spectral Gaps“ in the Free-Electron Lasers using a waveguide

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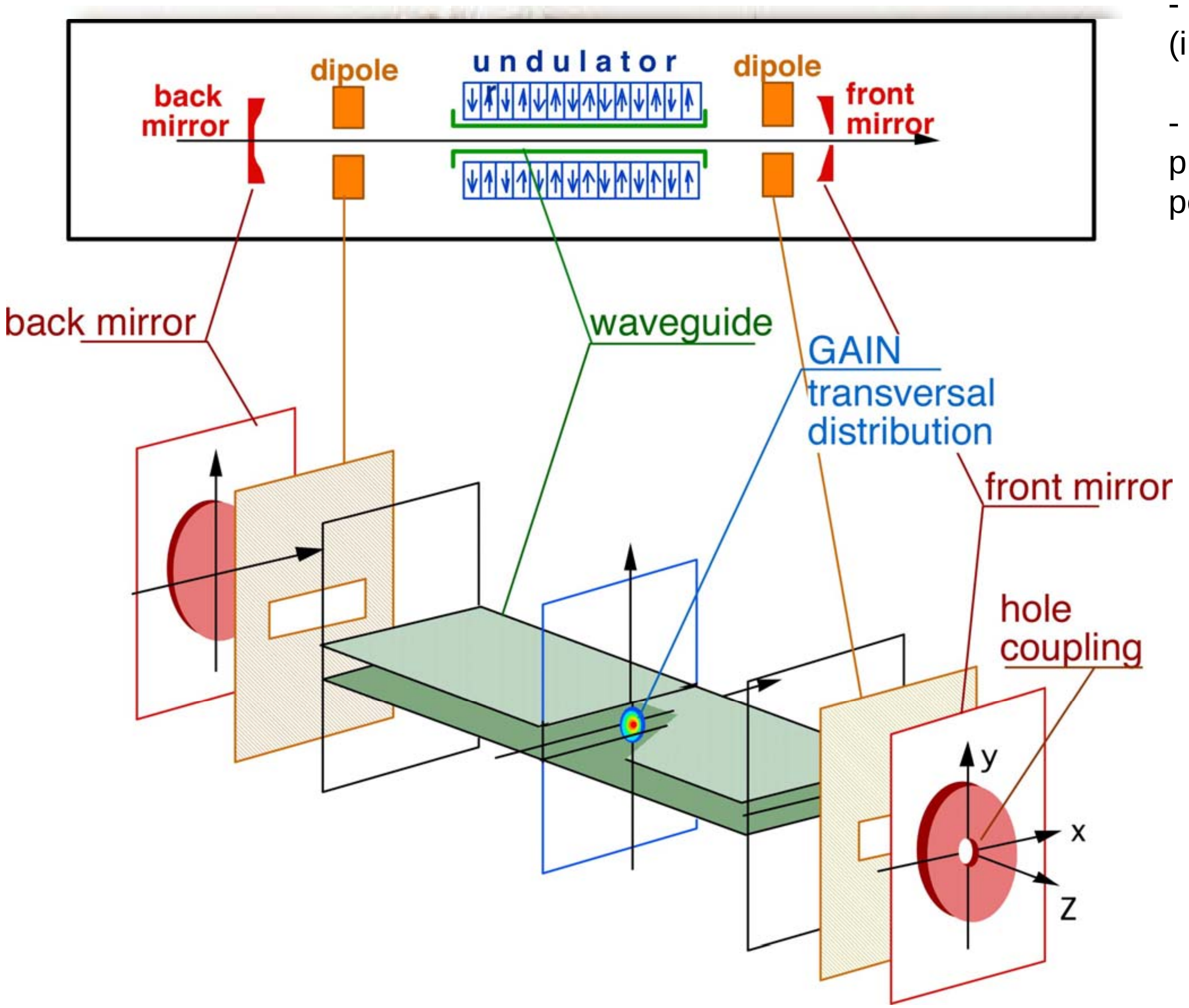
FRANCE

Configuration of the CLIO infrared FEL
3 μm up to 150 μm



waveguide :

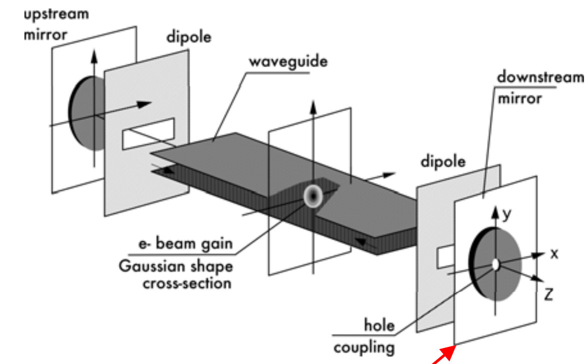
- reduces optical losses (infrared range)

- but it induces a phenomenon of : periodic **'Spectral Gaps'**

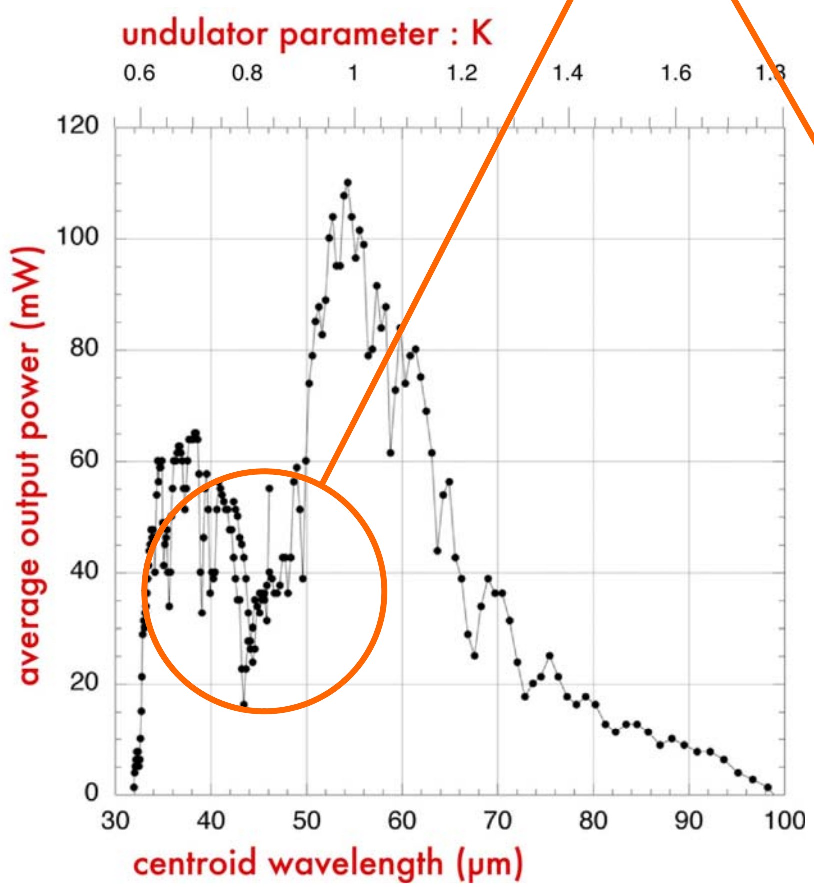
Measurements on CLIO at 15 MeV

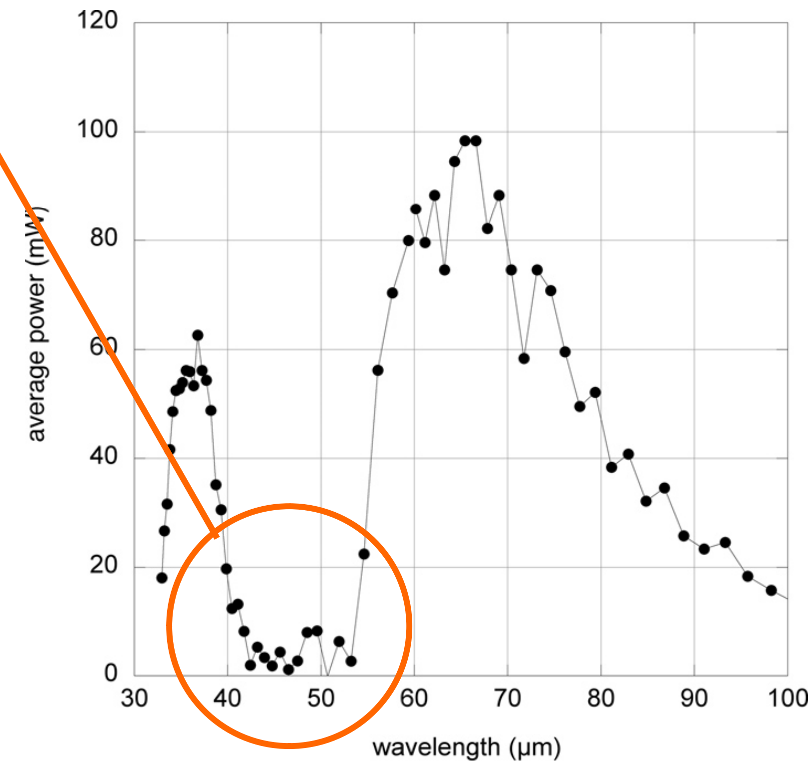
n° 031616470 et 031617015
23 mars 2007

Spectral
Gap



using a front toroidal mirror





FELIX 20 MeV

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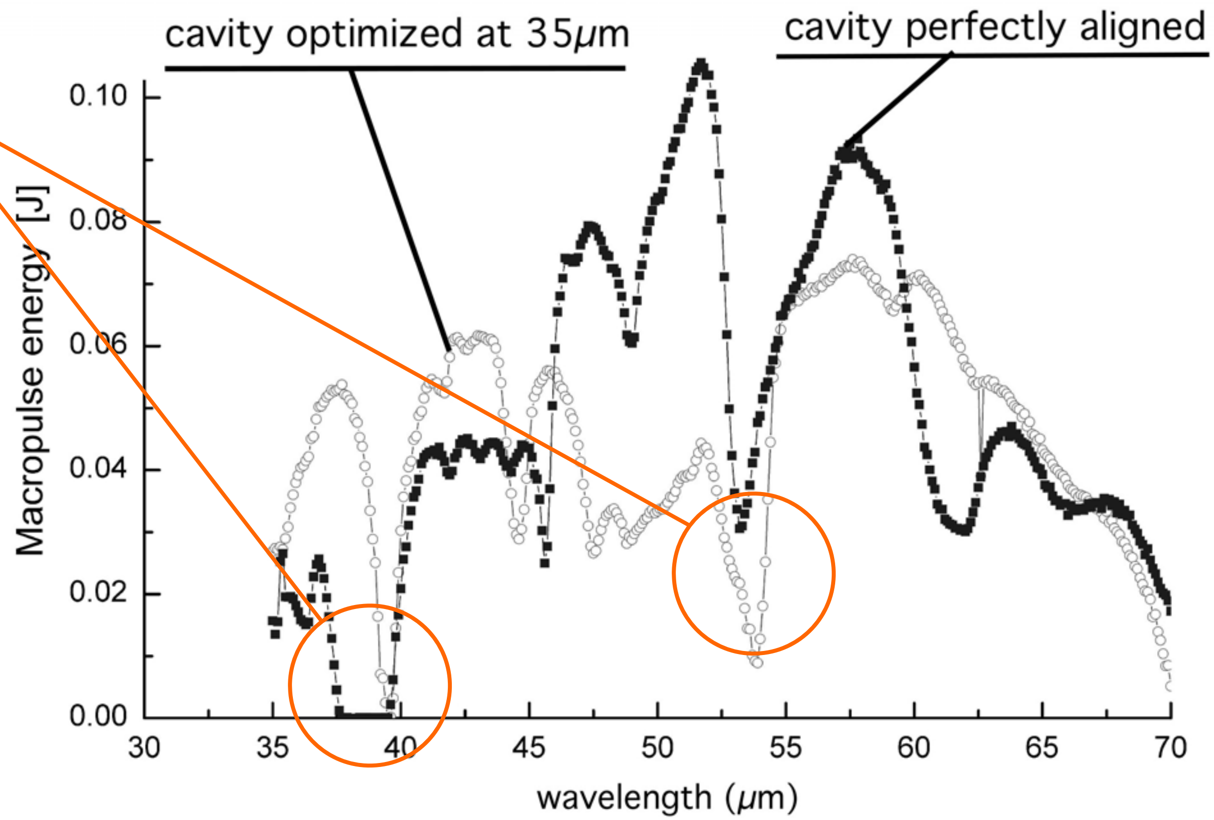
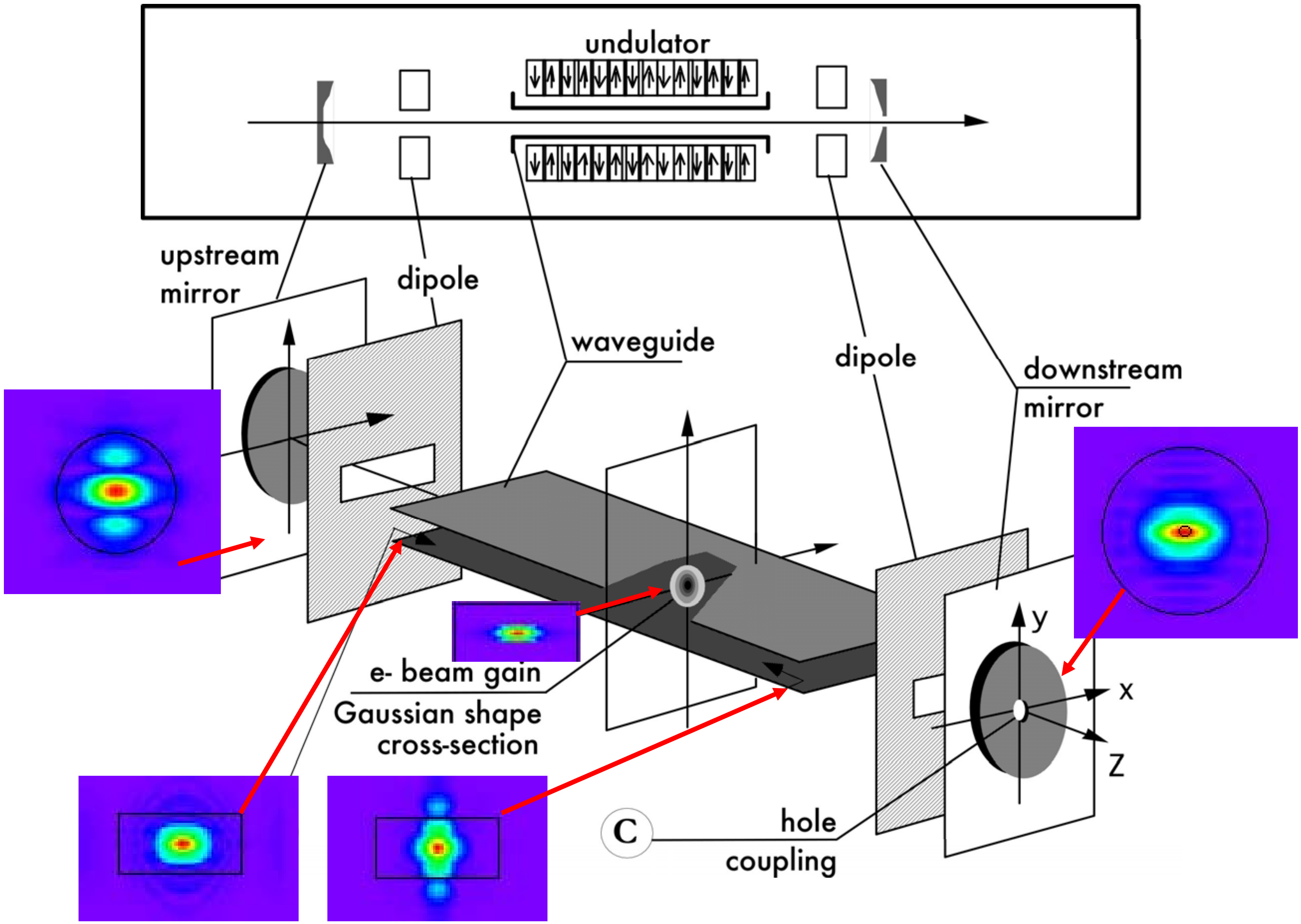
Spectral Gap



Study of Spectral Gaps : numerical simulation…

Numerical simulation of cavity losses and FEL power



Calculation of :

- cavity losses
- hole couping extraction rate
- small signal gain *
- intra-cavity laser power *
- output laser power *

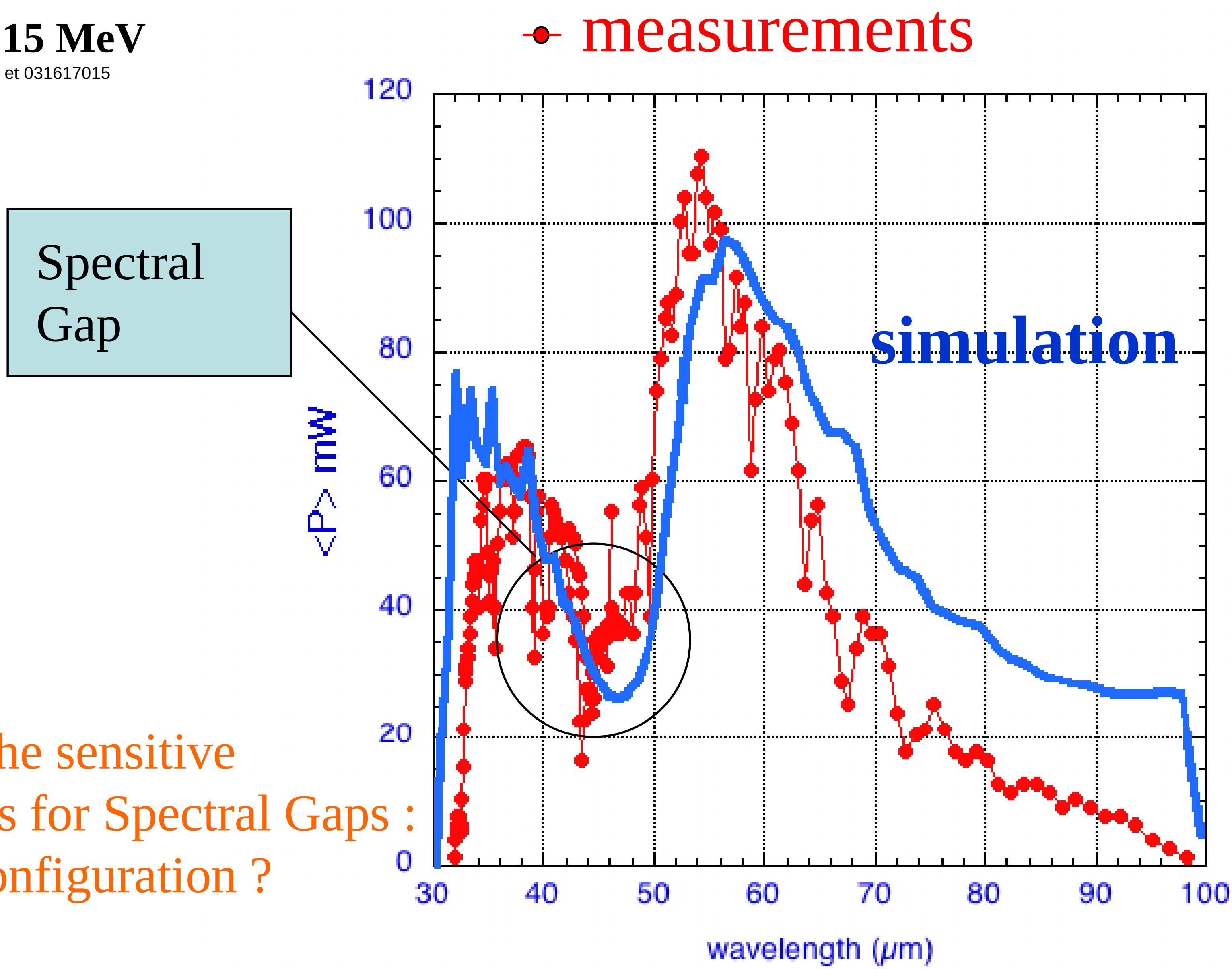
* using the theoretical model of FEL saturation : G. Dattoli

it is a 2D single wavelength model :

- does not include short pulse effects of the FEL
- limited to narrow linewidth FEL operation
- does not take into account resonance wavelength shift induced by the waveguide

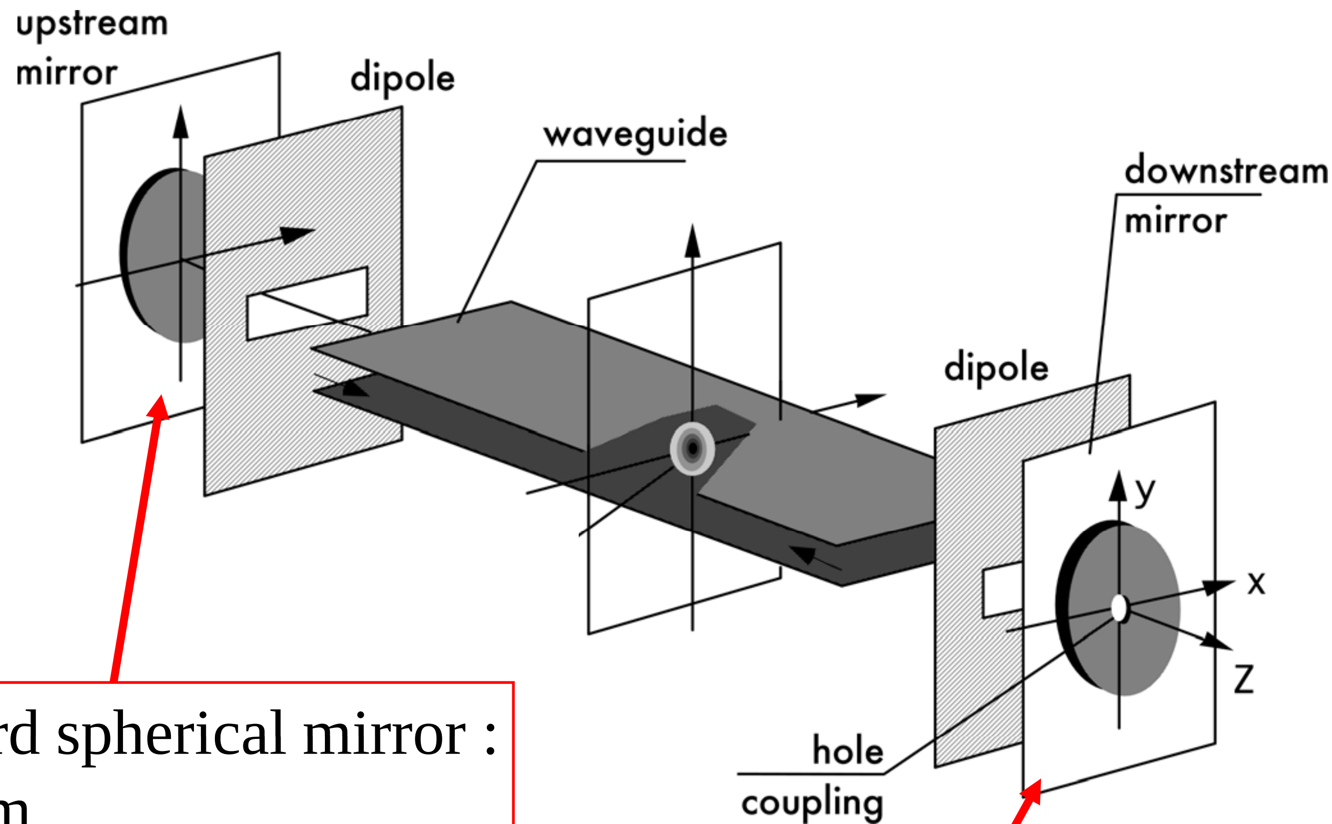
CLIO 15 MeV

n° 031616470 et 031617015
23 mars 2007



what are the sensitive parameters for Spectral Gaps :

- cavity configuration ?

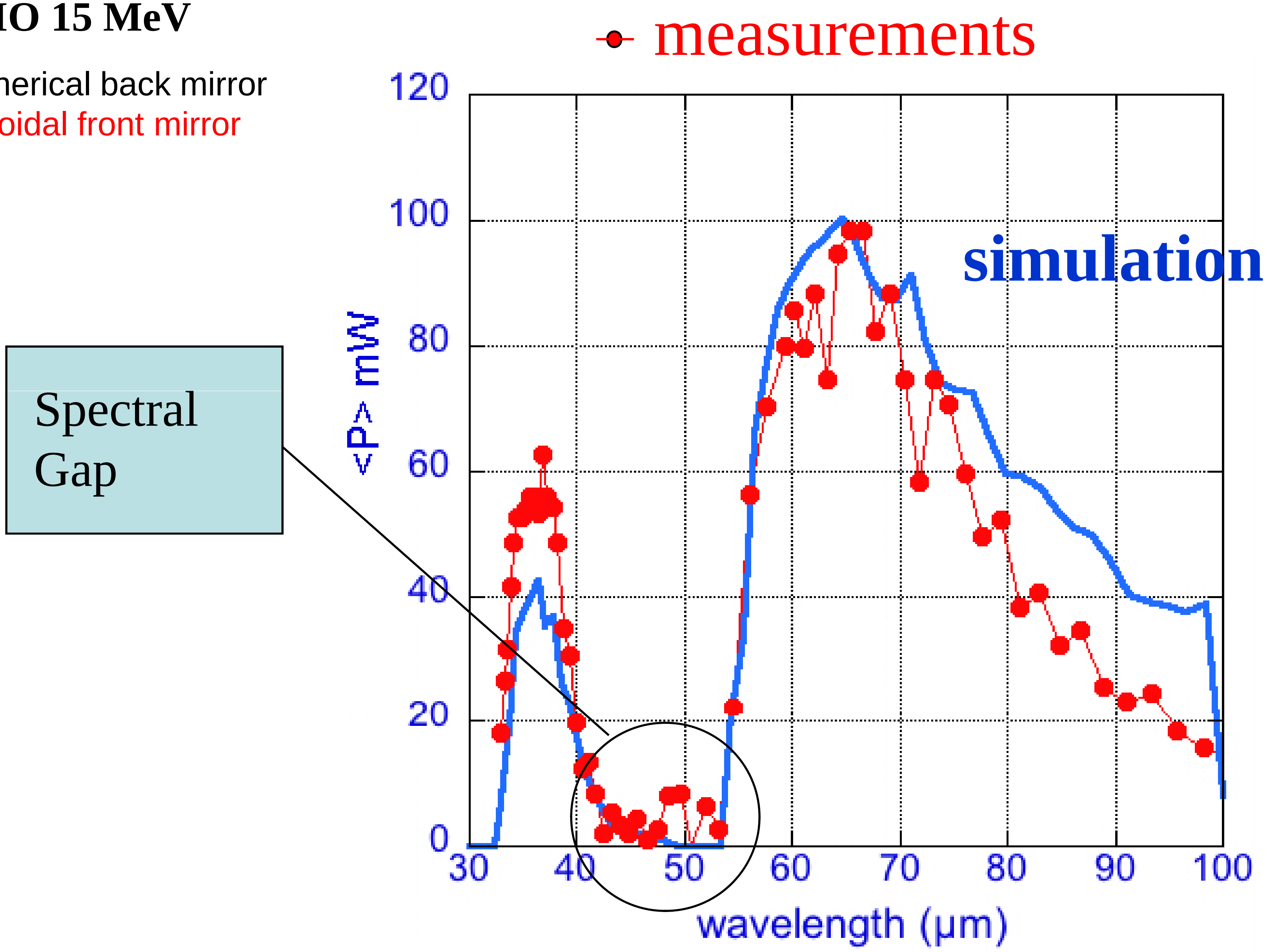


Standard spherical mirror :
RC= 3m

Toroidal mirror :
RC= 3m x 1.9m
Best compromise for λ>100µm

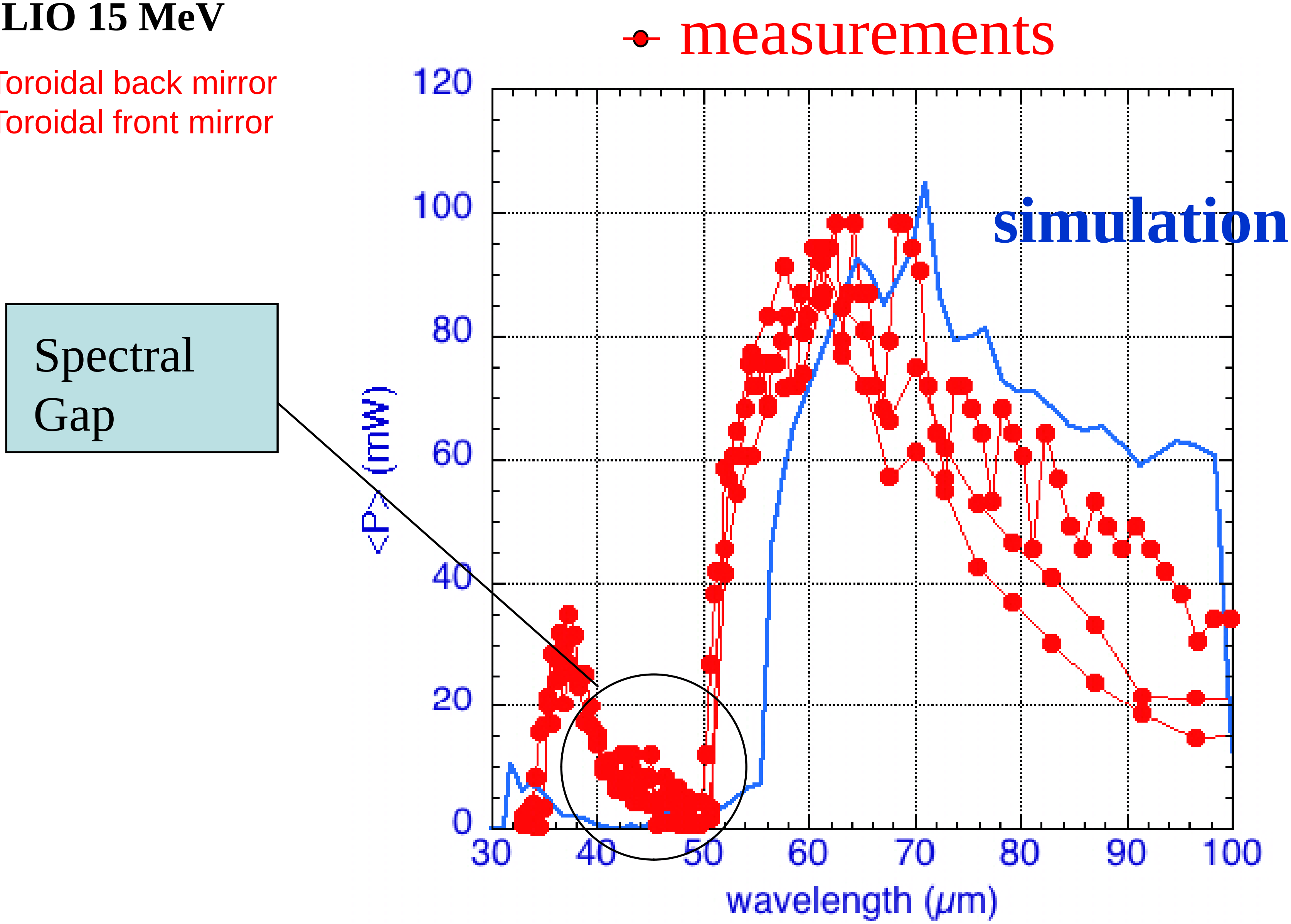
CLIO 15 MeV

- Spherical back mirror
- Toroidal front mirror



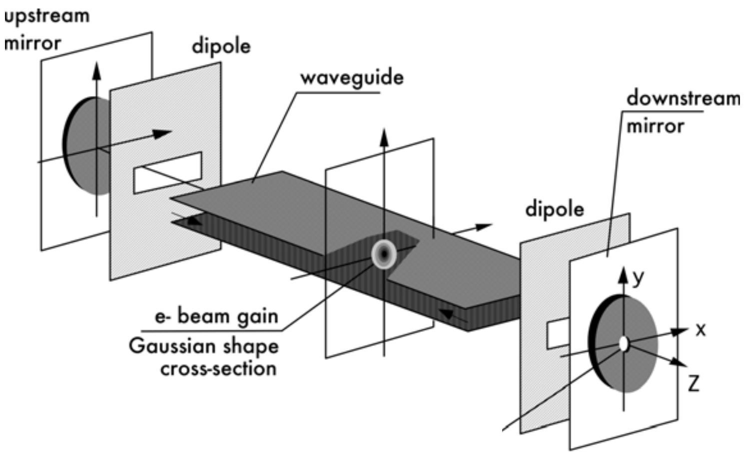
CLIO 15 MeV

- Toroidal back mirror
- Toroidal front mirror



simulation

Spherical cavity

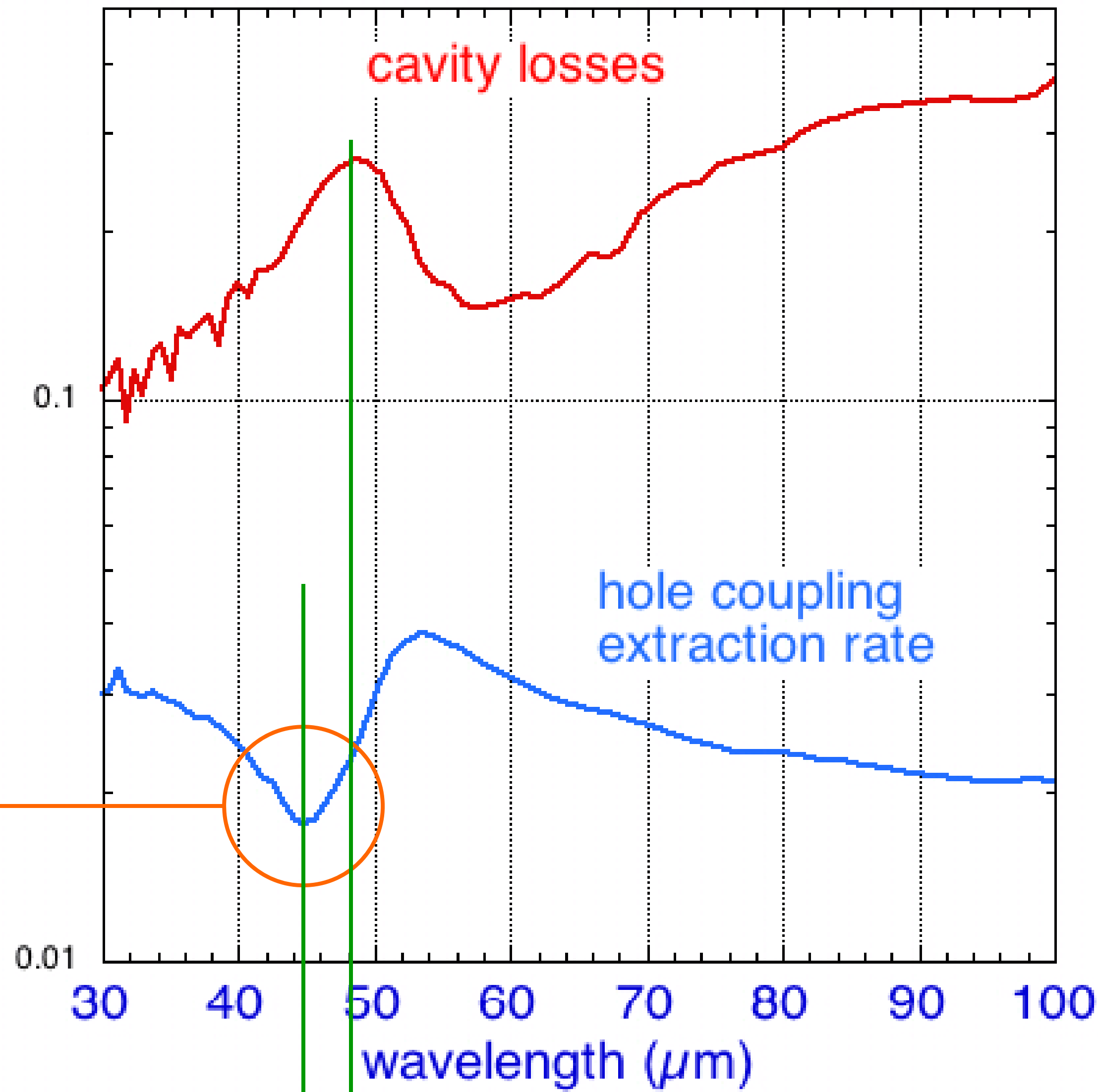


Analysis using the simulation…

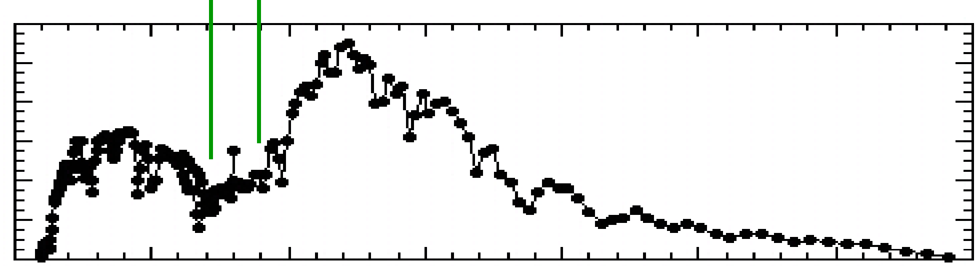
simulation

Spherical cavity

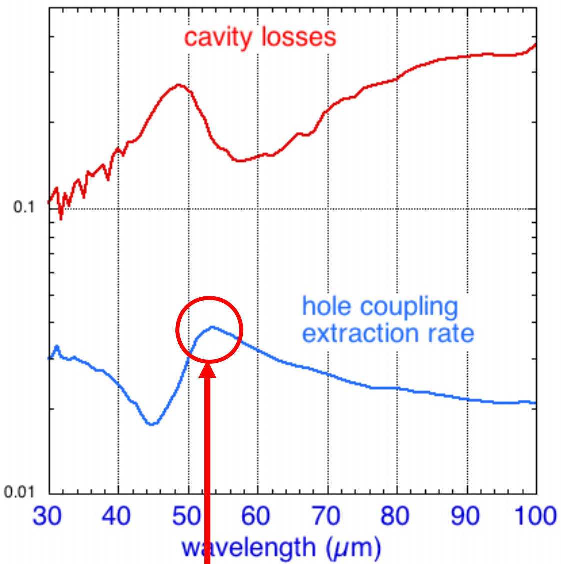
Why hole coupling
is decreasing ?

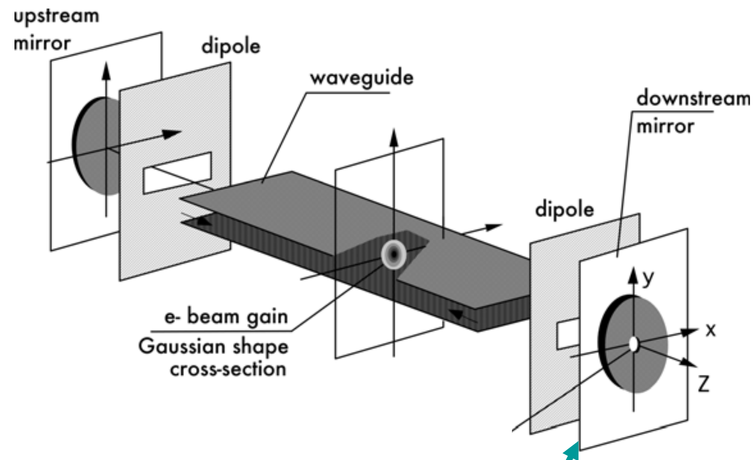


power
measurement



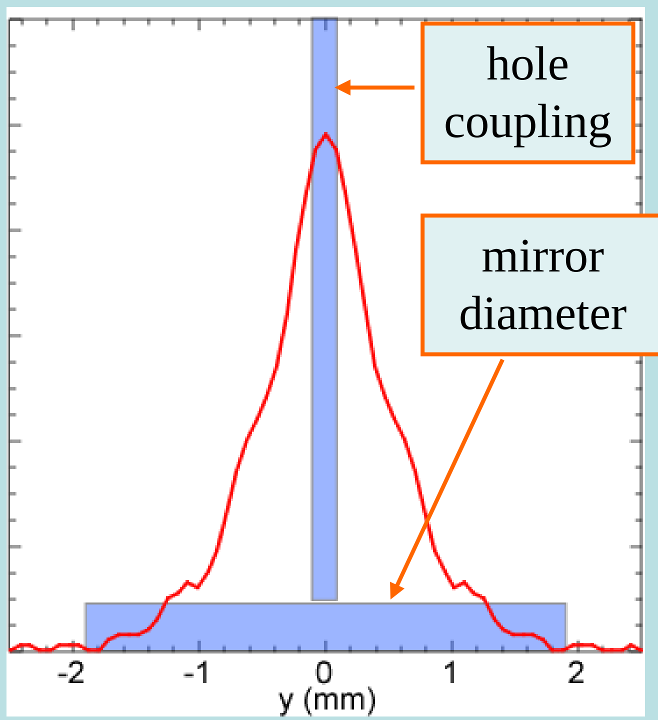
Why is hole coupling decreasing ?

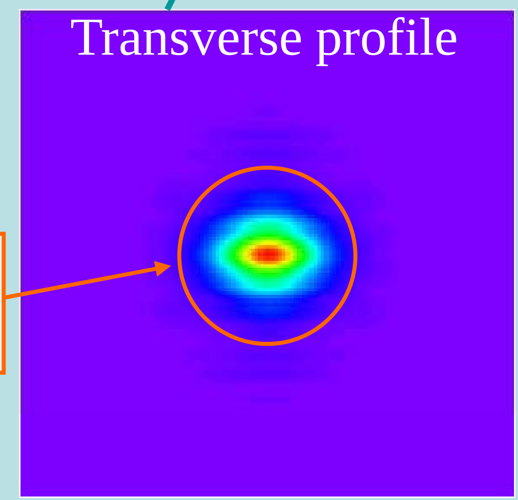




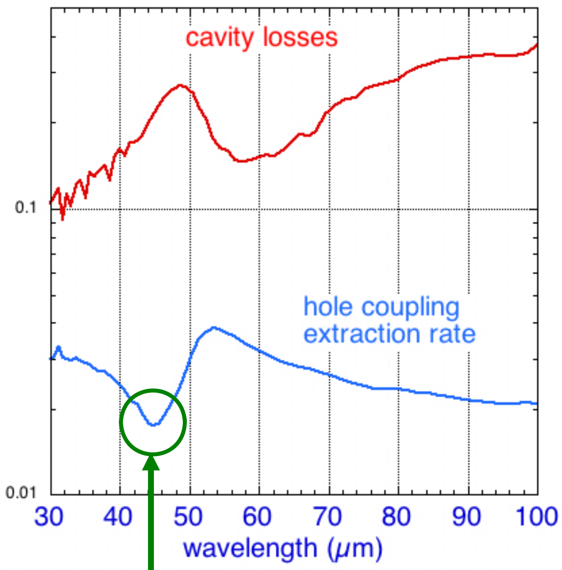
λ= 53.3 µm
Extraction= 3.7%

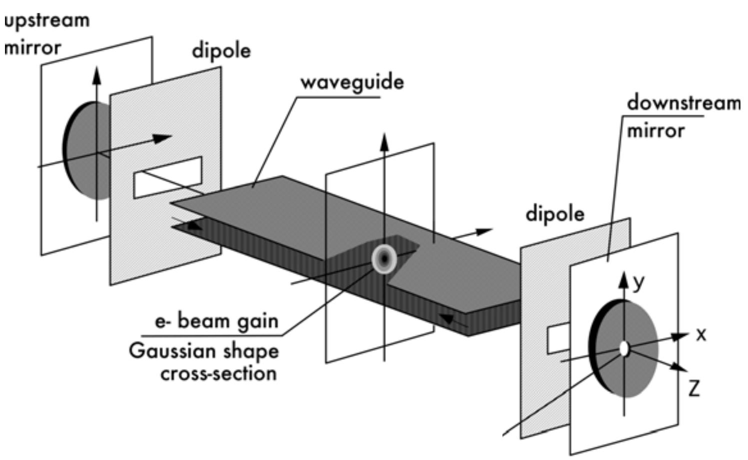
Y cut of profile





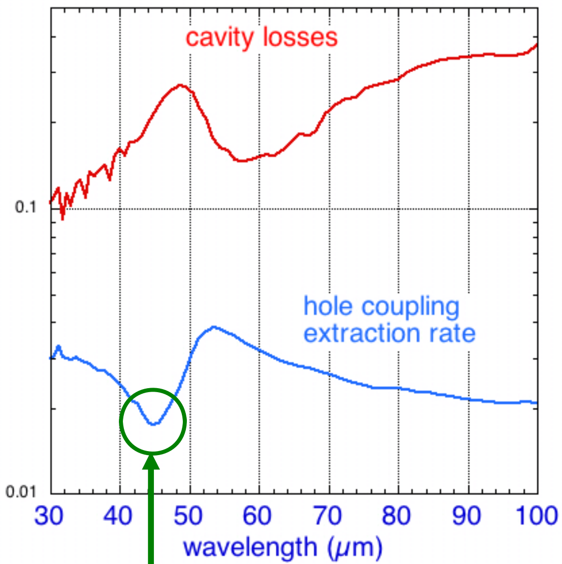
Why is hole coupling decreasing ?

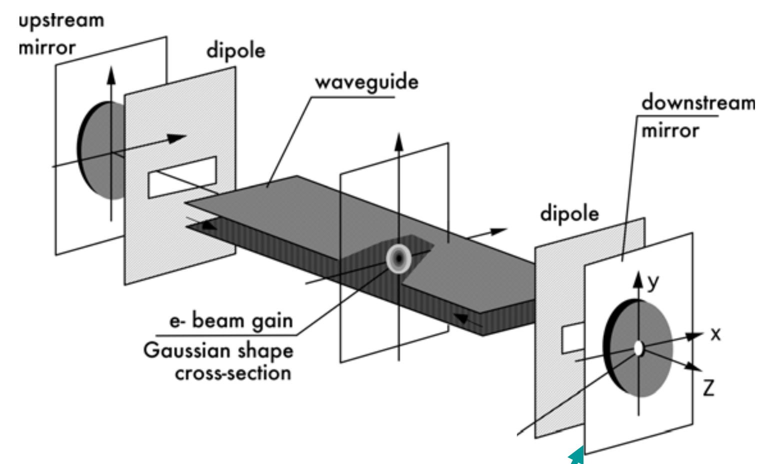


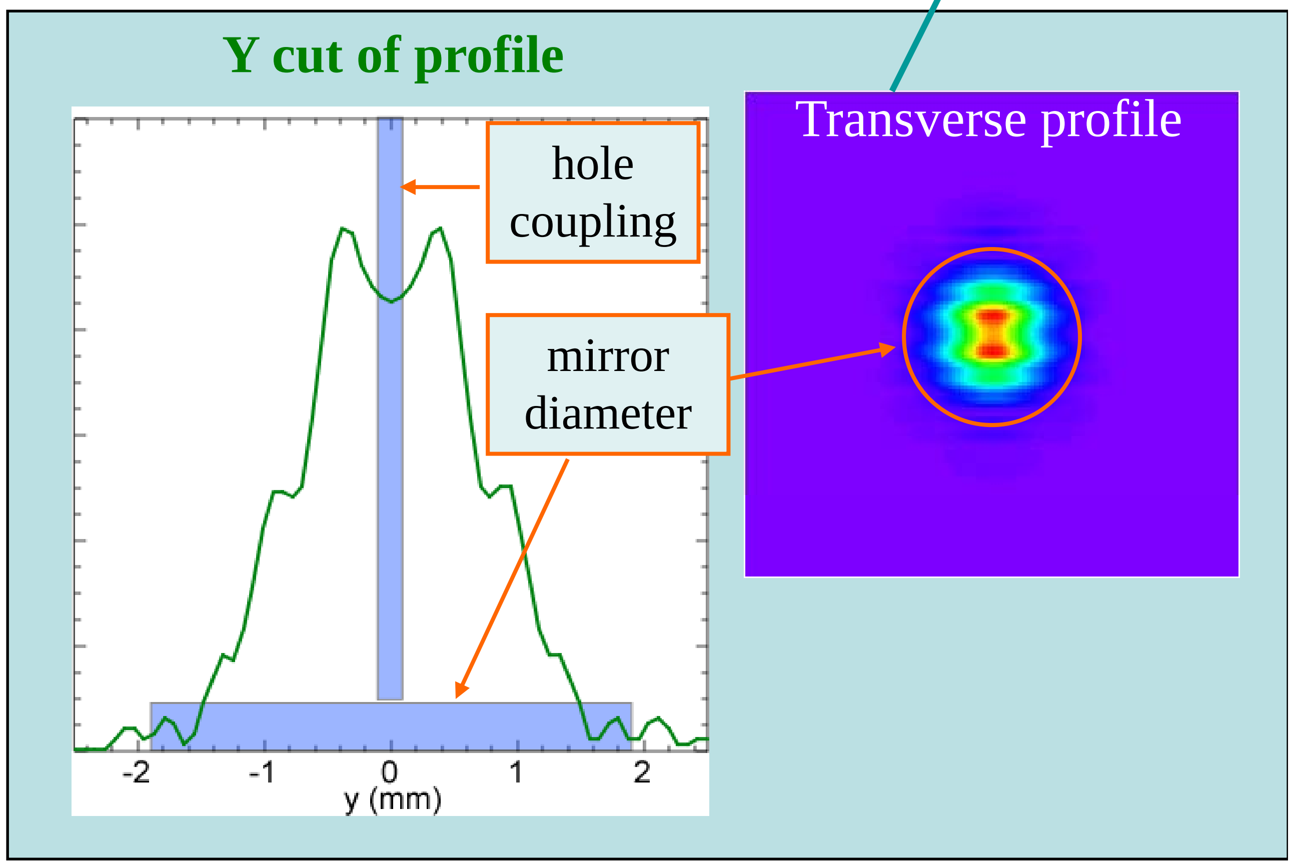


λ = 53.3 μm → 45 μm

Why is hole coupling decreasing ?

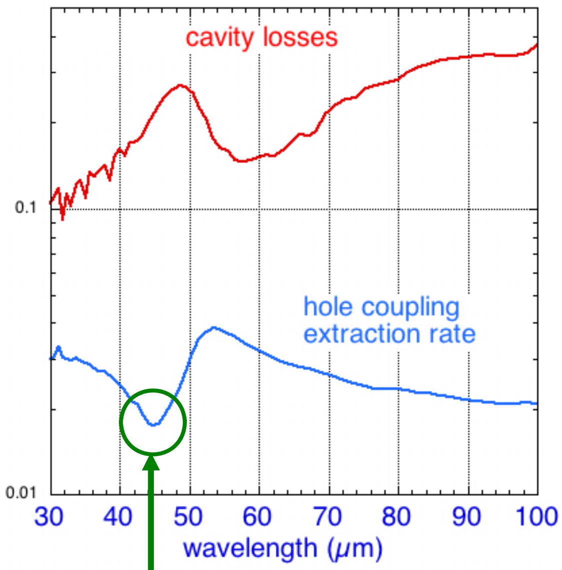


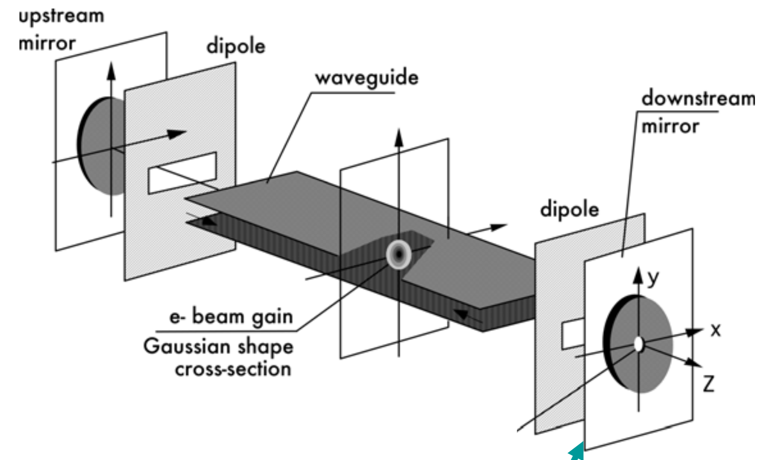




λ= 45 µm
Extraction= 1.7 %

Why is hole coupling decreasing ?



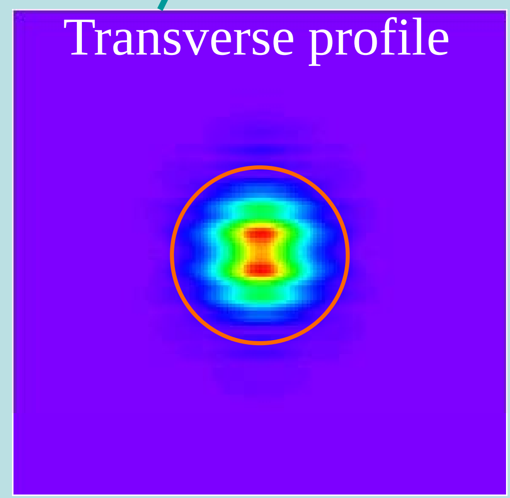


λ= 45 μm

Extraction= 1.7 %

<u>Spectral Gap :</u>

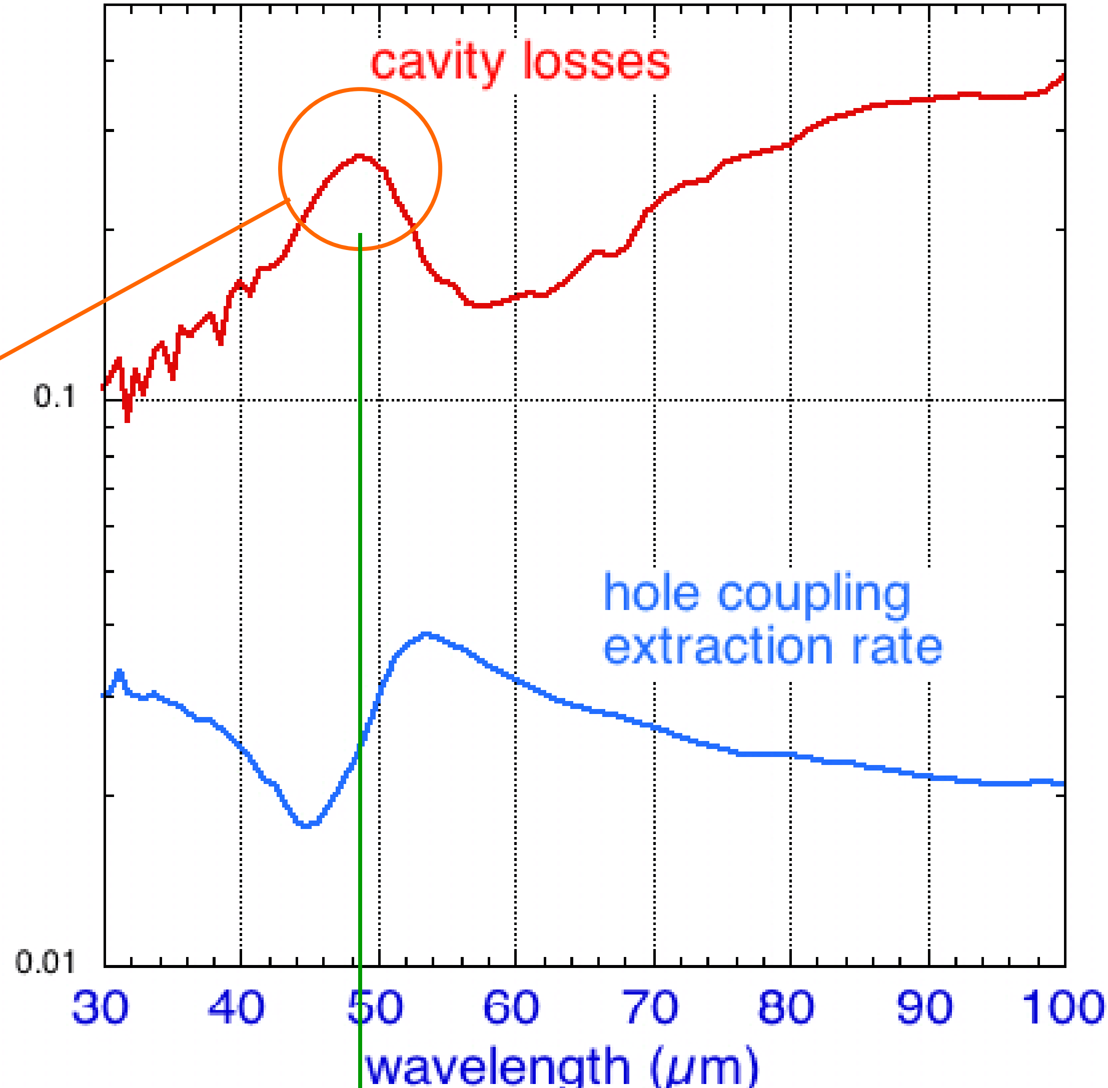
- bad output coupling of laser mode profile



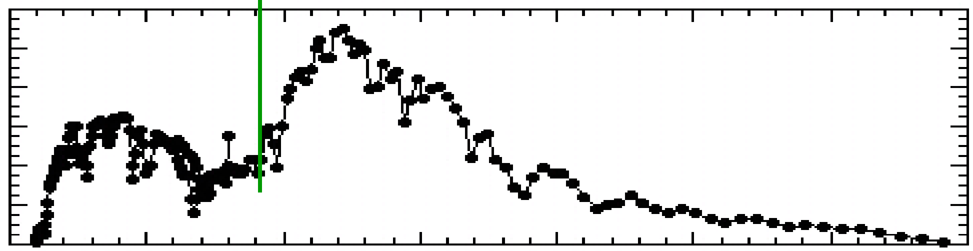
simulation

Spherical cavity

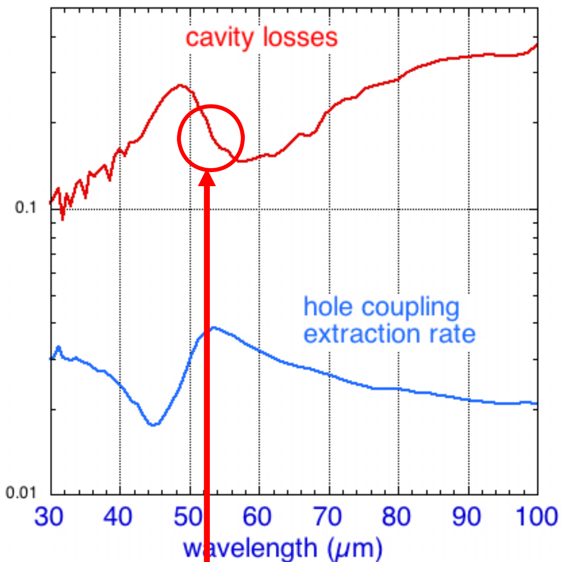
Why are losses increasing ?

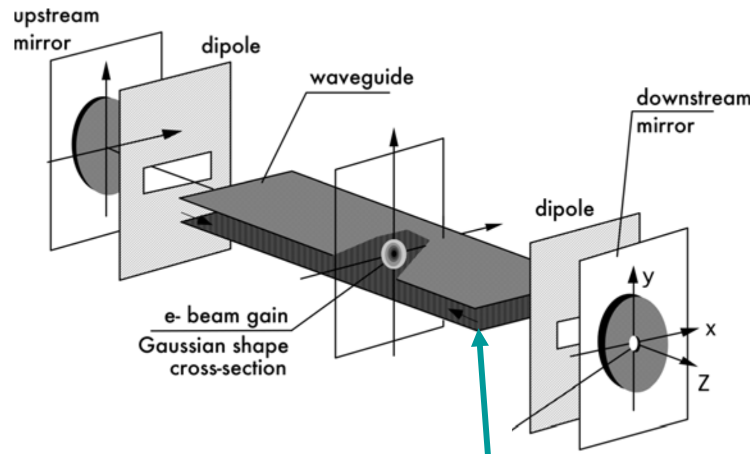


Power measurement



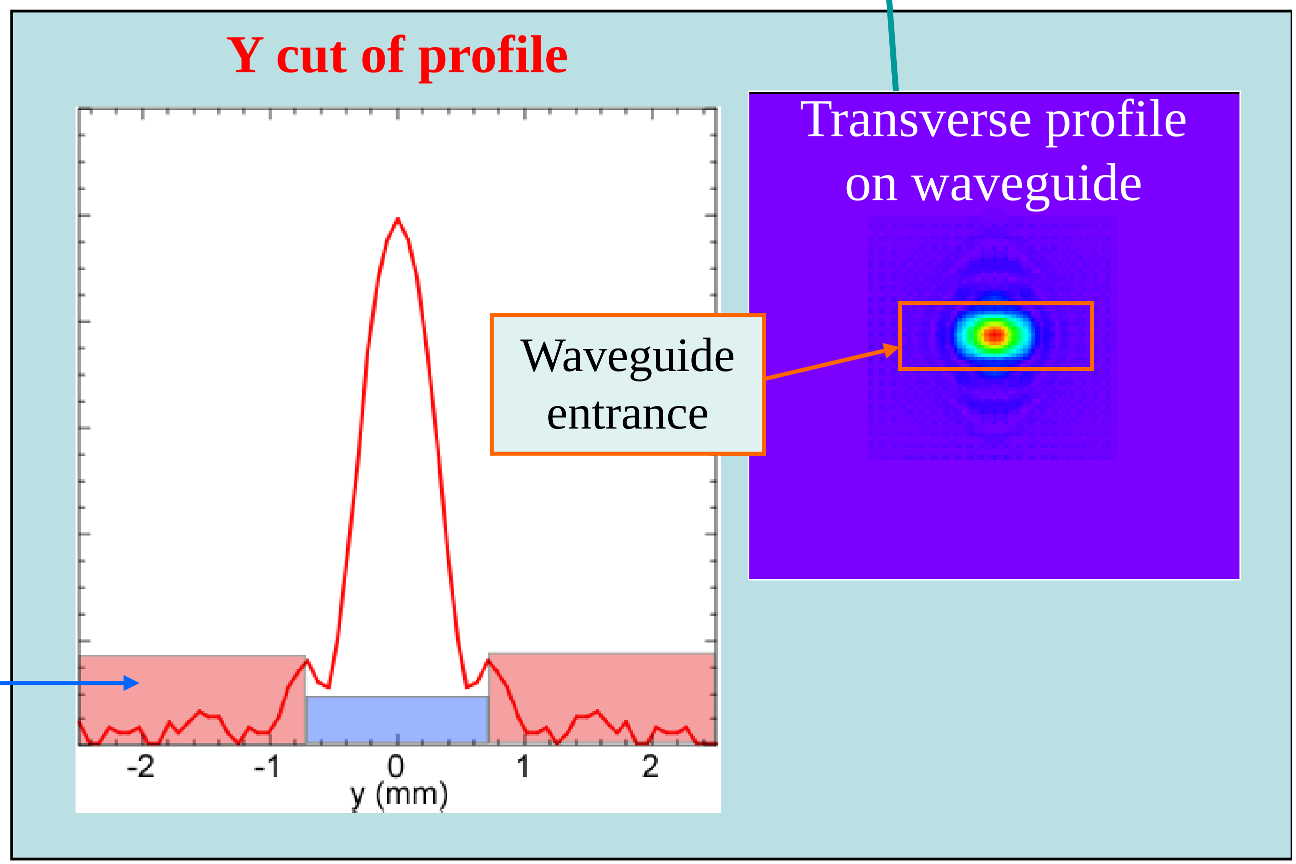
Why are losses increasing ?



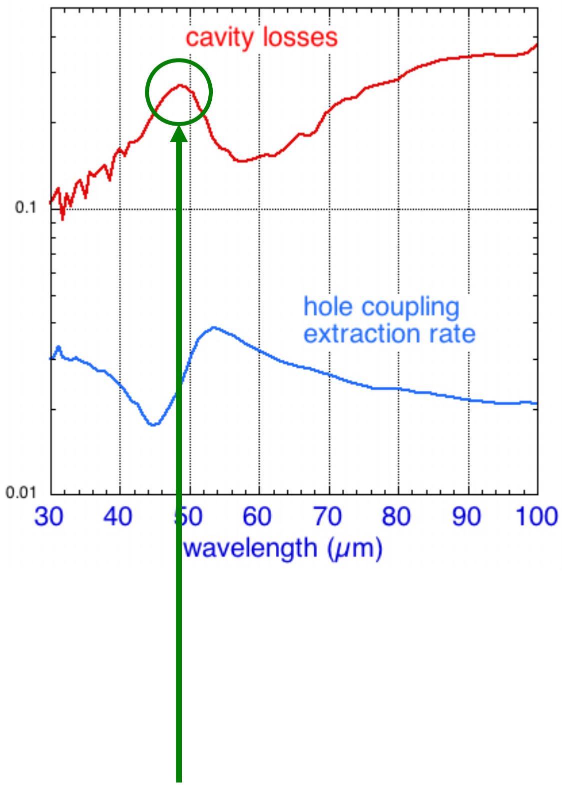


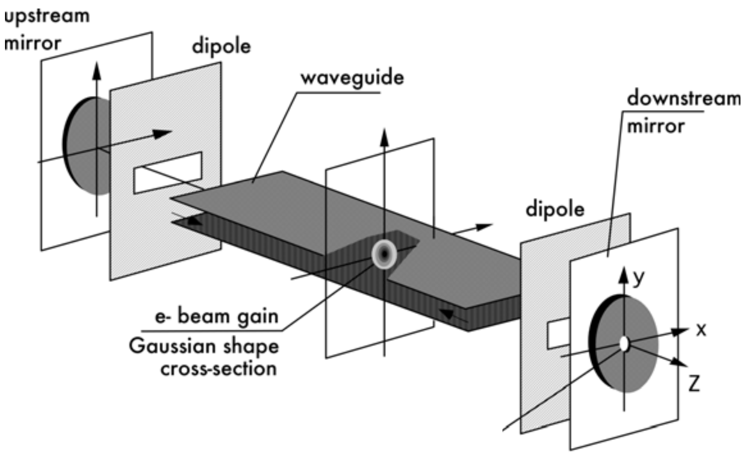
λ = 53.3 μm

small amount of energy
8 % lost
outside of the waveguide



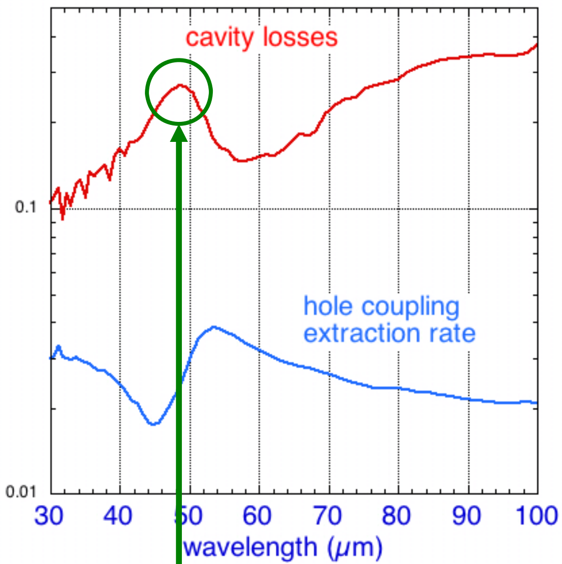
Why are losses increasing ?



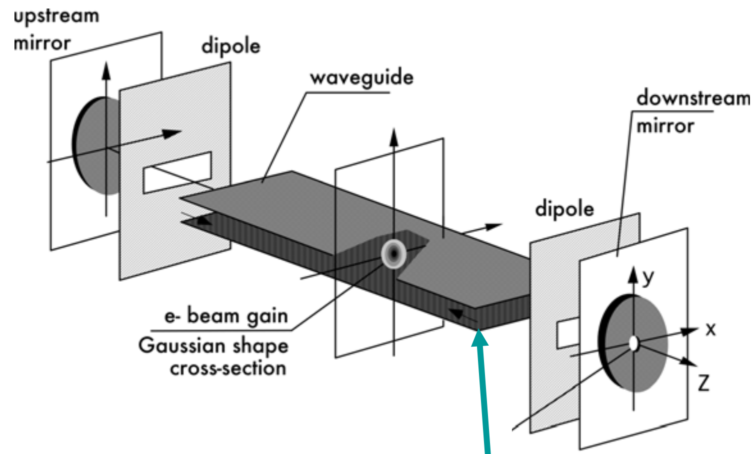


λ = 53.3 μm → 48.4 μm

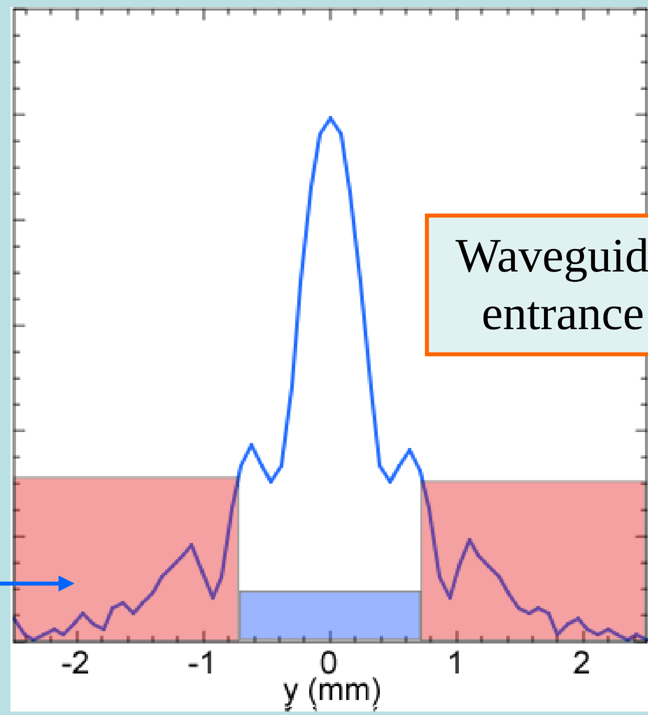
Why are losses increasing ?

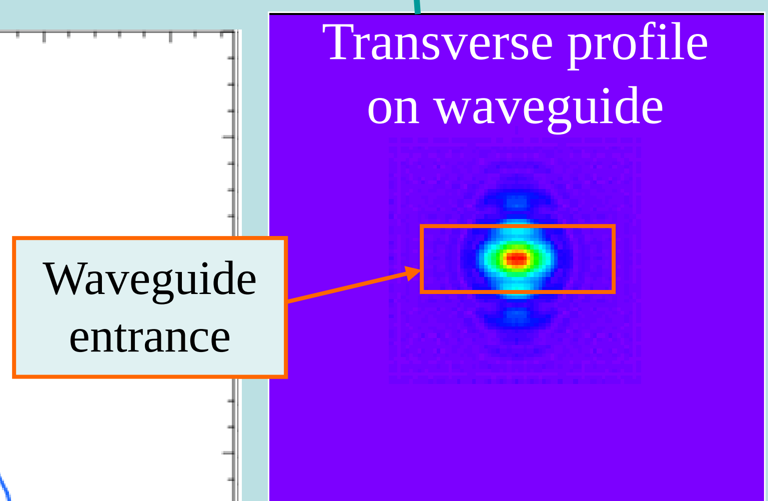


λ = 48.4 μm



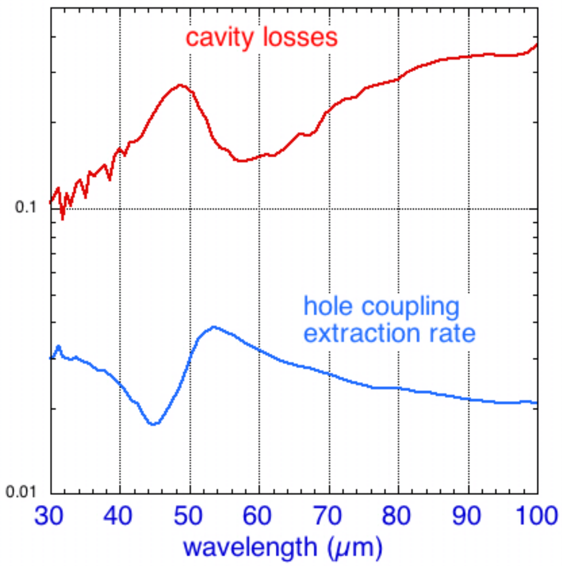
Y cut of profile

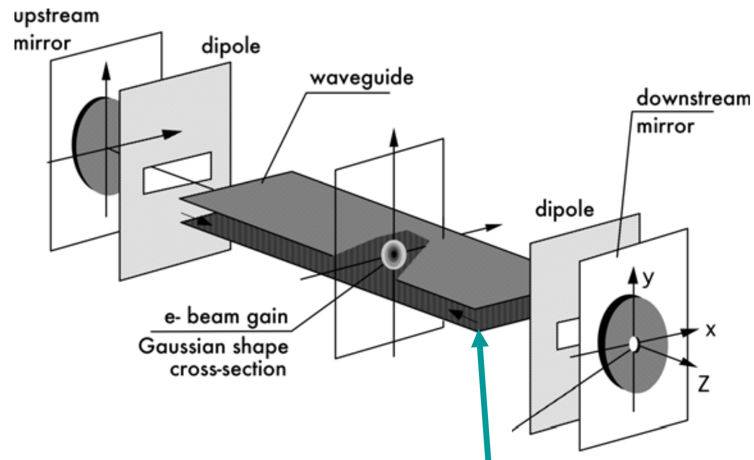




LARGE amount of energy
20 % lost
outside of the waveguide

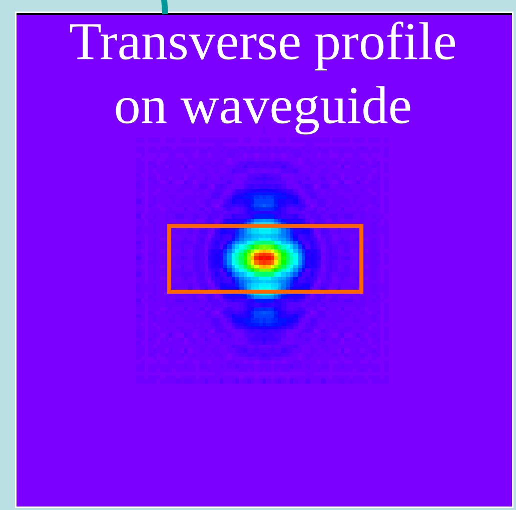
Why are losses increasing ?





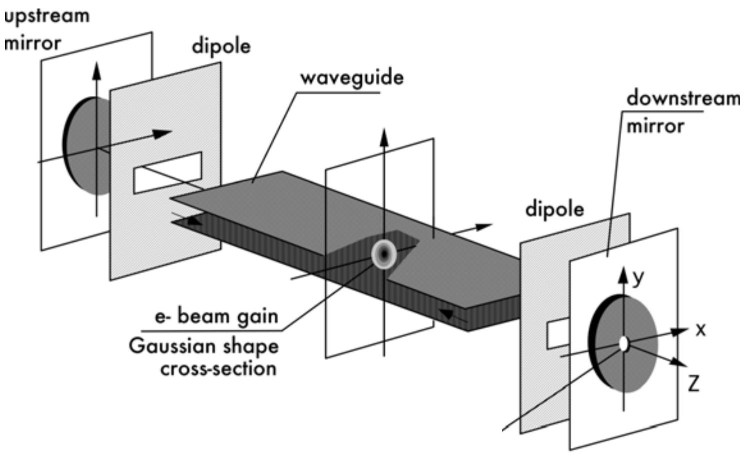
<u>Spectral Gap :</u>

-optical losses at waveguide entrance



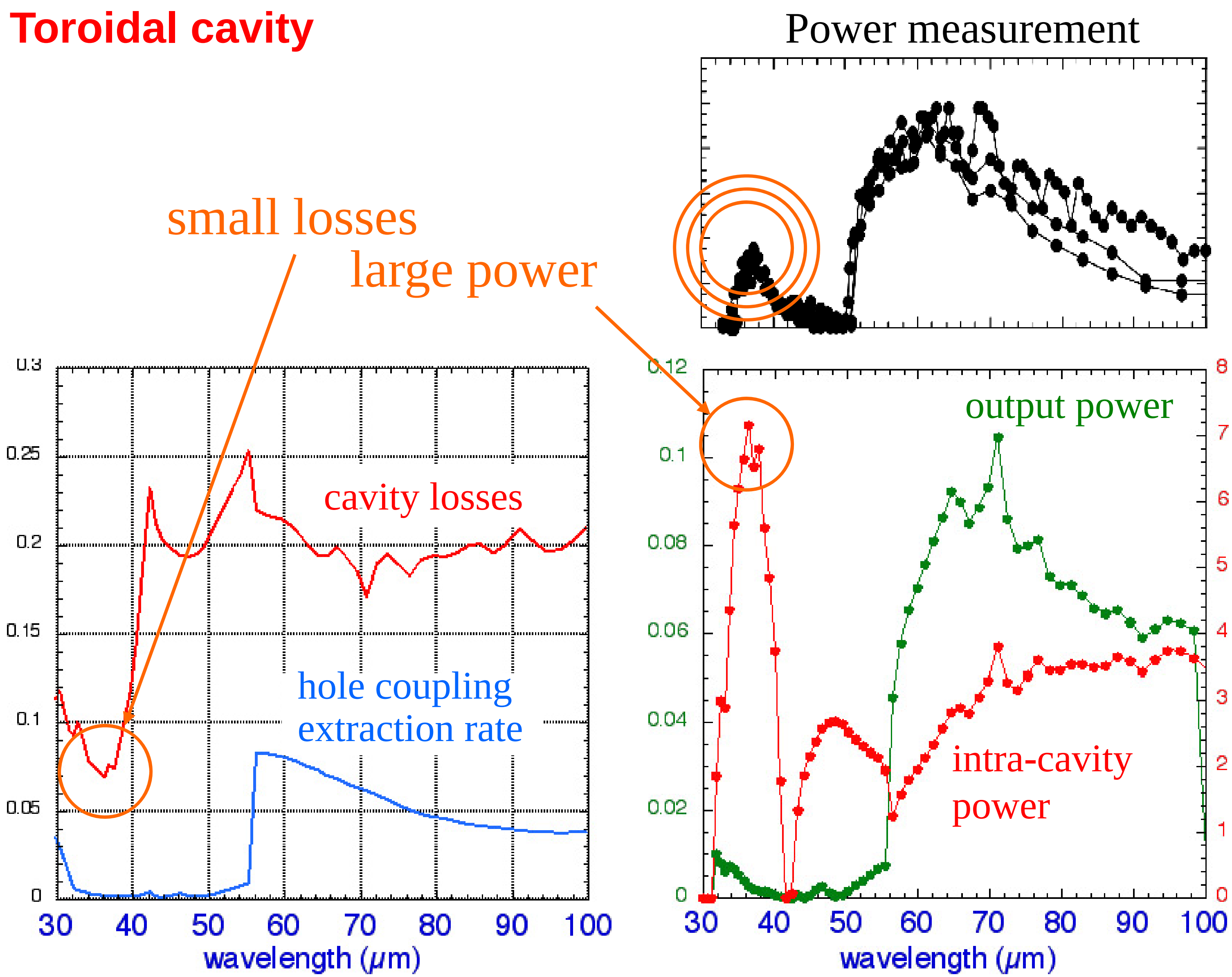
simulation

Toroidal cavity

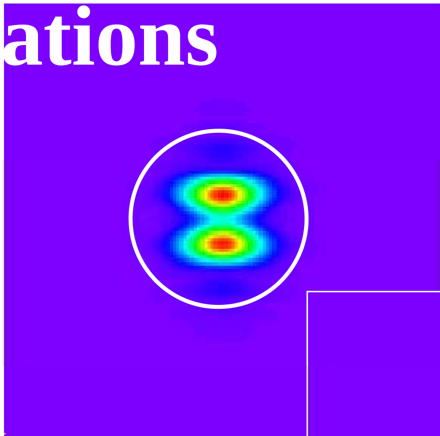


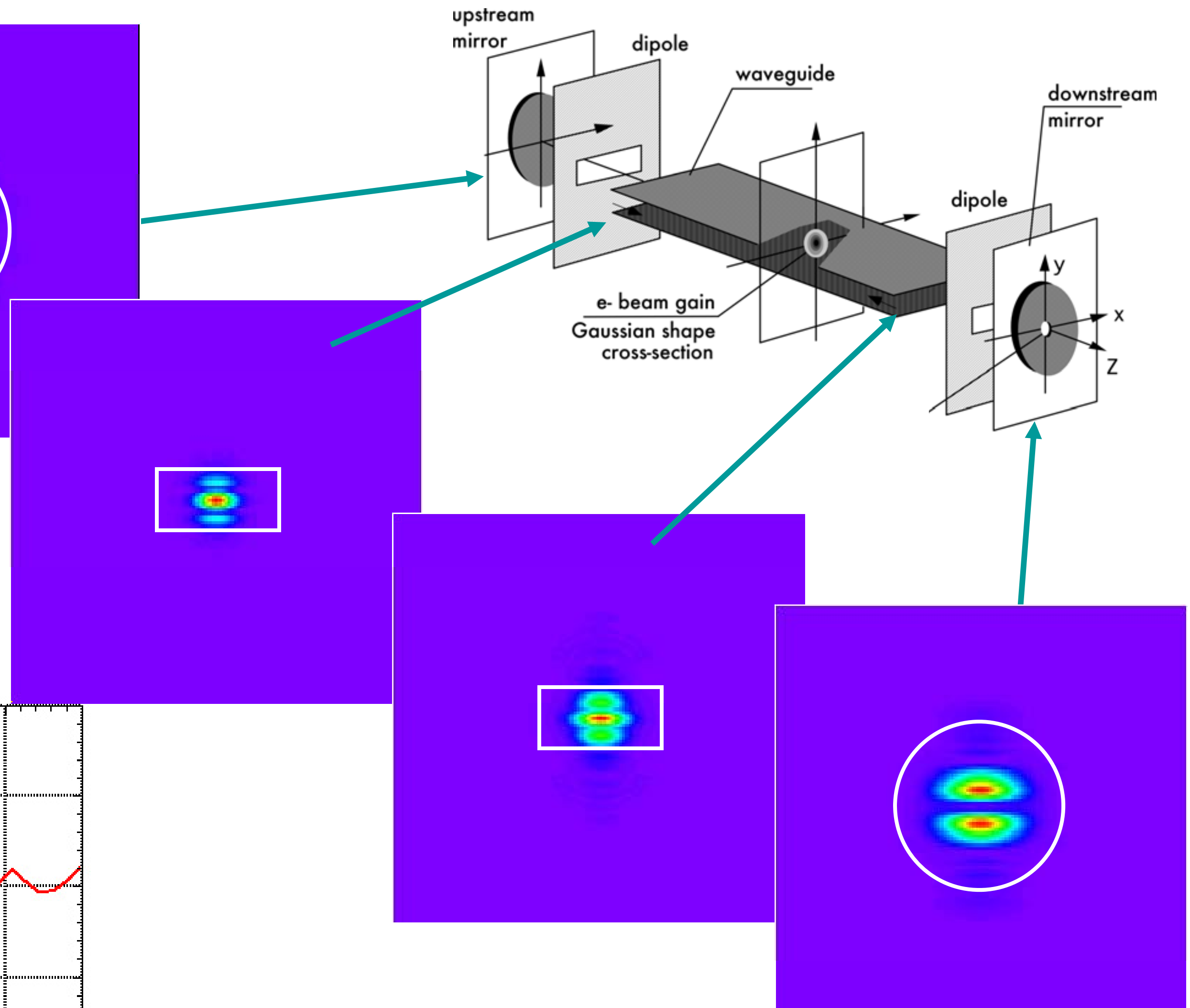
simulation

Toroidal cavity

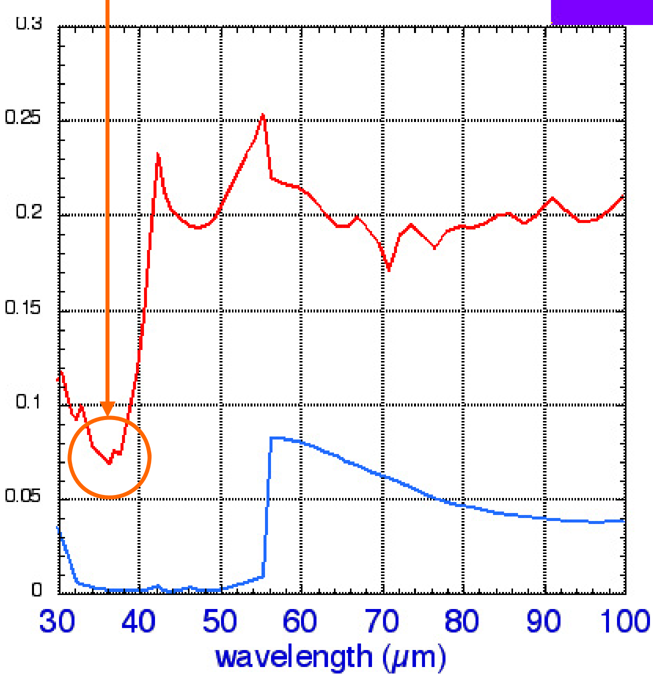


simulations



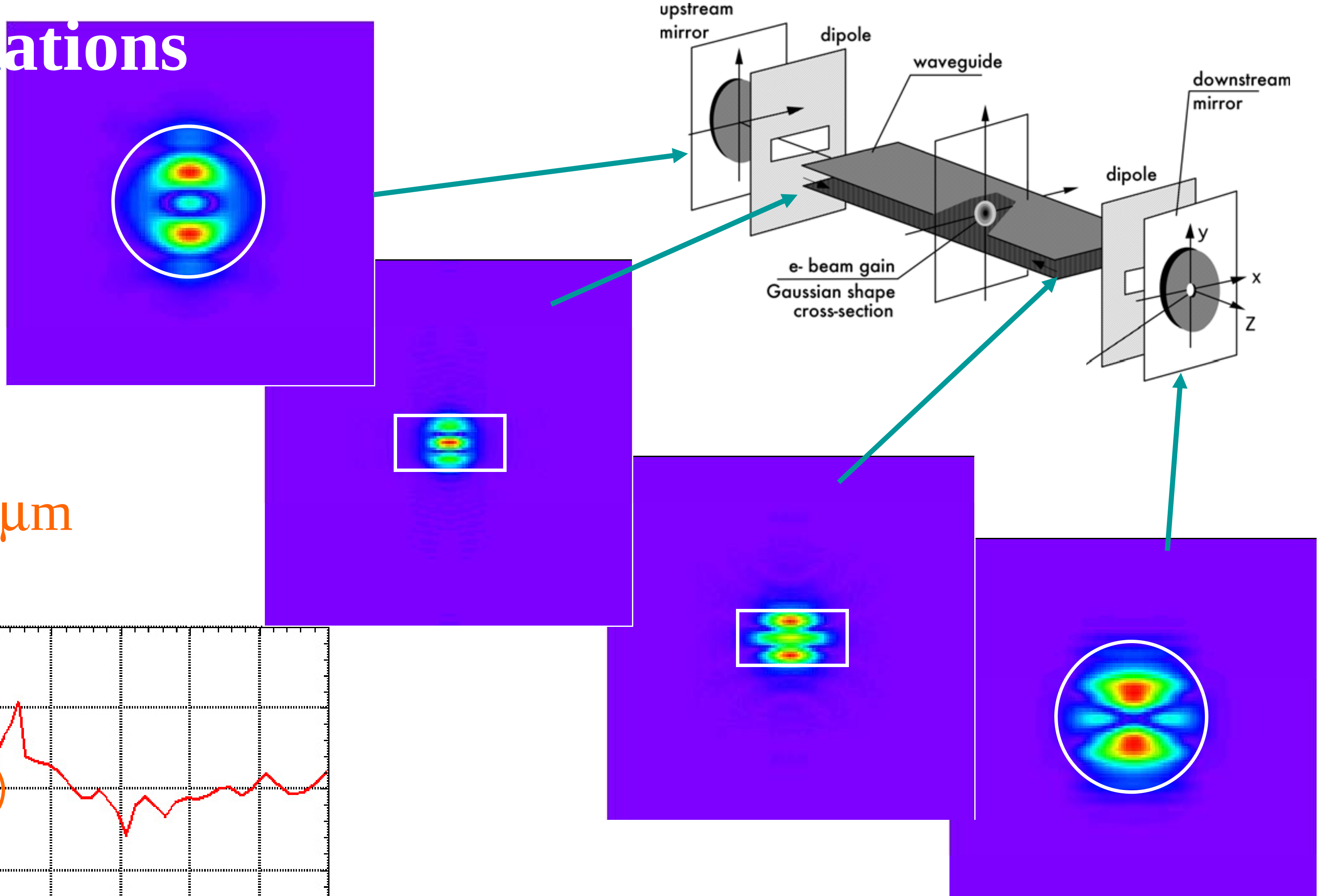


λ=36.3μm
minimum losses

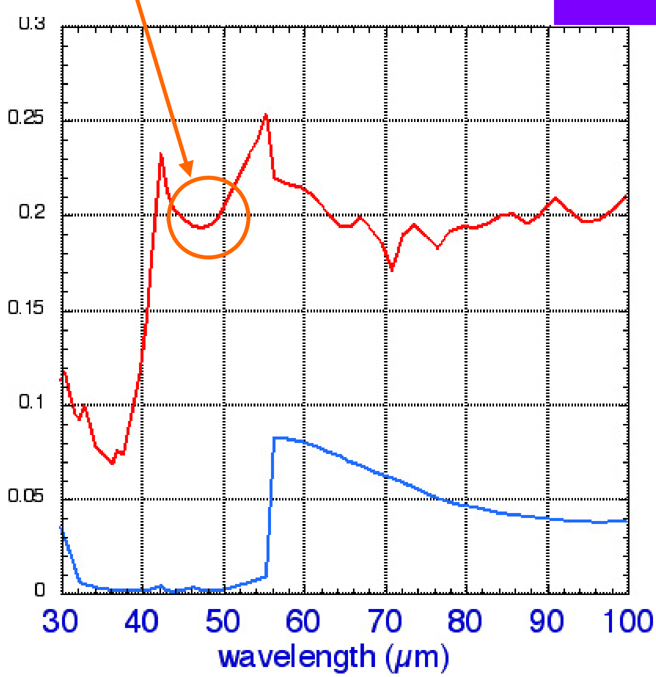


- wave fitting the waveguide
- small hole coupling

simulations

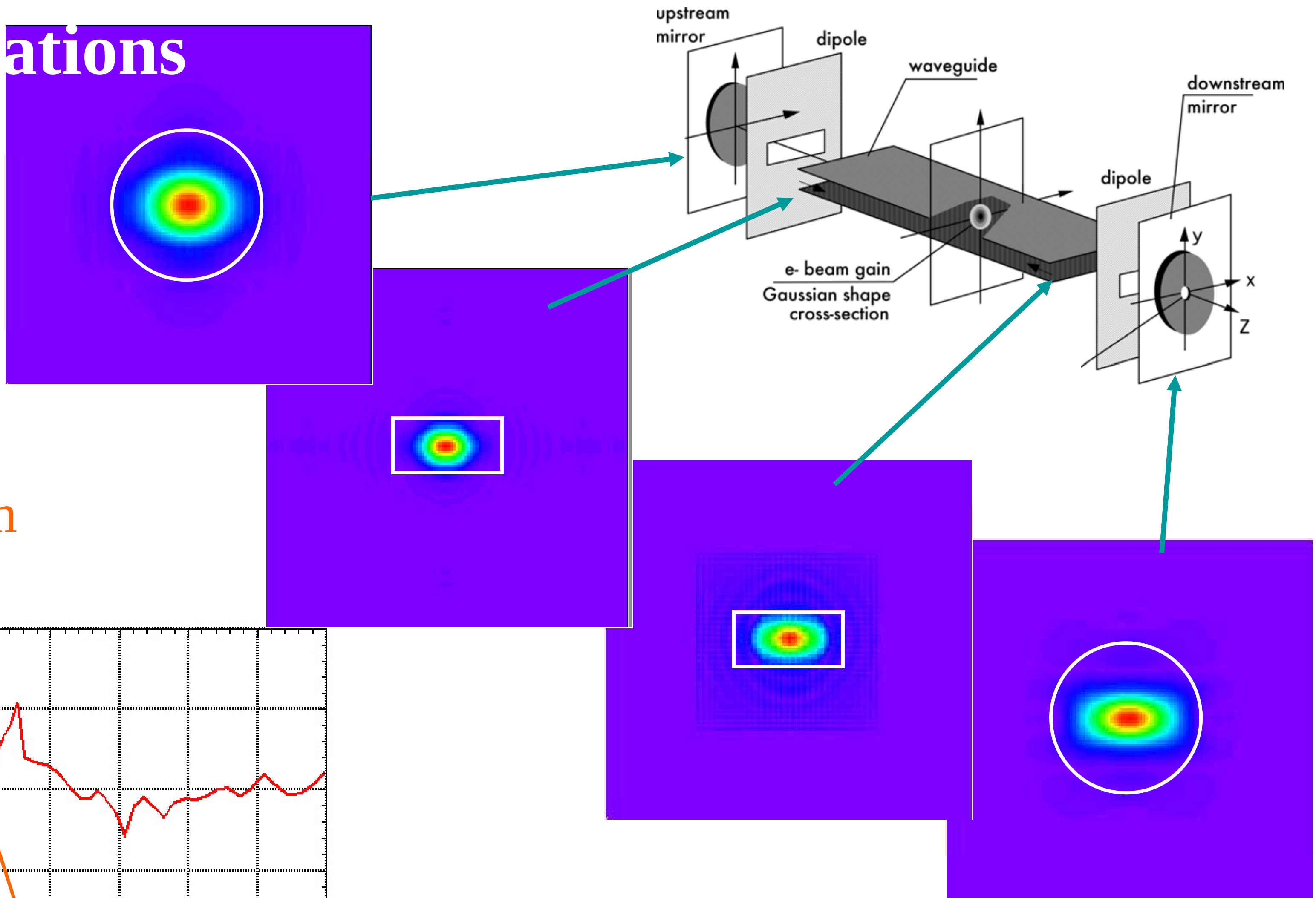


λ=48.4μm

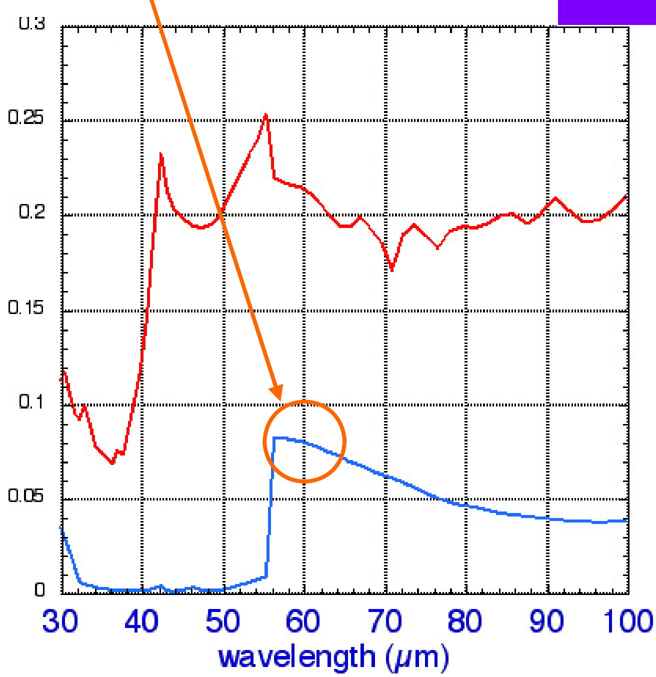


- larger losses on waveguide and mirror
- small hole coupling

simulations



λ=71µm



- wave fitting the waveguide
- LARGE hole coupling

Spectral Gaps :

(1) Bad output coupling by the hole

(2) Increasing of cavity losses, due to bad fitting of the wave on waveguide entrances

FELIX 20 MeV

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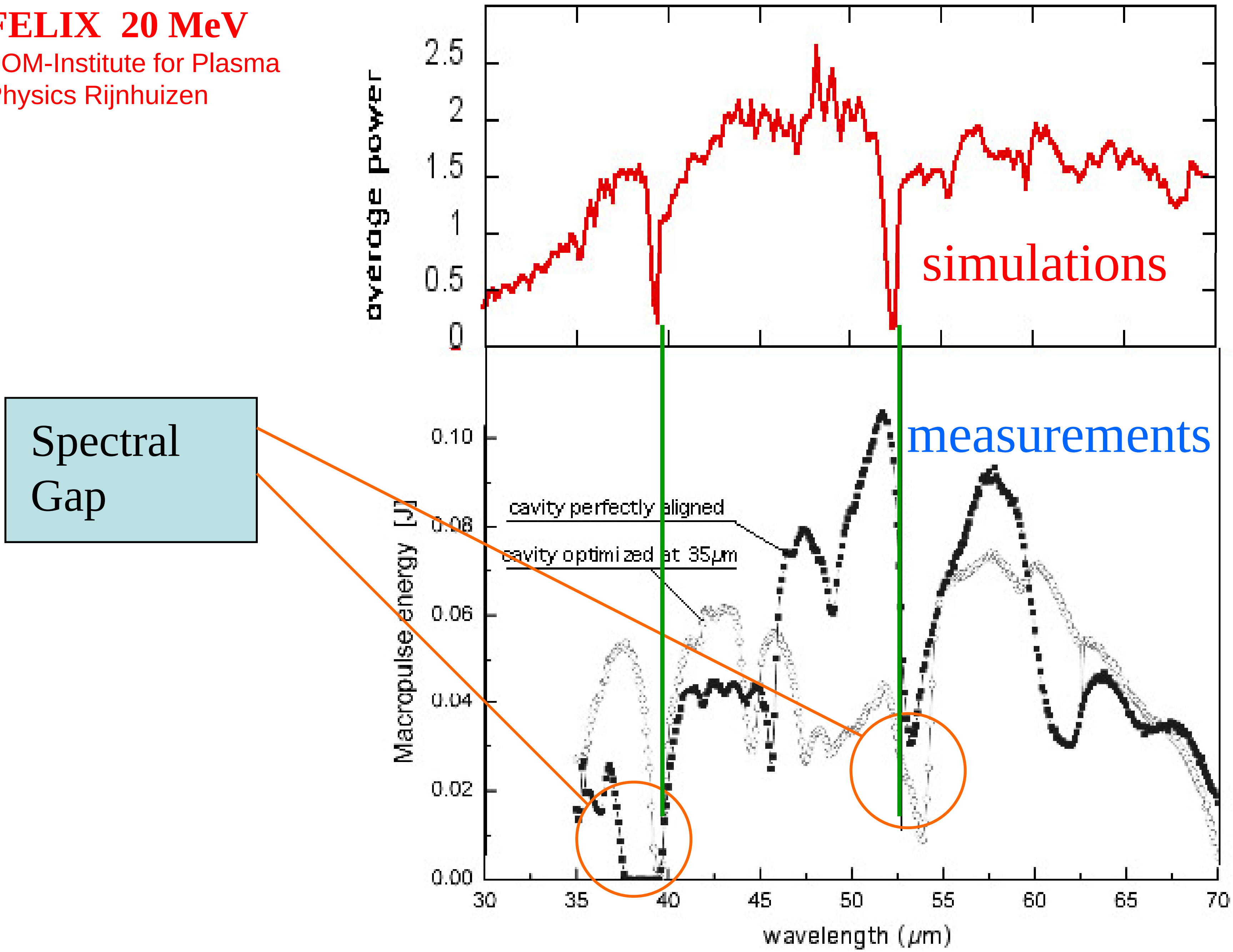

FELIX 20 MeV
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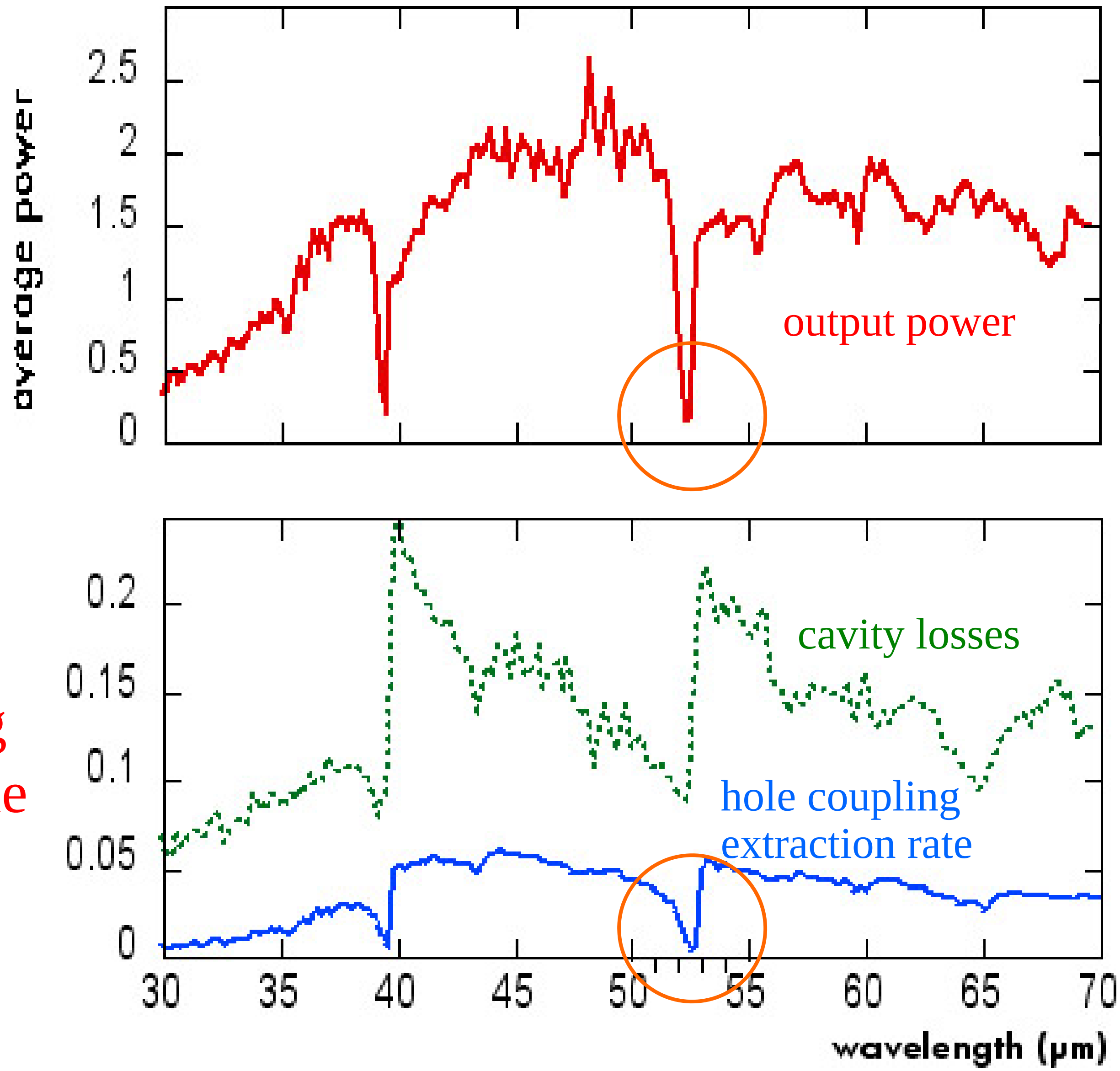
simulations

<u>Spectral Gap :</u>
bad output coupling of laser mode profile



FELIX 20 MeV

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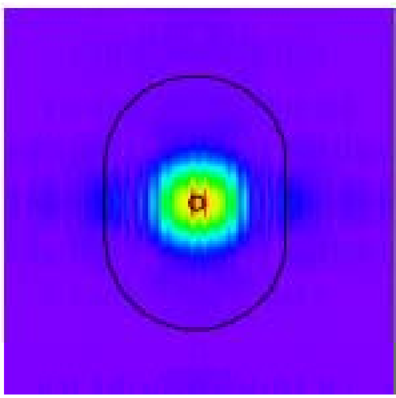
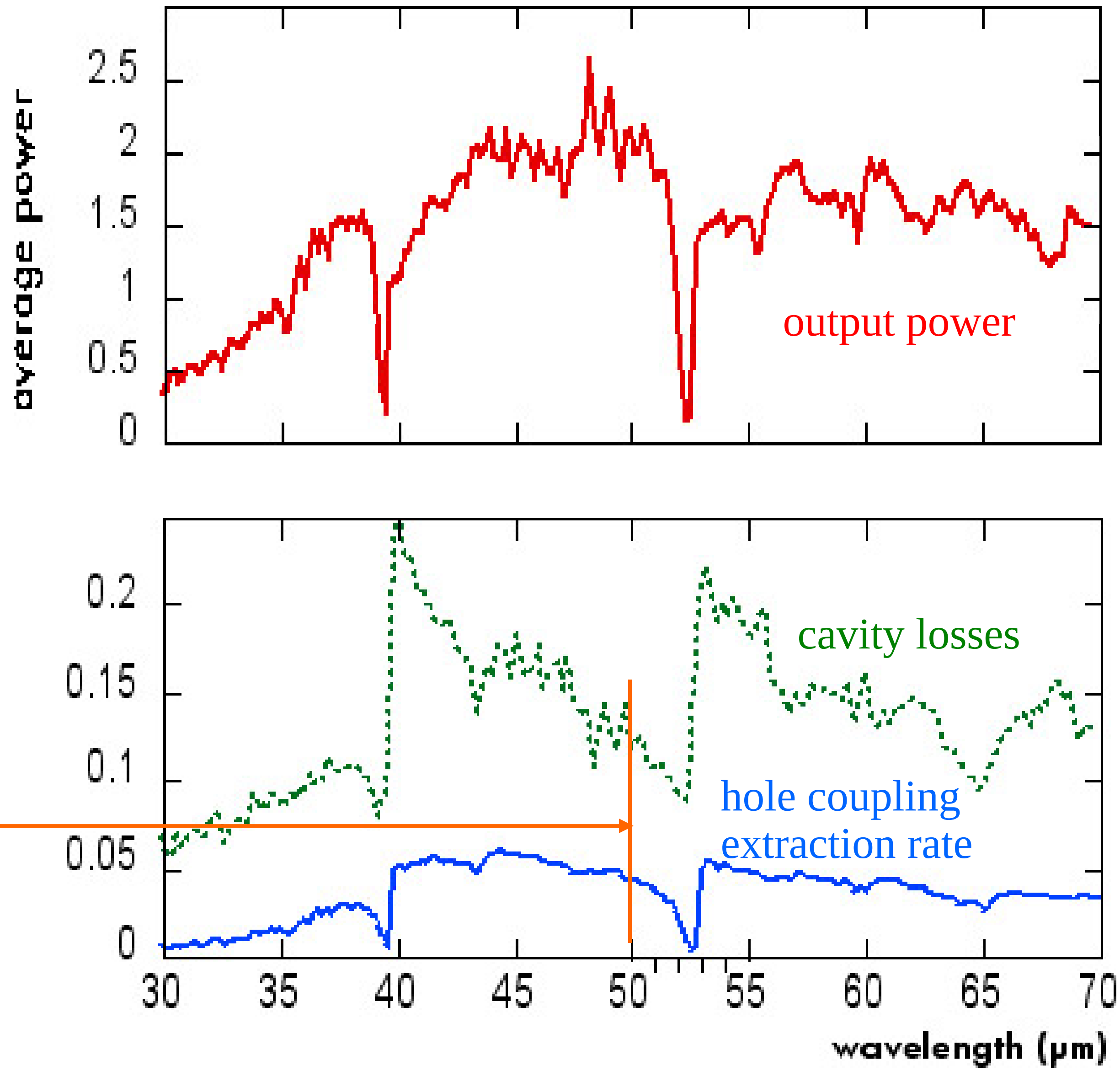
simulations

profile on output mirror





FELIX 20 MeV

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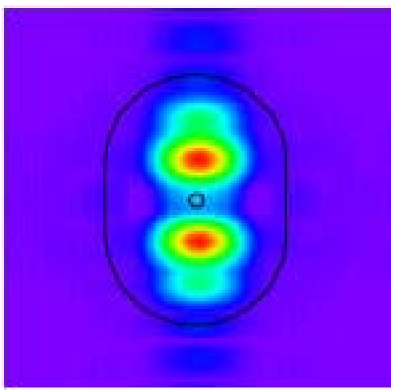
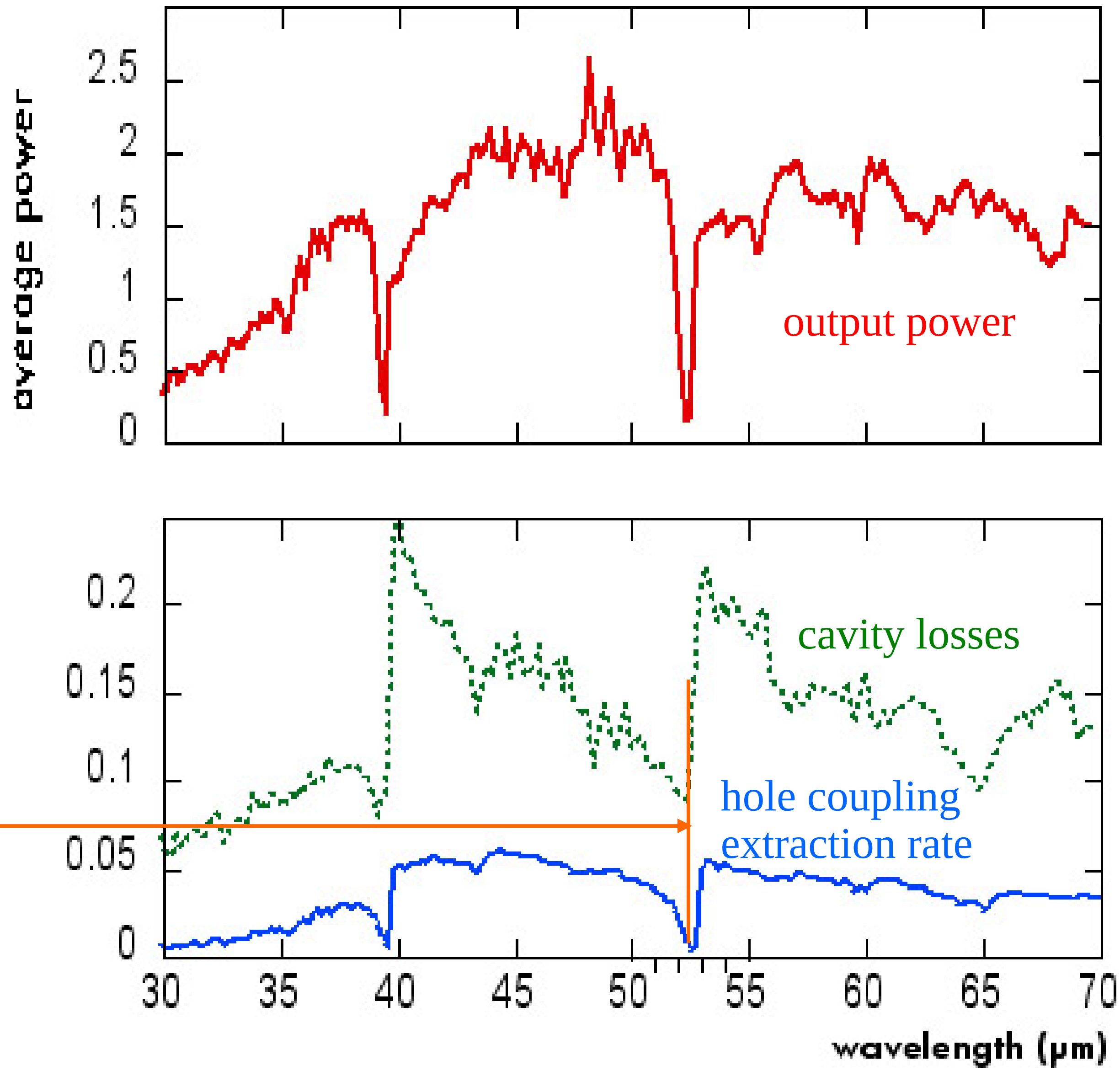
simulations

profile on output mirror





FELIX 20 MeV

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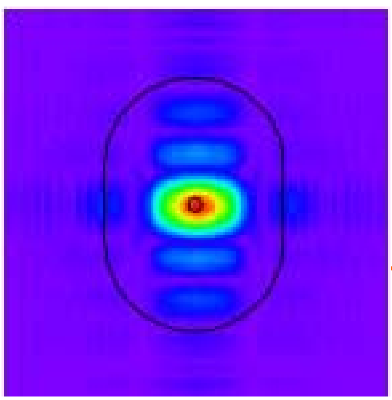
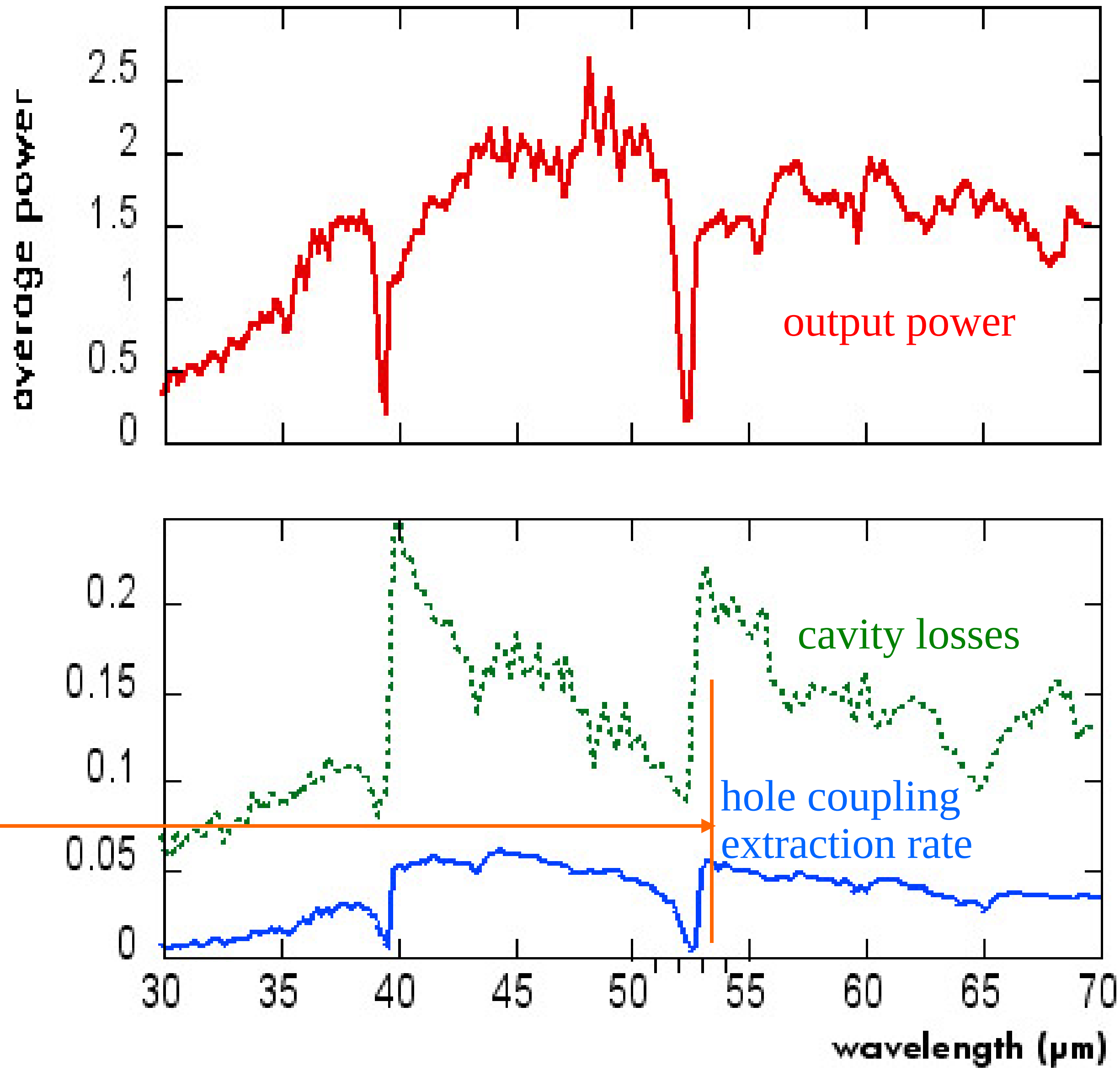
simulations

profile on output mirror

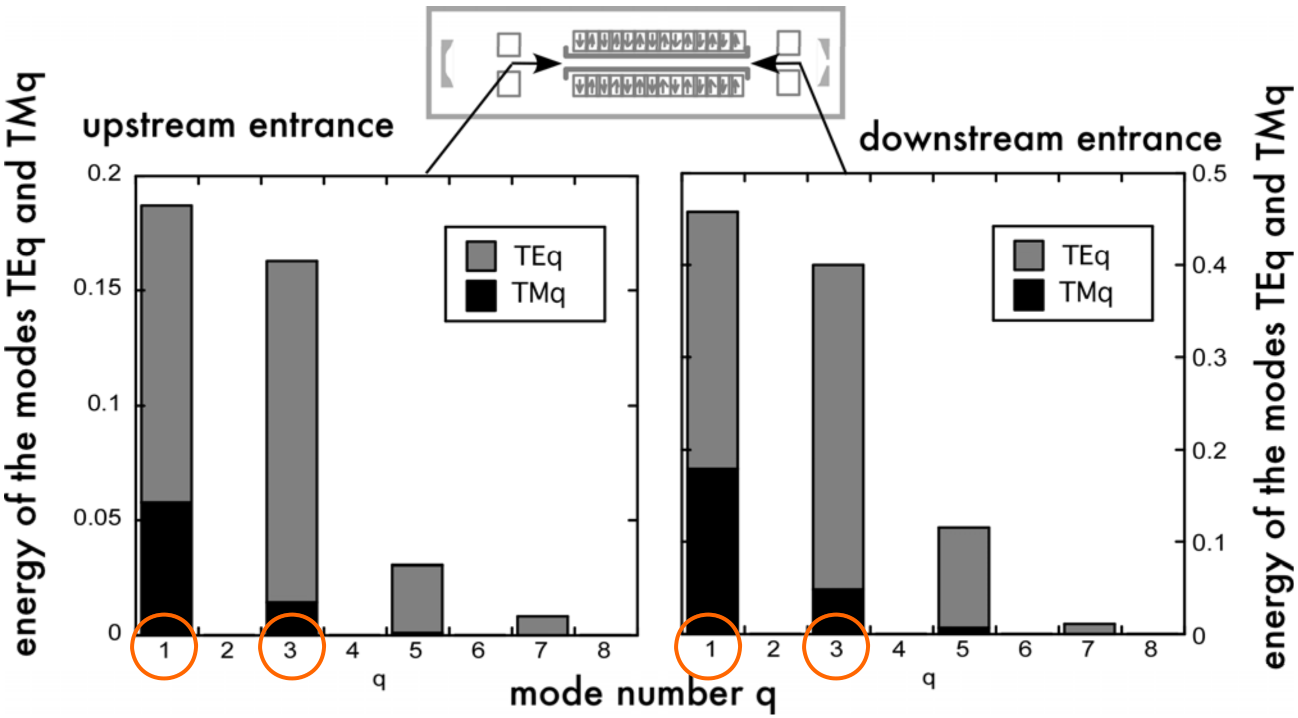




analytical model :

Analytical model :

- using theory of modes dephasing in waveguide
- gives the wavelength distribution of Spectral Gaps
- gives the number of Spectral Gaps in the FEL spectral range



Waveguide modes distribution

dephasing of mode q in the waveguide :
length L, size b

$$\phi_q \cong \frac{2\pi L}{\lambda}\left(1-\frac{\lambda^2 q^2}{8b^2}\right)$$

dephasing between modes q=1 and q=3 :
intensity on Z axis => only odd modes

$$\Delta\phi = \phi_1 - \phi_3 = \frac{2\pi L\lambda}{b^2}$$

dephasing for 2 following
Spectral Gaps :

$$\Delta\phi(\lambda)$$

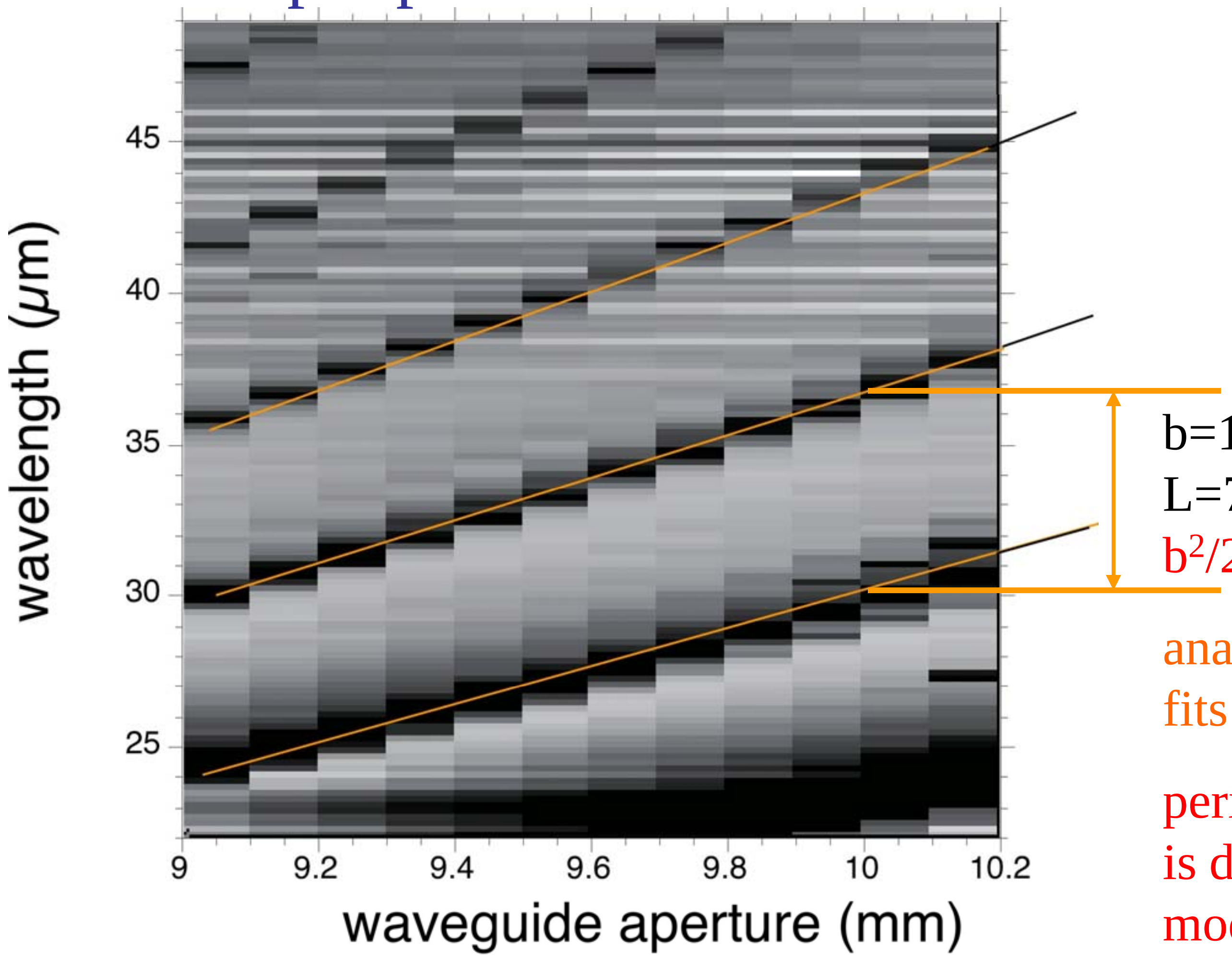
$$\Delta\phi(\lambda') = \Delta\phi(\lambda) + 2\pi$$

wavelength gap between 2 ‘Spectral Gaps’ :

$$\boxed{\delta\lambda = \lambda' - \lambda = \frac{b^2}{2L}}$$

Example : simulation for ELBE (small $\delta\lambda$)

output power of ELBE FEL



b=1 cm
L=7.9 m
$b^2/2L=6.3\mu m$

analytical model
fits the simulation

periodicity of SG
is due to waveguide
mode matching

Example : simulation for FELIX

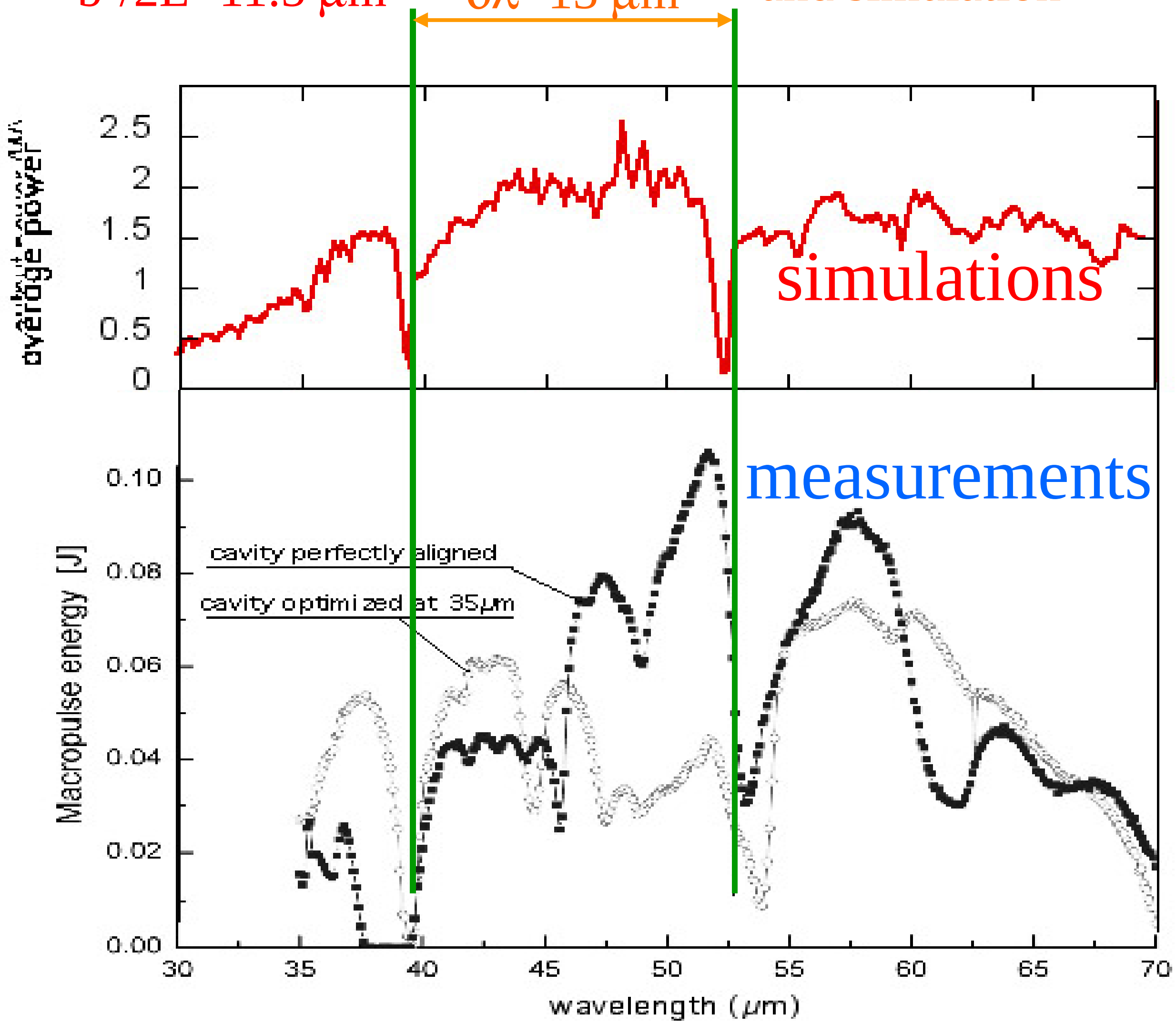
b=1 cm

L=4.34 m

$b^2/2L$=11.5 μm

δλ=13 μm

analytical model fits measurement and simulation



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CONCLUSION :

Number of Spectral Gaps in the FEL spectral range :

$\Delta\lambda$ = FEL spectral range

$\delta\lambda$ = distance between 2 ‘Spectral Gaps’

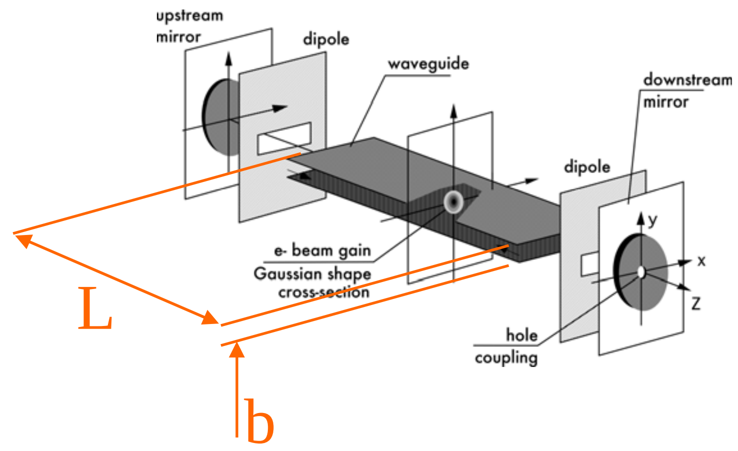
$$\boxed{N_{PG} = \frac{\Delta\lambda}{\delta\lambda} \propto \frac{L}{b^2}}$$

L = Length of the waveguide

b = transverse size of the waveguide

To reducing the number of ‘SG’ :

- large waveguide aperture ‘b’ (square low)
- small waveguide length L



CONCLUSION :

- Spectral Gap phenomenon has been observed on various infrared FELs using a partial waveguide (mixing free-space and waveguide areas)

- the explanation of SG is quite complex, because :
    - (1) it is dependant on two independant parameters :
        - (a) hole coupling extraction rate
        - (b) optical losses in waveguide entrance
    - (2) coupling of waveguide modes in free-space areas

- (a) and (b) are strongly dependant on slight variations of the transverse mode profile, and can be uncorrelated.

- a simple analytical model gives an order of magnitude of the expected number of Spectral Gaps in the FEL range

- detailed analysis by simulation code : good agreement with measurements

ACKNOWLEDGMENTS

FELIX team, FOM inst.

ELBE team, Rossendorf