Laser Pulse Train Amplification

Adi Hanuka

James Santucci, Chip Edstrom, Jinhao Ruan

22nd September 2016

In partnership with:

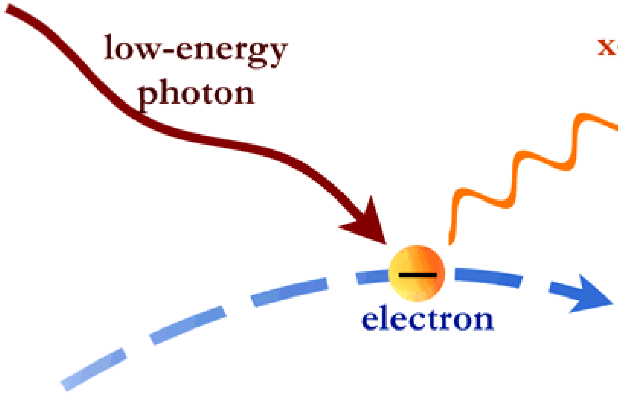
Motivation - Inverse Compton Scattering

- Experiment is planned for 2017
- ICS = Low energy photon bounces off a high energy (relativistic) electron, to become optical or X-ray photon.

Laser Amplifier

=

$$\lambda_X \cong \frac{\lambda_{\text{photon}}}{4\gamma^2}$$



Outline

- Project Goals
- Laser amplification process
- Experimental results
- Simulations
- Summary

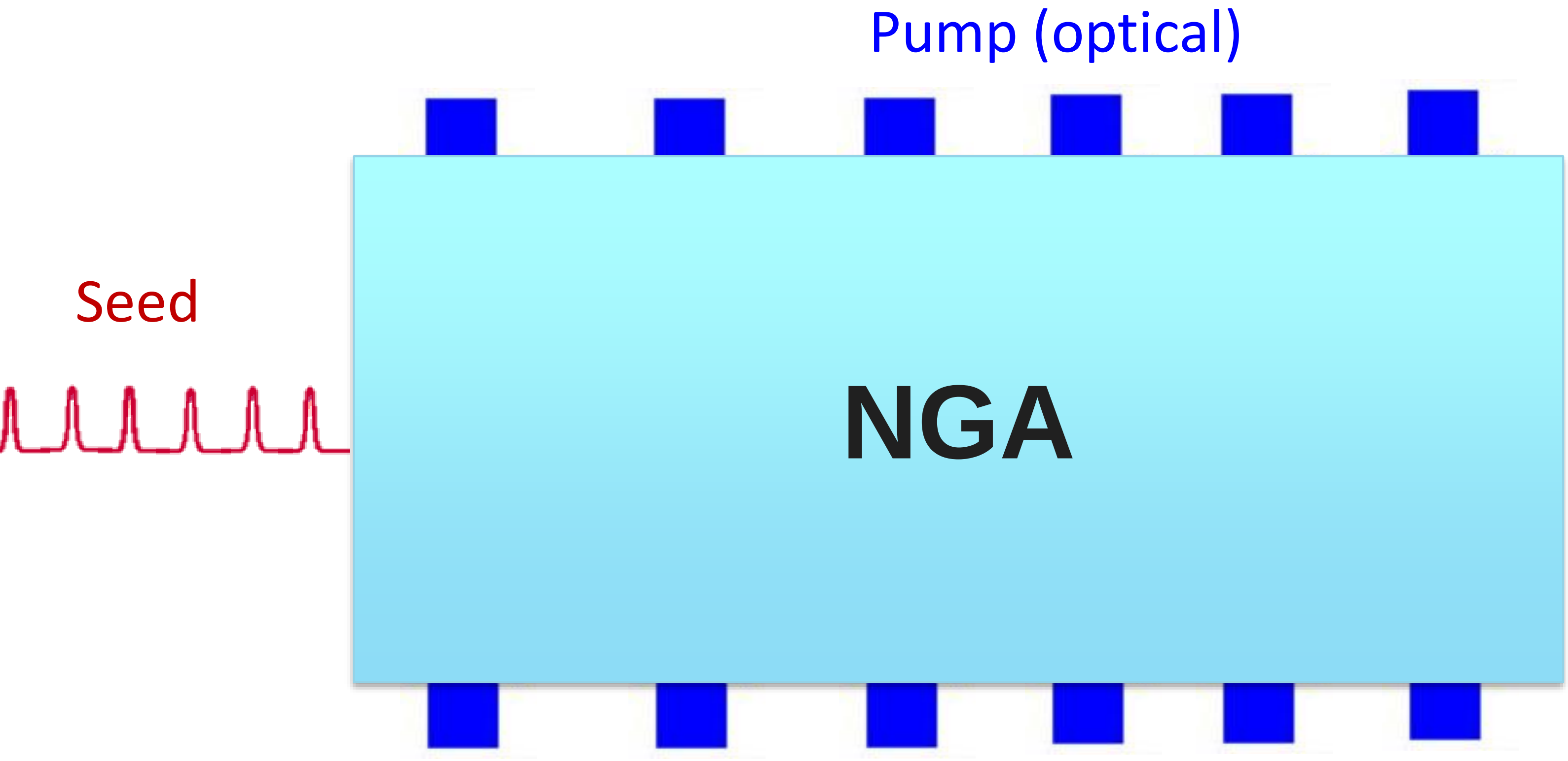
Project Open Questions – on Day 1

1. Why the simulations done by NG **don't match** our experimental results?

2. Does the current setup have the **best performance**?

3. Is there a better way to get **more output energy**?

Laser Amplification Process



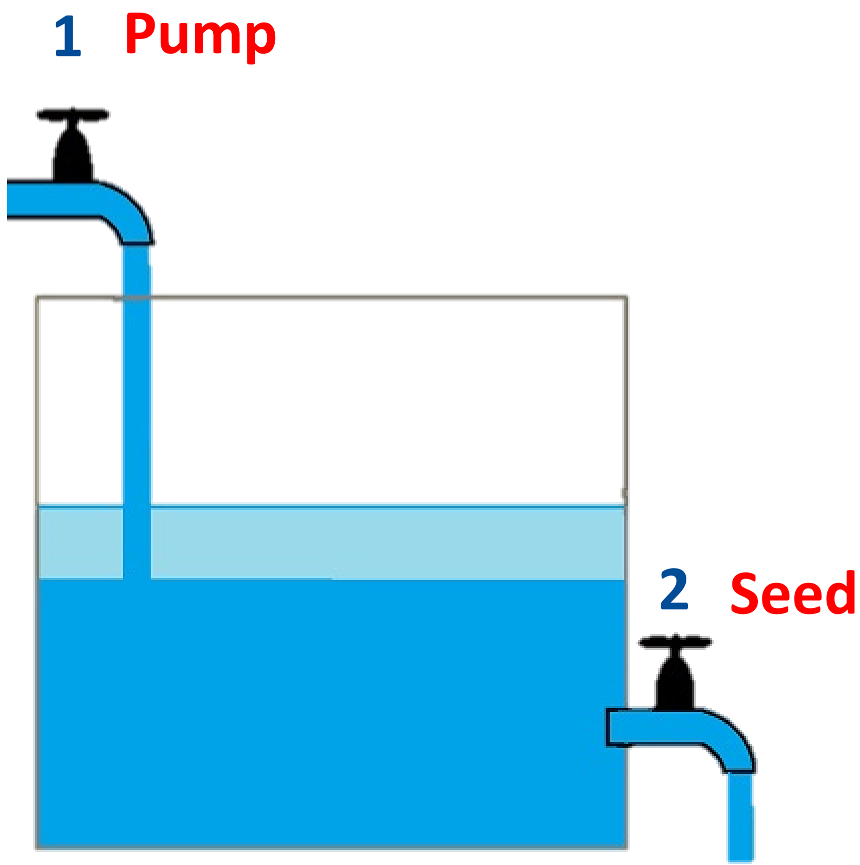
Pump (optical)

Seed

NGA

- ○ Ground state
- 🔵 Energy level 1
- 🟢 Energy level 2

Pulse Train Amplification Process - Illustration



- Relative rates:

  1>2

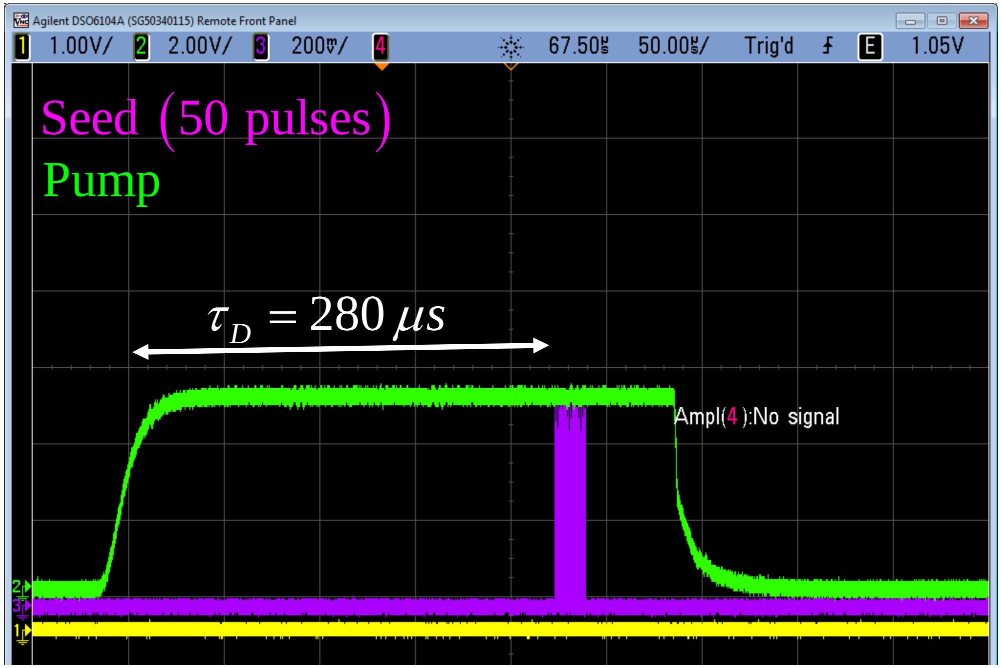
  1=2

  1<2

- Relative timing

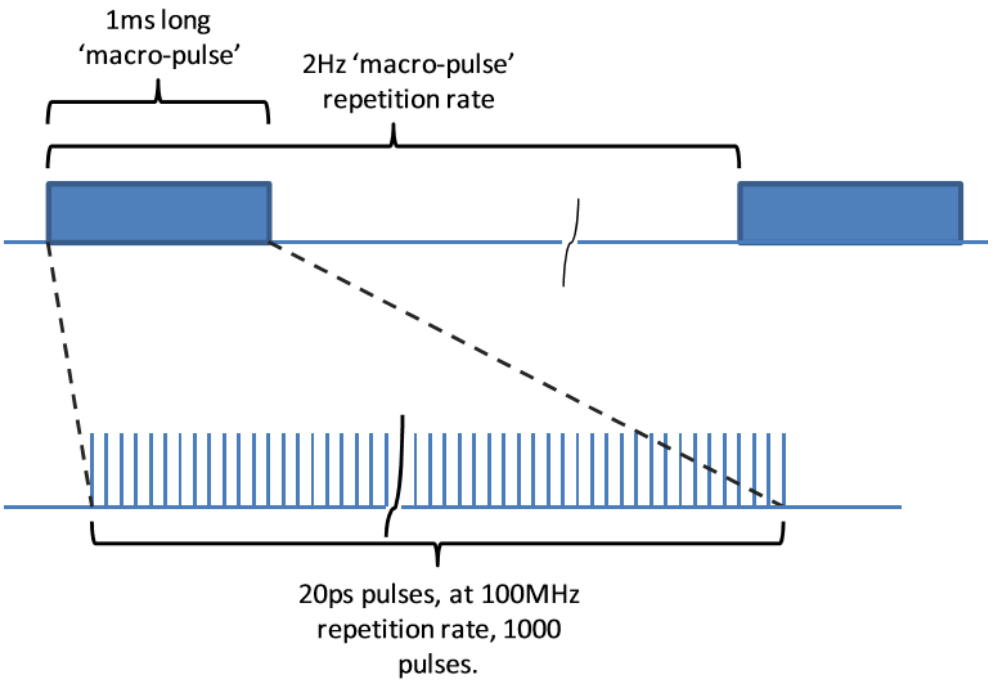
Pump-Train Delay

The phasing of the pump pulse and the pulse train is critical to obtain constant output energy per pulse.



Pulse Train Amplification Process - Assumptions

1. Full overlap between pump and seed laser (TEM mode)
2. Pump rate is constant transversely & longitudinally
3. Constant temperature
4. No reflected energy back from the end pump (Transmission=99.5%)



Pulse Train Amplification Process - Formulation

Pump rate

Total active ions

Excited state atoms

$$\frac{dn}{dt} = W_p \left(n_{tot} - n\right) - \frac{n}{\tau_f}$$

Fluorescence life time

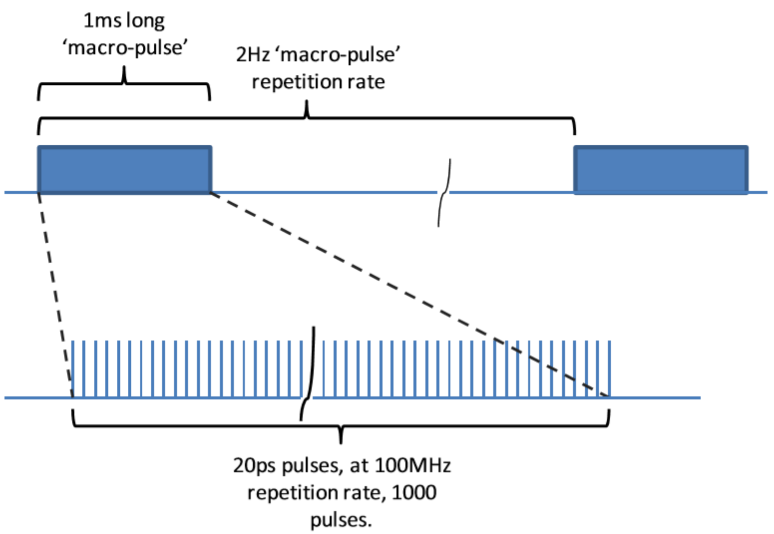
$$E_{stored} = \frac{h\nu}{\sigma} g_0$$

Emission cross section

$$g_0 = \sigma n$$

$$E_{out} = E_s \ln\left\{1 + \left[\exp\left(\frac{E_{in}}{E_s}\right) - 1\right]\exp\left(g_0 l\right)\right\}$$

Saturation energy

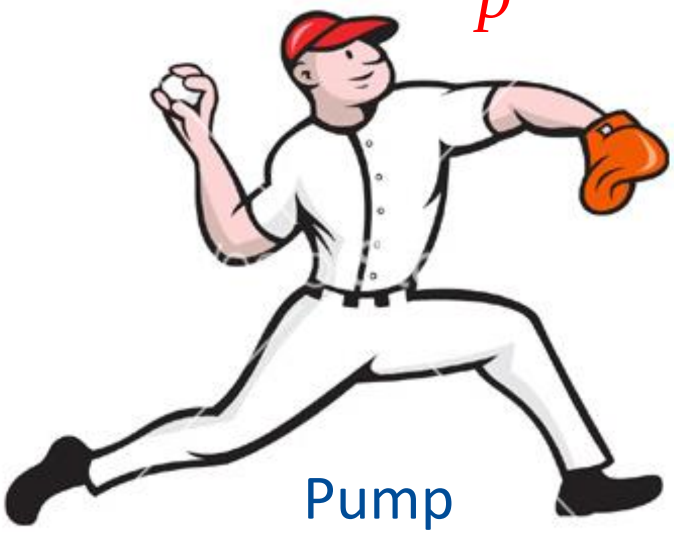


Pulse Train Amplification Process - MVP

τ_D

E_{in}

Seed



W_p

Pump

Simulation – Train of Pulses

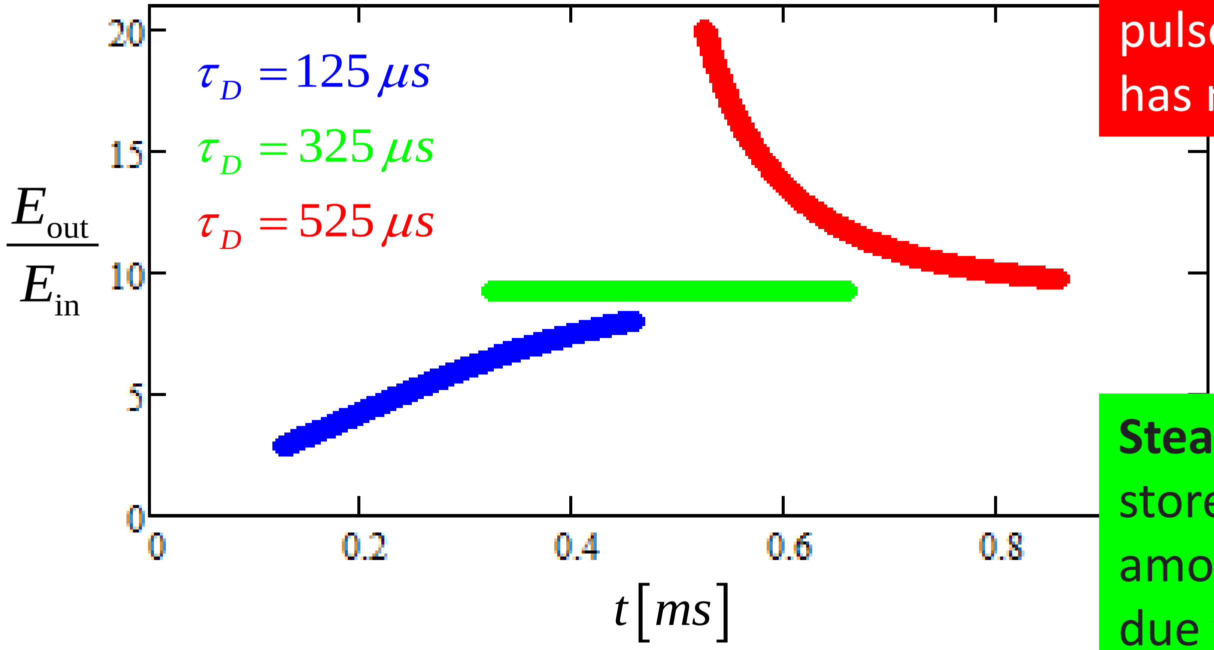
$N_{\text{pulses}} = 1000$

$\Delta T_{\text{train}} = 333\mu s$

$D_{\text{Rod}} = 0.3\,\text{cm}$

$\text{L}=7.3\,\text{cm}$

$W_p = 75\,\text{Hz}\ ; E_{\text{in}} = 7\,\mu\text{J}$

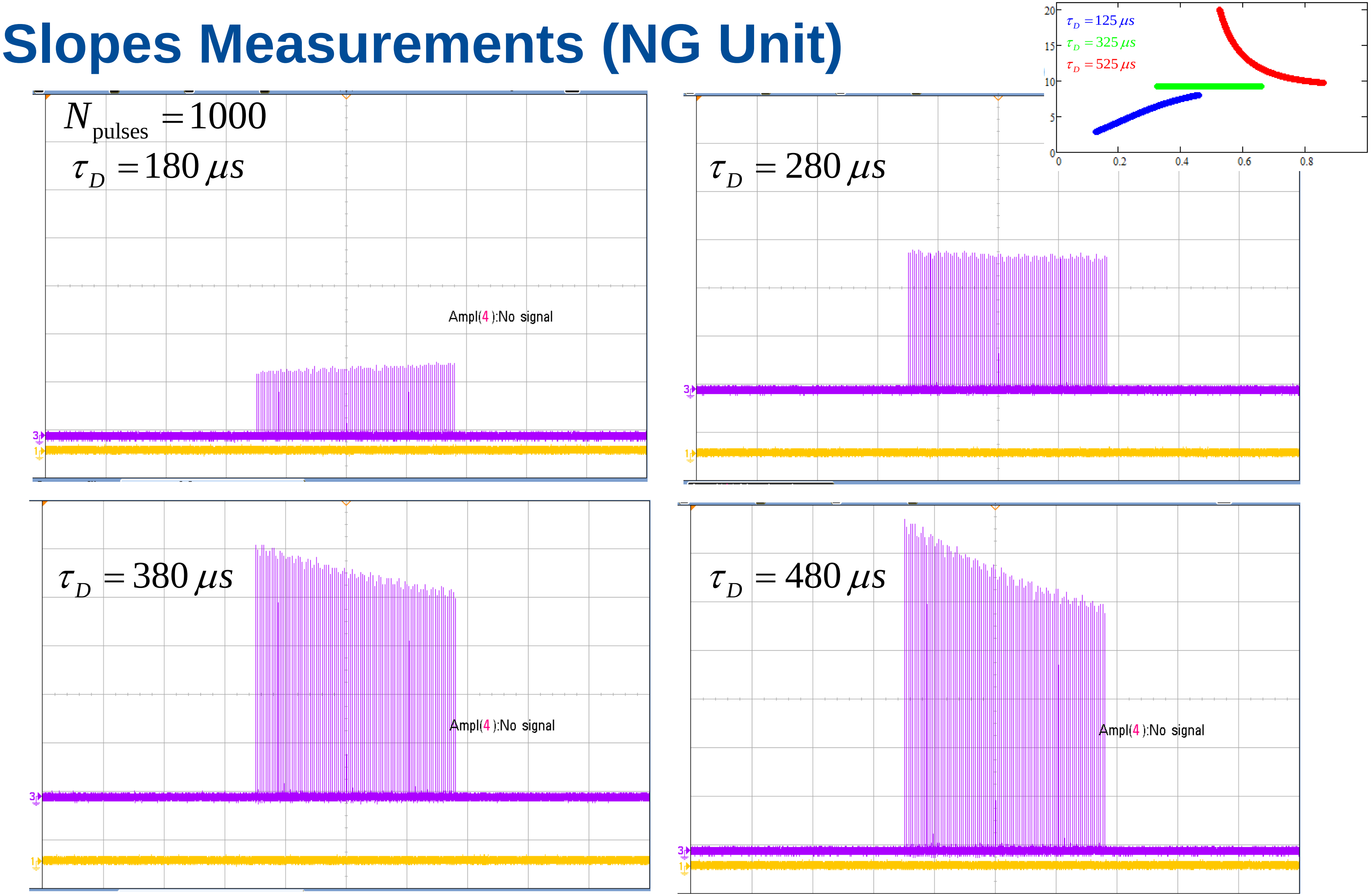


Stored energy in the first pulse but steady state gain has not yet been achieved

Steady state: the amount of stored energy removed = the amount of energy increase due to the pumping between each pulse.

Stored energy is the highest and the first pulse sees a large gain.

Slopes Measurements (NG Unit)



$N_{\text{pulses}} = 1000$

$\tau_D = 180\,\mu s$

$\tau_D = 280\,\mu s$

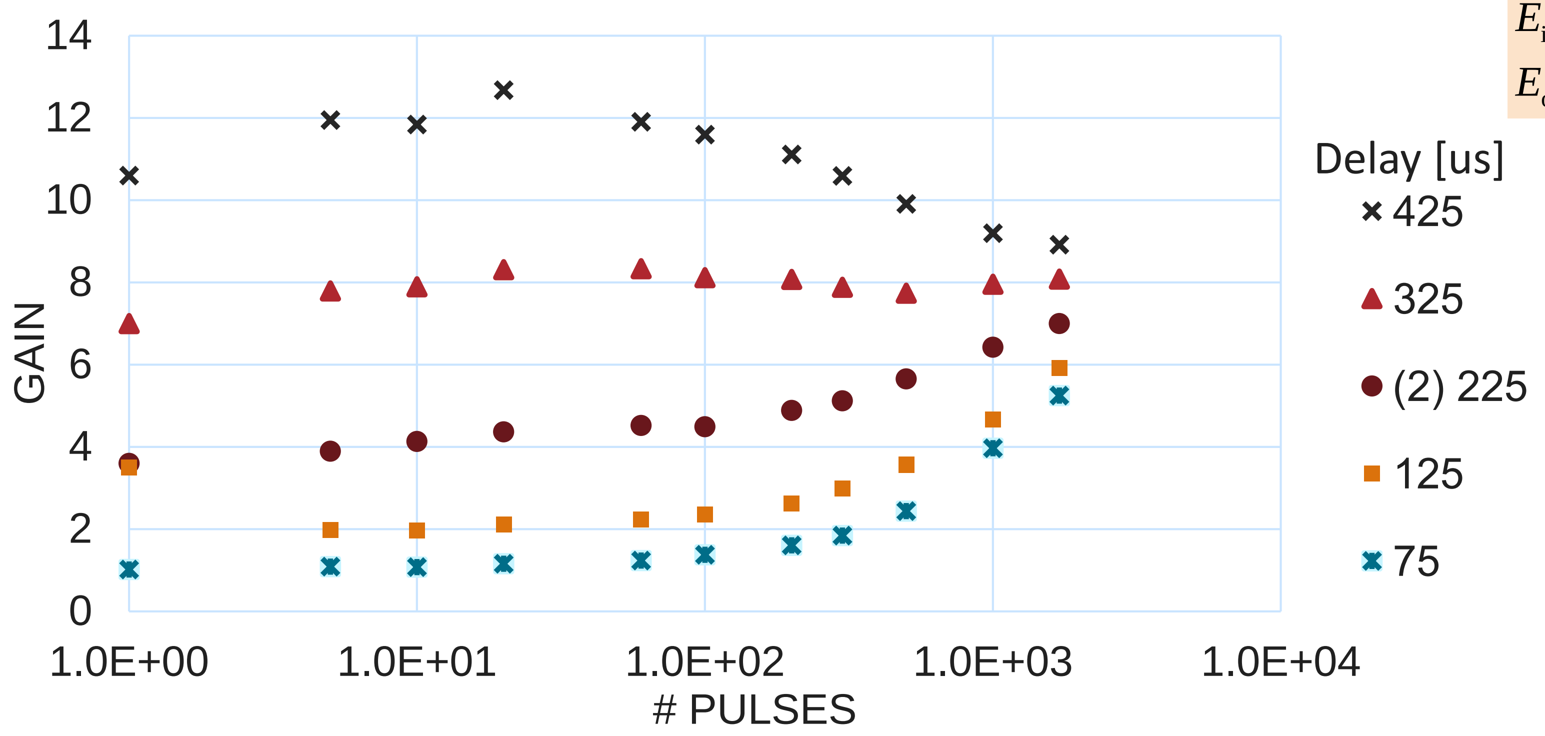
$\tau_D = 380\,\mu s$

$\tau_D = 480\,\mu s$

Experimental Results - Gain

$E_{\text{in}} = 7\mu J / \text{p}$

$E_{\text{out,ss}} = 56\mu J / \text{p}$

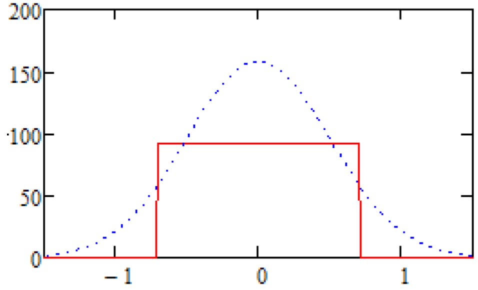


- For higher delay time, the gain is higher.
- For high number of pulses, the gain converges to about 8.
- The gain absolute values are a bit low (maybe due to a problem with the energy meter).

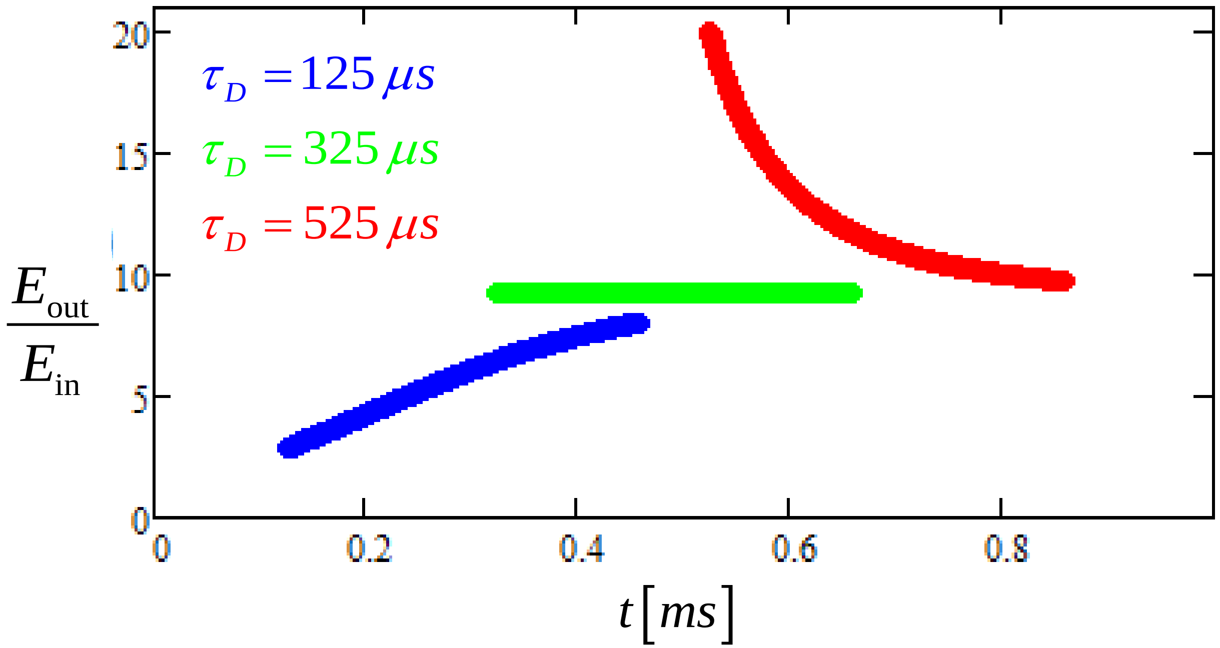
Simulation 1 – Transverse Uniform Distribution

Parameters	Symbol	Value	units
Rod diameter	D_r	3	mm
Rod length	L	7.3	cm
Pumping rate	W_p	75	Hz
Pump wavelength	λ_p	804	nm
Pump current	I	100	A
Fluoresence lifetime	τ_f	480	us
Emission cross section	σ	1.2e-19	cm^2
Saturation fluence	E_s	1.582	J/cm^2
Total active ions (>1% doping)	n_{tot}	1.46e20	cm^{-3}

Parameters	Symbol	Value	units
Delay time	τ_D	325	us
Seed wavelength	λ_s	1054	nm
Input energy	E_{in}	7	uJ/p
Seed diameter	D_s	1.72	mm
Repetition rate	f	3	MHz
# pulses	N_{pulse}	1000	



Simulation 1 - Results



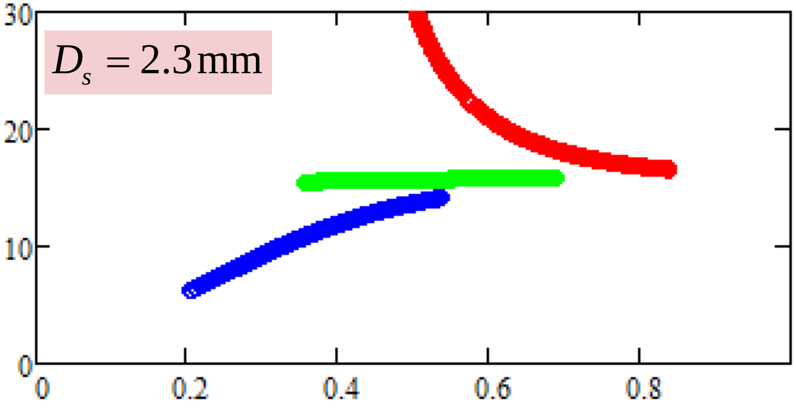
$E_{in} = 7\mu J\,/\,p$

$E_{out,ss} = 65\mu J\,/\,p$

- Spread on the **flat output** is <0.5%
- 50% drop on the **negative slope** was observed also in the experiment.
- Steady state is the same!
- Model is very sensitive to the spot size.

Simulation 1 – Model Sensitivity

Spot size could vary to match experimental results → Model isn't robust



$\tau_D = 125\,\mu s$

$\tau_D = 325\,\mu s$

$\tau_D = 525\,\mu s$

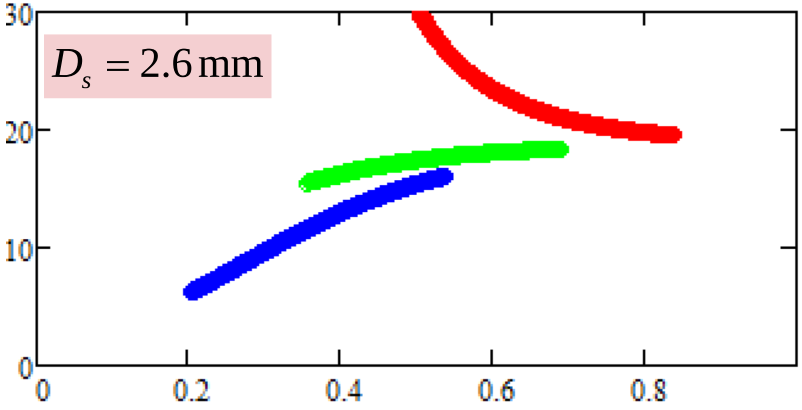
$E_{\mathrm{in}} = 7\,\mu J\,/\,\mathrm{p}$

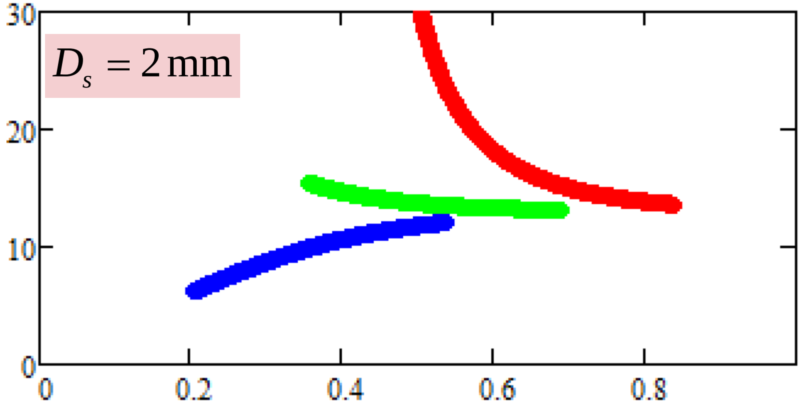
$W_p = 102\,\mathrm{Hz}$

$\tau_D = 355\,\mu s$

$\mathrm{L}=7.3\,\mathrm{cm}$

$\mathrm{n}_{\mathrm{tot}} = 1.25\mathrm{e}20\ \mathrm{cm}^{-3}$



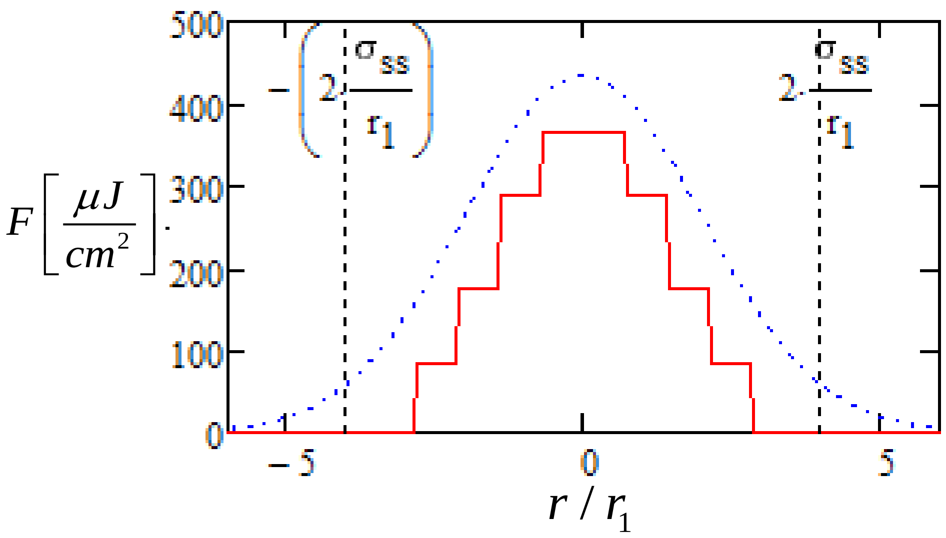


Simulation 2 - Gaussian Distribution

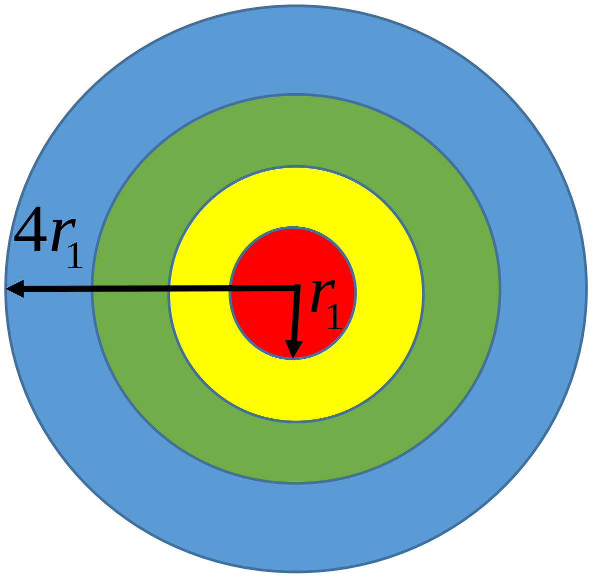
- We sliced the beam into 4 segments in order to get more realistic fluence
- Quantized Gaussian is 86% of the full one.

$$r_1 = \frac{\sigma}{2}$$

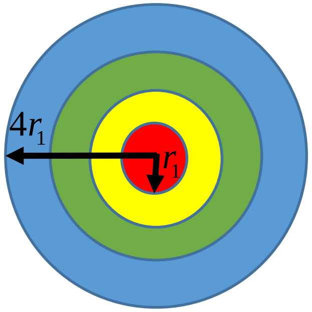
Side view



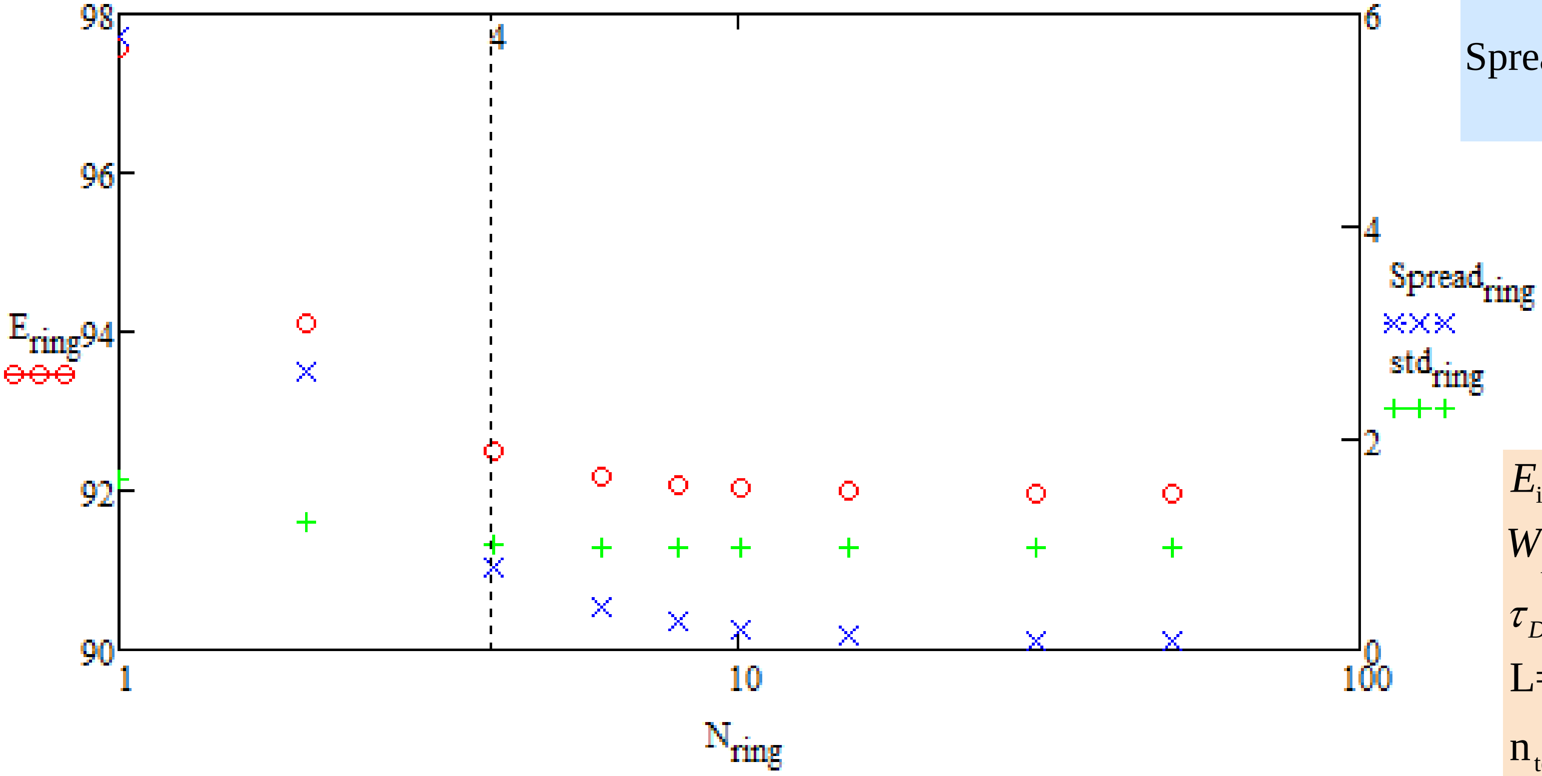
Top view



Simulation 2 - Gaussian Distribution



- Output energy and its STD doesn't change with number of rings
- 4 rings satisfy the spread<1%



$$\text{Spread}=\frac{E_1-E_{N_p}}{\max\left\{E_1,E_{N_p}\right\}}$$

$E_{in} = 7\,\mu J/\text{p}$

$W_p = 102\,\text{Hz}$

$\tau_D = 355\,\mu s$

$L = 7.3\,\text{cm}$

$n_{tot} = 1.25\text{e}20\ \text{cm}^{-3}$

Simulation 2 - Gaussian Distribution

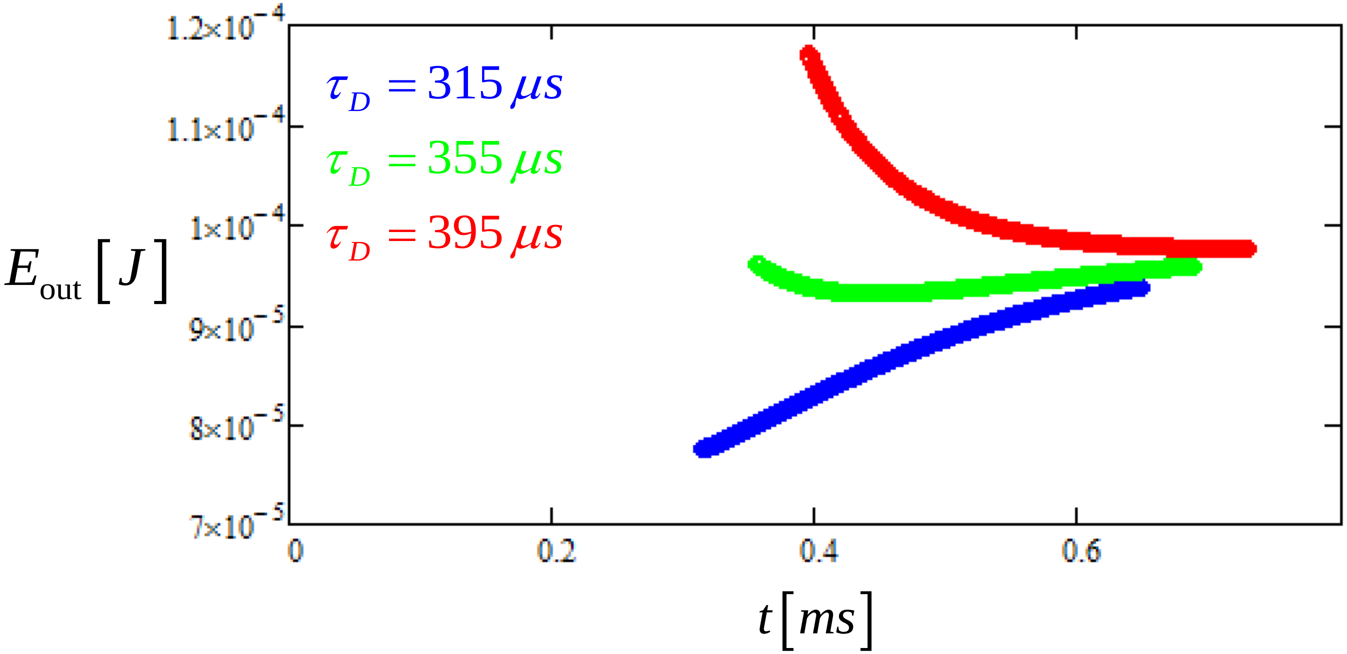
Parameters

Parameters	Symbol	Value	units
Rod diameter	D_r	3	mm
Rod length	L	7.3	cm
Pumping rate	W_p	75	Hz
Pump wavelength	λ_p	804	nm
Fluoresence lifetime	τ_f	480	us
Emission cross section	σ	1.2e-19	cm^2
Saturation fluence	E_s	1.582	J/cm^2
Total active ions (0.9% doping)	n_{tot}	**1.25e20**	cm^{-3}

Parameters	Symbol	Value	units
Delay time	τ_D	**355**	us
Seed wavelength	λ_s	1054	nm
Input energy	E_{in}	7	uJ/p
Seed sigma	σ_s	**0.535**	mm
Seed diameter	D_s	2.14	mm
Repetition rate	f	3	MHz
# pulses	N_{pulse}	1000	

Simulation 2 - Results

The “dip”



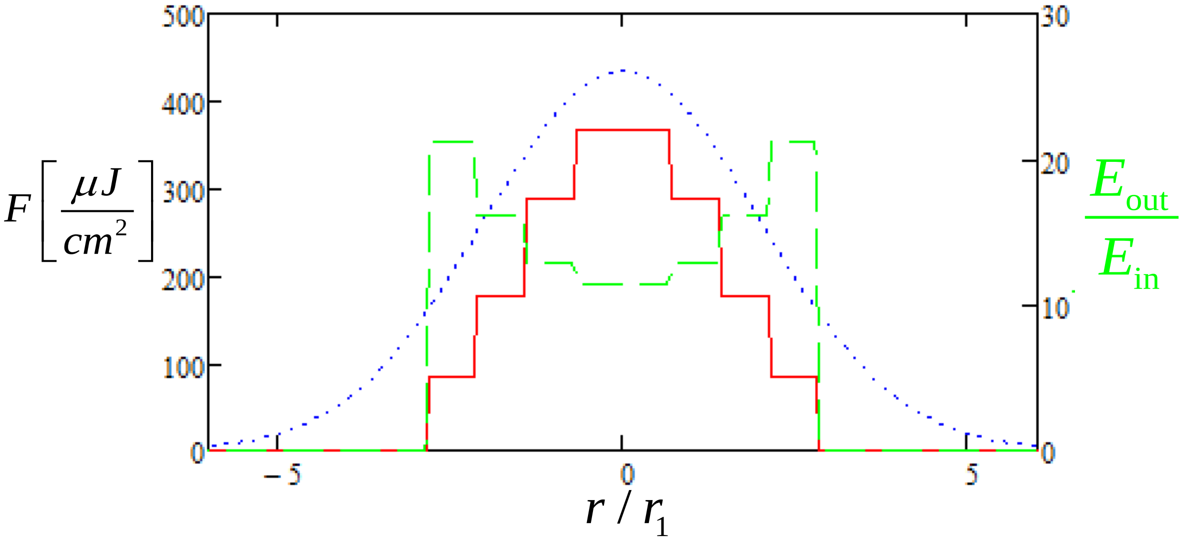
$E_{\text{in}} = 7\,\mu J\,/\,\text{p}$

$E_{\text{out,ss}} = 97\,\mu J\,/\,\text{p}$

- Spread on the **flat output** is <1%
- We assume that the curvature at the beginning of the **flat output**, is due to the Gaussian shape. This behavior was seen also in the experiment.

Simulation 2 - Results

Gain

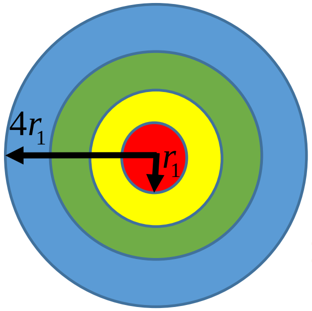


$E_{in} = 7\mu J/p$

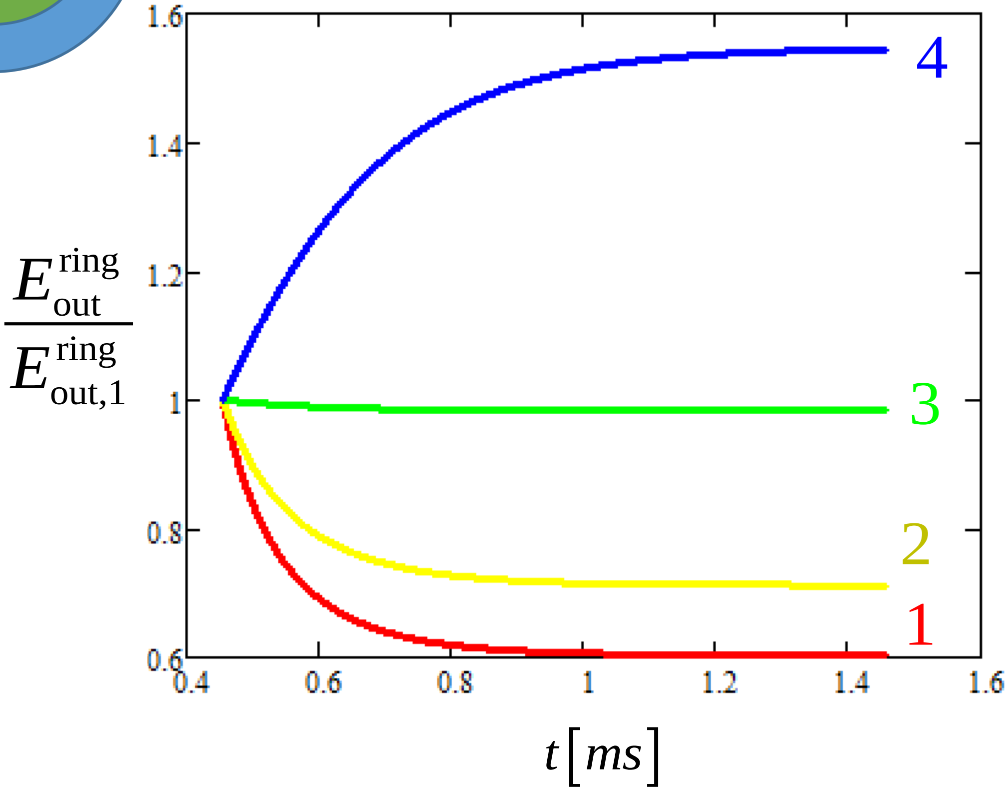
$E_{out,ss} = 97\mu J/p$

- Gain is about 10-20 → fits the experiment
- Output Gaussian sigma is higher since the outer segments have higher gain.
- Results doesn't change with the number of segments.

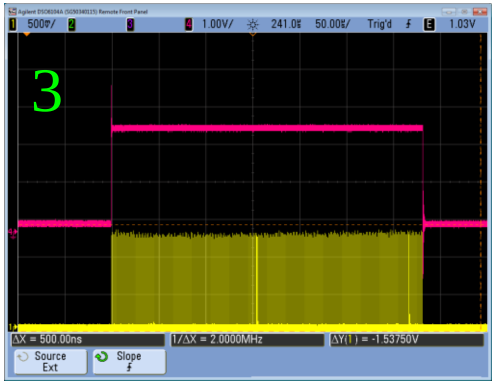
Rings – Simulation & Experiment



Contribution of each ring to the "flat" output case



ΔX = 500.00ns 1/ΔX = 2.0000MHz ΔY(1) = -1.53750V



ΔX = 500.00ns 1/ΔX = 2.0000MHz ΔY(1) = -1.53750V

ΔX = 500.00ns 1/ΔX = 2.0000MHz ΔY(1) = -1.53750V

Project Open Questions – on Day 1

1. Why the simulations done by NG **don't match** our experimental results?

2. Does the current setup have the **best performance**?

3. Is there a better way to get **more output energy**?

Conclusion I

- **Gaussian** model was developed, and all parameters were nailed down.

- The **curvature** on the “flat” out:
  - Seems to be present only for the segment
  - Is more pronounced for higher input en
  - Is mostly effected by the 1st ring

2. Does the current setup have the **best performance**?

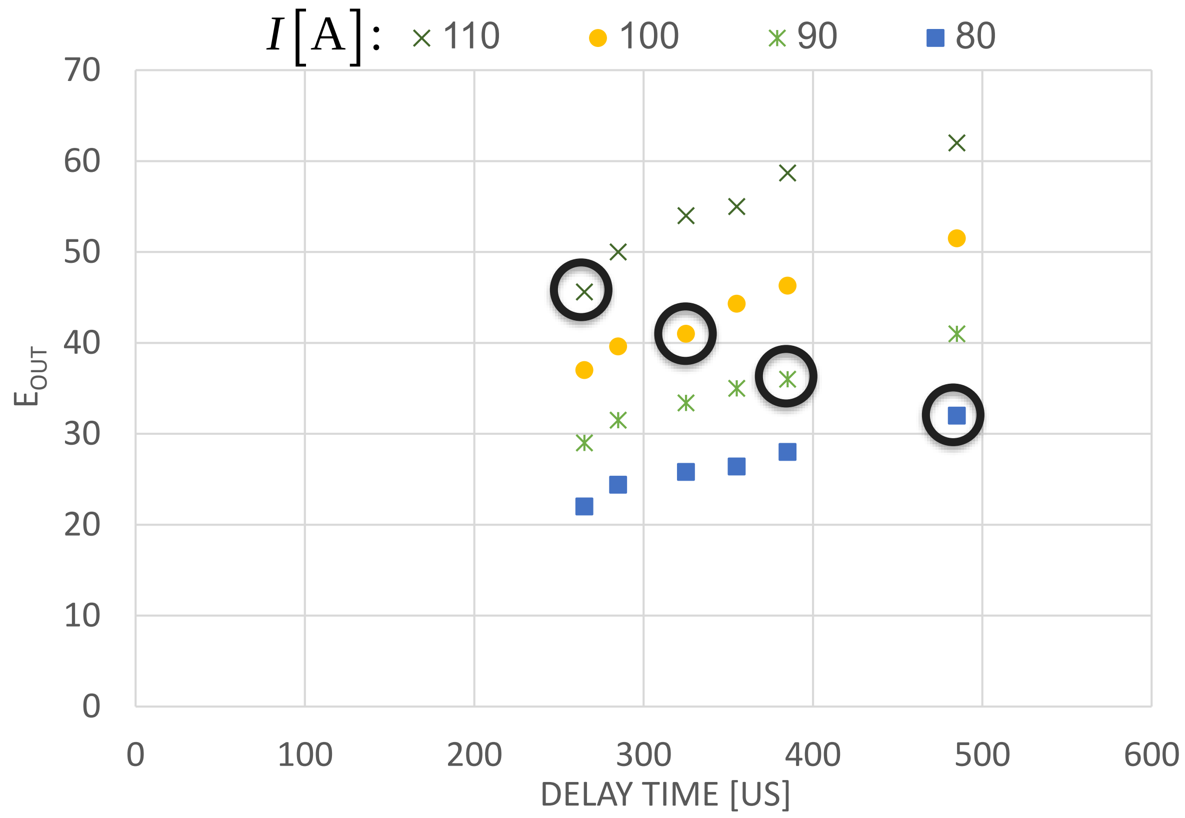
- **Diode** should be carefully calibrated.

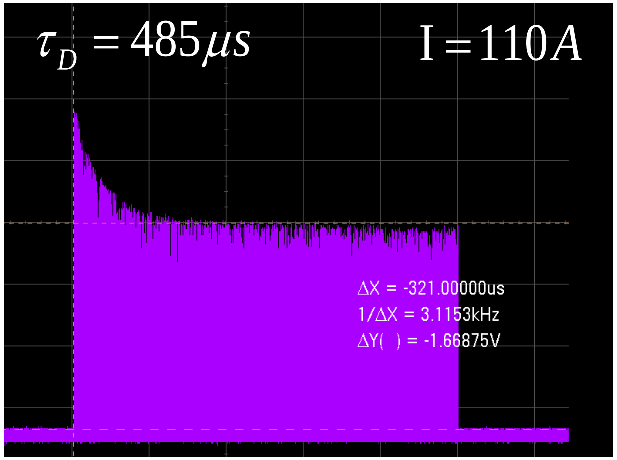
- In order to verify the slope, input energy is measured using **energy meter** for each 100 pulses (Chip’s script).

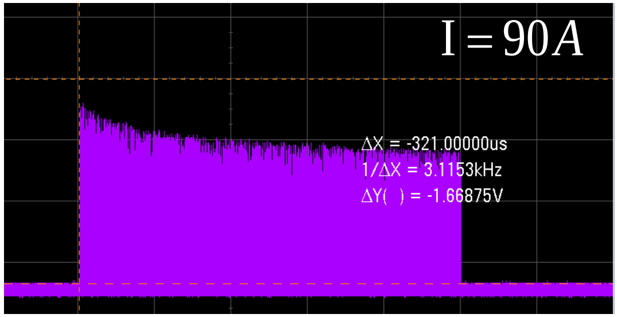
Current Dependence - Measurements

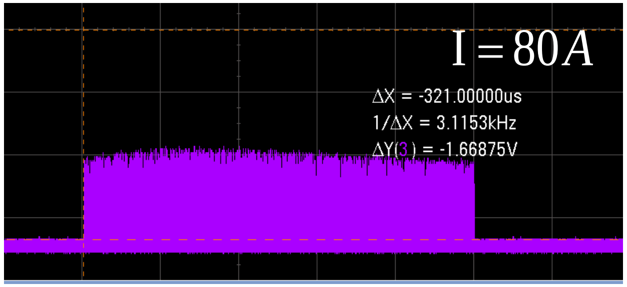
$E_{\text{in}} = 4\mu J\,/\,\text{p}$

Change the pump current (=pumping rate)









Simulation 3 - Current Dependence

Parameters

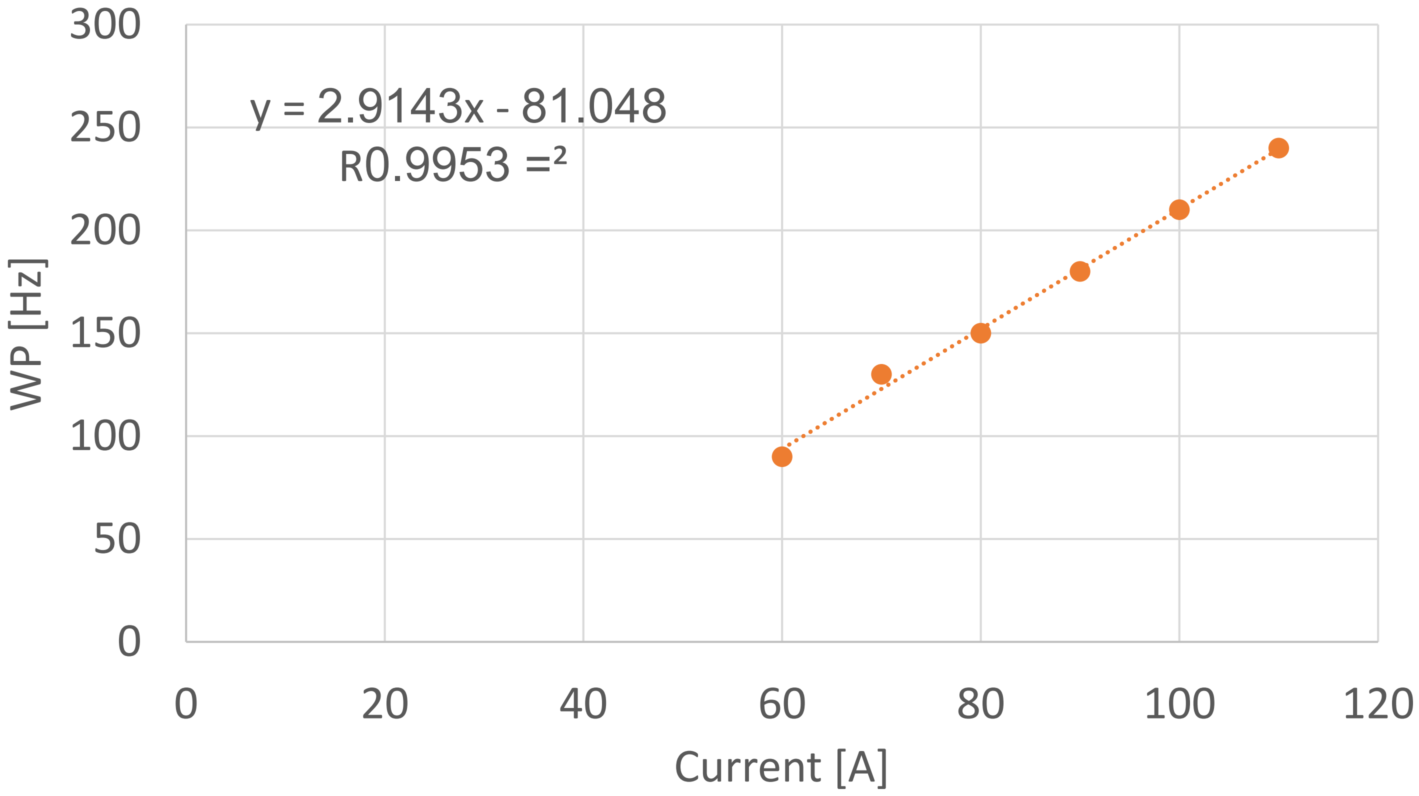
Parameters	Symbol	Value	units
Rod diameter	D_r	3	mm
Rod length	L	**3**	cm
Pumping rate	W_p		Hz
Pump wavelength	λ_p	804	nm
Fluoresence lifetime	τ_f	480	us
Emission cross section	σ	1.2e-19	cm^2
Saturation fluence	E_s	1.582	J/cm^2
Total active ions (1.0% doping)	n_{tot}	**1.46e20**	cm^{-3}

Parameters	Symbol	Value	units
Delay time	τ_D		us
Seed wavelength	λ_s	1054	nm
Input energy	E_{in}	4	uJ/p
Seed sigma	σ_s	**0.655**	mm
Seed diameter	D_s	2.622	mm
Repetition rate	f	3	MHz
# pulses	N_{pulse}	1000	

Simulation 3 - Current Dependence

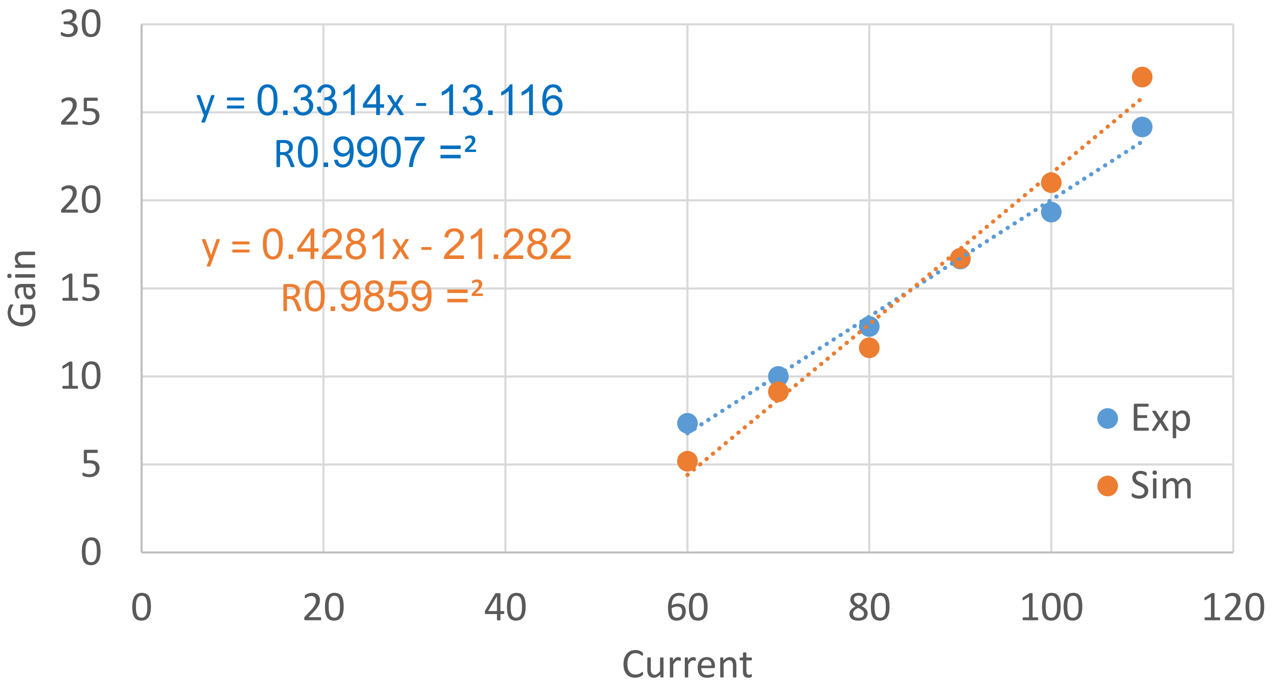
$E_{in} = 4\mu J / \text{p}$

Linear relation between pump current and pumping rate (WP)



Current Dependence – Flat Output

$E_{\text{in}} = 4\mu J / \text{p}$

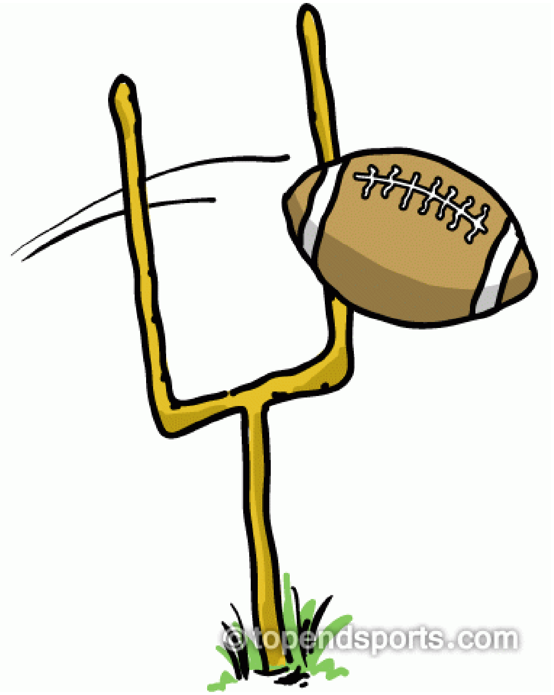


$$\frac{E_{\text{out}}^{\text{Exp}}}{E_{\text{out}}^{\text{Sim}}} = 50\%$$

→ Total output energy doesn't make sense.

Conclusion II

- Transmission is 50%!
  - Before NGA: E_{in}=4 μJ/p
  - After NGA (0 current): E_{in}=2 μJ/p
- Improved transmission to 75%:
  - Gain remained the same
  - Output energy increased to 75%



Project Open Questions – on Day 1

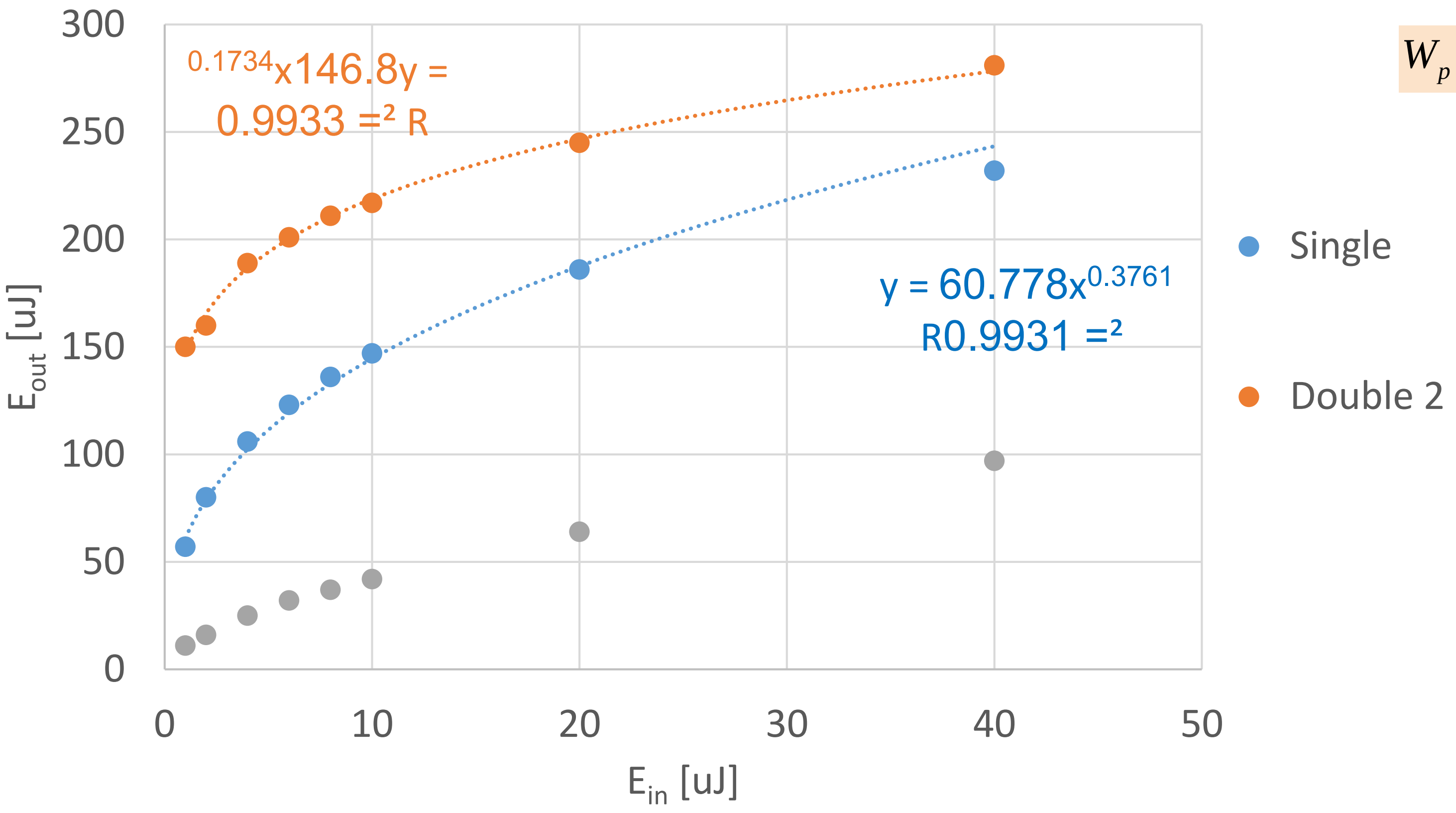
1. Why the simulations done by NG **don't match** our experimental results?

2. Does the current setup have the **best performance**?

3. Is there a better way to get **more output energy**?

Double Pass - Simulation

$$W_p = 230\,Hz$$



For low input energy, double pass has >50% output energy.

Conclusion III

- Double pass to gain more energy
  - Higher than single for low input energy
  - Difference is diminished for high input

- Experimental:
  - Avoid creating a cavity and free lasing

Summary

- A **Gaussian beam** model to train amplification process was developed and implemented.
  - Input energy, pumping rate, delay time dependence
  - Double pass
  - Model support experimental results

- **Experiment**:
  - Transmission through the rod should be improved.
  - New unit was ordered from NG – its performance was tested with our model.

- Hopefully see you next year!

Thanks for a Great Summer!