Application of machine-learning in pulse train tuning for multicycle THz generation

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

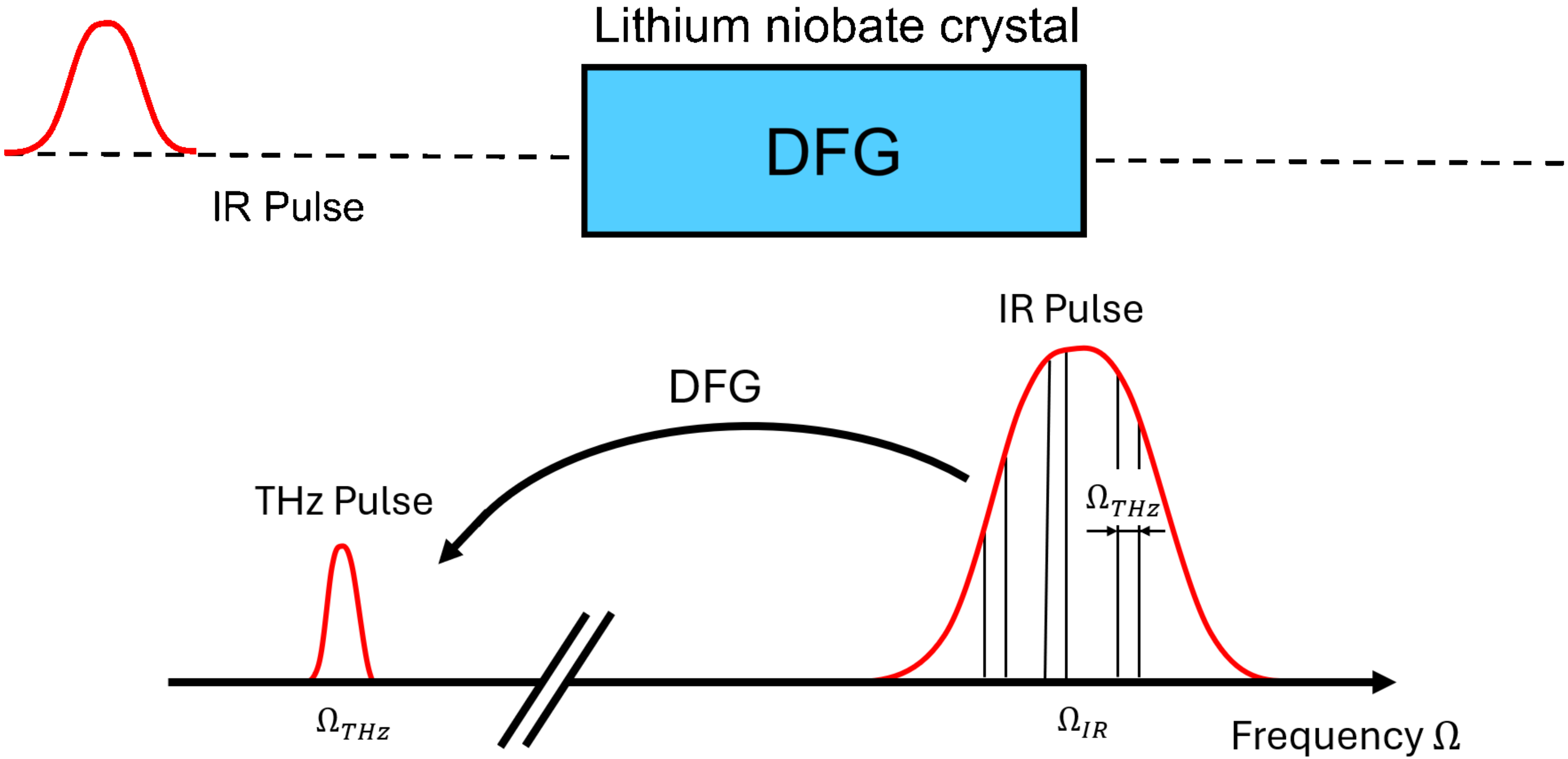
Which is the objective of AXSIS?

- Electrons accelerated by THz radiation:

Reduced size, cost and complexity

- Objective of AXSIS → Compact X-ray light source using THz pulses

Multicycle THz generation: Single pulse



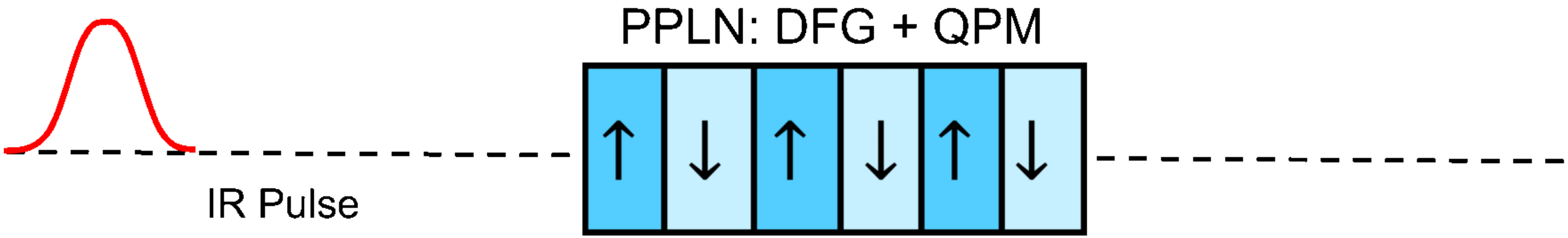
Multicycle THz generation: Single pulse

But phase-matching is not satisfied:

$$\boxed{\Delta k = k(\Omega_{IR} + \Omega_{THz}) - k(\Omega_{IR}) - k(\Omega_{THz}) \neq 0}$$

$\Rightarrow$ Quasi phase-matching! (QPM)

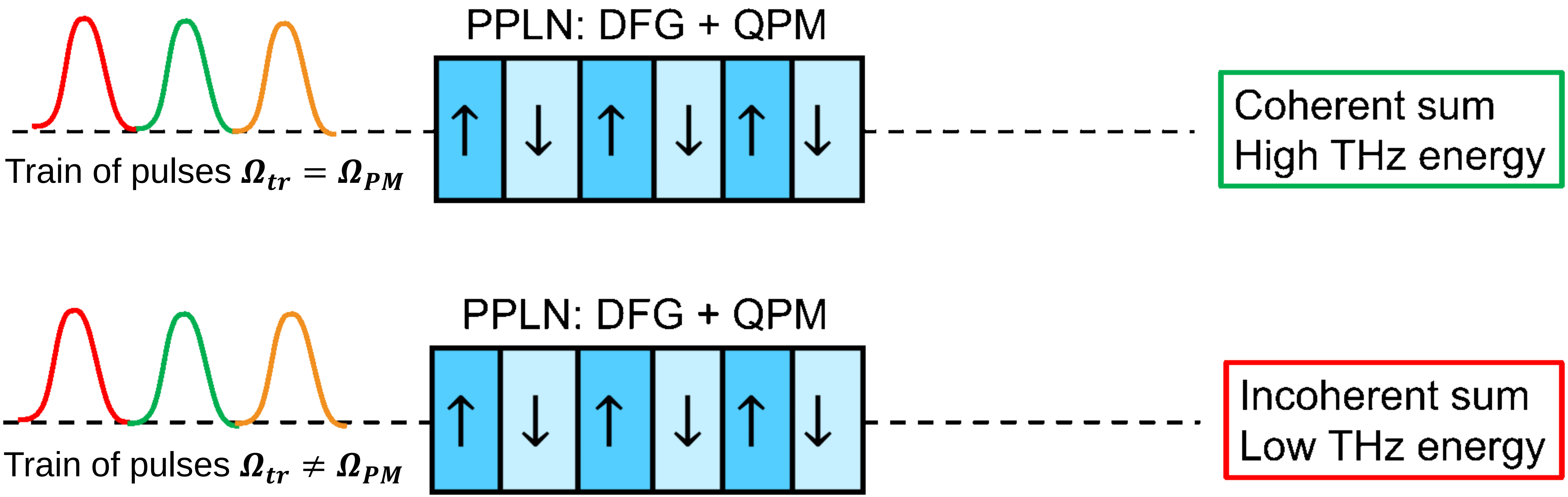
Multicycle THz generation: Single pulse



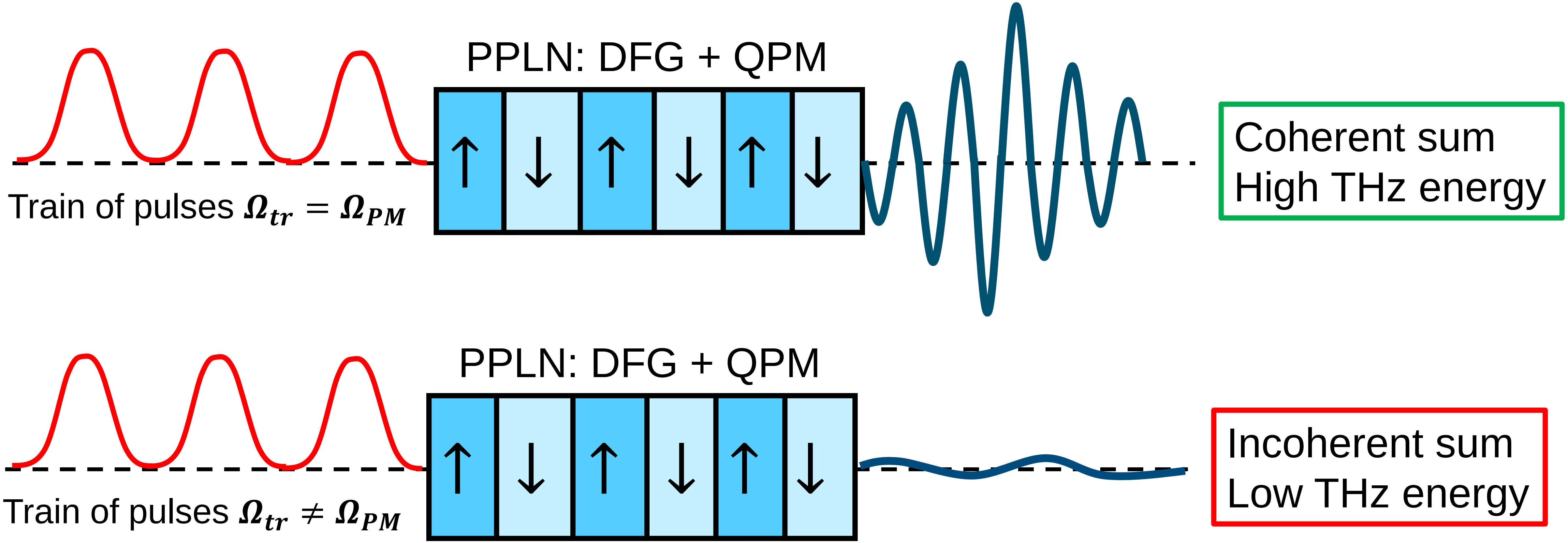
$$\boxed{\Delta k = k(\Omega_{IR} + \Omega_{PM}) - k(\Omega_{IR}) - k(\Omega_{PM}) + \boldsymbol{k_{PPLN}} = 0}$$

QPM fixes THz frequency: $\Omega_{THz} = \Omega_{PM} = 346\ GHz$

Multicycle THz generation: Train of pulses



Multicycle THz generation: Train of pulses

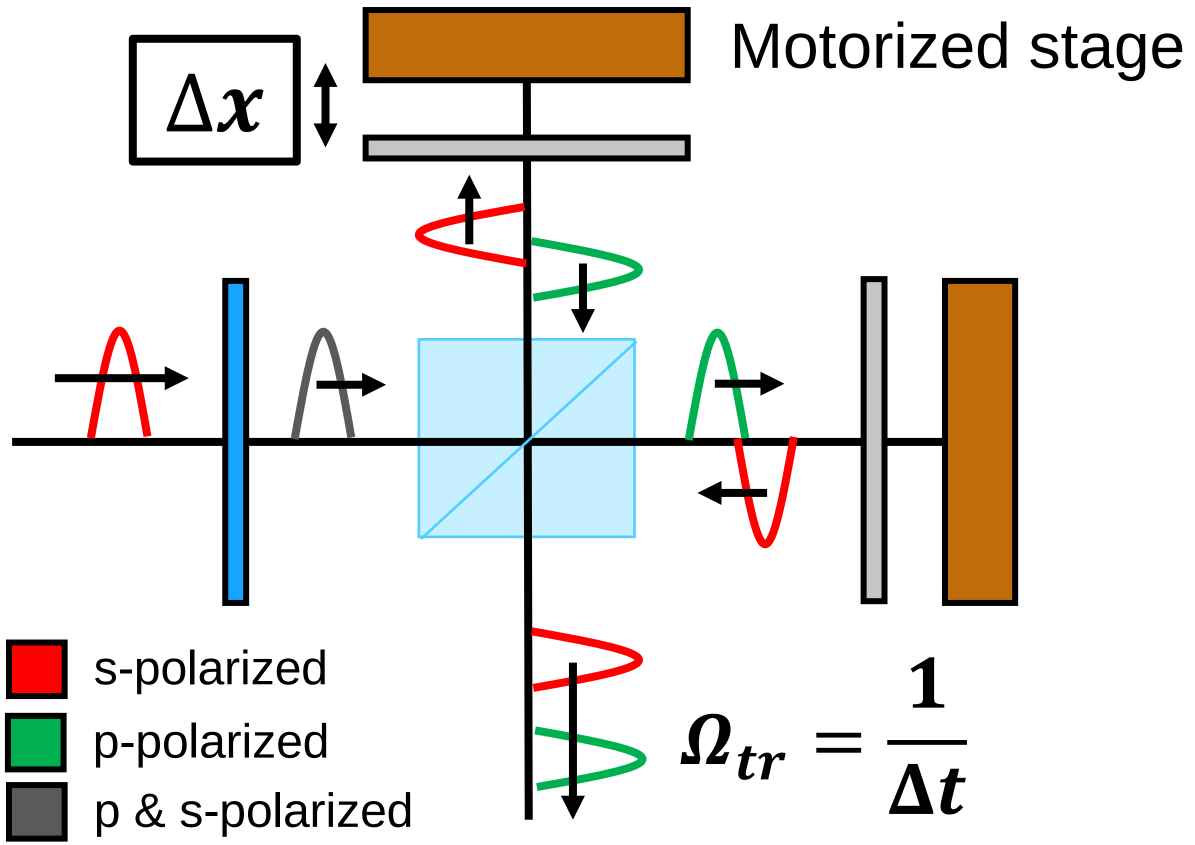


Train of pulses $\boldsymbol{\Omega_{tr}} = \boldsymbol{\Omega_{PM}}$

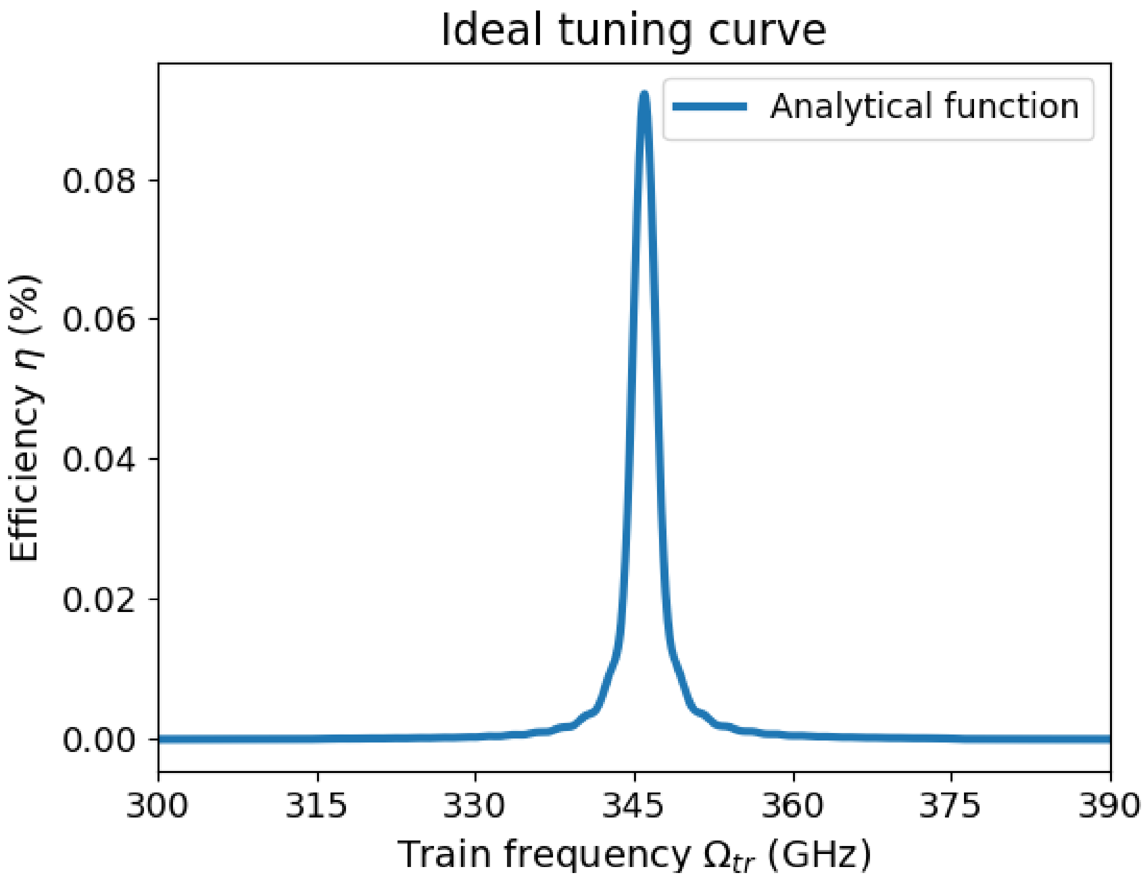
Train of pulses $\boldsymbol{\Omega_{tr}} \neq \boldsymbol{\Omega_{PM}}$

Experimental setup: Pulse divider

- Eight Michelson interferometers: **256 pulses**

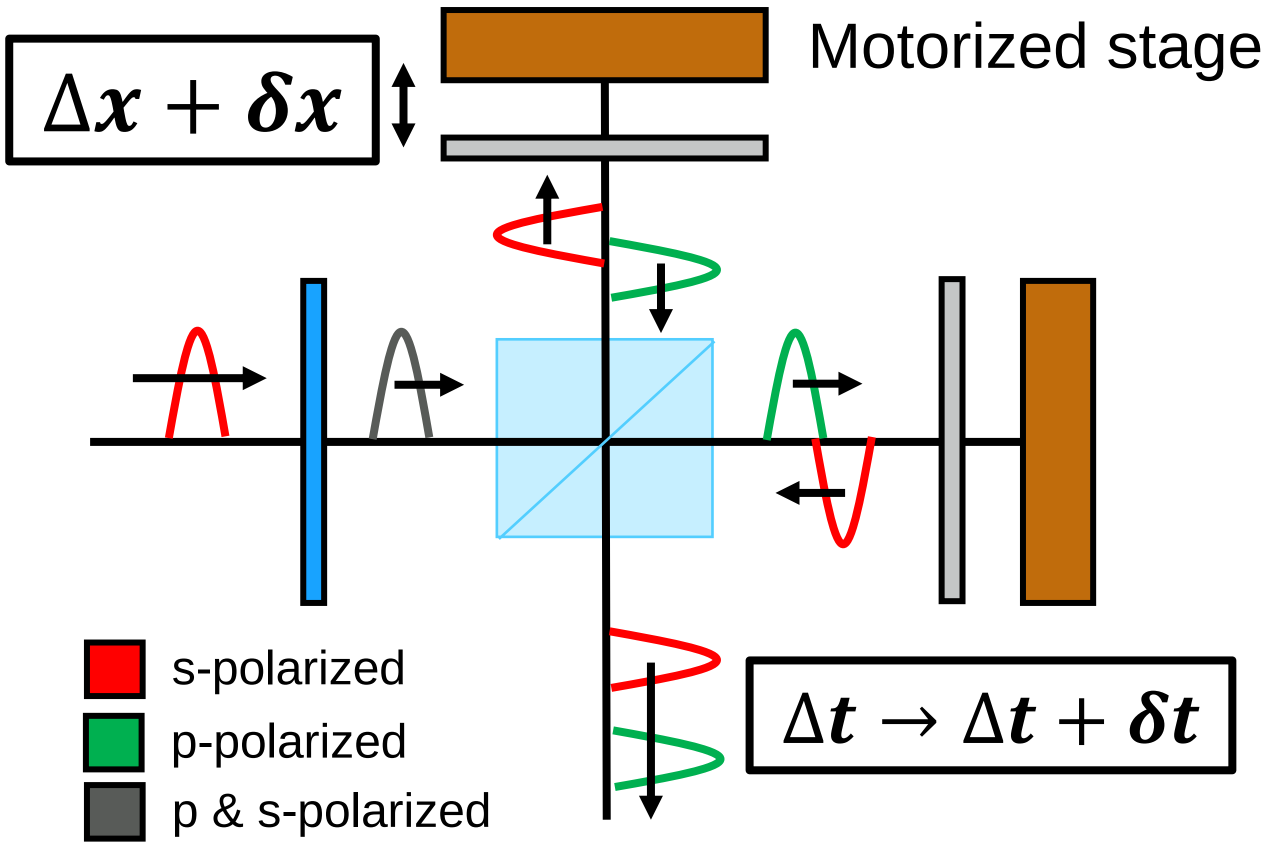


- Efficiency as function of Ω_{tr}

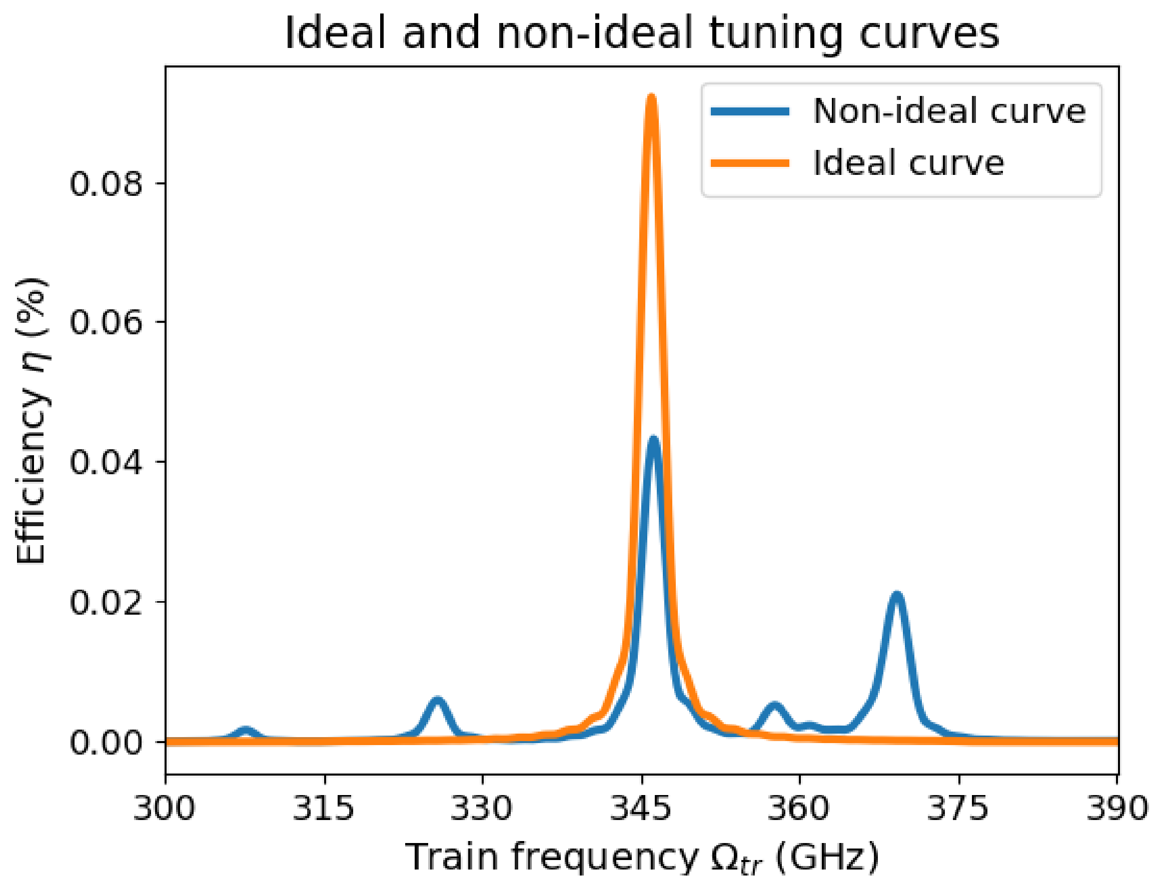


How is the curve affected by time errors?

- The pulses can be displaced by $\boldsymbol{\delta t}$

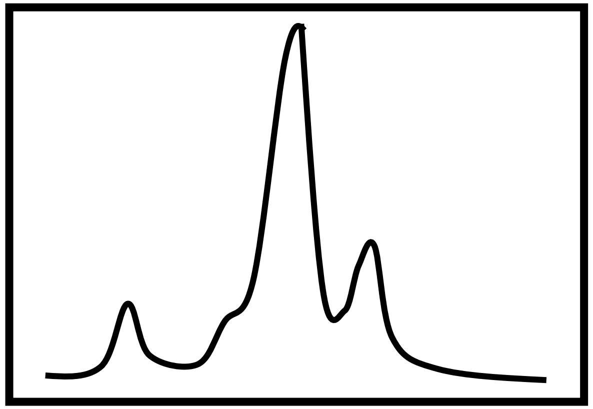


- We obtain lower THz efficiency



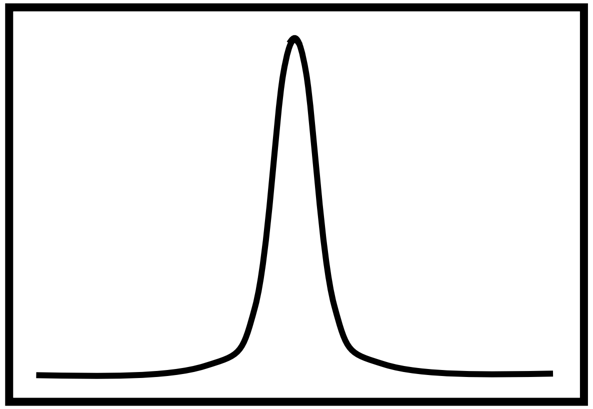
Application of ML algorithm: Methodology

- The input is a non-ideal tuning curve and the output is the set of eight time errors.



Tuning curve (η_{input})

→ ML algorithm → Eight delays $\boldsymbol{\delta t_i}$ →

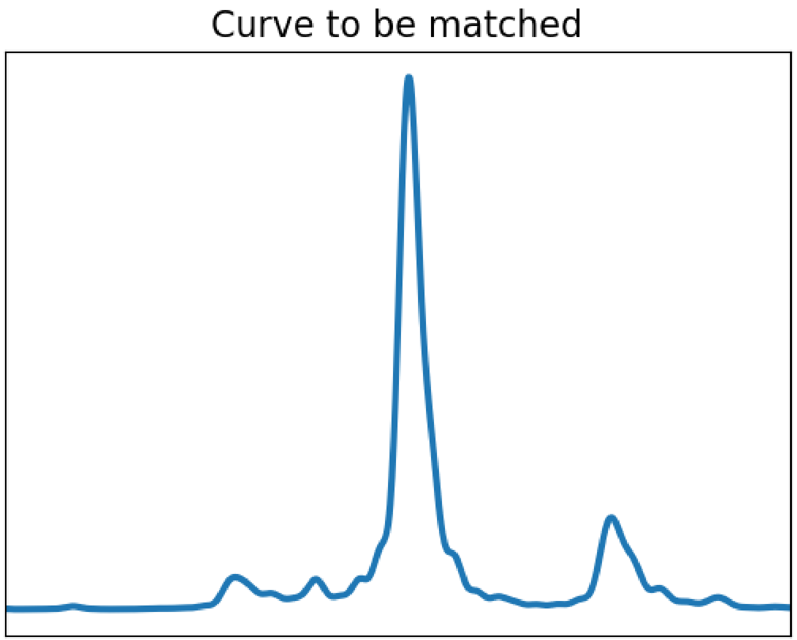


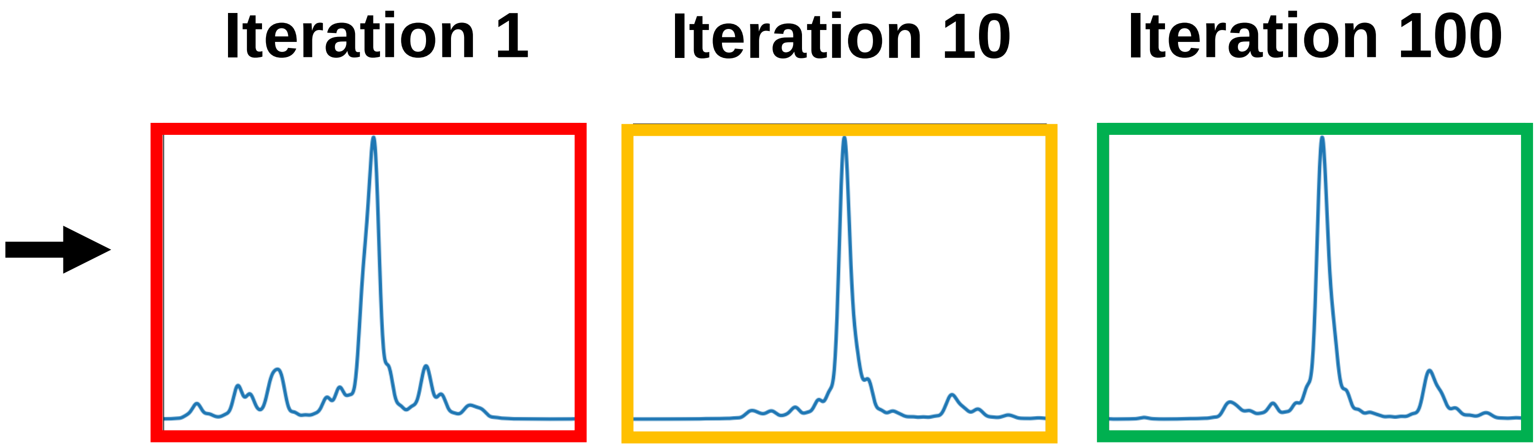
Corrected tuning curve

- $\mathrm{Fitness}(\delta t_i) = \sqrt{\sum_k \left(\eta_{input,k} - \eta_k(\delta t_i)\right)^2}$ The algorithm has to find the minimum

Application of ML algorithm: DE algorithm

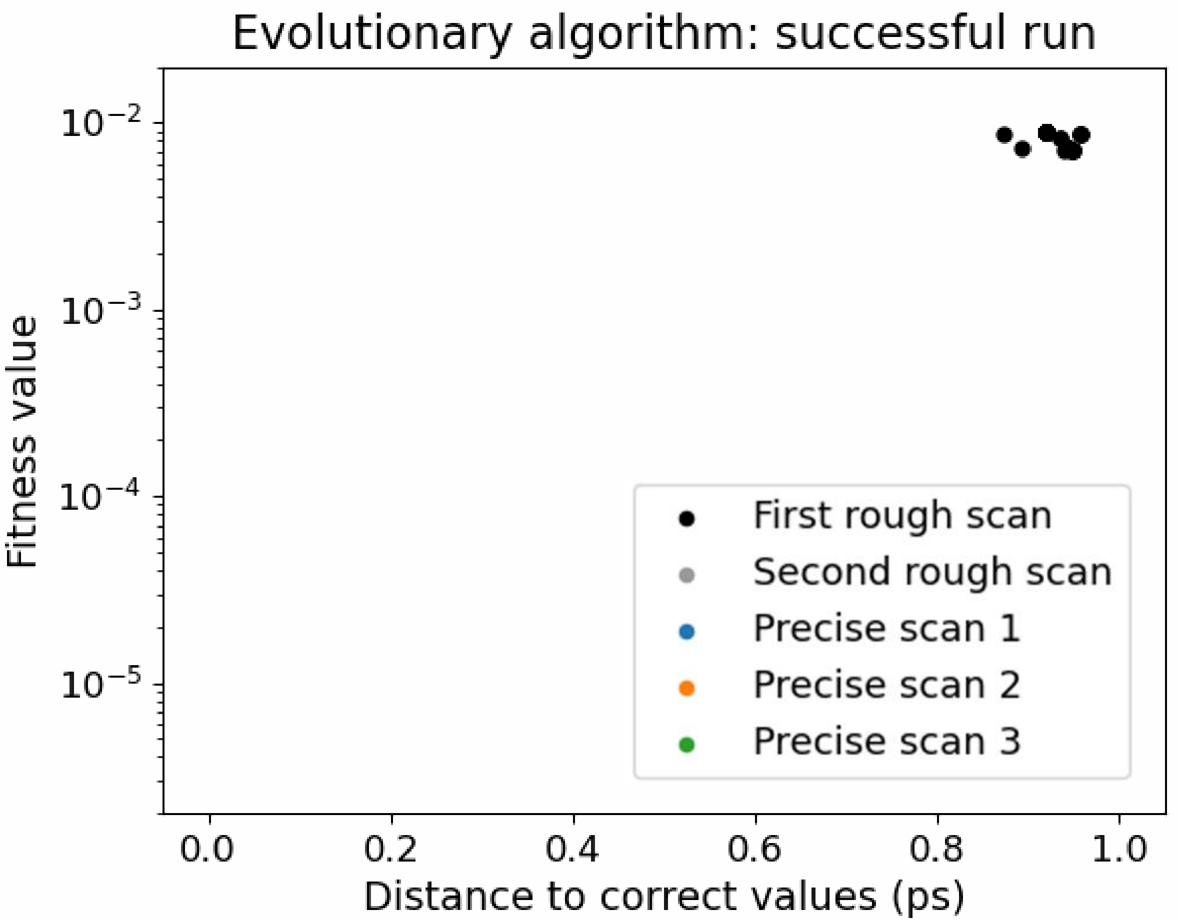
- Starts with an initial population and evolves it using the best individual





Application of ML algorithm: Simulated data

- To avoid local minima ⇒ two rough scans and a precise scan into each minimum

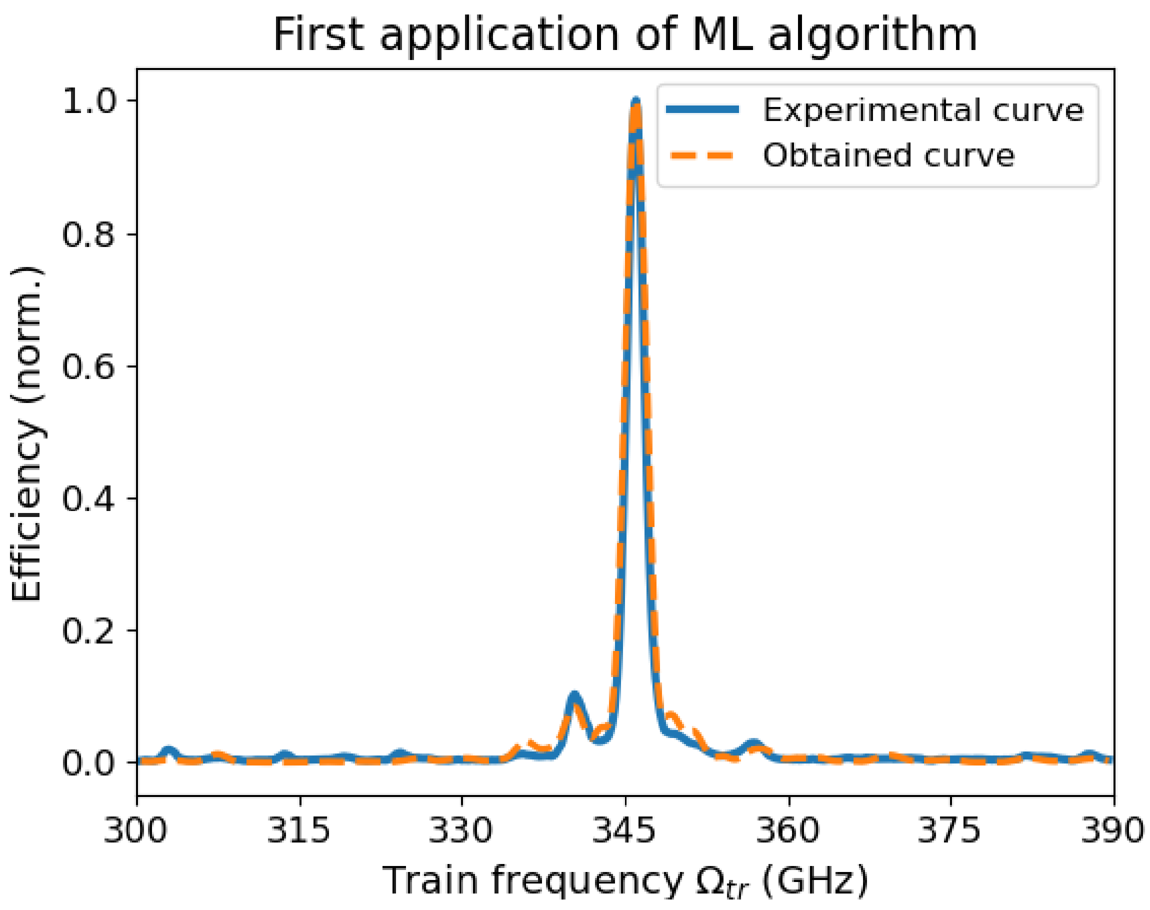


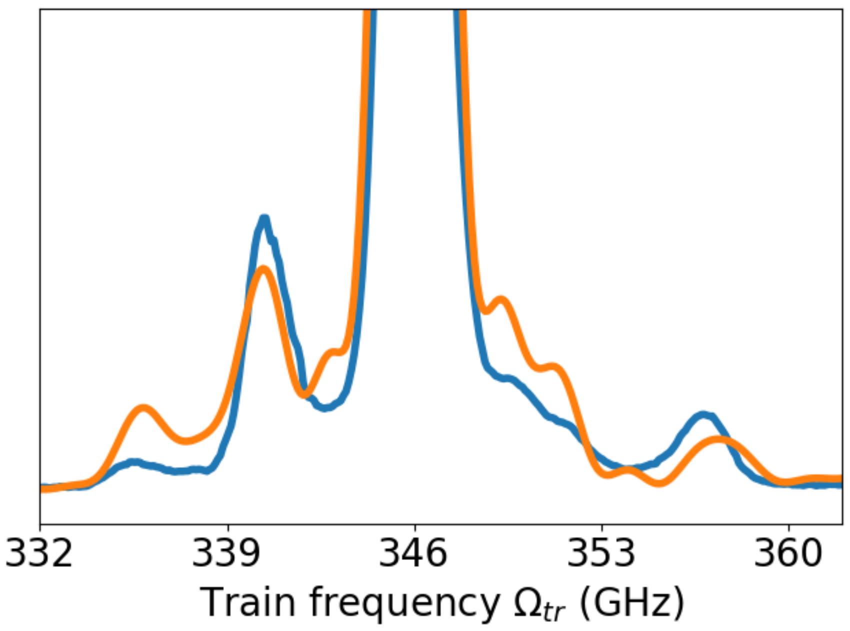
- Success rate: **70%**, **but** in the other 30% we know the global minimum was not reached looking at the fitness, so we can run it again!

- Average runtime: **25 minutes**, precise scans can be done in **parallel** for faster convergence

Application of ML algorithm: Experimental data

- First application to experimental curve. Scan range: 300 – 390 GHz

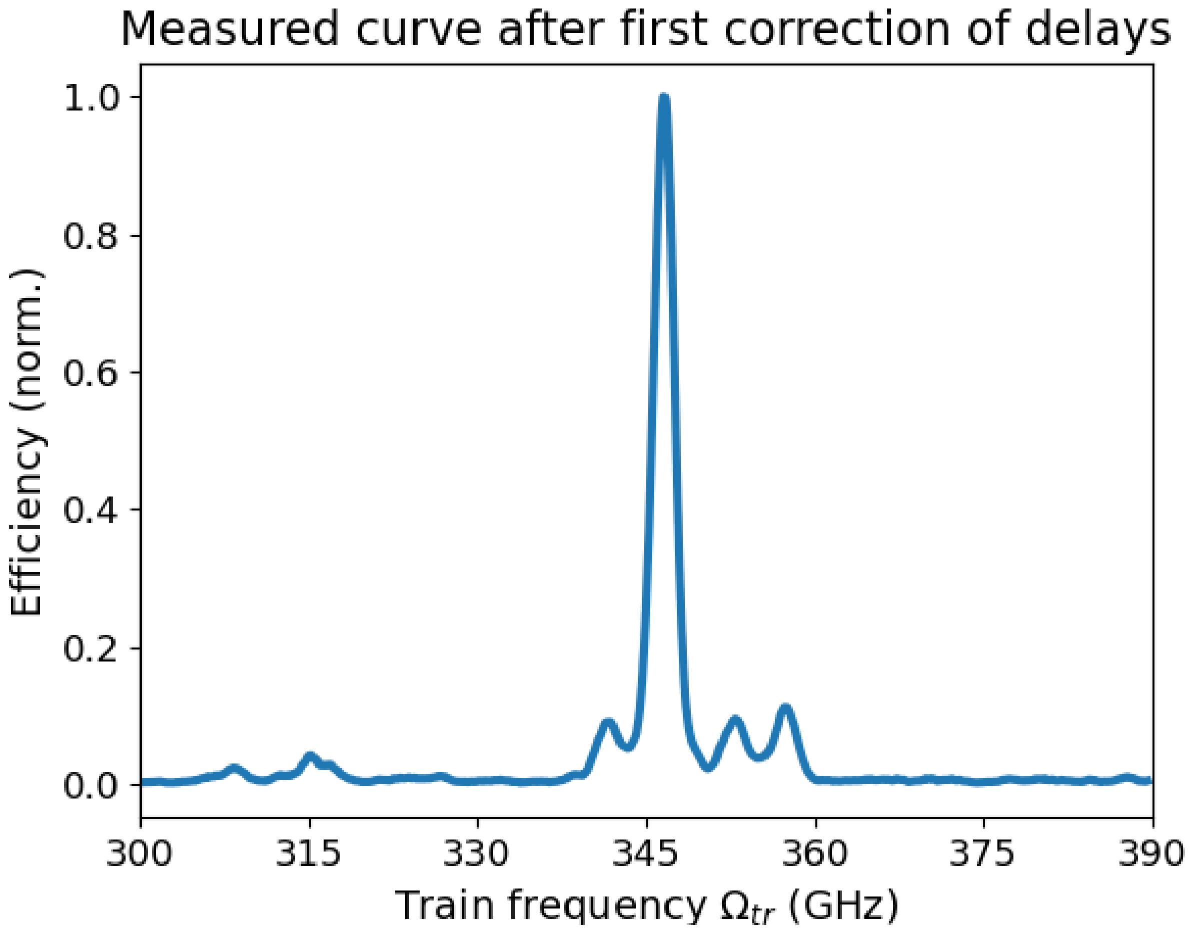




- Convergence not as good as expected

Application of ML algorithm: Experimental data

- Two corrections were applied. Results are not conclusive, more runs have to be done



Application of ML algorithm: Experimental data

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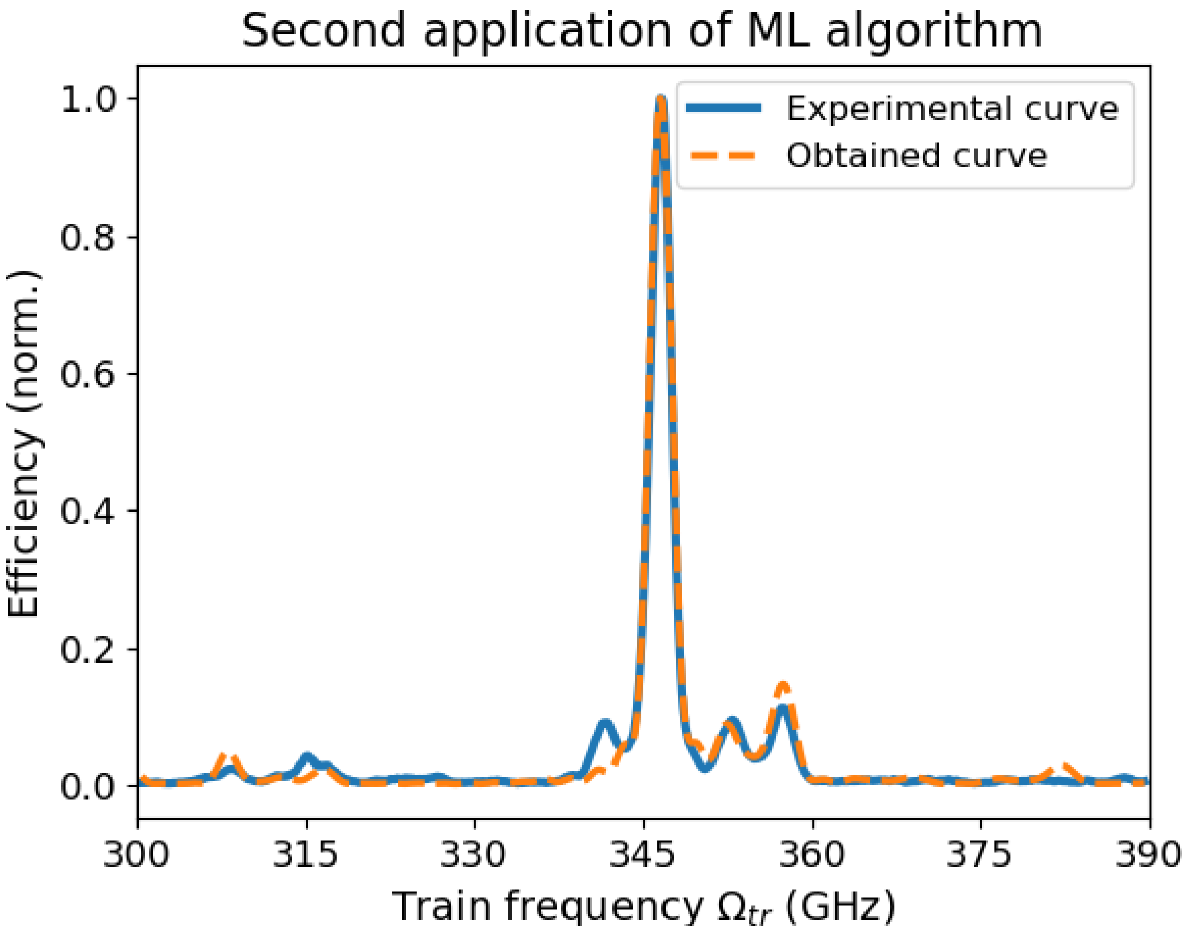

Application of ML algorithm: Experimental data

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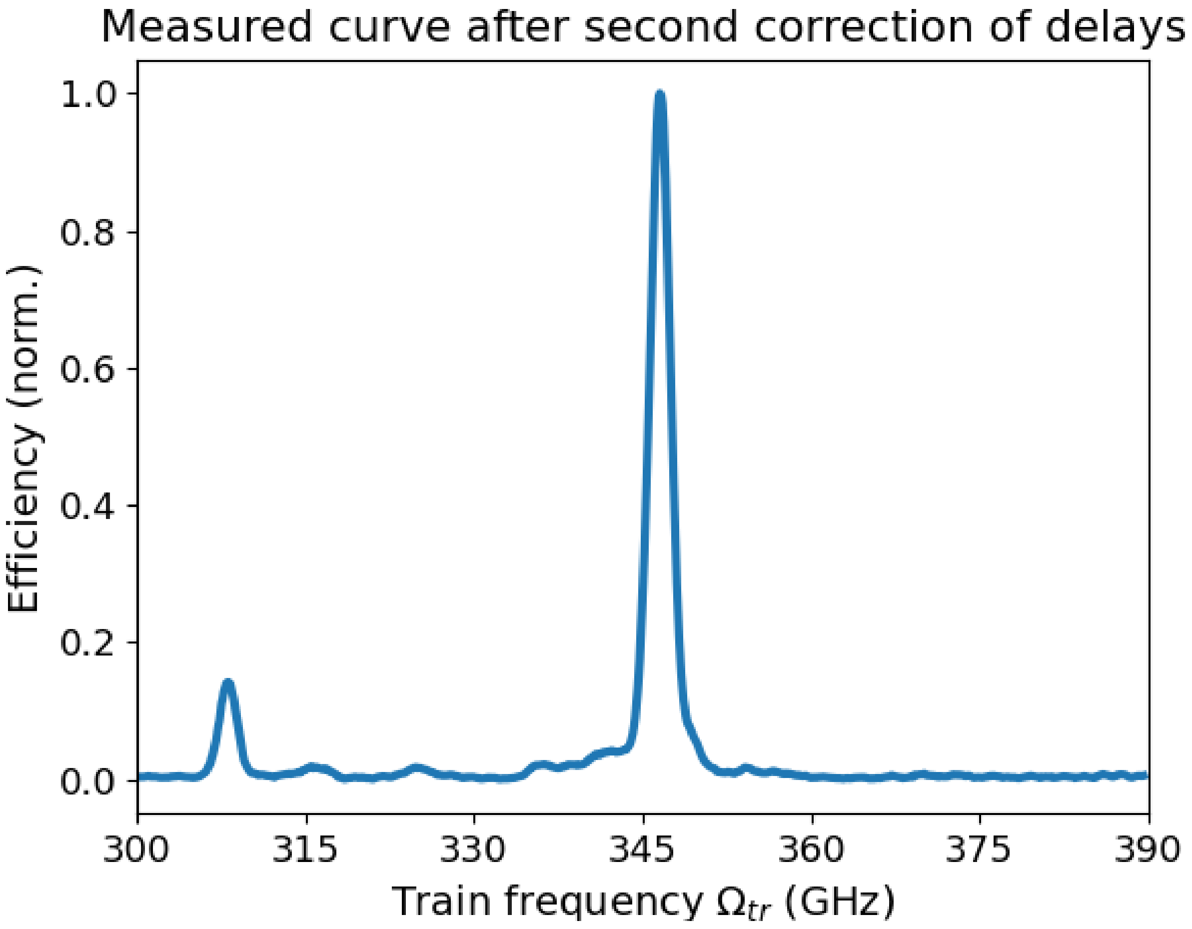
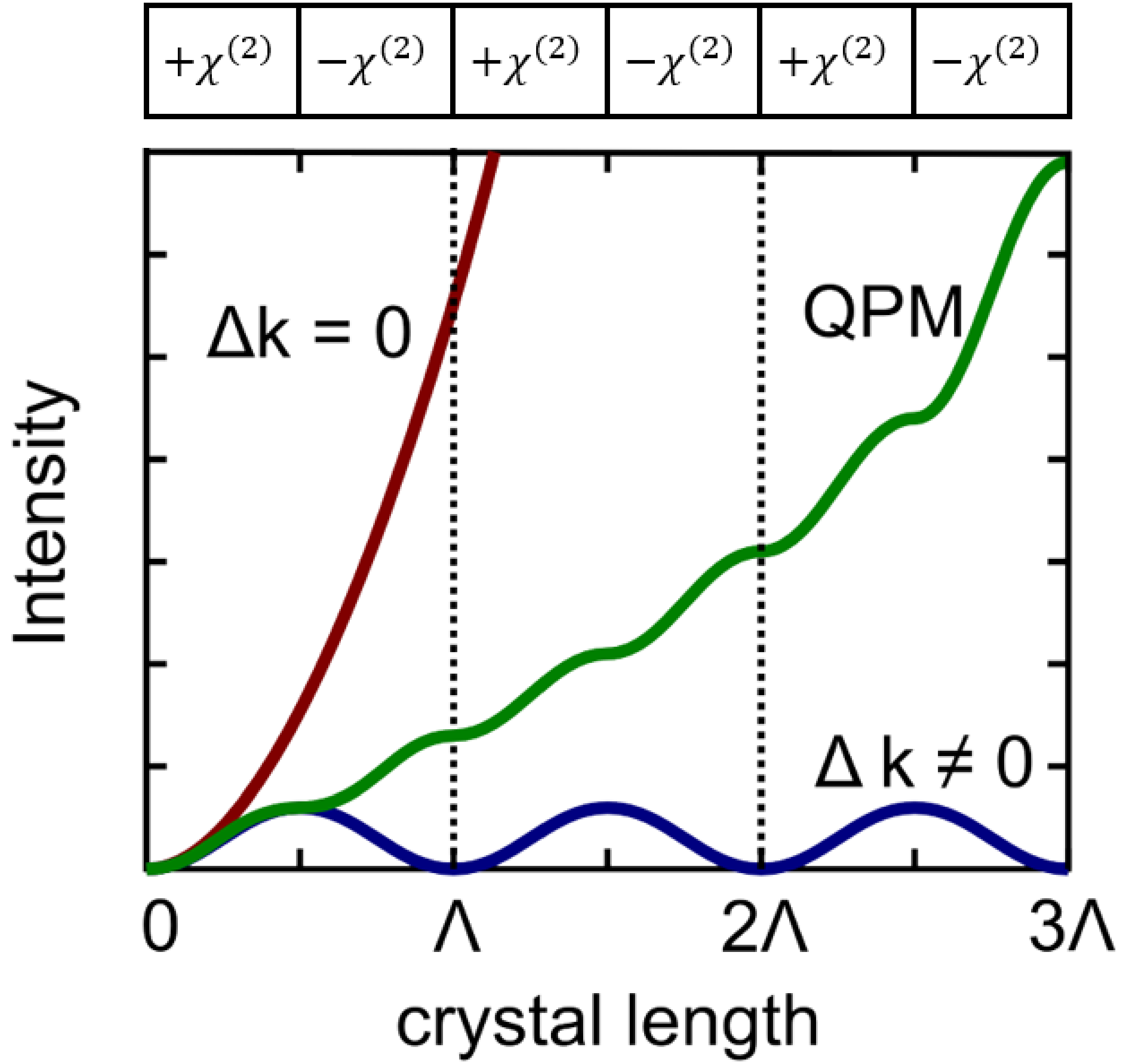


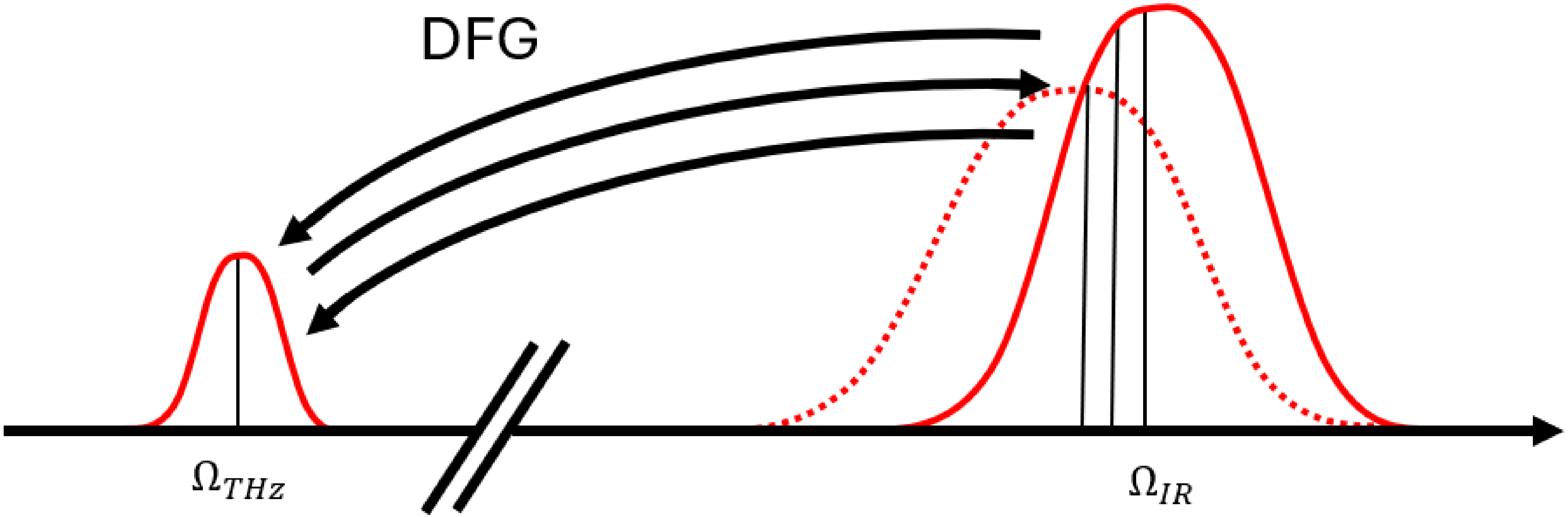
Conclusions

- Simulation of non-ideal tuning curves using eight time errors
- Created a ML algorithm able to identify those time delays
- Algorithm successfully applied to simulated data
- Application to experimental data is promising but not effective yet

Thank you for your attention

Backup figures

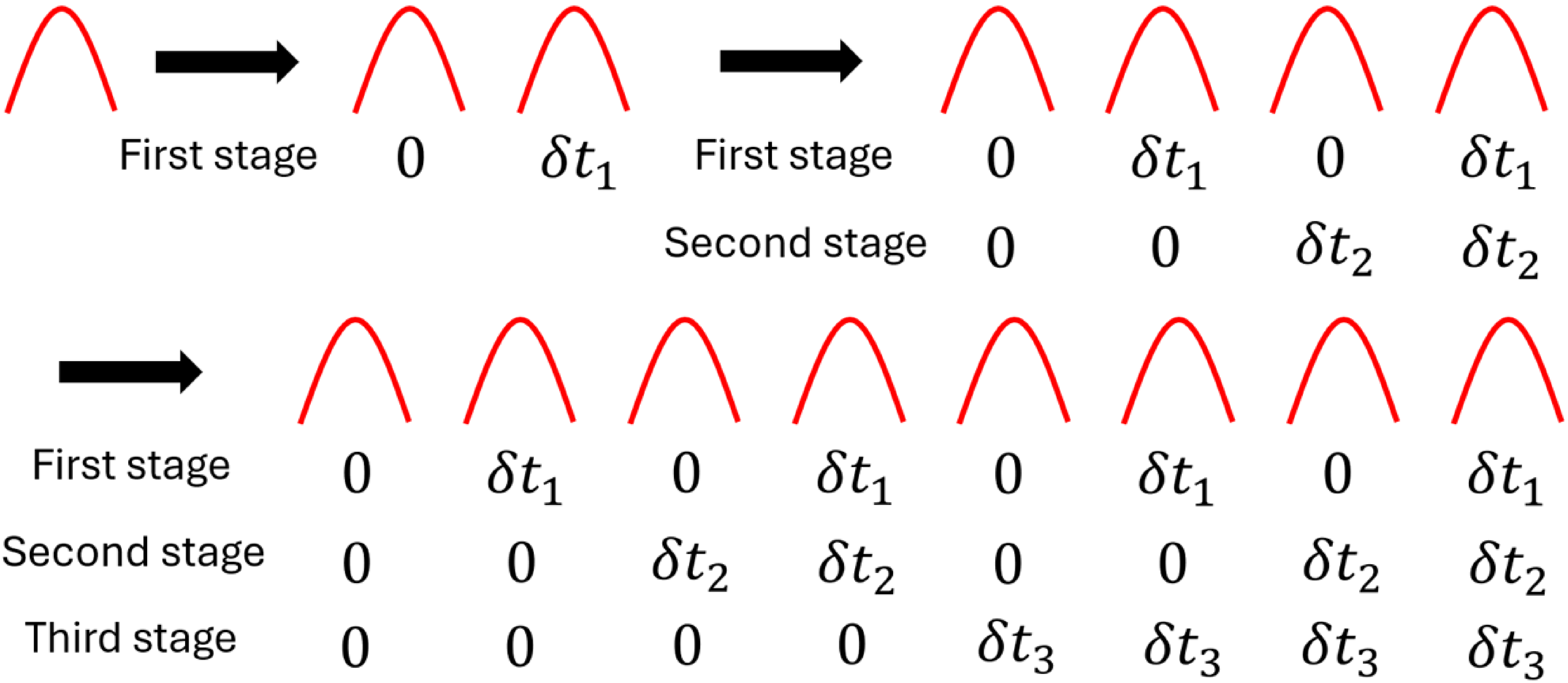

$+\chi^{(2)}$
$-\chi^{(2)}$
$+\chi^{(2)}$
$-\chi^{(2)}$
$+\chi^{(2)}$
$-\chi^{(2)}$
Δk = 0
QPM
Δ k ≠ 0
Intensity
0
Λ
2Λ
3Λ
crystal length


DFG
Ω_{THz}
Ω_{IR}

$$\eta_{THz}(L,\Omega_{tr}) = \frac{\left(\chi_0^{(2)}\right)L^2 F_0 n(\Omega_{PM})}{\pi^4 c^3 \epsilon_0 n^2(\omega_{IR}) N_{pulses}^2}\int_{-\infty}^{+\infty}\frac{\Omega^2}{n^2(\Omega)}g_{PPLN}(\Omega,L)g_{opt}(\Omega,\Omega_{tr})d\Omega$$

$$\Omega_{PM} = \frac{ck_{PPLN}}{n(\Omega_{PM}) - n_g(\omega_{IR})}$$

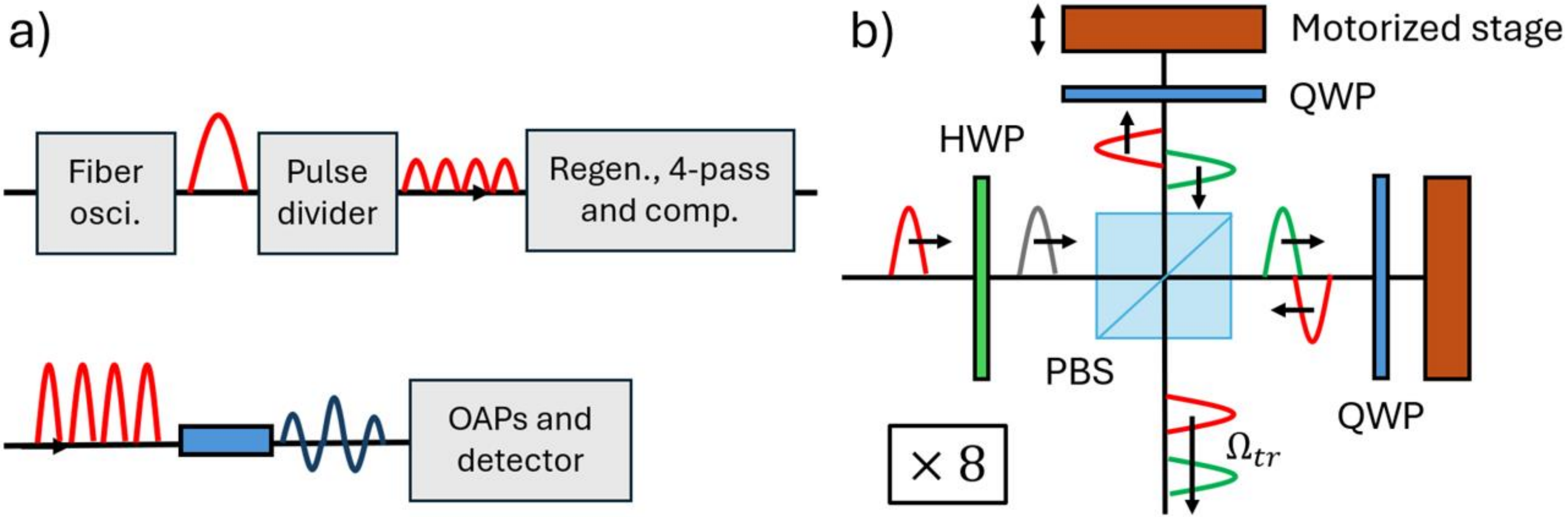
$$\delta L = -\frac{c\times\delta t}{2}$$

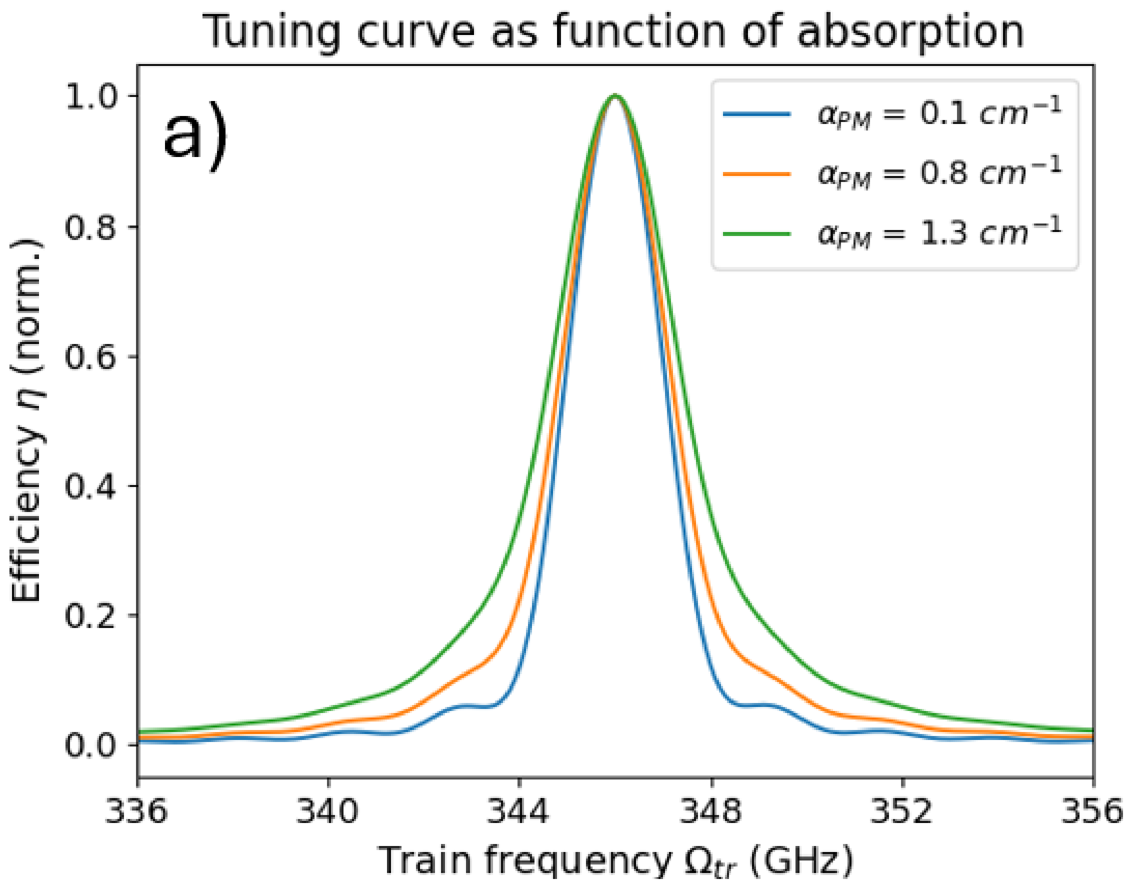


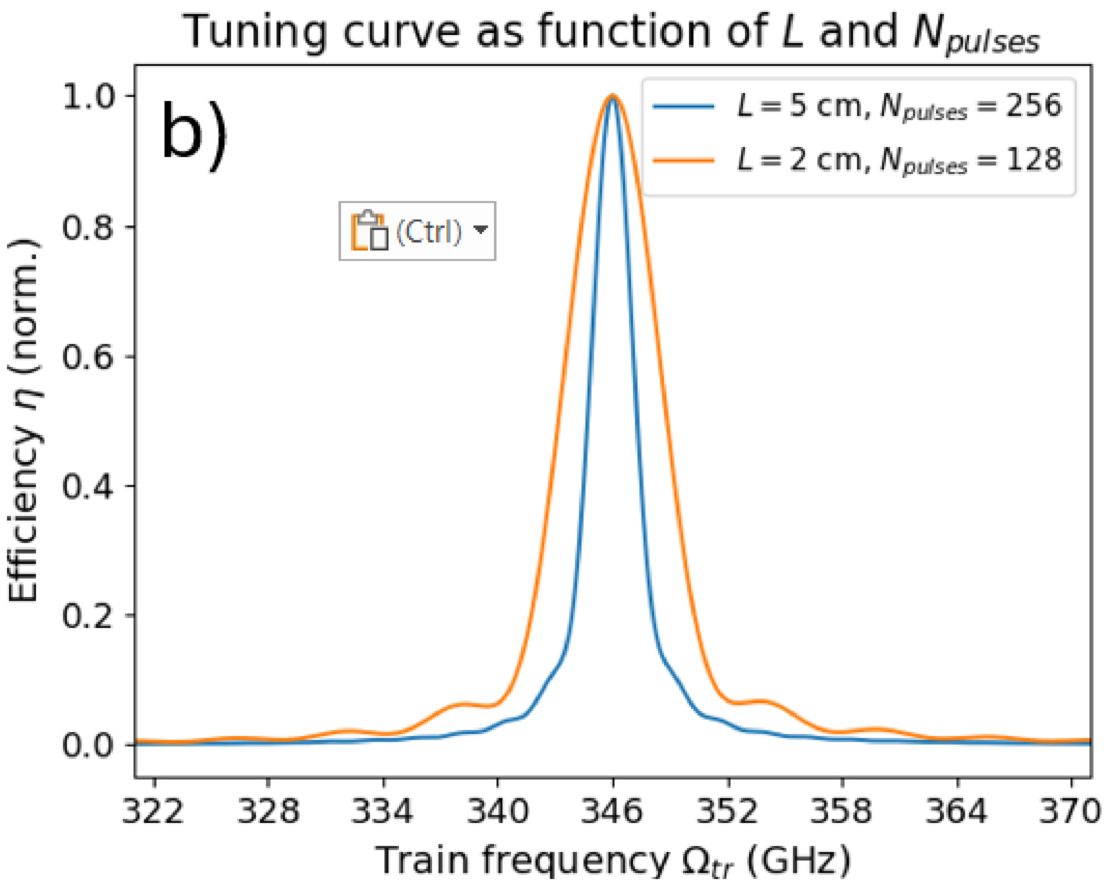
First stage 0 δt_1
First stage 0 δt_1 0 δt_1
Second stage 0 0 δt_2 δt_2
First stage 0 δt_1 0 δt_1 0 δt_1 0 δt_1
Second stage 0 0 δt_2 δt_2 0 0 δt_2 δt_2
Third stage 0 0 0 0 δt_3 δt_3 δt_3 δt_3

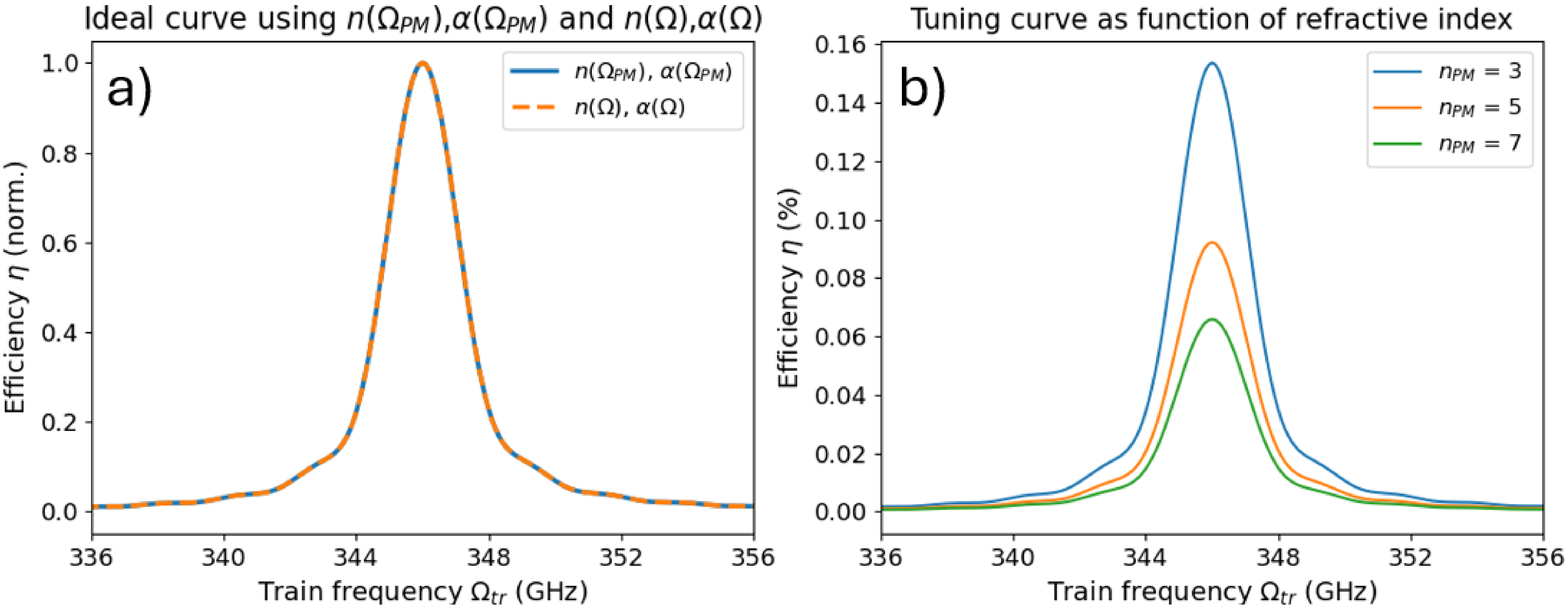
First stage	$\frac{1+\delta A_1}{2}$	$\frac{1-\delta A_1}{2}$	First stage	$\frac{1+\delta A_1}{2}$	$\frac{1-\delta A_1}{2}$	$\frac{1+\delta A_1}{2}$	$\frac{1-\delta A_1}{2}$
			Second stage	$\frac{1+\delta A_2}{2}$	$\frac{1+\delta A_2}{2}$	$\frac{1-\delta A_2}{2}$	$\frac{1-\delta A_2}{2}$

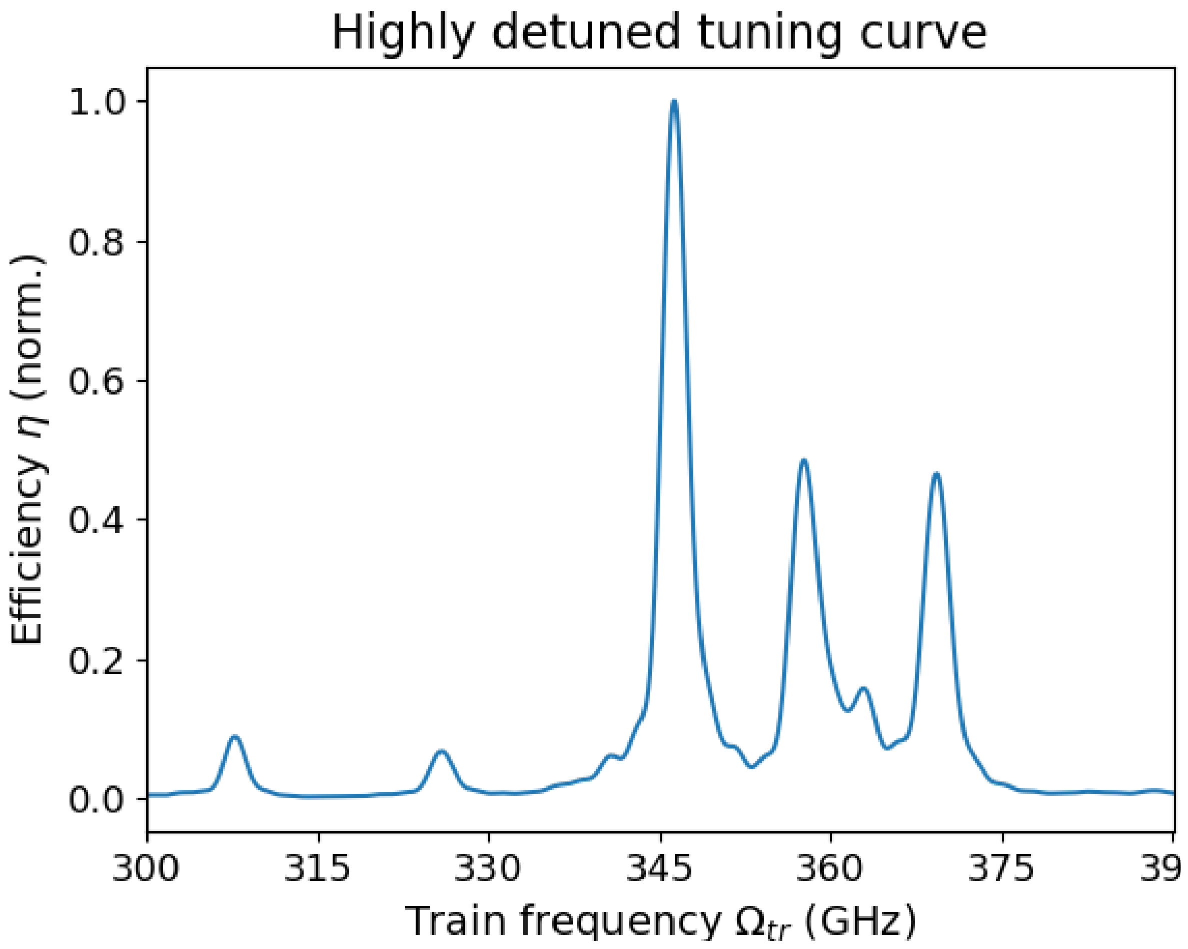
First stage	$\frac{1+\delta A_1}{2}$	$\frac{1-\delta A_1}{2}$	$\frac{1+\delta A_1}{2}$	$\frac{1-\delta A_1}{2}$	$\frac{1+\delta A_1}{2}$	$\frac{1-\delta A_1}{2}$	$\frac{1+\delta A_1}{2}$	$\frac{1-\delta A_1}{2}$
Second stage	$\frac{1+\delta A_2}{2}$	$\frac{1+\delta A_2}{2}$	$\frac{1-\delta A_2}{2}$	$\frac{1-\delta A_2}{2}$	$\frac{1+\delta A_2}{2}$	$\frac{1+\delta A_2}{2}$	$\frac{1-\delta A_2}{2}$	$\frac{1-\delta A_2}{2}$
Third stage	$\frac{1+\delta A_3}{2}$	$\frac{1+\delta A_3}{2}$	$\frac{1-\delta A_3}{2}$	$\frac{1-\delta A_3}{2}$	$\frac{1-\delta A_3}{2}$	$\frac{1-\delta A_3}{2}$	$\frac{1-\delta A_3}{2}$	$\frac{1-\delta A_3}{2}$


a)
Fiber
osci.
Pulse
divider
Regen., 4-pass
and comp.
OAPs and
detector
b)
Motorized stage
QWP
HWP
PBS
QWP
Ω_{tr}
$\times 8$

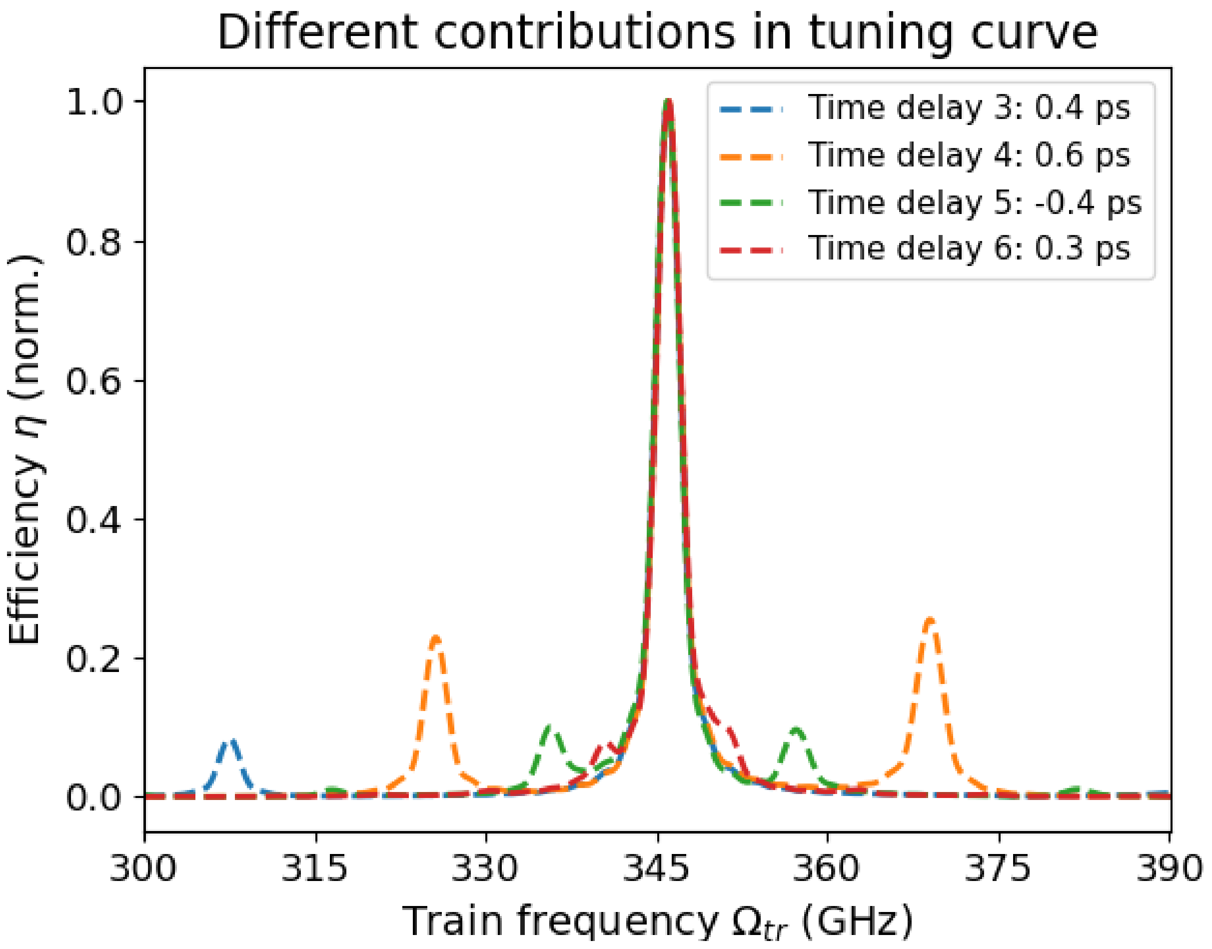

Tuning curve as function of absorption
a)
$\alpha_{PM} = 0.1\ cm^{-1}$
$\alpha_{PM} = 0.8\ cm^{-1}$
$\alpha_{PM} = 1.3\ cm^{-1}$
Efficiency η (norm.)
1.0
0.8
0.6
0.4
0.2
0.0
336
340
344
348
352
356
Train frequency Ω_{tr} (GHz)


Tuning curve as function of L and N_{pulses}
b)
$L = 5$ cm, $N_{pulses} = 256$
$L = 2$ cm, $N_{pulses} = 128$
(Ctrl)
Efficiency η (norm.)
1.0
0.8
0.6
0.4
0.2
0.0
322
328
334
340
346
352
358
364
370
Train frequency Ω_{tr} (GHz)

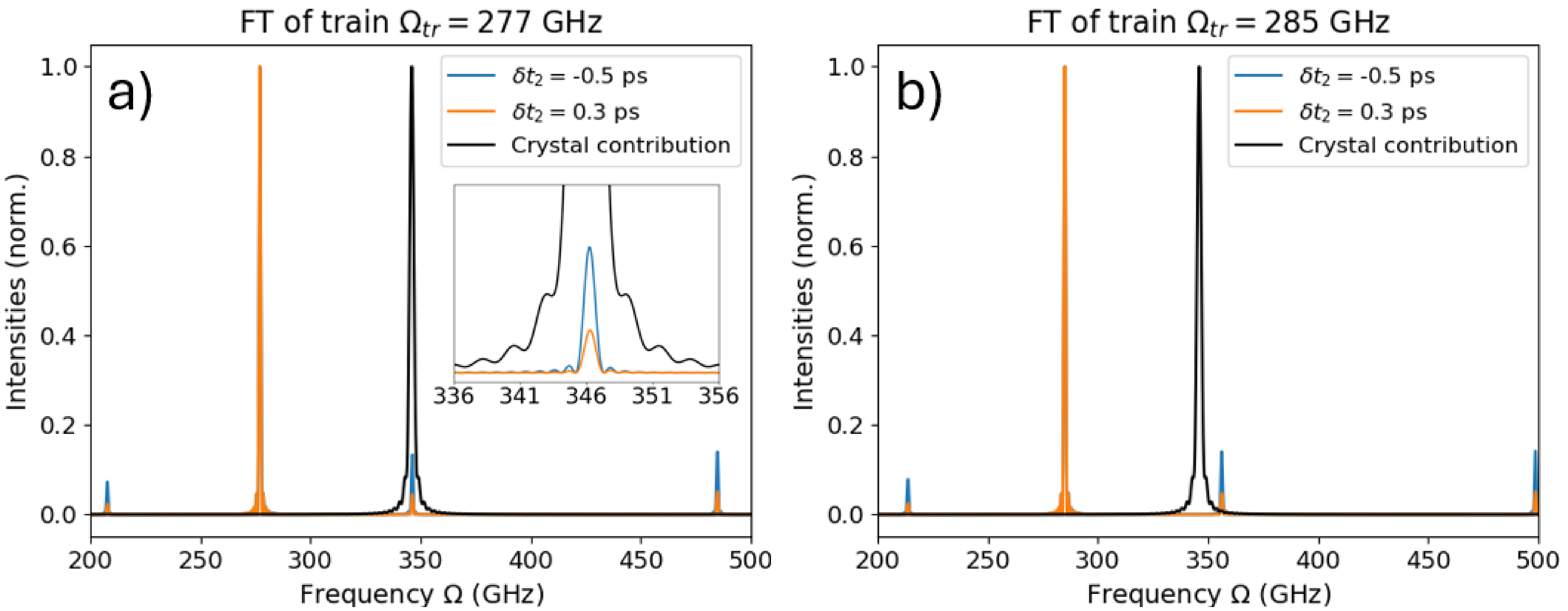

Ideal curve using n(Ω_PM),α(Ω_PM) and n(Ω),α(Ω)
a)
n(Ω_PM), α(Ω_PM)
n(Ω), α(Ω)
Efficiency η (norm.)
1.0
0.8
0.6
0.4
0.2
0.0
336
340
344
348
352
356
Train frequency Ω_tr (GHz)
Tuning curve as function of refractive index
b)
n_PM = 3
n_PM = 5
n_PM = 7
Efficiency η (%)
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
336
340
344
348
352
356
Train frequency Ω_tr (GHz)



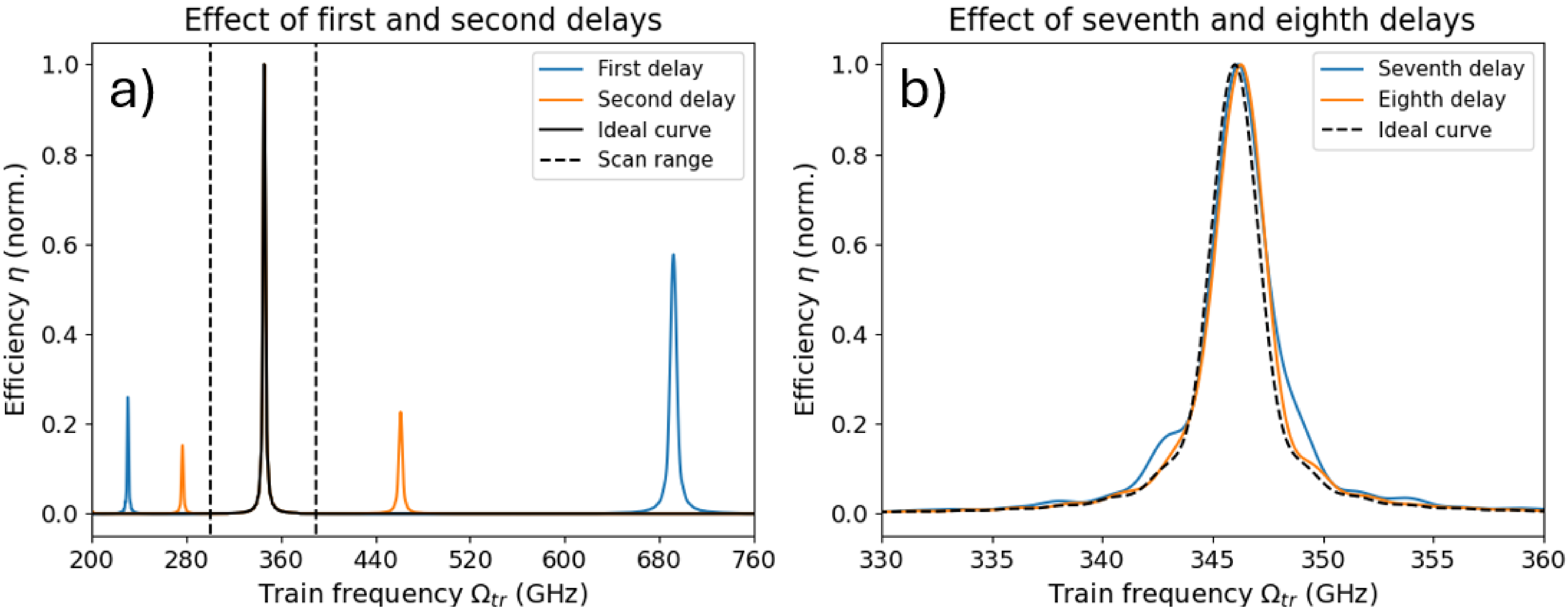
Highly detuned tuning curve
Efficiency η (norm.)
1.0
0.8
0.6
0.4
0.2
0.0
300
315
330
345
360
375
39
Train frequency Ω_{tr} (GHz)

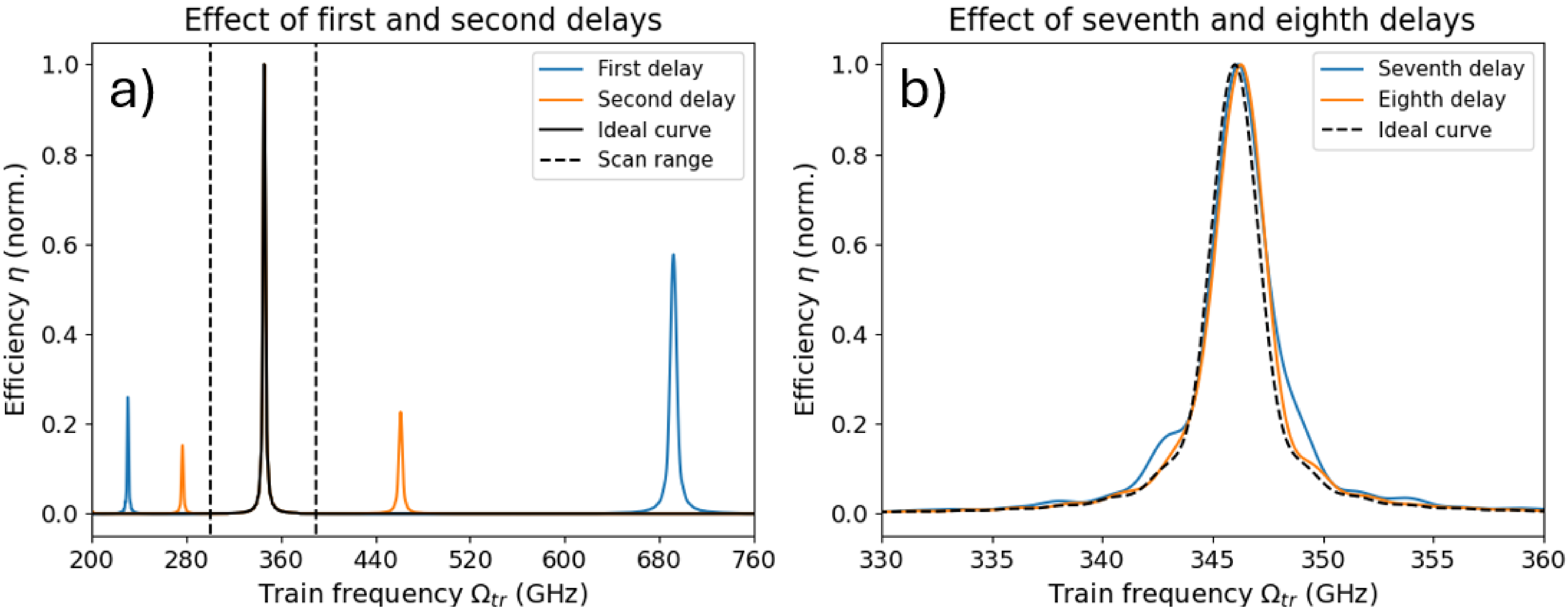


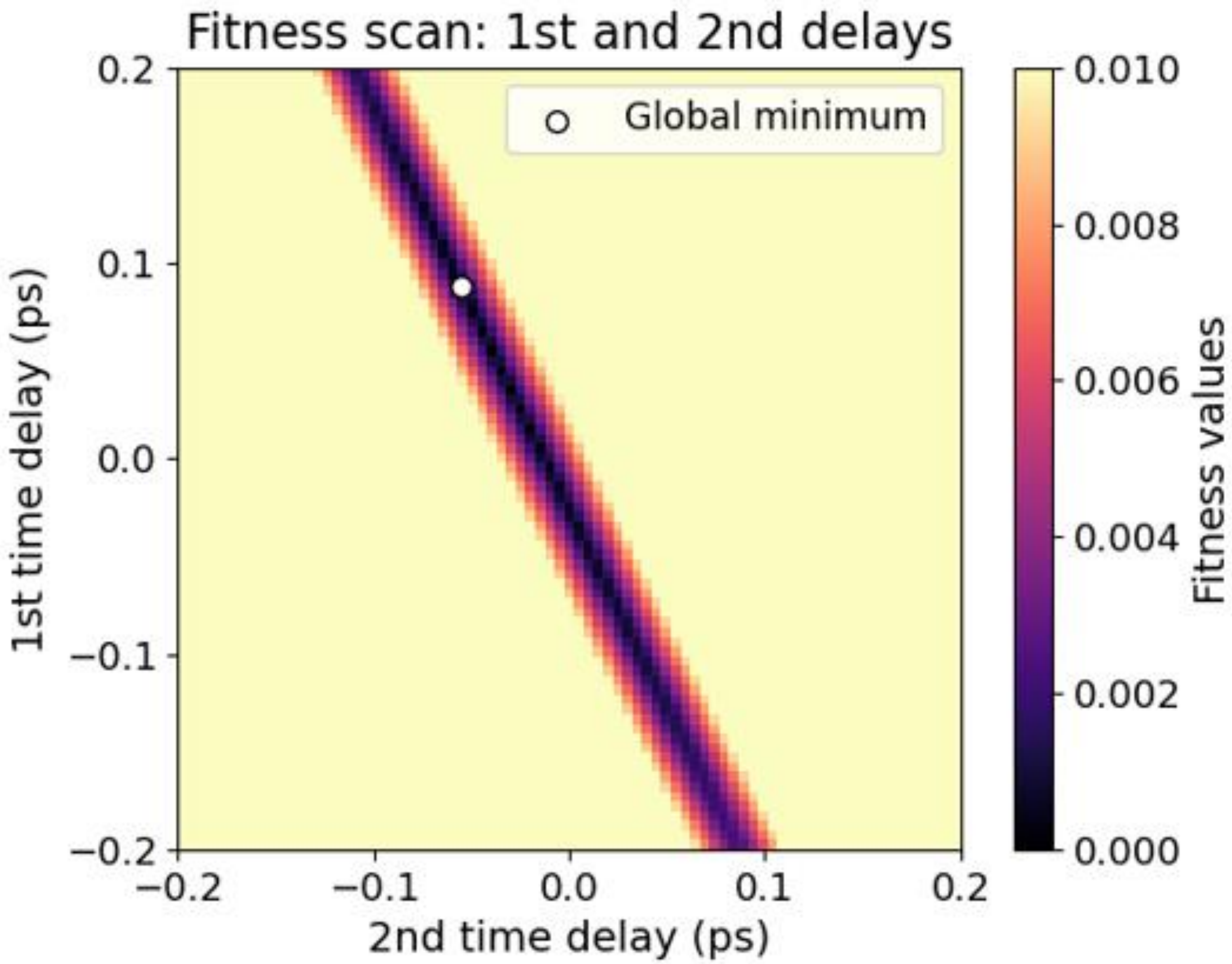
Different contributions in tuning curve
Time delay 3: 0.4 ps
Time delay 4: 0.6 ps
Time delay 5: -0.4 ps
Time delay 6: 0.3 ps
Efficiency η (norm.)
1.0
0.8
0.6
0.4
0.2
0.0
300
315
330
345
360
375
390
Train frequency Ω_{tr} (GHz)

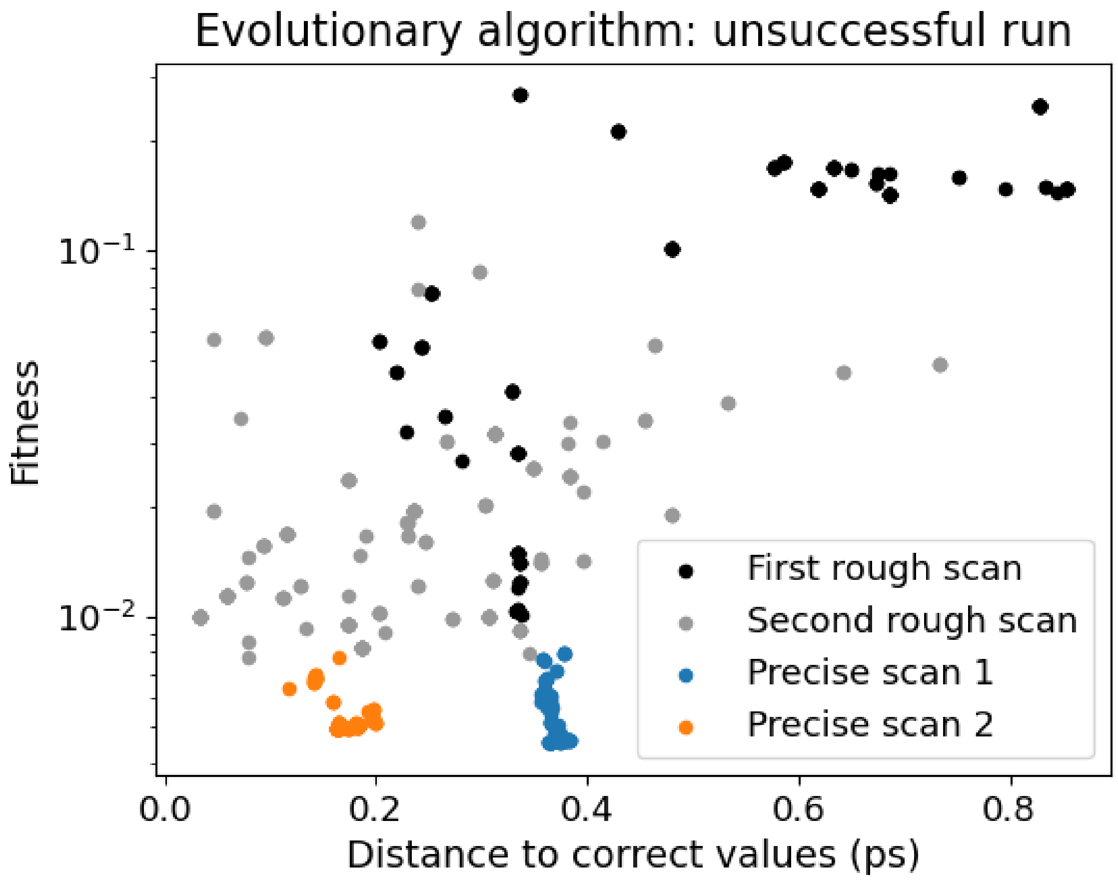


FT of train $\Omega_{tr} = 277$ GHz
a)
δt_2 = -0.5 ps
δt_2 = 0.3 ps
Crystal contribution
336 341 346 351 356
Intensities (norm.)
1.0 0.8 0.6 0.4 0.2 0.0
200 250 300 350 400 450 500
Frequency Ω (GHz)
FT of train $\Omega_{tr} = 285$ GHz
b)
δt_2 = -0.5 ps
δt_2 = 0.3 ps
Crystal contribution
Intensities (norm.)
1.0 0.8 0.6 0.4 0.2 0.0
200 250 300 350 400 450 500
Frequency Ω (GHz)

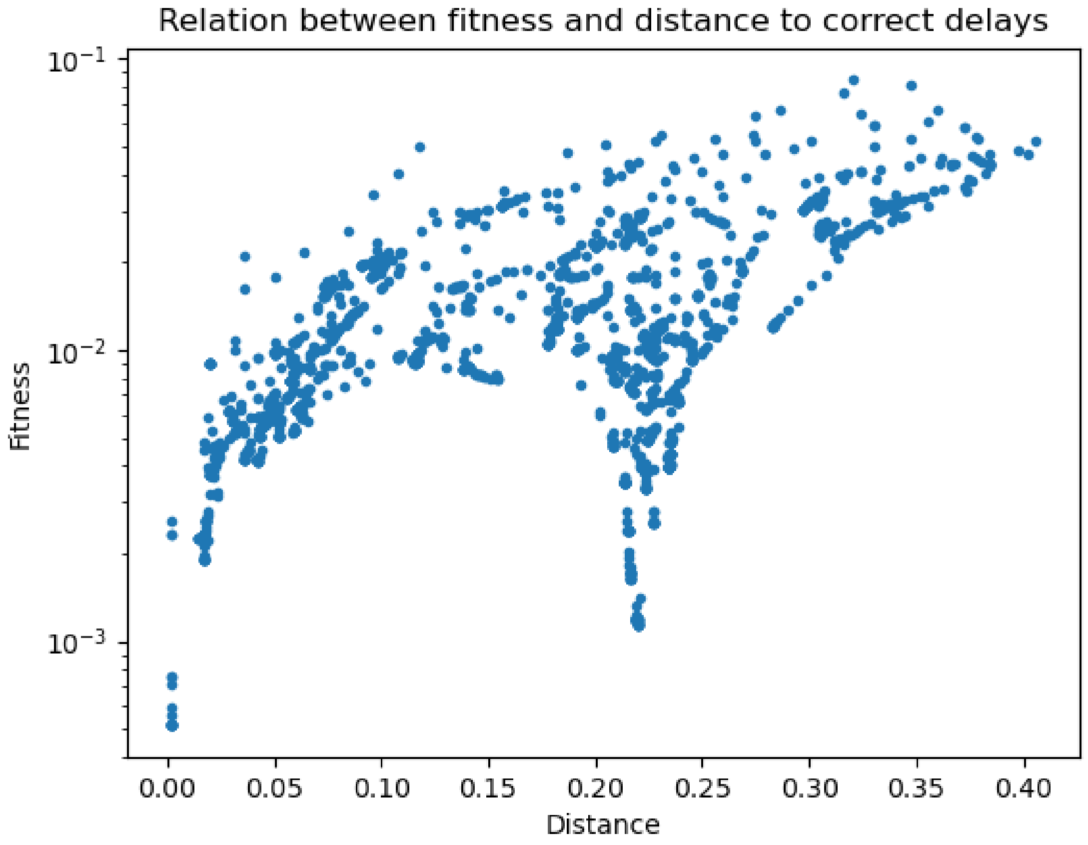

Effect of first and second delays
a)
First delay
Second delay
Ideal curve
Scan range
Efficiency η (norm.)
Train frequency Ω_{tr} (GHz)
1.0
0.8
0.6
0.4
0.2
0.0
200
280
360
440
520
600
680
760
Effect of seventh and eighth delays
b)
Seventh delay
Eighth delay
Ideal curve
Efficiency η (norm.)
Train frequency Ω_{tr} (GHz)
1.0
0.8
0.6
0.4
0.2
0.0
330
335
340
345
350
355
360


Effect of first and second delays
a)
First delay
Second delay
Ideal curve
Scan range
Efficiency η (norm.)
Train frequency Ωtr (GHz)
1.0
0.8
0.6
0.4
0.2
0.0
200
280
360
440
520
600
680
760
Effect of seventh and eighth delays
b)
Seventh delay
Eighth delay
Ideal curve
Efficiency η (norm.)
Train frequency Ωtr (GHz)
330
335
340
345
350
355
360


Fitness scan: 1st and 2nd delays
Global minimum
1st time delay (ps)
2nd time delay (ps)
Fitness values
0.2
0.1
0.0
−0.1
−0.2
0.010
0.008
0.006
0.004
0.002
0.000



Evolutionary algorithm: unsuccessful run
Fitness
10^{-1}
10^{-2}
First rough scan
Second rough scan
Precise scan 1
Precise scan 2
0.0
0.2
0.4
0.6
0.8
Distance to correct values (ps)

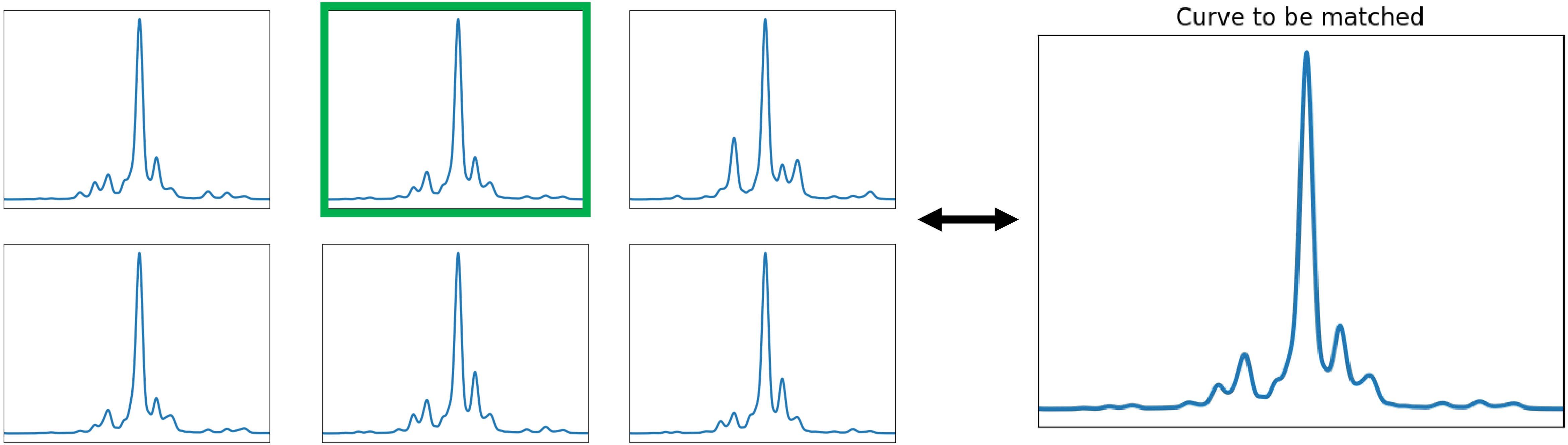


Relation between fitness and distance to correct delays
Fitness
10^{-1}
10^{-2}
10^{-3}
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Distance

Application of ML algorithm: DE algorithm

- Starts with an initial population and evolves it using the best individual

Iteration 100:



Multicycle THz generation