OPTIMIERUNG VON LASERPROZESSEN MIT MASCHINELLEM LERNEN

DR. ANDREAS MICHALOWSKI

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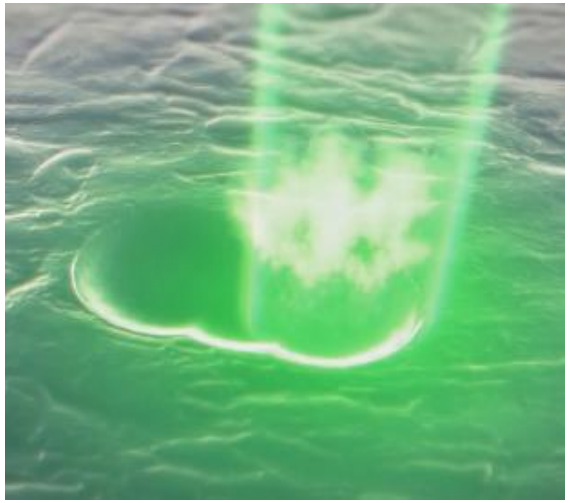
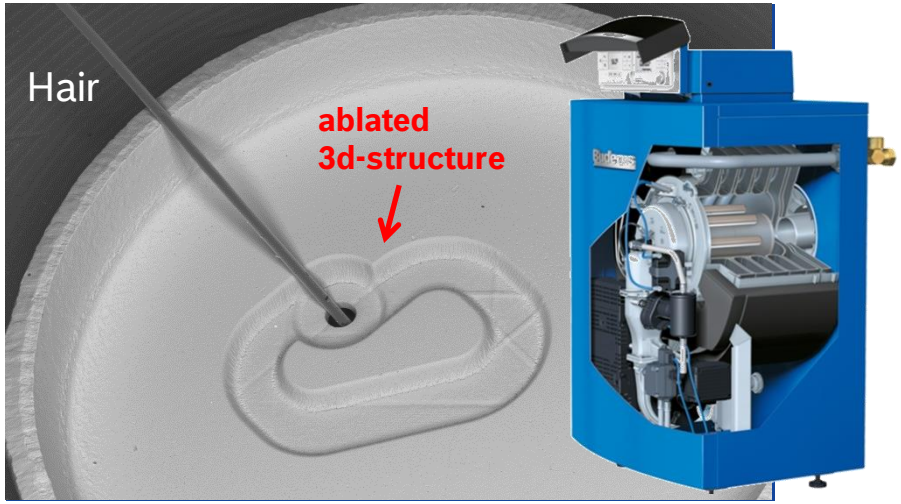
Optimierung von Laserprozessen mit Maschinellem Lernen
Applikationsbeispiel





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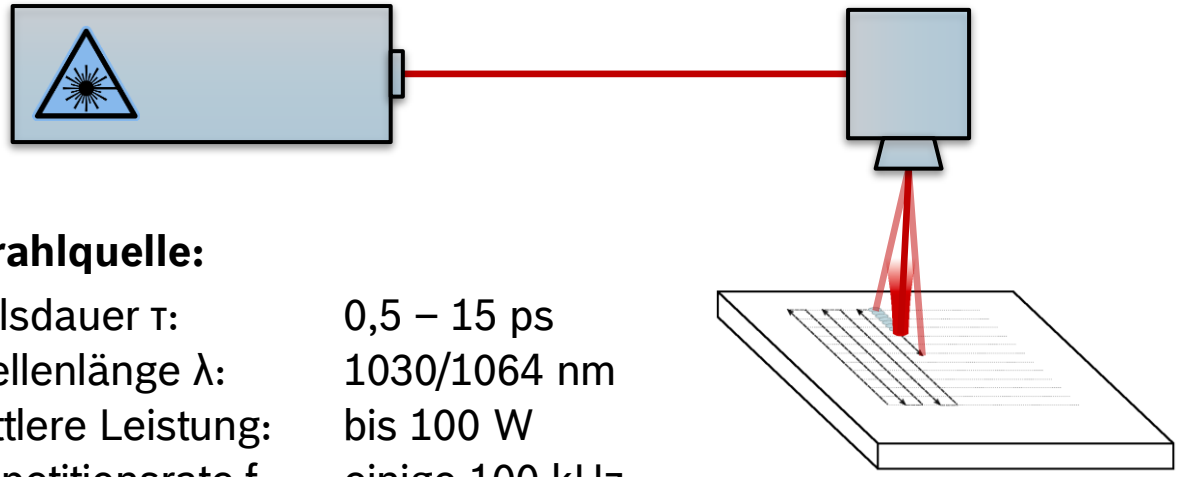
Optimierung von Laserprozessen mit Maschinellem Lernen
Equipment



Strahlquelle:

Pulsdauer τ:	0,5 – 15 ps
Wellenlänge λ:	1030/1064 nm
mittlere Leistung:	bis 100 W
Repetitionsrate f_{rep}:	einige 100 kHz

Galvanometerscanner:

Vorschubgeschwindigkeit bis ca. 15 m/s
fokussiert auf Spots mit einigen 10 µm ∅
ca. 75% Pulsüberlapp

Probe:

Testgeometrie:	1 mm x 1 mm x ~50 µm
Material:	1.4301 Edelstahl

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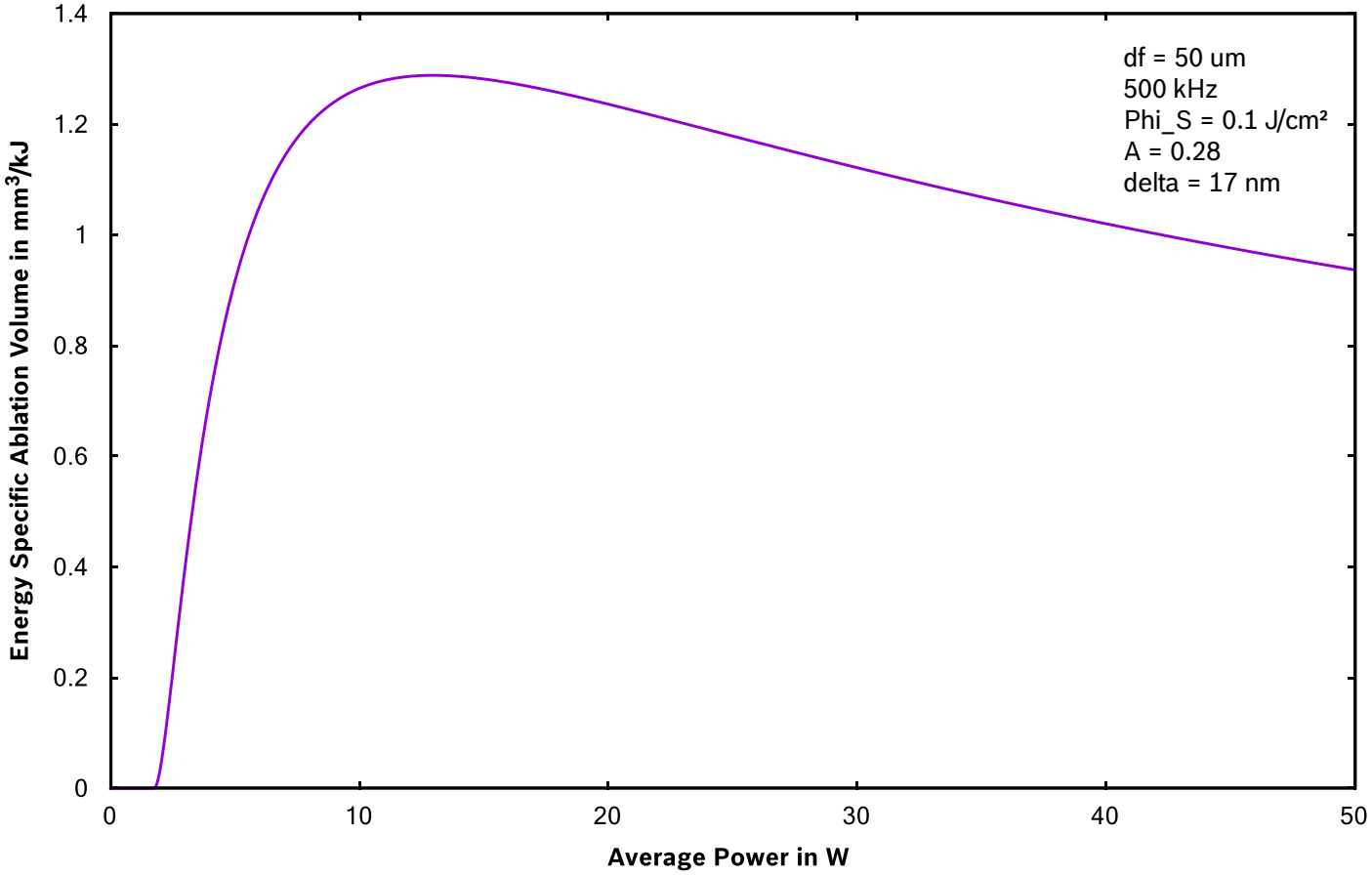
Energiespezifisches Abtragsvolumen: Neuenschwander Kurve



Verwendete Materialeigenschaften nur exemplarisch gewählt, nicht gültig für Stahl.

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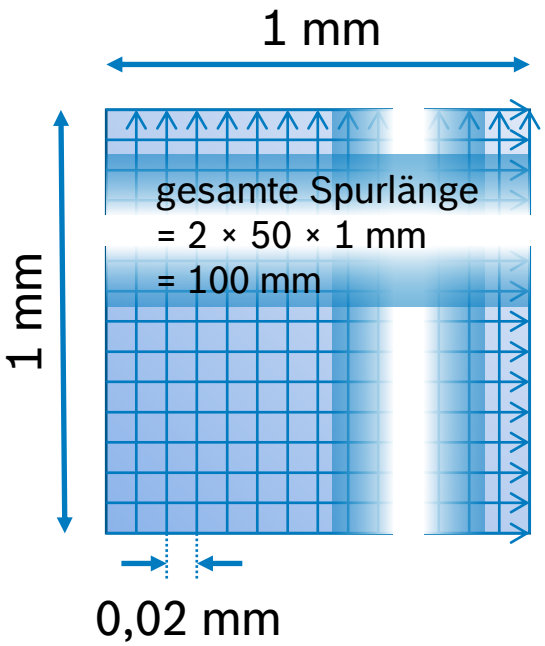
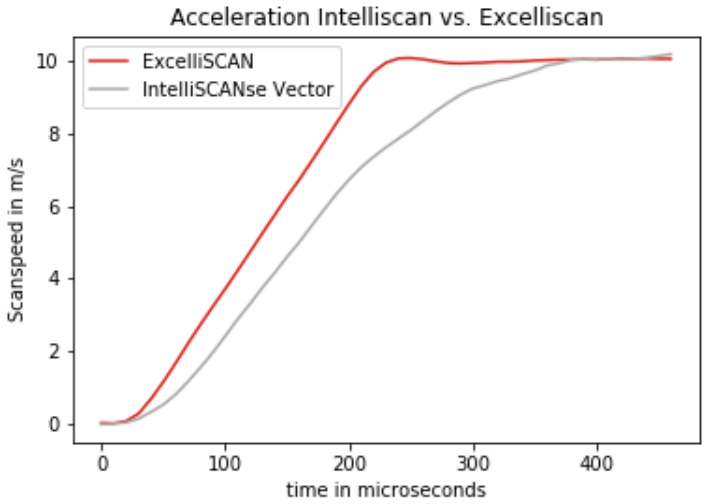
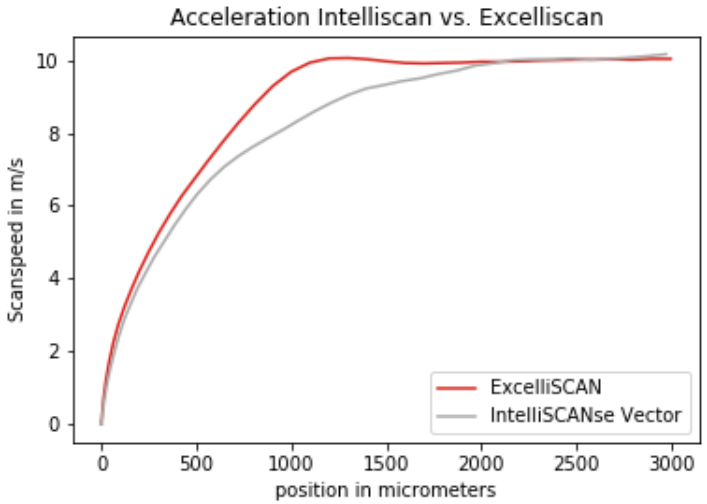
Prozessdauer begrenzt durch Scannerdynamik

gefülltes Quadrat







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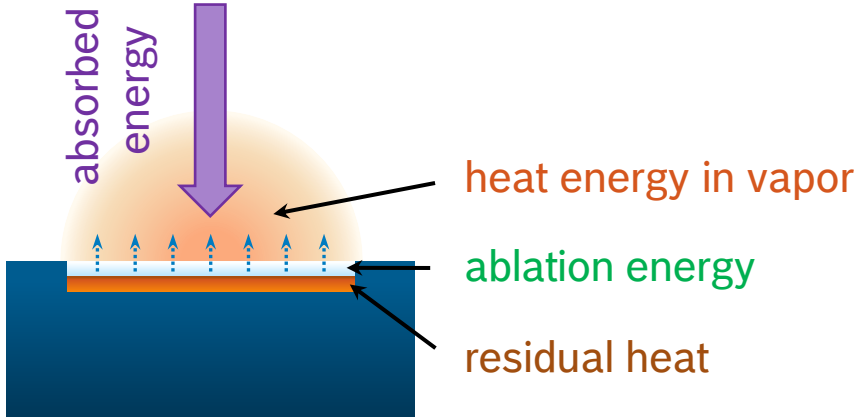
Nutzbare Leistung begrenzt durch Wärmeakkumulation

Heating of single pulse



Laser: 800 kHz Scanning speed **5 m/s**

100 µm

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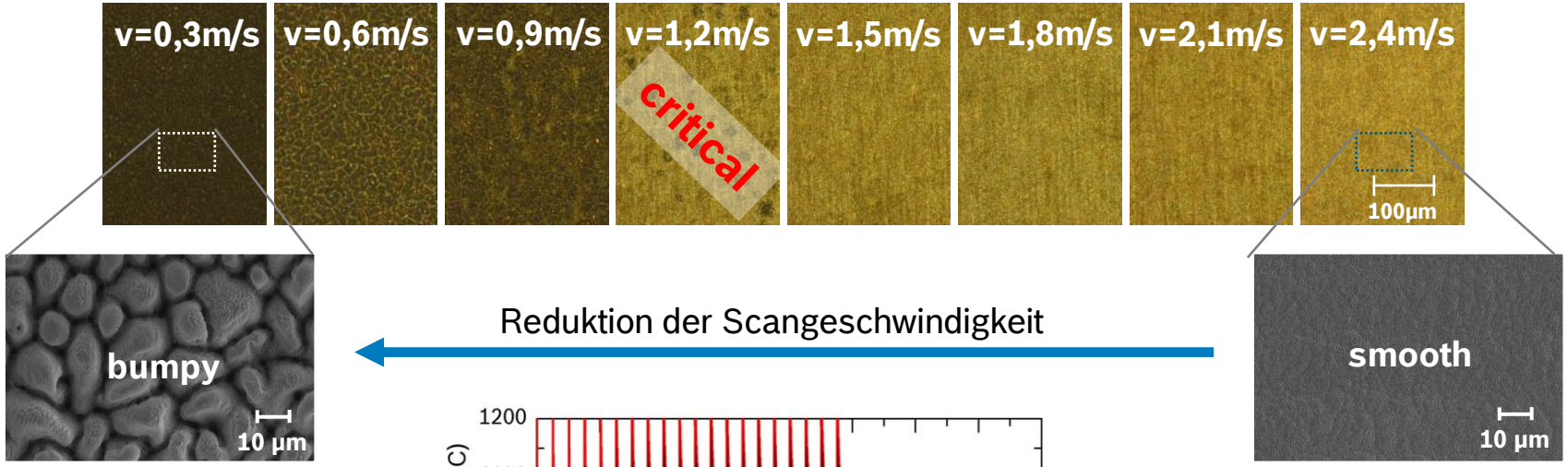
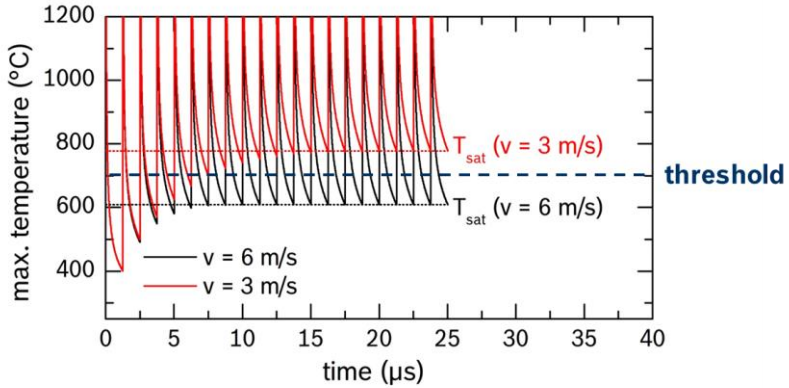
Einfluss des Vorschub auf die Qualität



Reduktion der Scangeschwindigkeit



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Einflüsse der Parametervariationen

Leistung ↑	Pulsenergie ↑	Prozessdauer ↓	☺
	Wärmeakkumulation ↑	notw. Vorschub ↑	☹
Repetitionsrate ↑	Pulsenergie ↓	Volumen / Energie ↑	☺
	Wärmeakkumulation ↑	notw. Vorschub ↑	☹
Vorschub ↑	Wärmeakkumulation ↓	Rauheit ↓	☺
	Sprungzeiten ↑	Prozessdauer ↑	☹

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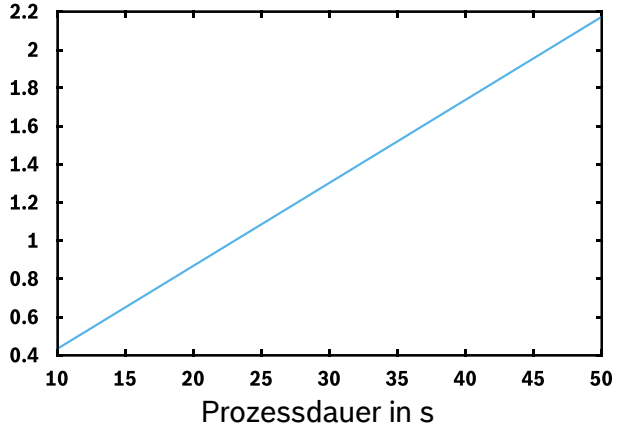
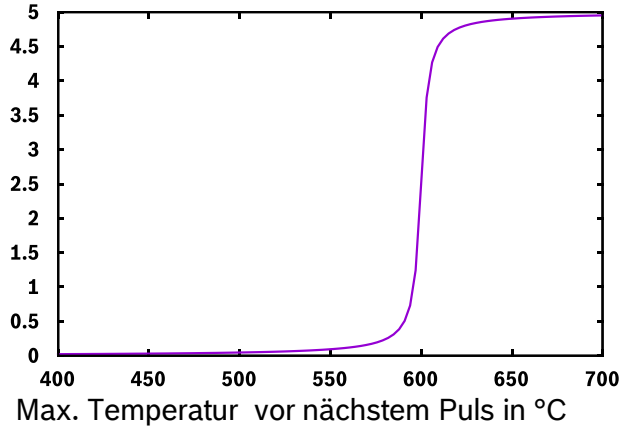
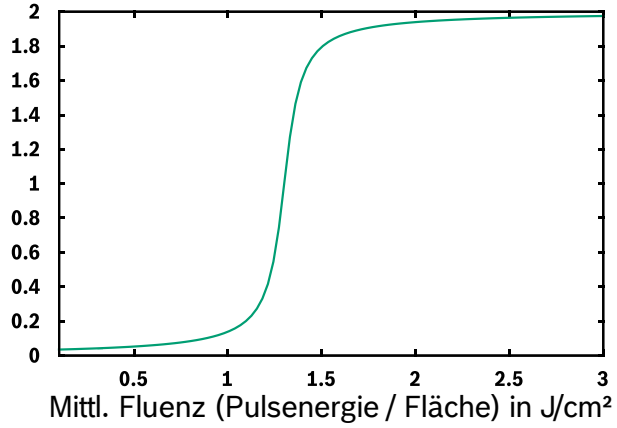
Optimierung von Laserprozessen mit Maschinellem Lernen

Definition einer Kostenfunktion für das Modell

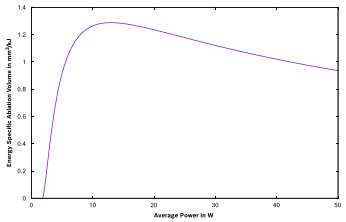






$$c_1 \cdot \text{Prozessdauer} \quad + \quad c_2 \cdot (0.5+\text{atan}(\,(x-600)/3.0\,)/\pi) \; + \quad c_3 \cdot (0.5+\text{atan}(\,15*(x-1.3))/\,\pi)$$

Minimiere die Kostenfuntion in der Domäne der zulässigen Werte von Laserleistung, Repetationsrate und Scannervorschub.



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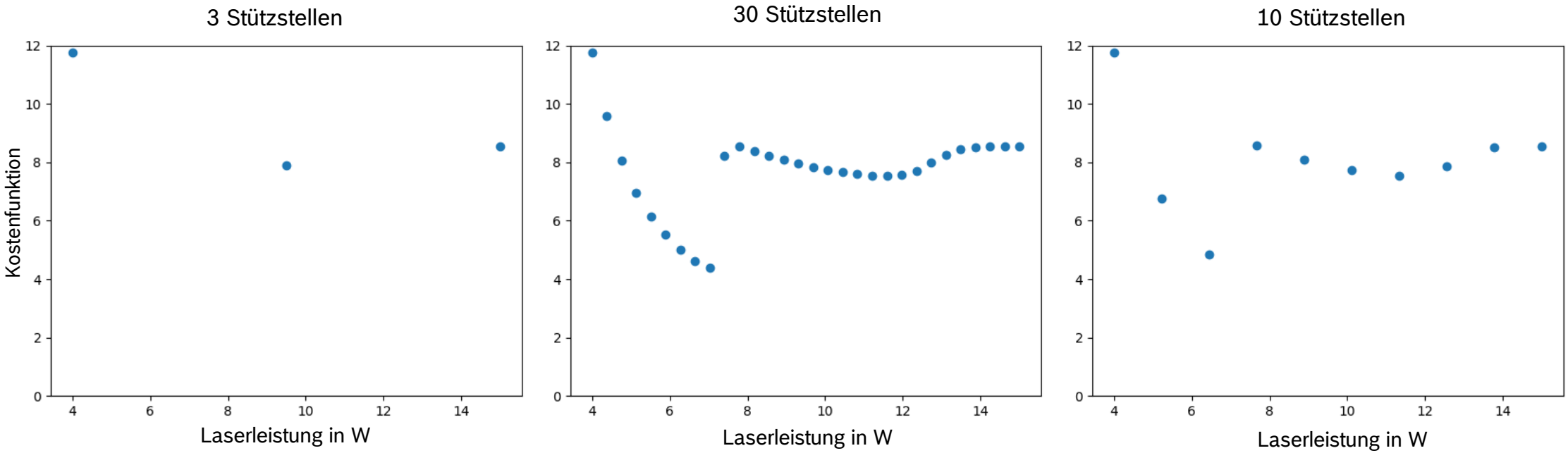
Optimierung von Laserprozessen mit Maschinellem Lernen

Auswertung der Kostenfunktion für das Modell



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Optimierung von Laserprozessen mit Maschinellem Lernen
“Fluch der Dimensionalität”

Dims	# Versuche	# Versuche	# Versuche
1	5	10	30
2	25	100	900
3	125	1 000	27 000
4	625	10 000	810 000
5	3 125	100 000	24 300 000

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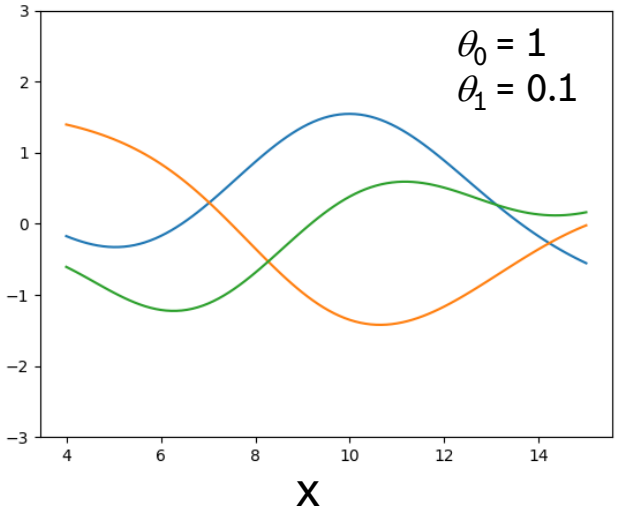
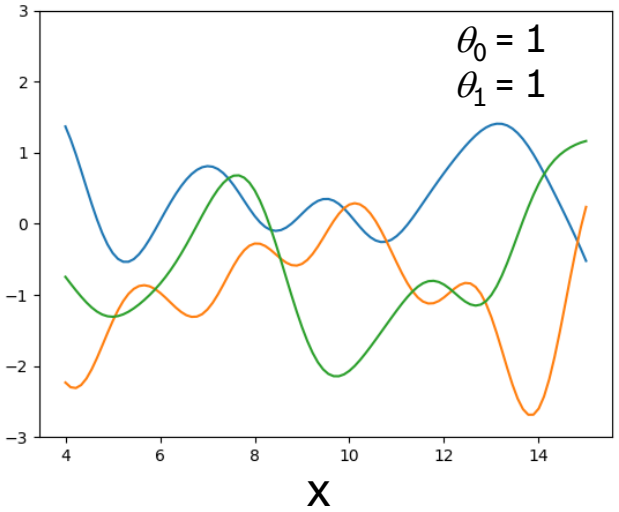
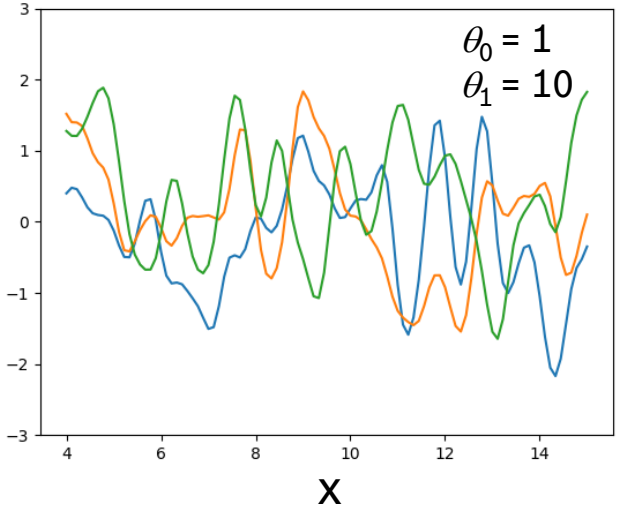
Optimierung von Laserprozessen mit Maschinellem Lernen

Zufällig gezogene Funktionen (Gaussprozesse)







Kovarianzmatrix: radial basis function (RBF)

$$k(\mathbf{x_n}, \mathbf{x_m}) = \theta_0 \exp\left(-\frac{\theta_1}{2}|\mathbf{x_n} - \mathbf{x_m}|^2\right)$$

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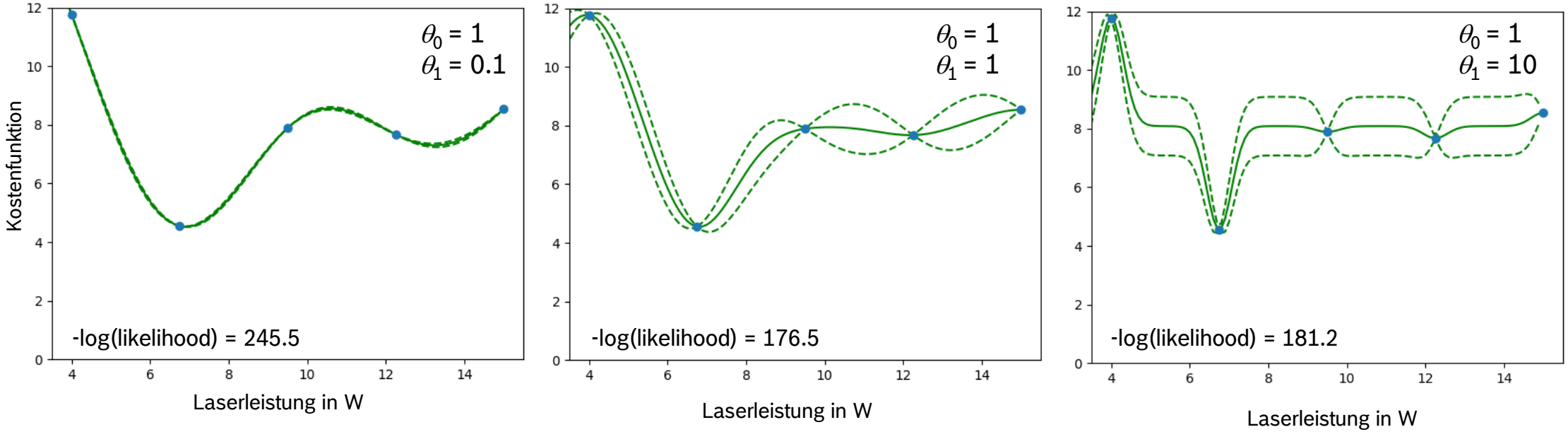
Optimierung von Laserprozessen mit Maschinellem Lernen
Einfluss der Modellparameter



Repetitionsrate 500 kHz
Scanvorschub 2 m/s

$$k(\mathbf{x_n}, \mathbf{x_m}) = \theta_0 \exp\left(-\frac{\theta_1}{2}|\mathbf{x_n} - \mathbf{x_m}|^2\right)$$

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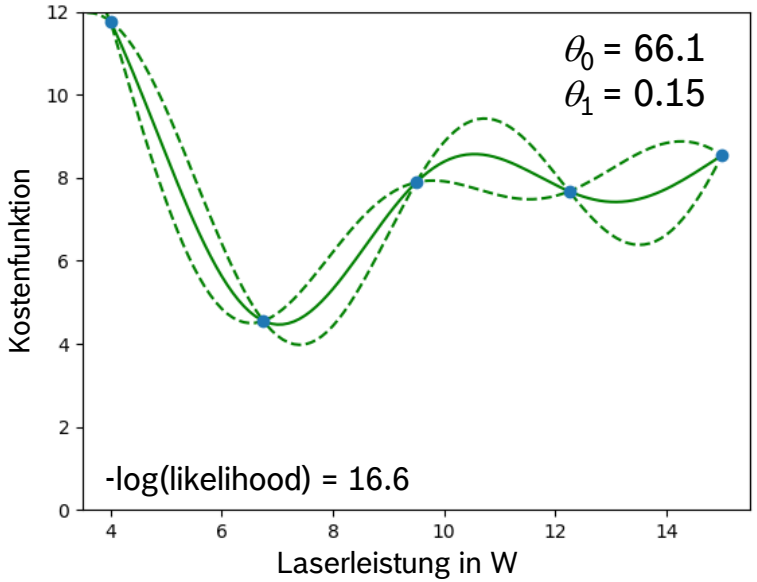
Optimierung von Laserprozessen mit Maschinellem Lernen
Optimierung der Modellparameter



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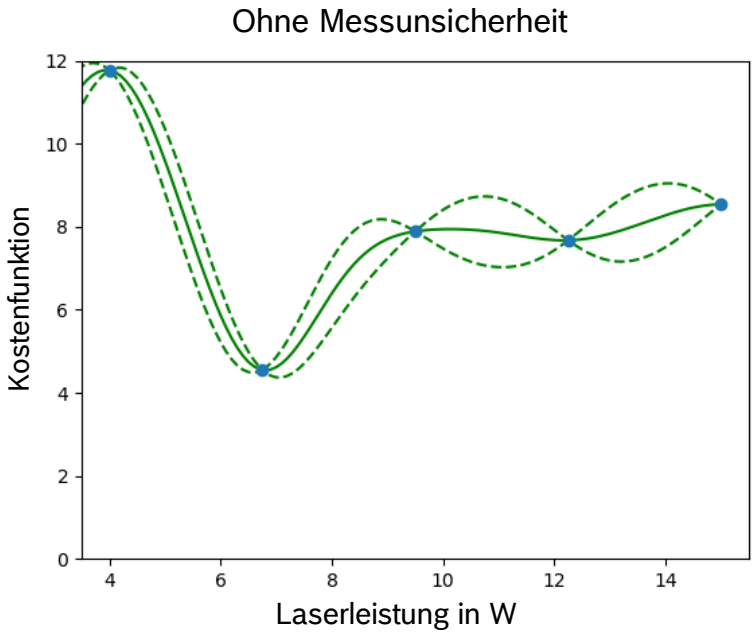
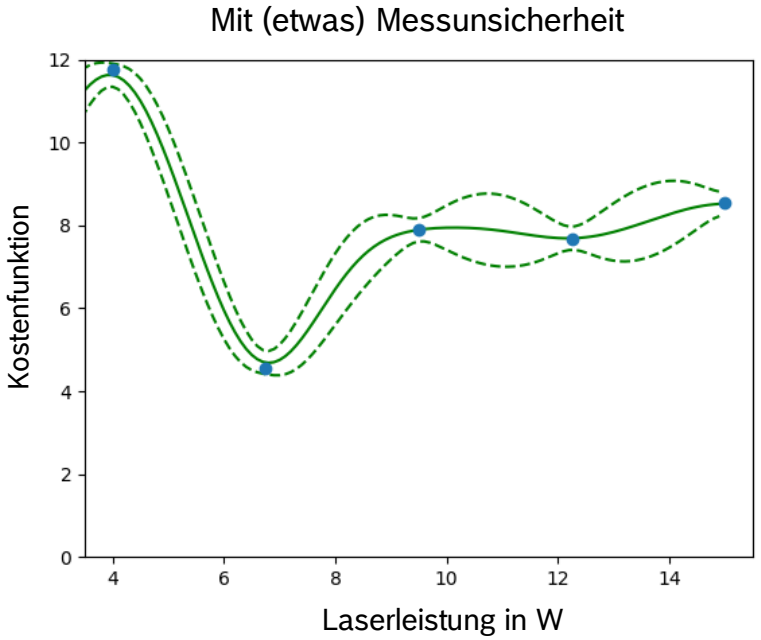
Optimierung von Laserprozessen mit Maschinellem Lernen
Gaussprozesse mit Berücksichtigung von Messunsicherheit





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Optimierung von Laserprozessen mit Maschinellem Lernen

Bayes' Theorem

Summenregel $$p(X) = \sum_Y p(X,Y)$$

Produktregel $$p(X,Y) = p(Y|X)p(X)$$

Aus der Produktregel folgt

$$p(X,Y) = p(Y|X)p(X)$$
$$p(Y,X) = p(X|Y)p(Y)$$

Die Argumente vertauschen ändert den Wert nicht

$$p(X,Y) = p(Y,X)$$

Bayes' Theorem

$$p(Y|X) = \frac{p(X|Y)p(Y)}{p(X)}$$

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Optimierung von Laserprozessen mit Maschinellem Lernen

Was ist die “Likelihood”?

“Likelihood” “Prior-Distribution”

“Posterior-Distribution”

$$p(\theta|\mathcal{D}) = \frac{p(\mathcal{D}|\theta)\,p(\theta)}{p(\mathcal{D})}$$

“Normierung”

$\mathcal{D}$: Daten

θ : Modellparameter

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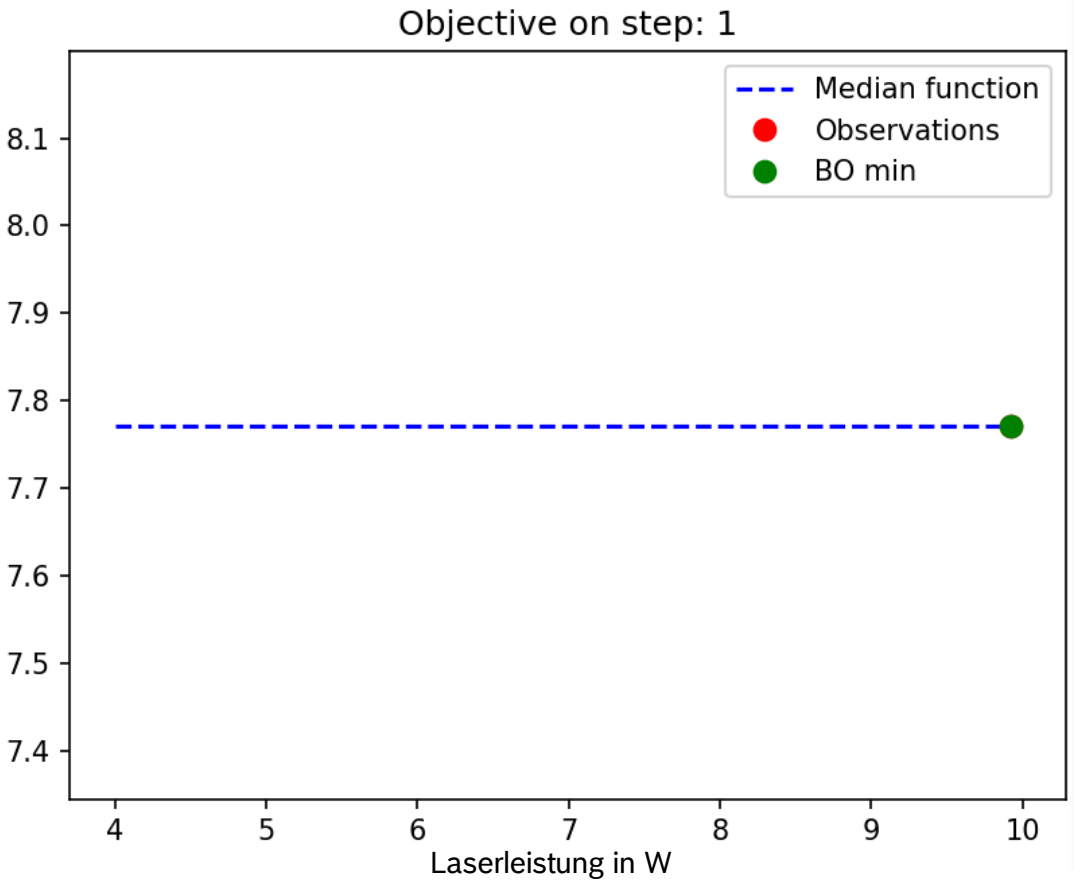
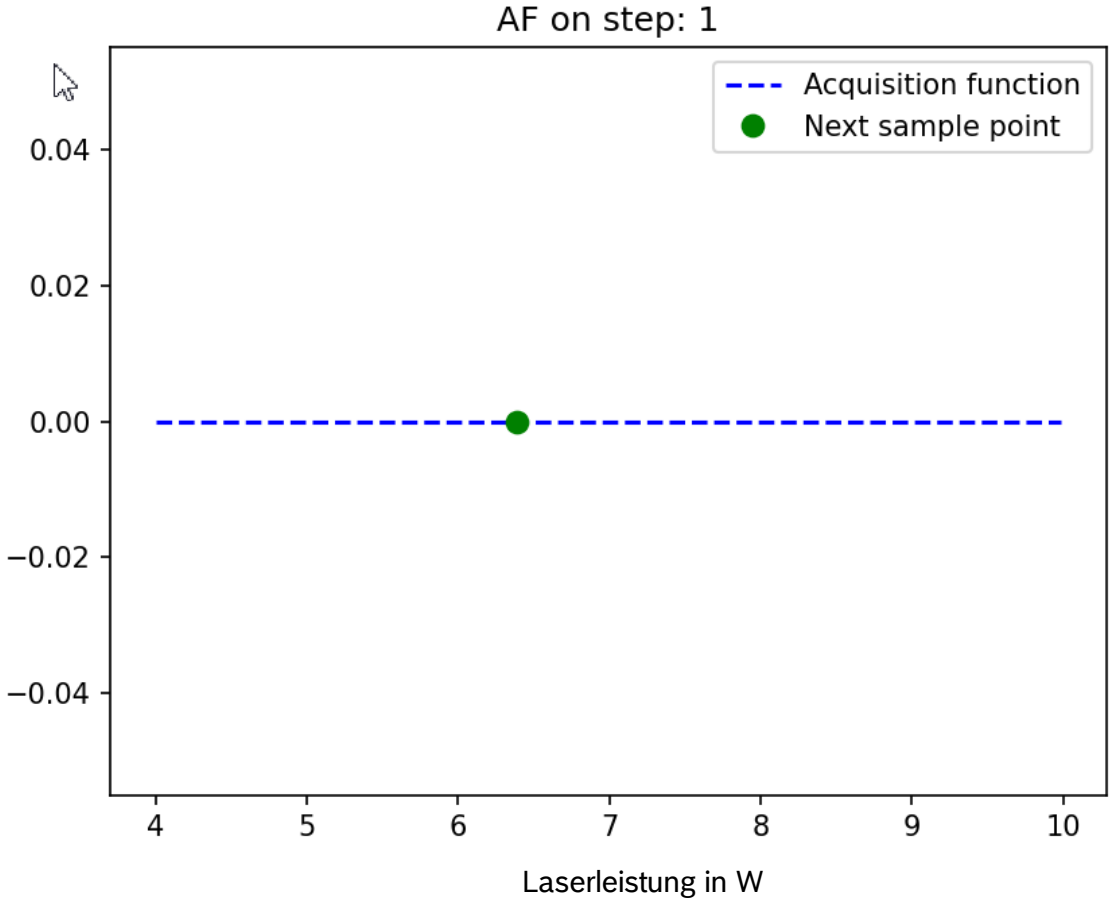
Optimierung von Laserprozessen mit Maschinellem Lernen

Bayesianische Optimierung





Repetitionsrate 500 kHz
Scanvorschub 2 m/s

AF: Expected Improvement

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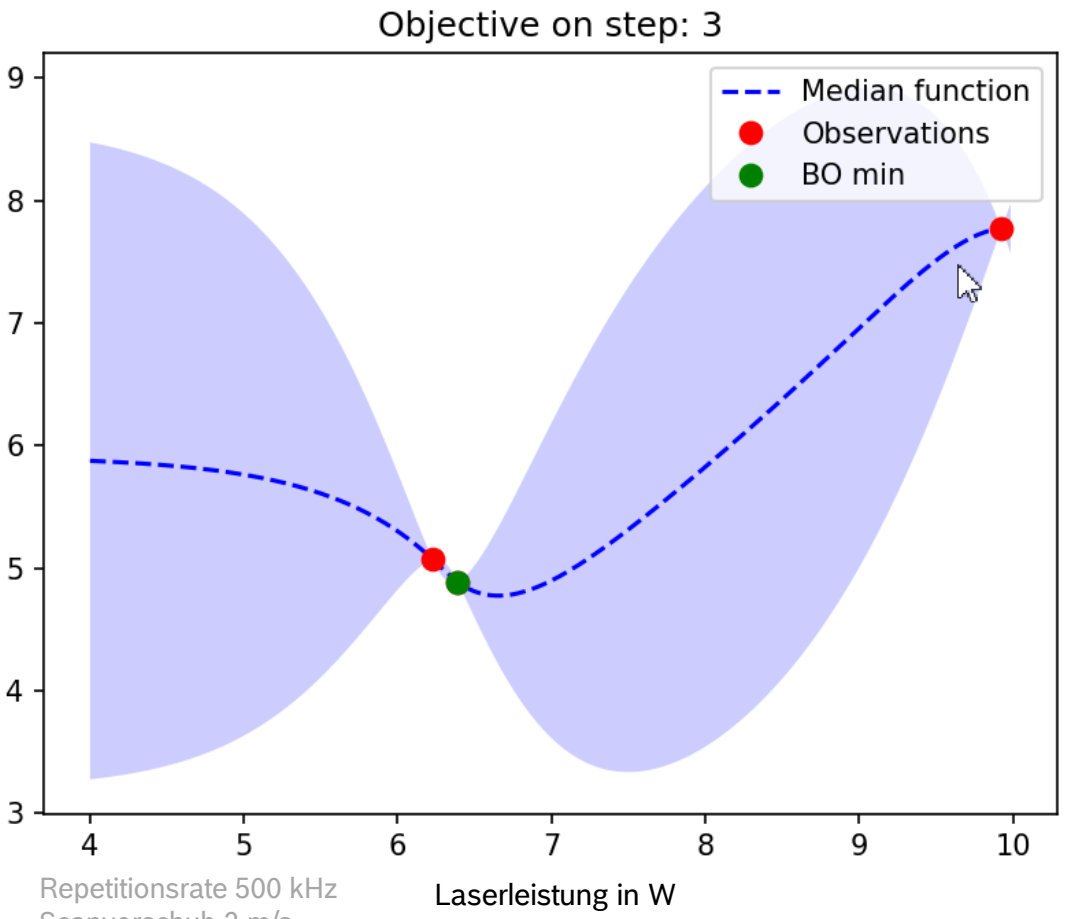
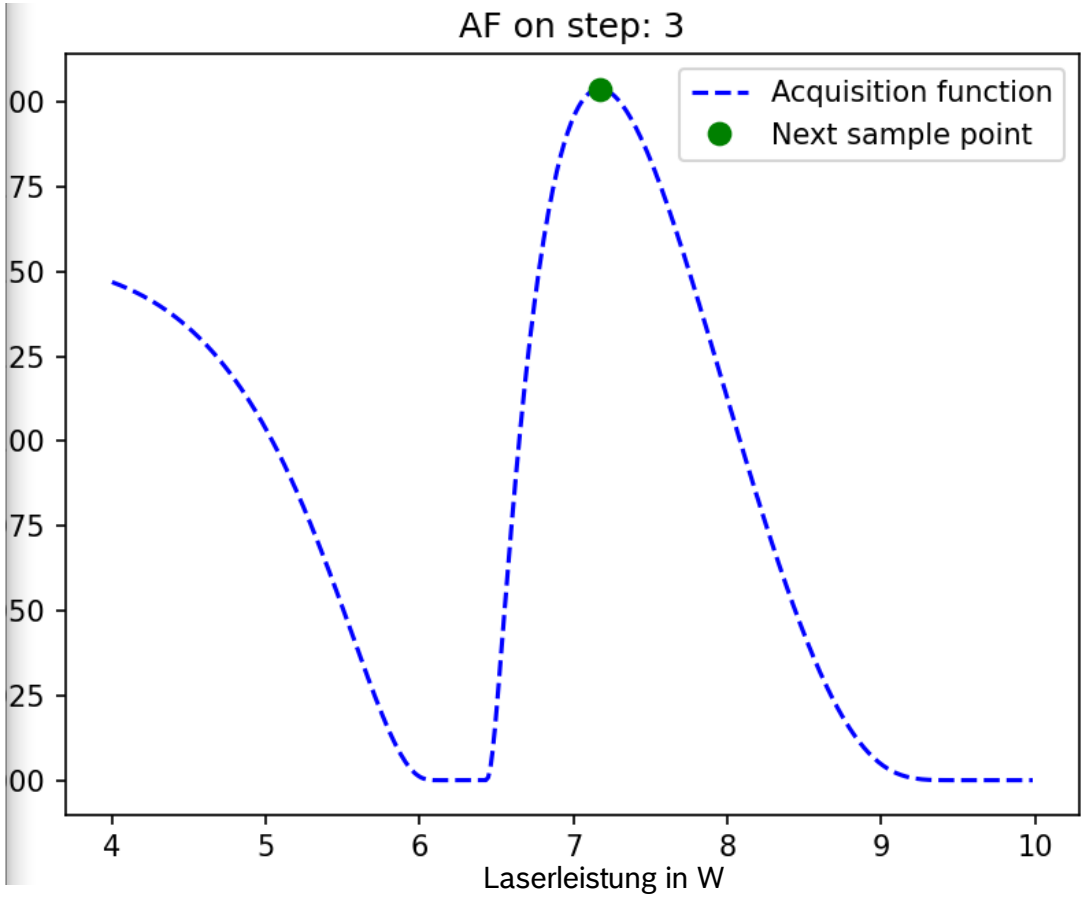
Bayesianische Optimierung





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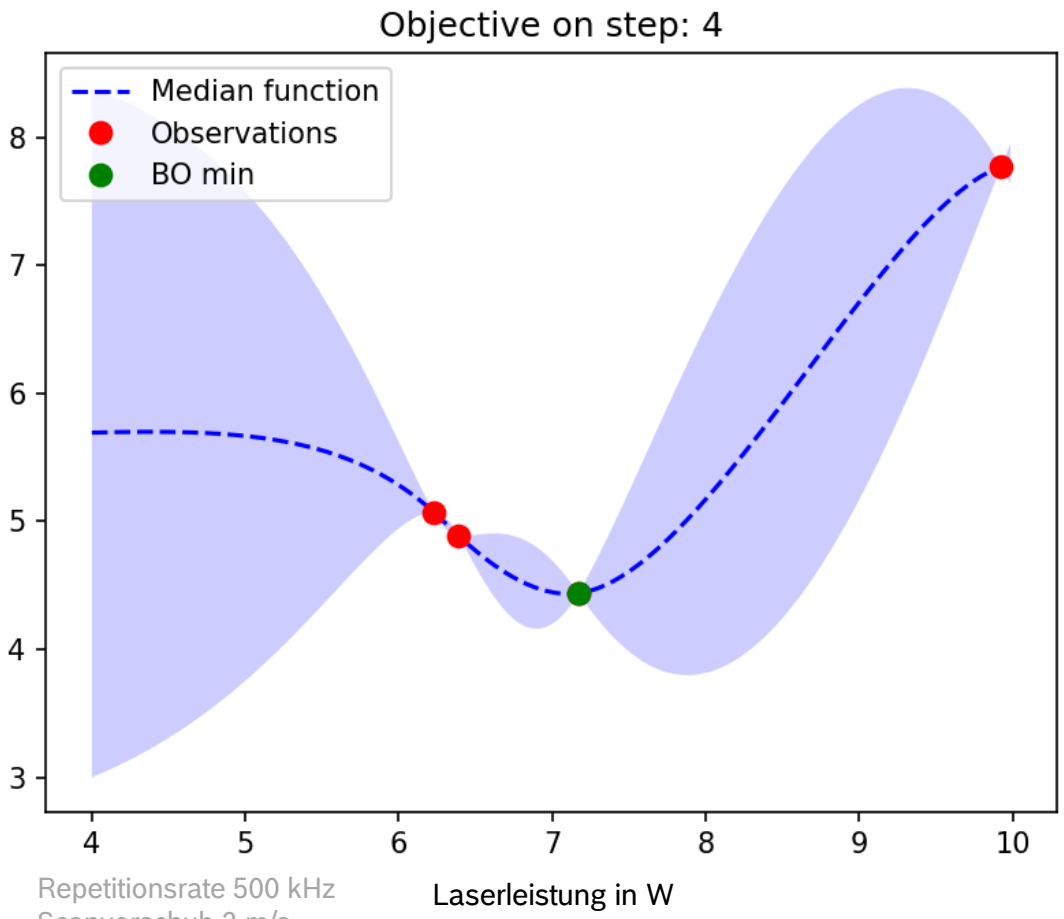

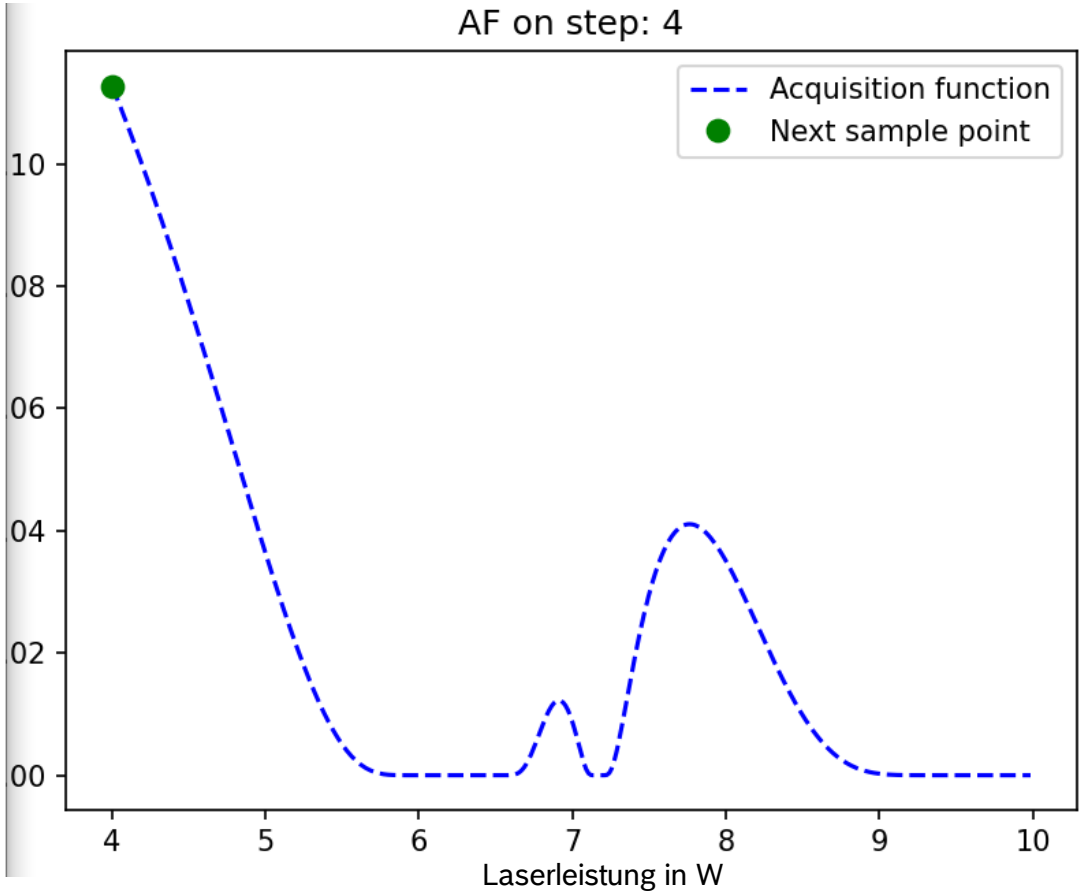

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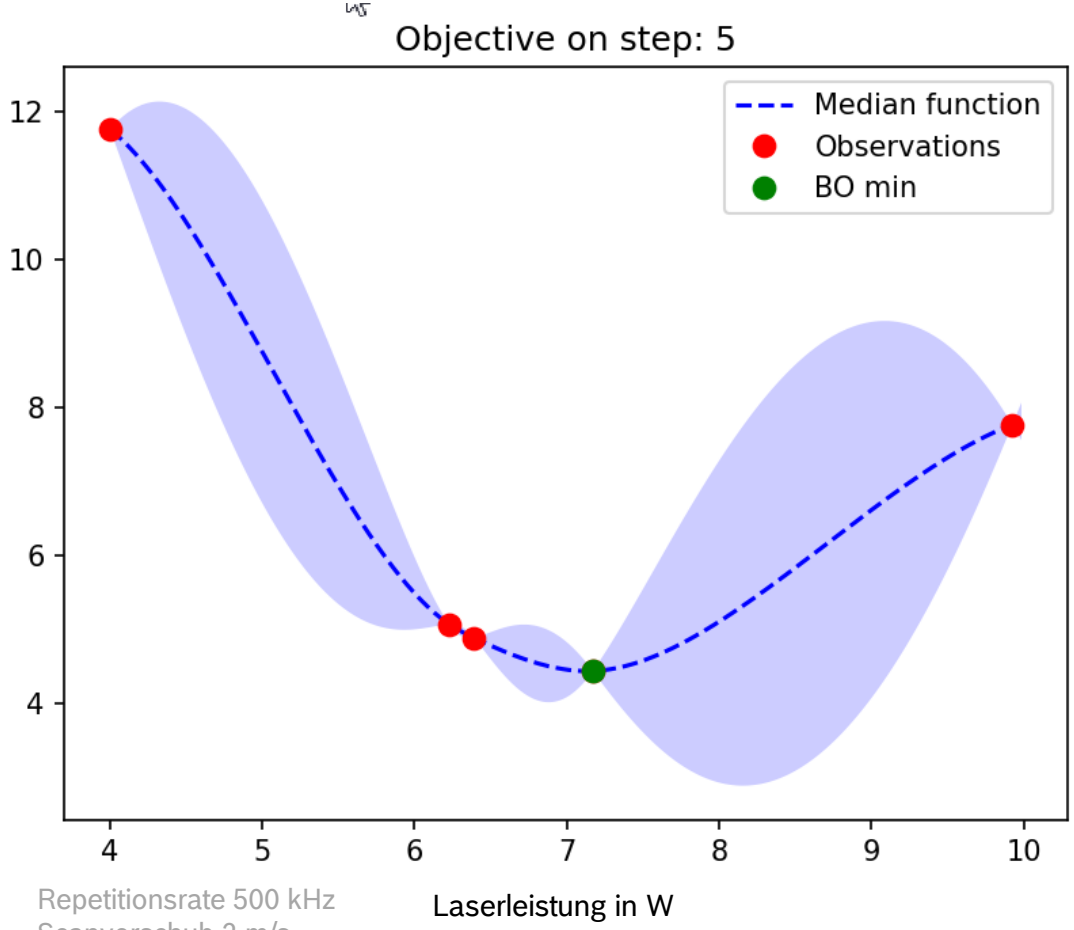

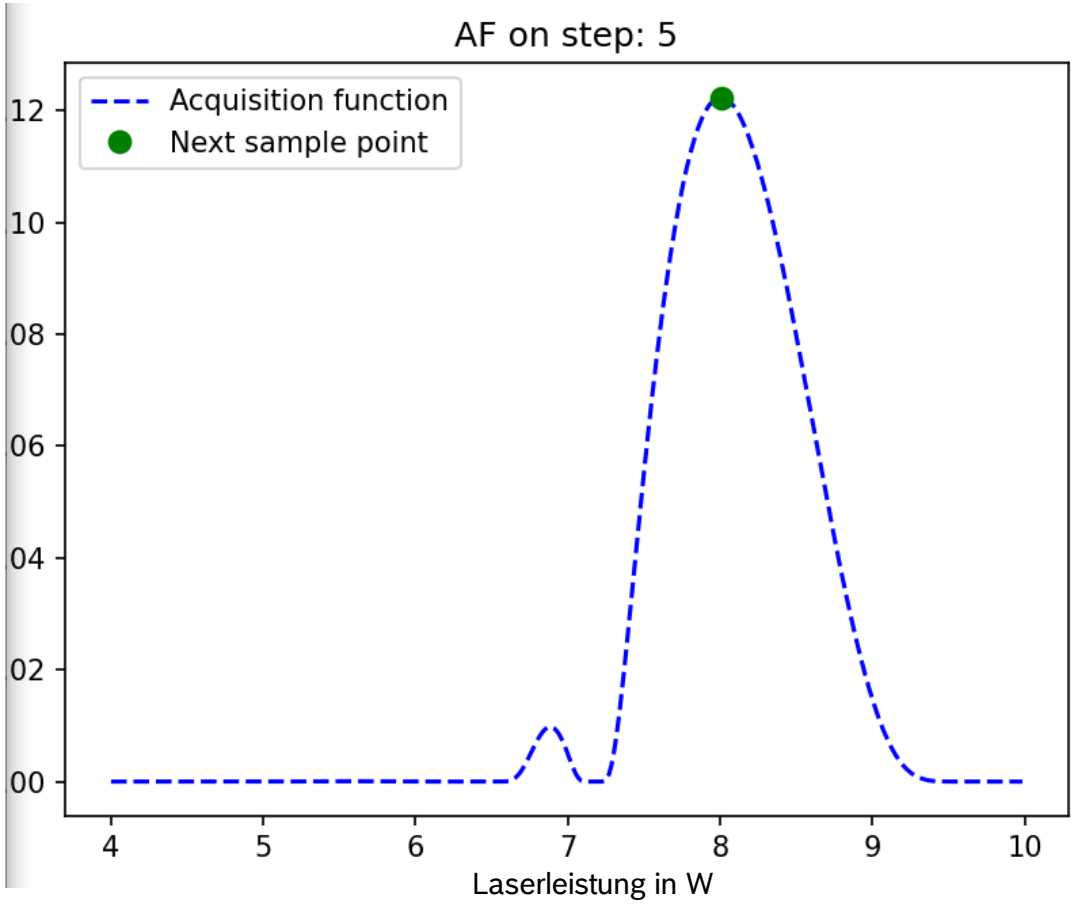

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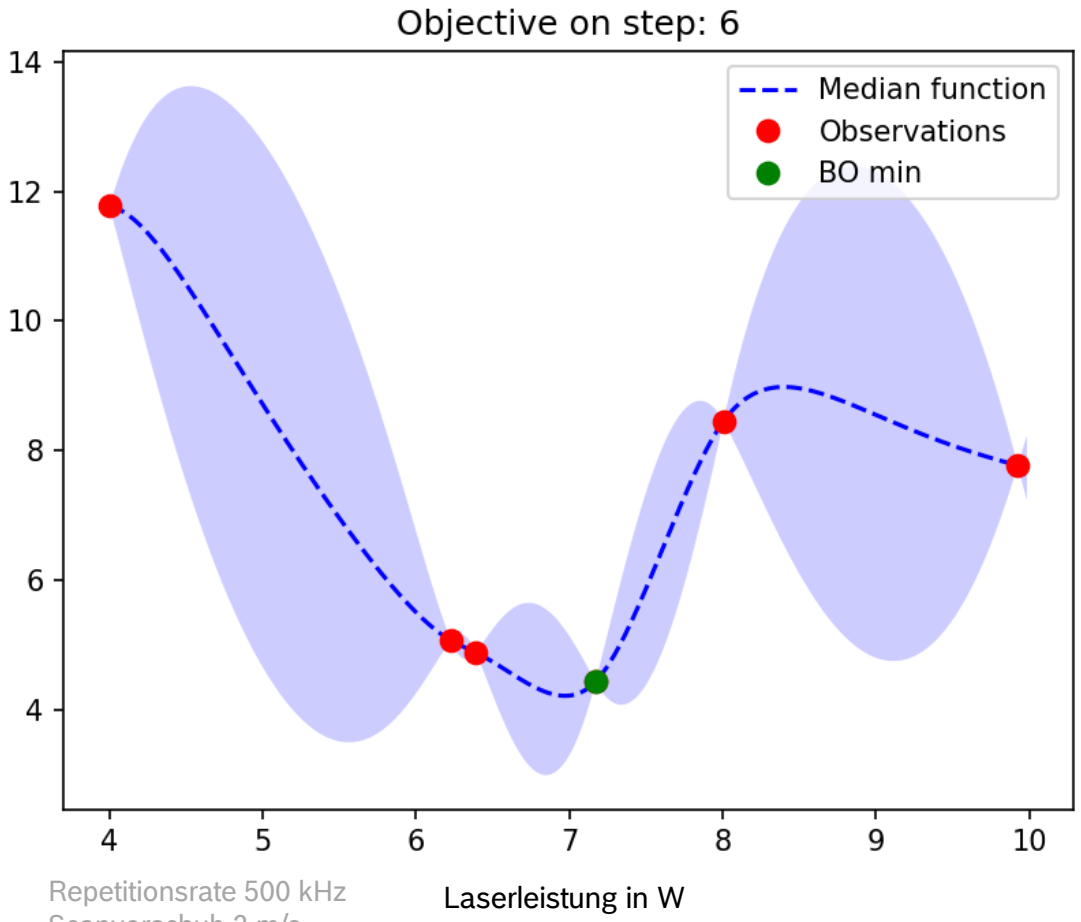

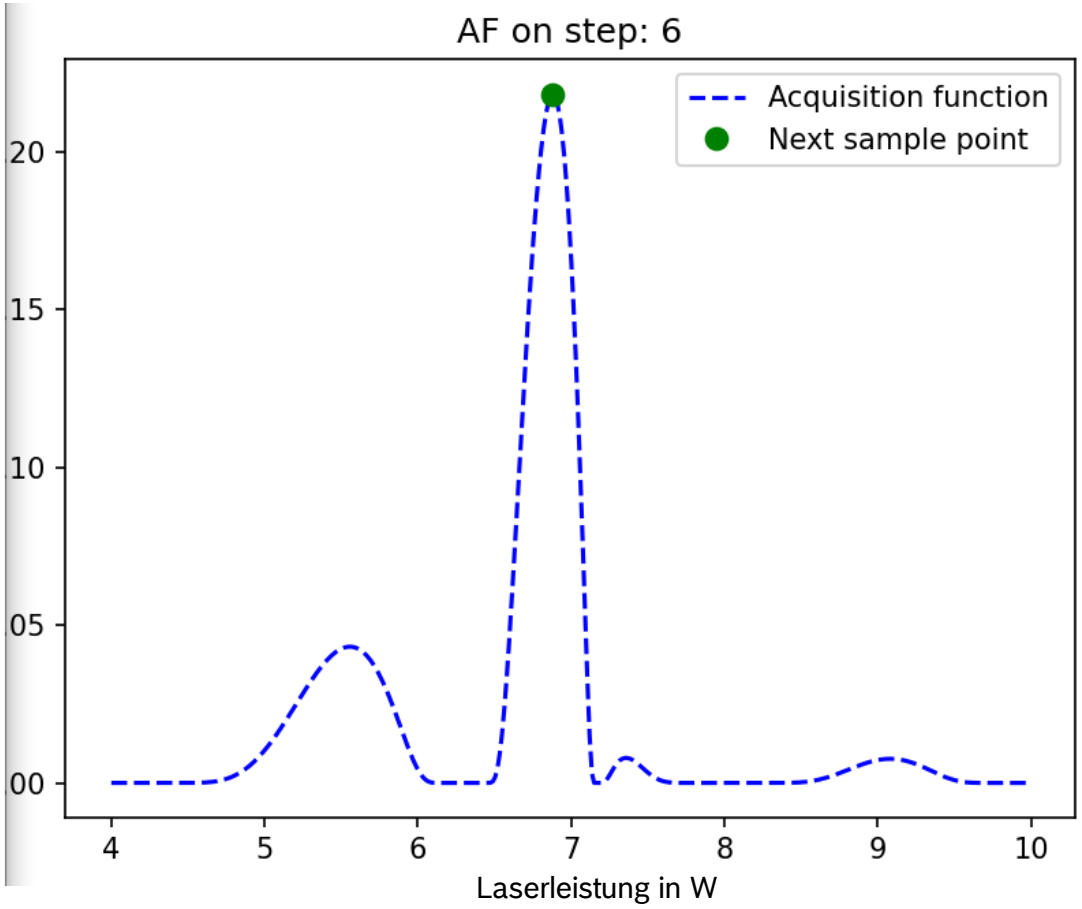

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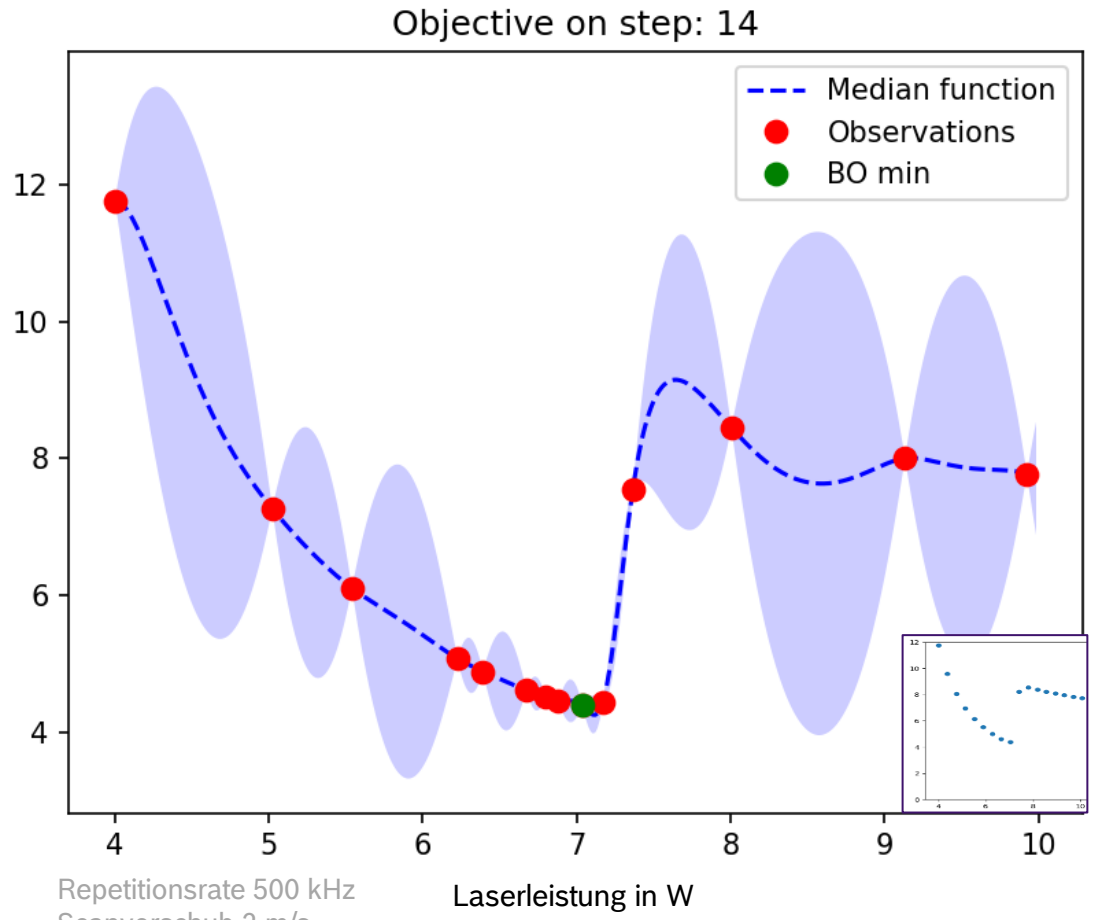

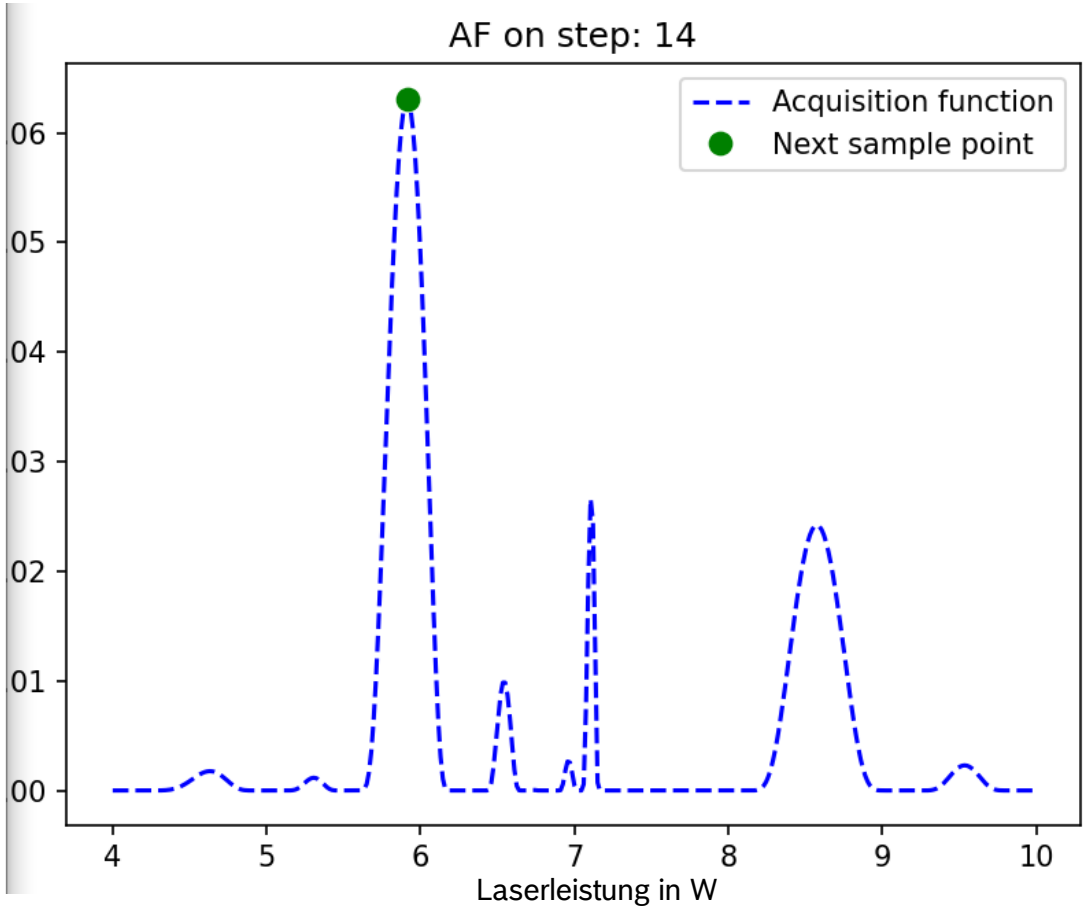

Repetitionsrate 500 kHz
Scanvorschub 2 m/s

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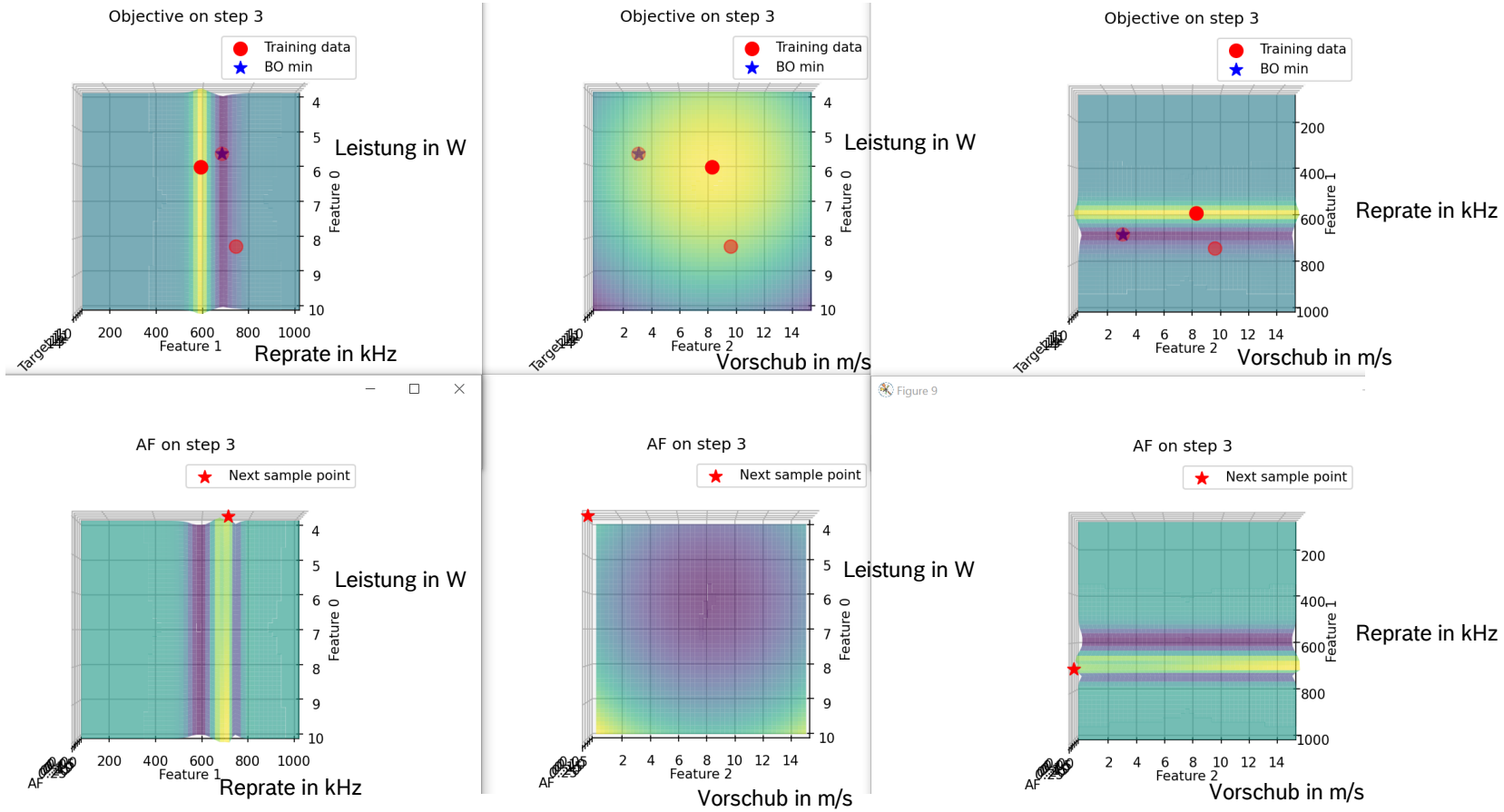
Optimierung von Laserprozessen mit Maschinellem Lernen

Bayesianische Optimierung, 3 Parameter



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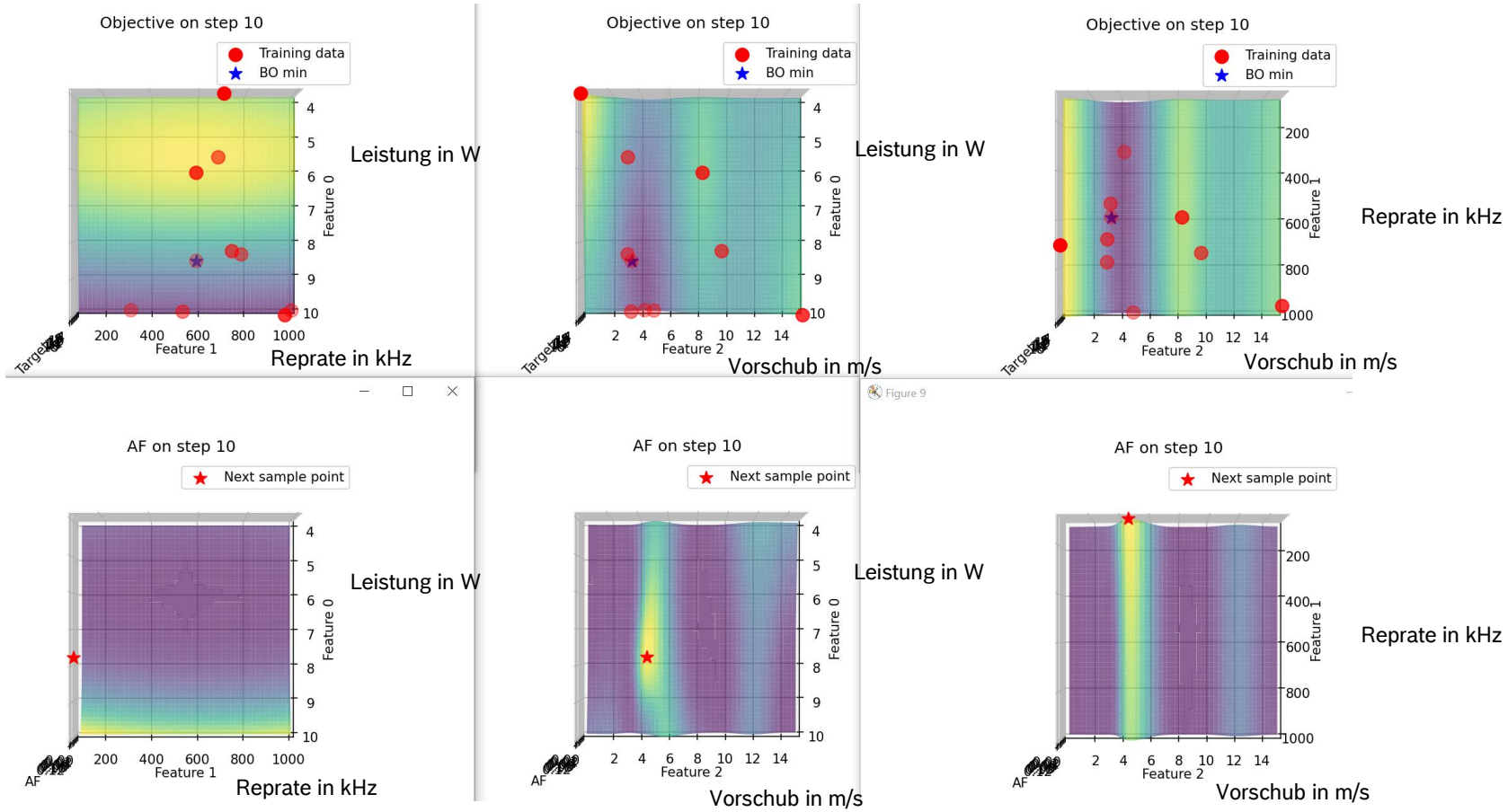
Bayesianische Optimierung, 3 Parameter



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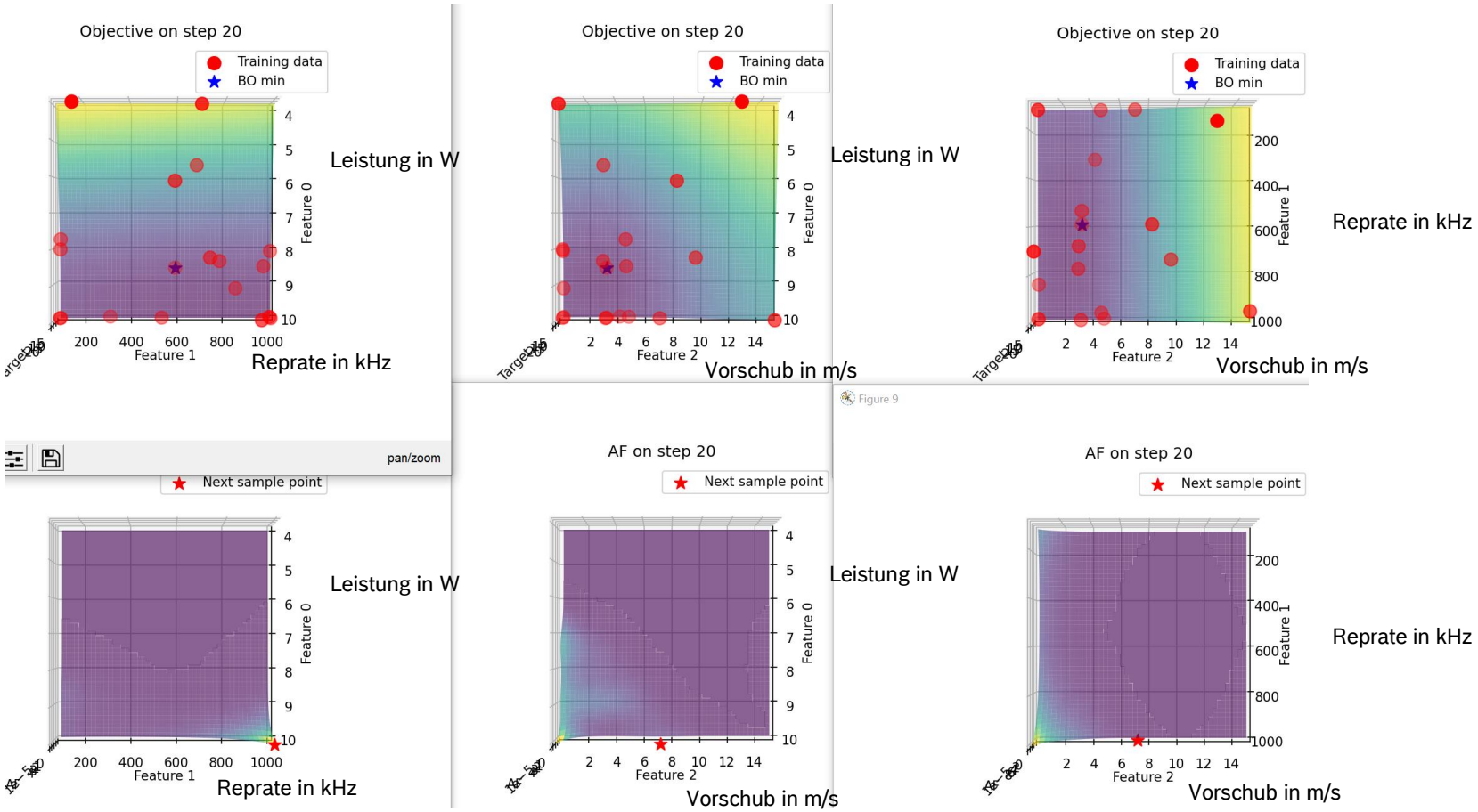
Optimierung von Laserprozessen mit Maschinellem Lernen

Bayesianische Optimierung, 3 Parameter



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BOSCH

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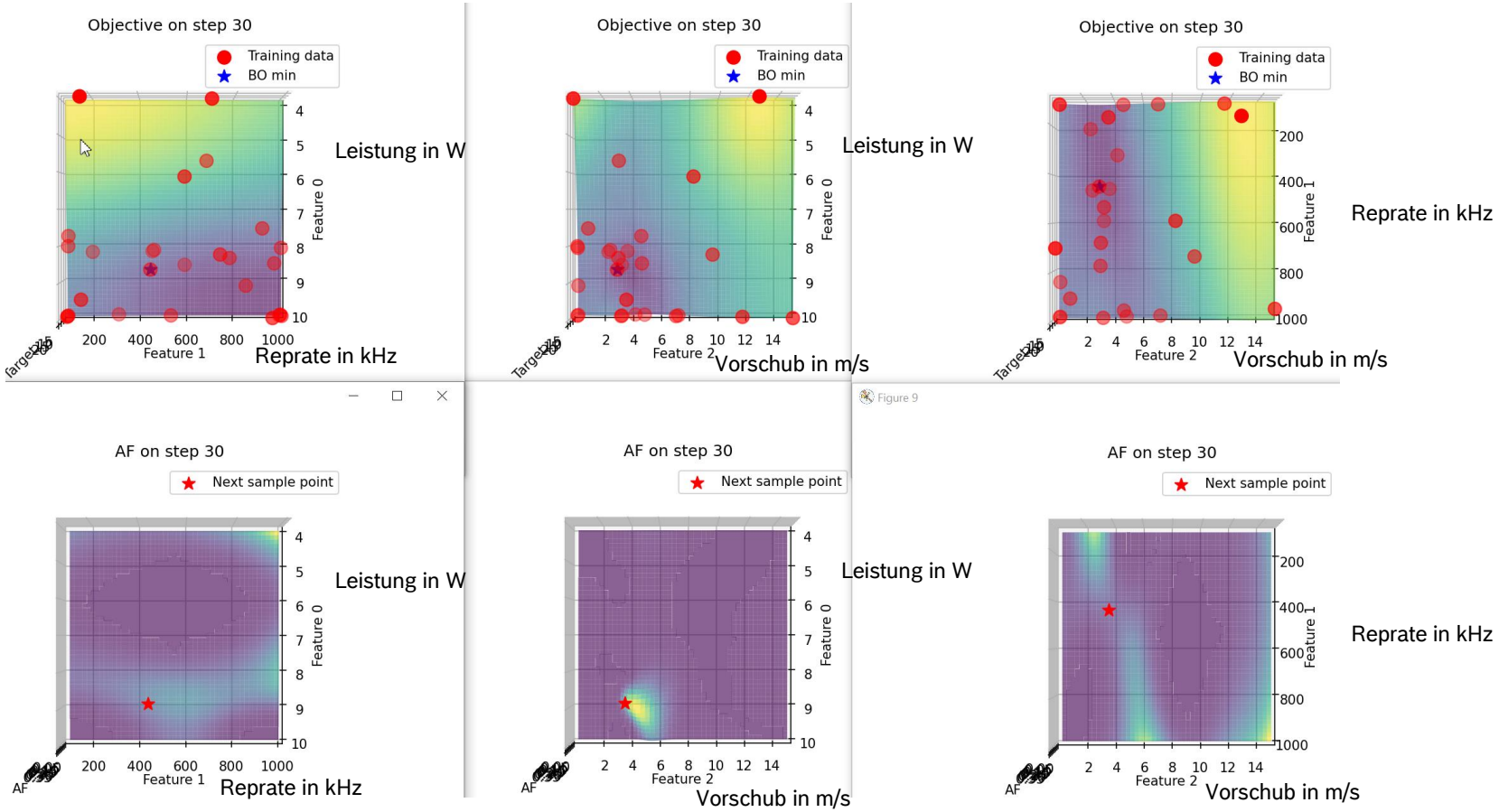
Bayesianische Optimierung, 3 Parameter



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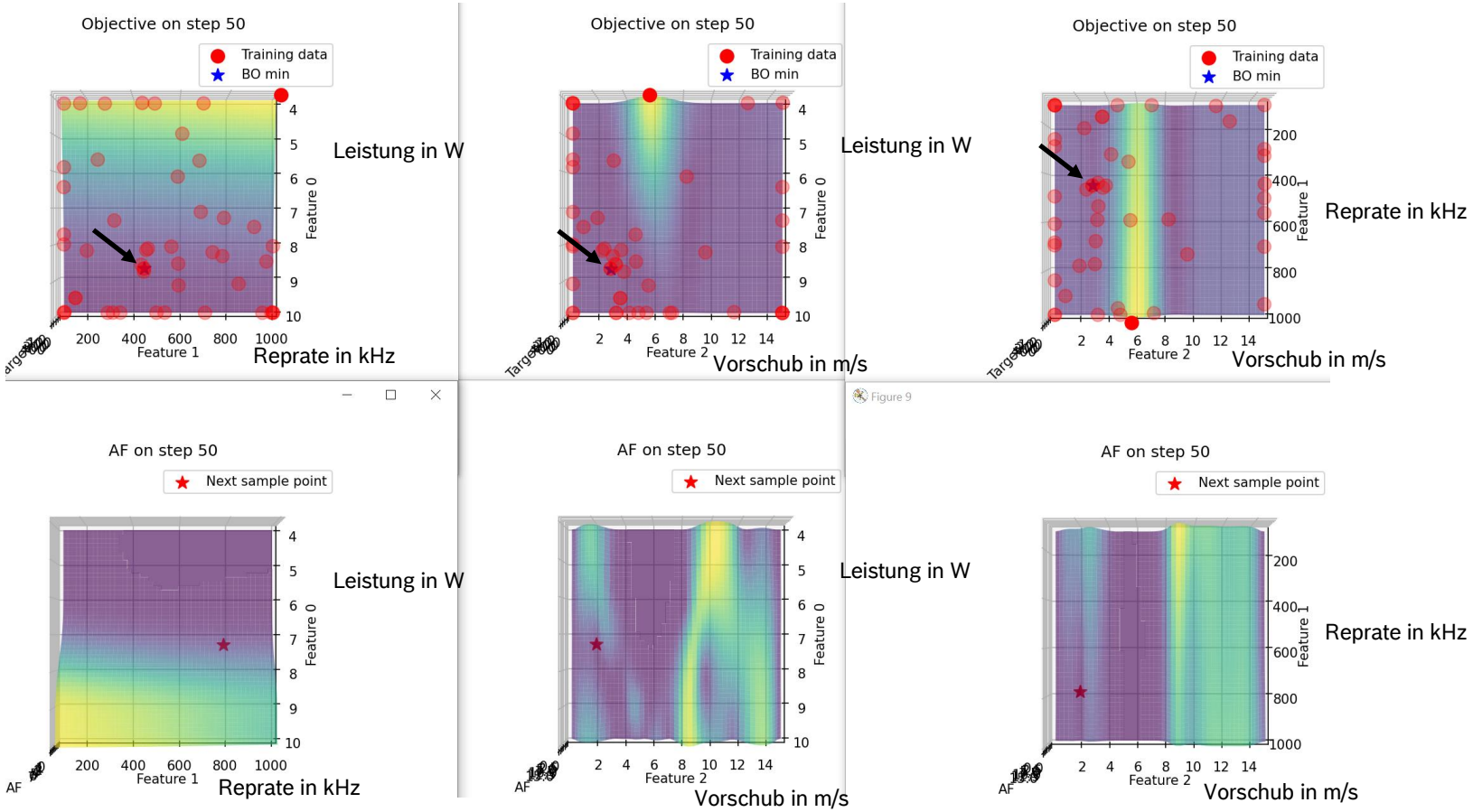
Bayesianische Optimierung, 3 Parameter



Optimierungergebnis*) nach 50 Iterationen

Parameter	Wert
Leistung	8.7 W
Reprate	440 kHz
Vorschub	2.8 m/s

*) Verwendete Materialeigenschaften nur exemplarisch gewählt, nicht gültig für Stahl.

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Anhand von Daten lernt die Maschine ein Modell der zu optimierenden Funktion.

Dieses Modell wird genutzt um zu entscheiden wo die nächsten Daten aufgezeichnet werden sollten.

(Bayesianische Optimierung, Active Learning)

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