Project “FairMillData2”

Analysis of Fair Milling Dataset

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Agenda

- Introduction
- Results of Data Analysis
  - End Milling
  - Plunge Milling
  - Slot Milling
  - Face Milling
- Summary & Outlook

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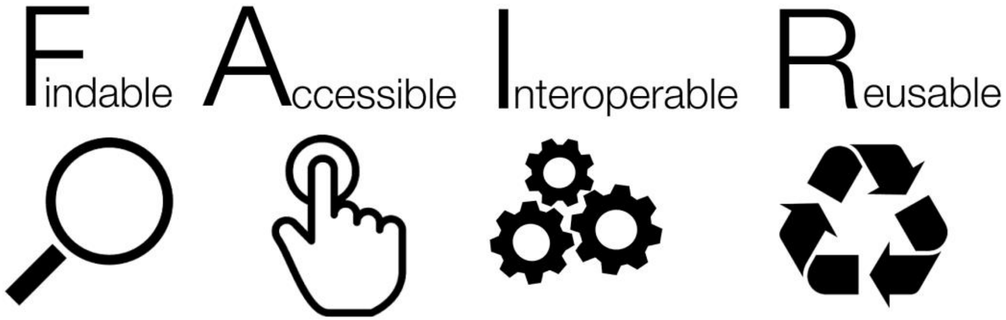
Analysis of FAIR Milling Dataset

- In February 2023, a milling dataset according to the FAIR-principles was recorded @smartfactory.
- Dataset made available: https://zenodo.org/records/7753181 (188 views till now)
- This presentation summarizes the results of data analysis.

Project “FairMillData2”

FAIR Principles



- FAIR principles aim at maximizing effective (re)use of acquired datasets

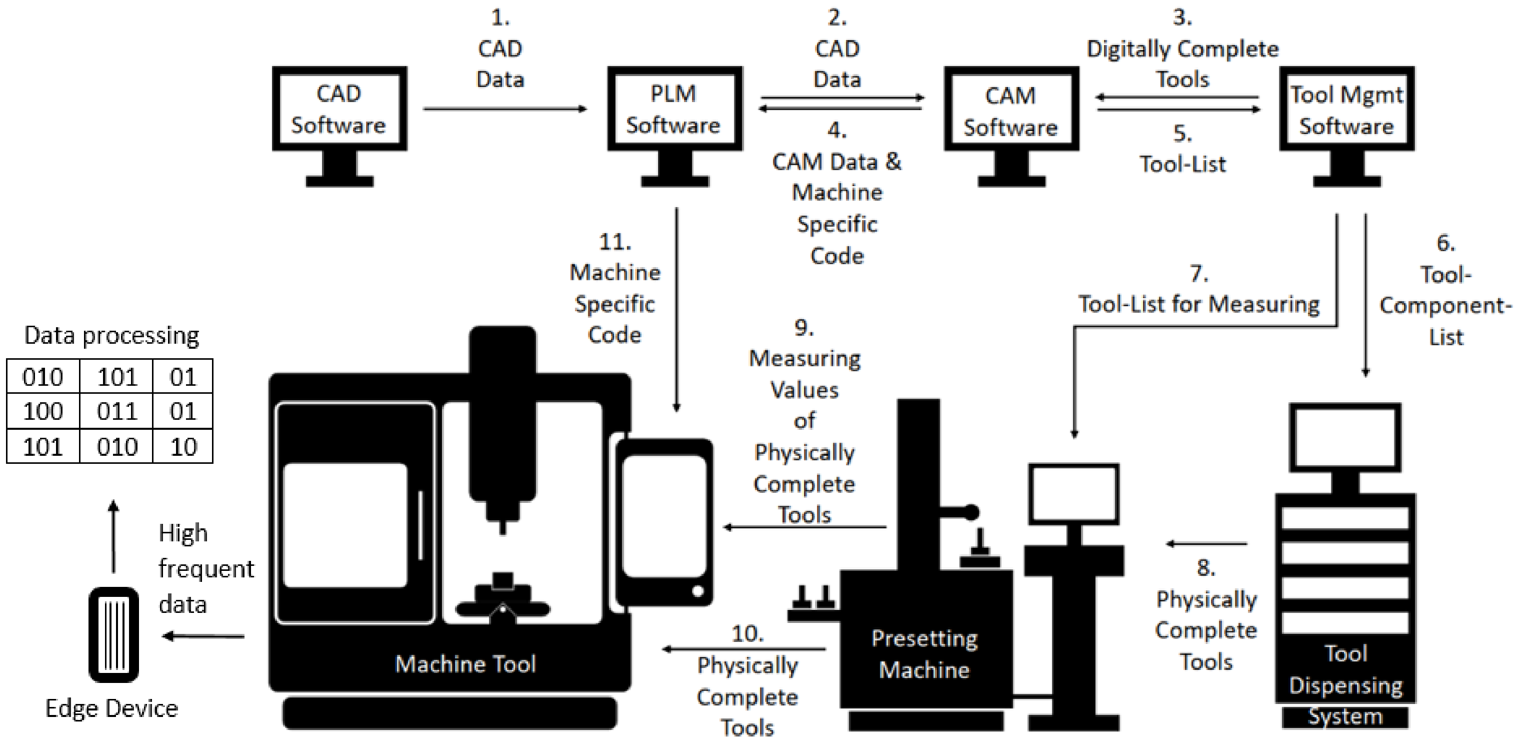
  → [Wilkinson2016], https://www.go-fair.org/fair-principles/

Publish dataset on Zenodo.org

- ❖ Receives DOI (digital object identifier) → **Findable**
- ❖ Funded by European Commission → **Accessible**

Adding relevant metadata:

- ❖ use precise & understandable language → **Interoperable**
- ❖ are richly described with a plurality of accurate and relevant attributes → **Reusable**



Documented in Schmidt et al.: "Seamless Data Integration in the CAM-NC Process Chain in a Learning Factory", January 2020, Procedia Manufacturing 45:31-36, DOI:10.1016/j.promfg.2020.04.038

Siemens Edge Device @smartfactory

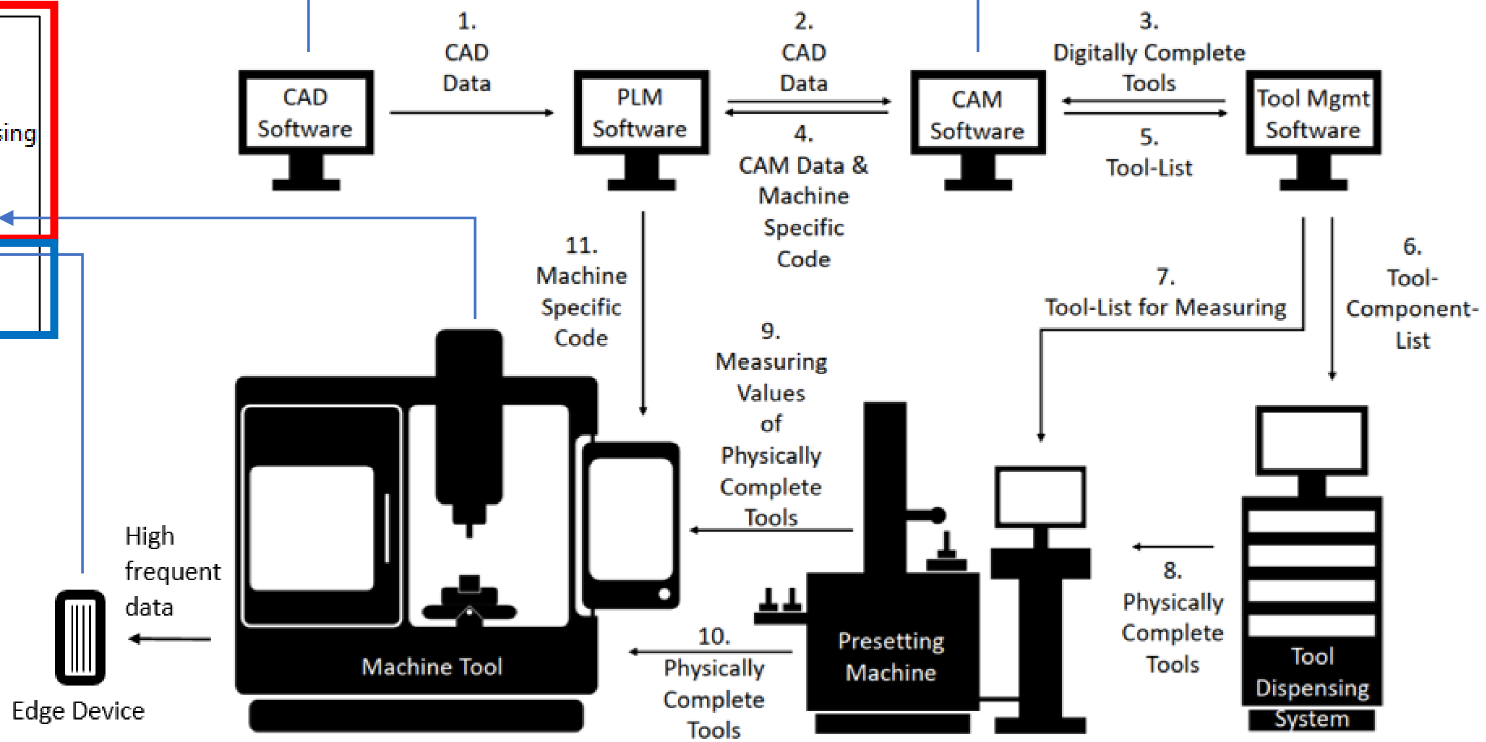
- Machine Data (91 channels) is captured by a SIMATIC IPC227E

- Software used: „Analyze MyWorkpiece /Capture4Analysis”
  “Capture4Analysis is a SINUMERIK Edge application which enables the user to acquire process data from the SINUMERIK CNC controller, store it locally on the EDGE device and provide it to other EDGE applications and also to external IT systems”
- Data is exported and processed by MCL in Python

	Name	Type	Axis	Address
61	CommandedSpeed	DOUBLE	C1	CMD_SPEED|6
62	TorqueFeedForward	DOUBLE	X1	TORQUE_FFW|1
63	TorqueFeedForward	DOUBLE	Y1	TORQUE_FFW|2
64	TorqueFeedForward	DOUBLE	Z1	TORQUE_FFW|3
65	TorqueFeedForward	DOUBLE	B1	TORQUE_FFW|4
66	TorqueFeedForward	DOUBLE	SP1	TORQUE_FFW|5
67	TorqueFeedForward	DOUBLE	C1	TORQUE_FFW|6
68	Encoder1Position	DOUBLE	X1	ENC1_POS|1
69	Encoder1Position	DOUBLE	Y1	ENC1_POS|2
70	Encoder1Position	DOUBLE	Z1	ENC1_POS|3
71	Encoder1Position	DOUBLE	B1	ENC1_POS|4
72	Encoder1Position	DOUBLE	SP1	ENC1_POS|5
73	Encoder1Position	DOUBLE	C1	ENC1_POS|6
74	Encoder2Position	DOUBLE	X1	ENC2_POS|1
75	Encoder2Position	DOUBLE	Y1	ENC2_POS|2
76	Encoder2Position	DOUBLE	Z1	ENC2_POS|3
77	Encoder2Position	DOUBLE	B1	ENC2_POS|4
78	Encoder2Position	DOUBLE	SP1	ENC2_POS|5
79	Encoder2Position	DOUBLE	C1	ENC2_POS|6
80	Load	DOUBLE	X1	LOAD|1
81	Load	DOUBLE	Y1	LOAD|2
82	Load	DOUBLE	Z1	LOAD|3
83	Load	DOUBLE	B1	LOAD|4
84	Load	DOUBLE	SP1	LOAD|5
85	Load	DOUBLE	C1	LOAD|6
86	ActualAxisPosition	DOUBLE	X1	ENC_POS|1
87	ActualAxisPosition	DOUBLE	Y1	ENC_POS|2
88	ActualAxisPosition	DOUBLE	Z1	ENC_POS|3
89	ActualAxisPosition	DOUBLE	B1	ENC_POS|4
90	ActualAxisPosition	DOUBLE	SP1	ENC_POS|5
91	ActualAxisPosition	DOUBLE	C1	ENC_POS|6

- 1_Hardware-Fingerprint
- 2_Software-Fingerprint
- 3_Machine-tool_tool-information
- 4_FACEMILLING-MEOP247
- 5_EndMILLING_MEOP245
- 6_PlungeMILLING_MEOP246
- 7_SlotMILLING_MEOP248

- 4.1_CAD-Files
- 4.2_CAM-Machining-Strategy
- 4.3_Toolpath-Simulation-before-Postprocessing
- 4.5_NC-Code-after-Postprocessing
- 4.6_NC-Code-after-check-at-machine-tool
- 5_High-frequent-machining-data
- 6_Photos_final-workpiece-REAL



Metadata describes the process leading to the actual milling operation

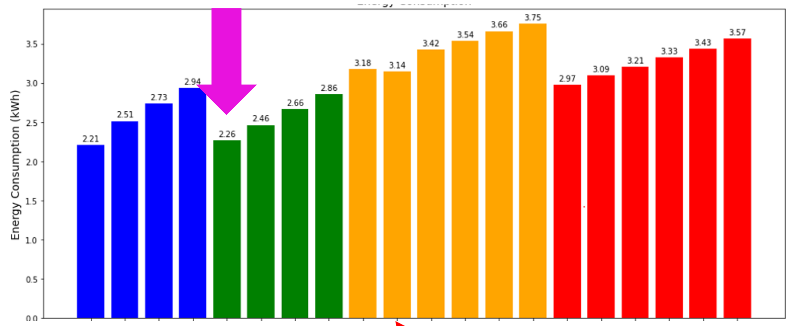
Dataset Metadata captures

- types and versions of machines and software used (fingerprint) and
- data leading to actual milling operation.

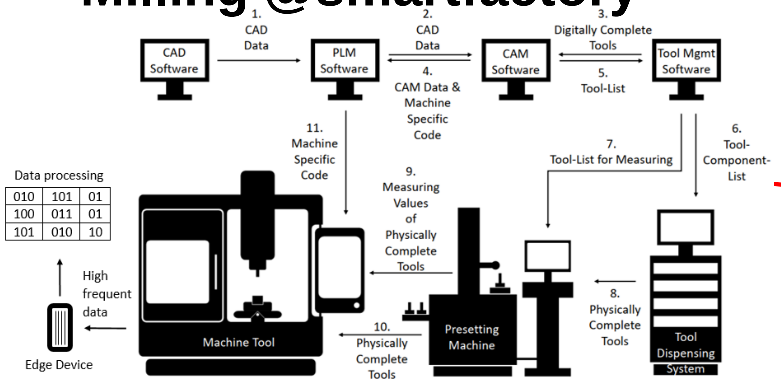
→ Well-structured metadata is prerequisite for efficient data analysis and portable results.

Question: What slot milling parameters result in lowest energy consumption?

Answer:



Milling @smartfactory



FAIR Dataset

- 1_Hardware-Fingerprint
- 2_Software-Fingerprint
- 3_Machine-tool_tool-information
- 4_FACEMILLING-MEOP247
- 5_EndMILLING_MEOP245
- 6_PlungeMILLING_MEOP246
- 7_SlotMILLING_MEOP248
  - 7.1_CAD-Files
  - 7.2_CAM-Machining-Strategy
  - 7.3_Toolpath-Simulation-before-Postprocessing
  - 7.4_NC-Code-after-Postprocessing_PARTLY
  - 7.5_NC-Code-after-check-at-machine-tool
  - 7.6_High-frequent-machining-data
  - 7.7_Photos_final-workpiece-REAL

Efficient Data Analysis

- Design of experiments according to problem statement (e.g. Milling of slots with varying parameters)
- Dataset contains all information required for efficient data analysis (ensured by data acquisition workflow)

Project “FairMillData2”

Channels Used for Analysis

- Analysis of poistional accuracy via position channels & desired position channels and control difference channels
- Analysis of energy consumption via power channels

	Name	Type	Axis	Address
0	Cycle	INTEGER	CYCLE	CYCLE
1	ControlDiff2	DOUBLE	X1	CTRL_DIFF2|1
2	ControlDiff2	DOUBLE	Y1	CTRL_DIFF2|2
3	ControlDiff2	DOUBLE	Z1	CTRL_DIFF2|3
4	ControlDiff2	DOUBLE	B1	CTRL_DIFF2|4
5	ControlDiff2	DOUBLE	SP1	CTRL_DIFF2|5
6	ControlDiff2	DOUBLE	C1	CTRL_DIFF2|6
7	Torque	DOUBLE	X1	TORQUE|1
8	Torque	DOUBLE	Y1	TORQUE|2
9	Torque	DOUBLE	Z1	TORQUE|3
10	Torque	DOUBLE	B1	TORQUE|4
11	Torque	DOUBLE	SP1	TORQUE|5
12	Torque	DOUBLE	C1	TORQUE|6
13	CommandedAxisPosition	DOUBLE	X1	DES_POS|1
14	CommandedAxisPosition	DOUBLE	Y1	DES_POS|2
15	CommandedAxisPosition	DOUBLE	Z1	DES_POS|3
16	CommandedAxisPosition	DOUBLE	B1	DES_POS|4
17	CommandedAxisPosition	DOUBLE	SP1	DES_POS|5
18	CommandedAxisPosition	DOUBLE	C1	DES_POS|6
19	Current	DOUBLE	X1	CURRENT|1
20	Current	DOUBLE	Y1	CURRENT|2
21	Current	DOUBLE	Z1	CURRENT|3
22	Current	DOUBLE	B1	CURRENT|4
23	Current	DOUBLE	SP1	CURRENT|5
24	Current	DOUBLE	C1	CURRENT|6
25	ControlDiff	DOUBLE	X1	CTRL_DIFF|1
26	ControlDiff	DOUBLE	Y1	CTRL_DIFF|2
27	ControlDiff	DOUBLE	Z1	CTRL_DIFF|3
28	ControlDiff	DOUBLE	B1	CTRL_DIFF|4
29	ControlDiff	DOUBLE	SP1	CTRL_DIFF|5
30	ControlDiff	DOUBLE	C1	CTRL_DIFF|6

	Name	Type	Axis	Address
31	ControlPos	DOUBLE	X1	CTRL_POS|1
32	ControlPos	DOUBLE	Y1	CTRL_POS|2
33	ControlPos	DOUBLE	Z1	CTRL_POS|3
34	ControlPos	DOUBLE	B1	CTRL_POS|4
35	ControlPos	DOUBLE	SP1	CTRL_POS|5
36	ControlPos	DOUBLE	C1	CTRL_POS|6
37	VelocityFeedForward	DOUBLE	X1	VEL_FFW|1
38	VelocityFeedForward	DOUBLE	Y1	VEL_FFW|2
39	VelocityFeedForward	DOUBLE	Z1	VEL_FFW|3
40	VelocityFeedForward	DOUBLE	B1	VEL_FFW|4
41	VelocityFeedForward	DOUBLE	SP1	VEL_FFW|5
42	VelocityFeedForward	DOUBLE	C1	VEL_FFW|6
43	Power	STRING	X1	POWER|1
44	Power	STRING	Y1	POWER|2
45	Power	STRING	Z1	POWER|3
46	Power	STRING	B1	POWER|4
47	Power	STRING	SP1	POWER|5
48	Power	STRING	C1	POWER|6
49	CountourDeviation	DOUBLE	X1	CONT_DEV|1
50	CountourDeviation	DOUBLE	Y1	CONT_DEV|2
51	CountourDeviation	DOUBLE	Z1	CONT_DEV|3
52	CountourDeviation	DOUBLE	B1	CONT_DEV|4
53	CountourDeviation	DOUBLE	SP1	CONT_DEV|5
54	CountourDeviation	DOUBLE	C1	CONT_DEV|6
55	Synchronuous Action variable	INTEGER		A_DBD|0
56	CommandedSpeed	DOUBLE	X1	CMD_SPEED|1
57	CommandedSpeed	DOUBLE	Y1	CMD_SPEED|2
58	CommandedSpeed	DOUBLE	Z1	CMD_SPEED|3
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	End Milling	Plunge Milling	Slot milling	Face Milling
Varied Parameters	Radial Depth $\mathbf{a_e}$ Axial Depth $\mathbf{a_p}$	Plunging Strategy	Radial Depth $\mathbf{a_e}$ Axial Depth $\mathbf{a_p}$ Corner Velocity $\mathbf{v_{EP}}$	Feed Rate $\mathbf{v_f}$ Cutting Speed $\mathbf{v_c}$
Number of Experiments (Runs)	10	12	20	48
Tool	End mill (d = 10 mm)	End mill (d = 10 mm)	End mill (d = 10 mm)	Indexable Cutter (d = 80 mm)
Material	1.2083 (X42Cr 13) Stainless Mold Steel			

- **FairMillData:** Four milling operations were performed using different parameters
- **FairMillData2:** Data analysis to study the effect of parameter variation on milling target quantities, e.g. energy consumption, positional accuracy.

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Varied Parameters	Radial Depth a_e Axial Depth a_p	Plunging Strategy	Radial Depth a_e Axial Depth a_p Corner Velocity v_{EP}	Feed Rate v_f Cutting Speed v_c
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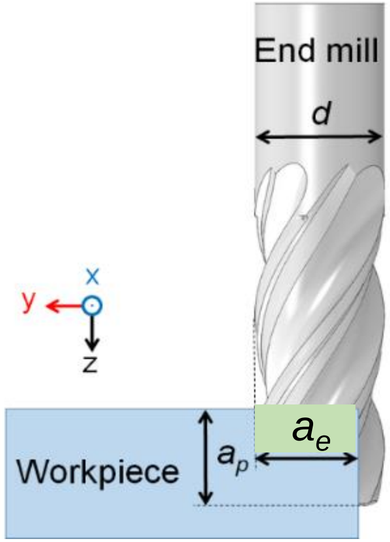
Tool	End mill (d = 10 mm)	End mill (d = 10 mm)	End mill (d = 10 mm)	Indexable Cutter (d = 80 mm)
Material	1.2083 (X42Cr 13) Stainless Mold Steel			

Question:

How does radial depth of cut (a_e) compare to axial depth of cut (a_p) w.r.t. their effect on energy consumption and maximum power?

Experiment Overview

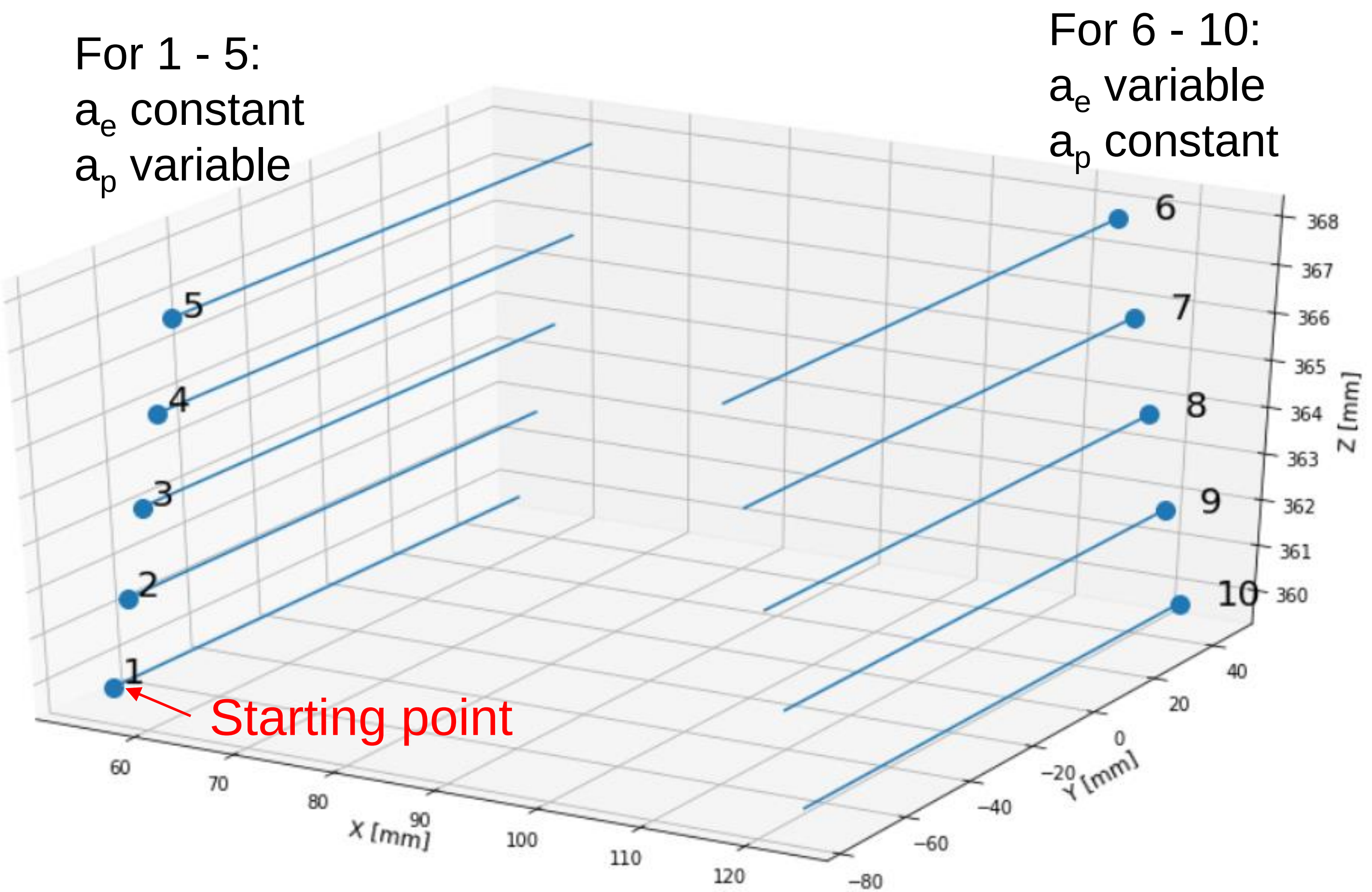
	v_c [m/min]	f_z [mm]	a_p [mm]	a_e [mm]	Material Removal Rate [cm^3/min]
Run 1	100	0,05	10	2	12,73
Run 2	100	0,05	8	2	10,19
Run 3	100	0,05	6	2	7,64
Run 4	100	0,05	4	2	5,09
Run 5	100	0,05	2	2	2,55

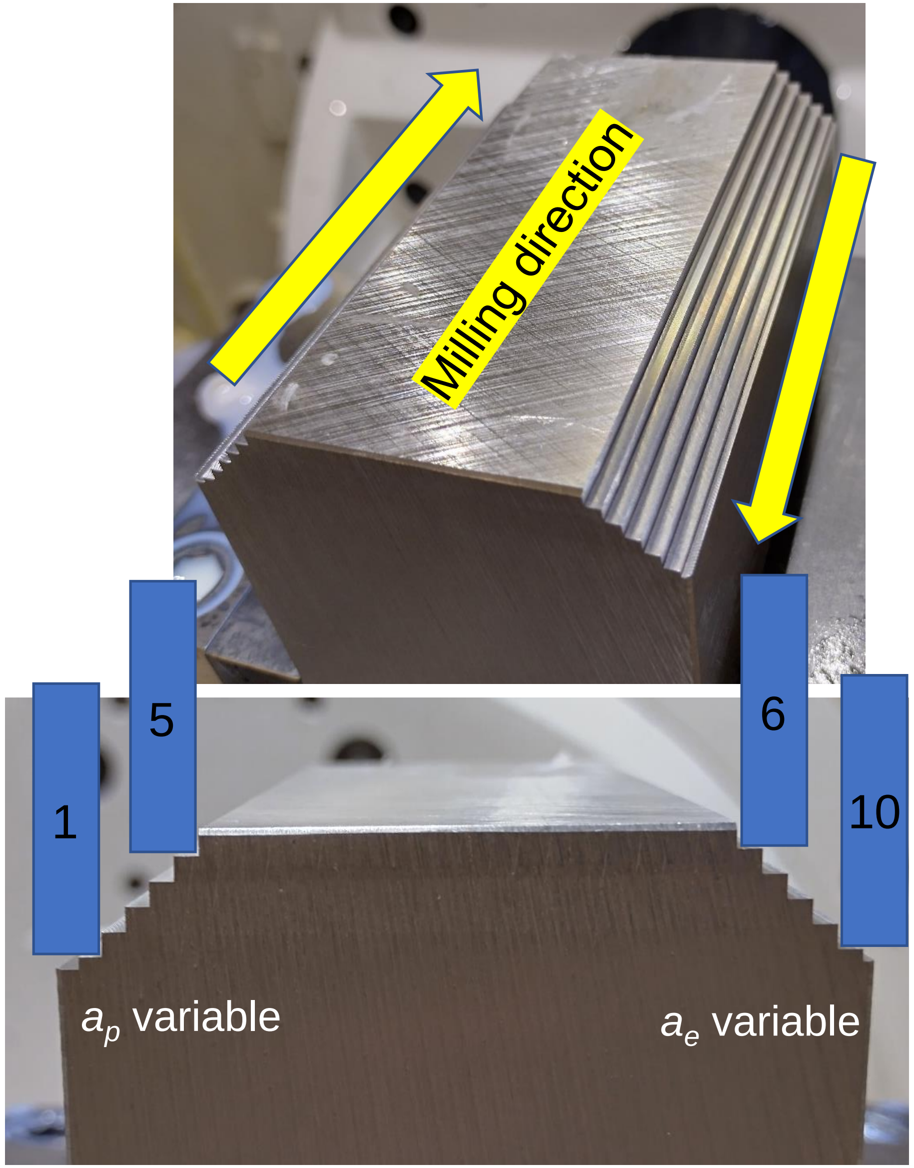


	v_c [m/min]	f_z [mm]	a_p [mm]	a_e [mm]	Material Removal Rate [cm^3/min]
Run 6	100	0,05	2	10	12,73
Run 7	100	0,05	2	8	10,19
Run 8	100	0,05	2	6	7,64
Run 9	100	0,05	2	4	5,09
Run 10	100	0,05	2	2	2,55

- 10 runs of end milling are performed
- For runs 1 to 5, a_p is varied while a_e is kept at a constant level
- For runs 6 to 10, a_e is varied while a_p is kept at a constant level

End Milling Strategy – Path Tool Center Point



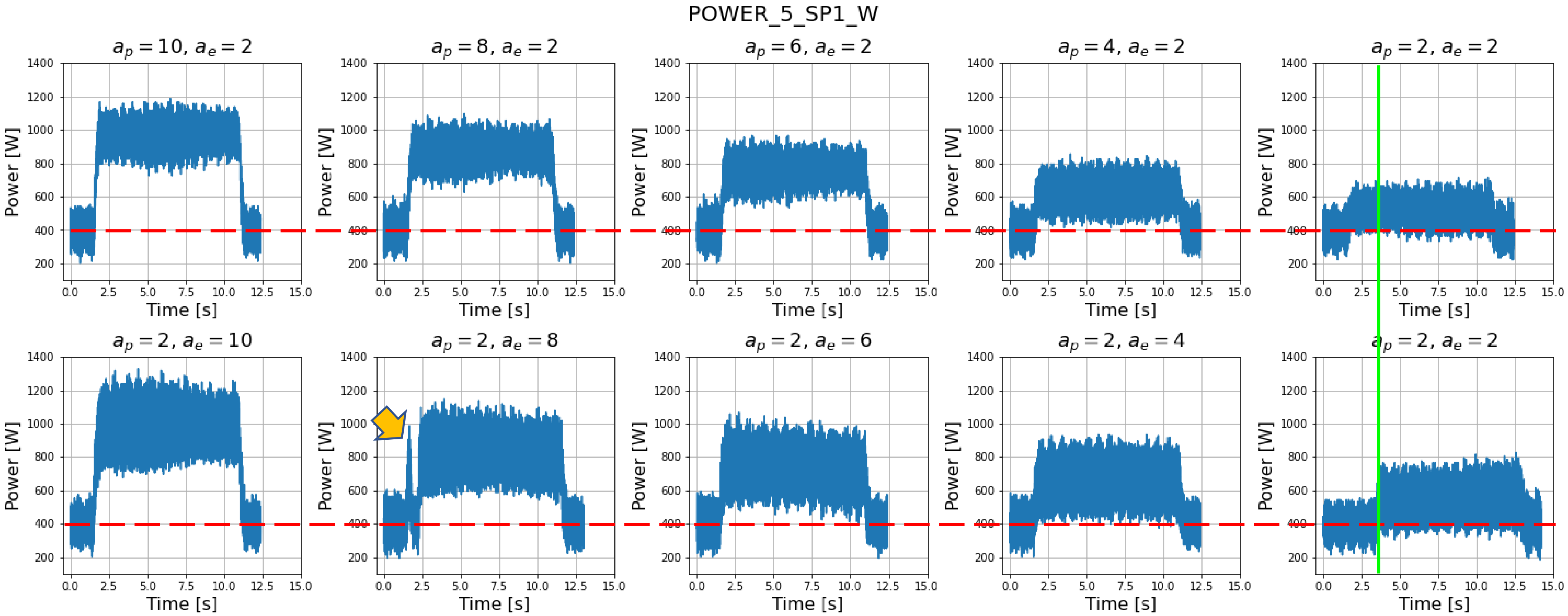


Question:

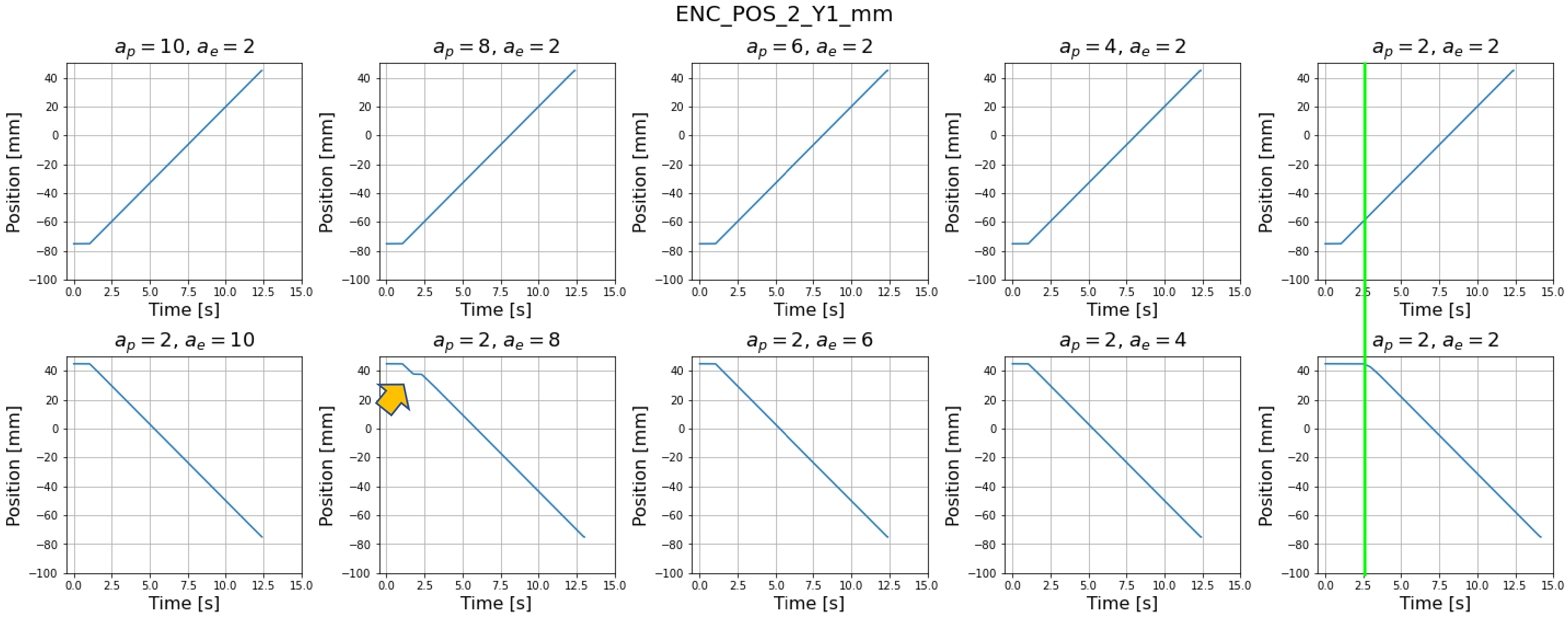
How does radial depth of cut (a_e) compare to axial depth of cut (a_p) w.r.t. their effect on energy consumption and maximum power?

End Milling – Maximum Power

Comparison of Spindle-Power for all Operations



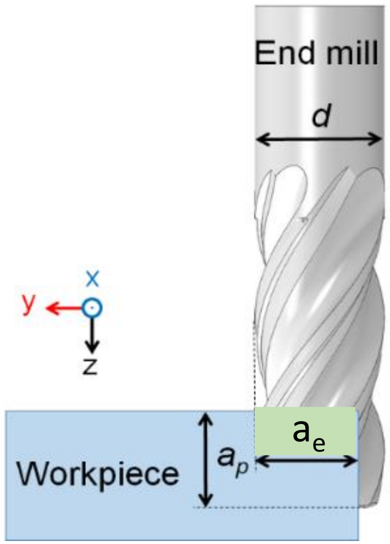
- Idle-power equal for all experiments → v_c and f_z
- Power level decreases with lower tool immersion
- Anomalous peak during Idle-phase for a_p = 2 mm, a_e = 8 mm
- Delay for a_p = 2 mm, a_e = 2 mm

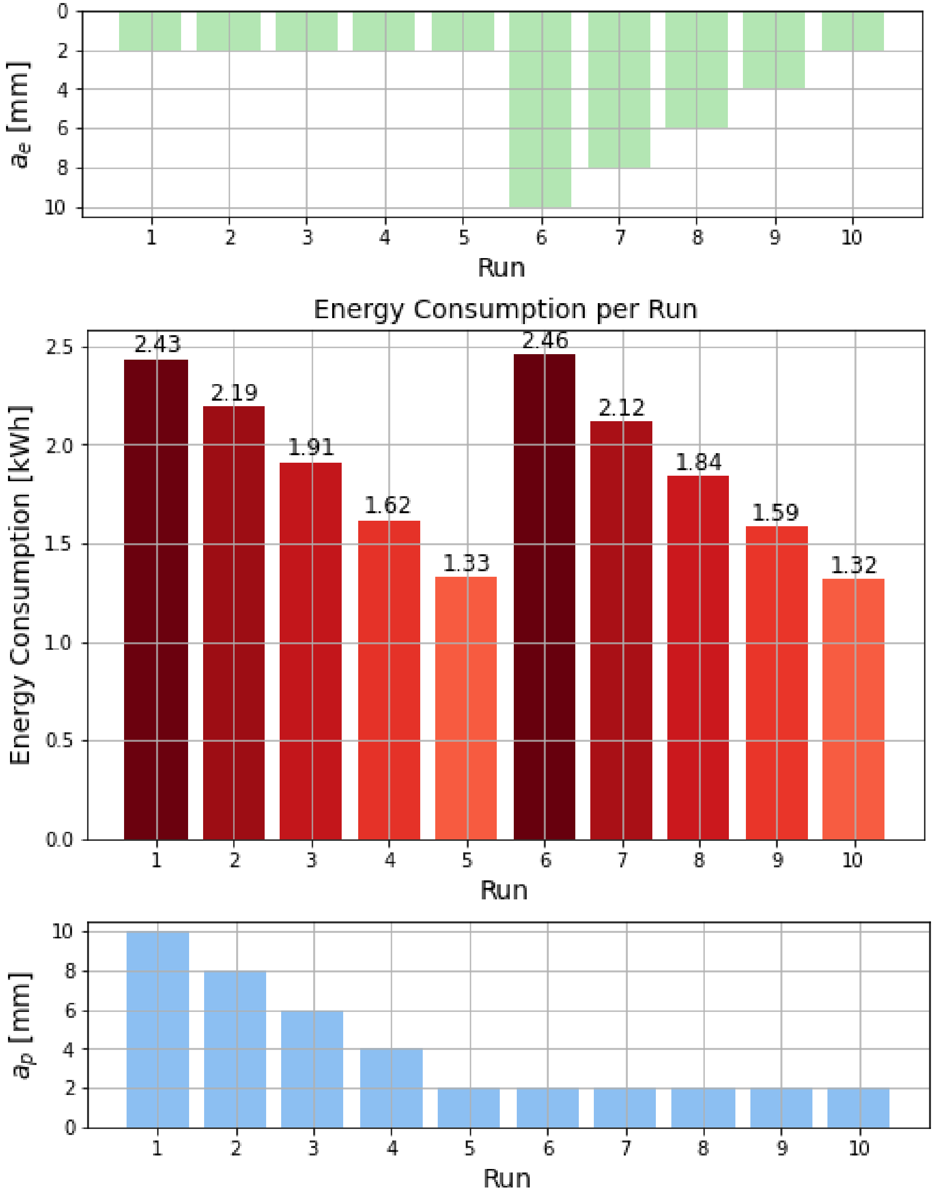


- Anomalies in spindle-power stem from interrupted / delayed change in y-position

End Milling – Energy Consumption

Varying a_p vs. Varying a_e: Effect on Energy Consumption





- Analysis for total energy consumption (sum of all power channels) in kWh.

- Maximum consumption for run 6:

  a_p = 2 mm,

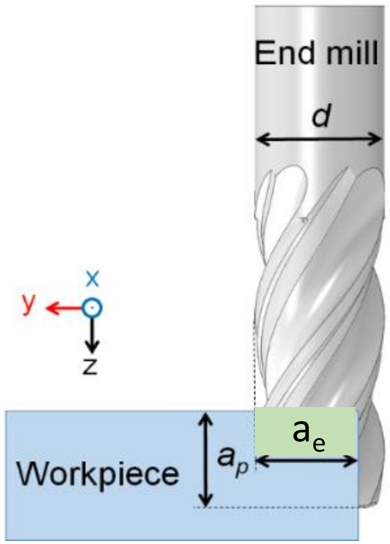
  a_e = 10 mm.

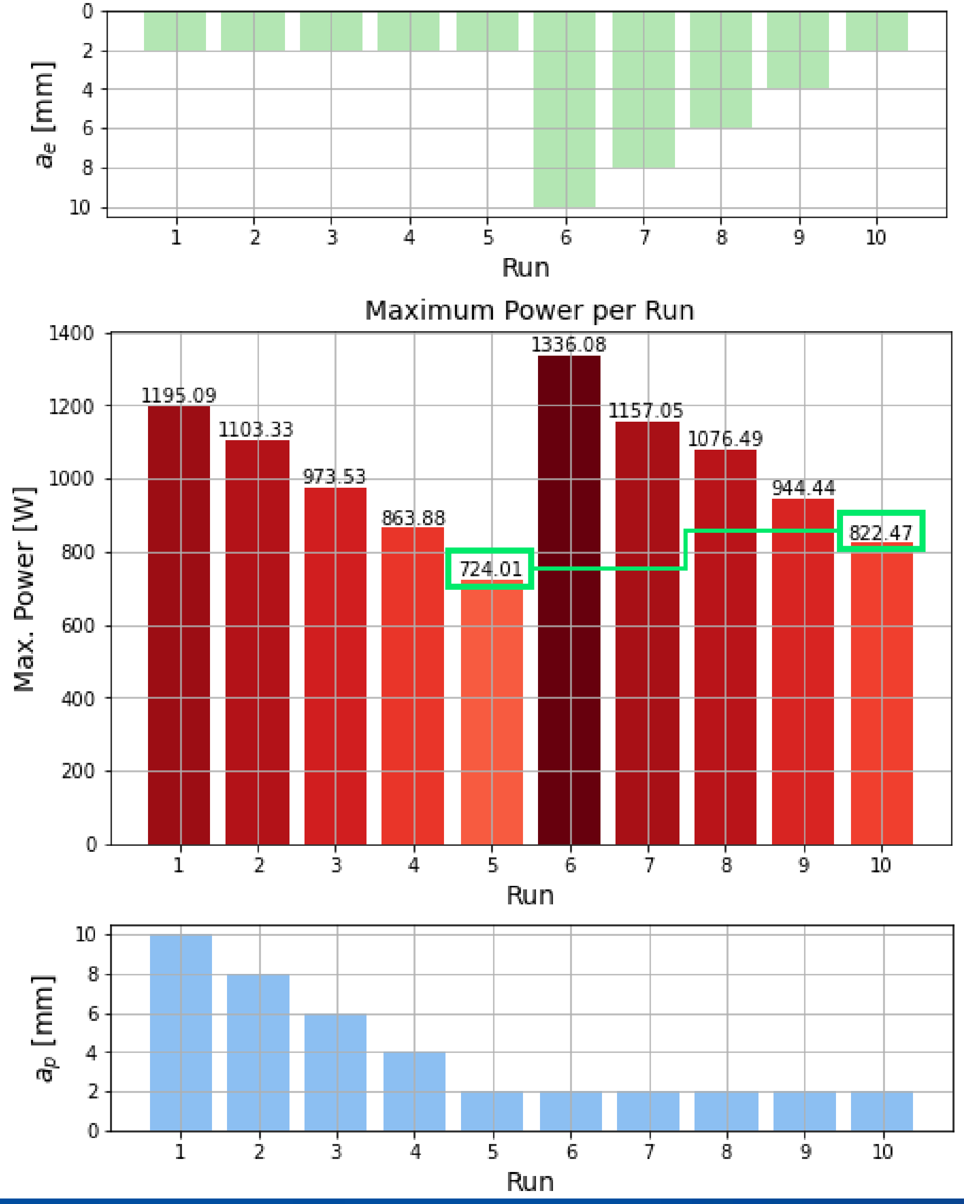
- We compare runs with same **material removal rate (MRR)**: 1-6, 2-7, 3-8….

- On average, increased $\boldsymbol{a_p}$ leads to higher energy consumption by **1.77%** for the **same material removal rate (MRR).**

End Milling – Maximum Power

Varying a_p vs. Varying a_e: Effect on Maximum Power





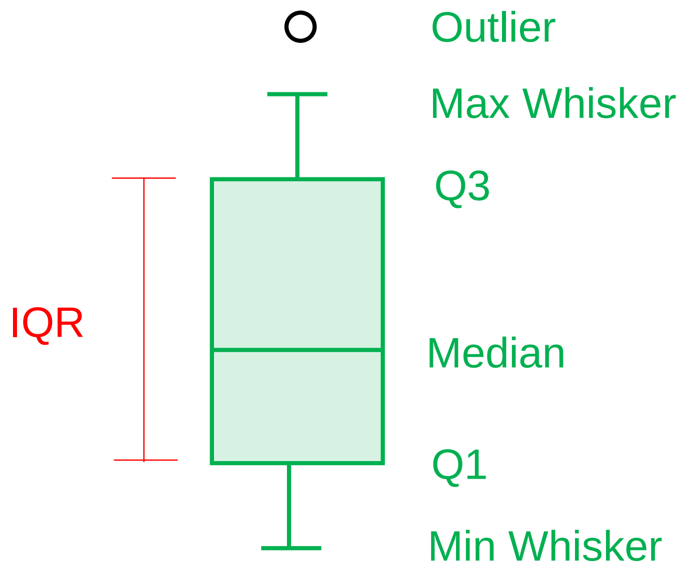
- Analysis for maximum value (sum of all power channels) in W.
- Maximum power for run 6:

  a_p = 2 mm,

  a_e = 10 mm.
- We compare runs with same **material removal rate (MRR)**: 1-6, 2-7, 3-8….
- On average, increased ***a_e*** leads to higher maximum by **9.52%** for the **same material removal rate (MRR).**
- Considerable difference for run 5 vs. run 10 **despite identical parameters**.

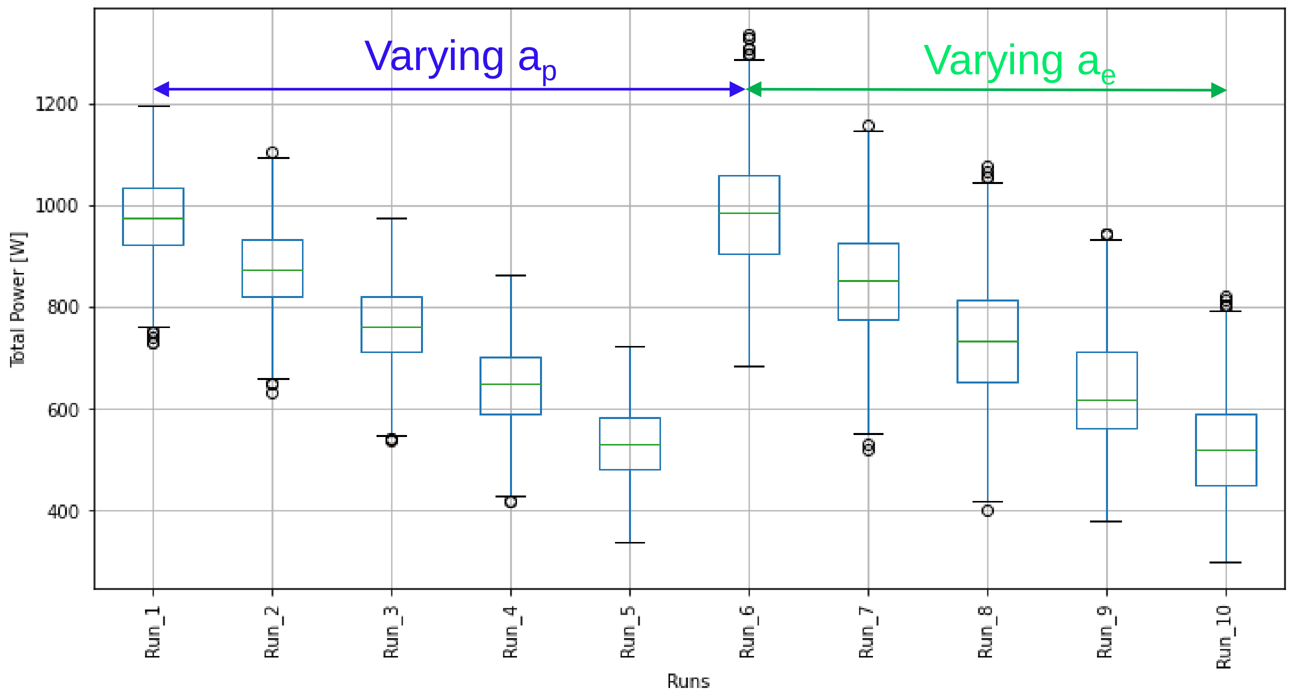
Varying a_p vs. Varying a_e: Effect on Maximum Power

Box Plot Explanation



- Q1: lowest 25% of data are below this point
- Q3: lowest 75% of data are below this point
- Whisker: last point within 1.5 * IQR
- Outliers: Data points outside of 1.5 * IQR

Box Plot for all Runs



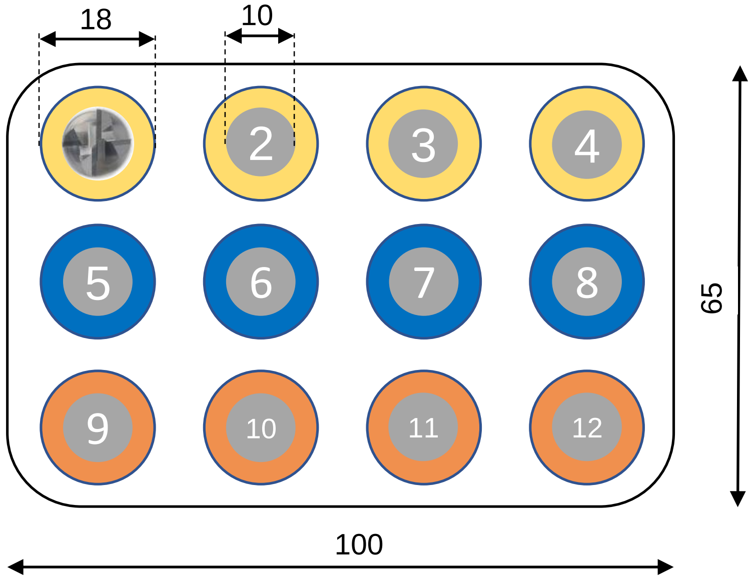
- Runs 6 – 10 (a_e variation) show **higher IQR** and **range** between whiskers.
- Also for run 5 vs. run 10 **despite identical parameters**

	End Milling	Plunge Milling	Slot milling	Face Milling
Varied Parameters	Radial Depth a_e Axial Depth a_p	Plunging Strategy	Radial Depth a_e Axial Depth a_p Corner Velocity v_{EP}	Feed Rate v_f Cutting Speed v_c
Number of Experiments (Runs)	10	12	20	48
Tool	End mill (d = 10 mm)	End mill (d = 10 mm)	End mill (d = 10 mm)	Indexable Cutter (d = 80 mm)
Material	1.2083 (X42Cr 13) Stainless Mold Steel			

- **Question:** What is the optimal immersion & finishing strategy w.r.t. energy consumption, machining time and maximum power for different hole depths?

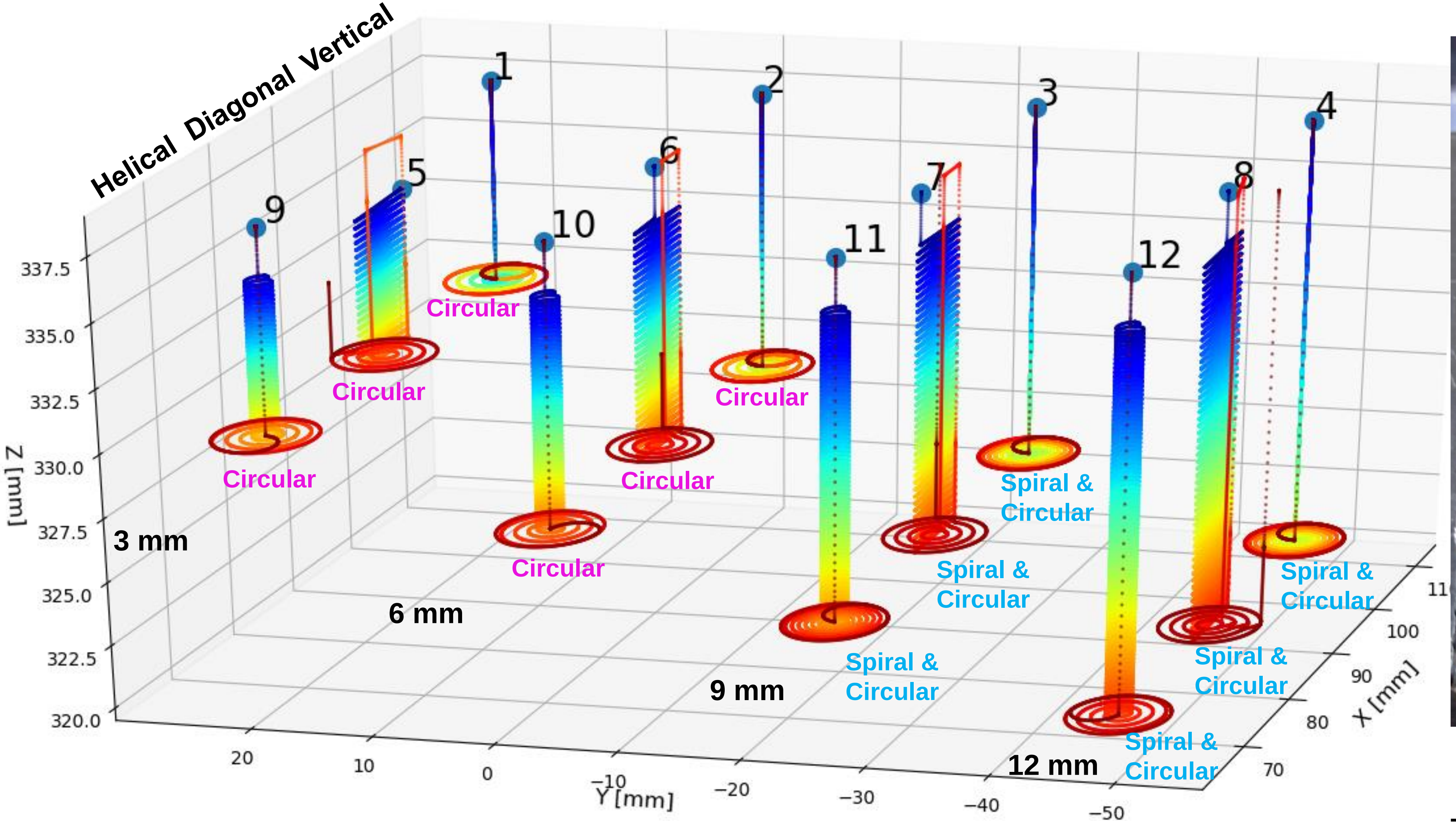
Experiment Overview - Comparison of Immersion & Roughing Strategies

Run	a_p	Removal [mm]	Strategy	Immersion	Feed Rate v_f [mm/min]	Roughing
1	a_{p1}	3	Vertical Immersion	Vertical	286,48	Circular
2	a_{p2}	6		Vertical	286,48	Circular
3	a_{p3}	9		Vertical	286,48	Spiral & Circular Finish
4	a_{p4}	12		Vertical	286,48	Spiral & Circular Finish
5	a_{p1}	3	Diagonal Immersion	Diagonal	286,48	Circular
6	a_{p2}	6		Diagonal	286,48	Circular
7	a_{p3}	9		Diagonal	286,48	Spiral & Circular Finish
8	a_{p4}	12		Diagonal	286,48	Spiral & Circular Finish
9	a_{p1}	3	Helical Immersion	Helical	286,48	Circular
10	a_{p2}	6		Helical	286,48	Circular
11	a_{p3}	9		Helical	286,48	Spiral & Circular Finish
12	a_{p4}	12		Helical	286,48	Spiral & Circular Finish



- 12 cylindrical pockets are milled into a workpiece with varying strategies
- Change in **immersion** (tool entering the workpiece) and **roughing** (extending the diameter from 10 to 18 mm)
  - Immersion is performed in a vertical, diagonal or helical manner
  - Roughing is performed circular or spiral with a circular finish
- Reasoning behind experiment: low tool wear, practical, interesting with respect to energy consumption

Plunge Milling Strategy – Path of Tool Center Point

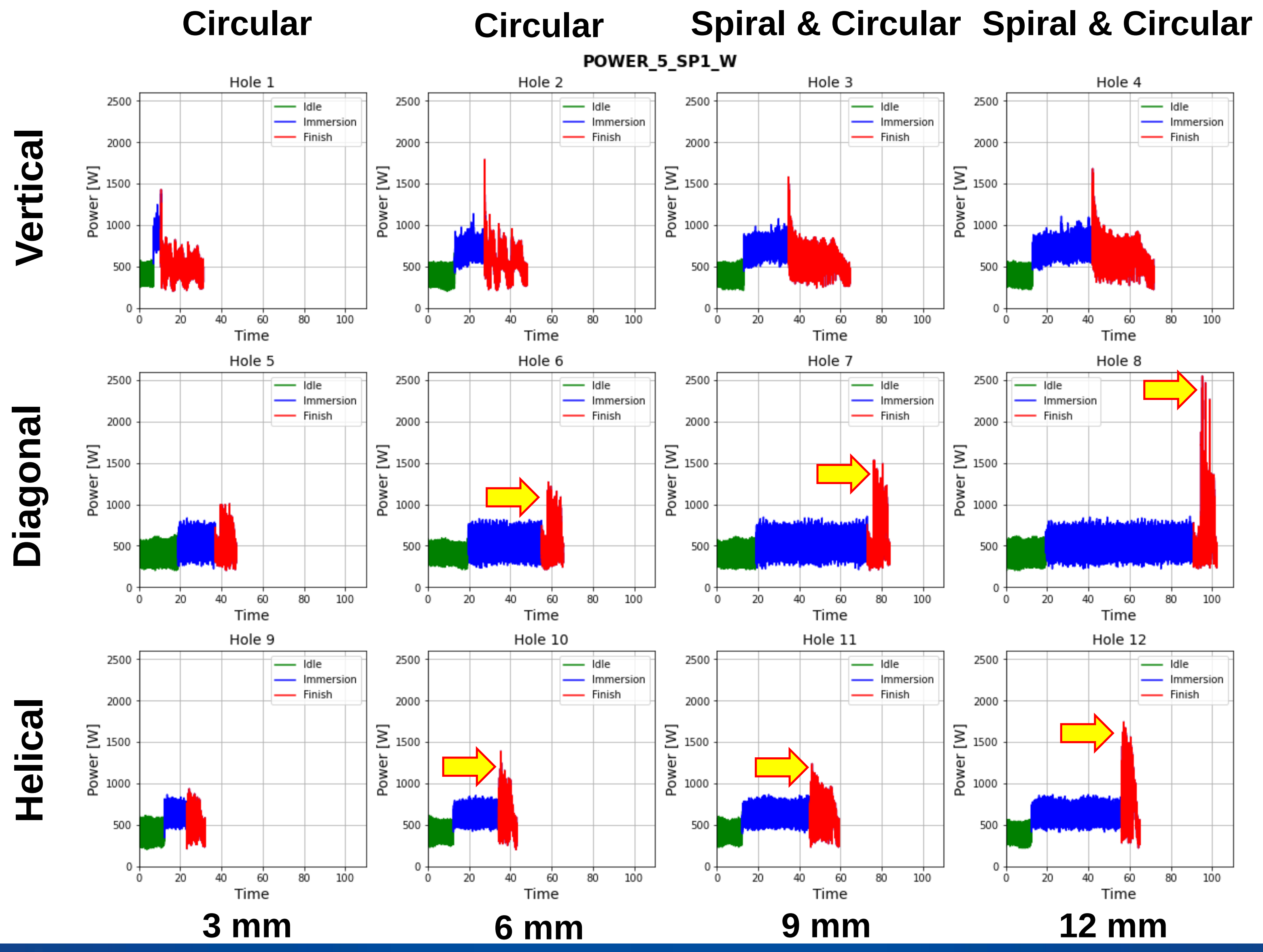


TCP visualized from early to late stage.

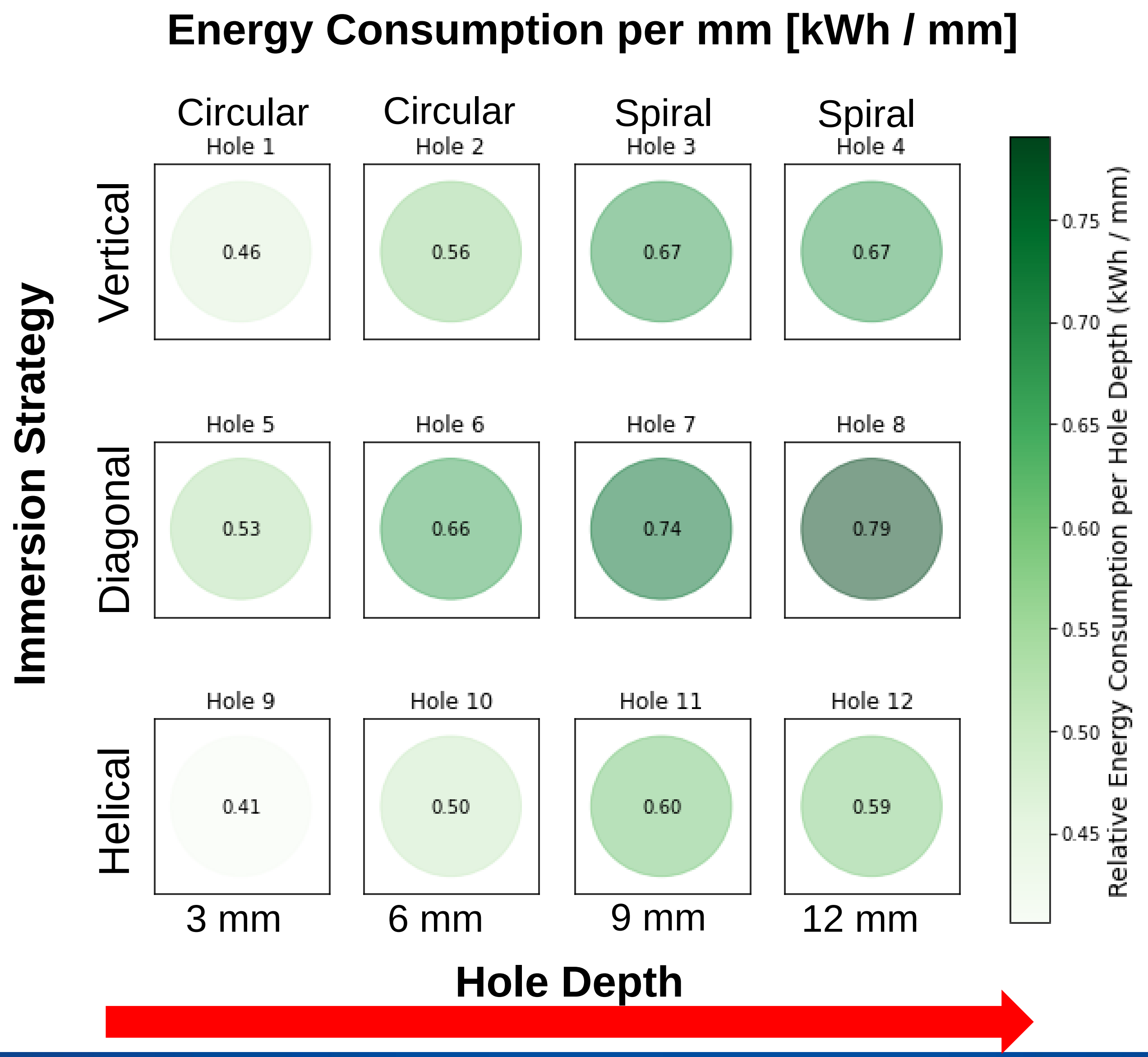
- **Question:** What is the optimal immersion & finishing strategy w.r.t. energy consumption, machining time and maximum power for different hole depths?

Plunge Milling - Introduction

Comparison of Energy Consumption



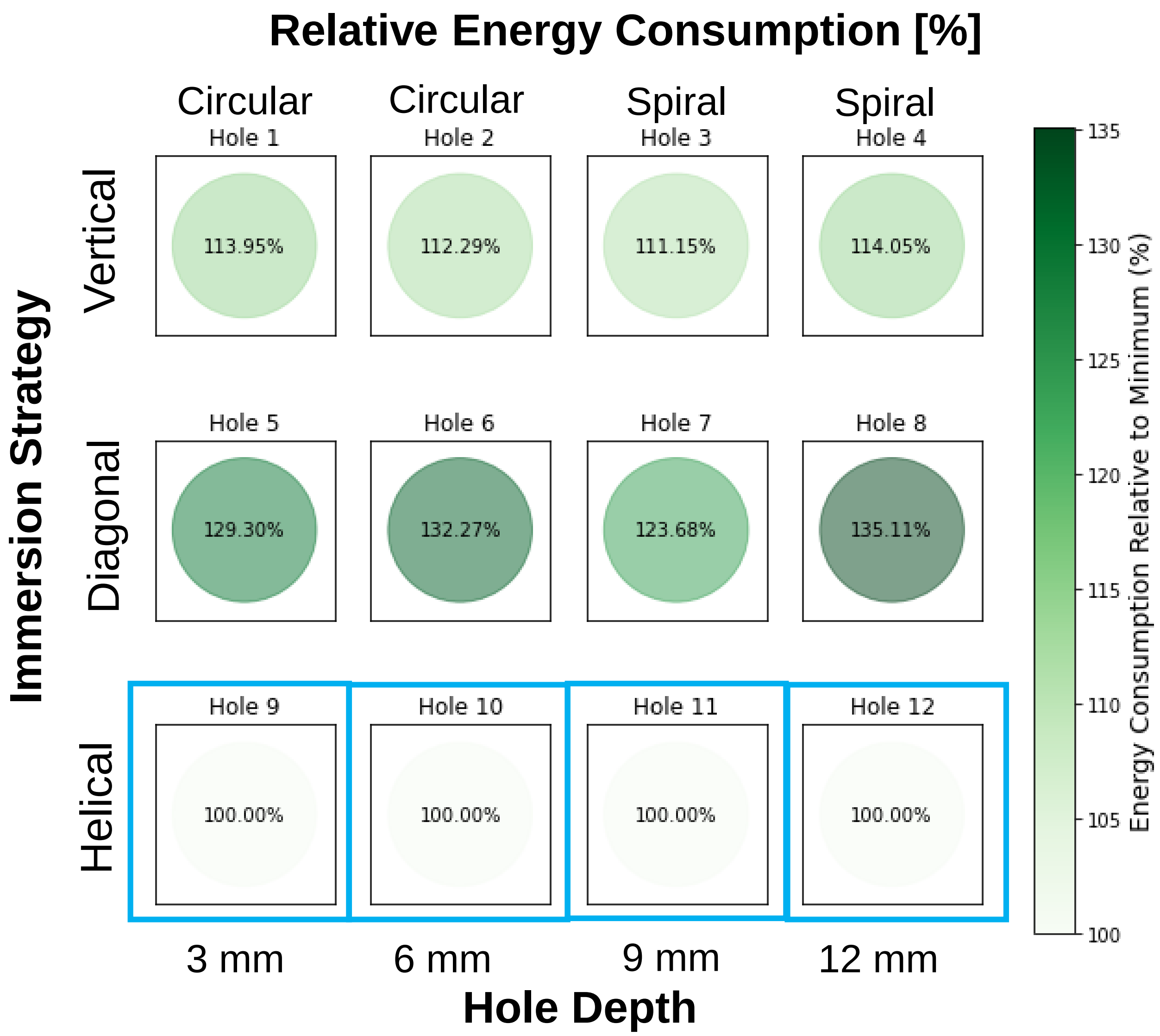
- Visualization of spindle power channel
- Holes are divided into Idle, Immersion and Finish
- Length of immersion depends on hole depth (trivial)
- Height of power peak when finishing **increases with hole depth** for diagonal and helical immersion



- Calculation of energy consumption (**for immersion + finishing**) via integration of channel 'POWER_5_SP1_W‘ & divide by 360 → kWh.
- Normalized with hole depth
- Disproportional trend of kWh/mm with hole depth

Plunge Milling – Energy Consumption

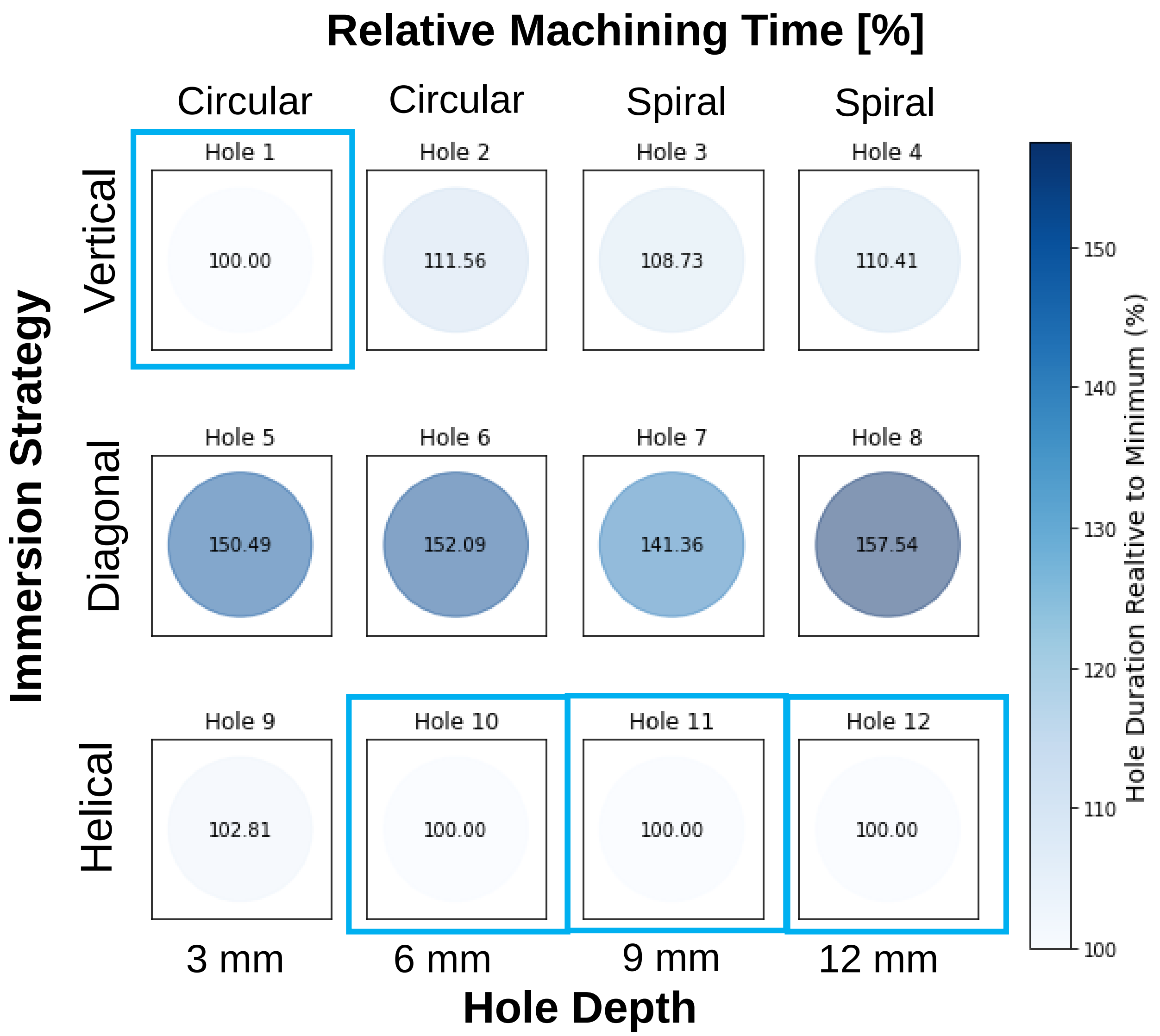
Find Optimal Strategy w.r.t. Energy Consumption



- Calculation of energy consumption (**for immersion + finishing**) via integration of channel 'POWER_5_SP1_W' & divide by 360 → kWh.
- <u>Normalized with best strategy per hole depth</u>
- Helical immersion **optimal** for all hole depths.

Plunge Milling – Machining Time

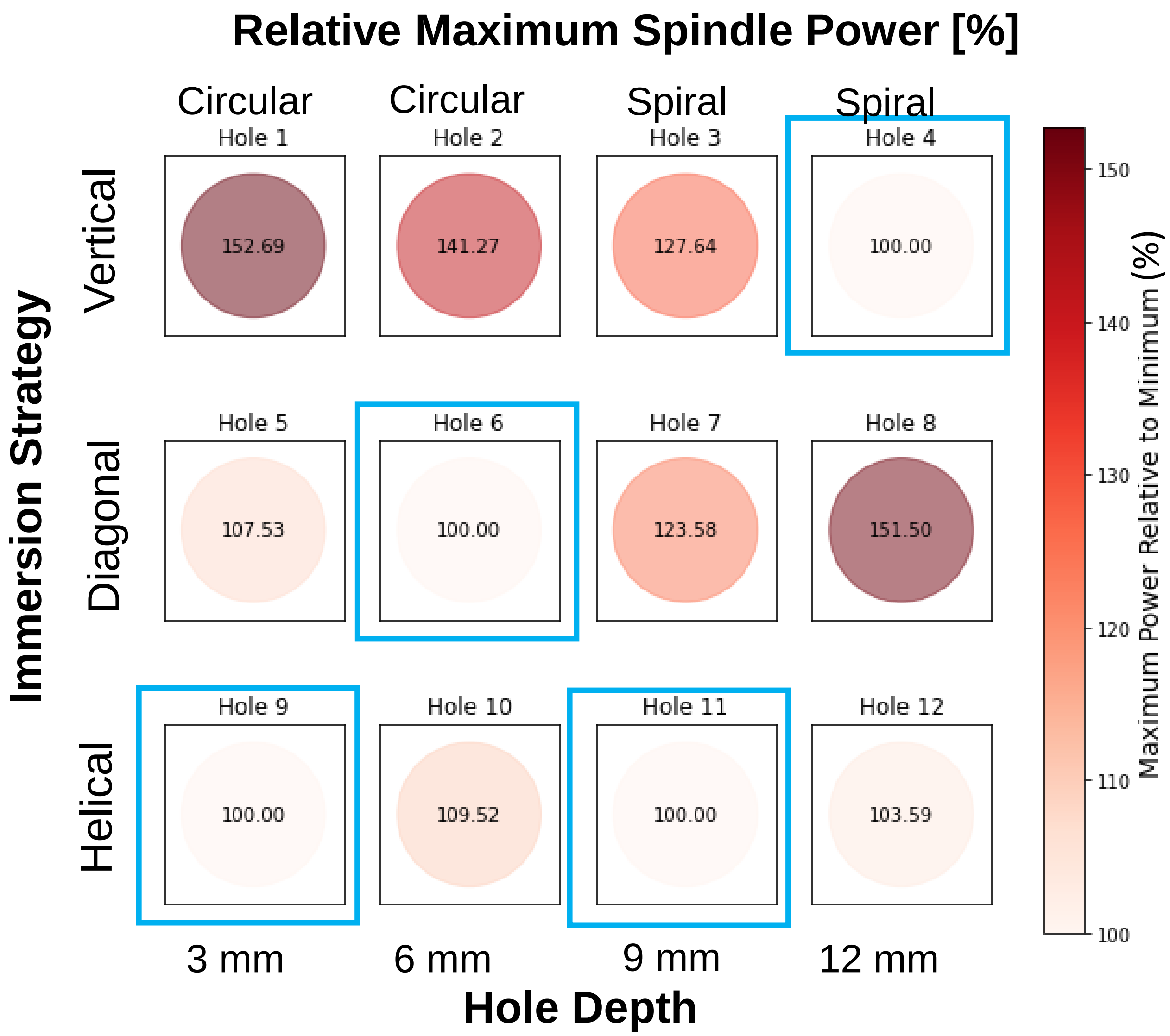
Find Optimal Strategy w.r.t. Machining Time



- <u>Normalized with best strategy per hole depth</u>
- Helical immersion optimal for 6, 9 and 12 mm hole depth
- Vertical immersion optimal for 3 mm hole depth

Plunge Milling – Maximum Power

Find Optimal Strategy w.r.t. Maximum Power



- <u>Normalized with best strategy per hole depth</u>
- Helical immersion optimal for 3 and 9 mm hole depth
- Diagonal immersion optimal for 6 mm hole depth
- Vertical immersion optimal for 12 mm hole depth
- → Optimal strategy varies, Vertical Immersion recommended for deeper holes

	End Milling	Plunge Milling	**Slot milling**	Face Milling
Varied Parameters	Radial Depth $\mathbf{a_e}$ Axial Depth $\mathbf{a_p}$	Plunging Strategy	Radial Depth $\mathbf{a_e}$ Axial Depth $\mathbf{a_p}$ Corner Velocity $\mathbf{v_{EP}}$	Feed Rate $\mathbf{v_f}$ Cutting Speed $\mathbf{v_c}$
Number of Experiments (Runs)	10	12	20	48
Tool	End mill (d = 10 mm)	End mill (d = 10 mm)	End mill (d = 10 mm)	Indexable Cutter (d = 80 mm)
Material	1.2083 (X42Cr 13) Stainless Mold Steel			

- **Questions:** Does corner velocity influence positional accuracy in slot milling? What parameters lead to lowest energy consumption?

Slot Milling - Introduction

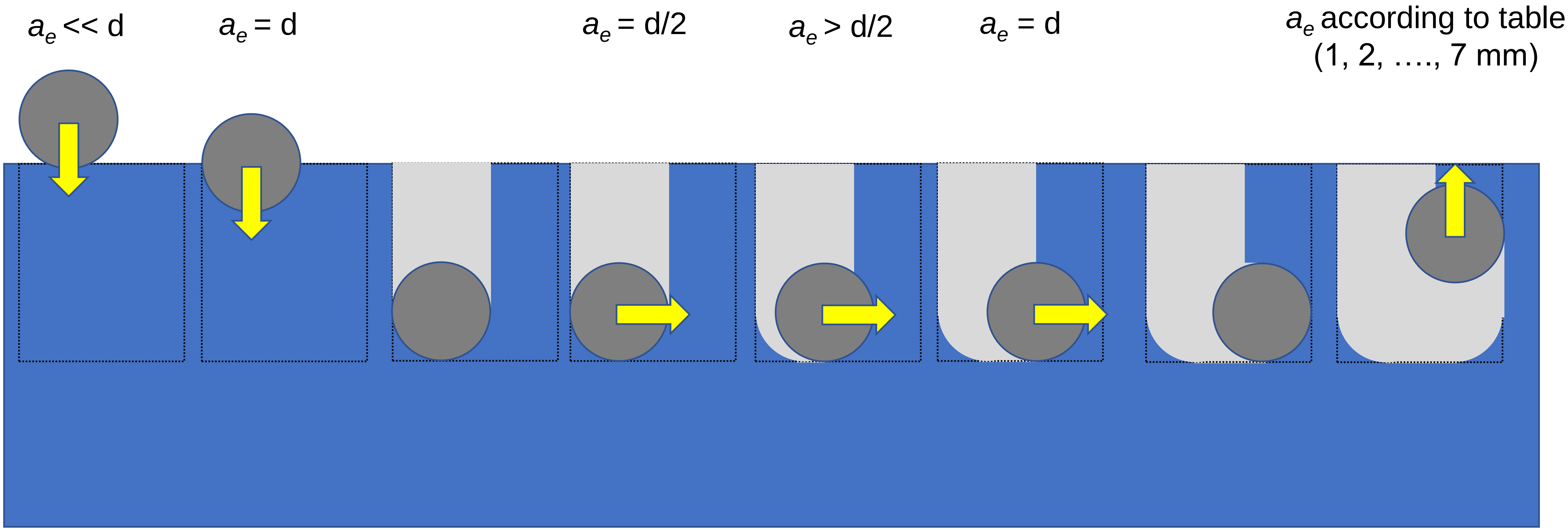
Parameter Overview

Run		a_p in mm	v_{EP} in mm/min			a_e in mm
1	a_{p1}	1	v_{EP1}	80,21	ae_1	1
2	a_{p2}	2	v_{EP1}	80,21	ae_1	1
3	a_{p3}	3	v_{EP1}	80,21	ae_1	1
4	a_{p4}	4	v_{EP1}	80,21	ae_1	1
5	a_{p1}	1	v_{EP2}	187,17	ae_1	1
6	a_{p2}	2	v_{EP2}	187,17	ae_1	1
7	a_{p3}	3	v_{EP2}	187,17	ae_1	1
8	a_{p4}	4	v_{EP2}	187,17	ae_1	1
9	a_{p4}	4	v_{EP1}	80,21	ae_2	2
10	a_{p4}	4	v_{EP1}	80,21	ae_3	3
11	a_{p4}	4	v_{EP1}	80,21	ae_4	4
12	a_{p4}	4	v_{EP1}	80,21	ae_5	5
13	a_{p4}	4	v_{EP1}	80,21	ae_6	6
14	a_{p4}	4	v_{EP1}	80,21	ae_7	7
15	a_{p4}	4	v_{EP2}	187,17	ae_2	2
16	a_{p4}	4	v_{EP2}	187,17	ae_3	3
17	a_{p4}	4	v_{EP2}	187,17	ae_4	4
18	a_{p4}	4	v_{EP2}	187,17	ae_5	5
19	a_{p4}	4	v_{EP2}	187,17	ae_6	6
20	a_{p4}	4	v_{EP2}	187,17	ae_7	7

- 20 milling runs overall
- Slot milling consisting of
  - Immersion
  - Synchronous milling (Counterclockwise)
- Two different corner velocities (v_{EP}) are tried:
  - Run 1 - 4: v_{EP1} with varying a_p and constant a_e
  - Run 5 - 8: v_{EP2} with varying a_p and constant a_e
  - Run 9 -14: v_{EP1} with constant a_p and varying a_e
  - Run 15 - 20: v_{EP2} with constant a_p and varying a_e

Goal of analysis:
Effect of varying $\boldsymbol{a_e}$, $\boldsymbol{a_p}$ and $\boldsymbol{v_{EP}}$ on positional accuracy and energy consumption

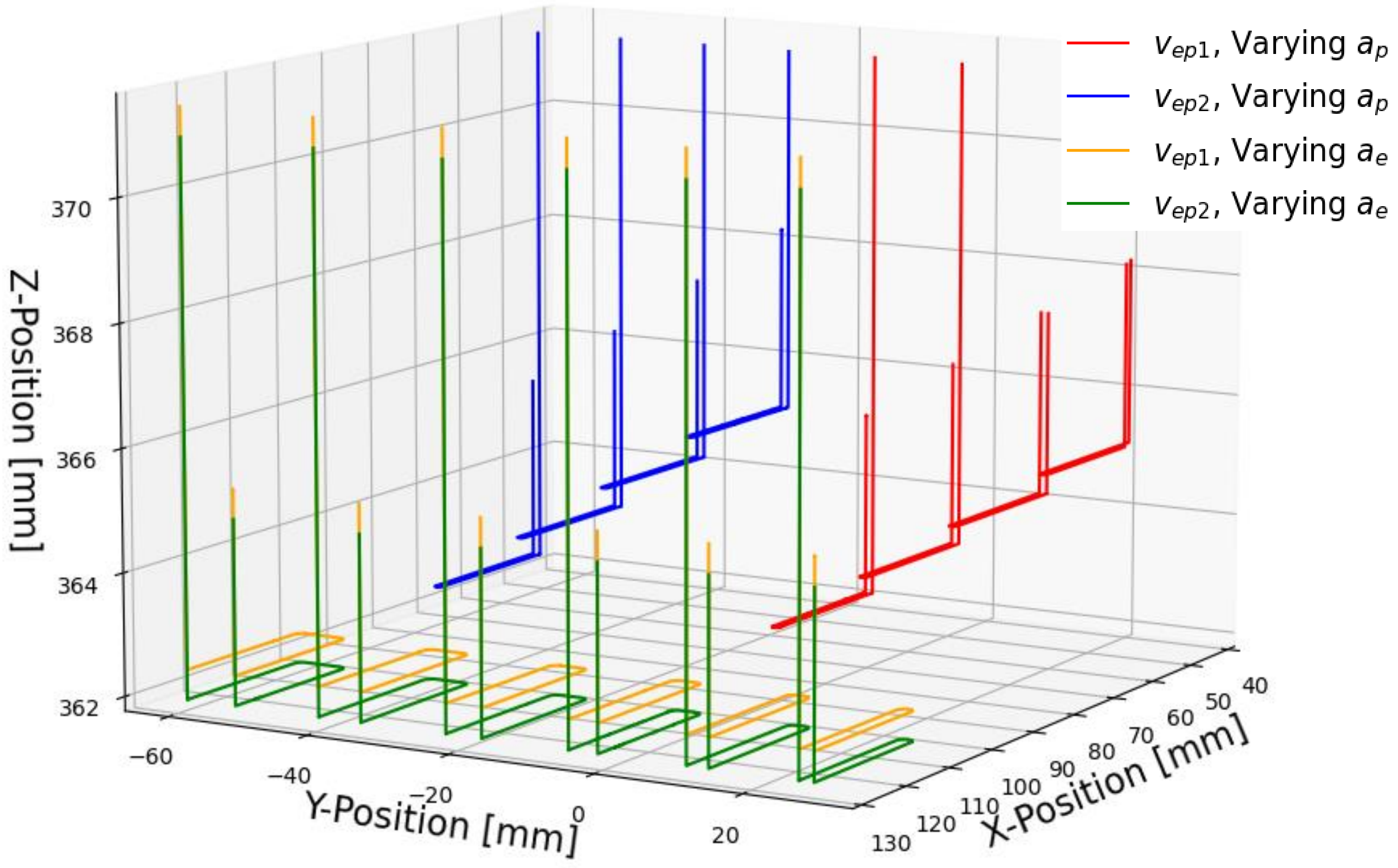
Sketch of Slot Milling Operation



- Sketch shows tool path while performing one-sided extension of slot
- Curve radius of 6 mm with d_{Tool} = 10 mm → simplification makes underlying phenomena easier to understand

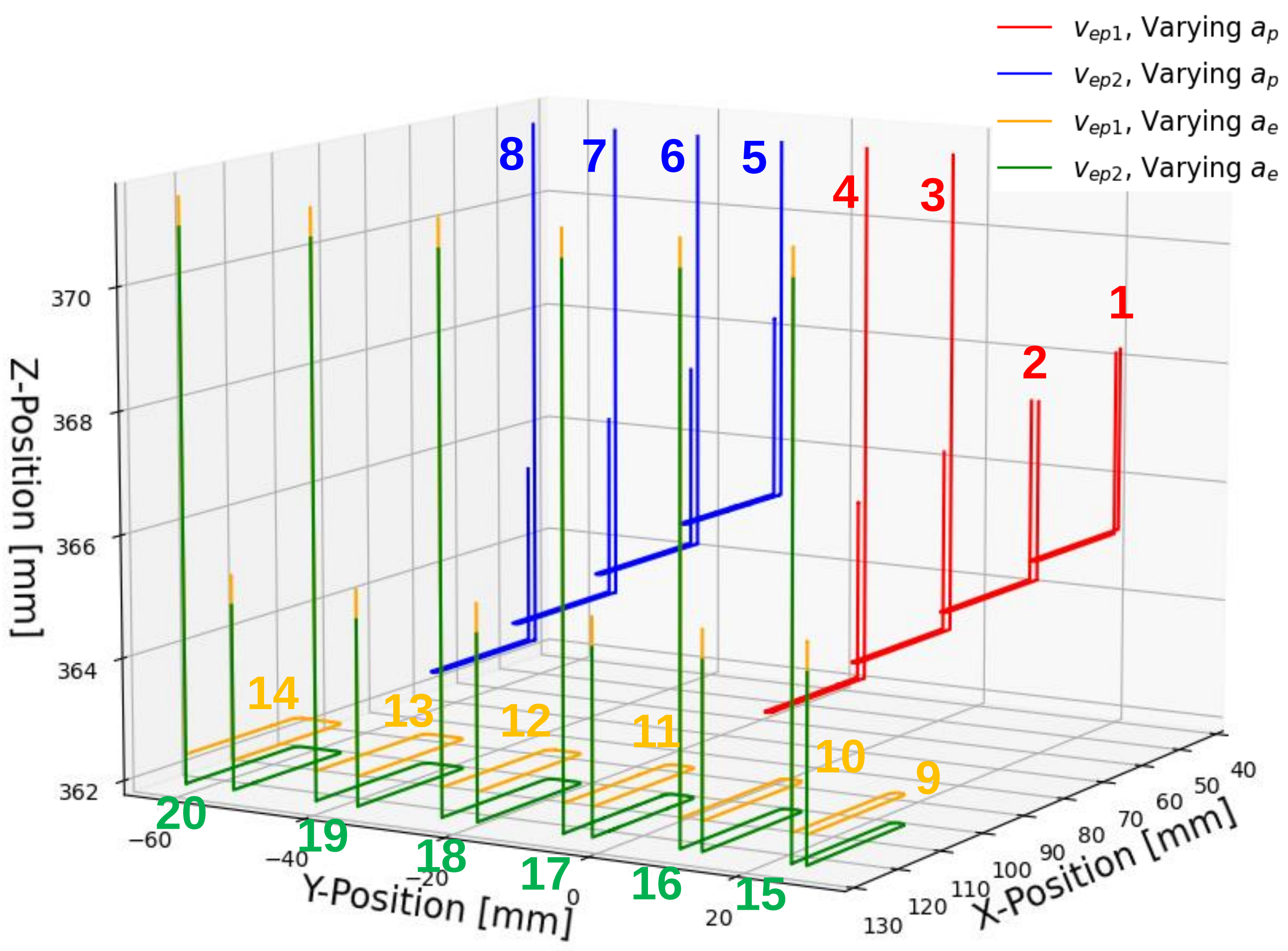
Slot Milling - Introduction

3D Milling Path for all 20 Runs

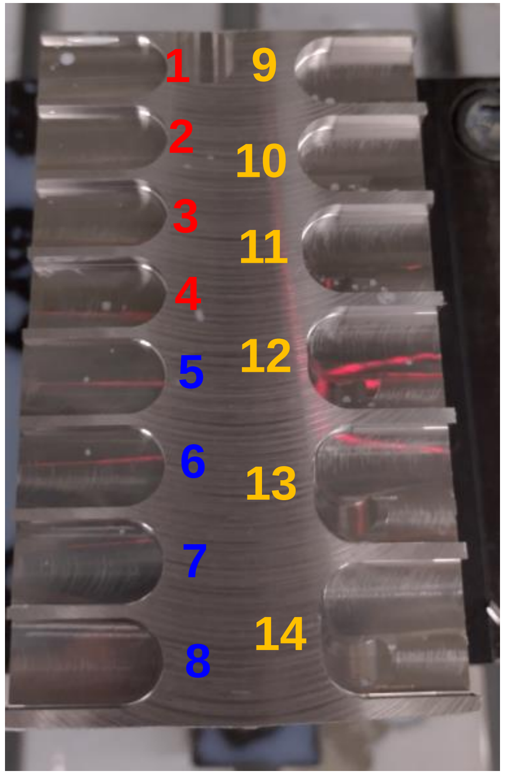


- For runs 1 – 4 and 5 – 8 the a_p-variation has an effect on Z-position
- For runs 9 – 14 and 15 – 20 the a_e-variation has an effect on the breadth of the milling path.

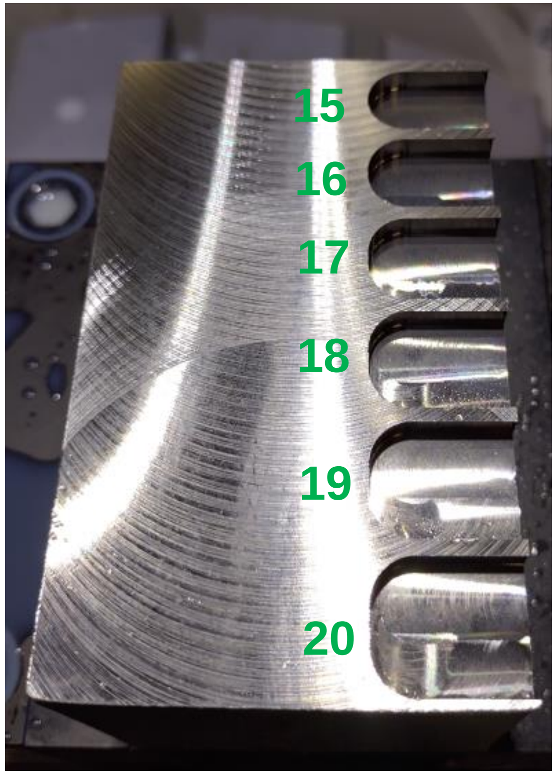
3D Milling Path for all 20 Runs & Position on Workpiece



Workpiece Frontside:



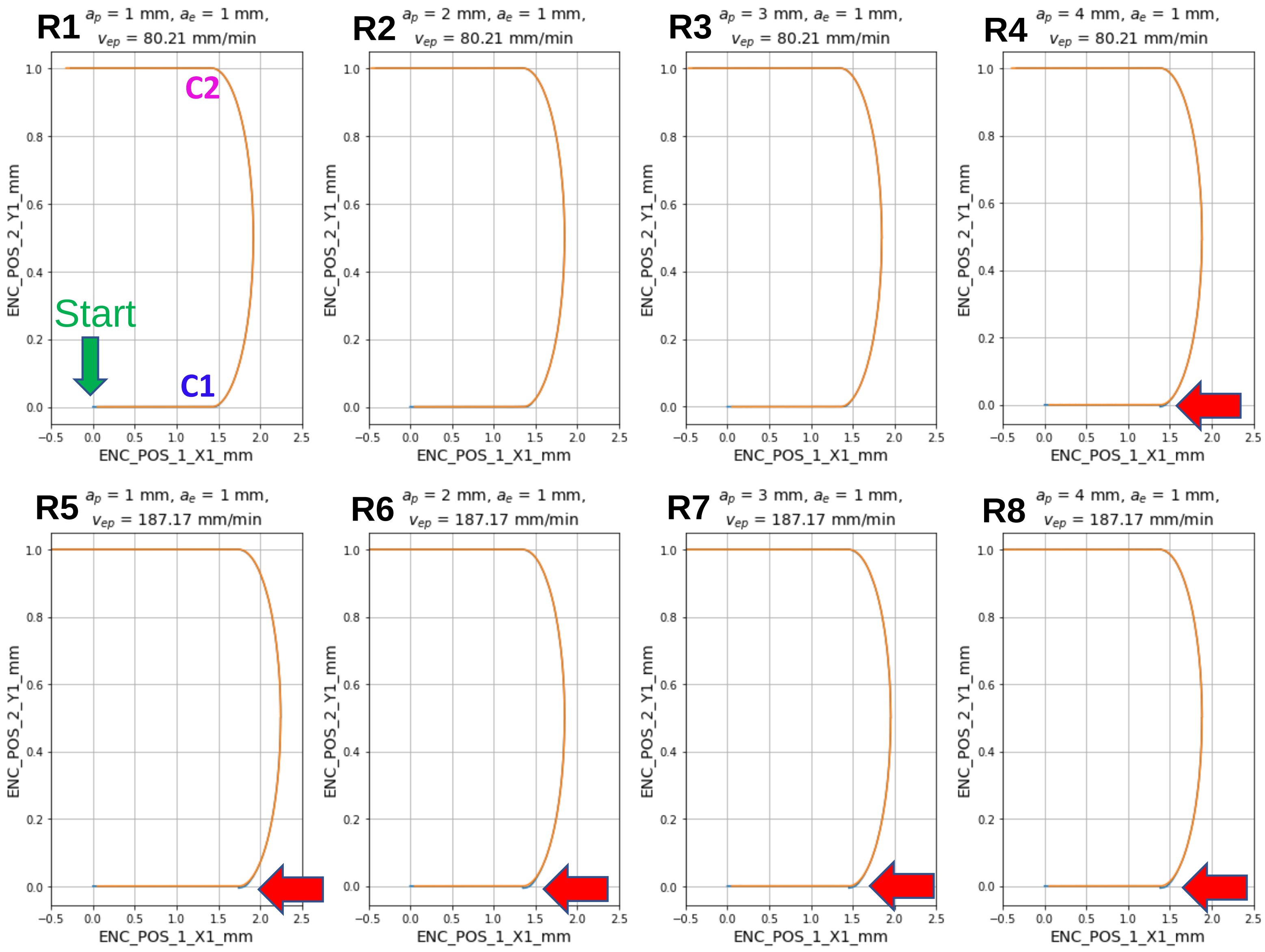
Workpiece Backside:



- After run 14, the workpiece was turned over to mill runs 15 – 20.

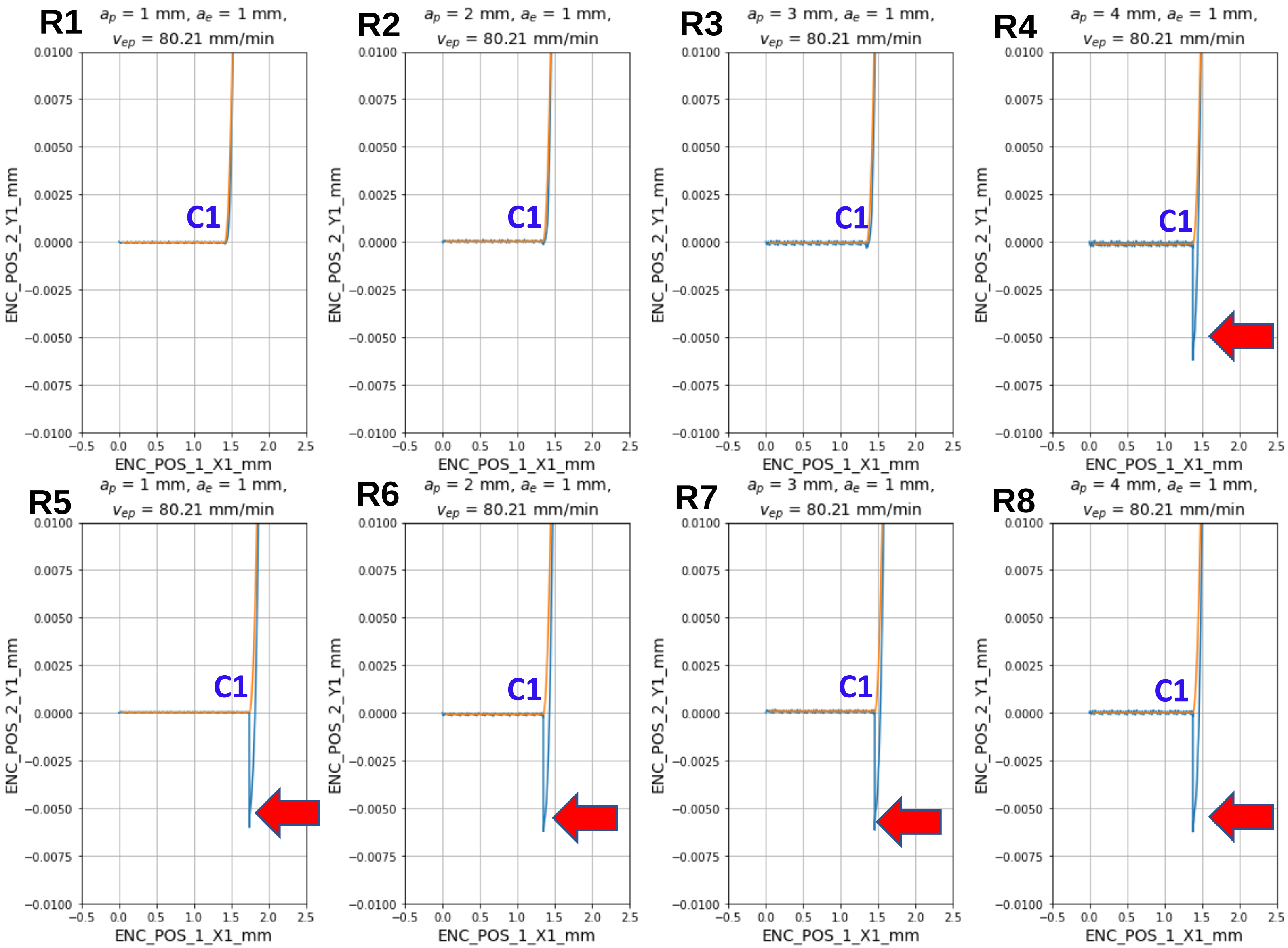
Slot Milling – Positional Accuracy

Runs 1 – 8 (Varying a_p, v_{EP1} & v_{EP2}): Actual vs. Desired Position



- Plot shows actual vs desired XY – position for runs R1 – R8.
- Deviation at first corner C1 for experiments with **high v_{EP}** and for one experiment with low v_{EP} and **a_p = 4 mm.**
- **Zoomed view** on following slide!

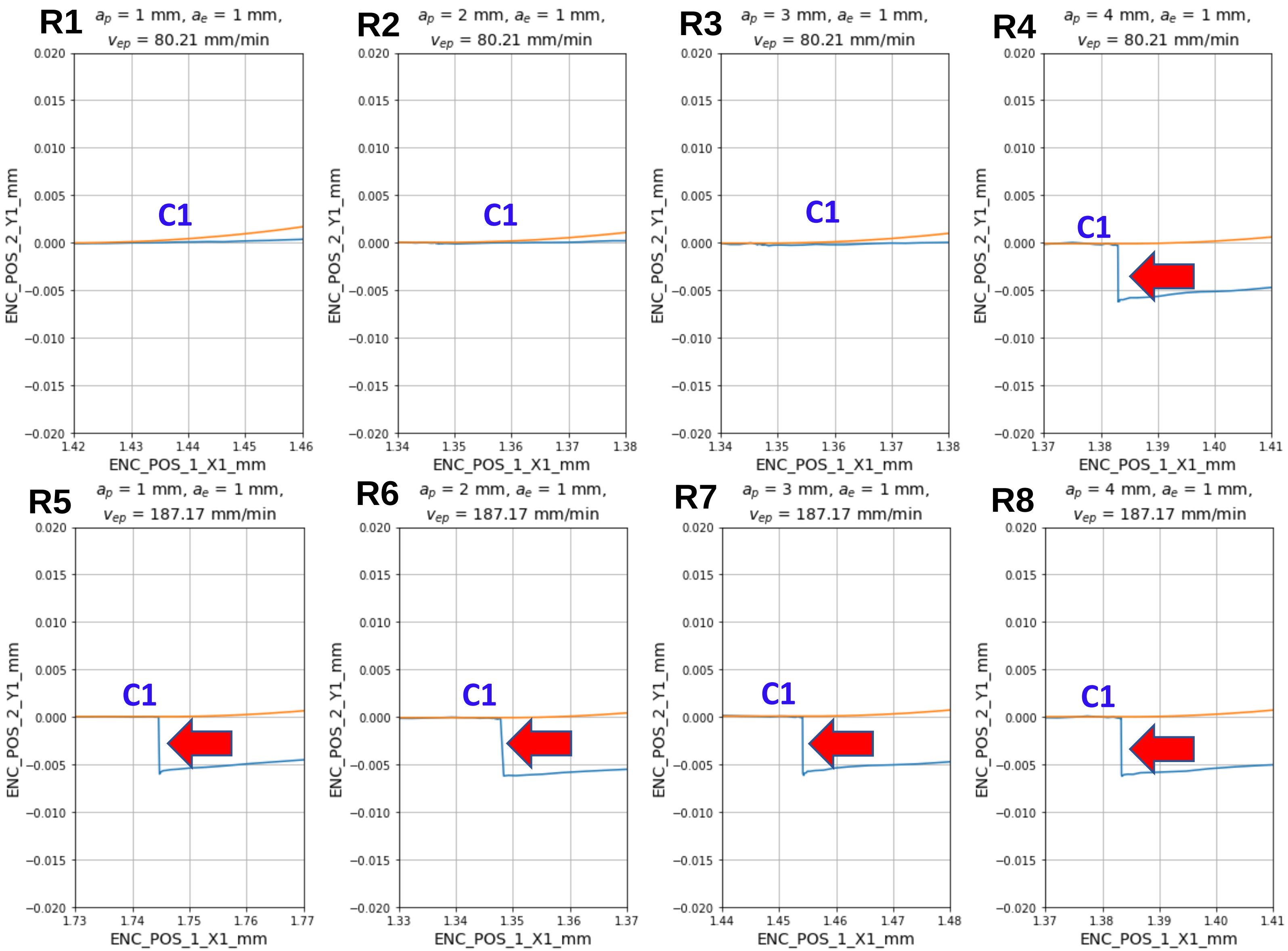
Runs 1 – 8 (Varying a_p, v_{EP1} & v_{EP2}): Actual vs. Desired Position (Zoomed)



- Plot shows actual vs desired XY – position for runs R1 – R8 zoomed for first corner C1.
- Deviation at first corner C1 for experiments with **high v_{EP}** and for one experiment with low v_{EP} and **a_p = 4 mm.**
- Deviation of **~ 0.005 mm (5 µm)** ➔ relevant for surface quality.

Slot Milling – Positional Accuracy

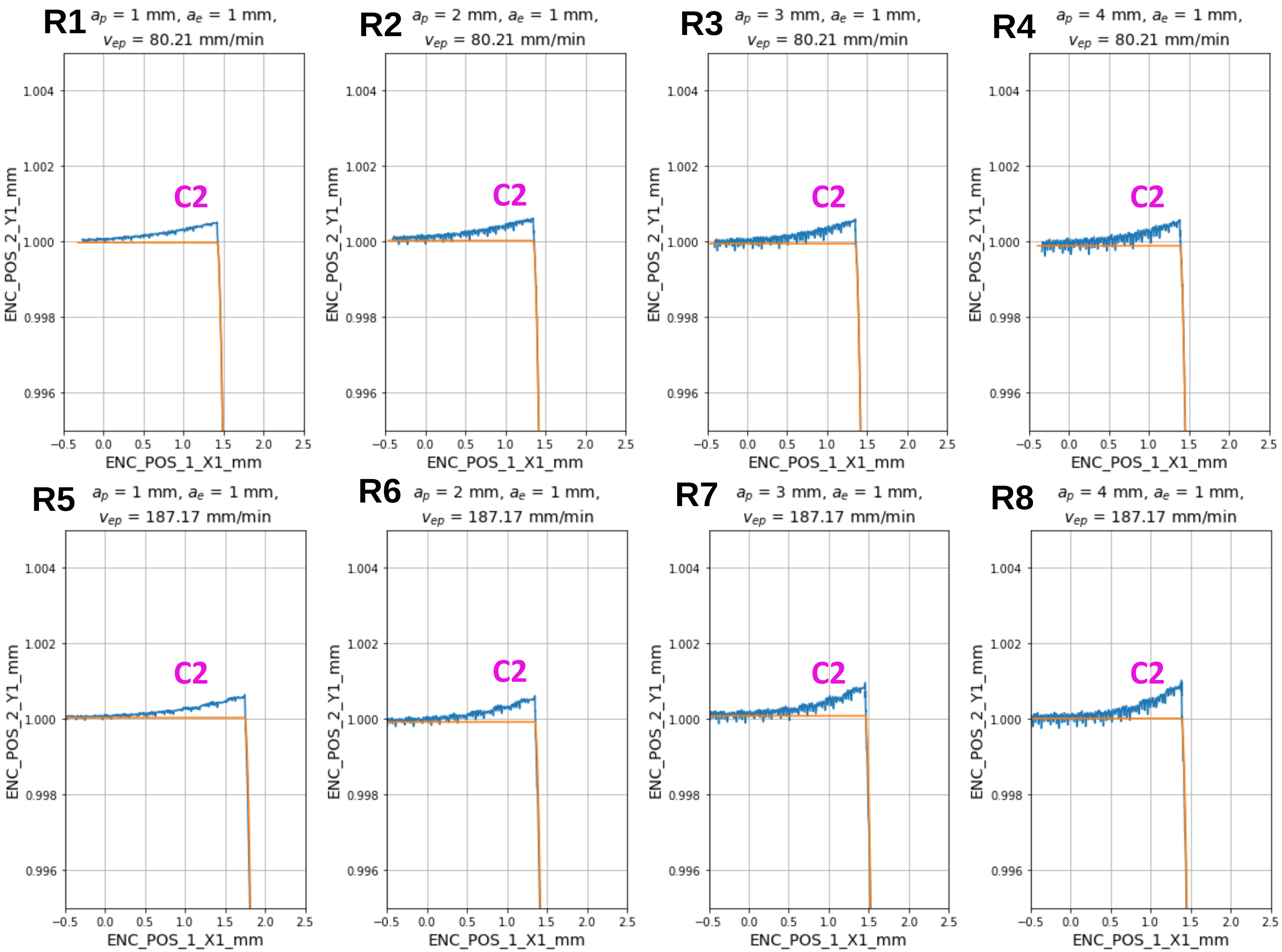
Runs 1 – 8 (Varying a_p, v_{EP1} & v_{EP2}): Actual vs. Desired Position (Zoomed & Rescaled)



- Plot shows actual vs desired XY – position for runs R1 – R8 zoomed for first corner C1.
- Deviation at first corner C1 for experiments with **high v_{EP}** and for one experiment with low v_{EP} and **a_p = 4 mm.**
- Deviation of **~ 0.005 mm (5 µm)** → relevant for surface quality.

Slot Milling – Positional Accuracy

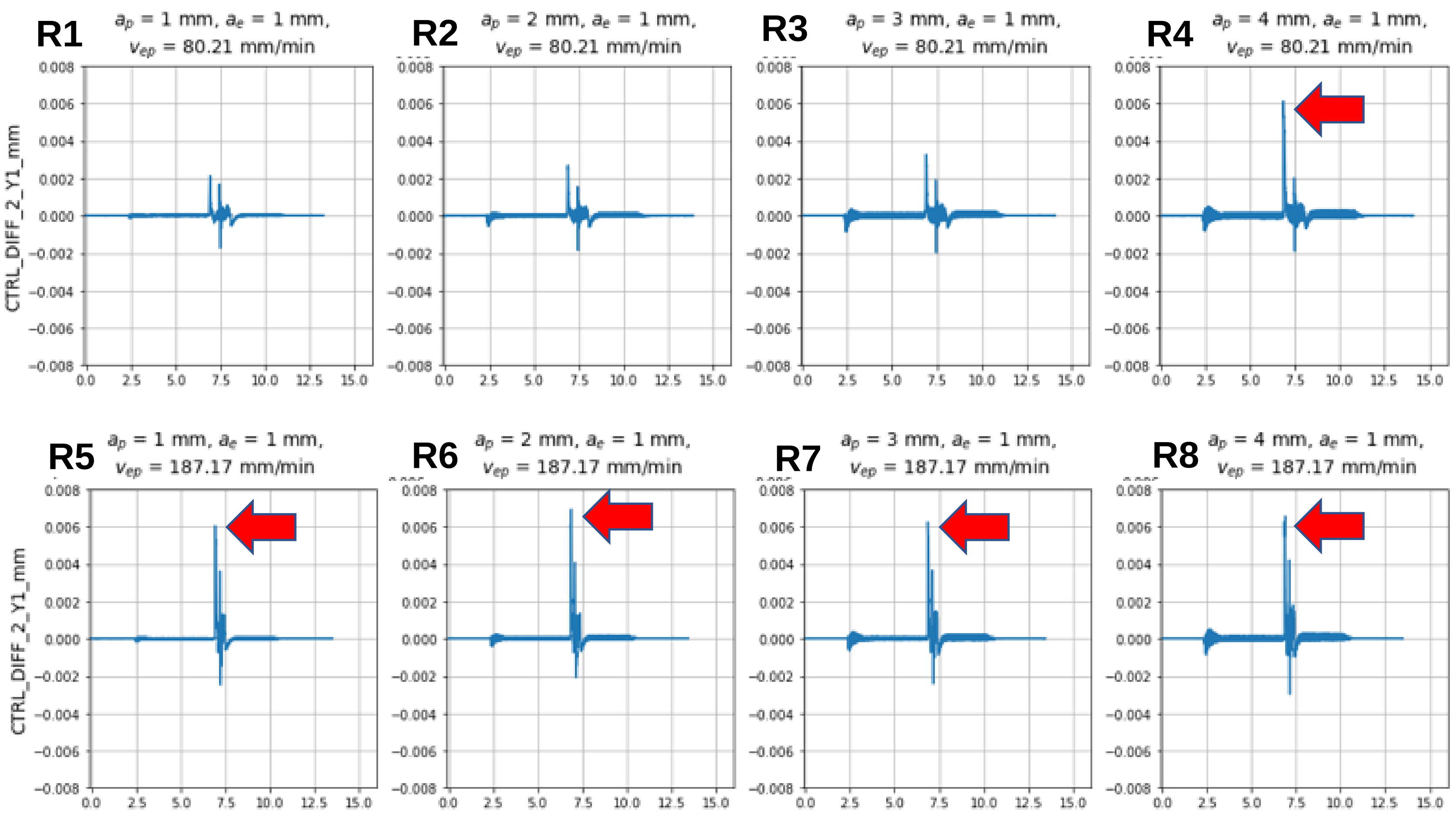
Runs 1 – 8 (Varying a_p, v_{EP1} & v_{EP2}): Actual vs. Desired Position (Zoomed)



- Plot shows actual vs desired XY – position for runs R1 – R8 zoomed for second corner C2.
- Deviation at second corner C2 for all experiments.
- Deviation of **~ 0.001 mm (1 µm).**

Slot Milling – Positional Accuracy

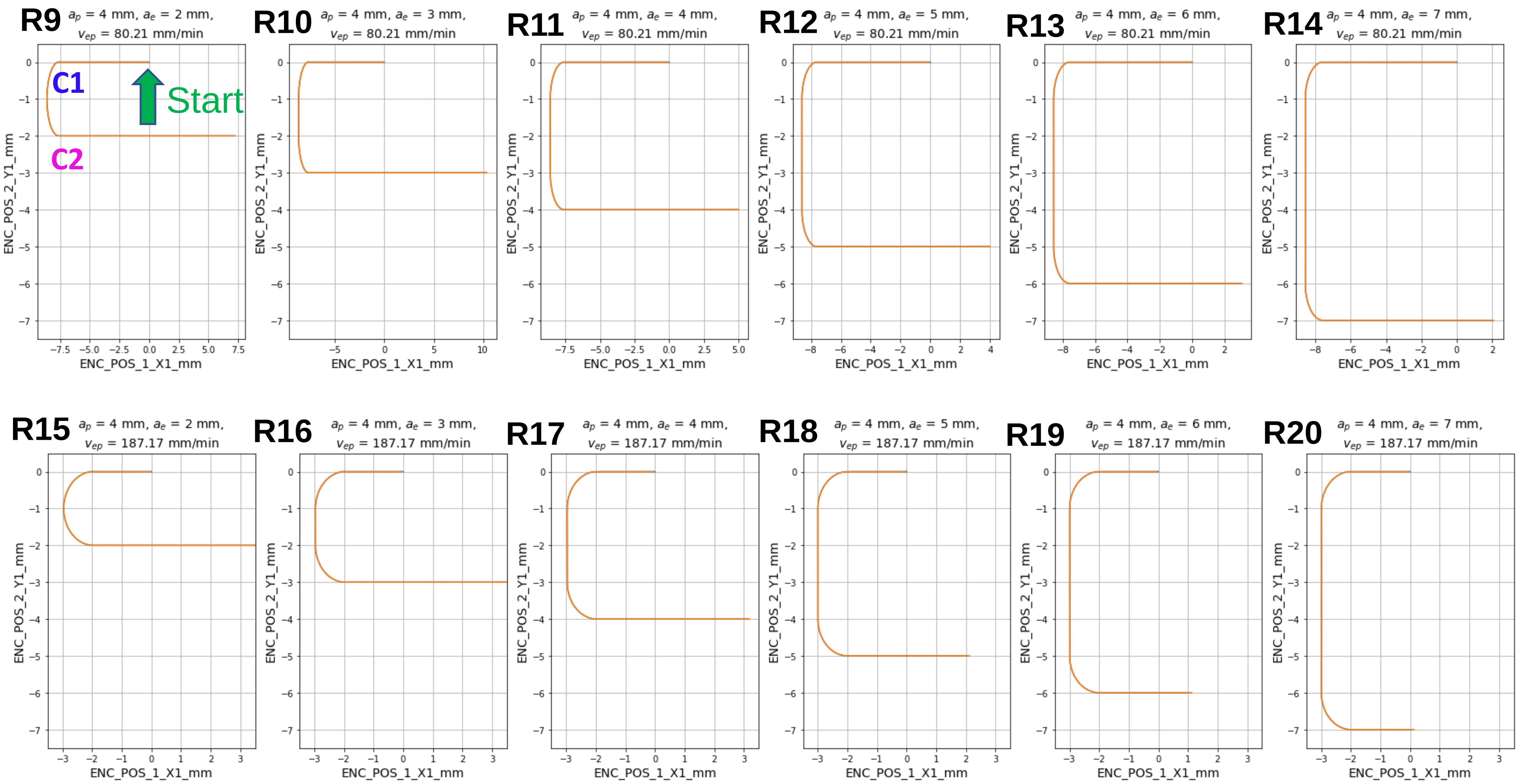
Runs 1 – 8 (Varying a_p, v_{EP1} & v_{EP2}): Control Difference in Y-direction



- Increased value in control difference in Y-direction is indicator of anomaly in first turn
- Threshold value of 0.006 mm could be used for detection.

Slot Milling – Positional Accuracy

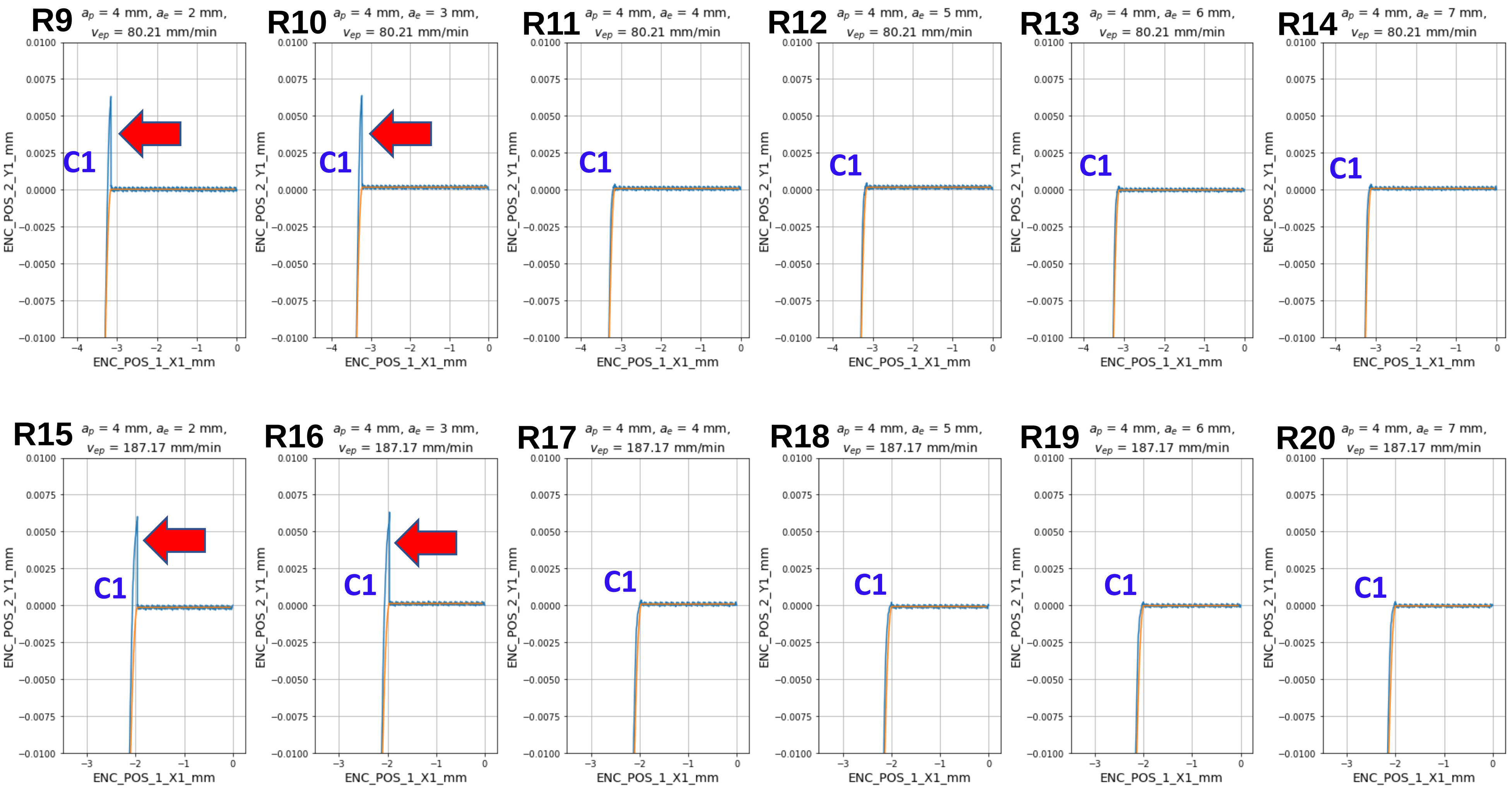
Runs 9 – 20 (Varying a_e, v_{EP1} & v_{EP2}): Actual vs. Desired Position



- Plot shows actual vs desired XY – position for runs R9 – R20.
- **Zoomed view** on following slide!

Slot Milling – Positional Accuracy

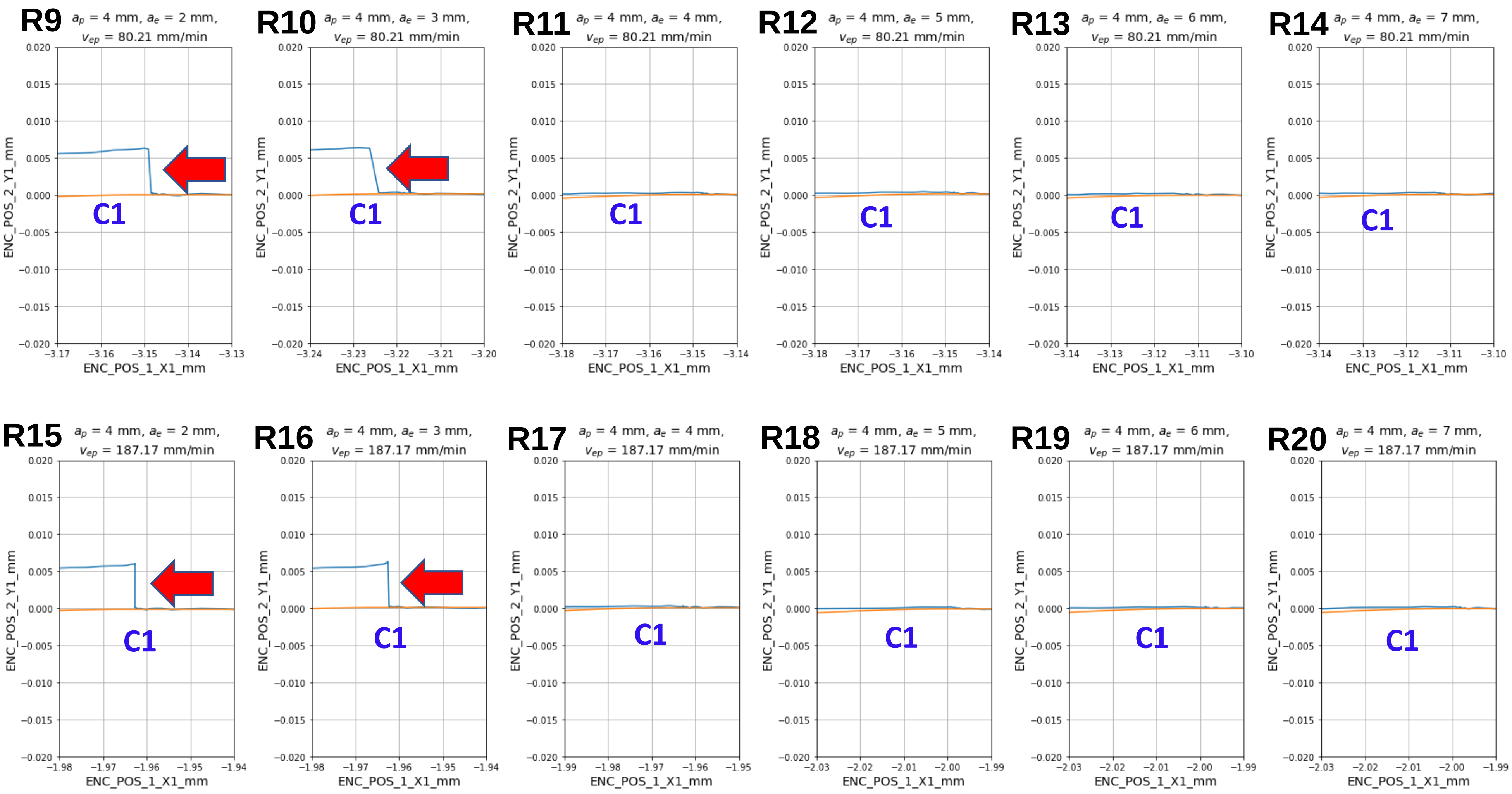
Runs 9 – 20 (Varying a_e, v_{EP1} & v_{EP2}): Actual vs. Desired Position (Zoomed)



- Plot shows actual vs desired XY – position for runs R9 – R20 zoomed on first corner.
- Deviation at first corner C1 for experiments with **a_e = 2 & 3 mm independent of v_{EP}**
- Deviation of **~ 0.005 mm (5 µm) →** relevant for surface quality.

Slot Milling – Positional Accuracy

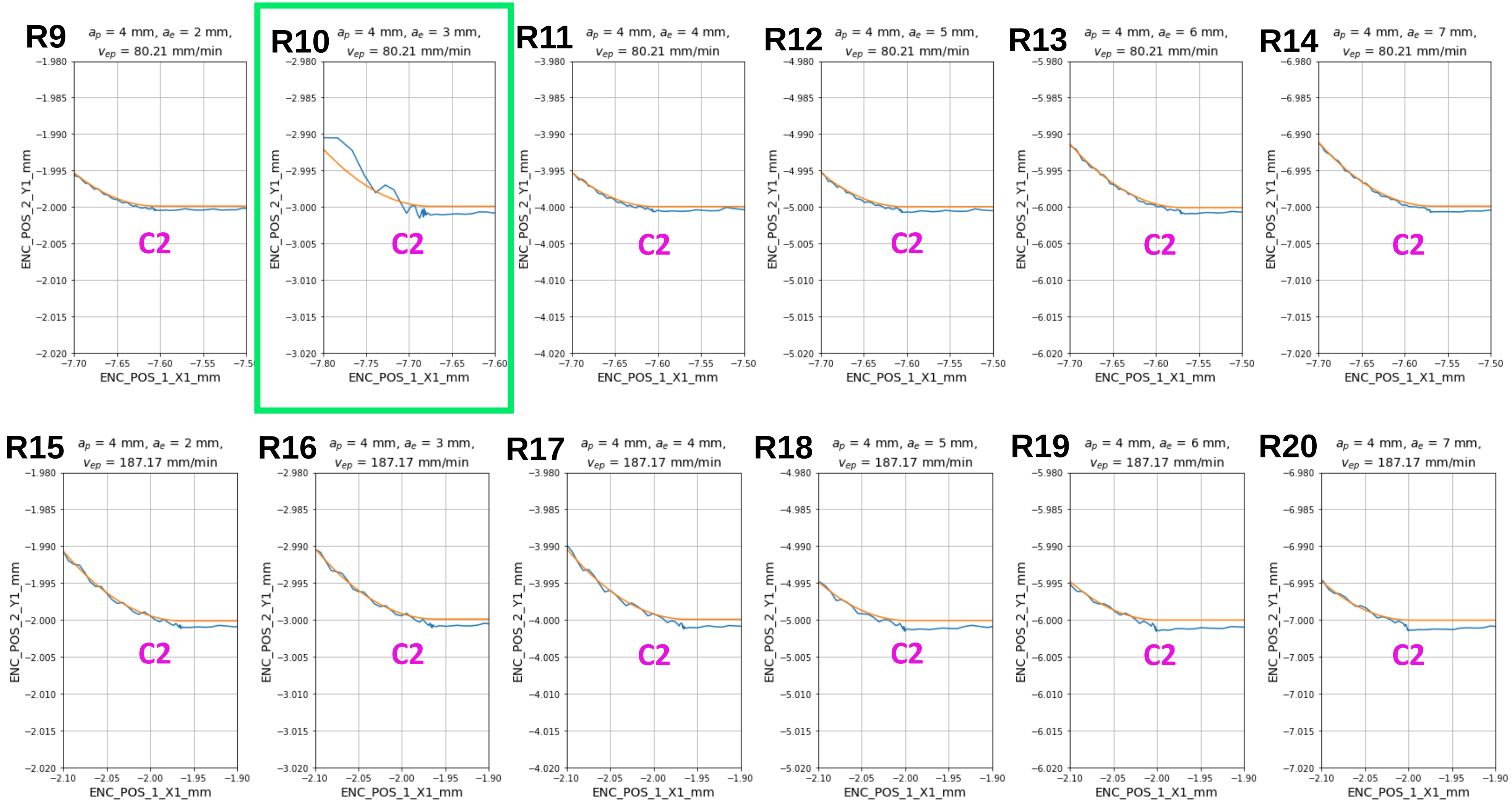
Runs 9 – 20 (Varying a_e, v_{EP1} & v_{EP2}): Actual vs. Desired Position (Zoomed & Rescaled)



- Plot shows actual vs desired XY – position for runs R9 – R20 zoomed on first corner C1.
- Deviation at first corner C1 for experiments with ***a*_*e*** **= 2 & 3 mm independent of *v*_*EP***
- Deviation of **~ 0.005 mm (5 µm) →** relevant for surface quality.

Slot Milling – Positional Accuracy

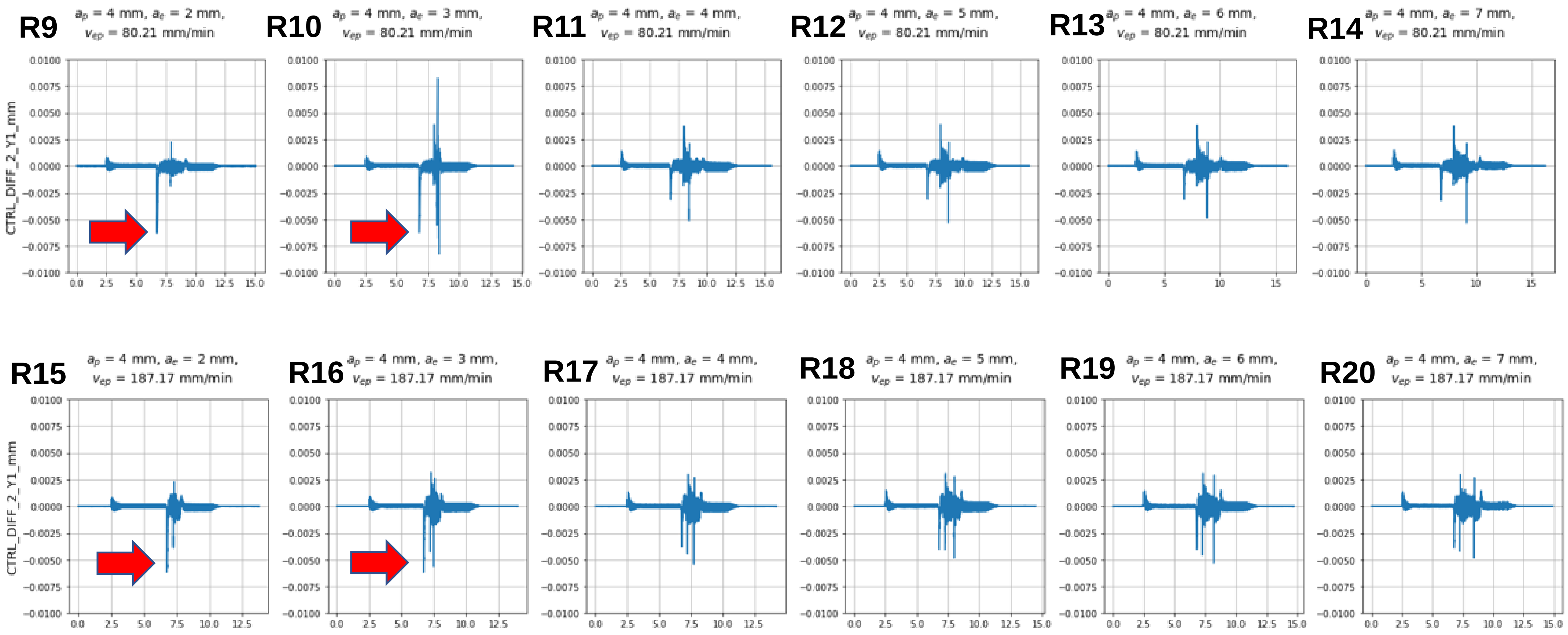
Runs 9 – 20 (Varying a_e, v_{EP1} & v_{EP2}): Actual vs. Desired Position (Zoomed)



- Plot shows actual vs desired XY – position for runs R9 – R20 zoomed on second corner C2.
- Deviation at second corner C2 for all experiments.
- Deviation of ~ **0.001 mm (1 µm).**
- Increased inaccuracy for run 10.

Slot Milling – Positional Accuracy

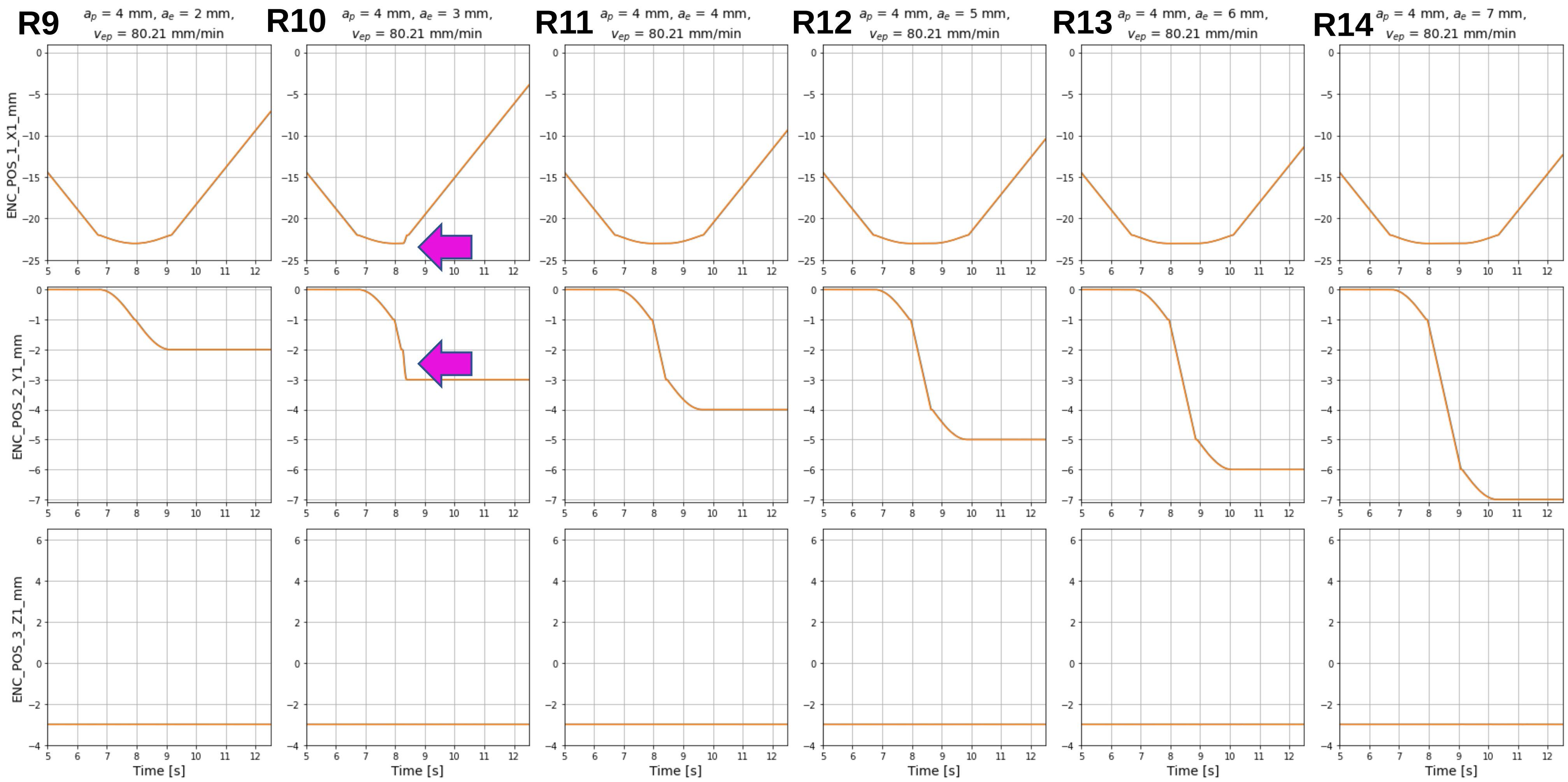
Runs 9 – 20 (Varying a_e, v_{EP1} & v_{EP2}): Control Difference in Y-direction



- Increased value in control difference in Y-direction is indicator of anomaly in first turn.
- Threshold value of 0.006 mm could be used for detection.

Slot Milling – Positional Accuracy

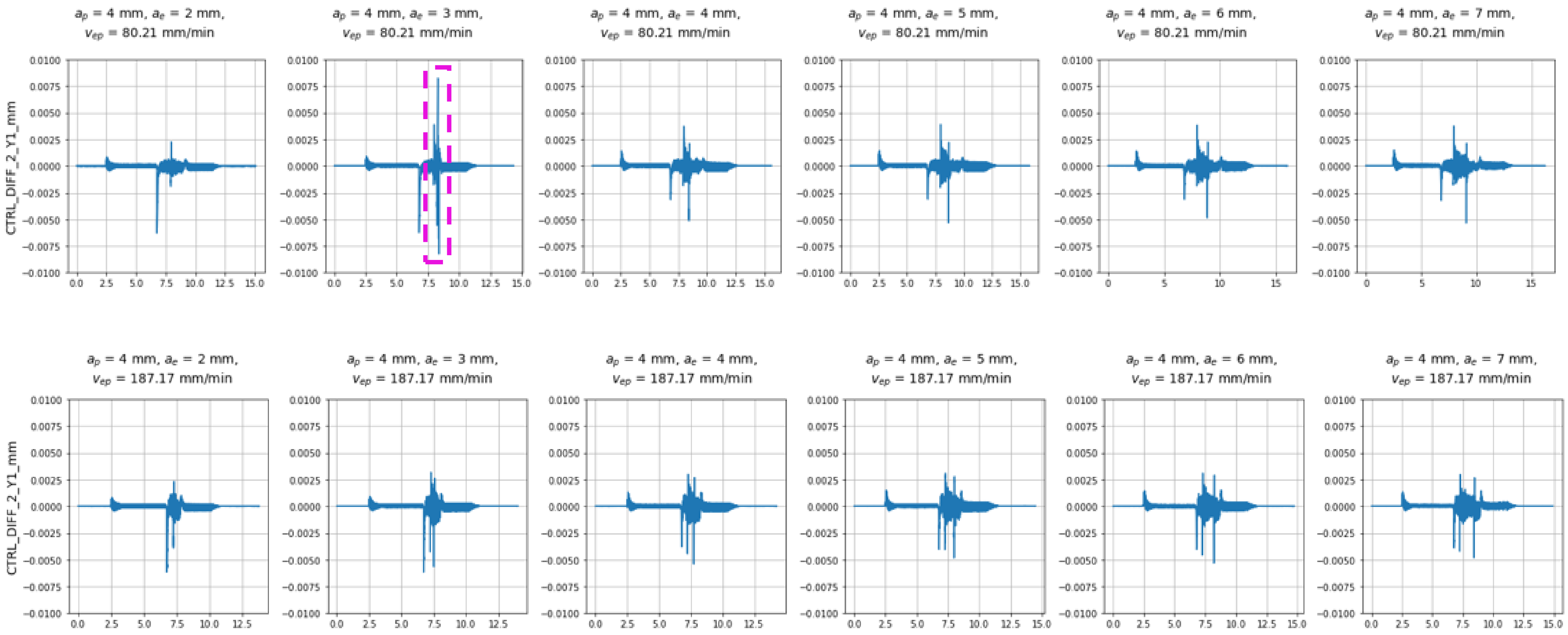
Runs 9 – 14 (Varying a_e, v_{EP1}): Actual vs. Desired Position for Center of Slot



- Plot shows actual vs desired X,Y,Z-position for runs R9 – R14.
- Asymmetric milling path for run 10.
- No deviation between actual and desired position → CAM?

Slot Milling – Positional Accuracy

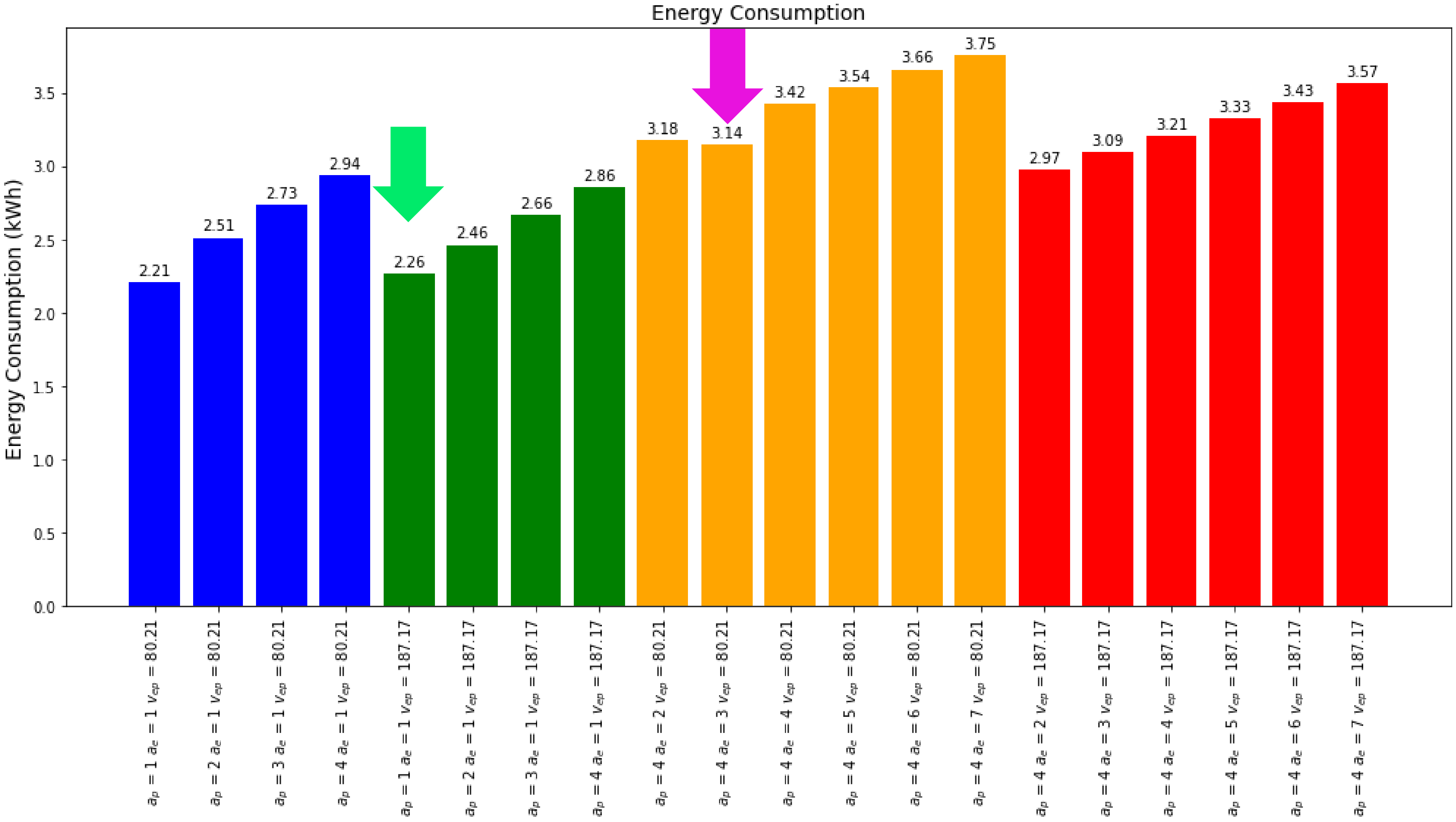
Runs 9 – 20 (Varying a_e, v_{EP1} & v_{EP2}): Control Difference in Y-direction



- Increased value in control difference in Y-direction is indicator of asymmetric milling path

Slot Milling – Energy Consumption

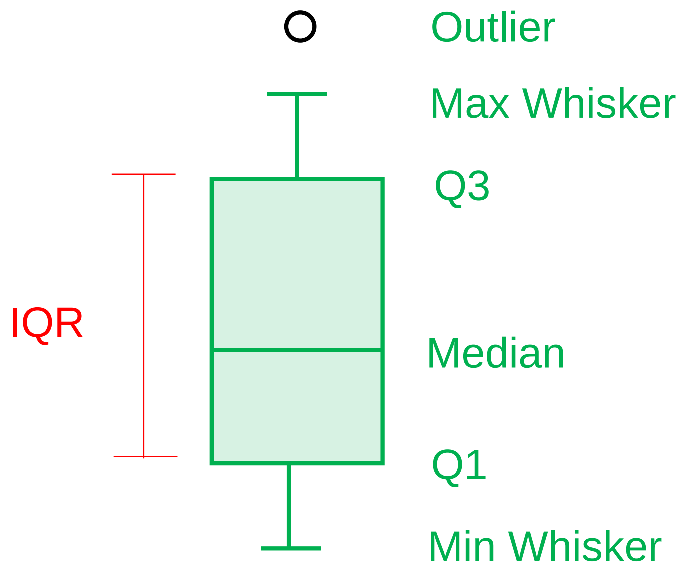
Energy consumption for all runs



- Energy consumption is calculated through integration of spindle power channel and divide by 360 → kWh
- Energy consumption increases with a_p and a_e (except assymetric path)
- Higher v_{EP} (run 5-8, 15-20) leads to lower energy consumption due to shorter processing time → **lowest** for run 6.

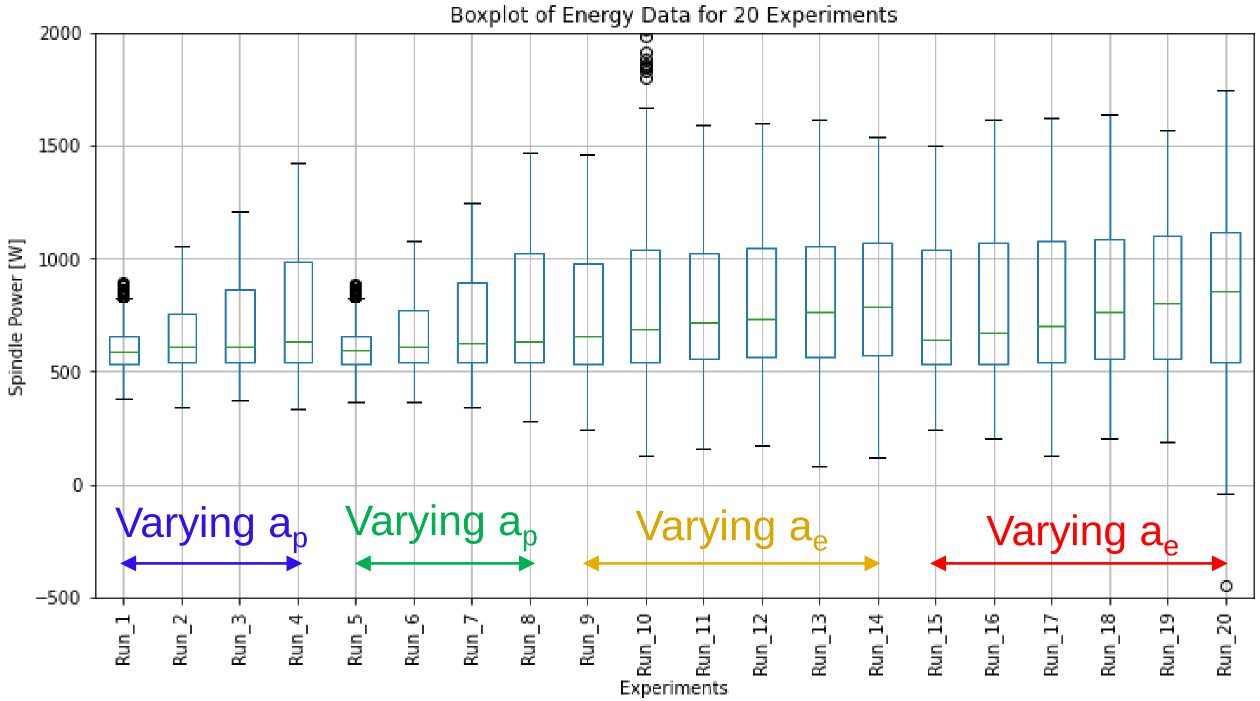
Box plots for spindle power for all runs

Box Plot Explanation



- Q1: lowest 25% of data are below this point
- Q3: lowest 75% of data are below this point
- Whisker: last point within 1.5 * IQR
- Outliers: Data points outside of 1.5 * IQR

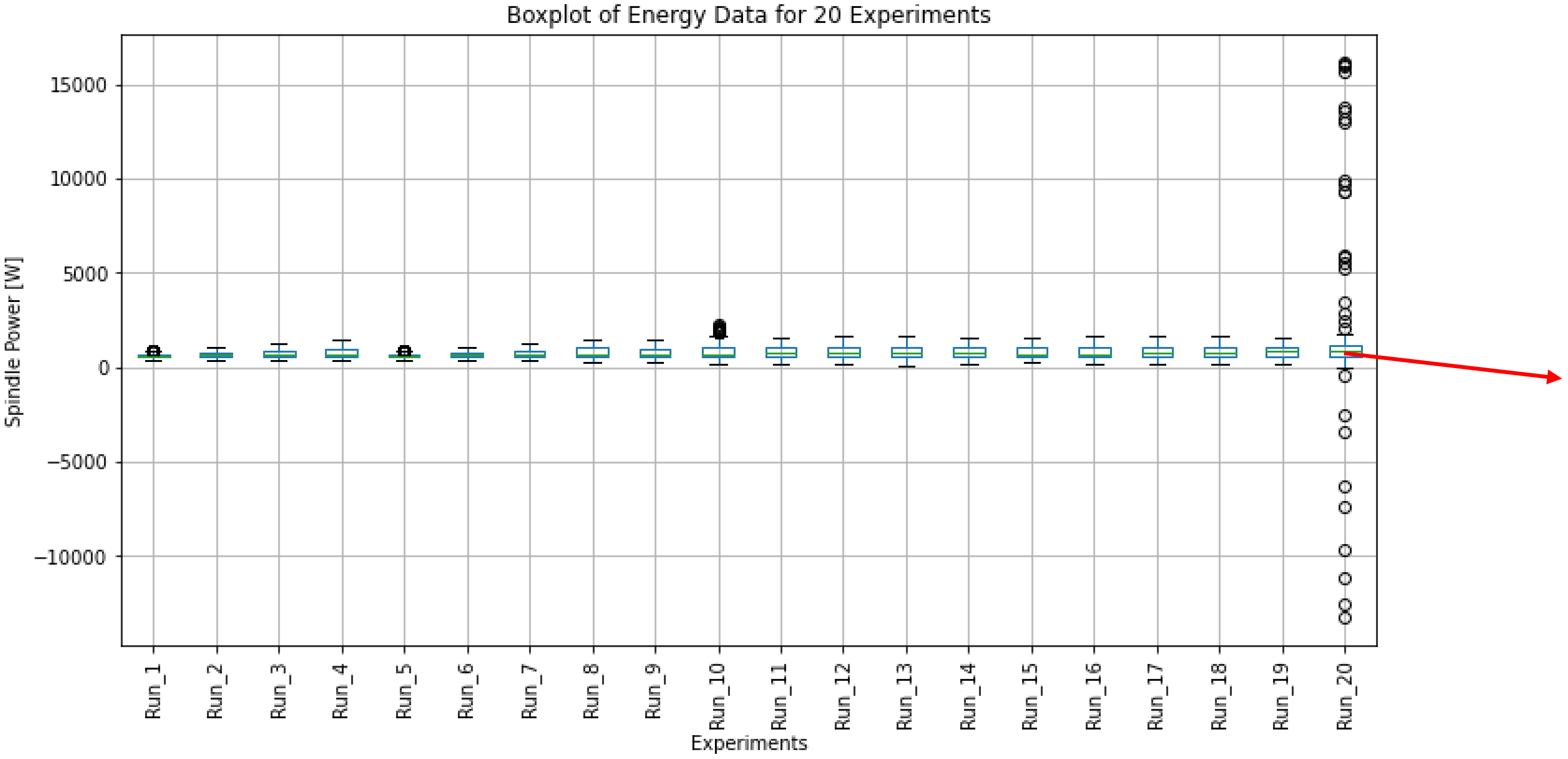
Box Plot for all runs (zoomed)



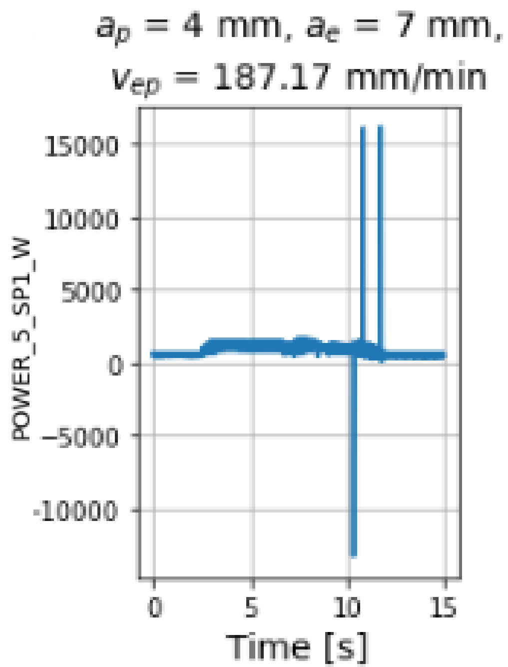
- IQR and distance between whiskers increase with a_p, but not with a_e
- Median increases with both a_p and a_e

Box plots for spindle power for all runs

Box plot for all runs



Run 20



- Box-plot without zoom shows heavy outliers for run 20.
- Plotting spindle power data for run 20 shows very high/low values.

Milling Experiments Performed in „FairMillData“

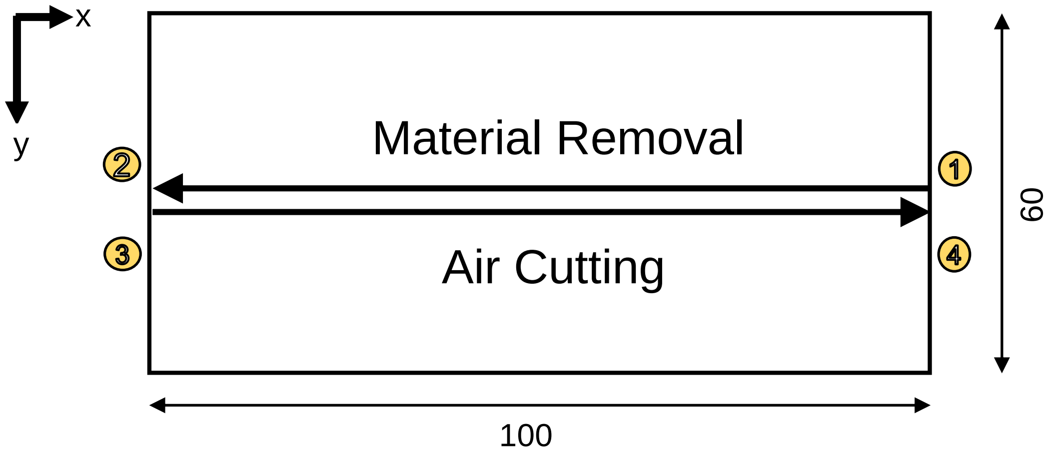
Overview

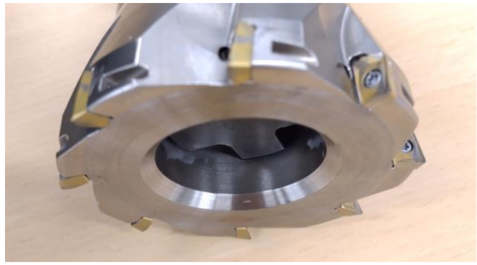
	End Milling	Plunge Milling	Slot milling	Face Milling
Varied Parameters	Radial Depth $\mathbf{a_e}$ Axial Depth $\mathbf{a_p}$	Plunging Strategy	Radial Depth $\mathbf{a_e}$ Axial Depth $\mathbf{a_p}$ Corner Velocity $\mathbf{v_{EP}}$	Feed Rate $\mathbf{v_f}$ Cutting Speed $\mathbf{v_c}$
Number of Experiments (Runs)	10	12	20	48
Tool	End mill (d = 10 mm)	End mill (d = 10 mm)	End mill (d = 10 mm)	Indexable Cutter (d = 80 mm)
Material	1.2083 (X42Cr 13) Stainless Mold Steel			

- **Question:** How do feed rate and cutting speed influence energy consumption?

Experiment Design

	Cutting Speed	Spindle Speed	Feed	Feed per Tooth	Feed Rate
Run Index	v_c [m/min]	n [1/min]	f [mm]	f_z [mm]	v_f [mm/min]
1-8	80,00	318,31	0,80 – 2,48	0,10 – 0,31	254,65 – 789,41
9-16	100,00	397,89	0,80 – 2,48	0,10 – 0,31	318,31 – 986,76
17-24	120,00	477,76	0,80 – 2,48	0,10 – 0,31	381,97 – 1184,11
25-32	80,00 – 108,00	318,31 – 429,72	0,80	0,10	254,65 – 343,77
33-40	80,00 – 108,00	318,31 – 429,72	2,00	0,25	636,62 – 859,44
41-48	80,00 – 108,00	318,31 – 429,72	2,96	0,37	942,20 – 1271,97





$n_{Inserts} = 8$
$d_{Tool} = 80$ mm

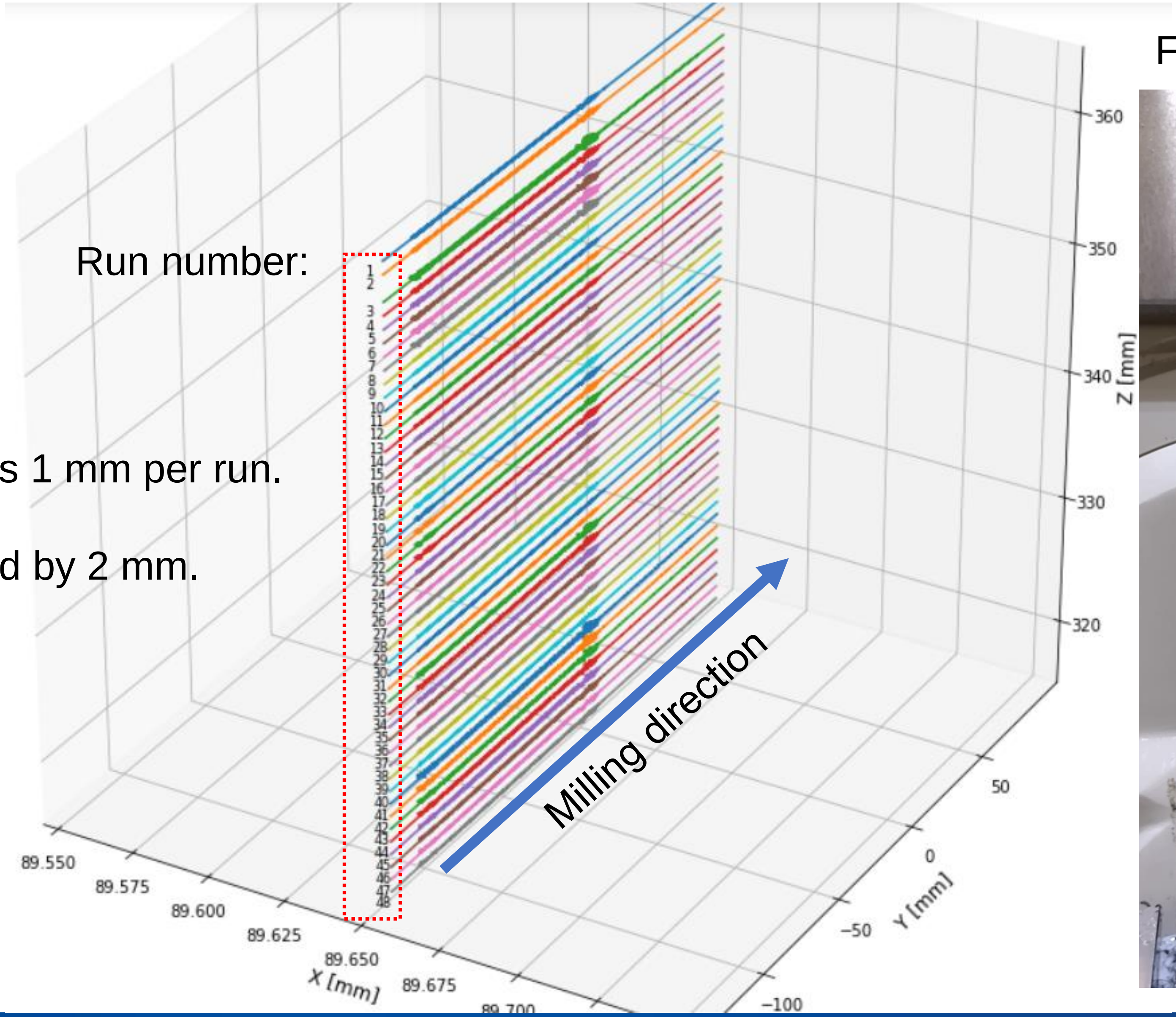
- For runs 1-24, feed parameters are varied with constant cutting speed
- For runs 25 – 48, speed parameters are varied with constant feed

Face Milling - Introduction

Visualization of Milling Path – Tool Center Point

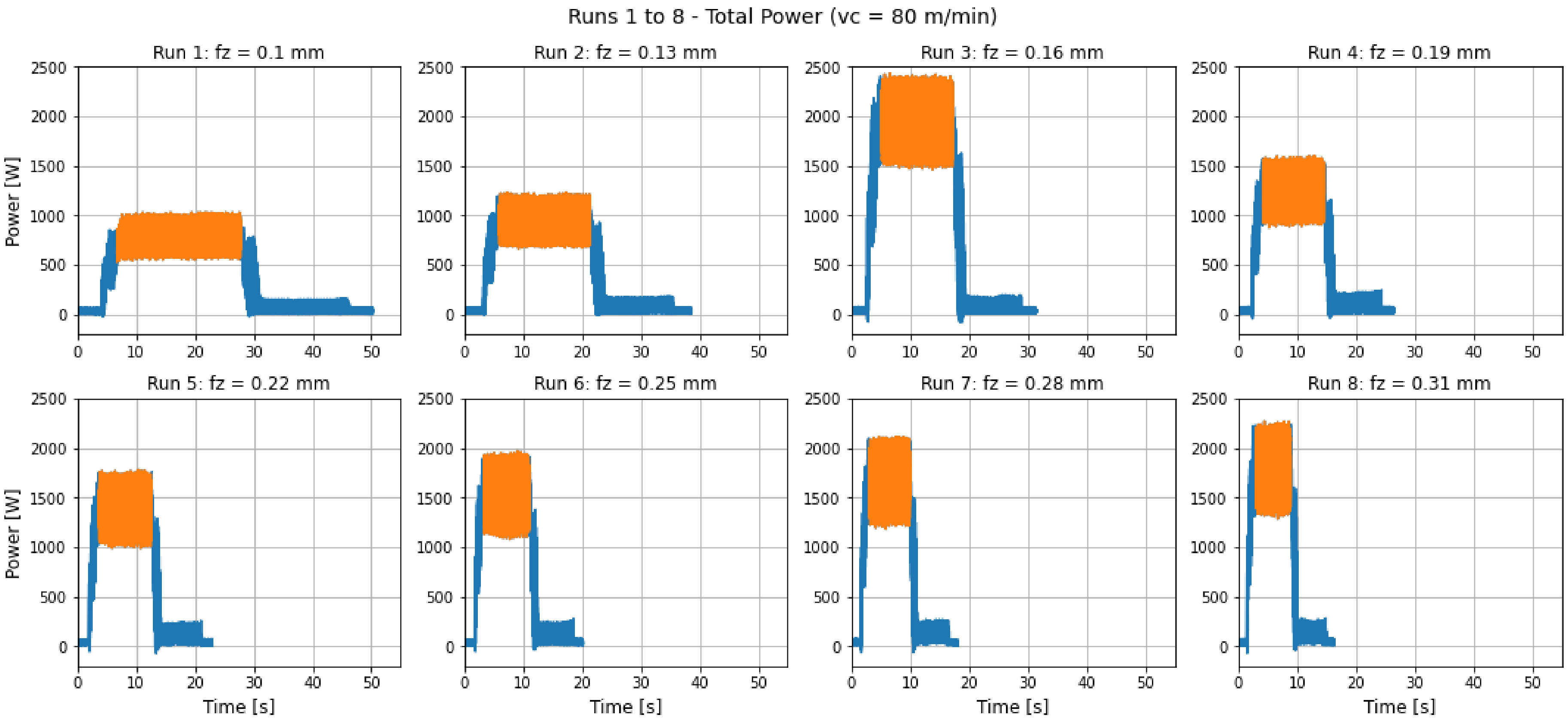
48 runs.
Z level decreases 1 mm per run.
Error for run 3:
Z level decreased by 2 mm.

Run number:

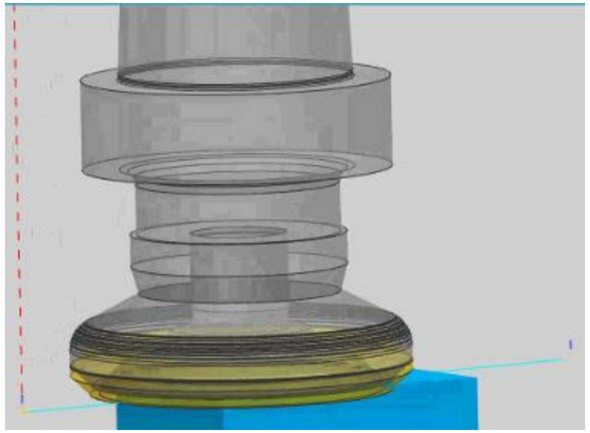


Final workpiece with tool:

Total Power for Runs 1 to 8 (v_c = 80 m/min, f_z = 0.10 – 0.31 mm) – Stable Cutting Phase



CAM Video:

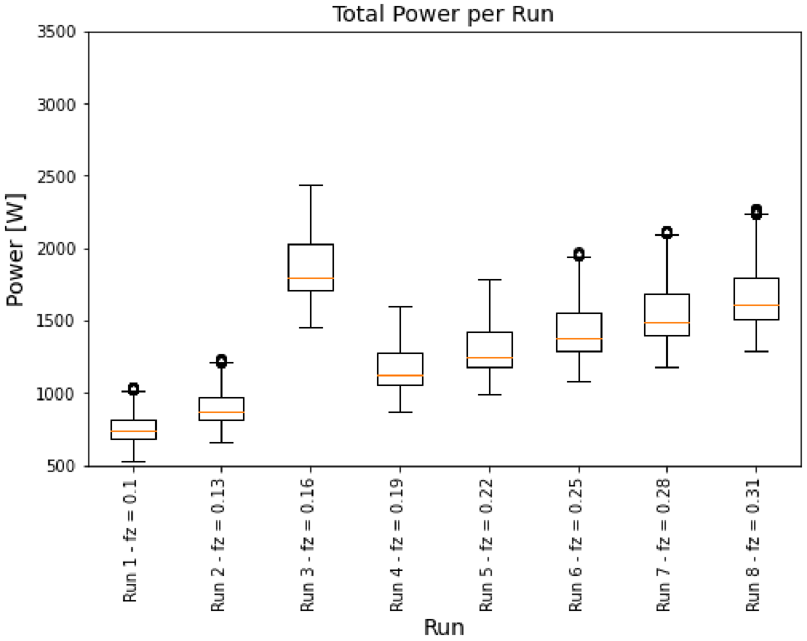


- Segmentation of stable cutting phase for further analysis.

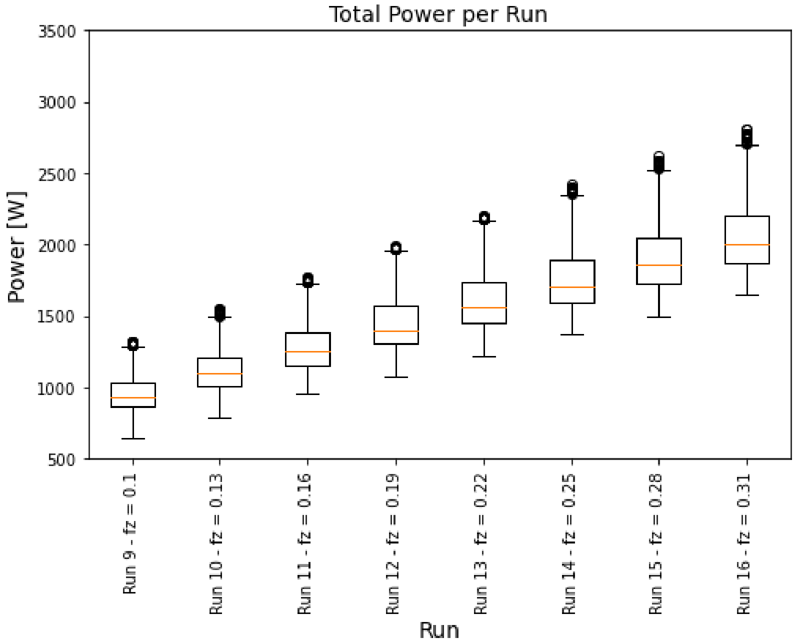
Face Milling – Power Consumption

Box Plots for Total Power for Runs 1 to 24

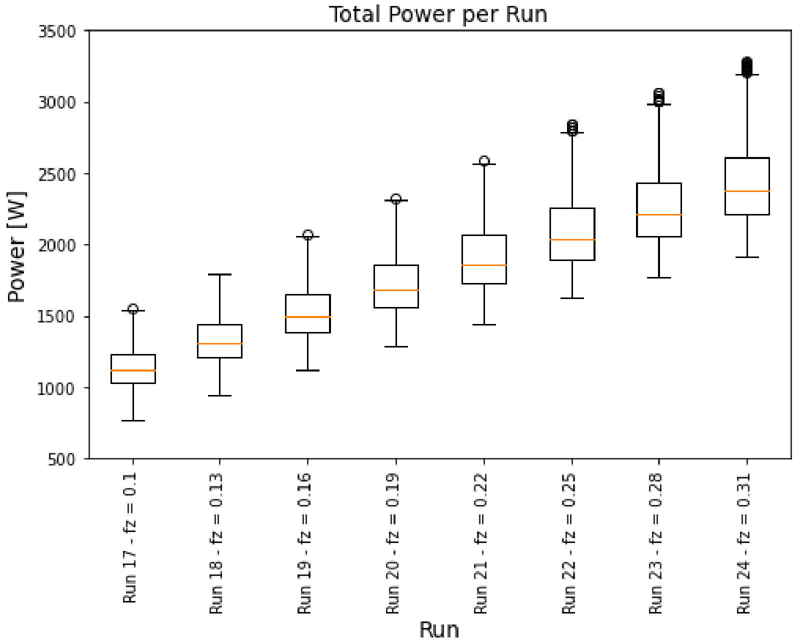
v_c = 80 m/min



v_c = 100 m/min



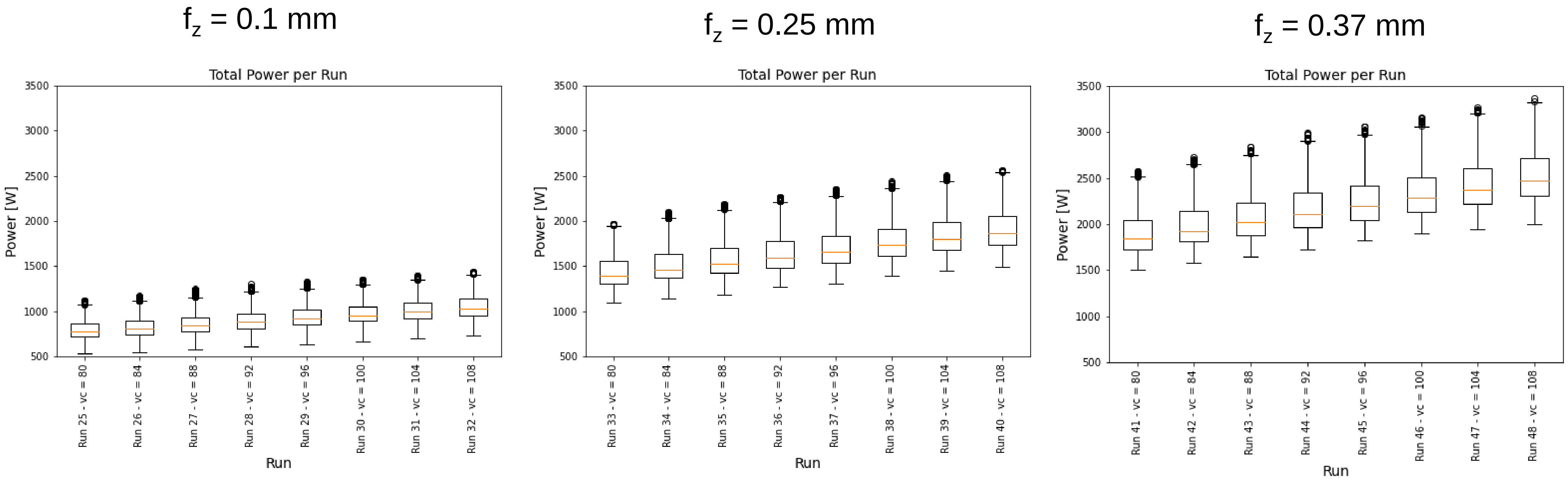
v_c = 120 m/min



- Higher power levels with increasing v_c.
- Median, maximum and minimum increase with f_z
- Width of box and distance between whiskers increases with f_z → increased standard deviation.

Face Milling – Power Consumption

Box Plots for Total Power for Runs 24 to 48

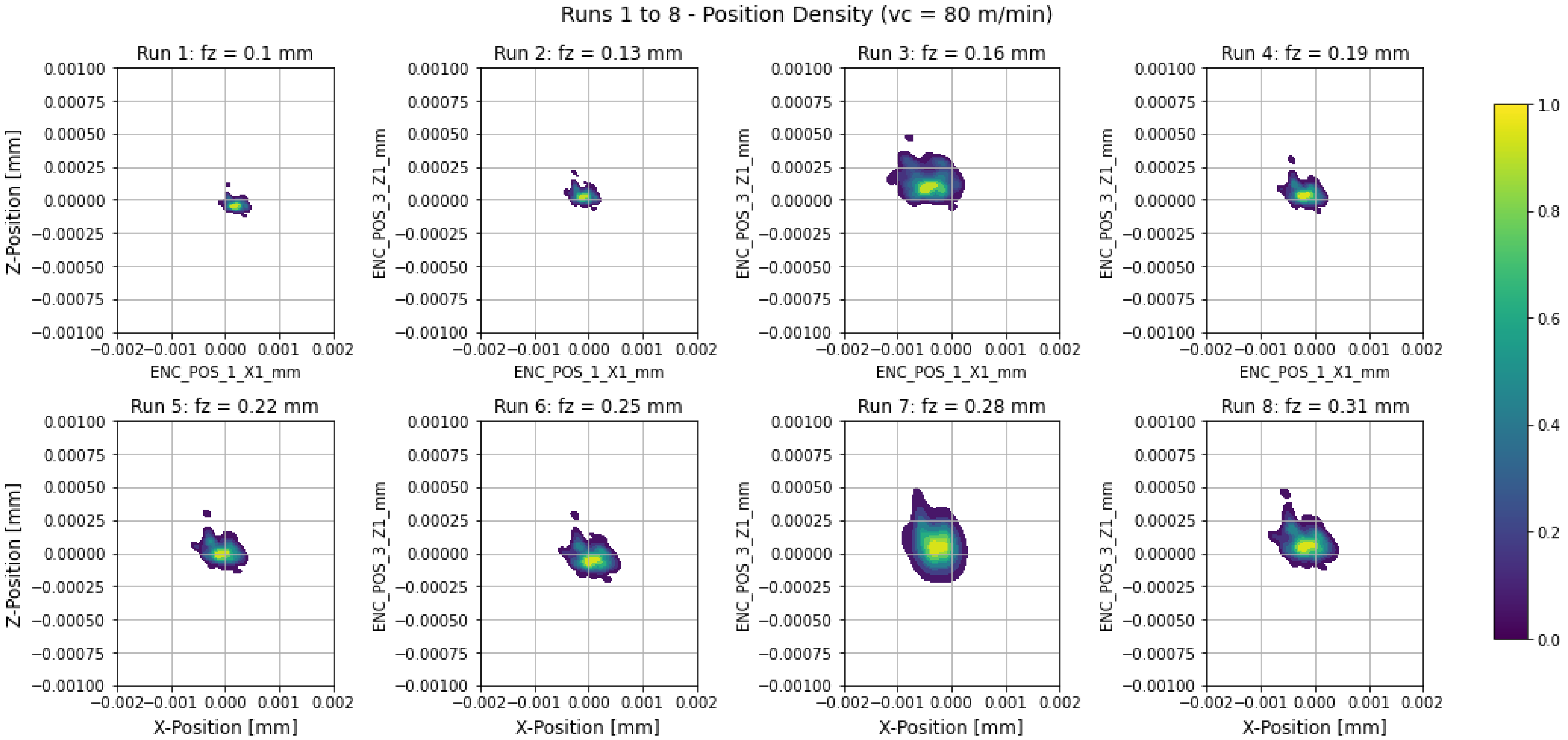


- Higher power levels with increasing f_z.
- Median, maximum and minimum increase with v_c.
- Width of box and distance between whiskers increases with v_c → increased standard deviation.

f_z has more significant impact compared to v_c

Face Milling – Positional Accuracy

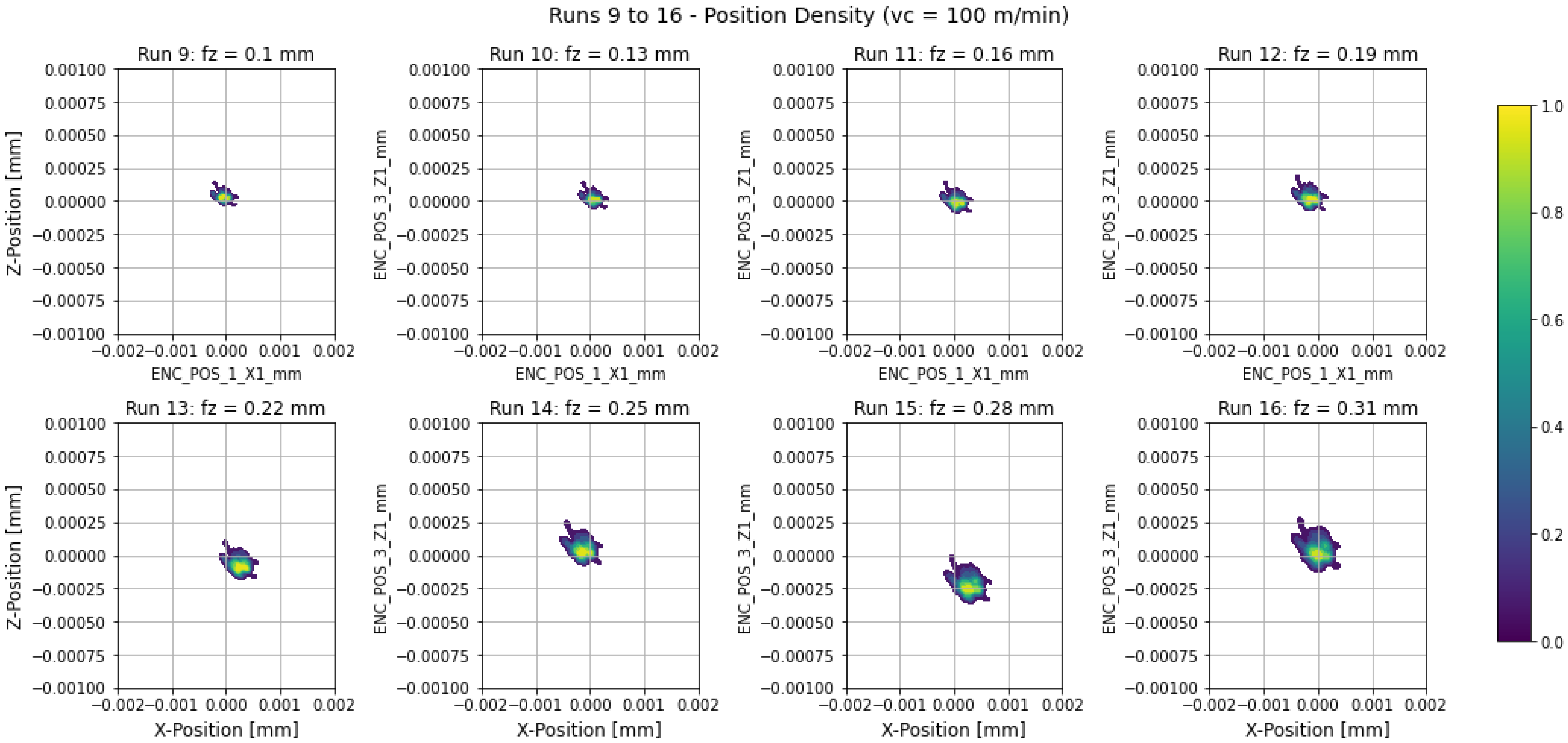
Runs 1 – 8: Density Plot of X,Z-position



- Scattering of X- and Z-position increases with f_z.
- Increased scattering for Run 3 (a_p = 2 mm) and Run 7.

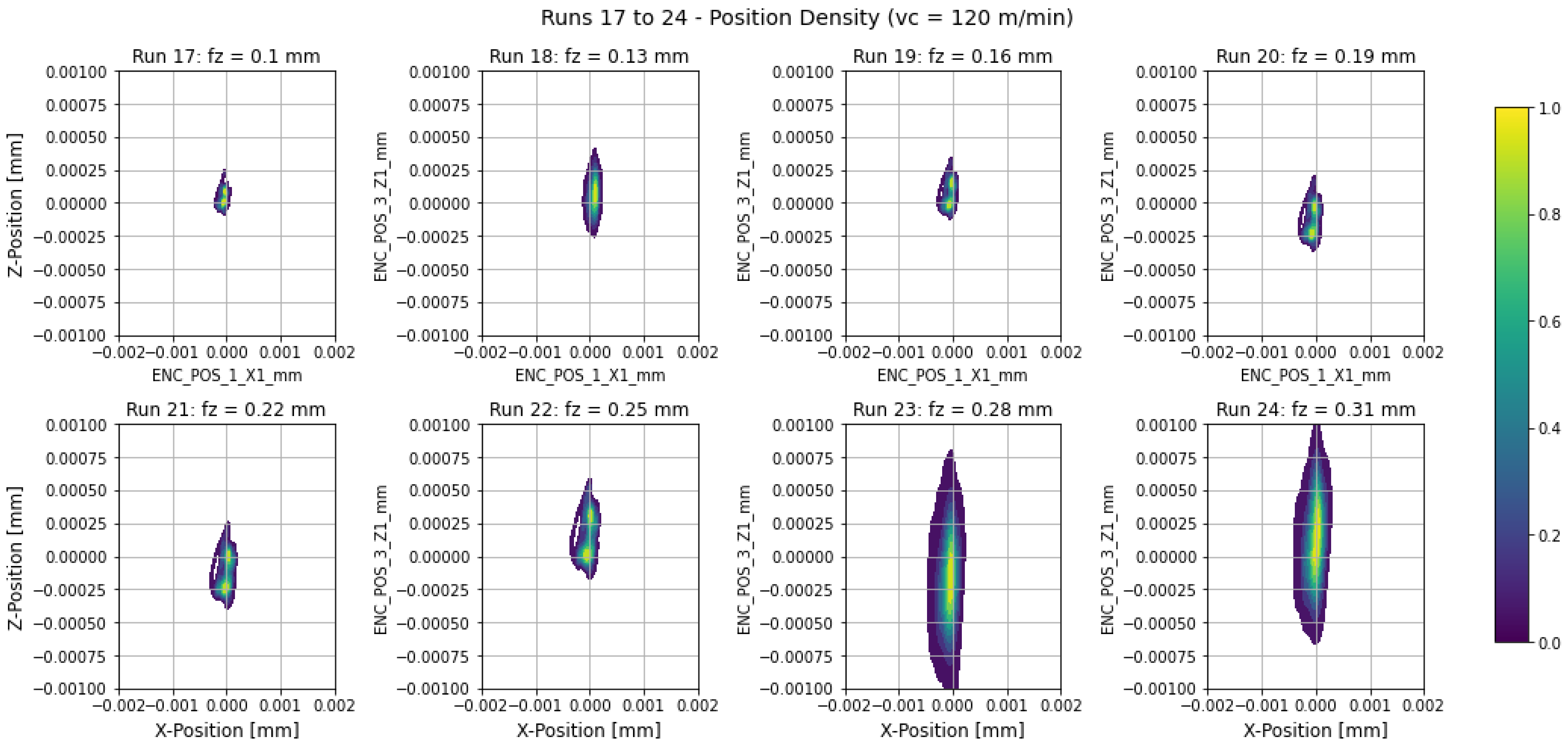
Face Milling – Positional Accuracy

Runs 9 – 16: Density Plot of X,Z-position



- Scattering of X- and Z-position increases with f_z.

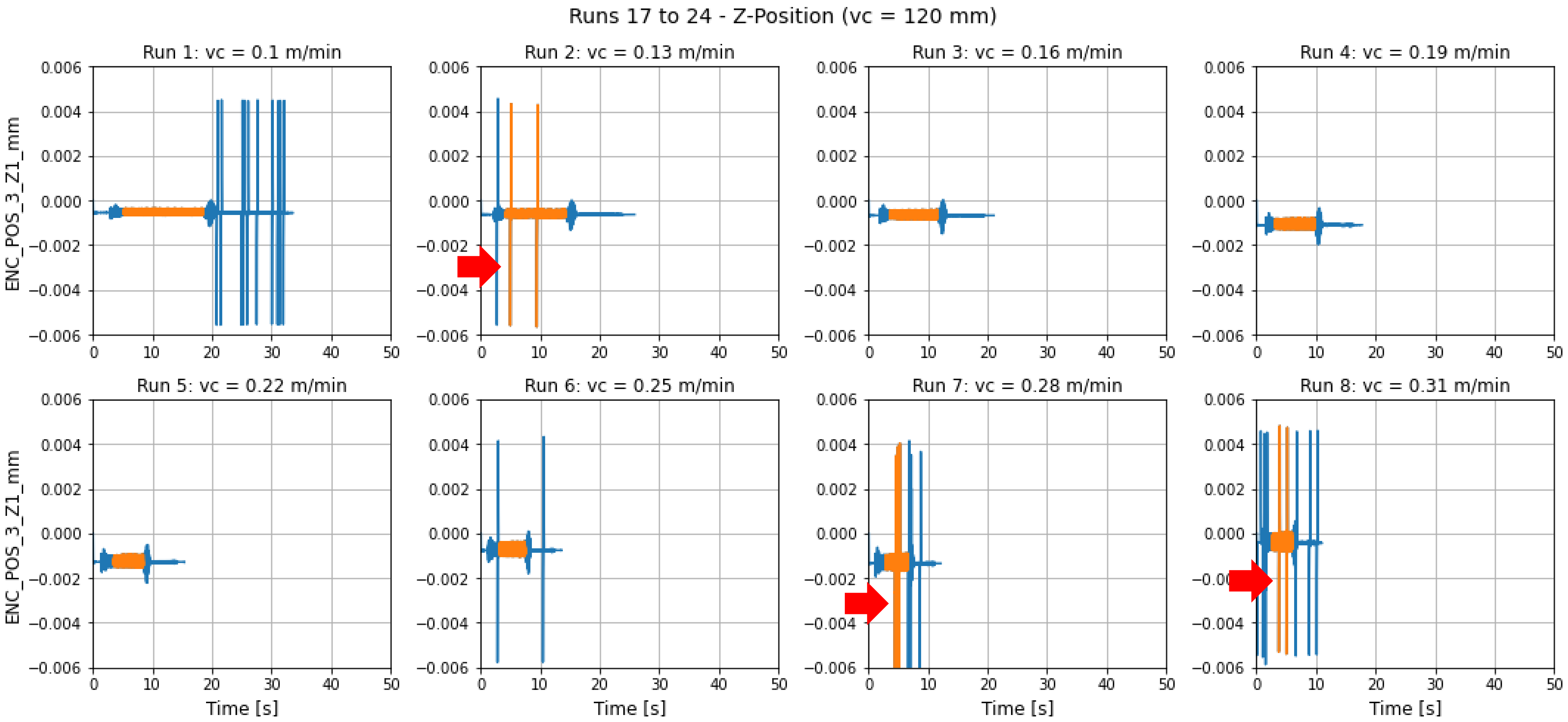
Runs 17 – 24: Density Plot of X,Z-position



- Highest position scatter for highest f_z = 0.28 and 0.31 mm.

Face Milling – Positional Accuracy

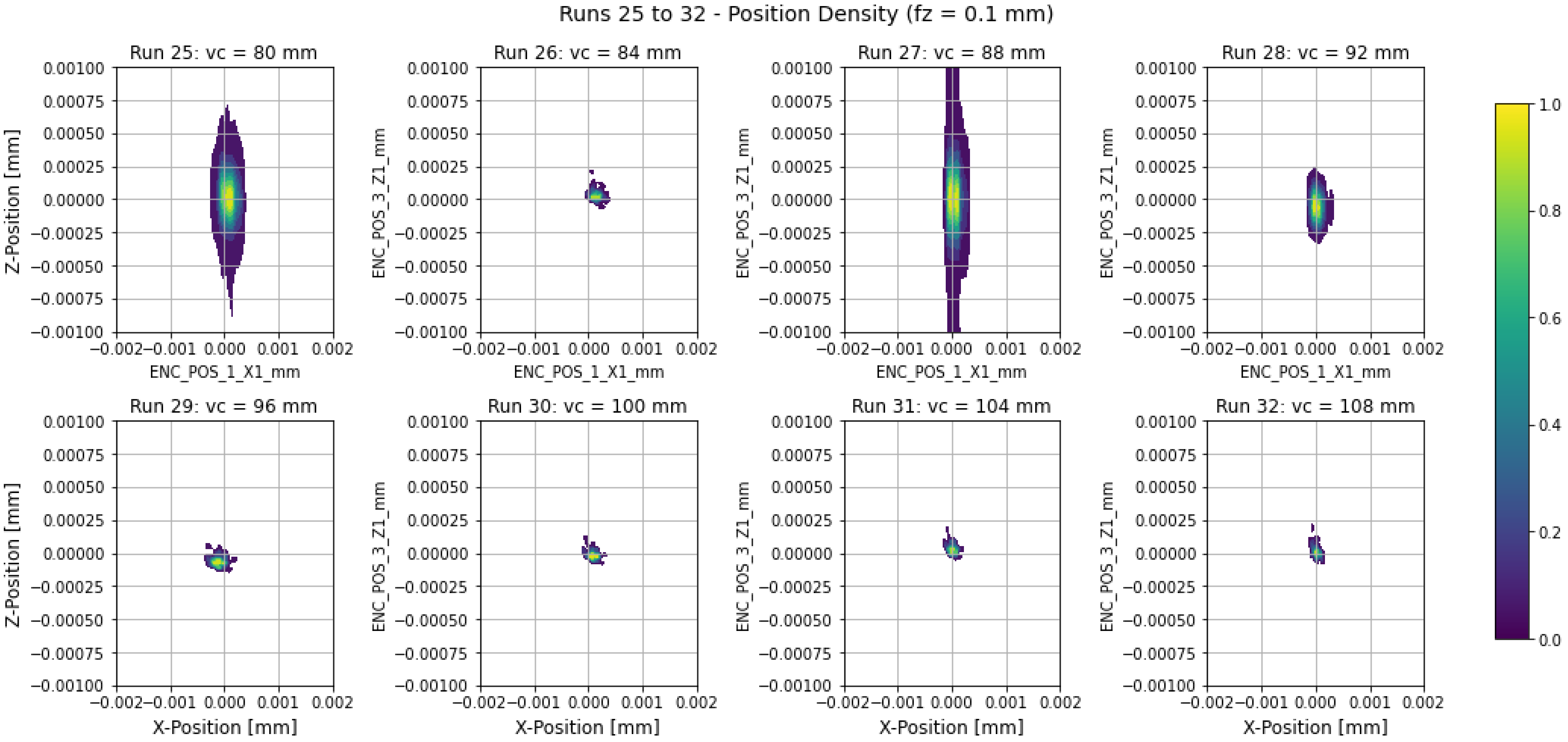
Runs 17 – 24: Visualization of Z-position to Explain Density Plots



- Explanation for increased scattering in density plots: abrupt changes in Z-position happen in stable cutting phase.

Face Milling – Positional Accuracy

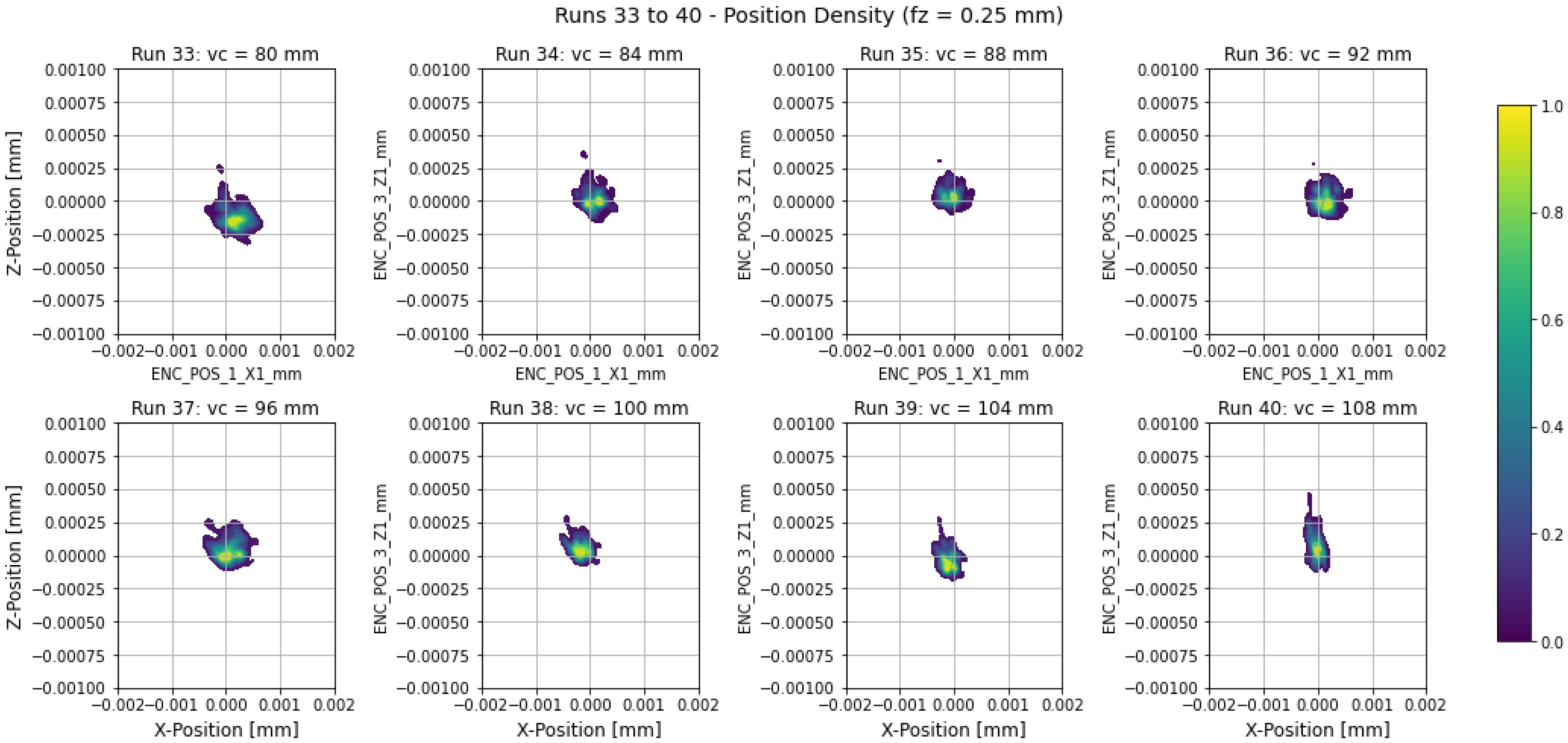
Runs 25 – 32: Density Plot of X,Z-position



- Position scatter **does not increase** with v_c.

Face Milling – Positional Accuracy

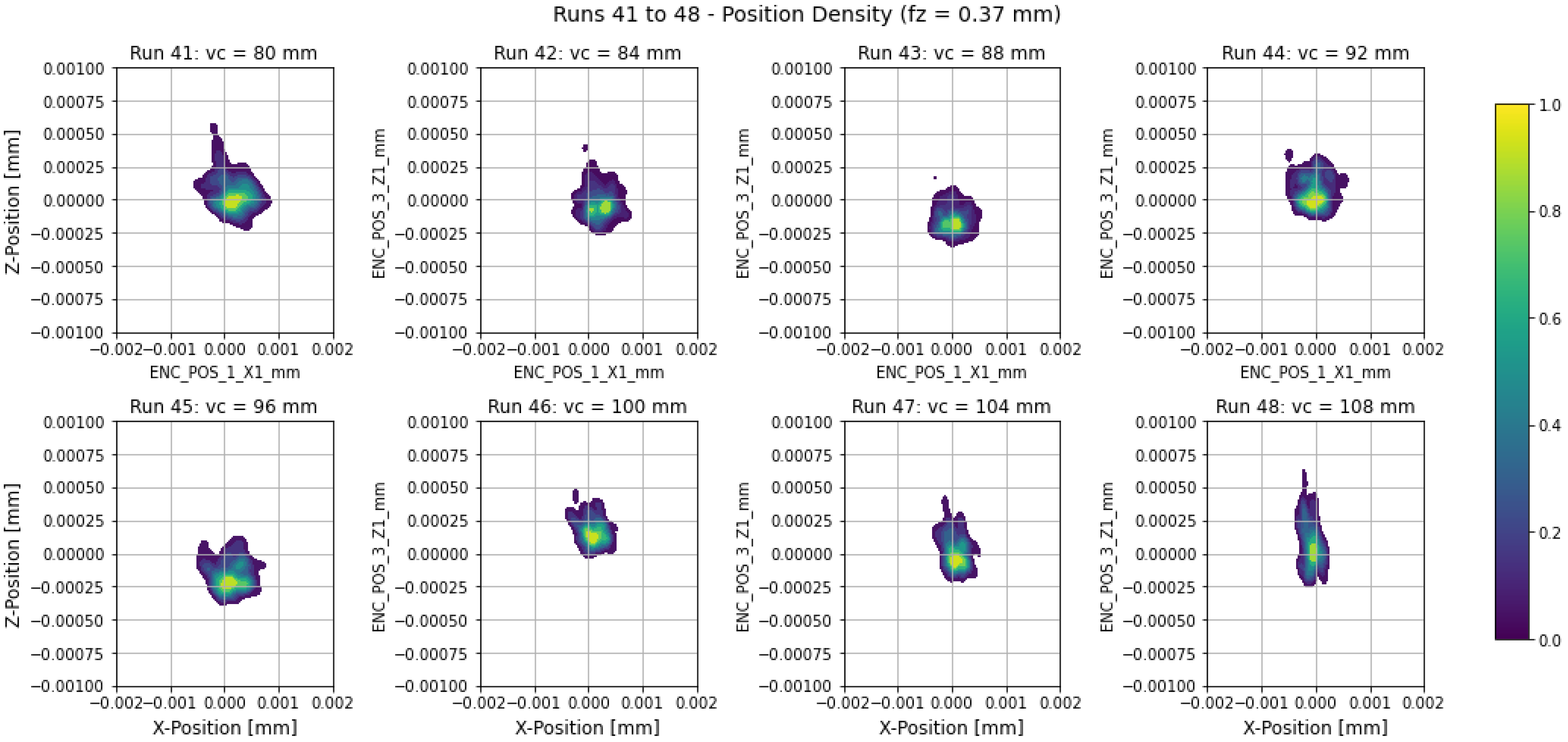
Runs 33 – 40: Density Plot of X,Z-position



- Position scatter **does not increase** with v_c.

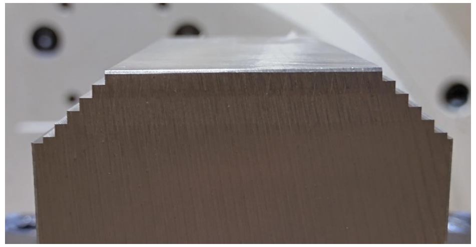
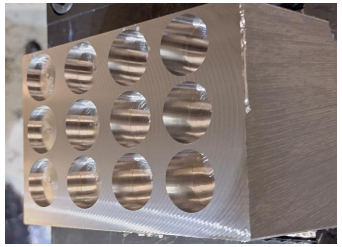
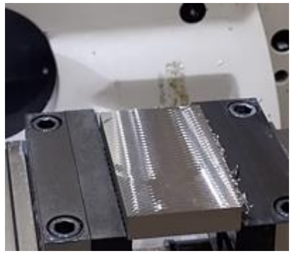
Face Milling – Positional Accuracy

Runs 41 – 48: Density Plot of X,Z-position



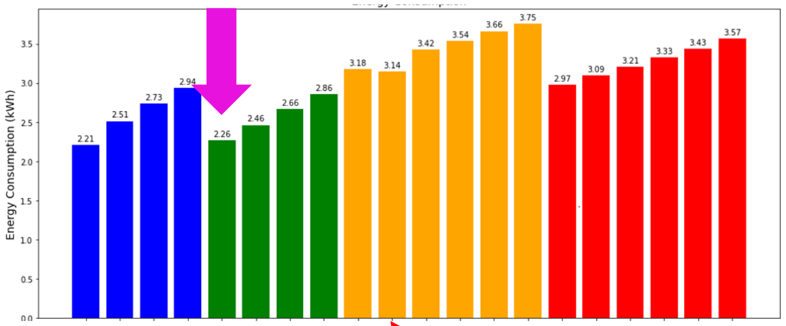
- Position scatter **does not increase** with v_c.

- Introduction
- Results of Data Analysis
  - End Milling
  - Plunge Milling
  - Slot Milling
  - Face Milling
- Summary & Outlook

	End Milling	Plunge Milling	Slot Milling	Face Milling
				
Key Findings	• Increasing a_e to achieve given MRR minimizes **energy consumption**. • Increasing a_p to achieve given MRR minimizes **maximum power**.	• **Helical** immersion minimizes **energy consumption** for **all hole depths.** • No clear recommendation w.r.t maximum power.	• Increased **positional inaccuracies** at first slot corner for several runs. • **No clear dependency** on specific parameter.	• **Median and IQR** of power channels increase with f_z more significantly than with v_c.
Additional Insights	• Increased IQR caused by **increased noise** in power channels for runs with **increased** a_e. • Difference in noise for runs with identical parameters.	• Maximum power for finishing increases with hole depth for diagonal and helical immersion.	• Run 20 shows **asymmetric** milling path also in desired position channels (**CAM?**) • IQR increases with a_p, but not with a_e.	• Scatter in X & Z-position increase with f_z but not with v_c.

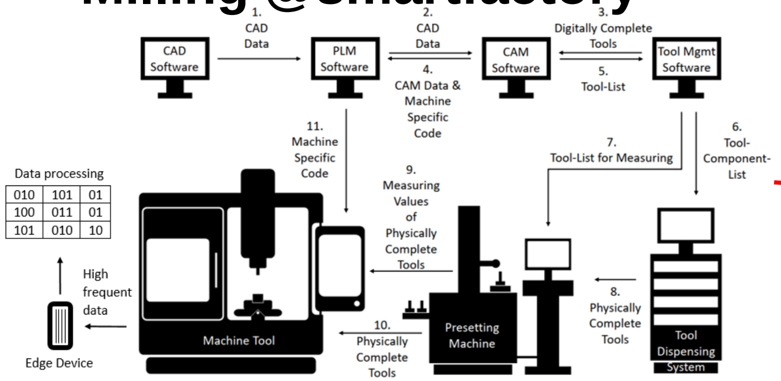
Workflow is Applicable to Many Probems!

Answer:



Question: What slot milling parameters result in lowest energy consumption?

Milling @smartfactory



FAIR Dataset

- 1_Hardware-Fingerprint
- 2_Software-Fingerprint
- 3_Machine-tool_tool-information
- 4_FACEMILLING-MEOP247
- 5_EndMILLING_MEOP245
- 6_PlungeMILLING_MEOP246
- 7_SlotMILLING_MEOP248
  - 7.1_CAD-Files
  - 7.2_CAM-Machining-Strategy
  - 7.3_Toolpath-Simulation-before-Postprocessing
  - 7.4_NC-Code-after-Postprocessing_PARTLY
  - 7.5_NC-Code-after-check-at-machine-tool
  - 7.6_High-frequent-machining-data
  - 7.7_Photos_final-workpiece-REAL

Efficient Data Analysis

- Offering: Manufacturing data acquisition and analysis as a service
- **What is your problem to be explored?**

We innovate Materials

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Vielen Dank für Ihre Aufmerksamkeit

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