Application Note

Dispensing on the fly

"Dispensing on the fly" in laboratory automation refers to the process of dispensing liquids or samples while the dispense head or the target container is in motion. This technique is commonly used to increase the throughput and efficiency of automated liquid handling systems.
This application note covers the following topics:

- The challenges of dispensing on the fly.
- Parameters to consider for dispensing on the fly.
- How to define the system and calculate the right parameter values to obtain accurate dispensing results.

VYKA
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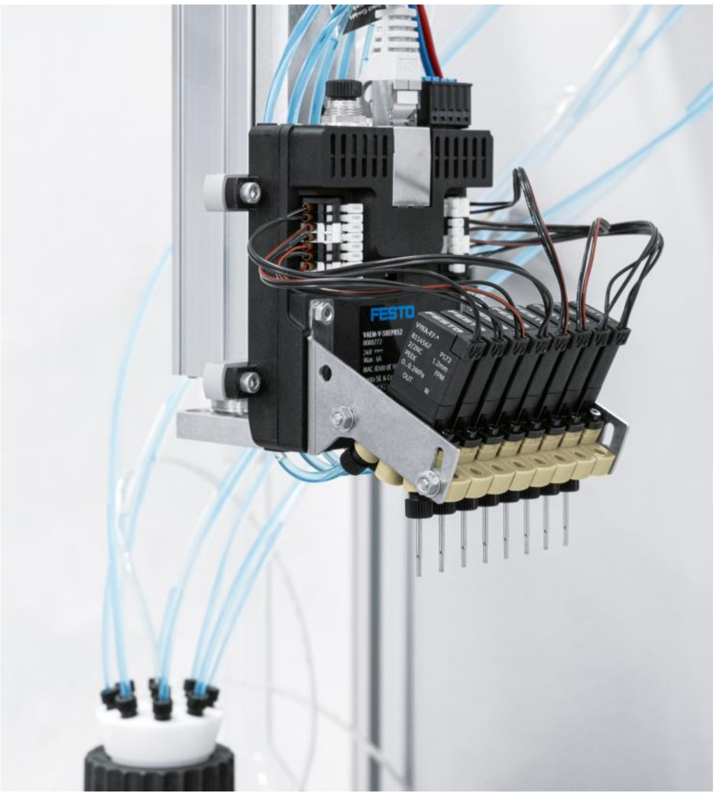

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1 Dispensing on the fly and its challenges

Dispensing on the fly refers to a process where fluid is dispensed in shots while the dispense head or the target vessel is continuously in motion. Without interrupting motion, manufacturers can achieve higher throughput and efficiency, making it a valuable technique in high-volume production environments.
Nevertheless, dispensing on the fly presents several challenges that need to be addressed to ensure accuracy, consistency, and efficiency.

- Precision and accuracy: maintaining precise liquid control over the amount and placement of the dispensed fluid while in motion can be difficult. A stable and precise liquid control must be part of the system.
- Synchronization: the movement of the dispense head and the target vessel must be perfectly synchronized. Any misalignment or timing issues can lead to inaccuracies.
- Speed reliability: changes in the speed of the conveyor can result in uneven application. The system must be able to vary the speed depending on the dispensing volume and precision without compromising the quality of the dispense.
- Teaching: the dispense head must be correctly positioned over the target vessel, it is important to ensure the starting and ending position of the system. The system must be taught carefully before the dispensing process begins.

Addressing these challenges requires a holistic view on the liquid handling system.

2 System concept

2.1 Architecture of a liquid handling system

For liquid handling applications, Festo relies on the time-pressure-controlled dispensing method. This involves supplying a controlled pressure from a compressed air source to a closed container. The liquid inside is displaced by overpressure and fed to valves of a dispense head via tubing. A control unit precisely specifies the opening times of the valves. The dispense head is mounted in an electrical handling system that accurately moves it over the target vessel.
Below there is an example of a typical Festo liquid handling system architecture for Laboratory Automation.

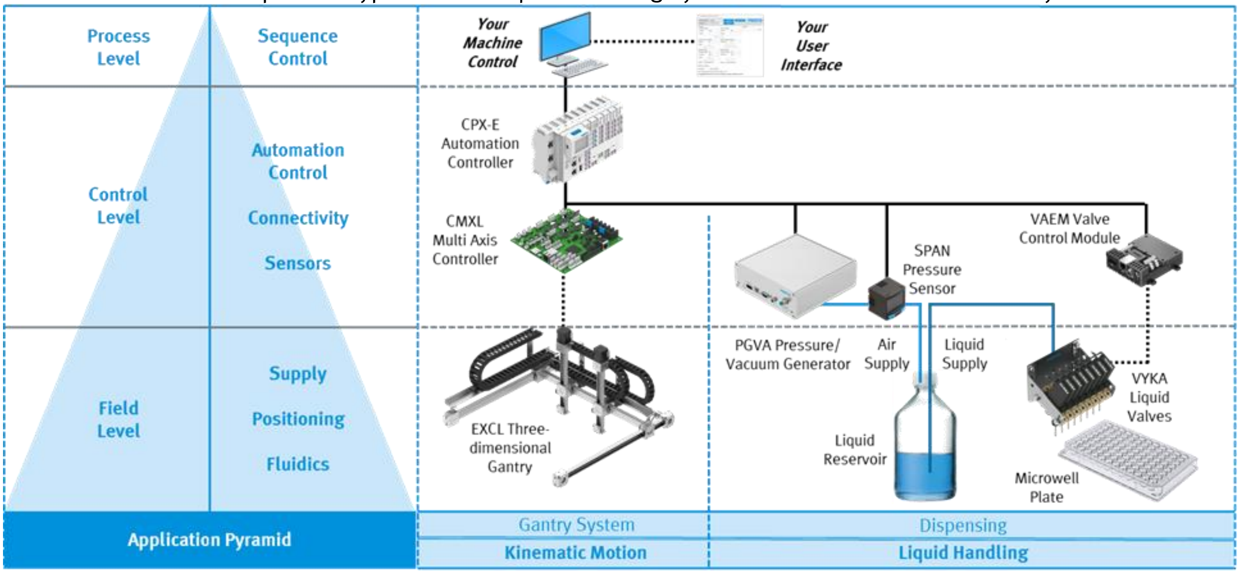


Fig. 2.1: Example of the architecture of a Festo Liquid Handling System for Laboratory Automation

2.2 Key parameters to consider for dispensing on the fly

Dispensing on the fly needs precise synchronization of motion and liquid control. To ensure even distribution of liquid to each target vessel from a dispense head during a dispense on the fly process, some key parameters need to be considered:

- The speed at which the dispense head traverses the target vessel during shot delivery.
- The pressure at which the fluid is pushed through the entire system until it leaves the needle.
- The opening time of the solenoid valve, which is the sum of the valve switching time and the real valve opening time.
    - The valve switching time is the duration it takes for the plunger to move after the switching signal reaches the valve.
    - The real valve opening time refers to the duration it takes for the valve's plunger to move from the closed position to the open position and then back from open to closed.
- The system latency, which is the time needed to send a signal from the controller to the valve to switch it.
- The viscosity of the fluid at the given temperature, which influences both flow delay and jet shape.

2.3 Definitions

2.3.1 Target vessel

A dispensing on the fly system can be used with different types of target vessels. It is important to consider the shape of the vessels as this will introduce extra geometrical tolerances into the system when moving over them during dispensing.

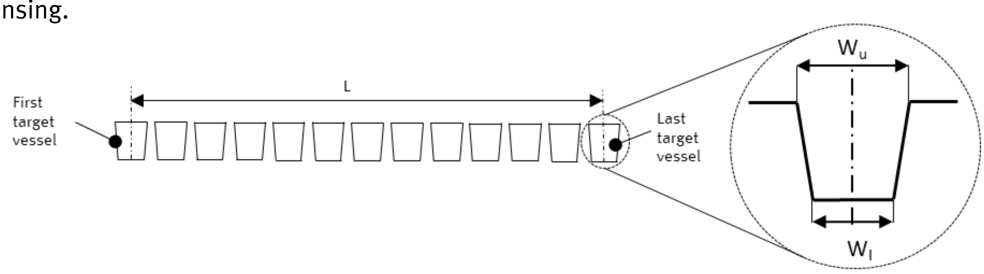


Fig. 2.2: Target vessel size and distance between first and last target vessel

Description	Parameter
Target vessel upper width [mm]	W_u
Target vessel lower width [mm]	W_l
Distance first to last target vessel [mm]	L

Table 2.1: Target vessel dimensions

2.3.2 Liquid handling system

Precise dispensing can be achieved in different ways. Festo offers a wide range of gantries, controllers and valves, which can be selected depending on the application and its requirements. For the selection the parameters listed below need to be considered, as they will limit the travel speed and the maximum volume to be dispensed.

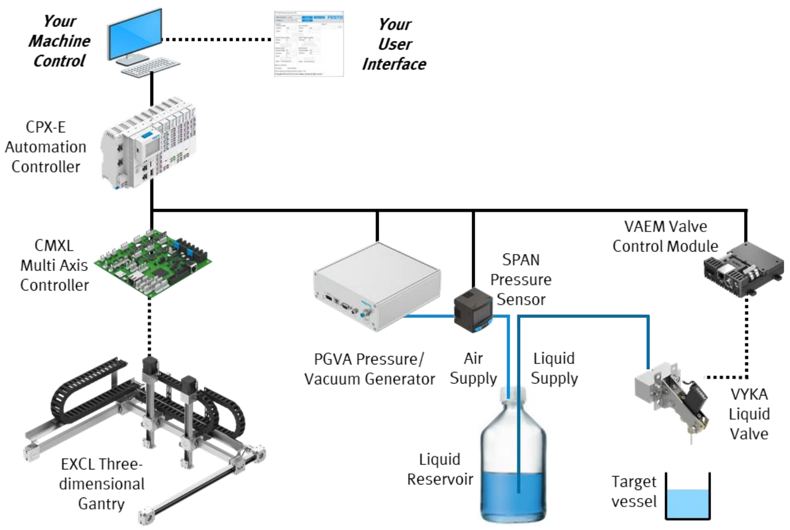


Fig. 2.3: Festo system

Description	Parameter
Gantry travel speed [m/s]	v
Gantry repetition accuracy [mm]	Δx
Needle inner diameter [mm]	ID
Max. System Controller delay [ms]	T_{dsc}
Max. Valve Controller delay [ms]	T_{dvc}
Valve switch on/off delay [ms]	T_{dv}
Valve opening time [ms]	T_o

Table 2.2: Festo system parameters

2.3.3 Fluid to dispense

The aim is to dispense a fluid into a target vessel. Since each fluid behaves differently under applied forces such as pressure, it is crucial to observe the fluid as it exits the needle. These observations help estimate two key parameters:

- Fluid Jet Shape Tolerance: This refers to the difference in shape between the width of the jet after it exits the dispensing needle and the internal diameter of the needle. This tolerance is also influenced by the gantry travel speed.
- Flow Delay: This is the time it takes for the liquid to start moving or to stop moving.

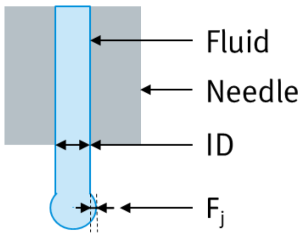


Fig. 2.4: Needle and jet shape

Description	Parameter
Fluid jet shape tolerance [mm]	F_j
Flow delay [ms]	T_{df}

Table 2.3: Fluid parameters

2.4 Calculations

2.4.1 Dispensing and trigger start and end positions

There is a limited time frame during which the dispense head can deliver liquid while traveling over the target vessel. This time frame can be determined by calculating the following parameters, all of which are relative to the center of the target vessel.

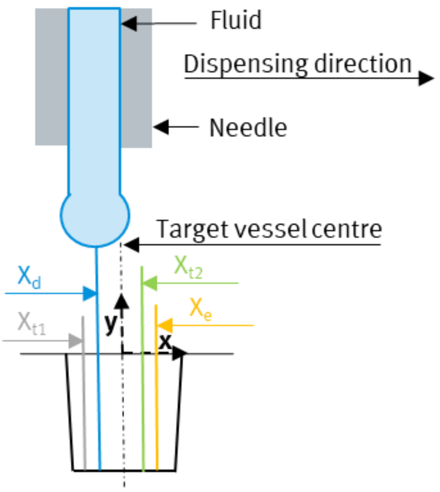


Fig. 2.5: Target vessel, valve trigger start position and dispensing start position

- Dispensing start position, denoted as X_d, is the gantry position at which the center of the fluid stream reliably the target vessel for the first time during motion.

$$X_d = -\frac{W_l - ID - 2 * F_j}{2}$$

- X_d is defined relative to the center target vessel position (i.e. the coordinate origin), which serves as the central teaching position. X_d solely describes the needle and the fluid jet in relation with the target vessel position.
-
- Valve trigger start position, denoted as X_{t1}, is the position at which the valve is triggered to open while the gantry moves with velocity v – differs from X_d due to gantry tolerances and time delays:

$$X_{t1} = X_d - X_{delay} + \frac{\Delta x}{2} = -\frac{W_l - ID - \Delta x - 2 * F_j}{2} - (T_{df} + T_{dv}) * v$$

  Here,

$$X_{delay} = (T_{df} + T_{dv}) * v$$

  is the distance equivalent to the valve switching and fluid inertia delays at gantry speed v, and Δx is the positioning error inherent to the gantry.

- Dispensing end position, denoted as X_e, is the gantry position at which the fluid stream reliably hits the target vessel for the last time during motion and is defined analogue to the dispensing start position:

$$X_e = \frac{W_l - ID - 2 * F_j}{2} = -X_d$$

- Valve trigger end position, denoted as X_{t2}, is the position at which the valve needs to be triggered to close while the gantry moves with velocity v – is determined similar to the valve trigger start position:

$$X_{t2} = X_e - X_{delay} - \frac{\Delta x}{2} - x_{cycle} = \frac{W_l - ID - \Delta x - 2 * F_j}{2} - \left(T_{df} + T_{dv} + T_{dc}\right) * v$$

Here,

$$X_{cycle} = T_{dc} * v = (T_{dsc} + T_{dvc}) * v$$

is the worst-case time delay due to the controller cycle times.

2.4.2 Limits of the system

- Maximum valve opening time, denoted as T_{max}, is the time equivalent to the distance between valve trigger start and end position at gantry speed v:

$$T_{max} = \frac{X_{t2} - X_{t1}}{v} = \frac{-2 * X_d - \Delta x}{v} - T_{dc}$$

The equation shows that the maximum valve opening time can be increased by decreasing the gantry speed and vice versa.

- Maximum gantry travel speed, denoted as v_{max}, is the time equivalent to the distance between valve trigger start and end position at the valve opening time, T_o.

$$v_{max} = \frac{X_{t2} - X_{t1}}{T_o} = \frac{-2 * X_d - \Delta x - X_{cycle}}{T_o}$$

2.4.3 Gantry travel start position

The gantry travel start position, denoted as X_{travel}, depends directly on the selected gantry. For a precise dispensing solution, it is crucial that the linear movement of the gantry begins before the first dispensing shot. This approach helps minimize any interference in the dispensing process during the initiation of the gantry's linear movement.

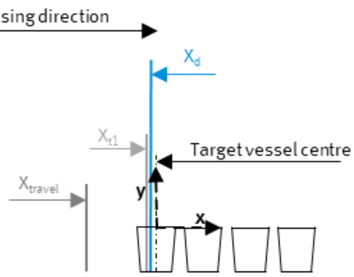


Fig. 2.6: Gantry travel start position

2.4.4 Distance from dispense head to surface target vessel

The distance from the dispense head to the surface of the target vessel should be as close as possible to avoid satellites of the stream. However, the needle of the dispense head should not touch the surface of the target vessel and even a gap between both should be considered to allow air leaving the target vessel when the fluid is entering it.

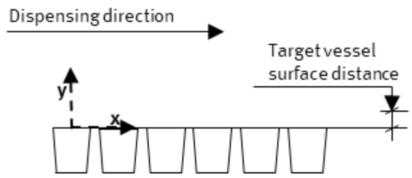


Fig. 2.7: Distance from dispense head to surface target vessel

2.4.5 Filling time

The filing time, denoted as $T_{filling}$ is the time needed to fill several target vessels in a row with the desired volume. This time will depend on the gantry travel start position, which is relative to the center of the target vessel, and the distance until the last target vessel.

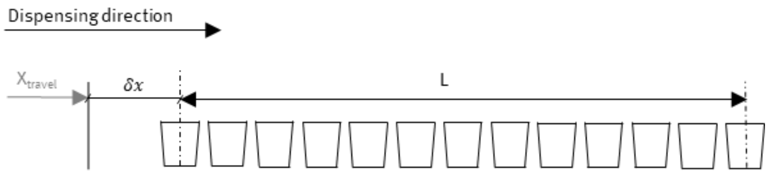


Fig. 2.8: Gantry travel distance

$$T_{filling} = \frac{L + \delta x}{v}$$

2.5 Adjustments and teaching of the system

Once the gantry is mounted and the valve trigger start position is calculated, the dispense head needs to be adjusted and taught according to the valve trigger start position.
There are various teaching methods including laser, camera or tactile measurements. In the following, the adjustment and teaching procedure is described independent of a specific method:

1. Position of target vessel to dispense head:
    - Adjust dispense head in a way that the needle has the same vertical distance to the target vessel and is perpendicular to the target vessel.
    - In this step it is also possible to adjust the depth of the needle in the fitting/valve and with an angle try to guide the needle to be perpendicular to the target vessel.

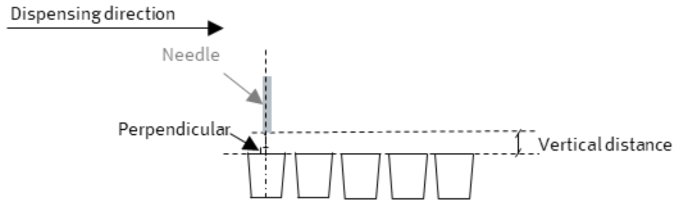


Fig. 2.9: Target vessel position relative to dispense head

- If a dispense head with multiple needles is used, adjust the position of the target vessel, so that the first needle is in line with the first row, the second needle with the second row, etc.

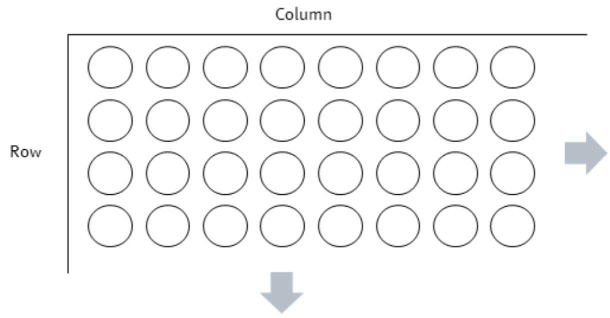


Fig. 2.10: Target vessel rows and columns

2. Verify the start and end position of the dispensing travel way:
    - Move the dispense head to the first column in a way that the needle is approximately in the middle of the target vessel. These gantry coordinates (x, y, z) can be saved as the center of the target vessel and will help you to calculate the valve trigger start position.
    - Move the dispense head in the dispensing travel direction to the last column. Verify that the needle is still centered in the target vessel. If the needle is not aligned with the center of the target vessel, adjust the position and save the new coordinates in the system. This adjustment will allow for the gantry's travel direction to be corrected, ensuring that it remains parallel to the row of target vessels.

Once finished with these steps, the dispensing on the fly can begin.

3 Exemplary implementation

For demonstration a system with eight precision dispensing valves was used to fill a 1536 microtiter plate with a volume of 4µl of water in less than one minute.

3.1 System design

A 1536 microtiter plate from the brand Greiner was used to validate the Festo dispensing on the fly system.

Description	Parameter	Value
Well upper width [mm]	W_u	1,7mm
Well lower width [mm]	W_l	1,5mm
Distance first to last well [mm]	L	105,74mm

Table 3.1: Well dimensions

For the demonstration application a EXCM-30 gantry, a VAEM-V valve control module and VYKA valves were chosen.

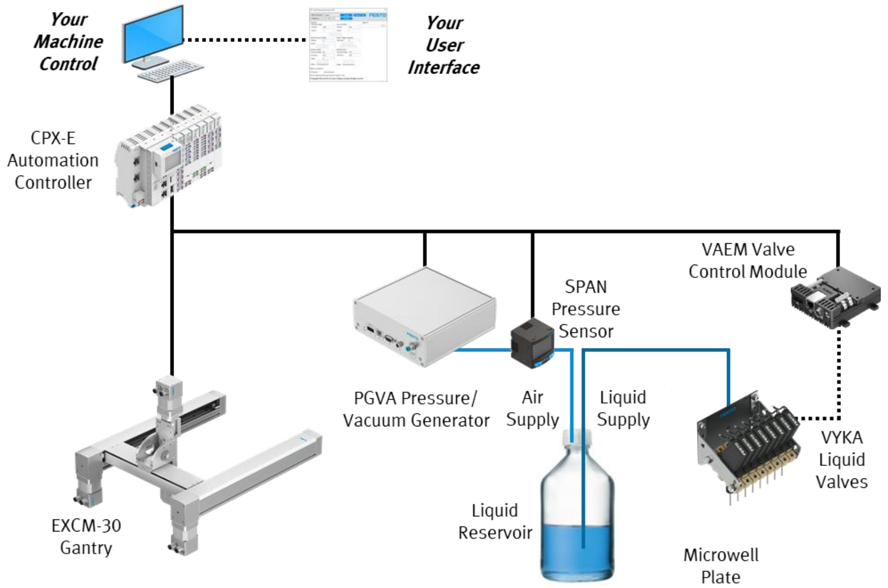


Fig. 3.1: Festo system to dispense a 1536 microtiter plate

Description	Parameter	Value	Product	Part number
Gantry travel speed [m/s]	v	10mm/s	EXCM-30	2226101
Gantry repetition accuracy [mm]	Δx	0,1mm		
Needle inner diameter [mm]	ID	0,3mm	VAVN	8104295
Max. System Controller delay [ms]	T_{dsc}	8ms	CPX-E	5237644
Max. Valve Controller delay [ms]	T_{dvc}	0,2ms	VAEM-V	8088772
Valve switch on/off delay [ms]	T_{dv}	5ms	VYKA	8170088
Valve opening time [ms]	T_o	26ms		

Table 3.2: Festo system parameters

The goal is to dispense distilled water into 1536 wells of a microtiter plate. After observing the liquid with a camera, the fluid jet shape tolerance and the flow delay were estimated as follows:

Description	Parameter	Value	Fluid
Fluid jet shape tolerance [mm]	F_j	0,05mm	Distilled water
Flow delay [ms]	T_{df}	1,5ms	

Table 3.3: Fluid parameters

3.2 Implementation

According to Chapter 2.4, the parameters were determined as follows:

Description	**Parameter**	**Value**
Dispensing start position	X_d	-0,55mm
Valve trigger start position	X_{t1}	-0,57mm
Dispensing end position	X_e	0,55mm
Valve trigger end position	X_{t2}	0,35mm
Maximum valve opening time	T_{max}	91,8ms
Maximum gantry travel speed	v_{max}	35,31mm/s
Gantry travel start position	X_{travel}	-10mm
Filling time	$T_{filling}$	50,3s
Distance from dispense head to surface target vessel		5mm

Table 3.4: Parameter values of the liquid handling system

The following pictures show images of the dispensing sequence recorded with a high-speed camera with 1000fps.

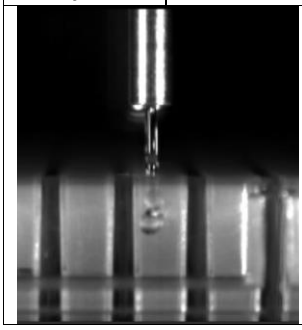
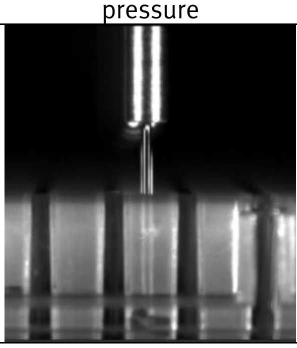
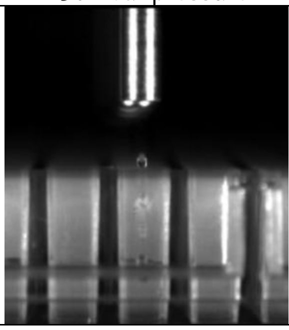
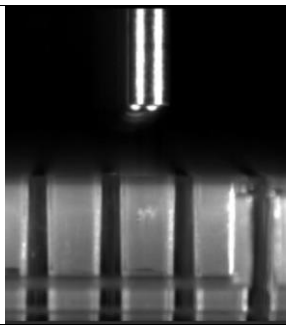
Frist drop shape at 150mbar pressure	Jet shape at 150mbar pressure	End of jet shape at 150mbar pressure	Valve closed and moving forward to next well
			

Table 3.5: dispensing sequence recorded by high-speed camera

3.3 Time partitioning with reference to the well

The figure below summarizes the times analyzed for optimizing the Festo liquid handling system, reinforcing the conclusions drawn from the calculations.
With a gantry travel speed of 10 mm/s and a well width of 1.5mm, the maximum time to dispense into one well is 150ms. However, due to latencies and tolerances in the system, only 91.8ms (comprising 26ms for valve opening and 65.8ms as buffer time) is available for the valve's maximum opening time.
To dispense 4 µL of distilled water at a pressure of 150 mbar, the valve requires an opening time of 26ms, leaving a buffer time of 65.8ms. This available buffer suggests that we could potentially increase the gantry travel speed if necessary. However, it is important to note that increasing the gantry speed will alter the fluid jet shape tolerance, which may become bigger due to the increase in speed.