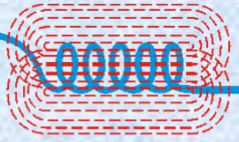


Dušan Prodanović  
Faculty of Civil Engineering  
Belgrade  
Yugoslavia



Intelligent instrumentation improves the  
value of acquired data

# Intelligent instrumentation ...



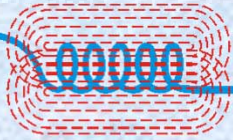
Instruments with “brain”: think, conclude, remember

They can adopt to different jobs

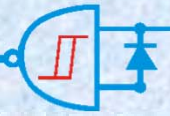
Improved accuracy due to complex algorithms

Two sensors developed in cooperation with electronic gurus:

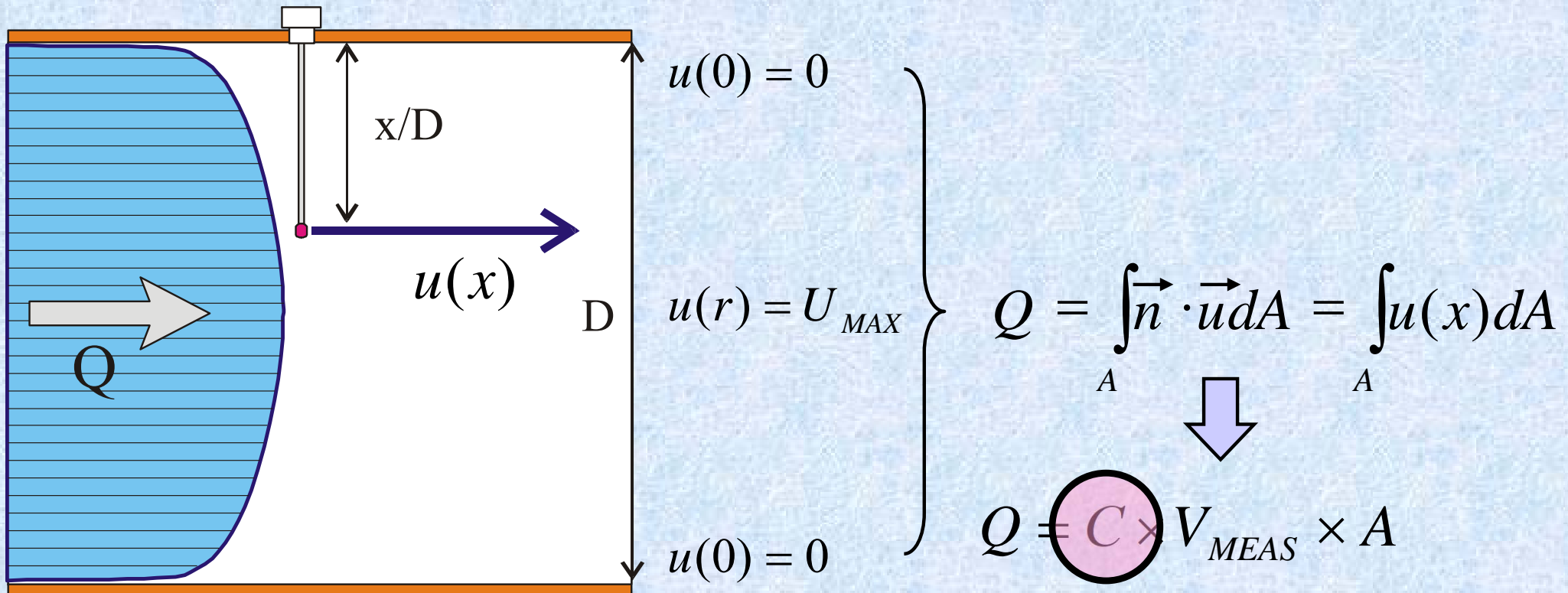
- Smart ElectroMagnetic Current Flow Meter →
- Mean and Transient Pressure Logger

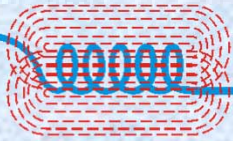


# ...Smart EM Current Meter

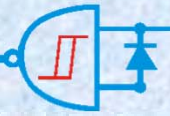


One of possible full pipe flow measurement methods is point velocity measurement (index velocity) and conversion from velocity into the flow rate

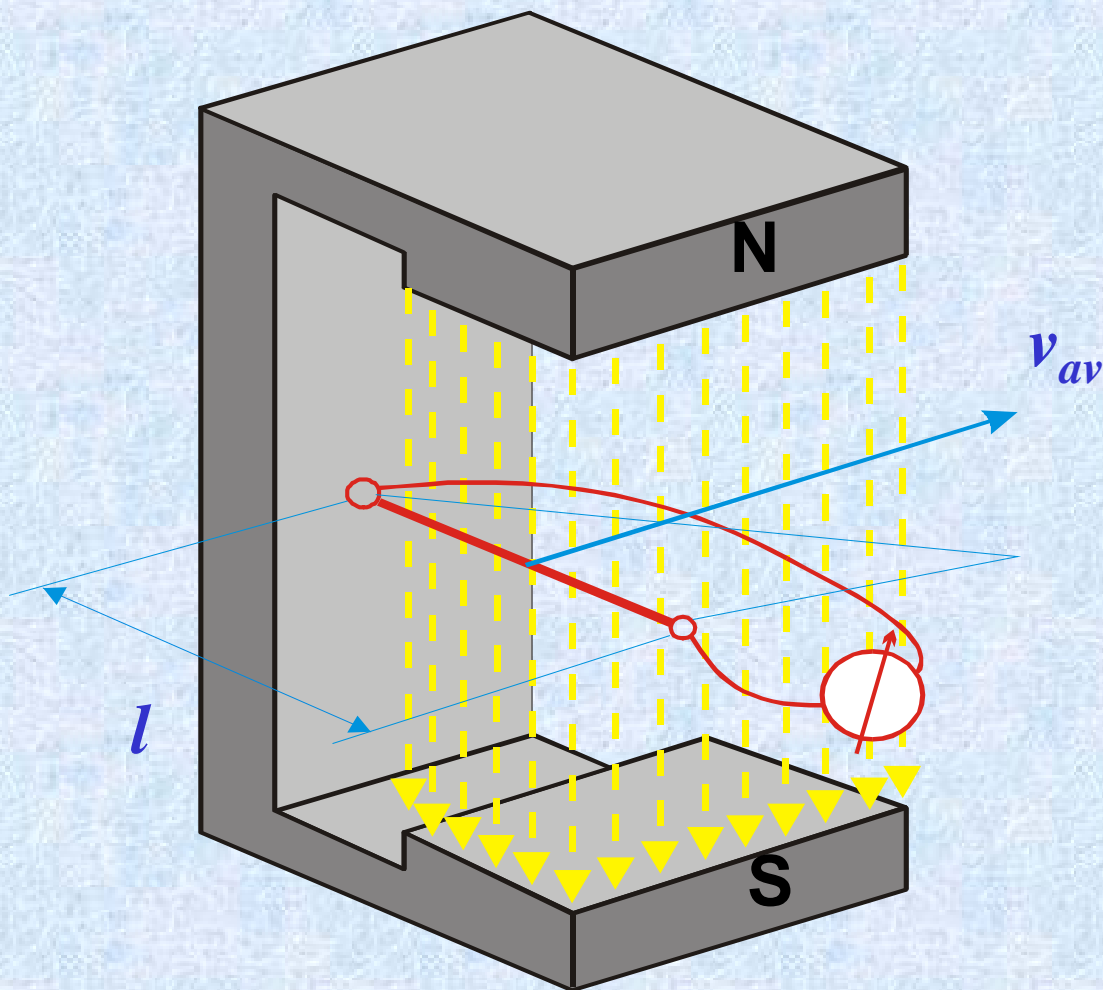




# ...Smart EM Current Meter



Electromagnetic probe can be used for point velocity measurement – general principle of work:

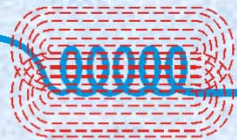


Direction movement  
of the conductor

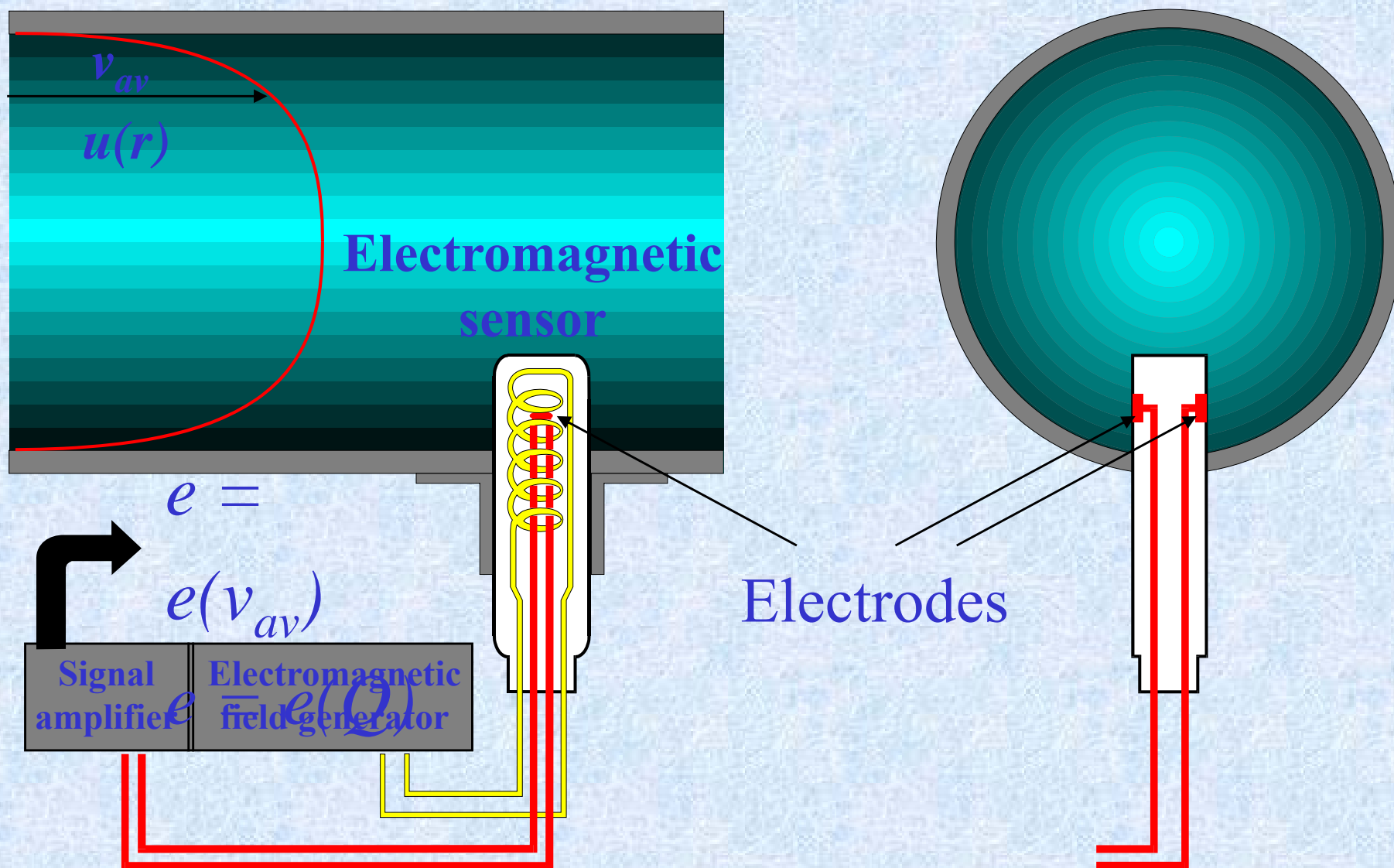
The conductor is a wire  
of length  $l$

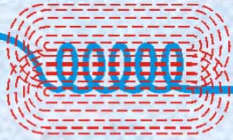


# ...Smart EM Current Meter



...and in EM probe, the conductor is the water!





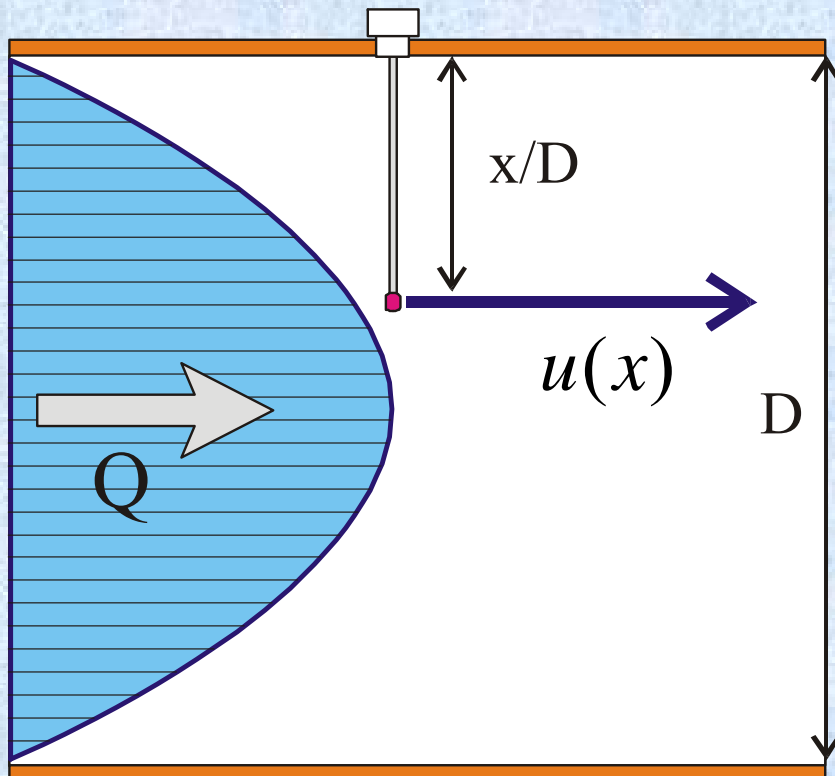
# ...Smart EM Current Meter



How to find the value of coefficient C?

For laminar flow an ideal velocity profile is analytically known:

$$\text{for } \text{Re} = \frac{V \times D}{\nu} < 2000$$



$$u(0) = 0$$

$$x/D$$

$$u(x)$$

$$D$$

$$u(r) = U_{MAX}$$

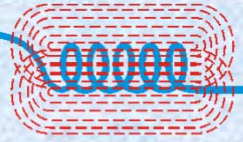
$$u(0) = 0$$

$$u(x) = U_{MAX} \left[ 4 \frac{x}{D} - 4 \left( \frac{x}{D} \right)^2 \right]$$

$$0 \leq \frac{x}{D} \leq 1.0$$



$$V = \frac{Q}{A} \text{ at } x/D = 0.1464$$



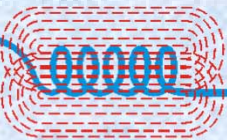
## ...Smart EM Current Meter



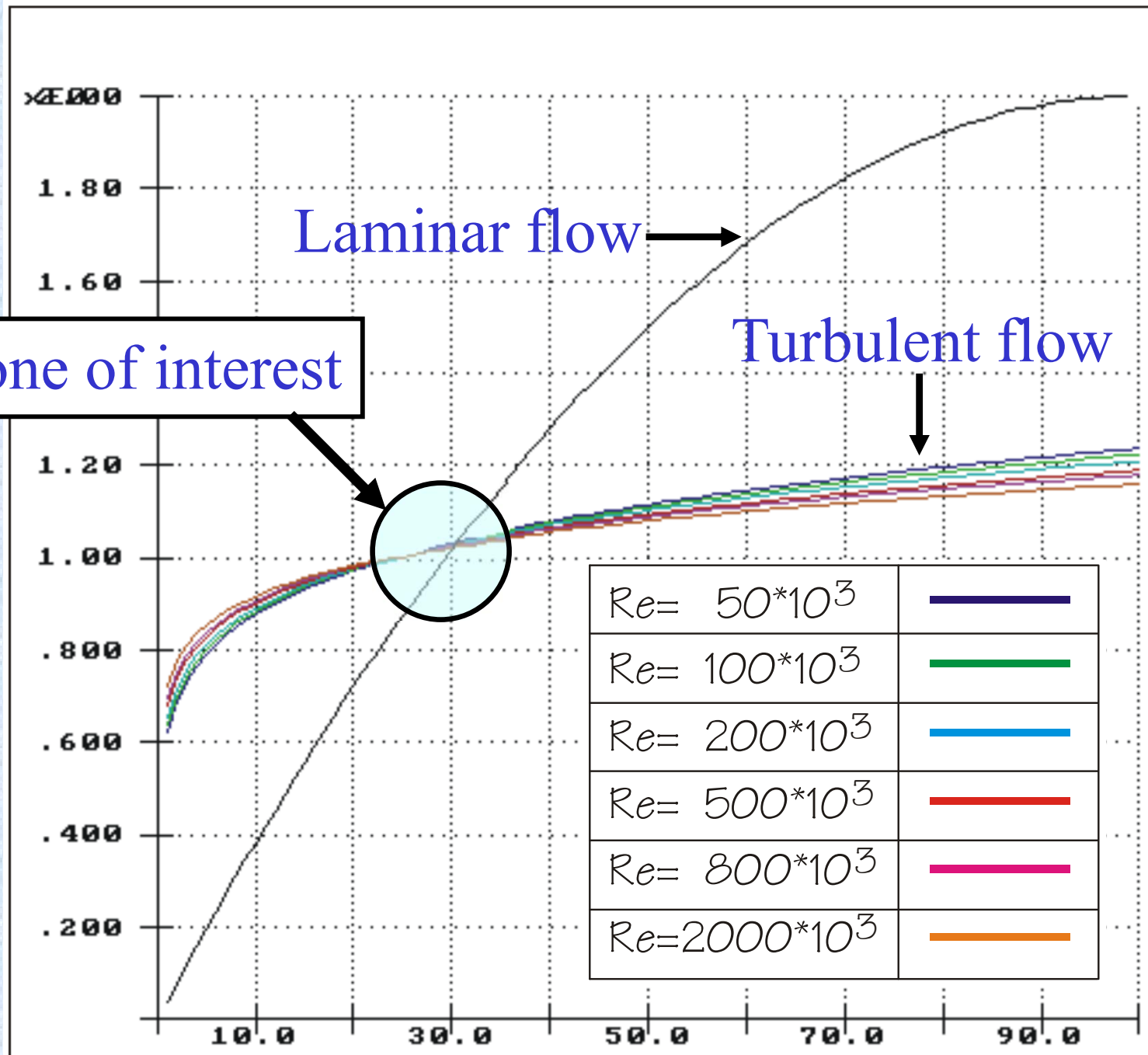
For turbulent flow an ideal velocity profile depends on  $Re$  &  $k/d$

Number of measurements were conducted...

# ...Smart EM Current Meter

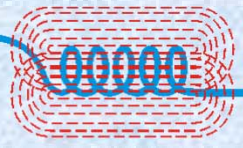


$$\frac{V}{V_{MEAN}}$$



$\frac{x}{r}$



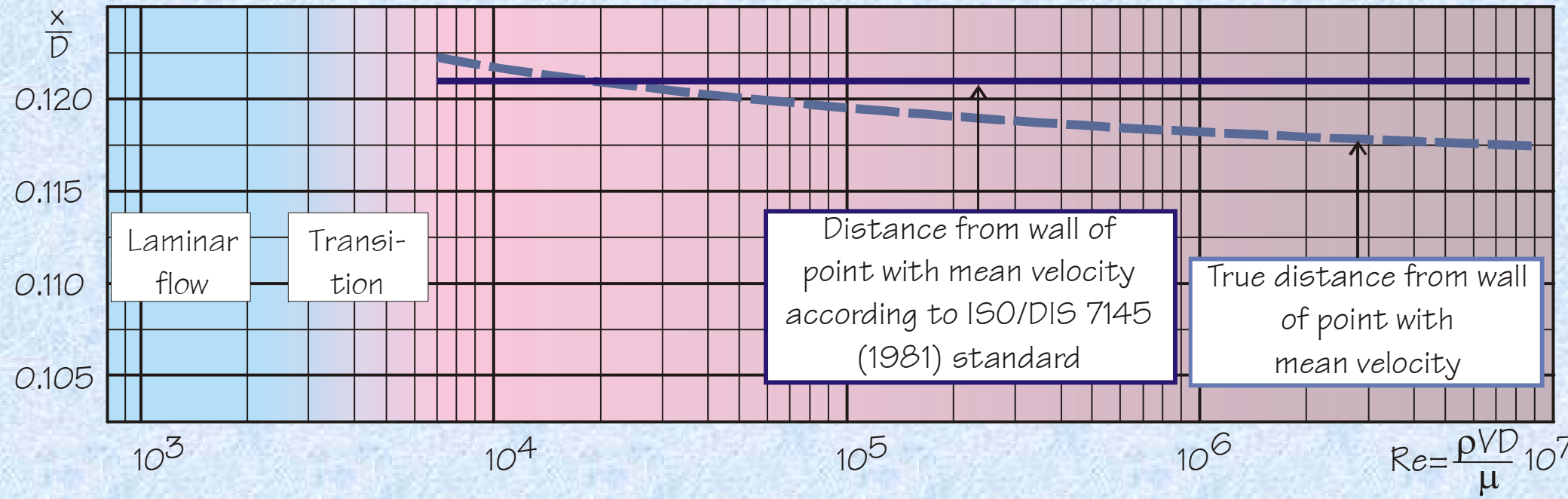


# ...Smart EM Current Meter



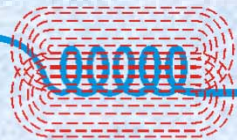
... and different view on the zone of interest:

## Position of avg. velocity

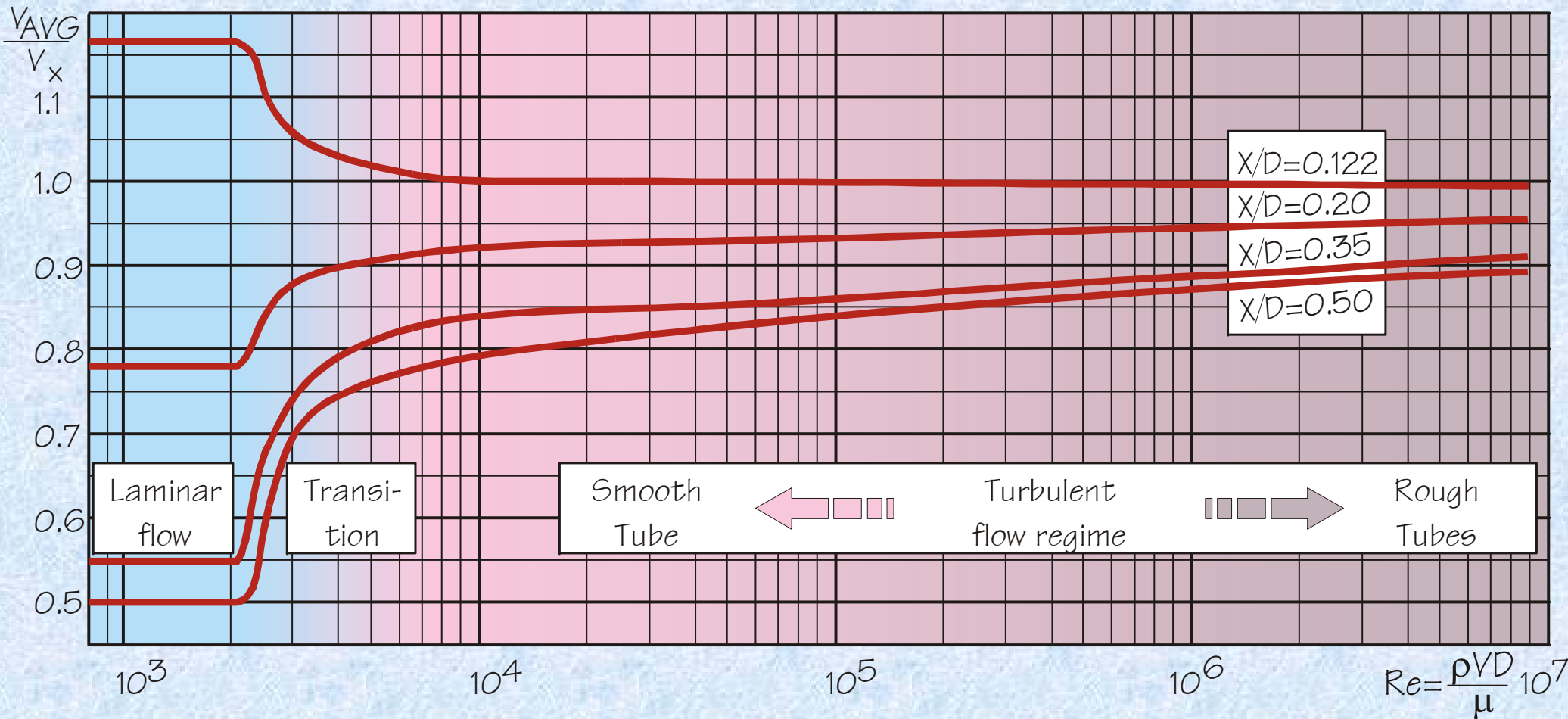


In same pipe, Re will change!

# ...Smart EM Current Meter

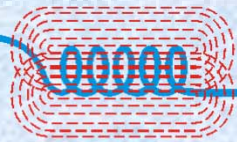


The ratio between avg. velocity and velocity at  $x/D$

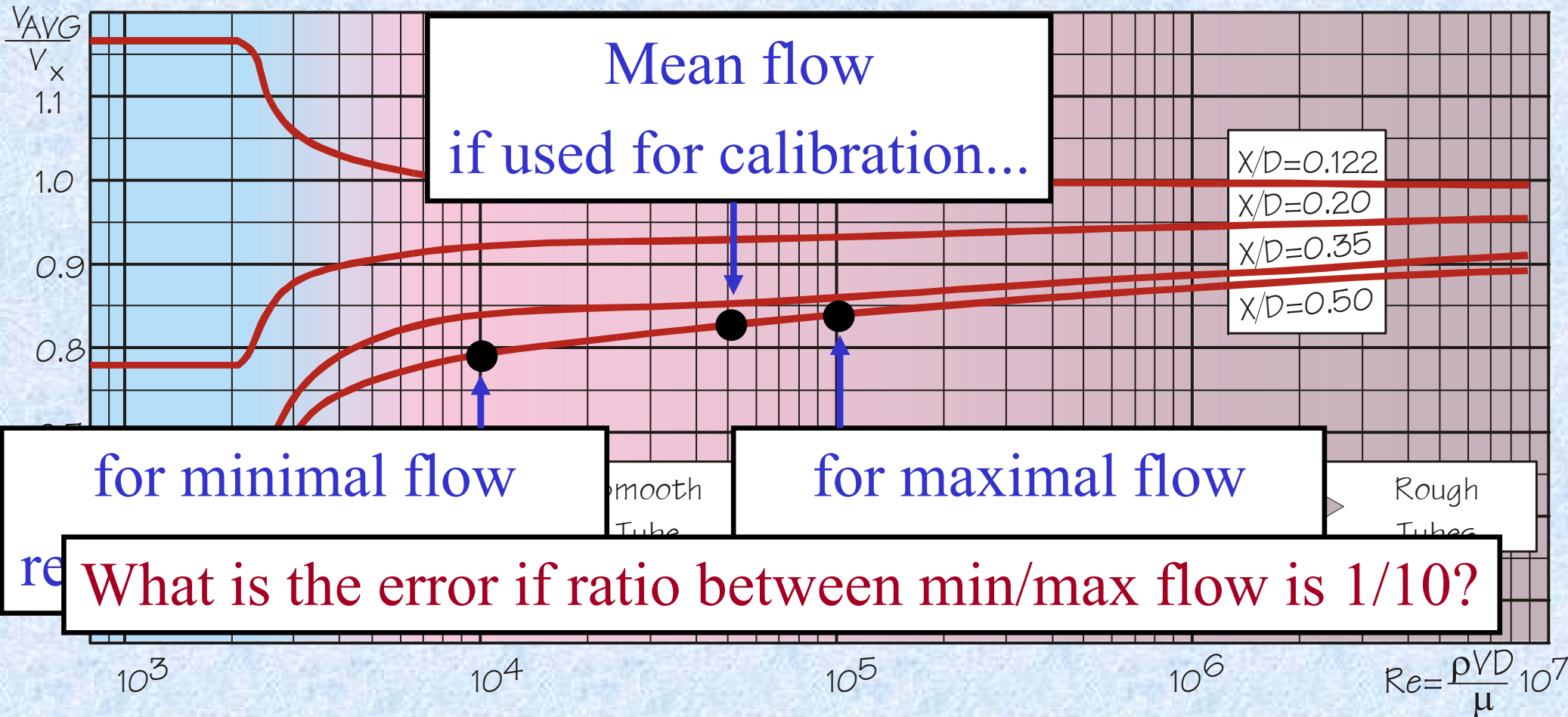


In same pipe,  $Re$  will change!

# ...Smart EM Current Meter

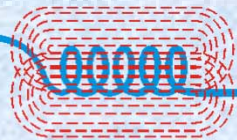


The ratio between avg. velocity and velocity at  $x/D$

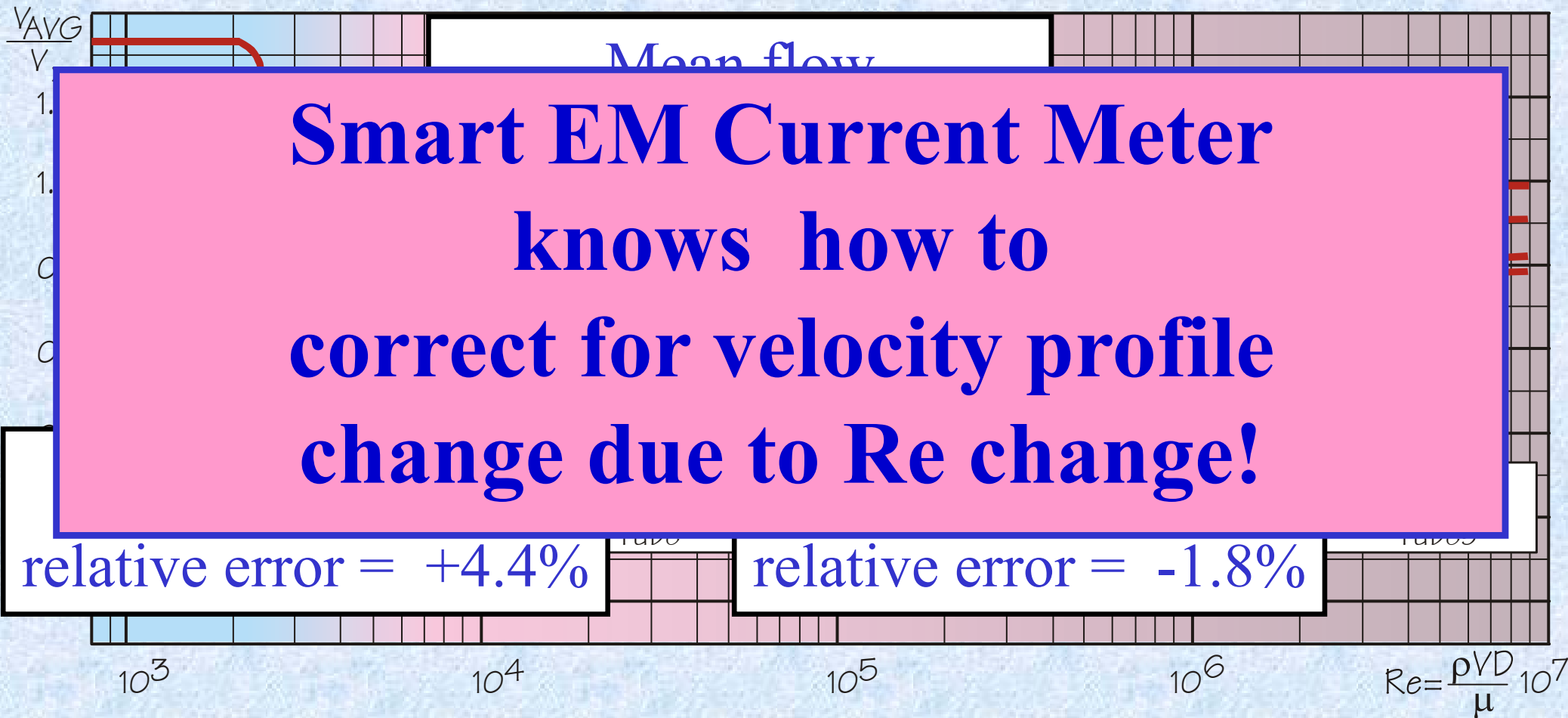


In same pipe,  $Re$  will change!

# ...Smart EM Current Meter



The ratio between avg. velocity and velocity at  $x/D$



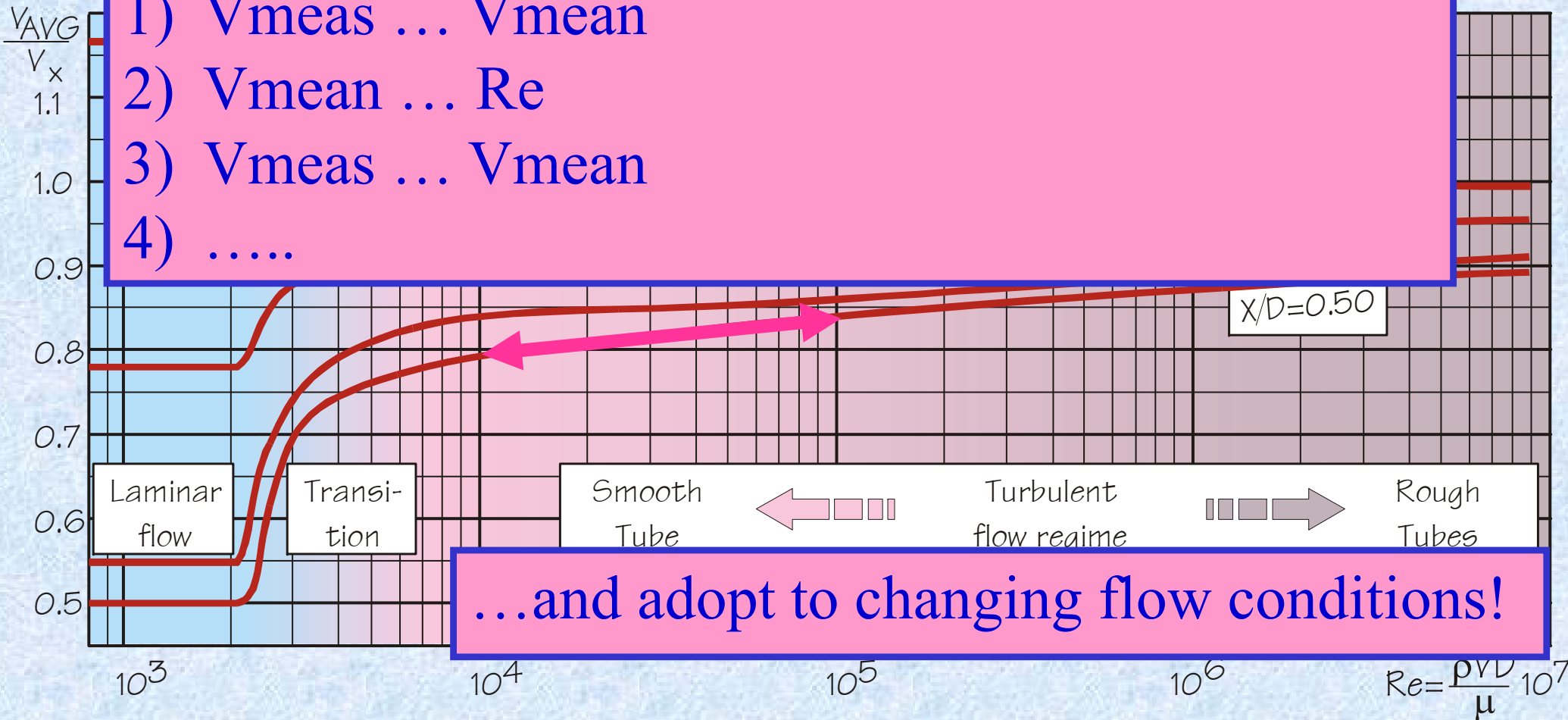
↔  
In same pipe, Re will change!



# ...Smart EM Current Meter

For selected  $x/D$  position, smart EM Current Meter will perform the iterative velocity calculation:

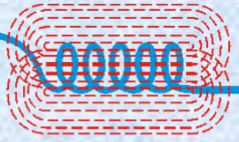
- 1)  $V_{meas} \dots V_{mean}$
- 2)  $V_{mean} \dots Re$
- 3)  $V_{meas} \dots V_{mean}$
- 4) .....



...and adopt to changing flow conditions!

In same pipe,  $Re$  will change!

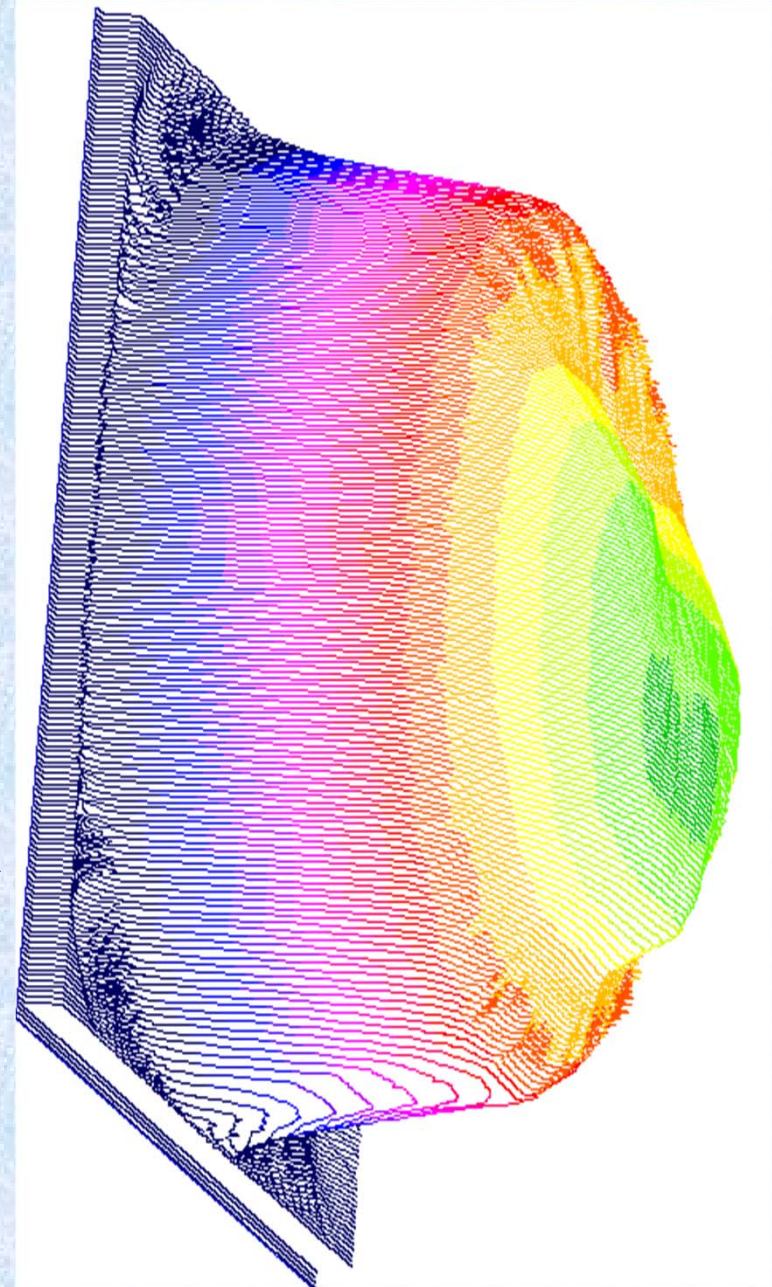
# ...Smart EM Current Meter

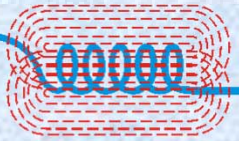


So, smart EM Current Meter will work if velocity profile is ideal

... but...

What can be done with velocity profile that looks like this one

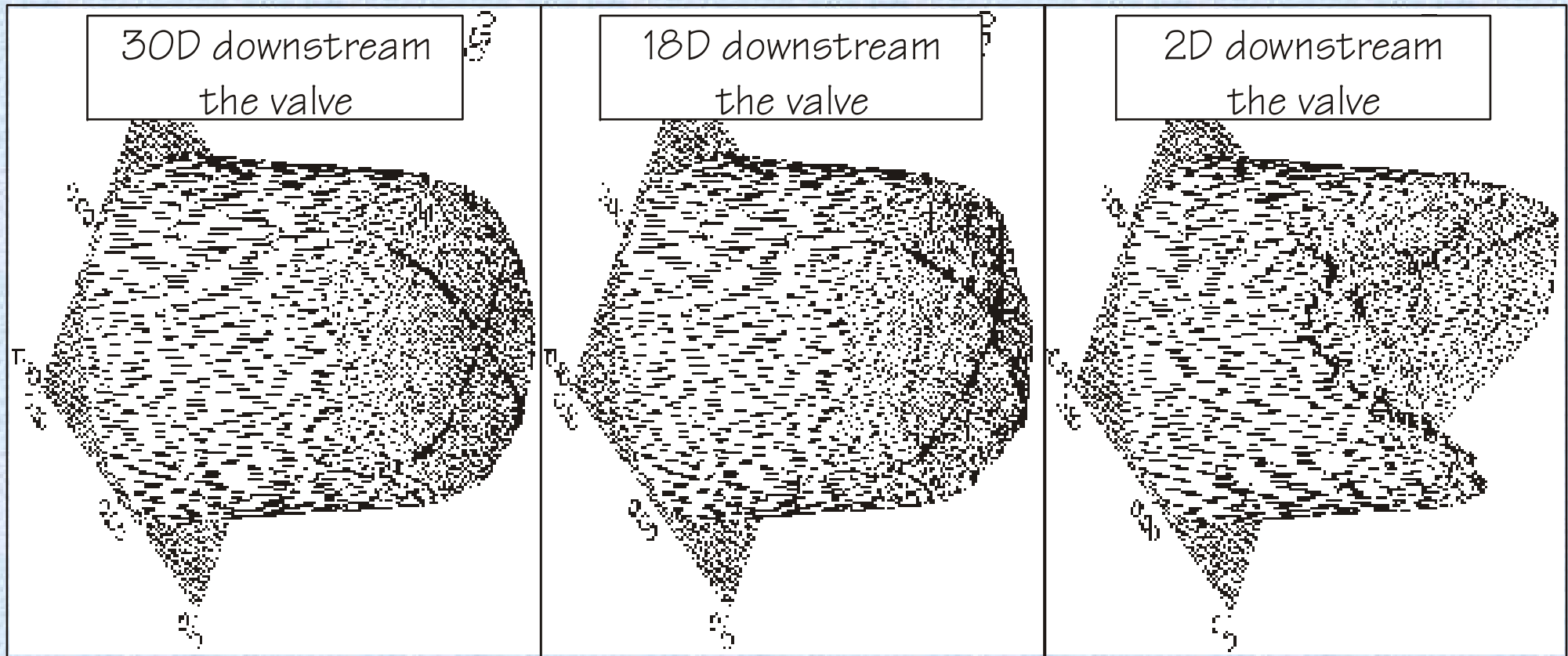


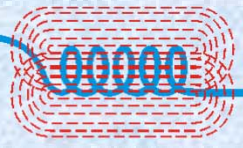


# ...Smart EM Current Meter



..or as one of those (downstream the butterfly valve)..

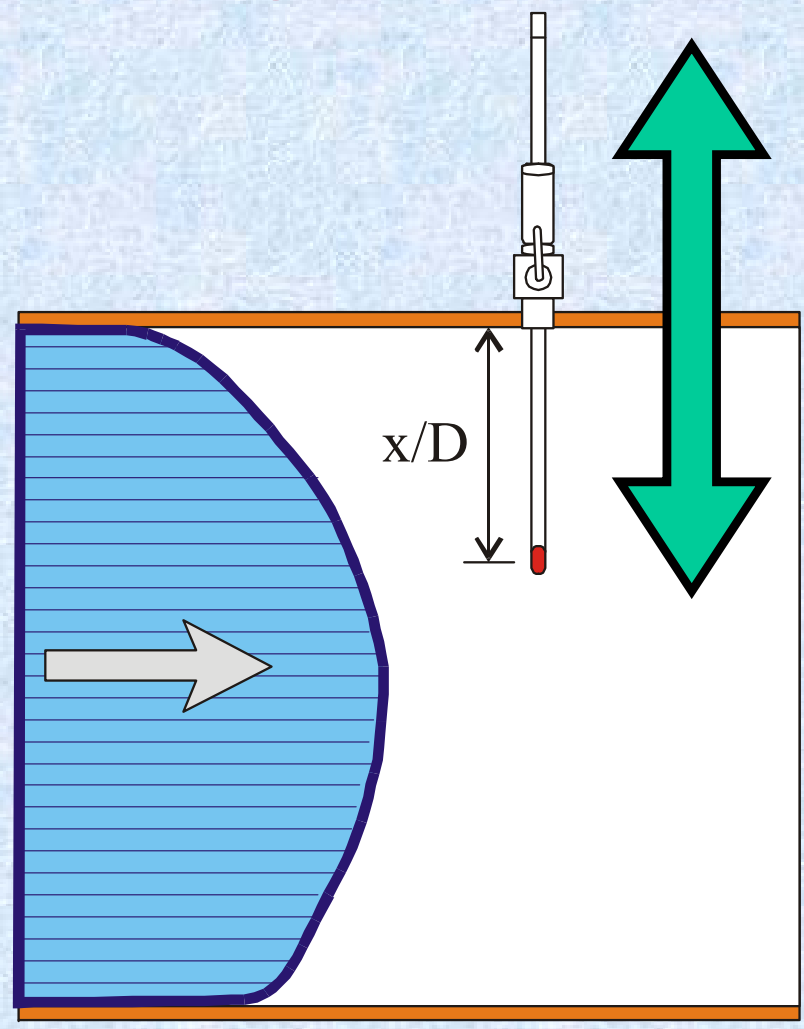




# ...Smart EM Current Meter



The solution is to perform the “profiling”:  
recording of true velocity profile along one diameter



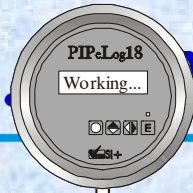
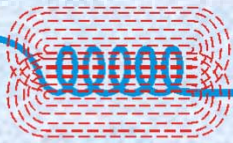
...move up...

along diameter,  
and record

...move down...

the point  
velocity



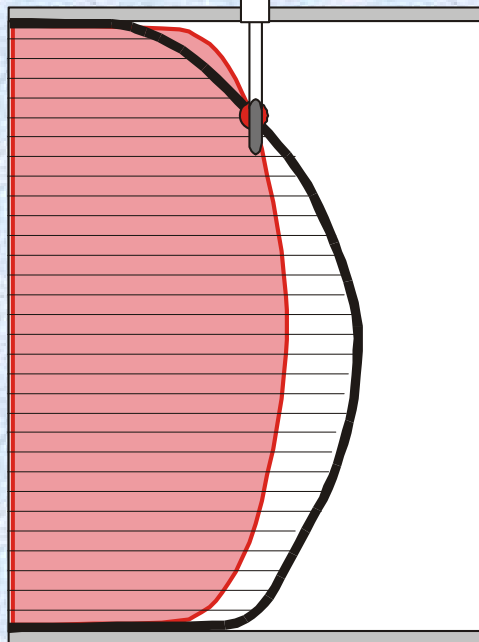


# Smart EM Current Meter



The built-in  
allows the  
and measu-  
theoretical

algorithm in Smart EM Current Met.  
iterative profiling: based on diameter  
red velocity, it will extrapolate using  
velocity profile between wall and the

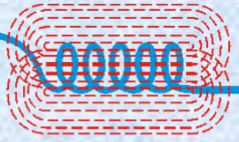


Extrapolation

first measu-  
red point...

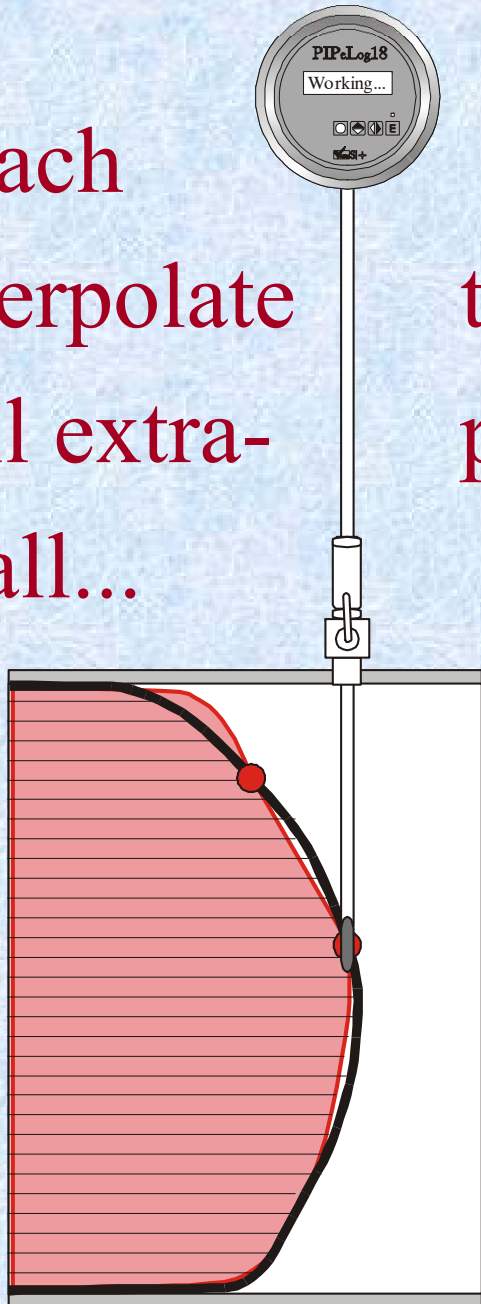
Extrapolation

# ...Smart EM Current Meter



... for each  
will interpolate  
and will extra-  
pipe wall...

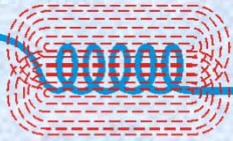
new measured velocity, it  
the velocity filed between them  
polate between last points and



Extrapolation

Linear interpolation

Extrapolation

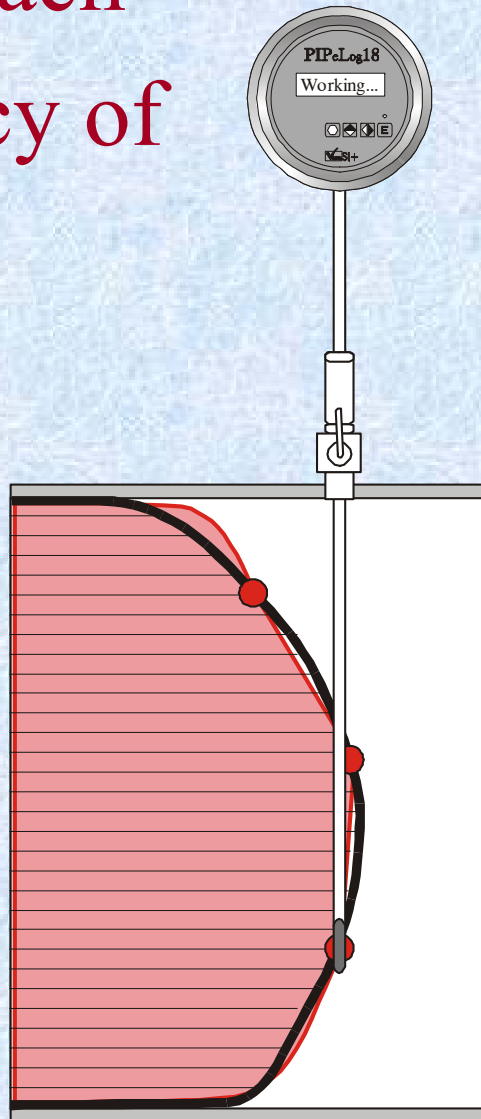


# ...Smart EM Current Meter



... for each accuracy of

new measured velocity, the calculated flow will increase!

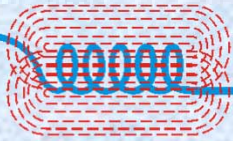


Extrapolation

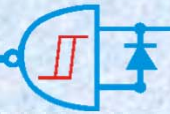
Linear interpolation

Linear interpolation

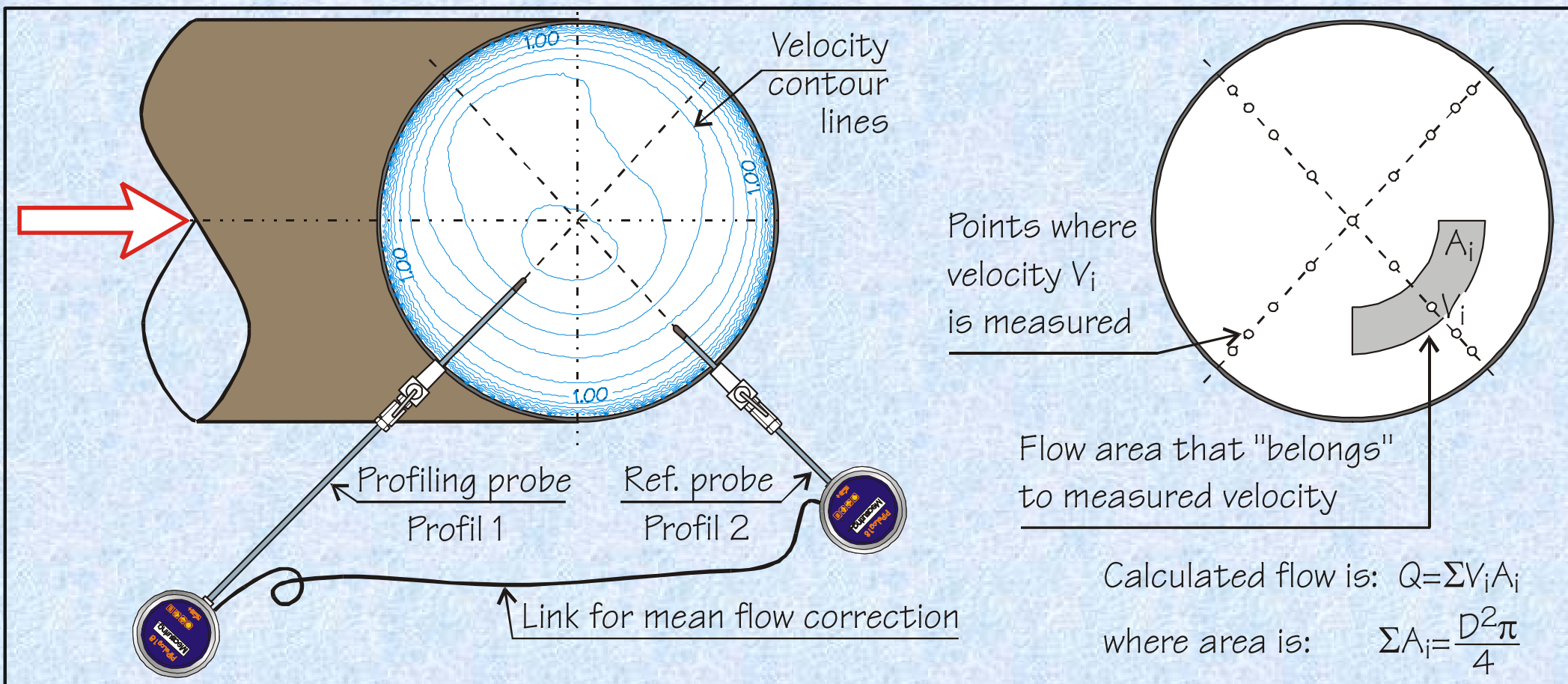
Extrapolation



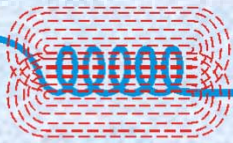
# ...Smart EM Current Meter



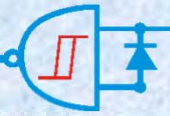
In difficult positions two or more profiles are needed



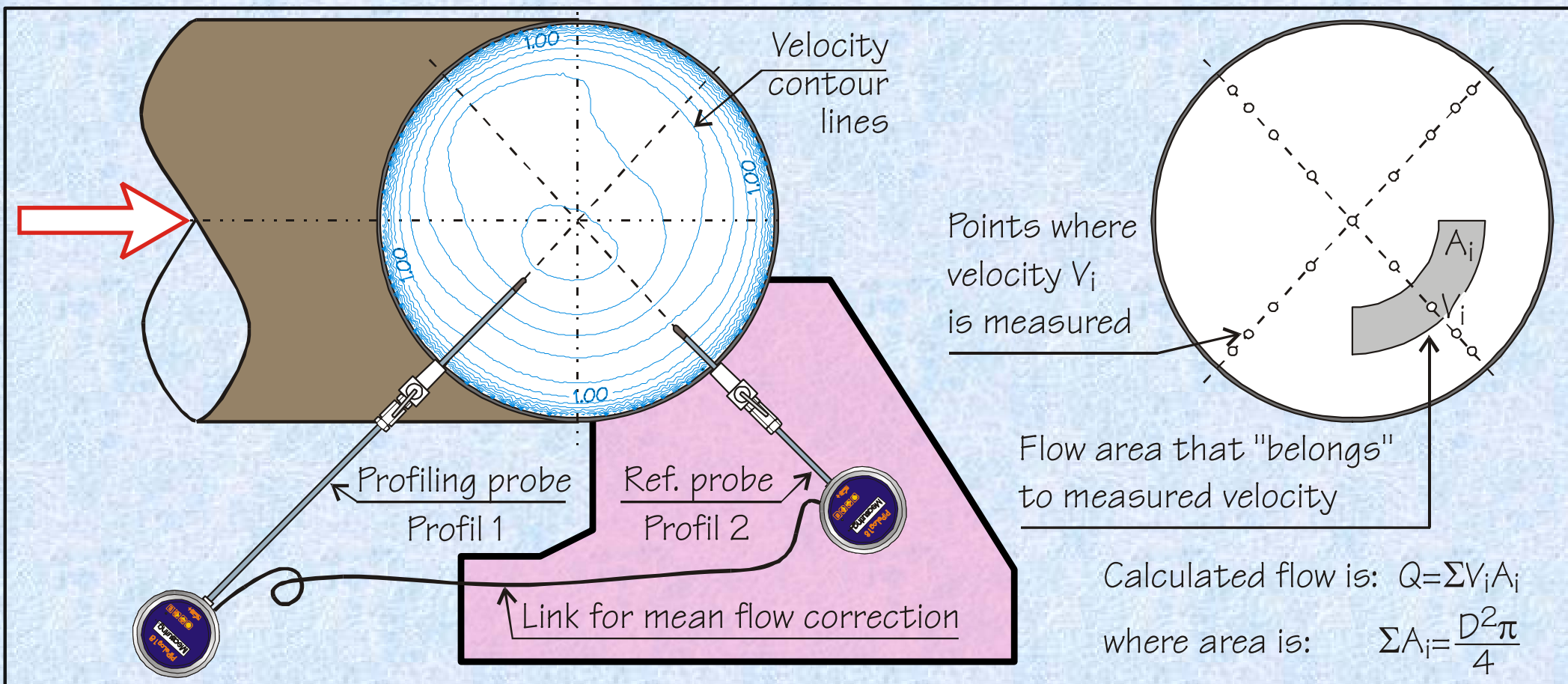




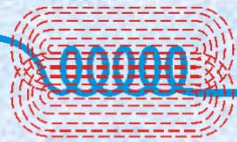
# ...Smart EM Current Meter



Big problem: profiling lasts 1 – 2 hours: meanwhile the flow will fluctuate! It has to be compensated!

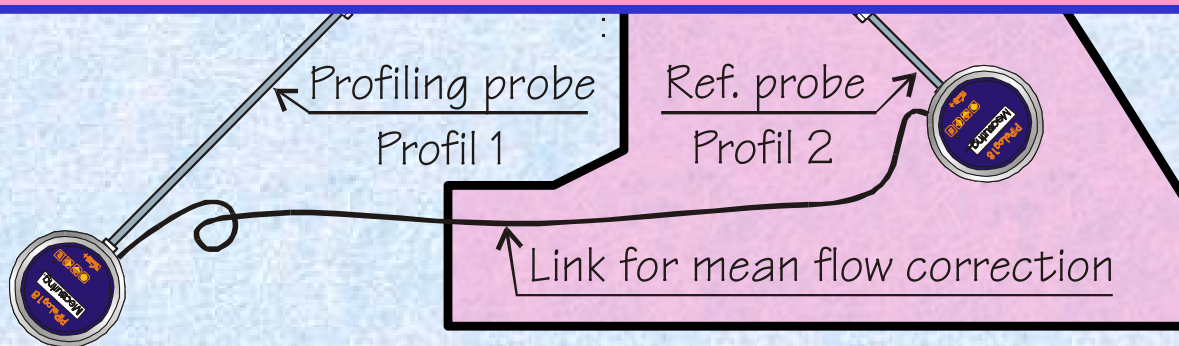


# ...Smart EM Current Meter



Big problem: profiling lasts 1 – 2 hours: meanwhile the flow will fluctuate! It has to be compensated!

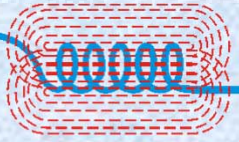
**Smart EM Current Meter  
knows how to  
assist the user in profiling  
of unsteady irregular flow!**



Flow area that "belongs" to measured velocity

Calculated flow is:  $Q = \sum V_i A_i$

where area is:  $\sum A_i = \frac{D^2 \pi}{4}$



# ...Smart EM Current Meter

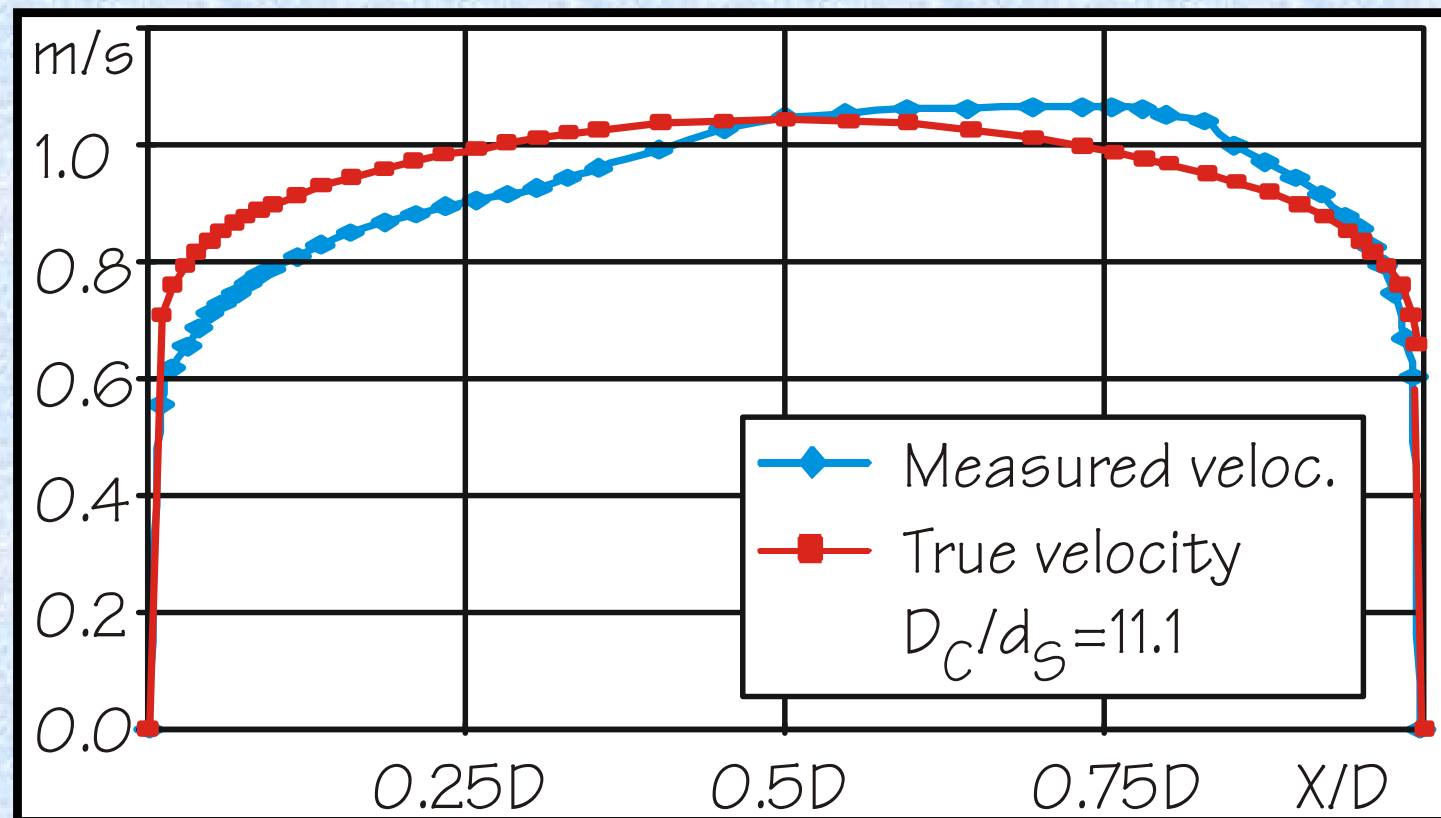


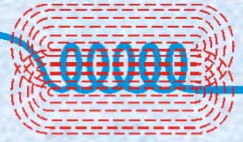
One more detail:

The EM probe will disturb the genuine velocities!

Solution:

The Smart EM Current Meter was tested on different pipe diameters...





## ...Smart EM Current Meter



One more detail:

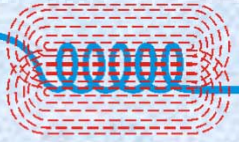
The EM probe will disturb the genuine velocities!

Solution:

...and its influence on point velocity is stored within it!

The Smart EM  
Current Meter  
was tested on  
different pipe  
diameters...





# ...Smart EM Current Meter



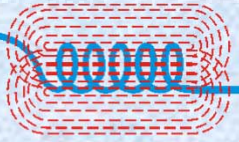
One more detail:

The EM probe will disturb the genuine velocities!

**Smart EM Current Meter**

**knows how to  
measure true  
point velocity!**

was tested on  
different pipe  
diameters...

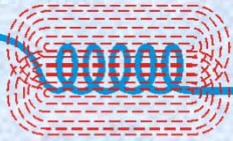


## ...Smart EM Current Meter

How the Smart EM Current Meter (PIPeLog18) looks like?

- pressure and velocity
- has batteries
- insertion hardware
- large memory
- LCD display and WP keys
- AUX input

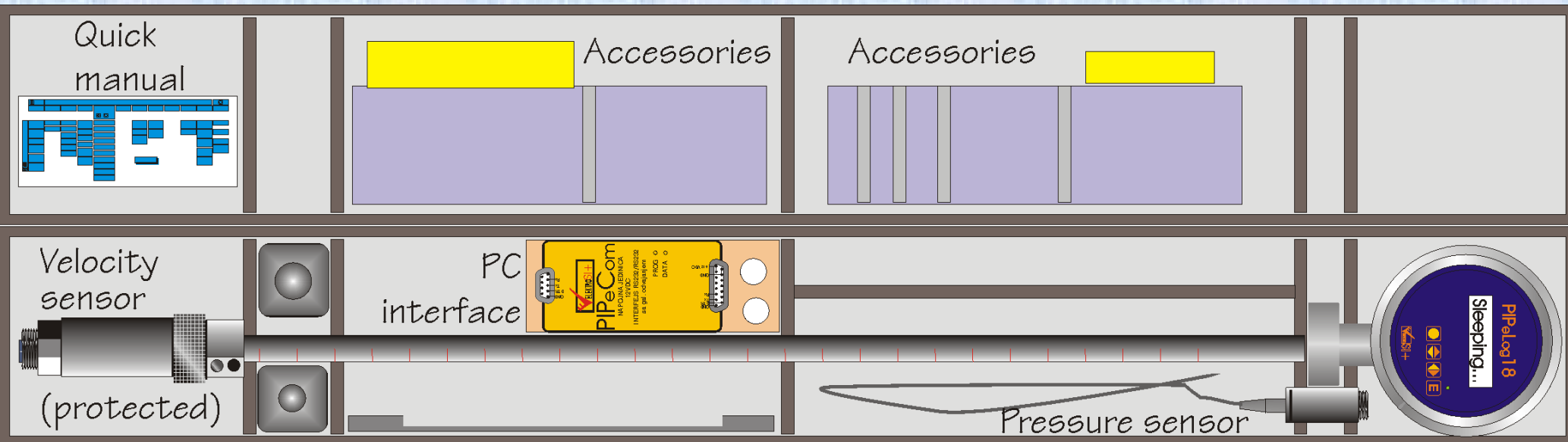




# ...Smart EM Current Meter

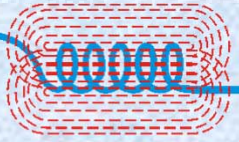


How the Smart EM Current Meter  
(PIPeLog18) looks like?



End of Smart EM Current Meter presentation...

# Intelligent instrumentation ...




Instruments with “brain”: think, conclude, remember

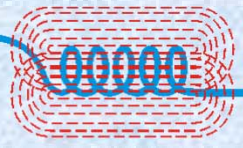
They can adopt to different jobs

Improved accuracy due to complex algorithms

Two sensors developed in cooperation with electronic gurus:

- Smart ElectroMagnetic Current Flow Meter
- Mean and Transient Pressure Logger 





# ...Intelligent pressure logger



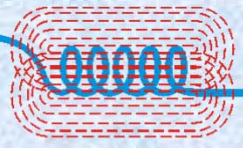
## Intelligent pressure logger

Aren't there on market enough pressure loggers?

They are with:

- Large memory
- Wide sampling rates (1sec - 1min - 1hour)
- With/without display
- With IR remote control/data download
- ...etc...

Is still something that we can't measure with those loggers? And why we need those measurements?



# ...Intelligent pressure logger

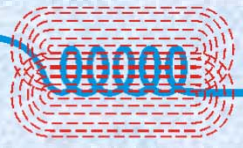


Two time scales are associated with pressure in pressurized pipe network:

- Slow pressure changes (minutes/hours) due to changed production/consumption
- Fast pressure changes (parts of seconds) due to pressure wave travel caused by sudden flow change (pressure transient)

Addressed by a number of existing pressure loggers

Addressed only in laboratory work or in diagnostic field measurements




# ...Intelligent pressure logger

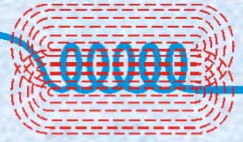


Two time scales are associated with pressure in pressurized pipe network:

- Slow pressure changes (minutes/hours) due to changed production/consumption
- Fast pressure changes (parts of seconds) due to pressure wave travel caused by sudden flow change (pressure transient)

What we need is a pressure logger that can be used in field measurements with both time scales!

...but why? 

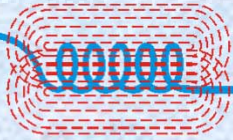


# ...Intelligent pressure logger



- Slow pressure changes:
  - For quasi unsteady simulation models
  - Monitoring of network performance
  - Customer compliance for low pressure
  - ...etc...
- Fast pressure changes
  - Incident event analysis (pump failure, valve closure...)
  - Leak detection
  - Continuous network dynamic performance monitoring





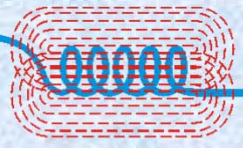
# ...Intelligent pressure logger



- Slow pressure changes:
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  - Monitoring of network performance
  - Customer compliance for low pressure
  - ...etc...
- Fast pressure changes
  - Incident event analysis (pump failure, valve closure...)
  - Leak detection
  - Continuous network dynamic performance monitoring

Usually performed during diagnostic measurements:

- high costs
- lab equipment
- occasionally



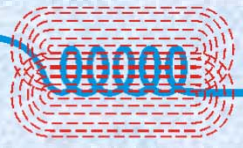
# ...Intelligent pressure logger



- Slow pressure changes:
  - For quasi unsteady simulation
  - Monitoring of network performance
  - Customer compliance for low pressure
  - ...etc...
- Fast pressure changes
  - Incident event analysis (pump failure, valve closure...)
  - Leak detection
  - Continuous network dynamic performance monitoring



New techniques:  
Using unsteady simulation models  
find the position and flow rate of the water leak -  
inverse transient method!



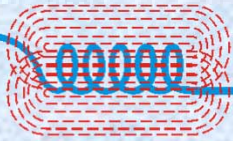
## ...Intelligent pressure logger



Inverse transient methods are promising but still in development phase.

- Present studies are mostly based on laboratory measurements on test rigs
- To widen the view on the problem, some field ad-hoc measurements were performed
- We need the continuous field measurements of both mean pressure values and transients!

This is why we need a new piece of equipment!

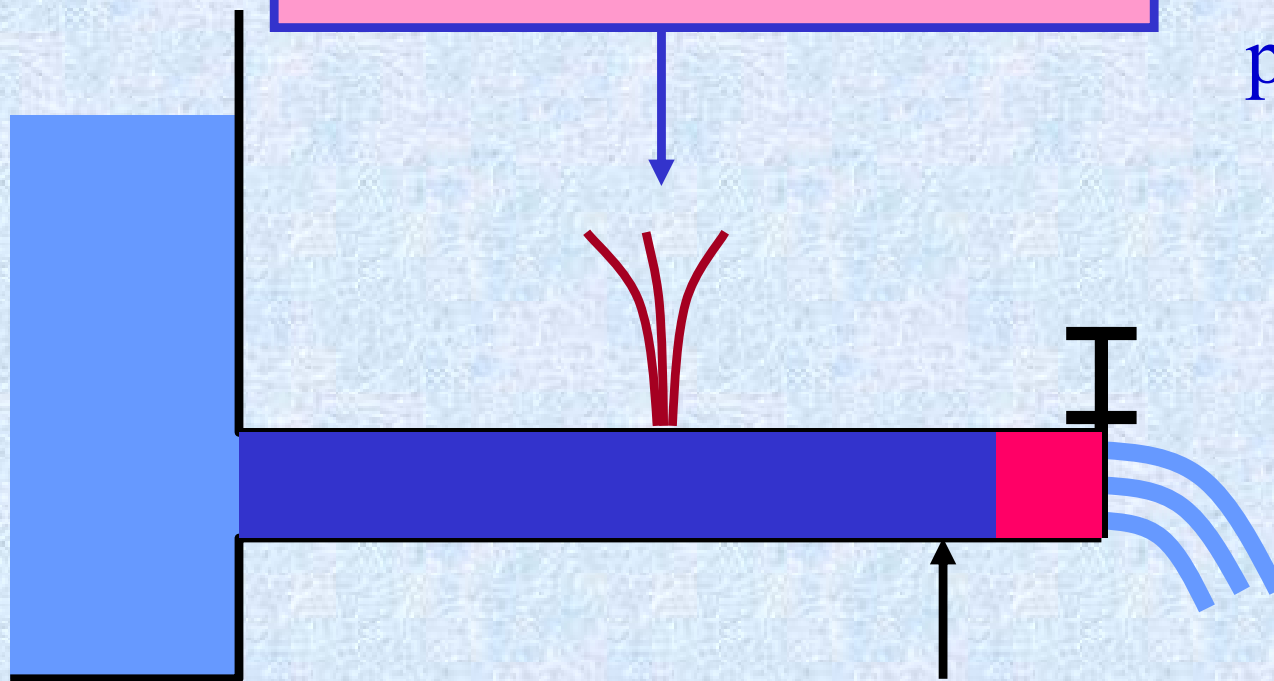


# ...Intelligent pressure logger



To tailor the new smart logger we must analyze the problems addressed with inverse transient p. method

If there is a leak of water

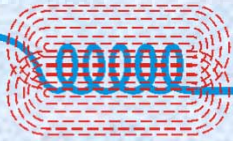


p logger

Dynamic char.  
will change!





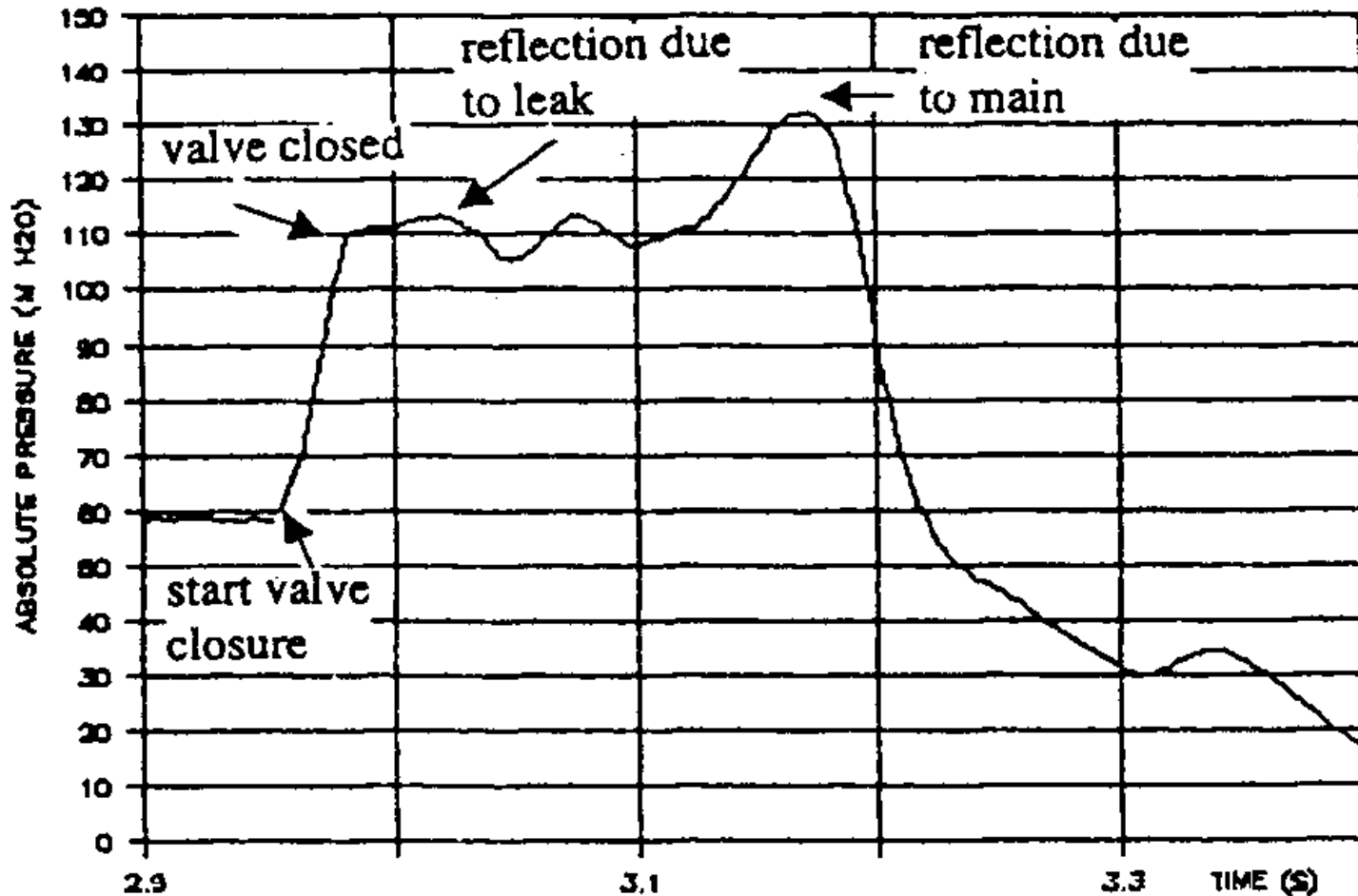


# ...Intelligent pressure logger

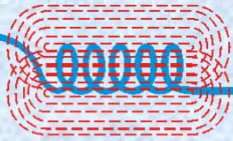


Few different approaches world-wide

1) Jonsson L. – Look at the first pressure transient



OK for simple networks and when leak is in same pipe where press. is measured

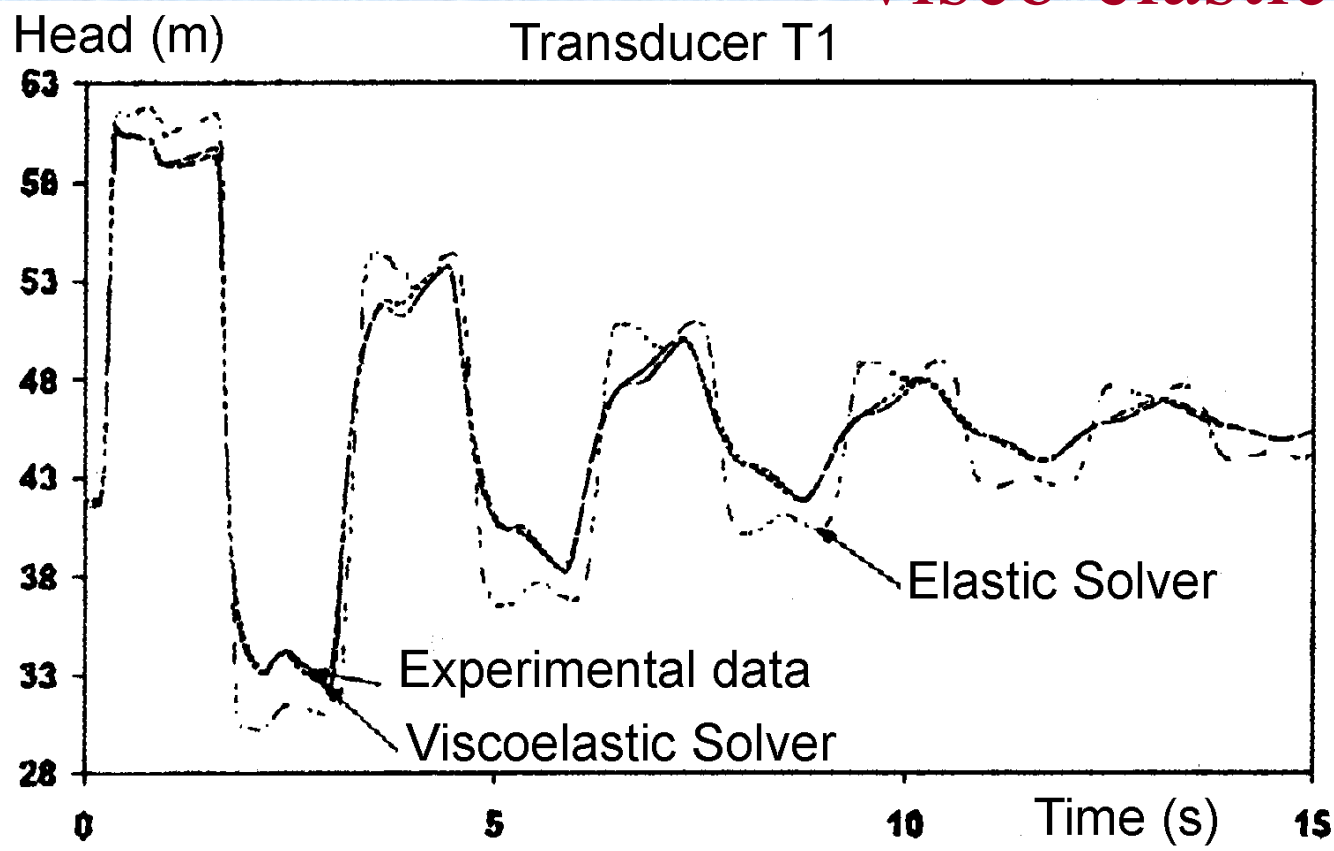


# ...Intelligent pressure logger

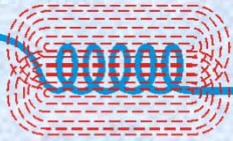


Few different approaches world-wide

2) Maksimovic C. – Fit the whole transient event to  
visco-elastic model



Model has to be  
“trained” on  
healthy network.  
High pressure  
transient has to  
be used!

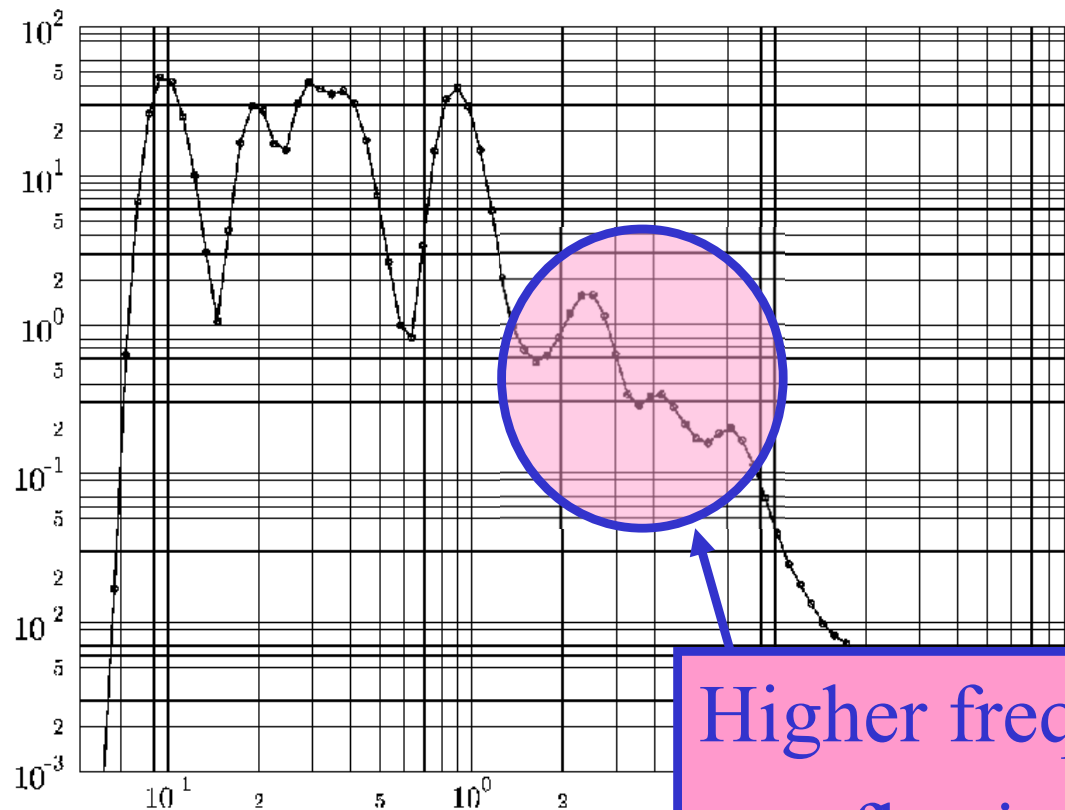


# ...Intelligent pressure logger



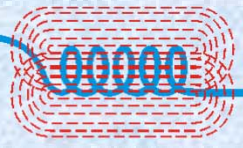
Few different approaches world-wide

3) Ivetic M. – Analyze network's dynamic character

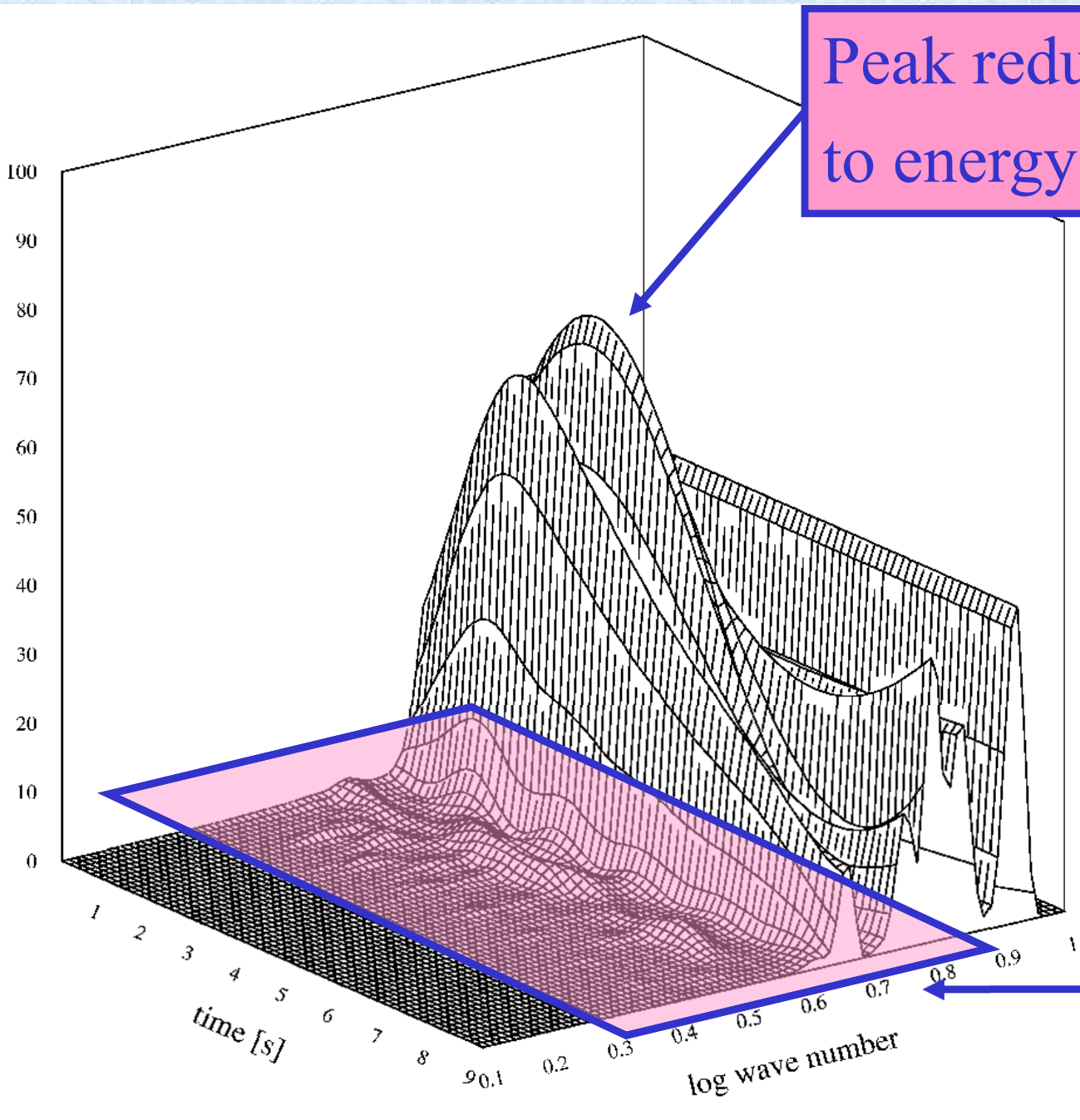


Fourier transform  
of captured  
transient **with**  
leakage

Higher frequencies introduced due  
to reflection from leaking place



# ...Intelligent pressure logger



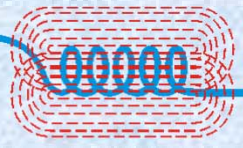
Peak reduced due to energy leak

dynamic character

Wavelet transform of captured transient without leakage

Look at shorter wave numbers..



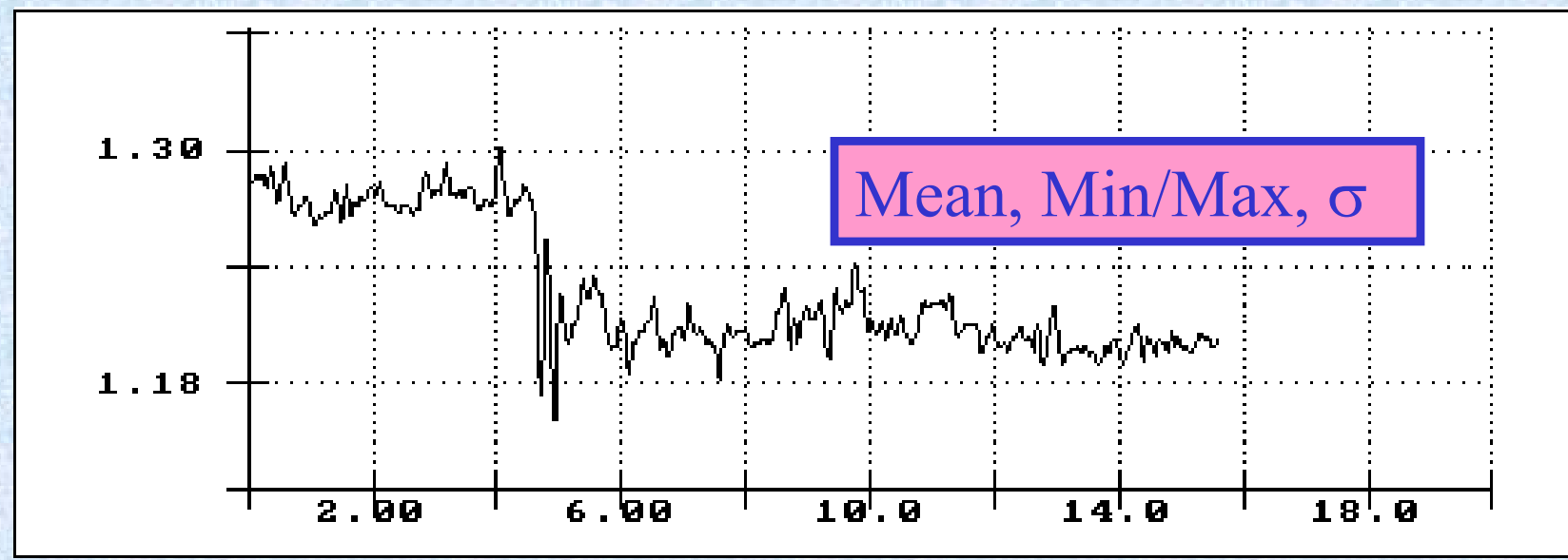


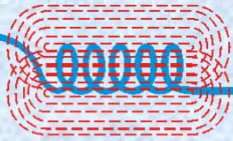
# ...Intelligent pressure logger



To support inverse transient research, we need:

- Continuous measurement using low data rates
- Basic statistical data averaged over minutes
- Recognition of transients
- Whole transient capture using fast data rates
- Back to continuous measurement using low data rates

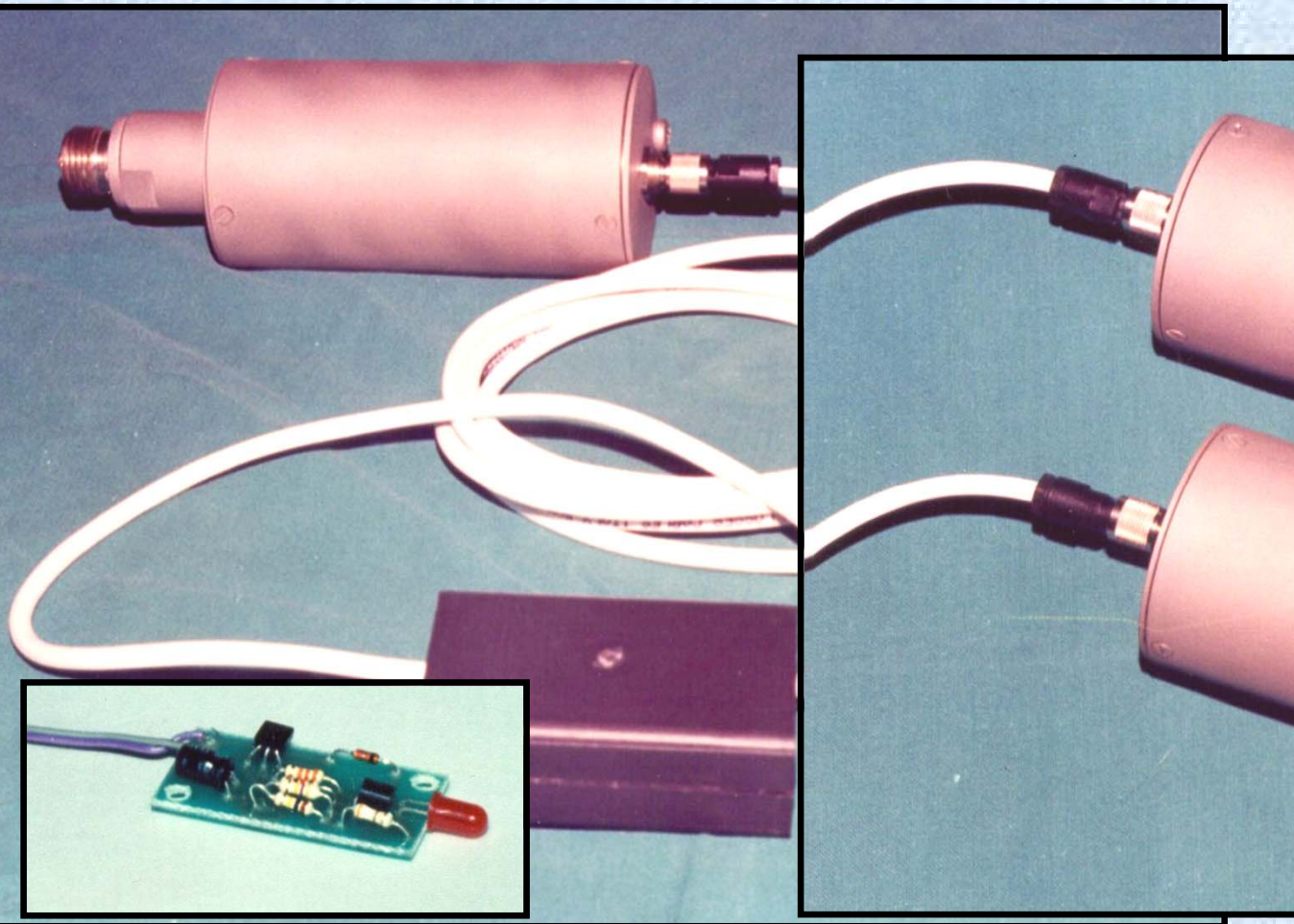




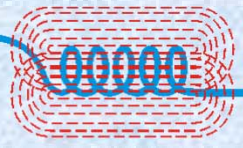
# ...Intelligent pressure logger



A pressure logger is developed that from the outside looks quite simple...







## ...Intelligent pressure logger



A pressure logger is developed that from the outside looks quite simple...

... but it is equipped with a “brain”- small dedicated microprocessor that handles all needed requests.

The block diagram of software built in logger... 

Circular data buffer

Moving stat. buffer

2 msec

data rate

1000 points

10-20 points

1 sec  
ticks

$X_i$

$\bar{X}, \sigma$

Trigger

**NO!**

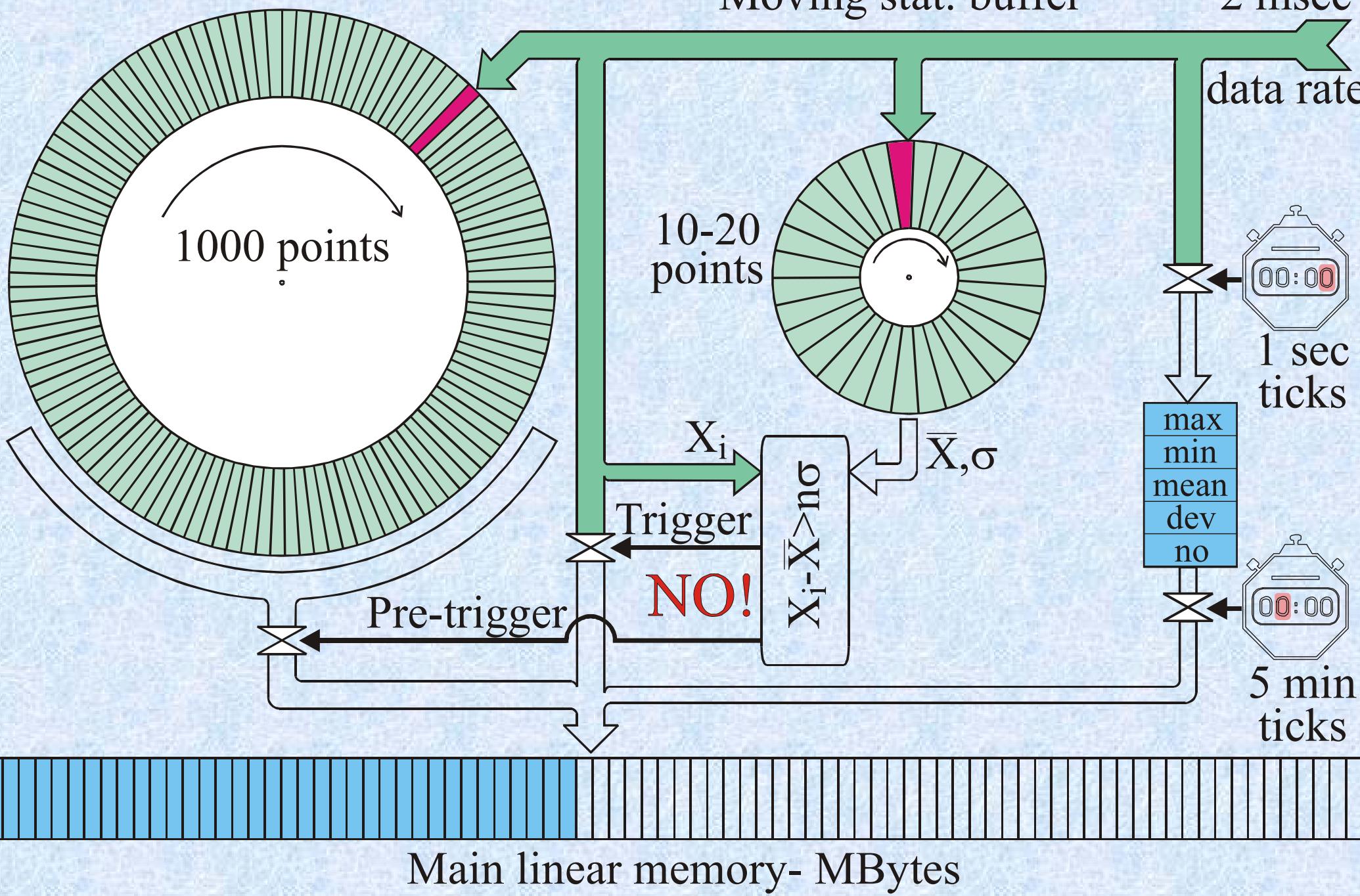
$X_i - \bar{X} > n\sigma$

max  
min  
mean  
dev  
no

5 min  
ticks

Pre-trigger

Main linear memory- MBytes





Circular data buffer

Moving stat. buffer

2 msec

data rate

1000 points

10-20 points

1 sec ticks

$X_i$

$\bar{X}, \sigma$

Trigger

**NO!**

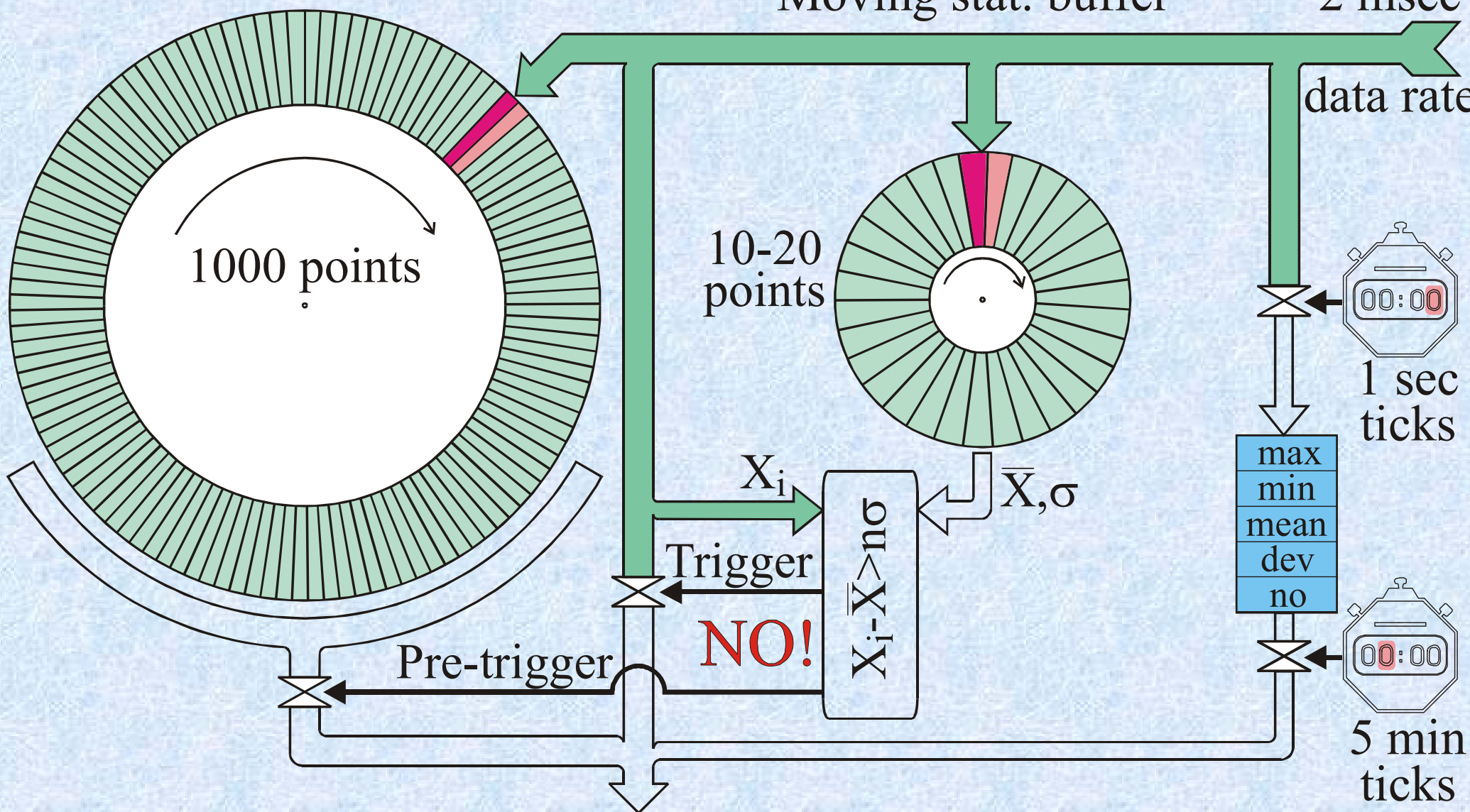
$X_i - \bar{X} > n\sigma$

max  
min  
mean  
dev  
no

5 min ticks

Pre-trigger

Main linear memory- MBytes



Circular data buffer

Moving stat. buffer

2 msec

data rate

1000 points

10-20 points

1 sec ticks

$X_i$

$\bar{X}, \sigma$

Trigger

**NO!**

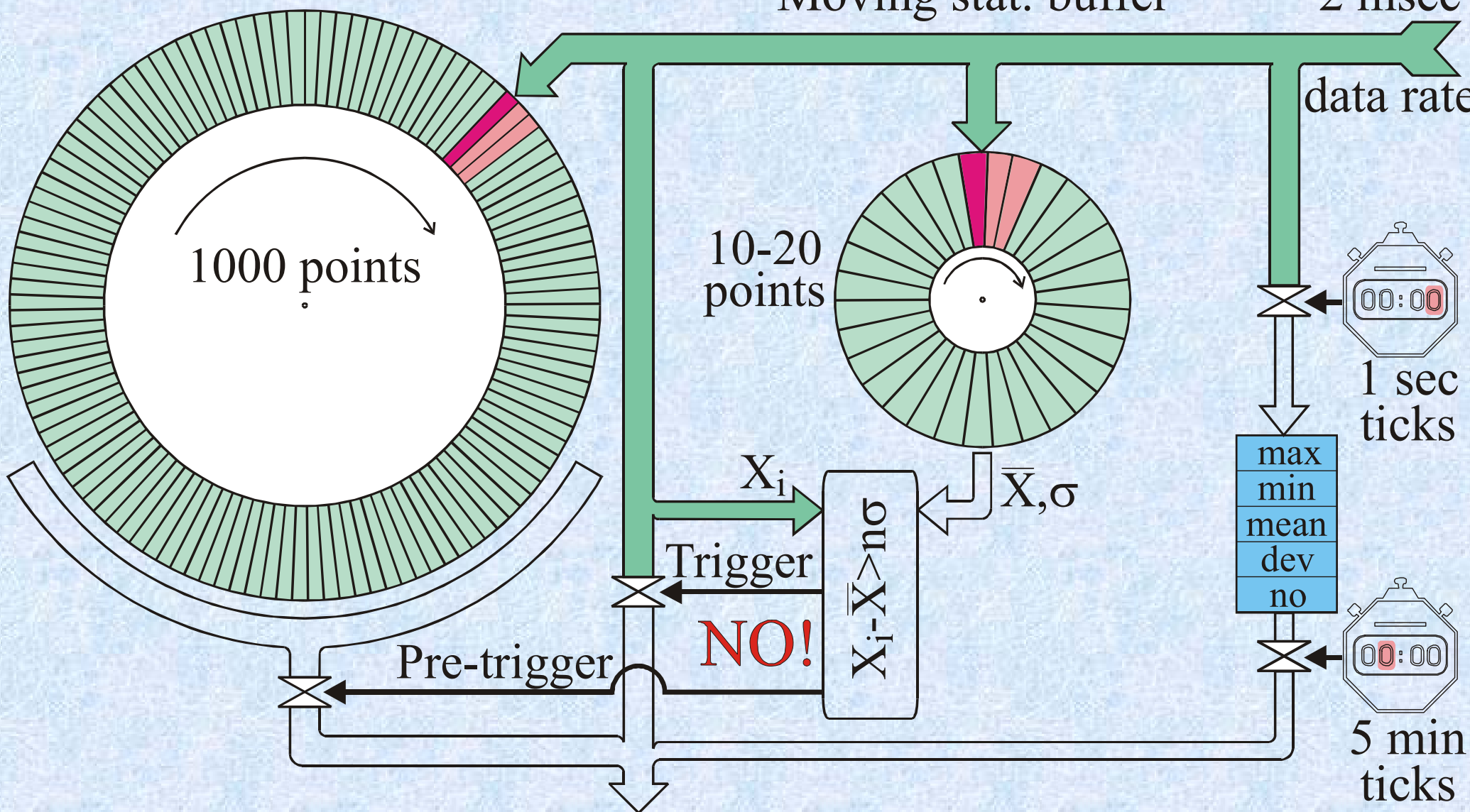
$X_i - \bar{X} > n\sigma$

max  
min  
mean  
dev  
no

5 min ticks

Pre-trigger

Main linear memory- MBytes





Circular data buffer

Moving stat. buffer

2 msec

data rate

1000 points

10-20 points

00:00  
1 sec ticks

$X_i$

$\bar{X}, \sigma$

Trigger

**NO!**

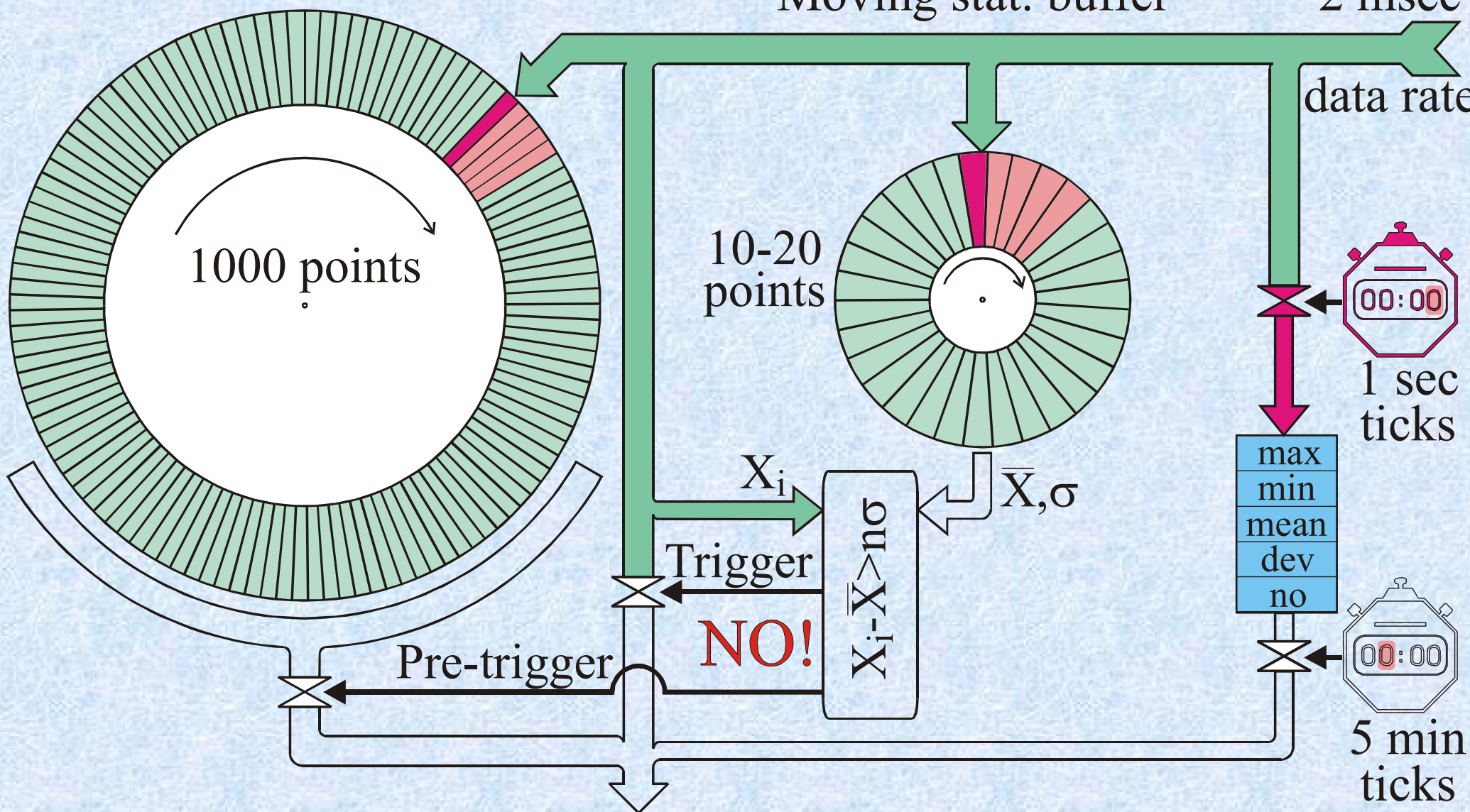
$X_i - \bar{X} > n\sigma$

max  
min  
mean  
dev  
no

00:00  
5 min ticks

Pre-trigger

Main linear memory- MBytes





Circular data buffer

Moving stat. buffer

2 msec

data rate

1000 points

10-20 points

1 sec ticks

$X_i$

$\bar{X}, \sigma$

Trigger

**NO!**

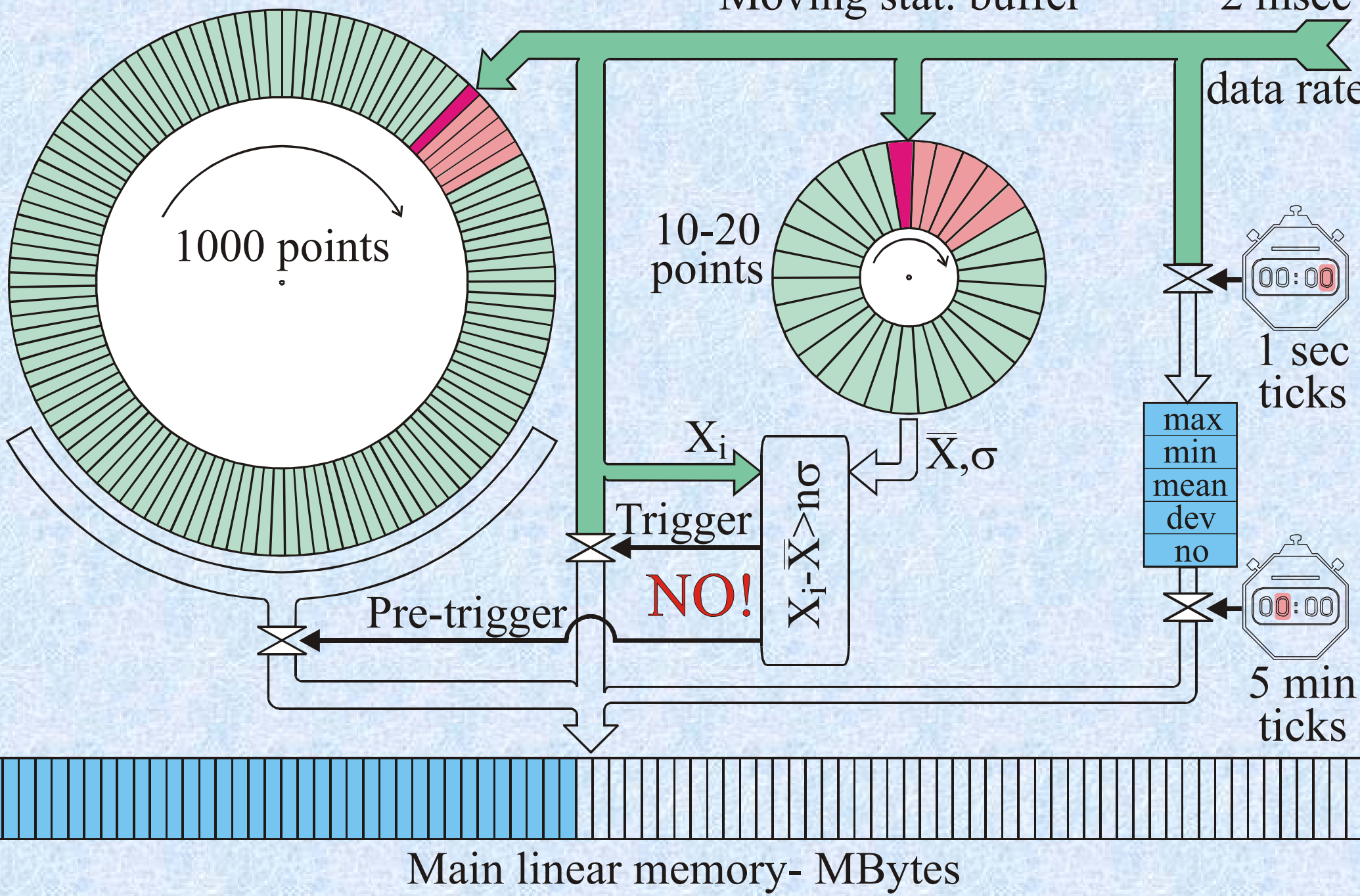
$X_i - \bar{X} > n\sigma$

max  
min  
mean  
dev  
no

5 min ticks

Pre-trigger

Main linear memory- MBytes



Circular data buffer

Moving stat. buffer

2 msec

data rate

1000 points

10-20 points

1 sec ticks

$X_i$

$\bar{X}, \sigma$

Trigger

**NO!**

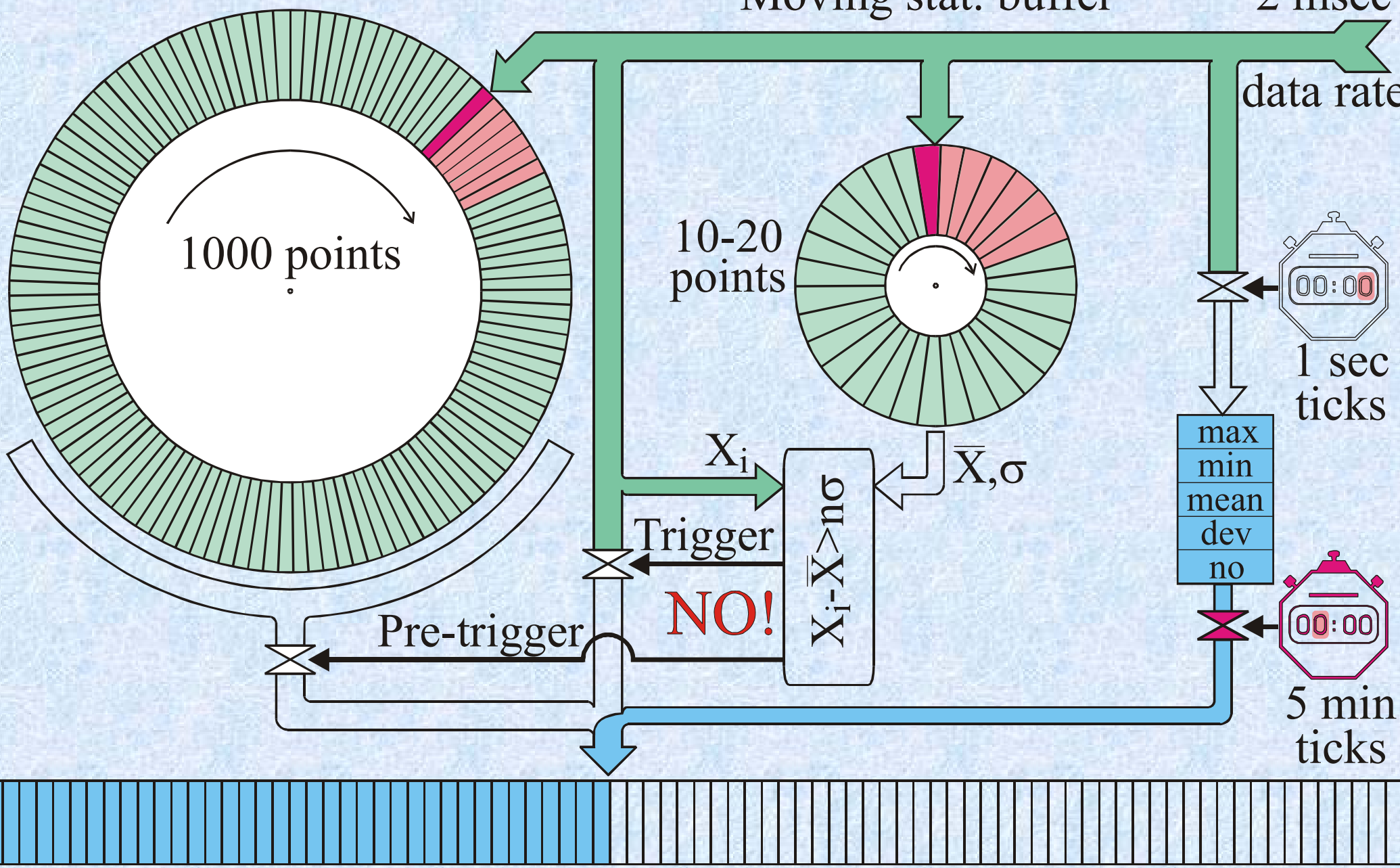
$X_i - \bar{X} > n\sigma$

Pre-trigger

max  
min  
mean  
dev  
no

5 min ticks

Main linear memory- MBytes



Circular data buffer

Moving stat. buffer

2 msec

data rate

1000 points

10-20 points

1 sec ticks

$X_i$

$\bar{X}, \sigma$

Trigger

**NO!**

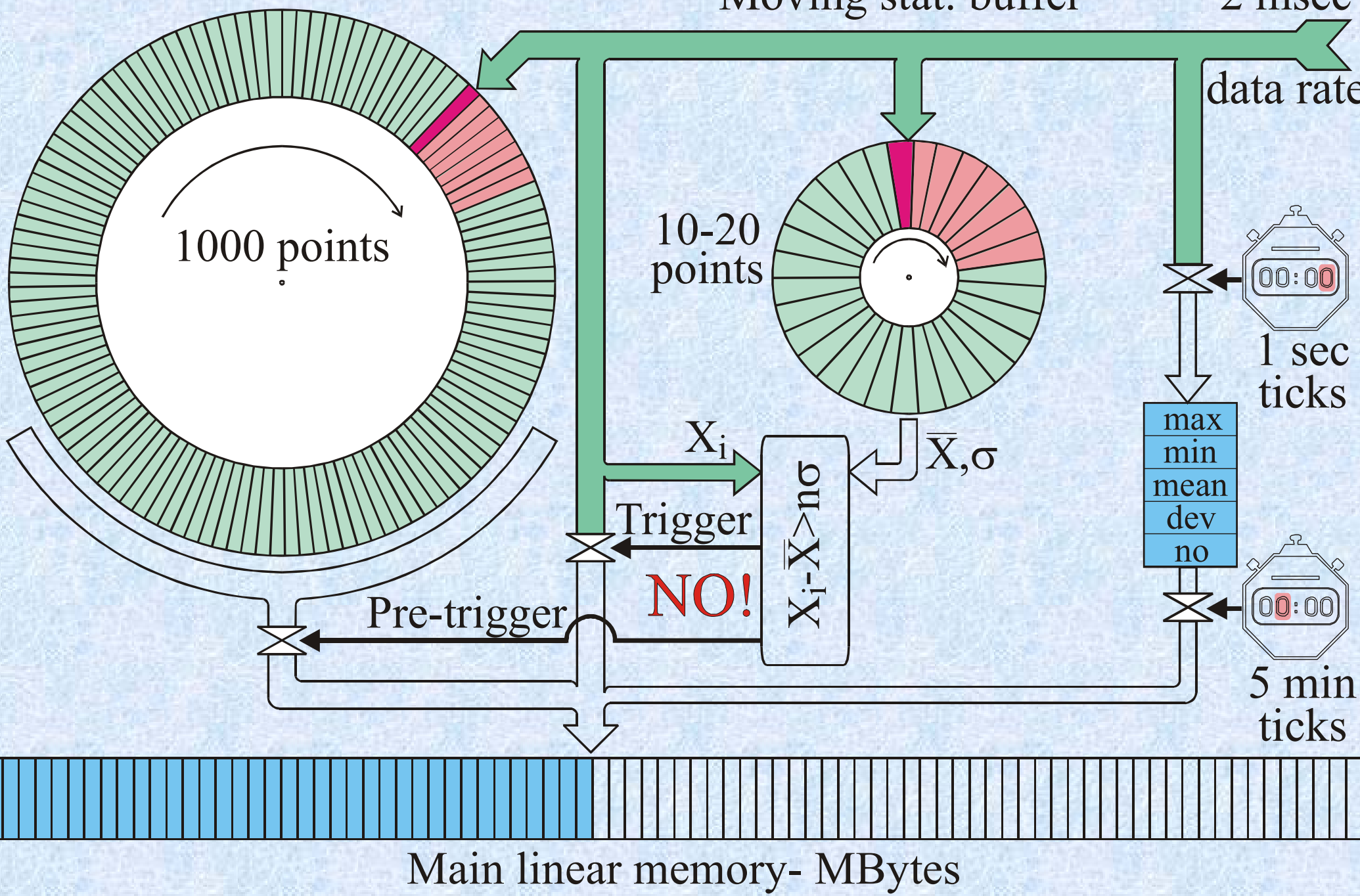
$X_i - \bar{X} > n\sigma$

max  
min  
mean  
dev  
no

5 min ticks

Pre-trigger

Main linear memory- MBytes



Circular data buffer

Moving stat. buffer

2 msec

data rate

1000 points

10-20 points

1 sec ticks

$X_i$

$\bar{X}, \sigma$

max  
min  
mean  
dev  
no

5 min ticks

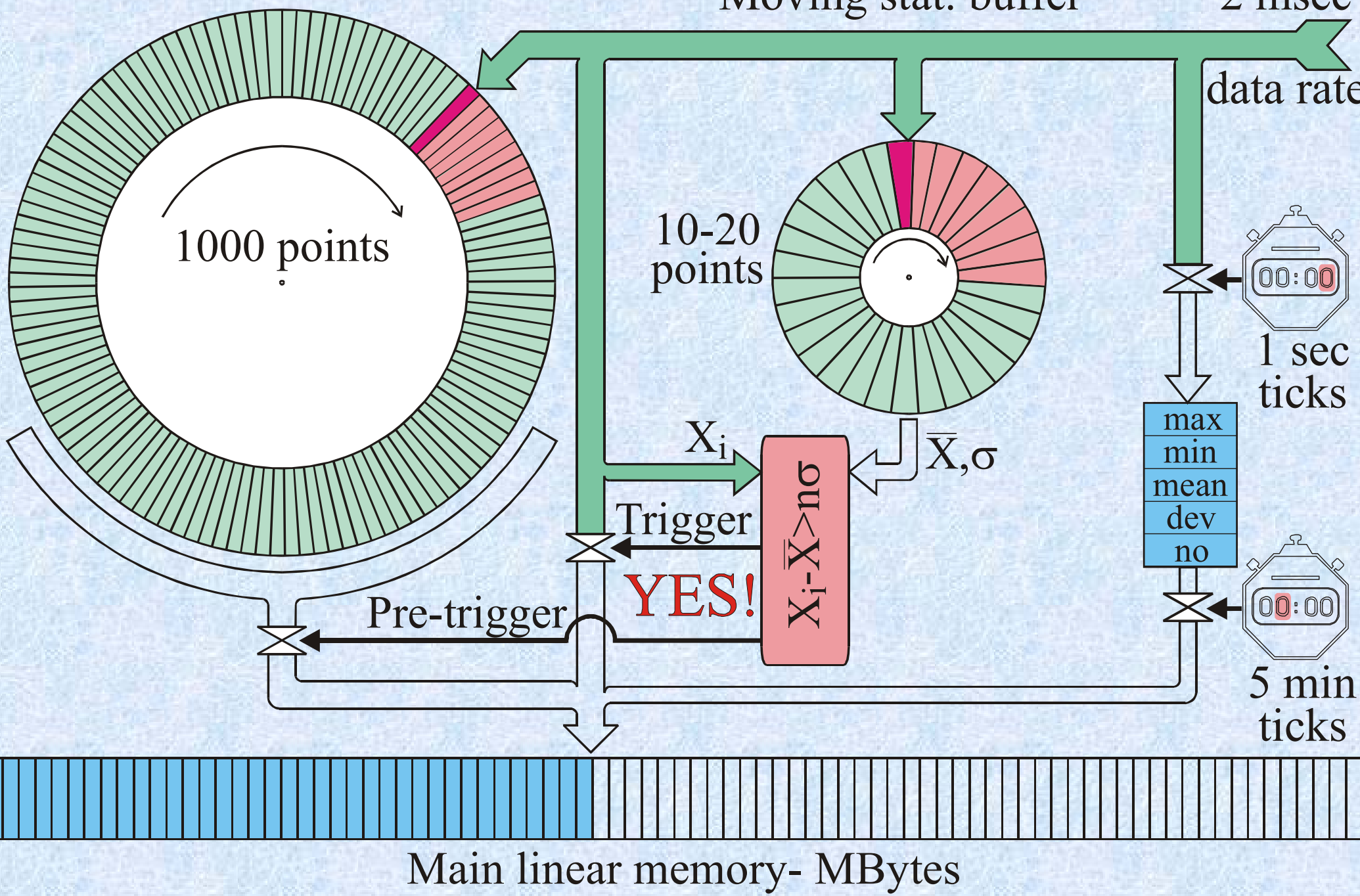
Pre-trigger

Trigger

**YES!**

$X_i - \bar{X} > n\sigma$

Main linear memory- MBytes





Circular data buffer

Moving stat. buffer

2 msec

data rate

1000 points

10-20 points



1 sec ticks

$X_i$

$\bar{X}, \sigma$

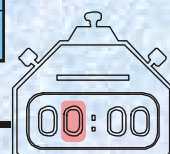
Trigger

NO!

$X_i - \bar{X} > n\sigma$

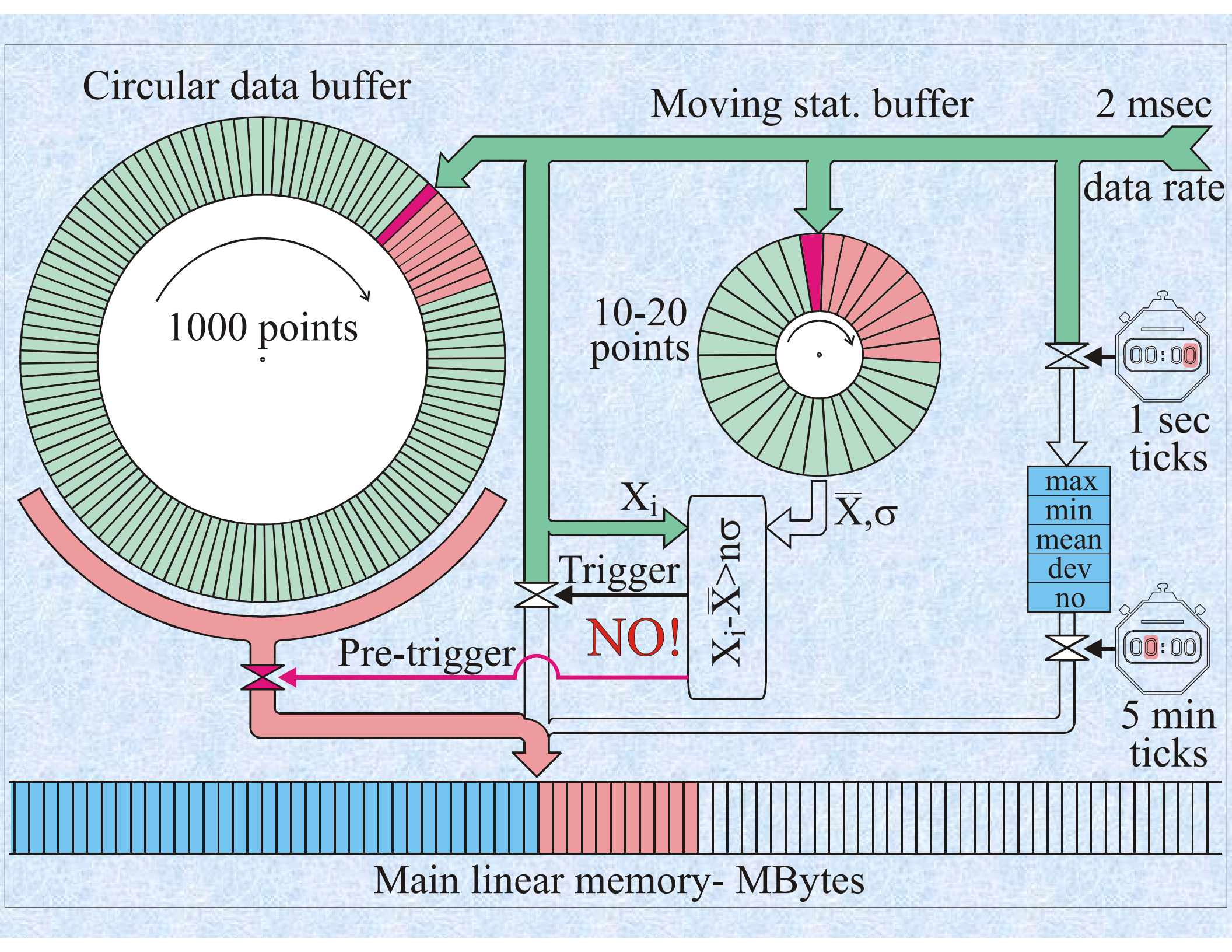
Pre-trigger

max  
min  
mean  
dev  
no



5 min ticks

Main linear memory- MBytes



Circular data buffer

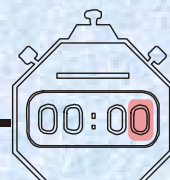
Moving stat. buffer

2 msec

1000 points

10-20 points

data rate



1 sec ticks

$X_i$

$\bar{X}, \sigma$

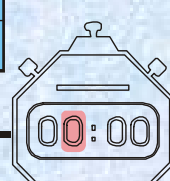
Trigger

NO!

$X_i - \bar{X} > n\sigma$

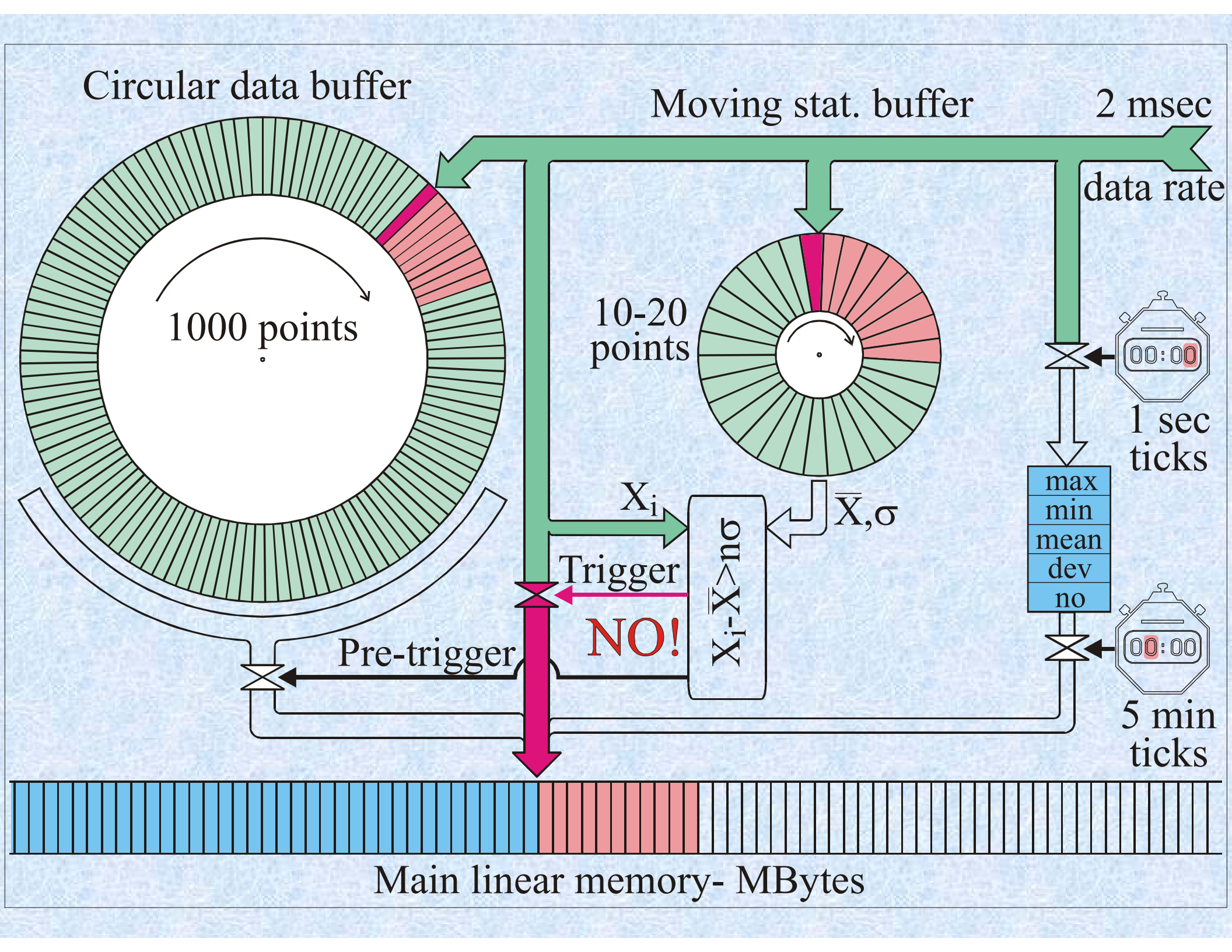
Pre-trigger

max  
min  
mean  
dev  
no



5 min ticks

Main linear memory- MBytes



Circular data buffer

Moving stat. buffer

2 msec

data rate

1000 points

10-20 points

1 sec ticks

$X_i$

$\bar{X}, \sigma$

Trigger

NO!

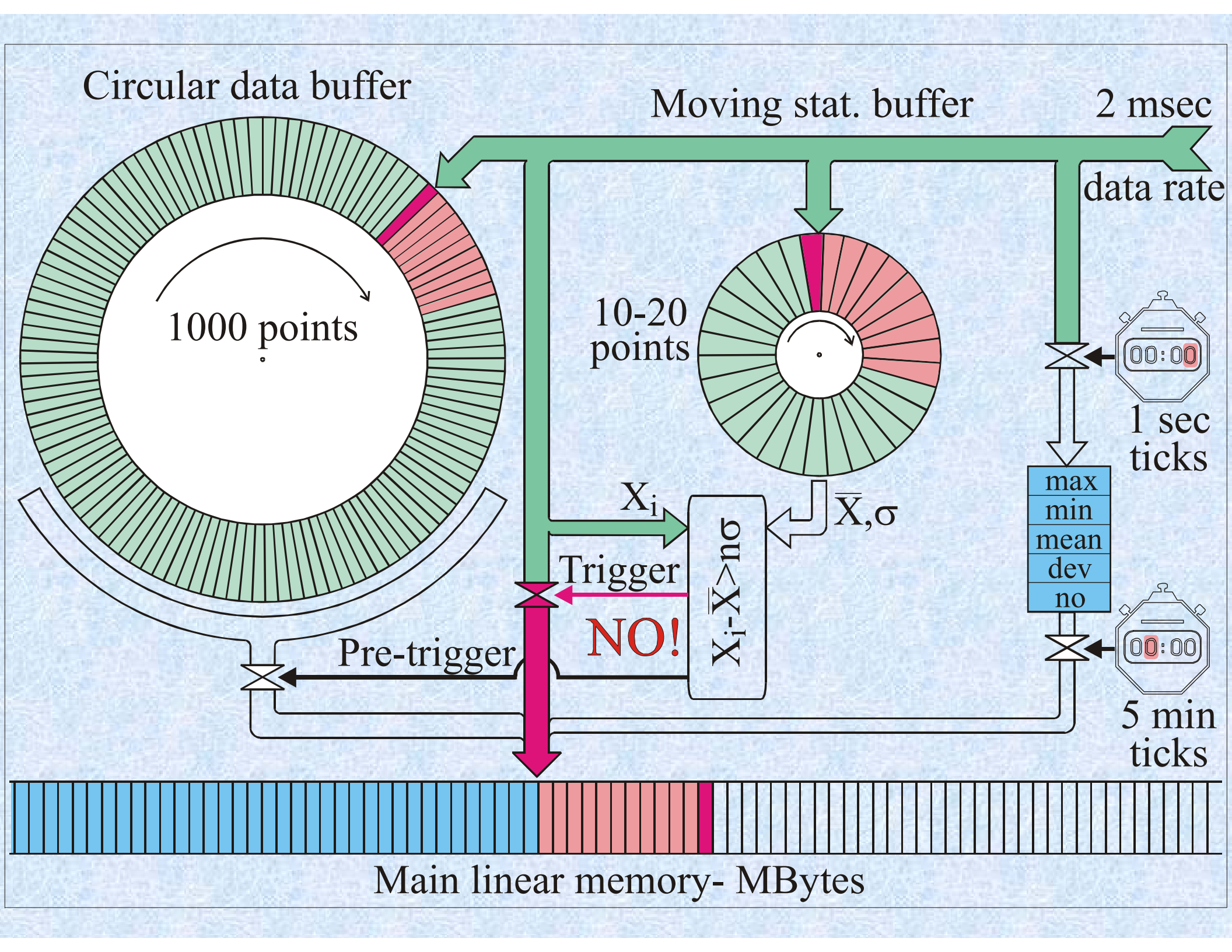
$X_i - \bar{X} > n\sigma$

max  
min  
mean  
dev  
no

5 min ticks

Pre-trigger

Main linear memory- MBytes



Circular data buffer

Moving stat. buffer

2 msec

data rate

1000 points

10-20 points

1 sec ticks

$X_i$

$\bar{X}, \sigma$

Trigger

NO!

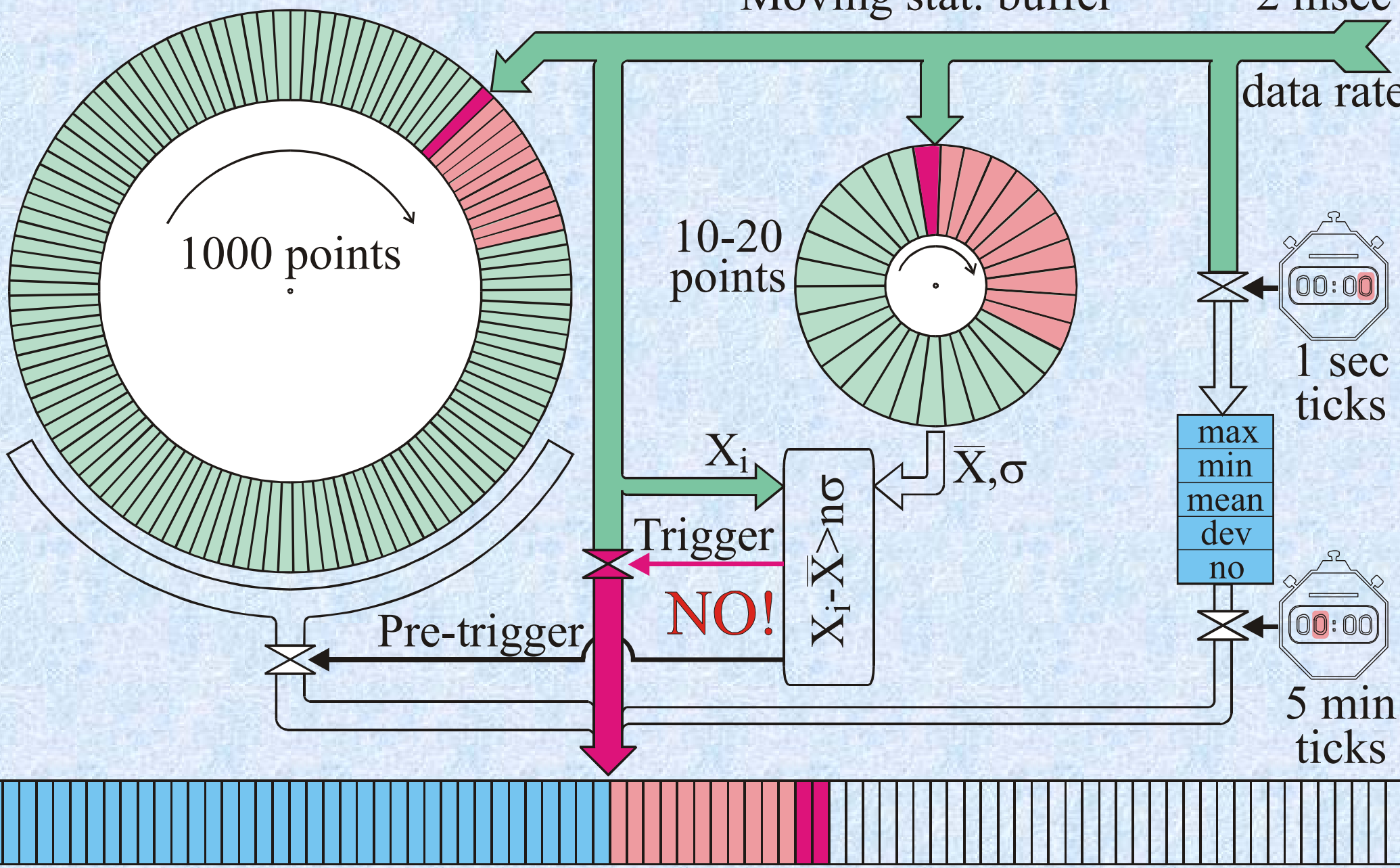
$X_i - \bar{X} > n\sigma$

max  
min  
mean  
dev  
no

5 min ticks

Pre-trigger

Main linear memory- MBytes





Circular data buffer

Moving stat. buffer

2 msec

data rate

1000 points

10-20 points

1 sec ticks

$X_i$

$\bar{X}, \sigma$

Trigger

NO!

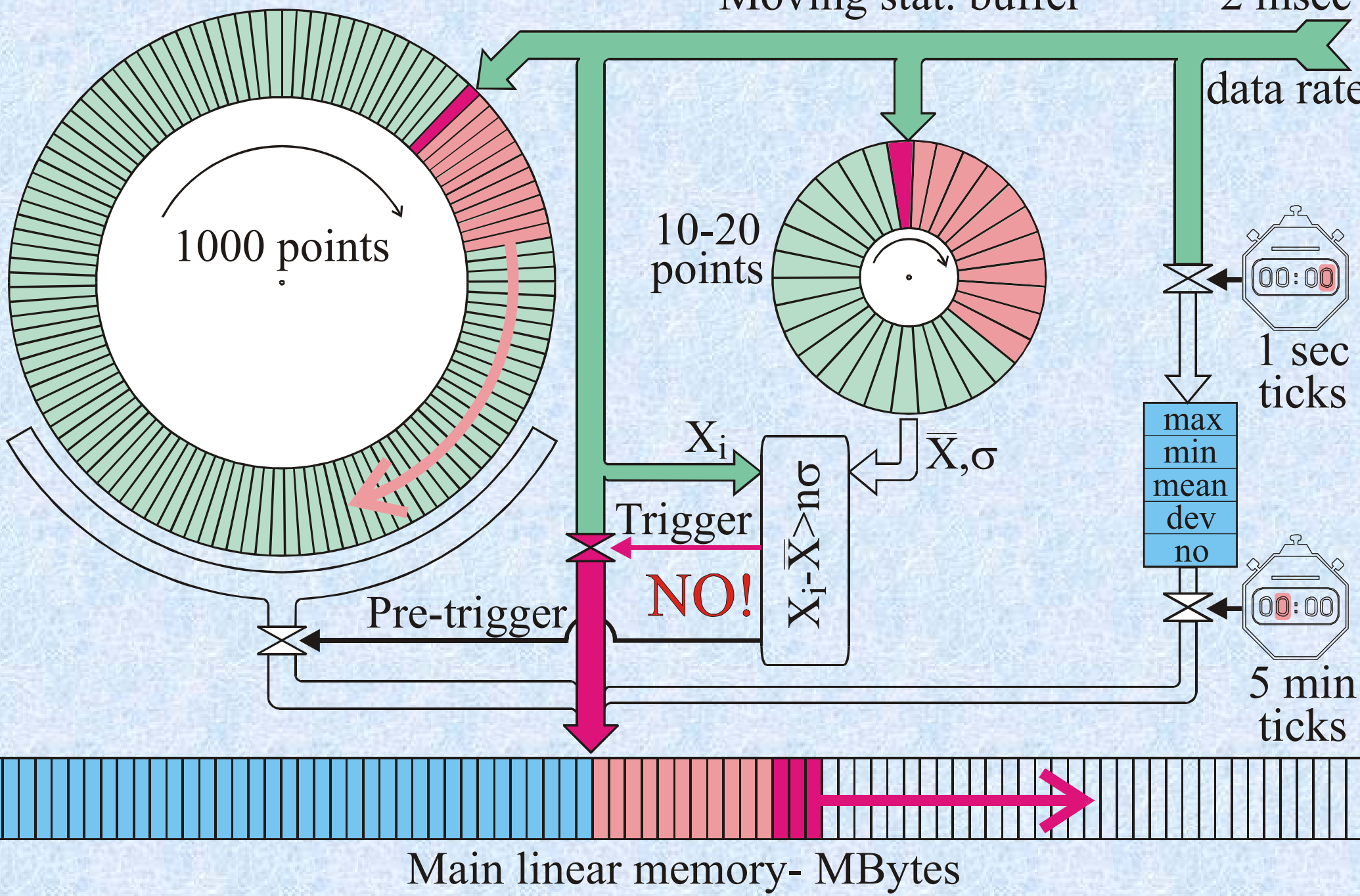
$X_i - \bar{X} > n\sigma$

max  
min  
mean  
dev  
no

5 min ticks

Pre-trigger

Main linear memory- MBytes



Circular data buffer

Moving stat. buffer

2 msec

data rate

1000 points

10-20 points

1 sec ticks

$X_i$

$\bar{X}, \sigma$

Trigger

**NO!**

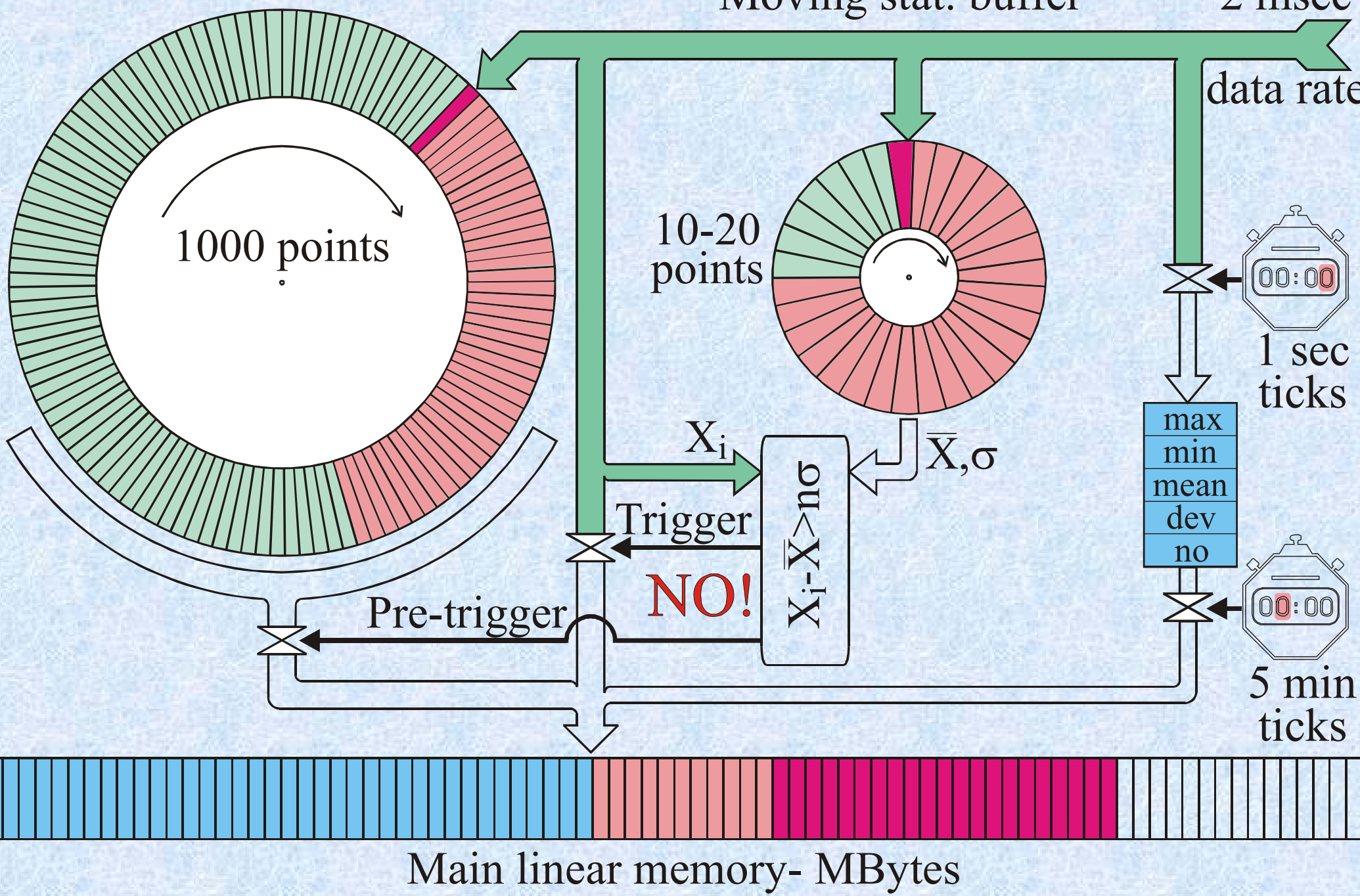
$X_i - \bar{X} > n\sigma$

max  
min  
mean  
dev  
no

5 min ticks

Pre-trigger

Main linear memory- MBytes



Circular data buffer

Moving stat. buffer

2 msec

data rate

1000 points

10-20 points

1 sec ticks

$X_i$

$\bar{X}, \sigma$

Trigger

NO!

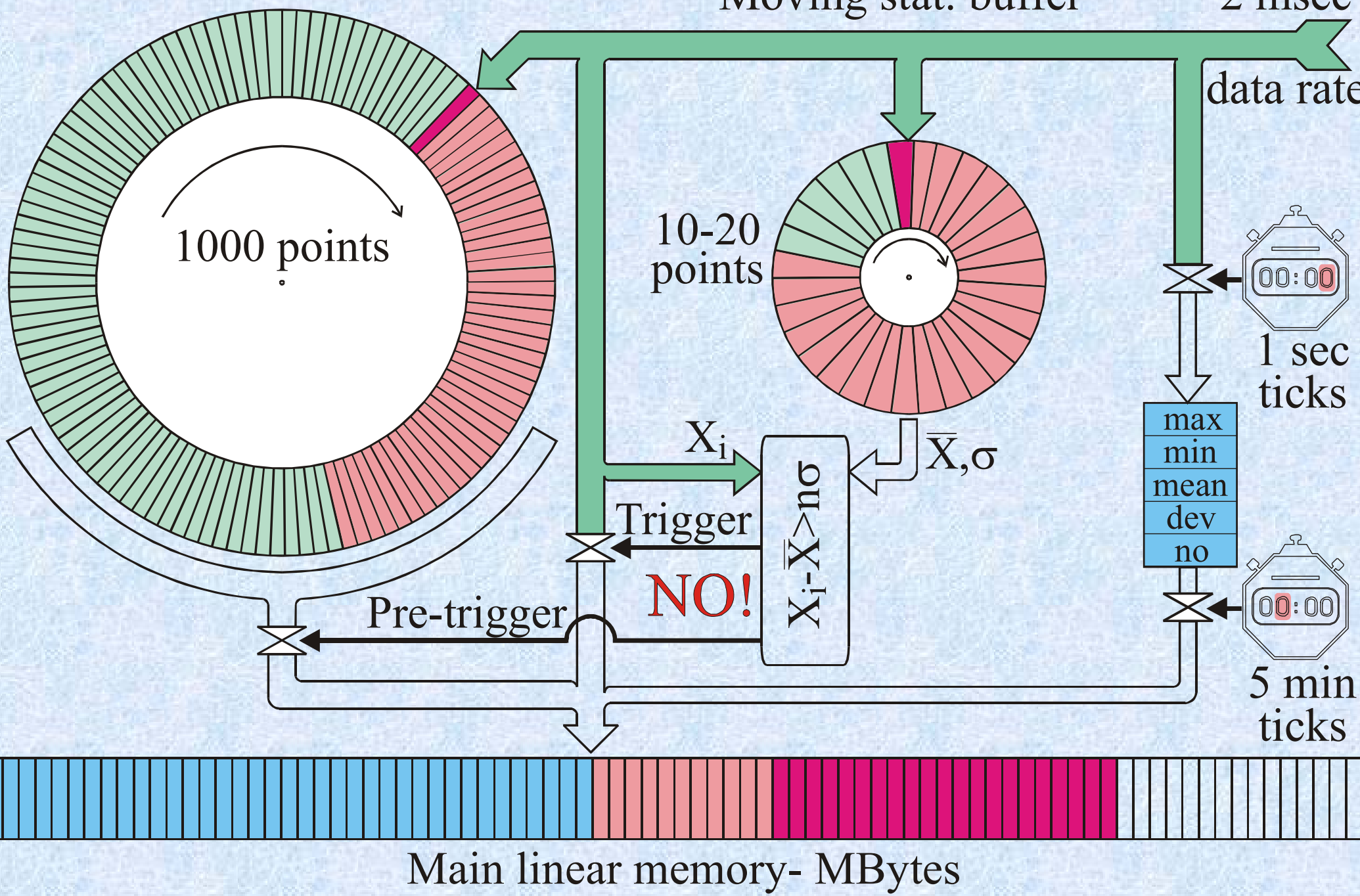
$X_i - \bar{X} > n\sigma$

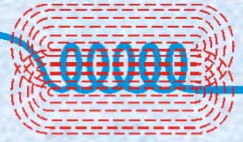
max  
min  
mean  
dev  
no

5 min ticks

Pre-trigger

Main linear memory- MBytes



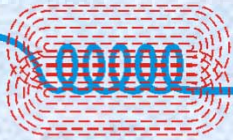


## ...Intelligent pressure logger



The key function is transient recognition – moving average and moving standard deviation is used for selected number of points (10 – 20)



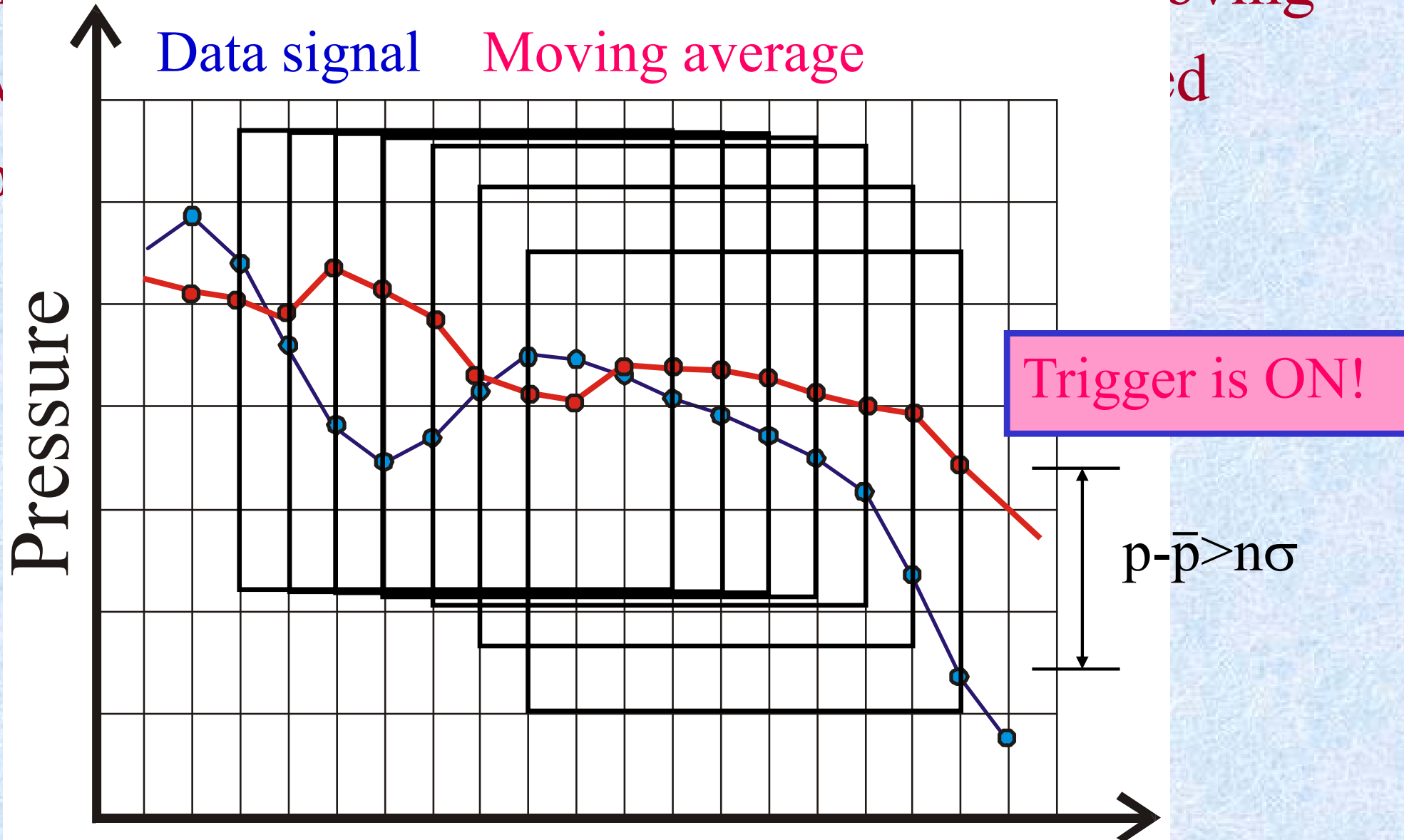


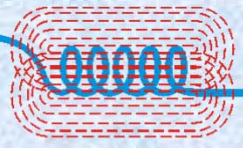
# ...Intelligent pressure logger



The key function is transient recognition – moving

av  
fo  
Data signal      Moving average

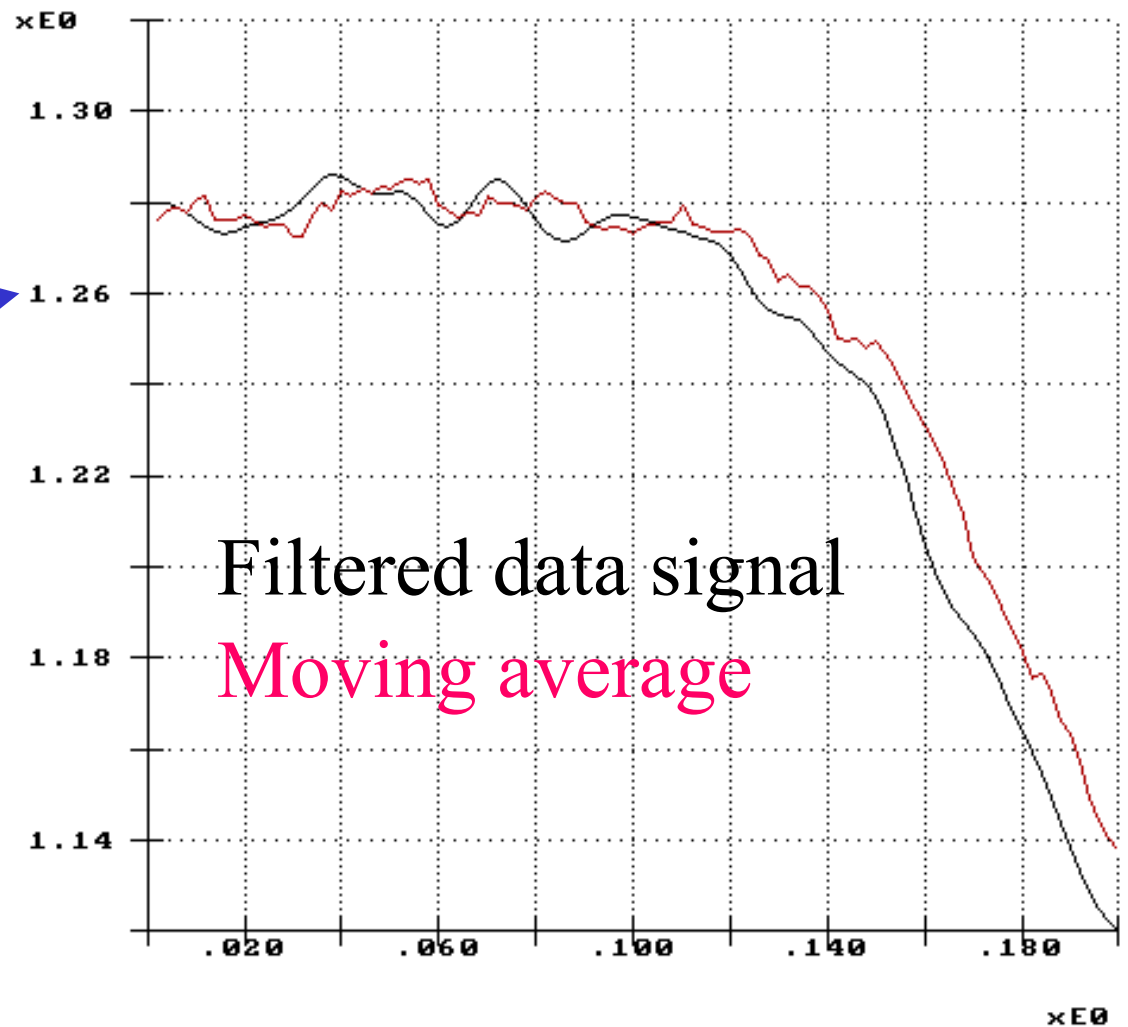
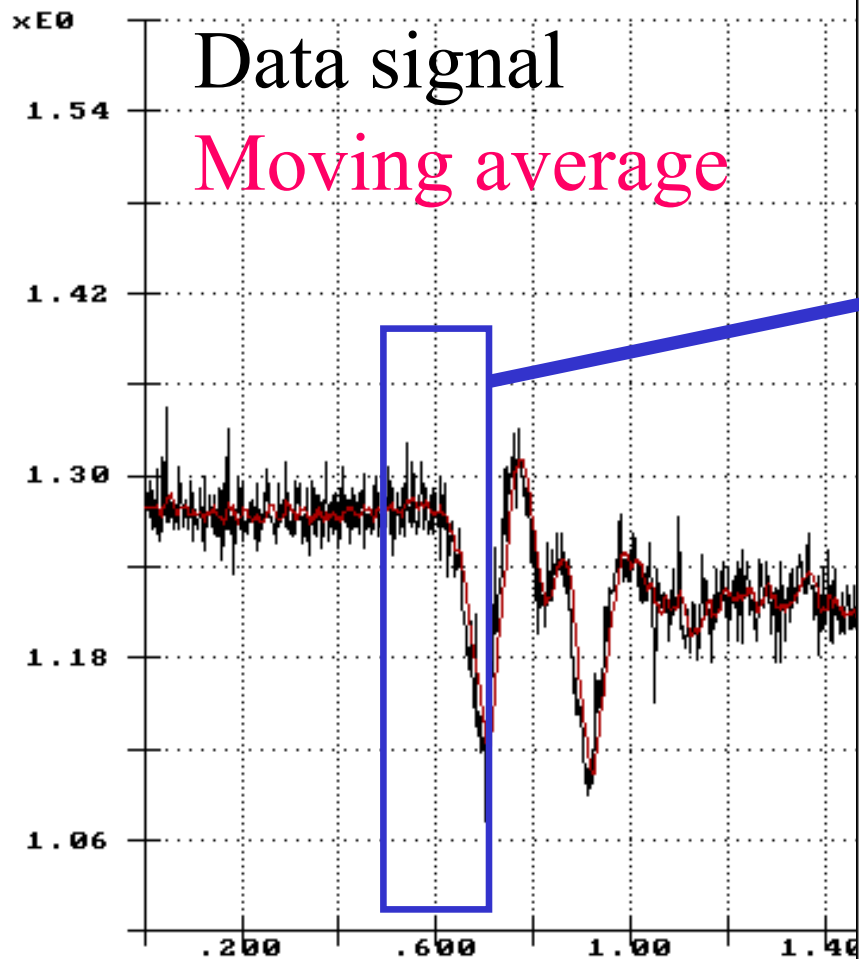




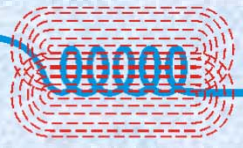
# ...Intelligent pressure logger



...the real data during processing (mean calculation):



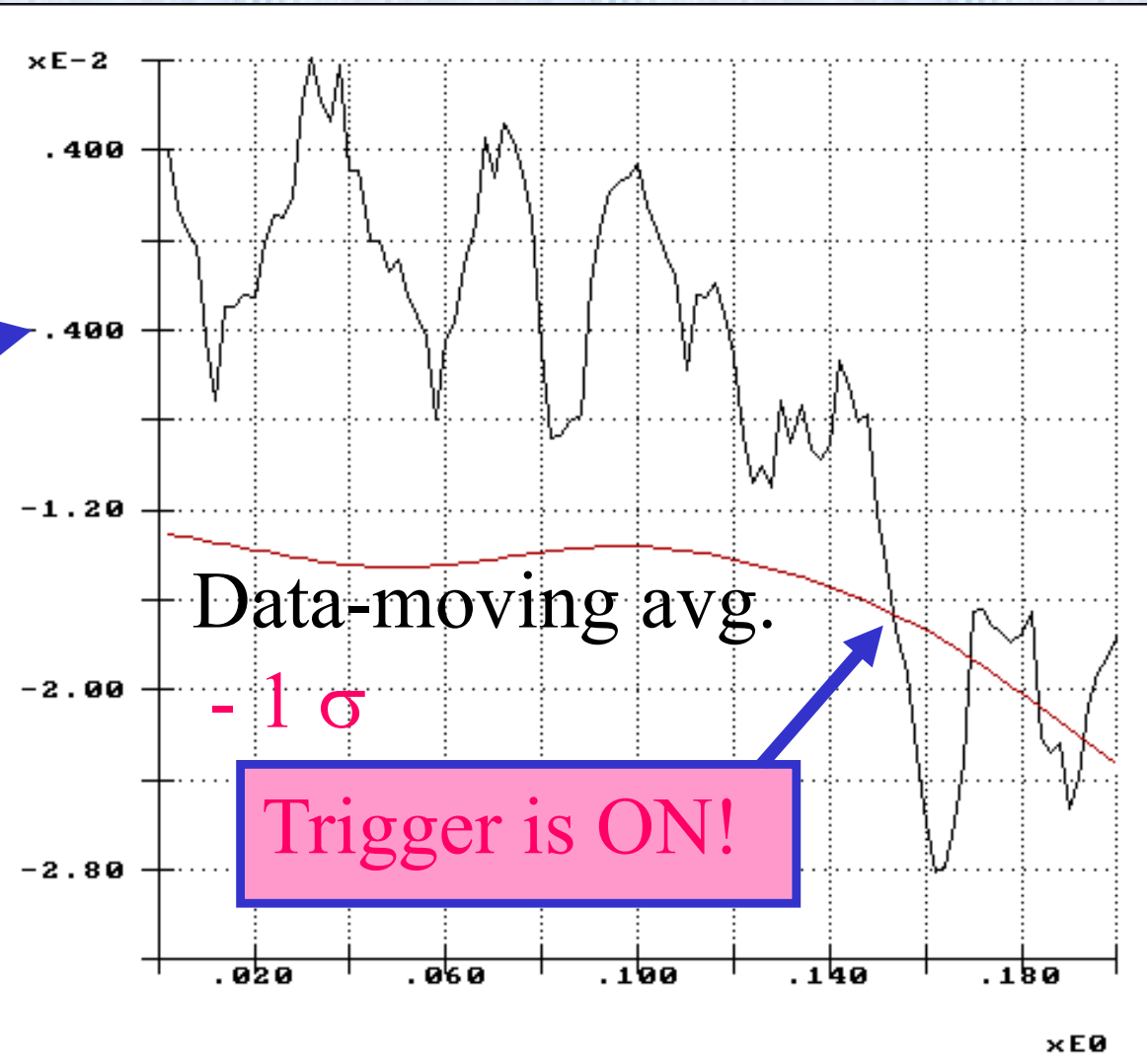
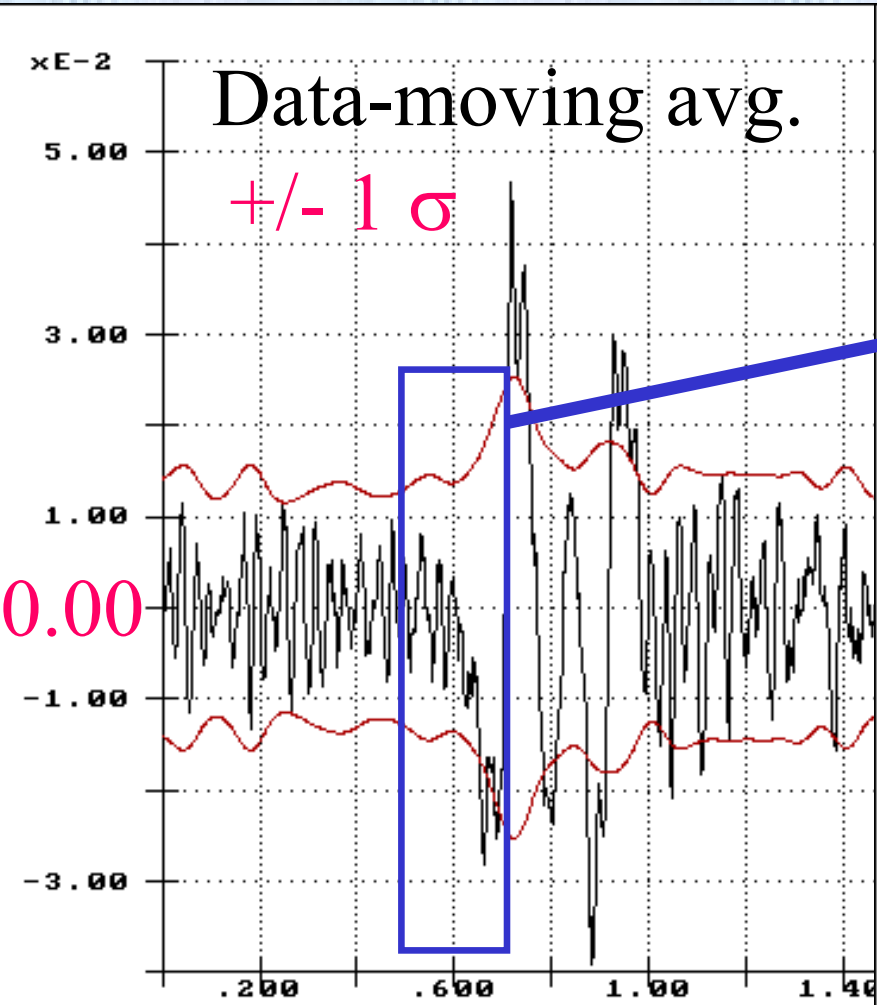
x E0



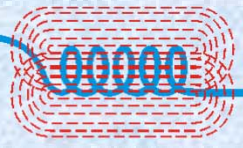
# ...Intelligent pressure logger



...the real data during processing (adding the  $\pm n\sigma$ ):



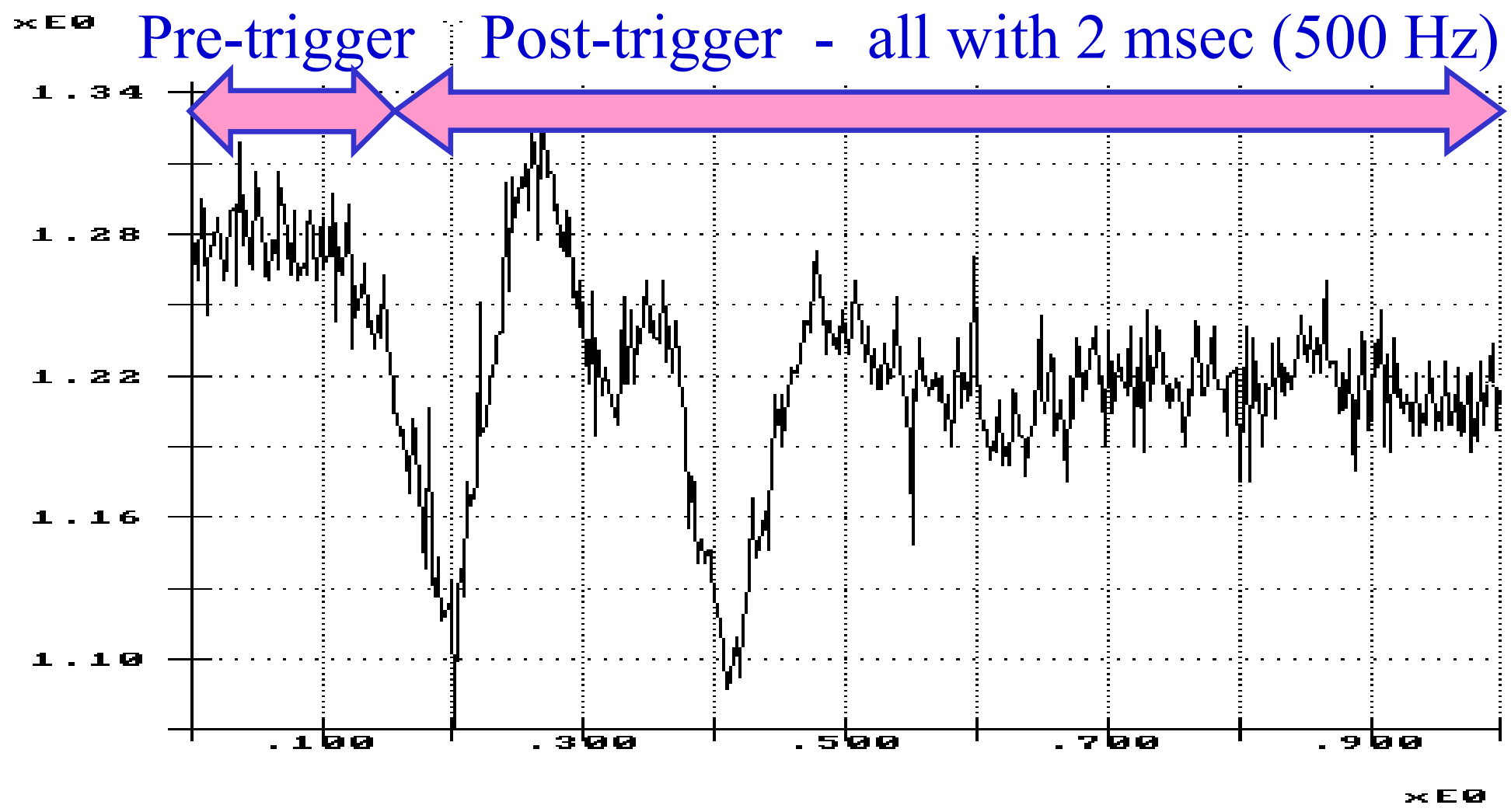
$\times E0$



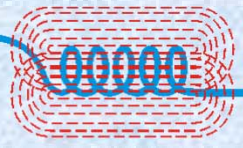
# ...Intelligent pressure logger



...and transient captured:



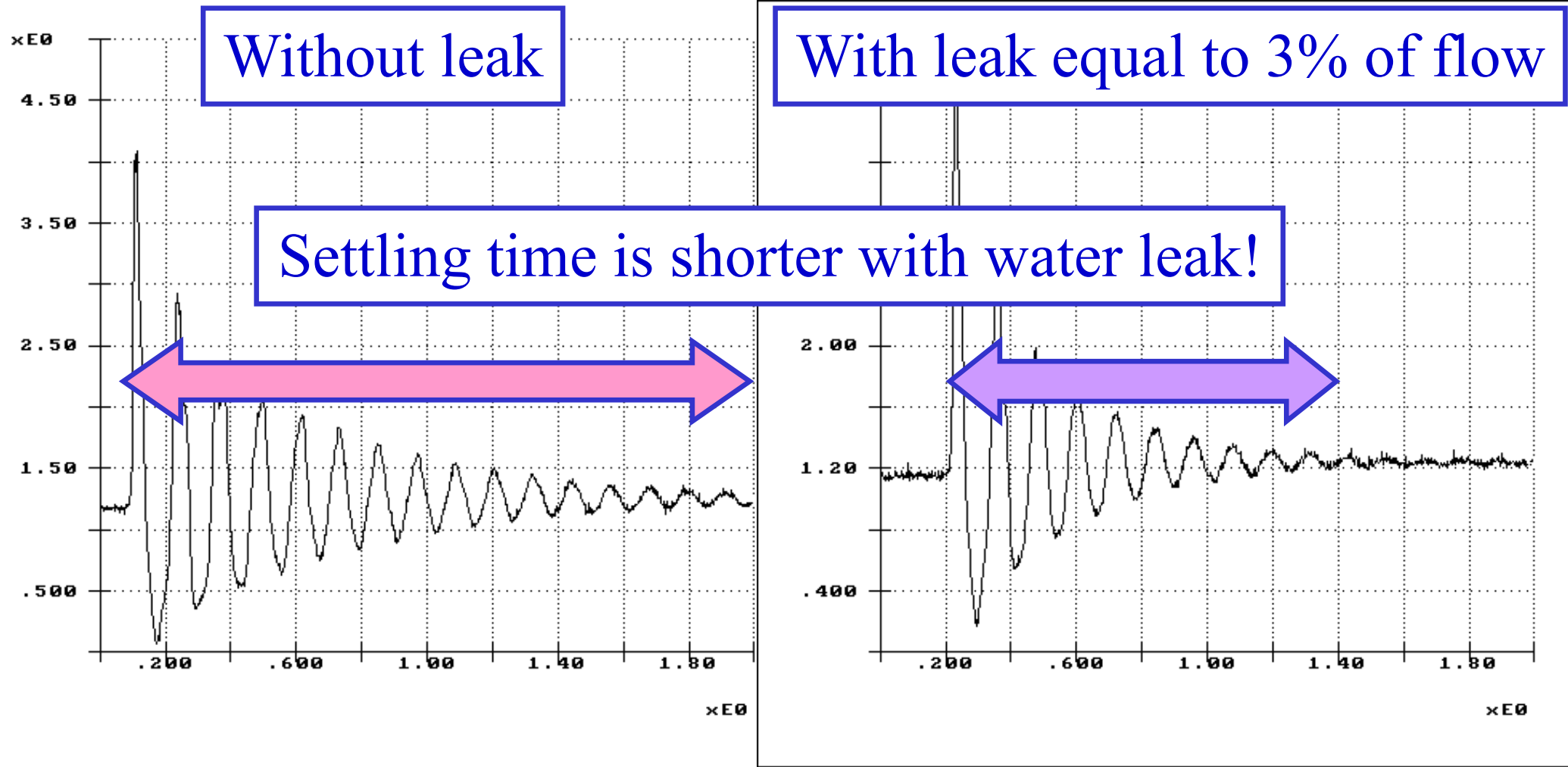


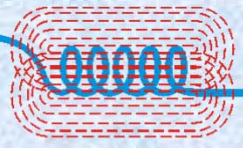


# ...Intelligent pressure logger



Some more results of large transients:

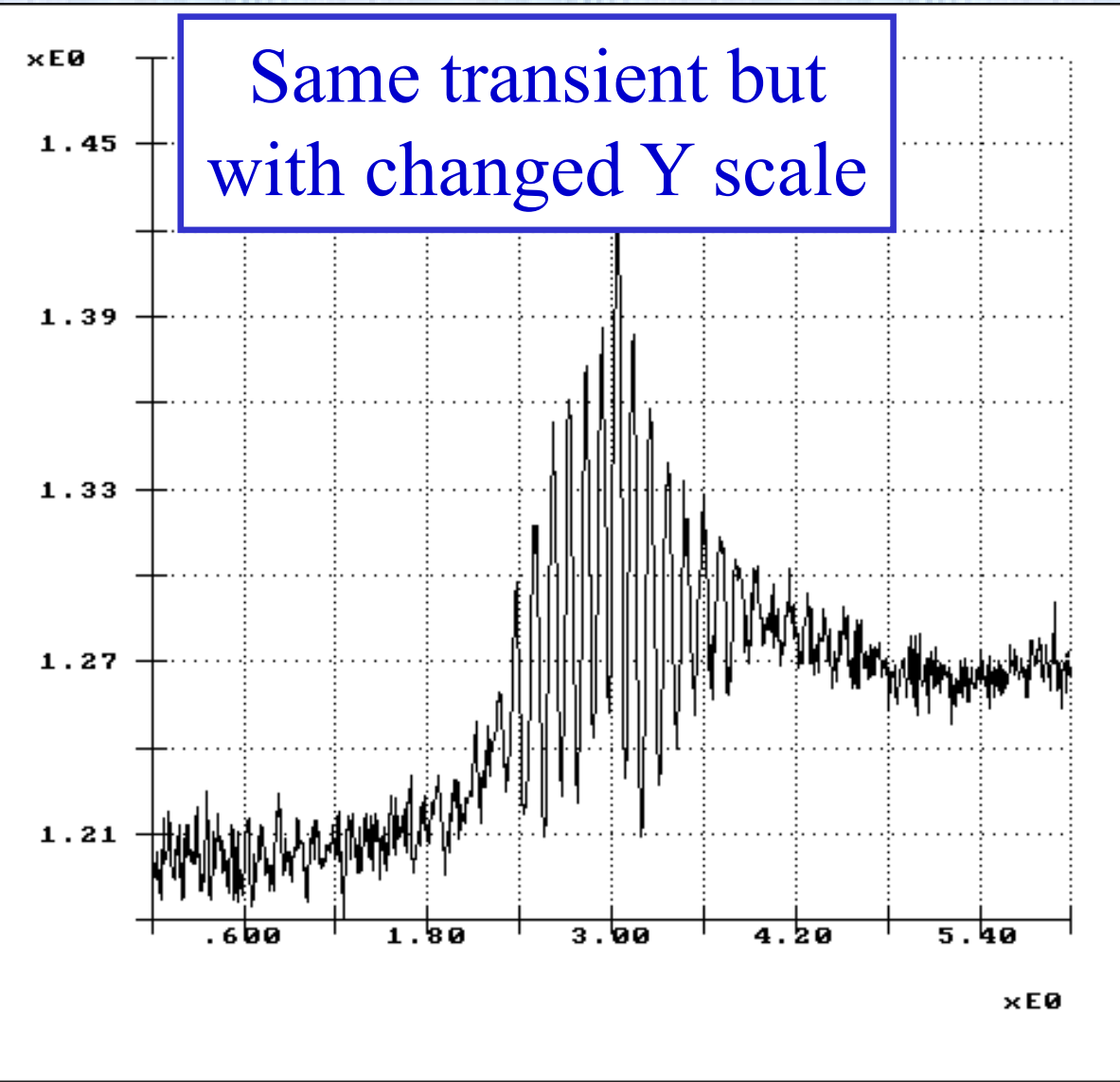
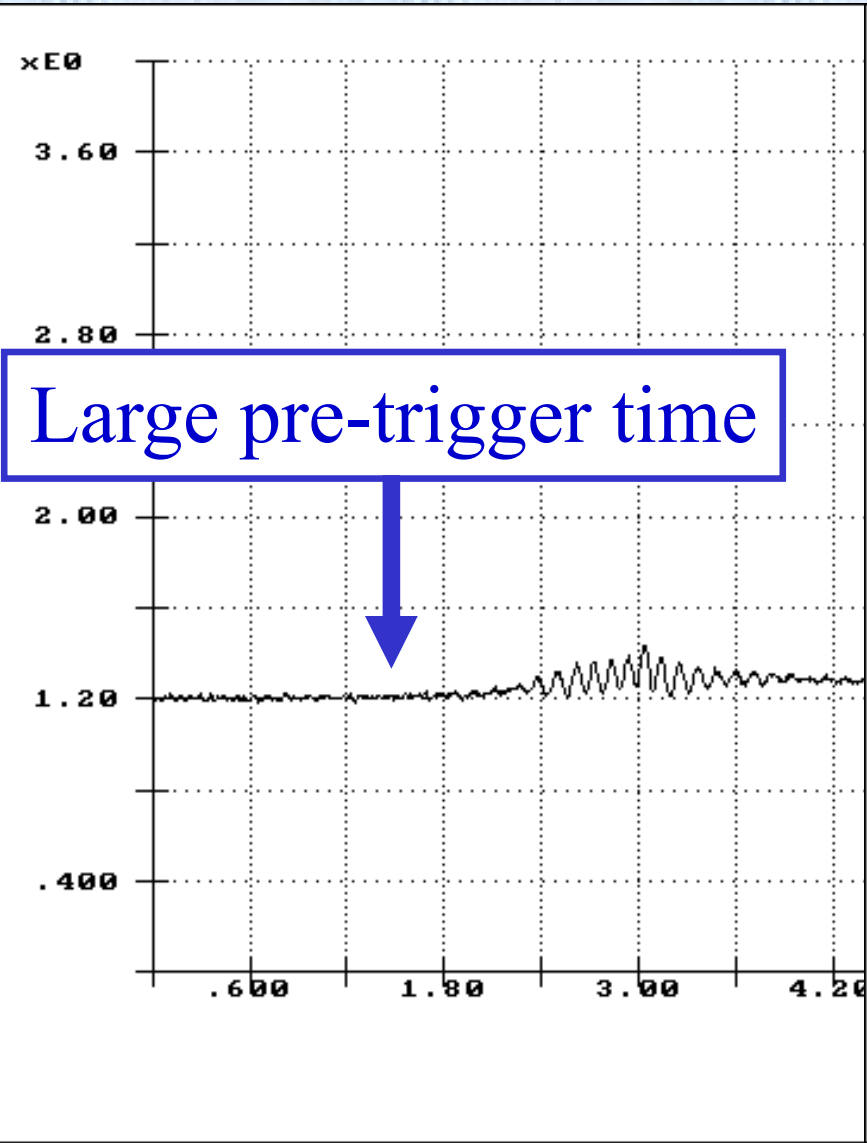


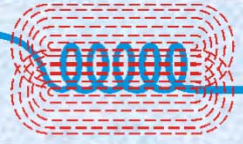


# ...Intelligent pressure logger



...and with everyday small transient:



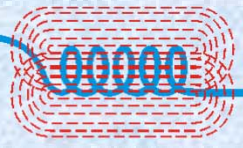


# ...Intelligent pressure logger



Future work to be done:

1. Gain some more experience in field usage
2. Time synchronization between loggers
  1. Manually using external clock signal (curr. used)
  2. Using radio clock (foreseen in the future)
  3. Using GPS clock
3. Spread among Water Supply Companies in YU
4. Initiate the international projects



# Intelligent instrumentation ...



End of presentation of two smart instruments:

Smart ElectroMagnetic Current Flow Meter

Mean and Transient Pressure Logger

Thank you for being so patient!