Automated Microscopy and prospects for MANDATE experiment

Andrey Alexandrov

INFN-Naples

Outline

- Automated microscopy for large-area nuclear emulsion detectors
- Automated microscopy prospects for MANDATE

Experiments with large-area nuclear emulsion detectors

Experiment	Years of data taking	Total emulsion area, m^2	Scanning speed, cm^2/h	Scanning system
CHORUS	1994-1997	~300	~1	TS, UTS
DONUT	1997-1998	~100	~1	TS, UTS
OPERA	2008-2012	~110'000 ~500 scanned	20,50	**ESS**, S-UTS
DsTau	2021-2023	~490	1000	HTS
FASER	2022-2026	~650	4500	HTS
SND@LHC	2022-2026	769	60-120	**ESS**

Automated microscopy
European Scanning System (ESS)

Automated Readout System Components

Optical microscope

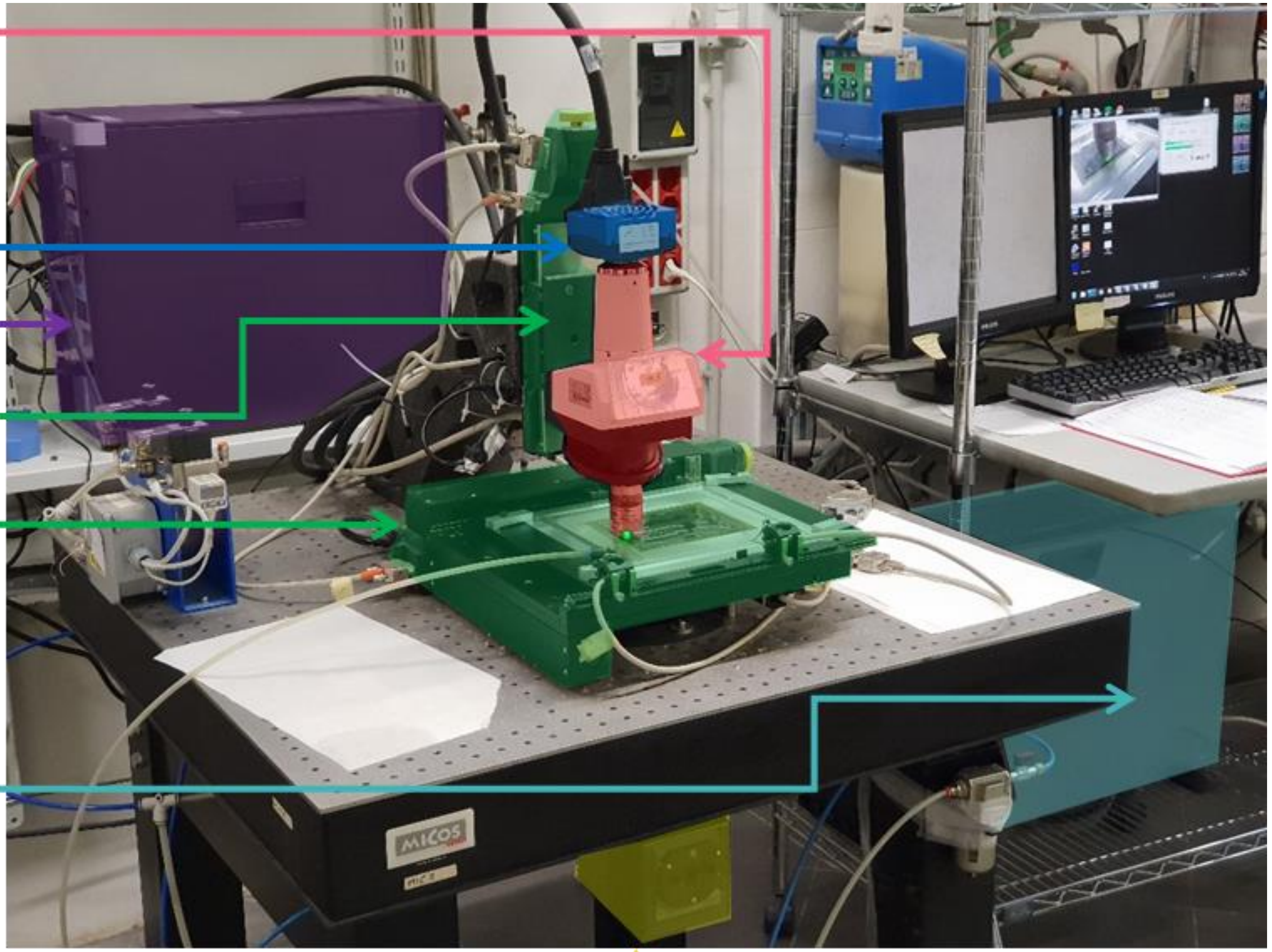
Illumination system

Image acquisition system

Motorized stages

Control computer + SW

Processing computer(s) + SW



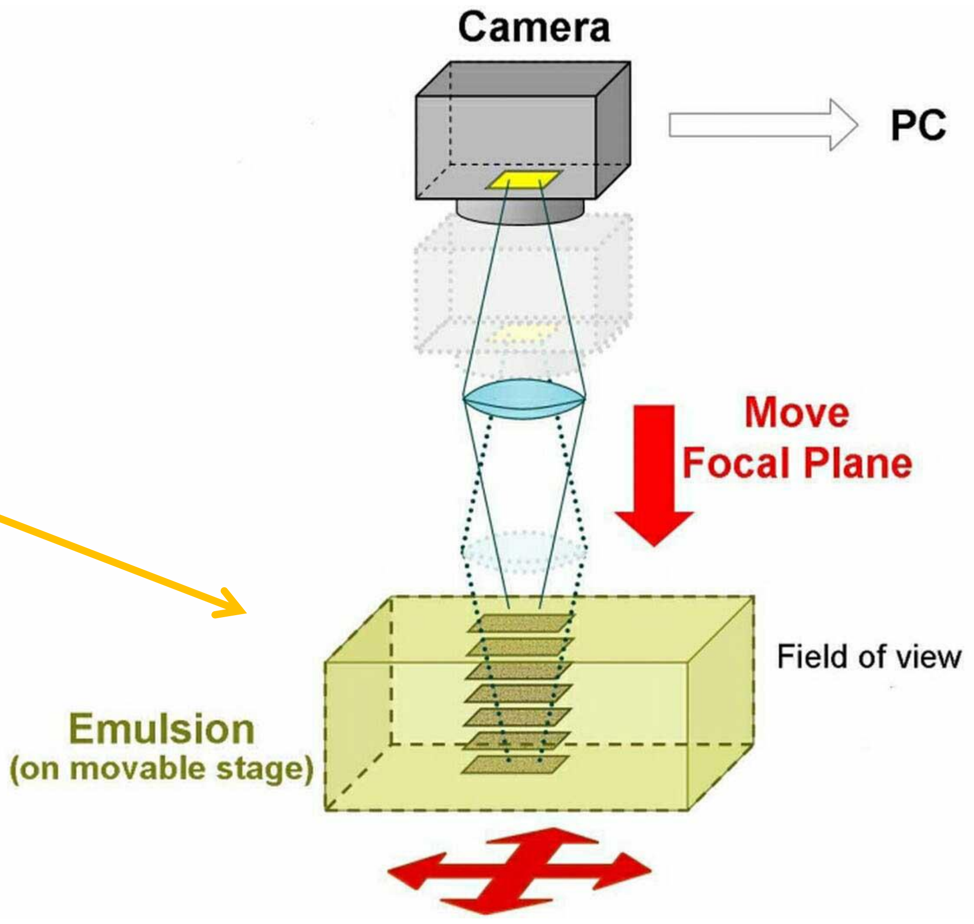
Data acquisition cycle

1. The vertical stage starts moving until it reaches the required velocity
2. Tomographic images taken through the emulsion layer at equal steps
3. Images are immediately sent to the control PC for processing
4. The vertical stage decelerates until a complete stop
5. The objective lens is moved to the beginning of the next FoV

DAQ phase

Reset phase

Work cycle



Readout Techniques

Stop& Motion (SG)

Old and reliable, but very slow

DAQ phase is only 30% of work cycle

Continuous Motion (CM)

~2 times faster than SG (same HW)

DAQ phase is 66% of work cycle

Requires the motion control precision better than 1 ms

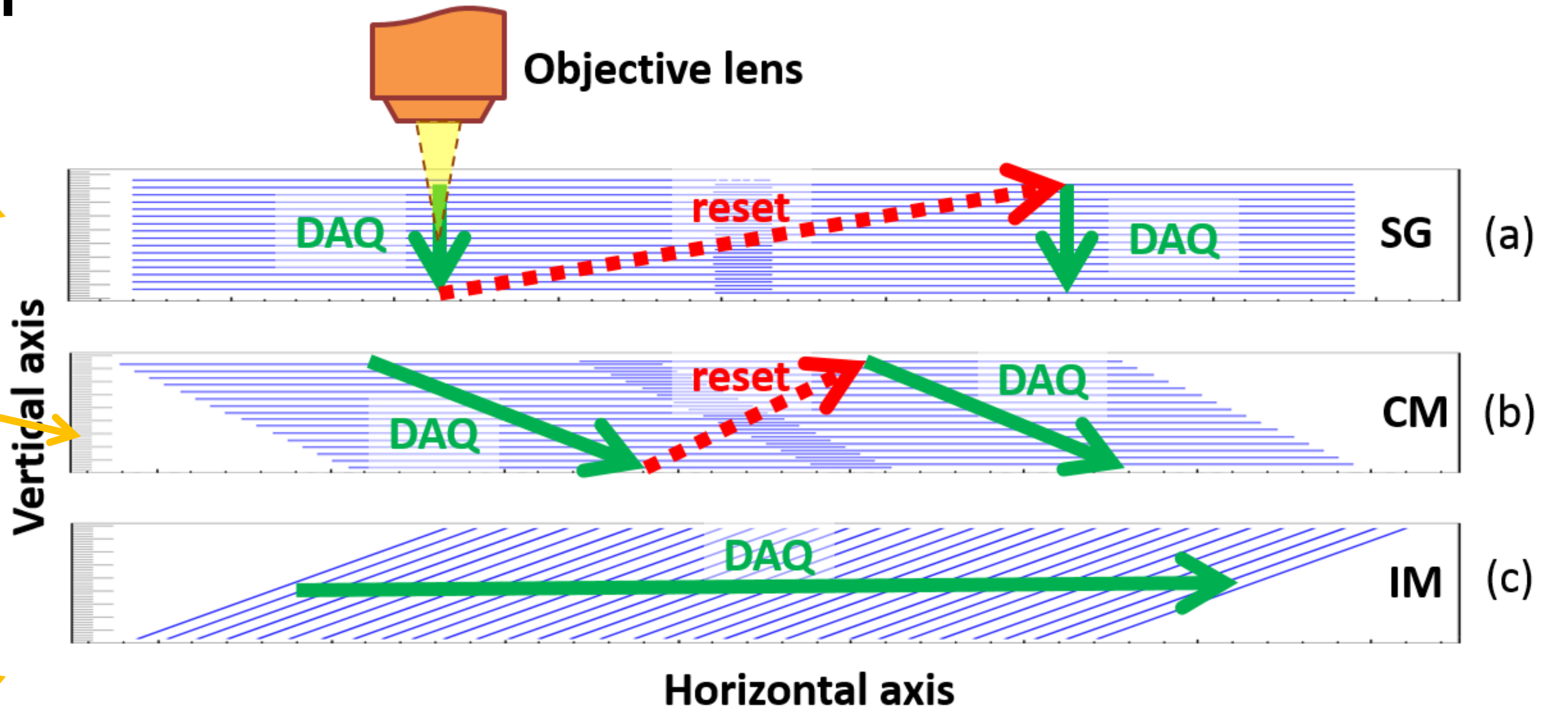
Inclined Focal Plane Motion (IM)

Reset phase eliminated!

DAQ phase is 100% of the work cycle

Best for multi-camera systems

Not suitable for thick emulsions



A new generation scanning system for the high-speed analysis of nuclear emulsions. *JINST* **11**, P06002 (2016). DOI:10.1088/1748-0221/11/06/P06002

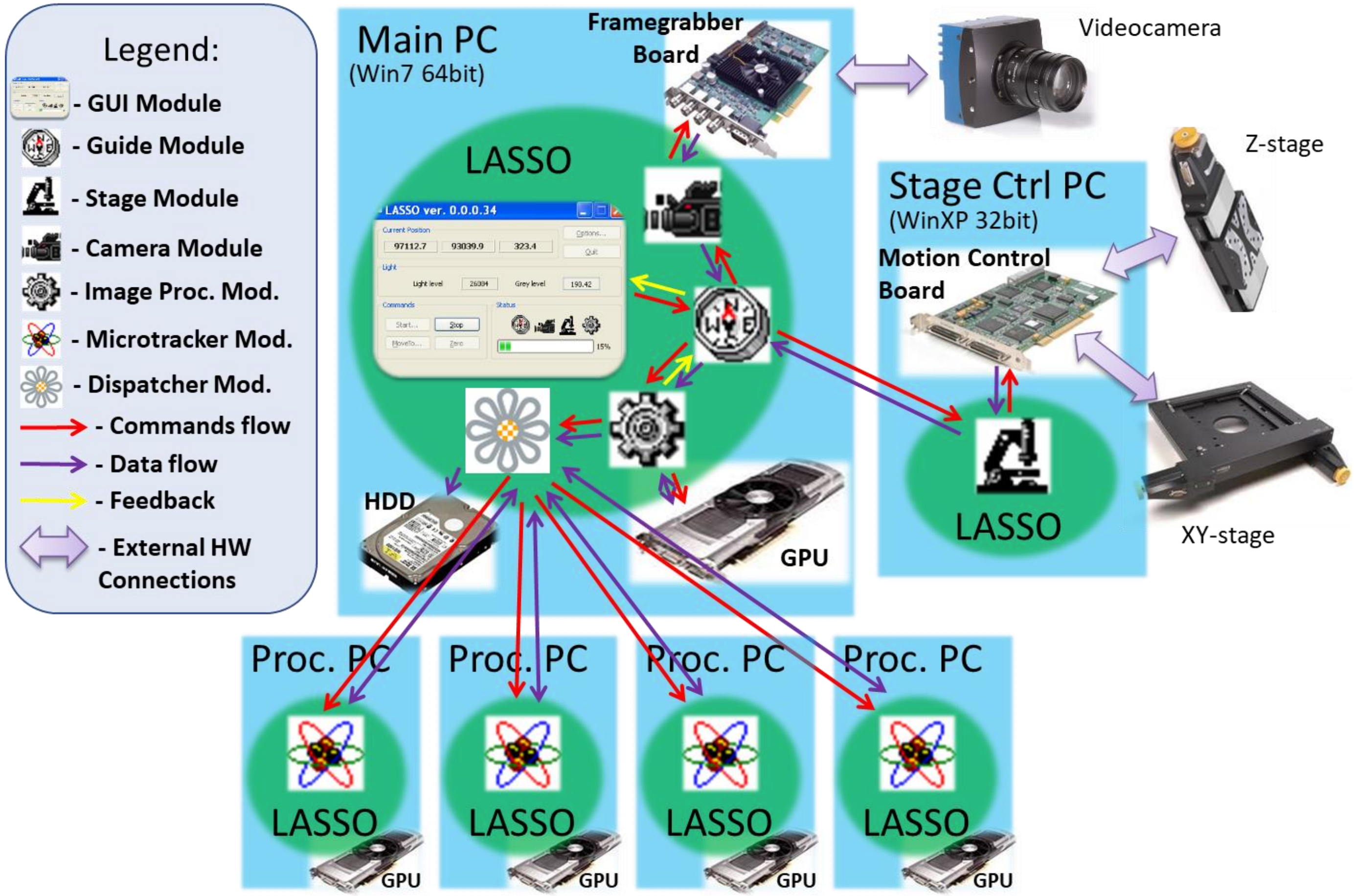
The Continuous Motion Technique for a New Generation of Scanning Systems. *Scientific Reports* **7**, 7310 (2017). DOI:10.1038/s41598-017-07869-3

A Novel Optical Scanning Technique with an Inclined Focusing Plane. *Scientific Reports* **9**, 2870 (2019). DOI:10.1038/s41598-019-39415-8

Software framework

Large Angle Scanning System for OPERA (LASSO) 2015 JINST 10 P11006

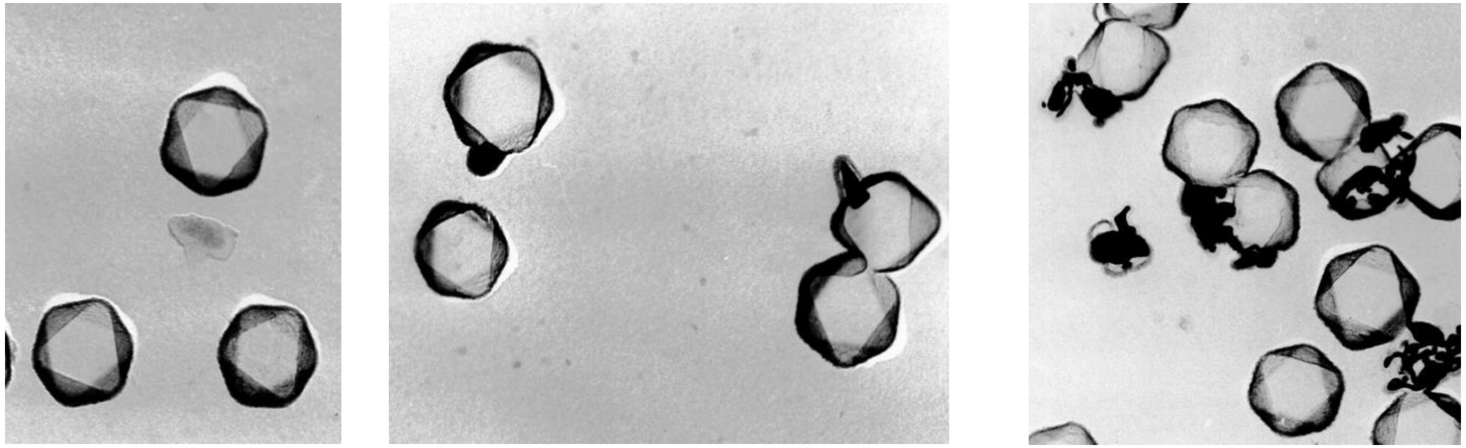
- Started in 2006
- Windows, XP-11, 32/64
- C++
- CUDA
  - Image flux ~2.5 GB/s
- Modular
- Scalable



Data Analysis Chain

Nuclear emulsion

The Silver Halide Crystals (diameter of 0.2 micron)



Pion track after development

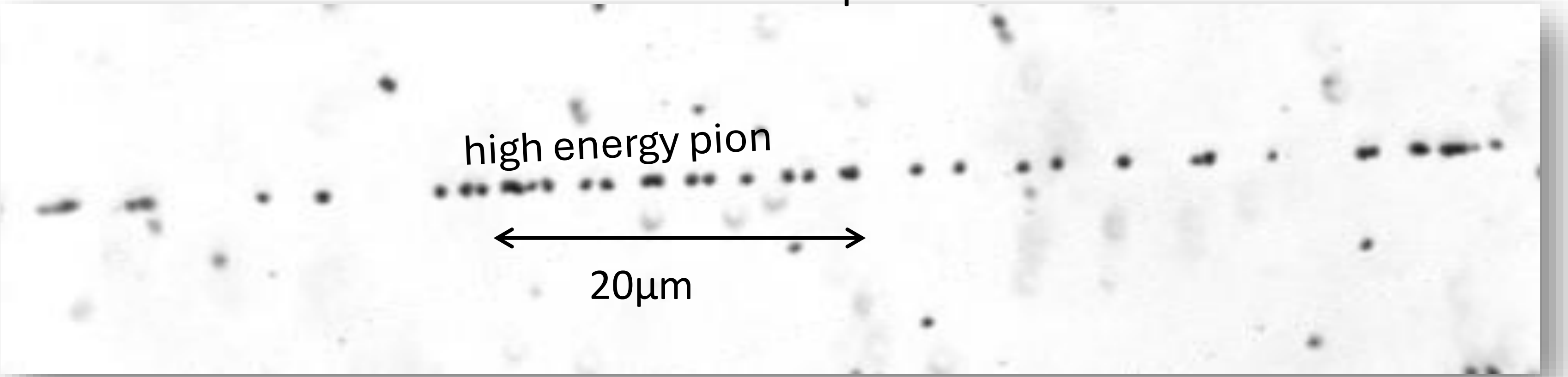
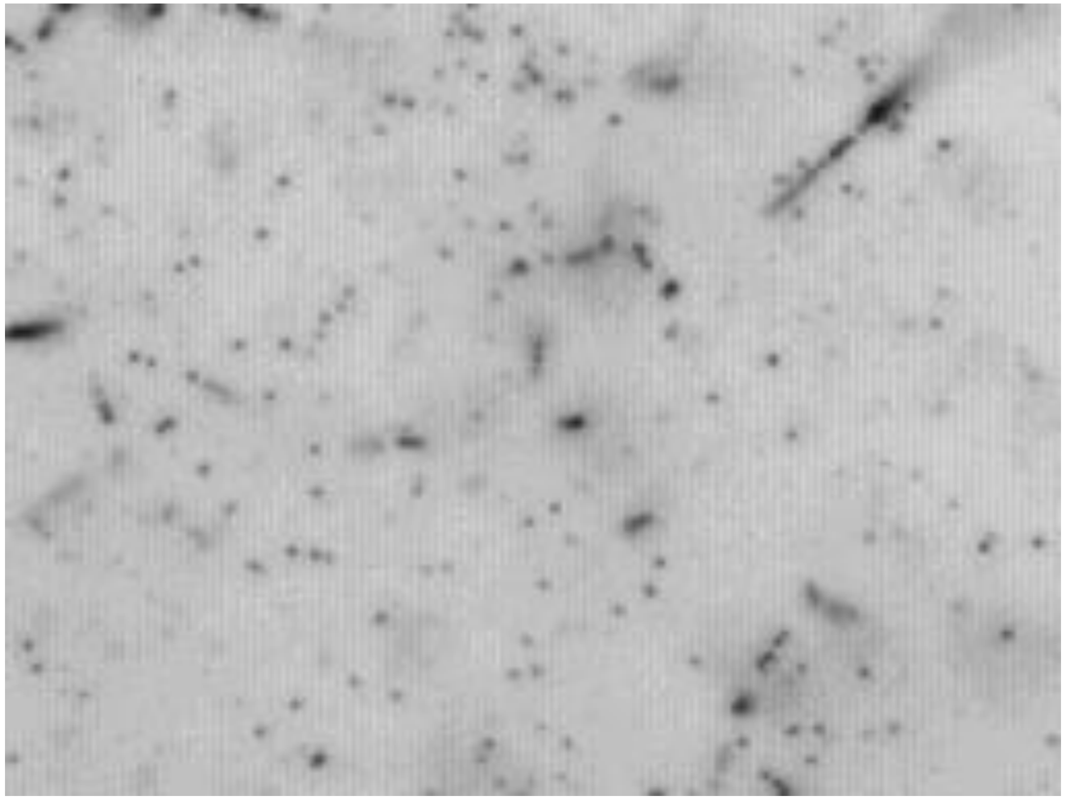
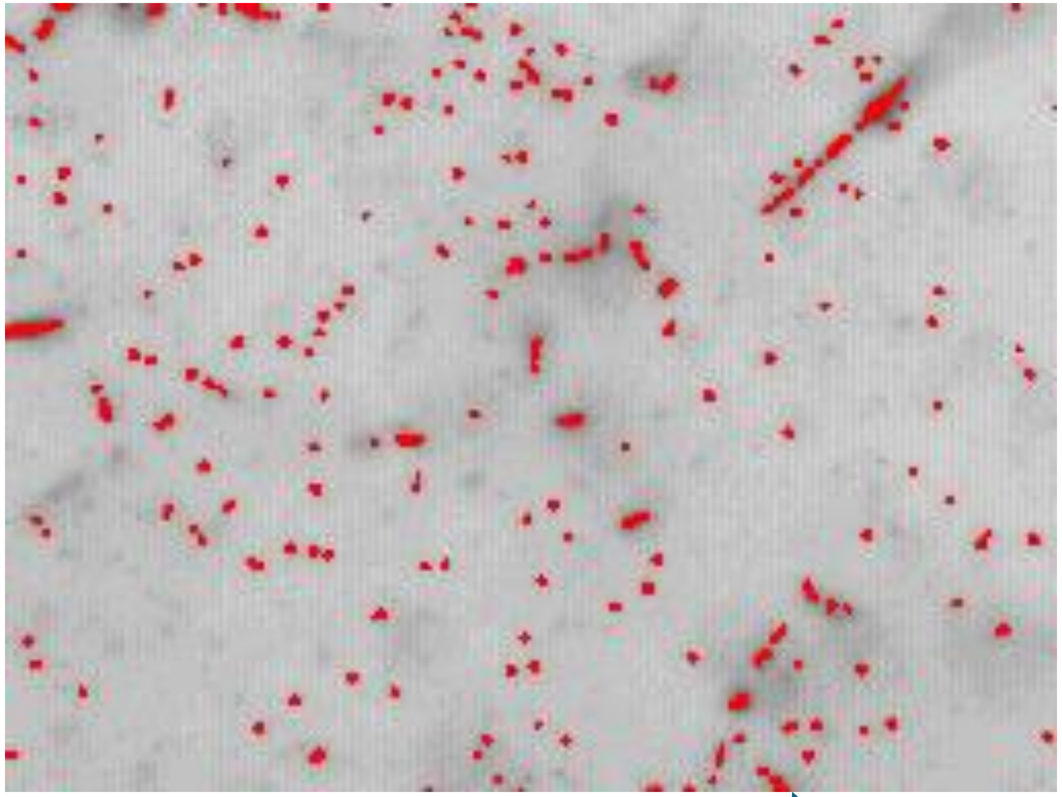


Image processing & Cluster reconstruction

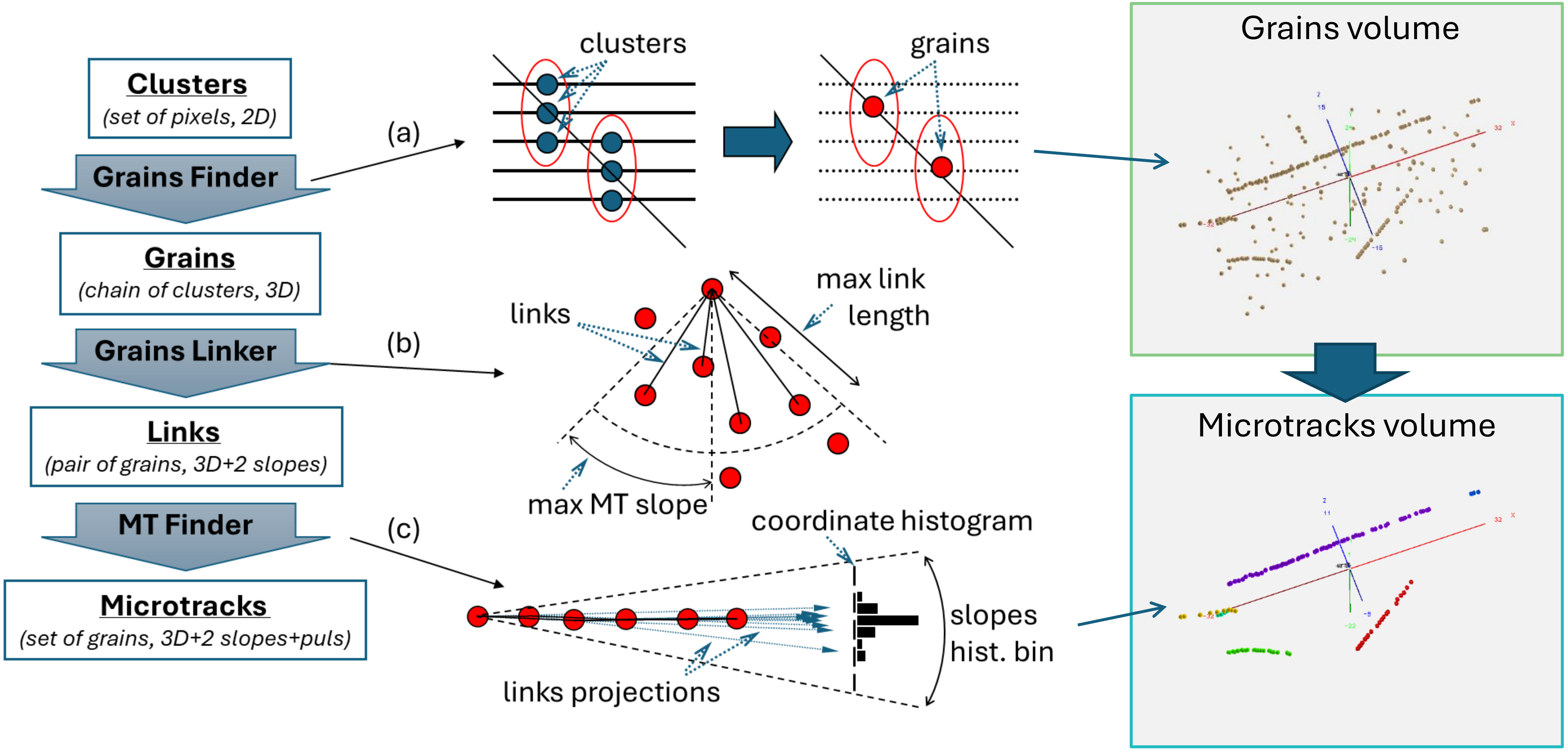


OPERA film
77x58 μm^2



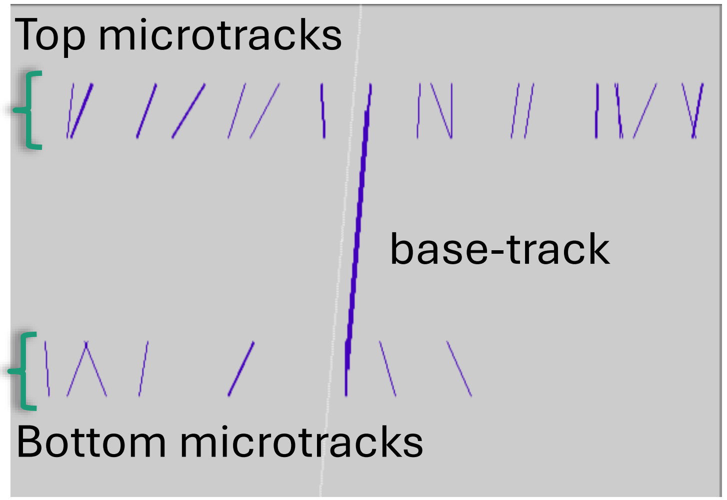
Cluster = a dense set of adjacent dark pixels (highlighted red)

Silver Grains & Microtracks reconstruction

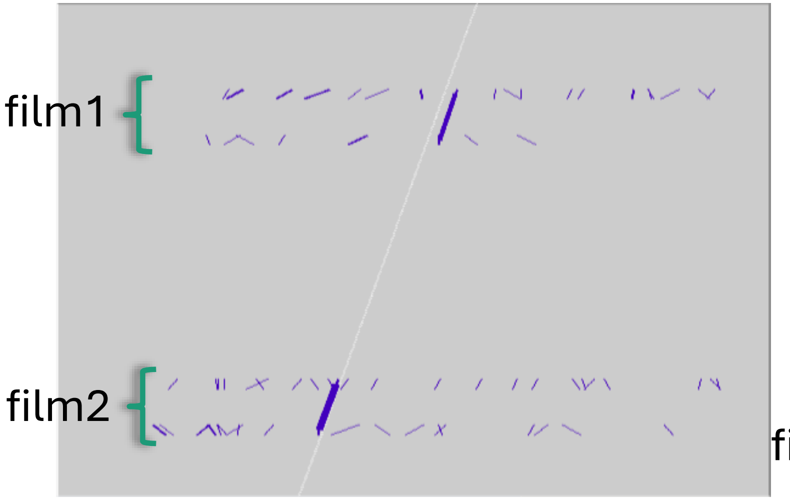


Offline analysis with FEDRA

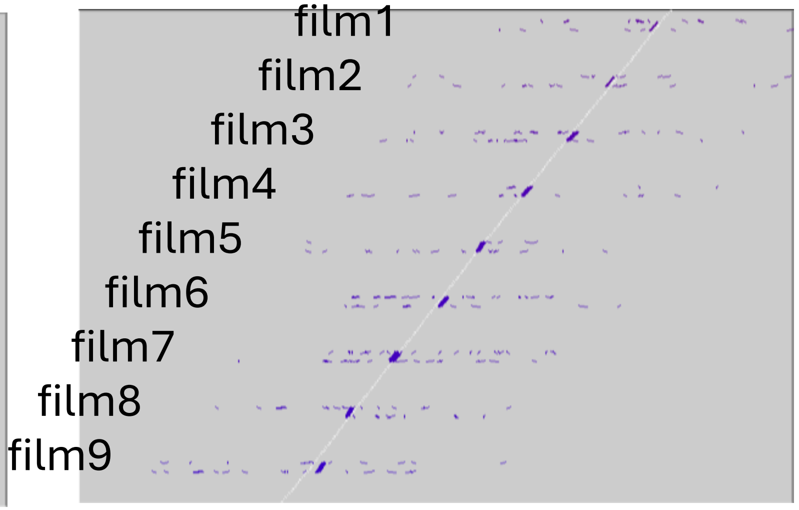
Tioukov et al. (2006), NIM A559:103–105.



Reconstruction of **base-track** in one emulsion film



Connection of the **base tracks** in two consecutive emulsion films



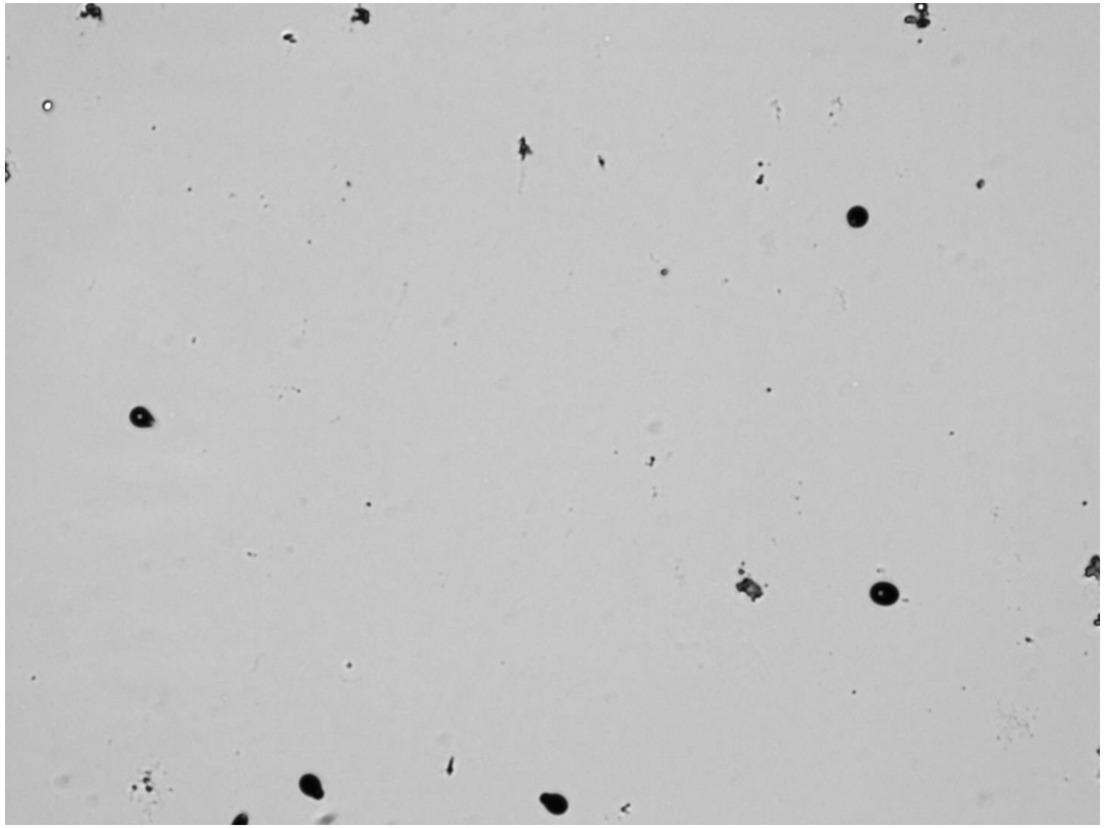
Reconstruction of a **volume track** in several emulsion films

ESS users: labs & experiments

Institution	Section	# of mic	Experiments
INFN	Naples	3	SND@LHC, FOOT, Muon Radiography
	Bologna	2	SND@LHC
	LNGS	2	SND@LHC, Muon Radiography
	Salerno	1	SND@LHC
CERN		4	SND@LHC
SAPHIR (Santiago, Chile)		1	SND@LHC
LPI (Moscow)		1	Muon Radiography

MANDATE
Automated Scanning Prospects

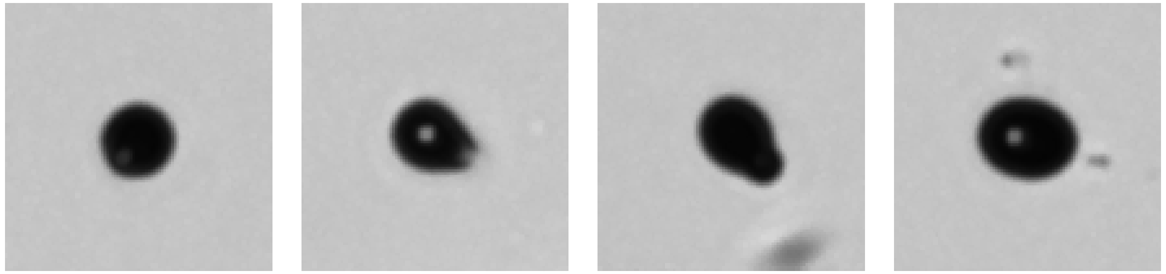
NTD etched pit images



1.005 × 0.755 mm^2

- CR-39 (1.5 mm), Makrofol (0.5 mm)
- Sheets 25 x 25 cm^2
- ~5–70 μm characteristic pit/track diameters
- monopoles expected ~60 μm
- Pit shape:
  - Vertical -> circular
  - Inclined -> elliptical
- Pits at both surfaces

72 μm



21 μm

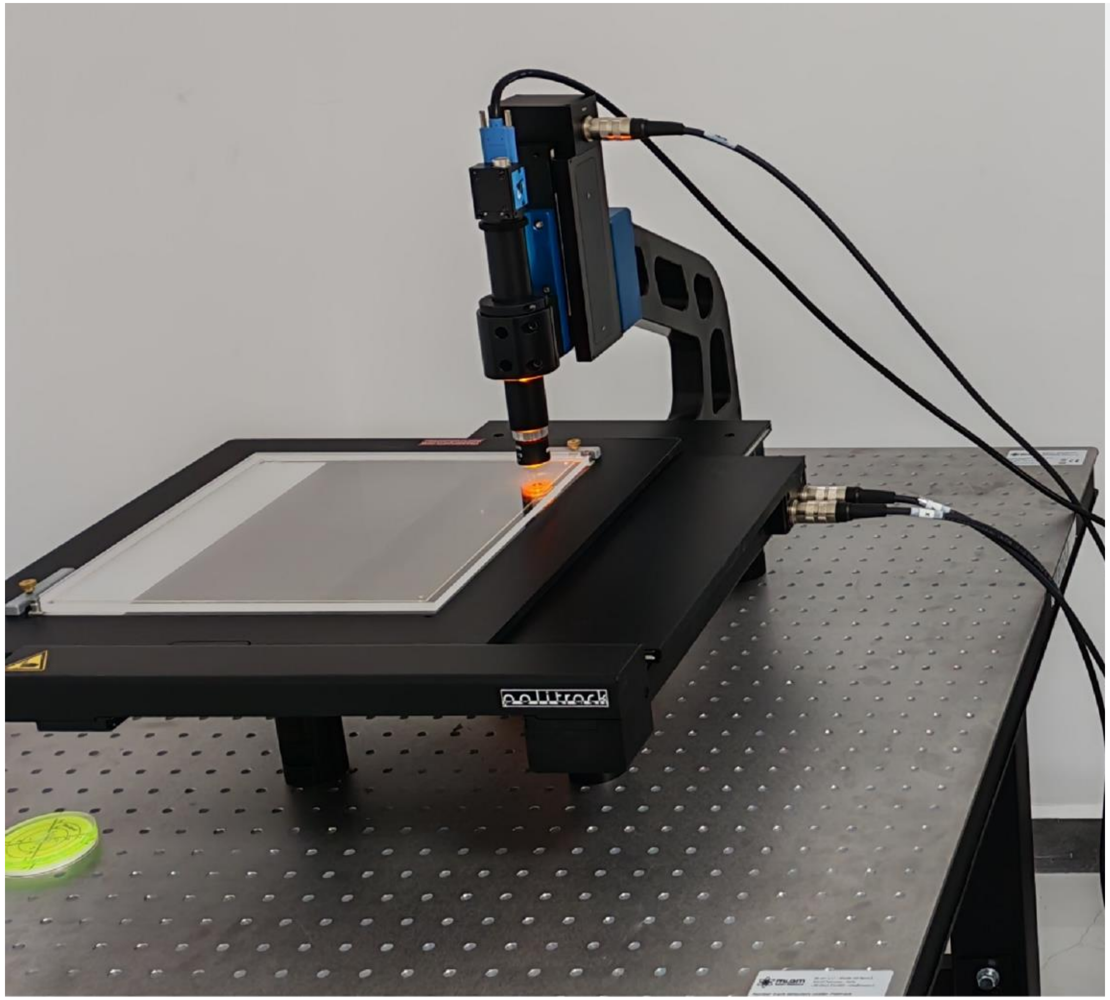
Analysis pipeline

- Image analysis
  - Signal/background separation by size and shape
  - (micro-)Track inclination estimation
- Top-bottom (micro-) tracks linking
  - Pattern matching
  - Signal/background separation by coincidence
  - (base-)Track inclination measurement
- Connection with (base-)tracks in adjacent sheets
  - Pattern matching
  - Signal/background separation by coincidence
- (volume-)Tracks reconstruction along the connected (base-)tracks
  - Physical parameters measurements

Real-time
Specific to MANDATE

Offline
Possible use of FEDRA

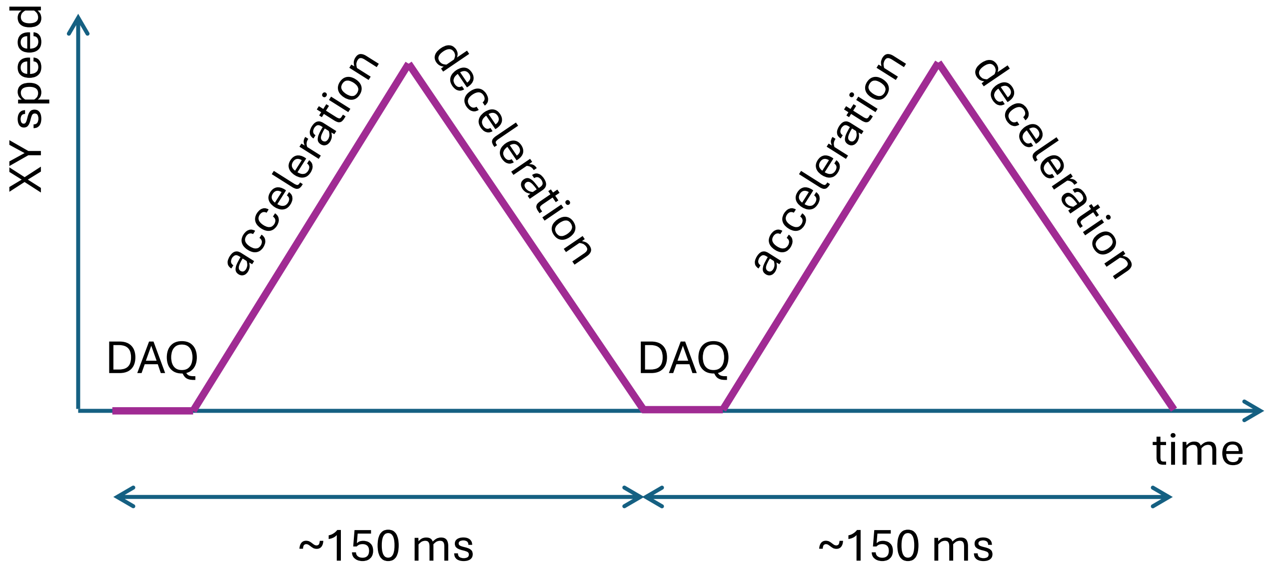
Current mic - Mi.Am POLITRACK RS25-CR



- Scan area: 250 × 250 mm^2
- Measured scanning speed: ~150-170 cm^2/h
  - with autofocus every 40 steps
  - full plate (600 cm^2) in ~3.5-4 hours
- XY stage (Märzhäuser SCAN 250×250)
  - speed: up to 90 mm/s
  - resolution: 0.1 μm
  - accuracy: ±3 μm
  - repeatability <1 μm
- Z stage (Märzhäuser Motorized Z-Axis 50 mm)
  - resolution: 0.1 μm
  - repeatability: ±1 μm
- Camera (The Imaging Source DMK 33UX273)
  - 200 frames/s
  - 1440 × 1080 mono
  - 3.45 μm pixels
  - USB 3.0
- Objective lens (OPTIKA N-PLAN M-164, 4×/0.10NA, 160/0.17)
  - Magnification/NA: 4×/0.10 (effective 5×)
  - finite 160 mm system
  - FoV: 1.005 × 0.755 mm^2

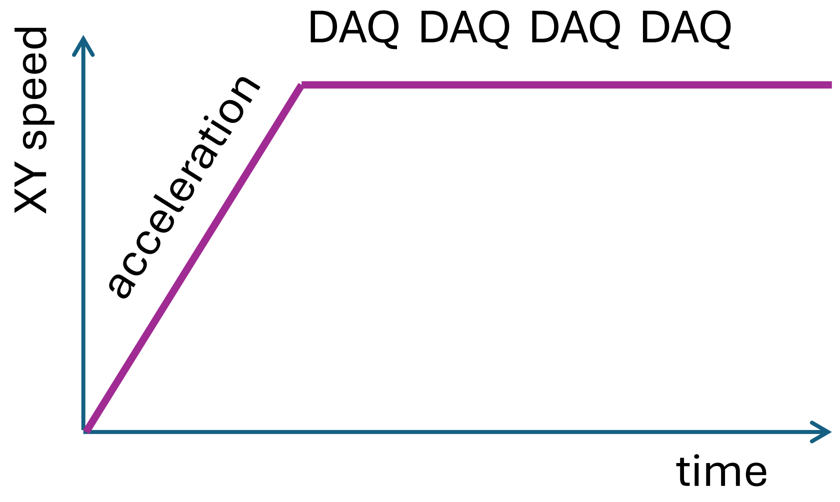
Scanning Technique analysis - SG

- Stop&Go (SG)
  - **DAQ when stopped**
  - ~150 ms/view
  - 200 fps = 5 ms/image
  - 150 ms = 30 images taken
  - Only 1/30 of images is used
  - Acceleration/Deceleration
  - Vibration dump
  - SG is the bottleneck



Scanning Technique analysis - CM

- Continuous Motion (CM)
  - **DAQ in motion @ const speed**
  - Down to 5 ms/view
  - No acceleration/deceleration
  - Tolerable vibrations at moderate speed
  - Lower requirements for XY stage
  - Top-bottom offset if cameras not synced



Scanning Speed limit

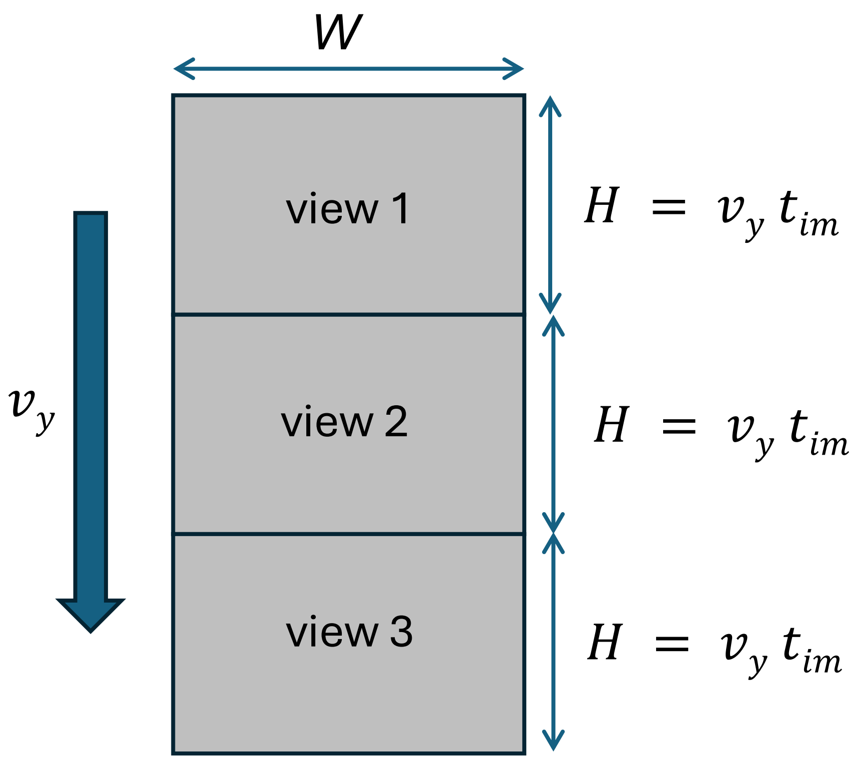
- **DAQ in const motion**
- **Every image is used**
- **No gaps, no overlap**
- 1 image in 5 ms
  - t_{im} = 5 ms
  - W = 1440*3.45/5 = 1.005 mm
  - H = 1080*3.45/5 = 0.755 mm
- Scanning speed limit:
  - v_y = 0.755/0.005 = 144 mm/s (> 90 mm/s)
  - t_{exp}= (3.45*10^{-3}/5)/144 = 5 μs
  - V_{scan} = 0.1005*14.4 = 1.45 cm^2/s = 5224 cm^2/h

Constraints:

$$\begin{cases} v_y \leq H/t_{im} \\ t_{exp} \leq (p/M)/v_y \end{cases}$$

Sensor pixel size

magnification

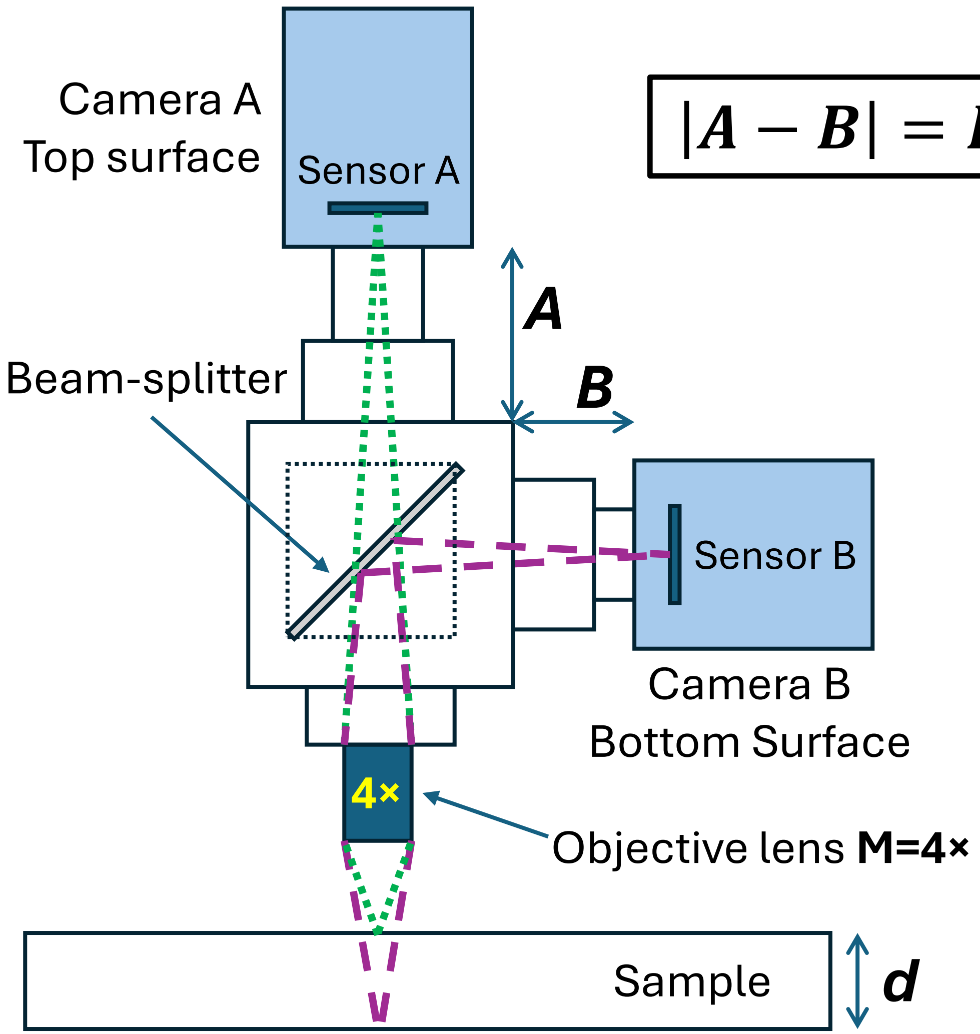


Realistic Scanning Speed estimation

- Realistic scanning speed:
  - t_{exp} = 50 μs
  - v_y = (3.45/5)/0.05 = 14 mm/s
  - V_{scan} = 0.1005*1.4 = 0.14 cm^2/s = 500 cm^2/h

- Speedup ideas:
  - Magnification change 5x -> 4x: V_{scan} = 760 cm^2/h
  - Try stroboscopic illumination to access smaller exposure times

New Optical Concept



$$\boxed{|A - B| = D = d \cdot M^2}$$

CR-39: d = 1.5 mm -> D = 24 mm
Makrofol: d = 0.5 mm -> D = 8 mm

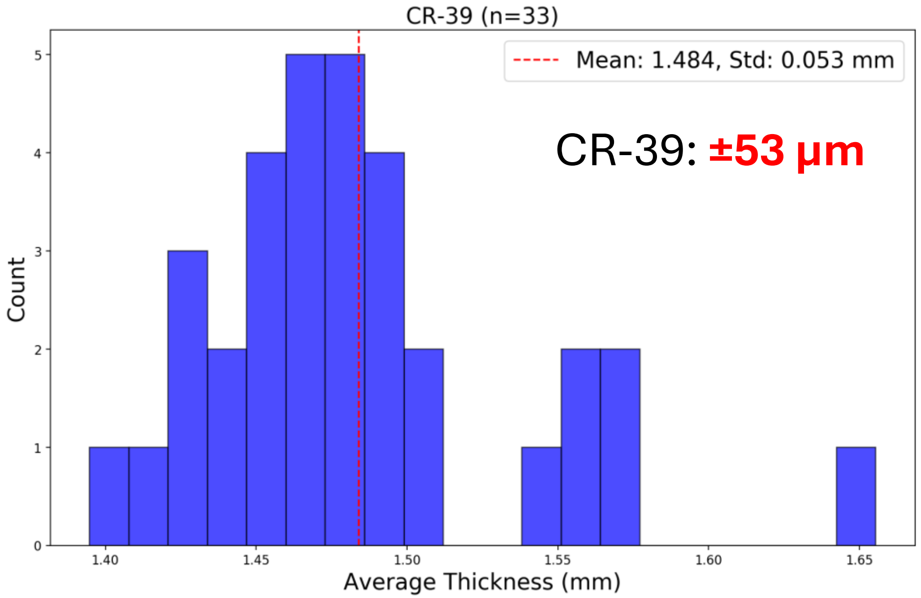
- Features:
  - Image ***simultaneously both*** surfaces
- Caveats:
  - Center/angular offsets
  - Different magnification
  - Different optical distortions
  - Sample thickness variation
    - Show-stopper if too large

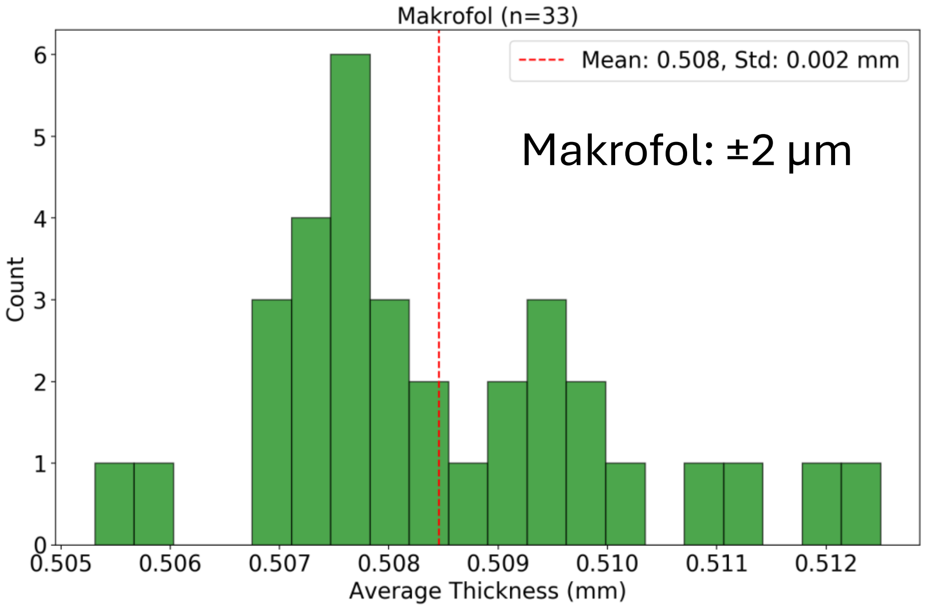
Fixed with calibration

Sample thickness variation vs depth of field

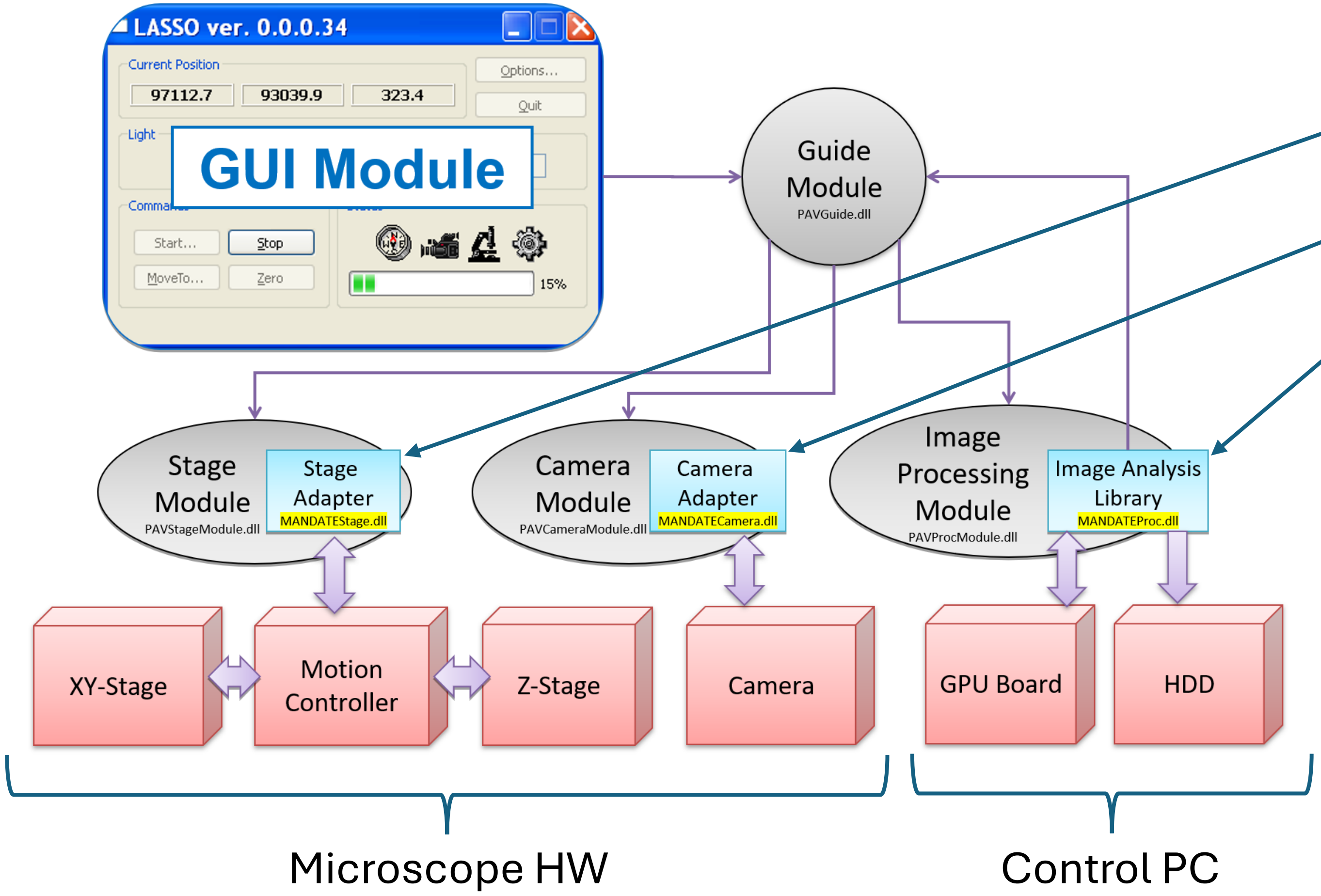
- Depth of Focus (DoF) - The distance the image plane can move from the ideal focus position before sharpness becomes unacceptable

$$DoF = \lambda/_{NA^2} = 0.55/_{0.1^2} = 55\ \mu m \Rightarrow \pm 22.5\ \mu m$$





LASSO configuration for MANDATE microscope



Specific to MANDATE:

- Stage Adapter library
- Camera Adapter library
- Image Analysis library

Summary & Prospects

- Automated microscopy experience of the NE domain can be transferred into NTD domain
- Microscope control SW can be adapted
- Online image analysis is specific to MANDATE and is to be developed
- Offline analysis SW (FEDRA) might be useful for NTD stacks analysis
- Scanning speeds of the order of 500 cm^2/h and higher should be achievable already with the existing microscope after
  - Control SW modification/replacement
  - Illumination system upgrade
- Proposed dual-camera configuration for simultaneous readout of both NTD surfaces.

THANK YOU!

Andrey Alexandrov

INFN- Naples