Science & Technology Facilities Council
Technology

532. Wilhelm and Else Heraeus-Seminar
High-Resolution Pixel Detectors and their Use in Science and Society
23-25 May 2013, Bad Honnef

CMOS Image Sensors at the Rutherford Appleton Laboratory

Dr Renato Turchetta
on behalf of the CMOS Sensor Design Group

Rutherford Appleton Laboratory (RAL)
Oxfordshire, UK
E-mail: renato.turchetta@stfc.ac.uk

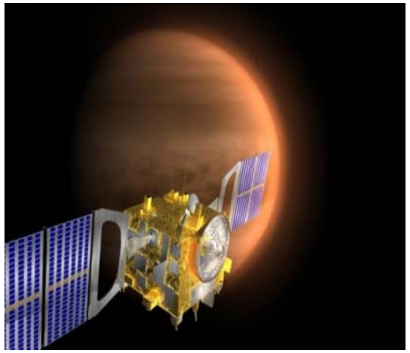
Science & Technology Facilities Council
Technology

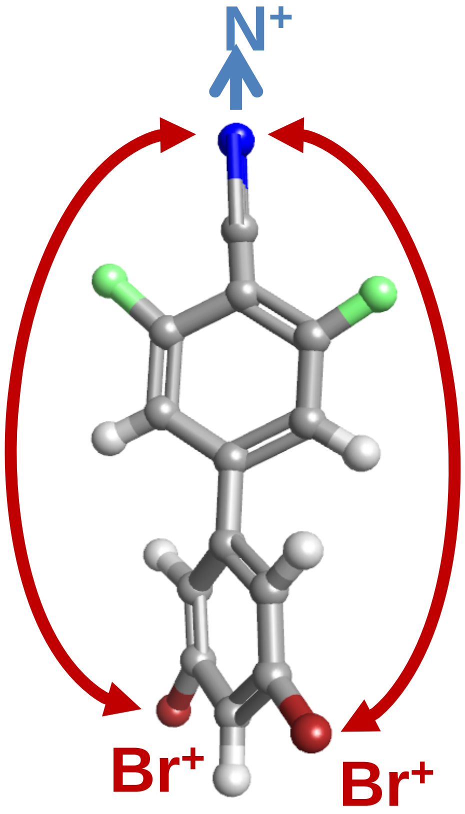
Outline

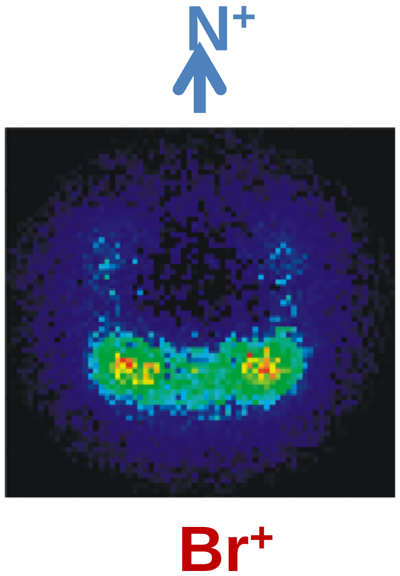
- Introduction
- Large area CMOS image sensor
- Ultra-high speed CMOS image sensors
- Conclusion

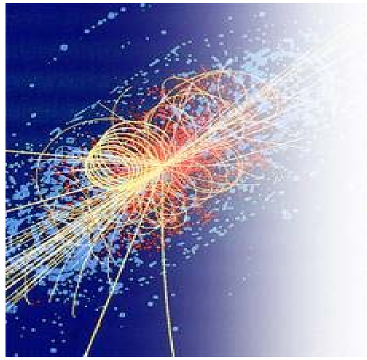
Science & Technology Facilities Council
Technology

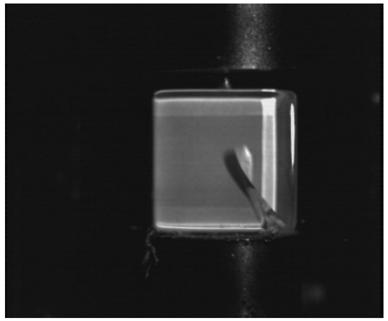
CMOS Image Sensor at RAL

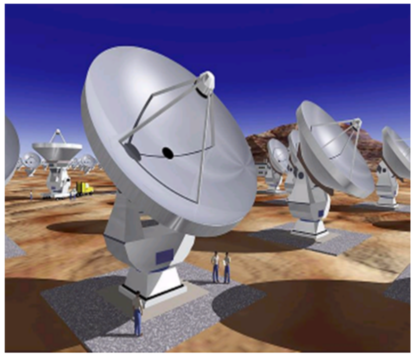


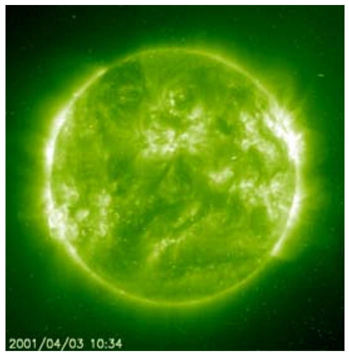












Science requirements

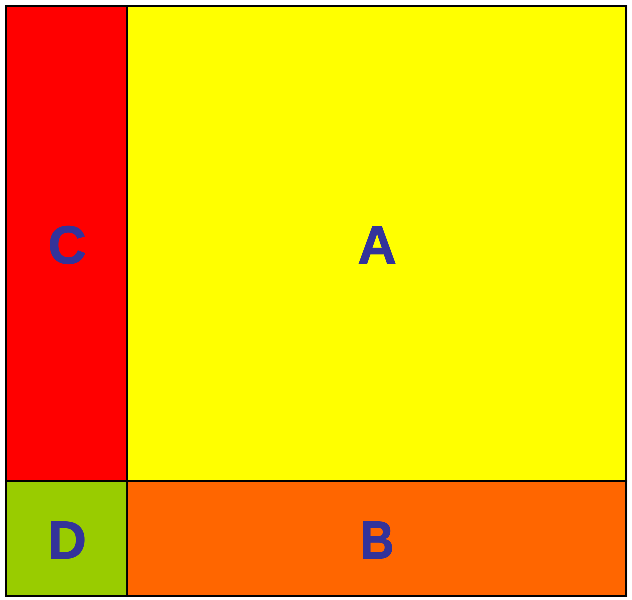
- Low noise
- High Dynamic Range (HDR)
- Radiation hardness
- High speed
- High Quantum Efficiency
- Large area sensor
- Low power
- Large data volume
- …
- Lossless compression

Science & Technology Facilities Council Technology

Large area sensor. Stitching.

Reticle size is just over 2cm x 2cm → 'stitching'

Reticle is subdivided in blocks

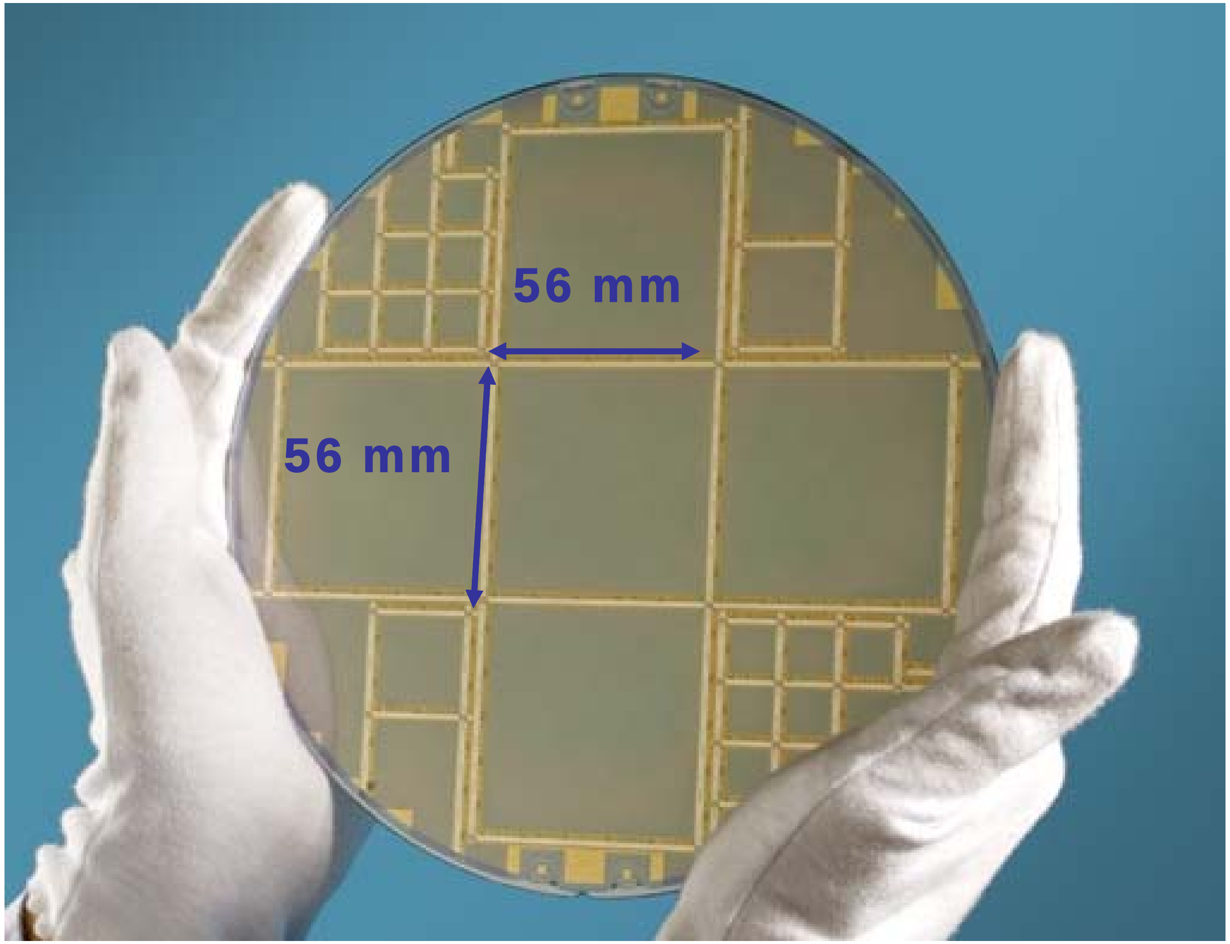


Sensor size freed from reticle limitation → up to single sensor per wafer

Sensors of different sizes can be manufactured

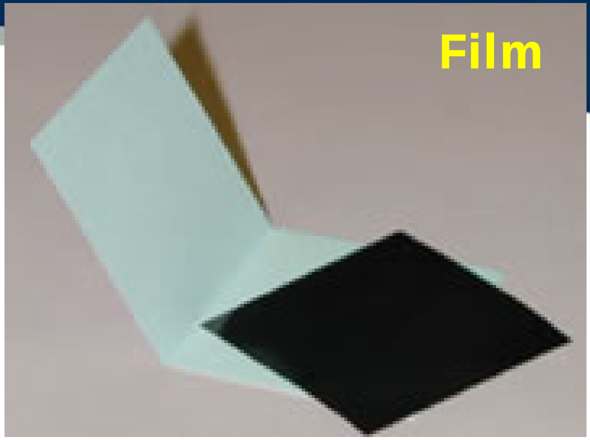
Science & Technology Facilities Council Technology

Large area sensor. Stitching.

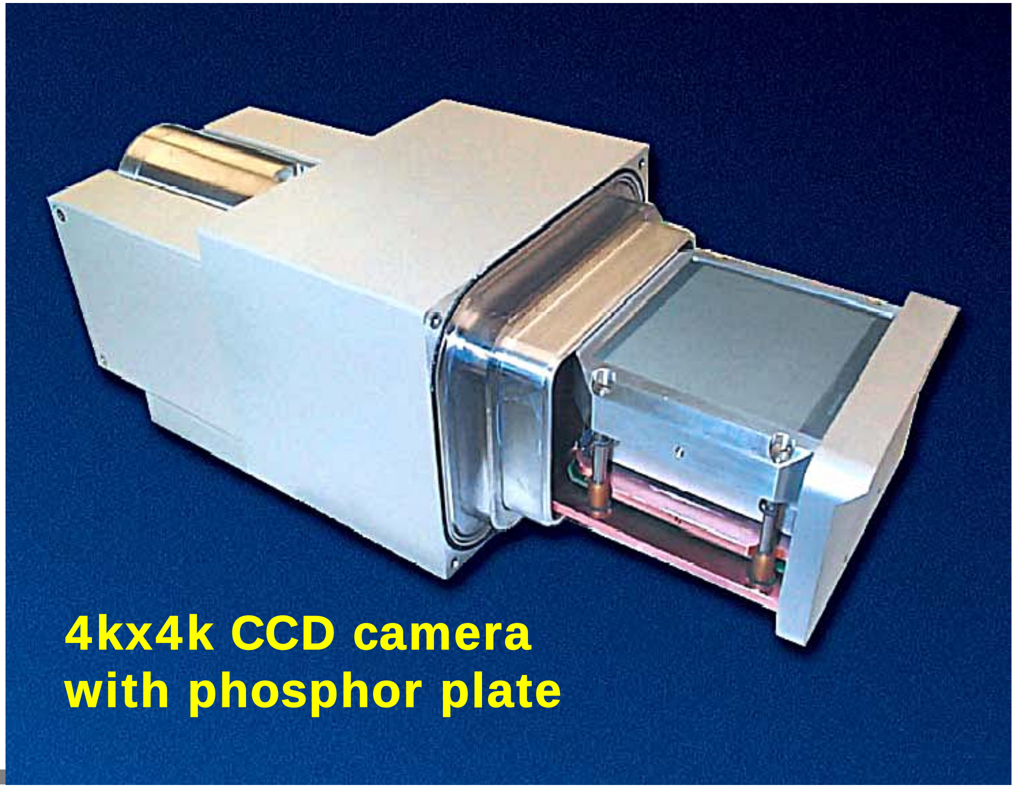


Science & Technology Facilities Council
Technology

Transmission Electron Microscopy (TEM). Prior art.



- Film: direct detection, very good resolution, non digital, poor S/N for weak exposure
- CCD with phosphor: indirect detection (radiation hardness), phosphor ruins spatial resolution, good for tomography



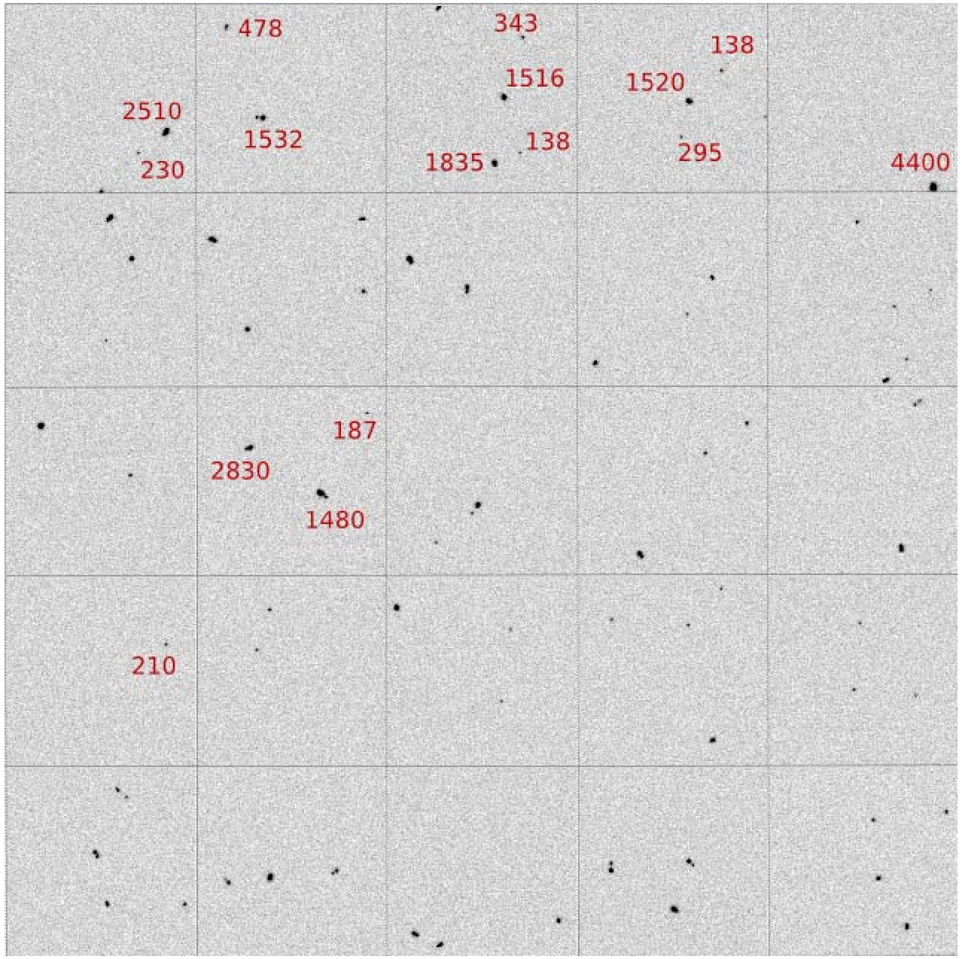
Science & Technology Facilities Council
Technology

CMOS Sensor for TEM

- Direct detection
- Good single electron sensitivity
- Good MTF and DQE
- Radiation resistant
- 4Kx4K array
- 16 million pixels

Science & Technology Facilities Council
Technology

Detection of electrons in CMOS



MRC Laboratory of Molecular Biology

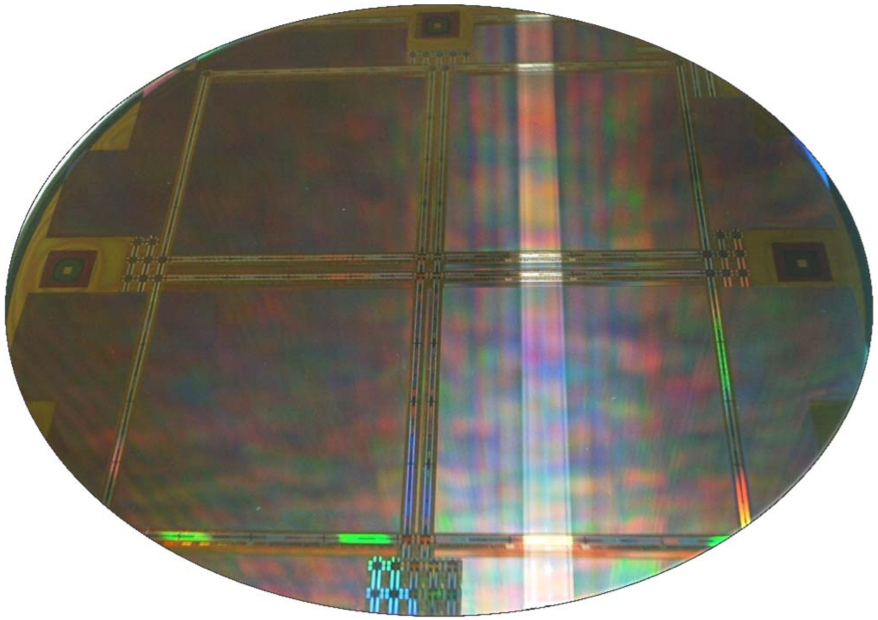
MAX-PLANCK-GESELLSCHAFT

FEI COMPANY
TOOLS FOR NANOTECH

Science & Technology Facilities Council Technology

A 16Mpixel sensor for TEM

- 61x63 mm^2 silicon area (4 dies per wafer)
- 0.35μm CMOS
- 16 million pixels, 4Kx4K array
- 14 μm pixels
- 32 analogue outputs
- 40 fps
- Pixel binning 1X, 2X and 4X
- ROI readout
- 83 e- rms noise
- Full well 120ke-
- Radiation hardness of >500 million of primary electrons/pixel (>20 Mrad)
- 20% QE for visible light



Science & Technology Facilities Council Technology

Wafer-scale sensor for X-ray medical imaging

Motivations

- Extra-oral dental
- with tiling:
  - Mammography
  - Chest imaging
  - Security
  - ...

Guidelines

- Wafer-scale sensor
- One sensor per 200 mm wafer
- 3-side buttable → 2xN tiling
- Radiation hard design
- Design for yield

Science & Technology Facilities Council
Technology

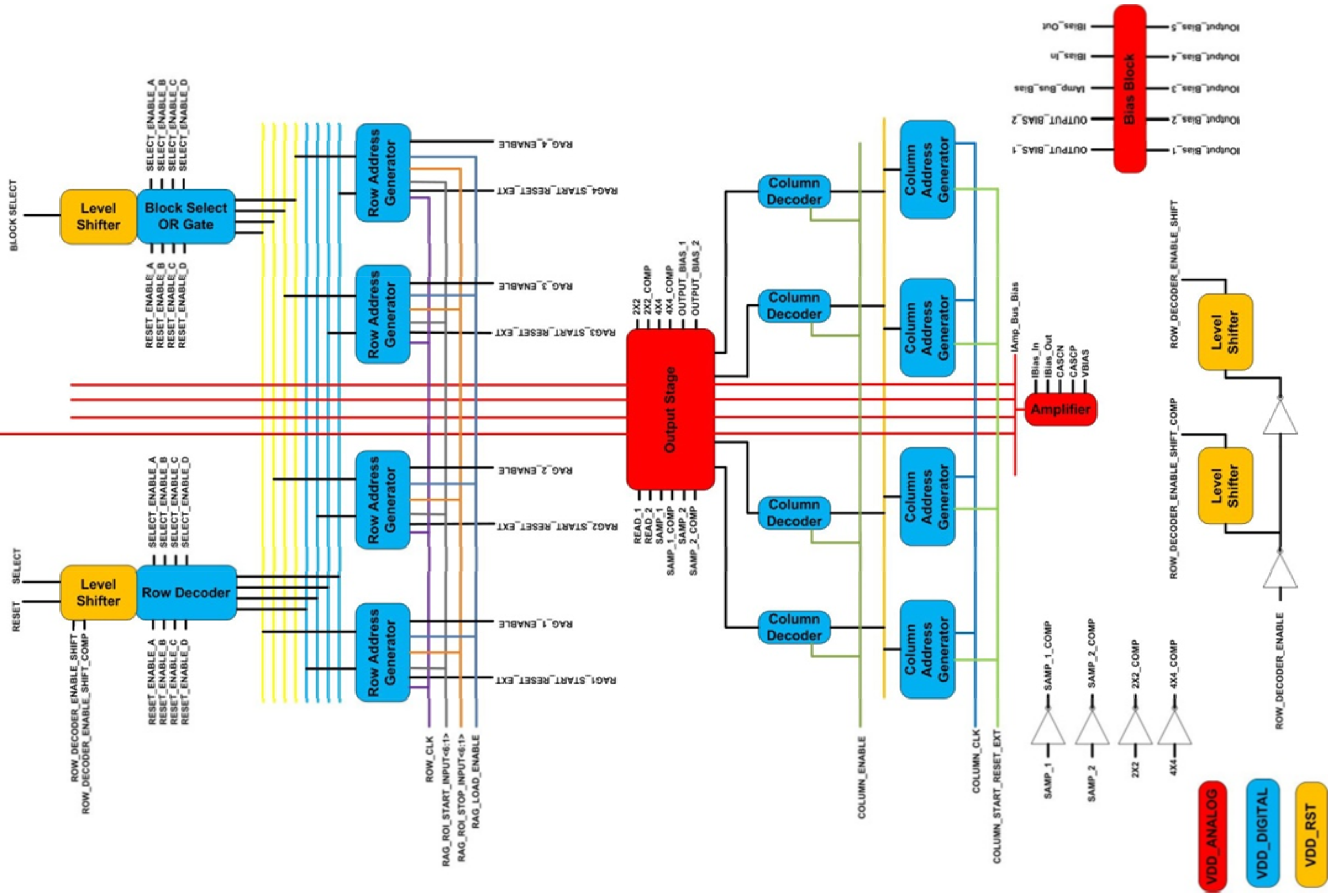
Lassena. Floorplan

To the pixel:

3T pixel base with

Low noise, large partially pinned diode

Binning capability

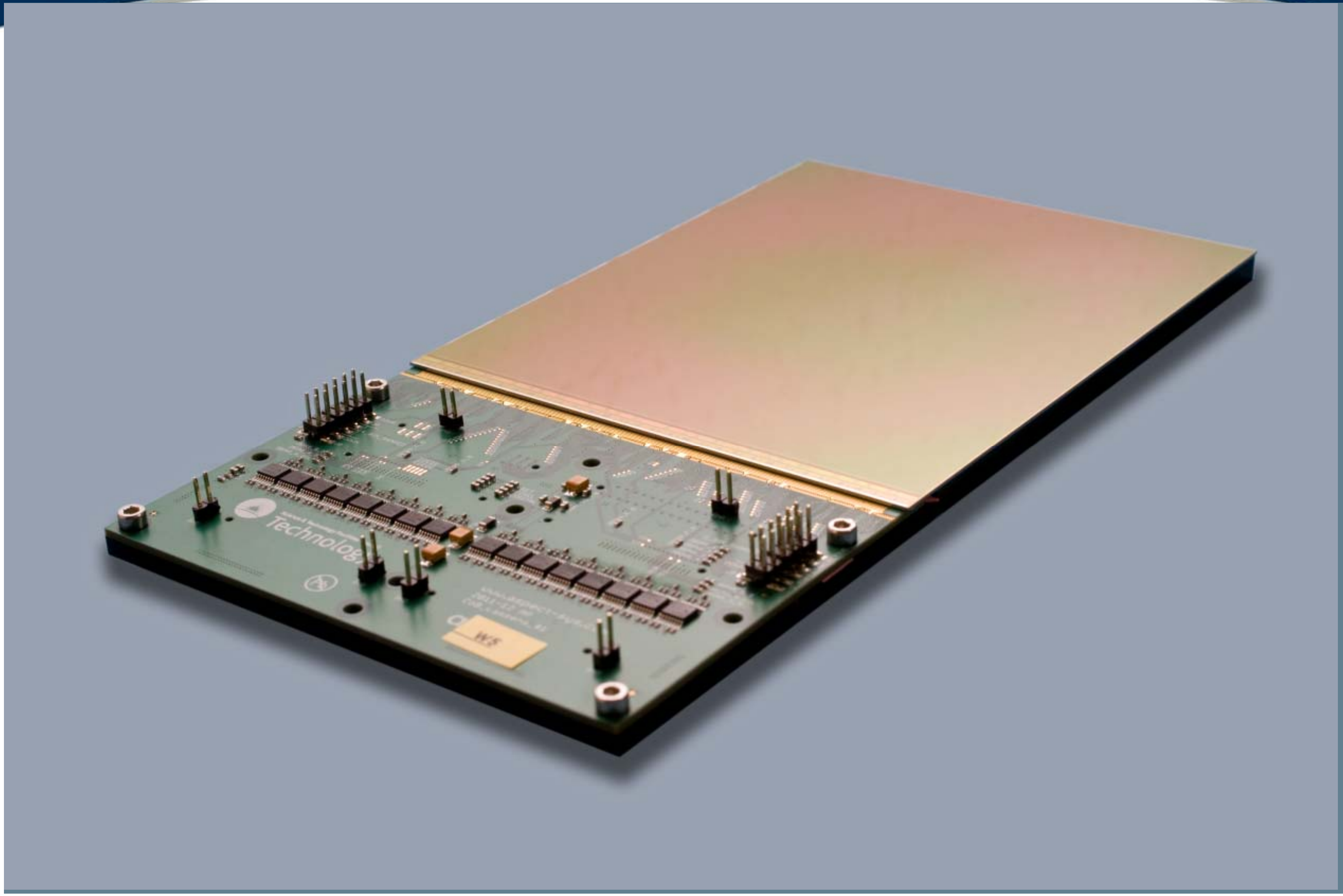


Science & Technology Facilities Council Technology

Main features

- High resolution. 50 μm pixel.
- High-speed. Over 30 frames per second at full resolution.
- Low noise. 68 e- rms in full frame to give very high sensitivity.
- Large area coverage. The sensor is 3-side buttable so that tiled sensors can cover any length of an area 28 cm wide.
- High dynamic range. Multiple programmable integration times
- Binning x2, x4
- ROI readout

Lassena. A 6.7Mpixel, wafer-scale sensor



Optical parameters

Optical performance			
Rms electronic noise	e- rms	68	Full resolution mode (i.e. no binning)
		335	Bin 2x2 mode
		608	Bin 4x4 mode
Linear full well	e-	112,000	Full resolution mode (i.e. no binning)
		1,253,000	Bin 2x2 mode
		5,012,000	Bin 4x4 mode
Maximum full well	e-	144,000	Full resolution mode (i.e. no binning)
		1,374,000	Bin 2x2 mode
		5,496,000	Bin 4x4 mode
Dynamic range (Linear)	bits	10.7	Full resolution mode (i.e. no binning)
		11.9	Bin 2x2 mode
		13.0	Bin 4x4 mode
Dynamic range (Maximum)	bits	11.0	Full resolution mode (i.e. no binning)
		12.0	Bin 2x2 mode
		13.1	Bin 4x4 mode
Readout speed	frames per second	35	Full resolution mode (i.e. no binning)
		70	Bin 2x2 mode
		140	Bin 4x4 mode
Quantum efficiency	Measured @ 540nm	50%	
Lag		Negligible	
Other			
Power supply	V	3.3	
Number of pads	480	All on one side	
Power Consumption (mW)	W	<2.5	CMOS only

PERCIVAL

Pixelated Energy Resolving CMOS Imager, Versatile and Large

DESY

elettra

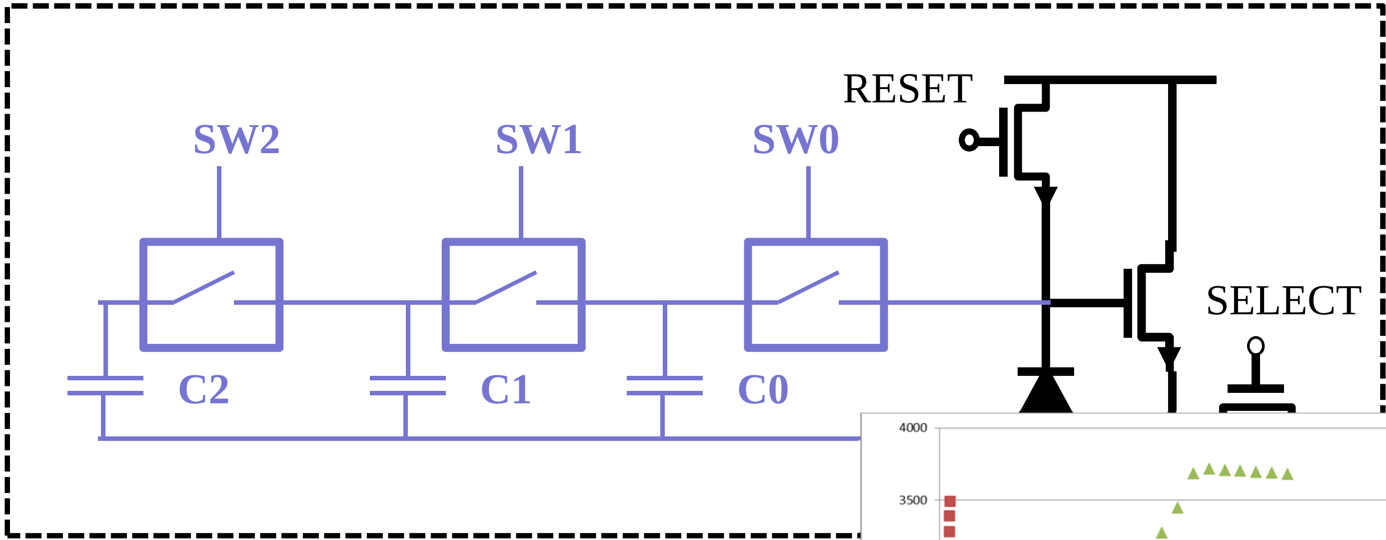
Science & Technology Facilities Council
Technology

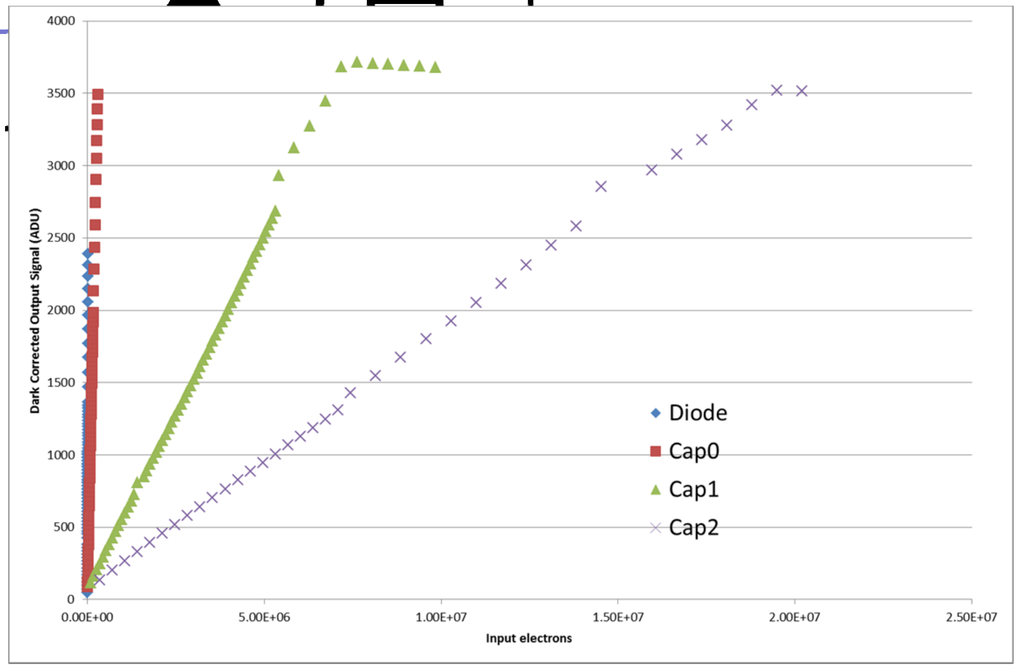
Percival target specifications

- Low energy X-ray detection <~ 2,000 eV
- High efficiency → back-side illuminated and direct detection
- High resolution → 4kx4k on a 25μm pitch
- Good single photon sensitivity → low noise
- High dynamic range, i.e. up to ~ $2*10^5$ photons @ 250 eV → high dynamic range (HDR) pixel --> ~120dB or full well >10 Me-
- High frame rate → 120 fps
- Fully digital

Science & Technology Facilities Council
Technology

HDR pixel

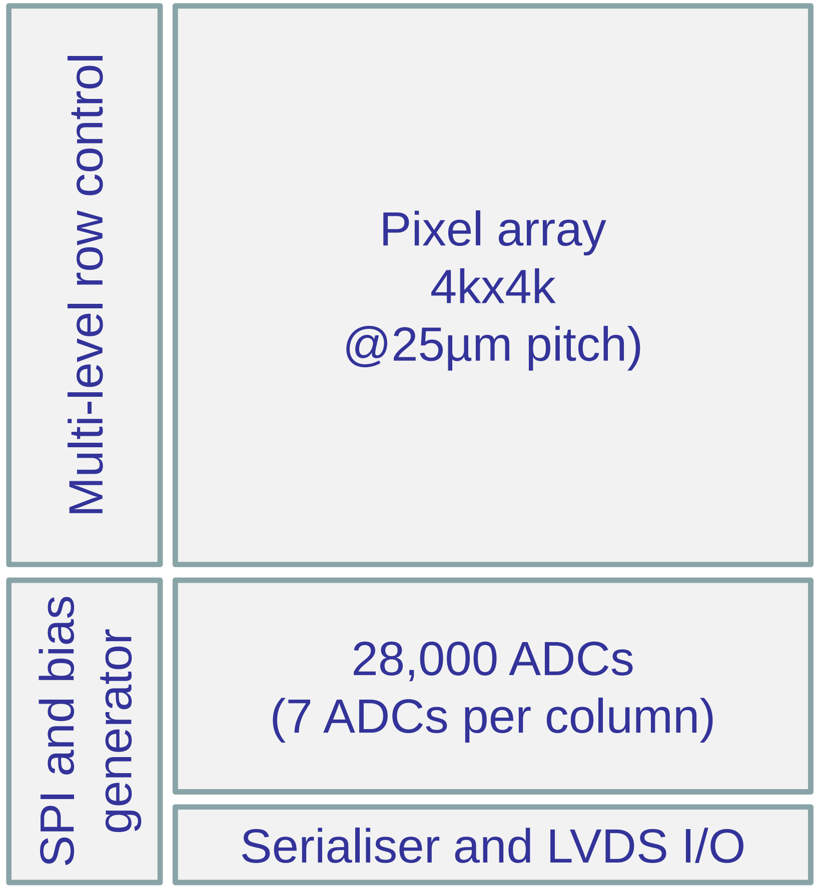




- ➢ Preliminary results from test structure
- ➢ 12 bit ADC
- ➢ 7 ADCs per column

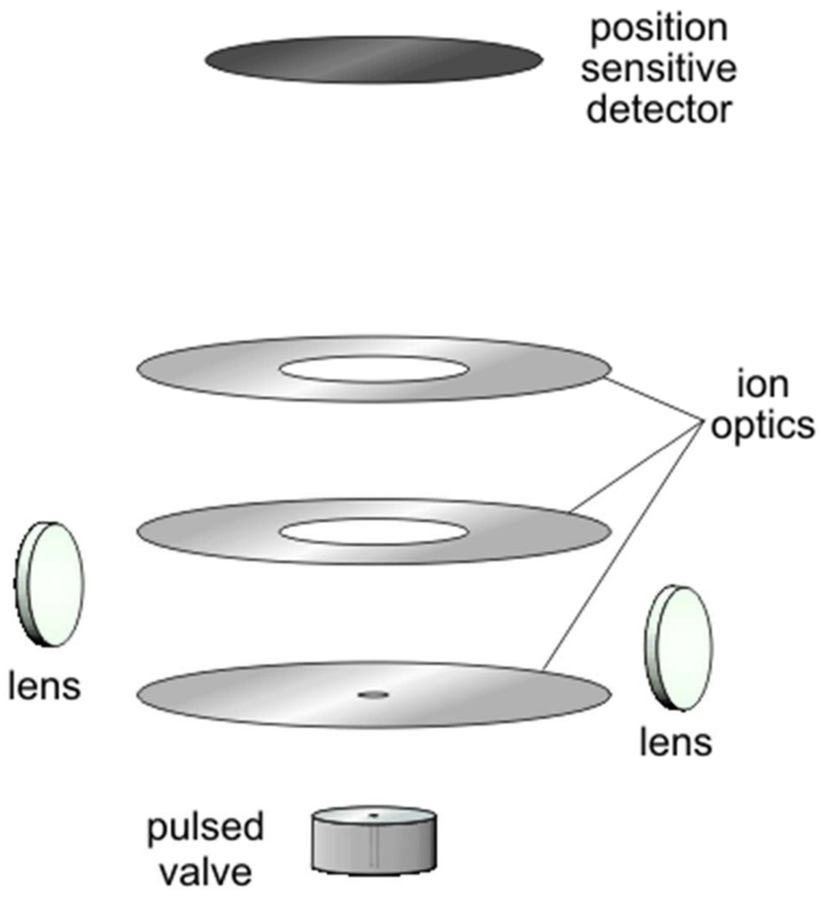
Percival sensor floorplan

- 16 MPix resolution
- 120 fps (digital CDS)
- High dynamic range (4 gains per pixel)
- 12+1bit ADC
- 15 bits per pixel (2 gain bits + 13 bits)
- Digital I/O (LVDS)
- 60 Gbit/sec continuous data rate



Science & Technology Facilities Council Technology

Time-Of-Flight Mass Spectroscopy



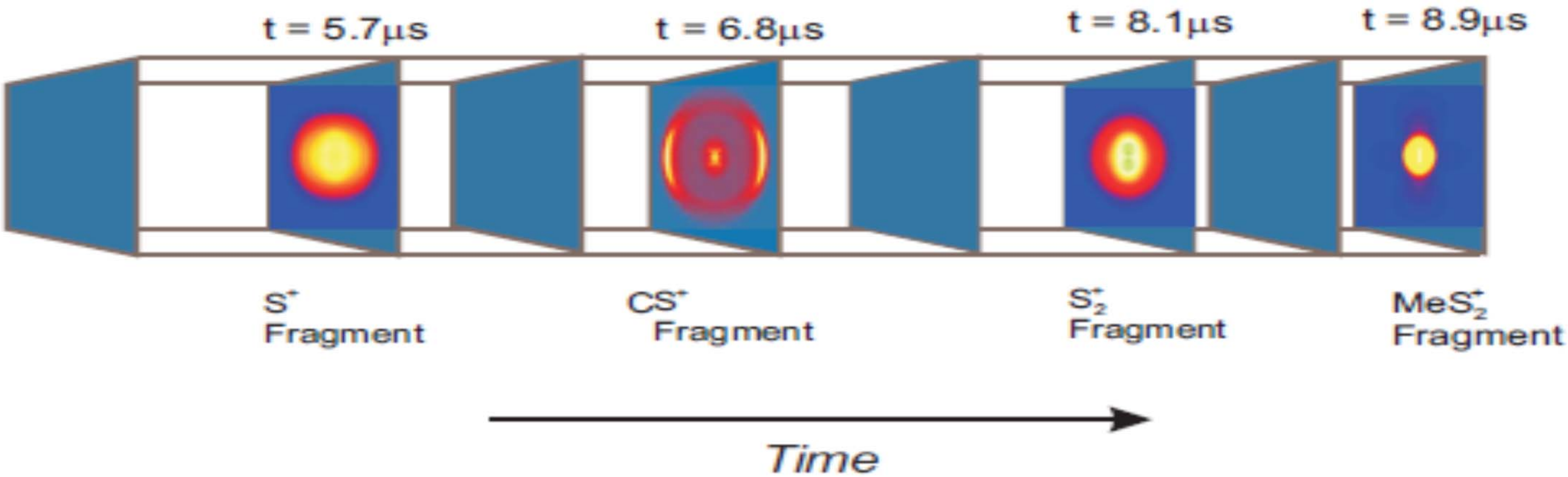
Requirements

- Spatial information
- Timing information

Courtesy of A. Nomerotski et al., Oxford University

Science & Technology Facilities Council
Technology

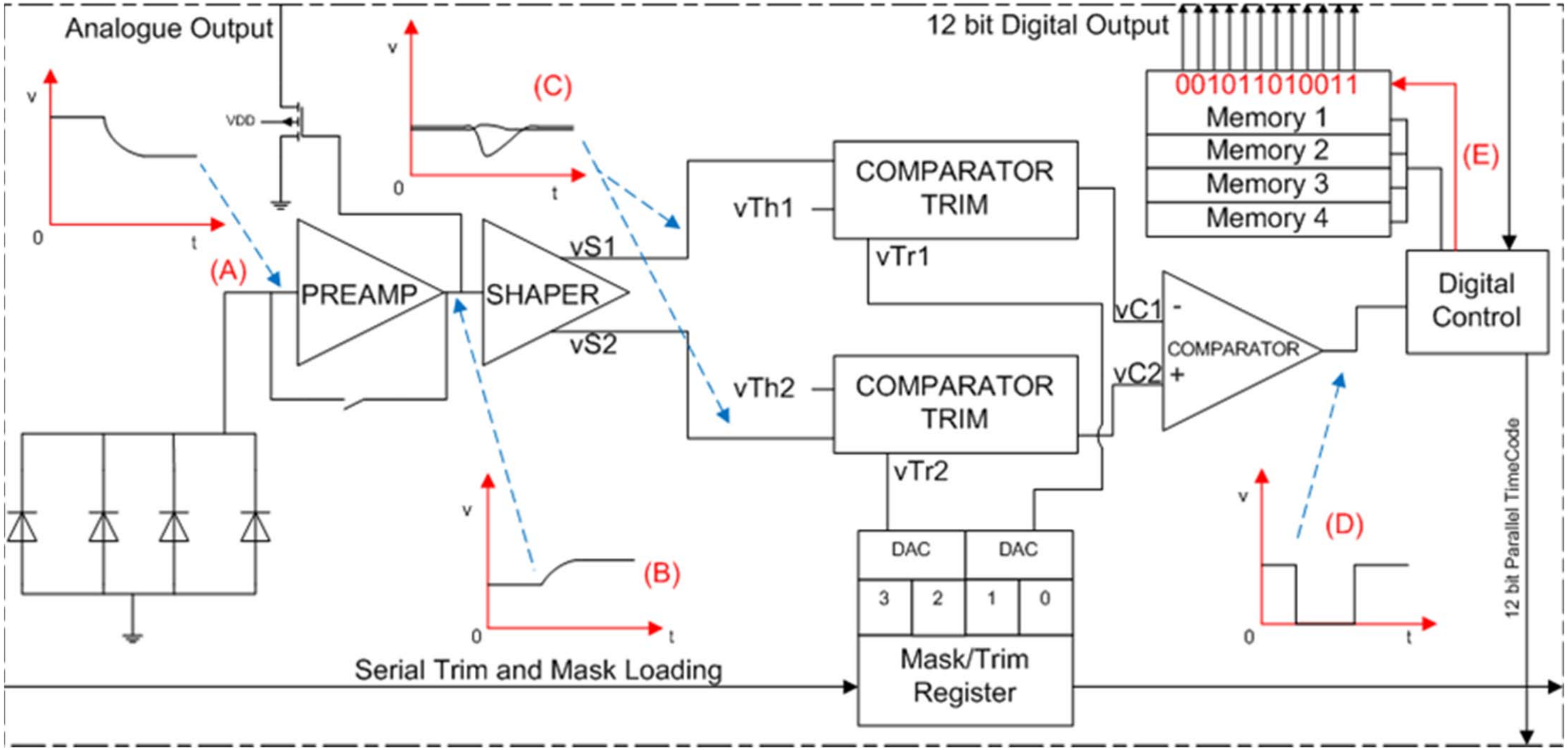
Time-Of-Flight Mass Spectroscopy



Science & Technology Facilities Council Technology

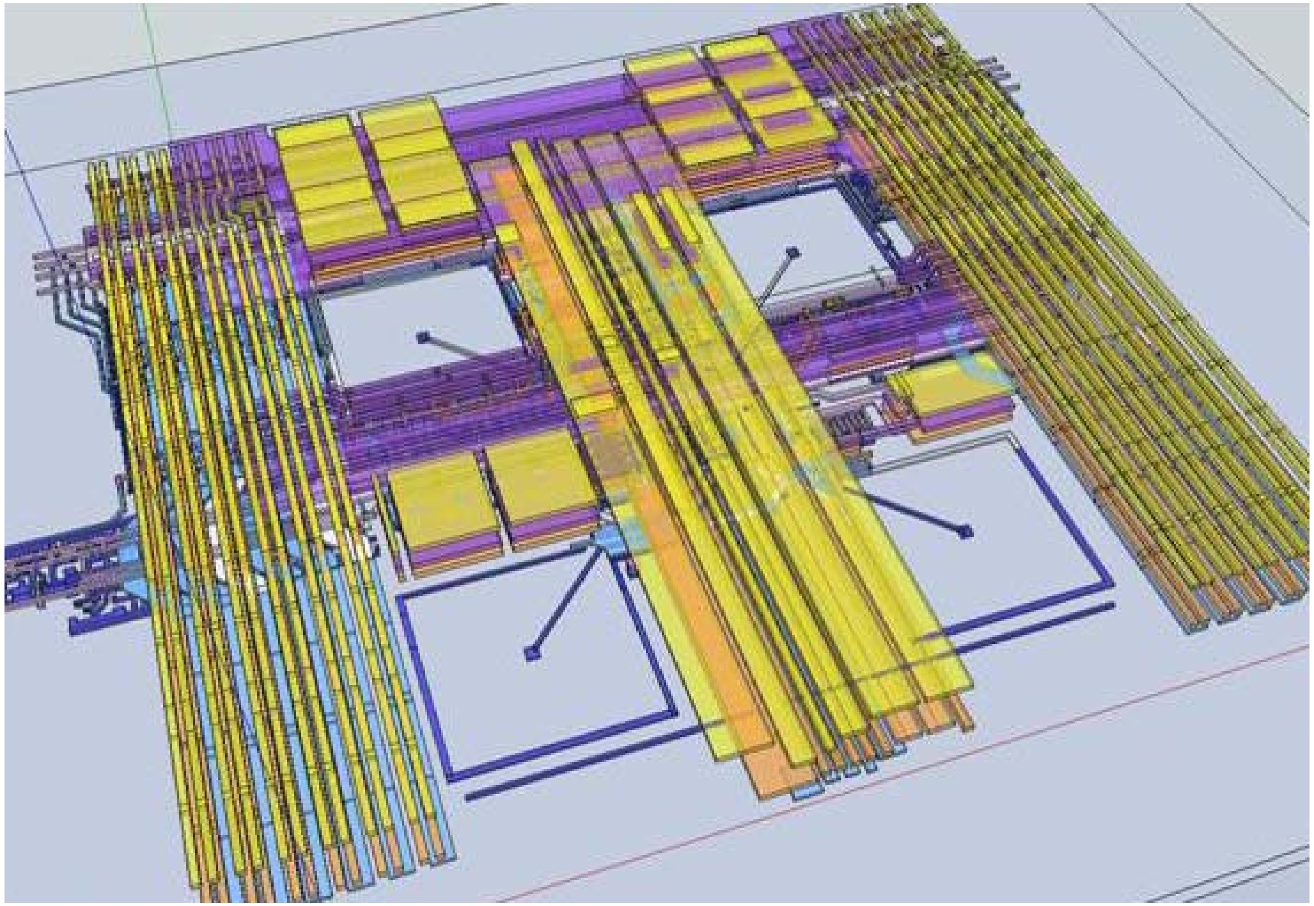
PImMS. A single particle CMOS Image Sensor.

PImMS – Pixel Imaging Mass Spectrometry



Science & Technology Facilities Council Technology

PImMS pixel layout



Over 600 transistors

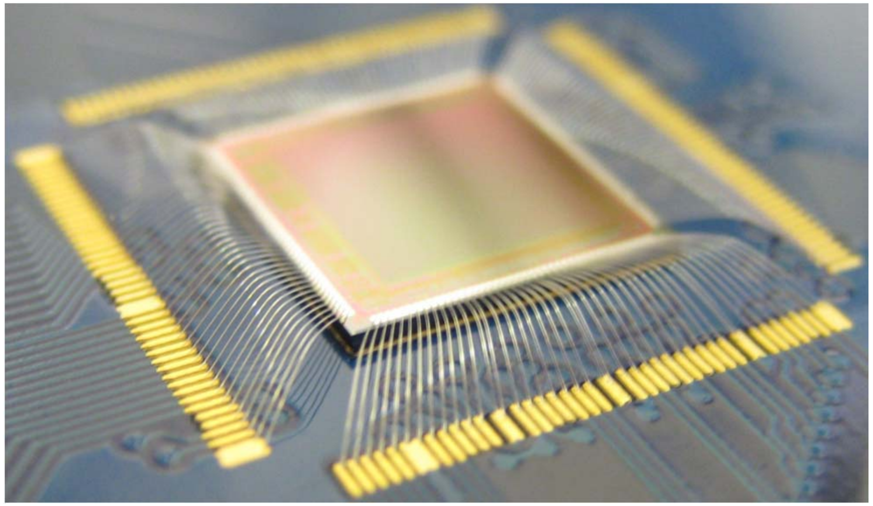
Modified process developed with TowerJazz: deep P-implant for 100% fill factor and true CMOS

Science & Technology Facilities Council
Technology

PImMS family

PImMS1

72 by 72 pixel array



~ $2*10^{11}$ pixel/sec

PImMS2

324 by 324 pixel array
70 µm x 70 µm pixel size

Time-code resolution
= 25 ns (12.5 demonstrated already on PImMS1)

4 event stored in each pixel

12 bit time-code resolution

Analogue readout of intensity information

Equivalent pixel rate for standard full frame camera

~ $4*10^{12}$ pixel/sec

Science & Technology Facilities Council
Technology

Target specifications

- Ultra-high speed (>1MHz) with high frame depth (~200 cells)
- High resolution (~Megapixel)
- High-speed (~kfps) for continuous readout
- 10 bit resolution
- Flexible trigger (pre/post/center)
- 35mm format

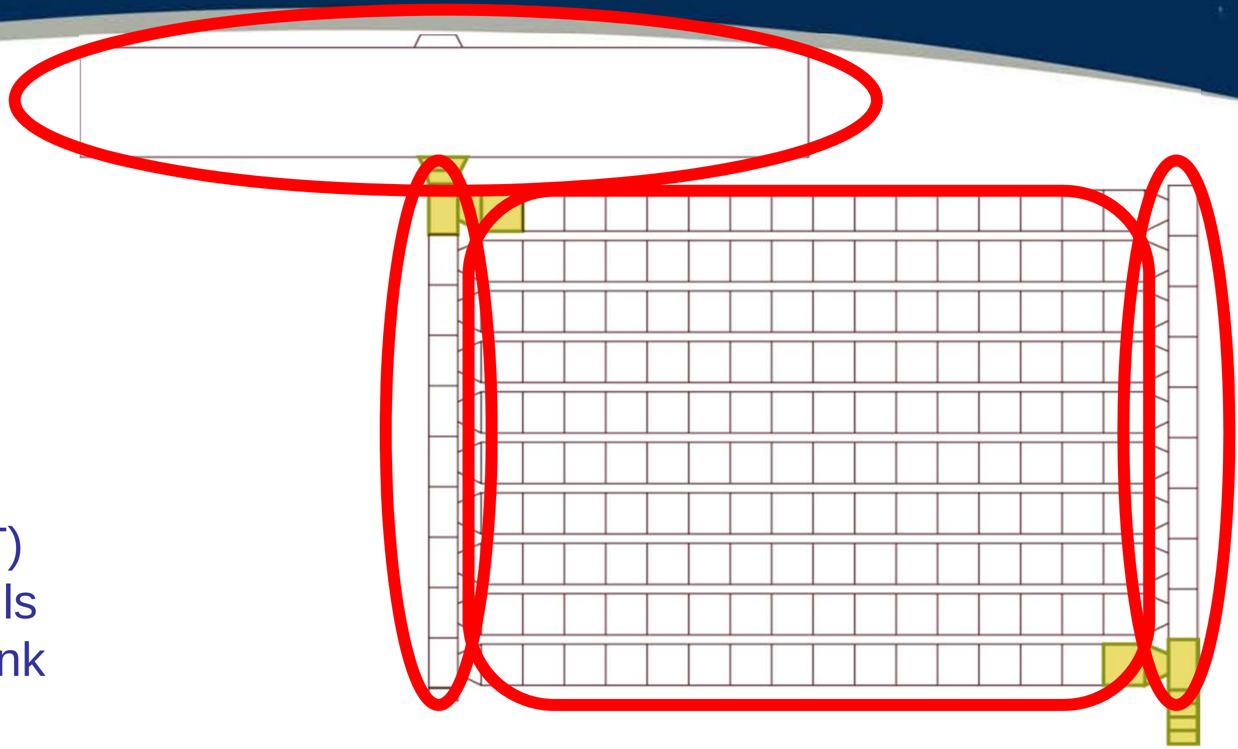
Science & Technology Facilities Council Technology

uCMOS technology

- u = Ultra-high speed
- CMOS for ease of use and readout speed
- CCD for in-pixel storage
- Start from Tower 180 nm CIS process with dual gate oxide: 3nm + 10nm
- Optimise process for high-speed, high-efficiency charge transfer

Science & Technology Facilities Council Technology

Kirana pixel. 1



Photodiode

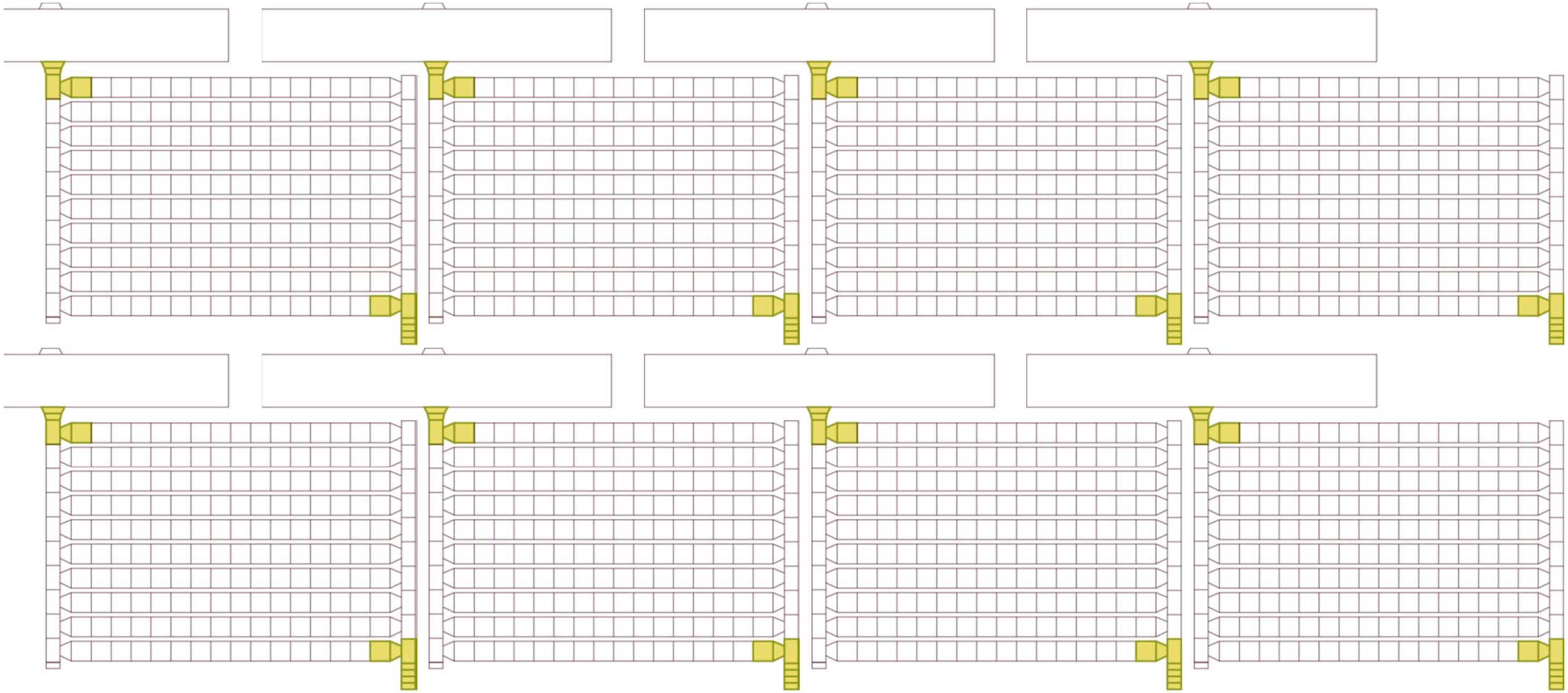
Memory bank

- A vertical entry (VEN) bank with 10 cells
- Ten rows of lateral (LAT) banks, each with 16 cells
- A vertical exit (VEX) bank with 10 cells

- Total of 180 memory cells

Science & Technology Facilities Council
Technology

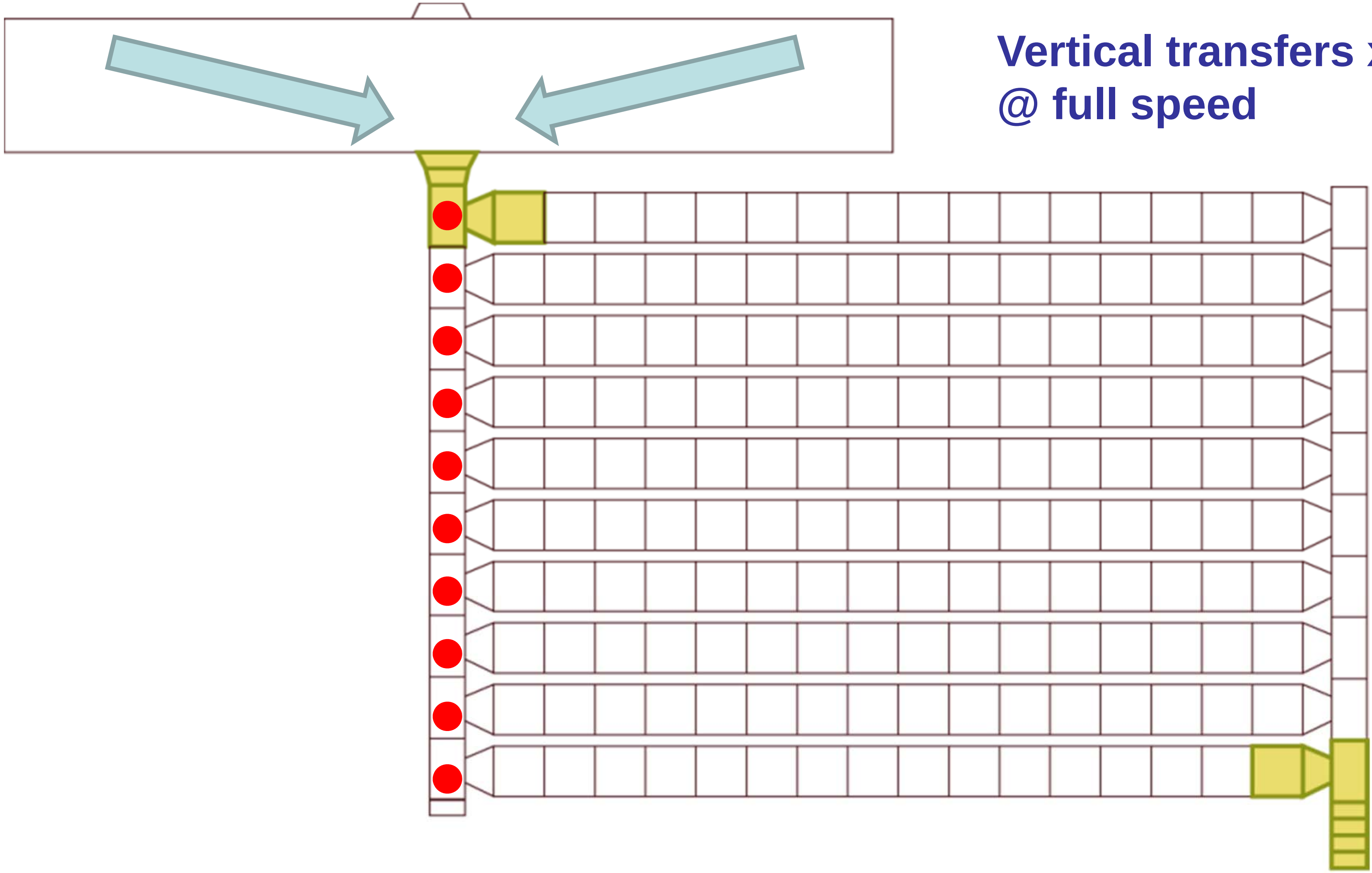
Kirana pixel. 2



Highly scalable architecture:

- **Number of memory cells**
- **Number of pixels**

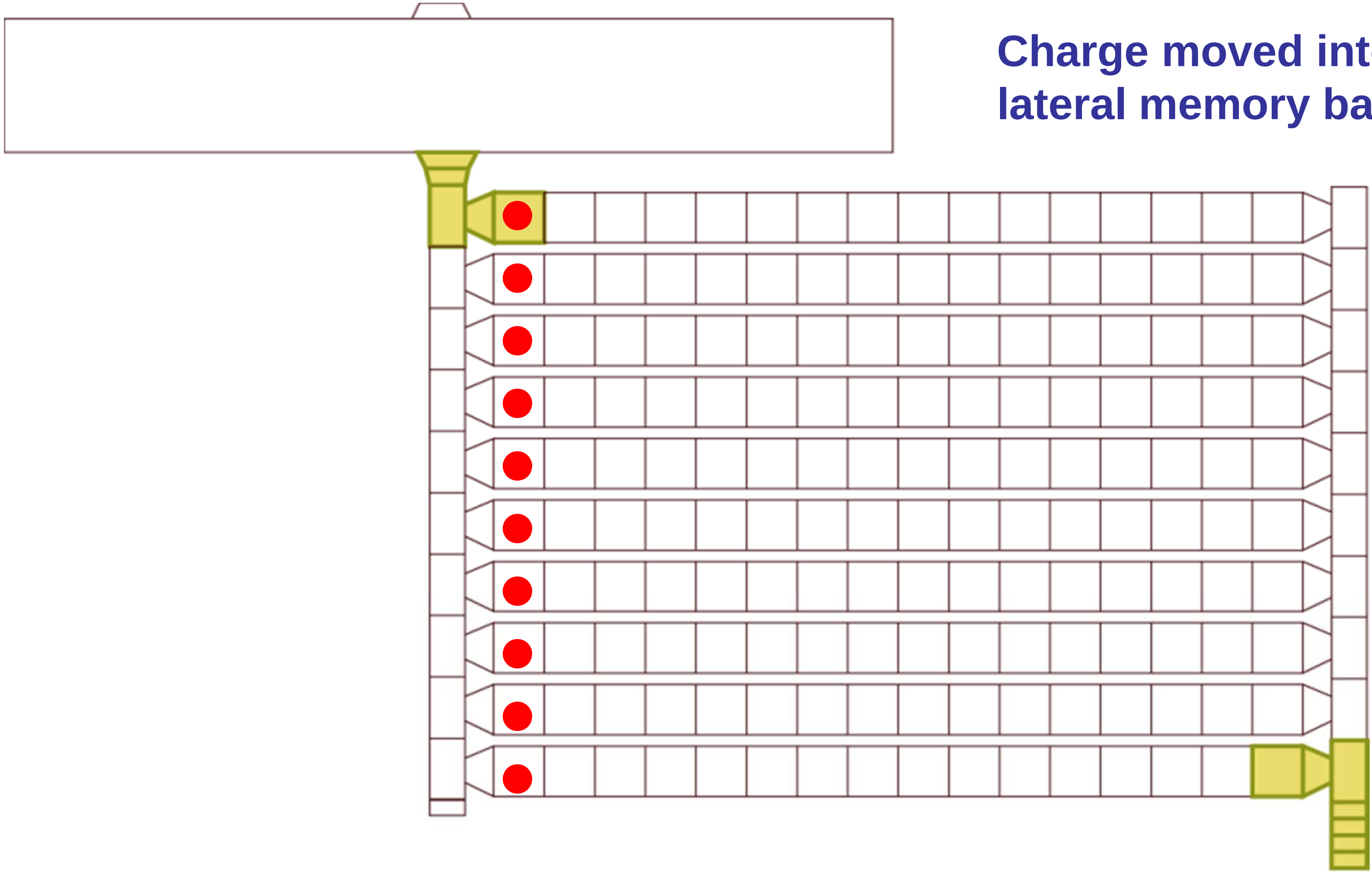
Burst mode



Vertical transfers x10 @ full speed

Science & Technology Facilities Council
Technology

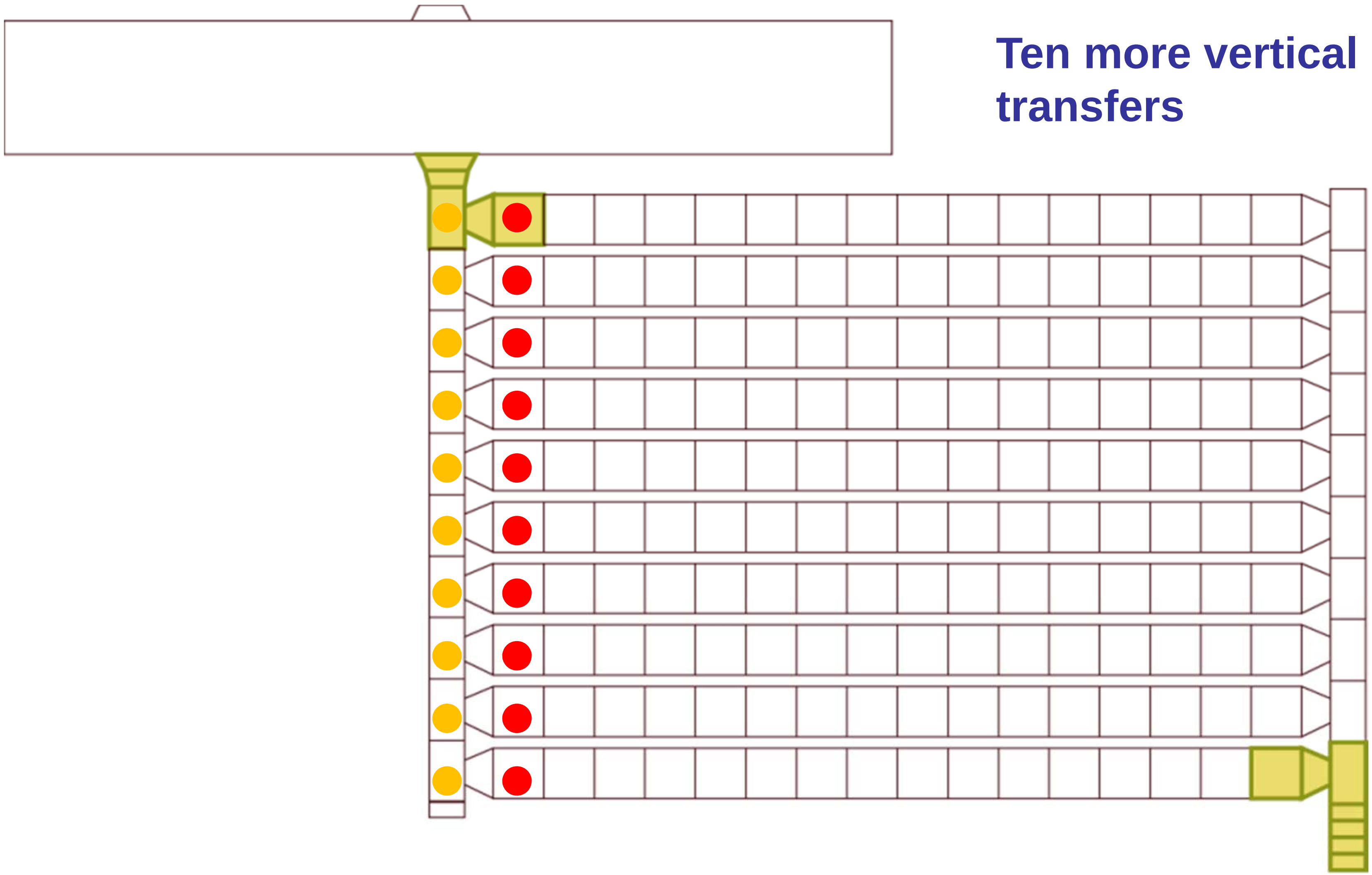
Burst mode



Charge moved into lateral memory bank

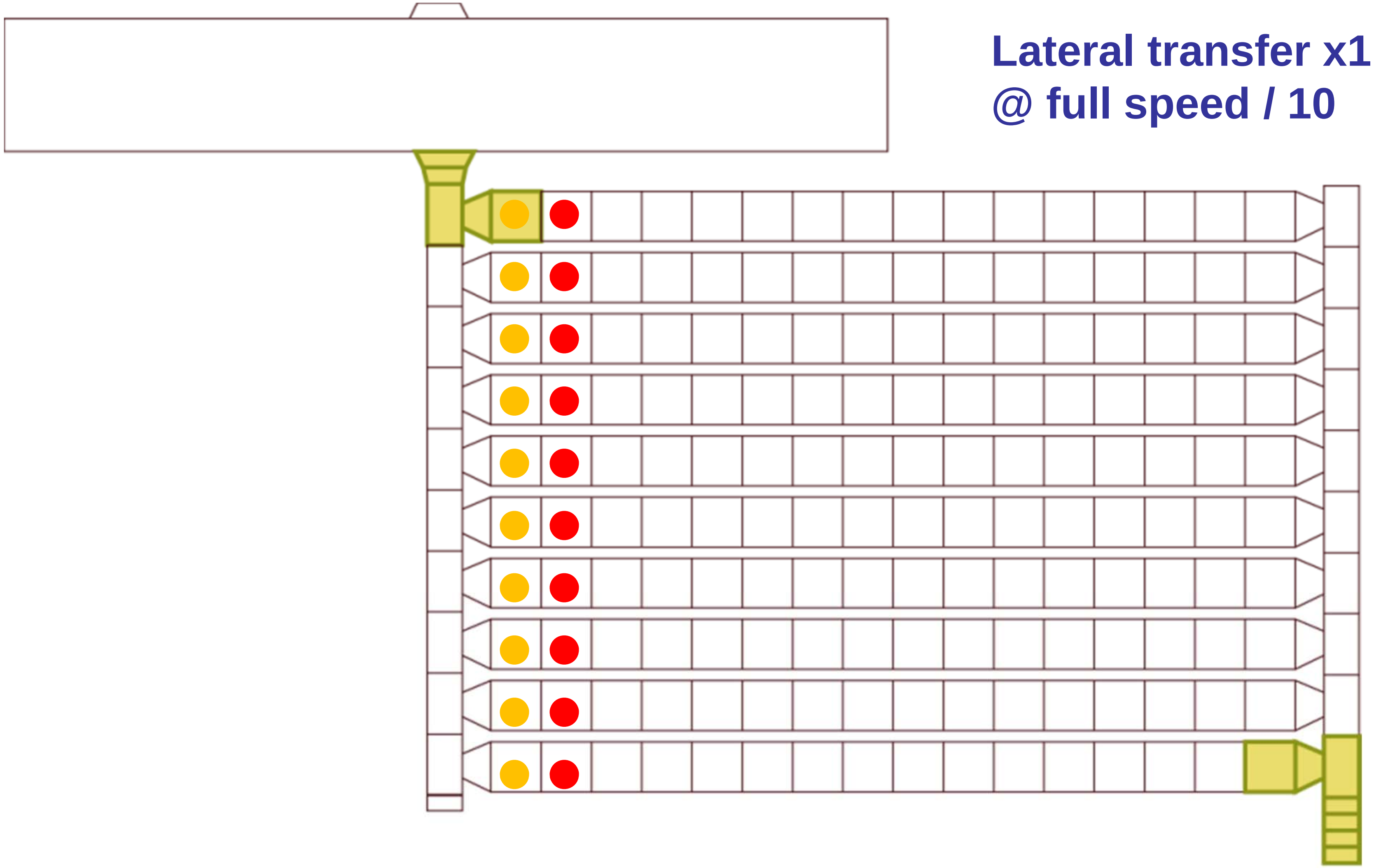
Science & Technology Facilities Council
Technology

Burst mode



Ten more vertical transfers

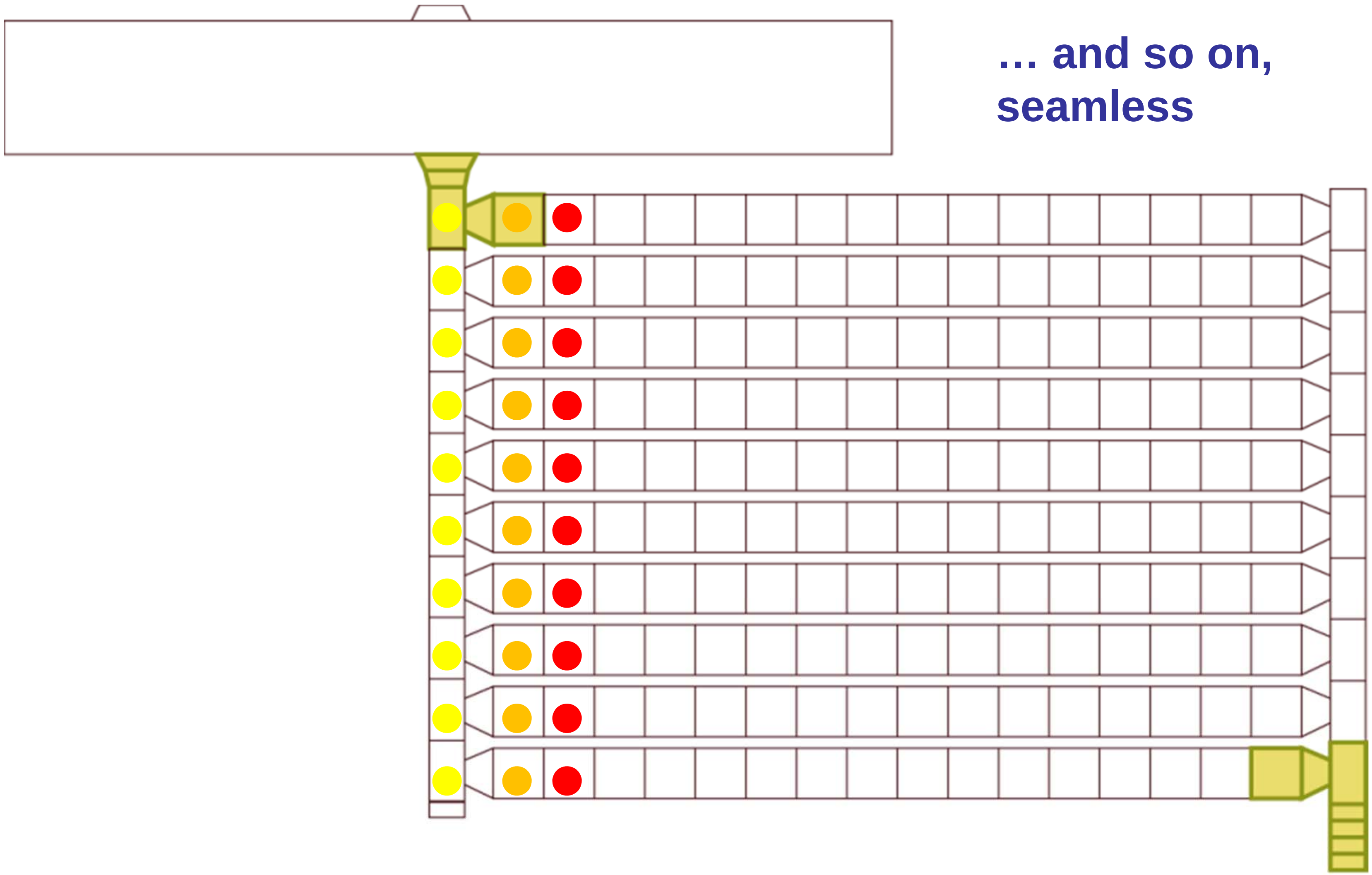
Burst mode



Lateral transfer x1
@ full speed / 10

Science & Technology Facilities Council
Technology

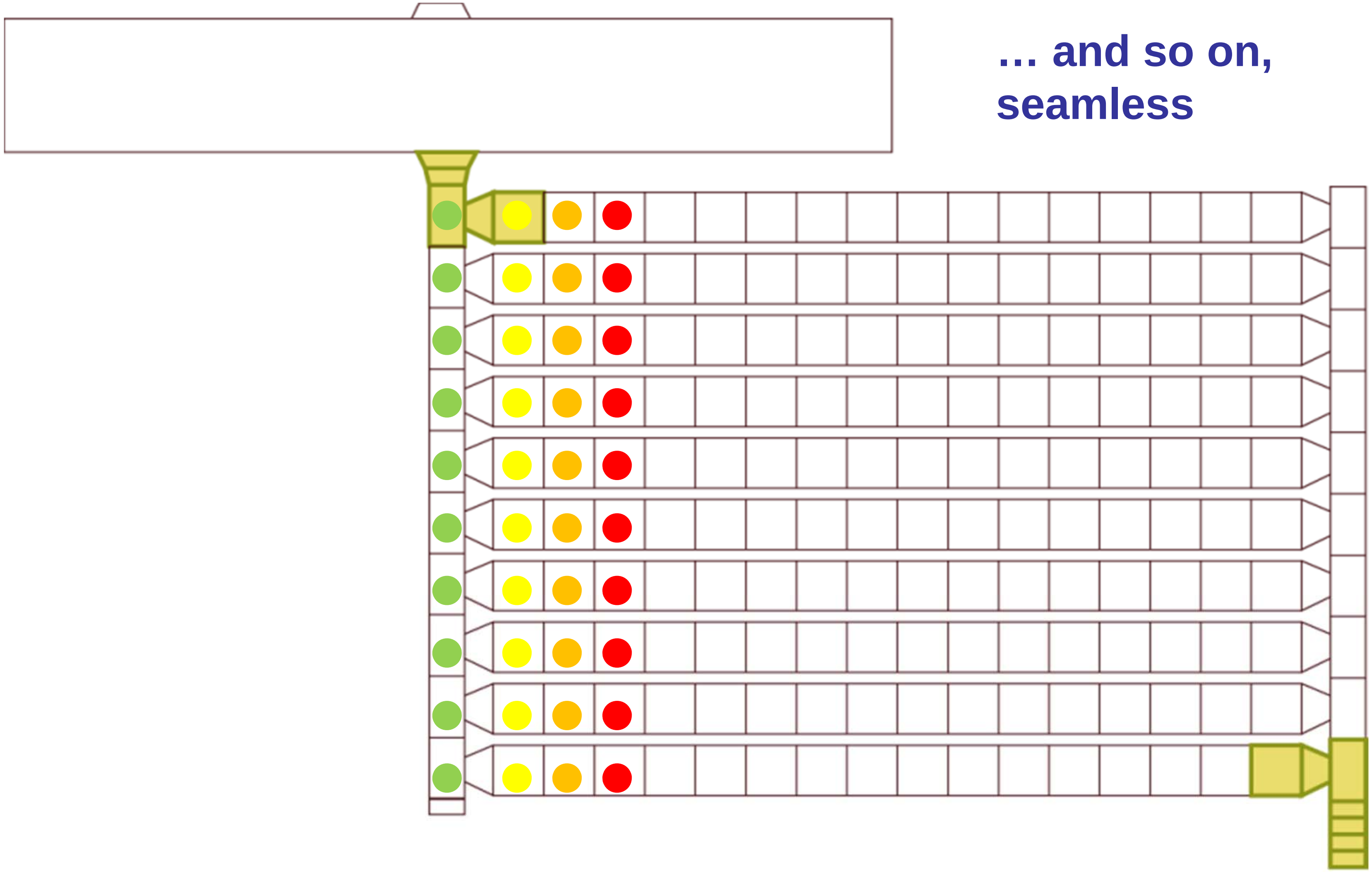
Burst mode



… and so on, seamless

Science & Technology Facilities Council Technology

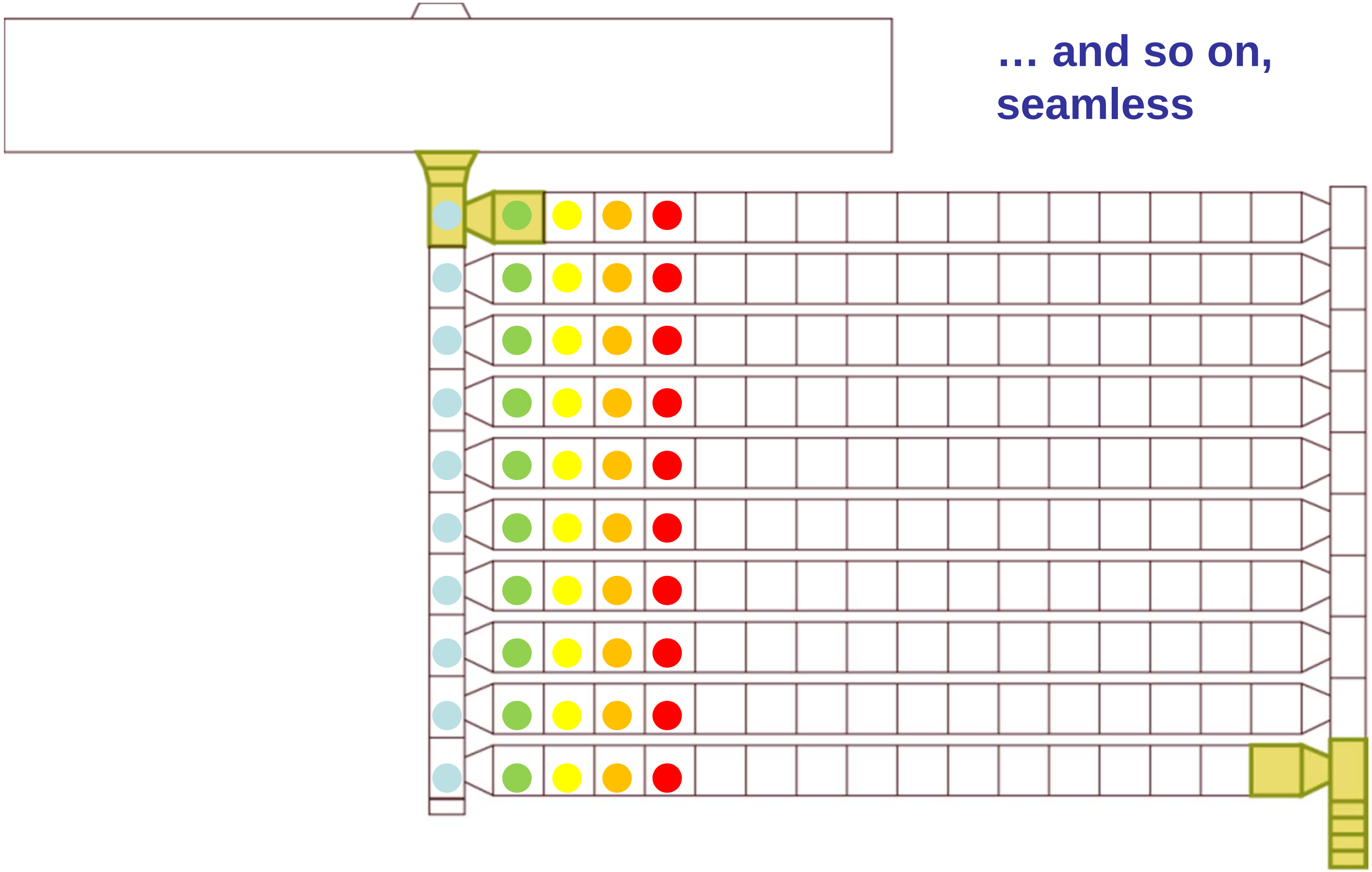
Burst mode



… and so on, seamless

Science & Technology Facilities Council Technology

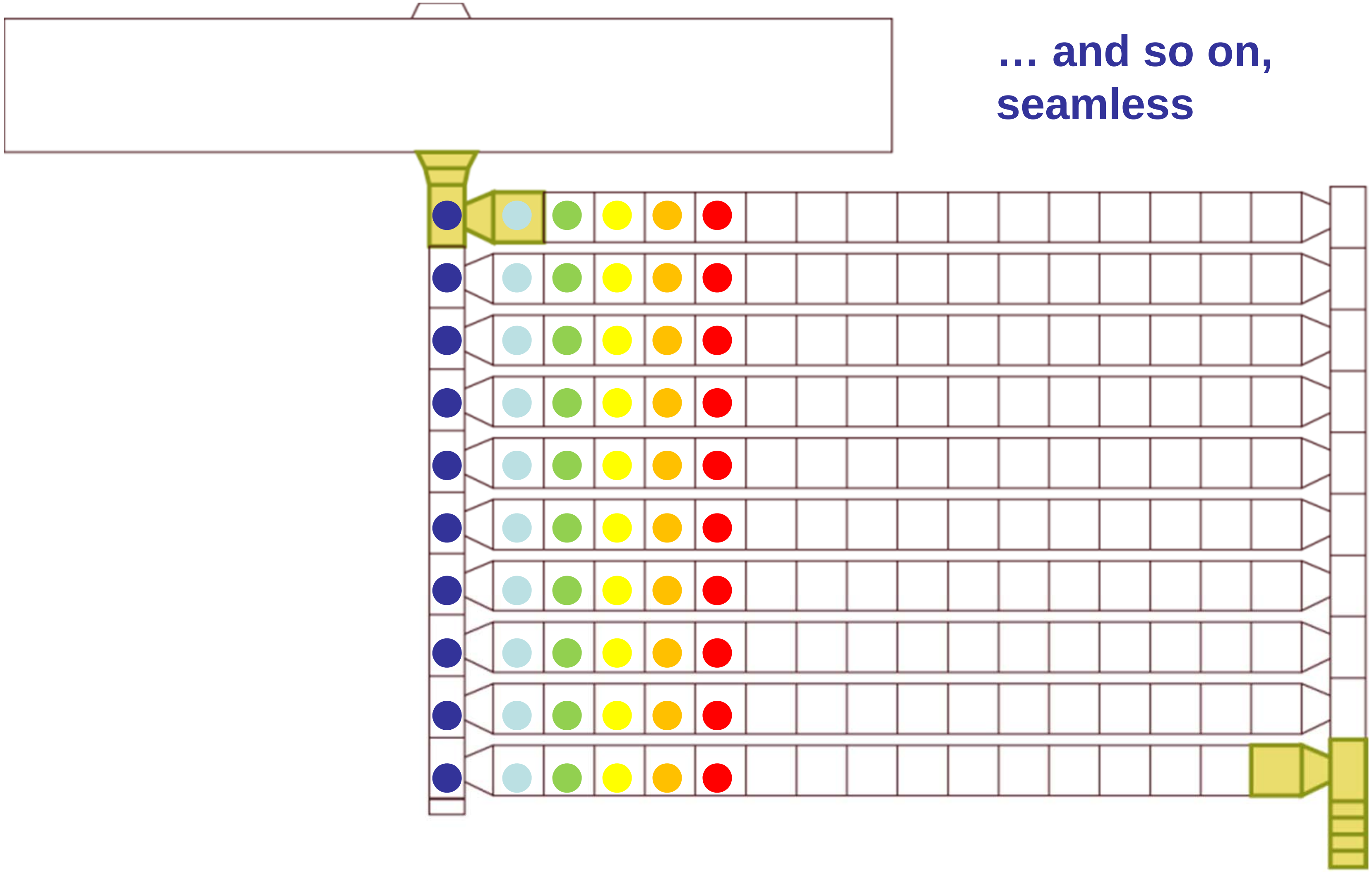
Burst mode



... and so on, seamless

Science & Technology Facilities Council Technology

Burst mode

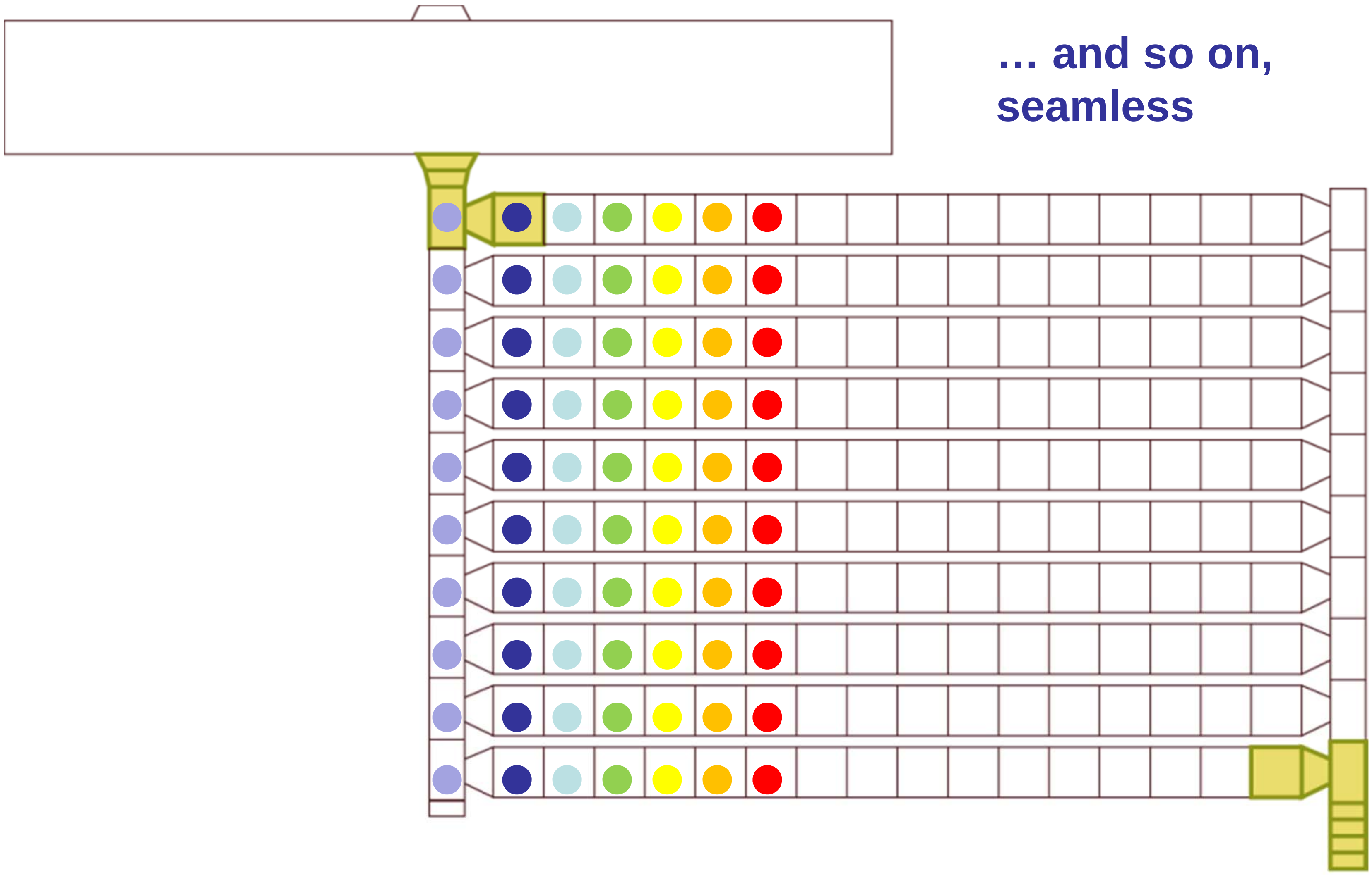


… and so on, seamless

Science & Technology Facilities Council Technology

Burst mode

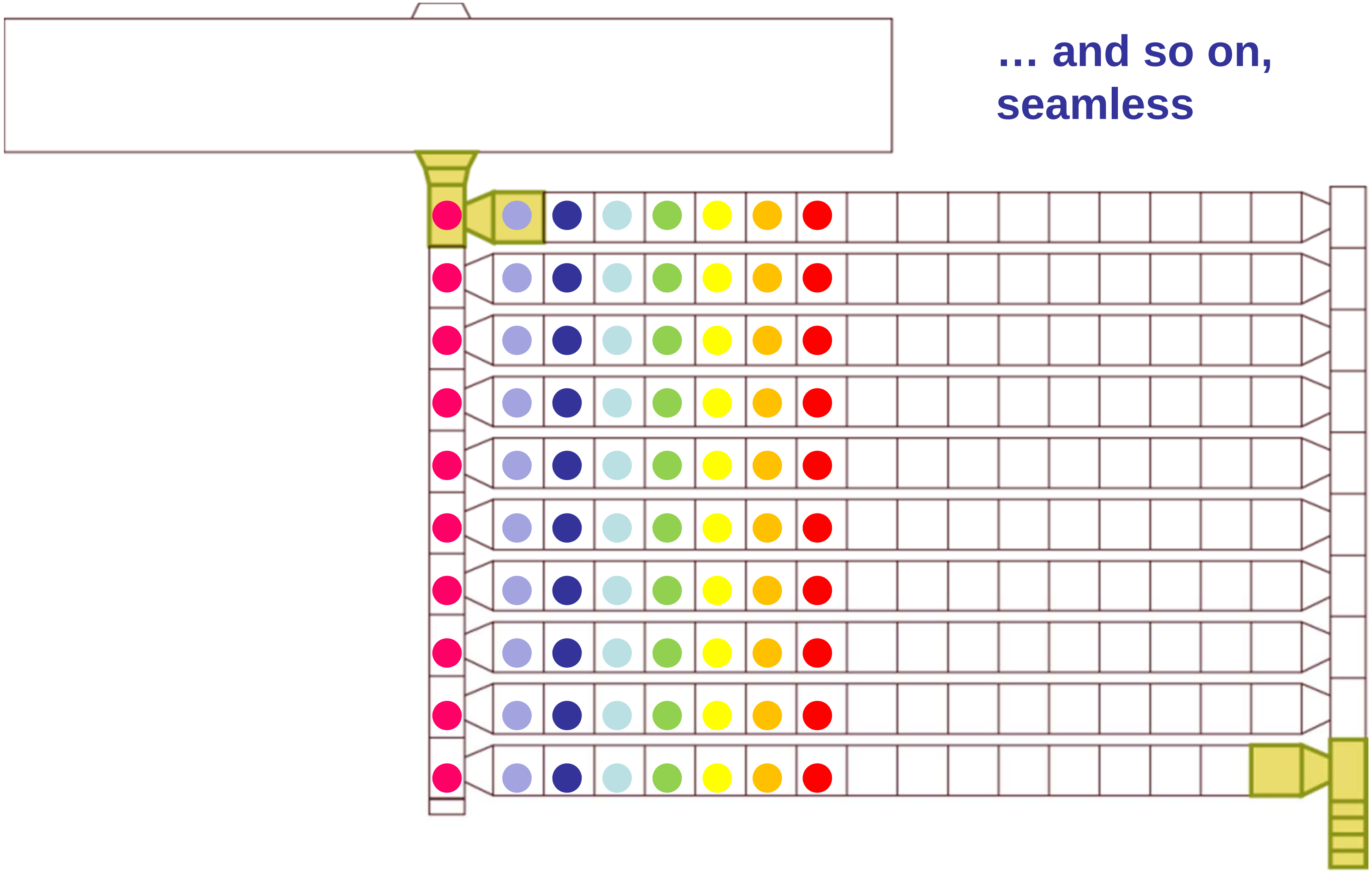
... and so on, seamless



Science & Technology Facilities Council
Technology

Burst mode

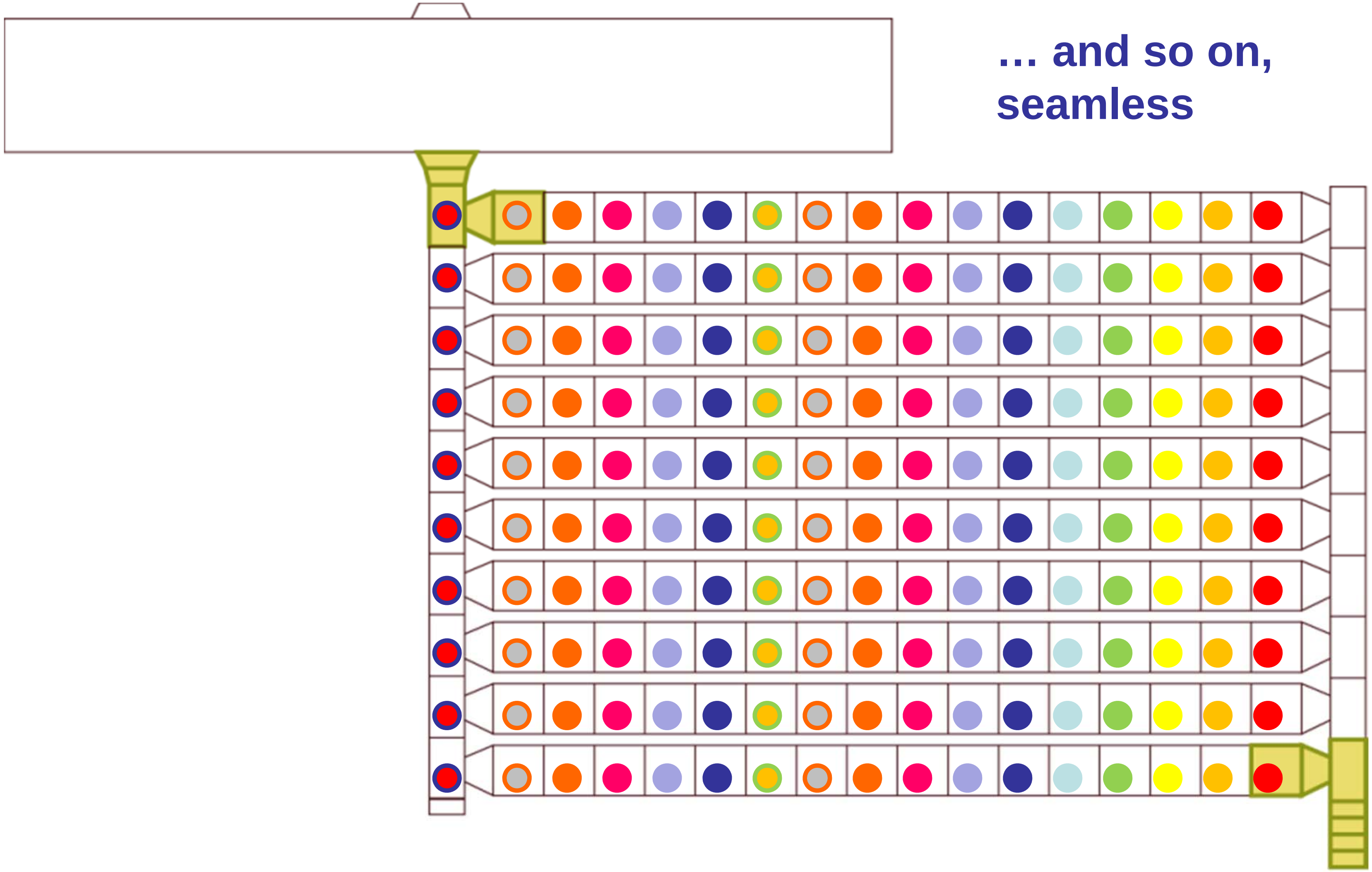
… and so on,
seamless



Science & Technology Facilities Council Technology

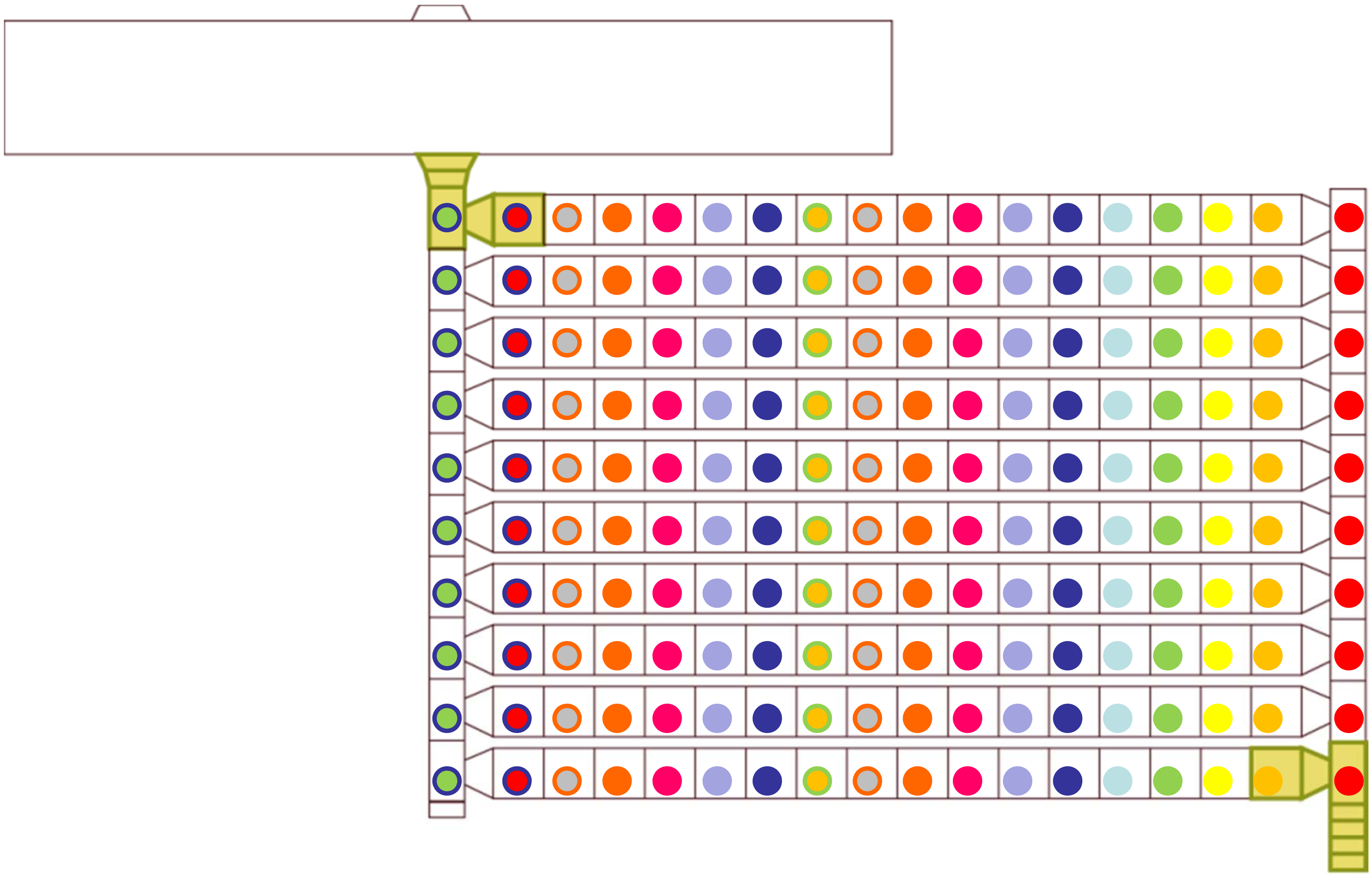
Burst mode

… and so on, seamless



Science & Technology Facilities Council
Technology

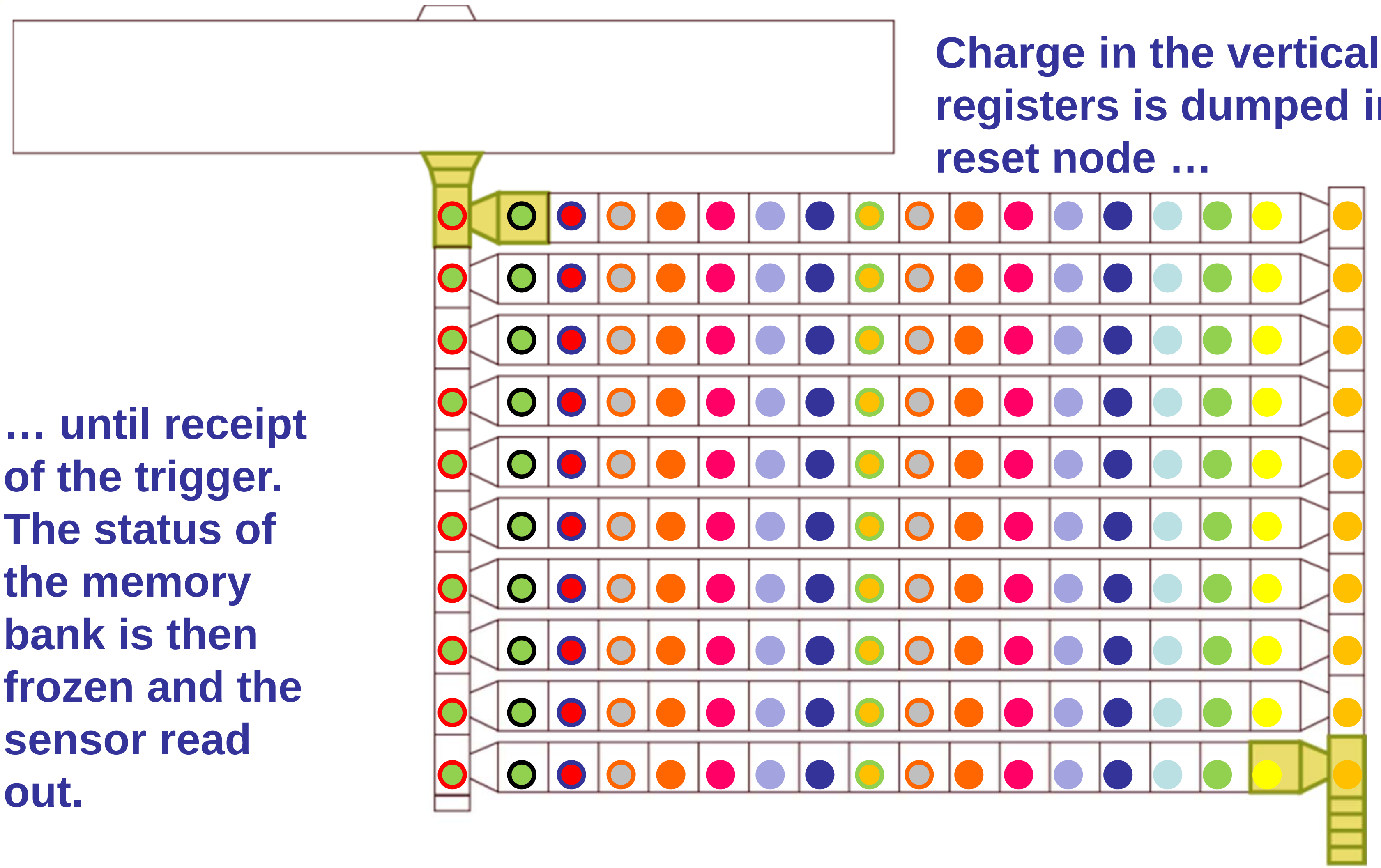
Burst mode



Science & Technology Facilities Council Technology

Burst mode

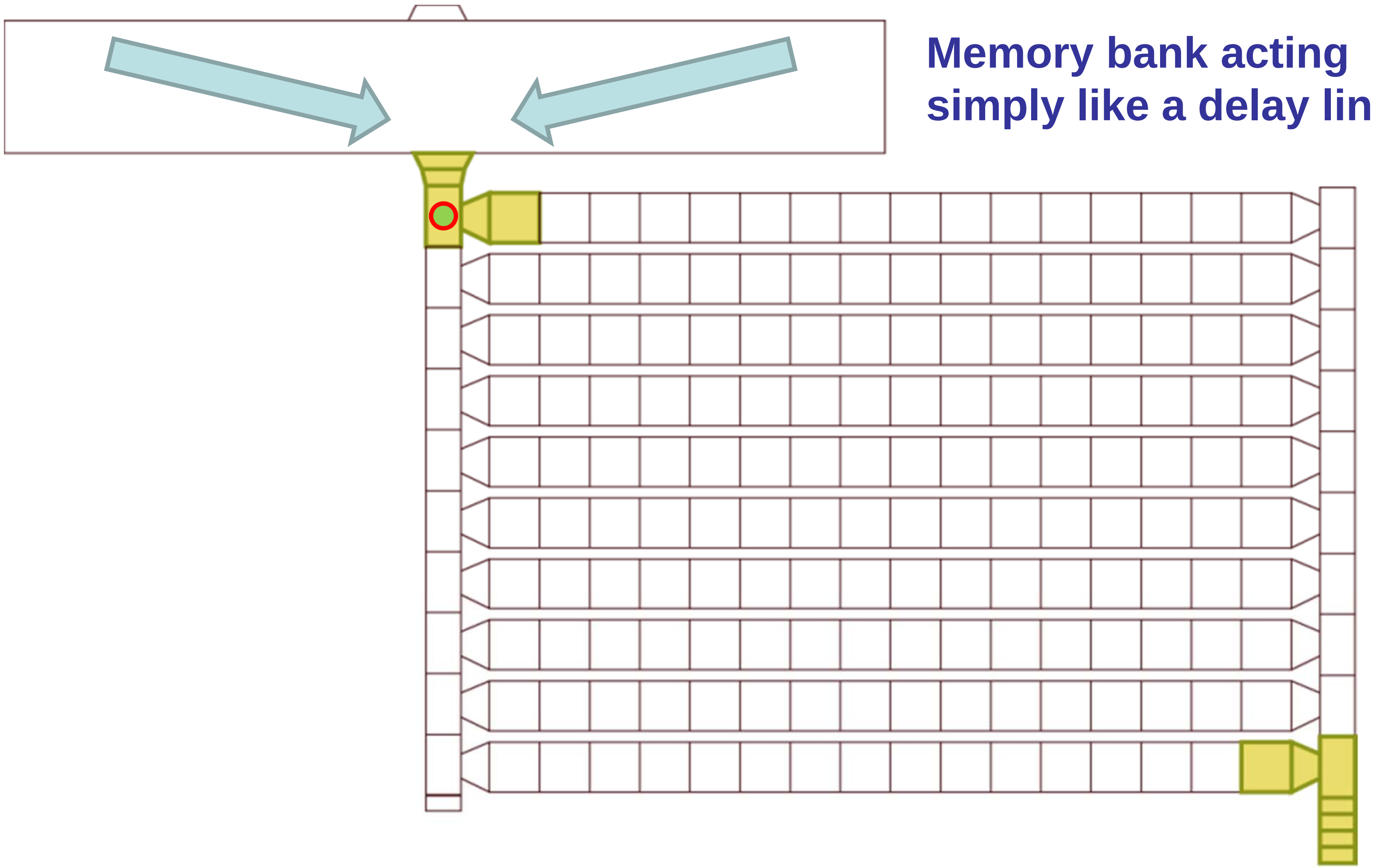
Charge in the vertical exit registers is dumped in the reset node …



… until receipt of the trigger. The status of the memory bank is then frozen and the sensor read out.

Science & Technology Facilities Council
Technology

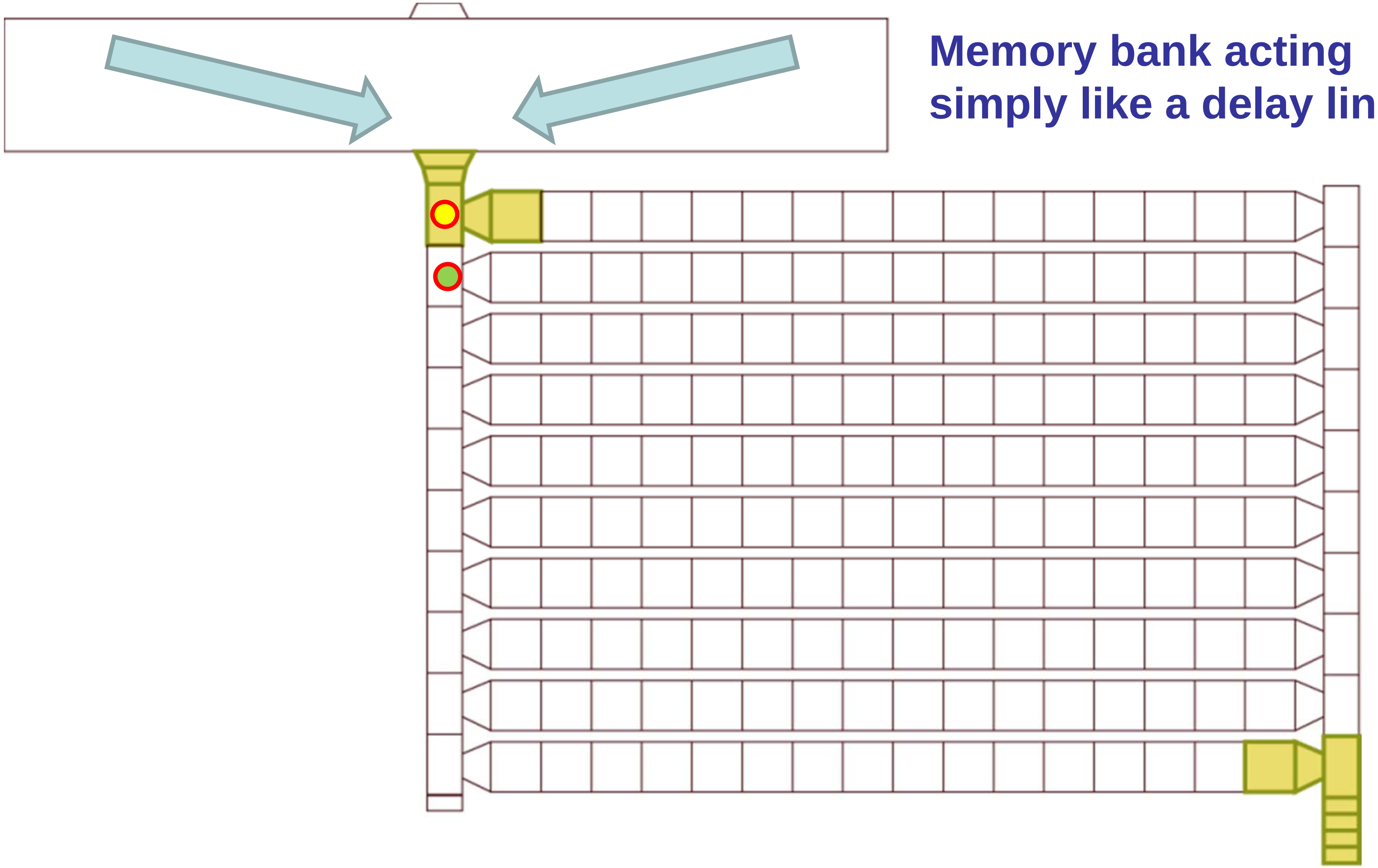
Continuous mode



Memory bank acting simply like a delay line

Science & Technology Facilities Council
Technology

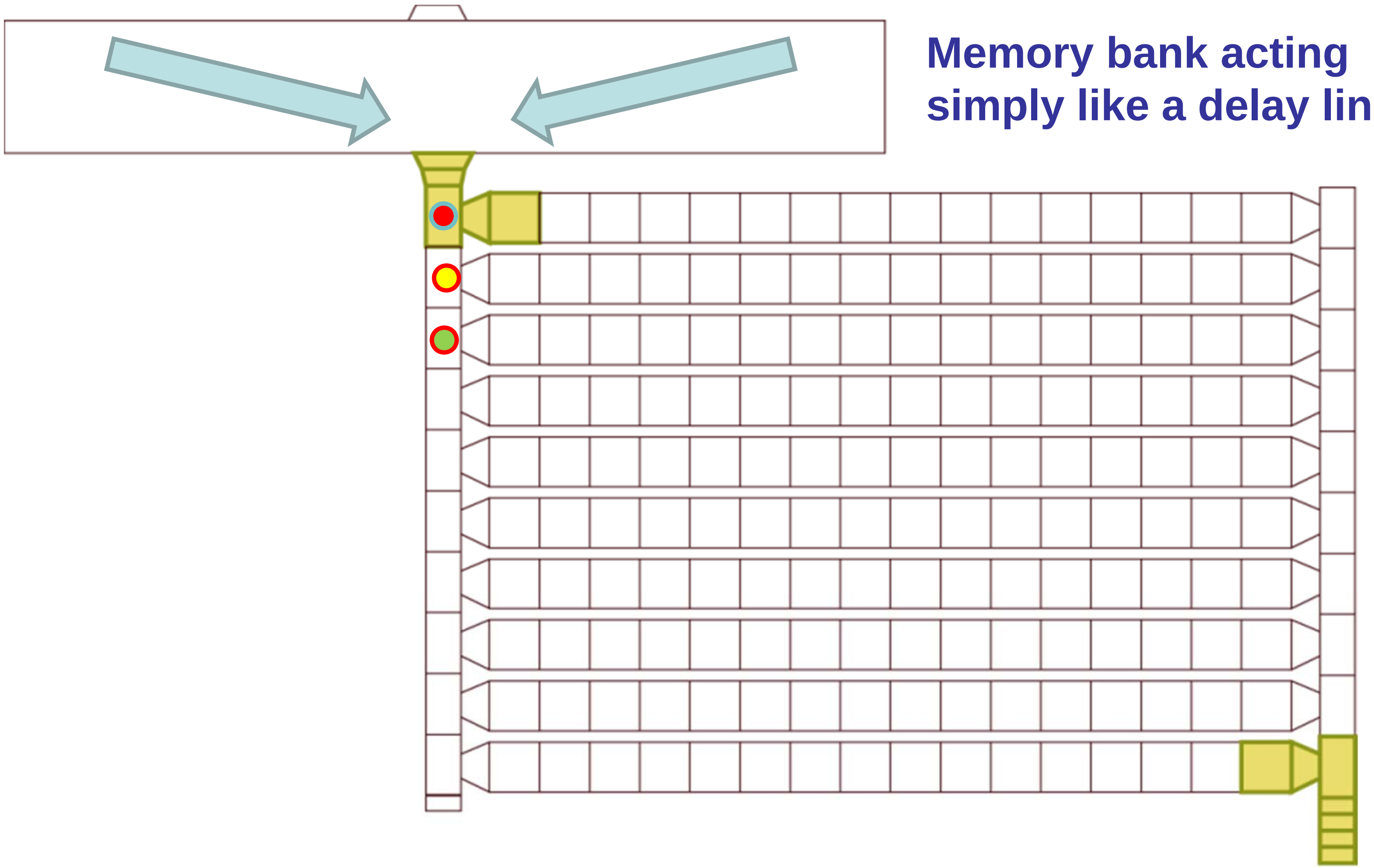
Continuous mode



Memory bank acting simply like a delay line

Science & Technology Facilities Council
Technology

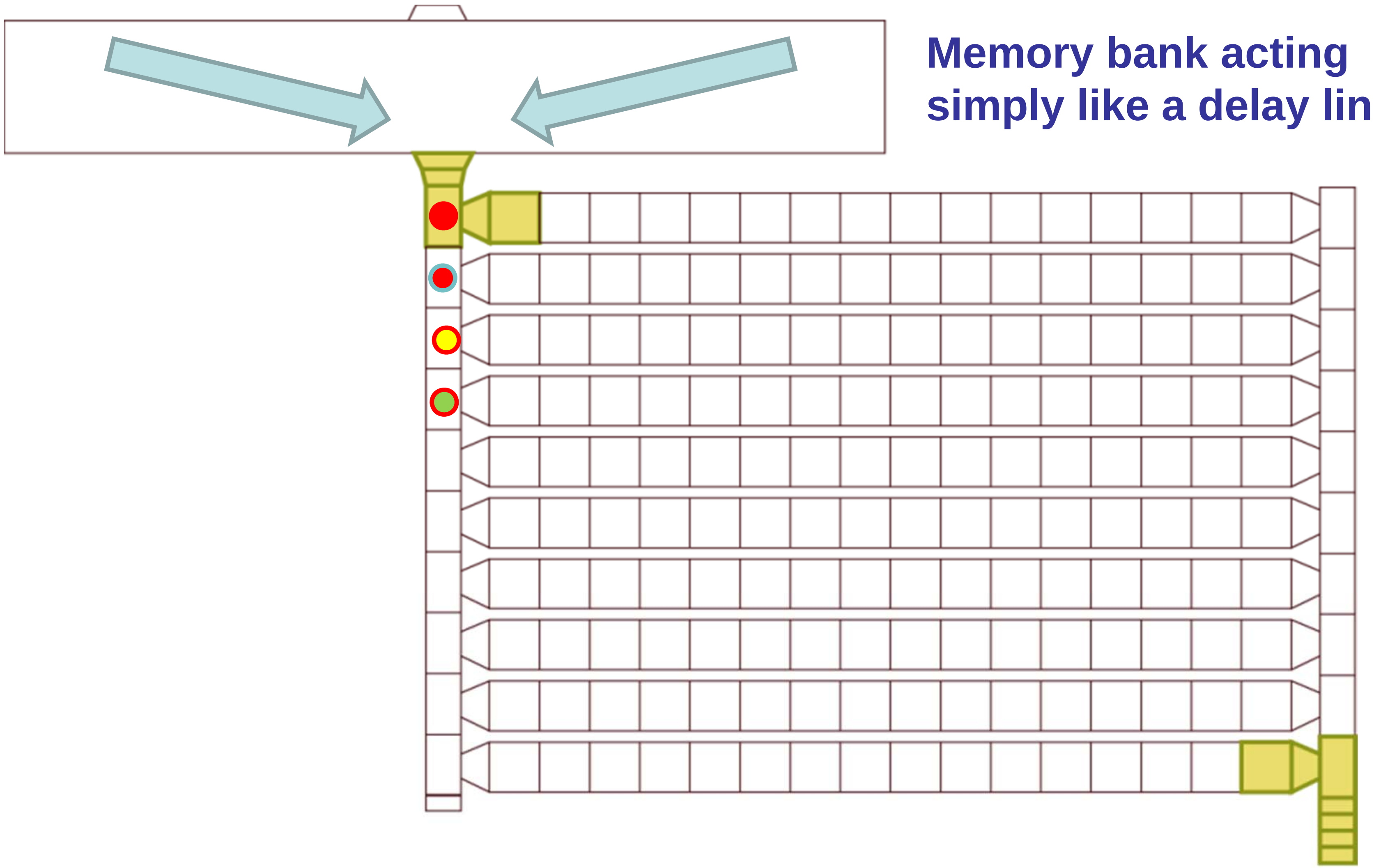
Continuous mode



Memory bank acting simply like a delay line

Science & Technology Facilities Council Technology

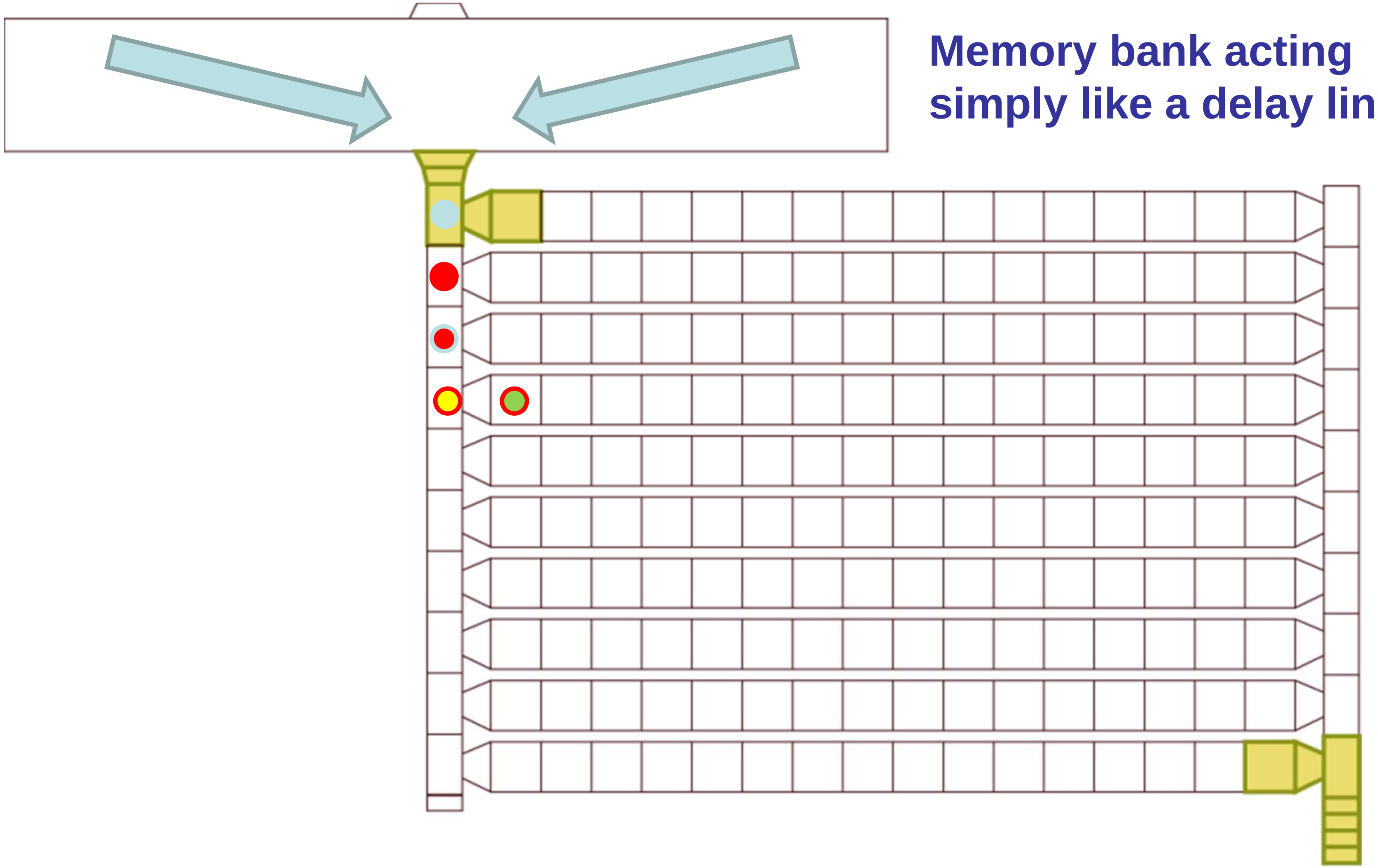
Continuous mode



Memory bank acting simply like a delay line

Science & Technology Facilities Council
Technology

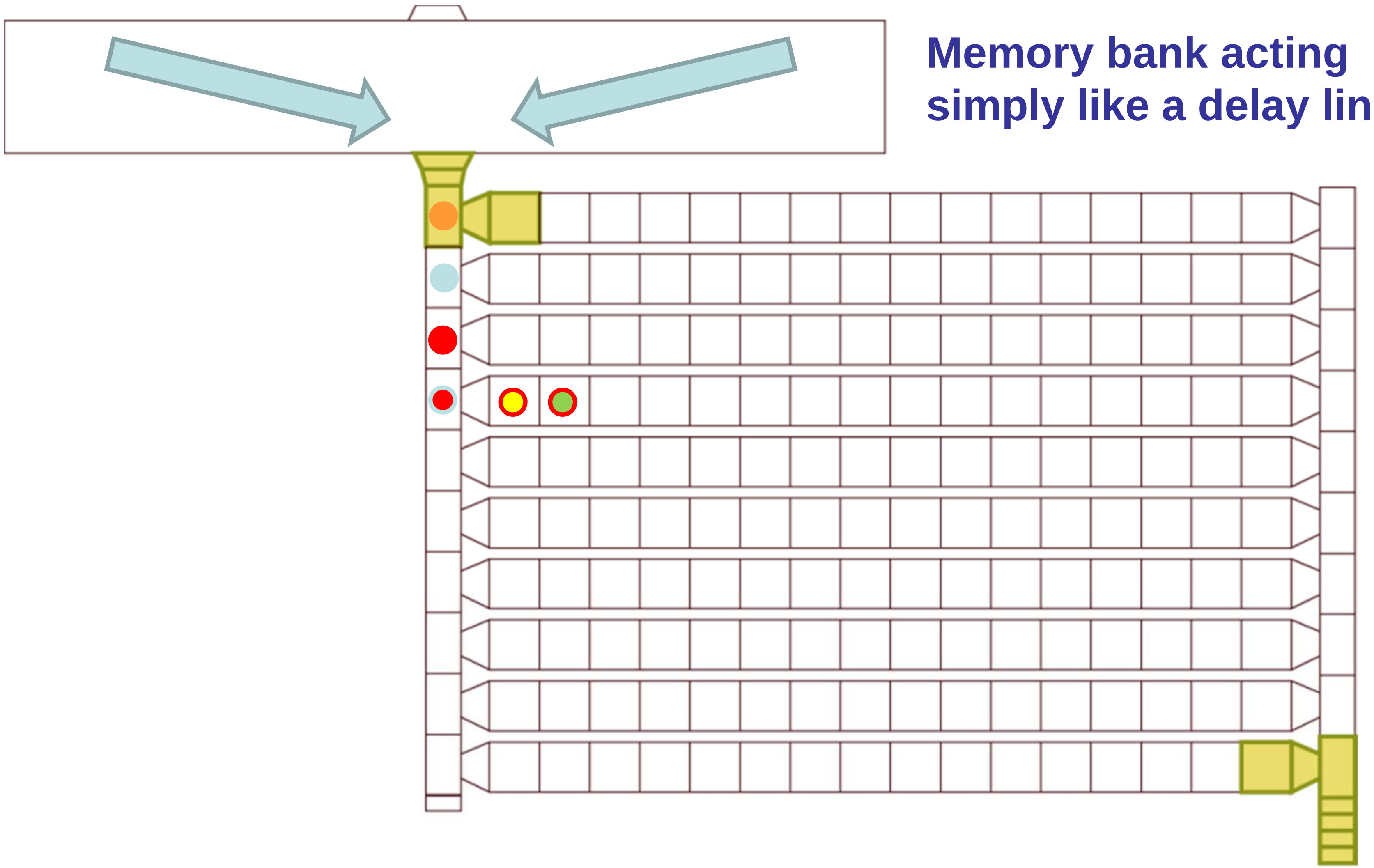
Continuous mode



Memory bank acting simply like a delay line

Science & Technology Facilities Council Technology

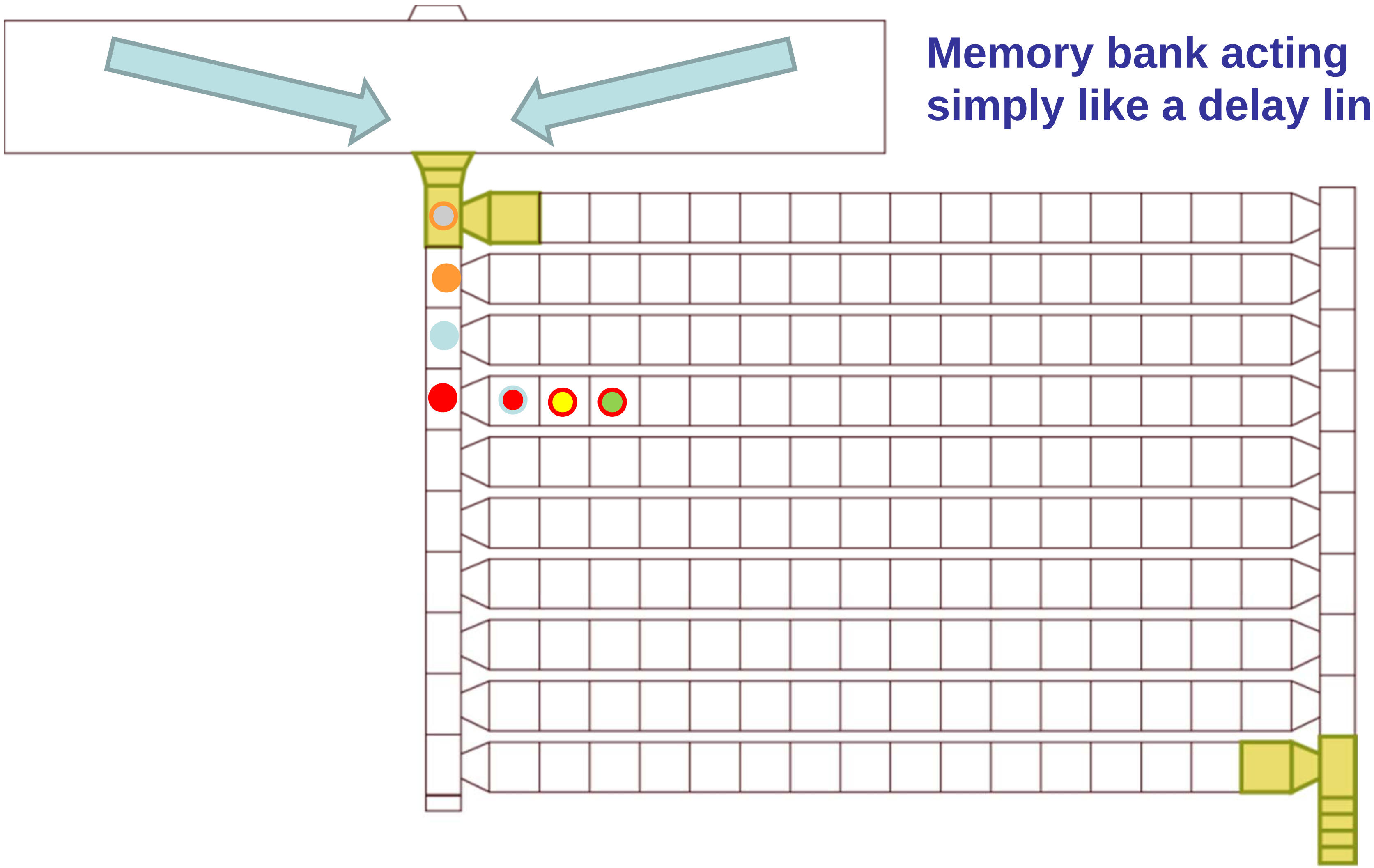
Continuous mode



Memory bank acting simply like a delay line

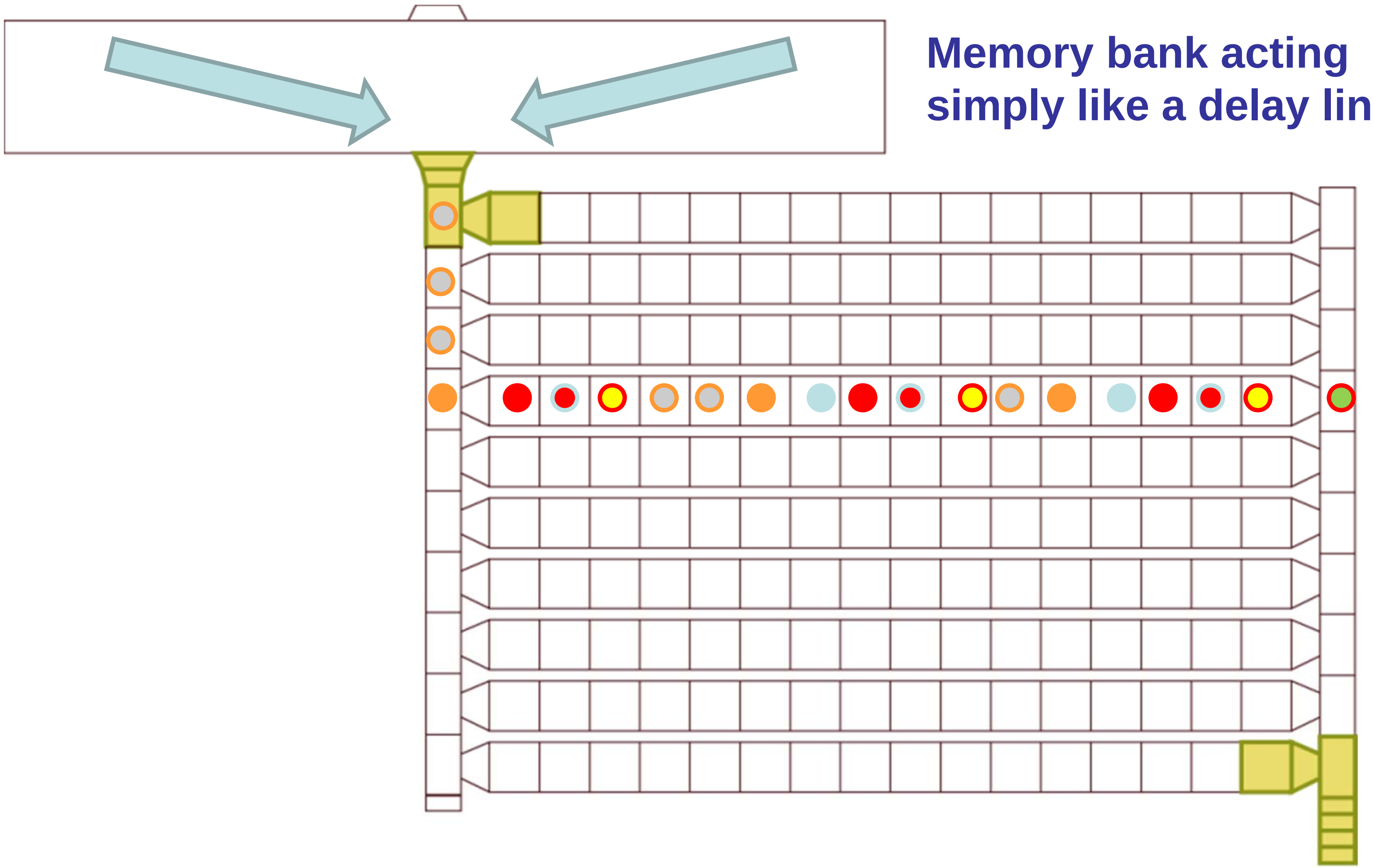
Science & Technology Facilities Council
Technology

Continuous mode



Memory bank acting simply like a delay line

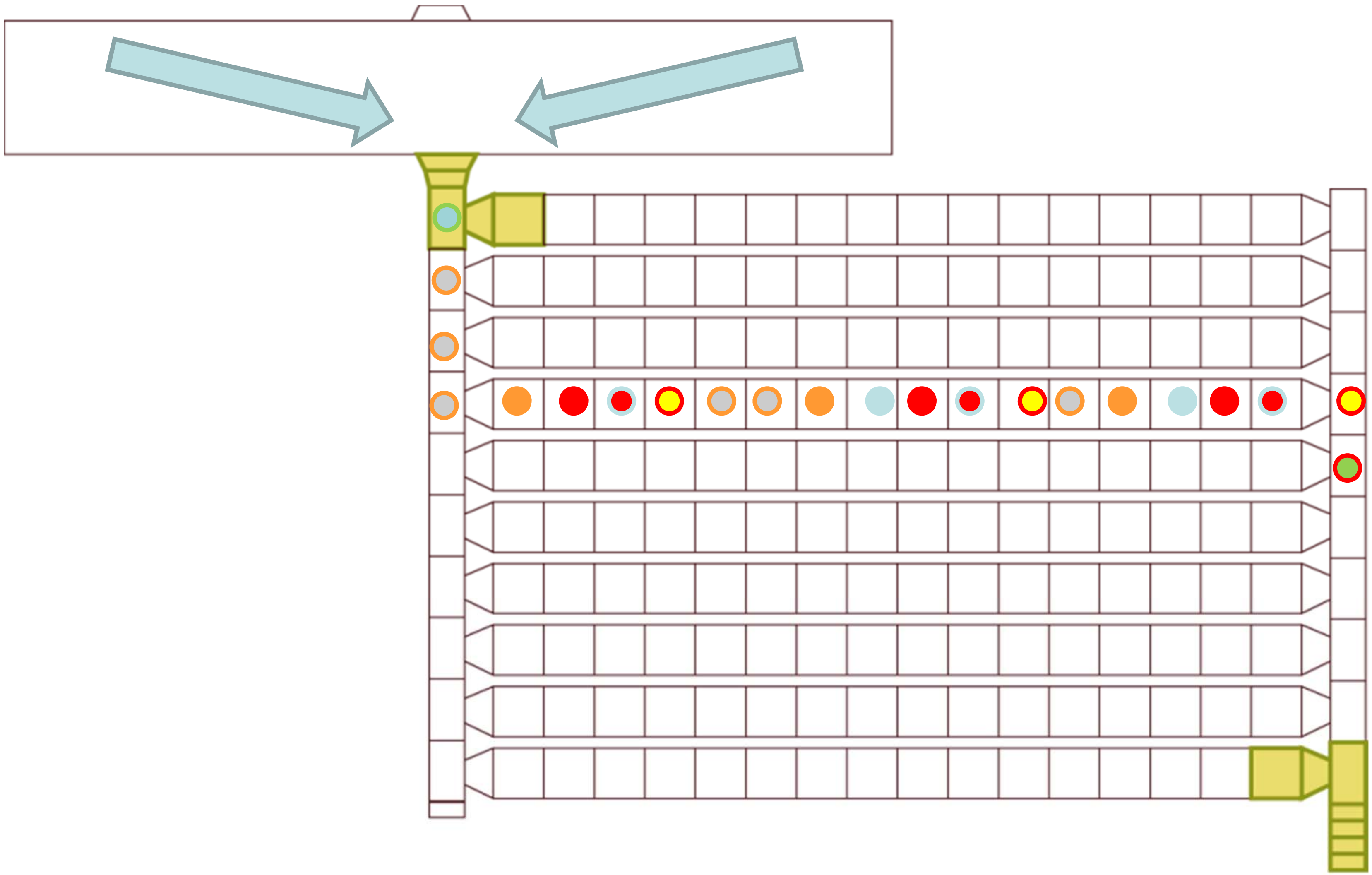
Continuous mode



Memory bank acting simply like a delay line

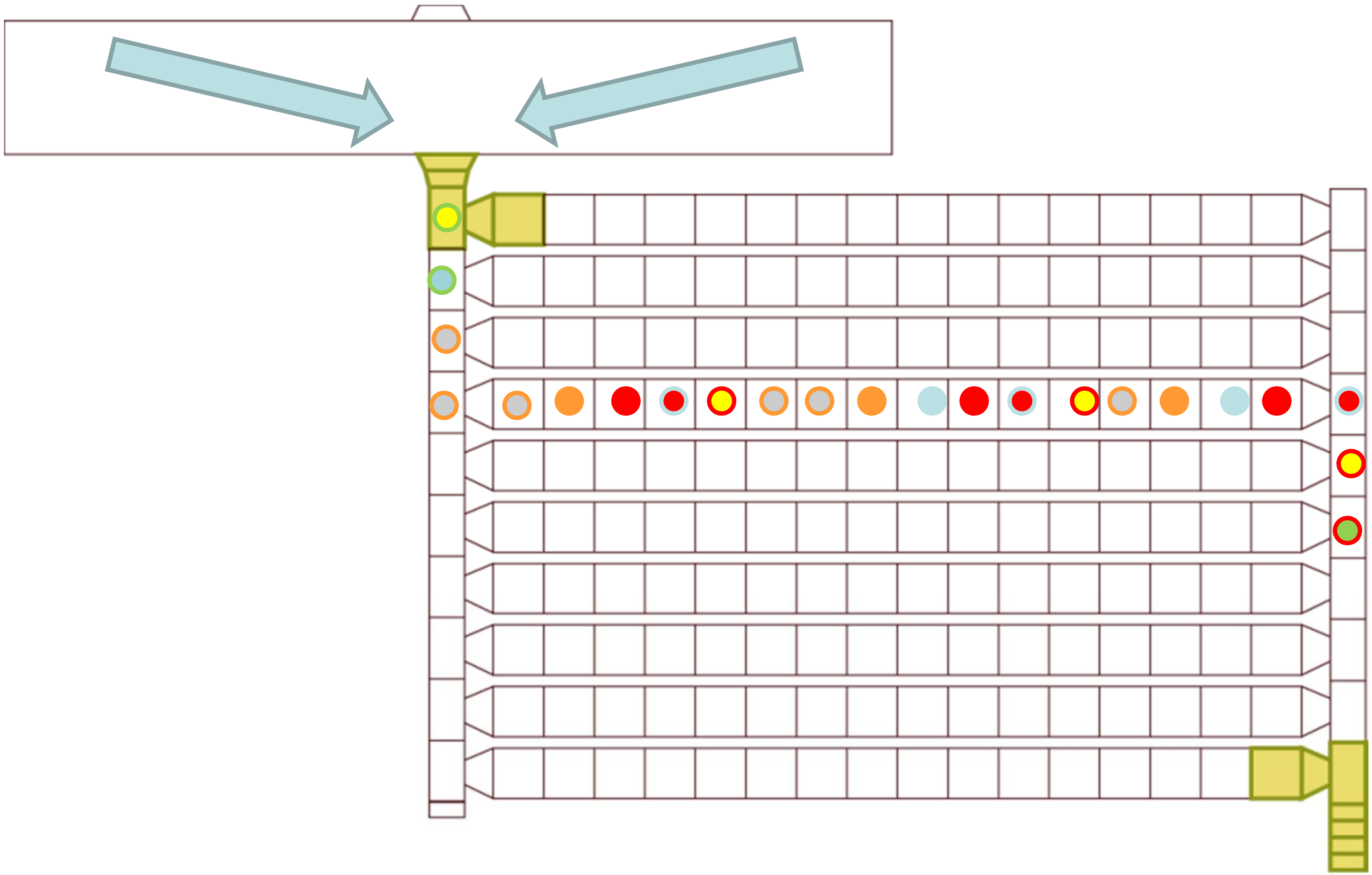
Science & Technology Facilities Council Technology

Continuous mode



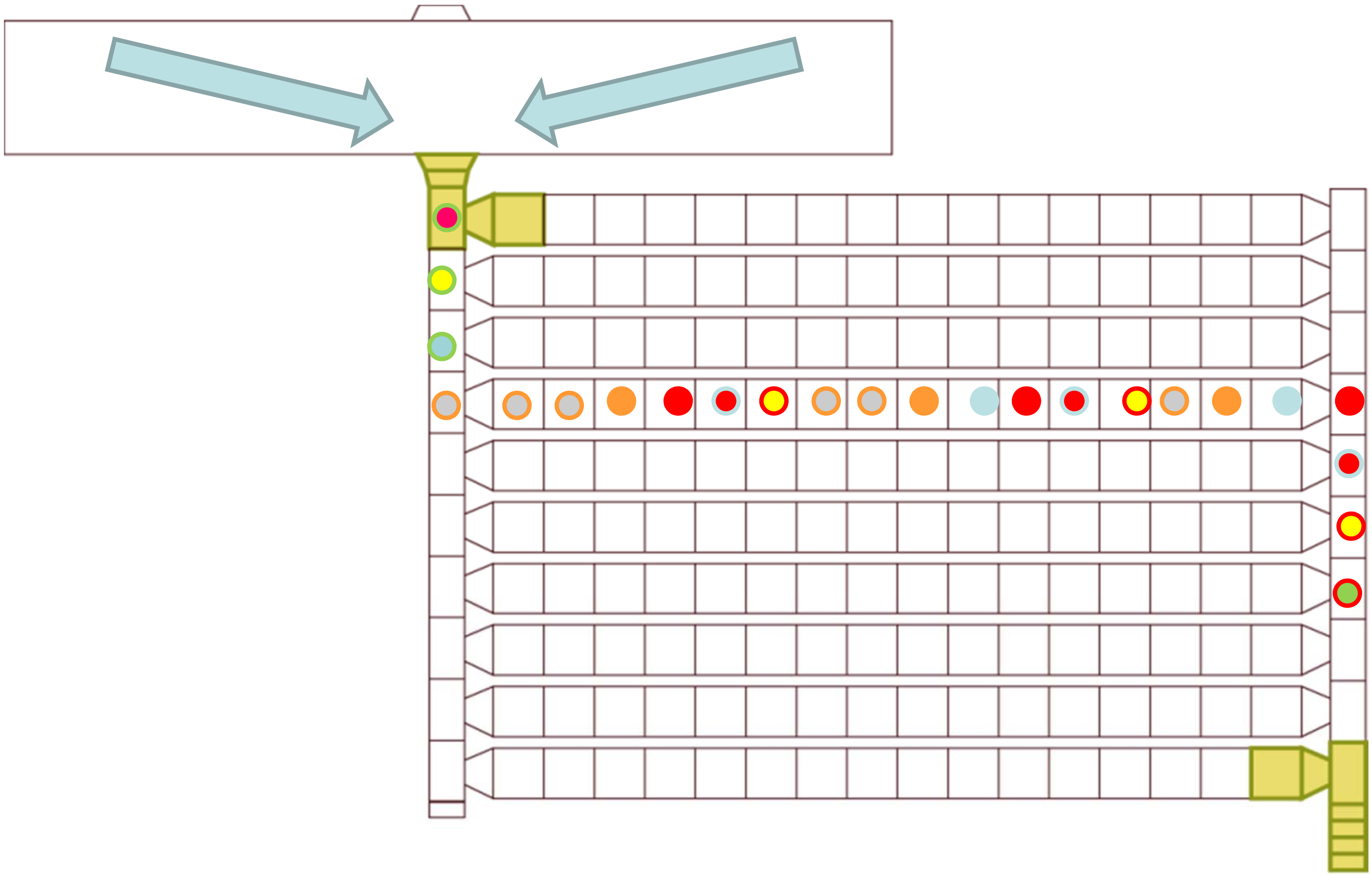
Science & Technology Facilities Council
Technology

Continuous mode



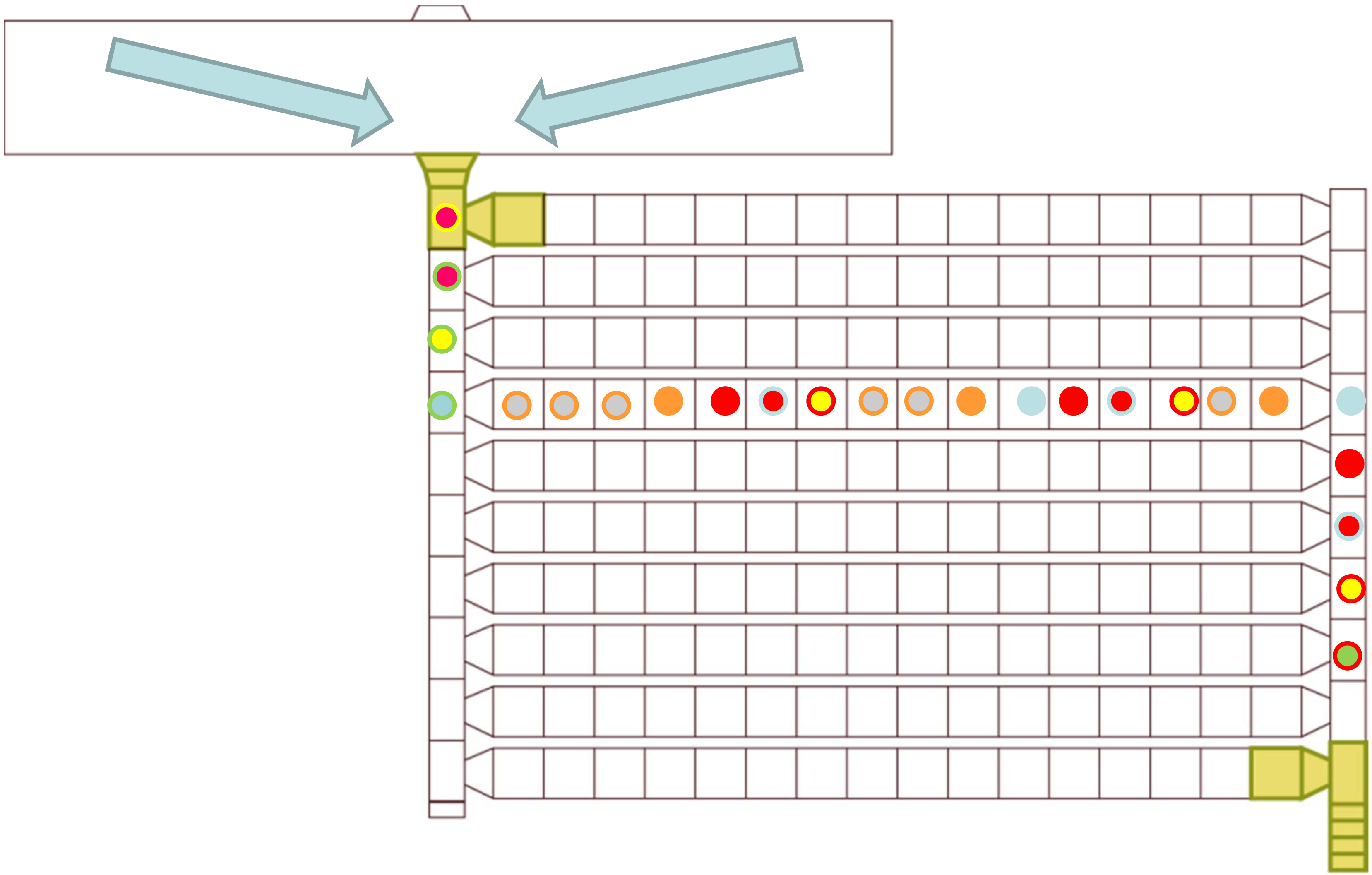
Science & Technology Facilities Council Technology

Continuous mode



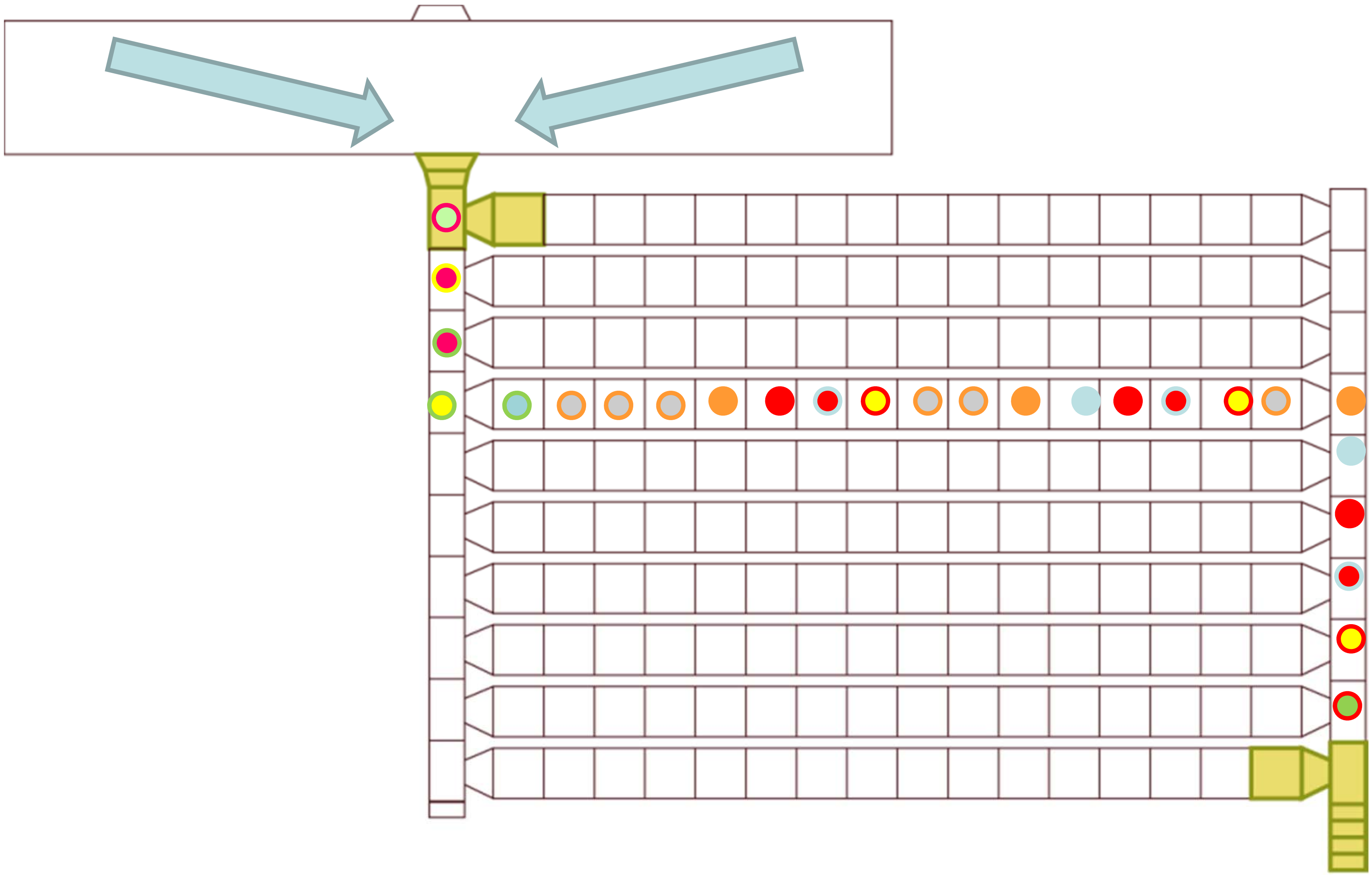
Science & Technology Facilities Council Technology

Continuous mode



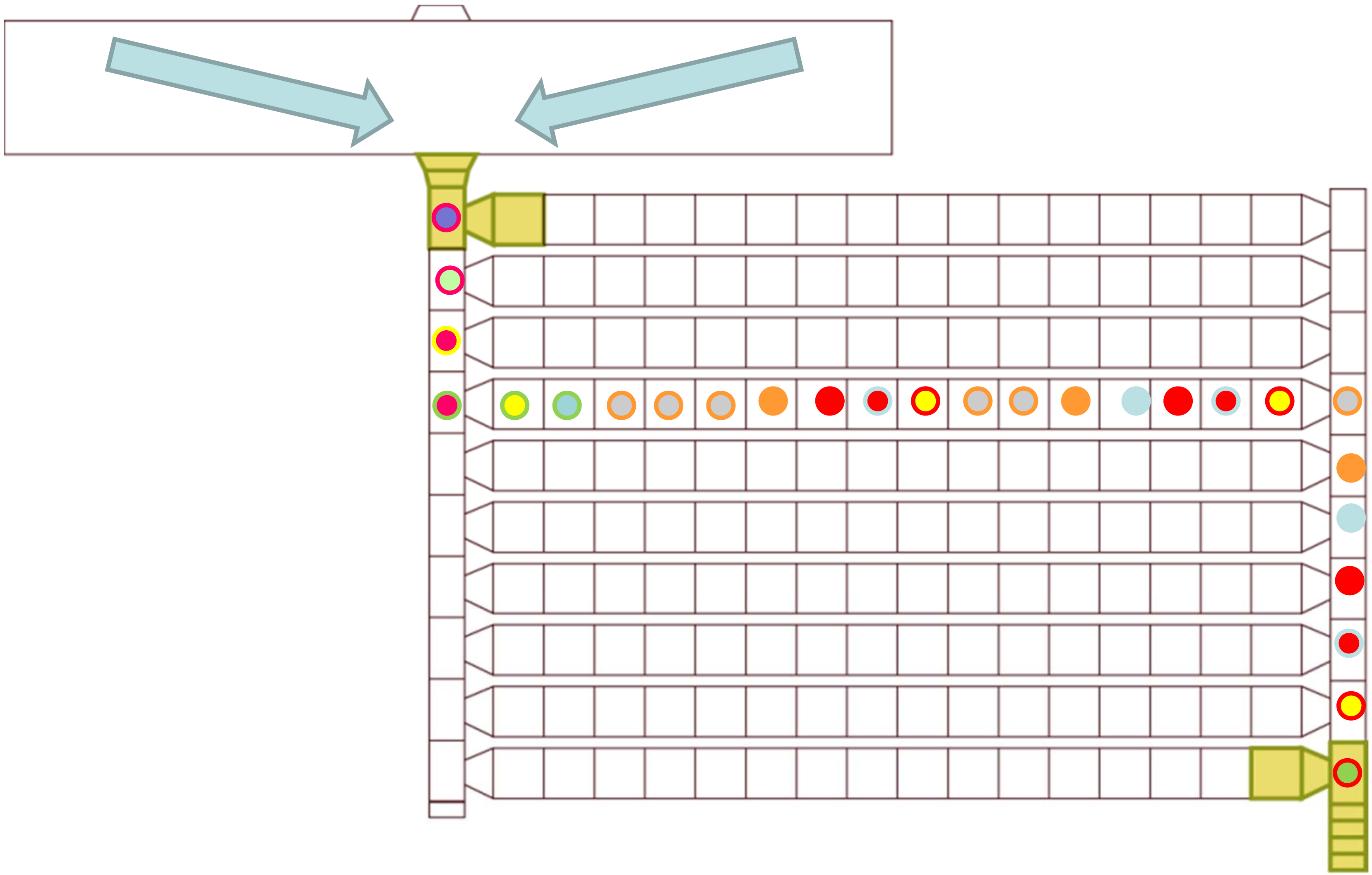
Science & Technology Facilities Council
Technology

Continuous mode

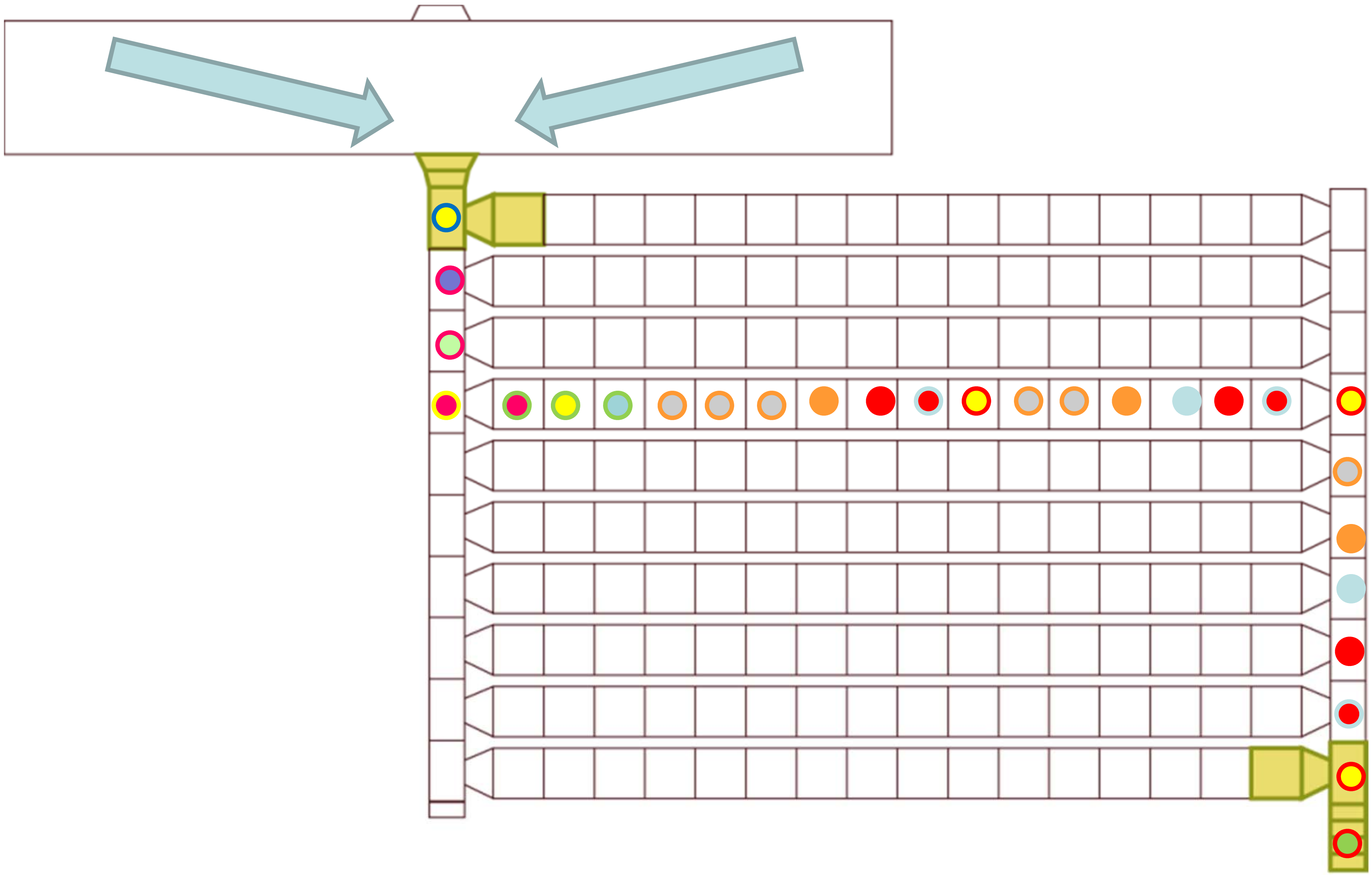


Science & Technology Facilities Council Technology

Continuous mode



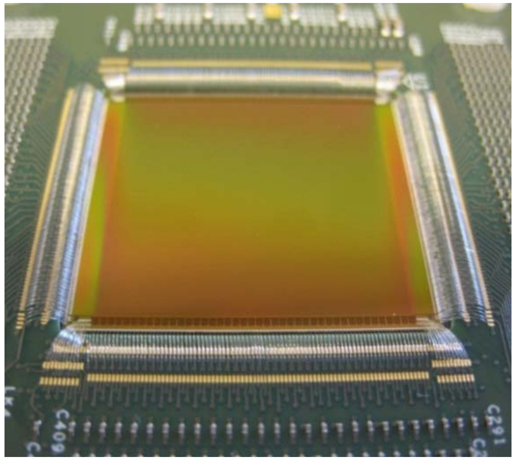
Continuous mode



Science & Technology Facilities Council Technology

Performance summary

Parameter	Unit	Value
Pixel pitch (X)	um	30
Pixel pitch (Y)	um	30
Pixel format (X)		924
Pixel format (Y)		768
Number of pixels		709,632
Frame rate (burst mode)	fps	5,000,000
Frame rate (continuous mode)	fps	1,180
Pixel rate (burst mode)	Pixel/sec	1.42 T
Pixel rate (continuous mode)	Pixel/sec	0.84 G
Noise	e- rms	<10 e- rms
Full well capacity	e-	11,700
Camera gain	µV/e-	80
Dynamic range		>1,170
	dB	61.4
	bit	10.2
Fill Factor		11%
Quantum efficiency	Without microlens	2.3% (red) 2.2% (blue)



Science & Technology Facilities Council
Technology

Imaging examples

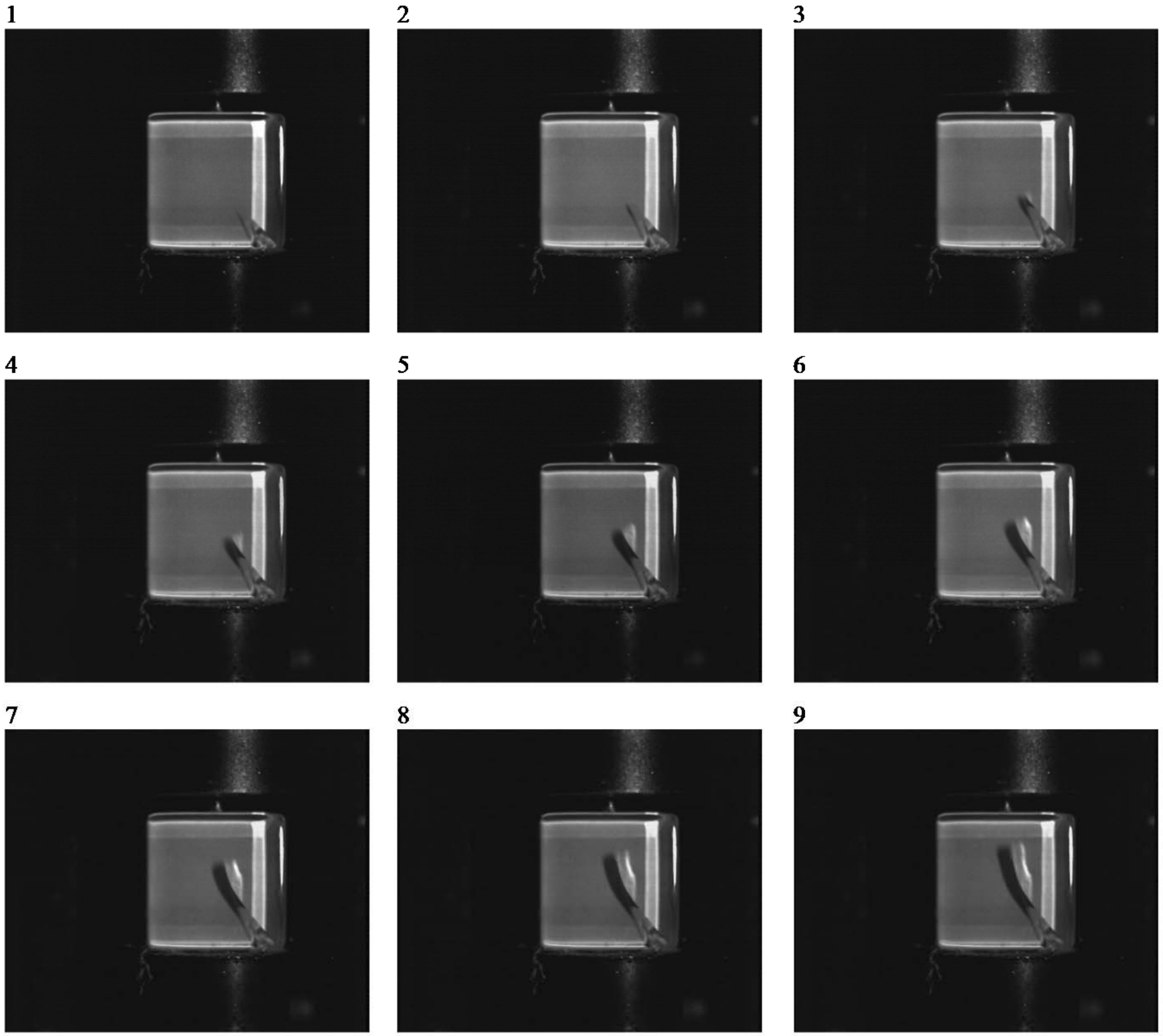


Figure 1: Consecutive images from a 1Mhz burst acquisition: Crack propagating through a glass tile at ~1km/sec

Science & Technology Facilities Council Technology

Conclusions.

… and also sensors for: ESA miniaturised radiation monitor, particle physics, neutron detection, high-energy X-ray detection, SPAD …

Demanding specifications from scientific instruments driving innovation → delivering to industry as well

Working to deliver optimal solutions: design, technology, post-processing, manufacturing, …

‘Dreaming is mandatory’ (*H. Graasfma*, yesterday) …

We can help you make your dreams reality