OPTima

Loma Linda 6th Annual Workshop – 20 July 2020

: Coping with more protons than you really need!

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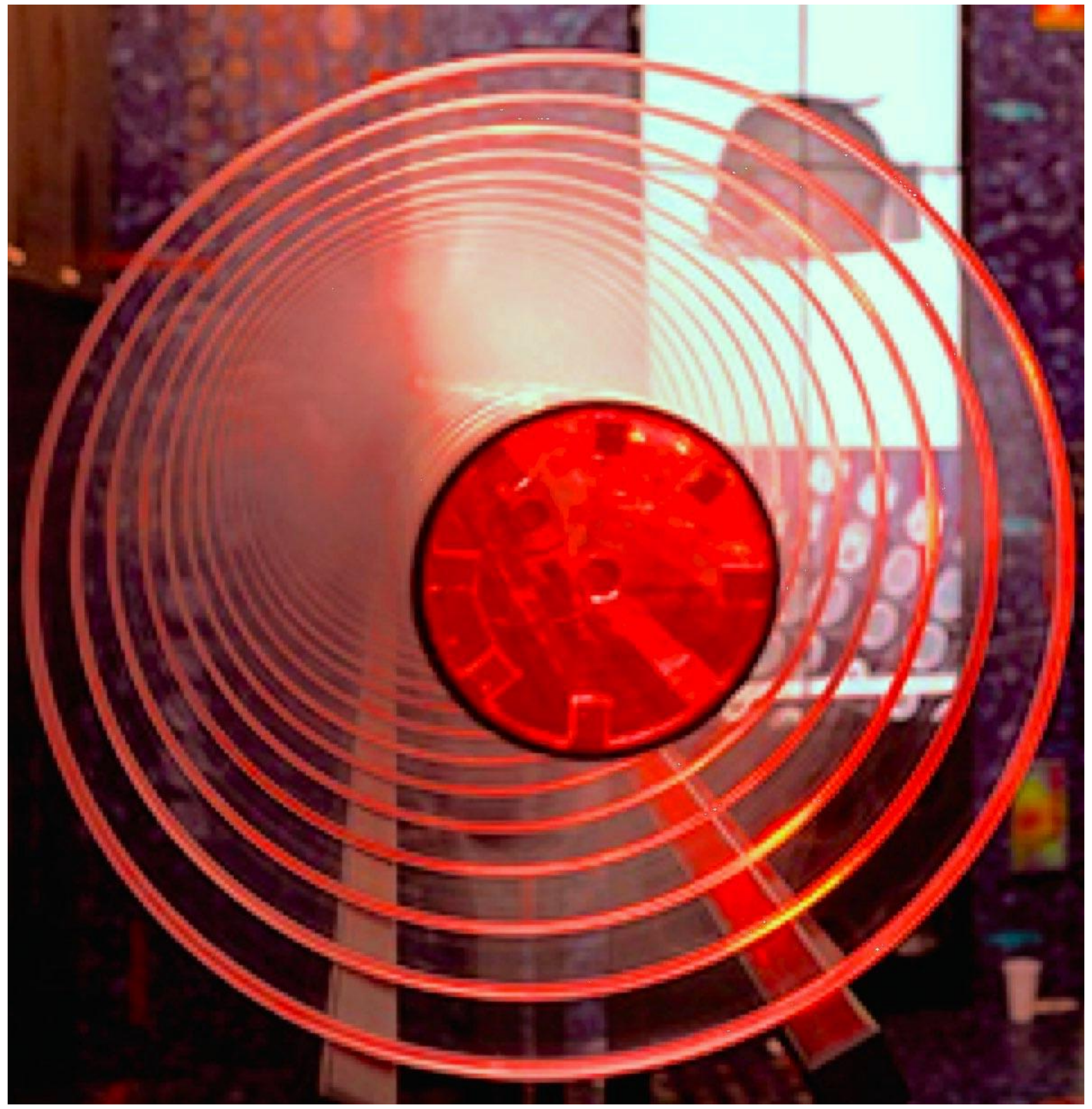
EPSRC
Engineering and Physical Sciences Research Council

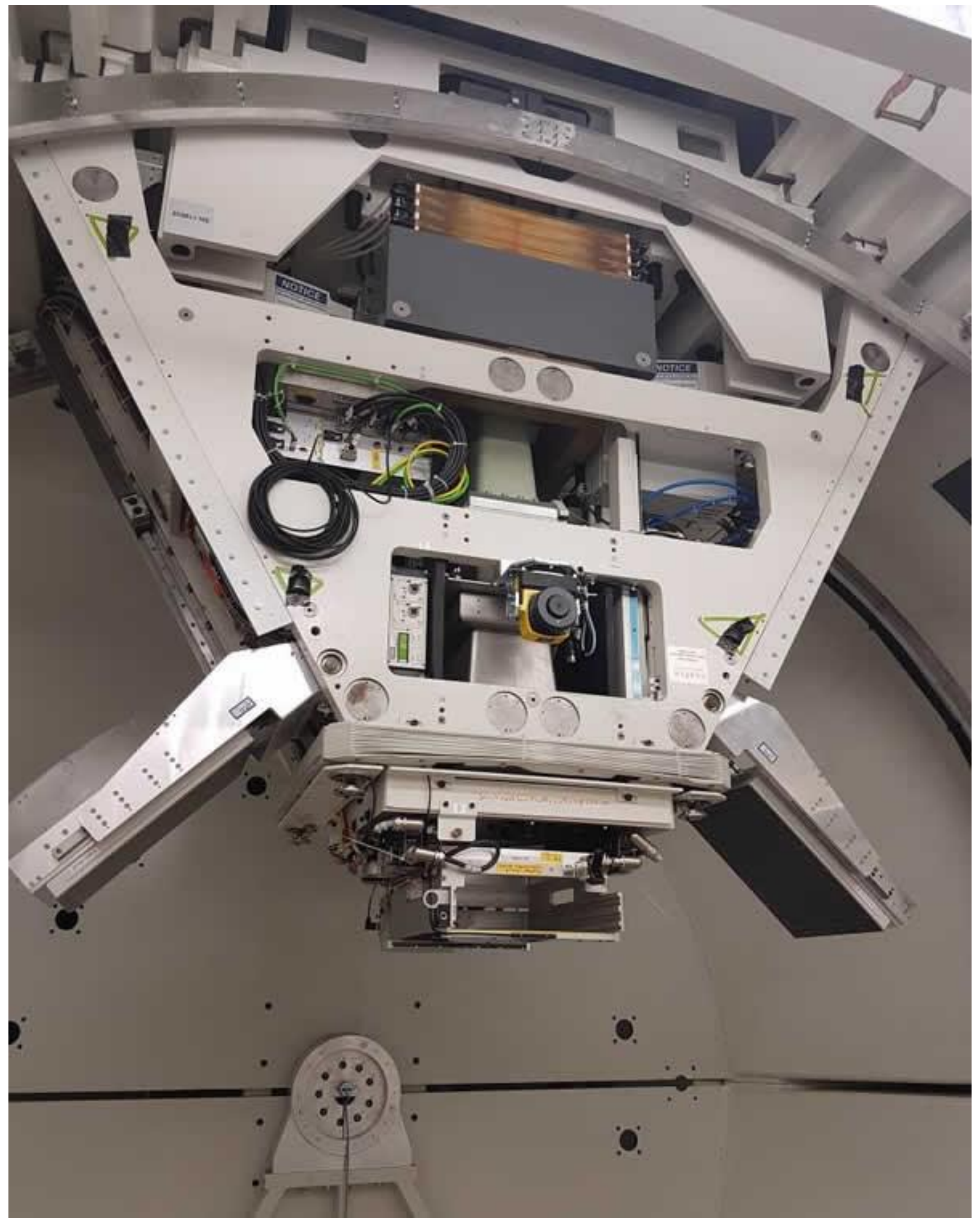
UNIVERSITY OF LINCOLN

: **Nigel Allinson:** **on behalf of the whole team**



Practical min. beam current ~ 10 pA

Practical max. spot diameter ~ few cm. & spot velocity ~ 10 ms^{-1}

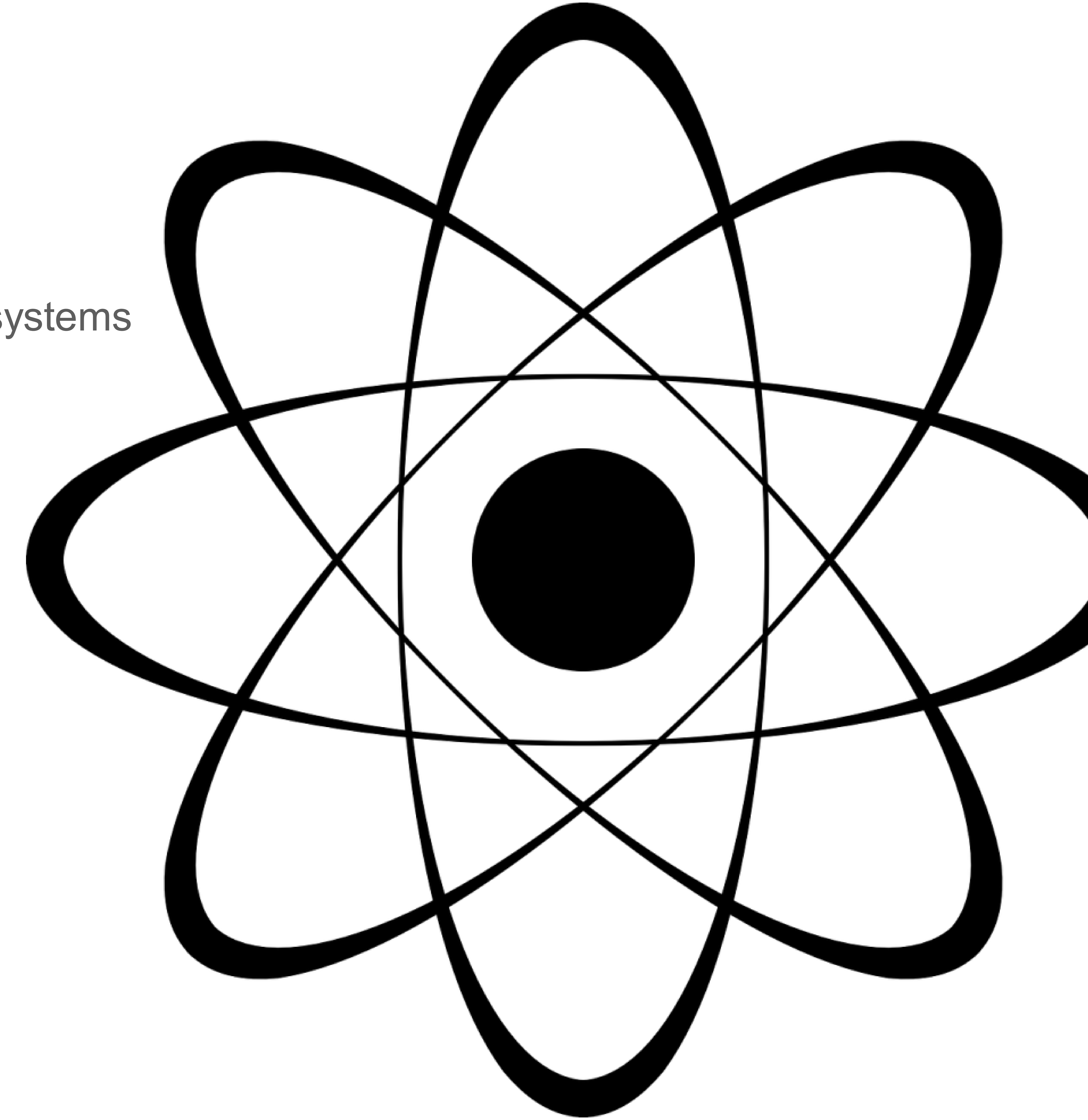


OPTima

- Operate on current/future pencil scanning delivery systems
- Operate with normal operational envelope
- Integrate with wide range of facilities
- Integrate with clinical workflows
- Provide final RSP to within 0.5% accuracy
- Route to gantry installation
- Recognise new treatment modes

Today

- Focus on design philosophy
- Synchronisation
- Tracker design



Practical Minimum Beam Currents

Christie PBT Centre

3 pA @70 MeV
10 pA @100 MeV
250 pA @230 MeV
Additional collimator in Research Room to allow 10 pA at 230 MeV

PSI Center for Proton Therapy

1 pA across full range of energy
0.37 pA measured @ 230 MeV

Also need to switch easily between treatment and imaging modes

Compromise – choose 10 pA (11.4 pA = one proton on average per pulse at 72 MHz)

Protons per bunch obey a Poisson distribution

About 1/3 empty, about 1/3 contain one proton, about 1/3 contain 2 or more protons

So need to design for more than one proton in the instrument at one time

k	$P(k)$
0	0.368
1	0.368
2	0.184
3	0.061
4	0.015

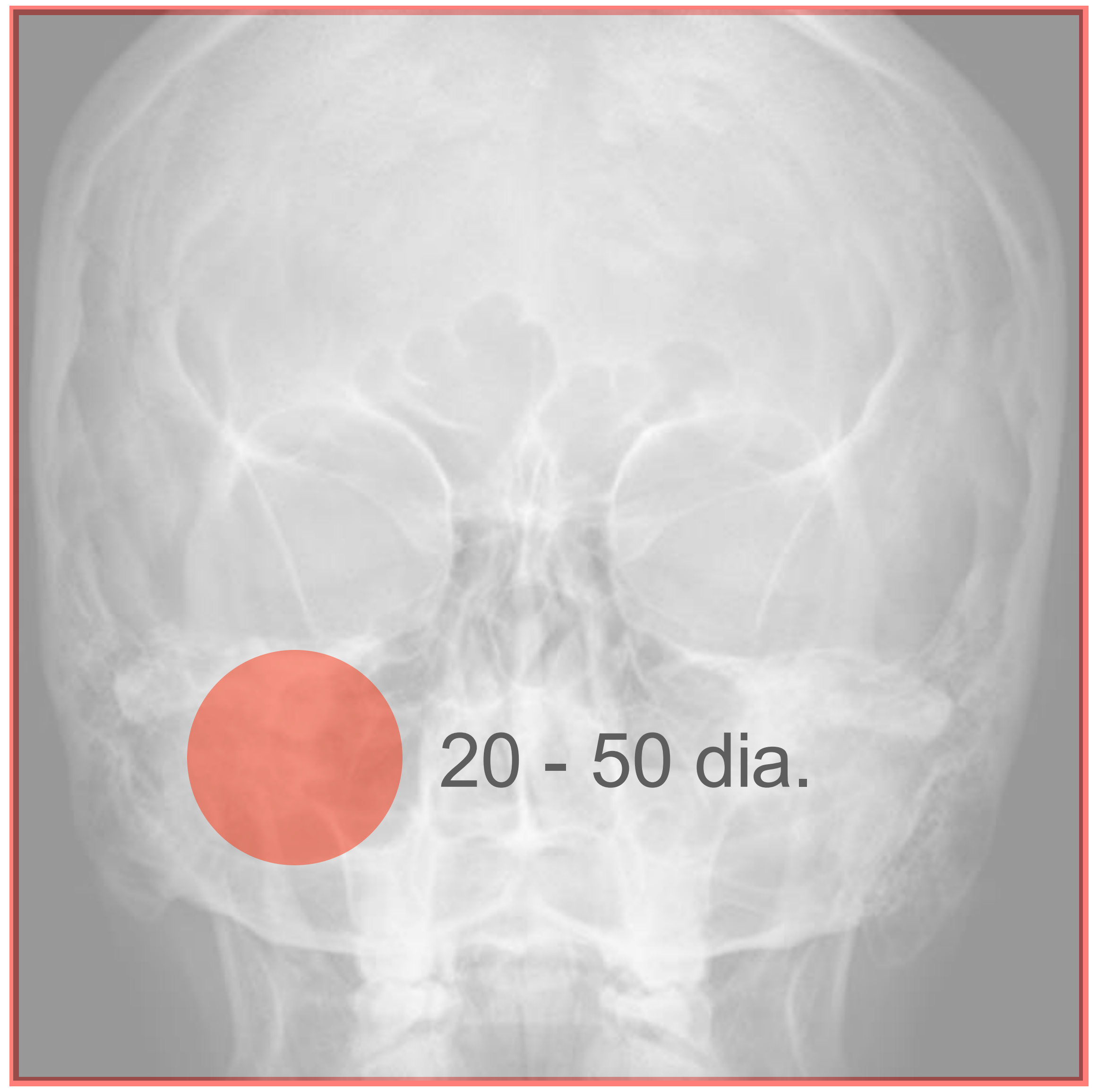
All dimensions in mm

Practical Maximum Spot Sizes

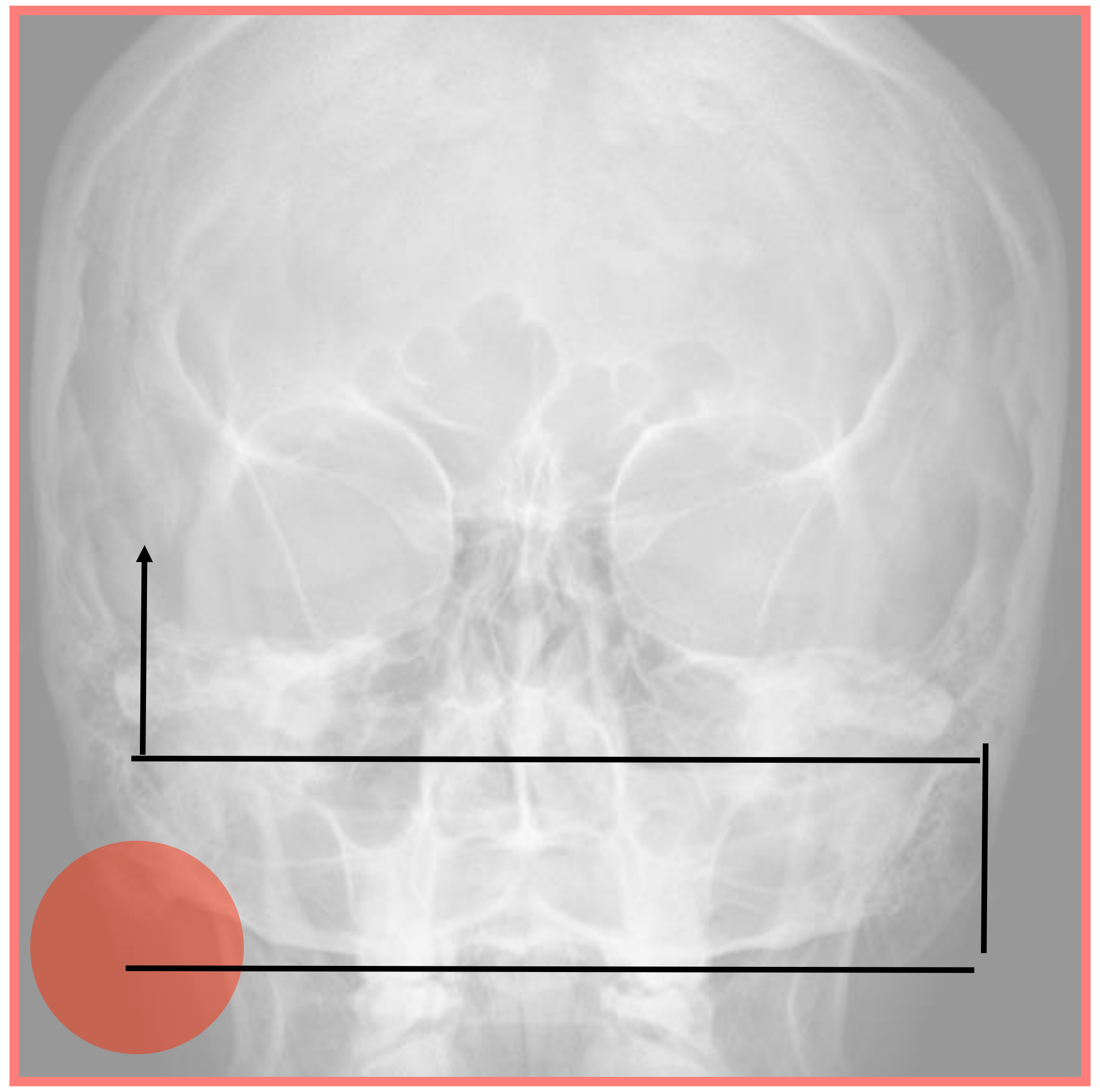
For imaging, would like this

Need post-nozzle scatter

300 square scan area



With nozzle, get this



Need to scan

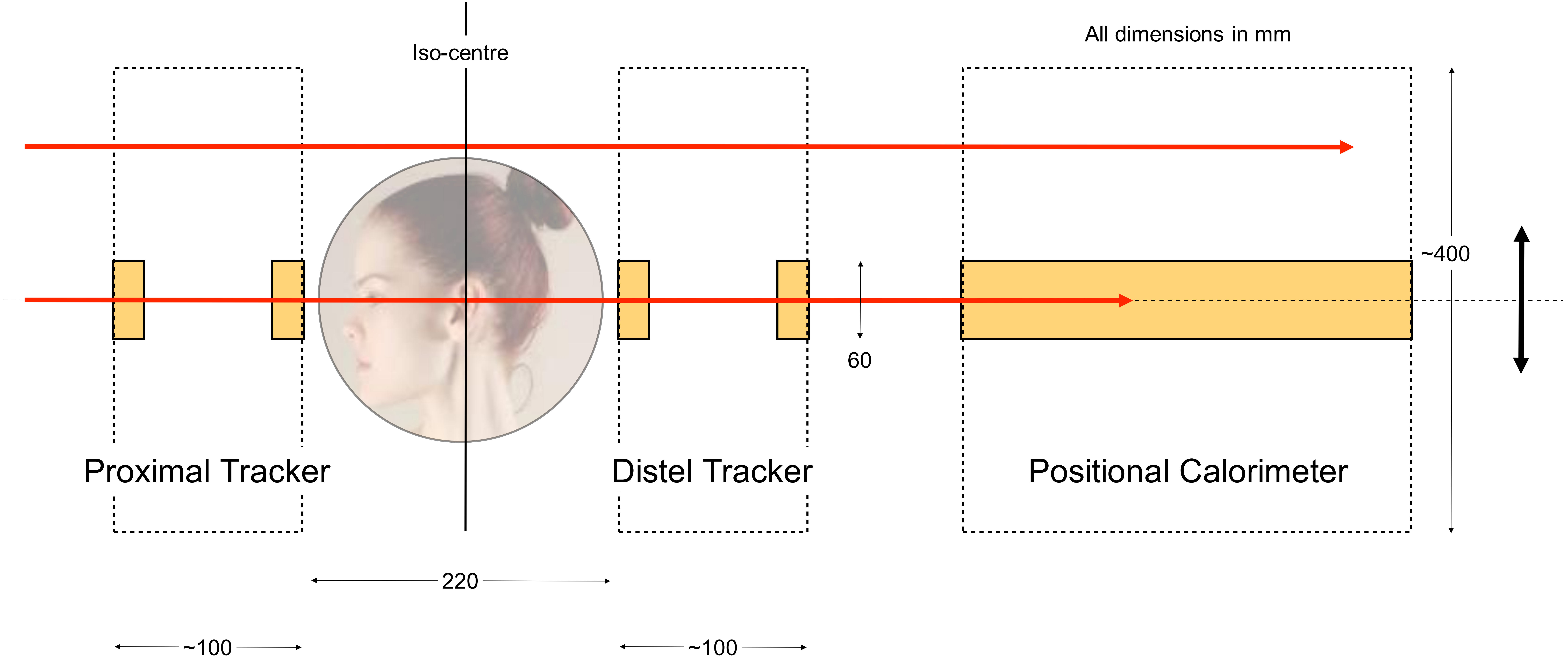
Maximum scan velocity ~ 10 ms^{-1}

Different Cyclotron Frequency

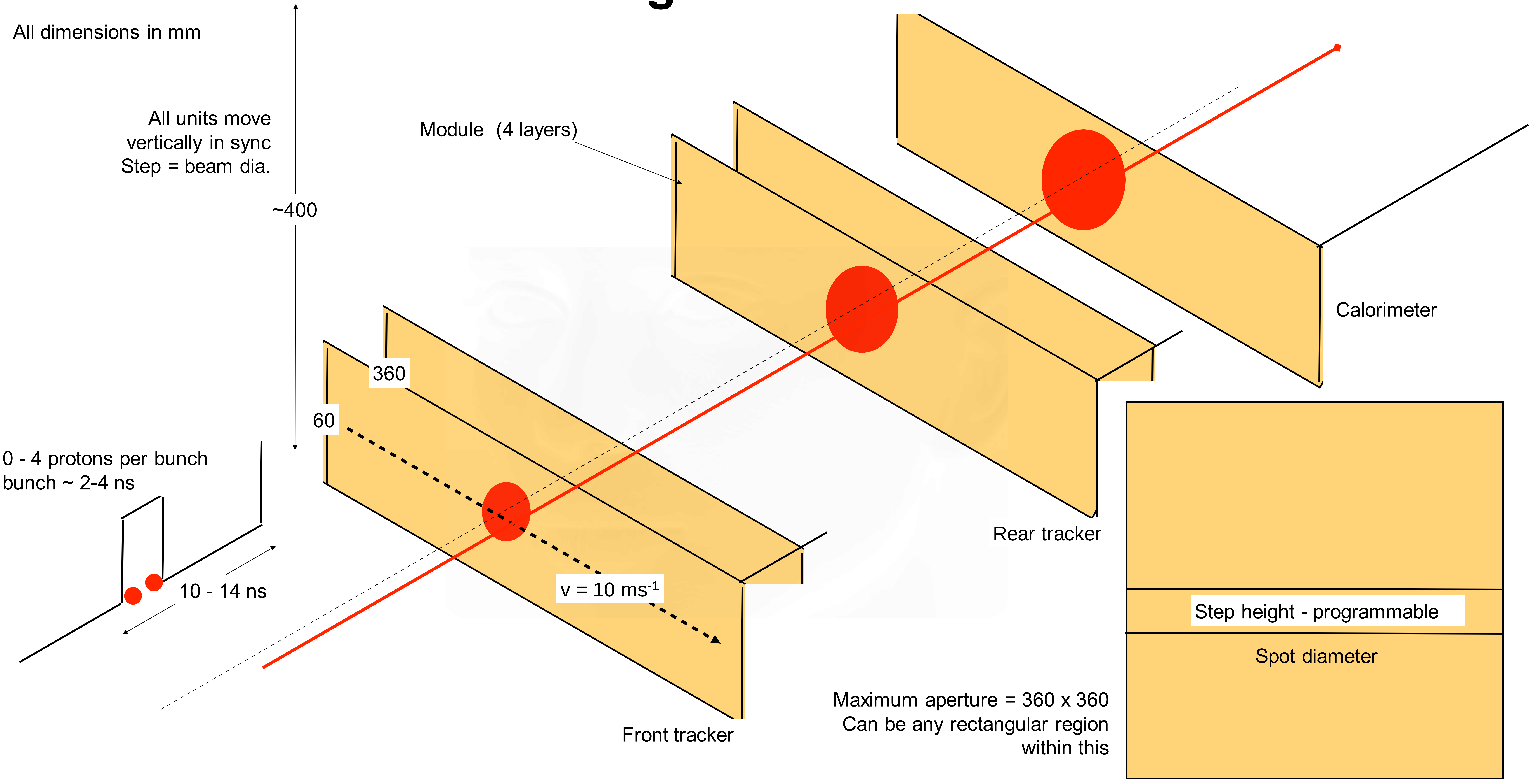
Varian 72 MHz
IBA 106 MHz

Wish to work with both vendors and others

Basic Arrangement

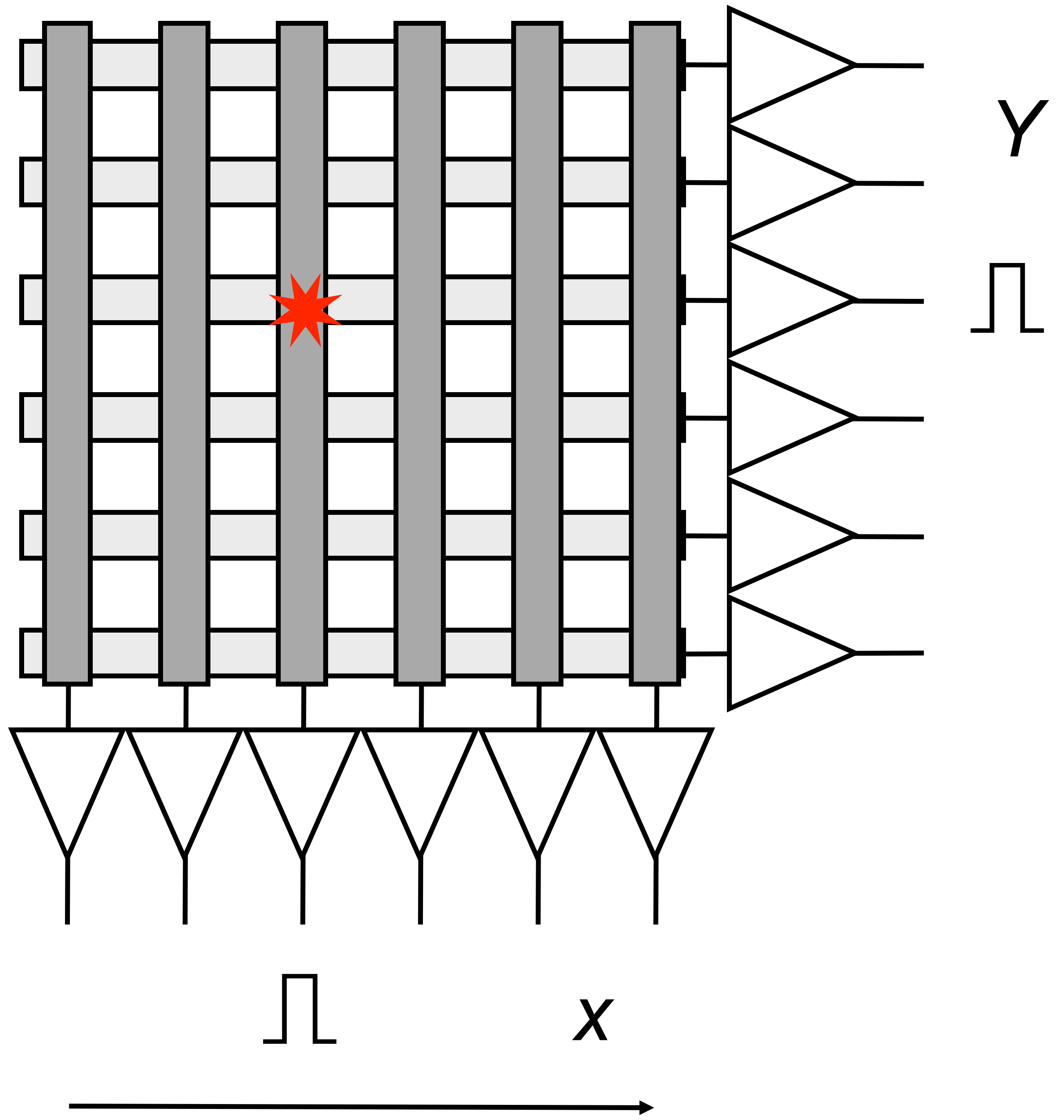


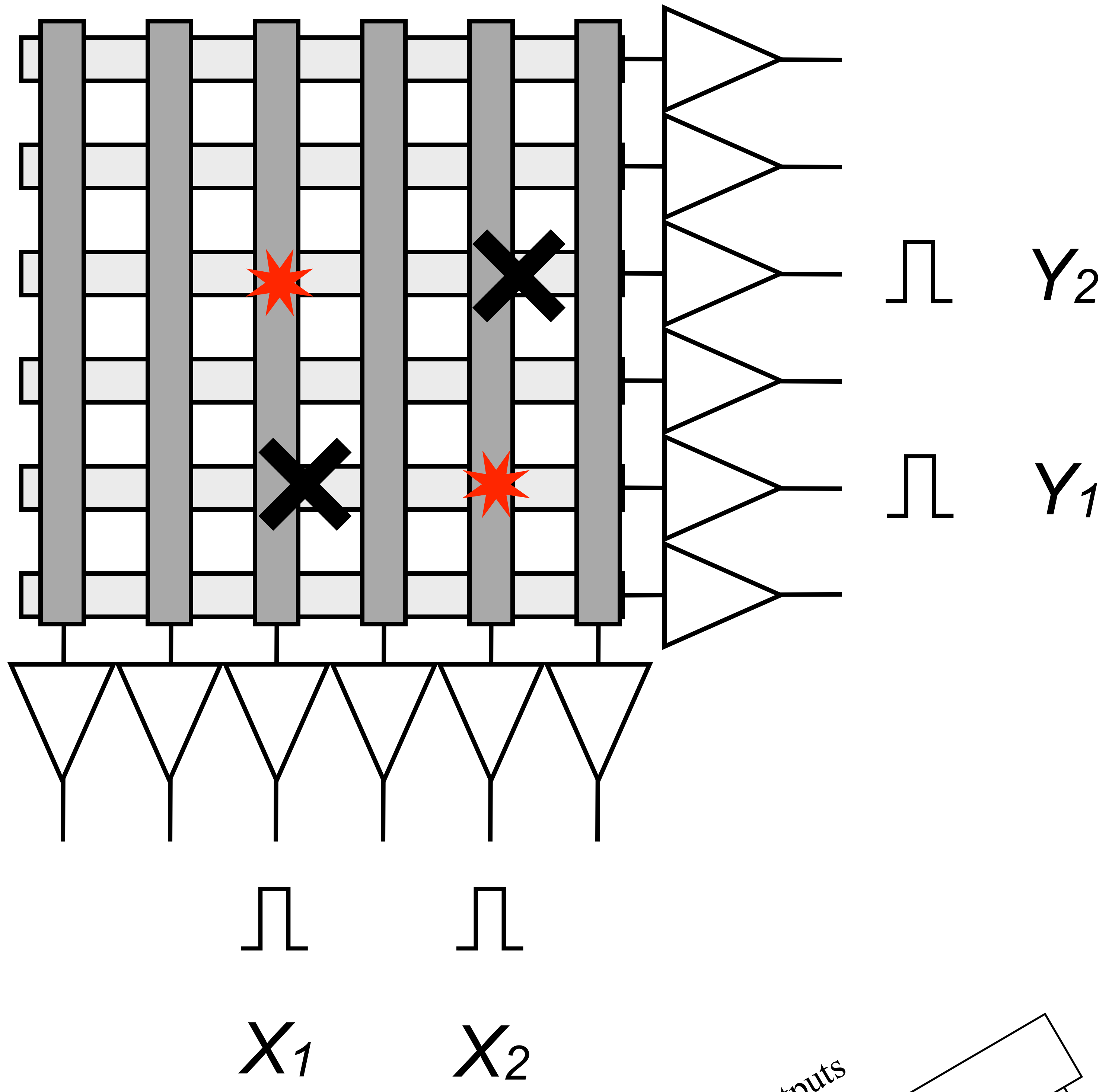
Basic Arrangement



Calorimeter
TATE
Tracker
Distel Tracker
Module
4
3
2
1
Layer
Proximal Tracker
Dia = 40 (at front tracker)
Area = 1,257 mm^2
About 170 strips at one time see active beam
60
360
Each die sees protons for 6 ms
Each strip *active* for ~ 4 ms
1536 strips iper layer
Dia = 40 (at front tracker)
Area = 1,257 mm^2
Average one proton per pulse
For notional 10 pA current
7.7 - 10 x 10^4 protons/ ms
2.6 - 3.6 x 10^6 protons per strip read

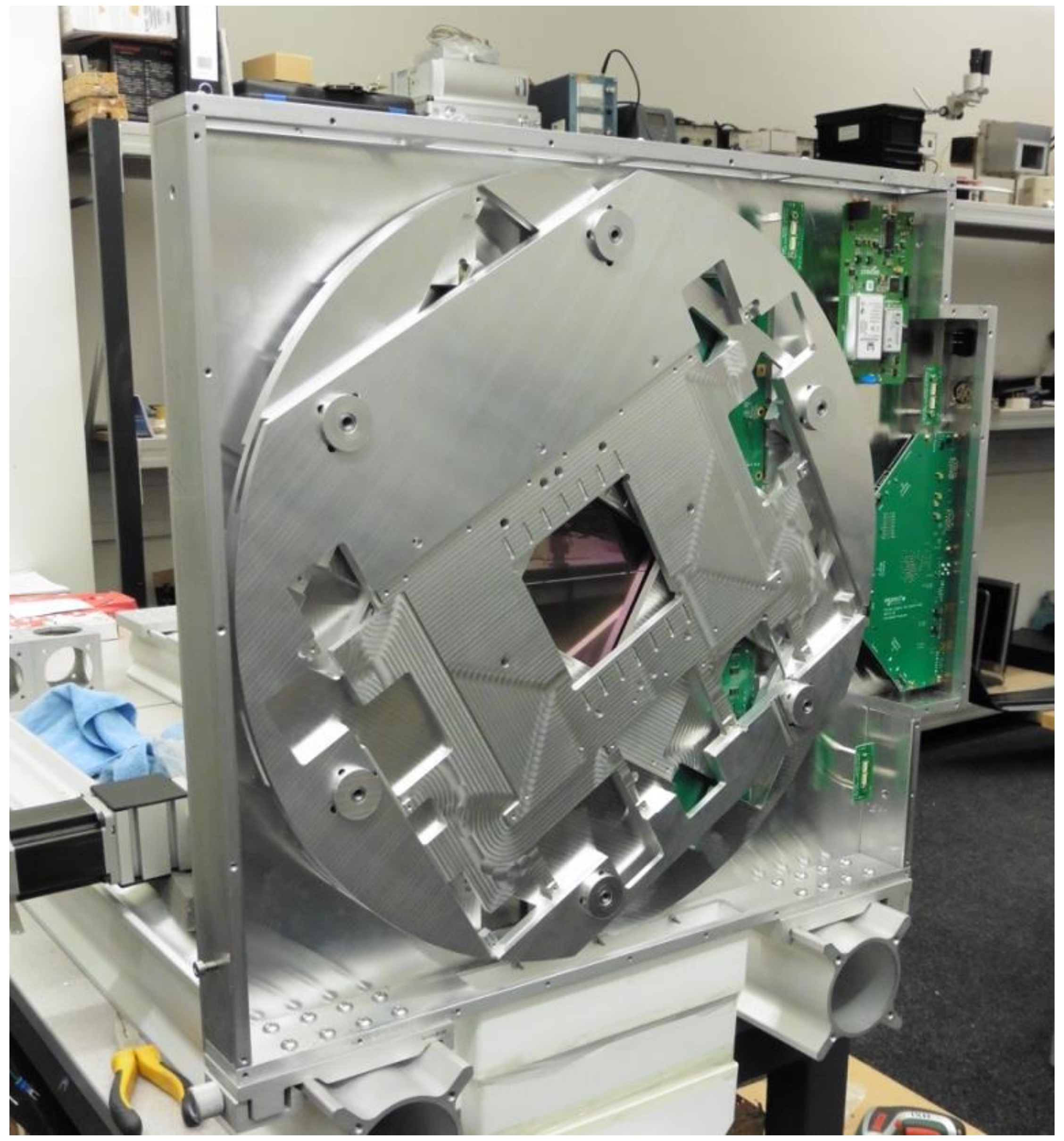
Silicon Strip Sensors

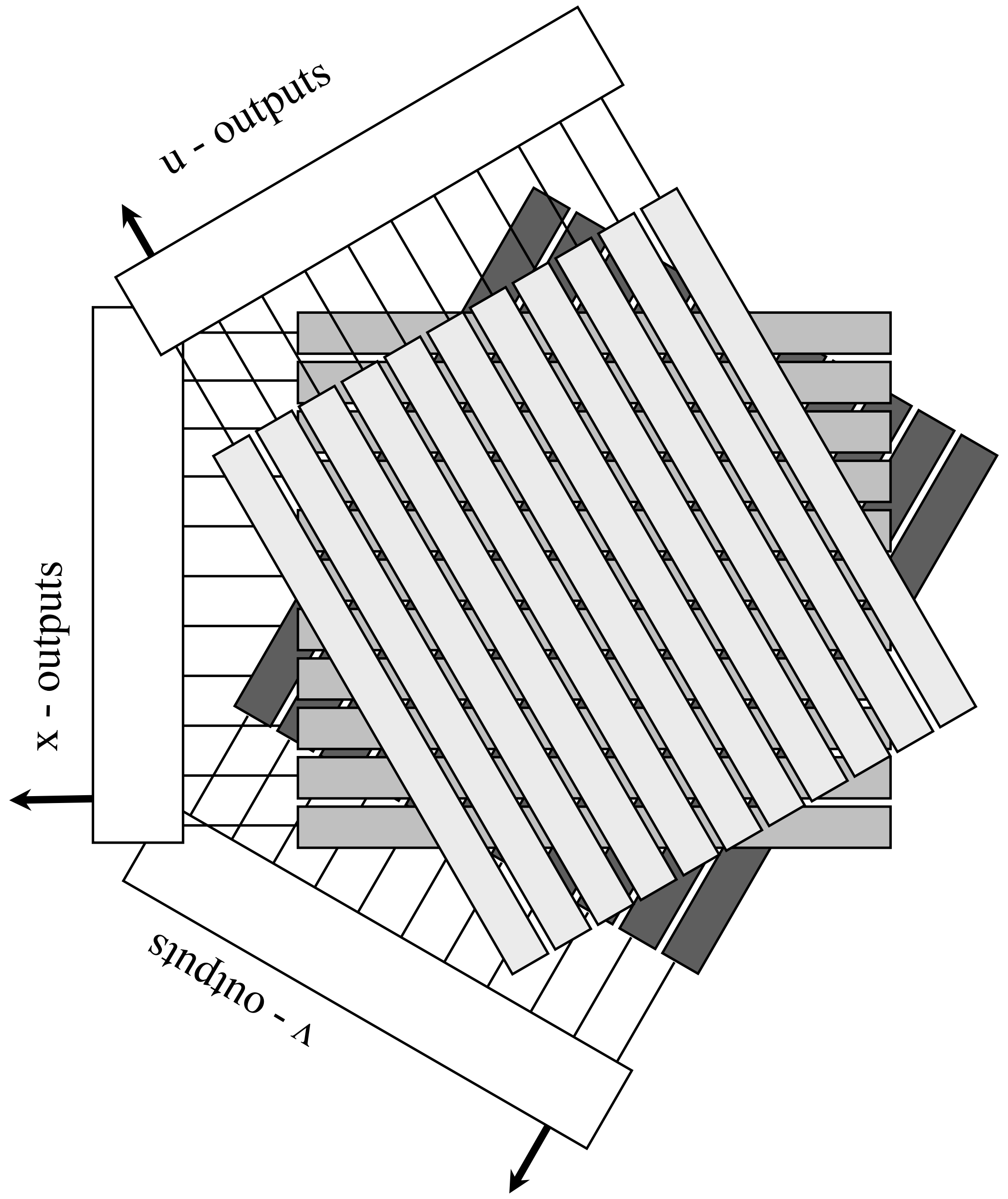




False hits = $N(N-1)$

Approx. 100 square

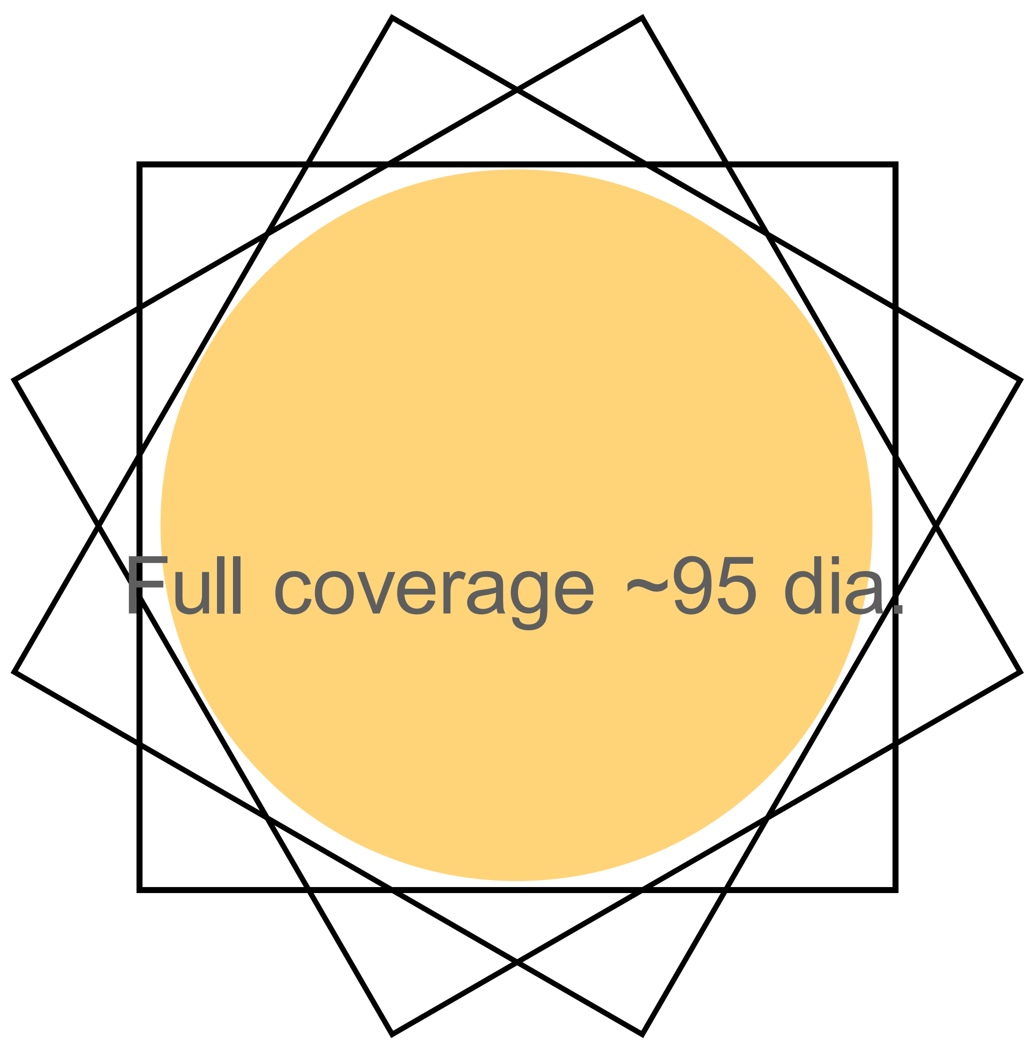




PRaVDA

- Three equi-rotated custom silicon strip sensors
- Copes with high flux levels (treatment beam)
- High count rate, in excess of 25 million/sec

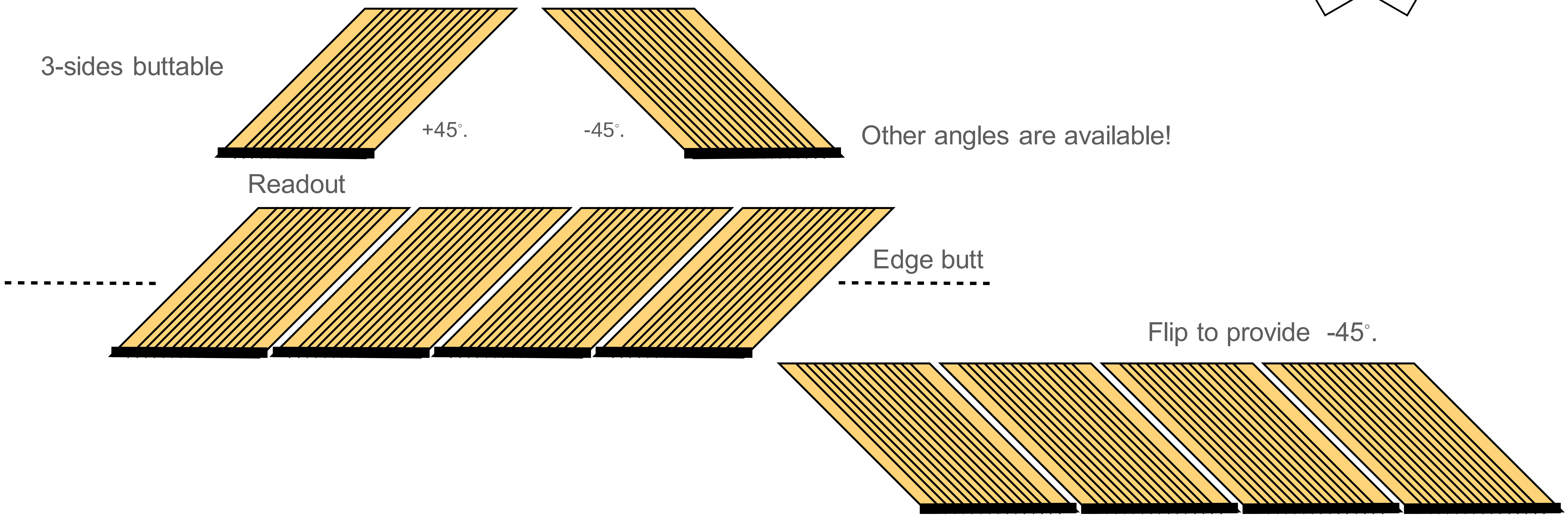
Strip Geometry



Can not cover large area with strips – normally on 6 inch wafers – maximum square 100 x 100 mm

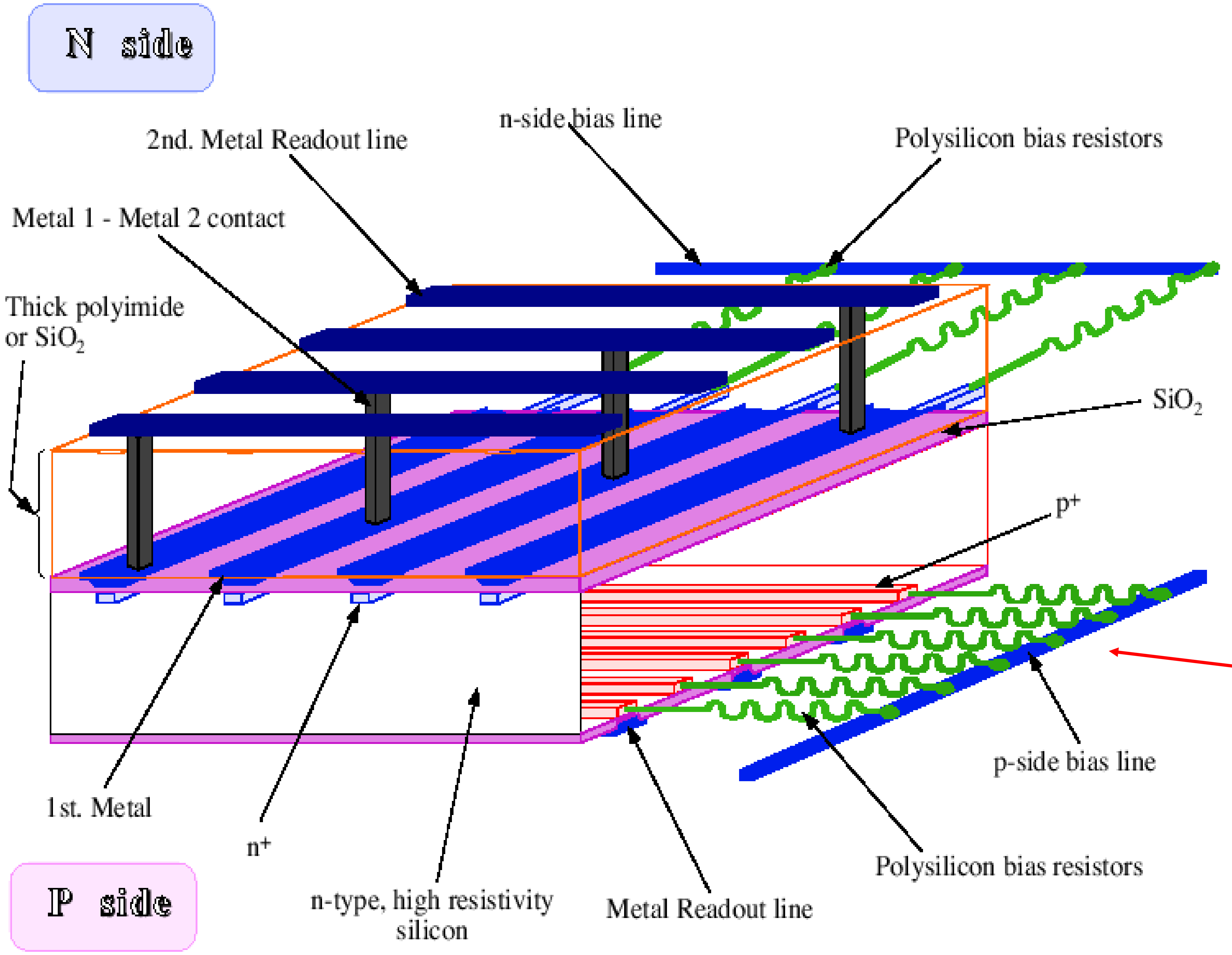
Can not butt to form larger mosaics

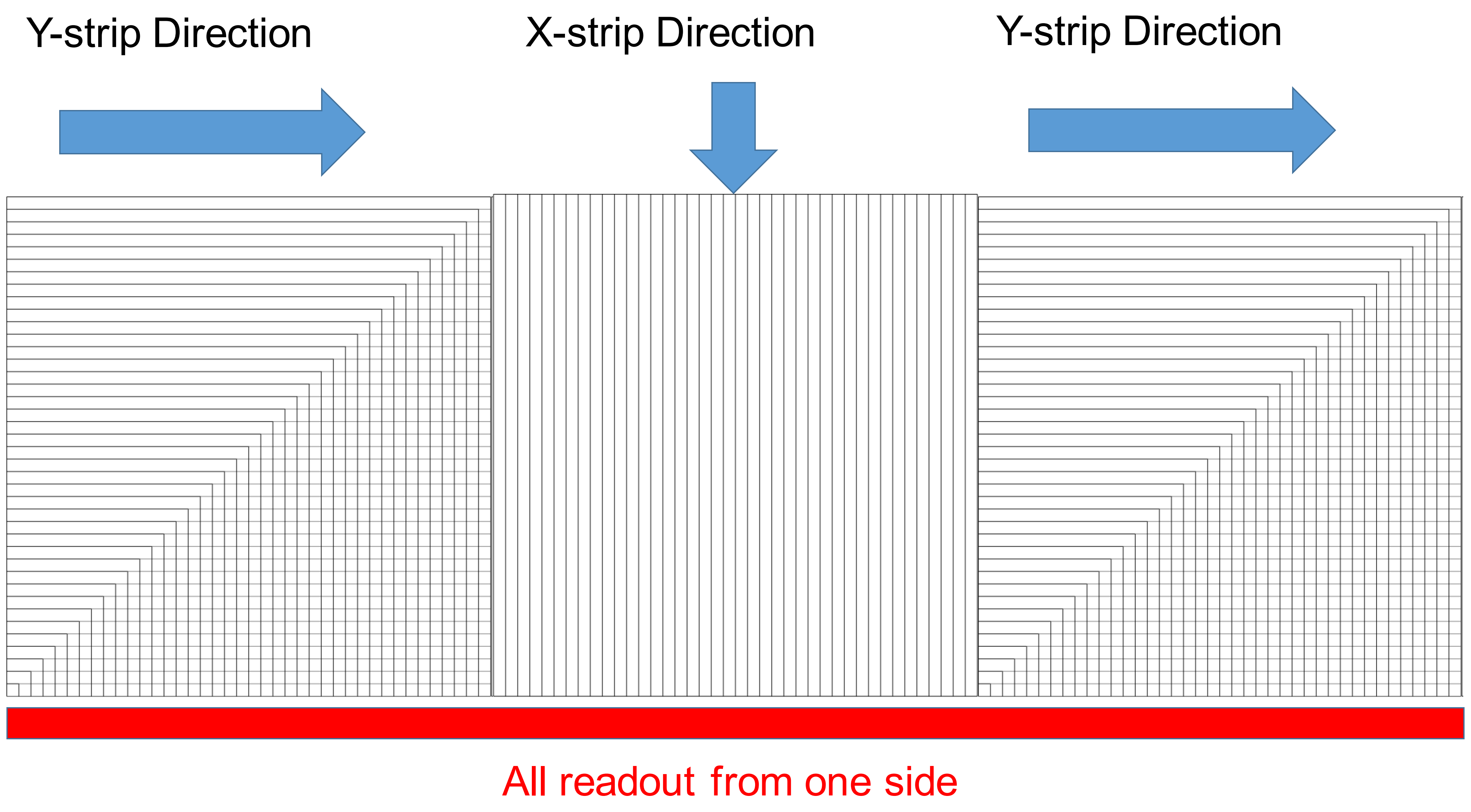
But can form *seamless infinite* strips in one direction



Strip Geometry

- Vias needed for Y strips to allow readout from common edge edge
- Introduces some extra capacitance



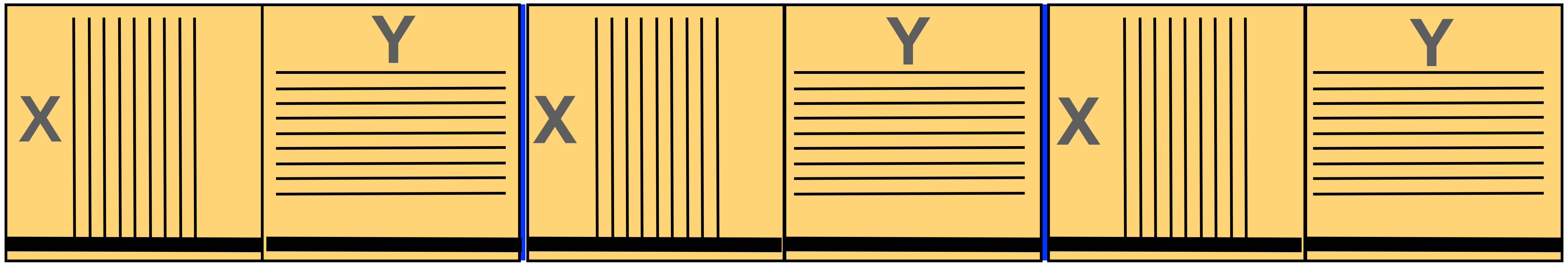


Note that in our case there will not be readout from the bottom side as suggested here

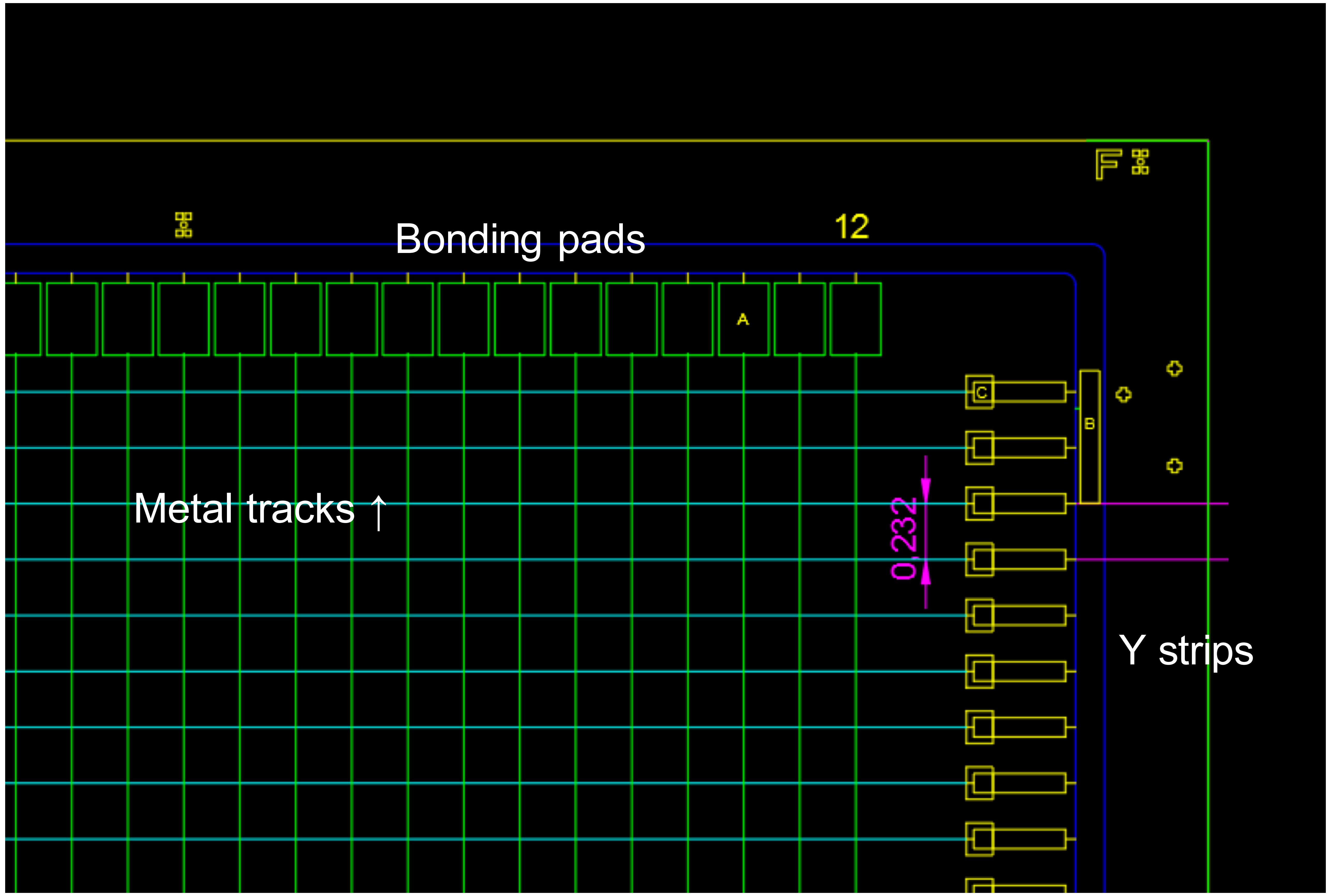
X-Y Sensors

Single sided strips

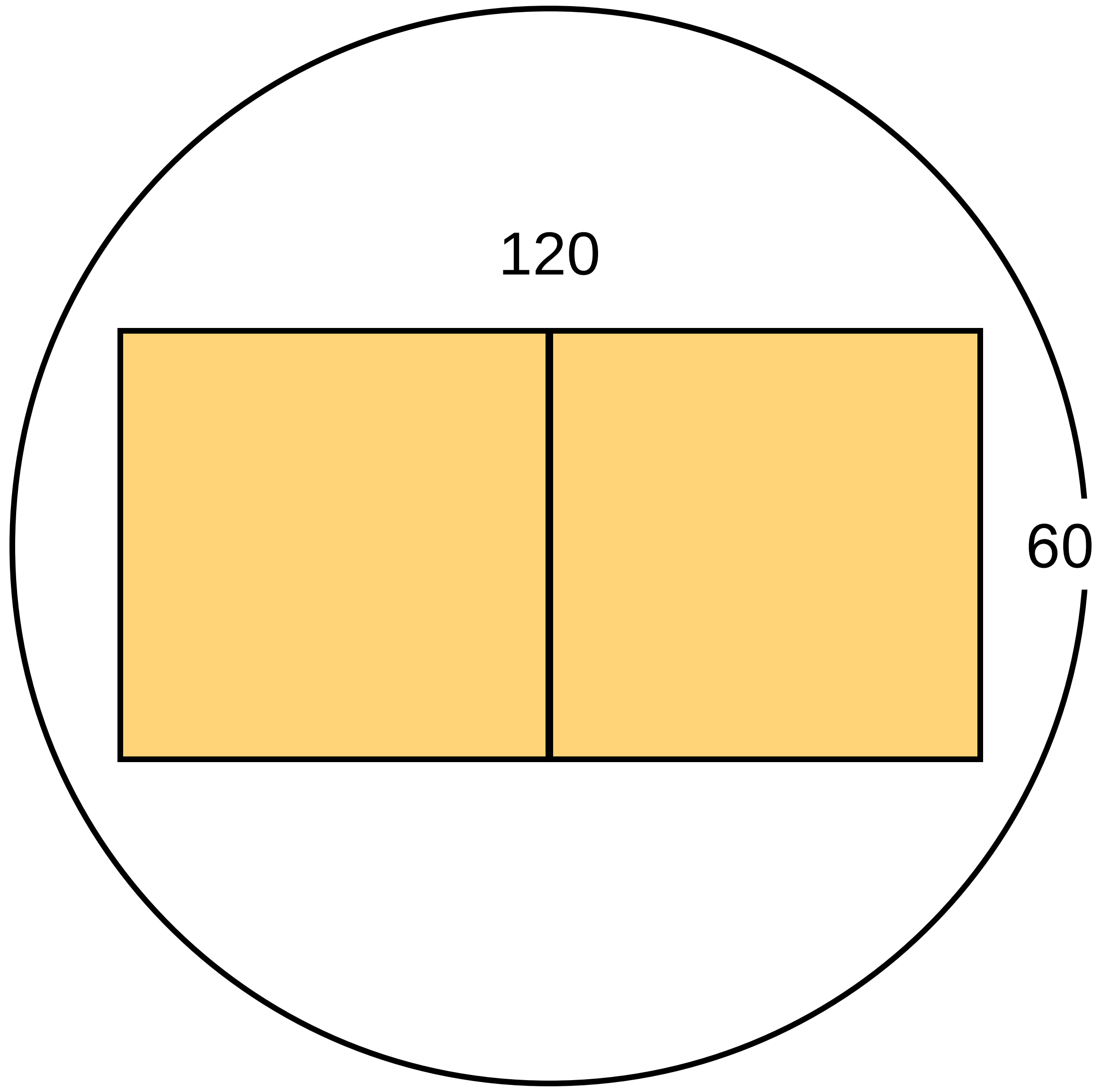
Edge butted (~ 1 gap)



Single edge readout

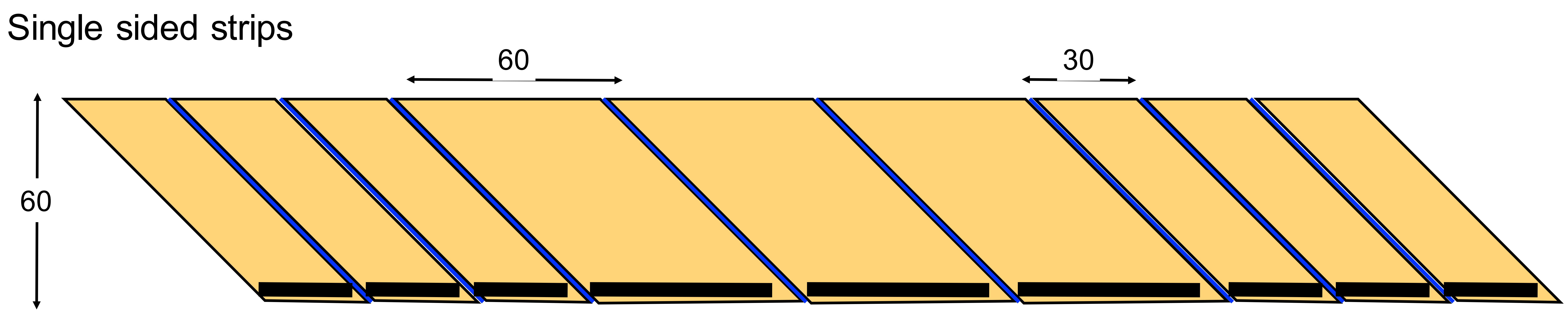


6 inch wafers

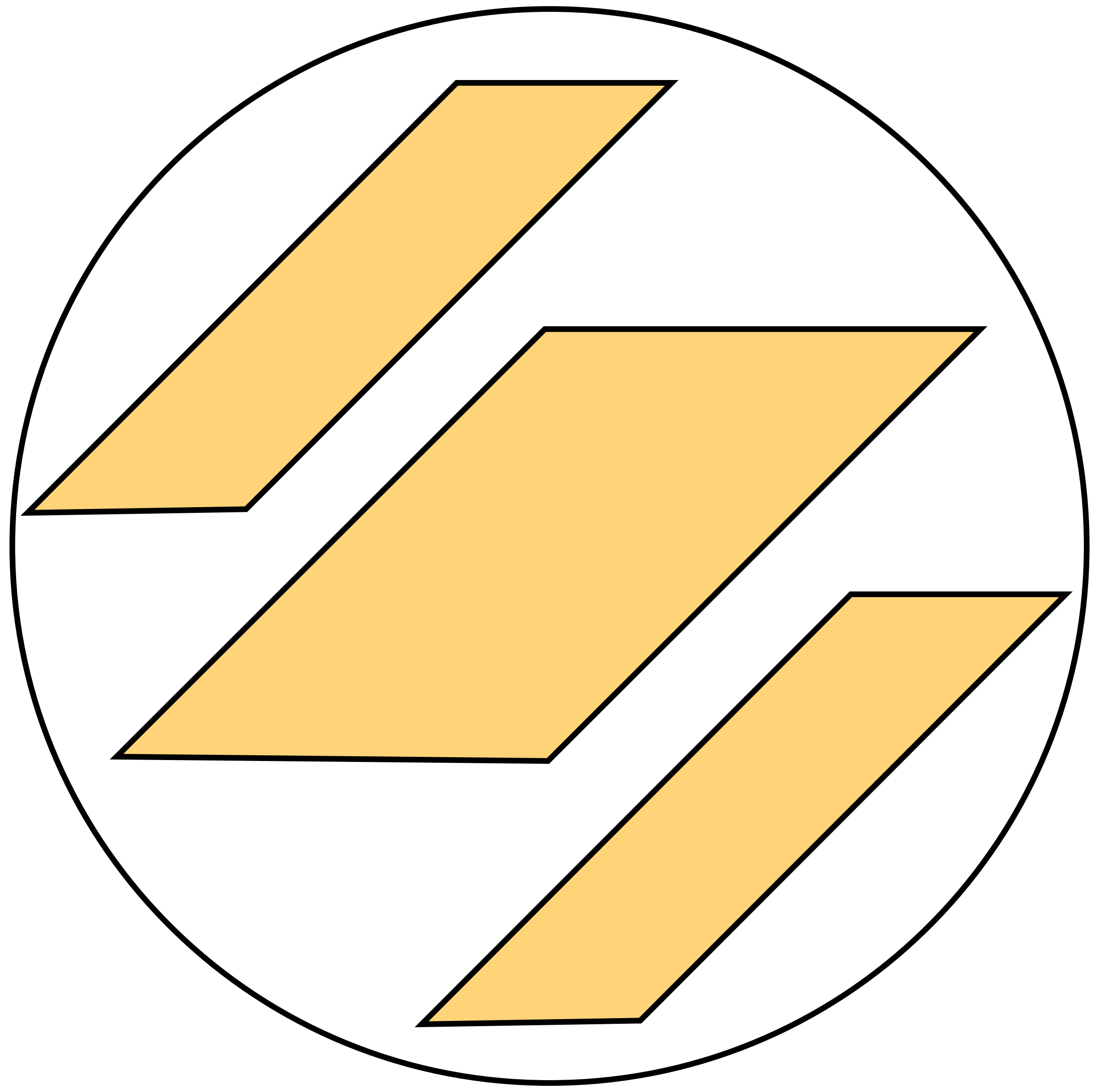


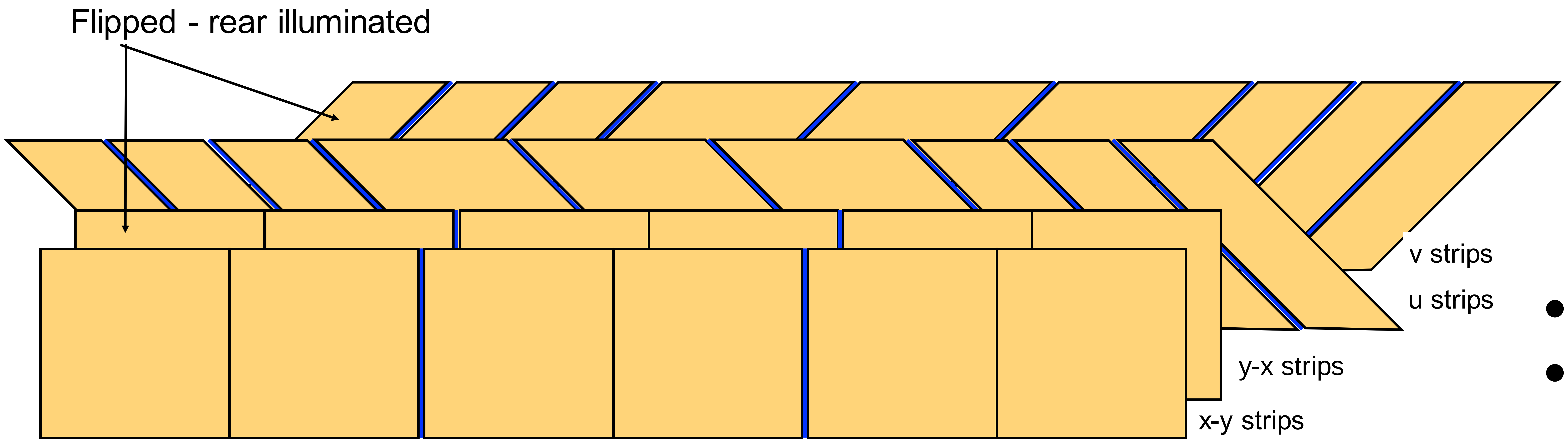
- **Strip pitch**: 235 um at edges
  - No benefit to going smaller as scattering limited
  - Going larger limits performance
- **Strip width:** 70 um XY, 60 um UV
  - Compromise between capacitance and efficiency
- **Strip thickness: 150um**
  - Avoiding thicker to minimise scattering

U-V Sensors



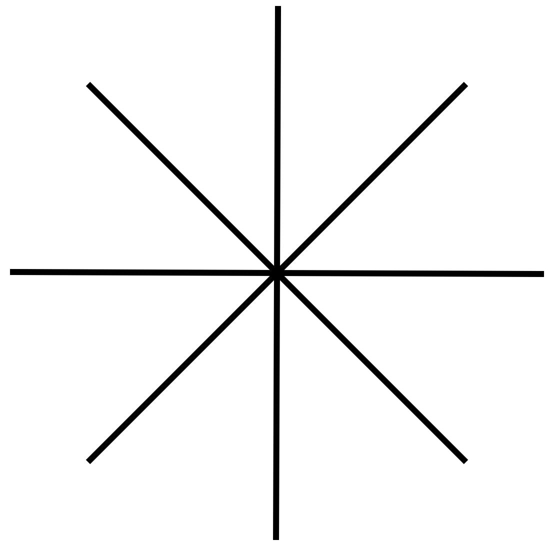
- 45 degree
- Effective pitch of 166 um for UV layers





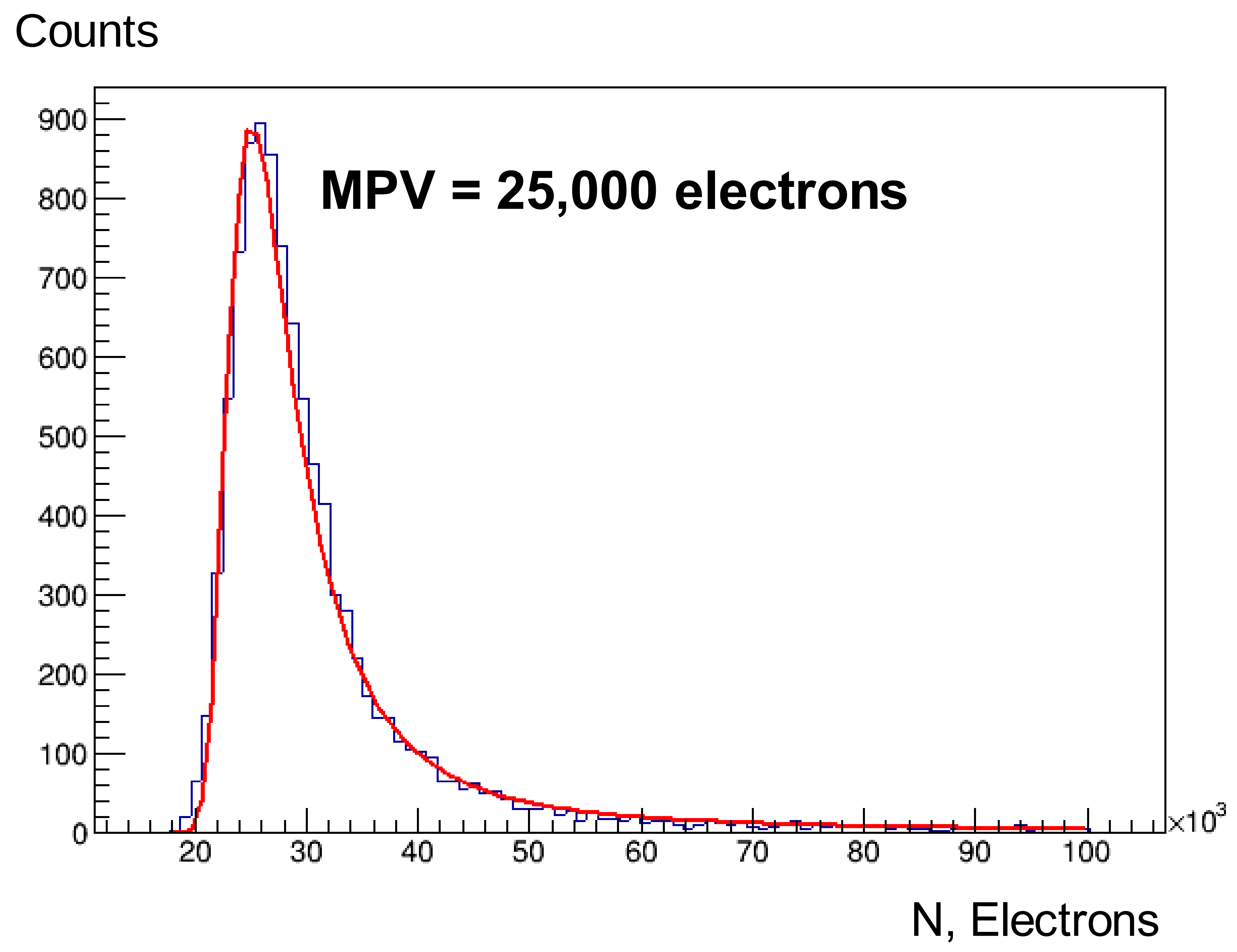
4 layers not 3

- Simulations demonstrate better accuracy in final x, y position
- Natural symmetry

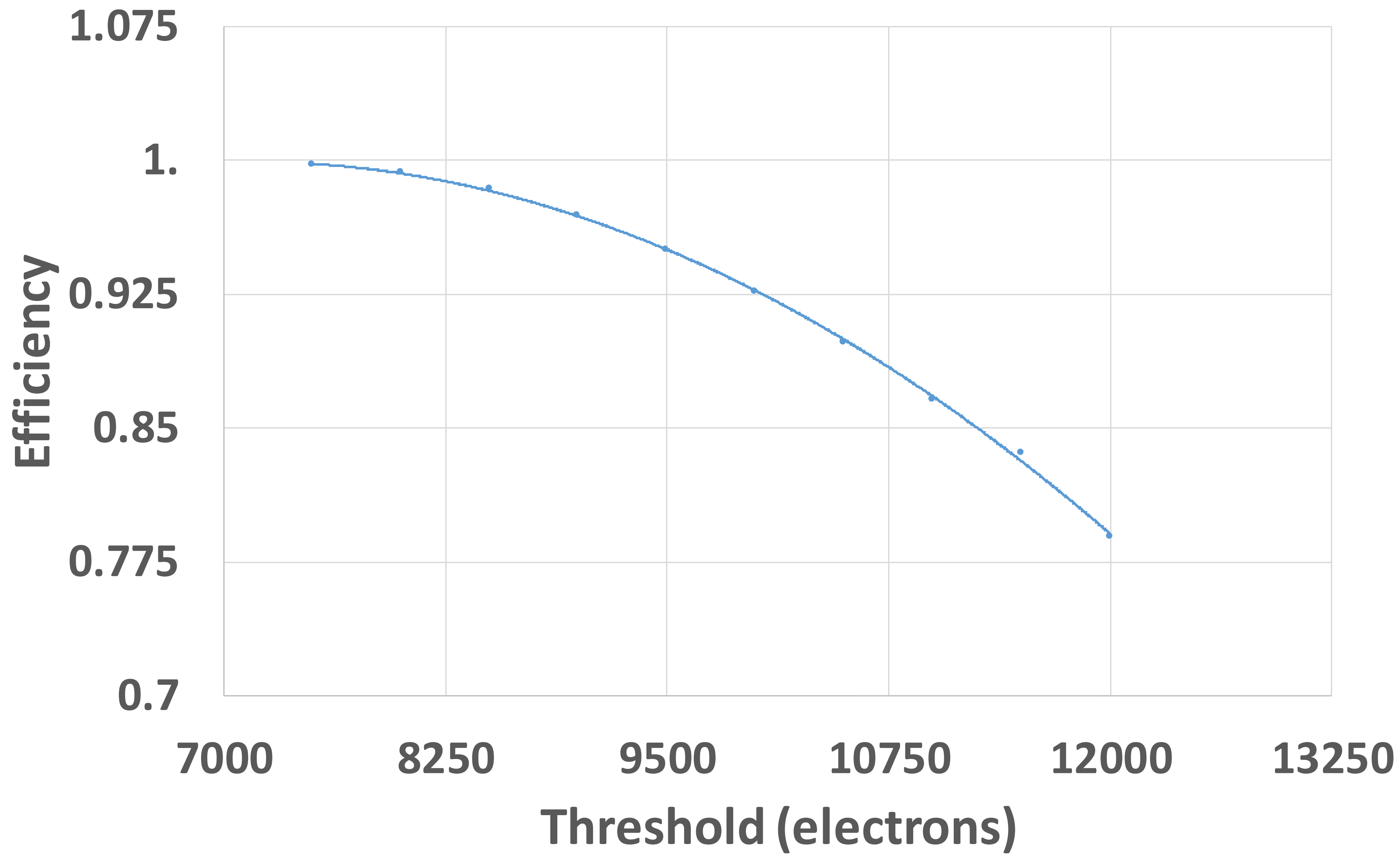


Signal Size and Thresholds

- Measured energy deposited in first tracker layer by 230MeV proton
- Convert to electrons and fit with Landau to find most probable value (MPV)



Need lower thresholds to maintain overall efficiency (16 layers)



- Typically set threshold to be ~half of MPV for high efficiency
- BUT, need to account for the fact we have multiple layers
  - Total efficiency= product of efficiency across all layers

- **Threshold of 8000e gives an efficiency of 99.3%**
- Would target noise rates of <1000e
  - Anticipating capacitances of ~16-22pF
  - Highest for Y strips due to extra metal

Module Geometry

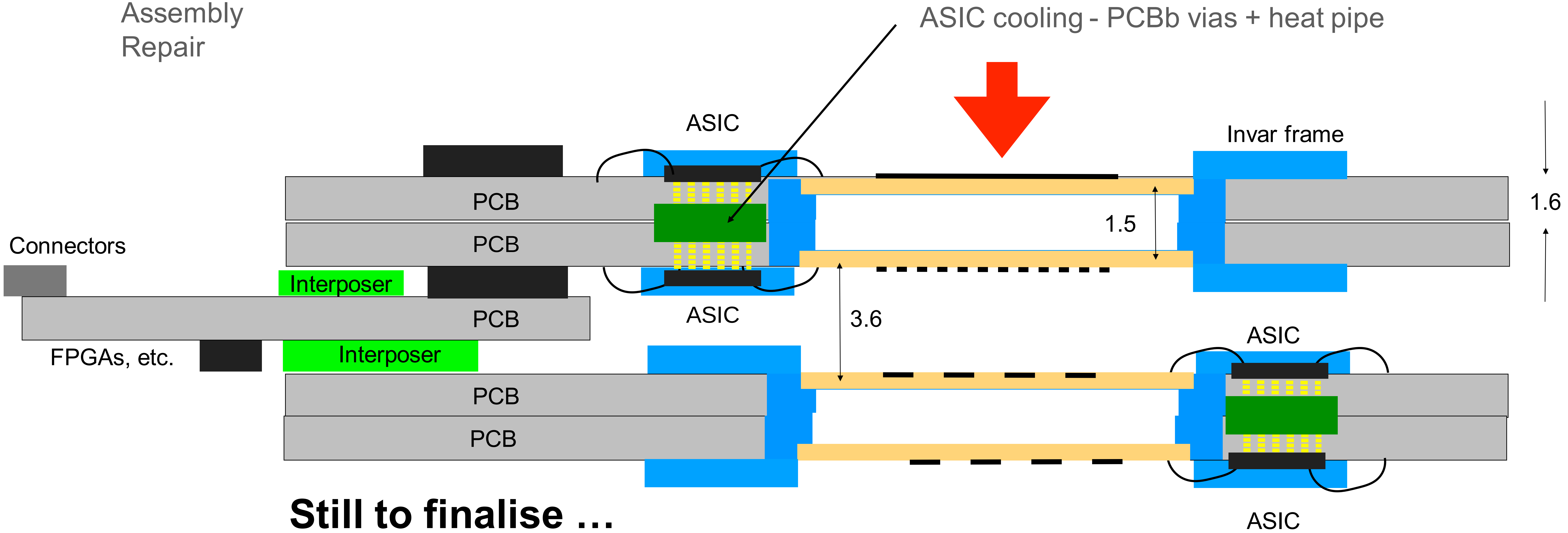
Estimating a point (x. y) in a plane from 4 vectors
Ideally all 4 layers should be co-located

Multiple vias for good heat path

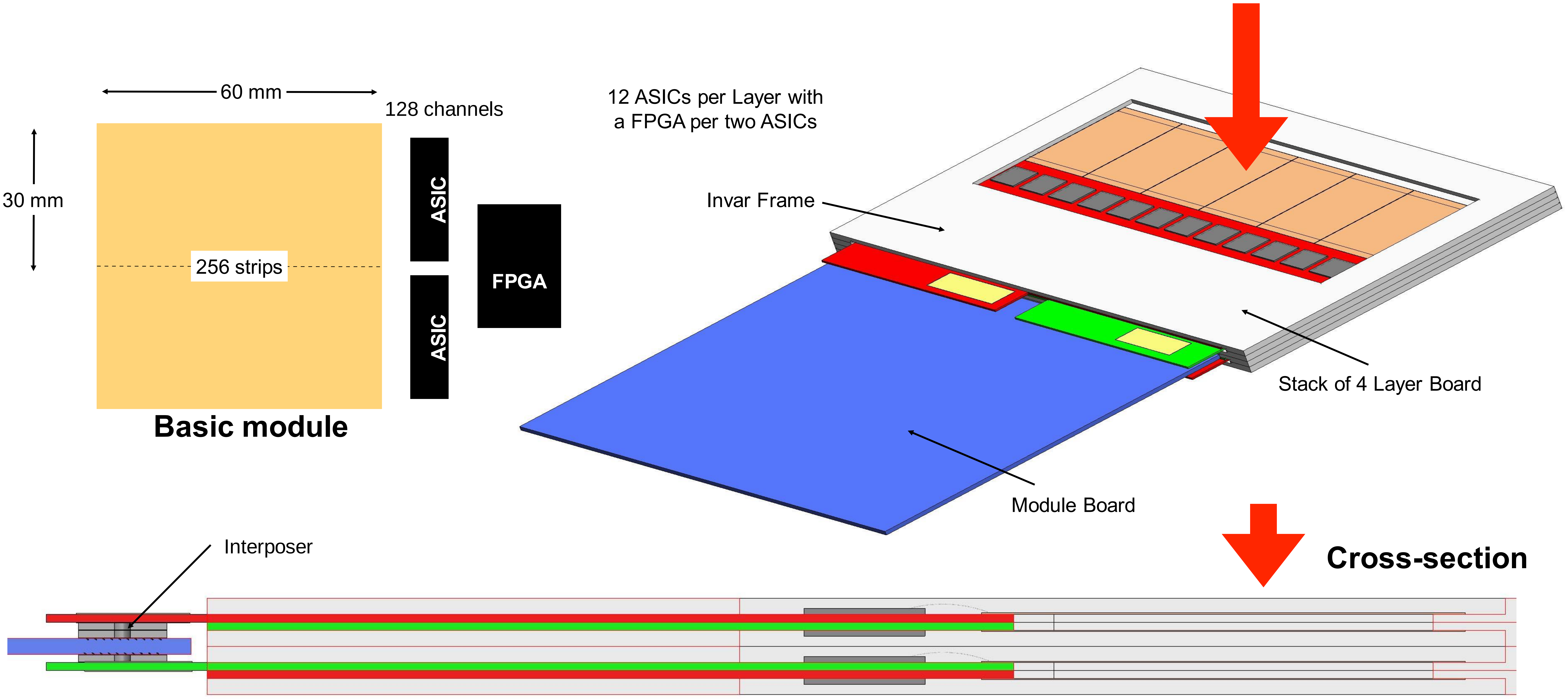
About the best we can do

Constraints

Wire-bonding
Component heights
Heat dissipation
PCB track density
Assembly
Repair

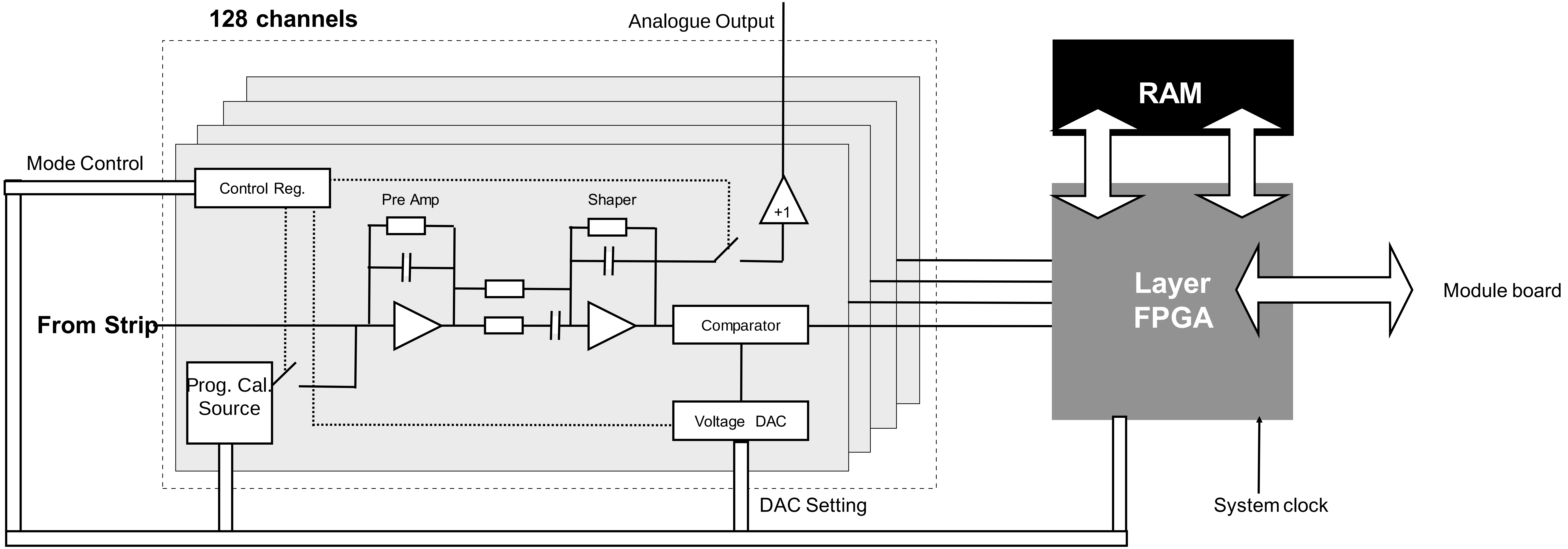


Still to finalise …


60 mm
128 channels
30 mm
256 strips
ASIC
ASIC
FPGA
Basic module
12 ASICs per Layer with
a FPGA per two ASICs
Invar Frame
Stack of 4 Layer Board
Module Board
Interposer
Cross-section

ASIC

Novel design: separate analogue (asynchronous) and digital (synchronous) parts

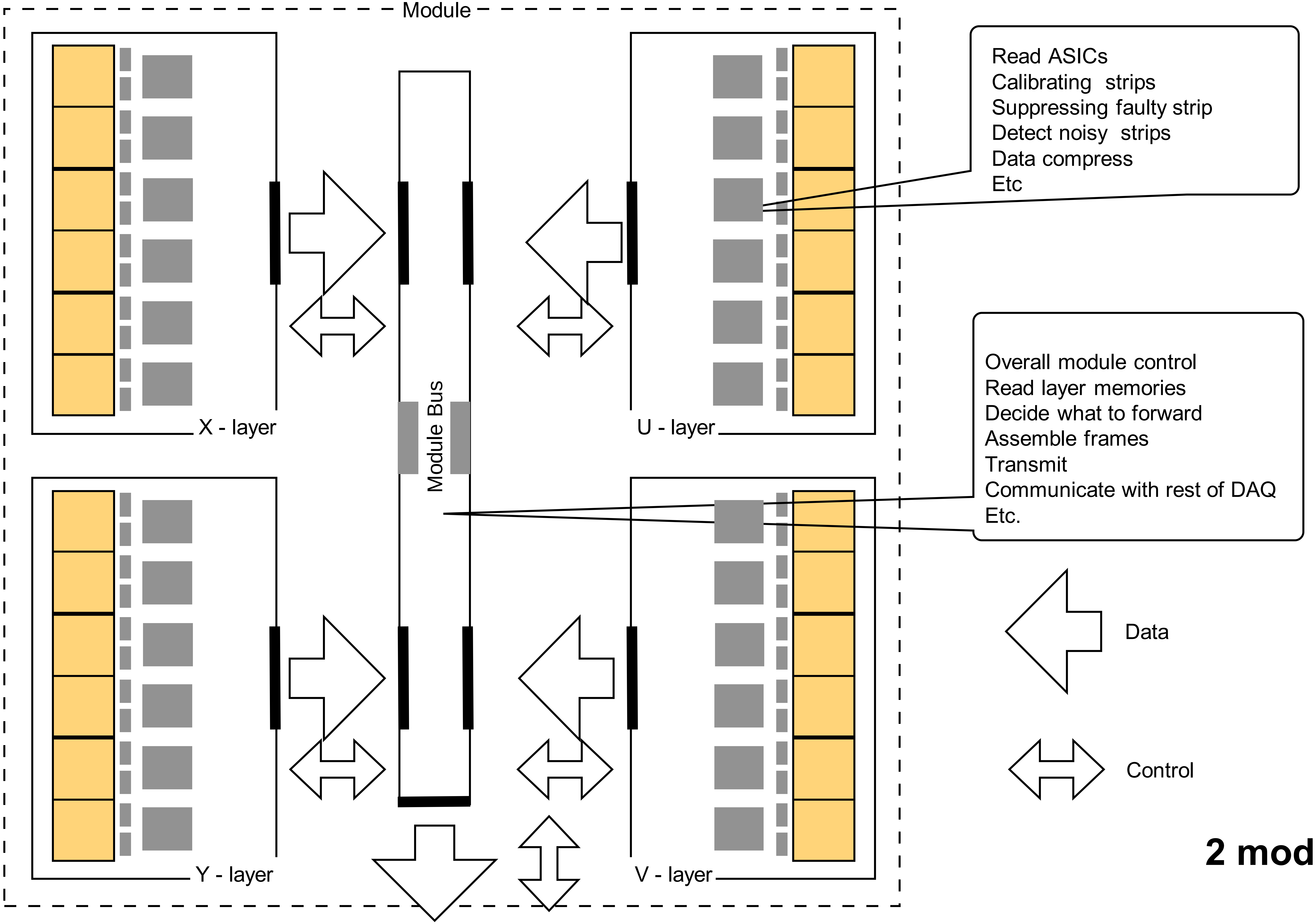


Single programmable threshold
5,000 - 35,000 e^- variable (6 bit DAC)
Maximum of 4 across one ASIC during normal acquire mode
Modes: Test, Analogue Output, Normal, disable

Zero deadtime

Interface with module FPGA
Control of strips, calibrate, prime start/stop acquistion, etc
Compress data
Maintain DAC values, faulty strips
Detect noisy strips
….

Module



2 modules = 1 tracker

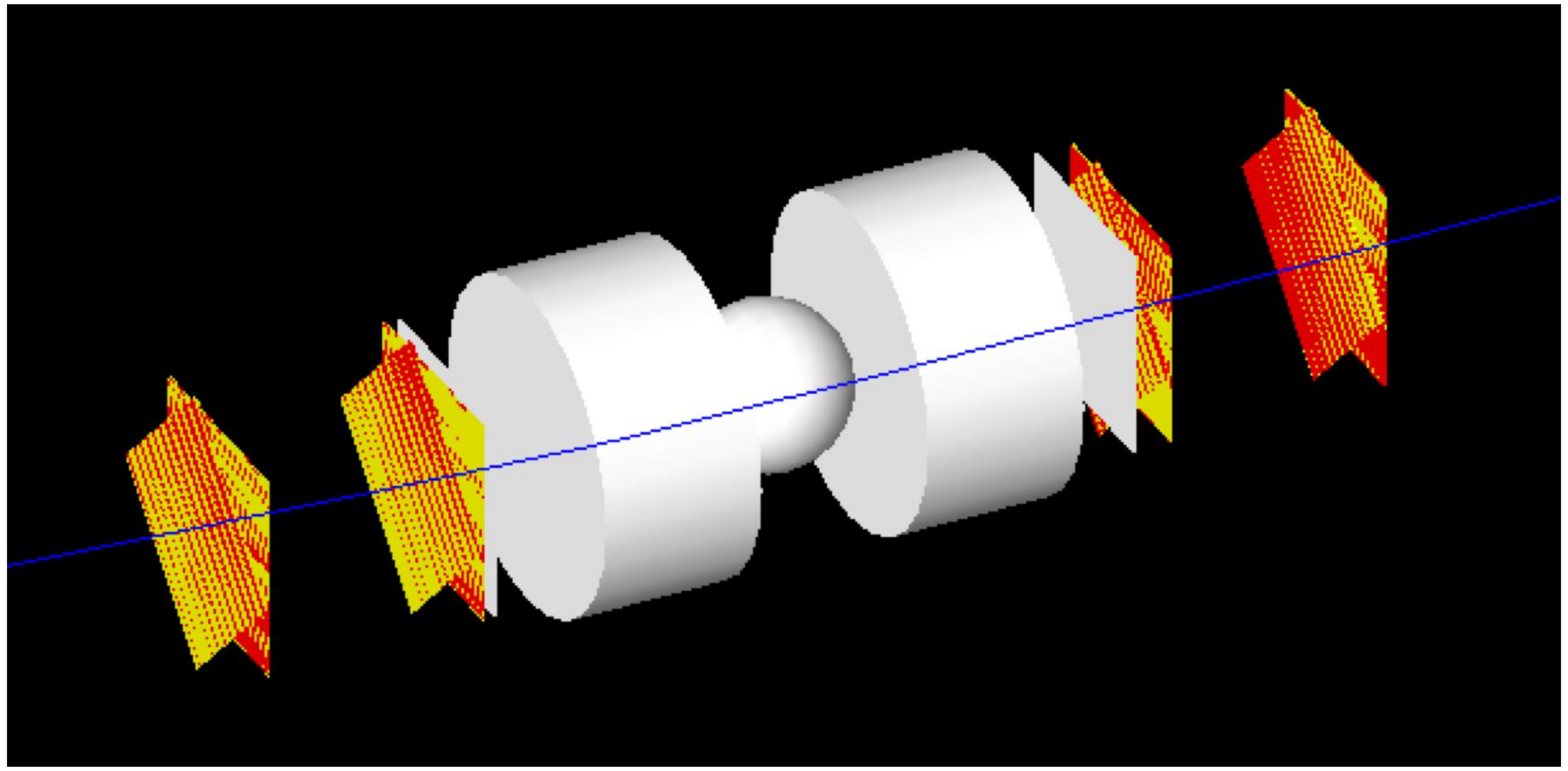

Overall DAQ
Resources included for performing real time track reconstruction, algorithm under development
Module 1
Unit 1 strip data odd
Unit 1 strip data even
Alternate memories every scan line
Front Tracker
Module 2
Unit 2 strip data odd
Unit 2 strip data even
Triangulate
~ 0.5 s processing time
X1, Y1
Triangulate
X2, Y2
Proximal Trajectory
Module 3
Unit 3 strip data odd
Unit 3 strip data even
Rear Tracker
Module 4
Unit 4 strip data odd
Unit 4 strip data even
Triangulate
X3, Y3
Triangulate
X4, Y4
Distel Trajectory
Residual Energy
From Calorimeter
X1, Y1
X3, Y3
X2, Y2
X4, Y4

Back to Basics

Max Hits Allowed	Efficiency (%)			
	No Background	Bkg@10^{-6}	Bkg@10^{-5}	Bkg@10^{-4}
3	94.3	94.1	93.5	91.4
4	98.7	98.6	98.8	97.9
5	99.8	99.8	99.8	99.6

Full Trackers Efficiency for Track Reconstruction
With background noise

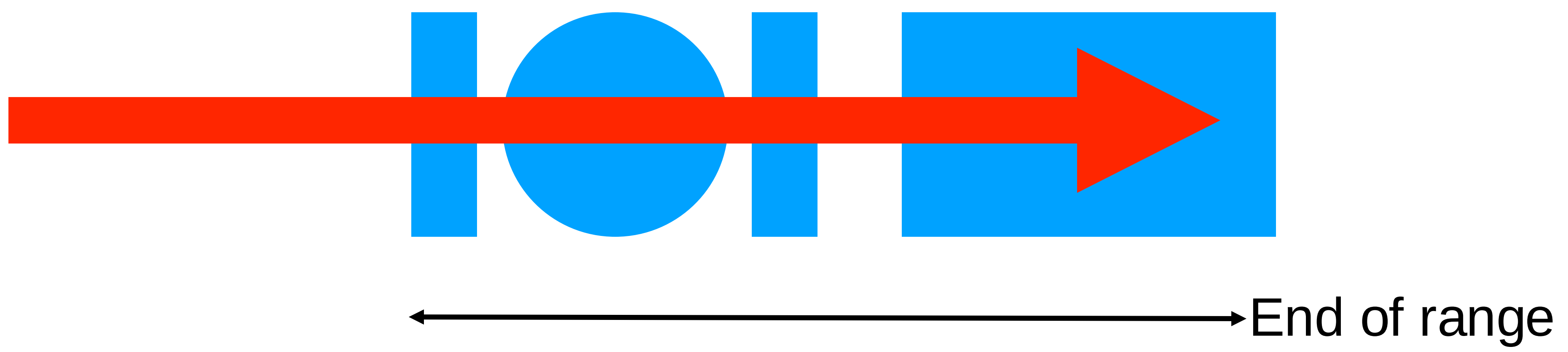
Don't have to worry about noise
Charge spreading has negligible effect



We do lots (and lots) of simulations

Next issue ☞

Proton Transit Times

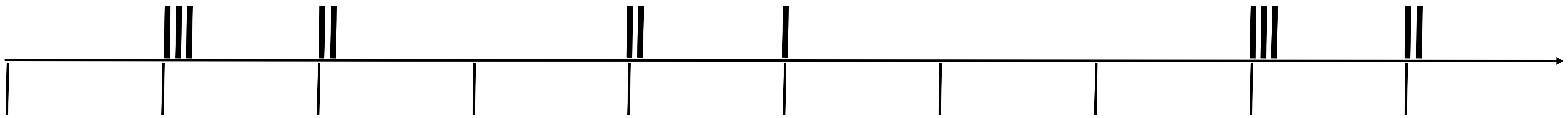


Transit Time

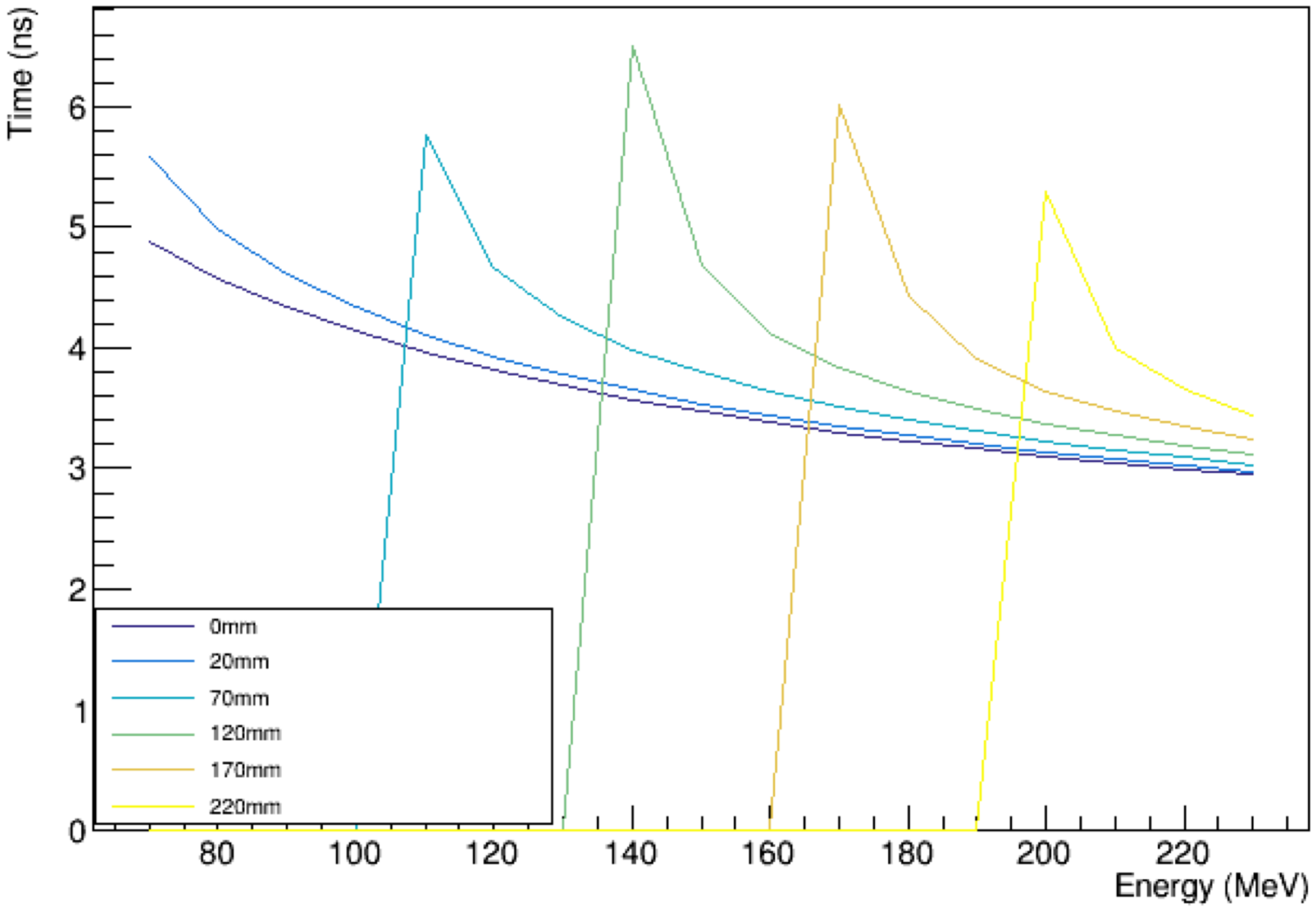
Depends on initial energy, material encountered and direction

If minimum time interval between proton's arrival > Transit time then do not need to sync with cyclotron

If minimum time interval between proton's arrival << Transit time then a lot of descrambling of data!



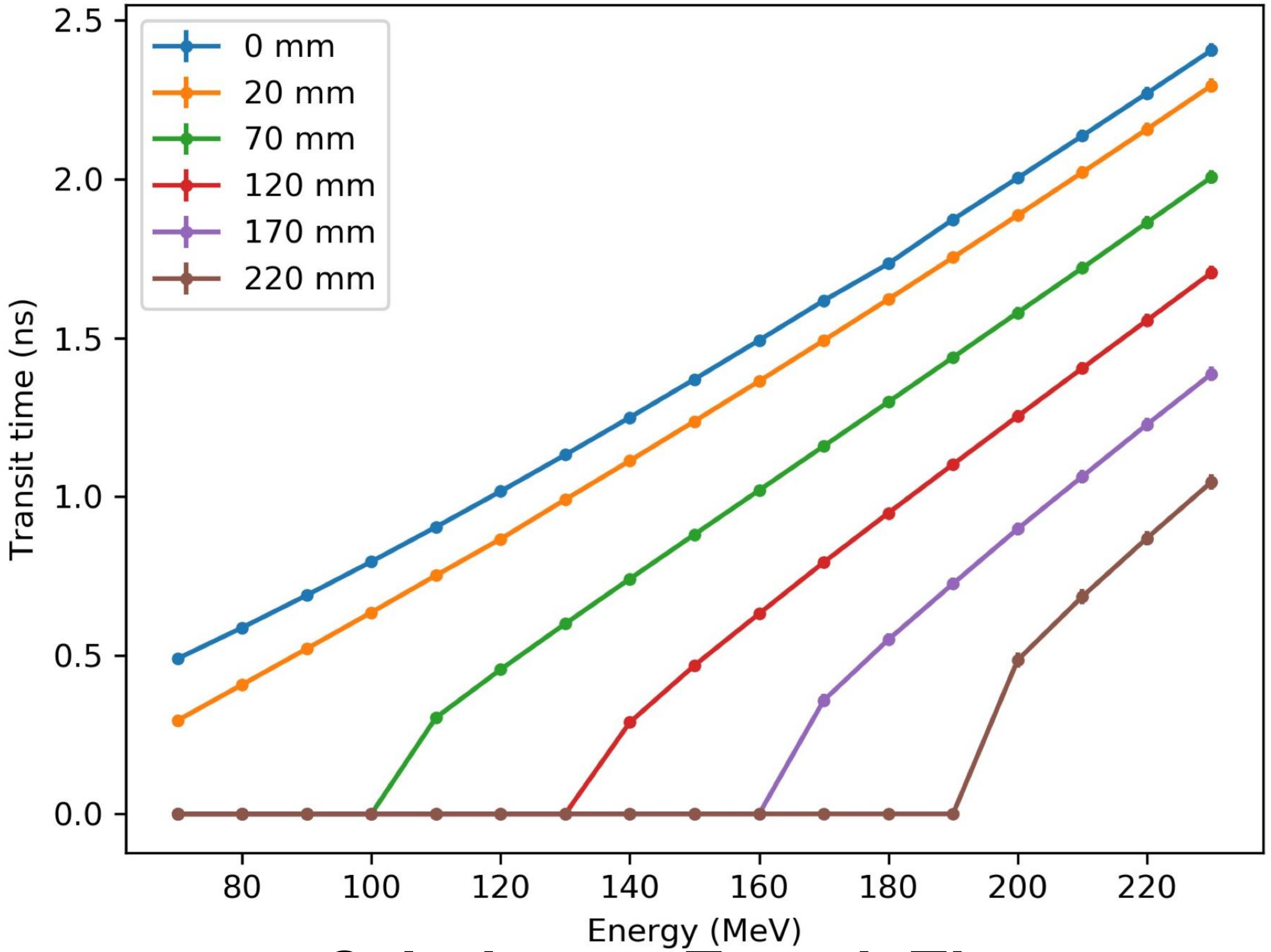
Protons arrive in 2 - 5 ns active pulse width every 10 ns or 14 ns



Full Tracker Transit Time

3 – 6.5 ns

+

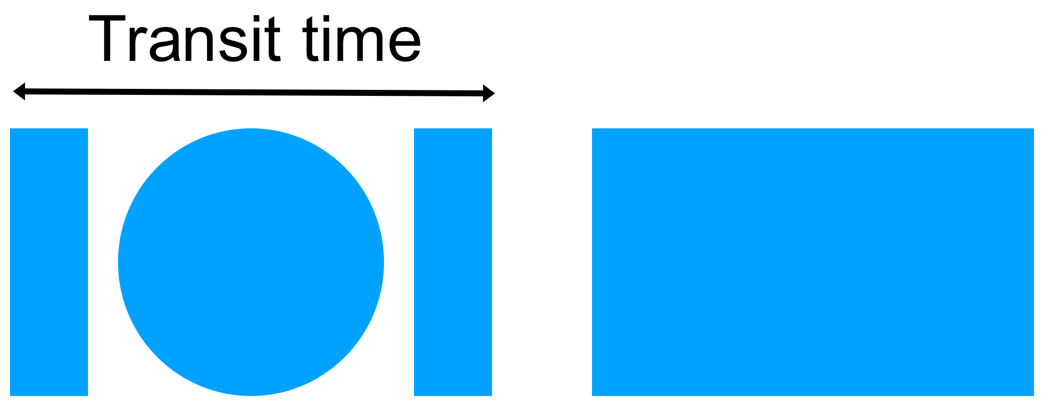


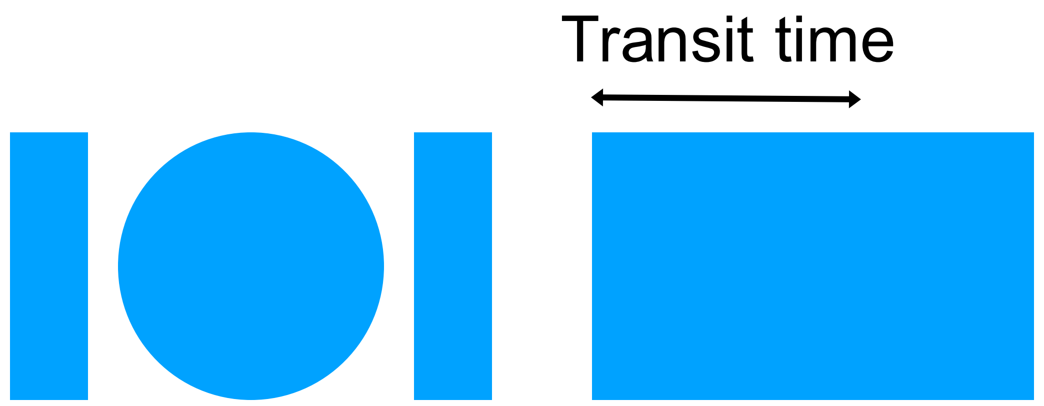
Calorimeter Transit Time

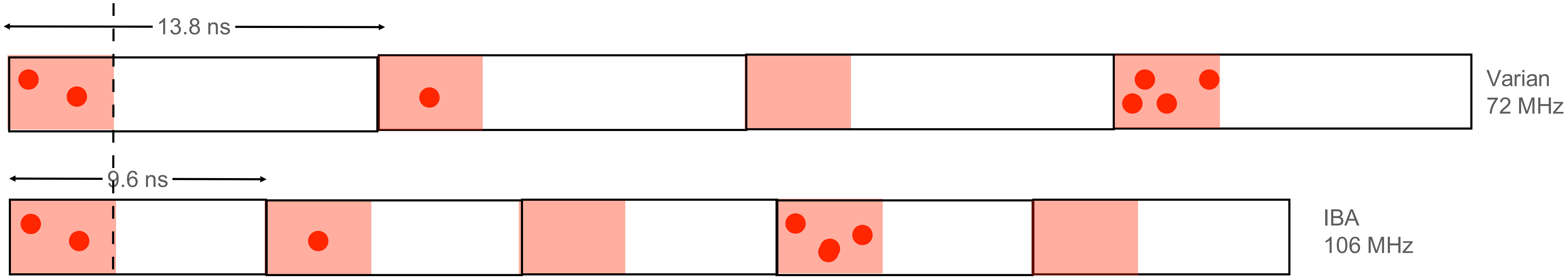
0.2 – 2.5 ns

=

3.2 – 9.0 ns







~4 ns

Maximum transit time

If sync to cyclotron RF, worst case is to search over two clock cycles
If we do not sync then have operate with very fast system clock
More proton events to consider then lower efficiency and accuracy

Large system - over a metre long - so difficult to sync to same clock
Limit system clock to cyclotron RF - 100 MHz is high enough

200 mm of copper = 1 ns propagation delay

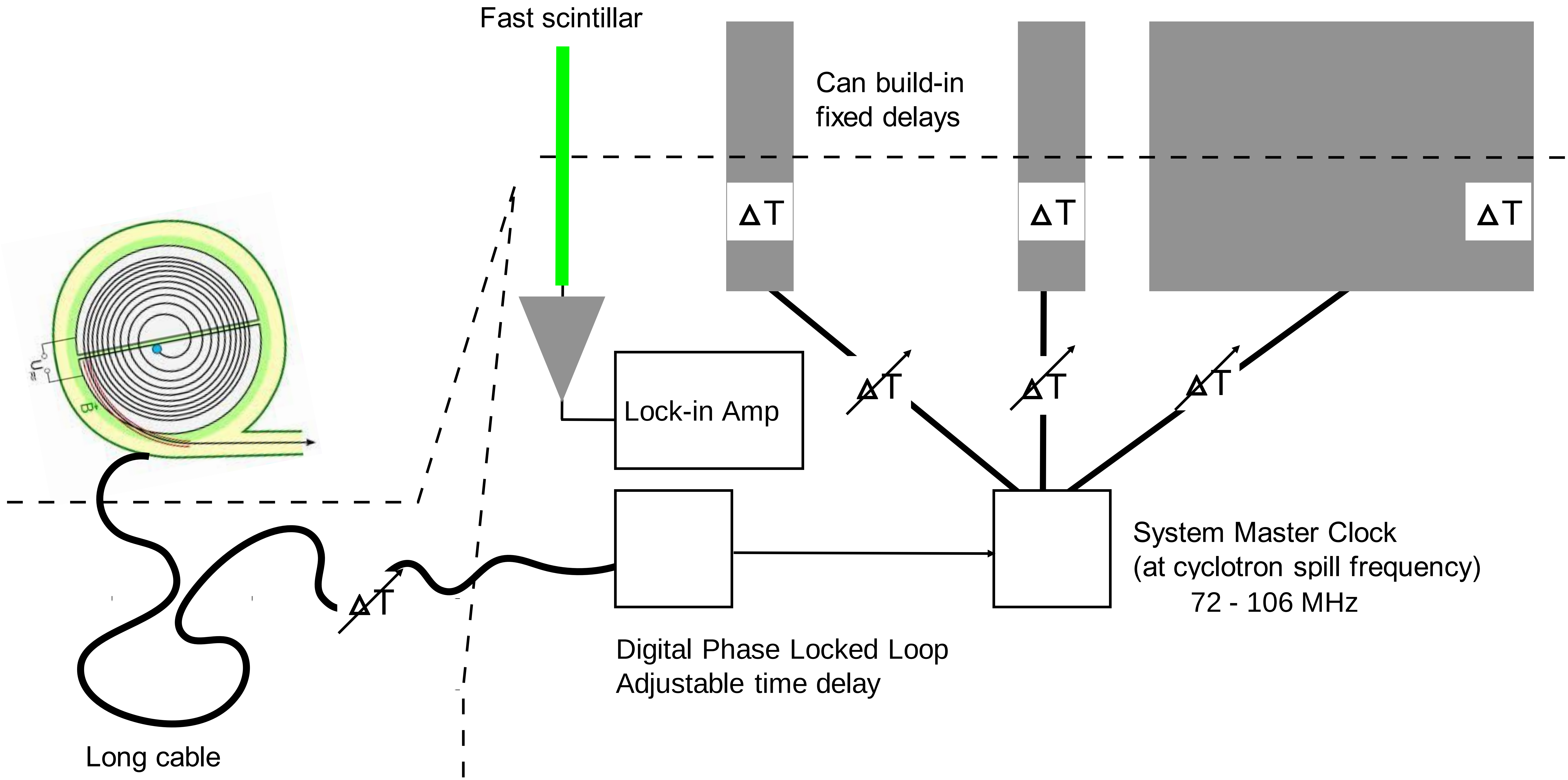
So we timestamp all data - either separate timecode or use clock cycle number
Increases data rate as not only strip number but some record of time
As sparse events can heavily compress data

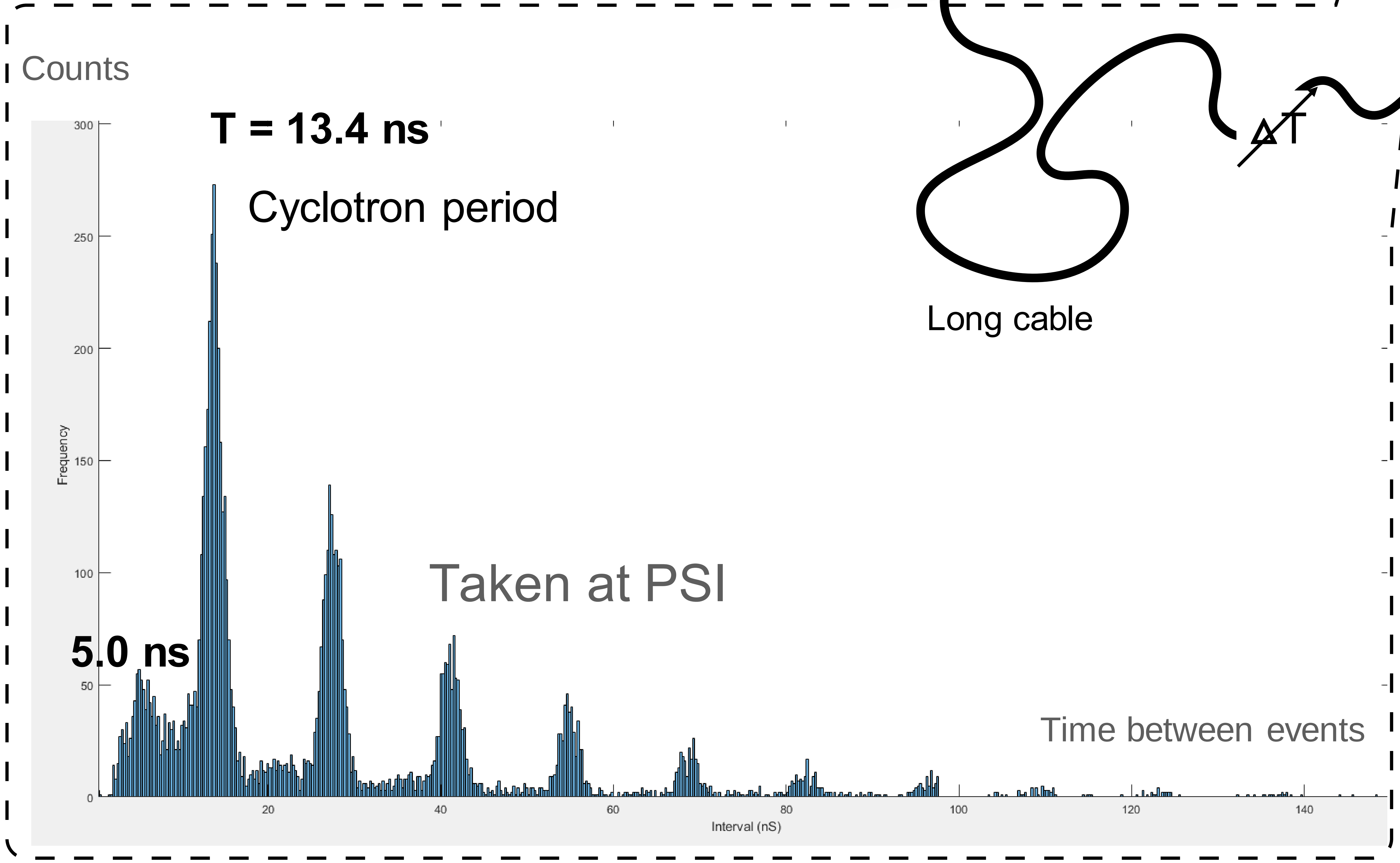
For full line scan ~ 24 Mbytes of data per layer

Synchronisation

Options

Direct link to Cyclotron RF
Not always allowable
Sync to proton arrival time





Computational effort to decide true paths through system much higher than CT reconstruction
Searching through multiple potential paths may be NP-complete problem

Acknowledgements

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Carla Winterhalter

Alexander Herrod

Christe PBT Centre

Ran Mackay

Adam Aitkenhead

University Hospitals Birmingham

Stuart Green

ISDI Ltd, London
aSpect Systems GmbH, Dresden

Summary

- Introduced some of the practical aspects in developing a proton CT system for operation at diverse facilities and for the normal operation envelope
- Aim for real-time data delivery – fully corrected trajectory co-ordinates and residual energy
- Positional Calorimeter not discussed due to patenting issues
- Advantages of developing custom sensors and ASICs
- Advantages of complete system approach and building to professional engineering procedures

Questions?