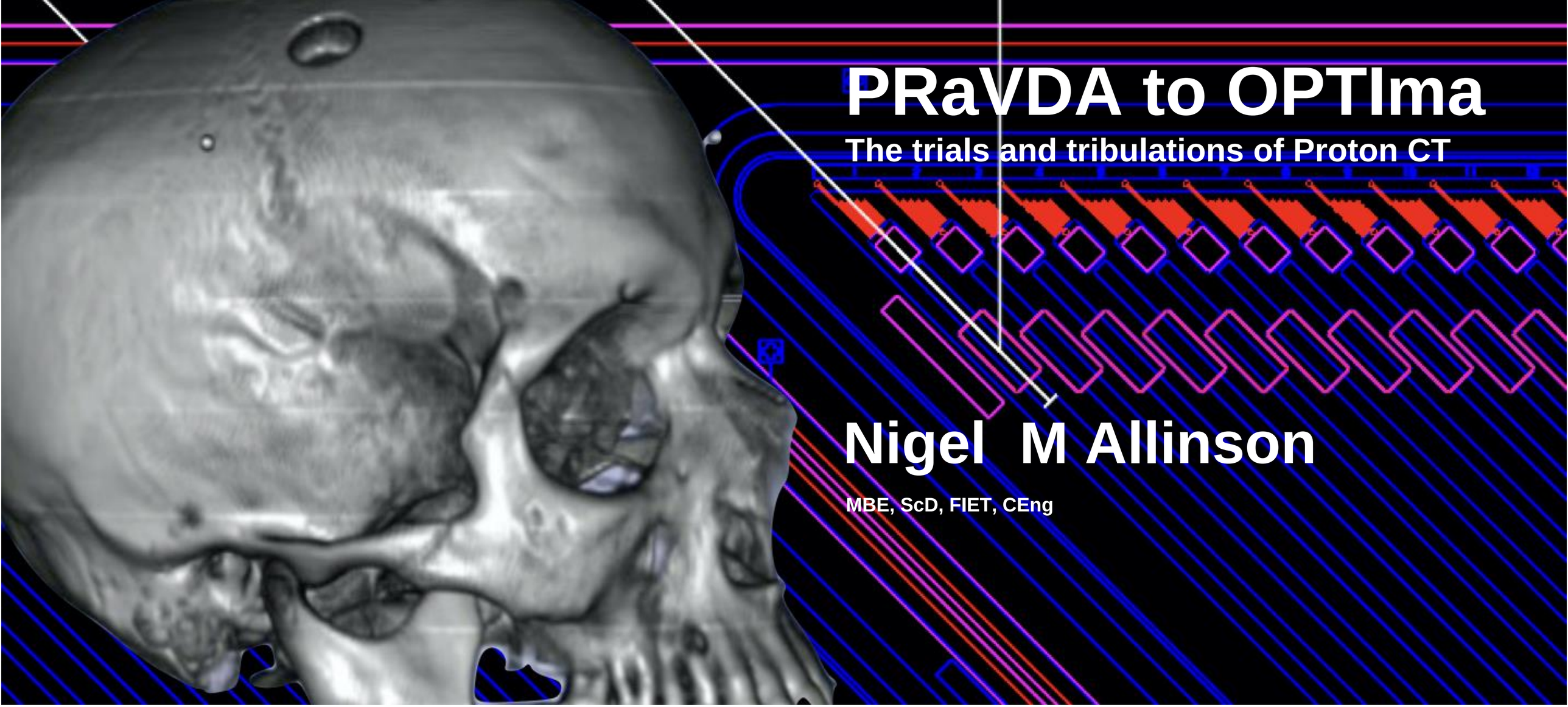

PRaVDA to OPTIma

The trials and tribulations of Proton CT

Nigel M Allinson

MBE, ScD, FIET, CEng

Detector Seminar
27 November 2020

PRaVDA wellcome trust OPTIma EPSRC

UNIVERSITY OF LINCOLN

First, apologies and a warning

I’m not a clinician
I’m not a medical physicist
I’m not a physicist

I’m an engineer

Arguing with an Engineer is a lot like wrestling in the mud with a pig. After a couple of hours, you realize the pig likes it.

Acknowledgements

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Daniel Schöne
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Across Europe
One new cancer diagnosis every 12 s
One death every 37 s

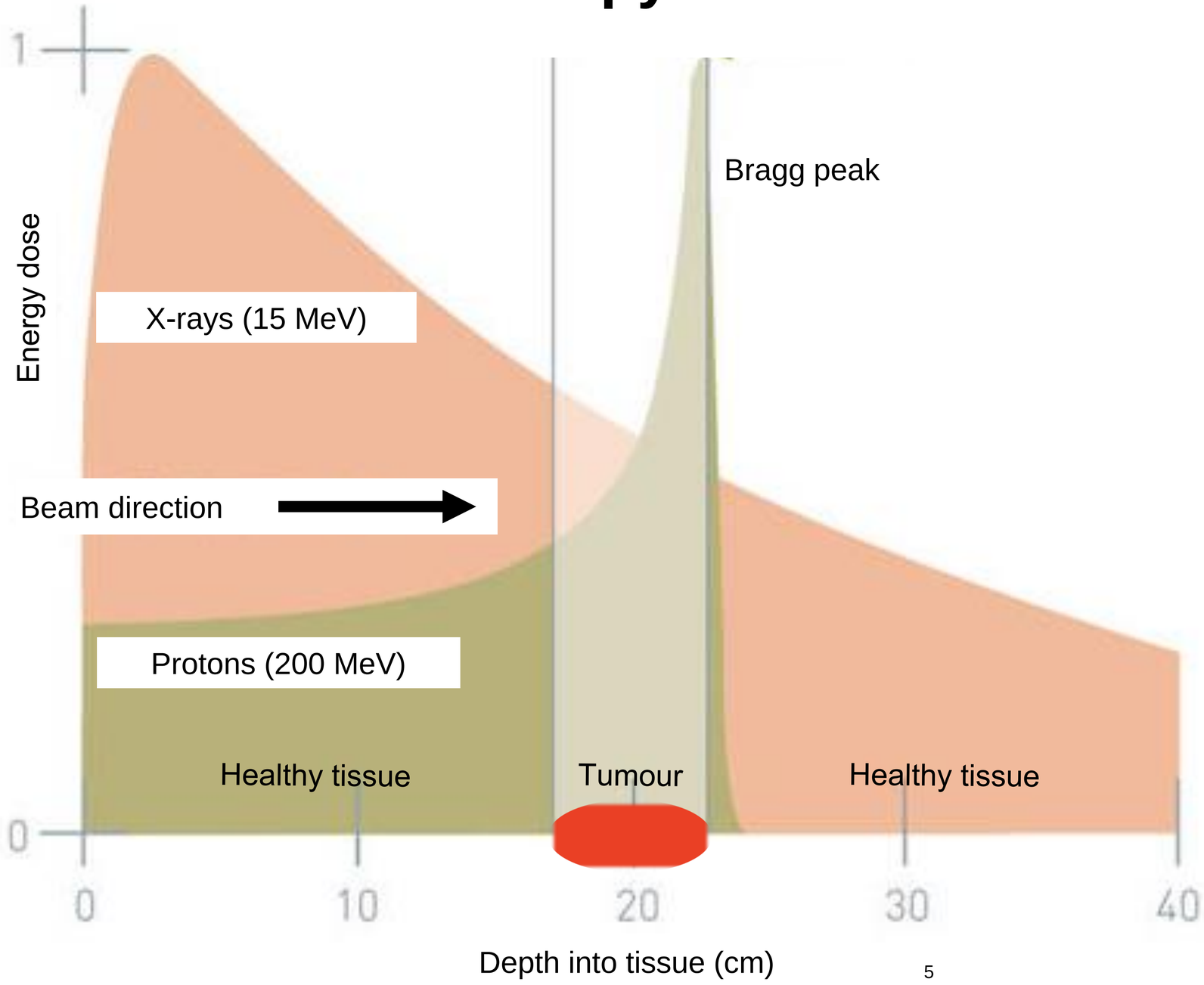
Estimated between 47% and 53% of cases require external beam radiotherapy for curative purposes

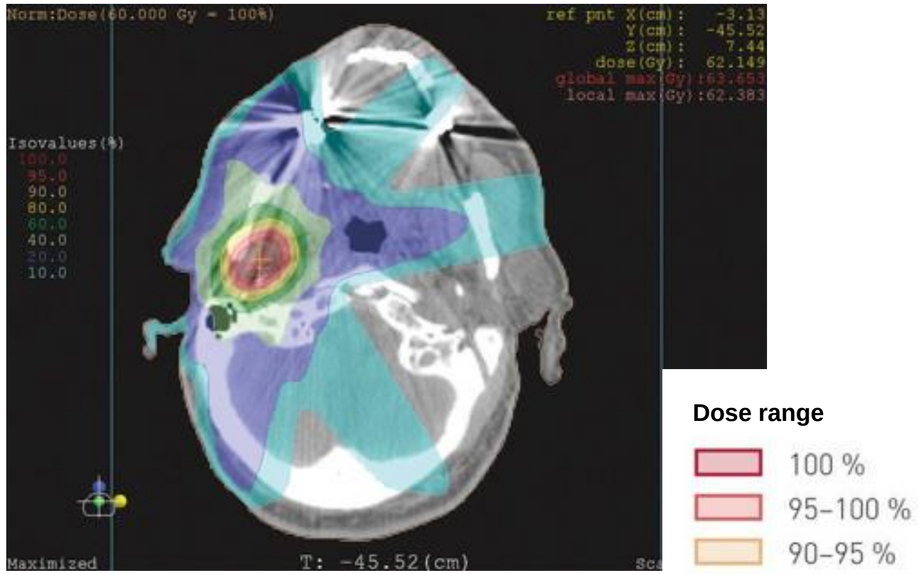
Most radiotherapy delivered by external x-ray beams from over 2,000 linacs across Europe

Over 30 operational proton beam therapy (**PBT**) centres across Europe

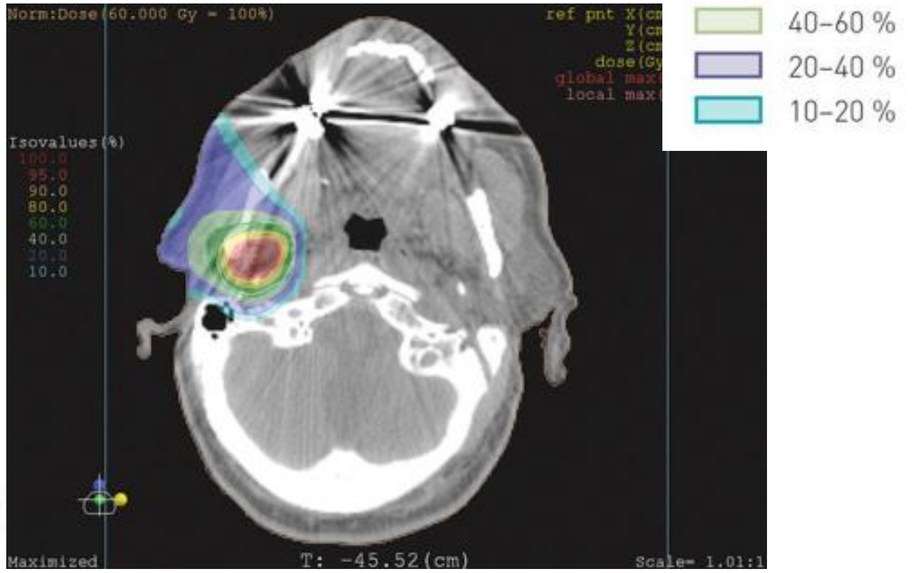
PBT today represents <1% of radiotherapy treatments, based on expert reports, at least 20% of patients could benefit from **PBT**

Proton Beam Therapy





X-ray radiotherapy



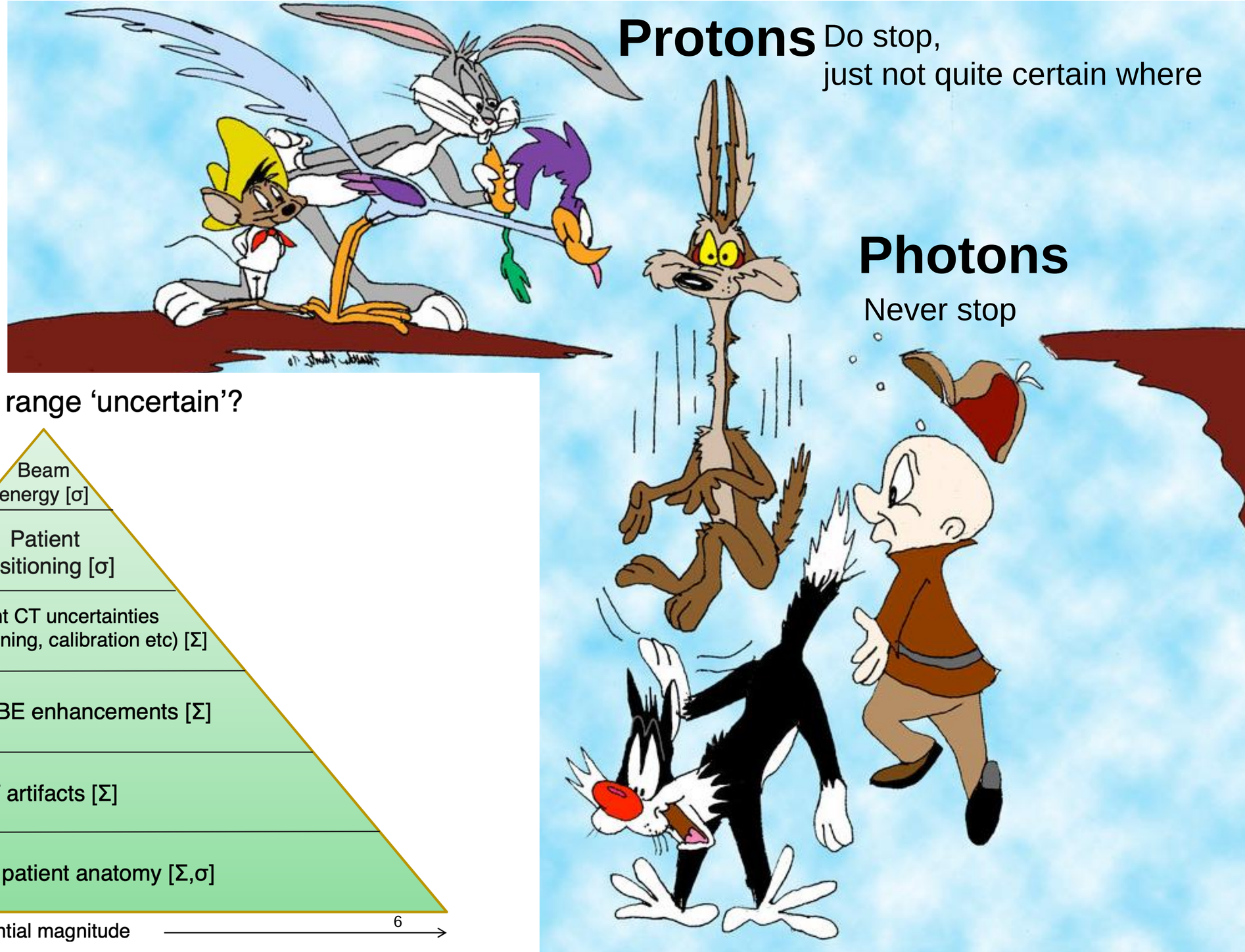
Proton radiotherapy

Dose range

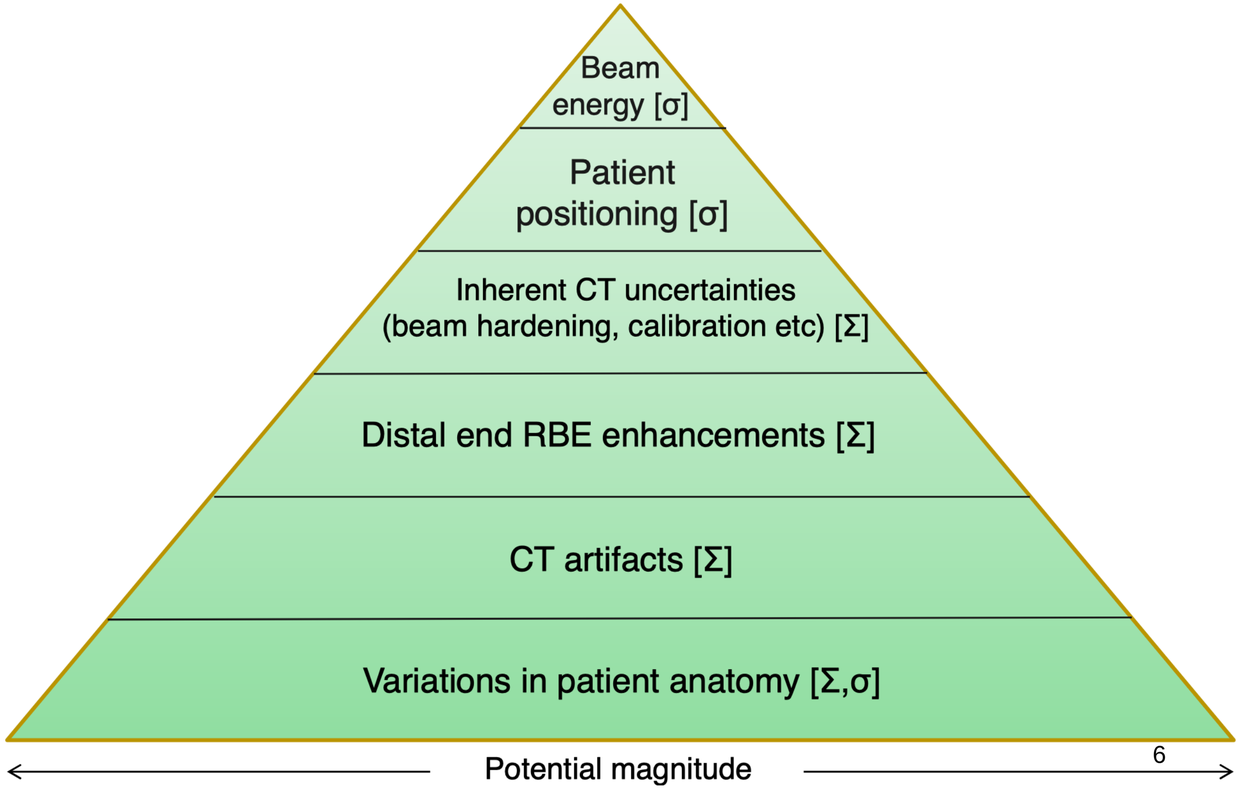
- 100 %
- 95–100 %
- 90–95 %
- 80–90 %
- 60–80 %
- 40–60 %
- 20–40 %
- 10–20 %

Why PBT?

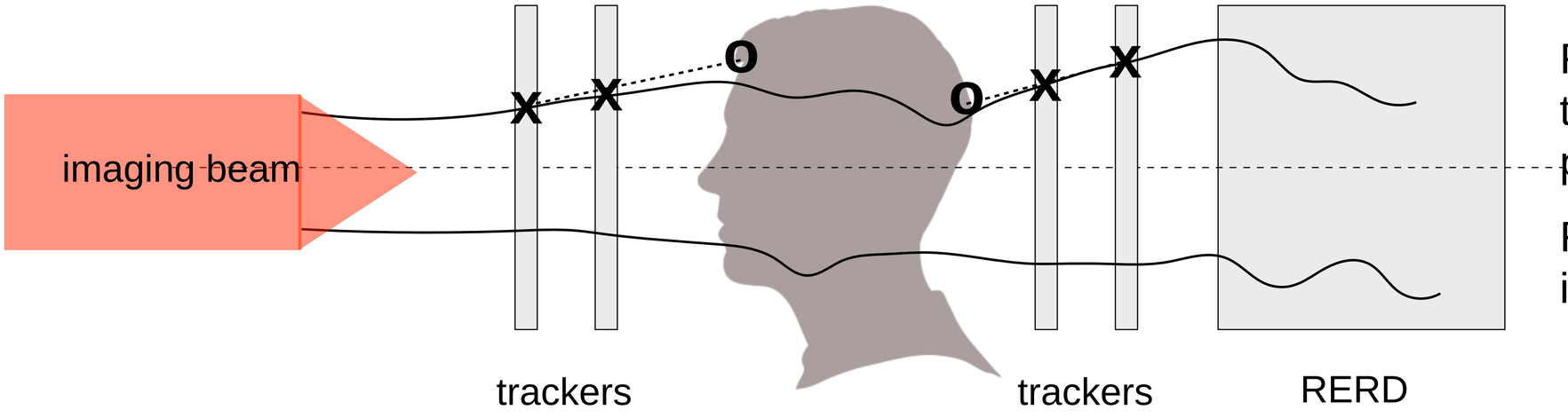
Essence of the advantage and the problem



What makes range ‘uncertain’?



Principles of proton CT instrument

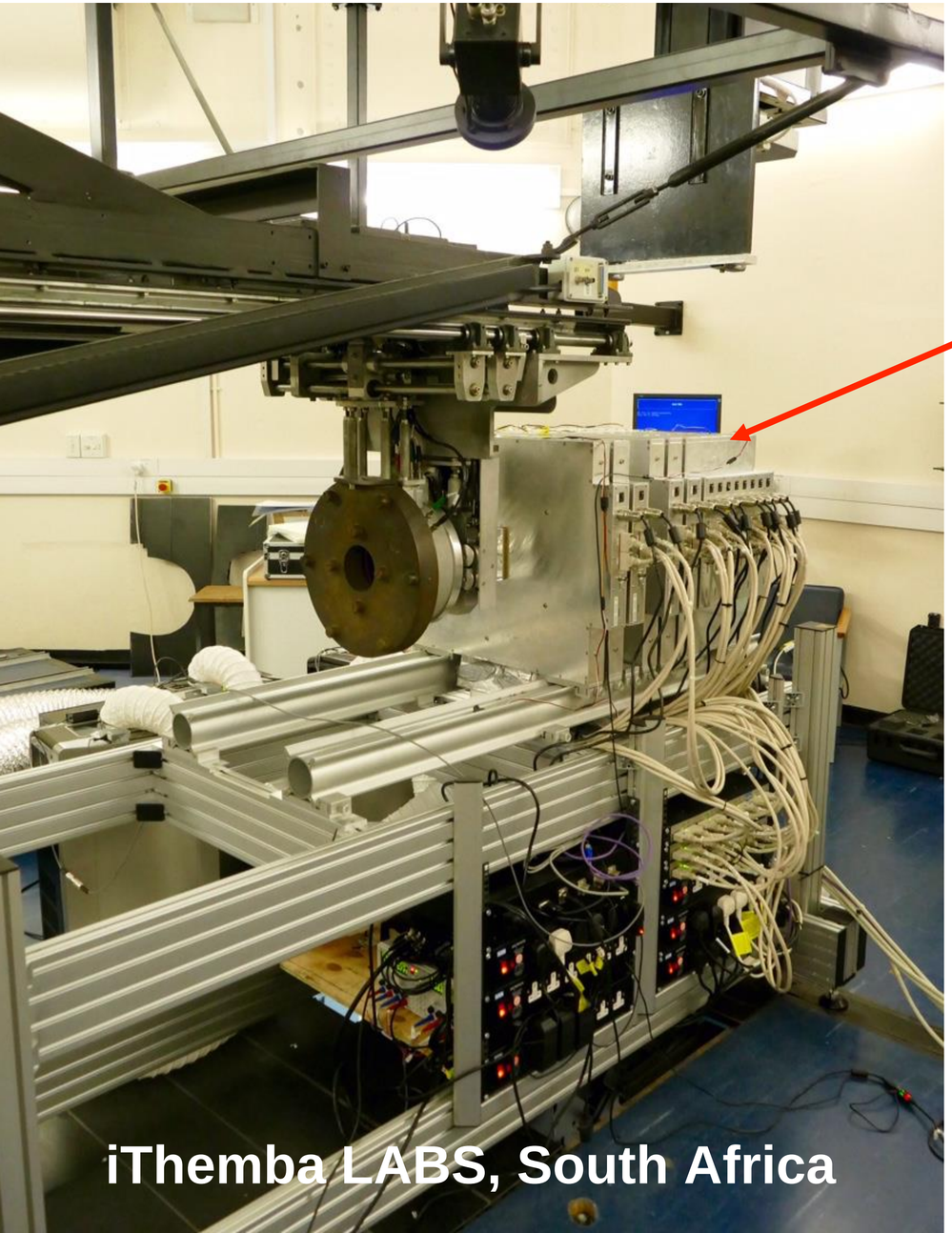


Record entry and exit trajectories of individual protons.

Record residual energy of the individual protons.

- Increase proton energy (ideally by about 70 MeV) and reduce intensity of beam by a factor of ~10,000.
- Pair of proximal position-sensitive trackers records trajectory of individual protons, and pair of distal trackers records corresponding exit trajectory
- Residual Energy Resolving Detector (RERD) logs the residual energy of each proton (*TATE*)
- For each proton: (entry position, exit position and energy absorbed).
- Rotate patient/instrument a degree or so, and repeat – require ~$10^{7\text{-}8}$ such triplets for full CT

Passively scattered broad beam (85 ϕ mm) - 192 MeV maximum



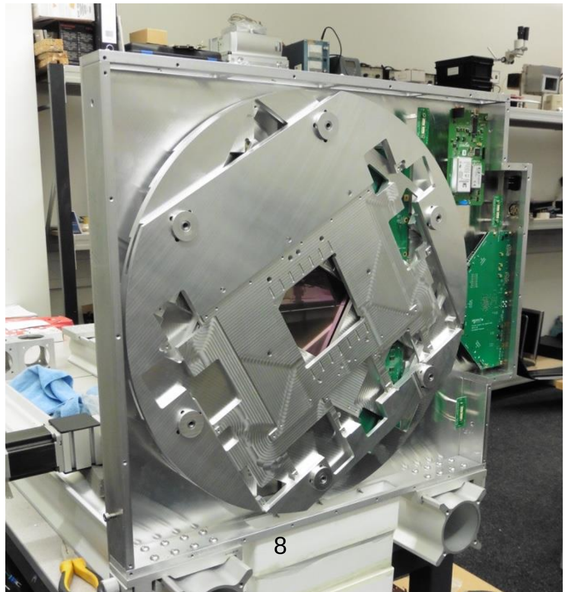
Distal trackers

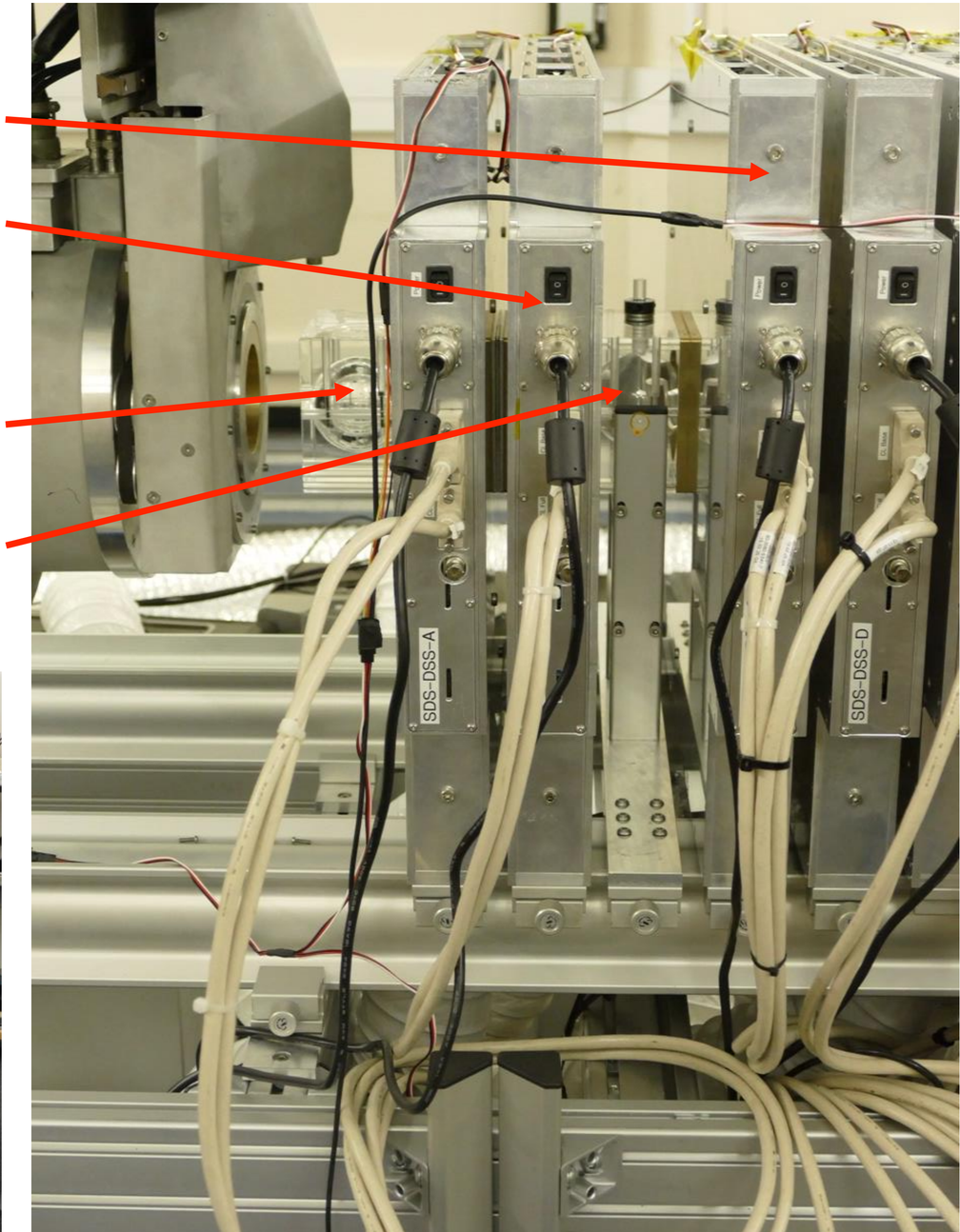
Proximal trackers

Range telescope

Compensator

Phantom





Proton trackers

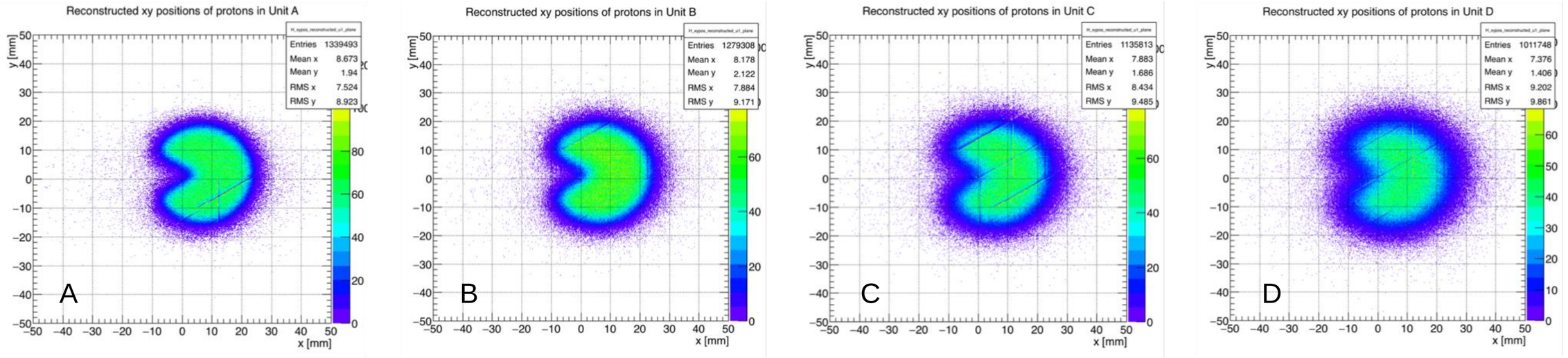
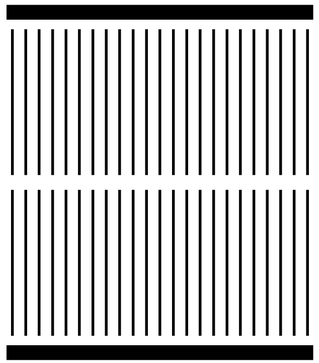
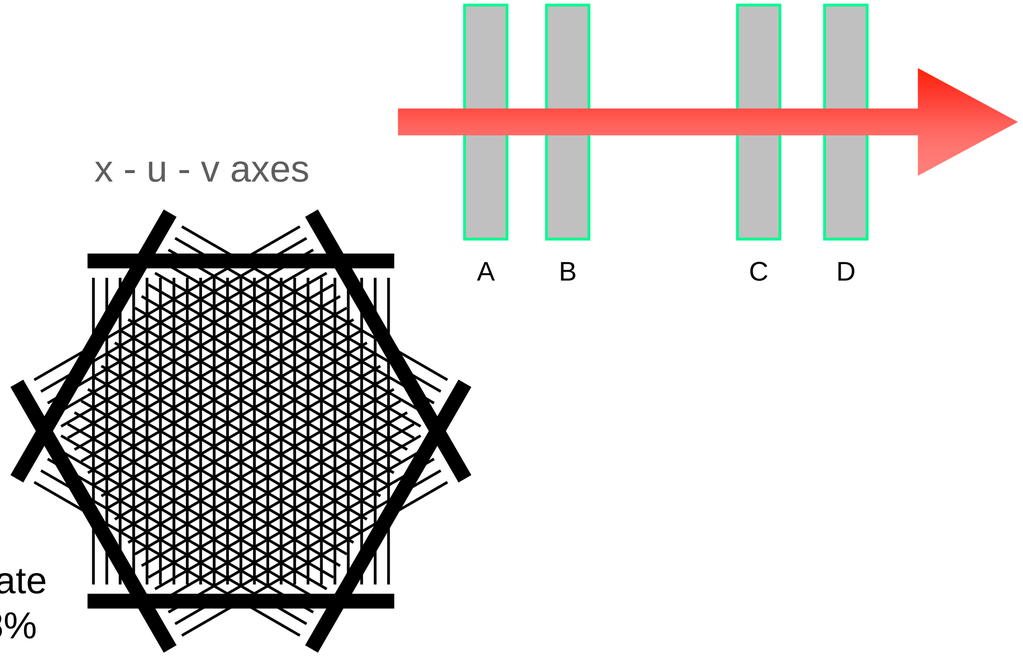


Image reconstructions – Pac-man collimator (29 MeV)



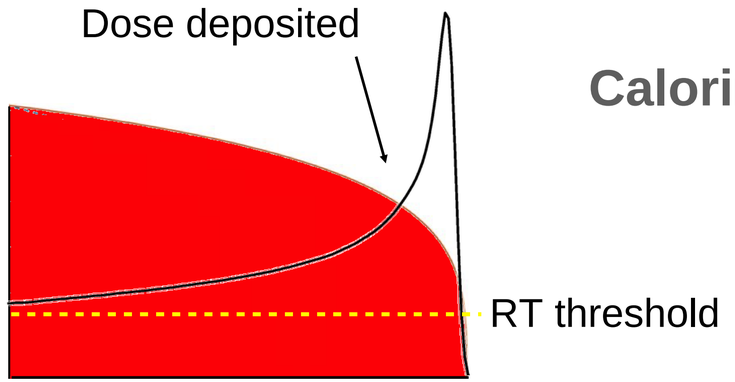
SSDs 150 μm *n-in-p* silicon with an active area of 93 × 96 mm^2 and a strip pitch of 90.8 μm. Detectors comprise 2048 split channels

Readout by 16 custom ASICs in 0.18 μm CMOS process, with two tunable thresholds, read out at 26 MHz and up to 8 channels can be read out per readout cycle (39 ns). Translates to 2 × 10^8 protons/s to be detected over the full detector area.

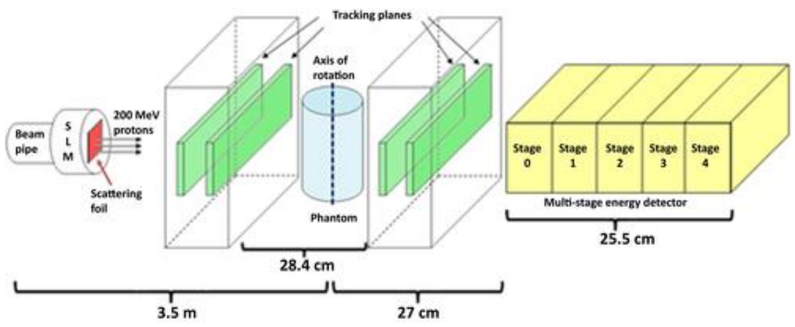


Three equi-rotated layers in increase count rate
Ambiguity rate of 30 hits per time-slot is ~8%

Range telescope



Calorimeter



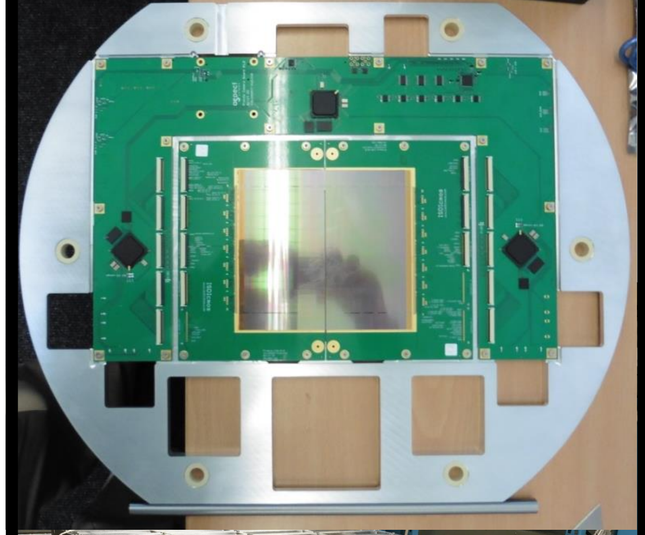
Loma Linda 5-stage scintillator RERD
(perhaps, current *Gold Standard*)

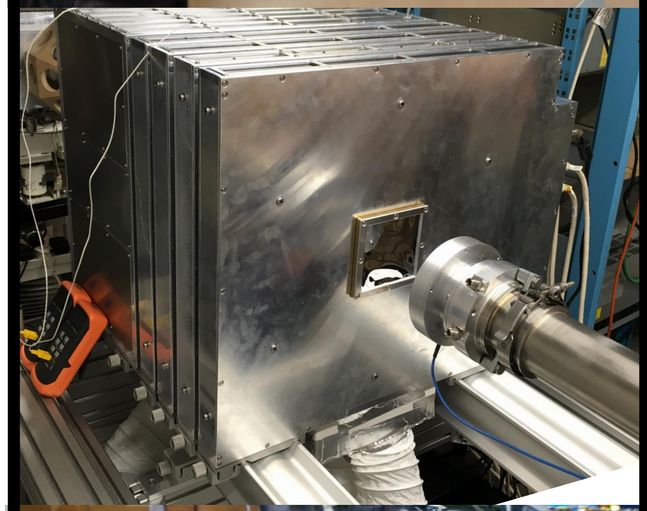
Range Telescope

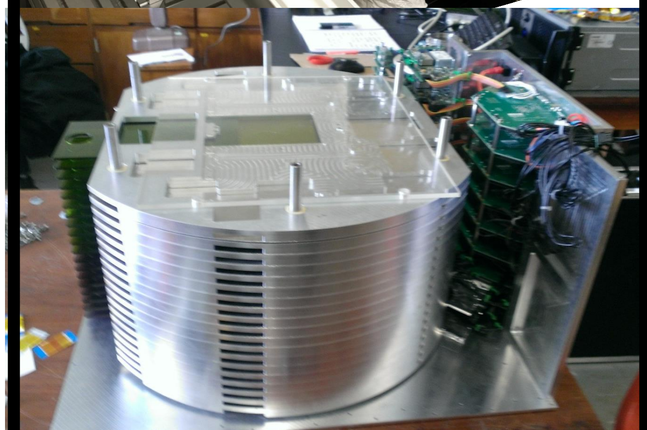
Record last layer activated
(range α^{al} to energy)

Comprises 21 layers of SSD interleaved with 2-mm thick PMMA absorbers, providing a Water Equivalent Thickness (WET) of 2.6 mm per layer and an overall WET of 55.4 mm.

Designed to stop protons in the range 30–80 MeV, as expected from a 125 MeV incident beam after passing through a 75 mm thick PMMA phantom. Thickness of a single layer optimised to allow detection of lower energy protons, while first and last layers used as *veto* layers.



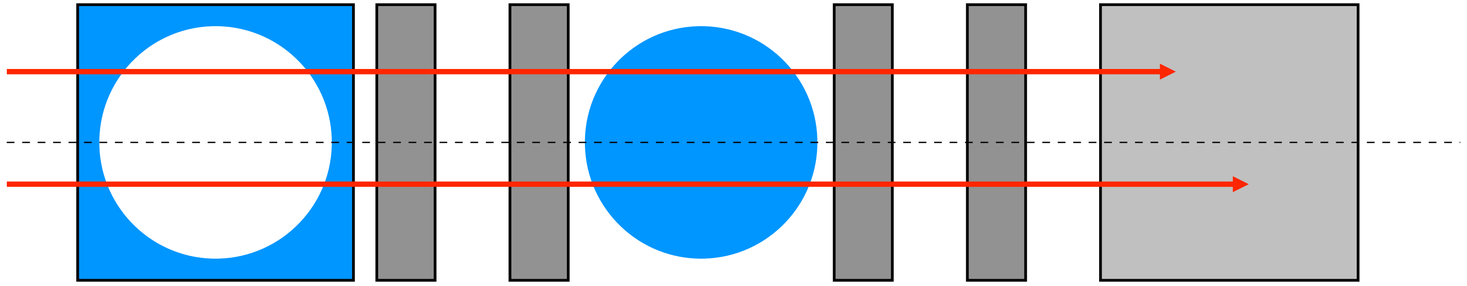




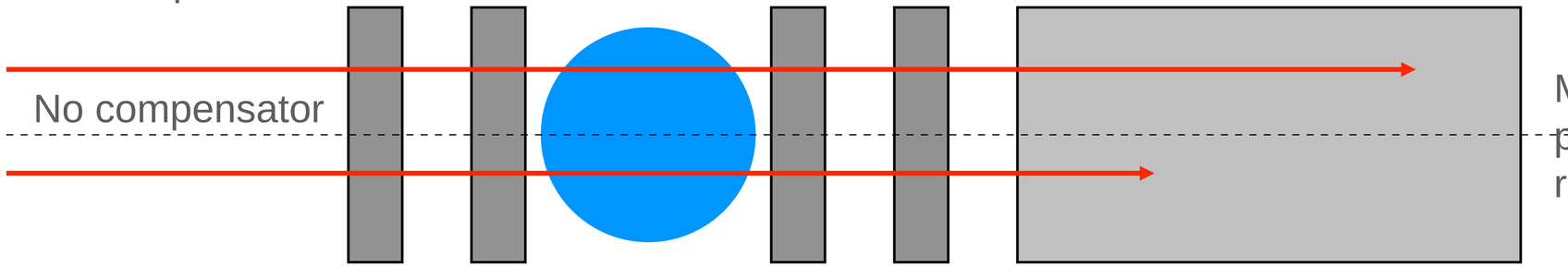
Esposito M, Waltham C, Taylor JT, Manger S, Phoenix B, Price T, Poludniowski G, Green S, Evans PM, Allport PP, Manolopulos S. PRaVDA: The first solid-state system for proton computed tomography. Physica Medica. 2018 Nov 1;55:149-54.

Limitations of range telescopes

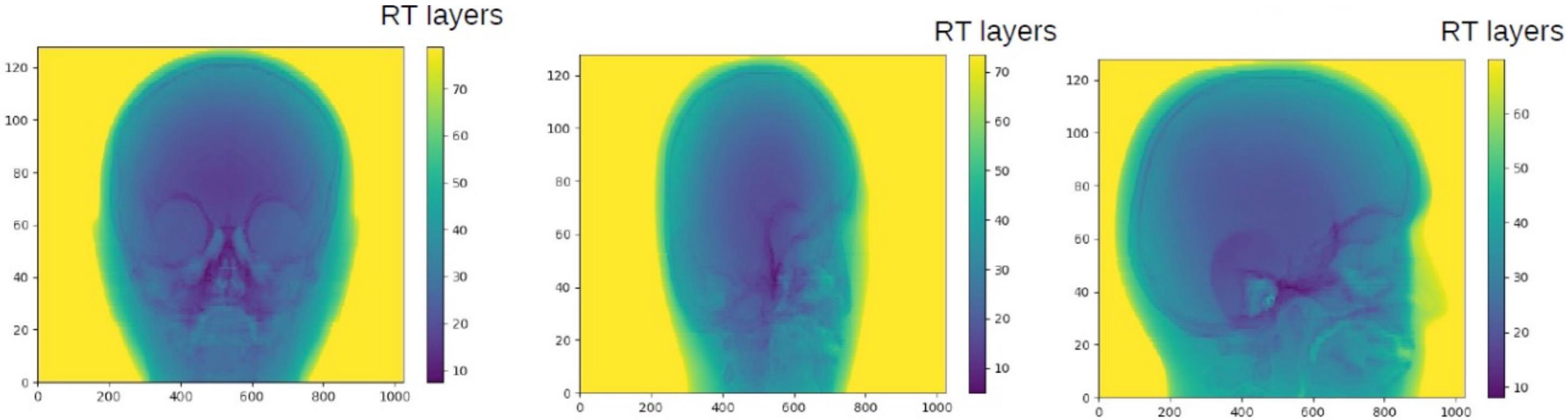
Radiotherapy bolus



PRaVDA employed a compensator

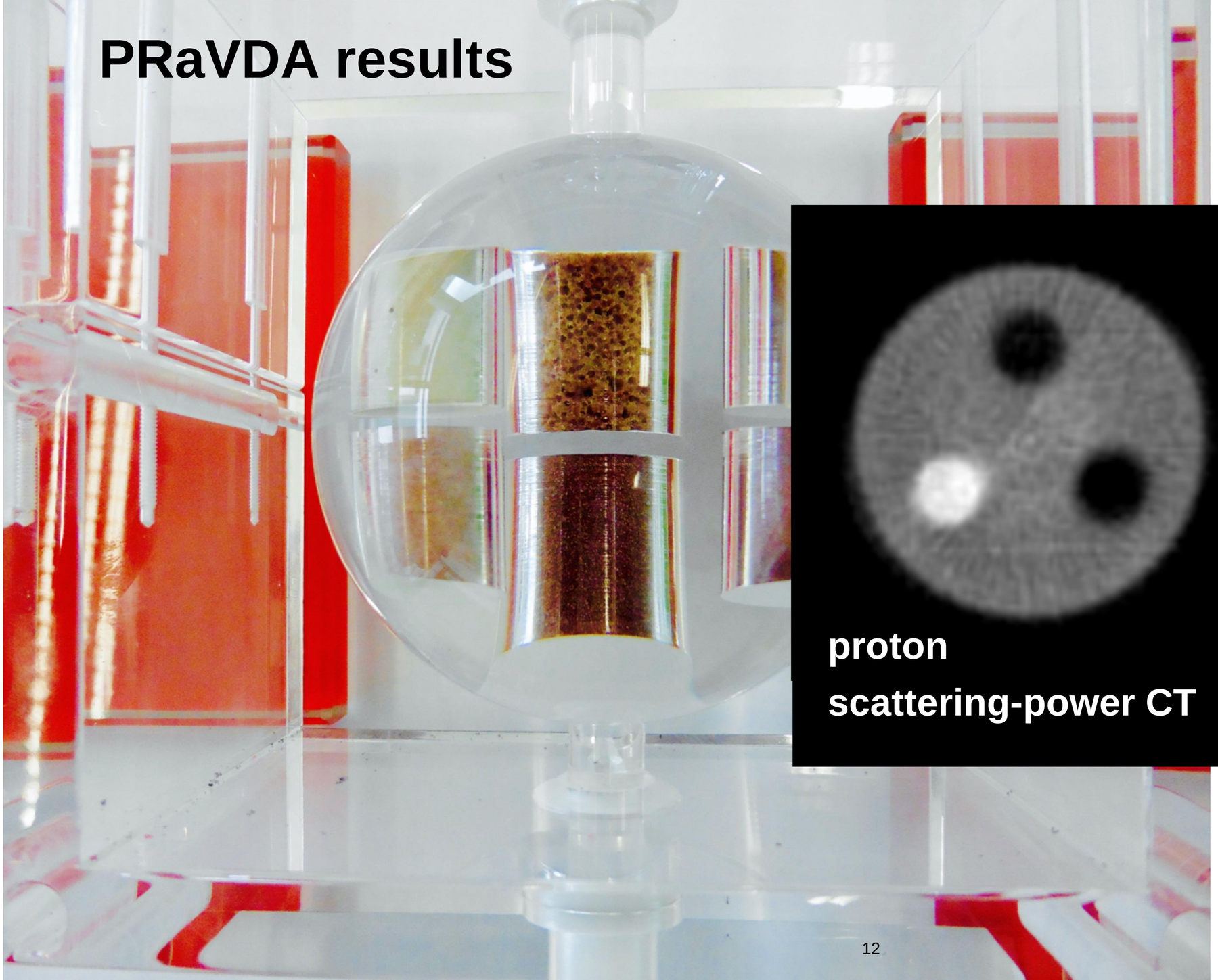


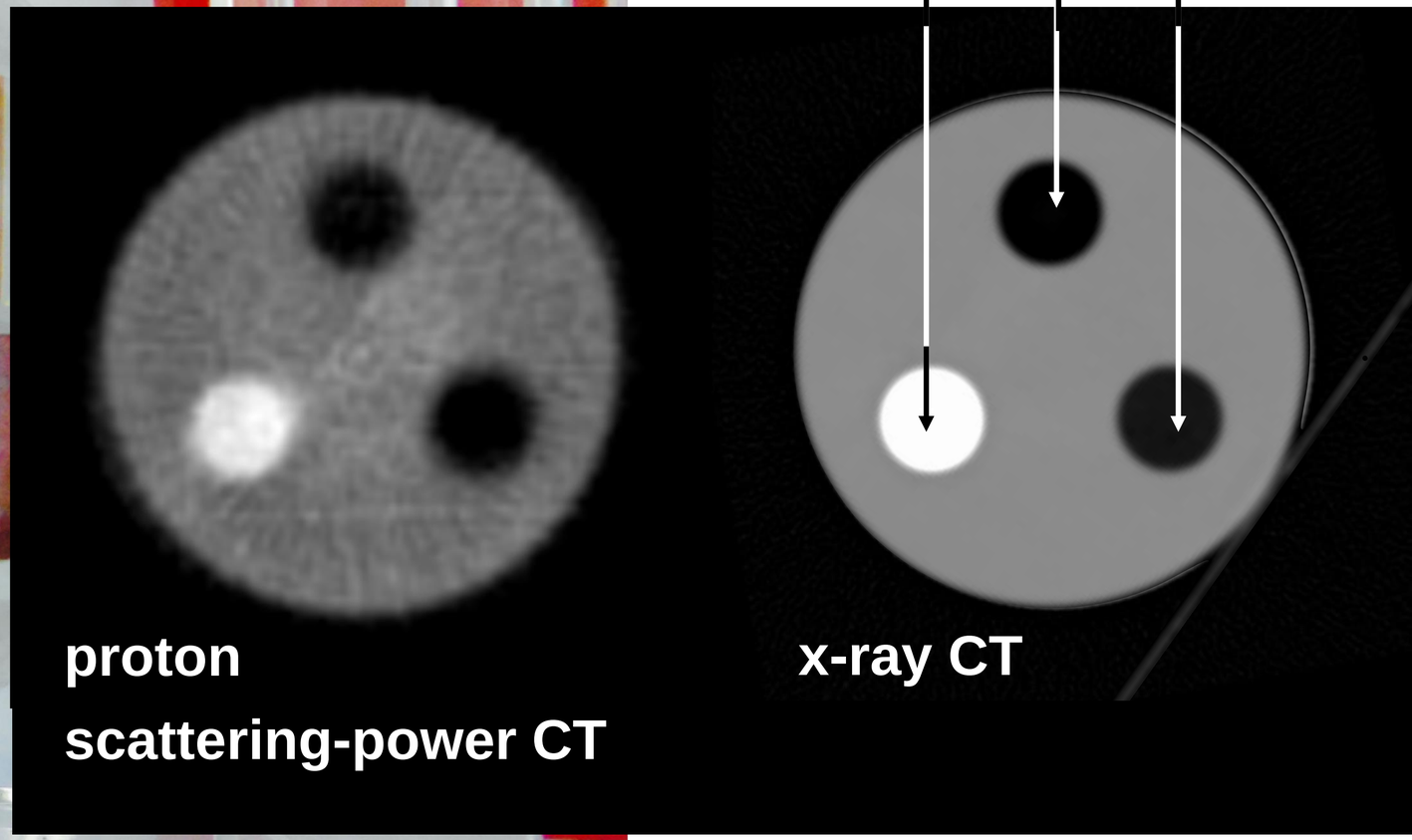
Many layers to preserve energy resolution



For nominal 1% energy resolution needs about 70 layers!

PRaVDA results

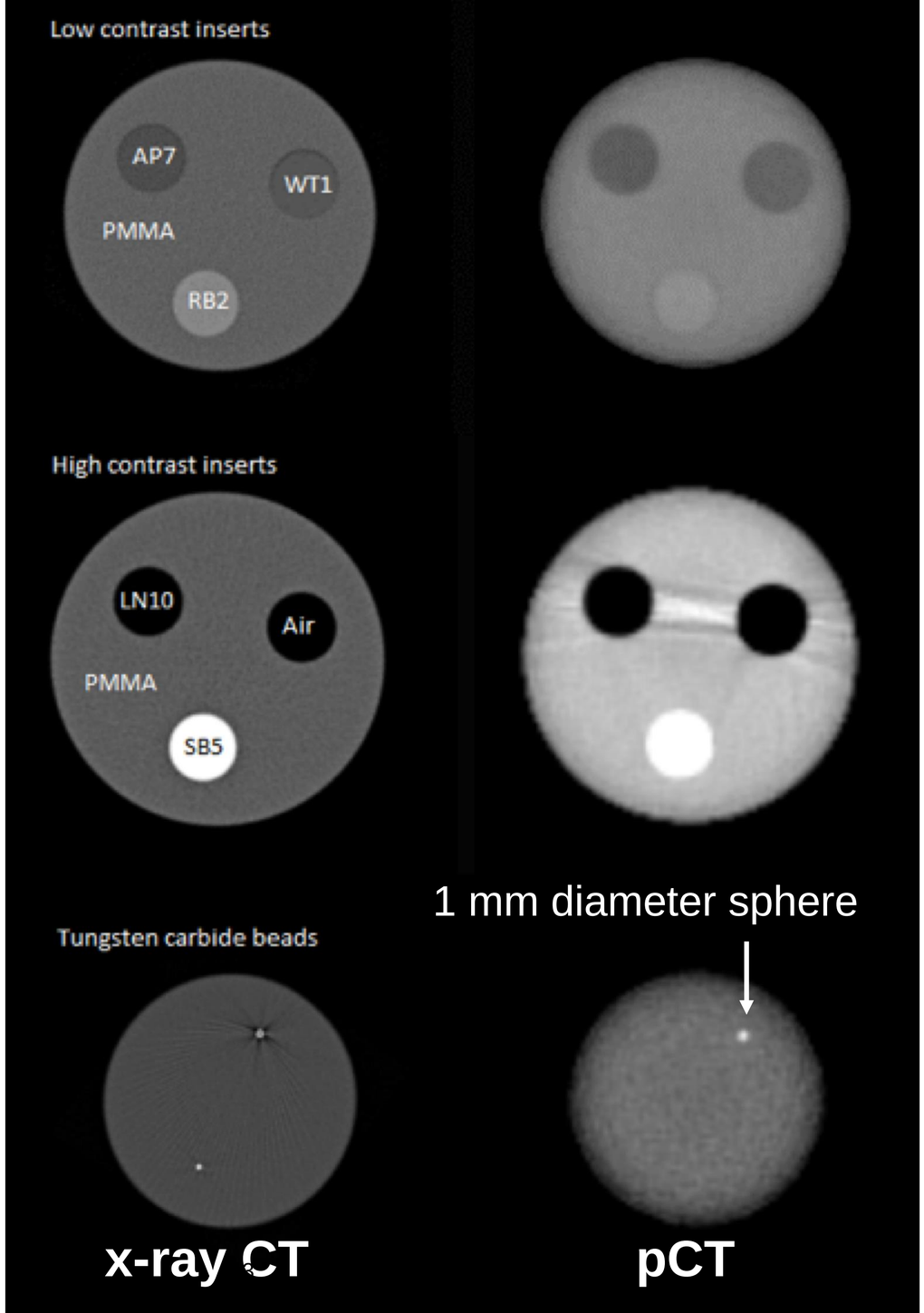




Taylor, J. T., et al., (2016), *An experimental demonstration of a new type of proton computed tomography using a novel silicon tracking detector*. Med. Phys., **43**: 6129–6136.

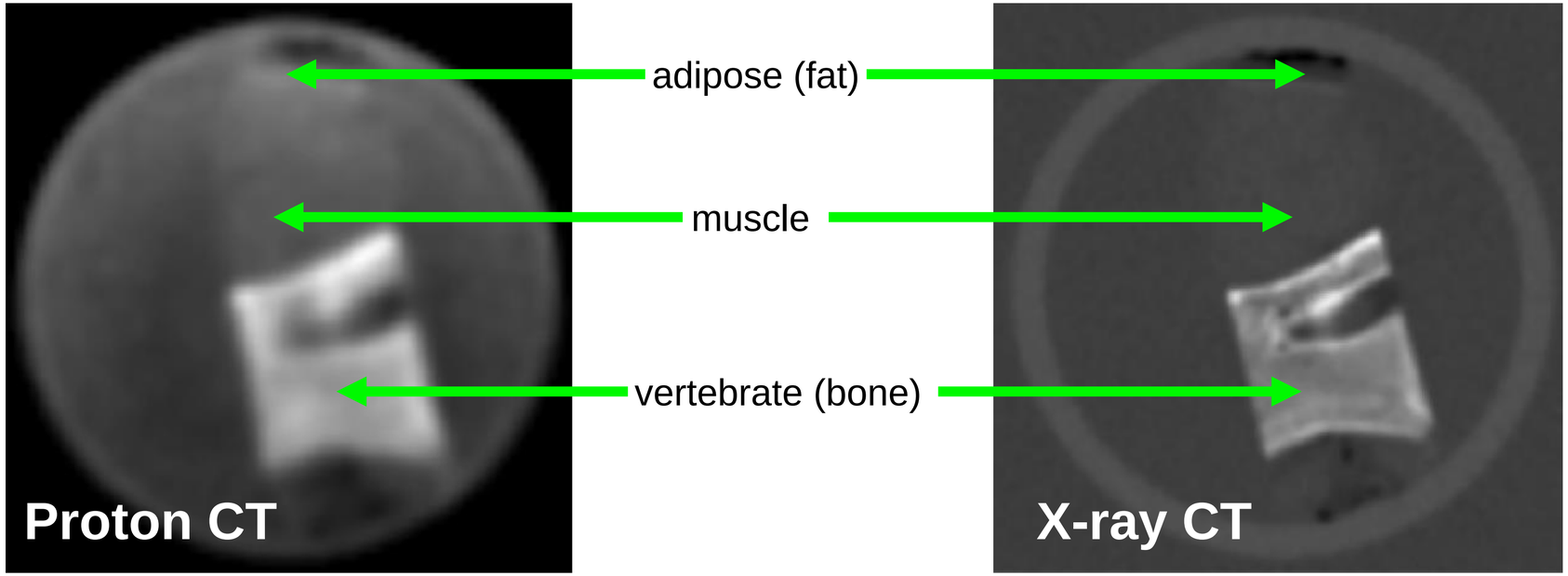
PRaVDA results

Material	Density [g/cc]	Expected RSP	pCT RSP	Percent error
PMMA	*~1.16*	*1.15*	*1.15*	*0.0*
AP7(adipose)	*0.92*	*0.95*	*0.94*	*-0.7*
WT1(water equivalent)	*1.00*	*1.00*	*0.98*	*-1.6*
RB2 rib/average bone	*1.40*	*1.21*	*1.22*	*1.2*
SB5 hard cortical bone	*1.84*	*1.63*	*1.62*	*-0.4*
LN10 *lung*	0.25-0.35	0.25	0.29*	-*
AIR	0.00	0.00	0.09*	-*

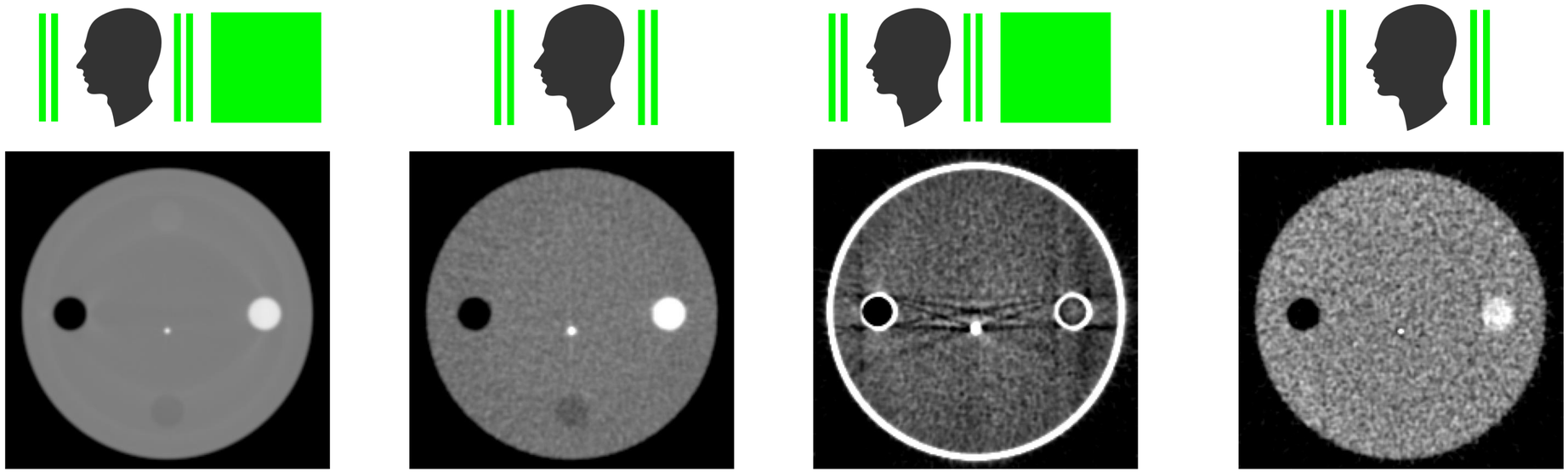


Comparison of film radiograph and PRaVDA radiographs

Lamb chop



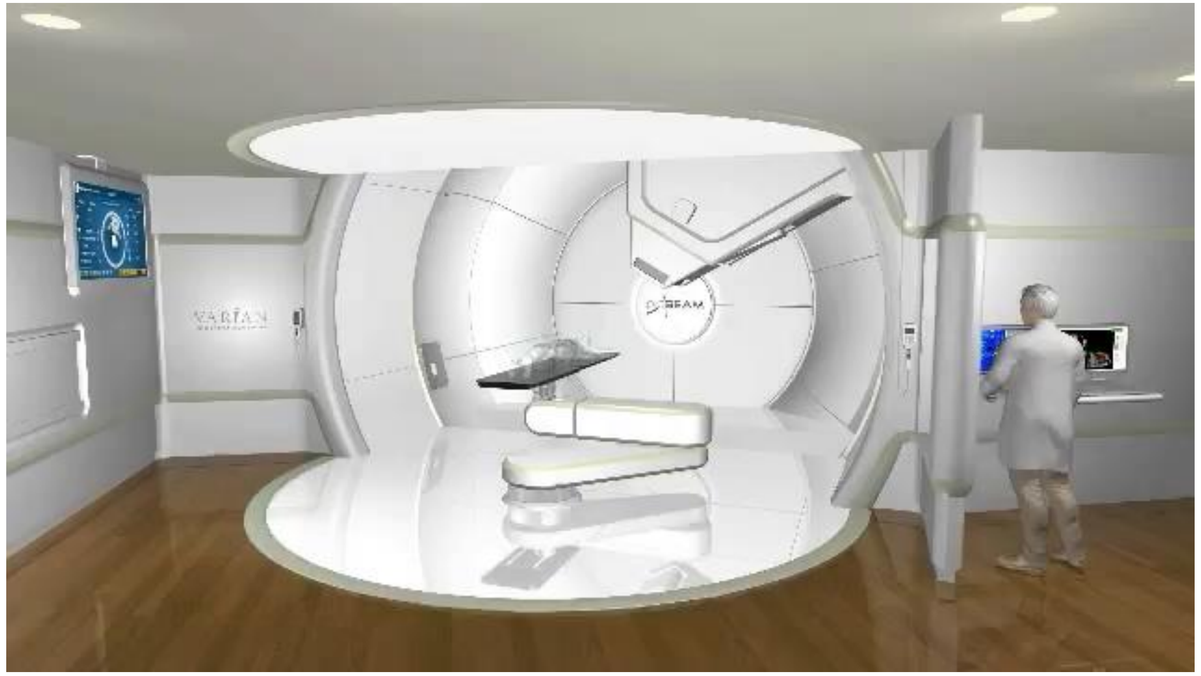
An aside



relative stopping-power | relative scattering-power | relative straggling-power | relative attenuating-power

Current PBT delivery

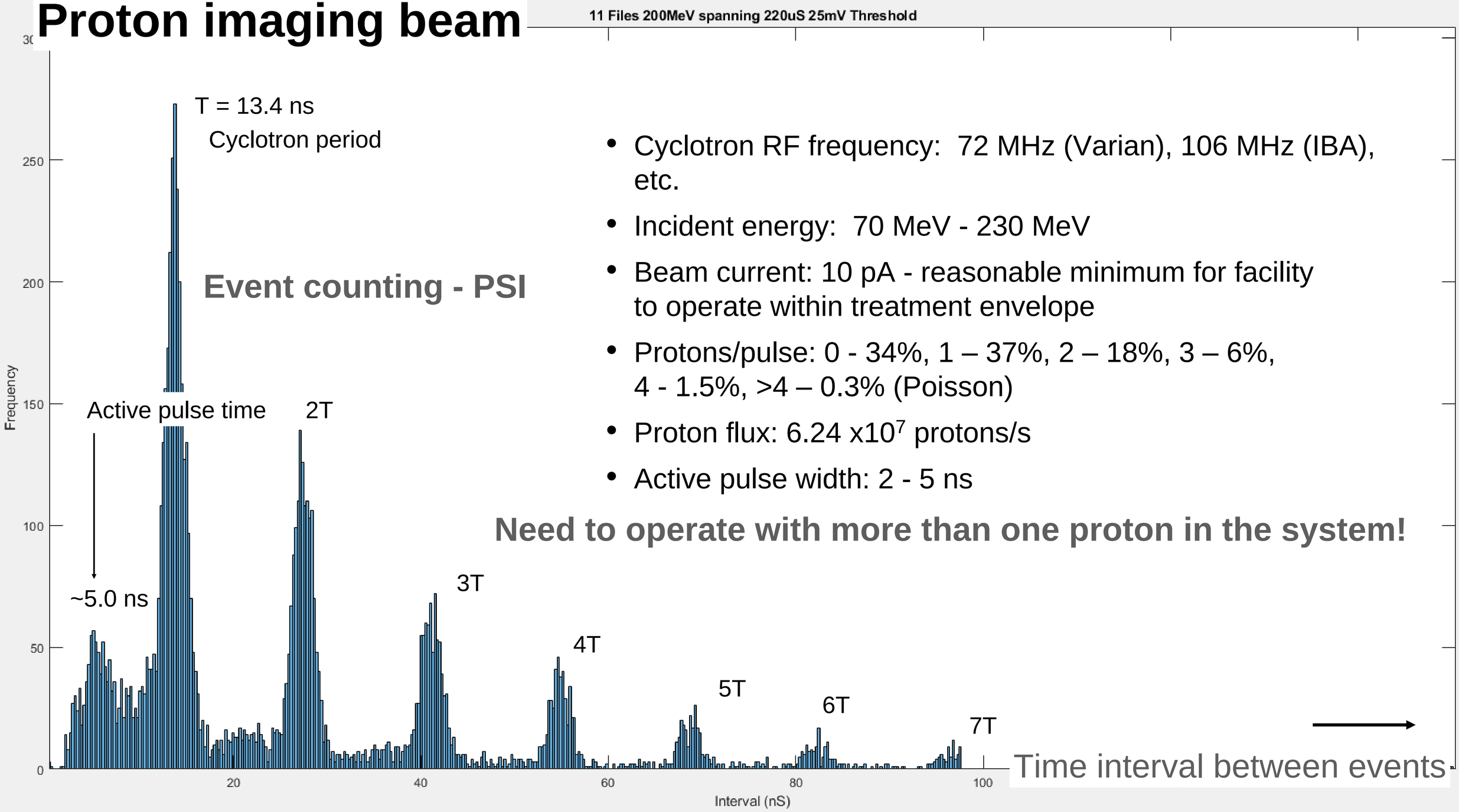
- Pencil-beam (few mm dia.) scanning
- Real-time energy changes
- Full scan area typically 30 - 40 cm square
- Spot scan velocities up to 10 ms^{-1}
- Gantry operation!
- Certified working envelope for cyclotron
- Must integrate with clinical workflows
- Must meet clinical needs
- For commercial take-up need wide usage across different vendor’s system



OPTima

Optimising Proton Therapy through Imaging

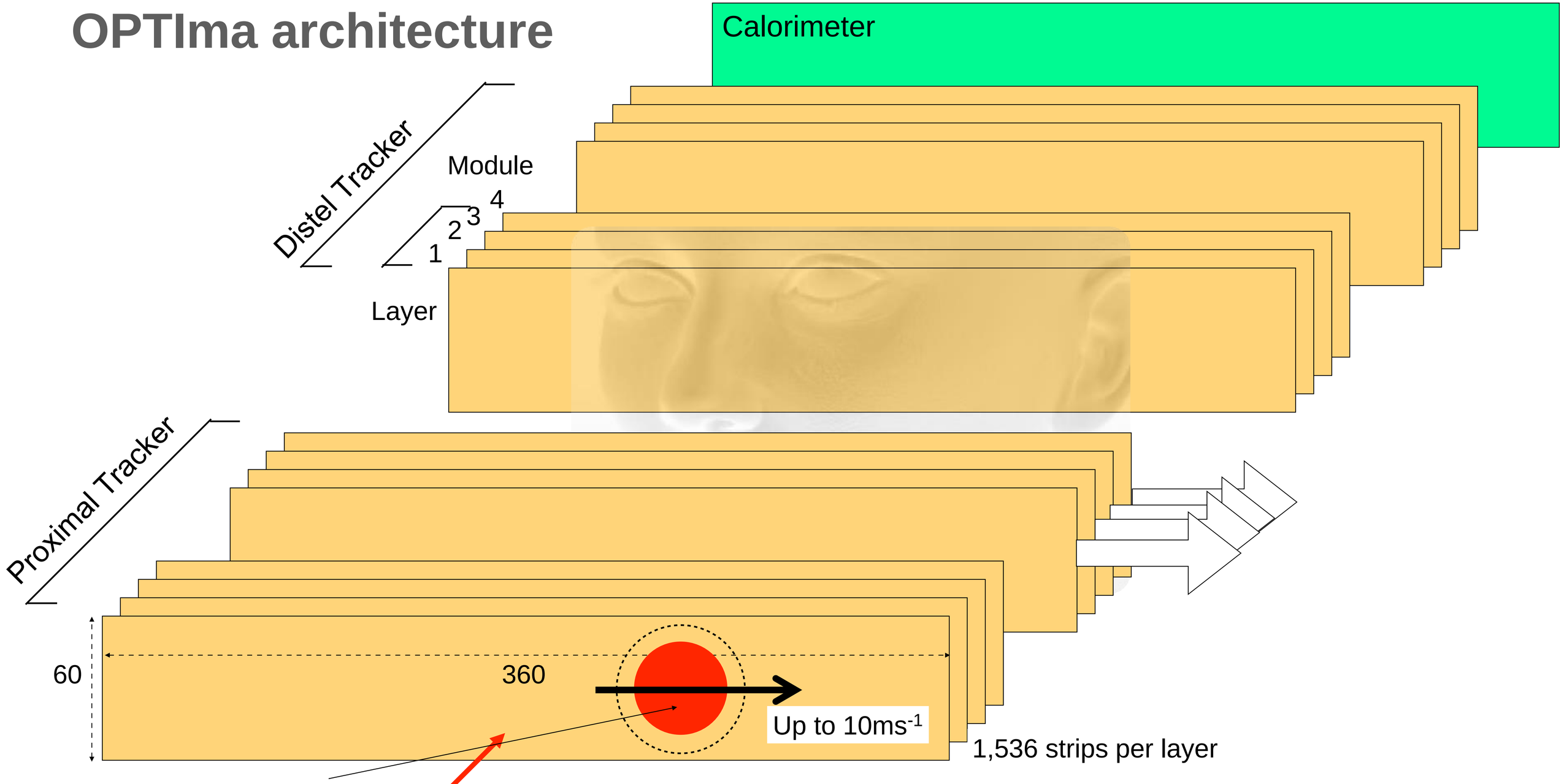
Proton imaging beam



- Cyclotron RF frequency: 72 MHz (Varian), 106 MHz (IBA), etc.
- Incident energy: 70 MeV - 230 MeV
- Beam current: 10 pA - reasonable minimum for facility to operate within treatment envelope
- Protons/pulse: 0 - 34%, 1 – 37%, 2 – 18%, 3 – 6%, 4 - 1.5%, >4 – 0.3% (Poisson)
- Proton flux: 6.24 x10^7 protons/s
- Active pulse width: 2 - 5 ns

Need to operate with more than one proton in the system!

OPTIma architecture



Dia = 40 (at front tracker)

Average one proton per pulse

For notional 10 pA current

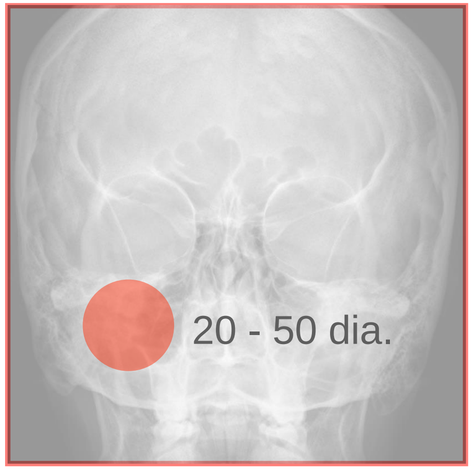
7.7 - 10 x 10^4 protons/ ms

Modular design: 60 x 60 blocks

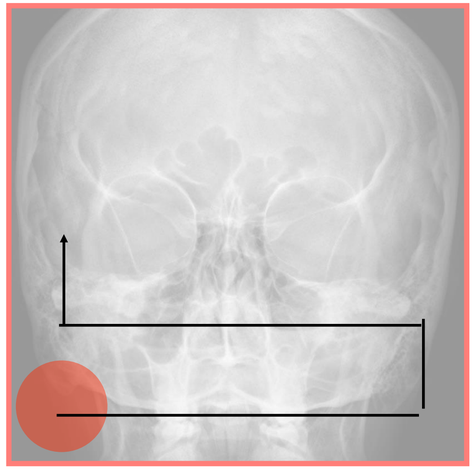
Instrument aperture

For imaging, would like this
Need post-nozzle scatter

300-400 square scan area

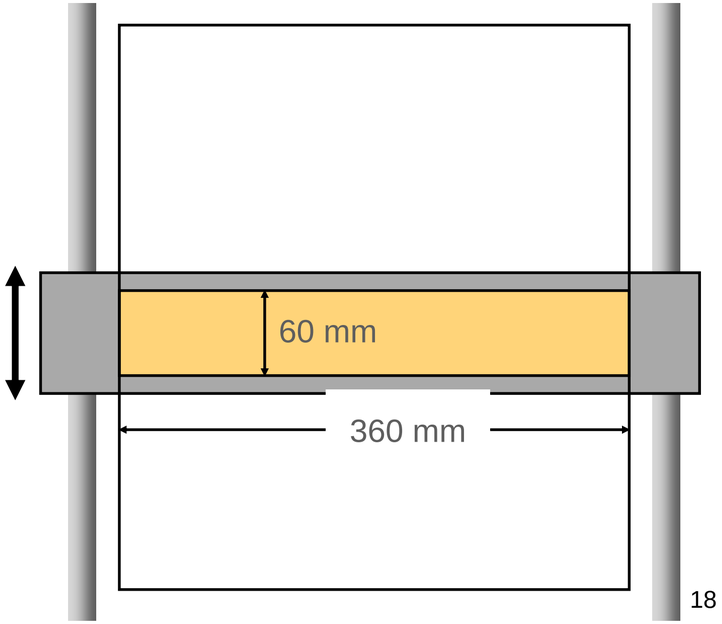


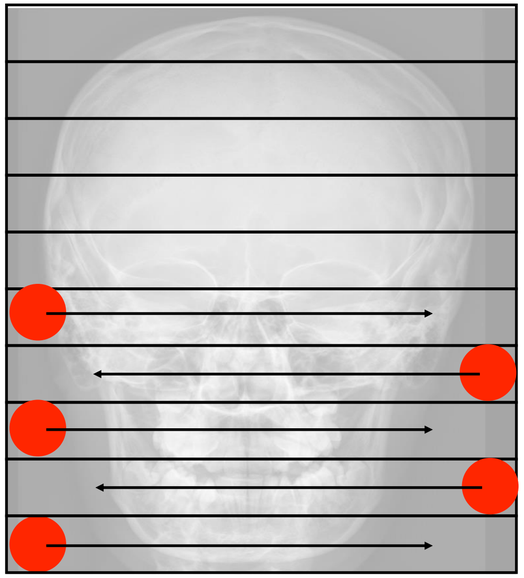
With nozzle, get this

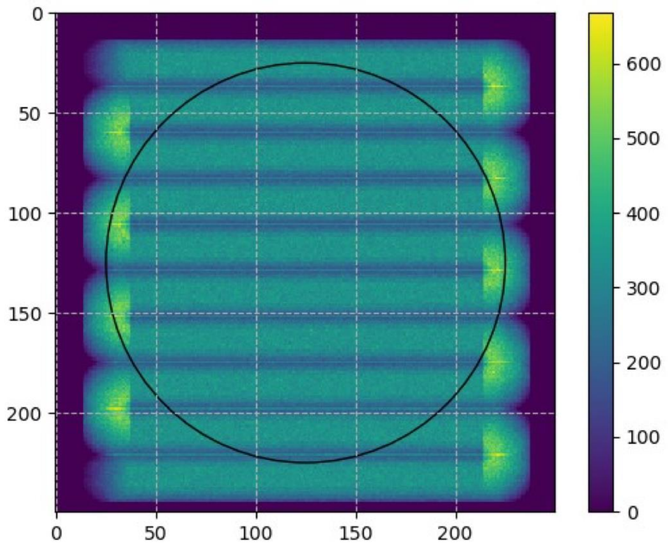


Need to scan
Maximum scan velocity ~ 10 ms^{-1}

Compromise

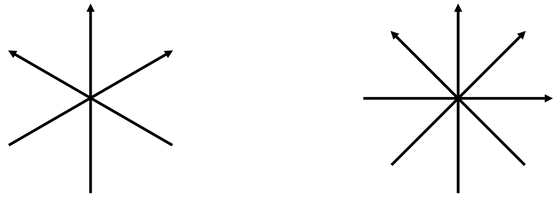






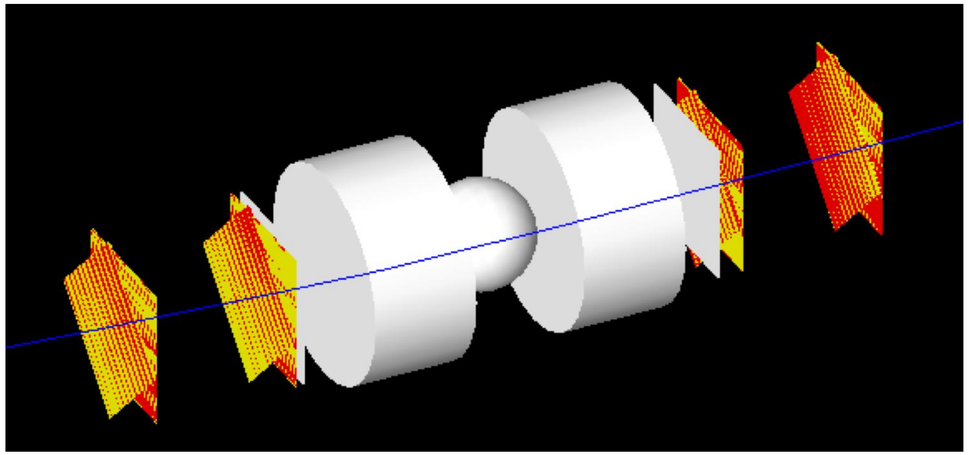
Dose map

Strip sensors - how many layers?

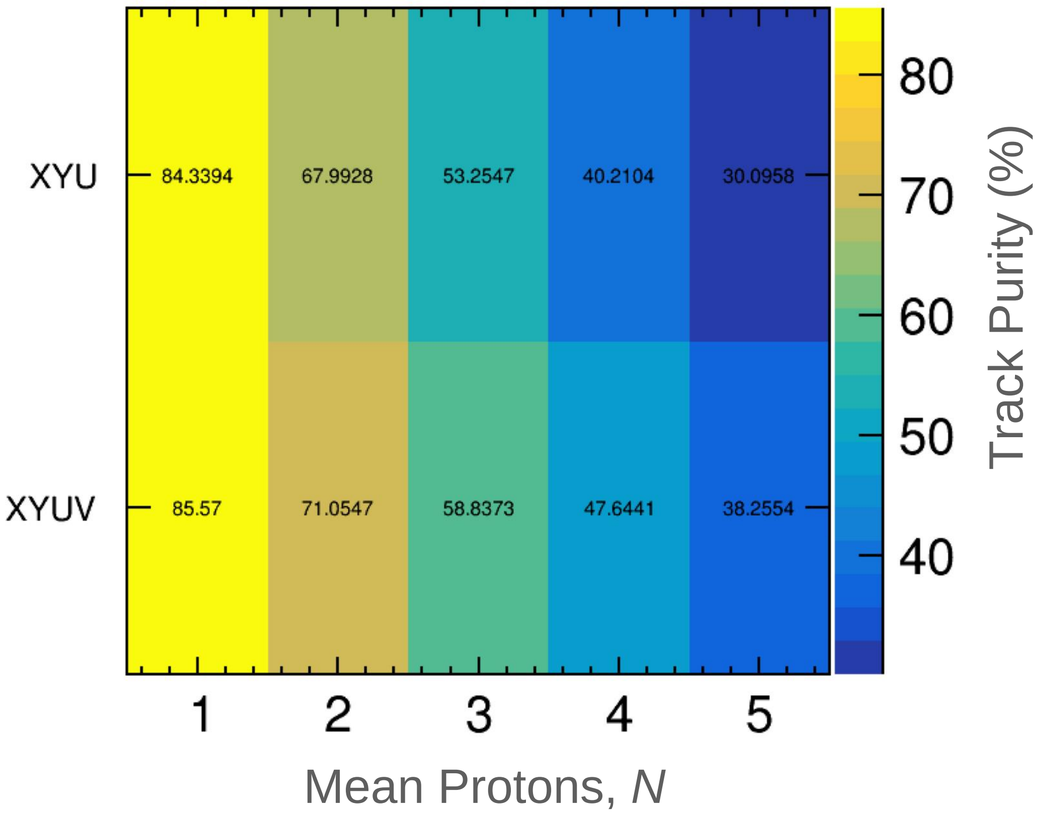


XUV XYUV

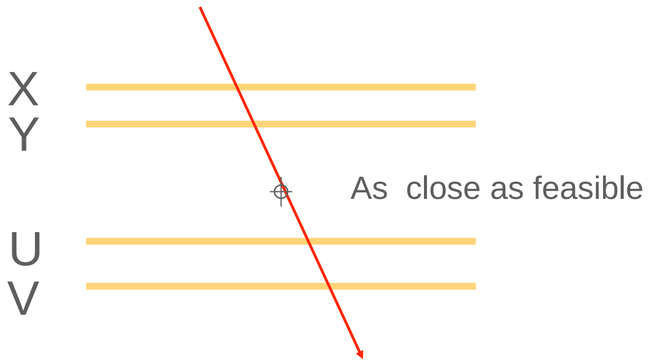
SuSi 2: Geant4 Simulator



Marked benefit of XYUV or XUV as simultaneous protons, *N*, increases and for larger phantoms

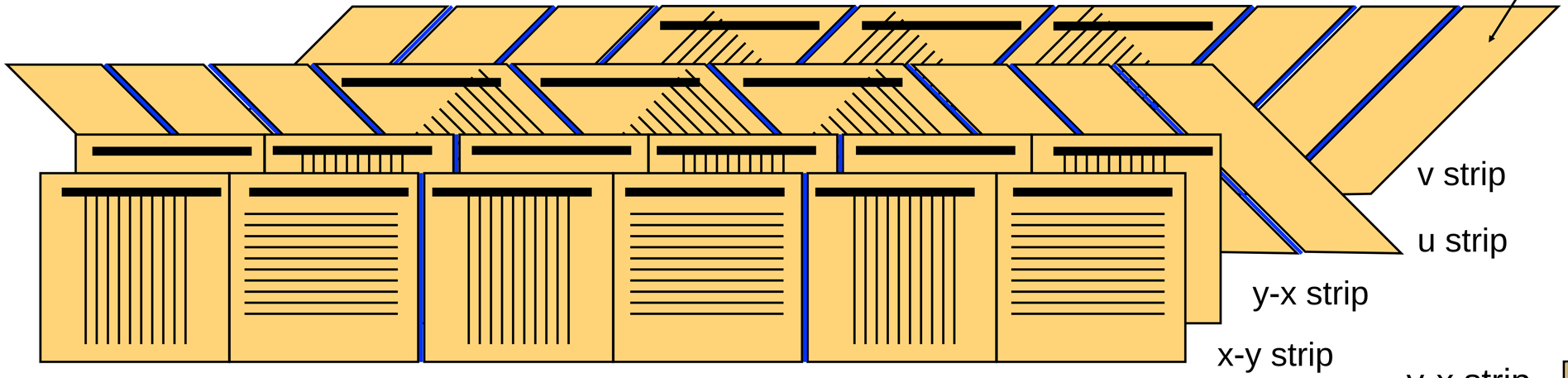


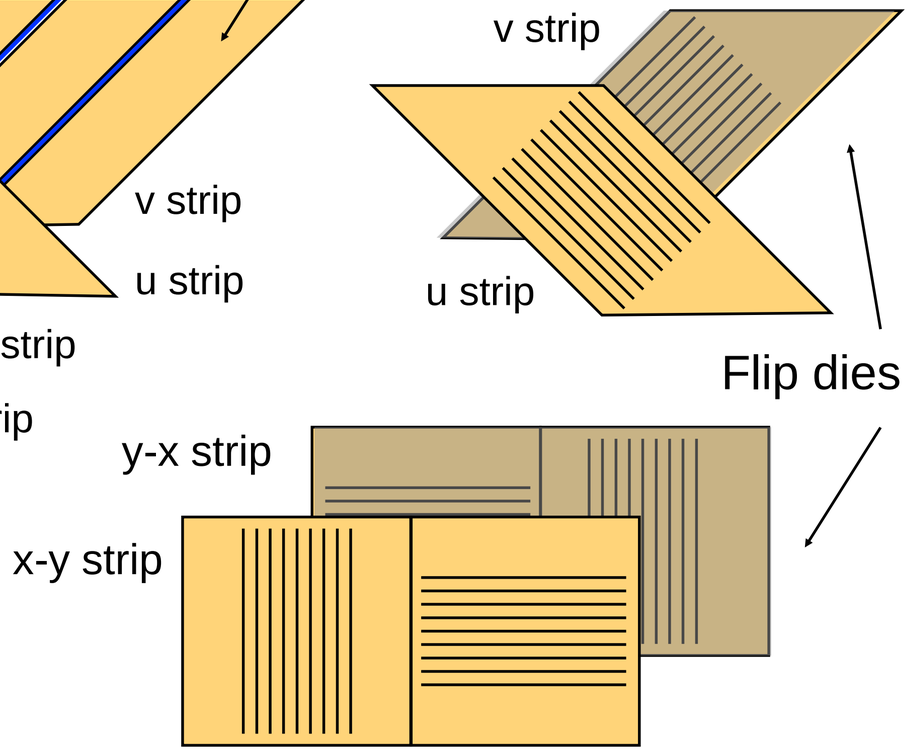
Similar studies for layer separation and channel pitch

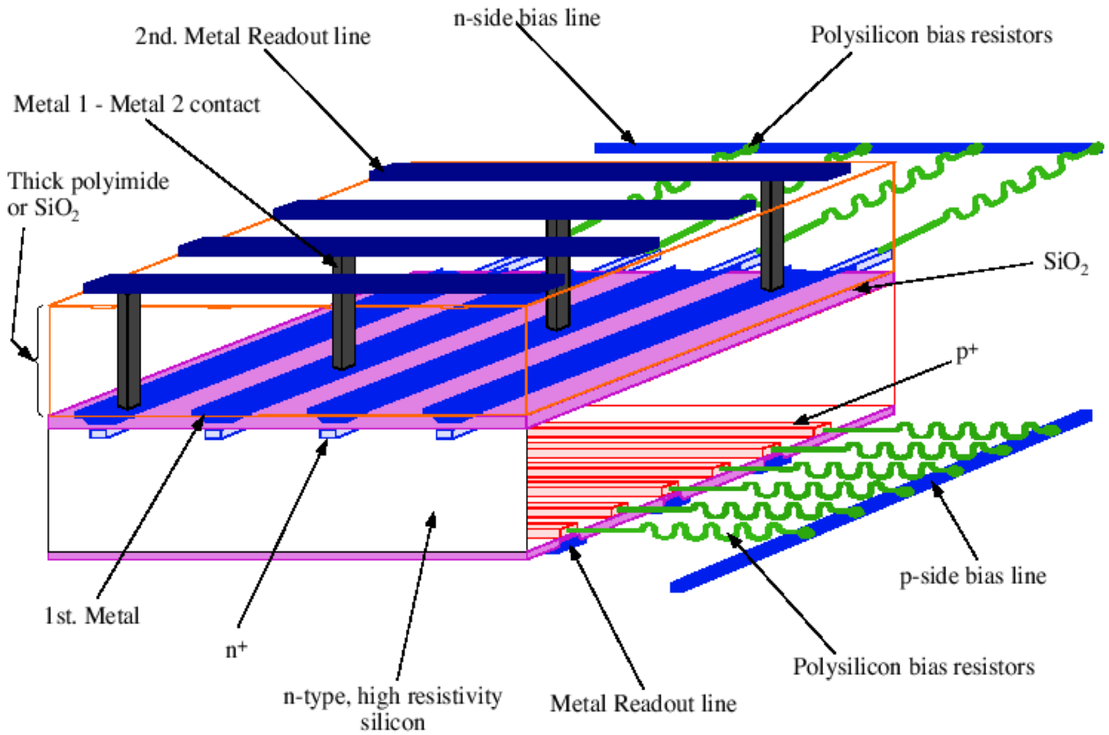


Strip ladders

Mini UV dies (30 mm) make better use of wafer







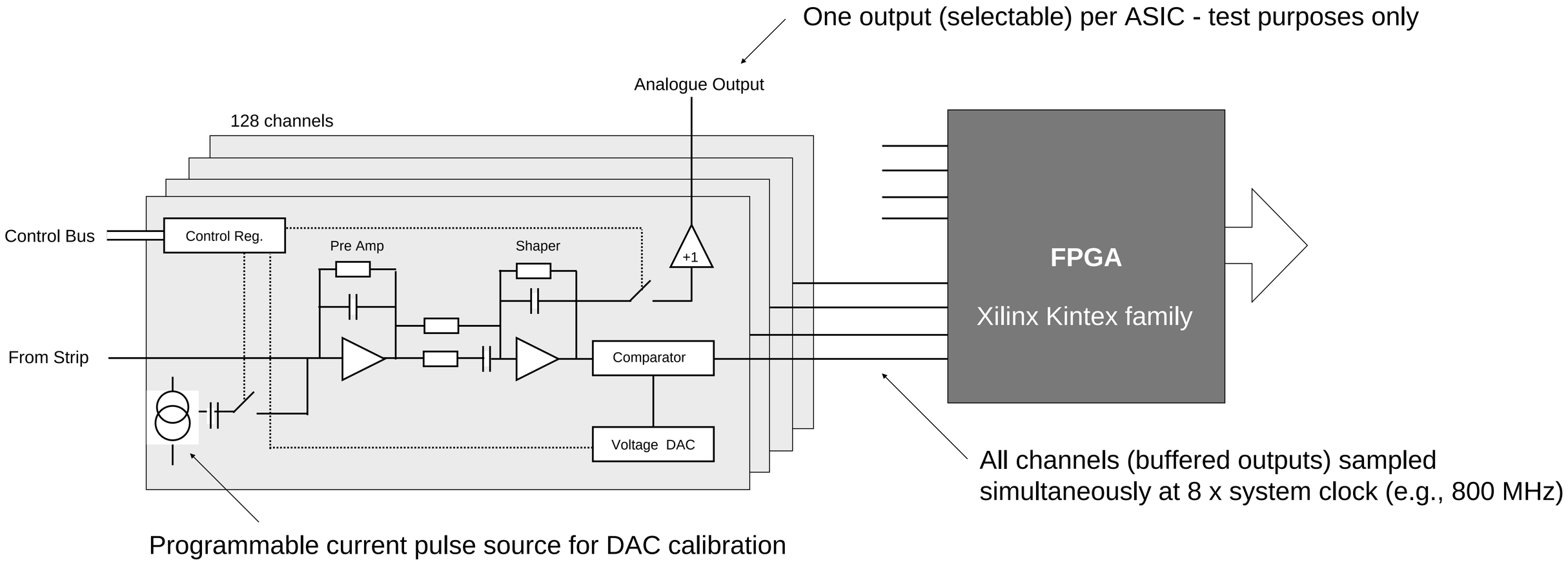
x and y channels brought to common edge for bonding

Pitch: 235 um (orthogonal to strip channel)
Thickness: 150 um
One ladder, total of 1,536 (11 bits).

Currently in fabrication by Hamamatsu

ASIC

Designed and supplied by ISDI Ltd



Staring sensors – always active except for recovery time

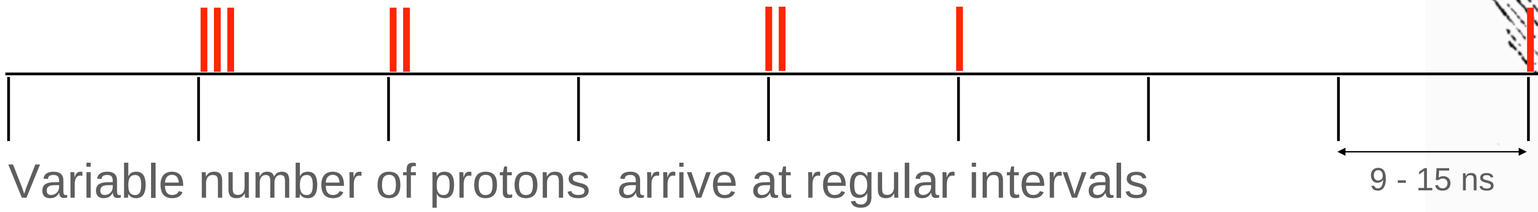
Operating modes – idle, set-up, calibrate and acquire

6-bit DAC, parameters held on-chip

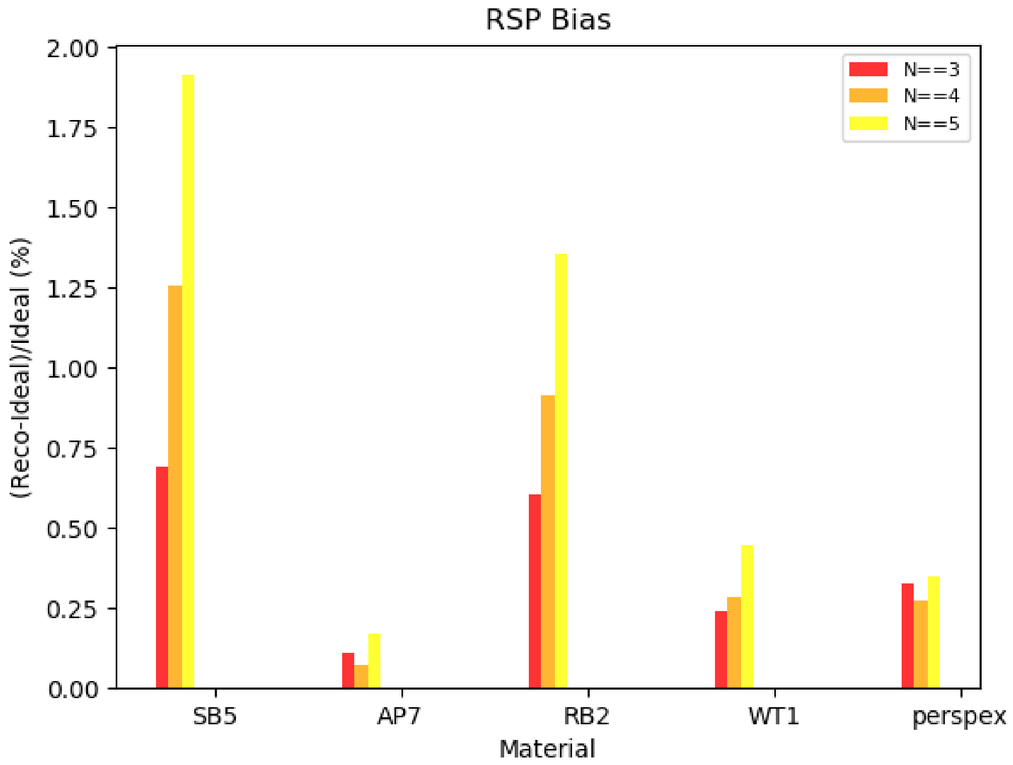
Die dimensions ~24 x 2.5 mm

Philosophy - separate analogue and logical elements, incorporate calibration functionality, and modular

It’s about time …



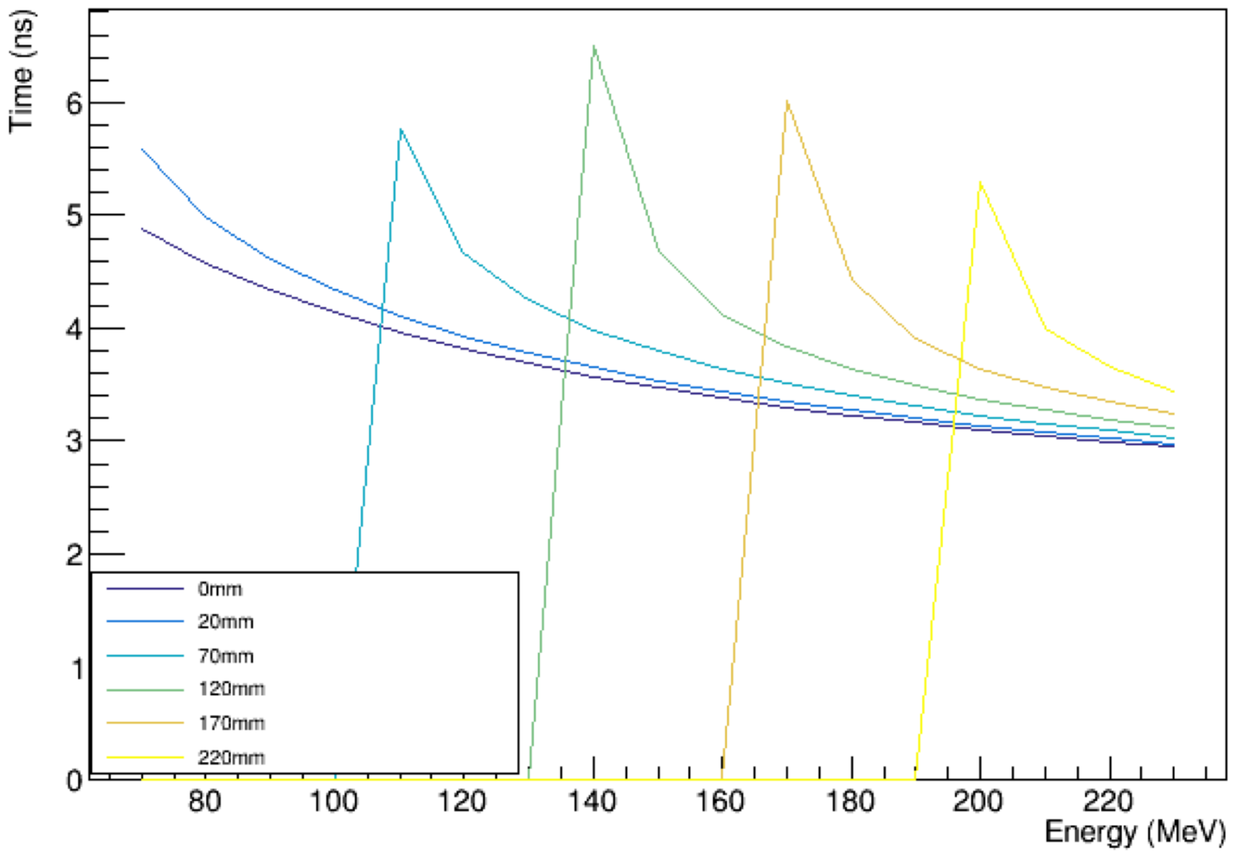
Variable number of protons arrive at regular intervals

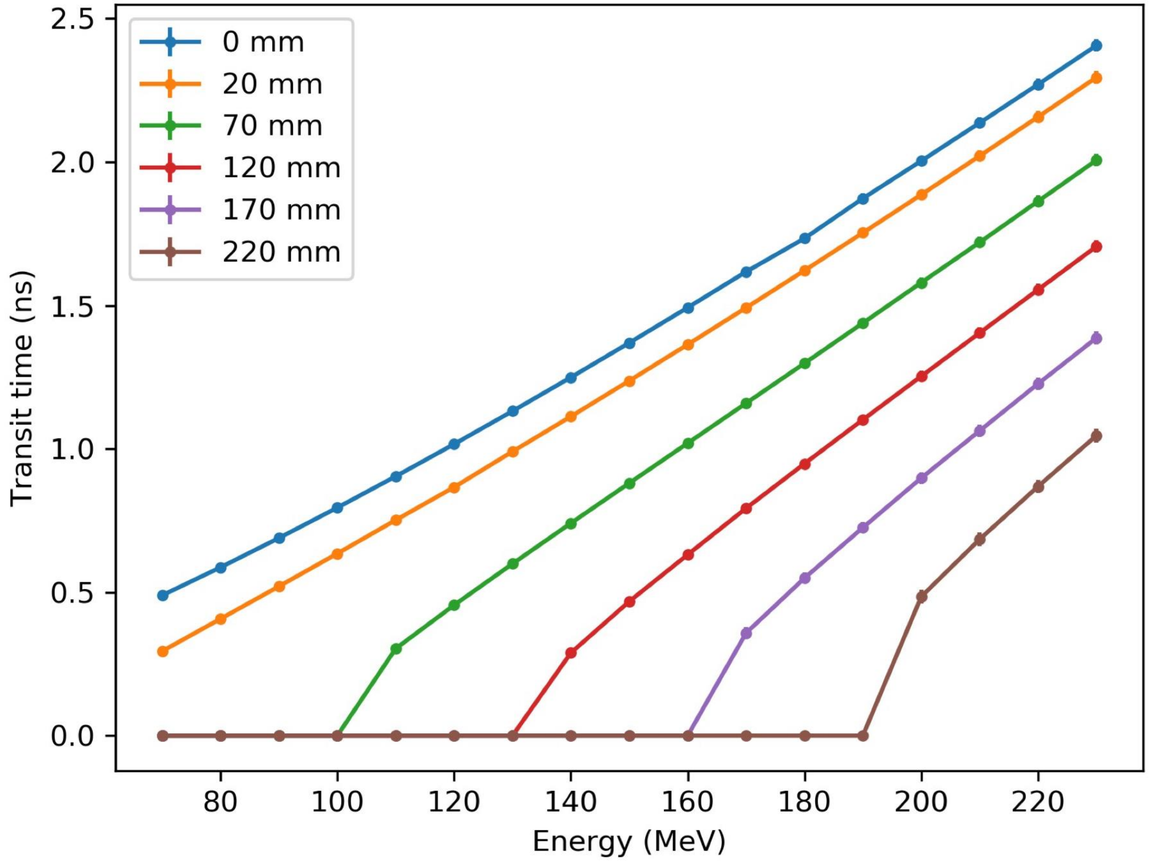


As number of candidate protons increases then RSP becomes more uncertain

Transit times Simulated

Time dominated by time-of-flight and not material





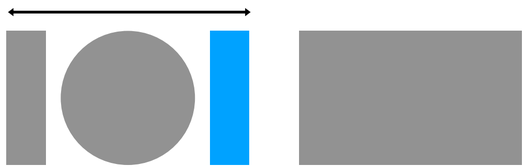
Trackers Transit Time
3 – 6.5 ns

+

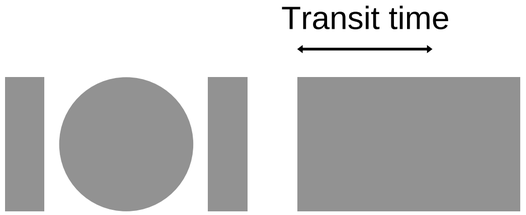
Calorimeter Transit Time
0.2 – 2.5 ns

=

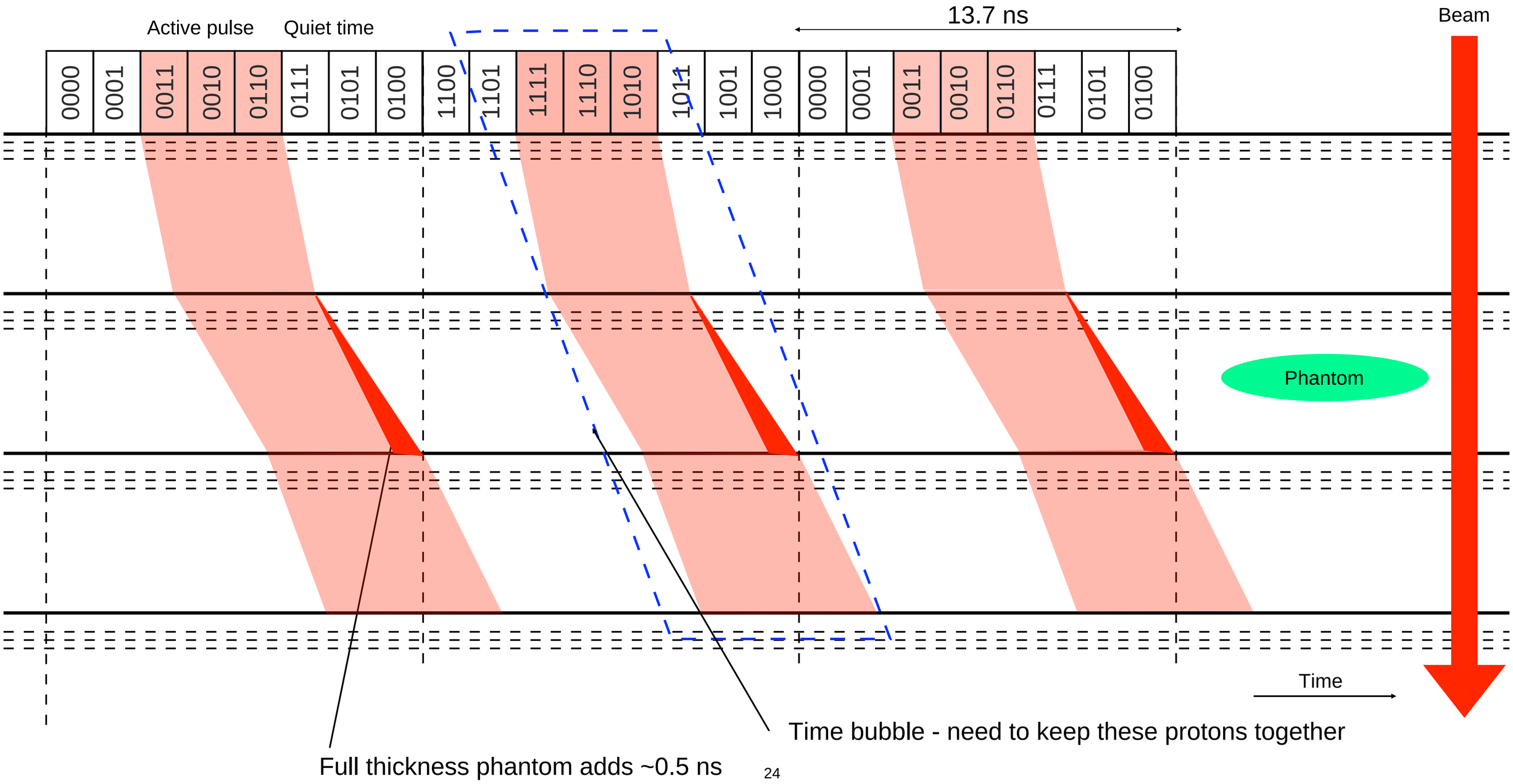
3.2 – 9.0 ns



Pulse period = 9.8 -13.7 ns
Active pulse width ~ 2 - 4 ns (est.)

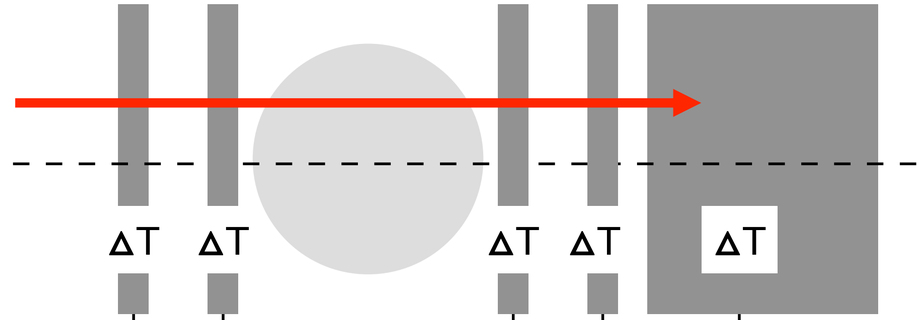


Transit times for Christie PBT Centre Similar for other facilities

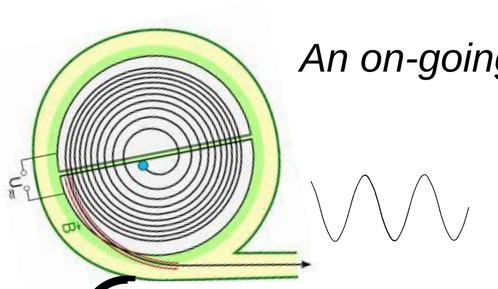


Synchronisation

Sync time across modules using proton transit times



An on-going debate!



Test point or RF pickup

72 - 106 MHz

DPLL

Programmable phase shift

(1 ns inc.)

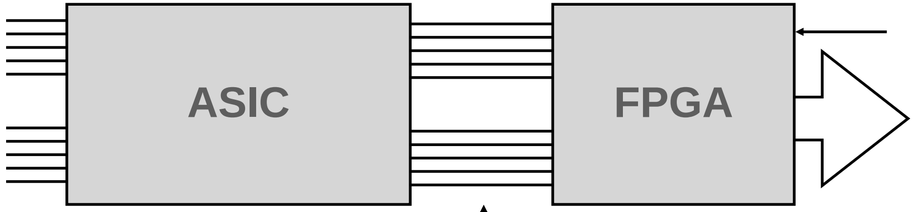
long cable

Say, 100 MHz

Xstal Osc.

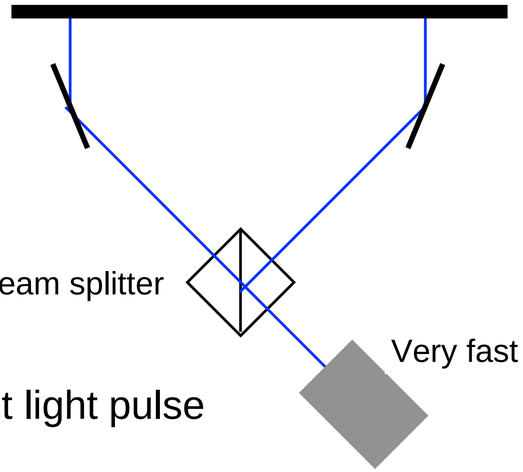
System Clock

Up-band 8x



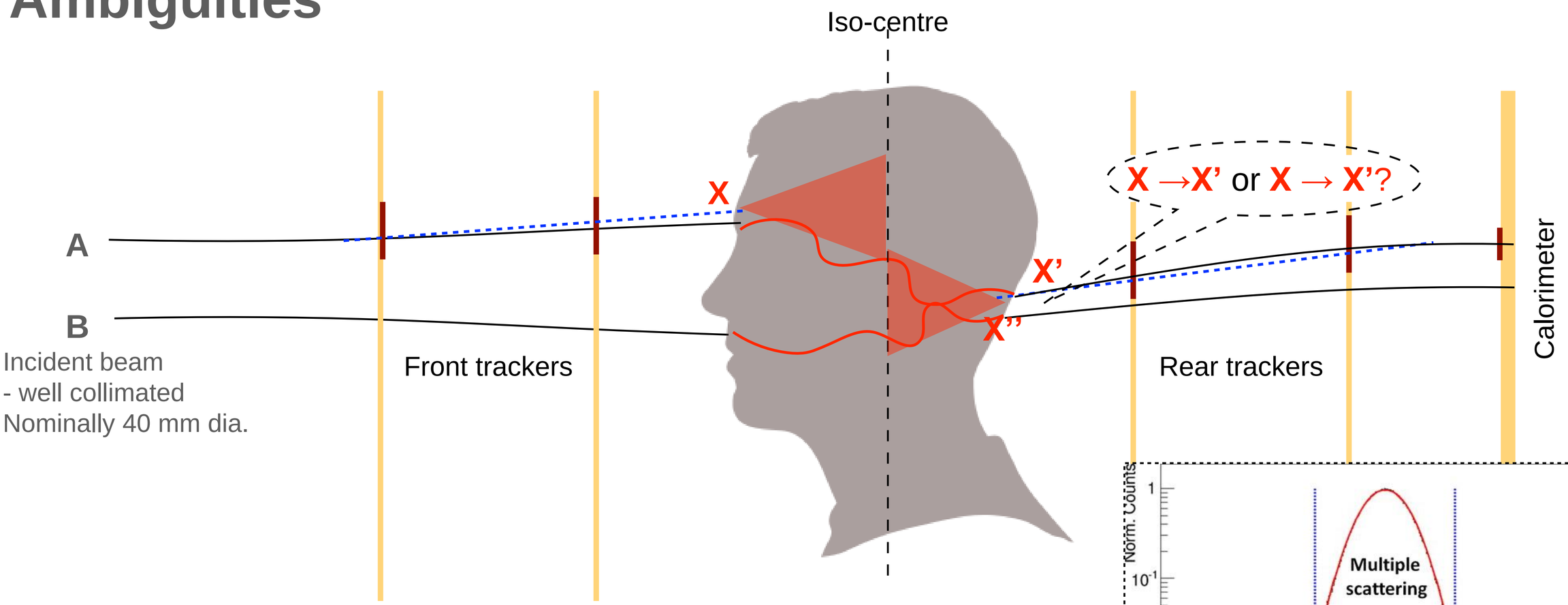
System Clock (100 MHz)

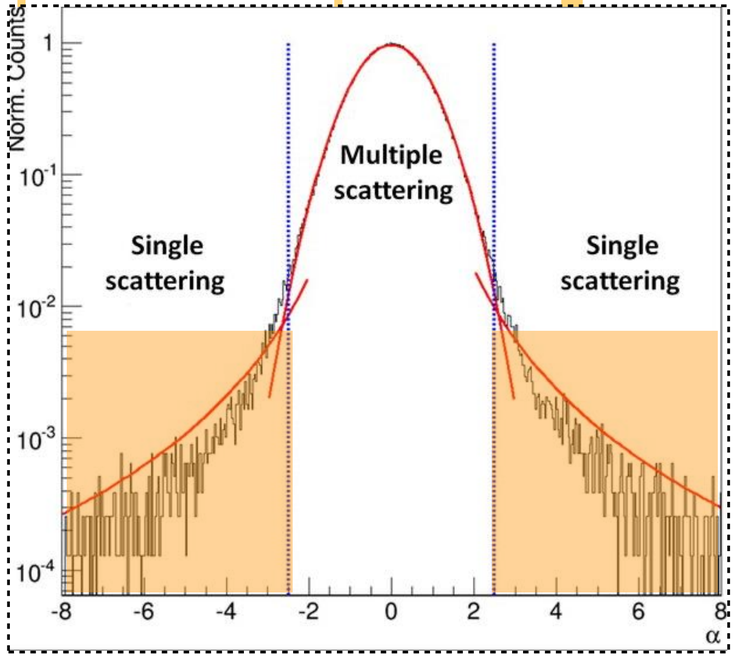
All channels read at 1.25 ns intervals



Sync time across layers using fast light pulse

Ambiguities

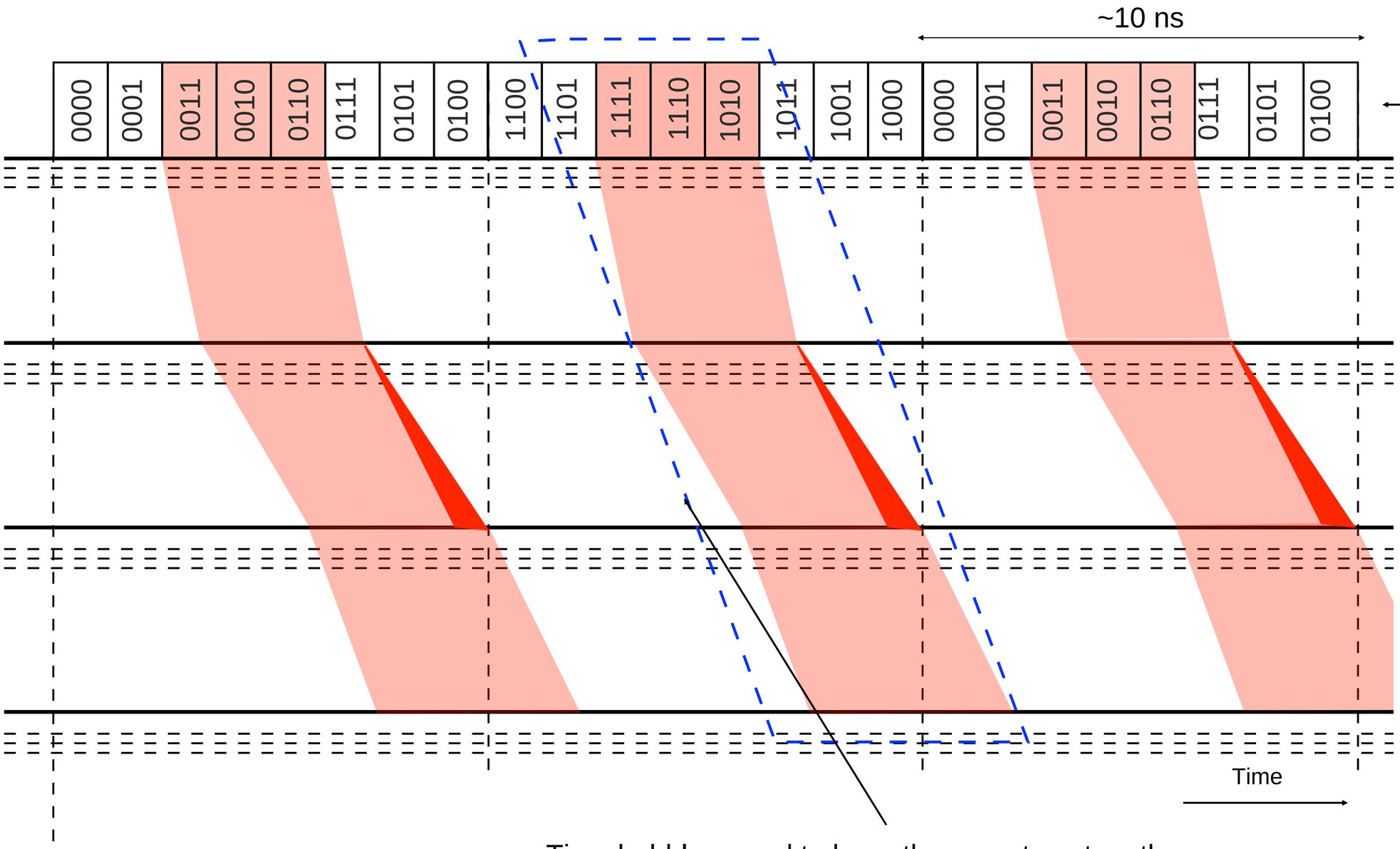




The Perils of Excess Protons

The physics does not help. Multiple Coulomb Scattering gives a fairly broad and smooth distribution. The high angle scatters are ‘cut’.

Keep protons in their bubbles



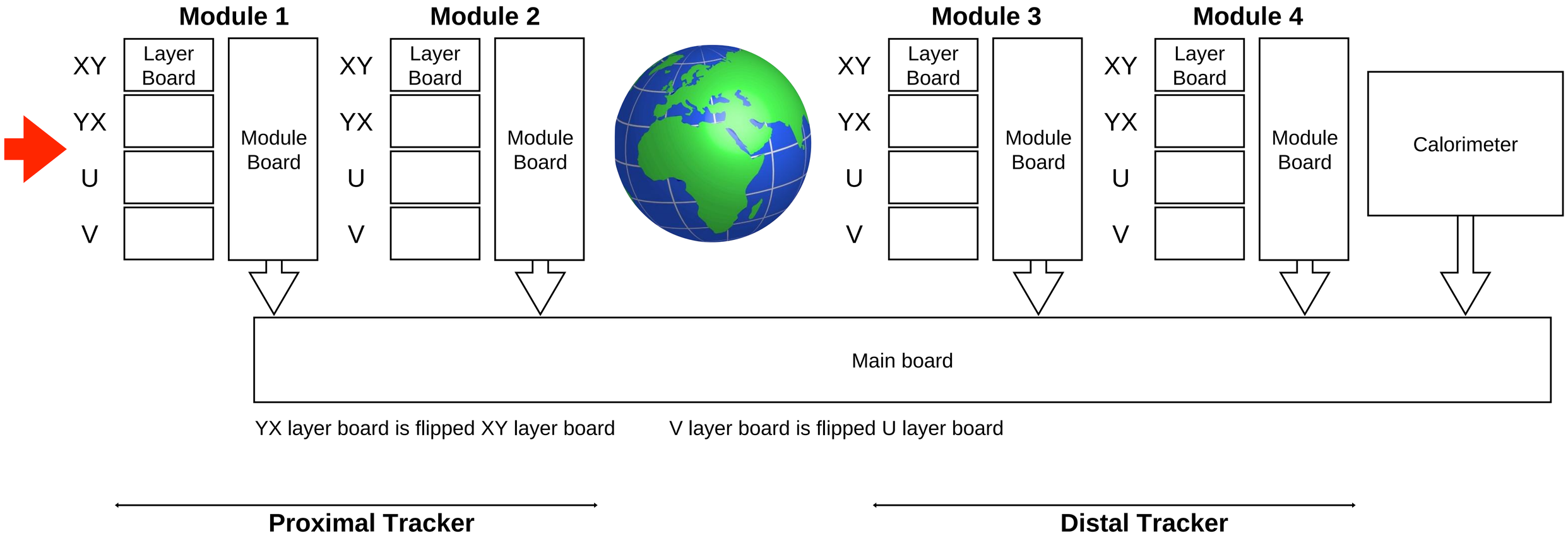
Super-sampling cyclic time code

800 MHz digital ‘scope

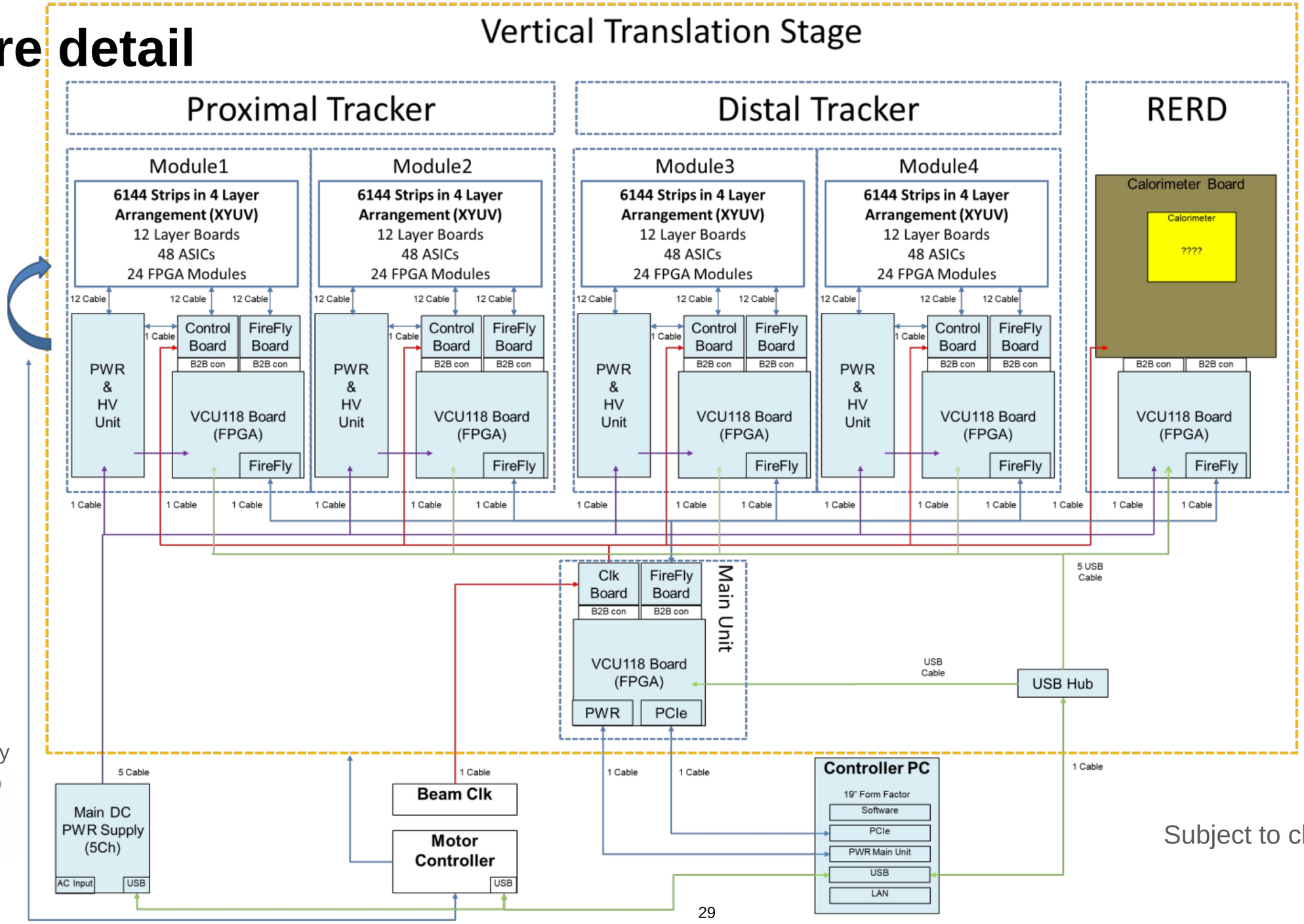
But, at the end of the day time no meaning!

Time bubble - need to keep these protons together

System architecture



In more detail



Design and supply by

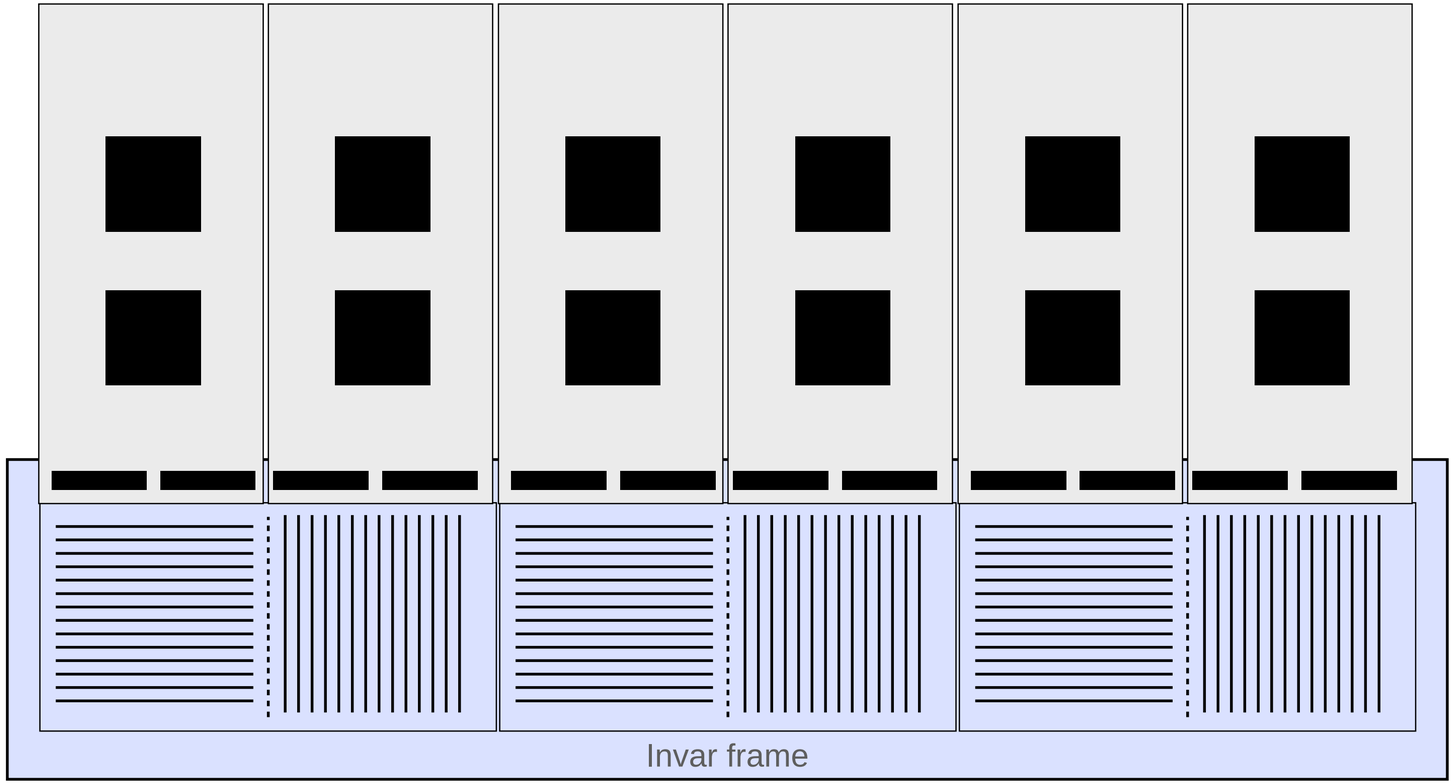
aspect systems

Dresden

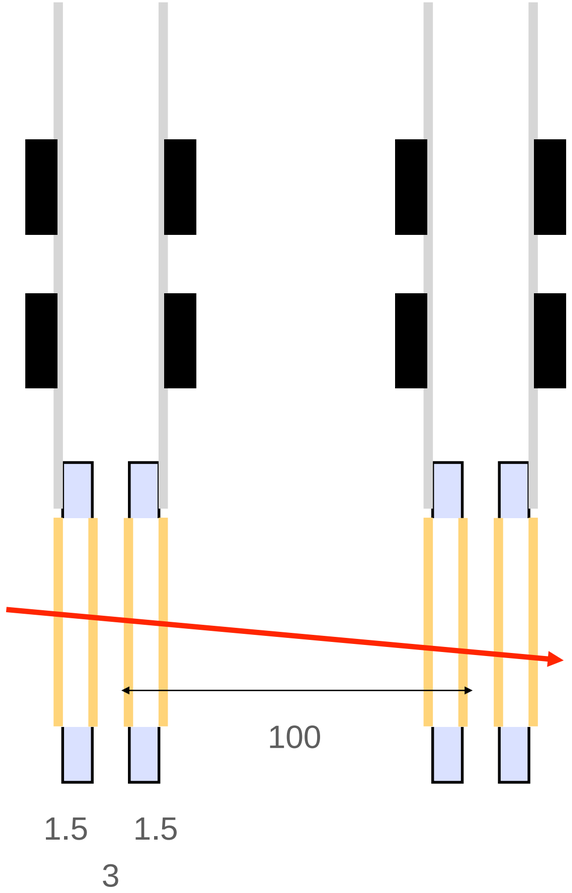
Subject to change

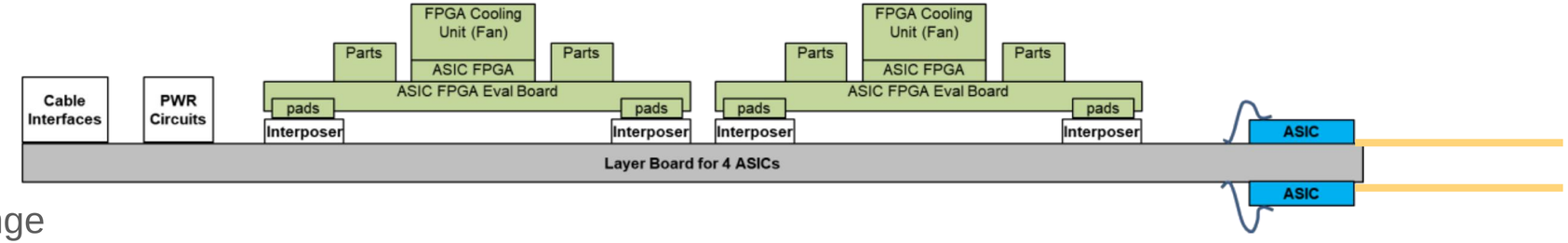
Modular design

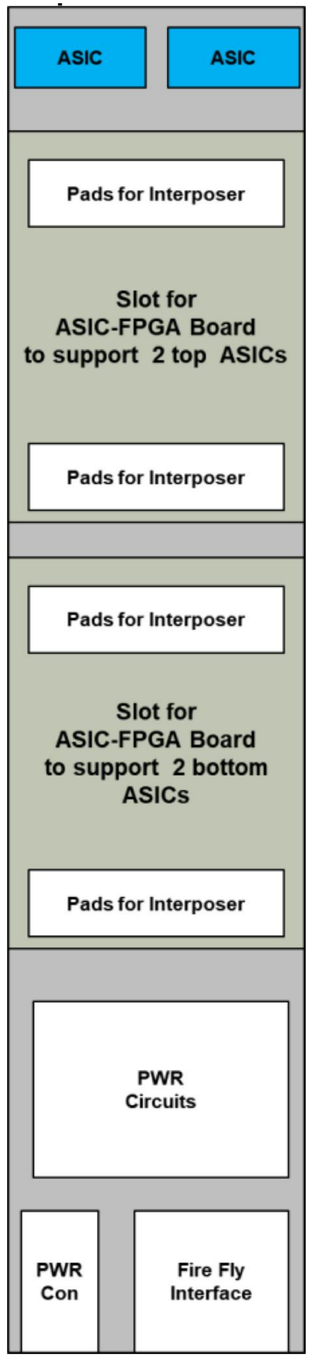
XY-YX Ladder



Complete Tracker



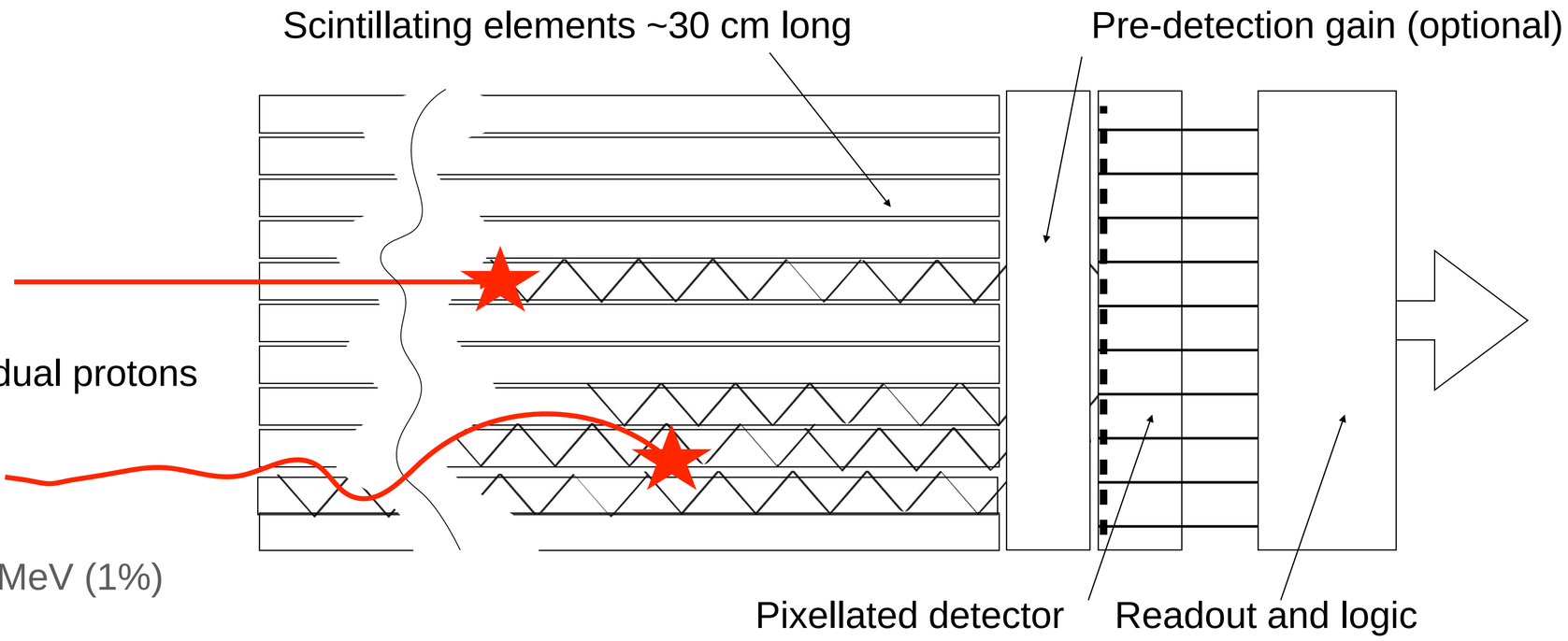




Subject to change

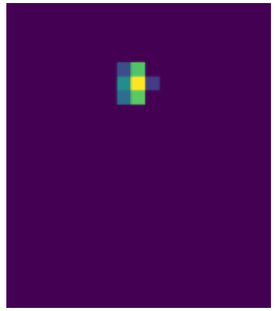
Calorimeter

Pixellated Calorimeter
Plastic scintillating fibres/bars
Read-out Multi-anode PMT or TimePix

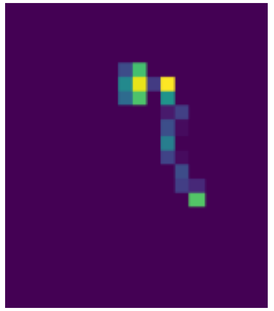


Energy Resolution: 230 MeV (3%), 70 MeV (1%)

1 proton

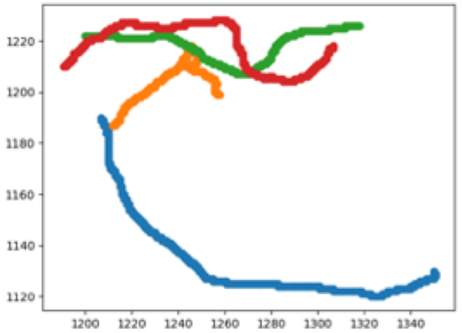


2 protons



1 mm fibres

4 protons



2 um fibres

Simulations

Calorimeter is the most challenging element

General Comments

Proton and other charged particle beam therapies are relative new and in a state of flux

Real need for optimised and adaptive treatments

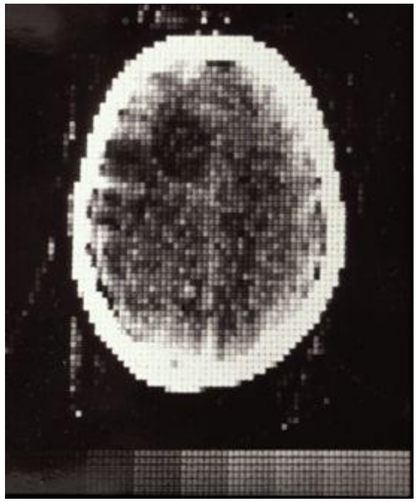
Range uncertainties are a major challenge and proton CT can assist in several ways

Proton CT is a challenge – evidenced by its long history

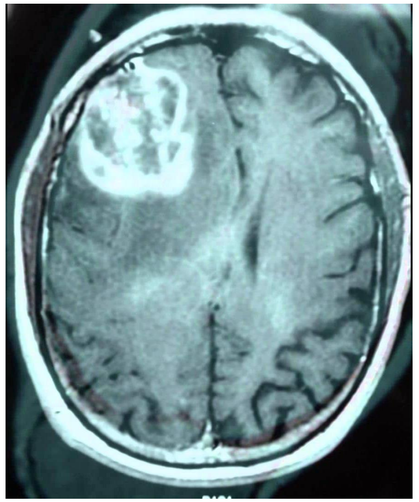
Proton CT will only reach patients if there are confirmed clinical advantage and industry invests

Project philosophy must be driven by the clinical professionals and developed to pre-production standards

October 1971
Atkinson Morley Hospital, London



Today



X-ray CT

Thank you
Any questions?