Technical Challenges for FLASH Proton Therapy

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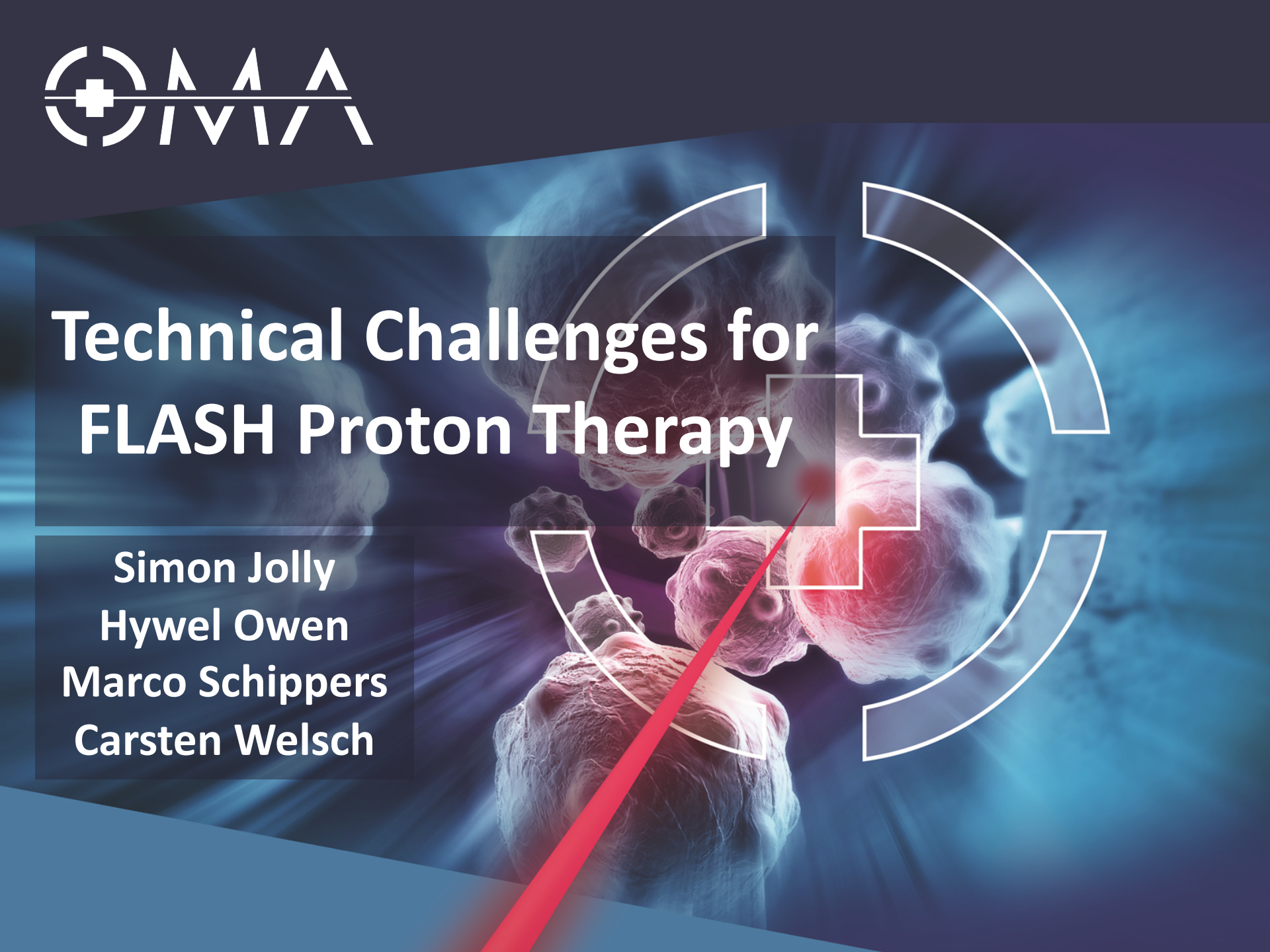
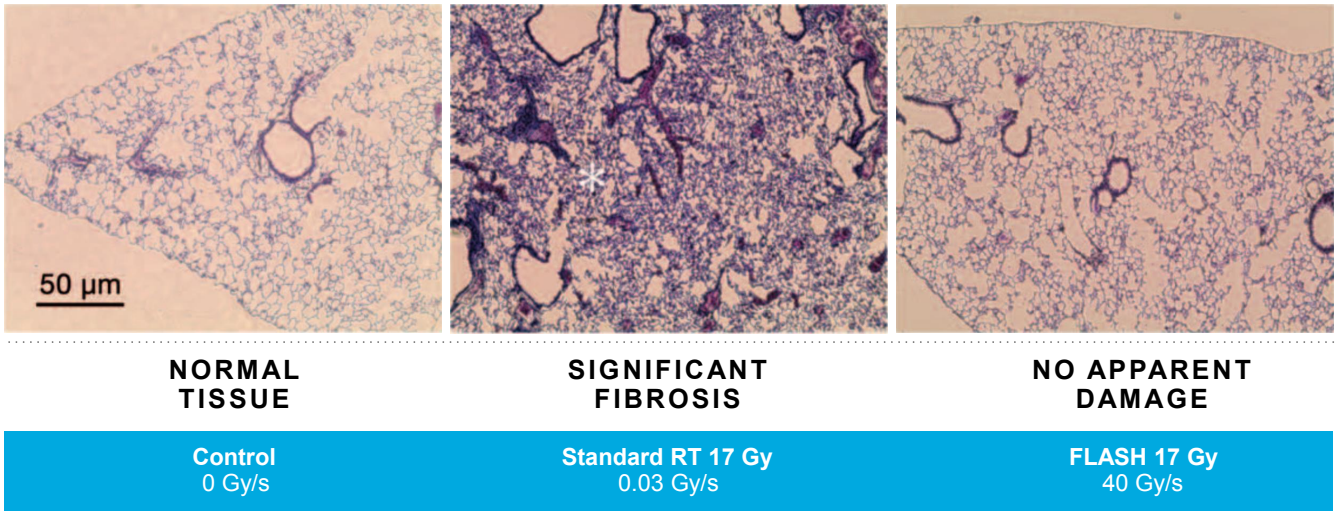


Abstract

There is growing interest in the radiotherapy community over the applications of FLASH radiotherapy, wherein the X-ray dose is delivered to the entire treatment volume in less than a second. Early pre-clinical evidence suggests that these extremely high dose rates provide significant sparing of healthy tissue compared to conventional radiotherapy without reducing the damage to cancerous cells. This interest has been reflected in the proton therapy community, with early tests indicating that the FLASH effect is also present with high dose rate proton irradiation. In order to deliver clinically relevant doses at FLASH dose rates, significant technical hurdles must be overcome before FLASH proton therapy can be realised, particularly for modern spot-scanning dose delivery.

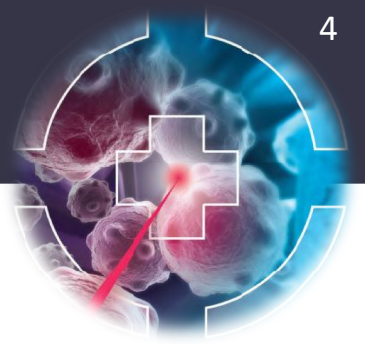
The current state of the art in clinical proton therapy technology is discussed, along with the current specification for clinical FLASH proton therapy. The technical challenges are outlined for each of the existing accelerator and beam delivery technologies, with possible routes discussed by which the technology can evolve to meet these challenges.

FLASH Radiotherapy



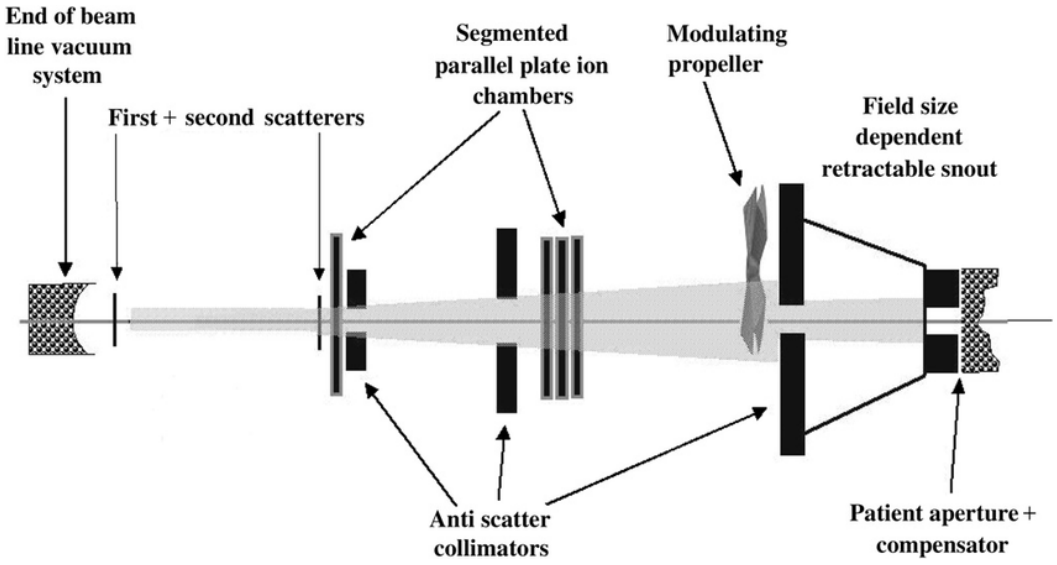
- As you have just seen, FLASH is a hot topic!
- Virtually all trials carried out so far with photons and electrons.
- Are FLASH effects also seen with protons? Yes!
- FLASH proton therapy system does not yet exist.
- Most main vendors have shown some sort of FLASH result:
  - Only very small volumes.
  - Uses plateau, not Bragg peak.
  - Not what we would consider clinical PBS delivery.

FLASH PBT Requirements



- Standard clinical spec for PBT system:
  - 2 Gy/l/min to cubic 1 litre water volume.
  - Situated 10–20 cm deep in larger water volume.
  - Requires 2×10^{11} protons $\simeq$ 30 nC.
  - 34 layers; 50x50 spots per layer; 2 mm spot spacing.
- Must deliver same spec ie. same number of protons in <100 ms:
  - 30 nC in 100 ms = 300 nA average current to patient.
  - Peak current will be higher since beam needs to be switched off between spots and energy layers.
- This is just for 2 Gy, so not even thinking about hypofractionation: may want to do 10 Gy or higher…

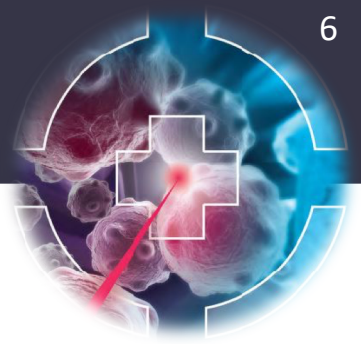
Double Scattering



- Double scattering beamline is easiest option.
- Broad beam produced from two scattering foils.
- Patient specific collimator required to reduce transverse beam size: unique to each patient.

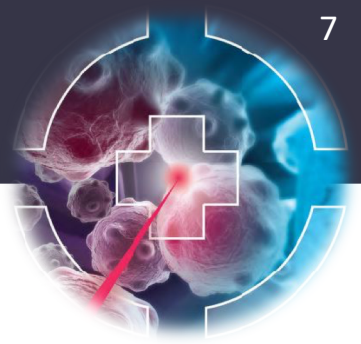
- Range shifter and patient compensator modulate range to cover entire tumour:
  - Proximal edge always incorrect.
  - Cannot deliver to complex geometries.
- Needs 300 nA average at patient: PSI COMET cyclotron can deliver 800 nA.
- Will need faster dosimetry since 30 nC delivered in 100 ms, not 100 s…

Spot Scanning

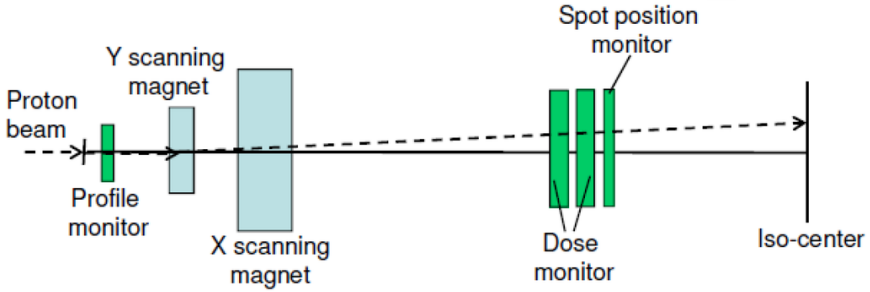


- Two types of scanning possible:
  - Step-and-shoot.
  - Continuous scan.
- Both extremely challenging!
  - 100 ms total delivery means ~3 ms total per layer:
    - ~1 ms to deliver all spots in single layer.
    - ~1 ms to adjust energy.
    - ~1 ms free time…
  - 2,500 spots per layer means 400 ns per spot:
    - Step-and-shoot: 200 ns per spot; 200 ns switching.
    - Continuous scan: ~400 ns per spot but much higher accuracy on dose delivery.
  - Have to be able to deliver **and monitor** at this speed…

Magnet Switching

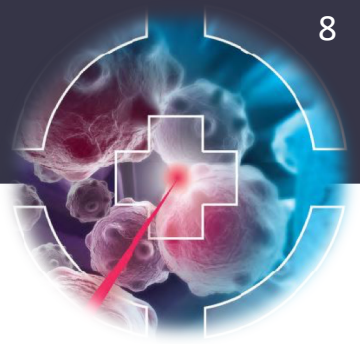


- Magnets take time to adjust and settle:
  - Iron yoke makes magnets cheaper (better flux return than air) but slower.
  - Air core magnets are possible but get very expensive.



- **All** beamline magnets must be able to adjust and settle in ~1 ms: about 1,000-fold increase over current systems.
- Steering magnets in nozzle must be able to steer beam 2 mm in 200–400 ns at isocentre:
  - 5–10 m/ms: very fast!
  - PSI gantry max speed is 2 cm/ms.

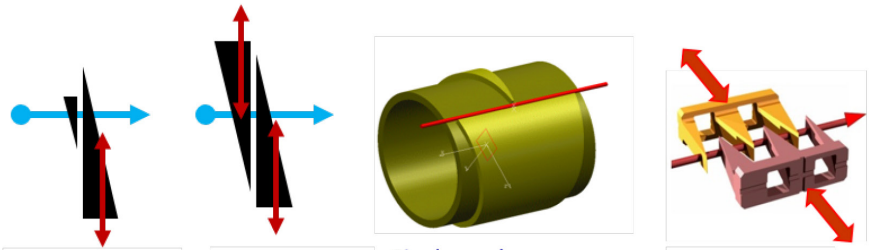
Dosimetry



- If you thought magnet scanning was tough…
- Current clinical systems “trickle fill” each spot:
  - Current delivered to single spot until dose within tolerance.
  - System then moves to delivering next spot.
- To do this at FLASH rates, continuous dose sampling at around 1 GHz will be required!
- Need larger dynamic range to cope with very fast spot delivery.
- Alternative is to change methodology:
  - Deliver **exactly** the right amount of charge from accelerator.
  - Dose monitoring no longer provides independent verification.
- In any case, ion chambers will not work quickly enough:
  - Recombination time of ions too slow.
  - Will need new technology: scintillators?
- Dosimetry also provides vital safety aspect:
  - Prevent under or over-dosing to patient.
  - Avoid unwanted exposure.
- Personal Protection System needs to be able to shut off beam 1,000 times more quickly:
  - Fast monitoring.
  - Fast accelerator control.
  - Speed of light starts to become an issue…

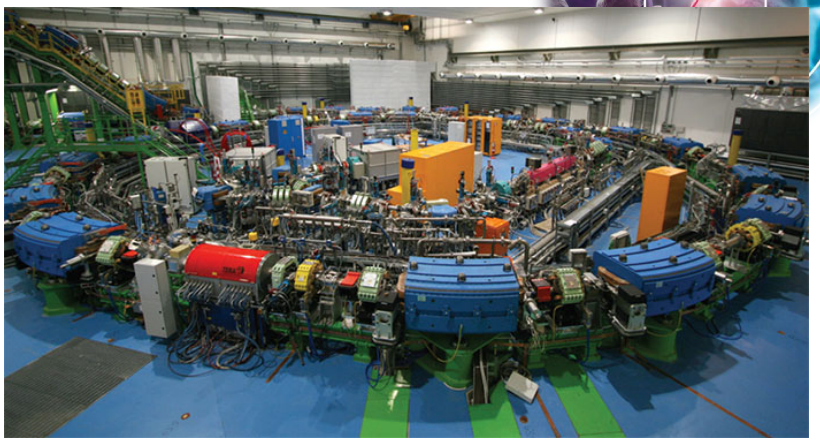
Cyclotrons

- Route to FLASH straightforward (not easy…):
  - Increase current output.
  - Improve transmission through ESS.
  - Reduce energy switching time to <1 ms.
  - Speed up current control or improve stability.
- Biggest challenge is mechanical movements of degrader:
  - Need to be able to make mechanical adjustment in ~0.1 ms, not 1 s…
  - Can take advantage of small beam spot size.
- May need to increase extracted current by a factor of 100 if transmission at low energies cannot be improved:
  - Transmission at lowest energy <1% of maximum energy.



Single wedge | Dual wedge | Single wedge rolled on a cylinder | Multi-wedge

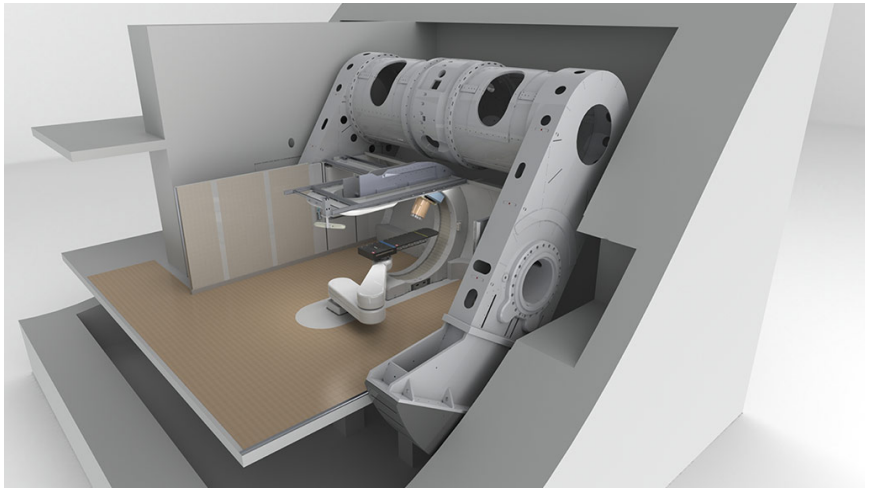
Synchrotrons



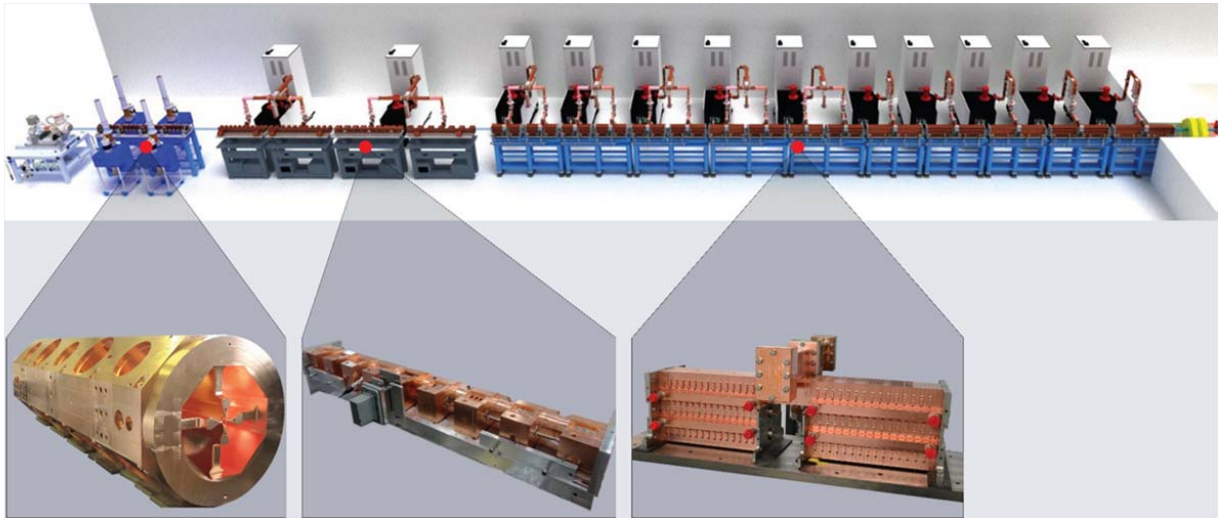
- Synchrotrons have one advantage over cyclotrons: no mechanical degrader.
- Everything else looks harder!
- Current cycle involves energy change every 2–5 s…
- Accelerating frequency a problem: 2–6 MHz close to spot delivery rate.
- Will need to shift to multi-energy extraction:
  - ALL protons (>10^{11}) must be injected at once (not 10^{10}).
  - Extract all protons for single energy layer in ~1 ms (not 2 s).
  - Adjust energy and stabilise in ~1 ms (not 5 s).
- Making such changes is difficult but not impossible:
  - Rapid Cycling Synchrotrons already do faster energy changes over larger energy ranges.
- BIG challenge is to make extraction more stable:
  - Large pulse-to-pulse variations cannot be tolerated when so few pulses delivered per spot.
- Accelerating frequency cannot be <2.5 MHz otherwise less than 1 bunch per spot:
  - Will need to capture DC bunch train from linac at much higher frequency.
- You either need EXACTLY the right number of protons extracted per bunch or much high frequency RF…

Synchrocyclotrons

- Synchrocyclotrons deliver short pulse (~5 µs) at ~1 kHz.
- Transition to FLASH rates very difficult:
  - Maximum rate 1 spot per millisecond.
  - Need ~30 energies in 100 ms.
  - Need all spots in layer delivered in 1 ms.
- Will need substantial change to design and pulse structure for spot scanning FLASH.

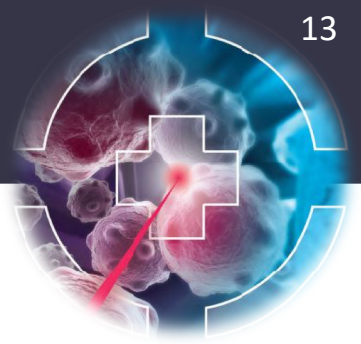


Linacs



- Only linac-based PBT system is AVO-ADAM prototype.
- Linac issues similar to synchrocyclotrons: 200 Hz rep rate means cannot scan energy layer in <50 ms.
- Need factor 10,000 increase in rep rate:
  - 1 spot per pulse, so 1% current stability per pulse.

Conclusions



- Scanning with FLASH protons is hard!
- First experiments with FLASH all use plateau: any reason to use protons at all…?
- First clinical systems will probably be double scattering:
  - Not nearly so technically challenging as scanning.
  - Poor tumour conformality may not be an issue due to FLASH effect.
- Hybrid system might be the way forward:
  - Large beam spots with fast Multi Leaf Collimator mean fewer spots and better lateral penumbra.
  - Might limit possible tumour geometries.
  - Will still need energy change in ~1 ms…