Linear Accelerating structures for Robust Radiotherapy systems

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On behalf of

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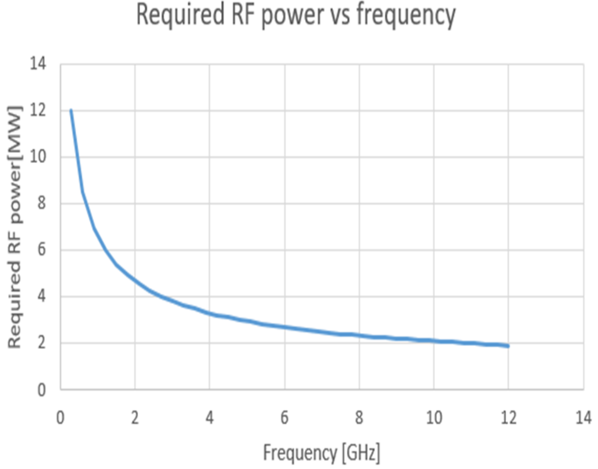
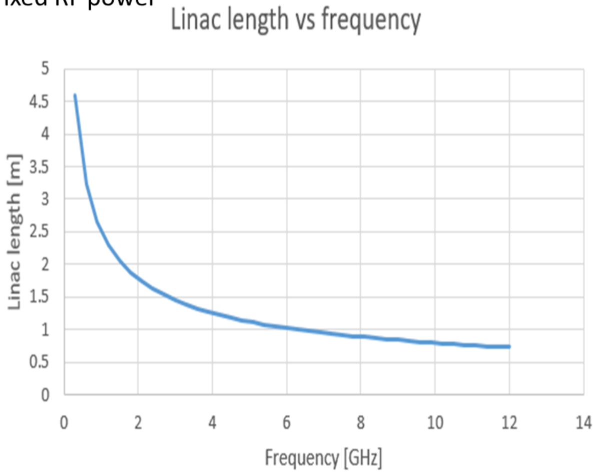
Thanks to Walter Weunch, Nuria Catalan Lashera and Igor Syratchev, CERN

Scaling length and power with frequency

Fixed linac length



Fixed RF power



The surface resistance of a copper cavity increases with frequency square and shunt impedance drops with aperture faster at higher frequency, so you would imagine that lower frequencies are better

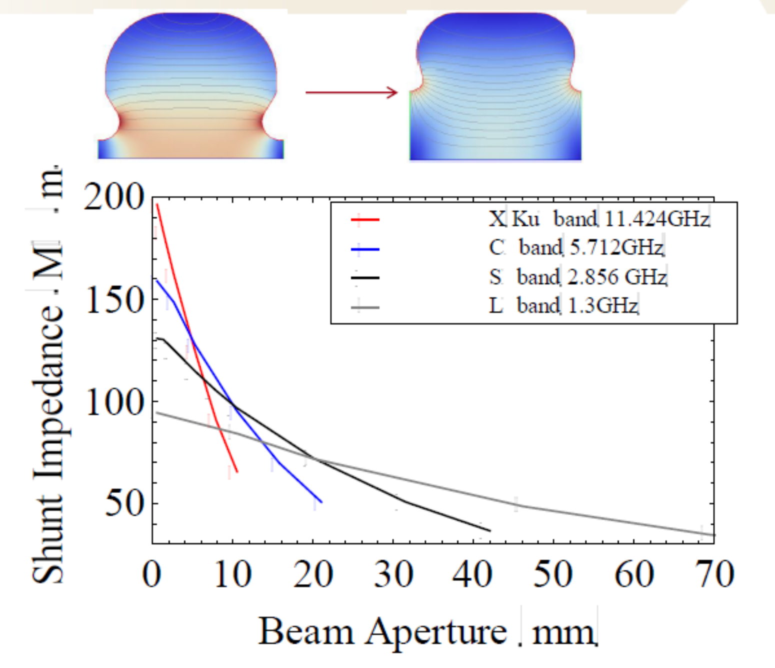
But the higher the frequency the shorter each cell is, hence the more cells you can fit in per meter

Shunt impedance is proportional to number of cells hence the shunt impedance scales with the square of the frequency and is proportional to length

Higher frequencies

There are three issues however when increasing the frequency

The shunt impedance drops with the ratio of the aperture to wavelength, a/λ



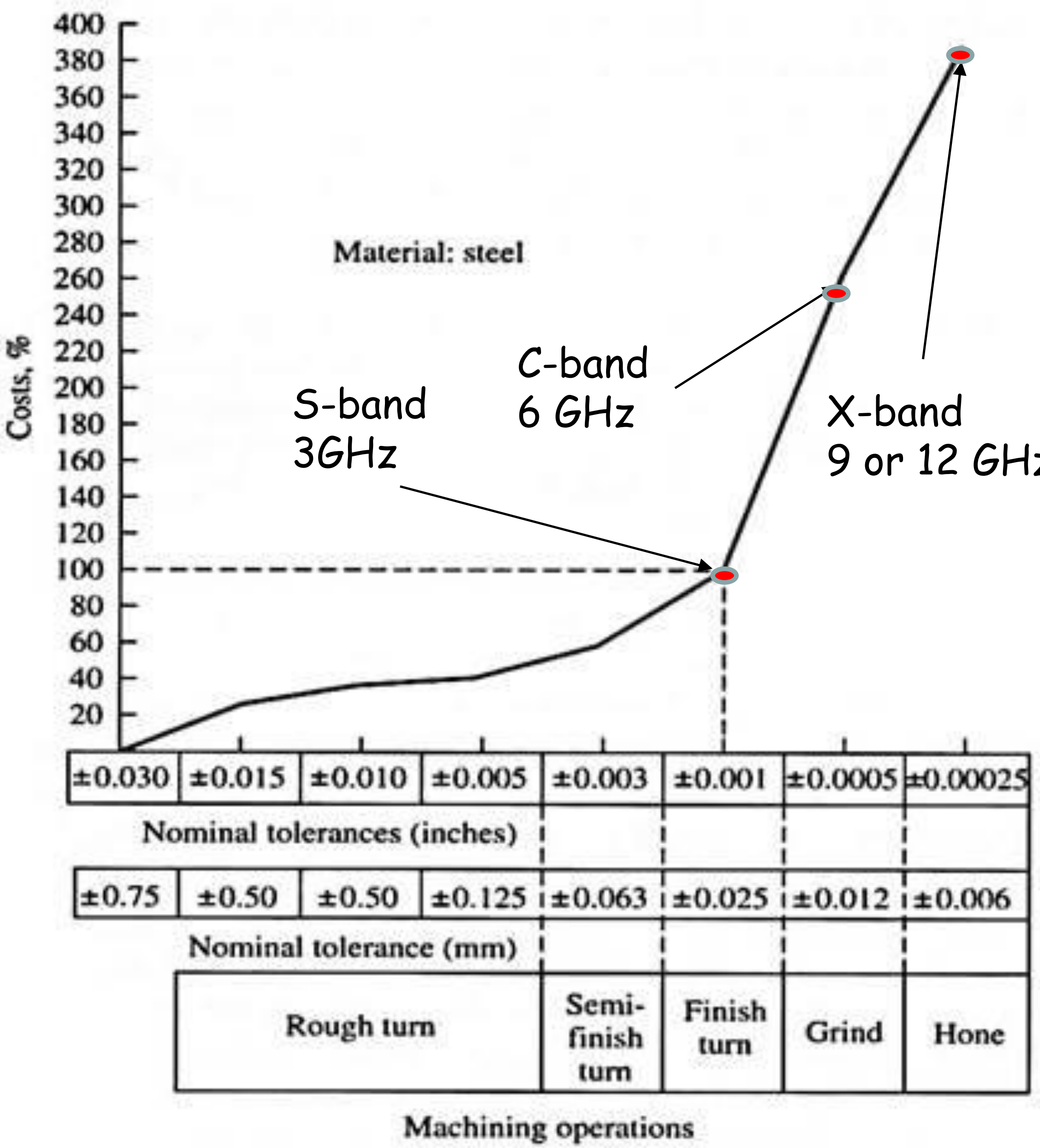
From S. Tantawi

- Precision manufacturing 15 μm (3 GHz)
- Diamond tipped lathes 5 μm (12 GHz)
- This is related to frequency errors by the ratio to the tolerances to the wavelength, $\Delta x/\lambda$
- This is the main limit on going to higher frequency linacs.
- *A* good machine shop can get tolerance appropriate up to S-band (3 GHz), higher frequencies need more precision and therefore cost more (~400%).

Smaller sizes (higher frequency) means less surface area for removing heat (limits duty cycle)

Cost for tolerances
(from Nuria and Joel at CERN)

- Costs increase with tolerances for machining (showing for steel opposite but believed to be similar for copper)
- C-band is 200% more expensive than S-band, X-band is 400% more expensive for machining only.
- Open structures will recover **<u>some</u>** of this in brazing and tuning costs
- Also for S-band you need a cheaper CMM metrology machine and razing alignment is easier

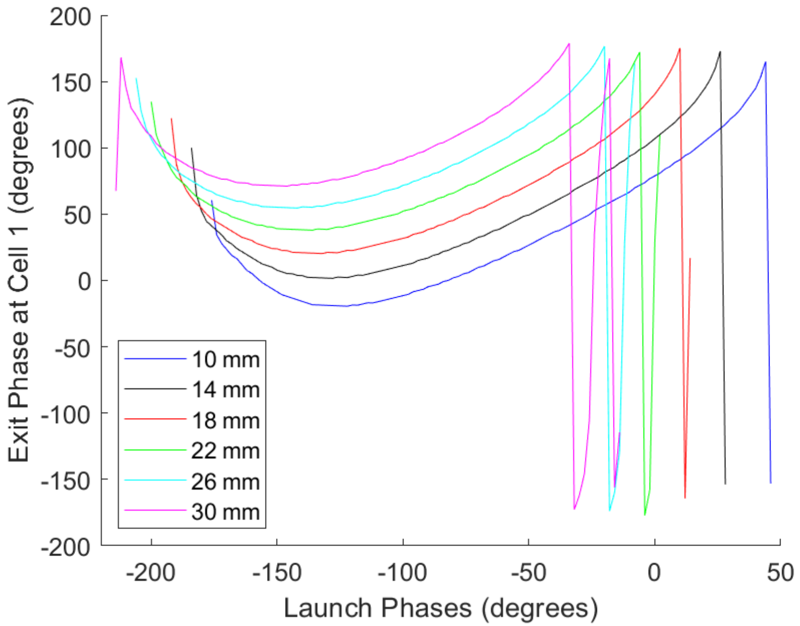


S-band
3GHz

C-band
6 GHz

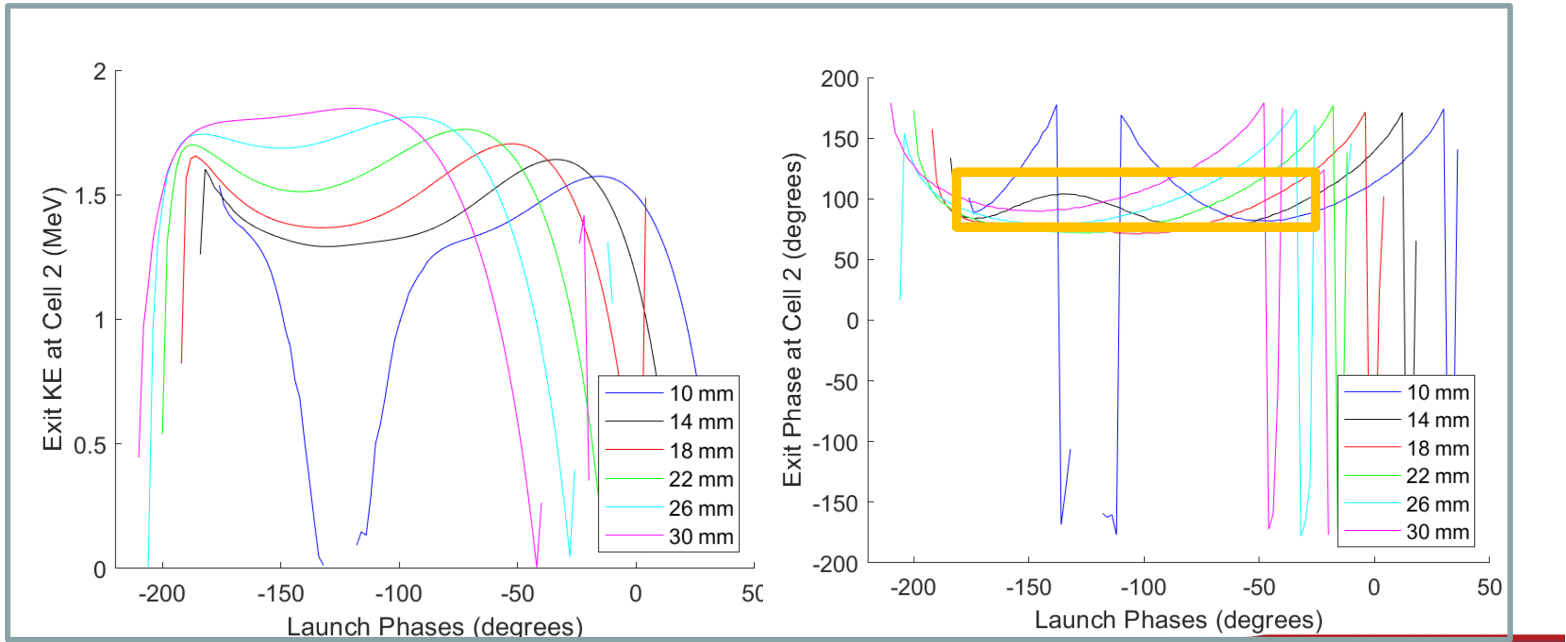
X-band
9 or 12 GHz

Optimisation of cell length

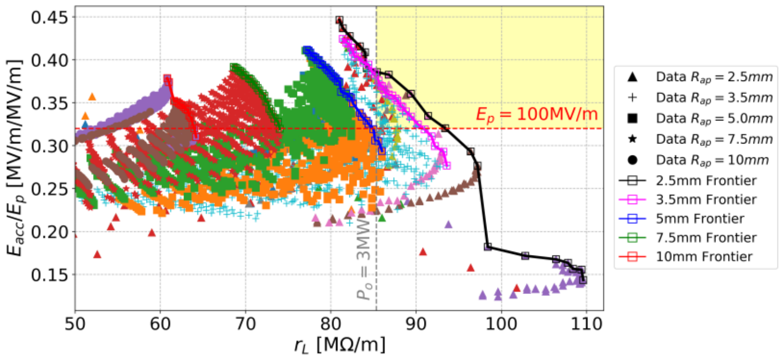


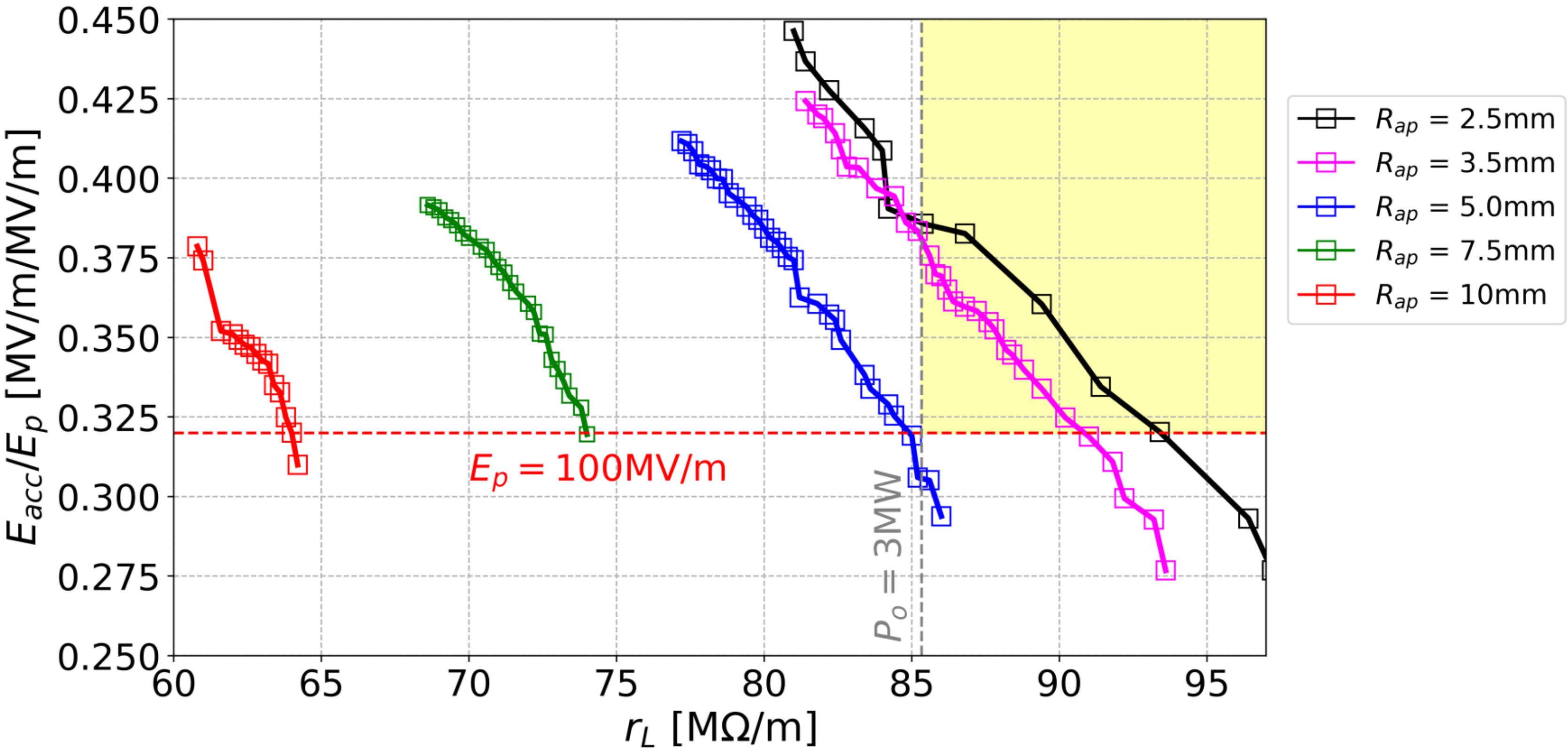
- The linac needs to first bunch the electrons into bunches then accelerate. This process is typically inefficient and 1/3rd of electrons are lost on the linac walls.
- We have developed a new code to optimise this to reduce wall losses (also in parallel looking at short pulse guns, see Deepa's talk)
- Borrow a concept from klystron design (from Igor at CERN) by looking at arrival/exit time functions.
- Can optimise the arrival function for each cell 1 by one.
- Ideal bunch has exit phases for all electrons within 40 degrees of each other.

The first cell see's electrons at all phases so it bunches at the zero crossing (when field flips from + to -) We can they vary the cell length to ensure the bunch arrives at the 2nd cell at the ideal phase.



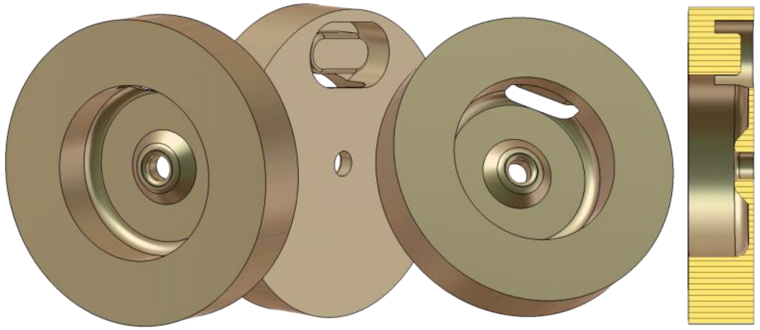
Nose Cone + Gap: A Generic Optimization





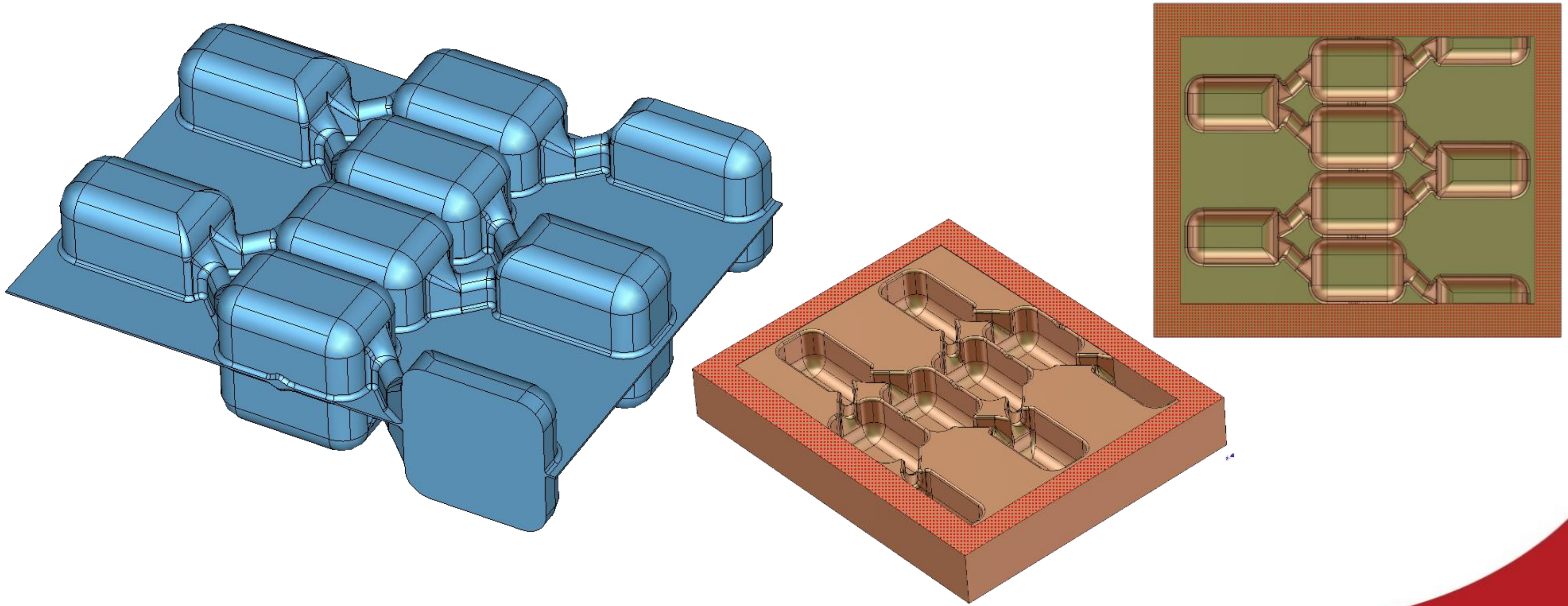
- Pareto plots allow to compare only the optimal options for different study cases and take decisions based on the specific requirements for the concerned application.

Manufacturing options: Milling in Halves



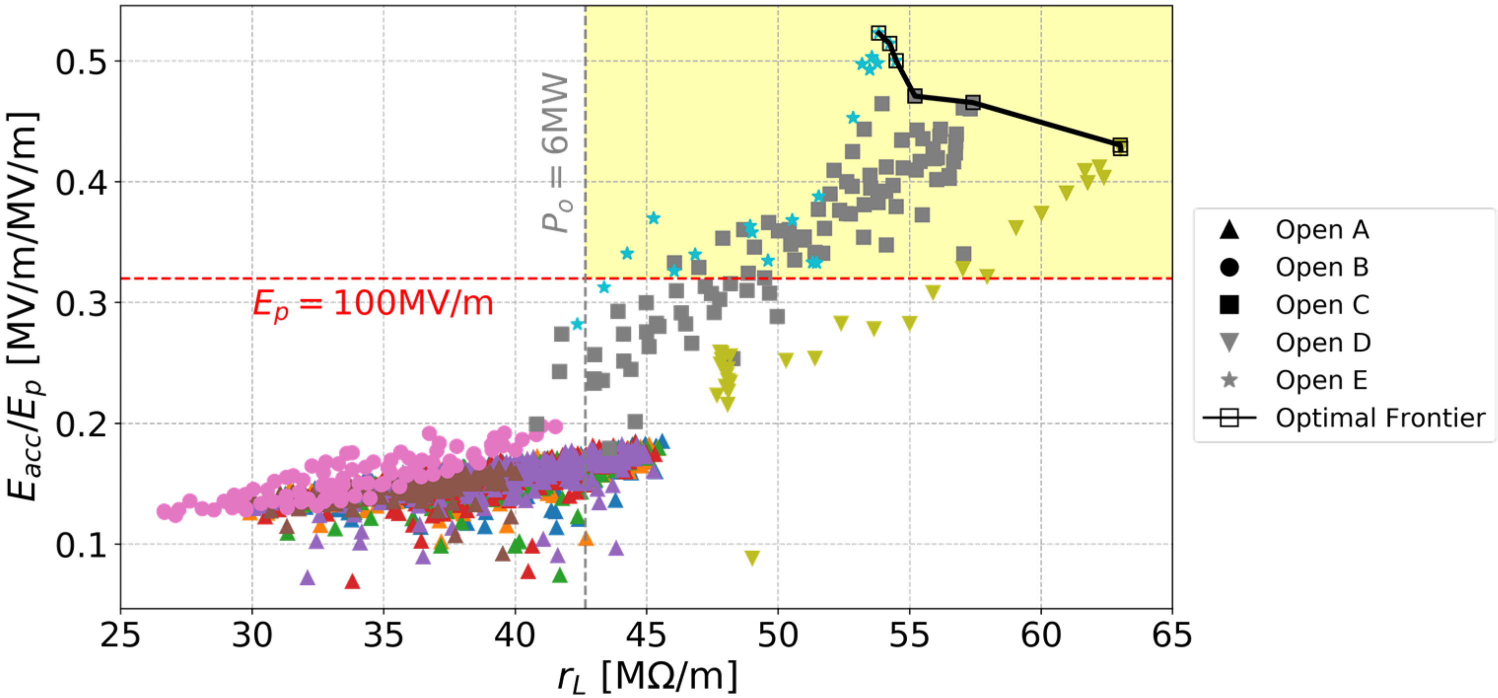
- Normally each cell is made in 2 parts plus 2 parts for the coupler. This is a lot of parts which increases cost
- Each part must be carefully aligned in the lathe/milling machine when machined
- Alignment when stacking to braze must also be done with care
- Making in two halves could simplify manufacture and reduce costs

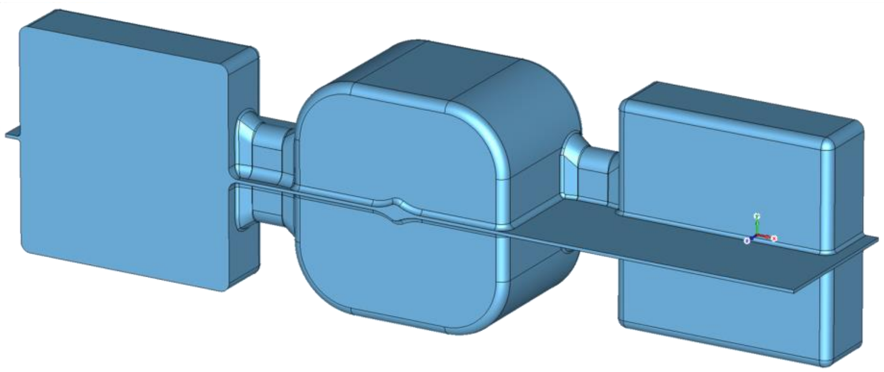
Studies on open structures at CERN found leaving a small gap between the two halves is better for structure conditioning



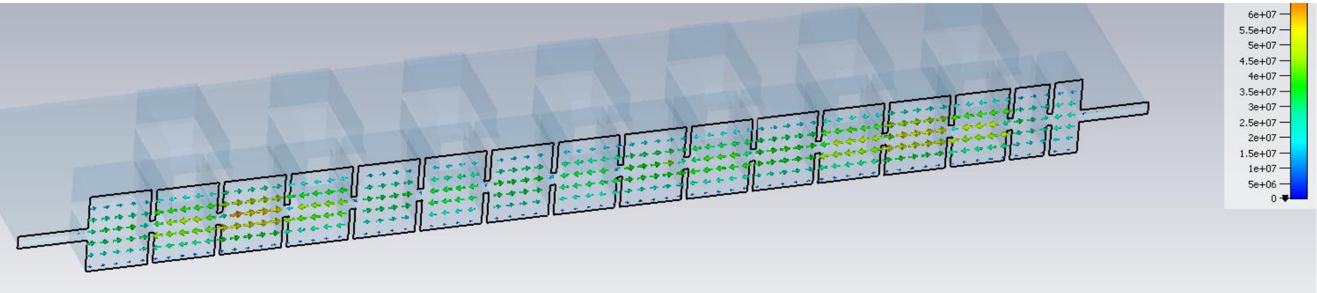
Open structures

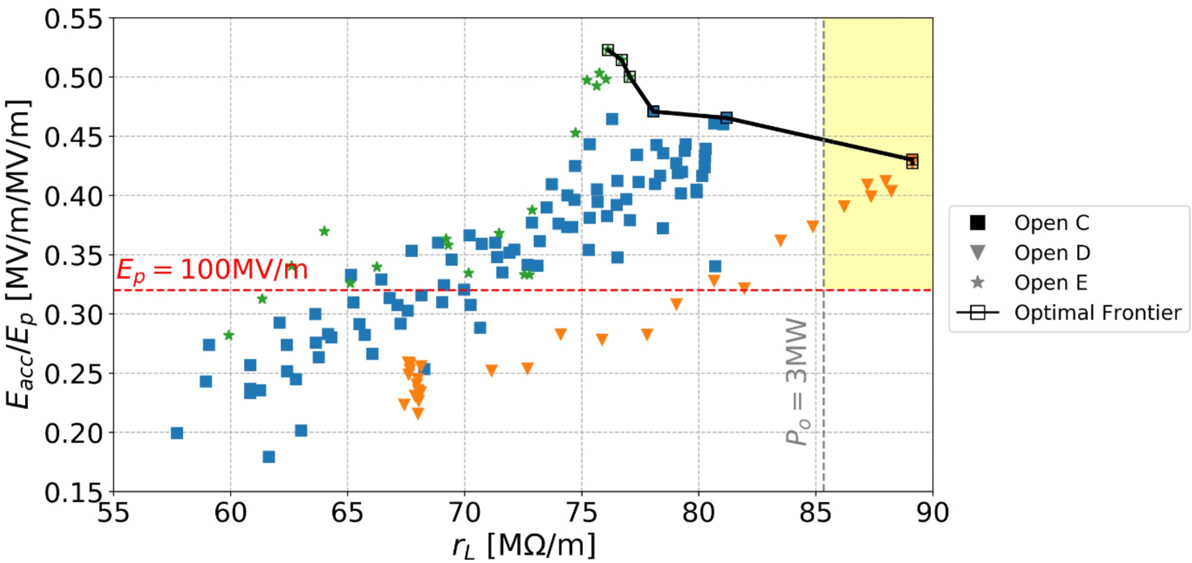
- An open structure would allow the structure fabrication to be made out of two parts, reducing manufacturing steps, complexity and therefore cost.
- Based on CERN travelling wave design for CLIV but ours is a standing wave which could be more efficient for radiotherapy



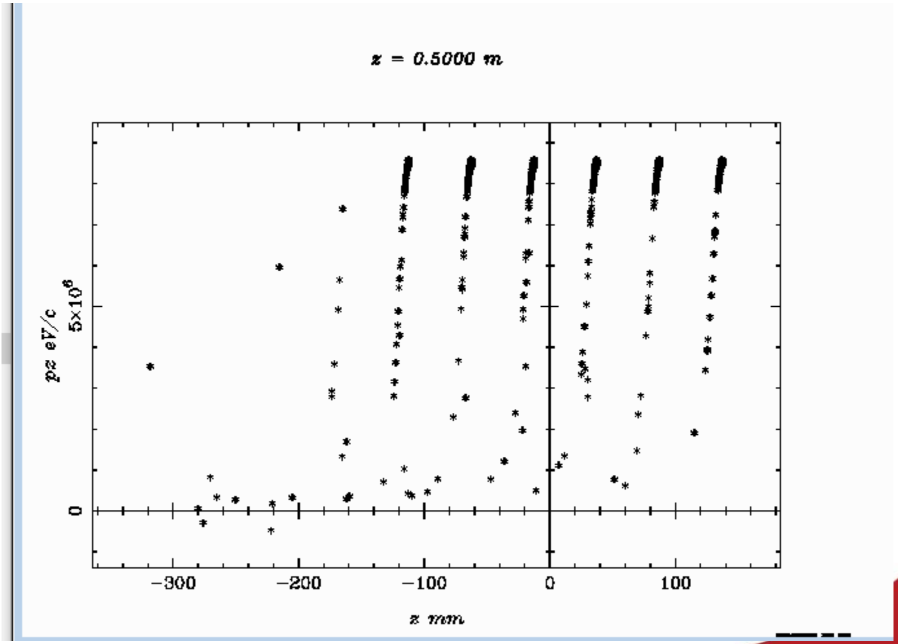


C-band 8 MeV design

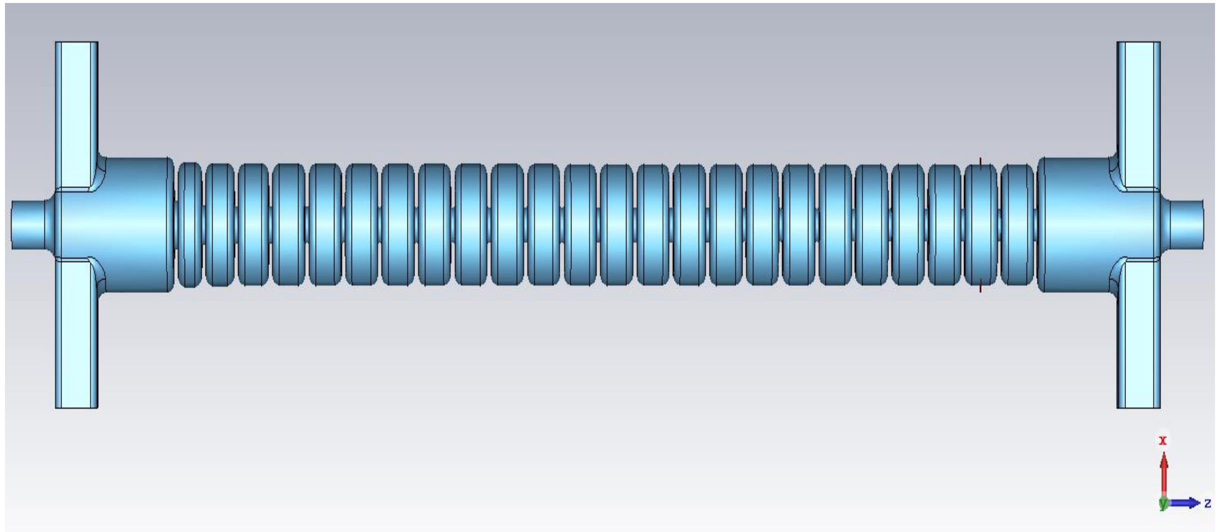




- Emax on axis = 60 MV/m
- Power required = 2.66 MW so can use a small and cheap magnetron, or the smaller C-band klystron
  Gradient = 24 MV/m
- 70% of electrons captured giving more dose than S-band system
- Can be optimised further



Medical LINAC: first design



Schematic diagram of the acceleration section including the RF couplers and accelerating cavities.

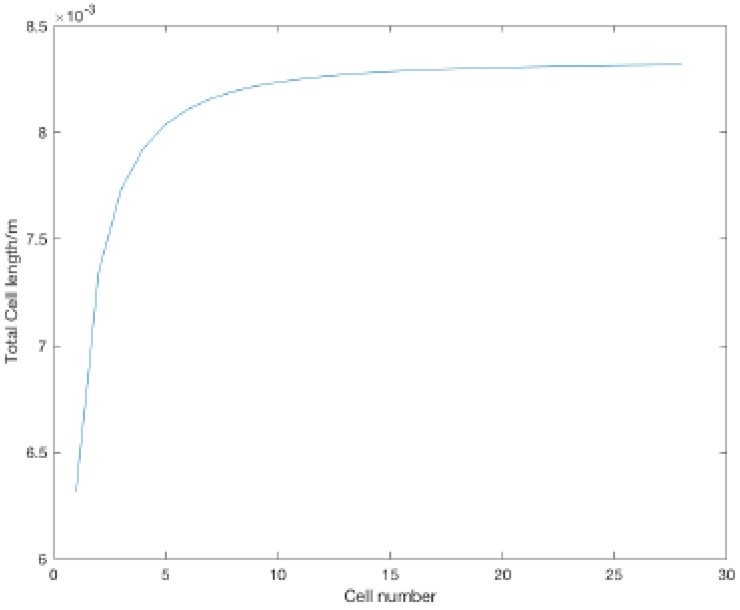
Prototype of the TW accelerating structure

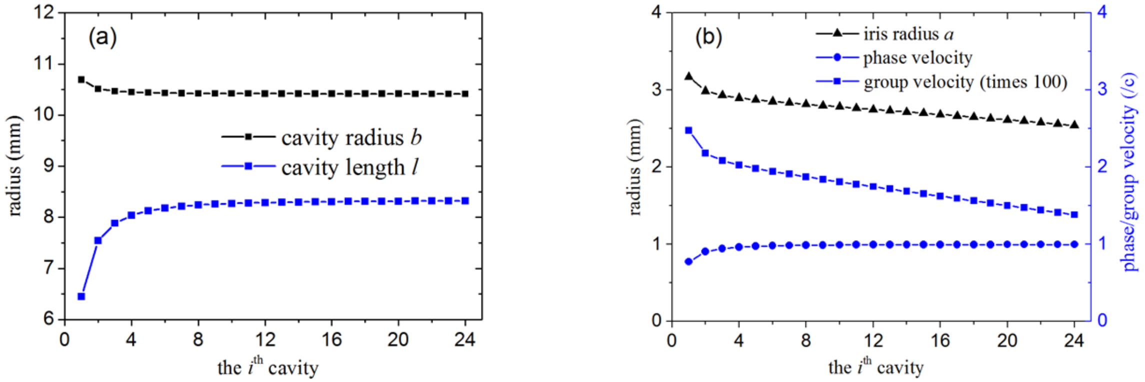
- **Objectives:**
  - Design and build TW 12GHz vacuum sealed, cathode included accelerating structure enabling acceleration of the electron beam from 50keV to 8MeV Minimise the construction and run cost
  - Compatible with permanent magnets
- **Requirements:**
  - Stability (no need to retune or service – “light bulb” approach)
  - Compactness
  - Modularity (same composition as for vacuum tubes used in aviation and industrial applications)

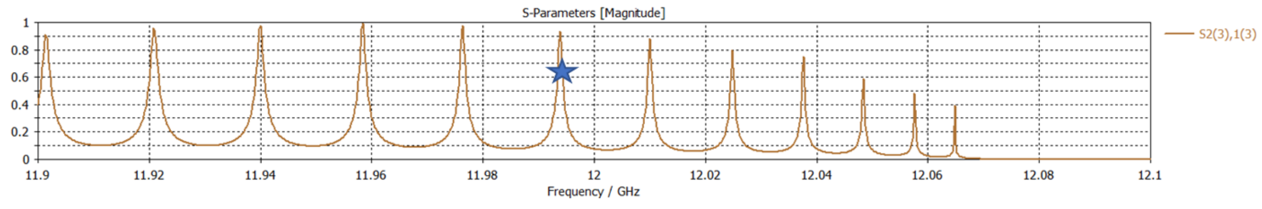
Open X-band: Initial design

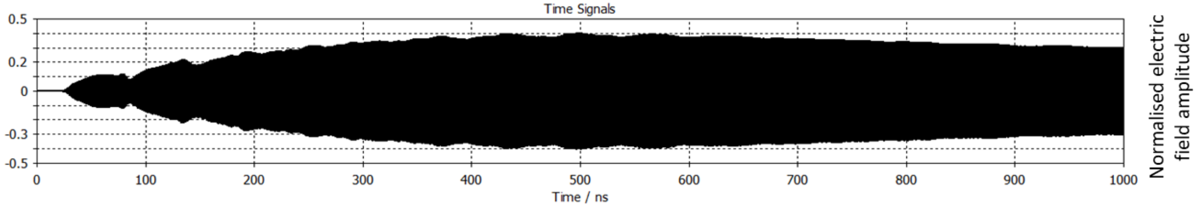
Parameters	Value
Beam energy before coupler	50 keV
Beam energy after coupler	150 keV
Final beam energy	10 MeV
Iris thickness t	1 mm
Total length of cavity array	20 cm
Filling factor τ_0	0.21

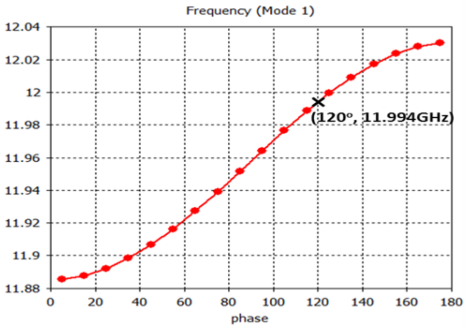
Modification of CERN X-band open travelling wave structure for radiotherapy. Initial prototype not optimised for application (gradient way too high)

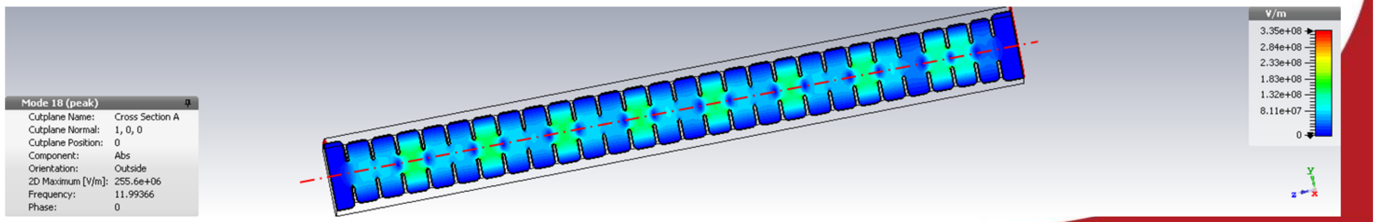












Mode 18 (peak)

Cutplane Name:	Cross Section A
Cutplane Normal:	1, 0, 0
Cutplane Position:	0
Component:	Abs
Orientation:	Outside
2D Maximum [V/m]:	255.6e+06
Frequency:	11.99366
Phase:	0

Some final thoughts.

Applying Machine Learning to Accelerators

- Classification, regression, clustering …
- Statistical techniques on Data to Learn
- Machine that optimises itself
- Combine online and simulation data with machine learning algorithms to provide optimal beam
- The machine **has learnt** the simulation and experimental data and sets itself up accordingly

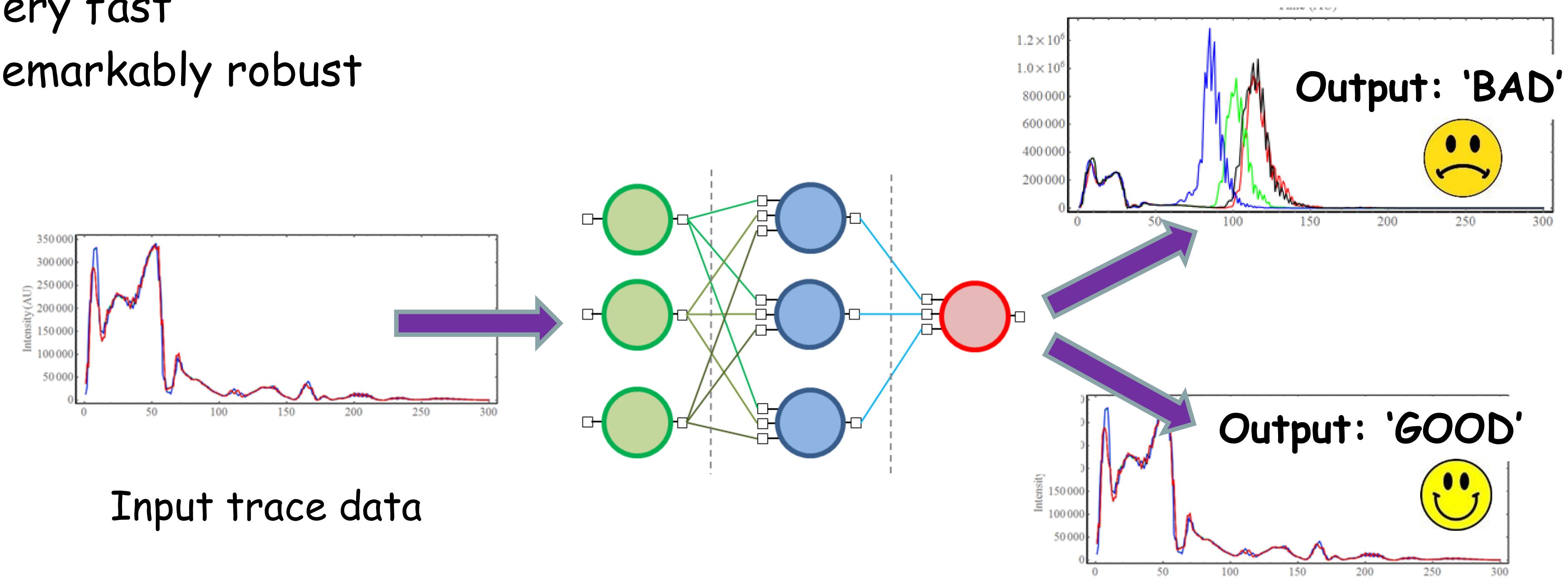
Intelligent Controls For Accelerators Workshop

- Over subscribed, 2 days, ~ 50 attendees Europe and North America
- Key Conclusions:
  - Much Interest, but still not coherent
  - Good Data is fundamental
    - You don't always know what data you will require upfront
    - Save your simulation data
  - Legacy Hardware Issues
    - Future proof yourself

New Initiative at ASTeC, Daresbury Laboratory. Duncan Scott, Accelerator Physics Group

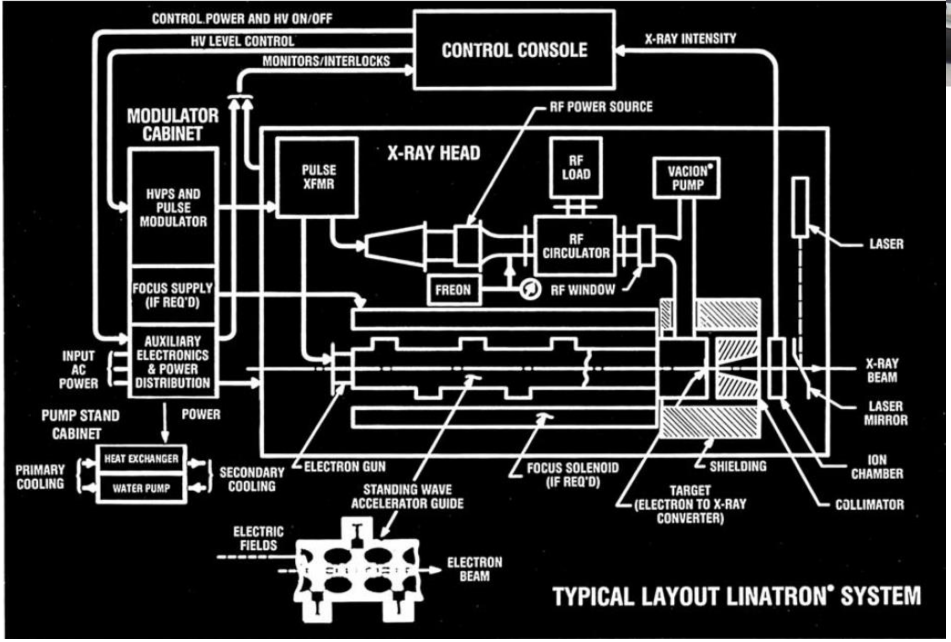
Example - RF Power Trace Classification

- Train Neural Network with 100 ‘Good’ traces (!)
- Then Passed 250 000, traces saved during Linac Conditioning,
- NN identified 55 outliers, confirmed as breakdowns traces
- Advantages:
  - Very fast
  - Remarkably robust



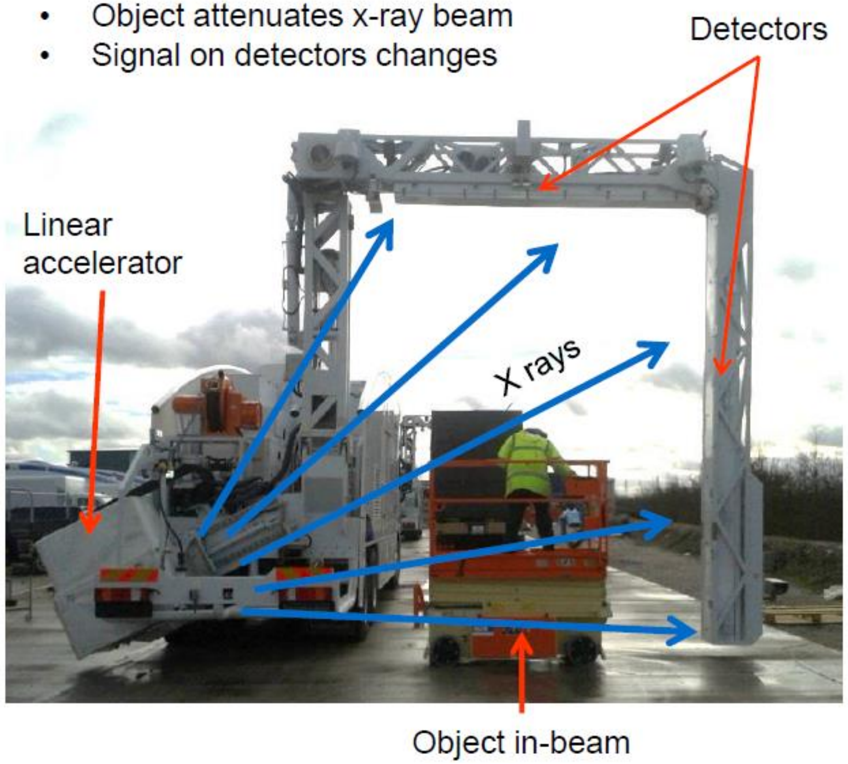
Input trace data

Mobile radiotherapy systems



Transmission imaging

- Object attenuates x-ray beam
- Signal on detectors changes



Rapiscan sell a "linac on a truck", it's a 6 MeV system with specs similar to a Varian 6 MeV Clinac. Its on a robotic arm.

Issues for treatment would be:

Alignment requirements
Rotating around the patient
Would need CT and MLC added
Less stable beam

Future work

- Beam dynamics
  - Need to perform full ASTRA optimisation with space charge and real cavity fields
  - Need to integrate with the electron gun simulations
- Standing wave
  - Need to finalise full EM design for open and standard structure
  - Need to investigate thermal and vacuum engineering design
  - Need to build aluminium prototype (not vacuum sealed)
  - Need to bold full vacuum sealed prototype
- Open X-band Travelling wave
  - Need to redesign for radiotherapy specifications and work out required power
  - Need to evaluate required tolerances
  - Need mechanical design for thermal
  - Needs a new prototype of the redesigned cavity
- Next steps
  - Need to construct a fully integrated linac at Daresbury linac test facility with electron gun, structures, RF sources, cooling and vacuum
  - Need to start on gantry design