Next Generation (Particle) Therapy Accelerators

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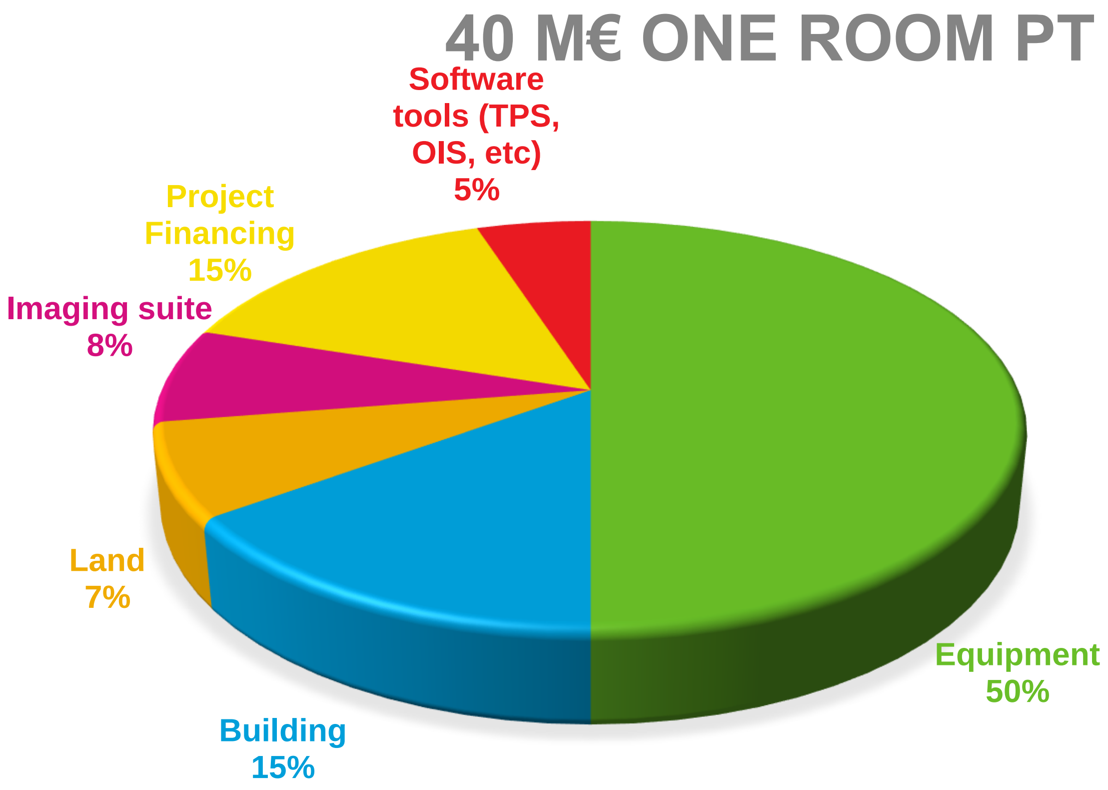
Outline of this presentation

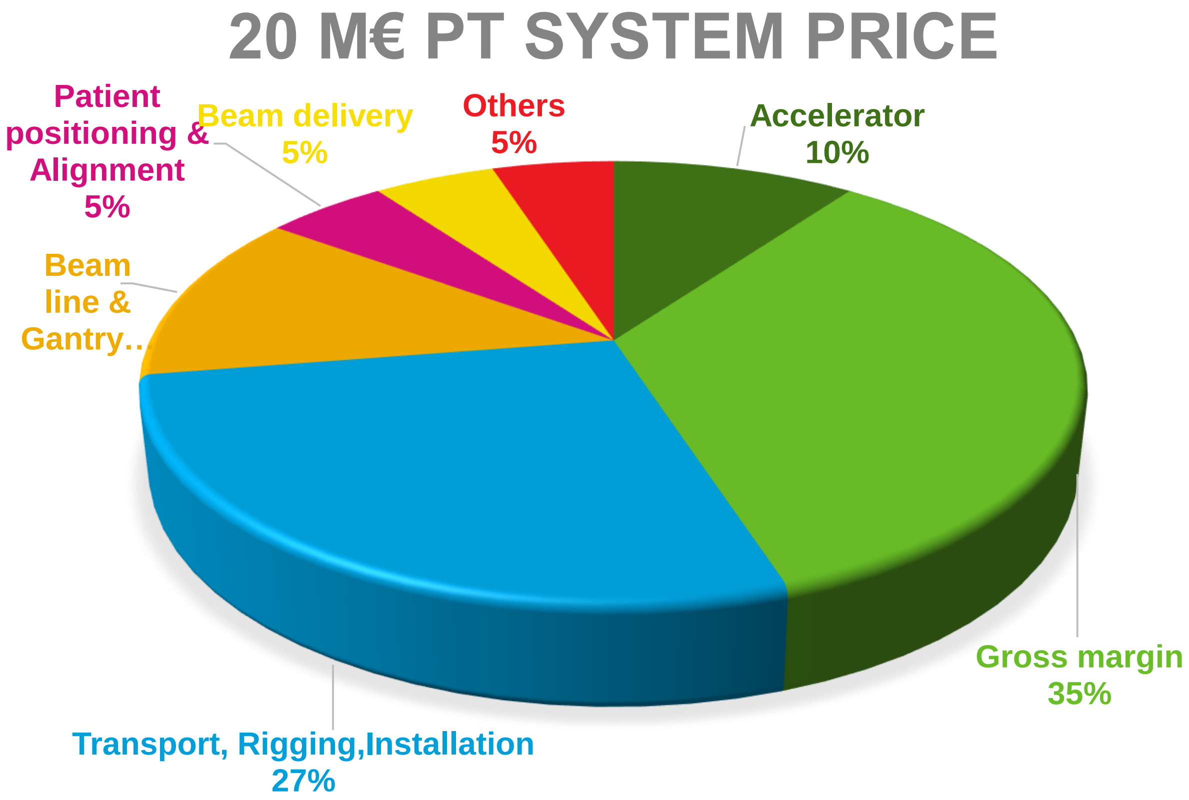
- The situation today
- One old myth to debunk: the expensive PT accelerator
- Main specifications (including Flash therapy)
- Superconducting synchrotrons
- FFAG's
- The DWA
- The linac for PT
- Laser acceleration of protons
- Isocentric gantries

The situation today in particle therapy

- A majority of the accelerators treating patients today in proton therapy are cyclotrons (isochronous cyclotrons or synchrocyclotrons)
- Today, a slight majority of these cyclotrons are superconducting. All new cyclotrons designed for PT are SC.
- The rest of the accelerators treating patients today in proton therapy are compact, resistive synchrotrons
- All the accelerators treating patients today with heavier ions (essentially carbon ions) are resistive synchrotrons
- Interestingly, despite a very significant amount of research invested in other accelerators for particle therapy, today, no other accelerator technology has reached the point where it is used routinely to treat patients

The myth of the expensive proton therapy accelerators





- If your accelerator, built, assembled, tuned and factory tested costs you more than 2 M€, you are not competitive in the PT market.

Main Specifications of proton therapy

Main specifications

- To be accepted by the market, a medical accelerator technology has to meet a set of minimum specifications detailed in the following slides.
- Improvements over these minimum specifications can offer interesting additional possibilities (example: higher range allowing to do proton radiography of the whole body, faster dose delivery allowing a 10 seconds lung treatment, higher efficiency allowing thinner shielding walls), but these added specifications will be accepted by the market only if the price penalty is not too severe.
- An exception to this could be the possibility to do Flash therapy which, if successful, could become a basic specification
- When the basic specifications are met, the experience of the last 20 years in proton therapy suggests that the life-cycle cost of the accelerator remains the first criterium of choice for prospective customers

The Range in patient

- For protons, 32 g/cm^2 is the current accepted standard. For Carbon, there is not yet a firm standard
- Higher ranges could be useful for proton radiography in the whole body, and are frequently discussed, but have never been sold even by manufacturers proposing synchrotrons where higher energies are not too costly.
- Conversely, even if it has been demonstrated that a lower range, like 20 g/cm^2, could treat a majority of patients, it is unlikely that an hospital will select a technology offering a lower range that would oblige him to reject a significant fraction of the prospective patients

The dose rate

- The dose rate is related to the particle current delivered by the accelerator
- But the time to treat a given tumor is much more significant that the dose rate. In addition to the dose rate, this time depends on the number of Bragg peaks needed to deliver a uniform dose, on the time needed to change energy (including the time needed to re-stabilize the beam line optics), on the time needed to move the spot and to perform the needed quality checks… etc.
- Being able to deliver a dose of 2 Grays in a one liter target in one minute is seen as a minimum standard
- But being able to treat a lung tumor in 10 seconds allows to get rid of respiratory gating, and to use breath hold.
- The big new challenge on dose rate or irradiation time will come from the possibility to do Flash irradiation (more on that later)

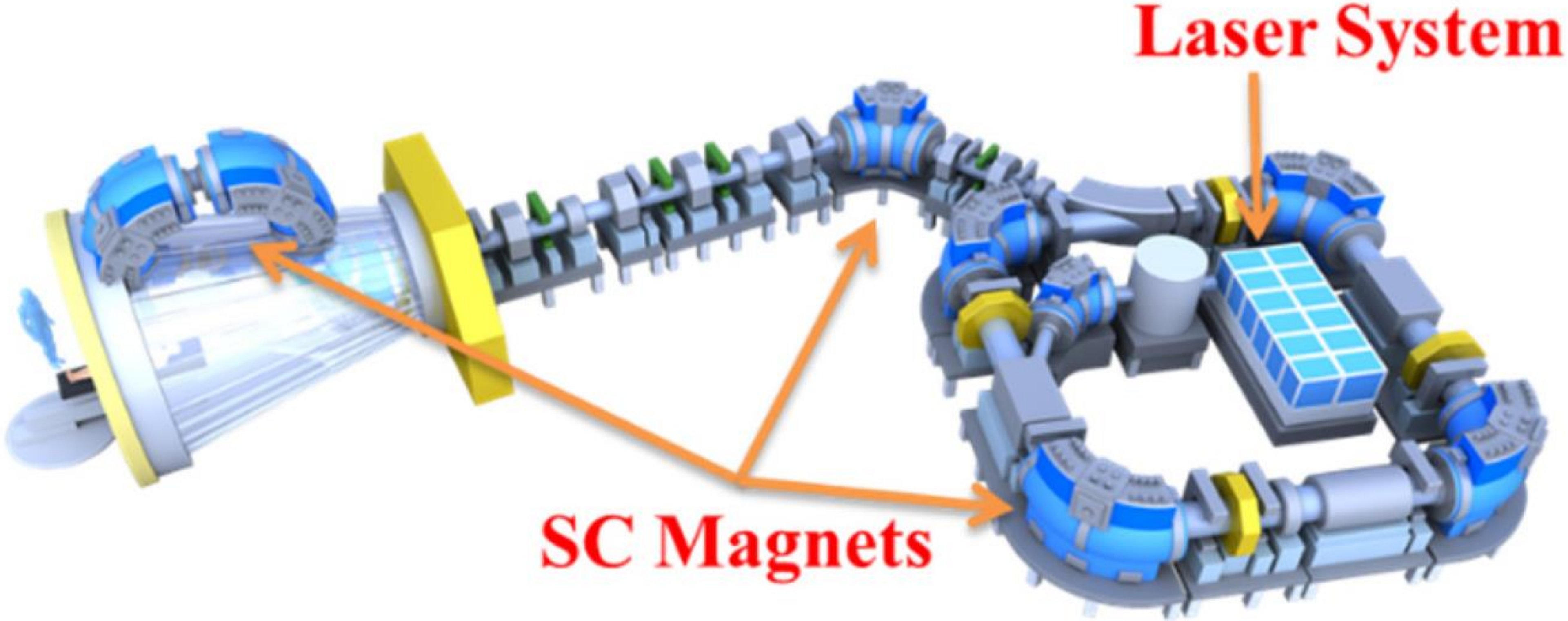
Flash Therapy

- Preliminary experiments indicate that, at very high dose rates (between 40 Gy/sec and 100 Gy/sec), the effects of radiation on heathy tissues are significantly reduced, while the radiation effect on the tumor is not reduced
- This is not new, but in the last year, the number of experiments has significantly increased, and the accuracy and reproducibility of the experiments as well
- This effect is observed with electron and with proton beams
- The effects of the time structure of the beam are currently investigated.
- The whole treatment dose can be delivered in a single fraction lasting less than one second, resolving the moving targets issues
- The reduction of the number of fractions increases the number of patients treated in one treatment room, reducing strongly the cost of the therapy
- This changes radically the dose rate requirements!!!

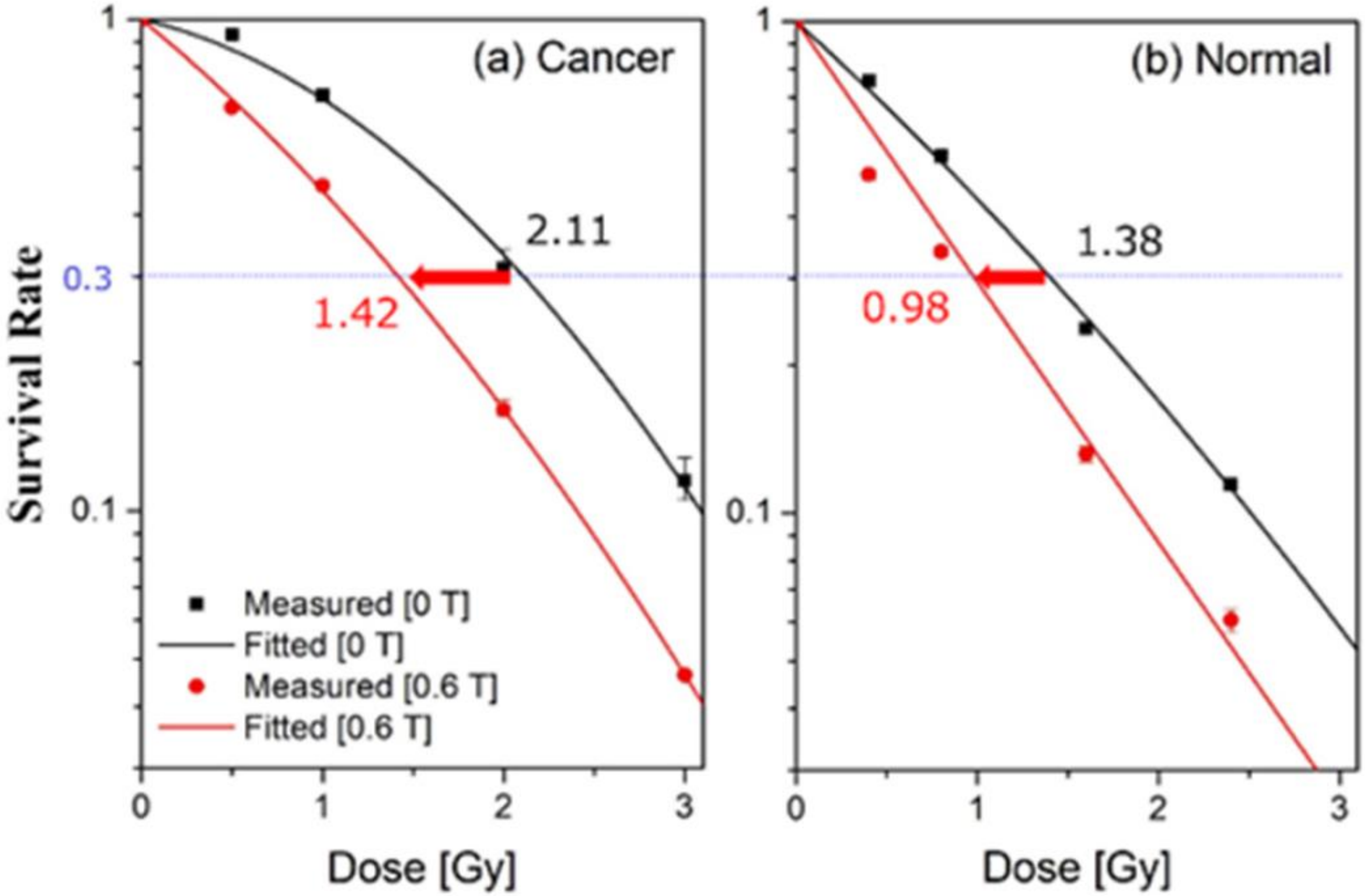
Superconducting Synchrotrons for Carbon Therapy

NIRS conceptual SC Carbon Synchrotron and Gantry

- This concept uses a laser acceleration Carbon injector at 4 MeV/u and 4 T dipoles
- For protons a SC synchrotron is less justified because the straight sections are not reduced like the magnets radius

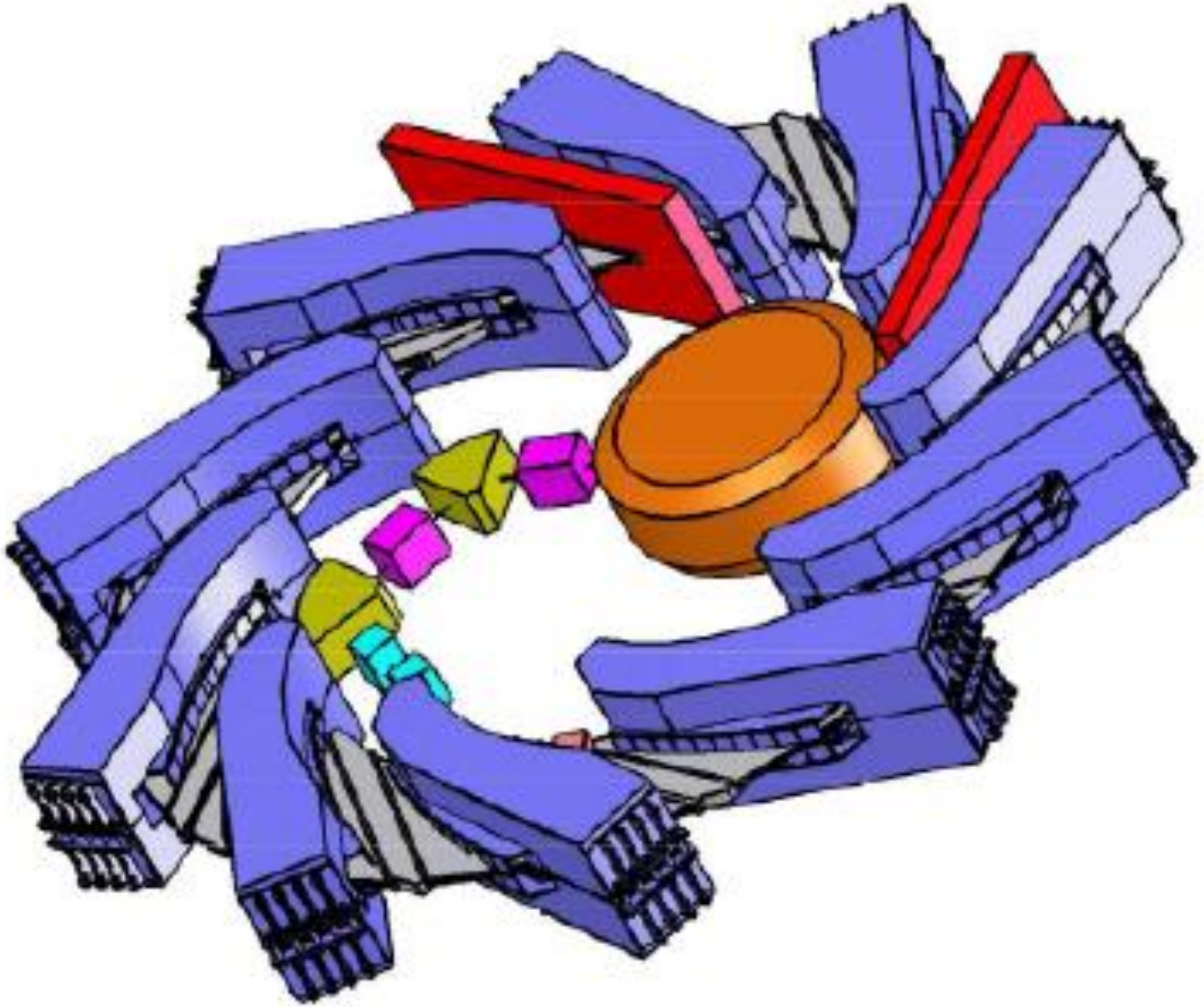


Adjusting the RBE of carbon ions with a longitudinal magnetic field



FFAG’s (Fixed Field Alternating Gradient Accelerators)

The RACCAM spiral scaling FFAG project (France 2006-2009)



Carol Johnstone 30 MeV to 230 Mev non scaling isochronous FFAG

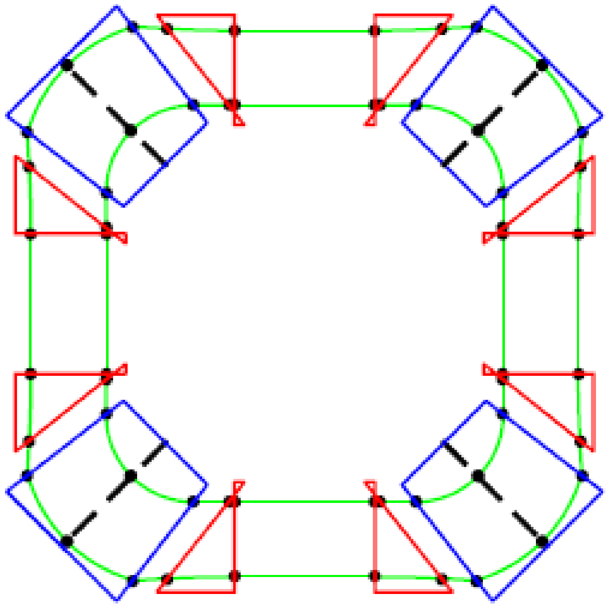


Figure 1: Layout of 4-cell 30-330 MeV FFAG.

Table 1: General parameters 4-cell, 30-330MeV FFAG

Parameter	**30 MeV**	**151 MeV**	**330 MeV**
Avg. Radius	1.923 m	4.064 m	5.405 m
ν_x/ν_y (cell)	0.264/0.366	0.358/0.405	0.-/0.441
Field F/D	0.97/0.00 T	1.24/-0.09T	1.51/-0.16 T
Magnet Size F/D	1.28/- m	2.4/0.92 m	3.18/2.08 m

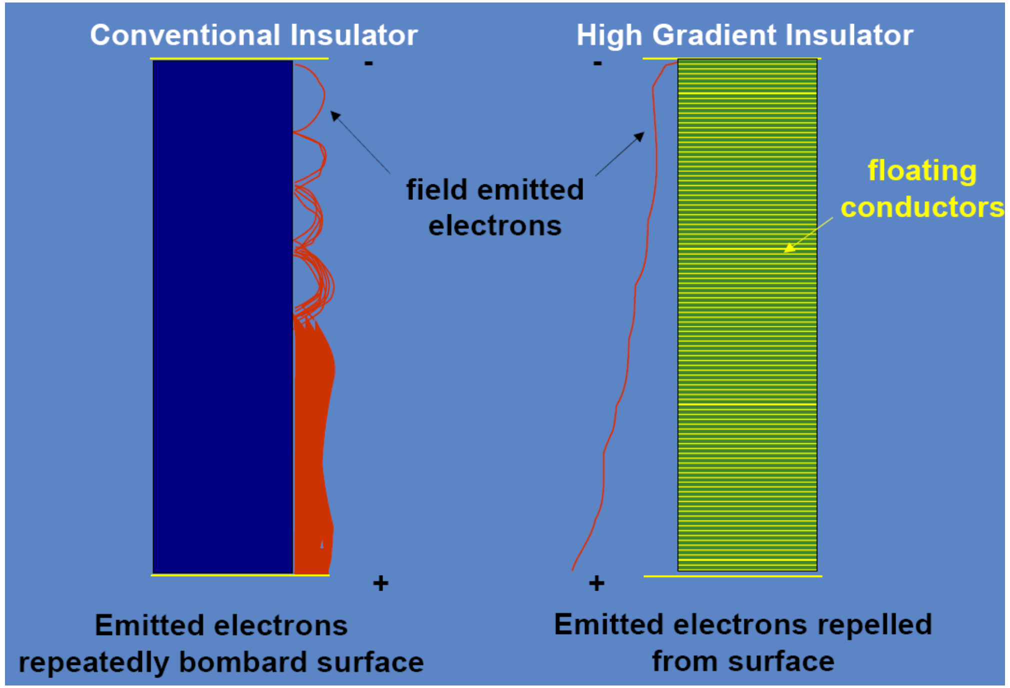
FFAG's in proton or carbon therapy

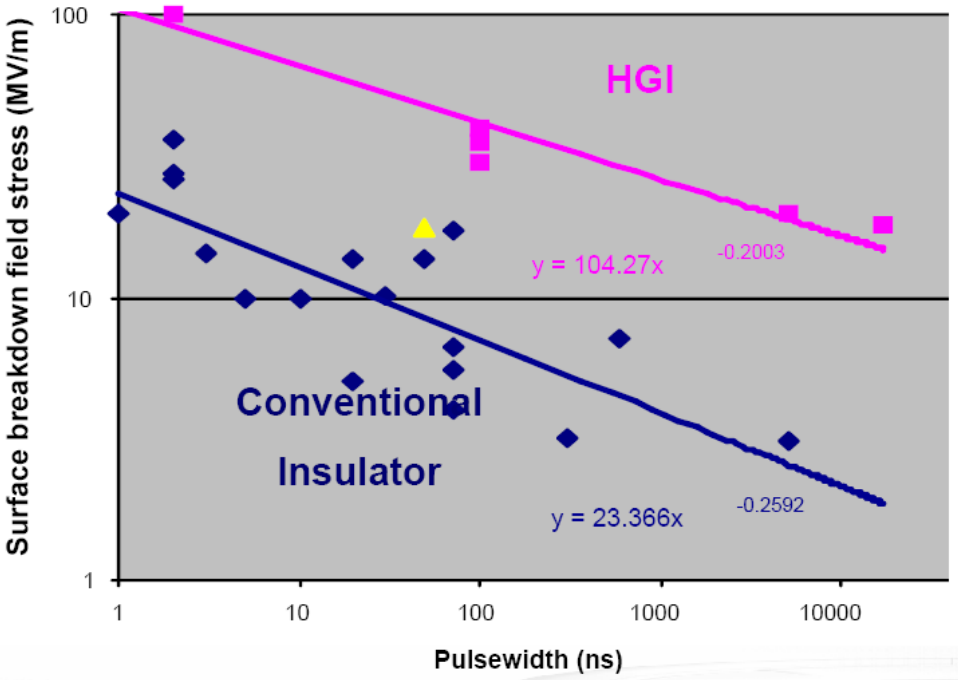
- Despite many studies (and even construction and testing of a prototype magnet for RACCAM), FFAG's have never been built for proton or carbon therapy.
- Compared to compact accelerators of the same energy, FFAG's are much more expensive to build (in part because they need a high energy injector) and do not offer significant advantages excepting, perhaps fast energy variation using extraction by fast (and large) kicker magnets
- But this fast extraction has never been the subject of a detailed design (to my knowledge)
- Most of the studies on FFAG's have concentrated on magnetic structure design and optics calculations. Other critical issues like the variable frequency RF system have been much less studied.

The Dielectric Wall Accelerator

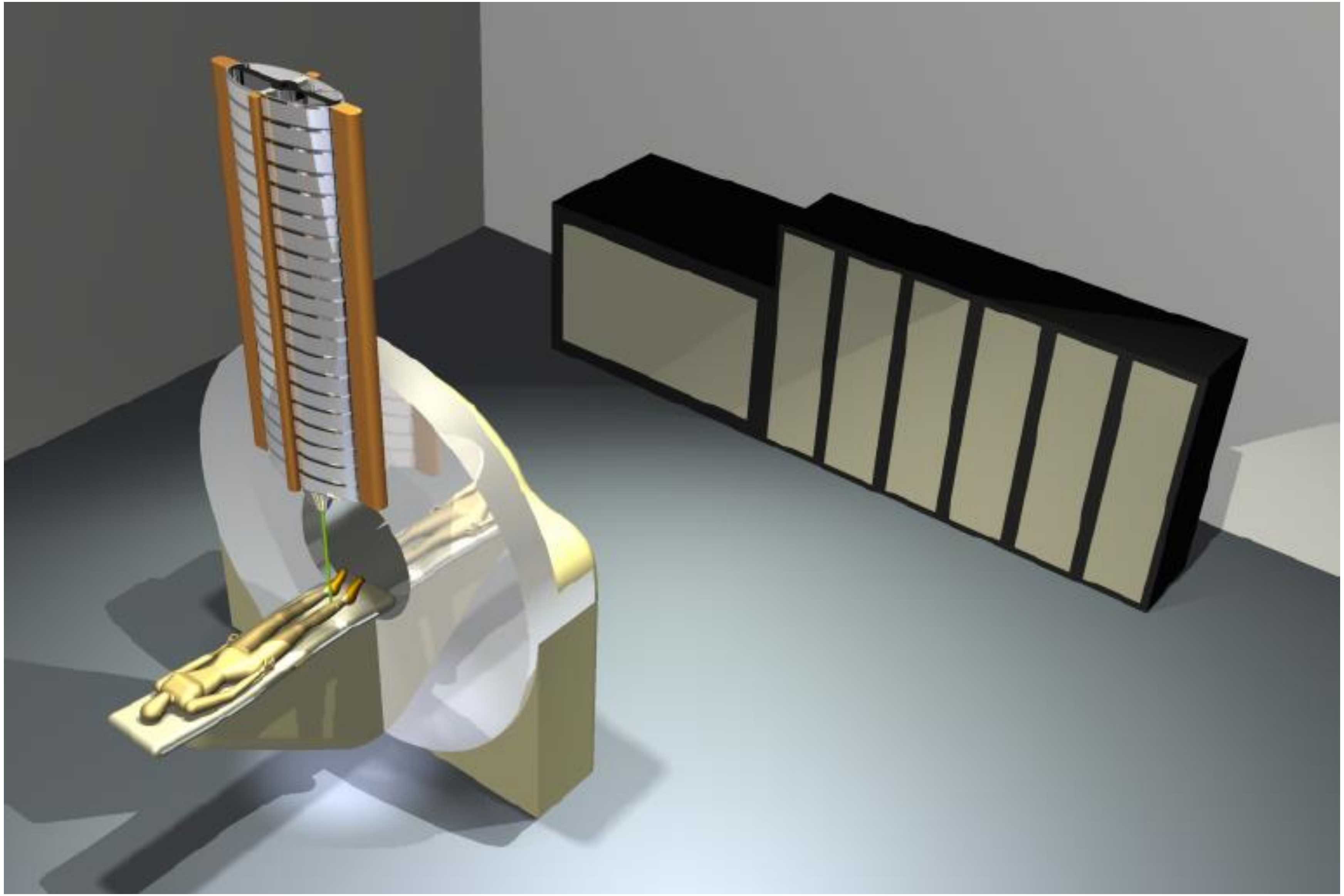
The Dielectric Wall Accelerator

- The DWA was a concept invented by the group of George Caporaso at LLNL
- The License to the DWA technology was given to the US Company Tomotherapy
- Later, the company CPAC was created as a subsidiary of Tomotherapy to develop the DWA
- The development of the DWA by CPAC was long and painful. The prototype failed. The development was abandoned when Tomotherapy was acquired by Accuray

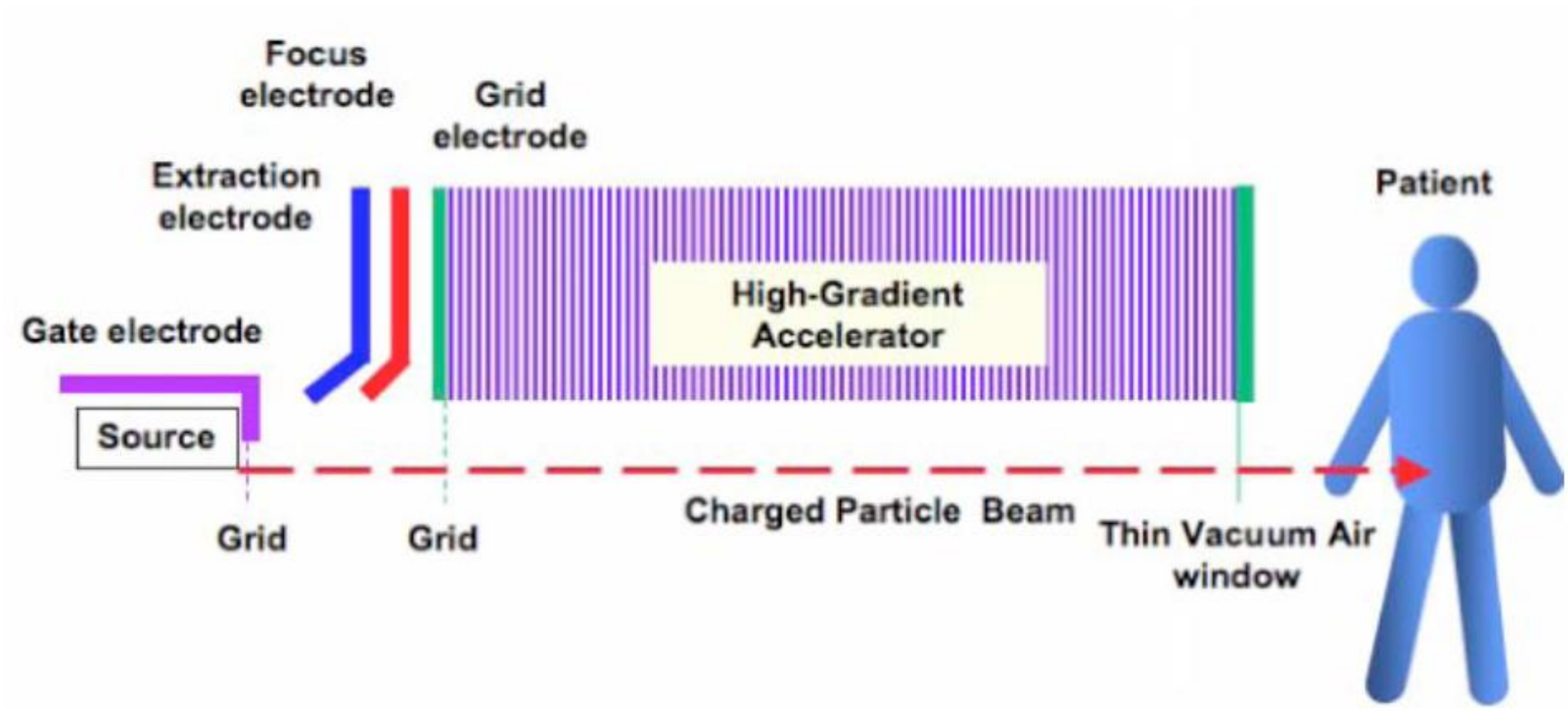




The DWA as presented by Tomotherapy

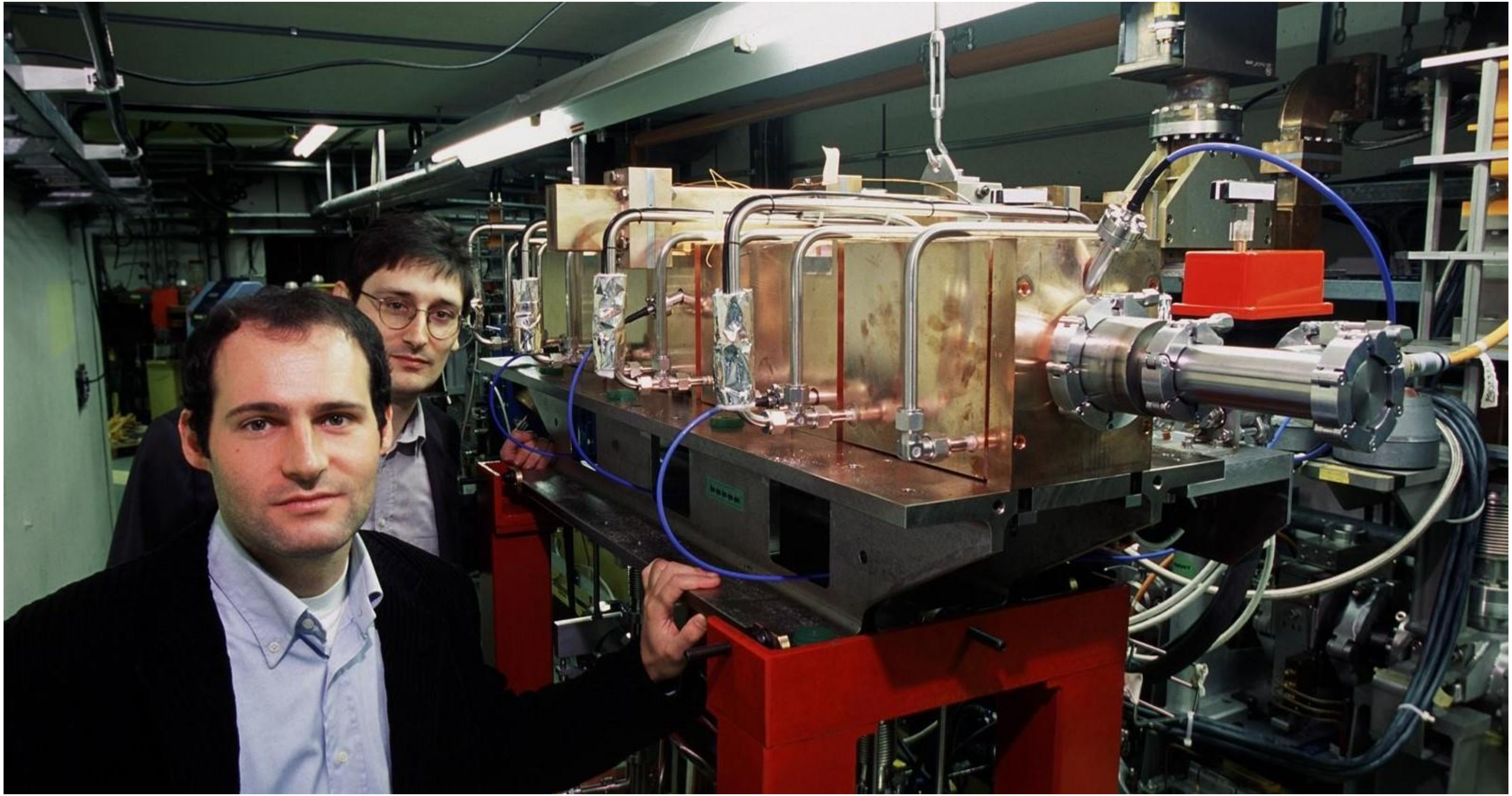


The main elements of the DWA



Linear accelerators for proton therapy

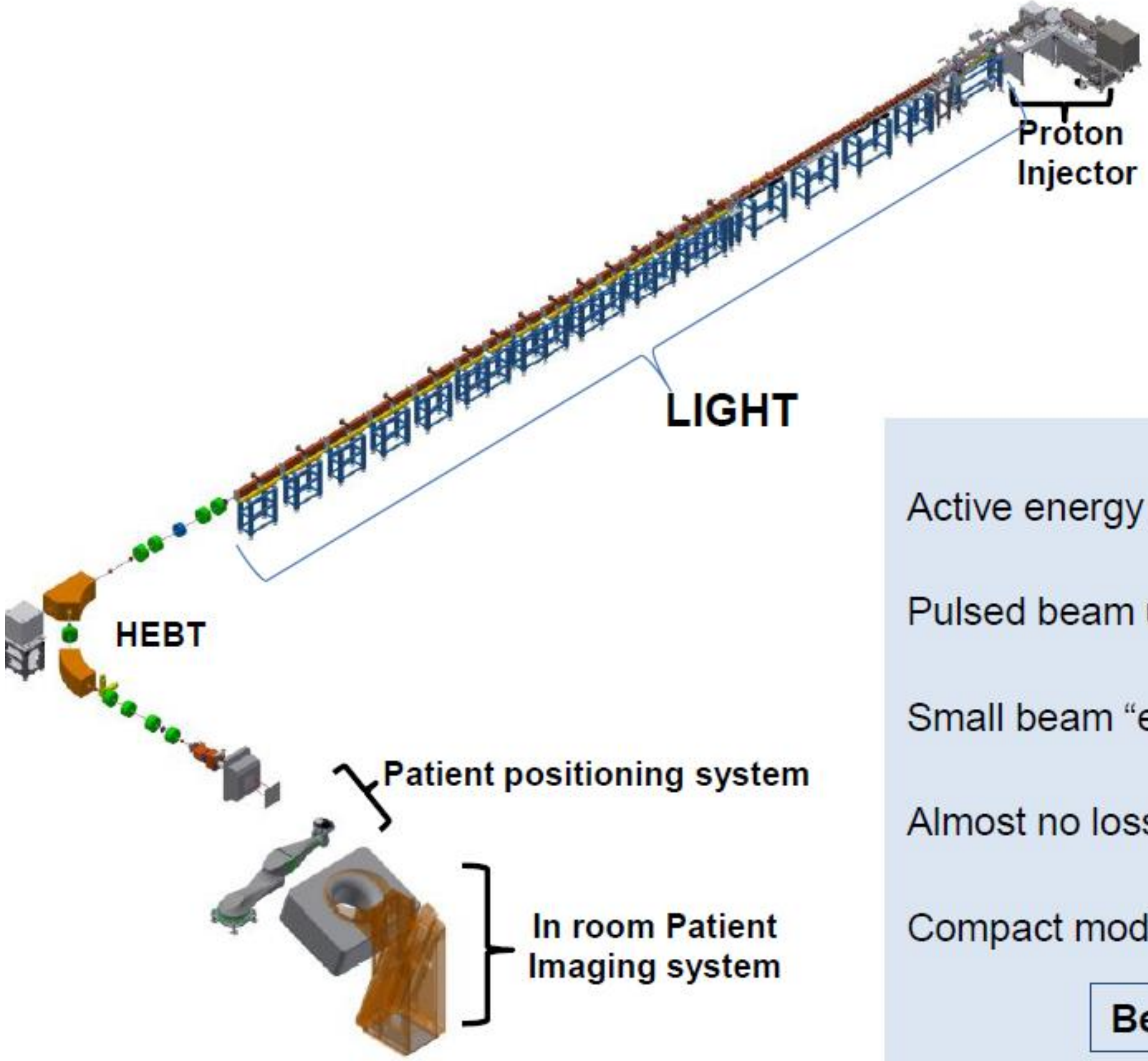
The origin: the LIBO project (1993-2002)



A 3 GHz linac for proton therapy

- The idea to use the 3 GHz hardware to design and build a linear accelerator for proton therapy was initially proposed by Ugo Amaldi in the TERA-CERN collaboration. The concept development started in 1993
- The prototype section, accelerating protons by 11 MeV, was successfully tested on the SC cyclotron at the LNS in Catania. The RF for this test was provided by IBA.
- In 2006, the company ADAM (Application of Detectors and Accelerators to Medicine) was founded to develop the LIBO toward a commercial system.
- In 2013, AVO (Advanced Oncotherapy) acquired ADAM, to further develop and commercialize the PT Linac technology.

AVO-ADAM LIGHT Linac for PT



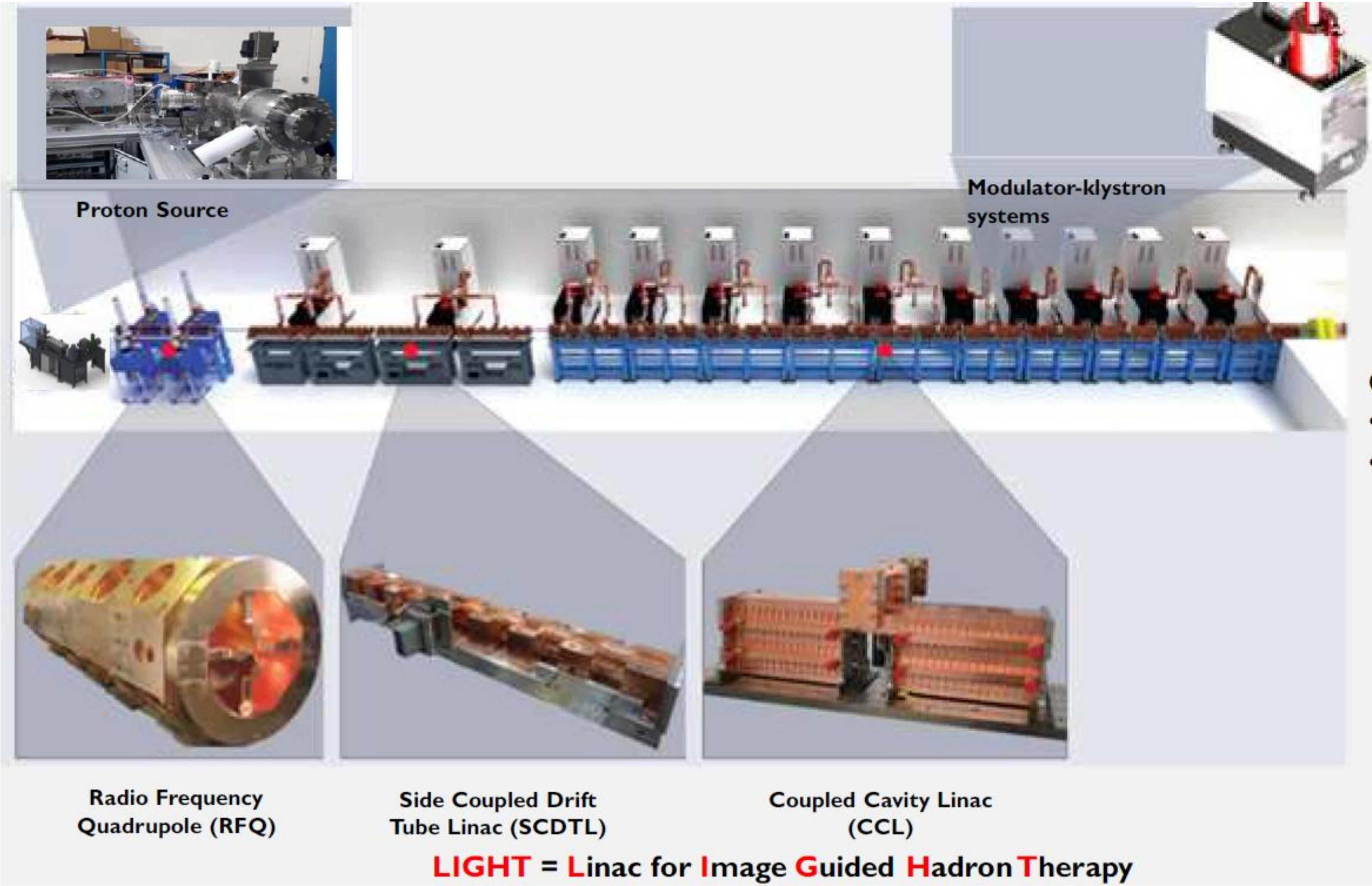
Active energy modulation	→ no absorber and degrader
Pulsed beam up to 200 Hz	→ fast intensity and energy change
Small beam “emittance”	→ small magnets aperture
Almost no losses!	→ reduced shielding
Compact modular design	→ easier installation

Beam suited for 3D spot scanning

Main data of LIGHT Linac

Parameter	Value	Unit
Length	~25	m
Max. Energy	230	MeV
Output Peak Current (at the end)	0.3 - 90	µA
Pulse Length	0.5-5	µs
RF Frequency	2997.92	MHz
Max. Repetition Rate	200	Hz
Peak RF Power	~60	MW

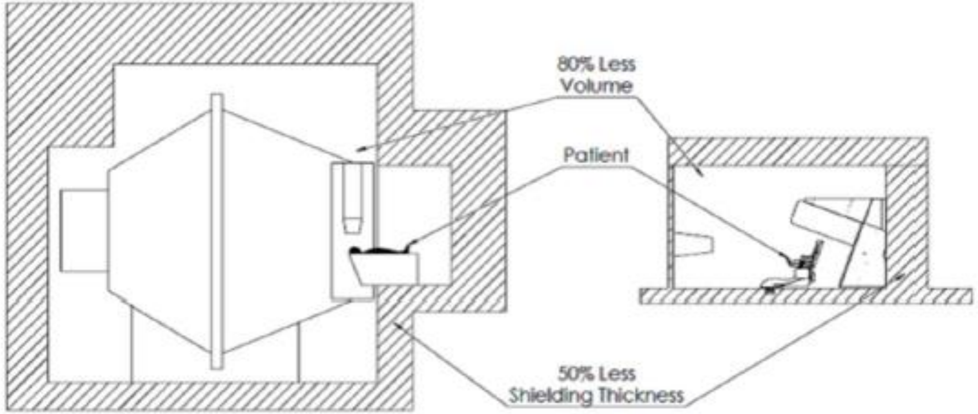
Main Linac Sections

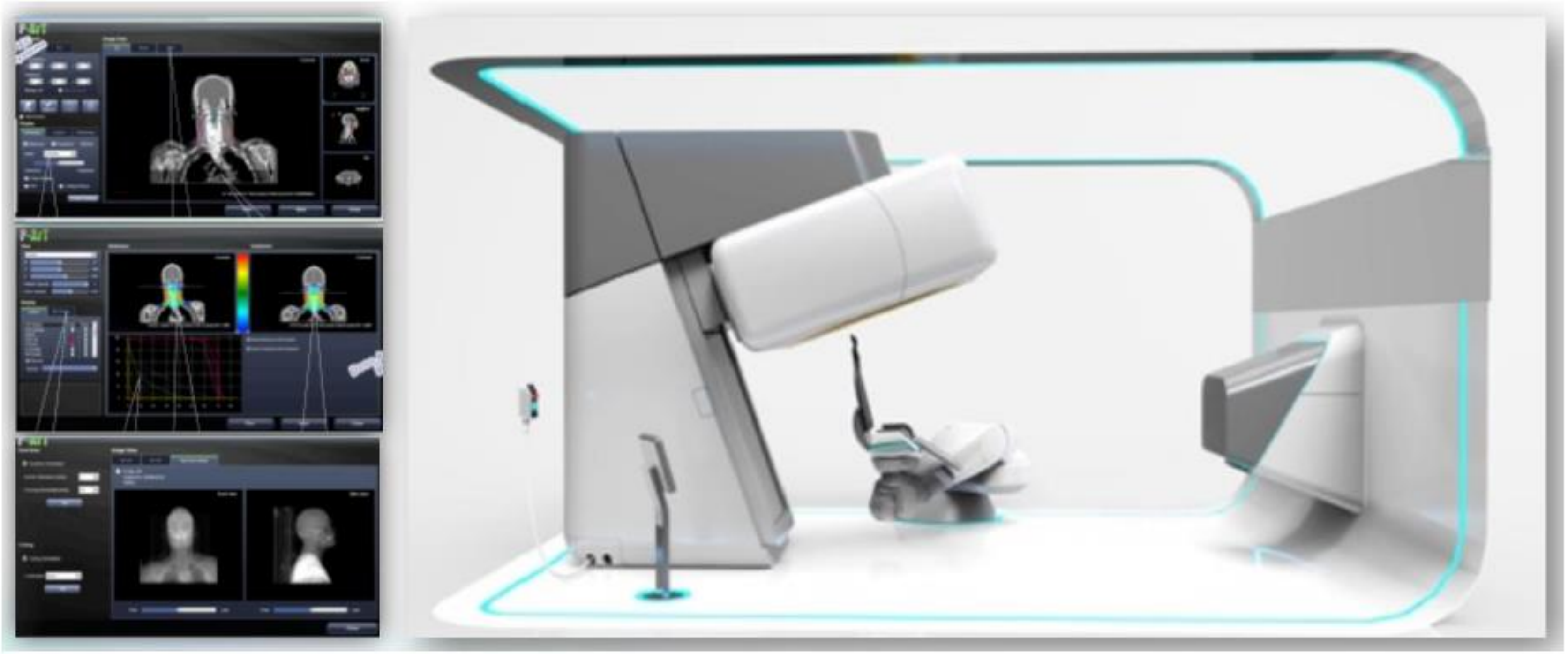


Currently under testing:

- CERN AP2, Geneva
- STFC, Daresbury, UK

Treatment Room setup: no gantry





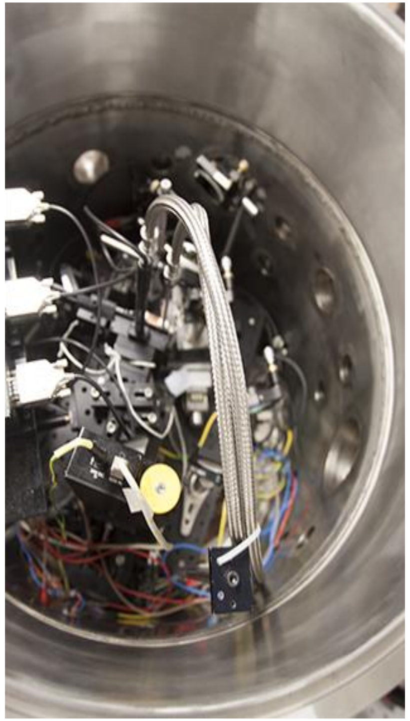
The AVO proton therapy system

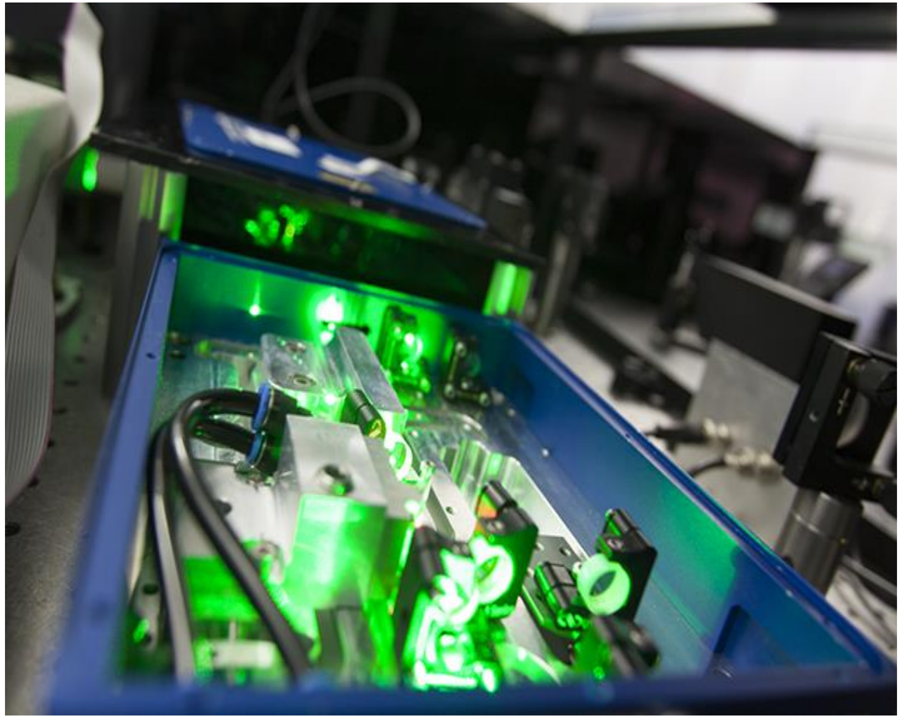
- Today, in 2019, the prototype is being assembled and tested at Daresbury laboratory, before being moved to its final location in Harley Street in London
- Since the start in 1993, the development of the 3 GHz proton linac has been long and the beam has not yet been accelerated to full energy.
- So far, AVO has invested 93 M£ (102 M€) in the development of the new system.
- For this first system, AVO has elected to skip the gantry, and to do the treatment in an horizontal beam line
- While it is very likely that the AVO system will perform very well according to its specifications, it remains to be seen if such a linac system without a gantry will be seen as cost-competitive on the proton therapy equipment market

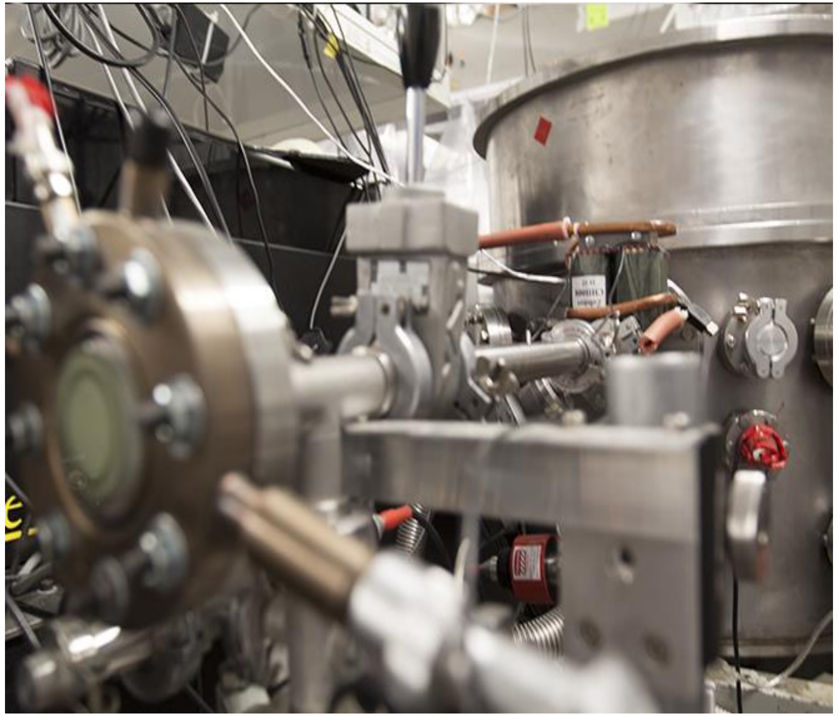
Laser Acceleration of Protons

HIL APPLIED MEDICAL

Next-Generation Proton-Beam Cancer Therapy



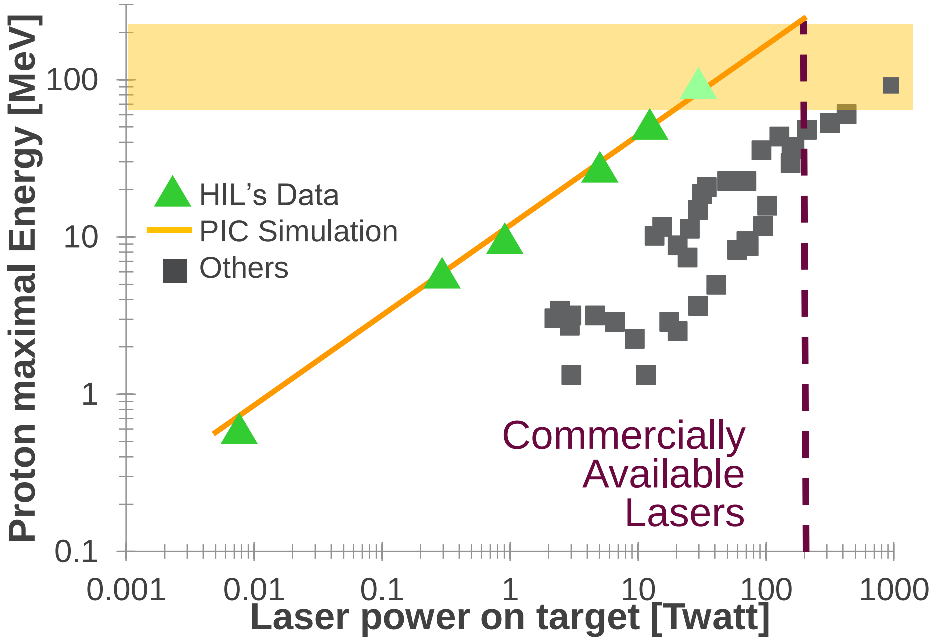




Basic Beam Parameters

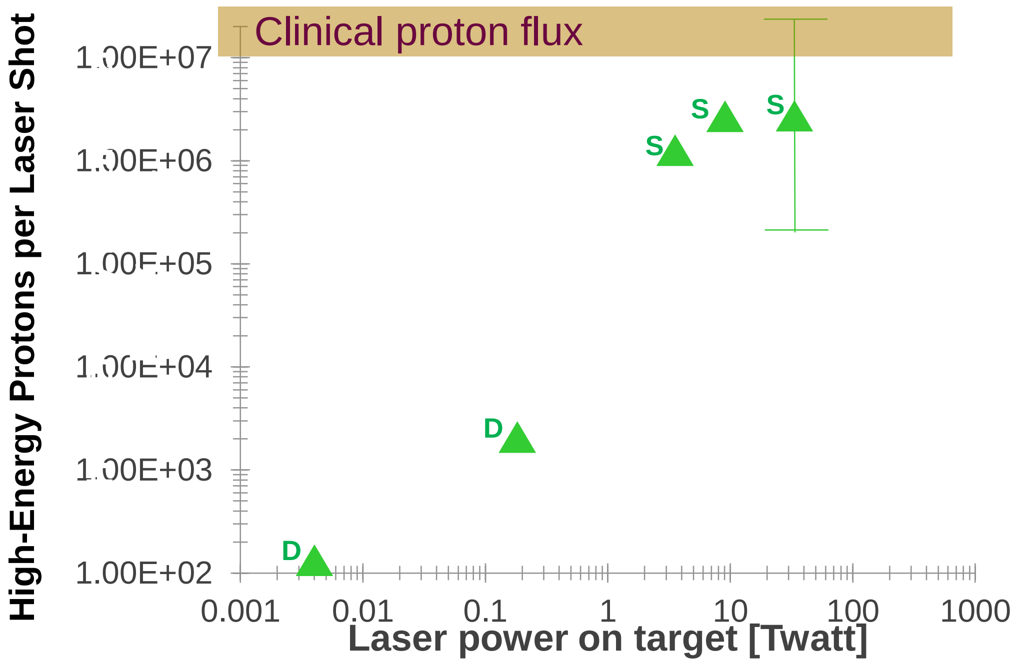
Compared to State-of-the-Art Competing Laser acceleration Groups

Acceleration – Max. Energy



Basic Beam Parameters – Cont'd

Near-Clinical Proton Flux



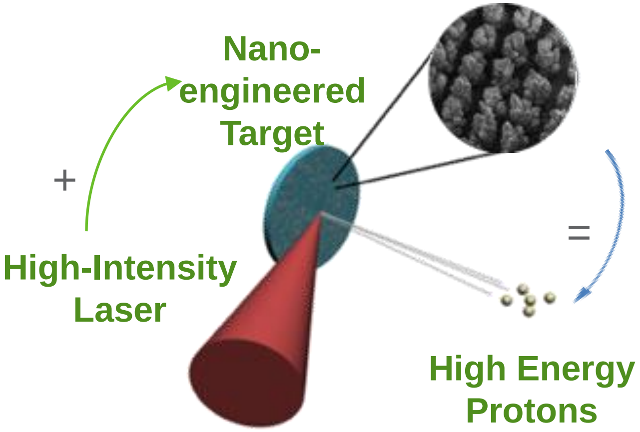
LASER BASED PROTON ACCELERATOR CONT'D:

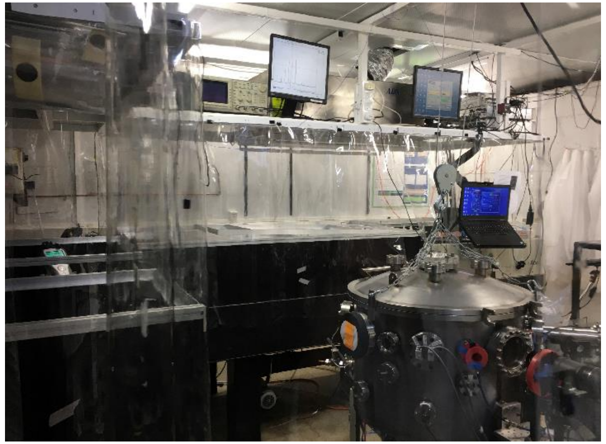
Bringing 21st-century tech to proton therapy

<u>The accelerator:</u>

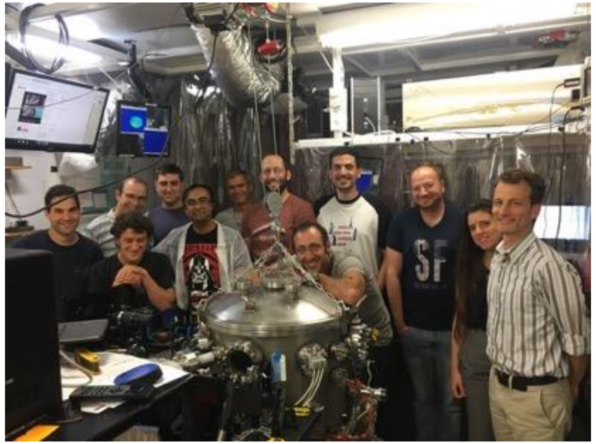
Nano – engineered target supported by a vacuum chamber

- Small dimensions (60 cm diameter, 200kG).
- Optional machine shielding against radiation.



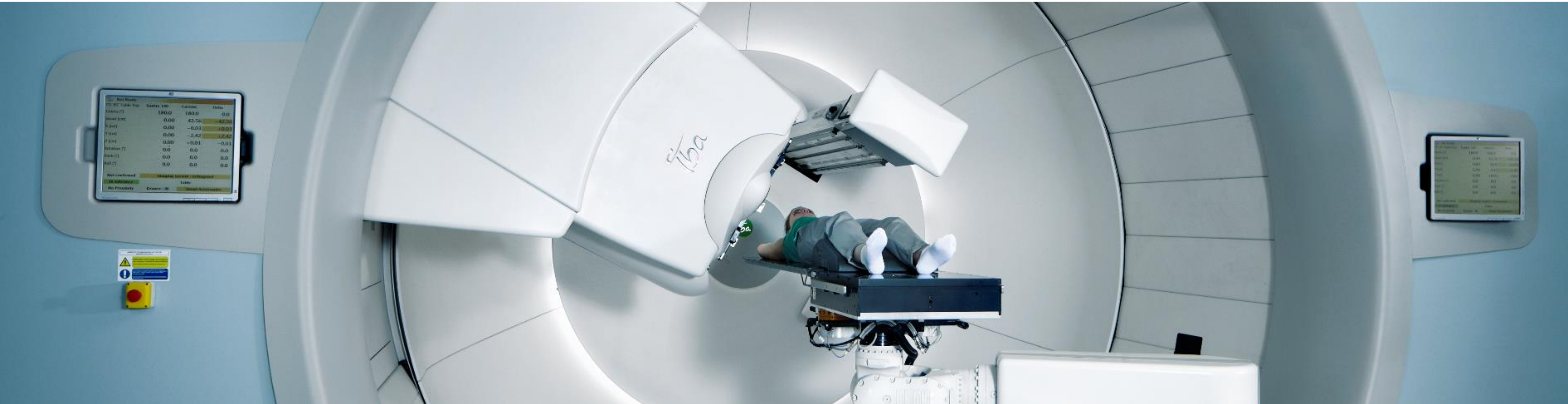


Laser system & Accelerator vacuum chamber



HILs proton accelerator and the team.

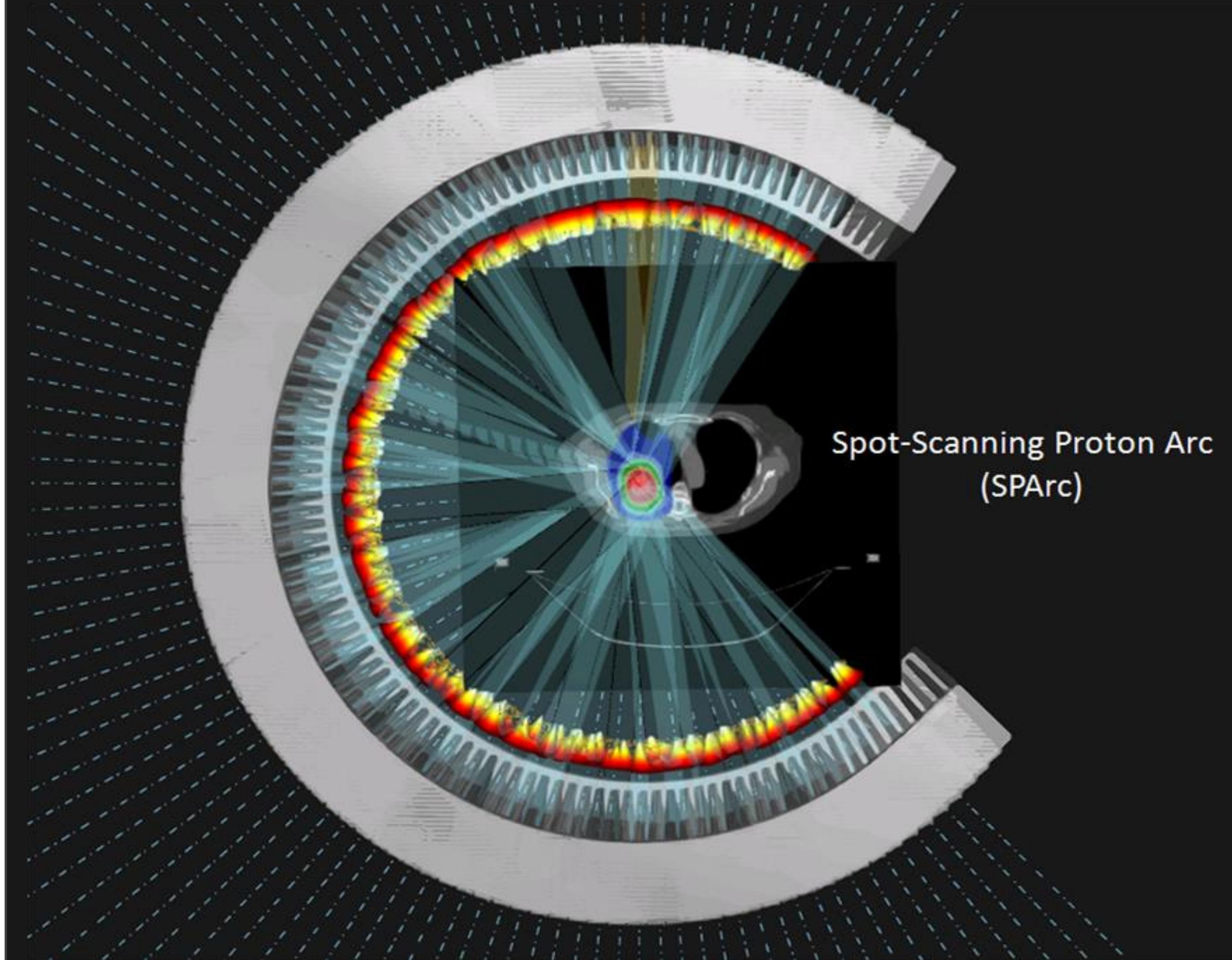
Patient-Beam interaction: isocentric gantries



Isocentric gantries (1)

- In the human body, and especially in the abdomen region, the relative position of the organs changes when the body orientation is changed.
- Therefore, the treatment planning will be valid only if the TPS imaging is made with the same body orientation as the treatment.
- To optimize the treatment plan, any position in the patient body should be reachable from any direction. Generally, several directions are selected in a treatment plan.
- In classical radiotherapy, this is done by imaging the patient in a supine position, and treating the supine patient with an isocentric gantry.
- In photon radiotherapy, in the technique named “Intensity Modulated Radio Therapy” (IMRT), the number of beam incidences becomes very large, and now arc therapy is commonly used
- Arc therapy in proton therapy is also under development and has been tested on IBA systems.

Proton arc therapy



A robust and efficient delivery technique with potential for continuous arc delivery

An advanced IMPT optimization algorithm

- First technical paper (IJROBP 2016)
- Advanced stage lung cancer (NA-PTCOG 2016)
- Prostate (PTCOG 2017)
- Brain Hippocampus sparing (AAPM 2017)
- Cranial SRS (ASTRO 2017)
- Spine SRS (ASTRO 2017)
- Bilateral Head & Neck (AAPM 2017)
- Mobile tumor – interplay (AAPM 2017)
- Dosimetric comparison study with Iowa
- More to come...

Beaumont

Ding X & Li X IJROBP 2016

Feature not currently available for sale

Isocentric gantries (2)

- Compared to 6 to 12 MeV electron beams, 230 MeV protons have 110 times larger magnetic rigidity, and therapeutic carbon ions beams 300 times.
- Gantries for proton therapy are therefore large, heavy and expensive. Carbon gantries using resistive magnets are just impractical.
- For our one treatment room proton system, the cost of the gantry and of the patient positioning and alignment system exceeds the cost of the accelerator.
- For this reason, many designers have looked for solutions where the patient would be rotated in front of a fixed horizontal beam. Although some of these solutions do work technically (P-Cure), they have never been popular with medical doctors. Example of Protom.

Open gantries or 360° gantries ?

- With a modern robotic patient positioner, all positions in a patient can be reached from any direction with a gantry rotating 180°, or a bit more. This solution offers to the therapist a much better access to the patient, and this design is therefore named the “open gantry”
- The choice between “open gantries” and “360° gantries” is hotly debated by sales people. Companies offering both alternatives, like IBA, see the open gantry selected by a slight majority of customers

Image-Guided proton therapy

Fisheye picture from the Miami Cancer Institute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THANK YOU