Advances in Accelerator Science Deliver Precision Beams for Cancer Therapy

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After the war

1946 Robert Wilson, at Harvard from the Manhattan project, is asked to write about the dangers of "fast" (10 to 100 MeV) protons.

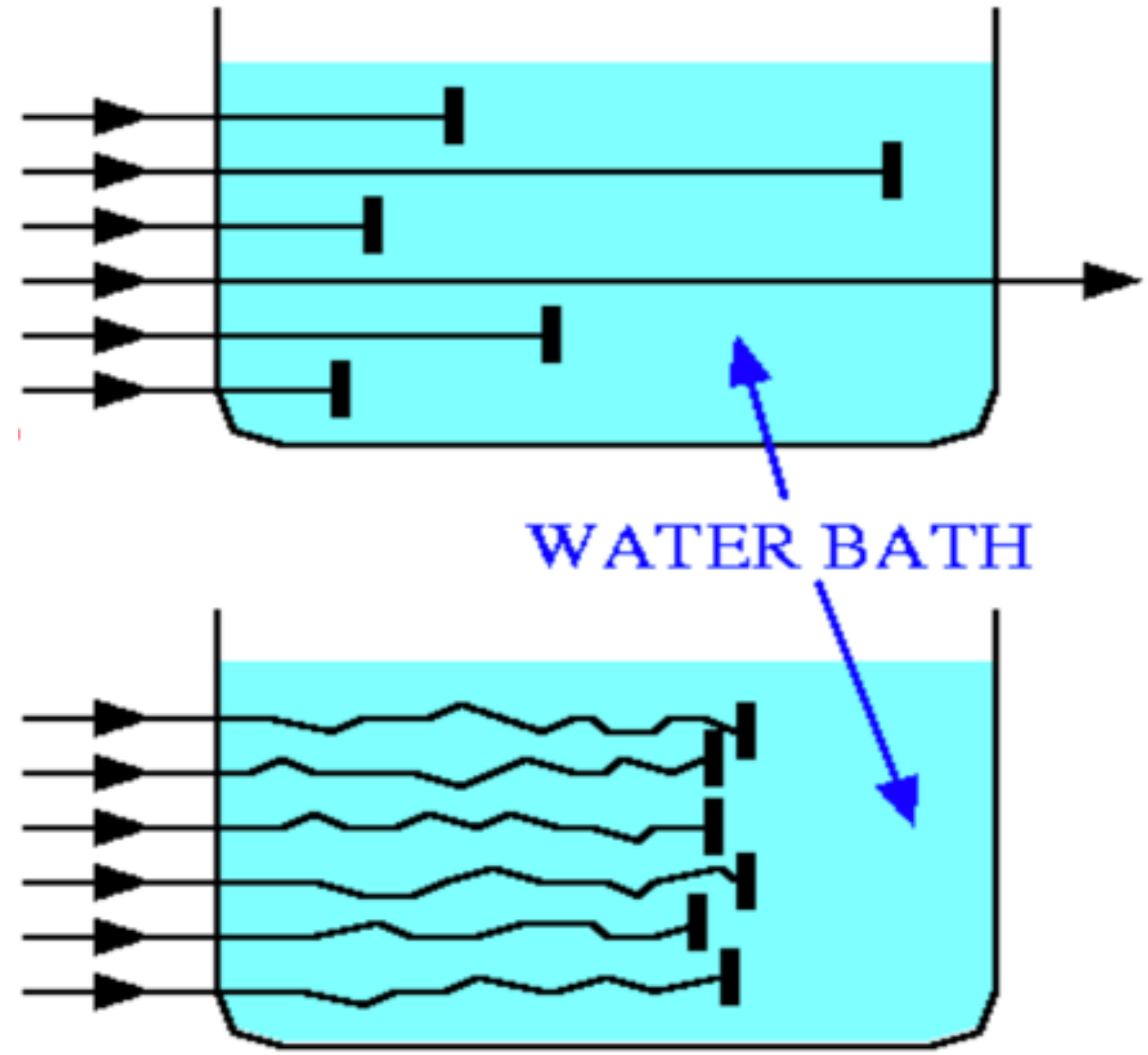
- Instead, he proposes proton therapy in the seminal paper *"Radiological Uses of Fast Protons"*
- "The proton proceeds through the tissue in very nearly a straight line .. until [it stops]. The dosage .. is many times less where [it] enters the tissue .. than .. in the last centimeter of the path."

1947 National labs like Brookhaven are born, to perform fundamental science (e.g. nuclear & high energy physics) that is too big for university-based programs. Accelerator Physics is born !

How X-rays & protons stop

X-rays (photons) have only one collision, stopping at a SPREAD OF RANGES.

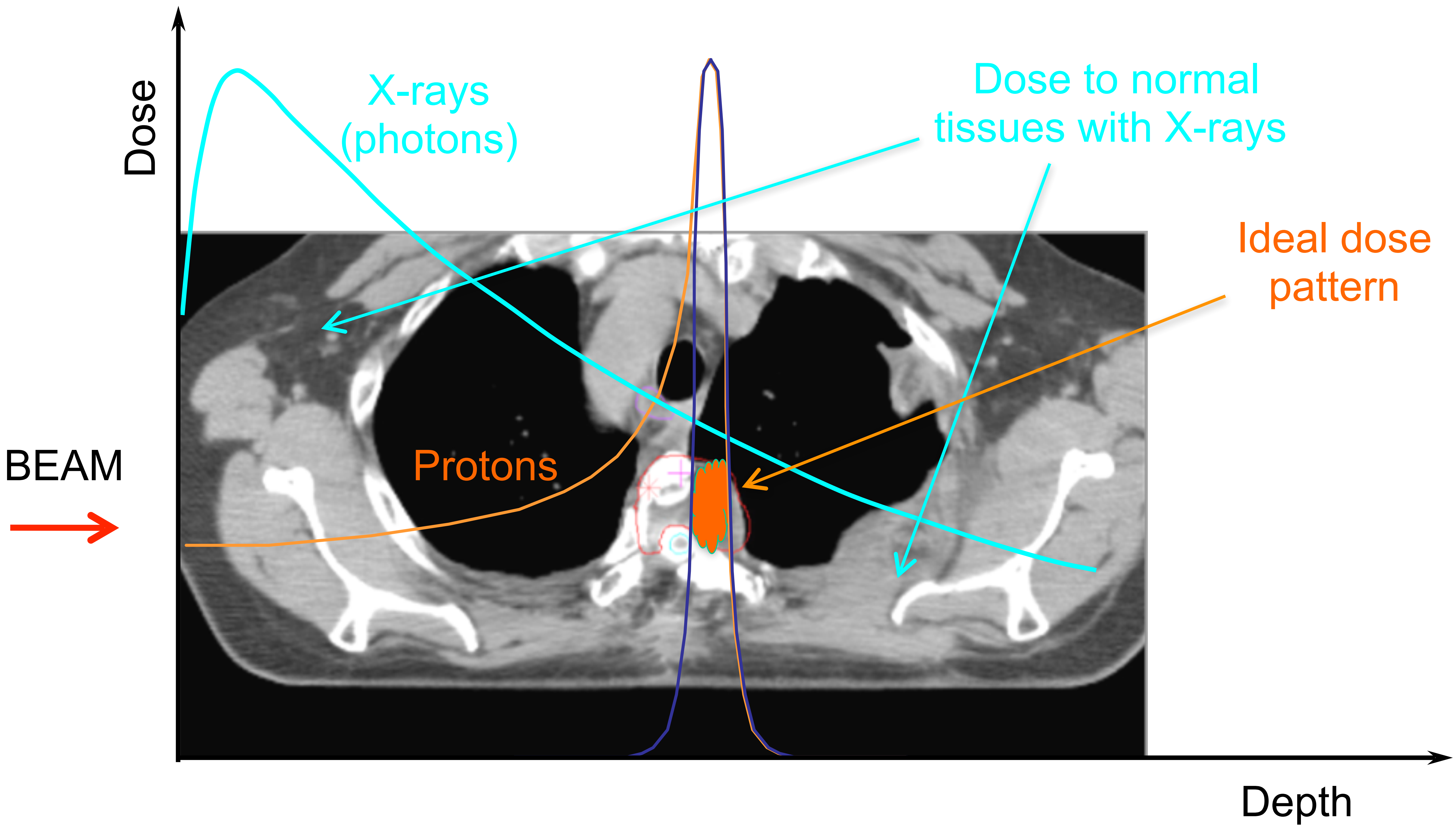
Protons (or ions) have many collisions. All stop at about the SAME RANGE.



Protons (or ions) are steered left/right (or up/down) with magnets.

Their range is adjusted by changing the input energy.

Dose localization - the Bragg peak



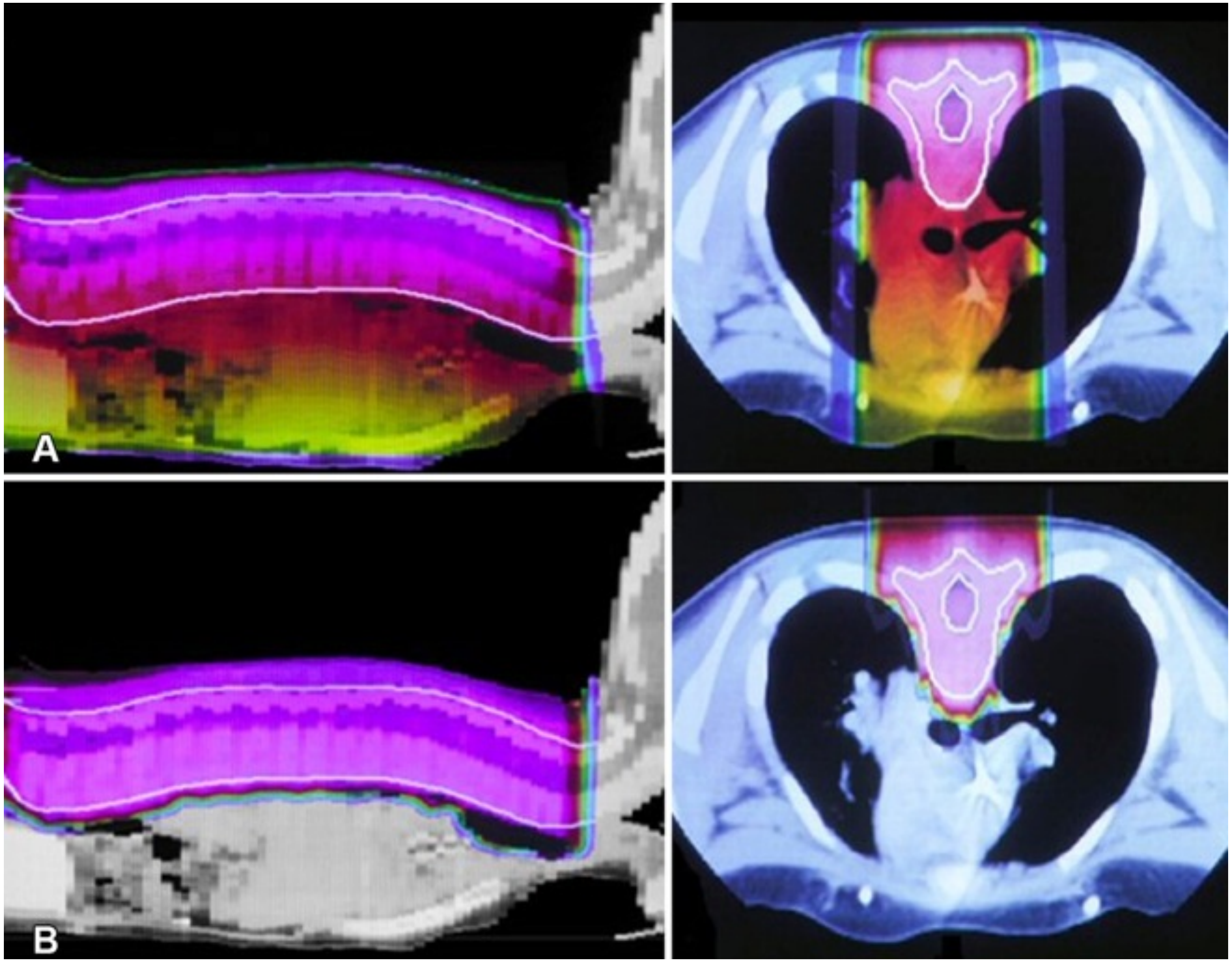
Slide courtesy of H. Paganetti & K. Held

Good dose distributions

Comparison of proton and photon radiation dose distributions in a patient receiving craniospinal radiation therapy for medulloblastoma.

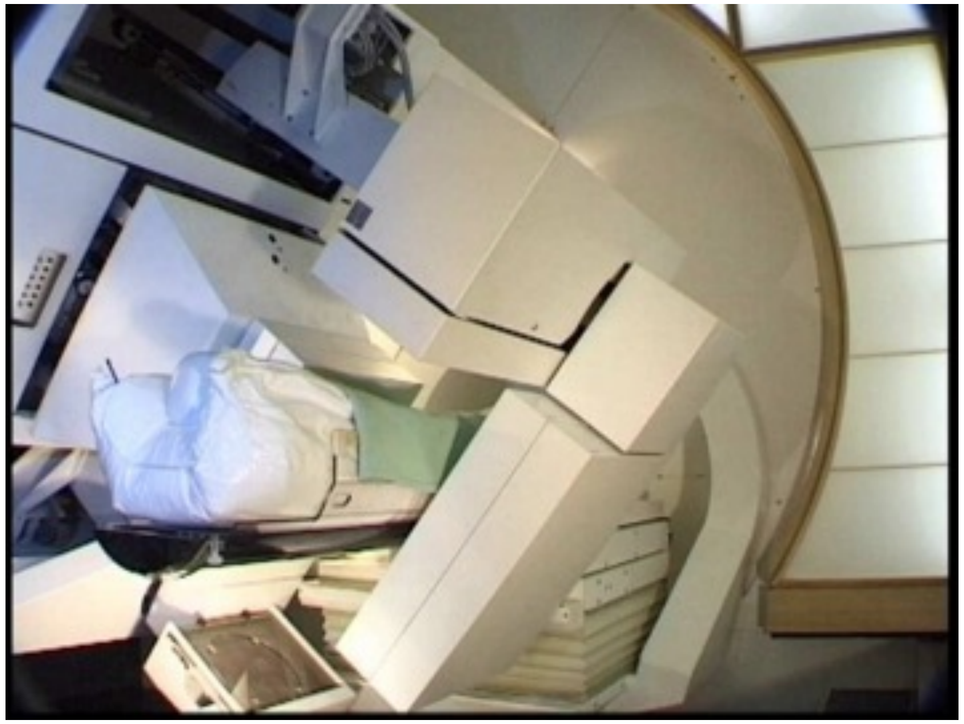
X-rays (photons)

Protons



The patient's perception





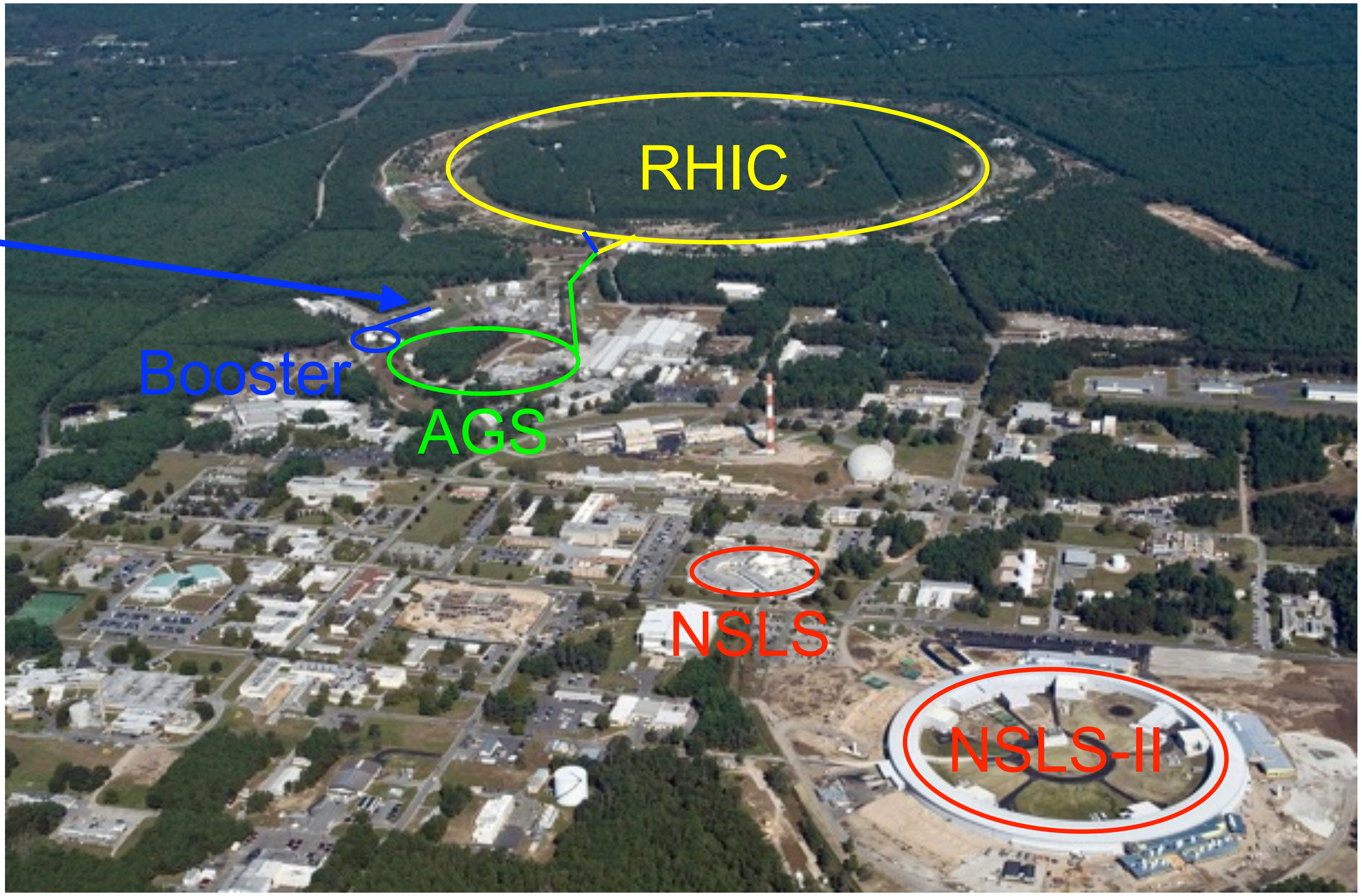
1984 Zurich (PSI)

- Left: The patient enters the gantry room to lie on a robotic couch.
- Middle: The gantry rotates to the optimum irradiation angle.
- Right: Detectors (eg, proton tomography) are used for imaging.

What is behind the wall?

Accelerator diversification

NASA Space Radiation Lab (NSRL)



2014 Brookhaven Lab accelerates

- species from electrons to Uranium via polarized protons & gold,
- to energies from 0.75 MeV to 250 GeV,
- serving biology, isotope production, radiobiology, chemistry, energy sciences, nuclear & high energy physics, ….

Whirlwind history

1954-1992 Ion synchrotron

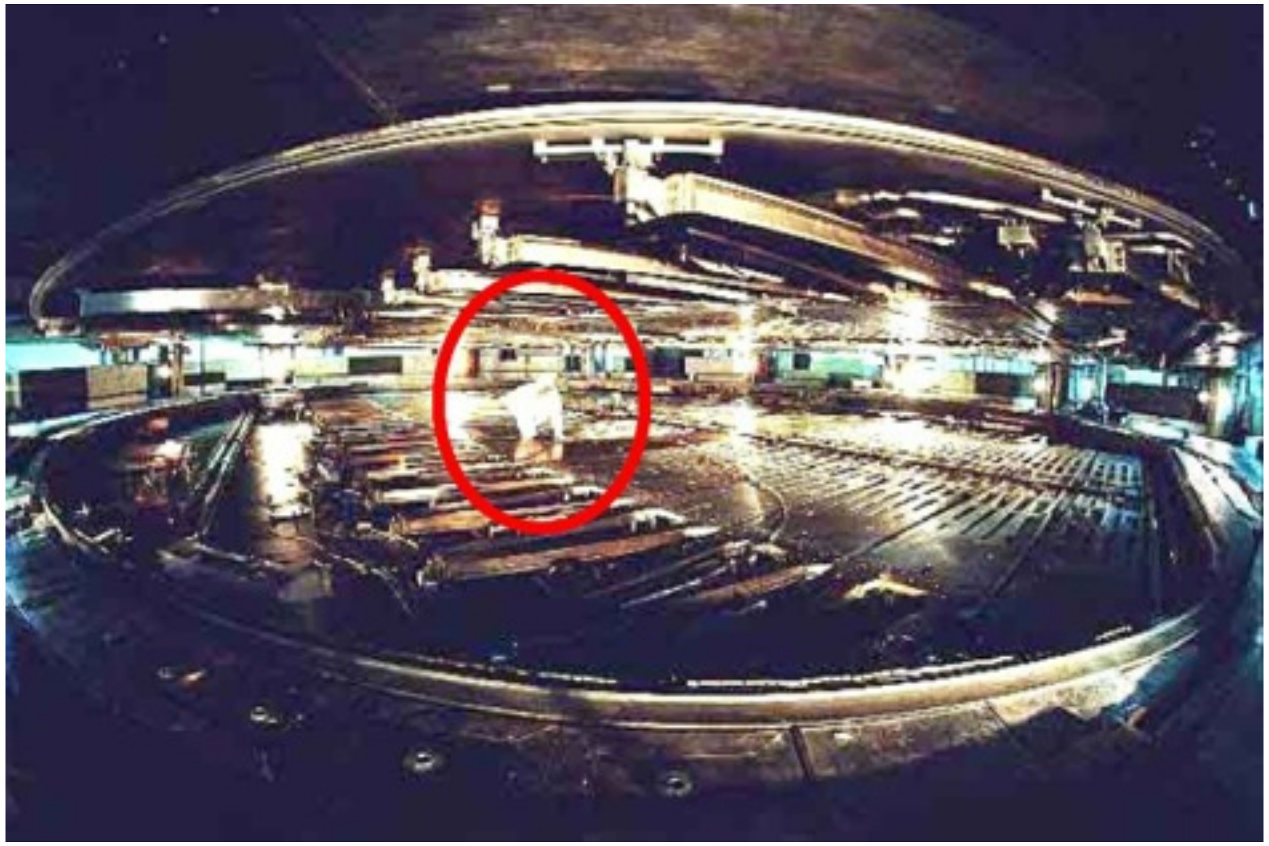
BROOKHAVEN NATIONAL LABORATORY

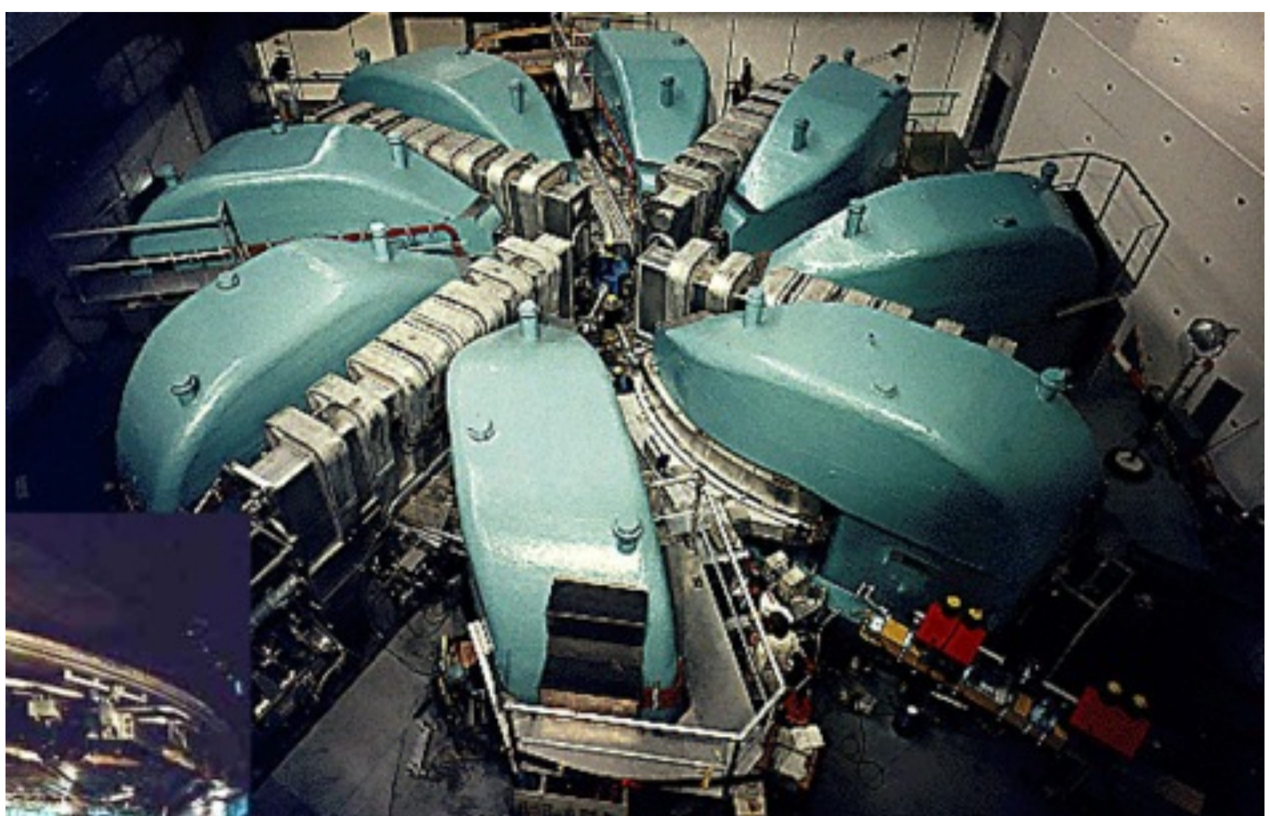
Primary goal of the Berkeley Bevatron was fundamental physics

Its unparalleled ground-breaking use in helium & ion therapy:

- enabled early radiobiological research & treatment techniques
- established a foundation for all subsequent ion therapy
- demonstrated tech transfer from DOE to medicine

1979-2010 Massive cyclotrons



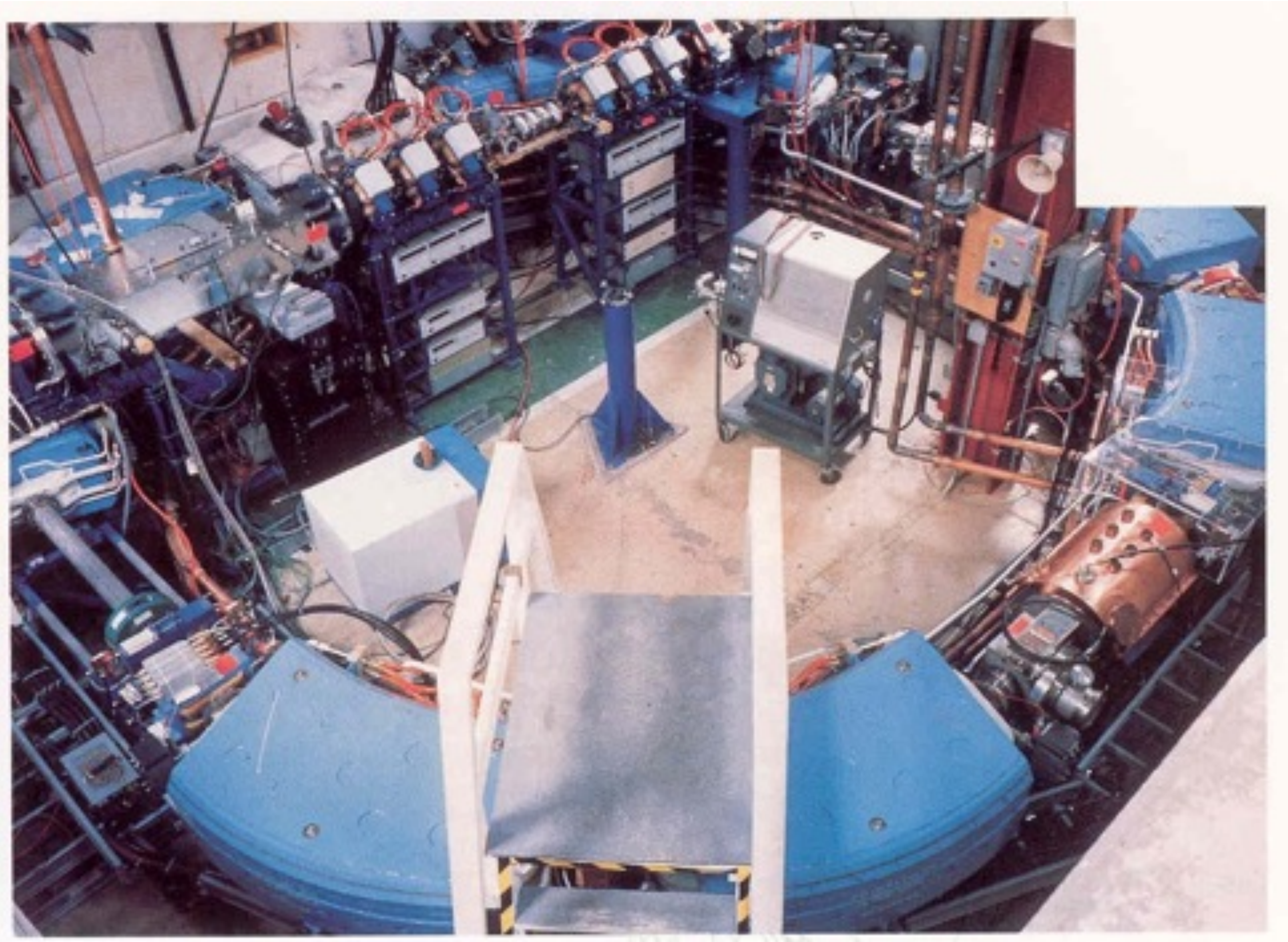


High power fundamental physics cyclotrons

- in Vancouver (TRIUMF)
- outside Zurich (PSI)

were used parasitically for proton & pion (!) therapy

1990 First hospital-based synchrotron



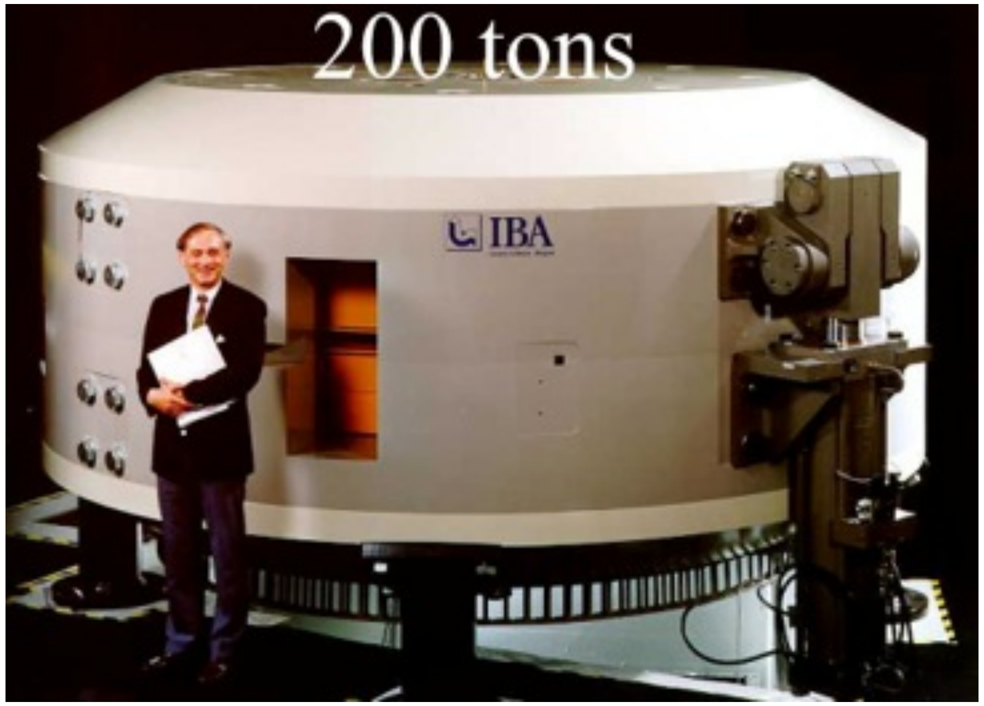
The Loma Linda (California) proton synchrotron is still a standard against which hospital-based synchrotrons are measured.

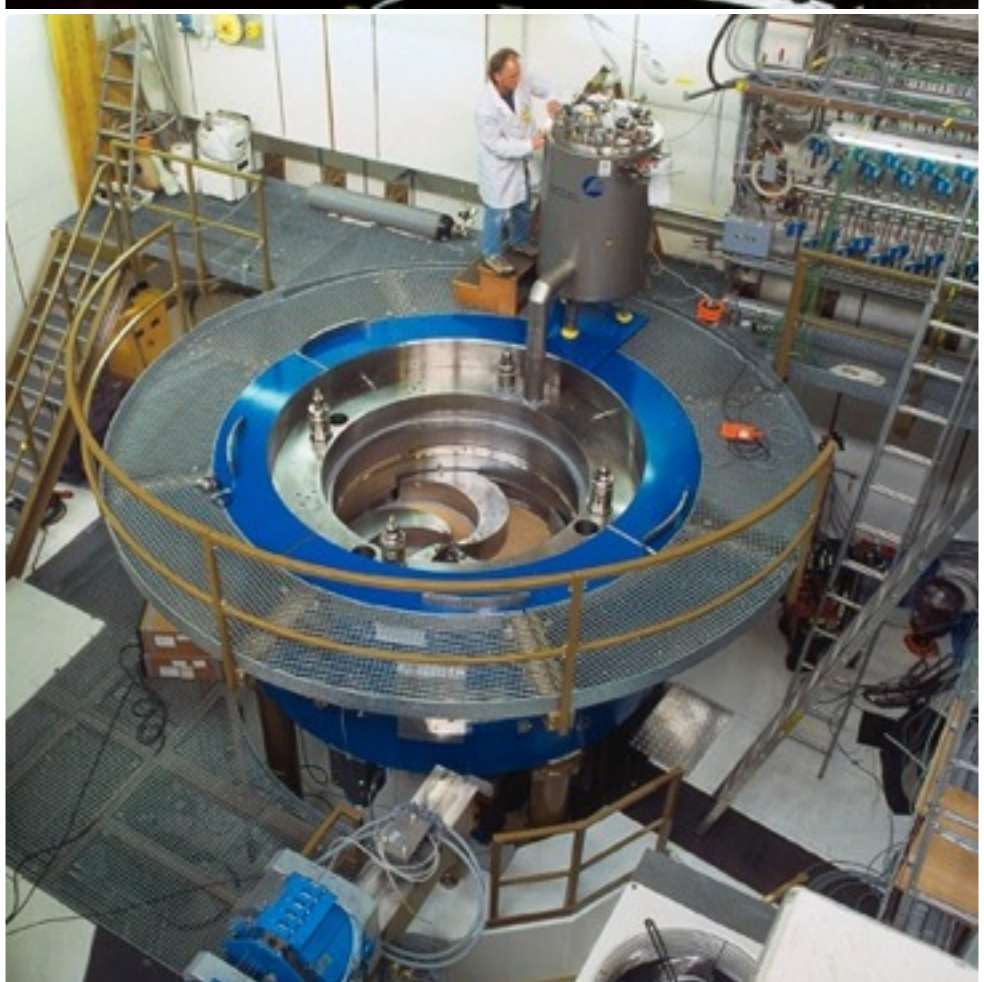
Designed and commissioned at Fermilab, with DOE support.

How to make it better — lighter, more affordable, more flexible? Thinking about this even before it left Illinois ….

2001 Hospital-based cyclotrons

BROOKHAVEN NATIONAL LABORATORY





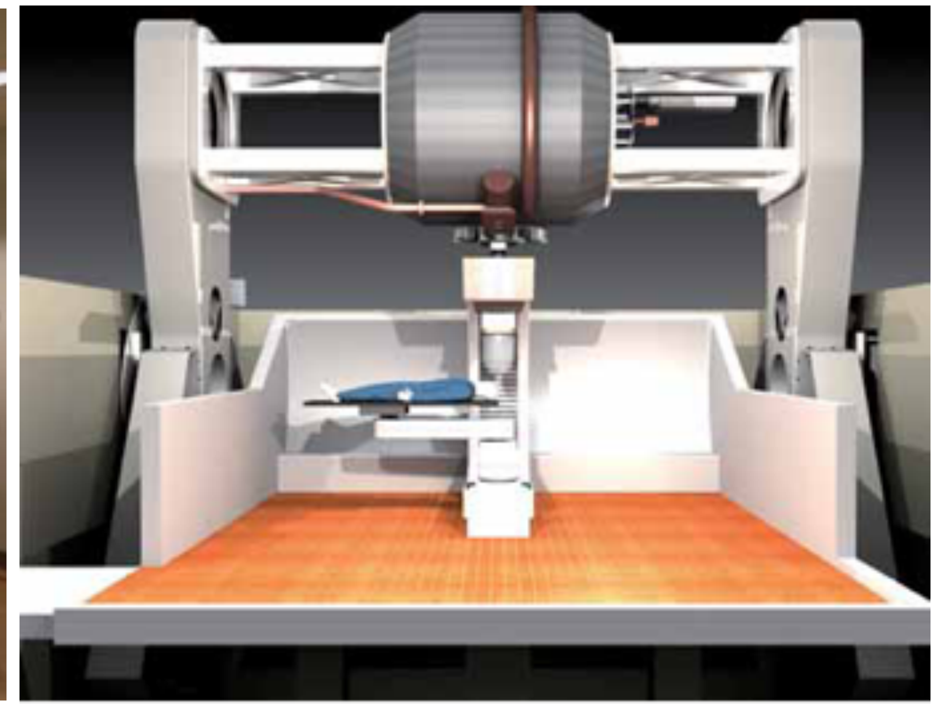
First installed in Boston (MGH) the IBA C230 is todays world-market leader

- Normal conducting
- 230 MeV protons
- 200 tons
- 4 m diameter

More recently, the Research Instruments COMET

- Superconducting
- 250 MeV protons
- 80 tons
- 3 m diameter

2013 Cyclotron-on-a-gantry



The MEVION S250 *superconducting* proton *cyclotron-on-a-gantry* in the Barnes-Jewish Hospital at Washington University.

Superconducting wire comes straight from a DOE conductor development program, via the LHC Accelerator Research Program

3,000 Amps per square millimeter !

History & future

1946 R.R. Wilson proposes proton & ion therapy.
1950's Proton & helium therapy, Berkeley cyclotron.
1975 Carbon therapy in Berkeley synchrotron with scanning.
1984 Proton therapy begins at Zurich (PSI).
1990 1st hospital-based proton synchrotron, Loma Linda, CA.
1993 Precision carbon raster scanning, Darmstadt (GSI).
1994 Carbon therapy begins in Asia, at Chiba (HIMAC), Japan.
1997 1st hospital-based proton cyclotron, Boston (MGH).
2013 Proton cyclotron-on-a-gantry, St. Louis.

Department of Energy labs crucially enabled:

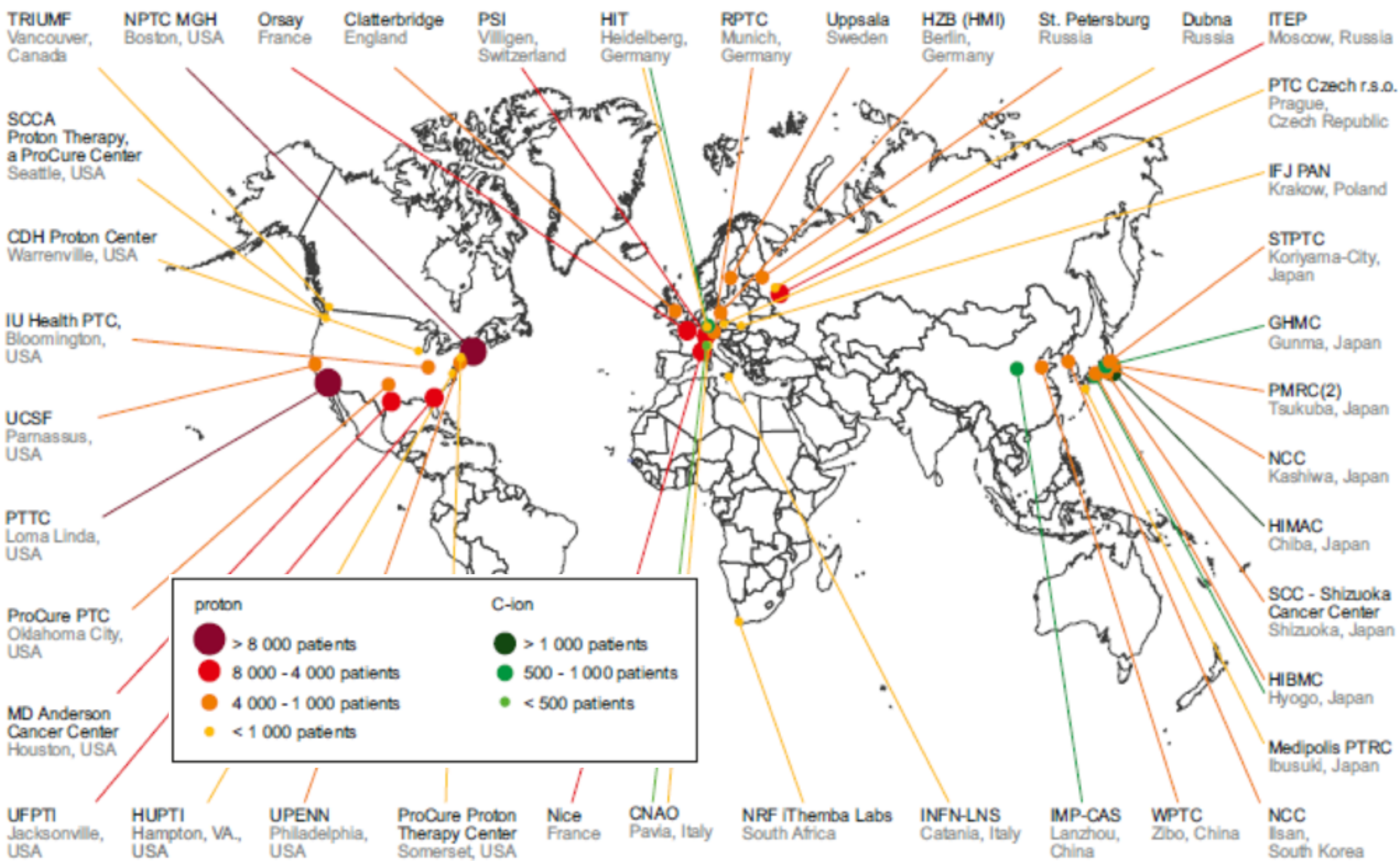
- the first carbon/ion therapy (LBL)
- the first hospital-based proton synchrotron (Fermilab).

What is the future tech transfer?

Carbon & other ions: treatment & radiobiology

Lighter, smaller, cheaper

Proton & Carbon facilities



Courtesy of Dr. Marco Durante

Carbon & other ions

Number of patients treated

Protons	Carbon/ion	Total
93,895	13,253	108,238

Number of therapy facilities

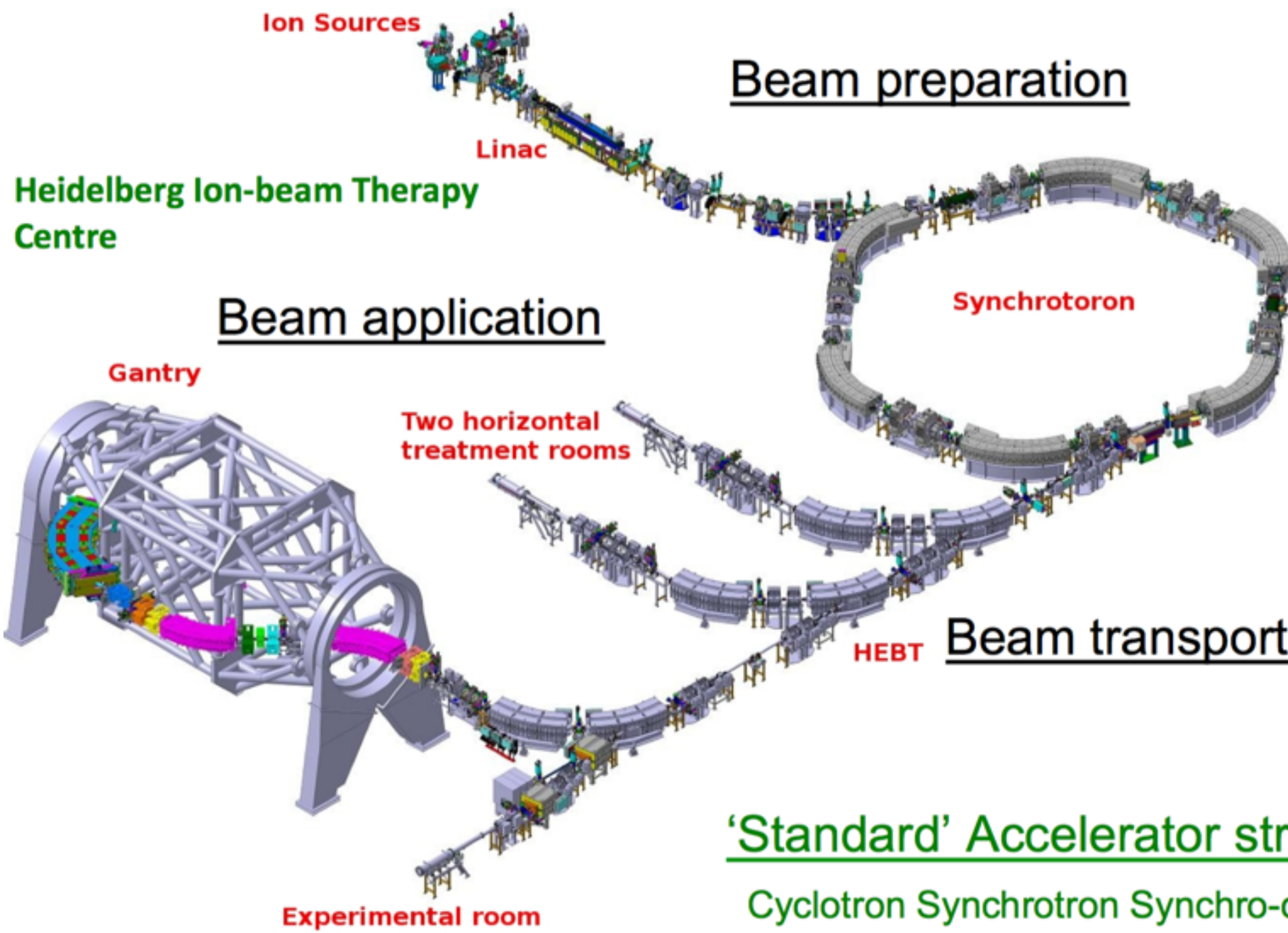
	Africa	Americas	Asia	Europe
Protons				
Decommissioned	-	3	3	4
In operation	1	12	8	15
Carbon/ion				
Decommissioned	-	2	-	1
In operation	-	-	4	2

North America has fallen behind in the trend towards carbon/ion therapy.

December 2013 data from http://ptcog.web.psi.ch

2010 Hospital-based carbon synchrotron

"Synchrotrons are better suited to high rigidity beams"



'Standard' Accelerator structures

Cyclotron Synchrotron Synchro-cyclotron

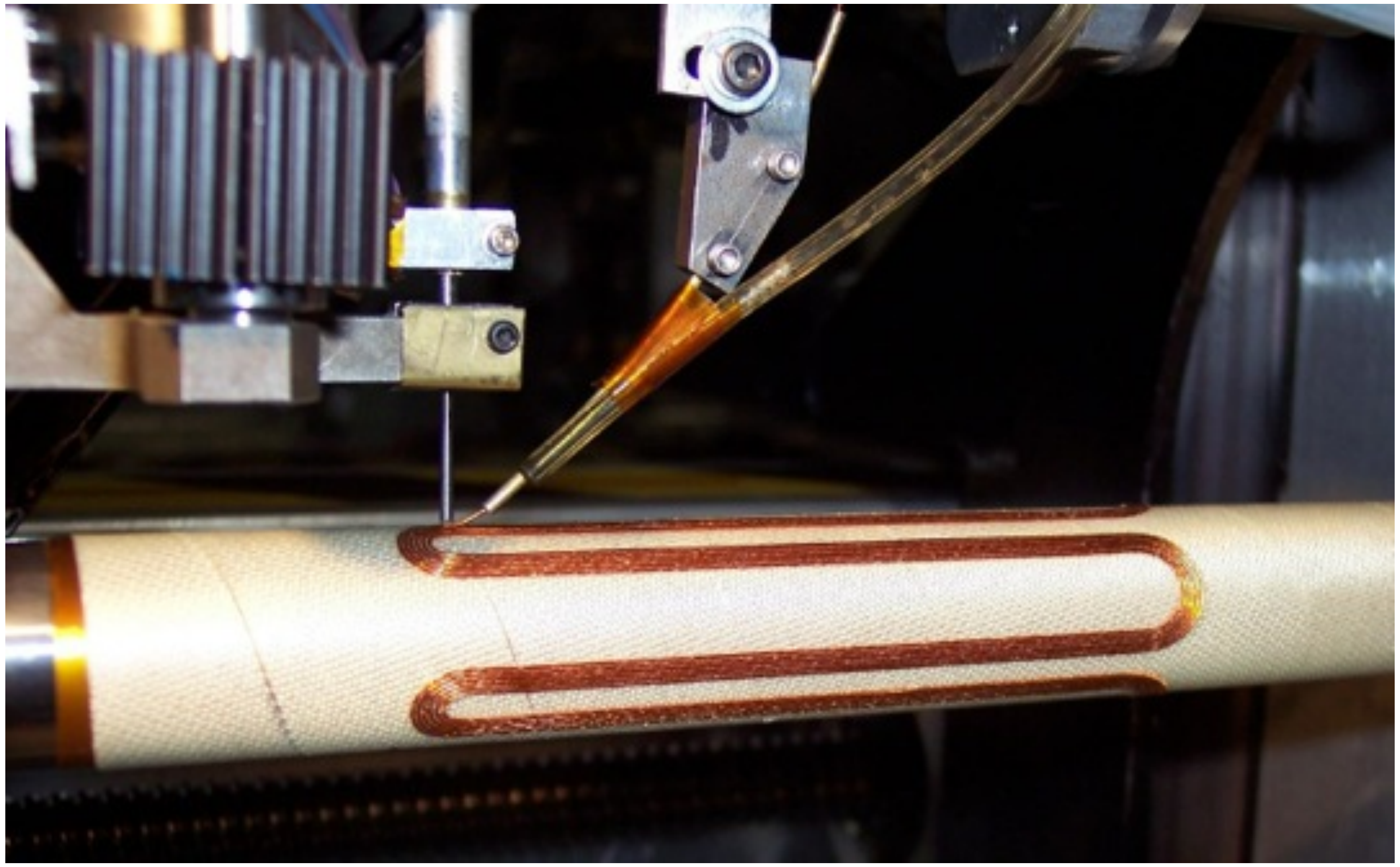
630 ton, 19 meter gantry

It's almost 3 times harder to bend carbon ions than protons.

Practical carbon gantries need new designs & technologies.

Can't just say "you don't want them"

Smaller lighter gantry magnets



BNL “direct-wind” superconducting magnets can play a role (top).

Or even permanent (low-field) magnets.

But the intrinsic beam size (emittance) & intensity must be small.

Rapid cycling - small beams

Goal: deliver N particles in a given pattern in 2 minutes.

Cyclotrons: simple & easy to use, big & heavy, inflexible, least upgradable.

Slow cycling synchrotrons: more complex, lighter, more flexible, 1 pulse every 2 or 3 seconds, medium intensity beam.

Rapid cycling synchrotrons: most modern, lightest, most flexible, upgrade potential, 15 or 30 pulses per second, low intensity beam, small emittance.

iRCMS

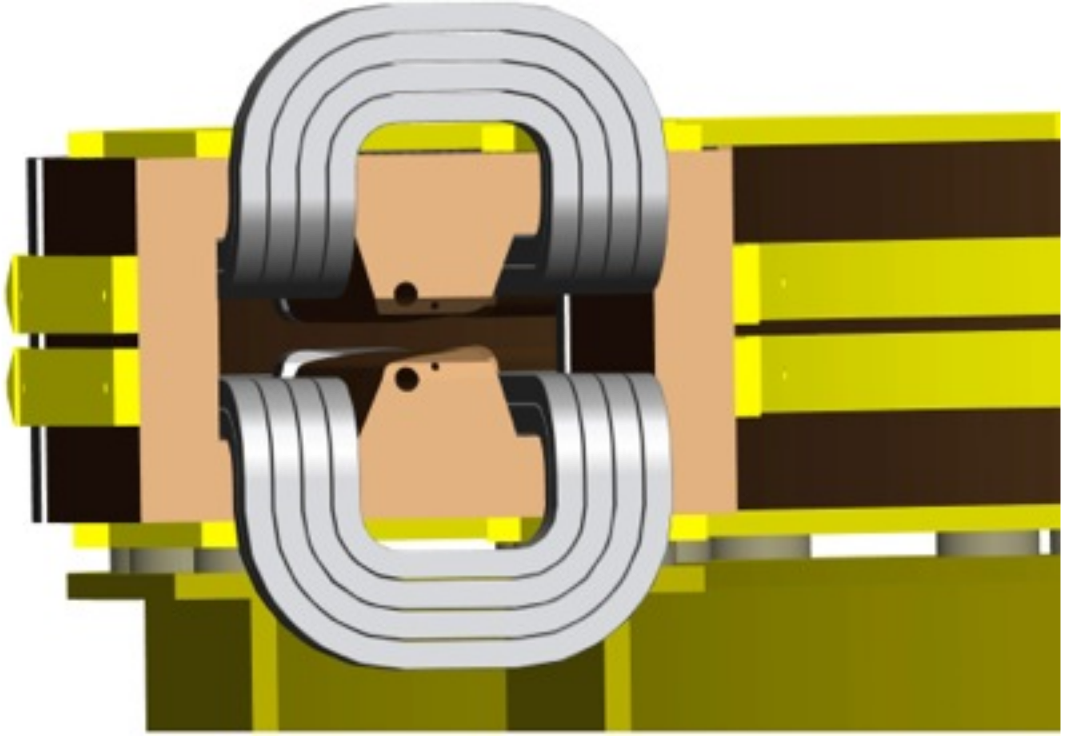
BNL is working with Best Medical International on a smaller, lighter "ion Rapid Cycling Medical Synchrotron"

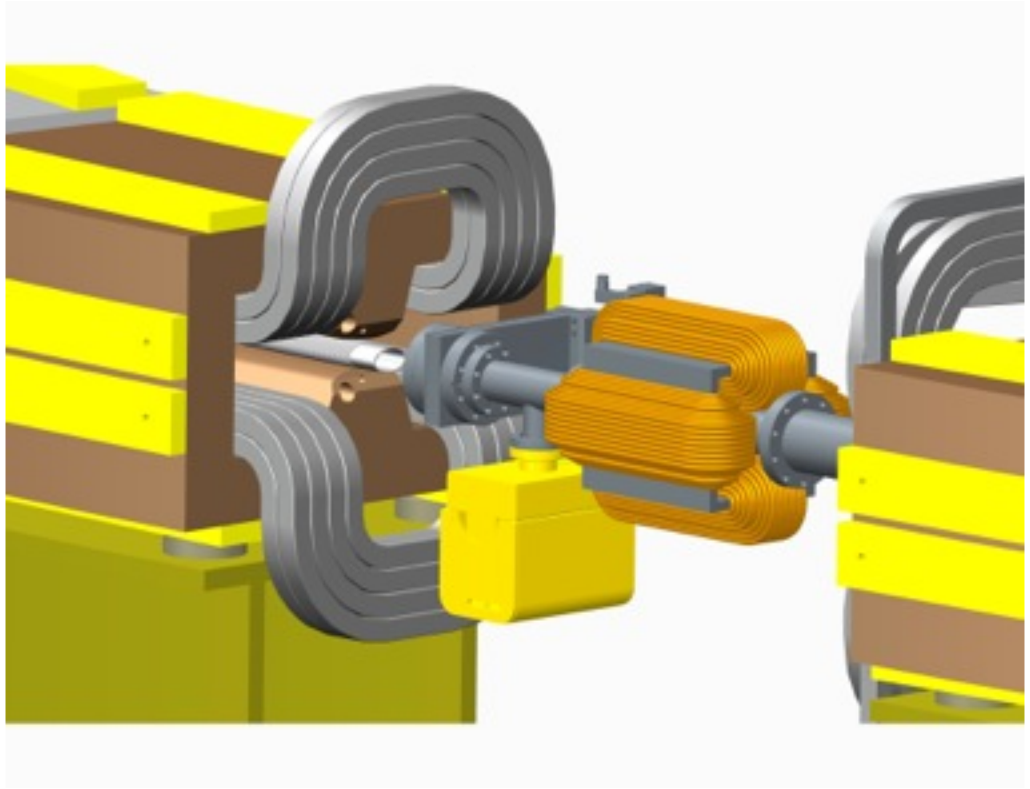
- delivering either protons, carbon, or other ions.

Currently: prototyping key accelerator components.

Soon: announce prototype site & commissioning plans …..

Clearly, more carbon/ion radiobiology is required.





Recommendations

From the 2013 DOE, DHHS, NIH, & NCI **"Workshop on Ion Therapy"**

http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Workshop_on_Ion_Beam_Therapy_Report_Final_R1.pdf

"Fundamental radiobiological research must be conducted in parallel with the development of imaging & accelerator technologies, … ."

"Future … ion beam therapy systems must be *reduced in size* … ."

"Future facilities will need *multiple ions,* at least protons & carbon & 1 or 2 others, to permit … *comparisons … & … optimal treatment.*"

"*Short dose … times* will require *rapid scanning* both transversely & longitudinally (thus *rapid energy modulation* will also be needed)."

"Cost-effective improvements … *demands on accelerator* … ."

"Developments in *gantries & beam lines* … will likely require superconducting devices."

Recognition

Accelerator Physics, born of nuclear & high energy physics, has left home and diversified.

National laboratories are still the centers of accelerator innovation & technology transfer.

The Department of Energy has enabled crucial advances that accelerated hospital-based particle therapy, worldwide — we thank them, and the taxpayer.

More information

For more information on hadron therapy, see the following news stories that feature Brookhaven's work:

"Particle Beam Cancer Therapy: The Promise and Challenges"

http://www.bnl.gov/newsroom/news.php?a=24672&btw=1

"Cancer treatment: Sharp shooters"

Nature 508, 133–138 (03 April 2014) (requires subscription)

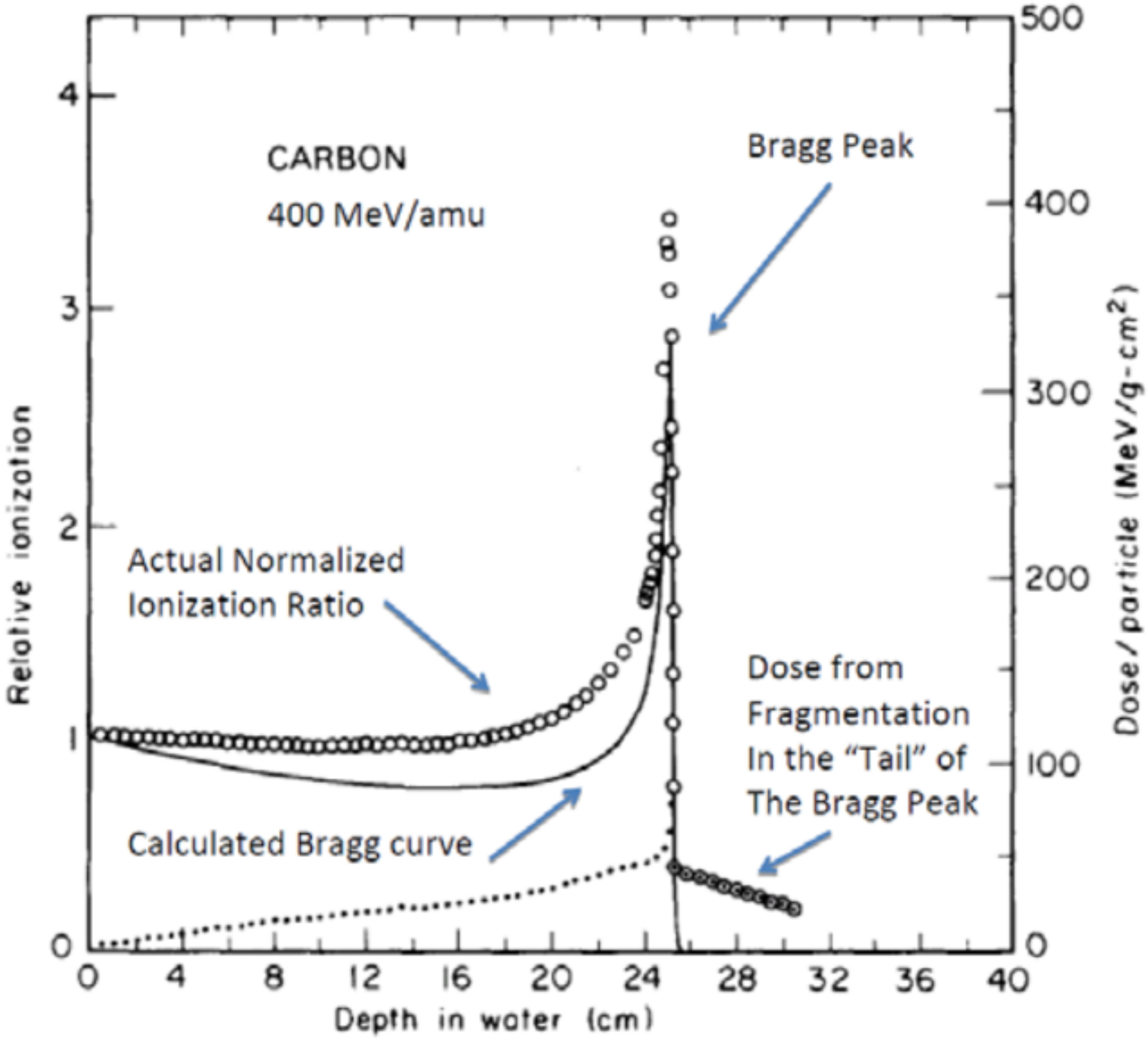
http://www.nature.com/nature/journal/v508/n7494/full/508133a.html

"Accelerator Applications for Cancer Therapy Highlighted in Nature Article"

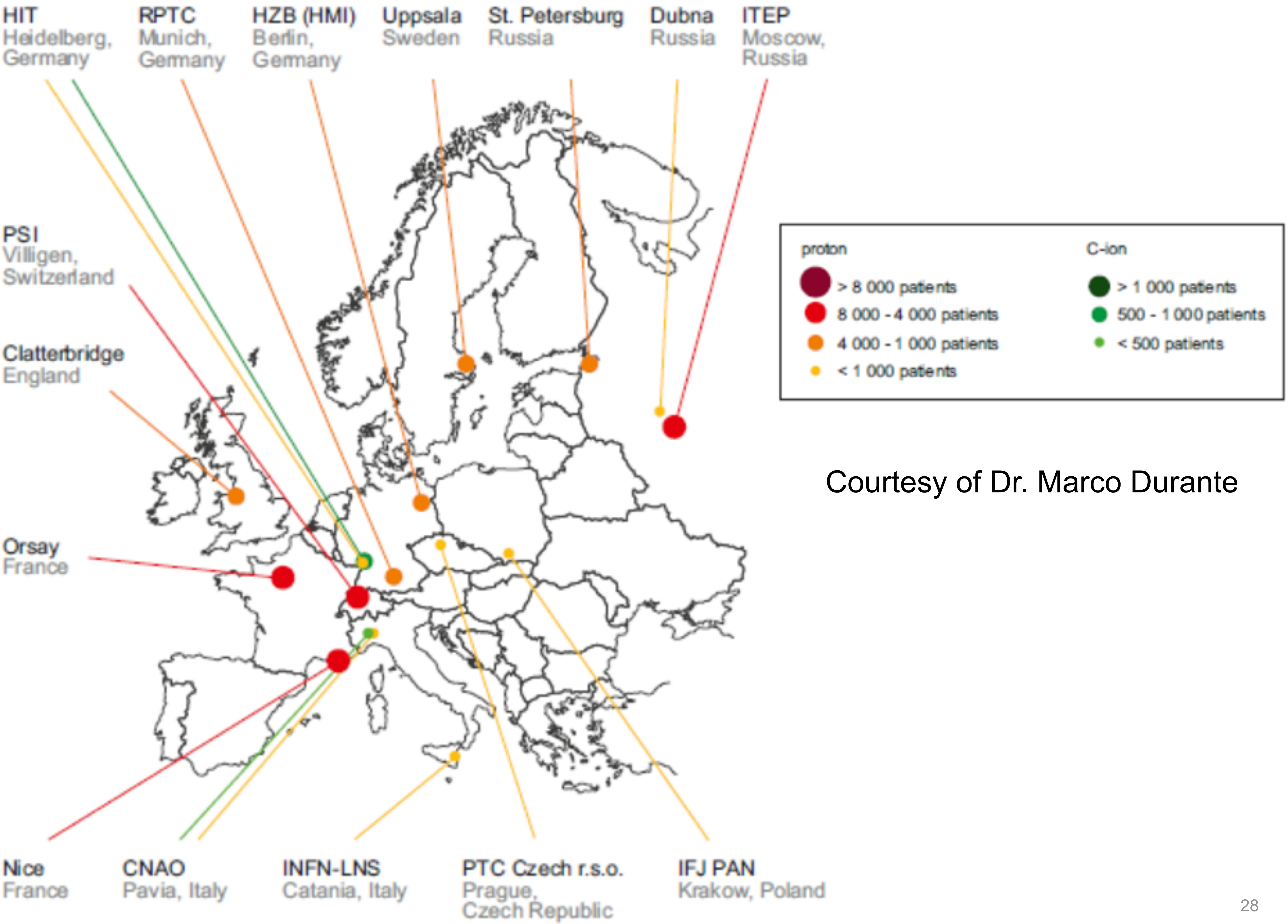
http://www.bnl.gov/newsroom/news.php?a=24782

Backup slides

Carbon Bragg peak

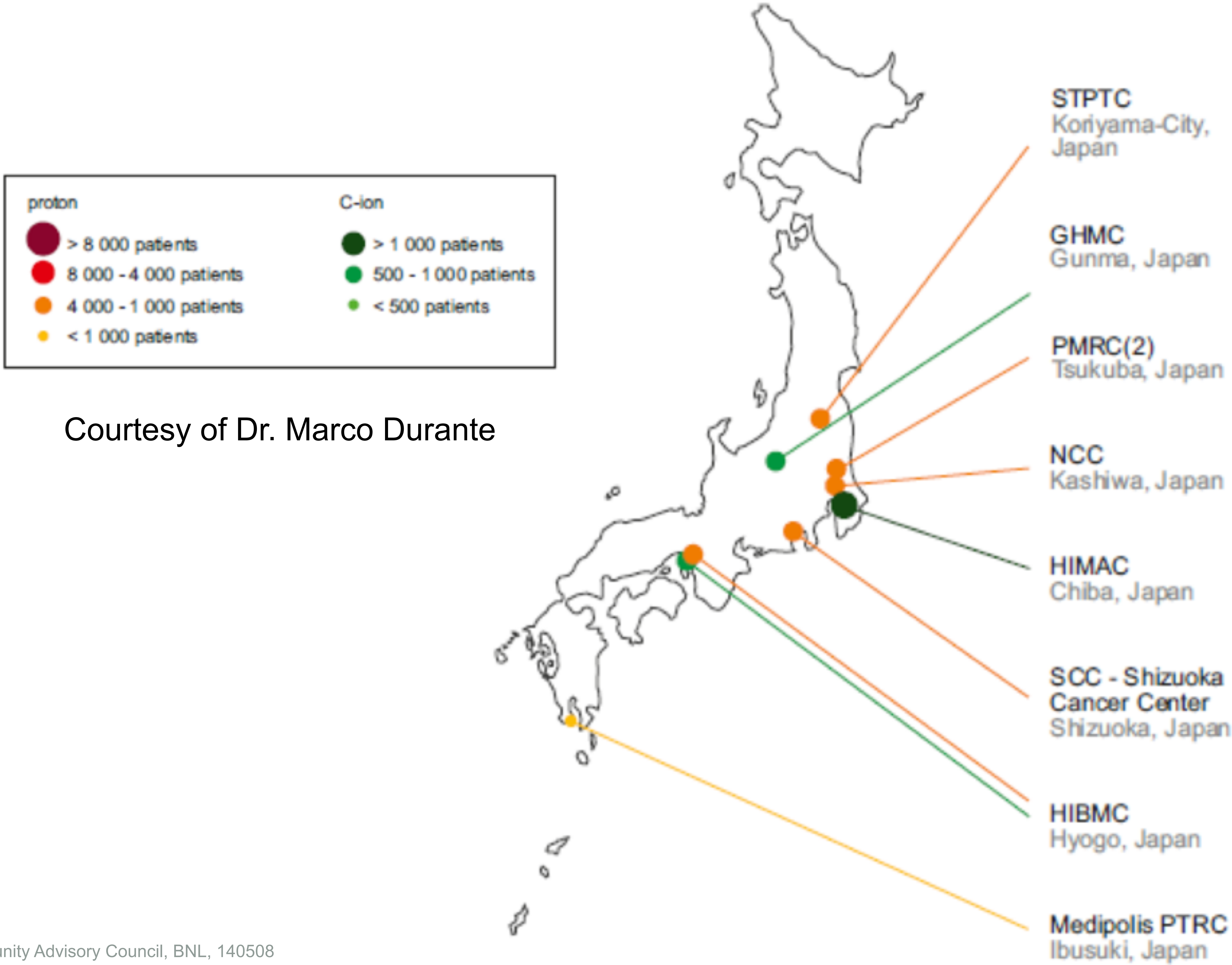


European facilities



Courtesy of Dr. Marco Durante

Japanese facilities



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