Cancer: A Medical Challenge for Physics

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Outline

- Cancer and radiotherapy
- Charged Particle Therapy
- Research
- Summary and Conclusions

Disclaimer

I am a physicist, and this is a physicist's view of cancer and cancer therapy.

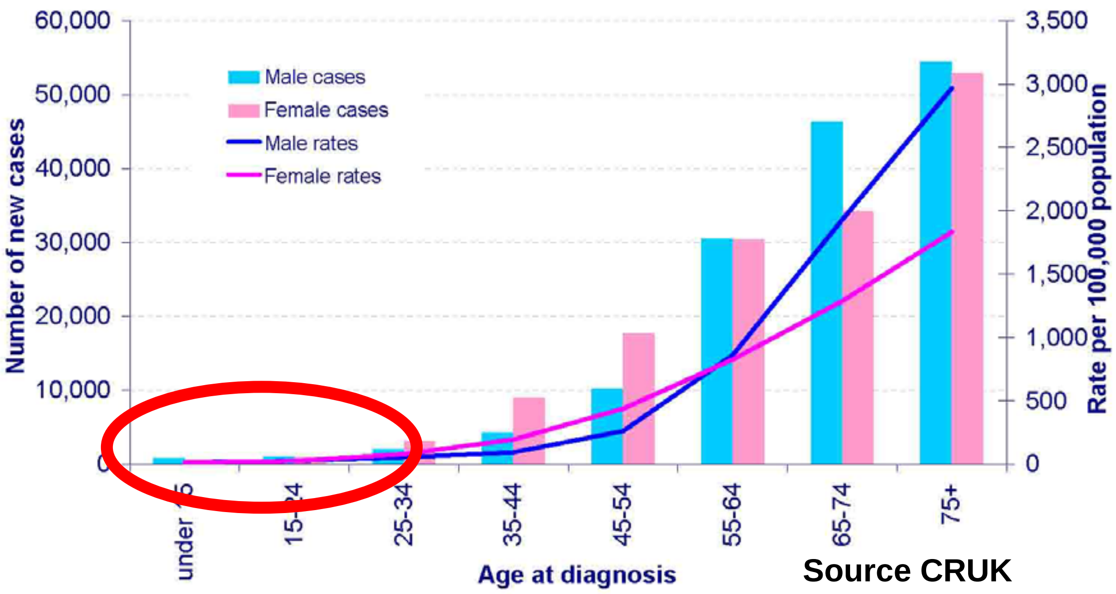
However, I do have associates who are oncologists, radiobiologists, biophysicists and accelerator scientists.

These are my own views of cancer and its challenges.

CANCER & RADIOTHERAPY

Cancer Statistics & therapies

Figure 2.1: Number of new cases and rates, by age and sex, all malignant neoplasms (exc NMSC), UK, 2007



Source CRUK

- **About one third of us will have cancer**
- **About two thirds of cancers are in people over 65**

Environmental factors & lifestyle choices can increase risk
Baseline risk of cancer remains that cannot be eliminated

- **Cancer is a terrible condition**

  but there have been great advances in therapy

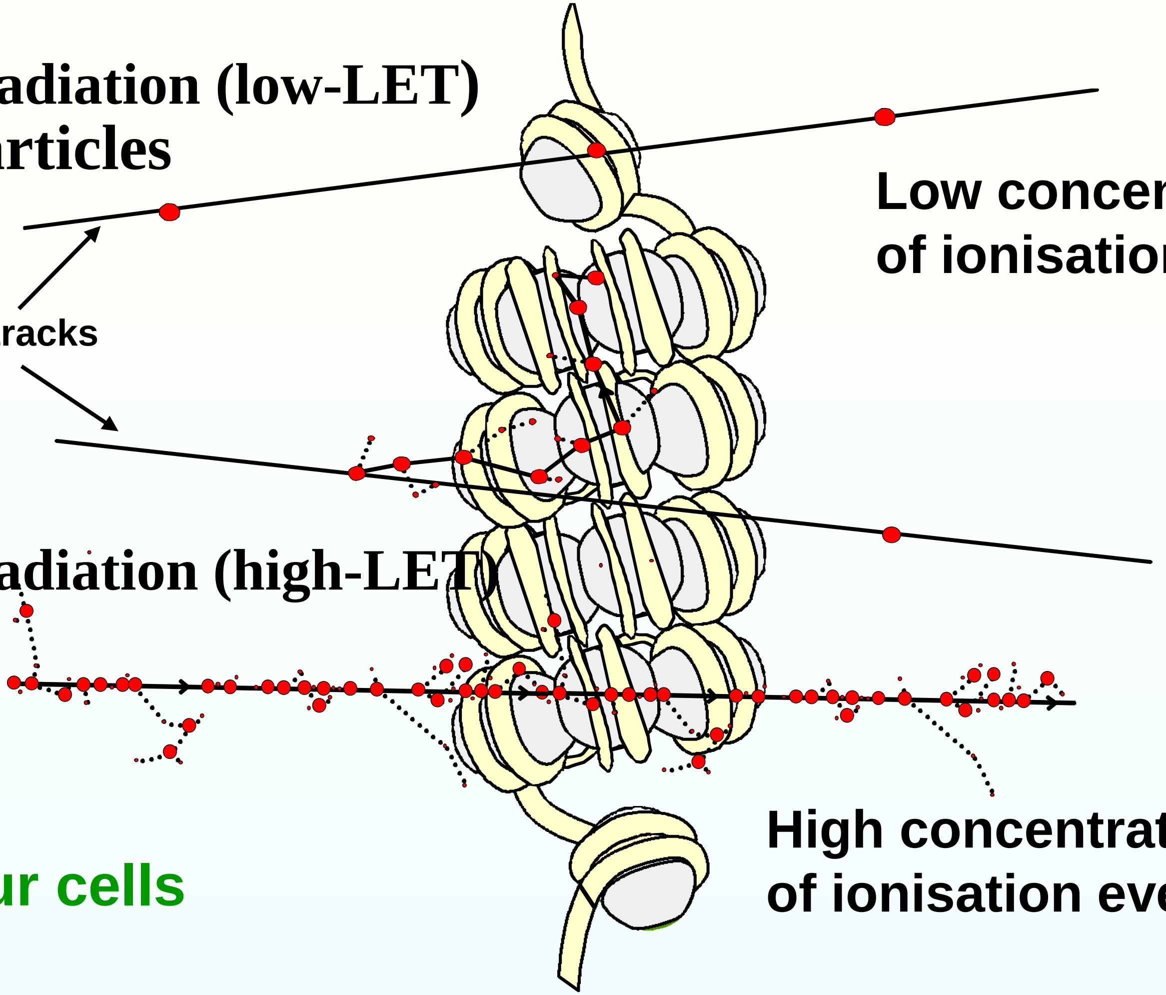
  Contributions to successful treatment of cancer

  45-50% surgery, 40-50% radiotherapy, 10-15% chemotherapy

  Radiotherapy is an important weapon in the battle against cancer

Radiation-induced DNA damage

Sparsely ionising radiation (low-LET)
e.g. γ-rays, β-particles



electron tracks

Low concentration of ionisation events

Densely ionising radiation (high-LET)

e.g. α-particles
C^{6+} ions

✓ **Kills tumour cells**

✗ **Damages normal tissues**

High concentration of ionisation events

DNA

Nuclear / Cellular scale damage

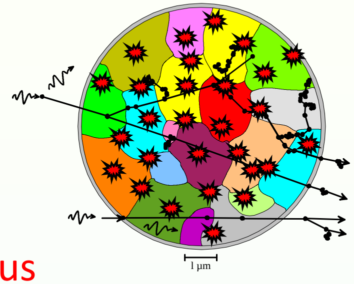
Low-LET (e.g. γ-rays)

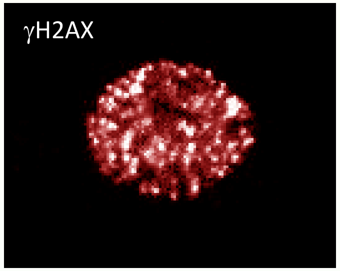
1 Gy corresponds to:

~1000 electron tracks

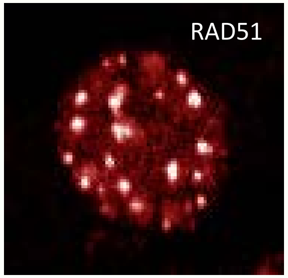
~20-40 DSB

Relatively homogeneous



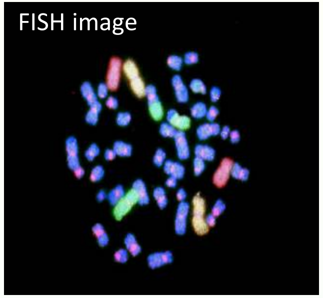


Induction of double strand breaks (DSB)



Repair

Simple aberrations



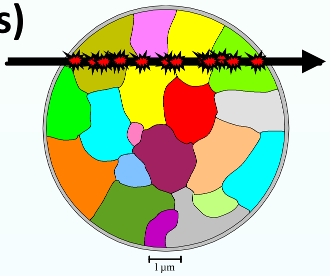
High-LET (e.g. α-particles)

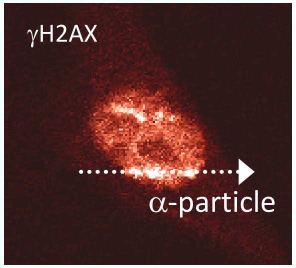
1 Gy corresponds to:

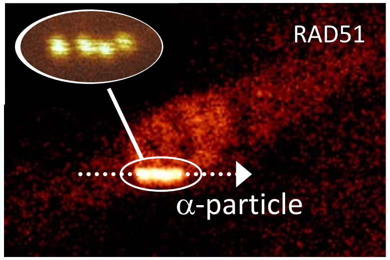
~2 alpha tracks

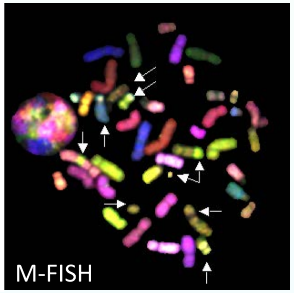
~20-40 DSB

Very non-homogeneous







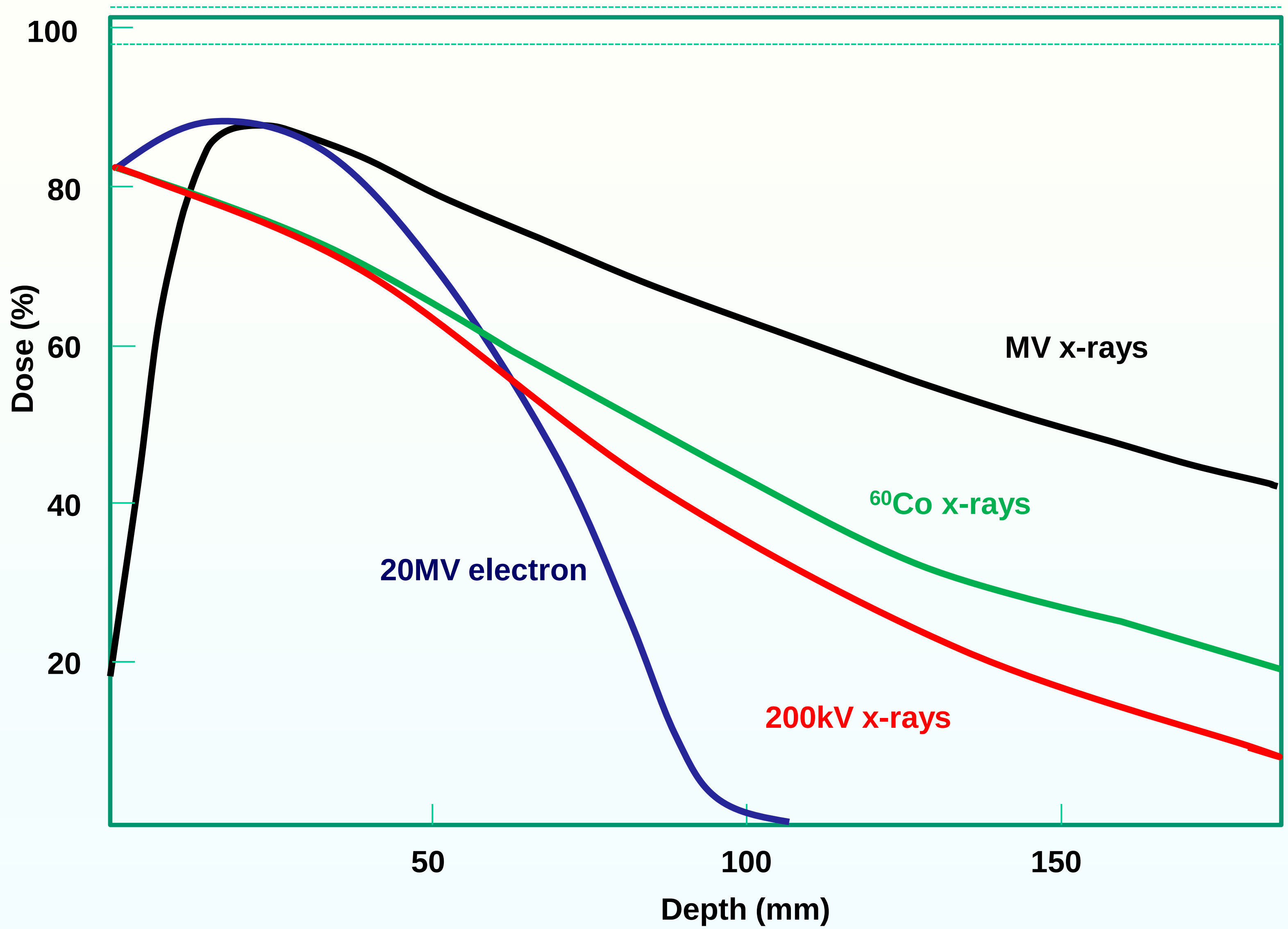


Complex aberrations

Chromosome aberrations

Mark Hill, Gray Institute

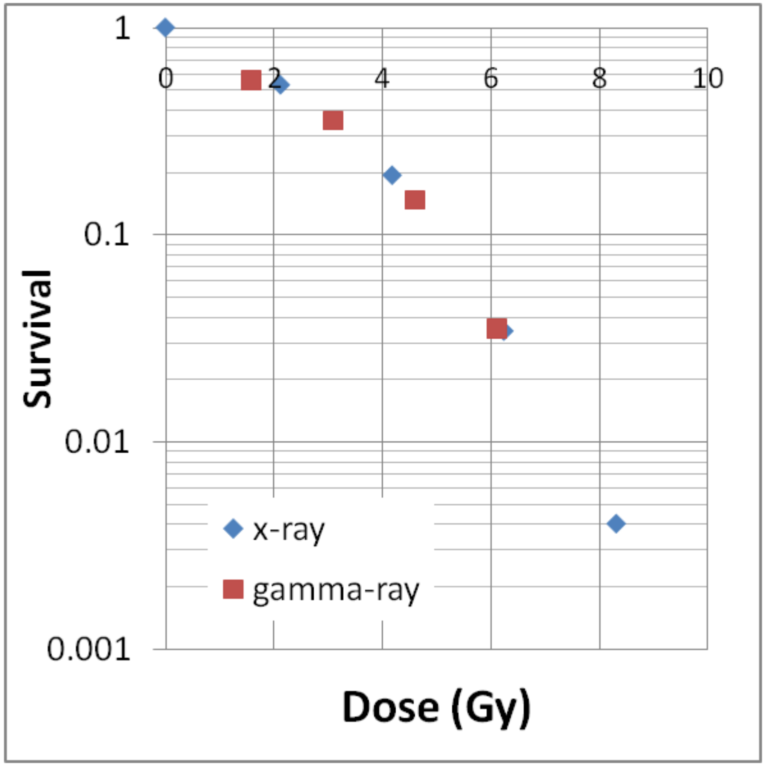
Depth Dose curves – x-rays & electrons



Materials and Methods
- Gamma-ray irradiation

- Gamma-ray irradiation system
  - Cesium irradiator
  - Dose rate of ~1.7 Gy/min
  - Dose correction factor was obtained from EBT film dosimetry based on the data of cobolt irradiator at Harwell
- Comparison with x-ray
  - To confirm the correction factor,

  →Gamma-ray survival curve was compared with x-ray(from X-ray tube) curve
  - Both plots agree well

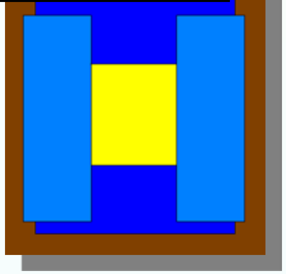


AI Nagano (PTCRi, private communication)

The Evolution of Radiation Therapy

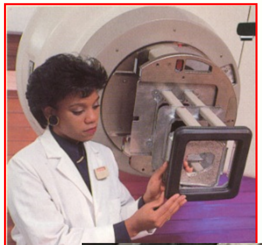
1960's

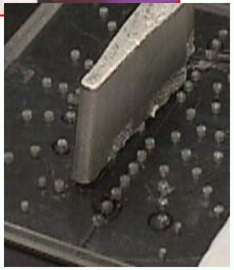
The First Clinac



Standard Collimator

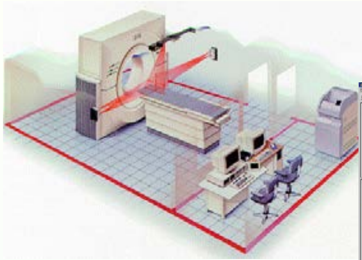
1970's

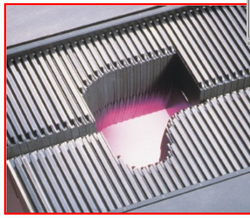




Cerrobend Blocks
Electron Blocks

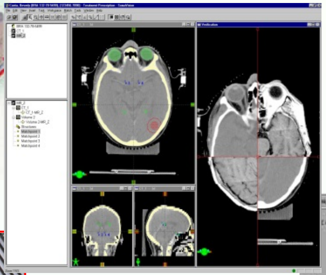
1980's





Multileaf Collimator

Computerized 3D CT Treatment Planning

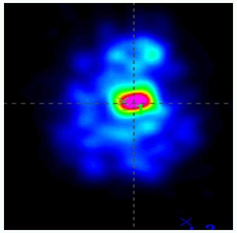


1990's

Dynamic MLC
and IMRT

High resolution
IGRT

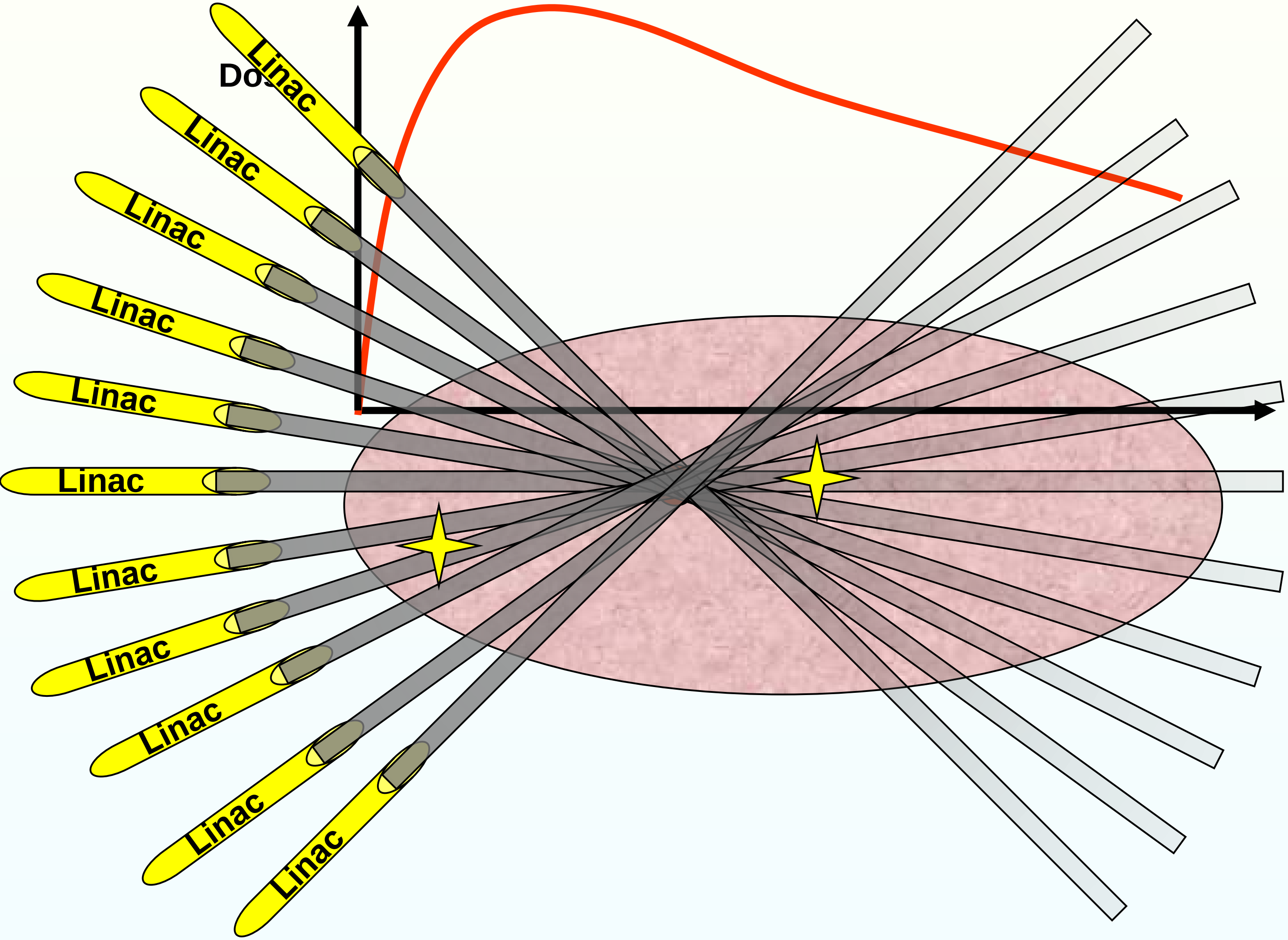
2000's?



Functional Imaging

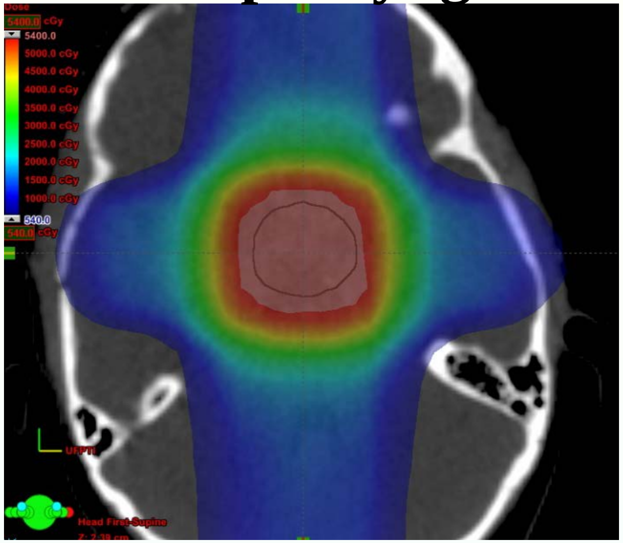
After Gillies McKenna

Curing Cancer with MV X-rays



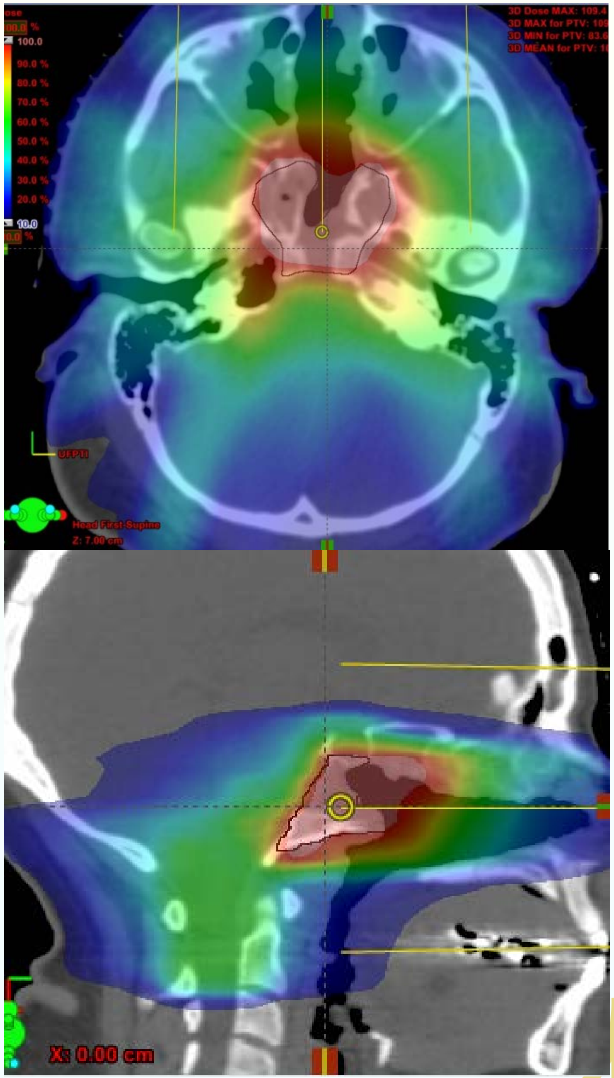
MV x-ray treatment plans

Craniopharyngioma



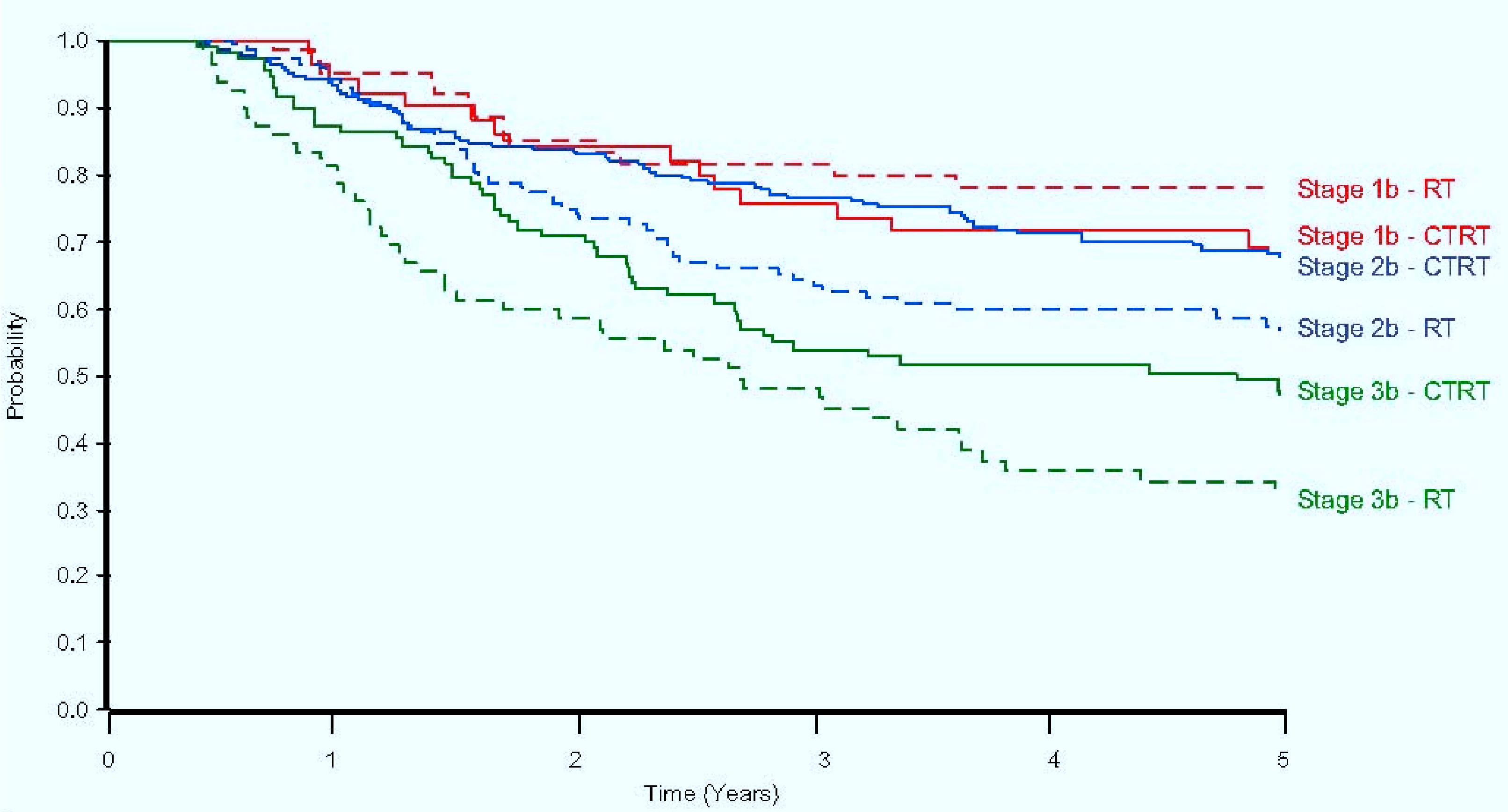
Hodgkin's Lymphoma

Base of Skull Sarcoma



Conventional Radiotherapy

- **Millions of people have benefited from x-radiation therapy**



From Vale et al, Clinical Oncology 22 (2010) 590e601

Survival curves for Radiotherapy (RT) and chemo+radiotherapy (CTRT) (locally advanced cervical cancer)

Inside the Linac

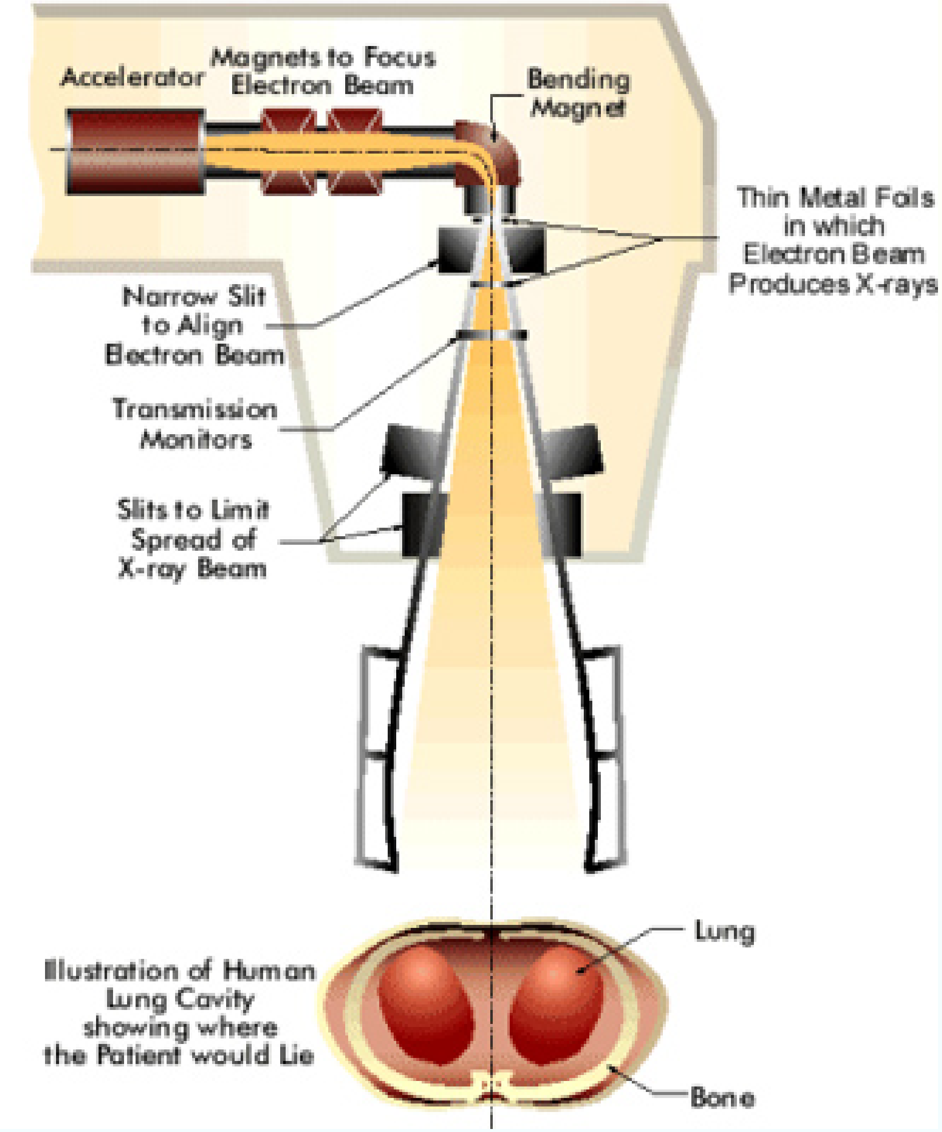
- **The conceptual design of the radiotherapy linac is *relatively* simple**

  but performance is crucial

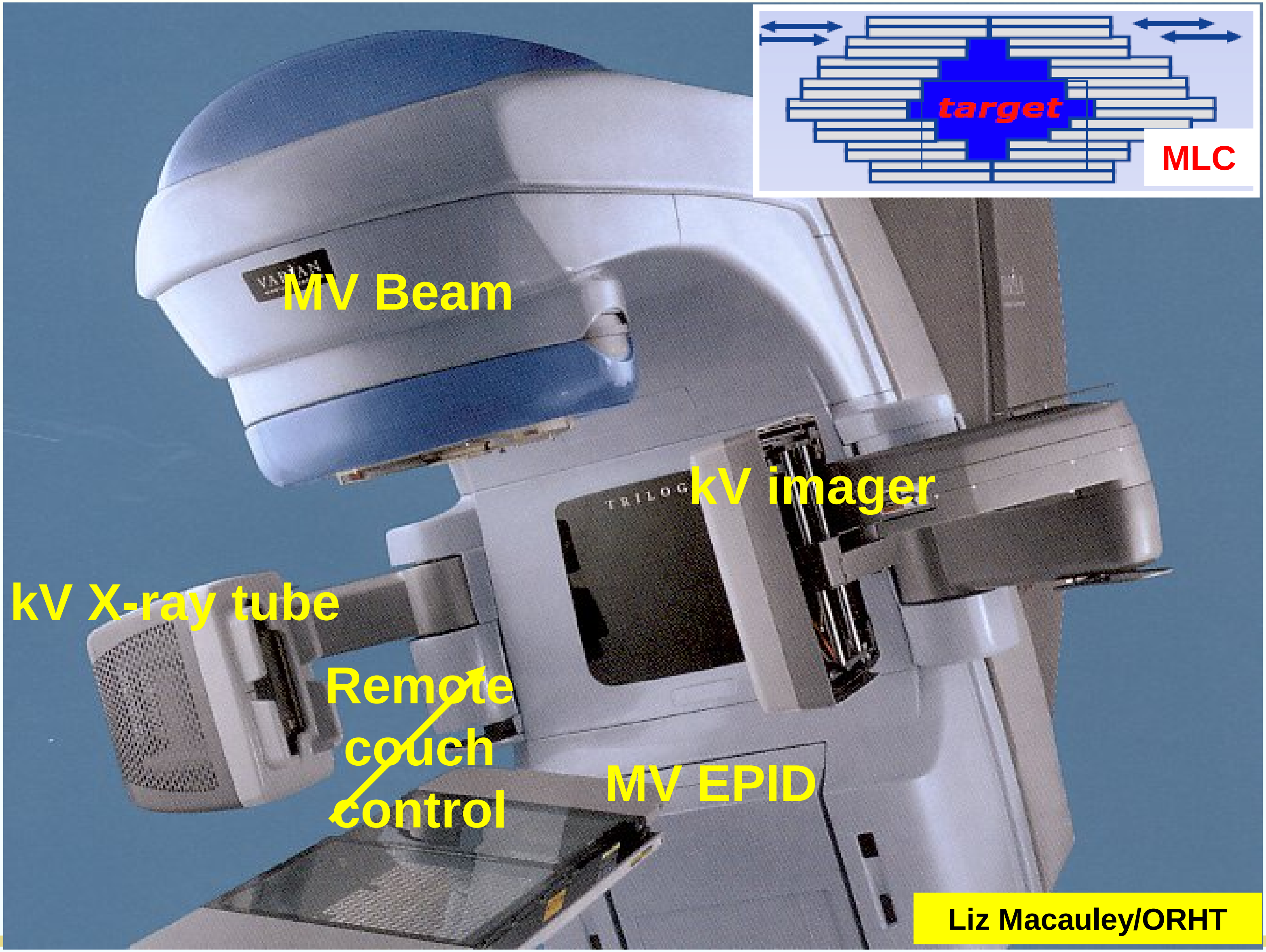
  - **Accuracy**
    - **Position, dose**
  - **Reliability**
    - **Interrupting treatment is very bad**
  - **Maintainability**
    - **Simple set-up and diagnostics**

  and affordability

challenges for physics

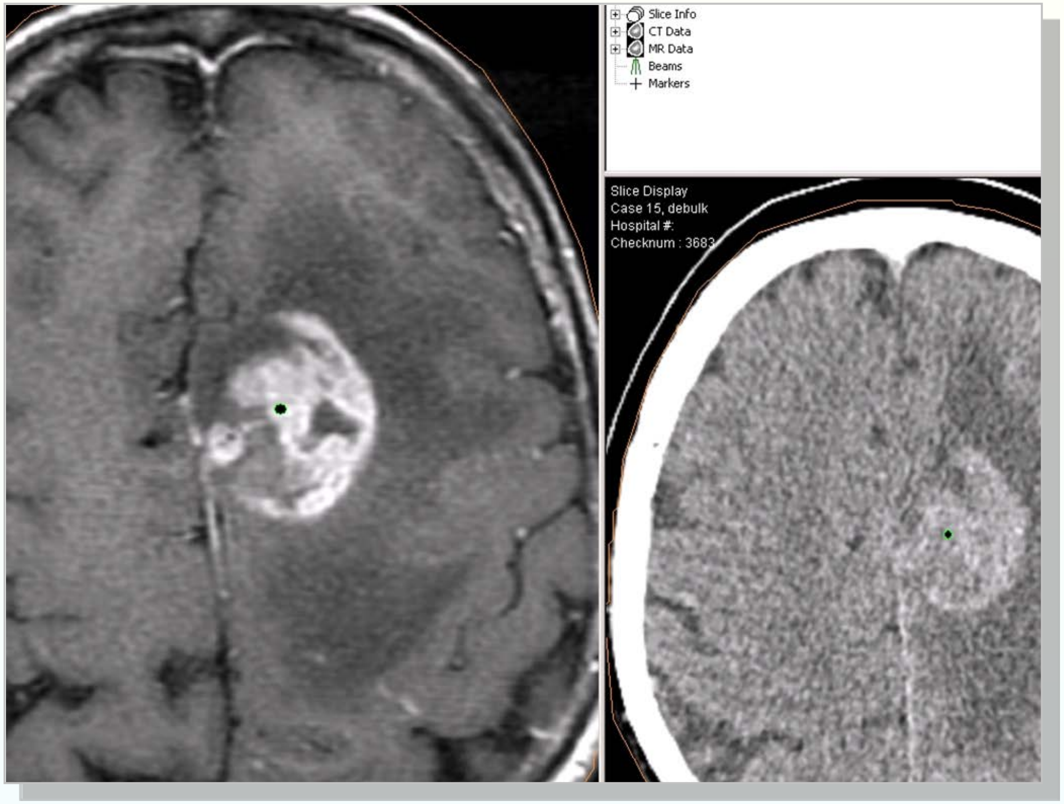


Linacs with on-Board Imaging

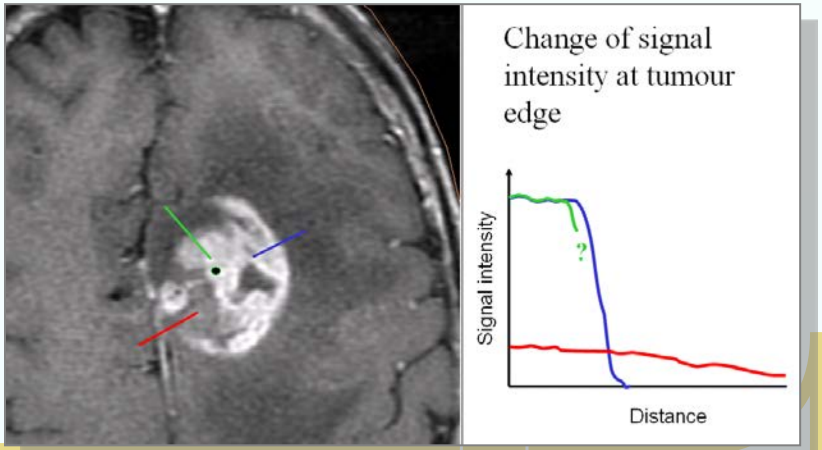


Liz Macauley/ORHT

Imaging & Tumour Definition



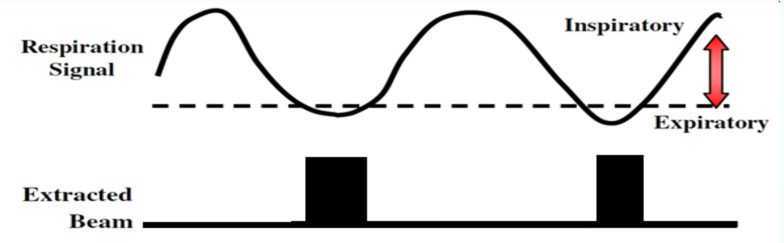
- **Imaging is crucial to better diagnosis**
  - **– and treatment**


Change of signal intensity at tumour edge

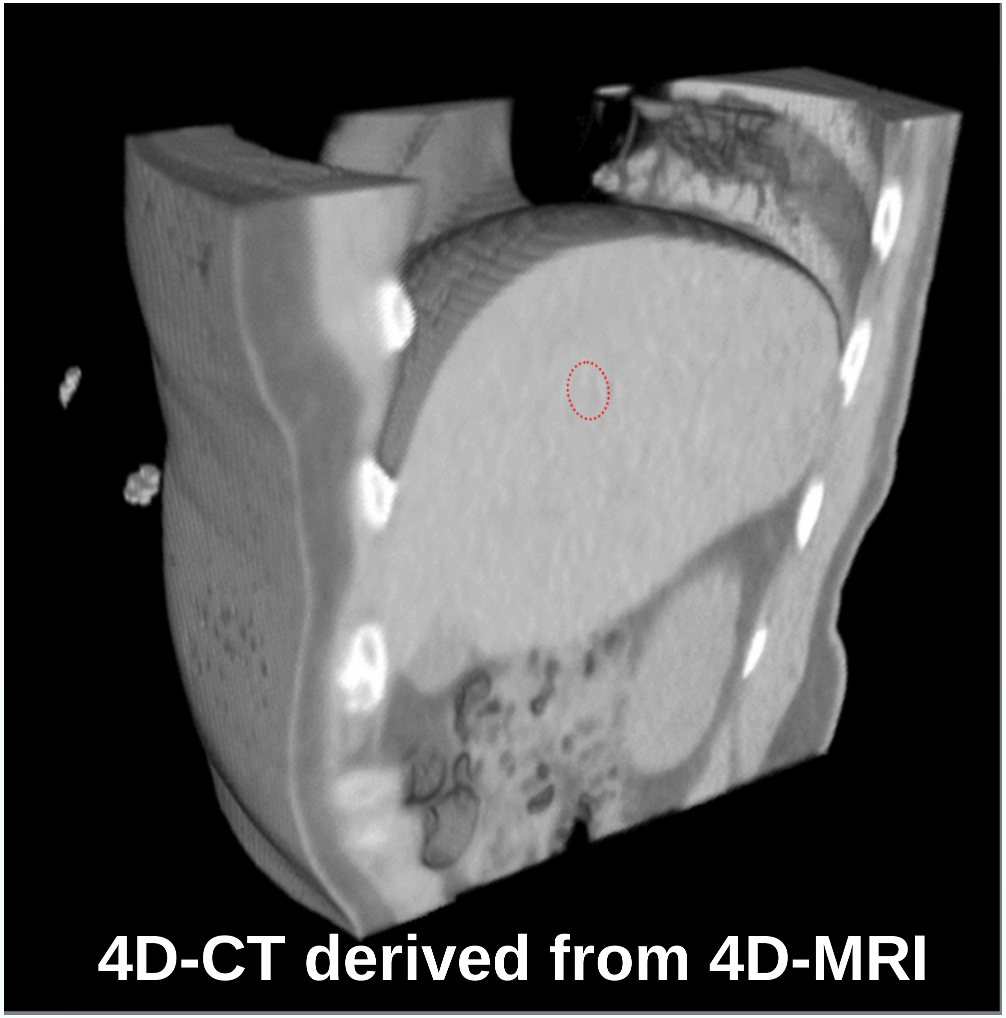
Credit: Neil Burnet

Organ motion: the problem

- **Patients breathe!**
- **Solutions?**
  - Motion tracking
    - Complicated
  - Active breathing
    - May be difficult
  - Gating



    - Long treatment

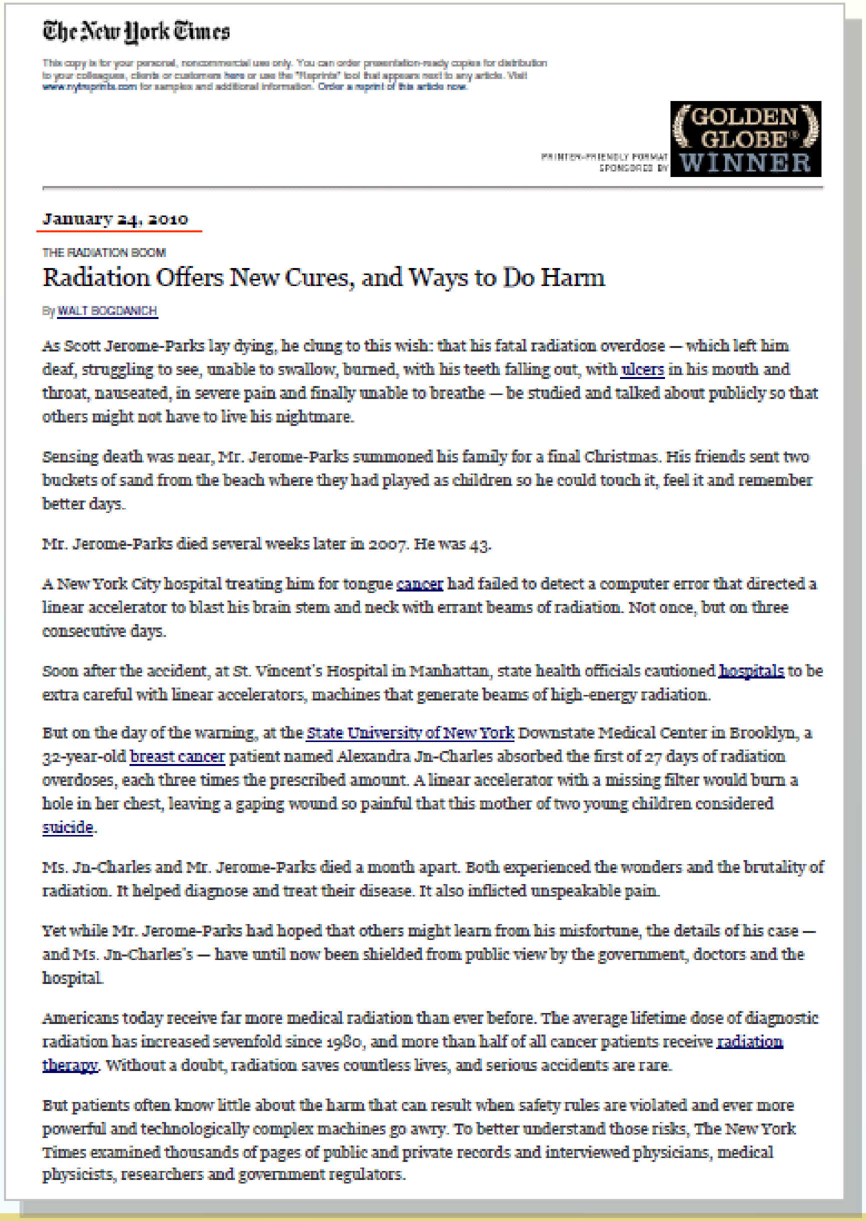

4D-CT derived from 4D-MRI

After Martin von Siebenthal, Phillipe Cattin, Gabor Szekely, Tony Lomax, ETH, Zurich and PSI, Villigen

… and much more

- **Diagnosis**
  - **Early diagnosis leads to better outcomes**
- **Tumour (and Organs At Risk)**
  - **identification and delineation**
- **Treatment planning**
  - **Optimising the therapeutic ratio**
  - **Fractionation strategies**
- **Calibration and dosimetry**
  - **Deliver the prescribed dose – no more, no less**
- **Follow-up**

The need for caution: Calibration & Dosimetry



The New York Times

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January 24, 2010

THE RADIATION BOOM

Radiation Offers New Cures, and Ways to Do Harm

By WALT BOGDANICH

As Scott Jerome-Parks lay dying, he clung to this wish: that his fatal radiation overdose — which left him deaf, struggling to see, unable to swallow, burned, with his teeth falling out, with ulcers in his mouth and throat, nauseated, in severe pain and finally unable to breathe — be studied and talked about publicly so that others might not have to live his nightmare.

Sensing death was near, Mr. Jerome-Parks summoned his family for a final Christmas. His friends sent two buckets of sand from the beach where they had played as children so he could touch it, feel it and remember better days.

Mr. Jerome-Parks died several weeks later in 2007. He was 43.

A New York City hospital treating him for tongue cancer had failed to detect a computer error that directed a linear accelerator to blast his brain stem and neck with errant beams of radiation. Not once, but on three consecutive days.

Soon after the accident, at St. Vincent's Hospital in Manhattan, state health officials cautioned hospitals to be extra careful with linear accelerators, machines that generate beams of high-energy radiation.

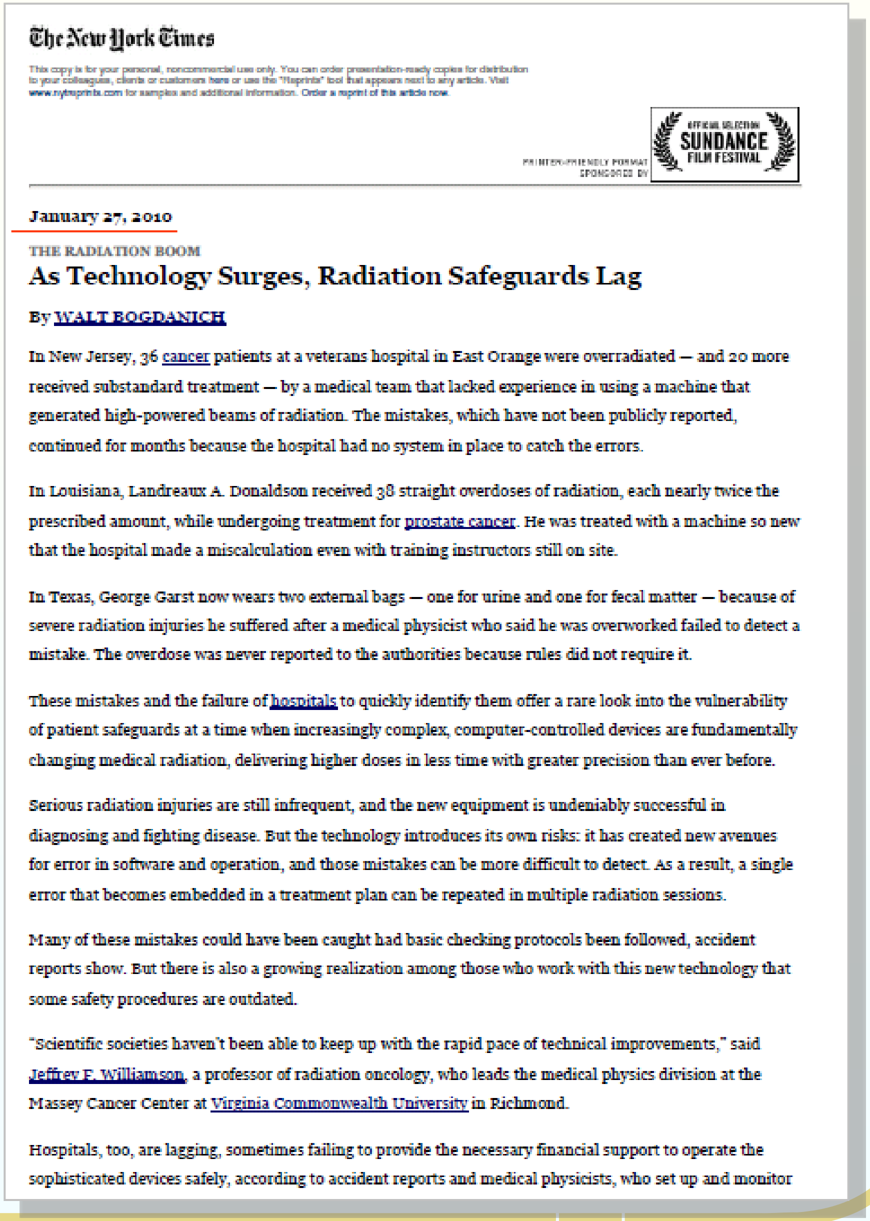
But on the day of the warning, at the State University of New York Downstate Medical Center in Brooklyn, a 32-year-old breast cancer patient named Alexandra Jn-Charles absorbed the first of 27 days of radiation overdoses, each three times the prescribed amount. A linear accelerator with a missing filter would burn a hole in her chest, leaving a gaping wound so painful that this mother of two young children considered suicide.

Ms. Jn-Charles and Mr. Jerome-Parks died a month apart. Both experienced the wonders and the brutality of radiation. It helped diagnose and treat their disease. It also inflicted unspeakable pain.

Yet while Mr. Jerome-Parks had hoped that others might learn from his misfortune, the details of his case — and Ms. Jn-Charles's — have until now been shielded from public view by the government, doctors and the hospital.

Americans today receive far more medical radiation than ever before. The average lifetime dose of diagnostic radiation has increased sevenfold since 1980, and more than half of all cancer patients receive radiation therapy. Without a doubt, radiation saves countless lives, and serious accidents are rare.

But patients often know little about the harm that can result when safety rules are violated and ever more powerful and technologically complex machines go awry. To better understand those risks, The New York Times examined thousands of pages of public and private records and interviewed physicians, medical physicists, researchers and government regulators.



The New York Times

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January 27, 2010

THE RADIATION BOOM

As Technology Surges, Radiation Safeguards Lag

By WALT BOGDANICH

In New Jersey, 36 cancer patients at a veterans hospital in East Orange were overradiated — and 20 more received substandard treatment — by a medical team that lacked experience in using a machine that generated high-powered beams of radiation. The mistakes, which have not been publicly reported, continued for months because the hospital had no system in place to catch the errors.

In Louisiana, Landreaux A. Donaldson received 38 straight overdoses of radiation, each nearly twice the prescribed amount, while undergoing treatment for prostate cancer. He was treated with a machine so new that the hospital made a miscalculation even with training instructors still on site.

In Texas, George Garst now wears two external bags — one for urine and one for fecal matter — because of severe radiation injuries he suffered after a medical physicist who said he was overworked failed to detect a mistake. The overdose was never reported to the authorities because rules did not require it.

These mistakes and the failure of hospitals to quickly identify them offer a rare look into the vulnerability of patient safeguards at a time when increasingly complex, computer-controlled devices are fundamentally changing medical radiation, delivering higher doses in less time with greater precision than ever before.

Serious radiation injuries are still infrequent, and the new equipment is undeniably successful in diagnosing and fighting disease. But the technology introduces its own risks: it has created new avenues for error in software and operation, and those mistakes can be more difficult to detect. As a result, a single error that becomes embedded in a treatment plan can be repeated in multiple radiation sessions.

Many of these mistakes could have been caught had basic checking protocols been followed, accident reports show. But there is also a growing realization among those who work with this new technology that some safety procedures are outdated.

"Scientific societies haven't been able to keep up with the rapid pace of technical improvements," said Jeffrey F. Williamson, a professor of radiation oncology, who leads the medical physics division at the Massey Cancer Center at Virginia Commonwealth University in Richmond.

Hospitals, too, are lagging, sometimes failing to provide the necessary financial support to operate the sophisticated devices safely, according to accident reports and medical physicists, who set up and monitor

Therapeutic Ratio: A Juggling Act

- The goal is:

  the highest therapeutic ratio
  - the greatest chance of cure
  - the least chance of serious toxicity

- *Oftentimes* radiation doses are limited to avoid toxicity.

- *Sometimes* the price of cure is a complication.

Mendenhall

What do the clinicians *want?*

- **Technology can provide many things**
  - **but clinical practice is conservative**
- **New ideas must satisfy clinical need**
  - **and be effective, reliable and affordable**
- **If we are lucky**
  - **we make life better for thousands**

    or millions
- **If we get it wrong**
  - **we do damage, perhaps only to a few**
- **Remember the Hippocratic Corpus**

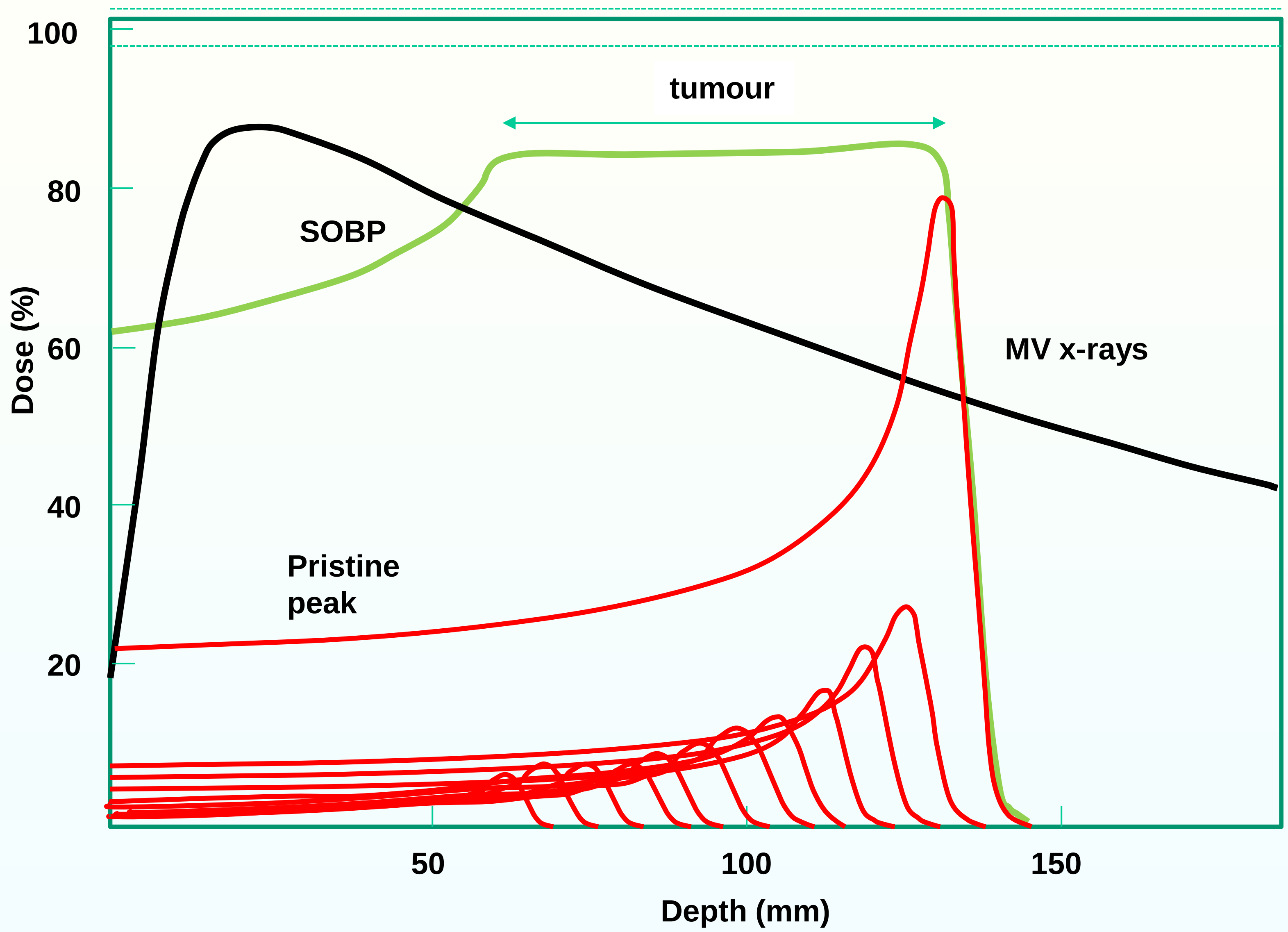
  "επι δηλησει δε και αδικιηι ειρξειν"

  "First, do no harm"

CHARGED PARTICLE THERAPY

Using protons and other light ions (e.g. carbon) to treat cancer

Depth Dose curves – photon and proton



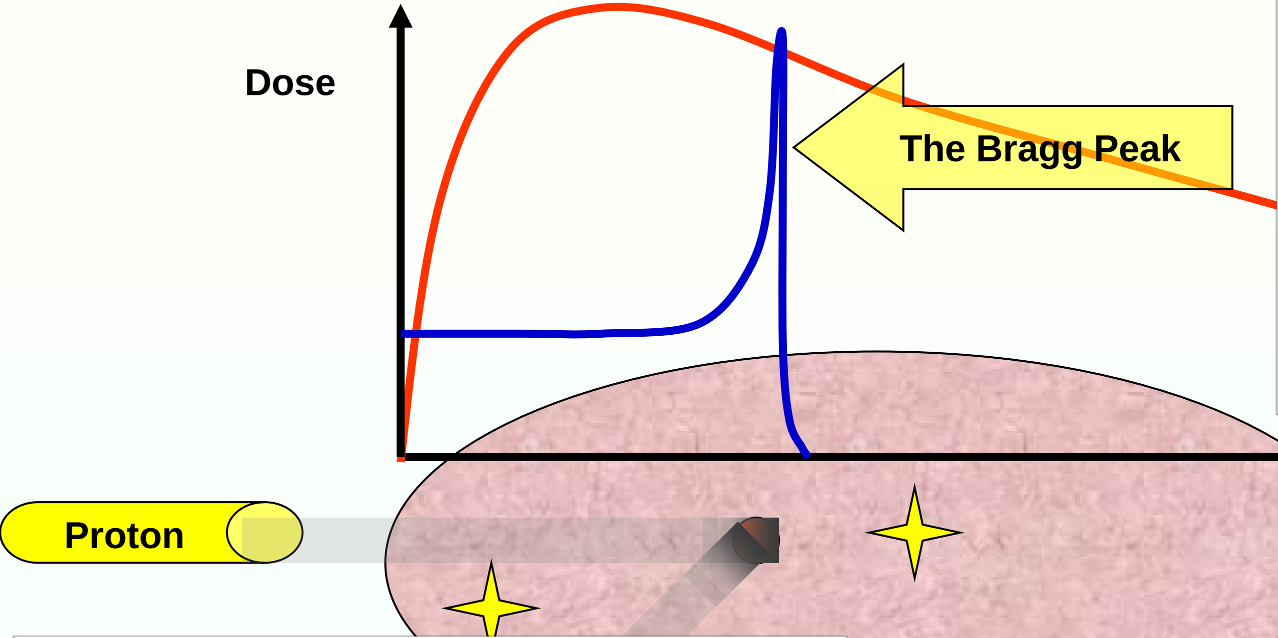
History of Proton Therapy

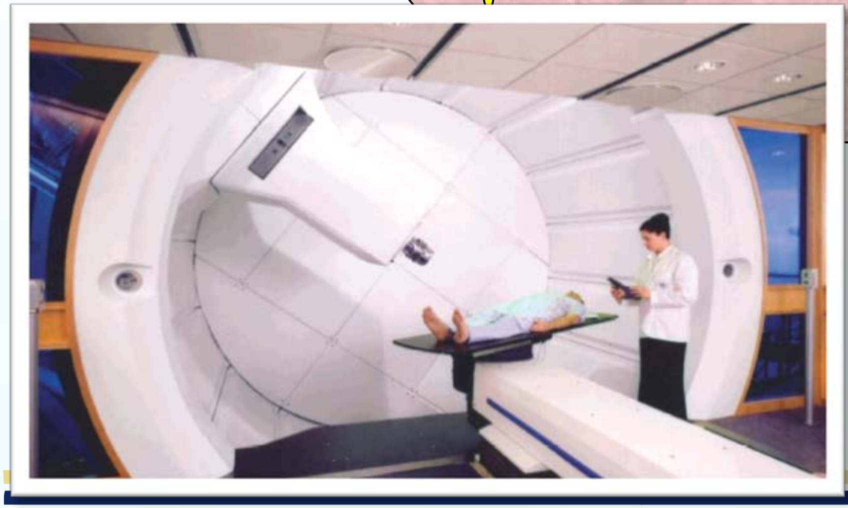
- **1946:**
  - **Therapy proposed by Robert R. Wilson, Harvard Physics**
- **1955:**
  - **1st Proton Therapy at Lawrence Tobias University of California, Berkeley**
- **1955-73:**
  - **Single dose irradiation of benign CNS lesions**
- **2010:**
  - **> 75 000 patients had been treated with protons worldwide**
  - **> 30 proton therapy centres operating worldwide**
  - **~ 20 more planned or under construction**

Proton Therapy Centres Worldwide

http://www.uhb.nhs.uk/ProtonsBirmingham/background/facilities.htm

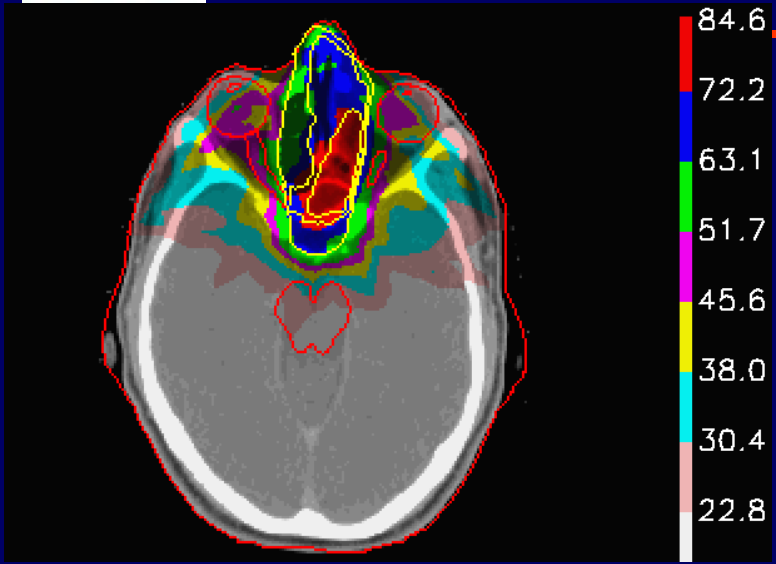
Can we do better?



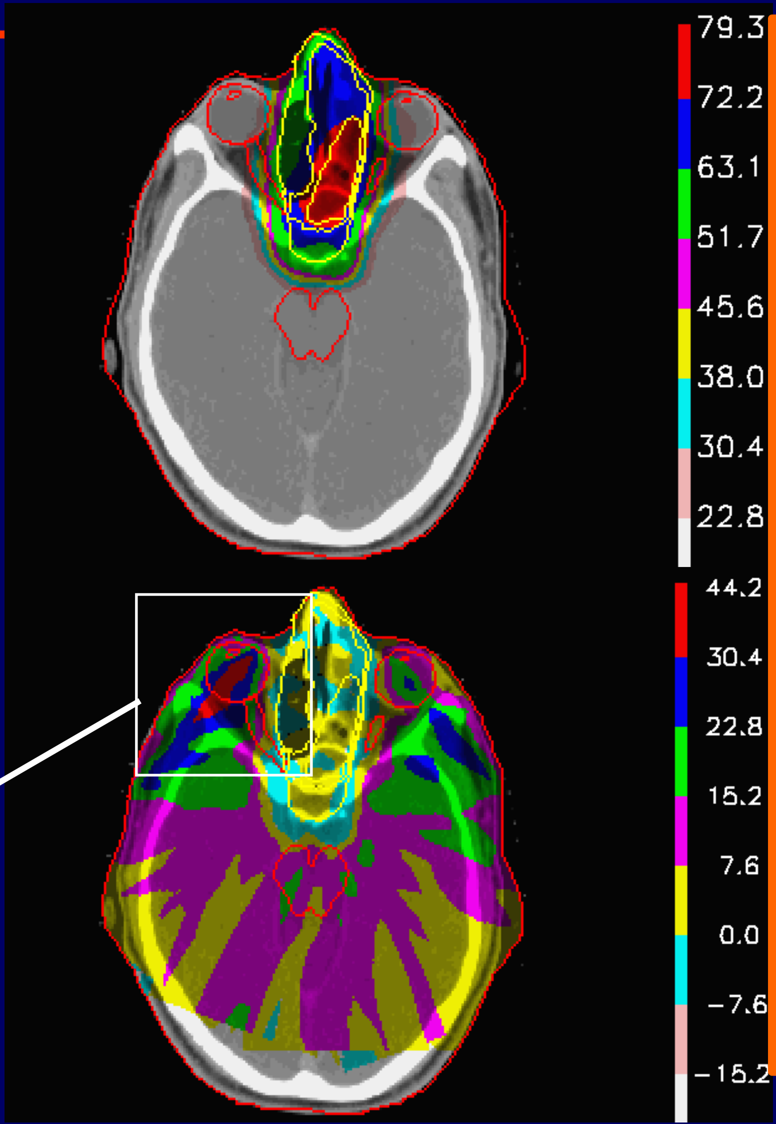


Paranasal Sinus

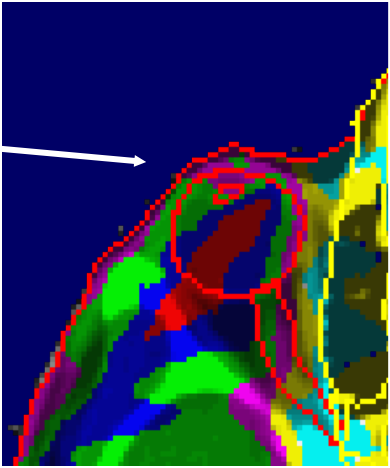
IMXT (X rays)



Protons



Dose Difference



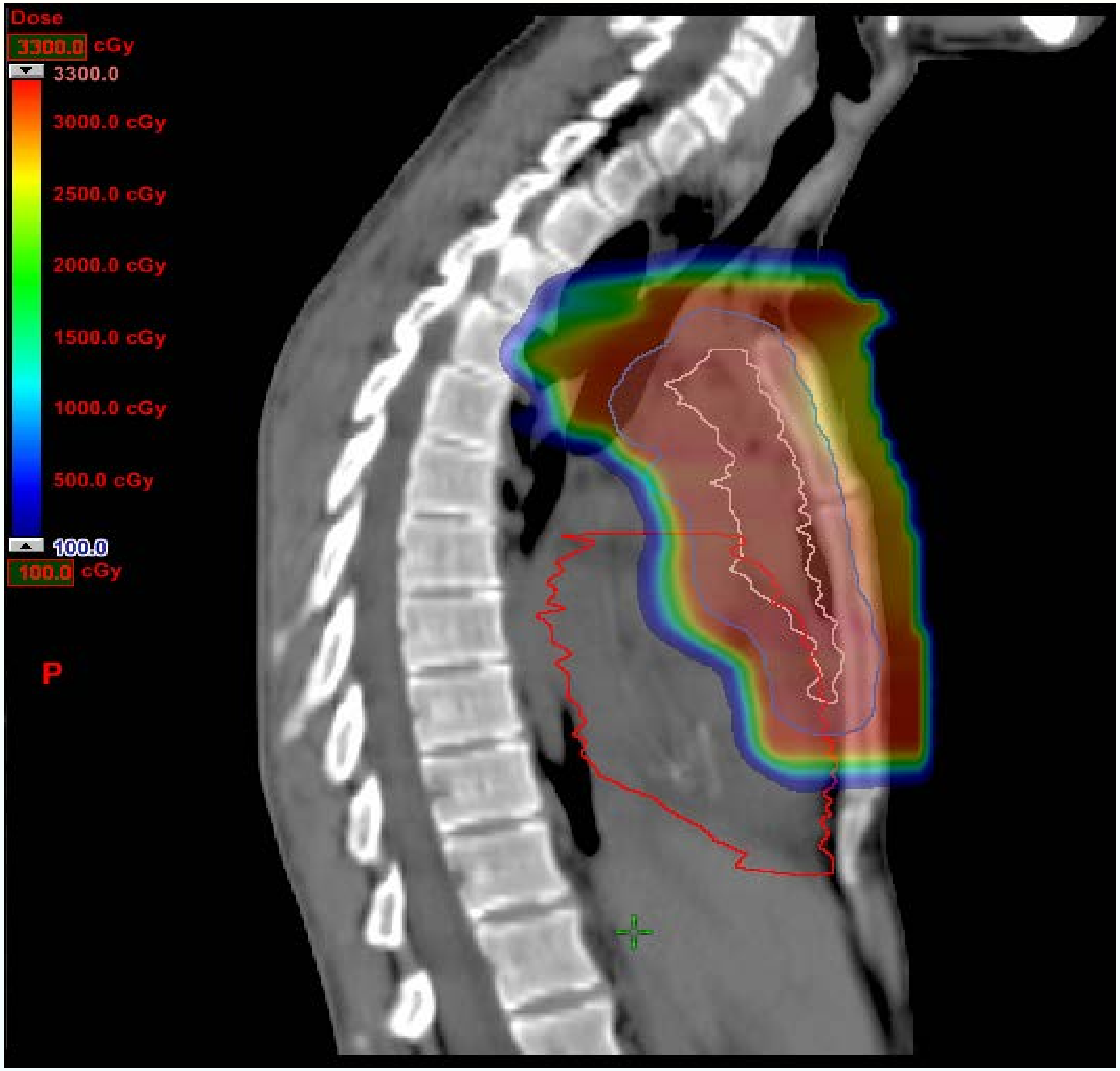
Studies at UF and MMSKCC have demonstrated either high blindess rates with moderate cure rates or low blindness rates with low cure rates, however MGH studies with PT and early experience at UF with PT suggests both low blindness rates and high cure rates.

Lomax et al, PSI

Mendenhall

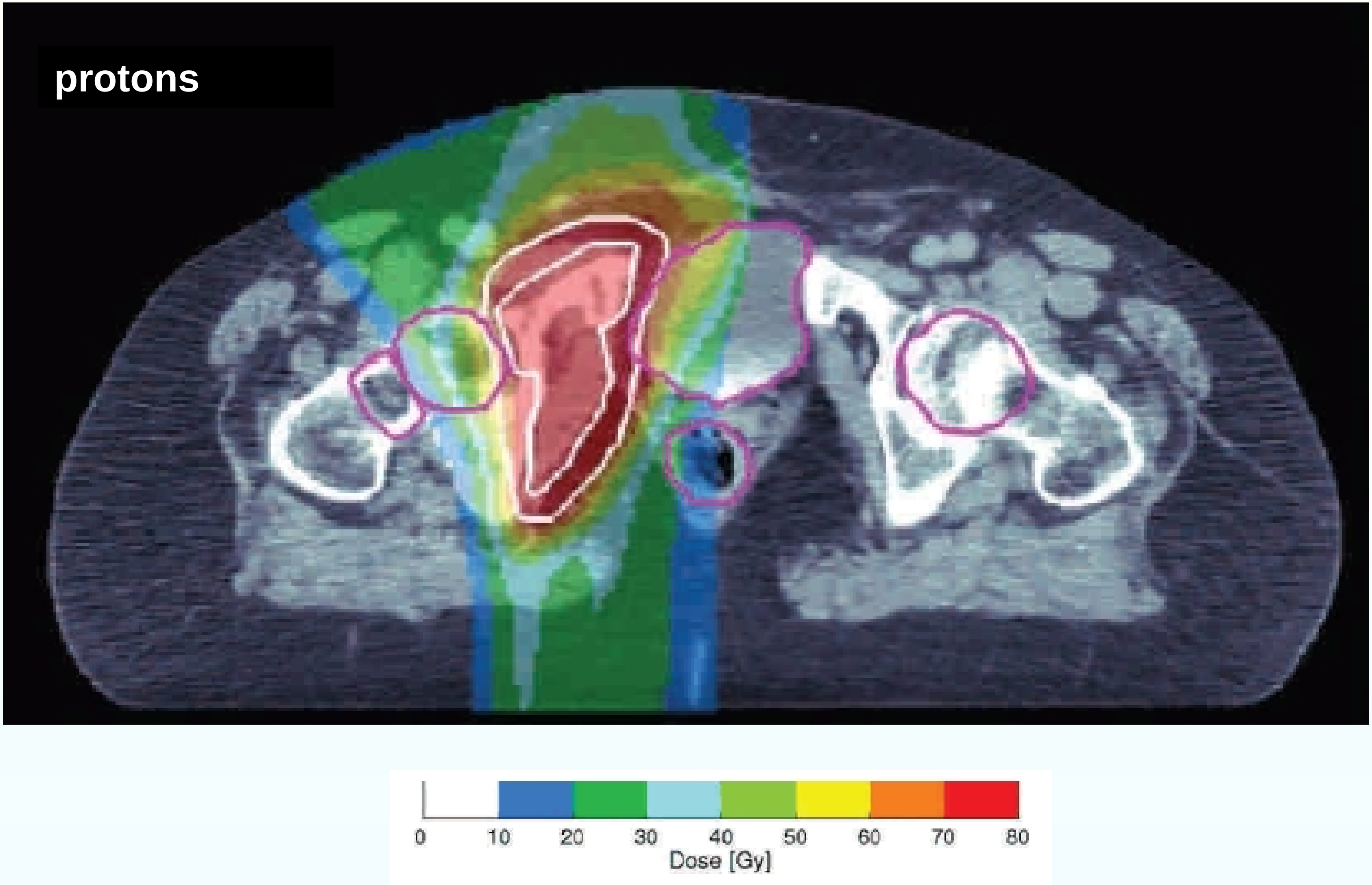
Hodgkin’s Lymphoma; Heart & Spine Sparing

Photons

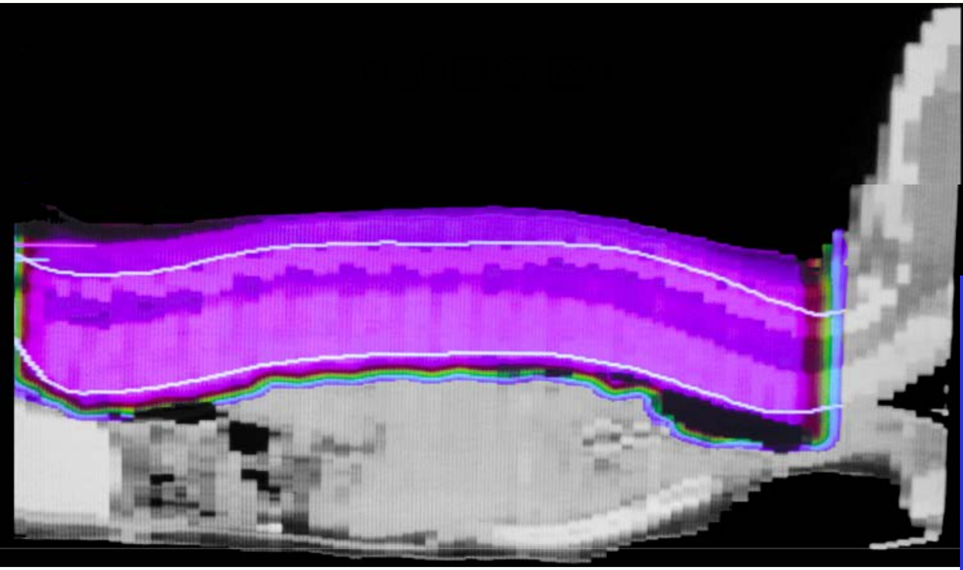


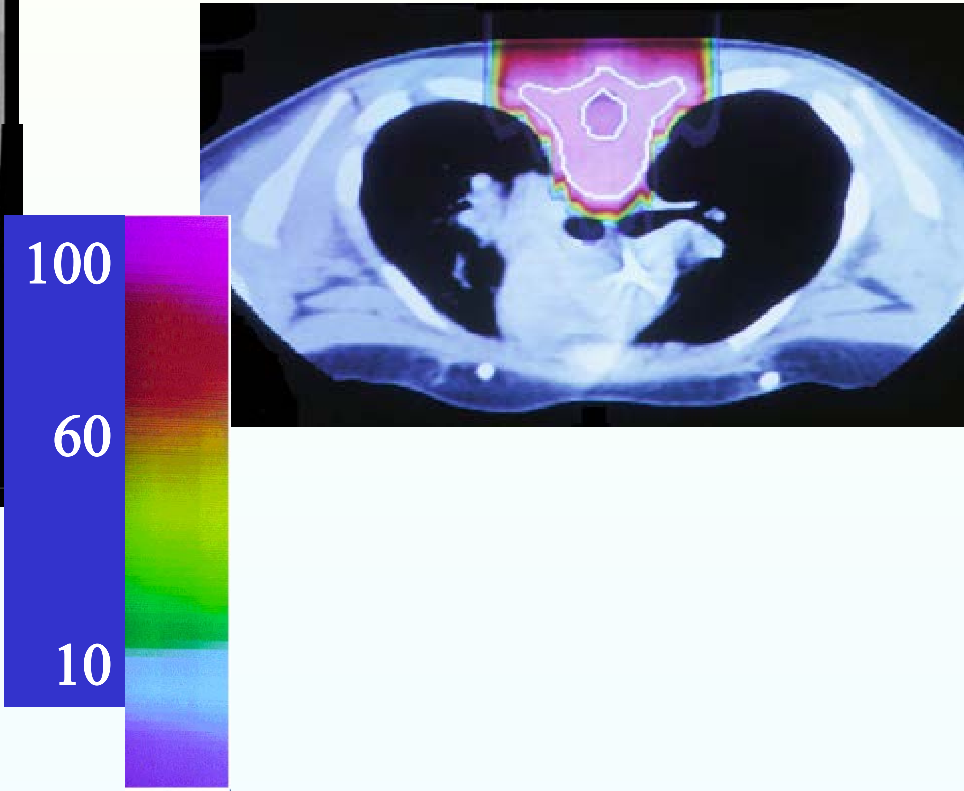
After Mendenhall

X-rays compared with protons



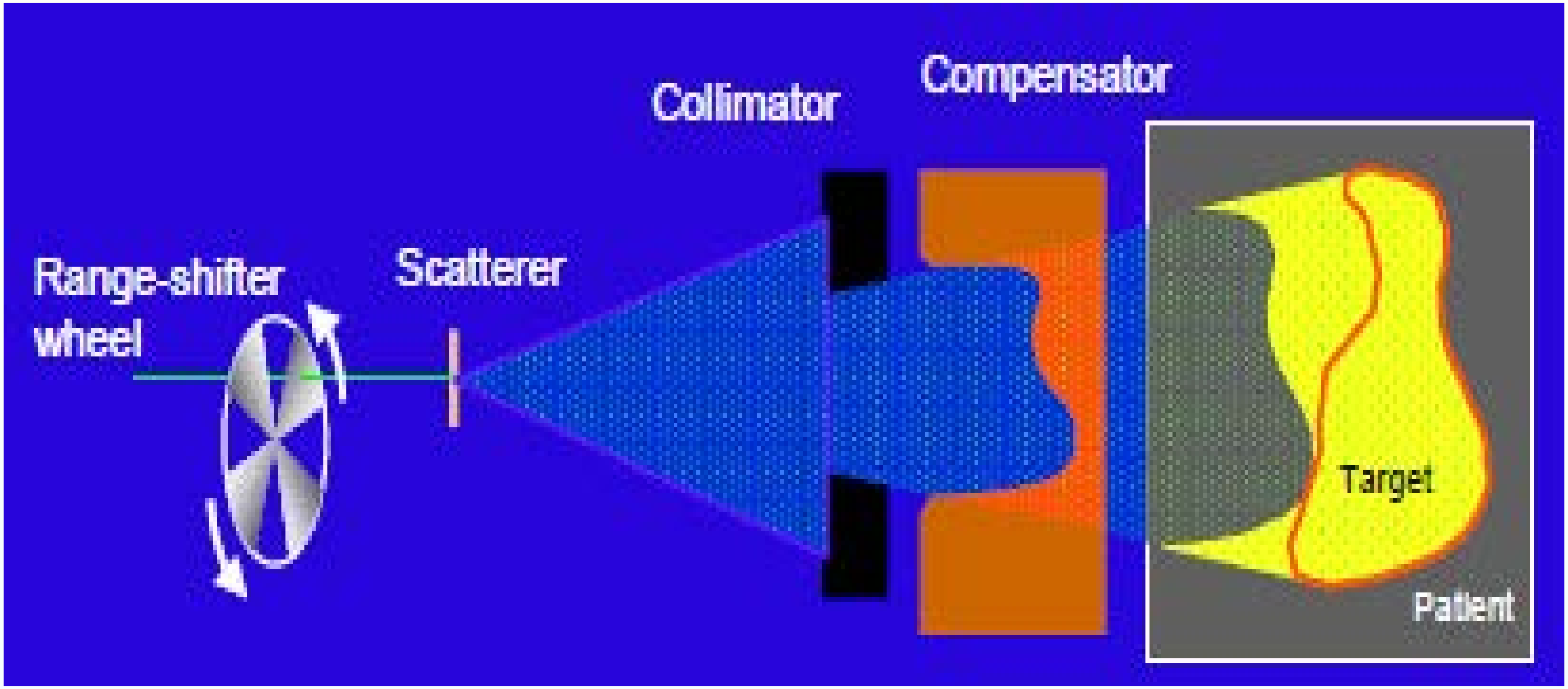
Medulloblastoma in a child





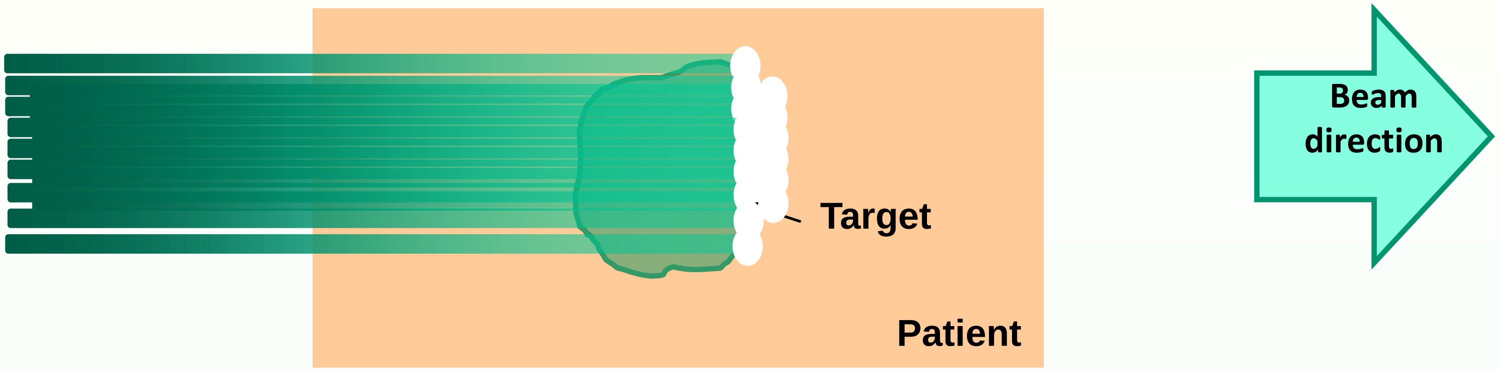
With Protons

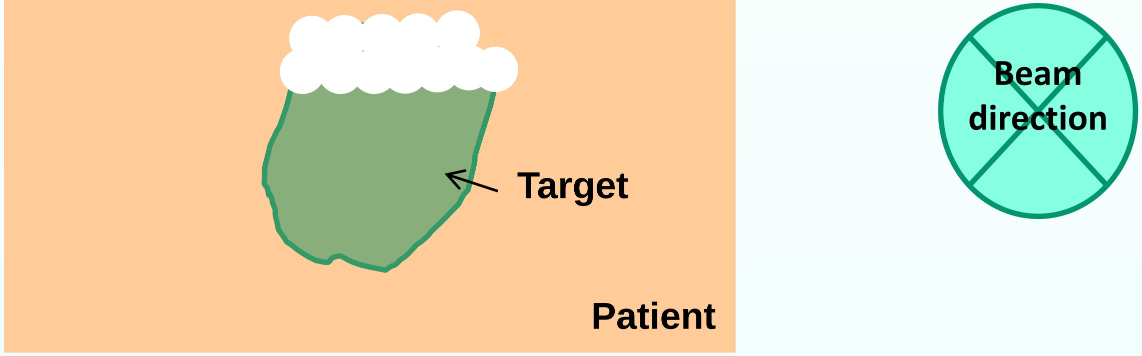
Beam Delivery - Scattering



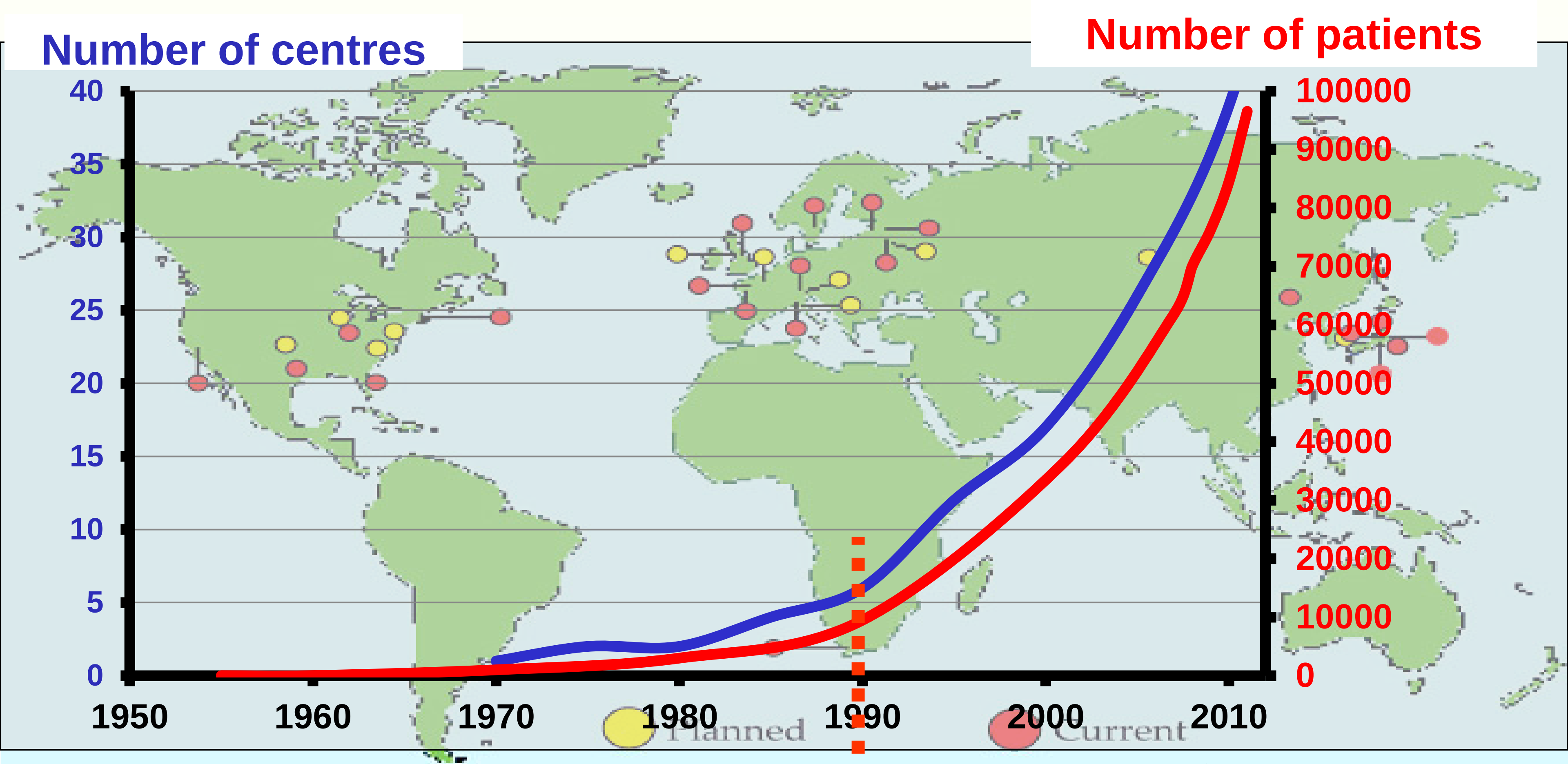
Courtesy of T. Lomax, PSI, Switzerland.

Beam Delivery - Scanning





CPT worldwide



In Physics Laboratories

In Hospitals (mostly)

83,667 protons, 96,537 total (Dec 2011)

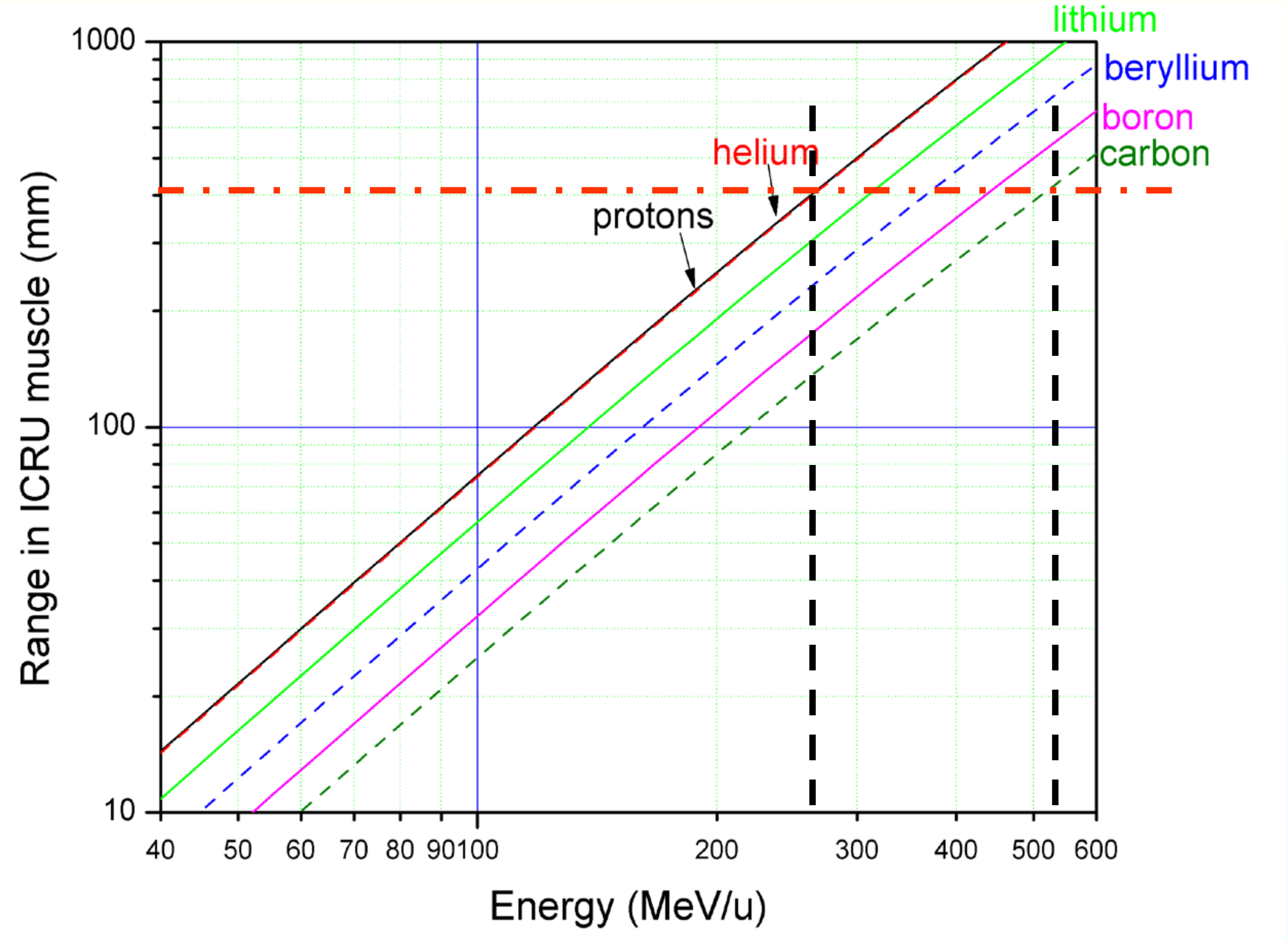
After Janet Sisterson, MGH

What remains to be done?

- Particle Therapy has moved from laboratory to hospital
  - where it belongs
- But there is still much to do
  - Improved accelerator technology
    - improved patient experience, better control
  - Improved beam delivery & instrumentation
    - Improved accuracy, lower healthy tissue dose, better control
  - Improved understanding of the evidence
    - better treatment planning, domains of applicability
  - Improved treatment regimes
    - better ways of delivering the lethal tumour dose
  - Improved understanding of mechanisms
    - better treatment planning, more effective outcomes

- Improve patient experience
- Increase effectiveness
- Decrease cost

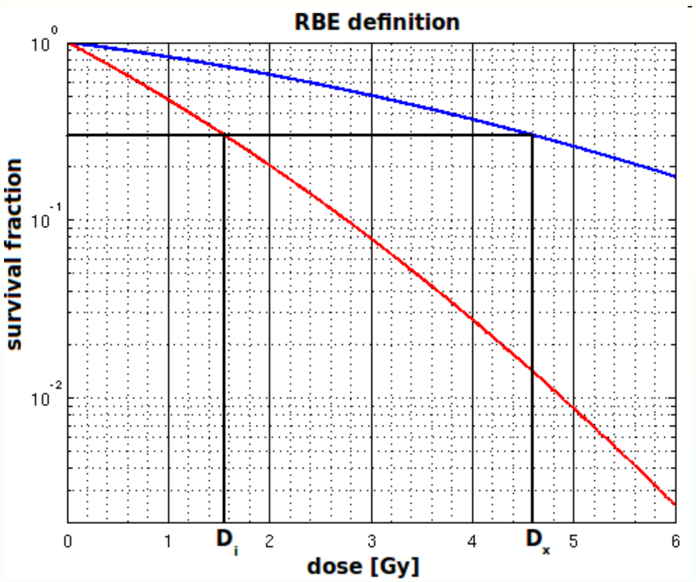
Parameters


lithium
beryllium
boron
carbon
helium
protons
1000
100
10
Range in ICRU muscle (mm)
40
50
60
70
80
90
100
200
300
400
500
600
Energy (MeV/u)

RBE & LET

Relative Biological Effectiveness

$$RBE = \frac{DOSE_{x-ray}}{DOSE_{test}}$$



Linear Energy Transfer

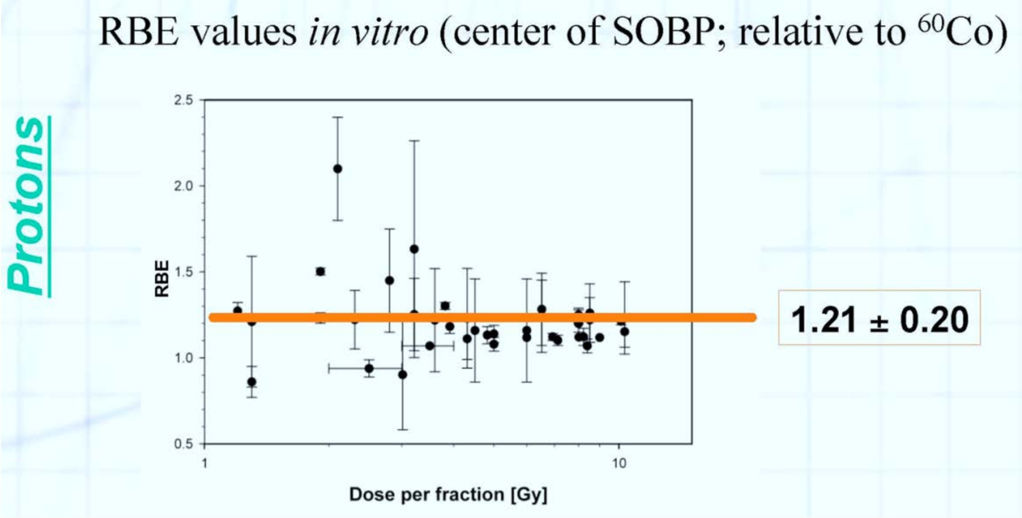
$$LET = \frac{dE_{transferred}}{dx}$$

- **LET is related to dE/dx (Bethe Bloch)**

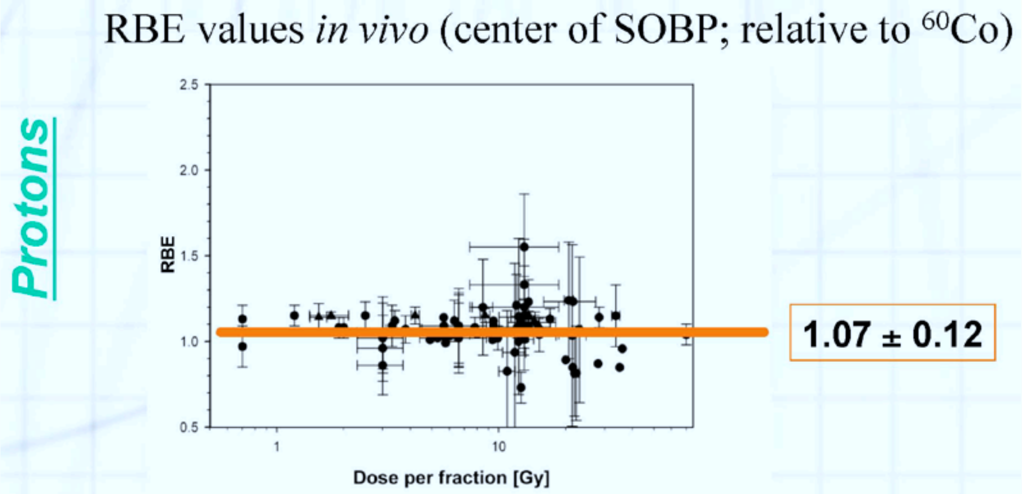
but is the energy transferred to the medium,

not the energy lost by the particle

More on RBE

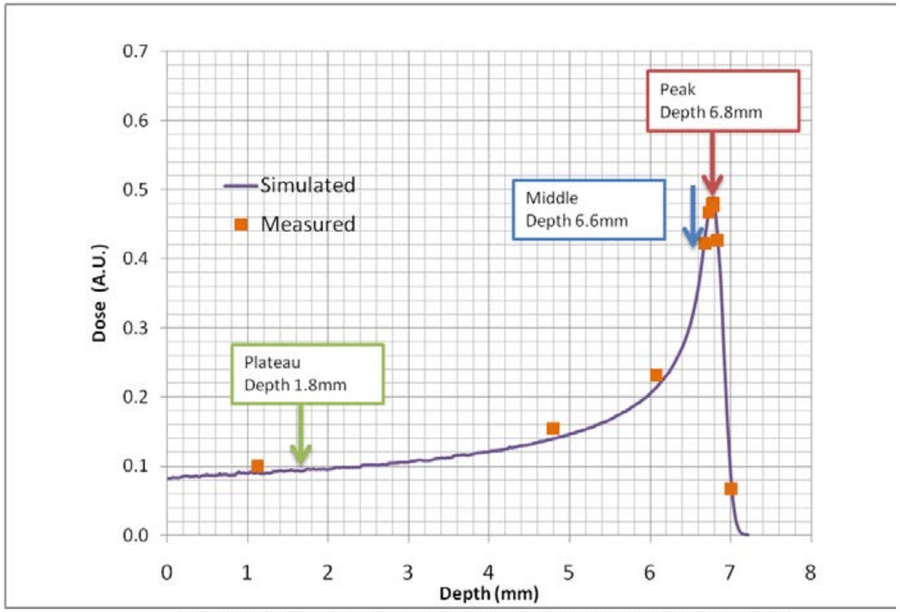

RBE values *in vitro* (center of SOBP; relative to ^{60}Co)

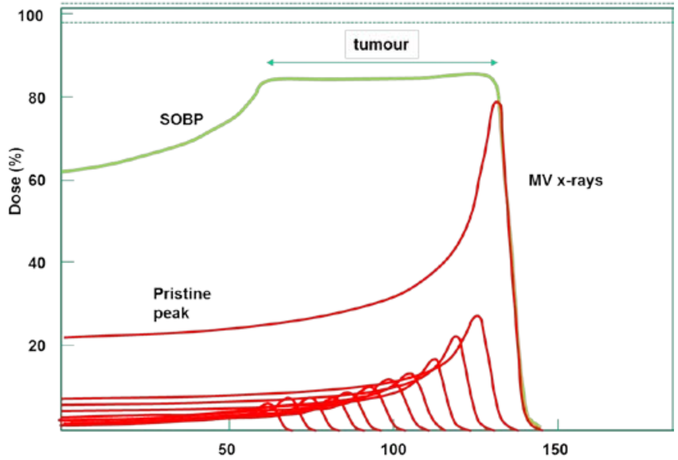
From Paganetti et al.: *Int. J. Radiat. Oncol. Biol. Phys.* 2002; 53, 407


RBE values *in vivo* (center of SOBP; relative to ^{60}Co)

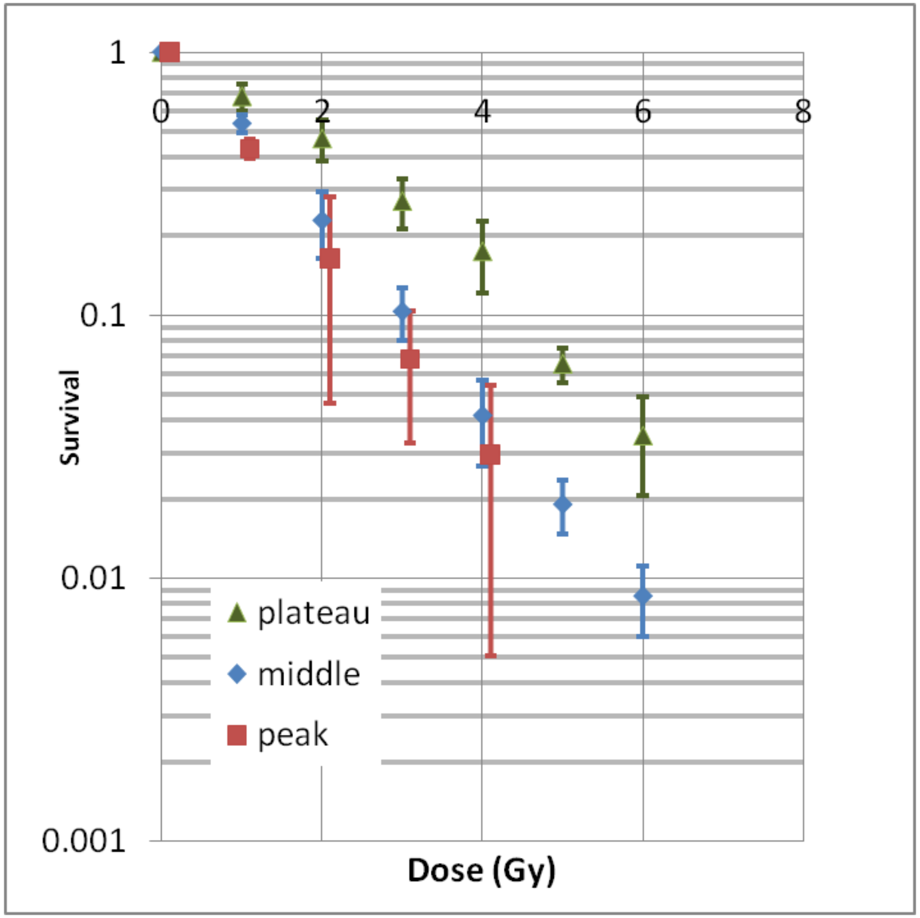
- **The recommended value of RBE for protons is 1.1**

Result –proton irradiation-





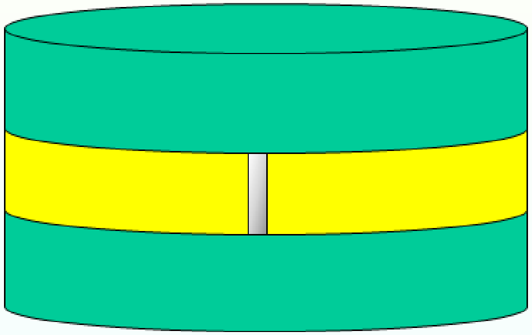
After Al Nagano (PTCRi, private communication)

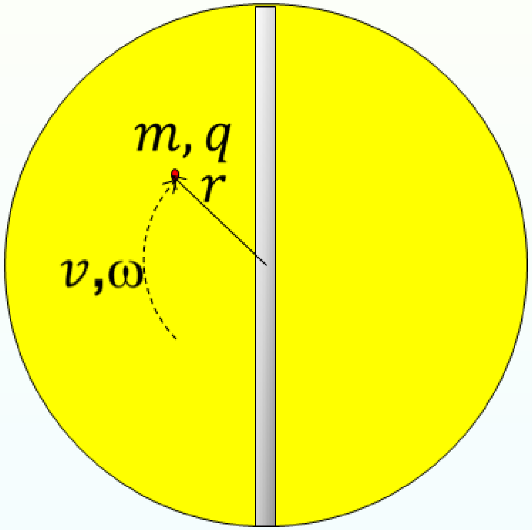


- Averaged survival fractions over 3 repeated experiments.

ACCELERATOR TECHNOLOGY

Cyclotrons

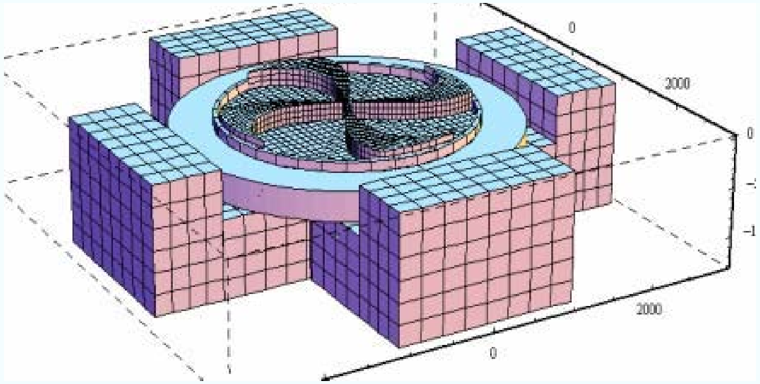




$$Bqv = \frac{mv^2}{r}$$

$$r = \frac{mv}{Bq} = \frac{p}{Bq}; \quad \omega_c = \frac{Bq}{m}$$

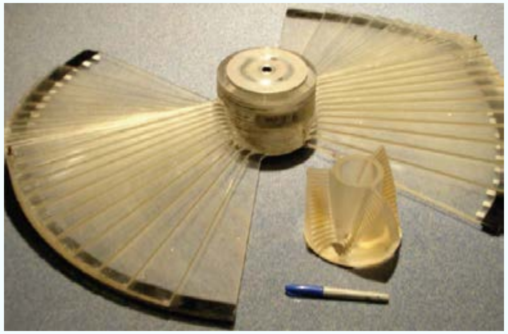
Units:
p in GeV/c, B in Tesla, m in GeV/c^2, r in m
$q_e = 0.3$



Yu. G.Alenitsky, Proceedings of RuPAC 2008, Zvenigorod, Russia

IBA & Varian cyclotrons

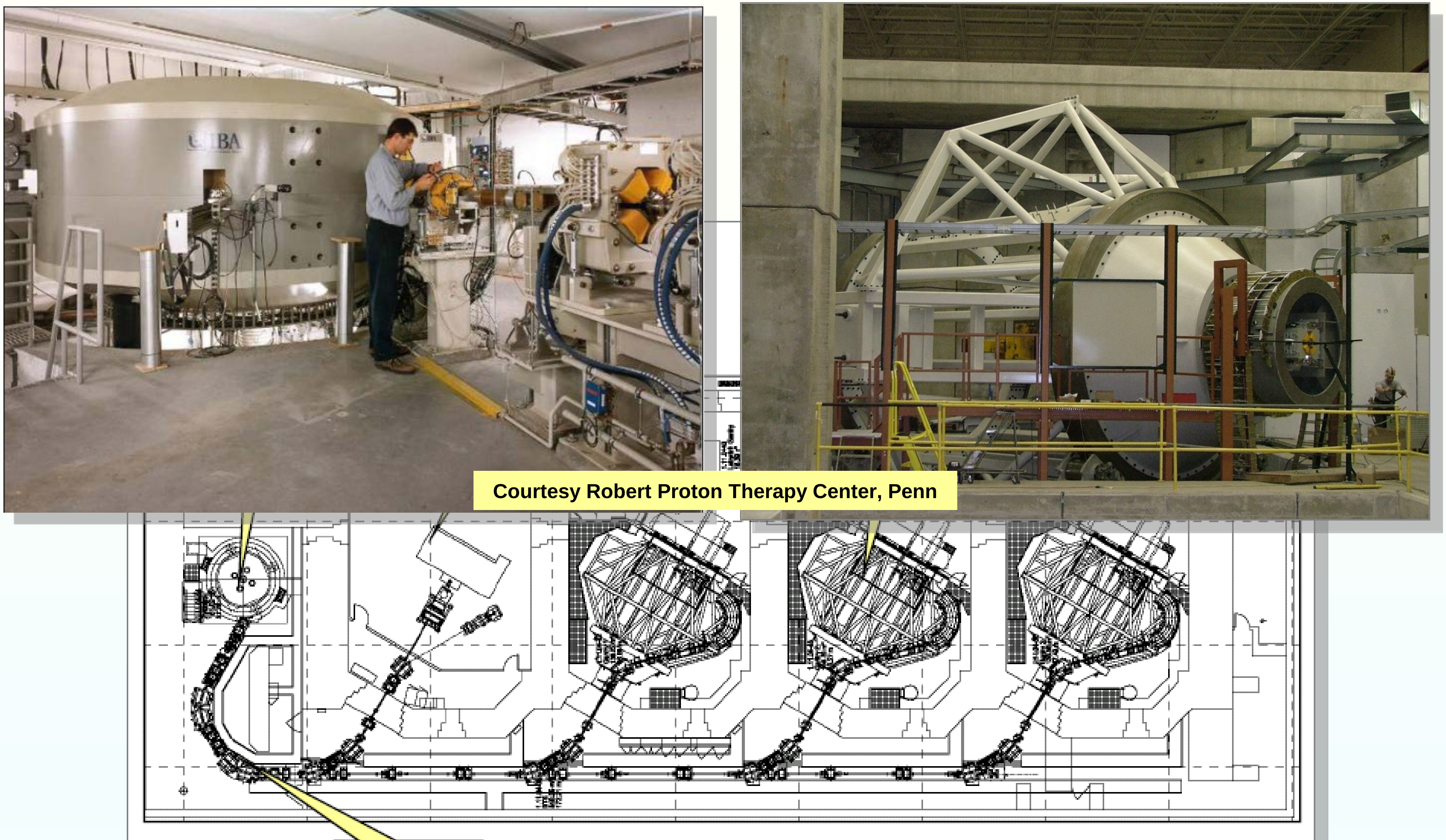
Cyclotrons are essentially fixed energy extraction



PSI

Courtesy PSI

IBA

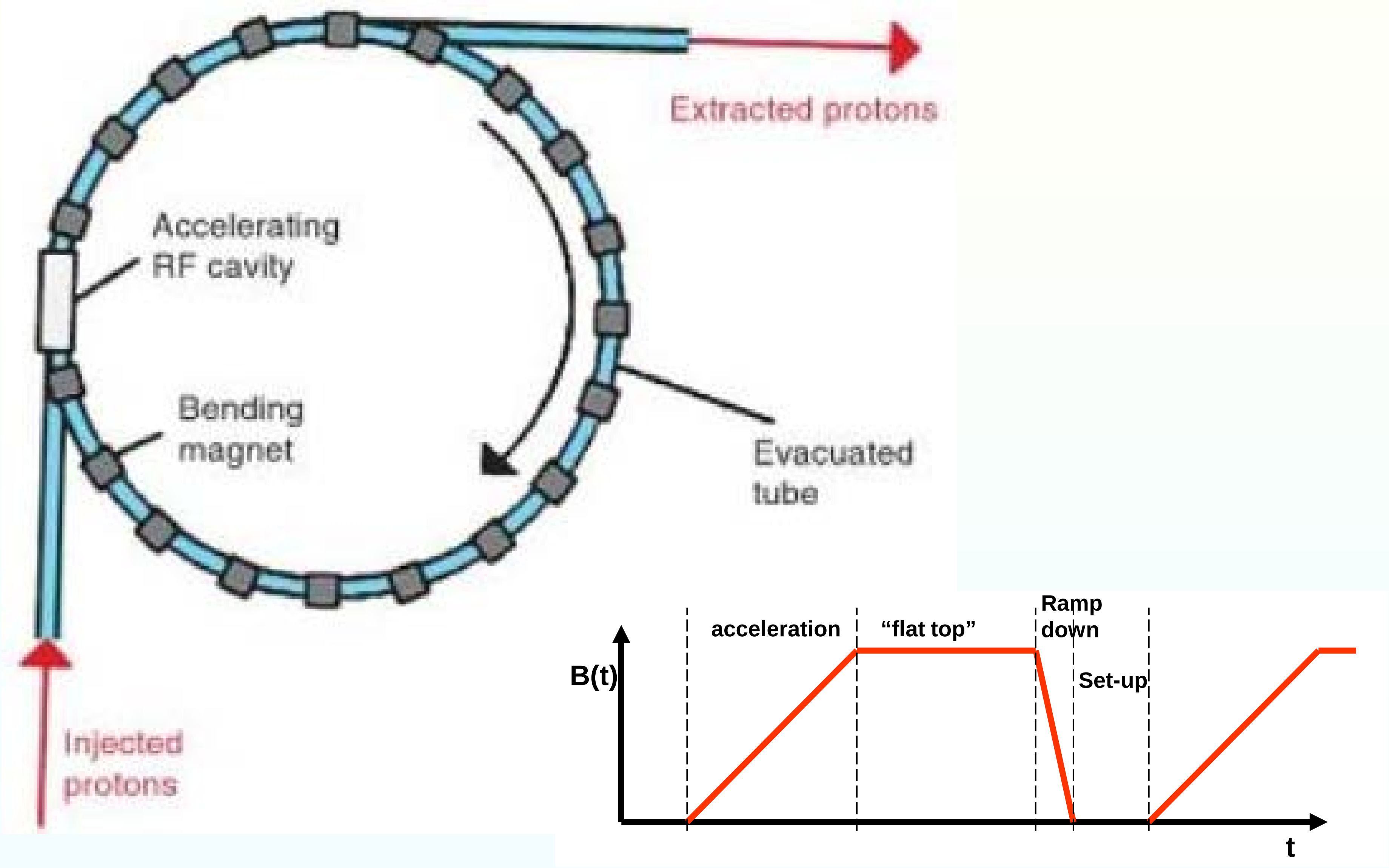


Courtesy Robert Proton Therapy Center, Penn

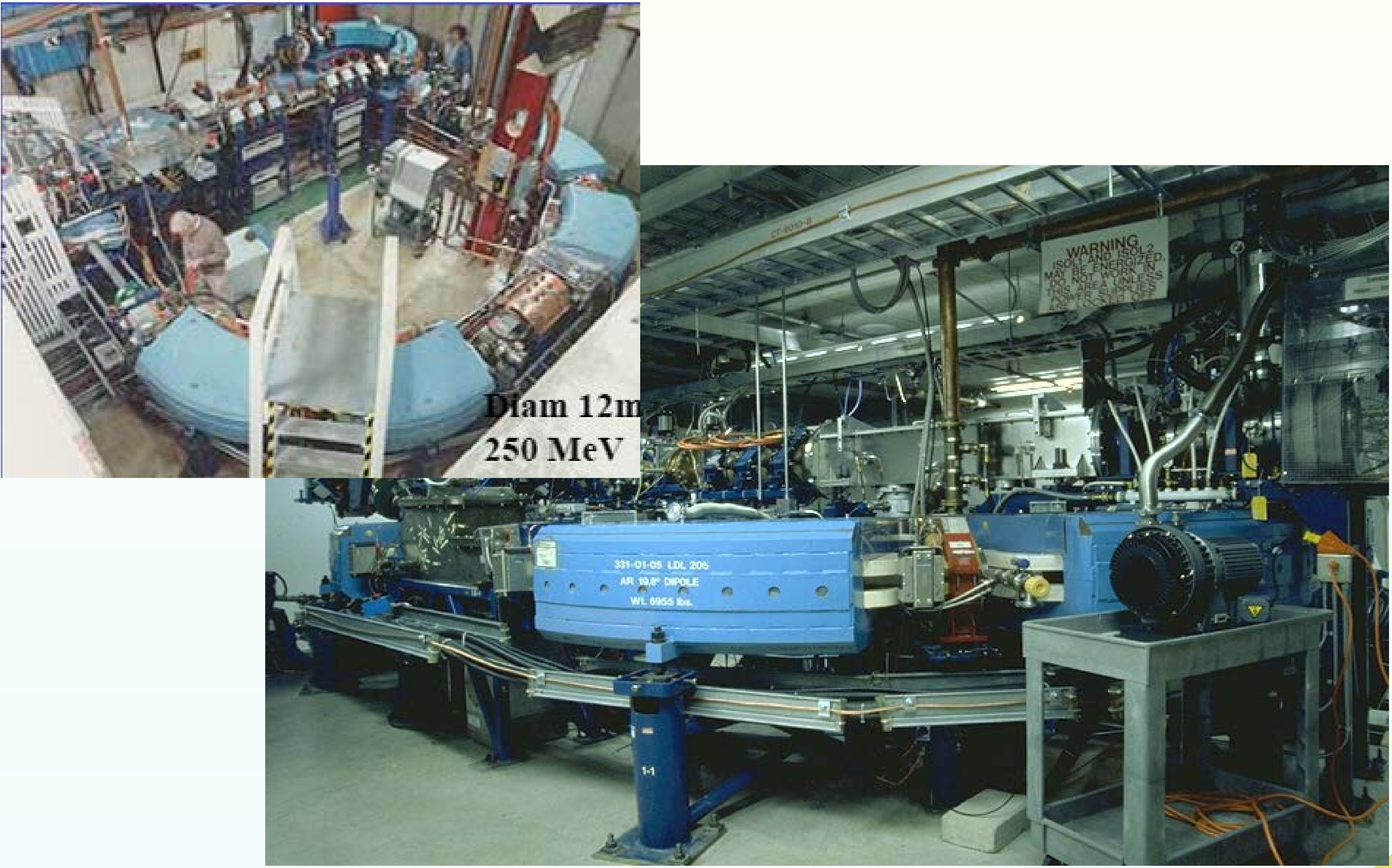
Energy Selection System

Courtesy IBA

Synchrotrons

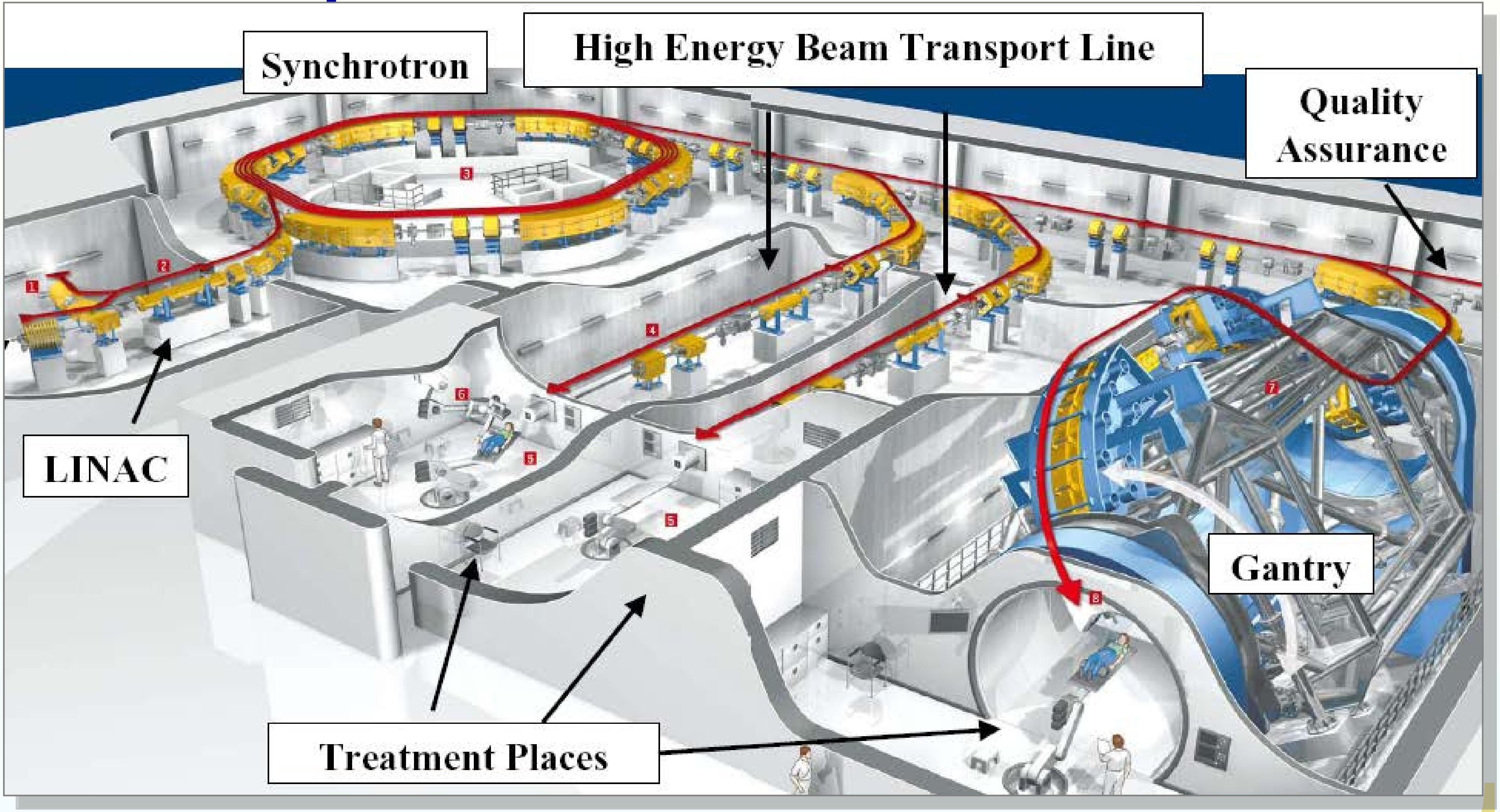


The Loma Linda Synchrotron



Heidelberger Ionenstrahl-Therapiezentrum (HIT)

- **First patient treated November 2009**

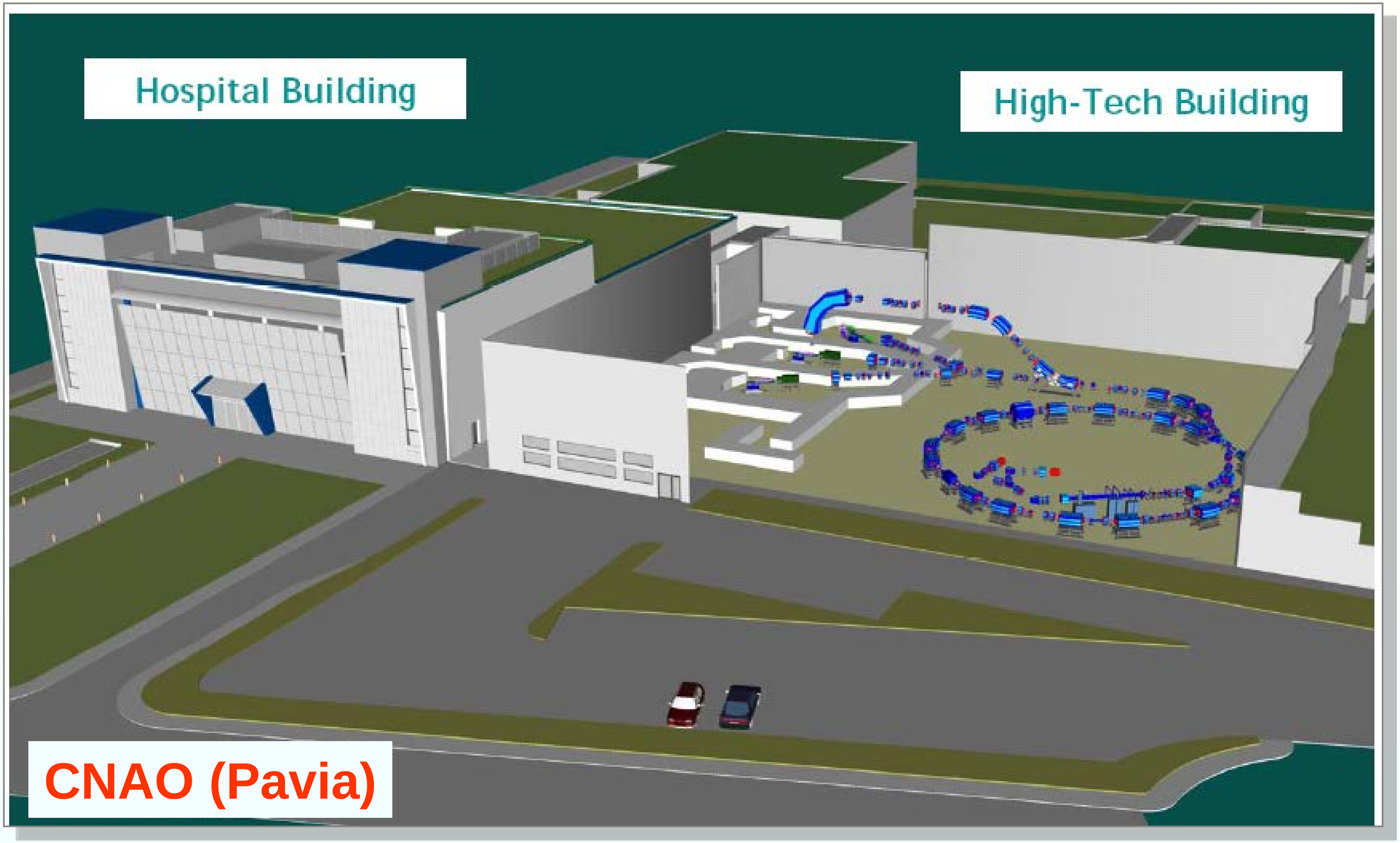


Courtesy HIT

HIT in action

Courtesy HIT

Centro Nazionale di Adroterapia Oncologica



CNAO (Pavia)

Courtesy Amaldi

PIMMS (CERN/TERA) Synchrotron Hall @ CNAO

2012

Courtesy Amaldi

Ugo Amaldi/TERA

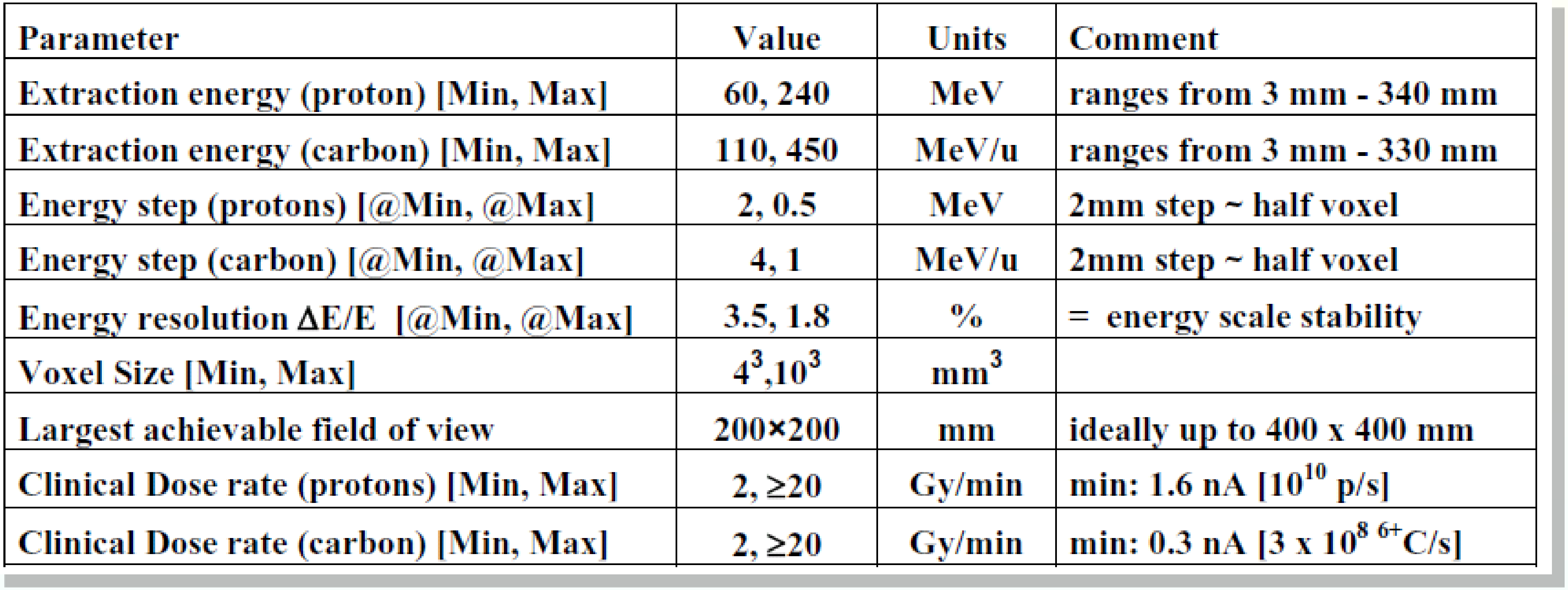
Physics Challenges

Better conventional technologies

Conventional Accelerator Technology

- **Cyclotrons**
  - Fixed energy extraction, difficult for Carbon at full energy (equivalent to 1.2 GeV/c protons)
- **Synchrotrons**
  - Flexible, but too slow?
- **FFAG**
  - Flexible, rapid cycling (fixed field), variable energy … but … new technology
    - Scaling (Mori) & non-Scaling (Johnstone, PAMELA)

Main requirements on the accelerator

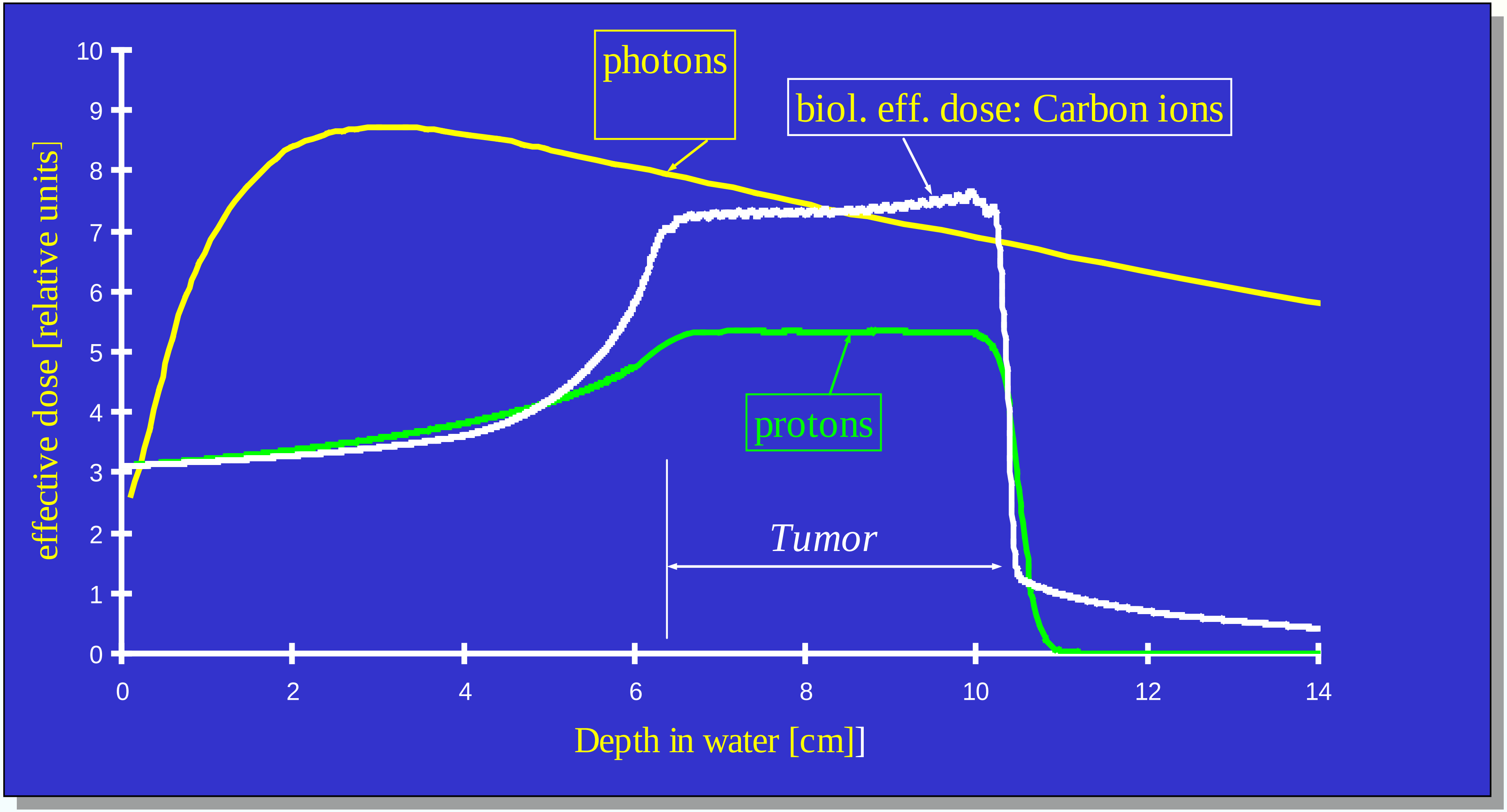


Parameter	Value	Units	Comment
Extraction energy (proton) [Min, Max]	60, 240	MeV	ranges from 3 mm - 340 mm
Extraction energy (carbon) [Min, Max]	110, 450	MeV/u	ranges from 3 mm - 330 mm
Energy step (protons) [@Min, @Max]	2, 0.5	MeV	2mm step ~ half voxel
Energy step (carbon) [@Min, @Max]	4, 1	MeV/u	2mm step ~ half voxel
Energy resolution ΔE/E [@Min, @Max]	3.5, 1.8	%	= energy scale stability
Voxel Size [Min, Max]	4^3,10^3	mm^3	
Largest achievable field of view	200×200	mm	ideally up to 400 x 400 mm
Clinical Dose rate (protons) [Min, Max]	2, ≥20	Gy/min	min: 1.6 nA [10^{10} p/s]
Clinical Dose rate (carbon) [Min, Max]	2, ≥20	Gy/min	min: 0.3 nA [3 x 10^8 $^{6+}$C/s]

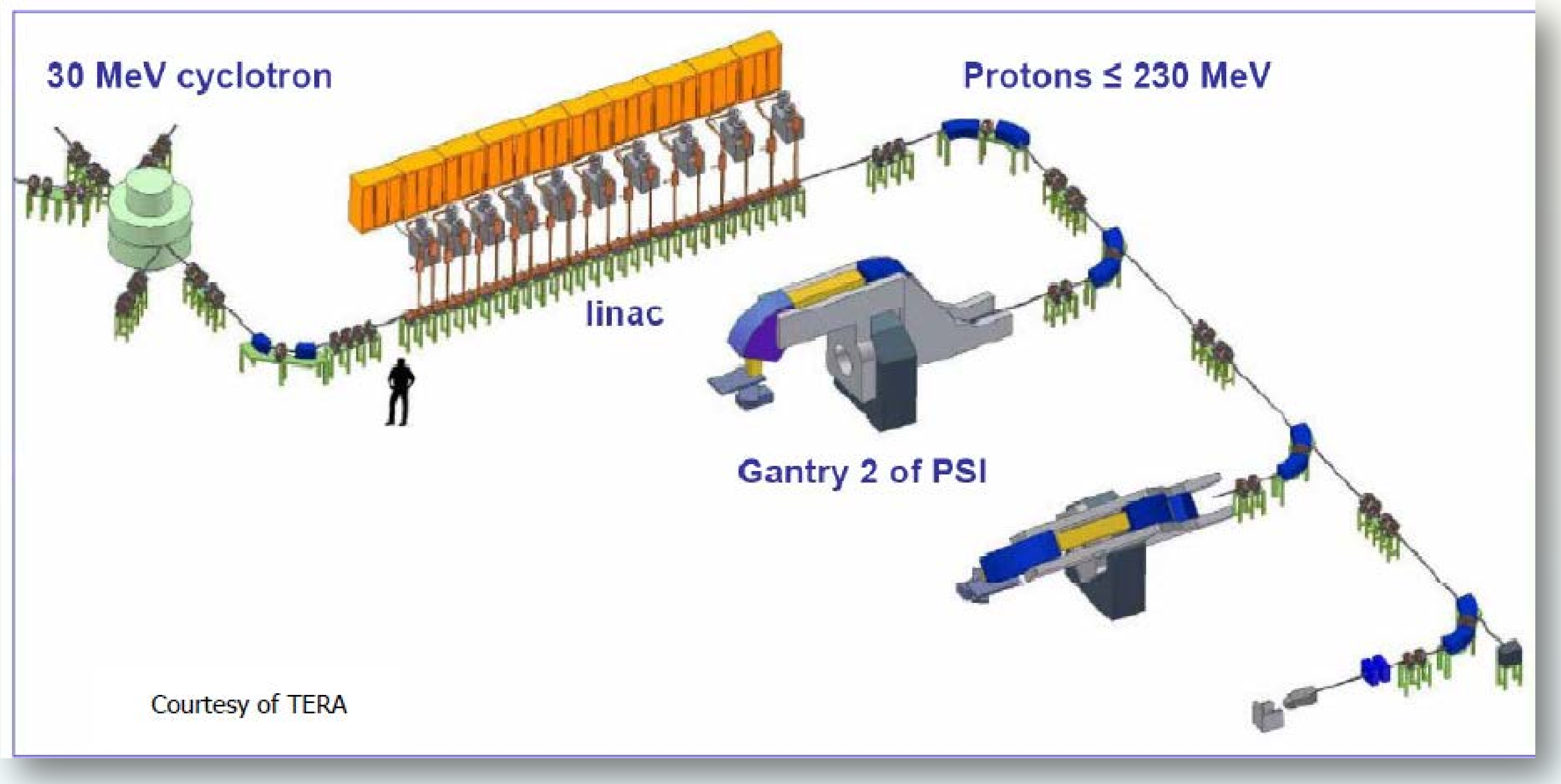
- **Question**
  - What would clinicians ideally like?

    i.e. without taking into account current limitations
  - Could technology deliver this?

Photons, Protons and Carbon

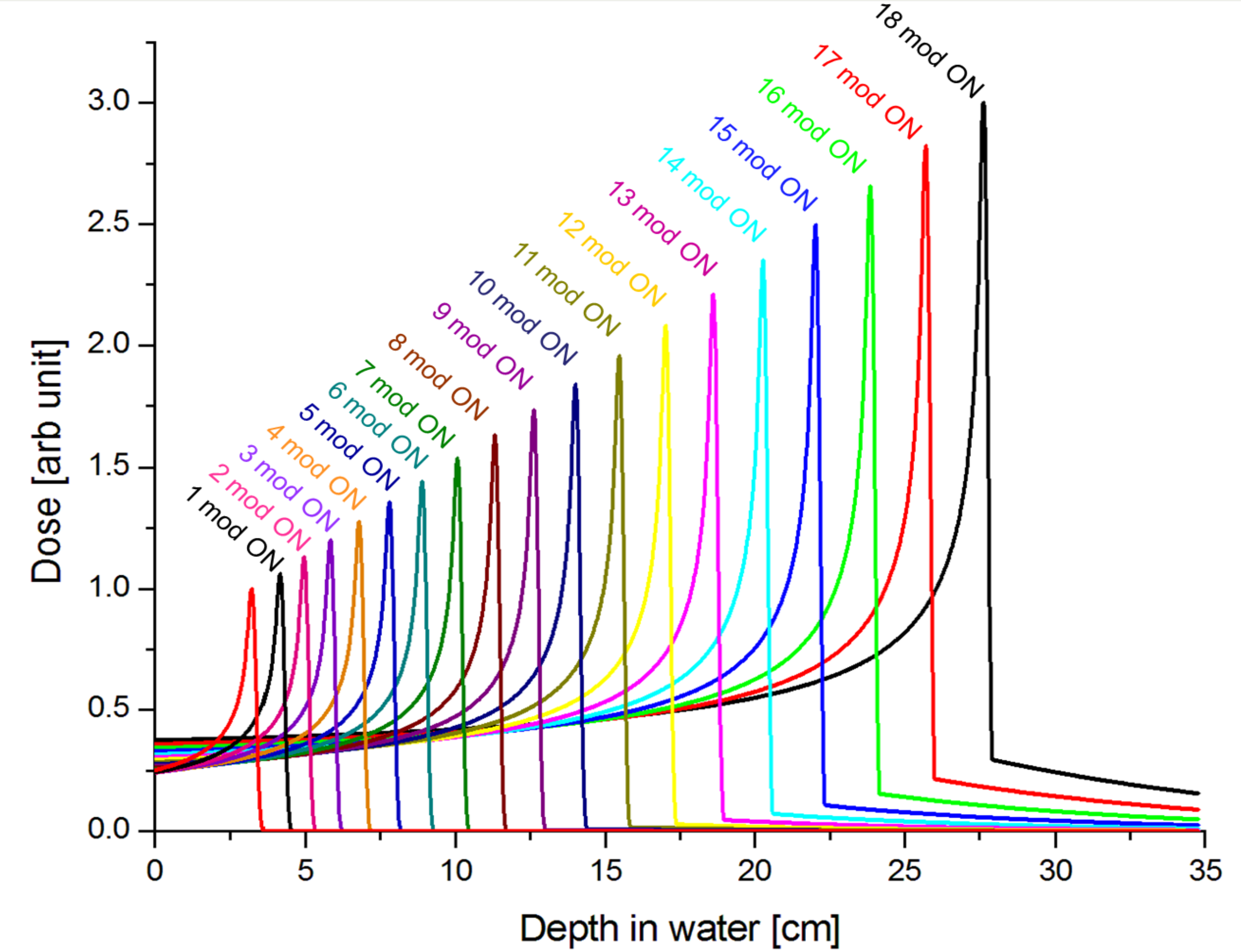


Some Accelerator Ideas; Novel technologies



Cyclinac (Italy)

Fast active energy modulation



Active Energy Modulation

+

3D feedback system

⬇

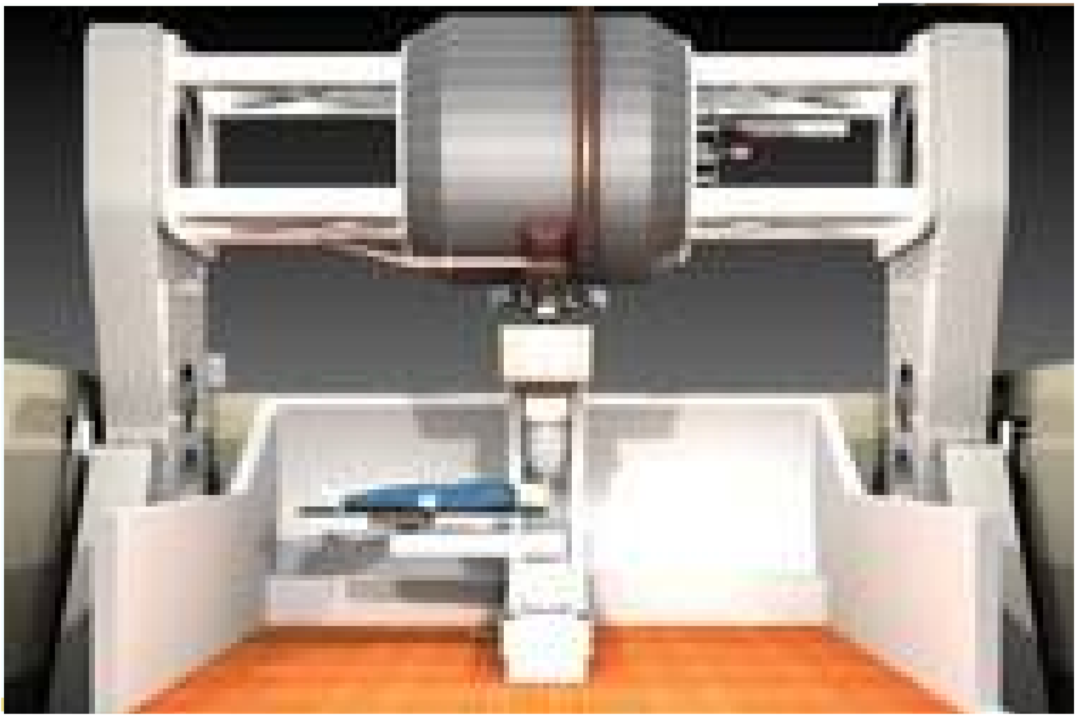
Treatment of MOVING ORGANS

Compact Cyclotron: Mevion

Compact s/c

Cyclotron (10 Tesla)

Mounted on gantry (25T)

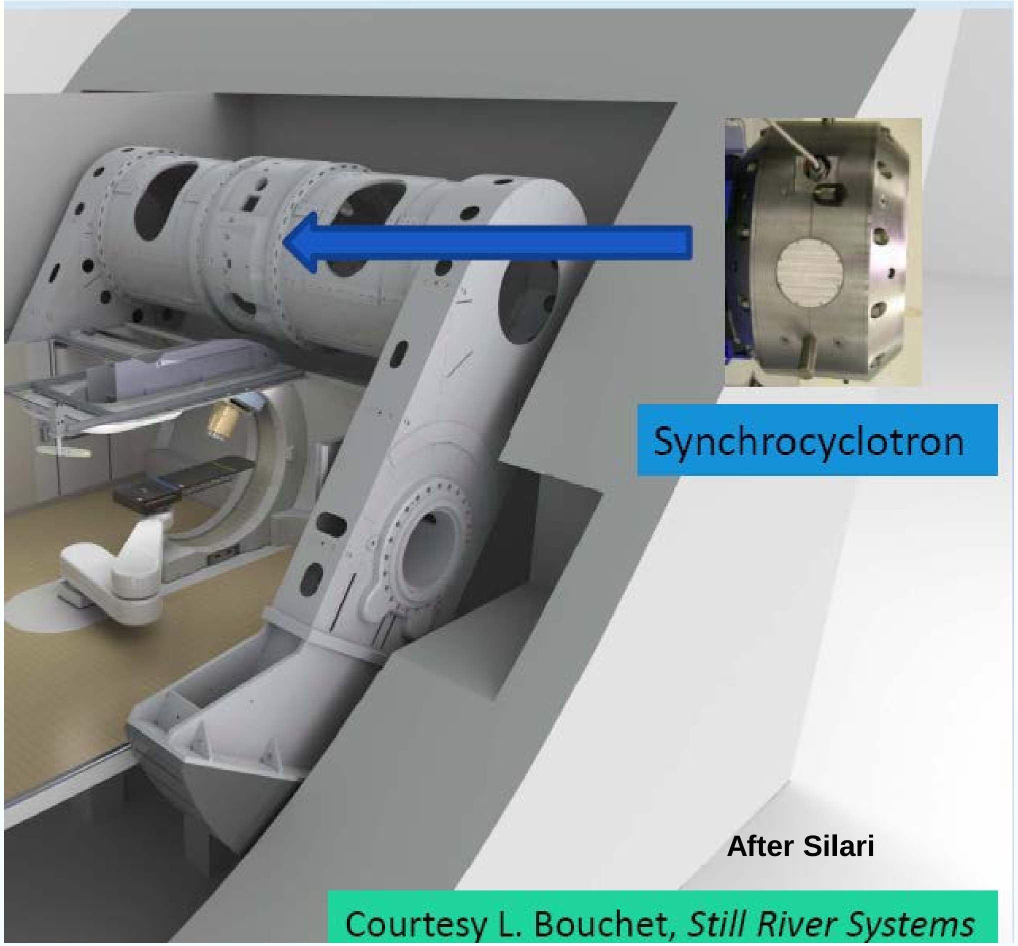


Single Room system

- **Expensive to operate**
- **Neutron Background?**

ne Still River

Compact Cyclotron

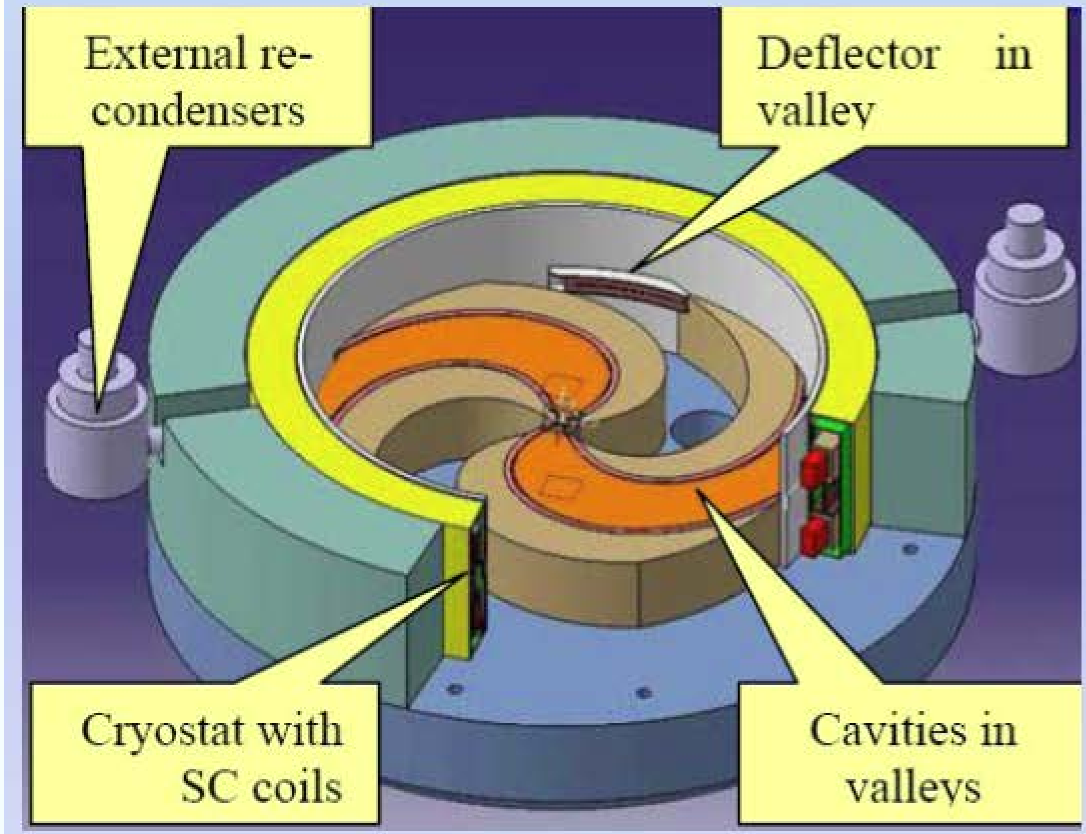


After Silari

Courtesy L. Bouchet, *Still River Systems*

Still River

The IBA 400 MeV/u cyclotron

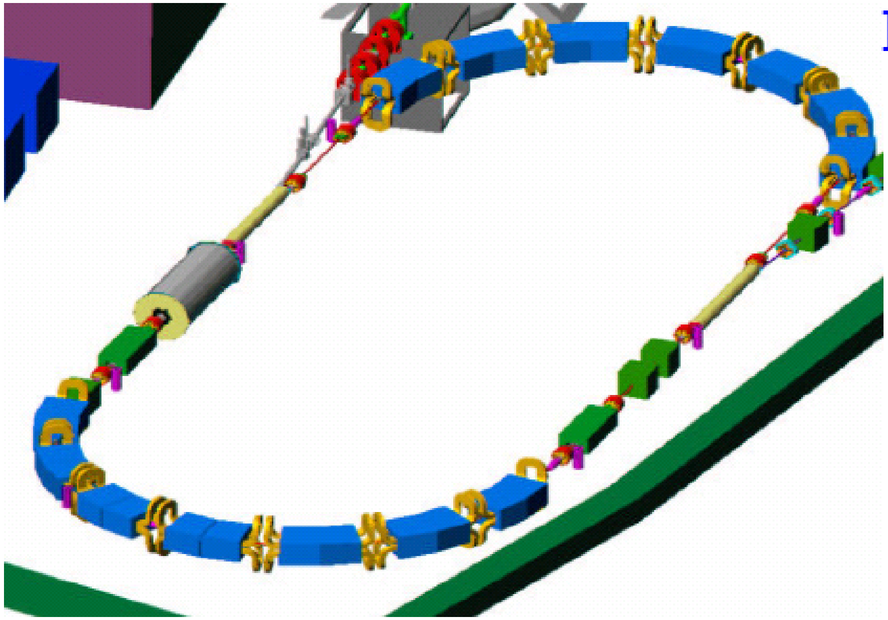


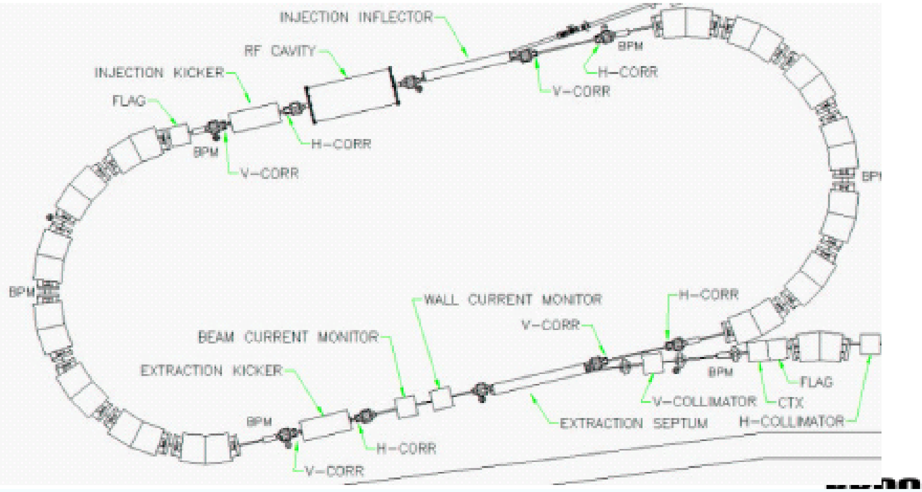
Courtesy Y. Jongen, *IBA*

- Maximum energy: 400 MeV/u, adjustable externally by ESS
- Superconducting magnet. Hill field 4.5 T
- Cooling by helium loop, with 4 external recondensers

After Silari

BNL RCS Design





Racetrack design

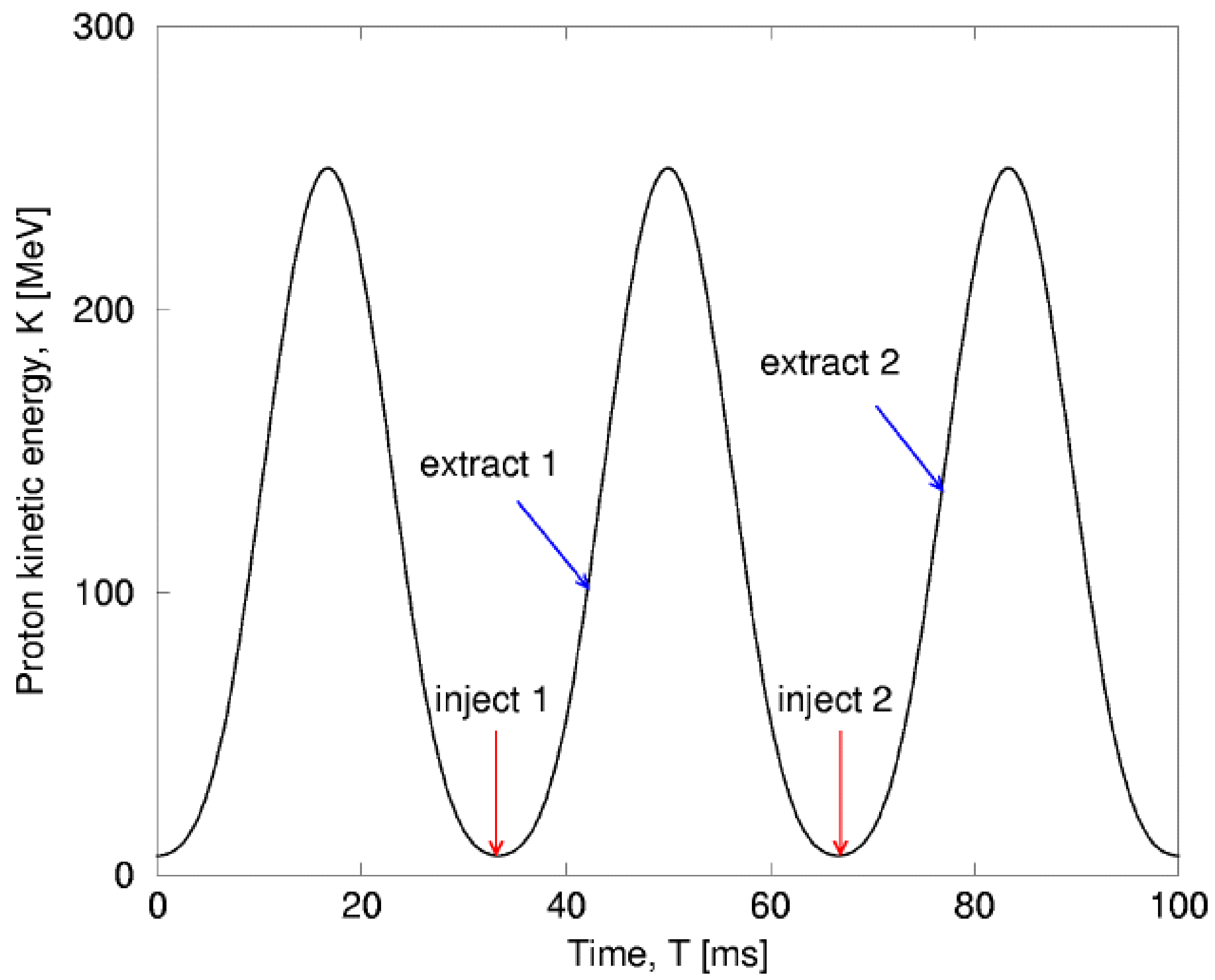
- 2 super-periods
- Strong focusing minimizes the beam size
- FODO/combined function mags with edge focusing
- 2x7.6m straight sections, zero dispersion, tune quads
- Working tunes: 3.38, 3.36

Compact footprint

- Circumference: 27.8 m
- Area: 37 sq m

Peggs/BNL

Rapid Cycling Synchrotrons



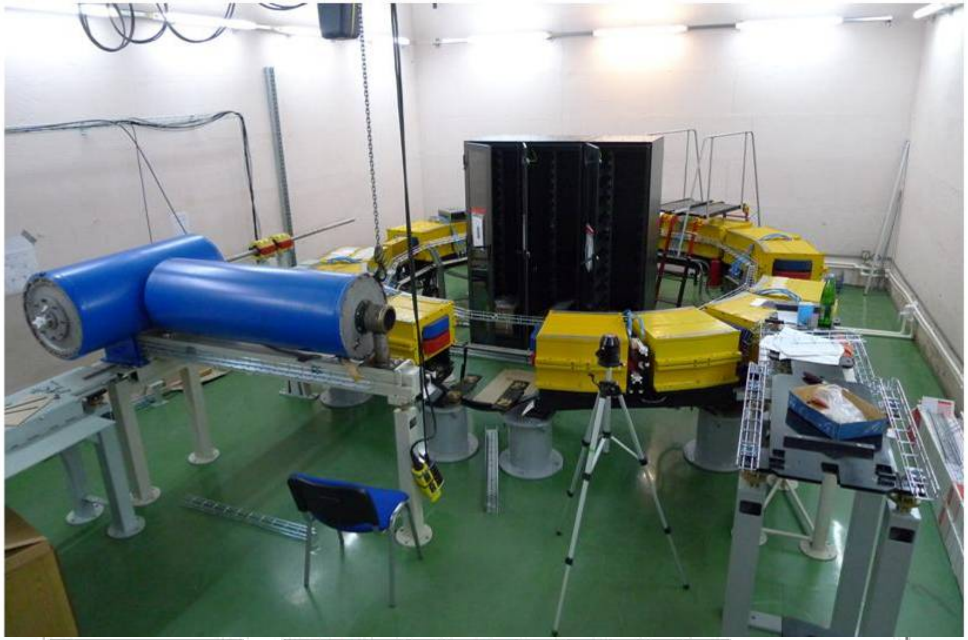
Inject in one turn, extract on any single turn (any energy)

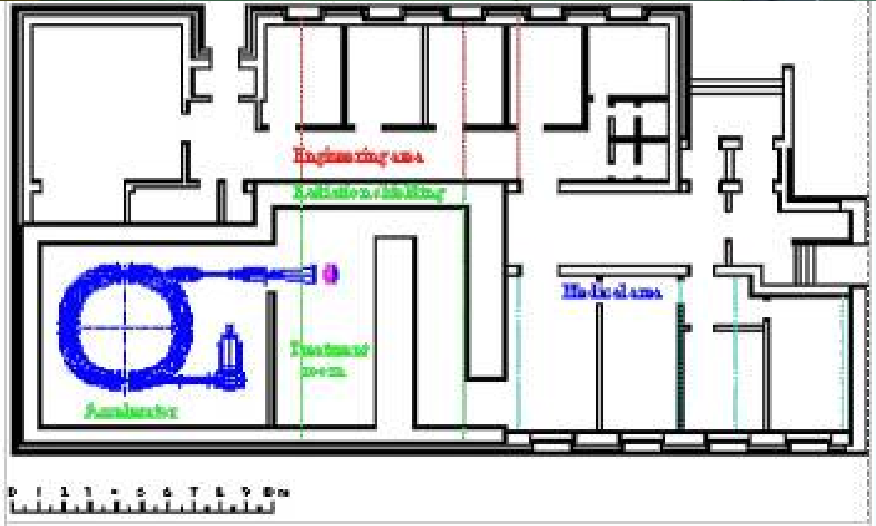
Peggs/BNL

Compact Synchrotron

5 meter diameter Synchrotron

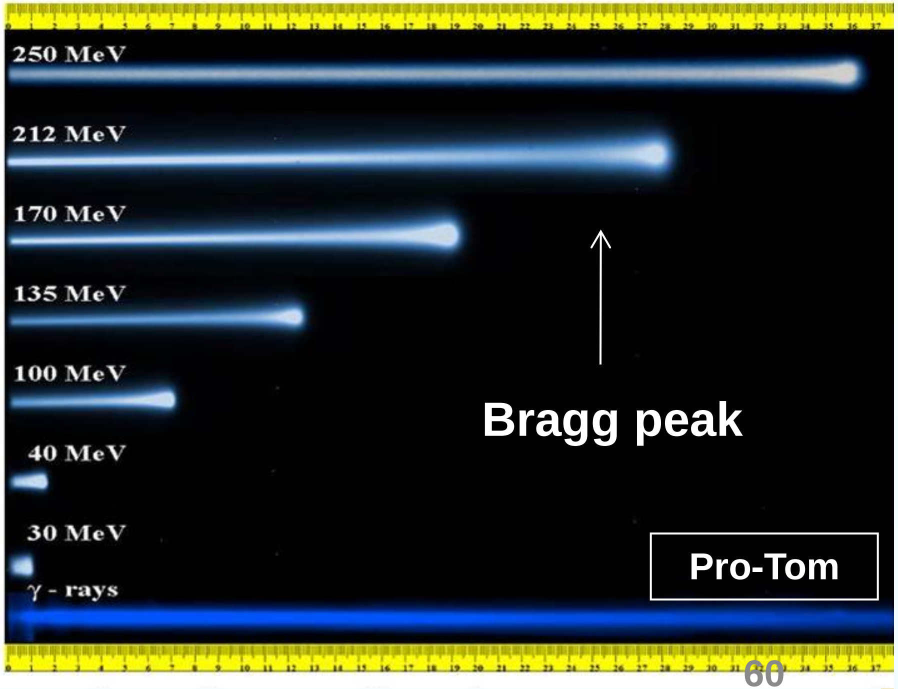
Lebedev Physics Institute
Commercialized
by the Company PRO-TOM
In collaboration with MIT/Bates





Typical layout for a single room treatment facility

Protons have been accelerated



The FFAG

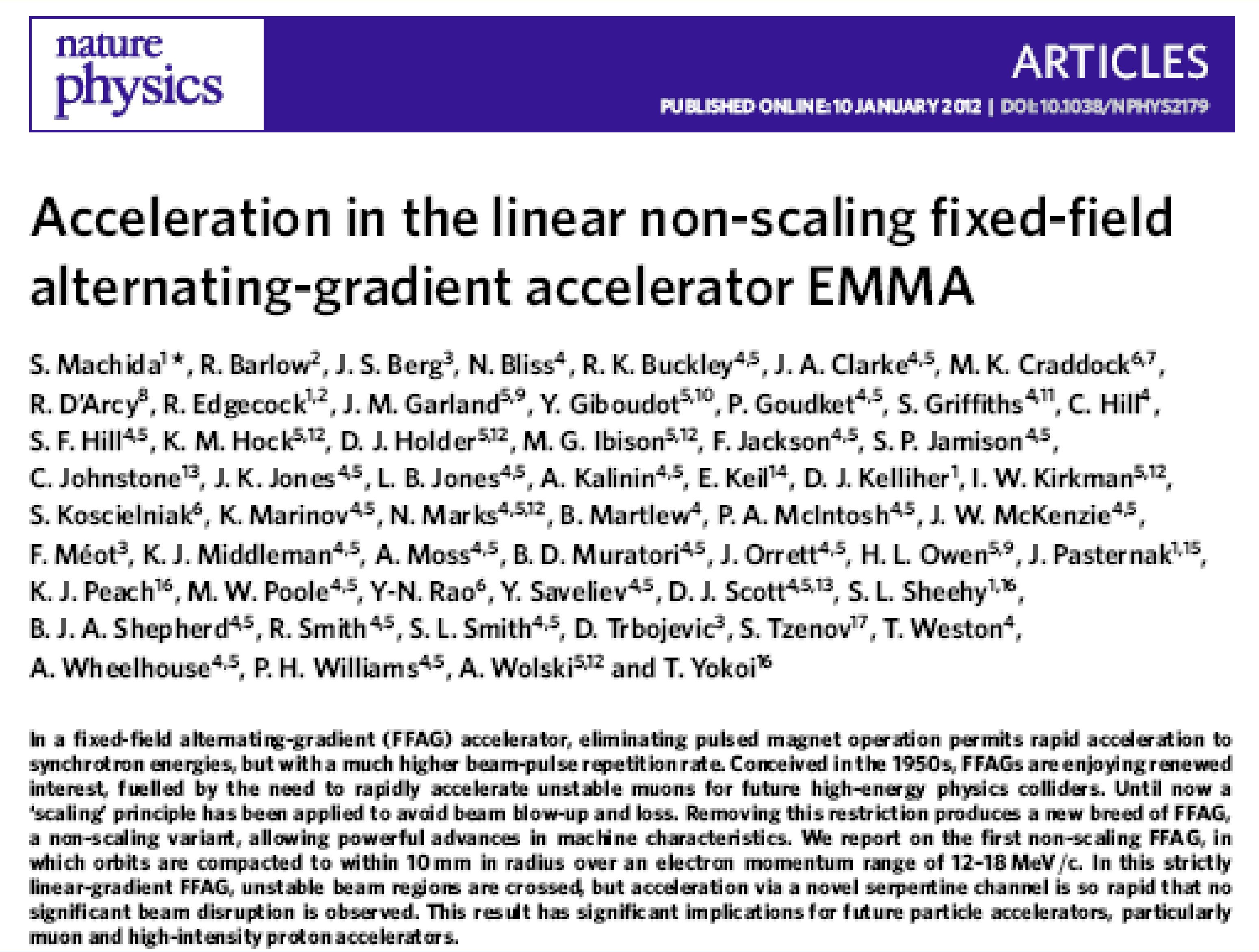
- ***Should*** **combine the advantages of FFAGs**
  - **Fixed Field**
    - **Fast cycling (limited essentially by RF)**
    - **Simpler, cheaper power supplies**
    - **No eddy-currents**
    - **High intensity (pulsed, ~continuous)**
    - **Low beam losses**
    - **Easier maintenance and operation**
    - **Lower stresses**
  - **Strong Focussing**
    - **Magnetic ring**
    - **Variable energy extraction**
    - **Higher energies (than cyclotrons)**
    - **Different ion species possible**
- **with relative ease of construction**

Declaration
of
Interest

This is what I do

Does it work?

YES!



nature physics

ARTICLES

PUBLISHED ONLINE: 10 JANUARY 2012 | DOI: 10.1038/NPHYS2179

Acceleration in the linear non-scaling fixed-field alternating-gradient accelerator EMMA

S. Machida[1]*, R. Barlow[2], J. S. Berg[3], N. Bliss[4], R. K. Buckley[4,5], J. A. Clarke[4,5], M. K. Craddock[6,7], R. D'Arcy[8], R. Edgecock[1,2], J. M. Garland[5,9], Y. Giboudot[5,10], P. Goudket[4,5], S. Griffiths[4,11], C. Hill[4], S. F. Hill[4,5], K. M. Hock[5,12], D. J. Holder[5,12], M. G. Ibison[5,12], F. Jackson[4,5], S. P. Jamison[4,5], C. Johnstone[13], J. K. Jones[4,5], L. B. Jones[4,5], A. Kalinin[4,5], E. Keil[14], D. J. Kelliher[1], I. W. Kirkman[5,12], S. Koscielniak[6], K. Marinov[4,5], N. Marks[4,5,12], B. Martlew[4], P. A. McIntosh[4,5], J. W. McKenzie[4,5], F. Méot[3], K. J. Middleman[4,5], A. Moss[4,5], B. D. Muratori[4,5], J. Orrett[4,5], H. L. Owen[5,9], J. Pasternak[1,15], K. J. Peach[16], M. W. Poole[4,5], Y-N. Rao[6], Y. Saveliev[4,5], D. J. Scott[4,5,13], S. L. Sheehy[1,16], B. J. A. Shepherd[4,5], R. Smith[4,5], S. L. Smith[4,5], D. Trbojevic[3], S. Tzenov[17], T. Weston[4], A. Wheelhouse[4,5], P. H. Williams[4,5], A. Wolski[5,12] and T. Yokoi[16]

In a fixed-field alternating-gradient (FFAG) accelerator, eliminating pulsed magnet operation permits rapid acceleration to synchrotron energies, but with a much higher beam-pulse repetition rate. Conceived in the 1950s, FFAGs are enjoying renewed interest, fuelled by the need to rapidly accelerate unstable muons for future high-energy physics colliders. Until now a 'scaling' principle has been applied to avoid beam blow-up and loss. Removing this restriction produces a new breed of FFAG, a non-scaling variant, allowing powerful advances in machine characteristics. We report on the first non-scaling FFAG, in which orbits are compacted to within 10 mm in radius over an electron momentum range of 12–18 MeV/c. In this strictly linear-gradient FFAG, unstable beam regions are crossed, but acceleration via a novel serpentine channel is so rapid that no significant beam disruption is observed. This result has significant implications for future particle accelerators, particularly muon and high-intensity proton accelerators.

S. Machida et al, Nature Physics Nature Physics, 8:243–247(2012) doi:10.1038/nphys2179

EMMA

The World's First non-Scaling FFAG

nature physics

ARTICLES

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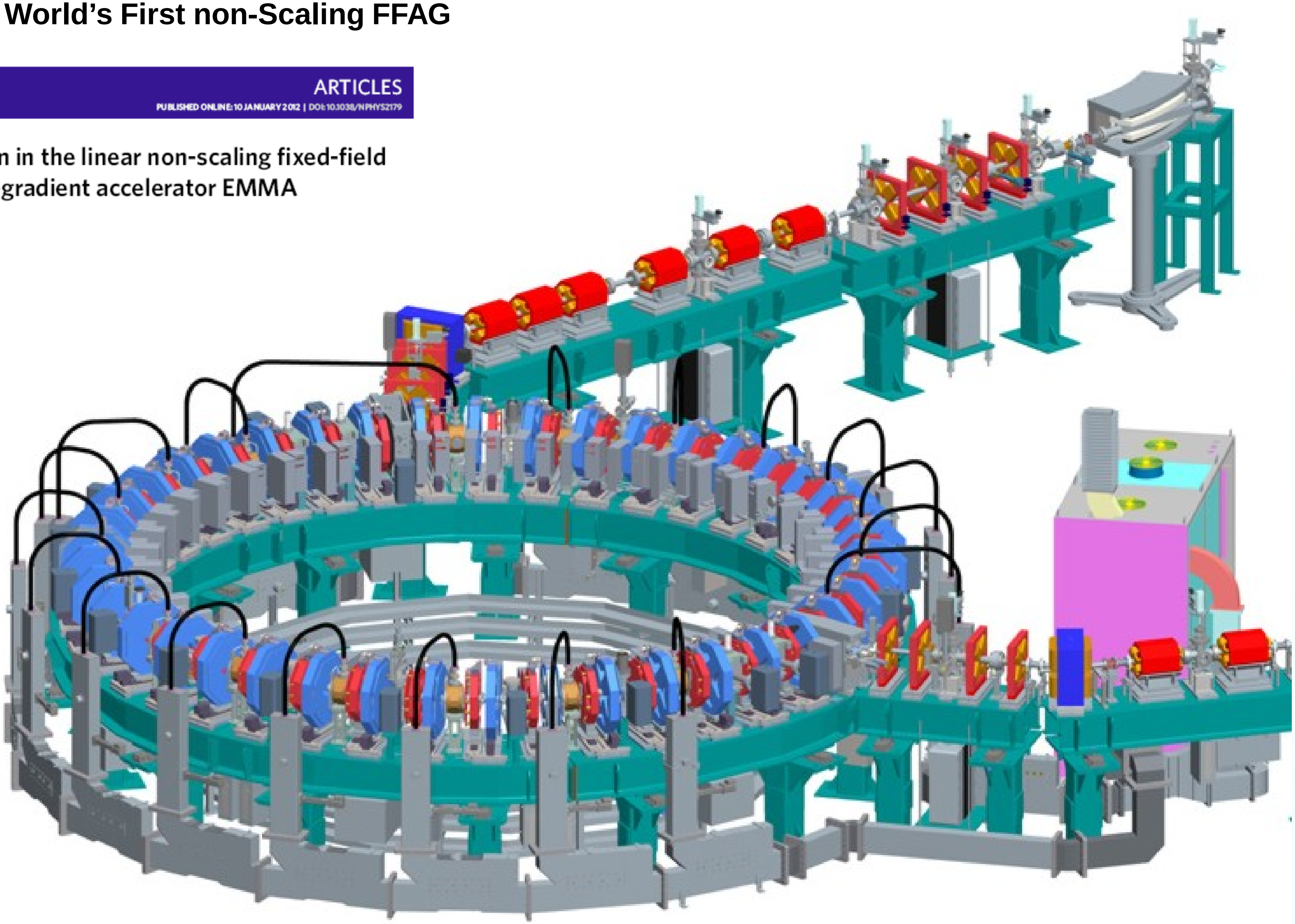
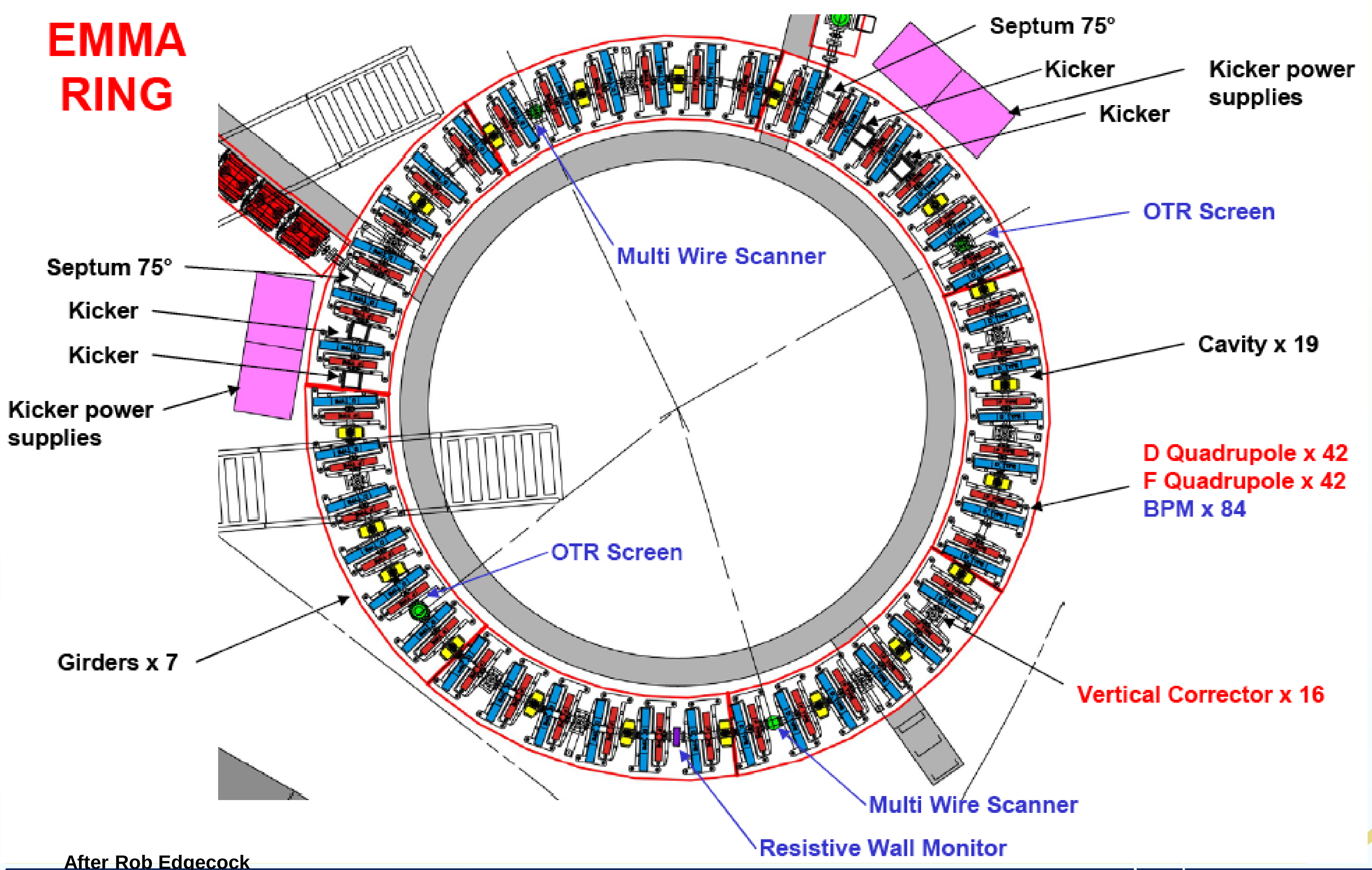
Acceleration in the linear non-scaling fixed-field alternating-gradient accelerator EMMA

S Machida *et al*



EMMA lattice

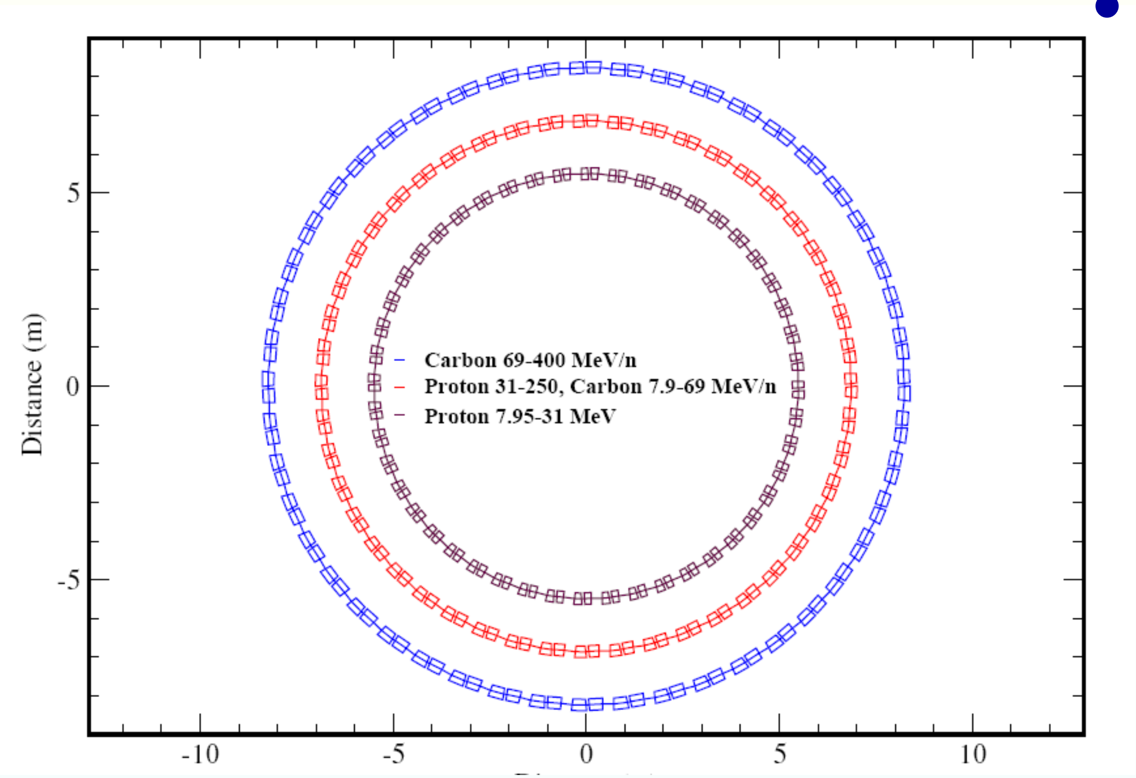


After Rob Edgecock

PAMELA

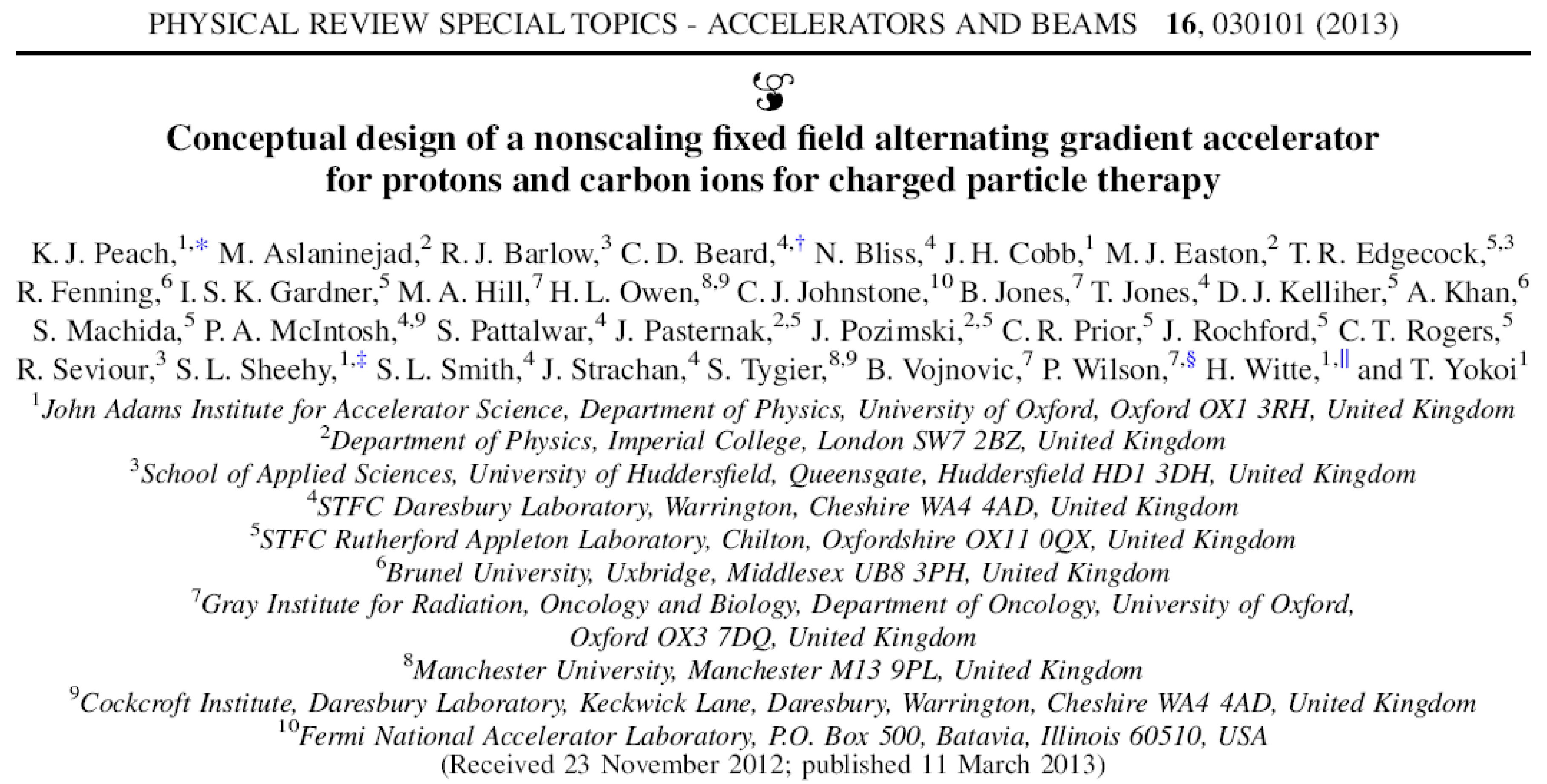
EMMA-like ns-FFAG machine

Keil, Sessler & Trbojevic



- Issues
  - Injection & extraction
  - Acceleration
  - Alignment

Application to Cancer?



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **16**, 030101 (2013)

Conceptual design of a nonscaling fixed field alternating gradient accelerator for protons and carbon ions for charged particle therapy

K. J. Peach,[1,*] M. Aslaninejad,[2] R. J. Barlow,[3] C. D. Beard,[4,†] N. Bliss,[4] J. H. Cobb,[1] M. J. Easton,[2] T. R. Edgecock,[5,3] R. Fenning,[6] I. S. K. Gardner,[5] M. A. Hill,[7] H. L. Owen,[8,9] C. J. Johnstone,[10] B. Jones,[7] T. Jones,[4] D. J. Kelliher,[5] A. Khan,[6] S. Machida,[5] P. A. McIntosh,[4,9] S. Pattalwar,[4] J. Pasternak,[2,5] J. Pozimski,[2,5] C. R. Prior,[5] J. Rochford,[5] C. T. Rogers,[5] R. Seviour,[3] S. L. Sheehy,[1,‡] S. L. Smith,[4] J. Strachan,[4] S. Tygier,[8,9] B. Vojnovic,[7] P. Wilson,[7,§] H. Witte,[1,||] and T. Yokoi[1]

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[4] *STFC Daresbury Laboratory, Warrington, Cheshire WA4 4AD, United Kingdom*
[5] *STFC Rutherford Appleton Laboratory, Chilton, Oxfordshire OX11 0QX, United Kingdom*
[6] *Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom*
[7] *Gray Institute for Radiation, Oncology and Biology, Department of Oncology, University of Oxford, Oxford OX3 7DQ, United Kingdom*
[8] *Manchester University, Manchester M13 9PL, United Kingdom*
[9] *Cockcroft Institute, Daresbury Laboratory, Keckwick Lane, Daresbury, Warrington, Cheshire WA4 4AD, United Kingdom*
[10] *Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510, USA*

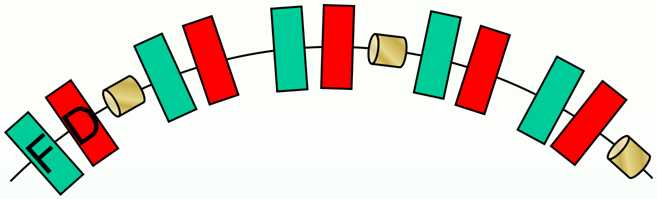
(Received 23 November 2012; published 11 March 2013)

From EMMA to PAMELA

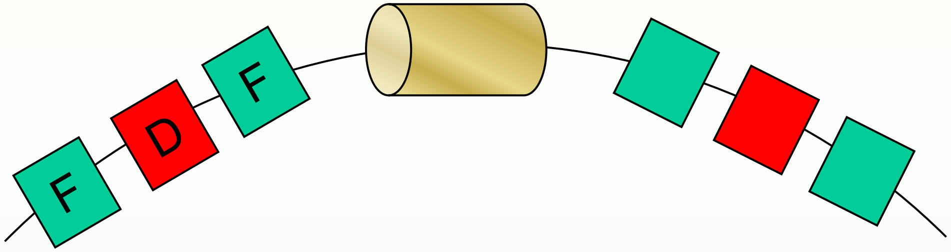
From Doublet to Triplet

From **EMMA** to **PAMELA**

The EMMA lattice



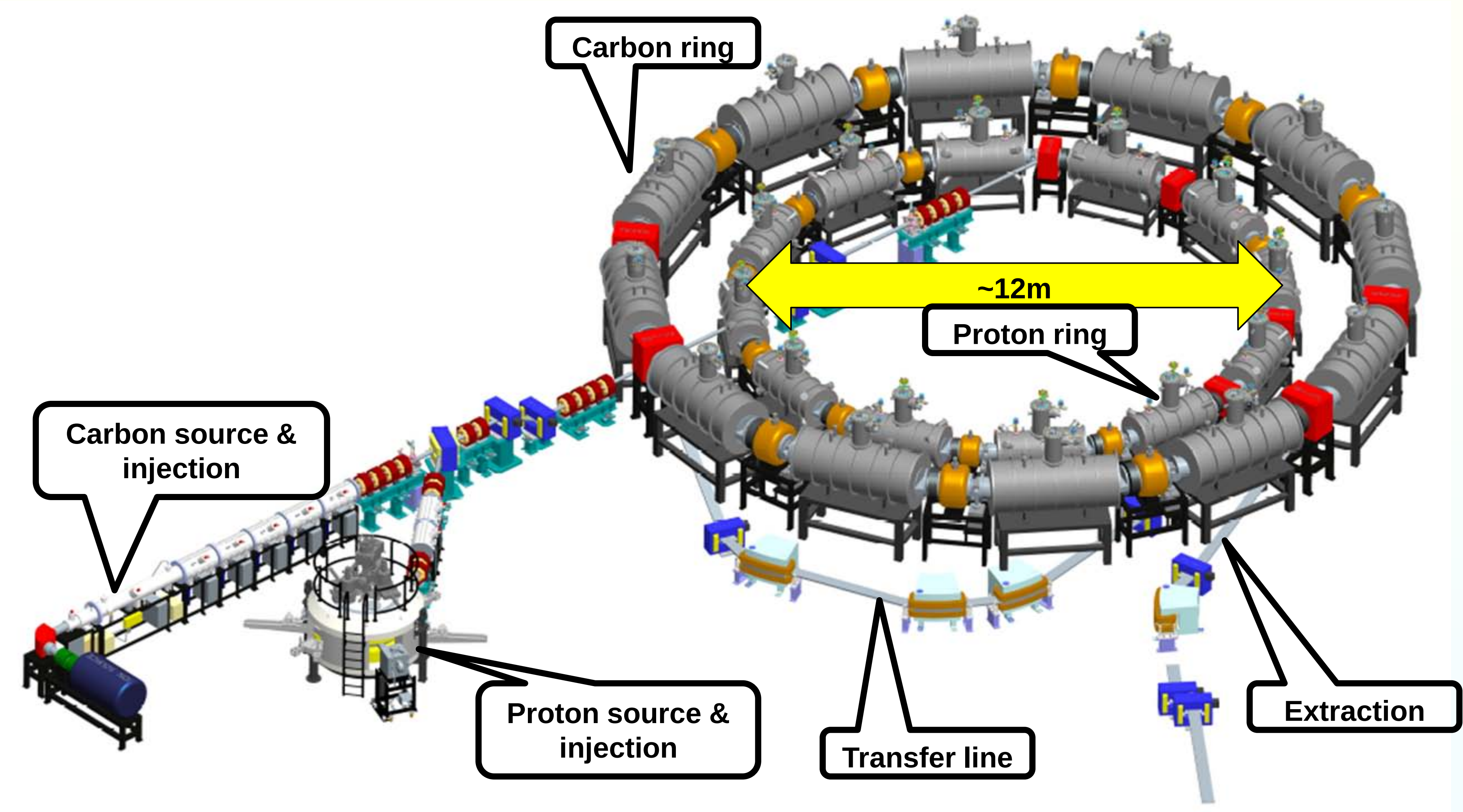
The PAMELA lattice



- Doublet structure
  - Focus and Defocus
- Dense lattice
  - Little space between magnets
- Lots of RF Acceleration
  - Almost every other cell

- Triplet structure
  - Focus, Defocus, Focus
- Less Dense lattice
  - Long straight sections
- Less of RF Acceleration
  - Larger cavities
  - Lower frequencies
- Larger radius

Overview


Carbon ring

~12m

Proton ring

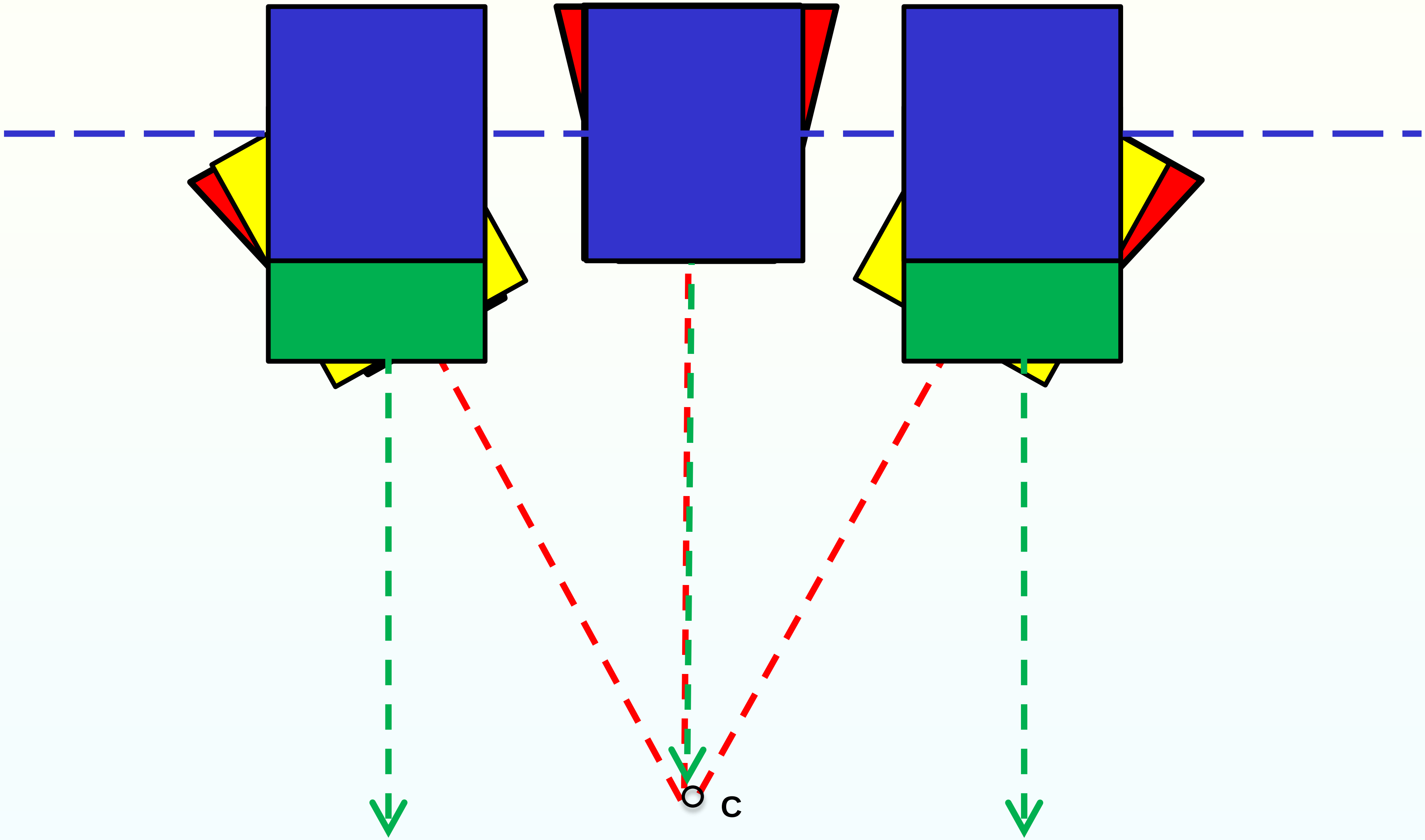
Carbon source & injection

Proton source & injection

Transfer line

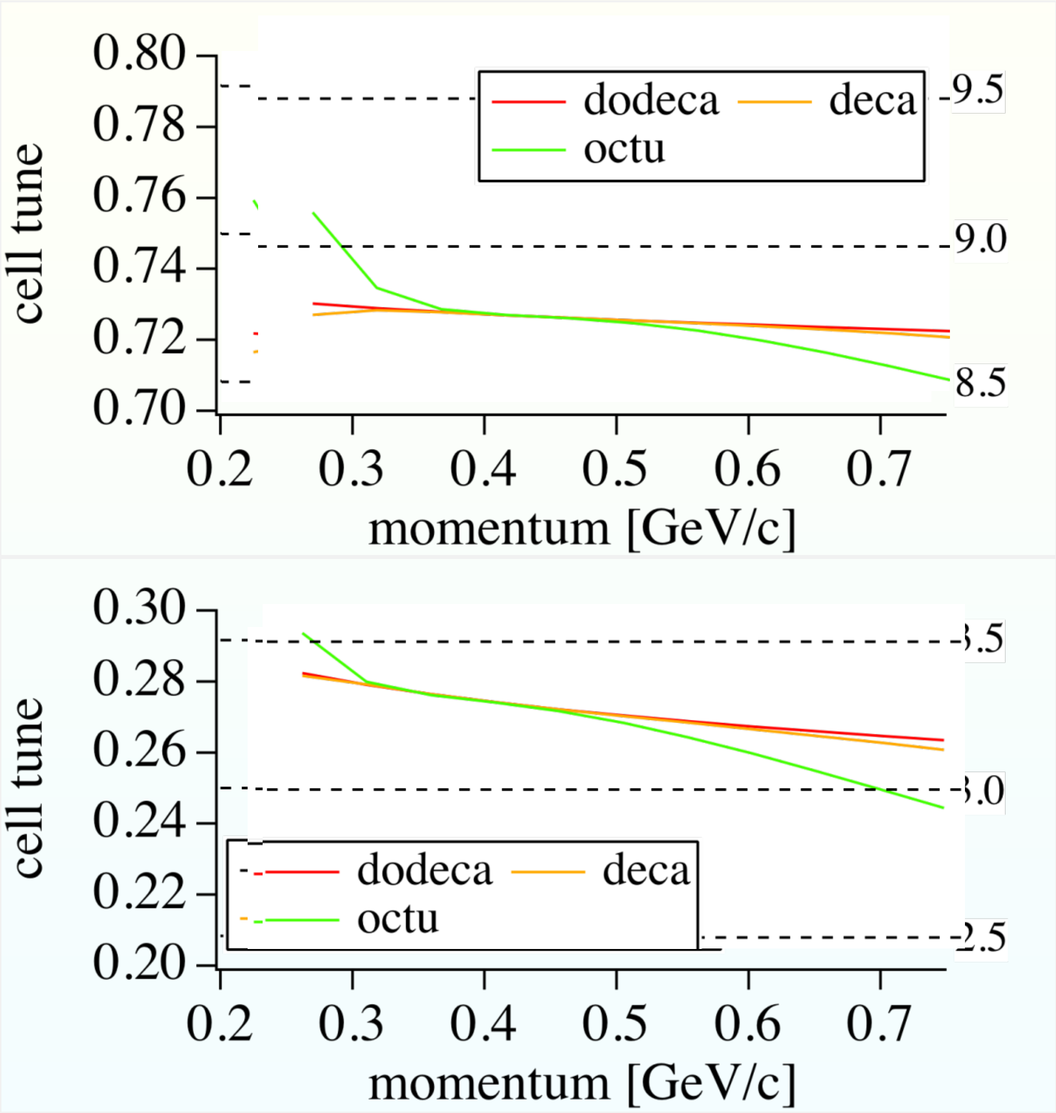
Extraction

From scaling to PAMELA

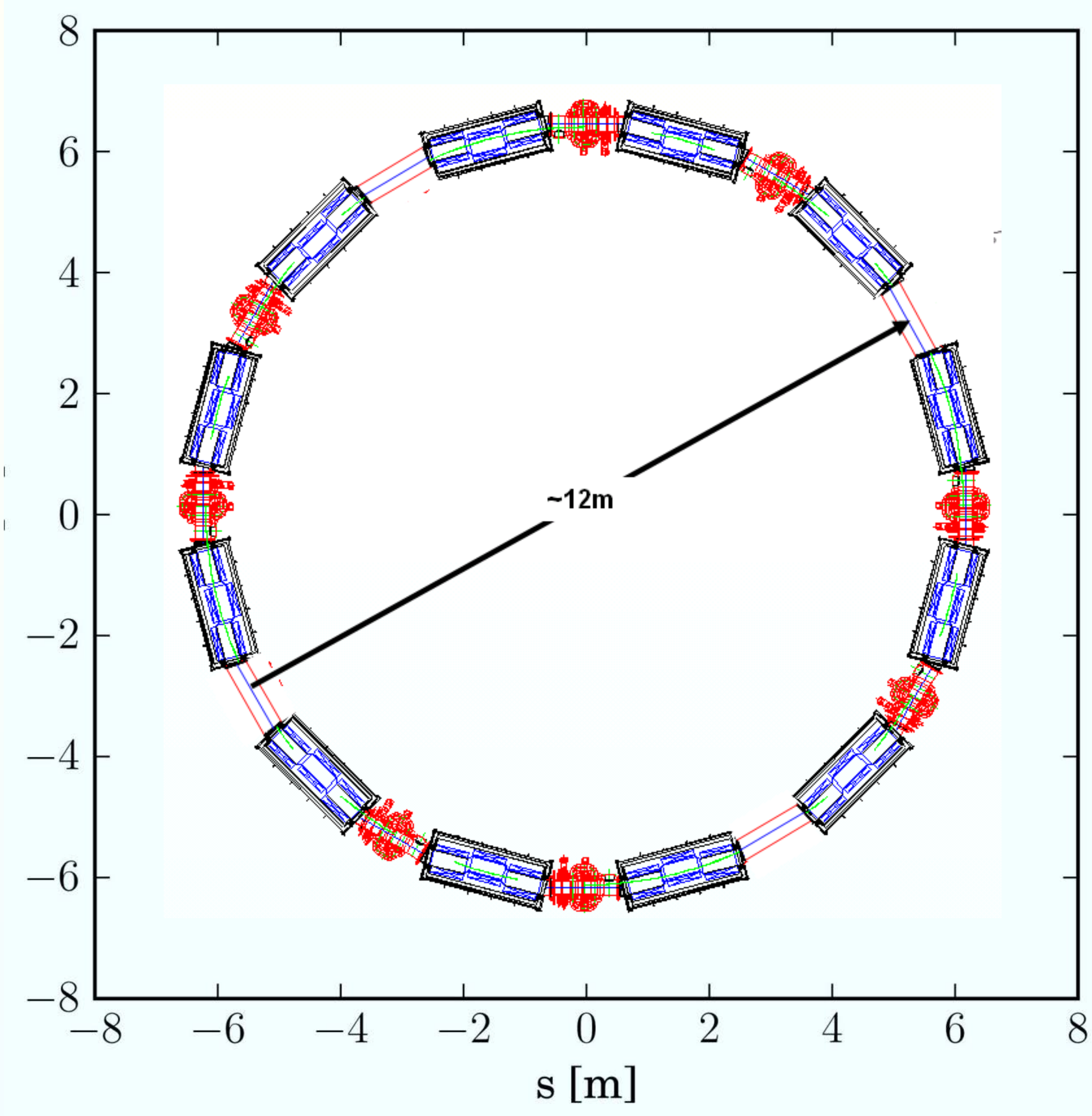


Scaling restoration

Rectangular
& parallel



PAMELA Layout



Double-Helix Principle

Current density:

Helix 1

$$x: \quad \frac{Jx}{J_0} = -R\sin(\Theta)$$

$$y: \quad \frac{Jy}{J_0} = R\cos(\Theta)$$

$$z: \quad \frac{Jz}{J_0} = \frac{nR}{\tan\alpha}\cos(n\Theta)$$

Helix 2

$$\frac{Jx}{J_0} = R\sin(\Theta)$$

$$\frac{Jy}{J_0} = -R\cos(\Theta)$$

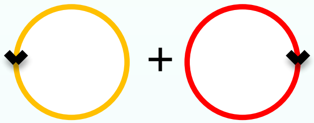
$$\frac{Jz}{J_0} = -\frac{nR}{\tan(-\alpha)}\cos(n\Theta)$$

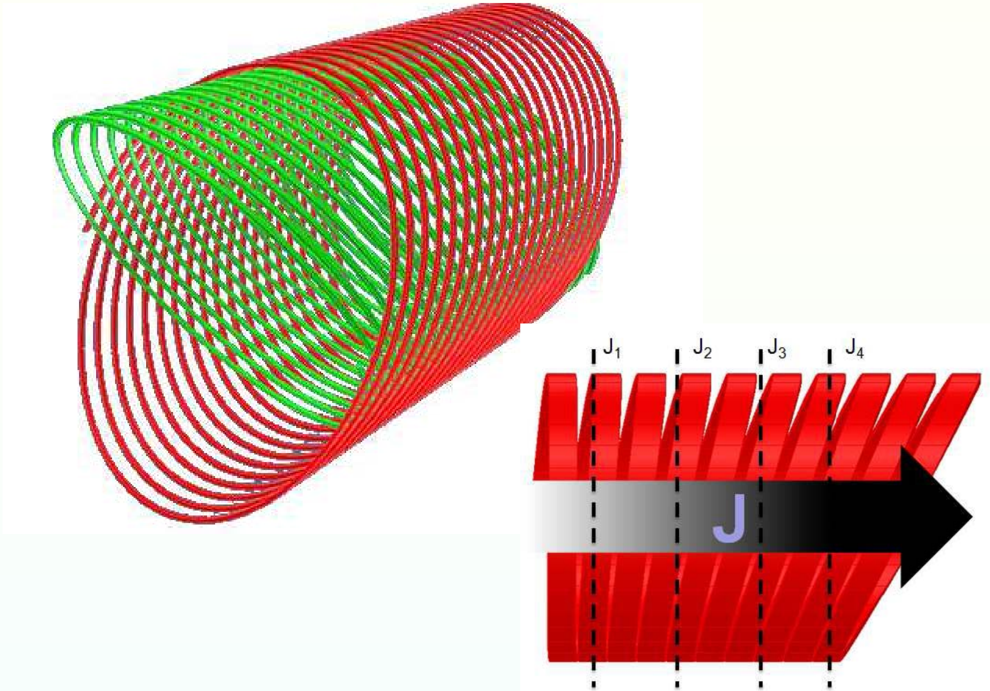
Double-Helix

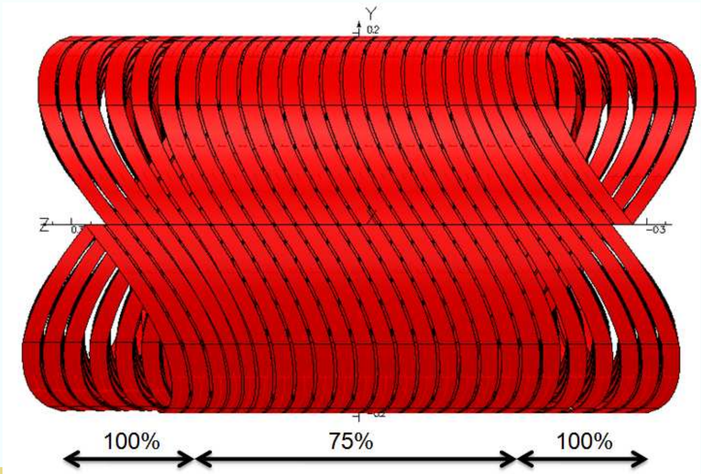
$$Jx = 0$$

$$Jy = 0$$

$$Jz = const\cos(n\Theta)$$

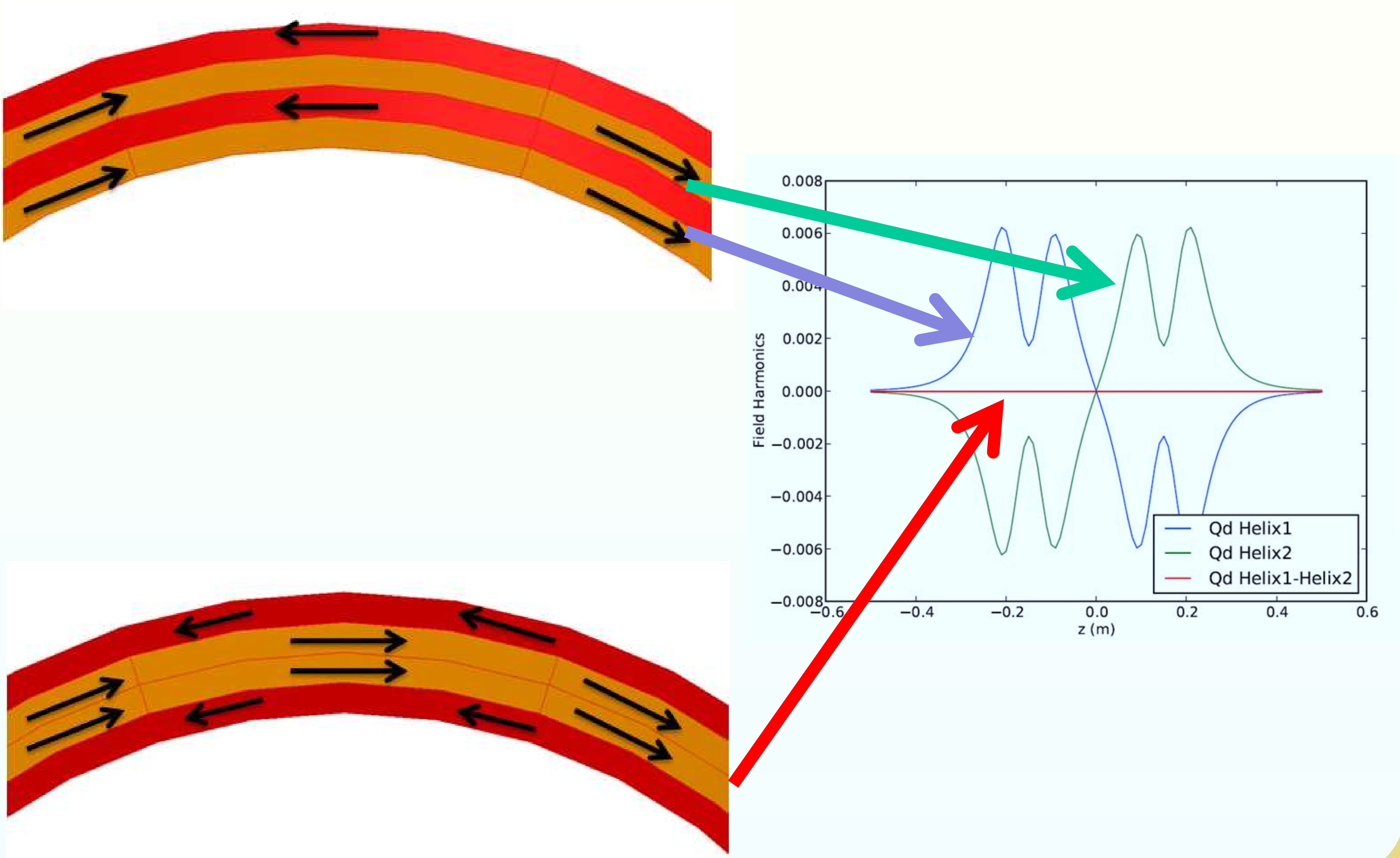






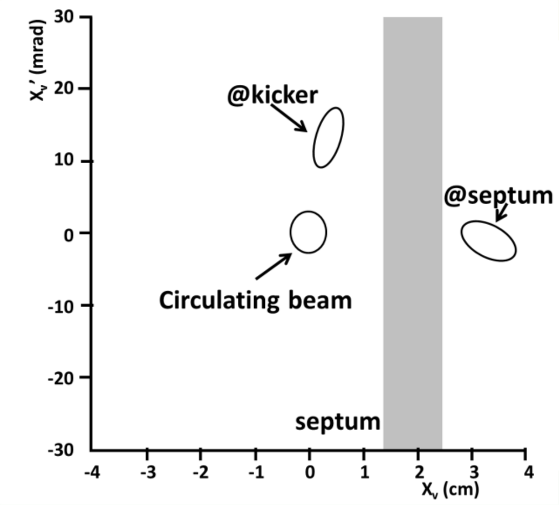
Double-helix coil:
Smart way of creating a cosine-theta magnet
Main advantage for PAMELA: **No coil end problem**

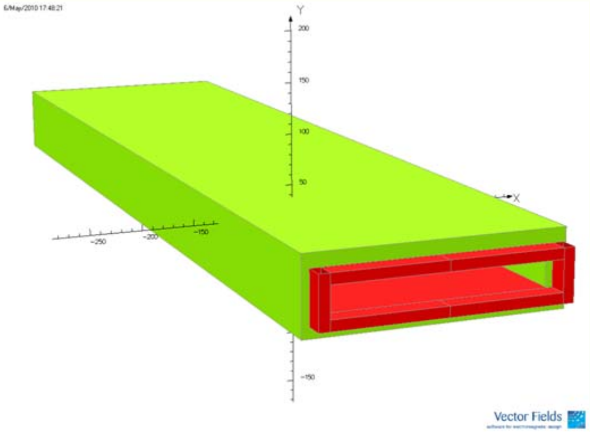
High field quality

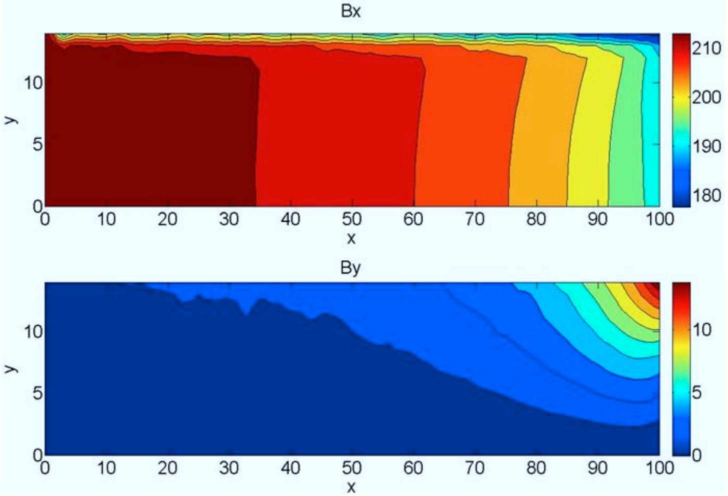


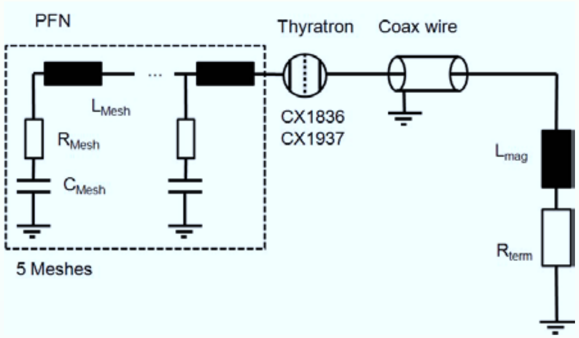
Patent GB 0920299.5

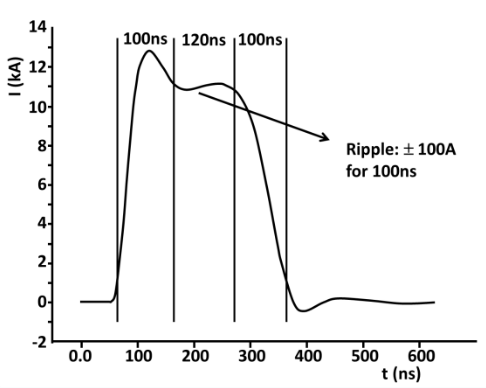
Kicker Magnets



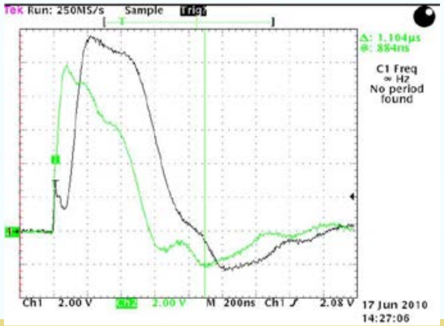


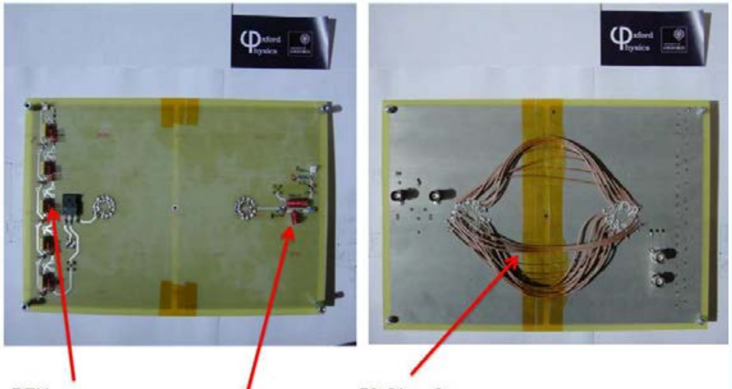






Ripple: ± 100A for 100ns



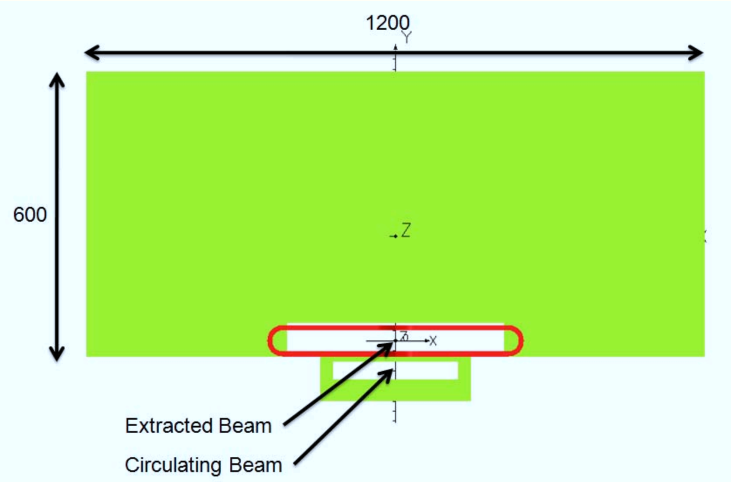


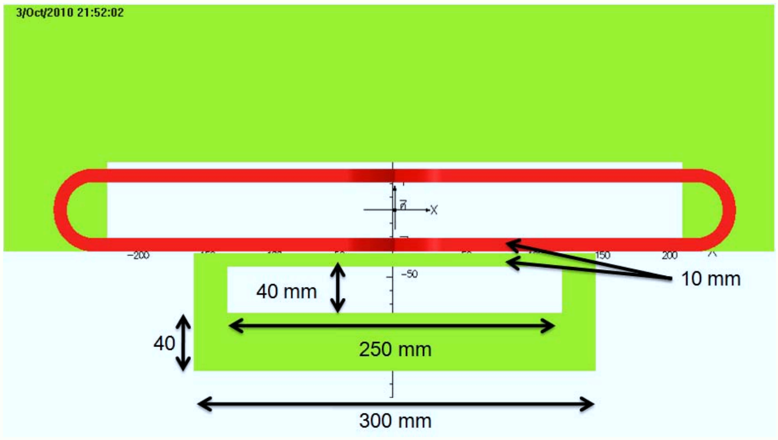
PFN

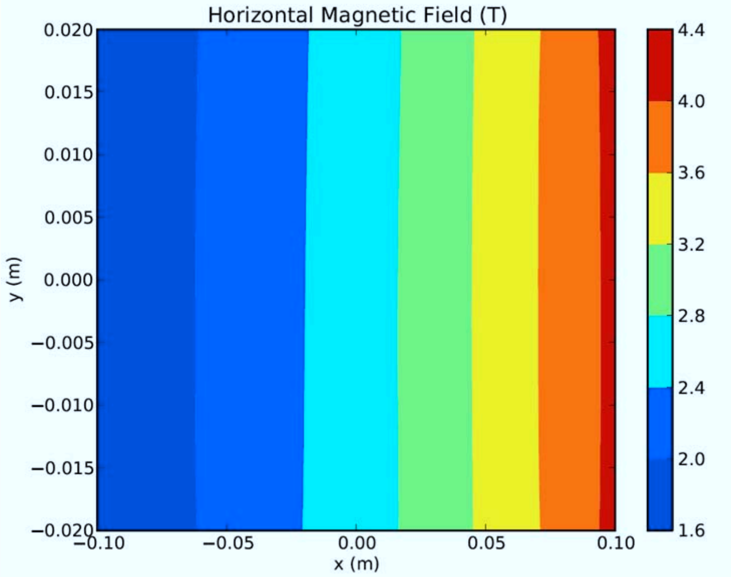
Compensation Network

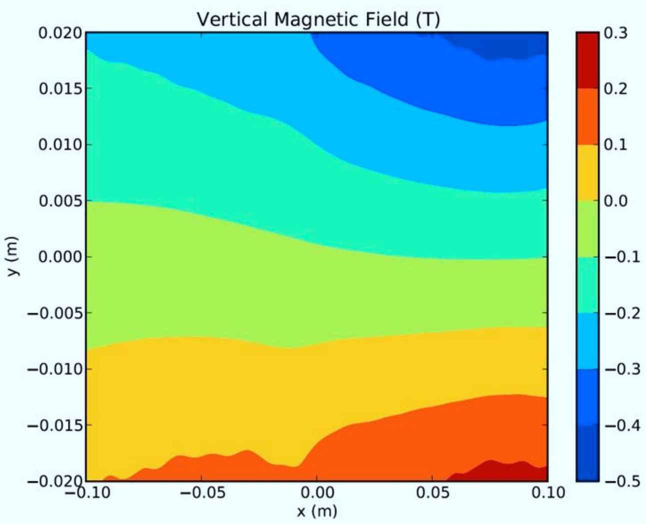
50 Ohm Coax 25 in parallel

Septum Magnets

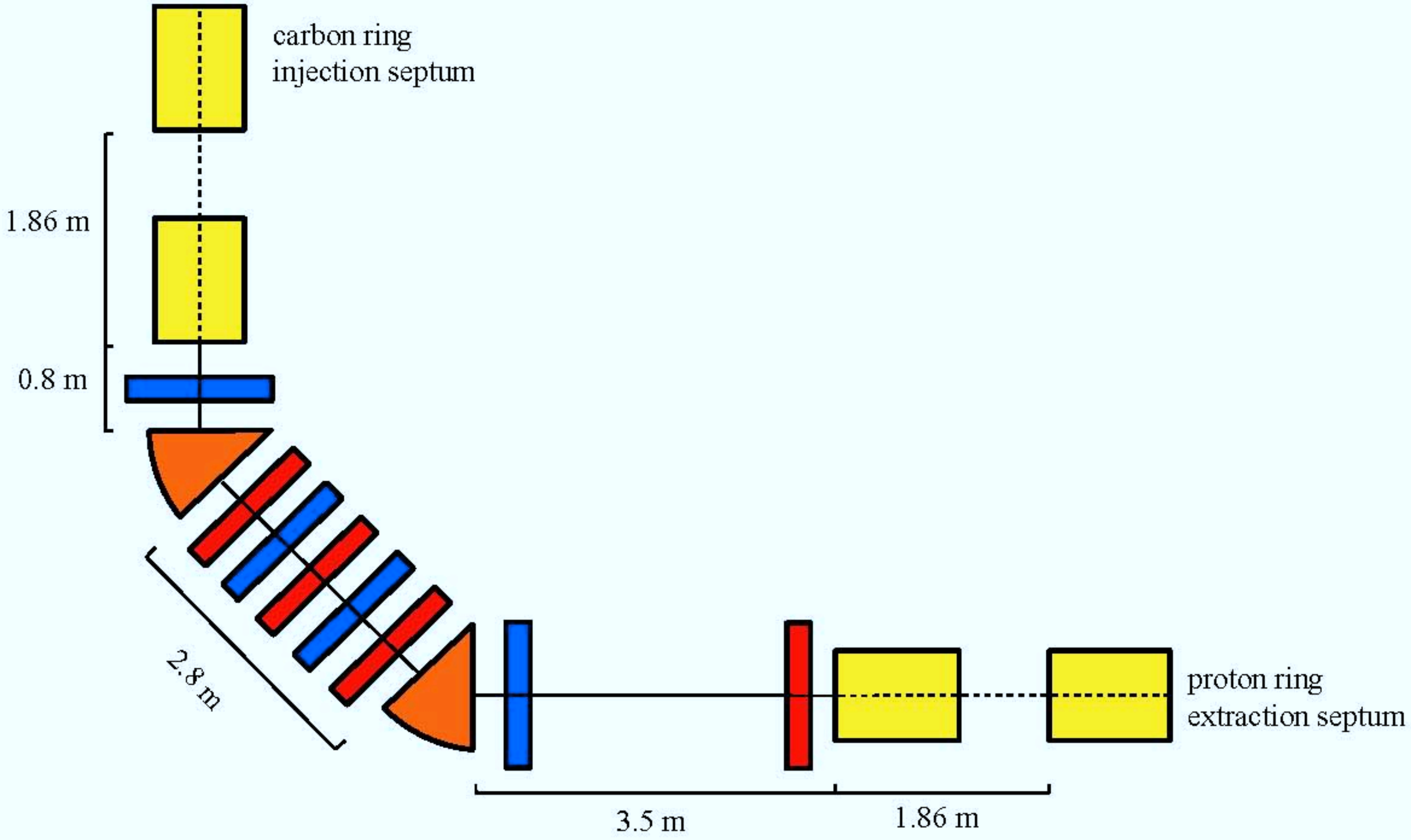






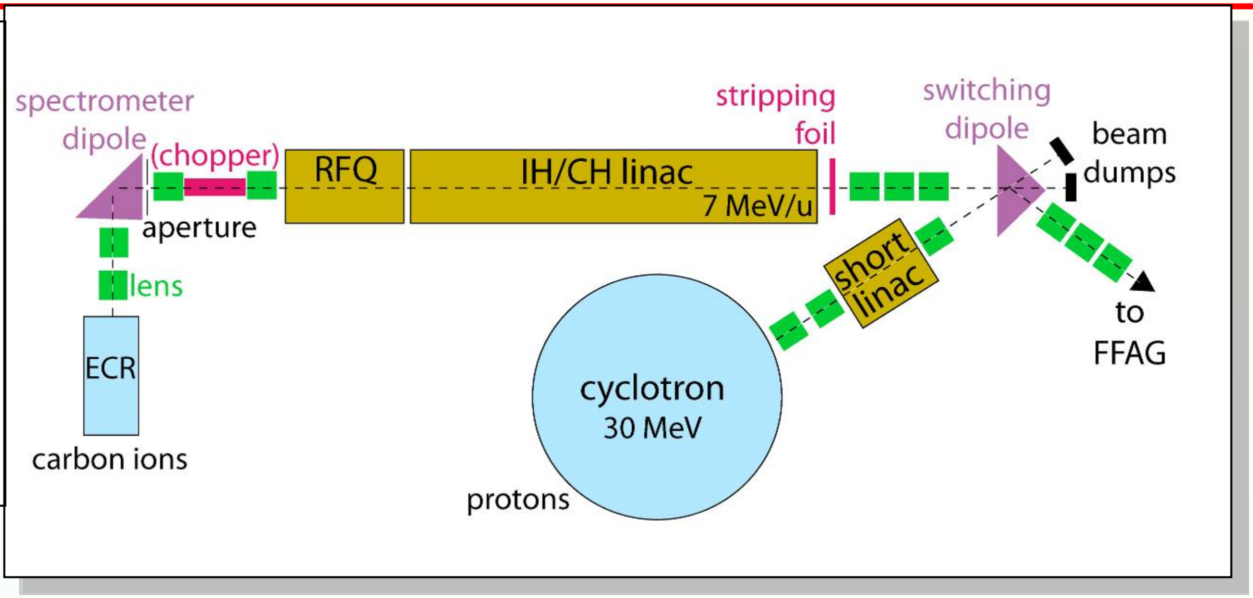


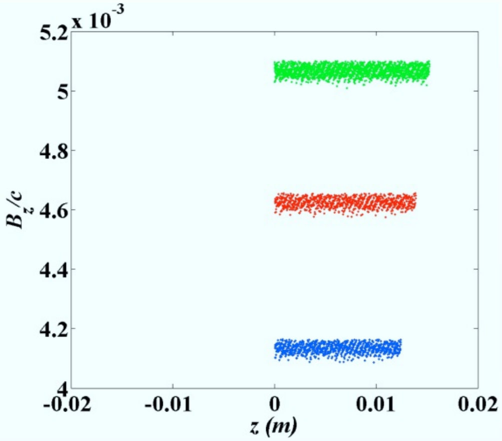
Ring-to-Ring transfer line

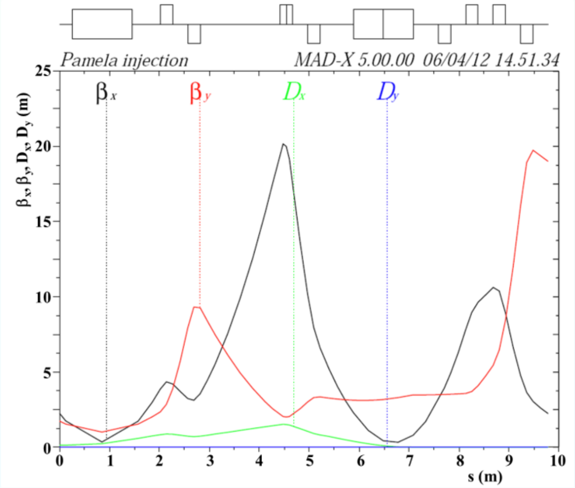


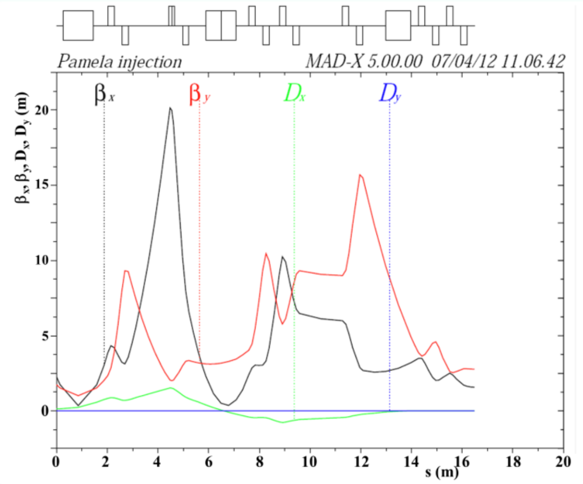
Ion sources

Carbon RFQ Parameters
E-field frequency 200MHz
E_I 8 keV/u
E_f 382 keV/u
Transmission 75%
RFQ length 2.4m
Electrode potential 80 kV

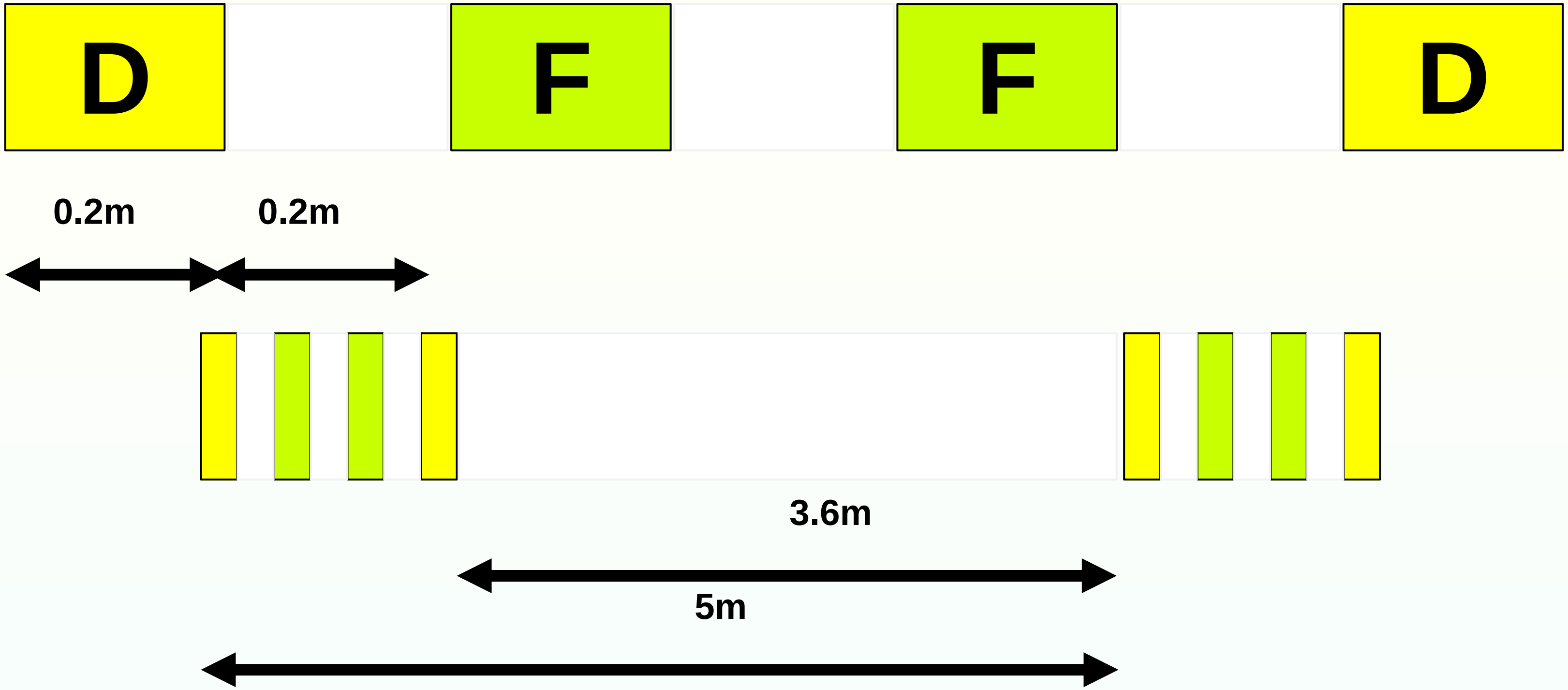








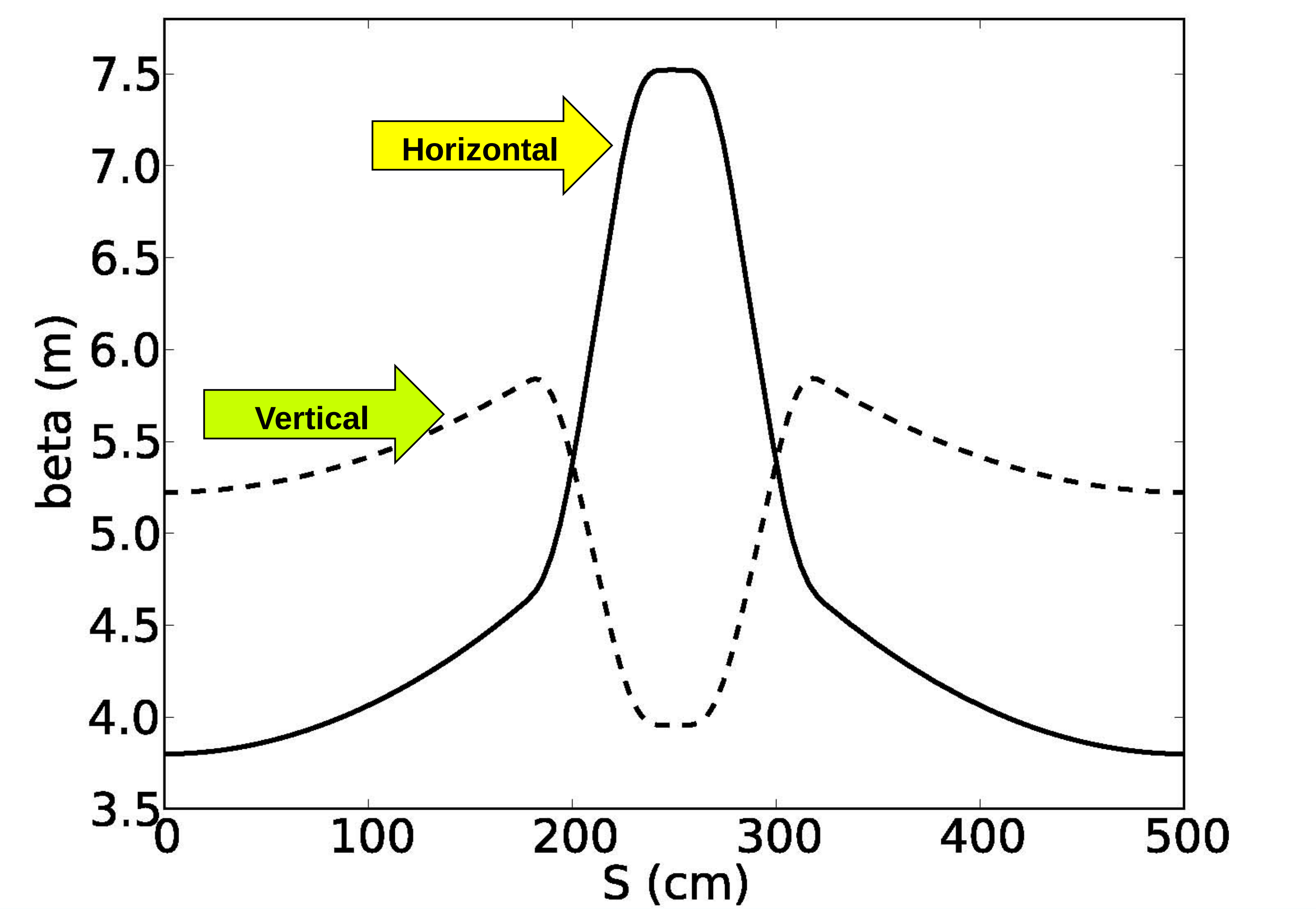
FFAG Beam Transport



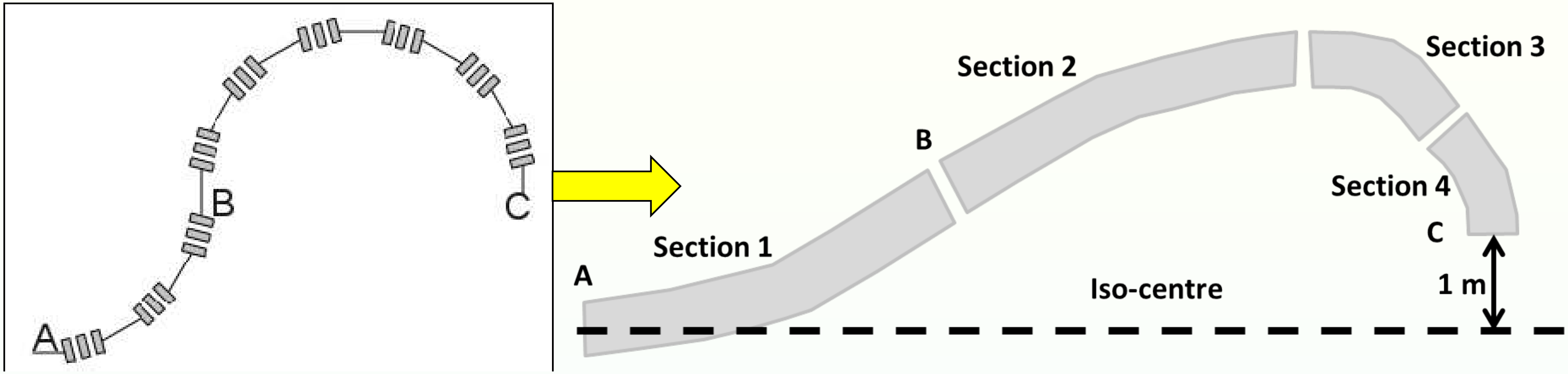
$$B_y(x,z) = B_{y.0}\left({(x+x_0)}/{x_0}\right)^k F(z)$$

$$n = \left({\rho}/{B_y}\right){dB_y}/{dx} \quad , \rho \text{ is radius of curvature}$$

Beam Transport



Gantry Design



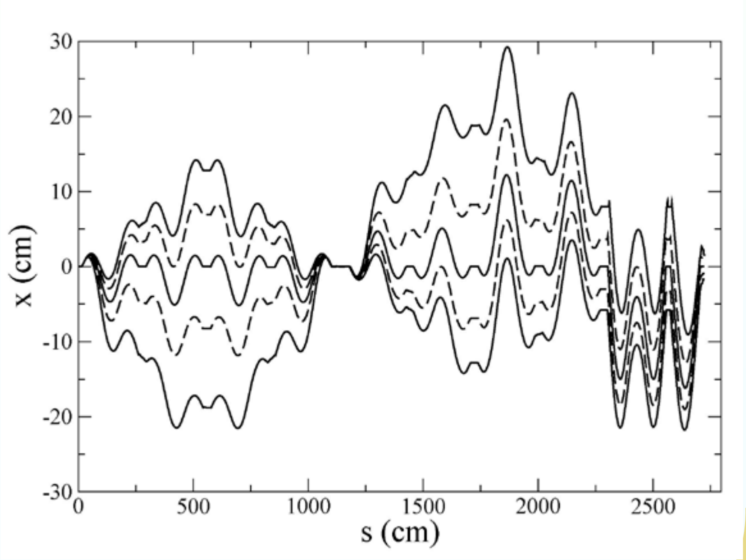
Upstream scanning

Gantry | **Scanner** | **Beam size tuner**

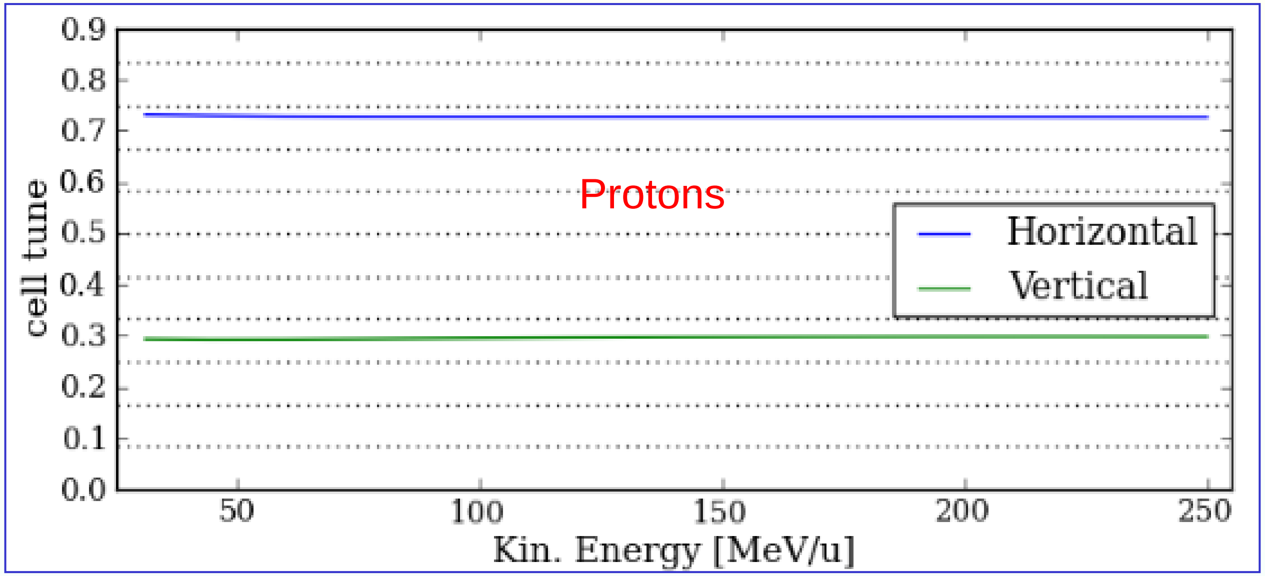
Downstream scanning

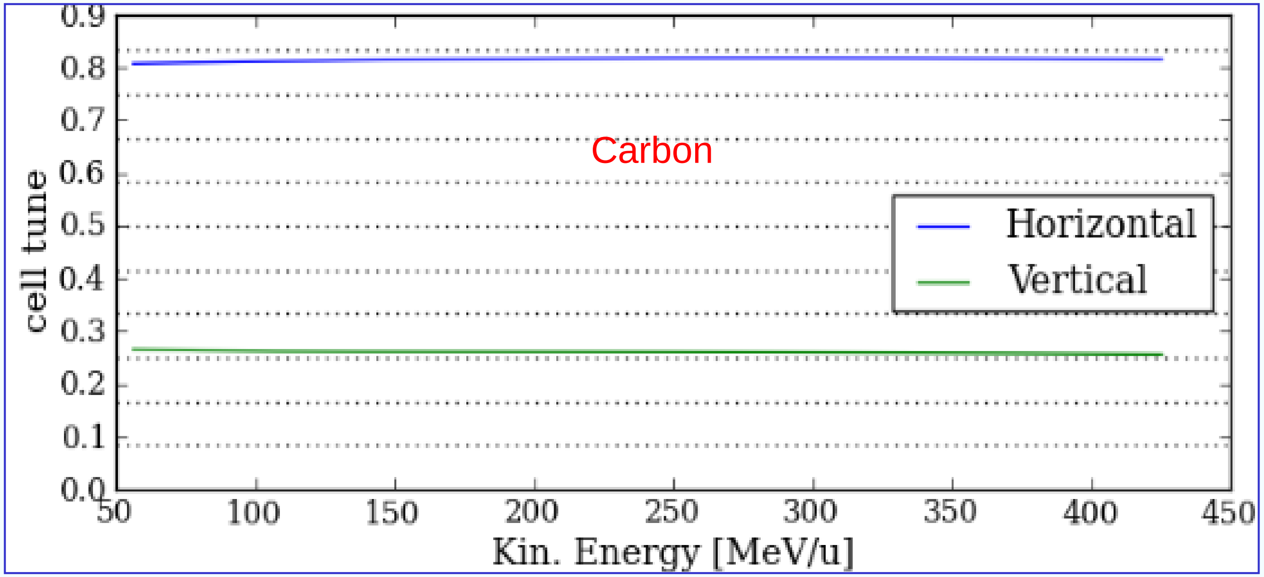
Gantry | **Beam size tuner** | **Scanner**

Patient couch

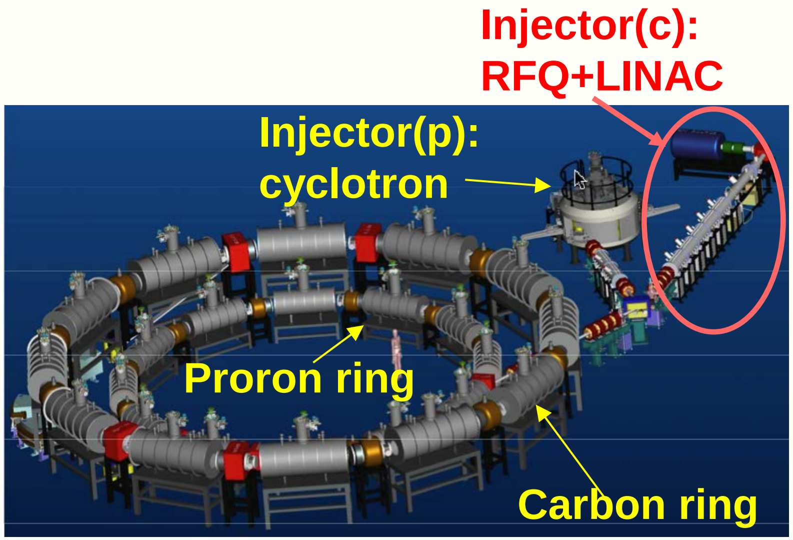


How does PAMELA work?





PAMELA: ring overview



$$\frac{B}{B_0} = \left(\frac{r}{r_0}\right)^k$$

scaling

$$\frac{B}{B_0} = 1 + k\frac{\Delta x}{r_0} + \frac{k(k-1)}{2!}\left(\frac{\Delta x}{r_0}\right)^2 + \ldots$$

PAMELA

- **Stable betatron tune Δν<0.1**
- **Long straight section (~1.3m)**
- **Small beam excursion(<20cm)**
- **Strong field (max 3.5T) ⇒ SC magnet**
- **High repetition rate(~1kHz) is a big challenge**

	Ring #1 (p, c)	Ring #2 (c)
Energy	30~250MeV (p) 8~68MeV/u (c)	68~400MeV/u
# of Cell	12	12
Diameter	12.5m	18.4m
K-value	38	41
Orbit excursion	18cm	21cm
Rev. freq	1.94~4.62MHz(p)	1.92~3.91MHz
	0.98~2.69MHz(c)	
Magnet	Triplet(FDF), SC	Triplet(FDF), SC
length	57cm	113cm
aperture	25cm	33cm
Long Drift	1.3m	1.2m
Packing factor	0.48	0.65
Inj./Ext	1turn inj/ext 2 LD (each)	1turn inj/ext 2 LD (each
RF	Max 8 LD	Max 8 LD

PAMELA

- Particle Accelerator for MEdicaL Applications
- There are obvious potential benefits from proton/light ion therapy
  - Need to maximise the benefits
- Requirements
  - Rapid variable energy extraction
  - Rapid variable transverse spot scanning
  - Variable ion species
  - Accurate dose measurements

SUMMARY AND CONCLUSIONS

Radiation Therapy: Benefits and Challenges

- **Radiation Therapy Cures Cancer**
  - **More than 50% of patients cured have RT**
- **Radiation Therapy is High Technology**
  - **It is not traditional medicine**
    - **Needs highly trained personnel**
      - **To commission, operate and maintain the equipment**
      - **To identify and delineate the tumour volume**
        - » **and associated treatment volumes**
      - **To define the treatment plan**
      - **To verify that the treatment plan was implemented**
        - » **and to modify it as necessary**
  - **and still requires biomedical research**

Conclusions

- Cancer is a terrible condition
  - but millions are cured every year
- Radiation therapy uses “physics”
  - high technology, many challenges
  - already good, but can be improved
    - in many ways
- Great opportunities to contribute
  - and reap the rewards, treating cancer

Summary

- **PAMELA Conceptual Design**
  - **“Proof of Principle”**

    on paper
  - **Main weaknesses**

ion source	**(can be fixed … known technology)**
RF	**(common problem for low E ions)**
Gantry	**(sketch solution, but needs work)**
Lattice	**(two rings – expensive, esp. carbon)**

  - **Possible new lattice**

    “Racetrack” configuration
    - **matching from arcs to long straights?**
    - **alignment sensitivity?**
    - **orbit excursion?**