PARTREC

High precision, innovation & patient comfort

beam sharing in cyclotron-based proton therapy facilities

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[4] PSI, Villigen

outline

- proton therapy market
- current facility operation
- fast switching
- beam splitting
- conclusions

EU proton therapy market

- population — 500 million
- cancer incidence — 2.7 million per year
- X-ray radiotherapy — ~1.4 million treatments per year
  - treatment units — ~3500
- annual turnover — ~15 billion € (< 1 % total healthcare)
- proton therapy — 2050 treatments per year (2011)
  - treatment units — 17 (2011)

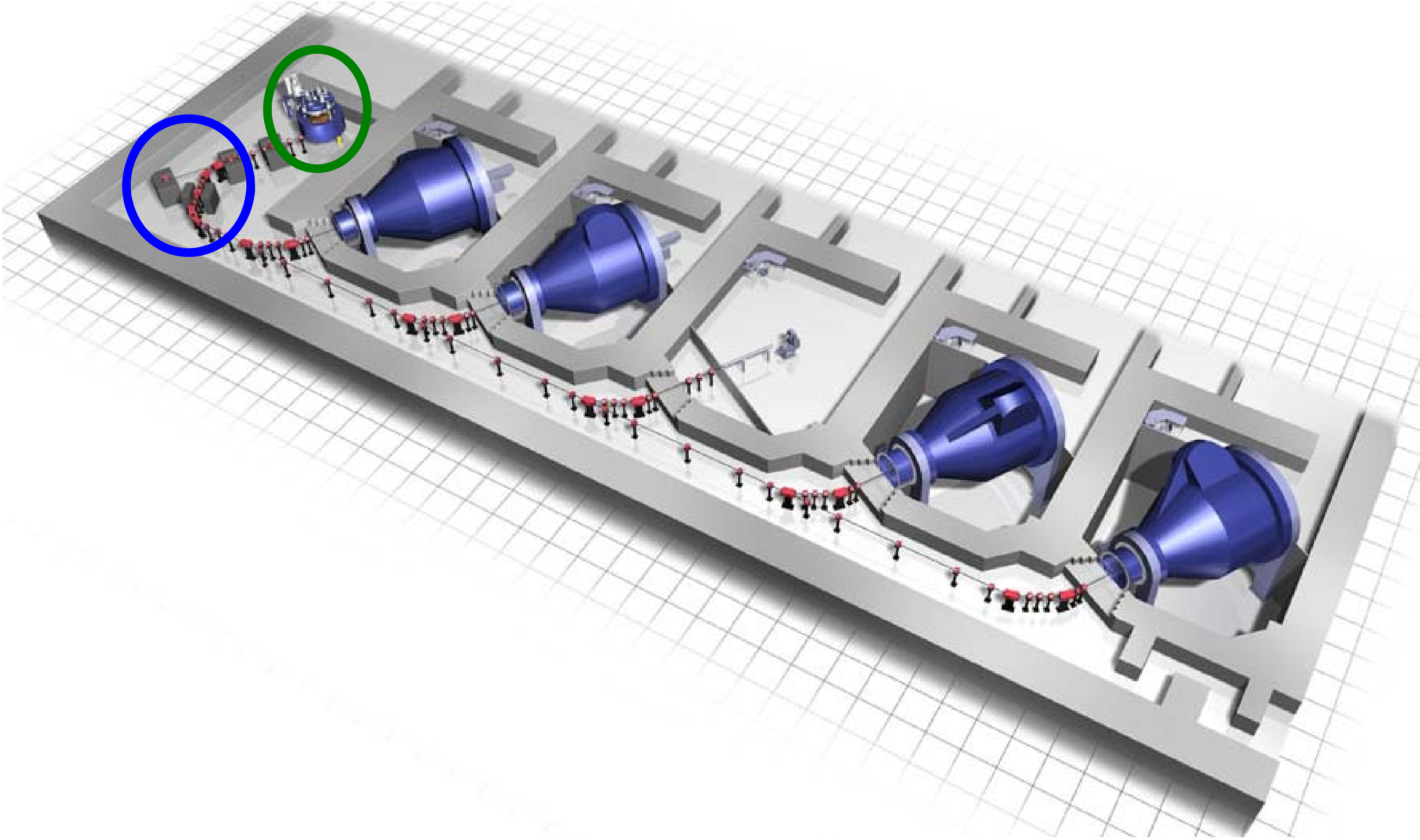
- market proton therapy
  - patients with expected benefit — 200000 per year
    - study Dutch Health Council, 2009
  - treatment units/centers — ~600/200
  - ú large expansion possible
  - what needs to be done to realize it ?

EU proton therapy market

- key requirements for expansion
  - more coordinated clinical validation studies
  - better treatment quality
    - scanning techniques
    - treatment planning
    - treatment verification
  - lower treatment cost
    - at this moment typically 3 × X-ray treatment
    - ingredients
      - investment reduction Ú compactness
      - operation efficiency Ú workflow optimization

proton therapy facilities

- mostly multiple treatment rooms
  - single accelerator
  - single degrader + energy selection system (ESS)
  - ⇒ interference between treatment rooms



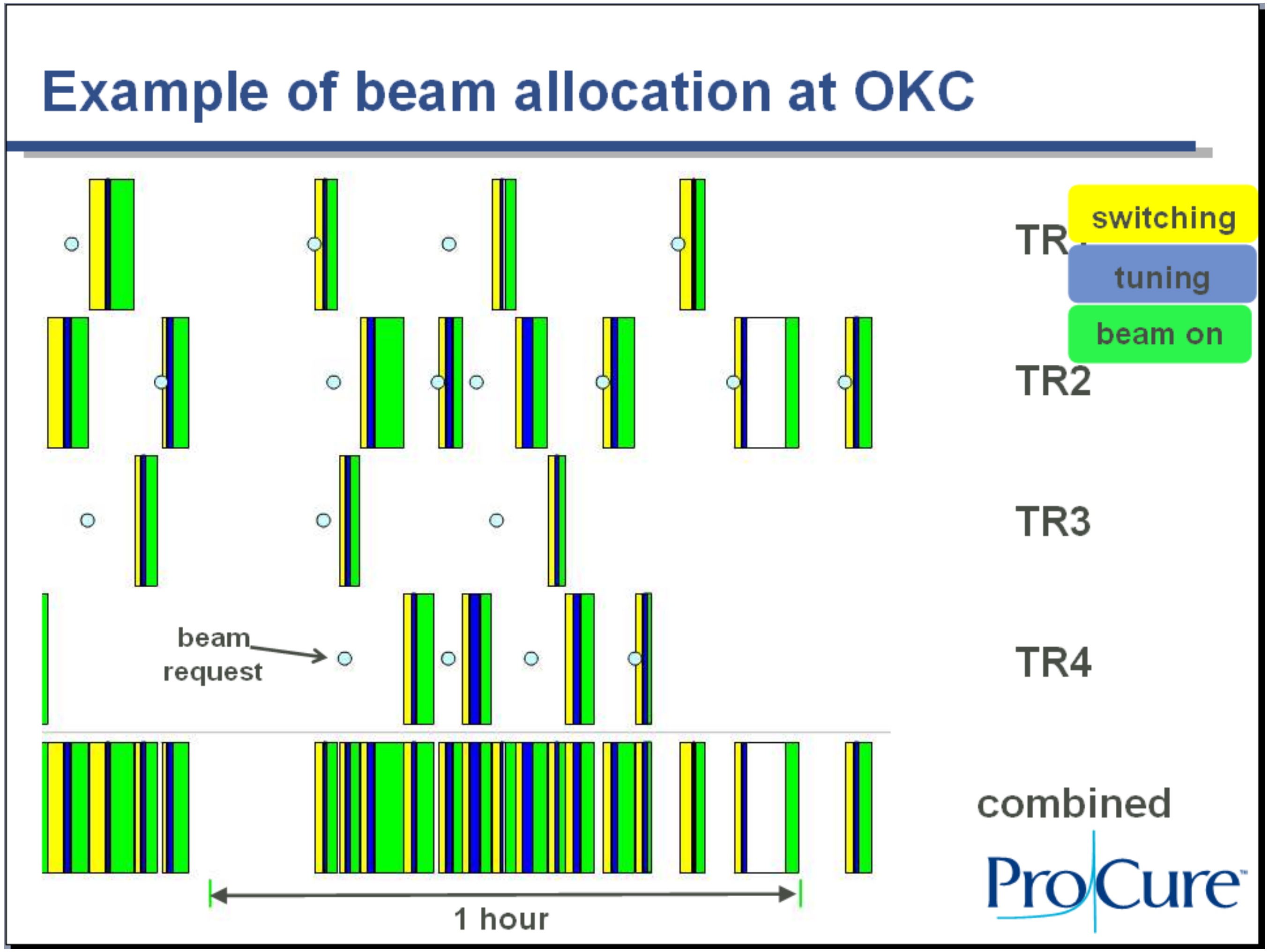
treatment delivery scheme

- scattering
  - “connect” degrader + ESS + beam line with gantry
  - tune degrader + ESS + beam line + gantry for maximum energy
  - deliver radiation field(s)
    - possibly retune for other energy inbetween fields
- scanning
  - “connect” degrader + ESS + beam line with gantry
  - tune degrader + ESS + beam line + gantry for starting energy
  - deliver radiation field(s)
    - retune for small energy steps inbetween layers

Ű frequent retuning 20 – 30 parameters
verification of tune (beam position, transmission etc.)

Ű simplify by reduction # parameters

beam use pattern

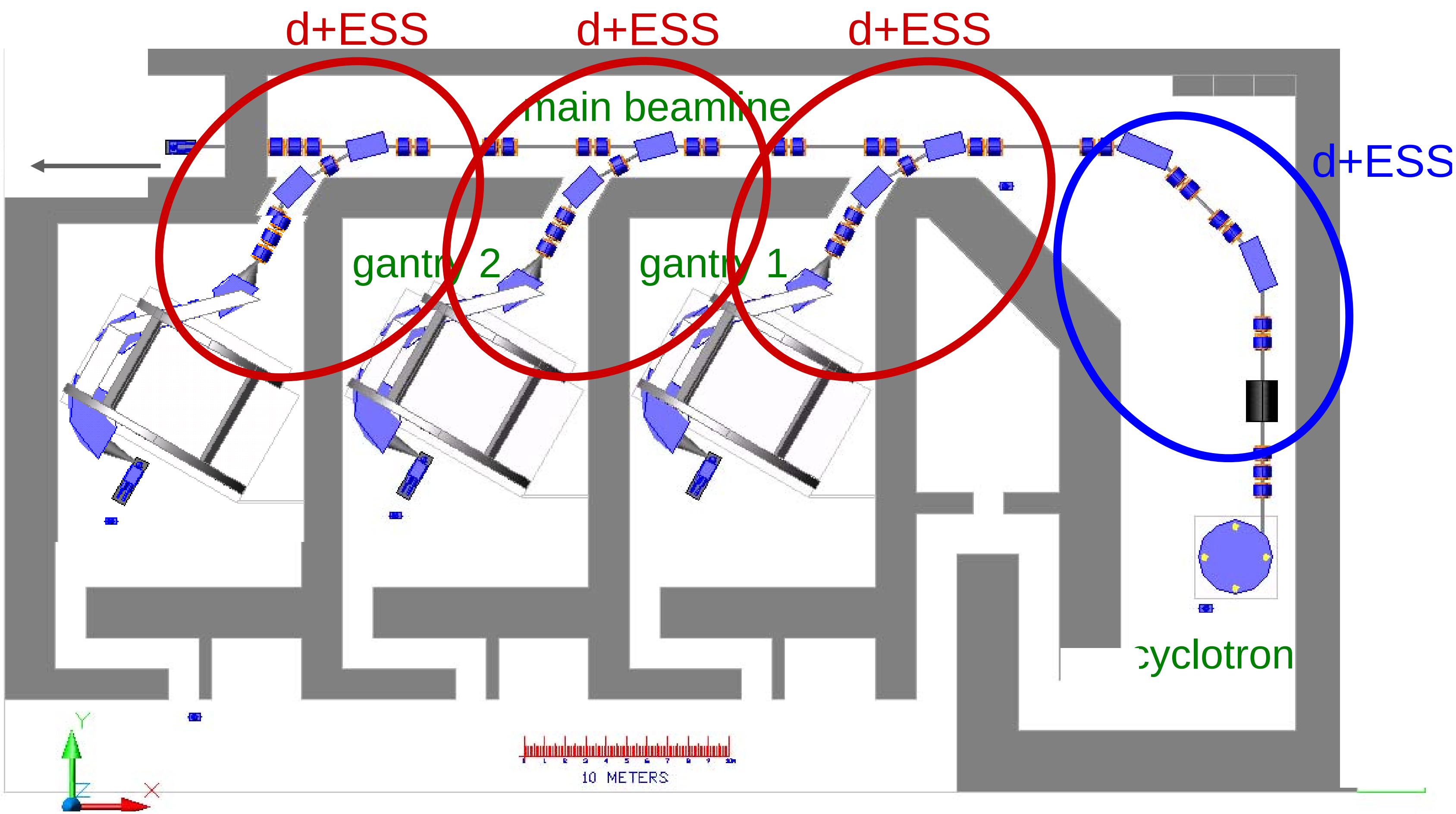


source ProCure Oklahoma Proton Therapy Center

- long waiting times due to interference
- significant time for switching and tuning

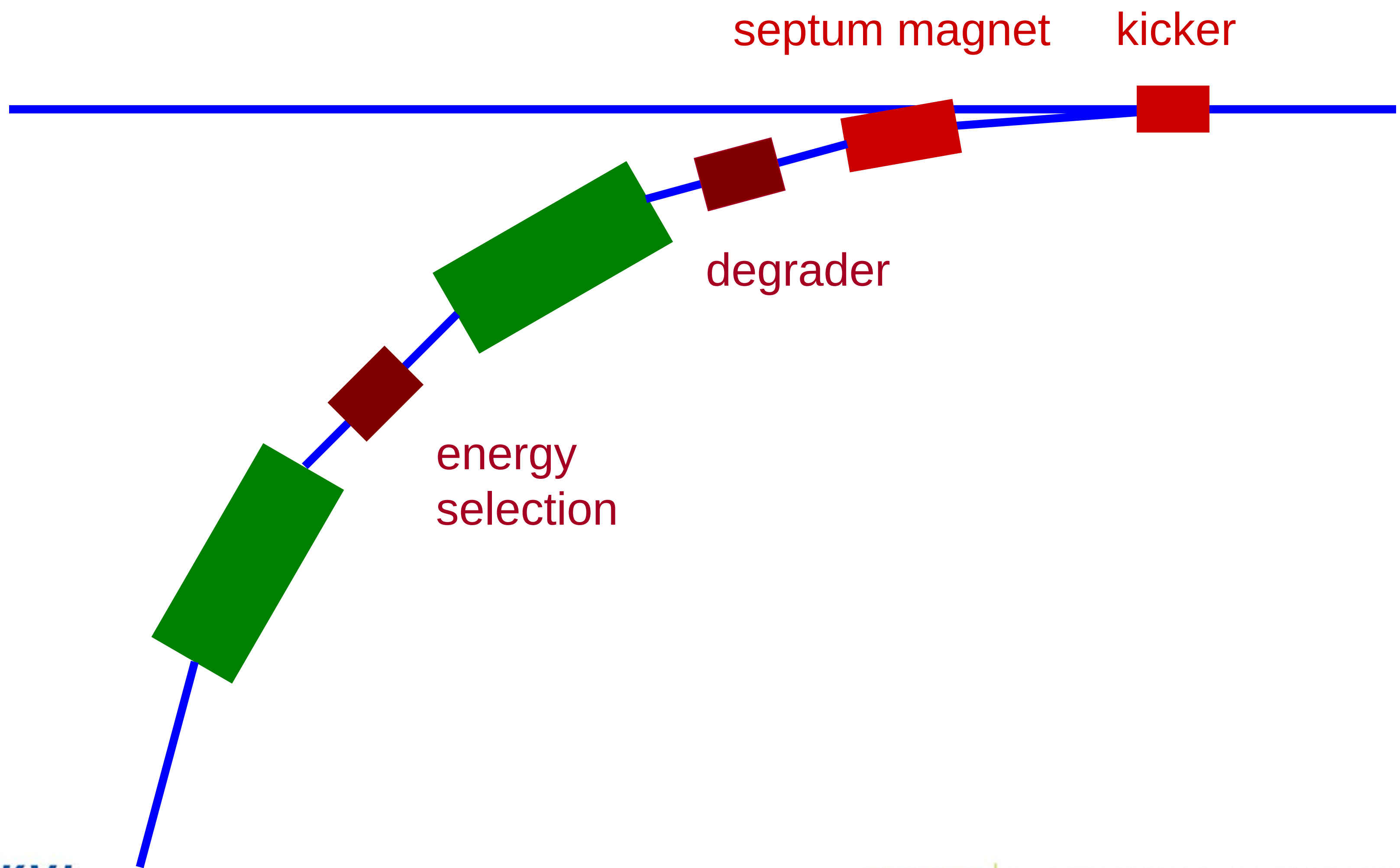
fast switching: facility lay-out

- fast kicker to switch between treatment rooms
  - already implemented at MPRI
- magnetic septum to increase separation
- integrate degrader + ESS in treatment unit



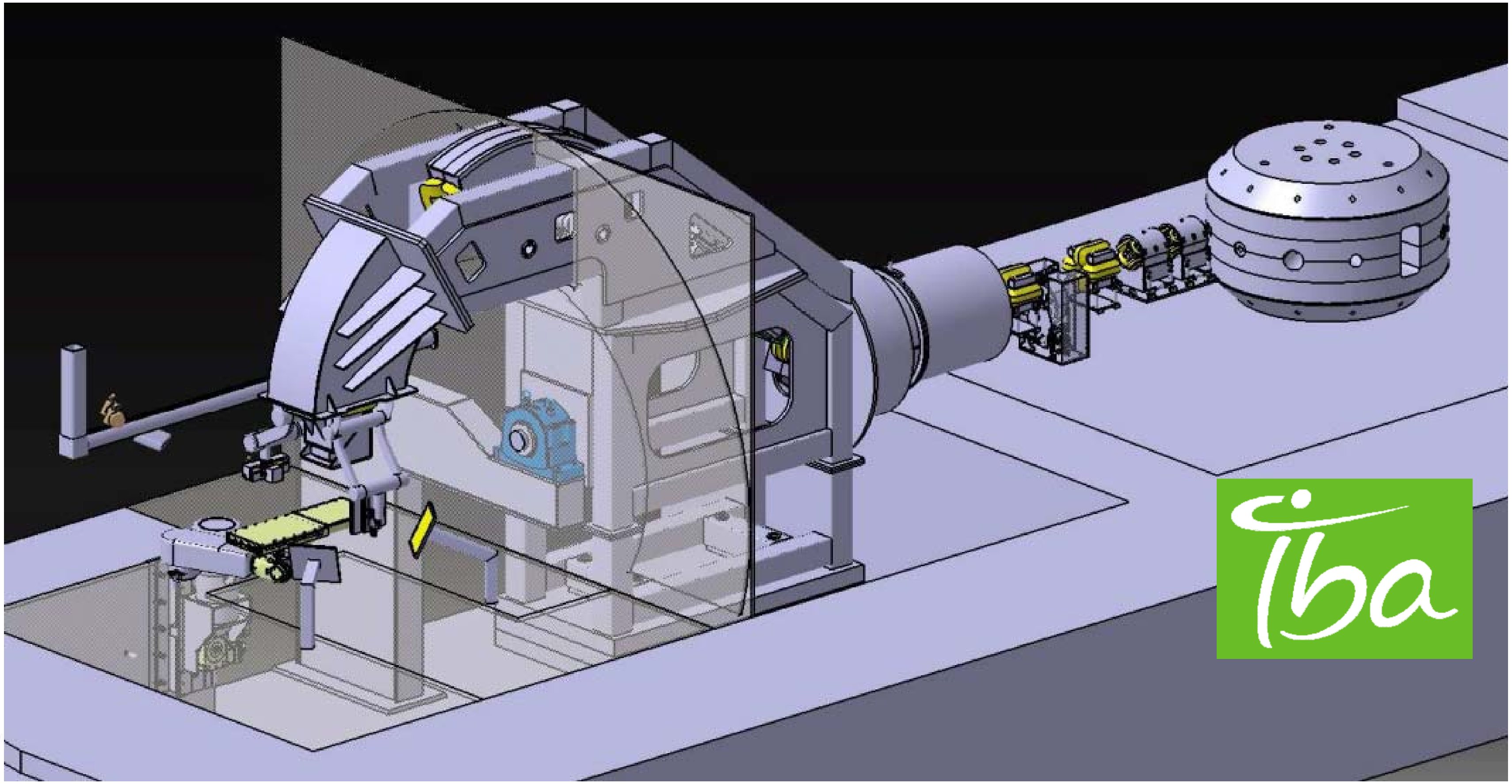
fast switching: degrader + ESS lay-out

- options for ESS
  - separate magnets in front of gantry
    - most magnets already there!



fast switching: degrader + ESS lay-out

- options for ESS
  - separate magnets in front of gantry
  - integrate in gantry (cf. IBA Proteus One)
    - neutron shielding inside rotating gantry



fast switching: beam control

- beam on – off switching
  - kicker (kicker off = beam off)
  - cyclotron (ion source/deflector central region)
- beam intensity during irradiation
  - ion source / deflector central region
- essentially same as current practice

fast switching: further possibilities

- interleaved irradiations in different rooms
  - multiple fields
  - fast volumetric scanning and repainting (moving tumors)
- combine with high dose rates

Ú further reduction waiting times and interference

fast switching: balance sheet

- productivity gain
  - logistics simulation study on-going
- shorter waiting time Ú smaller patient position error
- simplification operation
  - increased modularity (control system)
  - fixed tune main beam line: permanent magnets demonstrated: Fermilab antiproton storage ring

- higher investment
  - kicker and septum magnets (power supplies)
  - additional shielding degrader + ESS
  - less possibilities power supply sharing
  - possibly somewhat higher electricity cost/treatment
    - more equipment running simultaneously

beam splitting: towards real independence

- cyclotron delivers constant beam intensity
- replace kicker by electrostatic septum: split off fraction of beam
  - used at PSI up to 2005 for proton therapy

beam splitting: principle of operation

- cyclotron delivers constant beam intensity
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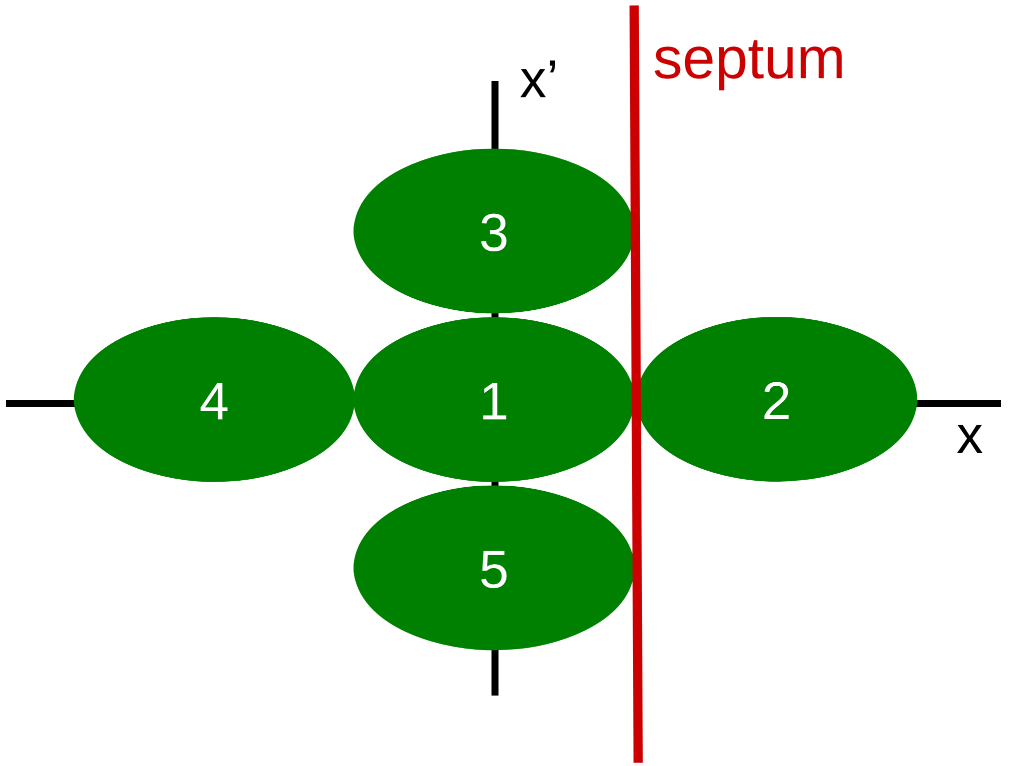
  - basically: inverse of stacking injection in ring



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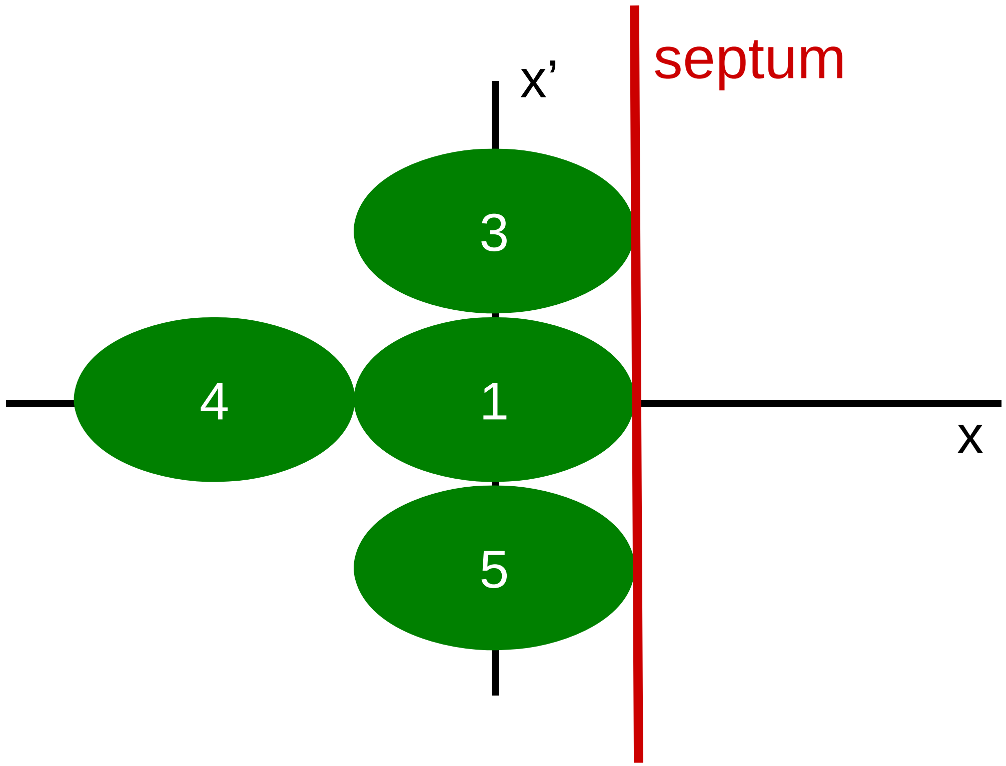

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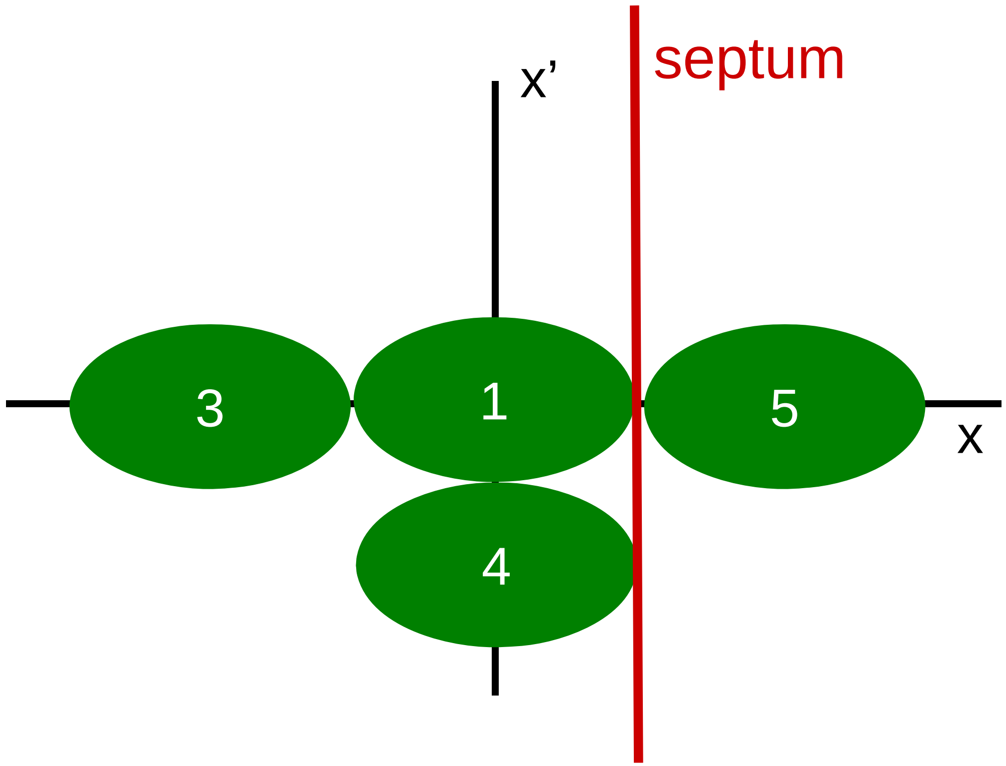

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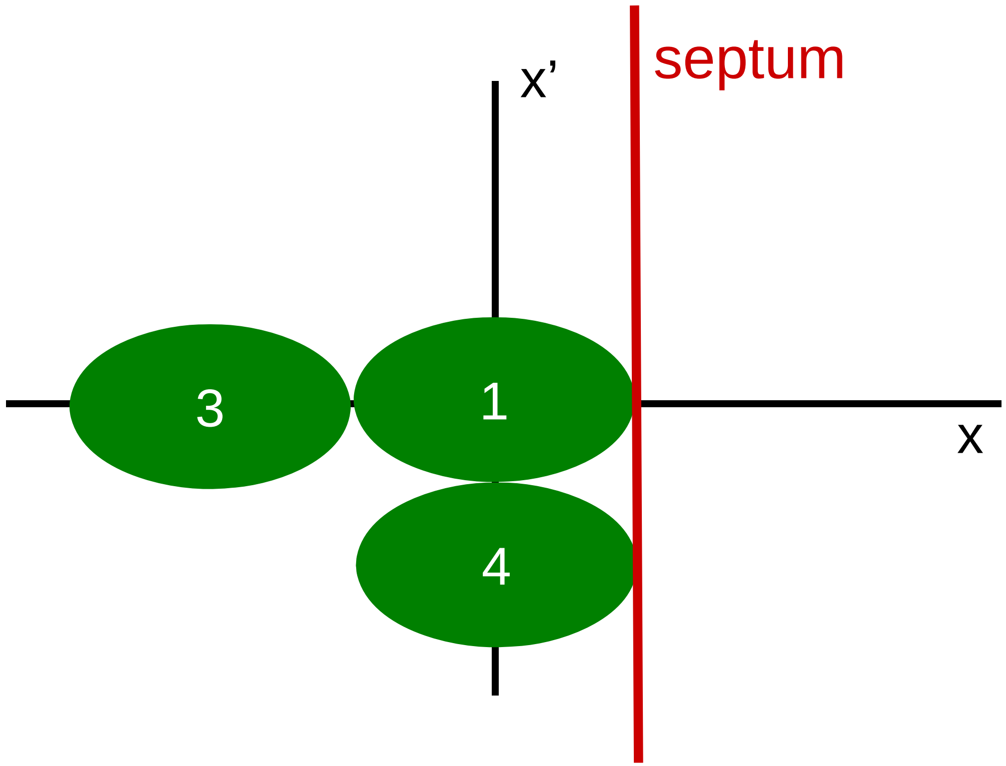

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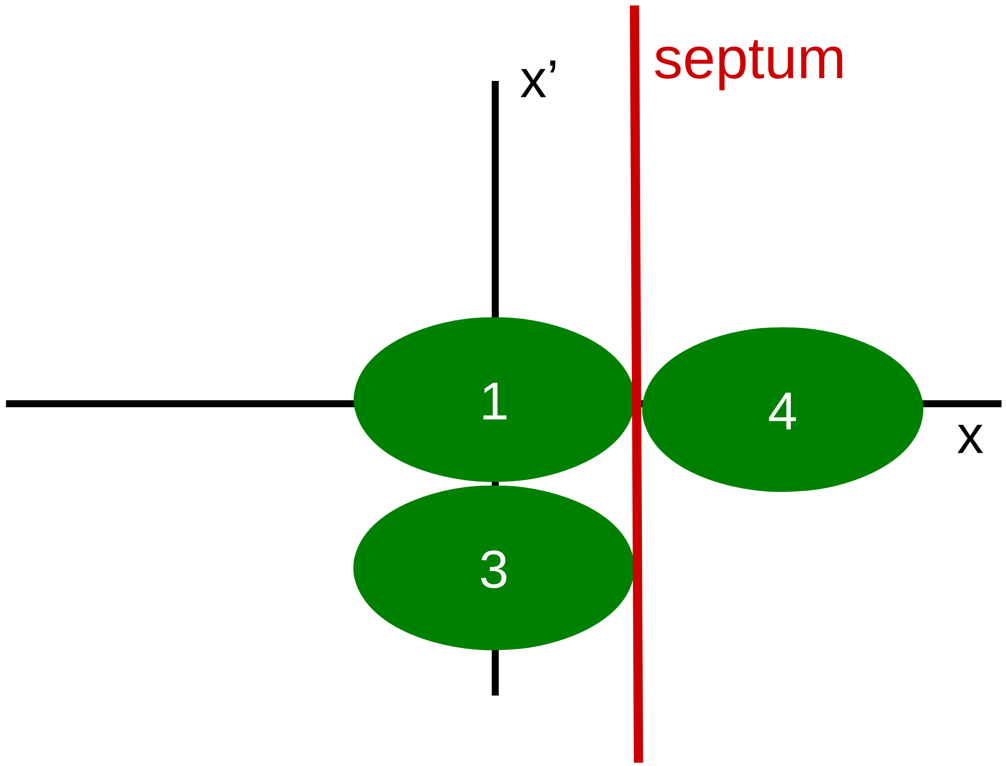

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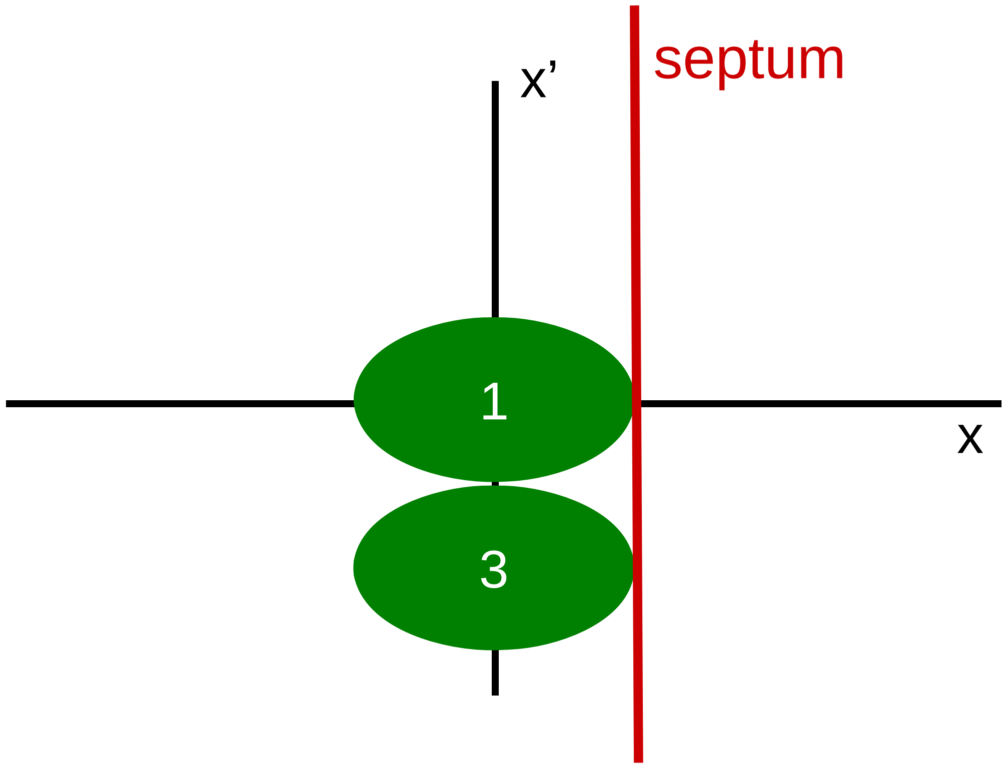

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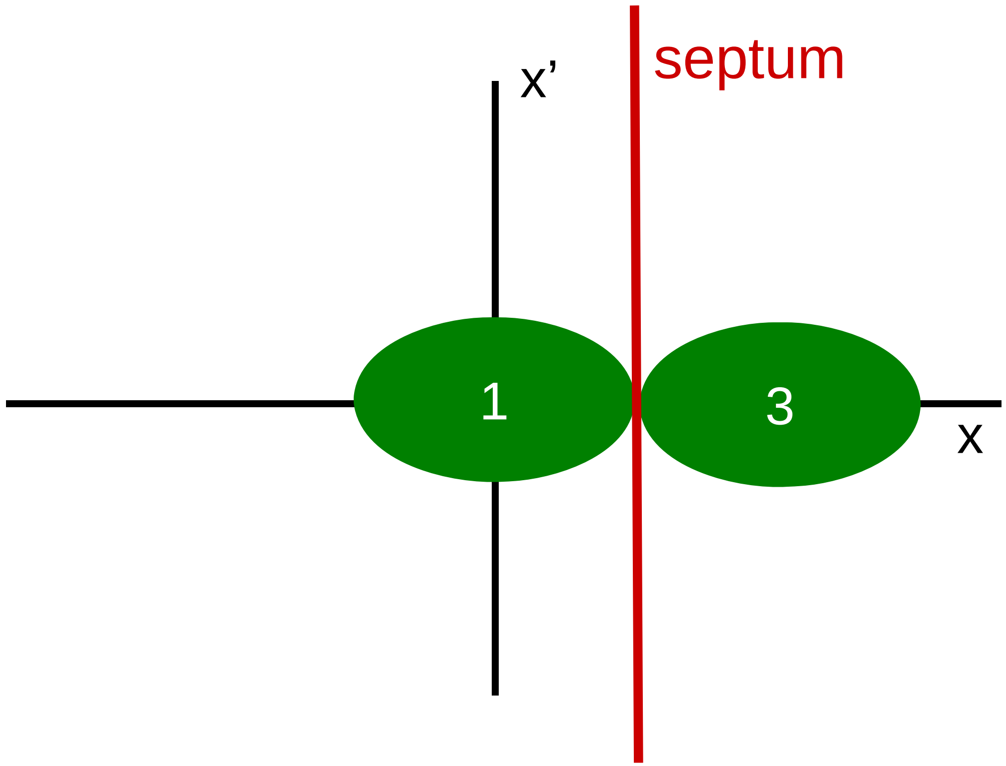
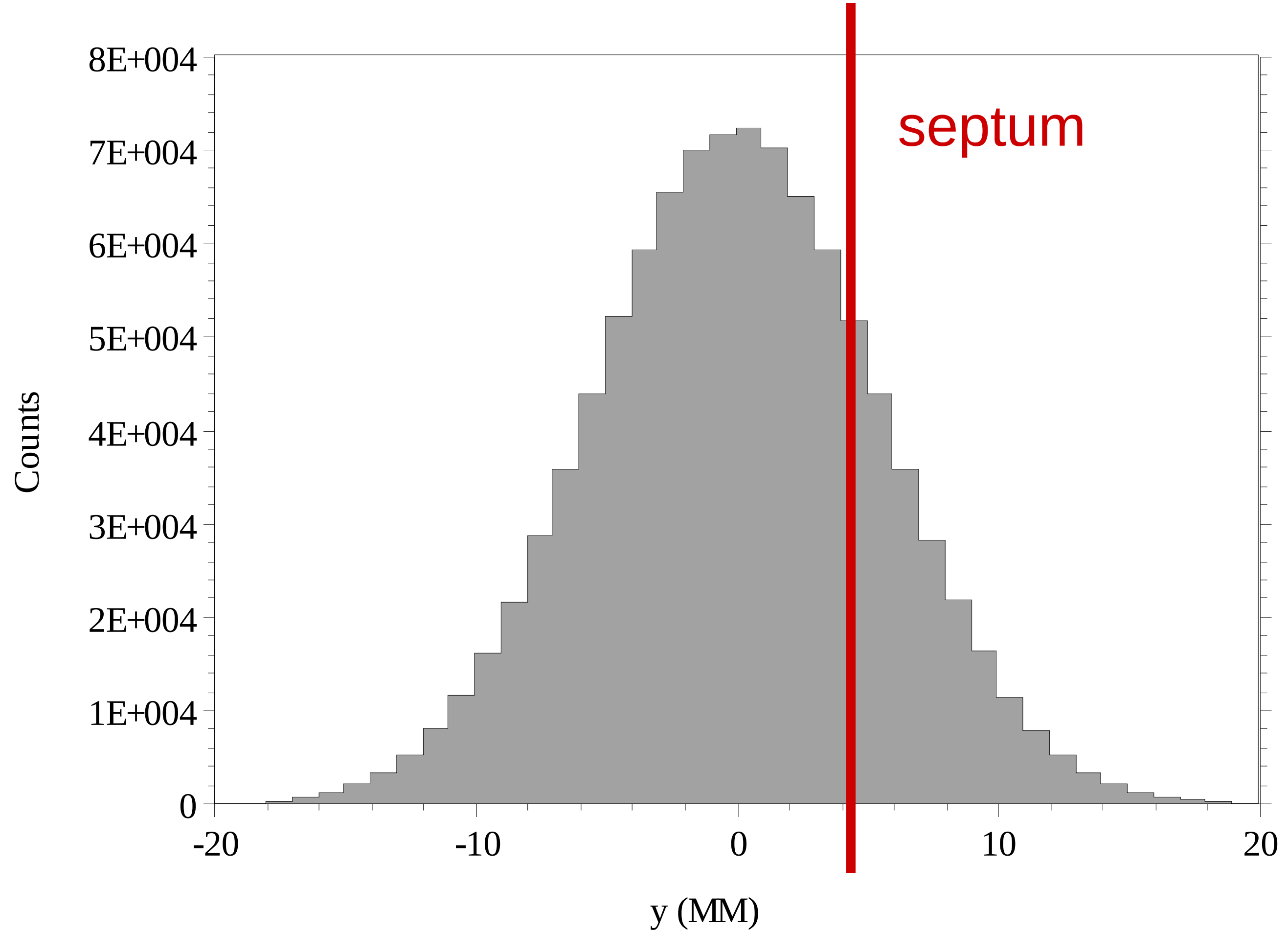


beam splitting: requirements

- beam optics
  - $\sigma(n) = R^n\,\sigma(0)\,(R^n)^T$; R transfer matrix septum – septum
  - constant betatron phase advance septum – septum
    - minimize overlap phase space area cut by each septum
  - wide beam at septum:
    - minimize septum losses
    - minimize sensitivity transverse beam motion
  - waist at degrader Ú convergent beam at septum
    - no quads main beamline between septa (steering)
    - focussing in septum magnet
- tuning beam distribution
  - septum position / steering magnets (parallel displacement)

beam splitting: TURTLE simulation

- TURTLE calculation
  - beam profile before first split



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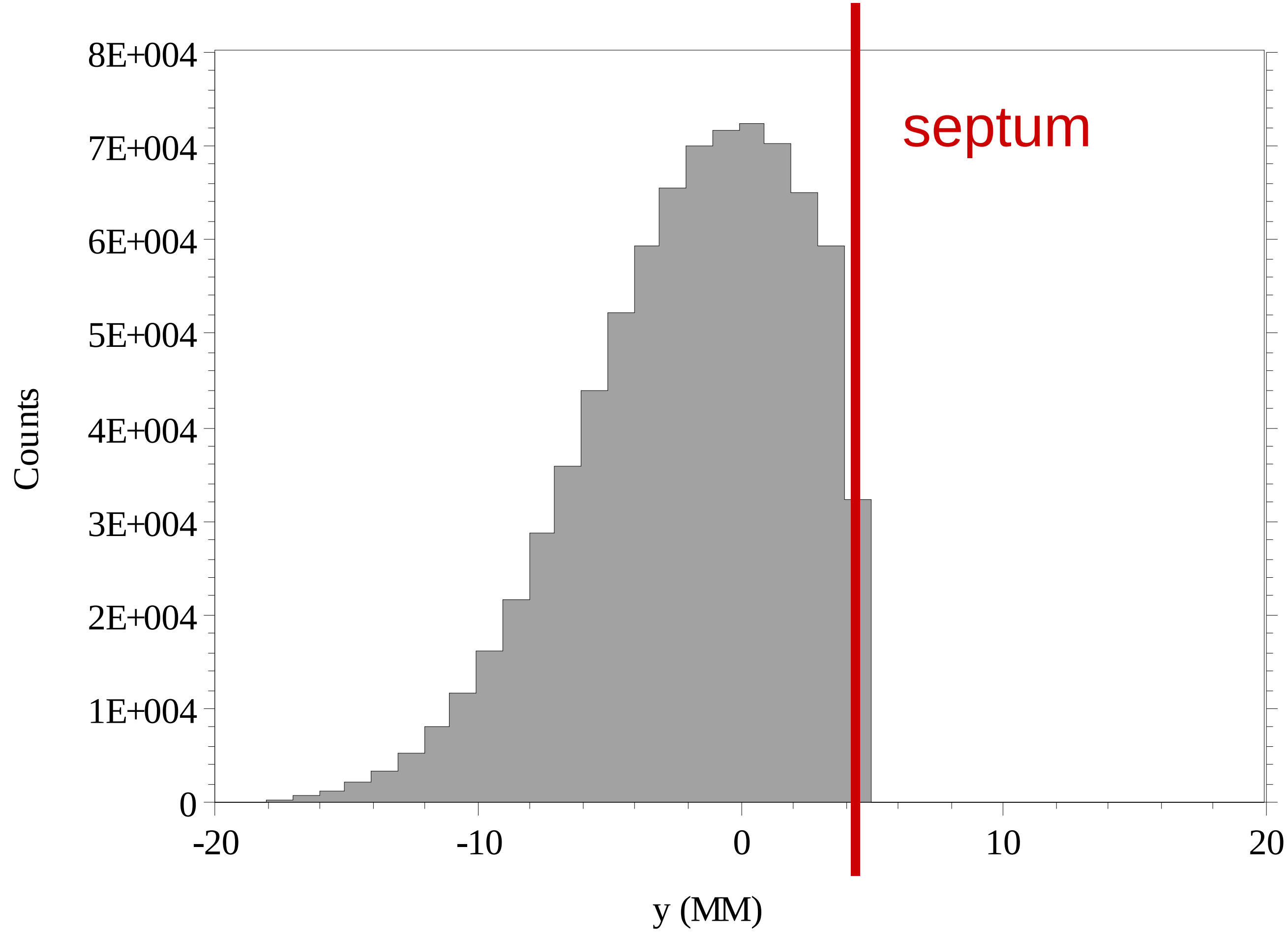

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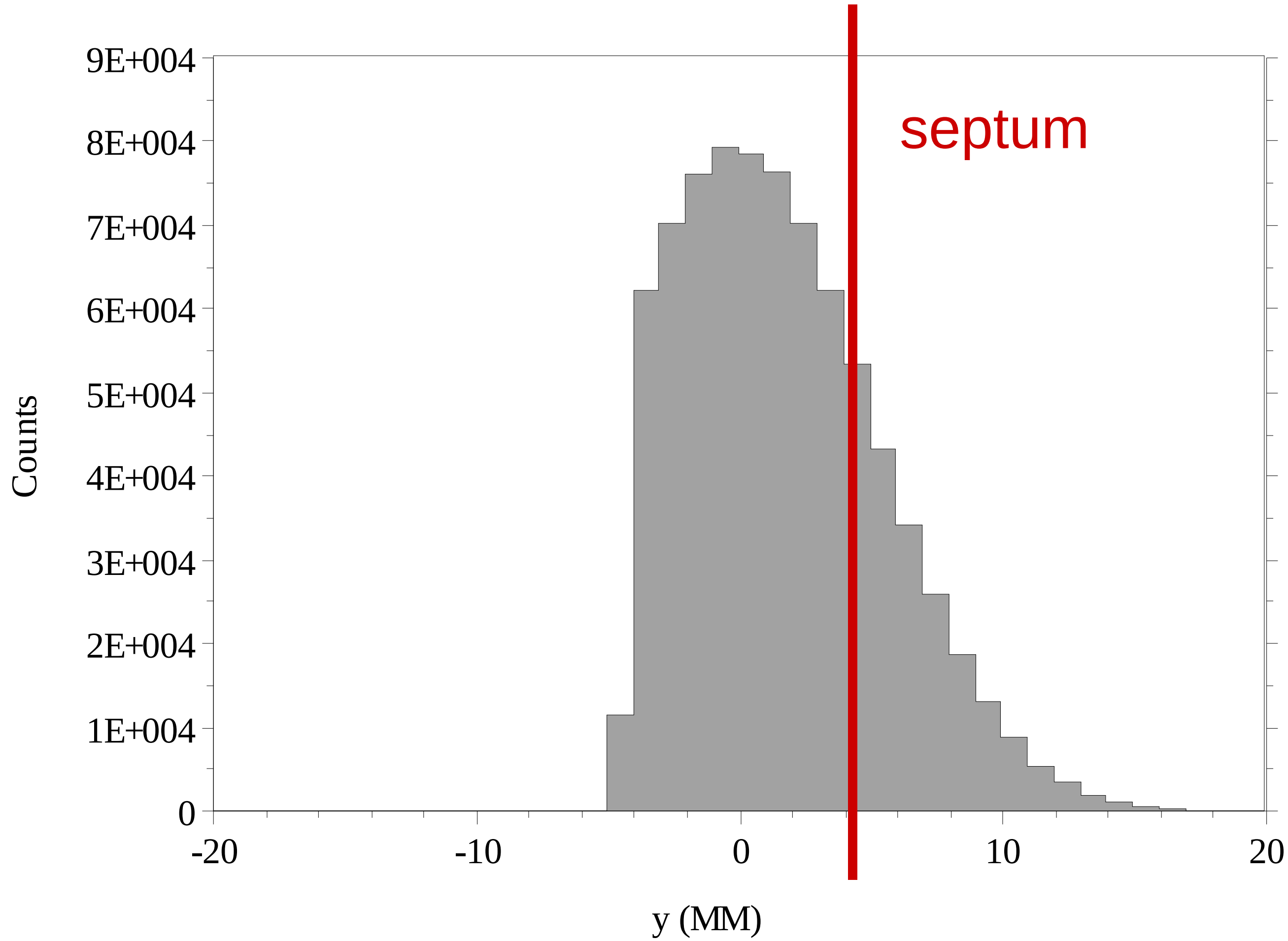

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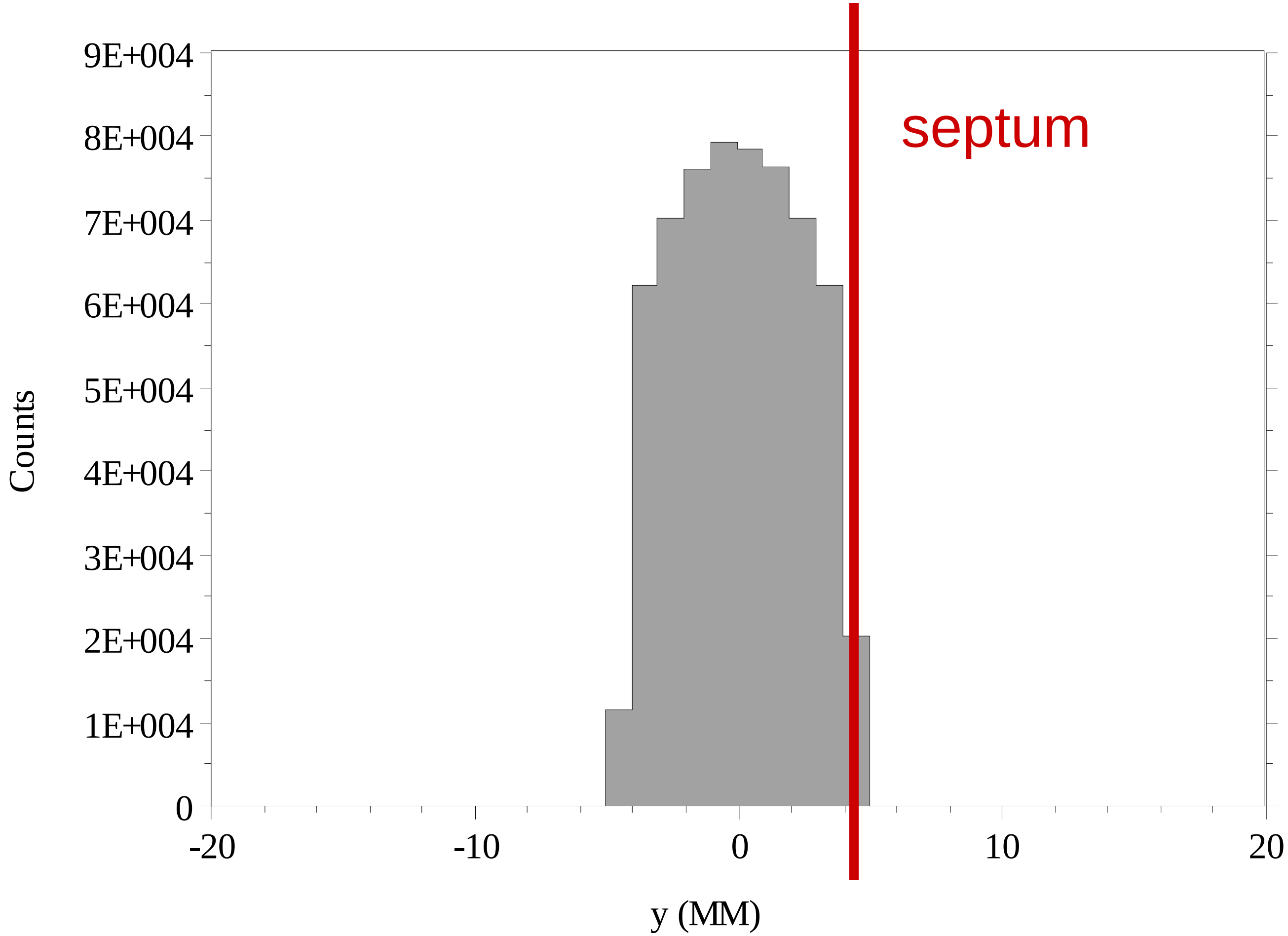
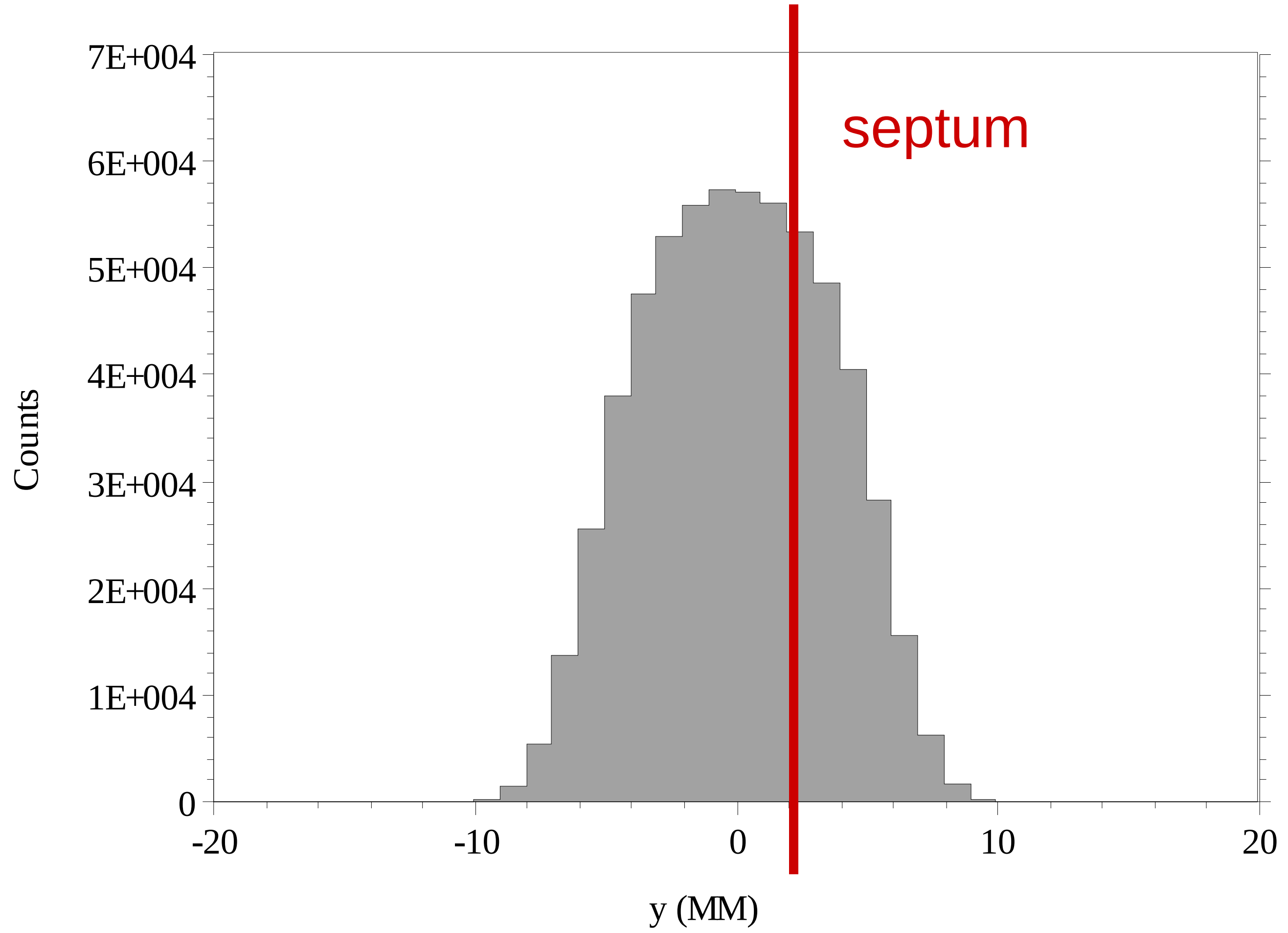


beam splitting: TURTLE simulation

- beam profile before third split



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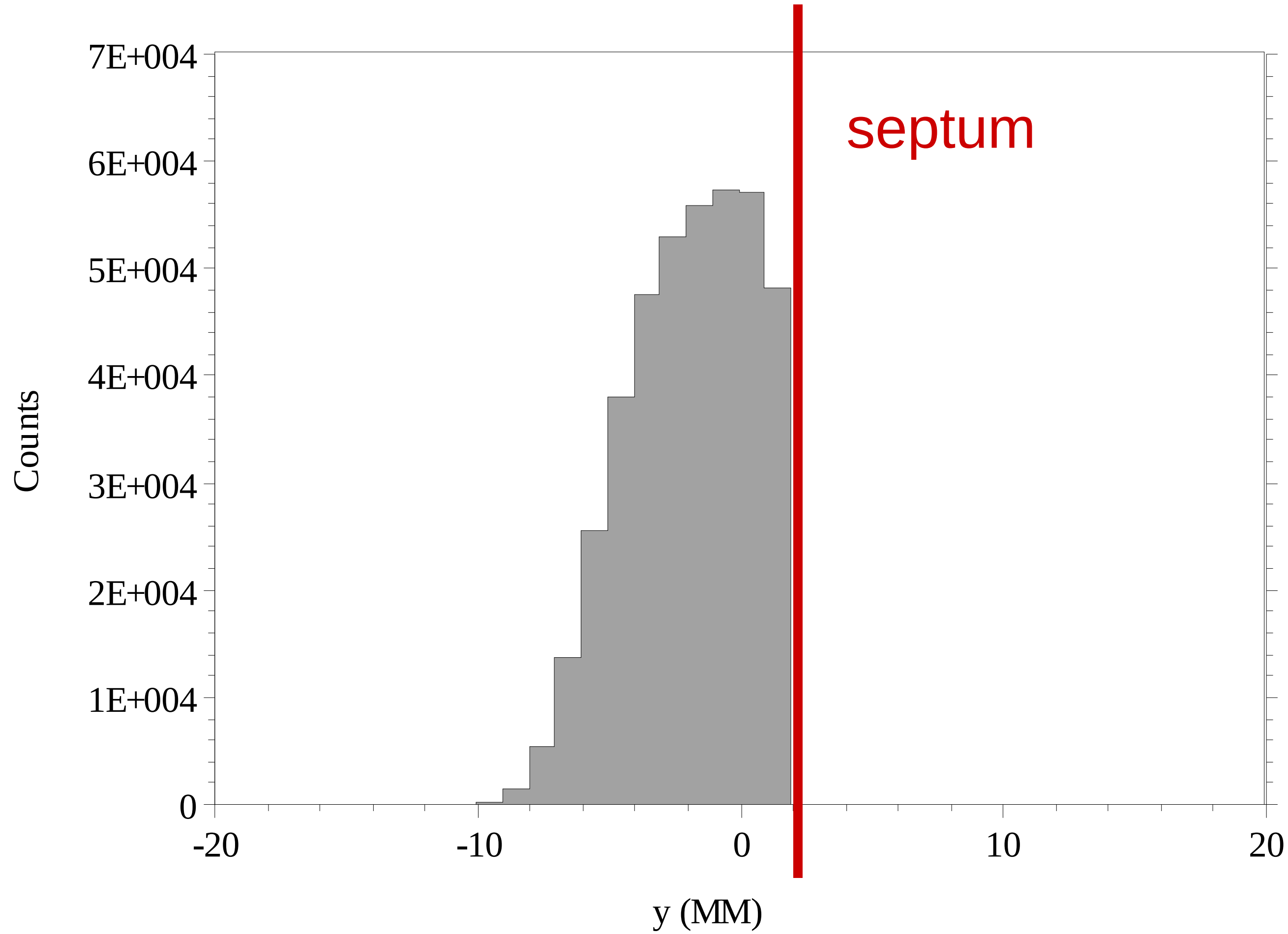
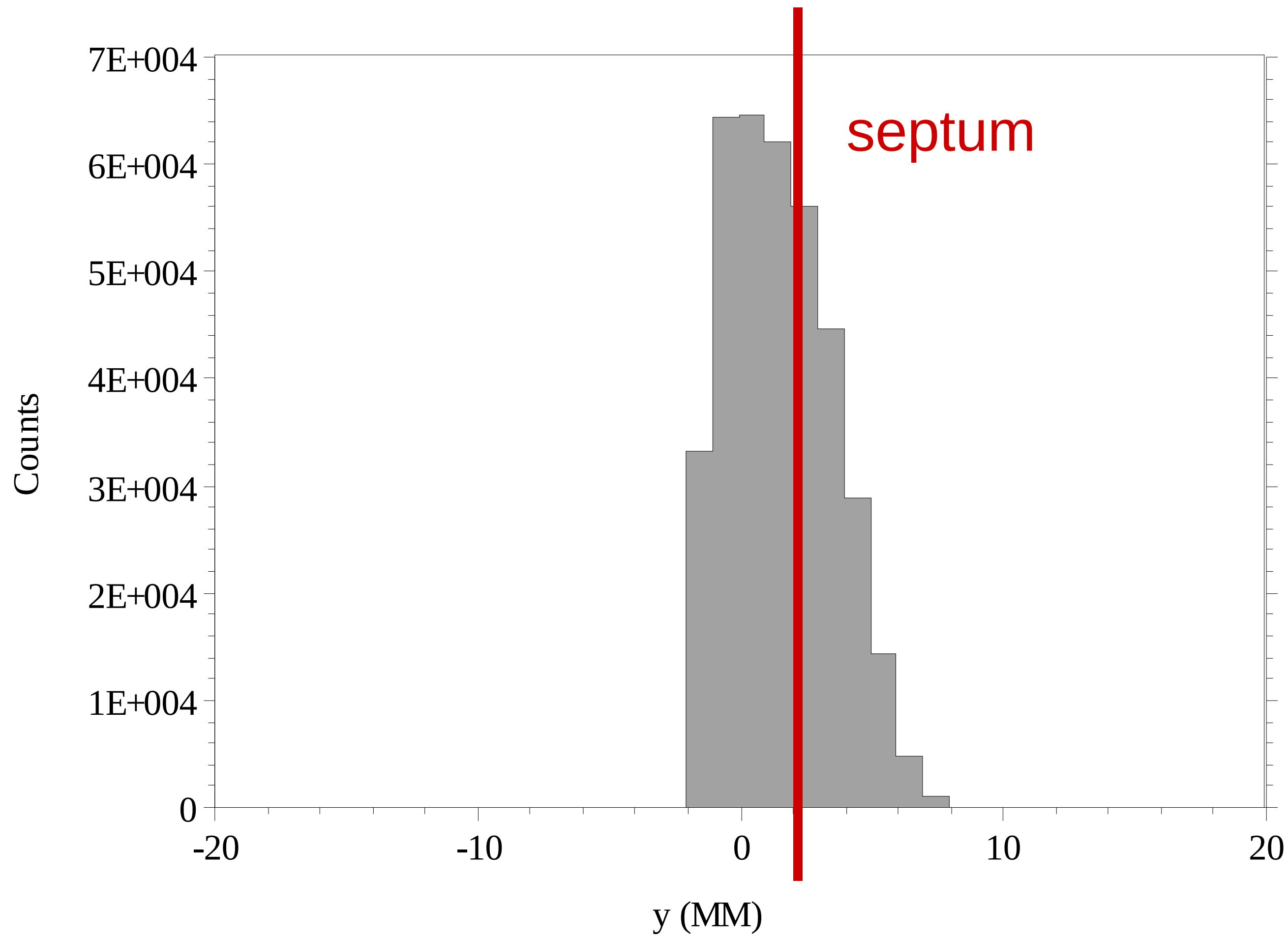


beam splitting: TURTLE simulation

- beam profile before fourth split



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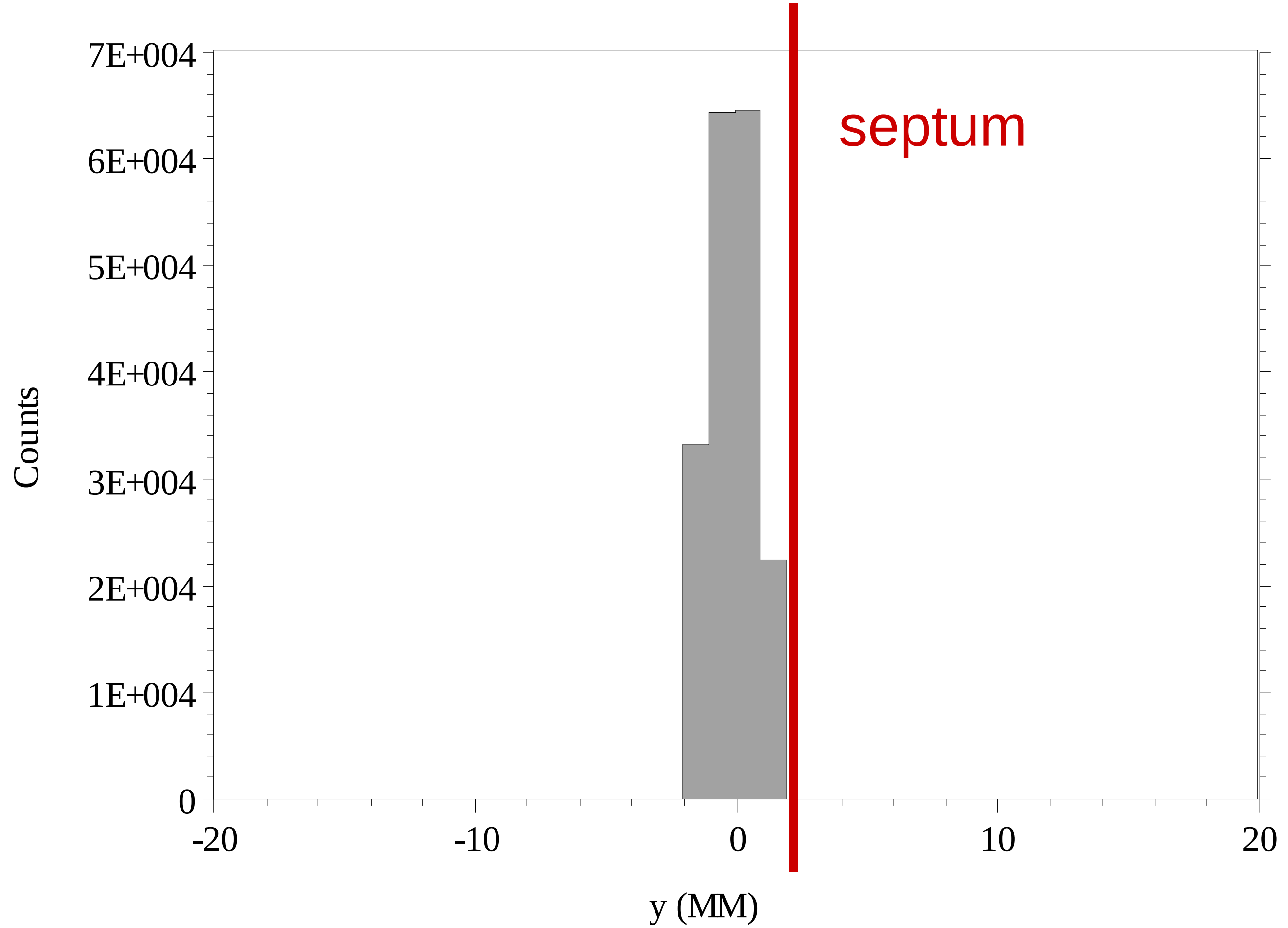


beam splitting: intensity control

- beam on – off switching
  - kicker (kicker off = beam off)
  - beam stop
- beam intensity during irradiation
  - collimation in front of degrader
  - beam size at degrader (quadrupoles after magnetic septum)
  - deflection at degrader (electrostatic septum or other)

beam splitting: balance sheet

- productivity gain
- no waiting time Ú smaller patient position error
- simplification operation
  - increased modularity
  - fixed tune main beam line (permanent magnets?)

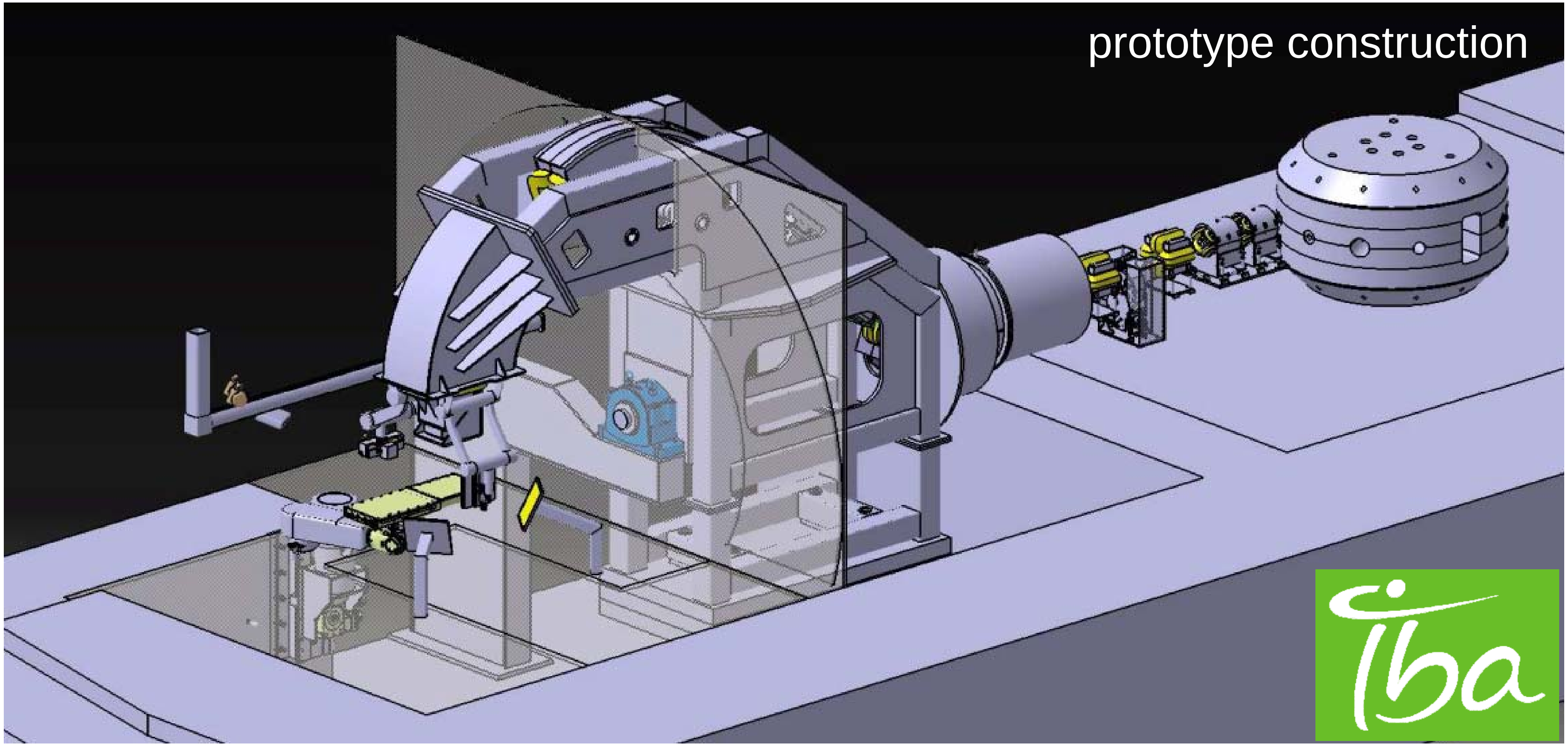
- higher investment
  - eletrostatic + magnetic septum + power supplies
  - additional shielding degrader + ESS
  - no possibilities power supply sharing
  - possibly somewhat higher electricity cost/treatment
    - more equipment running simultaneously
- more activation cyclotron, beam stops etc.

conclusions

- fast switching between treatment rooms straightforward
  - higher throughput
  - system simplification
  - investment
    - kicker + septum magnet
    - degrader
    - additional shielding
- beam splitting
  - true simultaneous operation
  - more additional shielding + activation
- fixed tune of main beam line ⇒ permanent magnets
  - demonstrated at Fermilab antiproton storage ring

development protons: near future

- 230 MeV superconducting synchrocyclotron
  - pulsed beam ~1 kHz repetition rate
  - no fast scanning for moving targets



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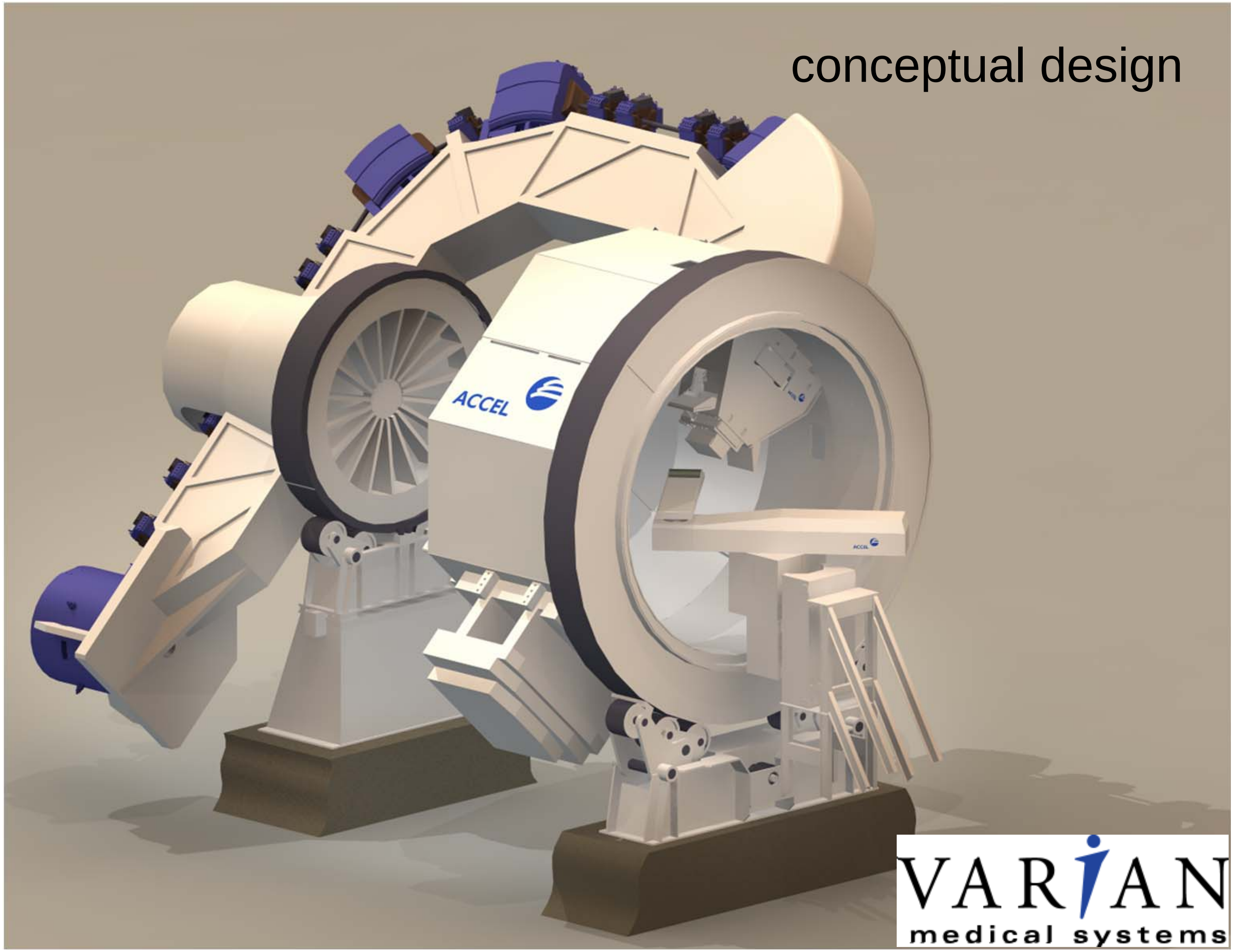


VARIAN medical systems

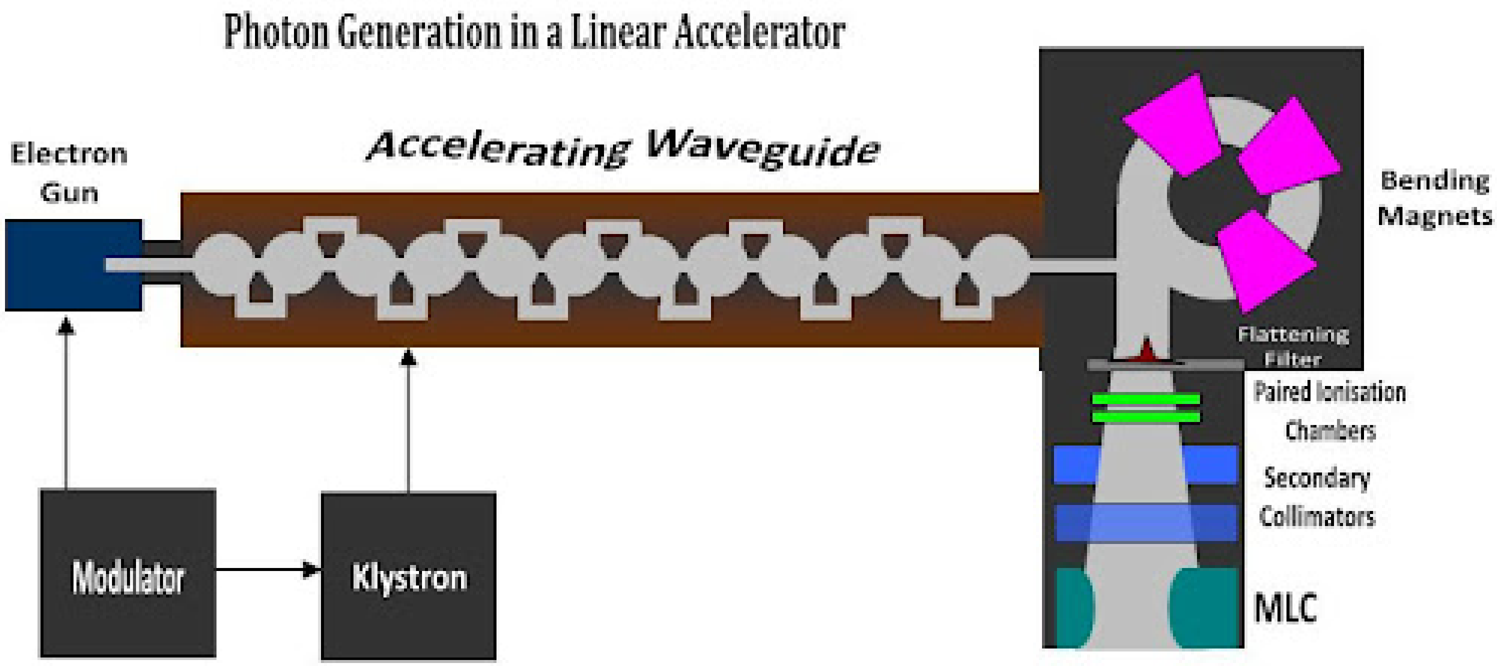
KVI

- European Union data
  - population 500 million
  - cancer incidence 2.7 million per year
  - X-ray radiotherapy 1.5 million per year
    - treatment units ~3500
  - share hadrontherapy < 1 %
    - treatment units ~20
  - annual turnover ~10 billion € (< 1 % total healthcare)
- ~50 % of cured patients have undergone radiotherapy
- ~50 % of patients undergoing radiotherapy are cured

⇒ radiotherapy important element in cancer care

X-ray radiotherapy: equipment

- accelerating structure
  - standing wave coupled cavity linac (copper)
  - operating frequency: 3 GHz (S-band)
  - gradient ~30 MV/m Ú length ~1 m
- mature and robust technology (50 years experience)



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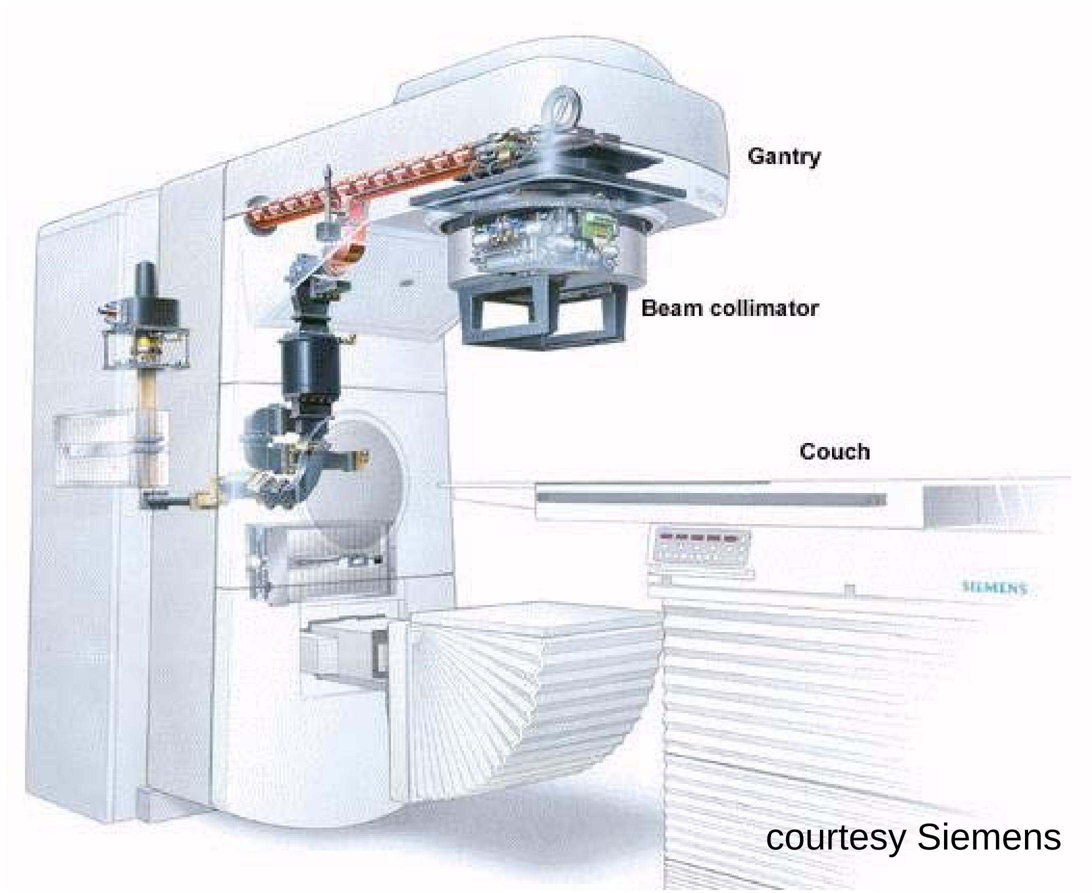
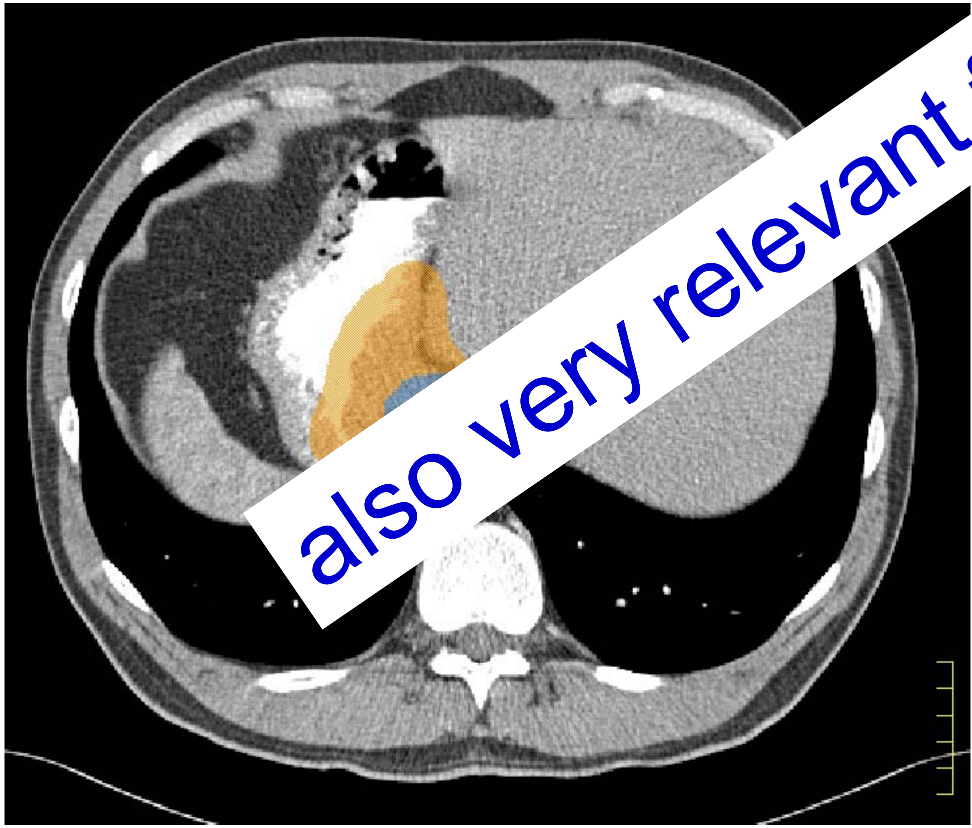


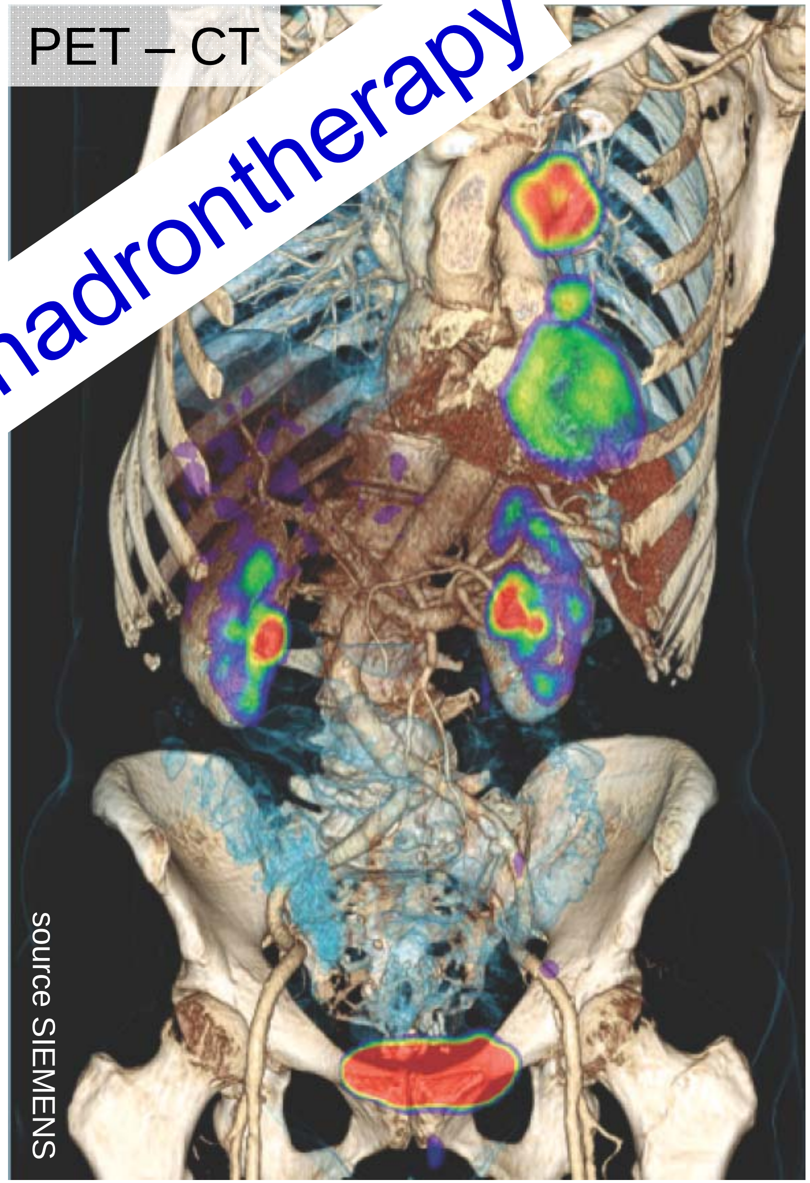
courtesy Siemens

X-ray radiotherapy: development

- better exploitation imaging information: CT, PET, MRI

oesophagus
blue: CT
orange: PET-CT

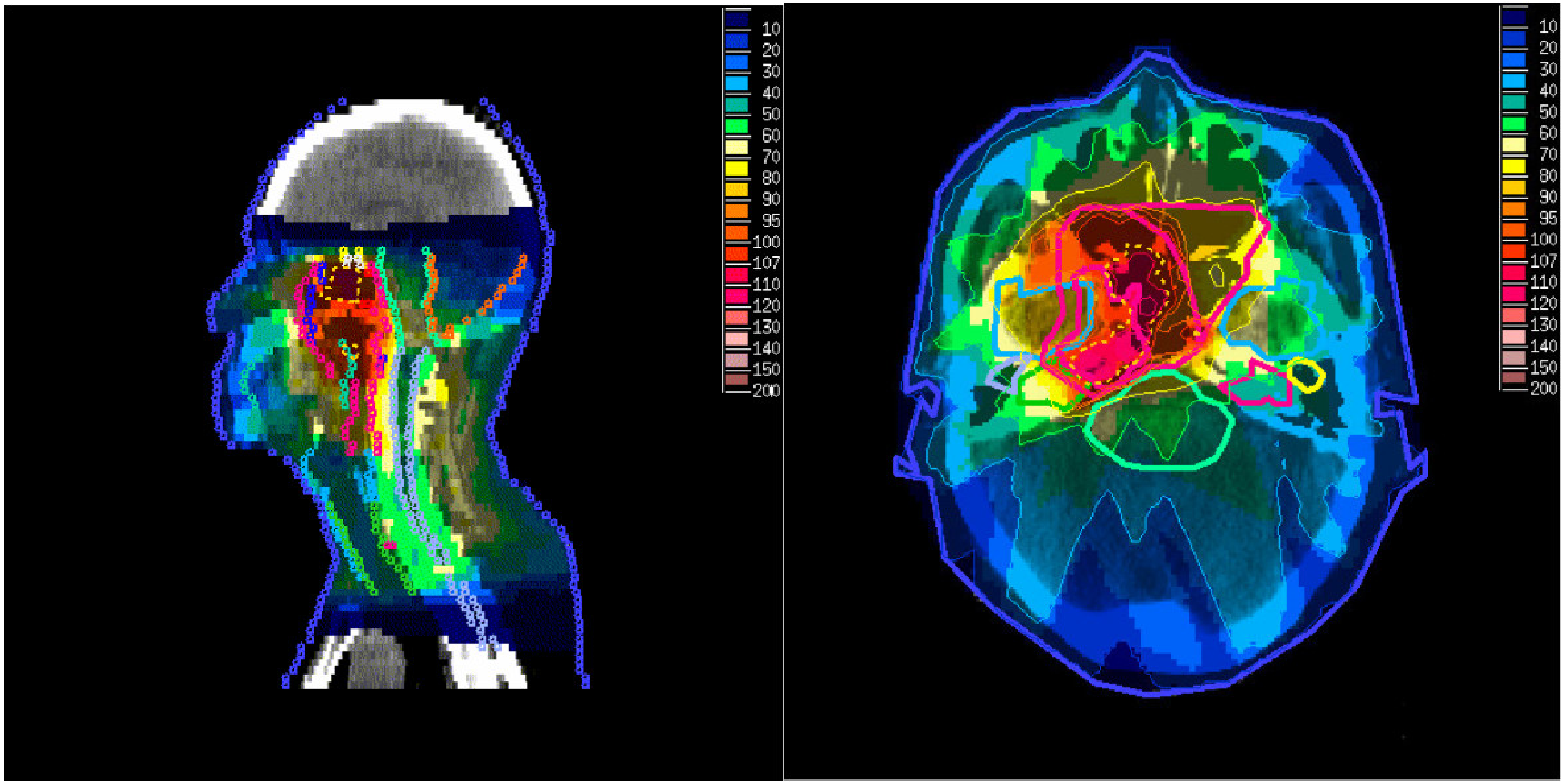




also very relevant for hadrontherapy

X-ray radiotherapy: development

- better exploitation imaging information: CT, PET, MRI
- optimize irradiation strategy: 3D-CRT Ú IMRT Ú VMAT



Taheri-Kadkhoda et al, Radiation Oncology 2008 3:4

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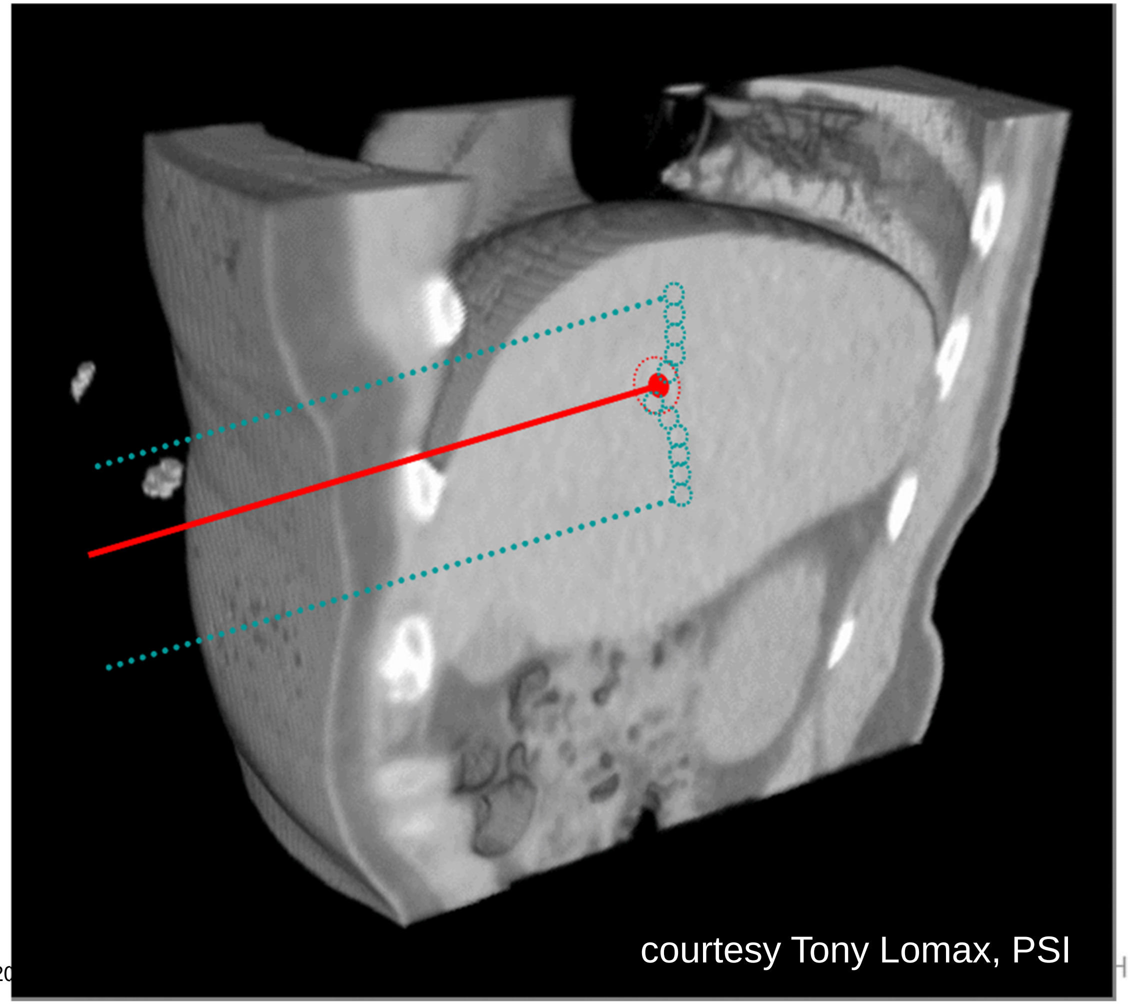
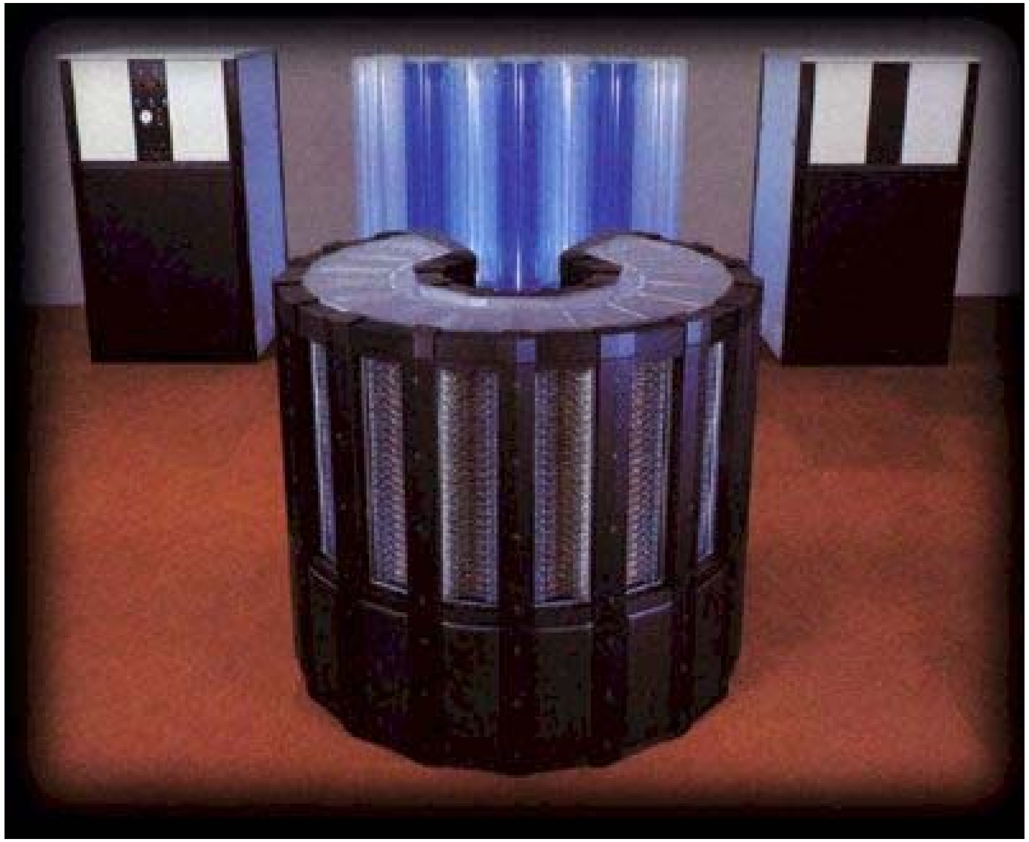
- motion: real time image guided radiotherapy



courtesy Tony Lomax, PSI

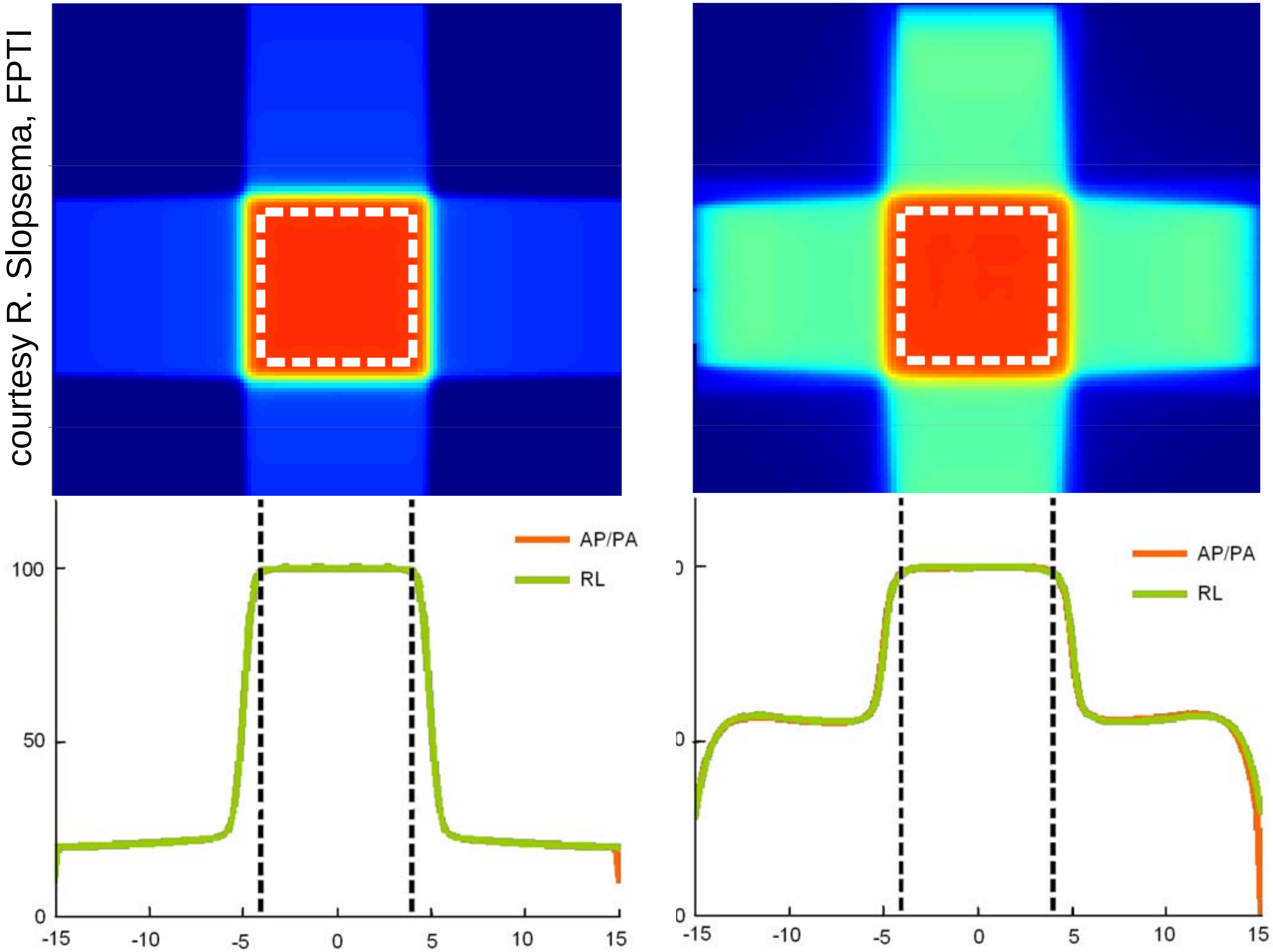
X-ray radiotherapy: development

- better exploitation imaging information: CT, PET, MRI
- optimize irradiation strategy: 3D-CRT Ú IMRT Ú VMAT
- motion: real time image guided radiotherapy
- main progress driver: development ICT technology



why move to protons and carbon?

- superior dose distribution Ú better treatment outcome

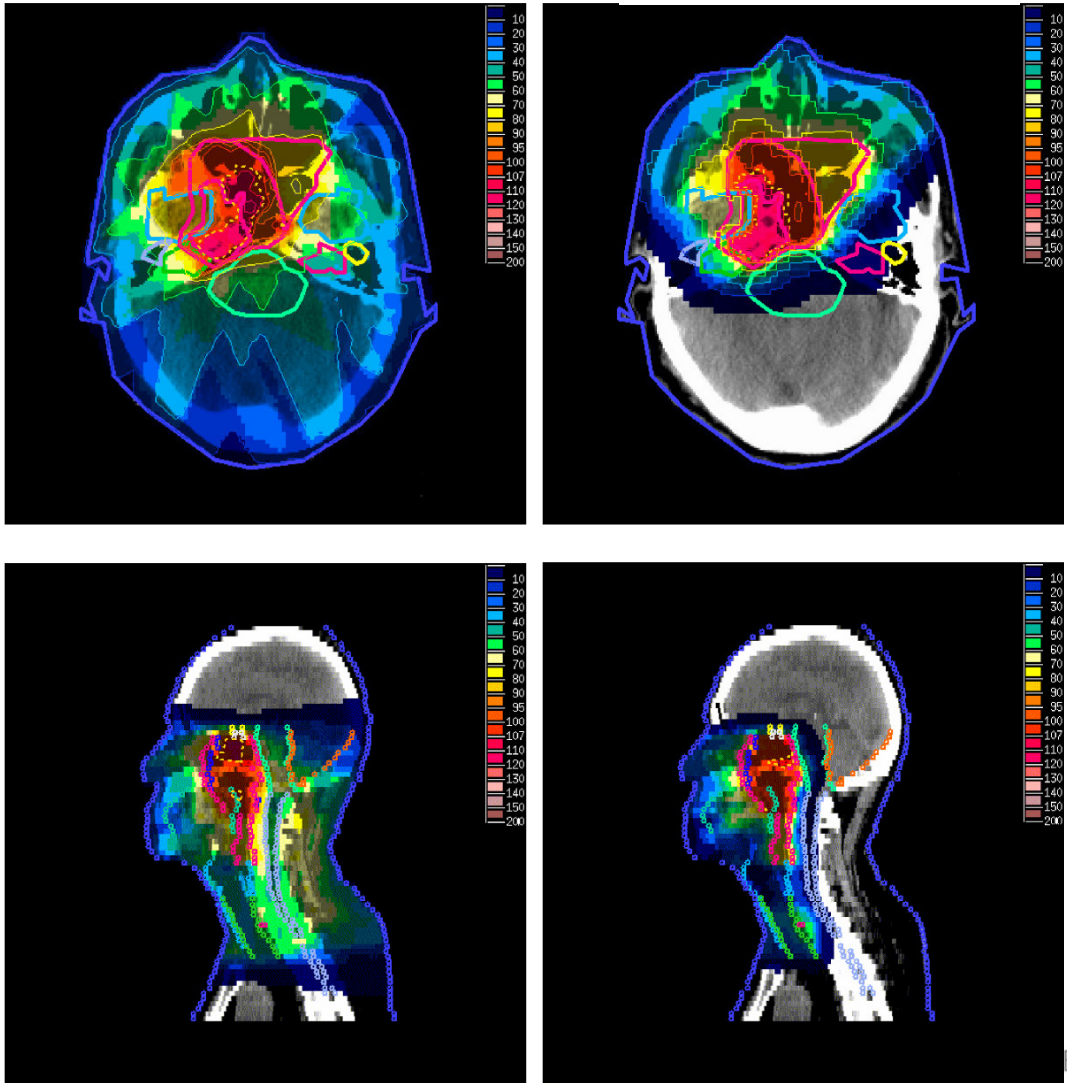


why move to protons and carbon?

- superior dose distribution ⇒ better treatment outcome

- irradiated volume
  non-specific tissue
  > 50 % reduction
  at all dose levels
- dose reduction
  critical organs
  10 – 60 %

9 fields photons   3 fields protons



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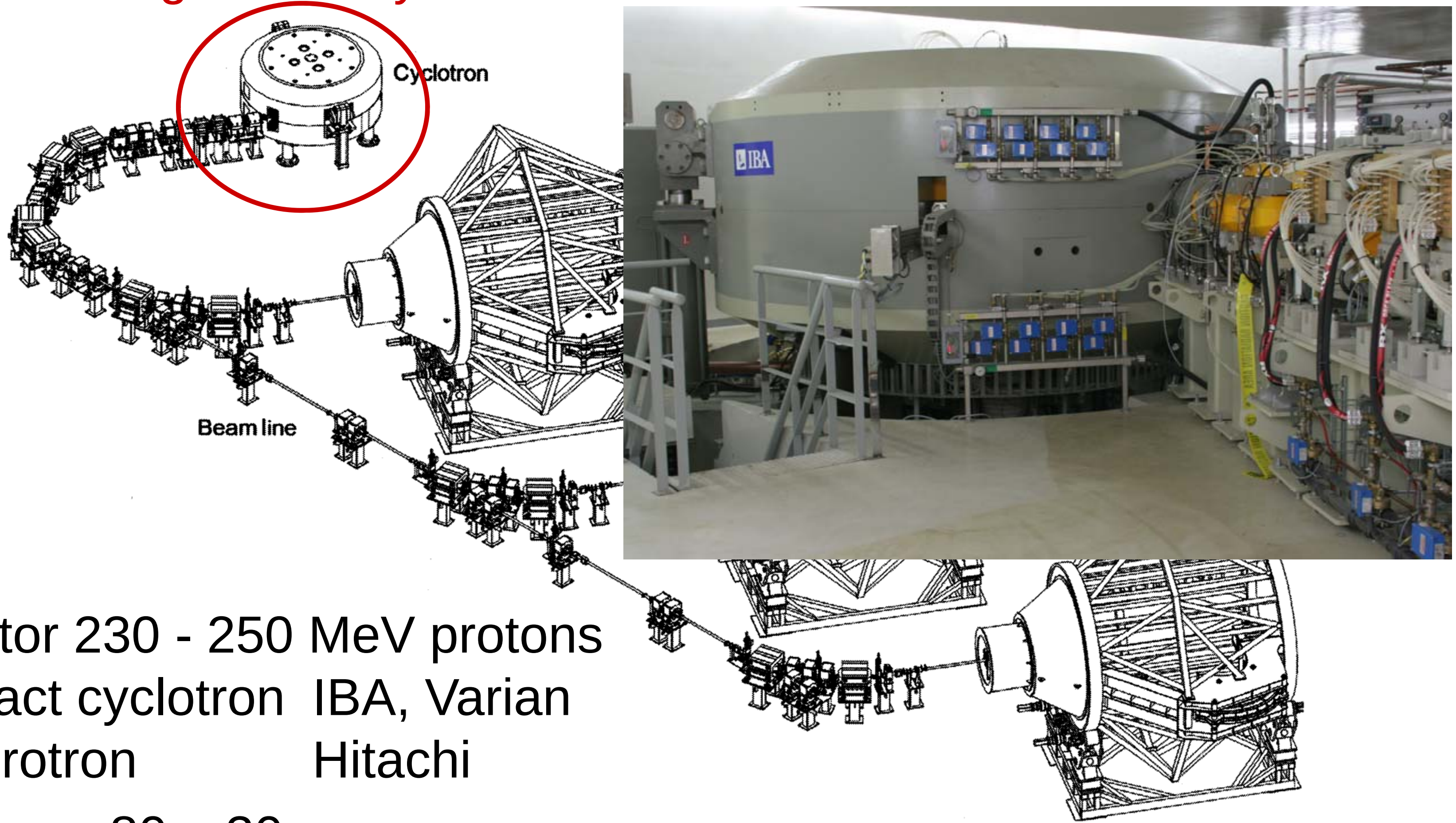
- superior dose distribution ⇒ better treatment outcome
- complex large scale system

courtesy IBA



accelerator 230 - 250 MeV protons

- compact cyclotron IBA, Varian
- synchrotron Hitachi

facility area ~80 × 30 m

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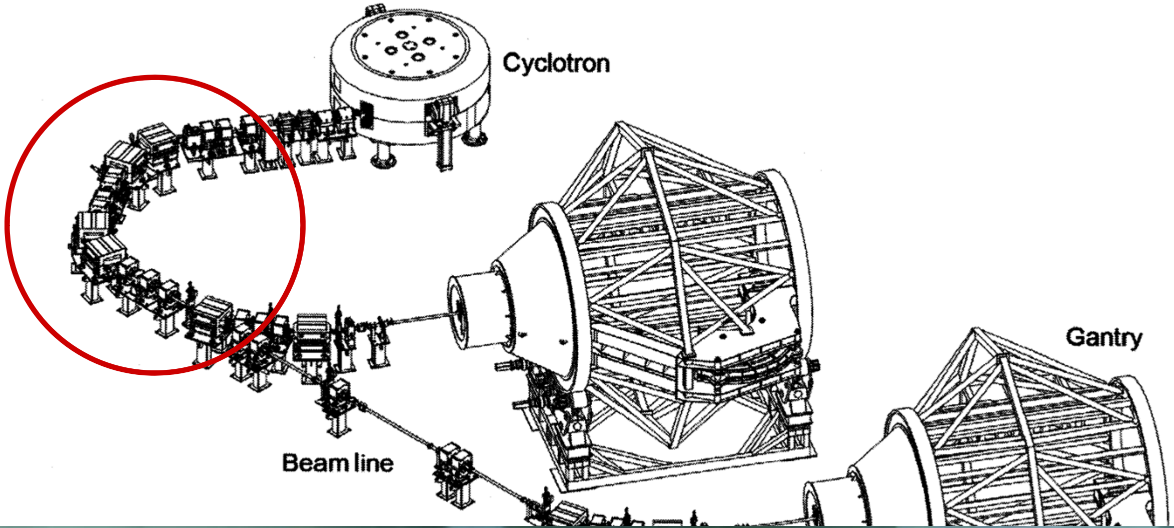

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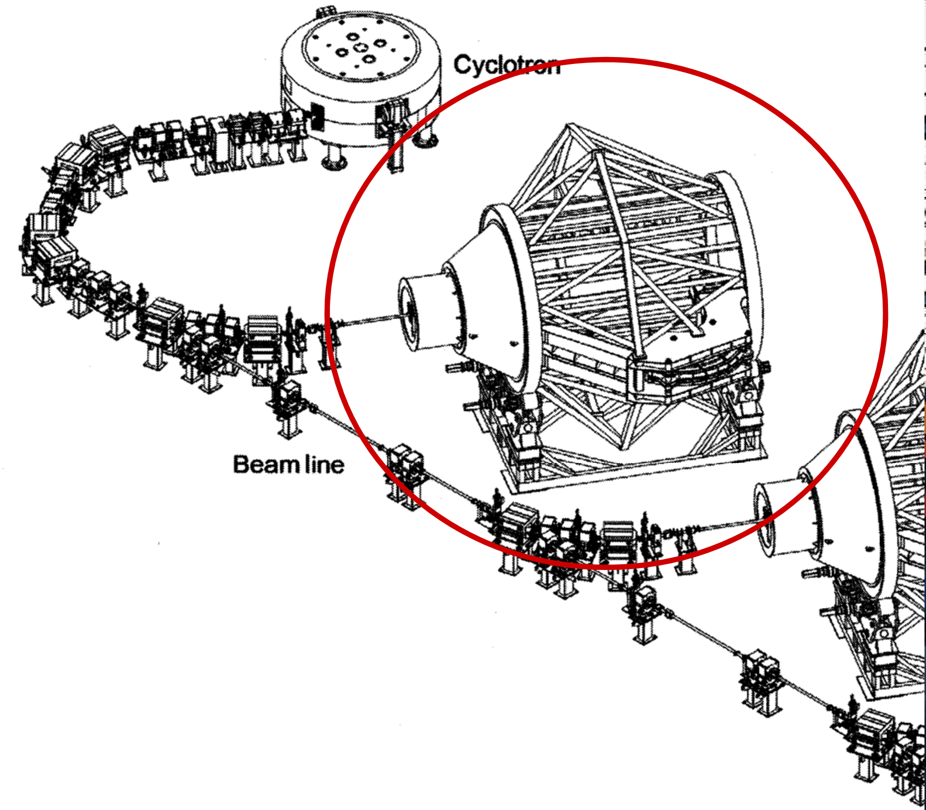

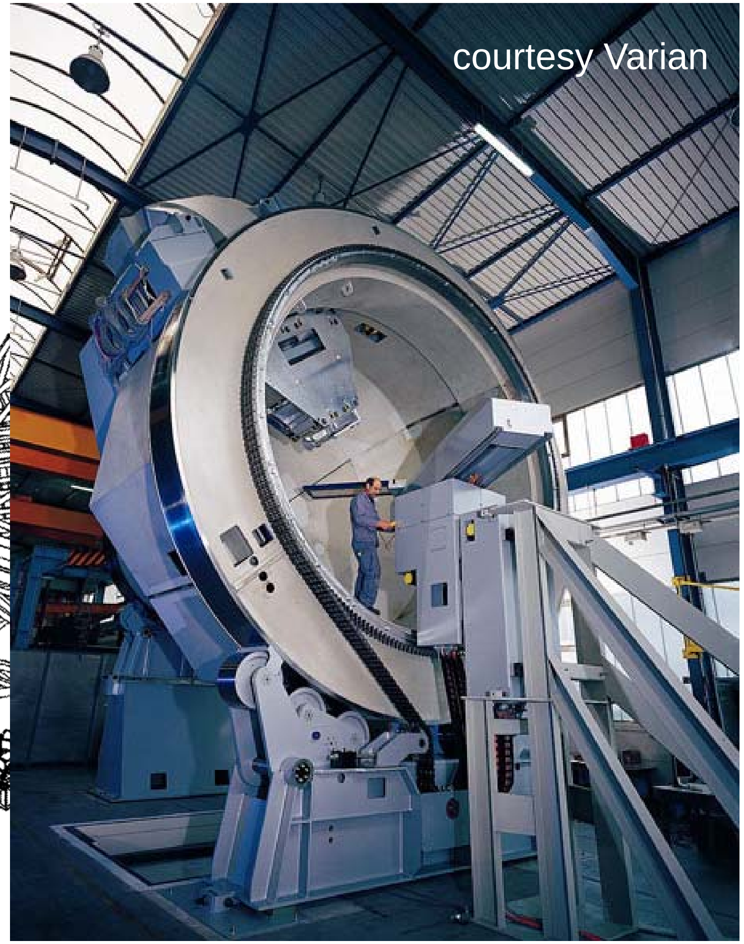

- gantry diameter ~12 m

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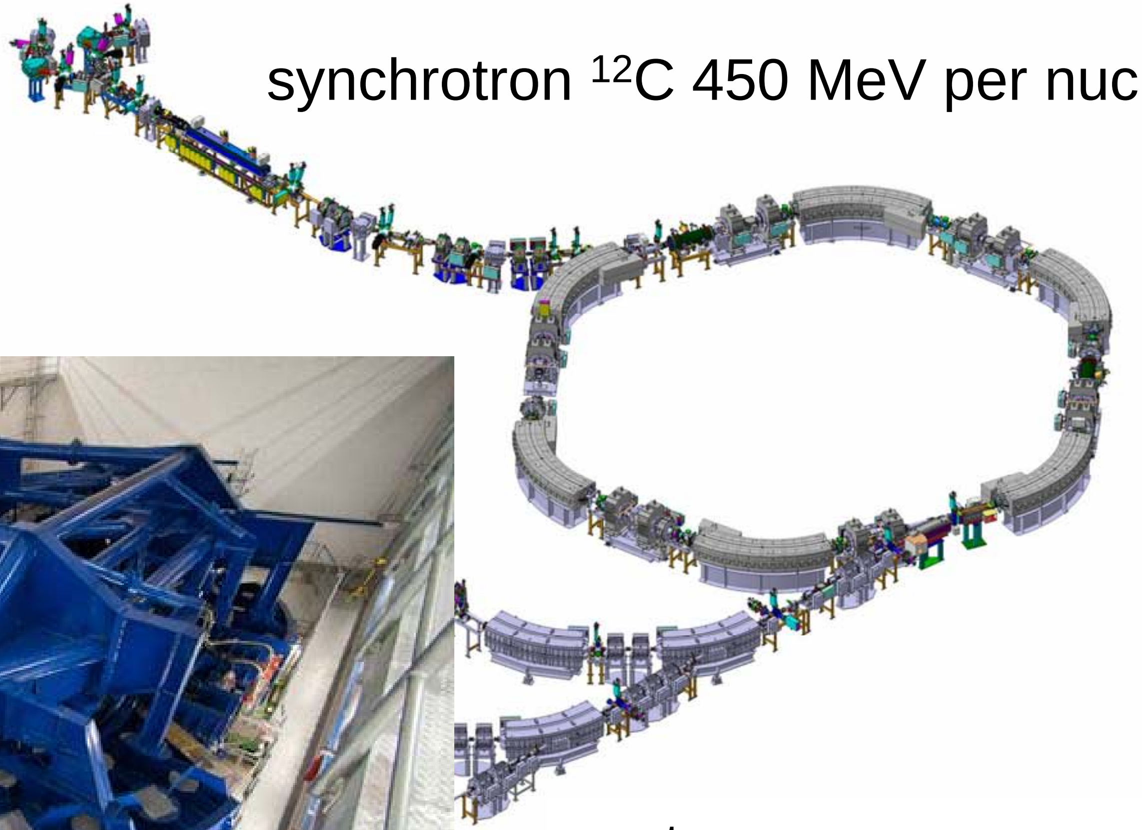

synchrotron ^{12}C 450 MeV per nucleon

gantry
- rotating mass 450 tons
- length 25 m
- diameter 13 m

why move to protons and carbon?

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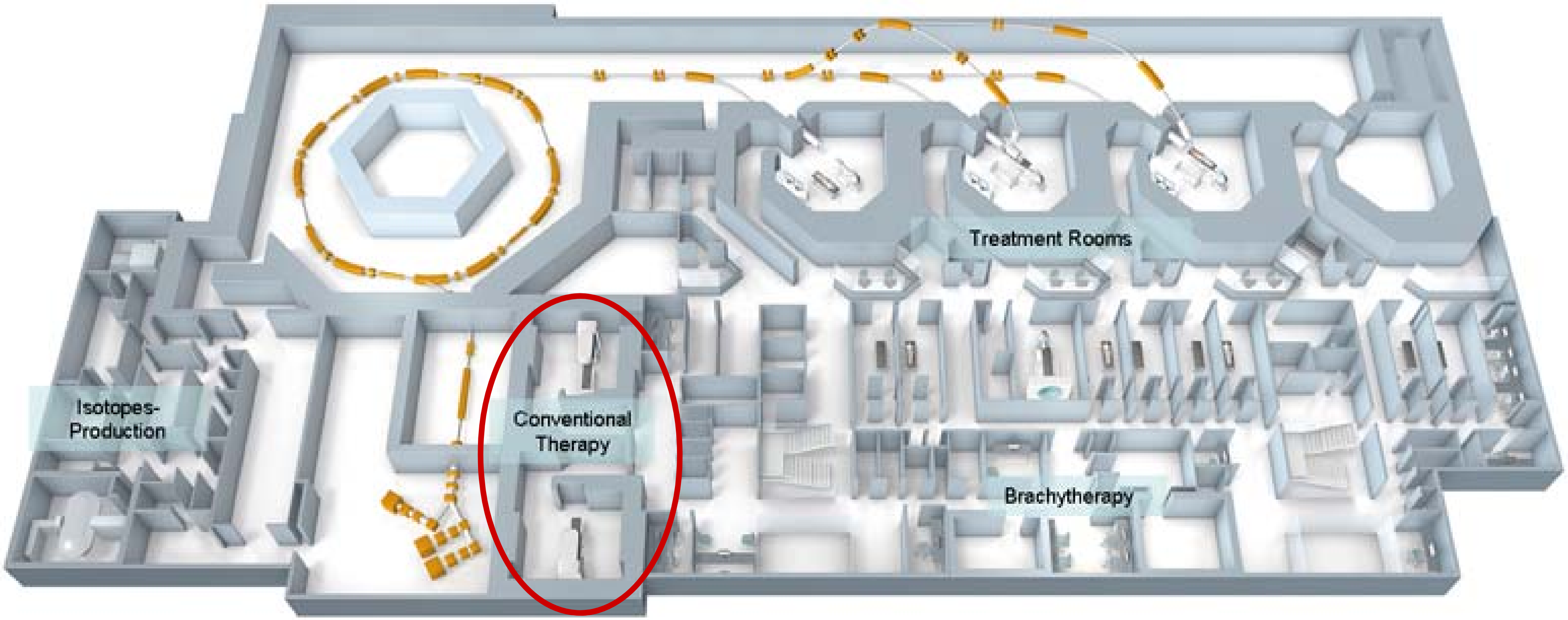


2 photon units

layout NRoCK, Kiel

why move to protons and carbon?

- superior dose distribution Ú better treatment outcome
- complex large scale system
- very high investment cost
  - complete facility
    - irradiation setups
    - diagnostic tools (CT, PET, M…
    - building
    - capacity 1500 patie… …ear
  - investment
    - X-rays 25 M€
    - protons 120 M€ (Skandion, Uppsala)
    - carb… 230 M€ (NRoCK, Kiel)

Ú exper… …ment

Ú m… …netration difficult….. even if better

our challenge: make it smaller, cheaper and better

current status proton

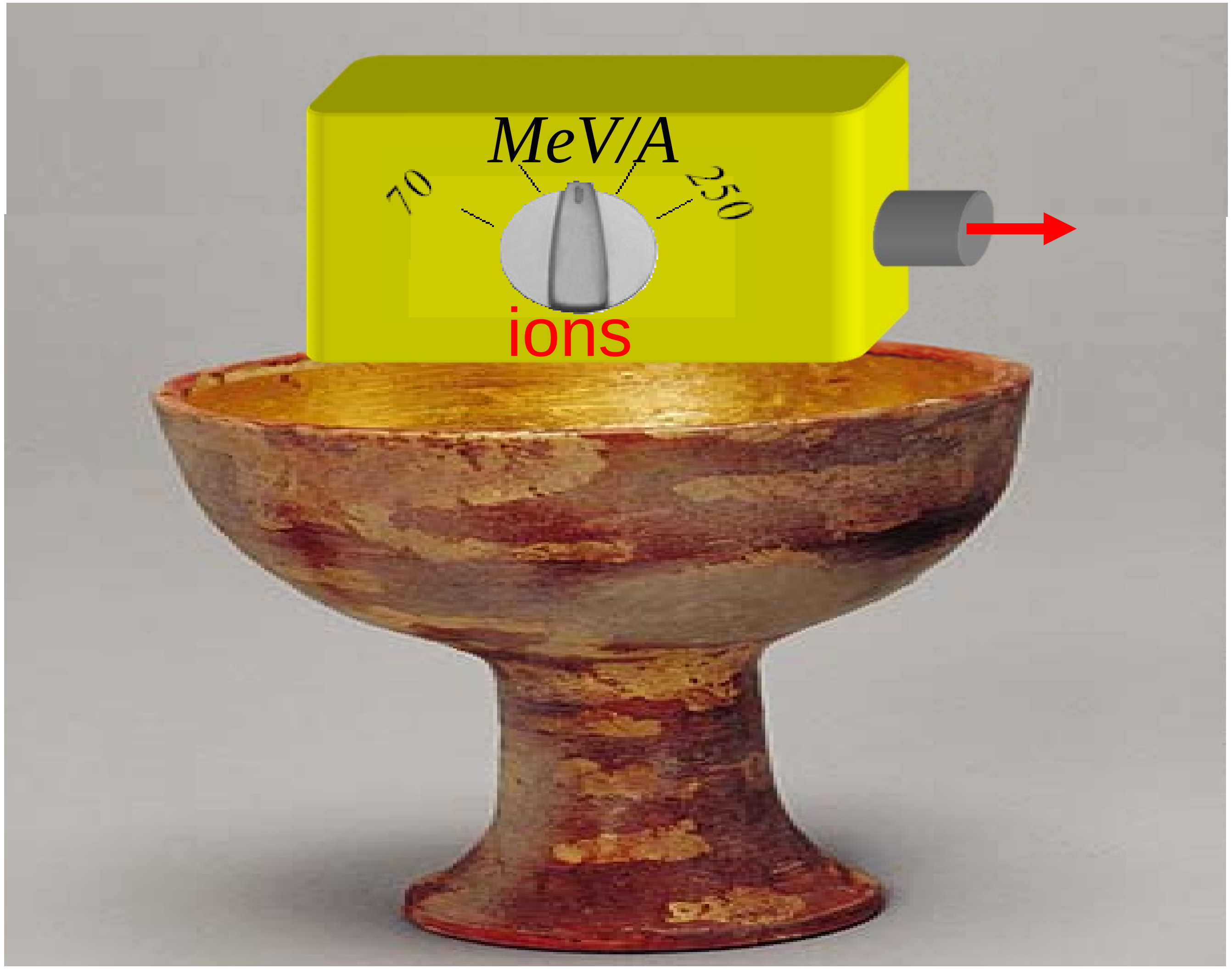
- 96000 patients treated since 1954; 12000 in 2011
- Japan
  - 6 centers operational
  - 2 centers under construction
- China
  - 2 centers operational
  - 2 centers under construction
- Taiwan
  - 1 center under construction
- Europe
  - 12 centers operational
  - 7 centers under construction
- North America
  - 10 centers operational
  - 6 centers under construction

current status carbon

- 9000 patients treated since 1975; 2000 in 2011
- Japan
  - three centers operational: Chiba; Hyogo; Gunma
  - two centers under construction: Kyushu, Tohoku
- China
  - one experimental center operational: Lanzhou
  - one center under construction: Shanghai
- Europe
  - two centers operational: HIT, Heidelberg; CNAO Pavia
  - one center under construction: MedAustron, Vienna
  - one center not active: Rhön Klinikum/Siemens, Marburg
  - one center cancelled: NRoCK, Kiel
  - one center in preparation: Etoile, Lyon
  - one research facility in preparation: ARCHADE, Caen
    - only superconducting cyclotron based facility
- North America: no activity

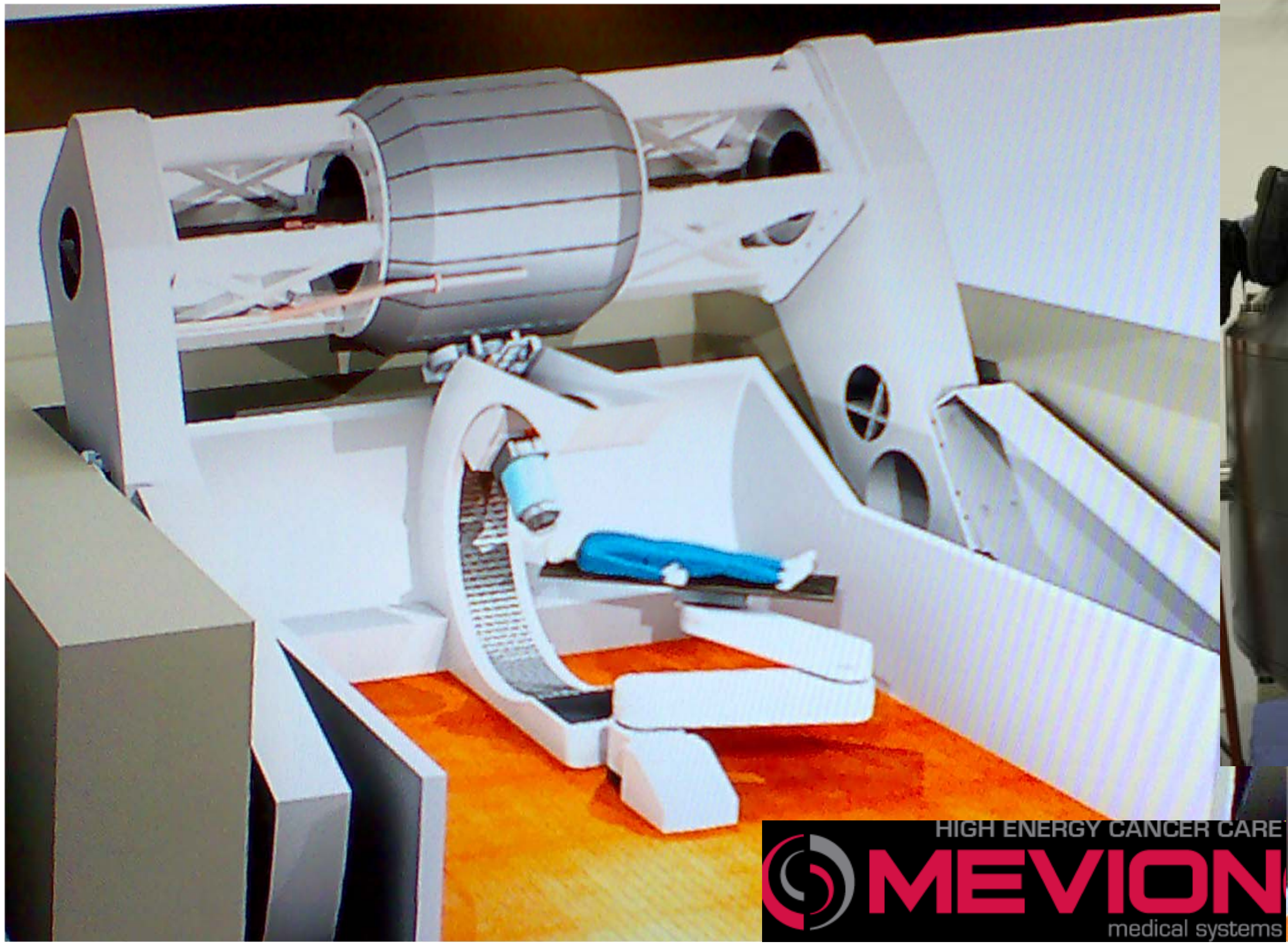
future development hadron therapy

- Holy Grail: one small and cheap accelerator per room



development protons: near future

- 250 MeV superconducting synchrocyclotron
  - pulsed beam ~1 kHz repetition rate
  - no degrader + energy selection system
  - no pencil beam scanning



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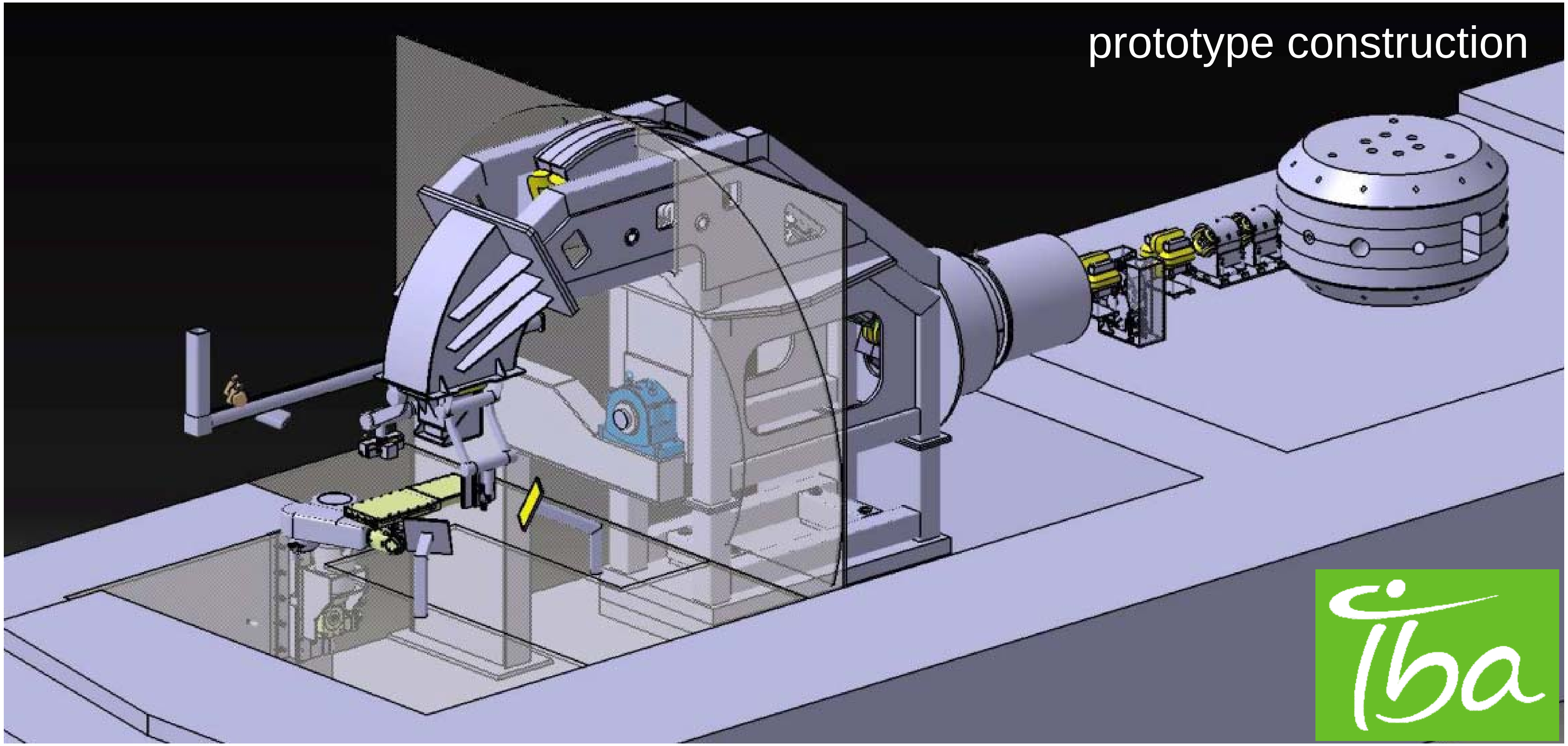

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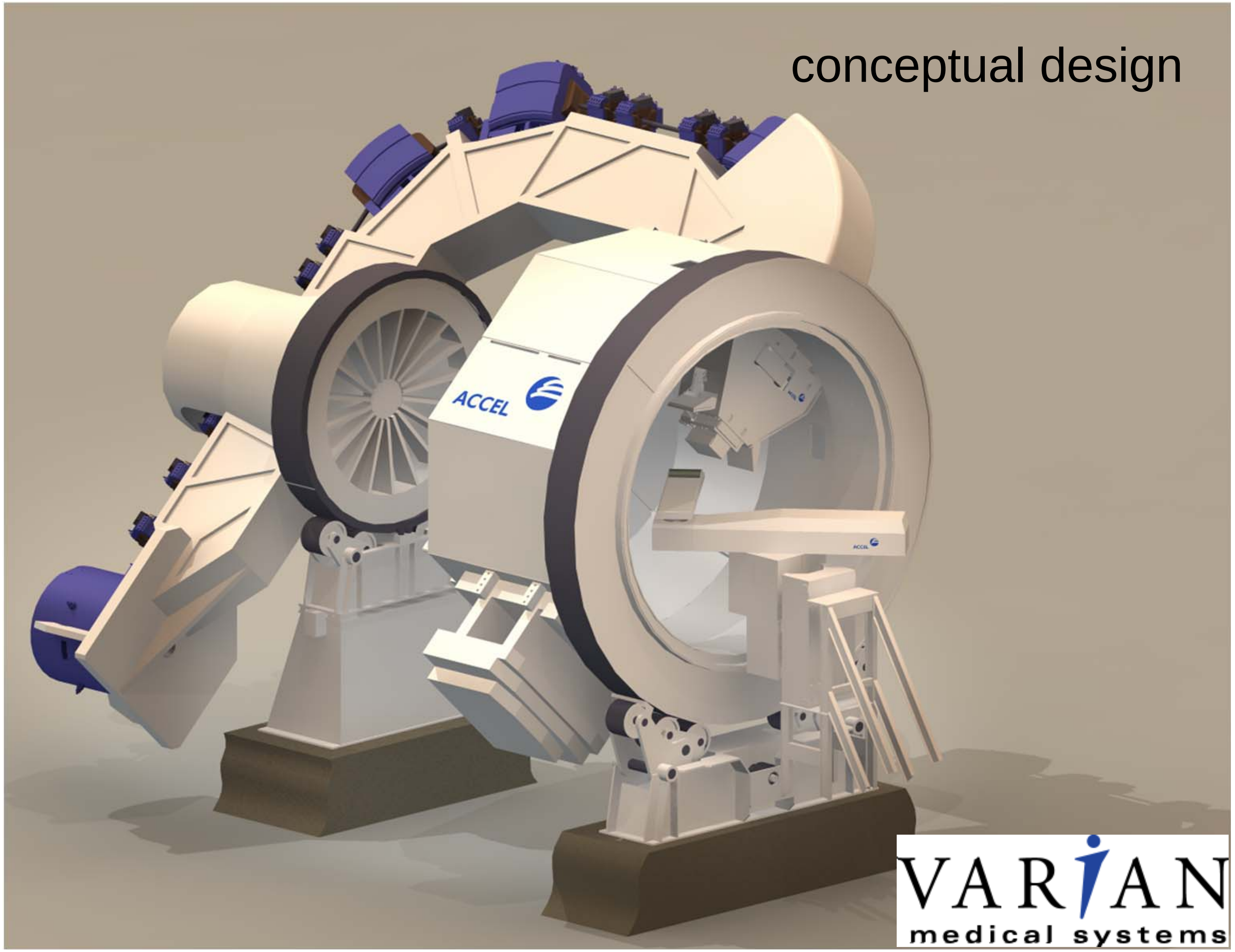


development protons: near future

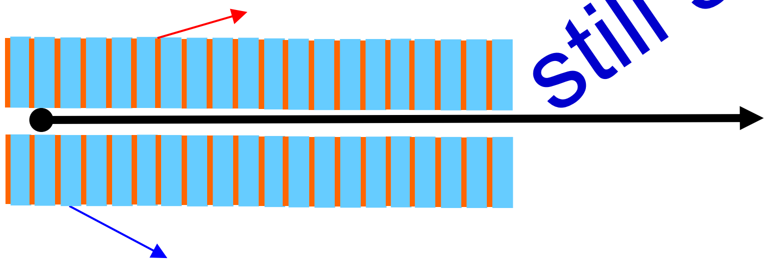
- keyword: superconductivity
- smaller yes
- cheaper yes
- better no
  - at best similar to current state-of-the-art
  - no upgrade dose delivery technique possible

development protons: long term

- Dielectric Wall Accelerator
  - 2.5 m pulsed linac for 250 MeV protons
  - pulse to pulse variable energy
  - many technological challenges
  - dose delivery technique not clear

still some years to go

metal electrode,
high voltage pulse along tube

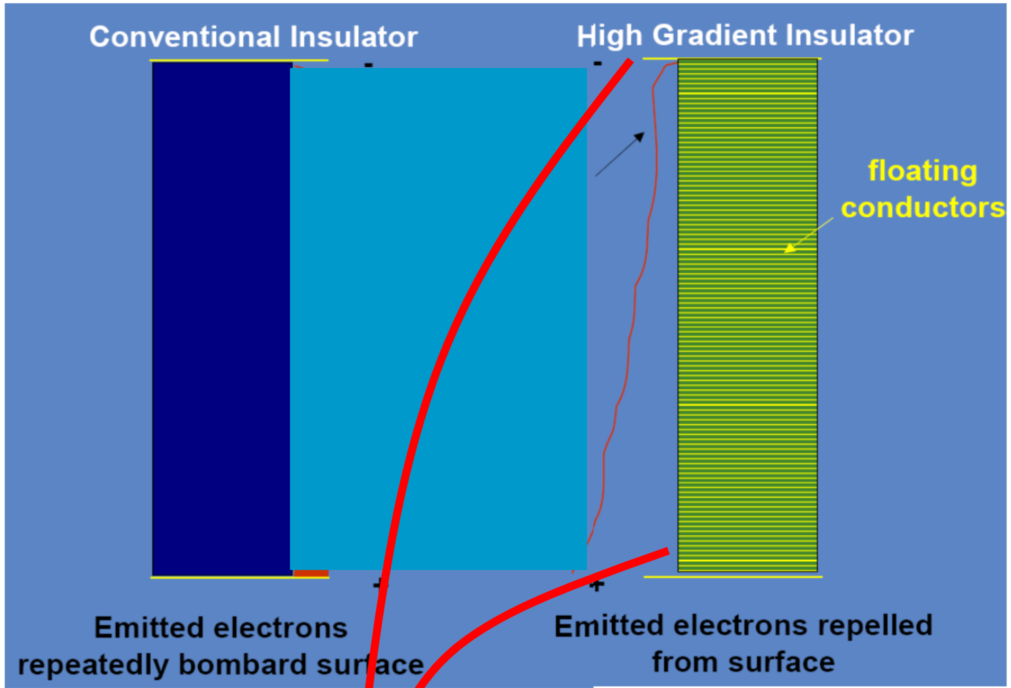


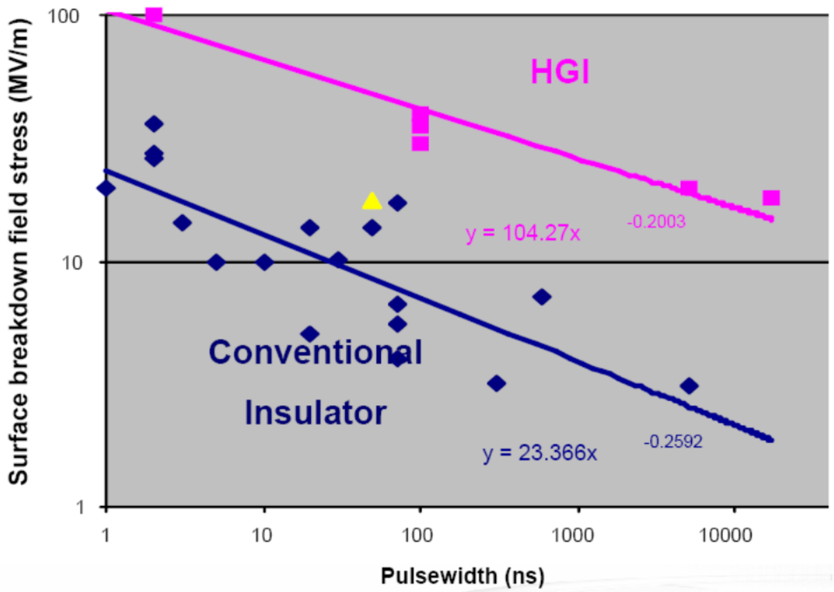
dielectric material

technology development CPAC + LLNL

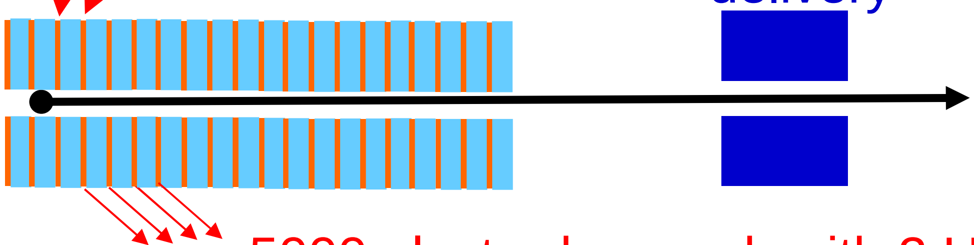
development protons: long term

- principle of operation DWA





dose delivery



2 ns pulses

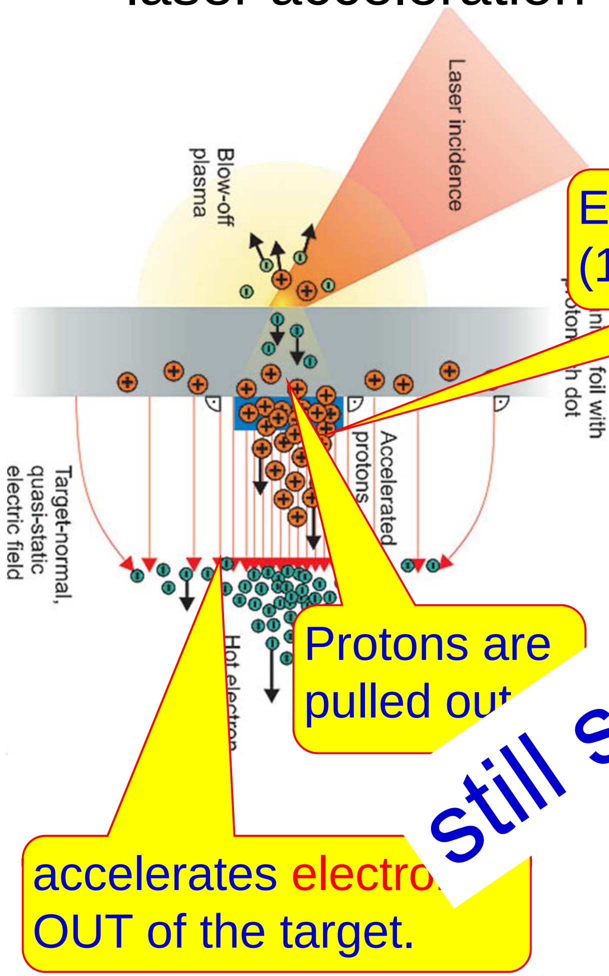
with 100mA protons

at 10 Hz

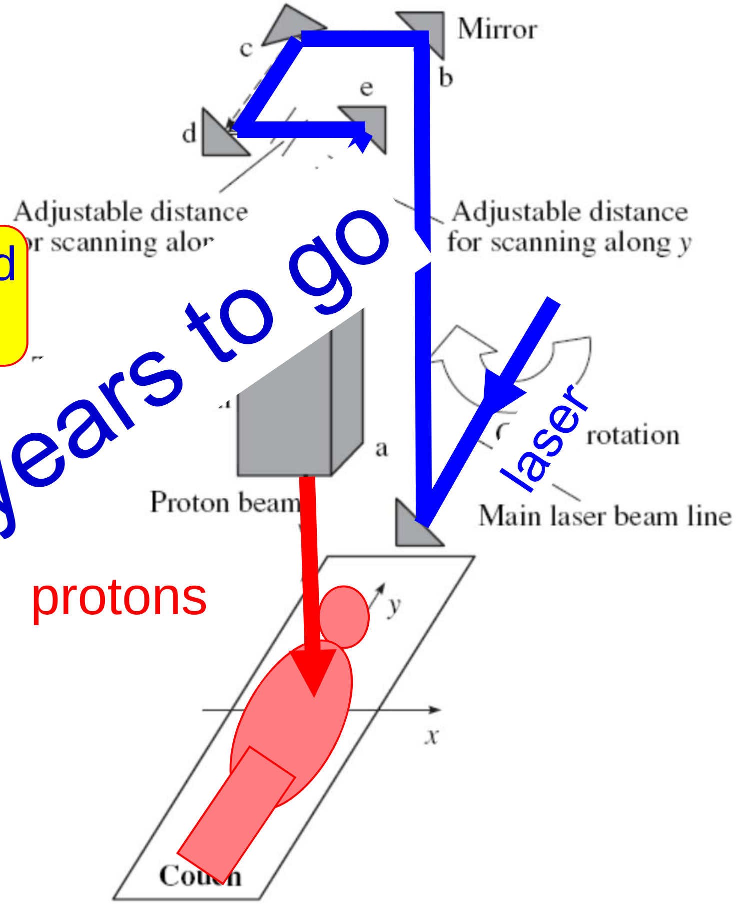
~5000 electrodes, each with 2 HV switches (25 kV)

development protons: long term

- laser acceleration



still some more years to go



- laser performance
- low duty cycle
- control proton energy
- dose delivery technique

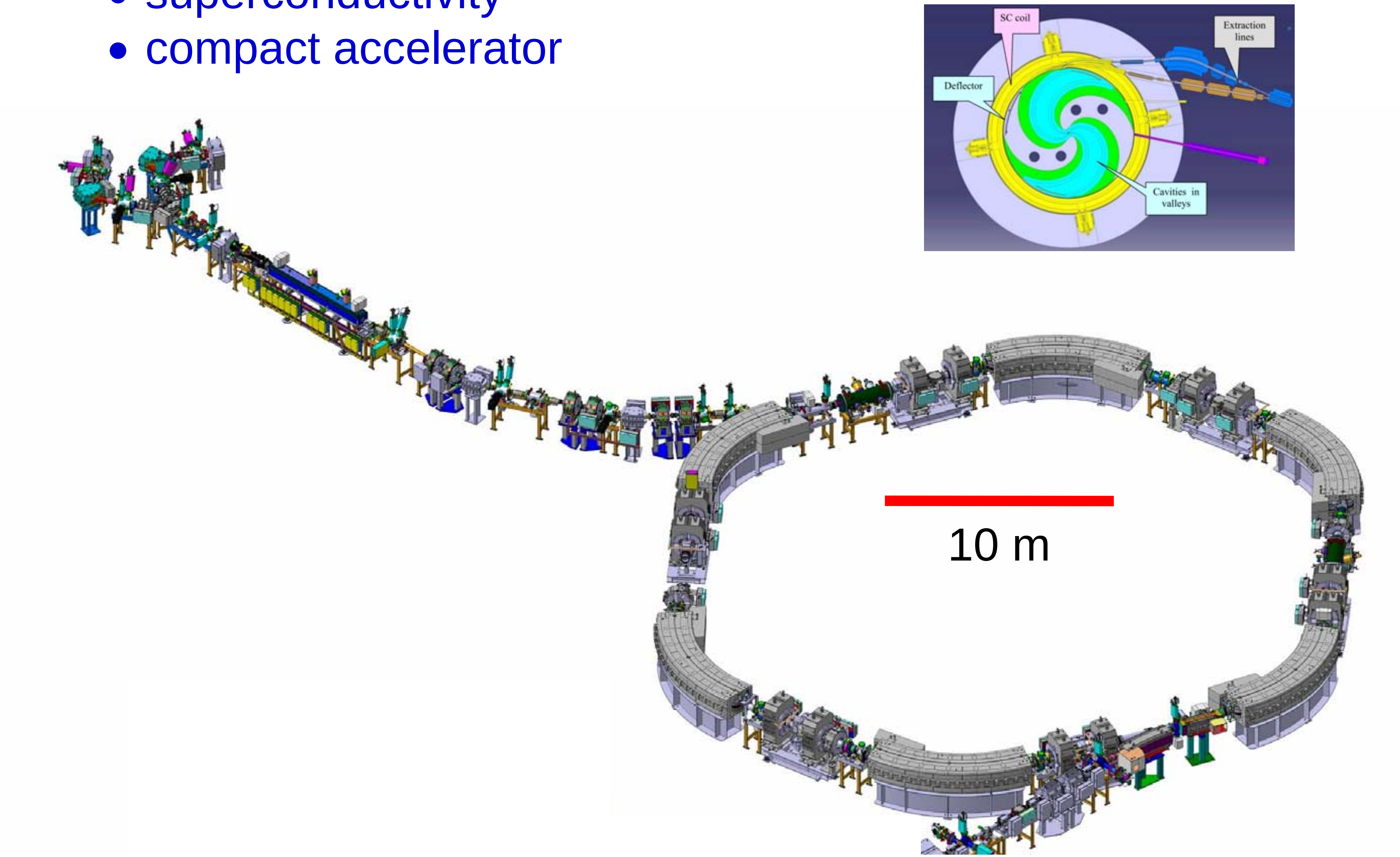
development protons: long term

- smaller probably
- cheaper maybe
- better not possible to predict

solutions looking for a problem ?

development carbon: accelerator

- comparison Heidelberg synchrotron – IBA C400 cyclotron
  - key factors
    - superconductivity
    - compact accelerator



development carbon: accelerator

- comparison Heidelberg synchrotron – IBA C400 cyclotron
  - key factors
    - superconductivity
    - compact accelerator
  - cyclotron: fixed energy, continous beam
  - synchrotron: variable energy, pulsed beam (< 1 Hz)
- differences in treatment quality?
  - compare proton facilities with cyclotron and synchrotron

  Ú no evidence

Ú superconducting cyclotron clearly more cost effective:
the way to go

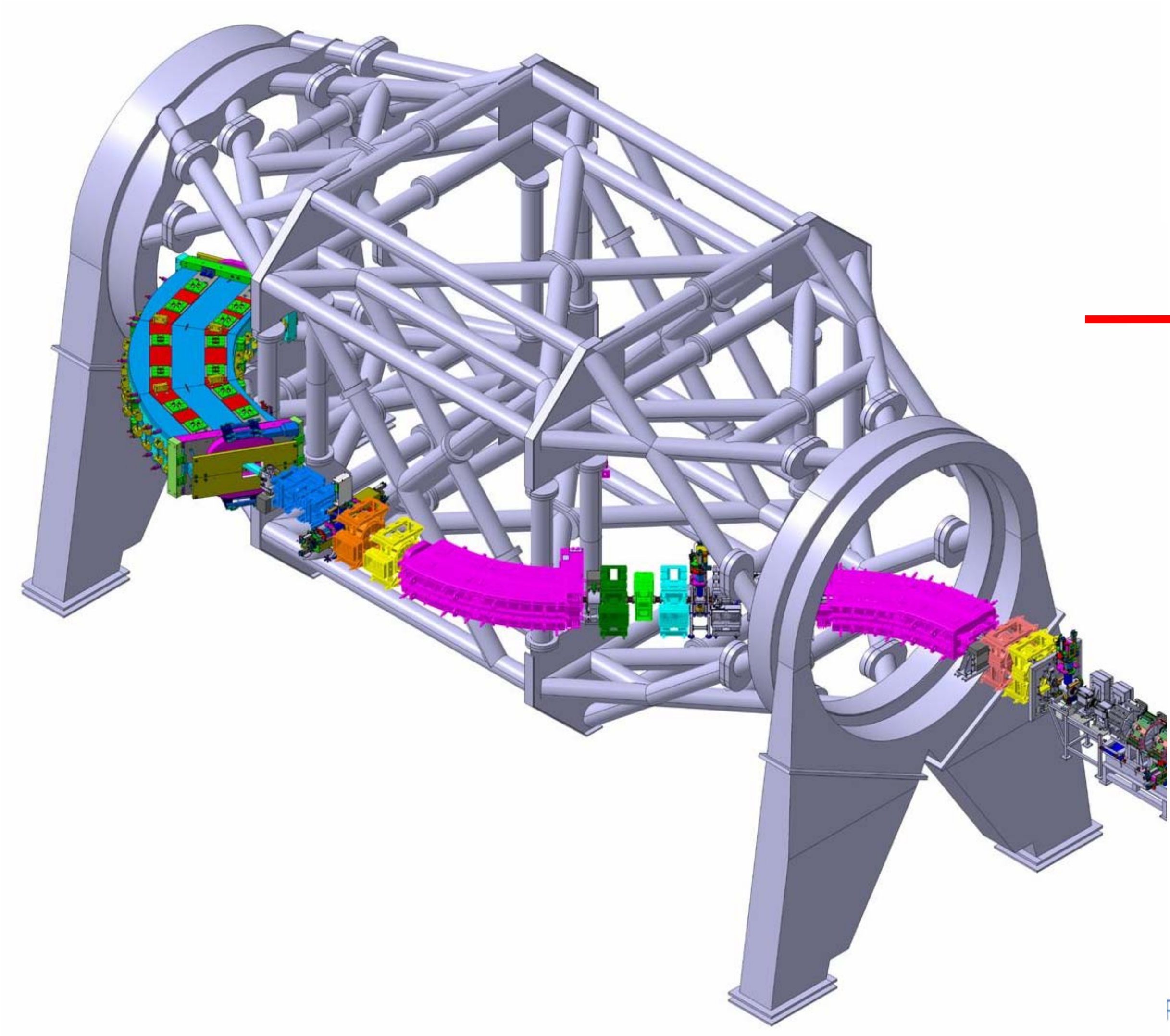
development carbon: dose delivery

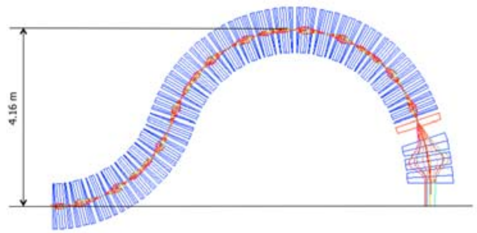
- need for gantry: what is loss in treatment quality
  - analysis by radiation oncologists and medical physicists
- superconducting magnets keyfactor to size reduction
- options
  - fast field variation (similar to current gantries)
    - challenge: quench behaviour
  - large momentum acceptance, achromatic gantry
    - slow field variation
    - challenge: patient safety (no energy selectivity)

development carbon: dose delivery

- HIT gantry vs. concept FFAG gantry Trbojevic (Brookhaven)

Ú large potiential for scale reduction





10m

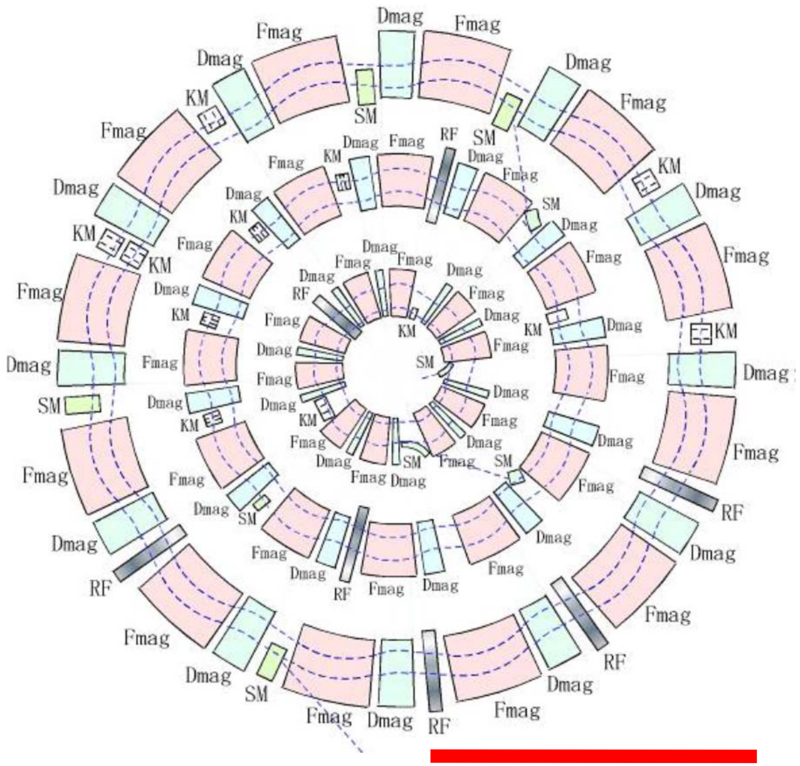
development carbon

- key factor: superconductivity
- cheaper yes
- smaller yes
- better most likely not worse
- good perspective for large increa... ...ectiveness

who takes up the challenge ?

development carbon: long term

- Fixed Field Alternating Gradient synchrotron
  - rapid energy variation
  - high frequency pulsed beam
  - does not solve size and cost issues



10 m

150 MeV proton FFAG KEK

development carbon: long term

- Fixed Field Alternating Gradient synchrotron
  - does not solve size and cost issues
- DWA and other high gradient techniques
  - maximum gradient ~100 MV/m Ú $\geq$ 40 m length
  - does not solve size and cost issues
- laser and plasma wakefield acceleration
  - for the moment dreams

conclusions

- high investment limiting factor market penetration
  - smaller and cheaper systems needed
  - no compromise on treatment quality
- several options under investigation
  - novel technologies still far from application
- most promising route to success
  - superconductivity
  - compact accelerator Ú cyclotron
  - compact gantry: FFAG-like ?

- at the age of 70 cyclotrons still have a long life ahead

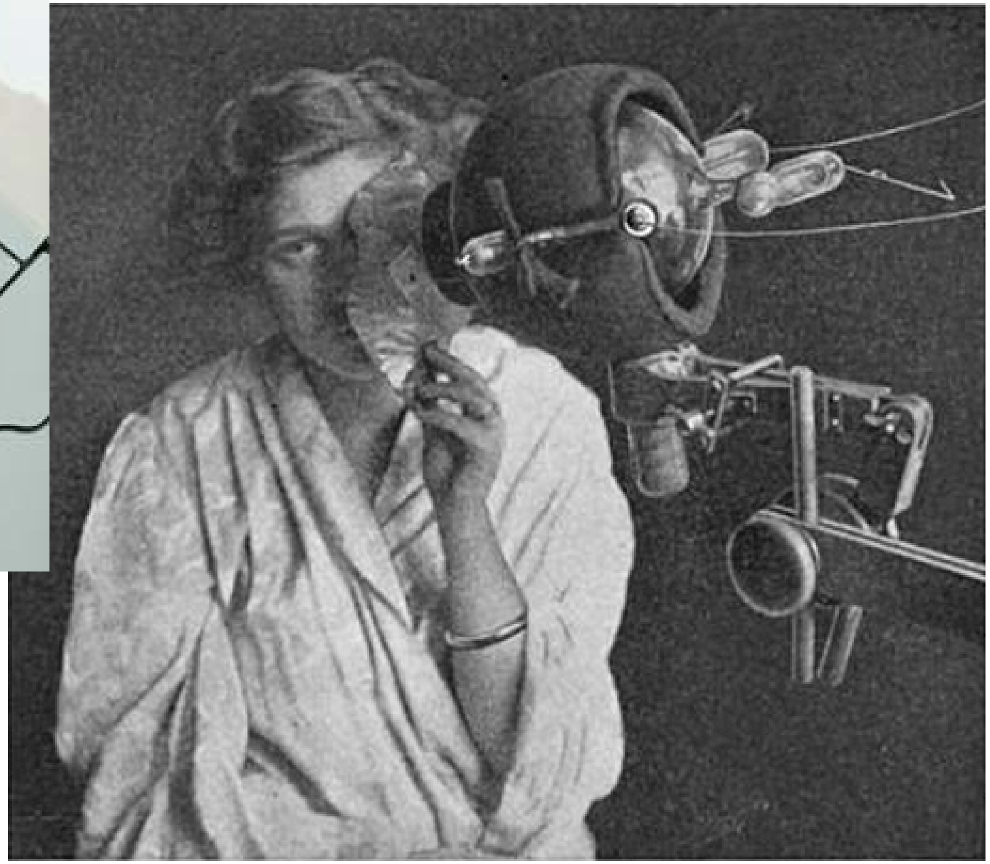
past results are no guarantee for the future

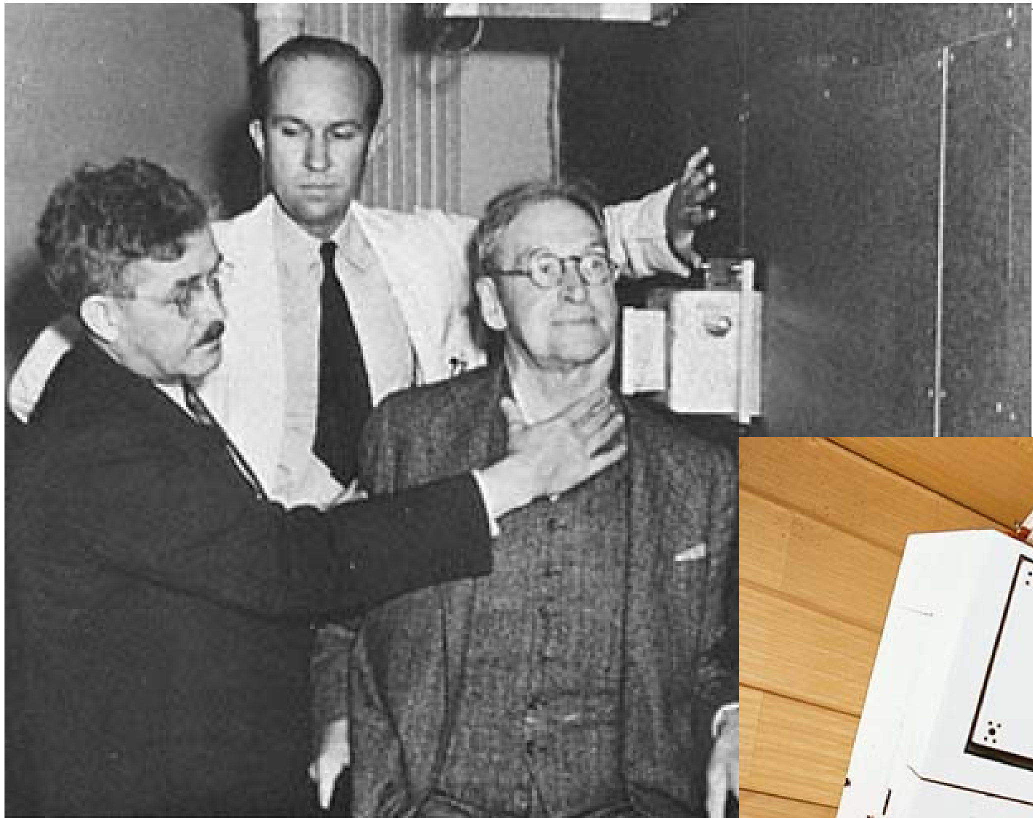
but….

some progress has been made over the last 100 years

X-ray therapy 2012

X-ray therapy 1910





1939: first neutron therapy

2012: scanned proton beams