beam sharing
in cyclotron-based proton therapy facilities

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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
- 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
      - compactness
      - operation efficiency
    - 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
  Ÿ frequent retuning 20 – 30 parameters
  verification of tune (beam position, transmission etc.)
  Ÿ simplify by reduction # parameters
beam use pattern

Example of beam allocation at OKC

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

source ProCure Oklahoma Proton Therapy Center
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!

![Diagram showing degrader, septum magnet, kicker, and energy selection.]

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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
- further reduction waiting times and interference
fast switching: balance sheet

- productivity gain
  - logistics simulation study on-going
- shorter waiting time  Ṣ  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

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  - basically: inverse of stacking injection in ring
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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 ü 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
beam splitting: TURTLE simulation

- beam profile after first split
beam splitting: TURTLE simulation

- beam profile before second split
beam splitting: TURTLE simulation

- beam profile after second split
beam splitting: TURTLE simulation

- beam profile before third split
beam splitting: TURTLE simulation

- beam profile after third split

![Graph showing beam profile and septum](image_url)
beam splitting: TURTLE simulation

- beam profile before fourth split
beam splitting: TURTLE simulation

- beam profile after fourth split

![Graph showing beam profile after fourth split](image-url)
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 Ū smaller patient position error
- simplification operation
  - increased modularity
  - fixed tune main beam line (permanent magnets?)

- higher investment
  - electrostatic + 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
development protons: near future

- 250 MeV superconducting synchrocyclotron
  - pulsed beam \( \sim 1 \text{ kHz} \) repetition rate
  - no fast scanning for moving targets
• 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 
  - length ~1 m
- mature and robust technology (50 years experience)
X-ray radiotherapy: equipment

- accelerator
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- mature and robust technology (50 years experience)

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 ☑️ IMRT ☑️ VMAT

Taheri-Kadkhoda et al, Radiation Oncology 2008 3:4
X-ray radiotherapy: development

- better exploitation imaging information: CT, PET, MRI
- optimize irradiation strategy: 3D-CRT  IMRT  VMAT
- motion: real time image guided radiotherapy
X-ray radiotherapy: development

- better exploitation imaging information: CT, PET, MRI
- optimize irradiation strategy: 3D-CRT, IMRT, VMAT
- motion: real time image guided radiotherapy
- main progress driver: development ICT technology
why move to protons and carbon?

- superior dose distribution → 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%
why move to protons and carbon?

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

accelerator 230 - 250 MeV protons
- compact cyclotron IBA, Varian
- synchrotron Hitachi

facility area ~80 × 30 m
why move to protons and carbon?

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

courtesy IBA
why move to protons and carbon?

- superior dose distribution → better treatment outcome
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- gantry diameter ~12 m
why move to protons and carbon?

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

synchrotron $^{12}$C 450 MeV per nucleon

gantry
- rotating mass 450 tons
- length 25 m
- diameter 13 m
why move to protons and carbon?

- superior dose distribution → better treatment outcome
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why move to protons and carbon?

- superior dose distribution → better treatment outcome
- complex large scale system
- very high investment cost
  - complete facility
    - irradiation setups
    - diagnostic tools (CT, PET, MRI etc.)
    - building
    - capacity 1500 patients per year
  - investment
    - X-rays 25 M€
    - protons 120 M€ (Skandion, Uppsala)
    - carbon 230 M€ (NRoCK, Kiel)

- expensive treatment
- market penetration difficult….. even if 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
development protons: near future

- 230 MeV superconducting synchrocyclotron
  - pulsed beam ~1 kHz repetition rate
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development protons: near future

- 250 MeV superconducting synchrocyclotron
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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

metal electrode, high voltage pulse along tube

dielectric material

technology development CPAC + LLNL

still some years to go
development protons: long term

- principle of operation DWA

- Conventional Insulator
- High Gradient Insulator

- Emitted electrons repeatedly bombard surface
- Emitted electrons repelled from surface

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

- 2 ns pulses
- with 100mA protons
- at 10 Hz

- Dose delivery

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development protons: long term

- laser acceleration

Electric field generated (10^{12} \text{ V/m})

Protons are pulled out

Accelerates electrons OUT of the target.

Laser

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

$10\,\text{m}$
development carbon: accelerator

- comparison Heidelberg synchrotron – IBA C400 cyclotron
  - key factors
    - superconductivity
    - compact accelerator
  - cyclotron: fixed energy, continuous beam
  - synchrotron: variable energy, pulsed beam (< 1 Hz)
- differences in treatment quality?
  - compare proton facilities with cyclotron and synchrotron
    - no evidence
    - 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)
  - large potential for scale reduction
development carbon

- key factor: superconductivity
- cheaper: yes
- smaller: yes
- better: most likely not worse
- good perspective for large increase in cost effectiveness
development carbon: long term

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

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 $\sim 100$ MV/m $\geq 40$ 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 ű 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
1939: first neutron therapy

2012: scanned proton beams