Proton beam delivery technique and commissioning issues: scanned protons

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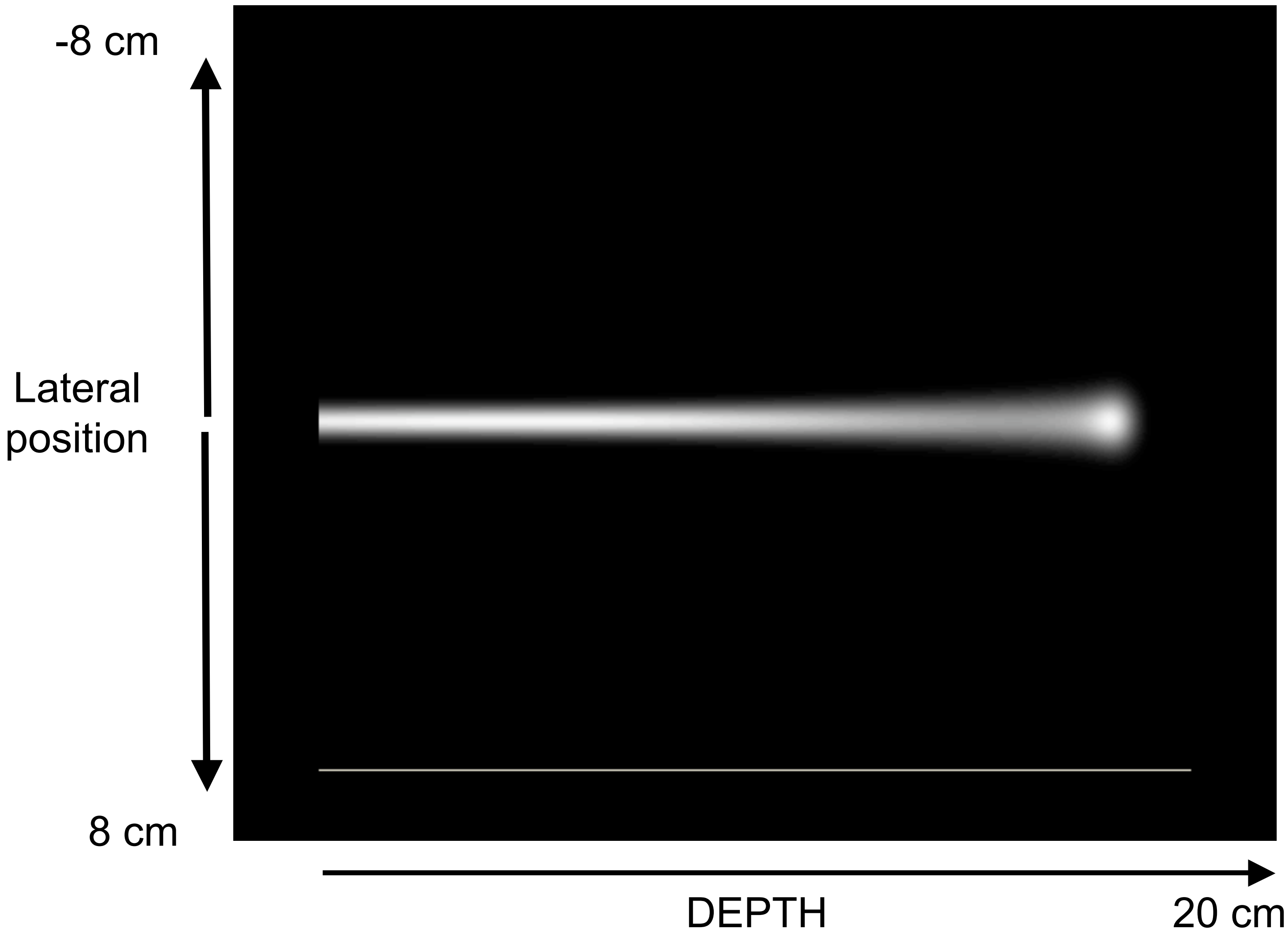
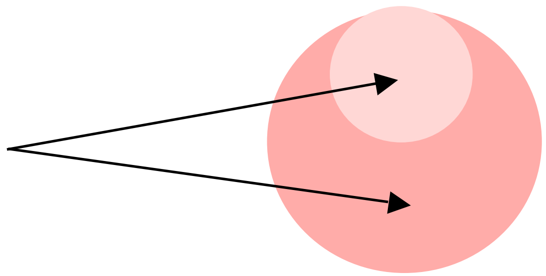
BASIC CONCEPTS

Scanning = Superposition of pencil beams laterally and in depth – dose shaping



Options for beam spreading in the lateral direction

- Uniform particle fluence
  - Wobbling
    - Circular - rectangular– spiral - BEV shaped
  - Dose shaping with collimators and compensators

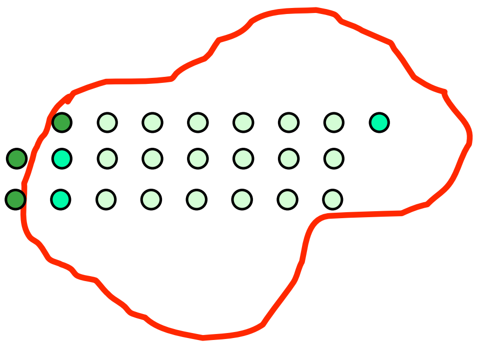


- Modulated particle fluence
  - Full 3d-conformation and IMPT
    - Without collimators and compensators (optional)
  - Methods
    - Magnetic scanning (fast)
    - Or motion of the patient table (slow)

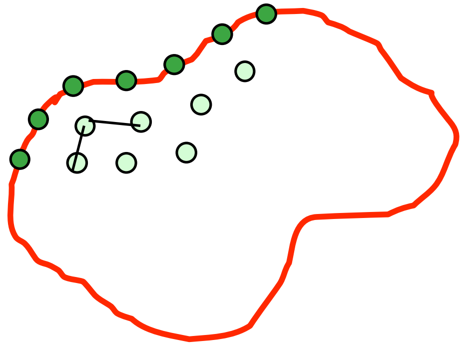
- Parallel vs. divergent scanning
  - Apparent position of the source
- Relation to gantry design

Lateral scanning modes

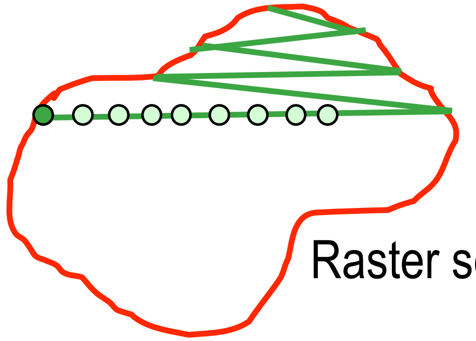
- Spot scanning
  - Single spots – dose shaping by changing the spot time duration
    - beam OFF in between spots
      - PSI Gantry 1
    - beam ON from spot to spot
      - GSI raster scanning
- Continuous scanning
  - Magnetic painting
    - Dose shaping by adapting the magnet speed to the dose rate
      - PSI Gantry 2
  - Beam intensity painting
    - Max. speed – dose shaping by beam intensity modulation
      - PSI Gantry 2



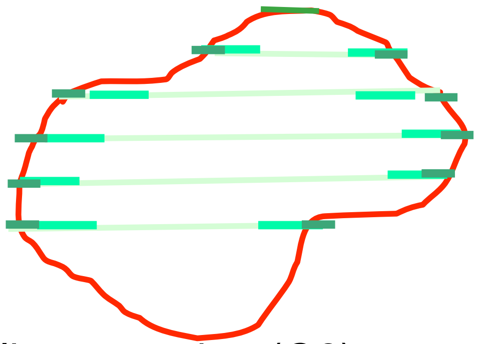
Spot scanning (G1)



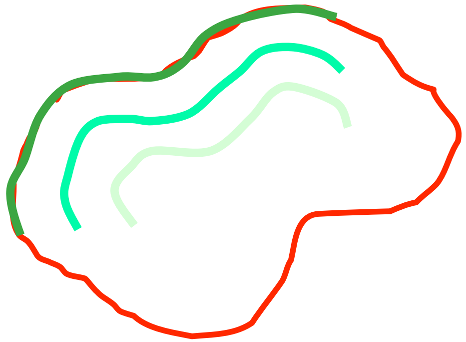
Spot scanning (G2)



Raster scanning (GSI)



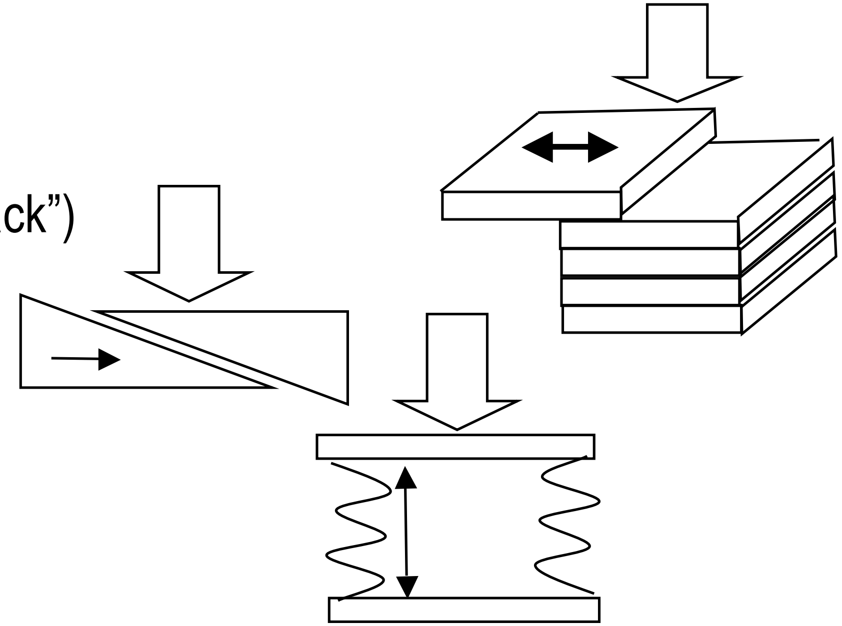
I.M. line scanning (G2)



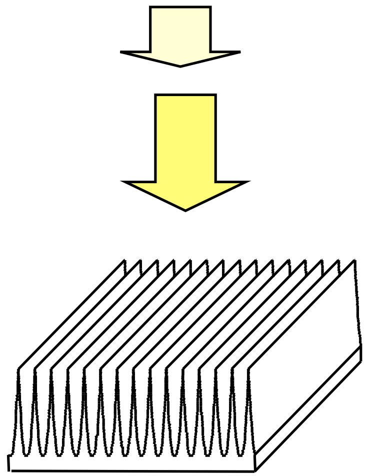
I.M. contour scanning (G2)

Options of beam formation in **depth**

- Range shifter - > PSI Gantry 1
  - Insert material in the beam
    - Plates (of fixed thickness or “digital stack”)
    - Moving wedges
    - Water column
  - Major concern – MCS in the RS
    - beam spot broadening in the air gap



- Variable energy of the beam -> PSI Gantry 2
  - Major concern
    - very steep Bragg peaks at the lowest energies
      - Reduce effect with a ridge filter?
      - or with a pre-absorber block?
- What matters at the end is speed and precision



Dose shaping in both directions laterally and in depth

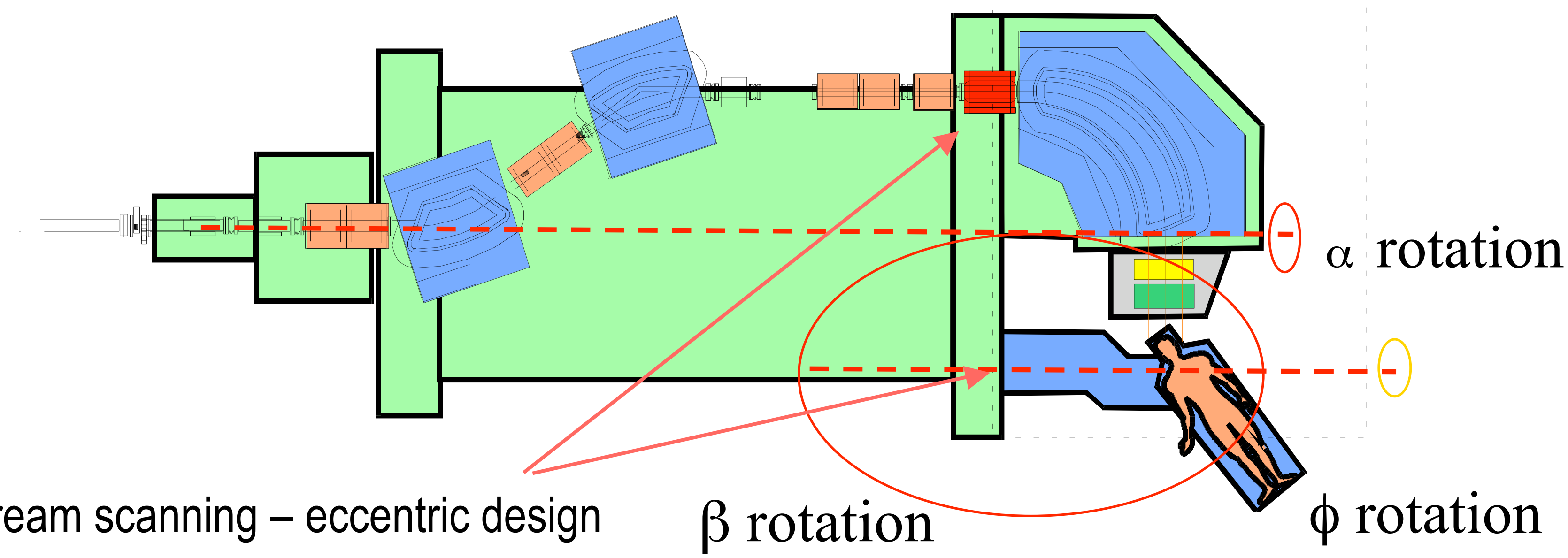
- Independence of the delivered spot dose laterally and in depth
  - Variable modulation of the range
    - Dose delivery close to the physics limits
  - Homogenous dose
    - 3d dose conformation – shape of the dose field
  - Non-homogenous dose distributions
    - Intensity modulated proton therapy (IMPT)
    - Biological targeting
  - No need to use individualized hardware

- Implicit capability to simulate scattering
    - Wobbling as a sub-mode of scanning

PRESENTLY OPERATIONAL SCANNING SYSTEMS

The Gantry 1 of PSI (treating since 1996)

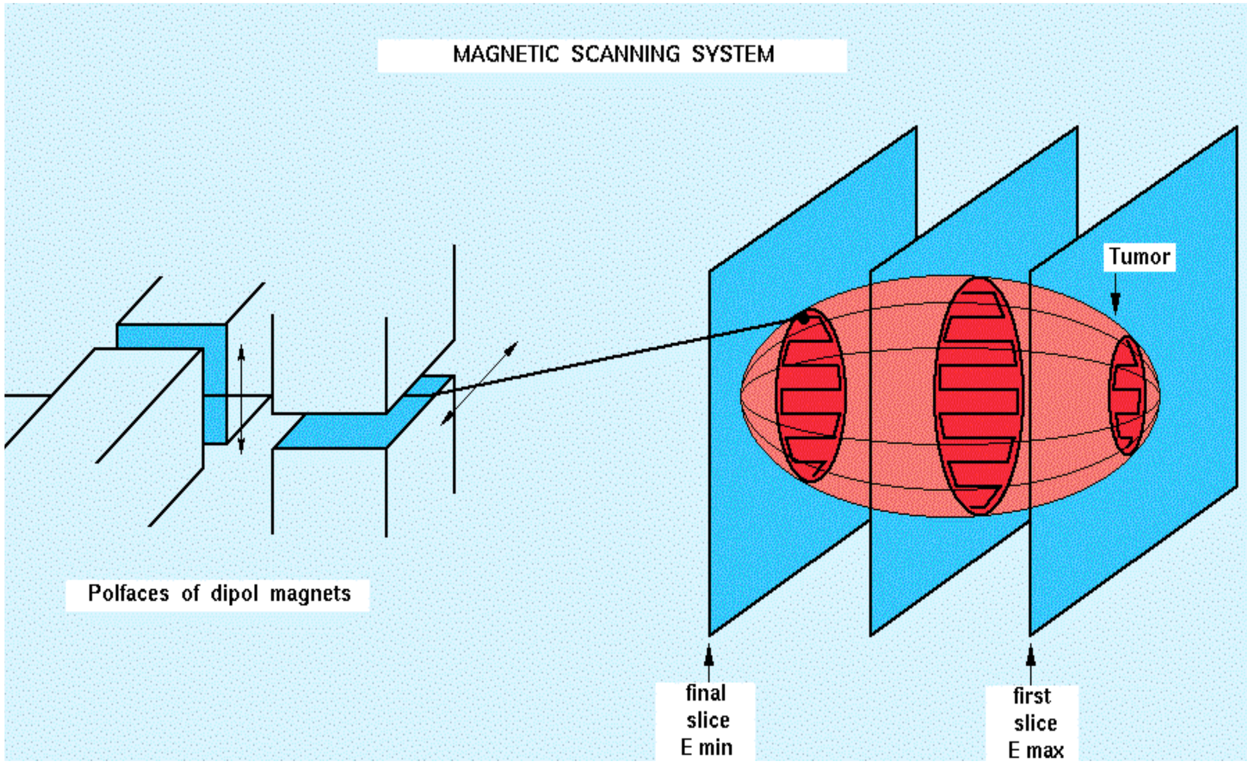
- The only gantry treating patients with scanning beams
  - Magnetic scanning started before the last bending magnet (upstream scanning)
    - parallel scanning (but only one magnetic scanning axis)
    - gantry radius reduced to only 2m
- Eccentric mounting of the patient table on the gantry front wheel
  - Patient moves away from the floor when treating from below
    - The major drawback of this solution



Upstream scanning – eccentric design

The GSI raster scanning system (treating since 1997)

- Carbon ions
- Horizontal beam line (long throw)
- Pulsed beam using a synchrotron with slow extraction
- 2-D magnetic scanning, iso-energy layers (fixed energy per pulse)
- Variable energy set by the accelerator (synchrotron)
  - ~250 beam tunes
  - “Virtual accelerators”

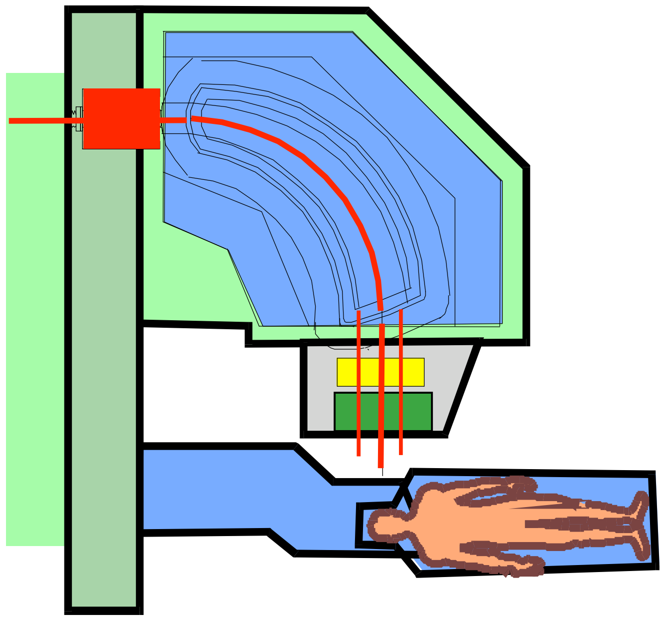


DIMENSIONAL CONSIDERATIONS
PSI GANTRY 1 AS EXAMPLE

Scanning axes on the PSI Gantry 1

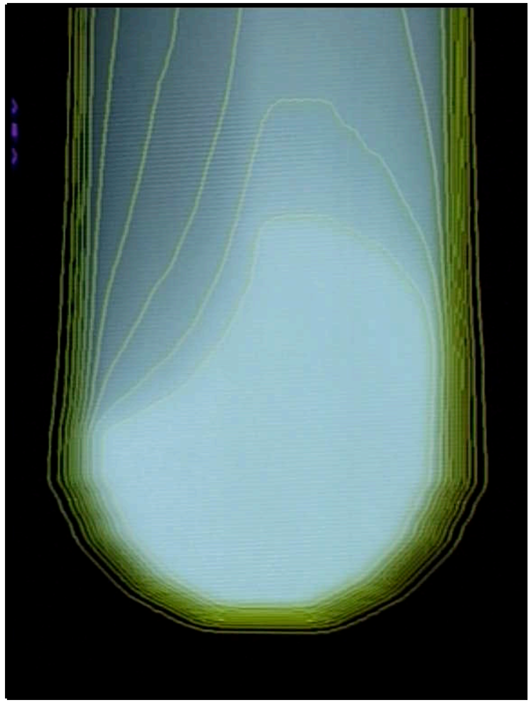
Discrete pencil beam scanning

- Gaussian pencil beam of 3 mm sigma (7 FWHM)
- Cartesian scanning (infinite SSD)
- "Step and shoot" delivery on a 5 mm grid



Scanning loop sequence

Time	Spot-Dose Monitor + Fast Kicker	
X	Sweeper magnet	most often used
Y	Range shifter	2nd
Z	Patient table	seldom



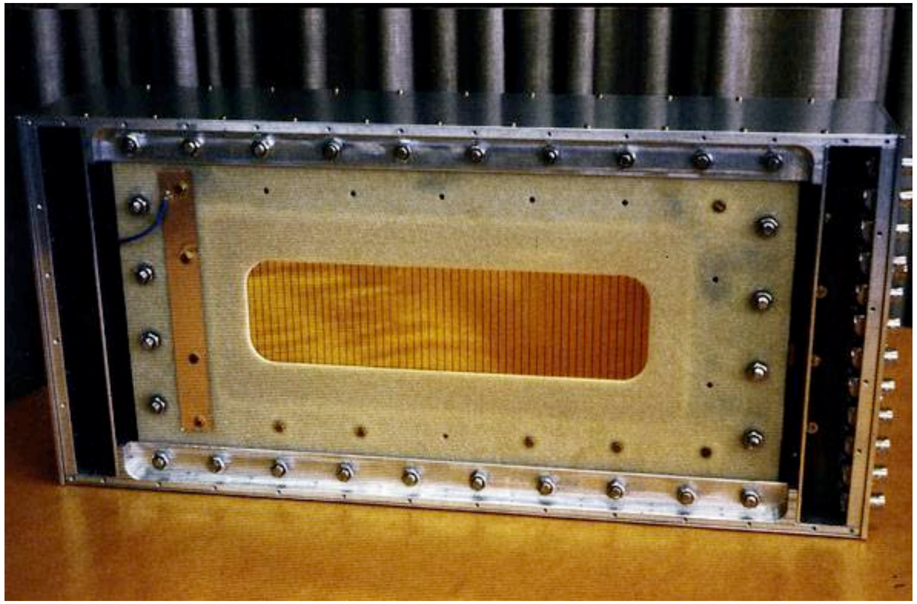
- Transverse scanning with patient table is the weak point
  - Slow motion (no repainting possible)
    - We can treat only non moving targets
      - In the head, spinal chord and low pelvis

Number of spots – spot time duration – treatment time

- Typical size of 1 liter (most often less, our max. value 4 liters)
  - Assumed beam size: 3 mm sigma
  - Derived grid size: 5 mm (21 spot lateral - 23 in depth)
    - 21 x 21 x 23 ~ 10'000 spots / liter
    - 21 x 21 x 10 cm = 44 m path length
  - We assume a beam-ON treatment time of 1.5 minute
    - Average 10 ms/spot
    - Due to the non-uniform spot weights distribution for a uniform SOBP
      - Most distal spots ~60 ms
      - Most proximal ~3 ms
        (with beam spot weight optimization we accept spots down to 0.5 ms)
- Treatment is roughly proportional to the volume
  or surface depending on the shape (beam ON time of high weighted distal Bragg peaks)
- Required intensity for 1 Min - 1 Gy - 1 Liter :
  - 0.2 nA proton current

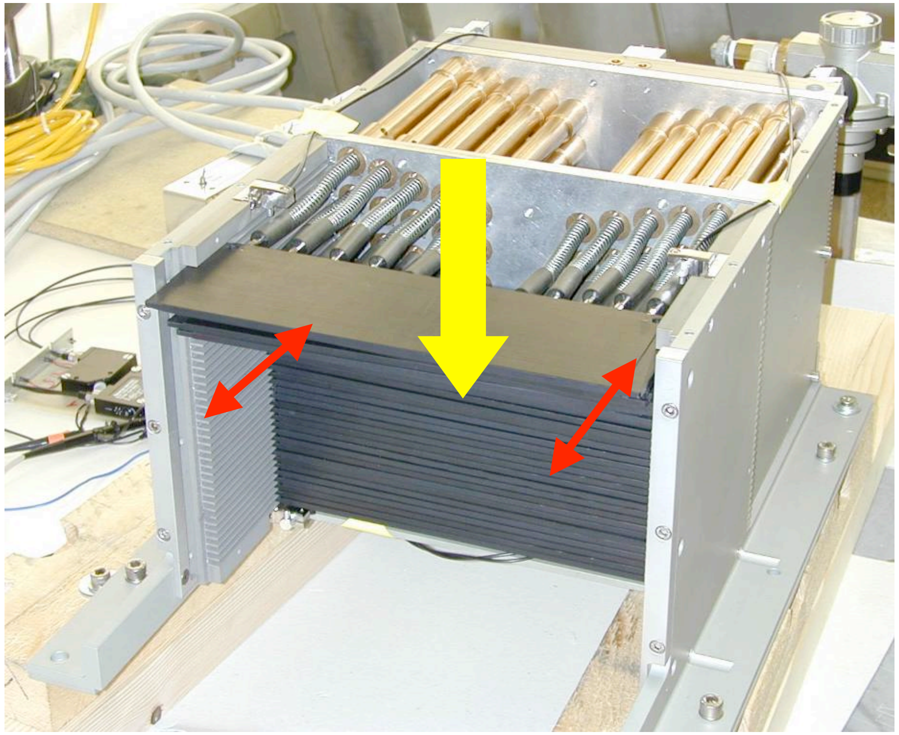
Beam monitoring - Dose control

- Transmission ionization chambers: M1 and M2 (M3)
  - Ionization in a 5 (10) mm gap with air – 2kV voltage
  - Response time < 100 μs
    - Same speed as the switching time of the kicker
    - = 1% of the mean spot time
    - Average counts due to the delay of the current measurement and of the kicker subtracted from preset -> 0.2%
- Strip-monitor chamber – 4 mm strips
  - Measure position and width of the beam after delivery of each spot
  - Position resolution 0.2 mm
  - Charge collection time 0.8 ms
    - Wait 1 ms before reading scalers at the end of each spot



Beam scanning devices

- Sweeper magnets
  - 30 ms for a full sweep over 20 cm
  - Time to move the beam to next spot and to stabilize: 3 ms for a 5 mm step
- Range shifter
  - 40 plates (80 pneumatic valves)
    - 4.5 mm wer each + one half plate
    - "Water-equivalent" arrangement
  - Dead time 50 ms (30 ms for motion)
- Patient table
  - Motion in steps of 5 mm
    - 1-2 seconds dead time per step
    - Acceleration and decelaration
    - Smooth motion for patient comfort
  - Makes impossible to apply repainting

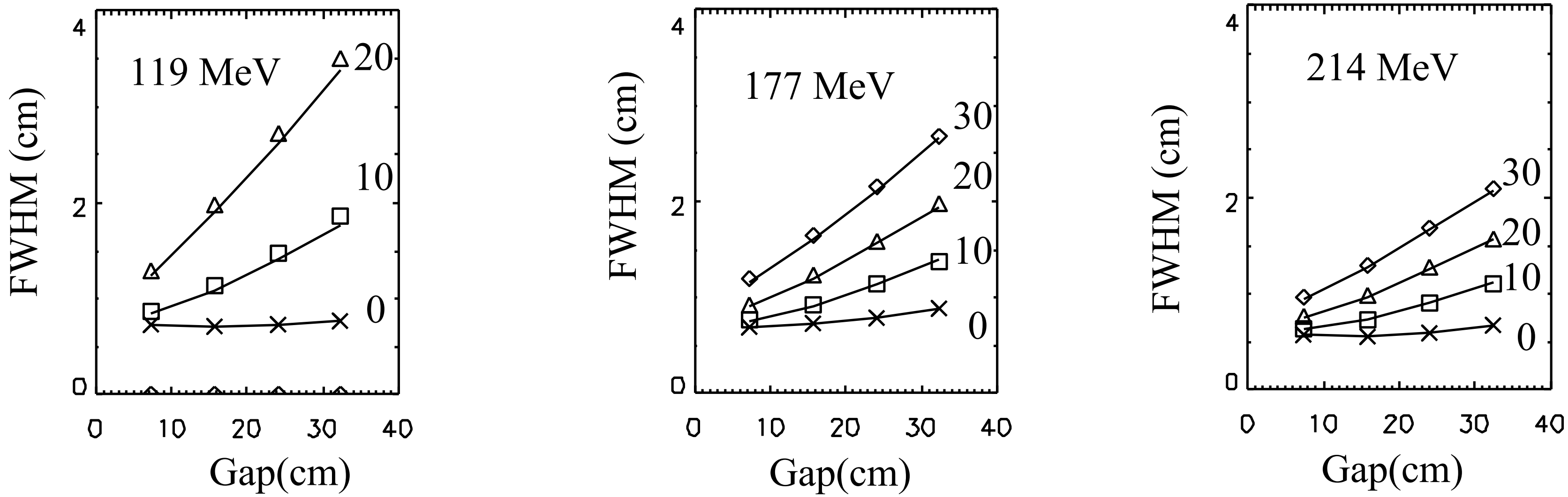


- Range shifter option ->PSI Gantry 1
  - Varying amount of material in the beam
  - "Water-equivalent"
    - Pencil beam is invariant with depth
    - But only with zero air gap
      (Be plates for water equivalence with non zero gap?)
  - Problematic
    - The spot broadening due to MCS in the RS when having a large air gap and using very many plates

The degrading from 590 MeV was too slow for thinking of using dynamic changes of the beam energy with Gantry 1
~ 3 min

The air gap problem when using a range shifter:

- Beam blow-up due to MCS in the range shifter in front of the patient
  - The reason with Gantry 2 to use dynamic energy variations with the beam line

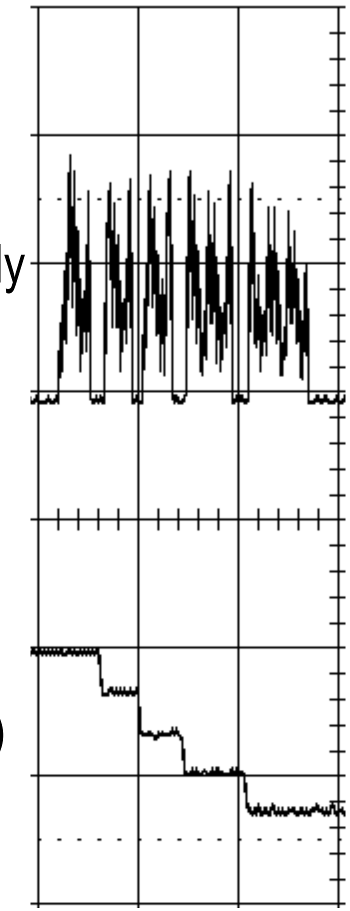


- Strategy for positioning beam modifiers in the beam
  - Either very close to the patient — Small air gap
  - Or very far — Loss of intensity
    - But not in-between — The worse one can do
- Problem similar as with scattering – air gap to compensator collimator– lateral penumbra

The reasons to switch off the beam in between spots (at PSI)

- Poor quality of the beam until 2006 (before COMET)
  - Beam was obtained
    by splitting 0.5% intensity from the beam of the PSI ring cyclotron
    and degrading it from 590 MeV down to 100-200 MeV
    - If accelerator vacuum was bad - > intensity spikes
    - It was therefore very important to check the monitor units precisely on-line at the end of each spot
- Avoid beam ON dose errors during motion to next spot
  - Errors in dose delivery
    - delay and non-linearity of the sweeper power supplies
  - Errors in checking the beam position with the strip monitor
    (time resolution of 0.8 ms – motion at 1 cm/ms = 8 mm position error)
- Preferred strategy
  - Perform all calculations with high precision at the end of each spot
  - Start next spot only if previous spot was correct in all respects
    -> overall dead time: 5 ms after each spot

Beam IC



Sweeper
Hall probe

The price for the beam OFF in between spots – the dead time

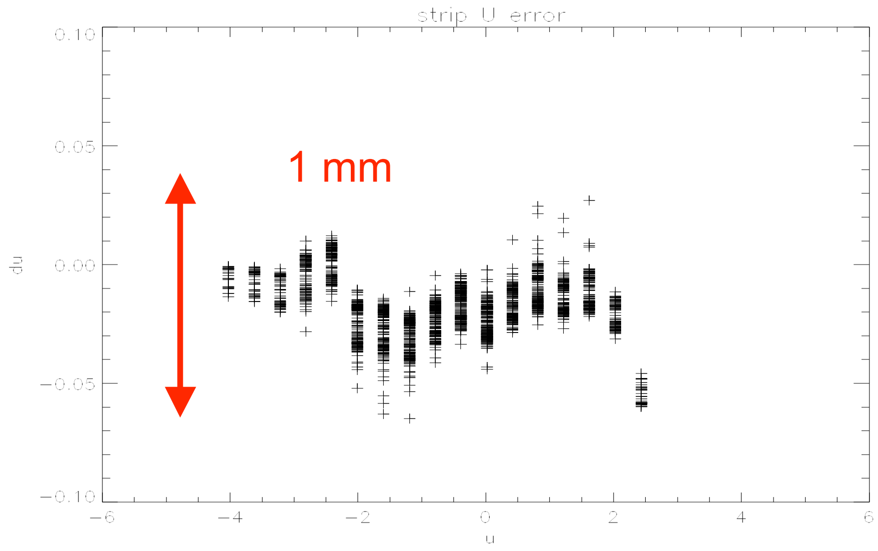
- Gantry 1
  - Beam off after delivery of each spot
    - Sweeper dead time 10'000 x 5 ms = 50 s
    - Range shifter 21x21x 50 ms= 22 s
    - Patient table 21 x 1s = 21 s
  - 1.5 minutes beam off vs. 1.5 minute beam on
    - Duty factor of discrete spot scanning low 50%
    - BUT precision of the dose delivery very good
      - Dose reproducibility of 0.2%

- Future: exploring more efficient solutions with Gantry 2
  - Painting of lines instead of spots (check of delivery at the end of a line)

The precision of setting up the beam line

- Inherent reproducibility of the beam tunes
  - Automatic set-up of the beam energy without retuning the beam during treatments (cyclic ramping of the gantry magnets before field delivery)
    - The beam appears at the correct position within 1-1.5 mm
- Position correction at the end of the first spot
  - Correction allowed if < + - 1.5 mm
  - All further spots appear with
    - Position deviation within +- 0.5 mm of the expected value
      - alarm if error > 1.5 mm

Beam position error



U sweeper position

- On-line and off-line analysis of the delivered spots
  - Retrospective analysis of the logged data

Patient safety and on-line delivery checks

- Double computer systems
  - Therapy delivery system
    - Active steering of delivery elements
  - Therapy Verification System
    - Redundant control of treatment execution based on diverse physical measurements
  - Tests before, during and after spot delivery
  - Agreement to continue at the end of each spot
- Multi-level switch-off of the beam
  - In case of malfunction ->stop the beam
- Hardware interlock chain
- Watch-dogs (max spot dose limits)
- Off-line checks (for the precision of dose)
  - Analysis of logged data
  - Logged scanning data used to characterize the machine – the basis for QA measurements

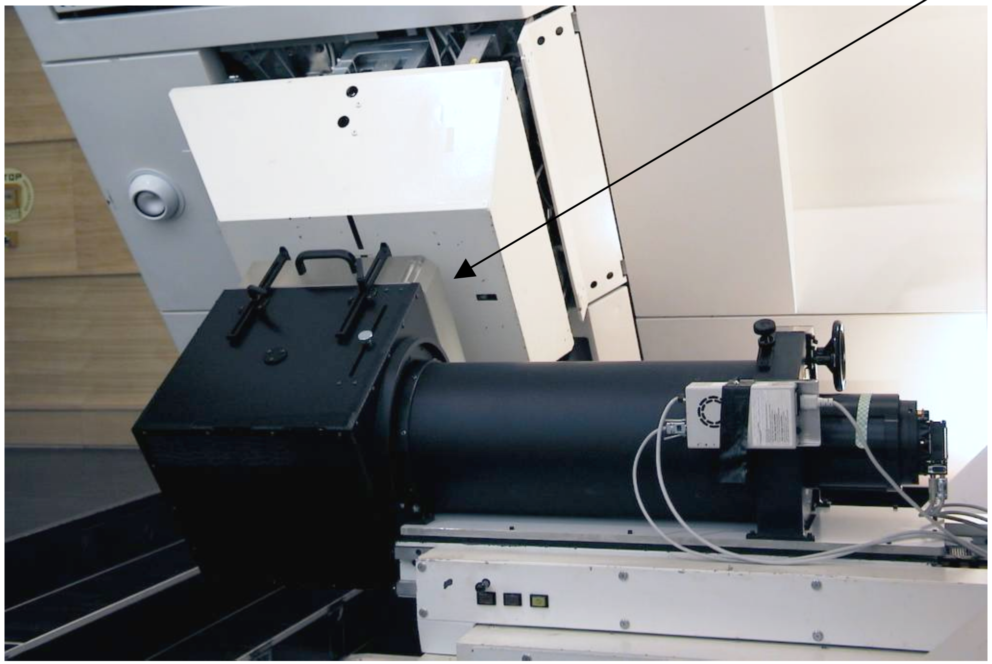
Dose Monitor 1	Dose Monitor 2 Monitor 3 Sum strip X Y Monitor ratios
Sweeper Current	Sweeper Hall probe Strip monitor
Range shifter Valves	Range shifter L-switches R-switches Lasers
Beam line Power supplies	Beam line Hall probes Strip monitor

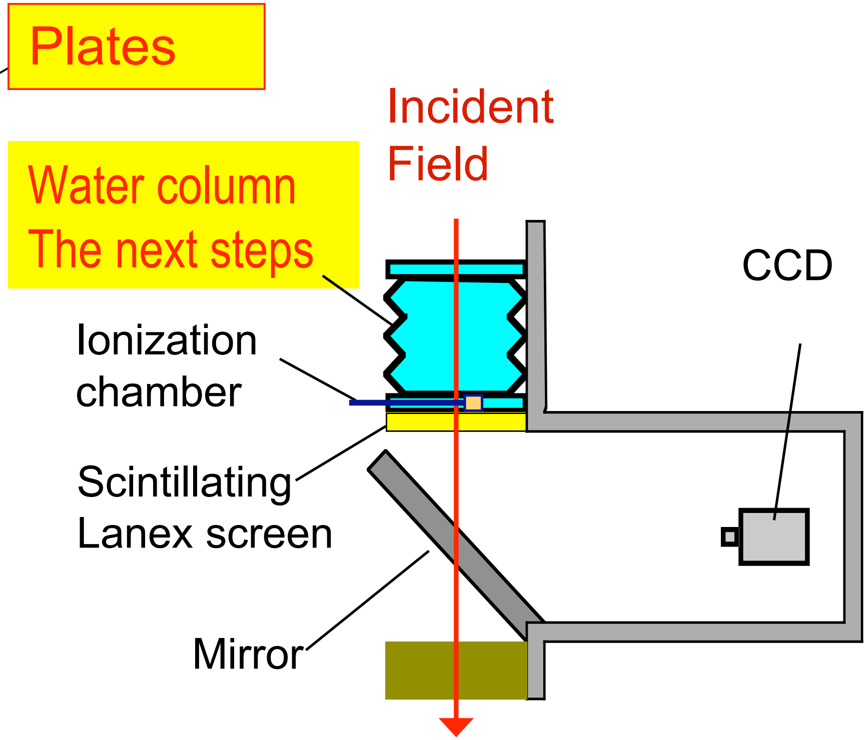
etc

COMMISSIONING AND DOSIMETRY

CCD screen viewed through a mirror on a CCD camera

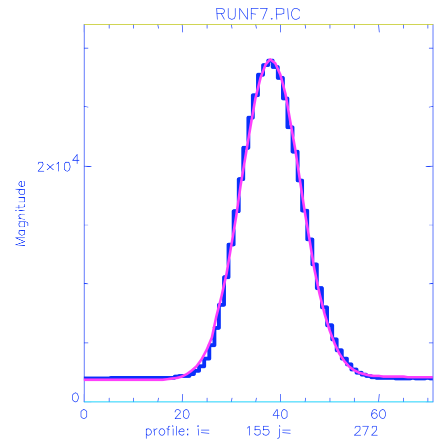
- CCD-dosimetry system build at PSI (derived from M. Schippers at KVI)
- good 2d position resolution – 0.5 mm
- good reproducibility 0.2 %
- Ideal tool to verify complex dose distributions
  and for doing beam studies and QA measurements



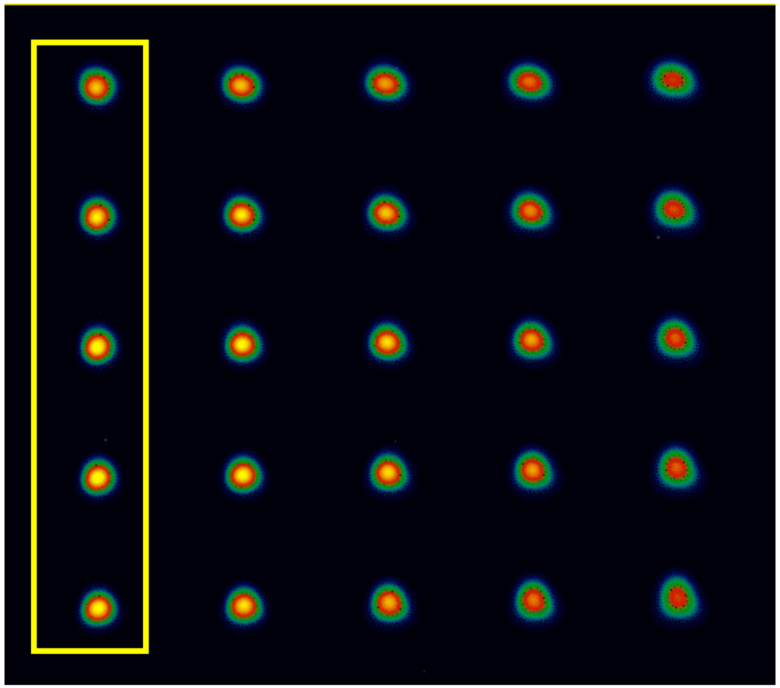


QA example : Proton pencil beam shape in air

- Scan sweeper +9,-9 cm
- At distances from nozzle of 7 - 37cm
- Apply a Gaussian fit
- Fit phase space (in air) – for each energy



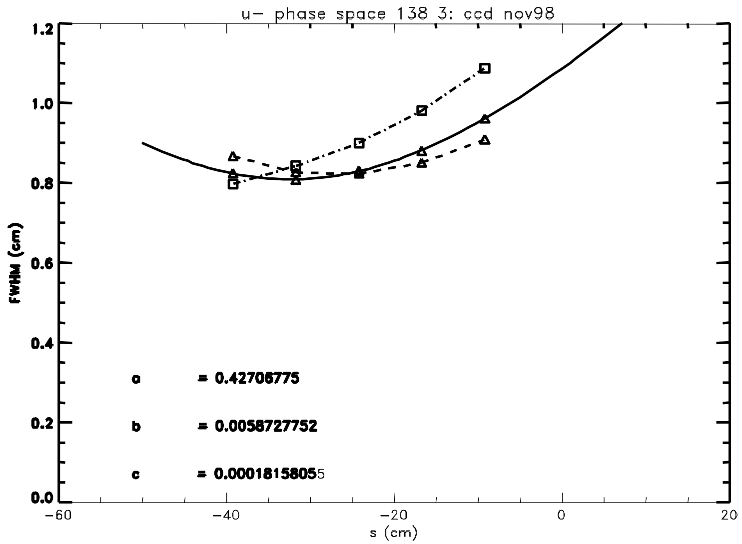
CCD Image



Sweeper

Distance from nozzle

Beam width

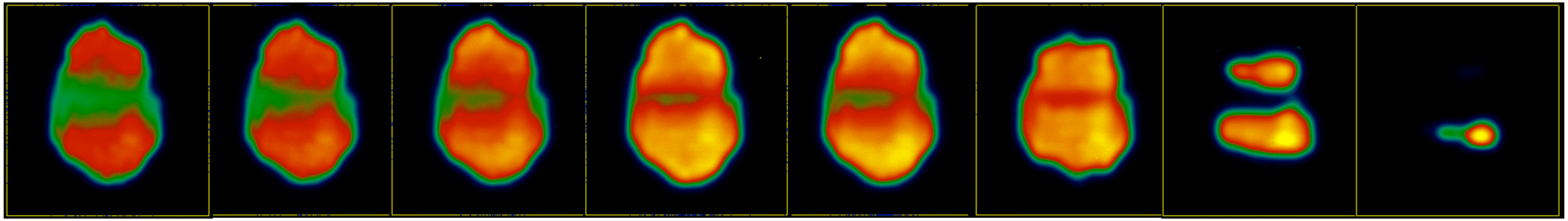


Distance along beam axis

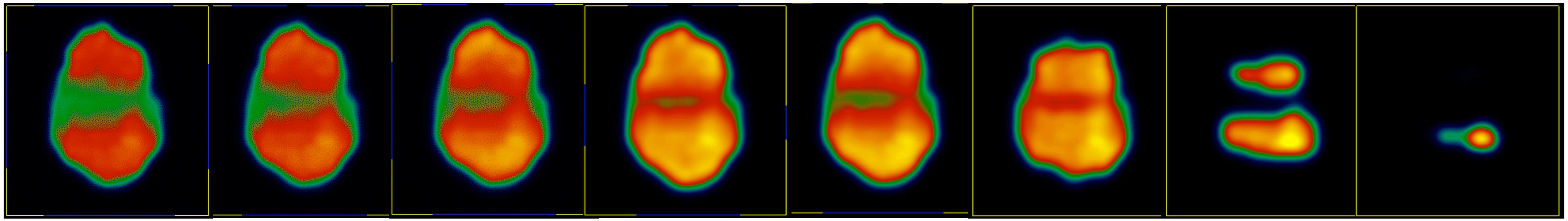
CCD dosimetry – visualizing the dose distributions

0.2% dose precision

0.5 mm resolution



Calculated vs measured dose distributions as a function of depth



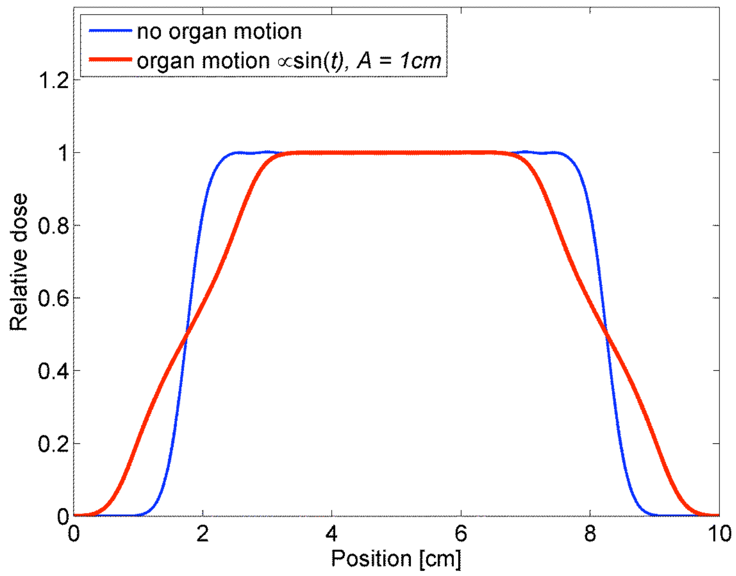
ORGAN MOTION SENSITIVITY OF SCANNING

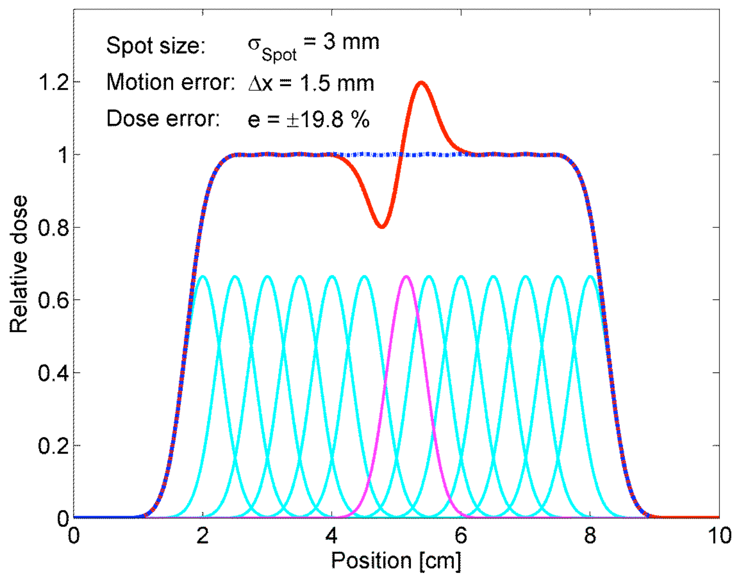
The organ motion problem

- Disturbance of the <u>lateral dose fall-off</u> (common to scattering and scanning)
  - Remedy - add safety margins
  - Reduce margins with <u>Gating</u> or <u>Tracking</u>

- Disturbance of the <u>dose homogeneity</u>
  - Scattering – highly repainted - insensitive
  - Single painted scanning – very sensitive
  - <u>Repainted scanning</u> – less sensitive
    - <u>Used alone</u> – for medium motion
    - With <u>Gating</u> or <u>Tracking</u> – for large motion

- The experience of treating moving targets with scanning is still inexistent
  - WE HAVE TO LEARN HOW TO DO THAT

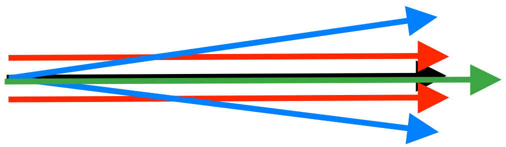




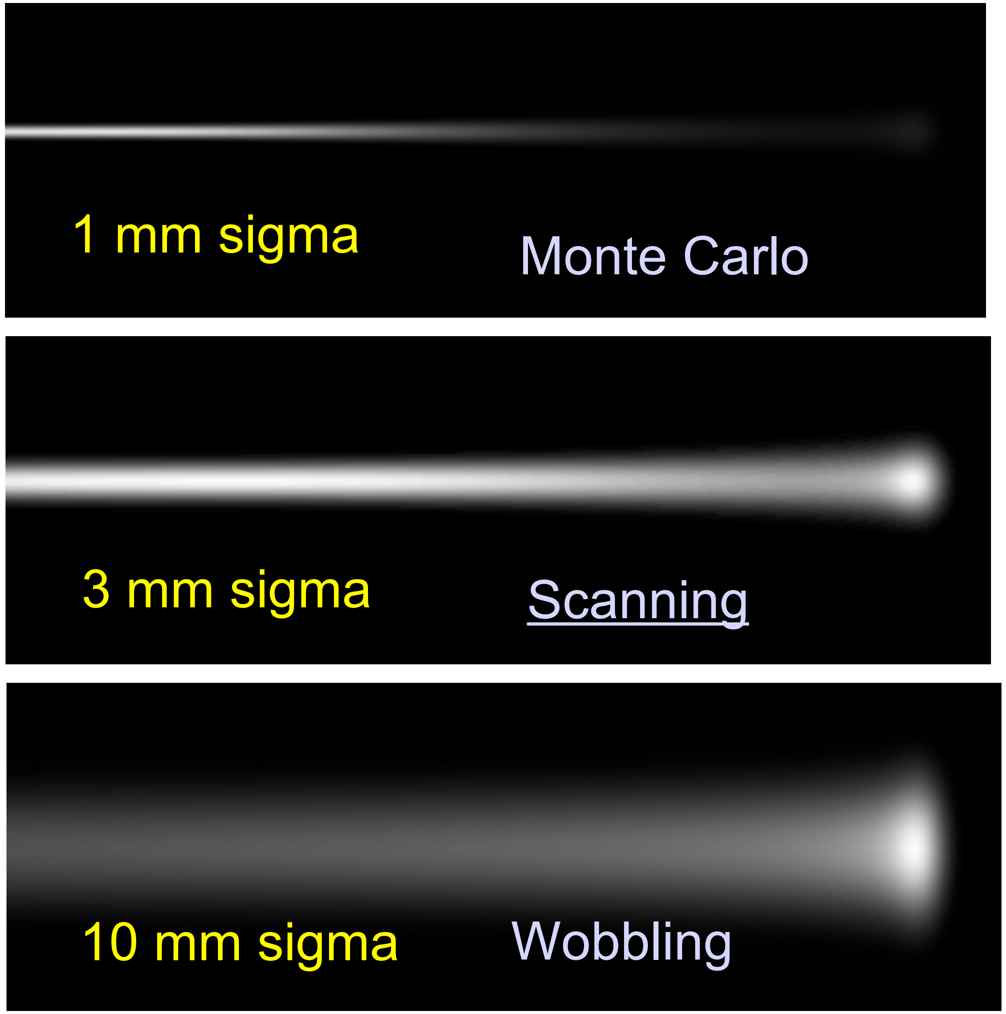
ACHIEVABLE DOSE PRECISION OF SCANNING

Size of the proton pencil beams

- Physical pencil beam in air
  - Typical phase space (150 MeV)
  - $x=y= \pm 3$ mm
    $\theta=\phi= \pm 10\text{-}7$ mrad (2 mm @ 20cm)
    $\delta p/p = \pm 0.2\%$



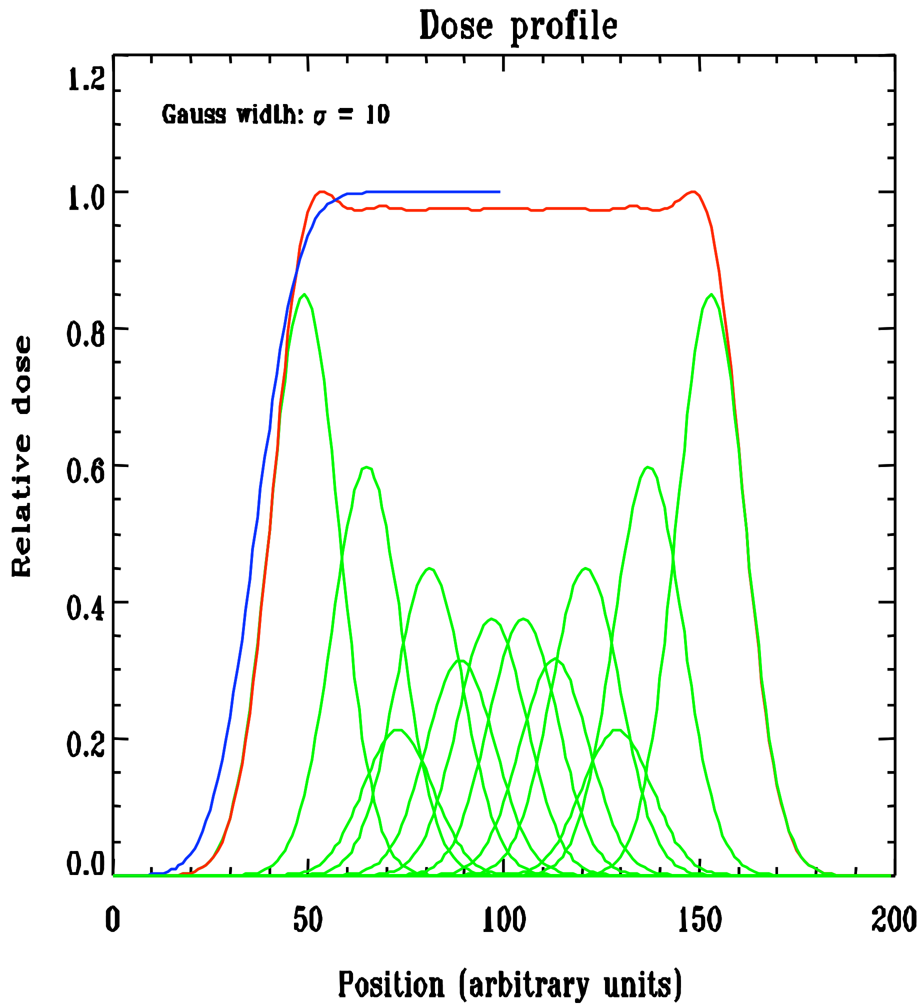
- If beam spot too small
  - Too many spots (for overlap)
    - increased treatment time
  - Higher sensitivity to organ motion
- If beam spot too large
  - Bad lateral fall-off
    - Reduced precision



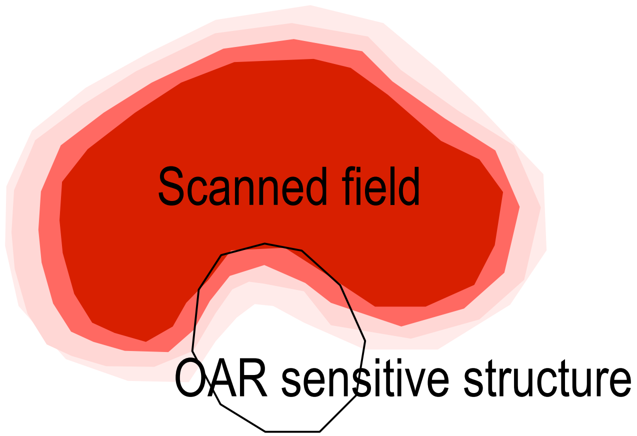
After integration in the lateral direction the difference in depth disappear

"Edge enhancement capability" of scanning

- Delivery of separated spots
  - Variable choice of the spot intensity
  - Lateral fall-off similar to original beam Gaussian
- Uniform proton flux
  - The case of collimation
  - Gaussian is folded with a step function => error-function
- Difference Gauss to error-function
  - Factor 1.7
- Scanning with optimization can produce a sharper lateral fall-off as compared to scattering
  - True for deep seated tumors
  - At high energy
  - When MCS in the patient is the dominating effect to the spot size

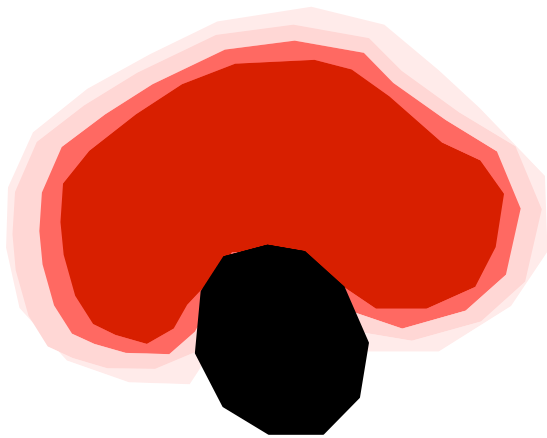


At low energy: scanning with additional collimation (option)



SCANNING ONLY

APERTURE



OAR- SHIELDING BLOCK

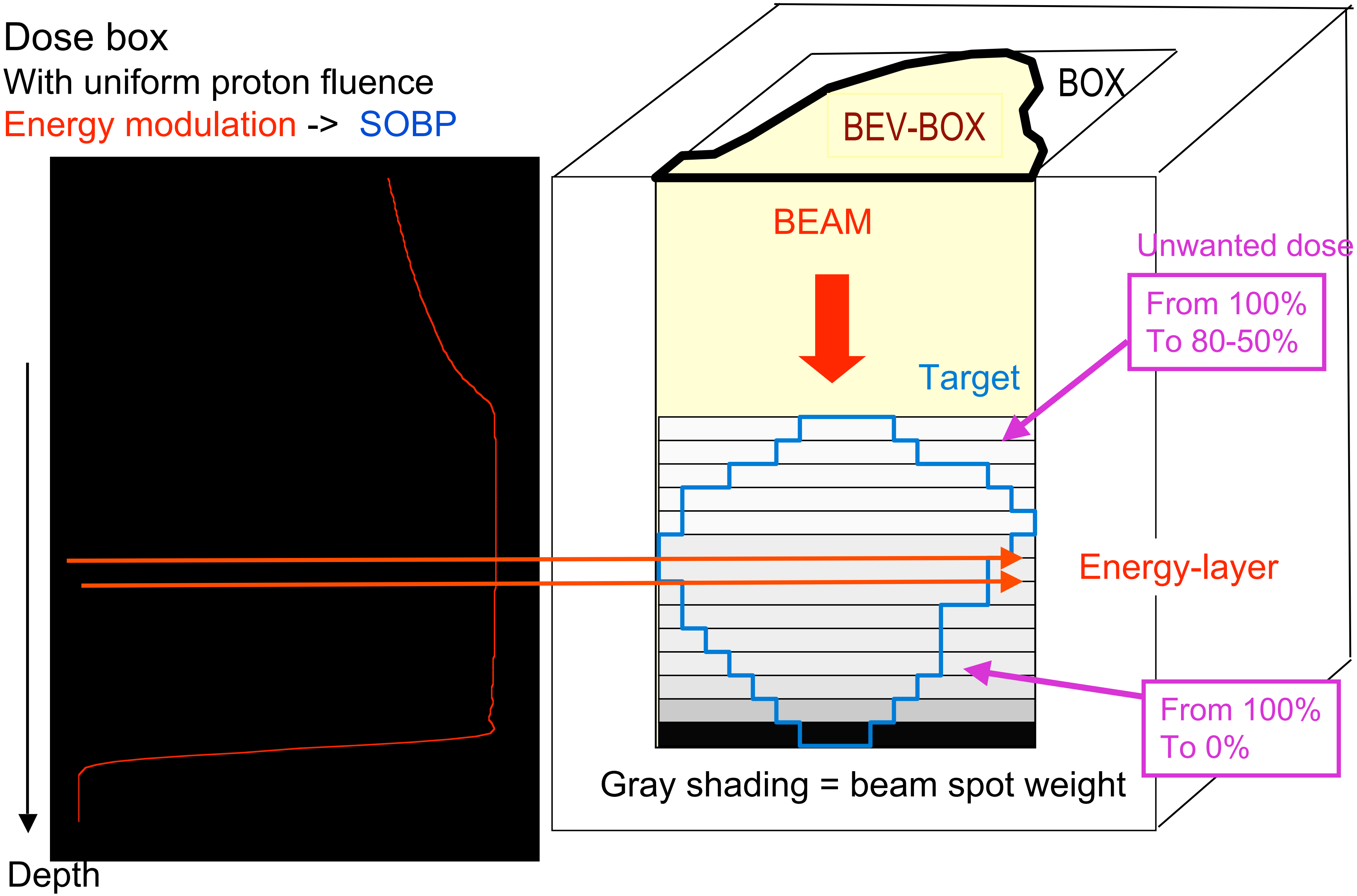
Shielding block

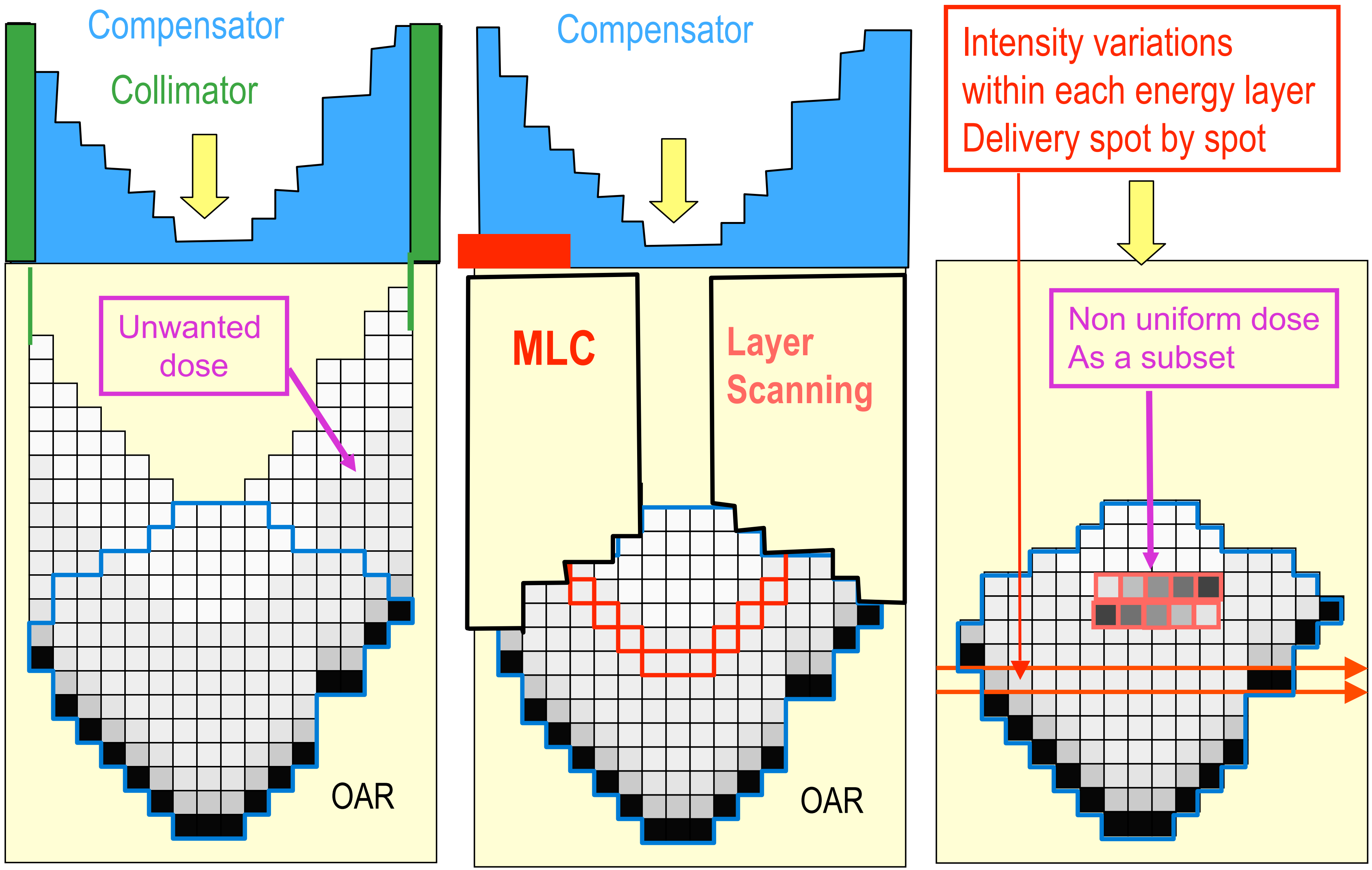
- Better visibility for BEV X-ray
- Less weight
- Easier alignment

BEAM DELIVERY CHOICES

Distribution of beam spot weights in 3d-space (in depth and lateral)

Dose box
With uniform proton fluence
Energy modulation -> SOBP





Scattering or wobbling
Collimator compensator

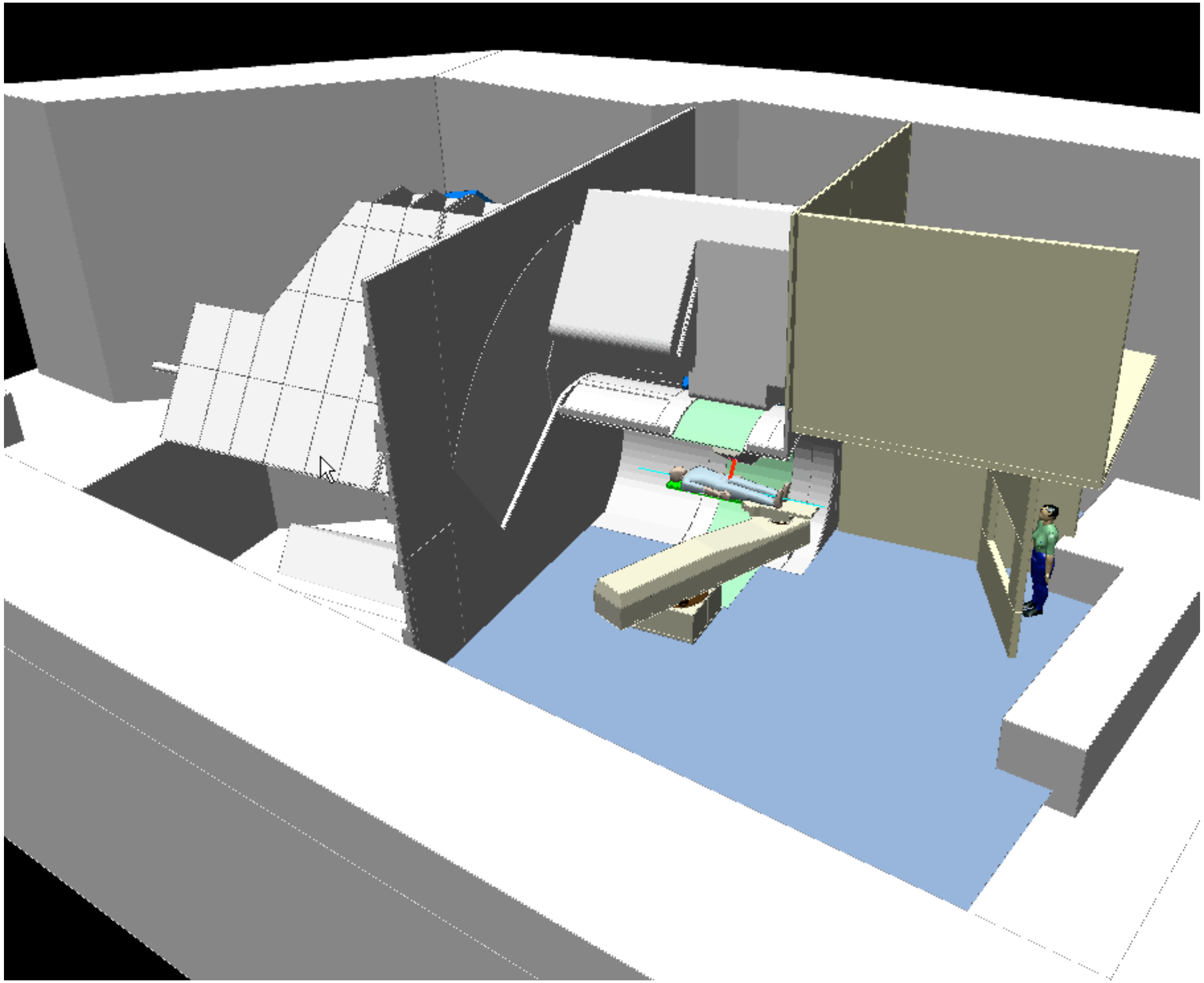
Energy layers -variable range modulation

3d or 4d-shaped dose
conformal scanning

THE NEW GANTRY 2 OF PSI
A NEXT GENERATION SYSTEM DESIGNED FOR ADVANCING SCANNING

A new gantry layout

- Gantry components



Beam Line

Support

Bearing axle

From -30°

to +180°

Patient table

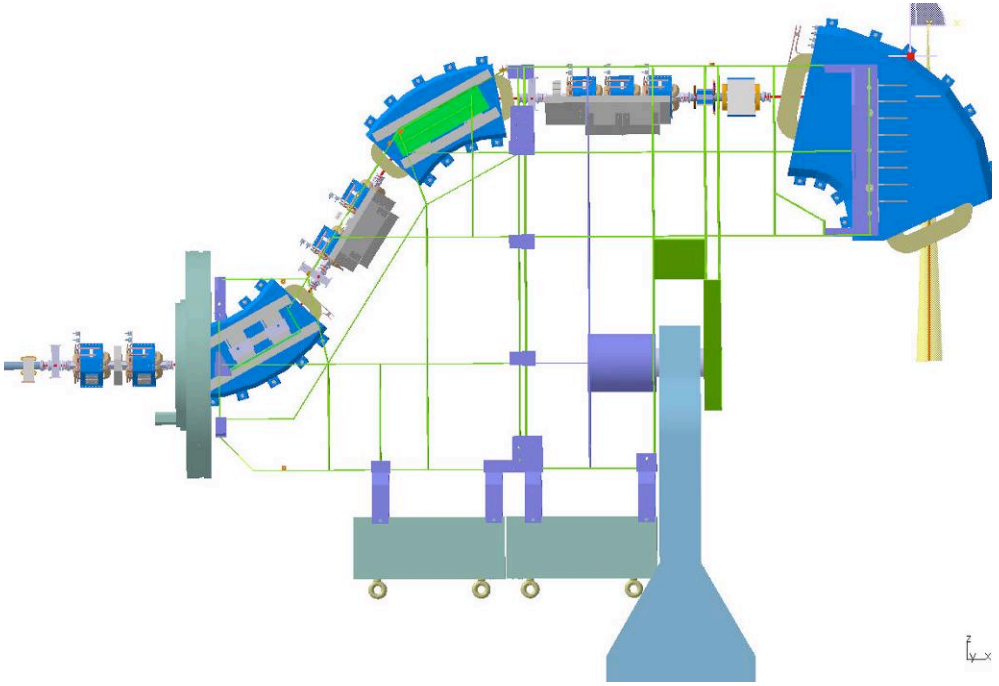
Room with
fixed floor

Services
X-ray console

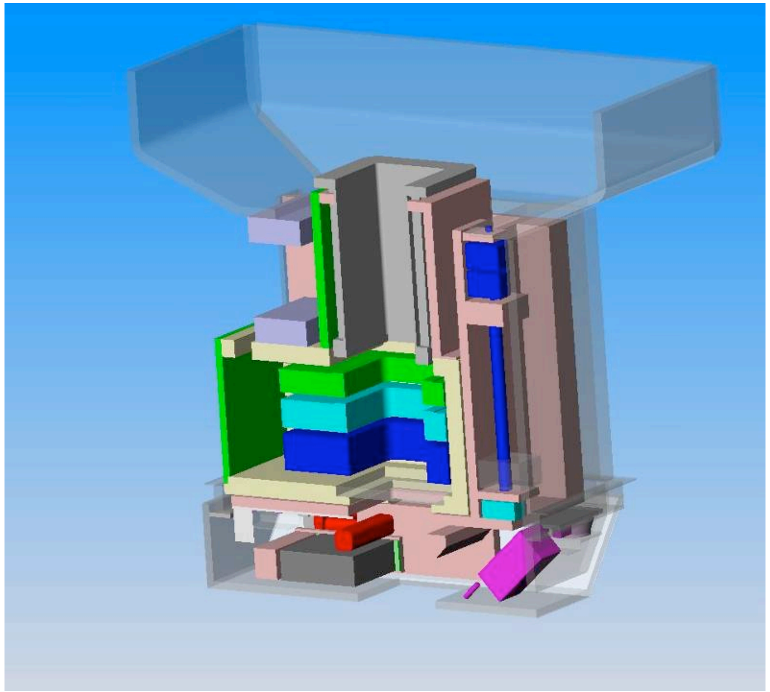
Patient and
doctor

A new system for advancing the beam scanning technology

- Iso-centric layout
- Double parallel magnetic scanning
  - Use of patient table only for extending the field size
- Compact nozzle
  - Optional mounting of collimators and compensators

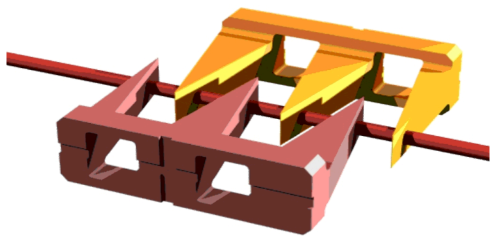


Optimized for scanning



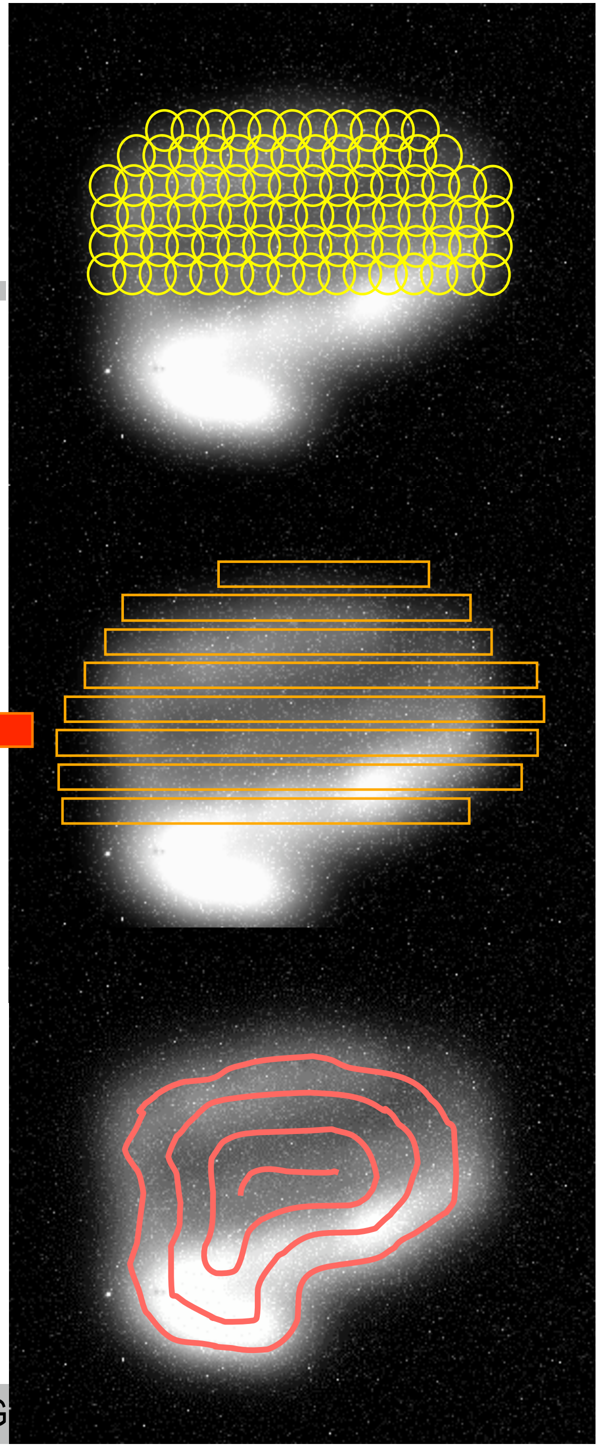
Cyclotron and beam line used as beam delivery components

- 250 MeV cyclotron
  - Delivering a very stable DC beam
    - Goal: ~3% sigma at a 100 μs time scale
- Dynamic modulation of the beam intensity
  - Vertical deflector plate at the first turn
    - At a 100 μs time scale (60 μs delay to patient)
- Fast dynamic energy changes
  - With beam line and degrader
    - 150 ms for a 5 mm proton range step
      - An order of magnitude faster than with any other machine (including synchrotrons)
      - For volumetric repainting



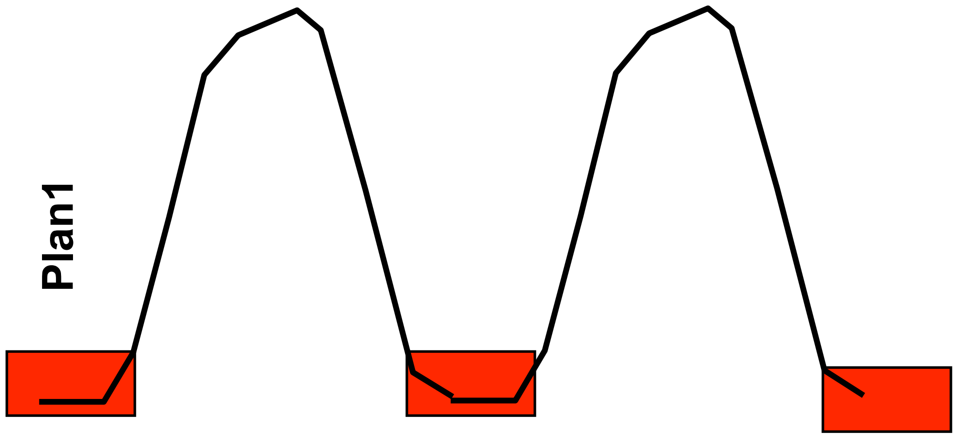
Flexible control system
spots - lines - planes - contours
aiming for very high scanning speed

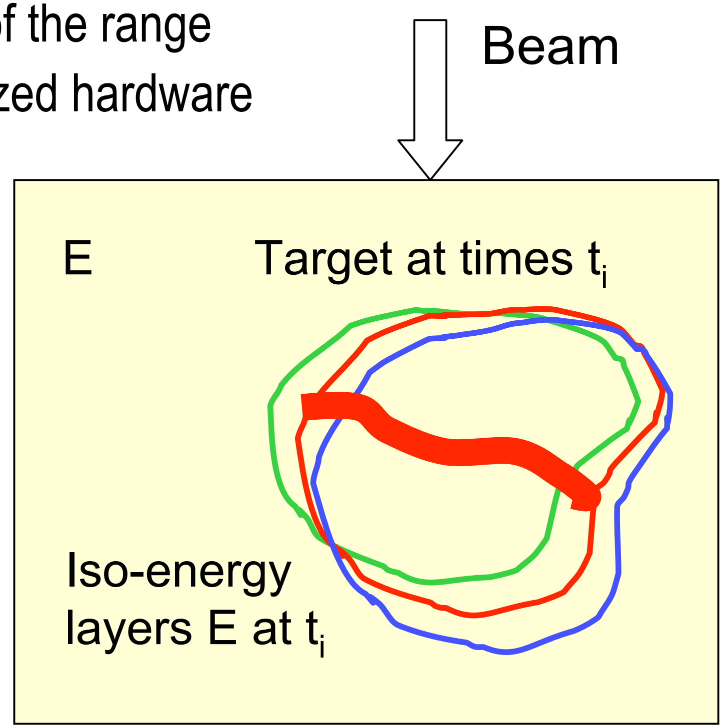
- Painting of lines (contours)
  - At max. velocity (~1-2 cm/ms)
  - Beam intensity modulation (I.M.)
  - < 10 ms per line (10cm + line step))
- Painting of an energy iso-layer
  - 200 ms per plane (20 lines x 5 mm)
  - Change of energy (100 ms - 5mm range)
- Painting of a volume
  - 6 s per liter (20 energies at 5mm steps)
- Volumetric repainting capability (aim)
  - 10-20 repaintings / liter in 1-2 minutes
- Possible future developments, refinements
  - Repainting as a function of requested proton fluence
  - Scanning along iso-centric contours



Our preferred solution for treating moving targets
Conformal repainted scanning + gating

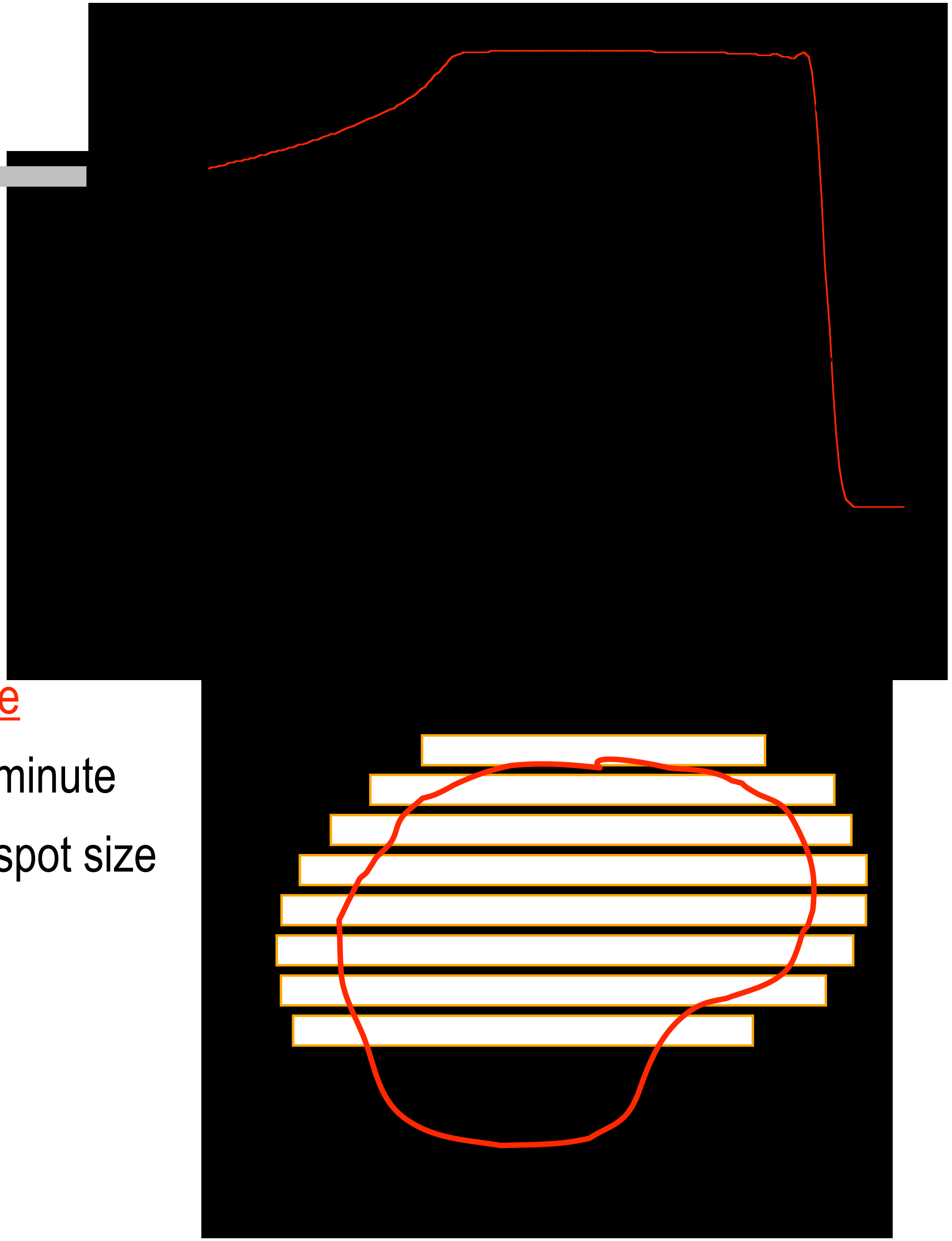
- Energy layer delivered completely within a single respiration gate
  - ~100 ms per layer
- Multiple-gating?
- Tracking as an alternative?
- The goal:
  - Treat moving targets with variable modulation of the range and IMPT without the need of using individualized hardware





Emulation of scattering with a scanning gantry

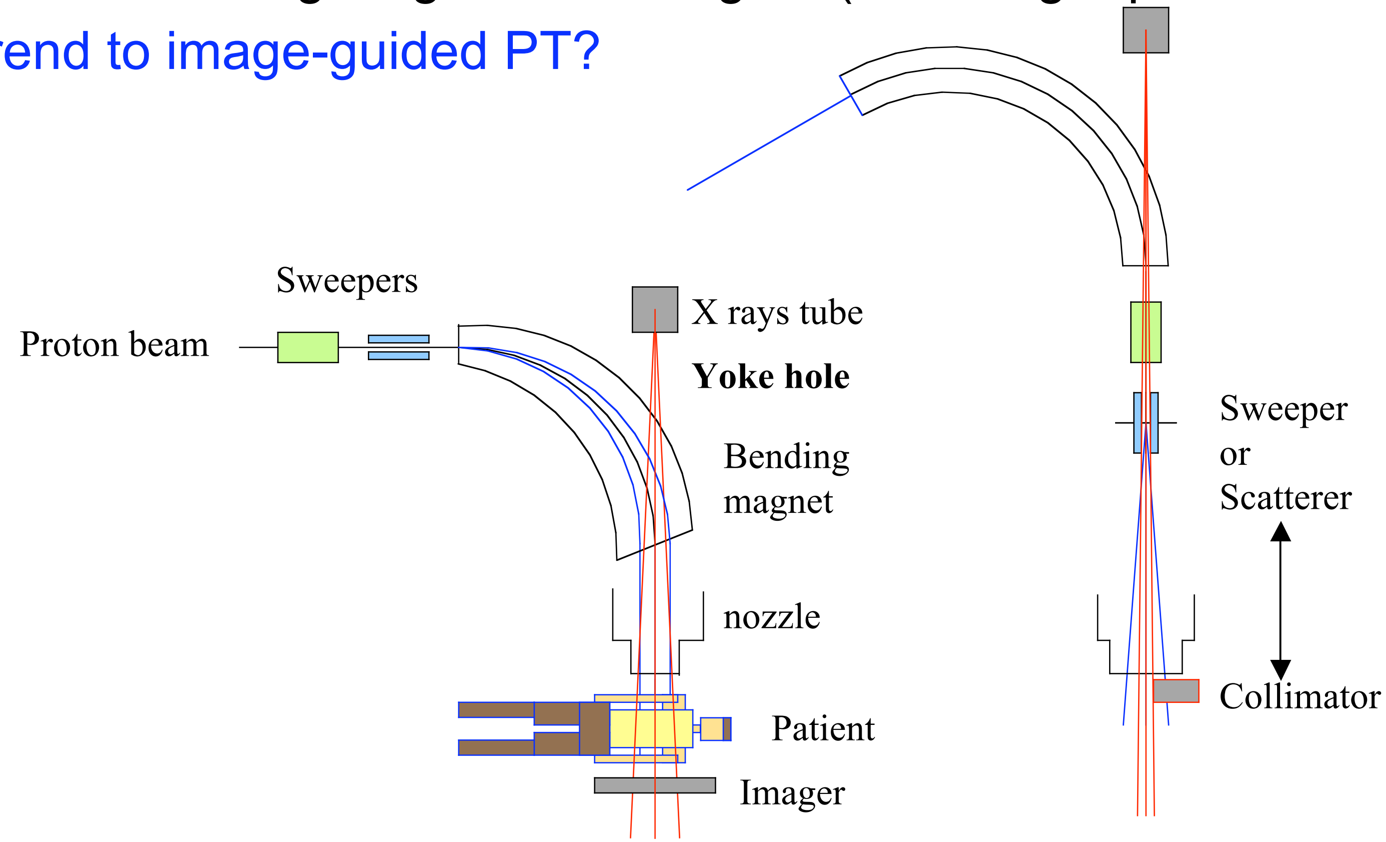
- Magnetic scanning at max. speed
  - constant intensity per energy layer
- Dose shaping
  - with compensators and collimators
- High repainting number
  - At 200 ms per layer
  - Most distal layer 88 times / liter /minute
  - Most proximal energy: 5 times / liter / minute
    - And higher numbers with a larger spot size



- A sub-mode of conformal scanning
  - "Parallel scattering"
  - With variable modulation of the range

Gantry 2 - BEV X-ray simultaneous with the proton beam

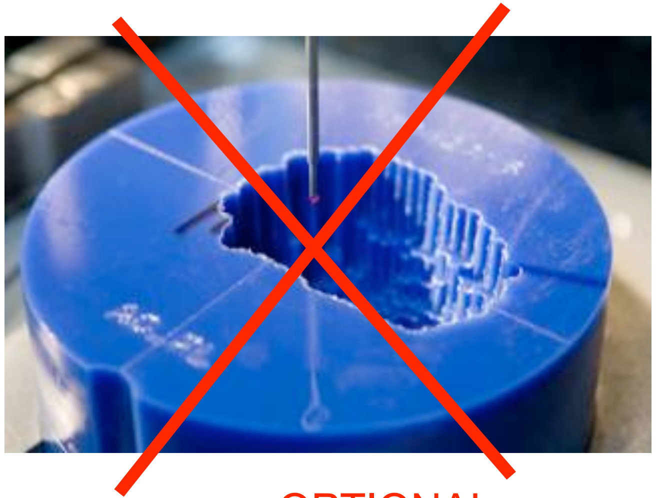
- Equivalent to portal imaging with KV photon
  - Large field-of-view area (26 cm x 16 cm)
  - not masked by equipment or collimators in the beam path
- QA control for gating and tracking (scanning + pulsed X-rays)
- Trend to image-guided PT?



a) compact gantry b) long throw gantry

EXPECTED ADVANTAGES OF USING SCANNING

All done by software – with minimal equipment

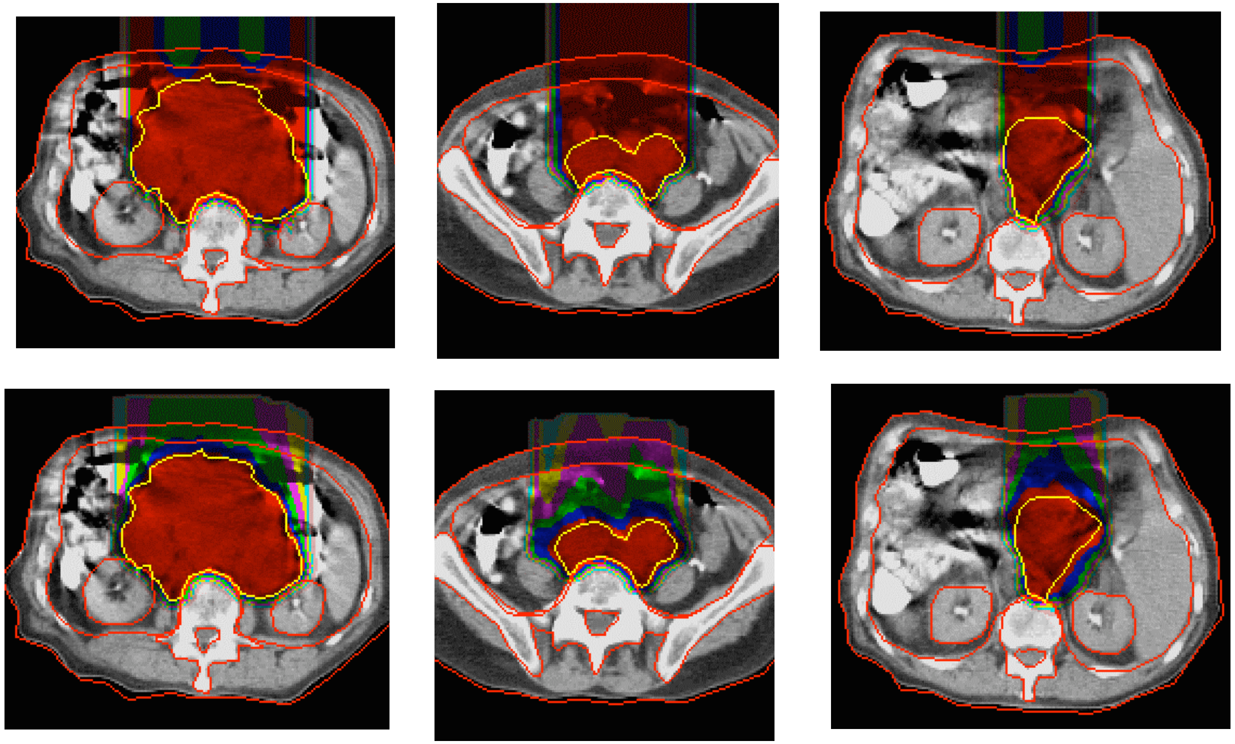


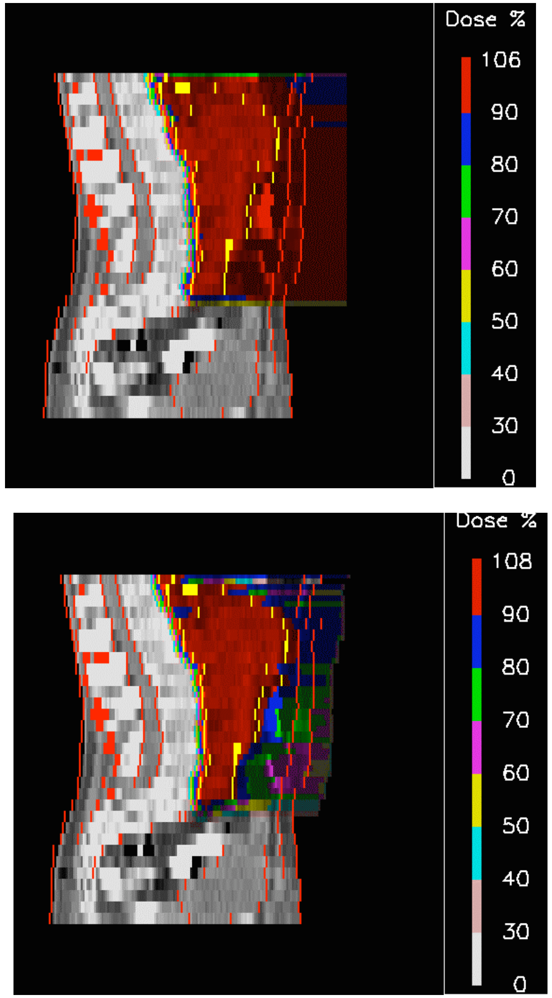
OPTIONAL

- No need to use individualized hardware
  - Avoid fabrication and mounting of patient's specific equipment in the nozzle
- Apply dose fields sequences in one go without personnel entering in the treatment room
  - To reduce treatment time
  - All fields of IMPT are delivered in the same fraction
- Most efficient use of the beam
  - "All" used protons reach the target (low intensity beam – only 0.2 nA)
    - Minimal neutron background (for the patient)
    - Minimal activation of the equipment (for the personnel)
- Flexibility to treat from small to very large targets without changing equipment
  - "All done by the beam" using minimal equipment
    - Monitors, sweeper magnets and beam line (pre-absorber, patient table)

Variable modulation of the range

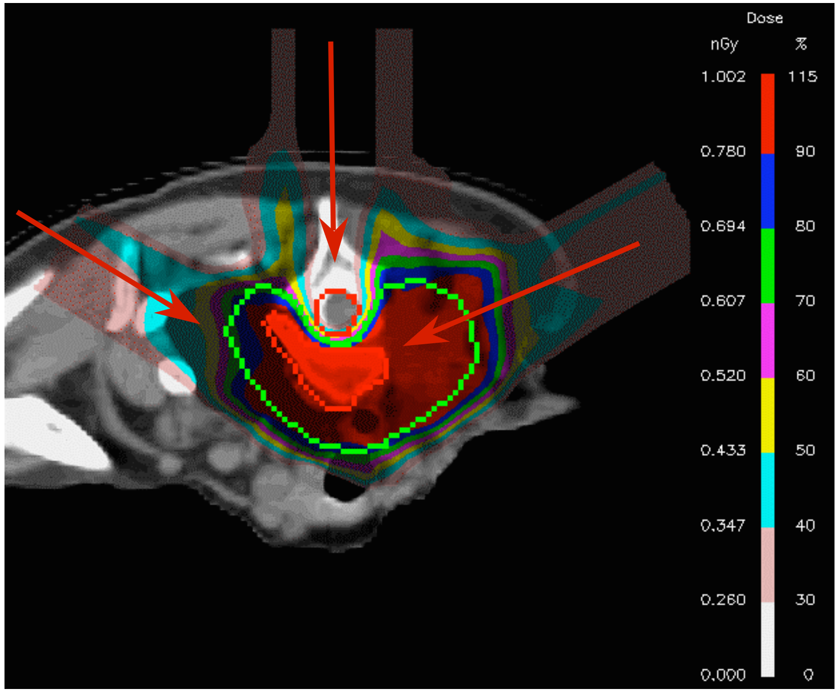
- For avoiding unnecessary 100% dose on the healthy tissues
  - Especially relevant for large tumors
  - Reduce skin dose

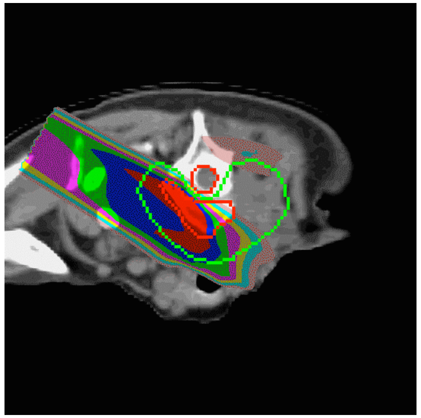


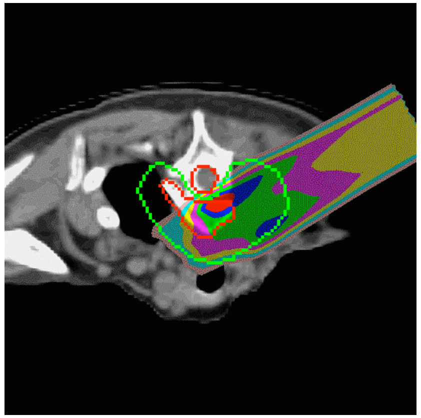


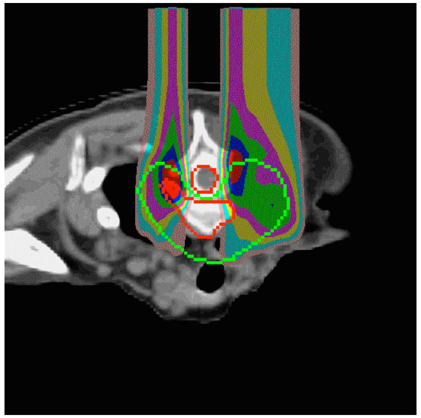
4D – (modulated dose distributions)

- Dose conformity (field shape)
- Dose modulation (dose variation within the target)
  - Used for
    - Intensity modulated therapy IMPT
    - Biological targeting
- A necessity for competing with IMRT









Other possible scanning related advantages

- Gantry design with "upstream scanning"
  - To reduce gantry radius
    - No need of additional radial distance for spreading the beam
  - To provide parallel scanning –source at infinite distance
    - Simplify dosimetry – treatment planning – field patching - collimation and compensation
  - To allow large field-of-view BEV X-ray during treatment
- Capability to simulate scattering (repainted BEV box scans)
  - Scanning can simulate and improve scattering
    - Scattering with variable range modulation
    - Scattering with a parallel beam
      - Collimators can be cut with normal edges
      - Compensators do not produce dose homogeneity errors
  - Scanning can simulate scattering – the opposite is probably not true
    - To provide backward compatibility - minimal equipment – all with the same gantry

THANK YOU

- First beam through the new PSI Gantry 2 on May 9