Proton Therapy

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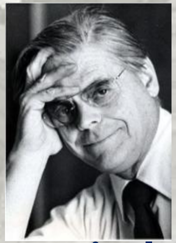
Proton Therapy Center

BASIC SPECIFICATIONS OF PROTON BEAM

History of Proton Therapy

- 1929 : Invented cyclotron, first particle accelerator, by Ernest Lawrence.



- 1946 : Proposed proton therapy by Robert R. Wilson.
- 1954 : The first proton patient (pituitary region, metastatic breast cancer??) at Berkley Laboratory.

- 1961, 1964, 1974 : Harvard Univ., U.C. Davis, Los Alamo tried proton therapy using cyclotron

- 1988 : Proton therapy got FDA approval.
- 1991 : The first hospital-based proton therapy facility using synchrotron in Loma Linda Univ.

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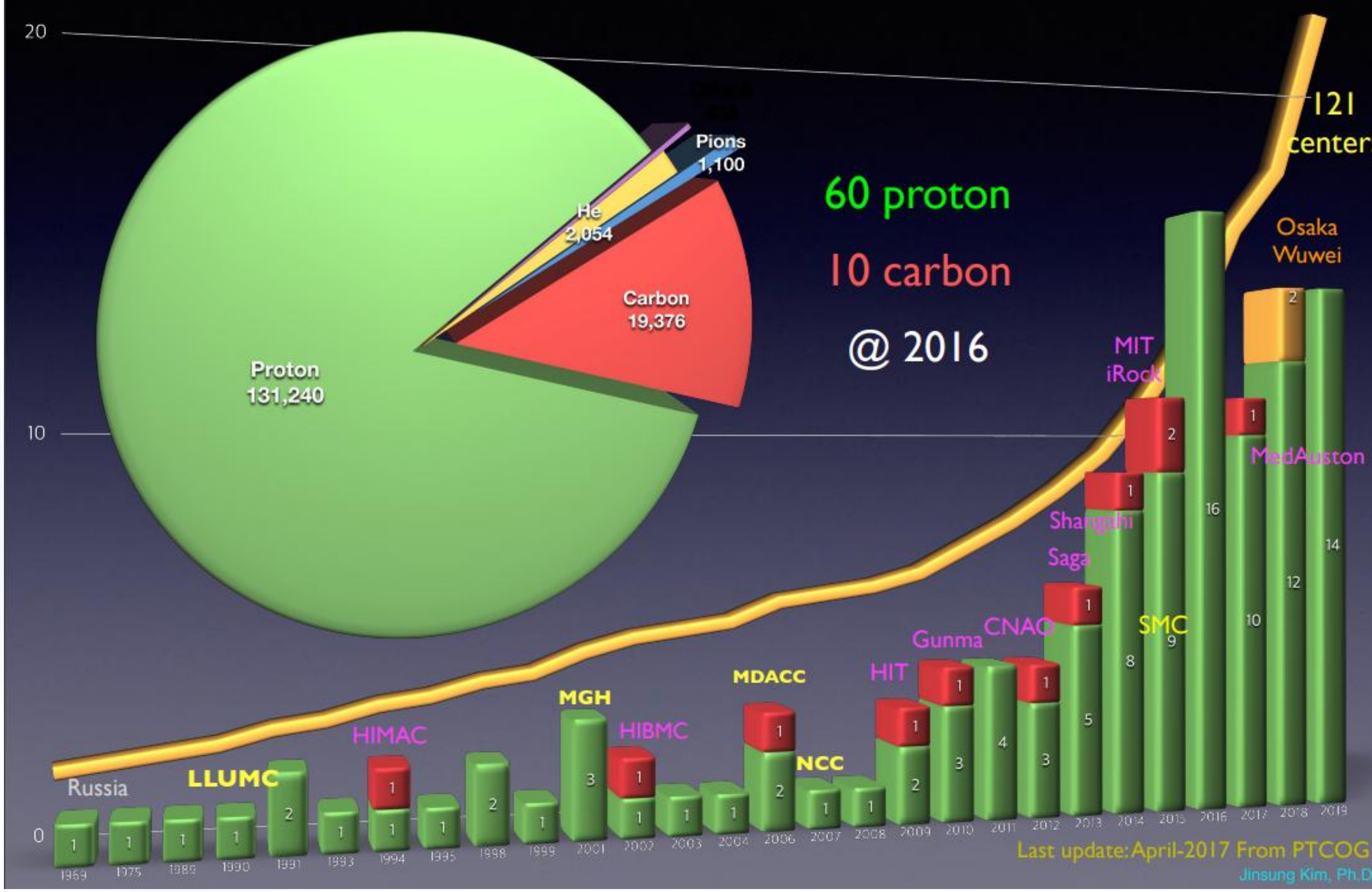
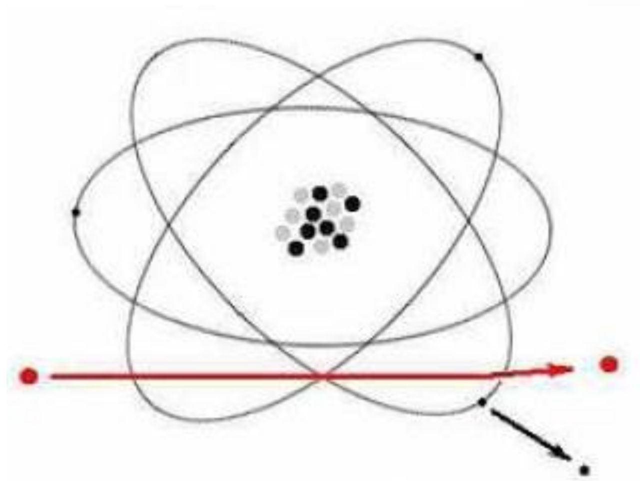
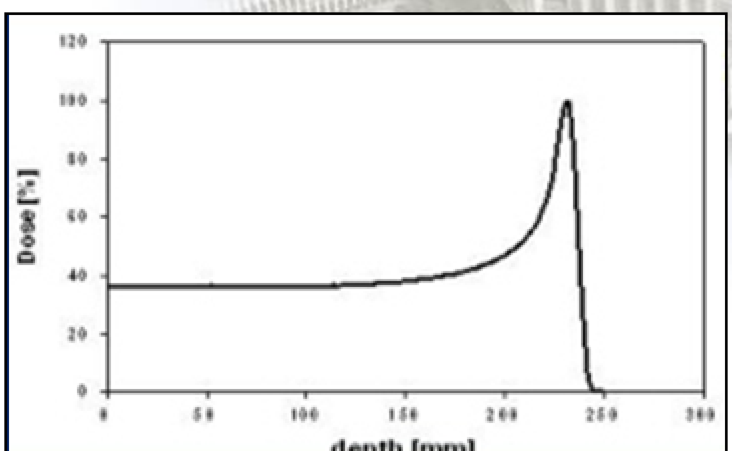
Particle Therapy Center in the world



Electromagnetic energy loss of protons
(Distal distribution)





2.2.2 The Bethe-Bloch Formula

The correct quantum-mechanical calculation was first performed by Bethe, Bloch and other authors. In the calculation the energy transfer is parametrized in terms of momentum transfer rather than the impact parameter. This, of course, is more realistic since the momentum transfer is a measurable quantity whereas the impact parameter is not. The formula obtained is then

$$\boxed{-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln \left(\frac{2 m_e \gamma^2 v^2 W_{max}}{I^2} \right) - 2\beta^2 \right].} \quad (2.26)$$

Equation (2.26) is commonly known as the *Bethe-Bloch formula* and is the basic expression used for energy loss calculations. In practice, however, two corrections are normally added: the *density effect* correction δ, and the *shell* correction C, so that

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln \left(\frac{2 m_e \gamma^2 v^2 W_{max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right], \quad (2.27)$$

with

$$2\pi N_a r_e^2 m_e c^2 = 0.1535 \text{ MeVcm}^2/\text{g}$$

r_e: classical electron radius $= 2.817 \times 10^{-13}$ cm
m_e: electron mass
N_a: Avogadro's number $= 6.022 \times 10^{23}$ mol^{-1}
I: mean excitation potential
Z: atomic number of absorbing material
A: atomic weight of absorbing material
ρ: density of absorbing material
z: charge of incident particle in units of e
$\beta =$ v/c of the incident particle
$\gamma =$ $1/\sqrt{1-\beta^2}$
δ: density correction
C: shell correction
W_{max}: maximum energy transfer in a single collision.

The maximum energy transfer is that produced by a head-on or *knock-on* collision. For an incident particle of mass M, kinematics gives

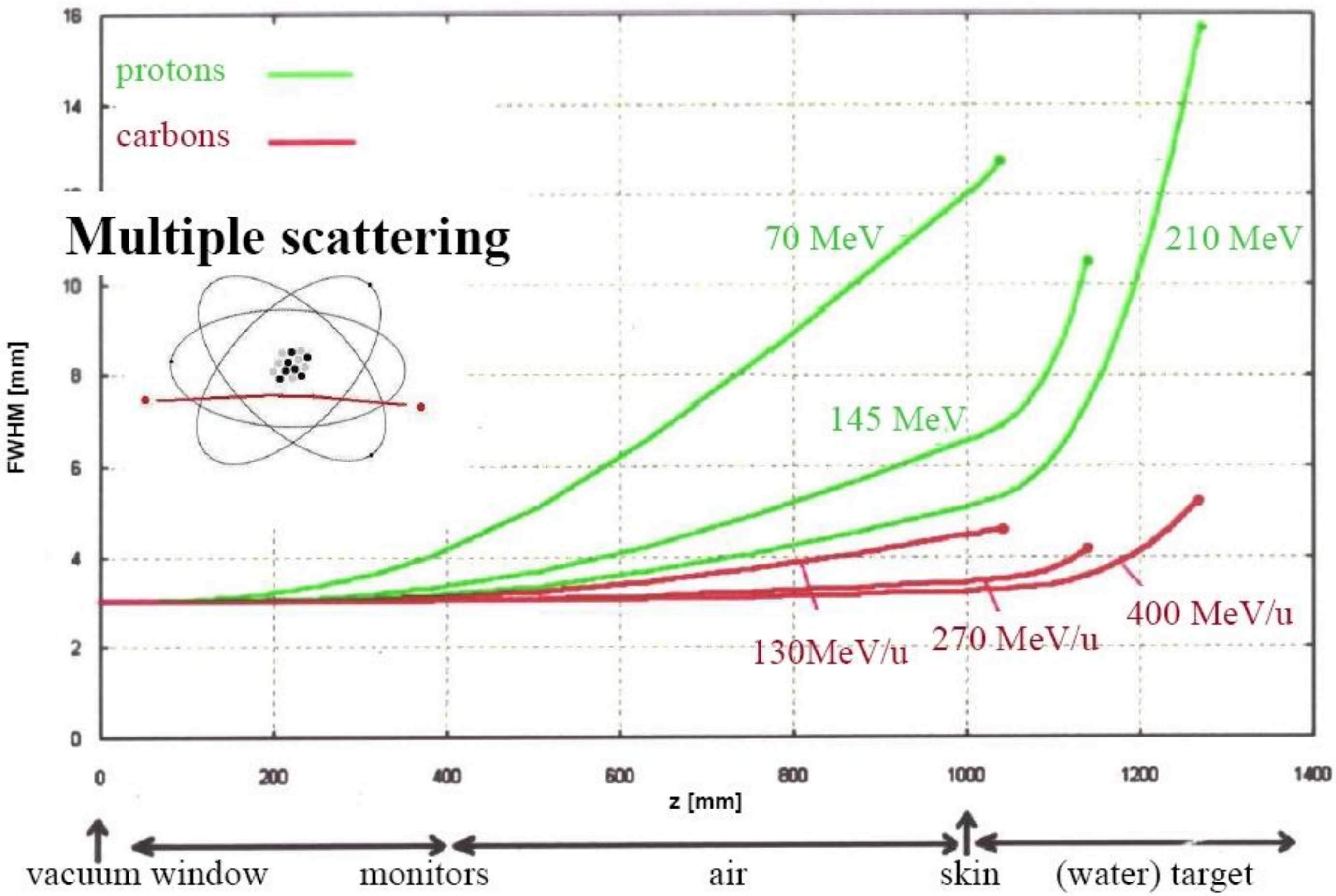
$$W_{max} = \frac{2 m_e c^2 \eta^2}{1 + 2s\sqrt{1+\eta^2} + s^2}, \quad (2.28)$$

where $s = m_e/M$ and $\eta = \beta\gamma$. Moreover, if $M \gg m_e$, then

$$W_{max} \simeq 2 m_e c^2 \eta^2 .$$

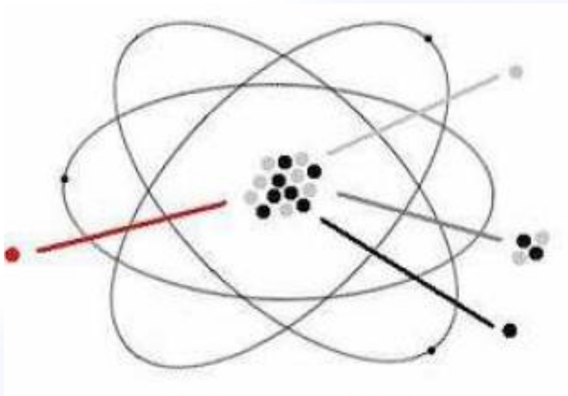
G.F. Knoll

Multiple Coulomb Scattering (Lateral distribution)

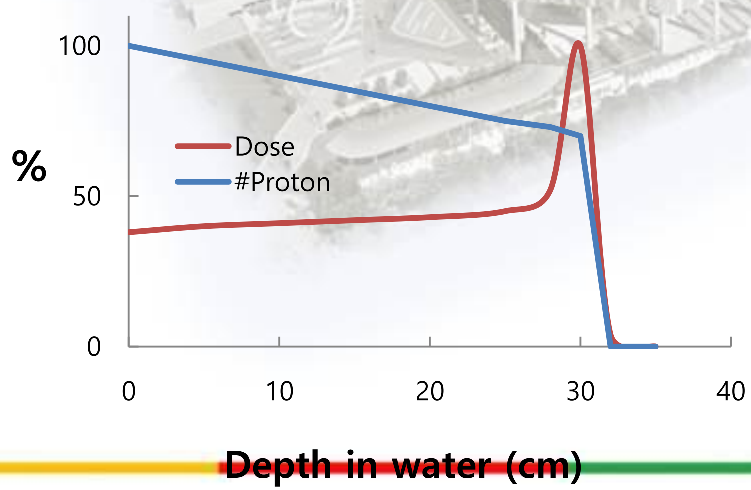


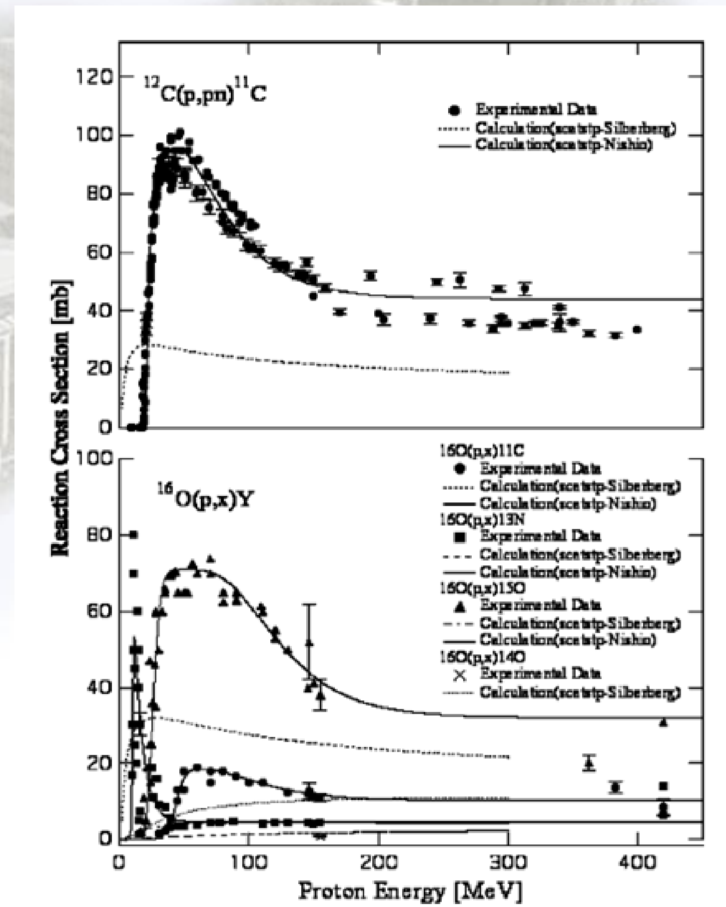
Calc. U. Weber, RKA AG

Nuclear interaction



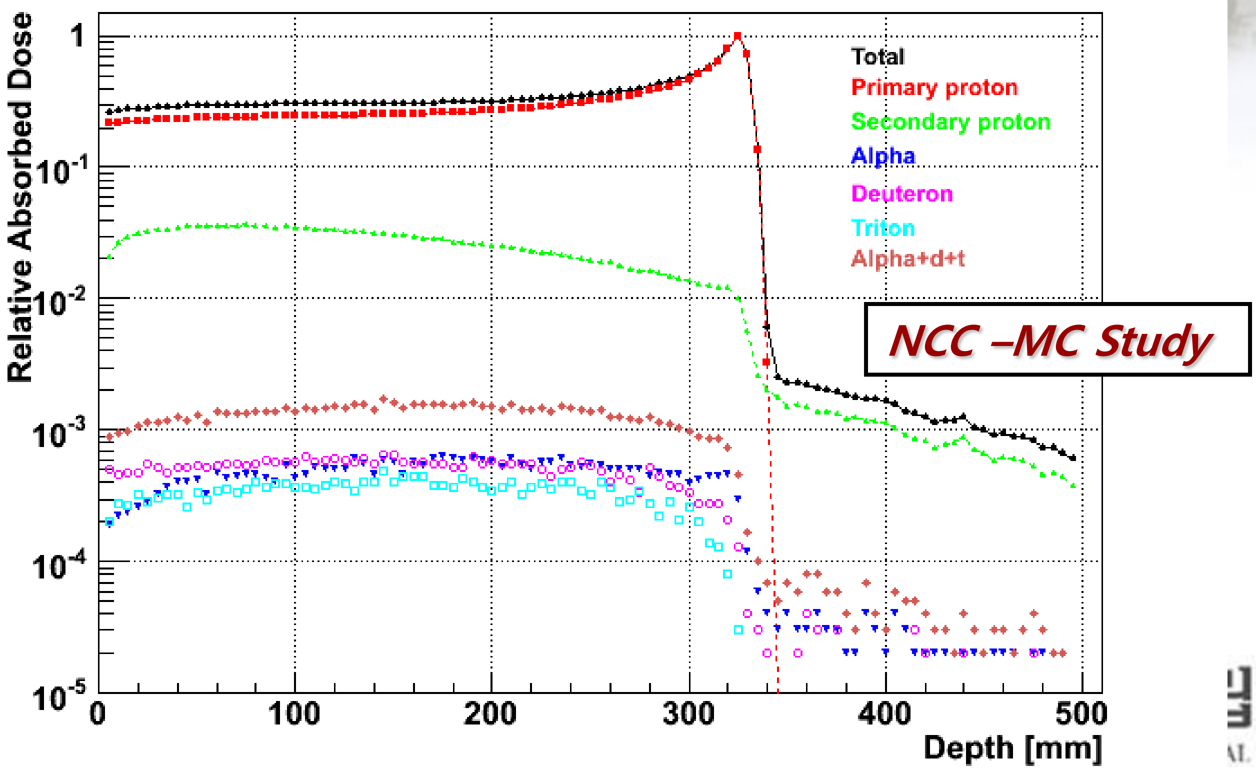
Primary P loss ~ 1% per cm in water



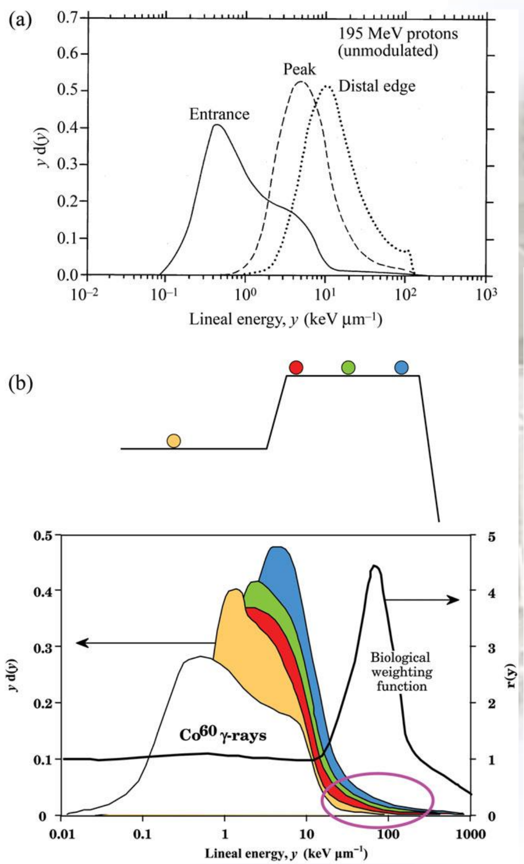


Absorbed dose contributions in Proton therapy

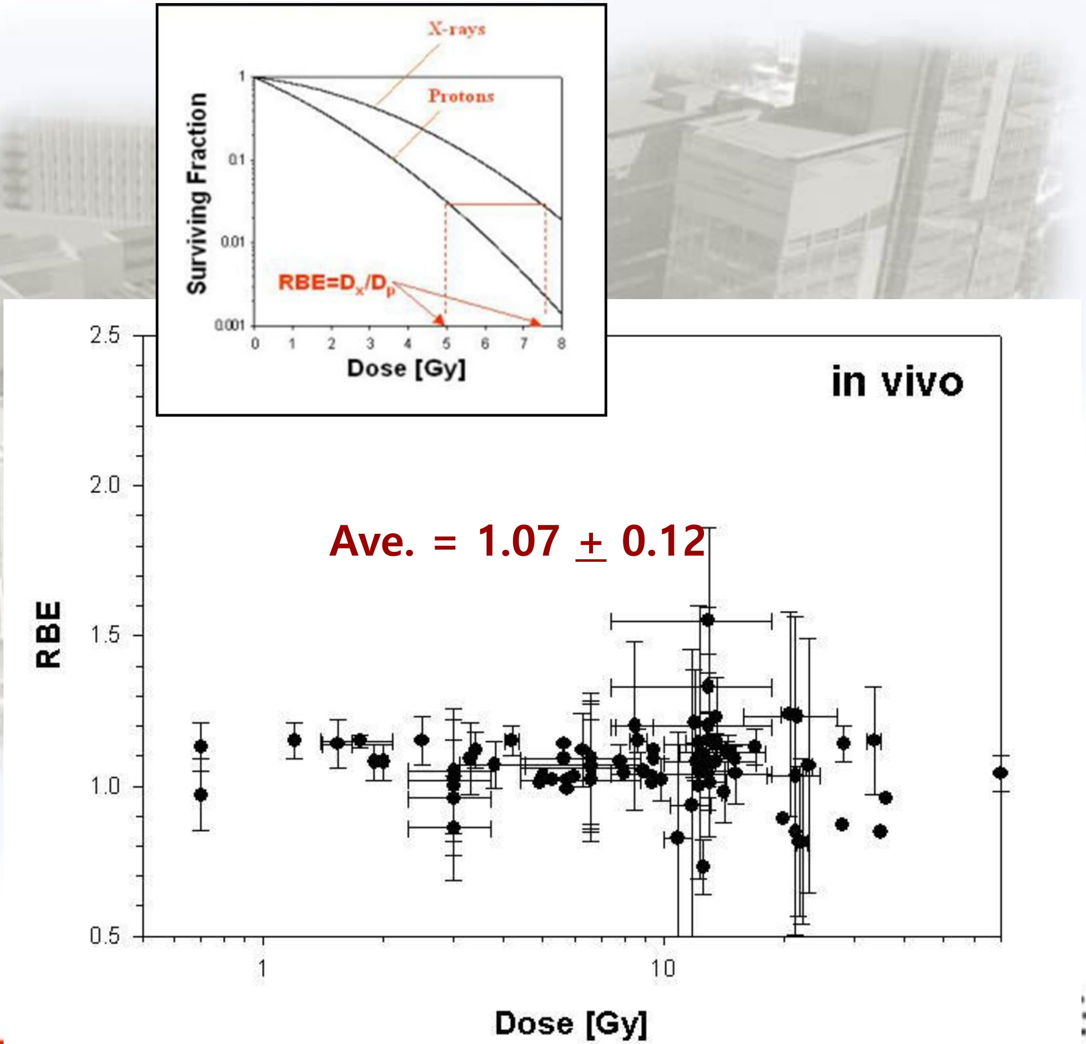
- ✓ Incident Energy : 230 MeV
- ✓ Each line presents relative absorbed dose as a function of water depth.
- ✓ Dose contribution by alpha, d, t, is less than 1% of total dose.
- ✓ In the case of secondary particle, dose contribution of each slice is from 2% up to 12% before the bragg peak region.
- ✓ Absorbed dose beyond the bragg peak is mostly caused by secondary proton.



Relative Biological Effectiveness
(**Recommending RBE(P) = 1.1 @ mid. Of SOBP**)



ICRU 78



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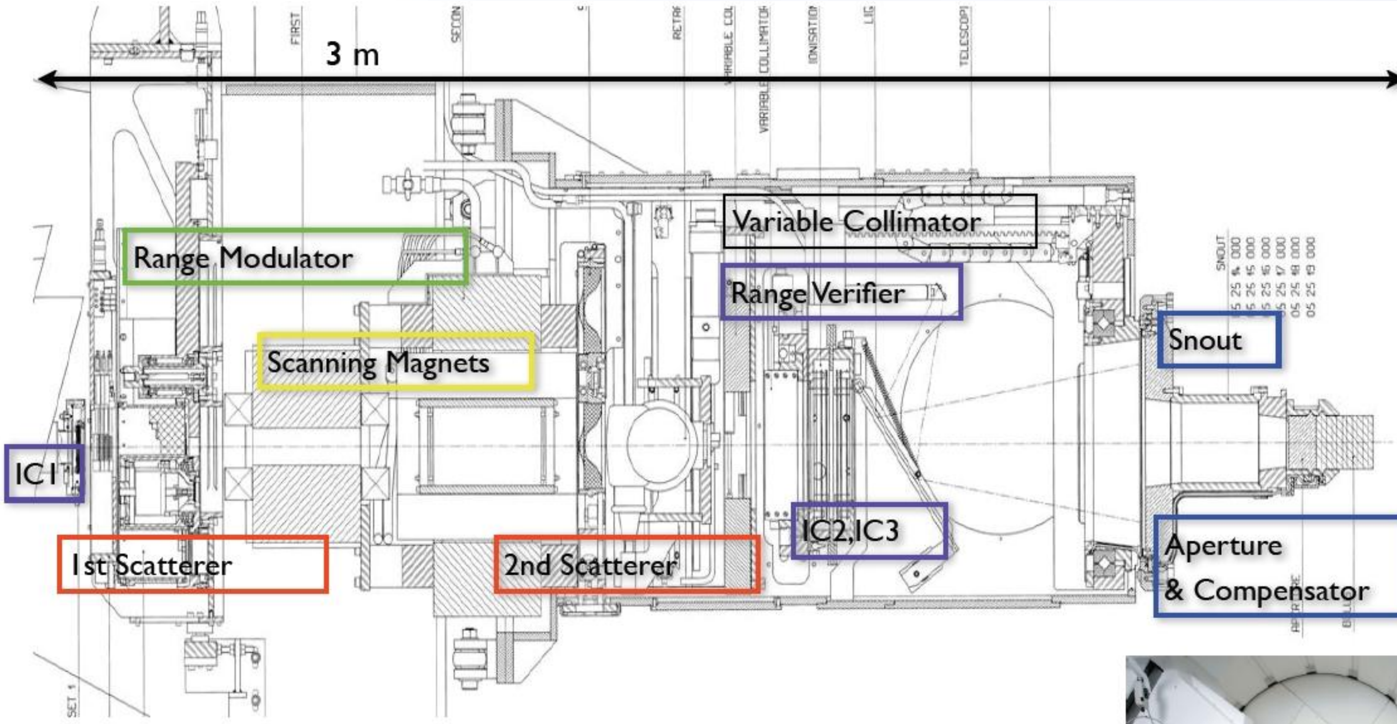
Dosimetry Tasks in Proton Therapy

- Acceptance testing and commissioning of treatment beam lines: *Vendor & User based on RFP.*
- Reference beam calibration of clinical beam
- Commissioning of treatment planning system: *Beam data measurements and TPS validation tests.*
- Periodic checks: *Daily, Monthly & Annual QA*
- Verification of dose delivery: *Patient QA*

PROTON BEAM DELIVERY NOZZLE SYSTEM

Schematic Plot of Beam Nozzle



➡ 1st scatter, 2nd scatter for **beam spread in lateral distribution**
➡ range modulator for **Spread Out Bragg Peak (SOBP)**
➡ ionization chamber 1,2 and Range verifier for **beam monitoring**
➡ snouts, aperture for **lateral beam shaping**
➡ compensator for **longitudinal beam shaping**

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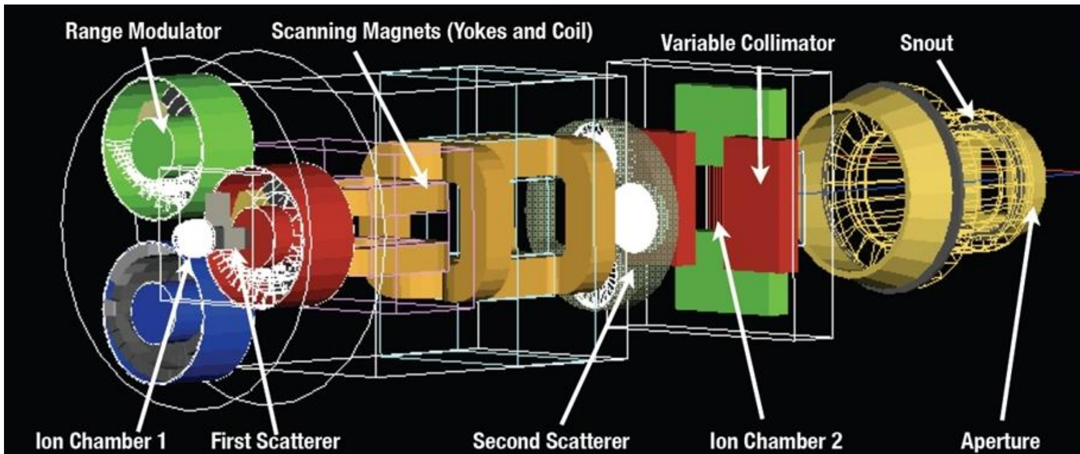
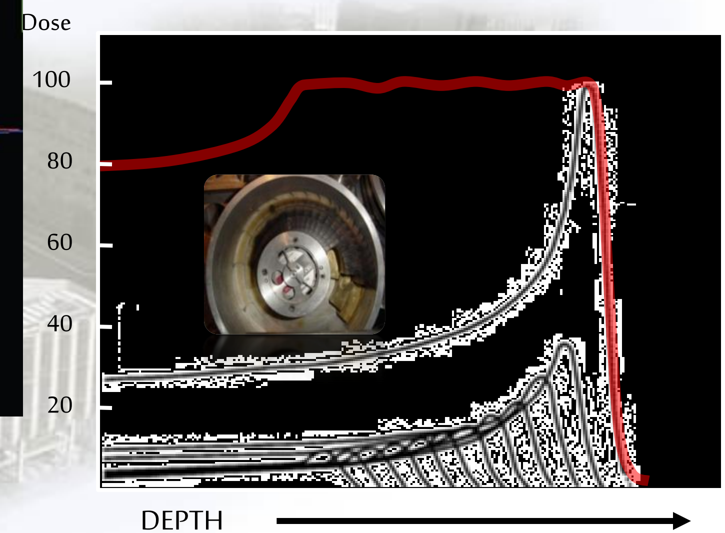
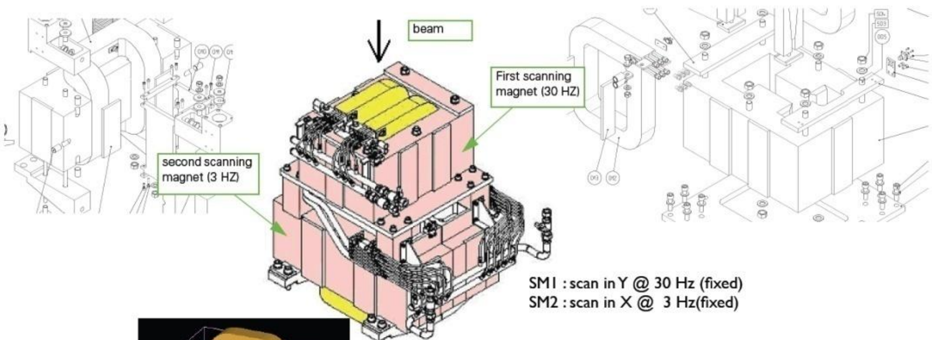
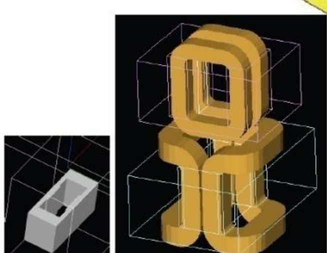
Beam Nozzle System
(IBA universal nozzle)

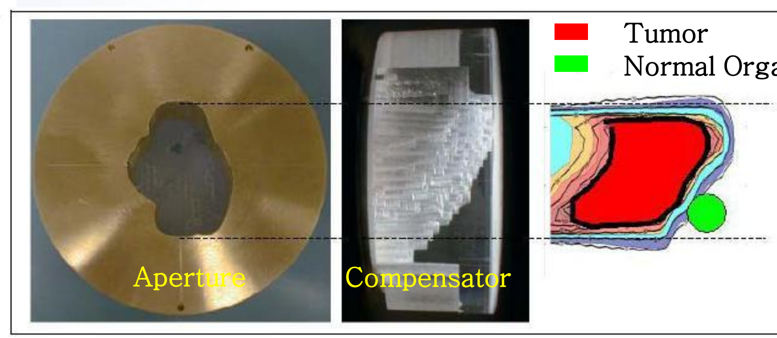




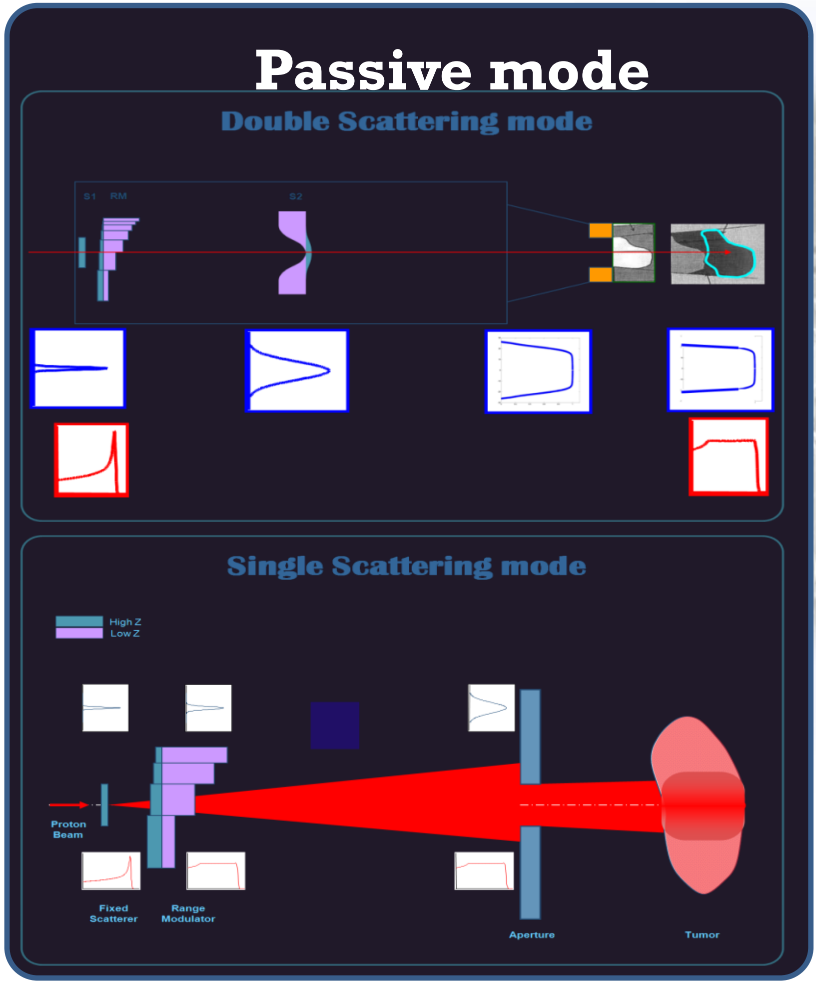


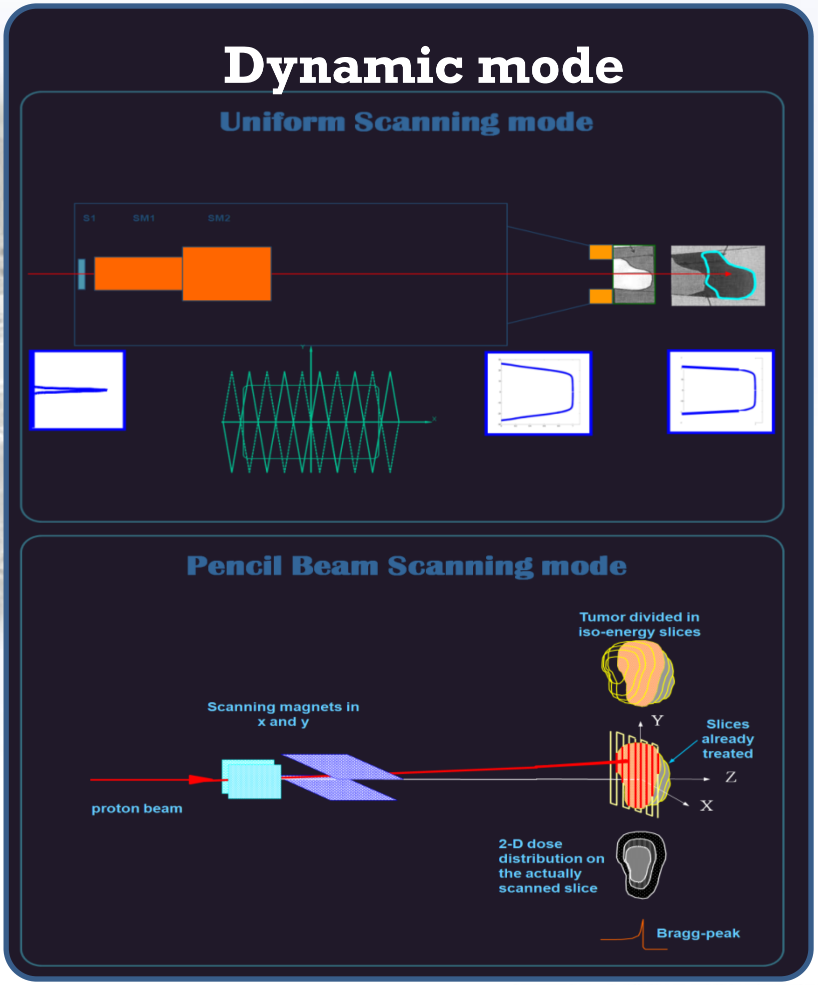


```
# User commands ( B-Field Y , X)
/GTR2/SMAG/magnet tesla 0.027 0.0049
/GTR2/SMAG/magnet cm   8     -5
#loop
loop /GTR2/SMAG/magnet tesla 0.027*i 0.0049*i
```



Proton Beam modulation methods





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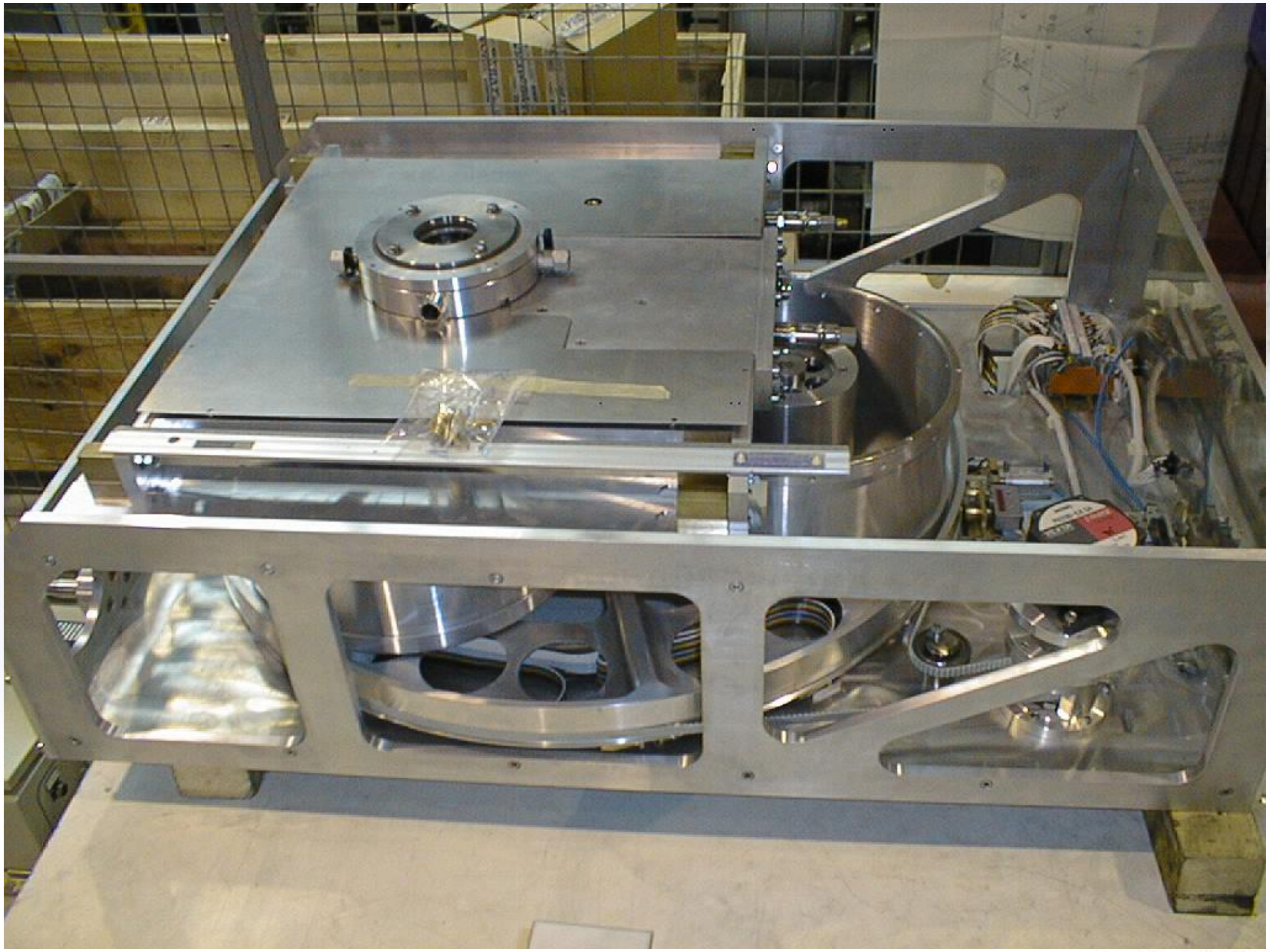
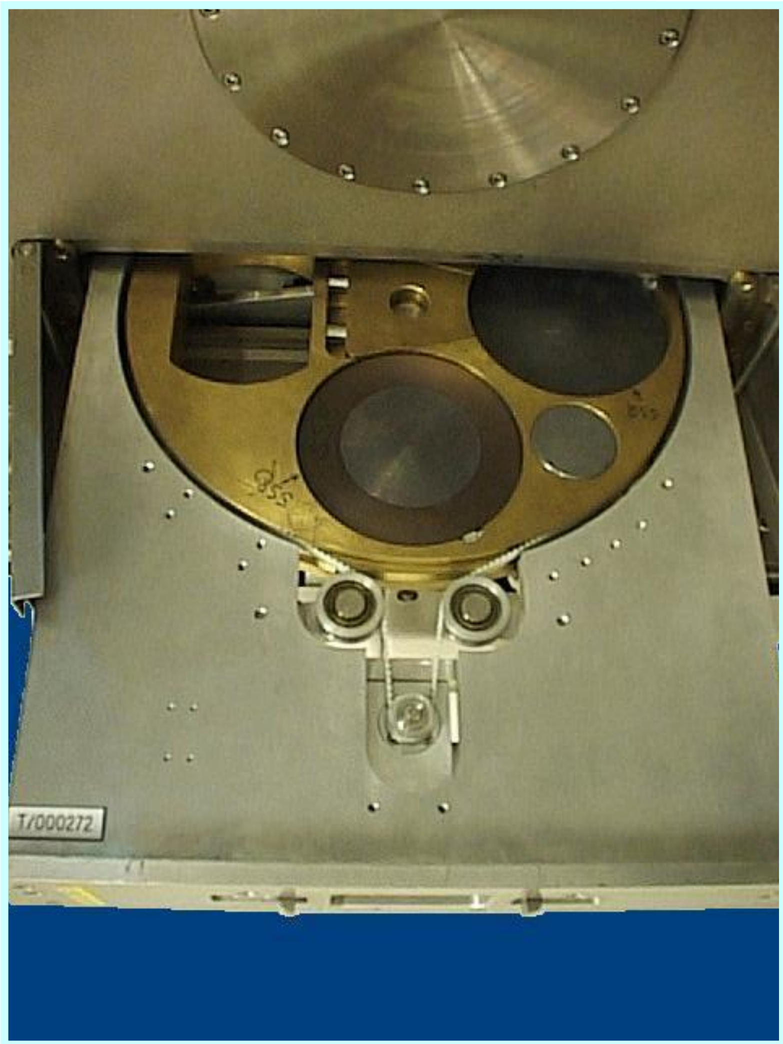
Specifications of Modulated Proton Beam

Item	Singles Scattering	Double Scattering	Uniform Scanning	Pencil Beam Scanning
Range in Patient (g/cm^2)	3.35–20.4	4.51–28.42	3.42–32.1	0.5–32 (7.5–32)
Range mod. Adjustment, max. modulation (g/cm^2)	0.4(R>6), 0.17 9.2	0.2 20.75	0.5 Full	0.4 24
Range adjustment(g/cm^2)	0.09(R>6),0.05	0.1	0.1	0.4
Ave. dose rate (Gy/min)	5.93	3	1.15	~1.0/1L
Max. Field Size (cm)	4 (D)	24.3 (D)	40X30	22.5X25 At high E
Dose Uniformity (%)	1.25	1.05	1.5(R), 2.6(L)	3
Effective SAD (m)	2.55	2.19	2.12	2.12
Distal Penumbra (g/cm^2)	0.21	0.23	0.13	Beam sigma
Lateral Penumbra (cm)	0.17	0.48	0.30(y), 0.22(x)	4.9mm@R32cm 10.4mm@R8cm
	H&N, RS	General	Large Size	IMPT

RM + FS + IC set A



Second Scatterer System



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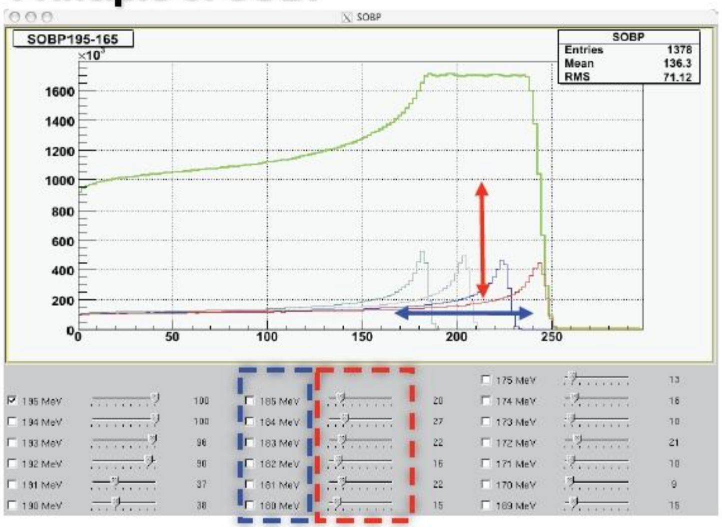
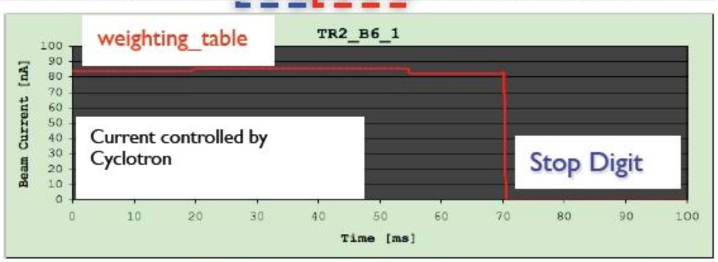
Range Modulation wheels

Principle of SOBP

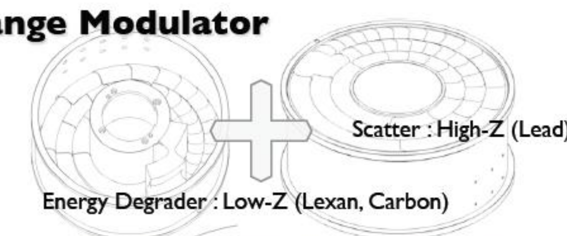


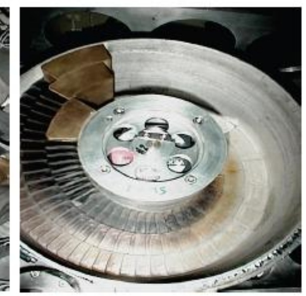


Beam Current Modulation (BCM) → Total 52 BCM records

Stop digit determines width of SOBP
Weighting_table stands for cyclotron current to determine flatness of SOBP

Range Modulator

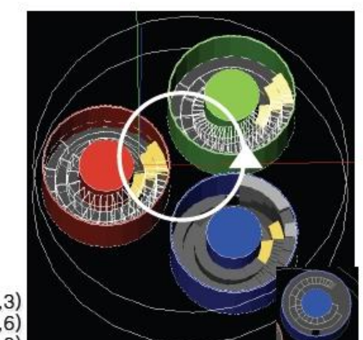




#user commands
#Track (Large wheel rotation)
/GTR2/RM/track 5
#SOBP (Small wheel rotation)
1. position mode (pristine beam)
/GTR2/RM/angle deg 80.26

2. speed mode (SOBP)

/beam/bcm weighting_table SD



– SW 1 (Track 1,2,3)
– SW 2 (Track 4,5,6)
– SW 3 (Track 7,8,9)

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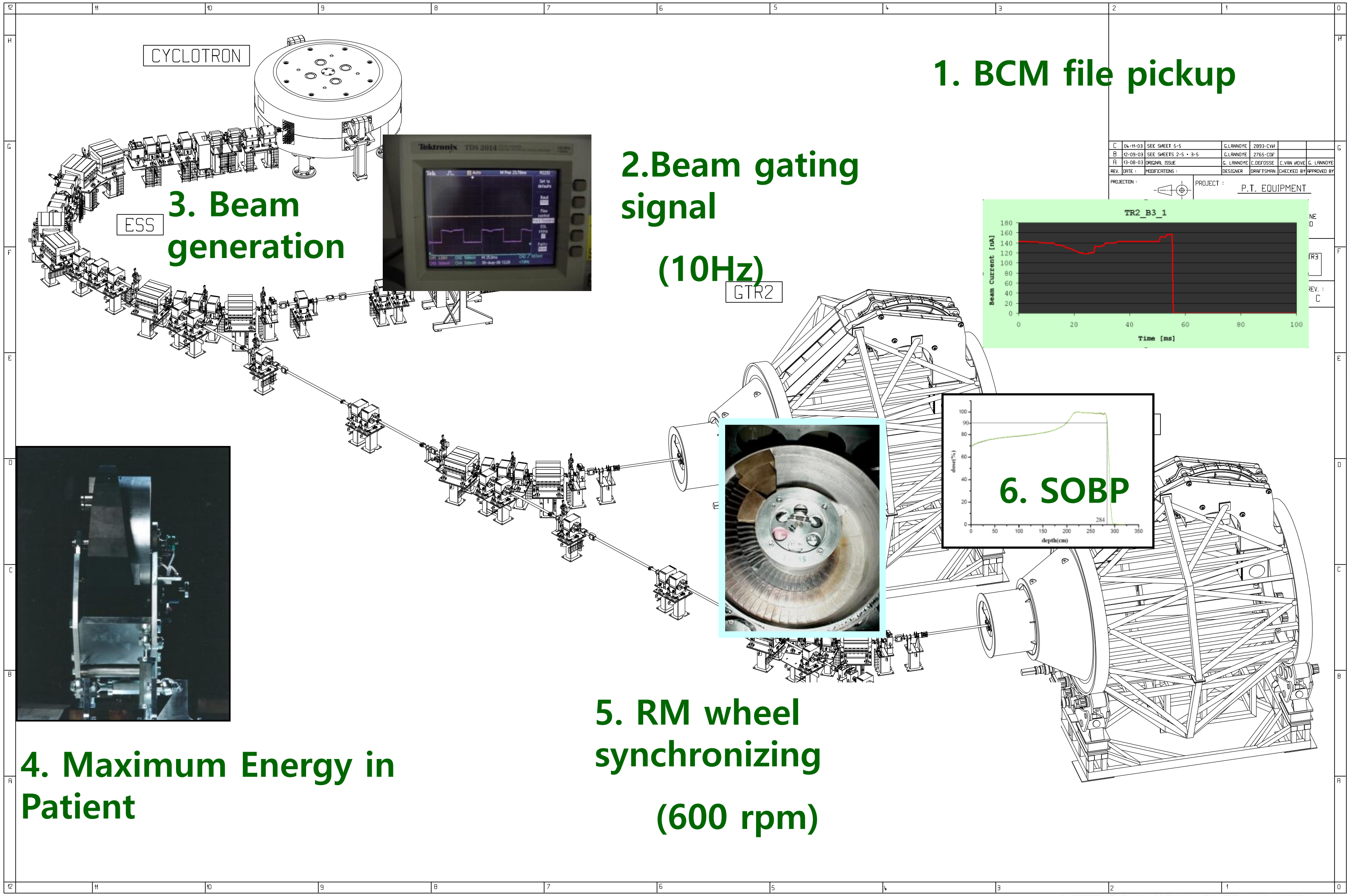
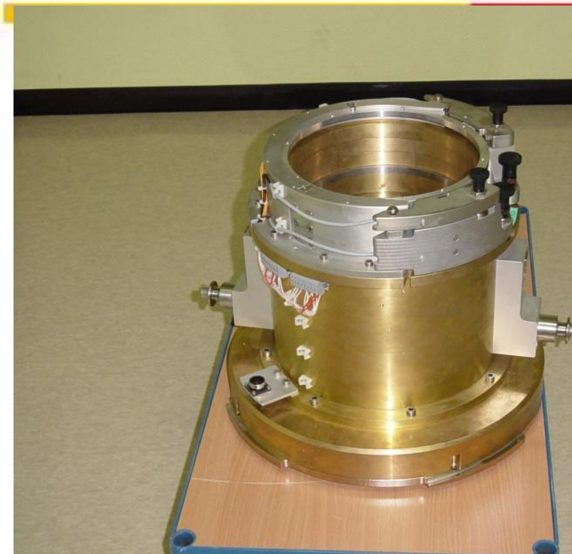
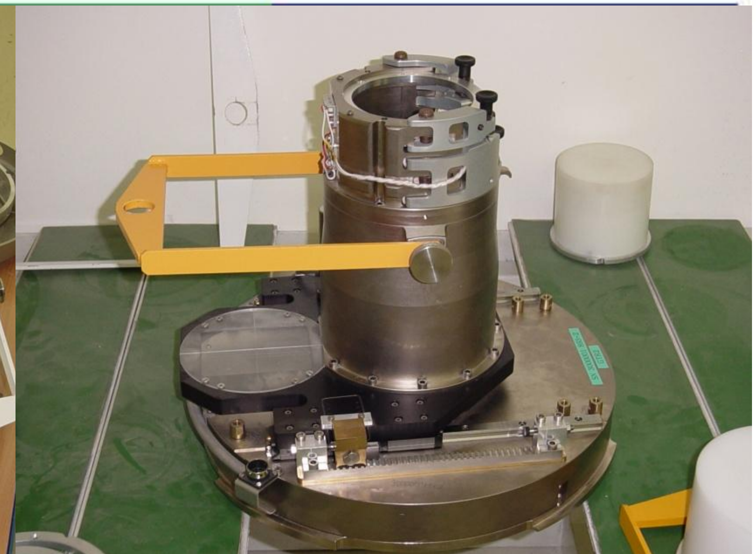
SOBP on Scattering mode



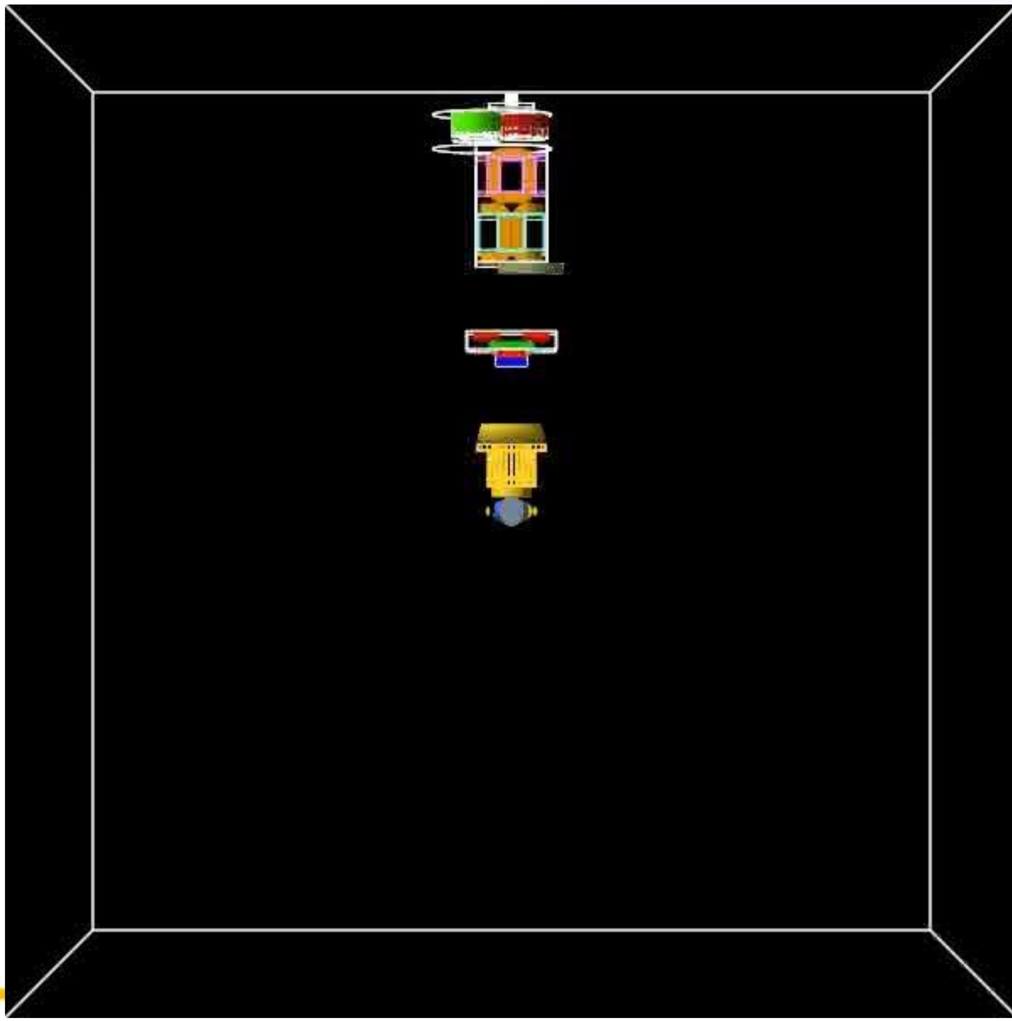


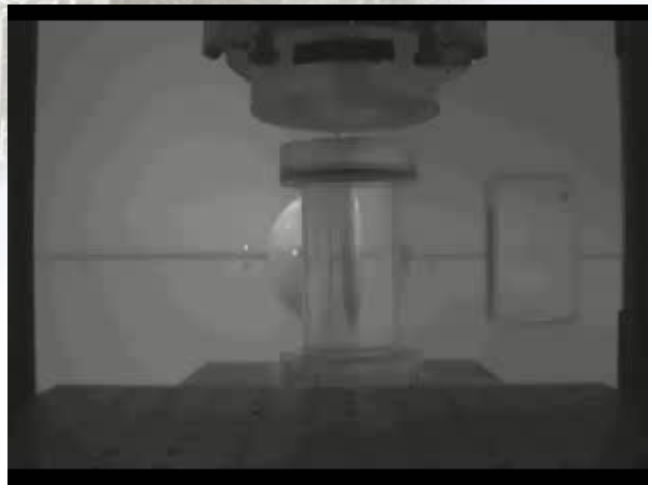


Snouts

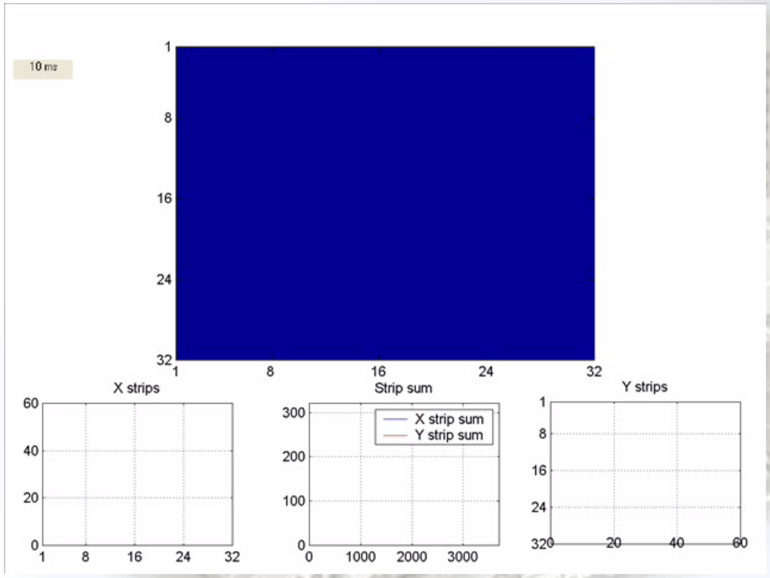
250, 180, 100 & Eye

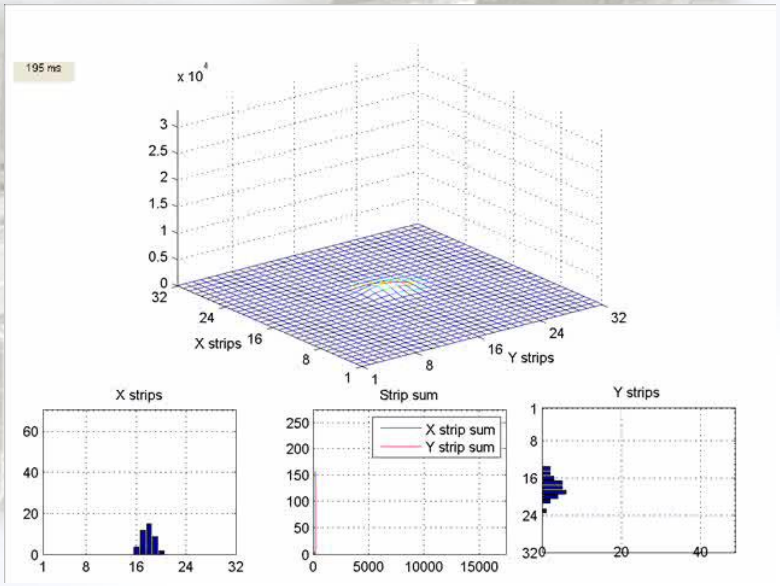
Demonstration of Proton Beam Irradiation





PBS Beam Irradiation





IBA demonstration

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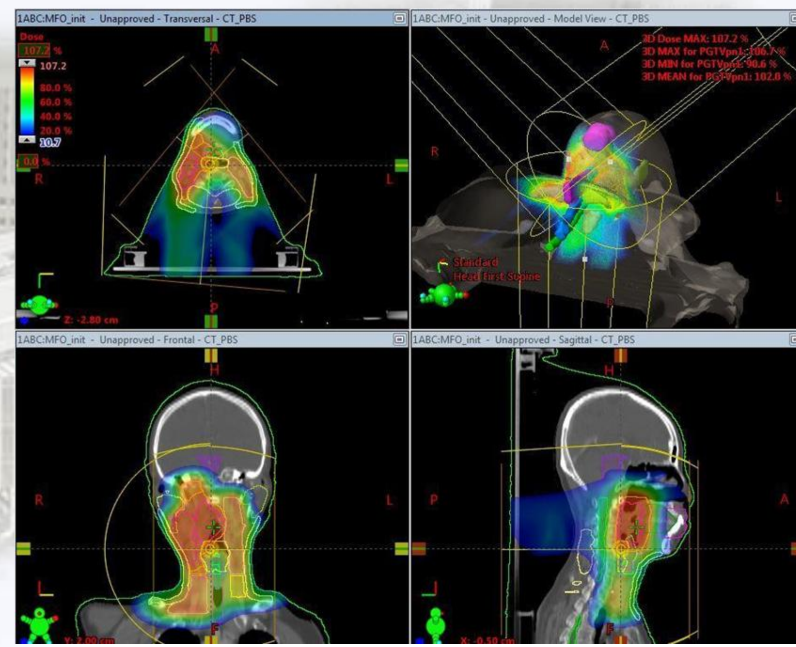
Example of Patient Treatment

DS+US Planning



PBS Planning

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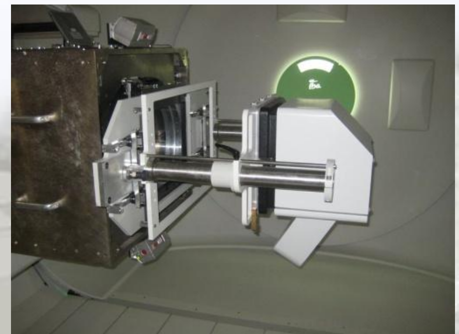
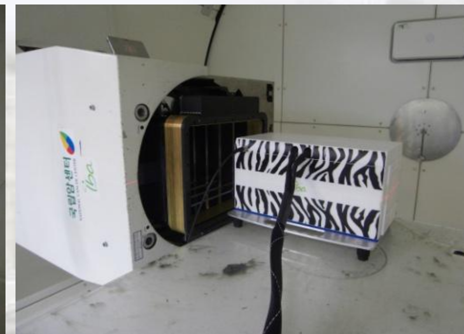
Tools for PBS measurement

3D Water Phantom



Lynx

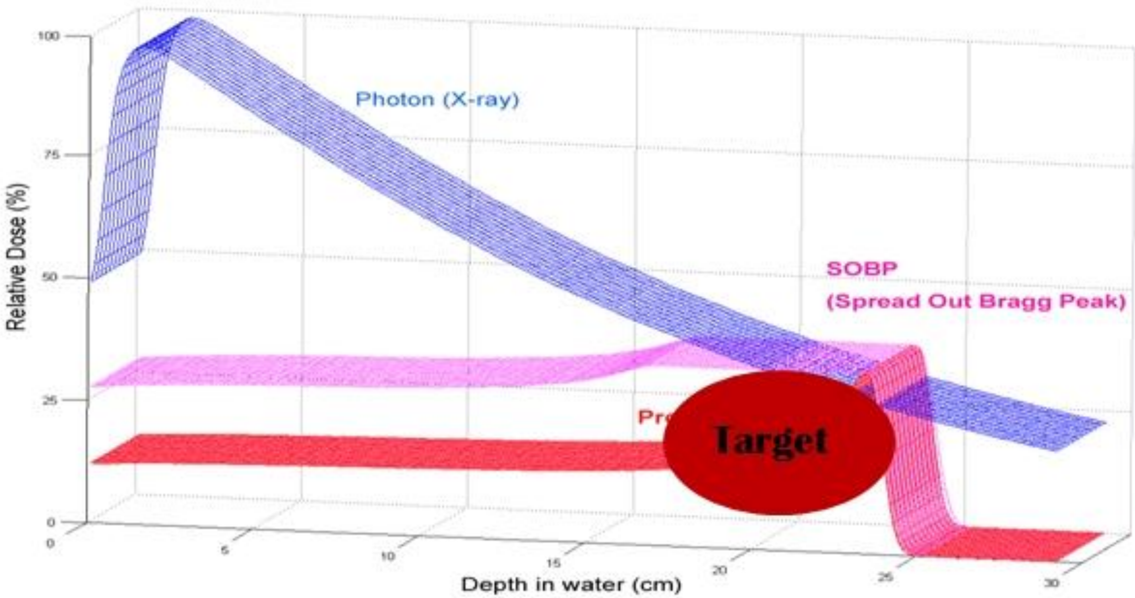


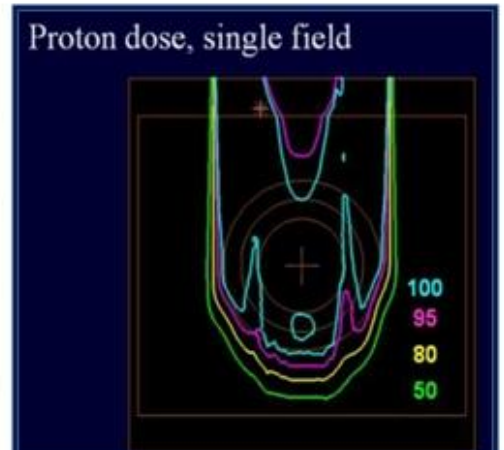
Zebra(MLIC)

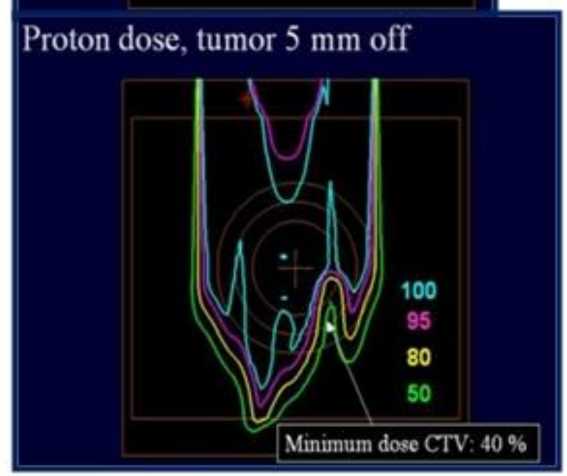
MatriXX

EBT Film

Concerning of Beam delivery Uncertainty

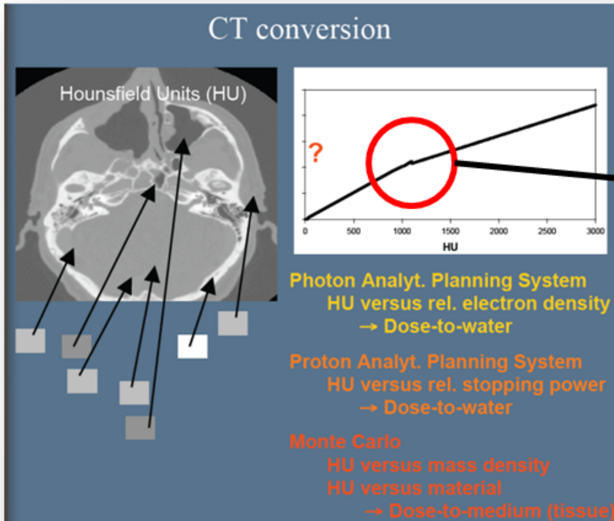


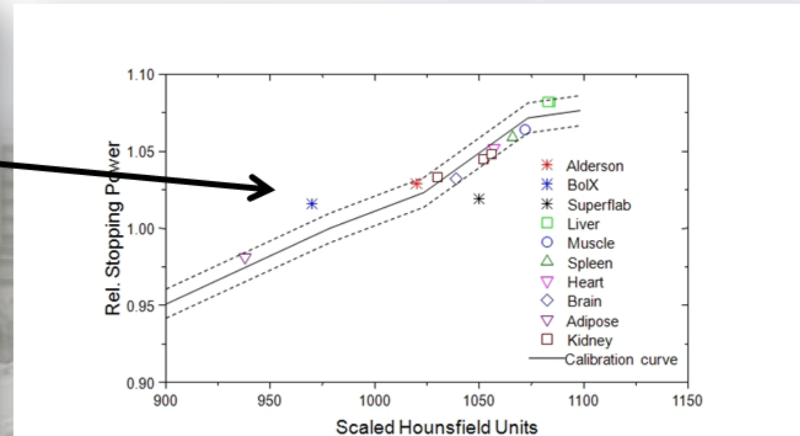




Ex.) 5mm beam off on Target (1 portal)
- Proton : 100% → 0% dose
- Photon : 100% → > 95% dose

Dose Cal. Error on TPS based X-ray CT





- Precision of SP_{rel} meas. 0.2%
- Variation of HU in ROI (1σ) 0.5-2.0%

- Overall expected maximum error in SP_{rel}:
  - ± 1.8% for bone
  - ± 1.1% for soft tissue

	Soft tissue Amount [cm]	Soft tissue wer [cm]	Soft tissue Abs. error [cm]	Bone Amount [cm]	Bone wer [cm]	Bone Abs. error [cm]	Total Abs. error [cm]
Brain	10	10.3	0.11	1	1.8	0.03	0.14
Prostate	15	15.5	0.17	5	9	0.16	0.33

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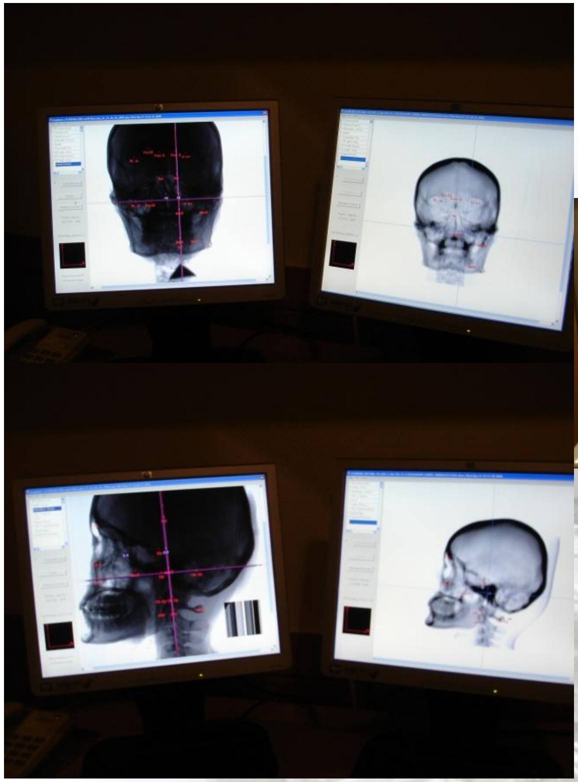
Patient Treatment Setup Verification



Example

Image registration & Position Correction

- VARIAN A277 X-ray tube
  - kV range: 40 kV to 150 kV
  - Target angle: 7°
  - Focal spot sizes: 0.6 – 1 mm
  - mA/mAs range: 1 to 500 mAs
- VARIAN B150 housing

- VARIAN flat panels PAXSCAN 4030 R
  - Receptor type: Amorphous Silicon
  - Conversion screen: Gadolinium Oxyde (Lanex Fast)
  - Energy Range: 40kV- 150 kV
  - Active area: 29,3 cm x 40,6 cm
  - Pixels: 2304 x 3200
  - Resolution: 127 µm x 127 µm

Dosimetry Devices for PB

There are several tools, useful for scanning beam.

Some of them are essential and others can save your beam data measurement time.

Ex.) MLIC, Scintillation Plate type detector, 2D Array type Ionization Chamber, Large size PP type chamber, etc.

Maintenance PBT Facility

- **Biomedical Engineers : 9 man/year**
  - 1 for RF & PT system
  - 1 for Beam optics
  - 1.5 for Electronics
  - 1.5 for Mechanics
  - 1 for Software
  - 3 for Cyclotron OP
- **Medical Physicist**
  - 1 for Beam Calibration & Dosimetry support
- **IBA 0n-site Engineer**
  - 1 for General technical support

** **Preventive Maintenance : 320 items (including daily, weekly, monthly and yearly items)**

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Weekly Schedule of PT Facility

<table>
<tr><th>time</th><th>Mon</th><th>Tue</th><th>Wed</th><th>Thu</th><th>Fri</th><th>Sat</th><th>Sun</th></tr>
<tr><td>6</td><td colspan="5" rowspan="2">Morning QA work for daily Patient Treatment</td><td rowspan="16">Machine QA & PM</td><td rowspan="2"></td></tr>
<tr><td>7</td></tr>
<tr><td>8</td><td colspan="5" rowspan="13">Patient Treatment</td><td rowspan="14">Reserved for Research & PM</td></tr>
<tr><td>9</td></tr>
<tr><td>10</td></tr>
<tr><td>11</td></tr>
<tr><td>12</td></tr>
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<tr><td>21</td><td rowspan="4">Patient QA & PM</td><td rowspan="4">Patient QA & PM</td><td rowspan="4">Patient QA & PM</td><td rowspan="4">Patient QA & PM</td><td rowspan="4">Patient QA & PM</td></tr>
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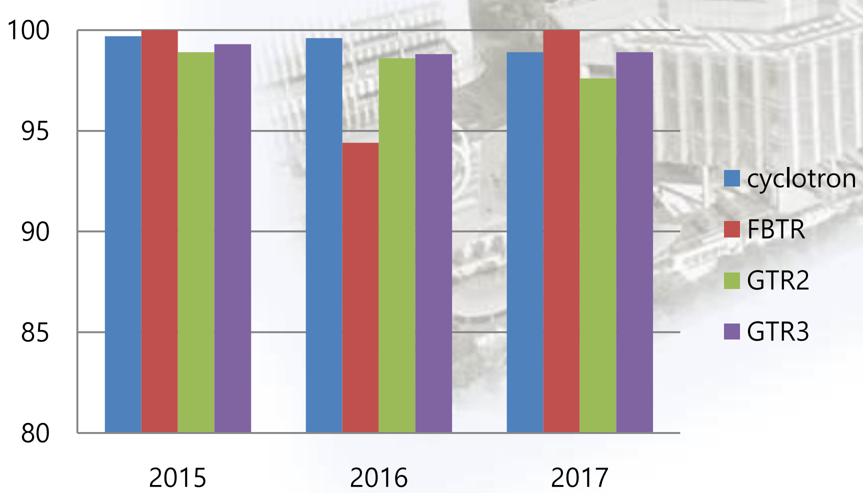
Maintenance Statues

- 9 Engineers & 3 shifts/day
- Machine : Proteus 235, Linac(trilogy, CL21EX, N21EX), SIMULATOR
- 10 years experience in PT

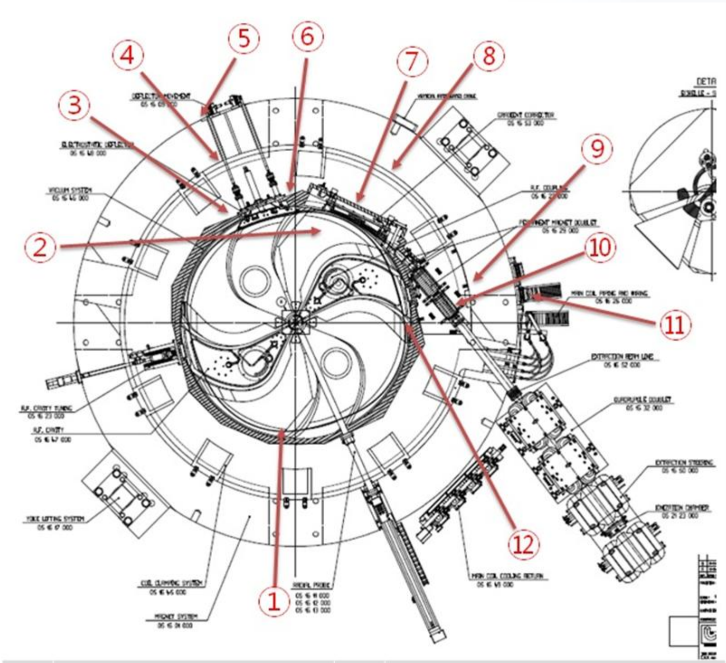
Recent Uptime per room(%)

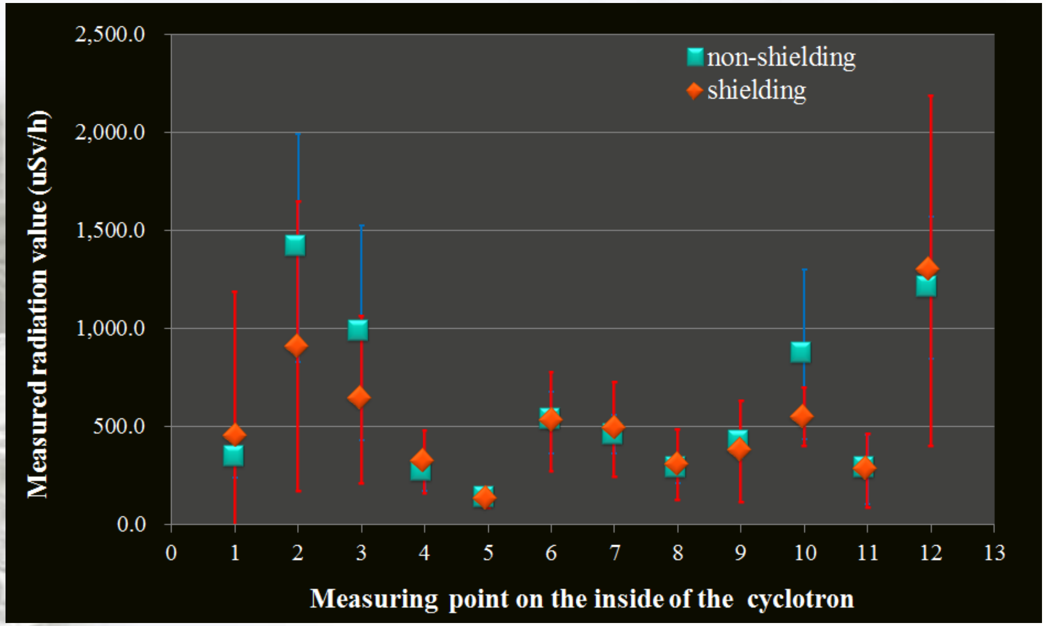


Work Scope :

1. PT Facility maintenance
- CM(corrective maintenance) : ~75 times/y
- PM(Preventive Maintenance)
: cyclotron PM 2 times(4days)/year,
Other part PM 2 times/year
- Proton Accelerator operation
2. Linac-3EA, SIMULATOR maintenance
CM : 50 times/year

Radiation Activity Distribution during Cyclotron PM

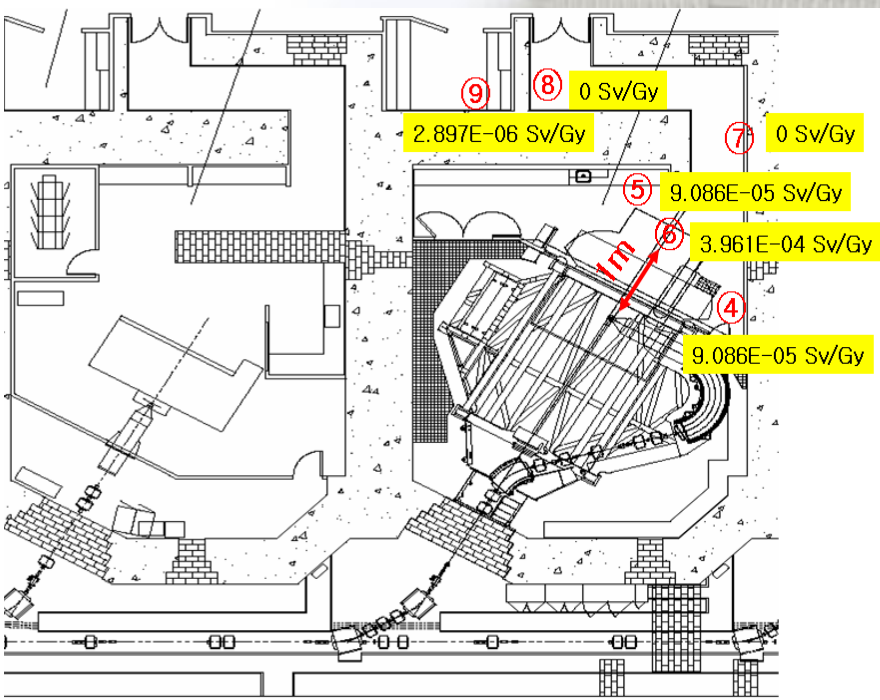


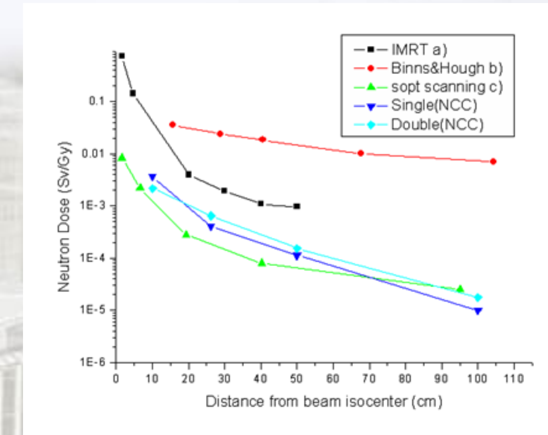


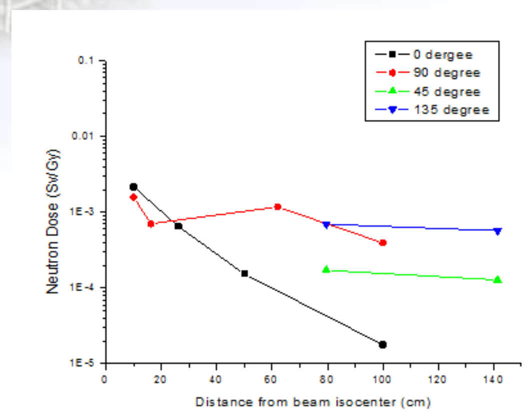
No.	Description	No.	Description
1	Opposite side of deflector	7	Rear end of gradient corrector
2	Front of Gradient corrector	8	Boundary of main coil back Gradient corrector
3	Right rear end of deflector	9	Boundary of main coil back permanent magnet
4	Boundary of main coil back deflector	10	Permanent magnet
5	Boundary of yoke back deflector	11	Boundary of yoke near permanent magnet
6	Left rear end of deflector	12	Front of fixed cavity tuner

- 6 times measurements(2014. 4~ 2017. 4)
- 1 day after beam shutdown(survey meter: 450B-DE-SI, VICTOREEN & FH40 G-10, THERMO)

Treatment Room Radiation Level







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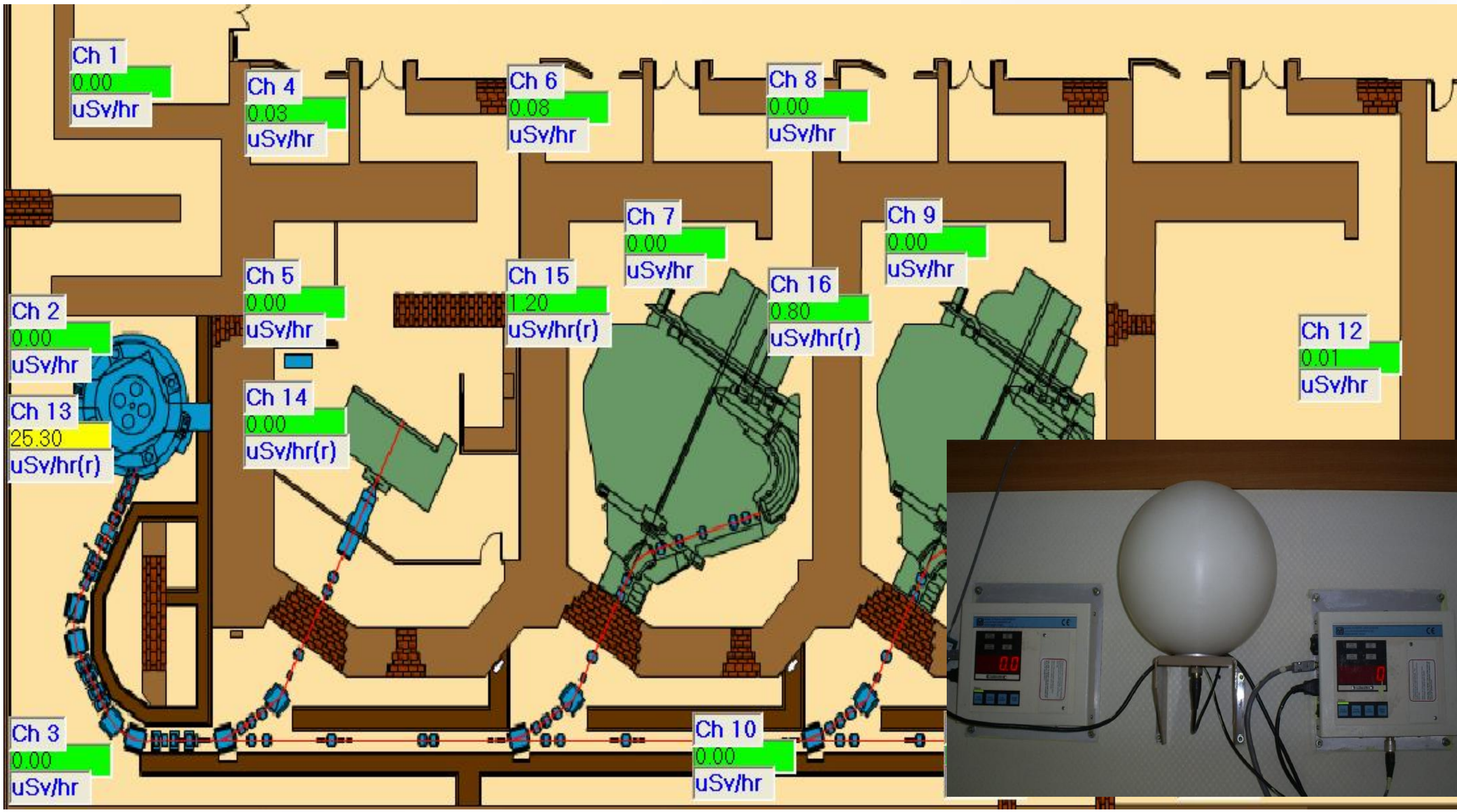
Radiation level monitor & area detector



Radiation Exposure statistics of radiation workers

Category	Exposure Dose in 2009
Therapists	< 1 mSv
Medical Physicists	< 1 mSv
MCR Operators	0.7 ~ 2.5 mSv
Maintenance Engineers	4.5 ~ 7.0 mSv

PROTON DOSIMETRY CODE OF PRACTICES

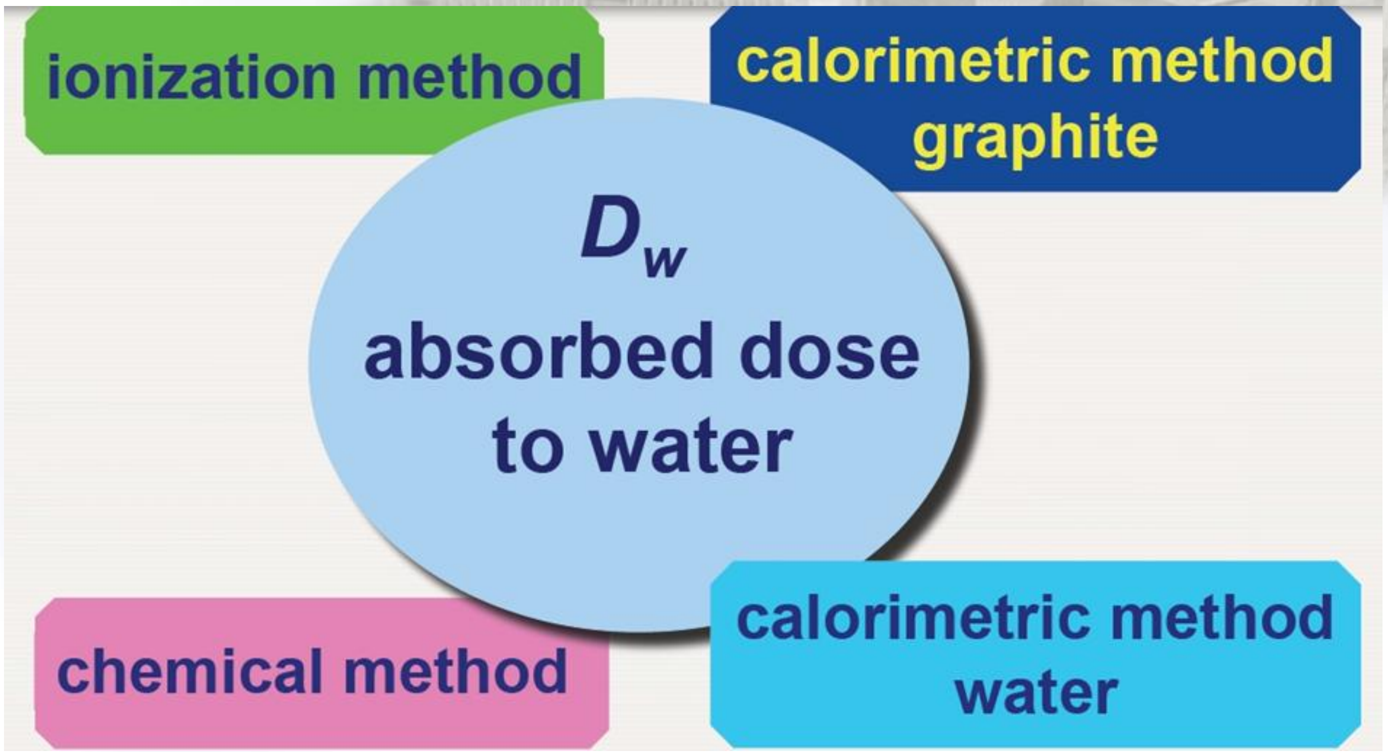
Words Definitions in Radiation Therapy

- Iso-effective Dose: Absorbed Dose*RBE, Cobalt-60 Equivalent Dose (CGy or GyE).
- Absorbed Dose(Gy): a physical quantity to measure the radiation energy absorbed by unit mass of substances. 1 Gy = 1 J/kg.
- Relative Biological Effectiveness(RBE): the ratio of biological effectiveness of one type of ionizing radiation relative to Cobalt-60.

References

- ICRU Report 78, “Prescribing, Recording, and Reporting Proton-Beam Therapy”
- IAEA TRS no. 398, “Absorbed Dose Determination in External Beam Radiotherapy”.
- IAEA TRS no. 461, ”Relative Biological Effectiveness in Ion beam Therapy”.
- C. P. Karger, T. Kanai, et al, “Dosimetry for ion beam radiotherapy”, PMB 55(2010) R193-R234.
- C. Goma, et al, “Proton beam monitor chamber calibration”, PMB 59(2014) 4961-4971
- Ion Beam Application(IBA) Technical Reports.
- PTCOG Education Course Presentation.

International standards of D_w



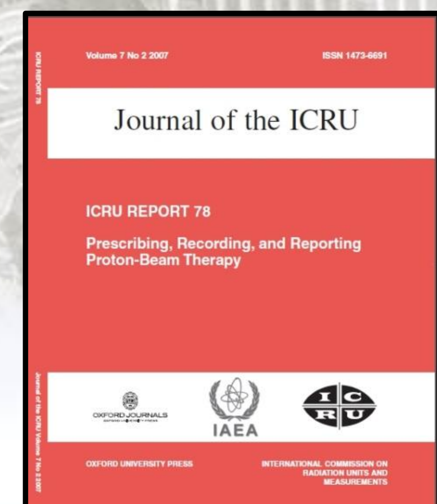
Absorbed Dose Determination

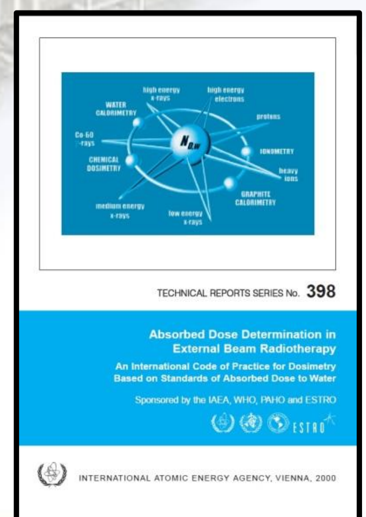
- ICRU Proton Dosimetry code : Report 78

  "Prescribing, Recording, and Reporting Proton-Beam Therapy"

- IAEA Proton Dosimetry code : TRS 398

  "Absorbed Dose Determination in External Beam Radiotherapy: An international Code of Practice for Dosimetry based on Standards of Absorbed Dose to water"





Ionization Chamber Dosimetry protocol

- IAEA/ICRU recommending protocol based on Absorbed dose to water(D_w).
- Providing the formalism and the data to related a calibration of an ionization chamber.
- Simple dosimetry system and easy to use in clinic.
- Availability to all kind of therapeutic beam modalities.

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$N_{D,w}$–based formalism

- Absorbed dose to water in a reference beam Quality : $Q_0(^{60}Co)$
- Absorbed dose of Q(X-ray, Electron, Proton, Heavy ion).

$$D_{w,Q} = M_Q \, N_{D,w,Q0} \, k_{Q,Q0}$$

M_Q : Corrected Q Reading of Electrometer (PTP corr.).

$N_{D,w,Q0}$: Calibration Coefficient of Ionization Chamber at ^{60}Co.

$k_{Q,Q0}$: Beam Quality correction factor btw Q_0 (^{60}C)o& Q.

K_Q factor

- **Measurements and MC Calculations based.**
- **I.C. perturbation of reference beam (Co) at PSSD/SSDL.**

$$k_{Q,Q_0} = \frac{(s_{w,air})_Q}{(s_{w,air})_{Q_0}} \frac{(w_{air}/e)_Q}{(W_{air}/e)_{Q_0}} \frac{p_Q}{p_{Q_0}} ,$$

$$p = p_{cav} p_{cel} p_{dis} p_{wall} ,$$

P ~ 1 for proton
P = 1 for Carbon
P ≠ 1 for ^{60}Co

Table 4.11. Estimated relative standard uncertainties, u_c, of the calculated values for k_{Q,Q_0} for proton beams (IAEA, 2000).

Chamber type	Cylindrical		Plane parallel	
Component	Protons, u_c (%)	^{60}Co + protons, u_c (%)	Protons, u_c (%)	^{60}Co + protons, u_c (%)
$s_{w,air}$	1.0	1.1	1.0	1.1
Assignment of $s_{w,air}$ to beam quality	0.3	0.4	0.3	0.4
W_{air}/e	0.4	0.5	0.4	0.5
p_{cav}	0.3	0.3	0.3	0.3
p_{dis}	0.2	0.4	0.2	0.3
p_{wall}	0.6	0.8	0.6	1.6
p_{cel}	0.4	0.5	–	–
Combined relative standard uncertainty in k_{Q,Q_0}	–	1.7	–	2.1

$S_{w,air}$ & $W_{air/e}$ of Proton Beam

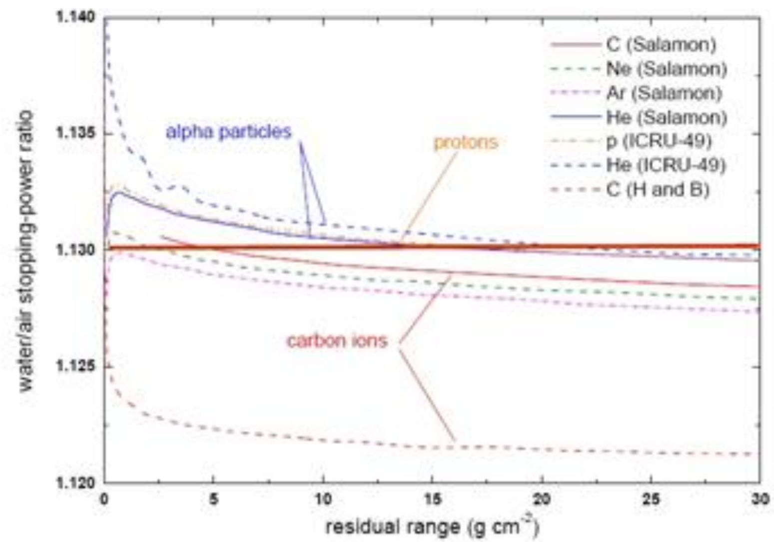
$S_{w,air}$ at ICRU 78

- ICRU 59 values
- PETRA MC calculations
  (Spencer Attix cavity theory)
- Secondary electrons and
  Nuclear inelastic processes.

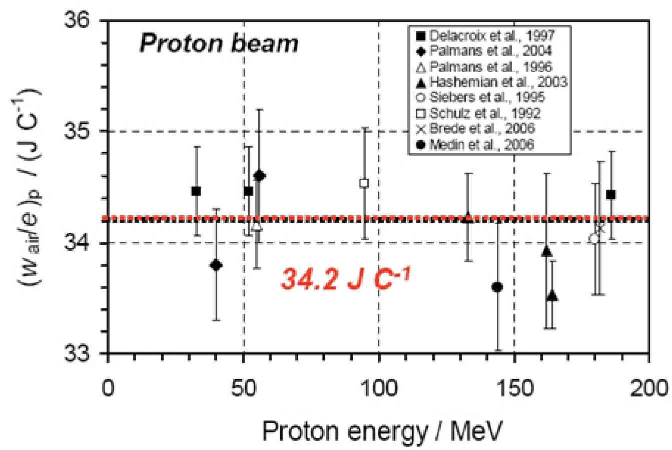
*TRS 398 use the constant value of 1.13 for proton.

$W_{air/e}$ at ICRU 78 & TRS 398

Inaccuracy reduction from Calorimeter and I.C. measurements

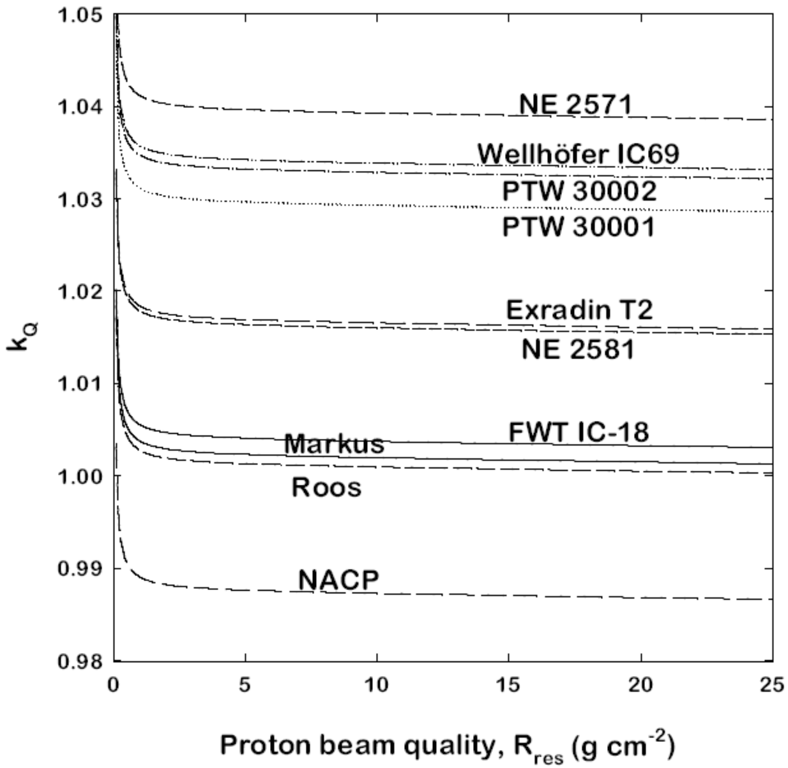


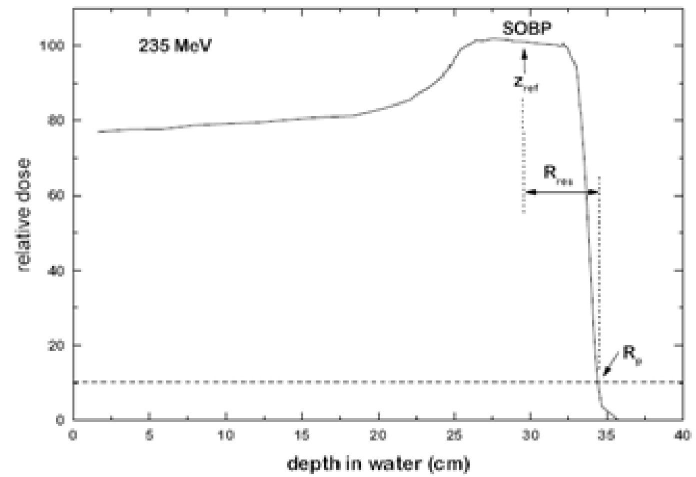
1.13



ICRU 78

K_Q values for Ionization Chambers





$$R_{res} = R_p - Z_{ref}$$

Fig 10.2. Calculated values of k_Q for various cylindrical and plane-parallel ionization chambers commonly used for reference dosimetry, as a function of proton beam quality Q (R_{res}). Data from Table 10.III.

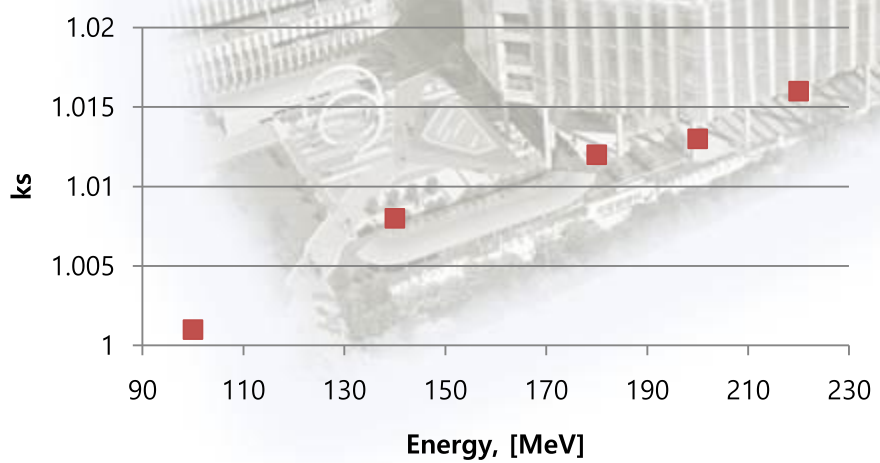
Reference Conditions

Table 4.7. Reference conditions for the determination of absorbed dose in proton beams (IAEA, 2000).

Quantity	Reference value or reference characteristics
Phantom material	Water
Chamber type	For $R_{res} \geq 0.5$ g cm^{-2}, cylindrical and plane parallel chambers For $R_{res} < 0.5$ g cm^{-2}, plane parallel chambers
Measurement depth, z_{ref}	Middle of the SOBP[a]
Reference point of the chamber	For plane-parallel chambers, on the inner surface of the window at its centres For cylindrical chambers, on the central axis at the center of the cavity volume
Position of the reference point of the chamber	For plane-parallel and cylindrical chambers, at the point of measurement depth z_{ref}
SSD	Clinical treatment distance
Field size at the phantom surface	10×10 cm^2, or that used for normalization of the output factors whichever is larger For small field applications (*i.e.*, eye treatments), 10×10 cm^2 or the largest field clinically available

Recombination Corrections for proton

- Recombination (k_s) for continuous and scanned continuous beam
  - Two voltage method: $(V1 / V2)^2$ instead of $(V1 / V2)$
  - Energy / depth dependent



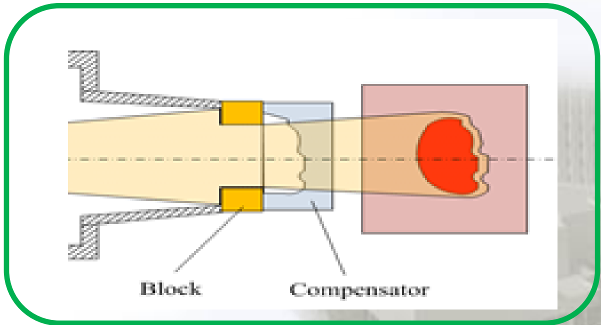
Reference dosimetry in a scanned pulsed proton beam using ionisation chambers and a Faraday cup

Stefan Lorin[1], Erik Grusell[1], Nina Tilly[1], Joakim Medin[2], Peter Kimstrand[1] and Bengt Glimelius[1]

[1] Department of Oncology, Radiology and Clinical Immunology, Uppsala University, Akademiska sjukhuset, SE-751 85 Uppsala, Sweden
[2] Department of Radiation Oncology, Copenhagen University Hospital, DK-2100 Copenhagen, Denmark

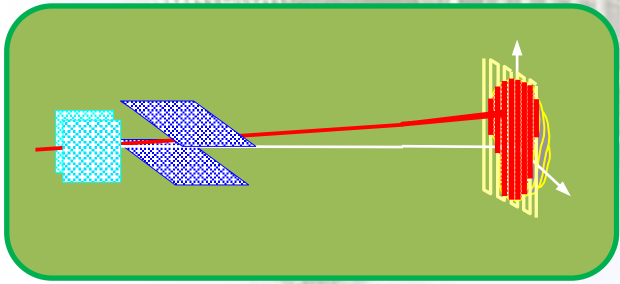
Independent Verification of Recombination correction needed by user!

Reference Conditions for Spot Scanning



Passive Scattering Beam

Calibration at SOBP



Spot Scanning Beam

Calibration at SOBP

(or Calibration at plateau)*

** Reference condition are facility specific. Required for TPS Beam data.*

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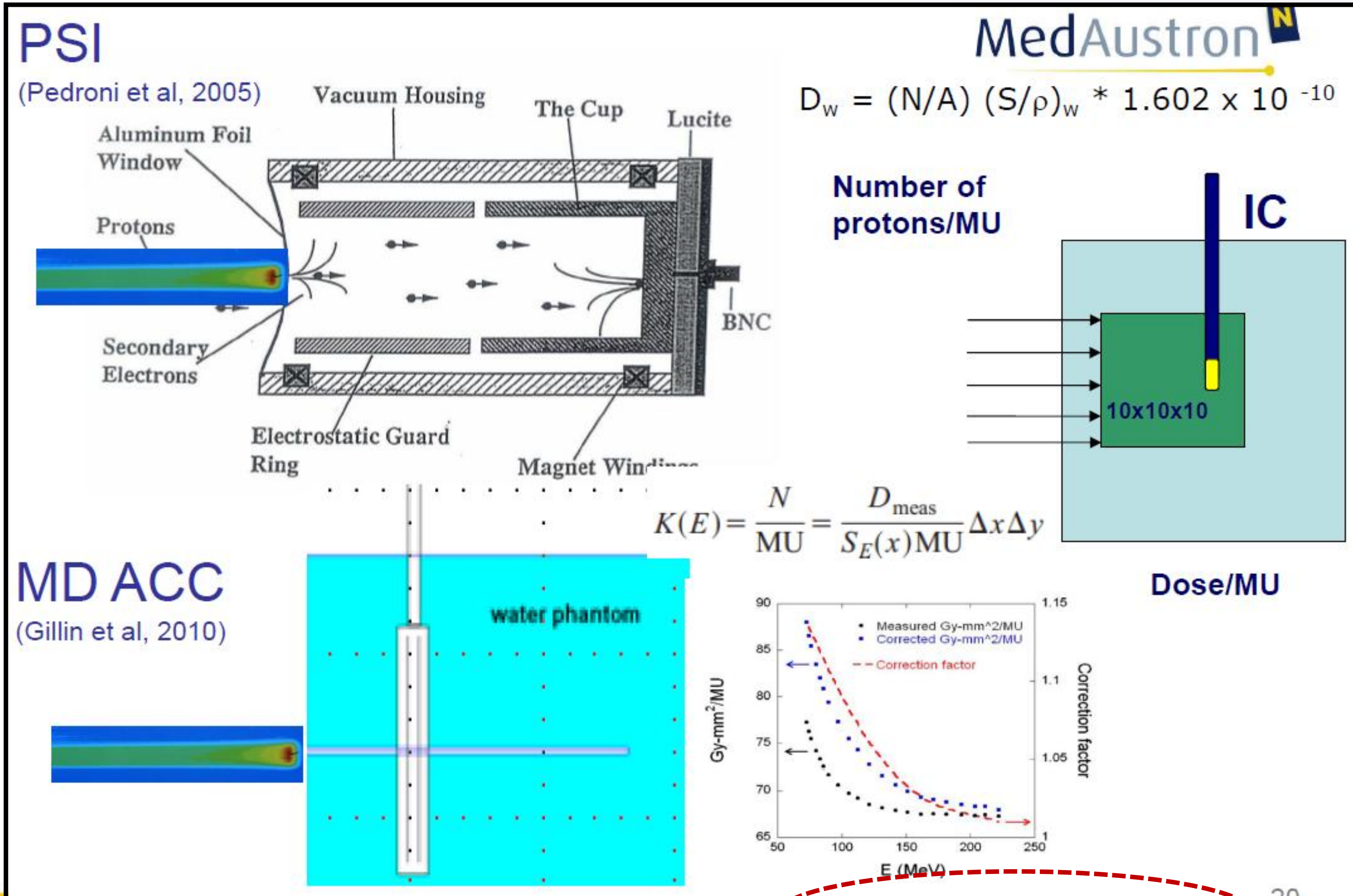
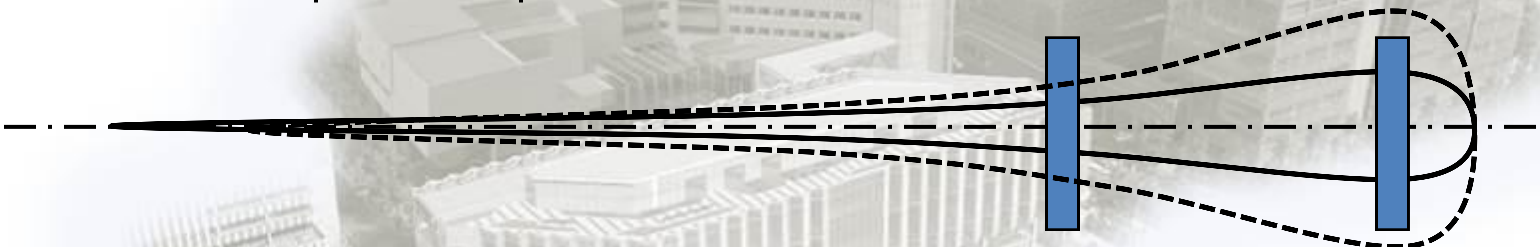
Proton spot scanning Calibration

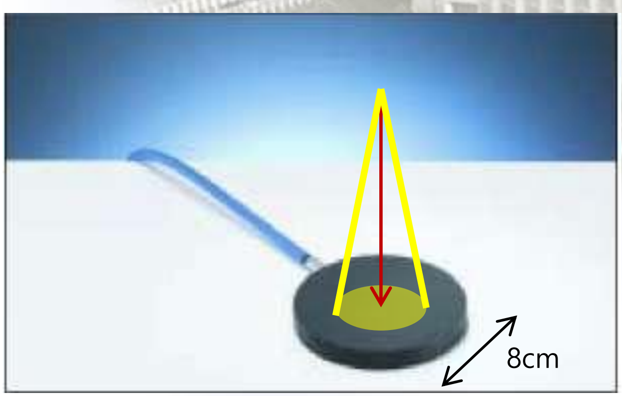


Measuring depth dose curve of Pencil beam

Detector size comparing to beam size matters!

– Bragg Peak Chamber is not large enough to collect signal from all protons present in the beam.





Correction parameter needed !

$$D_{\mathrm{exp}}(R_0(k), z_p) = \mathrm{corr}(R_0(k), z_p)^{*}\, D_{\mathrm{mea}}(R_0(k), z_p)$$

$$\mathrm{corr}(R_0(k), z_p) = \int_0^{\infty} r\dot{D}_{\mathrm{mea}}(r, z_p)\,\mathrm{d}r \Big/ \int_0^{4.08} rD_{\mathrm{mea}}(r, z_p)\,\mathrm{d}r$$

Proton Beam Monitor Chamber Calibration

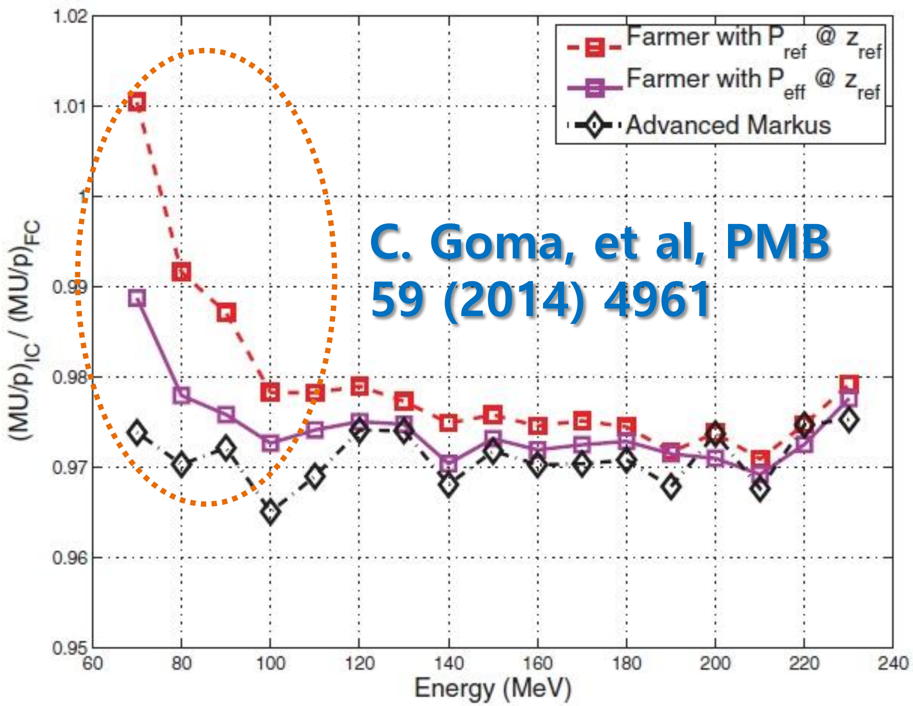


Figure 3. Ratio between the BMC calibration obtained with different ionization chambers—Farmer (□) and Advanced Markus (◊)—and the BMC calibration obtained with the Faraday cup. For the Farmer chamber, the BMC calibration is performed with both the reference point of the chamber positioned at z_{ref} (----) and the effective point of measurement of the chamber positioned at z_{ref} (——).

For the reference **Dosimetry of pristine bragg-peak** proton beam, **a plane-parallel I.C. is recommending rather than a cylindrical I.C.**

Comparison of ICRU 59 and TRS 398

Table 4.14. Comparison of ICRU 59 (ICRU, 1998) dosimetry protocol and TRS 398 (IAEA, 2000) dosimetry code of practice for clinical proton beams.

Feature/quantity	ICRU 59 (ICRU, 1998)	TRS 398 (IAEA, 2000)
Ionization chamber	Cylindrical	Cylindrical and plane-parallel ($R_{res} \geq 0.5$ g cm^{-2}) Plane-parallel ($R_{res} < 0.5$ g cm^{-2})
Wall material	Graphite or A-150 plastic	Graphite for cylindrical chambers
Gas filling	Ambient air	Ambient air
Chamber volume	>0.5 cm^3 for beams ≥ 5 cm diameter ~ 0.1 cm^3 for beams <5 cm diameter	–
Water proof sleeve	–	≤ 1 mm thick PMMA
Dose specification	Water	Water
Calibration beam	^{60}Co	^{60}Co
Calibration coefficient	Primarily N_K, also N_X, $N_{D,w}$	$N_{D,w}$ only
Beam quality	Residual range (to distal 10 % level)	Residual range (to distal 10 % level)
Phantom material	Water (or other materials which match electron density of water)	Water
Reference point for measurement	Middle of SOBP	Middle of SOBP Depth of 3 g cm^{-2} for plateau irradiations
Field size	–	10×10 cm^2
SSD	–	Clinical treatment distance
Stopping powers	ICRU (ICRU, 1993a)	PETRA (Medin and Andreo, 1997b)
$(w_{air}/e)_p$ (J C^{-1})	34.8 ± 0.7 (ambient air)	34.23 ± 0.13 (dry air)
$(w_{air}/e)_{^{60}Co}$ (J C^{-1})	33.77 ± 0.05 (ambient air)	33.97 ± 0.07 (dry air)
$(s_{w,air})_{^{60}Co}$	1.134	1.133
Chamber perturbation factors	No	Yes
Relative uncertainty in absorbed dose (1σ)	2.6 % (Jones, 2001d)	2.0 % (cylindrical chambers) 2.3 % (plane-parallel chambers)

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Practical absolute dosimetry formula

- Measurement in water phantom.
- Detector of choice:
  - PPC (R_{res} < 0.5 g/cm^2)
  - CC ($V_s \geq 0.6$ cm^3) (R_{res} > 0.5 g/cm^2)
  - Large **V**: ↑ V → ↑ Sensitivity → ↑ SNR

$$D_w = M \times N_{D_w} \times k_q \times k_{tp} \times k_s \times k_{pol} \times k_{el}$$

M – collected charge
N_{Dw} – calibration factor (*certificate*)
k_q – beam quality
k_{tp} – t/p correction factor
k_s – recombination factor
k_{pol} – polarity factor
k_{el} - calibration factor (*electrometer*)

$$k_{tp} = \frac{T \times p_0}{T_0 \times p}$$

$$k_s = a_0 + a_1\left(\frac{M_1}{M_2}\right) + a_2\left(\frac{M_1}{M_2}\right)^2$$

$$k_{pol} = \frac{|M_+| + |M_-|}{2M}$$

Standard condition
s

$$p_0 = 101.325\ kPa$$

$$t_0 = 20°C\ (in\ EU)$$

$$t_0 = 22°C\ (in\ US)$$

$$T = 273.15 + t$$

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Worksheet for Dw in Proton beam

Worksheet for the determination of the absorbed dose to water in a proton beam

User: Date:

1. Radiation treatment unit and reference conditions for $D_{w,Q}$ determination

Proton therapy unit: Gantry2 (Famer chamber)

			Nominal energy:		MeV
Nominal dose rate:	200.0	MU min^{-1}	Practical range, R_P:	15.0	g cm^{-2}
Reference phantom:	water		Width of the SOBP:	5	g cm^{-2}
Reference field size:	10	cm x cm	Reference SSD:		cm
Reference depth z_{ref}:	12.5	g cm^{-2}	Beam quality, $Q(R_{res})$:	2.5	g cm^{-2}

2. Ionization chamber and electrometer

Ion. chamber model: PTW 30006 / 30013 Serial No.: ☐ pp ☑ cyl

Chamber wall	material:	PMMA	thickness:	0.057	g cm^{-2}
Waterproof sleeve	material:		thickness:		g cm^{-2}
Phantom window	material:		thickness:		g cm^{-2}

Absorbed-dose-to-water calibration factor $N_{D,w}$ = 0.05398 ☑ Gy/nC ☐ Gy/rdg

Calibration quality Q_0: Co-60

Reference conditions for calibration

P_0: 101.3 kPa T_0: 22.0 °C Rel. humidity: 50 %

Polarizing potential V_1: 400 V

Calibration polarity: ☑ +ve ☐ -ve ☑ corrected for polarity effect

User polarity: ☑ +ve ☐ -ve

Calibration laboratory: Date:

Electrometer model: Serial no.:

Calib. separately from chamber: ☐ yes ☑ no Range setting:

If yes Calibration laboratory: Date:

3. Dosimetry reading [a] and correction for influence quantities

Uncorrected dosimeter reading at V_1 and user polarity: 45.3 ☑ nC ☐ rdg

Corresponding accelerator monitor units: 200 MU

Ratio of dosimeter reading and monitor units: M_1 = 0.2265 ☑ nC/MU ☐ rdg/MU

(i) P: 101.2 kPa T: 22.5 °C Rel. humidity: 50 %

$$k_{T,P} = \frac{(273.2+T)\ P_0}{(273.2+T_0)\ P} = 1.003$$

(ii) Electrometer calibration factor k_{elec}: ☐ nC/rdg ☐ dimensionless

(iii) Polarity correction [b] rdg at $+V_1$: M_+ = 40.65 rdg at $-V_1$: M_- = 40.62

$$k_{pol} = \frac{|M_+|+|M_-|}{2M} = 1.000$$

(iv) Recombination correction (two-voltage method)

Polarizing voltages: V_1 (normal) = 400 V V_2 (reduced) = 200 V

Readings at each [c] V: M_1 = 40.65 M_2 = 40.58

Beam type: ☐ pulsed ☑ pulsed-scanned

Voltage ratio V_1/V_2 = 2.0000 Read. ratio M_1/M_2 = 1.002

a_0 = 4.7110 a_1 = -8.2420 a_2 = 4.5330

$$k_s = a_0 + a_1\left(\frac{M_1}{M_2}\right) + a_2\left(\frac{M_1}{M_2}\right)^2 = 1.003$$ [d]

Corrected dosimeter reading at the voltage V_1:

$$M_Q = M_1\, k_{TP}\, k_{elec}\, k_{pol}\, k_s = 2.2786\text{E-}01$$ ☑ nC / MU ☐ rdg / MU

4. Absorbed dose rate to water at the reference depth, z_{ref}

Beam quality correction factor for user quality Q: k_Q 1.0310

taken from ☑ Table 31 ☐ Other, specify:

$$D_{w,Q}(z_{ref}) = M_Q\, N_{D,w}\, k_Q = 1.2681\text{E-}02 \text{ Gy / MU}$$

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Basic Beam Parameters

- Relative:
  - Depth dose curve.
  - Beam profile.

  ➔ Film, Scintillating screen, Ionization chamber

- Absolute:
  - Beam output.

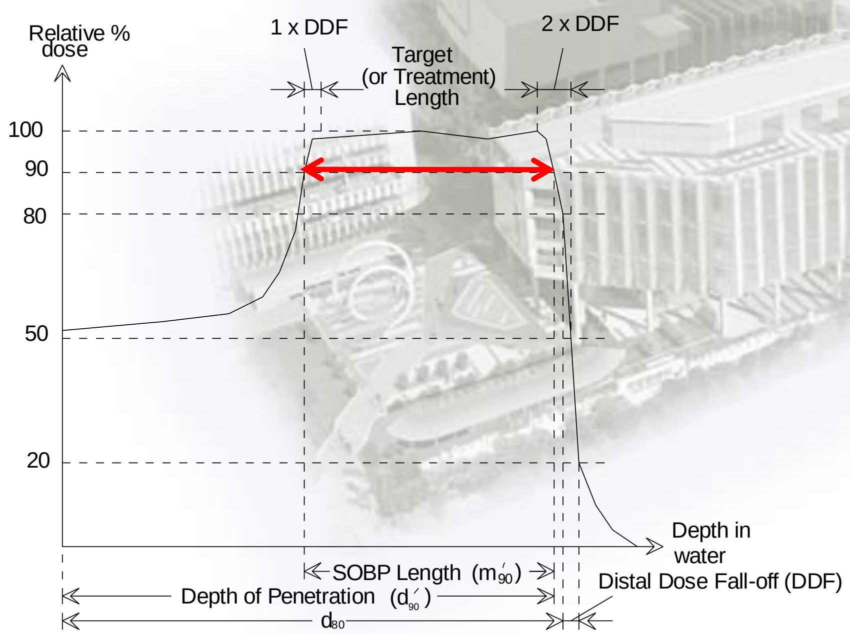
  ➔ Ionization Chamber, Calorimeter

Clinical Parameters

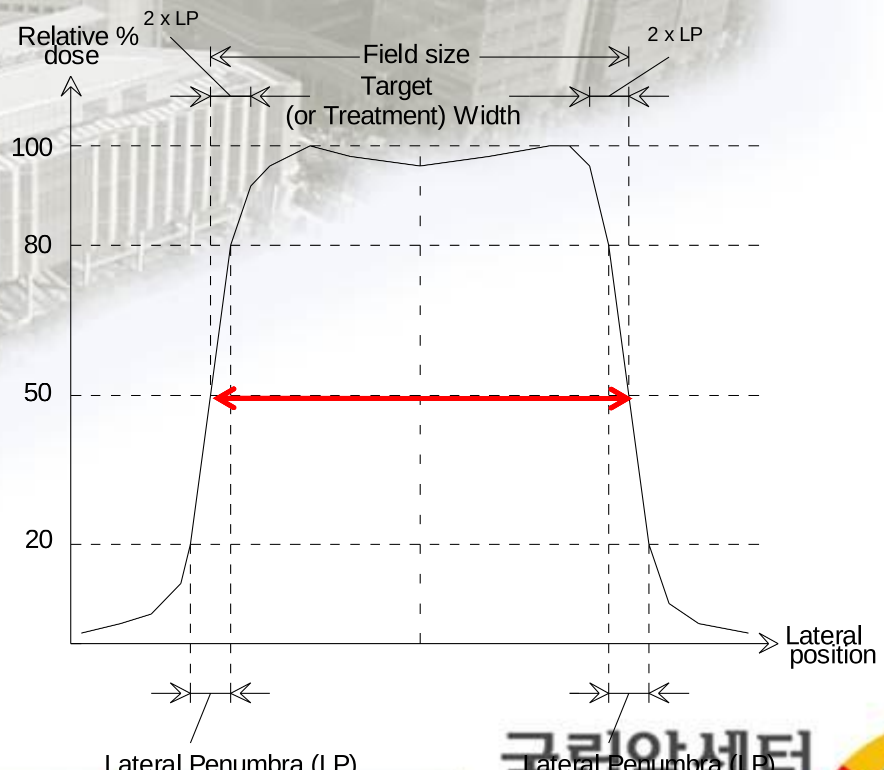
- 100% dose level : average dose in uniformly treated region
- Range : 90% distal dose point
- Field size : width of 50%-50% dose, treatment field size
- Lateral penumbra : width of 80%-20% lateral dose
- Distal fall-off : width of 80%-20% distal dose
- Dose uniformity of Single-field Uniform Dose
- Beam spot asymmetry : $\left(\frac{(\sigma x - \sigma y}{(\sigma x + \sigma y}\right)$

Field Definition

SOBP (90%-90%)



Field Size (50%-50%)



Summary

- Code of Practice TRS 398 (IAEA 2000, N_{dw} –base formalism) is widely adopted for proton beam dosimetry in the world.
- Still, the dosimetry standard of spot scanning proton beam is not sufficient.
- For proton spot scanning and IMPT trial, there are lack in the specialized dosimetry tool.
- Proton dosimetry has a dependency of beam delivery system and home developed practices are needed.

DOSIMETRY TOOLS FOR PROTON THERAPY

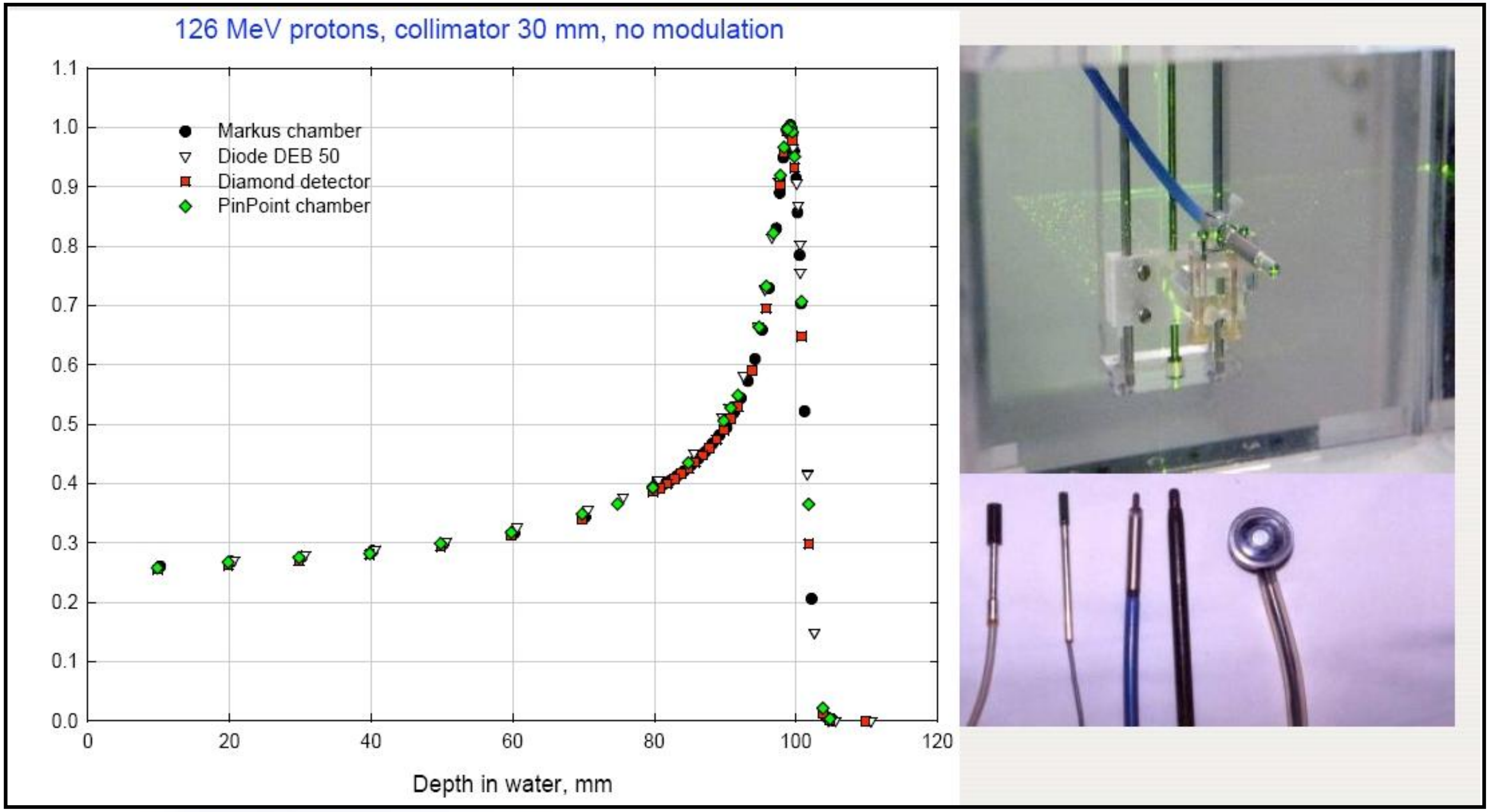
Detectors for Proton Beam Measurement

Detectors for absorbed dose applied in ion beam radiotherapy*

Detector	Advantage	Disadvantage	Application in ion RT
Calorimeter	Direct dose measurement	High effort, knowledge of chemical heat defect and thermal heat conduction required	Potential primary standard in the future, k_Q measurements
Ionization Chamber	High accuracy and reproducibility, small LET and energy dependence, easy to handle, many chamber types for different Applications	deviation from calibration conditions required, incomplete knowledge of corrections (chamber dependent)	Reference dosimetry, commissioning, dosimetric QA, dose verification, beam Monitoring
Radiochromic films	High spatial resolution, 2D measurement, Linear response, no daylight sensitivity, self-developing, less LET- and energy Dependent	LET and energy dependence, dose cannot be obtained from optical density in mixed fields, off-line analysis required Complex evaluation protocols, long term self-development, mechanical sensitivity	Measurement of lateral dose profiles, beam widths, field geometry and homogeneity, documentation of beam ports
Silicon diode and diamond	High spatial resolution, high signal, electronic read-out	LET, dose rate and energy dependence	Lateral profile Measurements
TLD	High spatial resolution	LET and energy dependence, off-line Evaluation	Point measurements, *in vivo* dosimetry
OSL detector	High spatial resolution, linear response, repeated electronic read-out	LET and energy dependence	Point measurements, Profiles
Scintillating screen	High 2D spatial resolution, linear intensity-independent response, electronic read-out	LET and energy dependence, large device	1D/2D distributions, field homogeneity, beam width, dose Verification

** "Dosimetry for ion beam radiotherapy" , C.P. Karger, … T. Kanai, P.M.B. 55(2010)R193-R234*

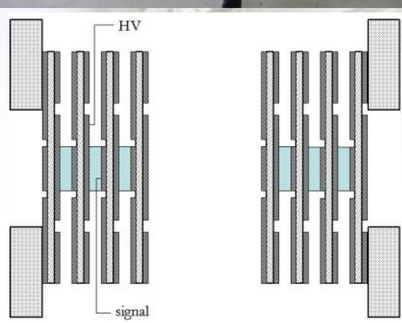
Depth Dose Measurement at Small field beam

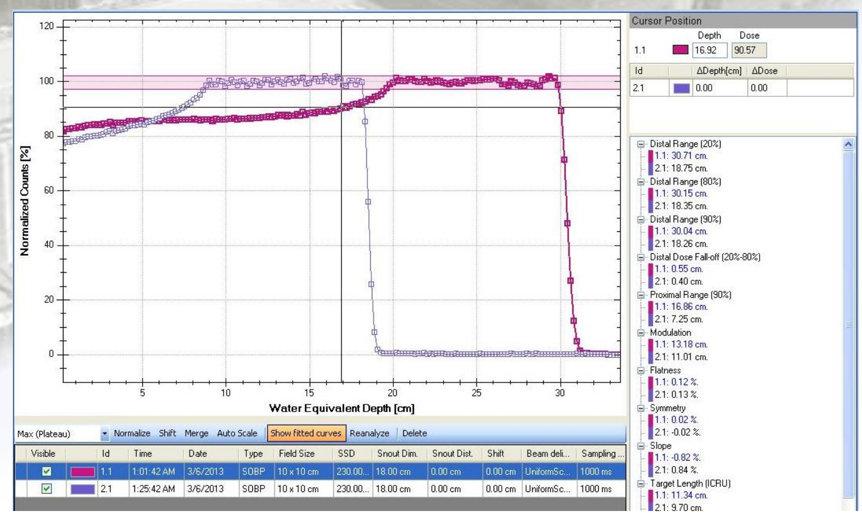


Careful selection of detect for small beam size needed.

Scanning Beam: depth dose curve

- Water phantom with a **single detector** is extremely slow in case of scanning beam modes: Full modulation has to be rerun for each POI.
- Multi-Layer Ionization Chamber(**MLIC**): whole DD should be captured at once.





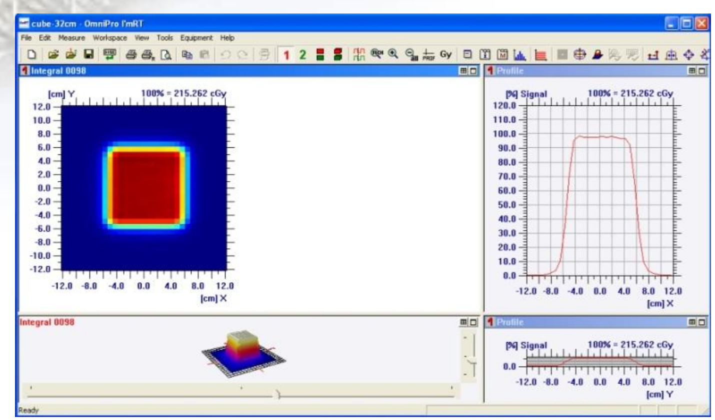
Beam Profile Measurement

- **2D Dose measurements for QA / validation purposes.**

MatriXX

1020 ICs covering area of 24.4x24.4 scm
Distance between ICs = 7.6 mm
I.C. Size = 4.5 mm, I.C. Height = 5 mm

Not recommended for high-res measurements:
- **evaluation of penumbras**
- **spot size measurements**
- **coincidence measurements**

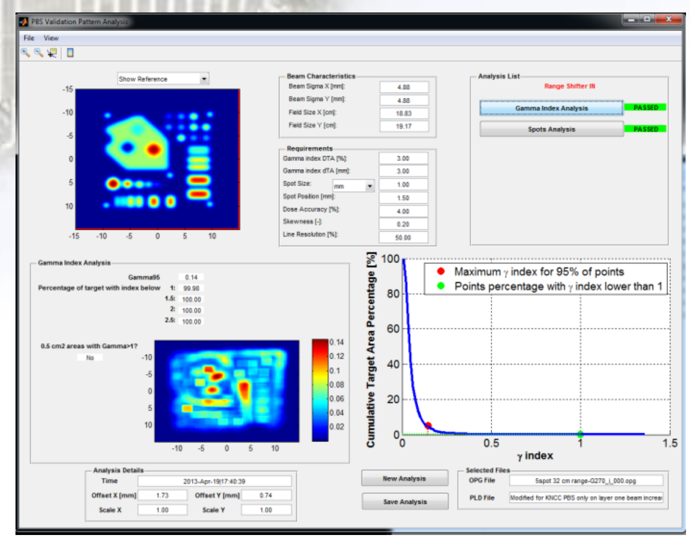


Beam Profile Measurement

- **2D Dose measurements for QA / validation purposes.**

Lynx

Scintillating screen + CCD camera
Good for high-res measurements: Evaluation of penumbras, Spot size measurements, Coincidence measurements
But.. Exposure control needed , Large detector size, Relative dose only, Quenching effect exist.

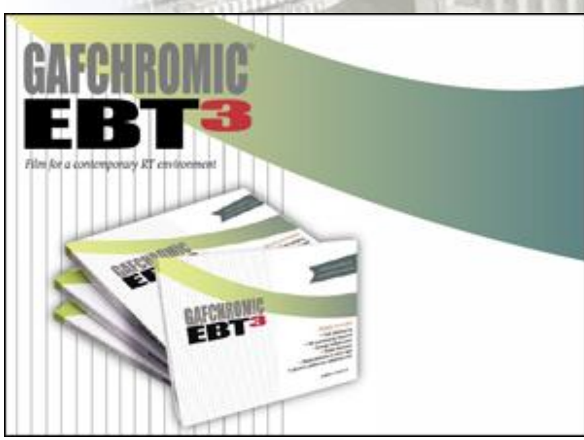


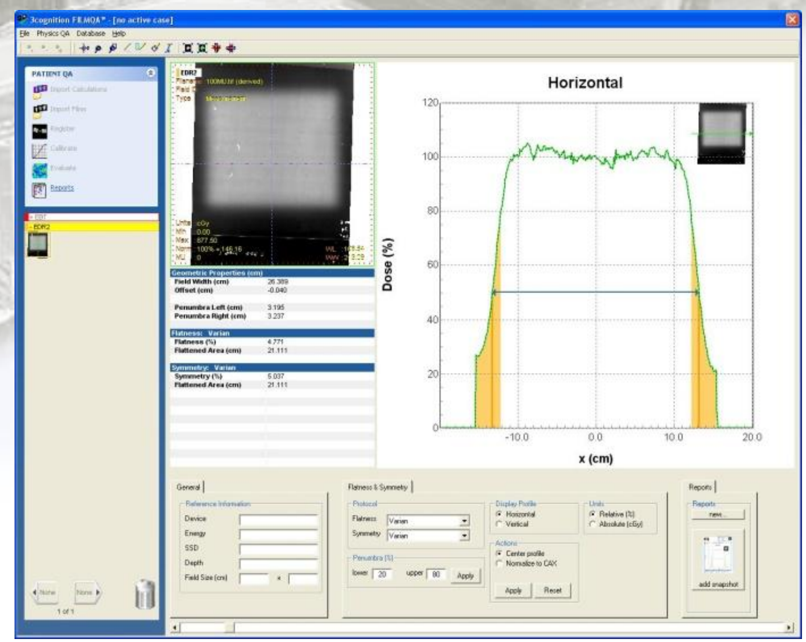
Beam Profile Measurement

- **2D Dose measurements for QA / validation purposes.**

Self developing Film, Easy to use,
High resolution 2D dos distribution,
Quenching Effect, Relative dosimetry,
Field size measurement,

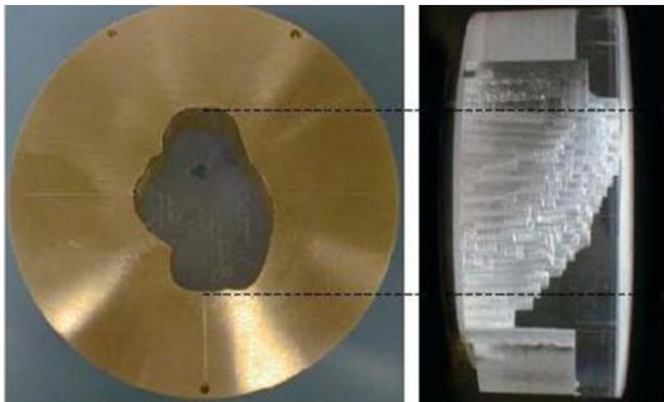
GafChromic
Film



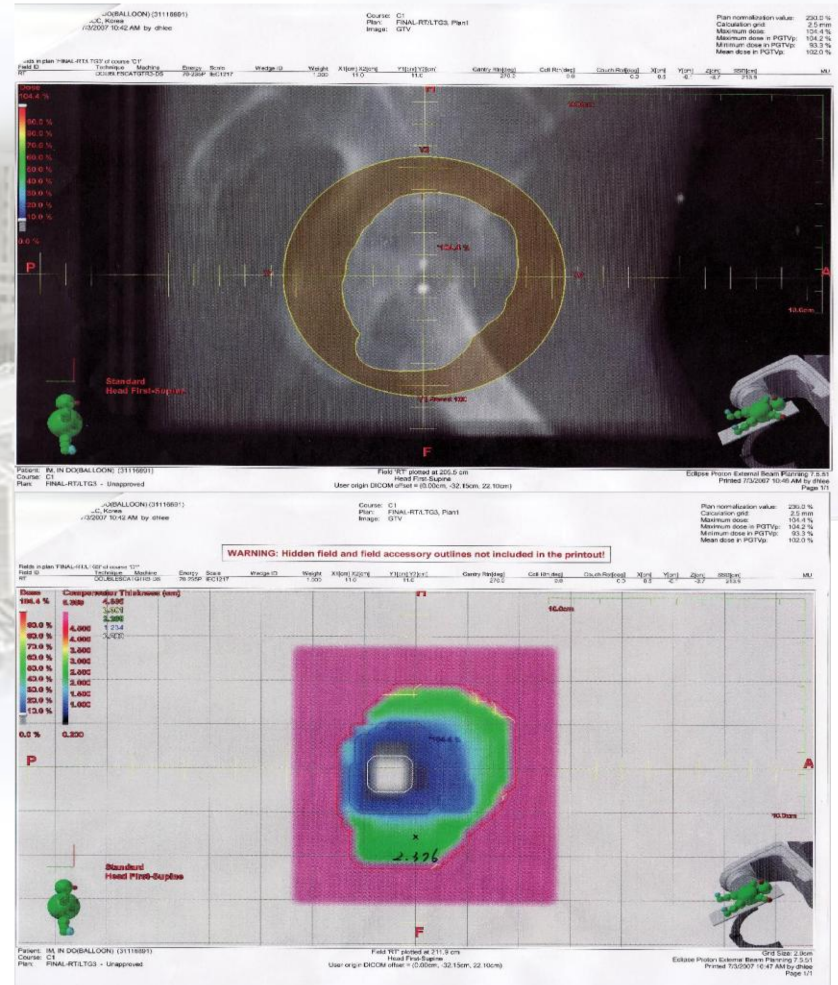


PATIENT QA

Patient dedicate Device QA



Aperture / Range Compensator



Mechanical checks are applied

1. opening shape overlap on the plan sheet.
2. RC x-y coordinate & thickness measurement/comparison
3. Rotation and translation checks

Treatment Field QA

- **Passive Beam Plan:**

  - Range/SOBP(Optional): fine beam parameter finding, Markus chamber & water phantom, MLIC, Peak finder.
  - Output: Verification Plan, Farmer chamber & water(or solid water) phantom, without range compensator.
  - 2D dosimetry(if needed): Film, water phantom, MatriXX.
  - In vivo dosimetry: Film(EBT).

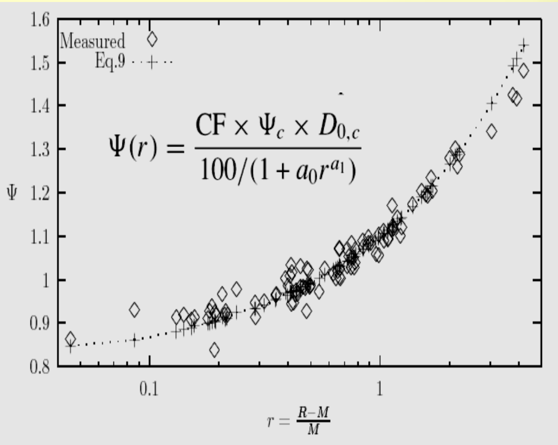
- **Spot Scanning Plan:**

  - MU confirmation: Verification Plan, Ion chamber/MatriXX & solid water phantom, 2 or more different depths.
  - 2D dosimetry: Verification Plan, MatriXX, solid water phantom, 2 or more different depths.
  - Depth dose: Central region with Markus/MatriXX and Solid water phantom.

2^{nd} check method : Output factor, Range, SOBP calculation

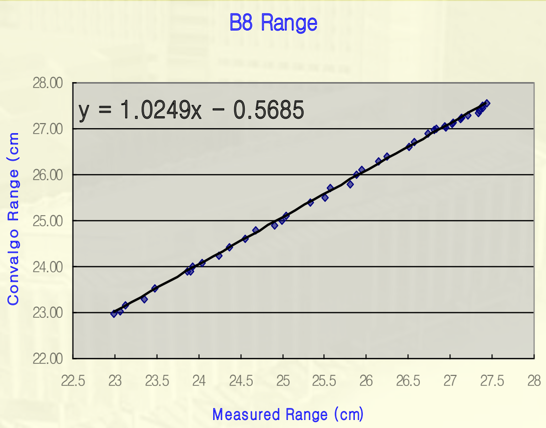
Output

Hanne Kooy's Paper



Ψ : Output factor
Ψc : Output factor (calib)
CF : Constant related
RM opt.
$D_{0,c}$: Entrance Dose (calib)
r : r = (R-SOBP) / SOBP
a_0, a_1 : theoretical values

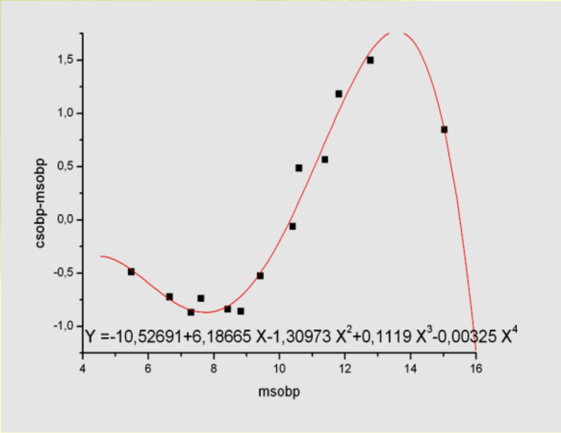
Range



Y : Machine nominal range
X : measured range
1D linear Fitting func.

→ Y = P1*X + P2

SOBP



Y : Mach. SOBP – Measur. SOBP
X : Measur. SOPB
4D polynominal fitting func.

→ $Y = P1*X^4 + P2*X^3 + P3*X^2 + P4*X + P5$

** It could be also used instead of beam measurement procedure.*

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Passive beam P-QA example:

Range/SOBP fine tuning finding & Output Measurement

1. RTP parameter

	Plan		Verification		Dose dist.	
Prescription Dose :	235	CcGE				
Range in patient :	25.05	g/cm²			25.07	g/cm²
SOBP width :	10.39	g/cm²			10.27	g/cm²
Snout position :	27.9	cm	27.9	cm		
Air Gap :	2	cm	12	cm		
SCD of V.P. :	230.6	cm	234.4	cm		
Dose at V.P. :	241.4	CcGE	230.8	CcGE		

2 . Range/Mod calibration

	Convalgo		Measurement			
	Rp	SOBP	Rp	SOBP	dRp	dSOBP
1	25.05	10.39	25.16	10.27	0.09	0
2	24.96	10.39	25.07	10.3	0	0.03
3						
4						
5						
final	24.96	10.39	25.07	10.3	0	0.03

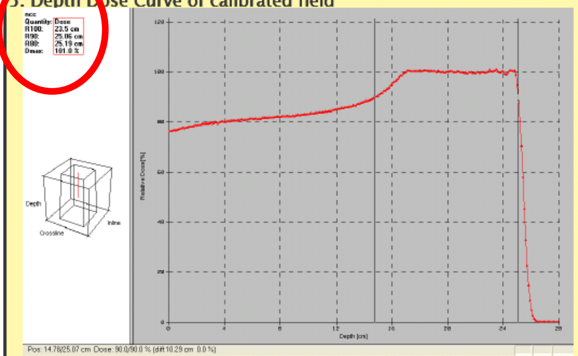
3. OutPut Calibration

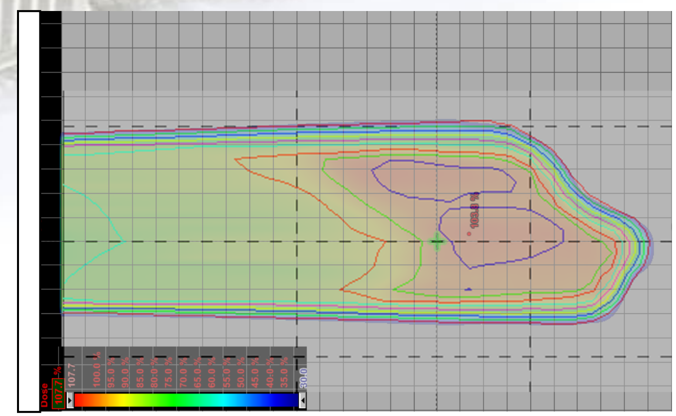
Range in patient :	25.07	g/cm²	RBE Correction :	1.1	
SOBP width :	10.3	g/cm²	Physical Dose :	209.8	cGy
Refernce depth :	20.4	g/cm²	Output factor :	1.4164	cGy/MU
Pratical Range :	25.88	g/cm²			
Calibration MU :	200	MU			
Fn :	1.045927		▷ Treatment MU :	148.13	MU

4. Summary – Field setup parameter

Range in patient :	24.96 g/cm²	Field radius :	B8 7 cm
SOBP width :	10.39 g/cm²	Gantry Angle :	270 °
Treatment MU :	148.1 MU	Snout extension :	27.9 cm
Dose rate :	2 Gy/min	Tolerence table :	TOL8

5. Depth Dose Curve of calibrated field





Eclipse: Colored spread

Measurement: line

NCC, Korea example

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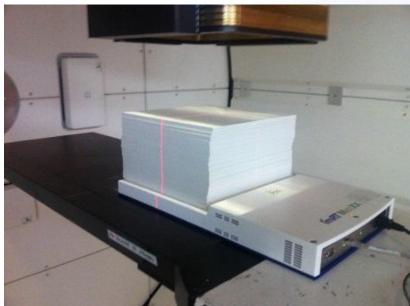
Spot beam Scanning P-QA example:

2D dose analysis, point dose comparison, etc.



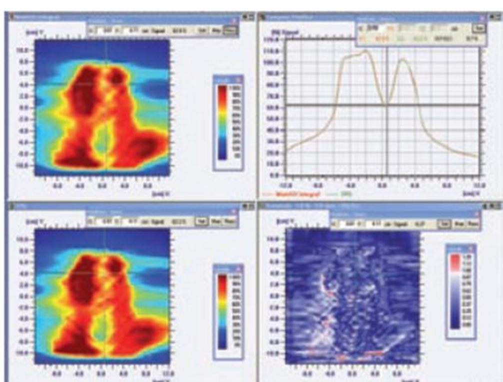
matriXX & S.W.P

Large dose gradient and small volume distribution.

➔ difficult to make a measurement with current dosimetry tools that have volumes and setup uncertainties.

Measured dose plane

Calculated dose plane



Dose profile comparison

γ - analysis result

# of Fileds : 2
Modulation Technique : MFO

Temperature : 22.60 ℃
Pressure : 1006.30 hPa

1A LAO	G30,C0 RS74		
Actual Depth (cm)	2.0	5.0	8.0
Max dose (cGy)	130.67	128.02	120.49
Init Gamma	91.59	96.74	100.00
AVG. Diff.	2.60	1.10	0.20
Final Renorm.		-2.00%	
Final Gamma	97.32	99.04	100.00
Final Avg. Diff.	1.18	0.13	-0.42
Renorm. 1% DOWN	95.41	97.93	100.00
Renorm. 2% DOWN	97.32	99.04	100.00
Renorm. 3% DOWN			

Final Renormalization	Plan Normalization	MU
Before correction (original plan)	99.100	429.17
After correction	101.122	420.59
Calculated Value (plan per field)	101.122	420.59
Final Plan Value (plan per field)	101.12	420.51

1B LPO	G100,C0 RS74		
Actual Depth (cm)	2.0	5.0	8.0
Max dose (cGy)	154.17	174.77	157.90
Init Gamma	97.32	97.66	99.74
AVG. Diff.	1.30	1.20	-1.50
Final Renorm.		-2.00%	
Final Gamma	99.99	100.00	97.00
Final Avg. Diff.	0.16	0.01	-1.61
Renorm. 1% DOWN	98.78	99.13	100.00
Renorm. 2% DOWN	99.99	100.00	97.00
Renorm. 3% DOWN			

Final Renormalization	Plan Normalization	MU
Before correction (original plan)	99.100	568.53
After correction	101.122	557.16
Calculated Value (plan per field)	101.122	557.16
Final Plan Value (plan per field)	101.12	557.42

PROTON THERAPY FACILITY IN NCC

NCC Project schedule

- **Release of final RFP : 2002. 04**
- **Contract with IBA : 2002. 06**
- **Ground breaking : 2003. 03. 21**
- **Equipments installation : 2004. 11 – 2005. 06**
- **Beam Production : 2005. 10. 21**
- **Beam tuning (Cyclotron → ESS → BTS → TR)**

  : 2005. 09 – 2006. 07

- **Treatment Beam Calibration (GTR1→FBRT1→GTR2)**

  : 2006. 05 – 2007. 04

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  : 2005. 09 – 2006. 07
- Treatment Beam Calibration (GTR1→FBRT1→GTR2)

  : 2006. 05 – 2007. 04

NCC Project History

- Acceptance test of Gantry treatment Room 2 : 2006. 10

- Acceptance test of Fixed beam treatment Room 1 : 2006. 12

- Acceptance test of Gantry treatment Room 3 : 2006. 12

- GTR1 (commissioning & Data taking) : 2006. 11 – 2007. 03

- 1st patient in GTR2 : 2007. 03. 19

- 1st patient in GTR3 : 2007. 09

- 1st patient in Fixed Beam Room : 2009. 06

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NCC Project History

- Start of International Patient Treatment: 2010. 11

- National insurance reimburse the proton therapy for pediatric cancer (< age 18): 2011. 04

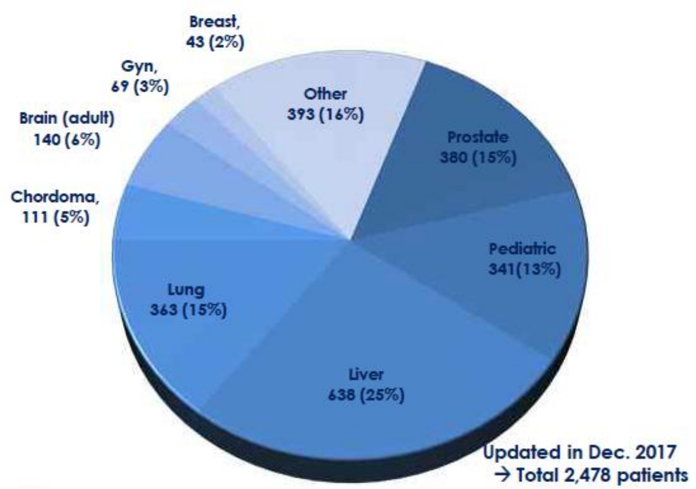
- National Insurance reimburse the proton therapy for most of cancers : 2015. 09

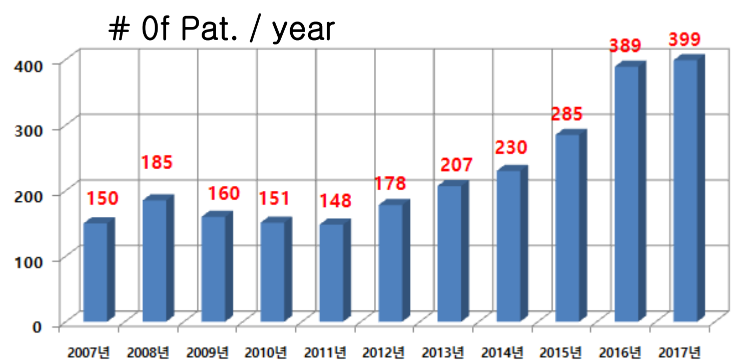
- 1st Pencil Beam Scanning Treatment in GTR3: 2015. 09

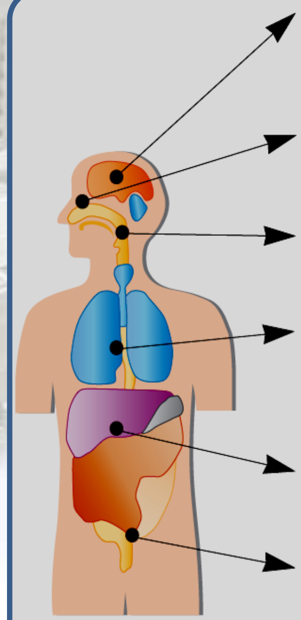
- 2400 patient treated in Proton Treatment Rooms by 2017

Statistics of PT Patients

(2007. 3 ~ 2017. 12 / 2,478 patients)







Central Nervous System (Brain & Spinal Cord)
- glioma
- vestibular schwannoma
- pituitary adenoma
- meningioma
- chordoma
- optic glioma

Orbit (Eye)
- choroidal melanoma
- retinoblastoma
- lacrimal gland tumor

Head & Neck
- oropharyngeal cancer
- nasopharyngeal cancer
- unresectable or recurrent cancer

Thorax and Breast
- lung cancer : selective
- breast cancer : selective
- esophageal cancer
- unresectable or recurrent cancer

Abdomen
- liver and pancreas cancer : selective
- unresectable or recurrent cancer

Pelvis and Extremities
- prostate cancer
- sarcoma
- chordoma
- soft tissue sarcoma
- unresectable or recurrent cancer

Pediatric (Child) Tumors
- Glioma, medulloblastoma and other primitive neuroectodermal tumors, germinoma, sarcoma, retinoblatoma, soft tissue sarcoma, skull base chordoma and chondrosarcoma
- recurrent cancer and others : selective

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Proton therapy Facility

Cyclotron

Proteus 235 Specification

Weight : 220 ton Height : 210 cm Diameter : 434 cm

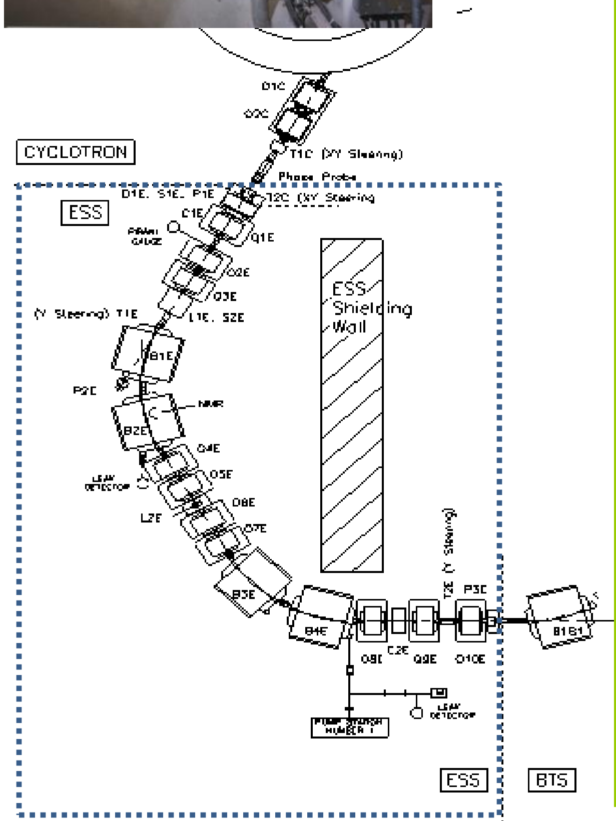
Energy : 230MeV

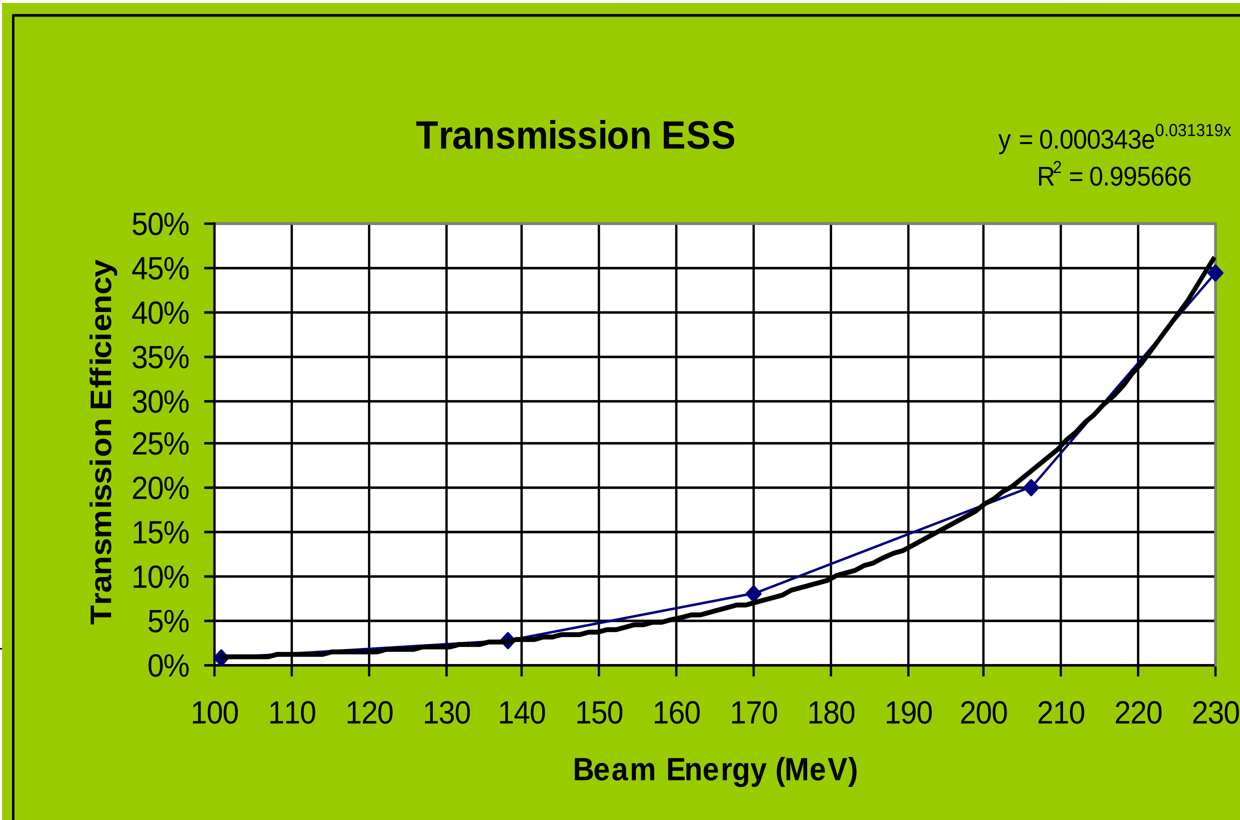
Max. extracted beam current : 300nA

RF frequency :106 MHz

Energy Selection System

Transmission efficiency ESS





Max Beam current in treatment room = 300 nA x Transmission ESS

* transmission ESS to treatment room = ~100%

* 300 nA = 4.8 x 10^{12} protons/sec.

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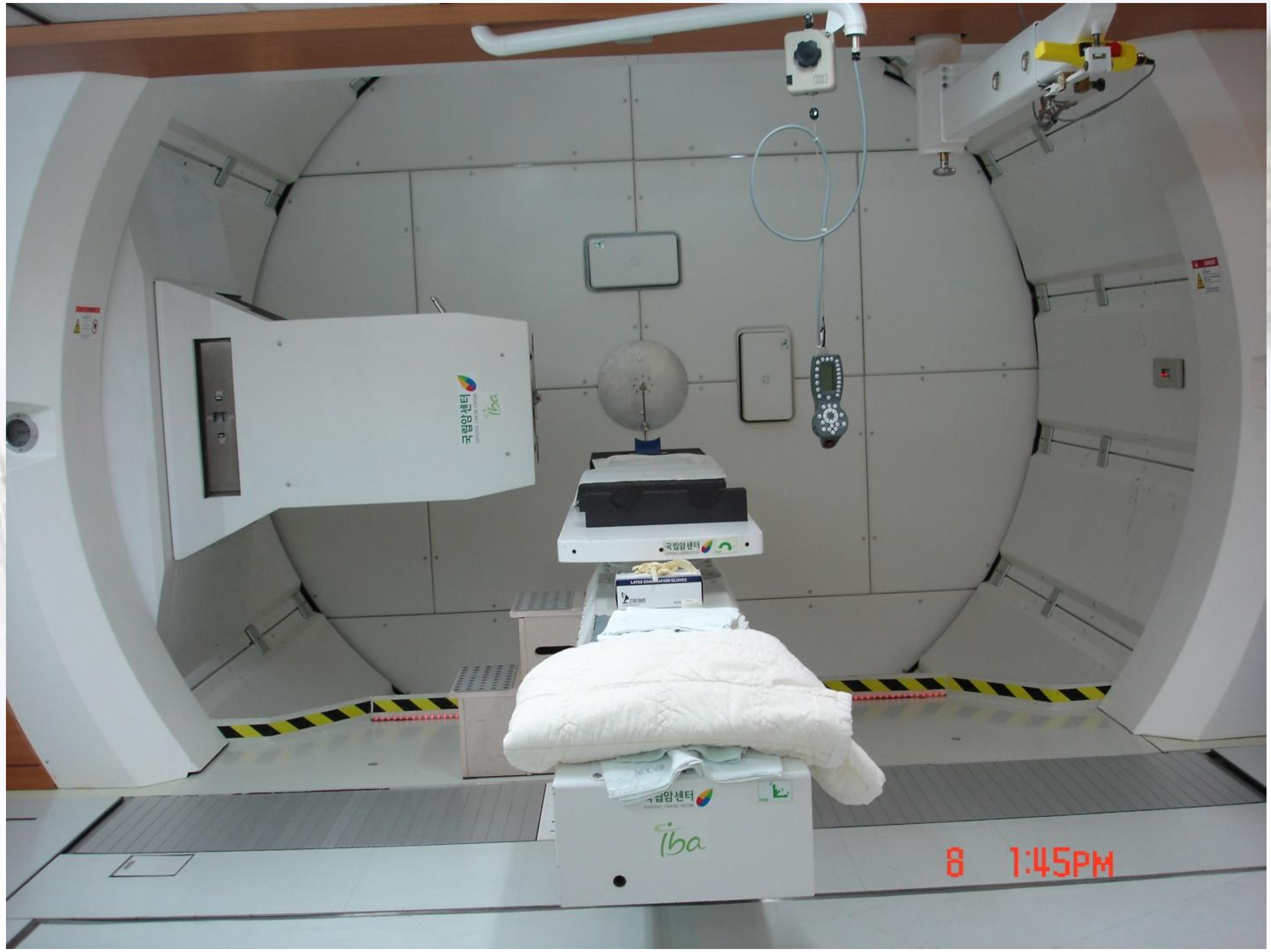
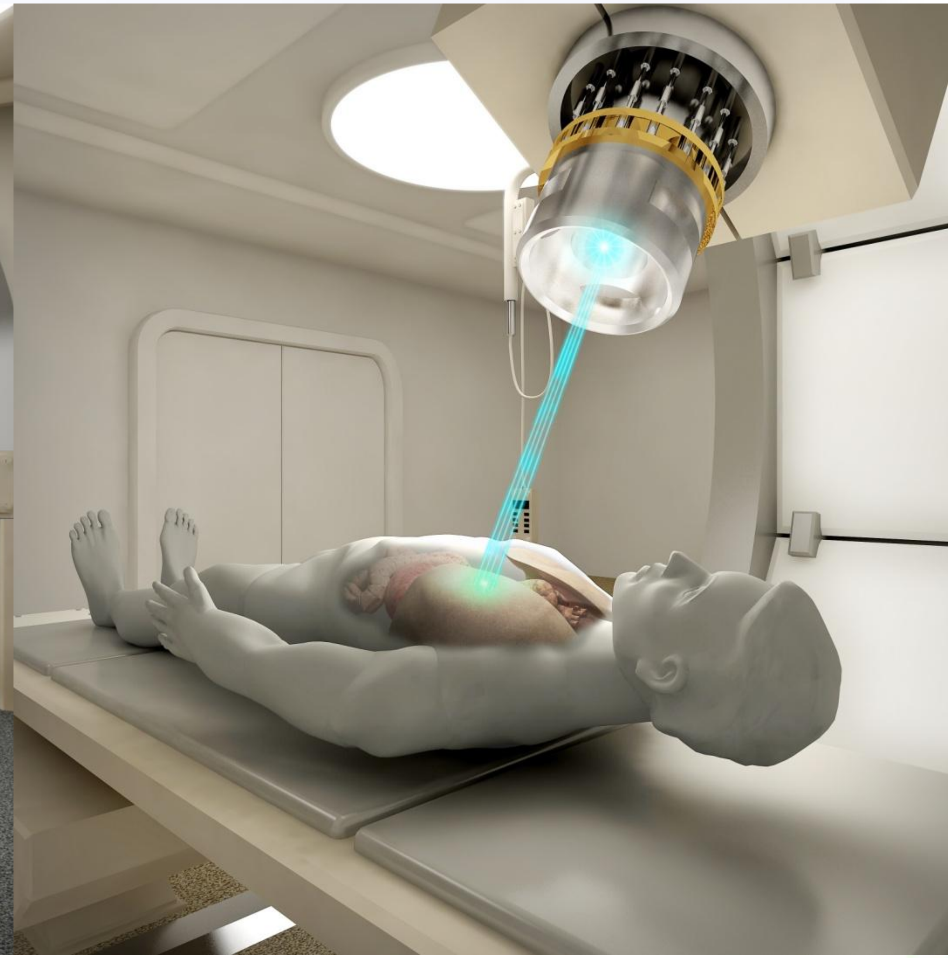
Beam Transportation System

Gantry Treatment Room - 1



Gantry Treatment Room - 2



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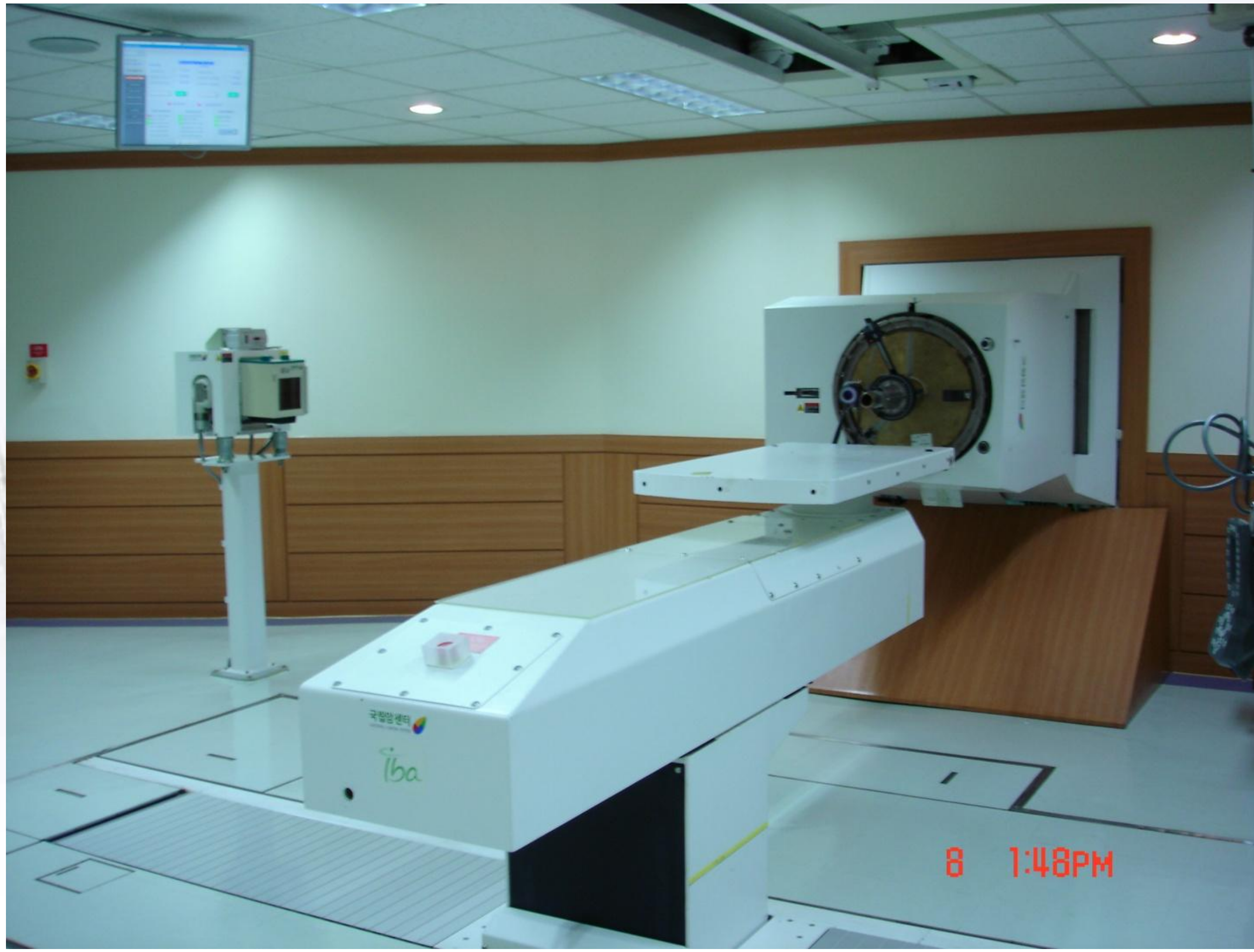
Fixed Beam Treatment Room

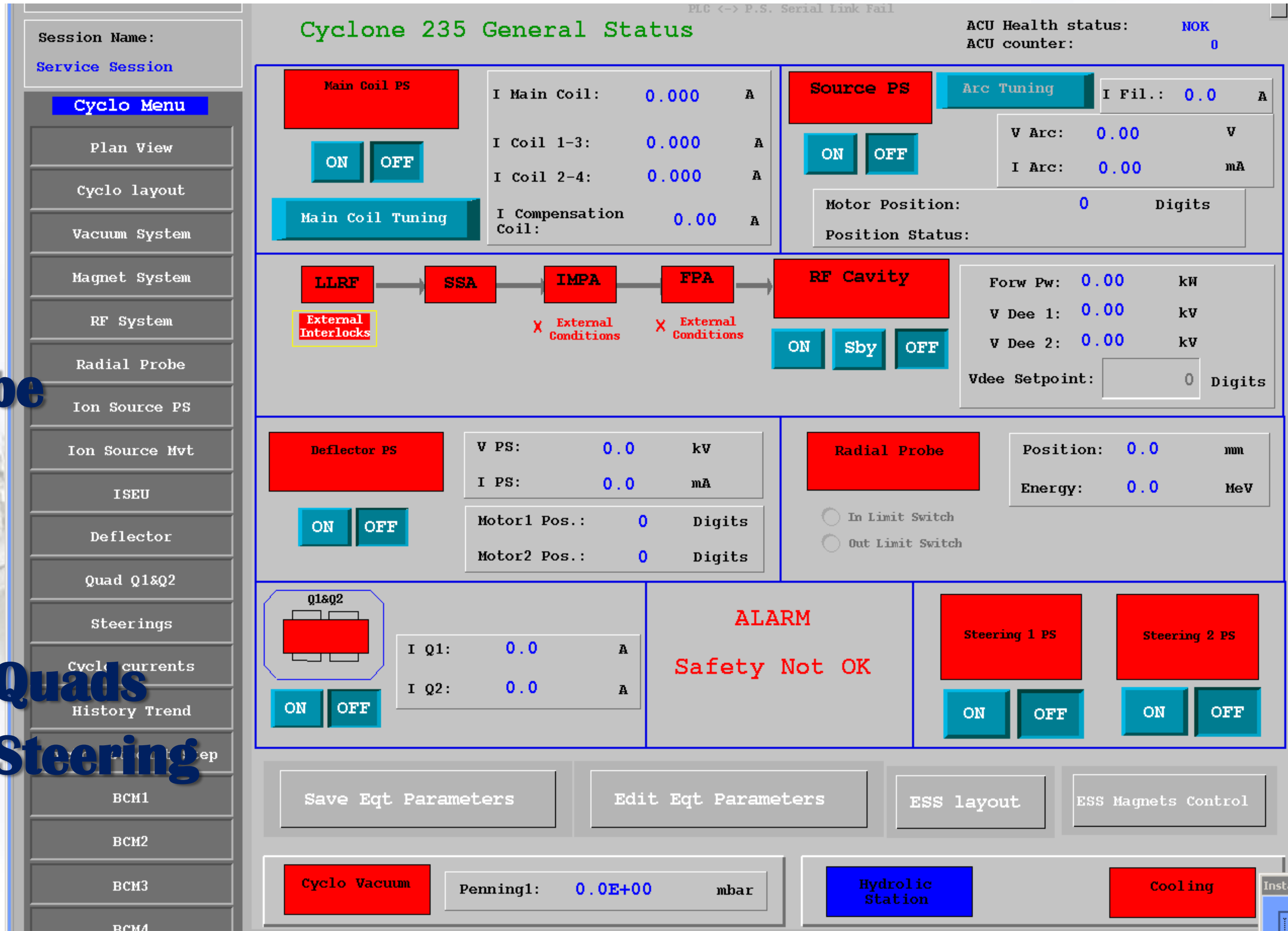


Experiment Room

Main Control Room : operation consoles

MCR - Beam Production

Cooling
Vacuum
Magnet
RF
Radial Probe
Ion Source
ISEU
Deflector
Extraction Quads
Extraction Steering
…



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Main Control Room : ISEU, RF, Magnet E

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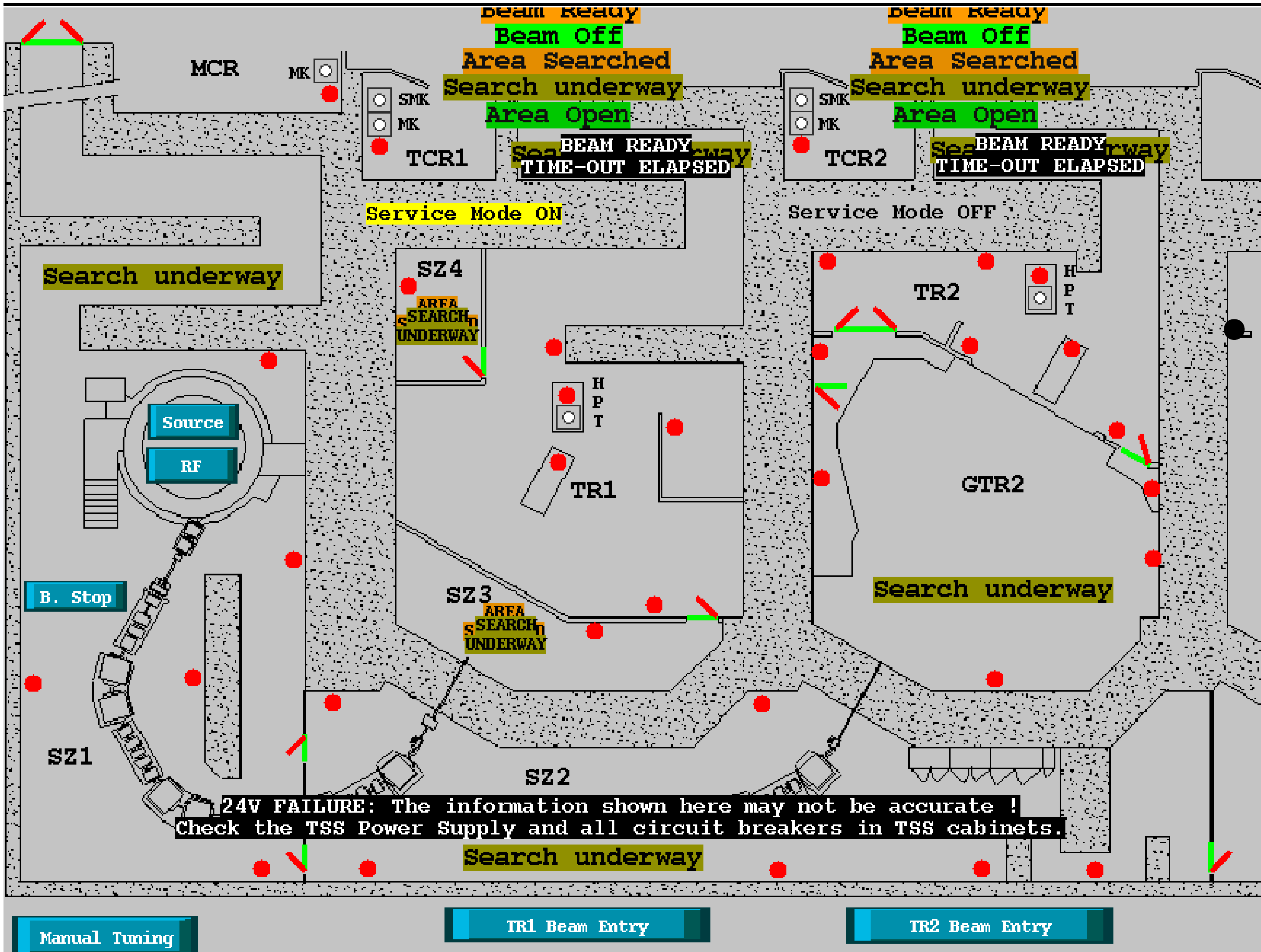
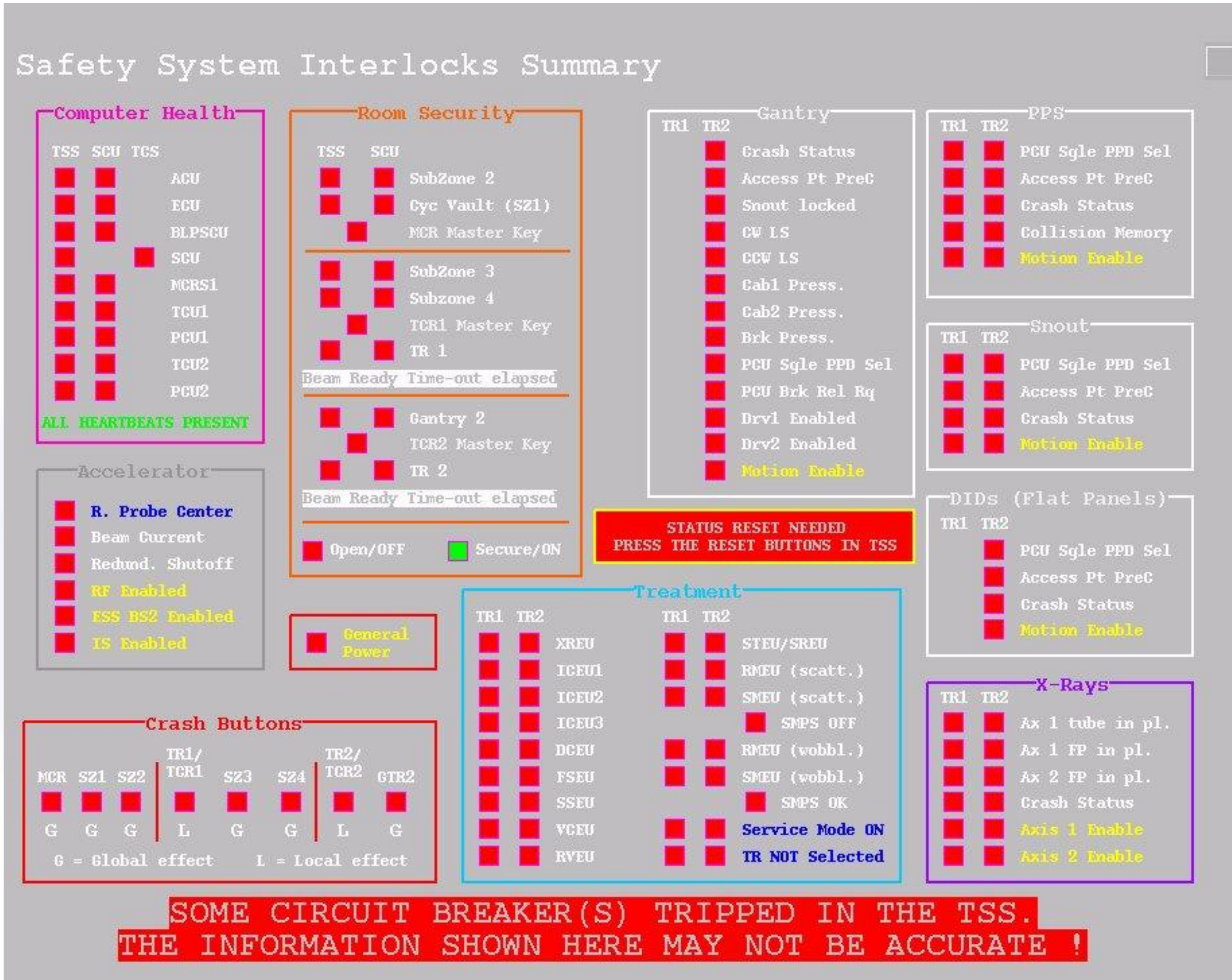
Building Interlock

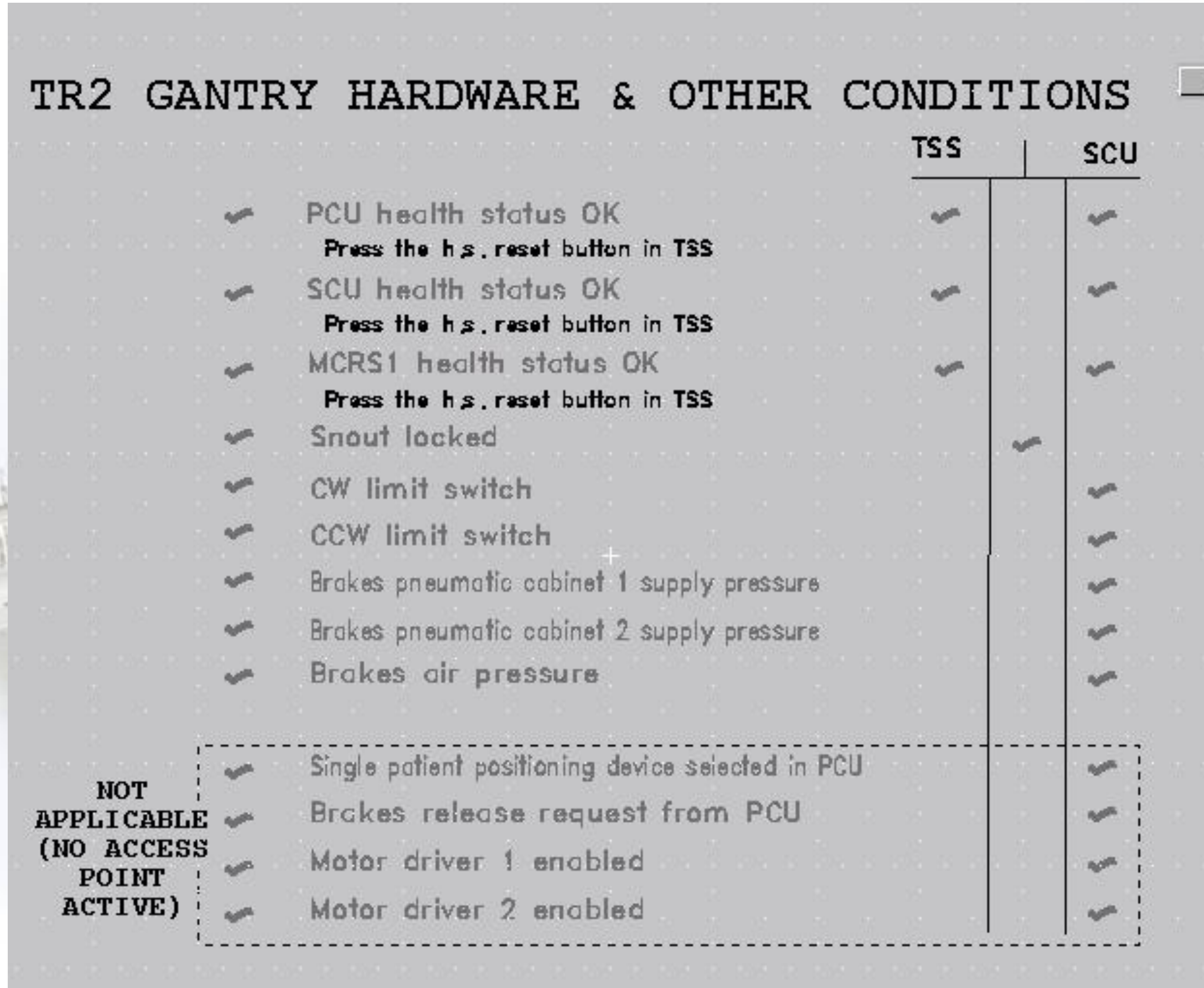


…

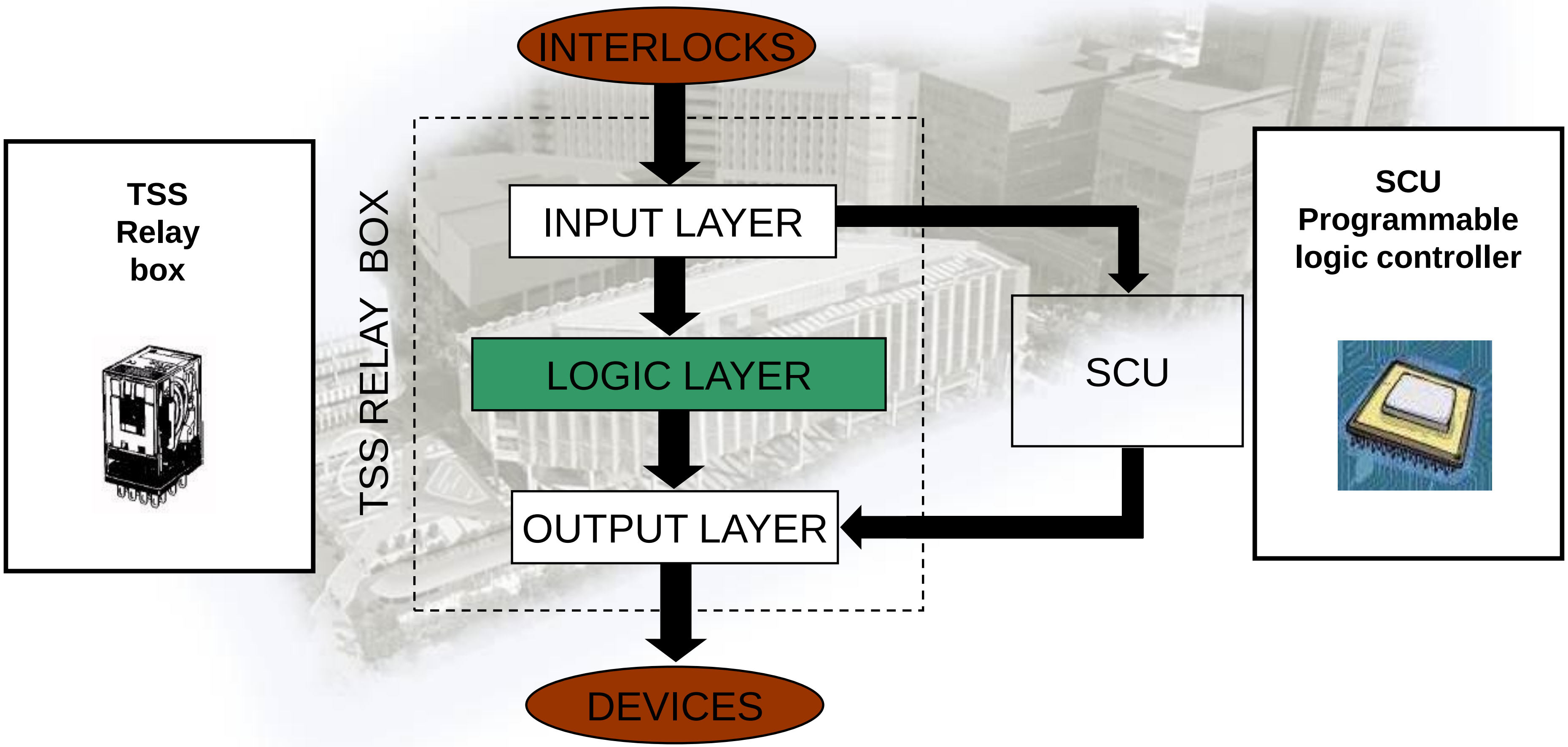
Monitoring & Safety System Interlock



Detailed Troubleshooting



Structure of the relay circuitry



Main Control Room : TSS relay racks

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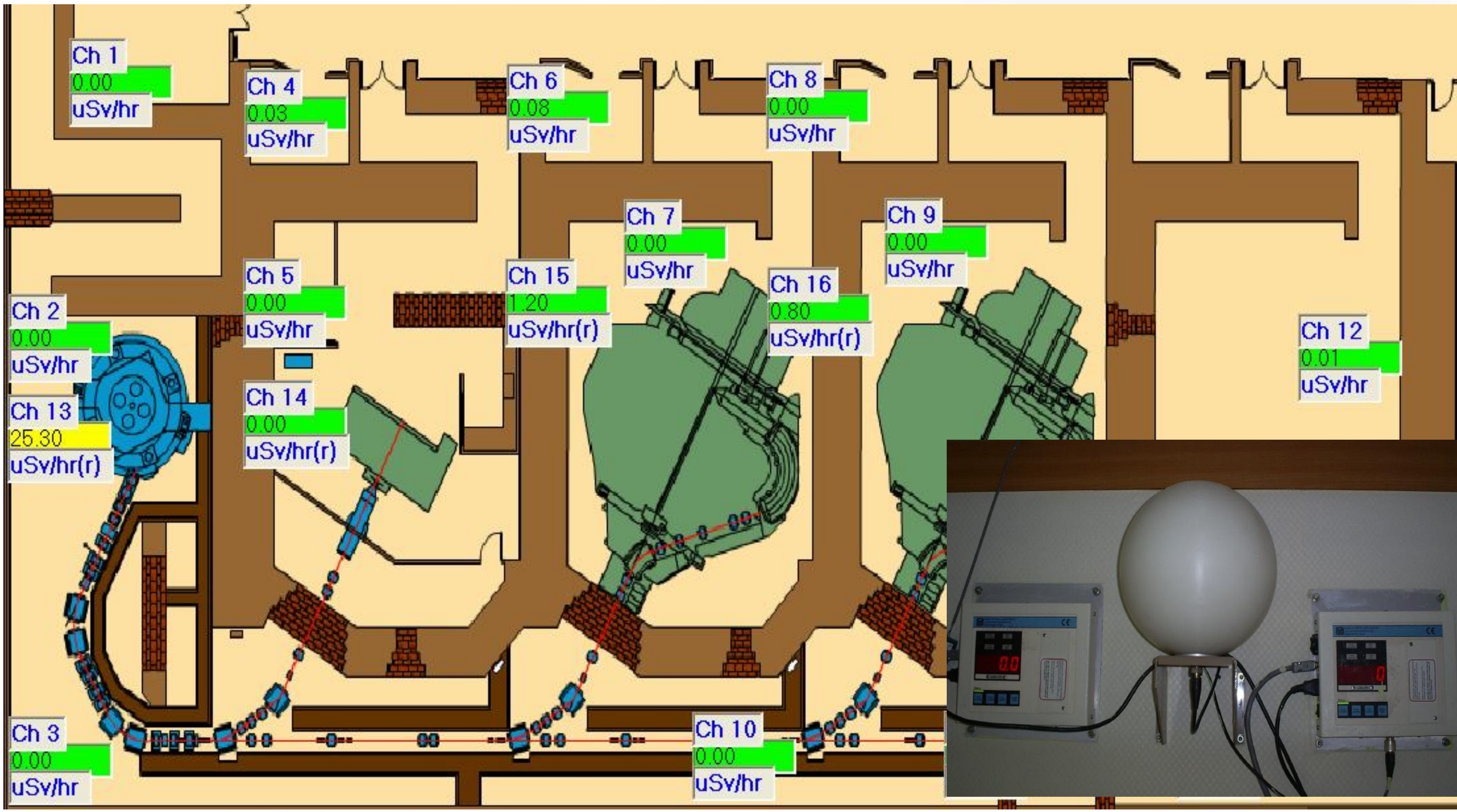
CCD camera system

CCD camera system

Radiation monitor with Area detectors



Milling Machine Shop


Thank you for your attention!
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