Radiation Protection for Particle Therapy Facilities

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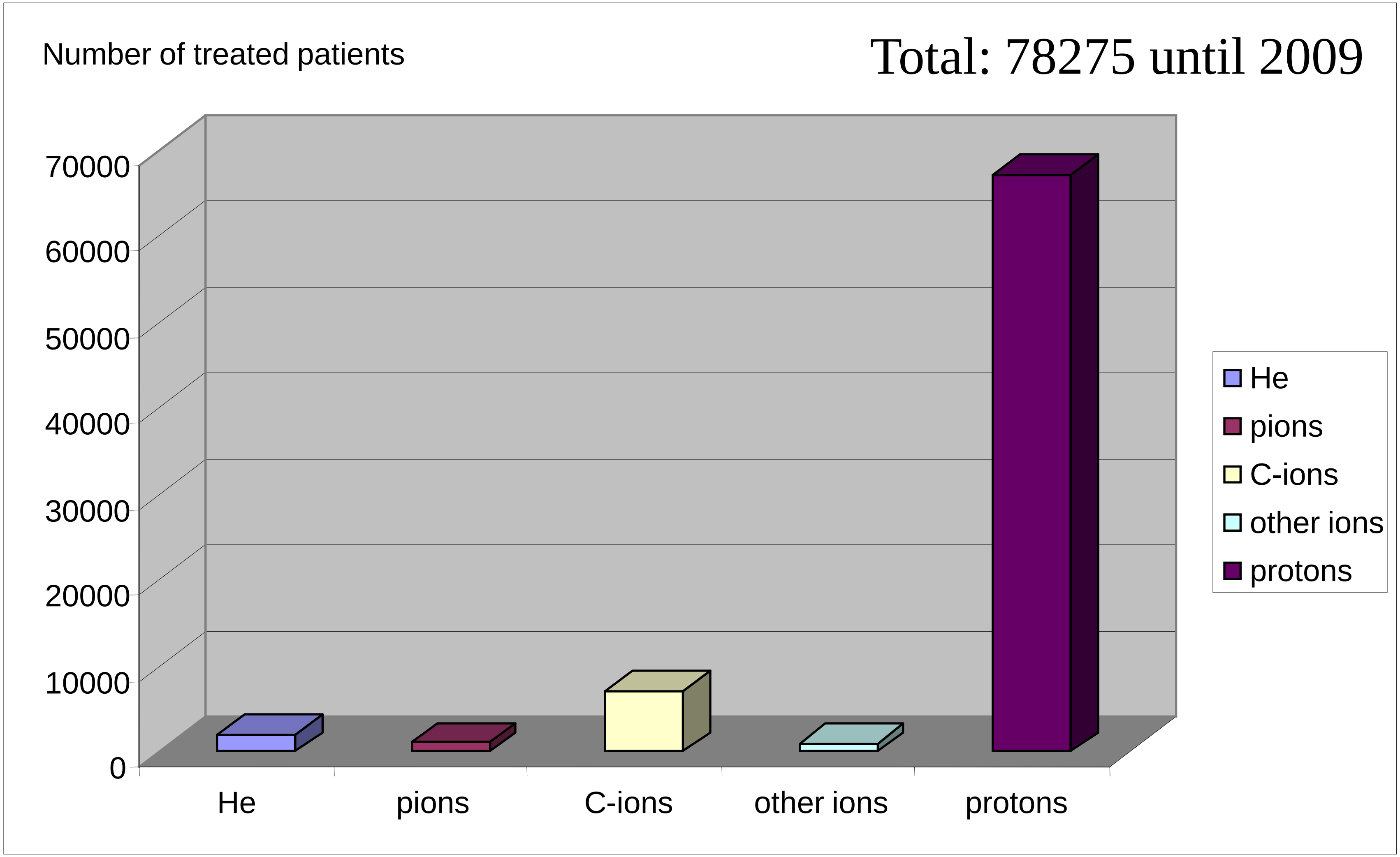
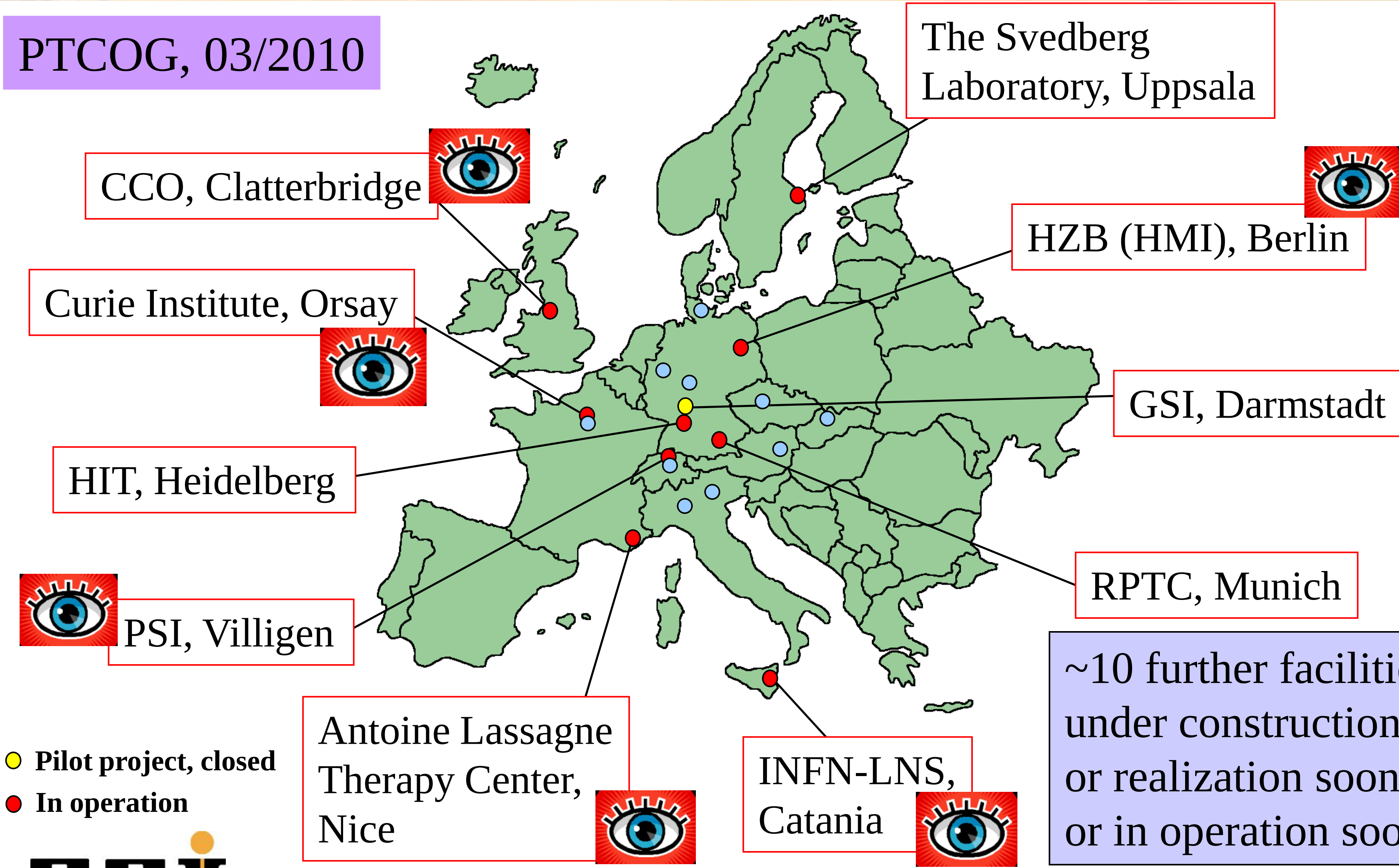
Number of Patients treated with Hadrons (PTCOG, 03/2010)



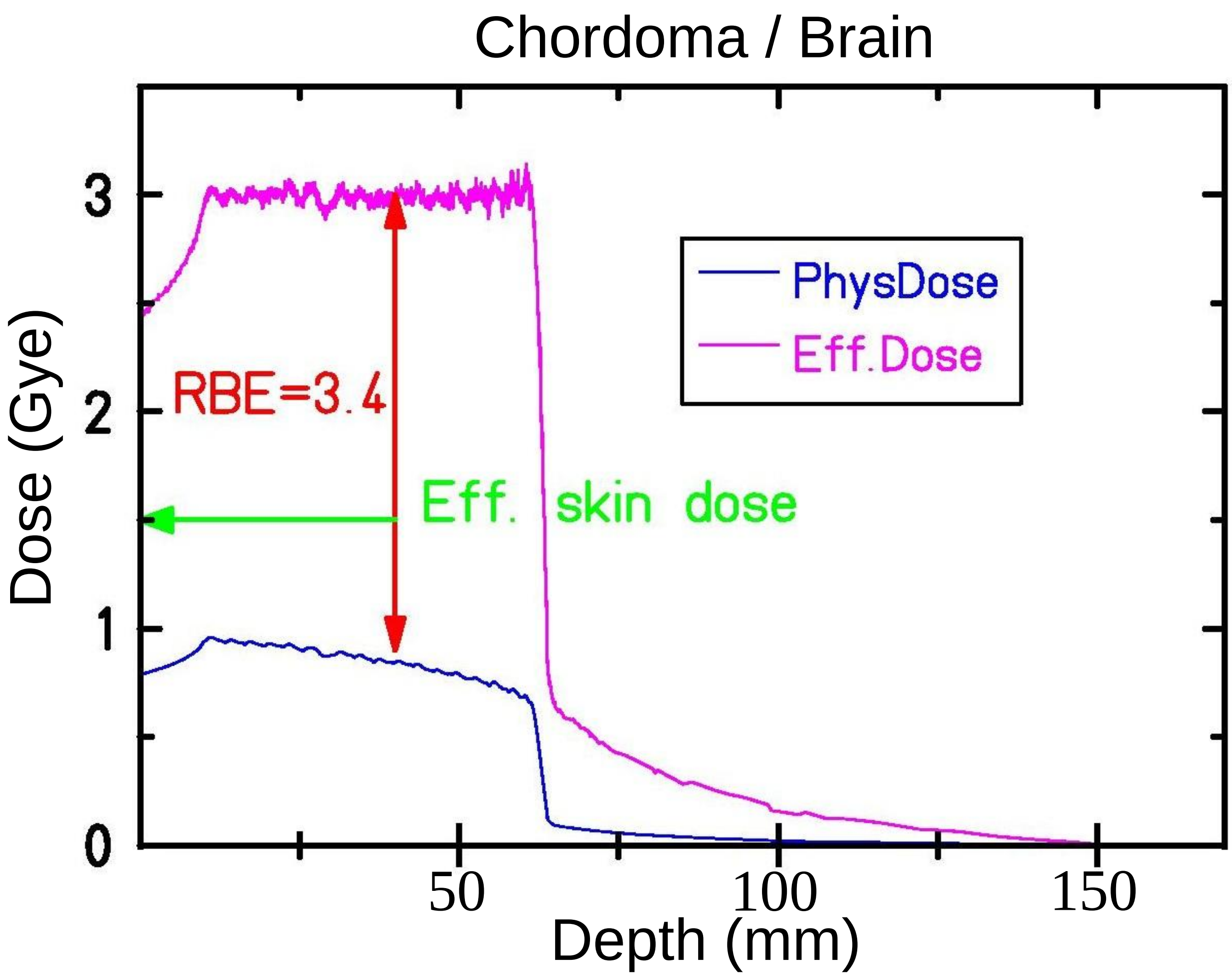
Survey PTF, West-Europe

PTCOG, 03/2010



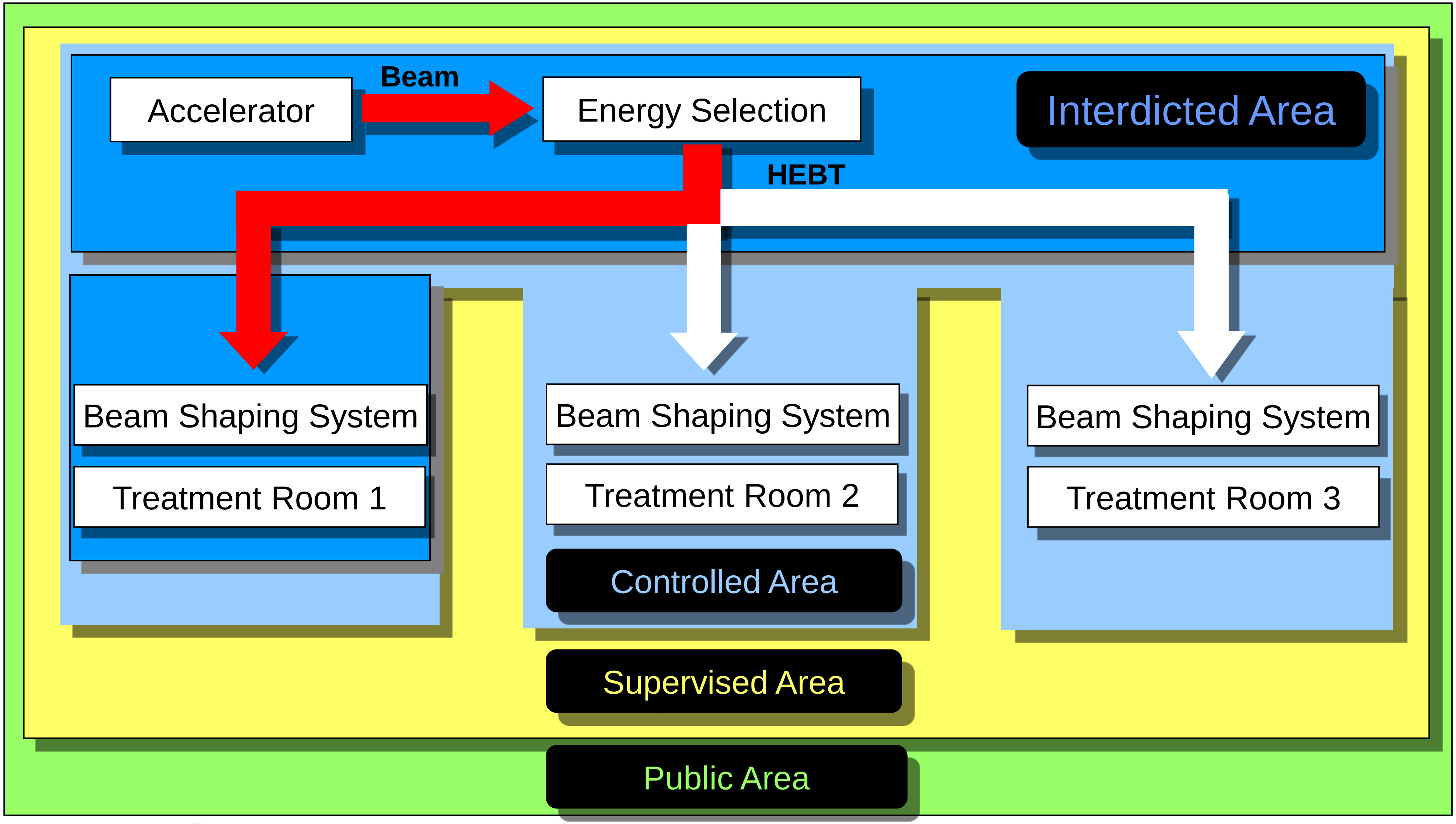
~10 further facilities under construction or realization soon or in operation soon

Motivation for Particle Therapy: Improved Dose Profile, here - Carbon Ions



G. Kraft-
Tumor Therapy with Heavy Ions
published by the Association for the Promotion of Tumor Therapy with Heavy Ions 2007

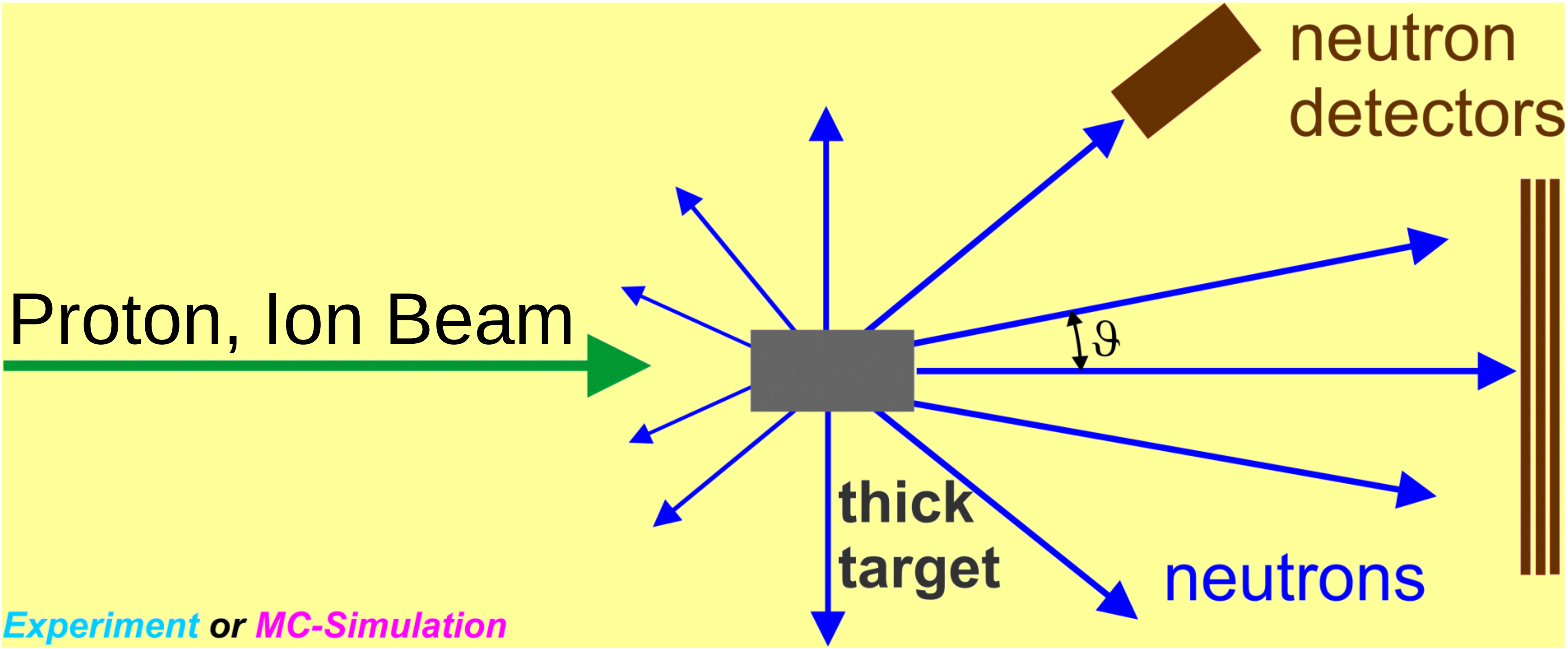
Radiological Areas



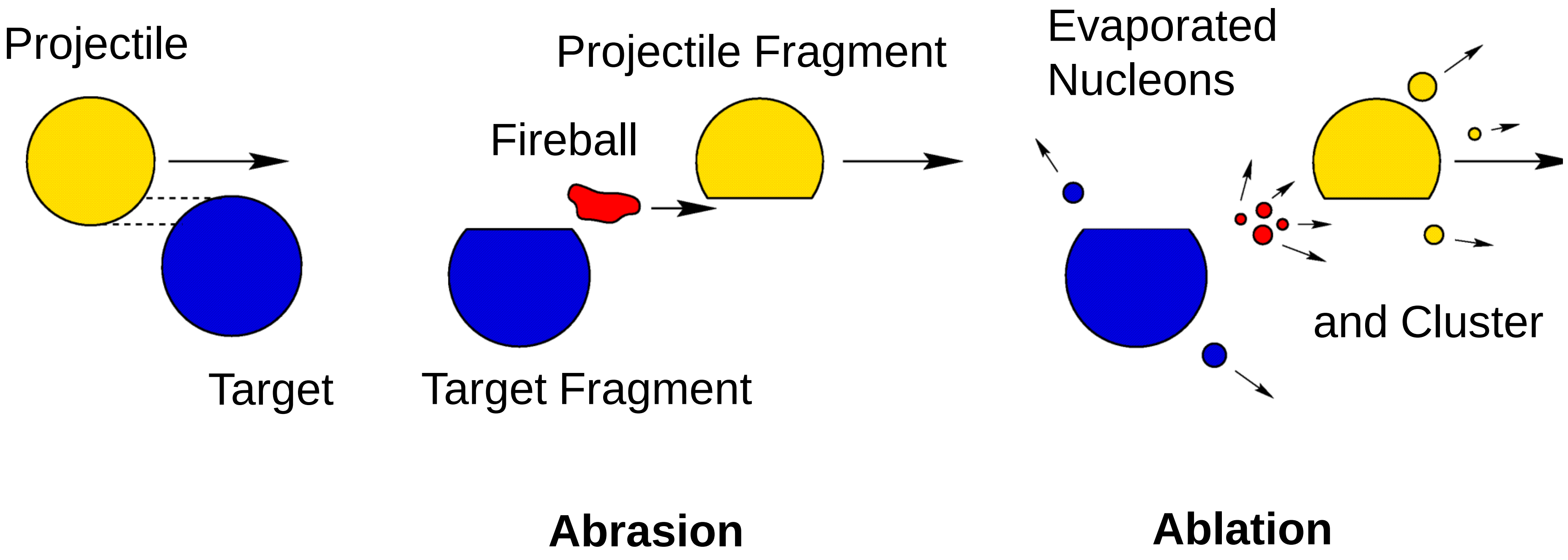
Dose Limits

	Dose Limit			
Area / Country	***Japan***	***Italy***	***Germany***	***USA***
Restricted	site specific	site specific	> 3 mSv/h	site specific
Controlled	> 1 mSv/week	> 6 mSv/a	> 6 mSv/a	≤ 5 mSv/a
Supervised	> 0.1 mSv/week - 1.3 mSv/3 months	> 1 mSv/a < 6 mSv/a	> 1 mSv/a < 6 mSv/a	-
Public	< 250 µSv / 3 months	< 1 mSv/a	< 1 mSv/a	≤ 1 mSv/a, 20 µSv/h for T=1

Determination of Neutron Sources

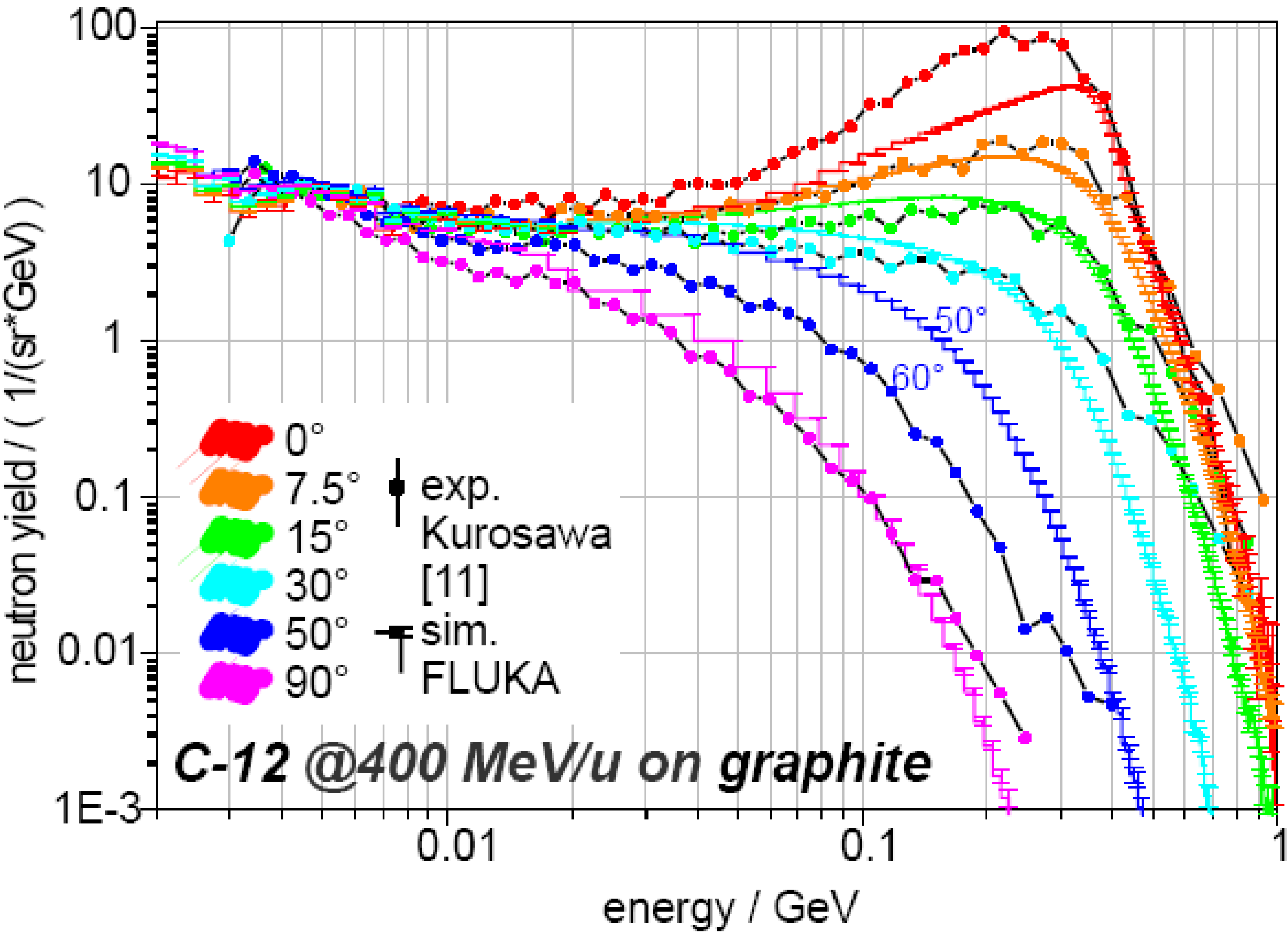


Fragmentation of Projectile Nuclei



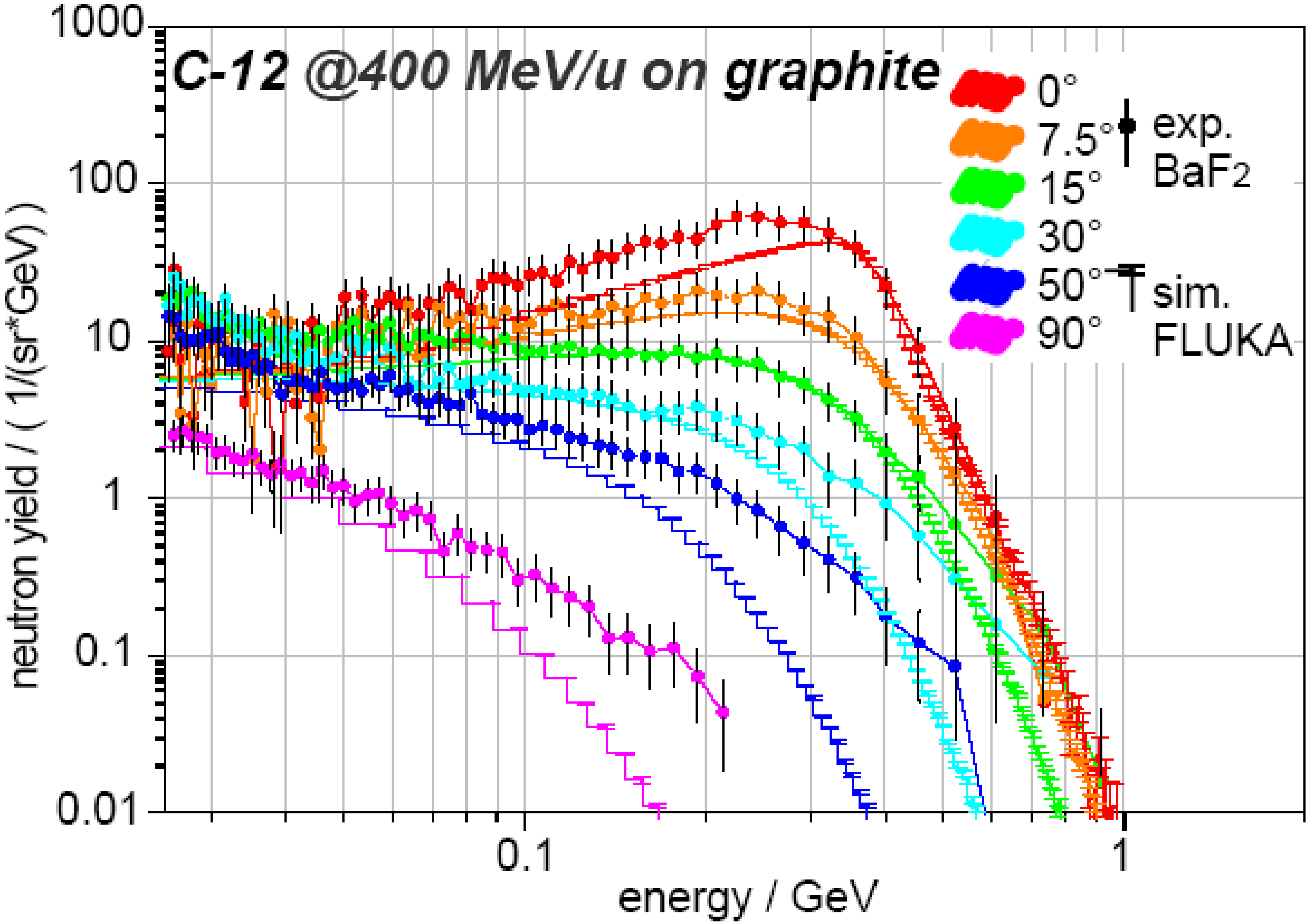
Measured/Computed Neutron Spectra C@400MeV/u→C

NE102A Data from Kurosawa et al. Nucl.Sc.Eng.1999 and Gunzert-Marx et al., PoS, 2006



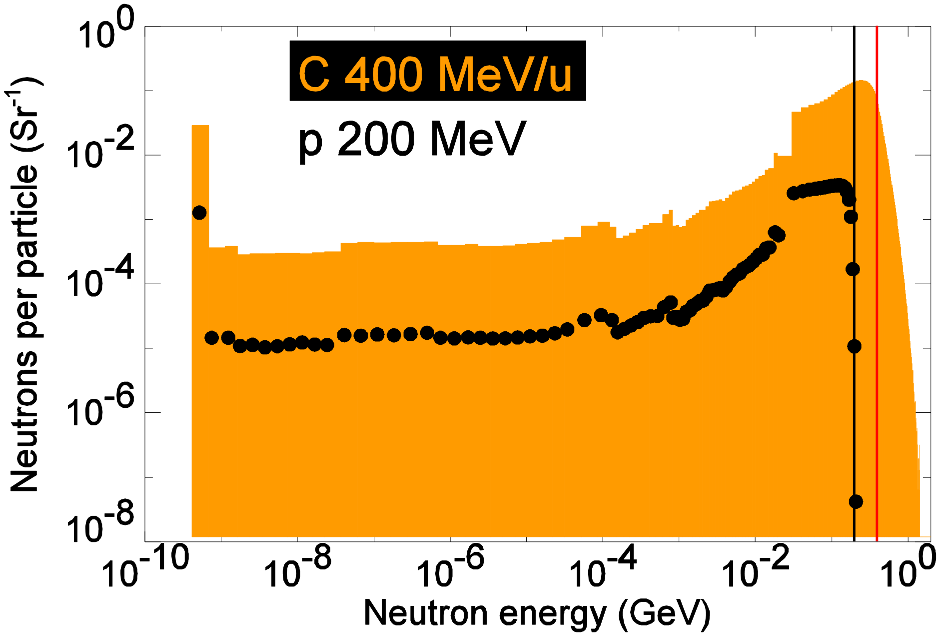
Measured/Computed Neutron Spectra C@400MeV/u→C

BaF_2 Data, Gunzert-Marx et al., PoS, 2006

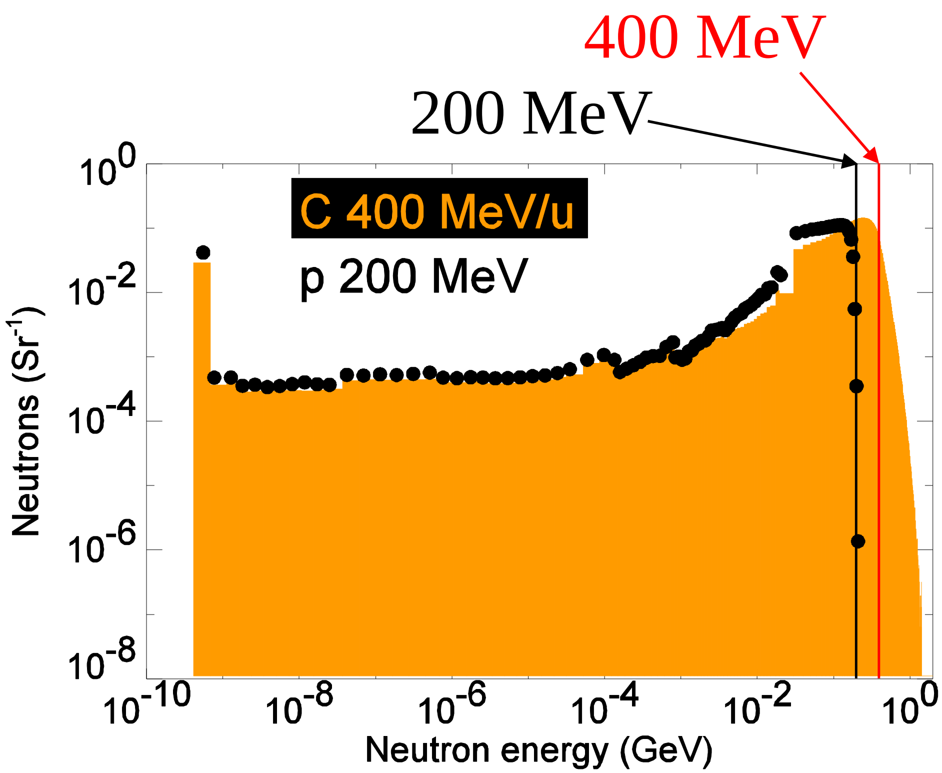


Neutron Energy Distribution produced by Protons/Carbon Ions in 0° Direction

Per Particle



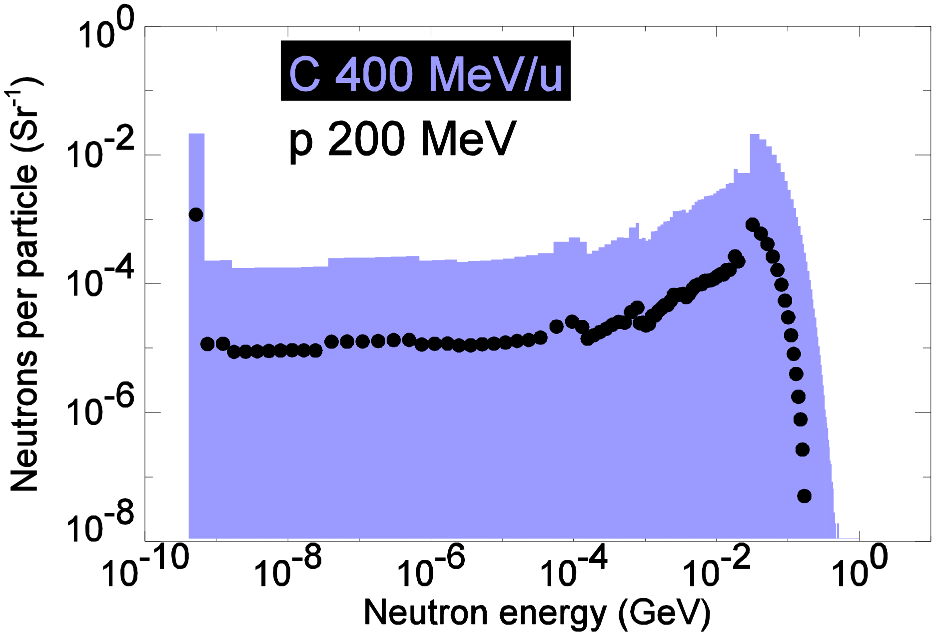
Same Therapy Dose



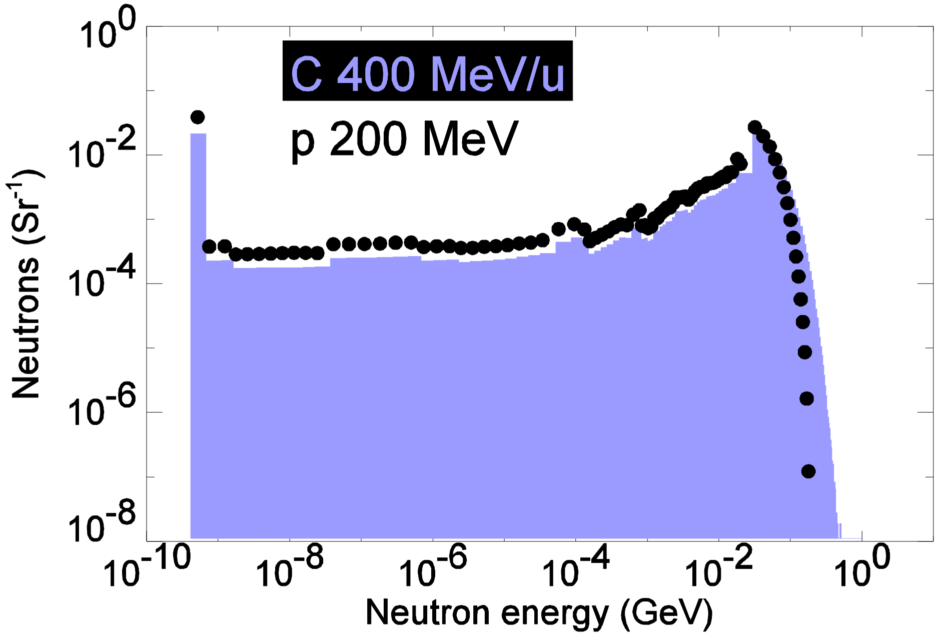
FLUKA Calculations; Porta et al. RPD 2009

Neutron Energy Distribution produced by Protons/Carbon Ions in 90° Direction

Per Particle



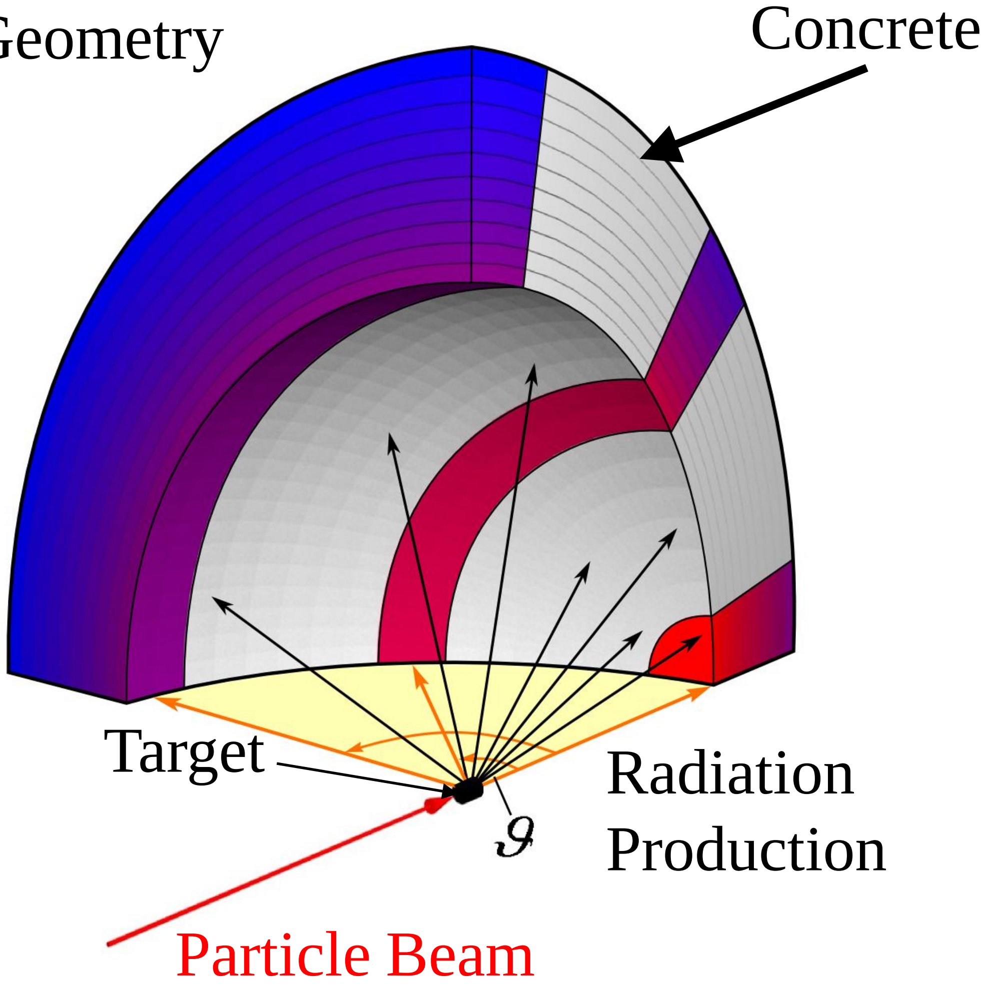
Same Therapy Dose

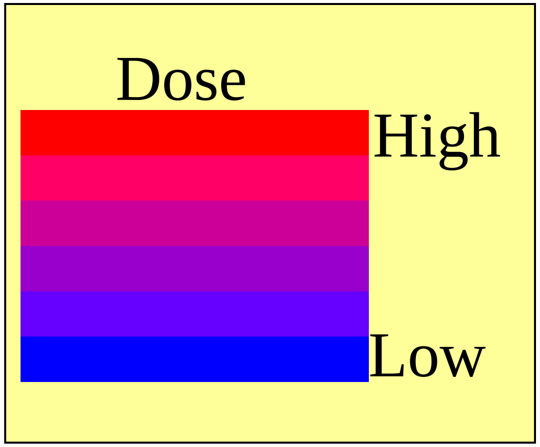


FLUKA Calculations; Porta et al. RPD 2009

Attenuation in Concrete: Line-of-Sight

see e.g. Agosteo et al. NIMB-2007





Parameters of the Attenuation Curve

see e.g. Agosteo et al. NIMB-2004

Lower Angles $\vartheta < 50°$

$$H(E_P, \vartheta, d, \lambda_\vartheta) = \frac{H_0(E_P, \vartheta)}{r^2} \cdot \exp\left[-\frac{d \cdot \rho}{\lambda_\vartheta}\right]$$

E_P: Particle Energy

r : Distance source to reference point

d : Shield thickness, ρ density

ϑ : Angle relative to beam

λ : Attenuation Parameter

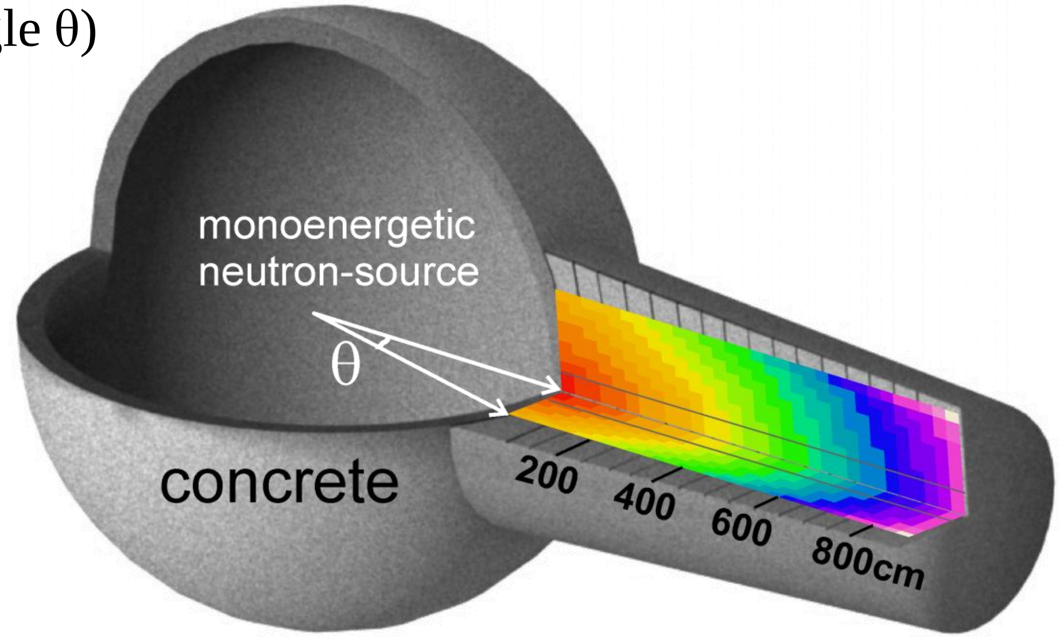
Larger Angles $\vartheta > 50°$

$$H(E_P, \vartheta, d, \lambda_{1,\vartheta}, \lambda_{2,\vartheta}) = \frac{H_1(E_P, \vartheta)}{r^2} \cdot \exp\left[-\frac{d \cdot \rho}{\lambda_{1,\vartheta}}\right] + \frac{H_2(E_P, \vartheta)}{r^2} \cdot \exp\left[-\frac{d \cdot \rho}{\lambda_{2,\vartheta}}\right]$$

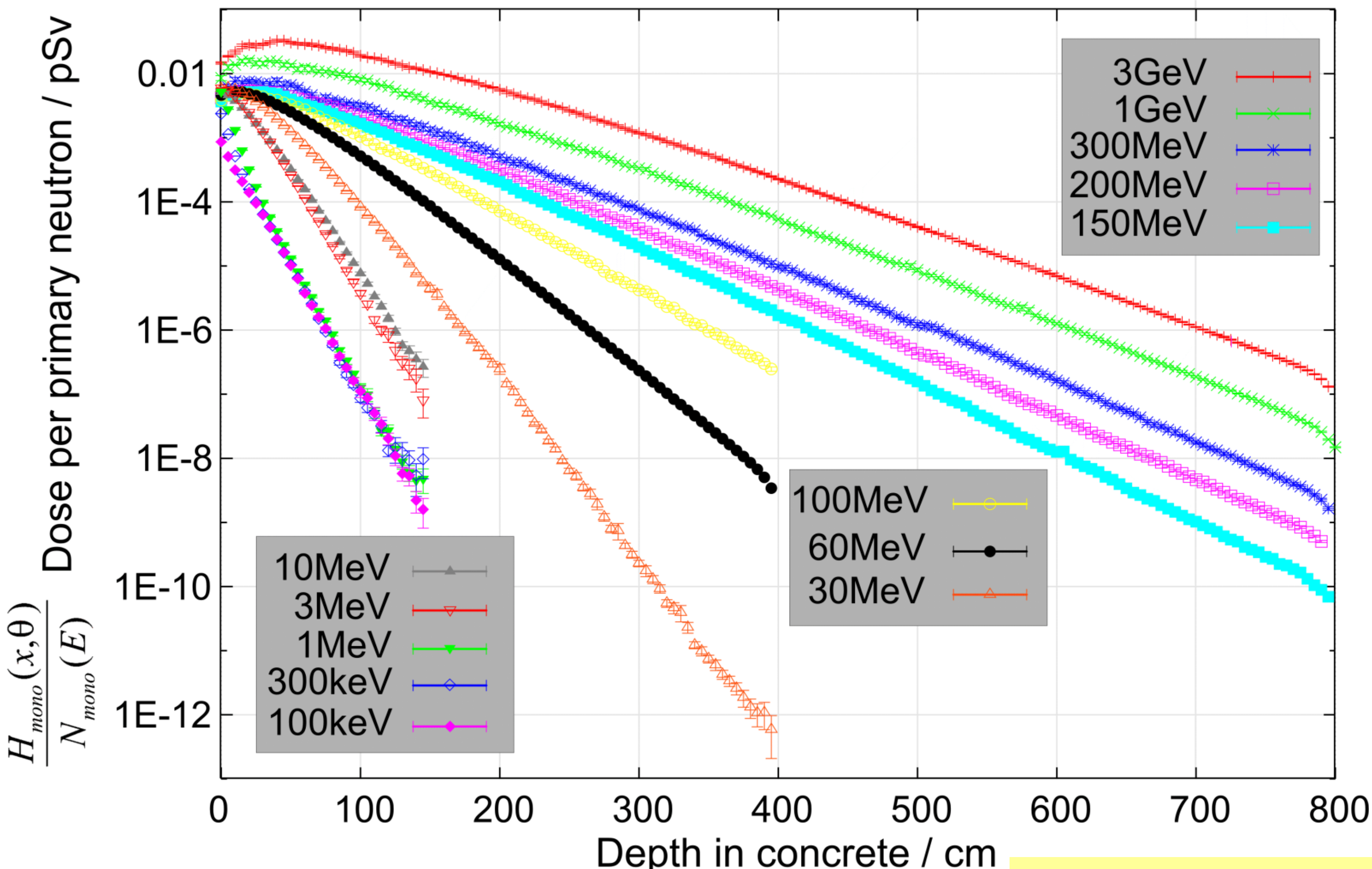
Computation of the Attenuation of Monoenergetic Neutron Radiation in the Shielding

- Neutron source in a spherical concrete geometry
- Emission of a neutron cone (solid angle θ) in direction of a concrete body
- Calculation of the radiation transport by means of FLUKA
- Computation of attenuation curves in the concrete body for a wide range of neutron energies (here: 100 keV up to 3 GeV)
- Use of measured/calculated neutron spectra
- Resulting attenuation curve for input neutron spectrum obtained by superposition of weighted (interpolated) monoenergetic attenuation curves

Fehrenbacher, Radon, Neudos11-2009

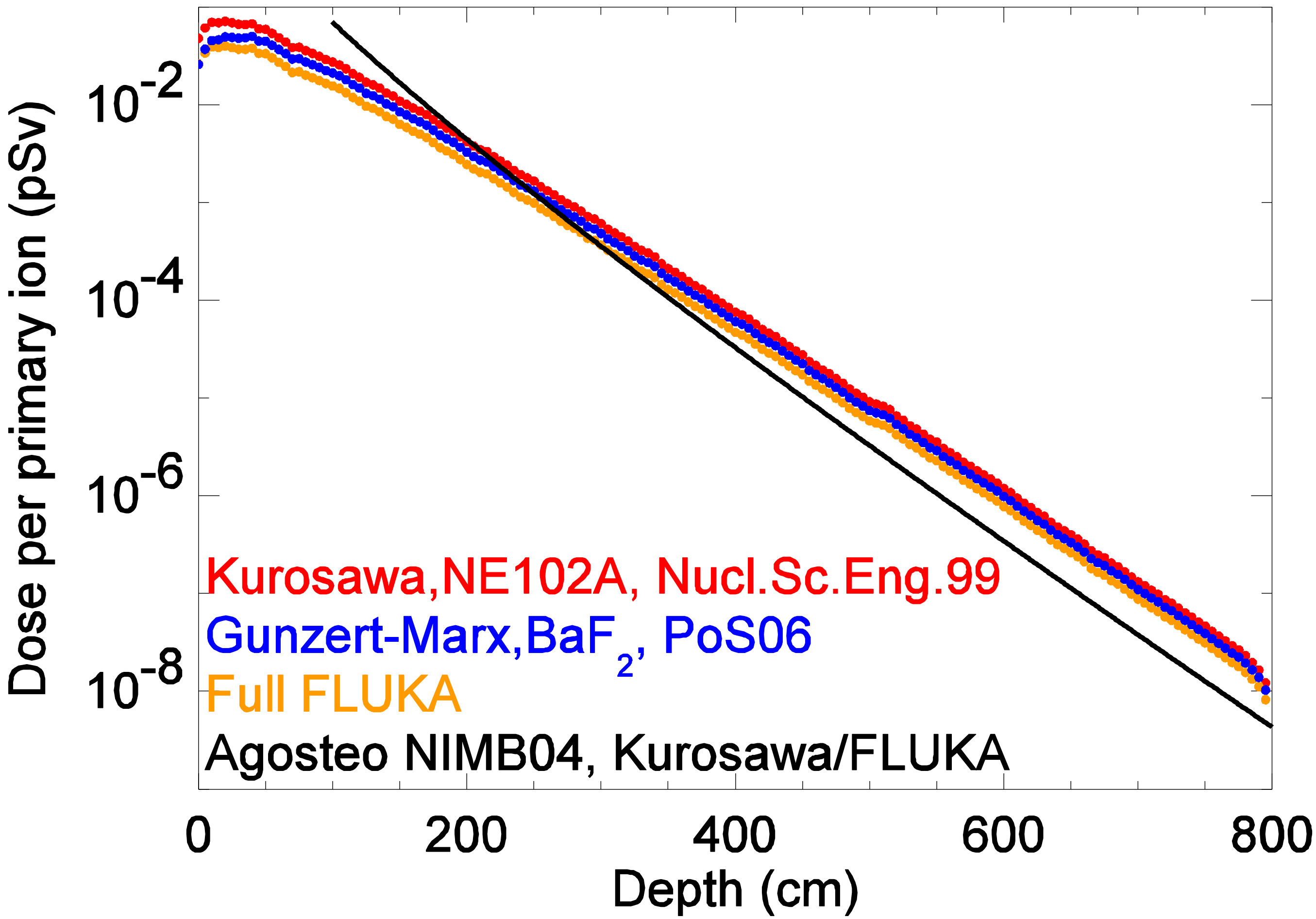


Attenuation Curves for Monoenergetic Neutrons



Neudos 11-Fehrenbacher, Radon, 09

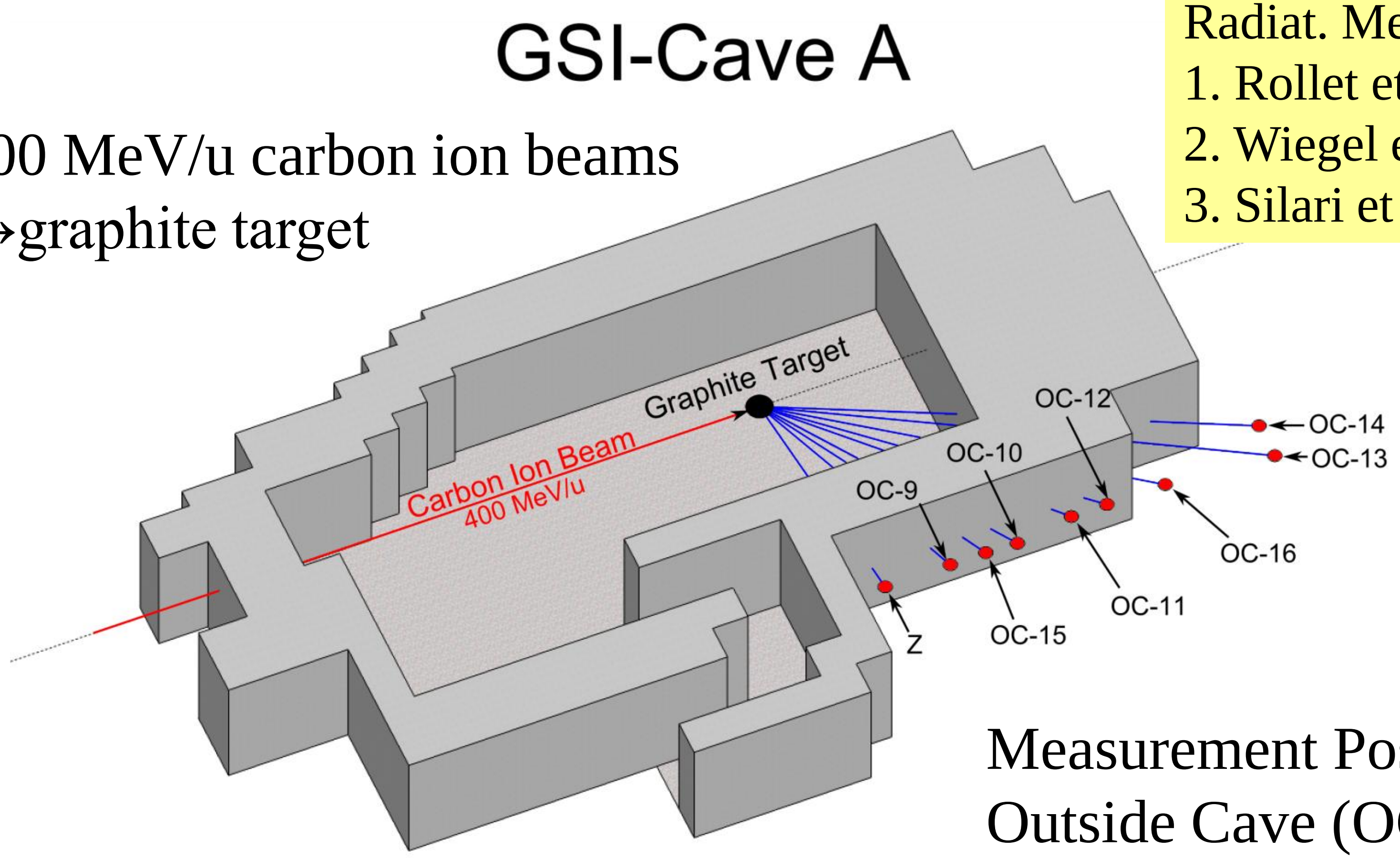
Resulting Attenuation Curve: C@400MeV/u→C, 0



Measurement Campaign Cave A@gsi

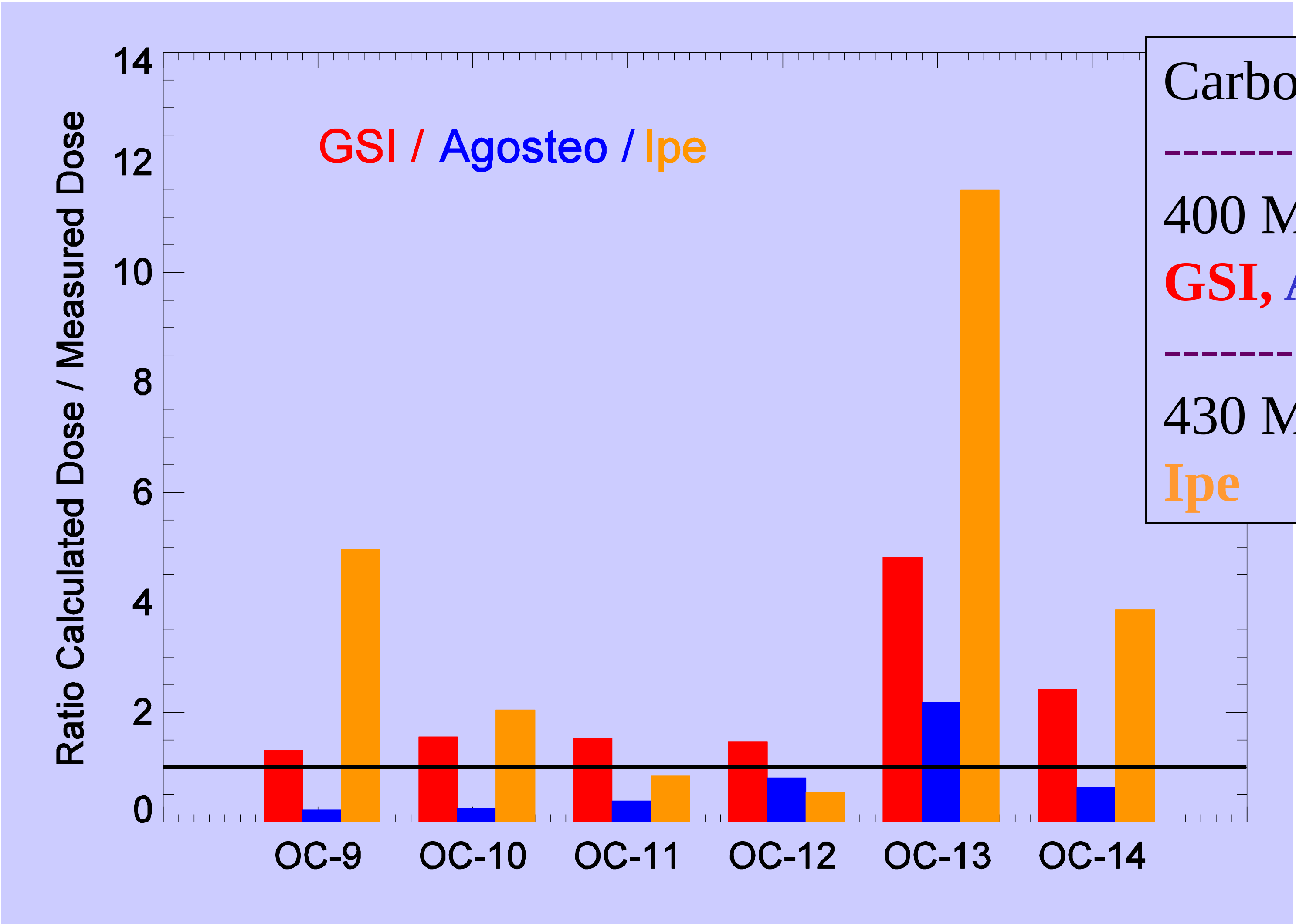
400 MeV/u carbon ion beams
→graphite target

Radiat. Meas. 2009:
1. Rollet et al.: MC Sim.
2. Wiegel et al.: BSS
3. Silari et al.: Instr. Resp.



Measurement Positions
Outside Cave (OC 9,....,16)

Comparison Line-of-Sight Models GSI/Agosteo/Ipe Reference Dose Values BSS Measurements



Carbon Beams

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400 MeV/u
GSI, Agosteo

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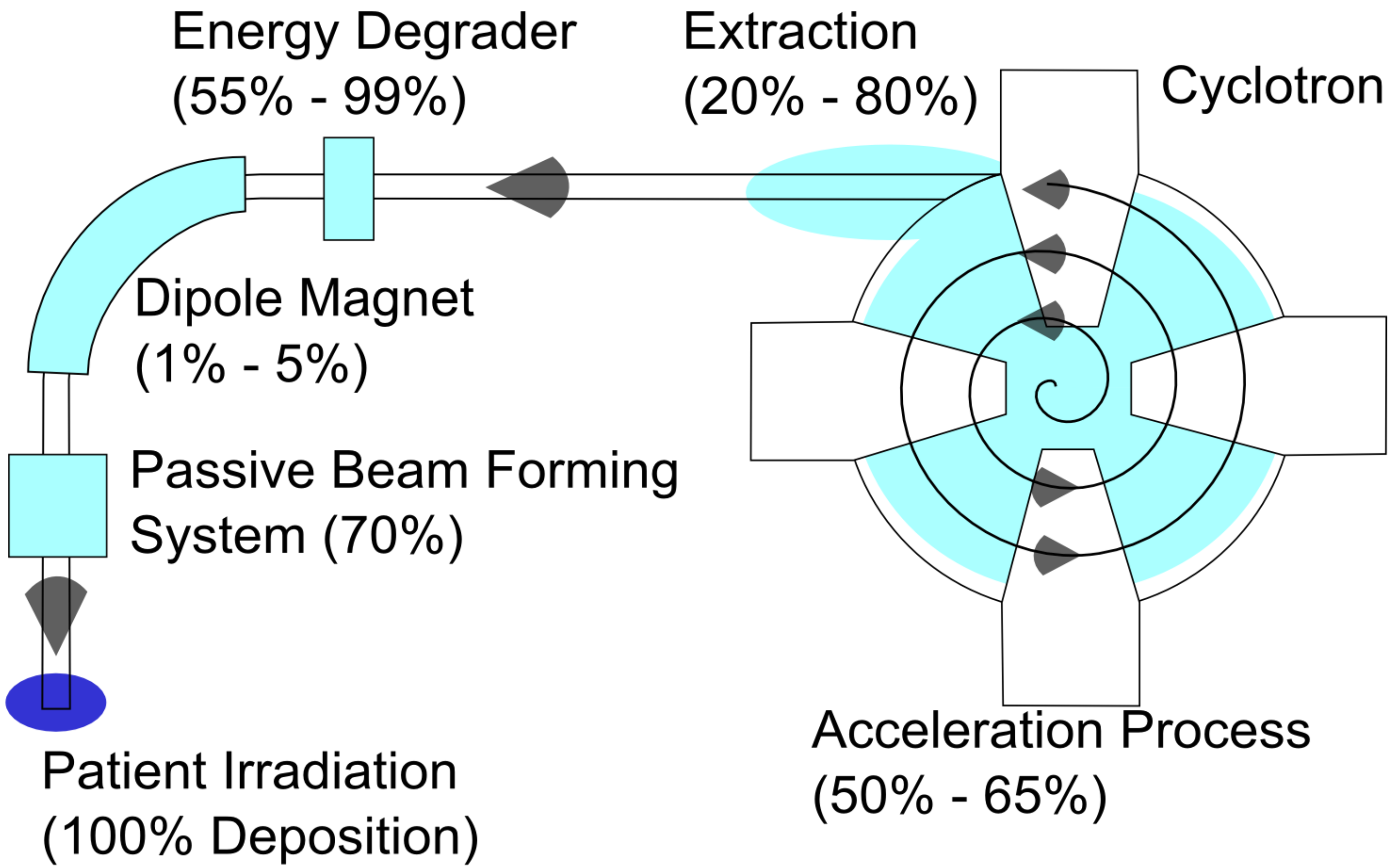
430 MeV/u
Ipe

Agosteo: NIMB04
Ipe: PTCOG10

Beam Losses: Cyclotron

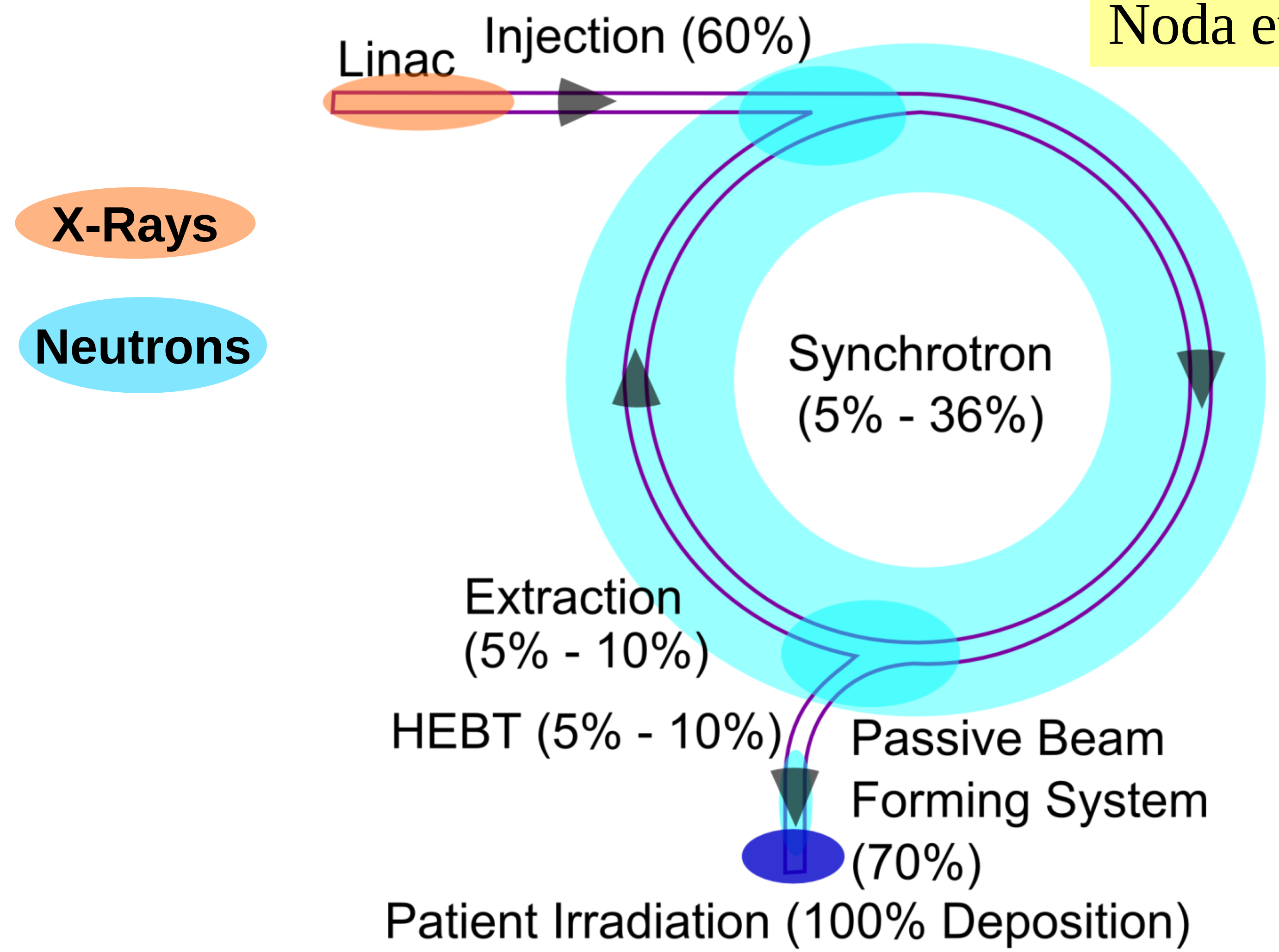


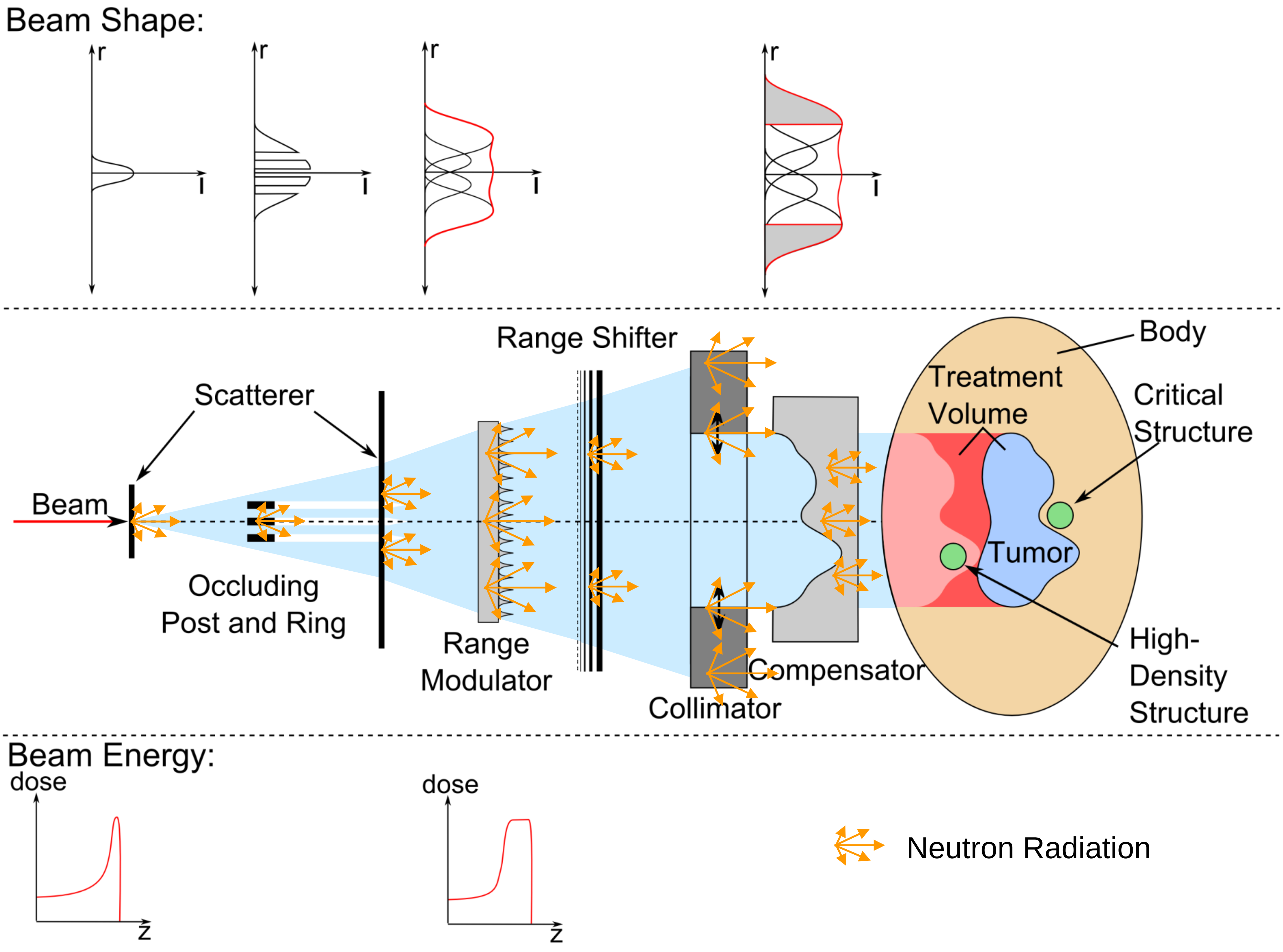
PTCOG, Publication Nr. 1, 2010

Neutrons

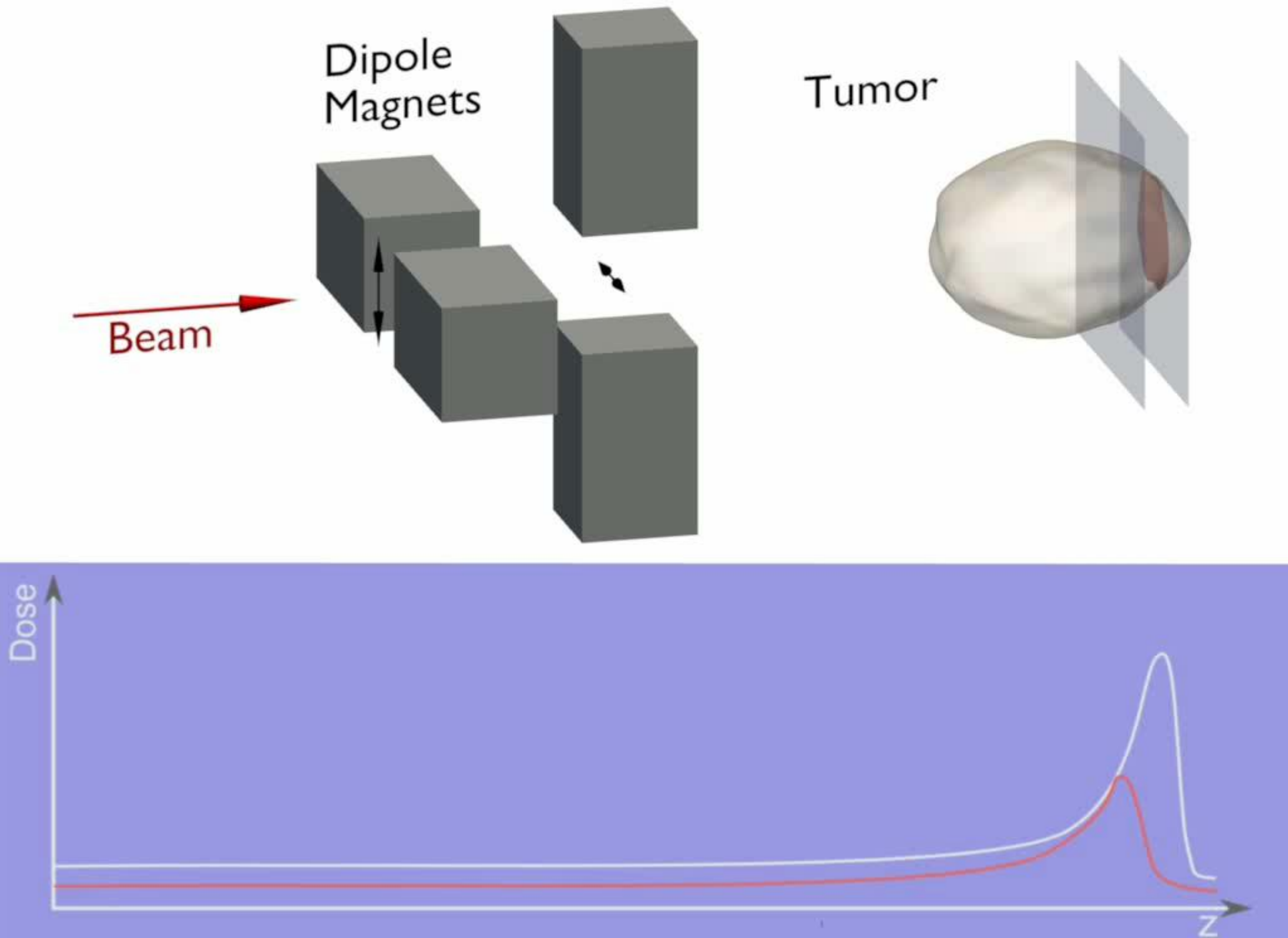
Beam Losses: Synchrotron

Noda et al., EPAC 2006





Beam Shape:
r
I
r
I
r
I
r
I
Range Shifter
Body
Scatterer
Treatment
Volume
Critical
Structure
Beam
Tumor
Occluding
Post and Ring
Range
Modulator
Compensator
Collimator
High-
Density
Structure
Beam Energy:
dose
z
dose
z
Neutron Radiation


Dipole
Magnets
Tumor
Beam
Dose
z

Example 1/3 Particle Therapy Facility: Proton Facility Loma Linda University Medical Center (USA)

- First plans in the 1970s
- Engineering design report 1987-Fermilab/LLU
- First patient treatments 1990
- Characteristics:

Facility partially underground
Synchrotron (7 m diameter)
Preacceleration RFQ (2 MeV)
Beam: 70 MeV to 250 MeV,
Extraction eff.: 95%, 10^{11}/sec
3 rooms with isocentric gantry
1 room with 2 horizontal beam lines
1 room for calibration measurements

- Beam shaping system: passive (scattering foils, ridge filters)
- Shielding investigations: Awschalom, 1987, Hagan et al. Nucl.Sc.Eng. 1988 (MC methods), experimental verification at Fermilab by Siebers et al., Nucl.Sc.Eng. 1993

Example 2/3 Particle Therapy Facility: HIMAC Heavy Ion Medical Accelerator (Japan)

- Planned and operated by NIRS National Institute for Radiol. Scien.
- First patient treatments 1994
- Characteristics:

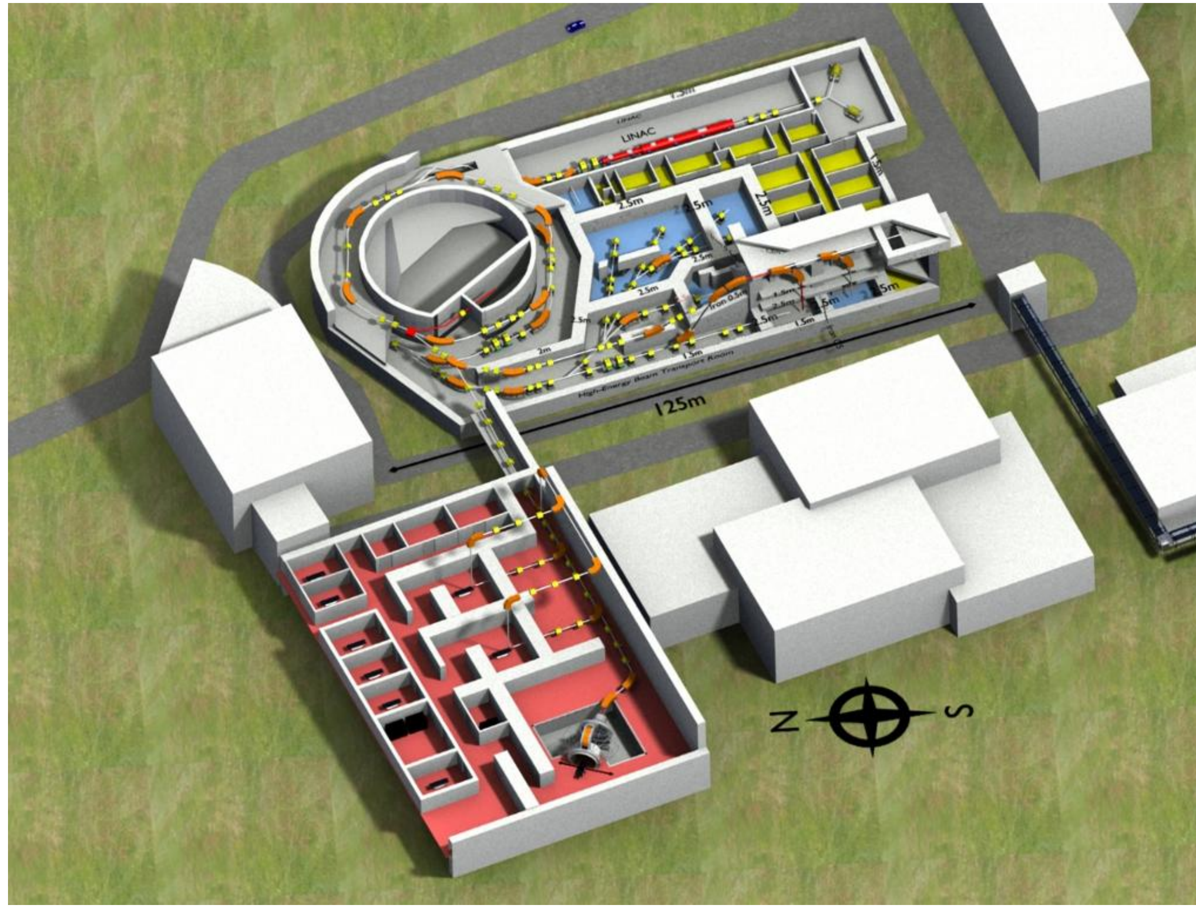
2 synchrotrons, 3 treatment rooms (1 H, 1 V, 1 H&V)

4 further rooms for research incl. radiobiology

Beams: p, He, C, Ne, Si, Ar

therapy: mainly carbon ions (energy > therapy energies up to 800 MeV/u) $2 \cdot 10^8$ carbon ions/sec, 95% extraction efficiency

- Shielding investig. by Ban (1982): Development of a line-of-sight model on basis of MC data obtained by the HETC/KFA-1 code for He beams
- Until 02/2009, 4504 patients were treated
- New Treatment facility@HIMAC: 2 H&V, 1 Rotating Gantry (to be completed 2010)



Example 3/3 Particle Therapy Facility: HIT Heidelberg Ion Therapy Center

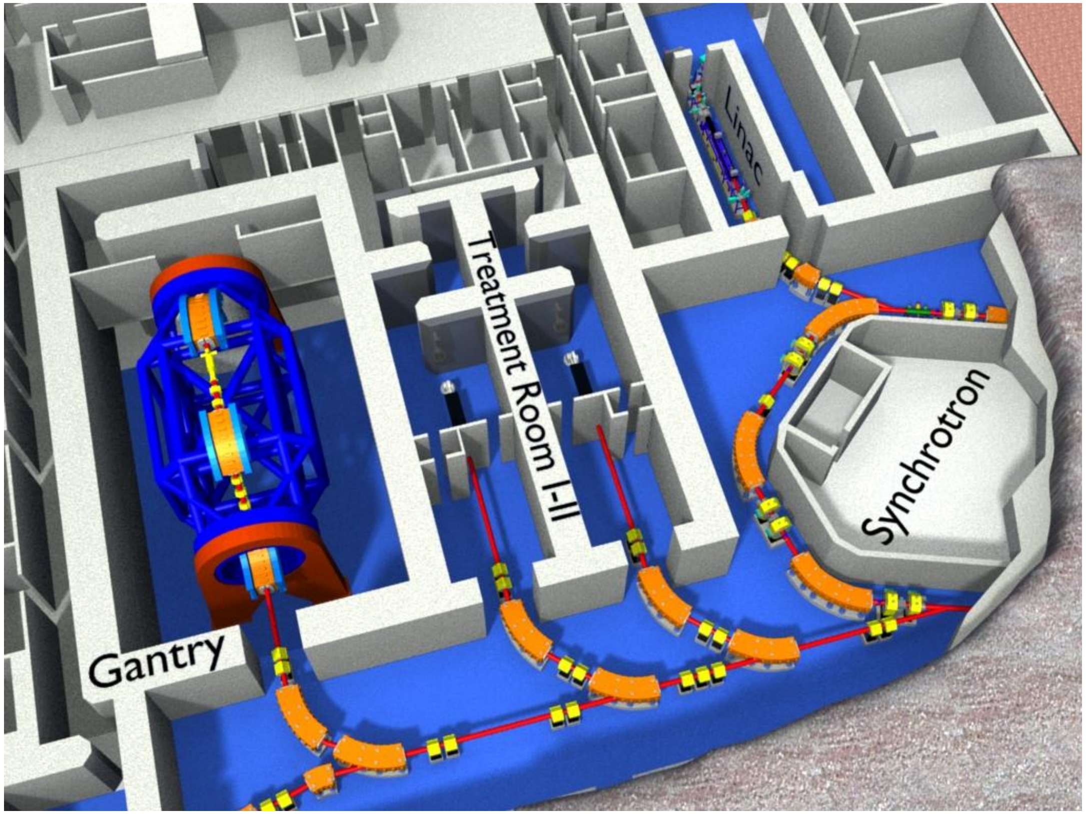
- Proposal for a dedicated ion beam facility for cancer therapy by GSI, University Clinic Heidelberg, Research Center Dresden (1998)
- Characteristics:

Synchrotron for particle accel.:
p, He, C, O, 3 treatment rooms:
2 H, 1 Gantry
Beam: (particles per pulse)
50-220 MeV/u for p, He ($4 \cdot 10^{10}$, $1 \cdot 10^{10}$)
85-430 MeV/u for C, O ($1 \cdot 10^{9}$, $5 \cdot 10^{8}$)

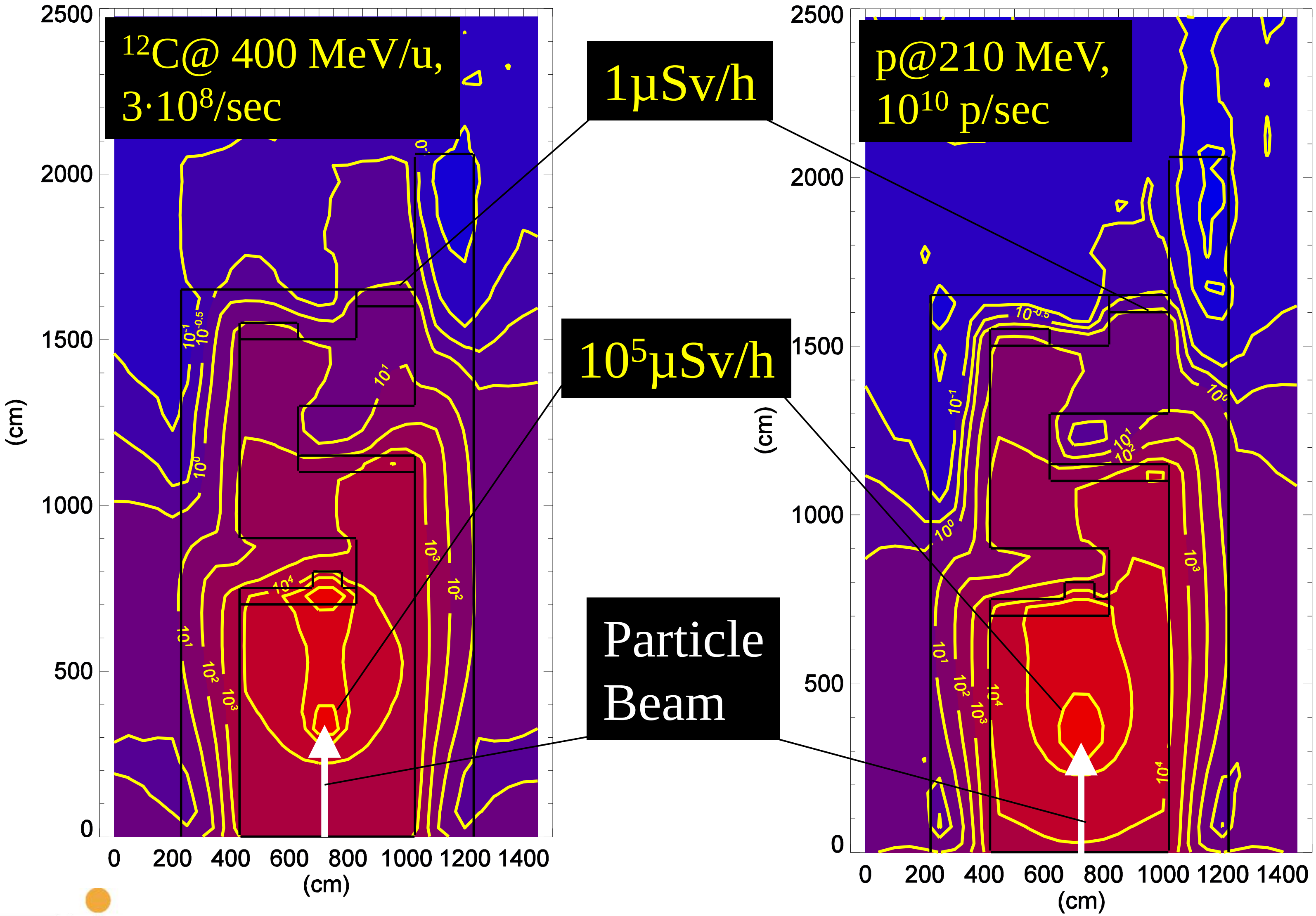
- Shielding (Concrete/Steel):

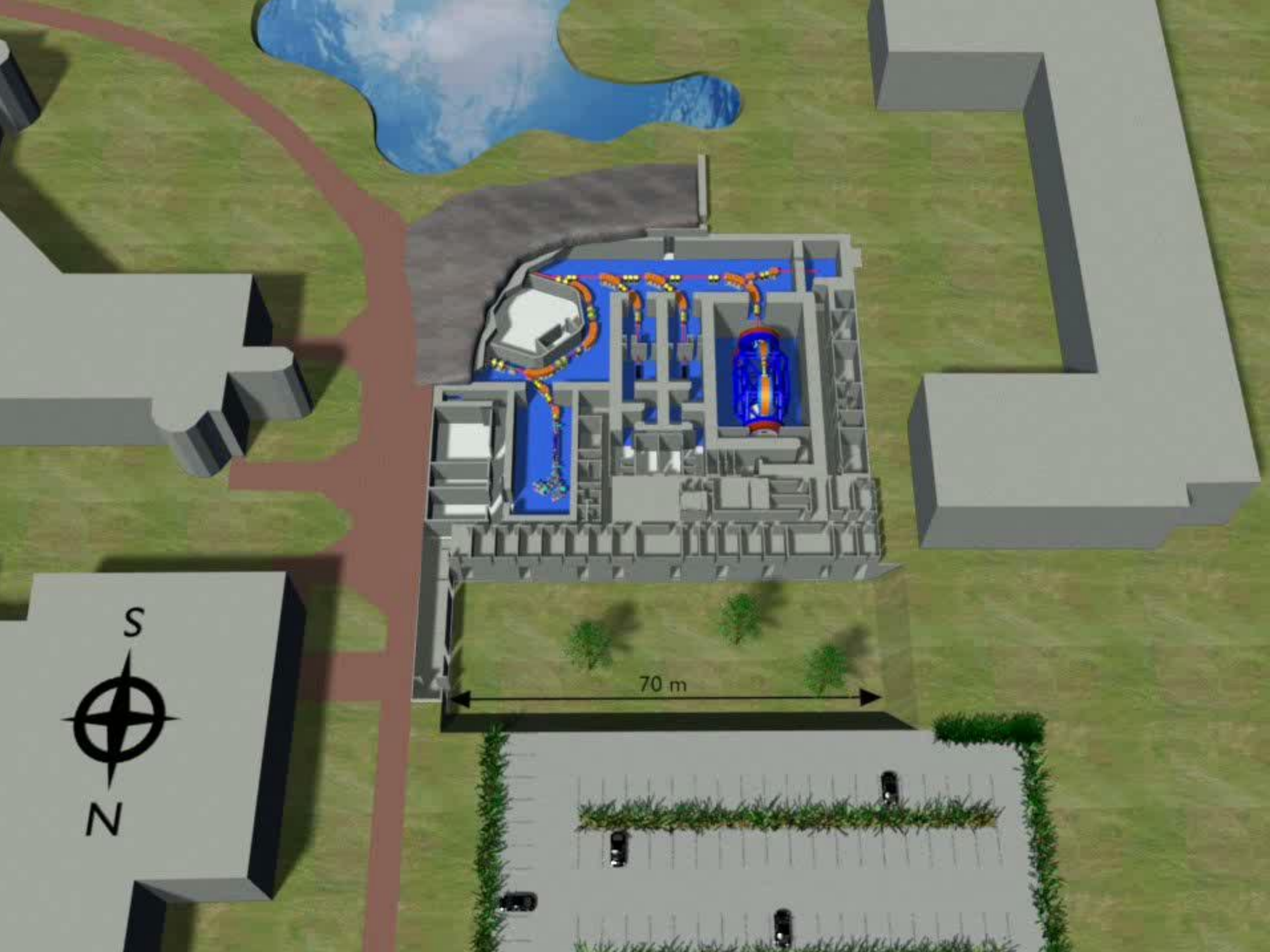
Line-of-Sight model on the basis of neutron spectra of Kurosawa (C@400 MeV/u), FLUKA calculations using Kurosawa data

- Patient treatments since November 2009

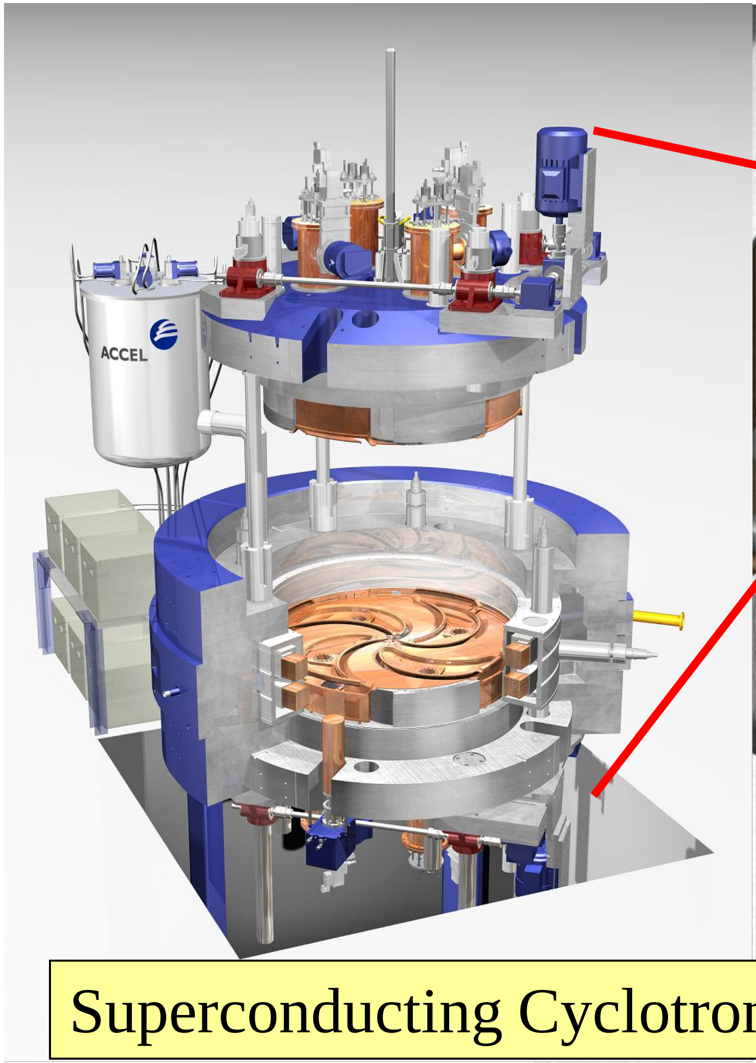


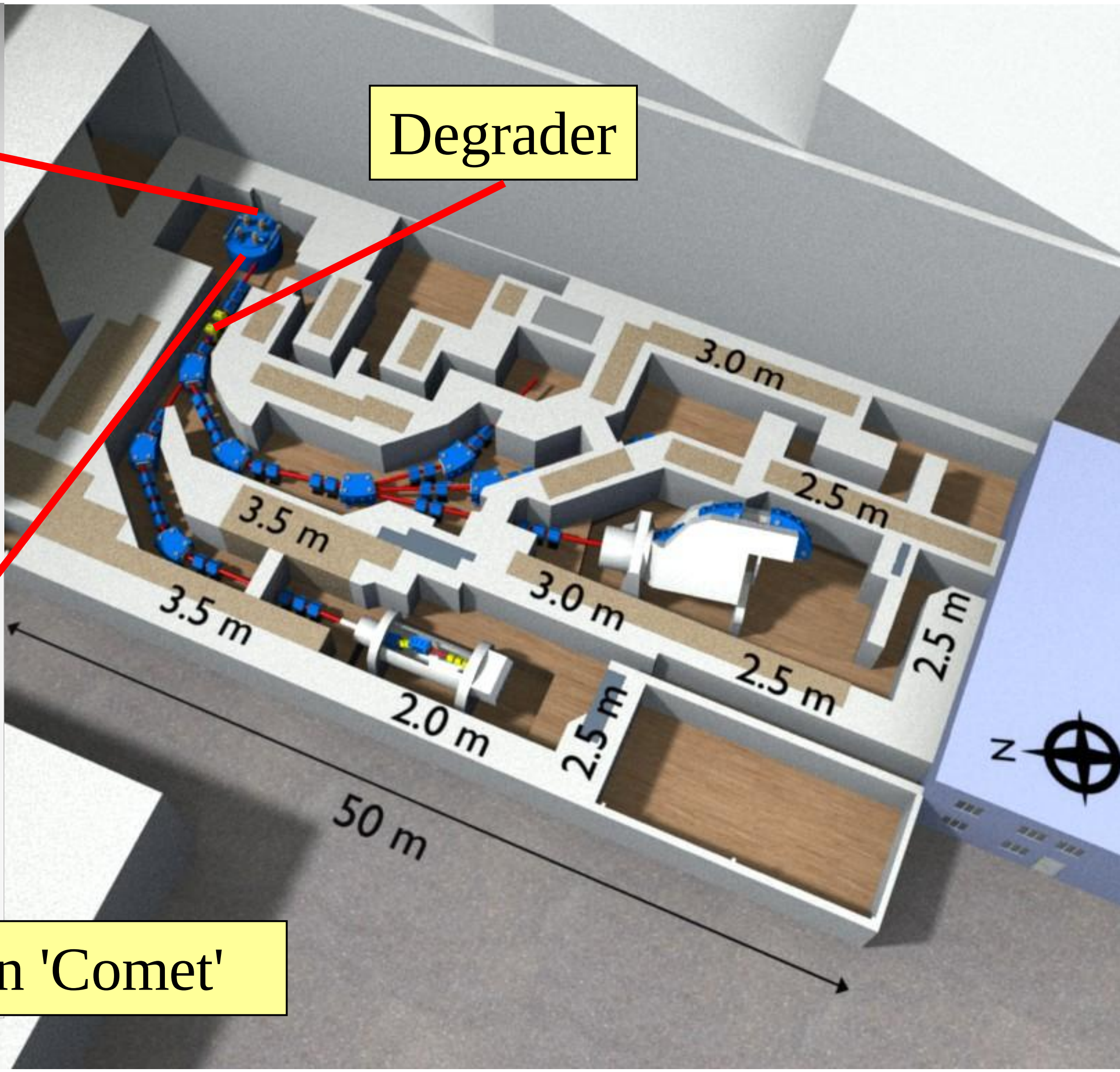
Proton and Carbon Ion Beams@HIT: Spatial Neutron Dose Distribution



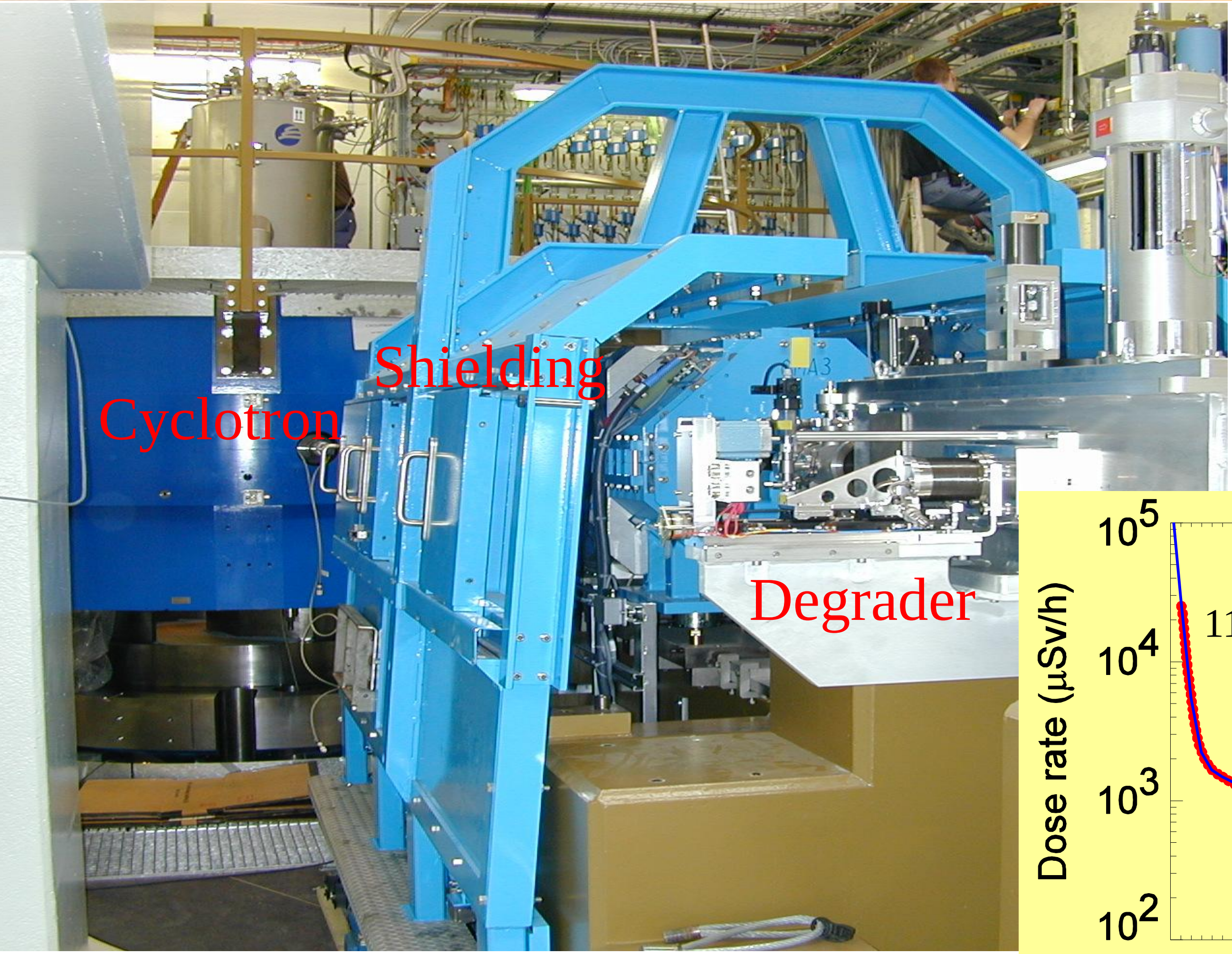

S
N
70 m

Activation of an Energy Degrader, PSI (1/2)

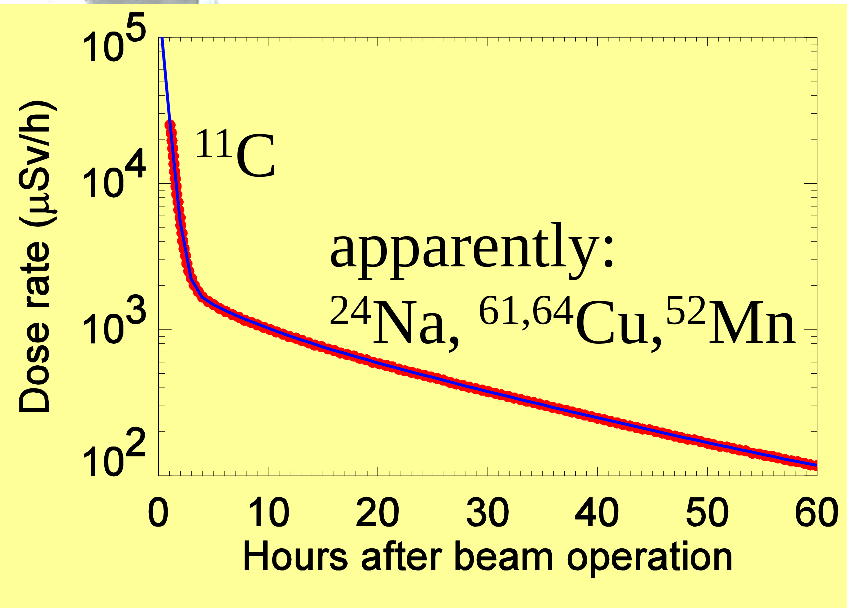




Activation of an Energy Degrader, PSI (2/2)



Data from Roser, 2006



Summary

- Increasing number of proton and light ion therapy facilities are under construction or already in operation (according to PTCOG ~44 facilities)
- Particularly in Japan and Europe there are some combined proton/light ion (carbon) facilities (HIMAC, Hyogo, Gunma, HIT, CNAO, Marburg, Kiel)
- Neutron source data are sufficient for shielding calculations for the whole angular range; improvements are desireable particular for the lowest angles (0° - 15°)
- There are appropriate calculational tools for the development of the architectural shielding layout (MC, line-of-sight), need for more shielding data for light ion facilities; improvements desireable for low angle for the line-of-sight approaches
- Comparable shielding requirements for proton and carbon ion beams (demonstrated for HIT facility)
- Use of active scanning techniques instead of passive scattering techniques provides advantages with regard to RP for both the patient and the planner of the building
- Cyclotron systems using ESS and passive scattering techniques implicate higher activation and radiation exposure of personnel working at activated components in contrast to synchrotron based facilities

Acknowledgement

- Yoshitomo Uwamino, Riken
- Frank Baumann, Tim Knoll, Jan Götze, Torsten Radon, Dieter Schardt, GSI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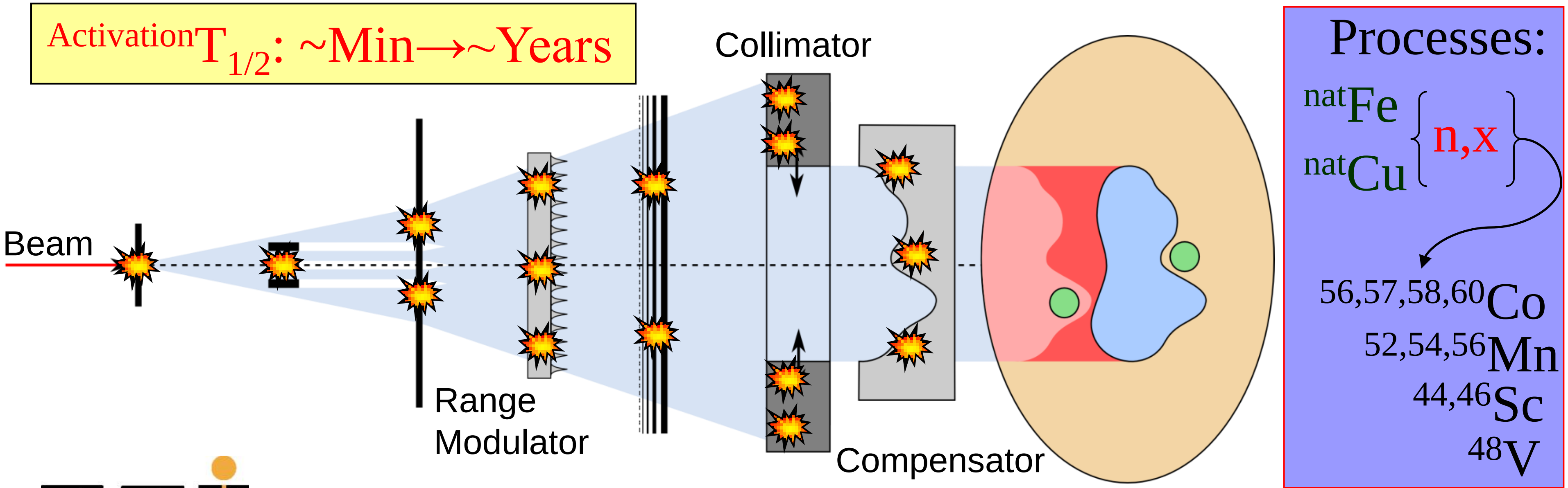
S

Activation and Exposure

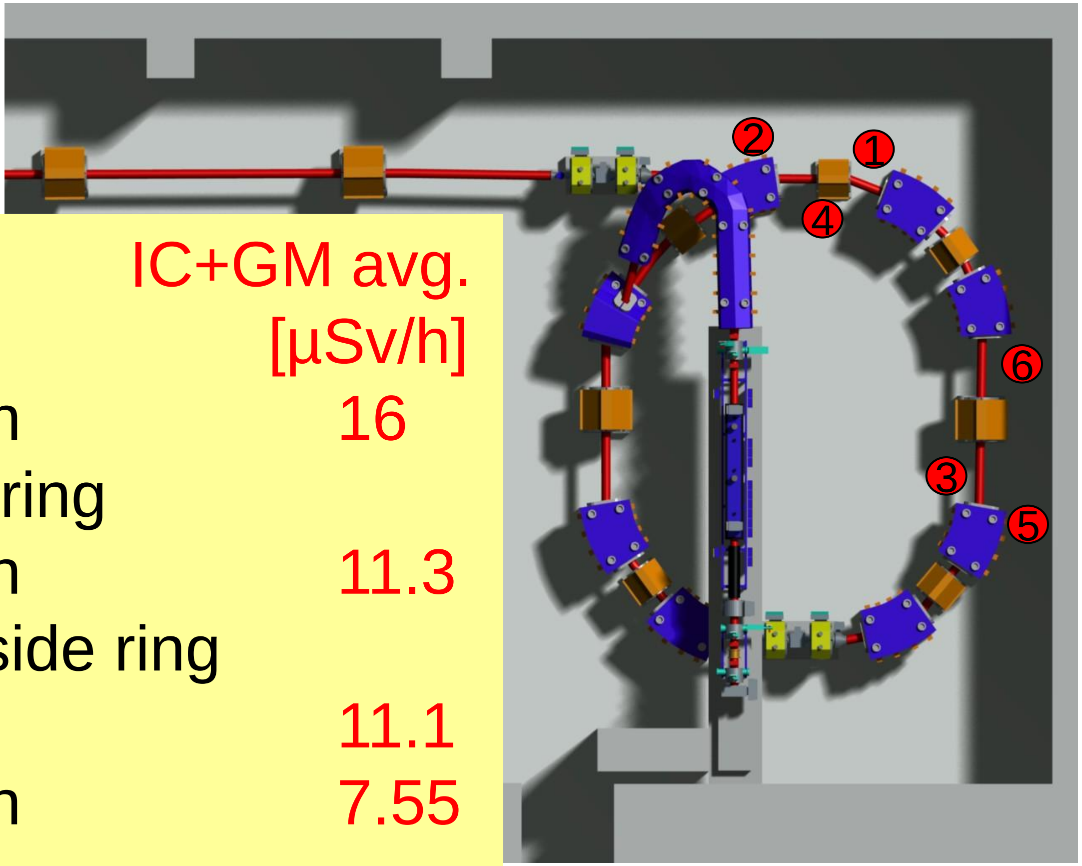
Tujii et al. Jpn. J. Med. Phys. Vol. 28 No. 4 (2009)

Beam Type (Facilities in Japan)	Effective Dose (mSv/a)			
	HIMAC	HIBMC	PMRC	SCC
Proton	-	3.04	2.28	5.53
Carbon Ion	0.67	0.53	-	-

$^{\text{Activation}}T_{1/2}$: ~Min→~Years

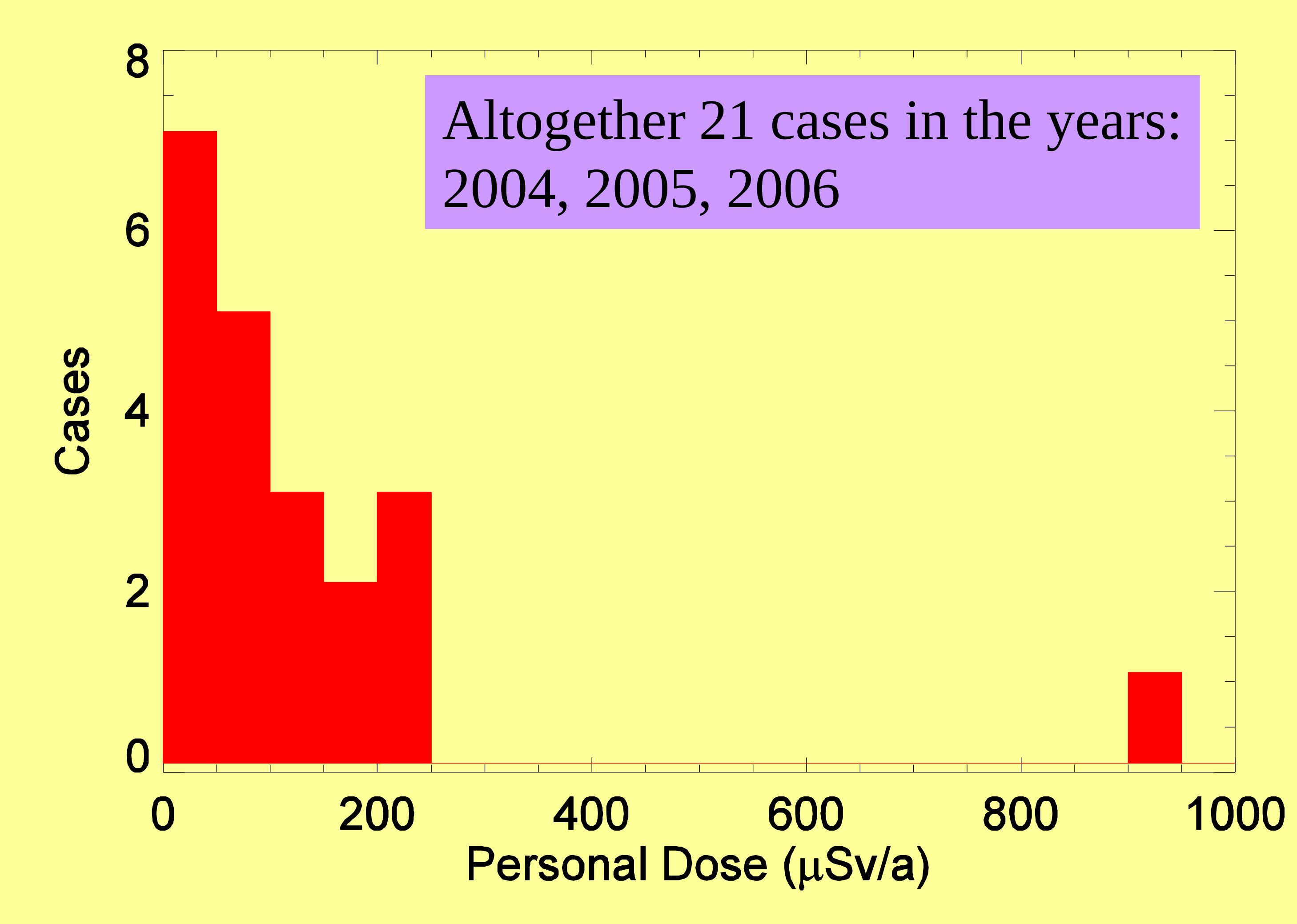


Example Activation of a Therapy Synchrotron: LLUMC Synchrotron, Moyers et al. – Rad.Meas. 2009



#	Location	IC+GM avg. [µSv/h]
1	Lambertson split extraction magnet - upstram outside ring	16
2	Lambertson split extraction magnet – downstream ouside ring	11.3
3	Extraction wire septum	11.1
4	Lambertson split extraction magnet – center inside ring	7.55
5	Long straight #2 – octopole	6.05
6	Sextapole in long straight #3	4.9

Personal Doses at LLUMC Synchrotron 2004-2006, Moyers et al. – Rad.Meas. 2009



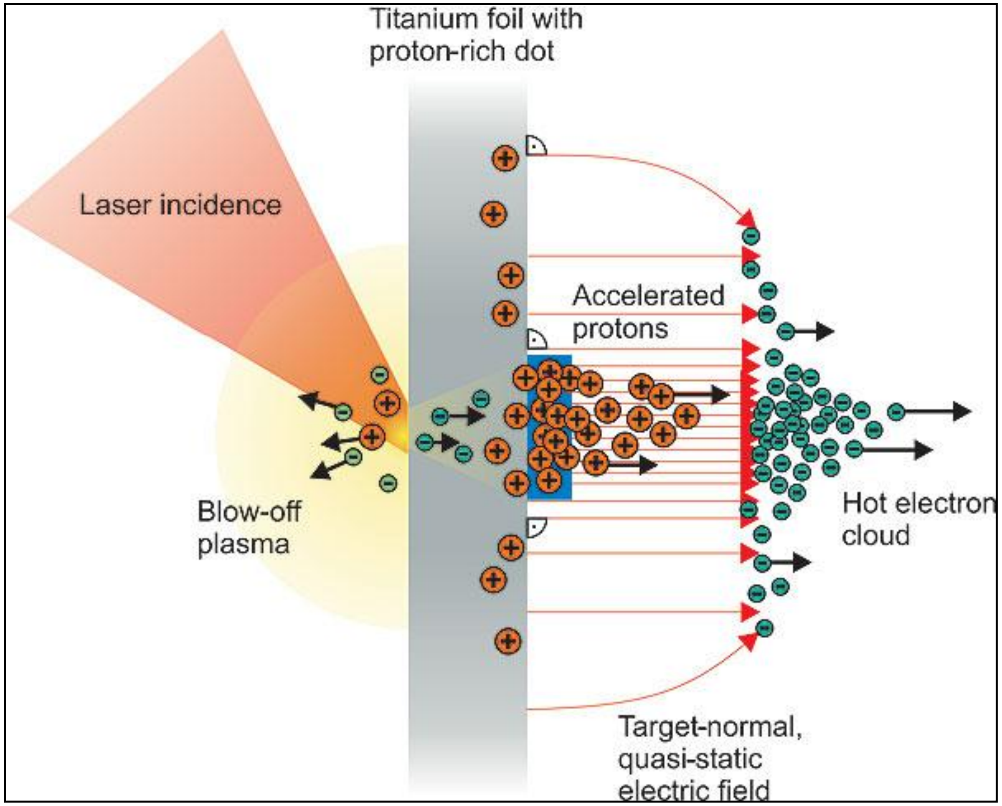
Further Developements of Particle Therapy Accelerators (Selection)

- Cyclotron for Carbon Ion Acceleration
- FFAG – Fixed Field Alternating Gradient Accelerator
- Dielectric Wall Accelerator
- High Frequency Linac (Booster) coupled with a cyclotron = CycLINAC
- Laser Particle Acceleration
- Proton therapy gantry with a synchrocyclotron

Laser produced Quasi-Monoenergetic Proton Beams

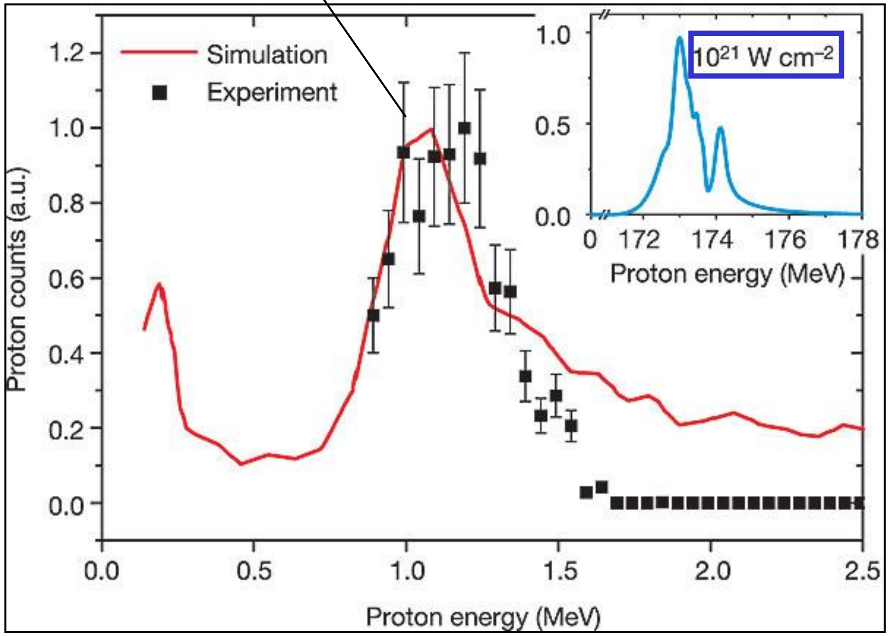
Schwoerer et al., Nature 2006

Principle



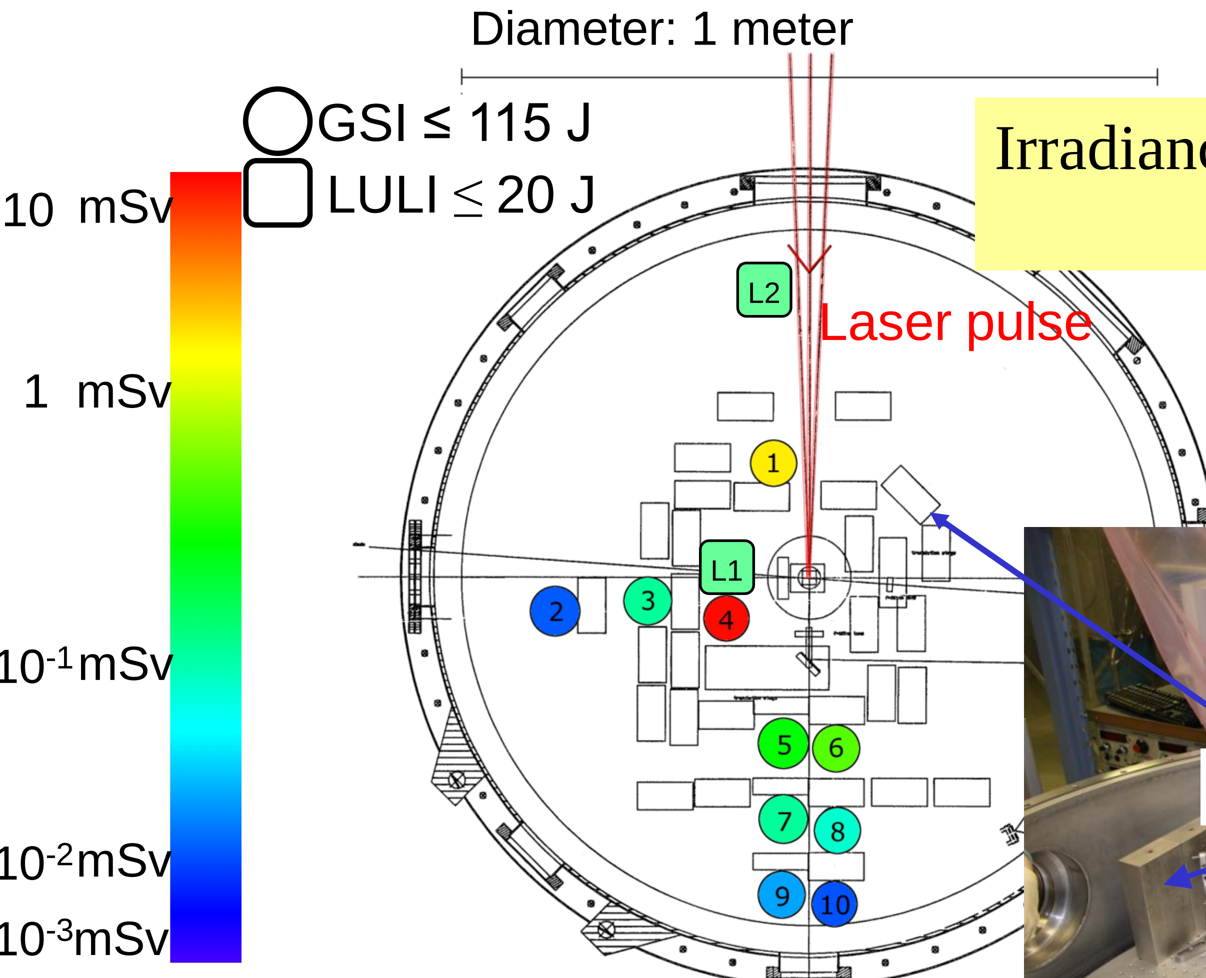
First Results

$3 \cdot 10^{19}$ W/cm^2

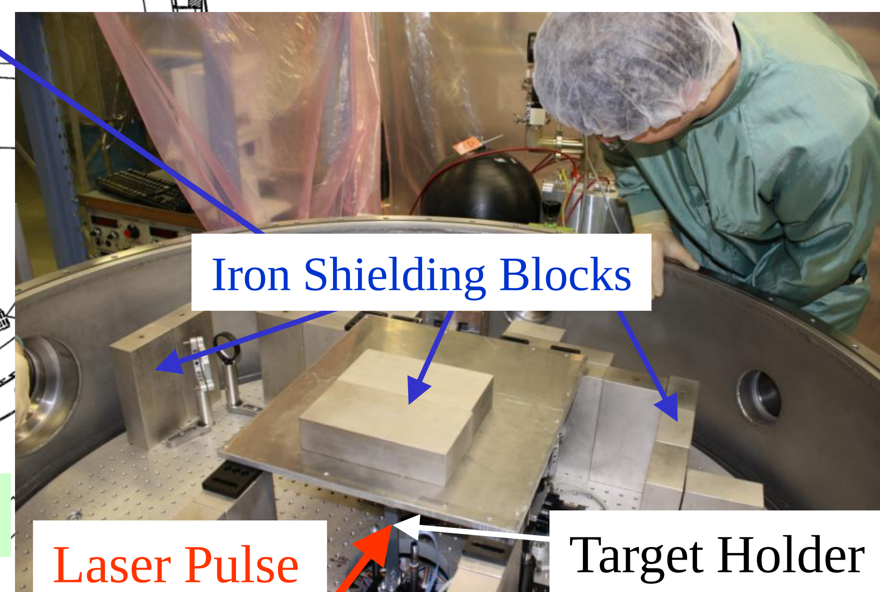


Laser produced Proton Beams: Dose Measurements at LULI/GSI-Phelix

Irradiance GSI: $1.6 \cdot 10^{19}$ W/cm^2
LULI: $\leq 2 \cdot 10^{19}$ W/cm^2



Gamma / Electron Dose



LULI Measurements:Borne et al., RPD, 2002

GSI