# Monte Carlo simulation of electron-photon transport: from particle physics to cancer radiotherapy


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# Disclosure statement

I worked for, and receive royalty payments from, the National Research Council regarding licensing agreements for Monte Carlo software with:

Elekta  Philips/ADAC  NOMOS
Nucletron  Varian

The following companies are supporting the Monte Carlo lab I am setting up at Carleton University:

Nucletron Canada  TomoTherapy Inc
Philips/ADAC  MDS Nordion  Varian

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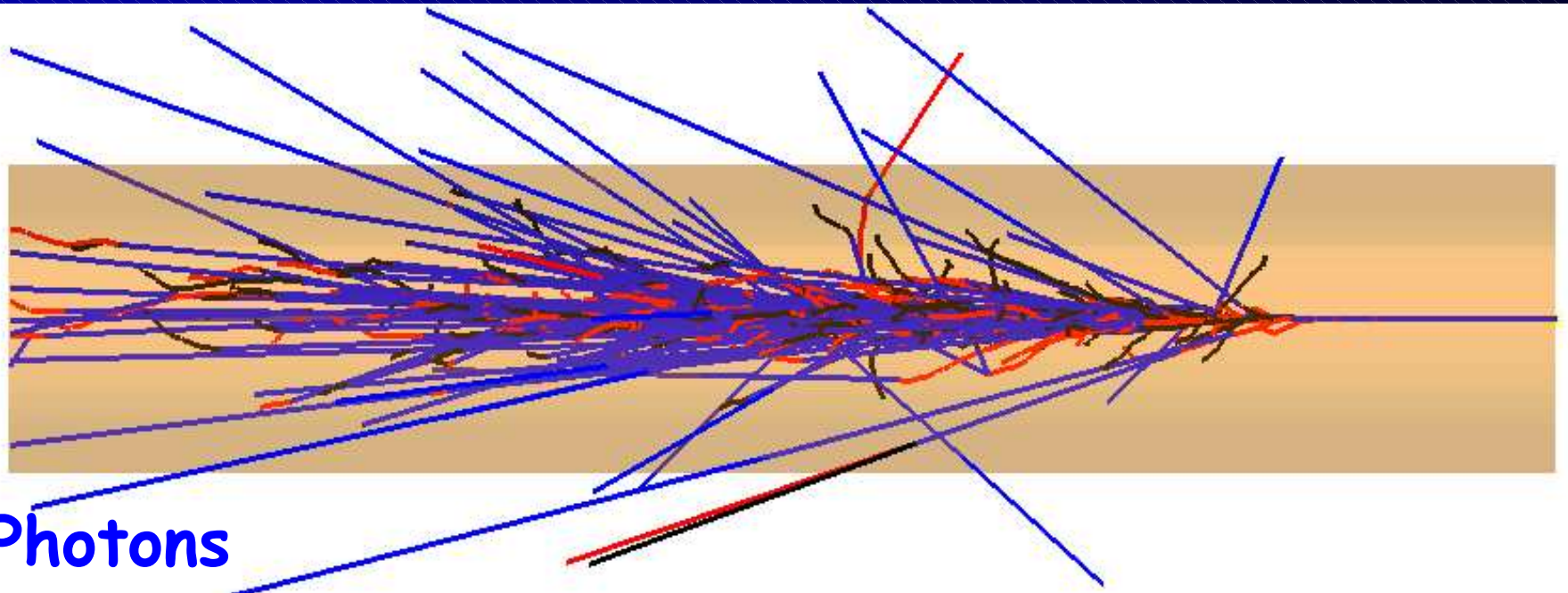
# Why Monte Carlo?

- electrons create
  - photons and $\delta$-rays (knock-on e-)
- photons create
  - electrons and positrons
- photons and e- scatter a lot
- know physics of all processes
- no analytic solution possible

# EGS: Electron Gamma Shower



**Photons**

**Electrons**

**positrons**

**10 GeV photon from right on 10 cm lead cylinder**

EGS3 Ford and Nelson, SLAC 1985

EGS4 Nelson et al, SLAC, NRC 1985

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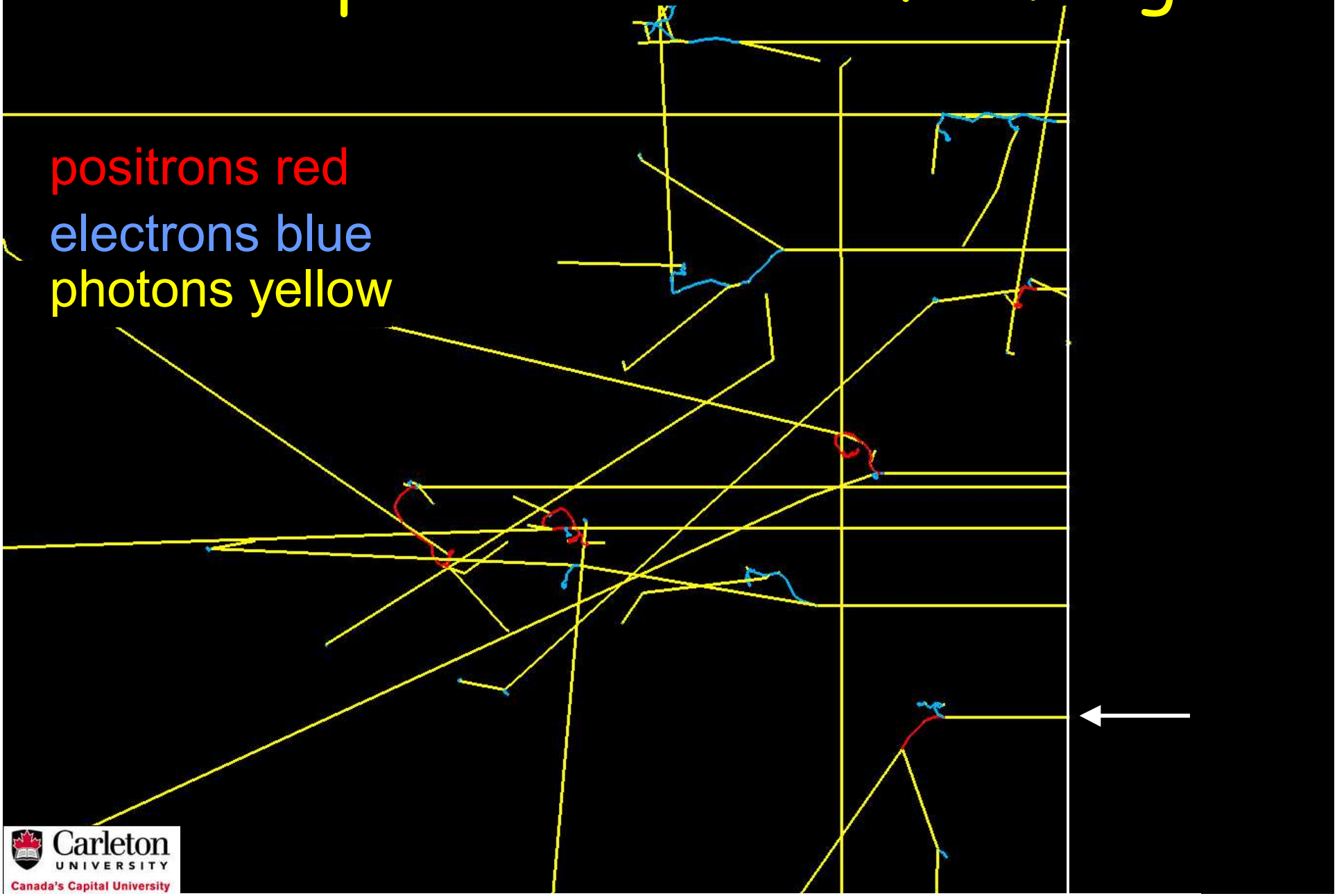
# 10 MeV photons on lead from right

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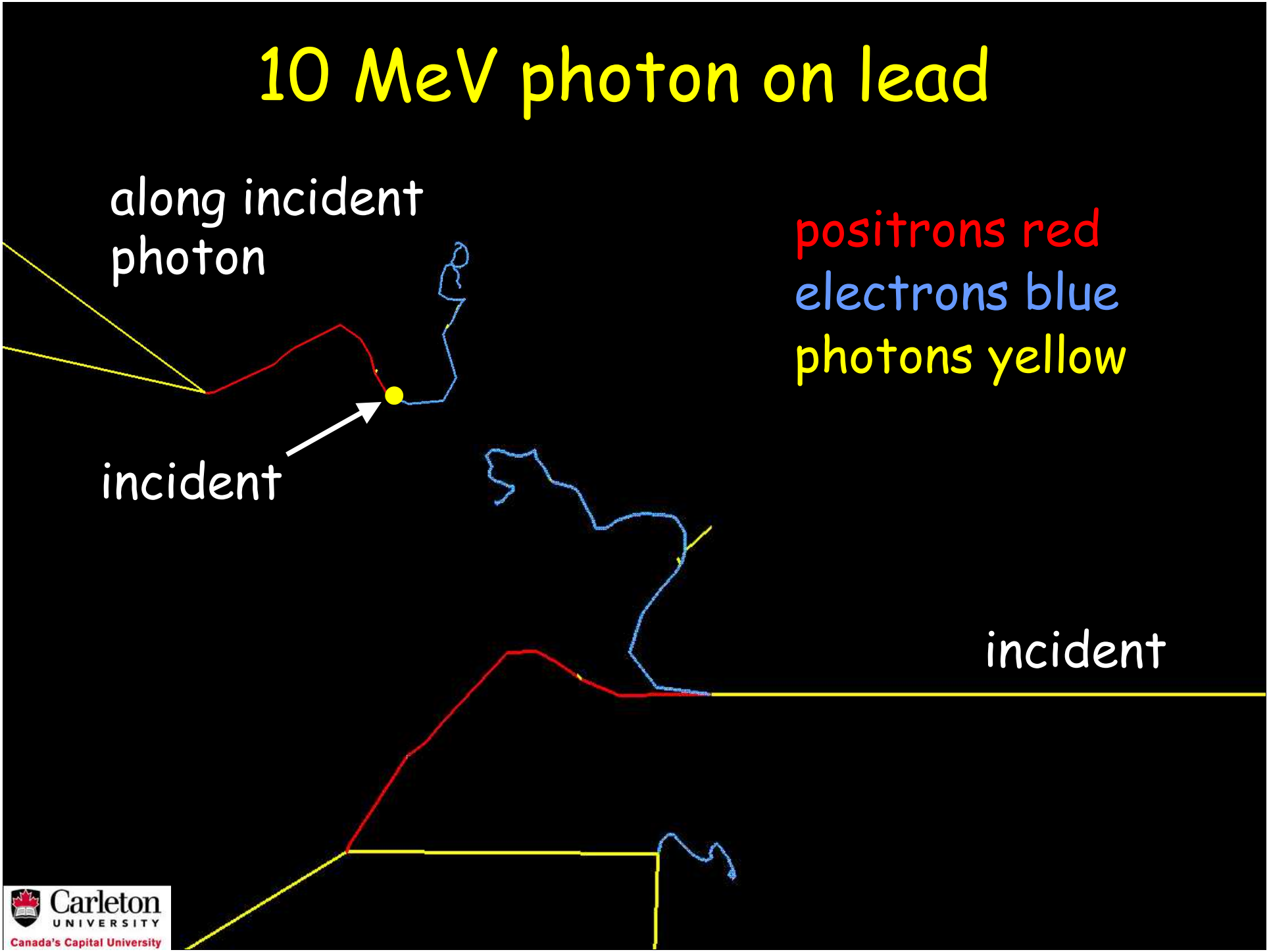
# 10 MeV photon on lead

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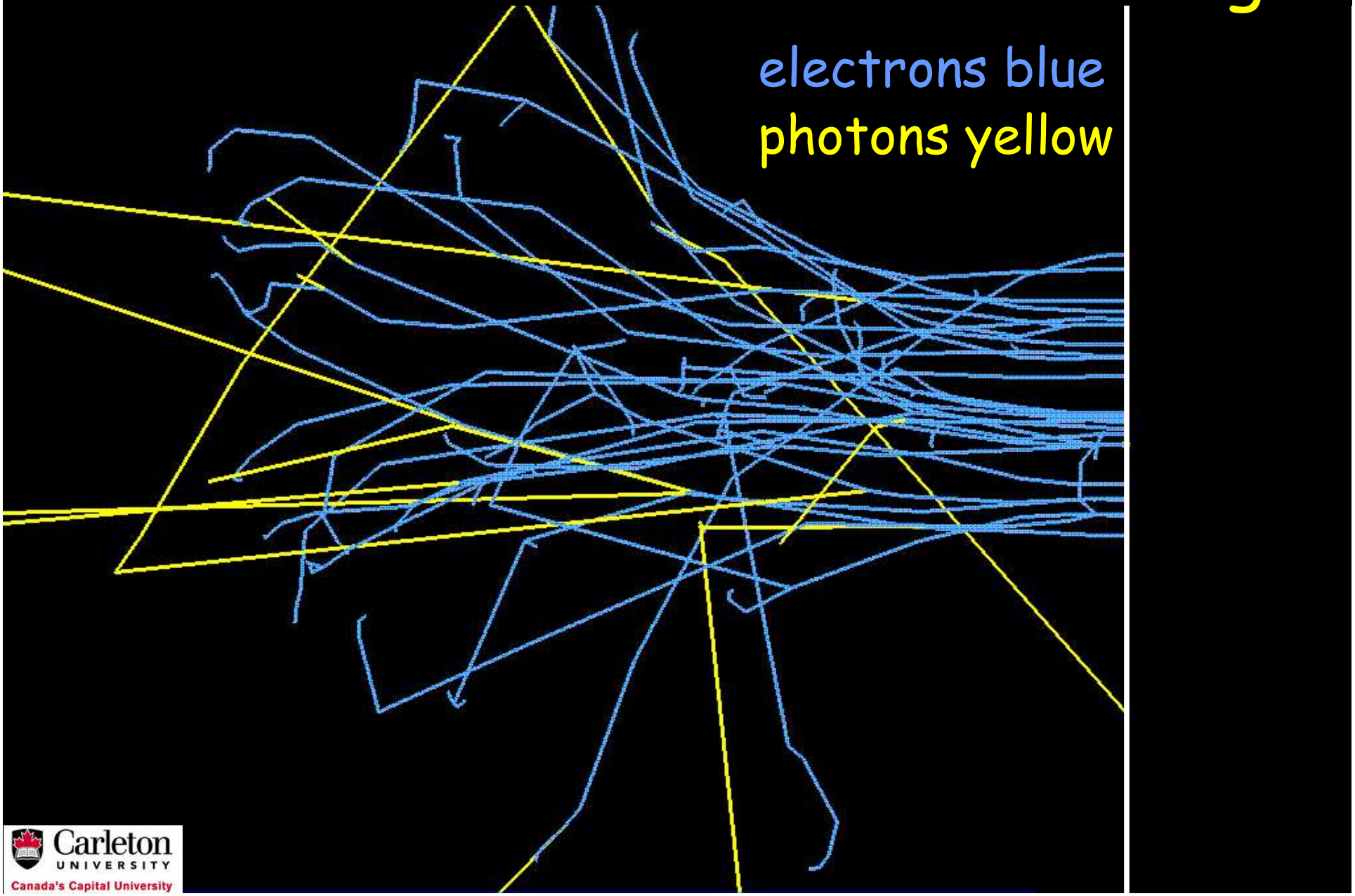
# 10 MeV electrons on water from right

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# Monte Carlo transport

- simulate paths of many particles
  - use random numbers
  - known probability distributions
    - from physics of interactions
- keep track of physical quantities
  - learn average properties
  - stochastic distributions of events

# Simple photon simulation

- say: $\Sigma_{total} = \Sigma_{compton} + \Sigma_{pair}$ $cm^{-1}$
- select 2 random numbers R1, R2
  - uniform between 0 and 1
  - whole careers devoted to doing this
  - cycle length now $10^{>40}$

# Photon transport (cont)

How far does photon go before interacting?

$$x = -\ln(R1) / \Sigma_{total} \quad cm$$

is exponentially distributed $[0,\infty)$

with a mean of $1/\Sigma_{total}$

# Photon transport (cont)

After going x, what interaction occurs?

$$\text{if } R2 < \frac{\Sigma_{compton}}{\Sigma_{total}}$$

then a compton scatter occurs
otherwise
a pair production event occurs

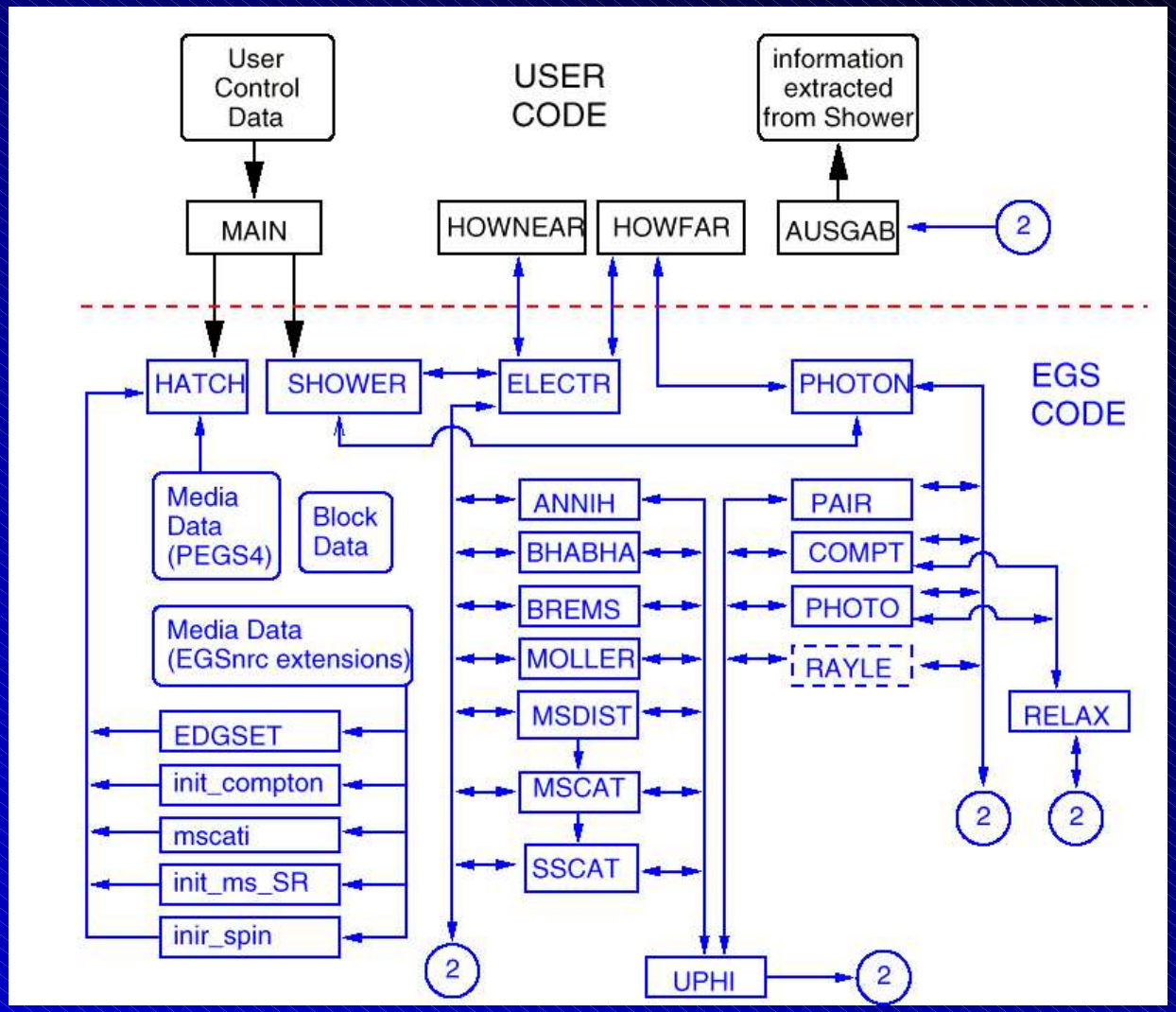
# How is simulation used?

- score whatever data wanted
  - average distance to interaction
  - how many of each type
  - energy deposited by each type
  - etc
- more useful in complex cases

# EGSnrc structure (2000)

Kawrakow added new physics

Code accurate to 0.1% relative to its cross-sections & geometry

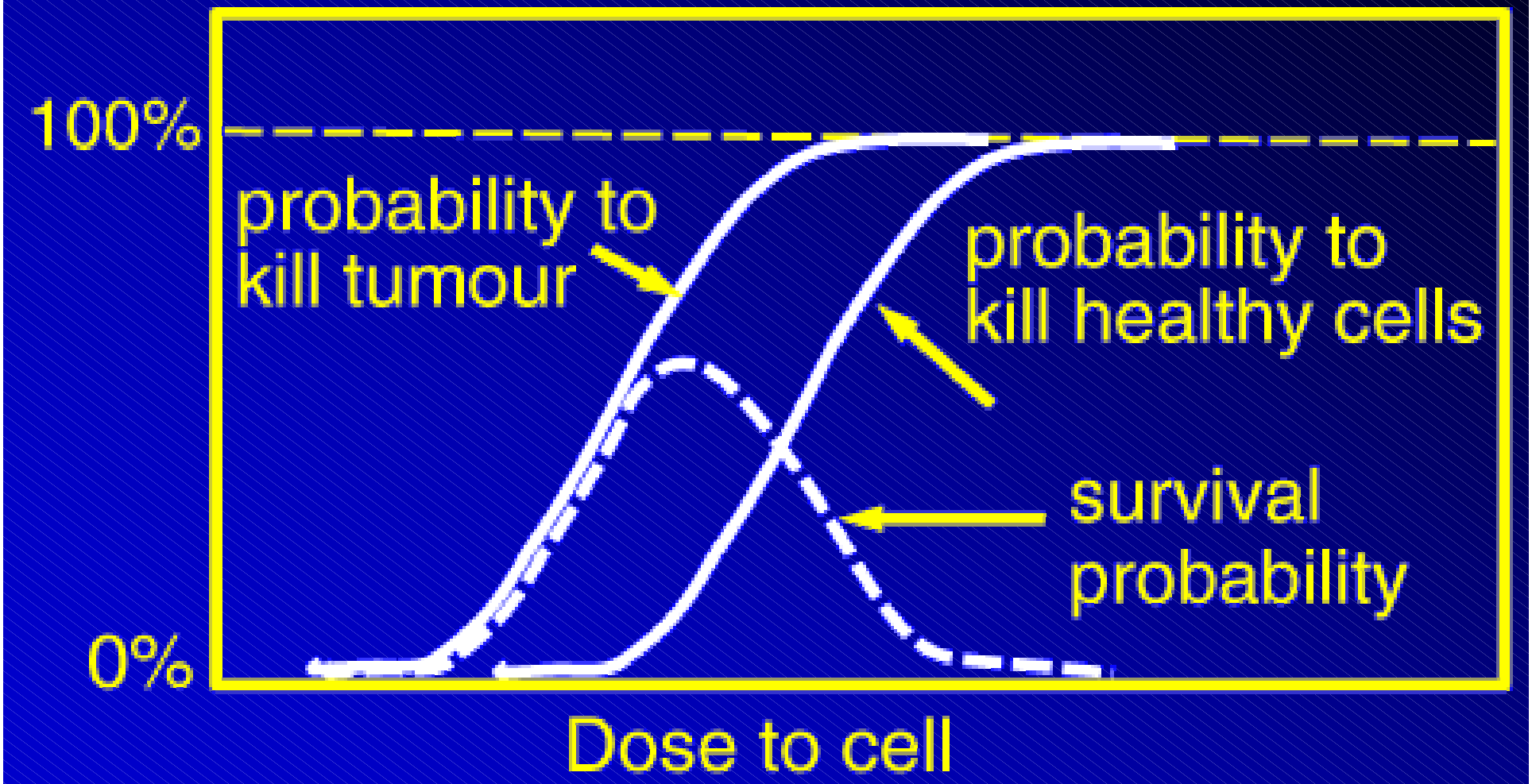



Kawrakow and Rogers, NRC Report PIRS-701,2000,

# What is medical physics?

- Application of principles of physics to practice of medicine
- Cancer radiotherapy
  - 70,000 people treated / year
  - cure rate 50% for curative Rx
- diagnostic radiology
  - x-rays, CT scans, MRI, ultrasound
- nuclear medicine
  - inject radioactivity and observe

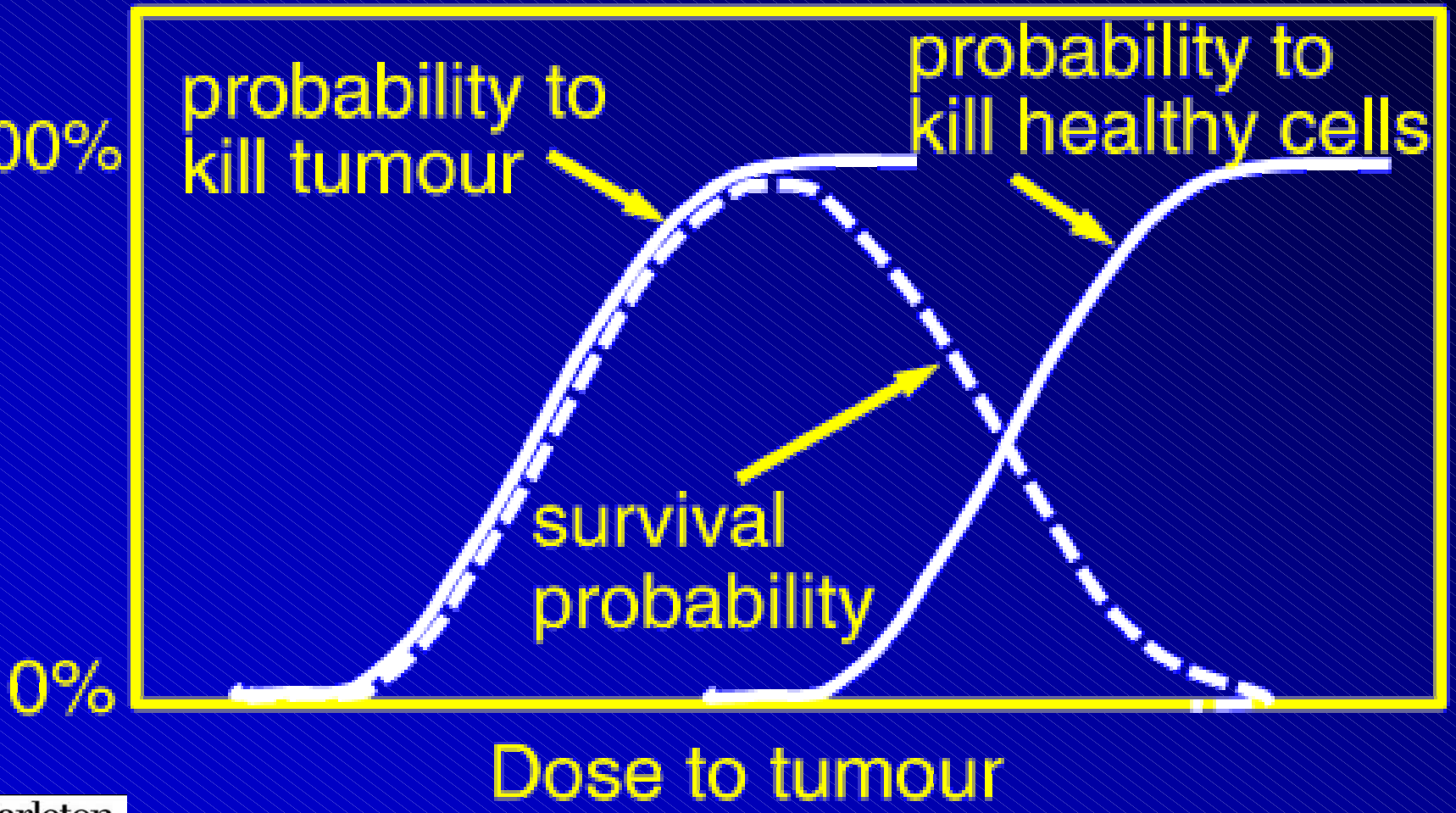
# Basis of radiation therapy



# Treatment planning

- process to plan treatment
  - maximize dose to tumour
  - minimize dose to healthy tissue
- need accurate measure of dose
- need calculated dose in patient

# Treatment planning

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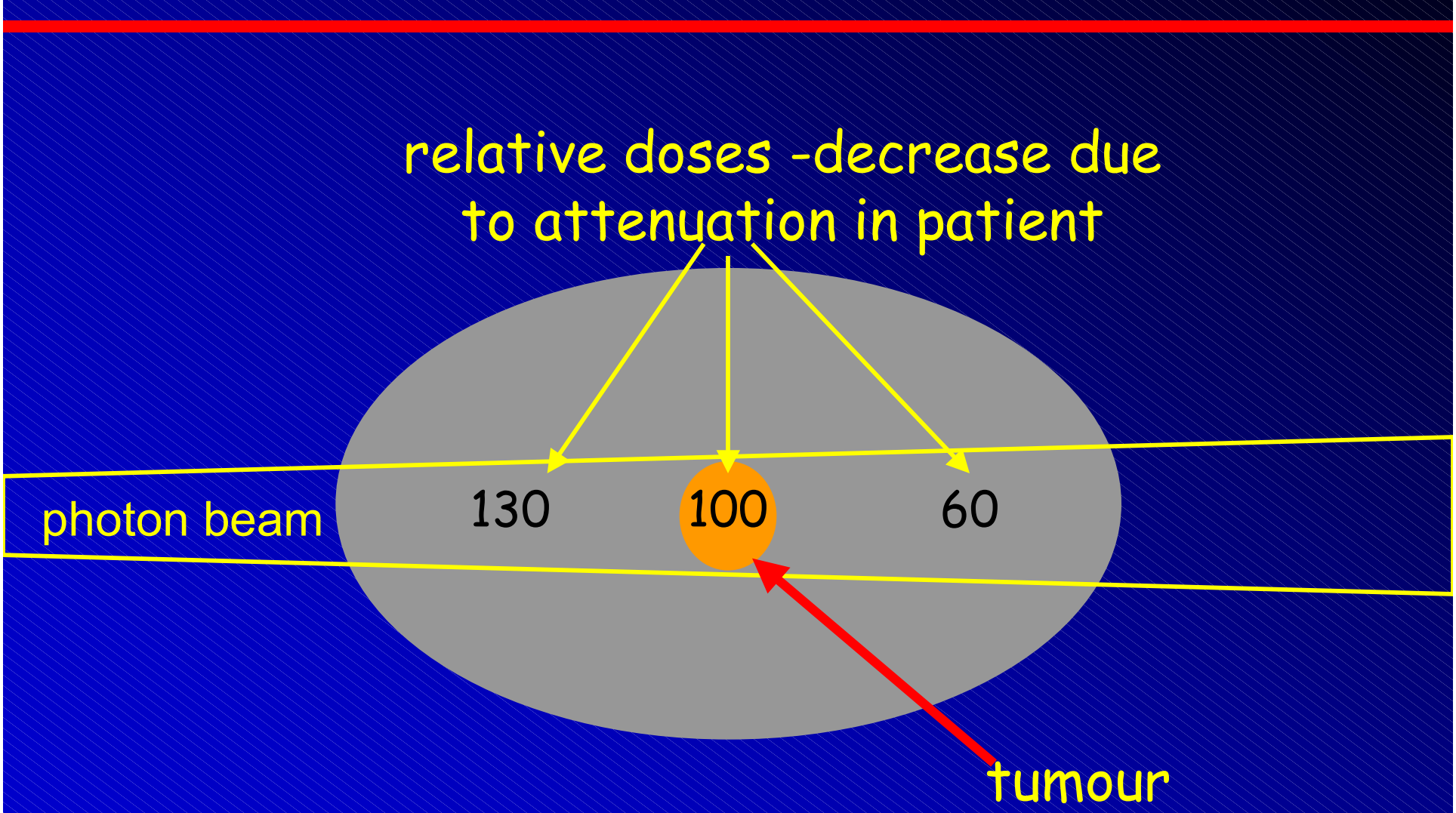
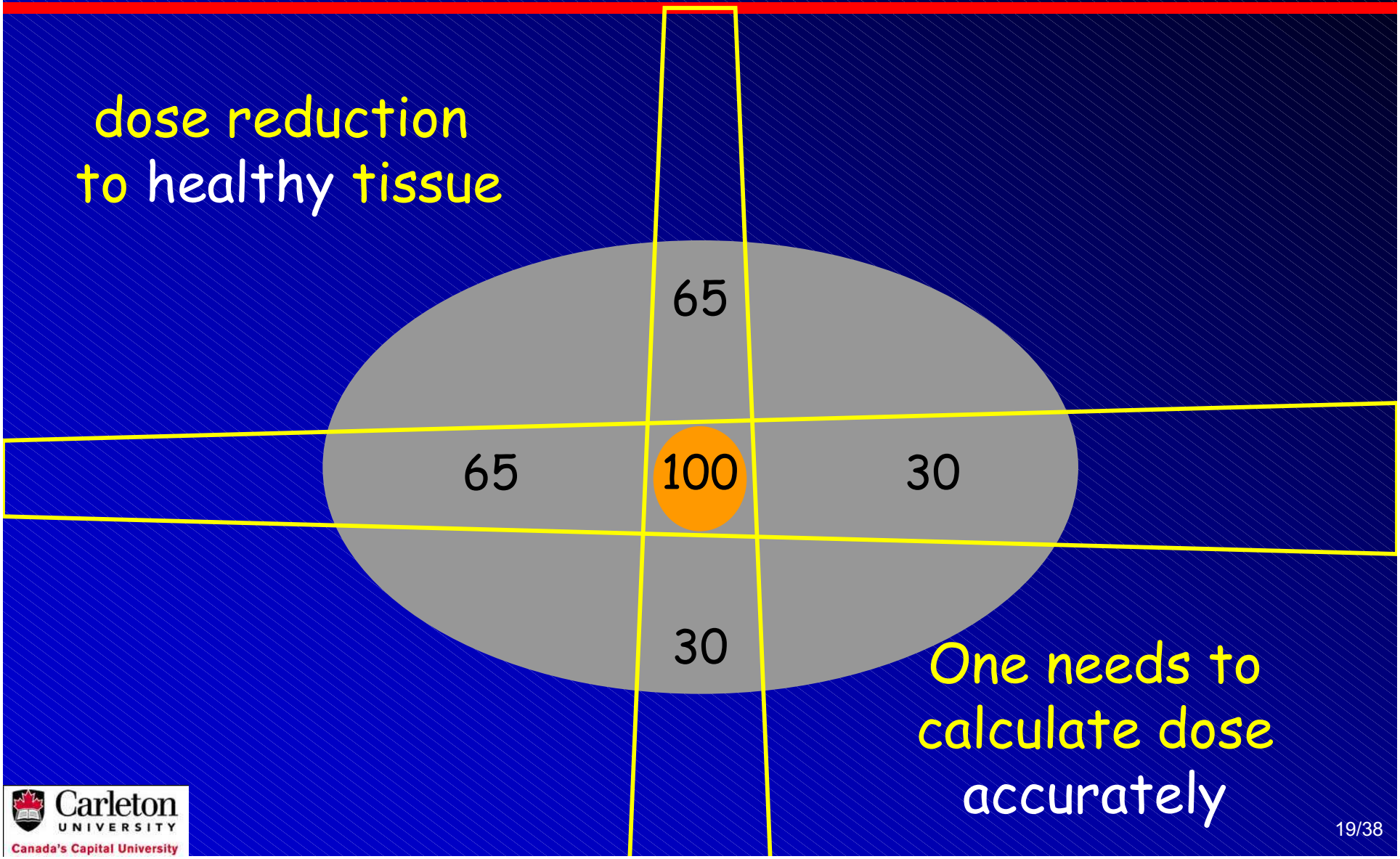
# Basis of treatment planning



# Basis of treatment planning

dose reduction
to healthy tissue




One needs to
calculate dose
accurately

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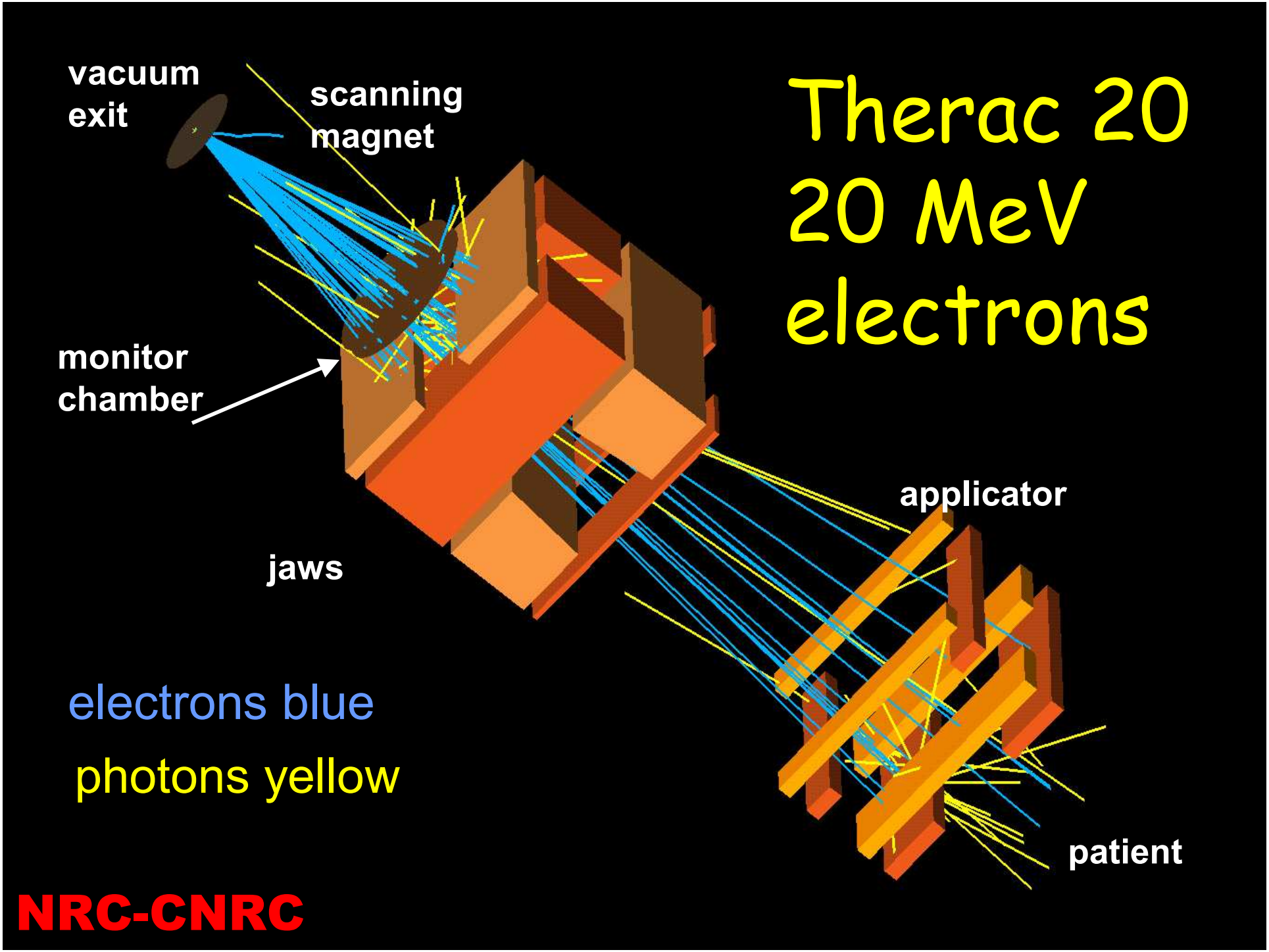
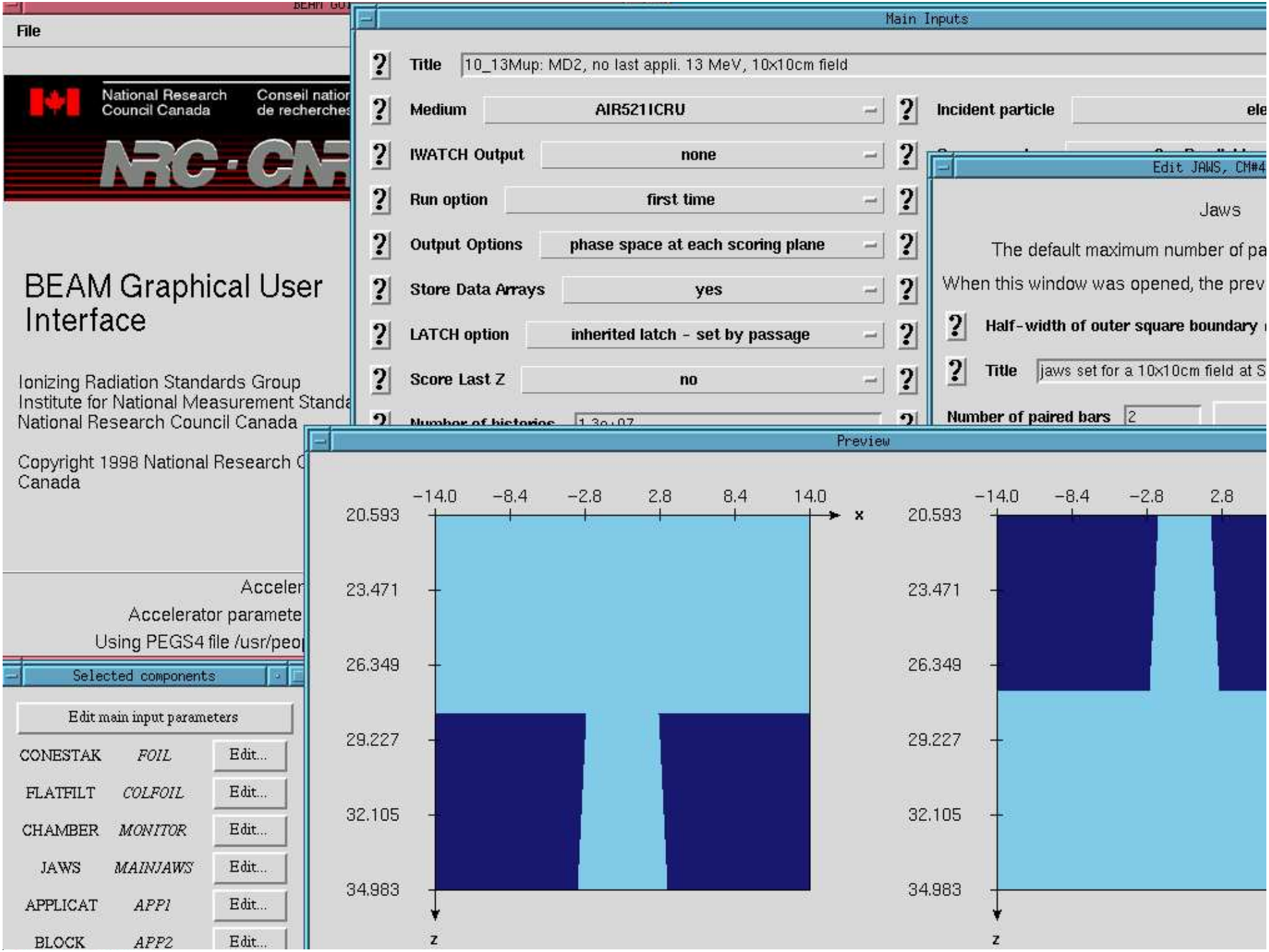
# BEAM code

- general purpose code to simulate radiotherapy beams
  - accelerators -electrons & photons
  - $^{60}$Co units
  - x-ray units

- Part of the OMEGA project with Rock Mackie's group in Madison
  - many grad students, RAs and TOs involved


vacuum exit
scanning magnet
monitor chamber
jaws
applicator
patient
Therac 20
20 MeV
electrons
electrons blue
photons yellow
NRC-CNRC


File
National Research Council Canada
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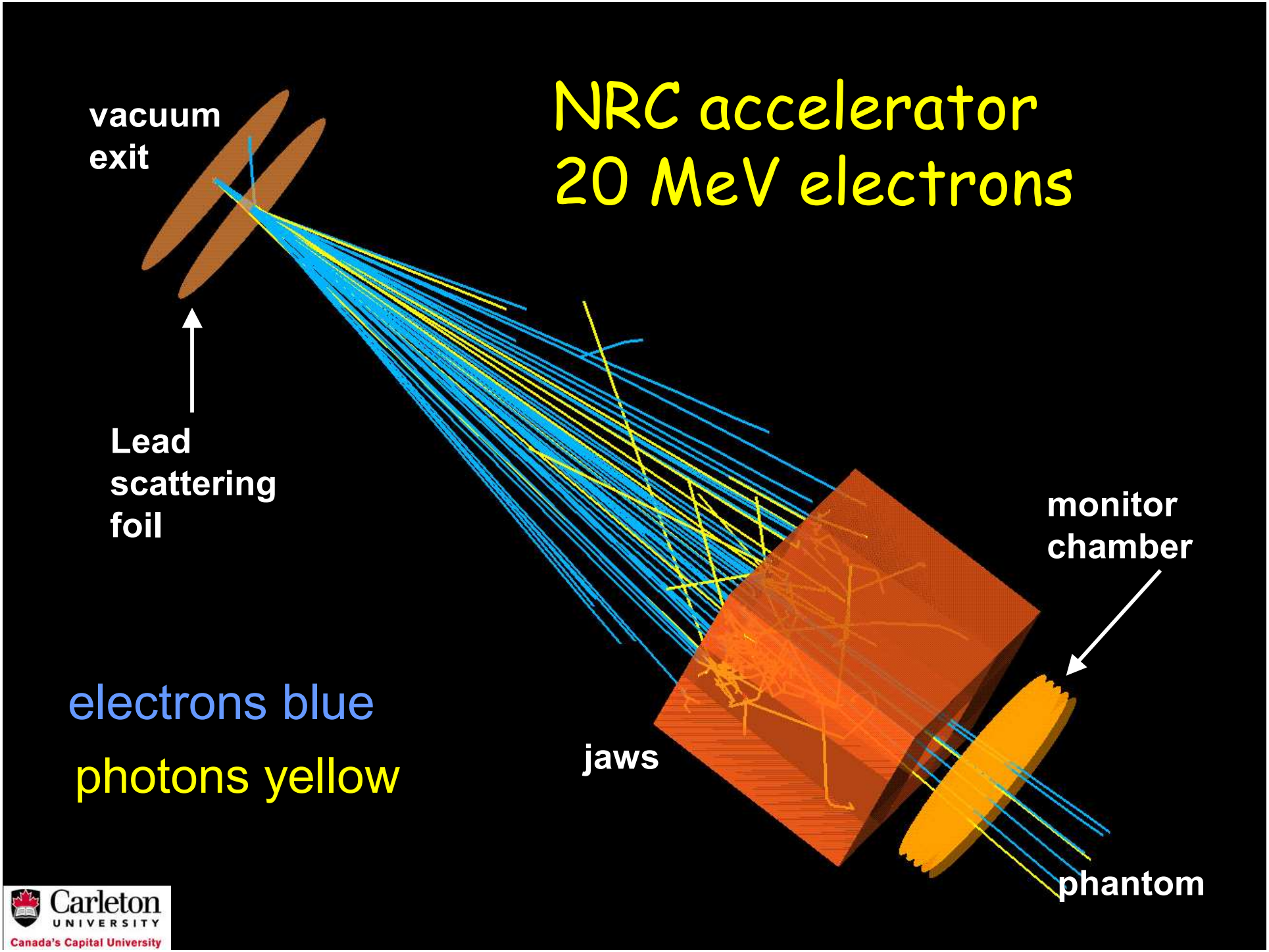
NRC-CN
BEAM Graphical User Interface
Ionizing Radiation Standards Group
Institute for National Measurement Standa
National Research Council Canada
Copyright 1998 National Research C
Canada
Acceler
Accelerator paramete
Using PEGS4 file /usr/peo
Main Inputs
Title
10_13Mup: MD2, no last appli. 13 MeV, 10x10cm field
Medium
AIR521ICRU
Incident particle
ele
IWATCH Output
none
Run option
first time
Output Options
phase space at each scoring plane
Store Data Arrays
yes
LATCH option
inherited latch - set by passage
Score Last Z
no
Edit JAWS, CM#4
Jaws
The default maximum number of pa
When this window was opened, the prev
Half-width of outer square boundary
Title
jaws set for a 10x10cm field at S
Number of paired bars
2
Preview
−14.0
−8.4
−2.8
2.8
8.4
14.0
x
20.593
23.471
26.349
29.227
32.105
34.983
z
Selected components
Edit main input parameters
CONESTAK FOIL Edit...
FLATFILT COLFOIL Edit...
CHAMBER MONITOR Edit...
JAWS MAINJAWS Edit...
APPLICAT APP1 Edit...
BLOCK APP2 Edit...


NRC accelerator
20 MeV electrons
vacuum exit
Lead scattering foil
monitor chamber
jaws
phantom
electrons blue
photons yellow
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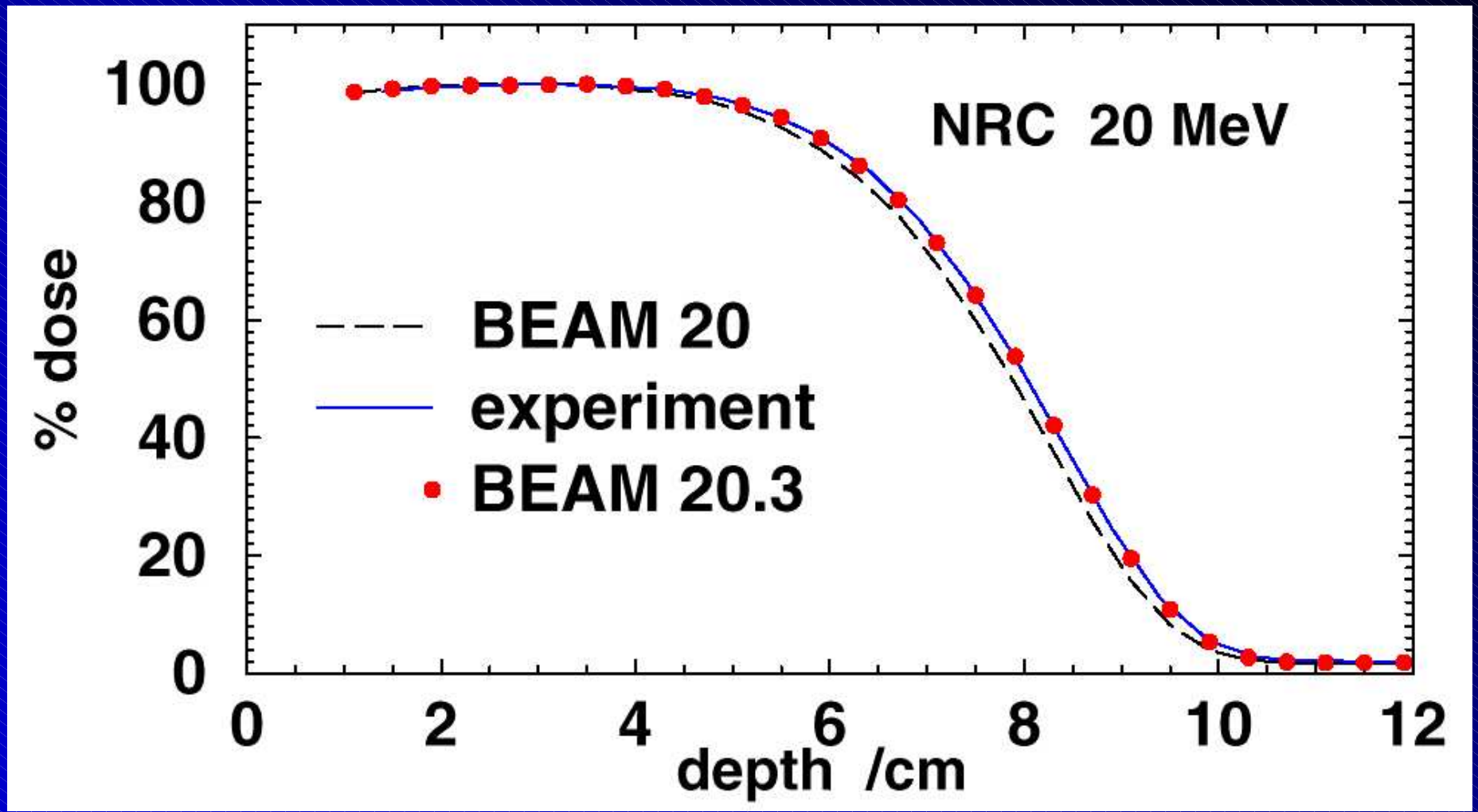
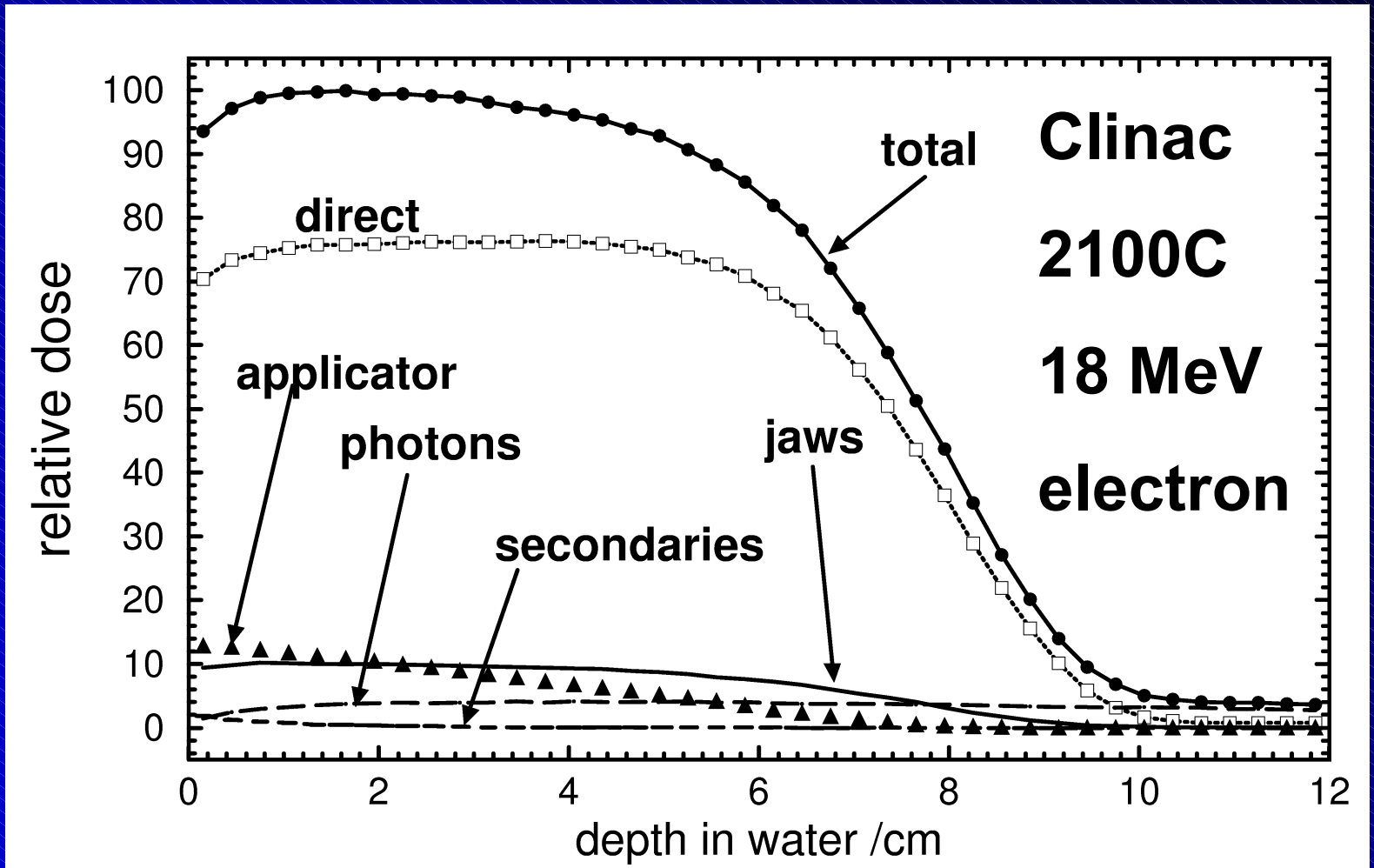
# 20 MeV NRC depth-dose

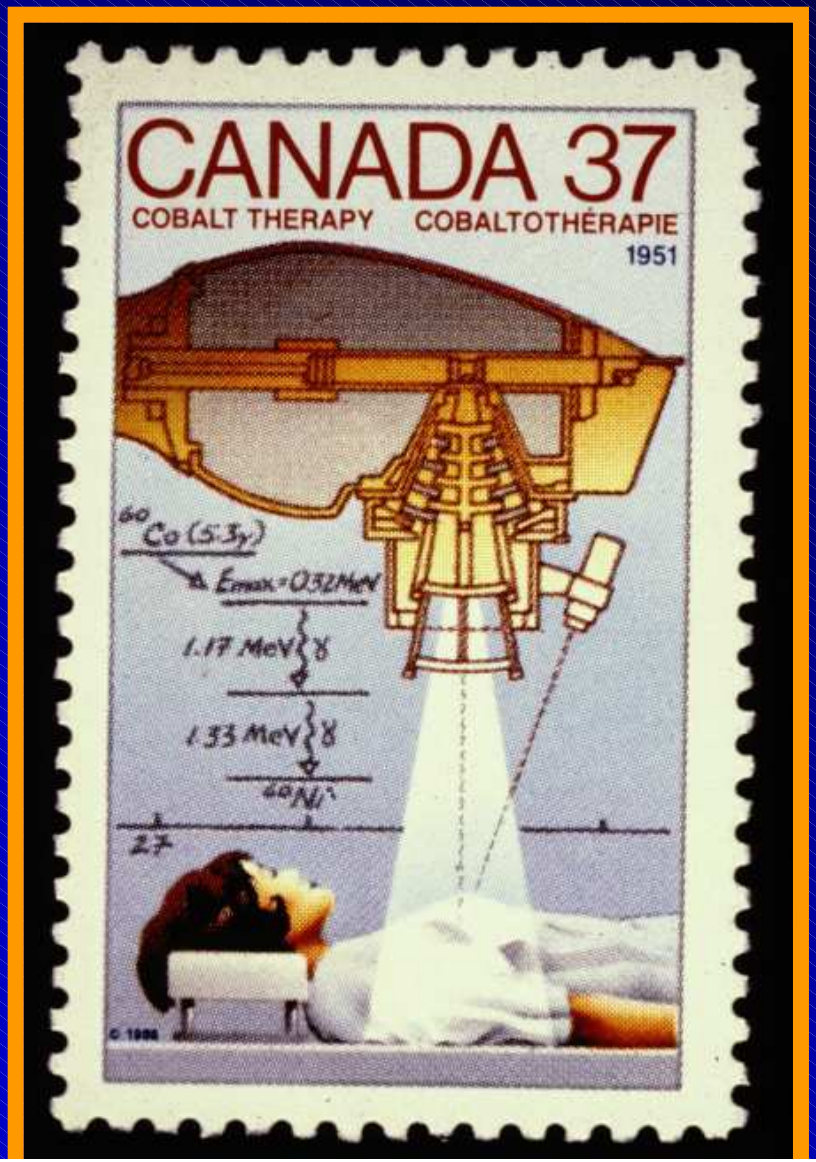



+similar studies for photon beams

# Dose Components



# $^{60}$Co therapy unit




Issued
June 17,
1988

Thanks to
Jerry Battista

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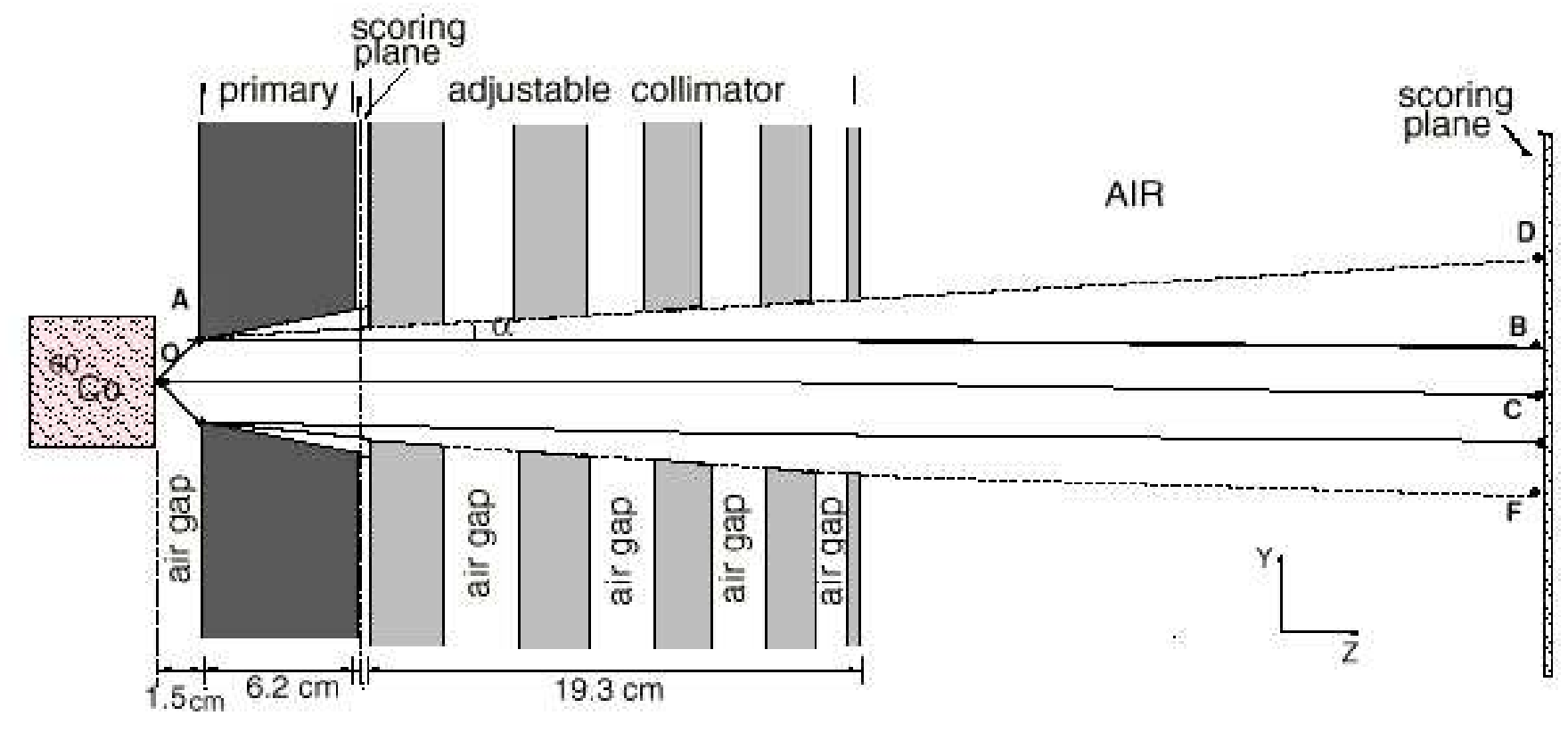
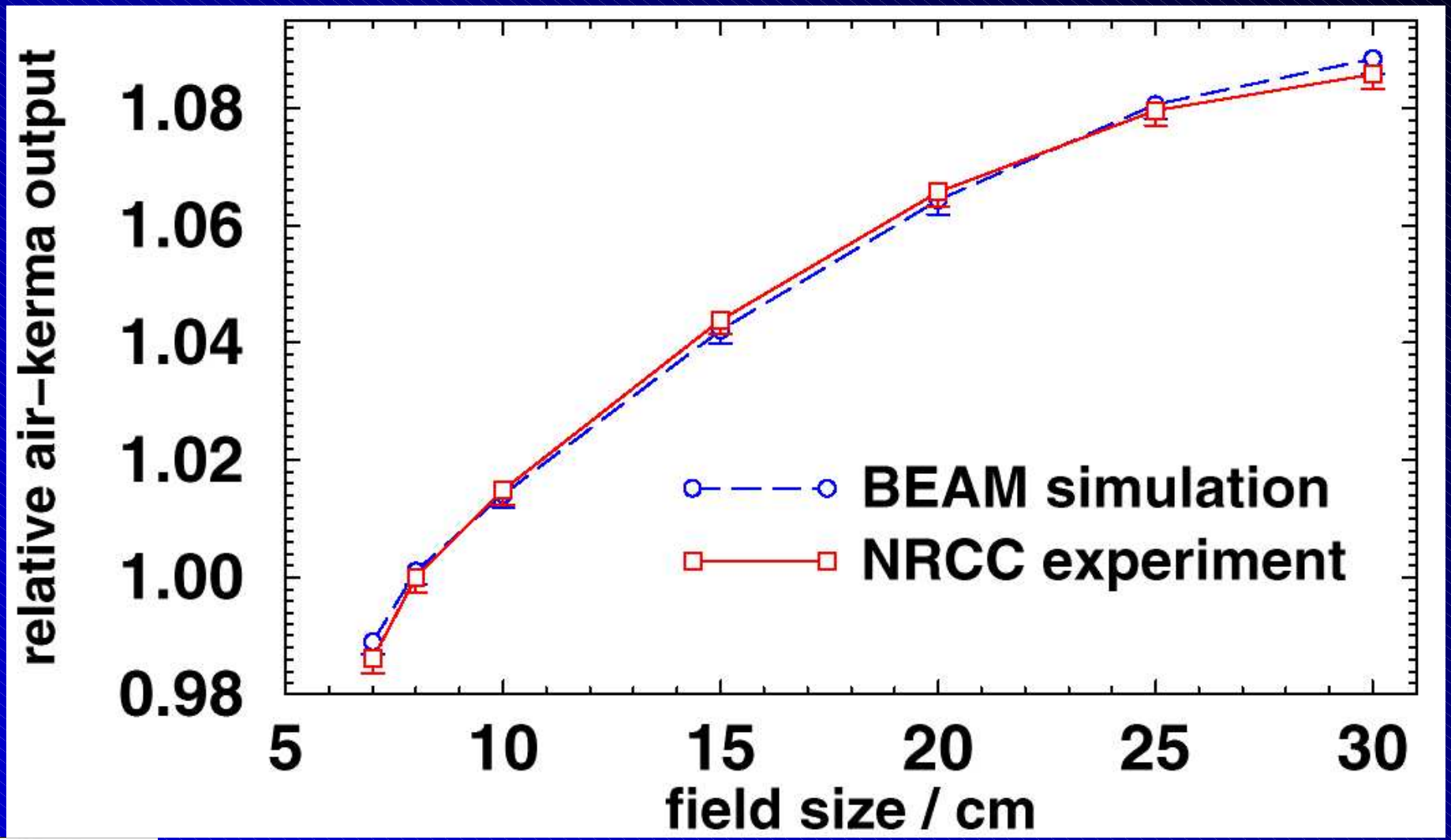
# Simulating an Eldorado6



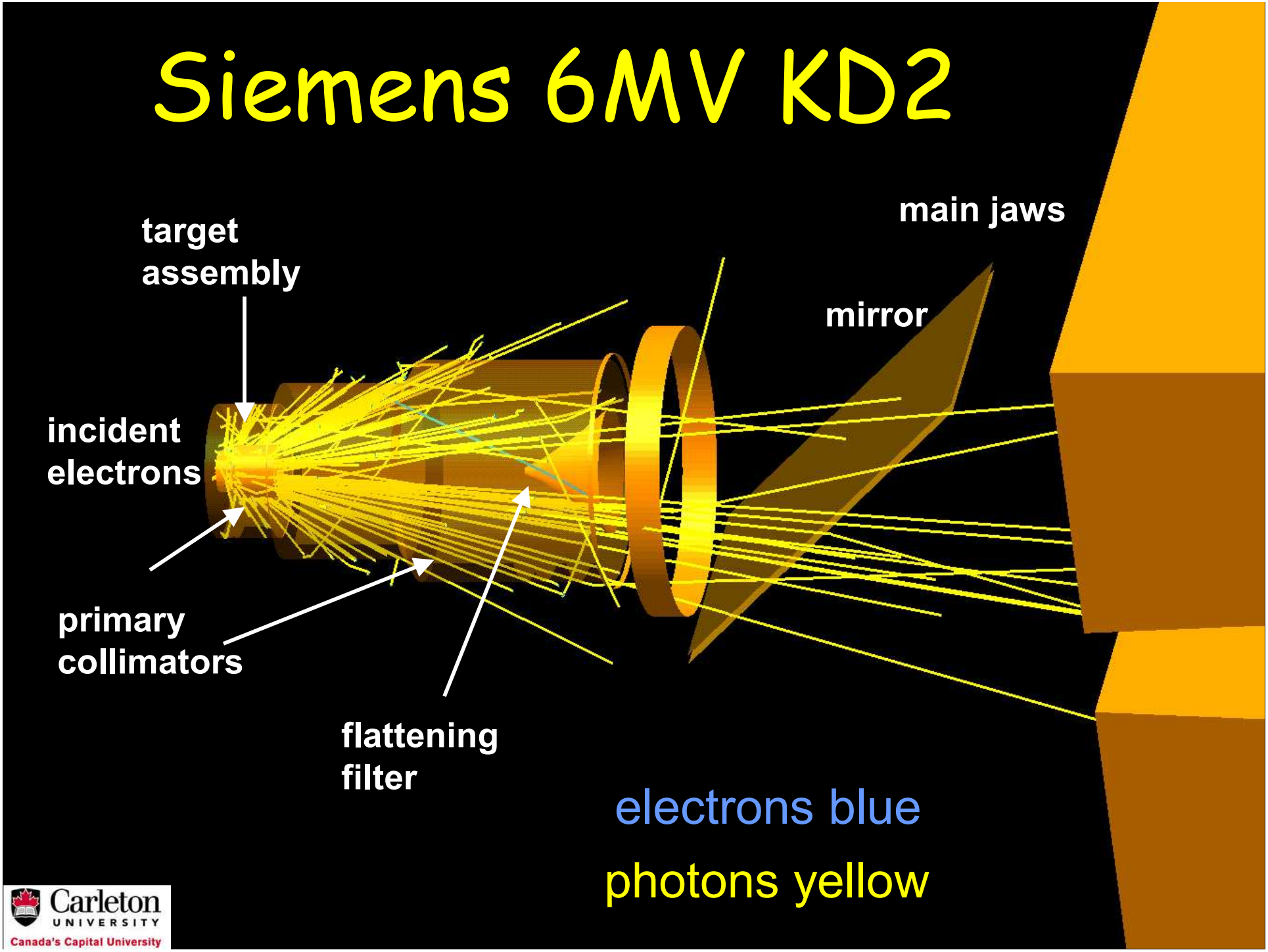

Mora et al Med Phys 26(1999) 2494

# Output variation vs expt




Mora et al Med Phys 26(1999) 2494

# Siemens 6MV KD2

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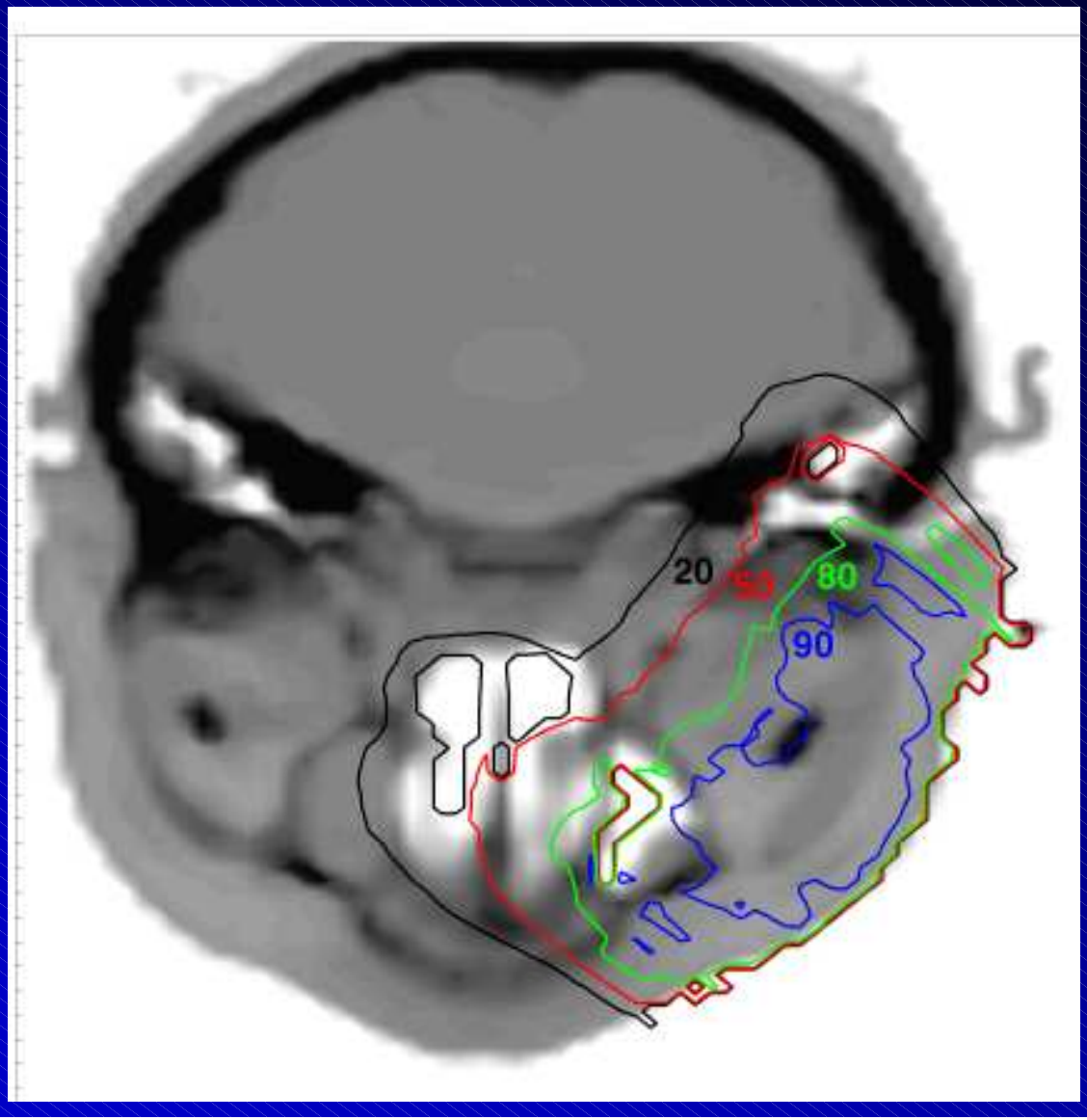
# Uses of BEAM

- accelerator design
- study physics of beams
- dosimetry studies
- beam characterization
  - 1st step to treatment planning
- commissioning accelerators

# CT Treatment Planning

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# Radiotherapy Treatment Planning

- plan how to deliver a dose to tumour
  - avoid critical organs
- need accurate calculation of patient dose
  - patient specified by CT data
- traditional analytic techniques are inaccurate
  - especially for electron beams
  - photons less so (already use MC energy deposition kernels)

# Clinical Electron Monte Carlo

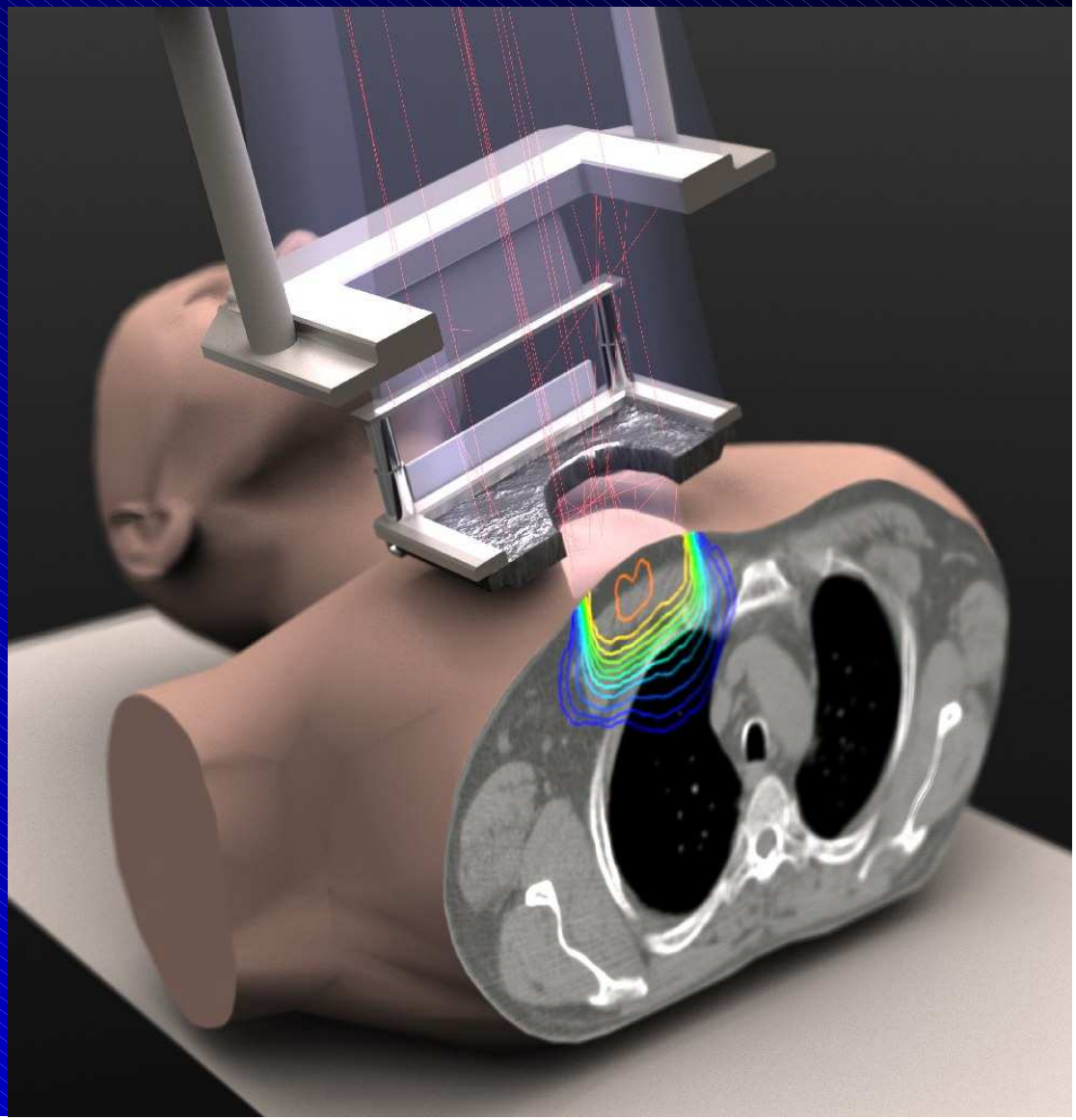
VMC Iwan Kawrakow & Matthias Fippel, 1996 working in Germany

2000 summer at NRC

Kawrakow VMC++ (C++)

Nordion (Nucletron) licensed

Cygler beta tested (ORCC)



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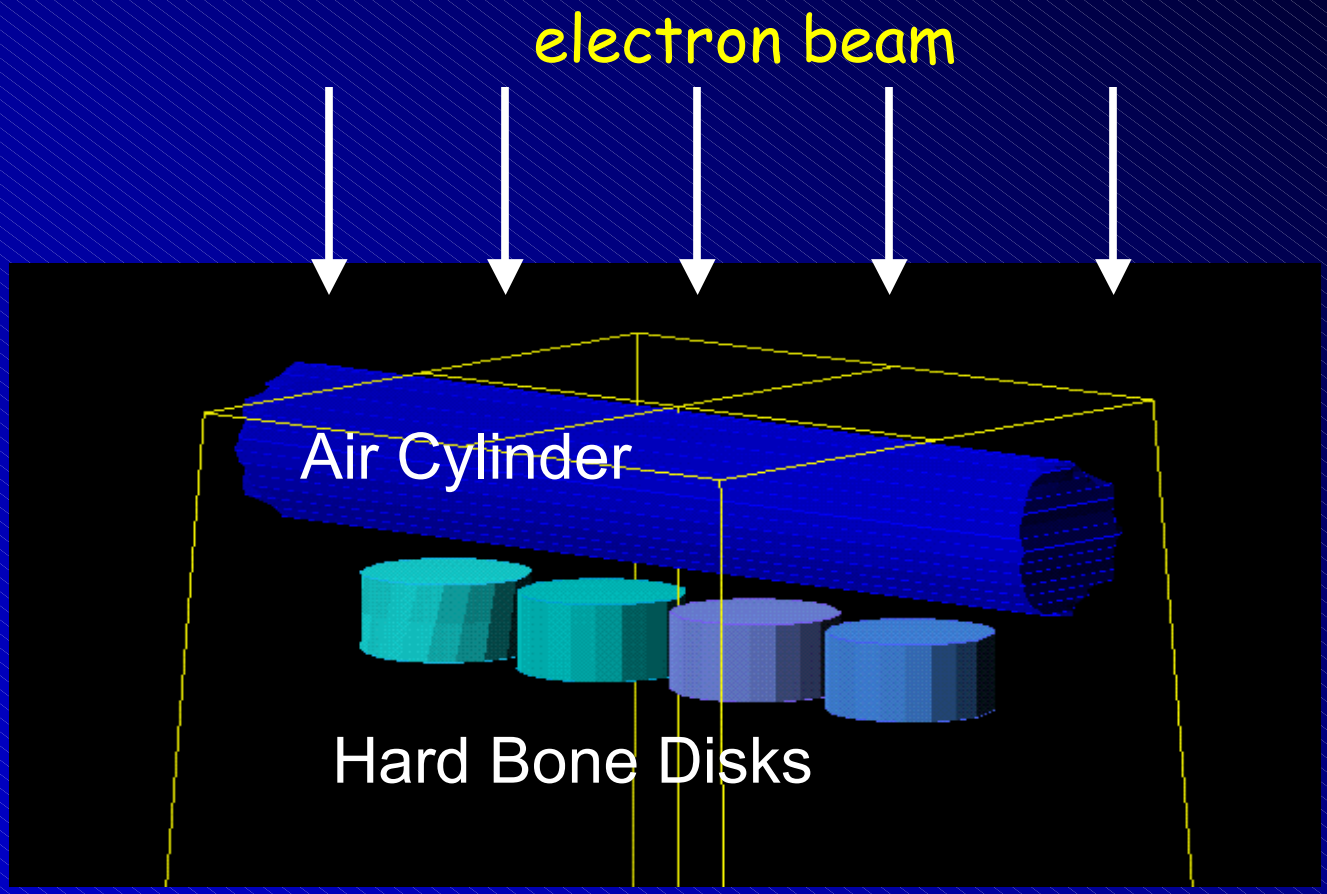
# Cygler's Trachea and Spine Phantom

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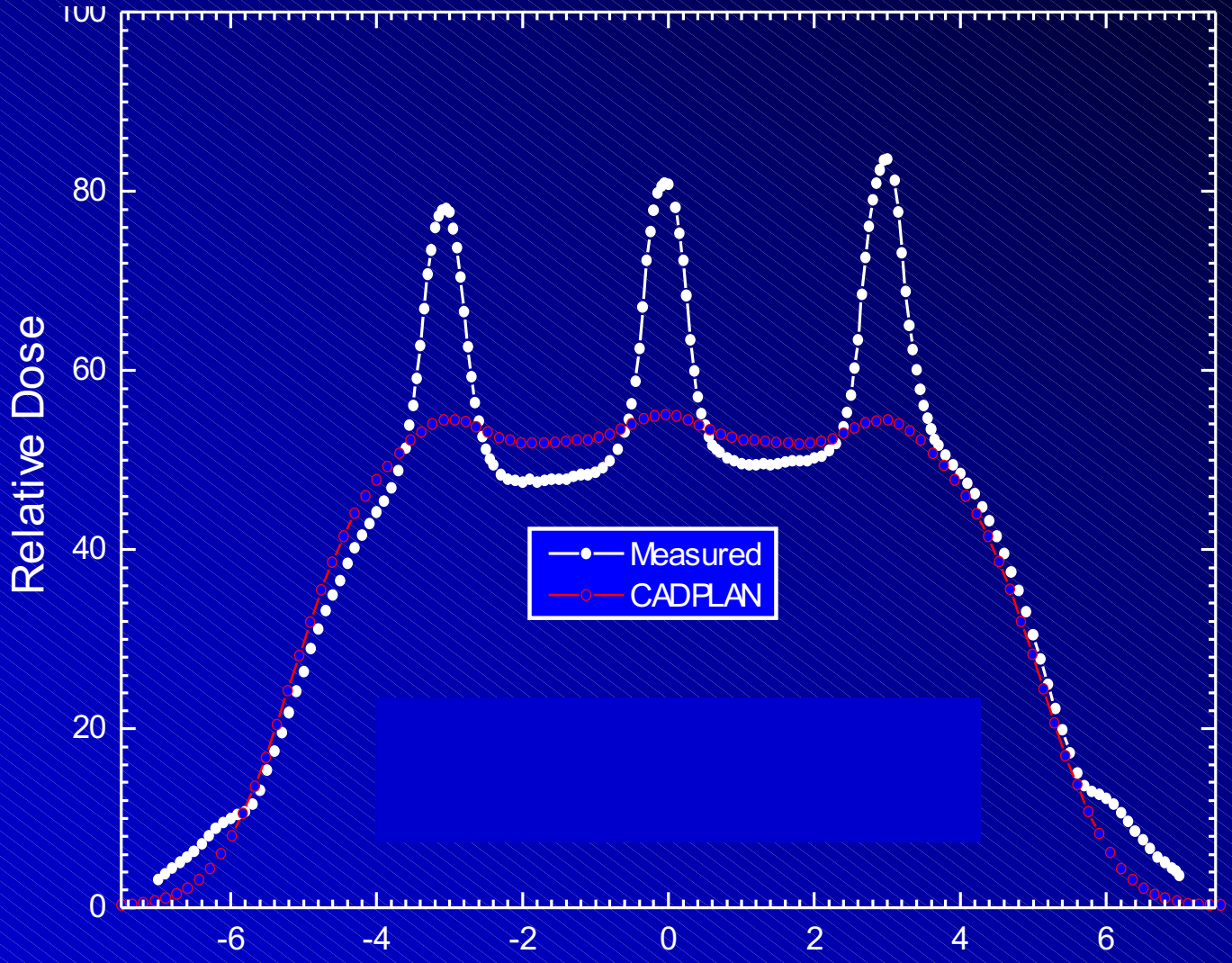
# 9 MeV: Trachea & Spine measurements vs pencil beam



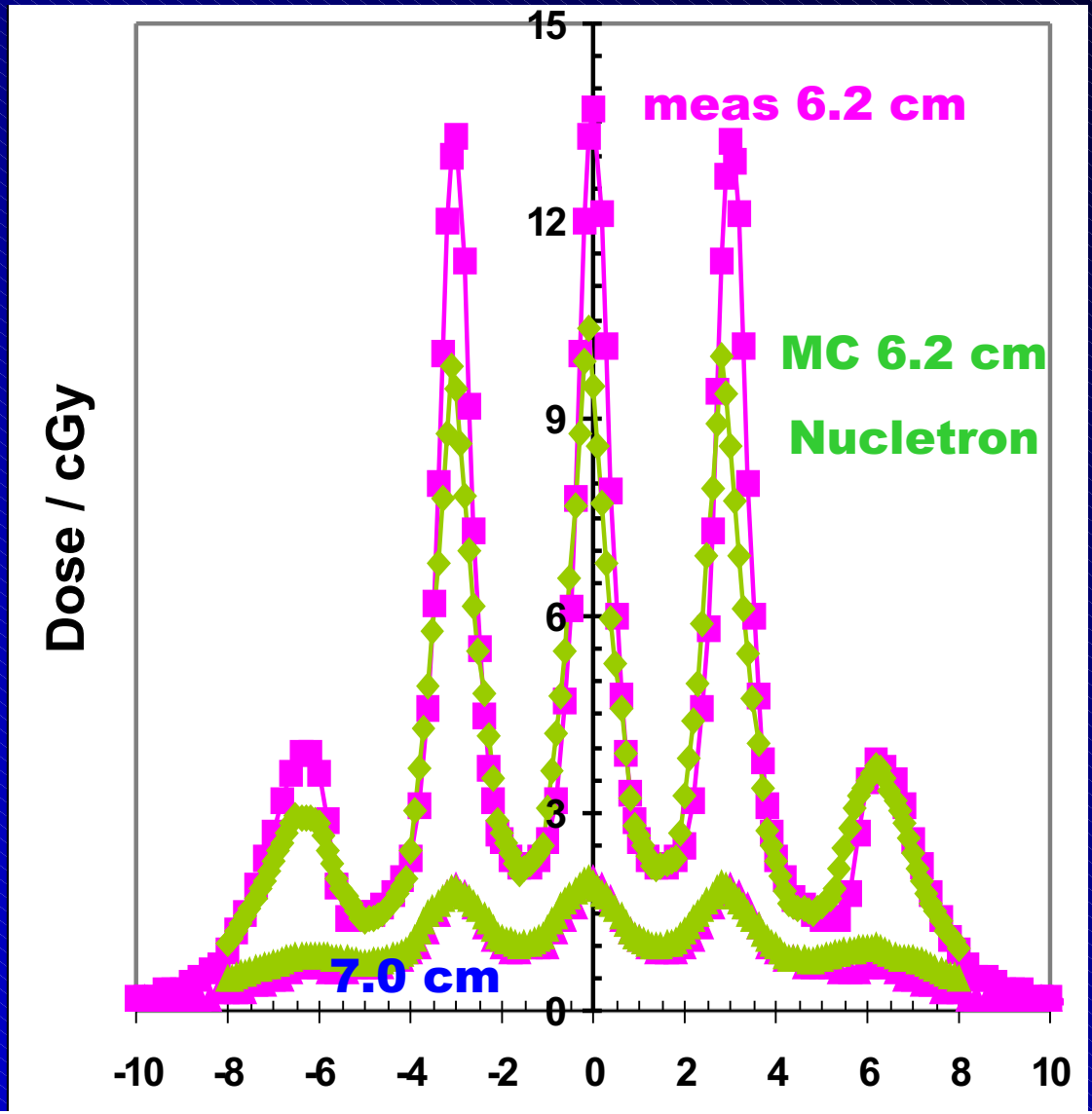

Ding, Cygler et al, Med Phys 26(1999)2571-2580

# 9 MeV beam: Trachea and spine

Cygler et al,

Med Phys

**31**(2004) 142

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# SNOMAN -MC for SNO

- the Monte Carlo simulation of the SNO detector (SNOMAN) uses EGS4 to simulate the slowing of electrons
  - this is critical in determining the light output
- recently a discrepancy with the calibration data has been removed by adding in a patch to include Mott scattering in the simulation
- comparisons with EGSnrc demonstrate that the SNOMAN patch gets the right answer

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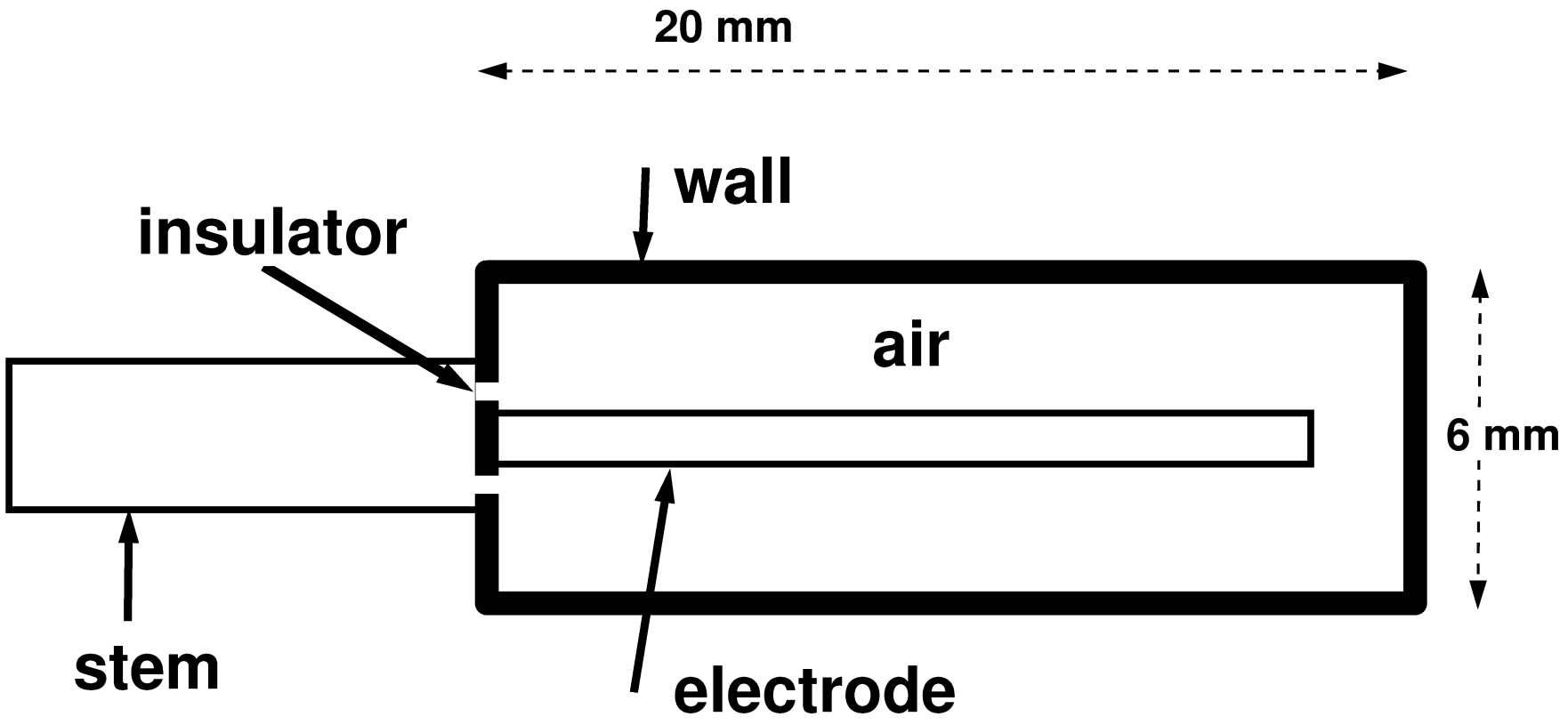
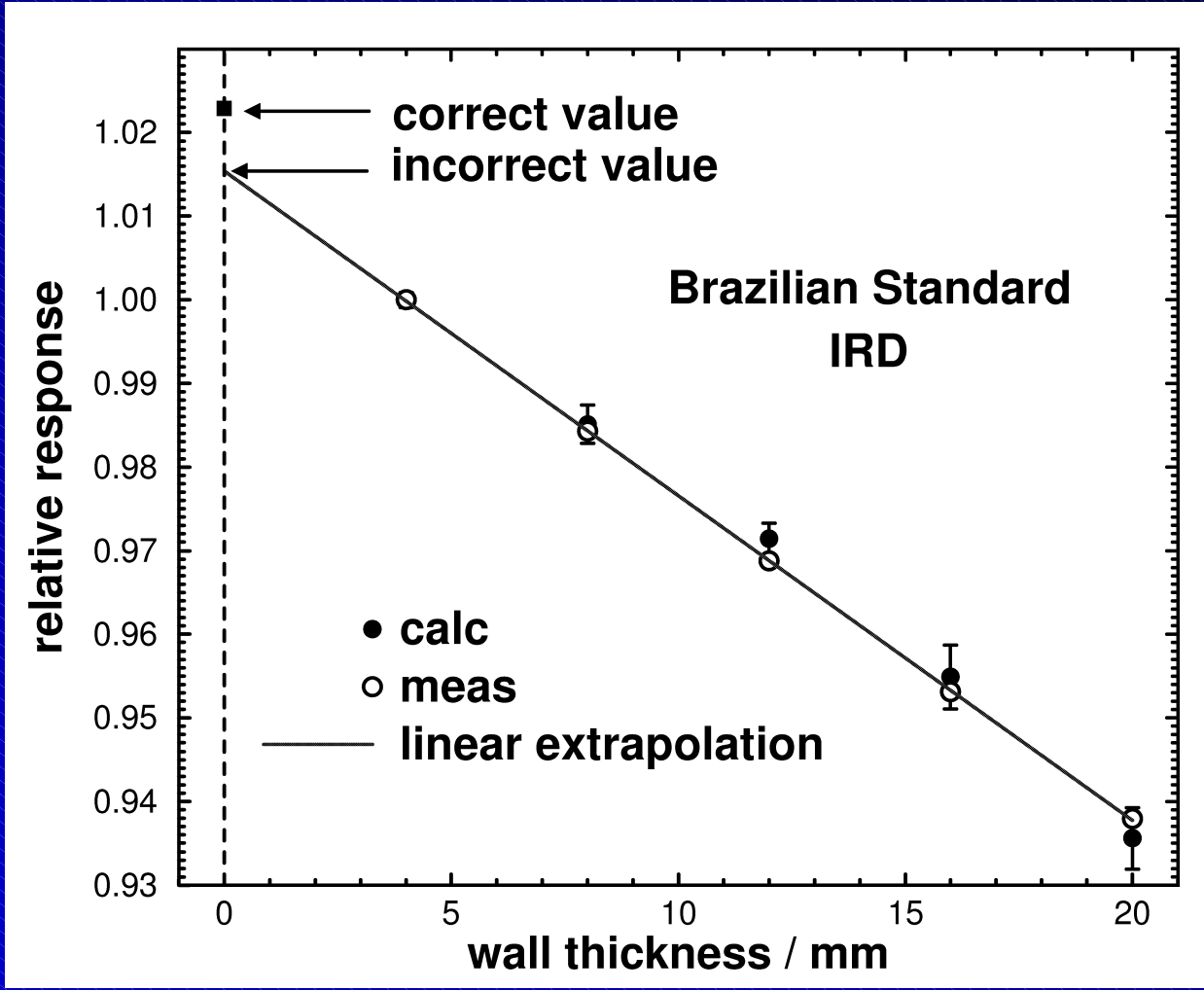
# Conclusions

- Monte Carlo is useful
- making dosimetry more accurate
- improving radiotherapy
- golden age ahead as machines and codes faster and more flexible
- the future will see modelling to the biological level, not just physical dose

# Ion chambers

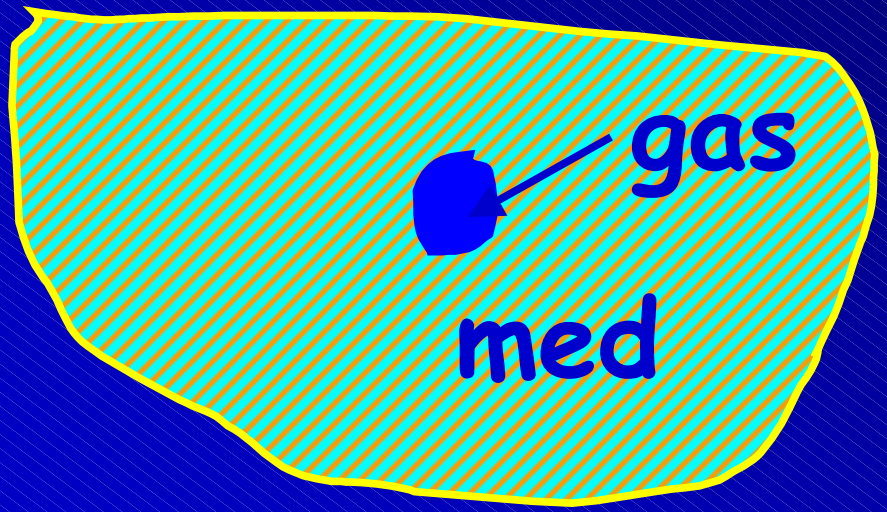


# $A_{wall}$ correction



# Stopping-power ratios

Relates dose in cavity to dose in medium.



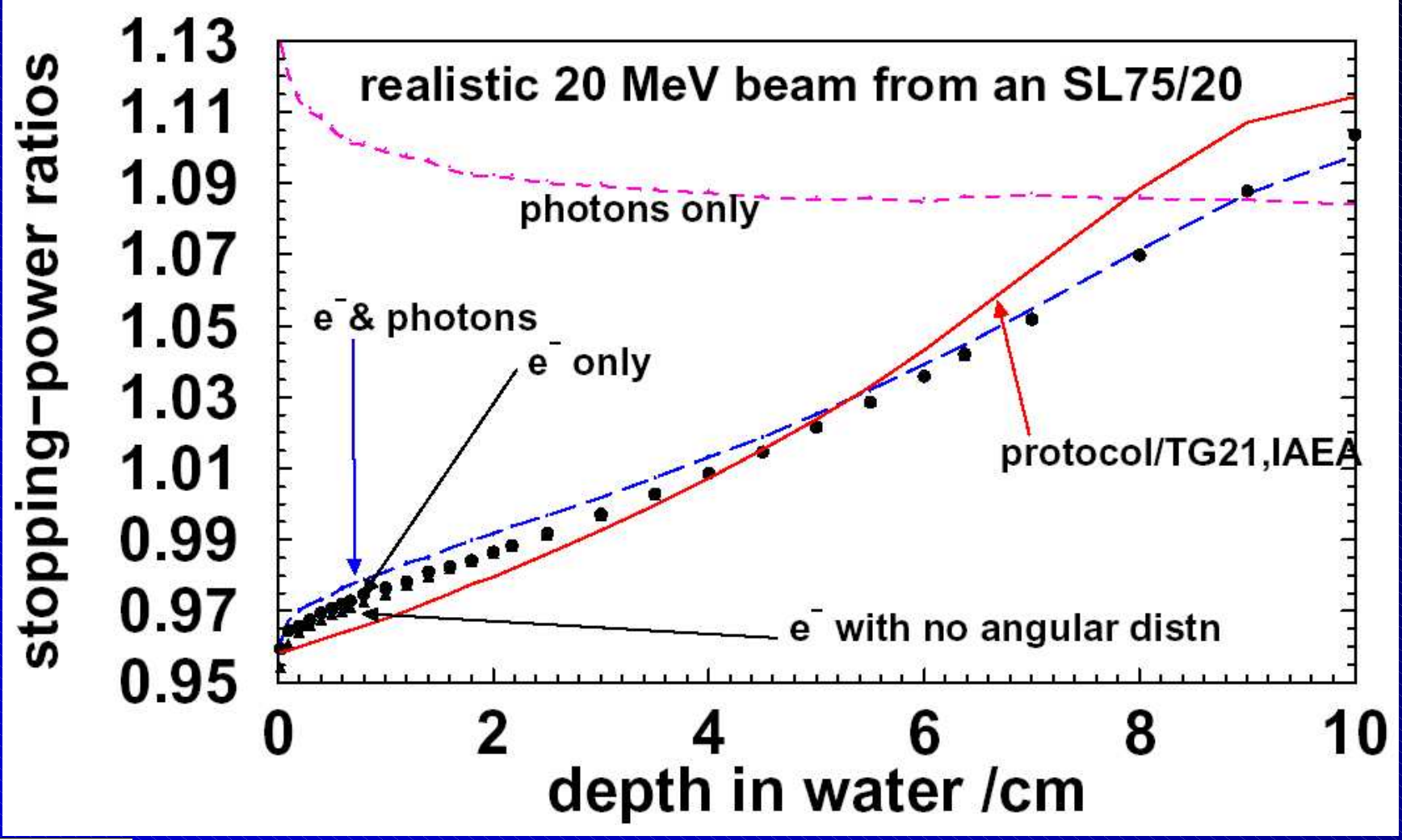

sprs fundamental to

-dosimetry protocols

-primary standards

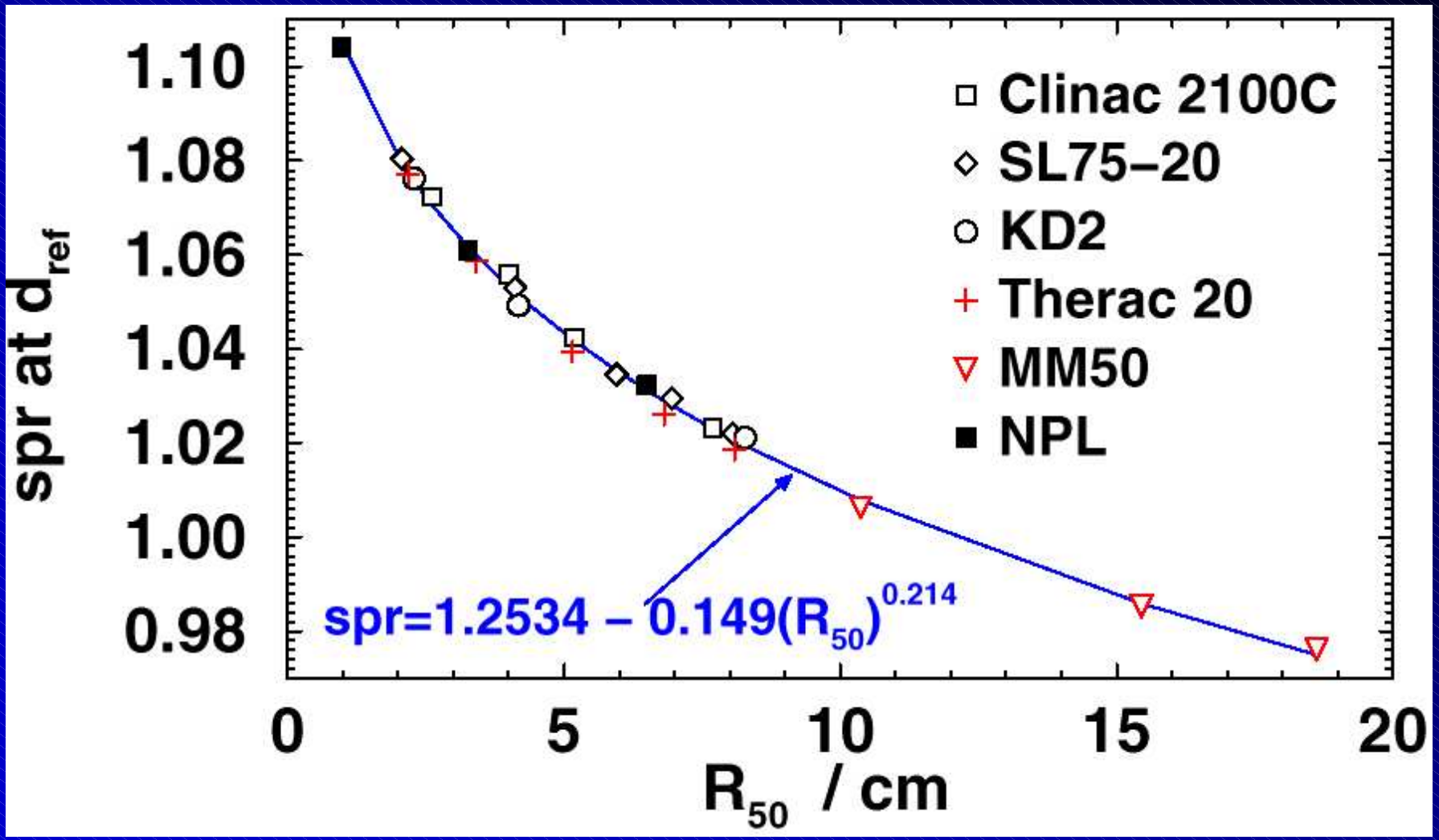
$$D_{med} = D_{gas} \left(\overline{L}/\rho\right)^{med}_{gas}$$

# Realistic electron beam sprs



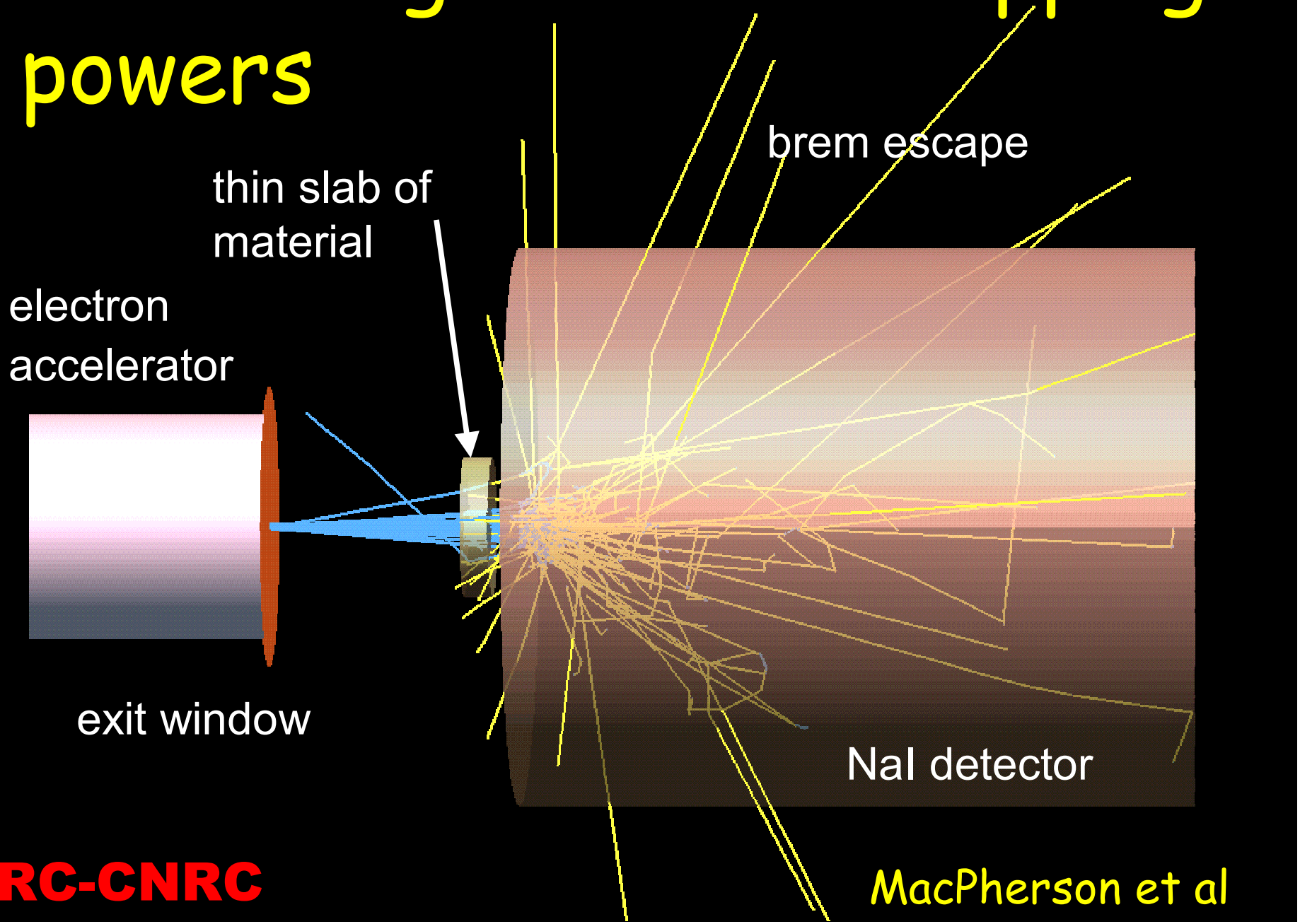

Ding et al Med Phys 22 (1995)489

# Realistic sprs at $d_{ref}$




Burns et al MP 23(1996)383

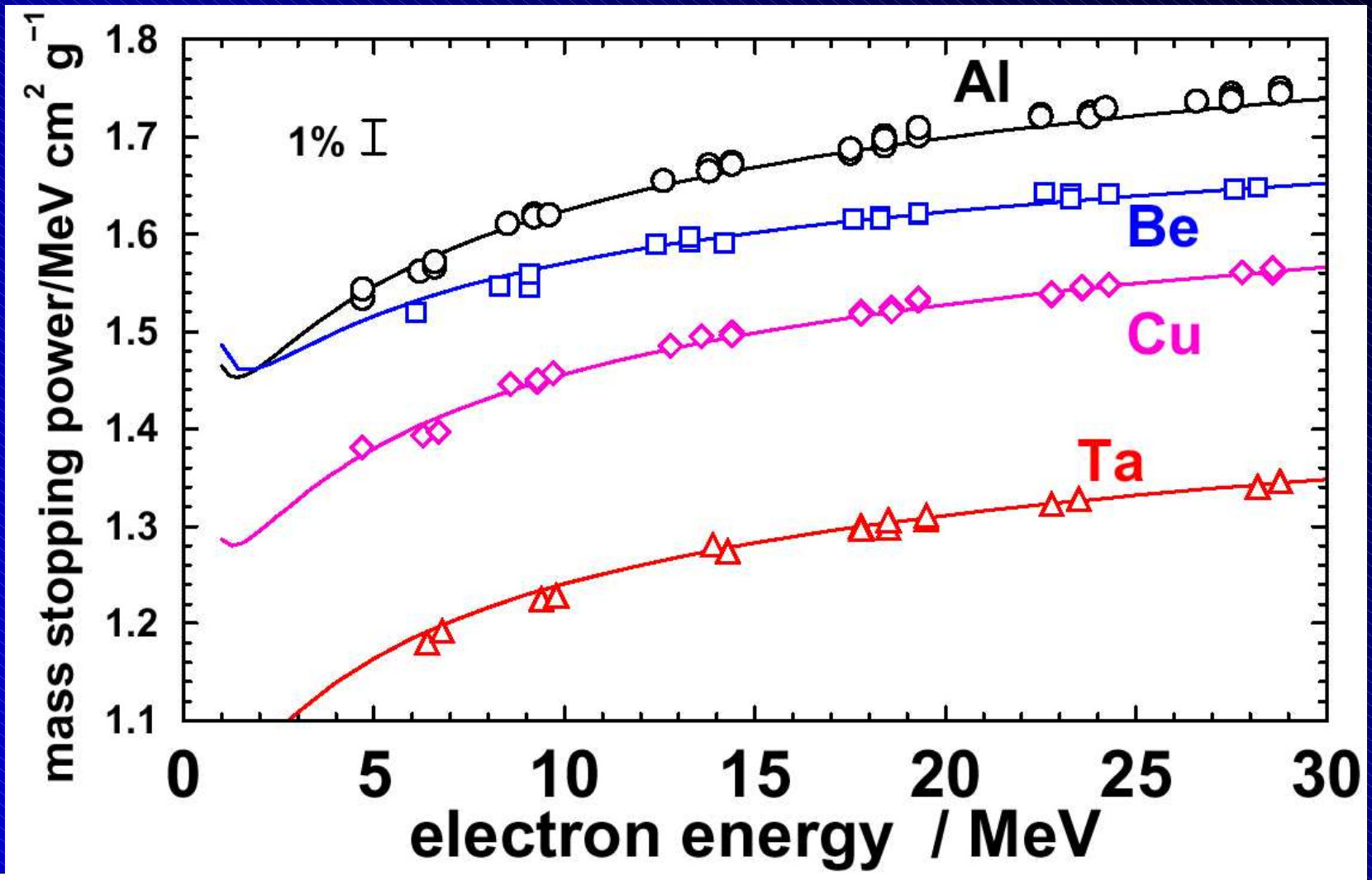
# Measuring electron stopping powers




NRC-CNRC

MacPherson et al

# electron stopping power measurements




MacPherson et al