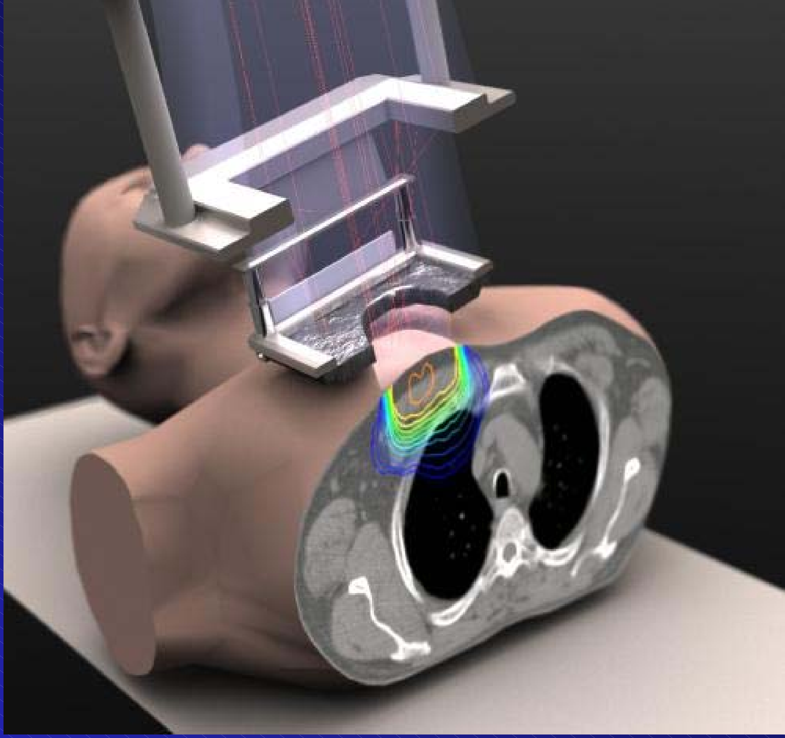
Fast Treatment Head Simulations For Photon Beams Using VMC^{++}



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Ionizing Radiation Standards

NRC, Ottawa

NRC-CNRC

MC treatment head simulations

- are useful tool for understanding the phase space distribution of particles emerging from the linear accelerator
- are difficult to use for routine clinical application and/or beam commissioning

Tools available

- BEAMnrc is a EGSnrc user code specifically developed for treatment head simulations
- MCNP, GEANT4, PENELOPE
- BEAMnrc is faster by at least one order of magnitude
- Well over 100 BEAM related papers published in the literature

Practical difficulties

- Very time consuming
  - several days of CPU time for a reasonable statistical precision
  - many simulations necessary to determine parameters of electrons incident on the target
- Difficult to obtain precise geometry specification from manufacturers

Goal

Develop a treatment head simulation tool that is faster than BEAM by 2-3 orders of magnitude

→ Much easier commissioning

→ On-the-fly treatment head simulation for each patient dose calculation

VMC^{++}

- Fast MC algorithm optimized for the simulation in the patient
- Accurate electron transport algorithm
- No restrictions on applicability
- Models all relevant interactions
- Object oriented design => use of arbitrary geometries possible

Why are photon beam treatment head simulations slow?

- Without use of Variance Reduction Techniques (VRT), most time spent tracking electrons
- Most photons absorbed in primary collimator and jaws (only 2-3% arrive at bottom of treatment head)

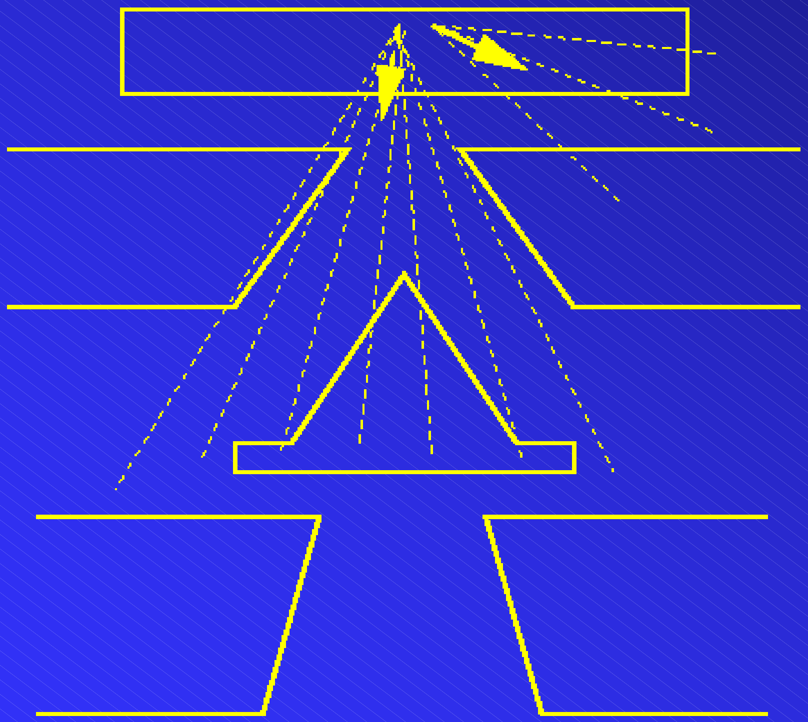
VRT implemented in BEAMnrc

- Uniform Bremsstrahlung splitting (UBS): split each interaction that produces photons N times
- Selective Bremsstrahlung Splitting (SBS): split bremsstrahlung events a variable number of times, depending on electron direction

UBS

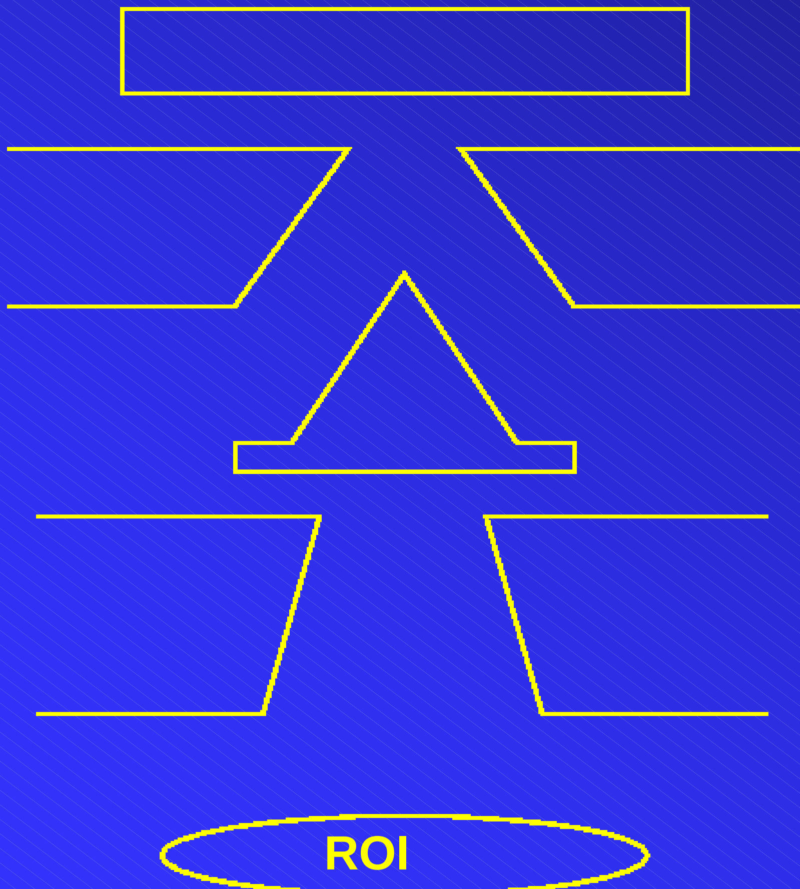
- Reduces the fraction of time spent for electron transport
- Still have to track many photons that don't arrive at the plane of interest
- Increases efficiency compared to no-VRT by a factor of ~8.

SBS



- Reduces time spent tracking non-contributing photons
- Increases variance
- Efficiency increase: about a factor ~3 compared to UBS, a factor of ~25 compared to no-VRT
- Not very widely used

New technique: Directional Radiative Splitting (DRS)



- Define a region of interest (ROI)
- Goal 1: many photons within ROI, few photons outside ROI
- Goal 2: all photons within ROI have the same statistical weight

DRS

- Split radiative events as in UBS
- Before transporting photons, check if they go towards the ROI and play Russian Roulette (RR) if they don't

➔ All photons within ROI have weight $1/N$

➔ All photons outside ROI have weight 1

➔ If N is large, only very few non-contributing photons to be transported, relatively little time spent on electrons

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DRS

- When a photon interacts: if it is a "thin" photon first play RR → weight 1
- Photo-absorption or pair-production: just set in motion the resulting electrons
- Compton scattering: split the interaction N times, keep photons going towards the ROI, play RR with non-ROI photons and the Compton electrons

DRS so far

- All electrons and non-ROI photons are "fat", all ROI photons are "thin".
- Many ROI photons → good statistics
- Very few electrons and non-ROI photons → efficient simulation
- But: bad statistics for contaminant electrons

DRS: other tricks

- One can calculate (estimate) the probability p of bremsstrahlung emission or scattering into ROI => need to simulate only $p\,N$ interactions

- Use cylindrical symmetry above the photon jaws

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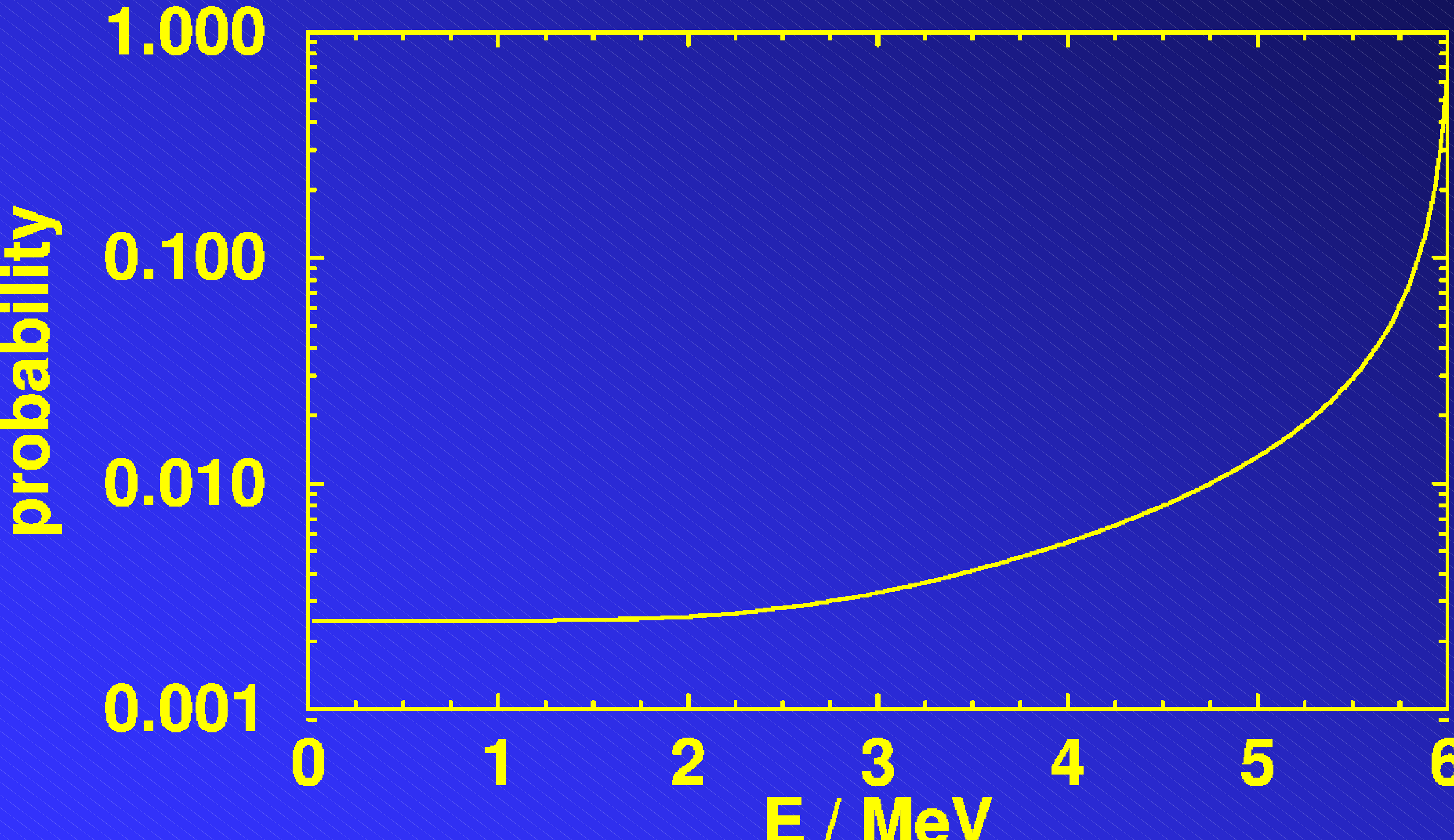
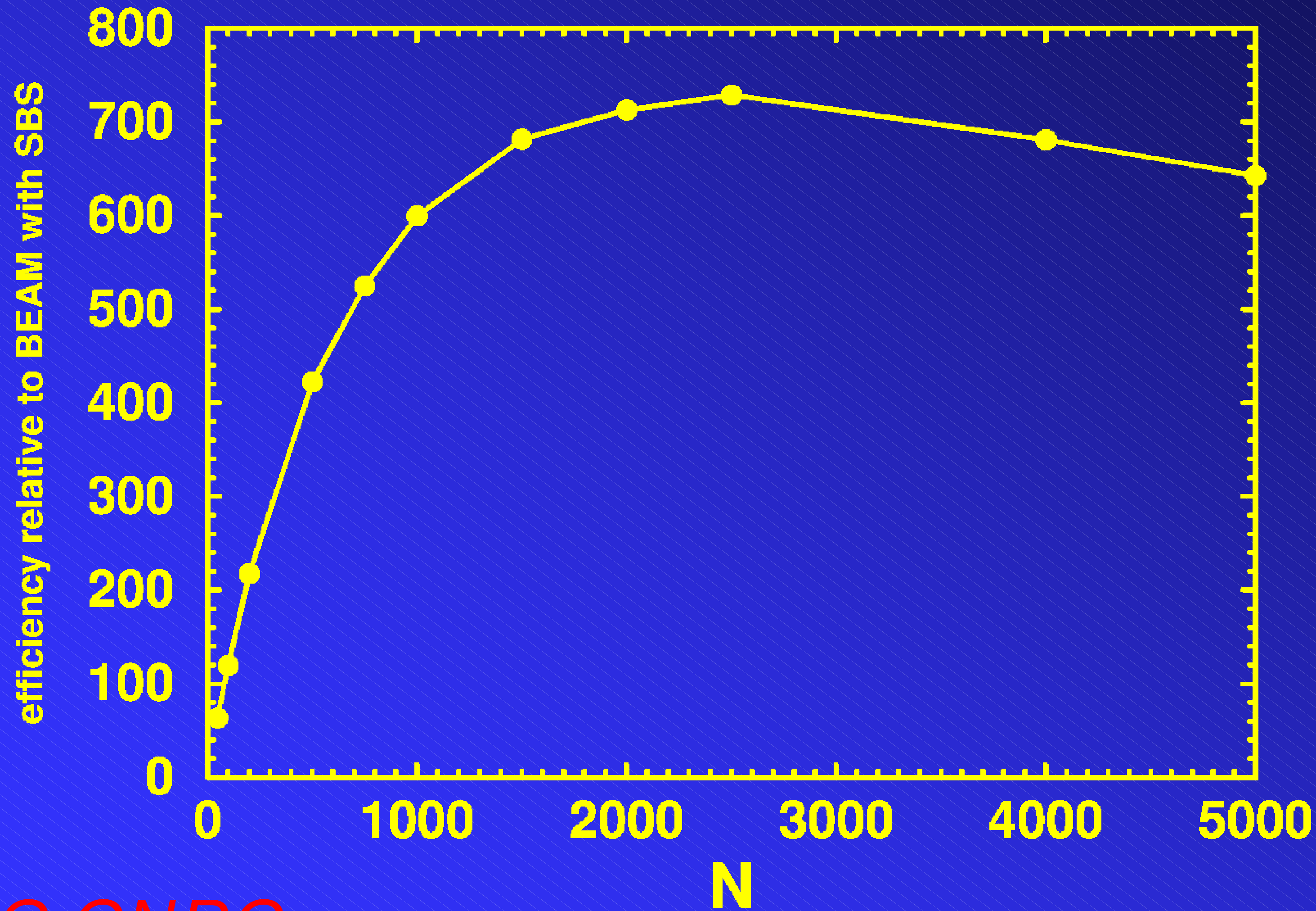
Probability for Bremsstrahlung



Efficiency

$$\varepsilon = \frac{1}{T\sigma^2}$$

- T time for the simulation
- σ uncertainty on the quantity of interest. Will use the photon (or electron) fluence in 1x1 cm^2 voxels in a plane 100 cm from the source


800
700
600
500
400
300
200
100
0
efficiency relative to BEAM with SBS
0
1000
2000
3000
4000
5000
N

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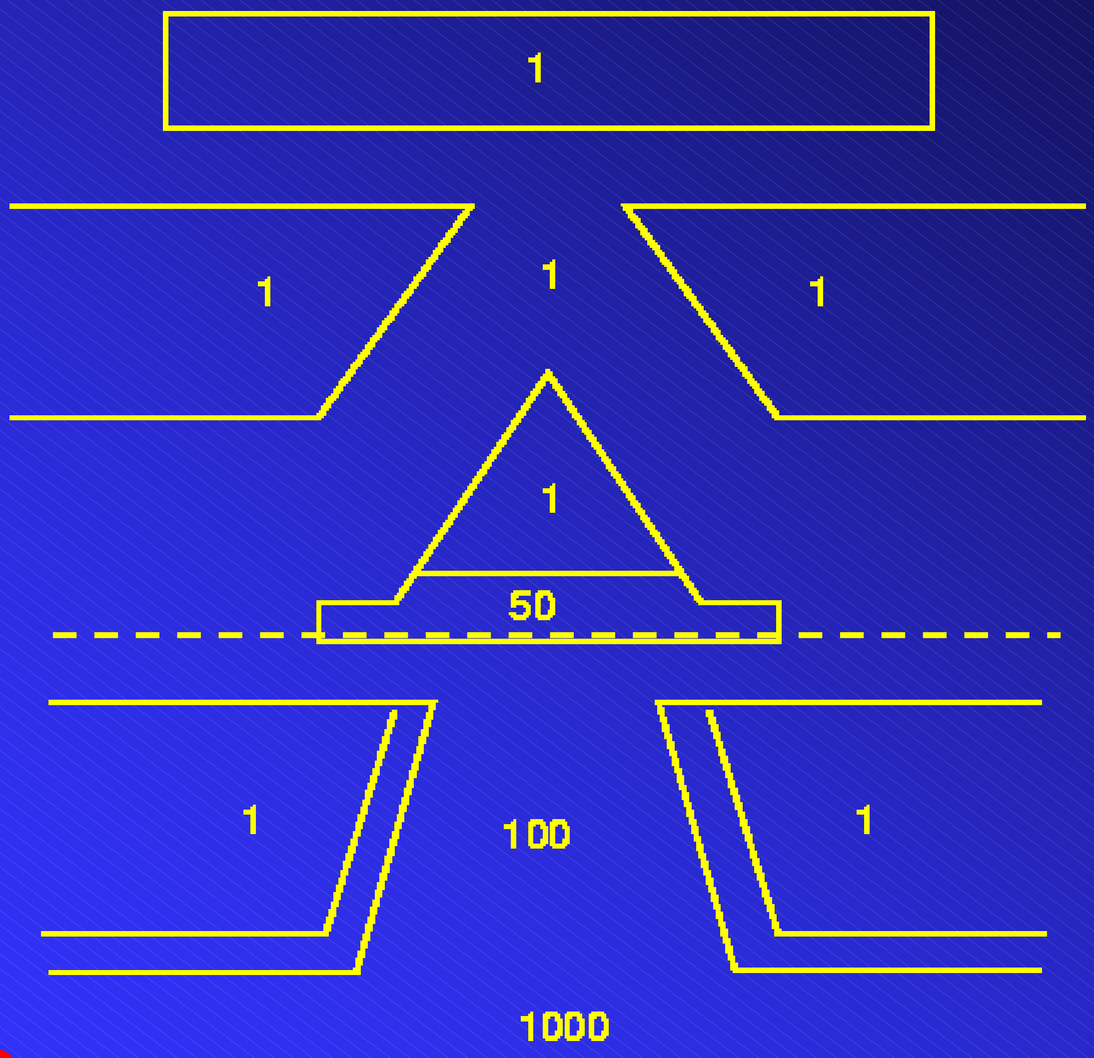
DRS: improving statistics of electron contamination

- Most contaminant electrons are set in motion in the lower portion of the flattening filter, the inner faces of the jaws and the air below the jaws.

➔Assign "electron importance" N_i to different regions of the treatment head

Electron importance (EI)



DRS with EI

1. When a photon interacts in a region with EI=N_i, then
   - Play RR if weight less than $1/N_i$
   - Split photon interaction if weight greater than $1/N_i$

so that weight always $1/N_i$

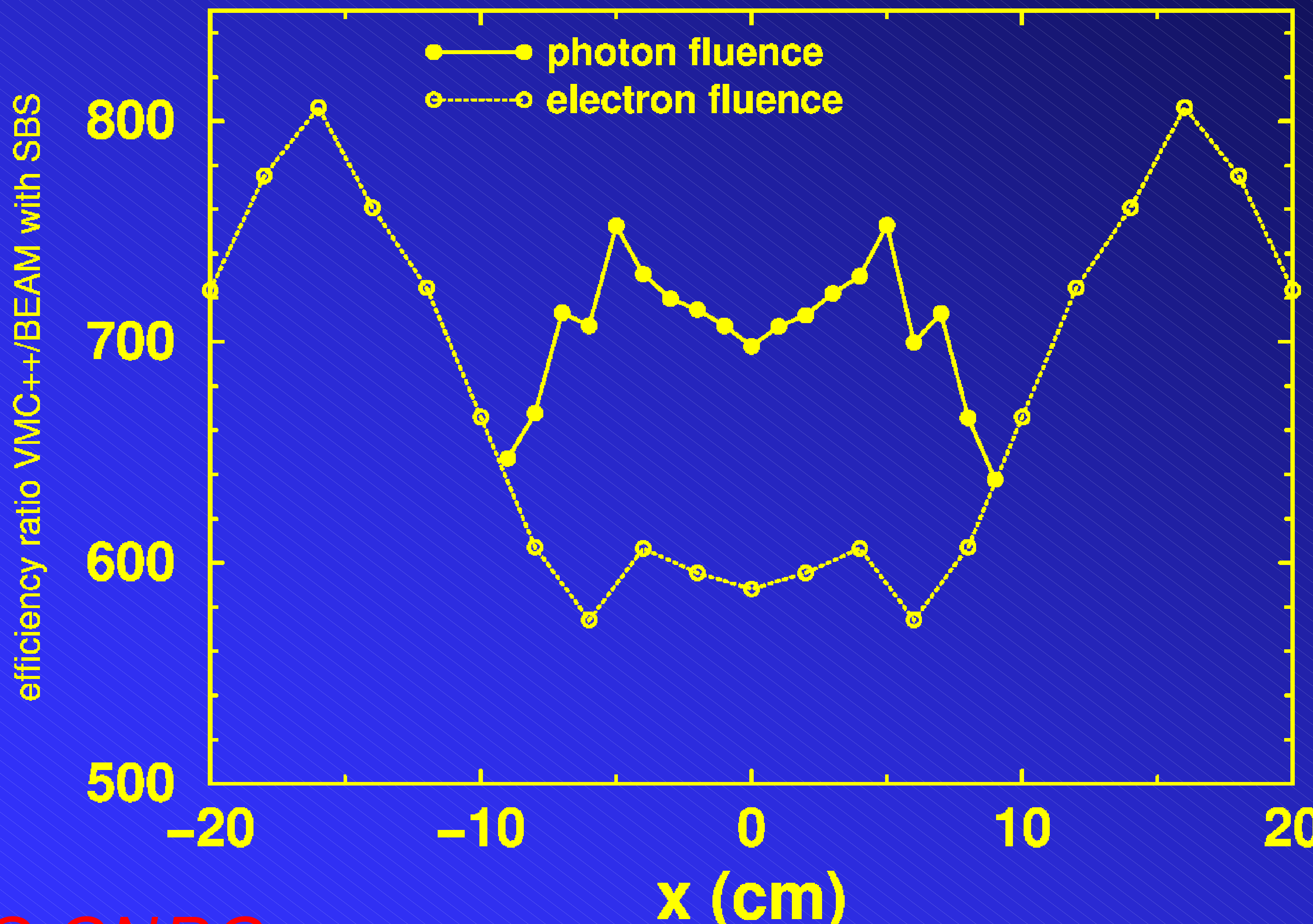
DRS with EI

2. If an electron goes from region with N_1 to region with N_2, then
   - Split the electron N_2/N_1 times, if $N_1 < N_2$
   - Play RR with the electron if $N_1 > N_2$

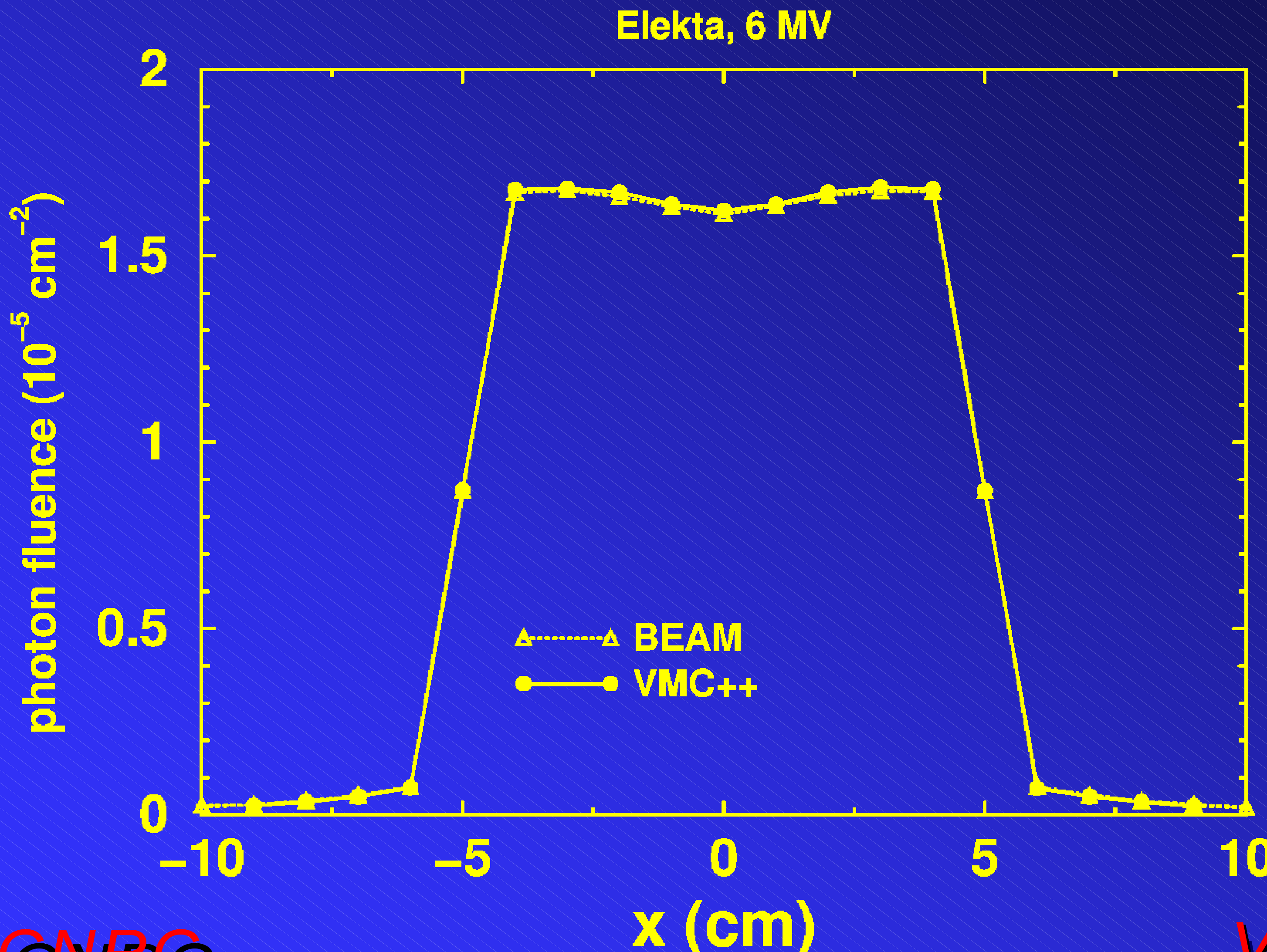
➔ Number of transported electrons in different regions proportional to their EI

➔ Few electrons in the upper part, many electrons in the lower part

VMC^{++} efficiency



Its fast, but is it accurate ?



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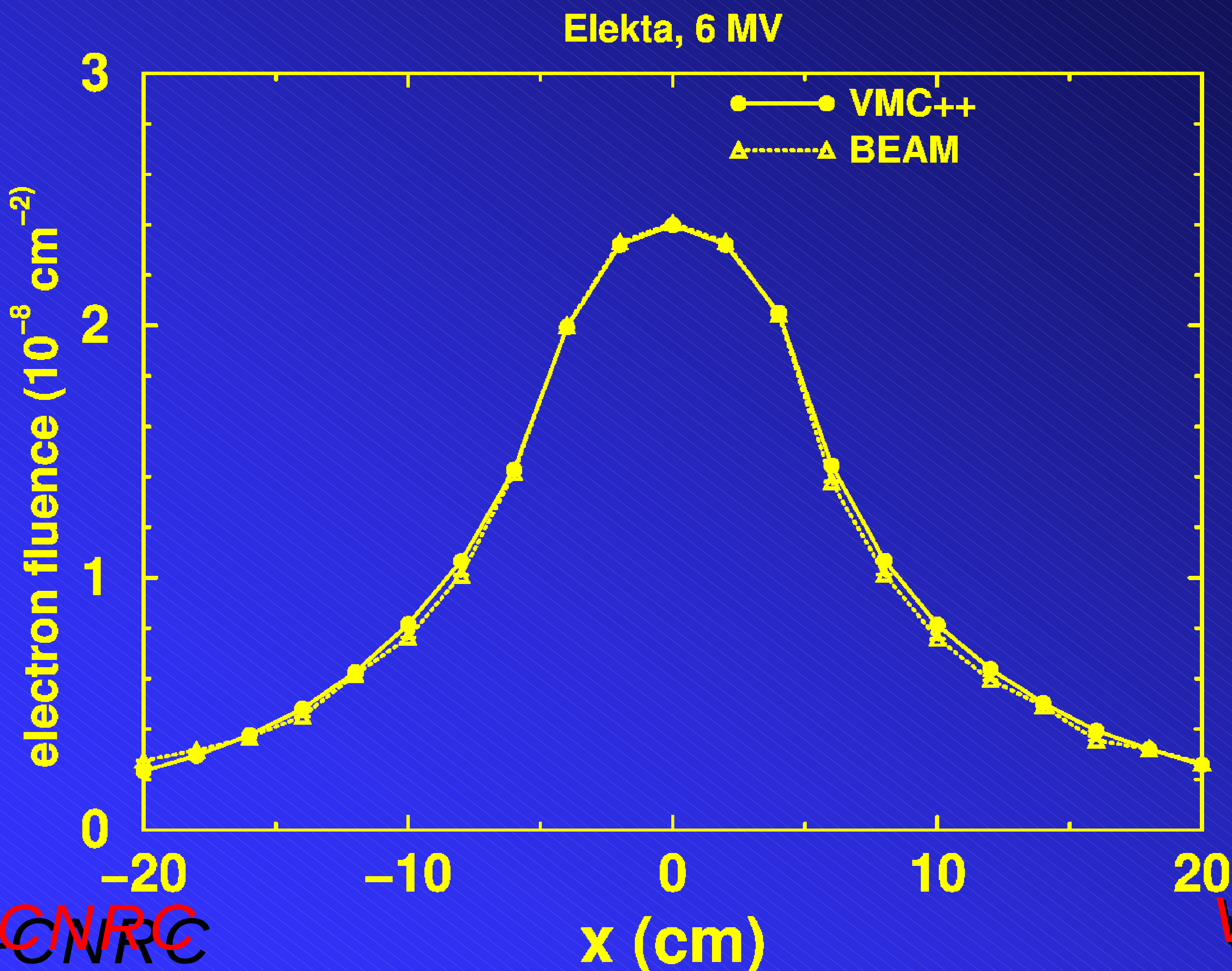
Its fast, but is it accurate ?



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What is accomplished

- VMC^{++} produces ~6 million photons and ~0.5 million electrons per minute
- This corresponds to ~10-20% of the CPU time spent for transport in the patient
- On-the-fly simulation possible
- If one wanted to write a phase space file, the 2 GB file size limit will be reached in ~10 minutes.

What needs to be done

- Implement geometry modules for MLC, wedges, compensators
- Check if the techniques described are fast enough for transport through MLC
- Work on automated beam commissioning tool
- Investigate use of quasi-random sequences

BEAM

- Some of the techniques presented here are implemented in a development version of BEAM
- New BEAM version is ~8 times faster than SBS but still 70-80 times slower than VMC^{++}
- BEAM paper submitted to Med.Phys. in January
- VMC^{++} paper in preparation

Advantages of full treatment head simulations

- Empirical and semi-empirical beam models are difficult to develop
- If a manufacturer comes up with a new design, new models will have to be developed (*e.g.* Tomotherapy)
- If the characteristics of a machine changes, re-commissioning is much easier

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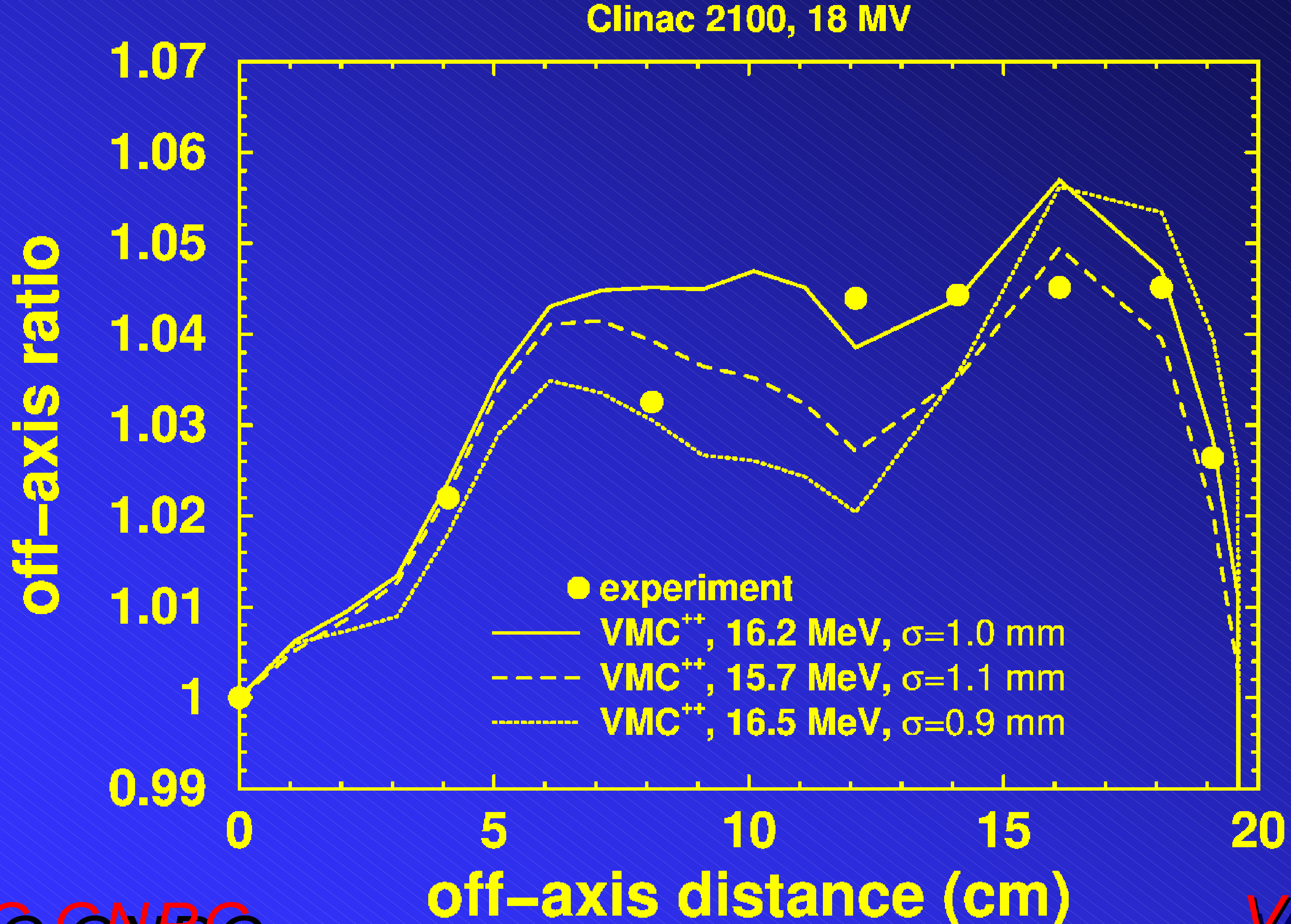
Example



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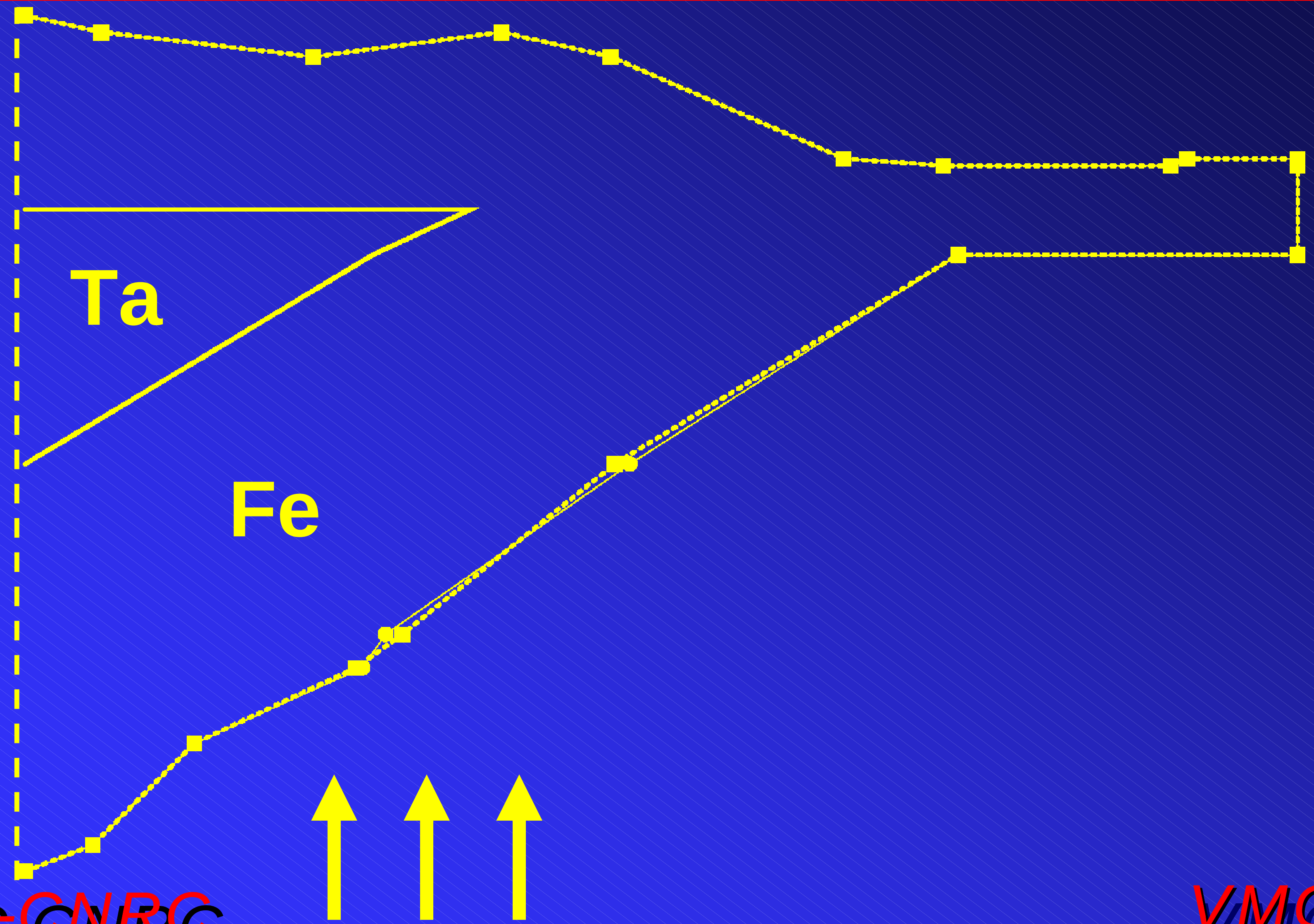
VMC++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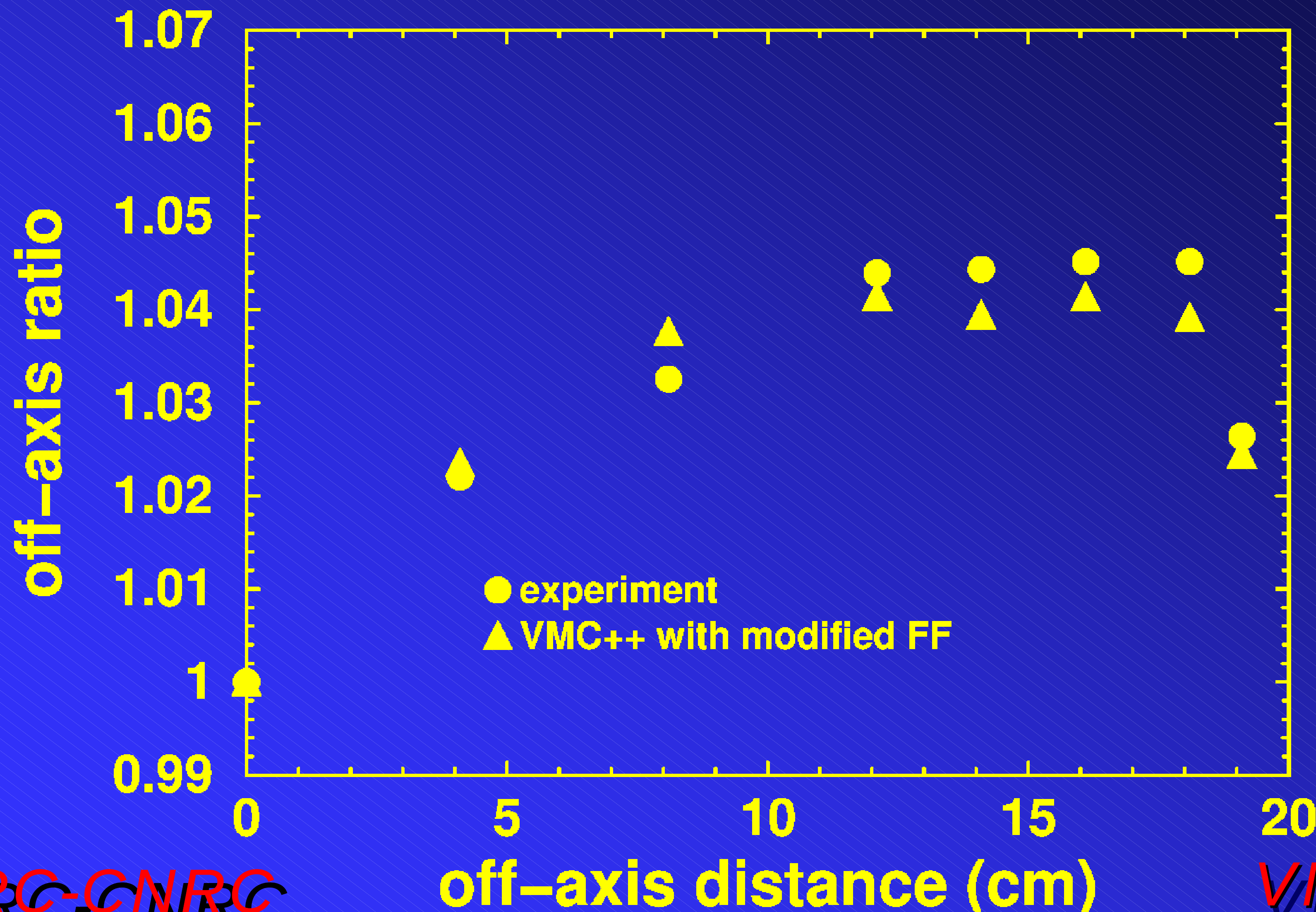
1.07
1.06
1.05
1.04
1.03
1.02
1.01
1
0.99
off–axis ratio
0
5
10
15
20
off–axis distance (cm)
experiment
VMC++ with modified FF