Spectrometer – screen simulations for PHIN tests, screen saturation - update

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- Simulations for PHIN tests
  - Screen output
  - Point spread function
  - Explanation of results
- Screen saturation
  - Checking of equation

Introduction

- These simulation results were initially presented at the AWAKE technical board meeting on June 24th
- I will present the material again and answer some of the questions raised during that meeting
- Working on the other questions

PHIN tests

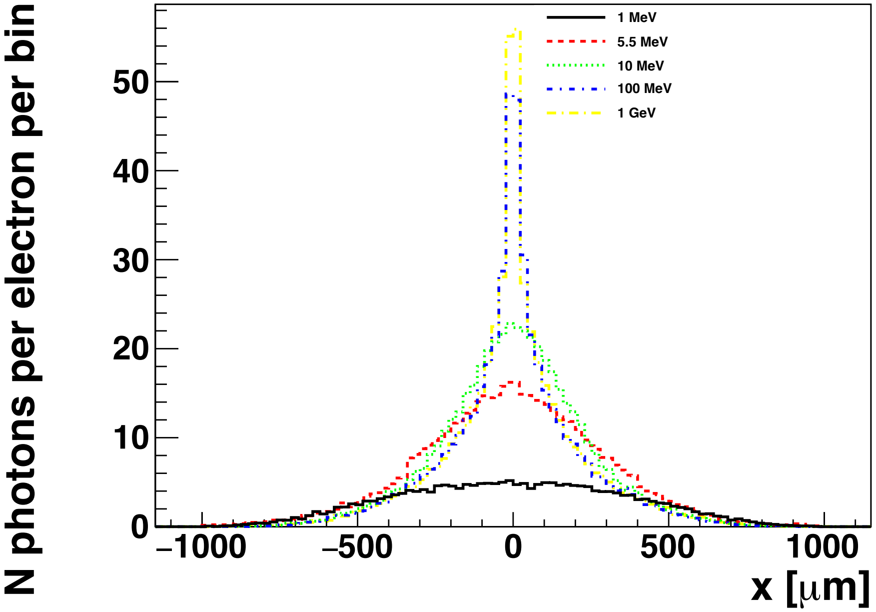
- Scintillator screen/camera setup tests are planned using the PHIN photoinjector [1] at CTF3
- Beam:
  - E=5.5 MeV
  - Up to 2332 bunches per train
  - 2.33 nC per bunch
  - 8 ps bunch length
  - 667 ps between bunches

PHIN test simulations

- Screen: Medex portal (applied scintillator technologies) – thicker version of Lanex (GOS:Tb) – 0.9mm thick scintillator layer (50:50 mixture by vol. of scintillator and PET binder.
- Screen output and point spread function (PSF) vs electron energy
- Screen output and point spread function vs. backing layer thickness
- In the following simulation results: input was incoming electron beam at x=0, perpendicular to screen

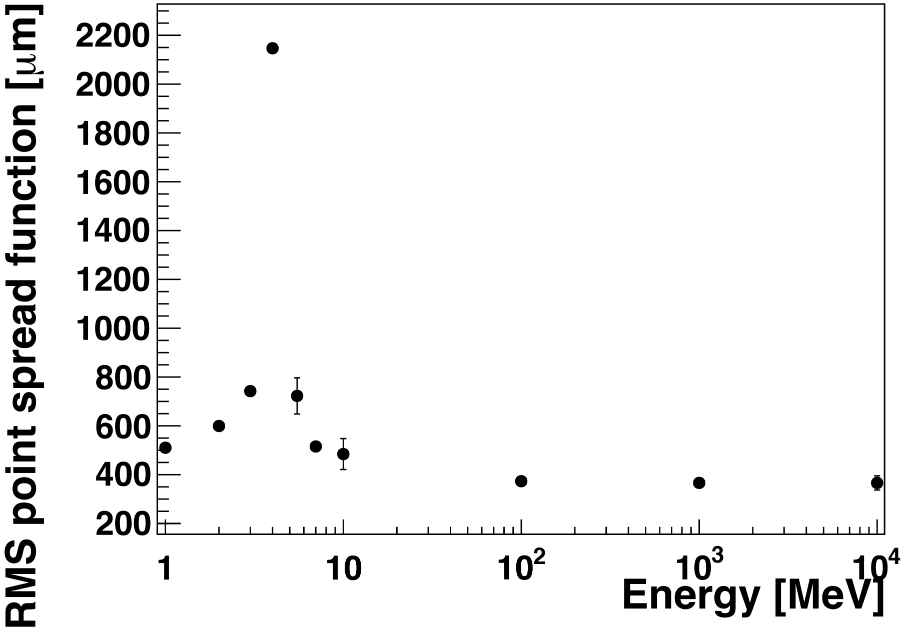
Screen output and PSF vs electron energy

- Positions of emitted photons at screen for various incoming electron energies



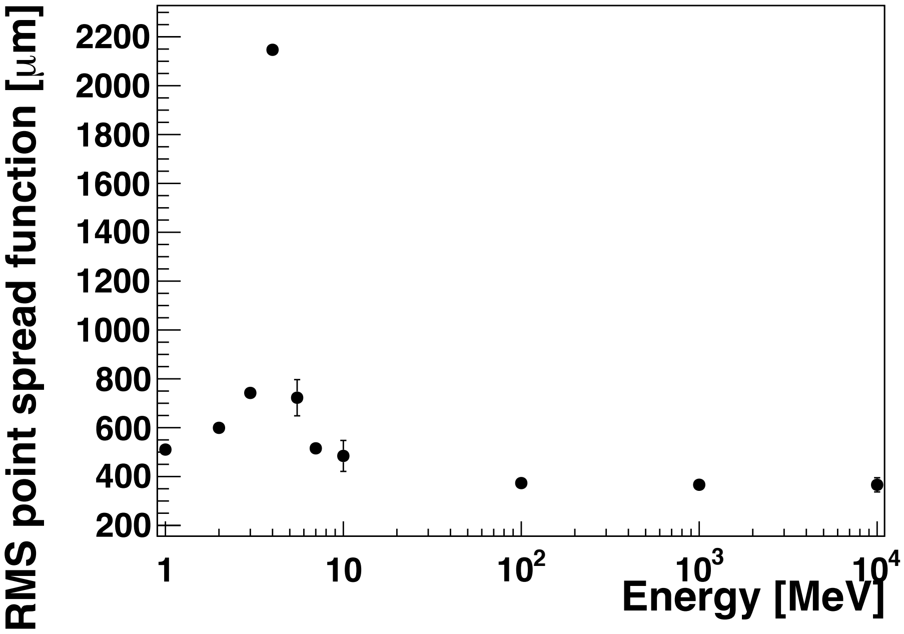
Screen output and PSF vs electron energy

- PSF vs energy
- Peak at 4 MeV?
  - ***Question – "bug? Property of scintillator? Geant feature?"***
    - Answer – there was a cluster of optical photons due to a single outlying scatter electron, energy 1.3 MeV, at -45mm



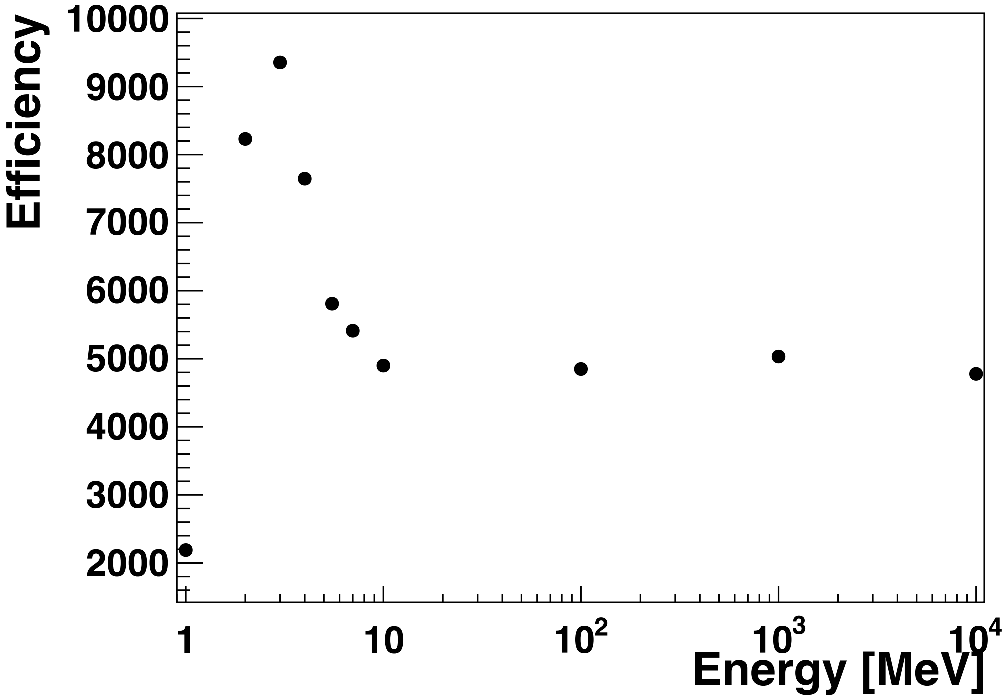
Screen output and PSF vs electron energy

- Answer
  - there was a cluster of optical photons due to a single outlying scatter electron, energy 1.3 MeV, at x=-45mm
  - The number of primaries was 1000
  - The EM low e cutoff was 1mm
  - *Running again with 100000 primaries and low energy cut at 1 micron (more accurate em cascade simulation, more statistics)*
  - *Checking analysis script (why no large error bar?)*



Screen output and PSF vs electron energy

- Photons per incoming electron vs. energy
- Simulations predict:
  - PSF and efficiency are independent of energy above a certain "threshold" energy – around 10 MeV
  - 5.5 MeV (PHIN) close to threshold energy
- ***Question: "why does the number of photons go down at low energies?"***



Explanation of processes contributing to the results

- The results can be explained if we consider the ionization and EM shower stopping power.
- Two main processes are involved:
  - Ionization
  - EM cascade consisting of
    - Bremsstrahlung
    - Pair production

Explanation of processes contributing to the results

- Ionization excited the scintillator and therefore contributes to optical photon emission.
- EM cascade does not – gamma emission by the electron followed by pair production - does not affect the scintillator atoms
  - However, the cascade produces multiple lower energy particles, and because energy loss by ionization is proportional to energy, EM cascade influences the scintillator excitation in an indirect way

Ionization stopping power

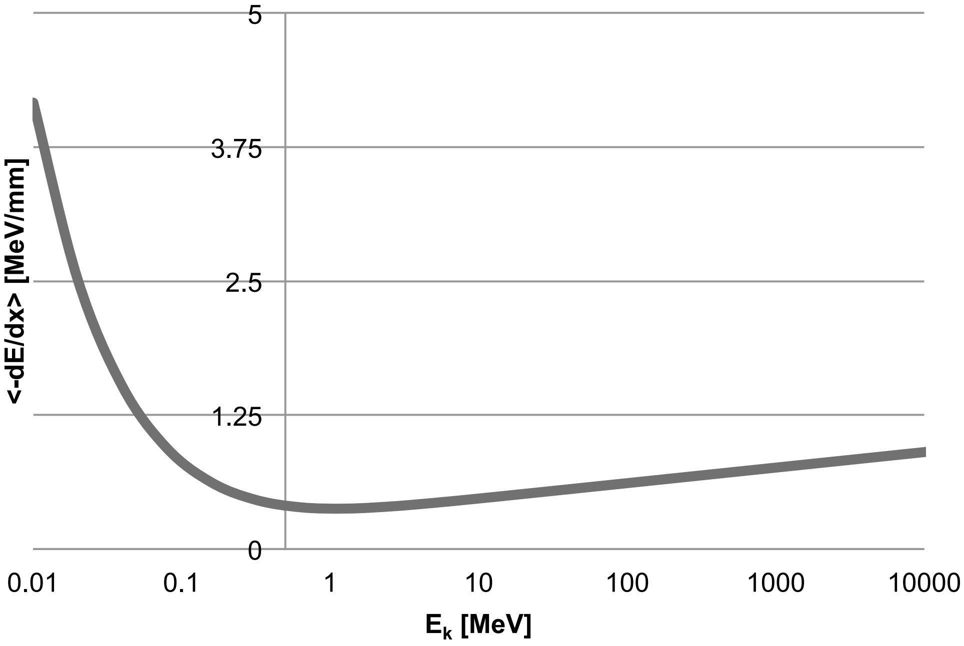
- From PDG Review of Particle Physics, “Passage of Particles Through Matter”
- Moller cross section divided by dx is the stopping power

$$\left\langle -\frac{dE}{dx} \right\rangle = \frac{1}{2} K \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \frac{m_e c^2 \beta^2 \gamma^2 \{m_e c^2 (\gamma - 1)/2\}}{I^2} \right.$$

$$\left. + (1 - \beta^2) - \frac{2\gamma - 1}{\gamma^2} \ln 2 + \frac{1}{8} \left(\frac{\gamma - 1}{\gamma} \right)^2 - \delta \right]$$

Ionization stopping power

- Using the relevant parameters for Gadox we obtain a plot for stopping power as a function of energy (without the density correction term “delta”)



EM cascade stopping power

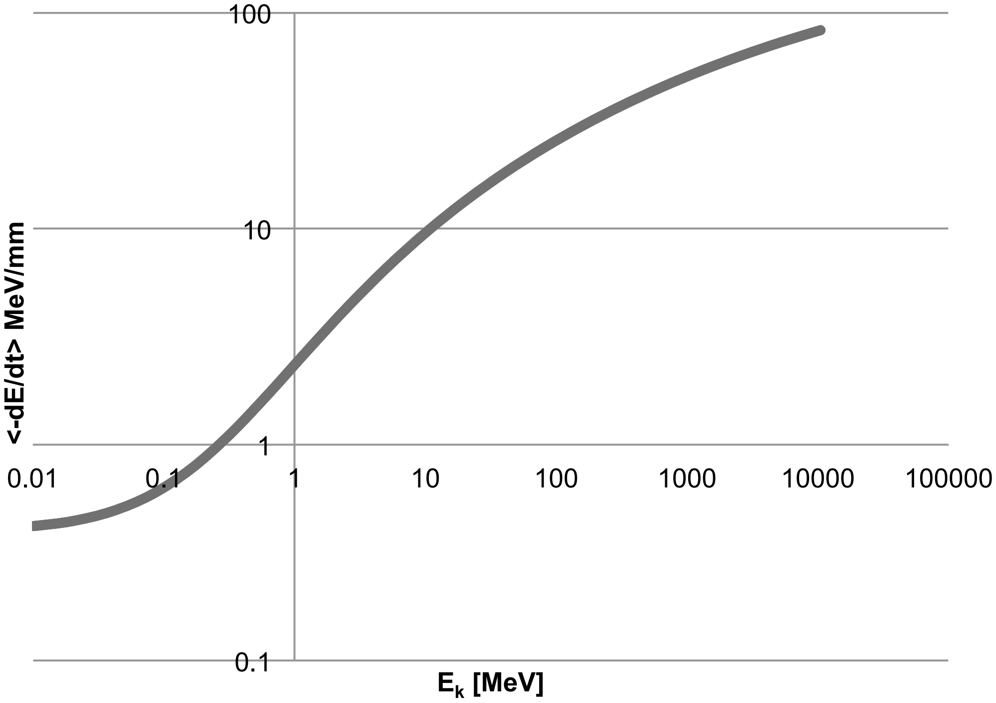
$$\frac{dE}{dt} = E_0\, b\, \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

$$t_{\max} = (a-1)/b = 1.0 \times (\ln y + C_j)\ , \qquad j = e, \gamma\ ,$$

- ‘b’ depends on Z of atoms in material and energy, approx. 0.5 for Gd
- y is energy in units of the critical energy (energy at which energy loss by brems. = particle energy, 11.27 MeV for Gadox (source: PDG)
- t is distance in units of radiation length (mean distance over which E is reduced to (1/e)E_0)
- C_e = -0.5, C_{gamma}=0.5

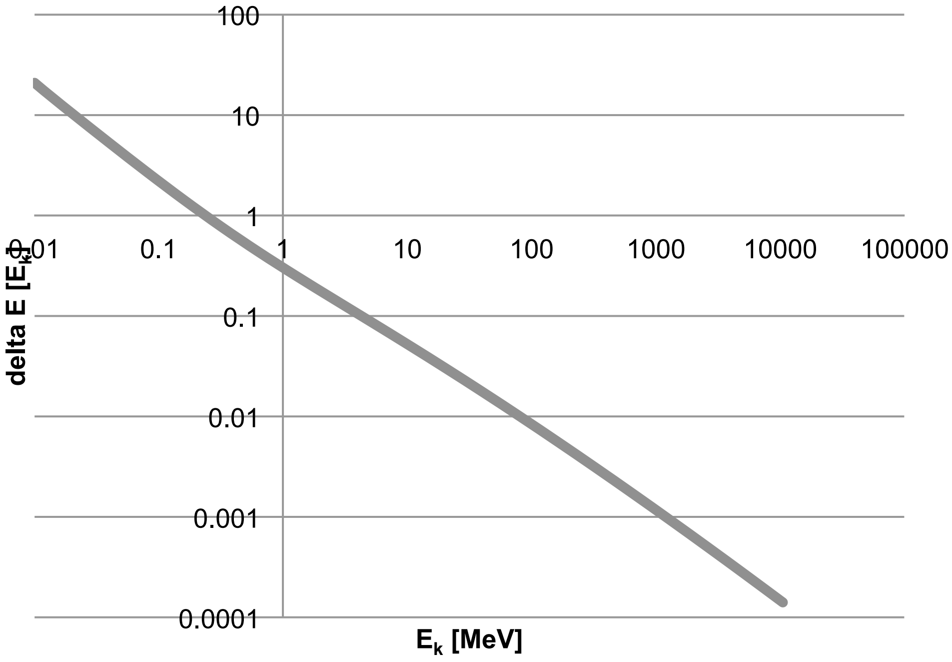
EM cascade stopping power

Using the above equations and Gadox parameters: stopping power due to EM cascade at x=900mum (thickness of our screen)



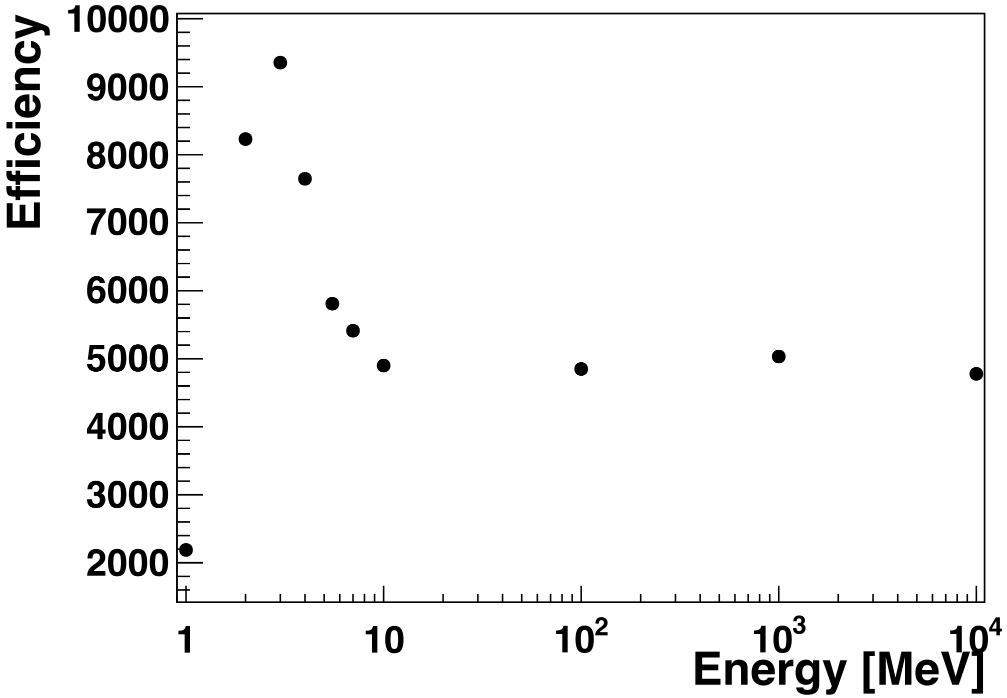
EM cascade stopping power

- Fractional energy loss from brems. of an electron with initial kinetic energy E_k over 900 microns of Gadox (screen thickness)
- Note: plot show that below about 10MeV, a significant fraction of the particle energy is lost in the screen to EM cascade



Screen output and PSF vs electron energy

- So the number of photons goes down at low energies because most or all of the particle energy is lost in either
  - The 200 micron PET backing layer of the screen
  - In the scintillator but far from the surface
    - Fewer photons reach the surface due to refraction from the particles

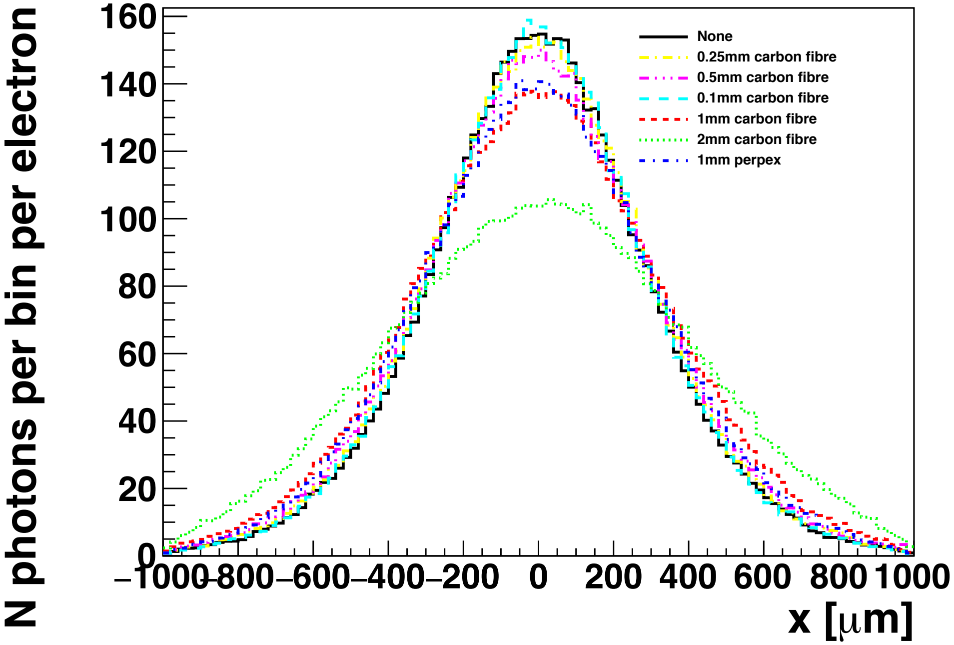


Screen backing thickness

- Screen will be mounted in some sort of frame
- We may need to mount the screen samples (10cm by 10cm) on a larger (~20cm by 20cm?) backing layer:
  - Would keep sample flat
  - Would keep the frame out of the edges of the beam

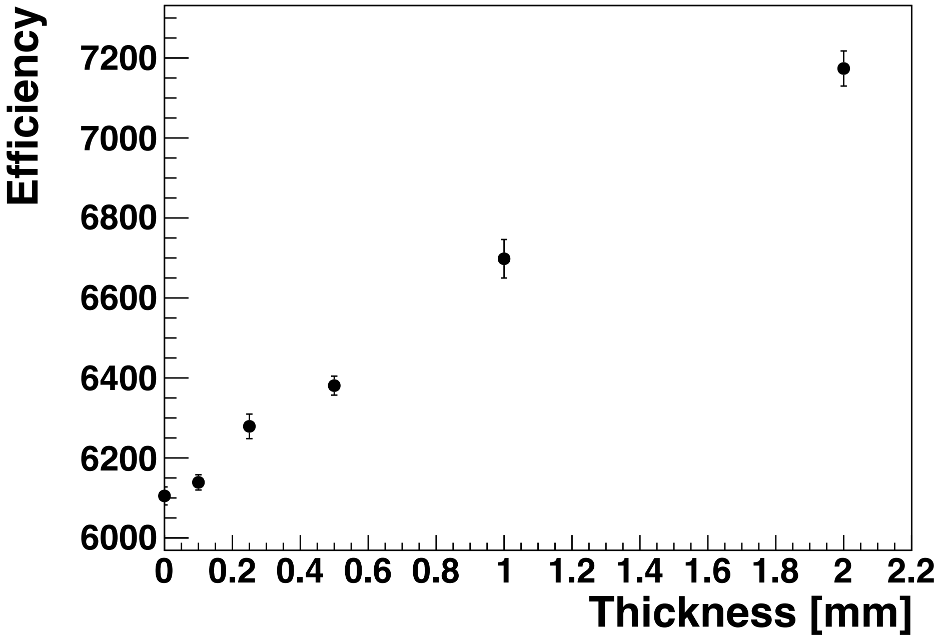
Screen backing thickness

- Photon emission profile for various backing thicknesses and materials



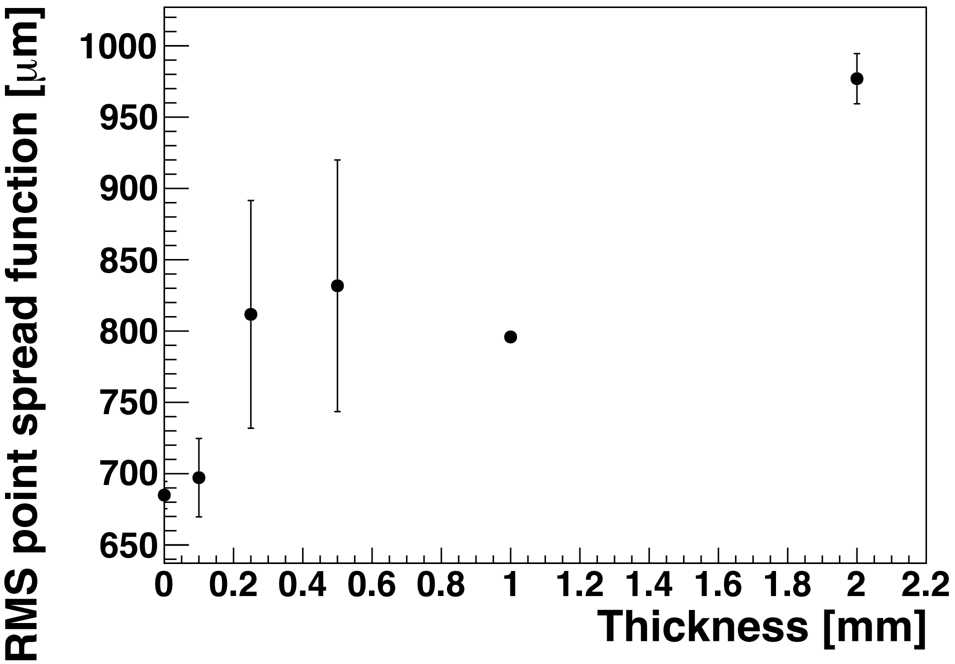
Screen backing thickness

- Efficiency vs. thickness of carbon fiber backing
- Efficiency improves slightly with thickness
  - **Reason: EM cascade produces more low E particles which have greater ionization stopping power**



Screen backing thickness

- PSF vs. thickness of carbon fiber backing



Saturation

- High energy electrons excite the scintillator, which then returns to the ground state, emitting photons.
- If excitation energy density in screen is too high screen can become saturated:
  - Light output no longer increases linearly with charge density – dL/dC decreases
  - Screen can be damaged
- Previous experiments have detemined *[1]* the charge density at which saturation occurs (linearity drops below 90%) for Lanex regular screens – 66 pC mm^{-2}

Saturation

- Rate of excitiation energy density change given by the sum of:
  - The incoming charge flux density (due to electron beam) – constant and positive
  - The decay of excitation energy into photons – negative, proportional to excitation energy density
- This implies the following equation (phi = excitation energy density, F = charge flux density, lambda = the scintillator decay constant)

$$\frac{d\phi}{dt} = F - \lambda\phi$$

Saturation

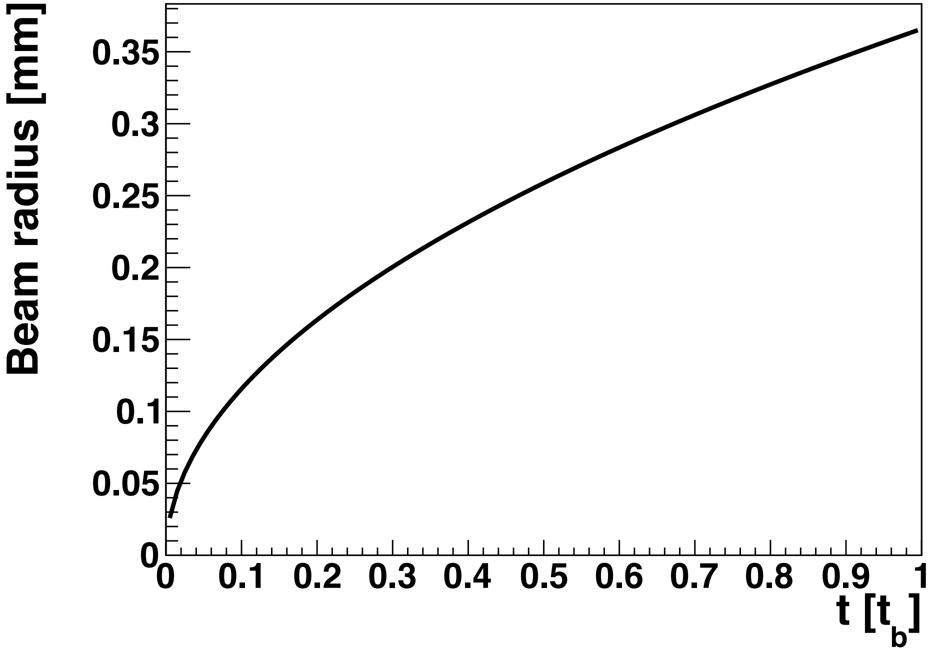
- Solving (with initial condition phi=0 at t=0) gives

$$\phi = \frac{F}{\lambda}\left(1 - e^{-\lambda t}\right)$$

- *F* is given by the PHIN beam parameters.
- The decay time (time for lanex to decay to 0.1 times the initial excitation energy) = 1.5 ms
- This gives lamba = 1.5 ms^{-1} (using $\phi = \phi_0 e^{-\lambda t}$)
- Using the above, and the saturation density of Lanex, we can predict the beam radius / time curve for saturation.
- **Have checked the above solution with MATLAB**

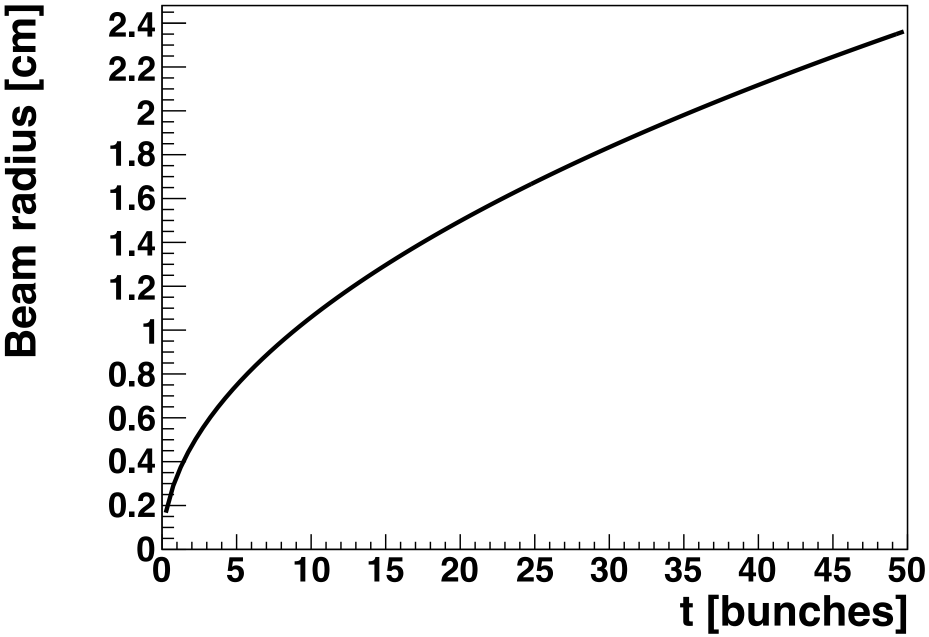
Intrabunch saturation

- Current is averaged over 1 bunch.
- Assumes circular beam profile.
- X-axis: time in units of bunch length.
- Below the curve saturation occurs.
- PHIN minimum beam size: 1.5 mm – saturation not possible during single bunch



Intratrain saturation

- Same as above, except current is averaged over a bunch train.
- X-axis: time in units of bunches.
- Predicts that saturation can occur at PHIN after a few bunches (depending on the beam size used).



Conclusions

- Simulations predict good screen output for 5.5 MeV electron beam at PHIN.
- Screen resolution will be ~factor 1.5 worse at 5.5 MeV compared to AWAKE beam (all energies above 10 MeV)
- Care should be taken not to saturate the screen at PHIN. Saturation conditions at PHIN have been predicted analytically using the measured decay constant and saturation density of Lanex.

References

[1]
THE PHIN PHOTOINJECTOR FOR THE CTF3 DRIVE BEAM, R. Losito et. al., EPAC06 Edinburgh

[2]
A. Buck *et al*, **Absolute charge calibration of scintillating screens for relativistic electron detection,** Review of Scientific Instruments **81**, 033301 (2010); doi: 10.1063/1.3310275