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On Radiation Damage and the Hadronic Calorimeter Choice of GEM

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Abstract:

The importance of radiation damage for the hadronic calorimeter choice of GEM is investigated. The radiation levels is this part of the detector stay well under 1 Mrad/yr for the entire barrel/endcap range ($-3 < \eta < 3$) when the SSC operates at design luminosity. At a luminosity of 10^{34} cm^{-2}s^{-1}, in 10 years less than 5 Mrad will be accumulated at $\eta = 2.5$ and at maximum 25 Mrad at $\eta = 3$. The accumulated doses in the entire barrel region stay well below 1 Mrad under these harsh conditions. The radiation hardness of commercially available fibers is such that no unacceptable degradation in the hadronic calorimeter performance occurs up to levels of about 10 Mrad. If one would decide to replace fibers after they receive 10 Mrad, only of the order of 1% of the fibers would qualify for this operation in a period of 10 years SSC running at $L \approx 10^{34}$ cm^{-2}s^{-1}. If liquid argon were chosen as the active material of the hadron calorimeter, the three time higher neutron flux created in that way would jeopardize the electronics buried inside the calorimeter volume and elsewhere. Moreover, it would proportionally increase the problems caused by induced radioactivity and by spurious hits in the tracking and muon detectors.

1. Introduction

The GEM Collaboration will soon have to choose the technology for its hadron calorimeter: Liquid argon or scintillating plastic fibers. Many aspects play a role in this choice, e.g. cost, energy resolution, speed of response, hermeticity, etc. In this note, the role of possible radiation damage and its effects on the detector performance are investigated. This note does not contain any original work, it summarizes work performed and published by others. In section 2, we determine the radiation levels that have to be expected in the various parts of the hadronic calorimeter system. In section 3, we review the experimental information concerning the radiation hardness of scintillating plastic fibers. In section 4, the effects of the neutron production, which is very sensitive to the calorimeter choice, are discussed. Conclusions are presented in section 5.

2. Radiation levels in GEM's hadron calorimeter

In agreement with the GEM baseline, we assume that what is usually called the barrel/endcap calorimeter system covers an area of 6 units in pseudorapidity ($-3 < \eta < 3$). In the very forward areas ($|\eta| > 3$), radiation hardness will probably be the single most important criterion for choosing a particular calorimeter technology. The radiation levels are extremely η-dependent and reach worrysome values in the $\eta \sim 3$ area. Therefore, a change in technology is foreseen at that point.

It should be emphasized that the radiation levels in the hadron calorimeter are considerably lower than in other parts of the detector. In particular, they are much lower than in the electromagnetic (e.m.) section of the calorimeter system. The e.m. section absorbs all the abundantly produced π^0's. Also, a good fraction of the e.m. component of hadronic showers is deposited in this section. And since the dose depends on the amount of energy deposited per unit detector volume and since the radiation length is at least an order of magnitude smaller than the nuclear interaction length, the radiation doses in the hadron calorimeter may be expected to be an order of magnitude lower than those in the e.m. calorimeter.

This is confirmed by the Monte Carlo simulations of which the results have been published. The most authorative results were obtained by Groom and coworkers[1] . In fig. 1, the calculated *maximum* dose annually induced by photons and hadrons in a lead sphere is shown as a function of pseudorapidity, for the SSC operating at $\mathcal{L} = 10^{33}$ cm^{-2}s^{-1}. The maximum dose induced by photons is about a factor 13 larger than for hadrons. The figure also shows that the hadron-induced dose changes as $1/R^2$ with the distance R between the interaction vertex and the front face of the hadron calorimeter.

In table 1, the maximum radiation doses in the GEM hadron calorimeter, as derived from the curves in fig. 1, are listed. The distance R was determined from the LAr/LKr baseline, assuming that the hadron calorimeter starts 70 cm beyond the front face of the e.m. calorimeter. The table shows that the doses accumulated *during 10 years running* at a *luminosity of* 10^{34} cm^{-2}s^{-1} stay well under 1 Mrad for the entire barrel region and for a good fraction of the endcap. Only in the area very close to $|\eta| = 3$ is the level of 10 Mrad exceeded.

It is likely that the numbers given in table 1 *overestimate* the radiation doses, since the GEM hadron calorimeter is not a lead sphere (as assumed in the calculations of ref. 1). The effective nuclear interaction length of both options is slightly larger than for pure lead. More importantly, the radiation length X_0 of copper is 14 mm, compared to 5.6 mm for lead. Since the maximum dose in hadron showers is reached in the e.m. core, it may be expected to scale as X_0^{-1}. Also, the maximum dose for hadron showers may actually occur *in front of the hadron calorimeter*, i.e. in the e.m. calorimeter, especially when the average energy is low (small η). This is confirmed by calculations by Efremenko (fig. 2), which show that the maximum dose in the hadron calorimeter always occurs at its front face (for $|\eta| < 2.5$).

The SDC Collaboration has also estimated radiation levels in their calorimeter system[2] . In the endcap region, their hadron calorimeter starts at about 4.5 m from the vertex, compared to $\sim$ 3 m for GEM. The radiation levels envisaged are about a factor 2 lower than the ones listed in table 1 (fig. 3). It is also interesting to note from their results that the maximum dose in the hadron calorimeter is reached at its front edge. The dose drops by an order of magnitude over a distance of 50 cm in depth (fig. 3b). These facts are in agreement with fig. 2.

We conclude that radiation damage, if a problem at all for the hadron calorimeter, is extremely localized. Even when considering a scenario of 10 years running at a luminosity of 10^{34} cm^{-2}s^{-1}, a dose level of 10 Mrad could only be reached very close to the high-η detector boundary ($|\eta| = 3$). For $|\eta| = 2.5$, the dose is already lower by a factor 3-5 and the dose stays well below 1 Mrad in the entire barrel region for this worst-case scenario.

3. The radiation hardness of scintillating plastic fibers

The radiation damage of plastic scintillators has been studied by a great many different authors. Several conferences and workshops were completely or partially devoted to this topic in recent years[3,4] . An excellent recent review of the state of the art can be found in ref. 5. Degradation of polymers occurs via chain scission and cross-linking.

Absorption of ionizing radiation is one of a variety of processes that may cause such effects. Heat, illumination and ultrasonic vibrations are a few other examples. The main effects of ionizing radiation on scintillating plastic fibers are a reduction of the light emission and/or increased light attenuation in the fibers. Both effects are extremely wavelength dependent (fig. 4). This is one of the reasons why fibers working in the green part of the spectrum (e.g. 3-HF) have become so popular.

At least part of the effects induced by ionizing radiation are nonpermanent. The annealing process can be stimulated by heat or by oxygen[6,7] (fig. 4). Oxygen also plays a significant role in the radiation damage itself. In the presence of oxygen, radiation damage appears to be dependent on the dose *rate*, the diffussion of oxygen in the exposed material being the determining factor[8] . The annealing process can also be accelerated in quite unexpected ways. Markley and coworkers developed a plastic consisting of a mixture of polystyrene (70%) and Dow Corning oil DC705 (30%). The latter product increases the rate of annealing considerably. They showed experimentally that a scintillator based on this type of plastic decreased only by 4% in light emission after receiving 10 Mrad of ionizing radiation[9] . Since the dose rates at the SSC (even for $\mathcal{L} = 10^{34}$) are much lower than the ones ued in most radiation damage studies, the results observed *after* annealing are probably the most relevant ones for assessing the effects at the SSC, where most likely some equilibrium between damaging and annealing processes will occur.

The effects of radiation on the light emitting fluor appear to be dependent on the fluor *concentration*. At increased levels of concentration, the effects of radiation decrease[10,11] . Clough and coworkers[12] found that the radiation damage of the base polymer depends on the type of fluo with which the plastic is doped. At 100 Mrad, enhanced color center formation was observed for some fluors (e.g. 3-HF), but not for others (e.g. PTP).

The mentioned dose levels illustrate the progress that is being made in this field. A few years ago, 10 Mrad was generally considered a very problematic dose level for plastic scintillators, nowadays the research focuses on the challenges at 100 Mrad. The detailed understanding of the mechanisms causing radiation damage has lead to better (more radiation hard) products and this trend will certainly continue.

It is well known that the signals from scintillator-based detectors are not a constant of nature. As mentioned before, effects other than ionizing radiation contribute to this fact. Yet, scintillator-based detectors have been essential in many major discoveries in particle physics experiments. Therefore, the correct question to ask is not if one can completely avoid the effects of ionizing radiation, but if one can live with it. To be more specific, one should ask:

1) Can the changes in the optical characteristics be monitored with sufficient precision?

2) At which dose level do the changes in the optical characteristics start to have unacceptable consequences for the performance of the calorimeter?

The first question can definitely be answered affirmatively. Both the UA2[13] and the CDF[14] Collaborations, who have operated scintillator-based calorimeter systems for a period of the order of 10 years, claim that they know the absolute calibration of their detector cells at any point in time with a precision of about 1.5%, which is better than the constant term in the energy resolution considered acceptable by the GEM Collaboration.

The second question was studied by Acosta and coworkers[15] . They investigated the effects of a change in the light emission and light attenuation in scintillating fibers on a number of calorimeter performance figures, i.e. the constant term in the e.m. and hadronic energy resolution, the signal linearity and the π^0/π^+ signal ratio. Once one defines what level of performance degradation is unacceptable, the maximum dose to be received by a given type of fibers follows automatically.

It turns out from this study that the e.m. performance is more sensitive to a given dose level than the hadronic performance. For example, when the radiation damage causes an increase of the constant term in the e.m. energy resolution of 0.8%, the constant term in the hadronic energy resolution changes only by 0.2% (fig. 5). The best fibers tested in this study gave a degradation in the calorimeter performance of this magnitude after having receivd 7 Mrad of ionizing radiation.

When considering fibers for the purpose of *hadron* calorimetry, where the requirements on performance are much less stringent than for the e.m. section, it is therefore very safe to assume that levels of 10 Mrad will not cause any significant degradation of the performance, *provided of course that the changes in the optical properties can be adequately monitored.*

4. Effects of neutrons

The choice between the two hadron calorimeter options will have important implications for the neutron flux, both inside and outside the calorimeter system. The calorimeter system is the single most important source of neutron production in the SSC environment, Experimental data show that, depending on details of the calorimeter configuration, up to 60 neutrons may be produced for every GeV of absorbed energy[16] These neutrons have a number of important consequences:

1) They are (almost exclusively) responsible for *induced radioactivity* in the detector[16] . This is due to their abundant production rates and to the large cross sections for nuclear reactions at low energies (MeV range), which occur since the

Coulomb barrier that prevents such reactions for charged particles does not apply. The induced radioactivity will determine and limit the accessibility of the detector in beam-off periods. It will also have undesirable side effects like pedestals depending on the luminosity history, etc.

2) Neutrons are a particular threat to silicon-based electronics. Elastic collisions (the main source of energy loss for neutrons below ~ 1 MeV) with Si nuclei cause lattice imperfections which increase the leakage current in the semiconductor material. The highest neutron fluxes are reached inside the calorimeter. Groom[1] finds values of $10^{16}\text{n}/\text{cm}^2$ for $\eta = 3$ after 10 years of running at $\mathcal{L} = 10^{34}\text{cm}^{-2}\text{s}^{-1}$ (fig. 6). This is orders of magnitude beyond the level that is considered acceptable for standard electronics. Therefore, radiation damage induced by neutrons in the preamplifiers buried in the liquid argon calorimeter should be a very serious concern if this option were to be chosen.
   Some fraction of the neutrons leak out of the calorimeter, both downstream (towards the muon chambers) and upstream (to the tracking systems). In an early report on radiation damage issues published by the SSC Central Design Group[17] damage of electronics by the latter neutrons was considered thee single mot worrysome item.

3) The neutrons leaking out of the calorimeter will cause spurious hits in the upstream tracking and downstream muon detection systems. This may seriously jeopardize the trigger function of these detectors.

The neutron yield is very sensitive to the choice of the active and passive calorimeter materials. This was experimentally observed by Leroy and coworkers[16], and confirmed by Monte Carlo simulations[18]. Table 2 lists the relative neutron fluxes for various calorimeter configurations. It turns out that for a given absorber material, the neutron flux is more than a factor three lower when plastic scintillator is used as active material, compared to liquid argon. This is due to the moderating effect of the hydrogen in the plastic, which rapidly slows neutrons down to the point where they don't multiply further through new nuclear interactions. The mentioned differences between the neutron yields in LAr and plastic-scintillator calorimeters works out proportionally in the problems caused by these neutrons.

The radiation damage caused by scattering neutrons is a very specific problem for semiconductor material. It has no equivalent in plastic scintillator. Radiation damage studies of plastic scintillators showed that there is no difference between the effects caused by neutrons and by photons if the ionization doses are the same[19,20]. And since neutrons carry only of the order of 10% of the shower energy and since they deposit this energy over a much larger area in depth than for example the π^0's generated in the core of hadron showers, the neutron contribution to the radiation doses in fiber calorimeters is in practice negligible.

5. Conclusions

From the facts as they are known today, I conclude that radiation damage considerations are certainly *not* an argument in favor of the liquid argon option. On the contrary. The specific hazards caused by the increased neutron fluxes for the experiment as a whole and for the inaccesible electronics buried inside the cryostat in particular, should be taken very seriously.

The effects of ionizing radiation on the performance of a scintillating-fiber hadron calorimeter are most likely completely negligible, even after a period of 10 years running at a luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Realistic estimates of the doses to be expected under such conditions give at maximum 25 Mrad at $|\eta| = 3$, dropping off by a factor of ~ 5 at $|\eta| = 2.5$. With fibers that are commercially available *today*, no significant deterioration of the *hadronic* calorimeter performance occurs up to levels of at least 10 Mrad. Further progress in the production of radiation hard scintillating fibers may be expected.

If, for some unforeseen reason, radiation damage in the fibers would cause an unacceptable degradation in the performance of the hadron calorimeter, this effect would be extremely local, because of the characteristics of the dose distribution profile (the dose scales like $e^{2.8\eta}$). In order to cope with such an unforeseen situation one might either:

1) Equip the detector in the region $2.5 < |\eta| < 3$ with special radiation hard fibers, e.g. the ones being considered for the forward calorimeters, or

2) Design the part of the endcaps between $|\eta| = 2.5$ and $|\eta| = 3$ as a separate plug, which can be removed/replaced if and when necessary, e.g. once every 3 years.

It is useful to remember that the mentioned area represents only of the order of 1% of the total hadron calorimeter. As was said before, such redundancy is very likely to be superfluous.

Finally, it is interesting to note that the SDC Collaboration, who plan to use plastic scintillator as active material for both the e.m. and the hadronic sections of their calorimeters in the region up to $|\eta| = 3$, and who therefore face much higher radiation levels in a much more critical component of their detector (58 Mrad in the e.m. calorimeter[2]) than in the GEM case, do *not* consider radiation damage of the plastic scintillator as a threat to their physics goals. However, SDC is taking this issue very seriously and therefore pursues a vigorous R&D program in collaboration with scintillator producing companies like Kuraray and Bicron, with the goal of producing plastic scintillators with better radiation resistent characteristics. Obviously, GEM could benefit from this at minimal expense.

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FIGURE CAPTIONS

1. The maximum dose induced annually by photons (dashed line) and hadrons (solid lines) in a lead sphere at the indicated radius. Monte Carlo data for the SSC operating at $\mathcal{L} = 10^{33}$ cm^{-2}s^{-1}. From ref. 1.
2. The dose as a function of depth inside the hadron calorimeter, for various values of η. Results of Monte Carlo simulations of a copper/fiber hadron calorimeter behind a BaF_2 e.m. calorimeter, starting at a distance of 2.4 m from the vertex in the endcap region (GEM baseline geometry). Private communication by Yuri Efremenko.
3. Maximum ionizing doses in the SDC calorimeter for one year of running at $\mathcal{L} = 10^{33}$ cm^{-2}s^{-1} and (in parentheses) for 10 years at $\mathcal{L} = 10^{34}$ cm^{-2}s^{-1} (a). Equal radiation dose contours for the SDC endcap calorimeter after 10 years of running at $\mathcal{L} = 10^{33}$ cm^{-2}s^{-1}. The separation into e.m. and hadronic compartments and several η boundaries are indicated (b). From ref. 2.
4. Transmission coefficient as a function of wavelength for 10 cm long polystyrene samples doped with 0.1% 3-HF: Before irradiation (A), after irradiation with 10 Mrad (B) and after annealing in oxygen (C), after irradiation with another 20 Mrad (30 Mrad in total, D) and after reannealing (E). The arrow indicates the maximum in the 3-HF fluorescence spectrum. From ref. 7.
5. The impact of fiber radiation damage on the hadronic energy resolution. Shown is the effect on the constant term of a decrease in the light attenuation length (λ_{min}), for three different values of f, which measures the reduction in the light emission. Monte Carlo results from ref. 15.
6. The maximum neutron flux for a uranium/plastic-scintillator calorimeter, with the SSC operating at a luminosity of 10^{33}cm^{-2}s^{-1}. The solid curve shows the results assuming that the maximum occurs at a distance of 2 m from the interaction vertex, the dashed line is the result for a radius of 20 m. The fluxes for lead/liquid-argon are 60% larger, and for lead/scintillator a factor two smaller than the ones shown here. From ref. 18.

TABLE CAPTIONS

1. Radiation levels in the hadron calorimeter. Listed are the pseudorapidity and the corresponding polar angle, the distance from the interaction vertex to the hadron calorimeter's front face, the annual dose for a luminosity of 10^{33} cm^{-2}s^{-1} and the calorimeter at a distance of 2 meters, and the integrated dose for 10 years operation at a luminosity of 10^{34} cm^{-2}s^{-1} and the hadron calorimeter at the real distance (R). The dose data are taken from ref. 1 and assume a hadron calorimeter consisting of pure lead. Because of this assumption, the doses in the GEM calorimeter, which uses copper as absorber medium, are likely to be a factor 3-5 lower. See text for details.
2. The relative maximum neutron flux and the backscattered neutron flux for various calorimeter configurations[18] .

Table 1 Radiation Levels in Hadron Calorimeter				
η	Polar angle (^{0})	R (m)	Mrad/yr @ 10^{33} @ 2m	Mrad/10yr @ 10^{34} @ R
0.0	90	1.5	0.0007	0.12
0.5	62	1.7	0.001	0.14
1.0	40	2.3	0.003	0.22
1.5	25	3.4	0.01	0.36
2.0	15	3.2	0.04	1.6
2.5	9.4	3.1	0.13	5.4
3.0	5.7	3.1	0.60	25

Table 2 Neutron Fluxes	
Calorimeter	*Relative flux*
^{238}U/LAr	1
Pb/LAr	0.5
^{238}U/plastic-scintillator	0.3
Pb/plastic-scintillator	0.15

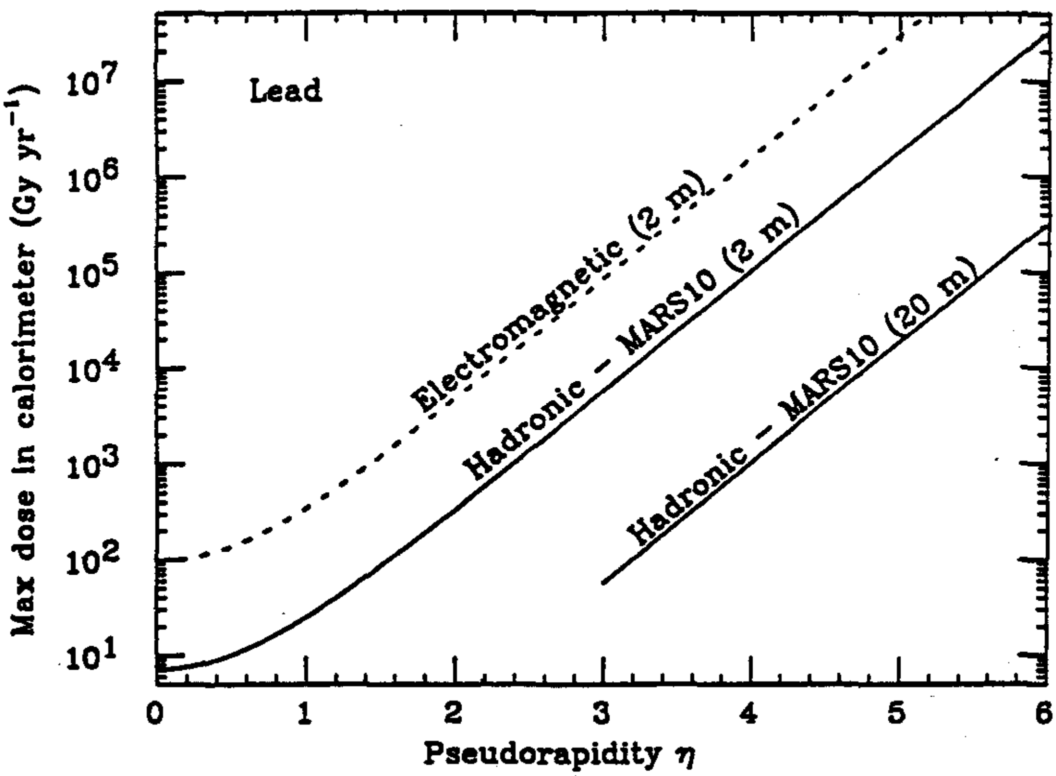

Lead
Electromagnetic (2 m)
Hadronic – MARS10 (2 m)
Hadronic – MARS10 (20 m)
Max dose in calorimeter (Gy yr^{-1})
10^1
10^2
10^3
10^4
10^5
10^6
10^7
0
1
2
3
4
5
6
Pseudorapidity η

Figure 1

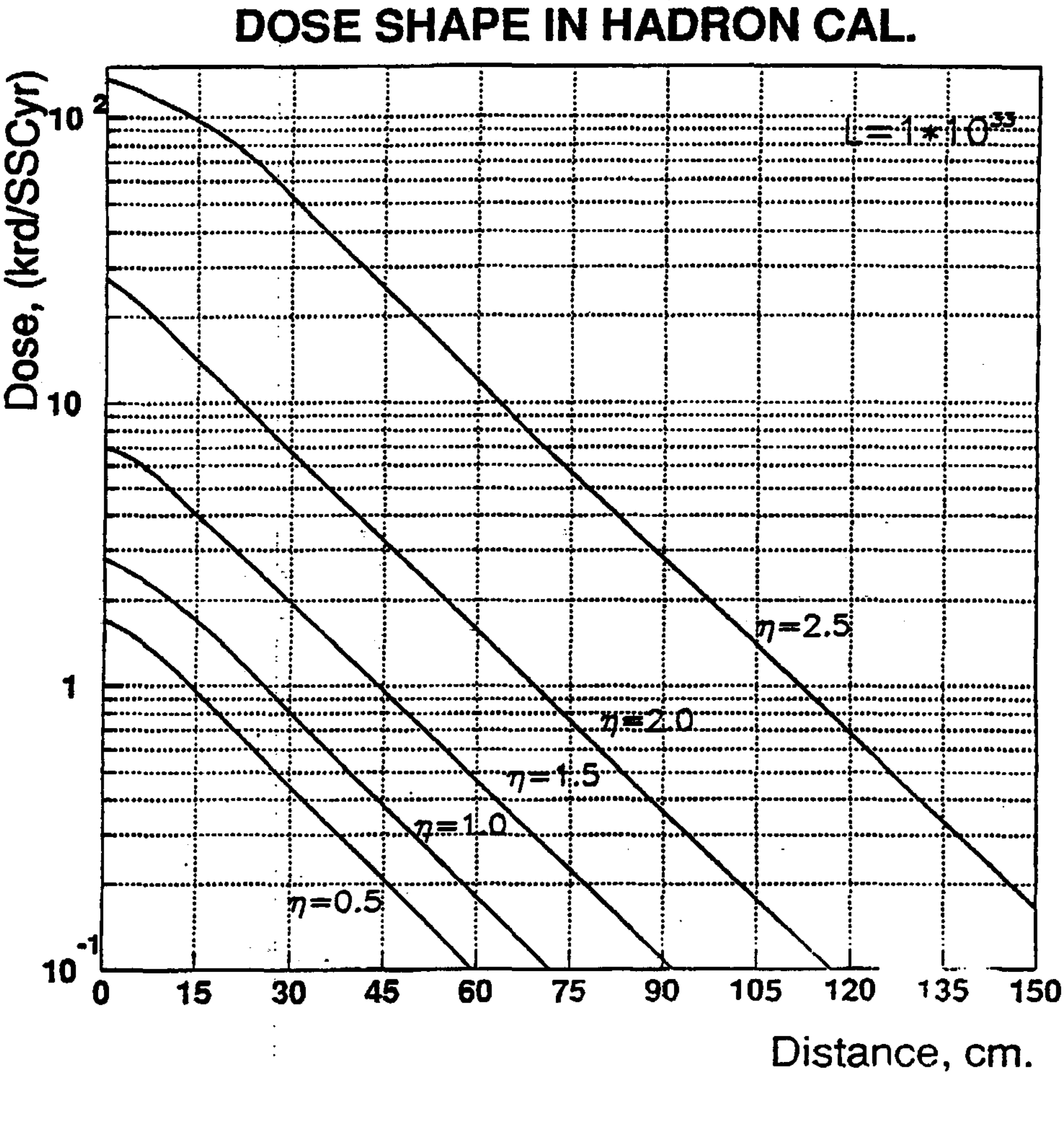

DOSE SHAPE IN HADRON CAL.
Dose, (krd/SSCyr)
L=1*10^33
η=2.5
η=2.0
η=1.5
η=1.0
η=0.5
10^2
10
1
10^-1
0
15
30
45
60
75
90
105
120
135
150
Distance, cm.

Figure 2

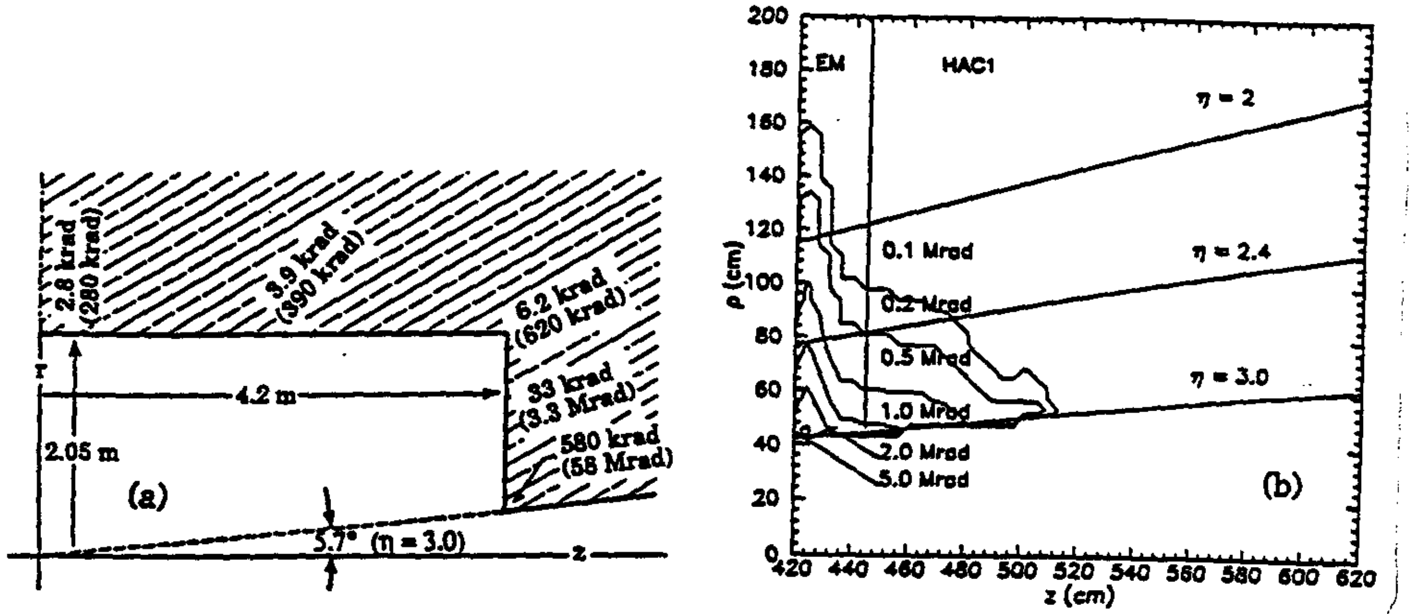
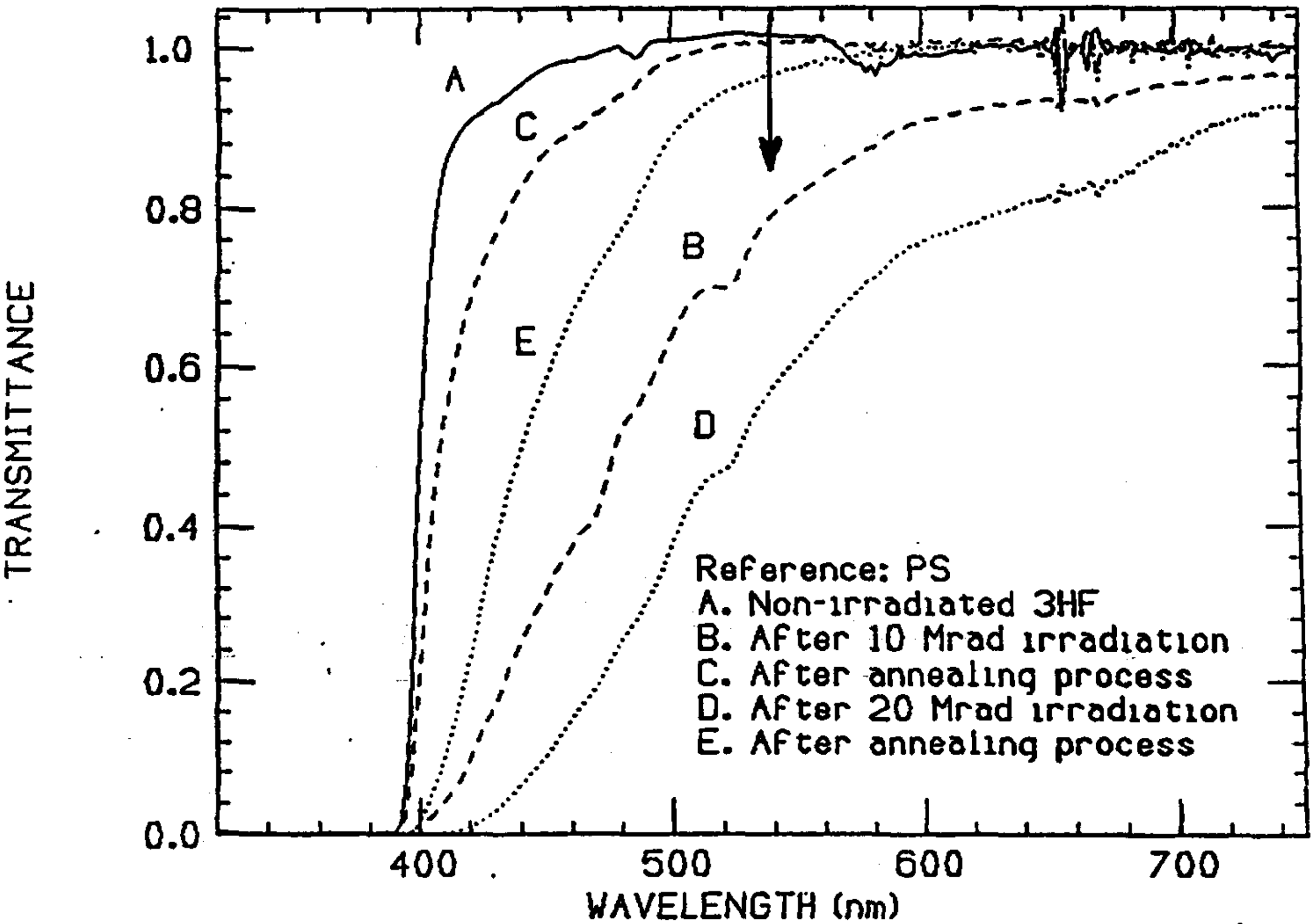

2.8 krad
(280 krad)
3.9 krad
(390 krad)
6.2 krad
(620 krad)
33 krad
(3.3 Mrad)
580 krad
(58 Mrad)
4.2 m
2.05 m
(a)
5.7° (η = 3.0)
z
EM
HAC1
η = 2
η = 2.4
η = 3.0
0.1 Mrad
0.2 Mrad
0.5 Mrad
1.0 Mrad
2.0 Mrad
5.0 Mrad
(b)
ρ (cm)
z (cm)

Figure 3



TRANSMITTANCE
1.0
0.8
0.6
0.4
0.2
0.0
400
500
600
700
WAVELENGTH (nm)
A
B
C
D
E
Reference: PS
A. Non-irradiated 3HF
B. After 10 Mrad irradiation
C. After annealing process
D. After 20 Mrad irradiation
E. After annealing process

Figure 4

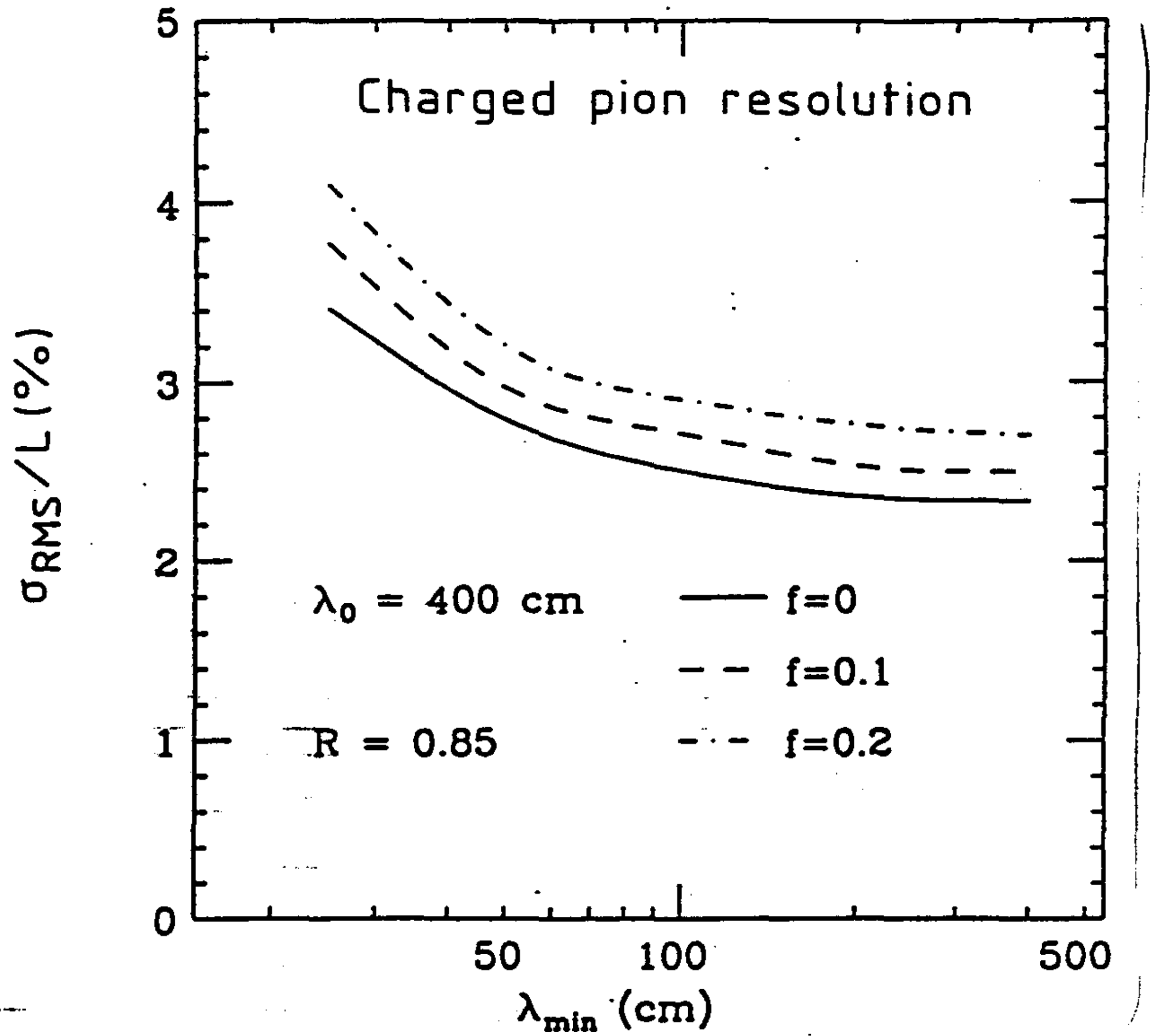
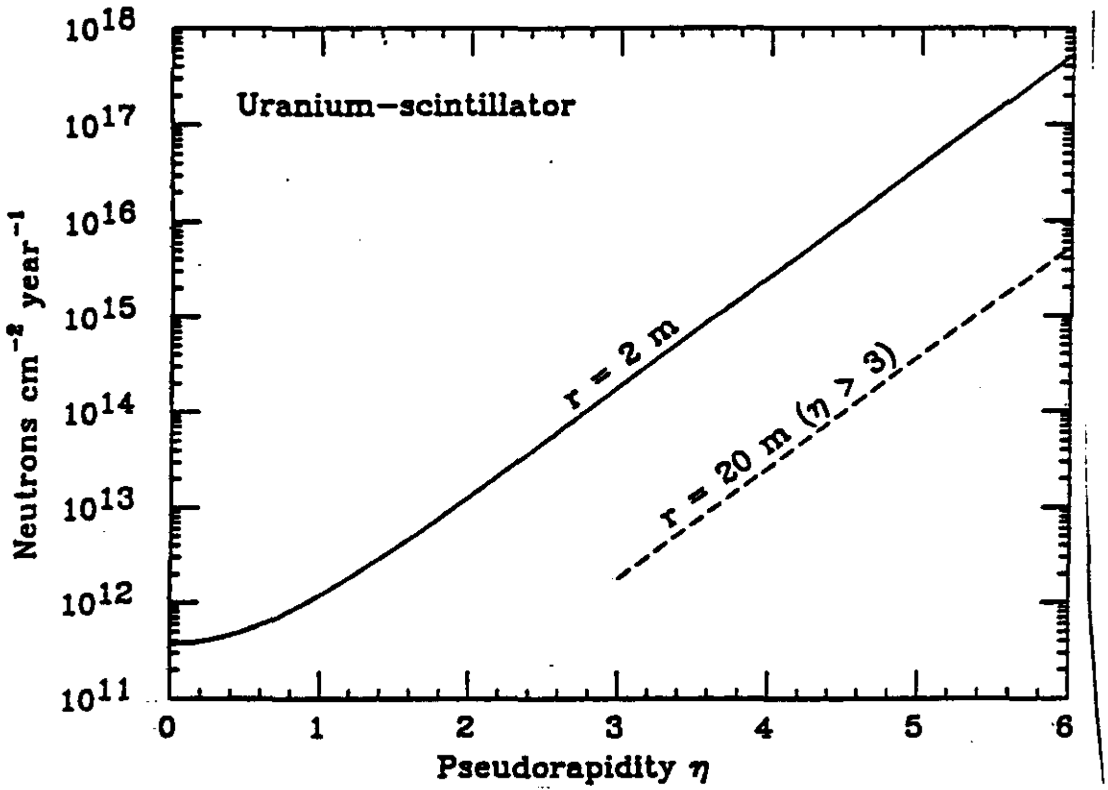

Charged pion resolution
σ_{RMS}/L (%)
λ_{min} (cm)
λ_0 = 400 cm
R = 0.85
f=0
f=0.1
f=0.2
0
1
2
3
4
5
50
100
500

Figure 5



Uranium−scintillator
r = 2 m
r = 20 m (η > 3)
Neutrons cm⁻² year⁻¹
Pseudorapidity η
10^18
10^17
10^16
10^15
10^14
10^13
10^12
10^11
0
1
2
3
4
5
6

Figure 6