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Ionization in the STAR TPC and Electronics Saturation

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This note calculates the total charge seen by a STAR preamplifier for one event. A GEANT simulation was used to find the primary ionization in the TPC (for P10), and the effects of gas gain, charge coupling to the pads, transverse diffusion and shaping time are treated to find the charge seen by the preamp. We expect the STAR preamp to become nonlinear when the voltage on the feedback capacitor reaches between 1 and 1.5 volts. The worst case scenario of the inner padrow of the inner sector for a Au + Au event is studied.

1 Maximum Charge into a Preamp

The following expression is used to calculate the maximum charge Q seen by any preamp:

Q = (P.I.) (G.G.) (C.C.(1))

(P.I.) = maximum primary ionization over a pad, from GEANT simulation, see III.

(G.G.) = gas gain, determined by S/N requirement, see IV.

(C.C.(1)) = charge coupling factor to a single pad, see IV.

= (6150 e^-) (220) = 1.35E+6 e^- = 0.22 pC

This result is the maximum charge seen by any preamp. The value of (G.G.)(C.C.(1)) = 220 is from section IV.

With regards to preamplifier saturation it is useful to calculate the voltage level on the 0.5 pf feedback capacitor which results from integrating this much charge:

$$V = Q/C = (0.22\ \mathrm{pC})/(0.5\ \mathrm{pf}) = 440\ \mathrm{mV}$$

Hence the preamp integration range (1 to 1.5 V) is roughly 3 times the maximum charge accumulated on a pad.

2 Average Charge into a Preamp

The calculation of the average charge seen by a preamp is similar to that for the maximum, except that we account for all of the charge coupling and use the average ionization over a pad:

Q = (P.I.) (G.G.) (C.C.(all))

(P.I.) = average primary ionization over a pad, see III.

(G.G.) = gas gain, determined by S/N requirement, see IV.

(C.C.(all)) = charge coupling factor to all pads.

= (P.I.)	(G.G.)(C.C.(1))	C.C.(all)/C.C.(1)	
= (731 e^-)	(220)	(2.32)	= 3.75E+5 e^-
			= 0.60 pC

The result from Appendix II, C.C.(all)/C.C.(1) = 2.32 has been used here. Again we calculate the voltage which would result from integrating this charge on a 0.5 pf capacitor:

V= Q/C = (0.060 pC)/(0.5 pf) = 120 mV

Hence the preamp integration range (1 to 1.5 V) is between 8 and 13 times the average charge accumulated on a pad.

3 Primary Ionization

The results of a GEANT simulation for one Au + Au event at RHIC are listed in Appendix I. Only one sector is shown, but similar results were obtained for other sectors. The table shows the total energy loss (GeV) over each pad of the innermost row of an inner sector of the STAR TPC. Pads with no ionization over them are not shown. Also shown are the number of hits on each pad, and the energy loss per hit (q/h). These results are summarized below:

average number of hits	= 2.6	
average energy loss	= 0.19E-4 GeV	= 731 e^-
average energy loss per hit	= 0.73E-5 GeV/hit	= 280 e^-/hit
maximum energy loss (pad 17)	= 0.16E-3 GeV	= 6150 e^-

The averaging was done only over those pads with hits on them. The last column shows the energy loss converted into ionization electrons assuming it takes 26 eV to produce each electron in P10 gas.

The following observations about the simulations are consistent with expectations:

For a minimum ionizing particle (MIP) passing straight over the center of the pad with dip angle of zero degrees the average energy loss in P10 is

$$(80\ \text{e/cm})(1.2\ \text{cm}) = 96\ e^-$$

The average energy loss per hit from the simulation is about 3 times this value, presumably due to more heavily ionizing particles as well as dip angle and crossing angle effects.

The simulation also produced plots of dE/dx vs rigidity which showed an energy loss for minimum ionizing particles (MIPs) of

$$dE/dx = 0.20\text{E-5 GeV/cm} = 77\ e^-/\text{cm}$$

This is consistent with the average energy loss for MIPs in P10 of 80 electrons/cm.

4 Gas Gain, Charge Coupling and Signal to Noise Ratio

The gas gain is determined by the requirement that the signal from a MIP (passing straight over the center of a pad with a dip angle = 0) has a signal to noise ratio of 20:

$$(80\ \text{e/cm})(1.2\ \text{cm})(\text{G.G.})(\text{C.C.}(1))(0.76) = 20 \times (800\text{e})$$

80 e/cm	= average ionization for a MIP in P10
1.2 cm	= inner sector pad length
G.G.	= gas gain
C.C.(1)	= the charge coupling to one pad
0.76	= fraction of signal which gets through shaper, due to finite shaping time (180ns FWHM). This value was measured directly by F. Bieser and H. Wieman, to become a STAR note. An EOS preamp and IC shaper were used.
800e	= expected rms noise level of PASA chip

Solving the above equation yields (G.G.)(C.C.(1)) = 220.

5 Appendix I. Output from GEANT simulation.

A = row + sector*l00 for rows 1–45 and sectors 1–24
what sector, 1–24:
1
what row, 1–45:
1
use sep=1 or use wid=2 (pad separation recommended):
1
Monte Carlo charge per hit on each pad of given row and sector.
row length 28.9231 rl/sep 86.3375 rl/wid 101.4844 expect 88 pads
xl 43.9230 x2 15.0000 xn 53.7945 yn 31.0583

```
A= 101 pad=  4 hits= 5 q= 0.1607E-04 q/h= 0.3213E-05
A= 101 pad=  5 hits= 2 q= 0.1563E-04 q/h= 0.7814E-05
A= 101 pad=  6 hits= 3 q= 0.2729E-04 q/h= 0.9098E-05
A= 101 pad=  7 hits= 2 q= 0.7626E-05 q/h= 0.3813E-05
A= 101 pad=  8 hits= 2 q= 0.2408E-04 q/h= 0.1204E-04
A= 101 pad=  9 hits= 1 q= 0.1466E-05 q/h= 0.1466E-05
A= 101 pad= 10 hits= 4 q= 0.1980E-04 q/h= 0.4950E-05
A= 101 pad= 11 hits= 2 q= 0.1469E-04 q/h= 0.7347E-05
A= 101 pad= 12 hits= 2 q= 0.8668E-05 q/h= 0.4334E-05
A= 101 pad= 13 hits= 1 q= 0.4315E-05 q/h= 0.4315E-05
A= 101 pad= 14 hits= 1 q= 0.1601E-05 q/h= 0.1601E-05
A= 101 pad= 15 hits= 4 q= 0.2720E-04 q/h= 0.6800E-05
A= 101 pad= 16 hits= 1 q= 0.6827E-05 q/h= 0.6827E-05
A= 101 pad= 17 hits= 4 q= 0.1581E-03 q/h= 0.3953E-04
A= 101 pad= 18 hits= 6 q= 0.2656E-04 q/h= 0.4427E-05
A= 101 pad= 20 hits= 2 q= 0.2085E-04 q/h= 0.1043E-04
A= 101 pad= 21 hits= 5 q= 0.1593E-04 q/h= 0.3187E-05
A= 101 pad= 22 hits= 3 q= 0.7426E-05 q/h= 0.24?5E-05
A= 101 pad= 23 hits= 3 q= 0.1253E-04 q/h= 0.4175E-05
A= 101 pad= 24 hits= 3 q= 0.1001E-04 q/h= 0.3338E-05
A= 101 pad= 25 hits= 2 q= 0.1067E-04 q/h= 0.5333E-05
A= 101 pad= 26 hits= 2 q= 0.1956E-04 q/h= 0.9778E-05
A= 101 pad= 27 hits= 1 q= 0.2171E-05 q/h= 0.2171E-05
A= 101 pad= 28 hits= 3 q= 0.7841E-04 q/h= 0.2614E-04
A= 101 pad= 29 hits= 2 q= 0.2460E-04 q/h= 0.1230E-04
A= 101 pad= 30 hits= 1 q= 0.3828E-05 q/h= 0.3828E-05
A= 101 pad= 31 hits= 6 q= 0.2354E-04 q/h= 0.3923E-05
A= 101 pad= 34 hits= 2 q= 0.7825E-05 q/h= 0.3913E-05
A= 101 pad= 35 hits= 1 q= 0.2115E-05 q/h= 0.2115E-05
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A=	101	pad=	36	hits=	2	q=	0.1544E-04	q/h=	0.7721E-05
A=	101	pad=	37	hits=	2	q=	0.1525E-04	q/h=	0.7625E-05
A=	101	pad=	38	hits=	1	q=	0.2348E-05	q/h=	0.2348E-05
A=	101	pad=	40	hits=	4	q=	0.1111E-04	q/h=	0.2778E-05
A=	101	pad=	41	hits=	3	q=	0.1333E-04	q/h=	0.4444E-05
A=	101	pad=	42	hits=	4	q=	0.7849E-04	q/h=	0.1962E-04
A=	101	pad=	43	hits=	1	q=	0.6321E-06	q/h=	0.6321E-06
A=	101	pad=	44	hits=	3	q=	0.1172E-04	q/h=	0.3908E-05
A=	101	pad=	45	hits=	2	q=	0.1342E-04	q/h=	0.6710E-05
A=	101	pad=	46	hits=	2	q=	0.1171E-04	q/h=	0.5855E-05
A=	101	pad=	47	hits=	3	q=	0.1754E-04	q/h=	0.5848E-05
A=	101	pad=	48	hits=	3	q=	0.9743E-05	q/h=	0.3248E-05
A=	101	pad=	49	hits=	2	q=	0.1425E-04	q/h=	0.7127E-05
A=	101	pad=	50	hits=	2	q=	0.1215E-04	q/h=	0.6074E-05
A=	101	pad=	52	hits=	3	q=	0.4889E-05	q/h=	0.1630E-05
A=	101	pad=	53	hits=	5	q=	0.3242E-04	q/h=	0.6484E-05
A=	101	pad=	54	hits=	1	q=	0.2063E-05	q/h=	0.2063E-05
A=	101	pad=	55	hits=	2	q=	0.9775E-05	q/h=	0.4887E-05
A=	101	pad=	56	hits=	2	q=	0.6343E-05	q/h=	0.3172E-05
A=	101	pad=	57	hits=	5	q=	0.2820E-04	q/h=	0.5640E-05
A=	101	pad=	58	hits=	1	q=	0.3367E-05	q/h=	0.3367E-05
A=	101	pad=	59	hits=	1	q=	0.1263E-04	q/h=	0.1263E-04
A=	101	pad=	60	hits=	3	q=	0.5984E-05	q/h=	0.1995E-05
A=	101	pad=	61	hits=	3	q=	0.1017E-04	q/h=	0.3389E-05
A=	101	pad=	63	hits=	1	q=	0.3782E-05	q/h=	0.3082E-05
A=	101	pad=	64	hits=	1	q=	0.1547E-05	q/h=	0.1547E-05
A=	101	pad=	65	hits=	4	q=	0.1447E-04	q/h=	0.3618E-05
A=	101	pad=	66	hits=	3	q=	0.1254E-04	q/h=	0.4179E-05
A=	101	pad=	67	hits=	1	q=	0.3635E-05	q/h=	0.3635E-05
A=	101	pad=	68	hits=	3	q=	0.1298E-04	q/h=	0.4328E-05
A=	101	pad=	69	hits=	2	q=	0.3774E-05	q/h=	0.1887E-05
A=	101	pad=	70	hits=	3	q=	0.6535E-04	q/h=	0.2178E-04
A=	101	pad=	72	hits=	4	q=	0.1477E-04	q/h=	0.3692E-05
A=	101	pad=	73	hits=	4	q=	0.1276E-04	q/h=	0.3189E-05
A=	101	pad=	75	hits=	3	q=	0.4677E-04	q/h=	0.1559E-04
A=	101	pad=	76	hits=	2	q=	0.9423E-05	q/h=	0.4711E-05
A=	101	pad=	77	hits=	1	q=	0.4694E-05	q/h=	0.4694E-05
A=	101	pad=	78	hits=	4	q=	0.1511E-04	q/h=	0.3778E-05
A=	101	pad=	79	hits=	2	q=	0.1350E-04	q/h=	0.6750E-05
A=	101	pad=	80	hits=	4	q=	0.7204E-04	q/h=	0.1801E-04

112438 hits looked at 178 hits used
TAK GO– processed 1 events.

note: some pads were not assigned hits, thus they are not recorded here.

6 Appendix II. Signal coupling to the pads.

In the STAR TPC the anode wires of the inner sector are 2mm the padplane, respectively. The pad response function (PRF) for such a geometry has been measured at Purdue. They found a Gaussian PRF, with

sigma (PRF) = 2.2mm.

In addition to the PRF the signal on the pads is also broadened by the effects of transverse diffusion during the drift of the electrons. The Purdue measurement used drift length of only a few centimeters, whereas in STAR we might expect an average drift length of about 100 cm. For P10 we expect the transverse diffusion to be given by

sigma (trans. diff.) = 220 microns/(cm)$^{0.5}$

= 2.2 mm, for a 100cm drift

Adding these two effects in quadrature gives the total expected width of the signals on the pads:

sigma (total) = $\sqrt{2.2^2 + 2.2^2}$

= 3.1 mm

The pad pitch in the STAR TPC inner sector is 3.35mm, or 1.08*sigma. We use the following expression to calculate the signal sharing on pads along a row:

$$PRF(x) = e^{-x^2/2\sigma^2}$$

Here x is the distance from the avalanche to the center of the pad. Using this function we can calculate the relative signals for a pad directly under a track (x=0) and the neighboring pads in the row:

PRF ($x = 0$)	= 1.0	
PRF ($x = 3.35$mm)	= PRF ($x = -3.35$mm)	= .56
PRF ($x = 7.70$mm)	= PRF ($x = -7.70$mm)	= .10

We now calculate the ratio of the charge coupling to one pad, C.C.(1), to the total charge coupling to all pads, C.C.(all).

C.C.(1)/C.C.(all) = (1.0)/(1.0 + .56 + .56 + .10 +.10 + ...)

= .43

Also, C.C.(all)/C.C.(1) = 1/0.43 = 2.32