A PROPOSAL OF SOLID STATE BALL FOR THE SSC

T. Kondo
National Laboratory for High Energy Physics (KEK)
Ohomachi, Tsukubagun, Ibarakiken, 305 Japan,

T.Ohsugi
Physics Department, Hiroshima University
Sendamachi, Nakaku, Hiroshima, 730, Japan,

and
K.Niwa
Physics Department, Nagoya University
Chikusaku, Nagoya, 464, Japan.

Summary

Use of silicon semiconductor devices for tracking as well as calorimetry is considered as a possible general purpose detector SSB (Solid State Ball or Silicon Semiconductor Ball) for the SSC. The design is based on the reasonably expected progress of semiconductor detector technology and associated electronics. We discuss how realistic such an idea is and its detector performance is crudely estimated in this paper.

Introduction

The requirements of SSC detectors are quite severe due to the high luminosity environment. At the highest luminosity of $L=10^{33}/cm^2/sec$, the detector has to stand the charged particle intensity of 10^6 $/cm^2/sec$ comming from minimum bias events at 10 cm from the beam pipe[1]. If one uses wire chambers with e.g. 35cm in length and 0.5cm drift distance, each wire encounters 30MHz hit rate on an average. Thus it is obviously impossible to use wire chamber technology in the vicinity of beam pipe. At larger distance wires could be used, but a model design ended up with more than 150K sense wires[2]. In addition, wires have to be long (> 5m) in order to cover the wide angle. One can divide wire chambers into two or three parts in z direction in order to avoid such long sense wires, but number of readout channels doubles or triples and many end plates intervene. It is pointed out that the support structure to sustain the total wire tension becomes non-trivial any more[3]. Such a dilemma stems from the intrinsic property of wires i.e. one wire covers a wide detector space. One possible solution is to make extremely compact modular wire chambers with a very narrow wire spacing[4]. In this report we propose to solve the dilemma of tracking detectors by introducing rapidly developing semiconductor detector technology.

Calorimetry for SSC is another headache. It has been believed that liquid Argon is the only detector to survive in high radiation environment such as the SSC[5]. However, due to highly collimated structure of high energy jets, each calorimeter unit has to be rather small, resulting huge number of readout channels(>150K). How to extract such many readout wires from cryogenic dewar is again a non-trivial technical problem. We point out that recent tests of electromagnetic calorimeters using silicon detectors are rather encouraging[1,6].

We assume an axial magnetic field just simply because the central region is expected to have the highest possibility for new physics. The magnetic field is excited by a conventional superconducting solenoid.

We aim the central part (trackers and calorimeters) as compact as possible in order to preserve a room for good muon detectors outside. However no considerations on muon detection are given in the present paper. No particle ID devices are included in the design, since we believe that they are incompatible with the high luminosity requirements.

Silicon Semiconductor Detectors

There are many advantageous features of silicon semiconductor detectors worth pointing in comparison with conventional wire and liquid Argon detectors[7].

Fast response: The mobility of electrons and holes in silicon crystal is an order of 3×10^6 and 10^6 cm/sec respectively. Therefore it take only 10 and 30 nsec for electrons and holes to be completely drifted to electrodes for wafer thickness of 300 μm, a factor of 10 faster than liguid Argon counters and comparable to 1mm drift in wire chambers. This collection time well matches the SSC bunch spacing of 15 nsec. However, one needs low noise electronics to be sensitive to an order of 1 fC for microstrip devices. For silicon sampling calorimeters, the large detector capacitance slows down the readout speed due to RC time constant. If one can narrow pulse width by

proper shaping, then the intrinsic detector speed will help appreciably.

Space resolution: It is not difficult to achieve better than 10 μm space resolution with silicon microstrip detectors even in high magnetic field[8]. Recent beam test demonstrated that two particle separation can be achieved at 150 μm without any efficiency and resolution losses[9]. It is almost impossible to realize such resolution and two particle separation with conventinal wire chamber technique.

Radiation damage: It is generally believed that solid state devices are weak against radiation due to their crystal structure. However there are a few high energy beam tests to indicate that silicon detectors can stand over several Mega-Rads[10,11]. The leakage current increases due to radiation, but it could be easily reduced by simply cooling the device[11]. Associated electronics (amplifiers, multiplexiers) are more vulnerable to radiation. It is obvious that we need more R&D in this field but there seems to exist enough established technology for radiation resistance in other fields such as space, nuclear plant and military[12,1]

Compactness: Detectors itself is very compact, taking only 200 μm of thickness to generate enough charge to be detected for minimum ionizing particles. Readout electronics and cables takes more space than detector itself at present. However, there are rapid progresses recently for the use of VLSI technology as demonstrated by μ-Plex[13]. Therefore it becomes possible to have integration of detectors and their readout electronics. For the calorimeter case, the expected compactness helps in preserving transverse shower size small and consequently keeping the shower overlap minimal.

Operation: Silicon devices can be operated at room temperature. It is rather easy to construct the detector system because neither special gas nor cryogenic liquid and containers are required.

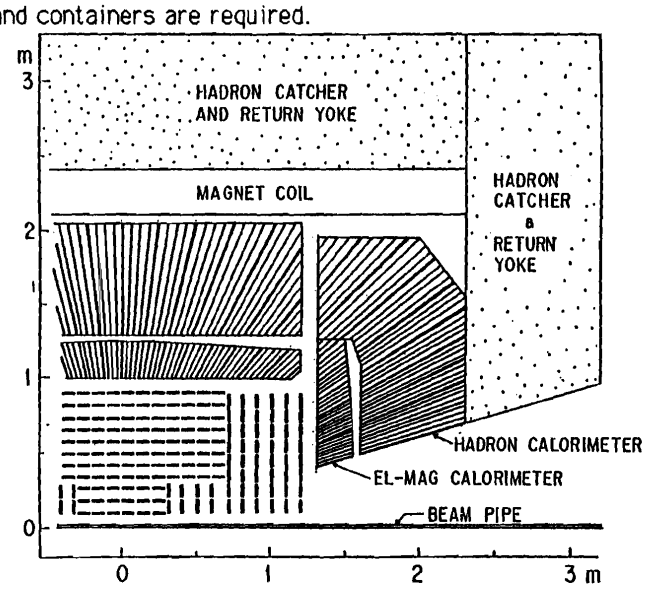

Fig.1 Cross section of the central part of the SSB.

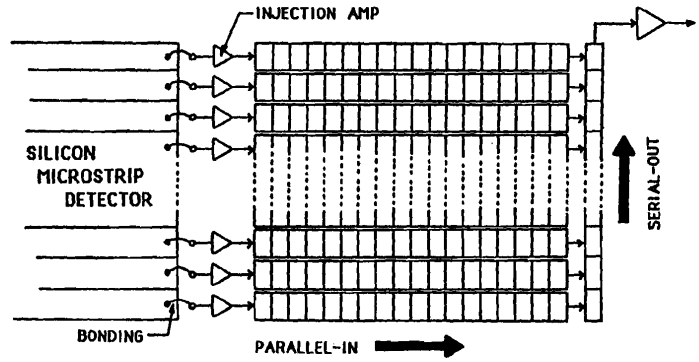

Fig.2 Parallel-in serial-out readout electronics of silicon microstrip detectors.

Central Tracking Detector

We use silicon microstrip detectors as basic building blocks of tracking system simply because they are the only semiconductor devices used in quantity in high energy experiments so far. In the design of the present tracking system, we assume two important technical progresses in near future:

(1) microstrip readout electrodes in both sides of silicon wafer with small (or large) angle stereo.

(2) readout microelectronics with parallel-in serial-out (PISO) buffer bonded to microstrip detectors.

Based on the past fixed target experiences with silicon microstrip detectors[14], we guess at least 10 hits along a charged particle track are needed for pattern recognition in multi-particle narrow jets. Small angle stereo strips in back side of silicon wafer provide z-reconstruction. Since each detector length is only 10cm in z direction in the design, one has to line up many detector elements with associated electronics as shown in Fig.1. The strip size is assumed to be 100μm in order to keep total number of readout channels reasonable.

Each detector has two readout chips. The chip has a charge buffering capability to keep time-sliced records for about 1 μsec for the 1st level triggering. Therefore it has to be fast CCD-like devices[15] and each strip has an independent buffer as shown in Fig.2. To readout such large number CCD-like channels, one needs parallel-in serial-out (PISO) transfer mechanism. However, unless one uses the charge division techniques for better precision, charge storage capability is not necessarily required for tracking microstrip detectors. It is sufficient to keep hit or no-hit information as was demonstrated in recent experiments[16]. In such a case, simple parallel shift registers with serial readout circuit are enough and consequently, one could gain higher speed with smaller power dissipation.

Table 1. Dimensions and Parameters of Trackig Detector

Rapidity range	-3.0 to 3.0
No. of layers	11
Inner radius	8 cm
outer radius	88 cm
Size of microstrip detector	10cm×5cm×0.02cm
Strip width	100 μm
Stereo angle	3.5^0
Position resolution expected	30μm in r-ϕ plane 500μm in z-r plane
Two track resolution	500μm in r-ϕ plane
No. of microstrip detectors	15304
No. of strips for readout	15304K
Momentum resolution	$\sqrt{(.00041P_T)^2+(.011)^2}$

As summarized in Table 1, we need to handle close to 2 million readout channels. Even if one manages to keep the power consumption of the PISO devices down to 1 mW/ch per readout channel (which is quite difficult for such high speed (>10MHz) devices with the present technology), total power consumption adds up to 15 KW. Special cooling techniques are required.

The hit rate at full luminosity of $10^{33}/cm^2/sec$ can be easily calculated based on the approximate formula[17];

$$dn^{ch}/dS = 10^8/r_T^2 \text{ particles/cm}^2\text{/sec}$$

where r_T is the transverse distance in cm from the beam pipe. By multipling the assumed strip size of $10cm\times0.01cm=0.1cm^2$, we obtain

hit rate = 156 KHz/strip at r_T = 8 cm
25 KHz/strip at r_T = 20 cm
1 KHz/strip at r_T = 100 cm.

Compared with time-slice interval of say 100 nsec or less, these hit rates are sufficiently small and therefore no overlap/pile-up occur, i.e. detectors are rather quiet.

Separation of in time and out of time tracks are easy if readout CCD or shift register run at more than 67 MHz (=SSC bunch interval). We are not certain at present whether one could achieve such high speed (and low noise) readout electronics. However, even with slower time sampling electronics, by phase shifting the clocks for different PISO readout chips, it may be possible to resolve in time from out of time tracks.

The momentum resolution is given by[18]

$$(\Delta P_T/P_T)^2 = [\sigma_x P_T/(0.3BL^2)]^2\times(720/(N+5))+(0.06/B/L)^2\times t$$
$$= (4.1\times10^{-4}\, P_T[GeV])^2+ (0.011)^2 \quad \text{(see Fig.3)}$$

where we assume B=2 Tesla, σ_x=30μm, N=11, L=90cm and

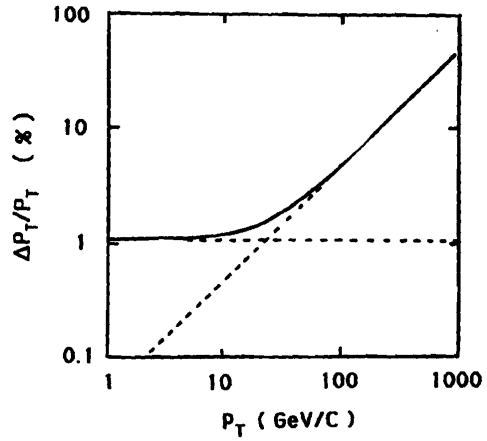

Fig.3 Transverse momentum resolution with the silicon microstrip tracking system.

total radiation length $t=0.11X_0$. The radiation length is based on assumed effective thickness of 1% radiation length per layer including electronics, cables and support structure. Due to high resolution of silicon microstrip detectors, $\approx2\sigma$ charge separation ($\Delta P_T/P_T$=0.41) could be possible even at P_T=1000 GeV/c. It should be noticed, however, that position alignment of microstrip detectors is a non-trivial mechanical problem to realize such a momentum resolution. This is one of the reasons why we employ a moderate strip width of 100μm, since alignment will be the dominant source of position errors.

Pattern recognition remains to be studied more in detail. The proposed eleven layers for axial and stereo strips are certainly not enough for high multiplicity jets if we recall the experiences of drift chambers. However, the superior position and double-track resolution of silicon microstrips will help pattern recognition. In addition, one is able to reconstruct z coordinate locally at each detector using front axial strips and back side small angle stereo strips. Obviously we need Monte Carlo detector simulations for quantitative evaluation of tracking performances.

Electromagnetic Calorimeter

Recent beam tests showed that large area silicon detectors could be used to form compact electromagnetic shower calorimeters[6]. According to these pioneering works, we can guess the energy resolution of

$$\Delta E/E = 17\%\sqrt{(\tau/E)} \qquad (E \text{ in GeV})$$

where τ is the sampling interval in unit of radiation length. With τ=0.5, one gets a moderate energy resolution of $12\%/\sqrt{E}$.

Shower counters need small transverse segmentations so as to be useful in jet reconstructions. It has been pointed out that one needs $\Delta\phi\approx\Delta\eta\approx0.02$ or 0.03 for

optimal W and heavy flavor tagging[19]. If we employ $\Delta\phi=\Delta\eta=0.03$, then the smallest detector cell is 1.05cm square at $\eta=2.0$ ($\theta=15^0$) and the largest one is 3.75cm square at 90^0.

A basic element of calorimeter tower is shown in Fig.4. In each calorimeter element, 16 silicon pad detectors are sandwiched by ceramic plates with readout electrodes. These pad detectors with 500μm delepetion depth are probably not so hard in mass production based on the present manufacturing technology of large area photodiodes[20]. The proposed size of detector elements (1cm to 3.75cm square) does not require large diameter silicon crystals and therefore high resistivity silicon wafers are available in quantity. Moreover the production yield can be kept high by limiting the area of detector elements.

We stack 50 layers of $0.5X_0$ uranium plates and ceramic silicon detector packages to form an electromagnetic shower tower. We believe that $25X_0$ is enough[21]. Its length in depth is 16cm (1.6mm uranium +1.6mm detector, 50times) + 5cm for local readout amplifiers + 5 cm for supprot and cabling, namely 26cm in total. As shown in the figure, 10-15 pad detectors are hardwire connected longitudinally and readout is divided into 4 sections in depth to get good e/π separation. As a possible option, a few additional silicon detectors with ≈1mm strip width located at shallow depth (say $5X_0$) will provide an accurate position detection of electromagnetic showers[21]. This will improve e/γ as well as e/π separations.

Table 2. Parameters of Electromagnetic Shower Calorimeter

Rapidity range	-2.0 to 2.0
Distance from I.P.	100(90^0)-164cm(37^0)
Radiation material	uranium
Total weight	37 tons
$\Delta\phi = \Delta\eta =$	0.03
Tower (pad) size	1×1 to 3.8×3.8cm^2
Depletion depth of detector	500μm
Active part/total area	90-97%
Sampling frequency	$0.5X_0$
Total depth	$25X_0$ and 16cm
No. of longitudinal segments	4
No. of calorimeter towers	27588
No. of silicon pad detectors	1379K
No. of readout channels	110K
Detector capacitance	260-5000pF/r.o. ch
Electronic noise level	1.6-30 fC/tower
Deposit by muons	320 fC/tower
Deposit by e/γ	2 pC/GeV
Energy resolution	12 %/$\sqrt{E[GeV]}$

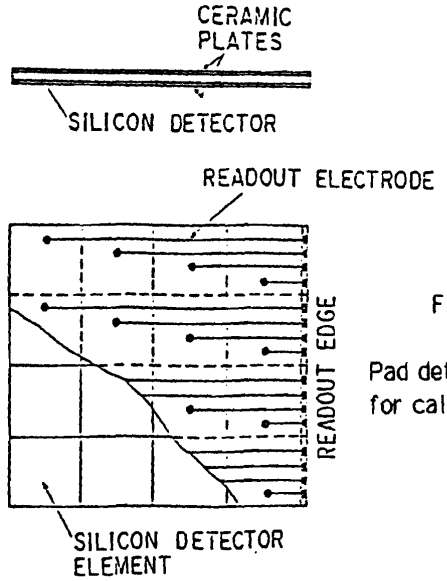

Fig.4

Pad detector array for calorimeters.

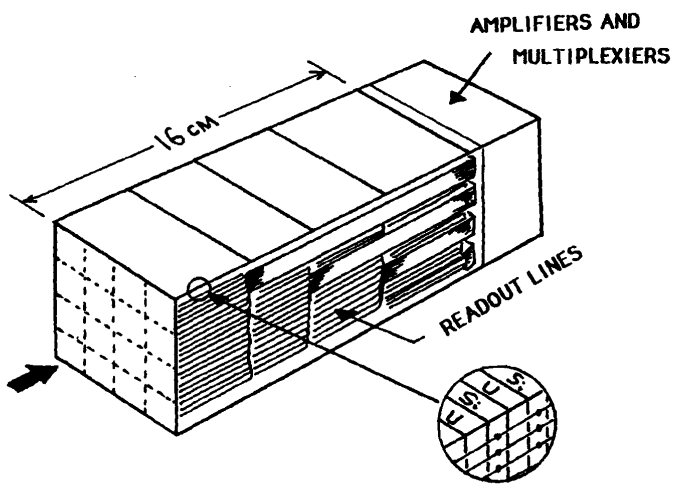

Fig.5 Schematic view of electromagnetic calorimeter module.

Problems of readout electronics come from detector capacitance, namely electronic noise and readout time constant. The detector capacitance adds up to 260 to 5000pF per readout channel since 10 to 15 silicon pad detectors are connected together. The electronic noise is estimated to be as high as 15 fC due to such large detector capacitances[22]. On the other hand, a simple Monte Carlo indicates ≈20 pC of charge expected from 10 GeV electromagnetic showers[7]. Penetrating muons deposit 60 to 100 fC per readout channel. Thus the S/N ratio is not bad. The more important problem is that it probably takes a few hundred nsec to collect full charge from the detector, though this situation is same as in the case of liquid Argon detectors.

Hadron Calorimeter

Hadron calorimeter is divided into two parts, a fine sampling part up to $5\lambda_0$ located inside the solenoid magnet and a hadron catcher outside as shown in Fig.1. This configuration, i.e. fine hadron calorimeter inside the magnet, is chosen to maintain the good $e/\gamma/\pi$ separation as well as the good energy resolution. Since the present calorimeter is rather compact, this is possible with a solenoid of reasonable diameter (4m).

For the fine calorimeter part, we use the same uranium-silicon sampling detectors with 500μm depletion depth for the inner part to keep the continuity from the electromagnetic calorimeters. We assume 40 samplings and three longitudinal segmentation. The transverse segmentation is assumed to be same as for the electromagnetic calorimeters i.e. $\Delta\phi=\Delta\eta=0.03$. A simple estimate of electronic noises indicates that one is able to see penetrating muons with S/N of 5 to10.

Since there exists neither beam test nor Monte Carlo estimate, we are not able to guess the energy resolution. But it should be similar to the resolution of liquid Argon detectors.

Table 3. Parameters of Fine Hadron Shower Calorimeter

Rapidity range	-2.0 to 2.0
Absorption material	uranium
Total weight	450 metric tons
$\Delta\phi = \Delta\eta =$	0.03
Tower (pad) size	1.8×1.8 to 6×6 cm^2
Depletion depth	500μm
Sampling frequency	$4.2X_0$, 1.35cm uranium
Total depth	$4.4\lambda_0$and 60cm
No. of longitudinal segments	3
No. of calorimeter towers	27588
No. of silicon pad detectors	1104K
No. of readout channels	83K
Detector capacitance	500-11500 pF/r.o. ch
Electronic noise level	2.6-58 fC/tower
Deposit by muons	260 fC/tower
Deposit by hadrons	250 fC/GeV
Energy resolution	$50\ \%/\sqrt{E[GeV]}$ (?)

As for the hadron catcher part locating outside the solenoid, we simply copy the iron-gas calorimetry of the SCD or Model-A design[23]. Assuming 6.0 λ_0 in thickness, we end up with 2100 tons of irons, substantially lighter than 10670 tons for the SCD.

Other Detector Components

The Superconducting Magnet locates in between two types of hadron calorimeters. It is a solenoid of 4.6m in diameter and 4.3m in length. We need 2 Tesla magnetic field inside. According to the excellent summary of superconducting solenoids[1], using present technology, its construction is certainly possible with only 1.2 X_0 in thickness.

The muon and forward detectors are not considered in this paper. We simply scale down the SCD(Model-A) design. Total weight for the muon toroid, for example, is reduced to 14000 tons from 36500 tons.

Cost Estimate

In the present design, basic detector elements are

silicon microstrip detector	15304 pieces
silicon pad detector	2483000 pieces.

We have no concrete ideas of the production cost of these elements. But suppose microstrip detectors cost $500 and pad elements $10 (we expect a fantastic cost reduction because of mass production), they add up to about $32.5M for basic detector elements.

As for electronics, we assume $1/ch. for silicon microstrip readout by using VLSI technology. On the other hand, for calorimetry we employ $120/ch. including triggering, the same number as was used in the DCEP[23].

In Table 4, we list up our rough cost estimate based of the same format as DCEP.

Table 4. Cost Estimate (unit = M$)

	SSB	Model A
Vertex Detector	-	1.0
Central Tracking Detector	10.0	10.8
Forward Tracking	1.2	1.2
Electromagnetic calorimeter	15.0	8.4
Precision Hadron calorimeter	17.0	39.2
Hadron Catcher	7.4	37.3
Muon Detector	6.0	8.2
Muon Magnet & Absorber	13.5	37.3
Magnet	6.0	10.5
Cryogenic System	2.0	5.0
Electronics for Tracking	15.0	30.0
for Calorimetry	25.0	58.3
for Muon Detectors	14.0	19.7
On-line System	5.0	5.0
EDIA	43.0	43.0
TOTAL	227.7	315.9

Considerable reduction of cost turnd out to come from the reduction in size. Also note that the Model A covers rapidity range of -6 to 6, but -2 to 2 for the present SSB.

Conclusions

A primitive description of the proposed SSB detector is presented. The momentum and energy resolution is more or less satisfactory for general purpose detectors for the SSC. Three most salient features expected in this detectors in comparison with other designs are

1. no pile-up or occupancy problems in central tracking detector,
2. no cryogenic is required for shower calorimeters,
3. compact.

Following R&D studies are badly needed

1. Pattern recognition capability using Monte Calro,
2. PISO readout electronics for microstrip detectors,
3. radiation hardened silicon microstrip detectors with double-sided readout electrodes,
4. large scale silicon sampling calorimeters and associated electronics.

before presenting the SSB design as an honest and realistic proposal.

Acknowledgement

We thank K.Yamamoto (Hamamatsu Photonics), M.Turala, C.Kim, T.Doke and K.Takigawa for their useful suggestions and advices. We are grateful to S.Ozaki, K.Takahashi, K.Niu and S.Mori for their continuing encouragements.

References

1. Report of the Task Force on Detector R&D for the Superconducting Super Collider, SSC-SR-1021.
2. Proceedings of the 1984 Summer Study on the Design and Utilization of the Superconducting Super Collider, Snowmass, 1984, p.590.
3. Summary talk of Tracking Subgroup by G.Hanson & D.Cassel in this Proceedings.
4. R.Bouclier et al., IEEE Trans. Nucl. Sci. NS-33(1986) 169.
5. Proceedings of the 1984 Snowmass Study, p. 541.
6. G.Barbiellini et al., Nucl. Instr. and Meth. A235 (1985)55, Nucl. Instr. and Meth. A236(85)316.
   A.Nakamoto et al., Nucl. Instr. and Meth. A238(85)53, Nucl. Instr. and Meth. A251(1986)275.
   M.Bormann et al., Nucl. Instr. and Meth. A240(85)63.
7. Proceedings of the 1984 Snowmass Study p. 562.
8. E.Belau et al., Nucl. Instr. and Meth. 214(83)253.
9. C.Adolphsen et al., SLAC-PUB-3924.
10. P.Borgeaud et al., Nucl. Instr. and Meth. 211(83)363.
    E.H.M.Heijne, CERN Report 83-06 (83).
11. Proceedings of the 1984 Snowmass p.612.
12. D.Hartil, IEEE Trans. Nucl. Sci. NS-33(1986)36, Ref.1 pp. 208-220.
13. J.T.Walker et al.,Nucl. Instr. and Meth. 226(1984)200, C.Adolphsen et al., IEEE Trans. Nucl. Sci. NS-33(1986) 57.
14. for example Fermlab E653, CERN WA75.
15. W.R.Then Kate and C.L.M. van der Klauw, IEEE IEDM-83 (1983)363, Nucl. Instr. and Meth. 228(1984)105.
16. Fermlab E691.
17. Ref.1 p. 45.
18. R.L.Gluckstern, Nucl. Instr. and Meth. 24(1963)381.
19. Proceedings of 1984 Snowmass, p.107 and p.491.
20. for example, Hamamatsu S1790-02 with 10×10 mm^2 sensitive area.
21. Proceedings of the 1984 Snowmass Study p. 559.
22. We assumed ENC=0.003fC/pF based on the specifications of LeCroy HQV810.
23. Cost Estimate of Initial SSC Experimental Equipment by SSC CDG, SSC-SR-1023, June 1986.