Plan for radiation damage test of new FPCCD sensors

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@ILC detector Annual Meeting

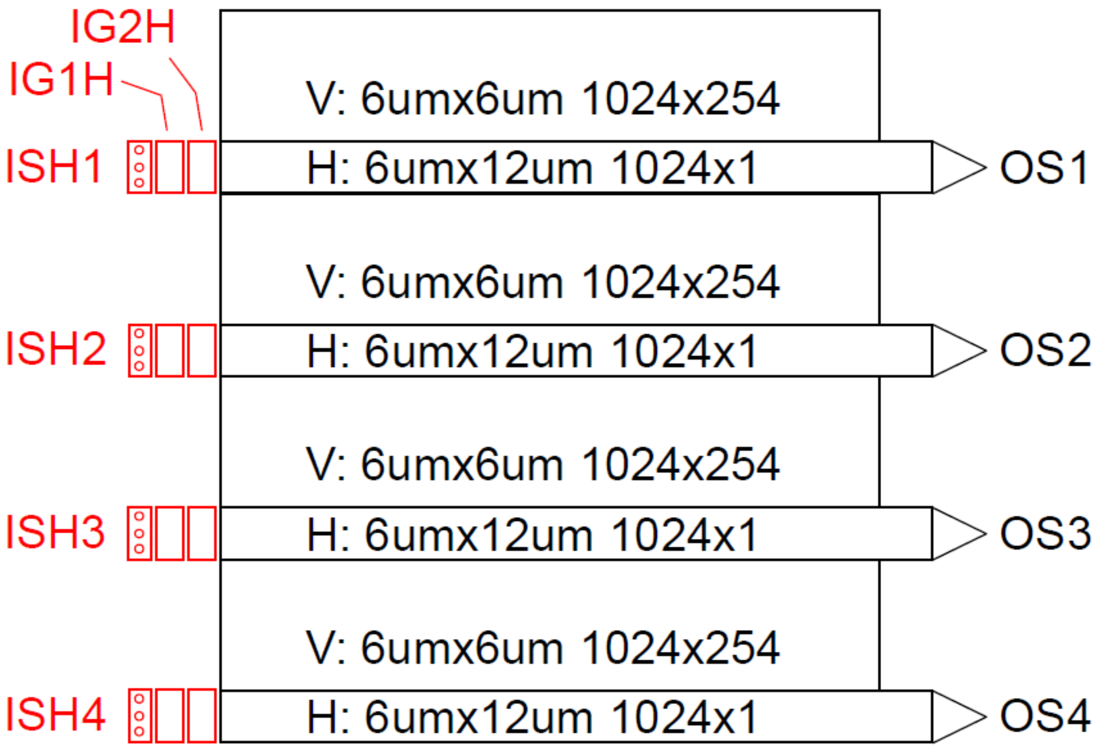
INTRODUCTION

FPCCD

- FPCCD (Fine Pixel CCD) is one of the sensor candidates for ILD vertex detector
- FPCCD has very small pixels of ~5um square
- The sensitive layer is fully depleted
- Because of its huge number of pixels, the hit occupancy remains at an acceptable level even if one full train hits are accumulated
- Signal charge is transferred over a long distance (~few cm) → Charge Transfer Inefficiency (CTI) due to the radiation damage caused by pair-background e+/e- can be a problem

New prototype sensor

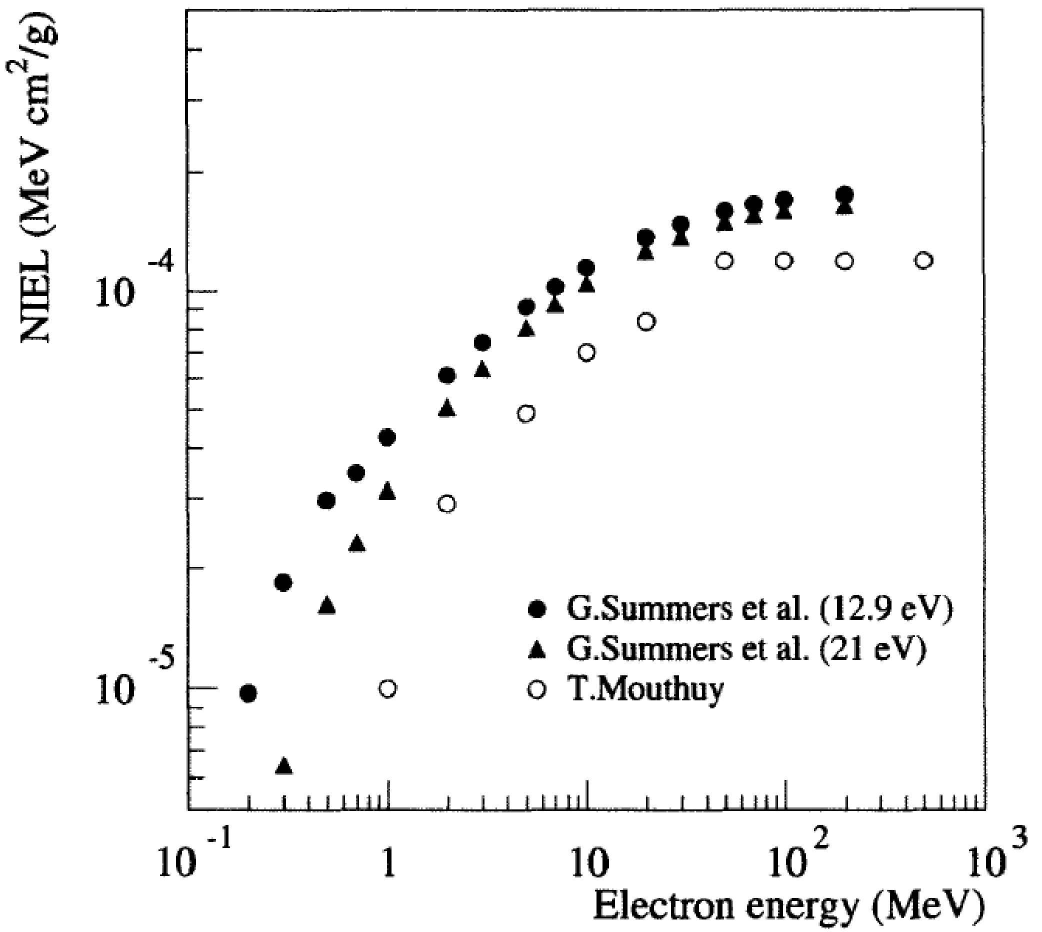
- New small prototype of FPCCD is being manufactured by Hamamatsu Photonics (see YS's presentation at ILC detector seasonal meeting on 12 July, 2021) → to be delivered on 3/14
- It has external charge injection function into the horizontal shift registers to improve CTI caused by radiation damage
- Radiation damage test using electron beam of ATF linac is planned to be performed in FY2022



SET UP FOR IRRADIATION

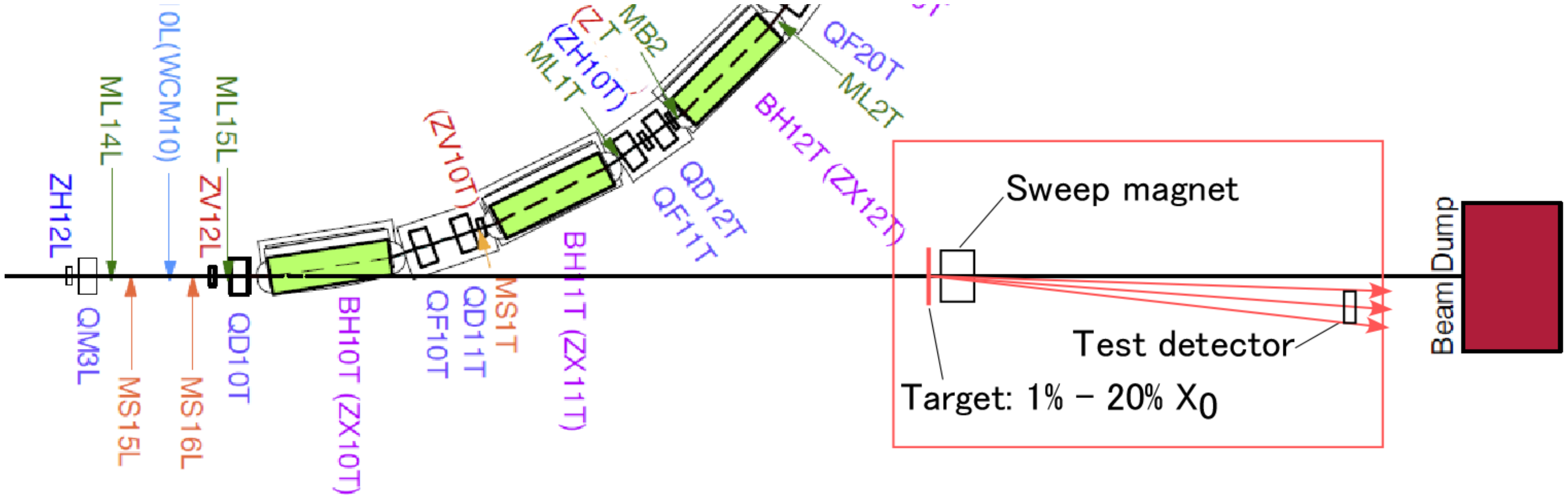
Electron energy

- NIEL hypothesis
  - Bulk damage of Si (damage in the Si, which causes traps of signal charge and increase of dark current) is proportional to Non Ionizing Energy Loss of incident particles
- NIEL of electrons saturates at ~50 MeV
- Electron of ~80 MeV, which is available at ATF, is suitable for bulk damage test

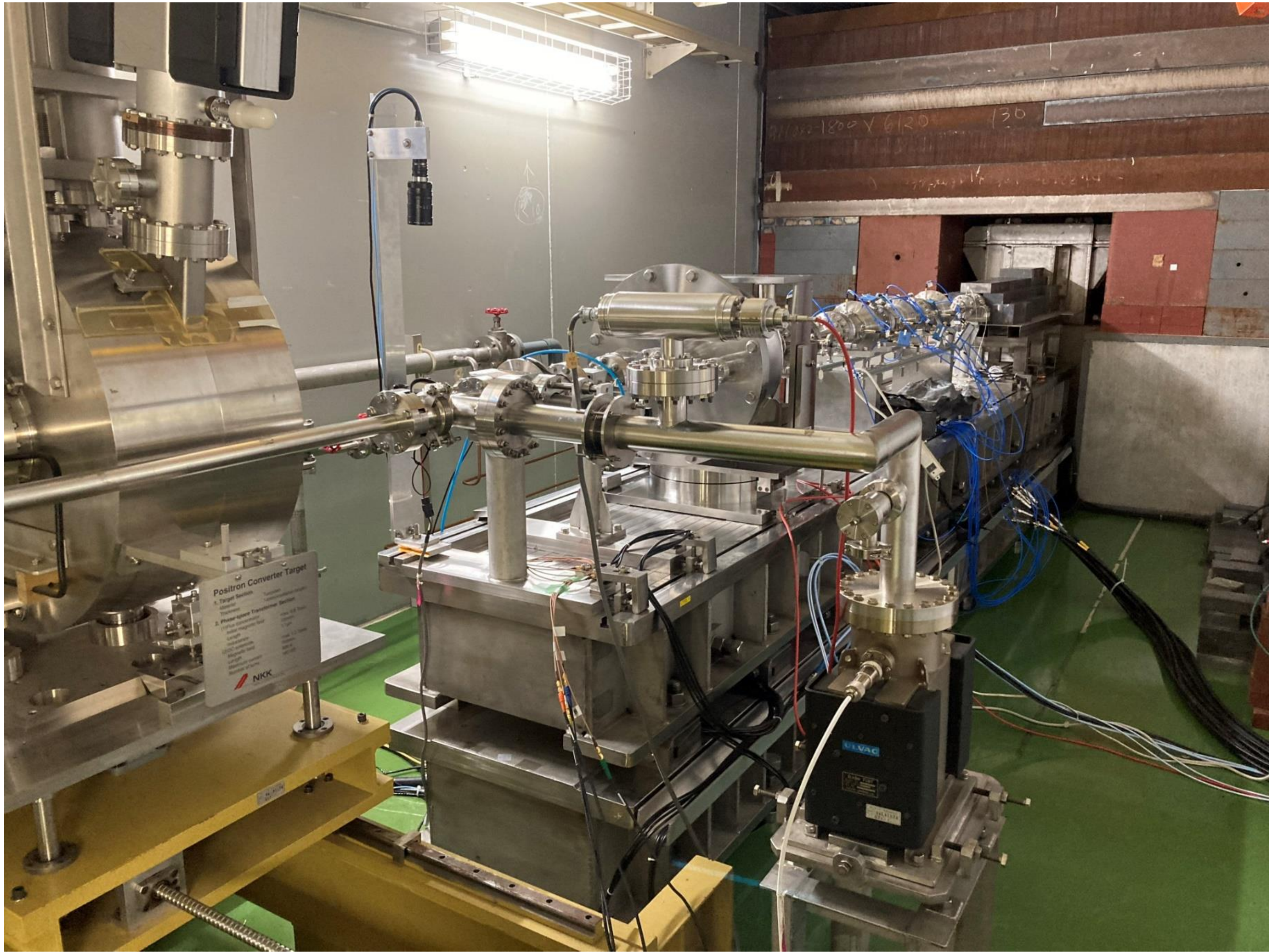


Electron irradiation at ATF linac

- Irradiate FPCCD sensors by electrons from ATF linac at the dump line
- Electron energy ~80 MeV (=energy at the exit of 3m S-band accelerator)
- Spread the beam by multiple scattering with a thin target (1~5% X_0, depending on the available distance between the target and the test detector) → FWHM > 10cm at the test detector
- Put a small magnet (B=3kG, L=12cm) just downstream of the target to separate the main beam from very low energy e+/e- and X/γ-rays

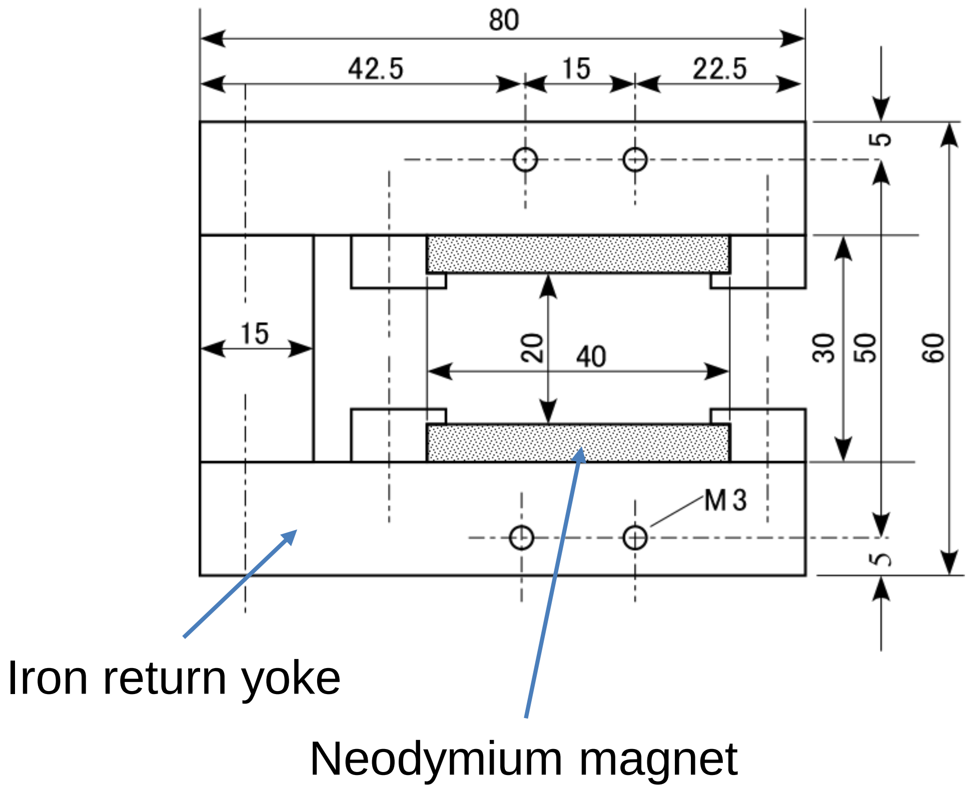


ATF Linac Beam Dump



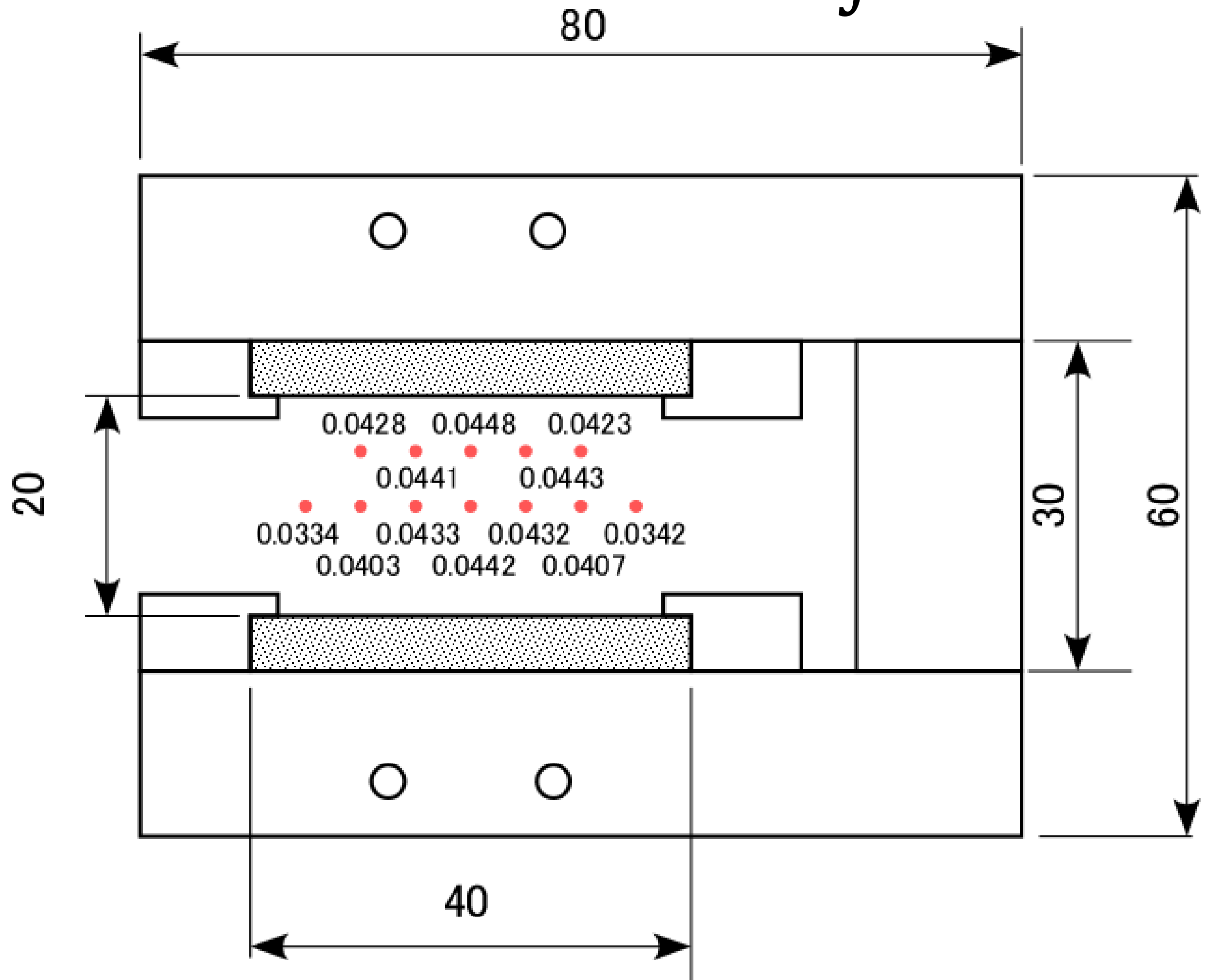
Sweep magnet

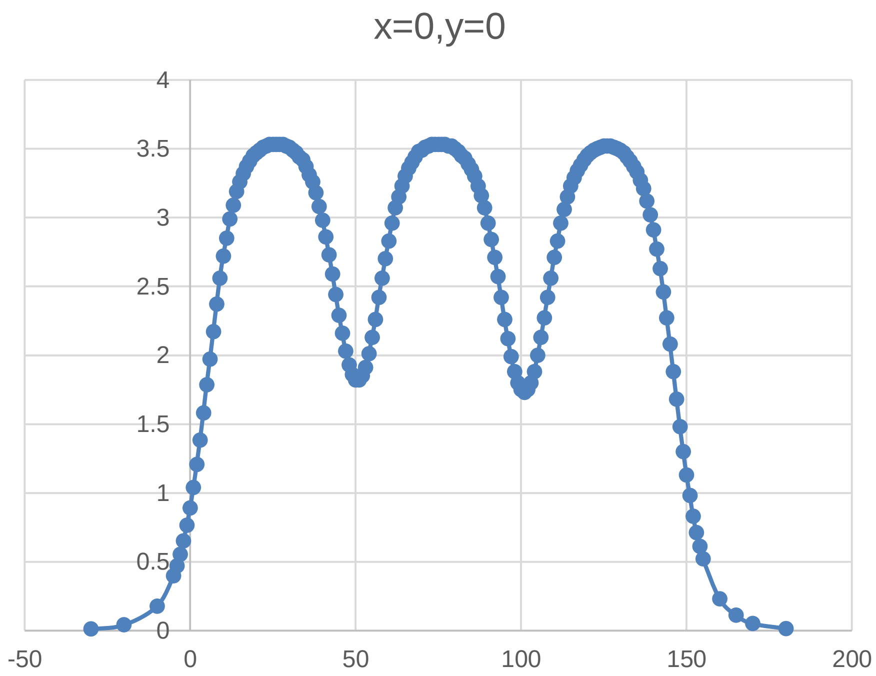
- Design : B=3kG, L=12cm (4cmx3)



Sweep magnet

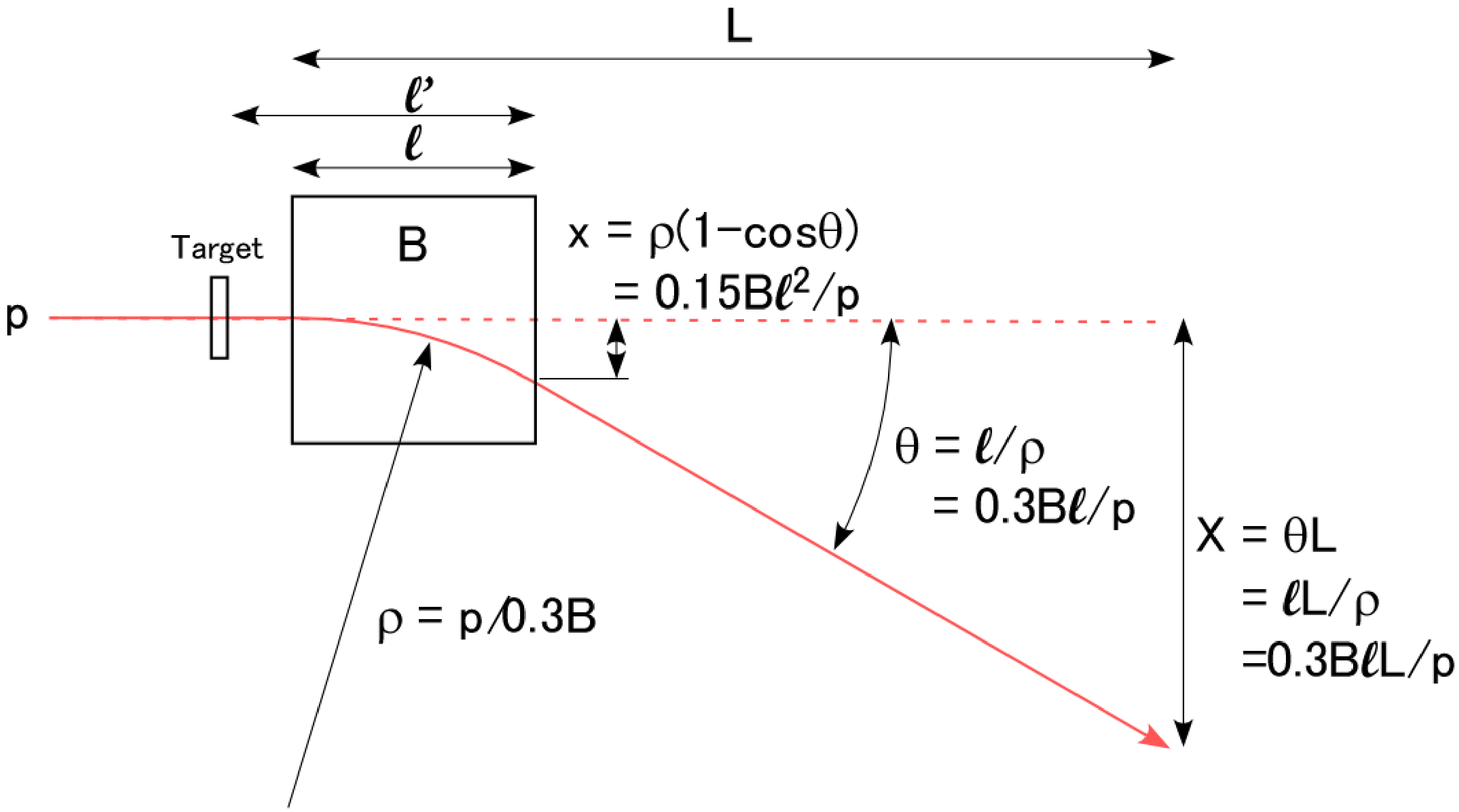
- Field measurement: $\int B dL$





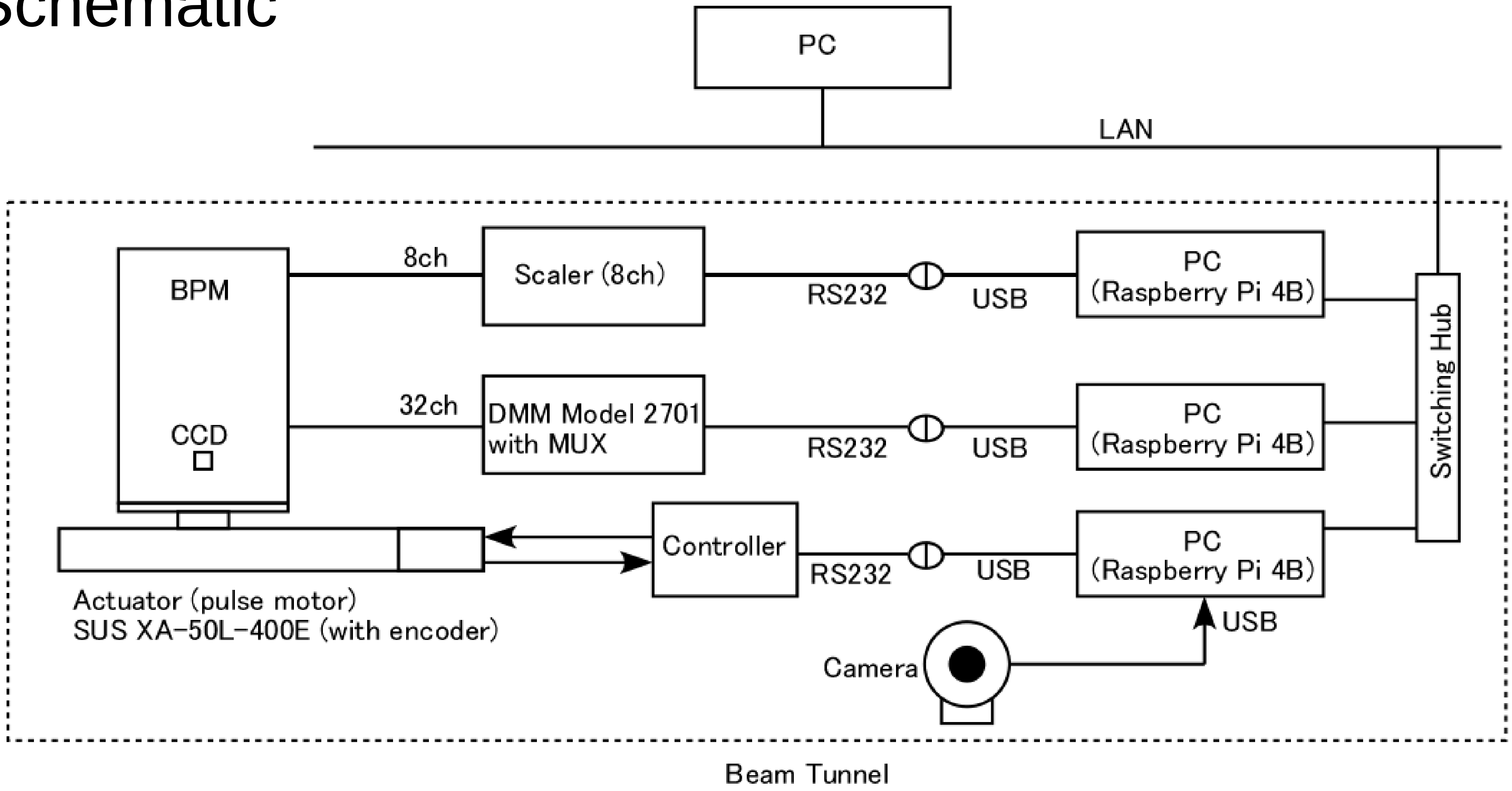
Beam bending

- Assumption
  - Target; 2%X_0
  - ℓ ; 15 cm
  - ℓ' ; 20 cm
  - L ; 2 m
  - P ; 0.08 GeV/c
- Beam spread due to MS
  - σ = 3 mm at magnet out
  - σ = 40 mm at CCD
- Maximum bending
  - θ = 168 mrad
  - x = 1.3 cm
  - X = 34 cm
- Expected dose
  - 1 nC/pulse, 5 pulse/s → ~5x10^8 e/s/cm^2

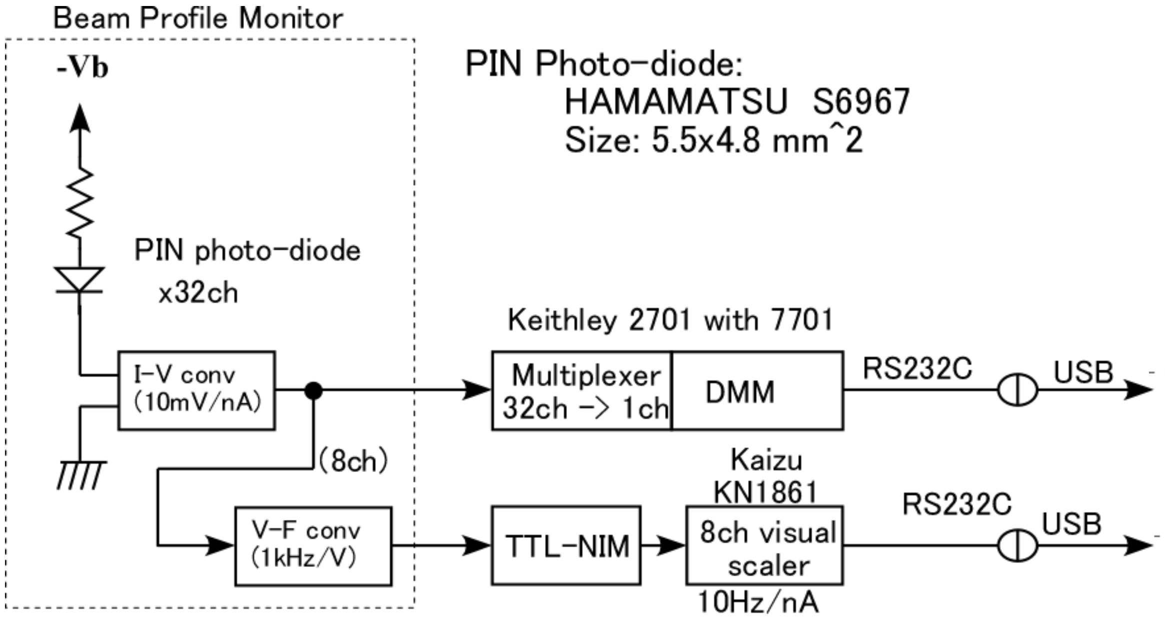


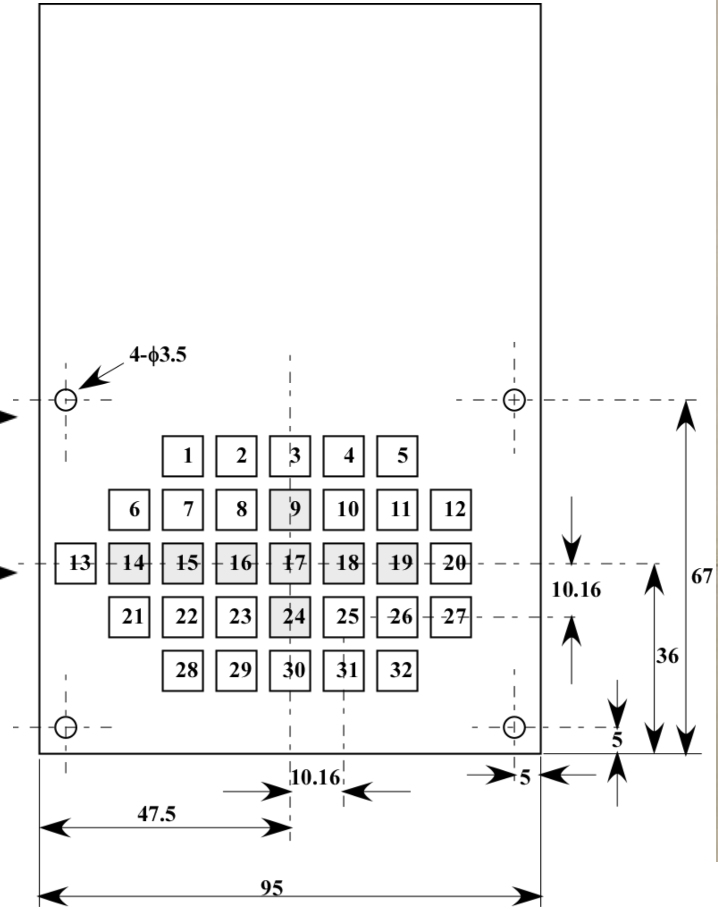
Irradiation set-up

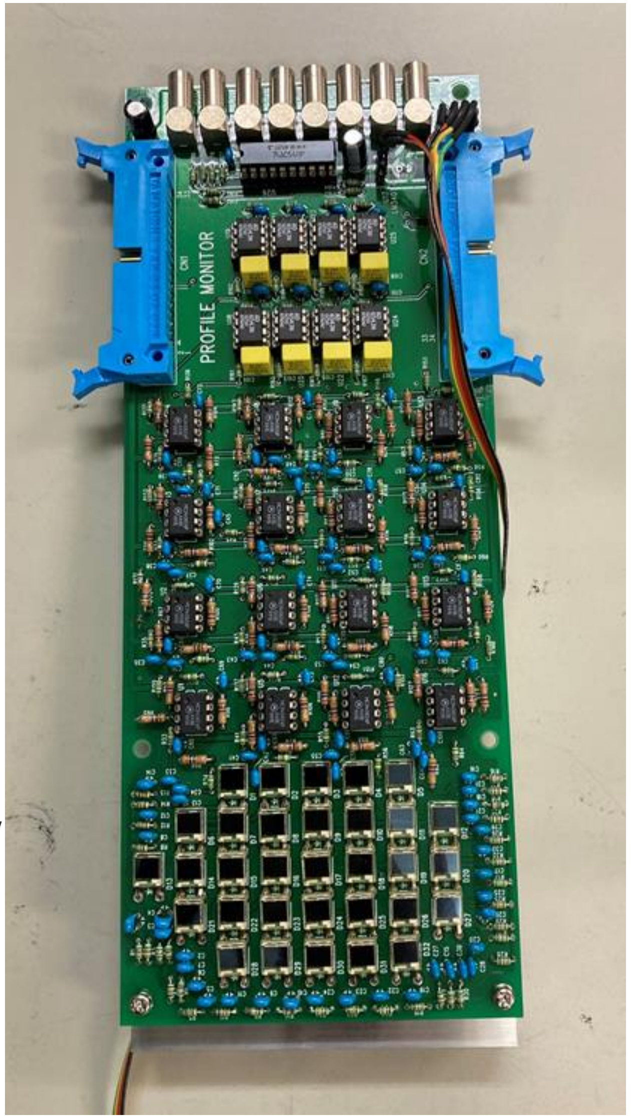
- Schematic



Beam profile monitor







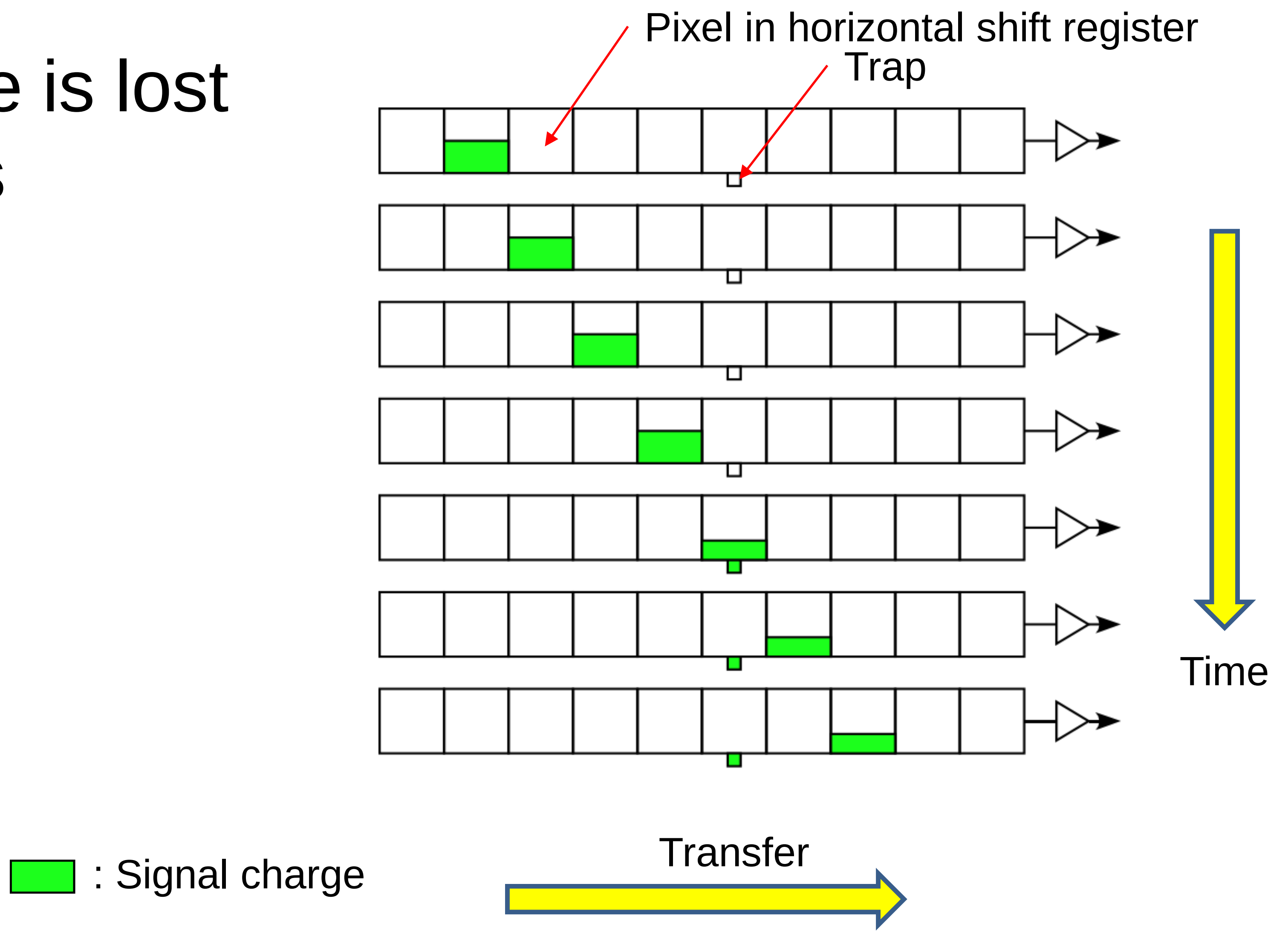
CTI MEASUREMENT

CTI measurement

- After electron irradiation, the effect of the radiation damage (CTI, dark current, etc.) is studied
- CTI is derived from position dependence of peak position of Fe55 X-ray signal
- CTI is measured as a function of temperature and injected charge
- For the charge injection, we will use “fat-zero charge injection” method

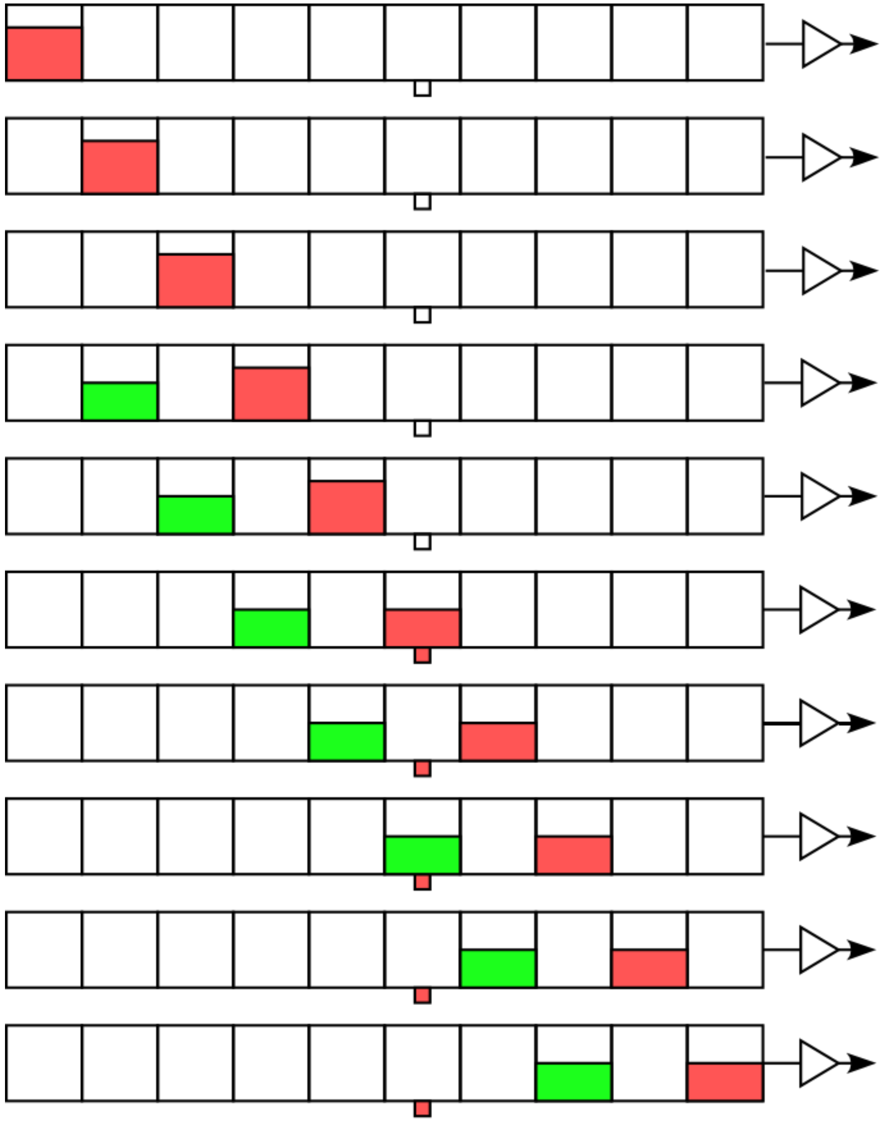
Charge trap

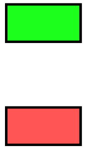
- Signal charge is lost by trap levels



Sacrifice charge injection

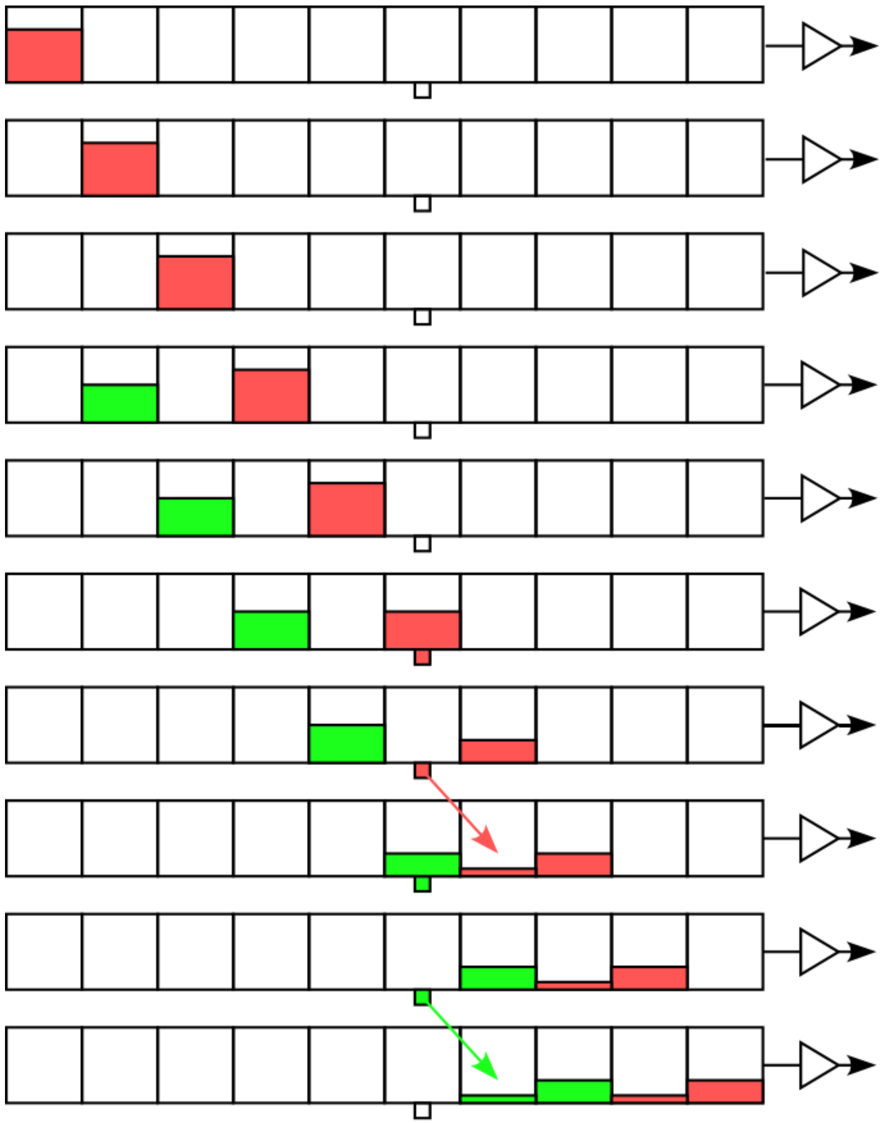
- Sacrifice charge can fill up the traps beforehand, and signal charge will not be lost
- Sacrifice charge can be injected from one end of the horizontal shift register





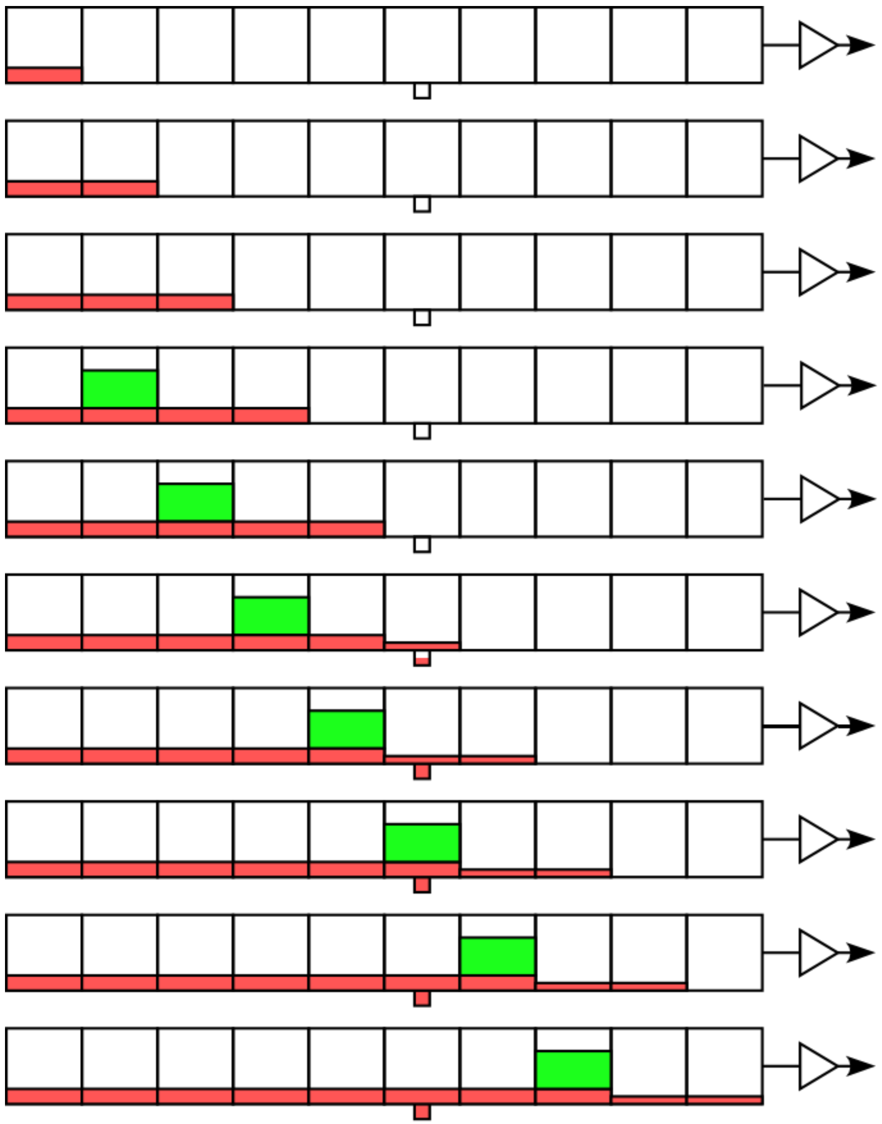
Ejection of trapped charge

- Trapped charge can be ejected from the trap due to thermal excitation of the charge
- If time constant of charge ejection from the trap is short, this method (one pulse trap filling) does not work
- At -40 degrees, the ejection time constant for 0.39 eV trap is $\tau_e = \frac{1}{\sigma X v_{th} N} \exp\left(\frac{E_t}{kT}\right) \sim 400\mu s$ < readout time of 1 line of FPCCD (~1ms)



Fat-zero charge injection

- If sacrifice charge is injected to every pixels, the problem is solved → called "fat-zero charge injection"
- But this method could cause increase of noise due to statistical fluctuation of the injected charge



SUMMARY

Summary and outlook

- We are planning electron radiation damage test of new FPCCD prototype sensors using 80 MeV electron beam at ATF beam dump
- New FPCCD prototype sensors have charge injection function which could improve radiation immunity of the sensors
- We would like to make the irradiation in 2022 fall, but the feasibility is not so clear
  - Radiation regulation issue
    - Application for ATF modification to the authority is necessary → takes time
    - Additional radiation shield → needs money
  - Manpower : Everything has to be finished by the end of Feb. 2023

BACKUP SLIDES

Rough calculation of time constants

- Charge ejection time constant

$$\tau_e = \frac{1}{\sigma X v_{th} N} \exp(\frac{E_t}{kT})$$

- Charge capture time constant

$$\tau_c = \frac{1}{\sigma v_{th} n_s}$$

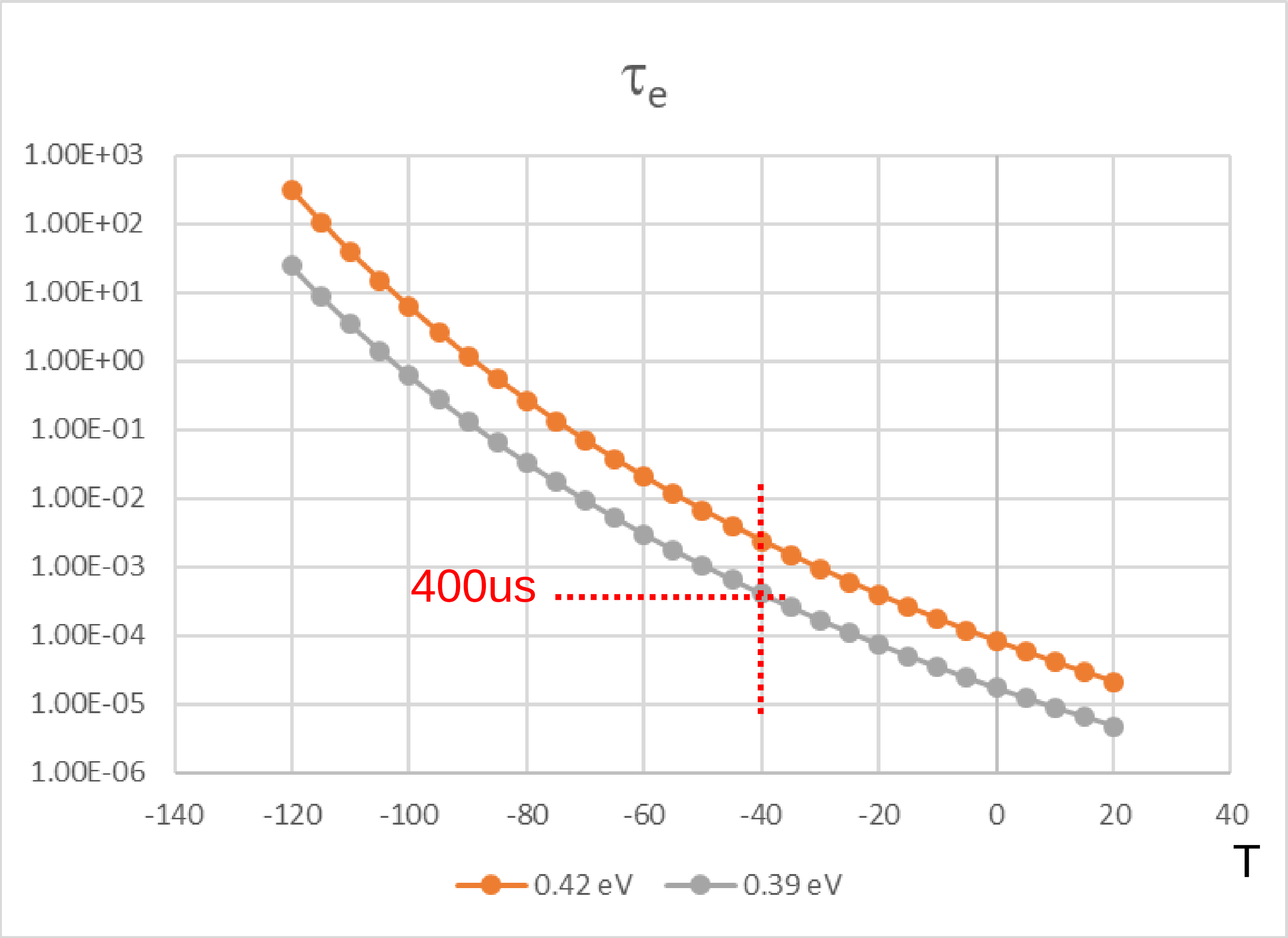
  - σ : electron/hole capture cross section
  - X : entropy factor
  - v_{th} : thermal velocity of electron/hole ($\propto \sqrt{T}$)
  - N : density of states in conduction/valence band ($\propto T^{1.5}$)
  - E_t : energy level of the trap
  - k : Boltzman's constant
  - T : temperature
  - n_s : density of signal charge

τ_e: Parameters & results

- $v_{th}N = 1.6 \times 10^{21} \times T^2$
- $k = 8.6 \times 10^{-5}$
- σX

Et	σX
0.39 eV	$8 \times 10^{-15} cm^2$
0.42 eV	$6 \times 10^{-15} cm^2$

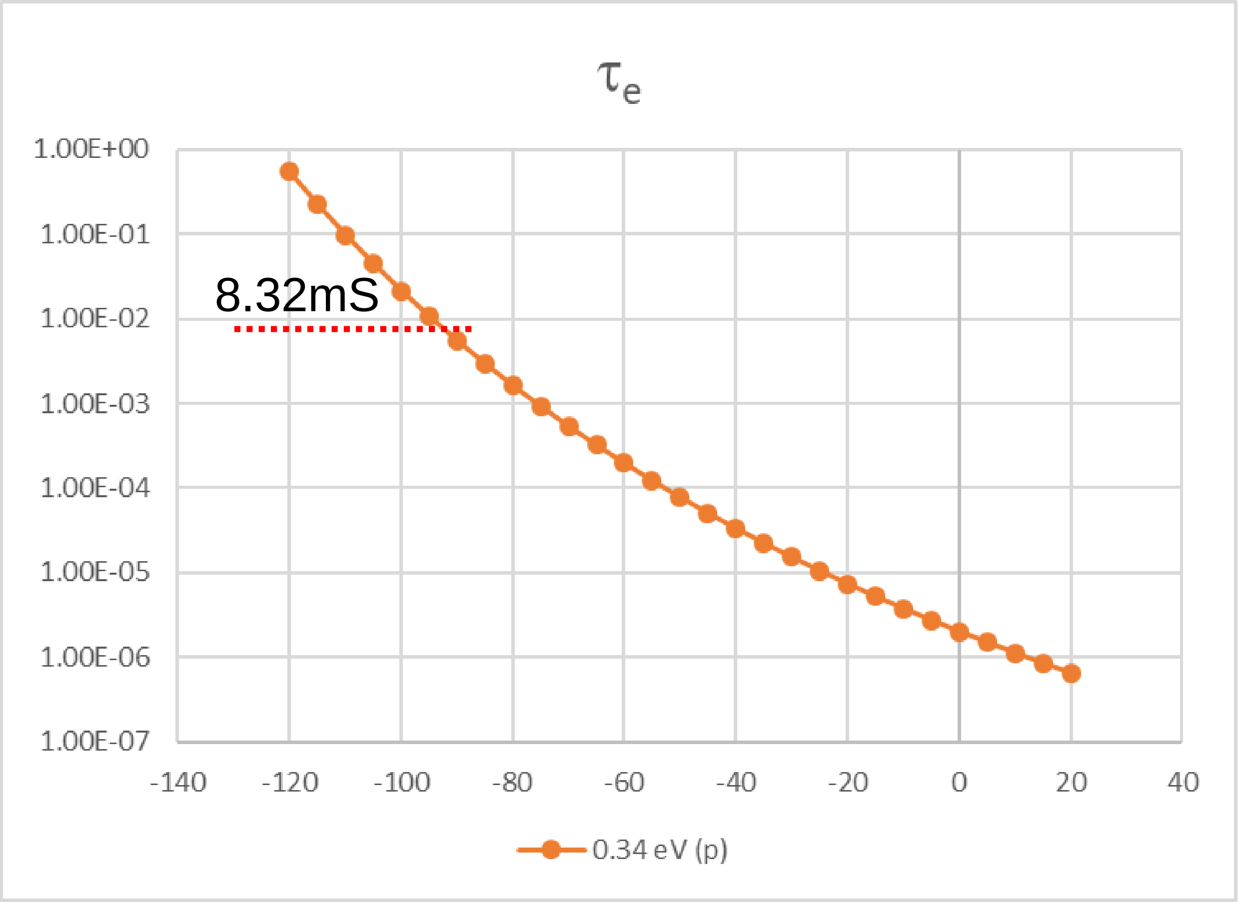
- Charge injection interval should be << 400uS
- In the real vertex detector for ILC, it takes ~1mS to read out 1 line (100nS/pixel x 10000pixels/line)
- So, charge injection to 1 pixel in 1 line is not enough



Charge Injection Interval << 400 us

Other example

- CCD for X-ray astronomy (master thesis of S.Ueda (Osaka Univ.))
- Operating temperature： -120℃
- P-type Si：Et = 0.34 eV
- Charge injection in every 8.32mS
- They don’t have to inject sacrifice charge in every pixels



（Same parameters as n-type 0.39eV are used except for Et)

τ_c: Parameters & results

- $v_{th} = 9.5 \times 10^5 \times \sqrt{T}$
- $n_s = N_{charge}/V$
- $V = 12\mu m \times 6\mu m \times 0.15\mu m/4$
- σ

Et	σ
0.39 eV	$4 \times 10^{-15} cm^2$
0.42 eV	$3 \times 10^{-15} cm^2$

- N_{charge} x Clock-pulse width >> 6x10^{-5} → N_{charge} >> 1.2x10^{-4} x f_{clock} =1200@10MHz
- Very large number of charge has to be injected to fill the traps by one pulse → could cause saturation in the readout electronics