Optical Fiber Based Loss Monitor for Electron Storage Ring

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   - Basics : interactions of stray electron with matter
   - Loss monitor Examples

3. Optical Fiber Based Loss Monitor at KEK-PF Electron Storage Ring

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References

- Many good documents have been published
  - CERN Accelerator School (CAS)
  - US-Particle Accelerator School (USPAS)
  - Joint US-CERN-Japan-Russia Accelerator School
  - many BIW, DIPAC, IBIC papers

- "Beam Loss Monitors" CAS2008, K. Wittenburg
- "Beam Loss Monitors (BLMs): Physics, Simulations and Applications in Accelerators", BIW2010, A. Zhukov

- Particle Data Group
  - "Review of Particle Physics" Phys. Rev. D 86, 010001 (2012)
    - 30. PASSAGE OF PARTICLES THROUGH MATTER
  - Particle Physics Booklet http://pdg.lbl.gov/

Why do we need loss monitor?

- Beam loss should be avoided for
  1. Personnel Protection
  2. Machine Protection

1. <u>Personnel Protection (PPS)</u>
   - Averaged loss inside/outside the shield : mSv/h
   - Measured with area monitor
   - typical time range : 1 sec – min – hour
   - Absolute value (calibrated value) is important
2. <u>Machine Protection (MPS)</u>
   - Important to avoid damages on Vacuum components and other accelerator components
   - time range : micro – msec (- sec)

Importance of MPS

- Proton (Hadron) Machine
  - LHC, J-Parc, SNS, etc

over MW class beam power

- High Luminosity electron storage ring
  - KEKB, PEP-II, etc
- High average DC-Gun machine
  - ERL (Energy Recovery Linac), ELBE, etc

In these machines, fast and reliable MPS is <u>mandatory</u> for operation

On the other hand,

how about in electron storage rings for SR?

- Electron storage ring for SR users
  - 3 GeV, 200 mA, C=800 m case, total charge stored in the ring is 530 nC;
    - Beam power : 1 – 2 kW range
- When the beam is lost :
  - within "one turn" or "several turns"?
  - [Watt/second] or [Joules] is a key
  - Loss Power per unit length [Watt/m] is a key

Ref. CAS2011, "Machine Protection and Collimation", Schmidt

Loss monitor for SR source

- In the past or moderate power machine,
  - We “should” have loss monitor.
  - Not a mandatory tool.
  - Much better if we have the monitor.

- Recent machine
  - Protection of Insertion Device : Important
  - Loss Monitor becomes a “Powerful Tool” for advanced machine tuning.
  - High position resolution
    - can be achieved with fiber + Cherenkov radiation.

Not only for PPS and MPS

- Loss monitor is also very useful for
  - Commissioning
  - Machine tuning
  - Advanced beam diagnostics

Requirements are far different for each case.
however,
Same or similar technique could be applied

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2. Review of Beam Loss Monitors

2-1 : Interaction of stray electrons with matter

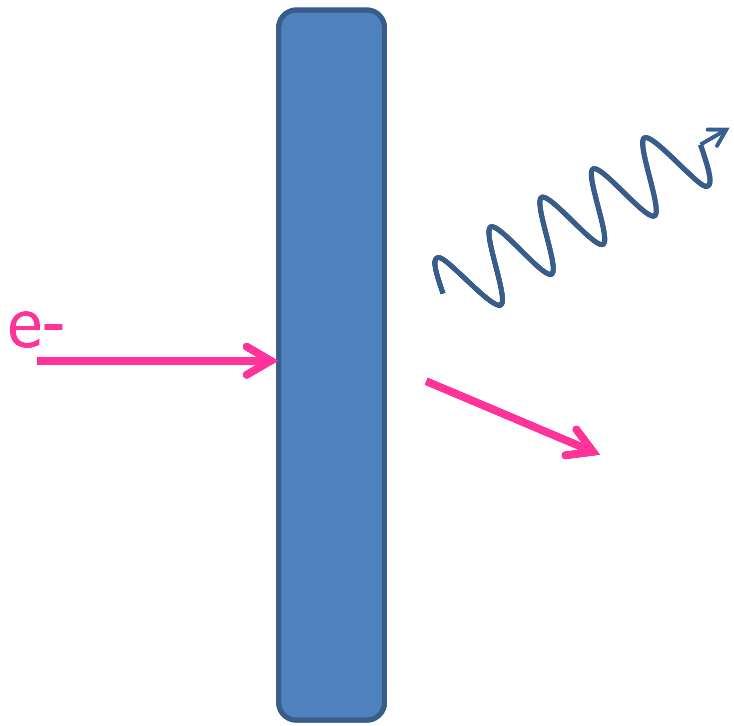
- Brief review of textbook : interaction between charged particle and medium

2-2 : Detection of lost electron

- Loss Monitor Examples
  - Scintillation counter
  - PIN Diode
  - Ion Chamber (Gas, Air)
  - Optical Fiber
    - Dosimeter
    - Cherenkov Radiation → detail description in Sec. 3

When electron enters into medium,

it loose its energy due to

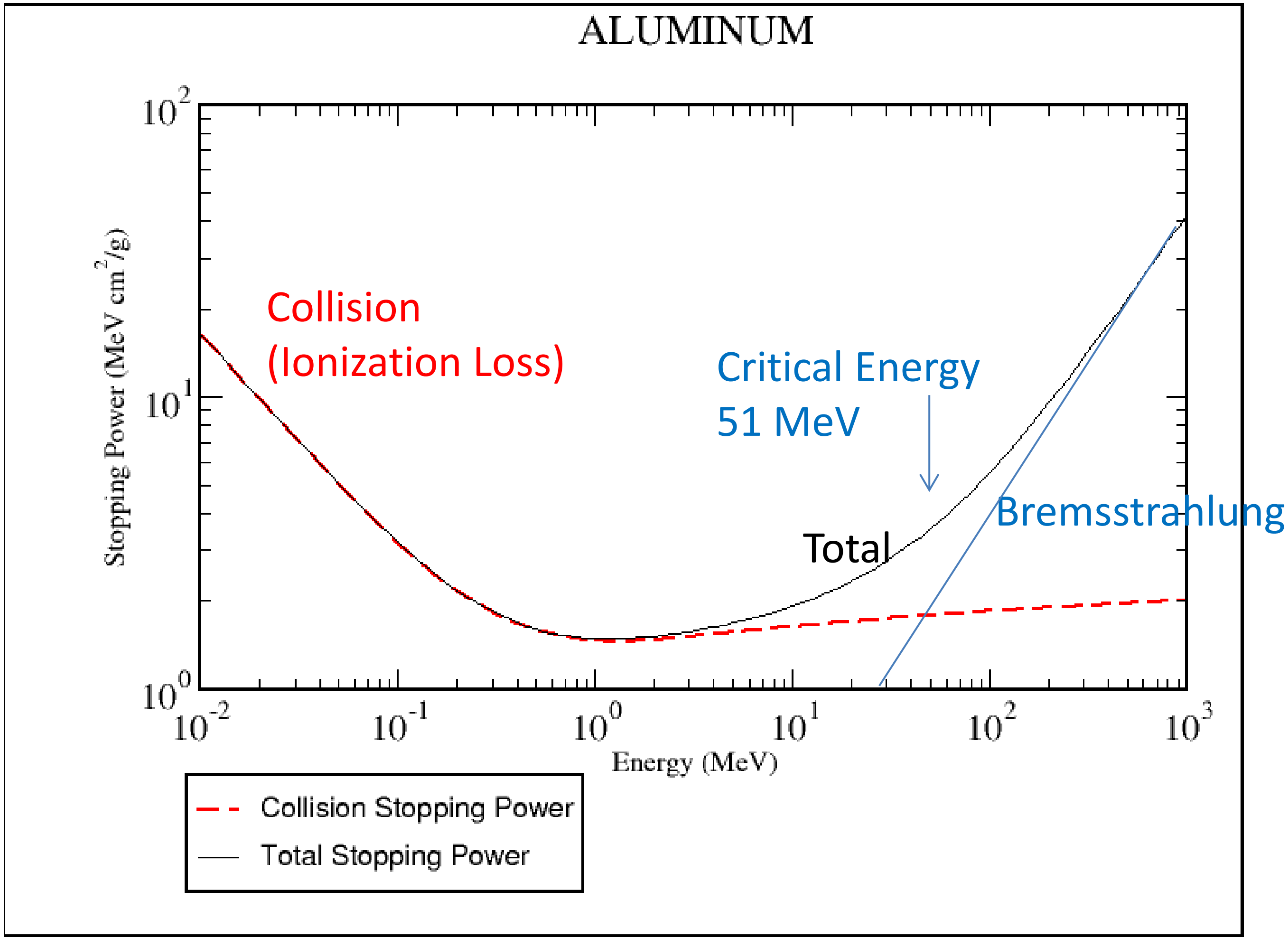


Low energy e-:
Ionization
Excitation

High energy e-:
Bremsstrahlung

Coulomb scattering
Rutherford scattering
Multiple scattering

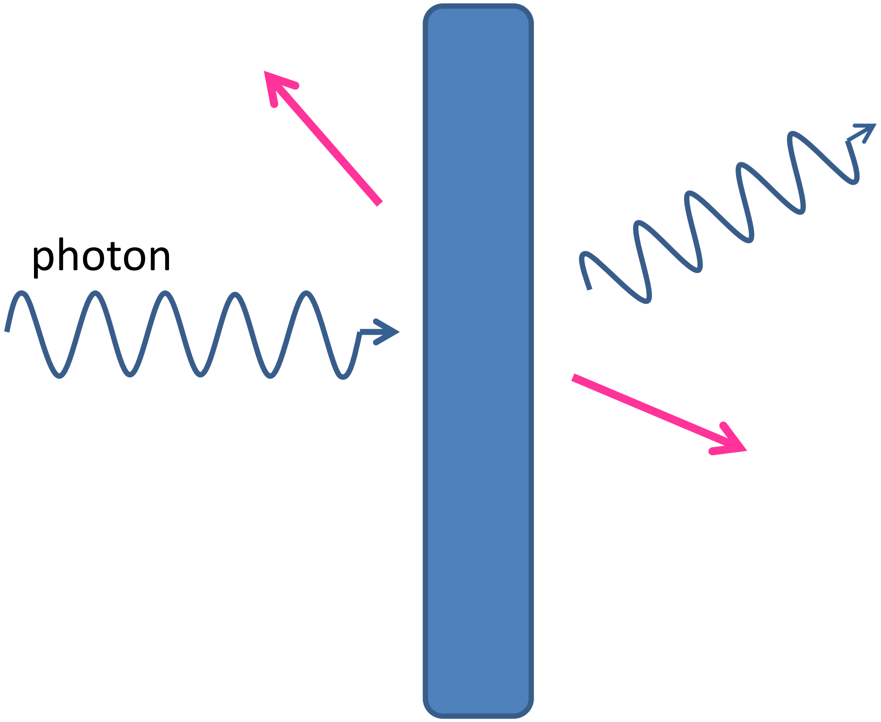
Electron stopping power



Stopping-power and range tables for electrons
http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html

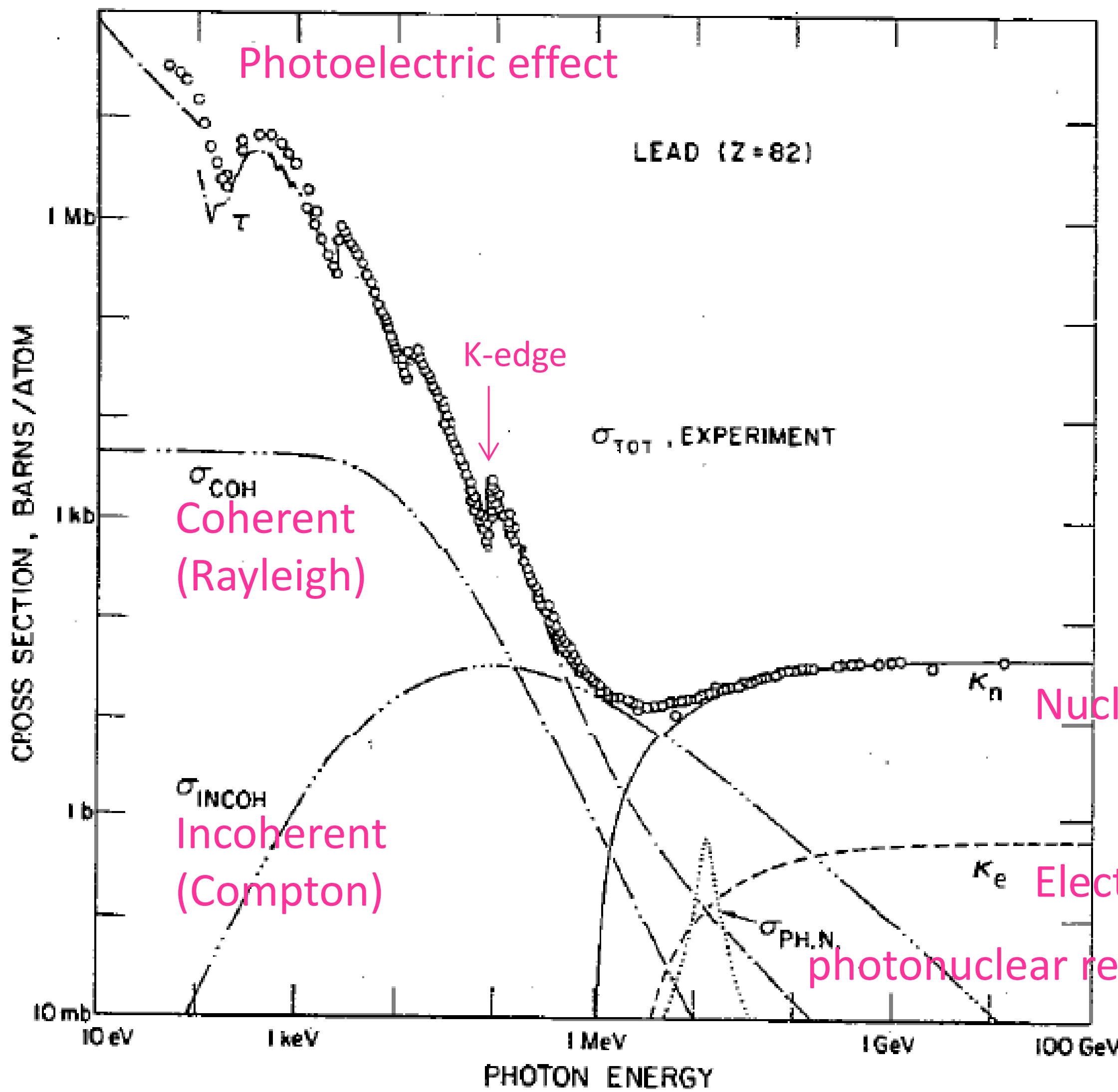
When photon into medium,

Various effects will occur depending on its energy



- Photoelectric effect
- Rayleigh scattering
- Compton scattering
- Pair creation

Photon cross section (Lead)



"Pair, Triplet, and Total Atomic Cross Sections (and Mass Attenuation Coefficients) for 1 MeV-100 GeV Photons in Elements Z=1 to 100", J. H. Hubbell, H. A. Gimm, I. Overbo; JPCRD 9(4) pp. 1023-1147 (1980) http://www.nist.gov/data/PDFfiles/jpcrd169.pdf

Simulation

Monte Carlo Simulation codes are available

Five Major Codes
Code comparison chart, for example,
http://mcnpx.lanl.gov/opendocs/misc/chart.ppt

Code	Institute	Language	Comment
MCNPX	LANL	Fortran 90/C	5 GeV
FLUKA	CERN, INFN	Fortran 77	20 TeV
MARS	FNAL	Fortran 95 / C	1 MeV – 100 TeV
PHITS	JAEA, RIST, GSI	Fortran 77	200 GeV
GEANT4	CERN, INFN, KEK, SLAC	C++	No limit

Code	Institute	Language	Comment
EGS5	SLAC, KEK	Fortran 77	Electron, Gamma

http://rcwww.kek.jp/research/egs/

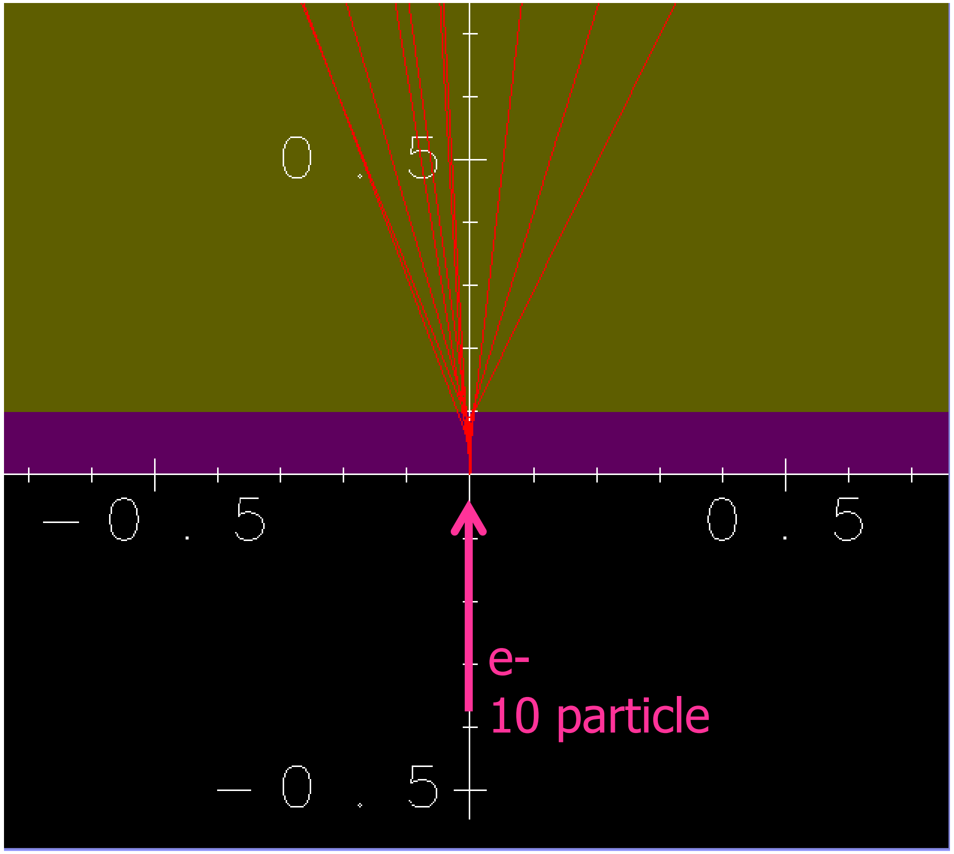
EGS5 ex1 : 2.3 MeV electron, Al

- Flat plate (slab) model
- Density (room temp) = 2.7 g cm^{-3}
- Maximum penetration range = 0.41 cm

Air (Vacuum)

Aluminum

Vacuum

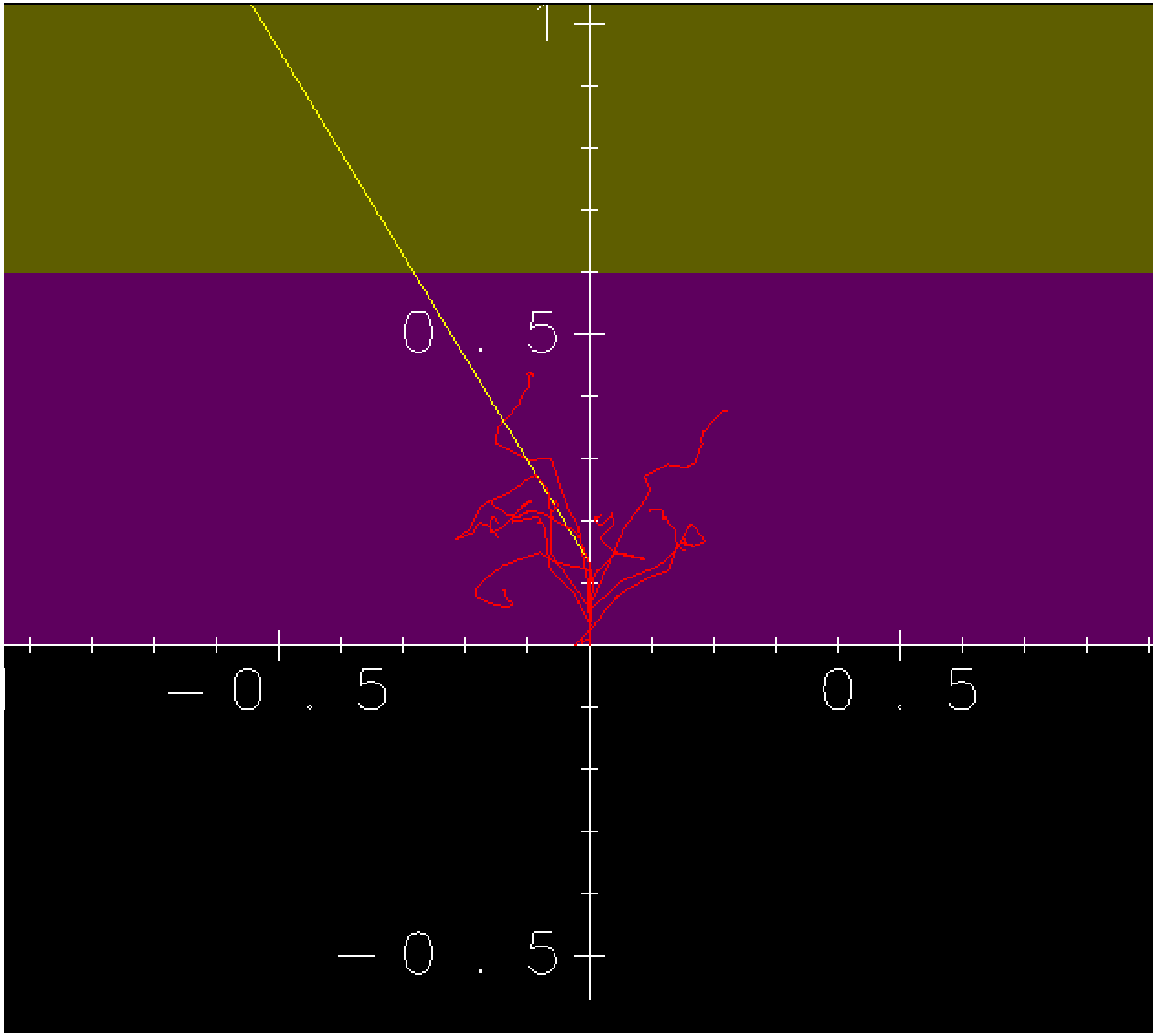


10 particle Passed through

0.1 cm

Inject 10 particle

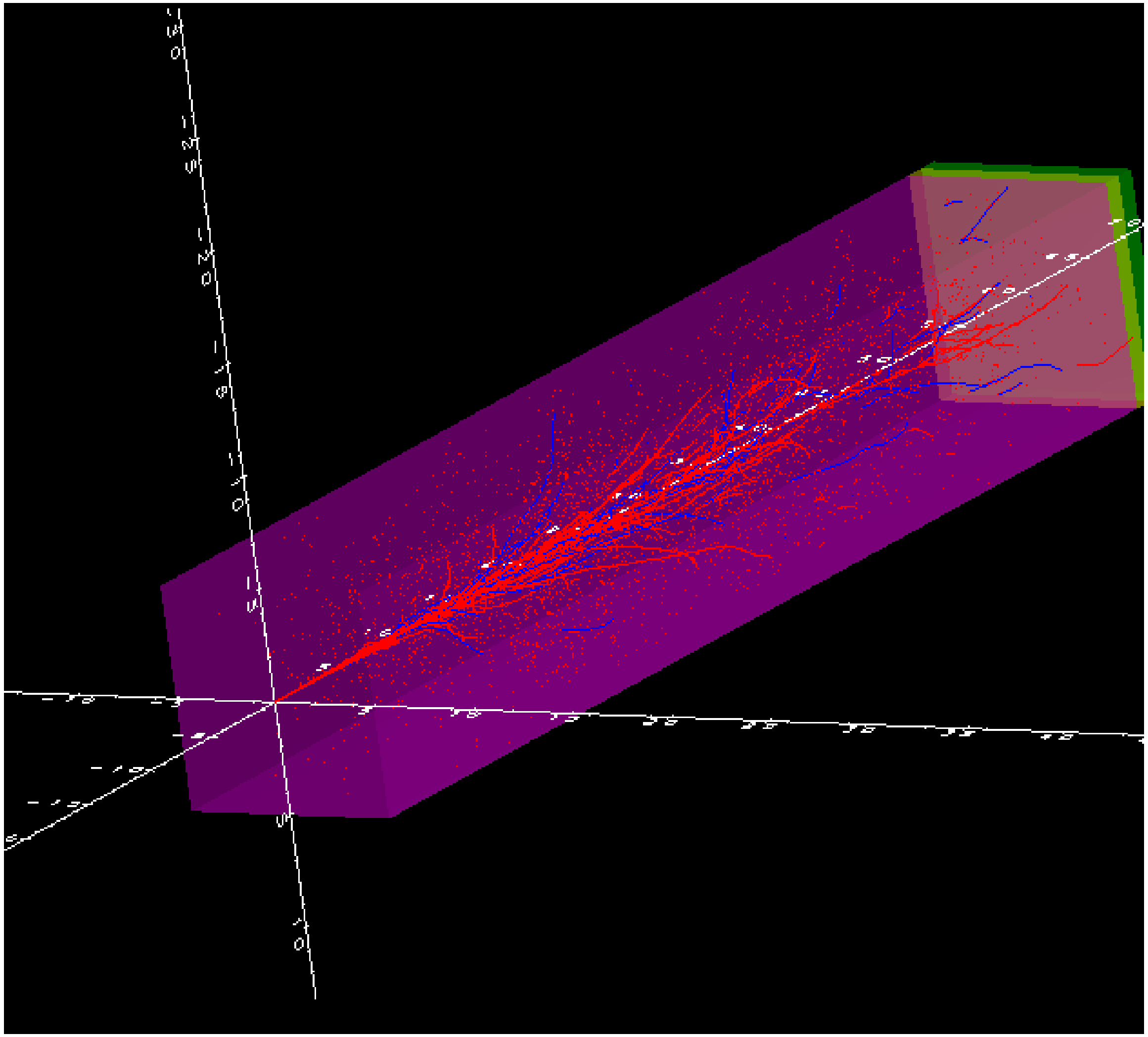
(Scale Unit: cm)



Aluminum 0.6 cm
no electron pass through

EGS5 Example 2

- 1GeV electron; Electromagnetic shower



60 cm AL

Red : e-
Blue: e+

2-2 Loss Monitor Examples

2-1 Interactions of stray electrons with matter
- Brief review of textbook : interaction between charged particle and medium

2-2 : Detection of lost electron
- Scintillation counter
- PIN diode
- Ionization chamber
- Optical fiber
  - Dosimeter
  - Cherenkov

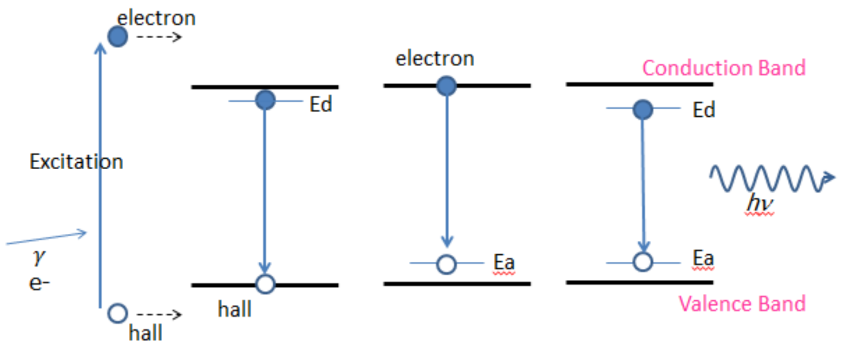
In today's talk, I just show one slides per item.
For detail, please refer to CAS2008, K. Wittenburg

Scintillation Detector

- Scintillator
  - NaI, Nai:Ta, CsI, …
  - YAG, YAG:Ce, …
  - Alumina Ceramic (Al_2O_3 + CrO_3 ;Demarquest)

There are many choice. Select material suitable for your purpose:

Gamma-ray absorption
Response time
Wavelength
Energy resolution

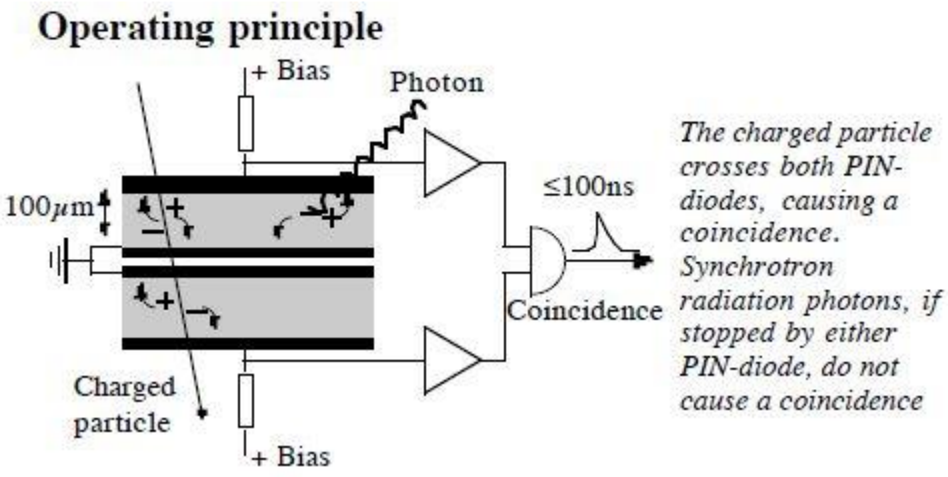


Typical setup

Scintillator

PIN Diode

- K. Wittenburg, DESY
- Key: two PD to reduce SR background

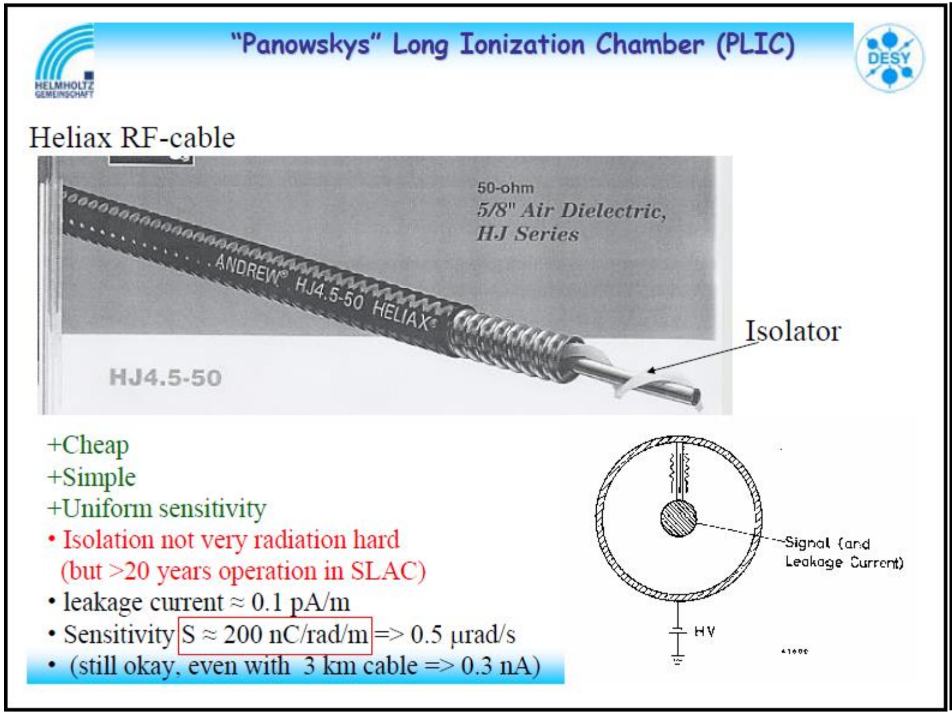


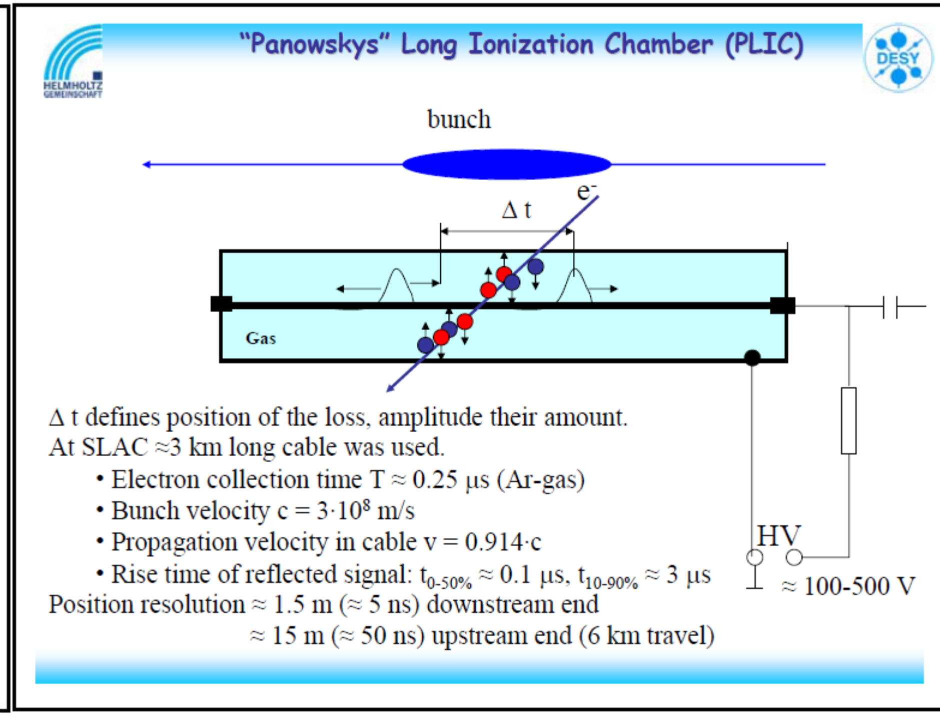
Commercially available from Bergotz

"Electron Beam Loss Monitors for HERA" by W. Bialowons, F. Ridoutt and K. Wittenburg

Ionization Chamber

- Gas or Air ionization chamber





"Beam Loss Monitors" CAS2008, K. Wittenburg

Optical fiber loss monitor : History

- 1970 -
  - 1970s : optical fiber as "light guide"
  - 1980s : optical fiber as "radiation detector" (Doped) for reactor
- 1990
  - "Optical fiber Cherenkov detector for beam current monitoring", I. Pishchulin et.al. PAC91 (1991) 1567
    - Theory/Calculation
  - "Quartz Fibre Calorimetry" P. Gorodetzky et.al. NIM A361 (1995) 161
    - For physics detector
  - "A Scintillating Fiber Beam Halo Detector for Heavy Ion Beam Diagnostics" M.A. McMahan et.al. PAC93 (1993) 2187
  - <u>Tesla Test Facility 1 (TTF1), DESY</u>
    - 100 m Ge+P doped fiber; Started from dosimetory using OTDR
    - Cherenkov radiation for high position resolution
    - Many papers are published
  - "Fiber Optic Radiation Sensing Systems for TELSA" H. Henschel et.al., TESLA-Report No. 2000-25, 2000

History (2)

- 2000
  - KEK PS (Proton Synchrotron) : T. Kawakubo ICANS-XV (2000)
  - DELTA : G. Schmidt , EPAC02 (2002) 1969
  - DESY: M. Körfer "Fiber optic radiation sensor systems for particle accelerators" NIM A526 (2004) 537
  - "BEAM LOSS AND BEAM PROFILE MONITORING WITH OPTICAL FIBERS" F. Wulf, M. Körfer DIPAC2009 paper and presentation
  - "Cherenkov Fibers for Beam Diagnostics at the Metrology Light Source" J. Bahrdt PAC2009 (2009) 1159
  - "Development of a Fiber-Optic Beam Loss Position Monitor for the Advanced Photon Source Storage Ring" J. C. Doolingy, PAC2009 (2009) 3438

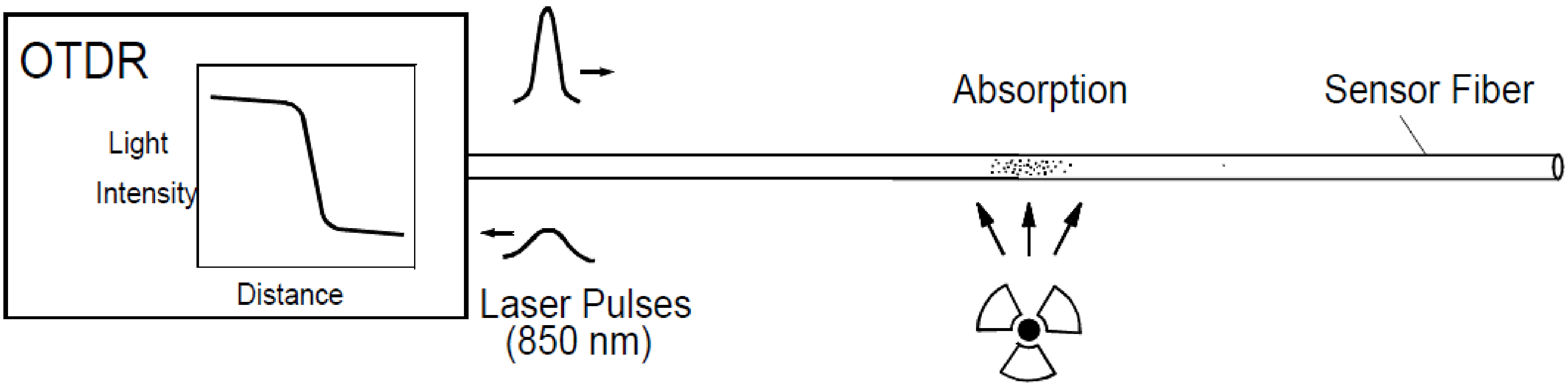
History (3)

- 2009-
  - Spring-8/SCSS/SACLA : utilize Cherenkov radiation (DIPAC09)
  - “Design, development, and operation of a fiber-based Cherenkov beam loss monitor at the Spring-8 Angstrom Compact Free Electron Laser” X. -M. Marechal, Y. Asano, T. Itoga, NIM A673 (2012) 32
  - ALICE DIPAC2009, IPAC2011

- 2012
  - “Cherenkov Fibers for Beam Loss Monitoring at the CLIC Two Beam Module” J. W. van Hoorne, Master thesis, Jun 2012, http://cds.cern.ch/record/1476746

- Many accelerator facility use optical fiber as loss monitor.
  - Not explicitly written in the paper, because now the fiber based loss monitor is very popular technique

Optical Fiber Dosimetry

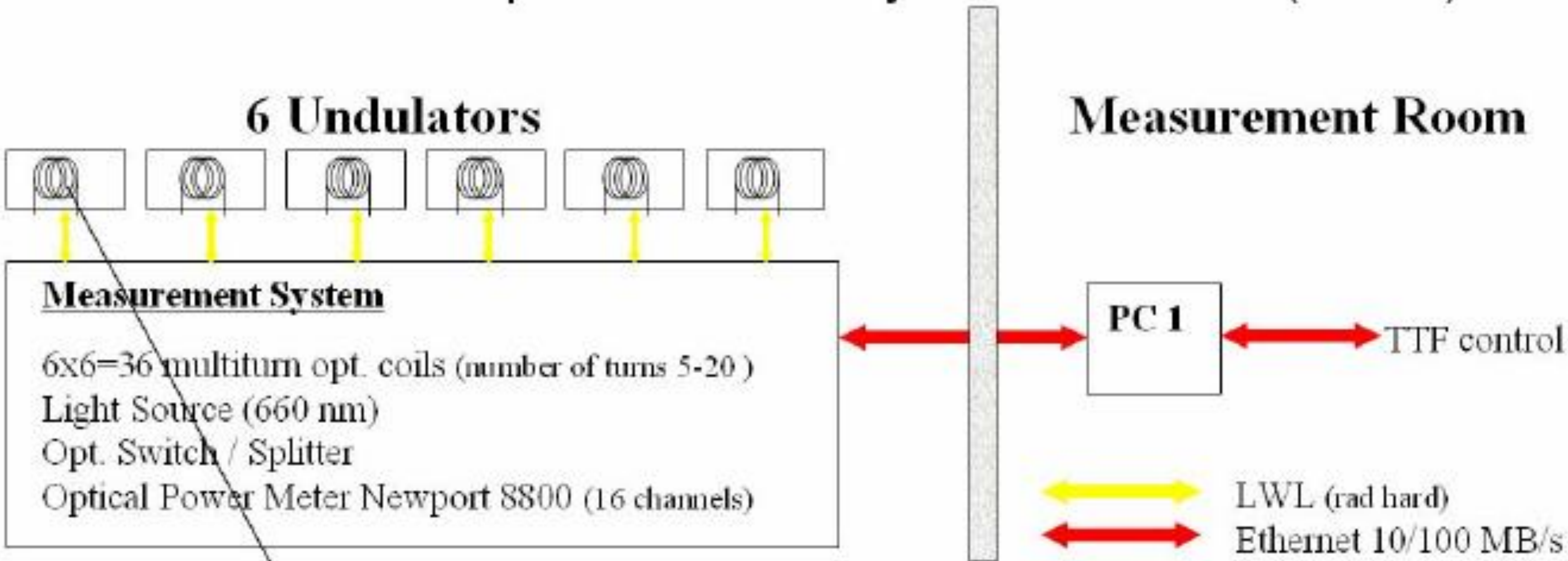


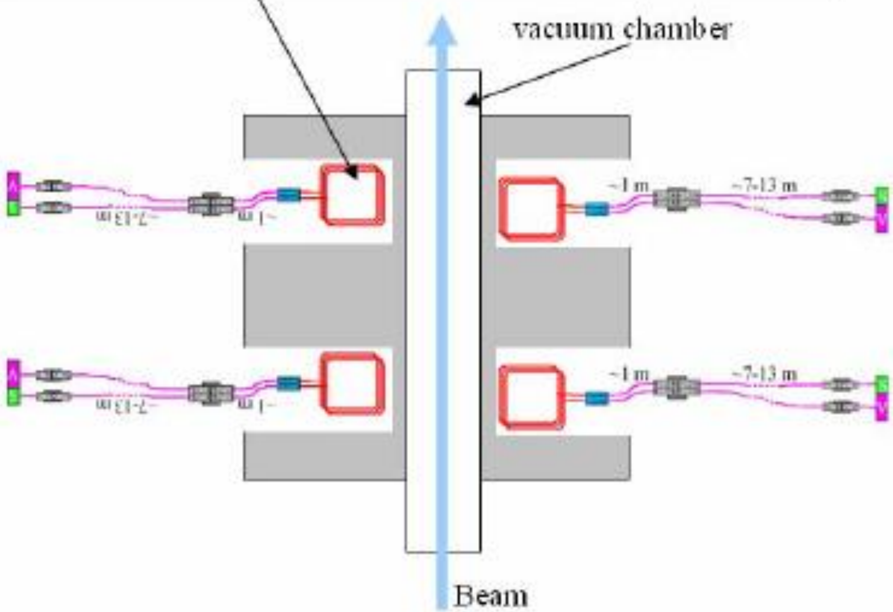
- Utilize optical fiber + OTDR
  - Optical Time Domain Reflectometry

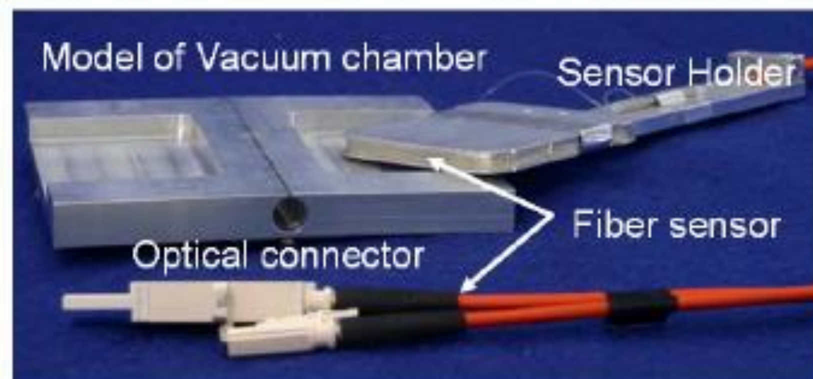
"FIBRE OPTICAL RADIATION SENSING SYSTEM FOR TESLA" H. Henschel, M. Korfer, F.Wulf, DIPAC 2001

3.1.1 Local dosimeter system (Optical Power Meter)

Schematic Set Up for the OPM System at FLASH (DESY)





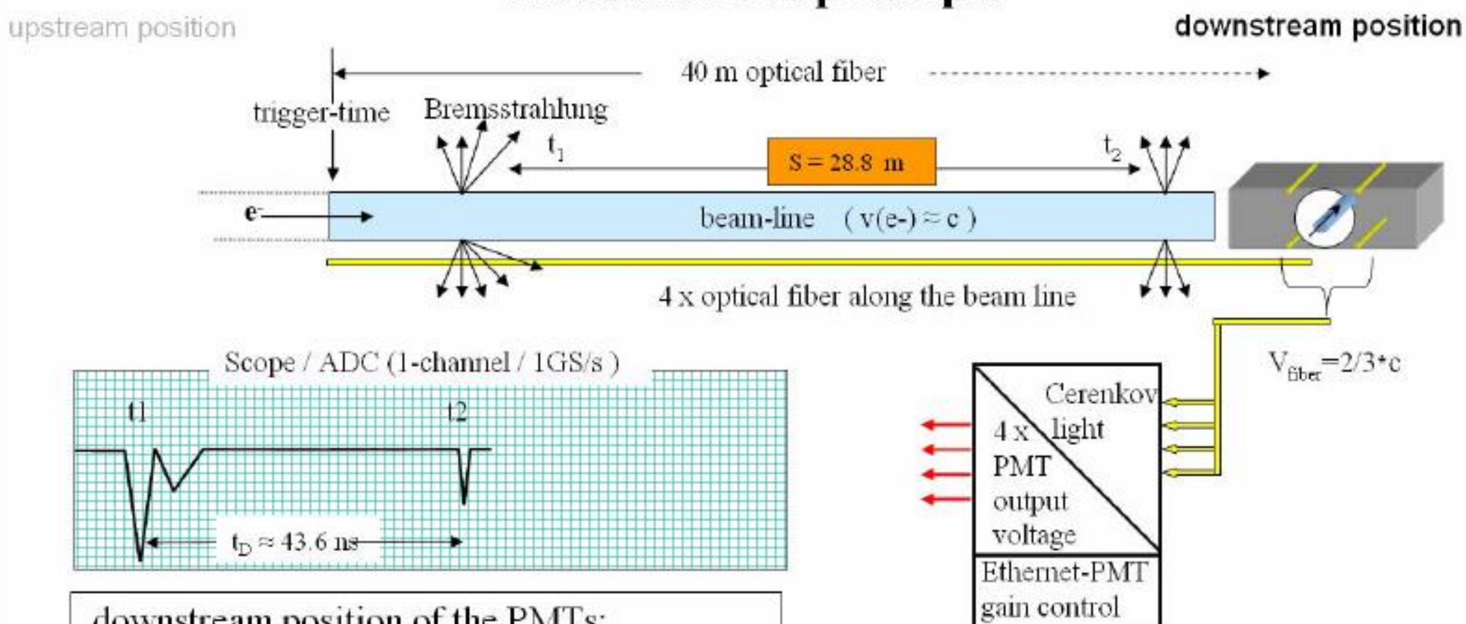


Fiber + Cherenkov Radiation

- F. Wulf, DIPAC09

3.2.1 Beam loss position monitor

Measurement principle



downstream position of the PMTs:

$\mathbf{S = t_D \cdot 2 \cdot c}$

$t_D = t_1 - t_2 = 48$ ns $\Longrightarrow$ S = 28.8 m

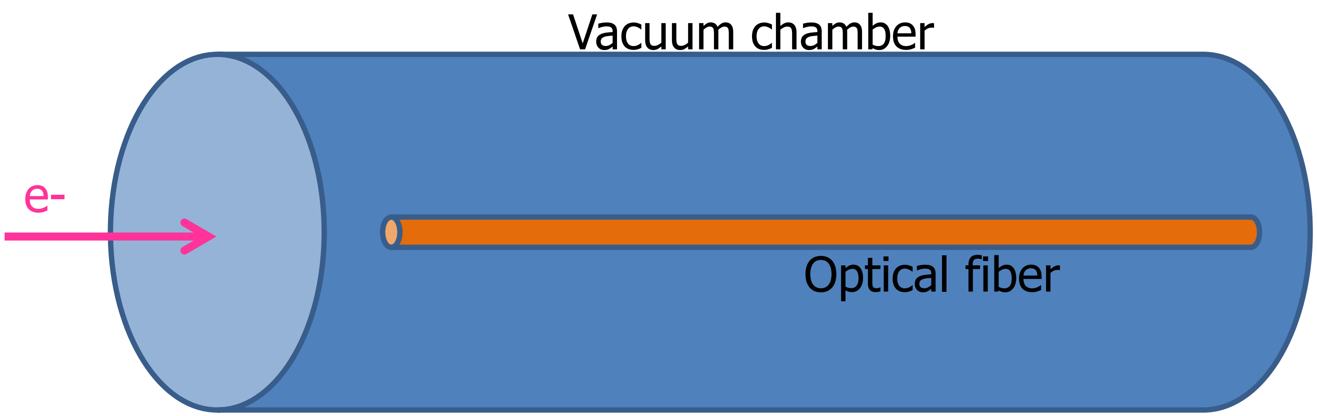
compression factor of 2

The required **observation window** at downstream position compared to the upstream position is 5 times shorter. The position resolution at same bandwidth and sample rate is worse

DIPAC 2009 (WEOA01) No. 29 27. Mai 2009 F. Wulf (HZB)

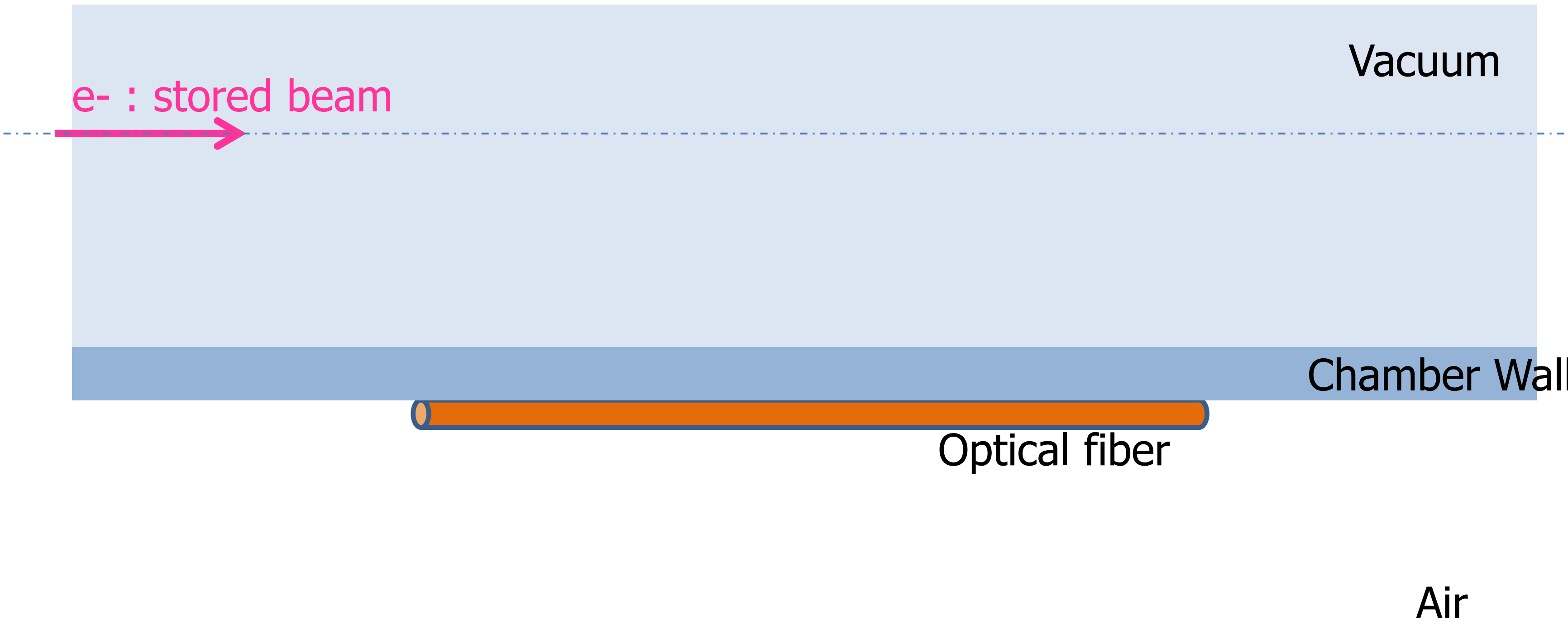
Principle of fiber loss monitor (1)

- Optical fiber could be attached <u>directly</u> to the vacuum chamber wall.



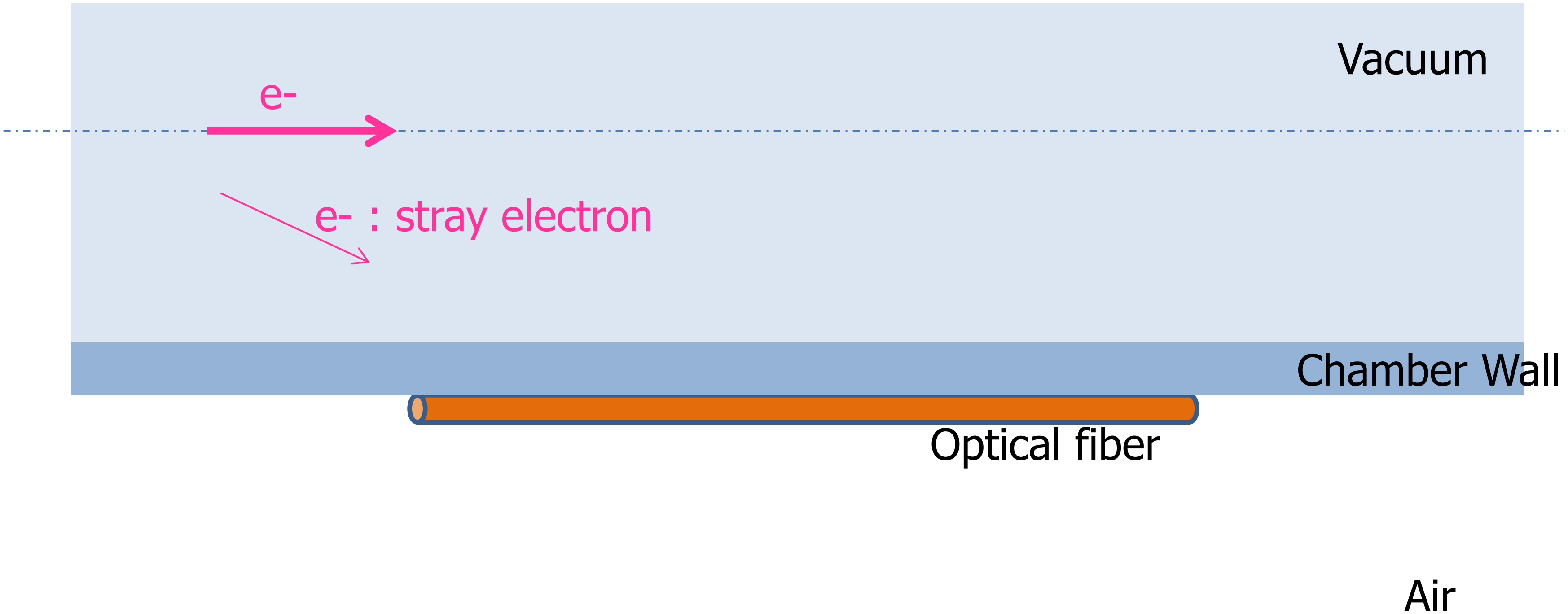
Principle of fiber loss monitor (2)

- Cross sectional diagram of vacuum chamber and a optical fiber.



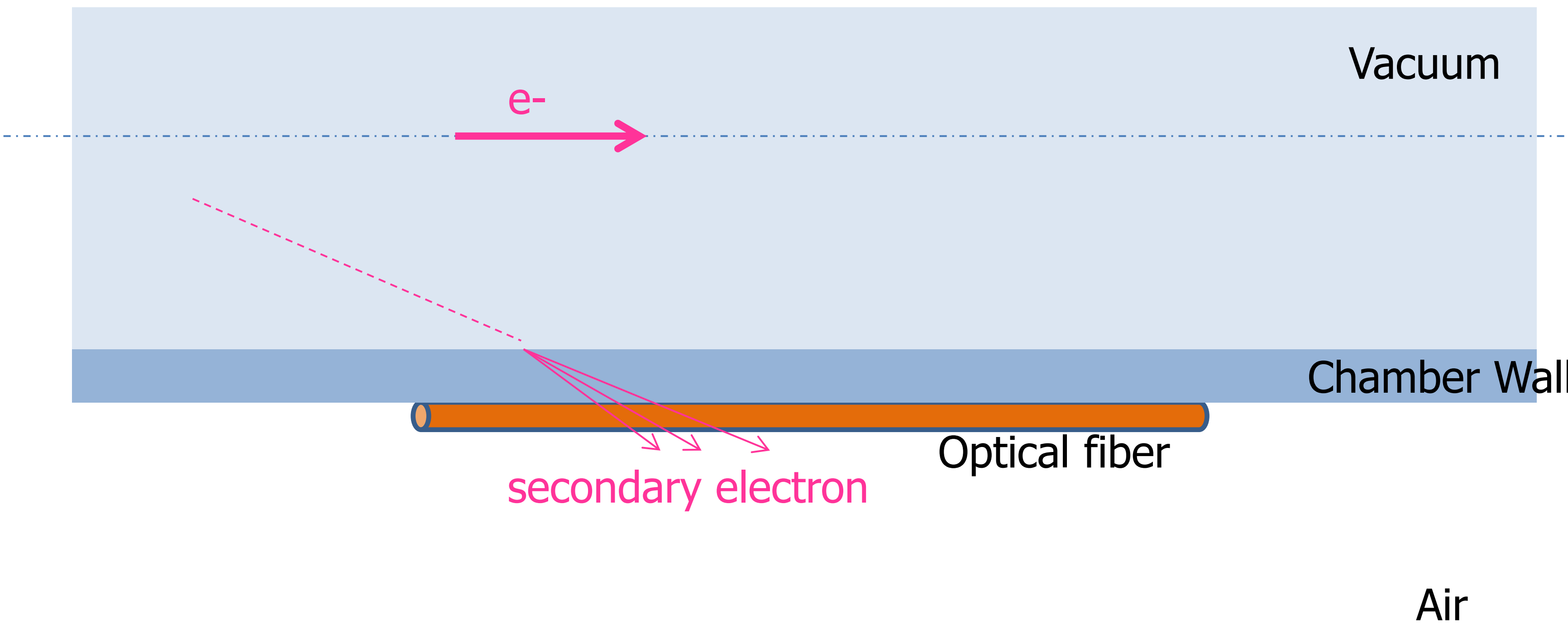
Principle of fiber loss monitor (3)

- Assume stray electrons : same speed as stored electron beam.



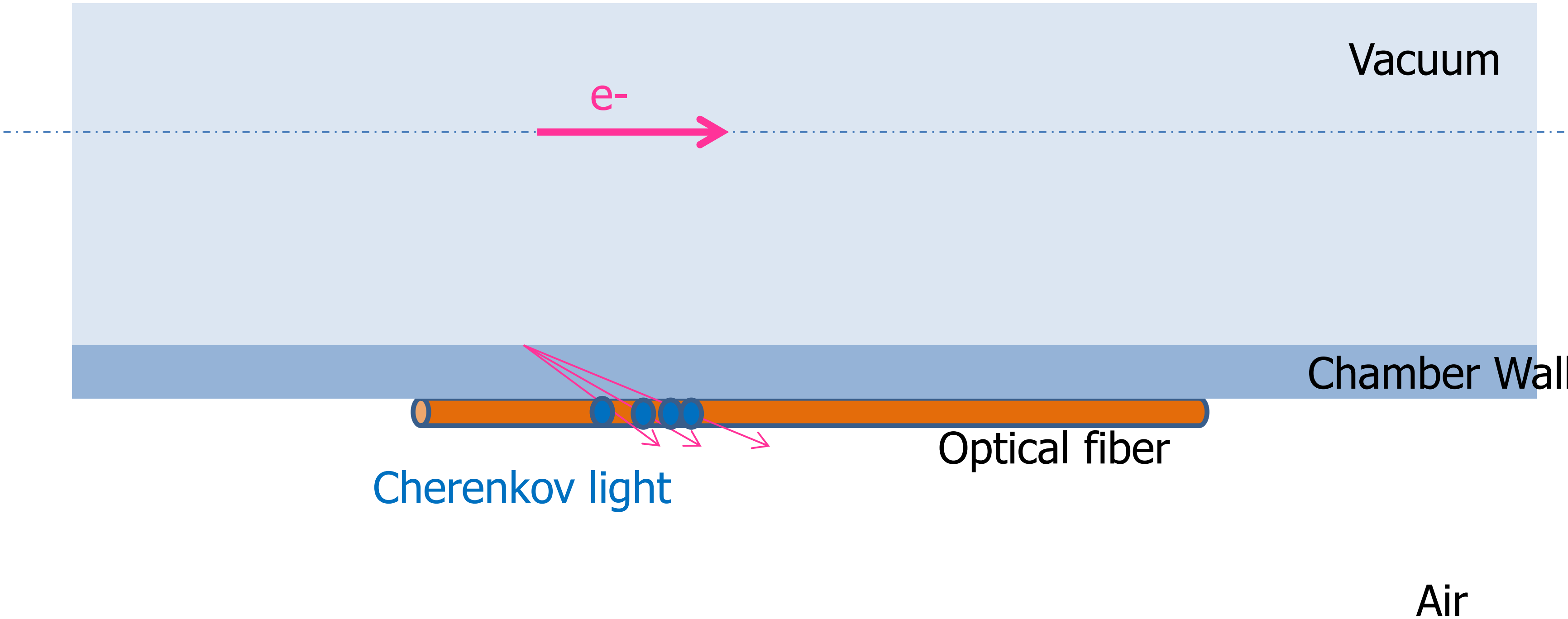
Principle of fiber loss monitor (4)

hit the wall, and produce secondary electron.



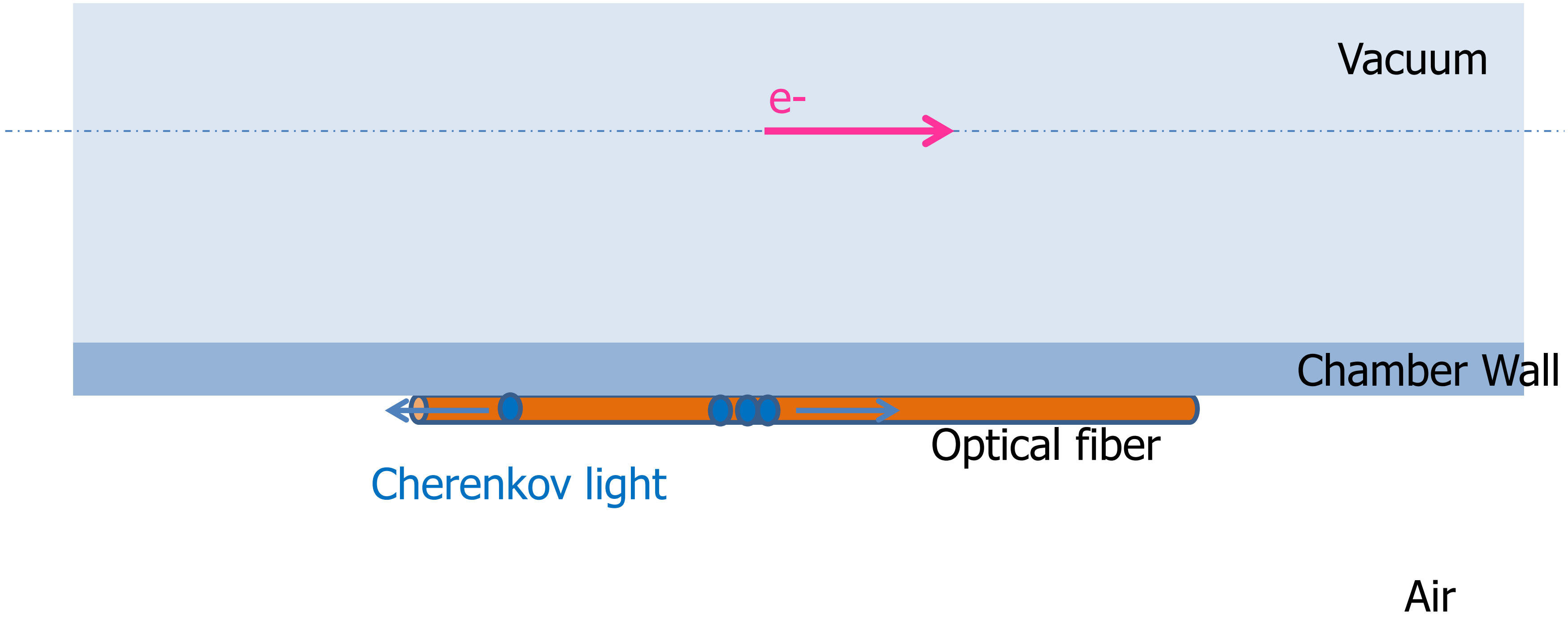
Principle of fiber loss monitor (5)

- Generation of Cherenkov radiation in fiber



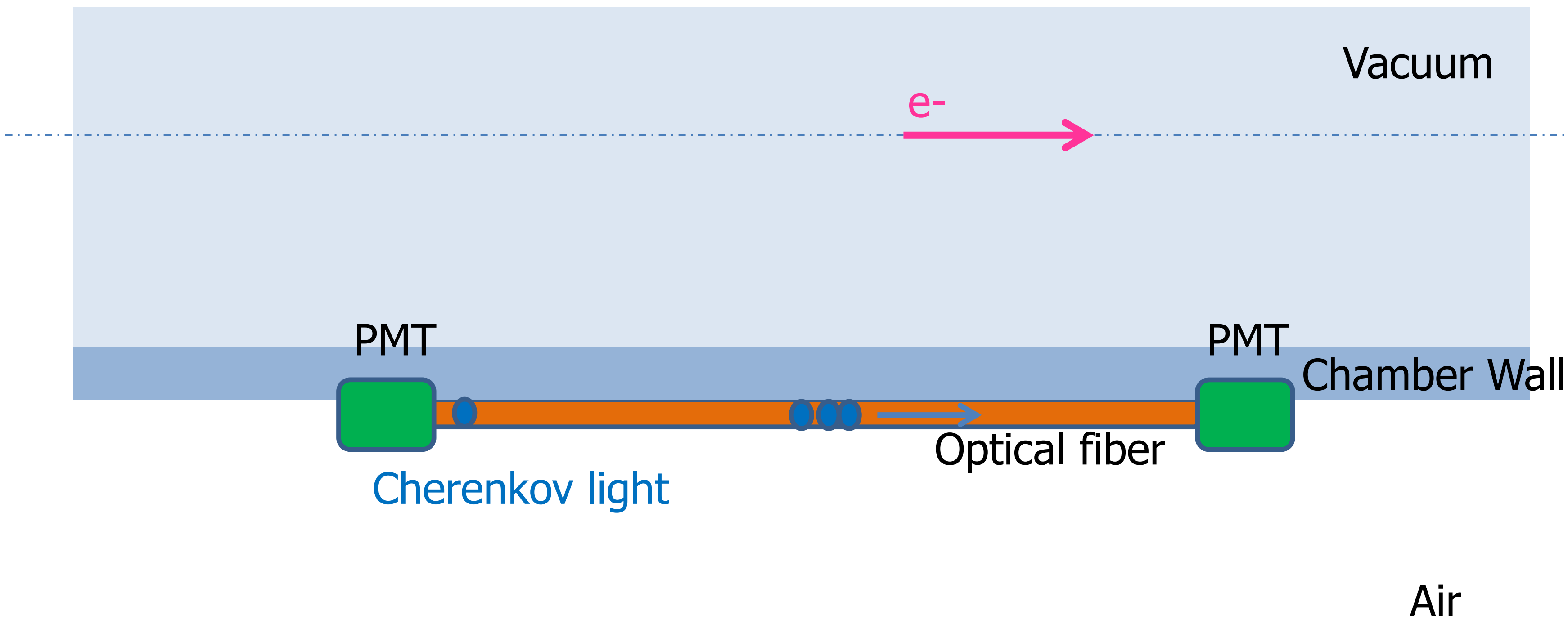
Principle of fiber loss monitor (6)

- Light pulse start to propagate



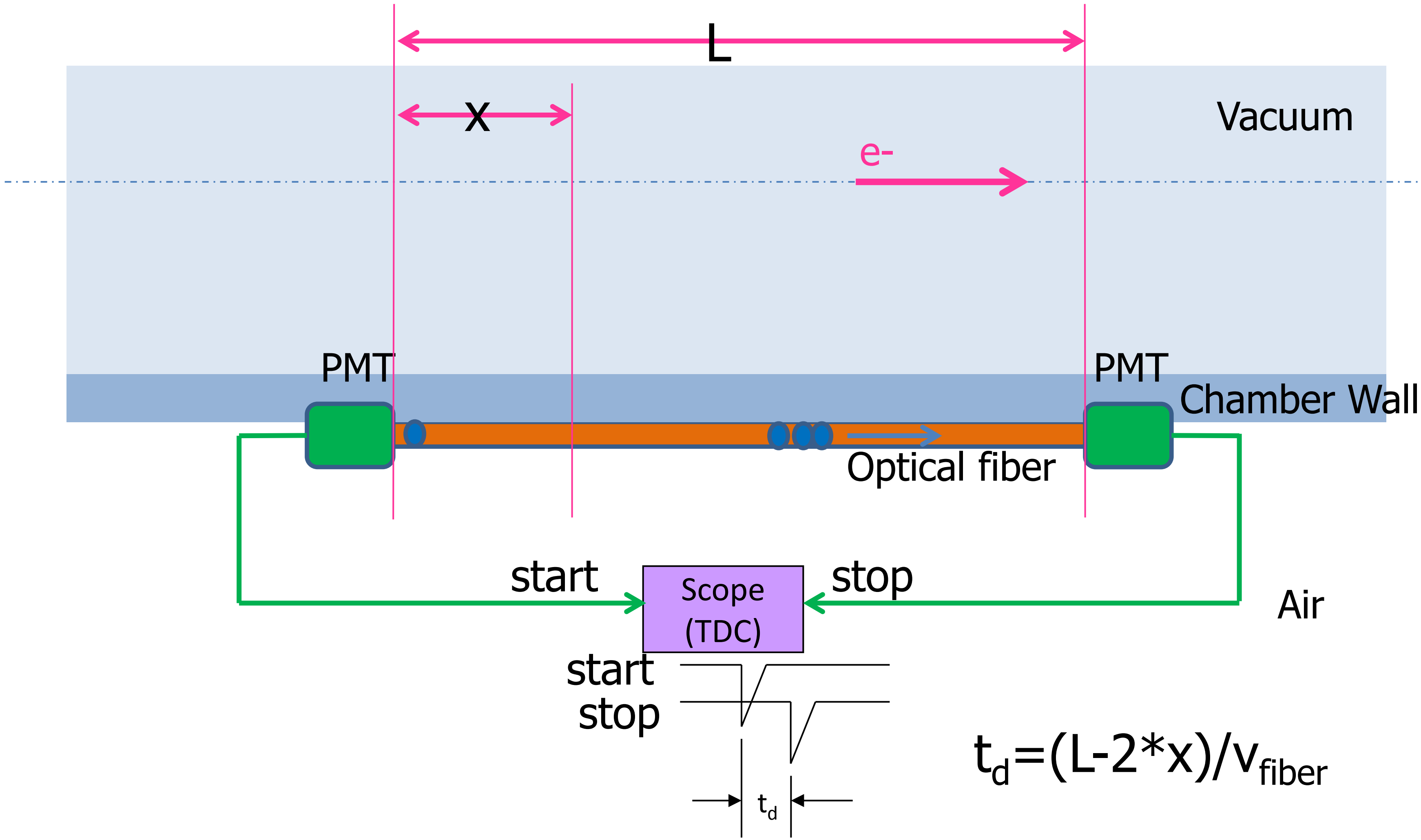
PMT Location 1

- Put PMT on both end. Detect light pulse.



Measure loss point

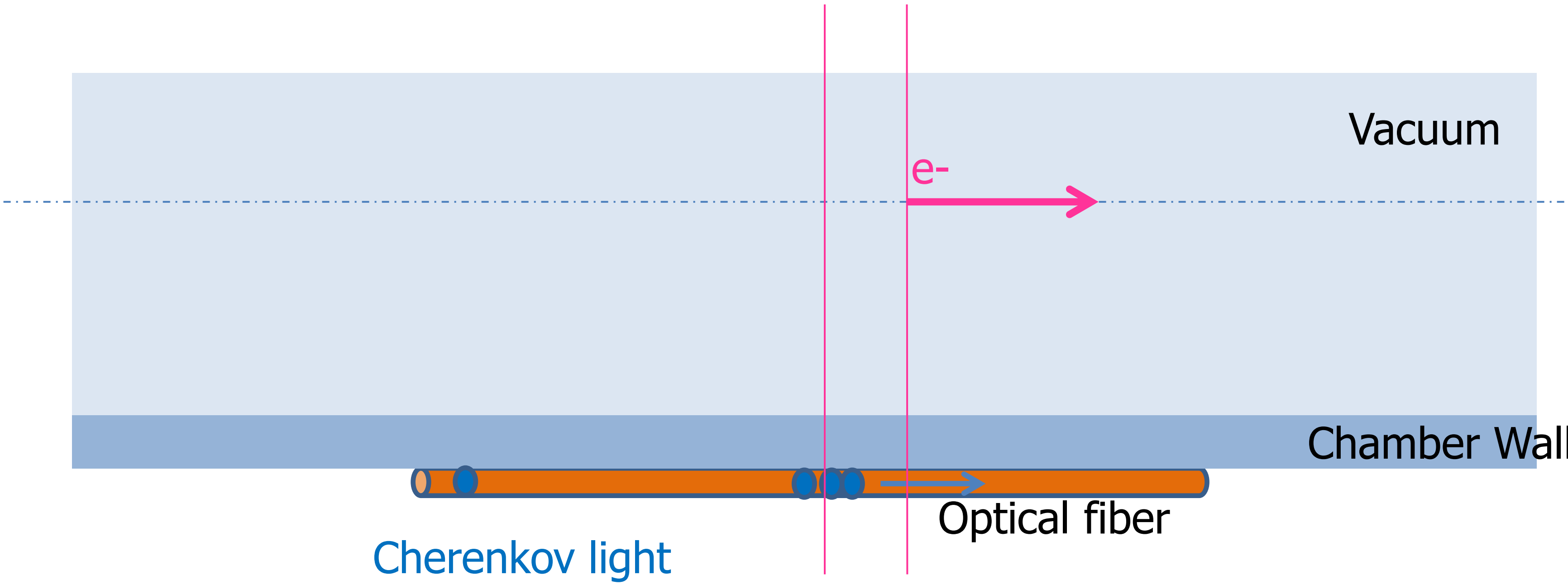
- Loss point is determined from time diff.



$$t_d=(L-2*x)/v_{fiber}$$

Remark

- Speed of light in fiber < speed of e- in vac

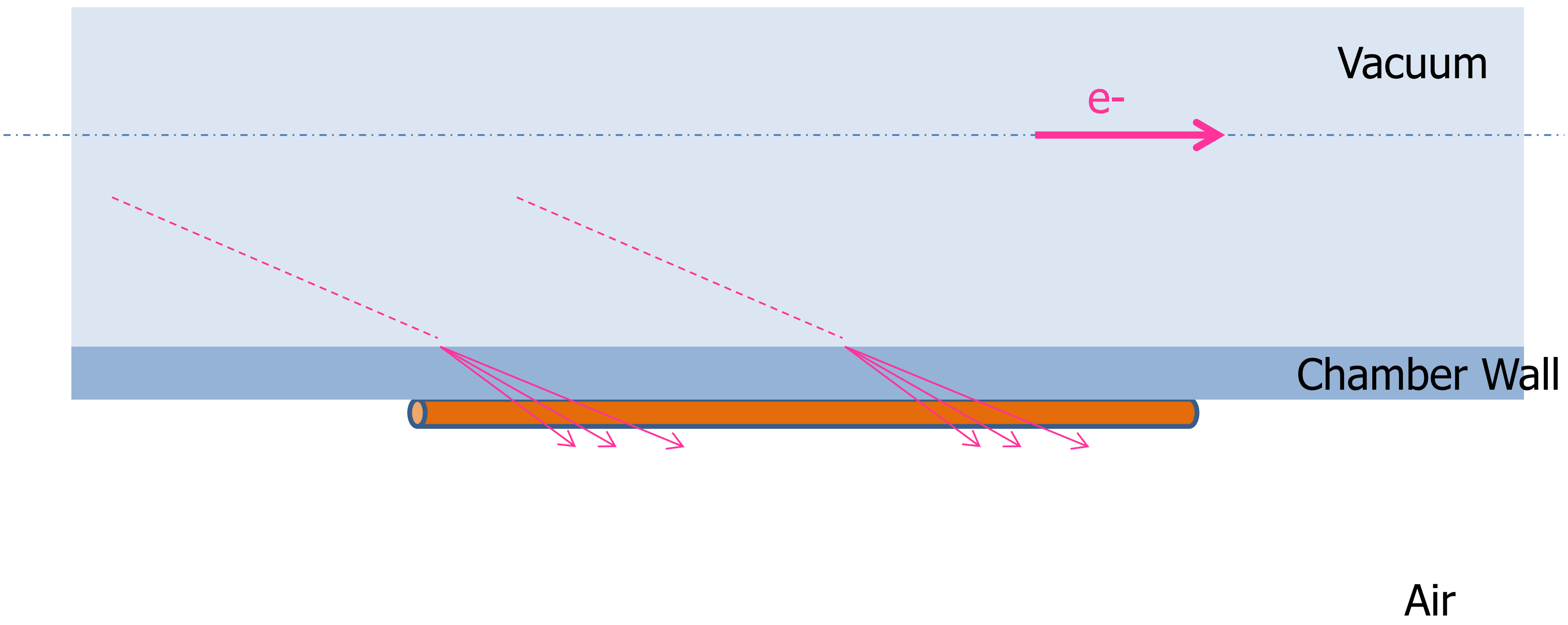


$v_e = c$

$v_{fiber} = 2/3*c$ (= 5.0ns/m)

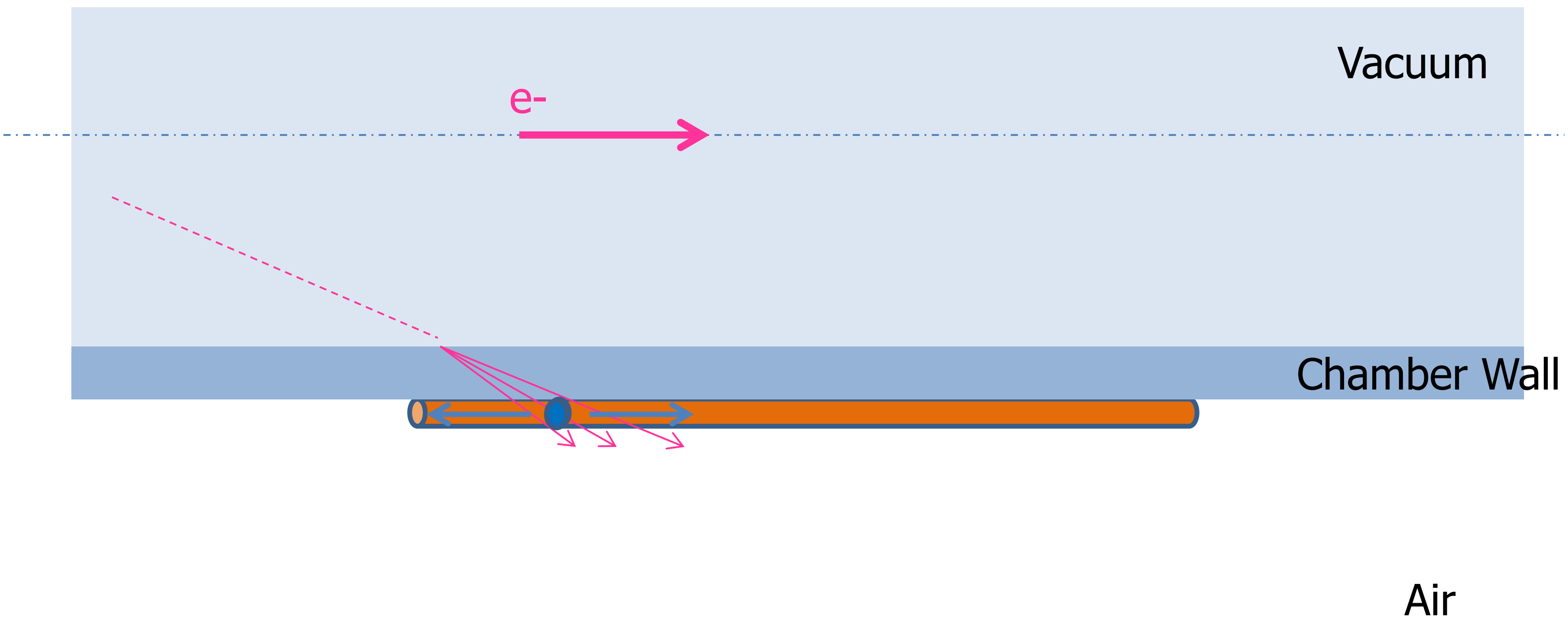
Next: think 2 loss points

- What kind of signal can we observe?

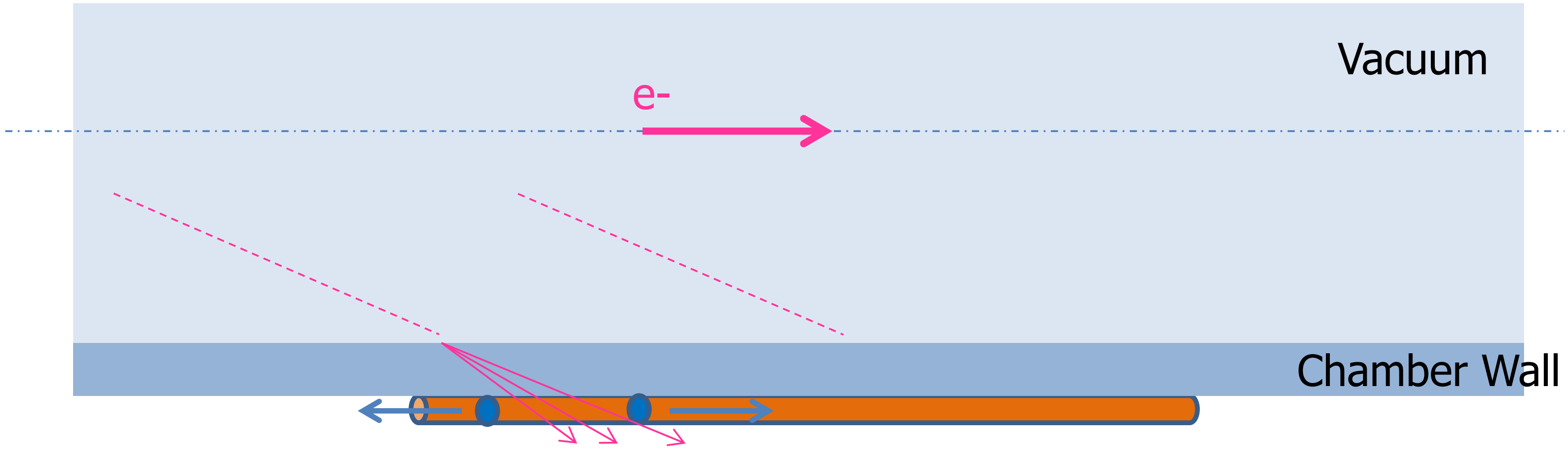


First loss point

- Light pulse start to propagate



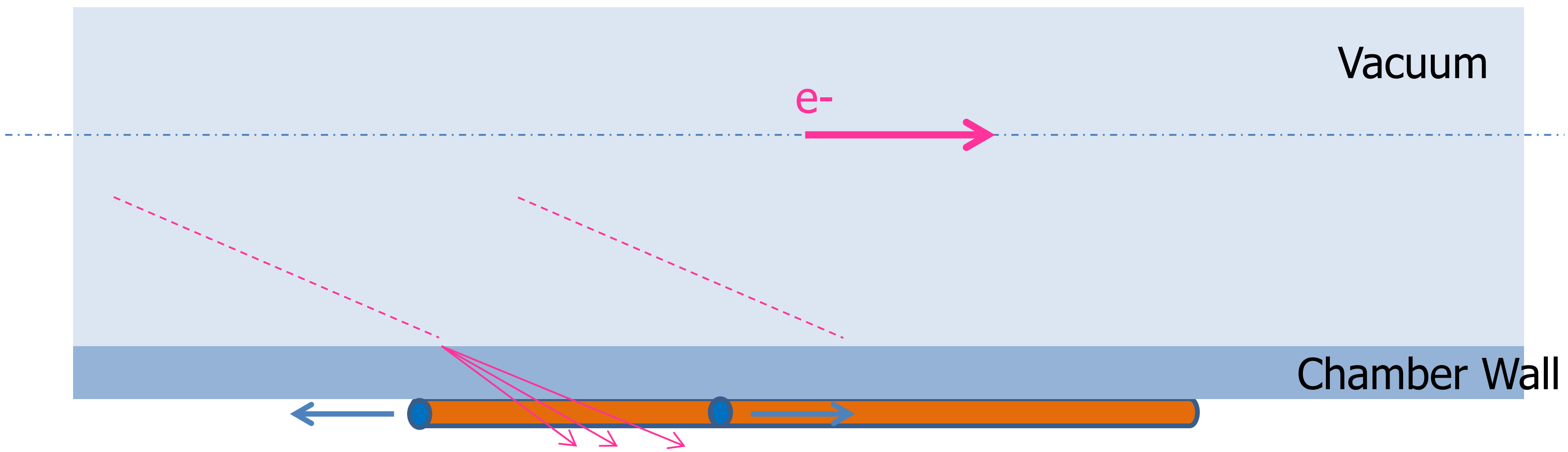
Difference of speed



Speed of light pulse < speed of electon

Sorry: this figure is not “scaled”

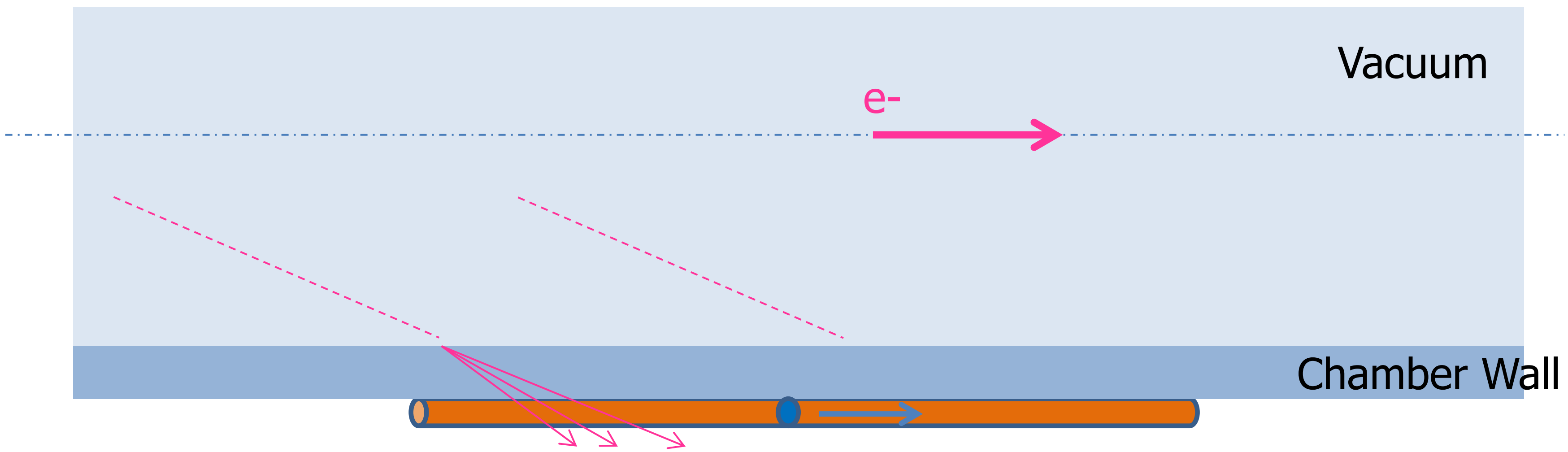
Electron is faster than light pulse



Electron overtake the light pulse

Sorry: this figure is not “scaled”

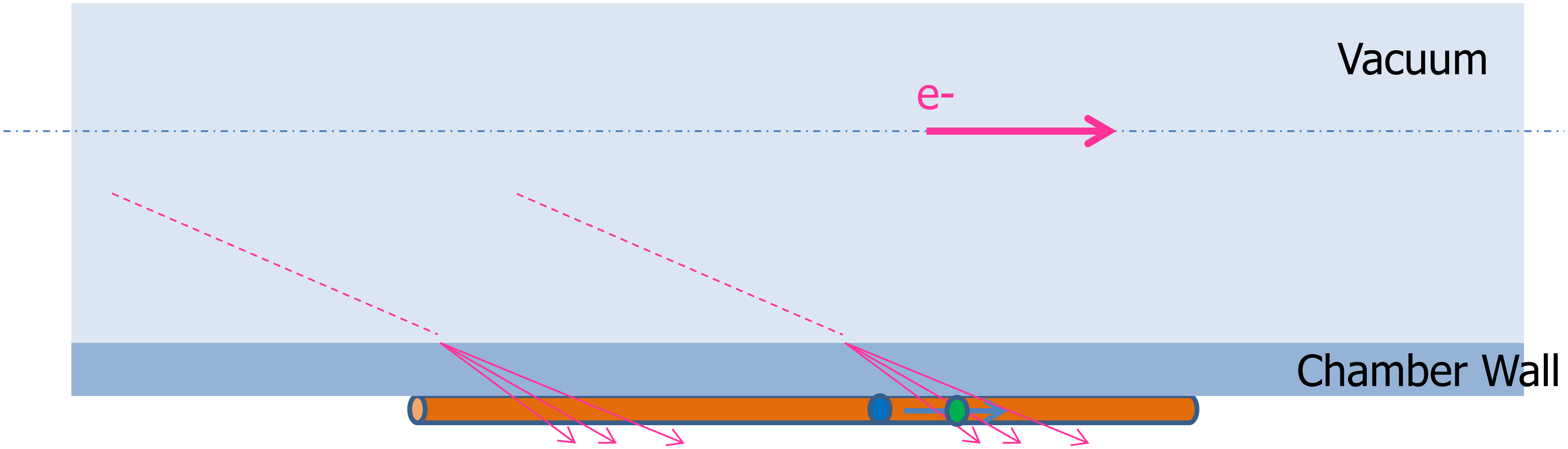
then…



Speed of light pulse < speed of electon

Sorry: this figure is not “scaled”

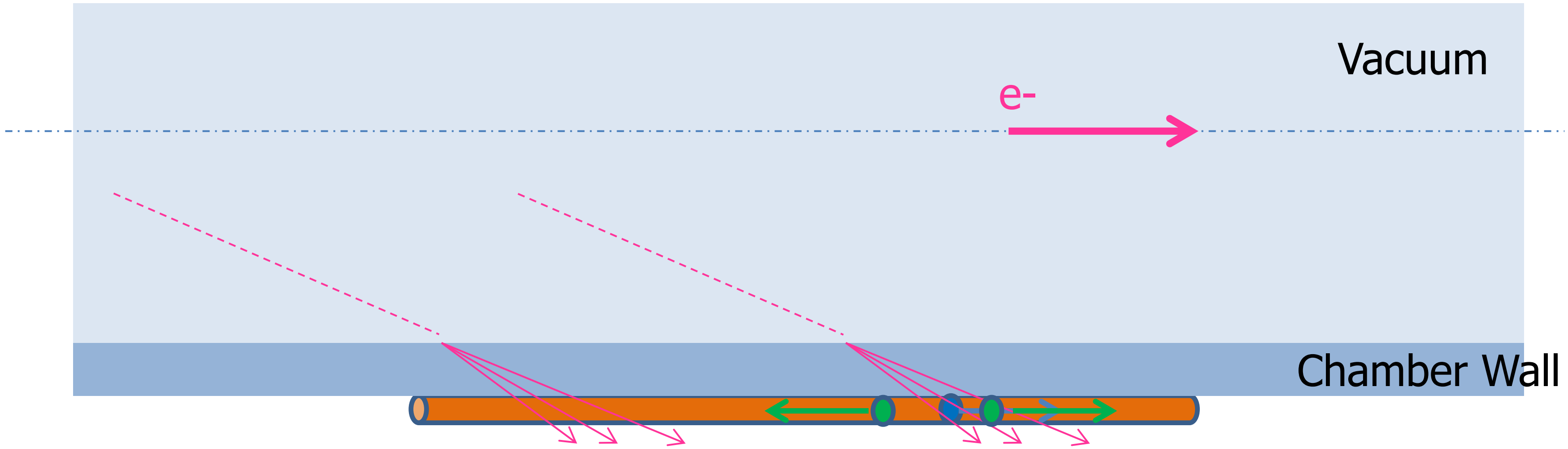
Next loss point



Cherenkov light at second loss point is produced

Sorry: this figure is not “scaled”

Light pulse of second loss point



Second light pulse start to propagate

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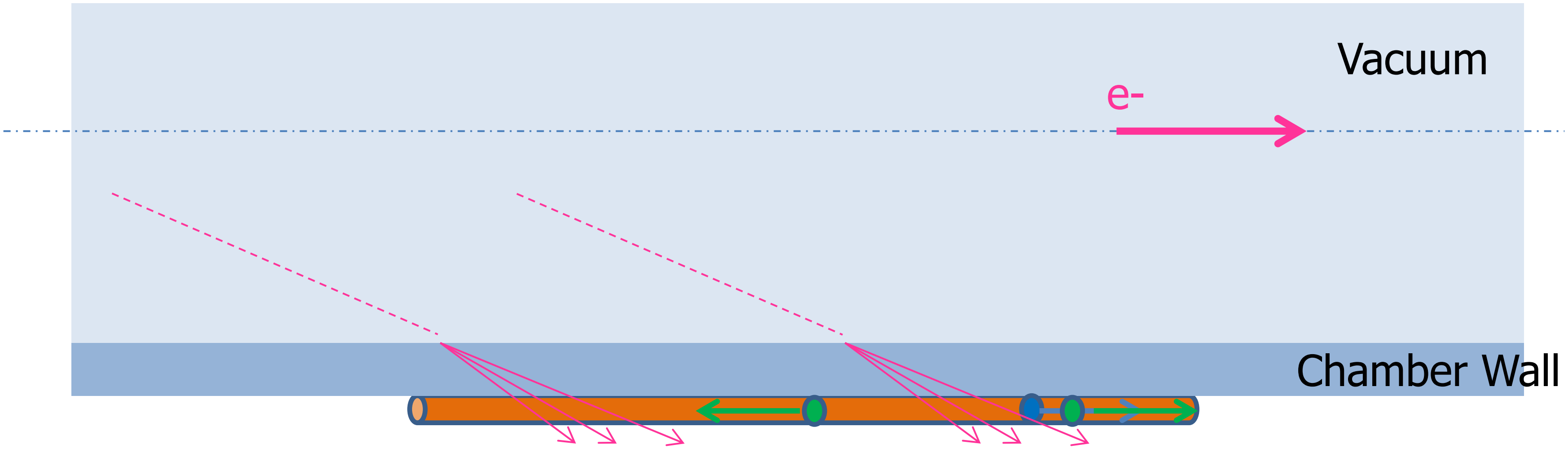
Time difference between two pulse



Both light pulses propagate

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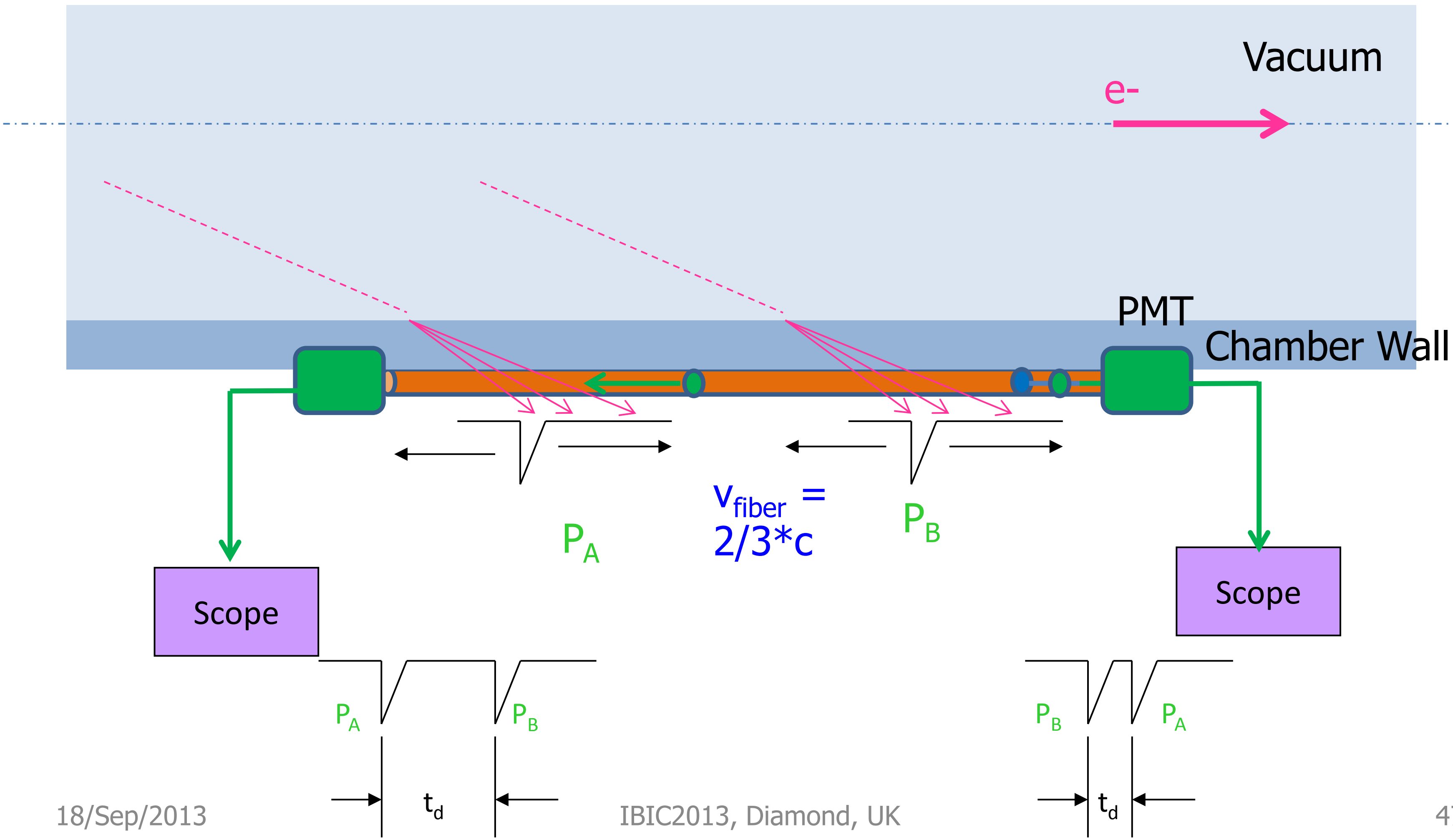
PMT signal

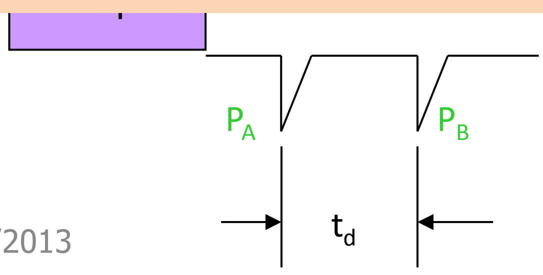
- Downstream time difference : <u>Compressed</u>
- Upstream time difference : <u>Expanded</u>

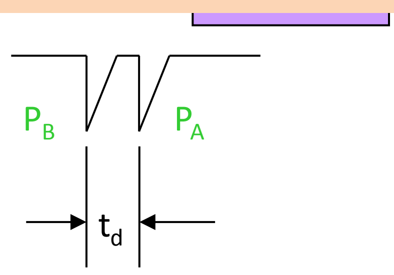


PMT signal

- Downstream time difference : <u>Compressed</u>
- Upstream time difference : <u>Expanded</u>

Use upstream signal to get better position resolution



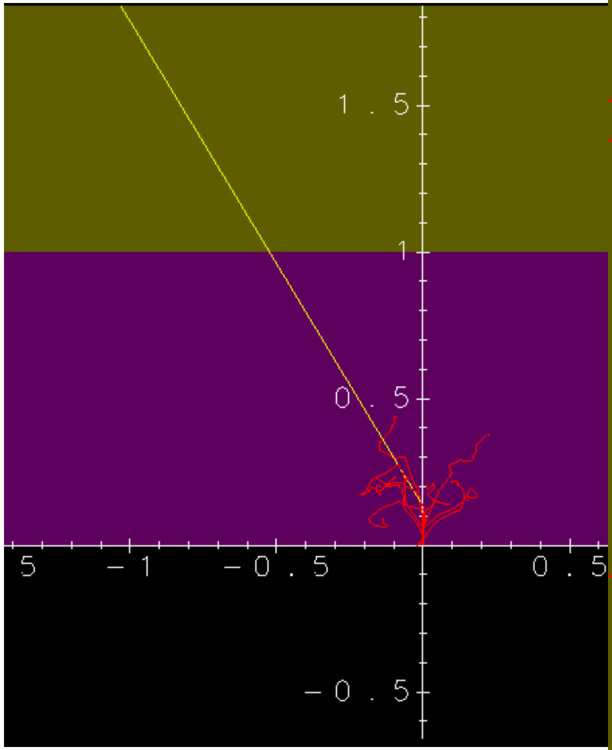


How many photons in fiber?

- Electron energy vs. Thickness of duct
- Property of Cherenkov radiation

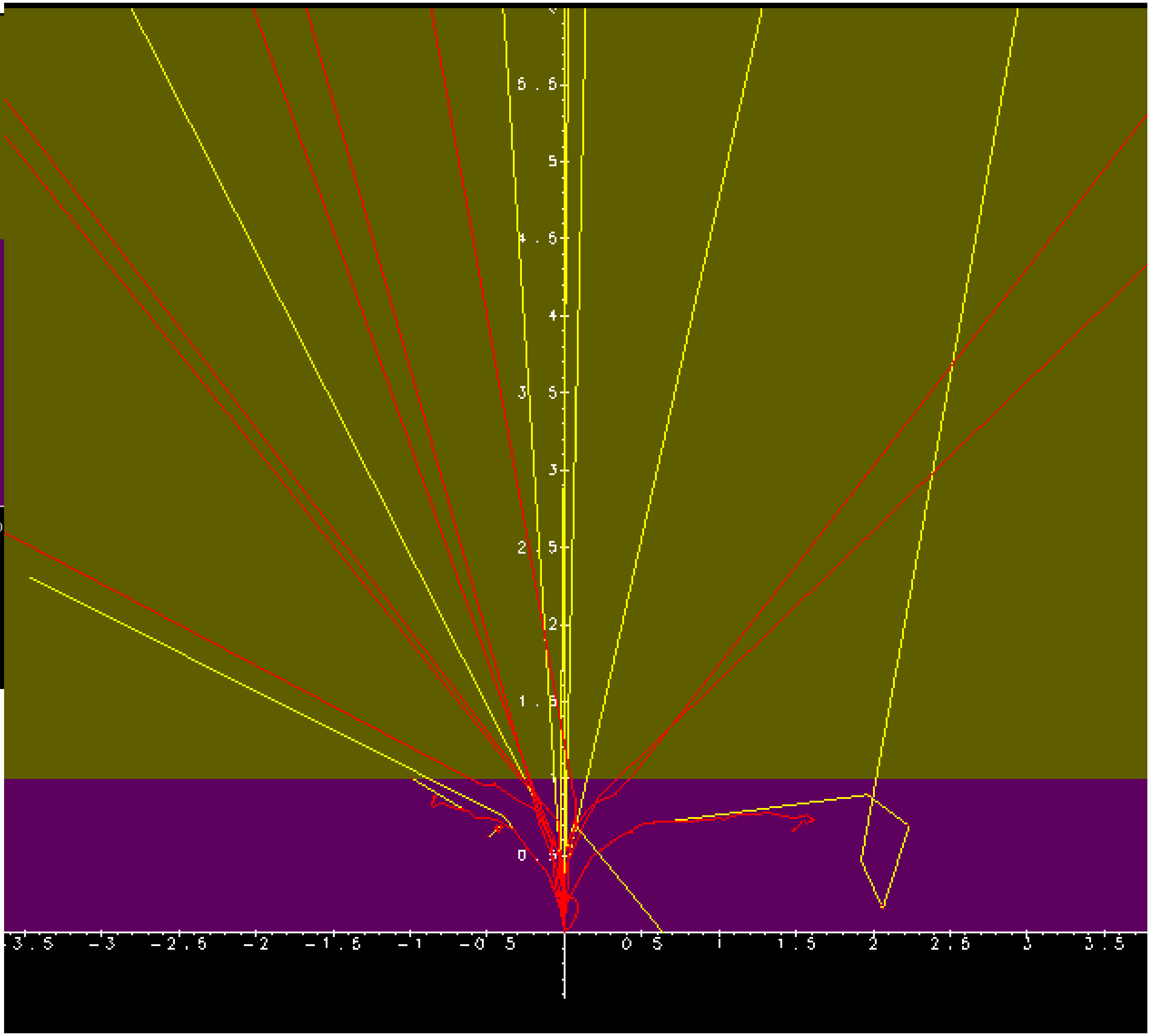
Example : 1 cm thick Aluminum

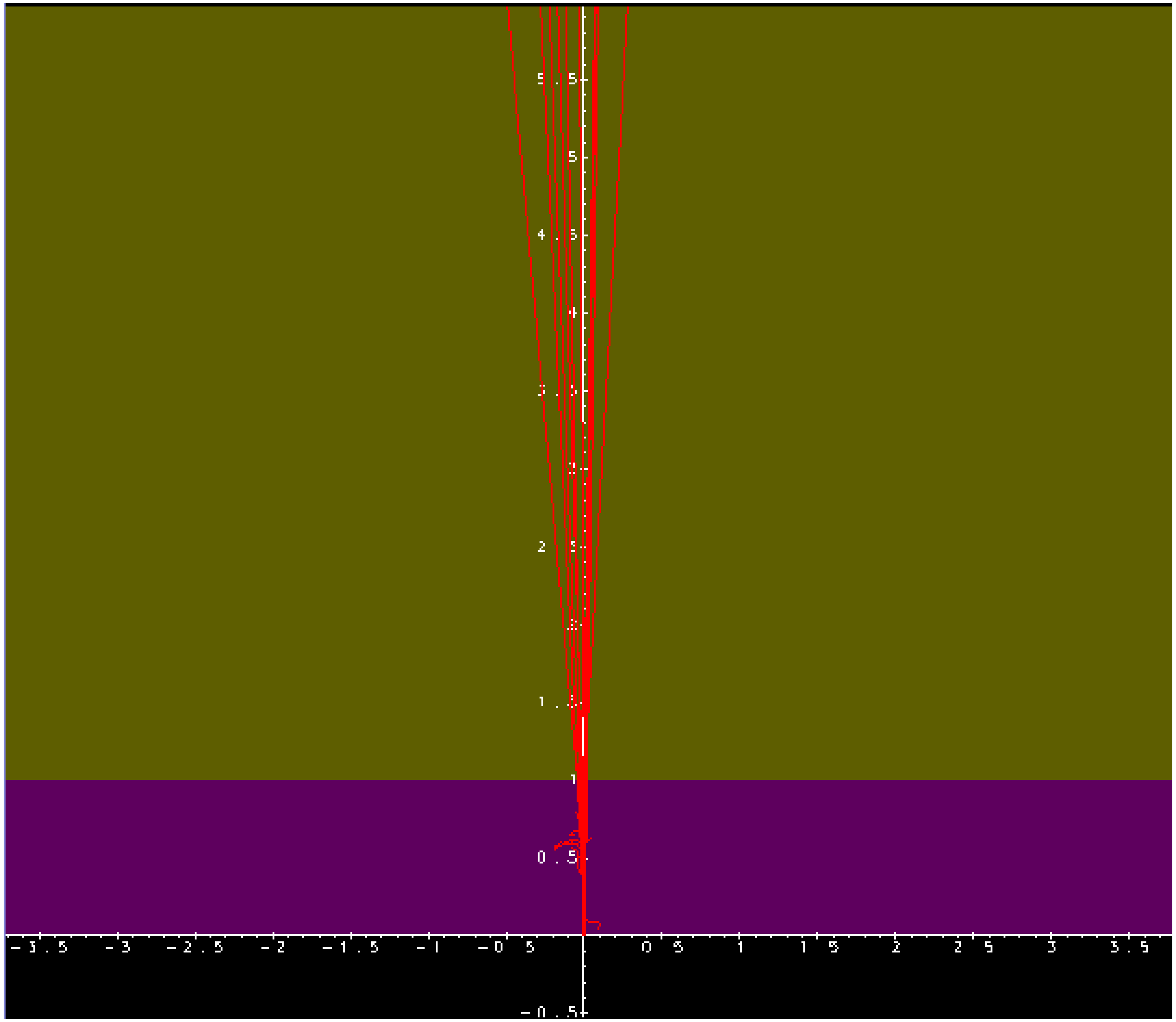
- Dependence on e- energy



1 MeV

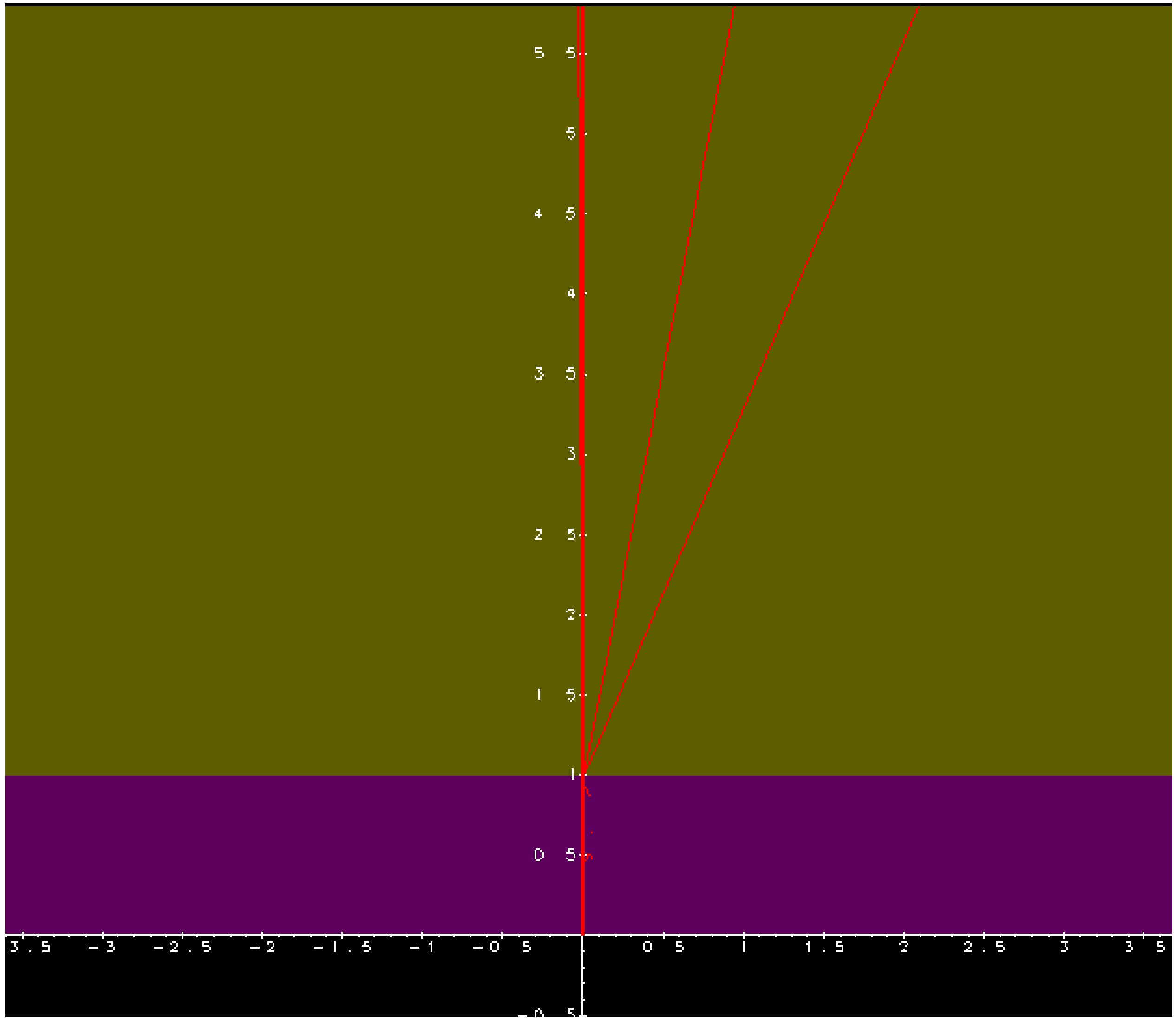
10 MeV





100 MeV

Photons (Yellow line) are not shown hereafter.



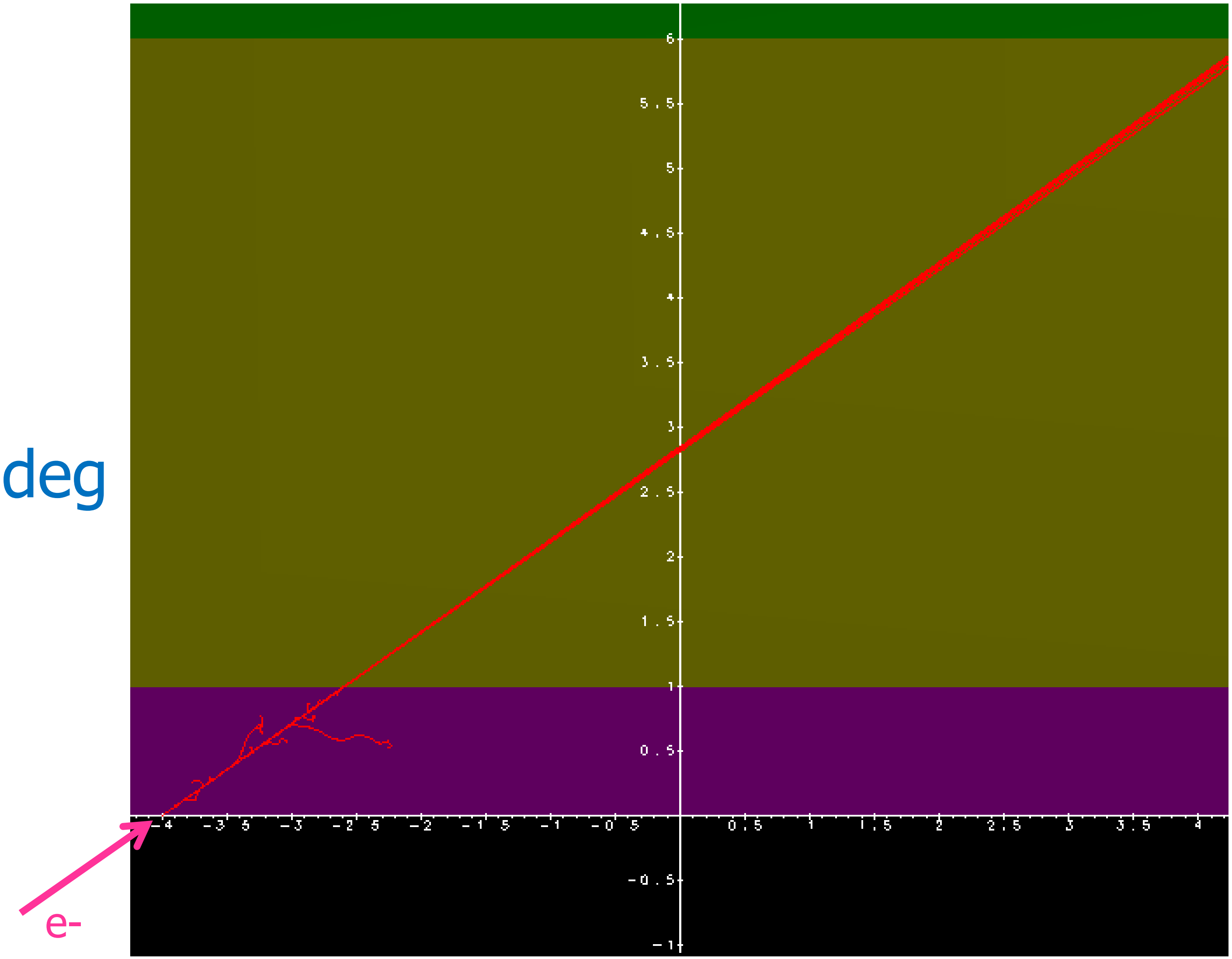
2000 MeV Most particle go straight, in case of 1 cm Al

In real accelerator,

Lost electron does not always hit vacuum wall in this “perpendicular” direction

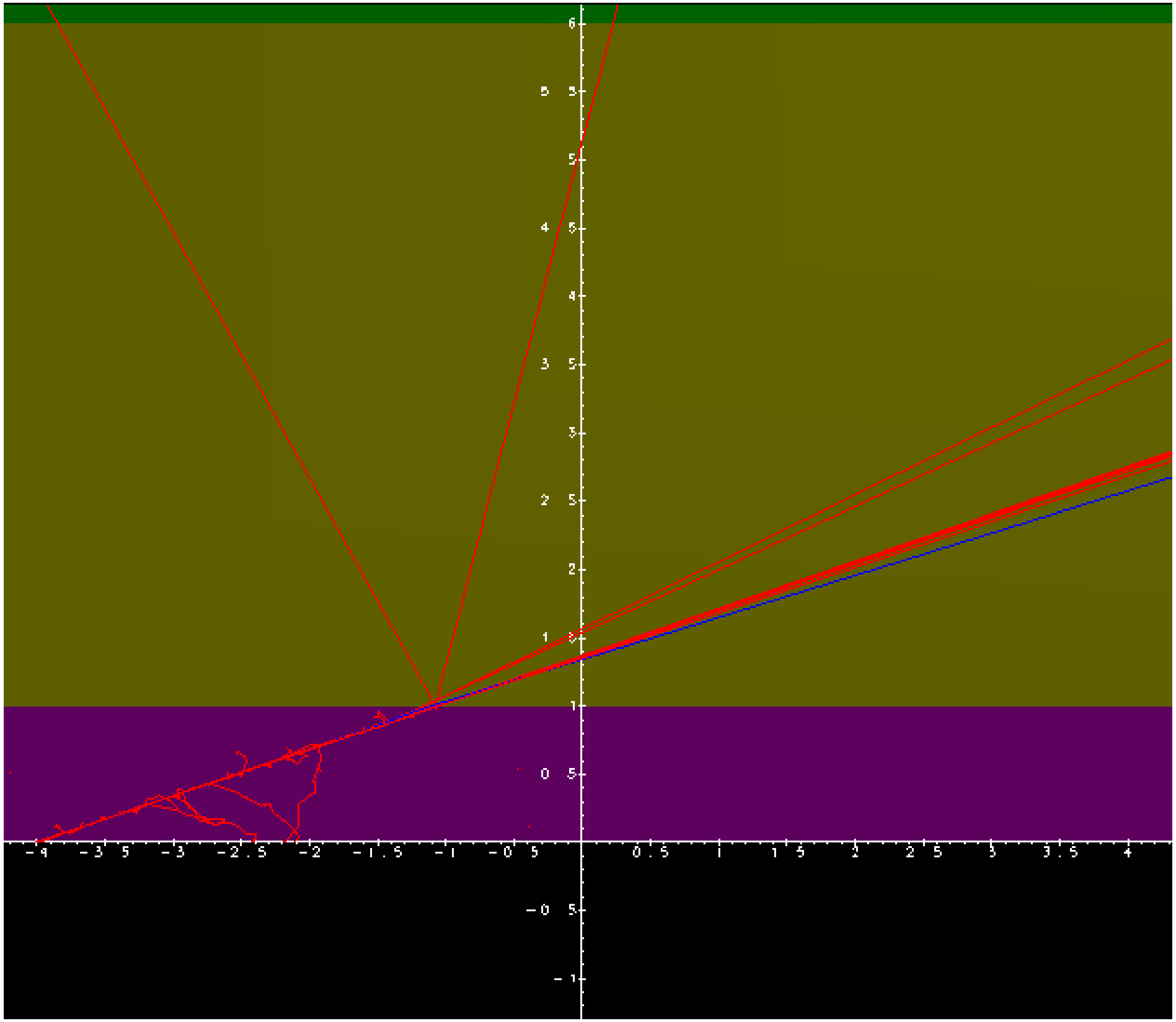
2000 MeV electron, 1 cm thick Aluminum chamber

45 deg

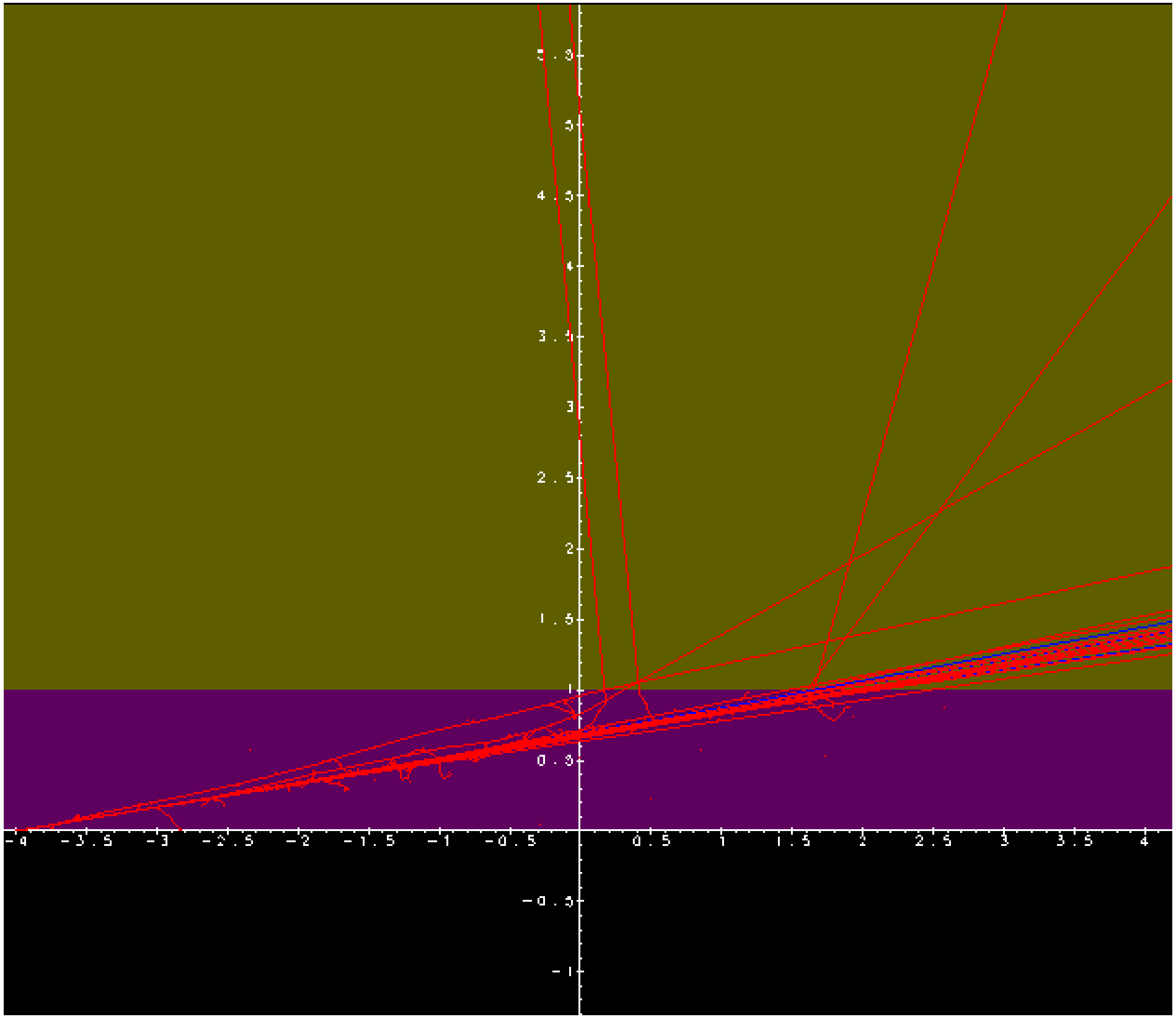


2000 MeV electron, 1 cm thick Aluminum chamber

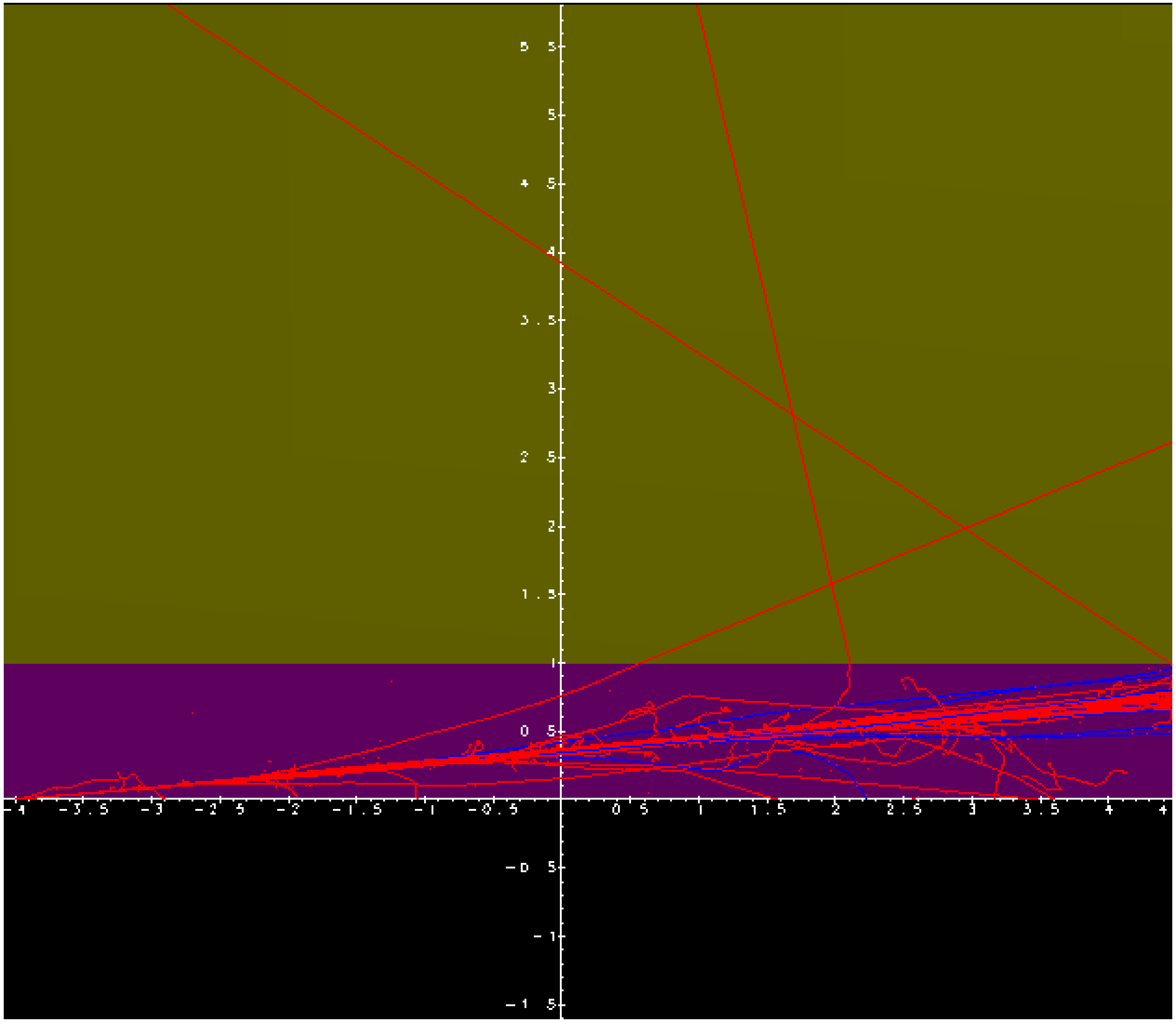
70 deg



80 deg



85 deg



Effective thickness of vacuum wall becomes large

Detect electrons with fiber

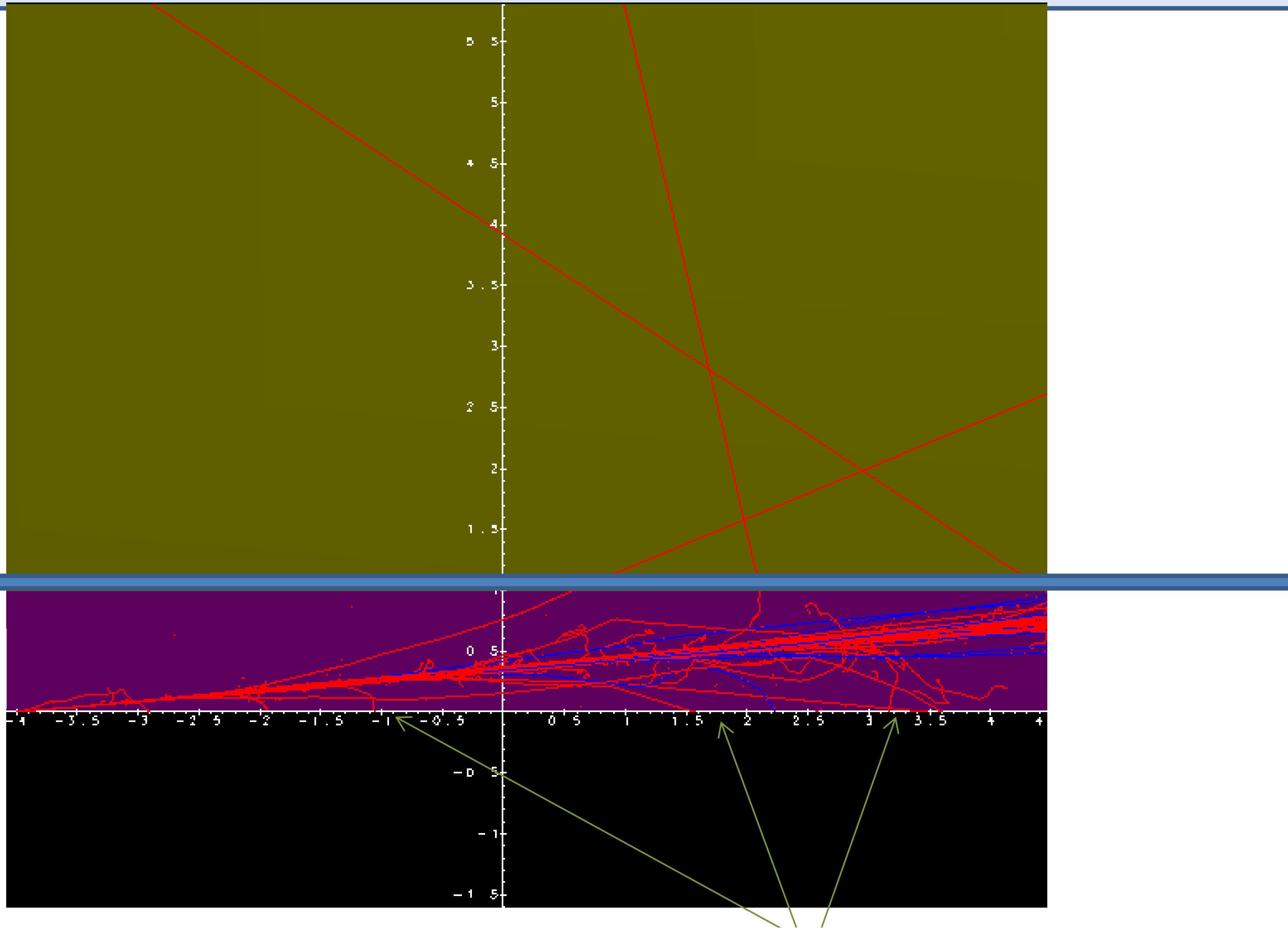
85 deg

Air

Fiber

Aluminum

Vac



These electrons will hit the other part of vacuum chamber

Cherenkov Radiation

- Cherenkov radiation is produced when a charged particle passes through a medium at a speed greater than the phase velocity of light in that medium

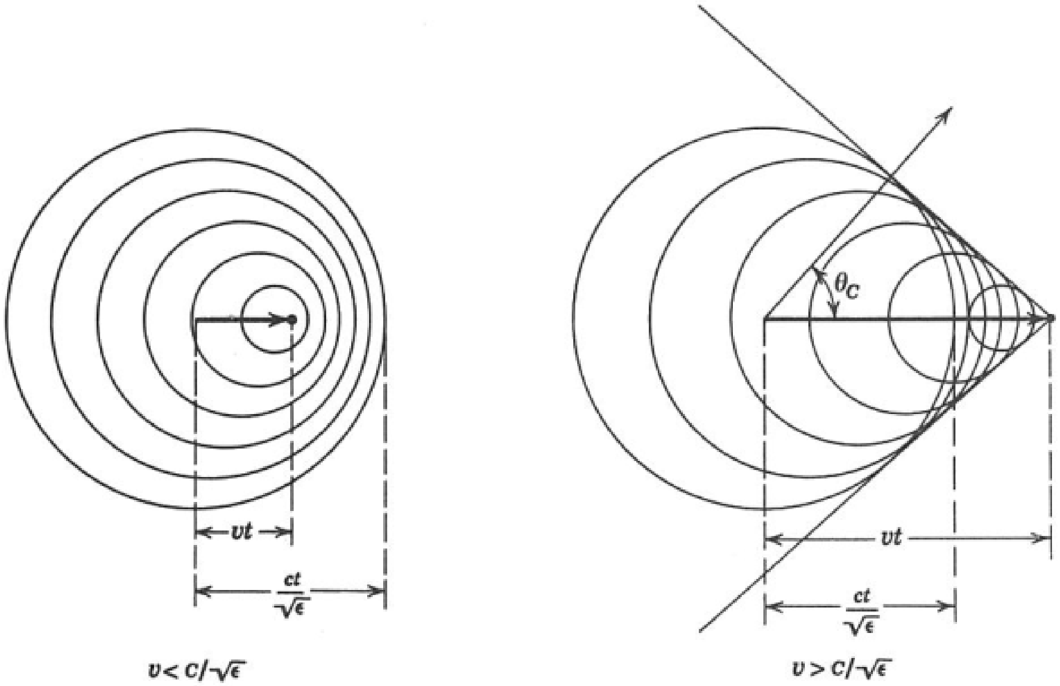


Figure 13.5 Cherenkov radiation. Spherical wavelets of fields of a particle traveling less than and greater than the velocity of light in the medium. For $v > c/\sqrt{\epsilon}$, an electromagnetic "shock" wave appears, moving in the direction given by the Cherenkov angle θ_C.

$$\cos\theta_c = \frac{1}{\beta n}$$

βc : speed of the particle
n : index of refraction

Glass medium : $n = 1.6$
If a charged particle speed in medium is faster than 0.625c, Cherenkov radiation propagate at the angle of 51 deg.

Ref : J. D. Jackson "Classical Electrodynamics"

Characteristics of Cherenkov Rad.

- In this talk : results for electron is shown
- Number of photons per unit length per unit energy interval

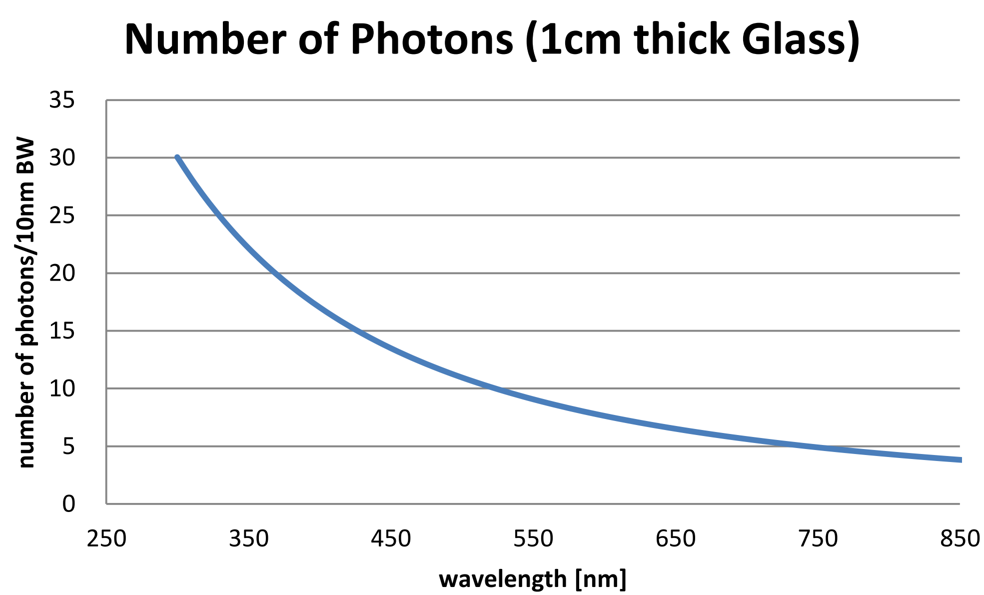
$$\frac{d^2N}{dEdx} = \frac{2\pi\alpha}{hc}\sin^2\theta_c = \frac{\alpha^2}{r_e m_e c^2}\left(1 - \frac{1}{\beta^2 n^2}\right)$$

α : fine structure constant

- Re-write with wavelength, and let β=1

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{n^2}\right)$$

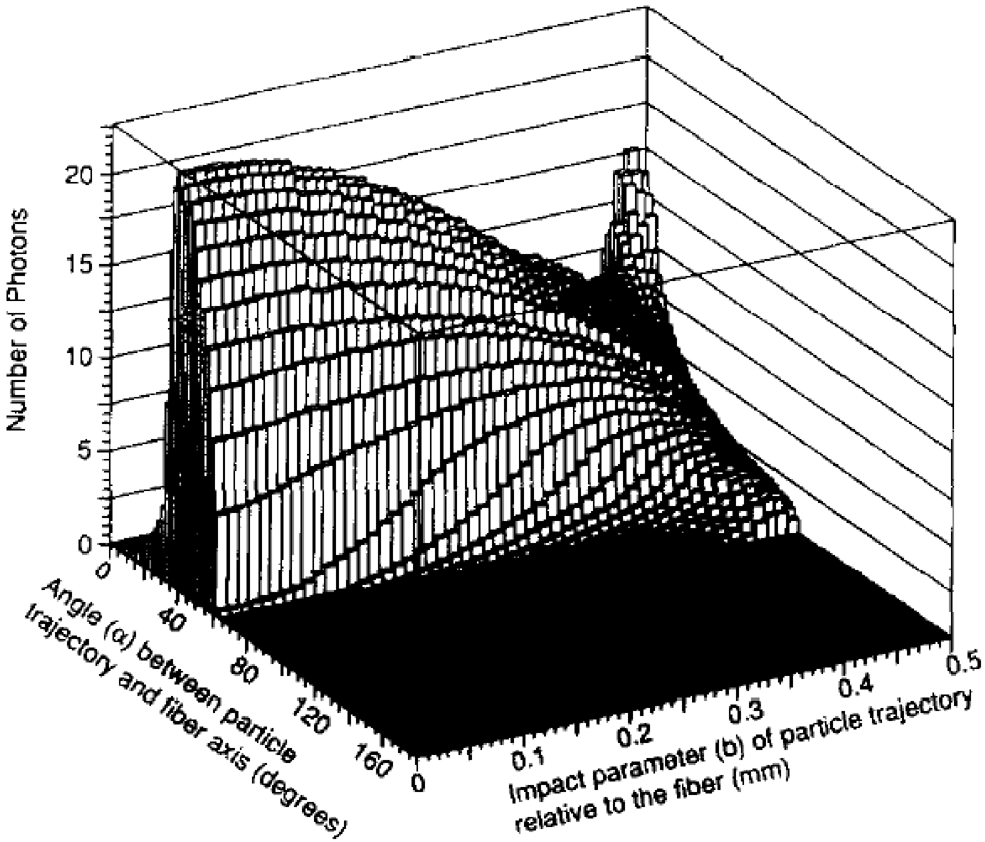
2-300 photons for PMT range



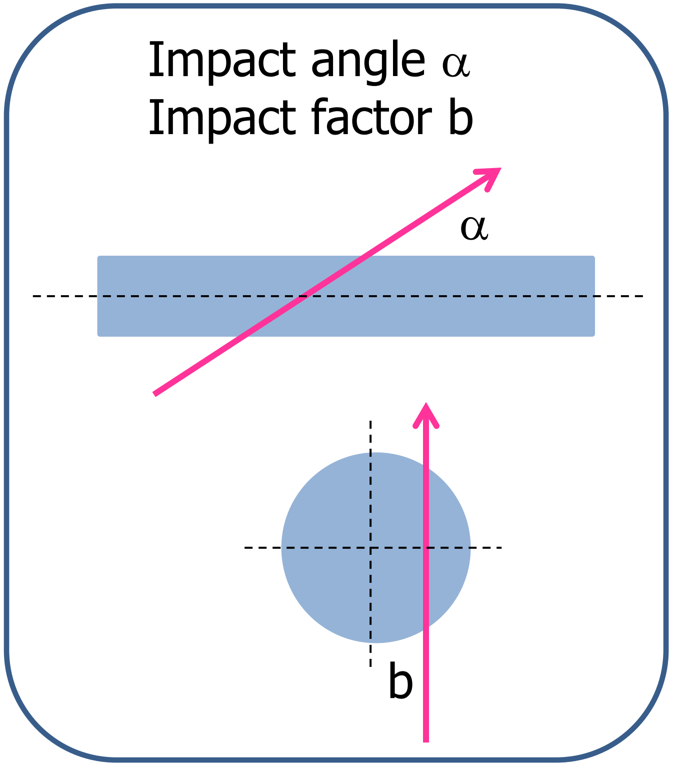
Ref : Particle data group, Particle Physics Booklet http://pdg.lbl.gov/

Number of photons that exit fiber

– "Quartz fibre calorimetry" P. Gorodetzky et.al., NIM A361 (1995) 161

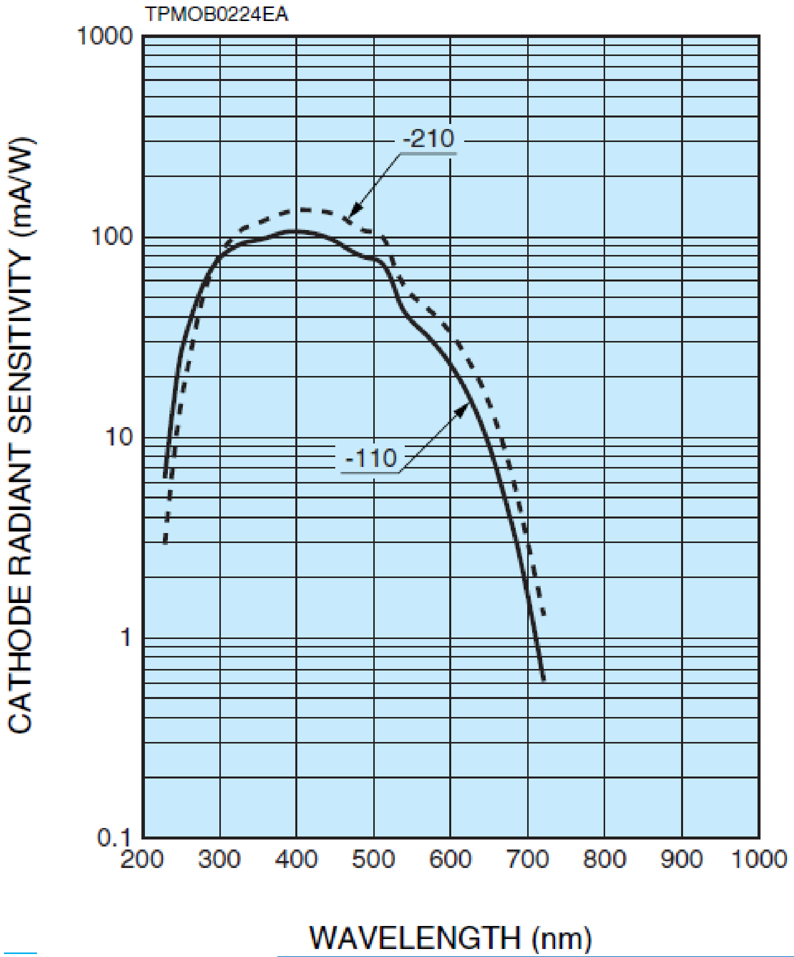


ϕ1mm, NA=0.37, β=1



Cherenkov Detector : PMT

- Hamamatsu H10721-110
- Built-in high voltage circuit (only 5 V DC required)
- Gain 5×10^3 - 4×10^6
  - Control 0.5 – 1.1 V DC
- FC adapter (option)
- Rise time : 0.57ns



Hamamatsu Co. PMT catalog

Selection of Optical Fiber

- Most "Large Core", "Pure Silica" cable OK
- Large core fiber is popular for high power laser
- Sensitivity, Attenuation, Radiation hardness, etc

Small Large

9μm 50μm 100μm 400μm 600μm 800μm

SM MM

Network Small coverage <u>Suitable for LossMon</u> Hard to bend

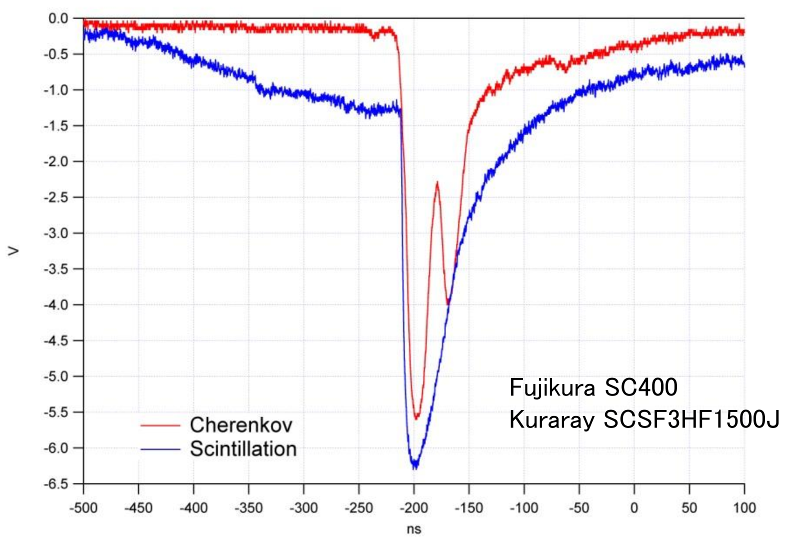
http://www.fujikura.co.jp/products/tele/o_applied_p/__icsFiles/afieldfile/2013/06/26/SpecialtyFibers.pdf

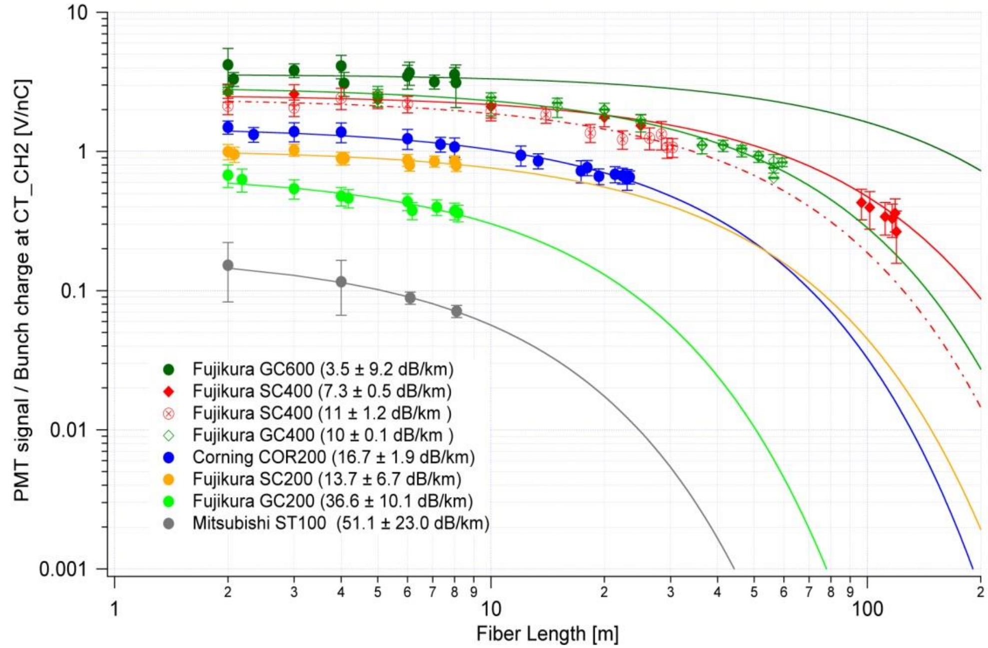
- Good reference for selection of fiber:
  - X. –M. Marechal et.al. NIM A 673 (2012) 32
  - Itoga, ERL2011

Fiber selection

Requirements for the fiber

- High optical transmission rate (low attenuation) ⇨ Non-plastic fiber
- Good timing (position) resolution ⇨ Non-scintillation fiber (long decay time)
- Radiation hardness ⇨ Non-plastic, non-doped fiber (except F-dope)
- High photon emission rate ⇨ Large core





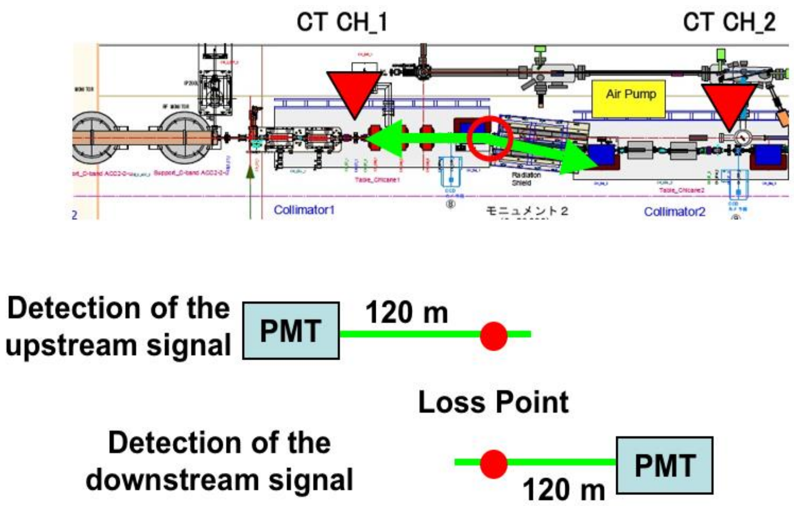
Fujikura SC-400 is suitable.

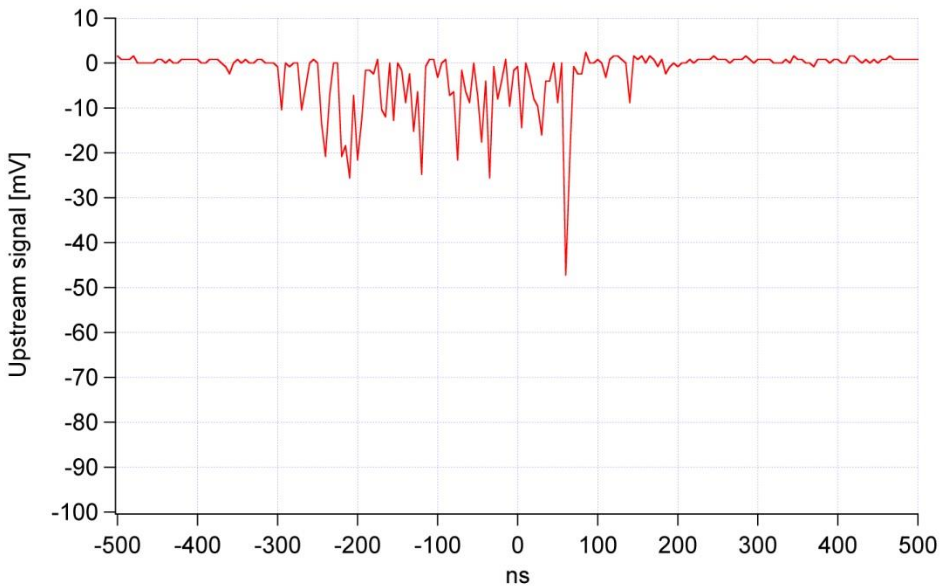
- Core, cladding: Pure SiO_2
- Core diameter: 400 um
- Radiation induced loss: below a few dB/km/Gy (expected)
- Attenuation of Cherenkov: 6.8 dB/km (measured)

Courtesy: S. Itoga, ERL2011

Specification: Sensitivity

Evaluation of sensitivity @ SCSS (250 MeV, prototype of SACLA)





Dark current

- Generated in the C-band accelerating structure
- Charge ≈ 10 pC (by CT monitor)
- Amplitude of beam loss monitor: ≈40 mV @ 120 m upstream from loss point.
- Number of secondary electron: SCSS < XFEL

⇨ We achieved the target specifications (≈1pC/pulse, 120m)

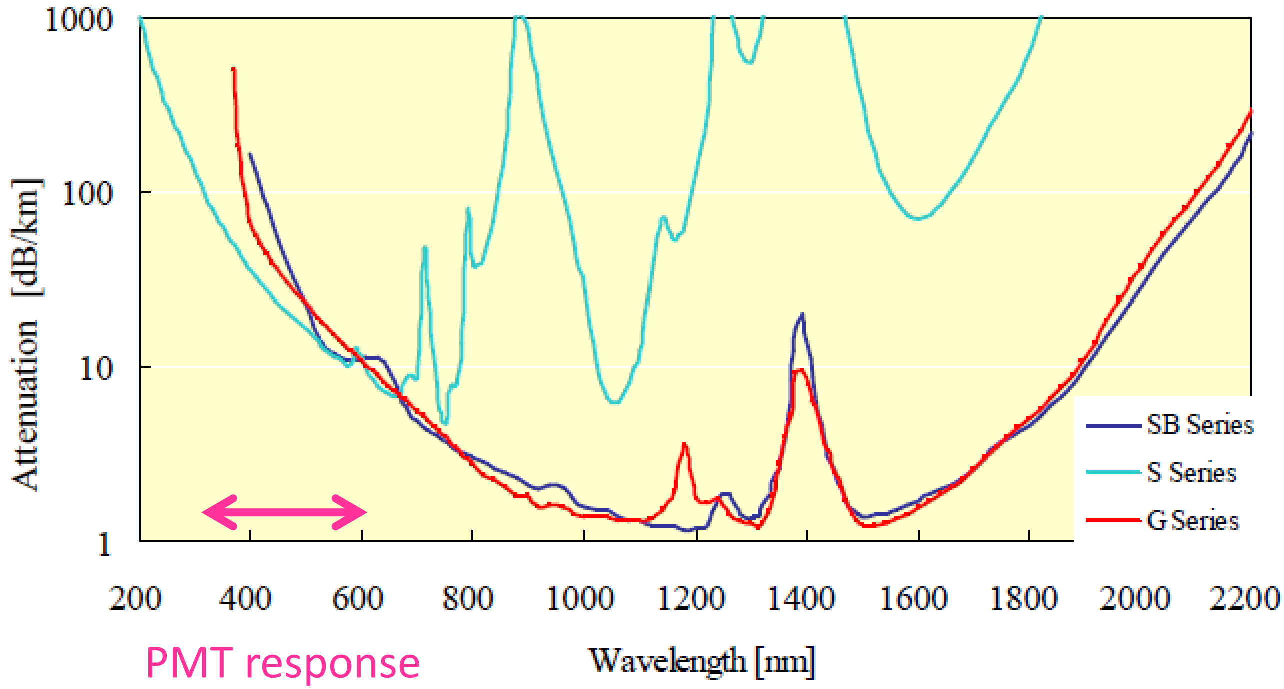
Courtesy: S. Itoga, ERL2011

Attenuation

SB series *(for VIS-NIR)*

Model Name	Refractive Index Profile	Core / Cladding Material	Core / Cladding Diameter [μm]	Jacket/ Cord Diameter [μm]	Attenuation [dB/km]	Coating/ Jacket/ Cord Material	NA	Operation Temperature [℃]	MInimum Bending Radius [mm]
SC.200/220B	Step Index	SiO_2 (Low-OH)/ F-SiO_2	200 / 220	900 / 2800	≦10 (@850nm and @1064nm)	Silicone / Polyamide / PVC	0.22	-20 to 60	44
SC.400/440B			400 / 440	1100 / 2800					88
SC.600/660B			600 / 660	1400 / 2800					132
SC.800/880B			800 / 1000	1700 / 3300					200

Spectral Attenuation (typical)



Fujikura Co. optical fiber catalog

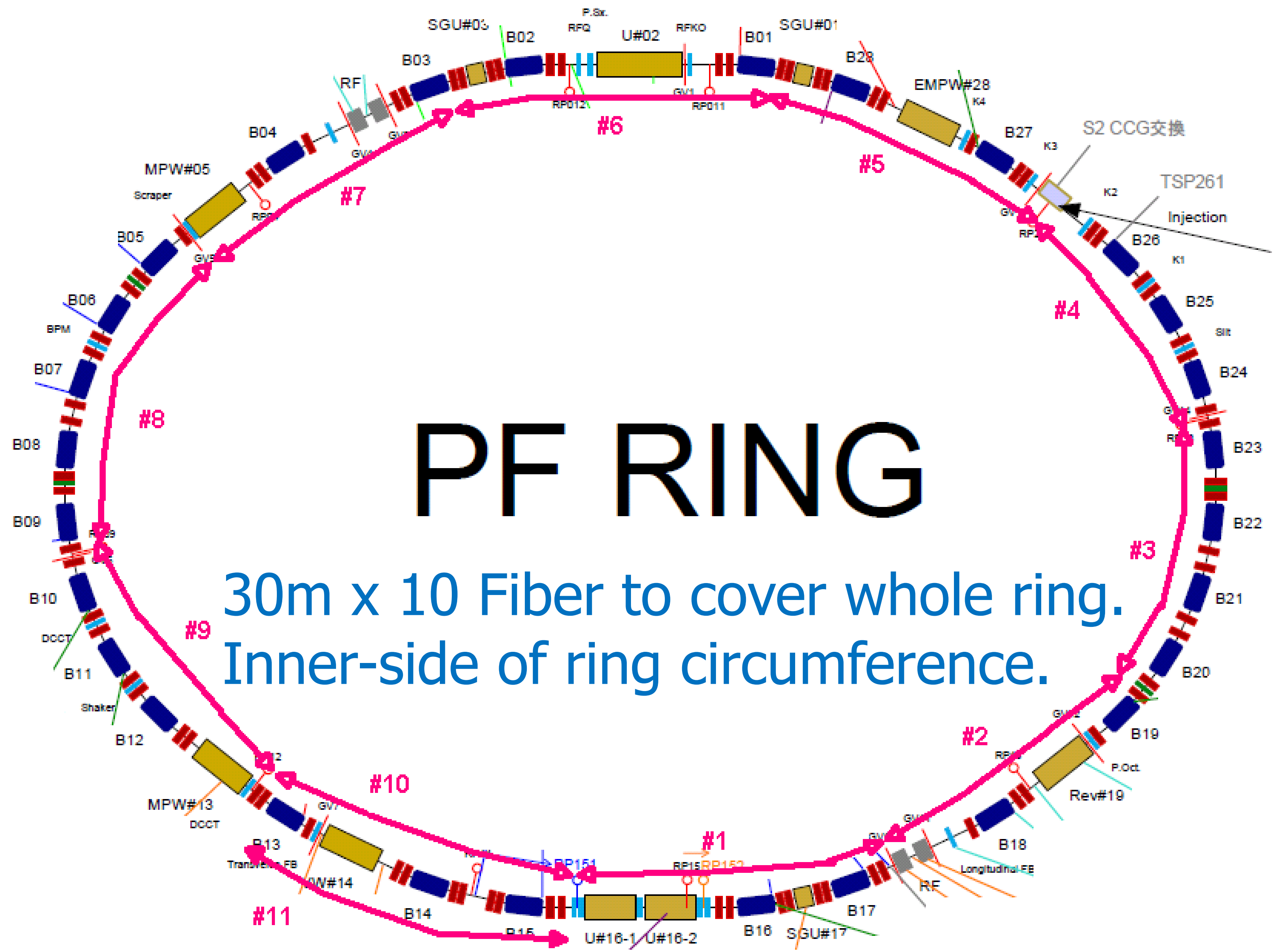
Table of Contents

Main parameter of KEK-PF

- Energy : 2.5 GeV
  - Full energy injection of Linac
  - Top-up operation
- Circumference : 187 m (frev = 1.6 MHz)
- Horizontal Tune : 10.61

- Two injection system
  - 4 Kicker magnets
  - 1 Pulsed sextupole magnet

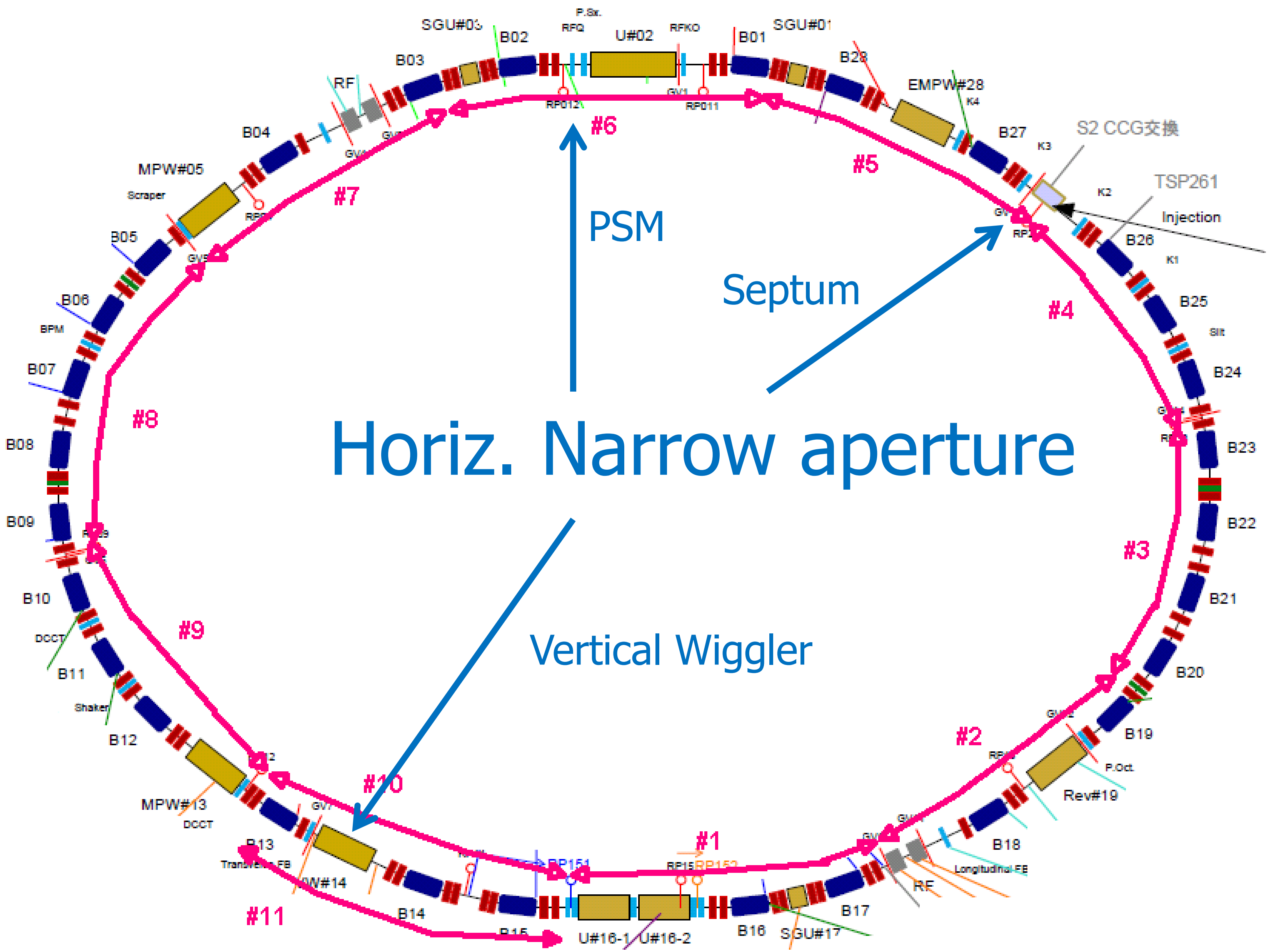
Fiber Location



30m x 10 Fiber to cover whole ring.

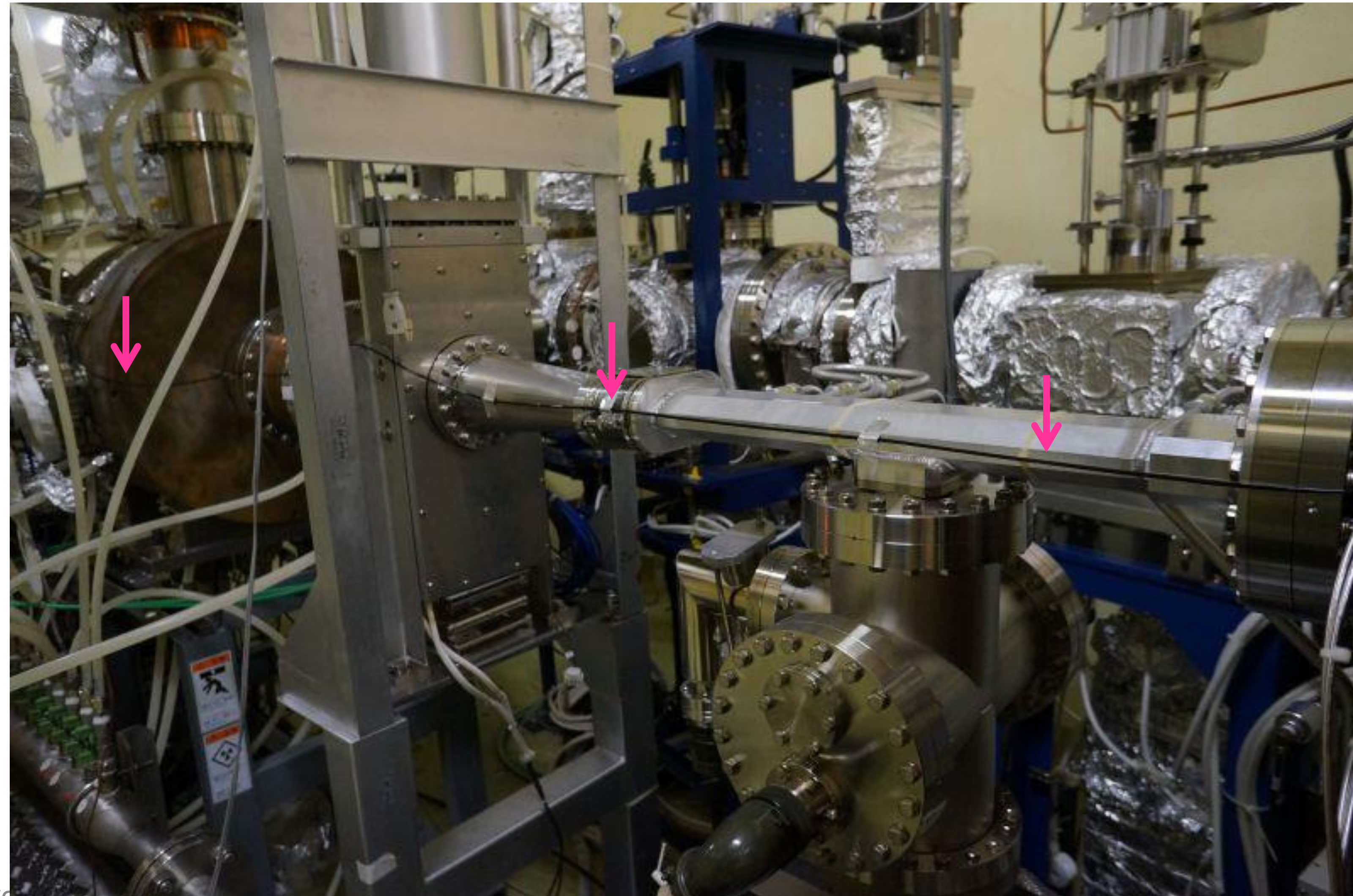
Inner-side of ring circumference.

Fiber Location

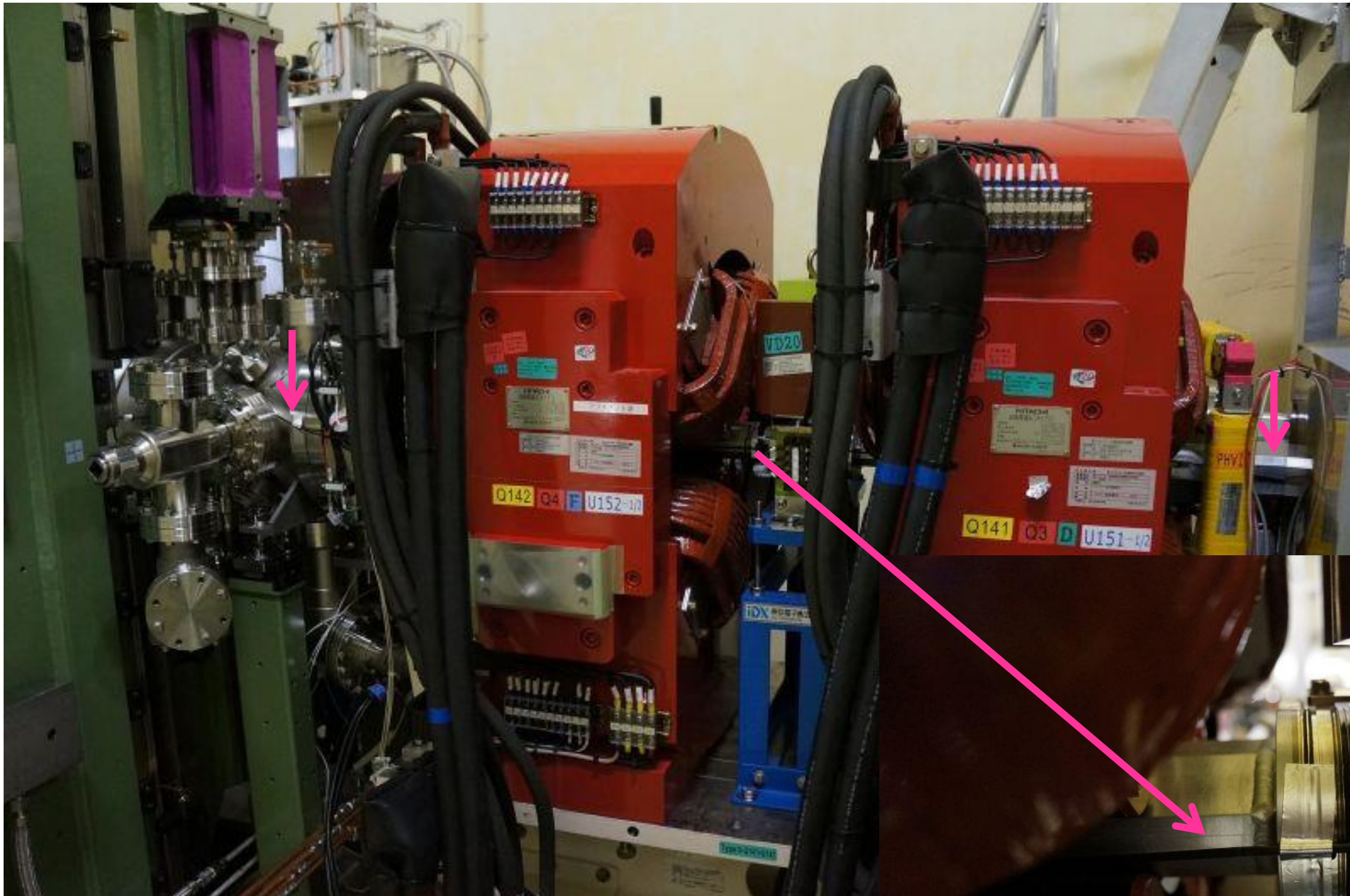


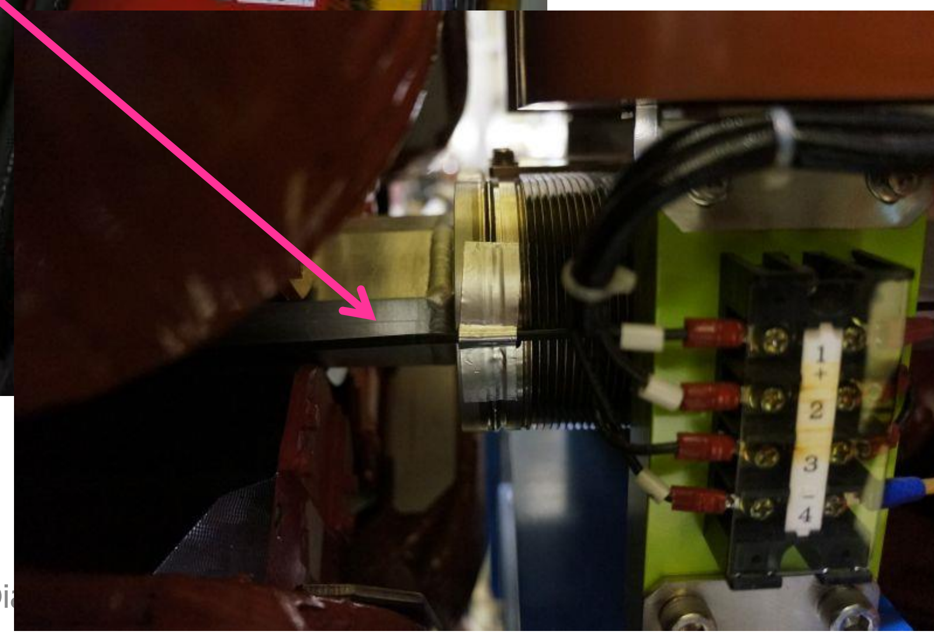
Installation Photo

- Attach on the chamber

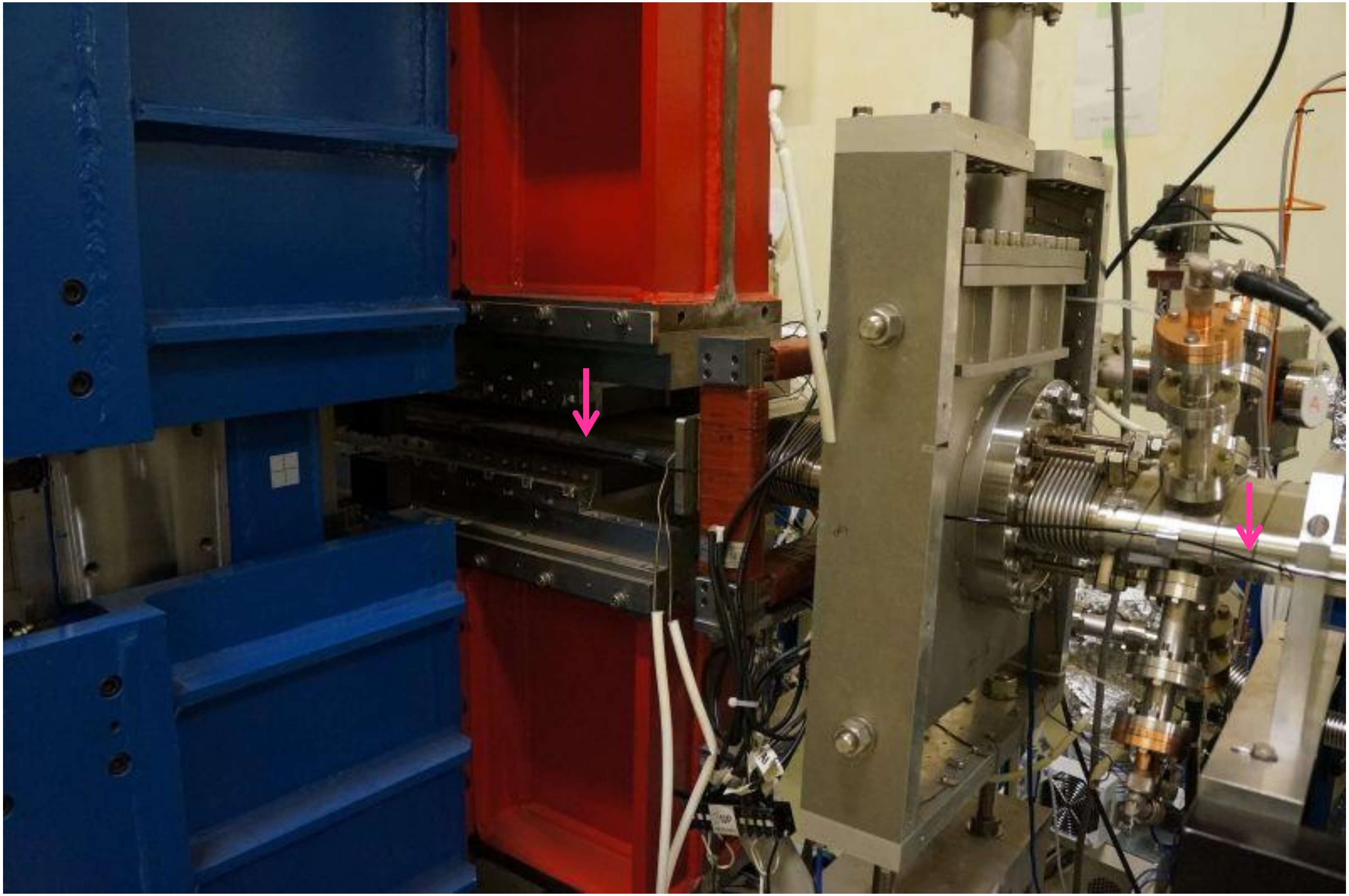


Inside of Q-magnet





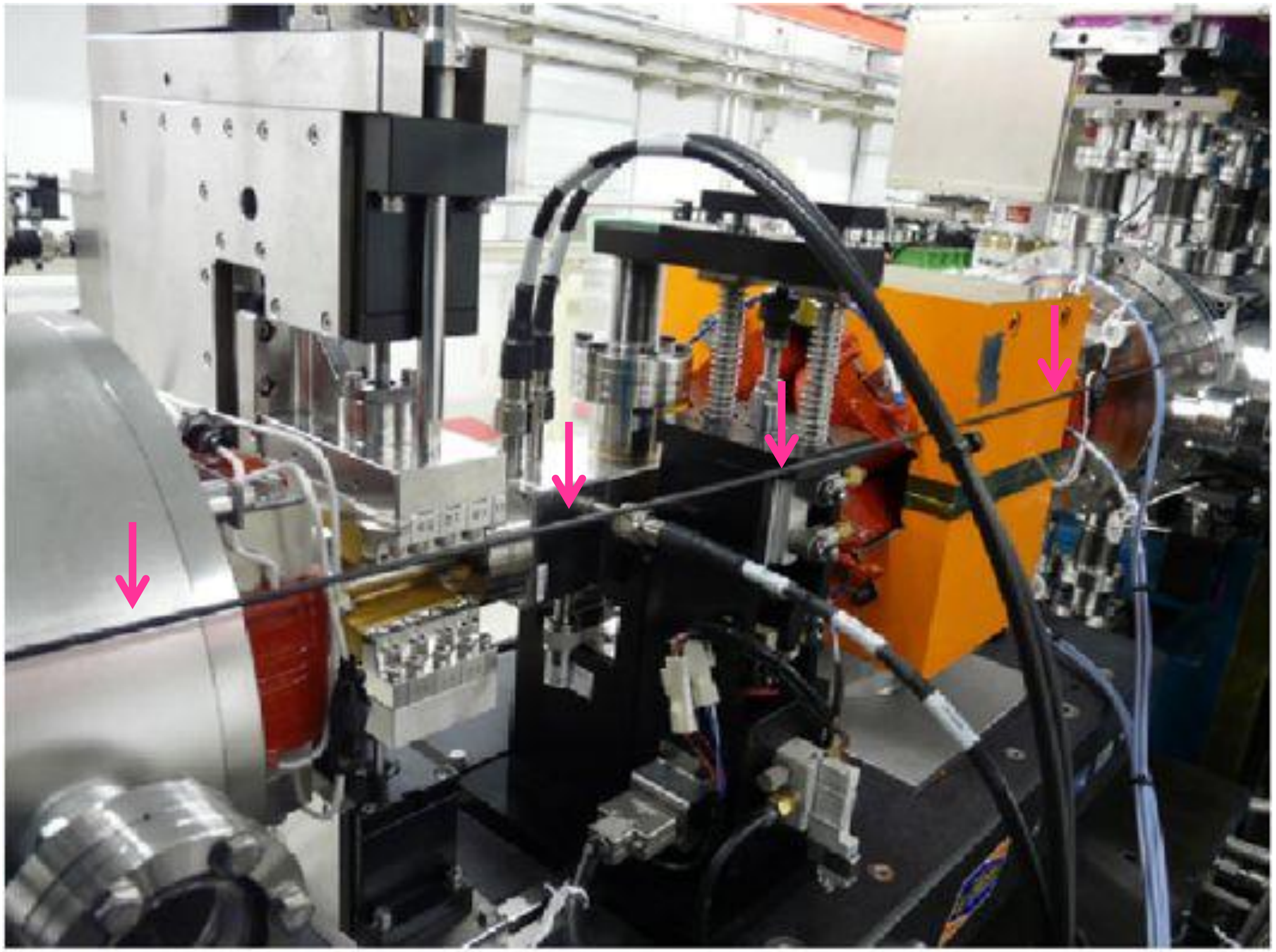
Insertion Device



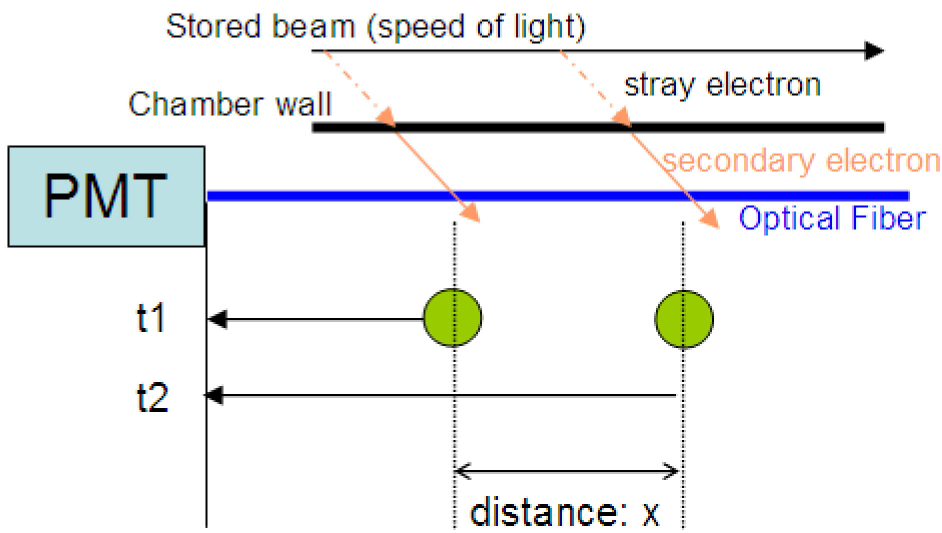
Another Installation Methodology

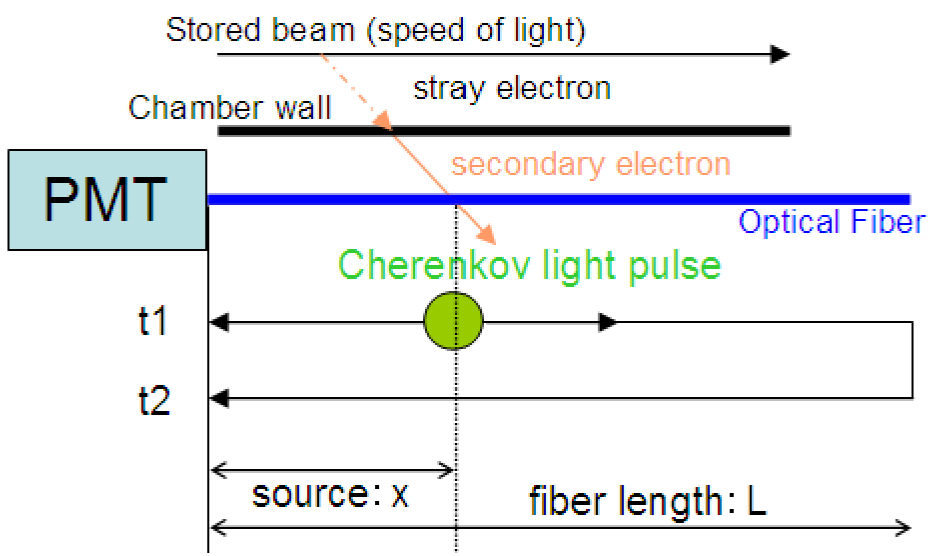
- SACLA/Spring-8

Set in strait along beamline



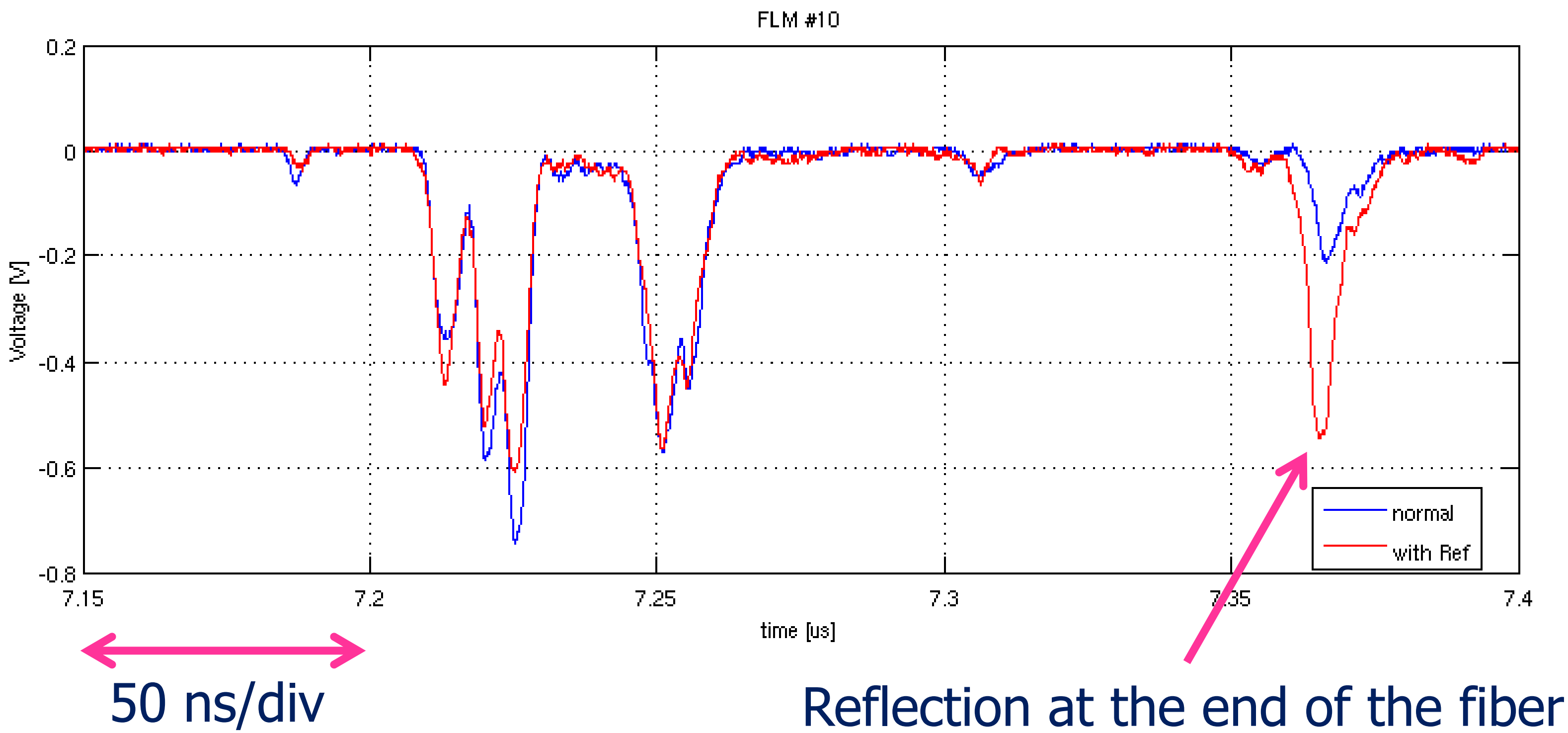
Loss Point Estimation : Reflection

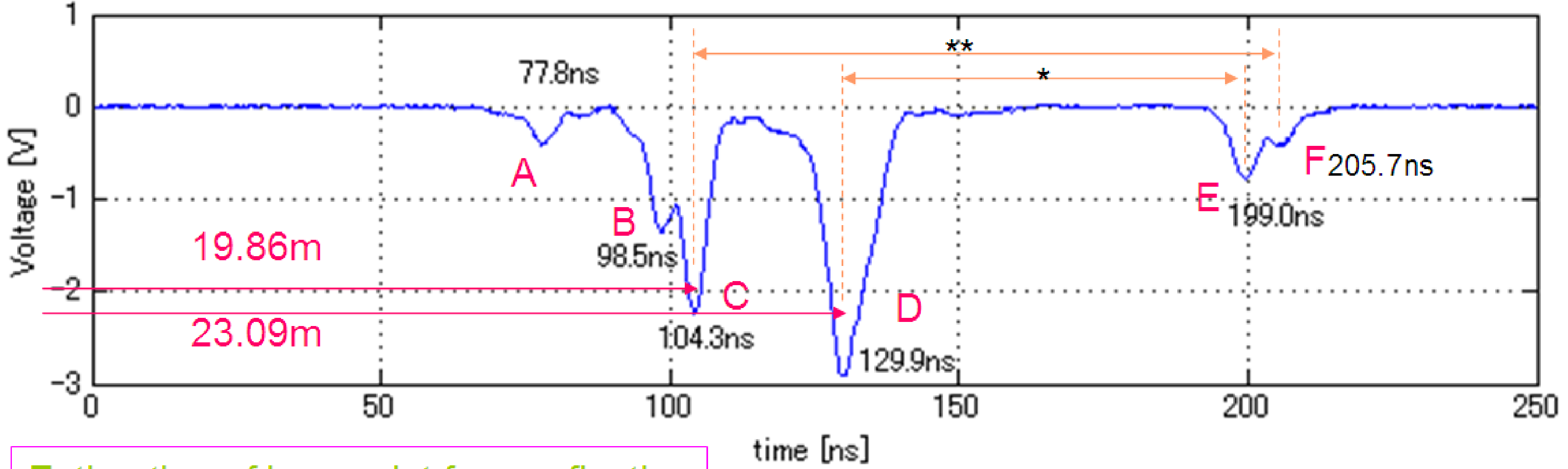




Measured signal example

- Estimation of each peak
- Add a “Reflector” on the fiber end
  - Reflector can be removed after I determined the reflection signal





Estimation of loss point from reflection

Trigger source : external or self

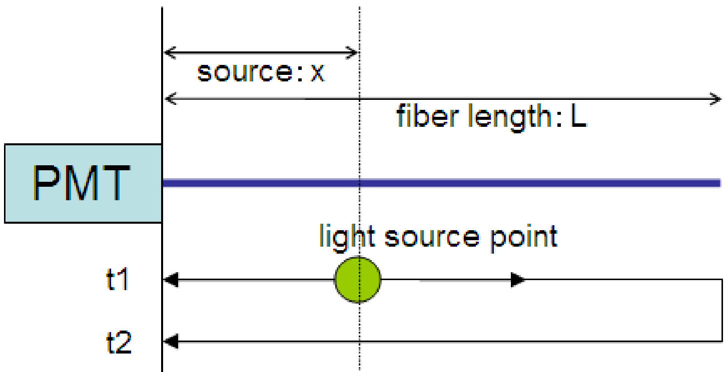
Assume peak E is the reflection of D :

* t2 - t1 = 199.0 - 129.9 = 69.1ns → 23.09m

Assume peak F is the reflection of C :

** t2 - t1 = 205.7 - 104.3 = 101.4ns → 19.86m

Distance between C and D = 3.23m



x=L-(t2-t1)*v/2

v = 2/3*vc (light speed in the medium)

v=2/3*vc = 5ns/m

veff = 8.3ns/m

Cross check

On the other hand, time between C and D is

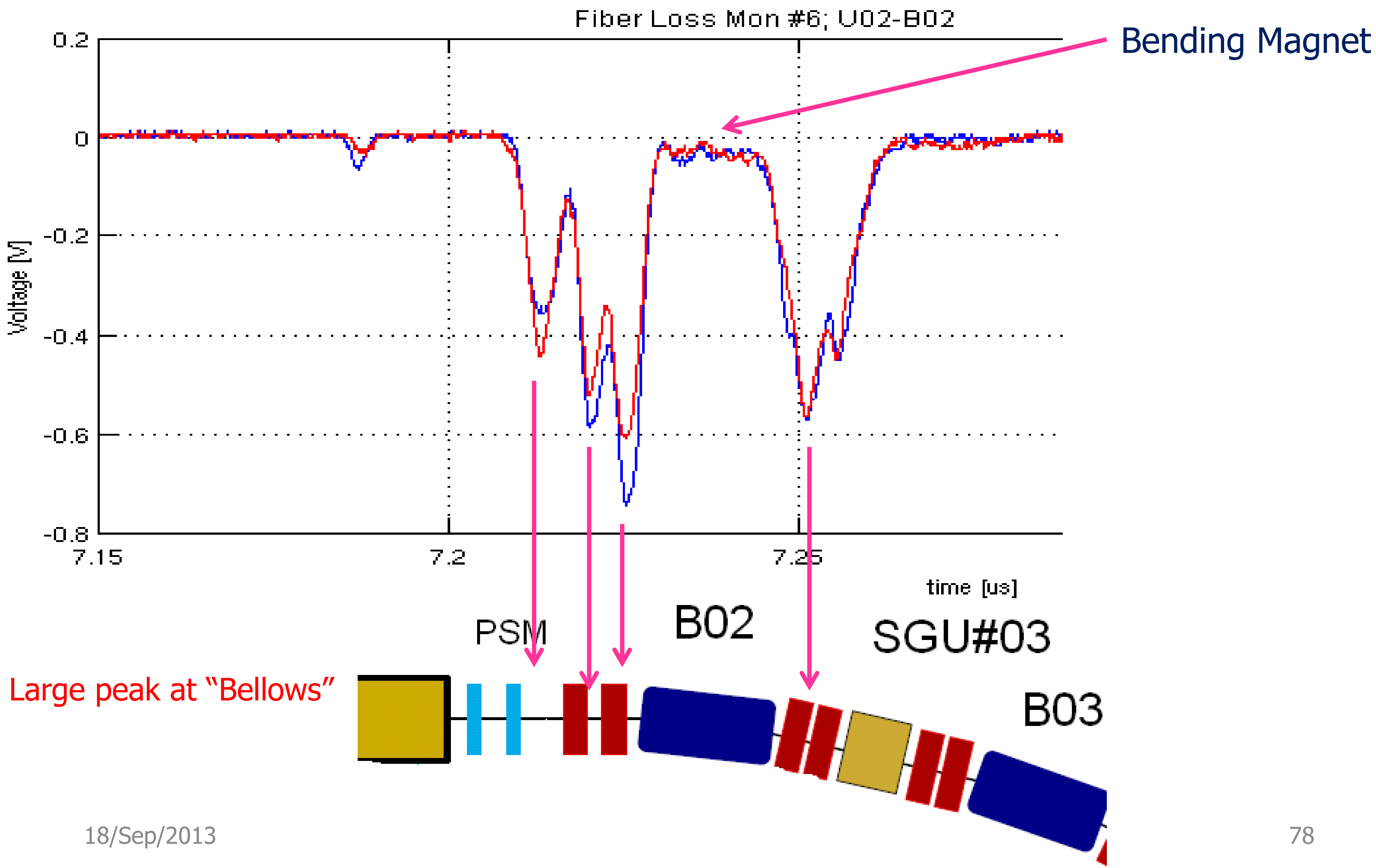
129.9 - 104.3 = 88.6 ns

applying CASE2, distance of C and D is

88.6ns/veff = 3.1m

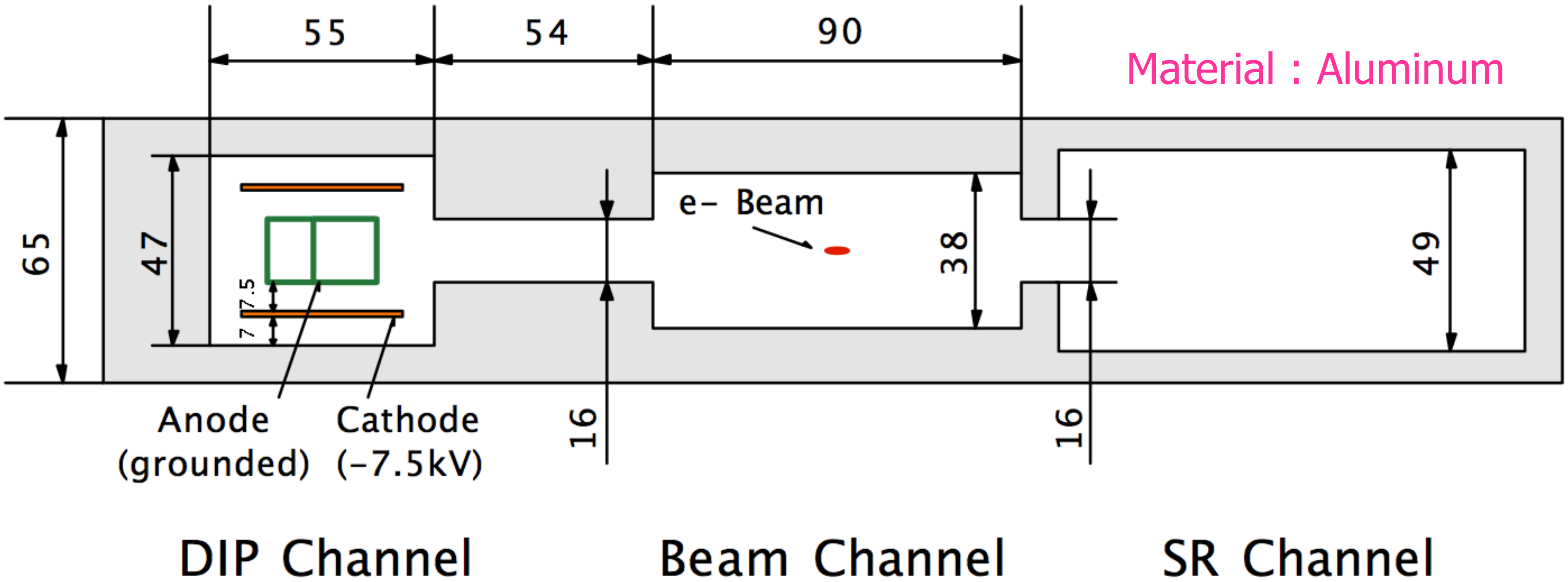
Good agreement!

Compare with drawing



Large peak at “Bellows”

Cross section of Bend-mag duct



Inside of the ring

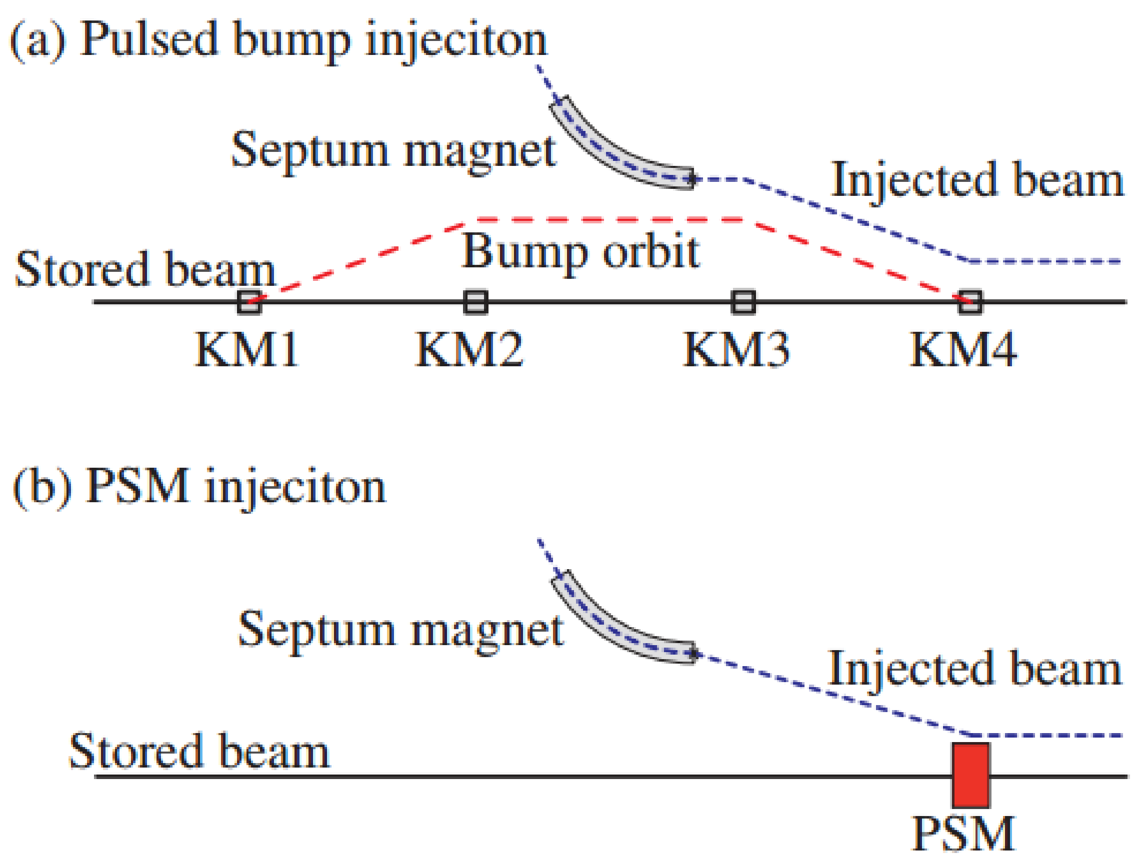
Outside of the ring

comment

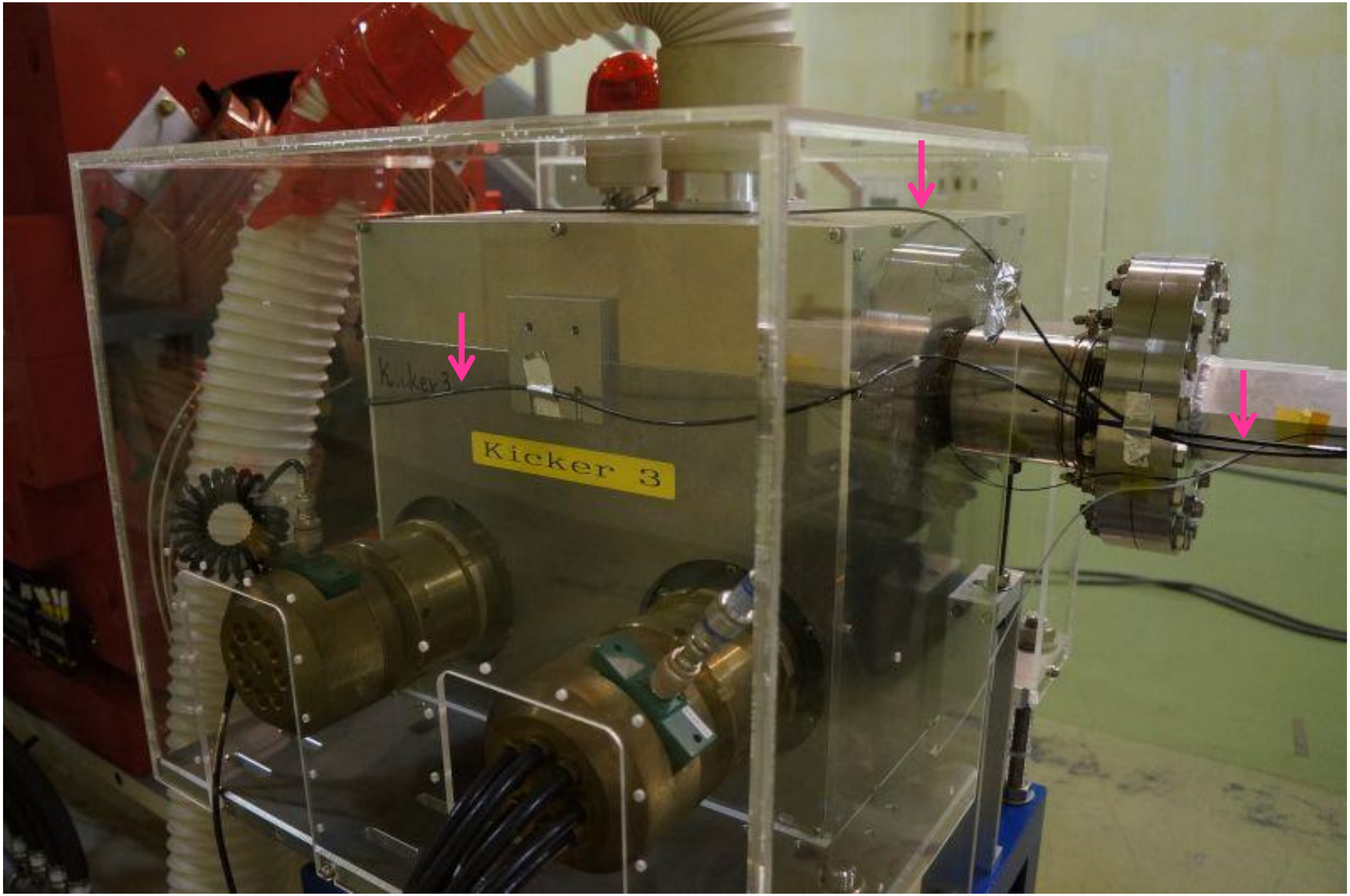
- When we stop the injection, loss signal was disappeared.
  - No signal from stored beam
  - Good S/N to observe the injection loss
  - It might be better to use other loss monitor if you want to observe the loss due to beam and residual gas bremsstrahlung.

Two injection method at KEK-PF

- Kicker injection (4 kicker + septum)
- Pulsed Sextupole Magnet (1 PSM + septum)
  - Suitable for top-up injection

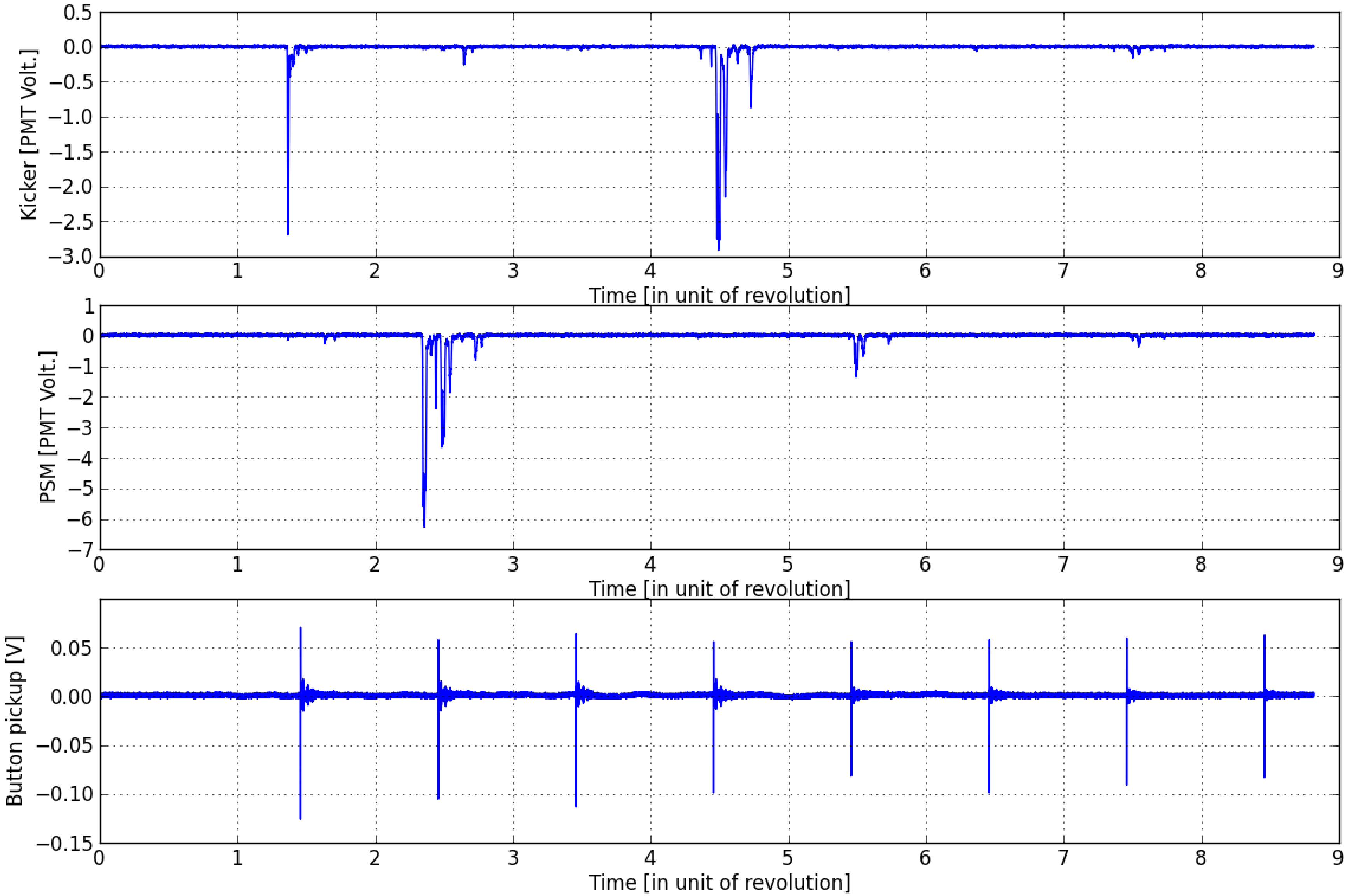


Kicker Magnet



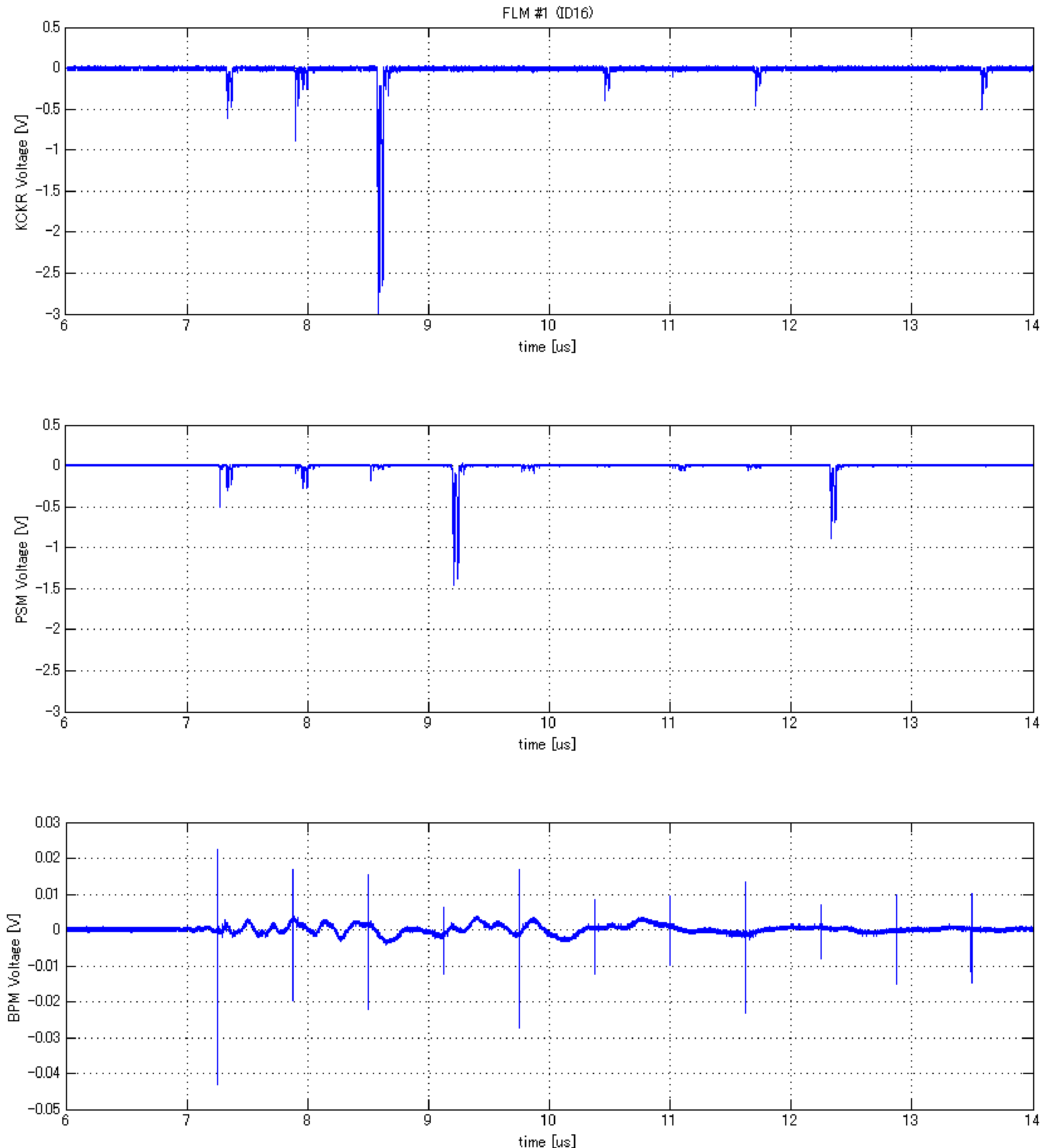
Pulsed Sextupole Magnet

Turn-by-Turn Signal : Kicker/PSM



Beam loss signal and BPM signal with two injection method (Kicker/PSM) at VW14.

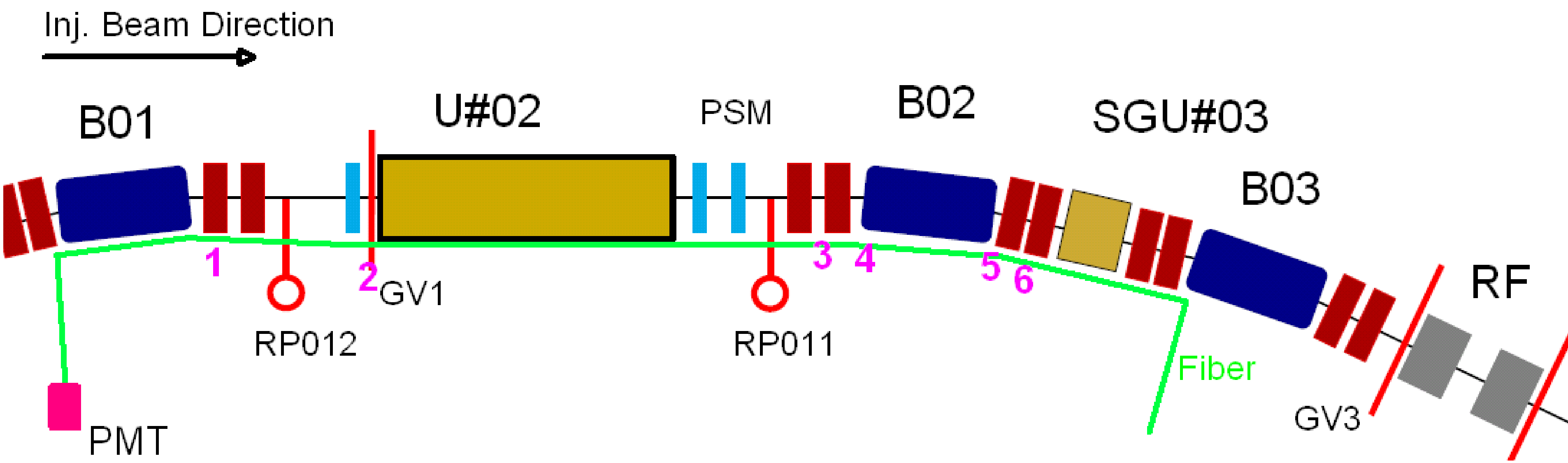
ID16



18/Sep/2013

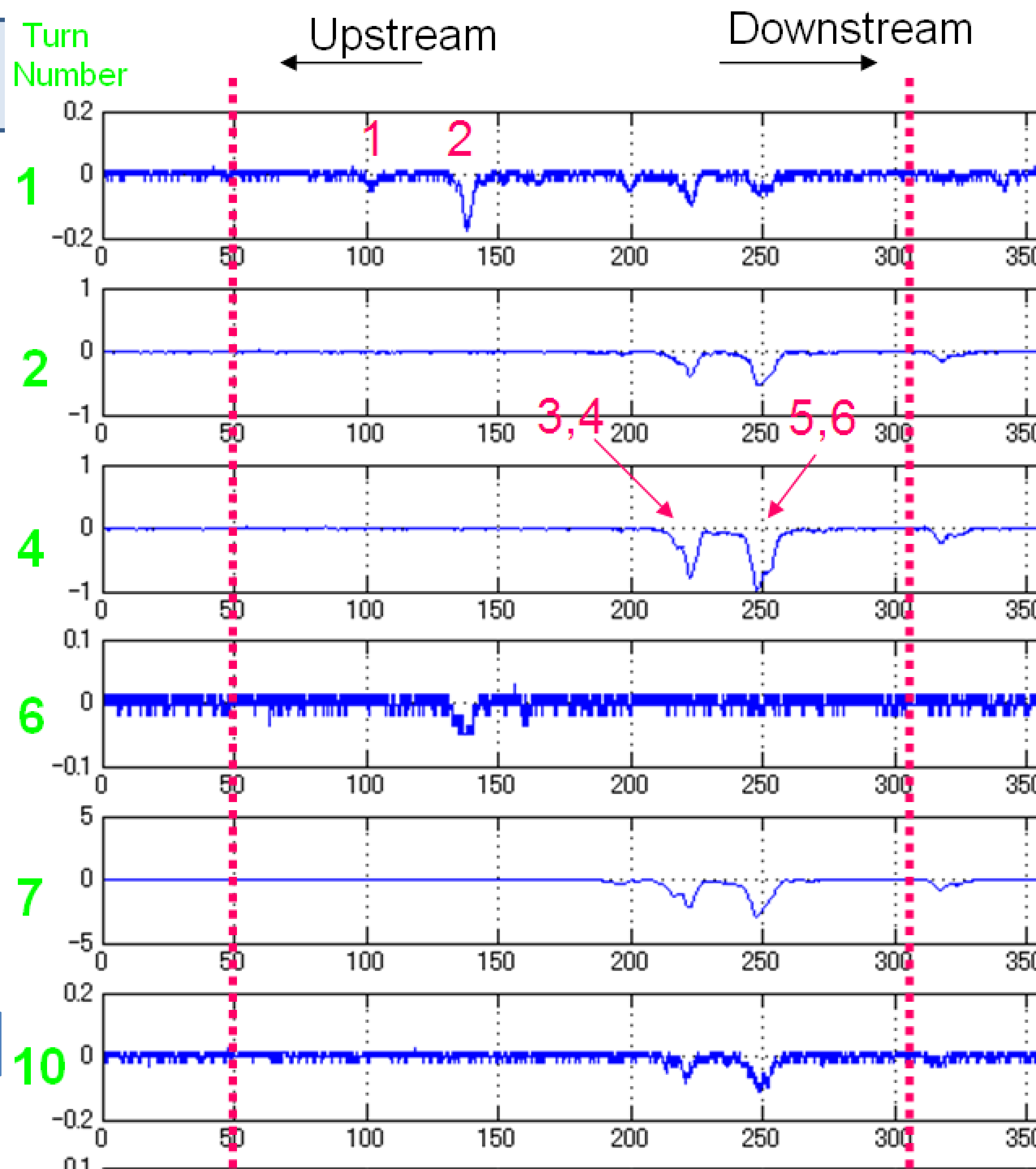
B01-B03 area

- Fiber is installed inside of Q-mag, B-mag



Narrow physical aperture at PSM

Kicker Injection



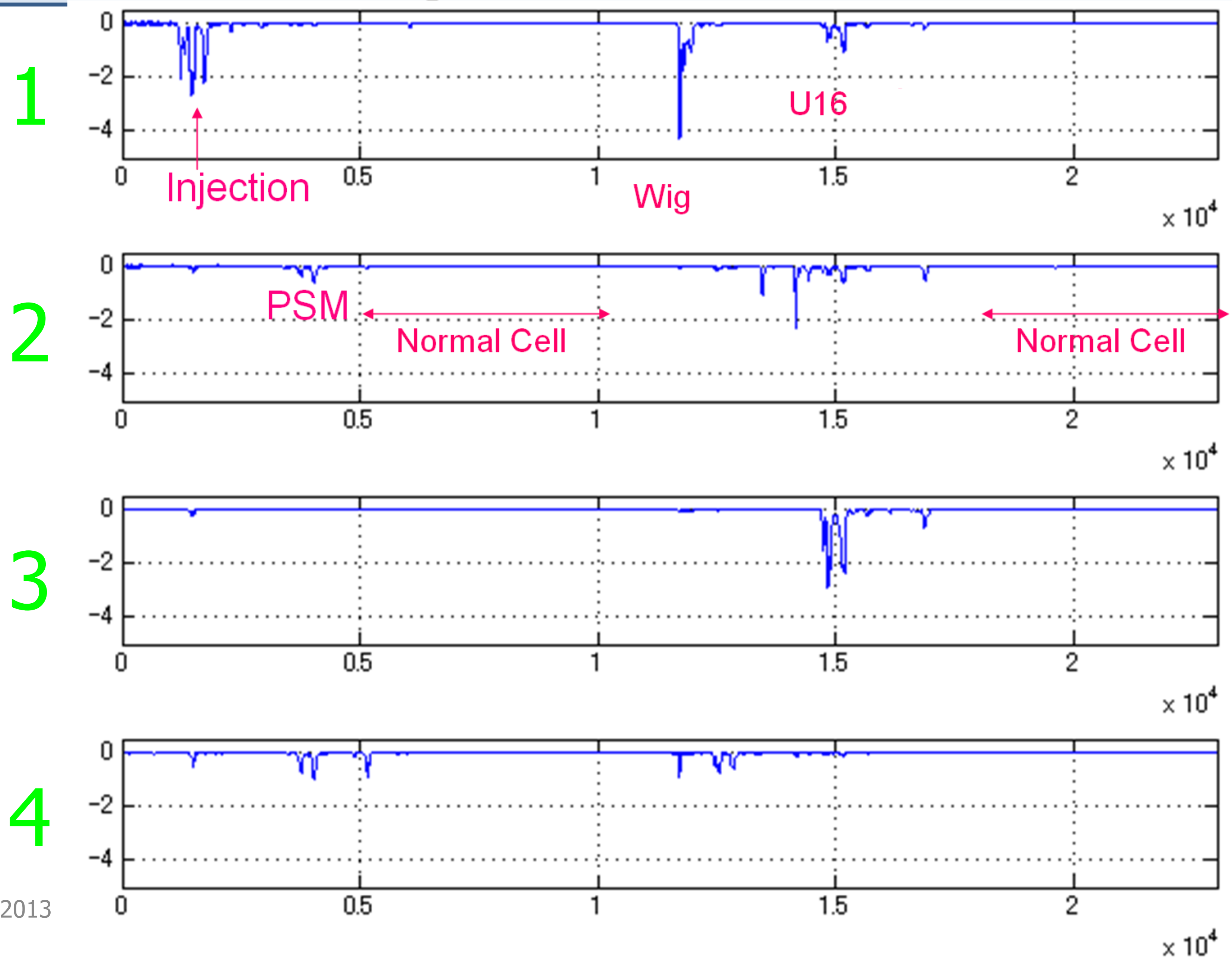
(V. Autoscale)

Comment 1

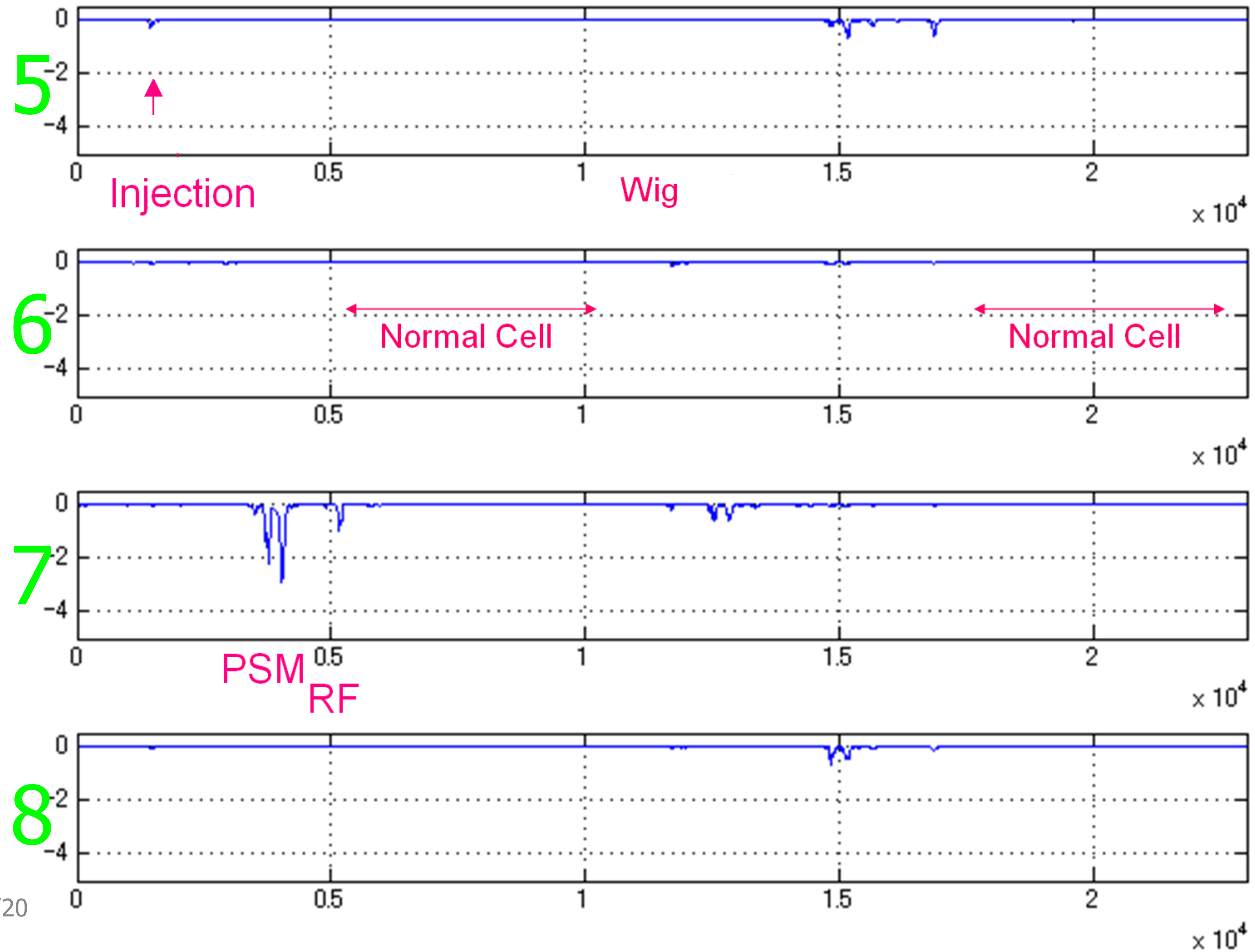
- Large loss in 7th turn
- Observed at the downstream of PSM (narrow aperture) and B02 Bending magnet.

Whole ring loss, 1 – 4 turn

Kicker Injection



Whole ring loss, 5-8 turn



Comment 2

- No loss in “normal cell” which has large horizontal aperture

- We tried to decrease the loss, but we have three horizontally narrow location :

  1. Septum, 2. PSM, 3. Vertical Wiggler

- For now, we have not yet succeeded to decrease the loss. (No problem for daily operation.)
- With the aid of the turn-by-turn loss detection system, we can decrease the loss in near future.

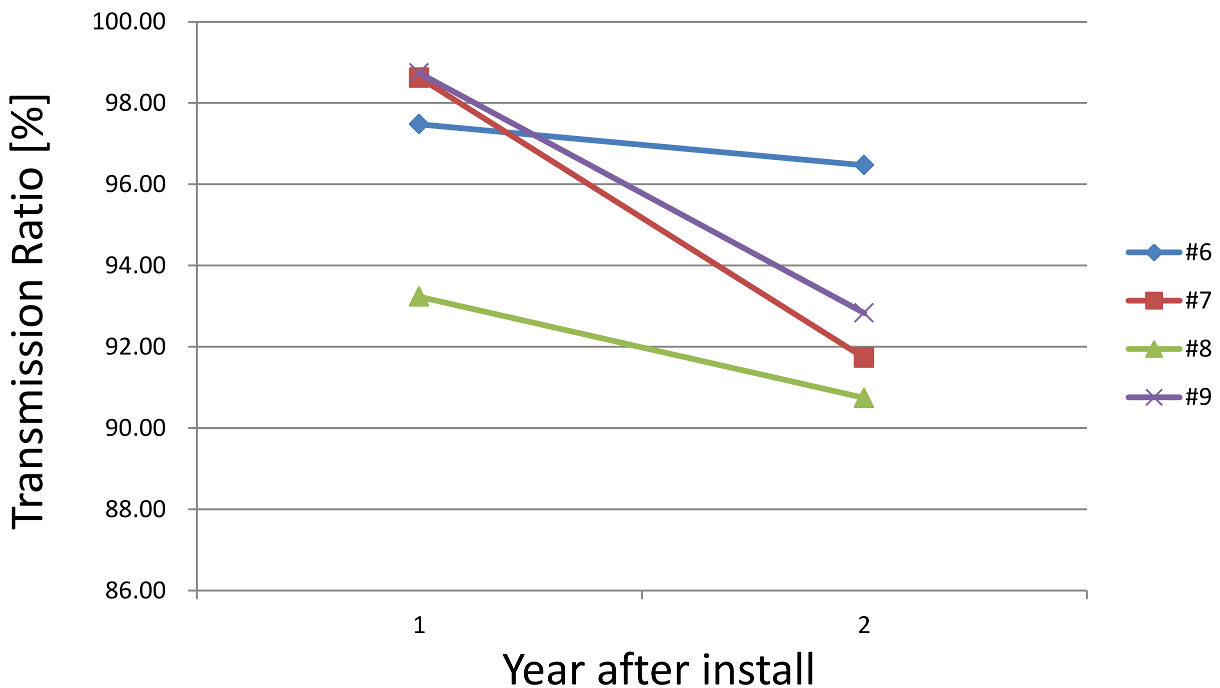
Data Acquisition

- Oscilloscope : 2 GHz analog BW, 10 GS/s
  - 500 MHz oscilloscope can be used (depends on resolution)
- At first, we used an oscilloscope to measure all loss monitor. It takes about one hour to measure whole ring.
- Large loss is observed at narrow horizontal aperture region, as expected.
  - We don't need loss monitor at normal-cell section → we plan to remove fiber in the part
- We plan to introduce an multi-channel digitizer to measure whole ring loss simultaneously.

- Before we introduce loss monitor, the injection-rate was a measure of capture efficiency during top-up operation.

Deterioration by Radiation

- Anritsu ML9002A power meter
  - 850 nm (note: different from Cherenkov range)



Max 10 % deterioration after 2 years operation in PF (2.5 GeV, 450 mA Top-up).
No problem for loss pattern measurement. (We don't need absolute loss in this case.)

Summary

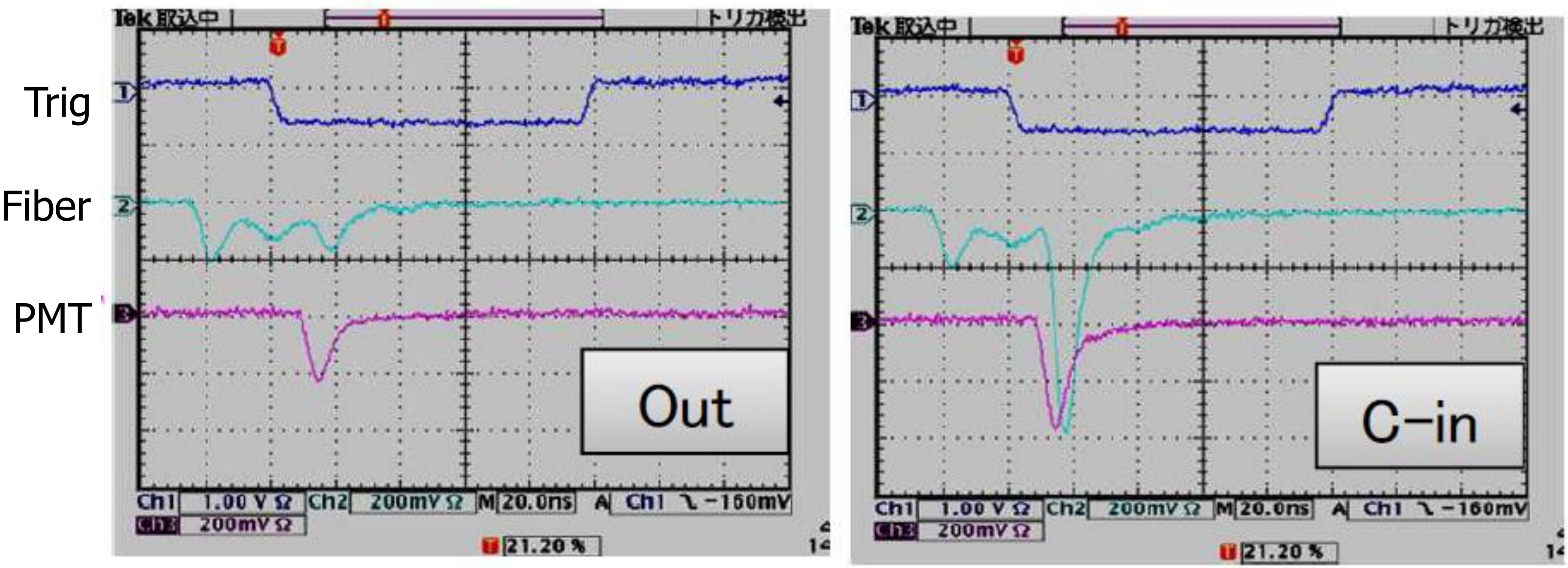
- Advantage of Fiber loss monitor
  - Position resolution : 30 cm is easy to achieve
  - Can locate very near to vacuum chamber
  - Easy to install / removal
  - Can cover long distance
  - Good S/N ratio (no X-ray background)
  - Can be a good tool for turn-by-turn analysis
  - Radiation hardness (pure silica)
  - Cost effective
  - Can cover wide range of energy
    - several MeV to GeV machine
  - Can use as detector for wire scanner
    - Freedom of location : dependence on beam energy

Thank you for your attention

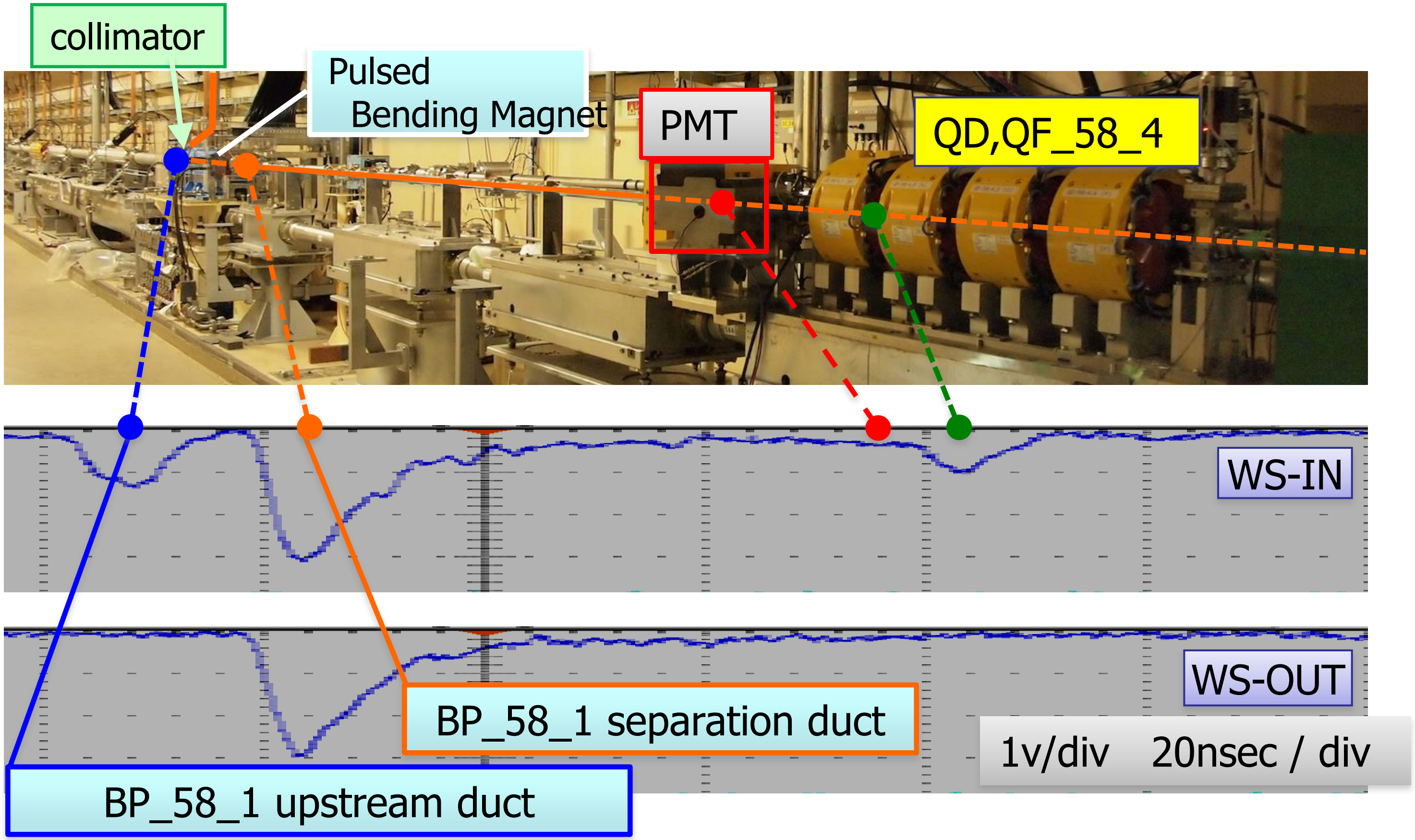
If time permits,

Advantage of Fiber

- PIN Diode or Scintillator +PMT
  – All loss signal in upstream is “compressed”
- Fiber
  – Possible to distinguish loss location



Example in KEK-Linac Wire Scanner



Loss at pulsed bending magnet always exists without the wire scanner