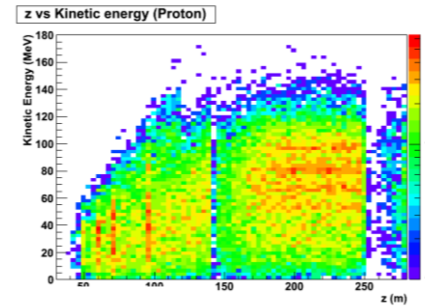
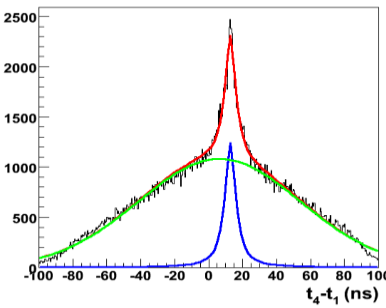
Scintillating Fiber Detector for the Beam Loss Proton Measurements at J-PARC Linac

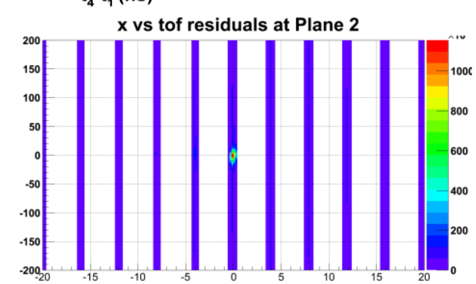
KONSTANTINOVA Olga A.,*
MARUTA Tomofumi*
High Energy Accelerator Research Organization
SAKO Hiroyuki**,
MIURA Akihiko**
***Japan Atomic Research Agency*

Contents

- Introduction and motivation
  - J-PARC Linac
  - Physical explanation of the beam loss
- Experimental setup
  - Measurement principal
  - Scintillation fiber detector
  - Theoretical basis of the measurement
- Experimental results
  - Track reconstruction
  - Time-of-flight distribution
  - Beam loss rate
- Simulation outline
  - GEANT4 simulation
  - Simulated proton distributions
- Summary and prospect
  - Results comparison





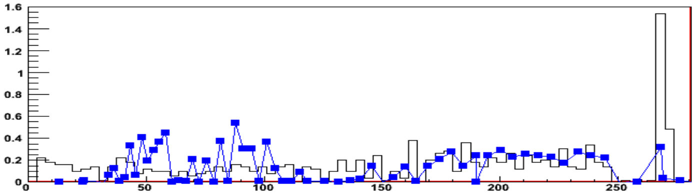


Contents

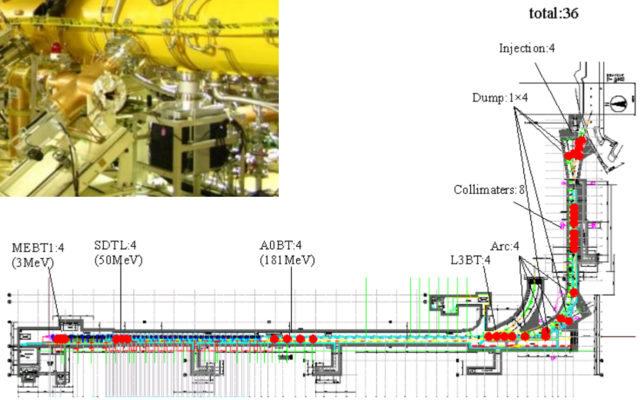
- Introduction and motivation
  - J-PARC Linac
  - Physical explanation of the beam loss

WHY & HOW

- Experimental setup
  - Measurement principal
  - Scintillation fiber detector
  - Theoretical basis of the measurement
- Experimental results
  - Track reconstruction
  - Time-of-flight distribution
  - Beam loss rate
- Simulation outline
  - GEANT4 simulation
  - Simulated proton distributions
- Summary and prospect
  - Results comparison



in J-PARC linac



J-PARC Linac

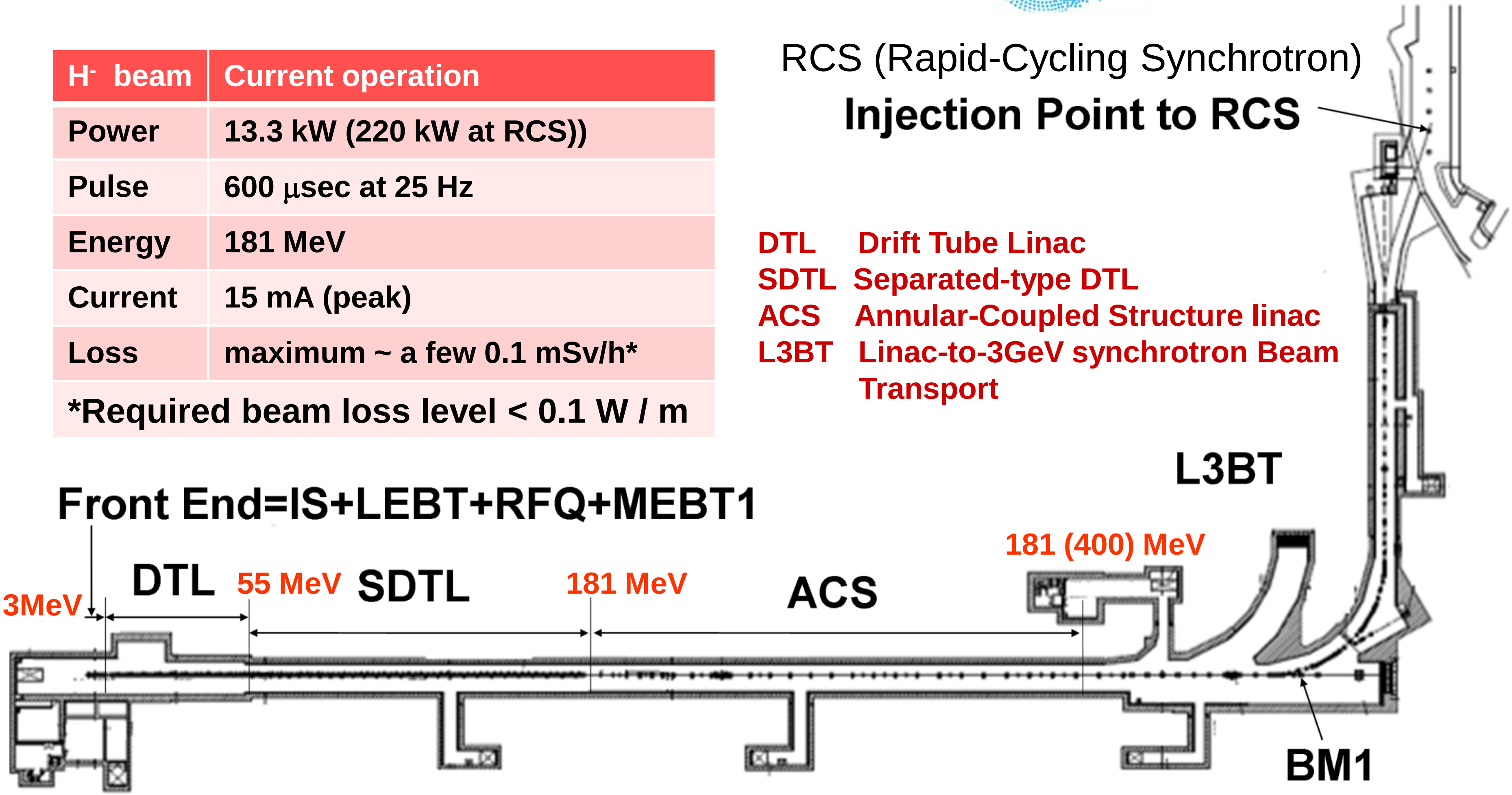
H^- beam	Current operation
Power	13.3 kW (220 kW at RCS))
Pulse	600 μsec at 25 Hz
Energy	181 MeV
Current	15 mA (peak)
Loss	maximum ~ a few 0.1 mSv/h*
*Required beam loss level < 0.1 W / m	

RCS (Rapid-Cycling Synchrotron)

Injection Point to RCS

DTL Drift Tube Linac
SDTL Separated-type DTL
ACS Annular-Coupled Structure linac
L3BT Linac-to-3GeV synchrotron Beam Transport

Front End=IS+LEBT+RFQ+MEBT1



IS Ion Source
LEBT Low Energy Beam Transport

RFQ Radio-Frequency Quadruple Linac
MEBT Medium-Energy Beam Transport

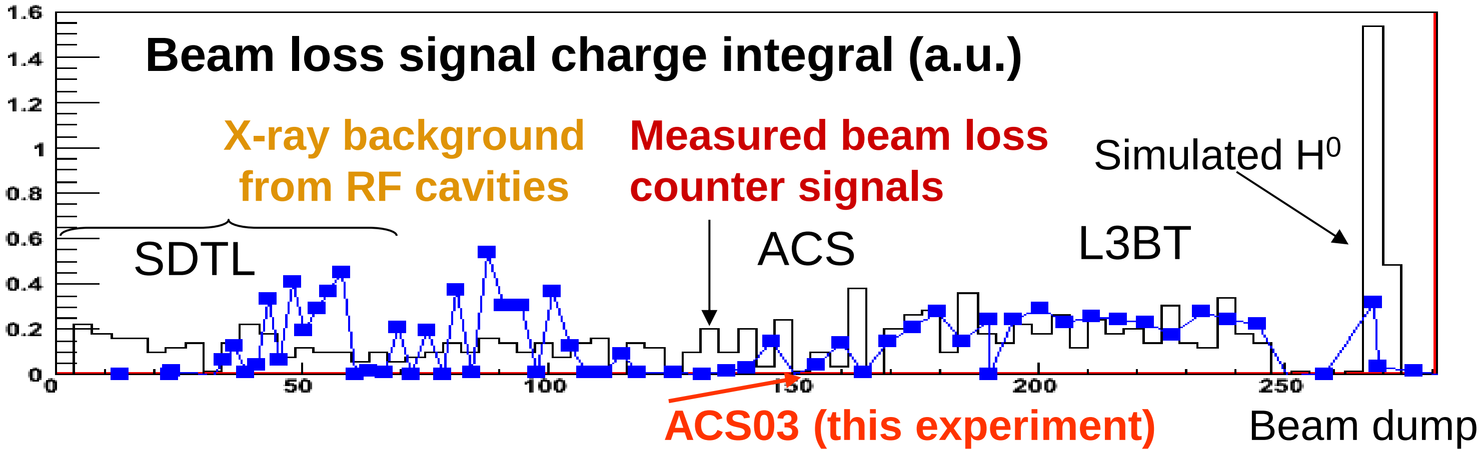
Introduction and motivation

Significant beam loss issue In the J-PARC linac

due to the high intensity H- beam, significant beam loss has been observed at the beam line section called ACS (Annular-Coupled Structure). The loss is mainly due to a proton which is produced due to the double electron stripping of the H- beam by the residual gas inside the titanium beam pipe.

- **High beam loss and radiation level (~ a few 0.1 mSv/h) observed in ACS at 7.2kW operation**
- **Beam loss measurement at SDTL is hard due to background X-ray from RF cavities**

GOAL:
To measure the beam loss rate
To understand the beam loss mechanism



Introduction and motivation

Methods

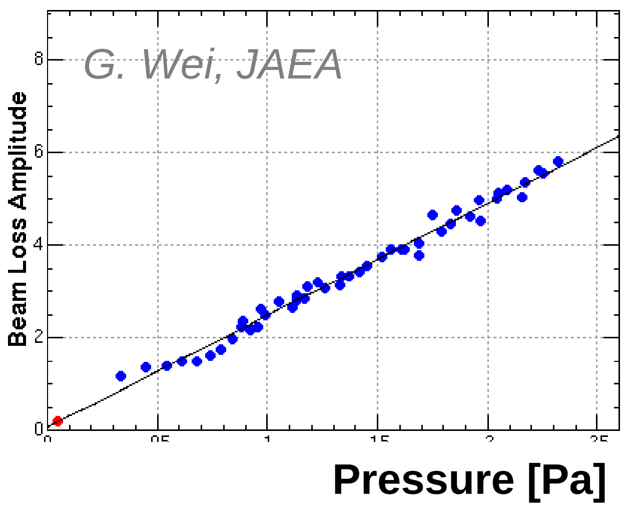
Experimental: measurement using fiber detector

- Count the number of H^+ from H^0 (residual gas interaction)
- One proton corresponds to one lost H^-
- Tracking (a charged particle from the beam duct)
- Time-of-flight measurement
- Evaluate absolute beam loss rates by counting H^+ tracks

Simulation: proof the experimental data

Physical explanation of the beam loss

Pressure at the ion pump SDTL 14B

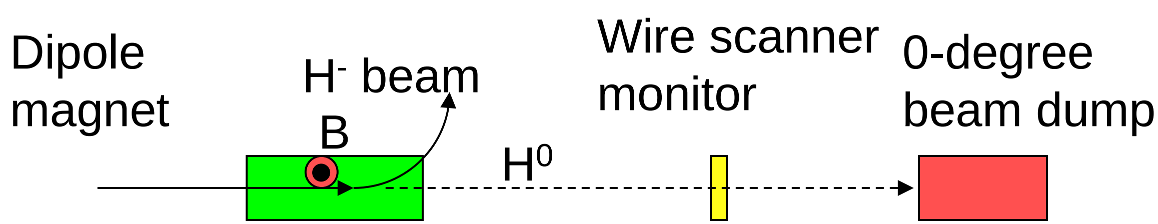


Vacuum pressure dependence of beam loss at ACS

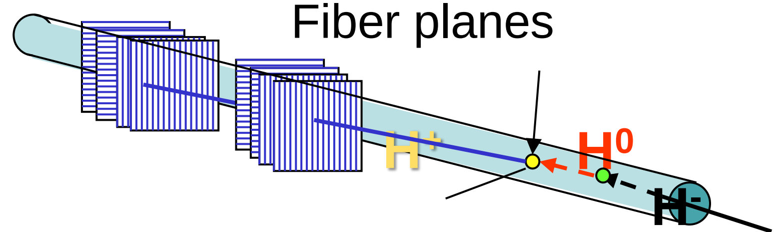
Beam loss signal level with a proportional counter is proportional to the residual gas pressure

Strongly suggest the beam loss is due to H^0 produced by H^- interacted with residual gas

H^0 was observed with a wire scanner monitor at the straight beam dump with bending magnet on.



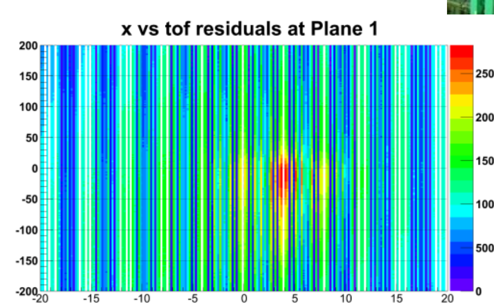
Contents

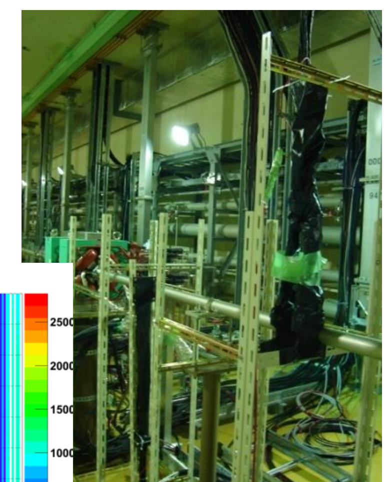


- Introduction and motivation
  - J-PARC Linac
  - Physical explanation of the beam loss
- **Experimental setup**
  - **Measurement principal**
  - **Scintillation fiber detector**
  - **Theoretical basis of the measurement**

PRINCIPLE & MEASUREMENT

- Experimental results
  - Track reconstruction
  - Time-of-flight distribution
  - Beam loss rate
- Simulation outline
  - GEANT4 simulation
  - Simulated proton distributions
- Summary and prospect
  - Results comparison



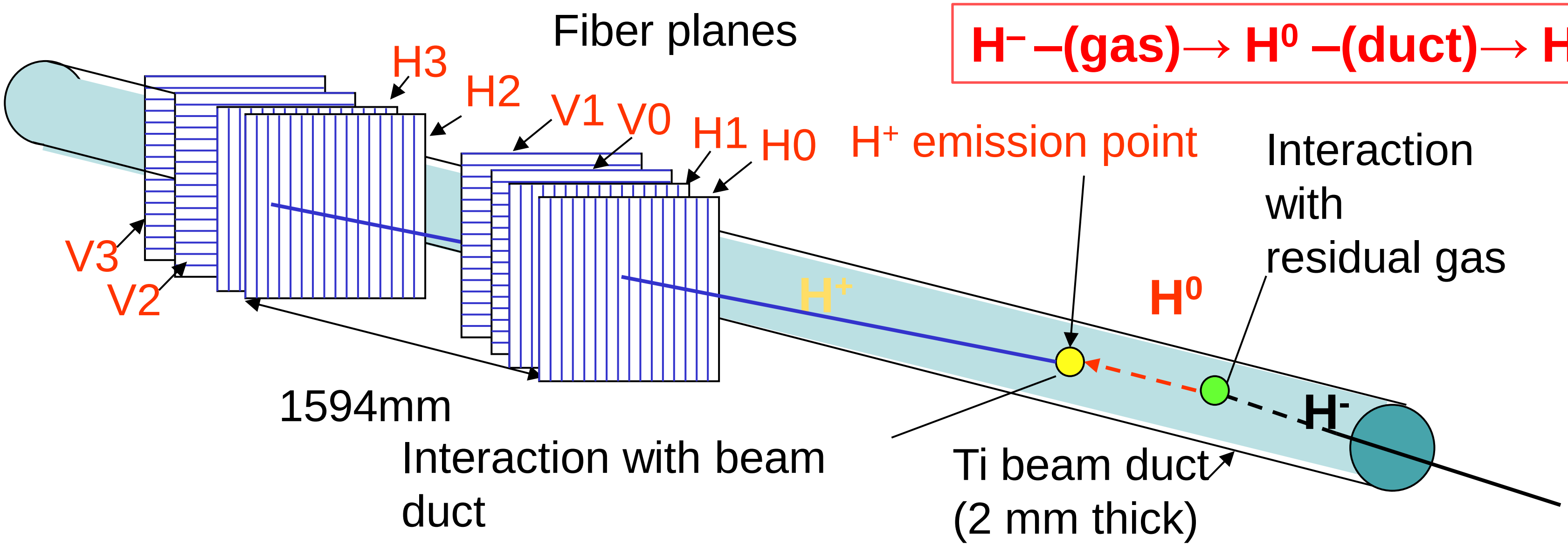


Measurement principal

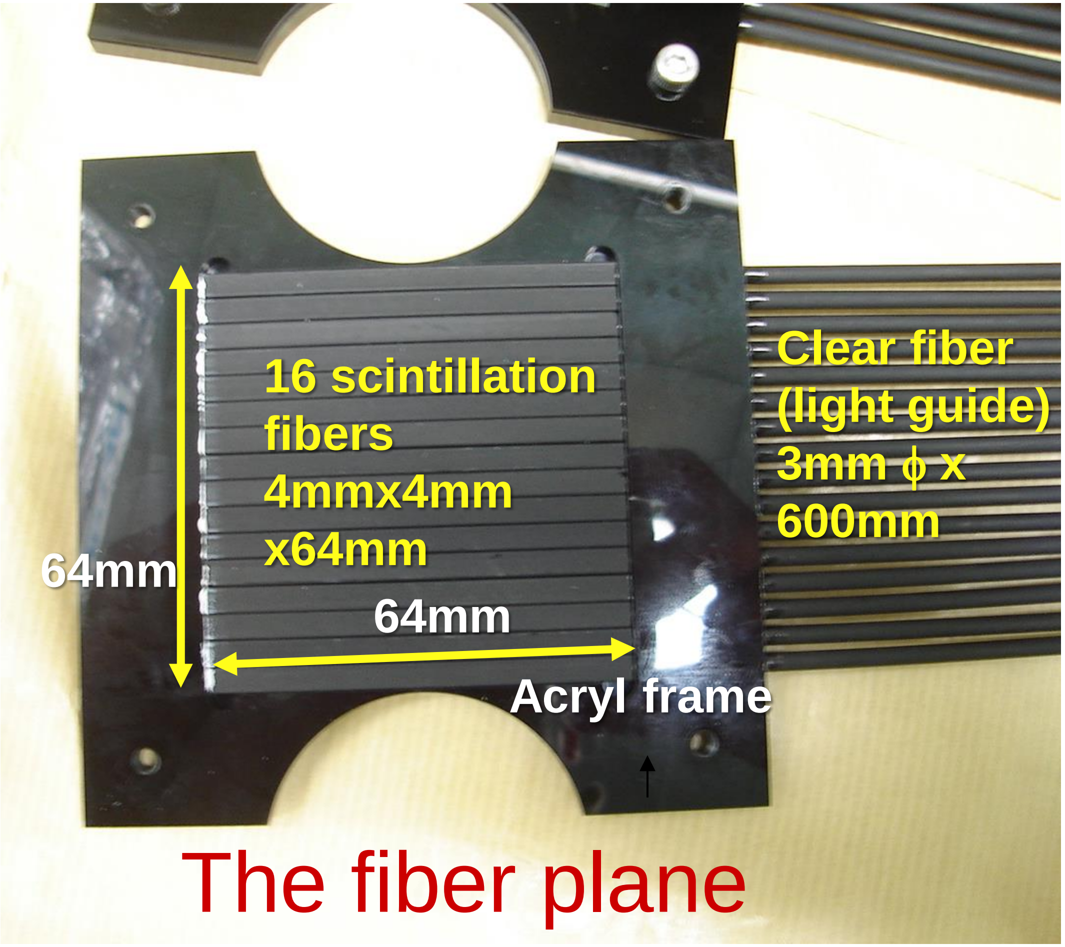
Count the number of H^+ from H^0 (residual gas interaction)

- One H^+ corresponds to one lost H^-
- Reconstruct a track passing through all fiber planes
- Energy measurement with time of flight
- To cope with high rate, use fibers

By fiber positions, emission point can be measured!



Scintillation fiber detector



Plastic fiber scintillators

- A few nsec pulse width
- High-rate capability
- Timing resolution (~ 600 psec)

64ch Multi-Anode PMT Hamamatsu H8500C

- 2 fiber planes (16 fibers x 2) are connected
- Gain~1.5×10^6
- Q.E.~24%

Experimental setup

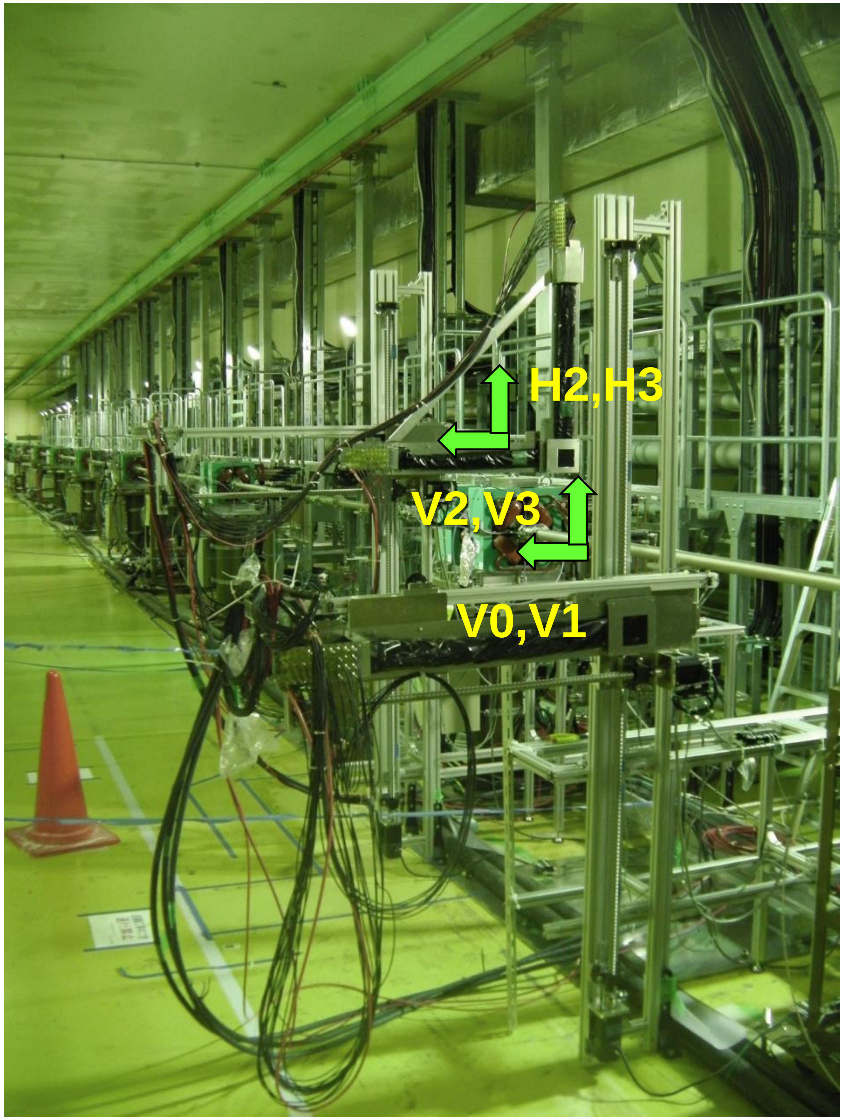
<u>Installed on Sep. 2012</u>
upstream mover (H0,1,V0,1)
downstream mover (H2,3,V2,3)

Each mover can move detector positions

- **horizontally (50~700mm),**
- **vertically (-600~ 600 mm)**

with stepping motors

<u>Since Oct 2012, we measure</u>
X(up) =0,100,200,300,350,400 mm
X(down) = 0-600 mm



Physical basis of the measurement

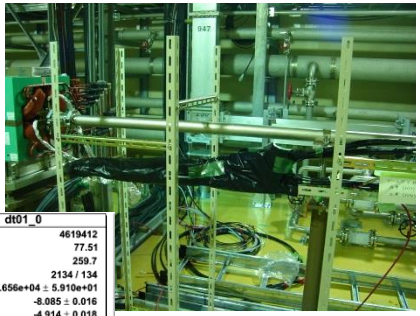
Only charged particles can be detected by fiber planes

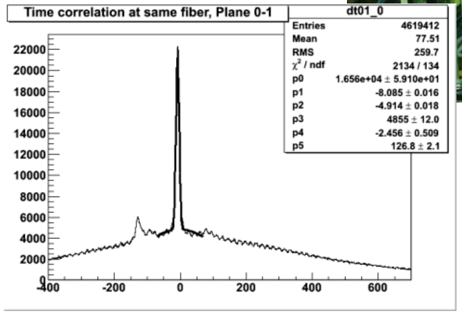
- Insensitive to neutrons
  - In rare case, fast neutrons might interact in one of the fiber planes and produce protons
- Insensitive to gamma-rays
- Probability of nuclear interaction of proton in Ti duct or fibers is negligible
  - In 0.2cm Ti duct: Exp(-0.2/17.6):(17.6cm=nuclear interaction length)
  - In 1.6cm fiber (4plane): Exp(-1.6/56.7),
    - Prob. of high-energy gamma-ray to produce e+e- : Exp(-1.6/42.4)
- Electron can be rejected with time-of-flight from protons
  - Electron energy threshold = 2.9 MeV (in 4 fiber planes)

Essentially, only protons from H^- can be detected!

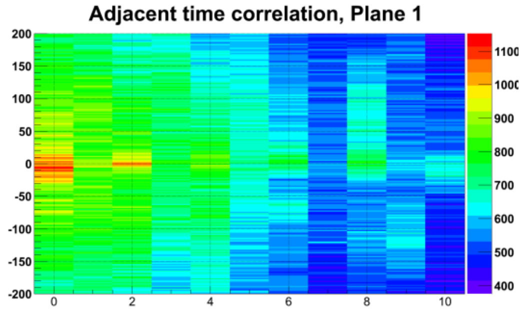
Contents

- Introduction and motivation
  - J-PARC Linac
  - Physical explanation of the beam loss
- Experimental setup
  - Measurement principal
  - Scintillation fiber detector
  - Theoretical basis of the measurement
- **Experimental results**
  - **Track reconstruction**
  - **Time-of-flight distribution**
  - **Beam loss rate**
- Simulation outline
  - GEANT4 simulation
  - Simulated proton distributions
- Summary and prospect
  - Results comparison

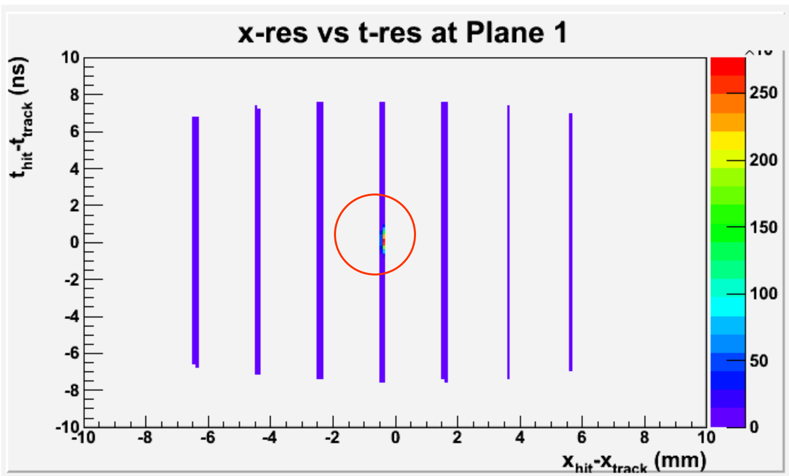


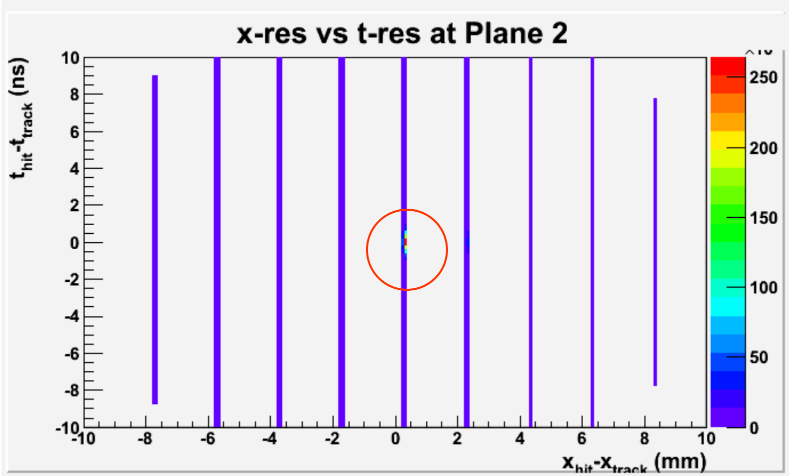


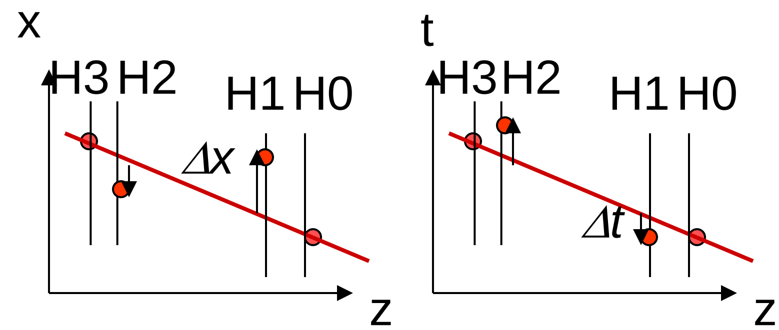
WHAT DID WE GET?



Track reconstruction





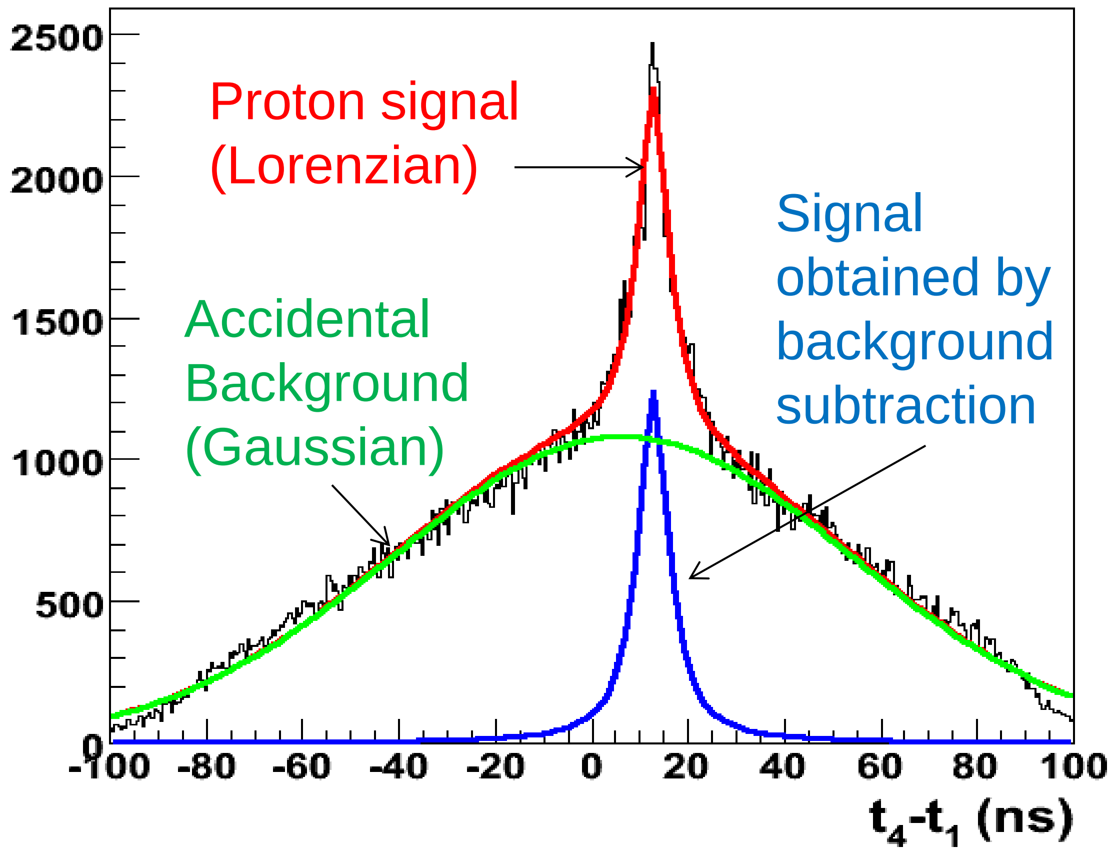


Projection of a line connecting hits in H0 and H3 onto H1 and H2 (both x-z and t-z planes)

- Residuals have peaks
  - **Charged tracks detection**

Time-of-flight distribution

- **Require hits in H0,H1,H2,H3,V0, V1,V2**
- **χ^2 cuts in z-x track and z-y tracks**

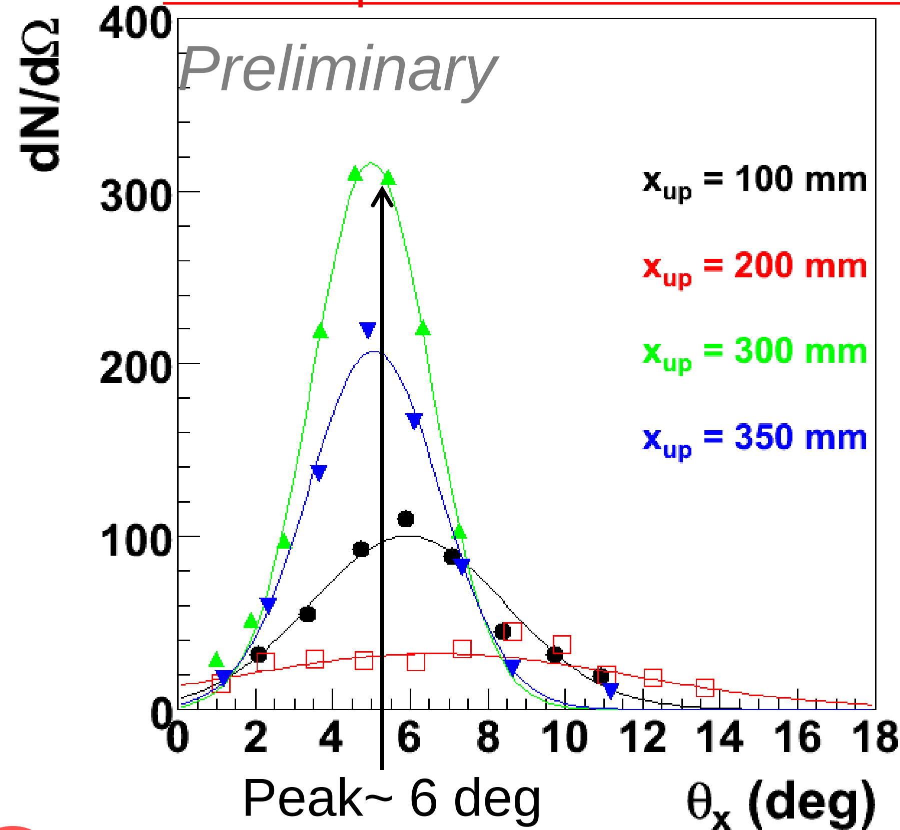


Beam loss rate (1)

Proton spatial density per beam pulse

$$\rho(\theta_x) = \frac{dN}{d\Omega}$$

Theta-dependence of the beam loss



Number of protons per beam pulse

$$N = \frac{N_{track}}{N_{beam}} \cdot \frac{N_{trigger}}{N_{DAQ}}$$

N_{track} : #reconstructed proton tracks
N_{beam}: #beam pulse
$N_{trigger}$: #triggers in a beam pulse
N_{DAQ}: #triggers taken by DAQ

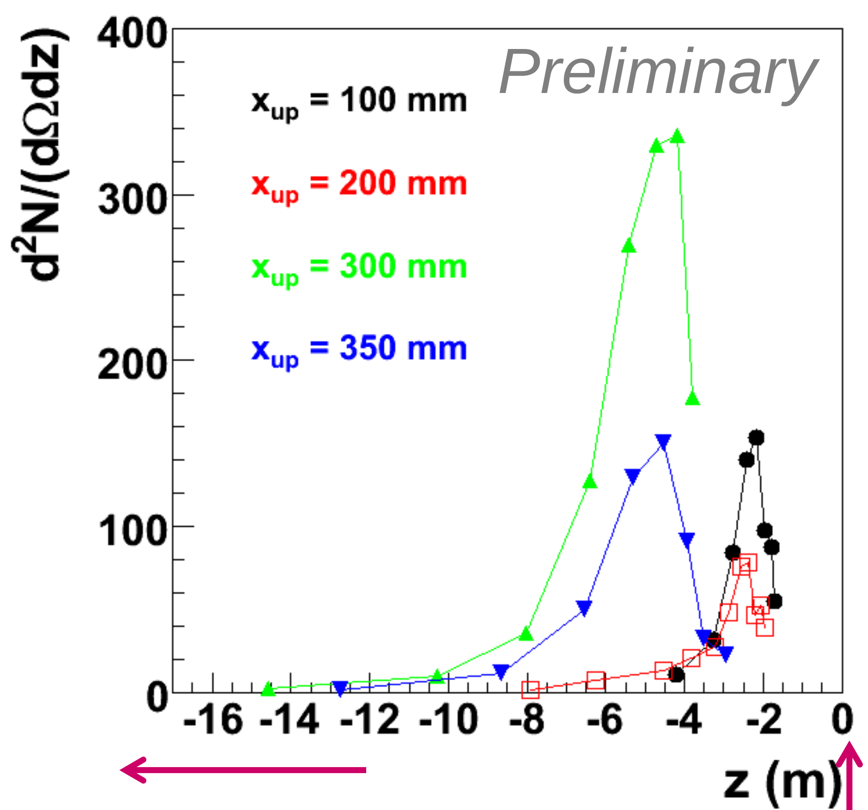
Trigger = coincidence of dynode signals of 4 PMTs

N- = 2.5e+13
Estimation from gas pressure and ionization cross section = 2.7e-8

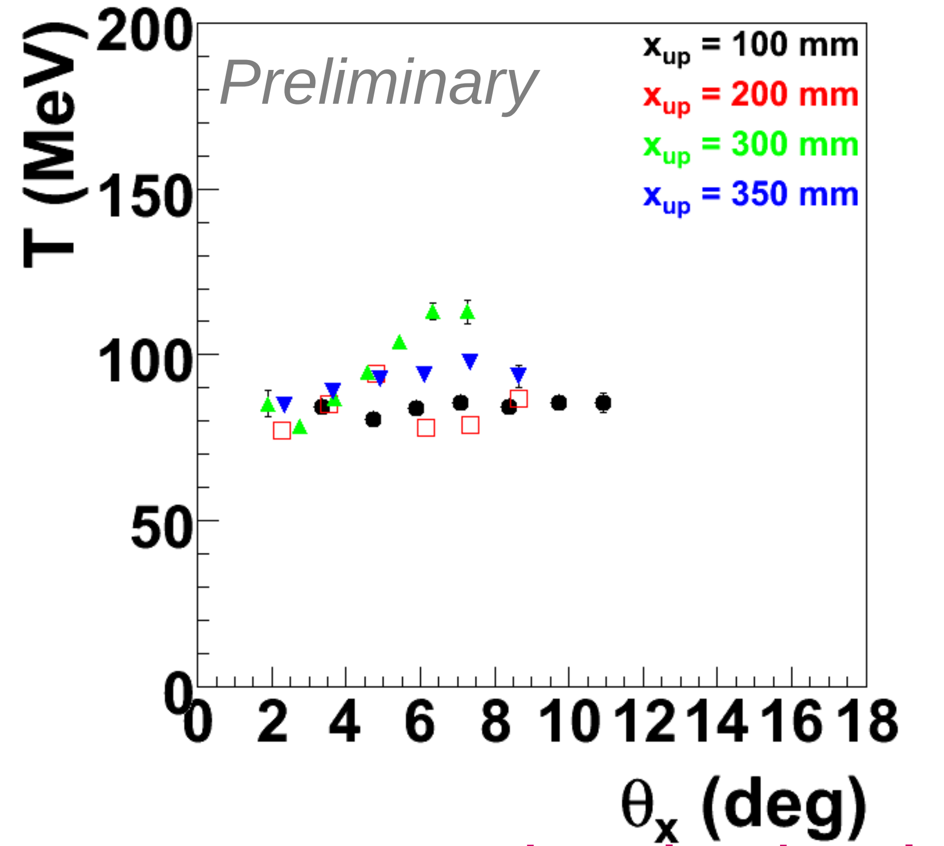
x_u (mm)	dN/dz	H^+/H^-
100	316538	1.27e-8
200	180189	7.21e-9
300	441681	1.77e-8
350	211315	8.45e-9
400	180407	7.22e-9

Beam loss rate (2)

Z-dependence of the beam loss



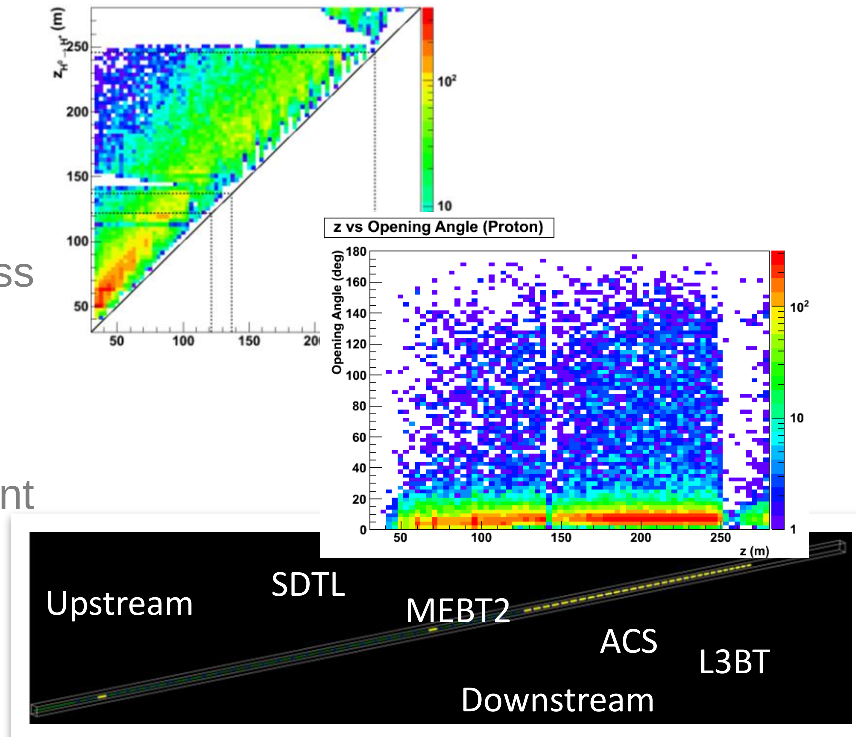
Theta-dependence of the mean energy



Measurements in upstream positions ranges 2~16 m

Contents

- Introduction and motivation
  - J-PARC Linac
  - Physical explanation of the beam loss
- Experimental setup
  - Measurement principal
  - Scintillation fiber detector
  - Theoretical basis of the measurement
- Experimental results
  - Track reconstruction
  - Time-of-flight distribution
  - Beam loss rate
- **Simulation outline**
  - **GEANT4 simulation**
  - **Simulated proton distributions**
- Summary and prospect
  - Results comparison



HOW CAN WE CHECK?

GEANT4 simulation

Simulation from SDTL to 1st Bend magnet at L3BT

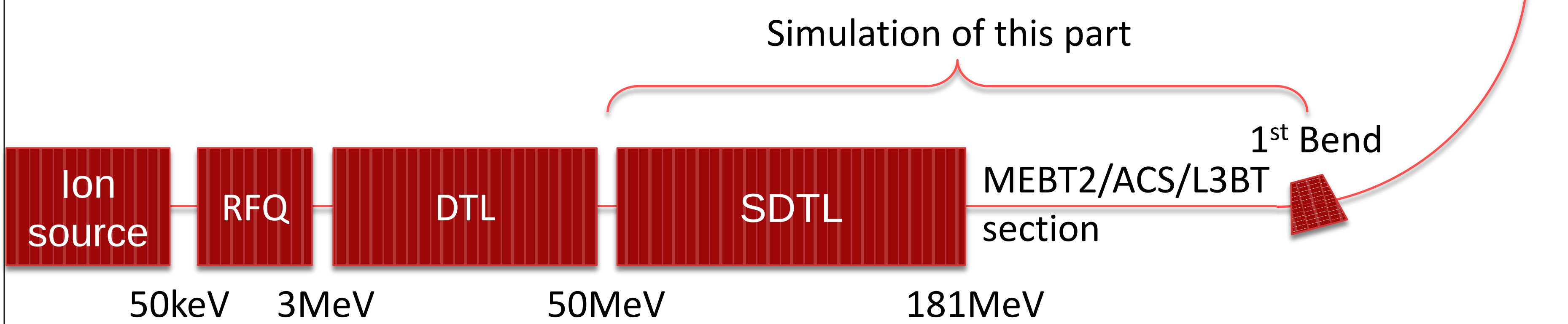
- The total length of 250m
- Beam ducts, RF cavities, and Q magnets
- Inside the ducts: N^2 gas of 10^{-5} Pa

H^{-} –(gas)→ H^{0} –(duct)→ H^{+}

Initial phase space distributions of H^{-} are generated to reproduce Twiss parameters in Trace3D simulation at the entrance of SDTL

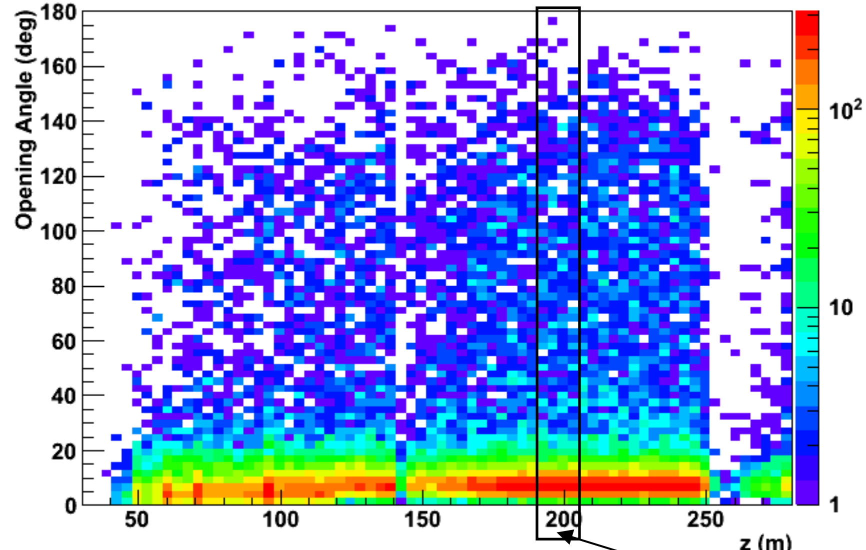
Since H^{-}/H^{0} was undefined in Geant4, we implemented C++ classes for that

➢ We have not included space-charge effects

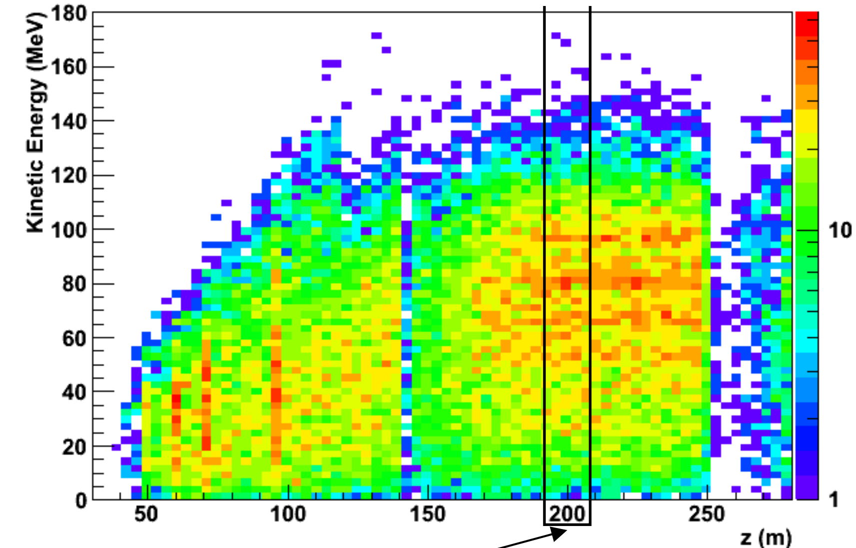


Simulated proton distributions outside the beam duct

H^+ polar angle distribution



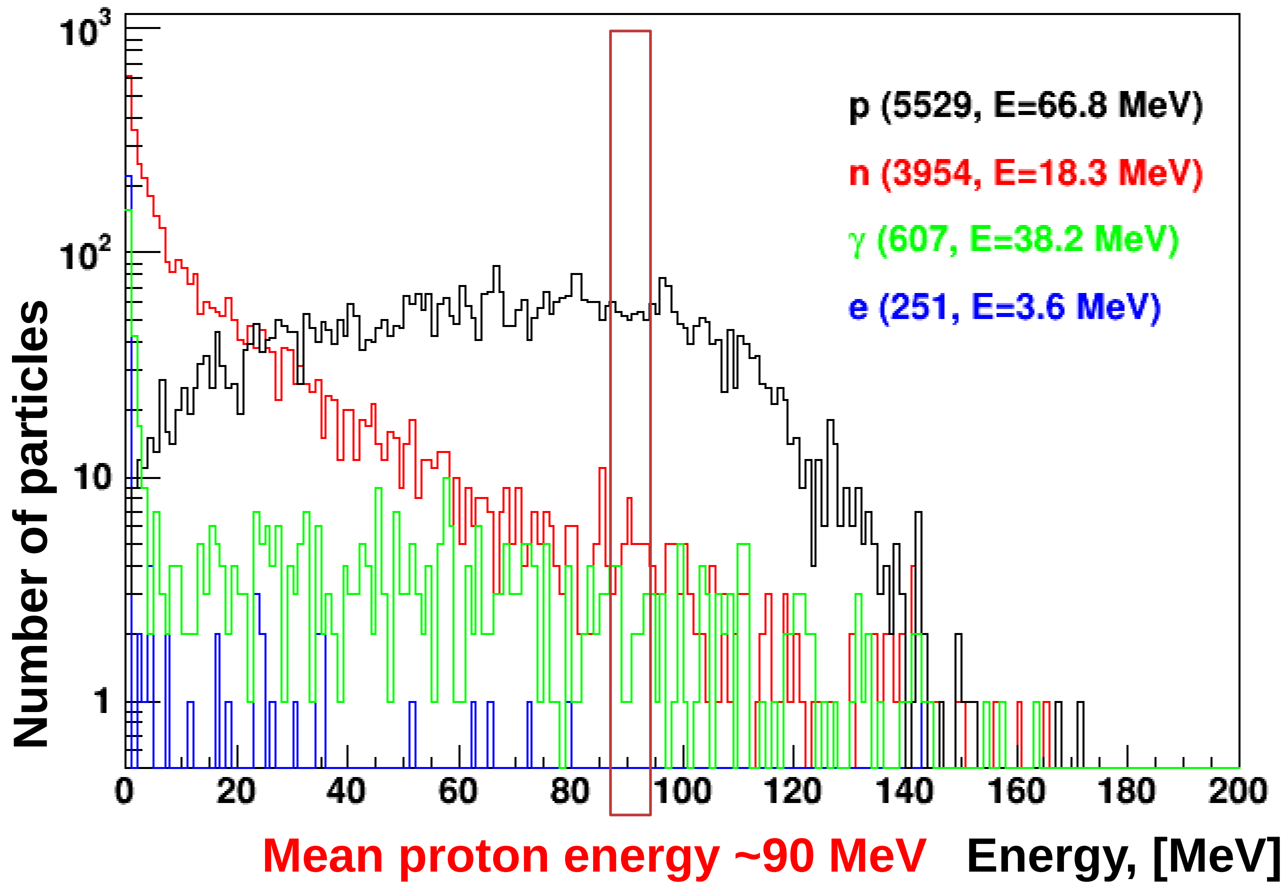
H^+ kinetic energy distribution



ACS12 (detector location)

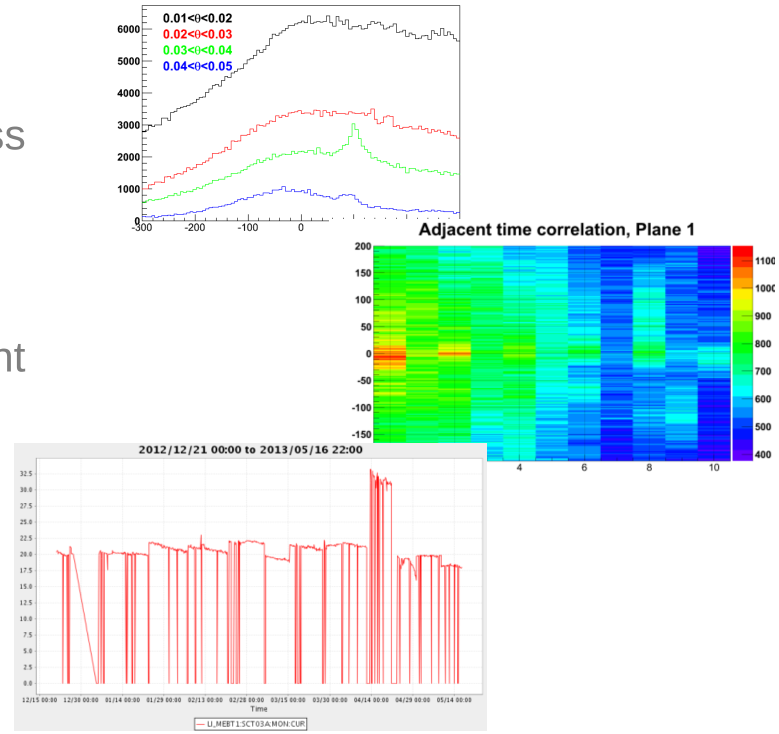
- Emission polar angle distribution (with respect to the beam axis) has peak around 6 degrees.
- Increase of kinetic energy up to z=150m is due to 181 MeV H^- accelerated beam.
- Broad energy distribution

Simulated energy distribution



Contents

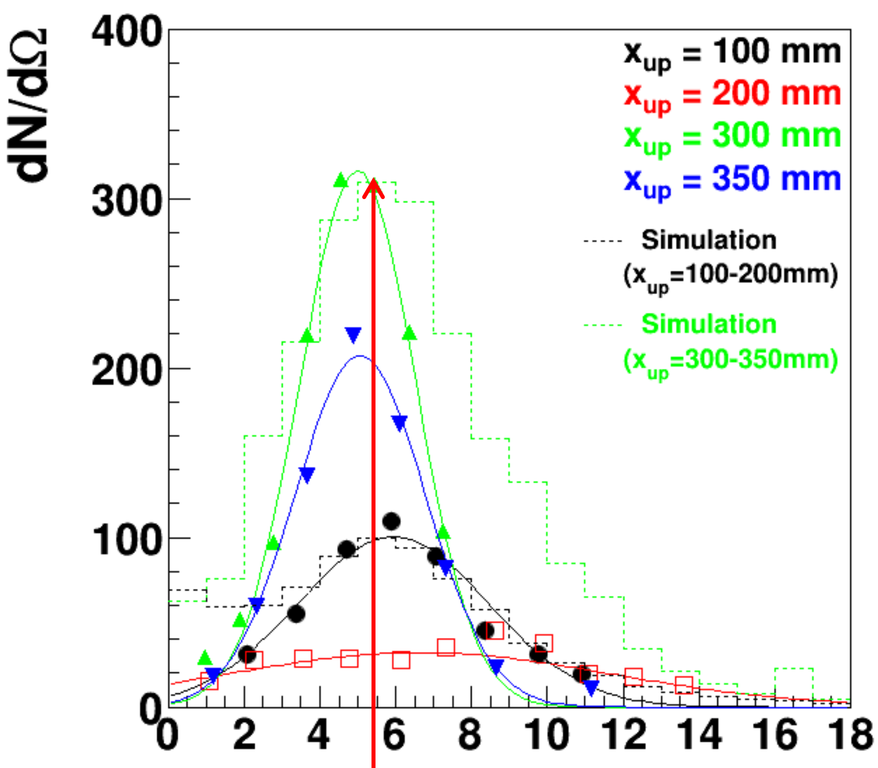
- Introduction and motivation
  - J-PARC Linac
  - Physical explanation of the beam loss
- Experimental setup
  - Measurement principal
  - Scintillation fiber detector
  - Theoretical basis of the measurement
- Experimental results
  - Track reconstruction
  - Time-of-flight distribution
  - Beam loss rate
- Simulation outline
  - GEANT4 simulation
  - Simulated proton distributions
- **Summary and prospect**
  - **Results comparison**



WHAT DO WE LEARN?

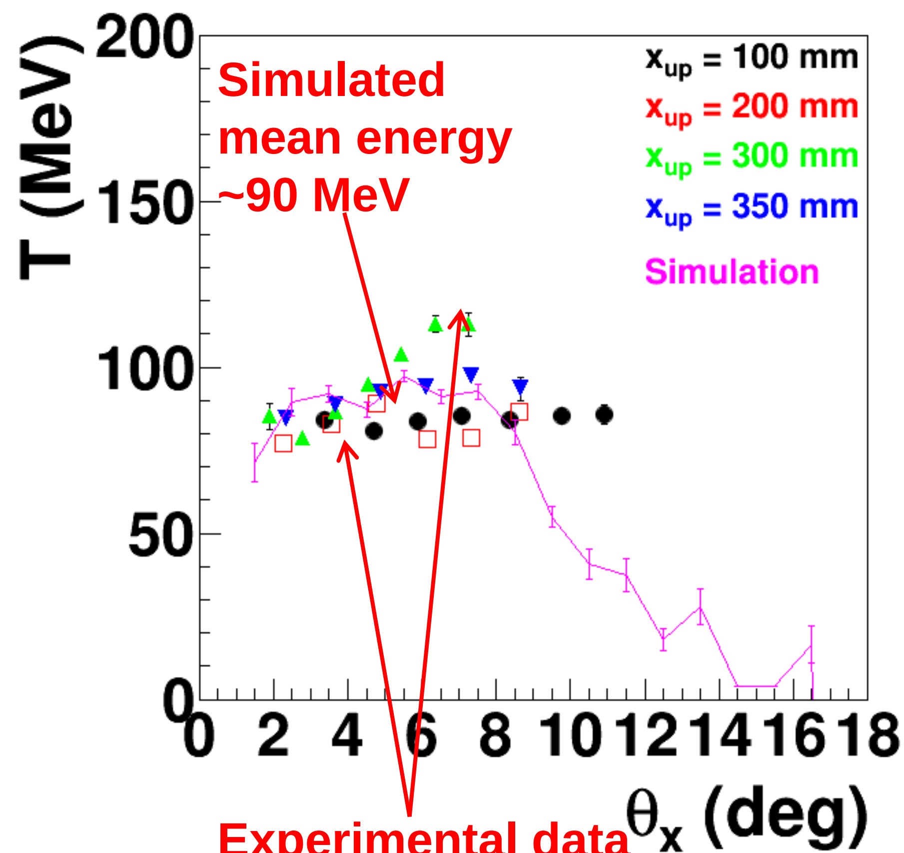
Results comparison

Theta-dependence of the beam loss



Peak of theta ~6 deg

Theta-dependence of the mean energy



Experimental data 80~120 MeV

Summary and prospect

What do we learn ?

- Scintillation fiber detector developed for beam loss measurement tested at J-PARC Linac
- Clear charged particle track signals of protons observed
- **Quantitative loss rate has been measured for the first time at J-PARC Linac ($1.8 \sim 3.2 \cdot 10^5$, [proton / beam pulse])**
- **Measured H^+ / H^- ratio of $0.7 \sim 1.8 \cdot 10^{-8}$ is close to the estimation from residual gas interaction rate of $2.7 \cdot 10^{-8}$**
- Theta distribution peak at 6 deg. Is reproduced by simulation
- Measured mean proton energy is 80~120 MeV (~90 MeV simulated) → consistent

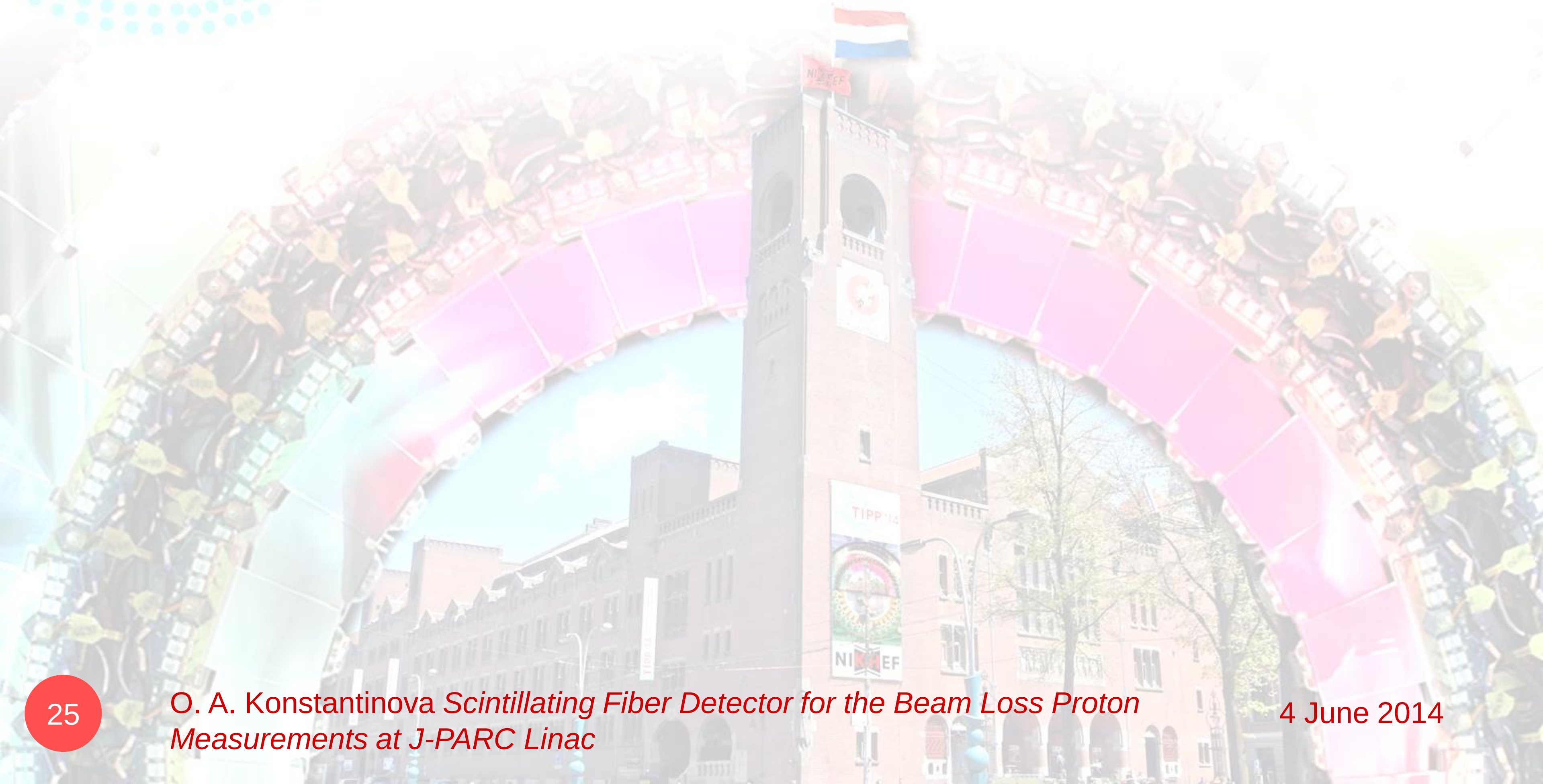
Any other possible improvements ?

- Acceptance and efficiency corrections using simulations
- Evaluation of radiation damage for fibers

Prospects

Since J-PARC Linac has been upgraded from 181 MeV to 400 MeV, we are planning to restart the proton measurements from October 2014

Dank u voor uw aandacht!

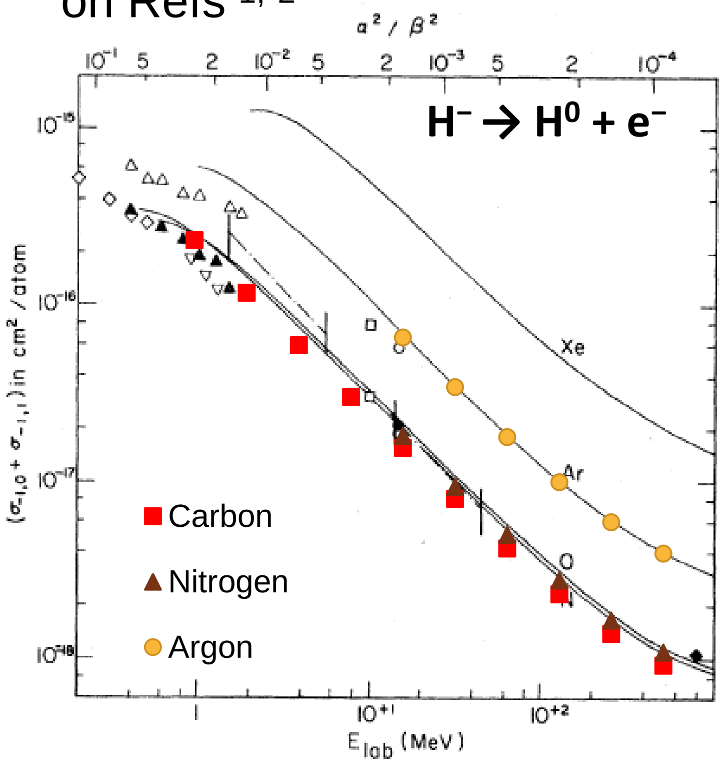


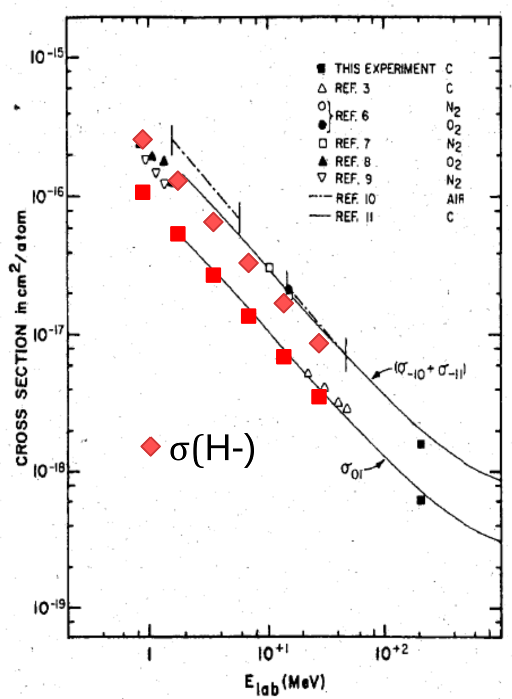
Backup slides

Definition of H⁻ and H⁰

The simulation reproduce both H⁻ and H⁰

- Mass: 939.294 MeV/c^2 (H⁻), 938.783 MeV/c^2 (H^0)
- Lorentz stripping is not defined
- Stripping cross sections: ($H^- + X \rightarrow H^0 + e^- + A$), s ($H^0 \rightarrow H^+ + e^-$) defined based on Refs[*1,*2]





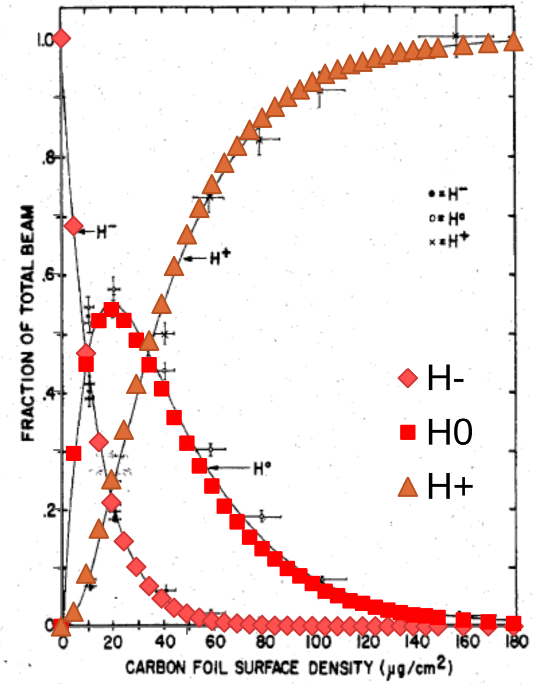


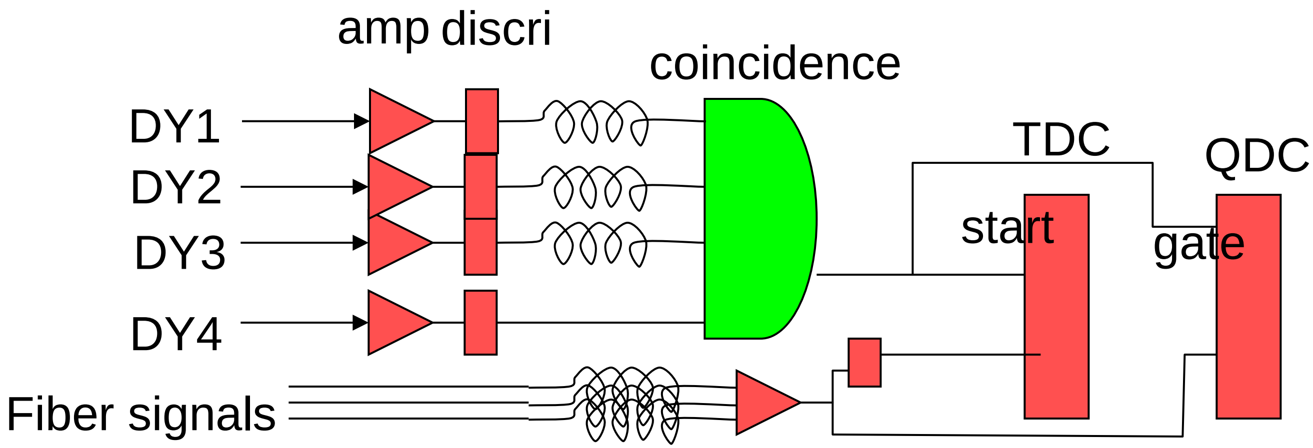
Fig. 3. Comparison of measured charged fractions to the theoretical curves.

*1: R.C. Webber and C. Hojvat, IEEE Transaction on Nuclear Science, Vol. NS-26.
*2: G.H. Gillespie, Phys. Rev. A16 (1997) 943.

Trigger

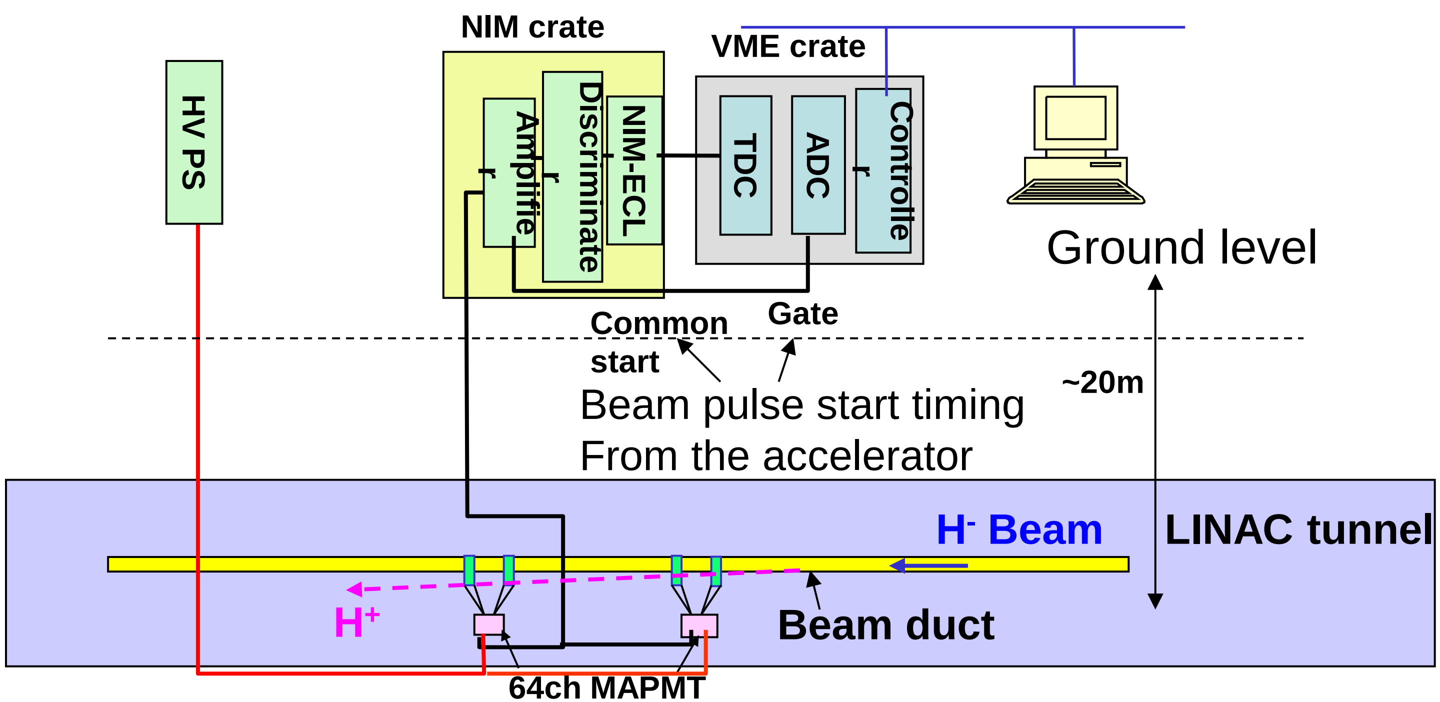
Use of dynode signals of 4 PMT's

- The PMT (H8500C) is 64-ch multi-anode PMT
- PMT dynode signals are "analog sum" of individual anode signals
- By taking AND of dynode signals of PMT1(H0,H1),PMT2(V0,V1),PMT3(H2,H3), and PMT4(V2) trigger signal is defined.
  - Used for start timing of time measurement (TDC), and gate signal for charge measurement (QDC)
- Pulse-by-pulse timing and charge measurement

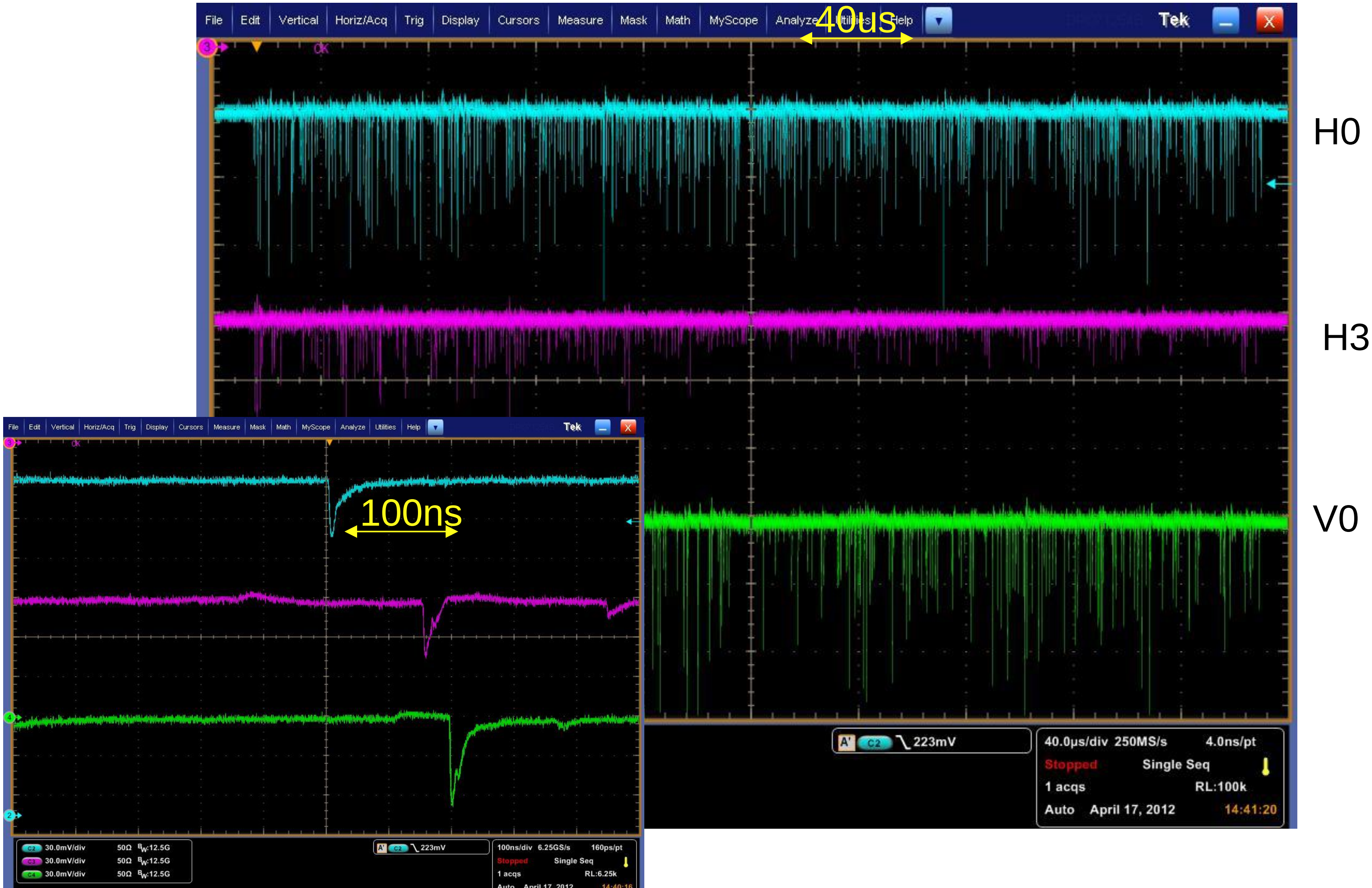


Data acquisition system

- Long signal and HV cables (~20m) from the accelerator tunnel to electronics crates in Klystron Gallery
- Charge of raw signals measured with QDCs (CAEN V792)
- Timing of discriminated signals measured with TDCs (CAENV785)
- Data collected with a VME controller (GEFunac XVB601)
  - 25Hz data acquisition rate



Fiber signals



H^- interaction position vs H^0 hit position

- H^0 generated by H^- interacted with remnant gas collide with the beam duct at 20-40 m downstream from the interaction point
- The reason of more upstream interactions are due to decrease of、$H^- \rightarrow H^0$ cross section as a function energy
- At the 3 connection points of smaller to larger ducts, loss is small
- Protons, neutrons, electrons and positrons are produced from H^0 interaction with the duct
- Protons and neutrons are produced most