高統計ラムダ陽子散乱のためのビームTOF用読み出しシステムの開発

Contents
- Physics motivation
- Aim of this GRANT
- CDCM
- Summary

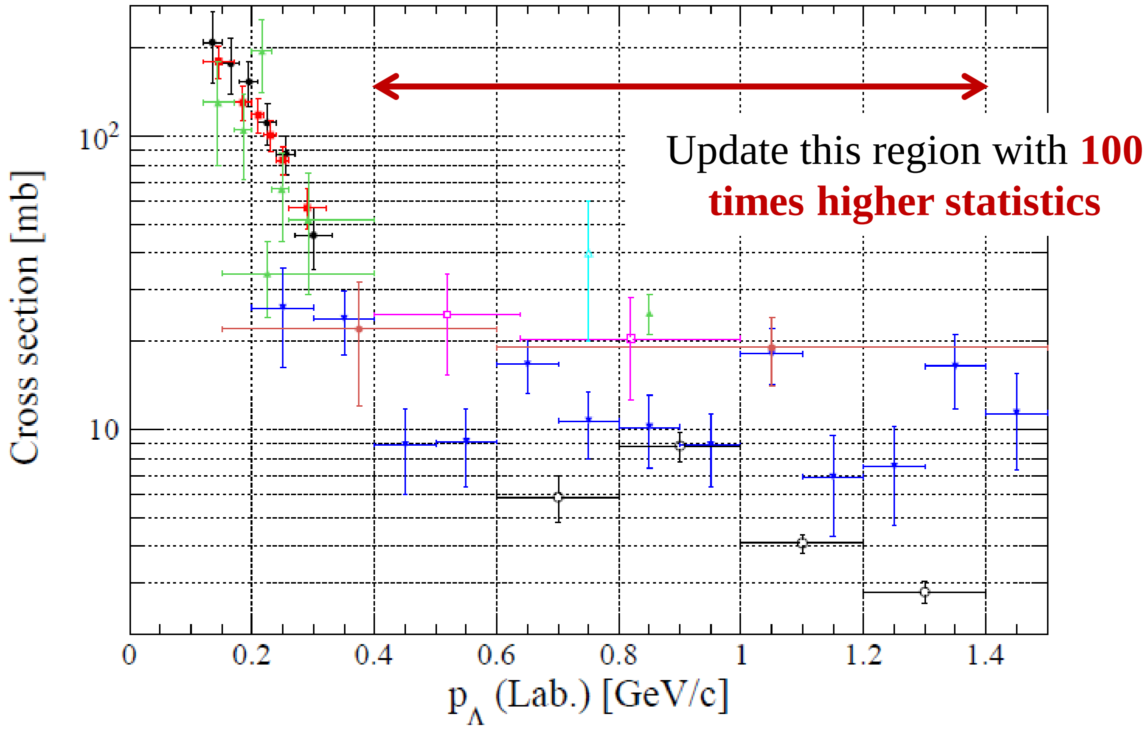
KEK素核研 E-sys
本多良太郎

2021.06.14
新学術領域研究「量子クラスターで読み解く物質の階層構造」
第6回クラスター階層領域研究会

Introduction

Overview of this experiment

Total cross sections of $\Lambda p \rightarrow \Lambda p$ measured so far.



Our aim

Measure precisely the cross sections of Λp scatterings in the momentum range between 0.4 and 1.4 GeV/c

100 times higher statics of past experiments for

- **Total cross section**
- **Differential cross section**

for each 0.1-GeV/c momentum region

Study of two-body ΛN interaction by **scattering experiment**

Approach to the hyperon puzzle of neutron star

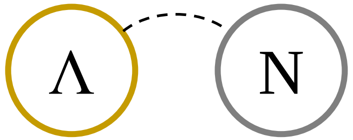
Collaborate with

- B01 ストレンジ・ハドロンクラスター
- A02 クォーククラスター

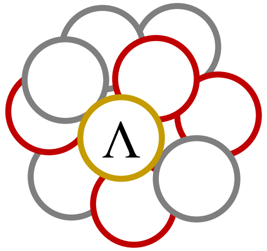
[1] Phys Rev 175, 1735 (1968).
[2] Phys Rev Lett. 13, 282 (1964).
[3] Phys Rev. 173, 1452 (1968).
[4] Nucl. Phys. B27, 13 (1971).
[5] Phys Rev. 129, 1372 (1963).
[6] Phys. Rev. Lett. 7, 348 (1961).
[7] Phys. Rev. Lett. 2, 174 (1959).
[8] J. Rowley, K. Hicks, and John Price, Talk in 52nd Reimei workshop.

Introduction

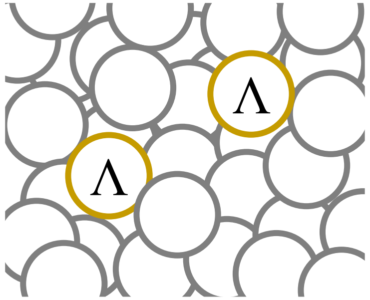
Two-body
ΛN interaction



Λ Hypernuclei



Neutron star



Constructed by
scattering data
at the dawn.

Explain

Hypernuclear calculation

Constraint

Biding energy.
Level spacing.
Decay mode.

2⊙ mass
neutron star

Hyperon puzzle

Lack of data.

Not precise enough to discuss many-body effect from hypernuclei data.

Impede

Trying extract many-body force.

J-Lab

HIHR

Support massive
neutron star

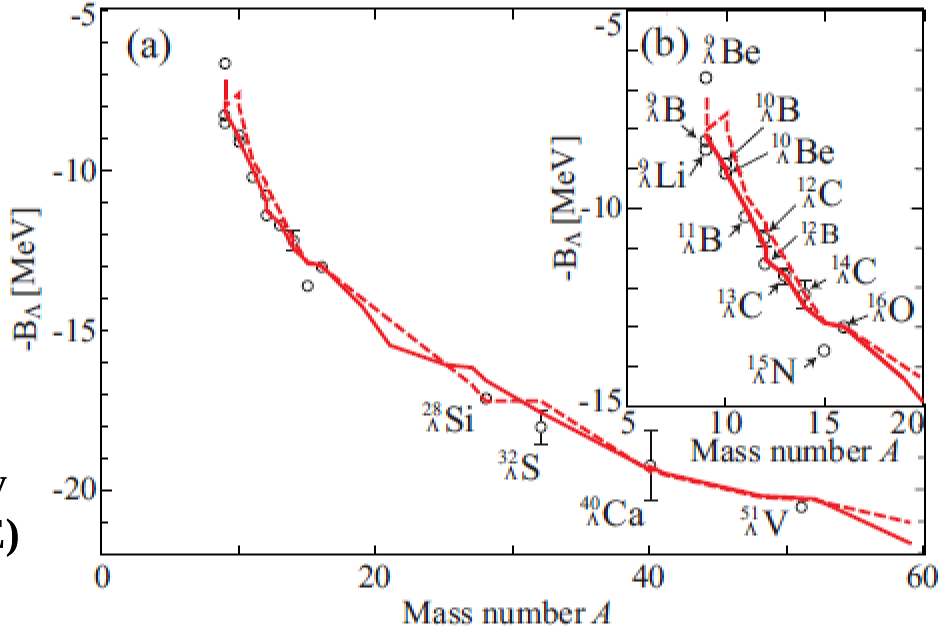
ΛN interaction and hypernuclei

Authors reproduced experimental data using

ΛN interaction
(Nijmegen models)
+
Multi-pomeron exchange potential (MPP)
+
Phenomenological three-body attraction (TBA)

Many-body effect (MBE)

Comparison between experimental data and Hyper-AMD calculation.



M. Isaka et al., PRC95, 044308 (2017)

They discussed the room to add extra repulsion caused by MBE.

ΛN interaction and hypernuclei

Authors reproduced experimental data using

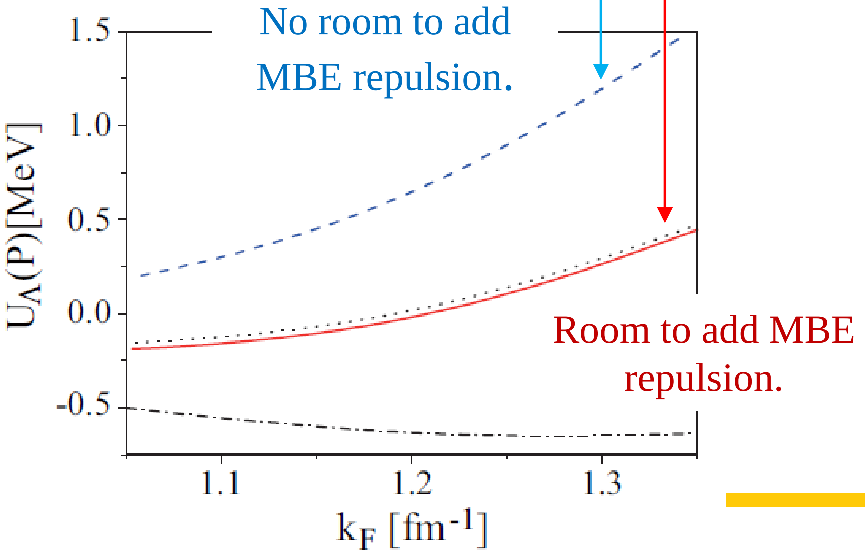
ΛN interaction
(Nijmegen models)
+
Multi-pomeron exchange potential
(MPP)
+
Phenomenological three-body attraction
(TBA)

U_Λ from G-matrix calculation
(and *S*-state and *P*-state contribution.)

	U_Λ	$U_\Lambda(S)$	$U_\Lambda(P)$
ESC08a	−40.6	−39.5	+0.5
ESC08b	−39.4	−37.0	−0.6
ESC14	−40.8	−39.6	+0.4
ESC12	−40.0	−40.0	+1.5
ESC04a	−43.2	−38.4	−3.7
NSC97e	−37.7	−40.4	+4.0
NSC97f	−34.8	−39.1	+5.6

M. Isaka et al., PRC95, 044308 (2017)

k_F dependence of U(P)



ΛN interaction and hypernuclei

Authors reproduced experimental data using

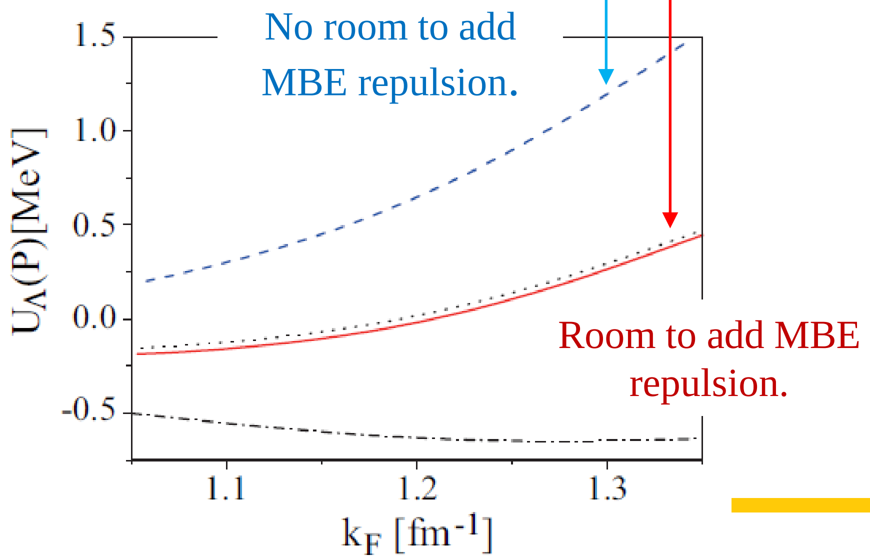
ΛN interaction
(Nijmegen models)
+
Multi-pomeron exchange potential (MPP)
+
Phenomenological three-body attraction (TBA)

U_Λ from G-matrix calculation
(and *S*-state and *P*-state contribution.)

	U_Λ	$U_\Lambda(S)$	$U_\Lambda(P)$
ESC08a	−40.6	−39.5	+0.5
ESC08b	−39.4	−37.0	−0.6
ESC14	−40.8	−39.6	+0.4
ESC12	−40.0	−40.0	+1.5
ESC04a	−43.2	−38.4	−3.7
NSC97e	−37.7	−40.4	+4.0
NSC97f	−34.8	−39.1	+5.6

M. Isaka et al., PRC95, 044308 (2017)

k_F dependence of U(P)



Present scattering data cannot solve this *P*-state (wave) uncertainty.

This is a quite important rising a problem to the ΛN interaction.

Experimental setup

Double scattering experiment.

- $\pi^- p \rightarrow K^*(892)^0 \Lambda$, $K^*(892)^0 \rightarrow K^+ \pi^-$
- $\Lambda p \rightarrow \Lambda p$

Beam condition

- Intensity: 60 M/spill
- Momentum: 8.5 GeV/c

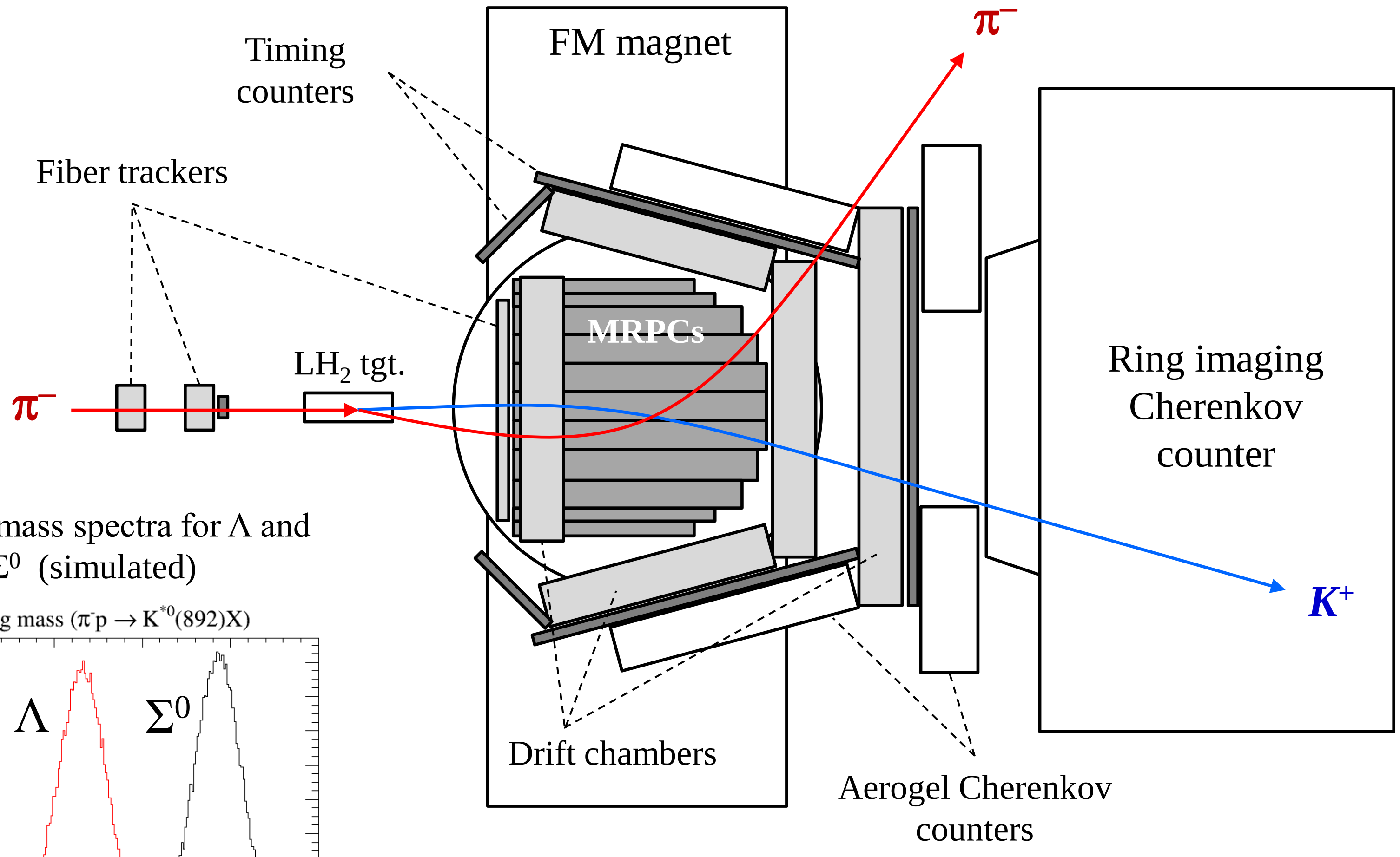
Experimental target

- Liquid hydrogen
- 100 mm in diameter
- 570 mm in length

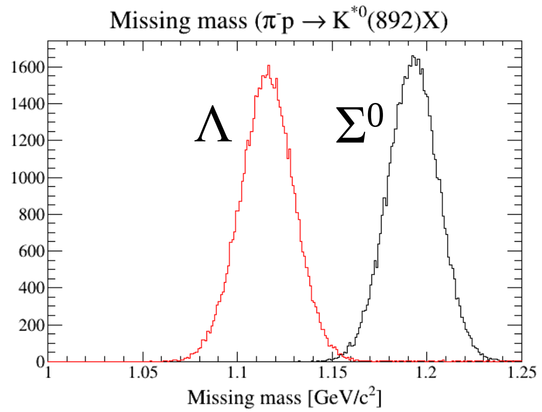
Spectrometer system

- Missing mass resolution $16\ \mathrm{MeV}/c^2$
- Reconstruction efficiency 66%

Experimental setup of the J-PARC E50 experiment.
(Charmed-baryon spectroscopy)



Missing mass spectra for Λ and Σ^0 (simulated)



Overview of this experiment

Double scattering experiment.

- $\pi^- p \to K^*(892)^0 \Lambda$, $K^*(892)^0 \to K^+ \pi^-$
- $\Lambda p \to \Lambda p$

Beam condition

- Intensity: 60 M/spill
- Momentum: 8.5 GeV/c

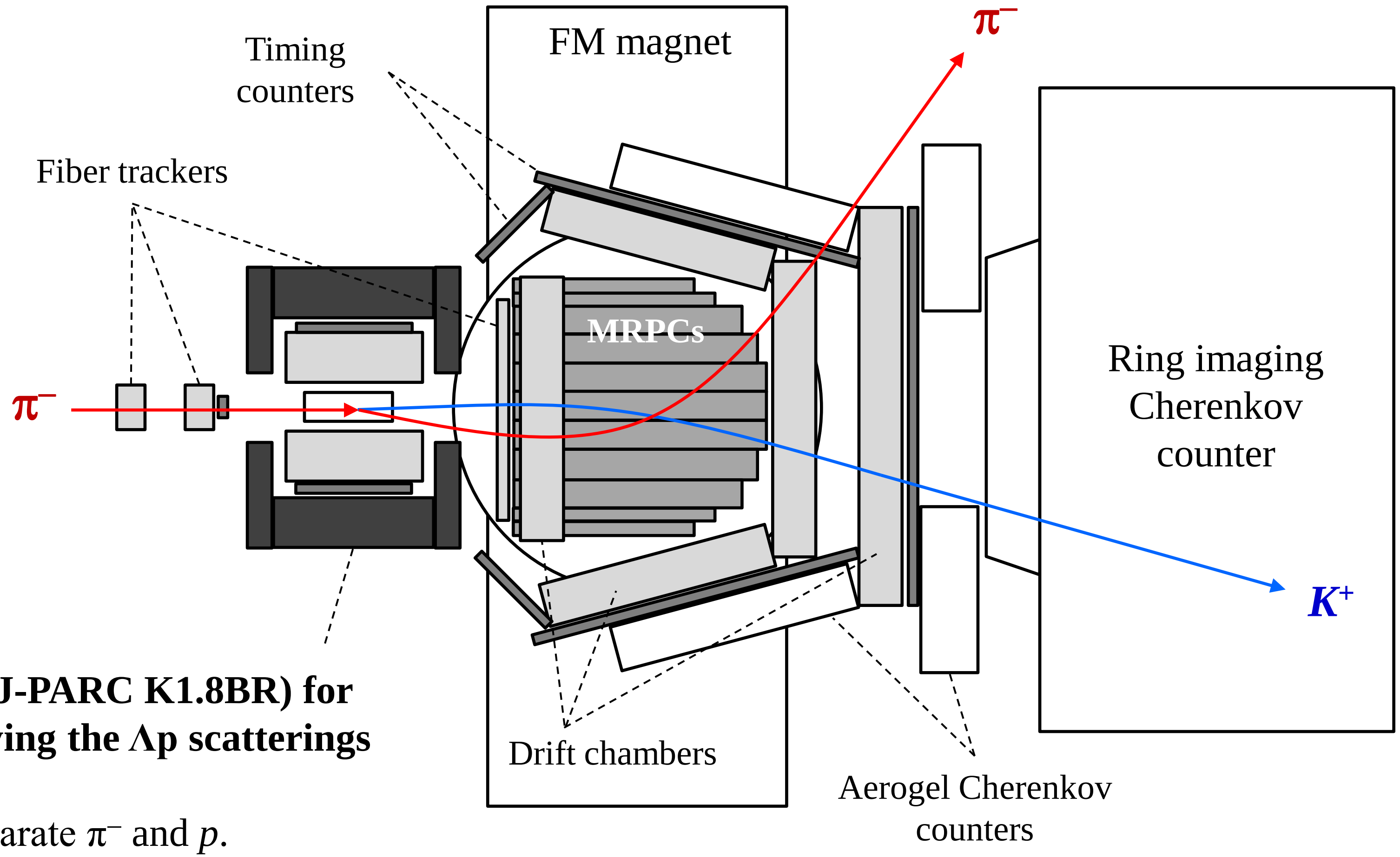
Experimental target

- Liquid hydrogen
- 100 mm in diameter
- 570 mm in length

Spectrometer system

- Missing mass resolution 16 MeV/c^2
- Reconstruction efficiency 66%

Experimental setup of the J-PARC E50 experiment.
(Charmed-baryon spectroscopy)



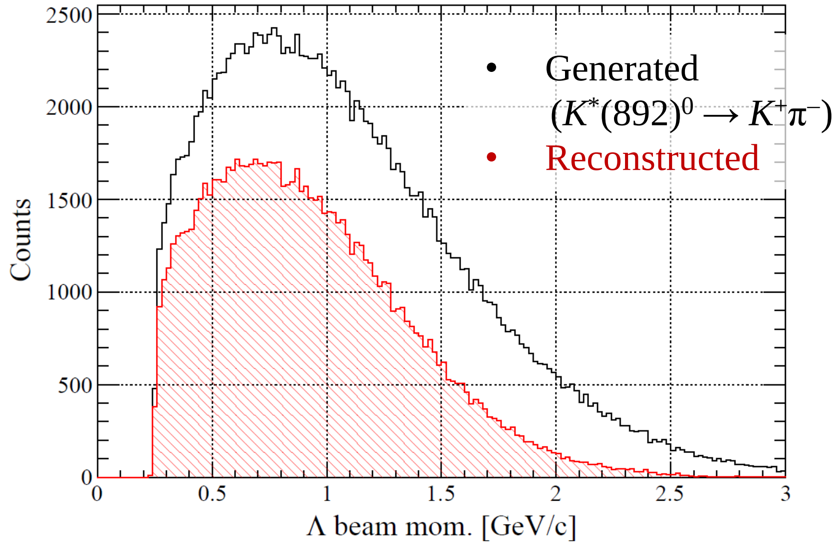
CDS (J-PARC K1.8BR) for identifying the Λp scatterings

Requirements

- PID to separate π^- and *p*.
- Momentum analysis to reconstruct Λ.

Reconstruction efficiency

Momentum distribution of the Λ beams (simulated)

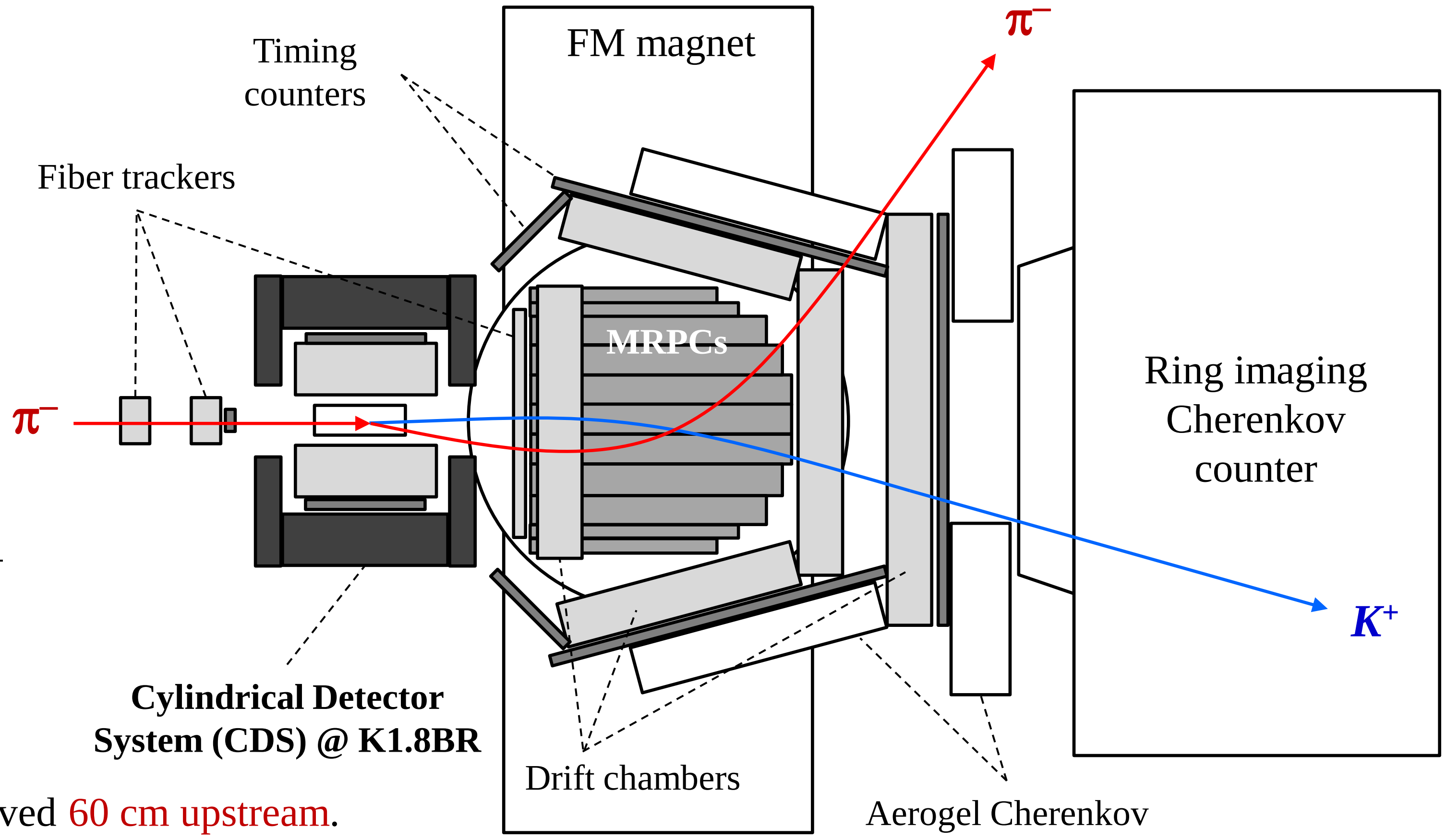


***Angular distribution of the $\pi^- p \rightarrow K^*(892)^0\Lambda$ reaction is taken into account

Reconstruction efficiency for $K^*(892)^0 \rightarrow K^+\pi^-$

66%

Experimental setup of the Λp scattering experiment



Beam detectors and the target are moved 60 cm upstream.
The target is moved 20 cm upstream from the center of CDS.
End guard hole size 30 mm (φ) → 40 mm (φ)

Acceptance of CDS for the Λ scattering

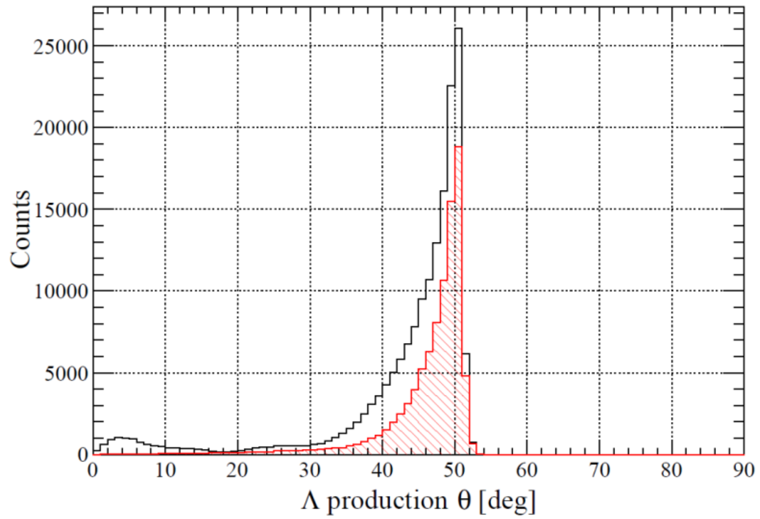
Procedure to identify the Λ*p* scattering

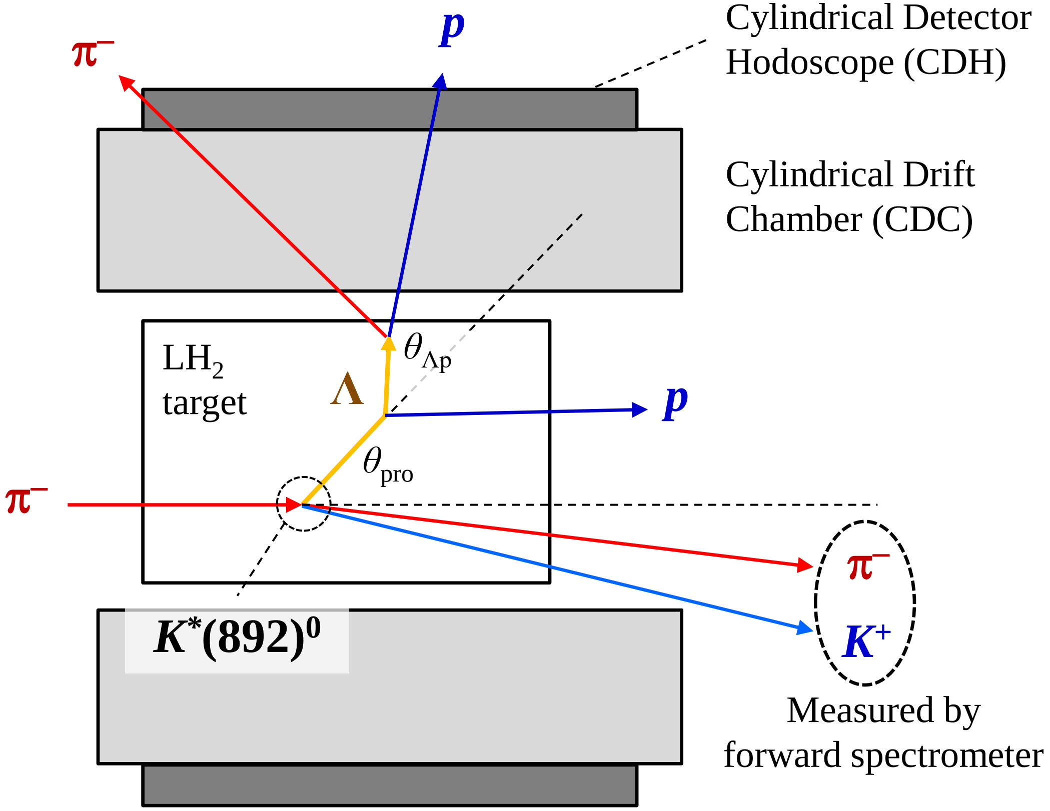
- Momentum vector of initial Λ — Known
- Momentum vectors of
  - Scattered proton
  - Scattered Λ

  } Measure either
- Scattering angle, $\theta_{\Lambda p}$, is obtained.

Check whether these vectors satisfy the Λ*p* scattering kinematics.

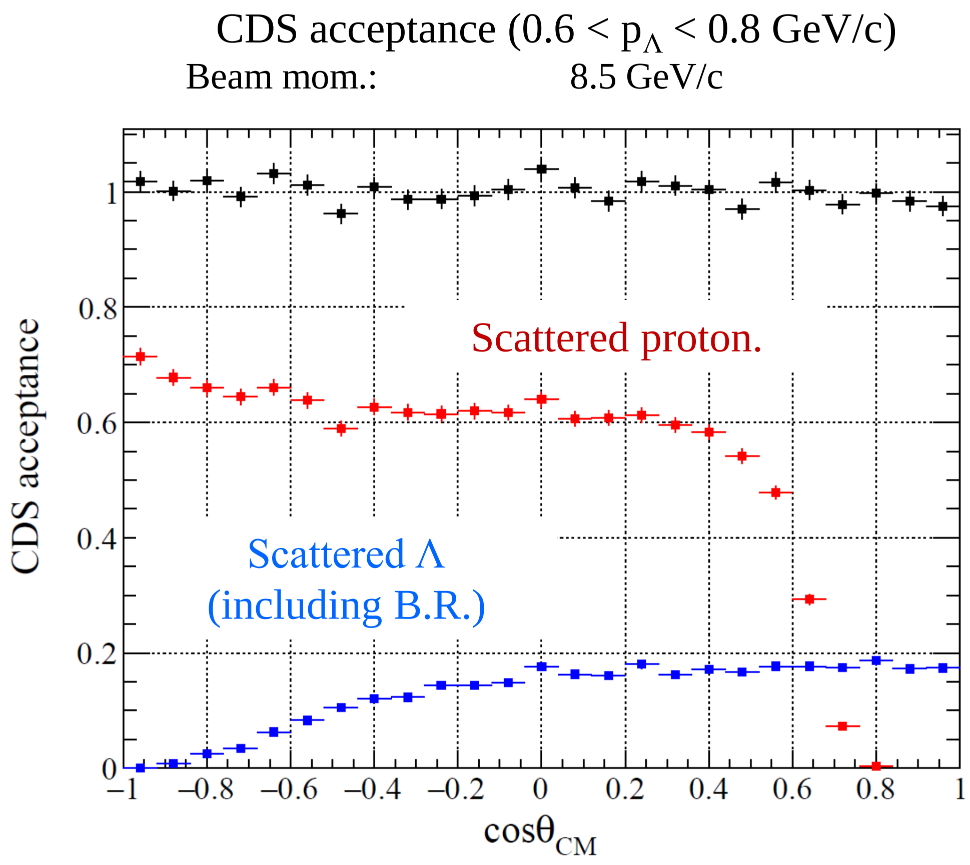
Distribution of the production angle, θ_{pro}.



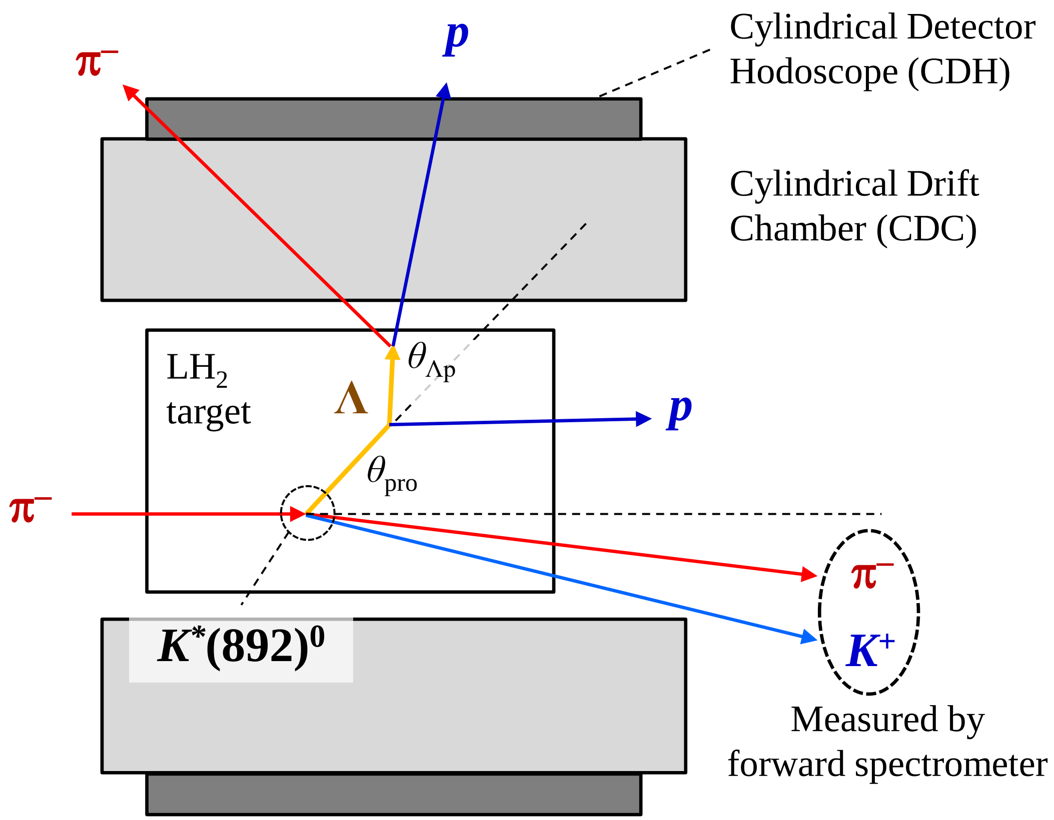


Event topology of the Λ*p* scattering
Decay products from the scattered Λ are detected.

Acceptance of CDS for the Λ scattering



All the region of $\cos\theta_{CM}$ is covered by CDS



Event topology of the Λp scattering
Decay products from the scattered Λ are detected.

Yield estimation of the Λp scattering events

The number of the Λp scattering events happened in the target.

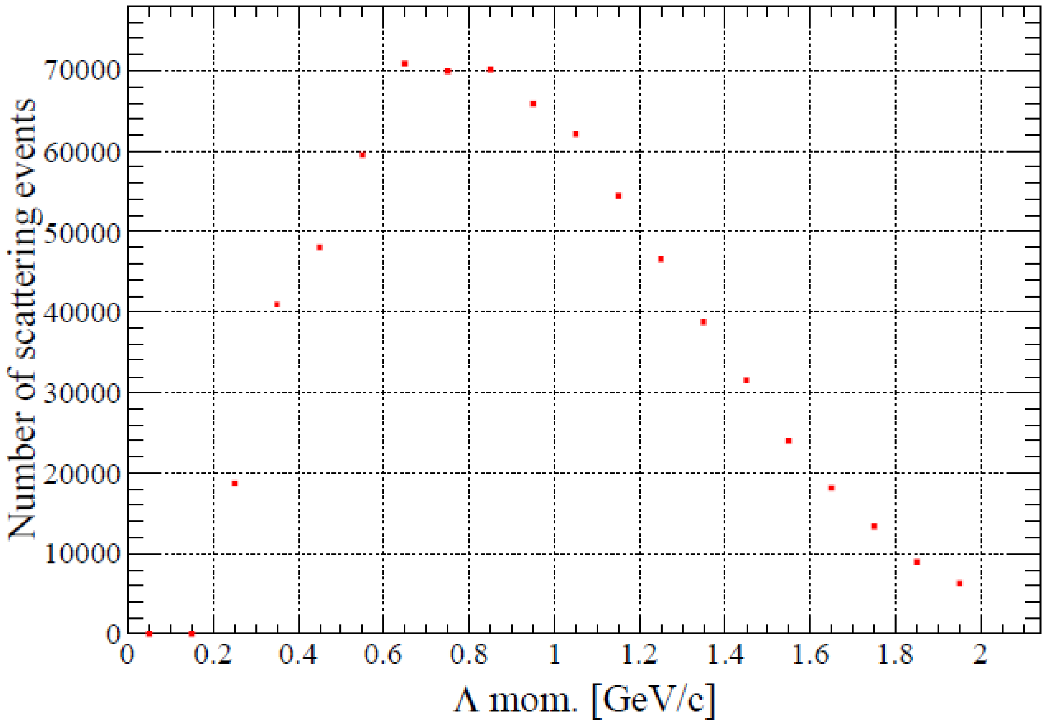
- 3900 events per 1 million Λ beams (Assume σ = 20 mb)

Assume

- CDS acceptance shown in prev. page.
- CDC tracking efficiency of 0.7

At least, 10 new data points between $0.4 < p_{\Lambda} < 1.4$ GeV/c will be obtained in this experiment.

Yields of the Λp scattering events as a function of the Λ beam momentum (30-day beam time)



Aim of this Grant

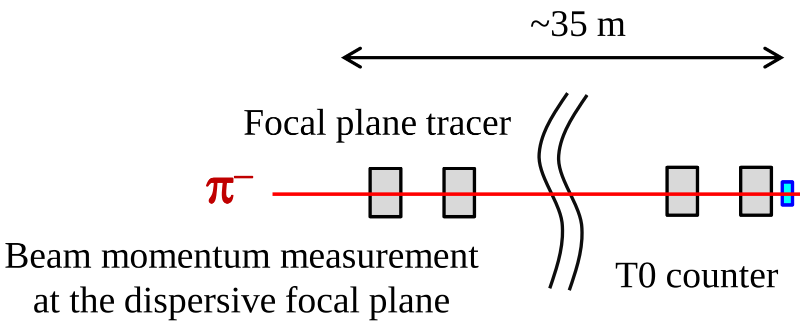
Detector system of the E50 experiment

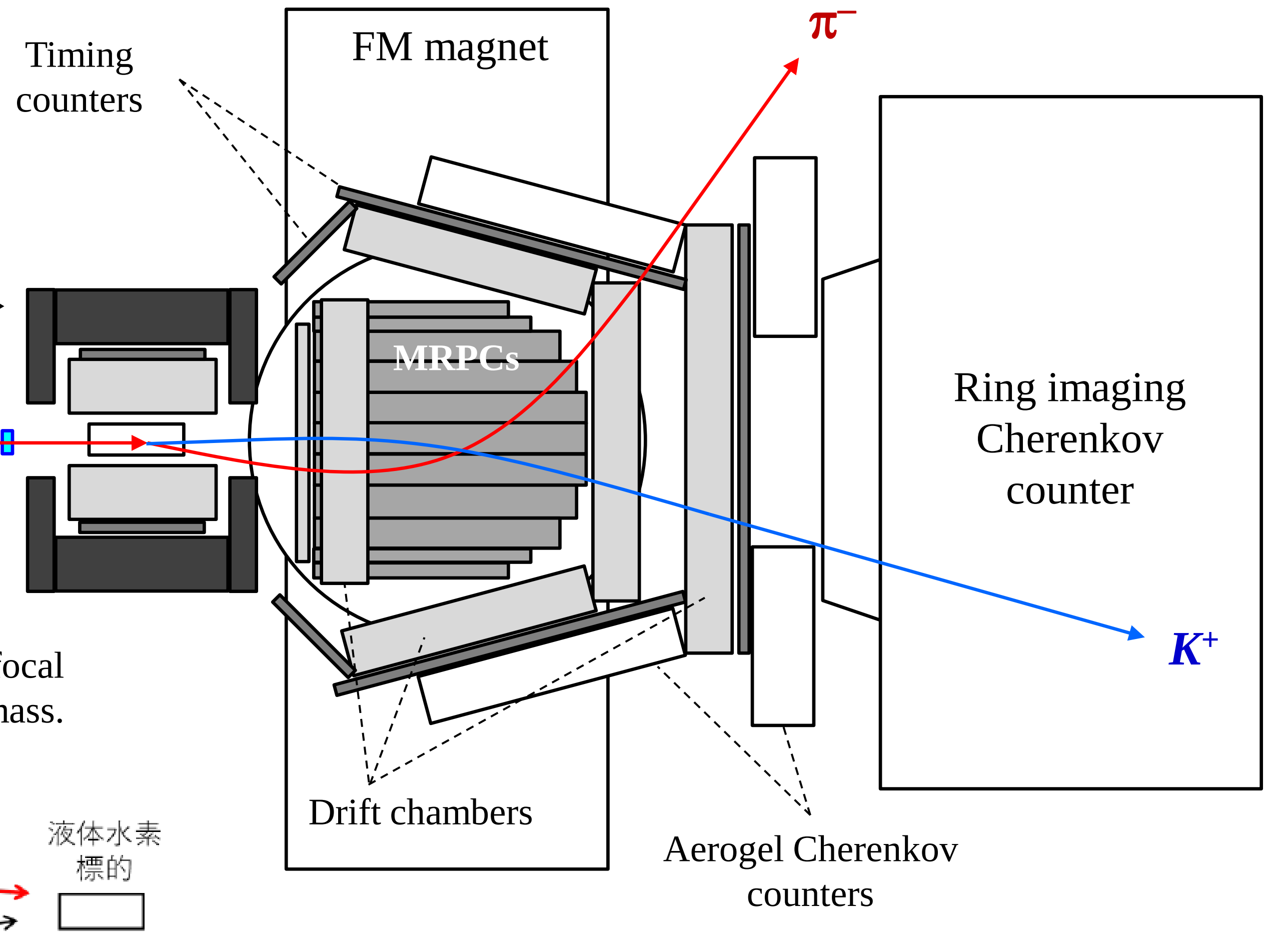
Probability of finding 2 particles in a 10 ns bin.
(Effect of transverse-RF is roughly taken into account)

- $p \sim 0.27$

These two are not distinguishable for the fiber detector having the timing resolution ~1ns.

Experimental setup for the Λp scattering





We need to connect the tracks at the dispersive focal plane and at the target to calculate the missing mass.

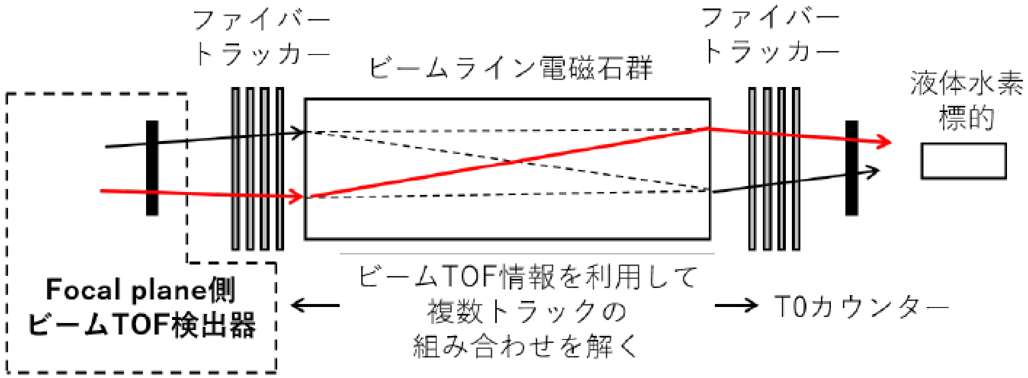
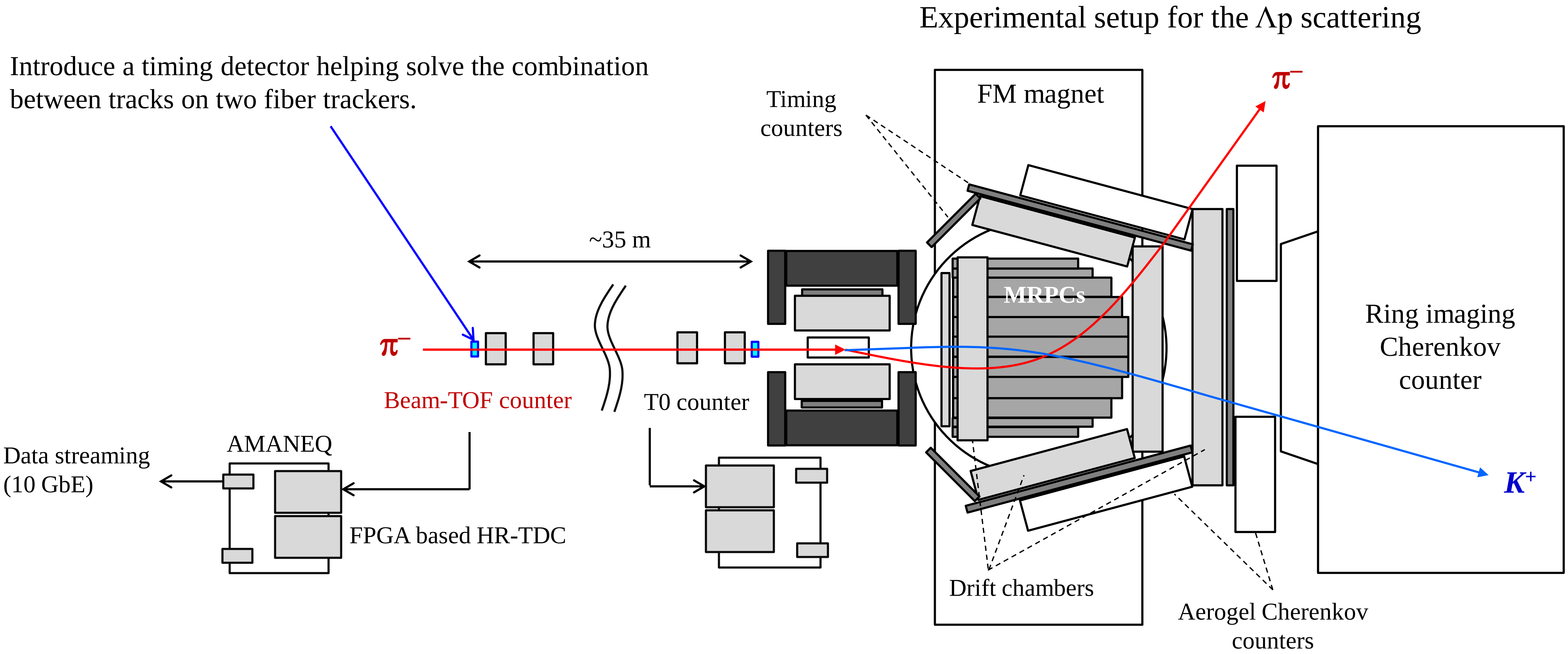


図1：ビーム運動量測定の概略図

Detector system of the E50 experiment

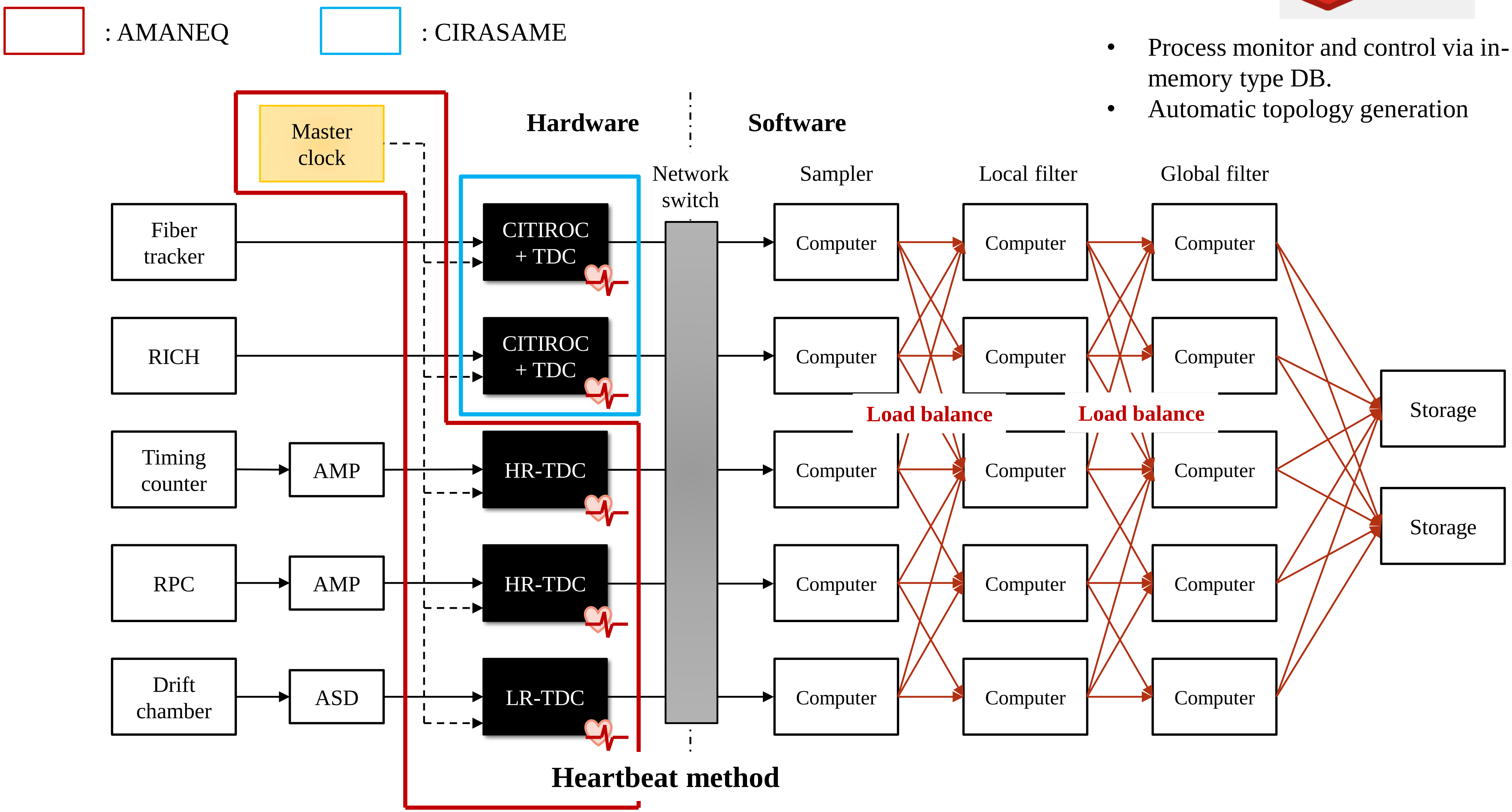
Introduce a timing detector helping solve the combination between tracks on two fiber trackers.



Trigger-less DAQ system of the E50 experiment

FairMQ + redis

- Process monitor and control via in-memory type DB.
- Automatic topology generation



Aim of this Grant

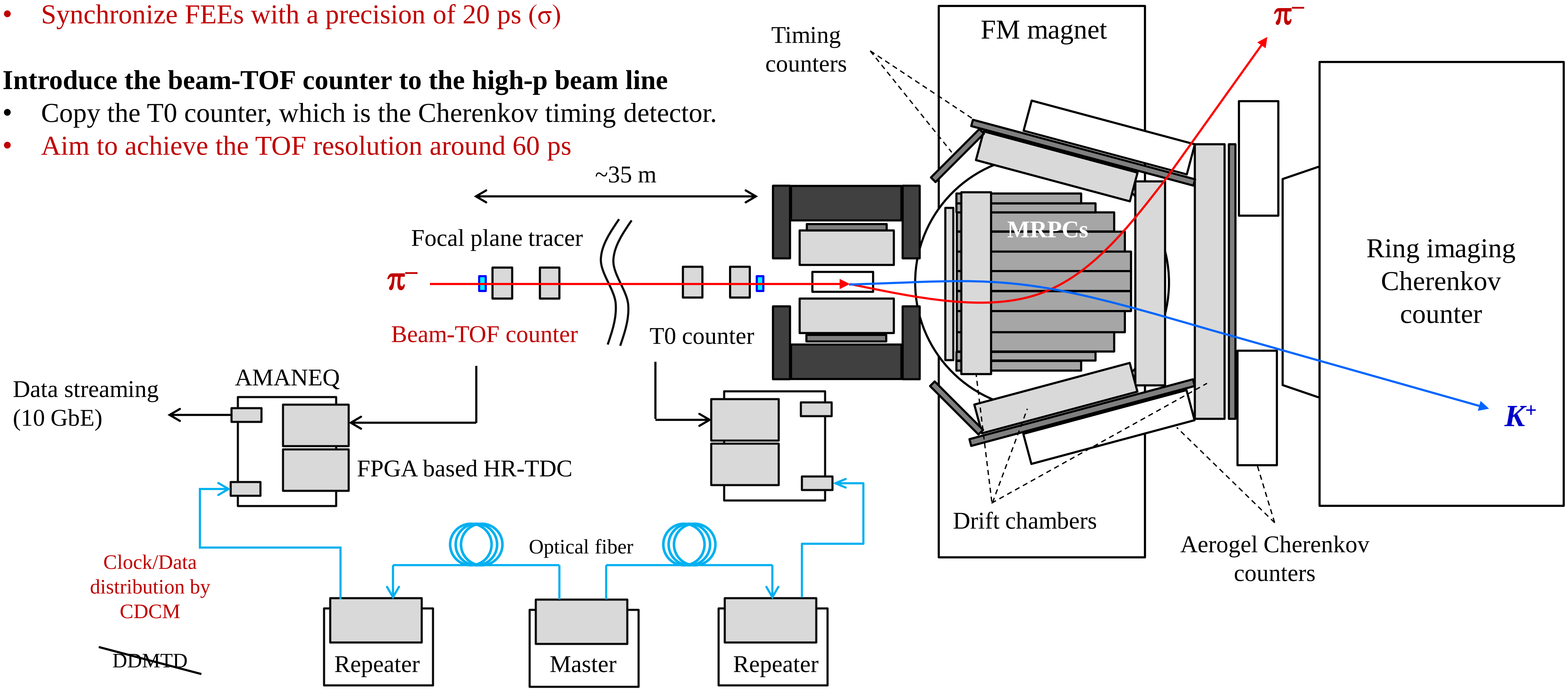
Develop the clock/data distribution system using AMANEQ

- Adopt Clock-Duty-Cycle-Moduration
- Synchronize FEEs with a precision of 20 ps (σ)

Introduce the beam-TOF counter to the high-p beam line

- Copy the T0 counter, which is the Cherenkov timing detector.
- Aim to achieve the TOF resolution around 60 ps

Experimental setup for the Λp scattering



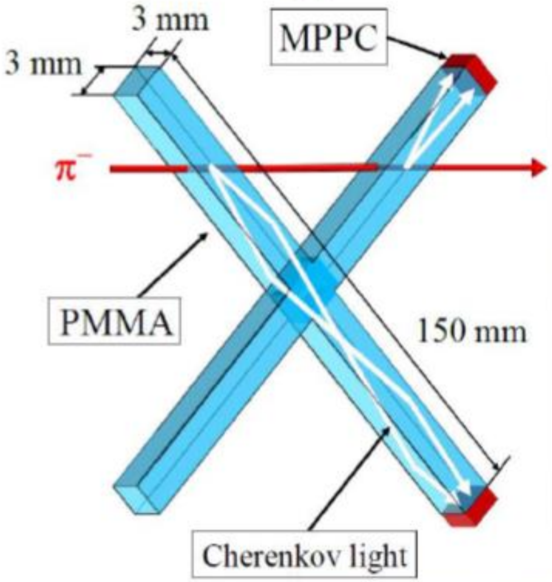
Clock/command distribution system by AMANEQ

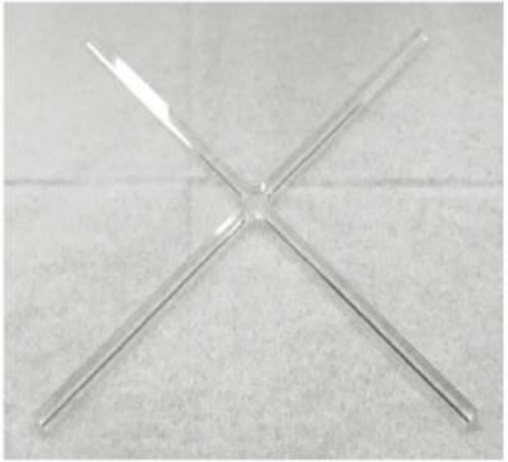
Taken from the slide,
K. Shirotori
In E50 collaboration meeting on Oct. 2020.

T0 detector: Acrylic Cherenkov timing detector

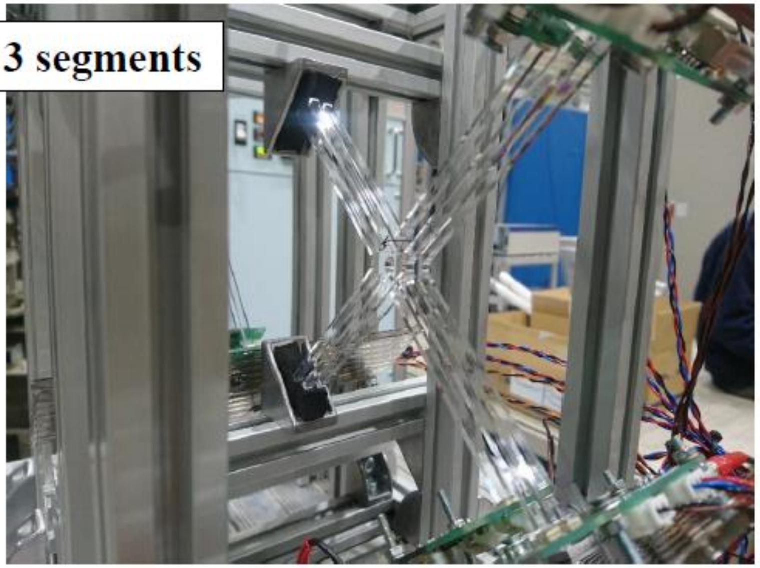
- **Radiator: Acrylic (PMMA)**
  - **Cross shape: X-type**
    - **3 mm× 3 mm cross section**
    - **150 mm length**
- **Photon sensor: MPPC**
  - **Hamamatsu S13360-3050PE**
    - **3 mm size, 50 μm pixel**
- **MPPC amplifier**
  - **AD8000 operation amp**
    - **Narrow width: ~10 ns**
- **Silicorn sheet btw PMMA and MPPC**
  - **~0.1 mm thickness with glue for fixing**
  - **Reflection index: n=1.405**

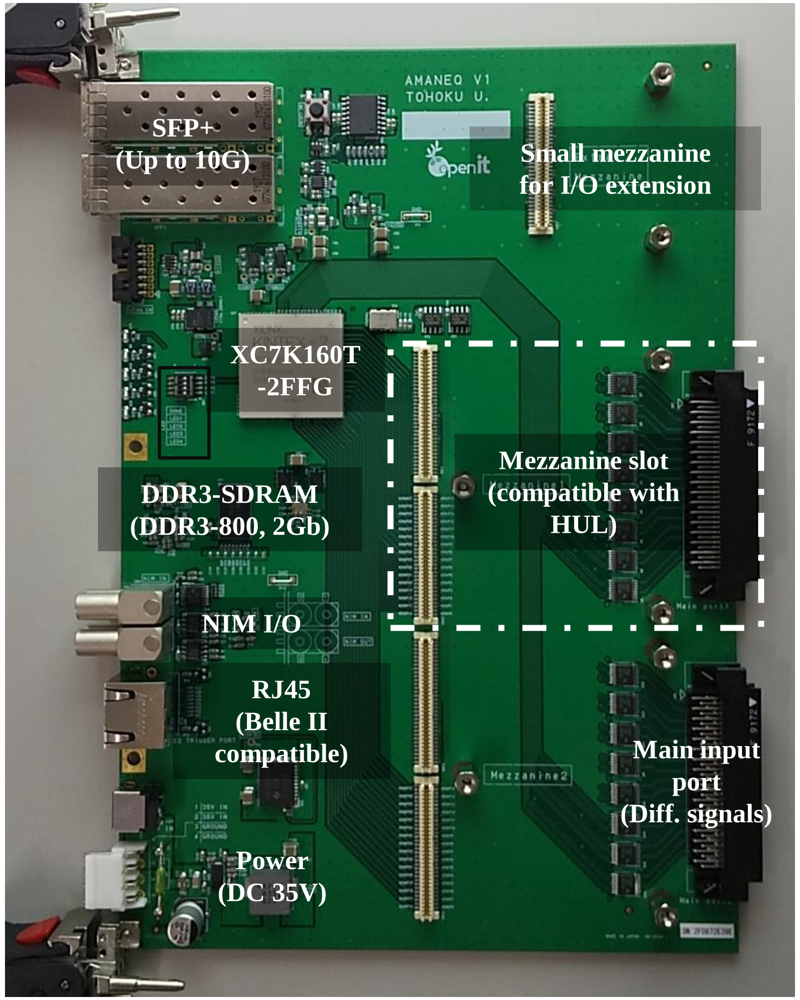
＊Time resolution: ΔT ~ 40 ps(rms)
- **Intrinsic: 30 ps + TDC: 20 ps**
  - **> 3 MHz counting rate**
  - **No position dependence**





Test detector: 3 segments





A main electronics for
network oriented trigger-less data acquisition system
(AMANEQ)

- VME 6U size but it doesn't have VME bus
- Kintex7 with speed grade -2
  - Can implement 10G SiTCP (SiTCP-XG)
- Main input ports compatible with HUL
- Has two mezzanine slots
  - Compatible with HUL
- Belle II link port (master clock)
  - Has a jitter cleaner to clean up the master clock
- DDR3-SDRAM as a de-randomizer
  - DDR3-1333 with 16-bit bus width.
  - 2 Gb
- Powered by the external power supply with DC 35V

Develop a mezzanine to distribute the modulated clock.
Develop a small mezzanine to receive the modulated clock.

FPGA based high-resolution TDC

A mezzanine card for
HUL/AMANEQ

Tapped-delay-line type high-resolution TDC using FPGA CARRY elements

Timing resolution: 20 ps (σ)
Built-in calibration LUT
Leading and trailing edges measurement

Common-stop type multi-hit TDC
- TDC range: 15.6 μs
- 16 hits/ch

Re-make this FW as a data streaming type HR-TDC

CDCM

Principle of CDCM

Precise clock distribution is a key issue for many particle and nuclear experiments.

Typical requirements

- Low jitter (a few tenth ps)
- Synchronous data with predictable latency (trigger in typical)
- Controllable phase of the recovered clock
- Distribute a clock over meters to kilo-meters
- As few transmission lines as possible

Usual solution

\+ 8b10b modulation + FPGA high-speed serial transceiver (e.g. Xilinx GT transceivers)

It actually works well, but

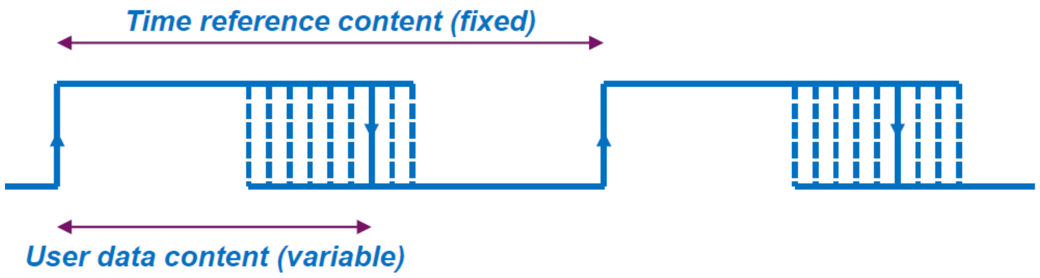
- Strongly depends on FPGA built-in blocks.
  - CDR circuit is not an user primitive.
  - Some of them are black boxes.
- Need a special electronics dedicated for distributing clock/data via serial transceivers.

Develop a serial transceiver independent clock/data distribution system

Principle of CDCM

Adopting clock-duty-cycle-modulation (CDCM) as a core technology

- CDCM is a data-on-clock type modulation. (8b10b is a clock-on-data type)
- Data bits are embedded to the trailing edges of the clock signal.



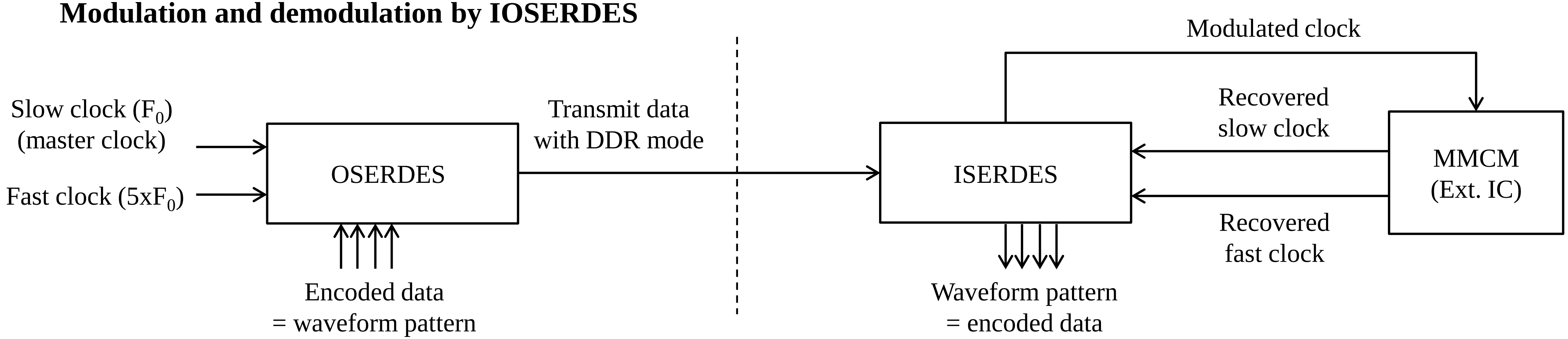
Denis Calvet,
IEEE TNS (Volume: 67, Issue: 8, Aug. 2020)

Advantages

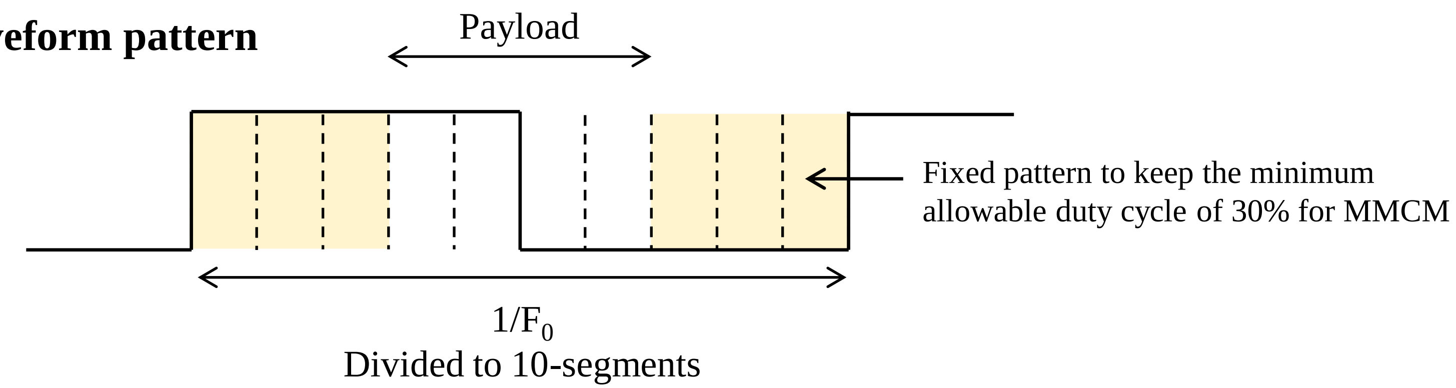
- This modulated clock can be directly input to PLLs and MMCMs in FPGA and external jitter cleaner ICs.
  - Because the leading edge is used by the phase detector to control VCO, but the trailing edge is not.
- Output clock skews from MMCMs respect to the input modulated clock are automatically adjusted by using the global clock network in FPGA.
  - Automatic phase alignment among front-end electronics.
  - Recovered clock by MMCM can give a phase reference for a clock from the external PLL, which does not have a zero-delay mode.

Principle of CDCM

Modulation and demodulation by IOSERDES



Waveform pattern



CDCM-10-2.5
CDCM-10-1.5
are realized by IOSERDES

*0.5 means idle pattern
Naming rule is defined in Ref. [1]

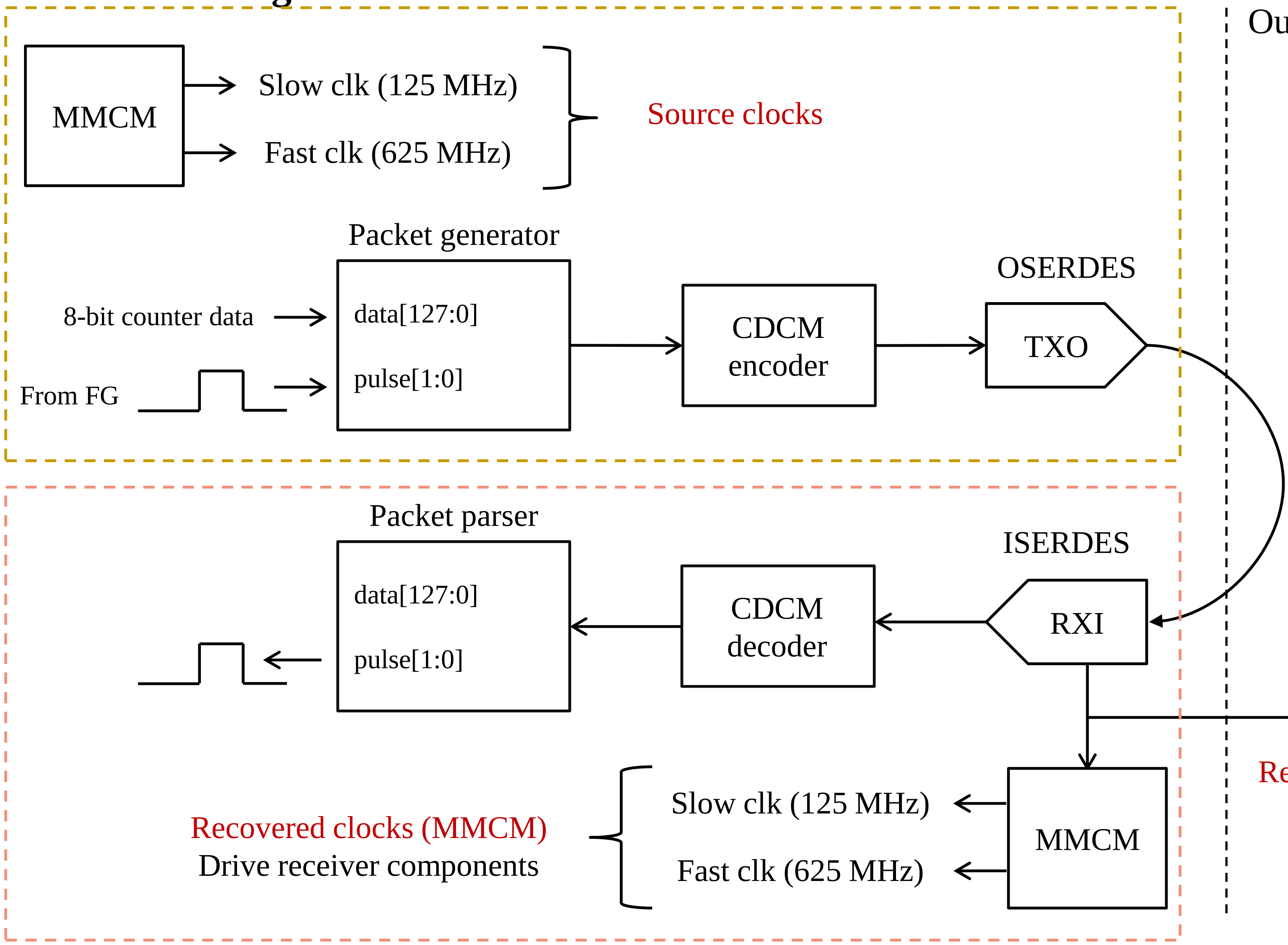
For skew adjustment between slow and fast clocks, the global clock buffer is necessary.

- Maximum transferrable frequency: 125 (142) MHz due to the limitation of the BUFG performance.
- For g-2/EDM experiment, distribute the 100 MHz clock and generate synchronous 200 MHz clock on FRBS.

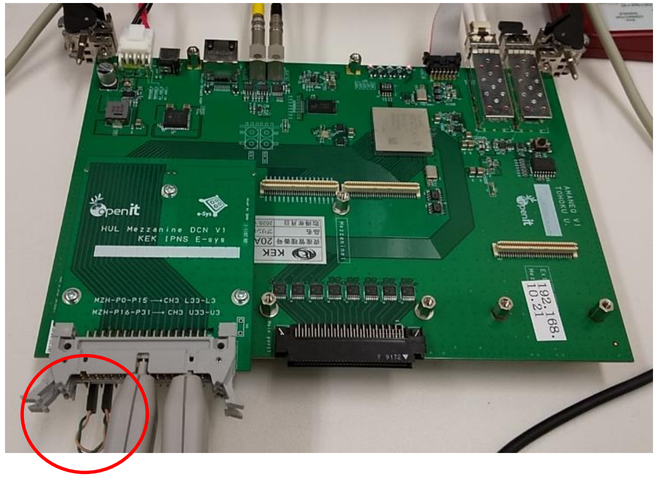
[1]. D. Calvet, IEEE TNS (Vol67, Issue8, Aug. 2020)

Test configuration

Test configuration



Outside of FPGA



At preset, I don't have two AMANEQs.
I tested them by making loop-back.

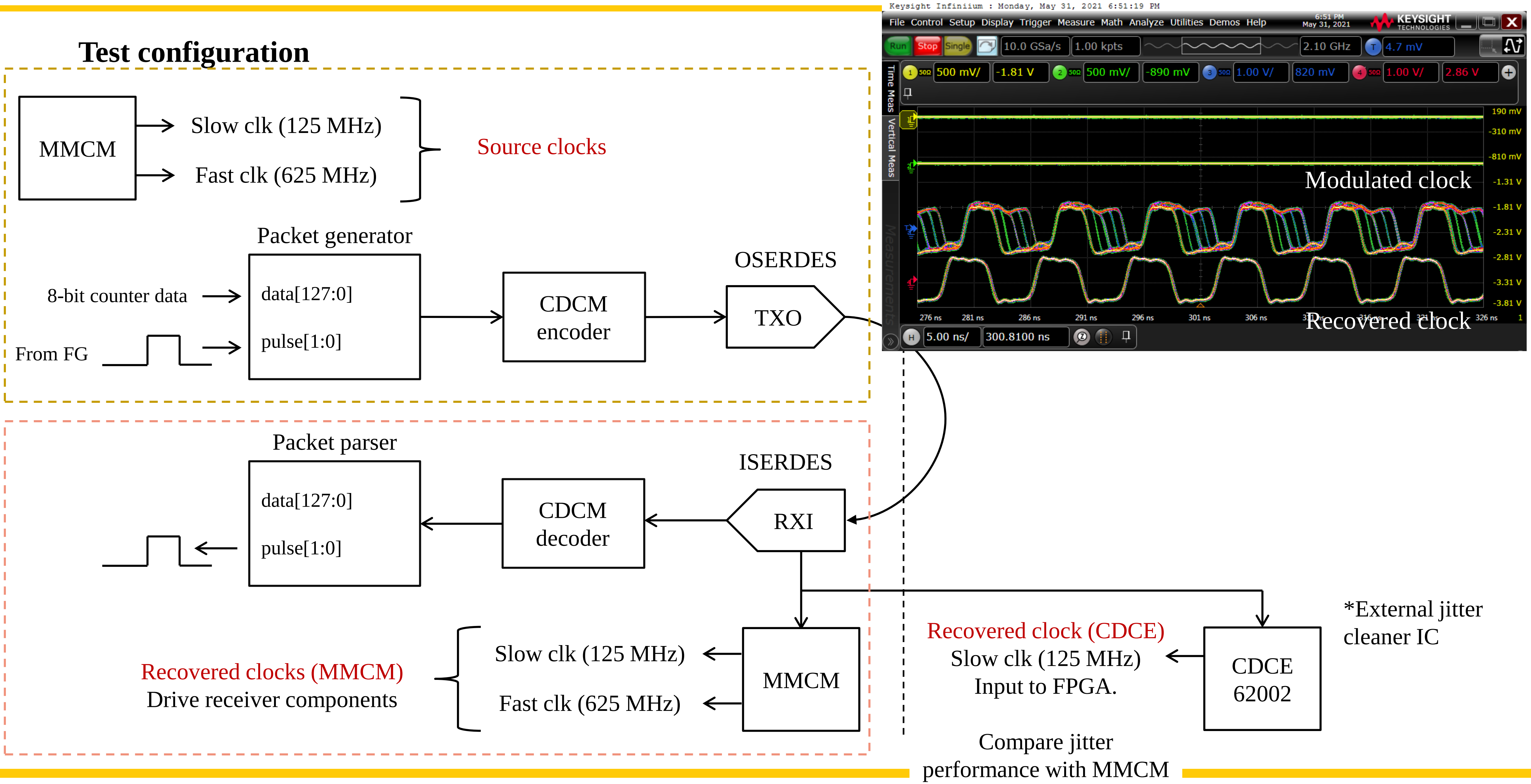
Recovered clock (CDCE)
Slow clk (125 MHz)
Input to FPGA.

CDCE
62002

*External jitter
cleaner IC

Compare jitter
performance with MMCM

Test configuration



Schedule

	2019.04-09	2019.10-2020.03	2020.04-09	2020.10-2021.03
Development of CDCM transceiver	*Complete*			
Development of communication protocol				
Prototyping mezzanine card with optical modules		*Complete*		
Development of actual mezzanine cards				
Develop the data streaming type HR-TDC				
Test clock/data distribution system	We are here			
Fabricate beam-TOF counter				Beam test @ ELPH
Combine and test all the system				
Analysis				

Summary

Physics motivation

- Precision of present two-body ΛN interaction is not enough to discuss the existence of the extra repulsion caused by many-body force.
- Determination of partial wave phase shift is necessary.

A plan of the Λp scattering experiment at the high-p beam line.

- Produce Λ via $\pi^- p \rightarrow K^{0*}(892)\Lambda$
- Measure and identify Λ production by the forward spectrometer in the J-PARC high-p beam line.

Aim of this Grant: Introducing beam-TOF counter to the high-p beam line.

Develop the clock/data distribution system using clock-duty-cycle-modulation

- Synchronize front-end electronics with a precision of 20 ps (σ)

Develop the data streaming type FPGA high-resolution TDC.

Fabricate the Acryl based Cherenkov detector, which is identical to the T0 counter of the E50 experiment.

- Aim to achieve the TOF resolution of 60 ps (σ)