DEVELOPMENT OF LARGE ACCEPTANCE SPECTROMETER FOR SYSTEMATIC STUDY OF KAONIC NUCLEI AT J-PARC

Takuya Nanamura for the J-PARC E80 and P89 collaboration

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- Successful "K^-pp" search experiment (J-PARC E15 experiment)
- Upgrade plan of J-PARC K1.8 BR beamline and spectrometer system for systematic study of kaonic nuclei
- Proposed physics programs with upgraded experimental setup
  - *Search for KbarNNN via $^4He(1\ GeV/c\ K^-,n)$ reaction*
    - J-PARC E80 experiment
  - *Investigation of the spin and parity of the KbarNN state*
    - J-PARC P89 experiment
- Design and development status of detectors composing the new spectrometer system(CDS)
- Detectors composing the K1.8 BR beamline

KbarN interaction

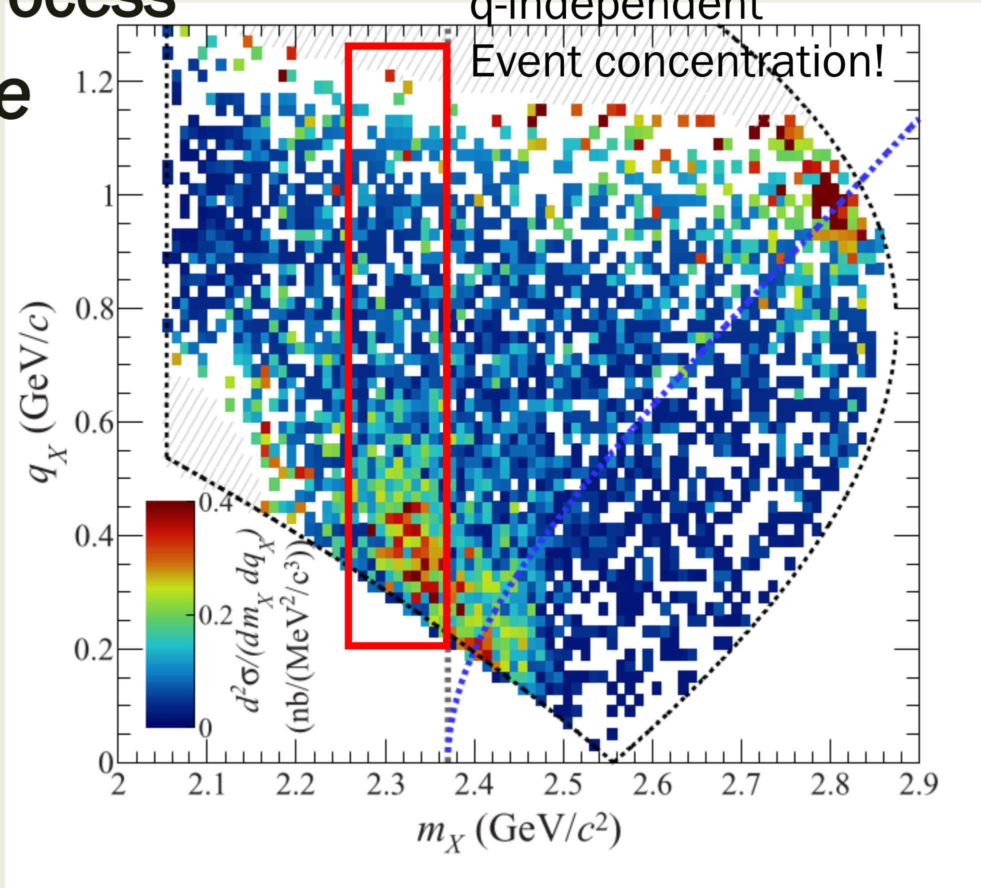
- Important subjects to understand meson-baryon interactions in low-energy QCD
- Attractive KbarN (I=0) interaction
  - *Specific property of KbarN interaction*

    ⇔πN interaction is repulsive in S-wave
  - *Λ(1405) can be interpreted as a quasi-bound state of KbarN*
  - *The lightest Kaonic nuclei: "K^-pp"*
    - Many experiments tried to establish the existence
      - *However, various results have been reported.*
      - *Positive: FINUDA@DAFNE, DISTO@SATURNE, E27@J-PARC*
      - *Negative:AMADEUS@DAFNE, HADES@GSI, LEPS@SPring-8*

Successful experiment:J-PARC E15(-2nd)

- "K-pp" search experiment
  - *Using the in-flight $K^-+{}^3He$ reaction*
    - **Give a clear information on reaction process**
  - ***Exclusive analysis of the Λpn final state***
    - Not only the Λp invariant-mass (m_X) but also momentum transfer to the Λp system (q_X) were reconstructed
      - *"Bound state" is efficiently distinguished from Quasi-free K^- absorption*

PRC102(2020)044002.



Successful experiment:J-PARC E15 (-2nd)

- Fitting 2D-plot with PWIA

$$\sigma(M,q) \propto \rho(M,q) \times \frac{(\Gamma_{Kpp}/2)^2}{(M-M_{Kpp})^2+(\Gamma_{Kpp}/2)^2} \times exp\left(-\frac{q^2}{{Q_{Kpp}}^2}\right)$$

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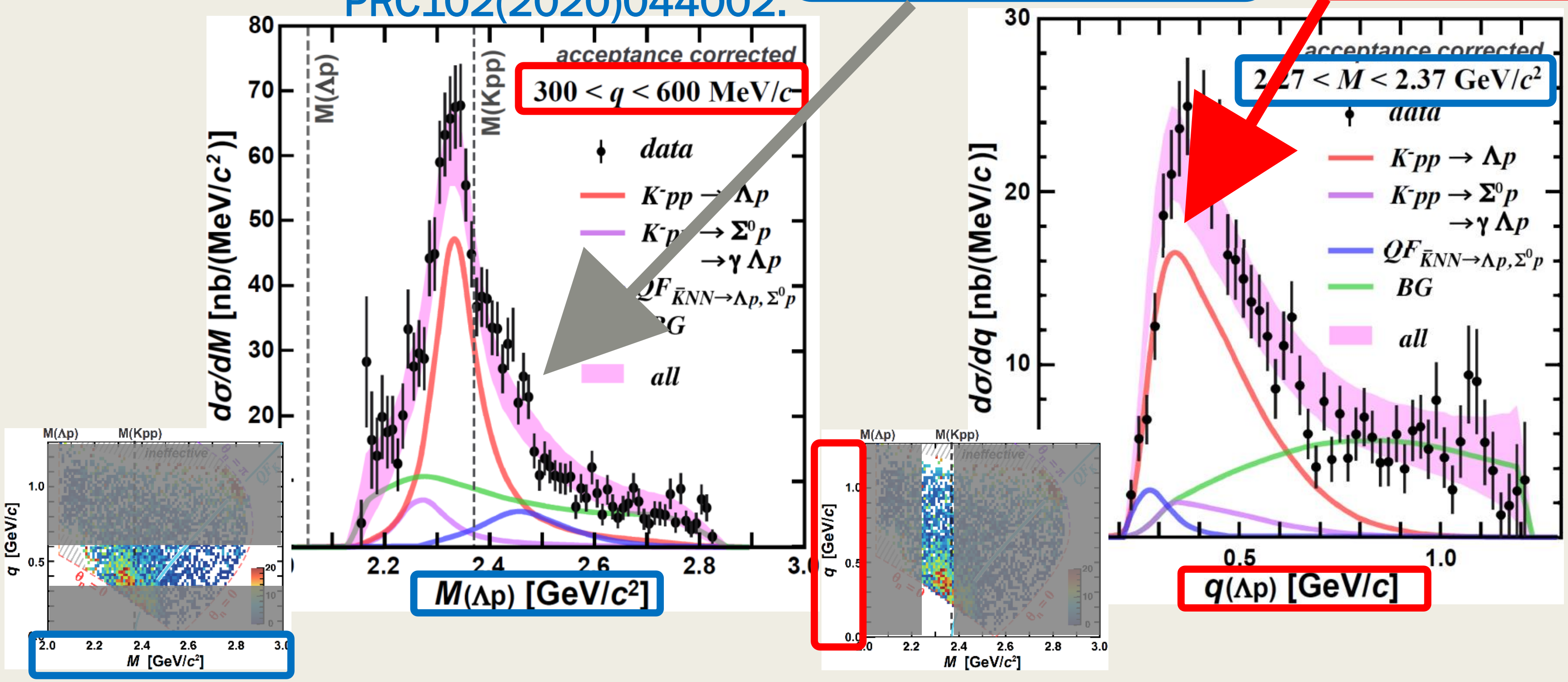

B_{Kpp} ~ 40 MeV, Γ_{Kpp} ~ 100 MeV

→ *large binding energy*

Q_{kpp} ~ 400 MeV (c.f. Q_{QF} ~ 200 MeV)

→ *wide momentum transfer*

suggest the "K⁻pp" is quite compact($R_{Kpp} = \hbar/Q$ ~ 0.6 fm)

Aims of upgrading beamline & spectrometer

- Expanding this successful experimental method
  - *Keys: the (K^-,n) reaction and exclusive analysis*
- to various systems in order to establish kaonic nuclei
  - *Precise measurement of Λ(1405)*
  - *Investigation of the spin and parity of the KbarNN state (J-PARC P89)*
  - *Systematic study for heavier kaonic nuclei, such as KbarNNN, Kbar NNNN, . . . (J-PARC E80)*

- Increasing the K^- beam intensity for sufficient statistics
  - *By shortening the beamline (～2.5 m)*
- Enlarging an acceptance of spectrometer
  - *By constructing a large solid-angle spectrometer*
  - *Exclusive analysis requires detections of decay particles as many as possible to specify the reaction*
    - Neutron detection efficiency is important to reconstruct various decay channels

Upgrade plan of J-PARC K1.8 BR beamline and spectrometer system

Present K1.8 BR beamline @J-PARC

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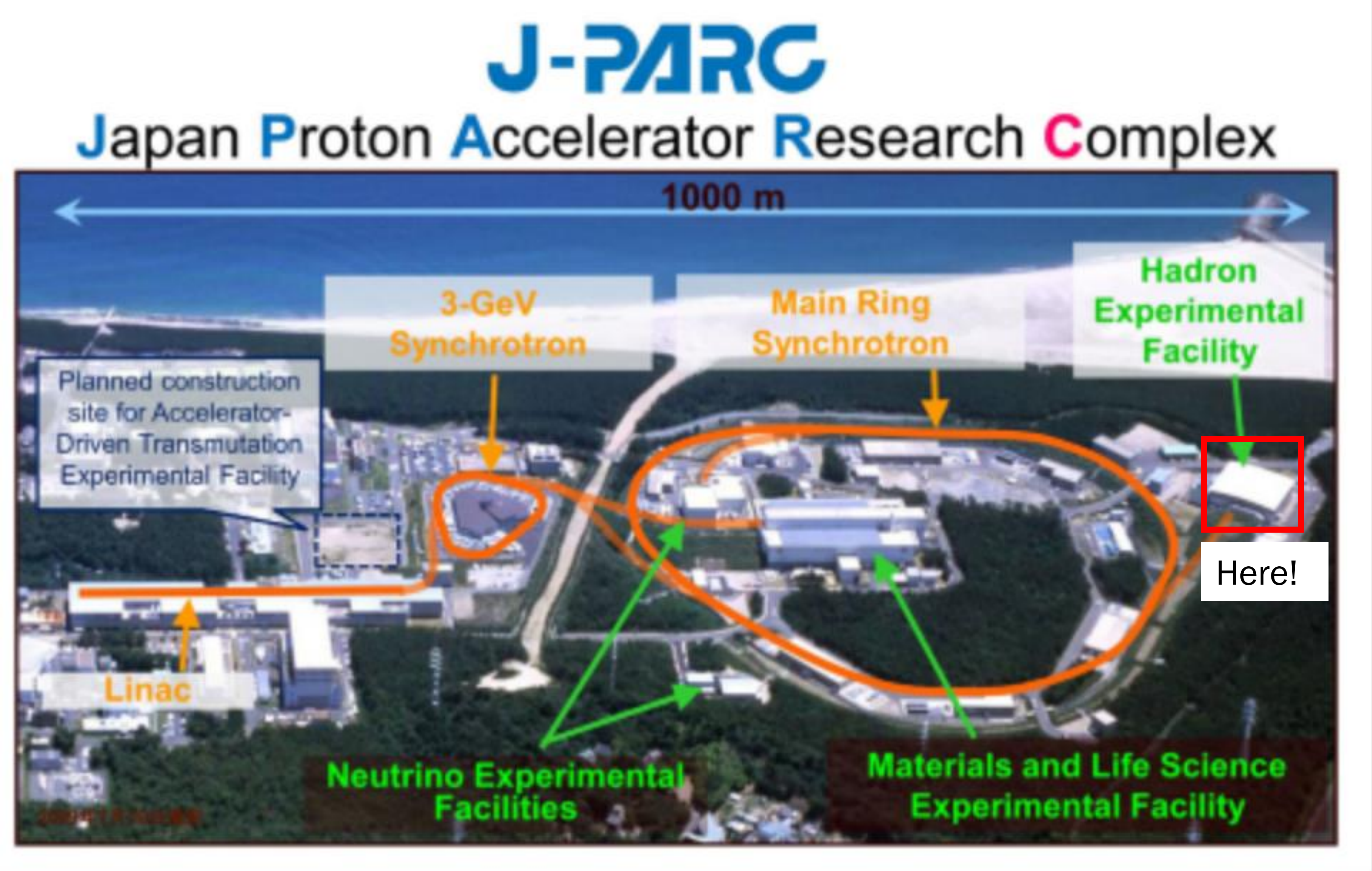
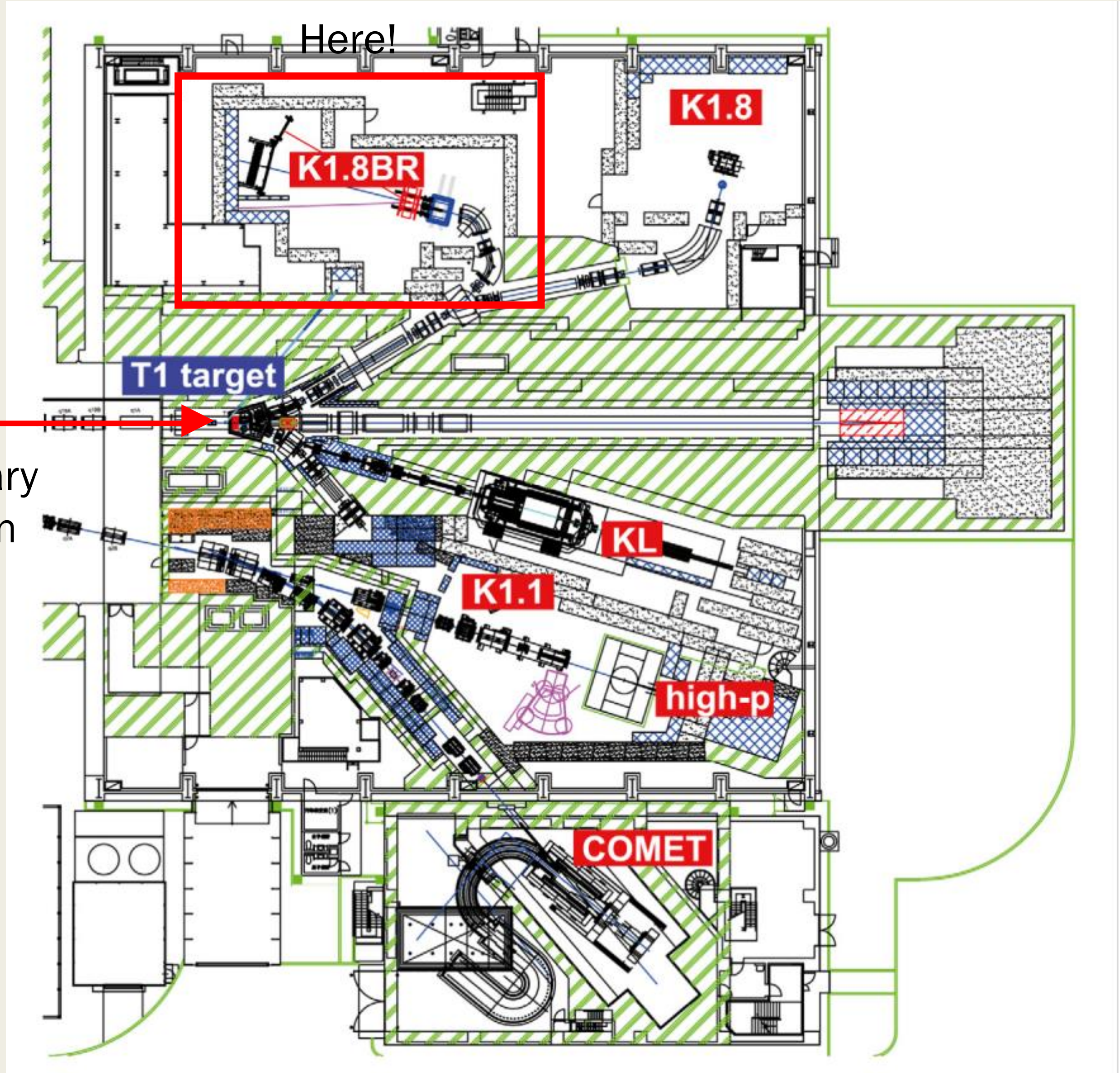


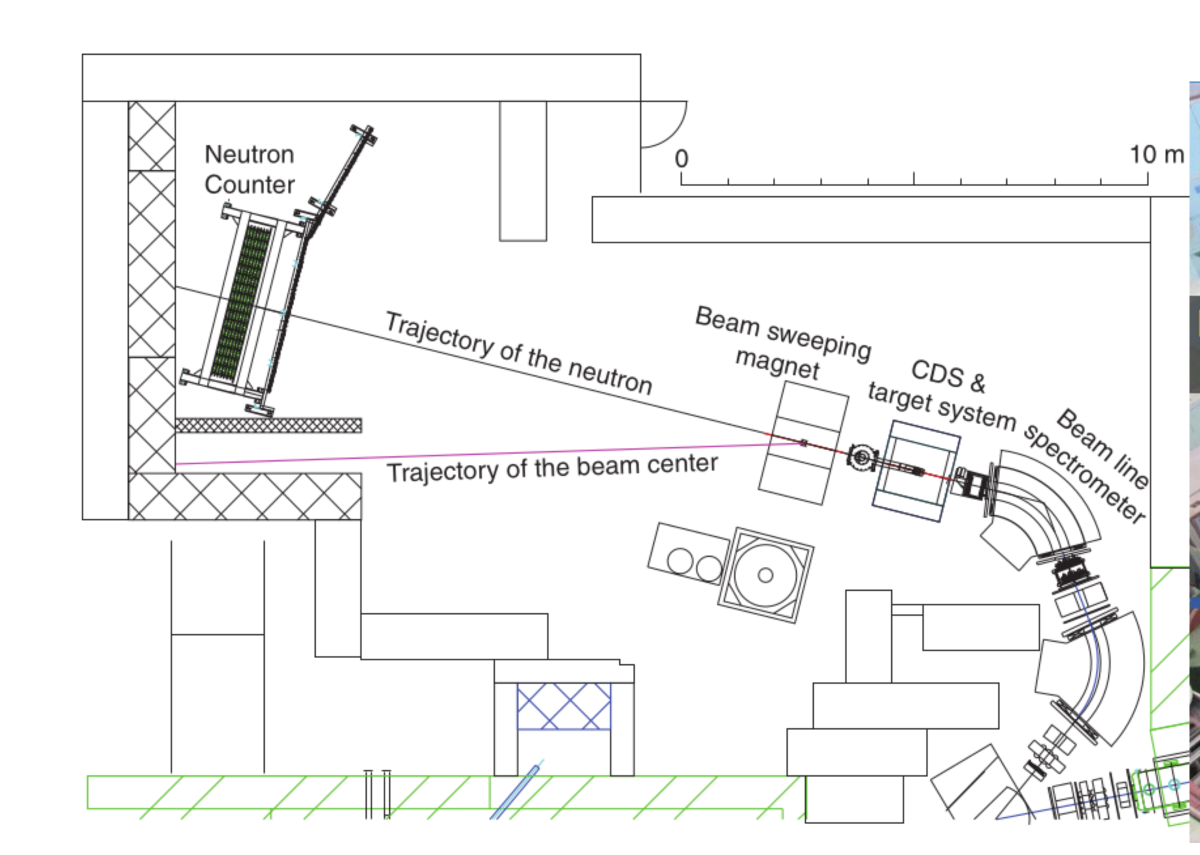
Present K1.8 BR beamline @J-PARC

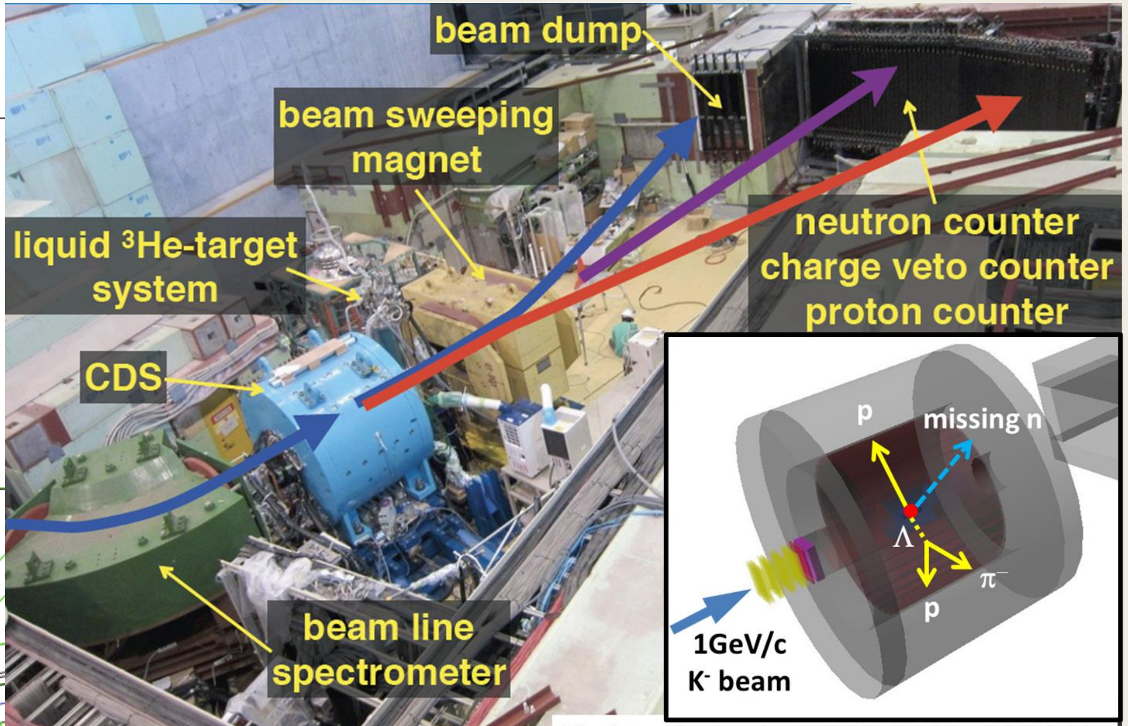


Primary
Proton
beam

Present K1.8 BR beamline @J-PARC

- 31.3 m beamline with 1-stage electrostatic separator
  - *Maximum momentum:1.2 GeV/c, $\pi^{\pm}$, $K^{\pm}$, p, pbar beams are available*
- Typical K^- beam (accelerator power 51kW)
  - 1.0 GeV/c, 210 k /(spill=5.2 s), K^-/pi^-=0.5,

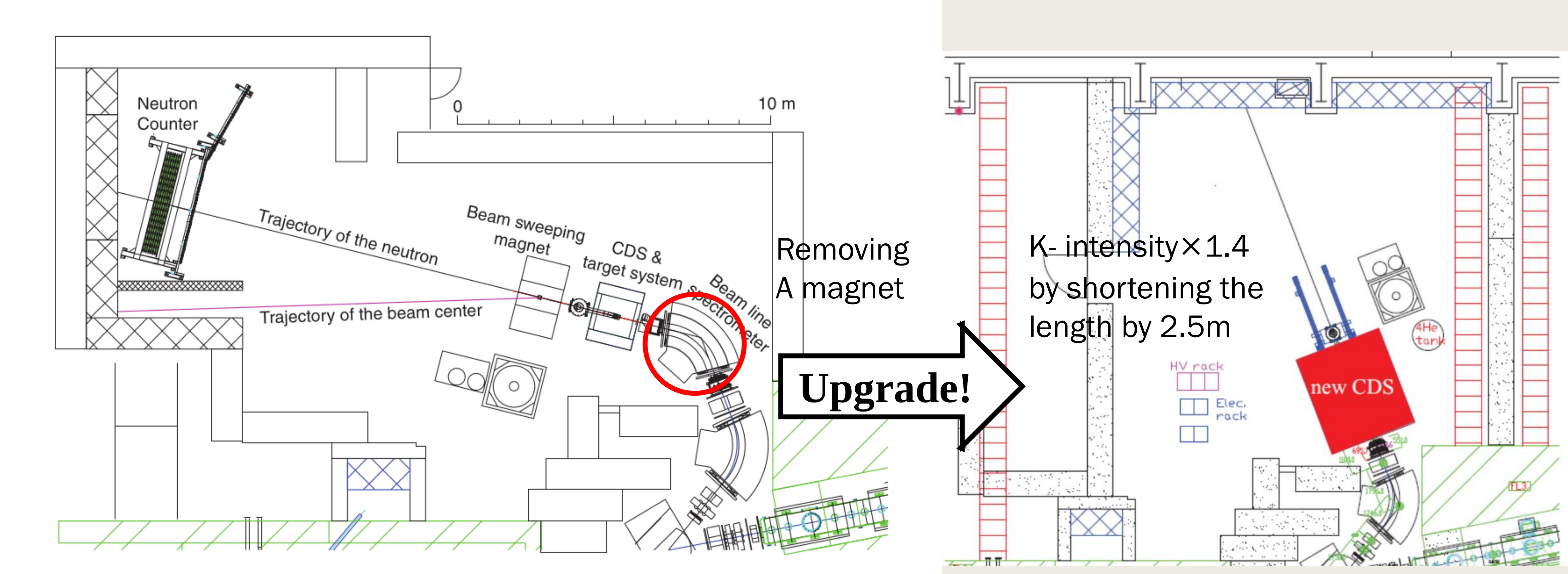




K. Agari et. al., PTEP 2012, 02B011

Upgrade plan of K1.8 BR beamline

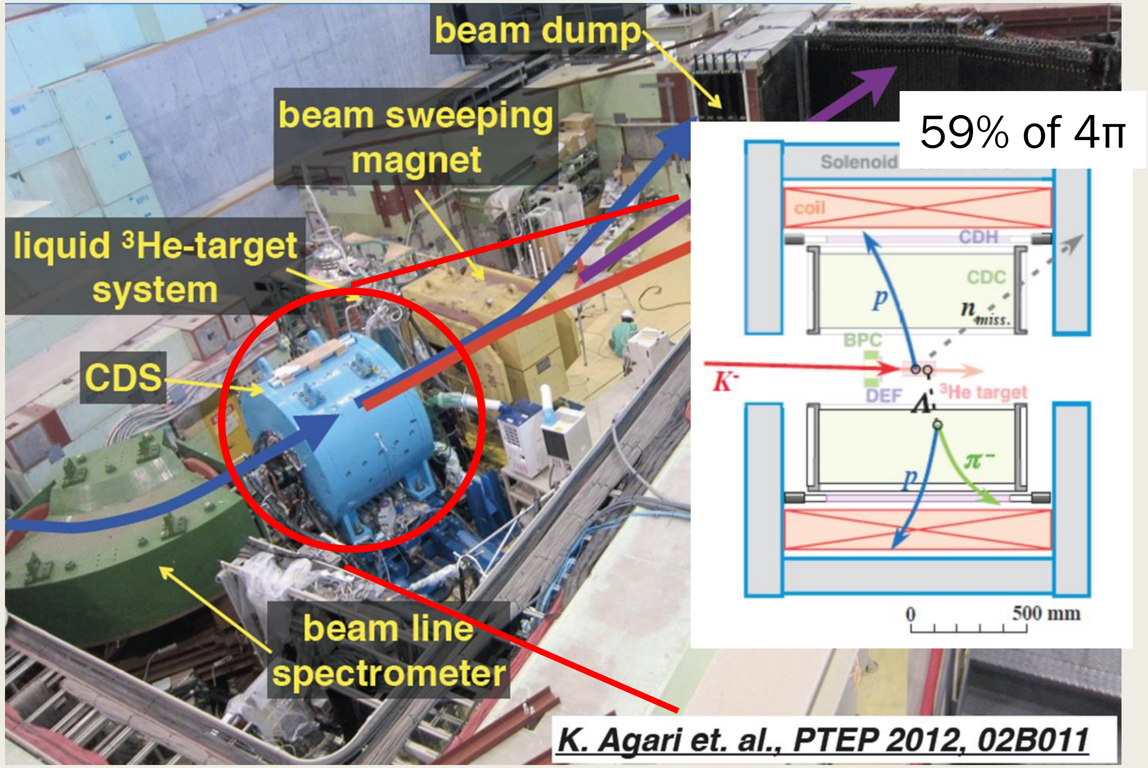
- **28.8 m** beamline with 1-stage electrostatic separator
- expected K^- beam (accelerator power **90kW**)
  - 1.0 GeV/c, **420 k/(spill=4.2 s), K^-/pi^-=~*0.7*** *(1.2M particle /spill)*
    - On target: 270k/spill
    - Spill cycle will be shortened due to upgrade of Accelerator



Present Spectrometer system @J-PARC

Momentum resolution 5.3 % for p_T
Vertex resolution:
σ_r～2-3 mm, σ_z～1cm
β resolution 0.5 %

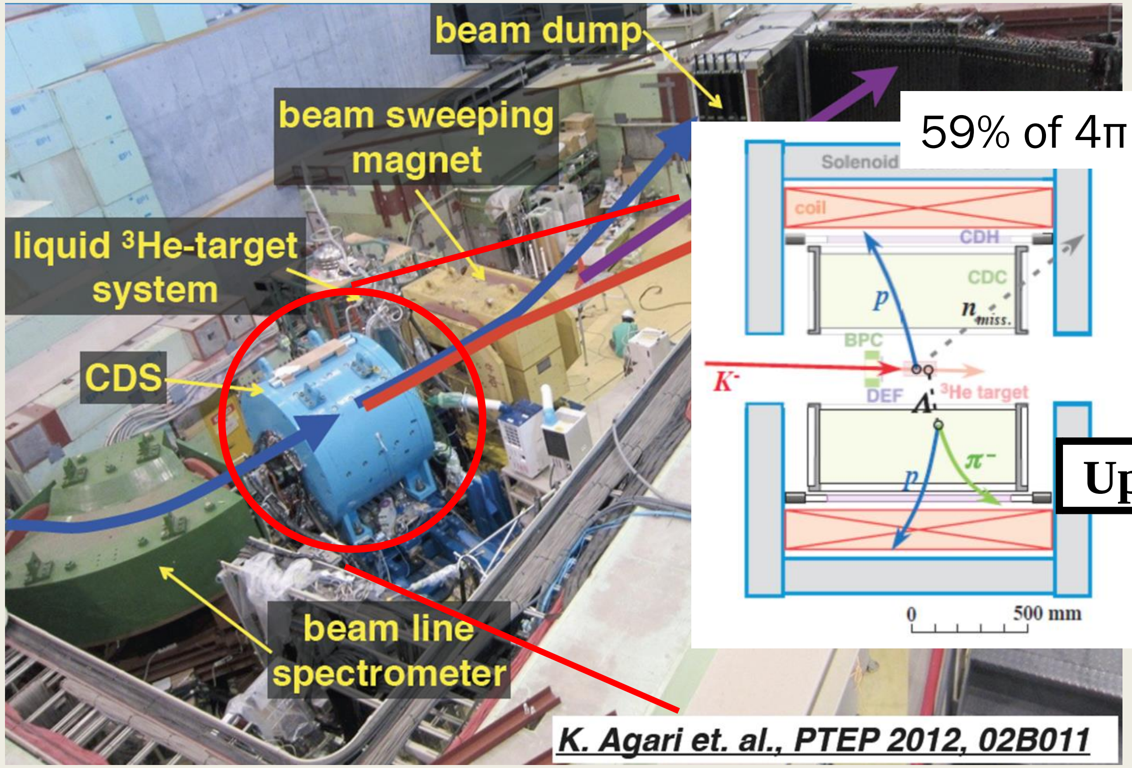
- solenoid spectrometer
  - *Normal-conducting solenoid magnet (0.7T over tracking volume)*
  - *CDC (Cylindrical Drift Chamber)*
  - *CDH (Cylindrical Detector Hodoscope)*
    - 3cm-thickness, neutron detection efficiency ～3%



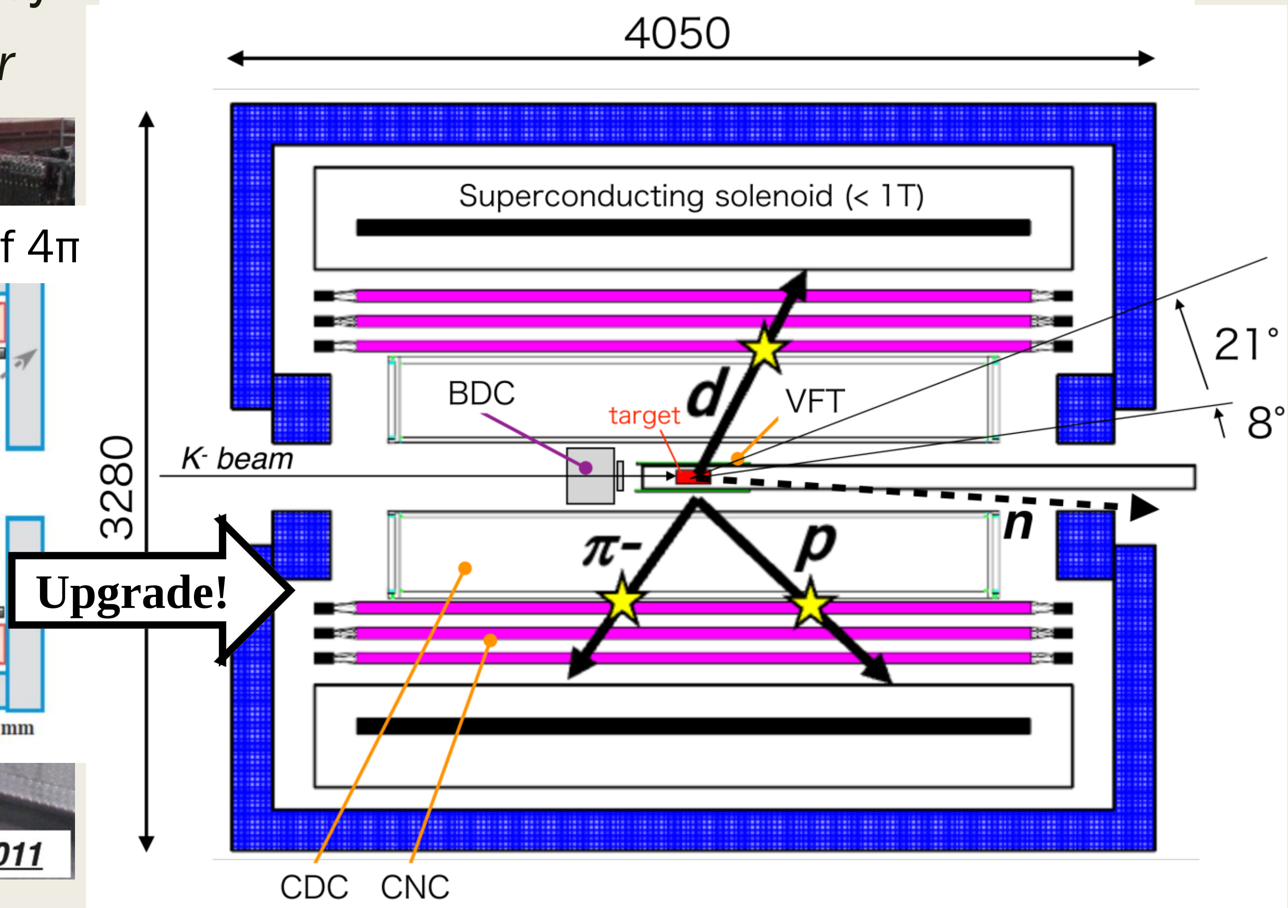
Upgrade plan of Spectrometer system @J-PARC

- solenoid spectrometer with larger acceptance
  - *Superconducting solenoid magnet (0.7T over tracking volume)*
  - *CDC (Cylindrical Drift Chamber)*
  - *CNC (Cylindrical Neutron Counter)*
    - **5×3 cm thickness plastic scintillator array**
  - *VFT (Vertex Fiber Tracker)→new detector*

Momentum resolution **2-3 %** for p_T
Vertex resolution:
σ_r～2-3 mm, **σ_z～1mm**
β resolution 0.5 %
Performances will retain or will be improved!



93% of 4π, detectors will be ～3 times longer



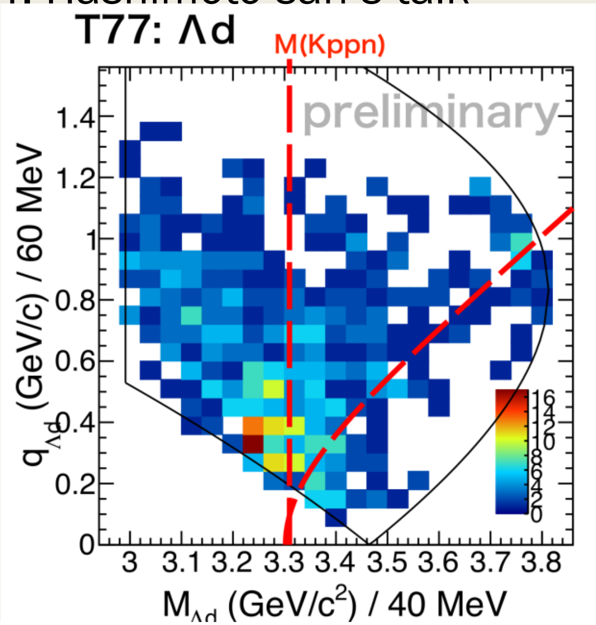
Proposed physics programs with upgraded experimental setup

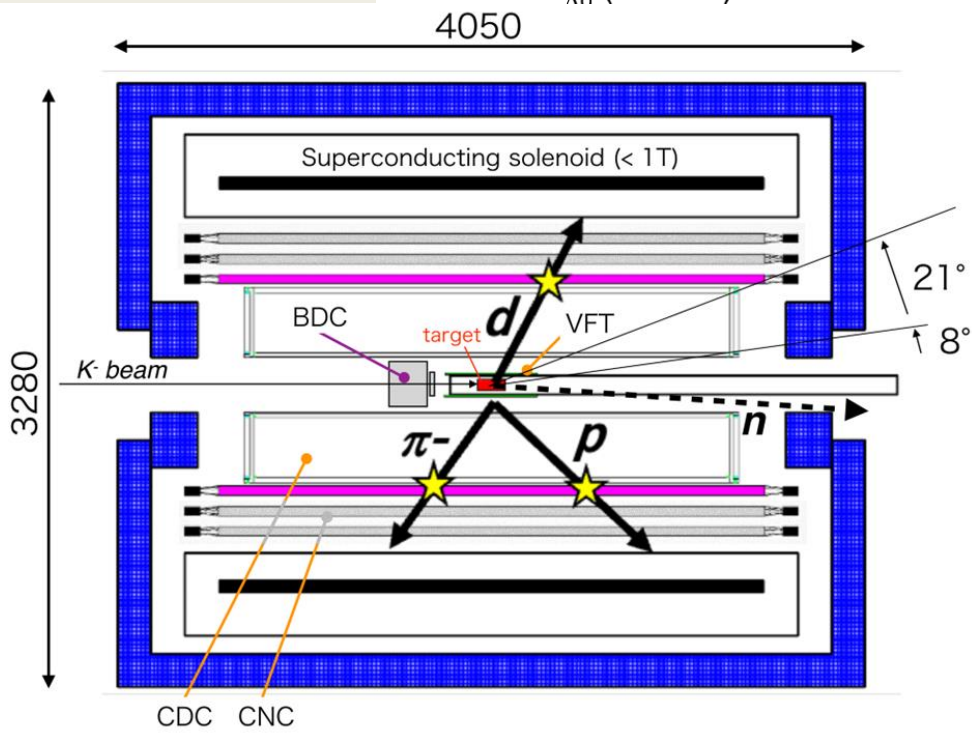
Proposed physics program

- Search for KbarNNN via ^{4}He(1 GeV/c K^-,n) reaction
  - *J-PARC E80 experiment*
  - *The K^-ppn state will be easily observed Via 2-body Λd decay Even minimum setup with 1 layer-CNC*

  ->1st step experiment of new CDS
    - Limited statistics data with Existing CDC
      - *J-PARC T77, 6G K^-*
      - *Details are talked in*
      - *T. Hashimoto-san's talk! (Thursday)*
  - *We also have a chance to reconstruct K^-ppn state via 3-body Λpn decay*

Result with existing CDC
T. Hashimoto-san's talk

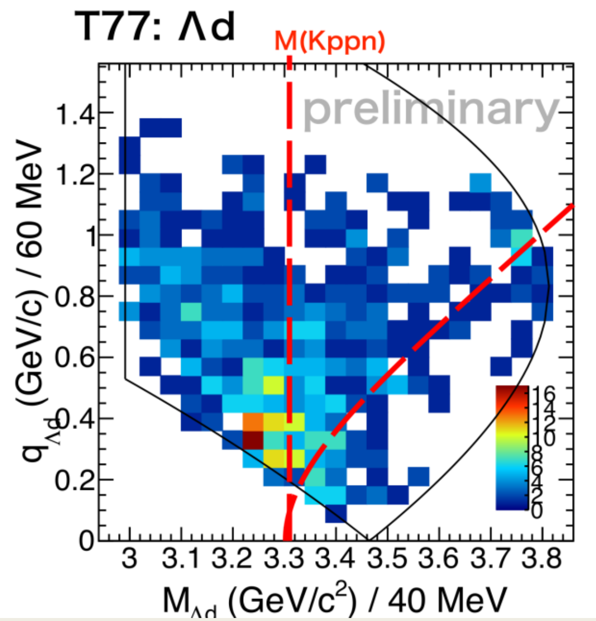


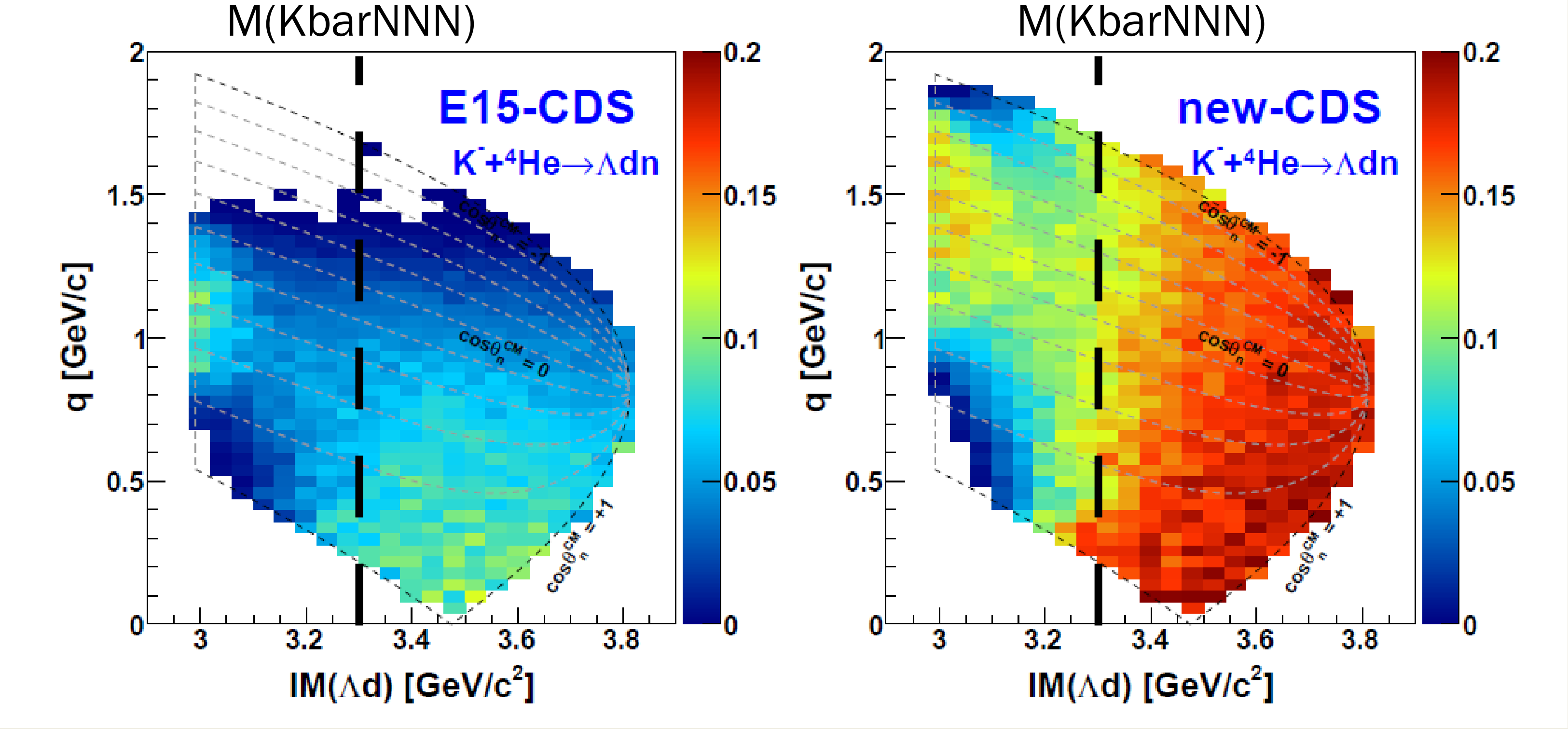


Proposed physics program

- Search for KbarNNN via ^{4}He(1 GeV/c K^-,n) reaction
  - *Detector acceptance for the Λd detection*
    - A few times larger than existing CDS!

Result with existing CDC
T. Hashimoto-san's talk





Proposed physics program

- Search for KbarNNN via ^{4}He(1 GeV/c K^-,n) reaction
  - *Yield estimation for Λd detection*

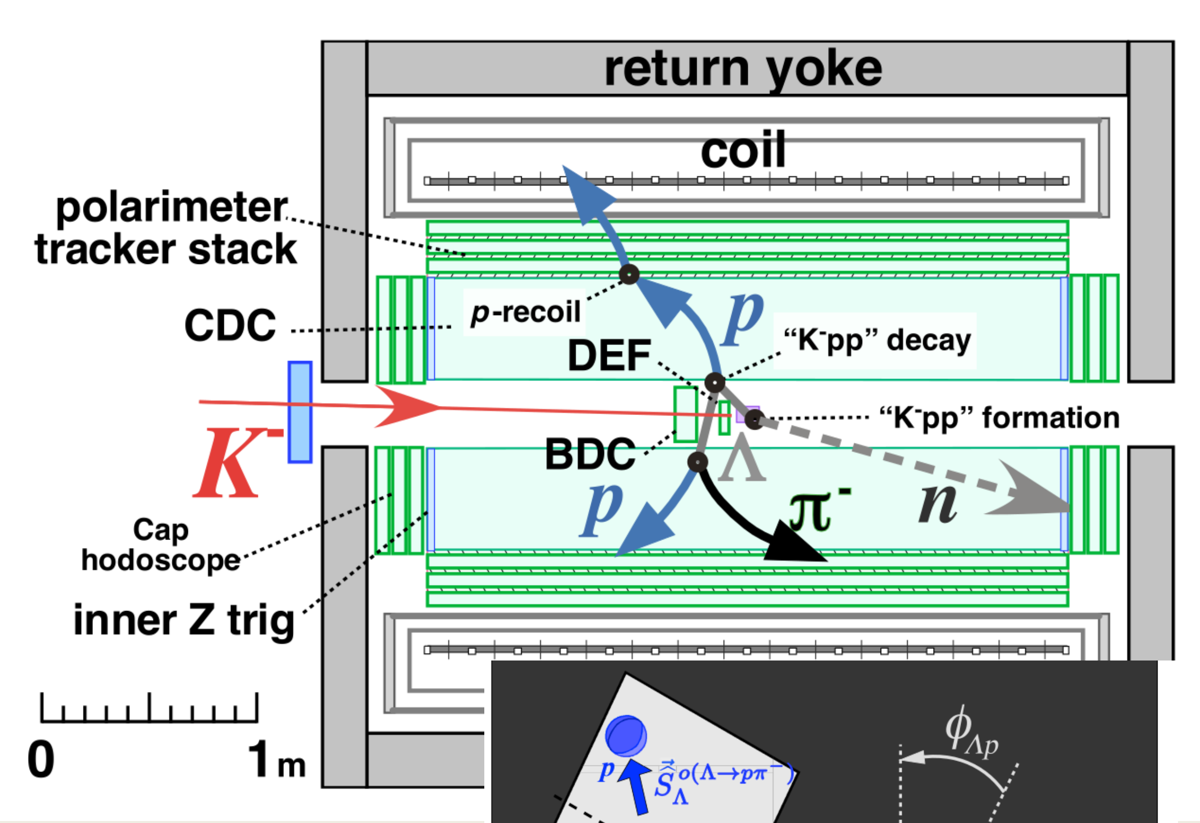
$$N = \sigma \times N_{beam} \times N_{target} \times \epsilon,$$
$$\epsilon = \epsilon_{DAQ} \times \epsilon_{trigger} \times \epsilon_{beam} \times \epsilon_{fiducial} \times \Omega_{CDS} \times \epsilon_{CDS},$$

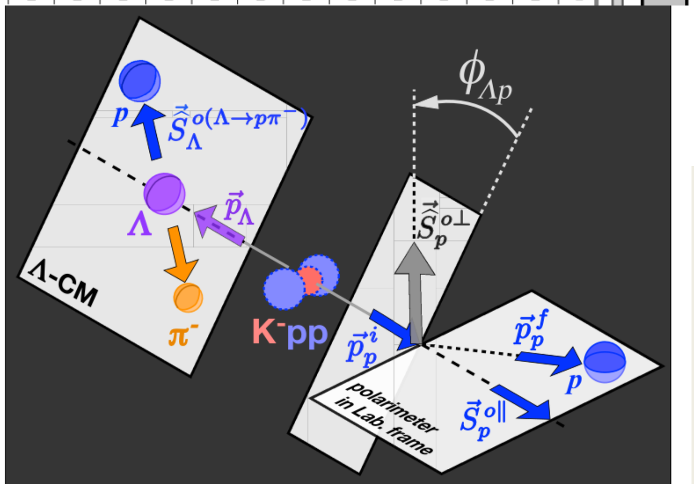
  - *N_{beam} = 100 G K^- on target*
    - Corresponding to ～3 weeks data taking
  - $\boldsymbol{\sigma(K^- ppn) \cdot Br(\Lambda d)} \sim \mathbf{5\ \mu b}$
    - Assumption From the T77 result (Hashimoto-san)
  - **N(K^-ppn→Λd) ~ 12 k events**
    - 1.7 k "K^-pp"→Λp events in E15 (40 G K^-)

	Λd
σ(K^-ppn)*Br	5 μb
N(K^- on target)	100 G
N(target)	2.56 x 10^{23}
ε(DAQ)	0.92
ε(trigger)	0.98
ε(beam)	0.72
Ω(CDC)	0.23
ε(CDC)	0.6
N(K^-ppn)	12 k

Proposed physics program

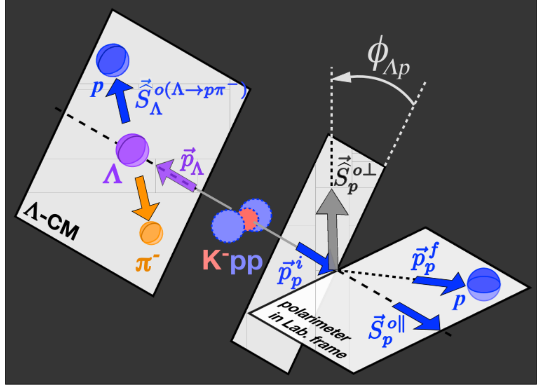
- Investigation of the spin and parity of the KbarNN state
  - *J-PARC P89 experiment*
  - *Measuring the spin-spin correlation between Λ and p from "K⁻pp"→Λp decay*
    - $\alpha_{\Lambda p}=1$ ($J^\pi=0^-$), $\alpha_{\Lambda p}=1/3$($J^\pi=1^-$)
    - Spin direction of Λ can be Estimated from $p\pi^-$ decay
  - *To measure the spin direction of the proton, polarimeter tracker stack will be additionally equipped*
    - Scintillating fiber?
    - Straw tube?

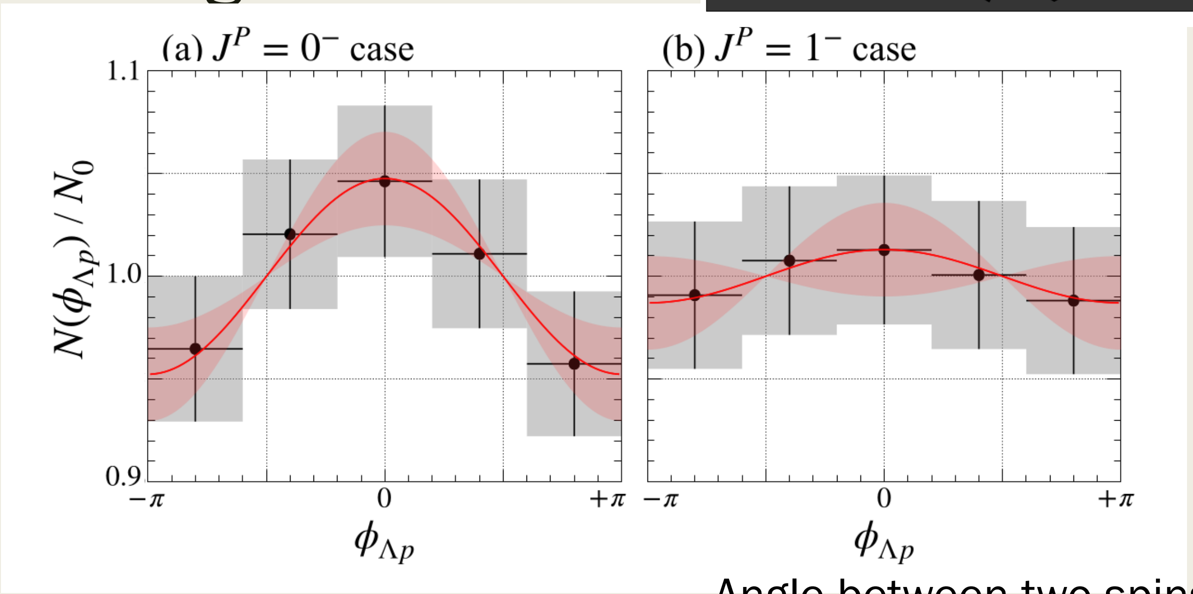




Proposed physics program

- Investigation of the spin and parity of the KbarNN state
  - *Expected result for 8-week data taking*
    - $\alpha_{\Lambda p}$ measurement
      - *420 k "K-pp"→Λp events*
        - 250 times larger than E15
        - When $J^P=0^-$ case, $J^P= 1^-$ hypothesis Would be excluded more than 95% C. L.
    - "K^0bar nn" measurement
      - *^{3}He(K^-,p) reaction, Reconstruct from "K^0bar nn"→Λn*
      - *Production cross section is expected to strongly depend on J^π due to spin-isospin selection rule.*
        - σ*BR～7μb/sr (1^- case), σ*BR～1.4μb/sr (0^- case)
    - These measurement would provide conclusive results of J^π!

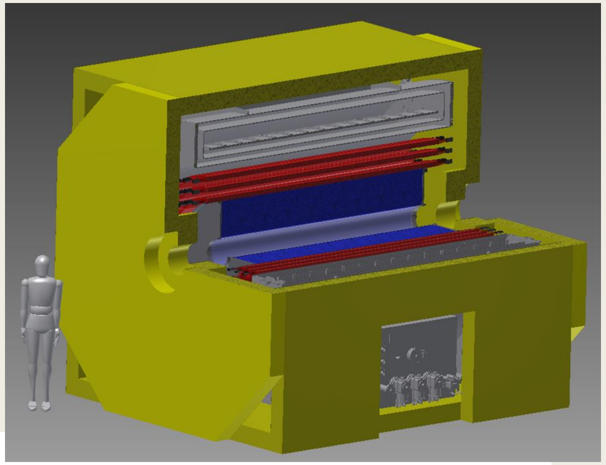




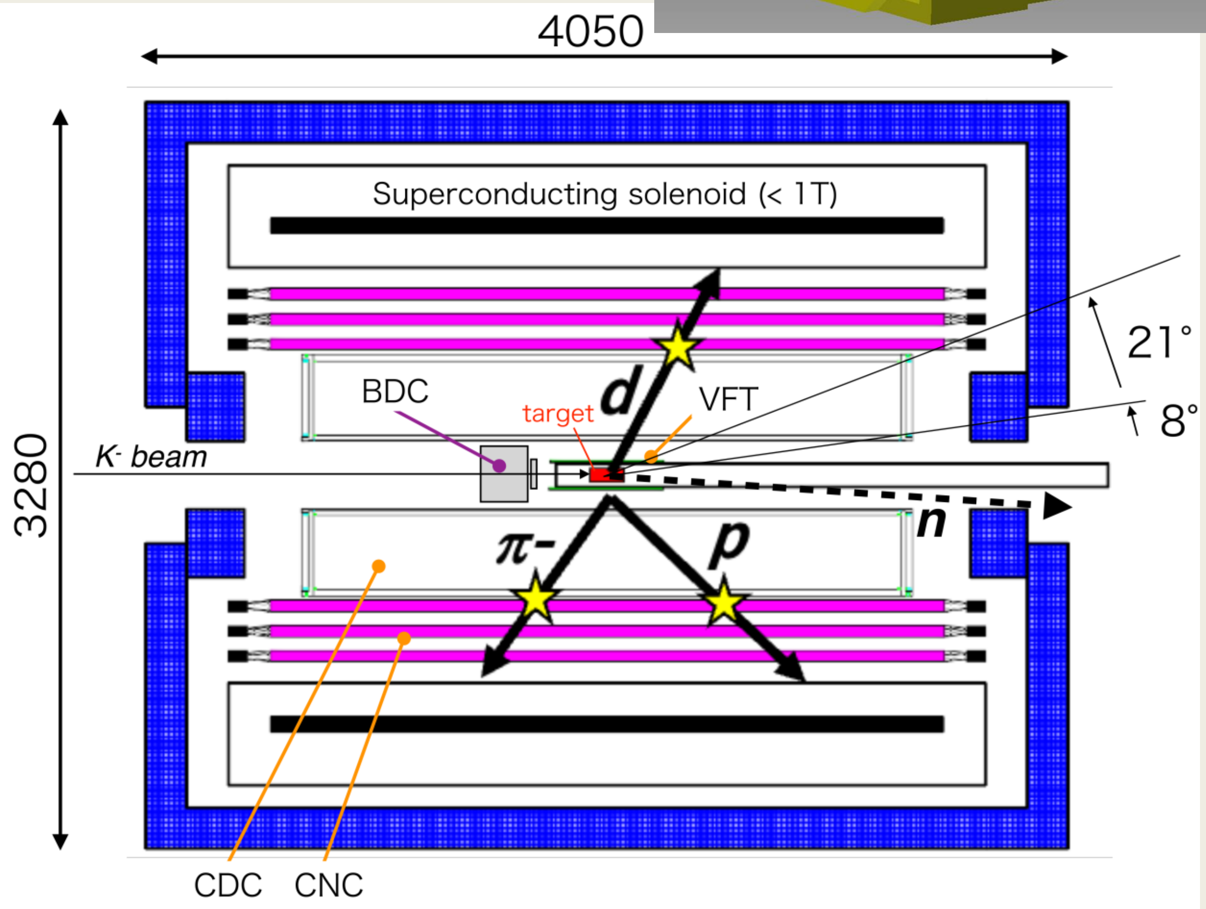
Angle between two spins

Design and development status of Detectors composing the new CDS

New Spectrometer system (New CDS)

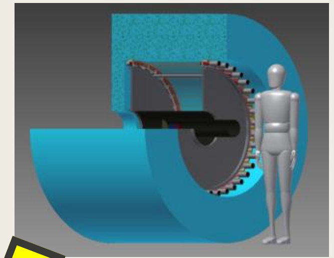


- Large acceptance solenoid spectrometer
  - ***Superconducting solenoid magnet***
  - *CDC (Cylindrical Drift Chamber)*
  - *CNC (Cylindrical Neutron Counter)*
  - *VFT (Vertex Fiber Tracker)*
- Improved performances for compared to existing CDS
  - *Solid angle ×1.6 (59%→93%)*
    - covers $29° < \theta_{lab} < 151°$
  - *Neutron detection efficiency*
    ×1.7×nlayer×solid angle improvement

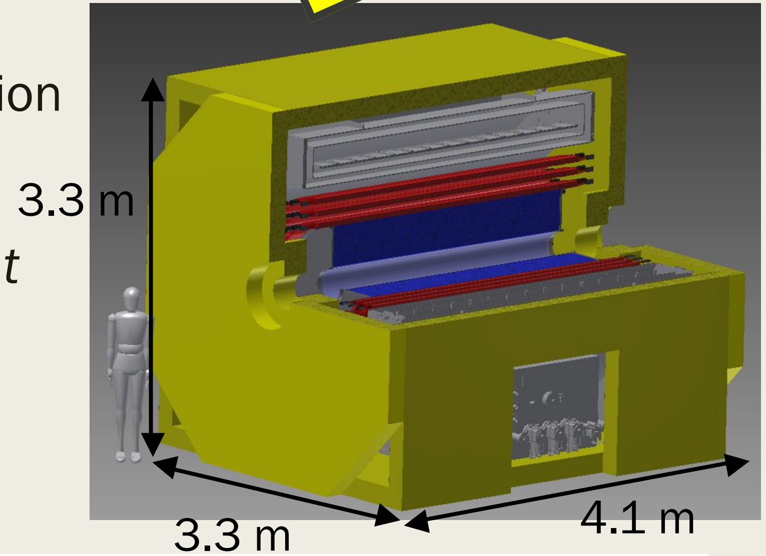


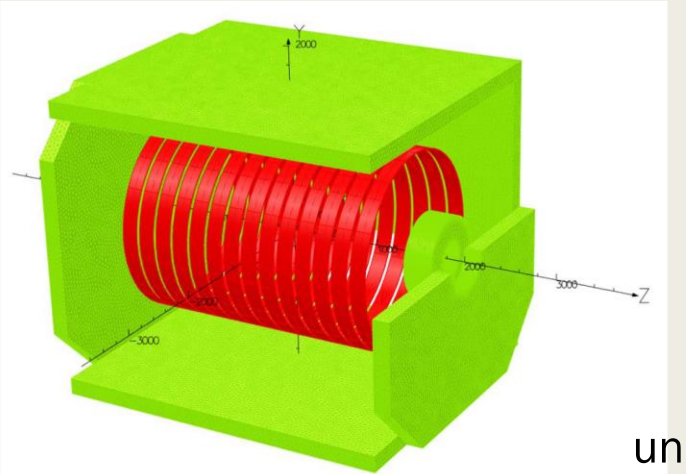
Superconducting solenoid magnet

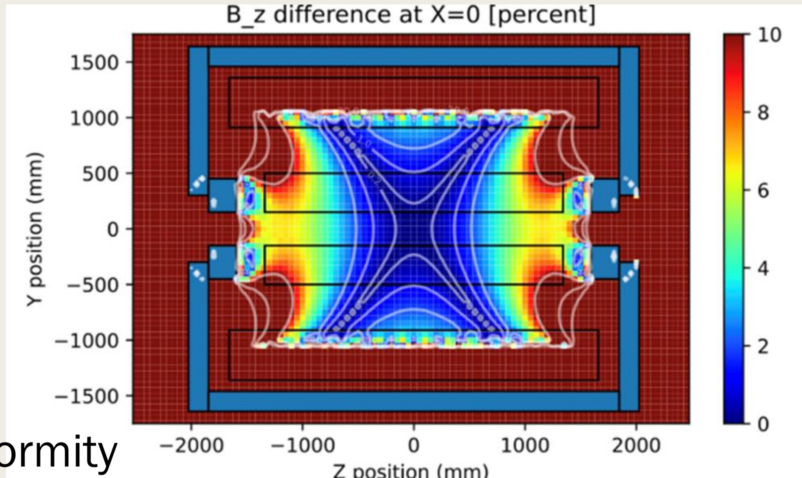
- In order to provide a uniform magnetic field over larger tracking volume, superconducting solenoid magnet is needed.
  - *3.3m x 3.3m x 4.1m*
- Developing with the cooperation of the J-PARC Cryogenics Section
- Maximum field of 1.0 T @center , 189A – 10V
  - *Basic design is the copy of the solenoid in COMET experiment*
  - *For experiments for kaonic nuclei, we will set 0.7 T, same as existing spectrometer.*
- Magnetic field calculation with OPERA-3D (TOSCA)



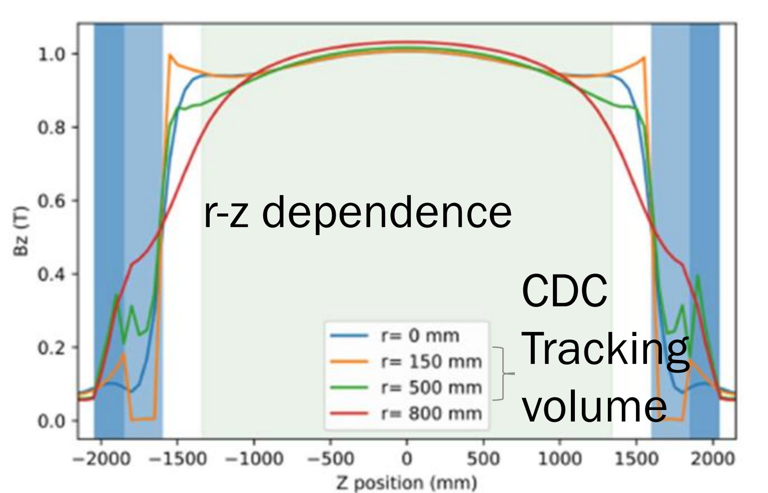
10 times larger in volume!







uniformity



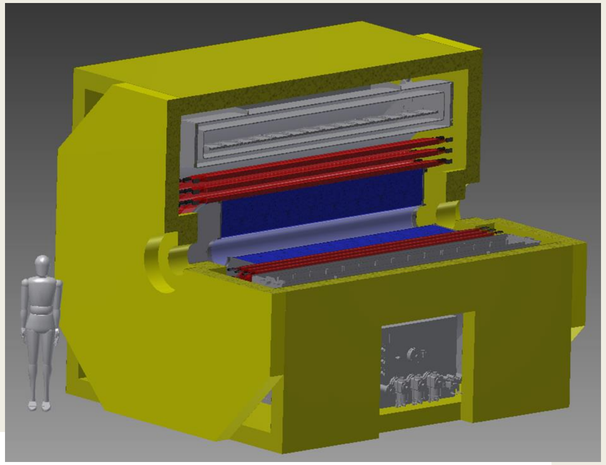
Superconducting solenoid magnet

- Present status
  - *Superconducting coil*
    - NbTi/Cu wire
      - *Cooled with 3-stage GM Refrigerator*
    - 14 coils, 13230 turns in total
    - Winding will be started next month!

Superconducting solenoid magnet

- Present status
  - *Return yoke*
    - Construction completed
    - ～115 t
  - *Monitor system for quench protection*
    - Under preparation
  - *Vacuum vessel*
    - Under consideration
      - *Bore dia. = Φ1.8m, Outer dia. = Φ2.7m*
      - *length = 3.3m, Weight = 5.9t*
      - *In design, installation mechanism for detectors is Coupled problem.*

New Spectrometer system (New CDS)



- Large acceptance solenoid spectrometer
  - *Superconducting solenoid magnet*
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  - *CNC (Cylindrical Neutron Counter)*
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- Improved performances for compared to existing CDS
  - *Solid angle ×1.6 (59%→93%)*
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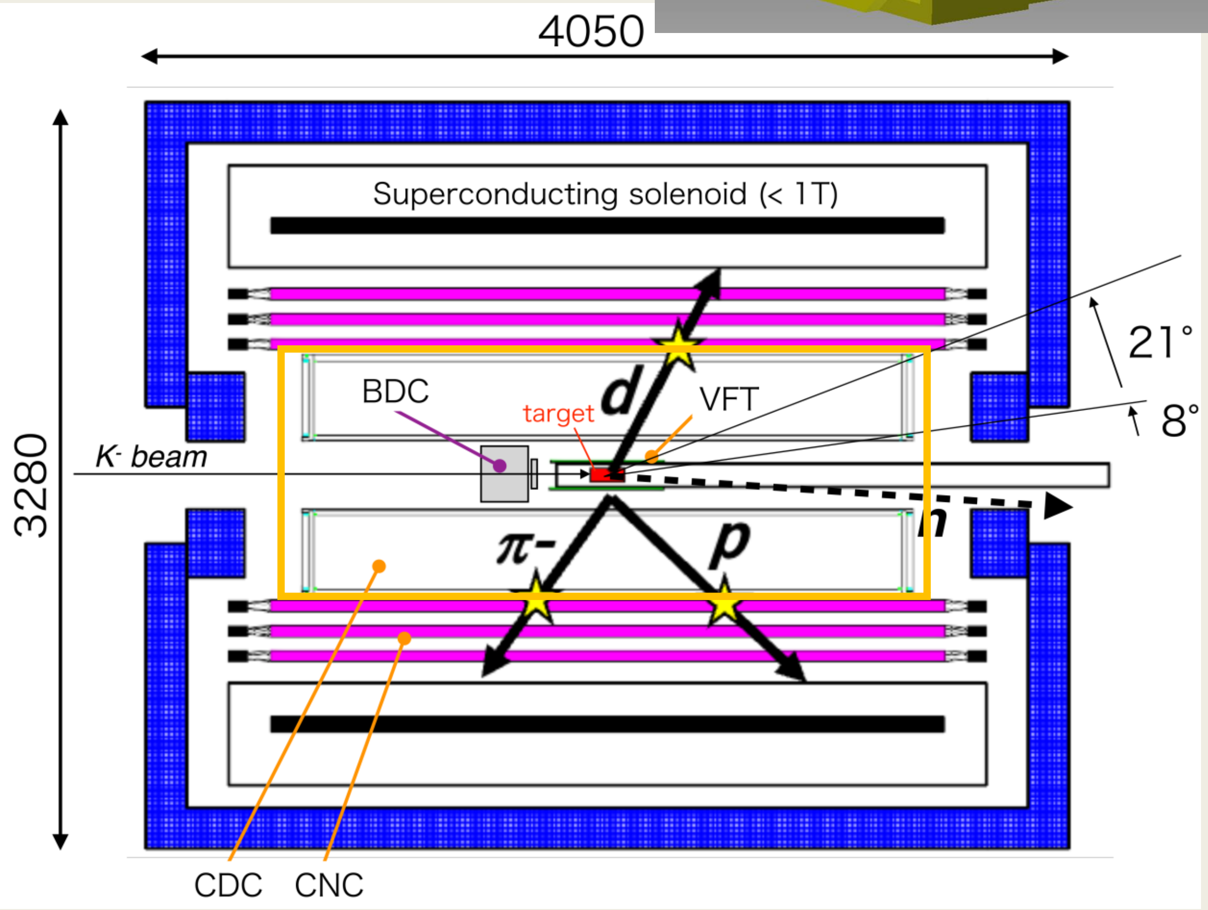
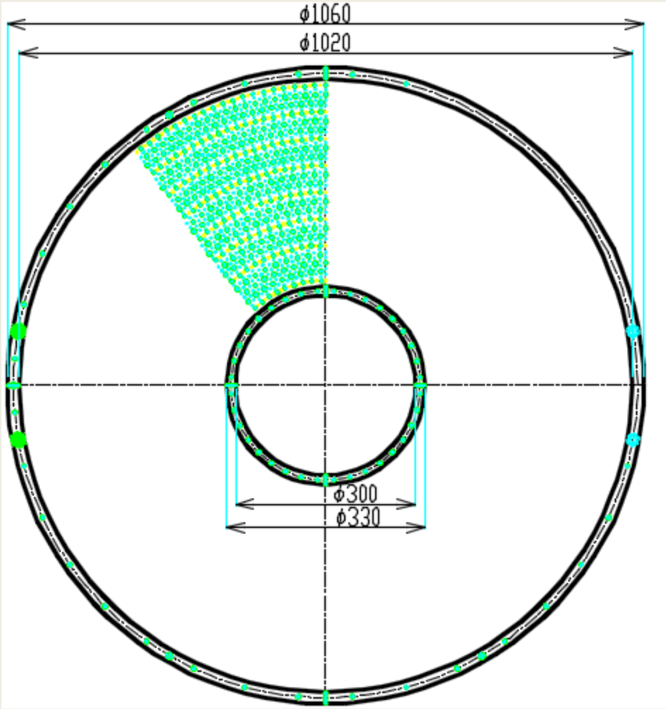
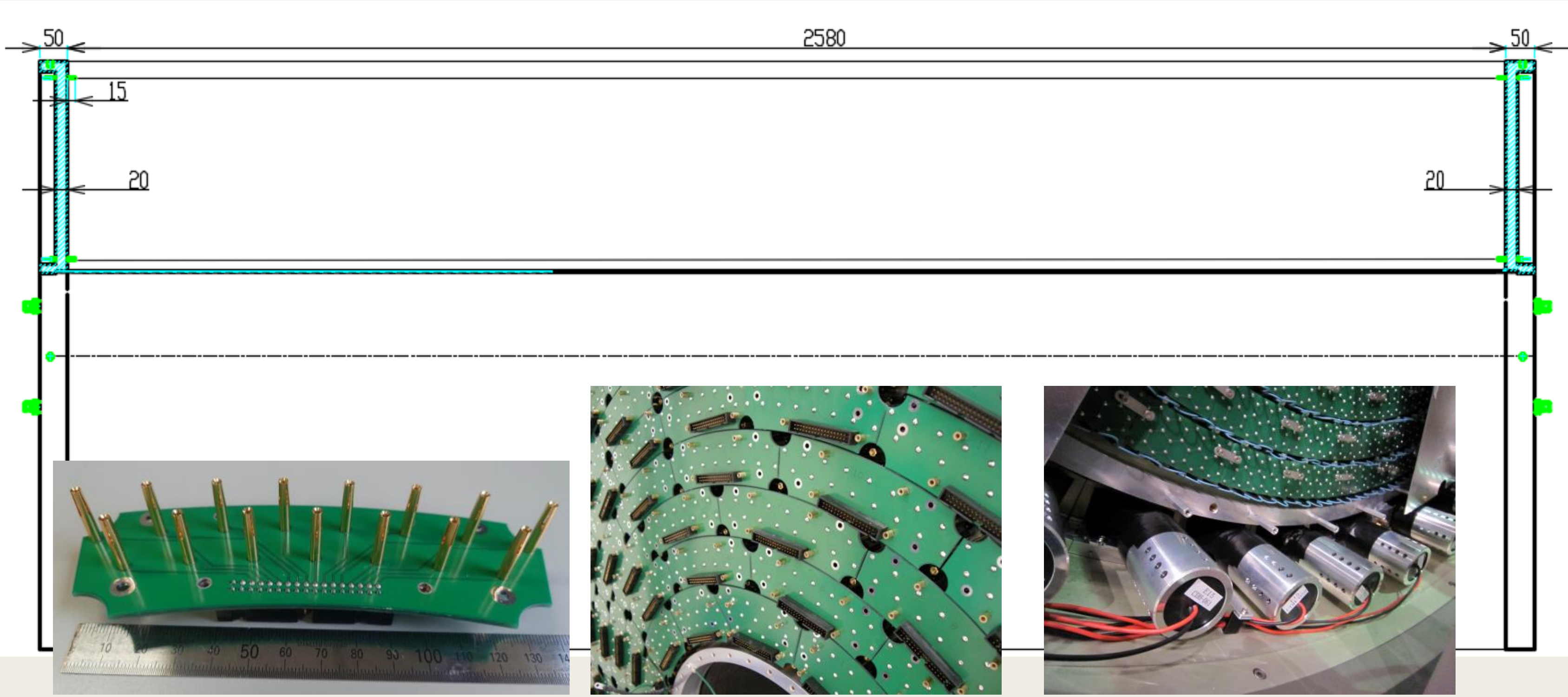


Cylindrical drift chamber

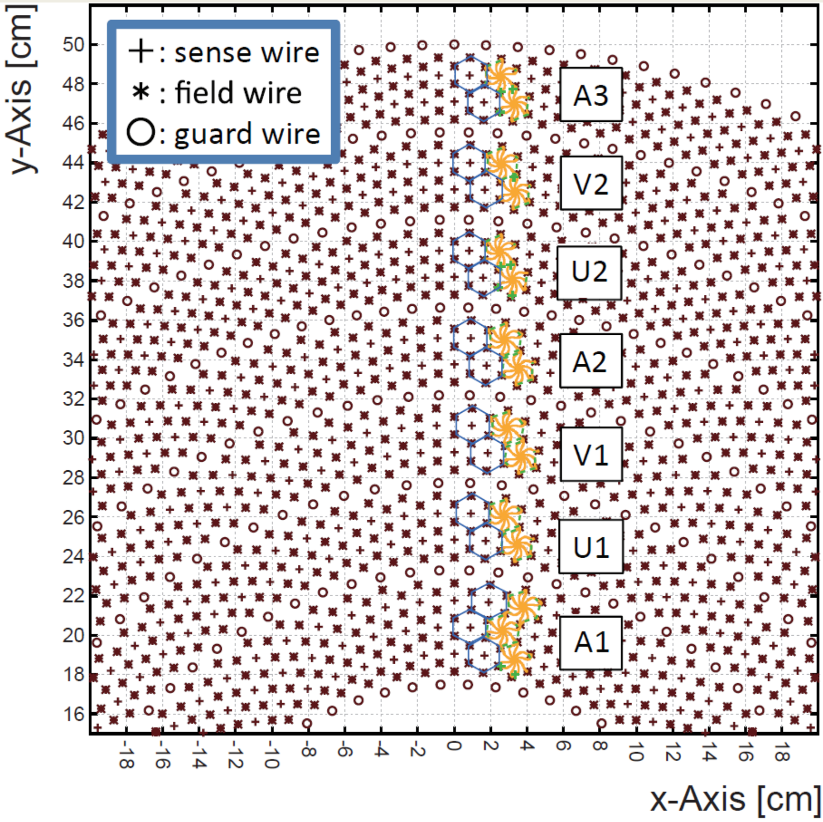
- New CDC is 3 times longer than the existing CDC along beam axis
- For radial direction, the design of new CDC is similar to existing CDC.
  - *We can reuse the existing readout/HV-distributor boards*





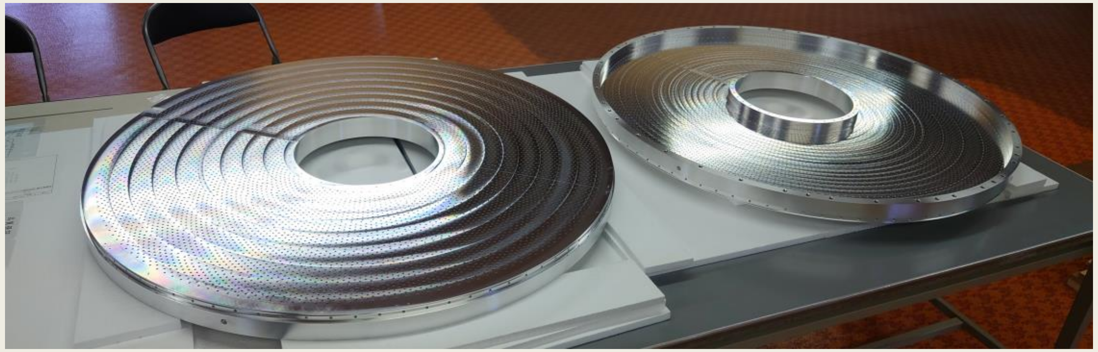
Cylindrical drift chamber

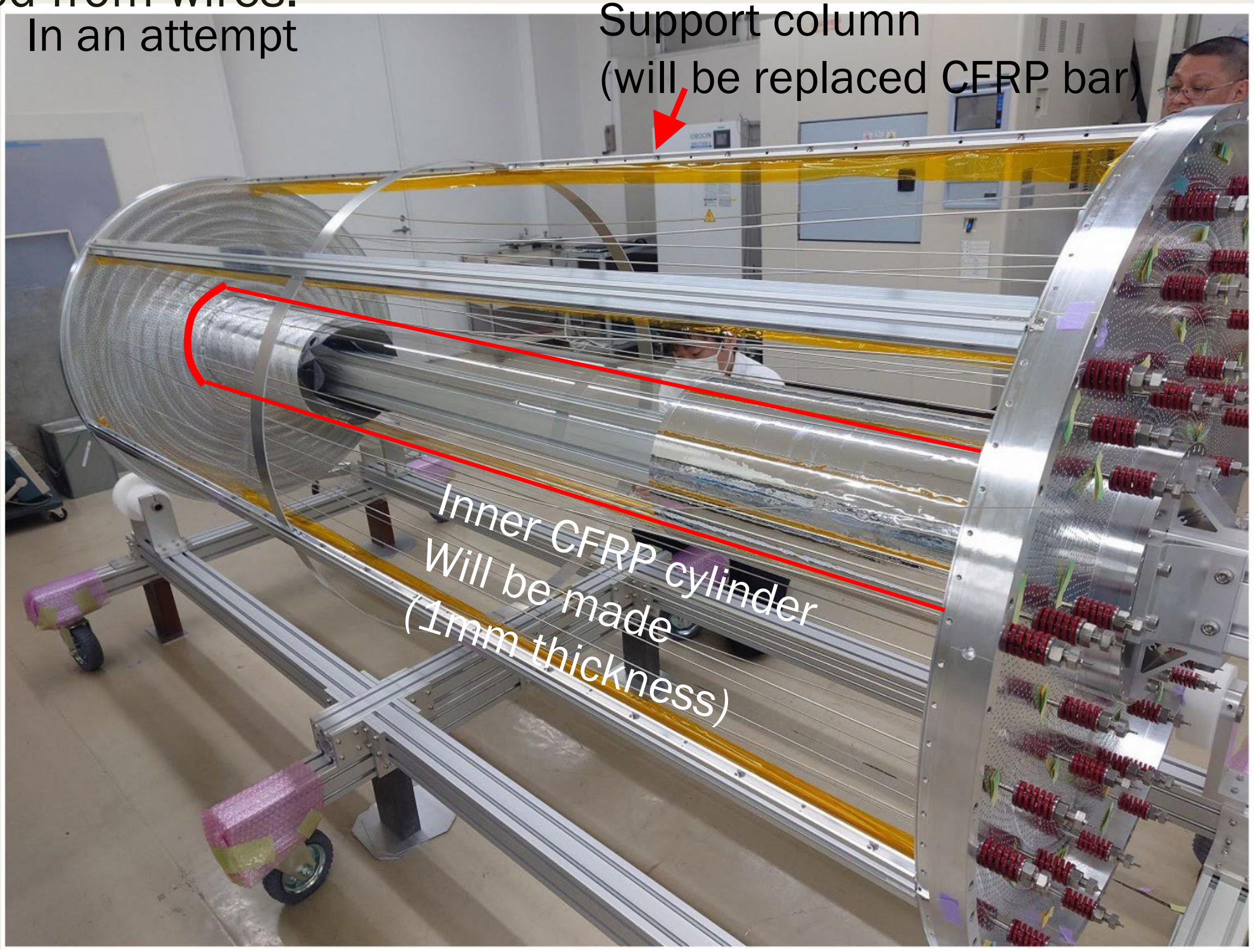
- Structure
  - *Wire configuration is similar to the existing CDC*
    - 15 layers grouped into 7 super layers (AUVAUVA)
    - Wires in U,V layers are tilted by ± 2.3-3.0 degrees
      - Slightly smaller tilt angle than existing CDC (～3.5 degrees)
    - 1,816 ch with hexagonal cells
    - 8,064 wires are supported by feedthroughs
  - *Resolutions will retain the existing CDC performance*
    - 5.3 % for p_T and 0.5 % for β
- Drift gas
  - *Ar-Ethane (50:50)*
    - Same as the existing CDC
  - *or Ar-CO_2(90:10)*
    - Cheaper than Ar-Ethane, costs will be saved even for the large drift chamber



Cylindrical drift chamber

- Present status
  - *Production of Endcaps is completed.*
  - *To make CDC body, we are considering the best balance of rigidity and mass thickness.*
    - In total, 1.6 t tension would be applied from wires.
      - *3 times larger than existing CDC*
      - *Buckling calculation is difficult…*
    - Connecting endcaps with “inner CFRP cylinder” and CFRP support columns
    - Wire implementation will be started The beginning of the next year!





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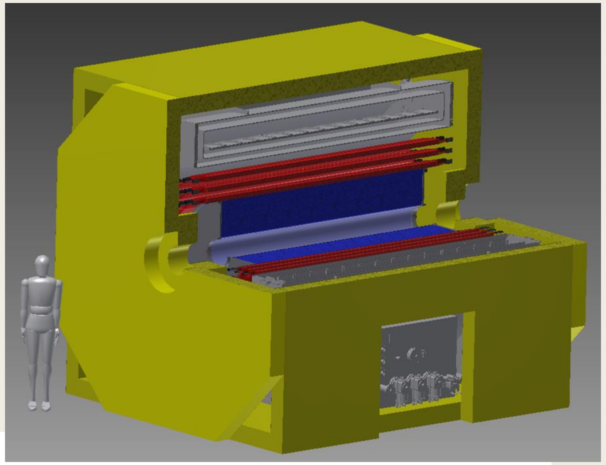

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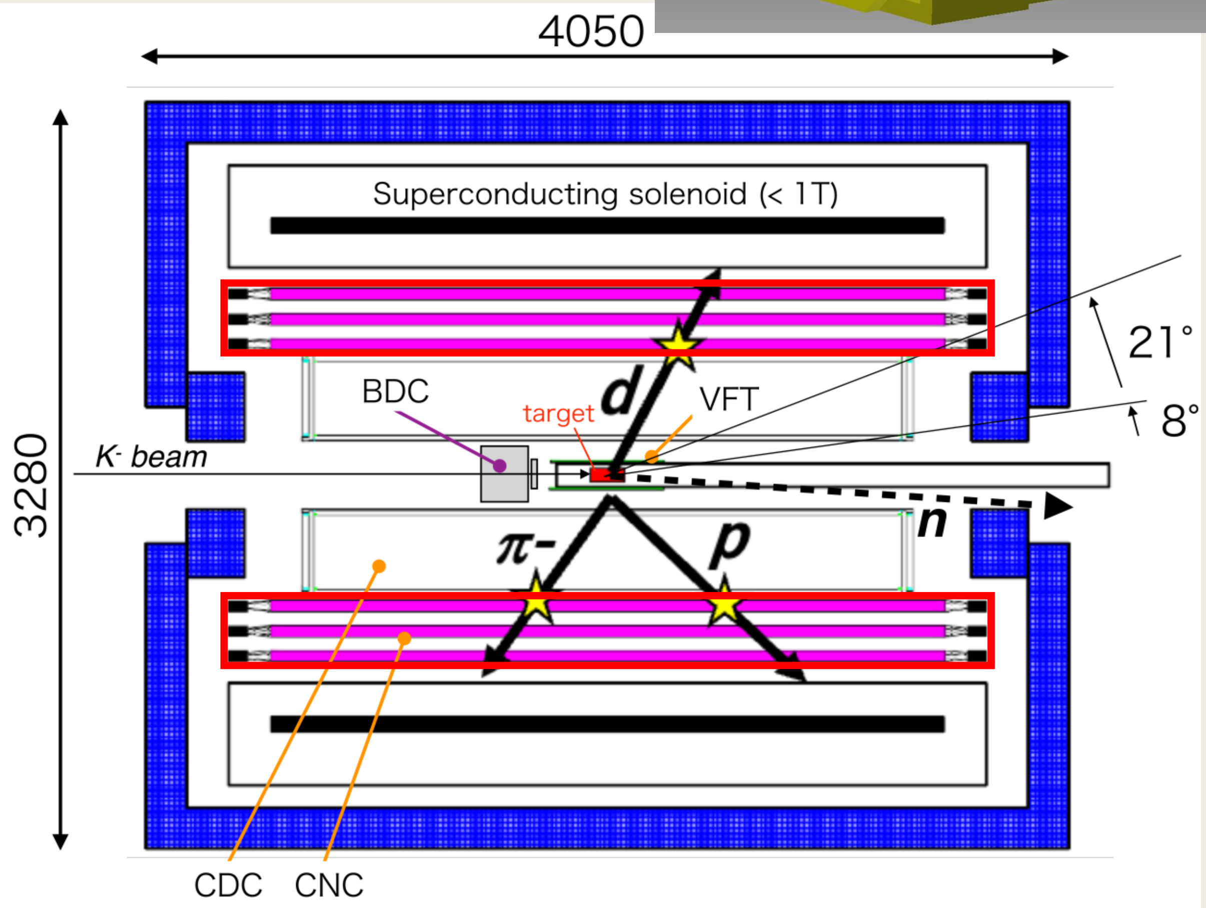
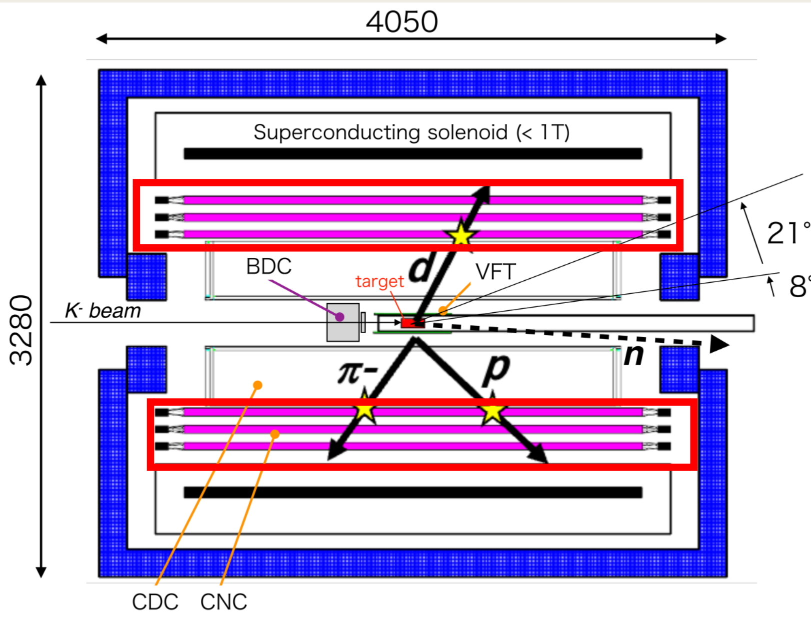
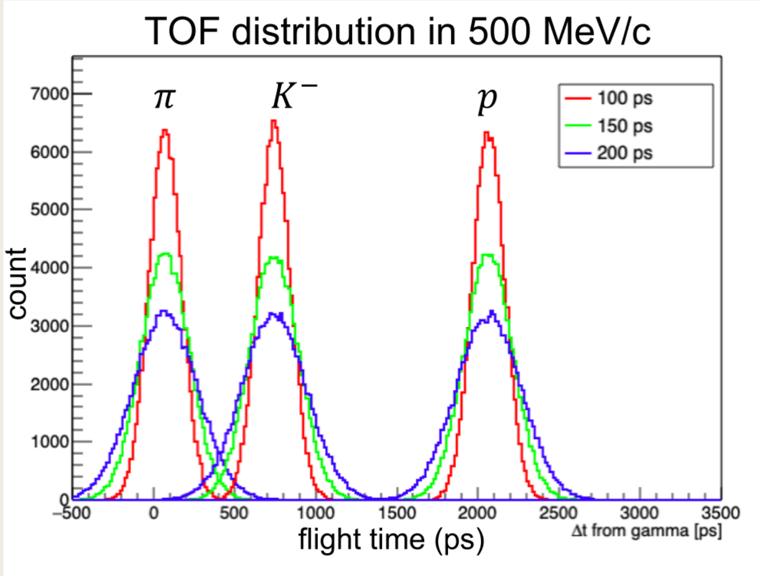


Cylindrical Neutron Counter

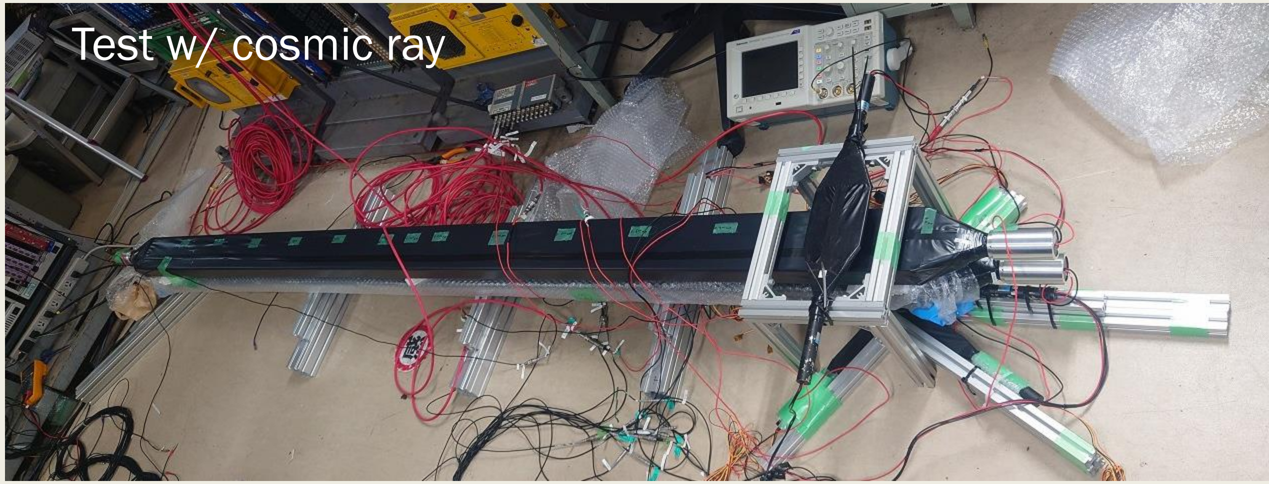


- scintillator array: 32 segments for one layer
  - *3 layer (full setup), One layer (1st phase)*
  - *(T)50mm, (W)~130mm, (L)~**3,000mm** Long!*
    - Important to realize large solid angle
    - neutron detection efficiency ～1% per 10mm thickness
      - *Existing CDS:30 mm*
  - *1.5-inch FM-PMT [H8409(R7761)]*
    - Worked well in the existing CDS environment (0.7T magnetic field along PMT)

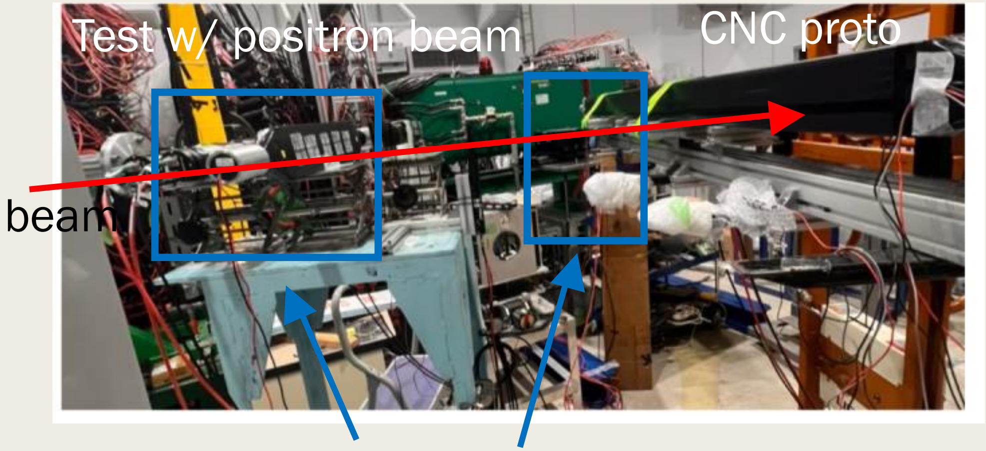
- Required timing resolutions
  - *For identification of charged particles (π, K, p, ...)*
    - →150 ps (flight length ～50cm)
  - *For detection of neutron with good position resolution*
    - →100 ps (δz～2cm)



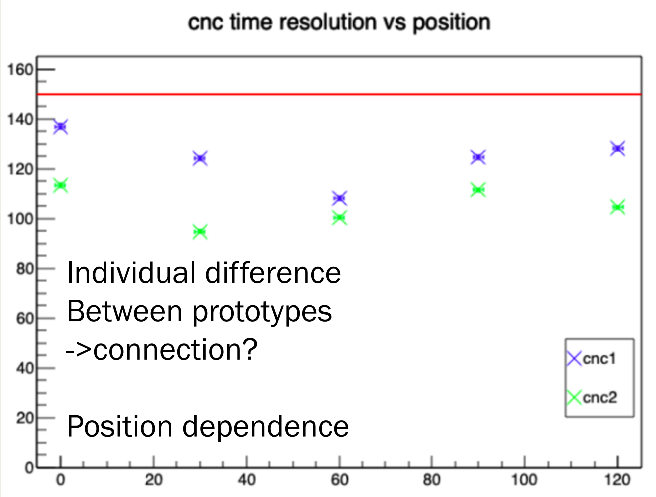
Cylindrical Neutron Counter



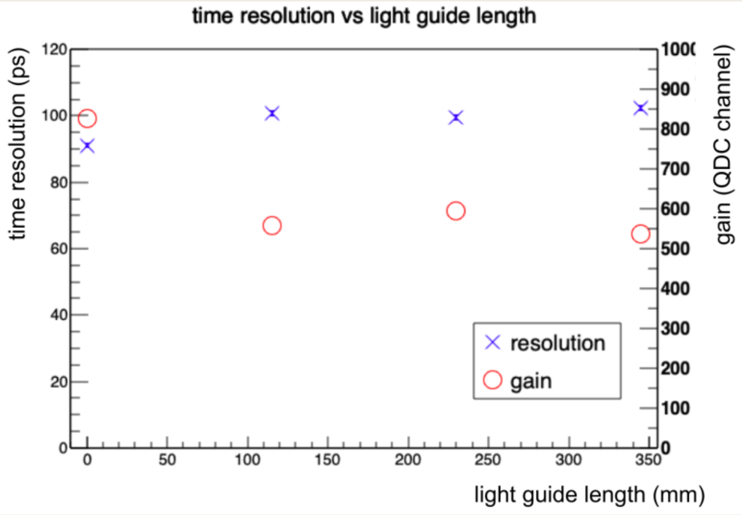
- Present status
  - *Prototype tests are ongoing...*
  - *150 ps resolution is achieved*
  - *To achieve 100ps resolution, more studies are needed.*
    - Position dependence? w/ or w/o light guide?



Trigger/timing reference counters

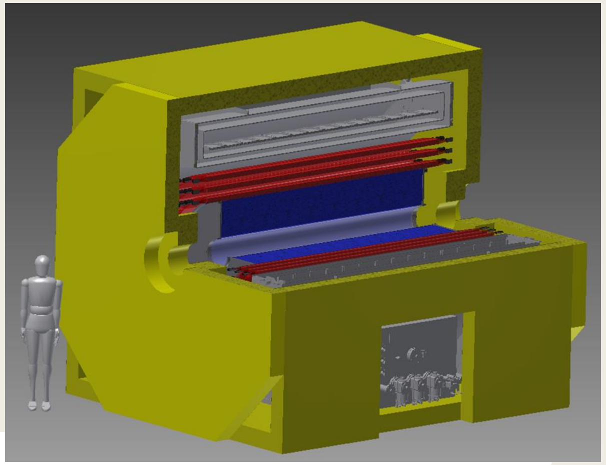


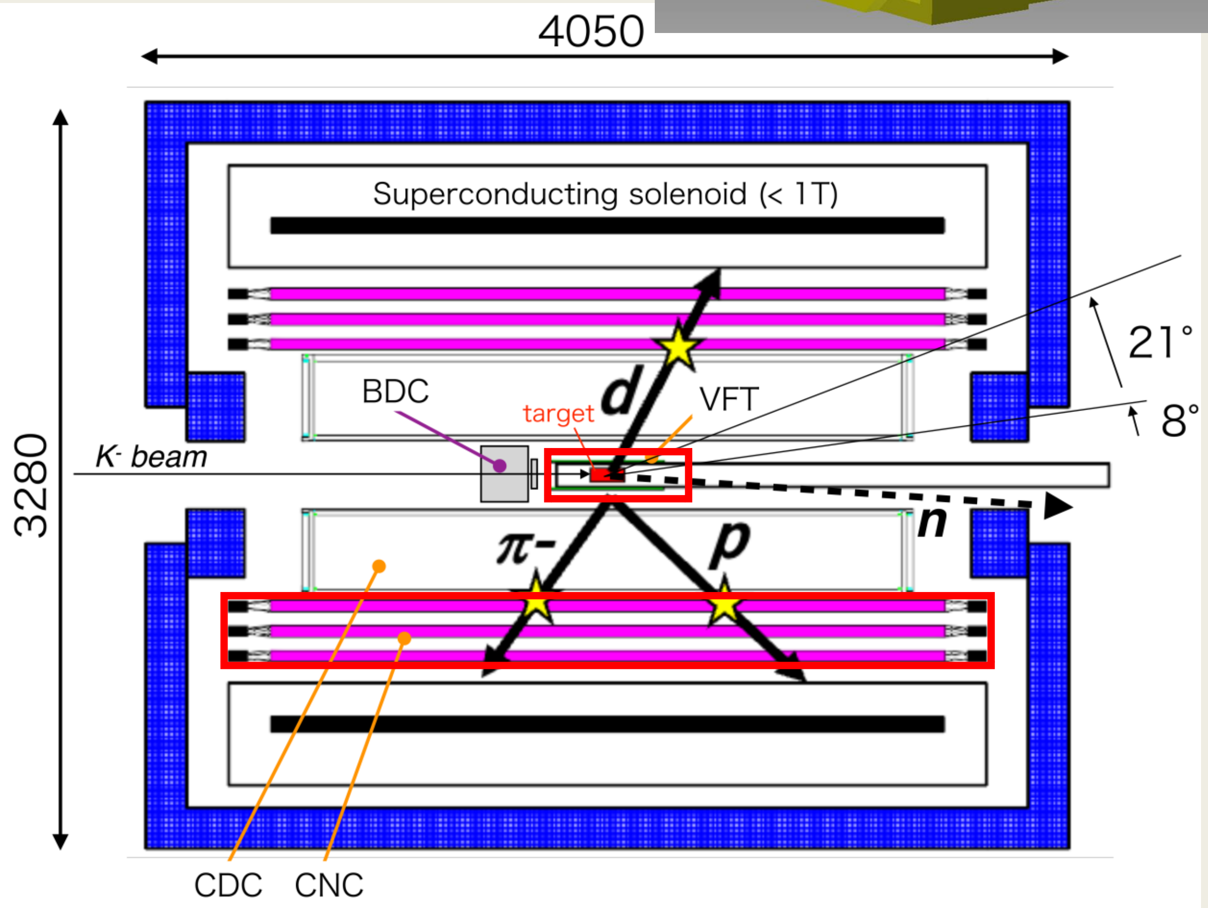
Distance from center



New Spectrometer system (New CDS)

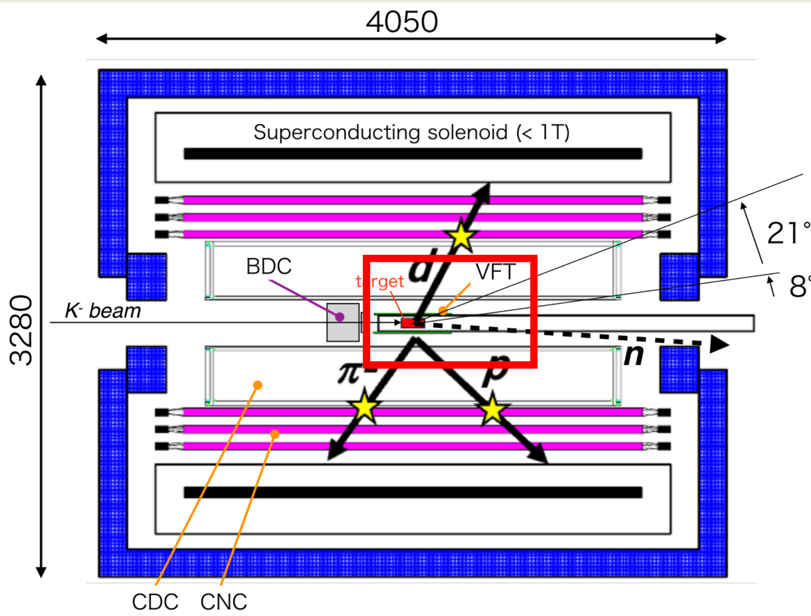
- Large acceptance solenoid spectrometer
  - *Superconducting solenoid magnet*
  - *CDC (Cylindrical Drift Chamber)*
  - *CNC (Cylindrical Neutron Counter)*
  - ***VFT (Vertex Fiber Tracker)***
- Improved performances for compared to existing CDS
  - *Solid angle ×1.6 (59%→93%)*
    - covers $29° < \theta_{lab} < 151°$
  - *Neutron detection efficiency*
    ×1.7×nlayer×solid angle improvement





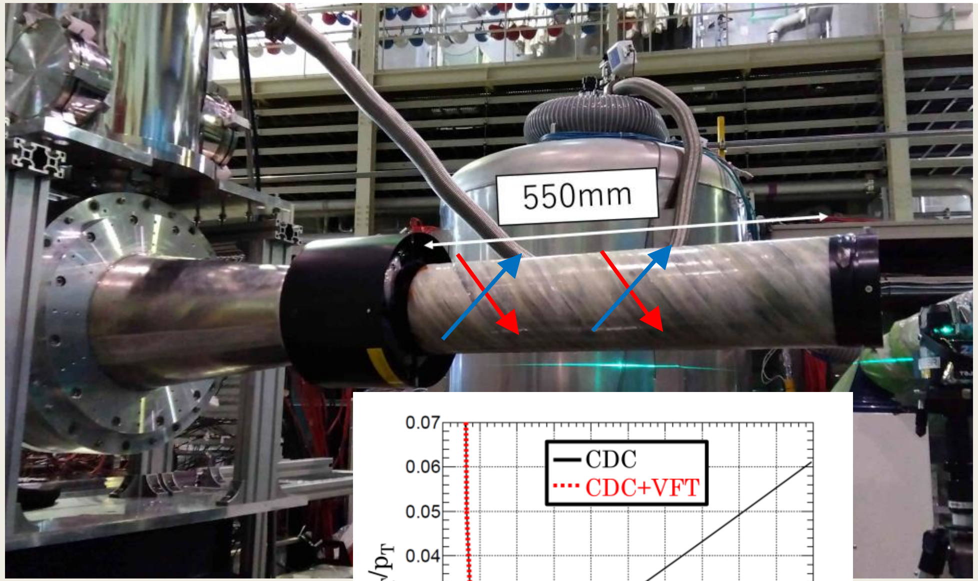
Vertex Fiber Tracker

- Detector just around the target (r～55 mm)
  - *4 layers of Φ1mm scintillating fibers – UU'VV'*
    - Each layer tilted by ～±50 degrees
  - *896 (= 224x4) channels*
  - *Readout: MPPC + "CIRASAME" module*
    - Multihit TDC for Leading and Trailing edge

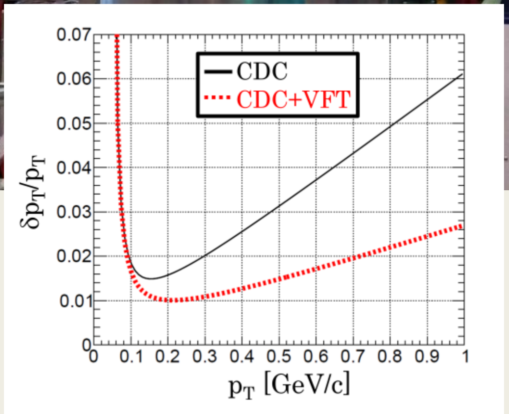


- Spectrometer performance will be improved
  - *Vertex resolution of the beam direction ~1cm (CDC only) → ~1mm (CDC+VTF)*
  - *Solid angle covering the target region 97% of 4π (15°-165°)*
  - *Momentum/mass resolution L=~30cm (CDC only) → ~43cm (CDC+VFT)*

Efficient for Background reduction

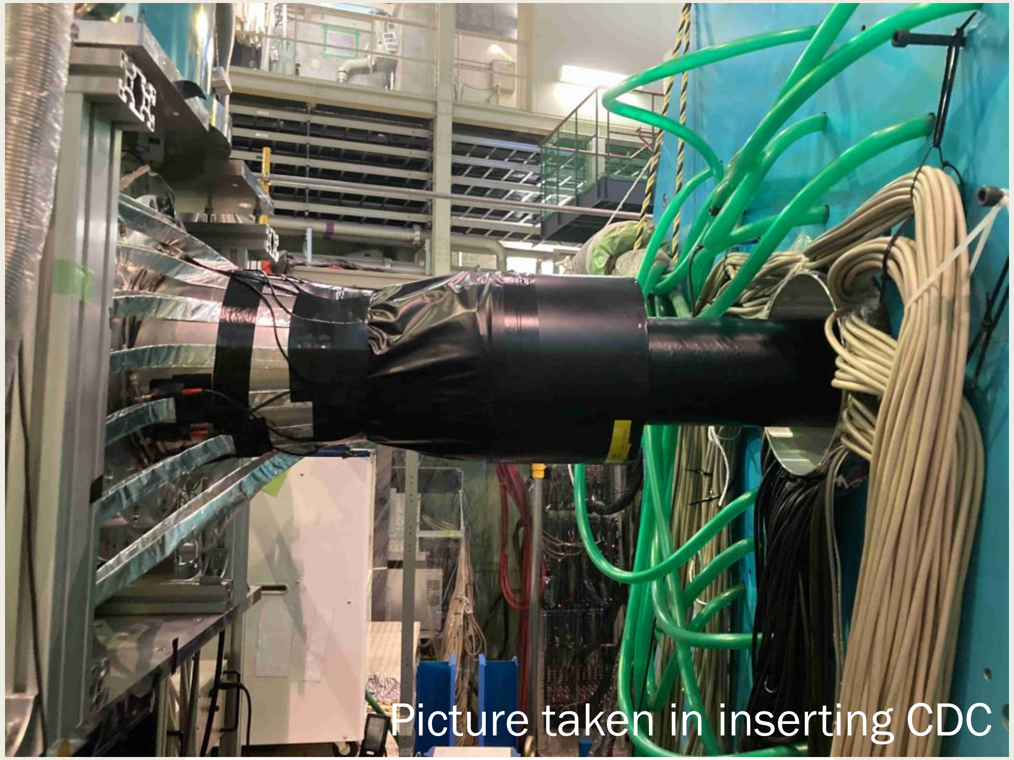


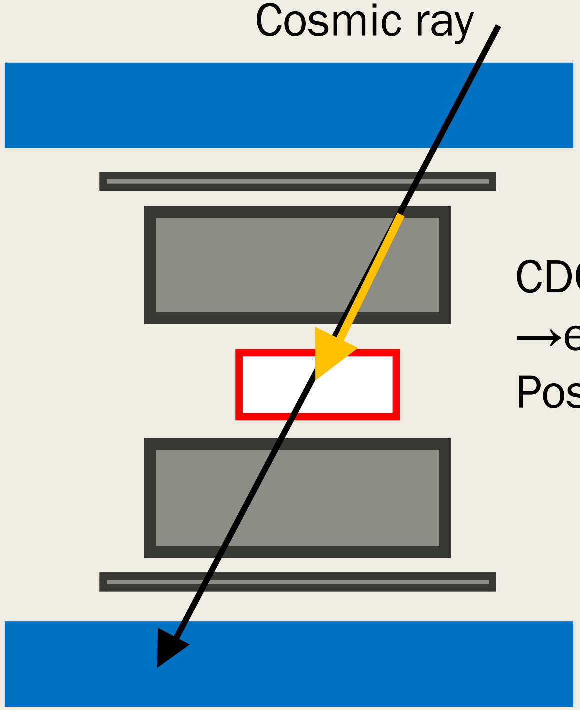
$$\left(\frac{\delta P_T}{P_T}\right)_m = \frac{P_T \sigma_{r\phi}}{0.3 L^2 B}\sqrt{A_N}$$



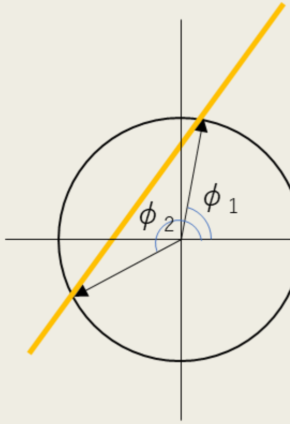
Vertex Fiber Tracker

- Present status
  - *Inserting VFT to existing CDC, test data was taken*
    - w/cosmic ray and π^-, (K^-) beam
    - Analysis and performance evaluation is ongoing…



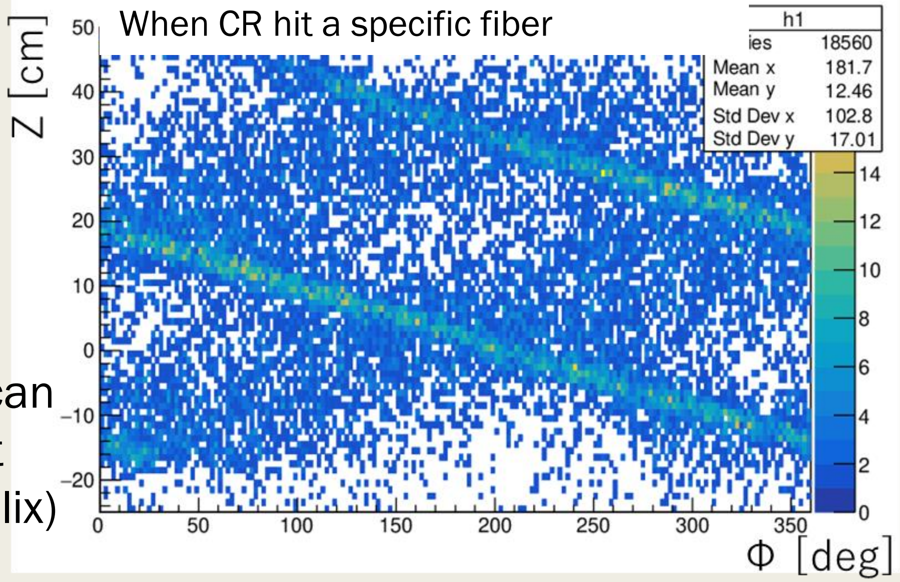


CDC Track
→expect
Position on VFT



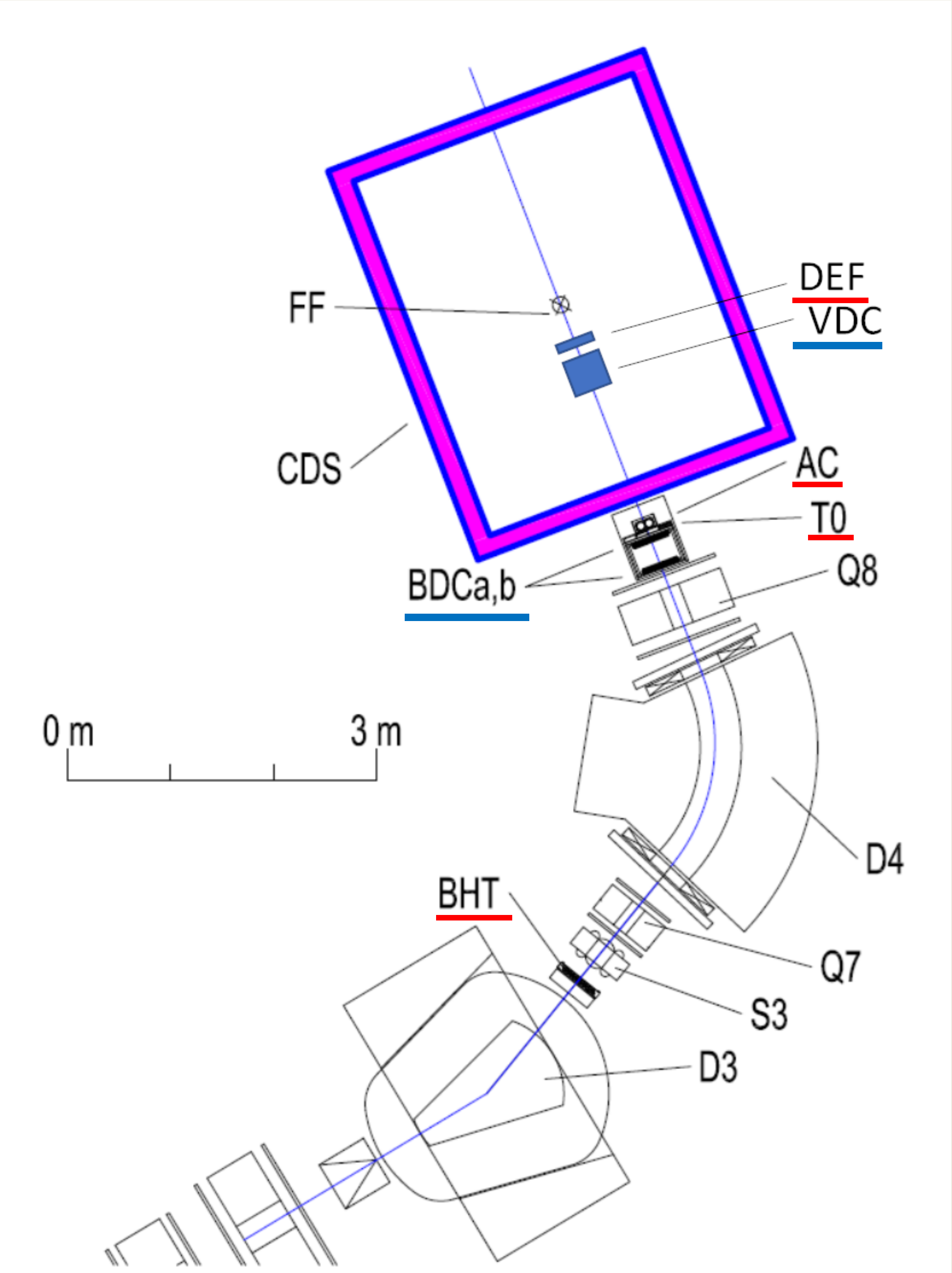
Geometry of a fiber can be seen as a straight line in Z-Φ plane! (helix)

Expected position on VFT
When CR hit a specific fiber



Beamline Detectors

- Expected beam condition
  - *K^-: 420k /(spill=4.2 s)*
  - *K^-/π^- ~0.7 (1.2M particle /spill)*
- Trigger counters
  - *Three hodoscopes(BHT, T0, DEF)*
  - *One Aerogel Cherencov counter*
- Chambers
  - *Two beam line chambers (BDCa,b)*
  - *A chamber just before target (VDC)*
- Basically, existing detectors can be used.



Beamline Detectors

- Expected beam condition
  - *K-: 420k/(spill=4.2 s)*
  - *K-/π- ～0.7 (1.2*
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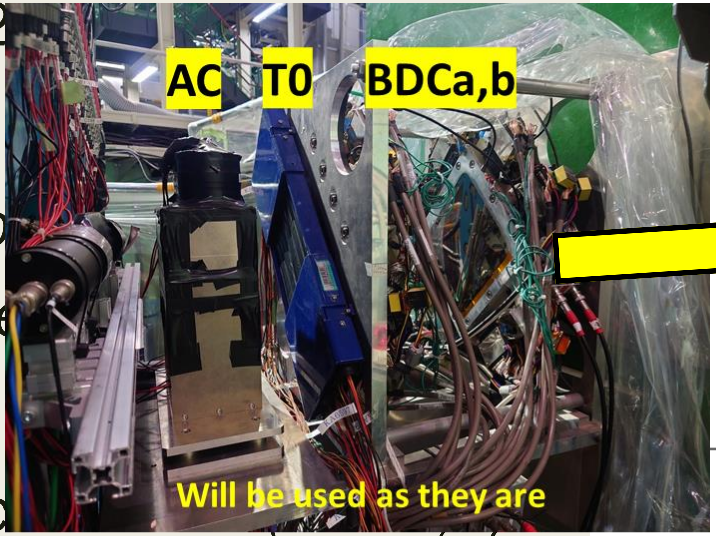
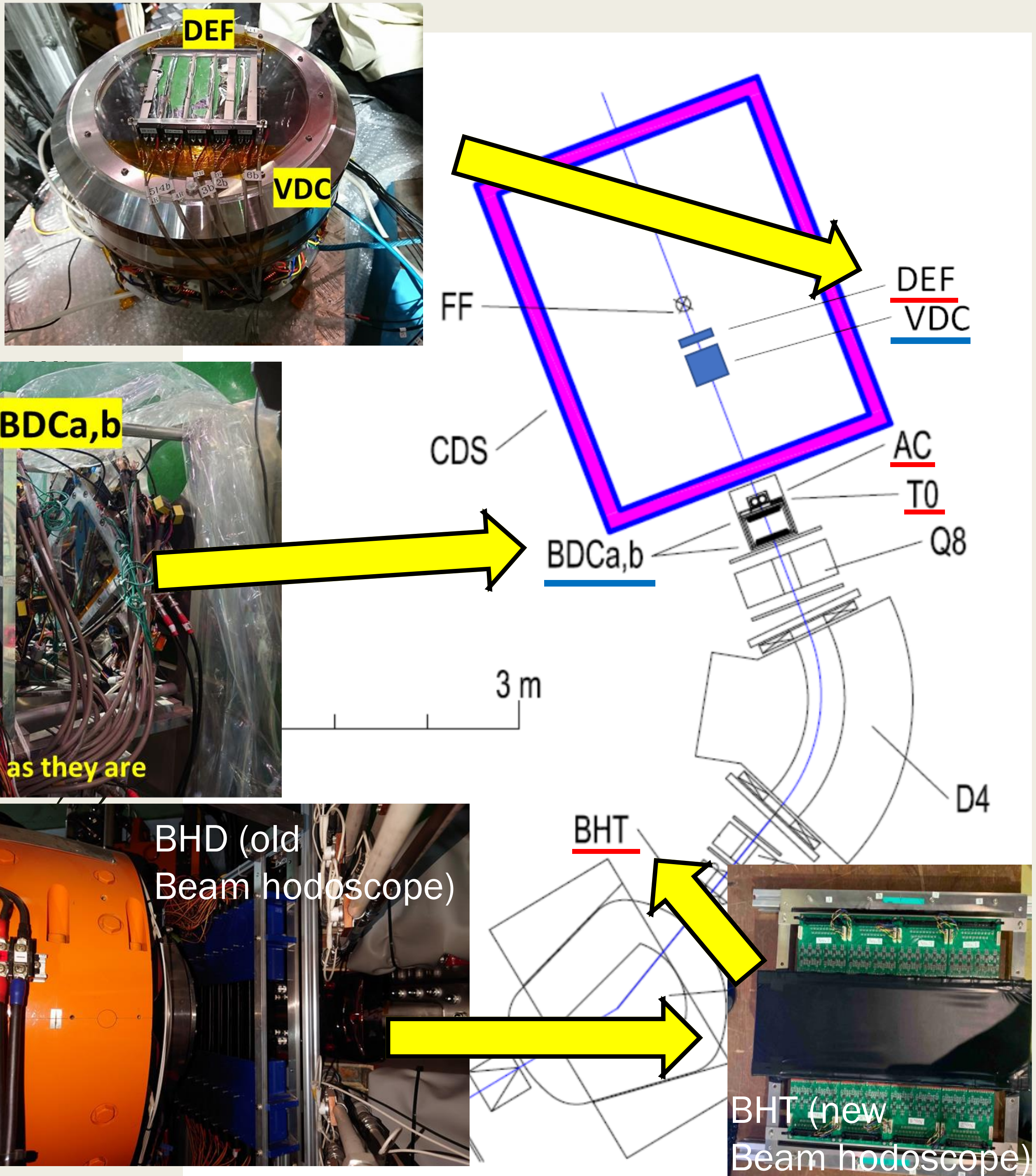




Construction schedule

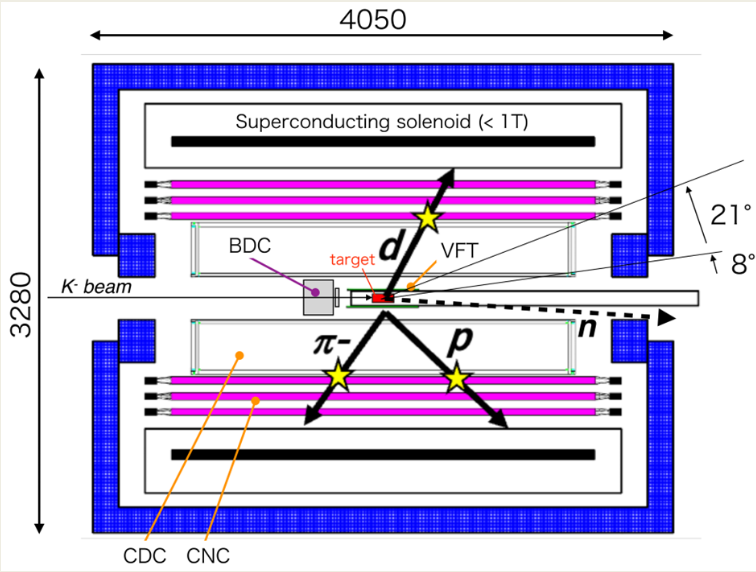
- Installation and Beam line upgrade will start the end of FY2024- or beginning of FY2025.
- Commissioning run for new spectrometer will be performed the end of FY2025.
  - *LH_2 target, for about 1 week beamtime*
- physics run with new spectrometer will be started FY2026
  - ***1st step: J-PARC E80 experiment***
  - *Search for KbarNNN via ^{4}He(1 GeV/c K^-,n) reaction*

<table>
<tr><th rowspan="2"></th><th colspan="4">FY2022</th><th colspan="4">FY2023</th><th colspan="4">FY2024</th><th colspan="4">FY2025</th><th colspan="2" rowspan="2">FY2026-</th></tr>
<tr><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td></tr>
<tr><td>SC Sorenoid</td><td colspan="2">Design</td><td colspan="2">Purchase
(Yoke, SC wire)</td><td colspan="7">Construction</td><td colspan="3">Installation & test</td><td rowspan="4">Integration</td><td rowspan="4">Commissioning</td><td rowspan="4">Physics run</td><td rowspan="4">Analysis & publication</td></tr>
<tr><td>NC</td><td colspan="7">Design & prototype test</td><td colspan="4">purchase & assemble</td><td colspan="3">test & commissioning</td></tr>
<tr><td>CDC</td><td colspan="7">Design</td><td colspan="2">Construction</td><td colspan="5">test & commissioning</td></tr>
<tr><td>VFT</td><td colspan="3">Design & production</td><td colspan="5">test & performance evaluation</td><td colspan="6"></td></tr>
<tr><td>K1.8BR beam line</td><td colspan="9">E73 (lifetime measurement of hypertriton) experiment</td><td colspan="3">E72 (Λ* resonance search with HypTPC)</td><td colspan="3">upgrade</td><td colspan="3">1st experiment with new CDS:
J-PARC E80 experiment</td></tr>
</table>

Summary

- J-PARC E15 experiment @ K1.8 BR beamline successfully founded the existence of “K^-pp” states using the in-flight $K^- + ^3He$ reaction with an exclusive analysis of the Λpn final state.
- Further investigations for kaonic nuclei are needed

  to establish the kaonic nuclei
  - *Mass number dependence?*
  - *Spin and parity of the “K^-pp”?*



- We are developing a new magnetic spectrometer
  - *Large solid angle (93 % of 4π)*
  - *thicker plastic scintillator (×5 neutron detection efficiency)*
  - *Momentum/position resolutions will retain or will be improved*
- Construction will be finished in FY2025 andPhysics run with new spectrometer will be started FY2026
- If you are interested in or/and have ideas for the experiments with the spectrometer, we are welcome!