Sept. 28, 2023
@ Tsukuba U.

Tomonaga Center Symposium
at the 50th Anniversary of the University of Tsukuba

Origins and Evolution of the Universe, Matter and Life

28/Sep/2023 (Thu)
Tomonaga Center for the History of the Universe (TCHoU)
Institute of Pure and Applied Sciences, University of Tsukuba

Particle and Nuclear Physics at J-PARC

Takashi Kobayashi
J-PARC, JAEA/KEK

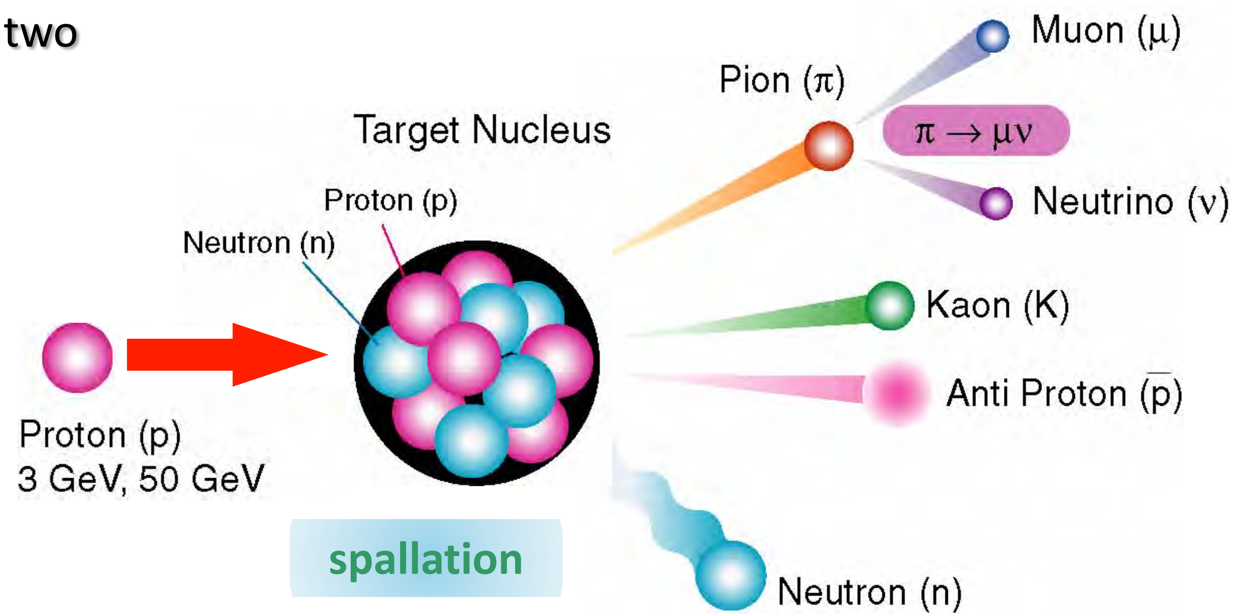
Versatile Quantum Beams for Microscopic World

J-PARC

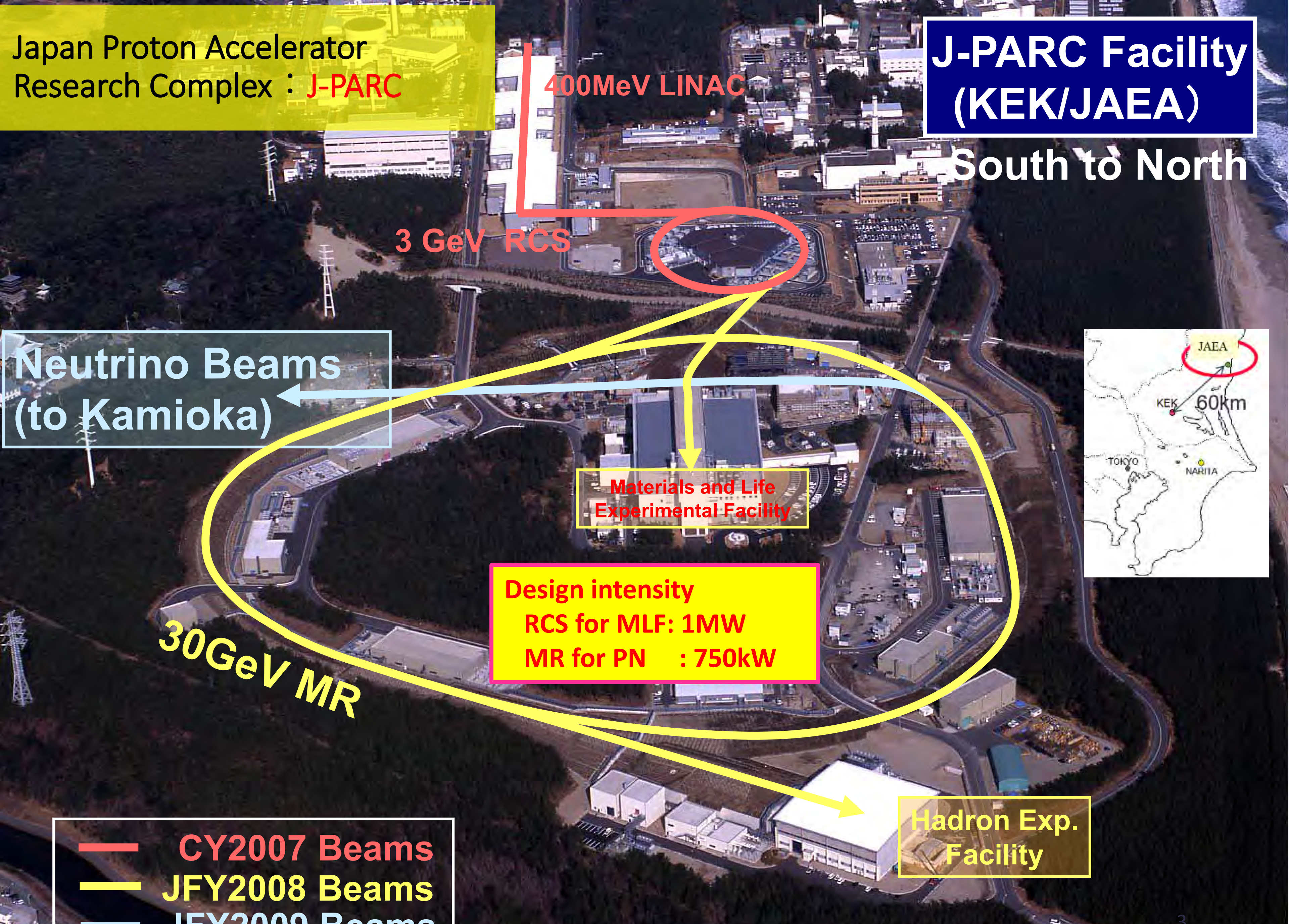
Japan Proton Accelerator Research Complex

Power-frontier accelerators and multi-purpose user facilities

Jointly operated by two organizations:
- KEK, and
- JAEA

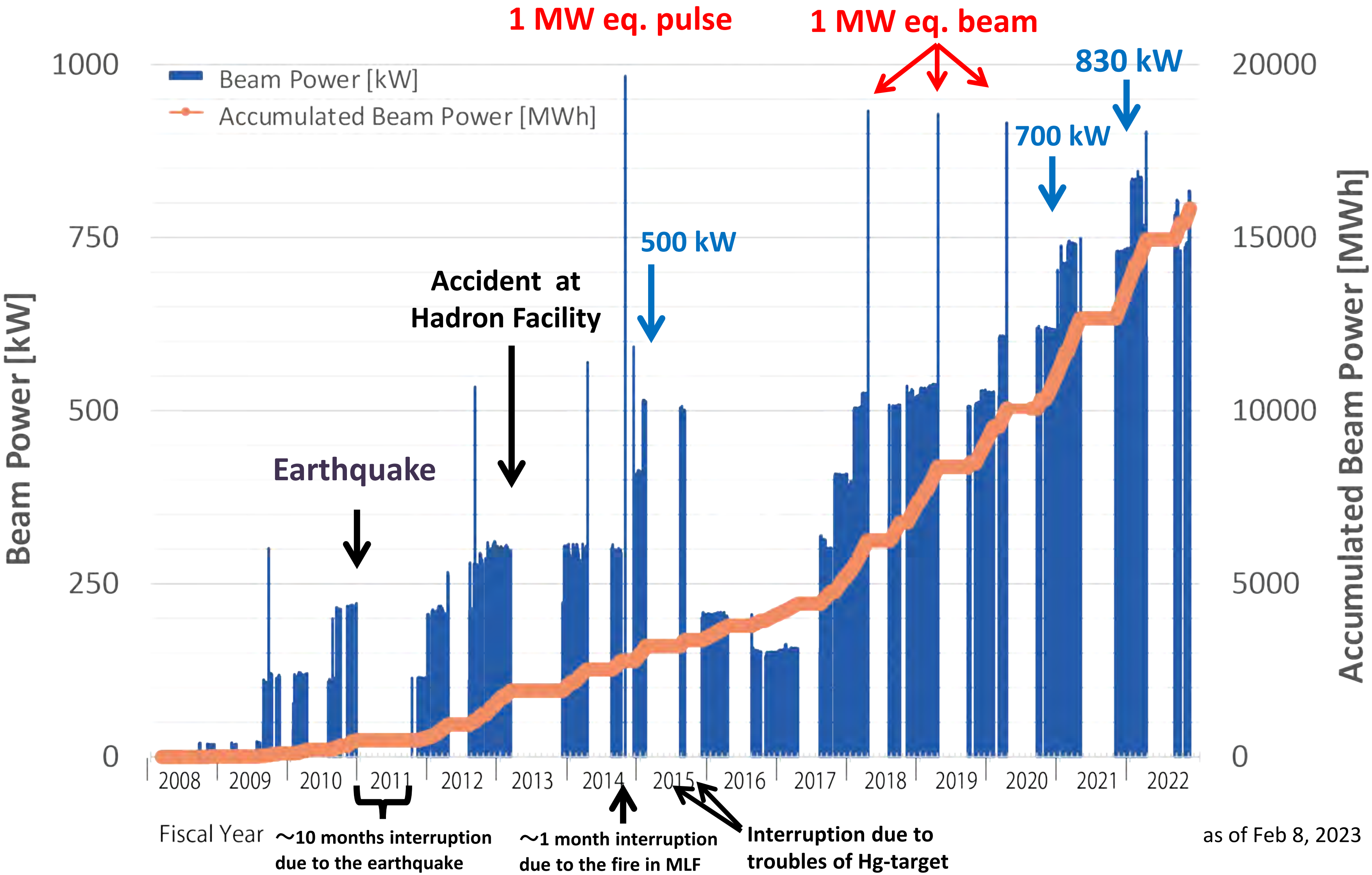


Variety of secondary particles generated with high-energy and high-intensity protons



Bird's eye photo in January of 2008

Beam Power History at MLF



Main ring upgrade plan

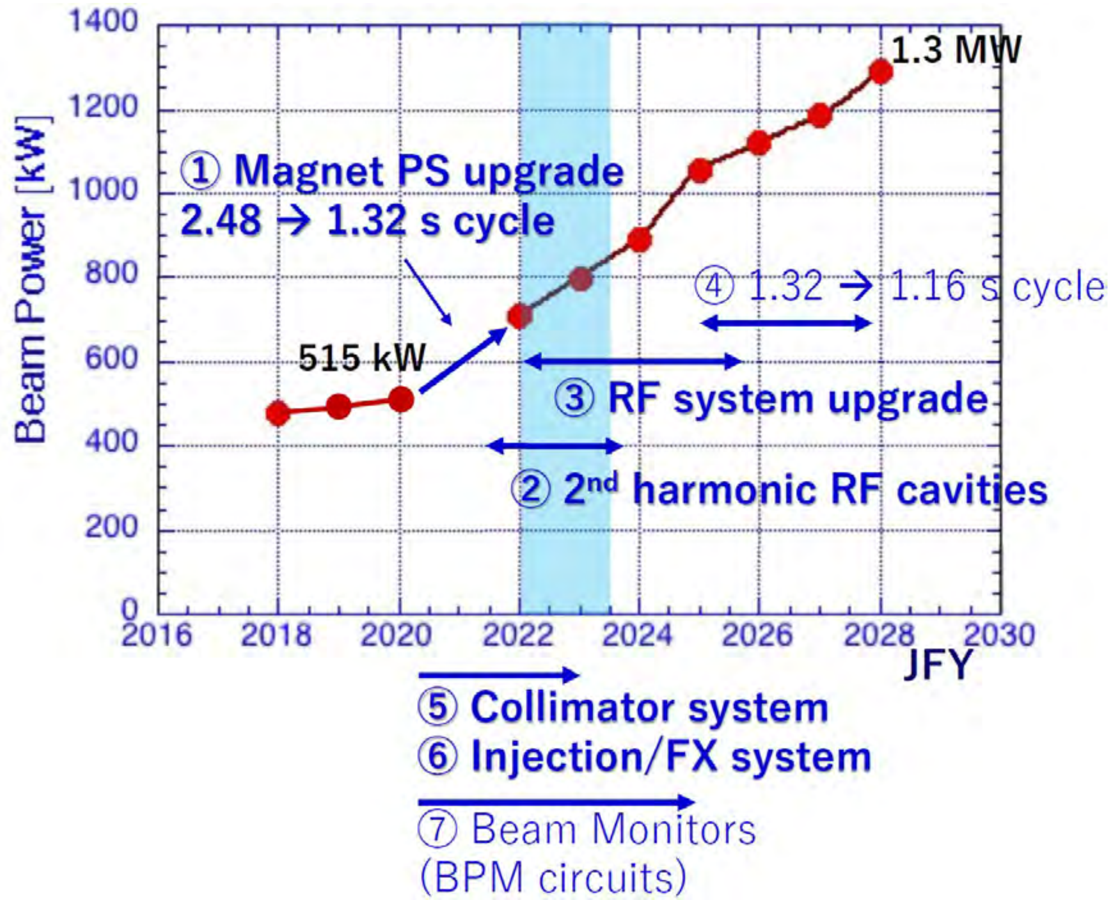
More Rapid Cycle:

2.48 s → 1.32 s → 1.16 s

- Main Power Supply to be renewed
- High gradient RF Cavity
- Improve Collimator
- Rapid cycle pulse magnet for injection/extraction

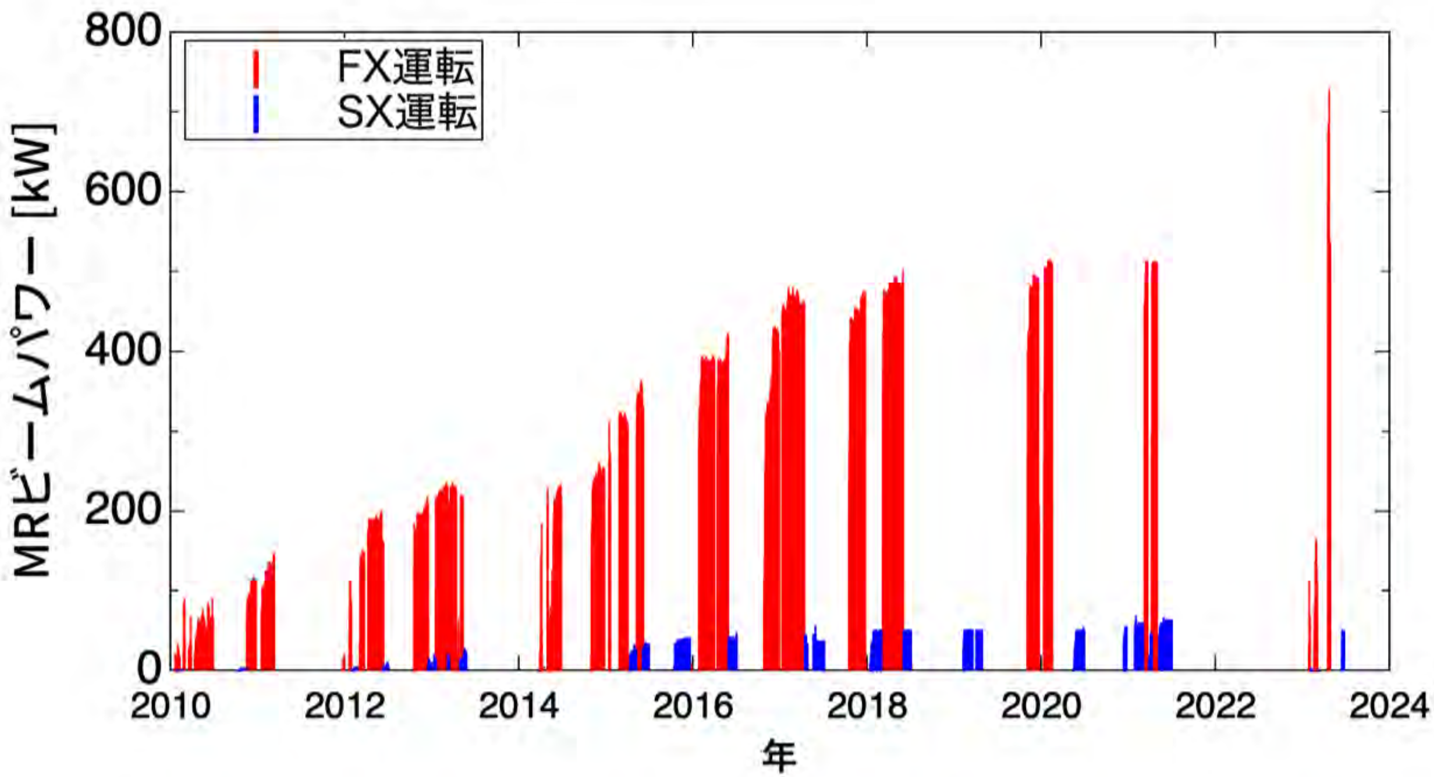
More Protons / Pulse：

- Improve RF Power
- More RF Systems
- Stabilize the beam with feedback



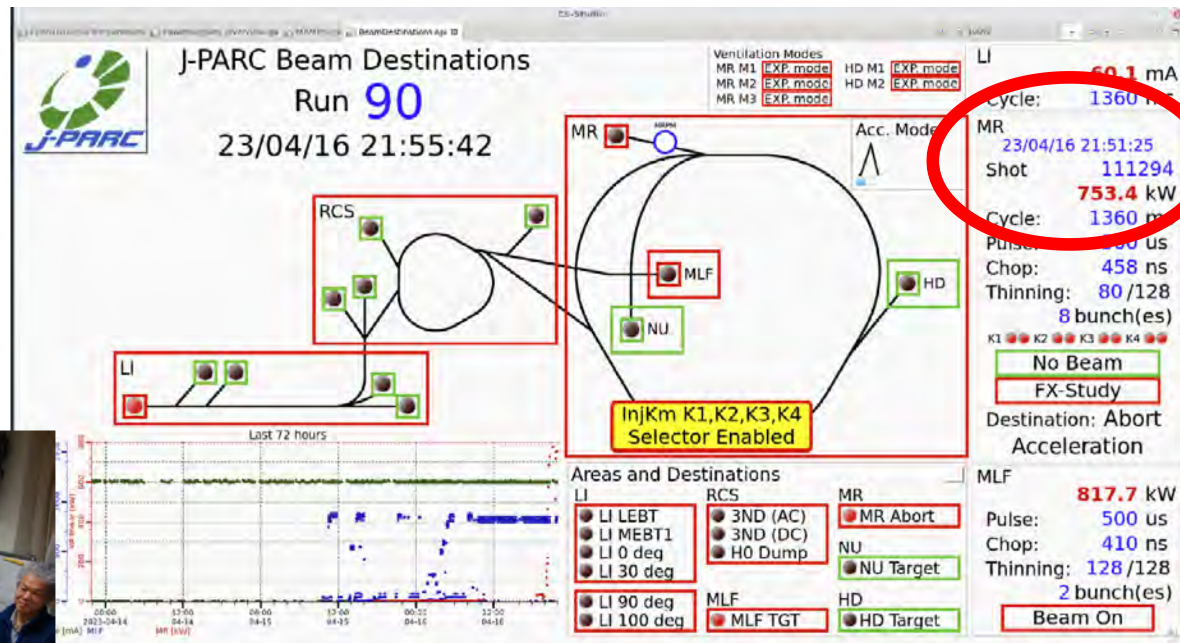
In April 2023
Successful demonstration of
MR-FX 30 GeV acceleration
766 kW eq. (2.17e14 ppp) in 1.36 s cycle

MR beam power history



- Before upgrade
  - FX:535kW、SX64kW achieved
- After upgrade
  - FX:750kWeq@1.38s (single shot) acceleration succeeded
  - SX: 50kW/5.2s cycle w/ 99.5% ext. eff

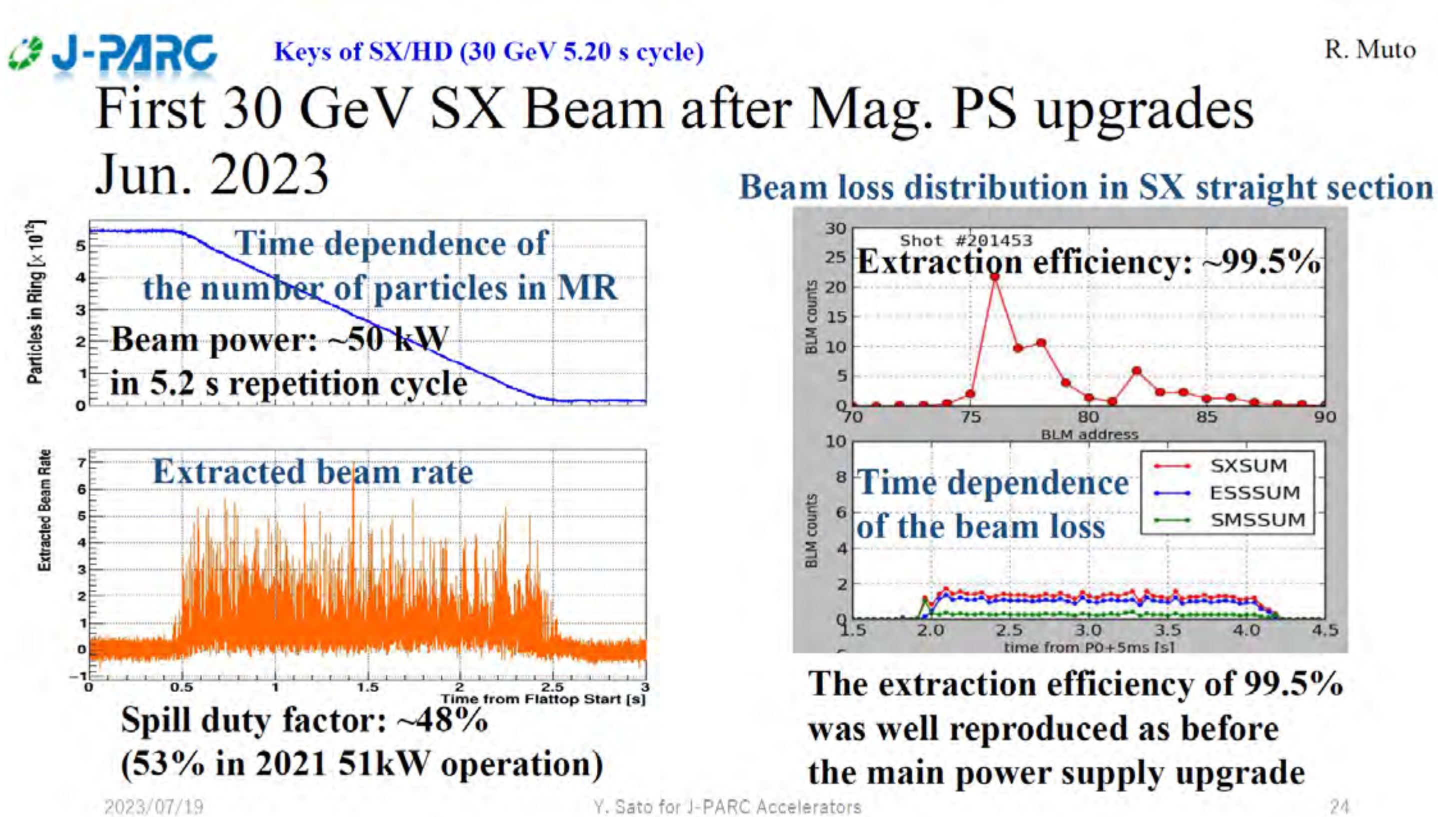
J-PARC MR: High power study



- 令和5年4月16日 21時51分
  J-PARC MRが、試験運転（1-shot運転）において、
  所期性能である750 kW相当の陽子ビームの30 GeV加速に成功
- 今夏にRF空洞一台を増設、その後、ビーム試験を重ねて
  ビームロスの低減を図りながら利用運転時の陽子ビーム強度を
  徐々に増加 ➡ 750 kWの定常運転を目指す

750kWeq pulse acceleration succeeded

SX30GeV study in June



- SX/HD 30 GeV tunings and operation in 5.2 s cycle were performed for a week
- Achieved 50 kW in 5.2 s cycle after the upgrades with extraction efficiency 99.5%.

Science at MLF w/ n/mu

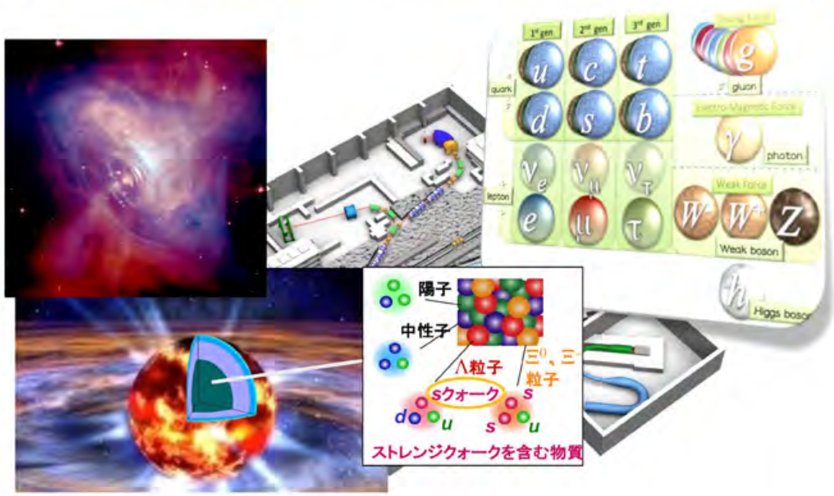
物質や Materials and life sciences 起源を探る

Neutrino experiment

Explore origin of matter in the universe

Hadron experiments

Explore origin of matter formation



Development Accelerator Driven nuclear transmutation System: ADS

Materials & Life Science Experimental Facility

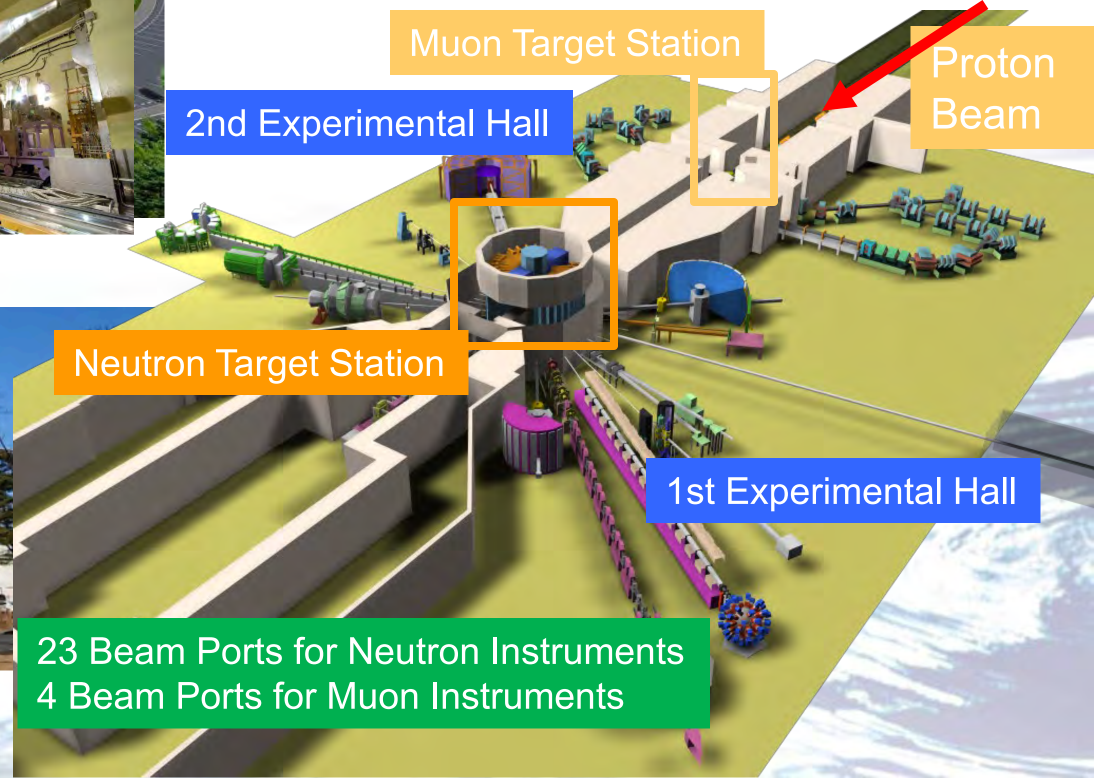
J-PARC, MLF

■ Neutron & Muon Beam Facility for Materials & Life S

The World Highest-Class Neutron & Muon Sources.

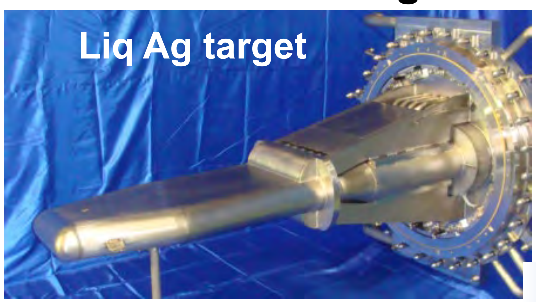
Neutron Source:

- 1MW
- Liq. Mercury Target
- Liq. H_2 Moderators



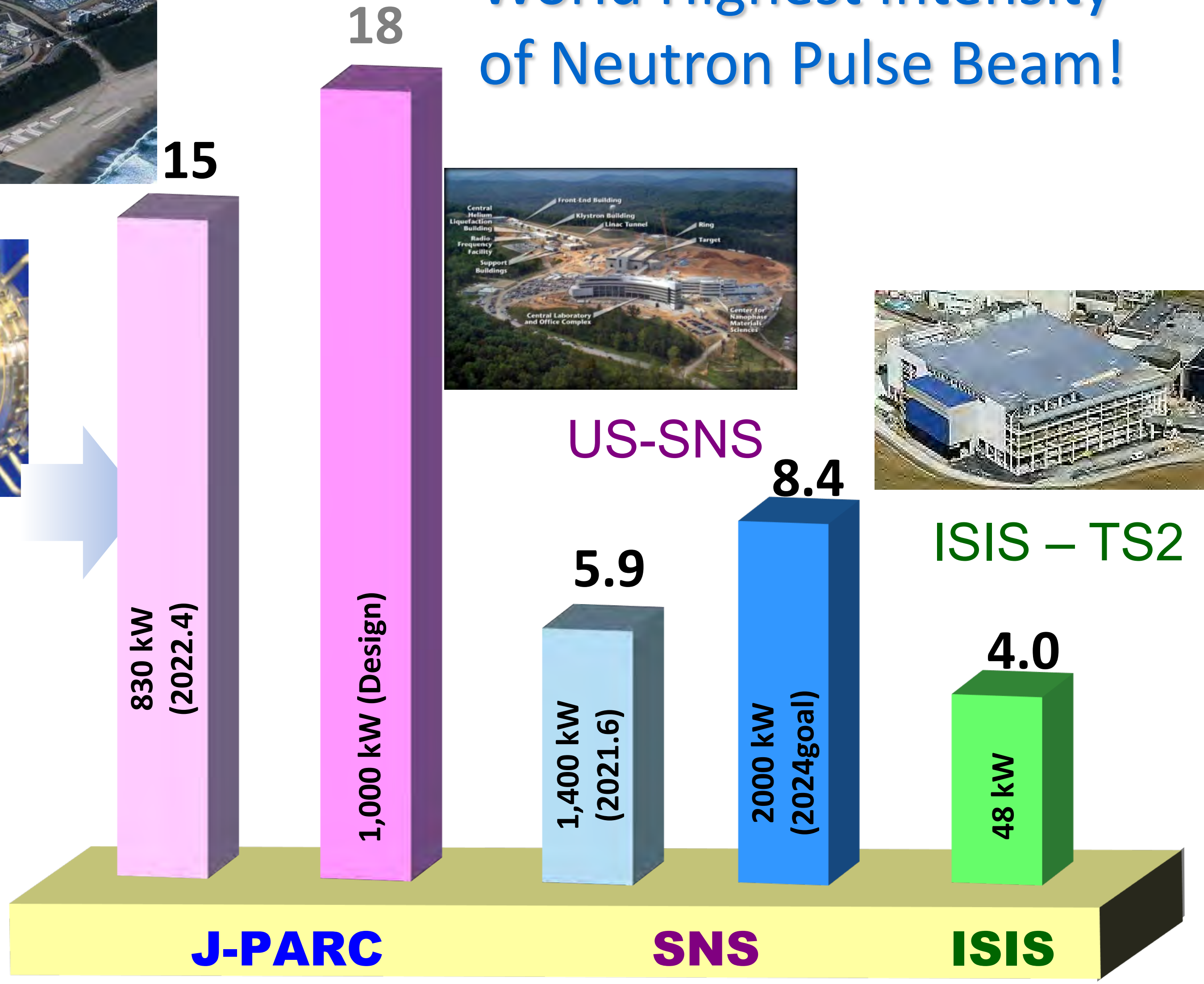
Materials and Life Science Facility（MLF）

JAEA's technologies



Coupled moderator

World Highest Intensity of Neutron Pulse Beam!



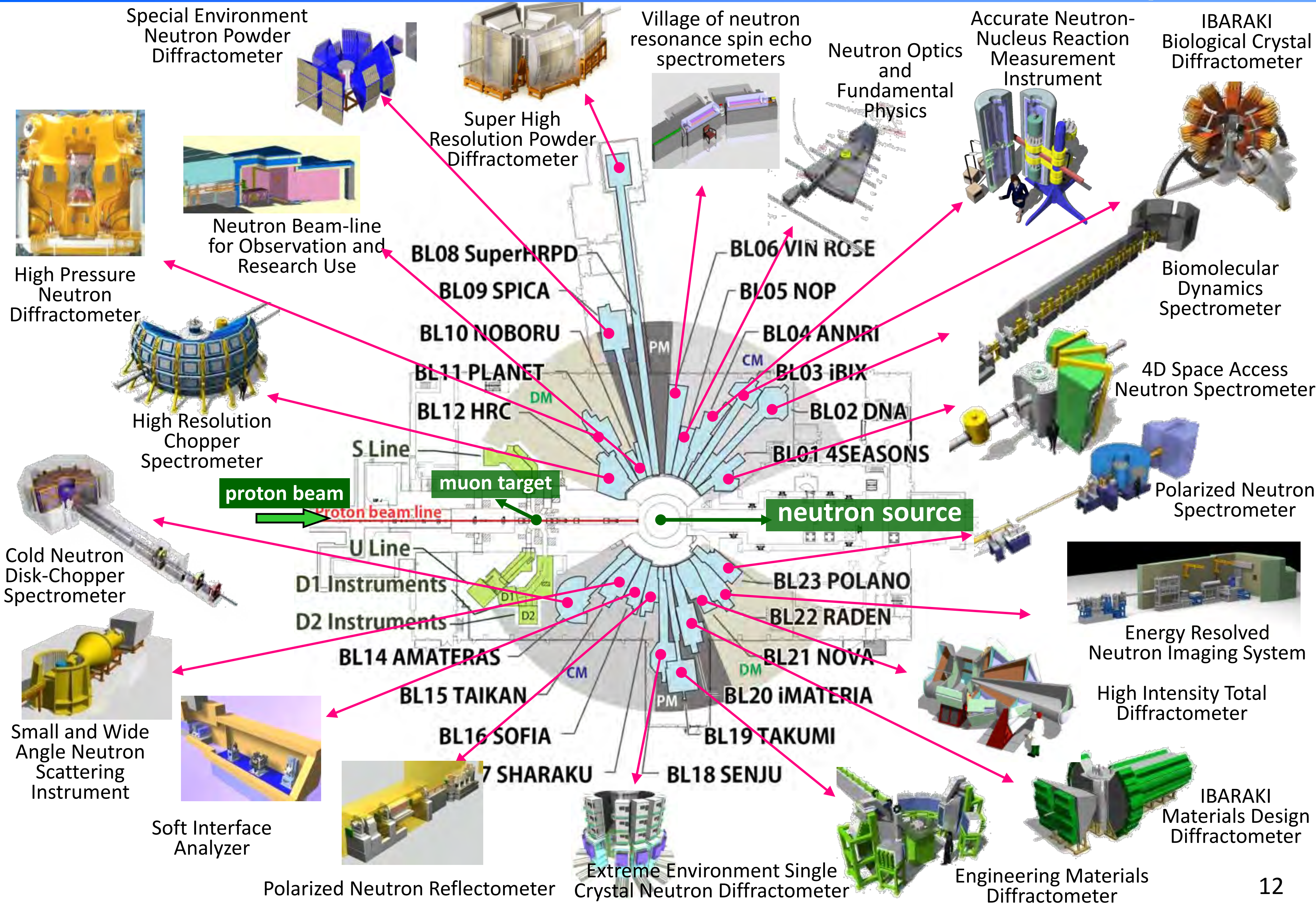
US-SNS

ISIS – TS2

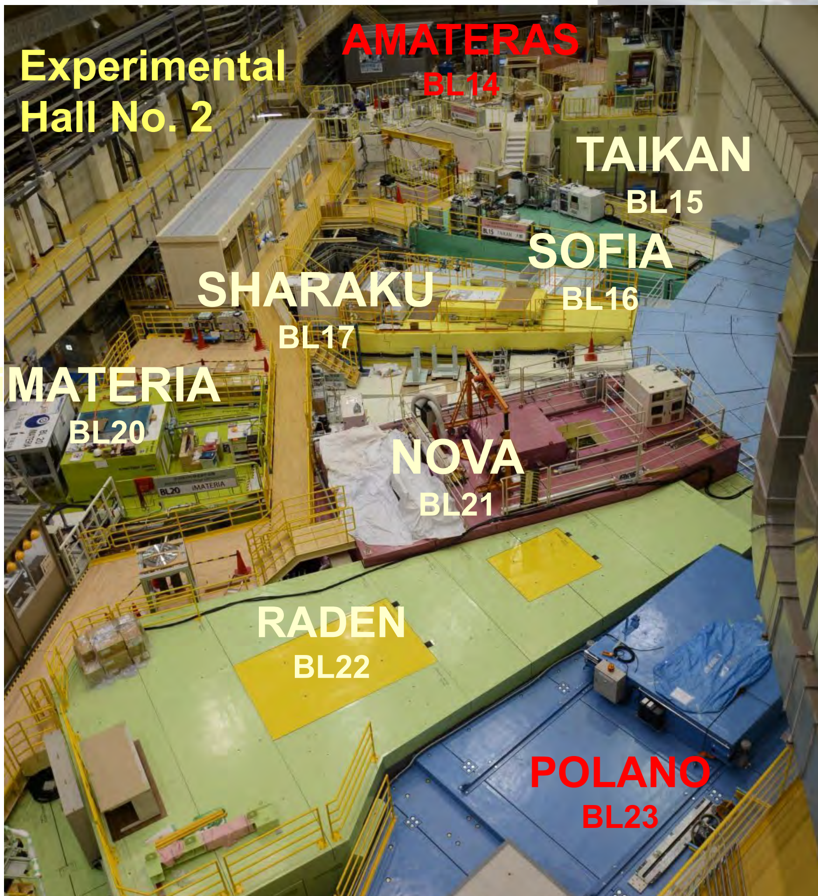
Unit： 10^{12} n/(sr･pulse)

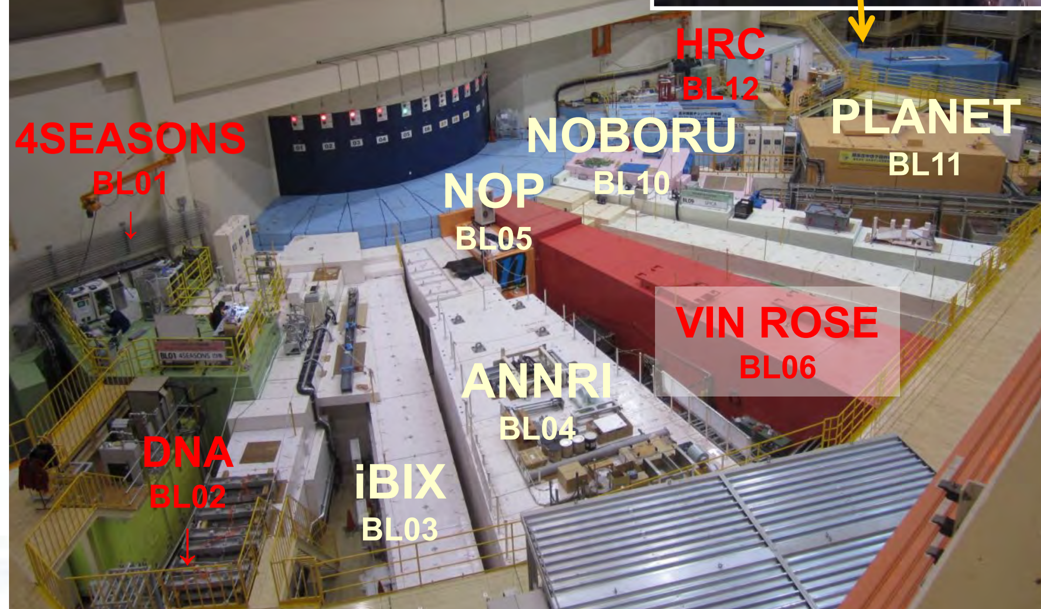
Neutron Instruments in MLF

23 beam ports
21 in operation

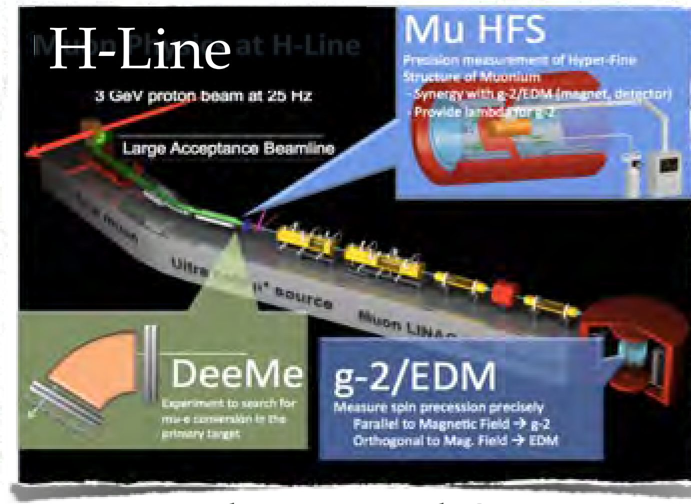


Neutron Instruments at MLF





Muon Facility MUSE @ MLF

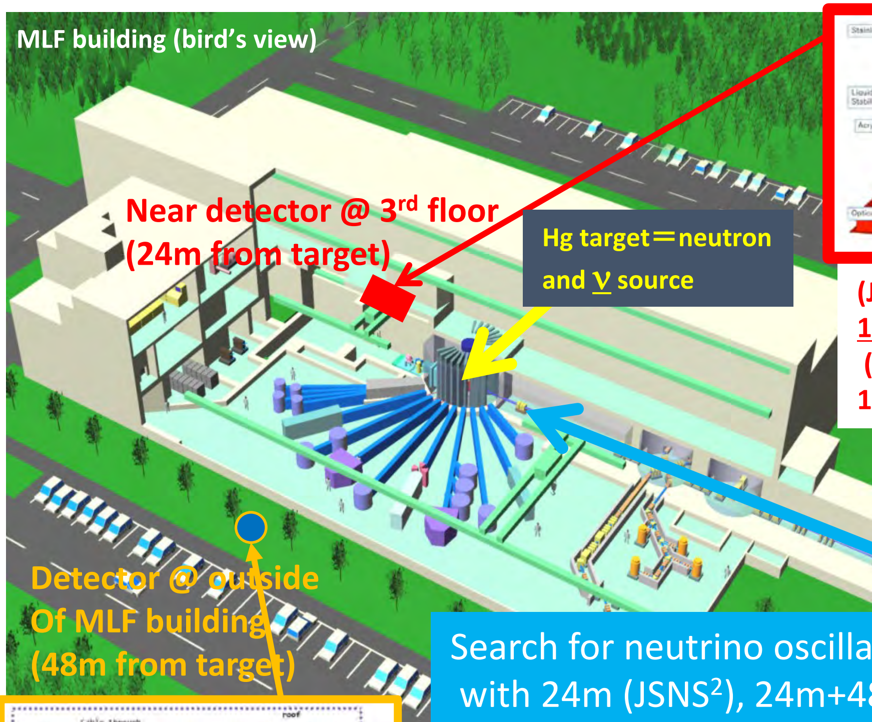


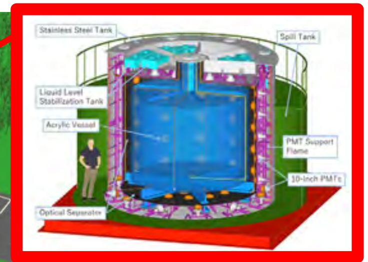
Fundamental Science with a large scale international coll.

Particle and nuclear physics at J-PARC

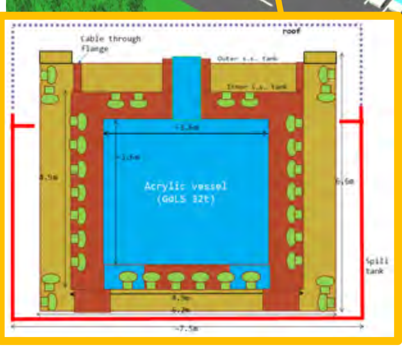
Experiments at MLF

Sterile neutrino search experiment: JSNS^2(-II) Experiment



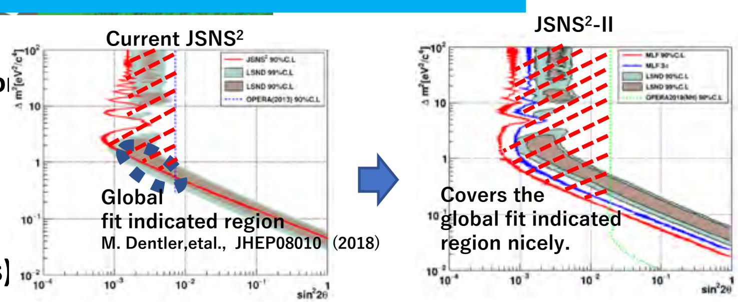


(JSNS^2): near detector
17t GdLS fiducial
(4.6m dia. x 4.0m height
120 10" PMTs)



(JSNS^2-II:
New far detector
32t GdLS

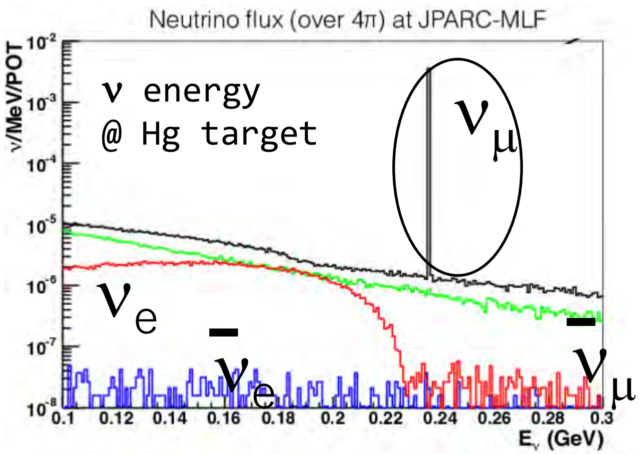
(6.2m dia, x
6.2m height
~228 10" PMTs)

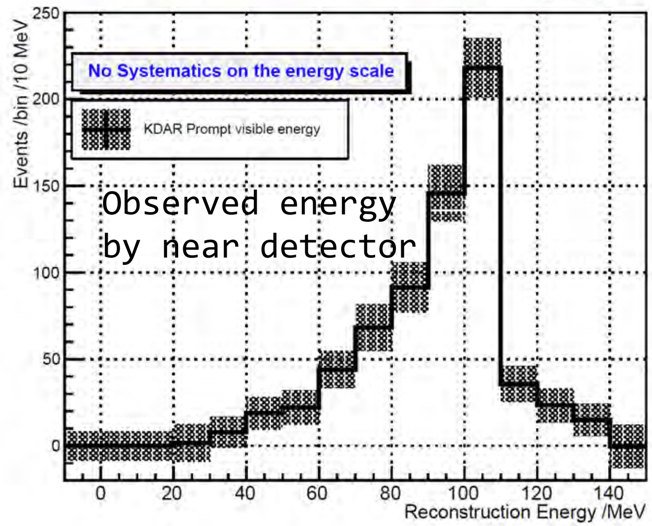


(JSNS^2) : 1MW x 3 years
- 24m (near) detector only
- 3 long physics data taking in 2021-2023. (~30% planned data)
- Analyses are on-going.

(JSNS^2-II): 1MW x 5 years
- Proposal in 2020 (arXiv:2012.10807)
  - New far detector will be added.
    - 32 tons fiducial
    - 48m baseline.
  - Good sensitivity for low Δm^2
  - 2022/4:stage-2 (out of 2) approval from J-PARC
  - ***Aim to start in 2024.***

Status





Near detector

→ Blind analyses for sterile ν search are on-going

→ Observed νμ from $K^+\mu2$ @ Hg target

→ Monochromatic energy ν

→feedback to ν interaction models.

→ Beam / detector are working well.

Far detector

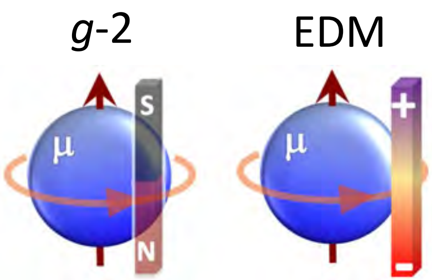
→ 172 out of 228 PMTs were installed.

→ All PMTs except for veto region.

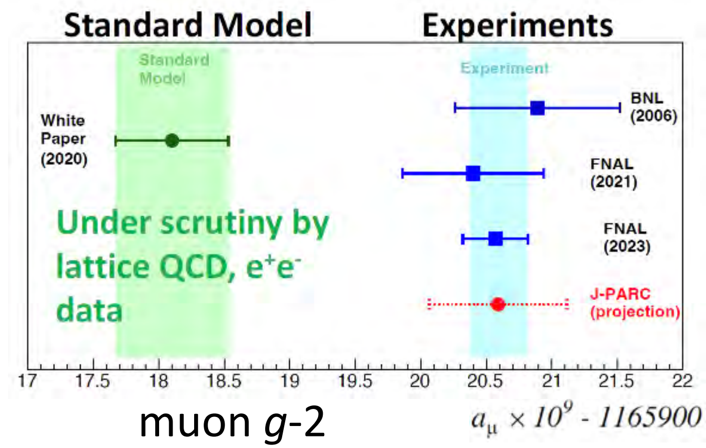
→ Rapid progress on construction

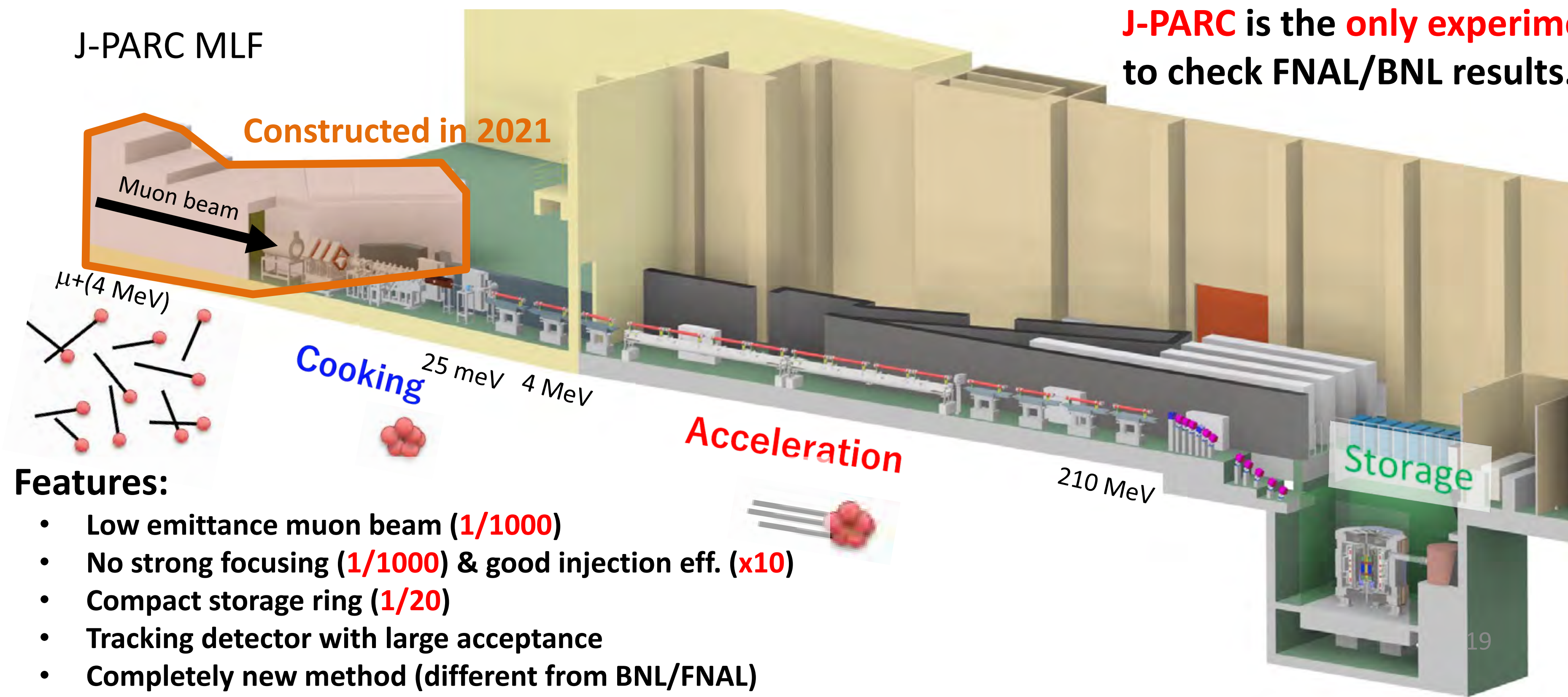
→ aim to start data taking in 2024.

J-PARC muon *g*-2/EDM experiment



- Aim to reach
  - **μ g-2: 450ppb**
  - **μEDM: 1.5e-19**
- Aiming for data taking from 2028





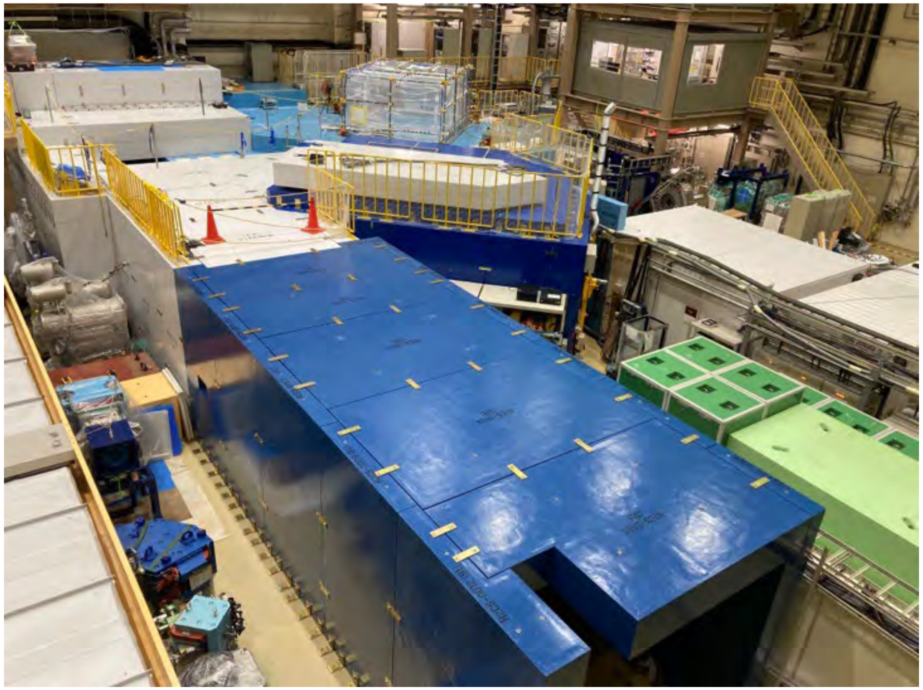
J-PARC is the only experiment to check FNAL/BNL results.

Features:

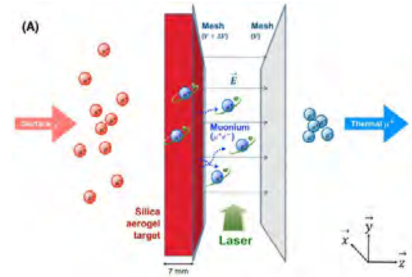
- **Low emittance muon beam (1/1000)**
- **No strong focusing (1/1000) & good injection eff. (x10)**
- **Compact storage ring (1/20)**
- **Tracking detector with large acceptance**
- **Completely new method (different from BNL/FNAL)**

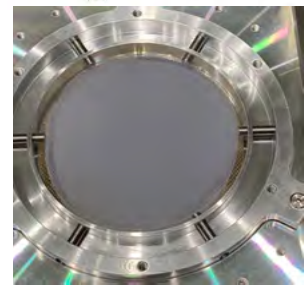
J-PARC muon *g*-2/EDM experiment

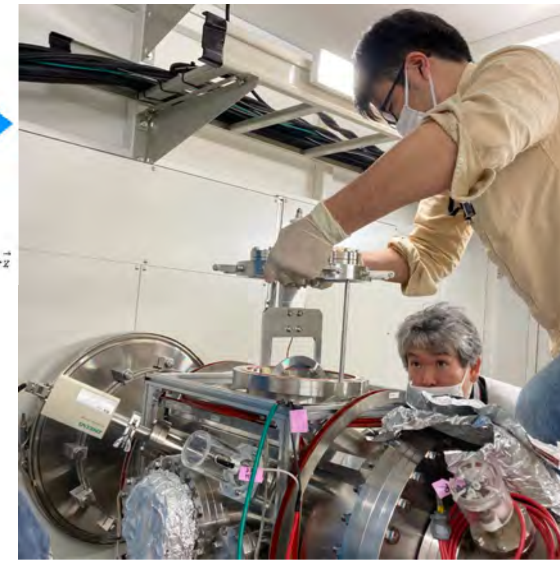
New radiation shields for beamline extension (2022)



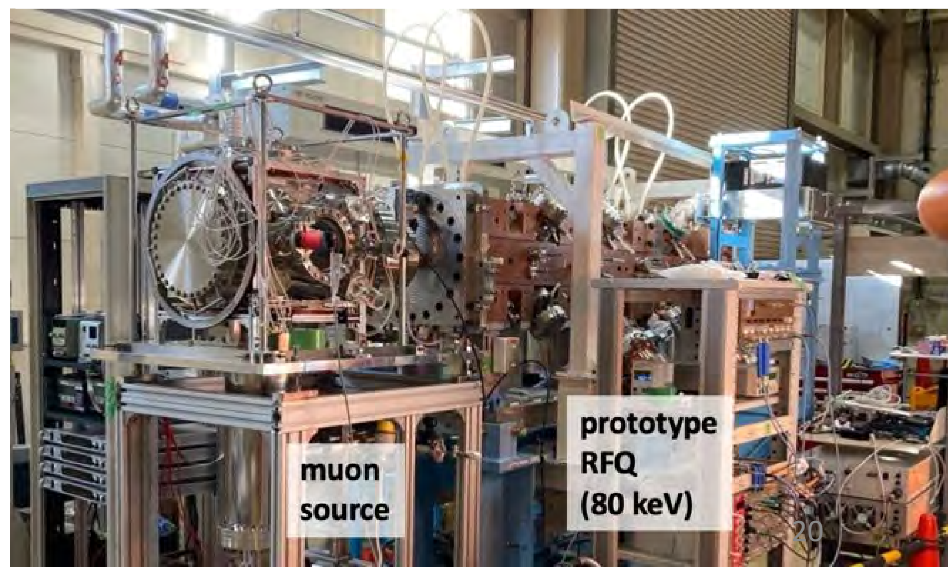
Muon cooling test (2022~)



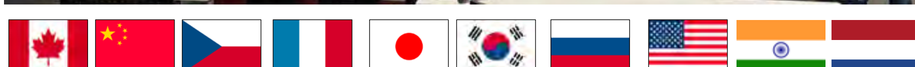




Muon cooling + acceleration test (2024~)

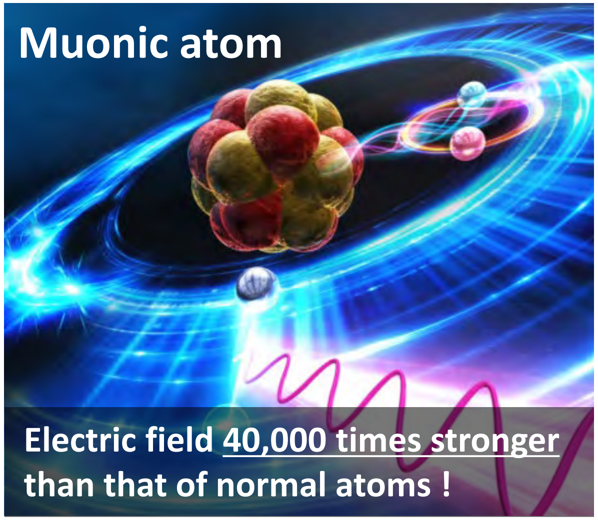


The collaboration (114 members fro 10 countries)



study @ Muonic atom J-PARC MLF

(1) Muonic X-ray measurement[Phys. Rev. Lett. 130, 173001 (2023)]



Goal : **Verify strong-field QED** with spectroscopy of muonic atom X-rays

Key technology : **Superconducting TES microcalorimeters**

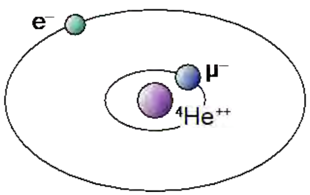
Result : Proof-of-principle experiment with μNe atom

Outlook : scheduling the main experiment (μAr atom) in next February, 2024.

towards QED test in ultra-strong electric fields **beyond the Schwinger limit**

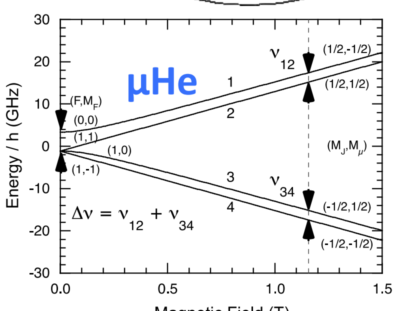
by introducing new TES detector for hard X-rays

(2) Muonic Helium Atom HFS



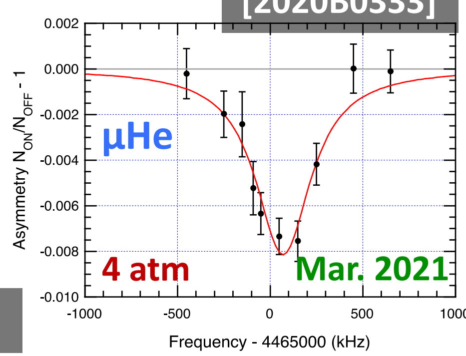
Muonic Helium

Hydrogen-like atom similar to muonium



Dn(μHe) = 4465.004(29) MHz

[2020B0333]



Goal : **Verify strong-field QED** with spectroscopy of muonic atom X-rays

Key technology : **Same technique as with Mu used to measure μHe HFS**

Result :**World record is achieved**

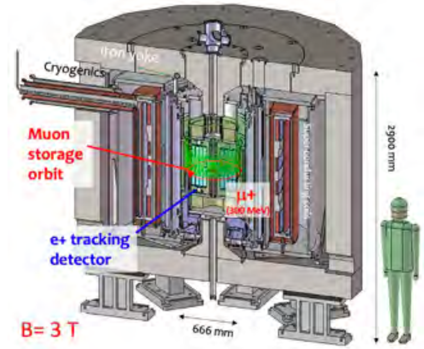
Previous date: 6.5 ppm → Our experiment: 4 ppm

Outlook :Sensitive tool to test **3-body atomic system** and **bound-state QED** theory and determine fundamental constants of the **negative muon magnetic moment** and **mass** to test **CPT** with 2nd generation lepton

Muon *g*-2 and muonium

These three quantities are mutually correlated. **Only J-PARC can close the triangle.**

450 ppb



g-2

FNAL
J-PARC

μ_μ

m_μ

J-PARC (MuSEUM)

Mu HFS

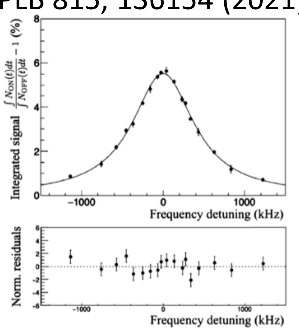
$$a = \frac{g-2}{2} \quad \vec{\mu} = g\left(\frac{e}{2m}\right)\vec{s}$$

J-PARC, PSI

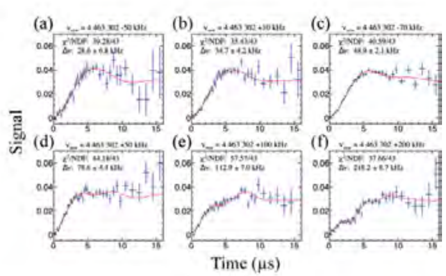
Mu 1S-2S

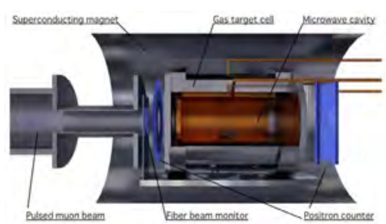
m_μ

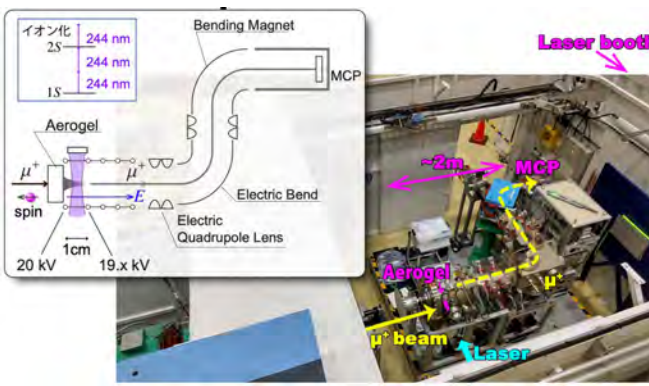
PLB 815, 136154 (2021)



PRA 104, 020801 (2021)





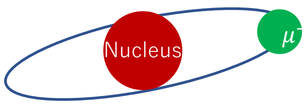


690 ppb$_{(2017)}$ → 160 ppb$_{(2018)}$ → 4 ppb

120 ppb → 1 ppb

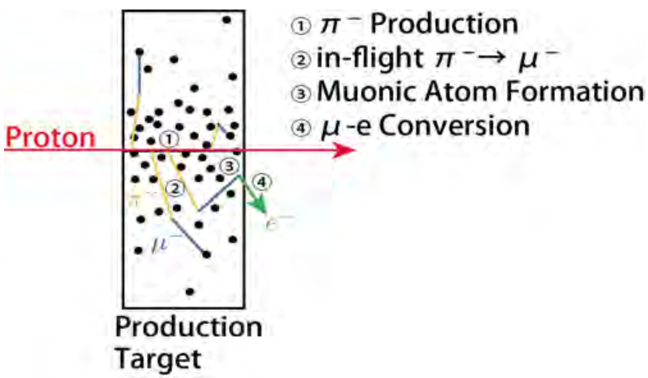
DeeMe Experiment

- Search for mu-e conversions in MLF muon target (Graphite)

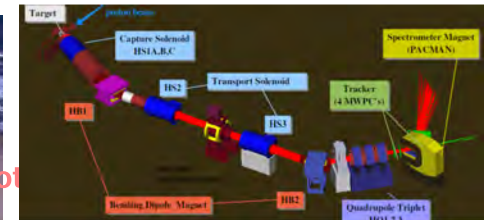


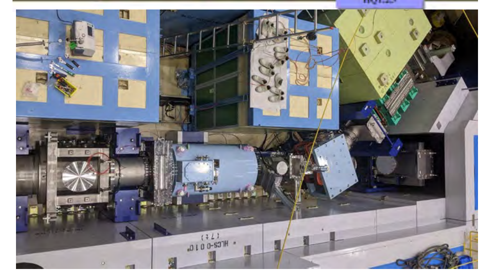
$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$

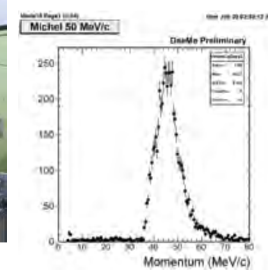
- Will be conducted at J PARC MLF
- Pulsed proton beams from 3 GeV RCS (fast extraction)



- μ^- production target = stopping target
- SES $\sim 10^{-13}$ (Carbon target, 1 year)







- Transport signal electrons by a new beamline (H line) to the DeeMe spectrometer.
- The DeeMe spectrometer consists of 4 MWPCs and a bending magnet.

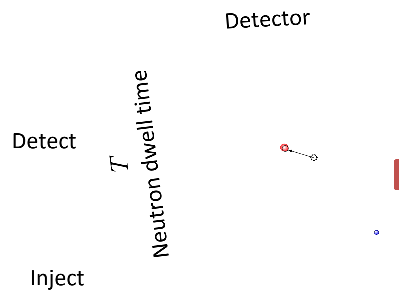
- Detector commissioning has started.
- Momentum reconstruction successful.
- Data analysis on going.

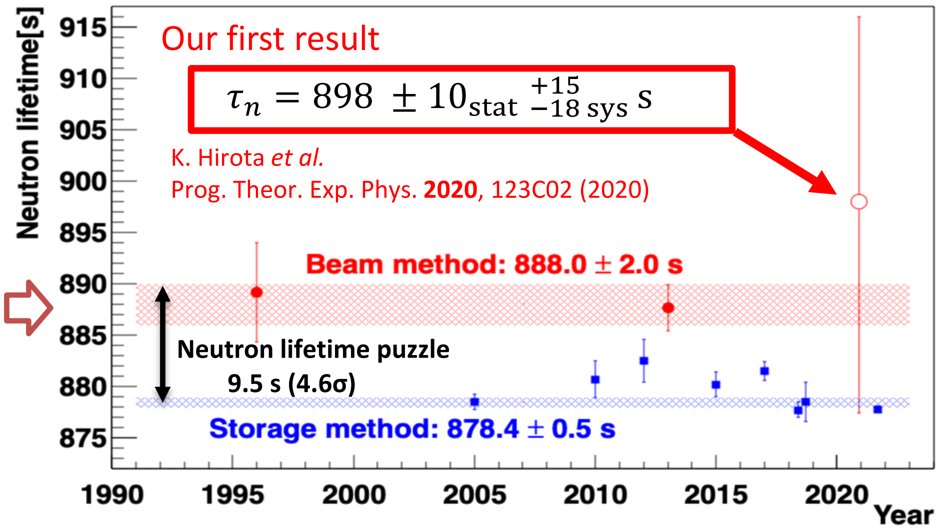
Neutron lifetime experiment

The neutron lifetime differs significantly between measurement of decay and disappearance. This discrepancy is known as the "**neutron lifetime puzzle**". It is still an open question, whether some errors of experiment, or indicating new physics.

Decay

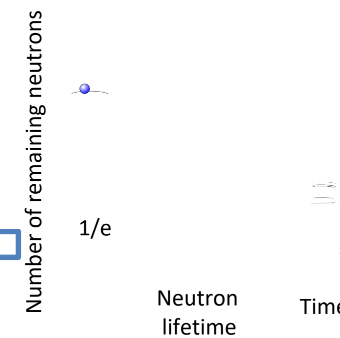
Beam method

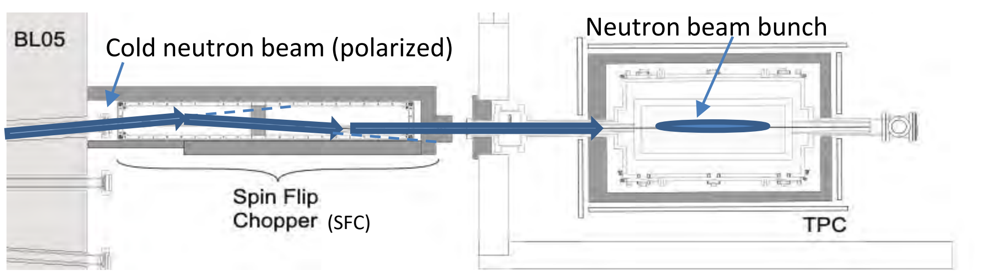


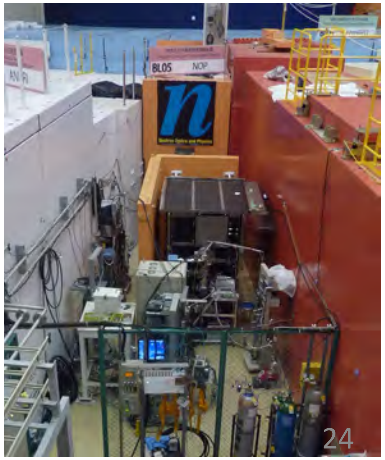


Disappearance

Storage method







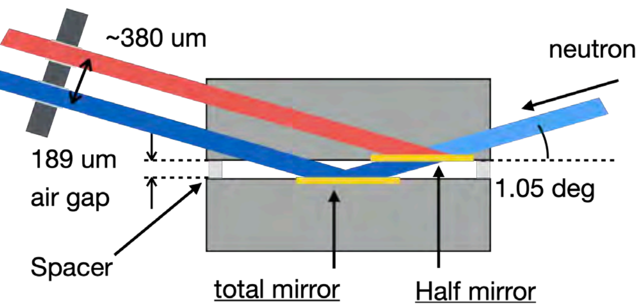
- To solve the neutron lifetime puzzle, a new type of experiment is on-going at a neutron beam line in J-PARC.

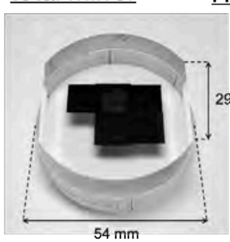
  <u>Goal: measurement with ~1 s accuracy</u>

Neutron Interferometer

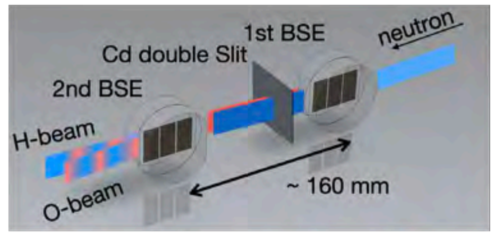
Neutron interferometers can precisely measure interactions with neutron as phase differences. The newly developed multilayer interferometer with a pulsed neutron source can use wide wavelength, simultaneously.

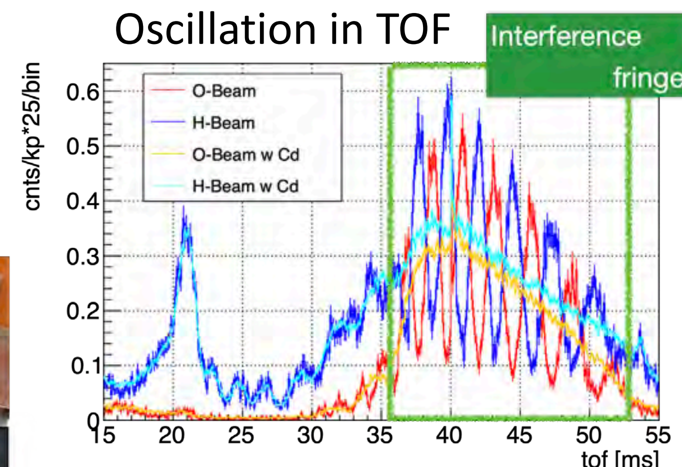
$$\Delta\phi = 2\pi \frac{m_n \lambda L}{h^2} \Delta E \propto \mathrm{TOF}$$

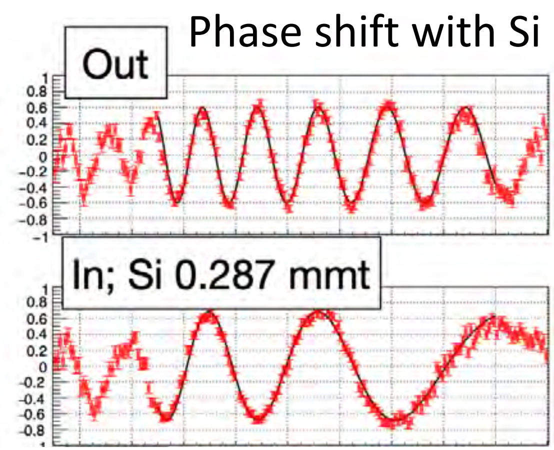




Beam Splitting Etalon (BSE)







- Oscillation by interference of neutrons were clearly observed (visibility ~70%).
- Phase shift by inserting sample in a path was measured.
  → successfully measured scattering length.
- Further wavelength extension is planned to increase statistics by a factor of 20.

T. Fujiie et al., arXiv:2308.01922

T-violation search using compound nuclei

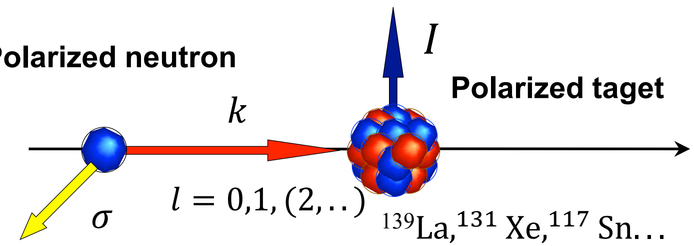
NOPTREX
Neutron Optical Parity and Time-Reversal EXperiment

P-odd and T-odd interactions can be largely enhanced in neutron induced compound nuclei
New T-violation search experiment based on optical behavior of neutron can be performed without final state interaction. The fundamental study and development of polarized target and neutron polarization device are ongoing.

T-odd cross section: $\sigma \cdot (k \times I)$

Polarized neutron

Polarized taget



1. Optical Test — **final-state interaction free**

2. Enhancement — **10^6 times enhancement**

3. New Type of New Physics Search — **chromo-EDM**

Development

~30% ^{139}La polarization

Polarized target : $LaAlO_3$

K. Ishizaki *et al*. NIM A1020, 165845 (2021)

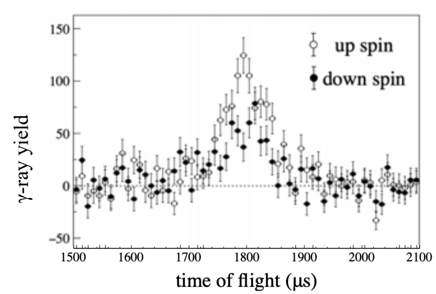
~40% neutron polarization

^{3}He neutron polarizer

T. Okudaira *et. al.* , NIM A 977, 164301 (2020)

Enhancement mechanism

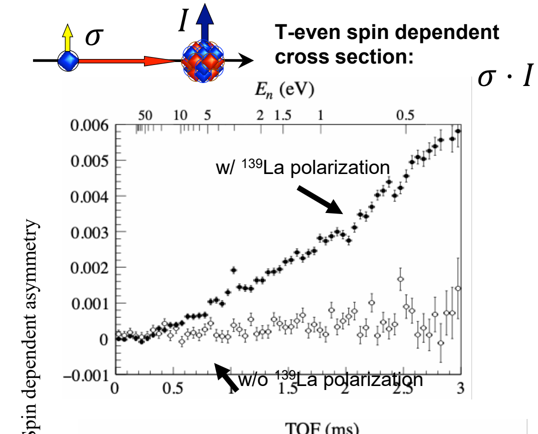
Neutron spin dependent asymmetry



T. Yamamoto *et al.* Phys. Rev. C. 101, 064624 (2020)

Enhancement factor was determined using (n,γ) reaction
→T-violation enhancement in ^{139}La+n : 10^6 times!

Experiment with polarized target + neutron



Spin dependent cross section of ^{139}La+n was successfully observed !

T. Okudaira *et al*, arXiv:2309.08905 (2023)

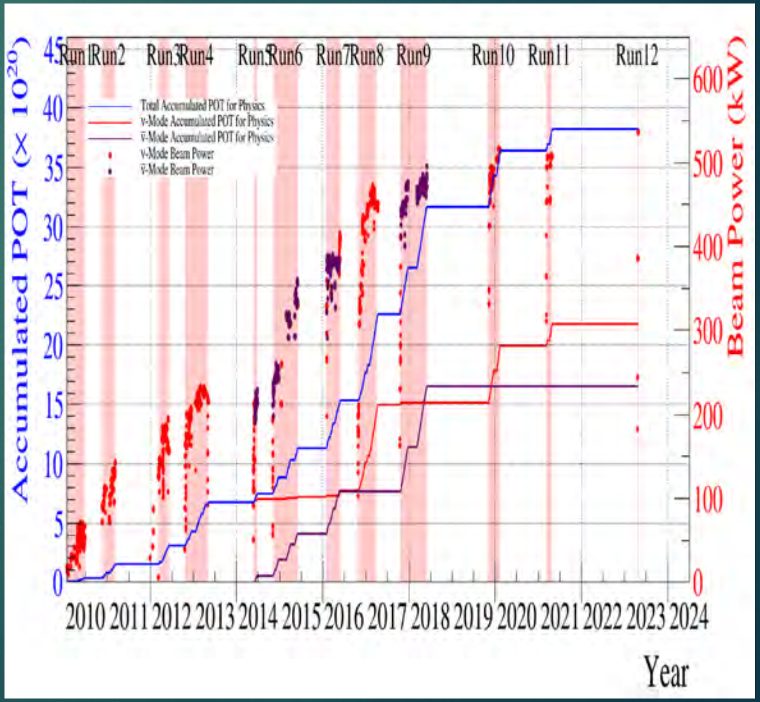
Neutrino experiments

T2K (Tokai to Kamioka) experiment

max. (kW) 540.961
POT total 3.82888e+21
nu-
2.17835e+
nubar-
1.65053e+2
%)

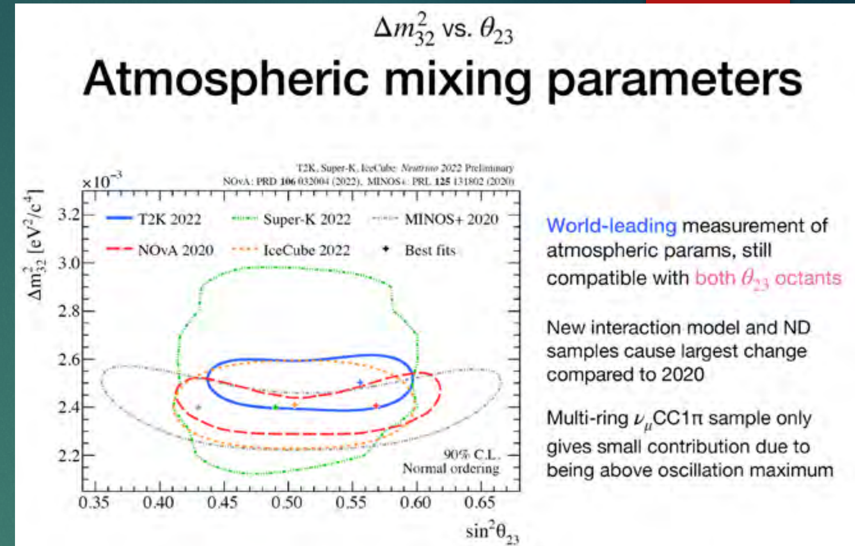
2010~ (Running)

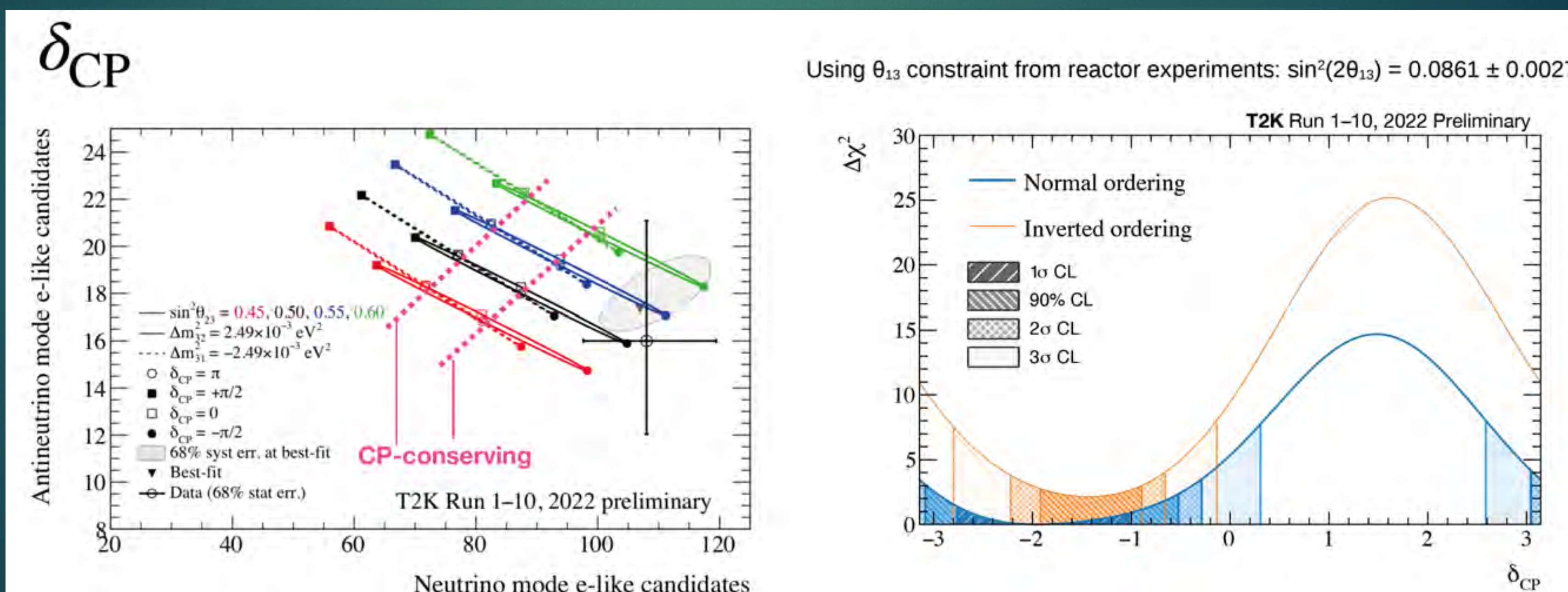
- Evidence → Observation of $\nu_\mu \rightarrow \nu_e$ (2011-2013)
- Updated goals
  - **Measure CPV phase, contribution to mass hier. determ.**
- Operation status
  - 540kW operation achieved (2023)
  - Delivered POT: 3.8e21 (nu:2.2/anu:1.7)



T2K latest results (2022)

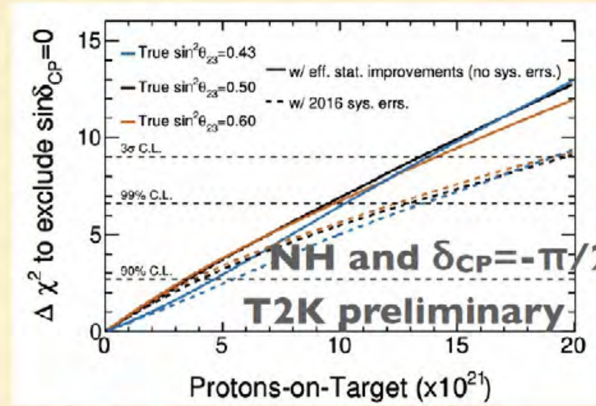
- 3.6×10^{21} POT (2010~2022) analyzed
- World leading measurement of atm param
- Large area of dCP excluded at 3s
- CP converving excluded at 90%
- Weak preference of normal ordering

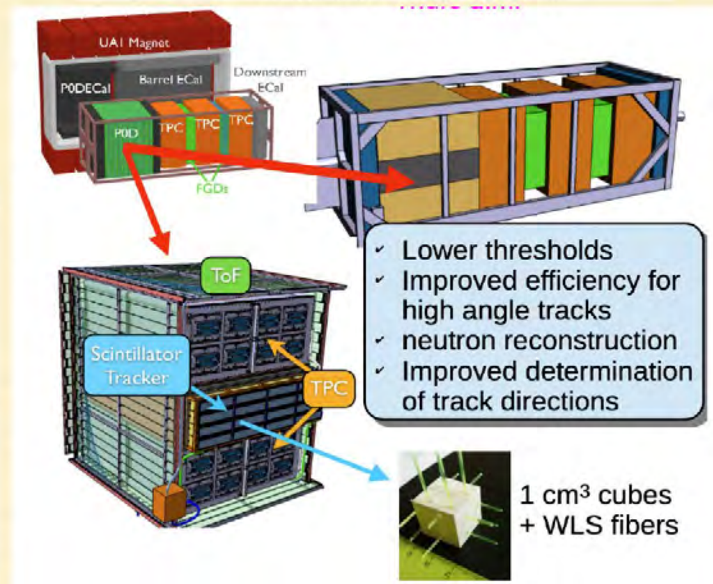


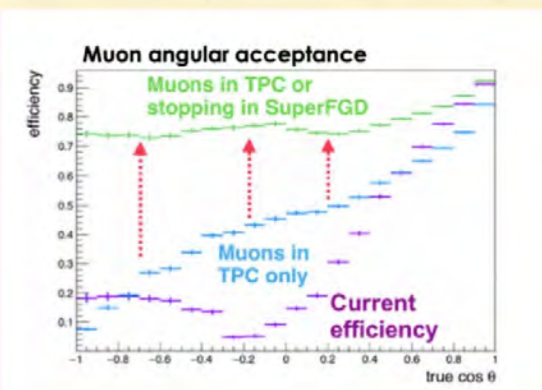


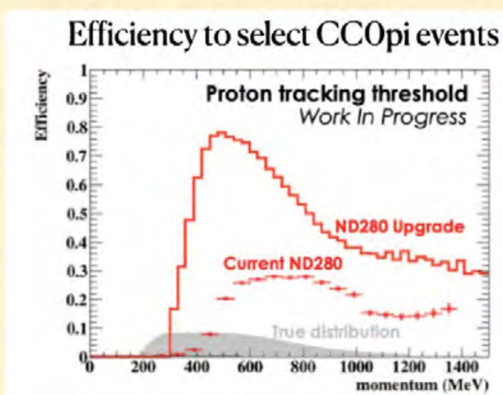
T2K FUTURE PROSPECTS: NEAR DETECTOR UPGRADE

- Reduction of systematic uncertainties is crucial
  - 18% (2011) → 5-7% (2022) → 4%(202X..)
- <u>ND280 measurements play the key role</u>
- Near detector upgrade
  - Key elements → **Super-FGD 3D-cubes** based segmented plastic scintillator active target surrounded by TPCs



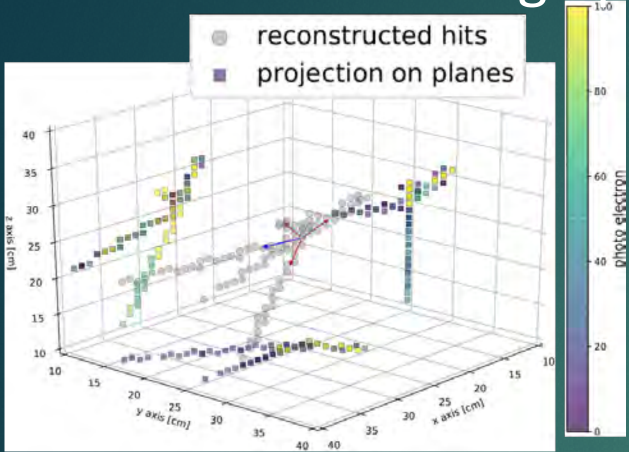


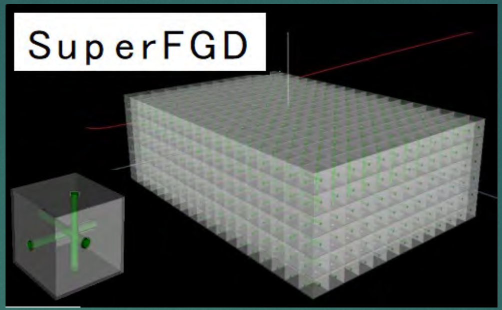




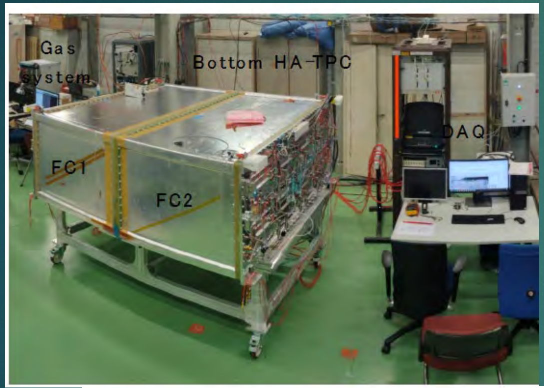
ND280Upgrade to start data taking in 2023

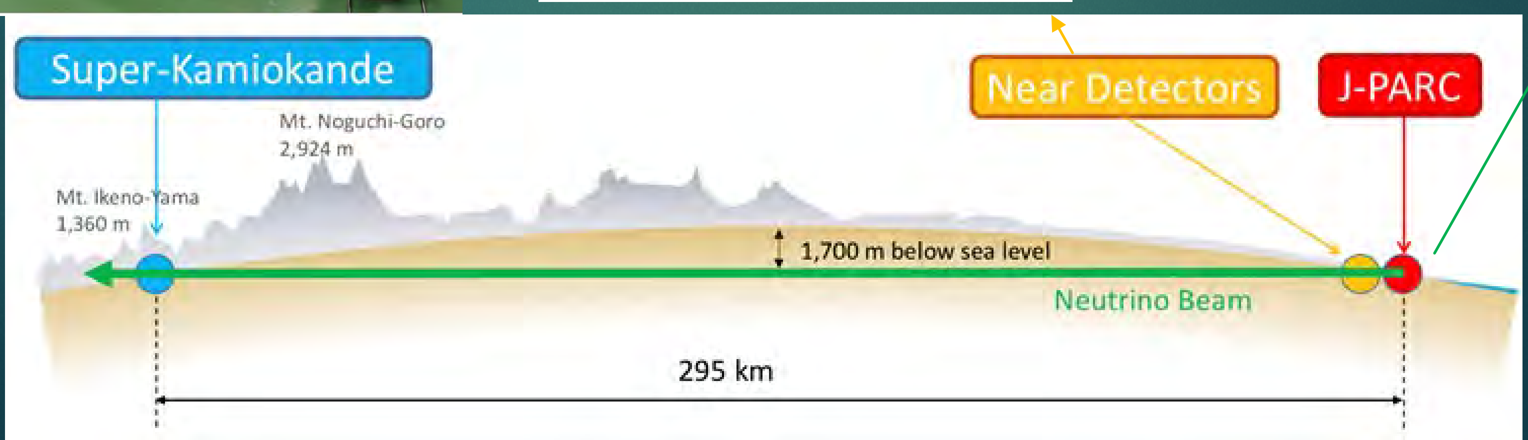
T2K future : Explore neutrino/anti-neutrino difference with intense neutrino beam & high precision measurements





1x1x1cm^3 scintillator cube x 2M





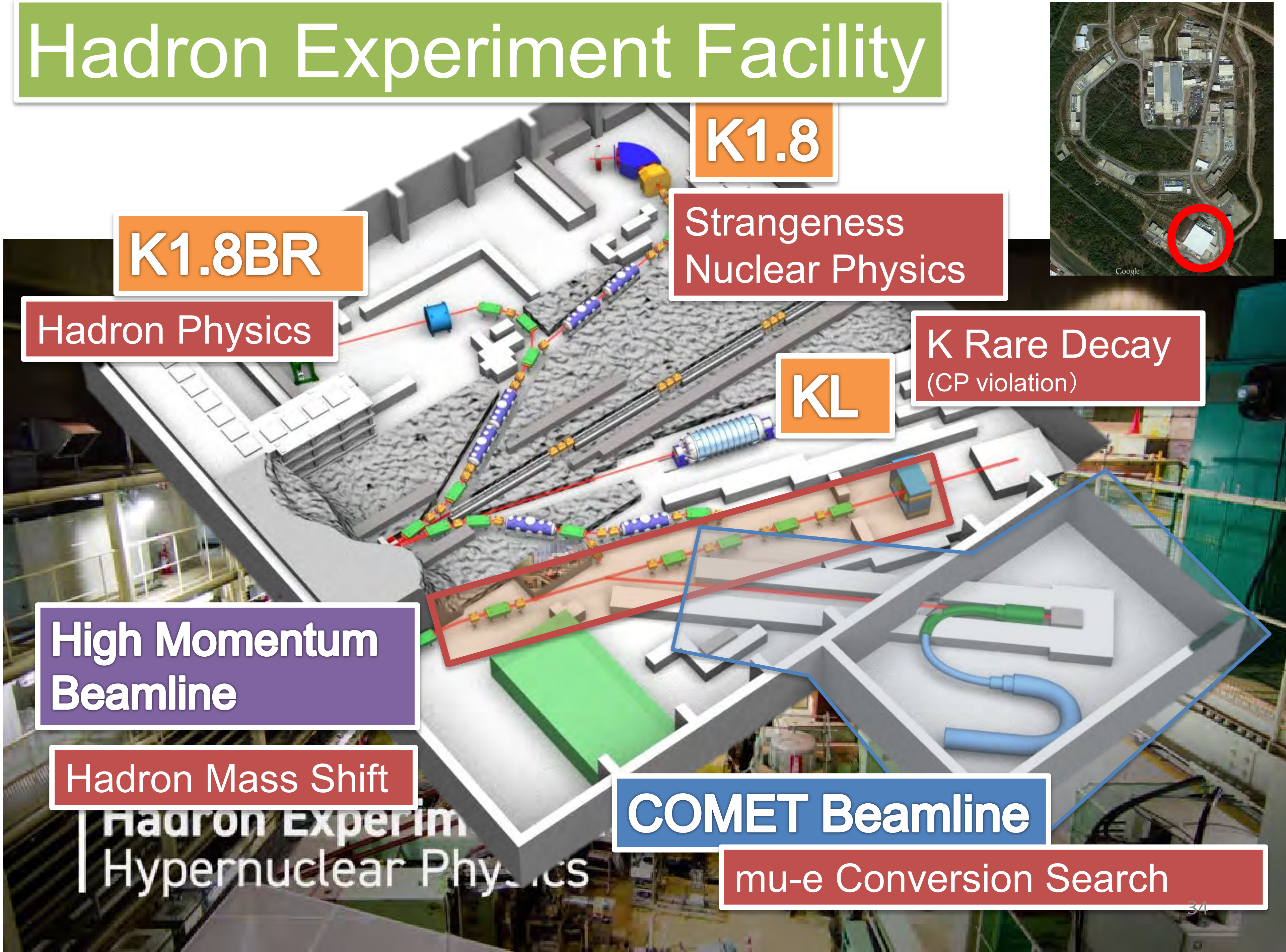
Hyper-Kamiokande construction ongoing

Funding started from FY2019 supplementaly budget
Start operation in 2027

- ~ 10 times larger detector
  - Fiducial mass: SK22.5kton→HK 190kton
- Beam power
  - 0.5MW → 1.3MW
- Aim to discover CPV and n decay etc
- Assuming 1e7s/yr operation (~114d/y)

Experiments at Hadron Experimental Facility

Hadron Experiment Facility



Origin & Evolution of Matter

Flavor Physics

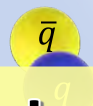
CP violation

weak interaction

Kaon rare decays

conversion

Matter-Antimatter Symmetry



matter domi

J-PARC Hadron Experimental Facility
is a unique facility
where we can conduct comprehensive studies
from elementary particles
to high-density hadronic matter

Origin of Matter Creation

formation of hadrons from quarks

sics

quark interactions

Hadron spectroscopy

eson in nuclei

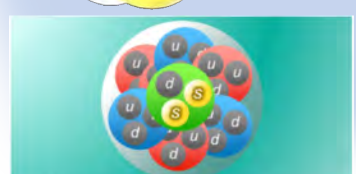
ear Physics

Matter in Extreme Conditions

hadron interactions
hadronic many-body systems

Hyperon-Nucleon scattering
Hypernuclear spectroscopy

dense matter in neutron stars



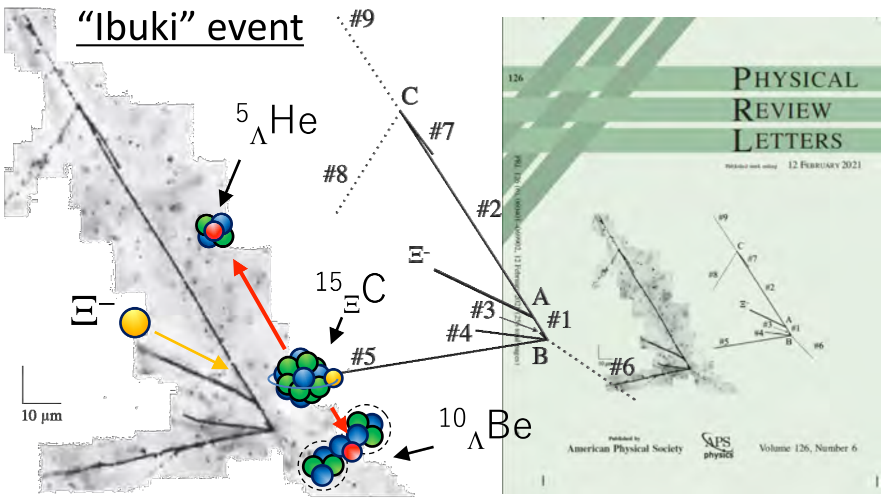
Credit: S. Hayakawa/Japan Atomic Energy Agency

【Nuclear physics at Hadron Experimental Facility】

大強度陽子加速器施設 J-PARC

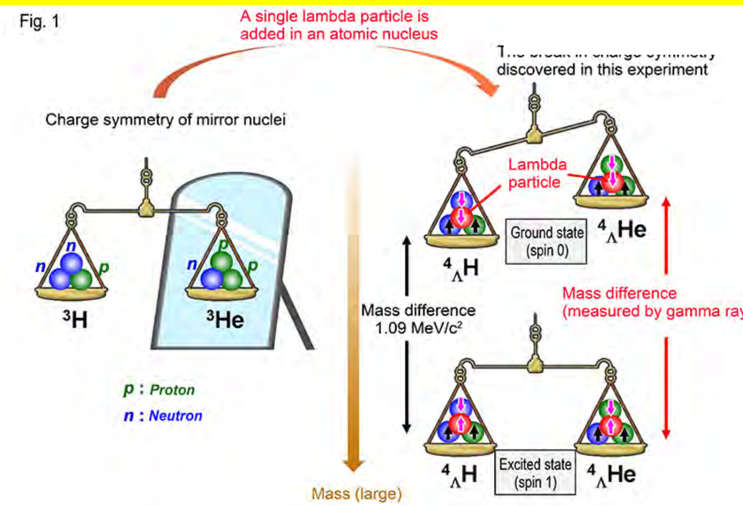
Elucidation of the property and origin of “generalized nuclear force” including strangeness

Mass measurement of Xi hypernuclei



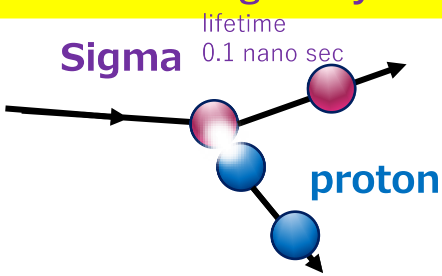
→ confirm the force between Xi (Ξ) and nucleon is attractive

Discovery of charge symmetry breaking in the force between Lambda(Λ) and nucleon

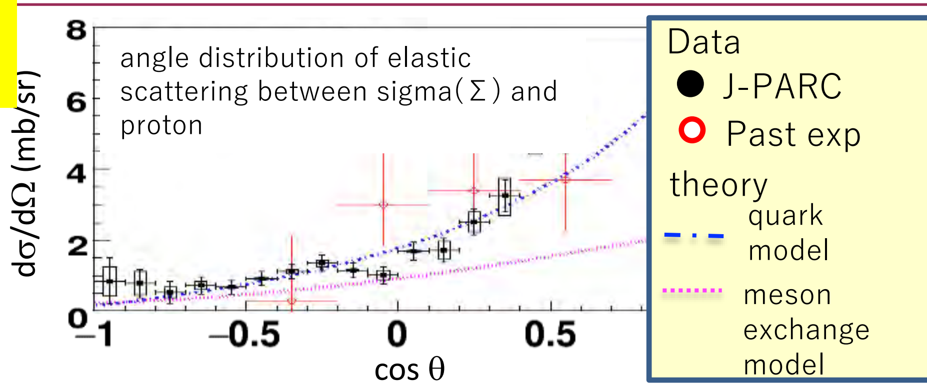


3H and 3He are the same on mass and structure in mirror images.
If a single lambda particle is added, it is found that a large difference appears in mas of ground state and excited state.

Establishment of scattering experiments between strange baryon and proton



→ improve the precision of scattering angle distribution by x10 for the first time in 50 years

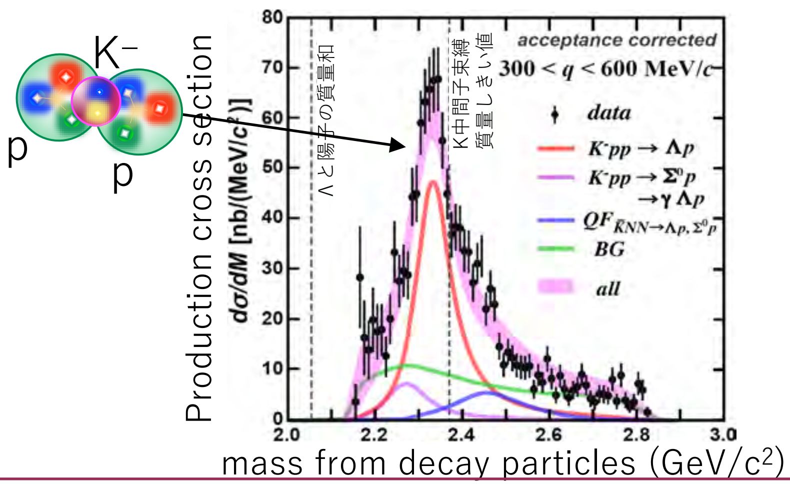


【Nuclear physics at Hadron Experimental Facility】

Discovery of new nucleus including K⁻ meson

X10 tighter binding energy than nucleus

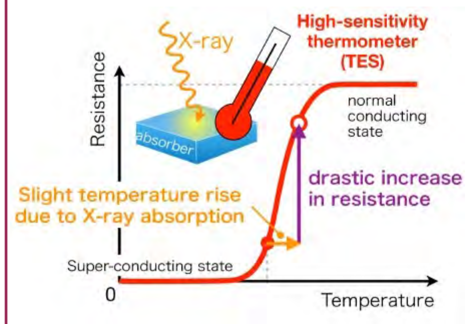
extremely **compact (dense)** and exotic nucleus

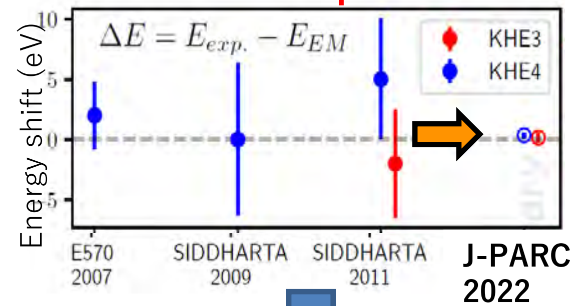


Precise measurement of X-rays from K⁻ mesonic atoms

introducing superconducting transition-edge sensor (TES) microcalorimeters, **the world's best resolution and the most accurate thermometer**, to to the X-ray measurement

X10 improvement





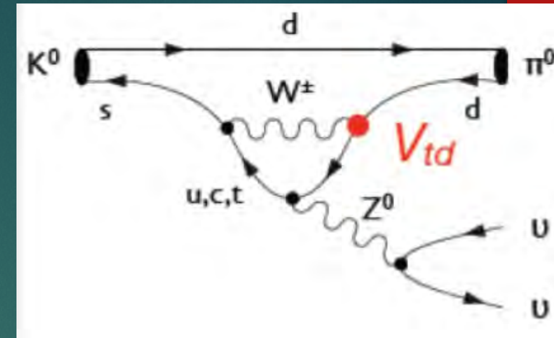
X-ray measurement from muonic atoms at MLF

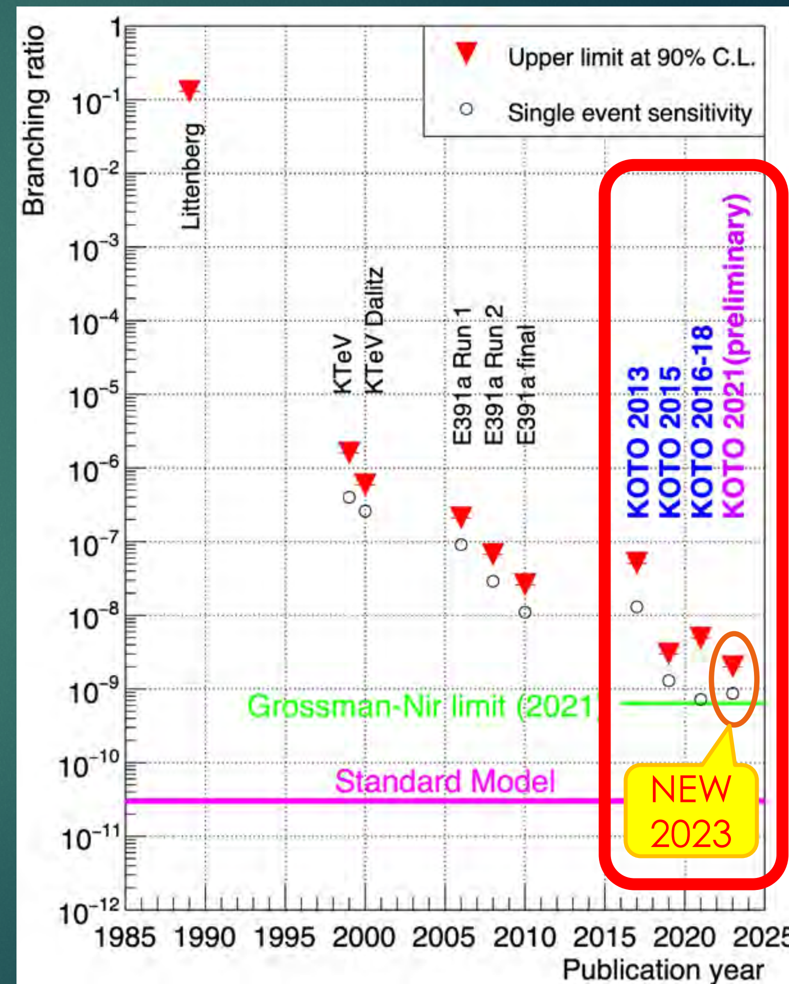
KOTO experiment

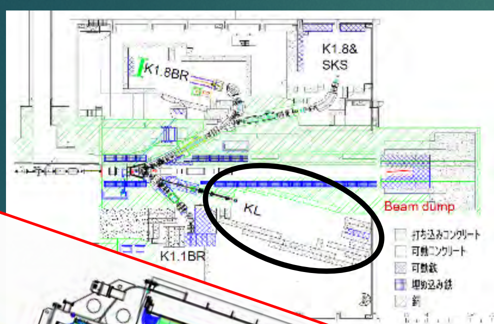
- Search for CP violating decay $K_L \rightarrow \pi^0 \nu \bar{\nu}$

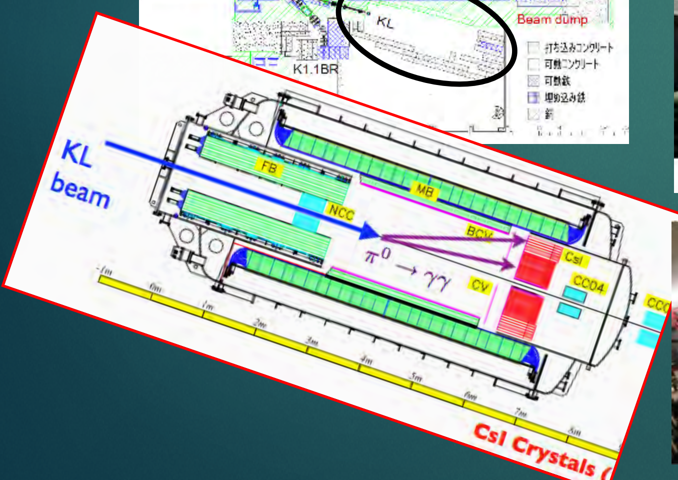
$$\overset{CP-}{K_L} \rightarrow \overset{CP+}{\pi^0 \nu \bar{\nu}}$$

- SM pred. is very small ~3e-11
  - → **Sensitive to New Physics**
- Upp bound: 4.9×10^{-9} (90%CL) PRL 126, 121801 (2021) **Editors' Suggestion**
- further accumulate physics data toward the sensitivity better than 1×10^{-10}









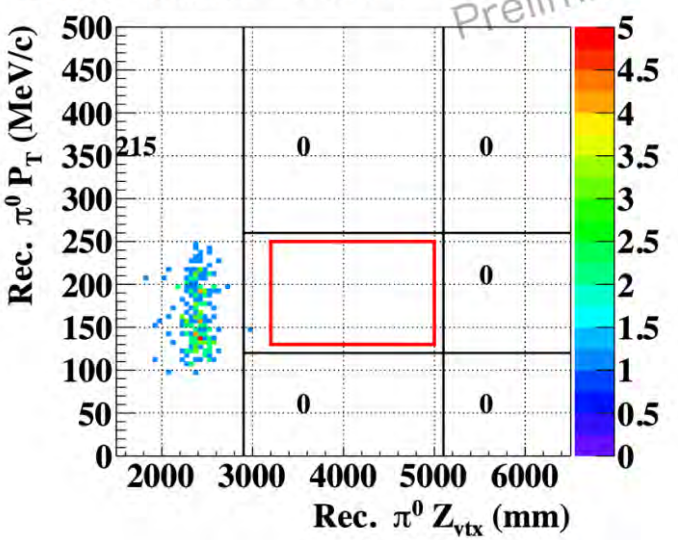

CsI calorimeter

New results from KOTO

Announced at KEK IPNS and J-PARC Joint Seminar on Sep.6, 2023

- Results based on data taken in 2021
  - Single event sensitivity = 8.7×10^{-10}
  - Expected number of backgrounds = 0.255
  - No signal candidate observed
    - $BR<2.0\times10^{-9}$@90% C.L.

World-best limit



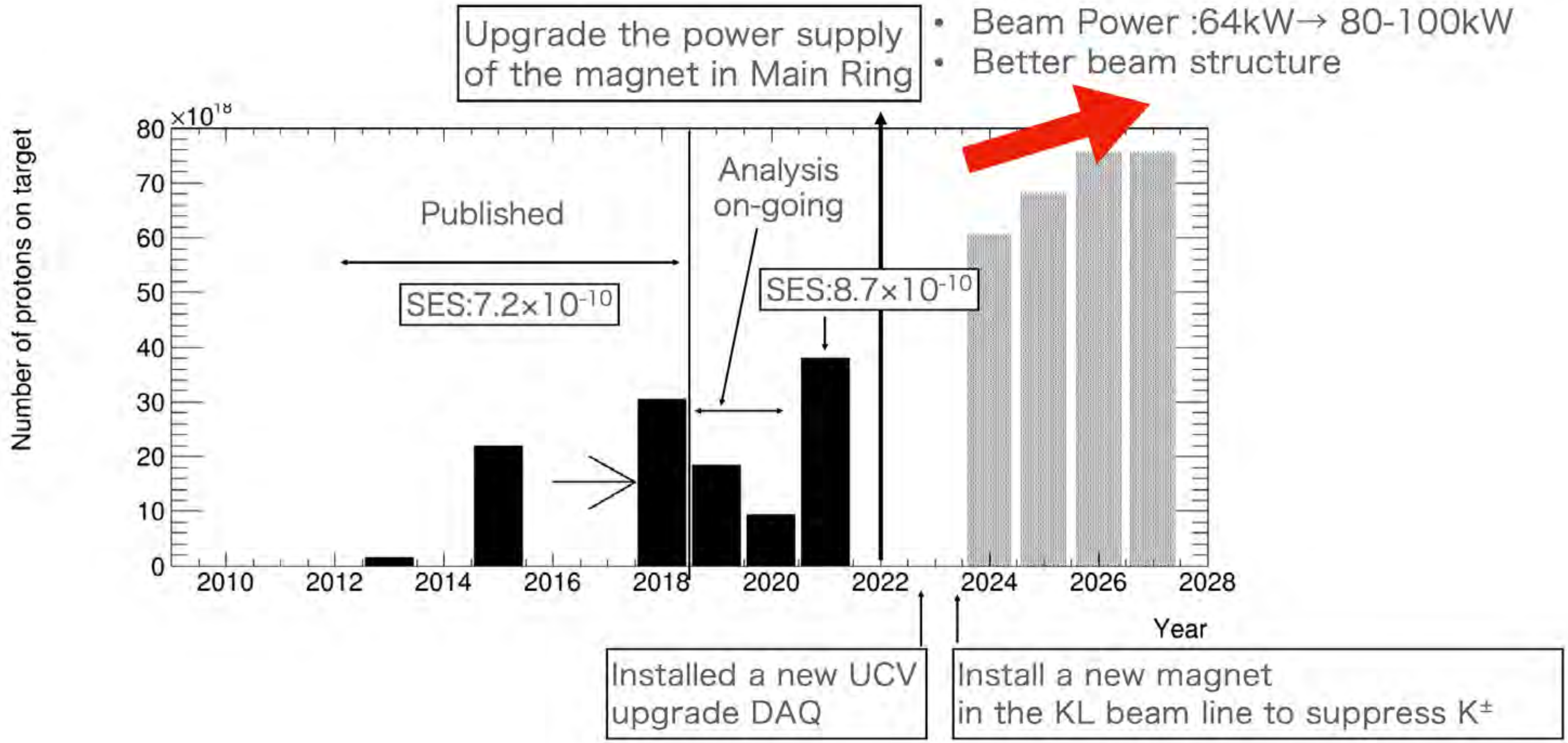
Preliminary

source	Breakdown of backgrounds
Upstream π^0	0.064 ±0.050(stat)±0.006(sys)
$K_L\to2\pi^0$	$0.060\pm(0.022)_{stat}(^{+0.051}_{-0.060})_{sys}$
K^+	$0.043\pm(0.015)_{stat}(^{+0.004}_{-0.030})_{sys}$
Hadron cluster BG	0.024 ±0.004(stat)±0.006(sys)
Scattered $K_L\to2\gamma$	0.022 ±0.005(stat)±0.004(sys)
Halo $K_L\to2\gamma$	0.018 ±0.007(stat)±0.004(sys)
η production in CV	0.023 ±0.010(stat)±0.006(sys)
Sum	$0.255\pm0.058(stat)(^{+0.053}_{-0.068})_{sys}$

<u>Next Step</u>

- KOTO continues taking physics data to achieve a sensitivity better than 10^{-10}.
- A next-generation experiment KOTO II with ~100 times better sensitivity are being considered.

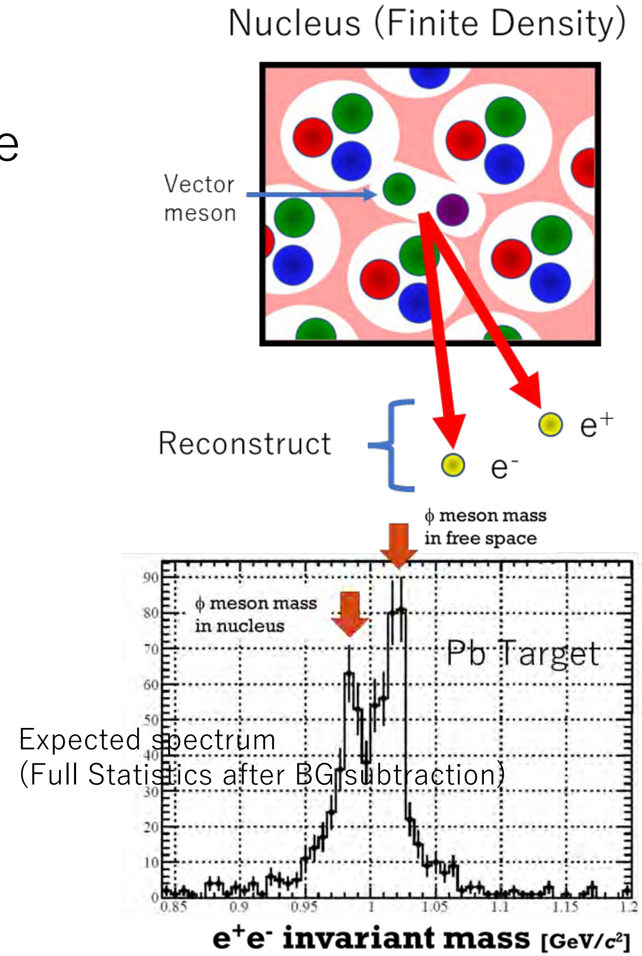
KOTO prospects for future run

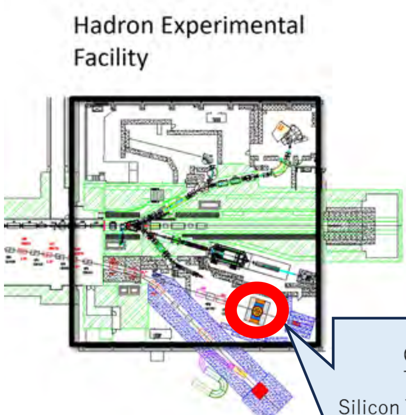


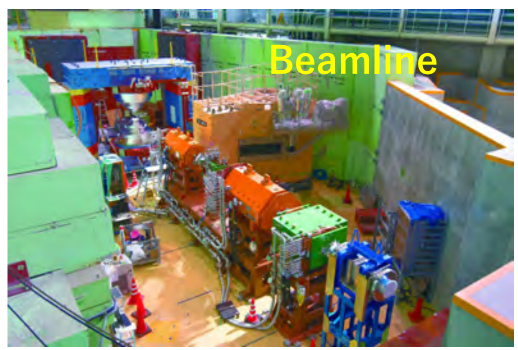
- The accumulated POT will be 10 times more in 3-4 years, assuming 60 days/year run.
  - ➢ Will reach a sensitivity better than 10^{-10}

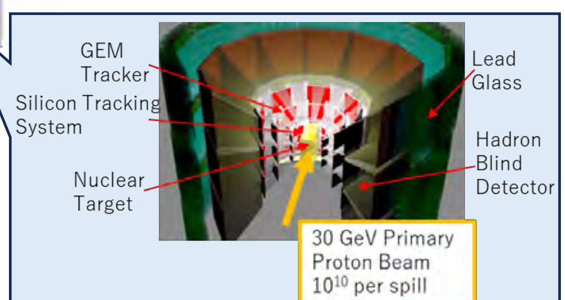
J-PARC E16 experiment

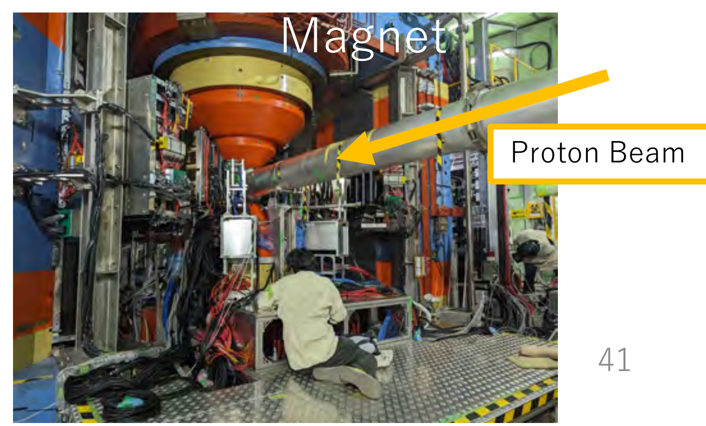
- Aim to measure changes of hadron mass in the finite density matter (nucleus)
- Study process of the dynamical generation of hadron mass
  - Hadron mass is dynamically generated by QCD.
  - Spontaneous breaking of chiral symmetry
- Status
  - First beam in May/2020
  - Commissioning of new beam line and detectors in 2020, 2021, 2023, 2024
  - Physics runs in 2024 or 2025 (Need approval of PAC)







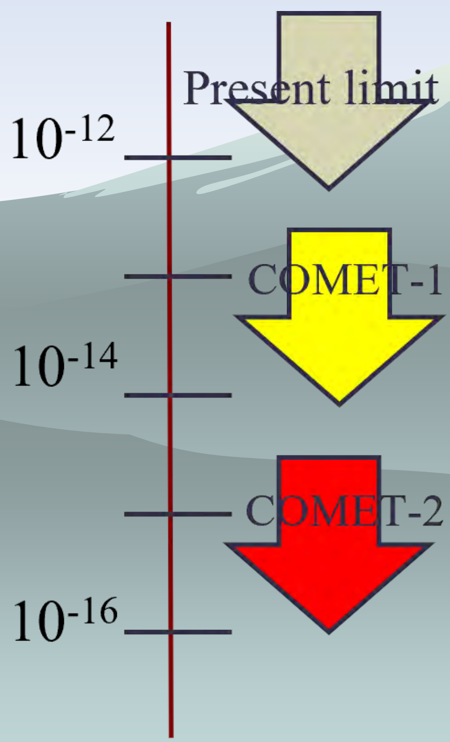


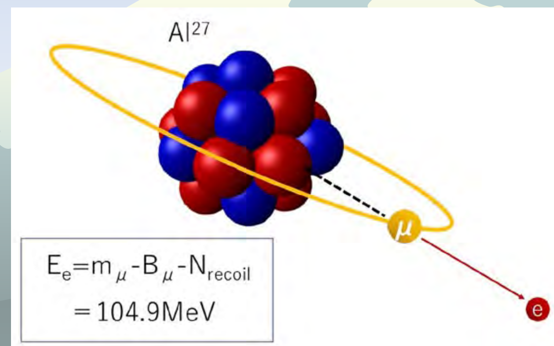


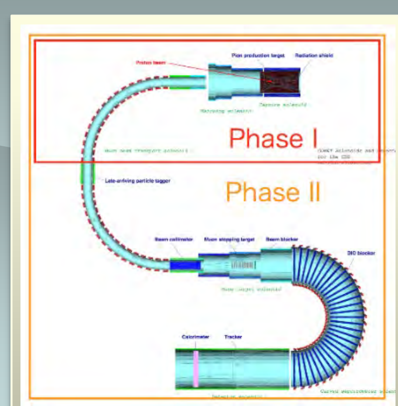
COMET experiment

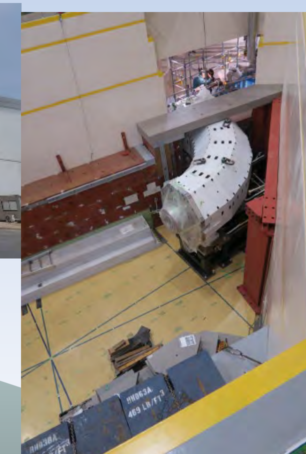
- μ→e conversion search
  $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
  - Very small $O(10^{-54})$ in SM
  - **Discovery = New Physics!**
- First commissioning in FY2022

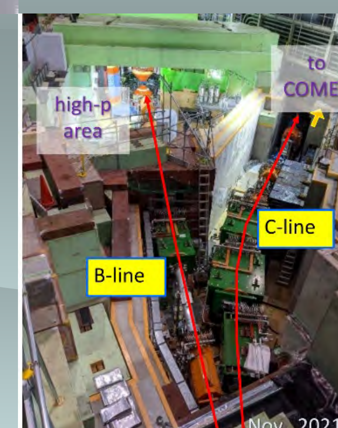
COMET Hall





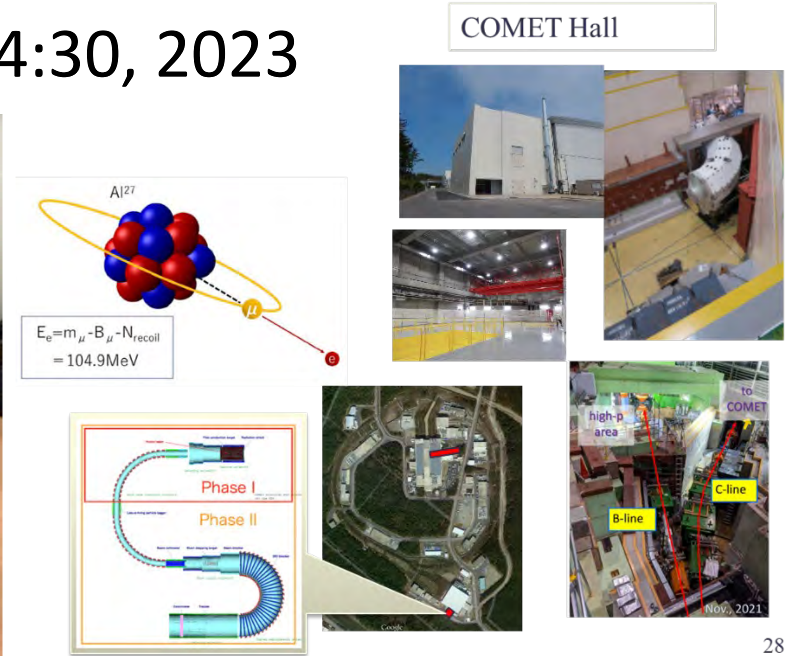


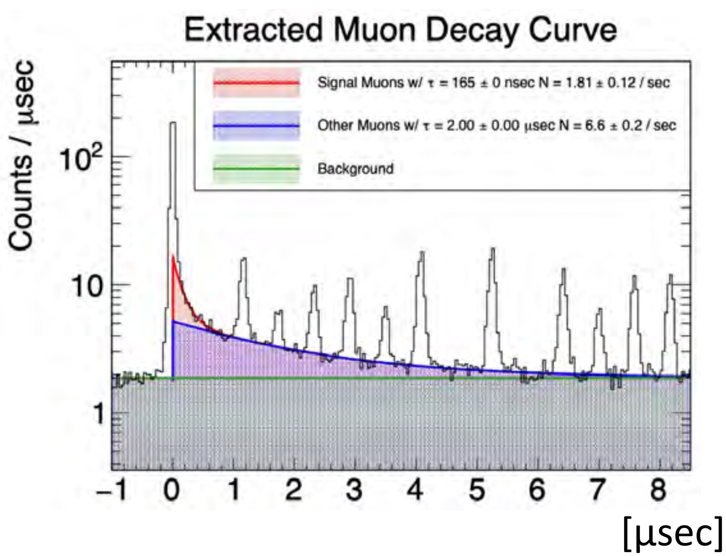


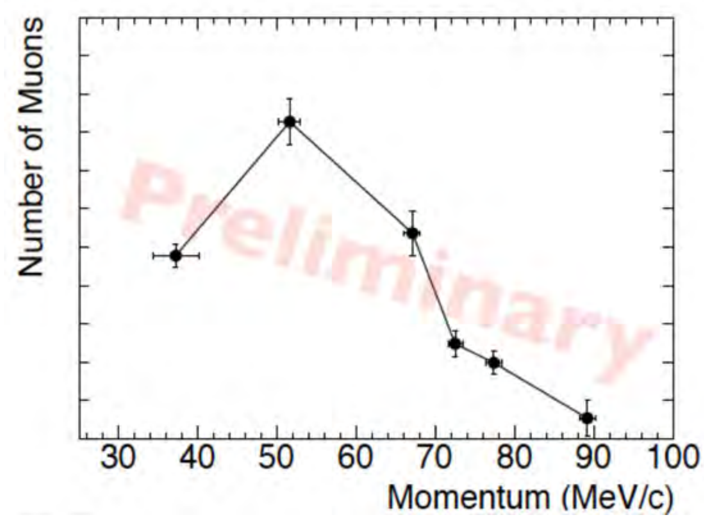


First beam to C-line for COMET!!

First beam on target @ Feb.9,19:44:30, 2023



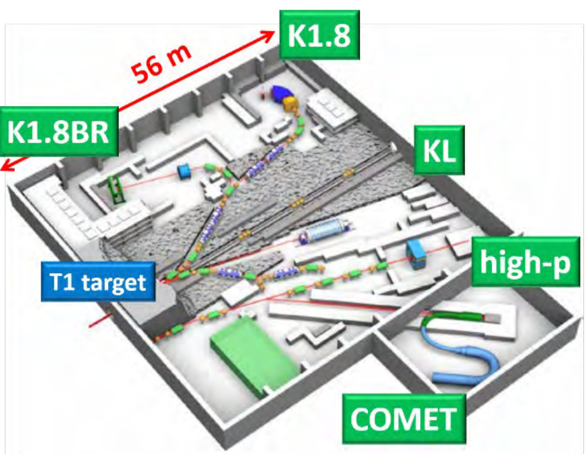




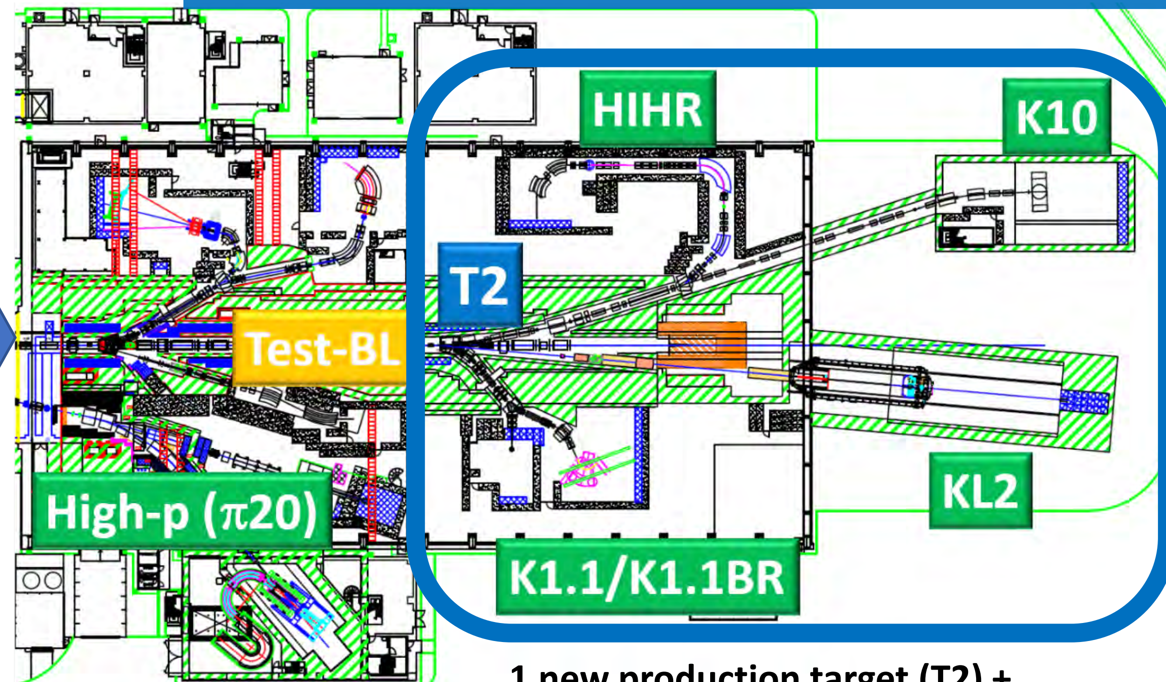
Hadron Experimental Facility EXtension (HEF-ex) project

Open new physics that cannot be implemented at the existing facility

Present facility



1 production target (T1) +
2 charged beamlines (K1.8/1.8BR, High-p)
1 neutral beamline (KL)
1 muon beamline (COMET)



1 new production target (T2) +
4 new beamlines (HIHR, K1.1/K1.1BR, KL2, K10) +
2 modified beamlines (High-p (π20), Test-BL)

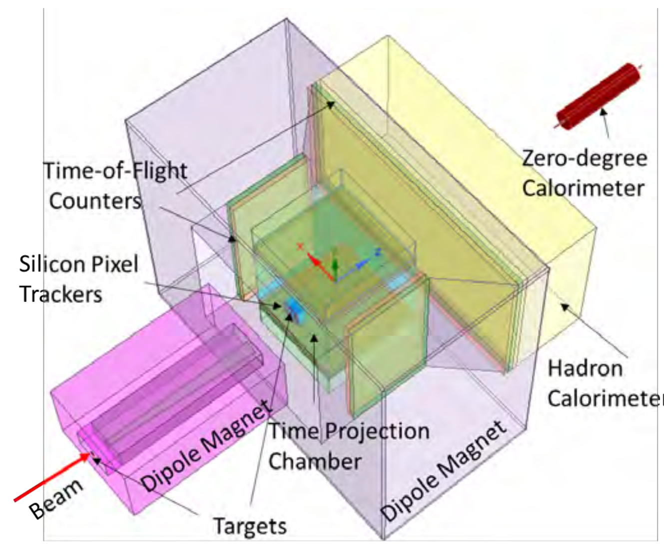
KEK-PIP 2022 Priory Number 1

Future J-PARC Heavy Ion program

Explore the QCD phase diagram

EOS of Neutron Star
New state of the matter
Quark Phase
Color Super conductivity
Hadron physics in finite density

- Facility Upgrades Plan
  - New accelerator injector
  - New spectrometer
- Staging approach
  - Phase1:
    - Beam Intensity: 10^8 Hz for Au
    - Upgrade of the current E16 spectrometer
    - New LINAC and reuse of KEK-PS booster
  - Phase 2
    - Beam Intensity: 10^{11} Hz
    - New booster and new spectrometer



Schematic view of final spectrometer

Summary

- J-PARC is the world leading intensity frontier proton accelerator research complex
  - 3GeV RCS/MLF: reached at 840kW stable operation
  - 30GeV MR
    - FX: 515kW/SX64kW achieved before major upgrade
    - Upgrading toward 1.3MW
    - **750kW (single shot) acceleration succeeded aft. PS upgrade**
- J-PARC is unique facility covering wide range of research fields
  - Particle, nuclear physics, material and life sciences and industrial applications, Archeology, planetary science
- Many exciting projects are being conducted/prepared
- KEK's next highest priority project is HD hall extension
- Stay tuned