the Institute of Physics Nuclear Physics, High Energy Particle Physics and Astroparticle Physics joint annual conference
Apr.11, 2024@Liverpool

The future programme at J-PARC

Takashi Kobayashi
J-PARC, JAEA/KEK

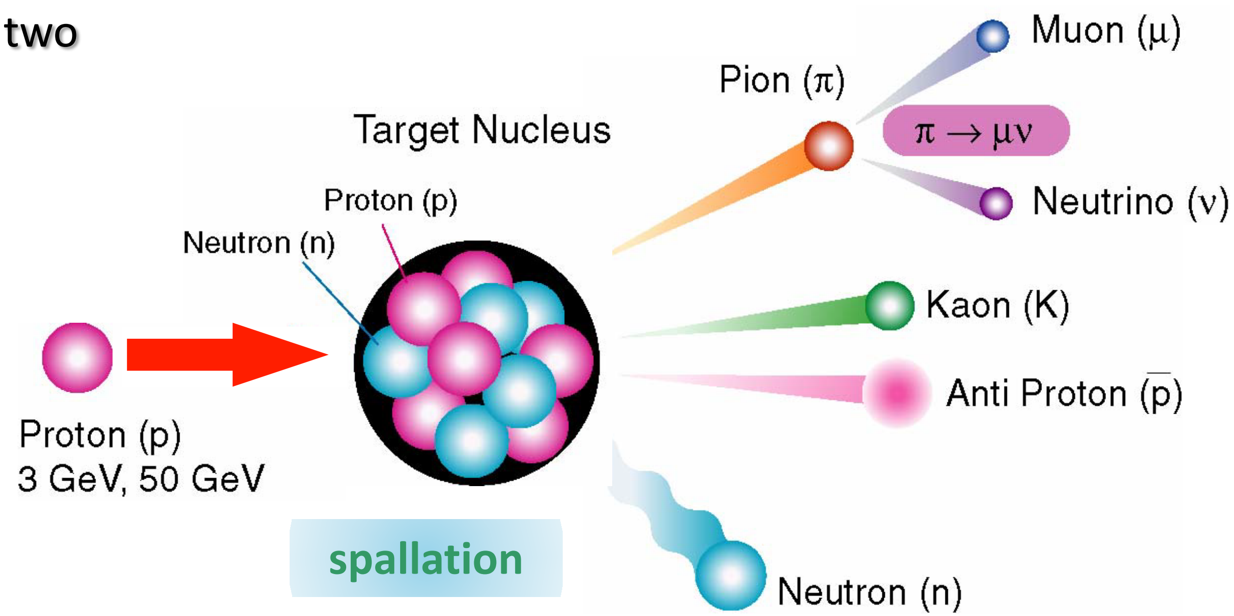
Versatile Quantum Beams for Microscopic World

J-PARC

Japan Proton Accelerator Research Complex

Power-frontier accelerators and multi-purpose user facilities

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



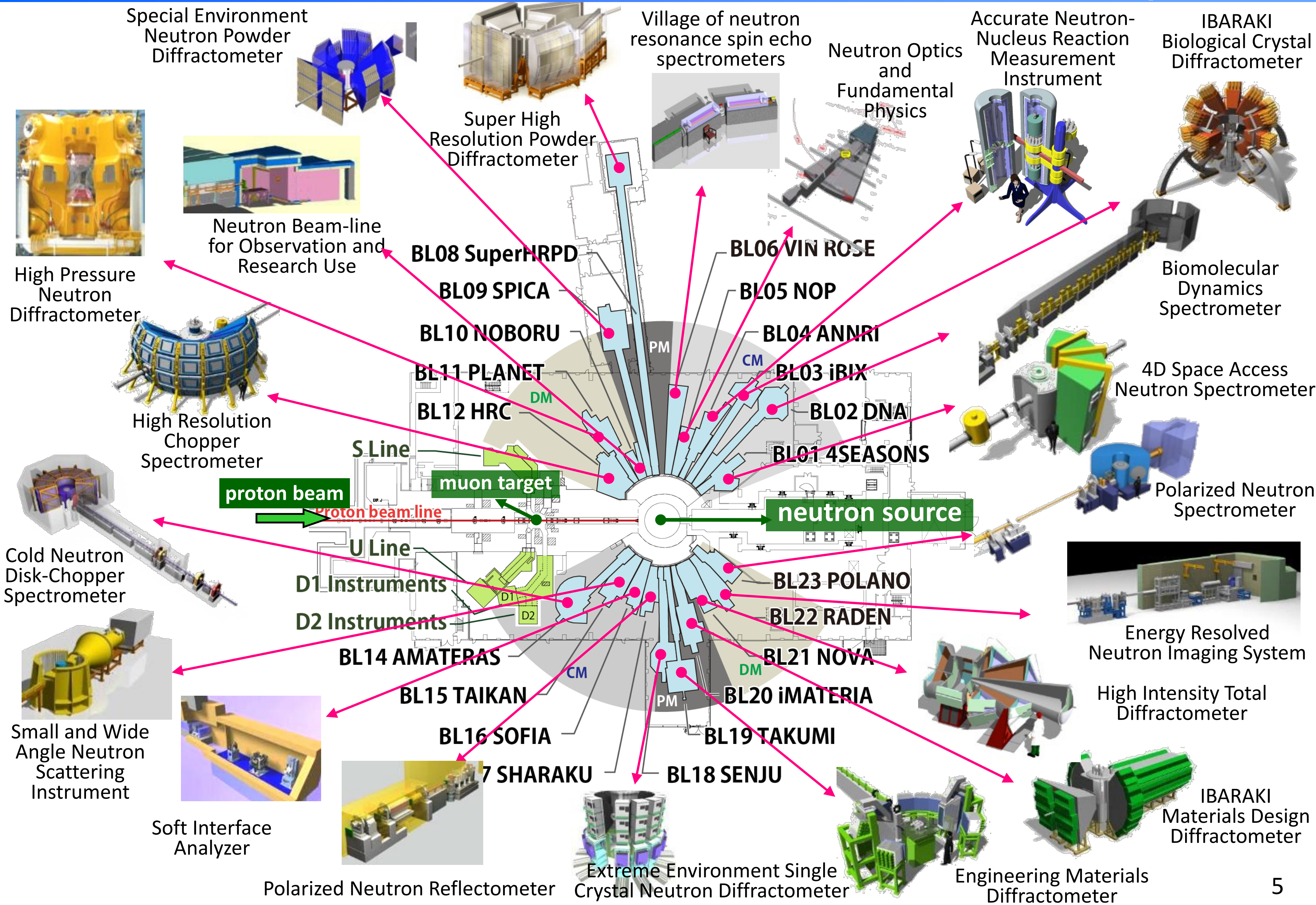
Variety of secondary particles generated with high-energy and high-intensity protons

Japan Proton Accelerator Research Complex：J-PARC
J-PARC Facility (KEK/JAEA)
South to North
400MeV LINAC
3 GeV RCS
Neutrino Beams (to Kamioka)
Materials and Life Experimental Facility
Design intensity
RCS for MLF: 1MW
MR for PN : 750kW
30GeV MR
Hadron Exp. Facility
JAEA
KEK
60km
TOKYO
NARITA
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008

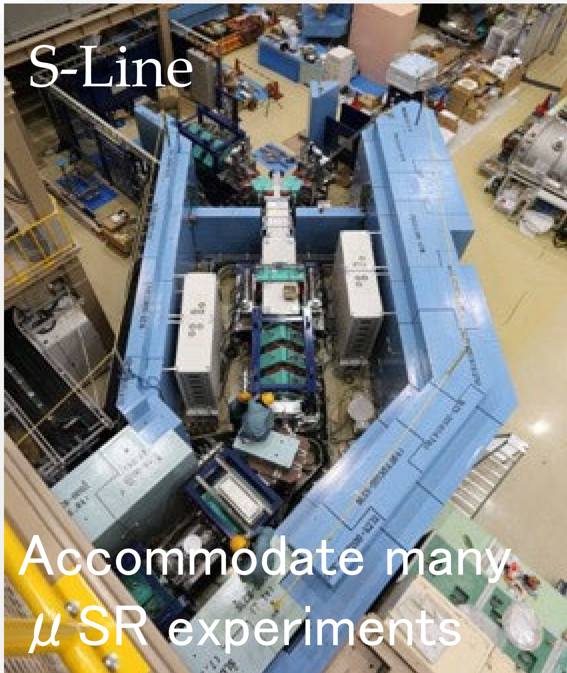
Projects at Material and Life science experimental Facility (MLF)

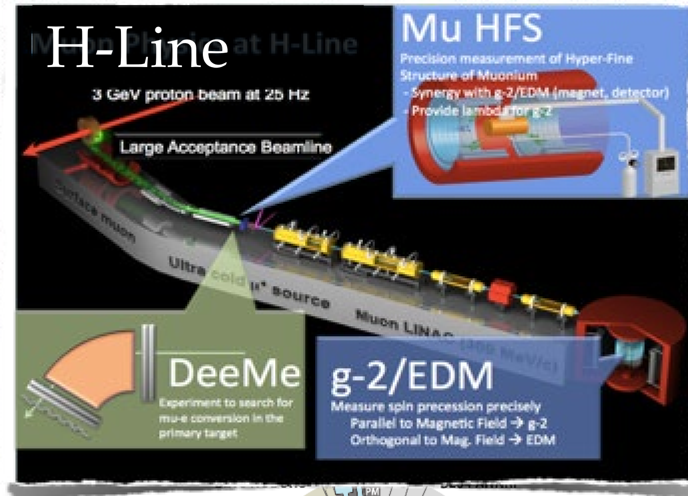
Neutron Instruments in MLF

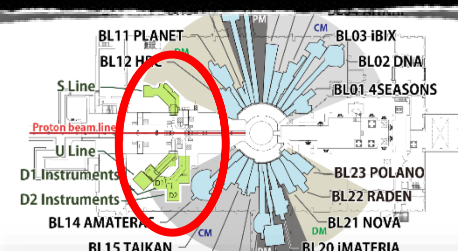
23 beam ports
21 in operation



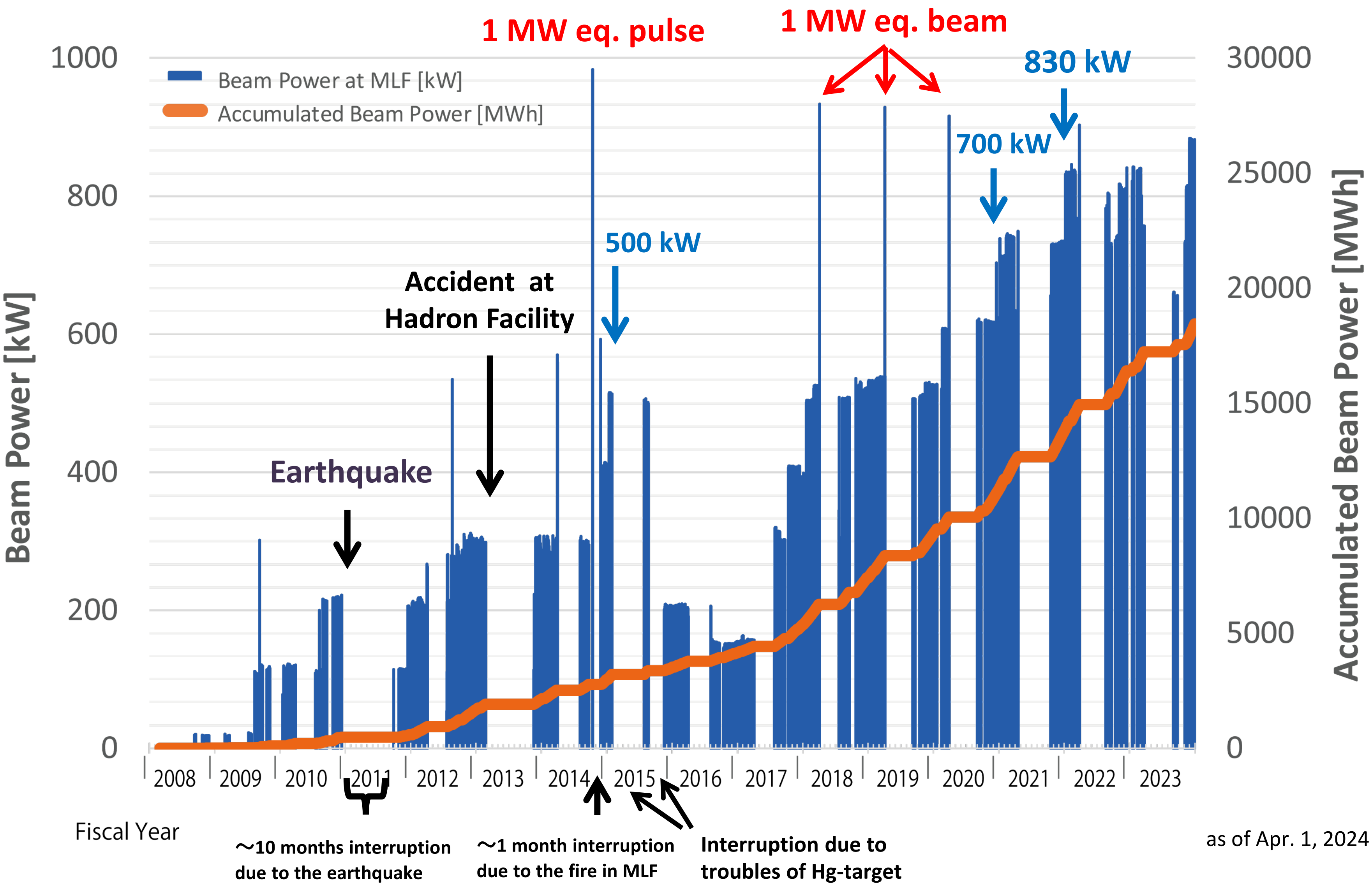
Muon Facility MUSE @ MLF





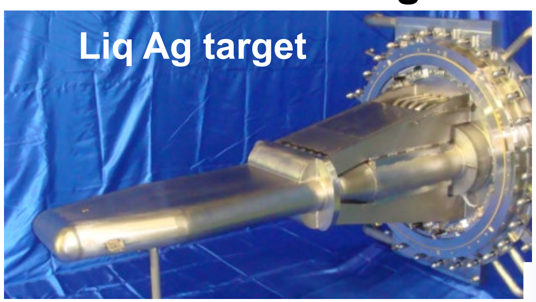


Beam Power History at MLF

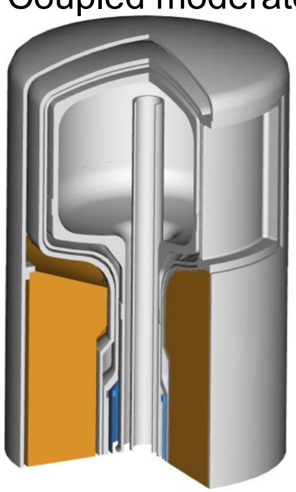


World leading neutron intensity

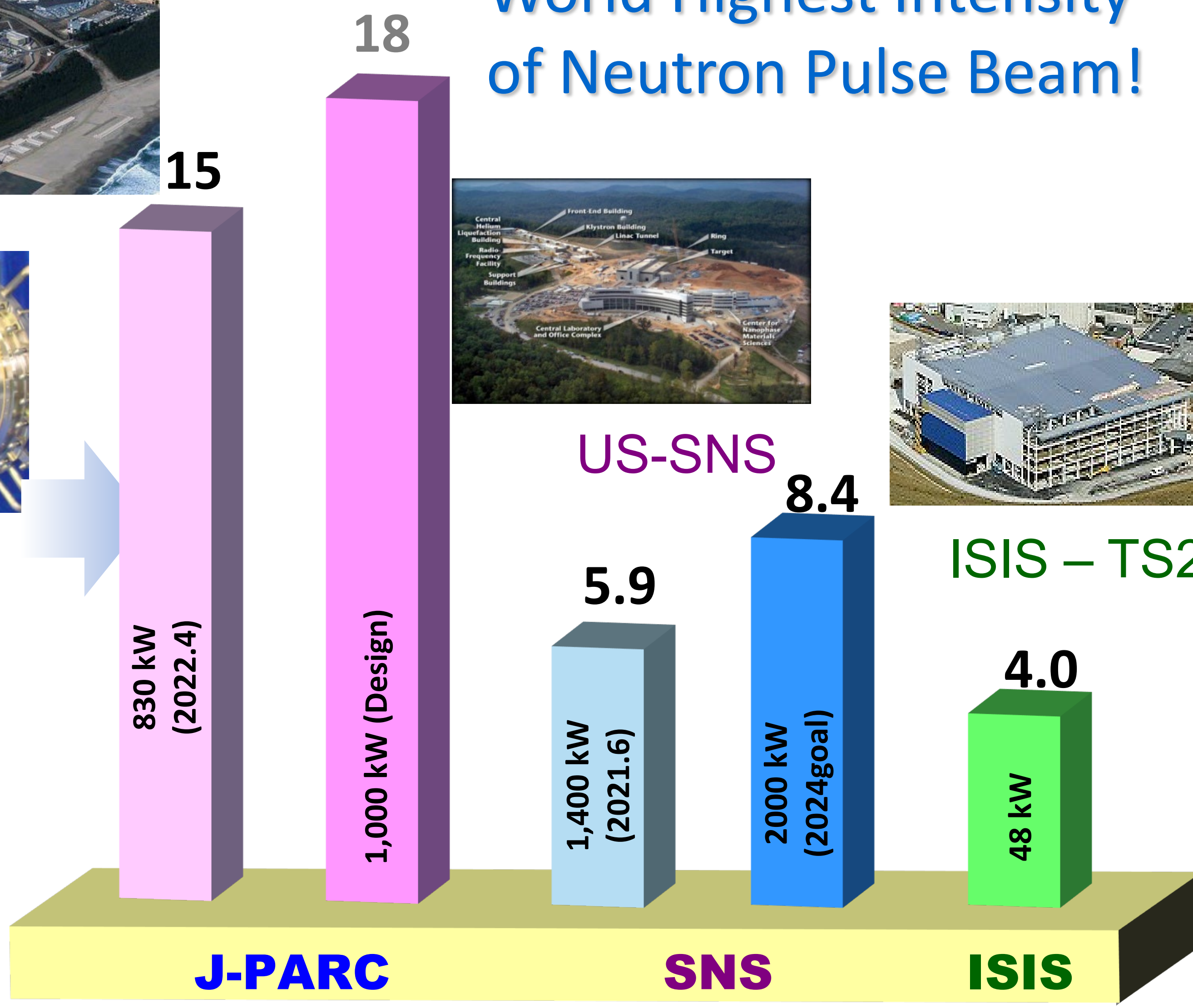
JAEA's technologies



Coupled moderator



World Highest Intensity
of Neutron Pulse Beam!



US-SNS

ISIS – TS2

Unit: 10^{12} n/(sr・pulse)

Only a few of recent outcome from MLF

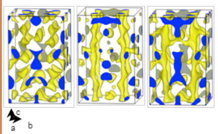
Neutron Science
Designing materials for All-Solid-State Li Batteries

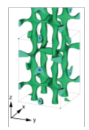
Tokyo Tech.、IMSS KEK、Univ. of Tokyo 、J-PARC Center

Science 2023 IF：63.832
11,663 download

$Li_{10}GeP_2S_{12}$
Nature Materials 2011

$Li_{9.54}Si_{1.74}P_{1.44}S_{11.7}Cl_{0.3}$
Nature Energy 2016





High ionic conductivity is observed when Li ions diffuse in 3D direction. However, high -T is required.

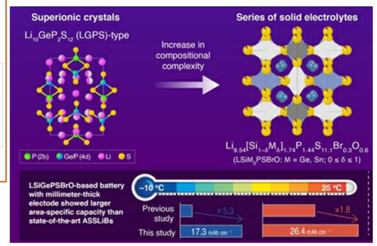
Discovered a material in which Li ions diffuse in a 3D direction even at room-T.

Tokyo Tech, IMSS KEK, TOYOTA, Ibaraki Pref., Ibaraki Univ.,J-PARC Center

Citations over 3,000 (Sum), TOP 0.01%

$Li_{9.54}[Si_{0.6}Ge_{0.4}]_{1.74}P_{1.44}S_{11.1}Br_{0.3}O_{0.6}$

Thick-film cathode with 1.8 times the current capacity per electrode area is fabricated. Combined with Li metal anode, all solid-state battery exhibiting high-capacity and high-current characteristics is realized.



Analysis of the crystal structure containing Li by neutron diffraction leads to an understanding of the Li ion diffusion mechanism, contributing to the development of all solid-state batteries

Elucidates that the super ionic conductivity of the new material originates from a crystal structure with a complex and highly disordered atomic distribution (High-entropy material).

Neutron Science
Development of high-strength magnesium alloy

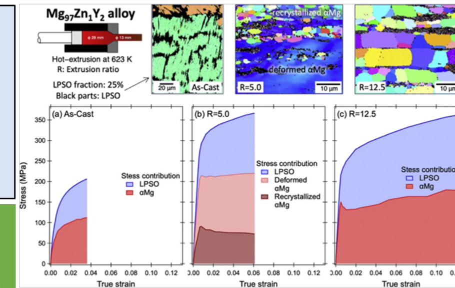
[15 Aug. 2023 Press Release] Why Are High-Strength Magnesium Alloys Developed in Japan So Strong？
In-situ Neutron Diffraction Experiments Elucidate the Behavior of Each Constituent Phase during Deformation

JAEA, Kumamoto Univ., J-PARC Center

IF:9.209
Acta Materialia (2023) Citation：7

- Because of their **lightweight and high strength per density,** Mg-alloys (LPSO-Mg alloys) developed at Kumamoto Univ. are expected to have various applications.
- The strength of LPSO-Mg alloys is greatly enhanced by high-T extrusion processing, but **the mechanism has not yet been clarified**.

In-situ neutron diffraction experiments revealed that **the extrusion conditions affected the overall strength and ductility of the alloy** due to different micro-structural development.



(upper) Mg alloys used in this study and EBSD images after high-T extrusion process. (lower) Contribution of each of the LPSO-Mg alloy constituent phases to strength during tensile deformation.

- Provides guidelines for the development of **lightweight, high-strength Mg alloy materials with ductility, rigidity suitable for specific purposes.**
- **Contribution to energy saving and safety of aircraft and** automobiles through practical use of lightweight and high-strength materials.

Water visualization in a fuel cell used in FCEV

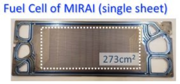
Supported by NEDO FC-Platform Program

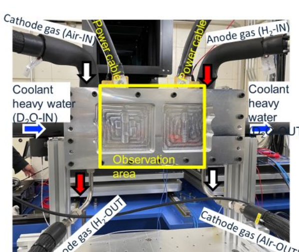
FC•Platform
NEDO

Visualization of water distribution inside an operating fuel cell of the 2nd generation TOYOTA MIRAI

FCEV TOYOTA MIRAI

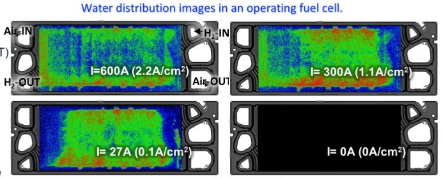
Fuel Cell of MIRAI (single sheet)





Fuel cell was assembled with thick Al end plates.

Water distribution images in an operating fuel cell.



14

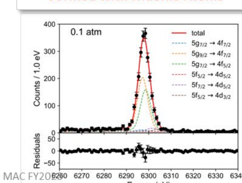
D line: High-resolution X-ray spectroscopy of muon atoms

Physics under ultra-high electric field opened up by Muon Atoms

The energy of muonic X-rays was determined **with extremely high accuracy using a TES detector** with an energy resolution **10 times higher** than that of conventional semiconductor detectors

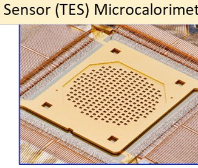
⇩

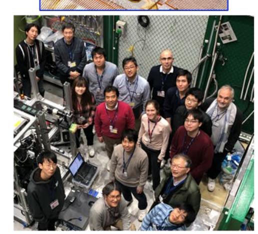
Quantum Electrodynamics Verified with Muonic Atoms



MAC FY2023
2024/2/22

Superconducting Transition-Edge Sensor (TES) Microcalorimeter





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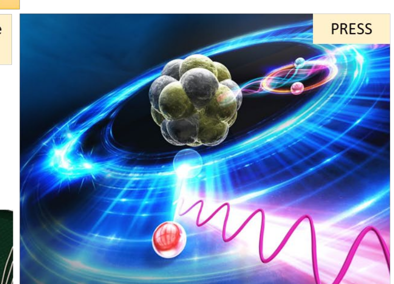
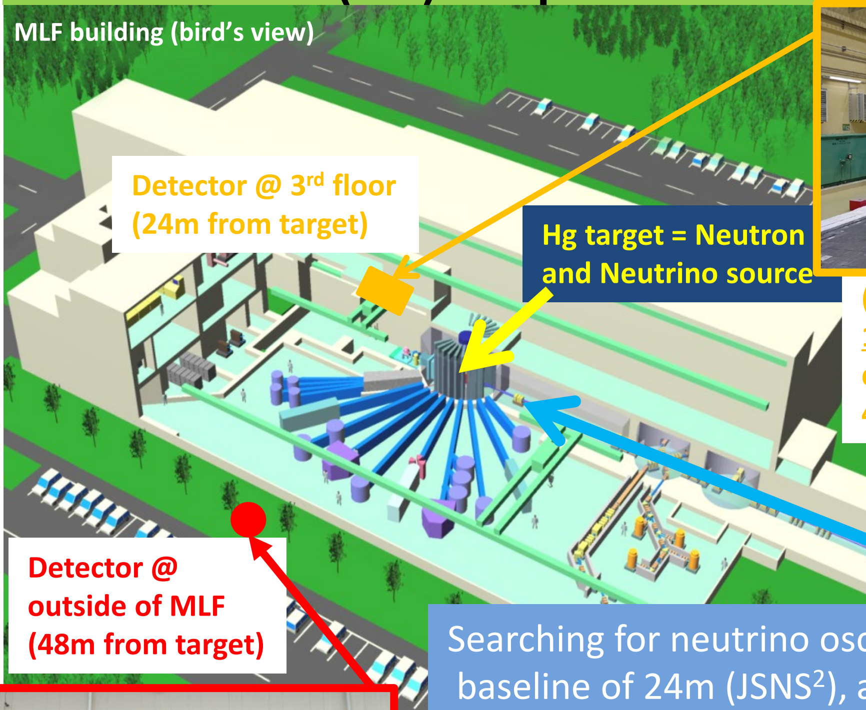


Proof-of-Principle Experiment for Testing Strong-Field Quantum Electrodynamics with Exotic Atoms: High Precision X-Ray Spectroscopy of Muonic Neon

T. Okumura *et al.*, Phys. Rev. Lett. 130, 173001 (2023)

~500 experiments/year

JSNS^2(-II) experiment : Search for sterile neutrinos

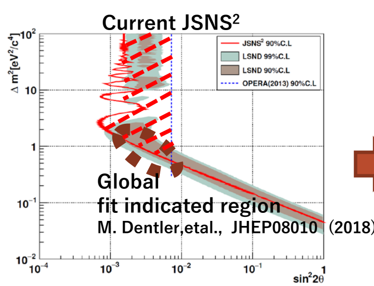


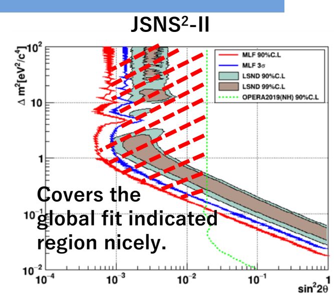
(JSNS^2)
17t GdLS fiducial (target) detector (4.6m dia. x 4.0m height, 120 10" PMTs)

Searching for neutrino oscillatio[…] th baseline of 24m (JSNS^2), and 48[…]

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

(6.2m dia. x 6.2m (h) ~230 10" PMTs)



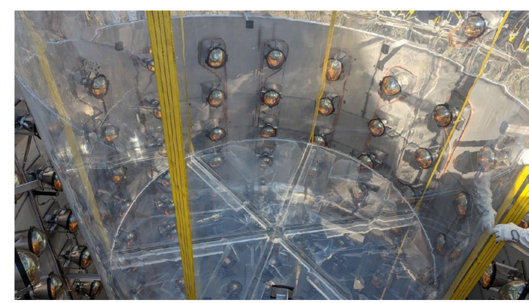


(JSNS^2) : 1MW x 3 years

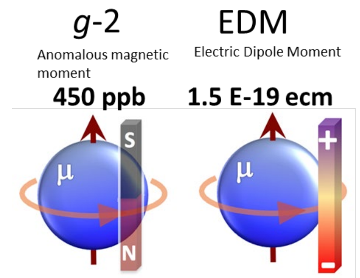
- The long physics runs (2021-2024)
  - In total, ~19 months.
  - 0.88 MW beam now.
  - 4.093 x 10^{22} POT so far
  - Sterile ν analyses are on-going
  - Will continue data taking !!

(JSNS^2-II): 1MW x 5 years

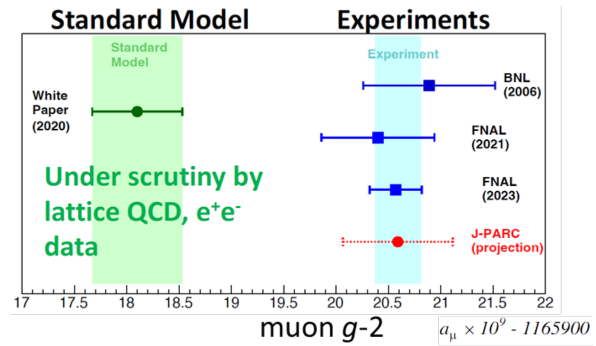
- 2nd phase of the experiment
  - new far detector : 32 tons fiducial in 48m baseline.
  - Improved the sensitivity, especially in low Δm^2 region.
  - Stage-2 approval was granted.
  - **Will take data soon !**



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

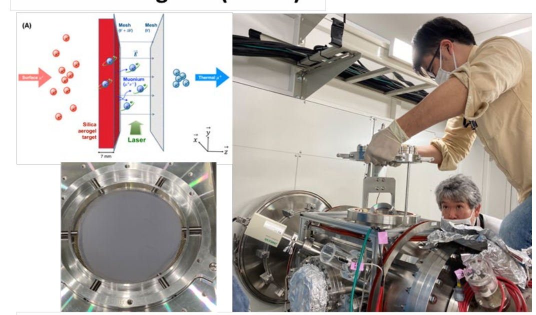


- Physics goal
  - High precesion measurement of mu g-2 to ~450ppb
  - Discovery of mu EDM with sensitivity down to 1.5e-19e.cm
- With totally different scheme/systematiscs from BNL/FNAL exp.
  - Accelerate ultra-slow muon and inject small ring
- **Construction budget start in JFY2024**
- First-ever muon acceleration in 2024
- Aiming for data taking from 2028

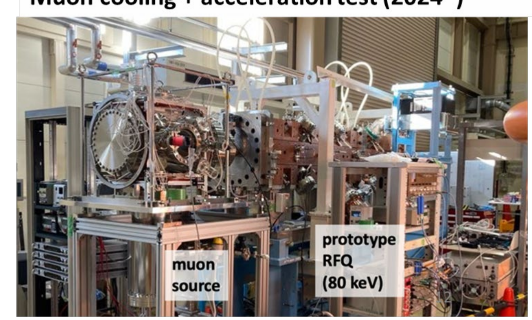


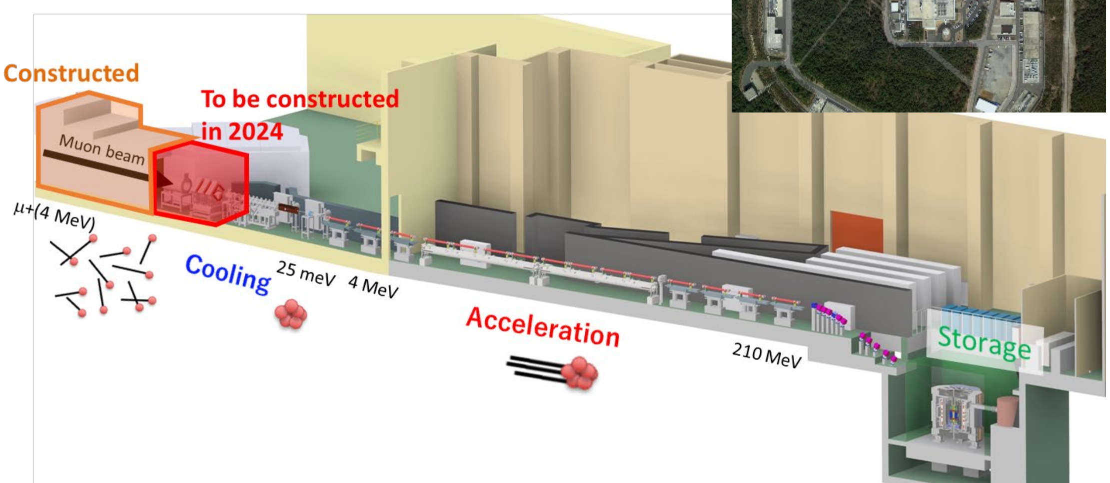
The collaboration (114 members from 10 countries)

Muon cooling test (2022~)



Muon cooling + acceleration test (2024~)





7th Plenary Workshop of the Muon g−2 Theory Initiative

September 9-13, 2024 @ KEK, Tsukuba, Japan

https://conference-indico.kek.jp/event/257

g-2

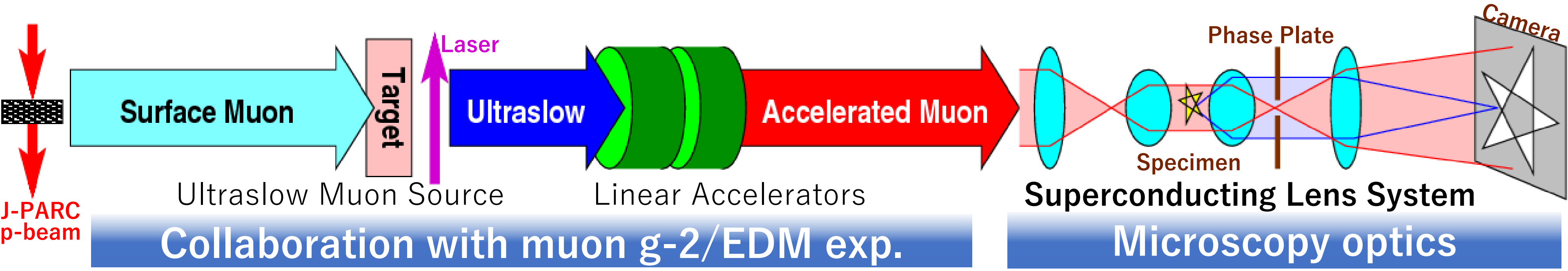
International Advisory Committee
- Gilberto Colangelo (University of Bern)
- Michel Davier (University of Paris-Saclay and CNRS, Orsay), co-chair
- Aida X. El-Khadra (University of Illinois), chair
- Martin Hoferichter (University of Bern)
- Christoph Lehner (University of Regensburg), co-chair
- Laurent Lellouch (Marseille)
- Tsutomu Mibe (KEK)
- Lee Roberts (Boston University)
- Thomas Teubner (University of Liverpool)
- Hartmut Wittig (University of Mainz)

$(g\text{-}2)_7$

Local Organizing C1ommittee
- Kohtaroh Miura (KEK)
- Shoji Hashimoto (KEK)
- Toru Iijima (Nagoya)
- Tsutomu Mibe (KEK)

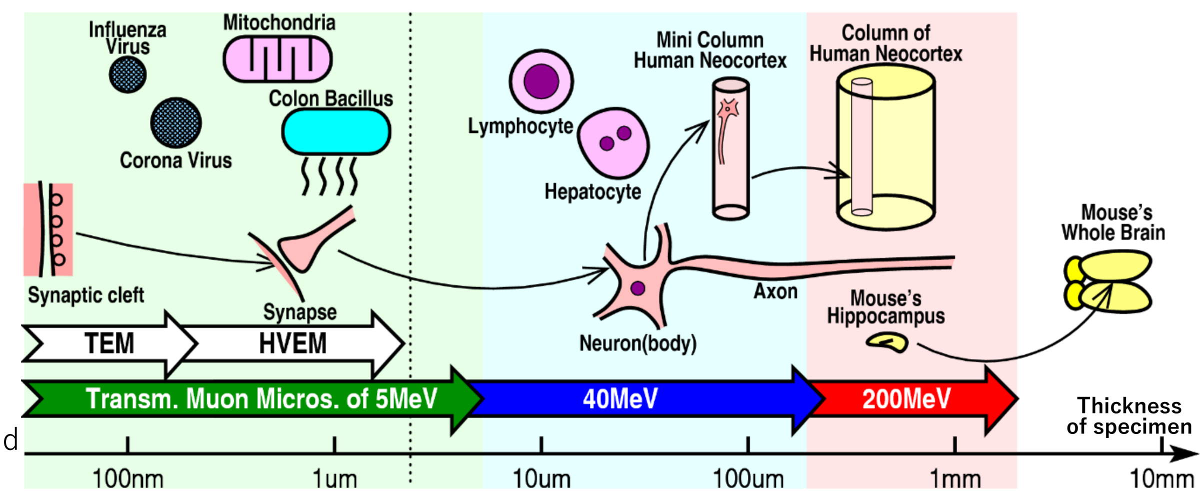
A future plan: Transmission Muon Microscope

= Accelerated Muon : Strong Penetration + Ultraslow Muon : High Luminance / Resolution

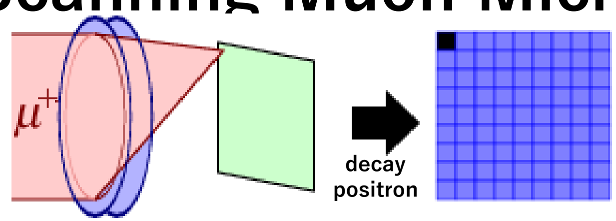


Nano scale visualization of electromagnetic fields in macroscopic objects

- Any methods for TEMs are applicable, like Lorentz imaging or Zernike phase contrast.
- Functional imaging of living/cryo-tissues: Cross scale understanding of our brain from synapse, neuron, network to organ.
- Industrial use: It can see EM fields in packaged IC/LSI, Li ion battery, solar cell, piezo, etc.

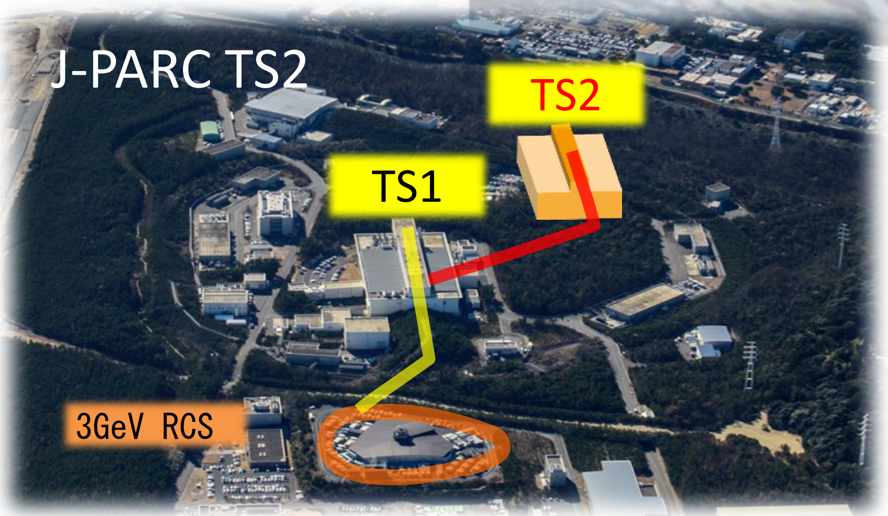


Scanning Muon Microscope



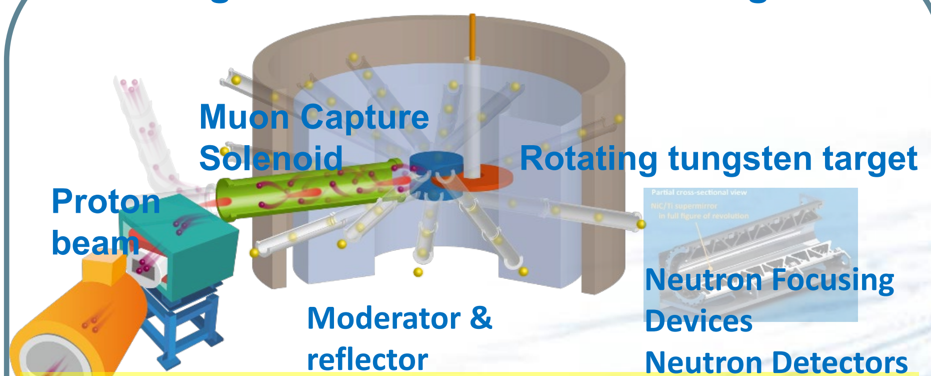
3-dim mapping of magnetic field and its fluctuation, density of Fermi surface, state of hydrogen, and etc. in nano resolutions. → **Scanning μSR microscope**

Target Station - 2



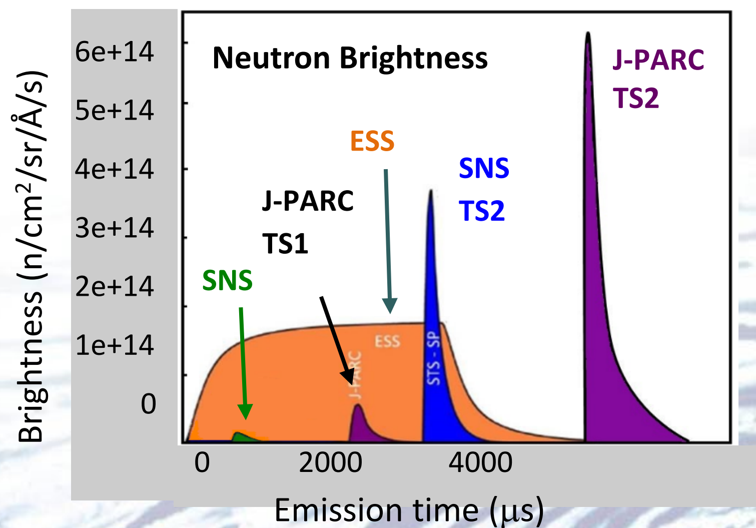
- Integration of neutron and muon sources (world's first)
- J-PARC proton accelerator intensity (1 MW) increased to 1.5 MW
- 1 MW (17 Hz) for TS1 and 0.5 MW (8 Hz) for TS2

Integrated neutron and muon target



Neutron:
10 (target) x 2 (device) → 20 times gain of brightness

Muon: :
10 (target) x 5~10 (Muon capture solenoid) → 50 ~100 times gain of flux



Brightness of MLF TS2 will be the world's highest compared to the next plan of overseas facilities

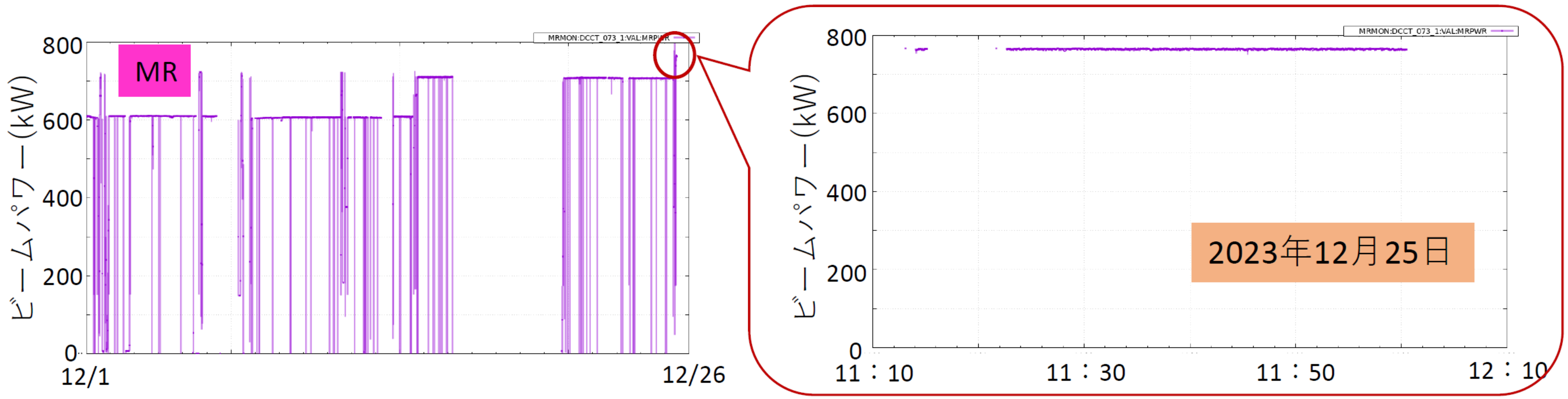
Projects using Main Ring

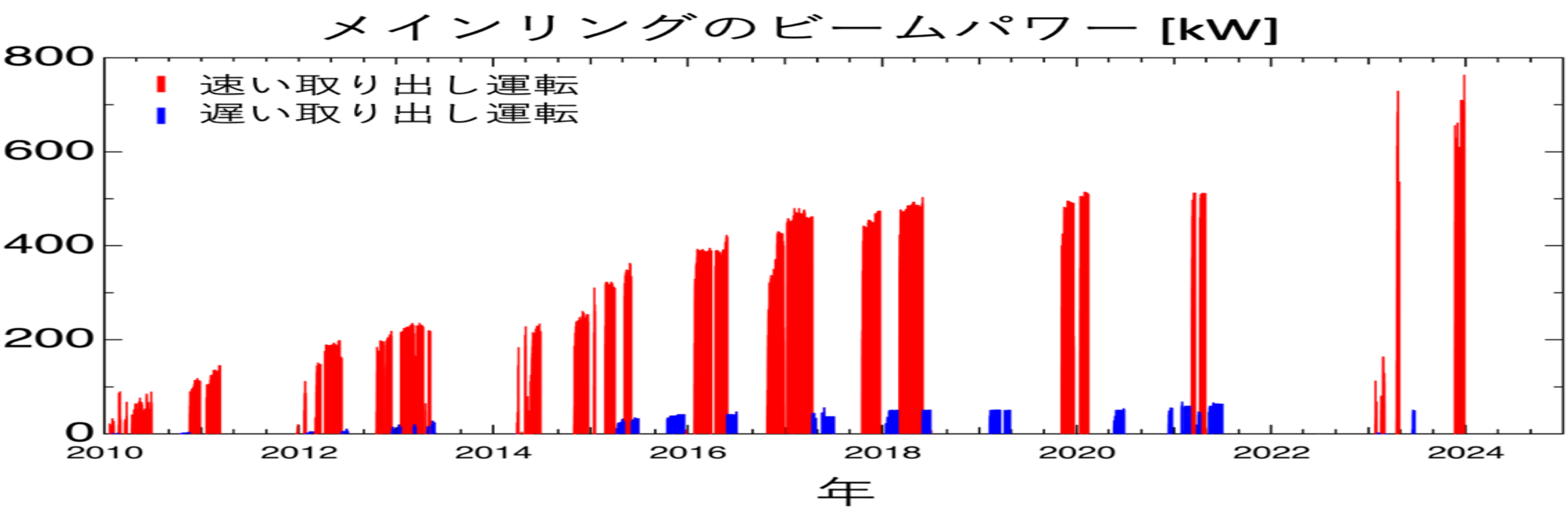
MR/NU achieved operation at 760kW!!

Original design goal: 750kW
(Current goal: 1.3MW)

MR Power 763.97 kW

2023/12/25 11:22 – 12:00; **38分間**安定にビームを供給





Main ring upgrade plan toward 1.3MW

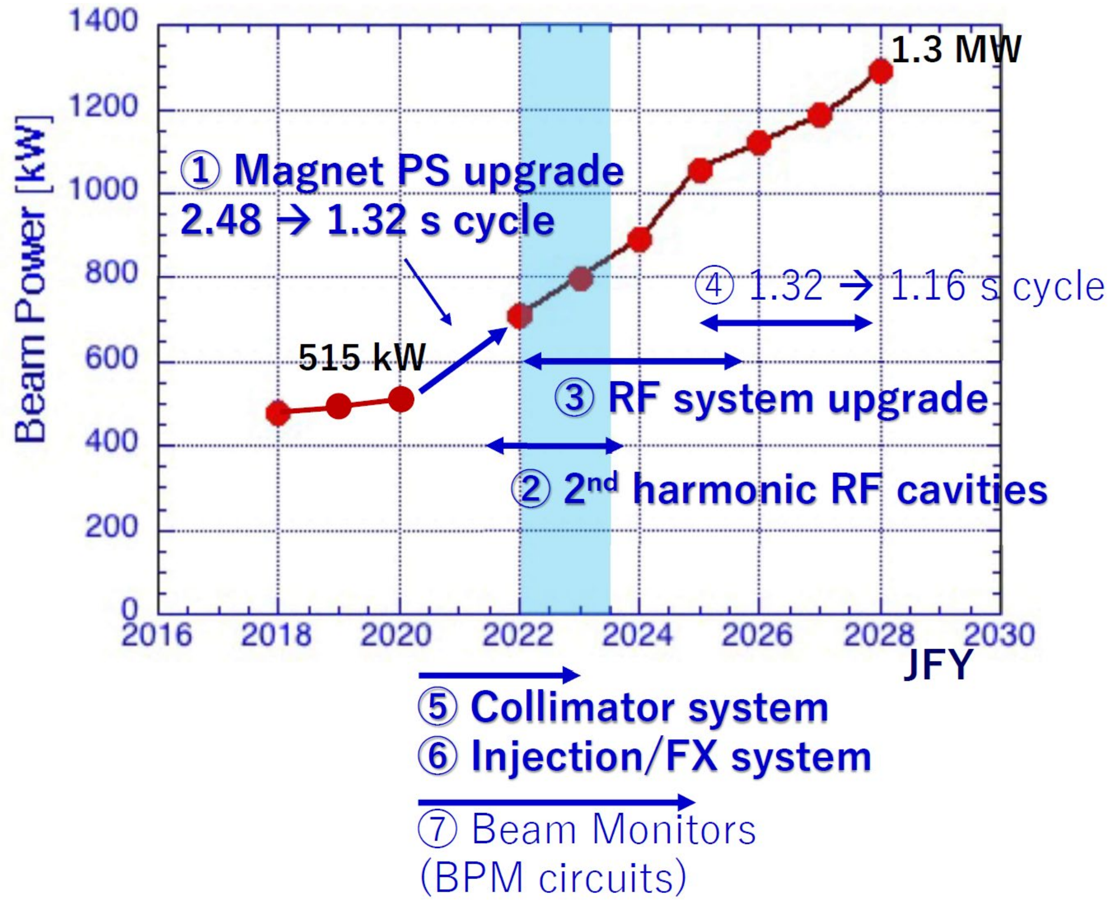
More Rapid Cycle:

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

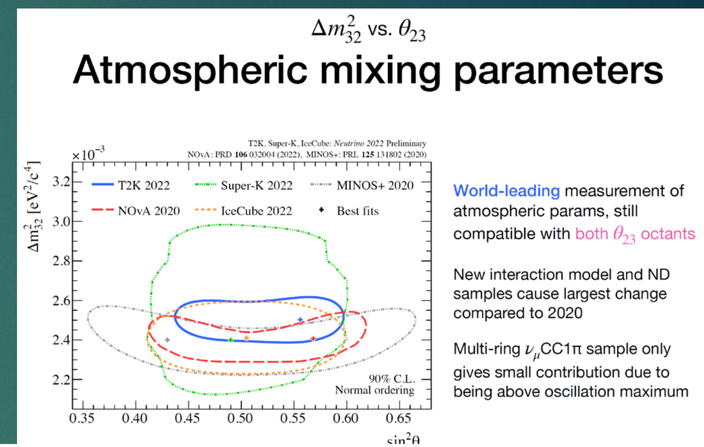


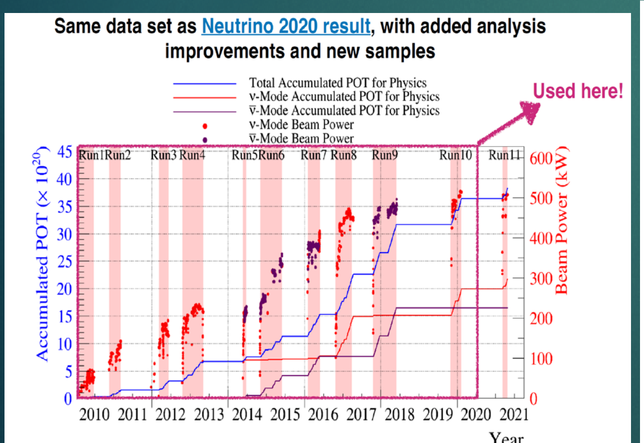
In April 2023
Successful demonstration of
MR-FX 30 GeV acceleration
766 kW eq. (2.17e14 ppp) in 1.36 s cycle

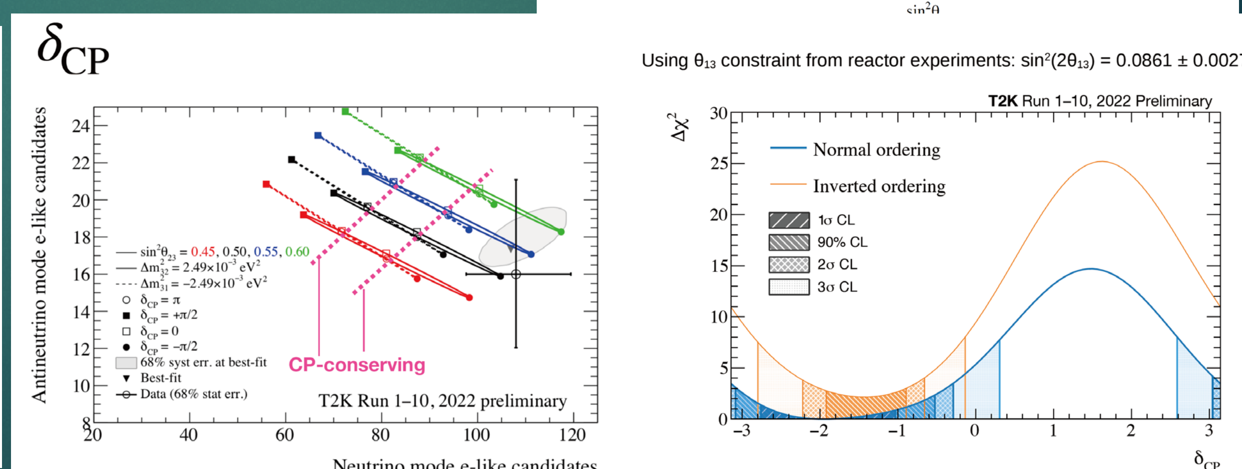
T2K experiment

- Status
  - **760kW operation achieved (2023)**
  - Delivered POT: 4.1e21 (nu:2.5/anu:1.7)
- Latest results
  - 3.6×10^{21} POT (2010~2022) analyzed
  - World leading measurement of atm param
  - Large area of δCP excluded at 3σ
  - CP converving excluded at 90%
  - Weak preference of normal ordering

~570 members, 78 Institutes, 14 countries (incl. CERN)

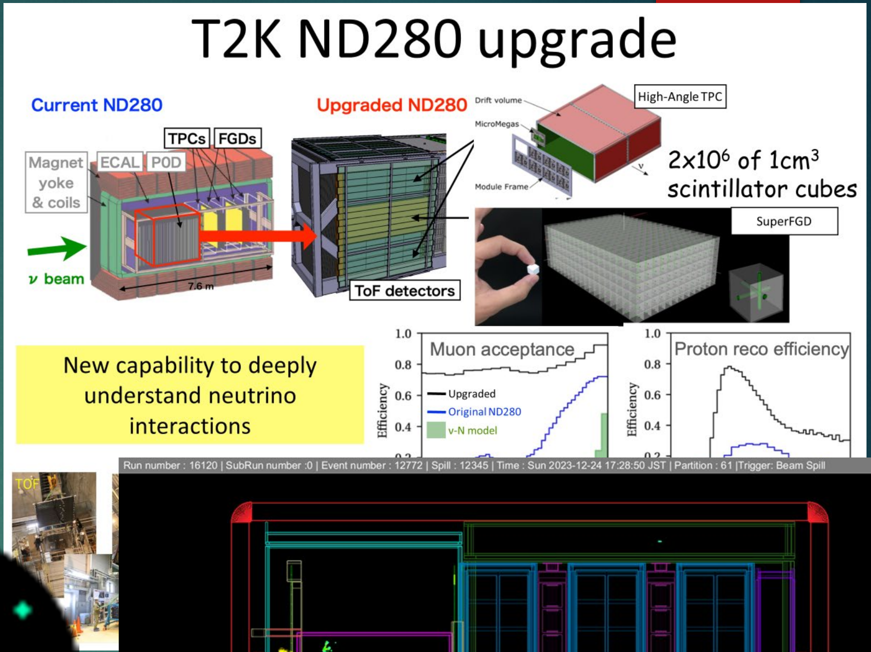


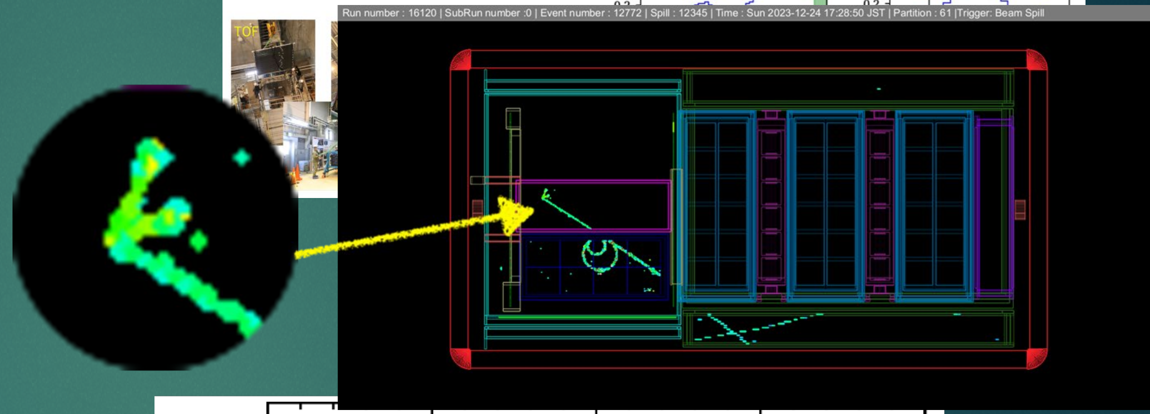


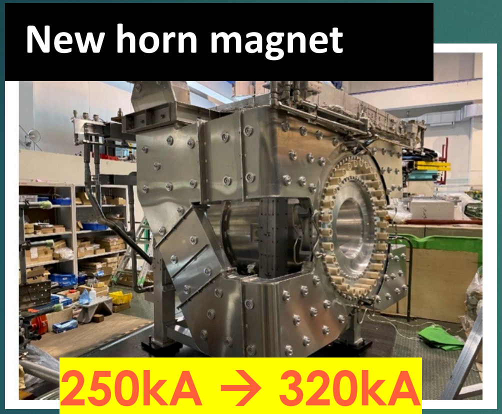


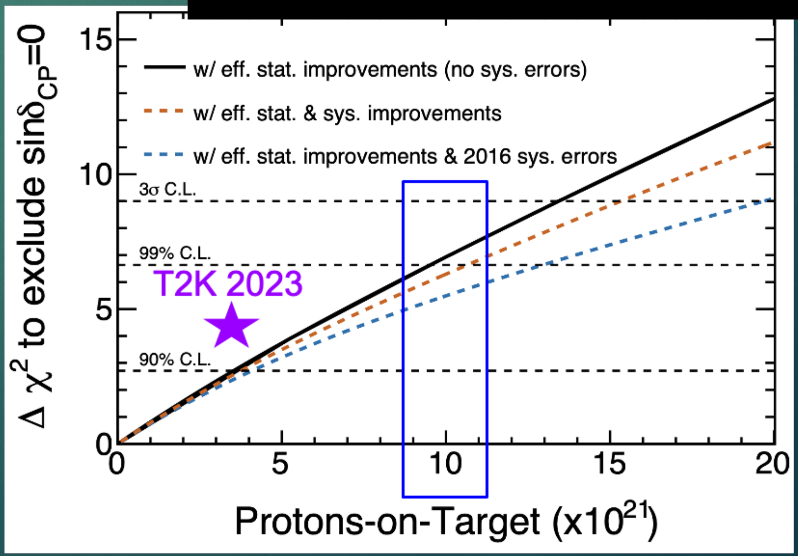
T2K upgrade & prospect

- To improve further sensitivity
  - Upgrade ND280 for systematics
  - Beamline upgrade for higher beam power upto 1.3MW
- KEK will make best effort to secure ~4 cycle (month) / year
- Aim to accumulate ~1x10^{22} pot



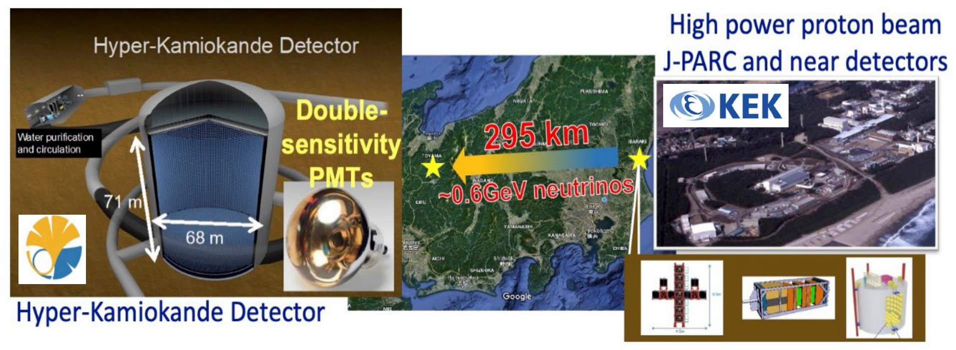


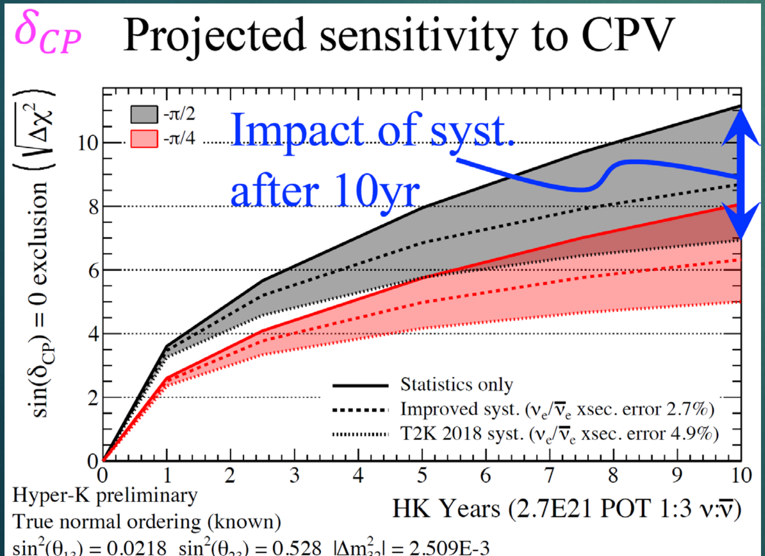


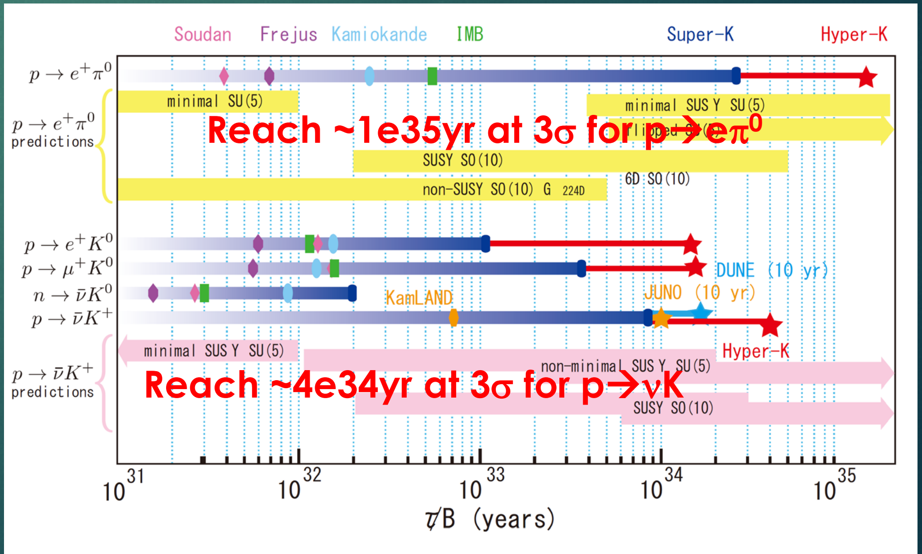


Hyper-Kamiokande project

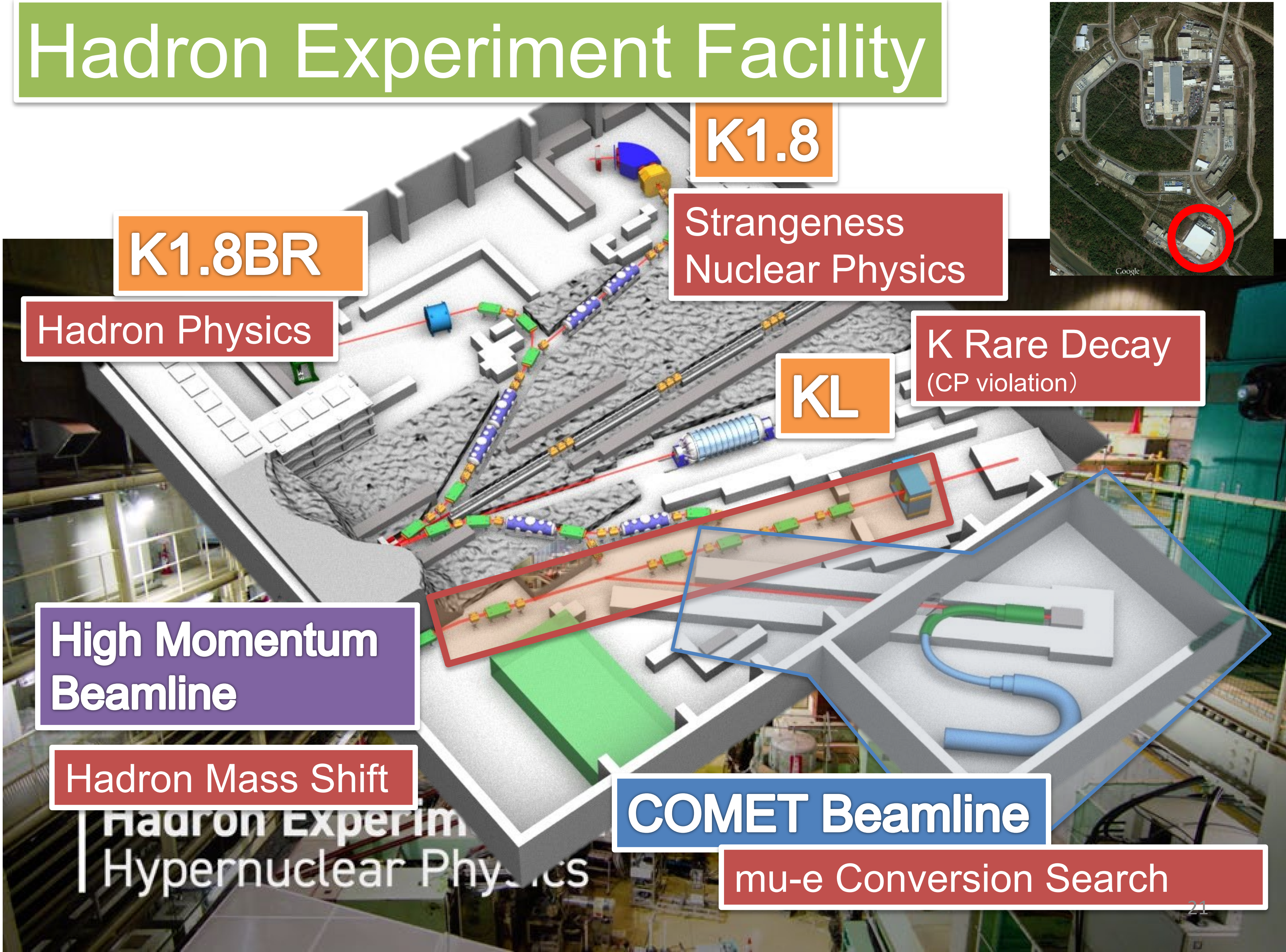
- Project consists
  - 190kt Hyper-Kamiokande det (UT & collab.)
  - Beam power upgrade to 1.3MW (KEK& collab)
  - Near detector upgrade (KEK& collab)
- Physics goals
  - CPV in neutrino sector
  - Search for proton decay
  - Atm-nu, solar-nu and supernova nu
- International project hosted by U.Tokyo & KEK
- Construction started in 2020
- **Aiming to start operation in 2027.**







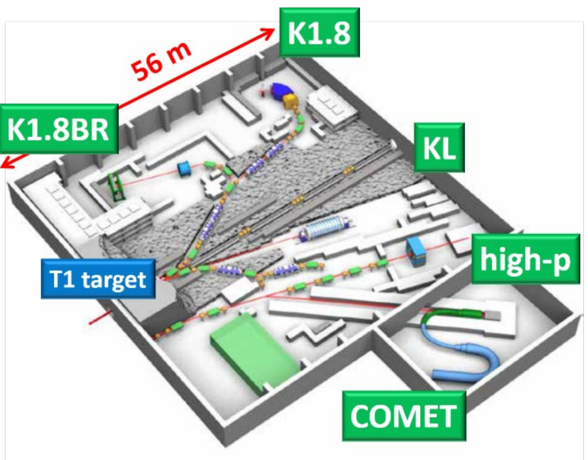
Hadron Experiment Facility



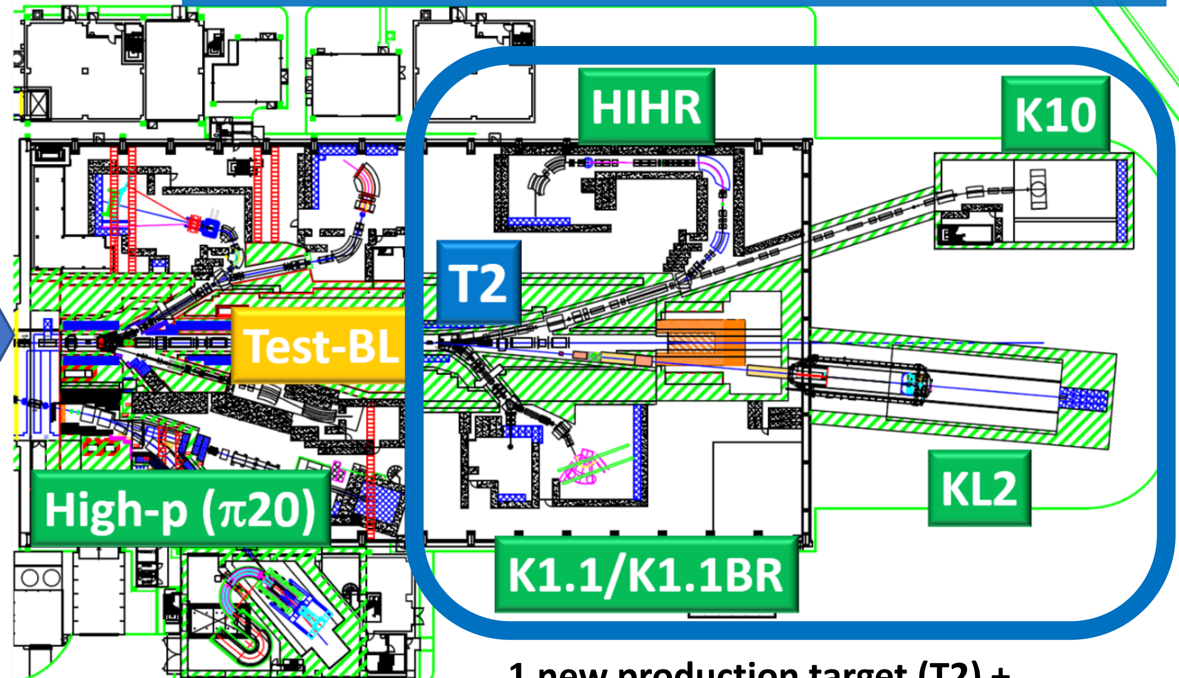
Hadron Experimental Facility Extension (HEF-ex) project

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

KOTO experiment

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

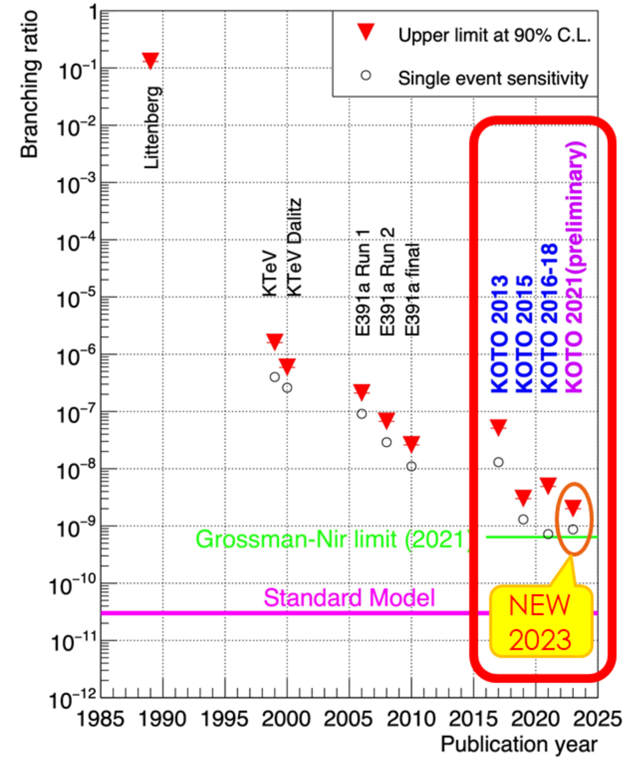
CP- CP+

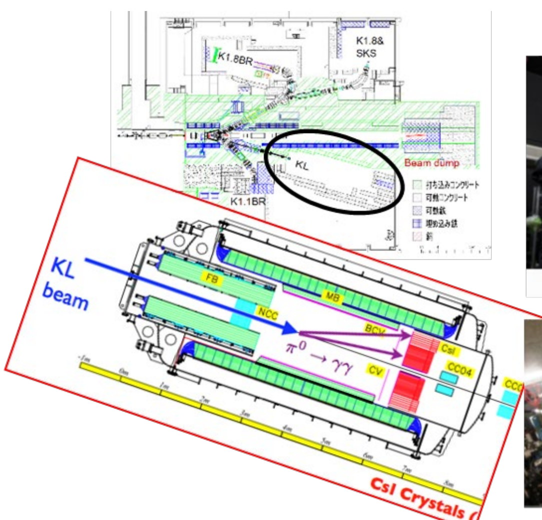
$$K_L \to \pi^0 \nu\bar{\nu}$$

- SM pred. is very small ~3e-11

→ **Sensitive to New Physics**

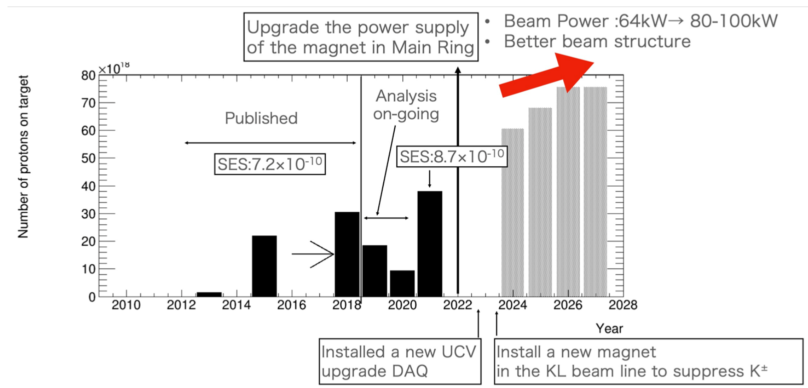
- Upp bound: 4.9×10^{-9} (90%CL) PRL 126, 121801 (2021) **Editors' Suggestion**
- further accumulate physics data toward the sensitivity better than 1×10^{-10}





CsI calorimeter

KOTO prospects for future run



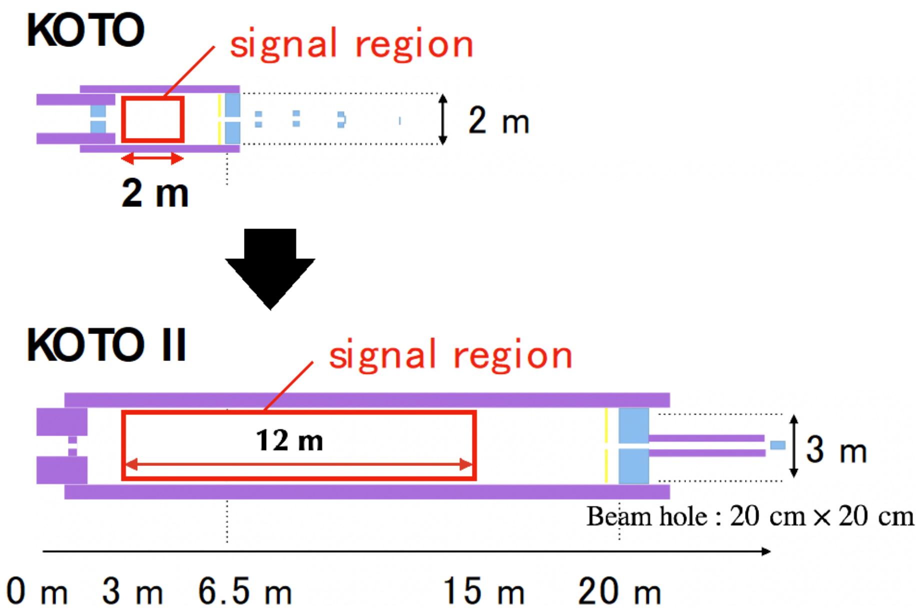
- The accumulated POT will be 10 times more in 3-4 years, assuming 60 days/year run.
  - Will reach a sensitivity better than 10^{-10}

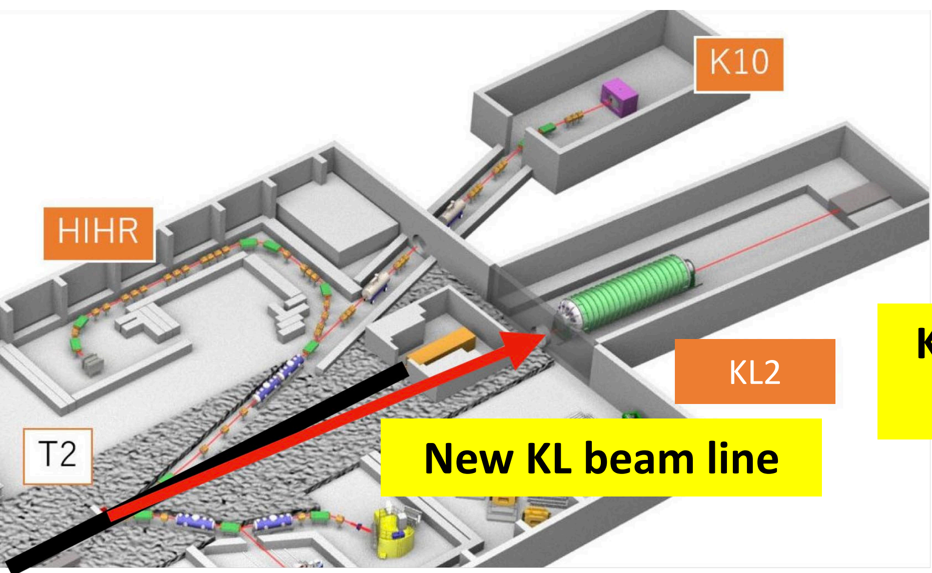
KOTO II @ HEF-ex

New Phase of the $K_L \to \pi^0 \nu \bar{\nu}$ study

- From "Search" to "Measurement of the branching ratio" -

- More K_L
  - Smaller extraction angle
    (16° for KOTO → 5° for KOTO II)
- Larger detector
- More signal acceptance





KOTO II detector behind dump at the end of extended hall

KOTO II @ HEF-ex

Search for new source of CP violation beyond Standard Model (SM)

New Phase of the $K_L \to \pi^0 \nu \bar{\nu}$ study

Expect 35 SM signal / 40 background events

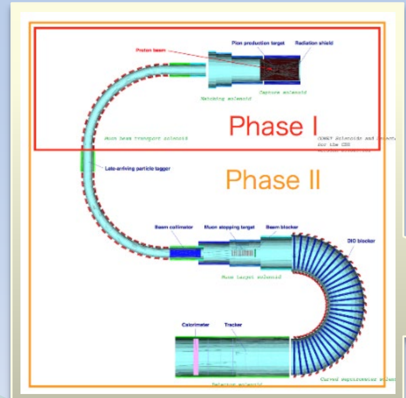
assuming 100kW beam, and 3×10^7 s running (corresponding to 6.3×10^{20} P.O.T.)

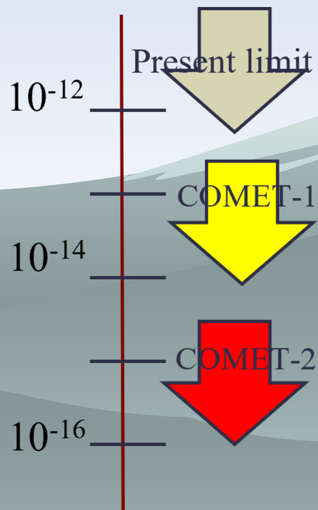
- Single Event Sensitivity (SES) = 8.5×10^{-13}
- 5.6σ observation of $K_L \to \pi^0 \nu \bar{\nu}$ (SM)
- 25% precision for the branching ratio
- If 44% deviation from SM prediction is observed
  → Indication of New Physics at 90% confidence level

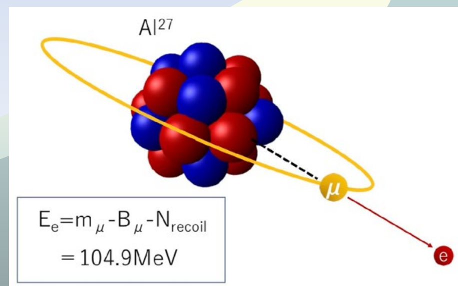
KOTO II detector behind dump at the end of extended hall

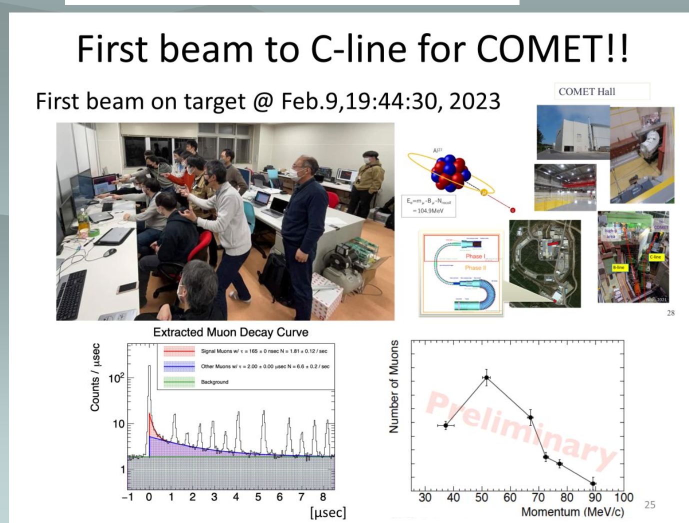
COMET experiment

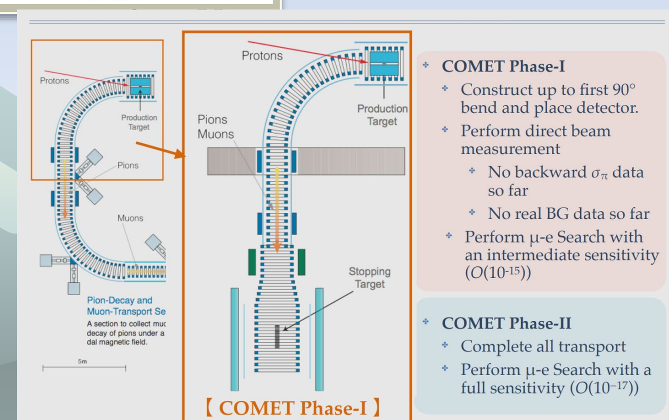
- μ→e conversion search
  $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
  - Very small $O(10^{-54})$ in SM
  - **Discovery = New Physics!**
- First commissioning in FY2022
- Strong participation from UK

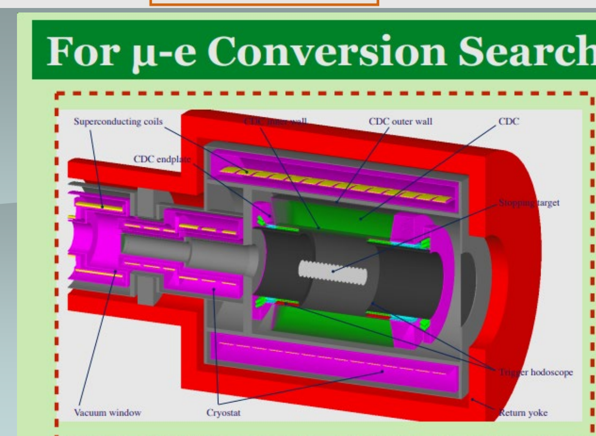










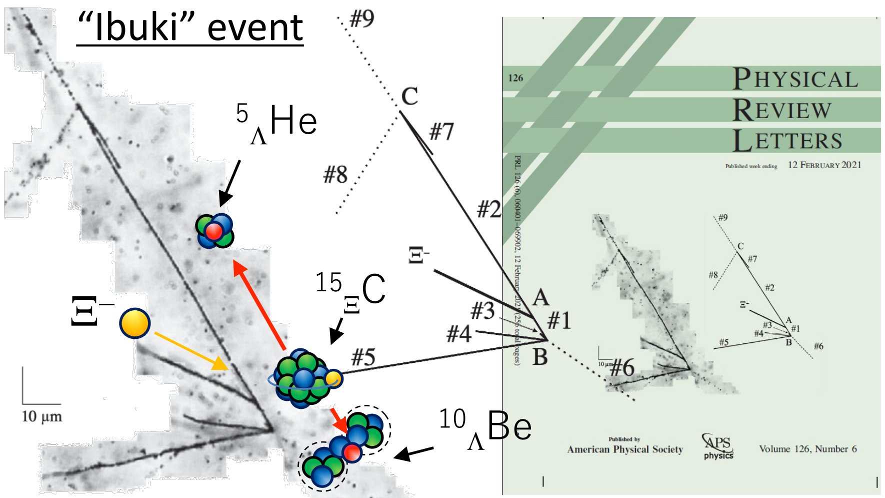


【Nuclear physics at Hadron Experimental Facility】

大強度陽子加速器施設 J-PARC

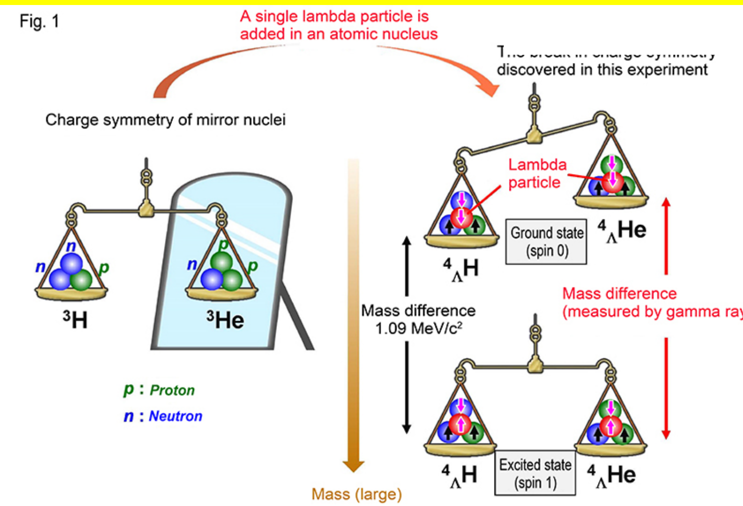
Elucidation of the property and origin of "generalized nuclear force" including strangeness

Mass measurement of Xi hypernuclei



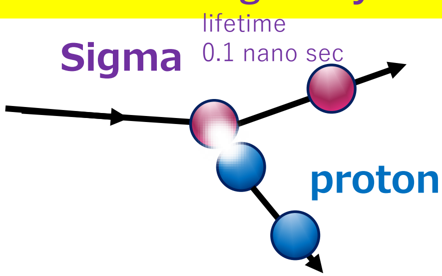
→ confirm the force between Xi (Ξ) and nucleon is attractive

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

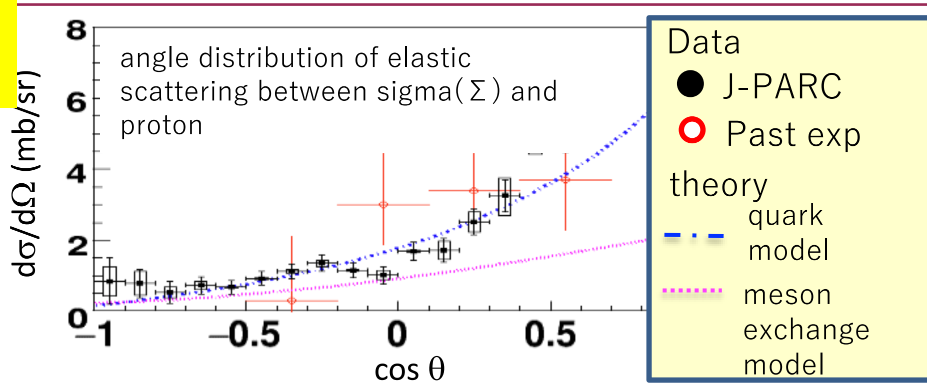


3H and 3He are the same on mass and structure in mirror images.
If a single lambda particle is added, it is found that a large difference appears in mas of ground state and excited state.

Establishment of scattering experiments between strange baryon and proton

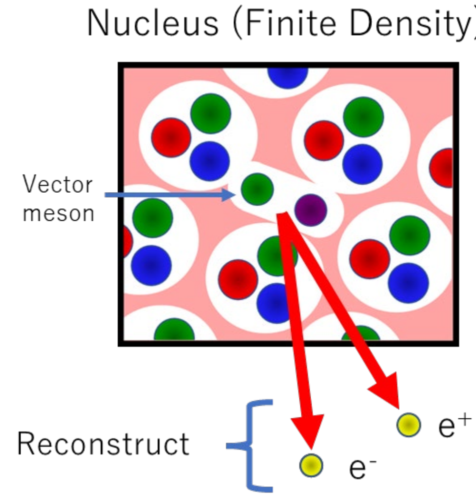


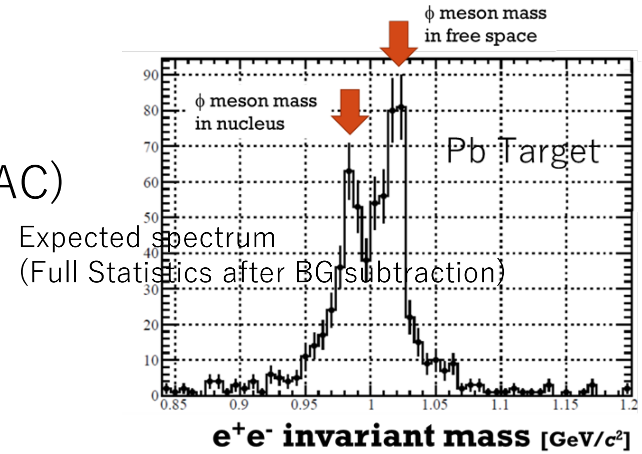
→ improve the precision of scattering angle distribution by x10 for the first time in 50 years



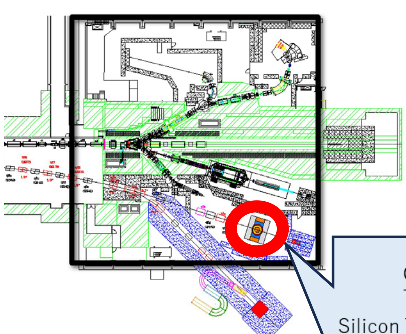
Hadron Mass in Nuclear Matter

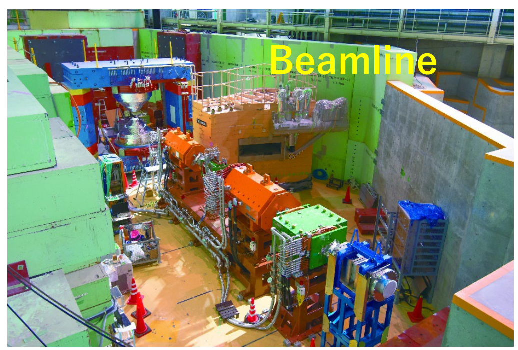
- The J-PARC E16 exp. aims to measure changes of hadron mass in nuclei
  - Hadron mass is dynamically generated by QCD due to a spontaneous breaking of chiral symmetry
  - The symmetry will be partially restored in the nuclear matter by a density effects and the mass is modified.
- Status
  - First beam 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)

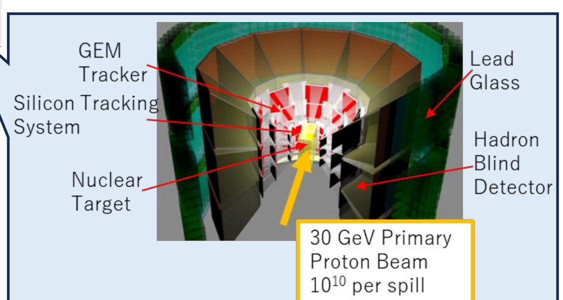


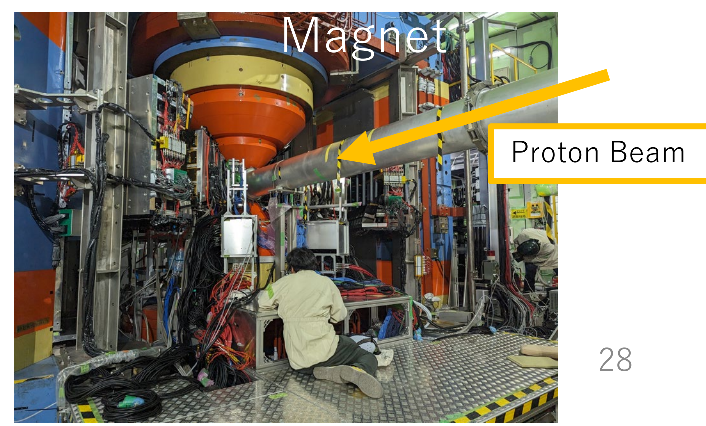


Hadron Experimental Facility

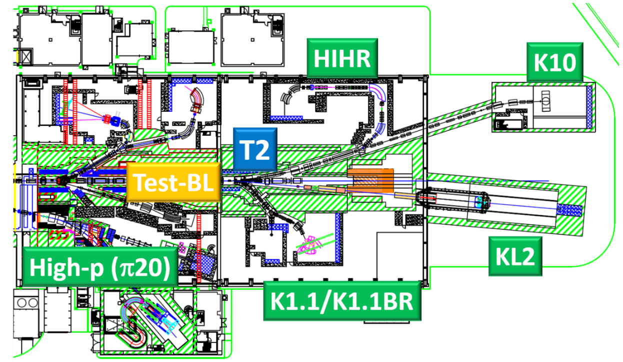






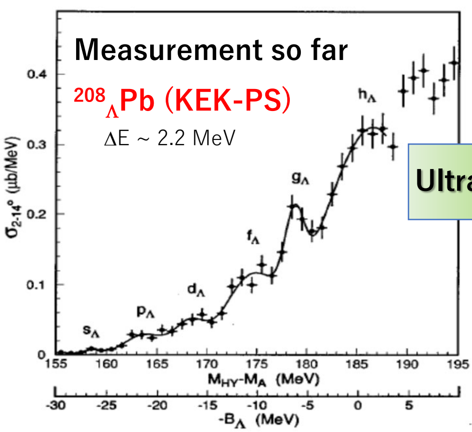


A Highlight of future nuclear physics at extended HD hall



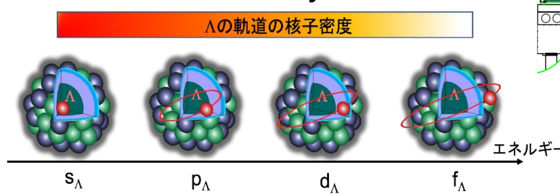
Elucidation of YN interaction in nuclear matter

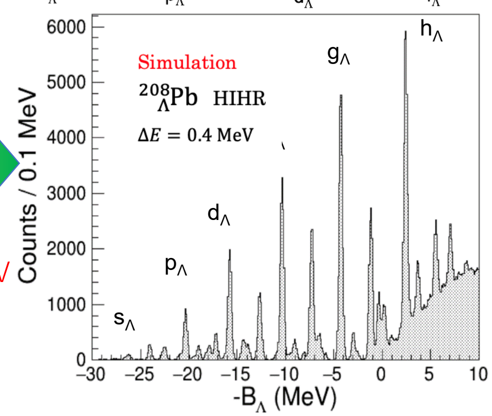
First high-resolution spectroscopy of the heaviest Λ hypernucleus at HIHR



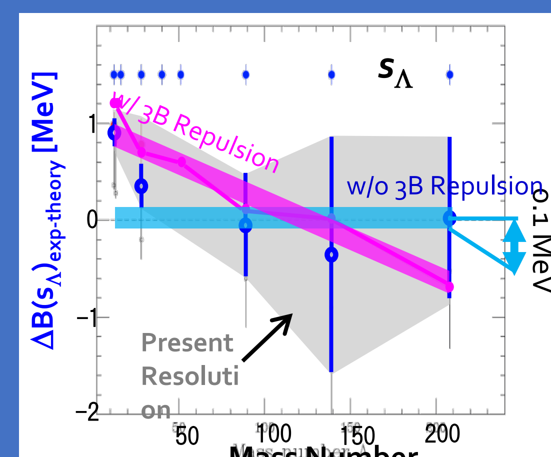
Ultra high-resolution

Resolution 400 keV (5 times better than KEK-PS)





Effect of multi-body force to the Λ single-particle energies



Clarify **density-dependent Λ interaction** and **multi-body force** via the systematic measurements for the **understanding high-density matter and neutron stars**.

R a D I A T E collaboration

radiate.fnal.gov

Radiation Damage In Accelerator Target Environments

Target and beam window survivability :

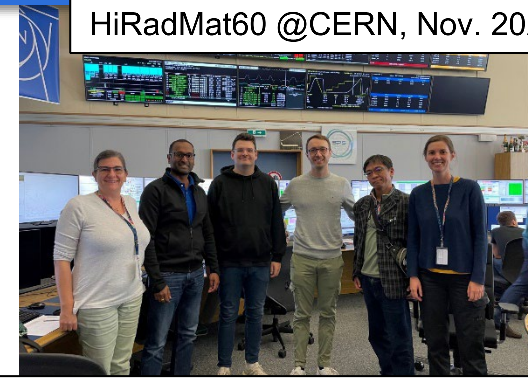
Limiting beam power in recent major accelerators

Radiation damage studies under RaDIATE collaboration:

Mutual utilization of accelerator & post-irradiation exam. facilities

RaDIATE collaboration meeting 2023 at BNL

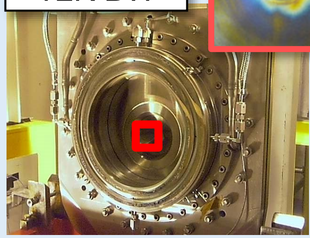
HiRadMat60 @CERN, Nov. 2022

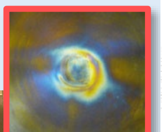


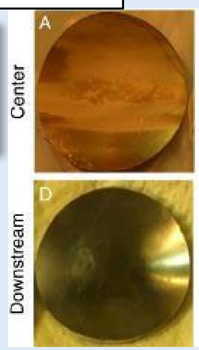
Led by FNAL & STFC, 13 institutions (~Dec. 2022) + 6 new institutions (Dec. 2022 ~), J-PARC joined with CERN in 2017.

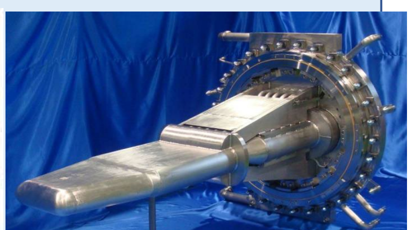
Need for RaDIATE

J-PARC, T2K BW

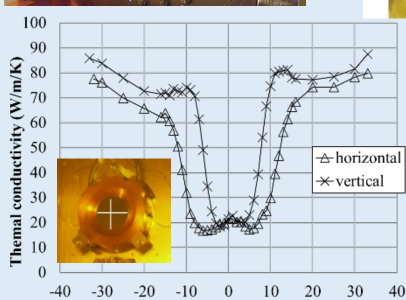


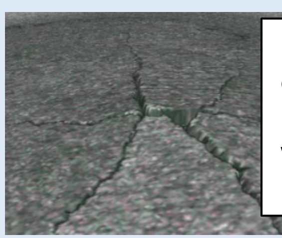






J-PARC Mercury vessel: Cavitation damage

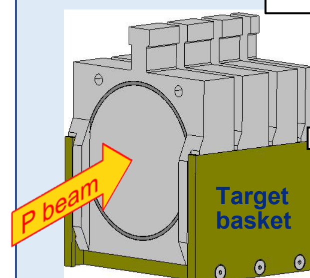


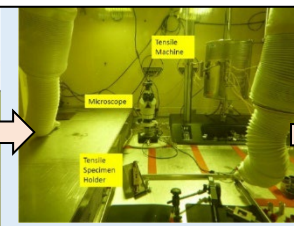


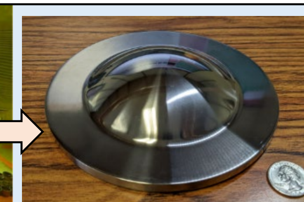
Be window embrittlement (FNAL, common with J-PARC, Hadron)

Thermal conductivity degrades in graphite, Muon, Nu, COMET

Highlight of achievements

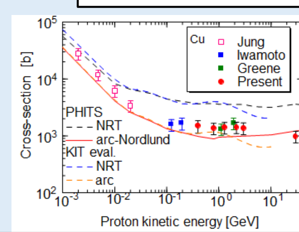


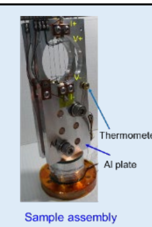




- P+ irradiation at Brookhaven N. lab.
- Post irradiation exam. at Pacific N.W.N. lab.

Prototyping of next-generation Neutrino beam window



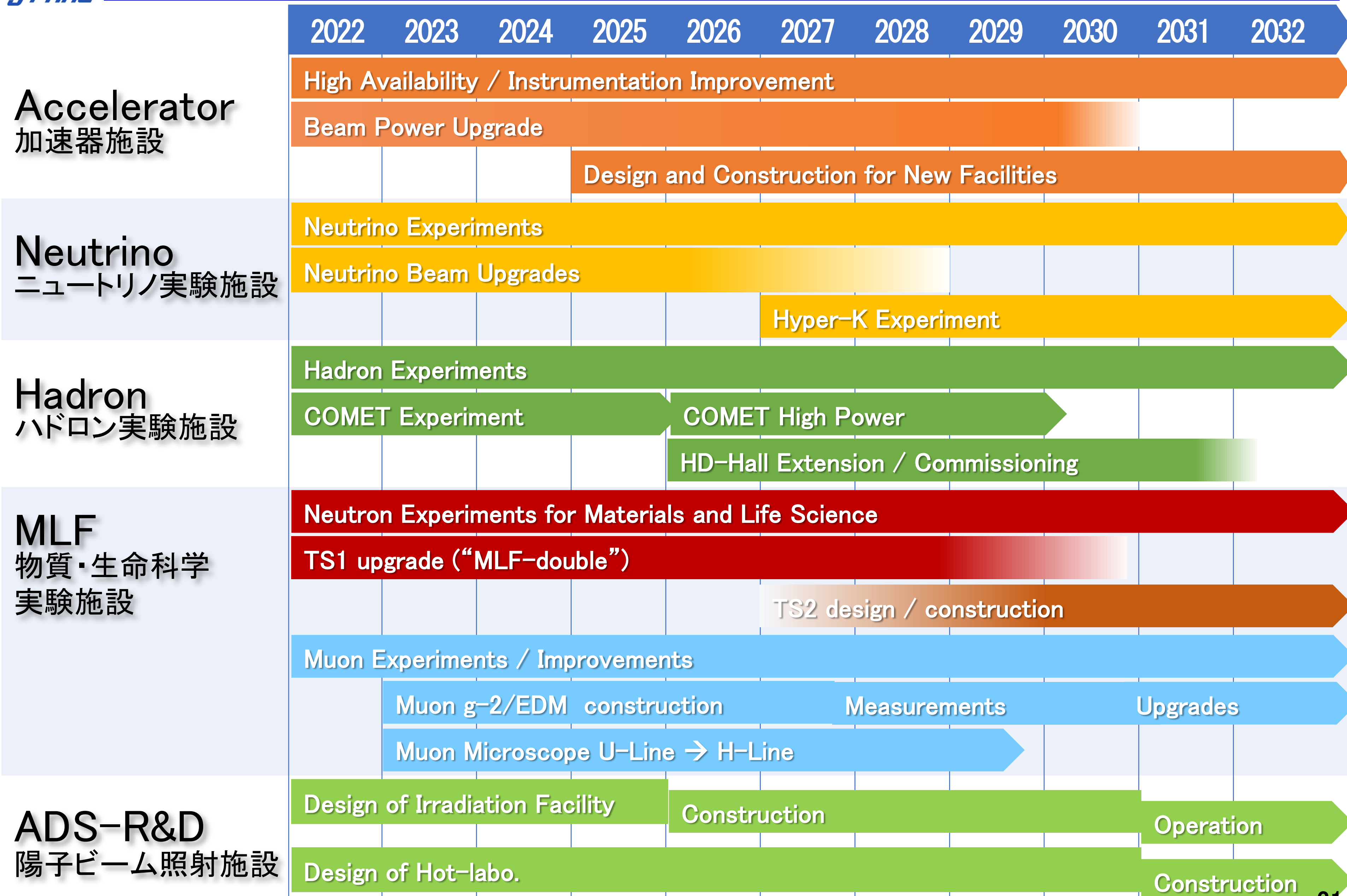


Experimental validation of DPA X-section

Thermal shock experiment at CERN HiRadMat

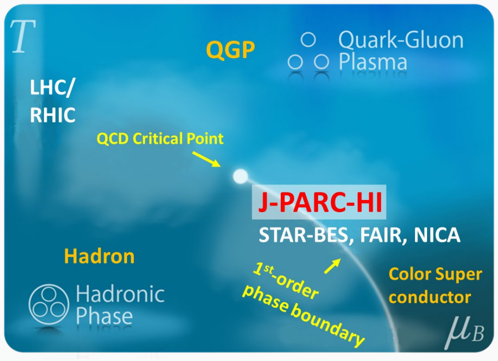
RaDIATE J-PARC for Next-gen. Target & B.W.

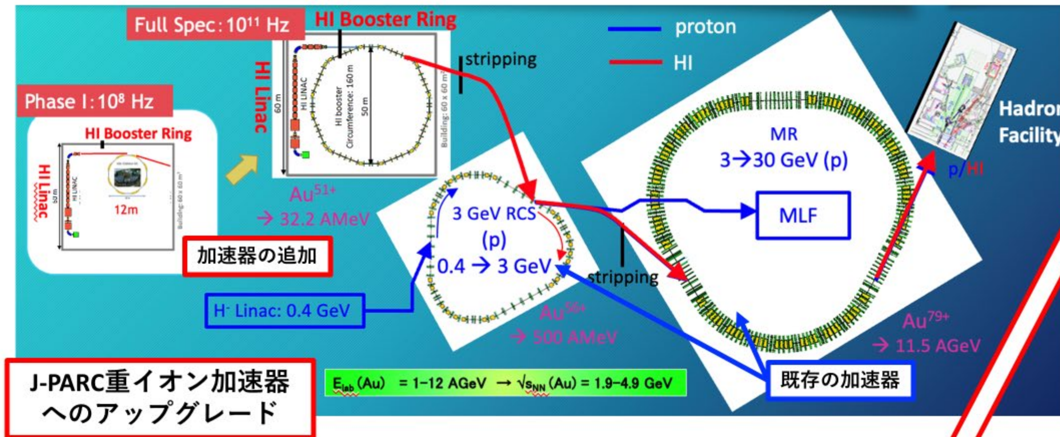
J-PARC future plan

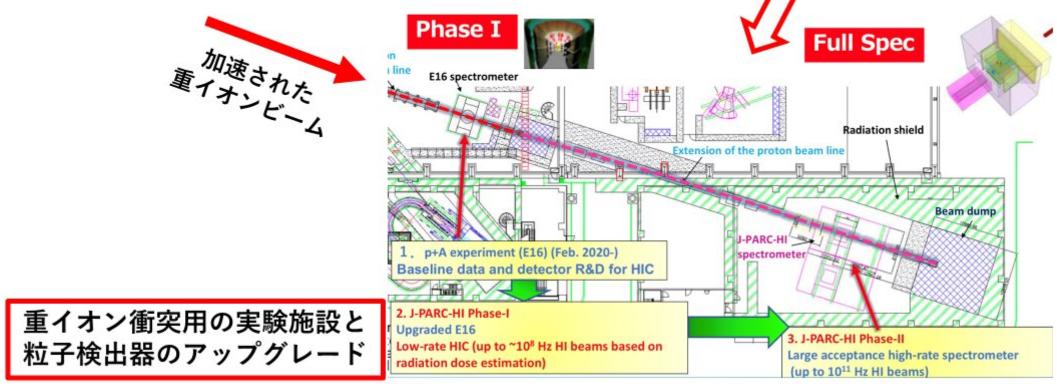


A future plan: J-PARC Heavy Ion program

Explore the QCD phase diagram







Physics goals:

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

- Staging approach
  - Phase1:
    - Beam Intensity: 10^8 Hz for Au
    - New LINAC and reuse of KEK-PS booster
  - Phase 2
    - Beam Intensity: 10^{11} Hz
    - New booster and new spectrometer

J-PARC Symposium 2024

- Discuss and appeal to the world
  - Scientific output/achievements in the last 15 years
  - (Attractive) Future projects for 20~30yrs or more
- Oct 14-17, 2024 @ Mito (new city culture center)

https://j-parc.jp/symposium/j-parc2024/

Summary

- J-PARC is the world leading intensity frontier proton accelerator research complex
  - 3GeV RCS/MLF: reached at 840kW stable operation
  - 30GeV MR
    - **760kW continuous operation succeeded**
    - **Aim to realize 1.3MW for HyperK experiment**
- 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 future projects are being conducted/prepared
  - MLF muon microscope, MLF target station 2
  - COMET
  - Mu g-2
  - Hadron hall extension : KEK's highest priority in KEK-PIP 2022
  - T2K → Hyper-Kamiokande
  - And more

We welcome your more participation for exciting physics at J-PARC!