Remote maintenance of the neutrino beamline at J-PARC in the megawatt beam power era

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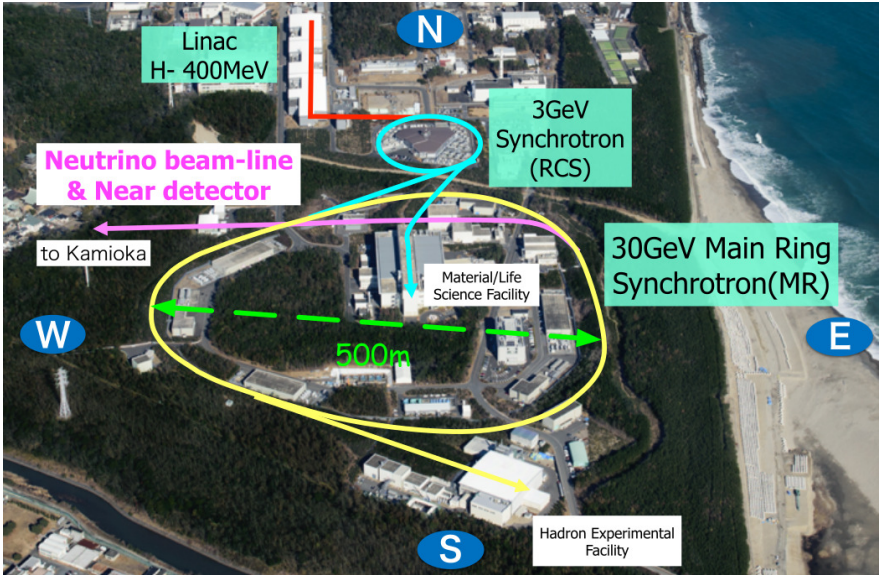
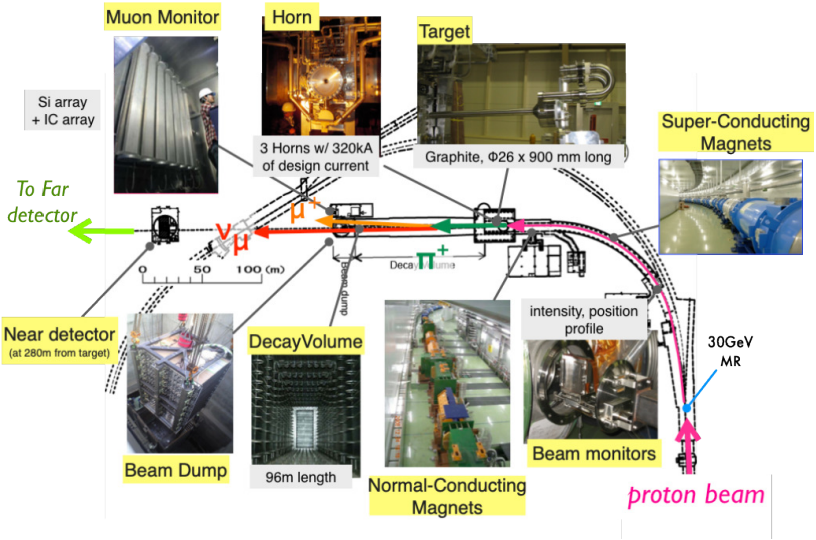
Introduction

- Overview of the J-PARC accelerator chain and neutrino beamline
- Final Focusing (FF) section: need for remote maintenance
- Motivation: high residual radiation in the most downstream FF region
- Current maintenance scheme and its limitations
- Goal: transition towards fully remote maintenance

J-PARC accelerator chain



Neutrino beamline



The most downstream end of the primary beamline is inclined down at a 3.64° angle to allow the off-axis neutrino beam creation method

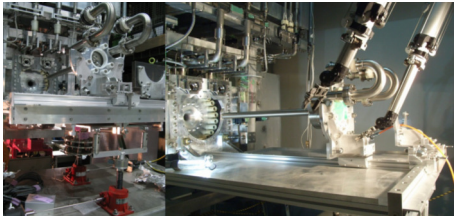
Maintenance of the neutrino beamline

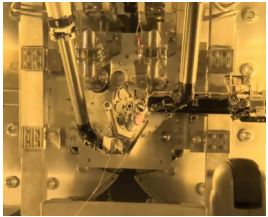
Primary beamline:

- built with hands-on maintenance in mind
- suitable design choice for radiation levels projected during T2K lifetime
- new solution needed in HK era

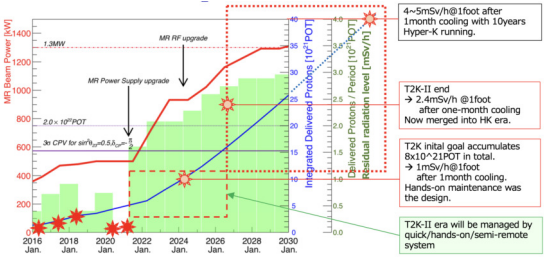
Secondary beamline:

- designed with a robust scheme of remote maintenance in mind
- component handling by crane operated from shielded control room
- dedicated maintenance area with remote manipulators





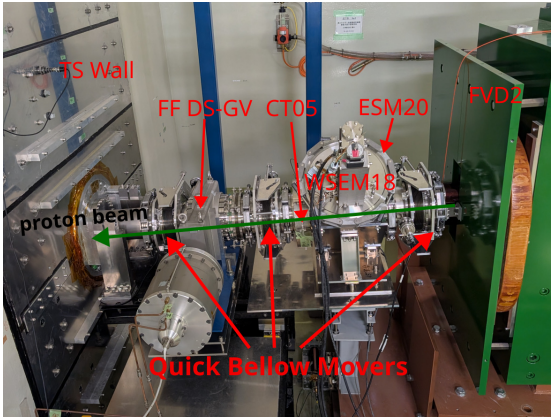
Projection of the residual radiation levels



- Even quick hands-on maintenance of the downstream part of the primary neutrino beamline at J-PARC is impossible for a long-term scenario with 1.3 MW operation in the Hyper Kamiokande era (starting from 2028)
- During 6 months/year operation during HK era, radiation levels will reach several mSv/h at 30cm distance **after 1 month of cooling**
- Main contribution comes from back-scattering from the neutrino production target and the beam window between primary and secondary neutrino beamlines

Fully remote maintenance scheme is needed!

Downstream End of Final Focusing Section



- Beam position monitor - ESM20
- Beam profile monitor - WSEM18
- Beam current monitor - CT05
- Final Focusing section Downstream Gate Valve separating primary and secondary beamlines – FF DS-GV

- Essential equipment located between the most downstream bending magnet (FVD2) and the wall between the primary and secondary beamlines
- We need to be able to replace it in case of any failure, minimizing beamline downtime

Basic Strategy for Remote Maintenance Scheme Upgrade

- **Always have a working spare of necessary equipment on hand**:
  - gate valve
  - full monitor triplet (ESM + WSEM + CT)
  - clamps
  - gaskets, etc.
- In case of failure, use the remote maintenance scheme to replace the failed gate valve or monitor triplet with a spare one
- Failed equipment can cool for months (or even years), then inspect it, repair or discard, depending on the failure mode

Upgrade status and plans

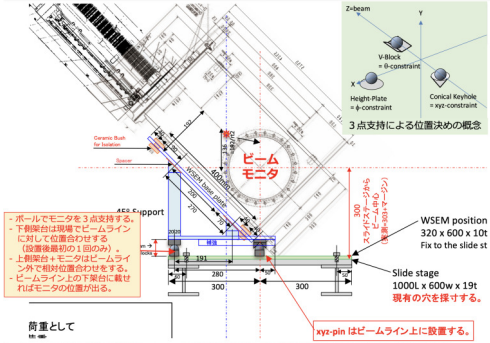
Status (implemented in an upgrade towards quick hands-on handling performed in 2021/2022):

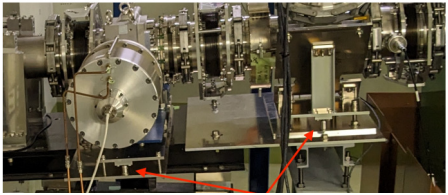
- Shorter FVD2 magnet installed, making space for hands-on quick maintenance
- Quick bellows movers and 3-point stages for repeatable positioning installed
- Quick hands-on chain clamps are in use
- Hand-operated crane with electric hoist installed over the beamline for line-IN and line-OUT of the components (added later)

Plans:

- Development of fully remote clamps, operated from a safe distance
- Revised design of the quick bellows mover - more constrained
- Custom vertical guide rails for line-IN/line-OUT of the components without hands-on assistance
- Modification of the overhead crane to reach the downstream part of the final focusing section

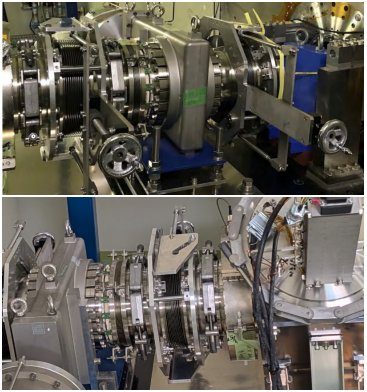
Kinematic mounts for position repeatability





- 3-point contact stage to constrain all degrees of freedom
- Currently, initial positioning requires hands-on assistance
- So far, two stages are installed: for the monitor triplet and the gate valve.
- Final solution: include vertical rails that will allow handling with a crane without hands-on manipulation

Upgrading bellows movers



- Bellow movers already installed in the beamline
- Current design needs update: 2-rod $\rightarrow$ 3-rod design
- Provides a reliable flange meeting without hands-on assistance
- They can be operated from a distance

Existing remote-friendly clamp designs

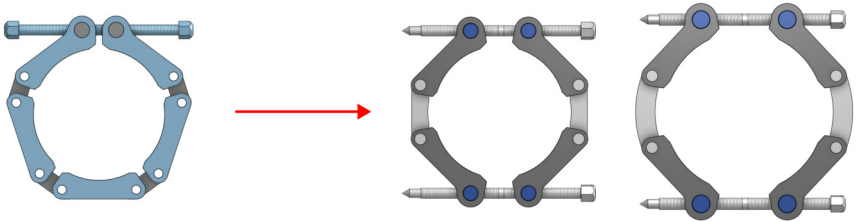
- Commercial, remote-friendly, Garlock/Cefilac clamps are in use at the neutrino beamline
- so far, the experience with this kind of clamp is unsatisfactory due to several reasons

Observed issues:

- bad visibility during flange meeting
- whole design is thick, large bellow contraction is needed
- significant failure rate in flange connection due to lack of visibility
- tightening can be done from a distance, but some hands on assistance is still needed

New clamp concept

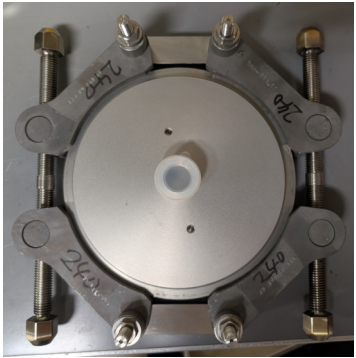
- Modify existing RH1 clamps to get RH2 clamps that can be split in half:
  - 290mm RH1 (5 blocks) $\longrightarrow$ 290mm RH2 (4 blocks)
  - 240mm RH1 (5 blocks) $\longrightarrow$ 240mm RH2 (4 blocks)

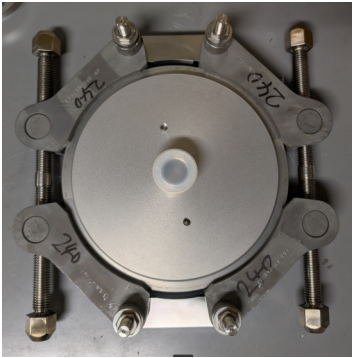


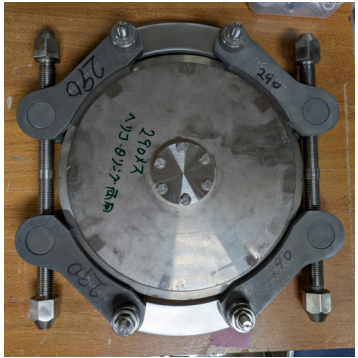
  - Possible obstacles:
    - angular coverage in 290mm case seems to be non-ideal
    - shape of connecting links had to be modified to provide enough clearance for the flanges - impact on mechanical strength

First mechanical test fits

After confirming, with 3D printed prototypes, that the geometry works, we ordered a set of parts made from stainless steel:



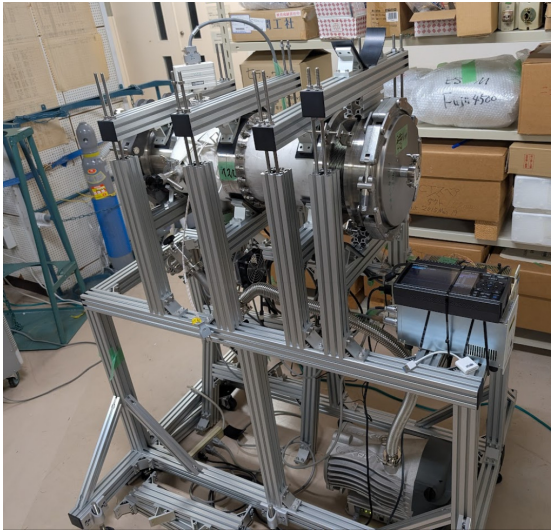




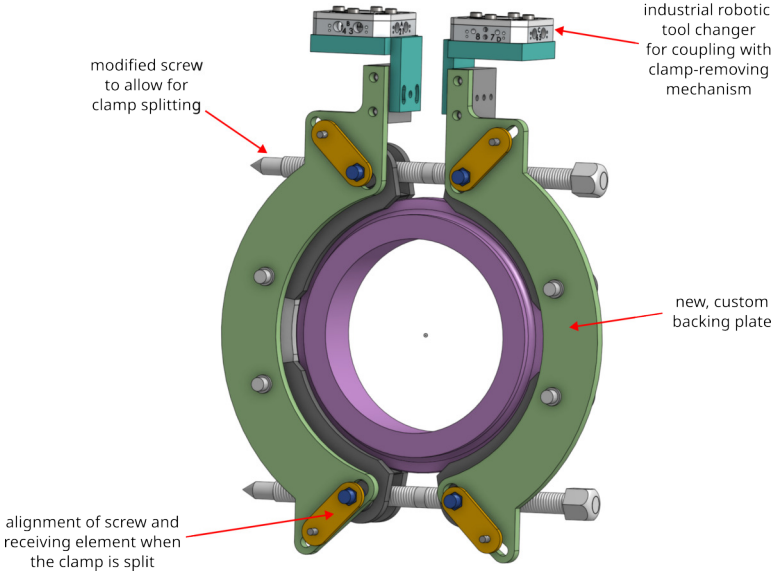
Modified links were confirmed to be strong enough with FEM calculations

Vacuum-holding test

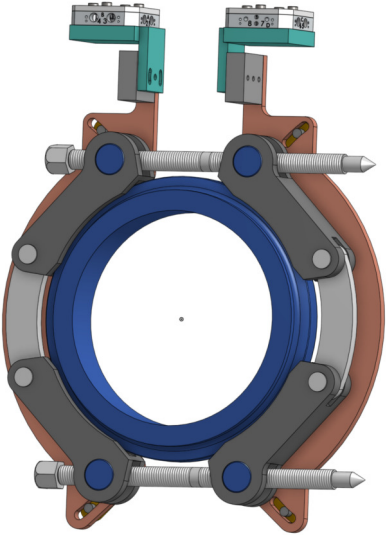
- Vacuum holding test was done for both clamp designs (240mm and 290mm)
- Vacuum tightness was achieved with tightening torque of 20 Nm - around a factor 10 less than the manufacturer's recommendation for single-screw clamp design
- The measured leak rate was smaller than $10^{-13}\ Pa \cdot m^3/s$
- Chamber was verified to be vacuum-tight for more than one month after the original test (to verify no immediate failure modes)

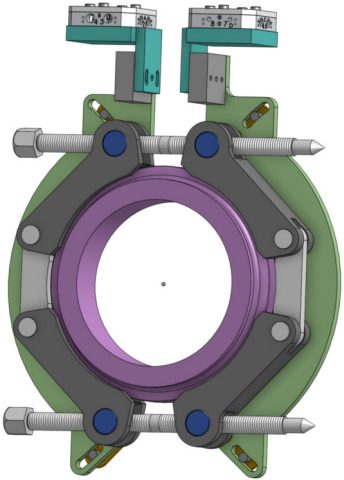


Making the clamp remote

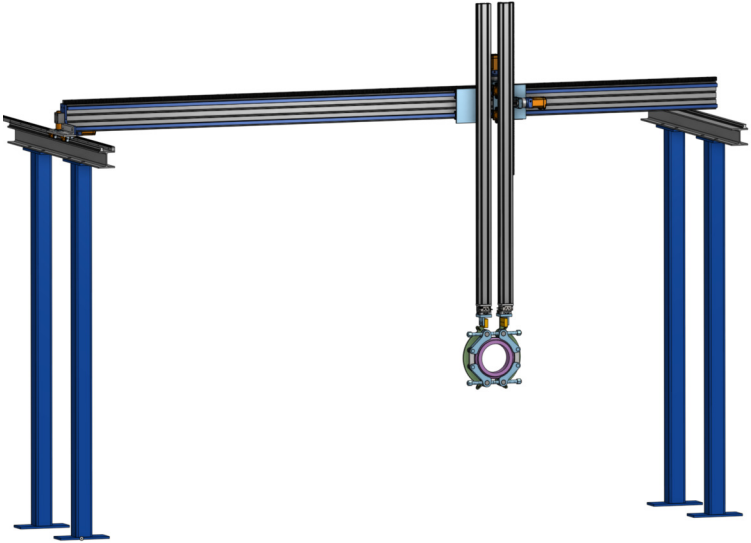


Design for 240mm and 290mm ready





Handling the clamp - gantry

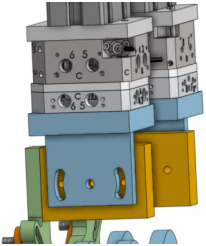


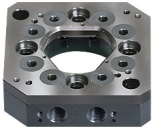
Handling the clamp - gantry

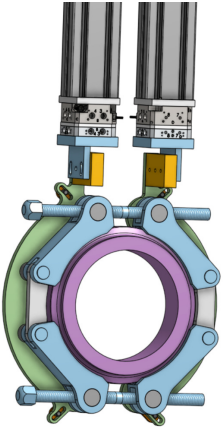
- Build a remote-controlled gantry-like manipulator to handle clamps (removal and installation)
- Re-use the existing blue frame, presently hosting the hand-operated hoist used for quick hands-on maintenance, not suitable in a full remote maintenance scheme, as the support structure
- Use aluminum extrusion profiles as the construction elements
- Motorize everything with closed-loop stepper motors
- Rely on hand operation of clamp screws from a distance - using torque wrenches and long extensions
- Top horizontal bar of the gantry will be installed using the overhead crane - it will be removed for normal beam operation

Clamp mounting

- Use commercially available robotic tool changer
- Include a pivoting joint to account for the inclined beamline

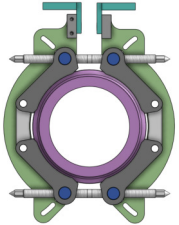






(Un)clamping process

1



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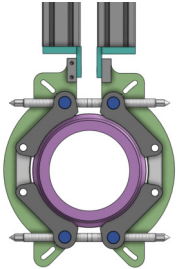

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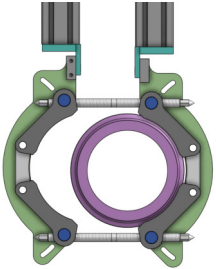

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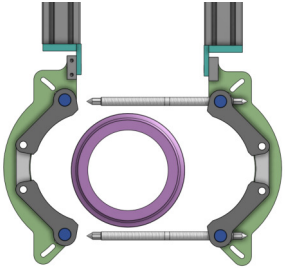

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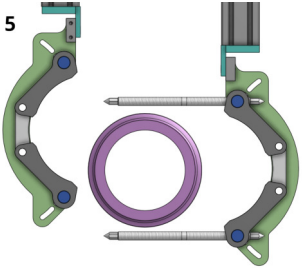
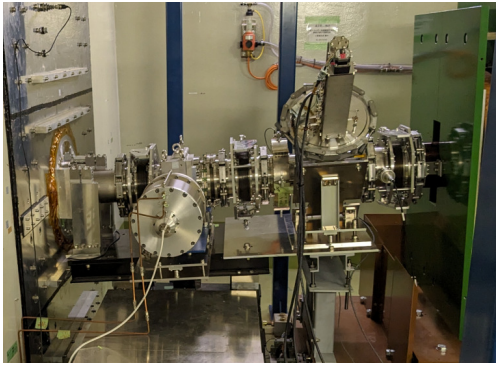
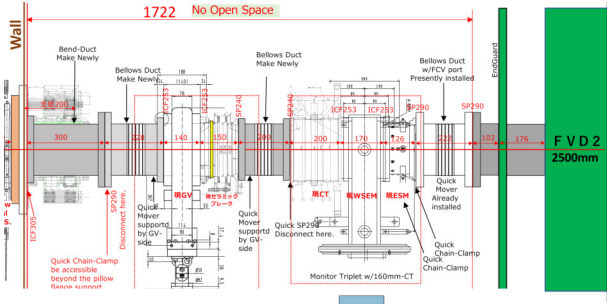
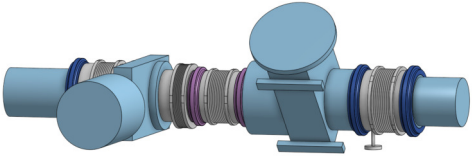


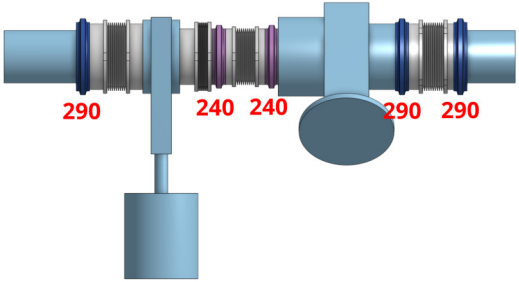
1. clamp installed
2. attach arms
3. undo screws and spread clamp halves
4. clamp detached
5. move away

Integration with the beamline

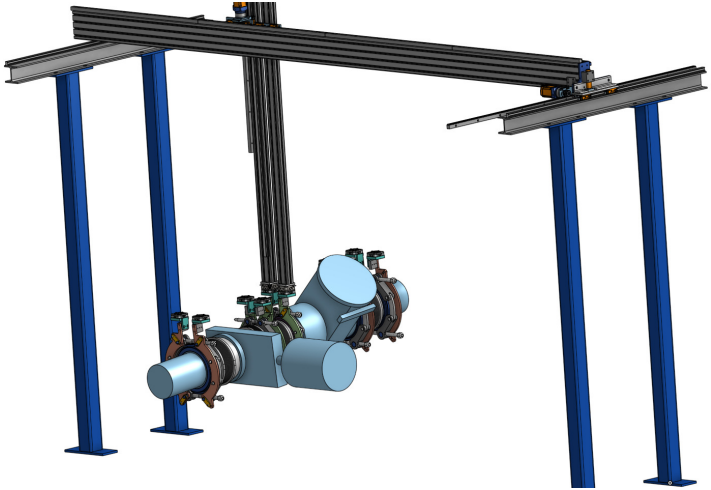


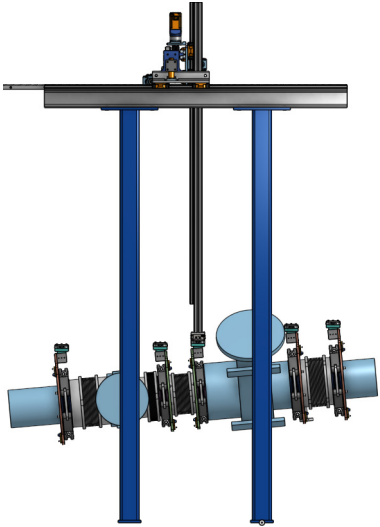






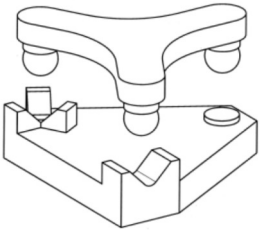
Integration with beamline

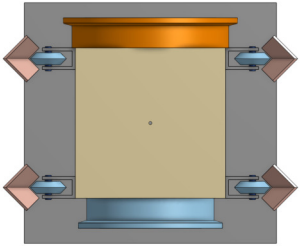


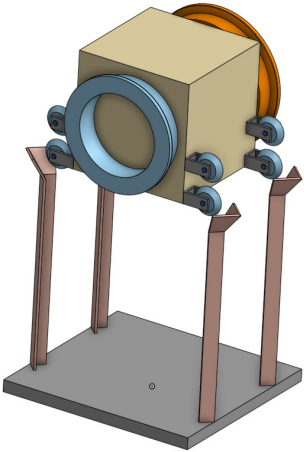


Vertical rails - design concept

- Use a simple set of guide rails to constrain all 6 degrees of freedom of a beamline stage during line-IN and line-OUT
- Rails will not require hands-on assistance - they will 'catch' the stage lowered by the crane
- Rails will provide sub-cm level positioning precision, enough to engage precise kinematic mounts that are already installed in the downstream part of FF section

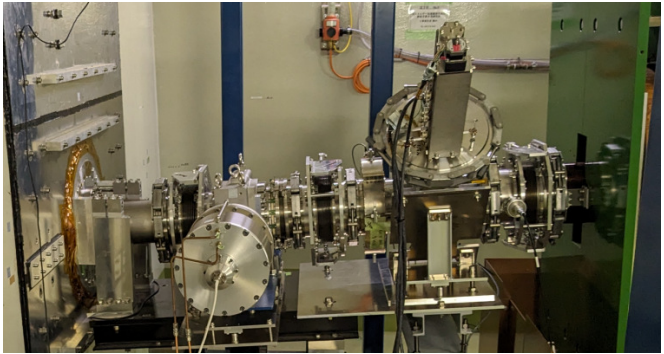






Fully remote maintenance scheme

- Install the horizontal beam of the gantry, together with the manipulator arms
- Remove clamps up- and downstream of the faulty component
- Contract quick bellows movers
- Use overhead crane to line-OUT the whole component
- Reverse the operation order for the installation of the replacement



Summary

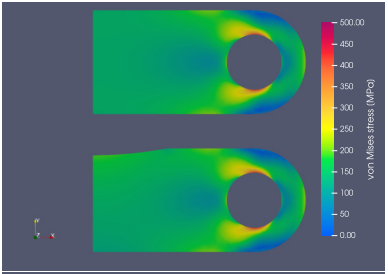
- High power operation of the J-PARC neutrino beamline generates radiation levels that require a fully remote maintenance scheme in most downstream parts of the primary beamline
- Upgrades to FF section are underway:
  - modification of the overhead crane
  - installation of vertical guide rails
  - development of fully remote clamps and clamp handling system
  - upgrade of bellows movers to 3-rod design
- R&D work ongoing
- Installation in the beamline tentatively planned for summer-fall 2026
- A dedicated test area for rehearsal and training work will be built

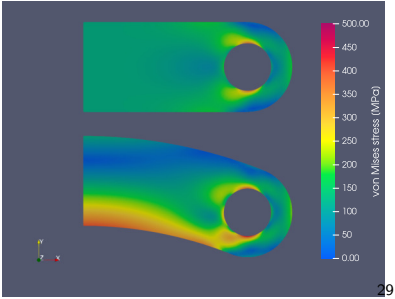
Thank You.

Backup slides

FEM simulation

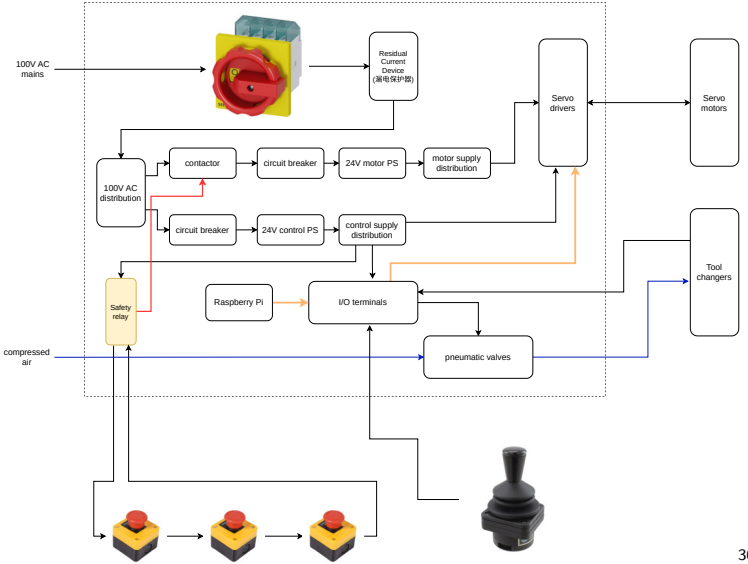
- It is challenging to predict/calculate the tensile load on the links in such a clamp
- I decided to do a comparative study - apply the same load to different configurations and compare internal stresses
- both links were stretched with the force of **50 kN**
  - 240mm: no significant impact of the cutout on internal stress distribution
  - 290mm: stress inside curved link comparable to one close to the hole of a straight one
  - Maximal deformation under such load was at the level of 100 μm





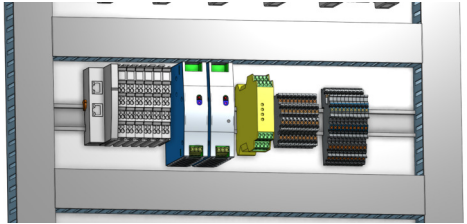
Control cabinet

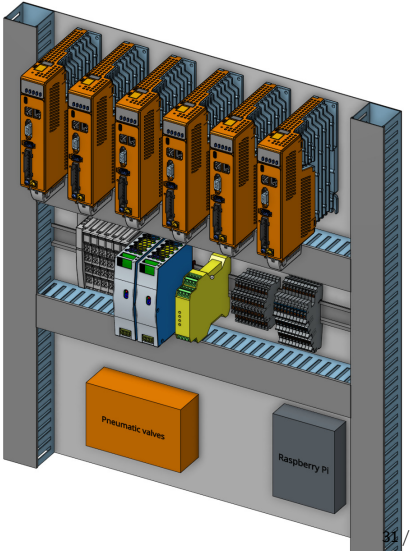
- plan is to build a control cabinet with a separate joystick unit
- it will require 100V AC mains and compressed air
- a display will be connected to the Raspberry Pi to monitor the device



Control cabinet

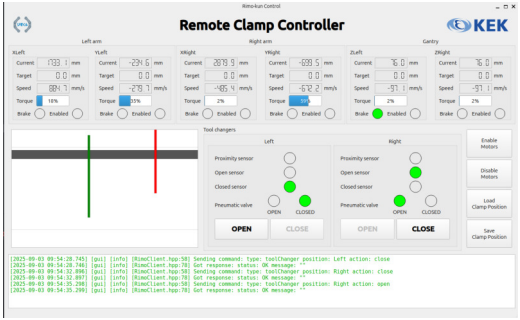
- use a standard commercially available enclosure
- it will be easy to connect/disconnect for installation
- preferably on wheels, for easy manipulation
- EtherCAT fieldbus will be used for communication with servo drivers and I/O module





Control software

- Server (control logic) - client (GUI) approach
- ROS2 (Robot Operating System) or custom C++ application under consideration
- ZeroMQ used for communication between nodes/processes
- EtherCAT master kernel module will be controlled by the user space application



Status and next steps

- **Aug 2025:** Parts ordered for the remote clamp prototype
- **Sep 2025:** Full remote clamp test, design of vertical guide rails
- **Oct–Dec 2025:** FF-section mock-up, integration and tests
- **Sep–Dec 2025 (parallel):** Control electronics development
- **Jan–May 2026:** Full gantry build & fully remote tests
- **Jun-Nov 2026:** Installation on the beamline