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Design choices, implementation and status of the PIP-II Warm Front End

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PIP-II Warm Front End L3 Manager



U.S. DEPARTMENT
of **ENERGY**

Fermi National Accelerator Laboratory is managed by
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Agenda

-
- ✓ Fermilab Accelerator Complex & Proton Improvement Plan-II (PIP-II)
 - ✓ PIP-II Warm Front End (WFE)
 - Guiding principle & design choices
 - Validation at the PIP-II Injector Test (PIP2IT)
 - ✓ Installation status & Outlook



Some Acronyms

- AD: Accelerator Directorate
- PIP-II: Proton Improvement Plan-II
- PIP2IT: PIP-II Injector Test
- CAM: Control Account Manager
- LEBT: Low Energy Beam Transport
- MEBT: Medium Energy Beam Transport
- HEBT: High Energy Beam Transport
- HBB: PIP-II's High Bay Building
- WFE: Warm Front End
- LBNF: Long Baseline Neutrino Facility
- DUNE: Deep Underground Neutrino Experiment
- DOE: US Department of Energy
- FNAL: Fermi National Accelerator Laboratory (a.k.a. Fermilab)
- SRF: Superconducting RF
- RF: Radio Frequency
- RFQ Radio Frequency Quadrupole

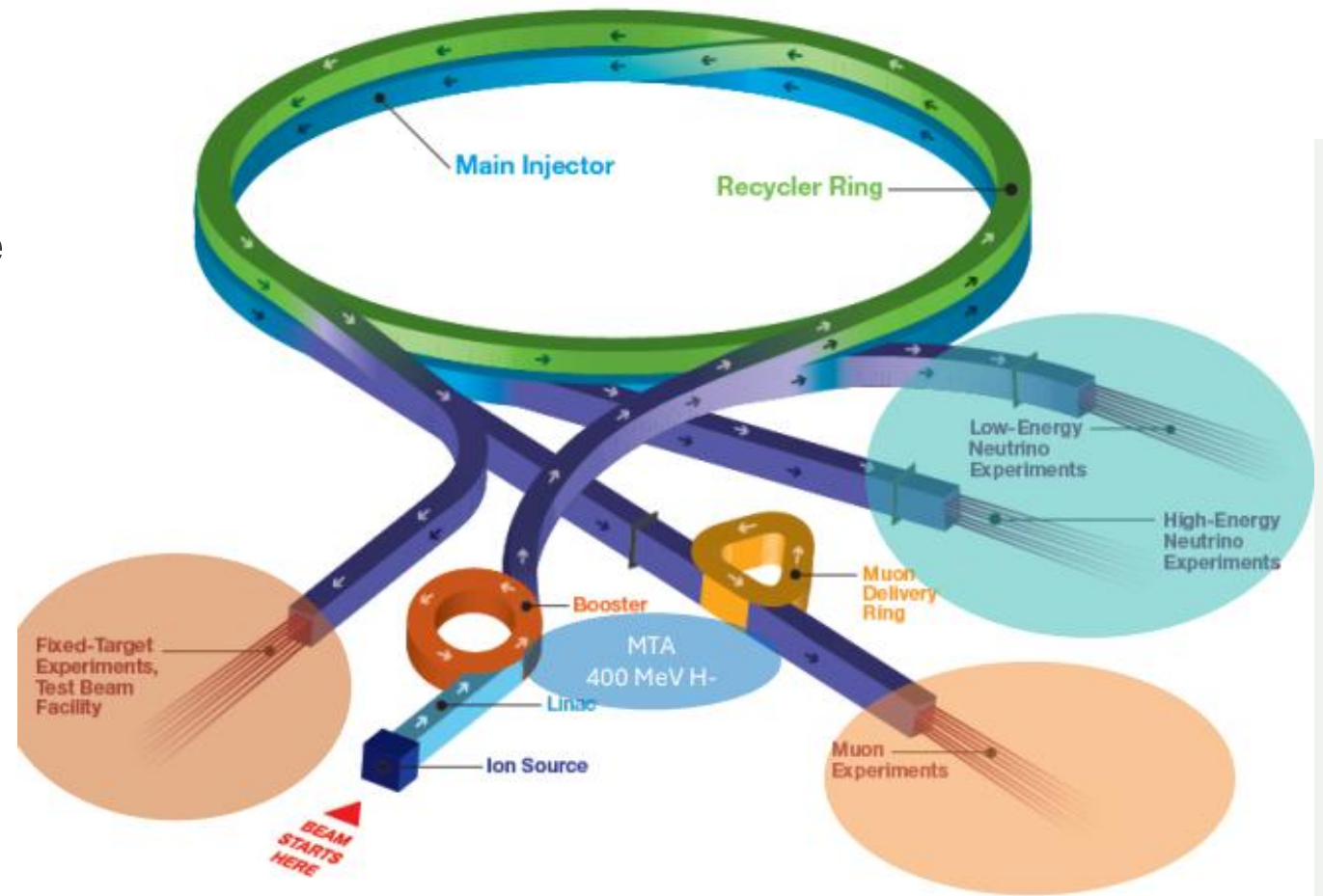


Fermilab Accelerator Complex

Fermilab Accelerator Complex

National User Facility

- Fermilab's Accelerator Complex is one of 28 DOE Office of Science National User Facilities
- Developed over 58 years, the Accelerator Complex comprises 5 particle accelerators and storage rings, 2 high-power target stations, several experimental areas and miles (kilometers) of beamlines





PIP-II Mission

PIP-II is an essential upgrade to Fermilab accelerator complex to enable the world's most intense beam of neutrinos to LBNF/DUNE, and a broad physics research program for decades to come

PIP-II Capabilities

Beam Power

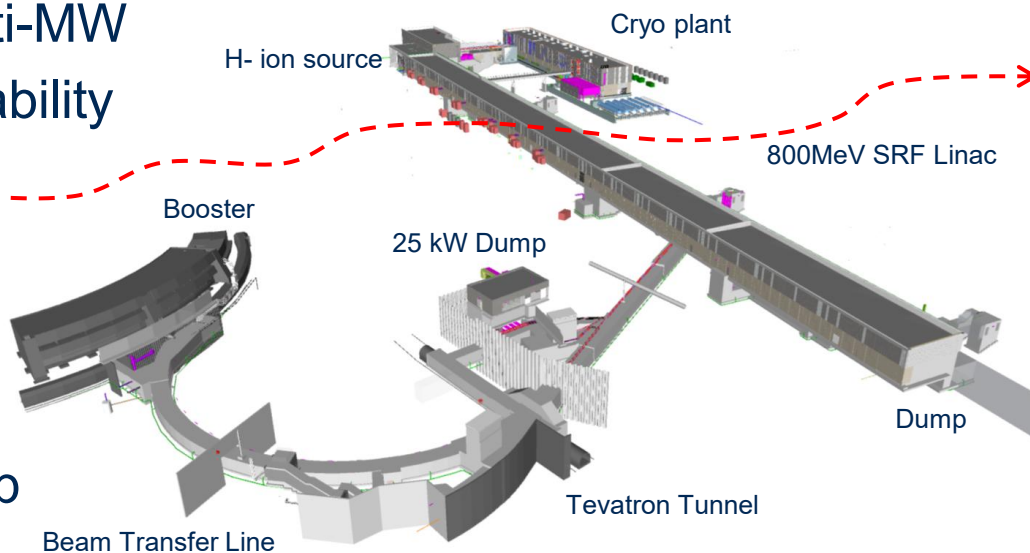
- 1.2 MW proton beam
- Upgradeable to multi-MW

Flexibility, multi-user capability

- **CW-compatible**
- Customized beams
- Multi-user delivery

Reliability

- Modernizes Fermilab accel complex



The PIP-II scope enables the accelerator complex to reach 1.2 MW proton beam on LBNF target

PIP-II Scope

800 MeV H⁻ SRF linac,
to replace the 50+
year-old warm linac

CW RF Operations

Linac-to-Booster transfer line

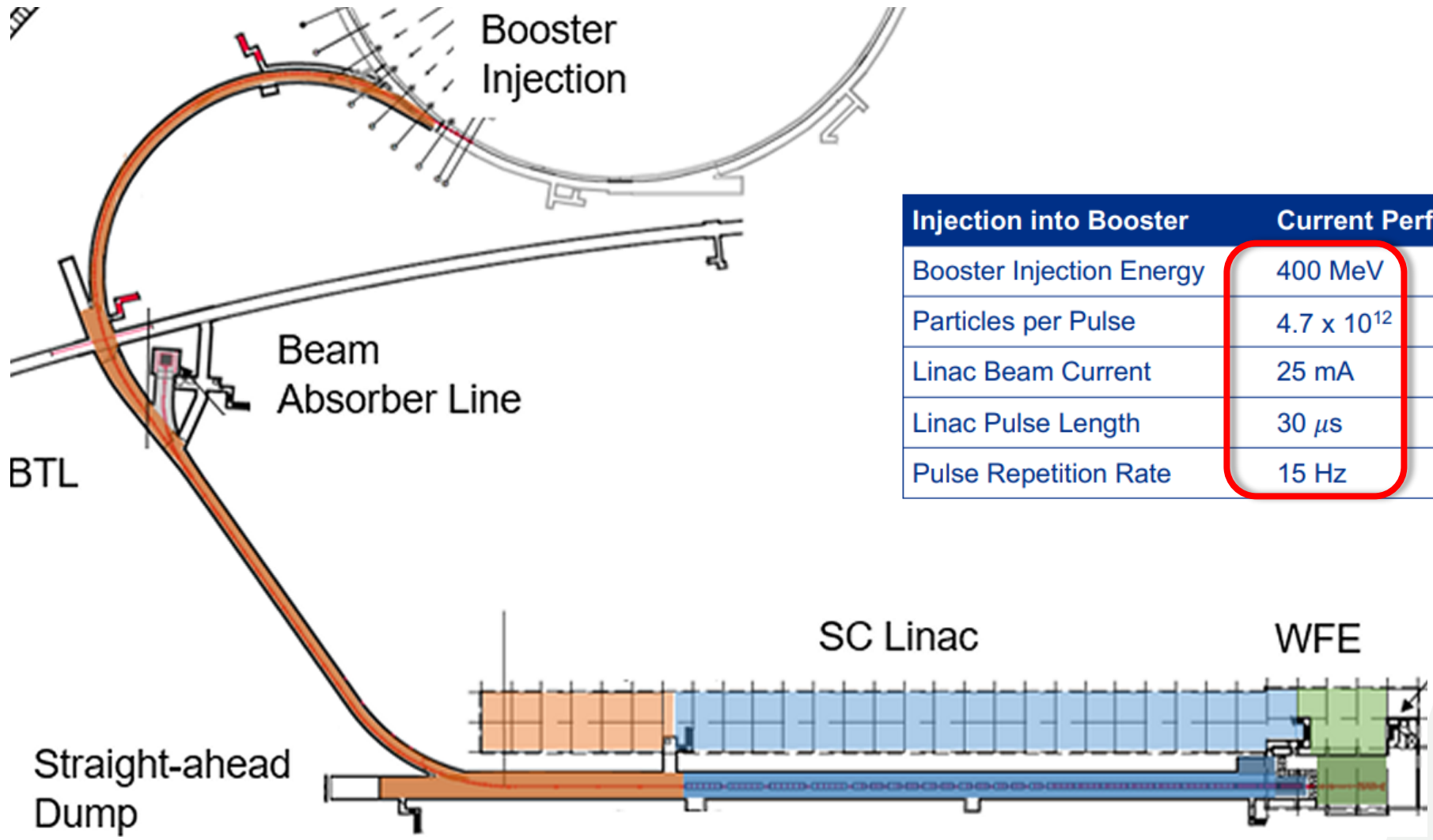
Accelerator Complex
Upgrades:

- Booster
- Recycler
- Main Injector

Conventional Facilities

PIP-II Accelerator Overview

Defining parameters



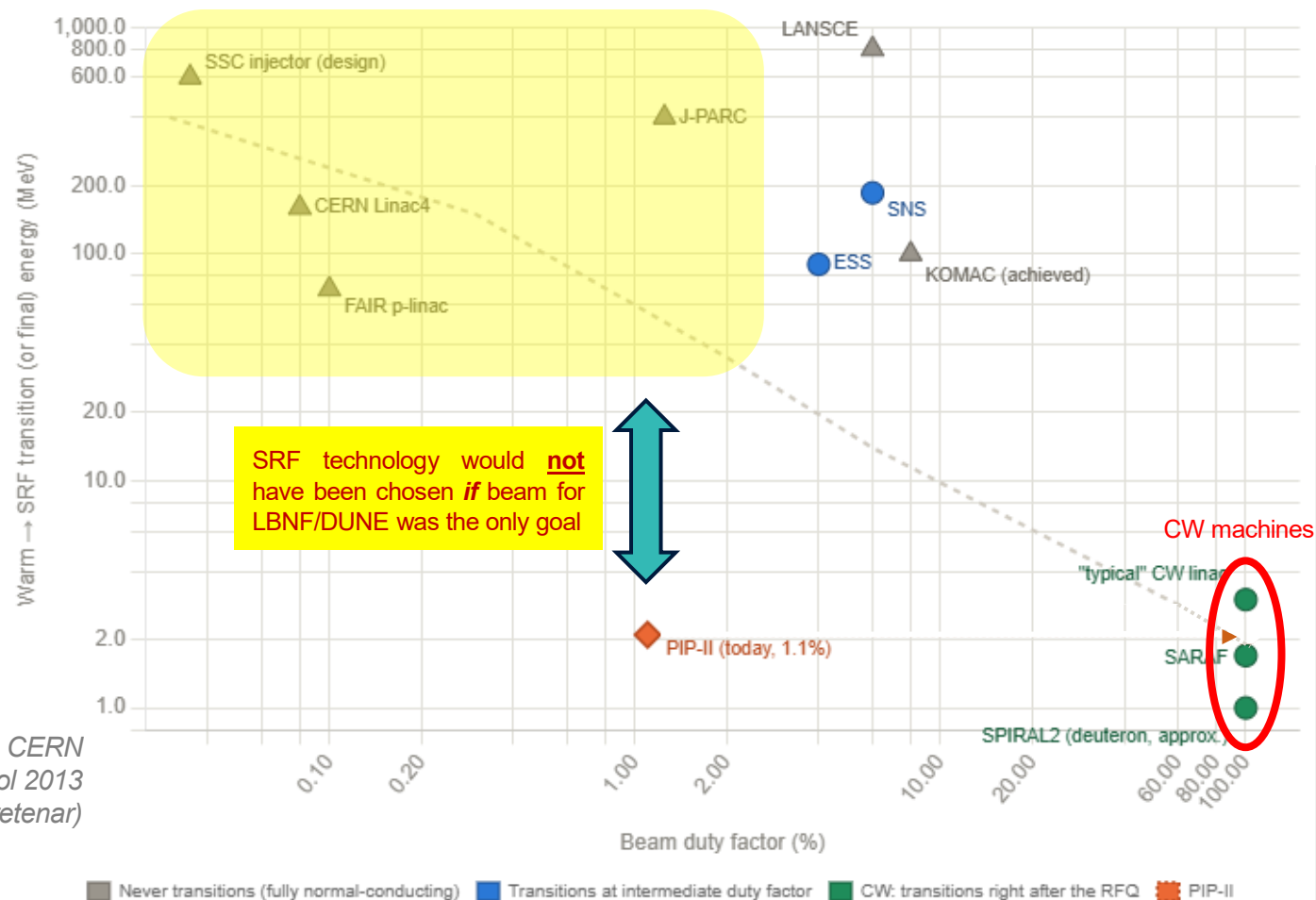
Injection into Booster	Current Performance	PIP-II (LBNF mode)
Booster Injection Energy	400 MeV	800 MeV
Particles per Pulse	4.7×10^{12}	6.7×10^{12}
Linac Beam Current	25 mA	2 mA
Linac Pulse Length	30 μ s	550 μ s
Pulse Repetition Rate	15 Hz	20 Hz

Boundary conditions

CW operations *economics*

- Acceleration in SRF cavities start at low energy (2.1 MeV vs. $> \sim 100$ MeV in most other superconducting **pulsed** linacs)
 - Transition from 'warm' (i.e. normally conducting) technology and 'cold' (i.e. superconducting) technology is *mostly* dictated by RF power operational costs


 - To first order**, the higher the duty factor, the lower the transition (but there is no universal criterion)



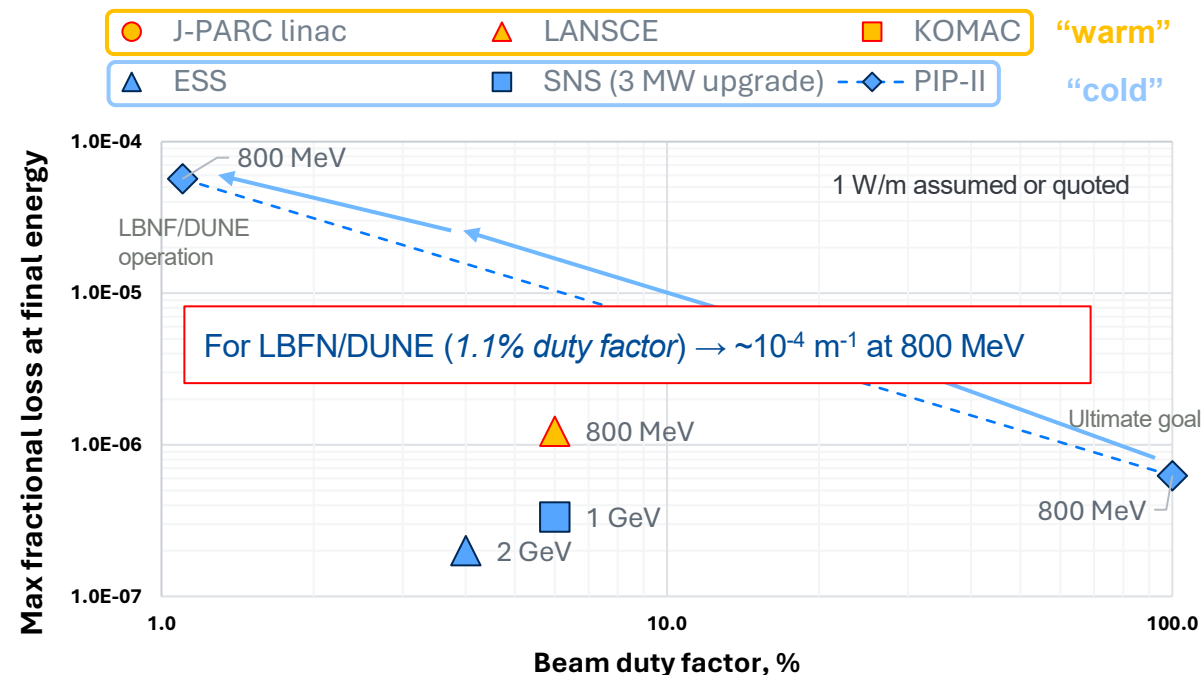
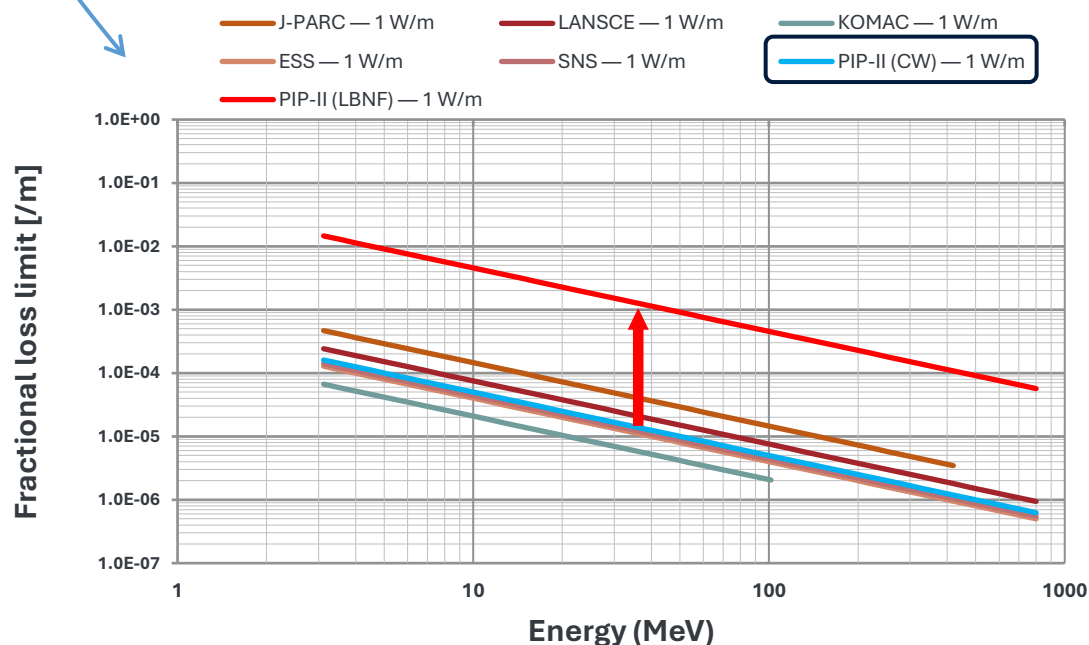
Plot adapted from CERN
Accelerator School 2013
(M. Vretenar)

Boundary conditions

CW operation implies stringent loss requirements (*absolute*)

- Generally accepted loss requirements for “hands-on” maintenance: 1 W/m
 - Exponential dependence as a function of energy

⇒ Fractional loss at 800 MeV (CW): $\sim 10^{-6} \text{ m}^{-1}$





PIP-II Warm Front End (WFE)

Warm Front End scope

- WFE prepares a H^- beam optimized for injection into the Booster and provides capabilities for *future* **CW operation**
- It is composed of:
 - Two Ion Sources (IS) and a Low Energy Beam Transport (LEBT)
 - **DC**/long pulse operation
 - RFQ (162.5 MHz)
 - **CW operation** (RF)
 - 30 keV $\Rightarrow$ 2.1 MeV
 - Medium Energy Beam Transport (MEBT)
 - Nominal *output* current: 2 mA averaged over $\sim \mu s$ (from μs to **CW operation**)
 - **Bunch-by-bunch chopping** capability

Ion Source

Robust and proven commercial solution

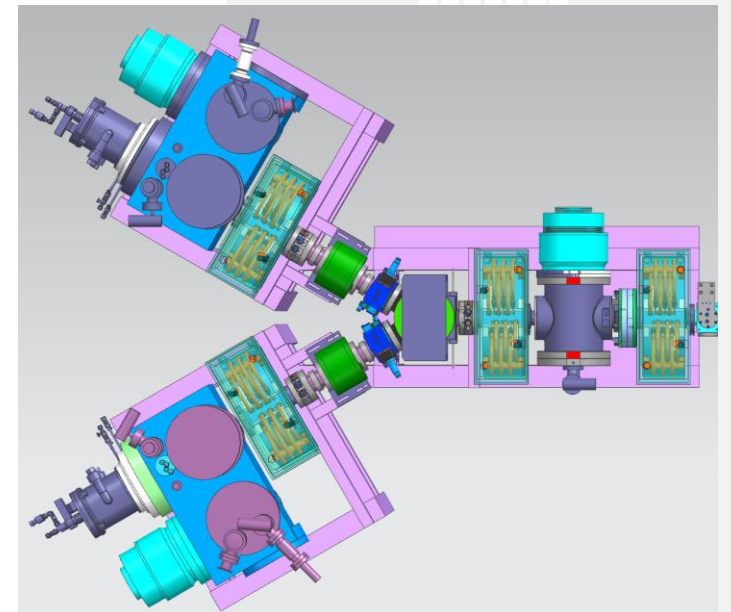
- Baseline requirements
 - **DC**, H⁻, 10 mA at 30 keV $\Rightarrow$ D-Pace's TRIUMF Type 15 mA H⁻ Volume-Cusp
- Filament driven (~300 hours filament lifetime) $\Rightarrow$ frequent changeout needed



Y-configuration

- Significant electron current is 'dumped' onto extraction electrode assembly (and surrounding 'baffles') $\Rightarrow$ may affect long term operation reliability and equipment longevity
- DC operation is not necessary for LBNF/DUNE

Developed pulsing of the ion source itself

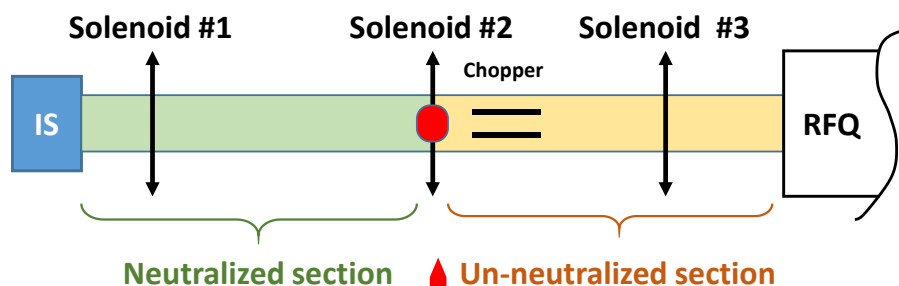


Low Energy Beam Transport (LEBT)

A long LEBT for tuning flexibility, vacuum management and operational robustness

- Design determining factors

- Optical matching (α , β) at RFQ entrance $\rightarrow$ **2 solenoids**
- Capability of tuning the beam line with short pulses representative of long pulse operation (i.e. constant beam parameters throughout the pulse) $\Rightarrow$ Transport scheme with **un-neutralized region** (next slide)



- High vacuum pressure
 - Gas load from ion source

- Neutralizing particles confined by potential barrier

- Low vacuum pressure
 - Vacuum pumping station
 - Limits rate of production of neutralizing particles
- Clearing electric field
 - Sweeps neutralizing particles out of the beam

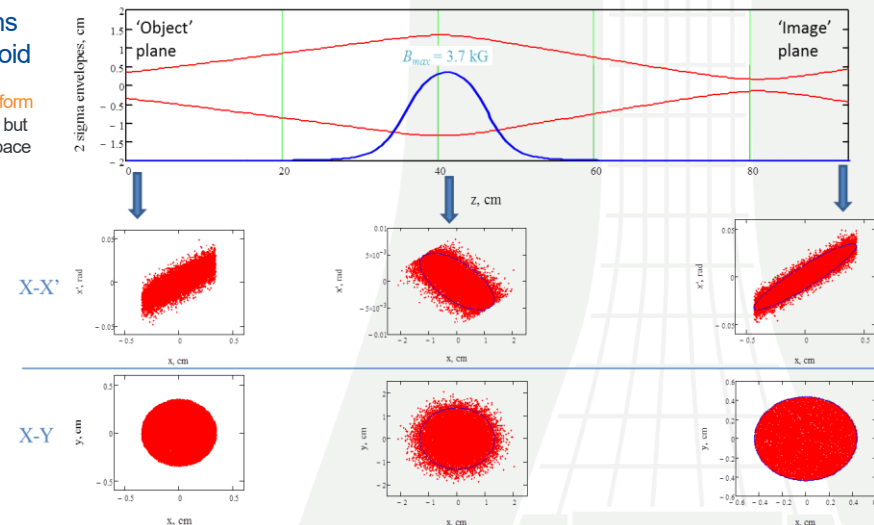
2 solenoids

3 solenoids

Scheme of LEBT with un-neutralized section requires transition from (nearly) fully neutralized to (nearly) fully un-neutralized to take place where the beam current density is uniform

PIC-like simulations through one solenoid

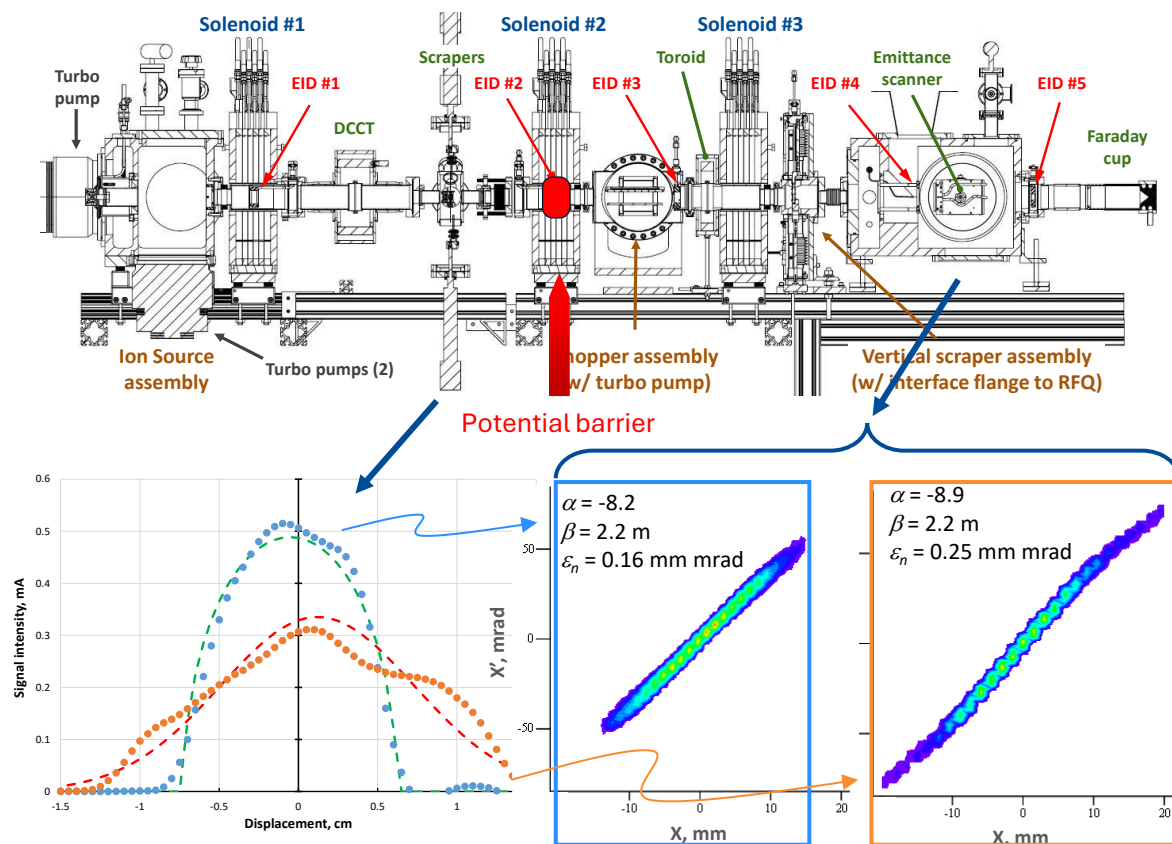
Initial distribution has a uniform current density distribution but Gaussian in the velocity space



Transport scheme validation at PIP2IT

PIP2IT was a nearly full replica of the PIP-II front-end (WFE + first 2 cryomodules) with *all* envisioned features

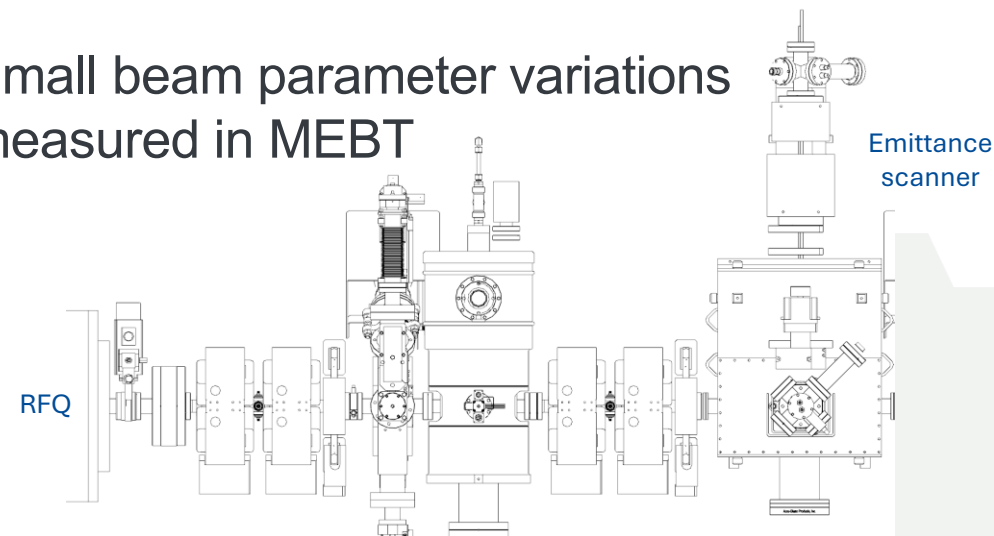
- Beam profile and emittance measurements in LEBT



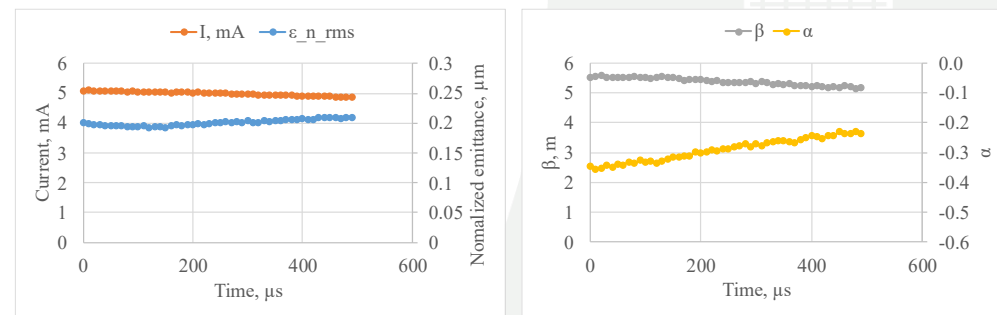
1D beam profiles at the scrapers. Dashed curves are fits, assuming a uniform (green) or a Gaussian (red) distribution, normalized to give the same integral

Phase space distributions for 2 different focusing solutions but same ion source tune

- Small beam parameter variations measured in MEBT



Beam parameters (current, normalized emittance, α , β) measured downstream of the RFQ over a 500 μ s pulse



Low Energy Beam Transport (LEBT)

A long LEBT for tuning flexibility, vacuum management and operational robustness

- Design determining factors

- Avoid/minimize bombardment of RFQ vanes

⇒ No direct line of sight from the source



Bending dipole magnet

⇒ Addition of multiple aperture restrictions (Electrically Isolated Diaphragms a.k.a. EID)

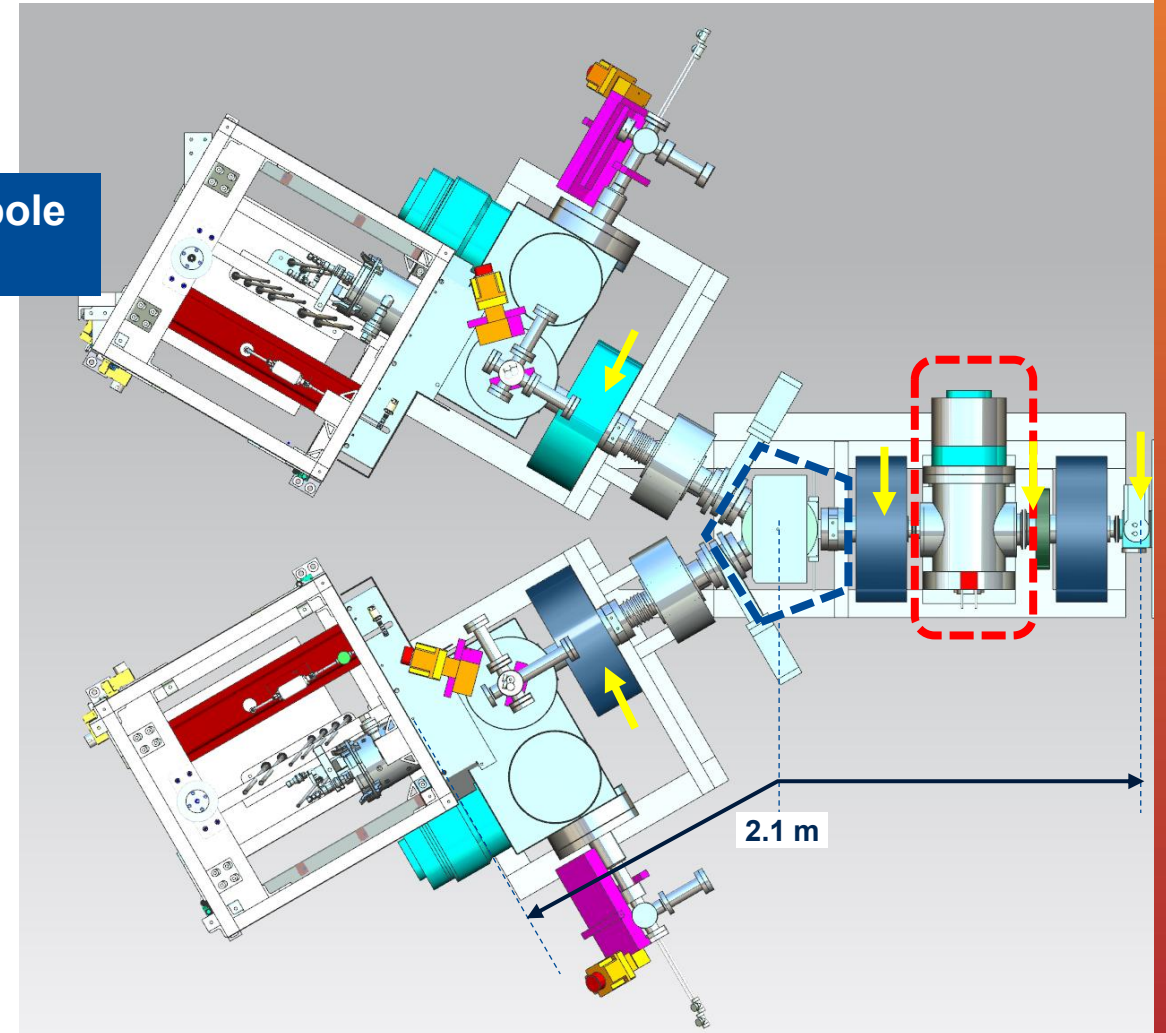
⇒ Robust chopper which includes a dedicated absorber



Space/length



Central component of Machine Protection System (MPS) for inhibiting beam



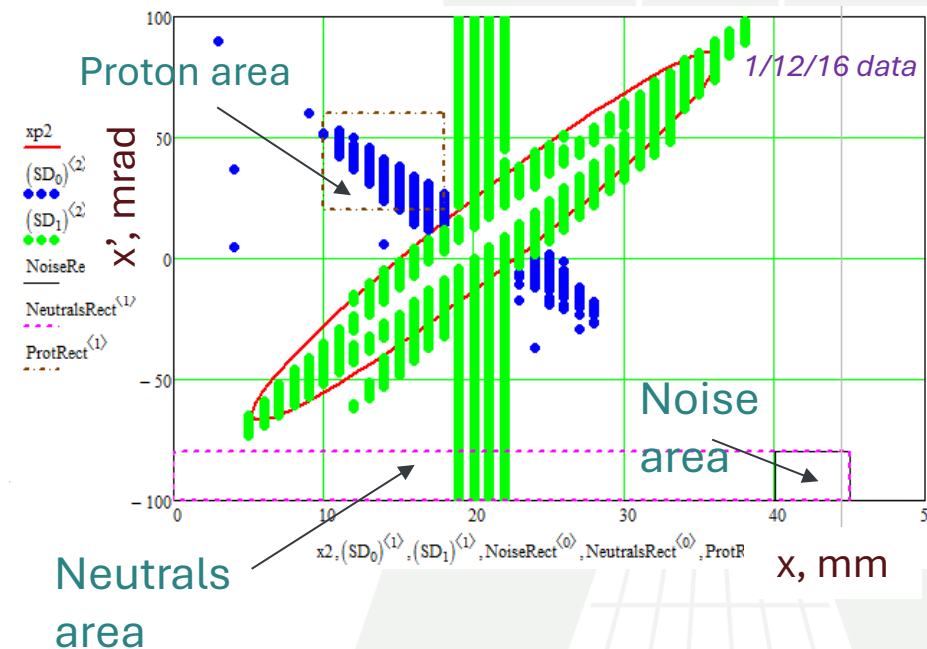
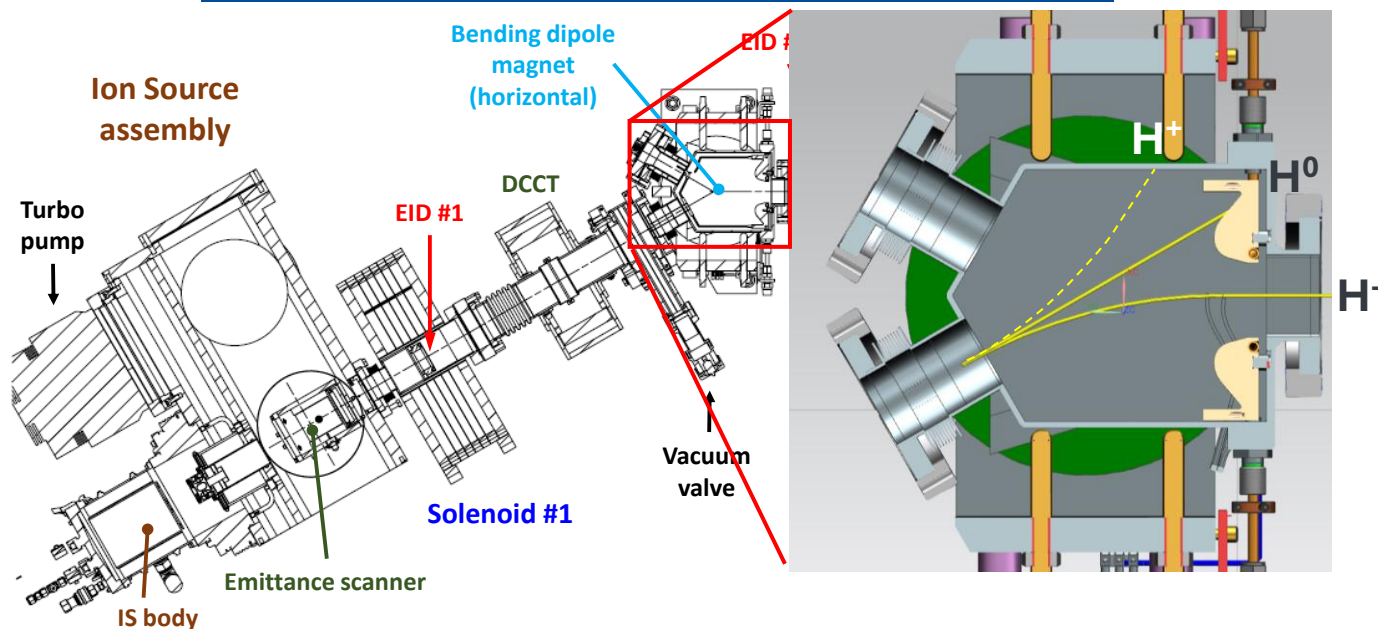
Neutrals and protons

Electron stripping in H^- collisions with gas immediately downstream of ion source extraction region

- Single stripping $\rightarrow$ Fast neutrals ($\sim 10\%$ of H^- beam current near ion source)
 - Ballistic flight
- Double stripping $\rightarrow$ Protons ($\sim 0.5\%$ of H^- beam current near ion source)
 - Same envelope as H^-

Estimated with Allison scanner

Bending magnet naturally 'filters' them out



Medium Energy Beam Transport (MEBT)

A long MEBT for **bunch-by-bunch chopping** and SRF protection

- Design determining factors

- Bunch-by-bunch chopping system



2 kickers

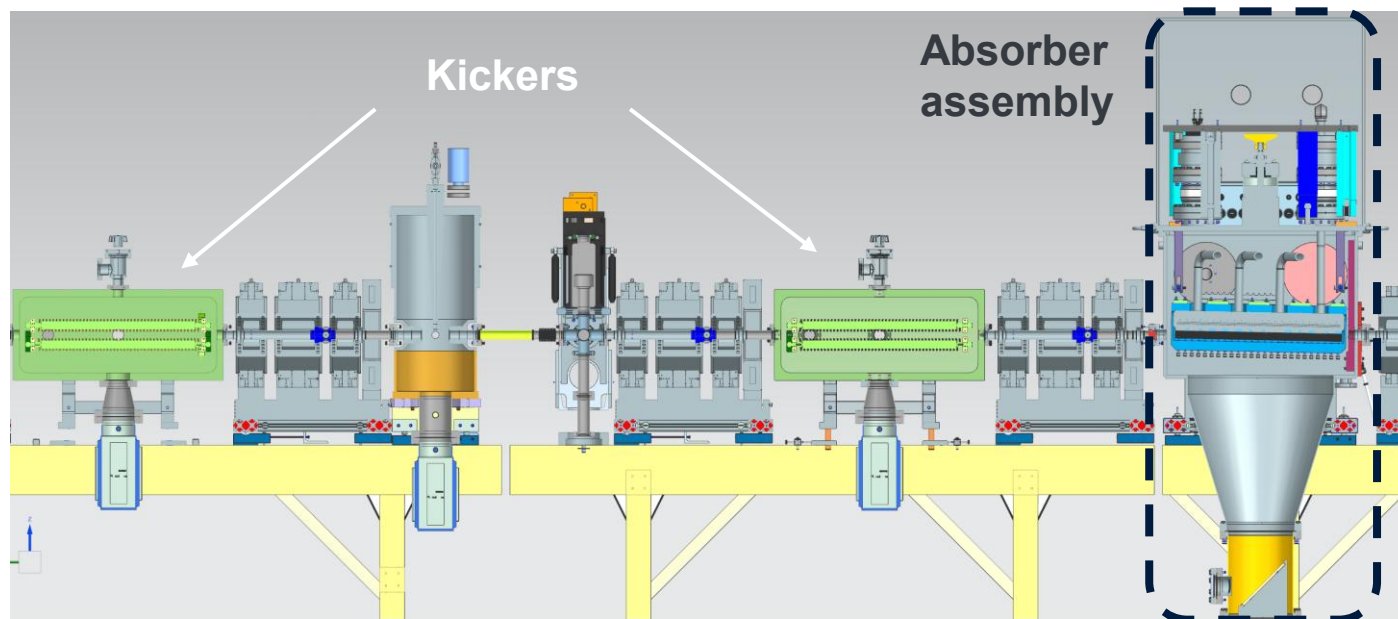


Large & complicated absorber
capable of sustaining 21 kW of
beam power continuously

- Long (~50 cm) restricting apertures
- Additional protection (entrance & exit) needed from transverse tails and/or erratic beam



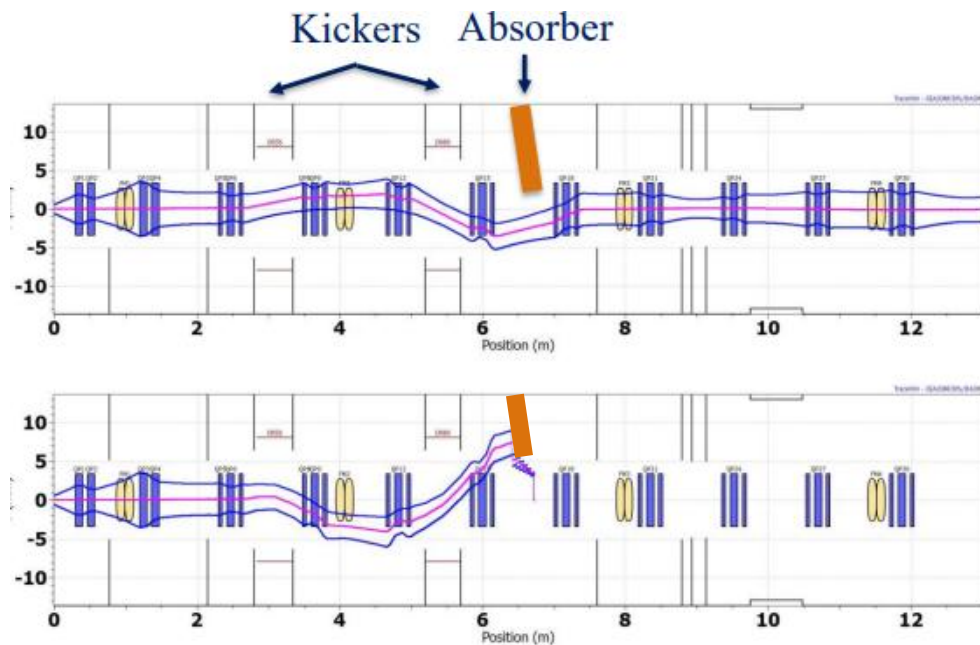
Lattice needs to
accommodate **two (2)** optics
solutions/trajectories
(passing and 'to be removed'
bunches)



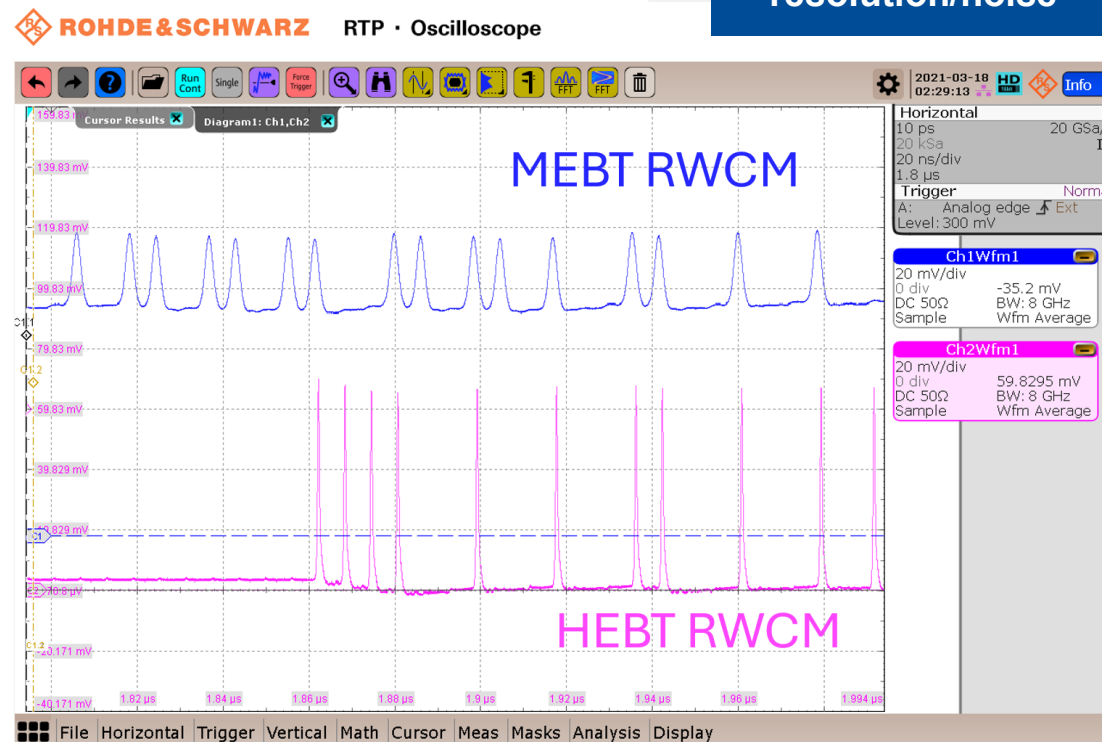
Bunch-by-bunch chopping at PIP2IT

- Any bunch from initially CW sequence can be either removed or passed (6.15 ns bunch spacing $\Rightarrow$ maximum switching frequency = 81.25 MHz)
- Driver electronics maximum average switching frequency is 500 kHz

Measured extinction
between bunches
 $< 5 \times 10^{-4}$ limited by
instrumentation
resolution/noise



Rms vertical envelopes in PIP-II MEFT. Top – passing bunches, bottom- removed bunches. A. Pathak.



Example of an arbitrary pattern

Medium Energy Beam Transport (MEBT)

A long MEBT for bunch-by-bunch chopping and SRF protection

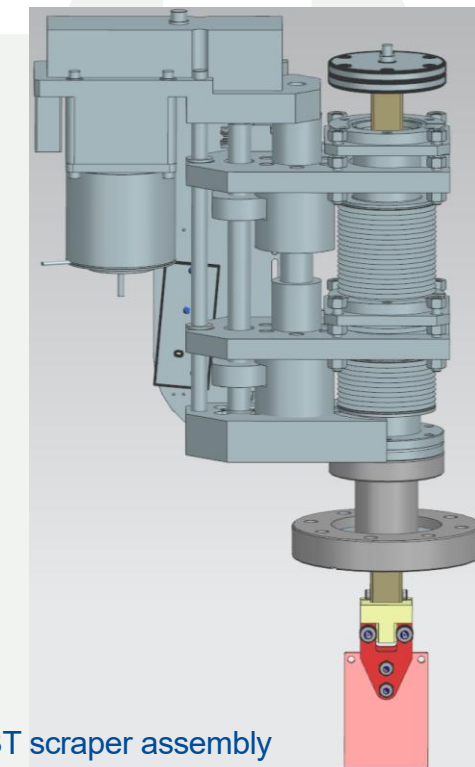
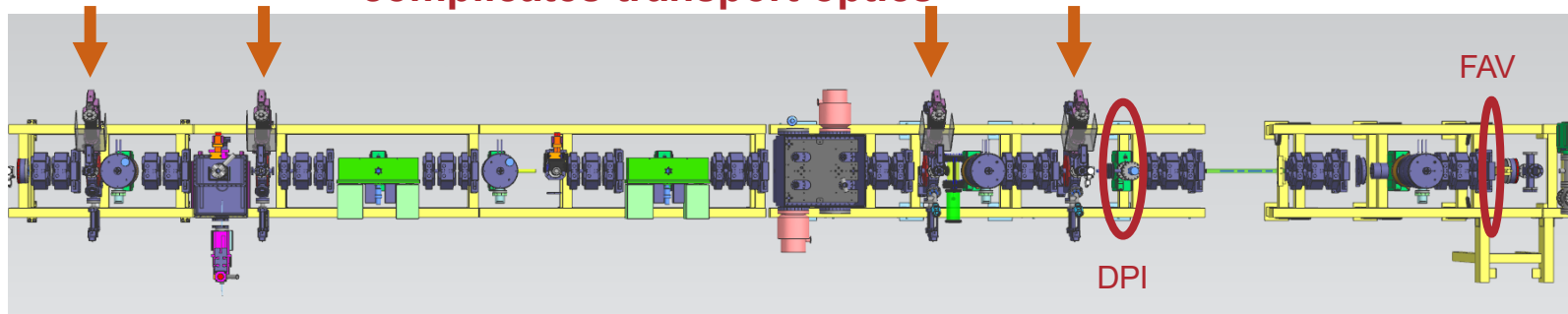
- Design determining factors
 - Protect SRF from beam far tails and erratic beam loss
 - Protect SRF from high vacuum section (absorber in particular) and vacuum incident

Extensive collimation system

Differential Pumping Insert (DPI) + beamline 'buffer' + Fast Acting Valve (FAV)

Four (4) sets of transverse movable scrapers arranged in pairs separated by $\sim\pi/2$ phase advance

Another long aperture restriction (20 cm x ϕ 1cm vs. ϕ 3cm) which complicates transport optics



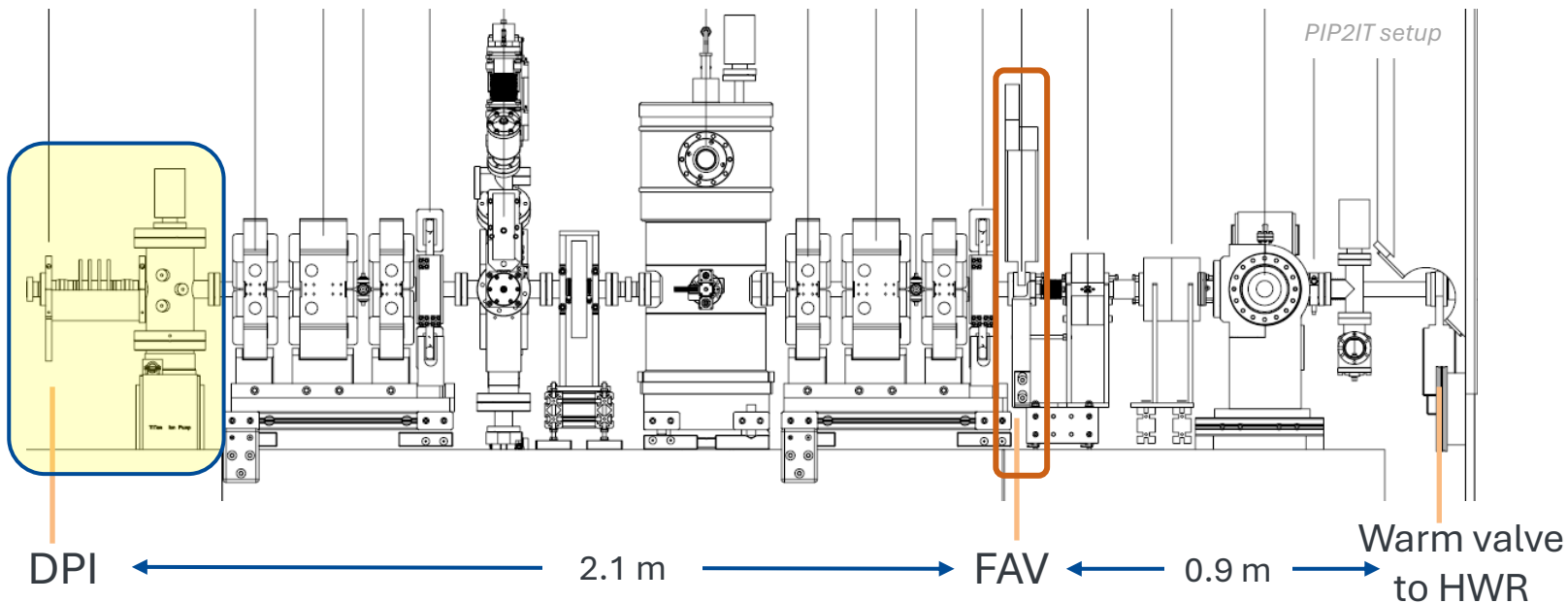
MEBT scraper assembly

Scraper is made out of TZM (Molybdenum alloy)
Radiation cooled, electrically isolated

Validation and Demonstration at PIP2IT

- Differential Pumping Insert (DPI)

- Provides 2-4 decades of isolation
- In conjunction with Fast Acting Valve (FAV) → $<10^{-6}$ torr liter of gas passes through FAV independently of leak size (up to atmosphere) upstream of DPI



Insignificant in terms of monolayer coverage on the cavity surfaces

Particle free practices during assembly

Medium Energy Beam Transport (MEBT)

A long MEBT for bunch-by-bunch chopping and vacuum management

- Design determining factors

- Ion Source/LEBT access while running (→ IS maintenance) and WFE beamline visible by the public (→ administrative choice)
- Extensive suite of diagnostics
 - Emittance scanner
 - Ring Pick Ups (RPU)
 - ACCTs, DCCT
 - Beam Position Monitors
 - Resistive Wall Current Monitor
 - Wire-scanners
 - Laser wire
 - Fast Faraday Cup (FFC)
- All other features already mentioned

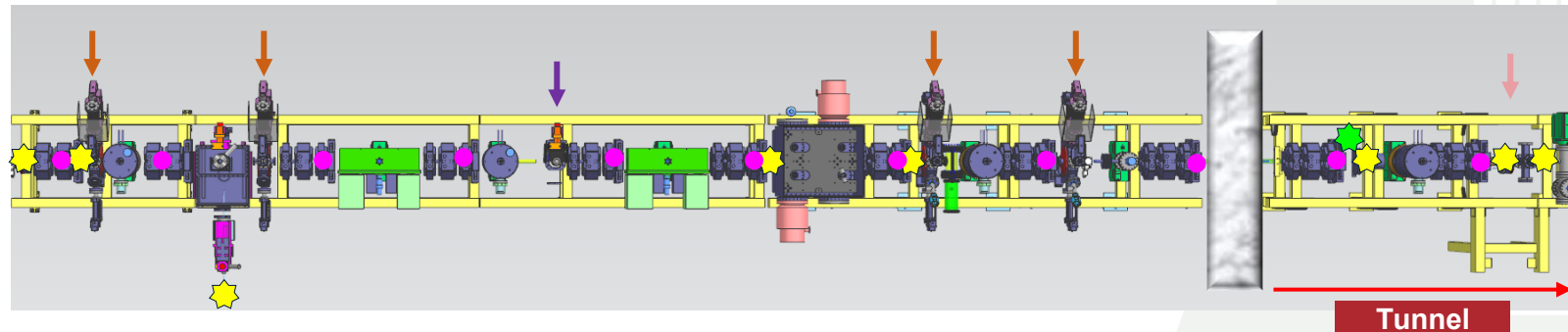
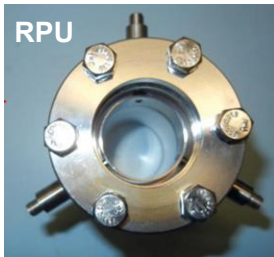


**Radiation shielding wall
separating warm
section from SRF
section**

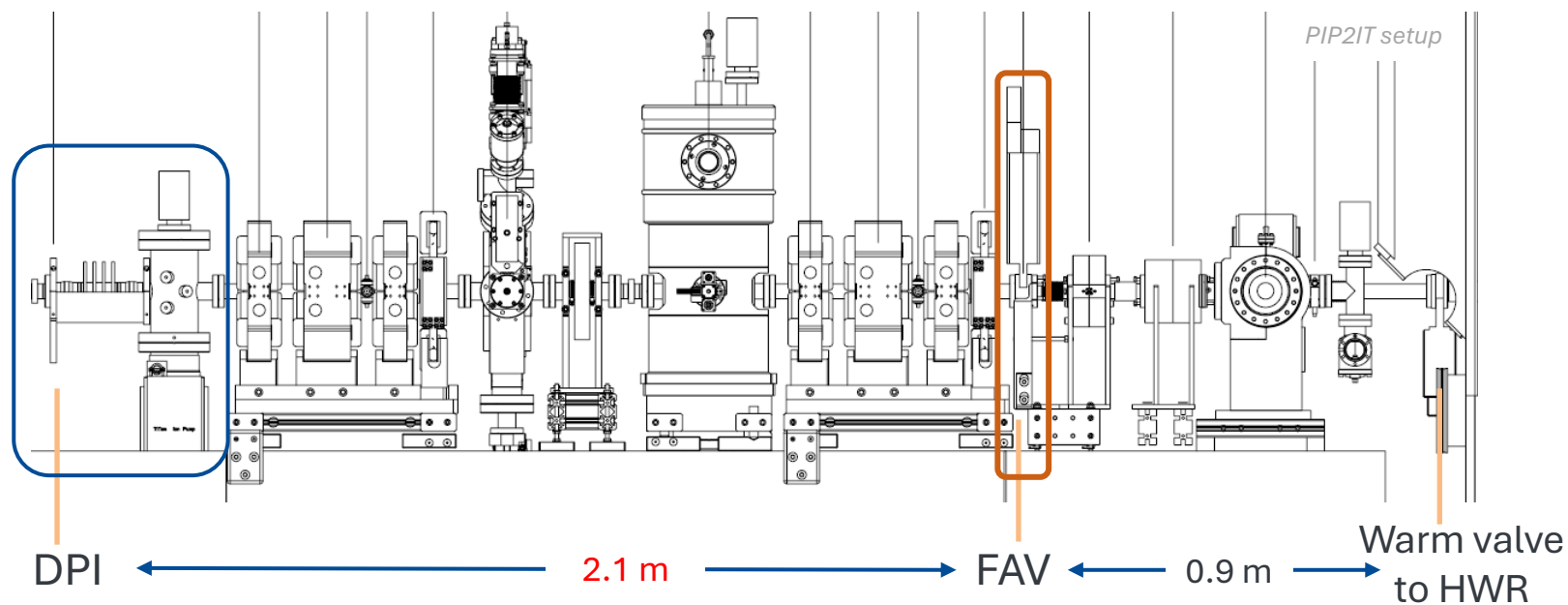


**One more complication for the
design of the optics although
not an aperture restriction**

**Very long beamline
(13 m)**



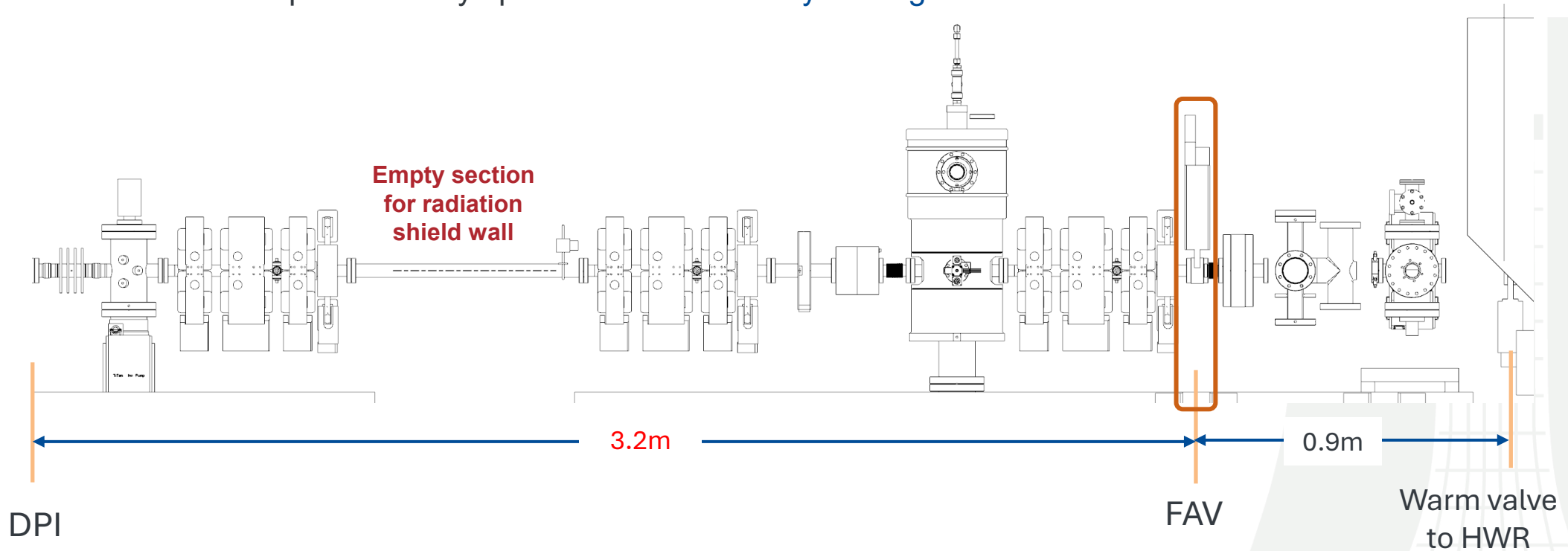
Particle free region at PIP2IT



Particle free region at PIP-II

Moved components and extended w.r.t. PIP2IT

- Extended to accommodate radiation shield wall
 - FAV to HWR distance maintained
 - Moved scraper assembly upstream of DPI → Only moving devices are the vacuum valves



Installation status & outlook

From PIP2IT WFE to PIP-II WFE

Small but important differences from lessons learned

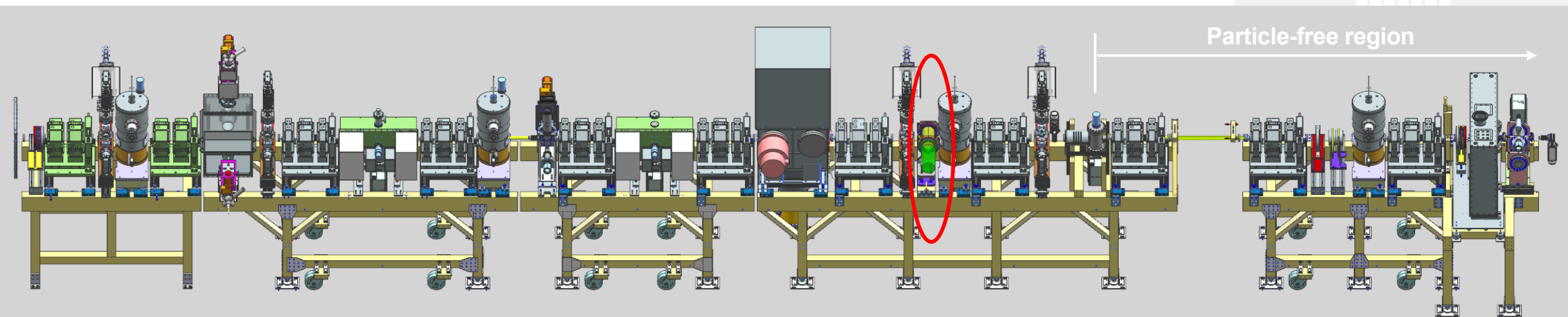
- New redesigned ion source power cabinets
- New/updated diagnostics (*ACCT*, *DCCT*, *RWCM*, *emittance scanner*)
- New water jacket downstream of MEBT absorber for better heat management of beam tube from secondaries bombardment
- Upgraded actuator assemblies for MEBT scrapers
- New bunching cavities (same design)
- New production kicker drivers (*small upgrade*)
- New MEBT girders/stands
- Some shuffling of components (no change to the beamline optics)



Fabrication/installation status

High-Bay Building (HBB) ready for installation of first beamline components in June

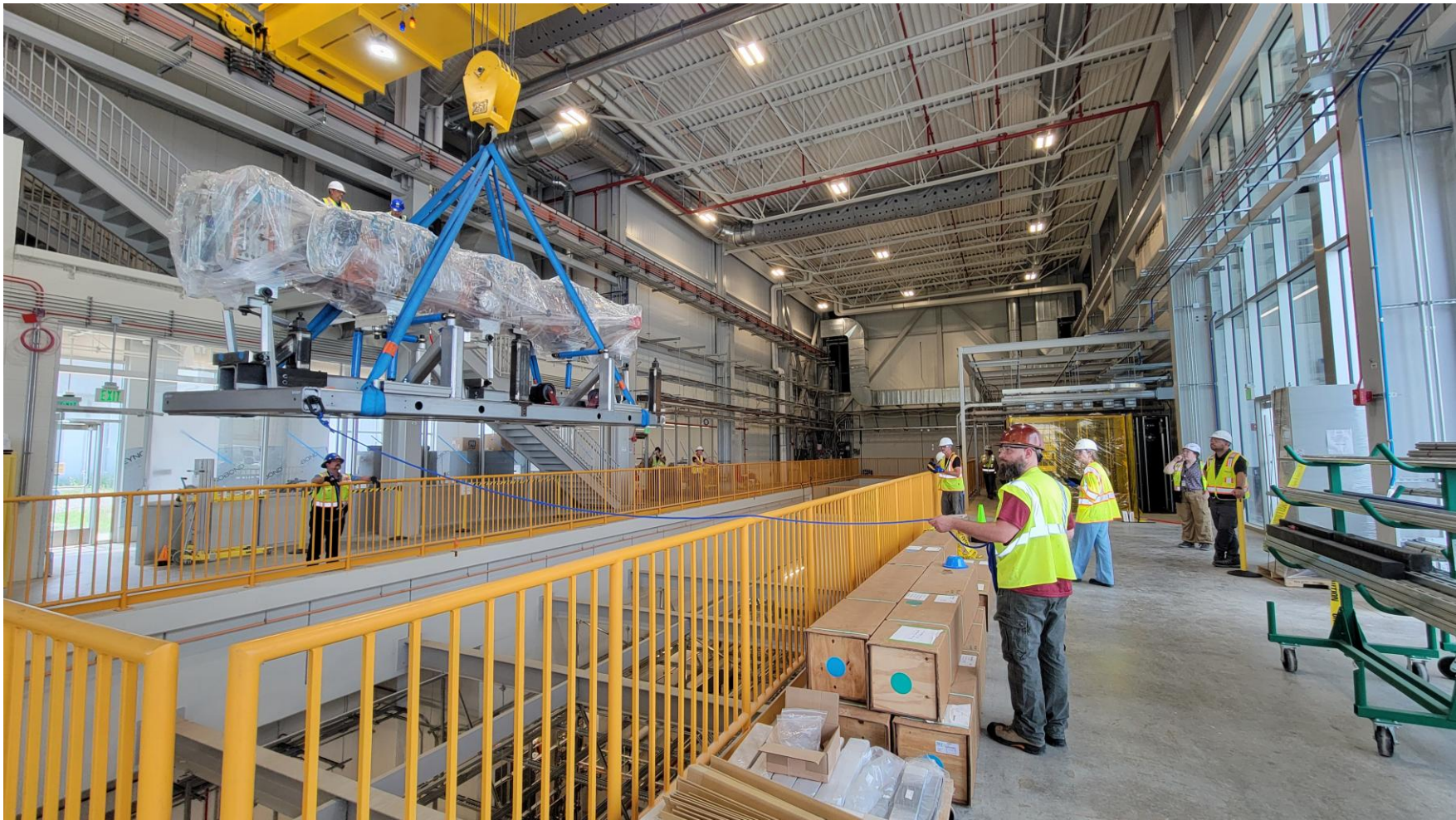
- RFQ was the first component moved from PIP2IT to the PIP-II HBB
 - Sets the 'origin' of the beam line
- Started to expand the beamline both upstream and downstream
- Cables pulled in August/September → Final alignment of LEBT and most of MEBT girders
 - Beamline configuration for WFE commissioning does not include "particle-free" region







Diaporama



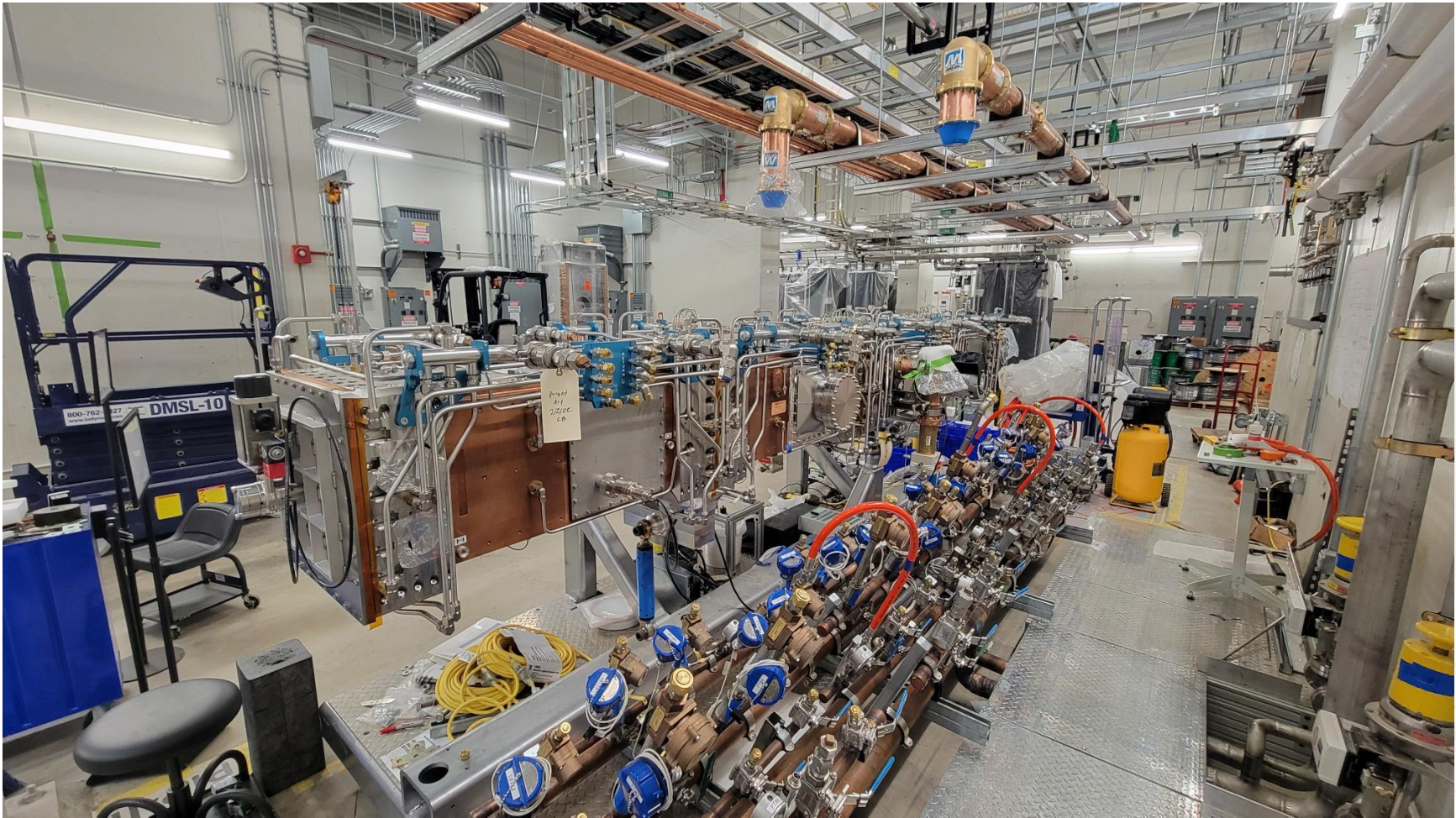


Diaporama





Diaporama





Diaporama



- Warm Front End beam commissioning starts in 1 year from now





Acknowledgement

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Thank you

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NLS-20



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Backup slides

Fermilab Accelerator Complex

Arial overview

