Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

PIP-II Project Overview

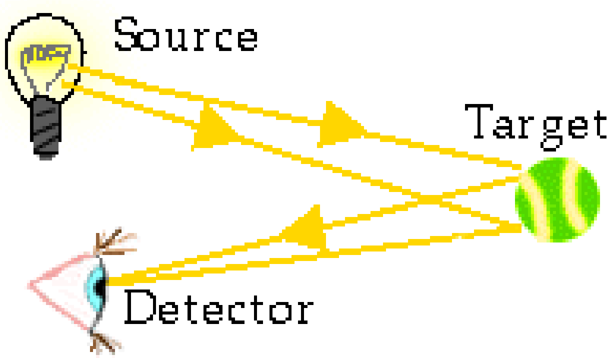
Arden Warner

FermiFusion Workshop

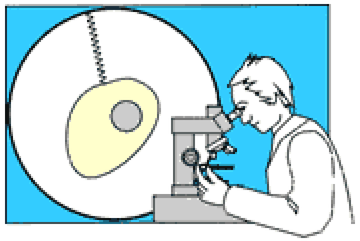
August 7th, 2024

A Partnership of:
- US/DOE
- India/DAE
- Italy/INFN
- UK/UKRI-STFC
- France/CEA, CNRS/IN2P3
- Poland/WUST

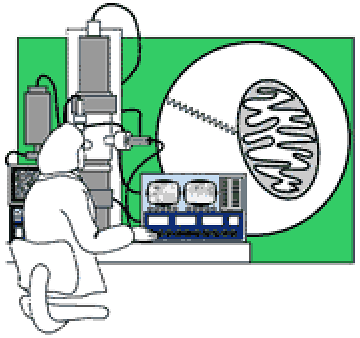
Accelerators – a tool to probe very small objects



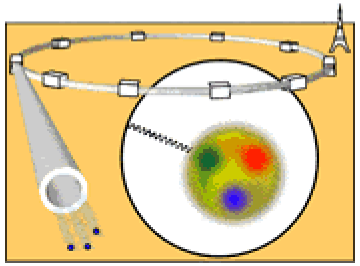
We aim source particles at target particles and detect the result



To view living cells, we use optical microscopes Resolution~ 10^{-6} m



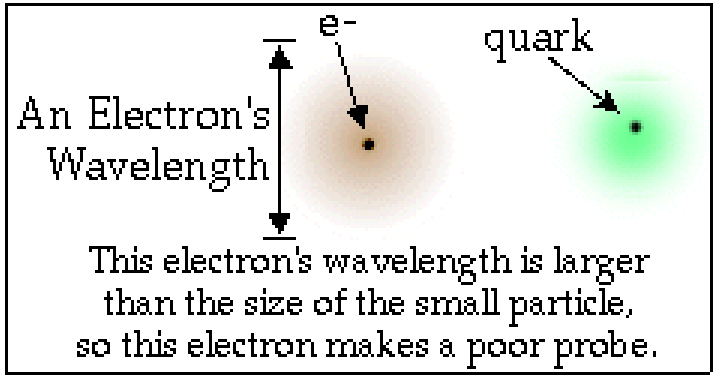
Down to the size of atomic dimensions we use electron microscopes, where electron of a few hundred KV are typical. Resolution ~ 10^{-10} m



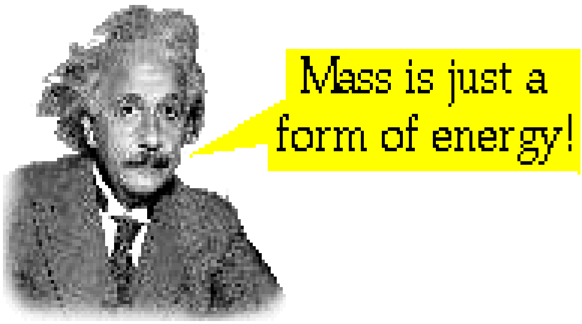
To view the inner workings of nucleons (protons and neutrons) we need particle accelerators . Resolution < 10^{-15} m

Accelerators – a tool to create and observe new particle states

- Since all particles behave like waves, physicists use accelerators to increase a particle's momentum, thus decreasing its wavelength enough that they can use them to poke inside atoms.



- "High energy" particles can have their energy converted into mass ($E = mc^2$), and so new particle states can be created and observed.



- Accelerators provide the ability to control the particles (steer, focus, increase/decrease intensity, for instance) to conduct experiments efficiently and in a controlled fashion.

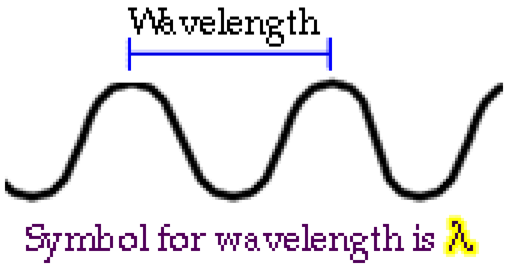
Accelerators – Resolving power

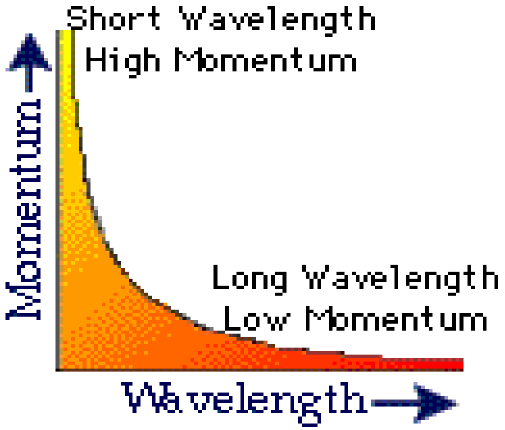
Nucleons inside atomic nuclei have a size ~ 10^{-15} m and are separated by distances of the same order. The electrons orbiting atomic nuclei as well as the quarks inside nucleons have a size, if any < 10^{-18} m

The resolving power of these devices is determined by the de Broglie wavelength of the source particles.

$$\text{Higher momentum} \Rightarrow \text{Shorter wavelengths}$$

$$\lambda = h / p$$

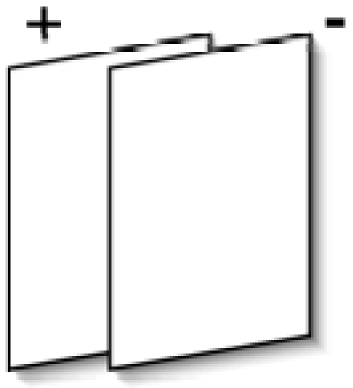




Example: if an electron is required to have a de Broglie wavelength comparable to the size of the nucleon, it must have a kinetic energy of 1200 MeV. Several thousand higher than an electron microscope.

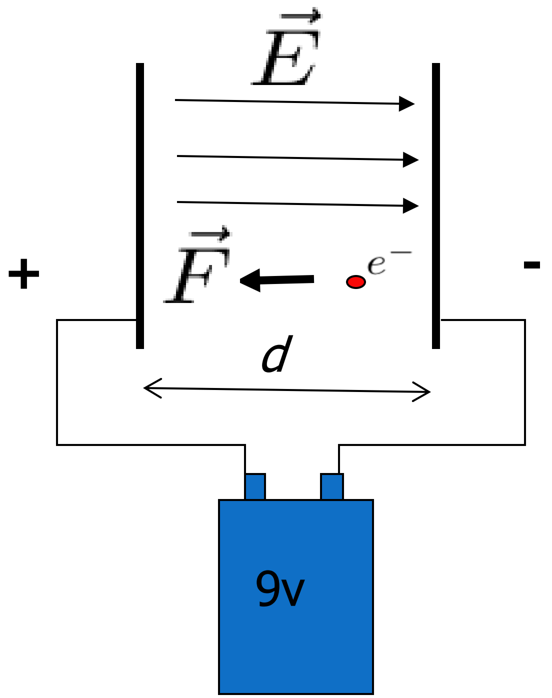
For an electron energy above 10 MeV, kinetic energy is proportional momentum.

Particle Acceleration



$$|\vec{E}| = V/d$$

$$|\vec{F}| = q|\vec{E}| = qV/d$$



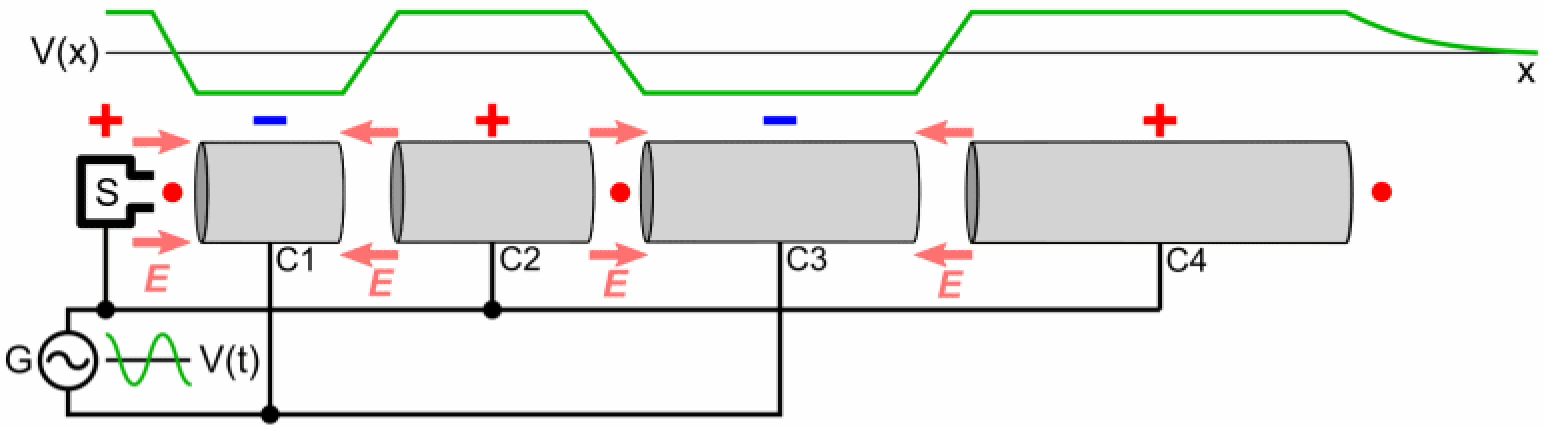
As the electron accelerates from the right-hand plate to the left, the change in energy is the work done,

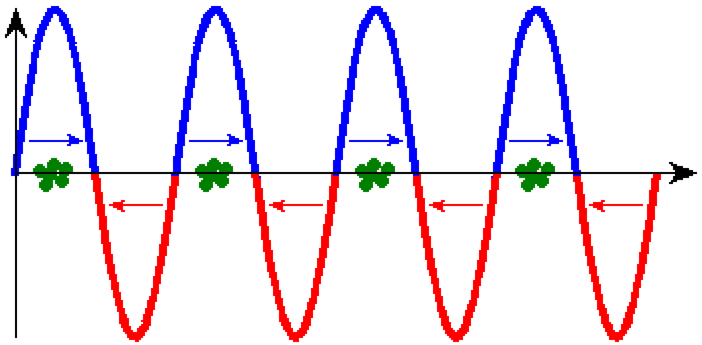
$$\Delta W = F \times d = qV$$

The charge on an electron is $q = -e = -1.6 \times 10^{-19}$ Coul
(on a proton, $+1.6 \times 10^{-19}$ Coul $= +e$)

So, we say that an electron/proton accelerated through 1-volt gains an amount of energy $\Delta E = 1$ eV (1 **electron volt**) ($= 1.6 \times 10^{-19}$ J)
In example above, the electron would gain energy of amount 9 eV.

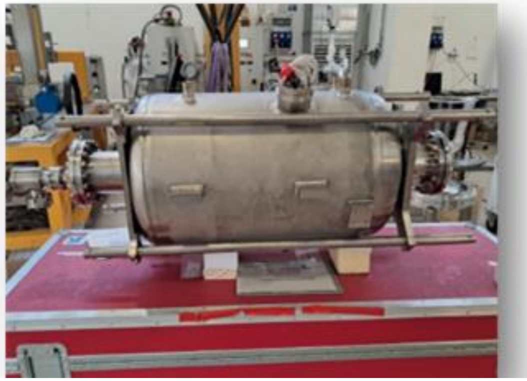
Linear accelerators

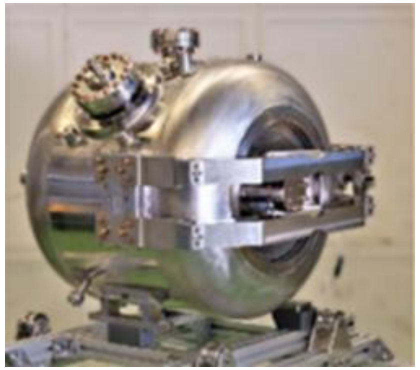


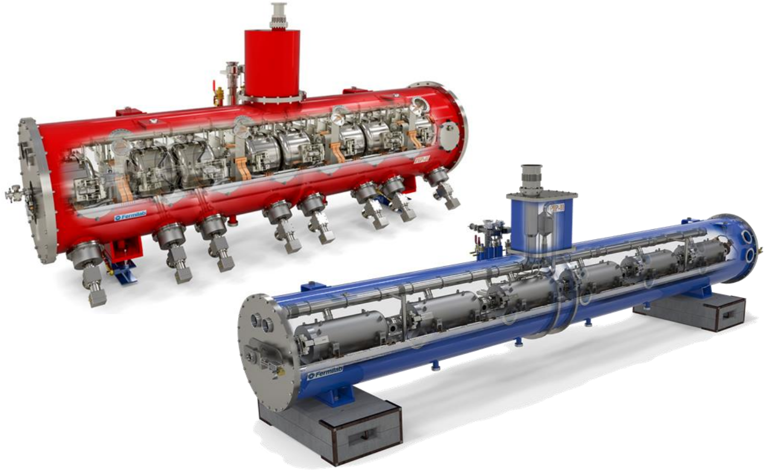


Accelerating Cavities

- RF Cavities are the ‘Accelerator’ in Particle Accelerator
  - Goal: Concentrate electromagnetic energy & give it to the beam as it passes through the cavity, accelerating it
- Three Major Design Criteria:
  1. Want the cavity to store as much energy as practical
  2. Cavities are carefully designed to transfer as much energy to the beam as possible
  3. Want this cavity to store this energy as efficiently as possible



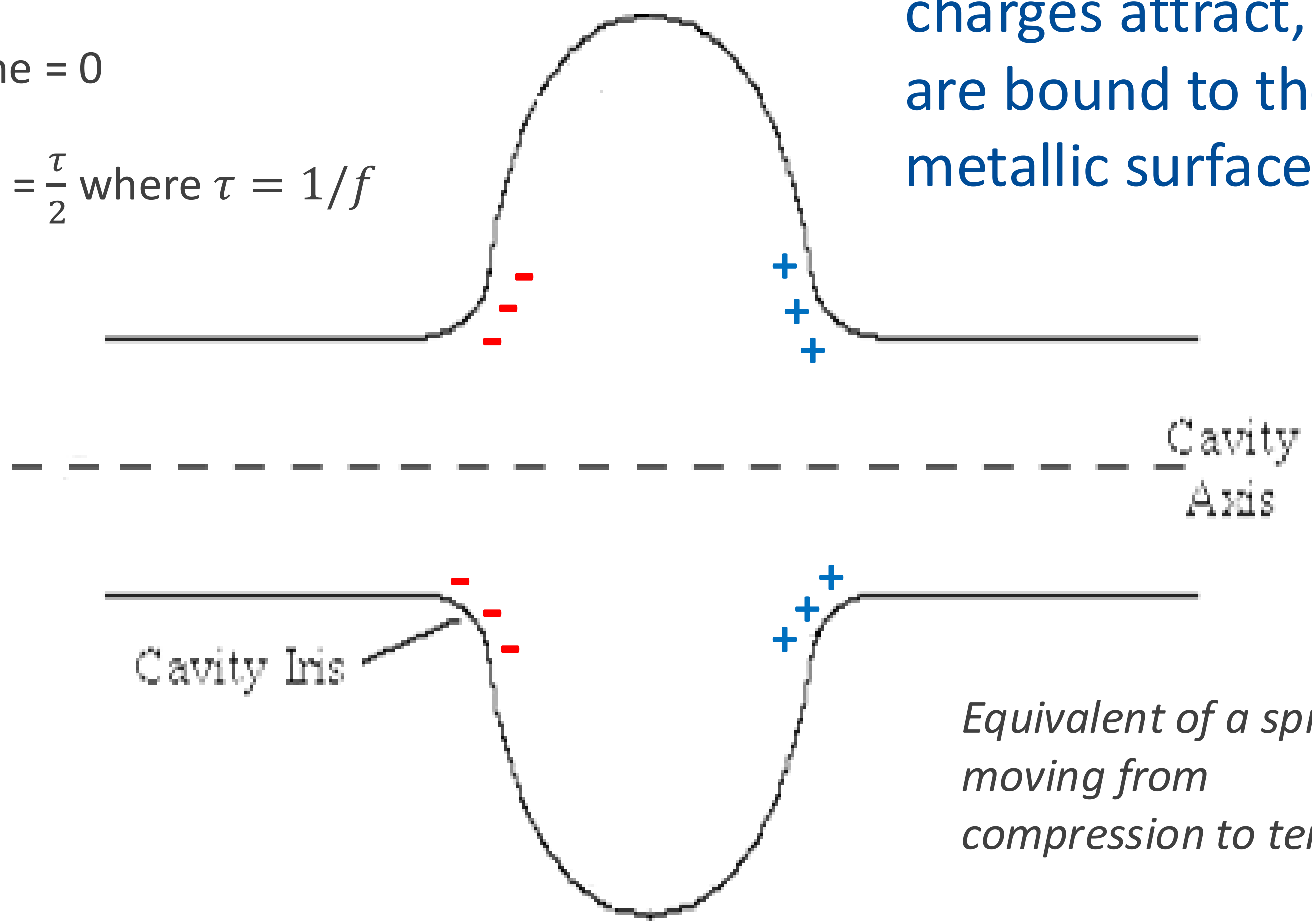




Releasing the Spring

Time = 0

Time = $\frac{\tau}{2}$ where $\tau = 1/f$

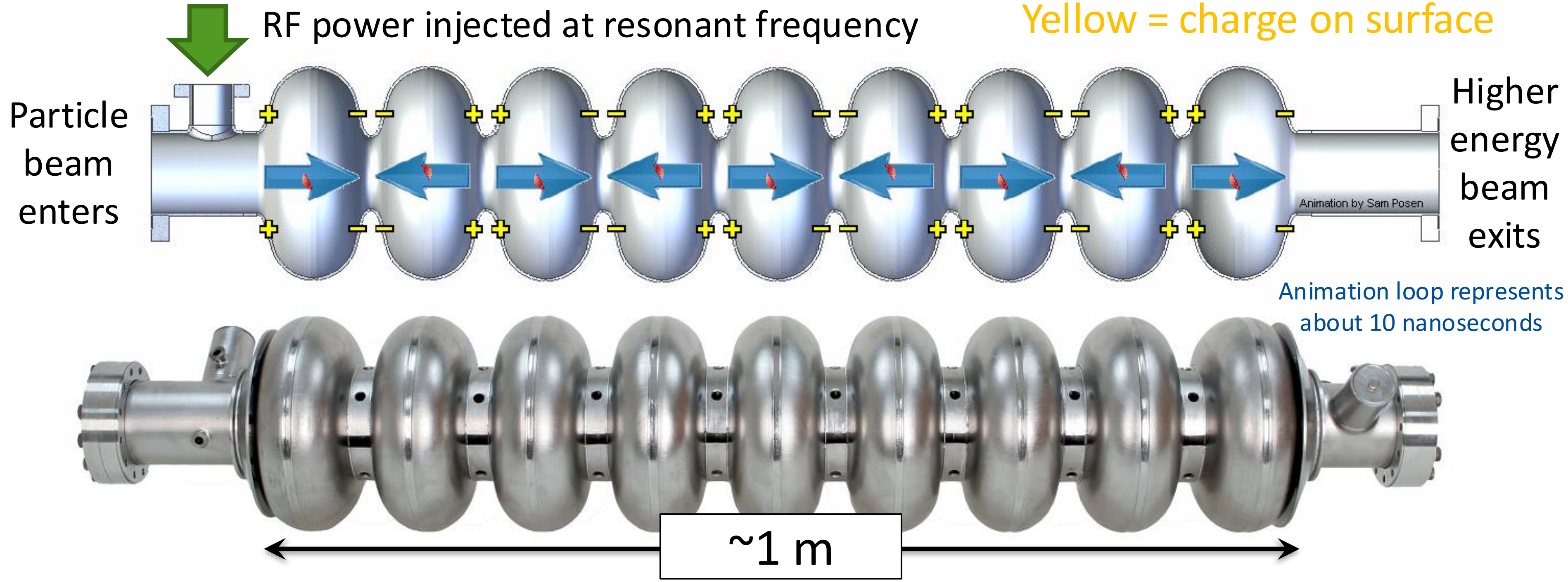


Remember: opposite charges attract, but are bound to the metallic surface

Equivalent of a spring moving from compression to tension

Radiofrequency Cavity

Blue = electric field
Red = magnetic field
Yellow = charge on surface



- Cavities are carefully designed for specific particle, particle speed, and timing
- Required magnetic fields are off-axis, so they don't disrupt the beam
- Note: If the speed of the particle is different, the efficiency of the acceleration is going to be very much harmed! Design Particle stays synchronized the whole time and gets full acceleration.

PIP-II….a new accelerator to generate neutrinos

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

CW RF Operations

Linac-to-Booster transfer line

Accelerator Complex Upgrades

Booster
Recycler
Main Injector

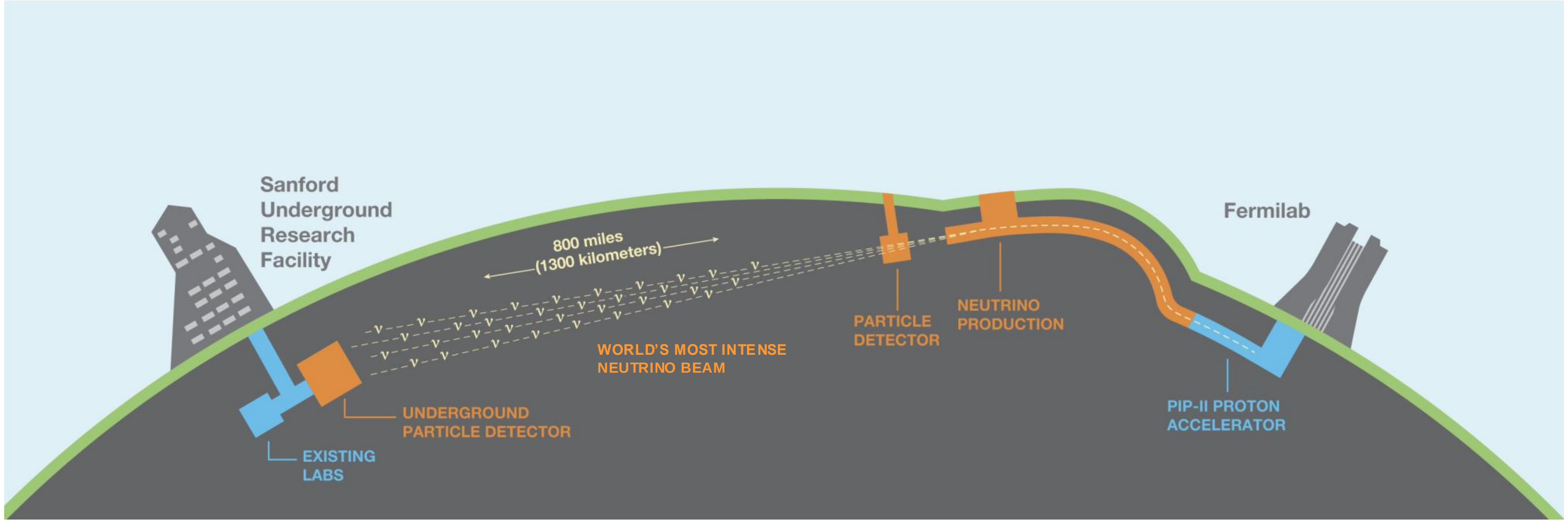
Conventional Facilities

Space reserved for two CMs for 1 GeV Upgrade

Neutrinos to Minnesota… NOνA:
Fermilab's present flagship neutrino experiment
Neutrinos to South Dakota… DUNE:
International neutrino experiment hosted by Fermilab

International Neutrino Program ➔ PIP-II / LBNF / DUNE

- Powerful proton beams (**PIP-II**)
  - 1.2 MW upgradable to multi-MW in energy range of 60-120 GeV to enable world's most intense neutrino beam
- Dual-site detector facilities (**LBNF**)
  - Deep underground caverns (1.5 km) to support 4 x 17 kt liquid argon volume detectors
  - A long baseline (1300 km) neutrino beam, with wideband capability
- Deep Underground Neutrino Experiment (**DUNE**)
  - The next-generation neutrino experiment



PIP-II will provide a highly capable, reliable, upgradeable and expandable scientific infrastructure with significant savings to DOE

PIP-II International Partners, Expertise and Capabilities

India, Department of Atomic Energy (DAE) (started 2009) BARC, RRCAT, VECC; and IUAC

Substantial engineering / manufacturing experience; Superconducting magnets for LHC; 2 GeV synch light source

Italy, INFN (started 2016)

Internationally recognized leader in superconducting RF technologies
SRF cavity and cryomodule fabrication for XFEL; SRF cavities for ESS

UK, STFC UKRI (started 2017)

Substantial engineering and manufacturing experience; Construction, operation of synch light & neutron sources SRF cavity processing and testing for ESS

France, CEA, CNRS/IN2P3 (started 2017)

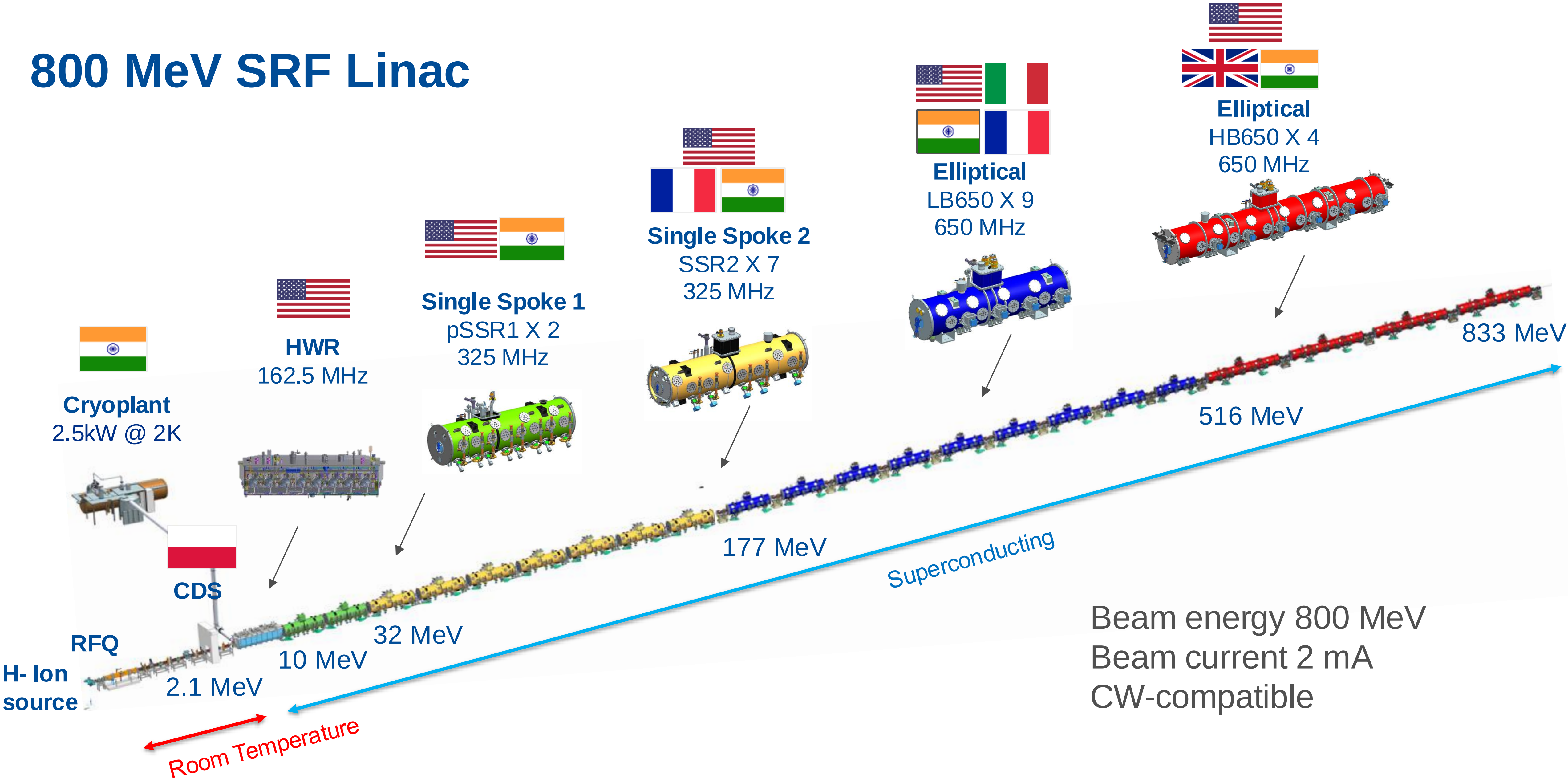
Internationally recognized leader in large-scale CM assembly
CM assembly for European XFEL and ESS; SSR2 cavities and couplers for ESS

Poland, WUST, WUT, TUL (started 2018)

Substantial engineering / manufacturing experience; CDS, LLRF, QC for XFEL, ESS

PIP-II is the U.S. first accelerator project to be built with major international contributions; benefits from world-leading expertise, capabilities

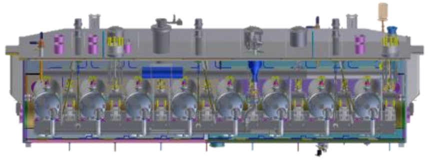
800 MeV SRF Linac



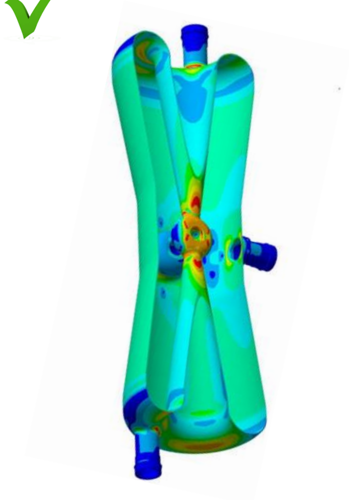
Beam energy 800 MeV
Beam current 2 mA
CW-compatible

PIP-II is the world's highest energy and highest power CW proton linac, and the first U.S. accelerator project to be built with major international contributions

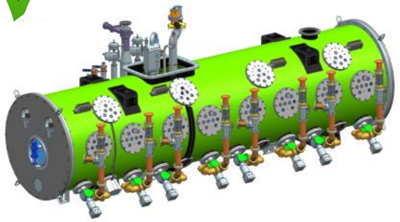
The state-of-the-art PIP-II Superconducting RF Systems



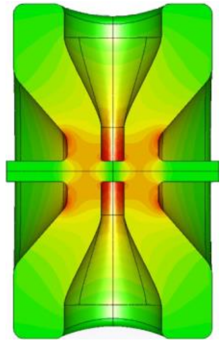
5.9 m



Half Wave Resonator
β=0.11 Q_0 =0.85x10^{10}

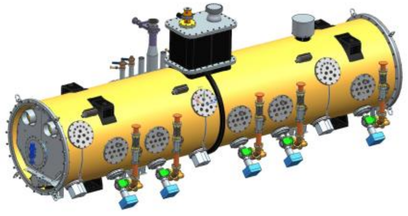


5.3 m



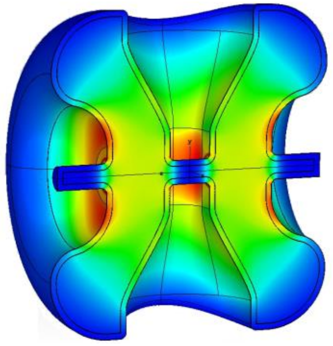
Single Spoke
SSR1
β=0.22 Q_0 =0.82x10^{10}

2023



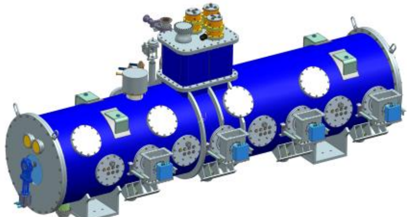
6.5 m

2022

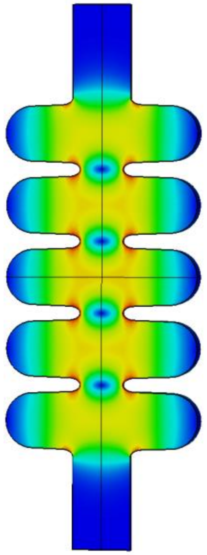


Single Spoke
SSR2
β=0.47 *Q_0 =0.82x10^{10}

2023

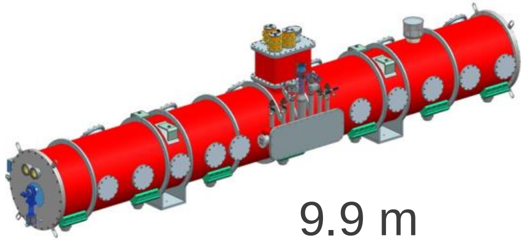


5.5 m

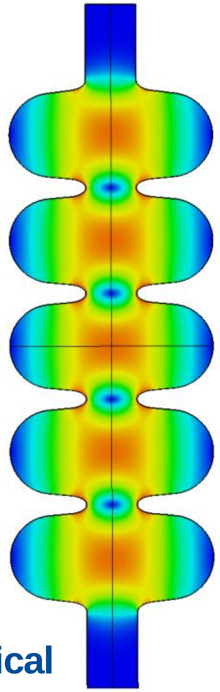


Elliptical
LB650
β=0.61 *Q_0 =2.4x10^{10}

2021-22



9.9 m

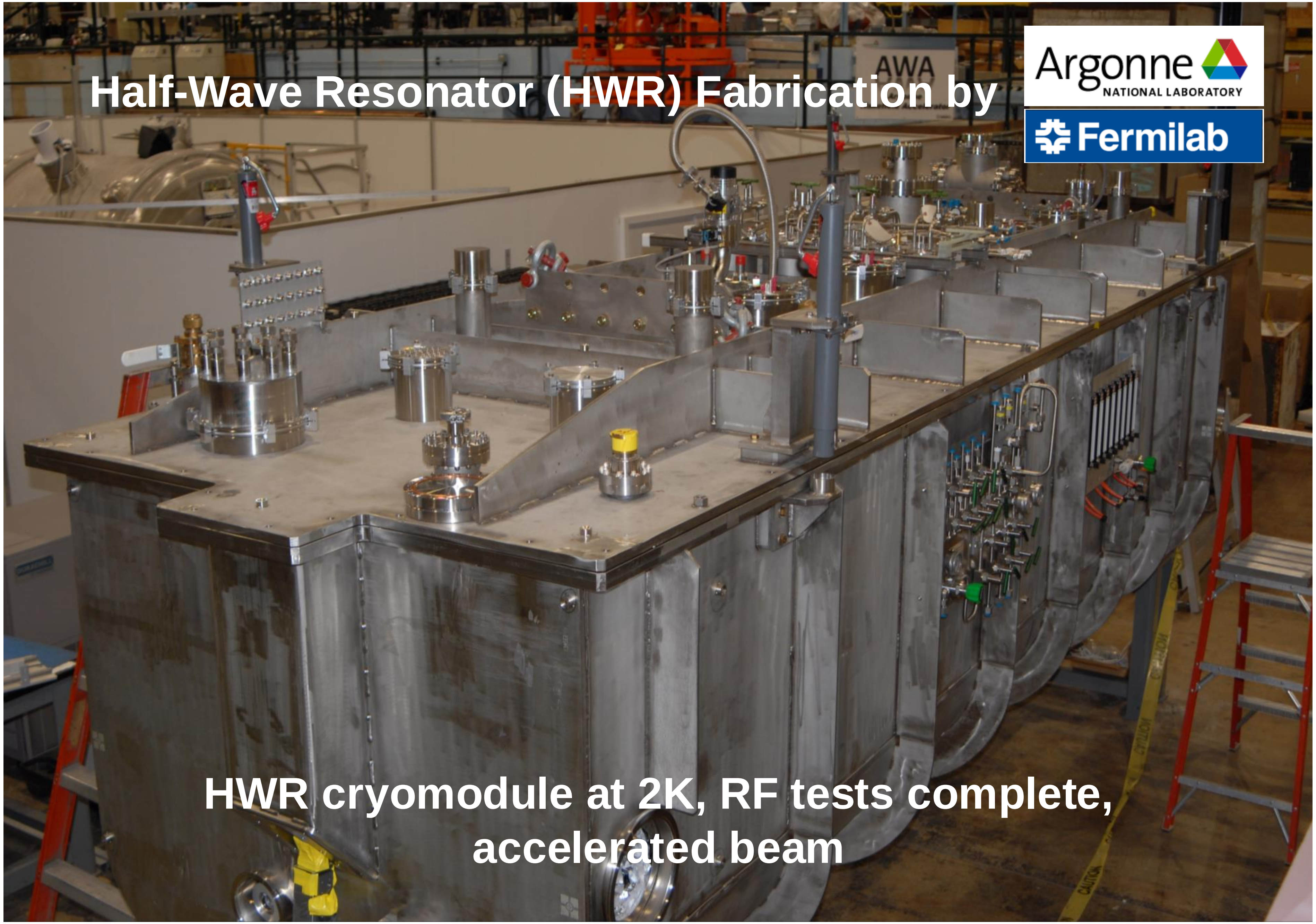


Elliptical
HB650
β=0.92 *Q_0 =3.3x10^{10}

✓ Performance validated   Dates: component is built

*state-of-the-art

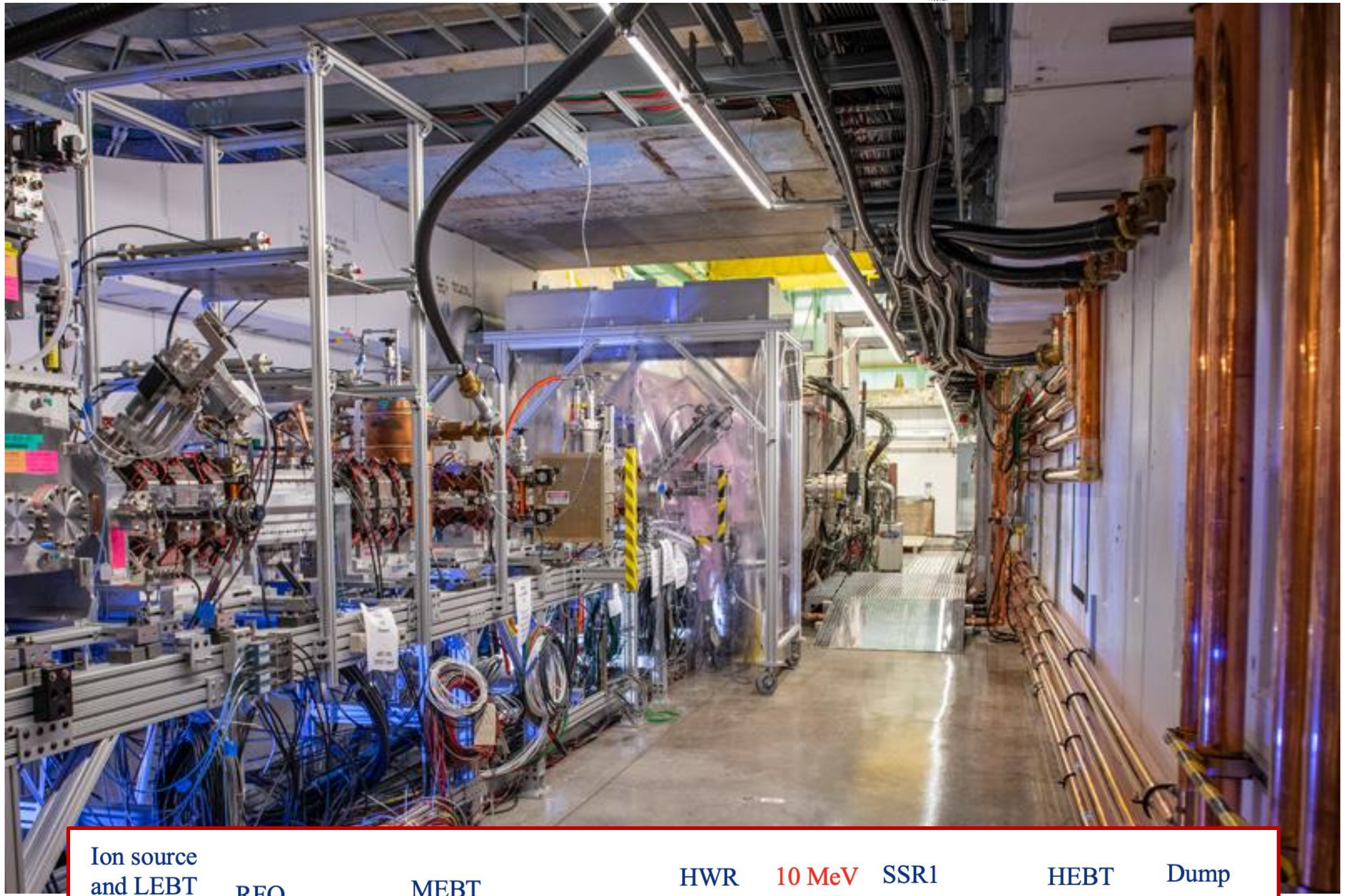
Half-Wave Resonator (HWR) Fabrication by Argonne National Laboratory / Fermilab

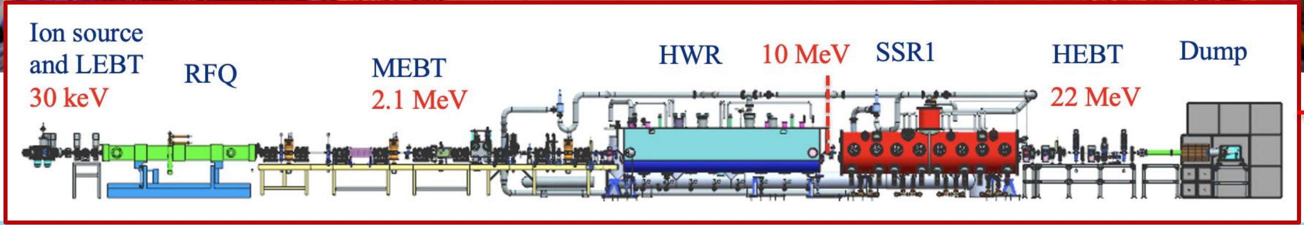


HWR cryomodule at 2K, RF tests complete, accelerated beam

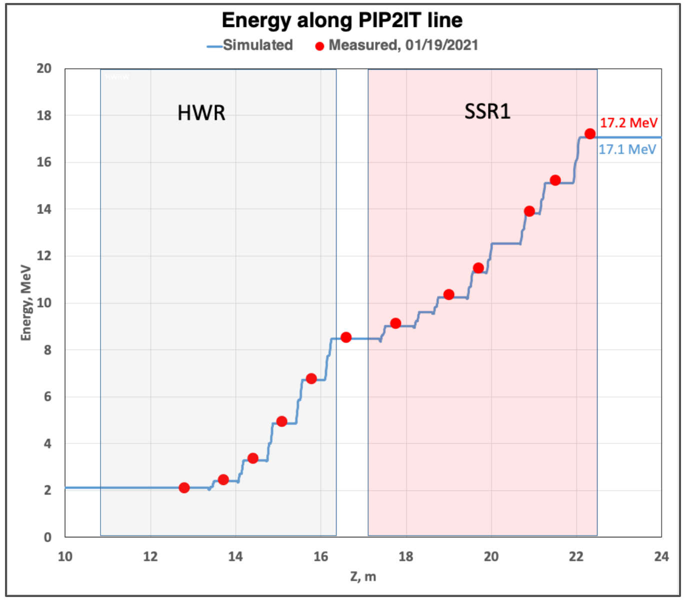
Single Spoke prototype cryomodule fabricated by Fermilab, one cavity from IUAC/BARC; 2K RF tests complete; accelerated beam

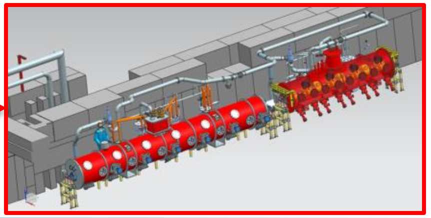
PIP-II Injector Test (PIP2IT) – Testbed for PIP-II Technologies



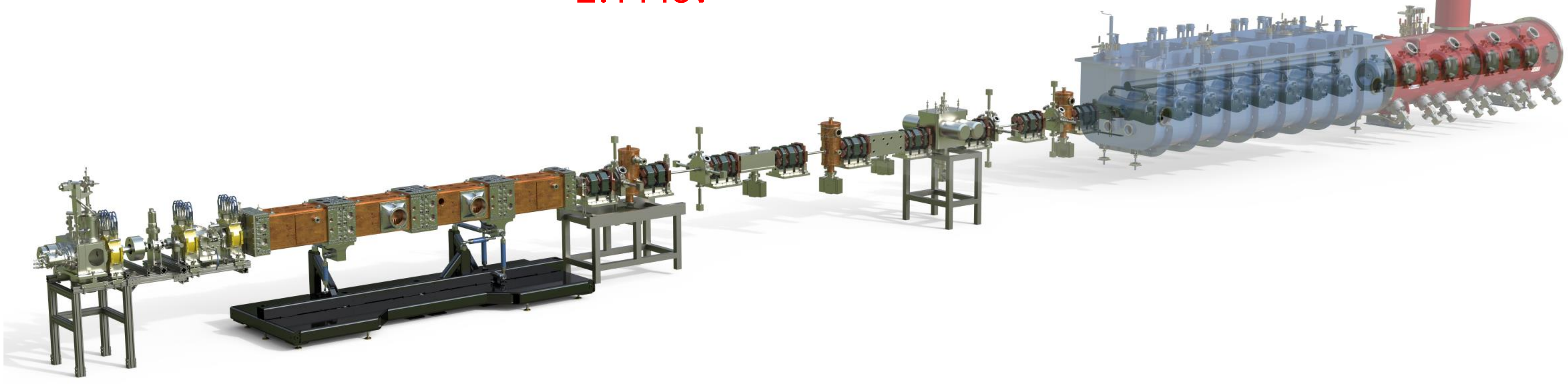


PIP2IT was a near full-scale Front End of PIP-II with first two cryomodules





PIP2-IT Accelerator Components



30 keV

2.1 MeV

10 MeV

22 MeV

Ion
Source

RFQ, B1
VXI Crate
2 MFC cards

Buncher2,3
1 SOCMFC
Chassis

HWR
4 SOCMFC
Chassis
1 Tuner
Signal Cond
Module

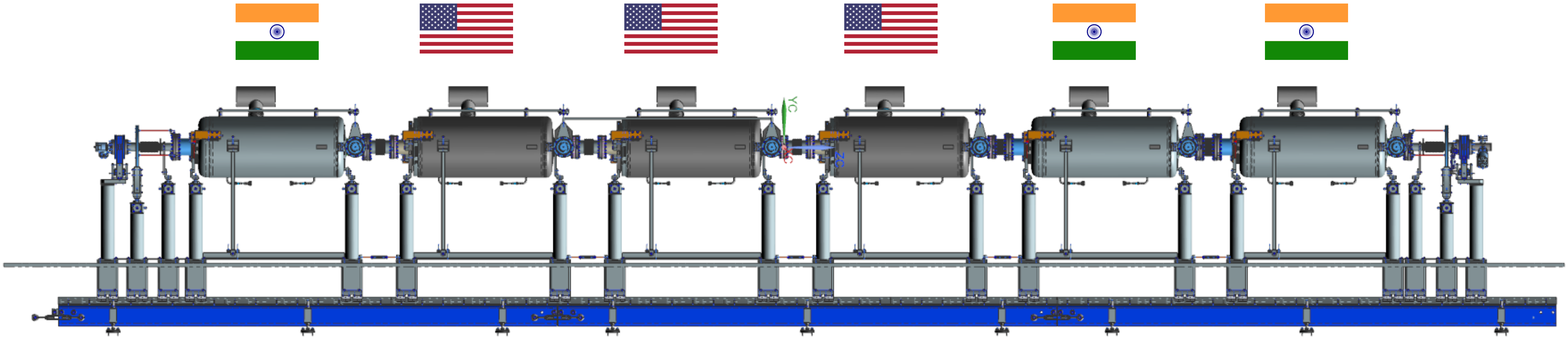
SSR1
4 SOCMFC
Chassis
2 Resonance
Control Chassis

DAE Solid-State Amplifiers

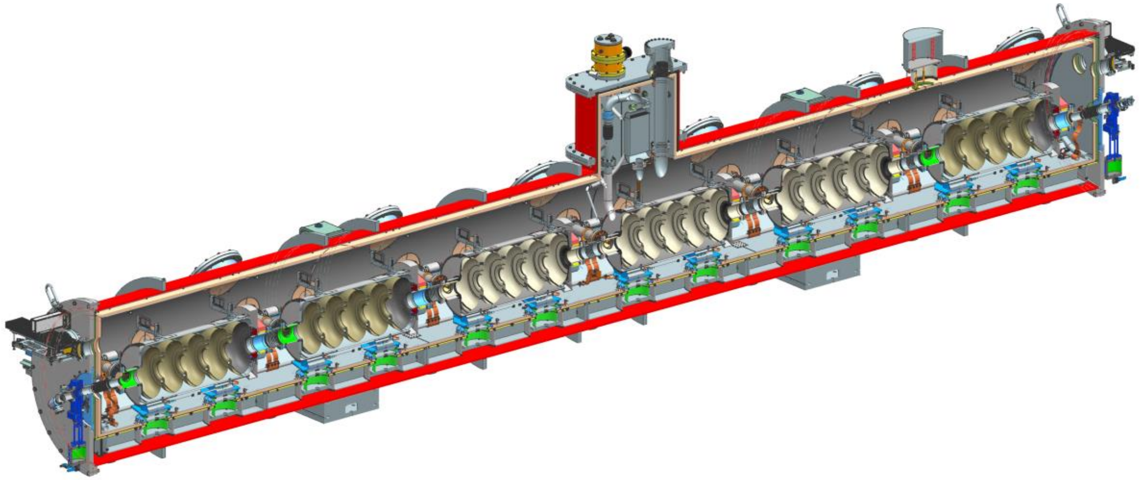
ECIL/BARC 7 kW 325 MHz amplifiers powering SSR1 cavities at PIP2IT

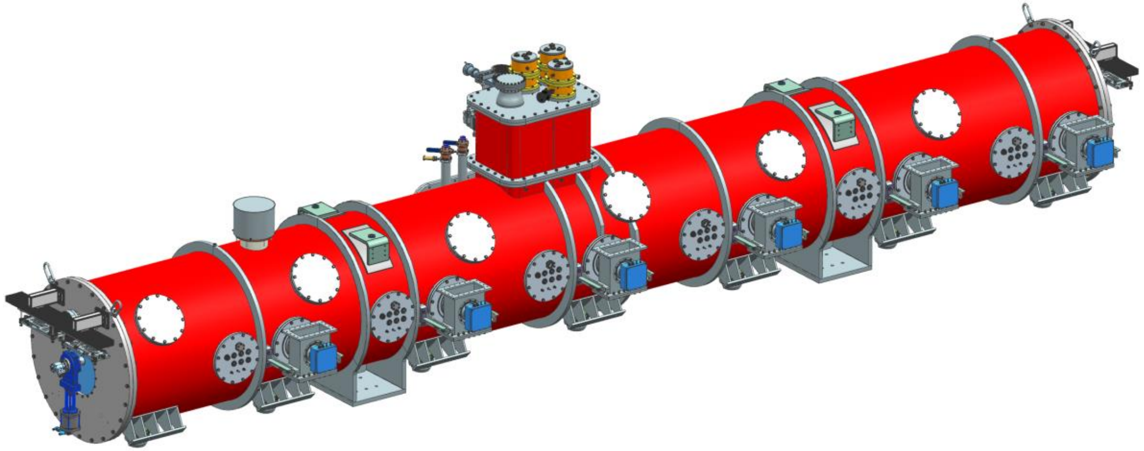
RRCAT 40 kW 650 MHz prototype amplifier just arrived, being assembled, in preparation for testing

HB650 Prototype Cryomodule: String Assembly



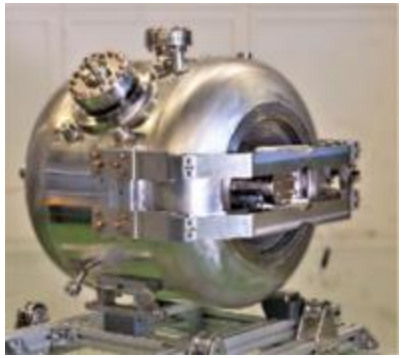
RRACT502 (I) AES007 AES008 (I) AES009 RRCAT-504 (I) RRCAT-506 (I)





More Recent Progress

- PIP-II Project has made considerable technical and management progress since the May 2023 DOE IPR
- Full construction activities
- Multiple designs have been finalized and many are in the prototype stage
- After several iterations, we now have a SSA delivery schedule that works for PIP-II
- Cryoplant construction is well underway: Warm compressors will arrive in Jun ’24 with coldbox arriving by the end of CY24 - Infrastructure at building being installed
- Qualified 3 SSR2 cavities @ IJCLab
- Significant accomplishment for CM transportation testing (FNAL➔ UKRI ➔ FNAL)



Linac Complex Design is Complete – Ready to Execute Civil Construction

Linac Complex design enables PIP-II multi-user capability and upgrade/expansion to 2 GeV linac in support of 2.4 MW program

Summary

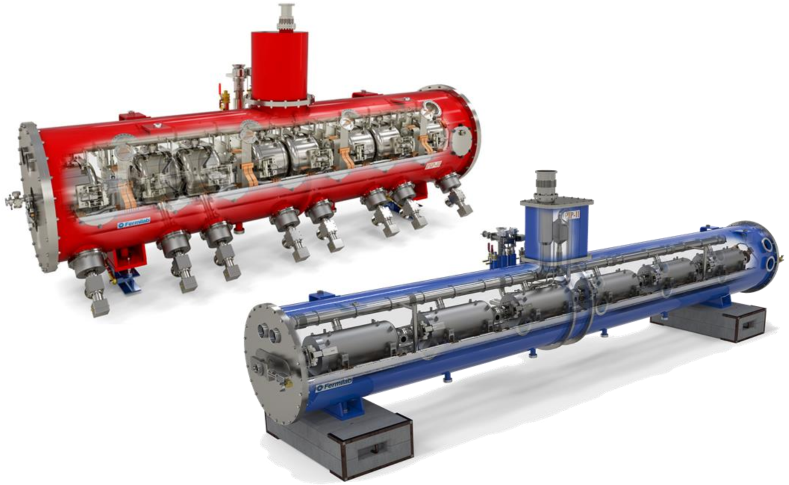
- PIP-II is a leading-edge SRF linear accelerator critical to the success of the LBNF/DUNE international neutrino program
- International partnerships are essential for the success of PIP-II
- Excellent, experienced project team and strongly committed partners ensure continued technical progress despite pandemic challenges
- We are building a highly capable accelerator that will power the world's most intense neutrino beam!

Tremendous opportunities for cutting-edge physics & engineering work!

Thank you!

RF Cavity Design Implications – Efficient Storage

- Efficient Energy Storage: Superconducting Materials
  - Can use low resistance materials (copper), but PIP-II/LCLS-II requires higher efficiency, otherwise we would melt the cavities
  - Use of superconducting material for cavity (Niobium) has two major implications:
    - Gain factor of ~1000 in efficiency vs Copper cavity (mΩ vs nΩ, but cooling efficiency is lower by ~1000)
    - Must operate cavities at very low temperatures



Why neutrinos?

- Neutrinos are pretty cool:
  - Elementary particles with smallest mass of known particles
    - < one millionth that of the electron
  - ‘neutrino’ - electrically neutral and so small (mass)
  - typically pass through matter unimpeded & undetected
  - come in three flavors: electron, muon, tau
  - neutrinos *oscillate* between different flavors in flight
  - parameters of the oscillations still not completely understood
    - could unlock our understanding of the universe!
  - been a focus of physics at Fermilab since the beginning
  - Current focus on the oscillations: short baseline (detectors on site) and long baseline (detectors in Minnesota and South Dakota)

DUNE Science Objectives

Neutrinos – most ubiquitous matter particle in the universe, yet the least understood. Opportunities for game changing physics discoveries:

- **Origin of matter**
  Investigate leptonic CP violation, mass hierarchy, precision oscillation physics
  - ➢ Discover what happened after the big bang: Are neutrinos the reason the universe is made of matter?

- **Neutron Star and Black hole formation**
  Ability to observe supernovae events
  - ➢ Use neutrinos to look into the cosmos and watch the formation of neutron stars and black holes in real time

- **Unification of forces**
  Investigate nucleon decay targeting SUSY-favored modes
  - ➢ Move closer to realizing Einstein's dream of a unified theory of matter and energy