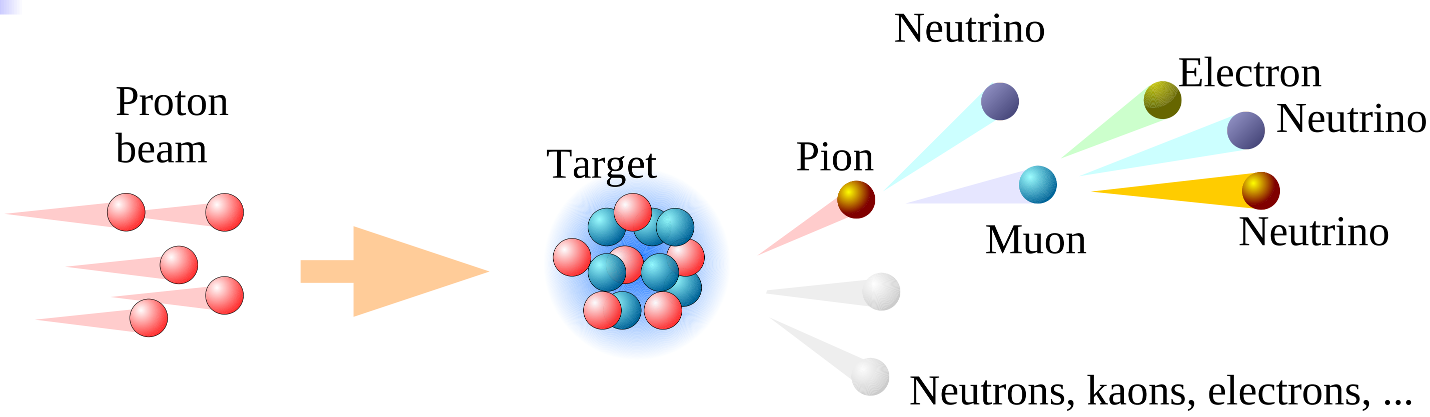
accelerator-driven
neutrino

Future ^ Facilities

C. T. Rogers

Science & Technology Facilities Council
ISIS Neutron and Muon Source

Where from? Where to?

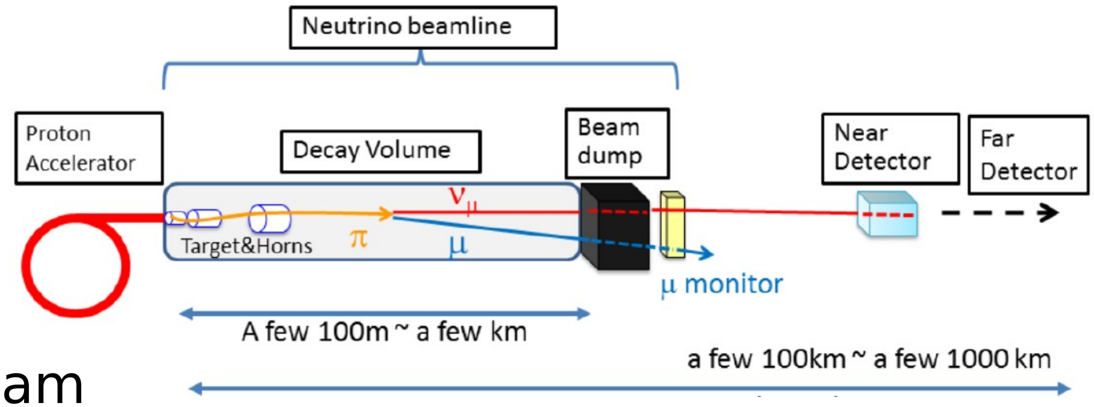


- Where from?
  - Nuclear fission
  - Nuclear fusion (in the sun)
  - Atmospheric protons
  - Accelerator-driven protons
- Where to?
  - The detector!
  - What are possible future neutrino sources?
  - What might future neutrino facilities look like?

Where to?

- Main existing or near-term facilities planned
  - JPARC (T2HK)
  - Fermilab (DUNE)
- Horizon scanning:
  - ESSnuSB – the ultimate superbeam
  - Cyclotron sourced neutrinos – Daedalus and Isodar
  - Neutrinos from exotic particles
    - ENUBET
    - NuSTORM
  - Neutrino factories – ultimate precision
  - Muon collider as a neutrino source
- Different high power proton sources
  - Linear accelerator (linac) → long straight accelerator
  - Synchrotron ring → ramp magnet with the acceleration
  - Cyclotron ring → beam radius changes with acceleration

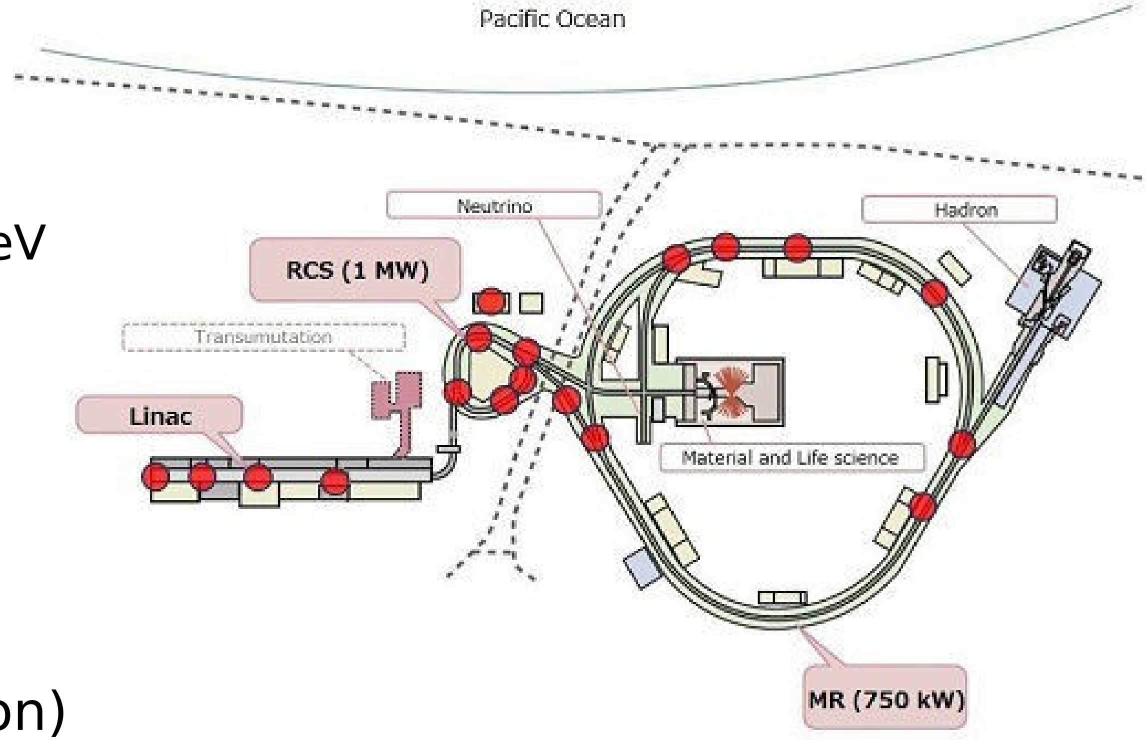
Superbeam

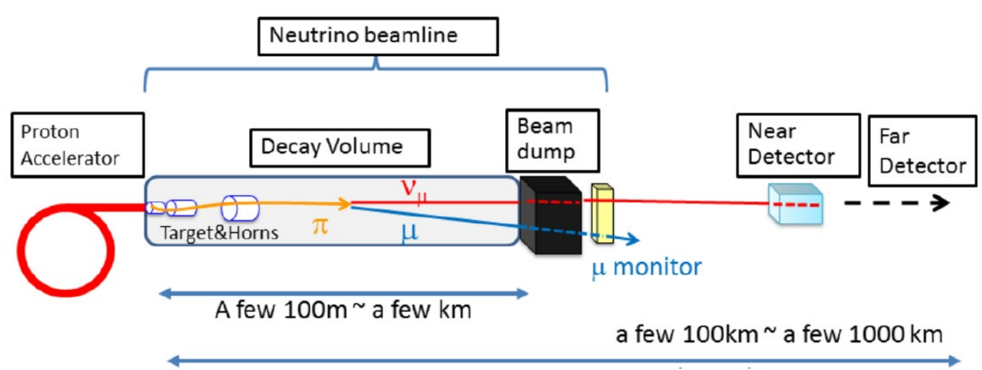


- Superbeam
  - Protons strike target
  - Pions focused through horn focusing
  - Decay in long beam pipe to make neutrinos
- Neutrino rate determined by beam power
  - More protons → more pions
  - More proton energy → more pions
  - As a 0th approximation, neutrino rate proportional to proton beam power
- Two facilities deliver superbeams
  - JPARC
  - Fermilab

J-PARC Complex

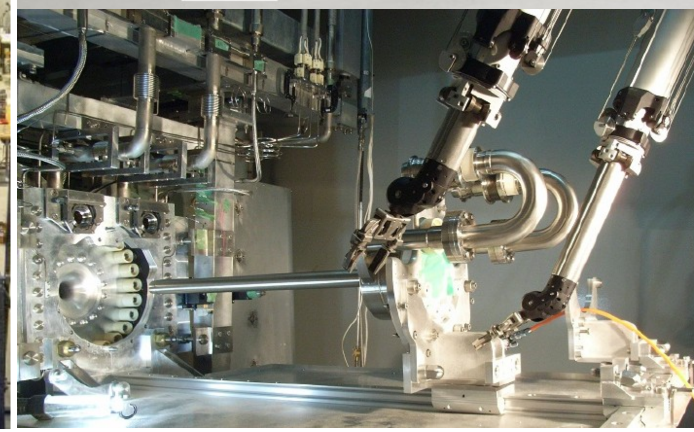
- Linac
  - H-
  - Accelerate to 400 MeV
- Rapid Cycling Synchrotron (RCS)
  - Charge exchange injection
  - Accelerate to 3 GeV
  - 15 Hz Rep Rate
- Main Ring (Synchrotron)
  - Accelerate to 30 GeV
  - 0.4 Hz Rep Rate





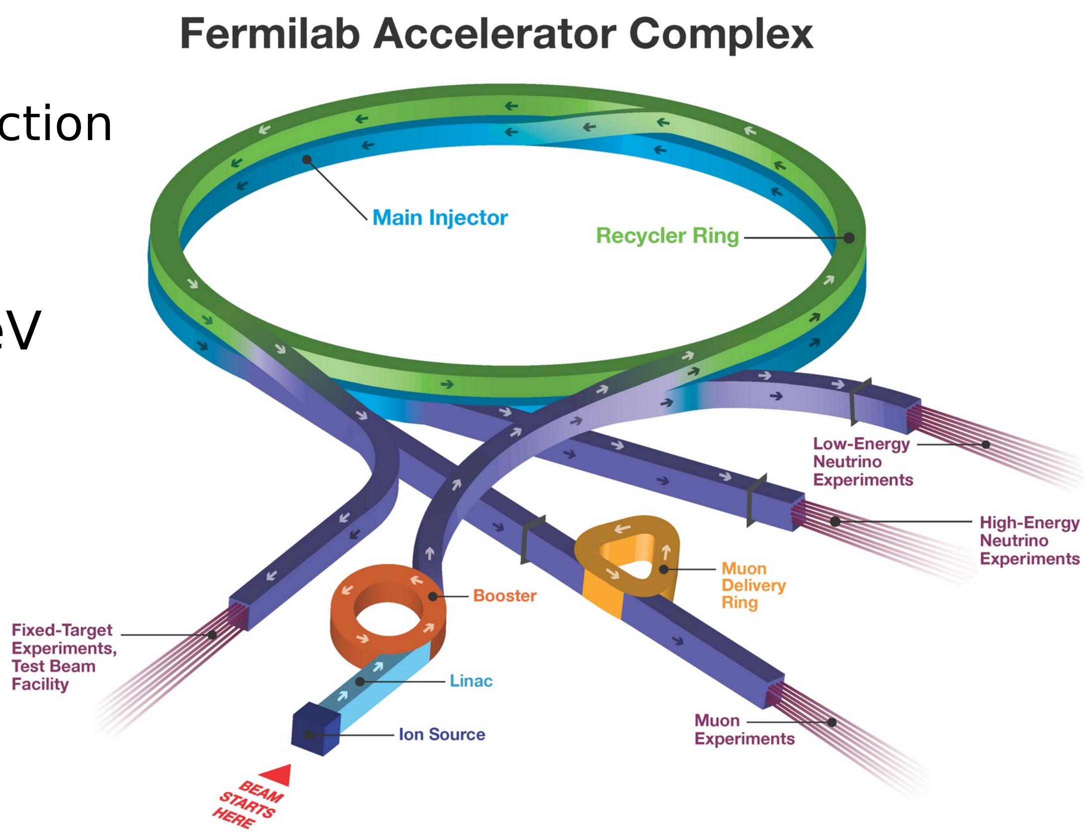
J-PARC Upgrades

- Proton facility
  - Increase rep rate 0.4 Hz → 0.86 Hz
  - Increase current 2.65×10^{14} → 3.2×10^{14}
- Improved beam diagnostics
- New horn → increased focusing
- New target with improved cooling
  - Probably limits beam power
  - UK is big player



Fermilab Complex

- Linac
  - H- accelerated to 400 MeV
- Booster
  - Charge exchange injection
  - Acceleration to 8 GeV
  - 15 Hz rep rate
- Main Injector → 120 GeV

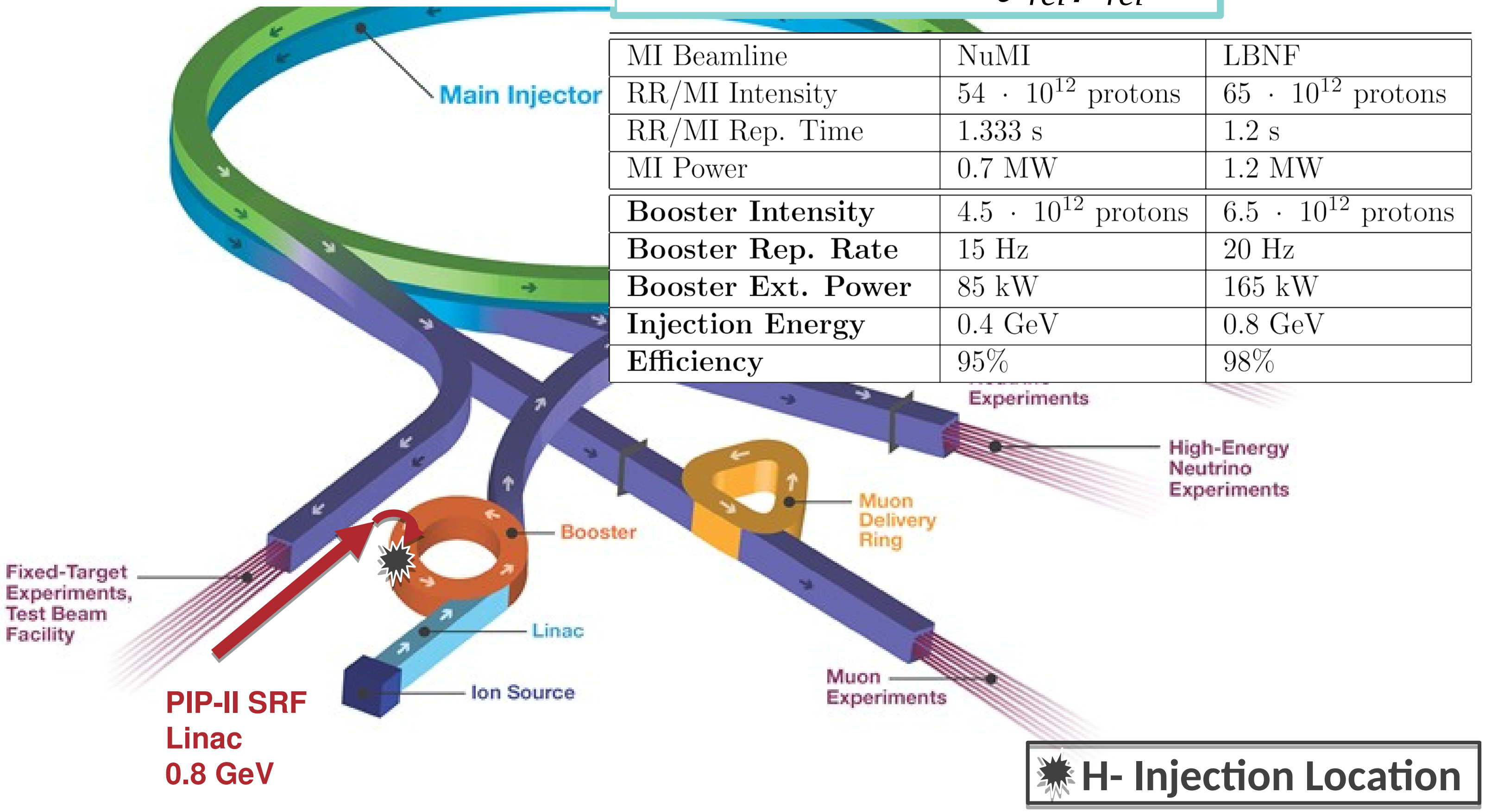


Fermilab Complex PIP-II

Defocusing strength due to space charge

$$K_{sc} = \frac{1}{2\pi\varepsilon_0}\frac{1}{a^2}\left(\frac{I}{\gamma_{rel}^3\beta_{rel}^2 c}\right)$$

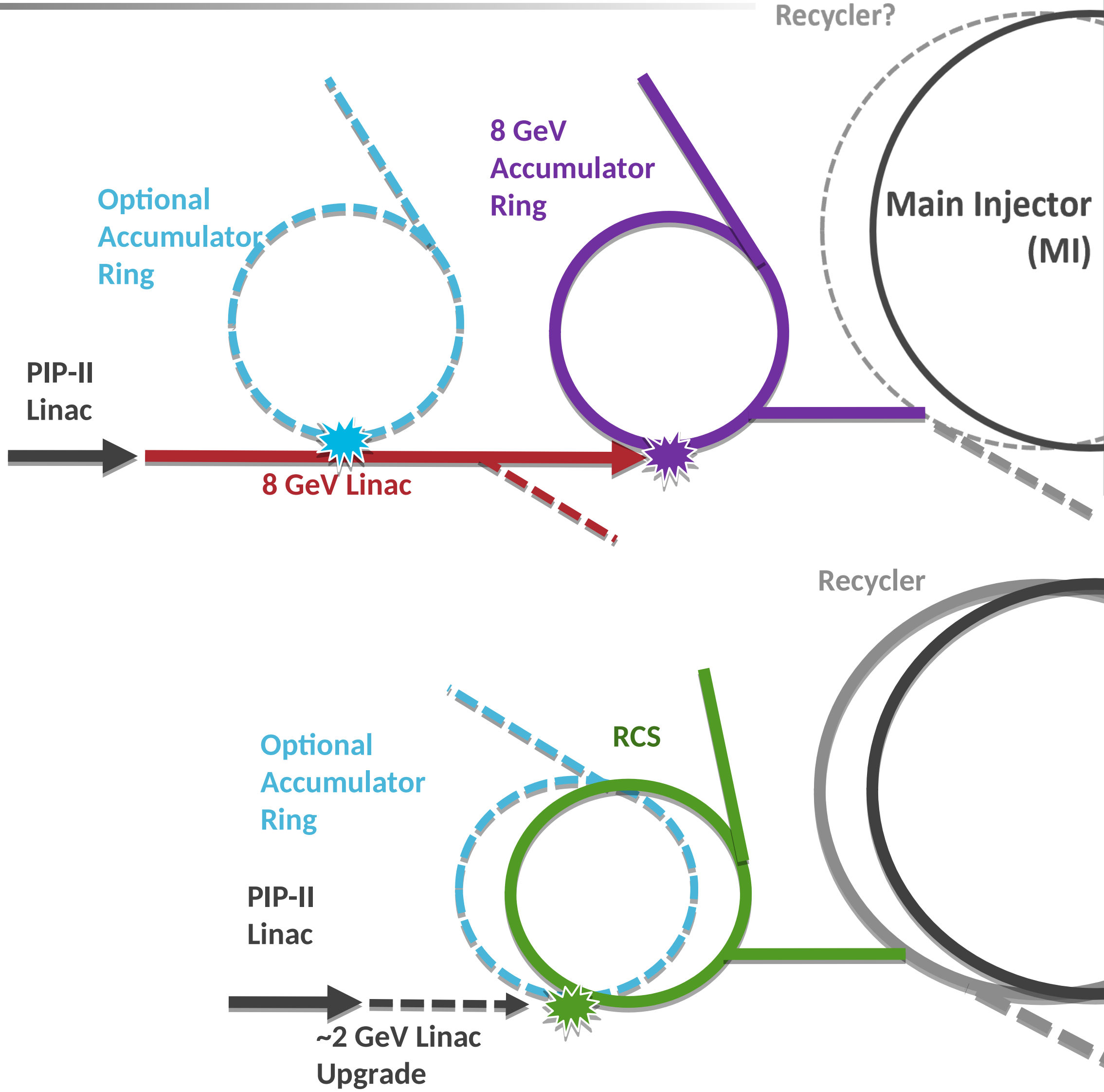
MI Beamline	NuMI	LBNF
RR/MI Intensity	$54 \cdot 10^{12}$ protons	$65 \cdot 10^{12}$ protons
RR/MI Rep. Time	1.333 s	1.2 s
MI Power	0.7 MW	1.2 MW
Booster Intensity	$4.5 \cdot 10^{12}$ protons	$6.5 \cdot 10^{12}$ protons
Booster Rep. Rate	15 Hz	20 Hz
Booster Ext. Power	85 kW	165 kW
Injection Energy	0.4 GeV	0.8 GeV
Efficiency	95%	98%



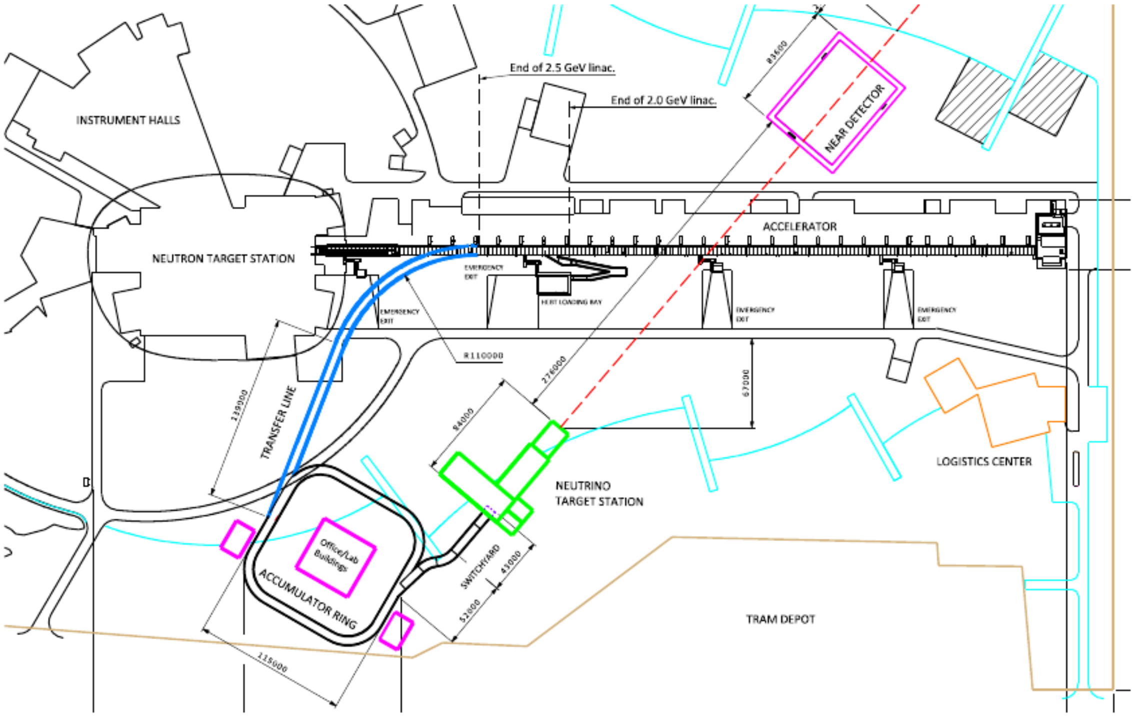
New SRF linac raises Booster injection energy, new LBNF beamline.

Fermilab Complex PIP-III

- At higher beam power the **booster** becomes the **bottleneck**
  - Protons at different momenta have same Time-of-Flight
  - No longitudinal focusing → unstable
  - Space charge losses
- Replace the booster
  - Linac to 8 GeV
    - Foil heating!
  - RCS
    - Magnet ramp time
  - Cost and risk…
- New target



A superbeam in Europe? ESSnuSB



- ESS will be the highest power proton source in the world
  - 2 MW at start of operation (2027)
  - Upgrade to 5 MW
  - Proton linac → ~3 ms pulse
- Need H^- ions to accumulate into ~ 1 μs pulse
  - Upgrade linac, interleaving H^- and H^+
  - “Ultimate” beam power

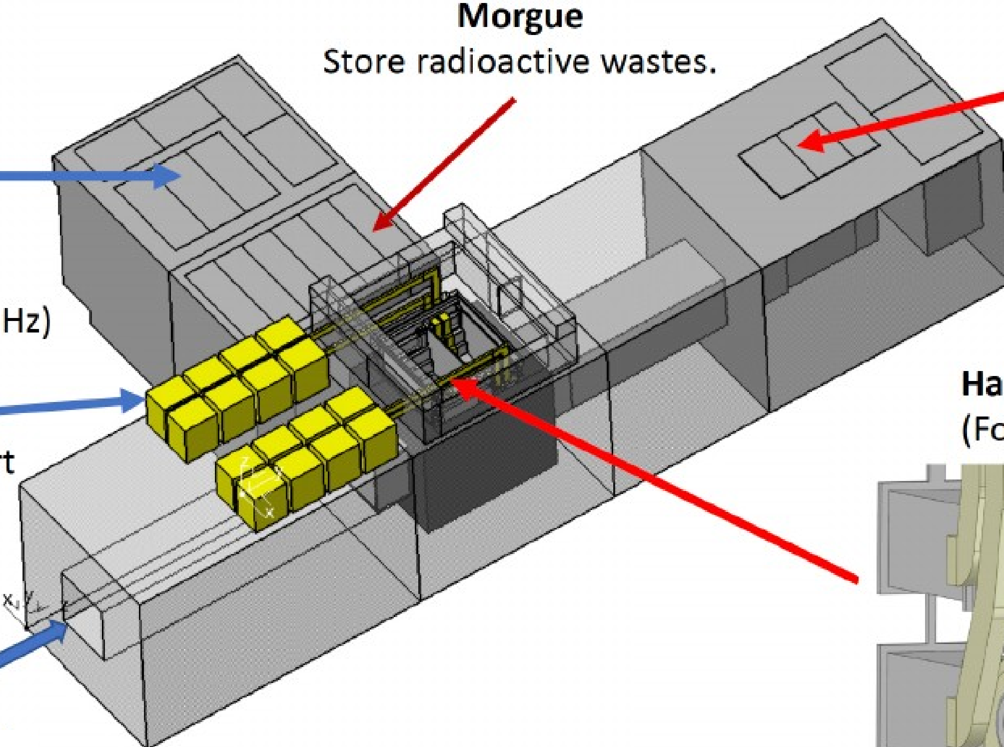
ESSnuSB

Hot Cell
- Able to manipulate/repair hadron collector.
- Work under radioactive environment.

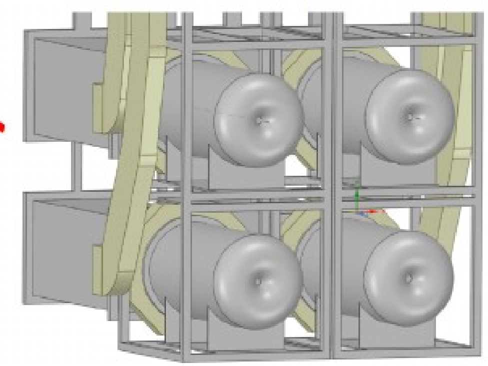
Power Supply Unit
- 16 modules (350 kA pulse/14 Hz)
- Located above the beam switchyard.
- Outside of the radioactive part of the facility.

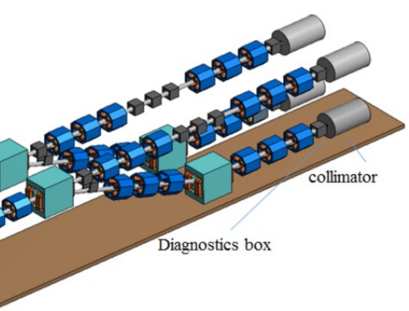
Morgue
Store radioactive wastes.

Beam Dump



Hadronic Collector
(Four Horn System)

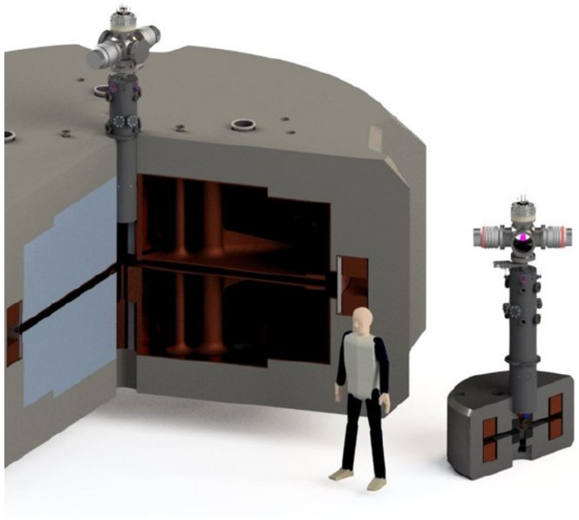


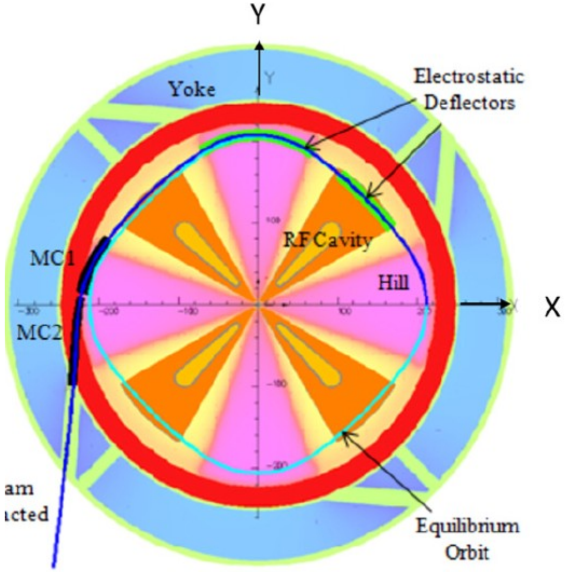


Target is the limit on beam power

IsoDAR

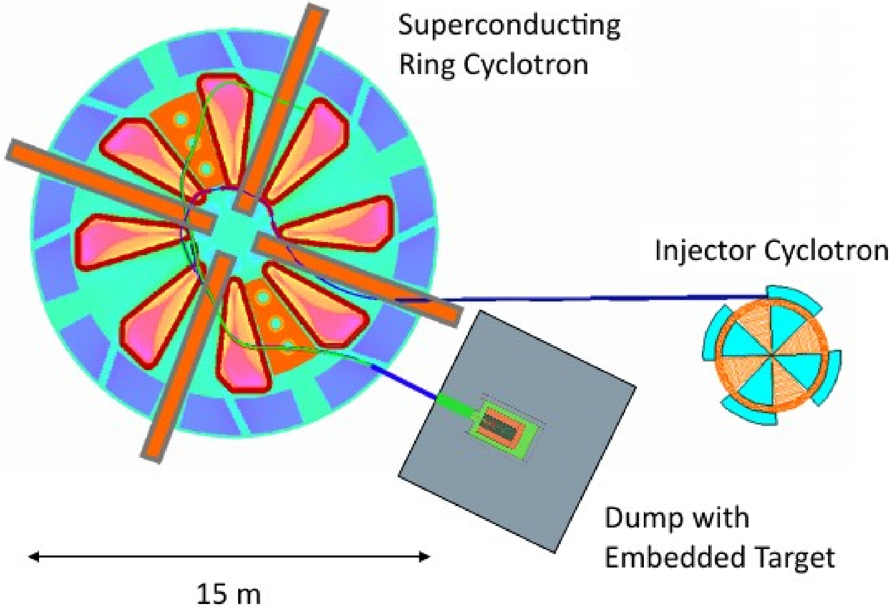
- Cyclotrons
  - e.g. PSI cyclotron (1.3 MW)
  - $f_{rf}=qB/2\pi m$
  - Independent of momentum
  - Non-relativistic only
- Current limits
  - Halo formation
  - Space charge
- IsoDAR
  - Accelerate H_2^+ → reduce space charge
  - Advanced injector → prebunching
  - Careful acceleration to 60 MeV/amu
- Neutrino production from β decay
  - Impact to ^{7}Li Target
  - Excite ^{8}Li → decay into Kamland detector
- Sterile neutrino searches possible



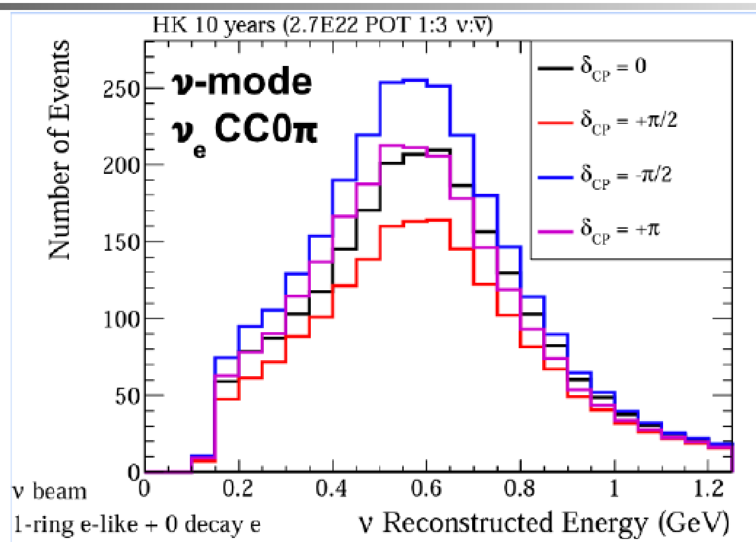


Daedalus

- Accelerate further to 800 MeV
  - Superconducting magnets
  - Extract by stripping foil
    - $H_2^+ \rightarrow H^+ + H^+$
- Pion production on target
  - Threshold for pion production ~400 MeV
  - “Conventional” pion production possible
  - Decay at rest
- Beam power comparable to JPARC
  - Pion yield comparable



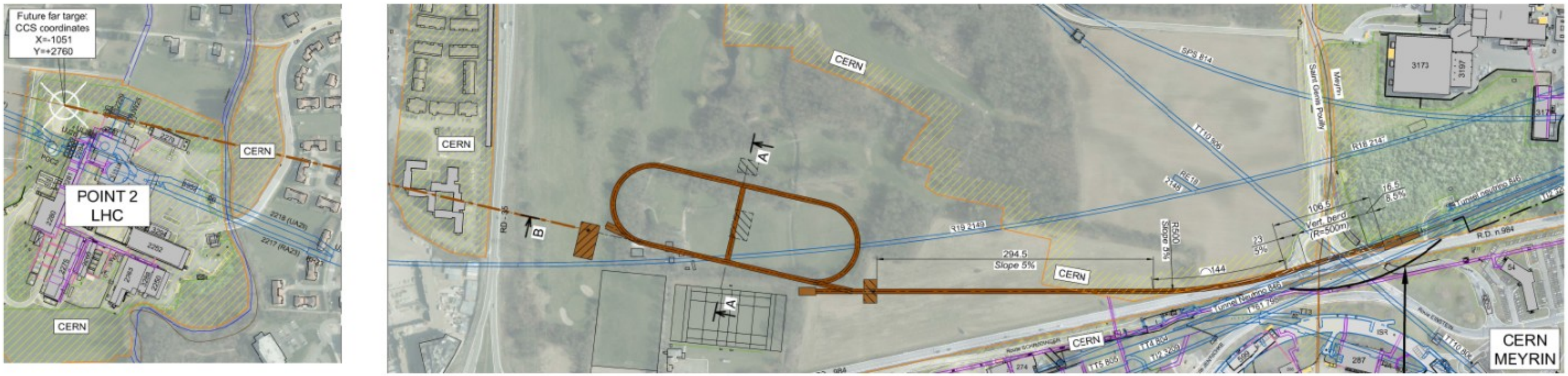
The systematics limit



- Increasing beam power helps with statistics
- Eventually systematic limitations dominate
  - Uncertainty in the beam
  - Uncertainty in the neutrino energy → neutrino interaction in the detector
- Use near detector to estimate neutrino interactions e.g. PRISM
  - Where is the limit? Is there another way?

nuSTORM facility

- What is the nuSTORM facility?

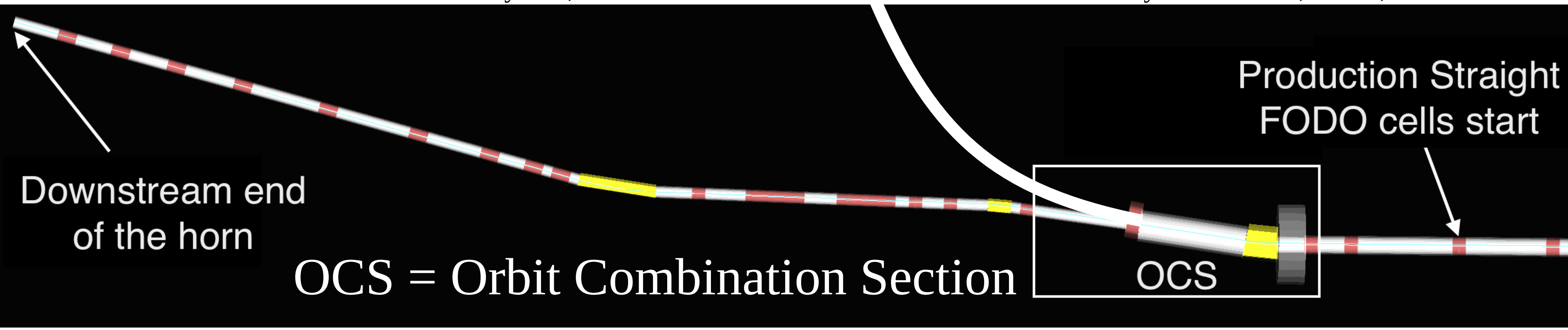


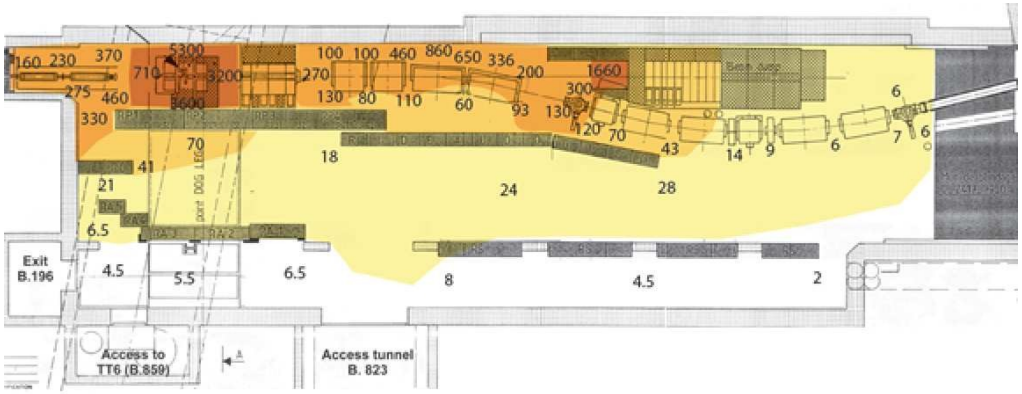
nuSTORM at CERN – Feasibility Study, Ahdida et al, CERN-PBC-REPORT-2019-003, 2020

- Main features
  - ~250 kW target station
  - Pion transport line
  - Stochastic muon capture into storage ring
  - Option for conventional FODO ring or high aperture FFA ring

Target and Pion Transport Line

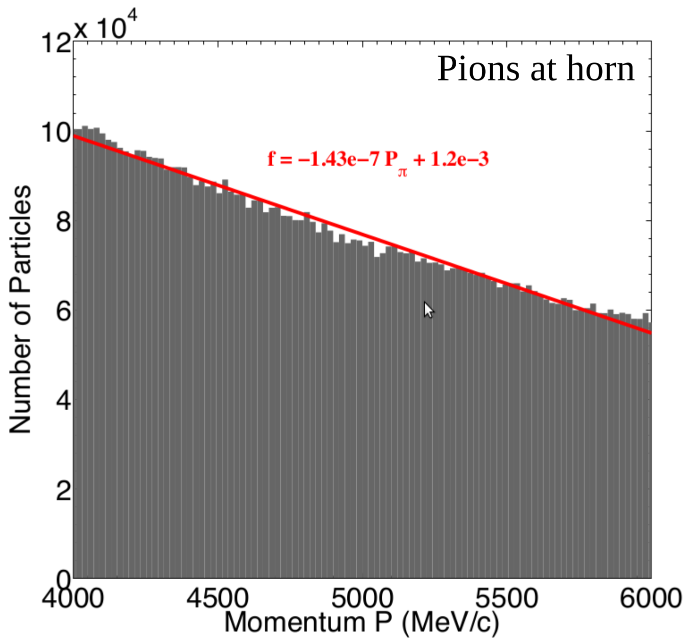
A. Liu et al, Design and Simulation of the nuSTORM Pion Beamline, NIM A, 2015
D. Adey et al, Overview of the Neutrinos from Stored Muons Facility – nuSTORM, JINST, 2017

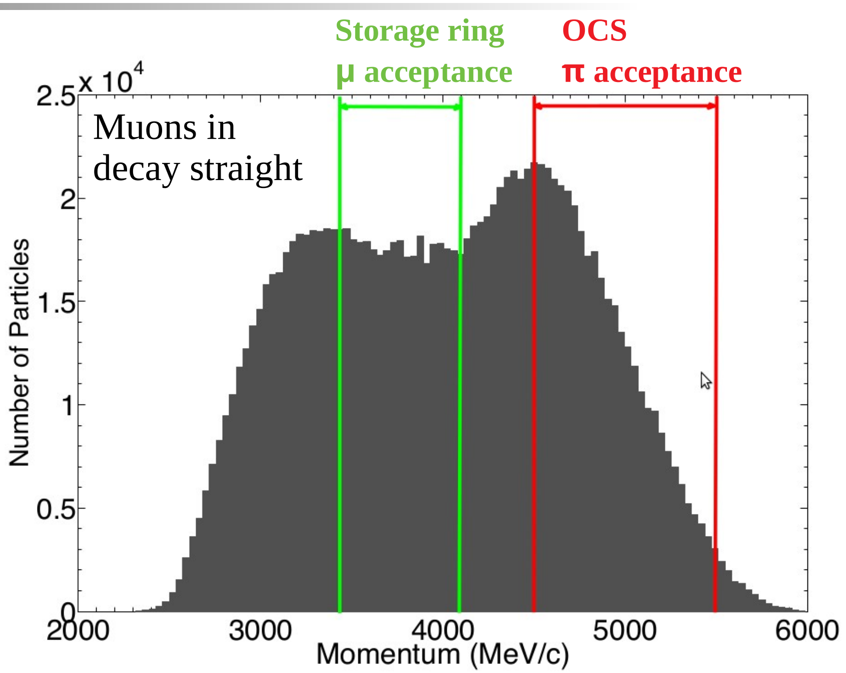




- Conventional 250 kW target horn
- Pion transport line
  - Proton beam dump
  - Momentum selection
  - Active handling

Stochastic Muon Capture

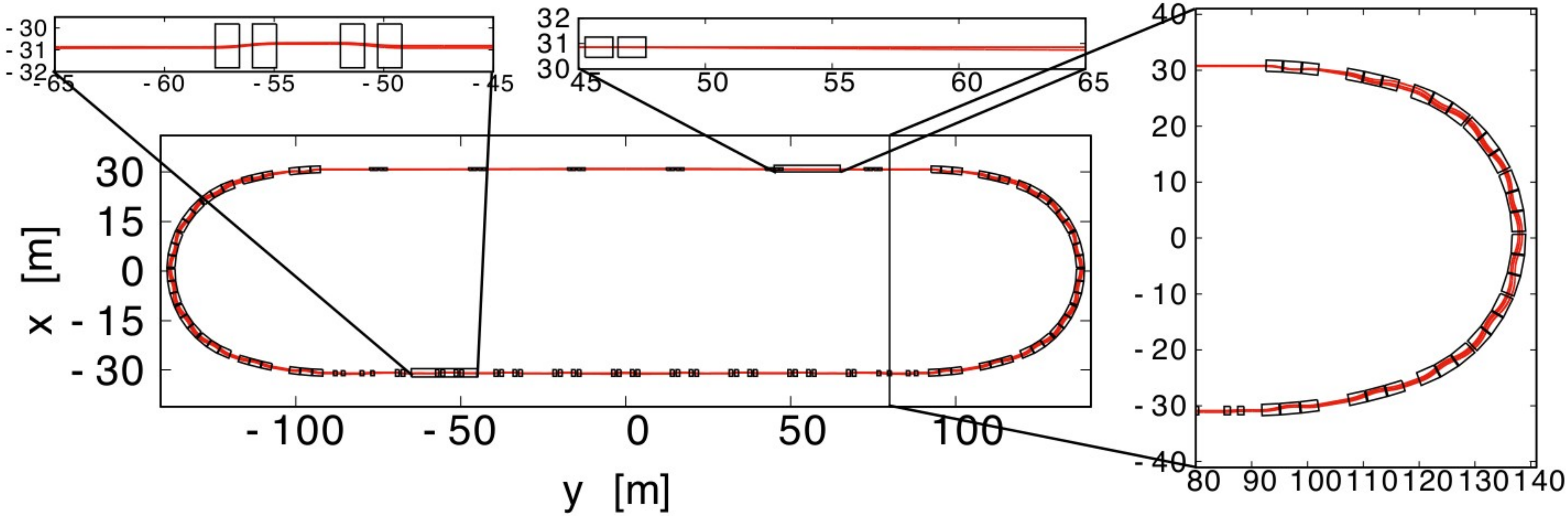




- Pions injected into the decay ring
- Capture muons that decay backwards in pion CoM frame
- Undecayed pions and forwards muons diverted into muon test area
  - Extraction line at end of first decay straight

Storage Ring

nuSTORM at CERN – Feasibility Study, Ahdida et al, CERN-PBC-REPORT-2019-003, 2020

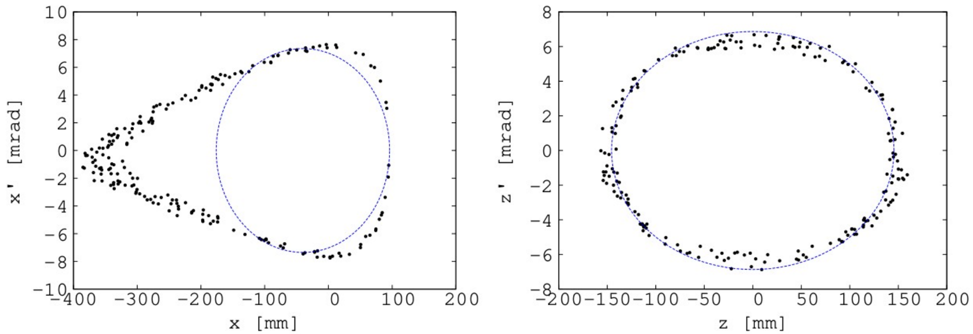


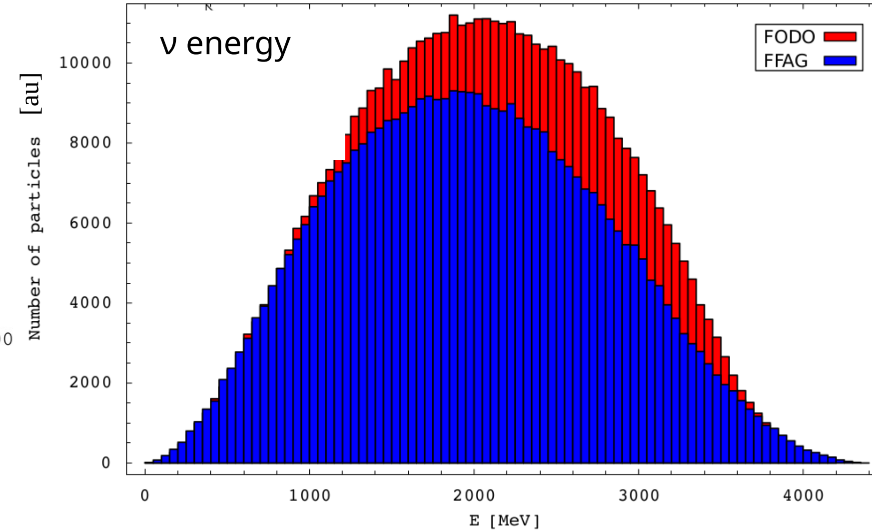
- Storage ring technologies:
  - Conventional FoDo ring
  - High acceptance FFA ring

Storage Ring

Lagrange et al, Racetrack FFAG muon decay ring for nuSTORM with triplet focusing, J. Inst 13 (2018)

μ phase space

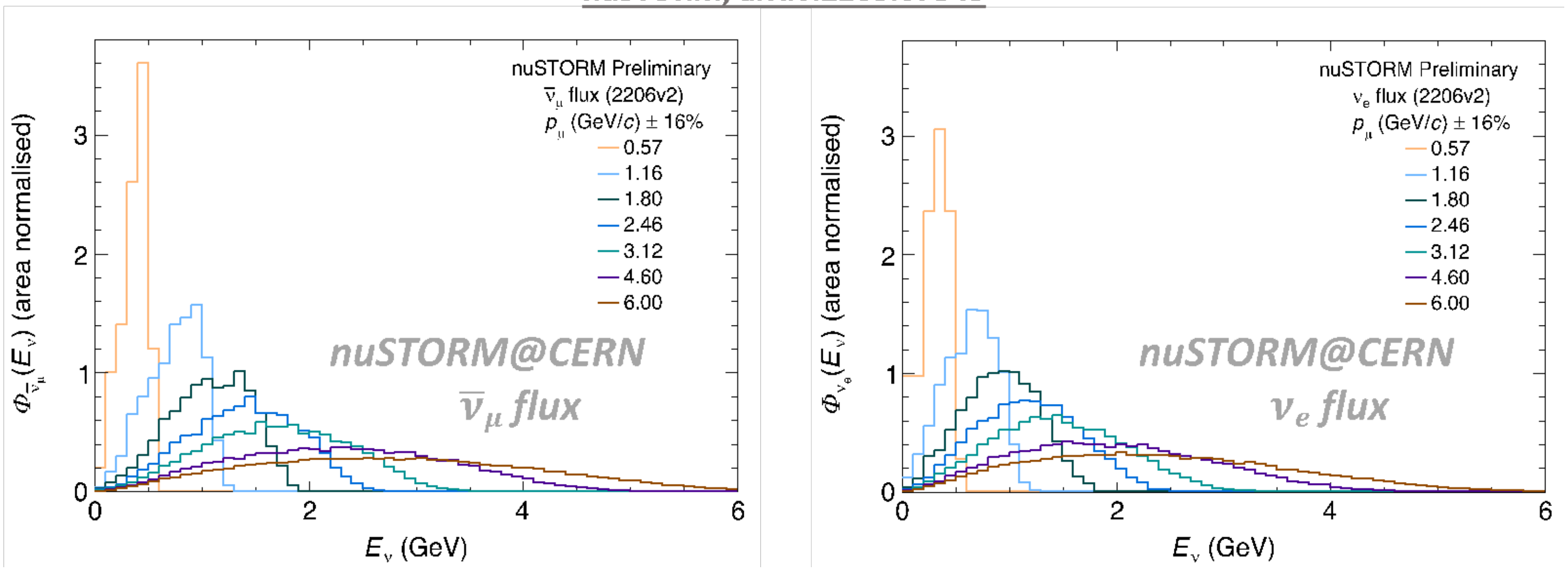




- Neutrinos momentum range up to 4 GeV
- Tunable ring energy under investigation
  - Optimisation so far has focused on 3.8 GeV μ
  - Higher energy would give more reach to cross section measurements
- Optimisation of storage ring to give improved neutrino flux
  - Hybrid FoDo straights with high acceptance FFA bends

Neutrino energy spectrum

nuSTORM, arXiv:2203.07545



- PRISM – move the detector off-axis → vary ν energy
- NuSTORM – tweak the storage ring energy → vary the ν energy
  - We know – to high precision – the neutrino beam parameters
  - Much more freedom to shape the neutrino beam

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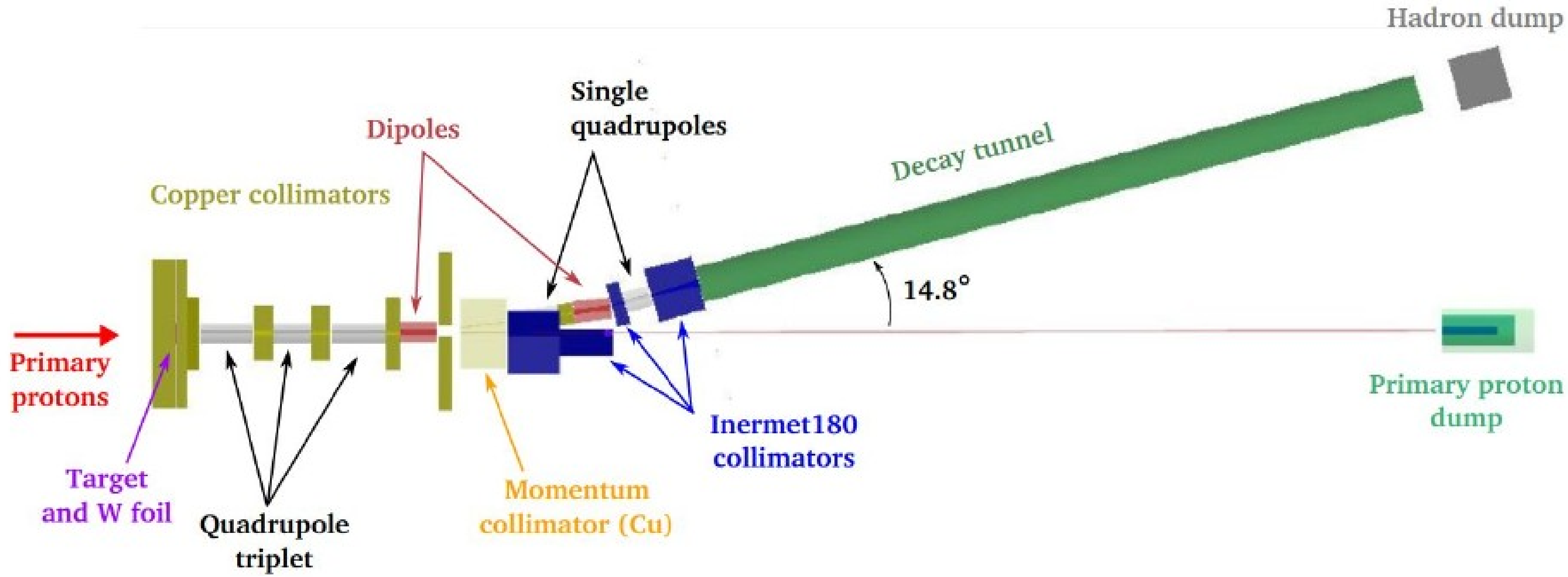
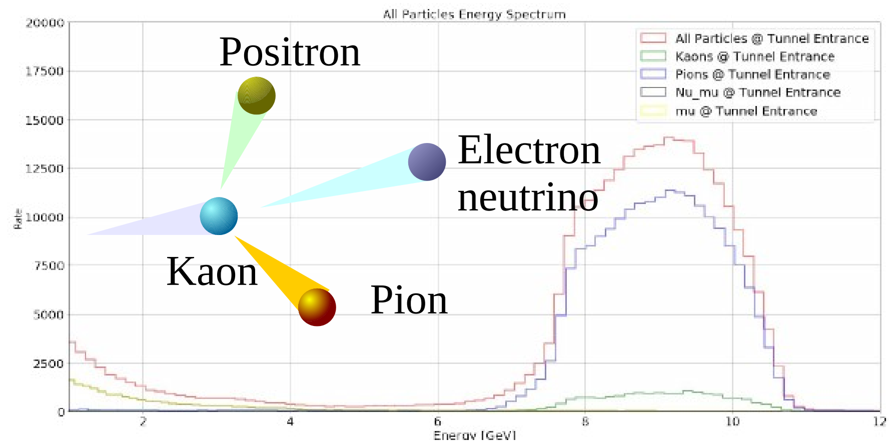
ENUBET

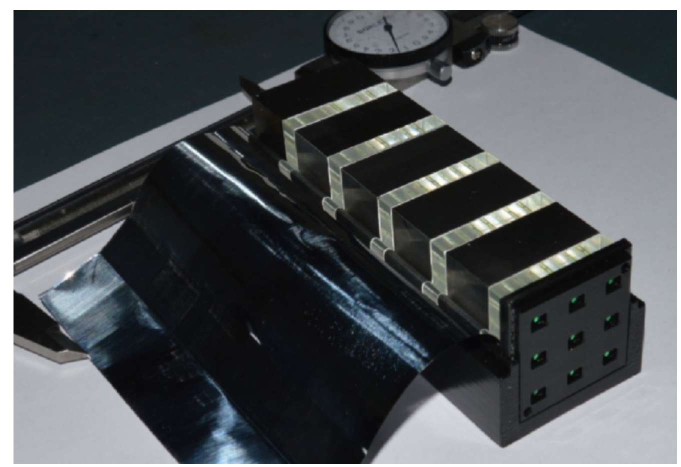


- Slowly extract protons to a target
- Produce pions and kaons
- Monitor decays of kaons in the decay tunnel
- Either pulsed extraction or CW extraction
  - 1 kaon every 70 ps or every 1 ns

ENUBET

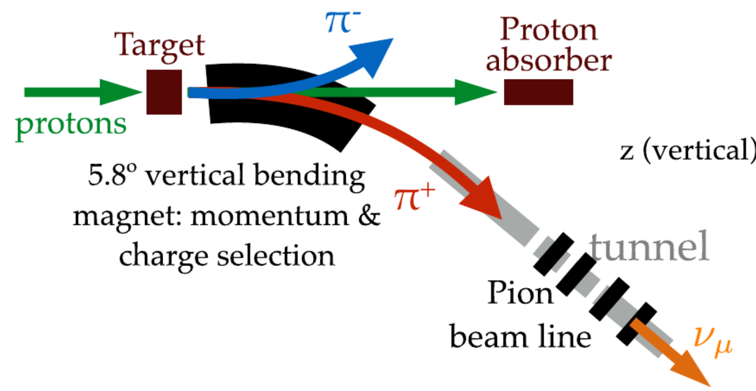
- Identify positrons from kaon decay
  - Understand ν_e rate and beam kinematics
  - Estimate pion rate → ν_μ
- Map individual kaons to neutrinos using time coincidence
  - Understand individual neutrino kinematics
  - Requires slow extraction

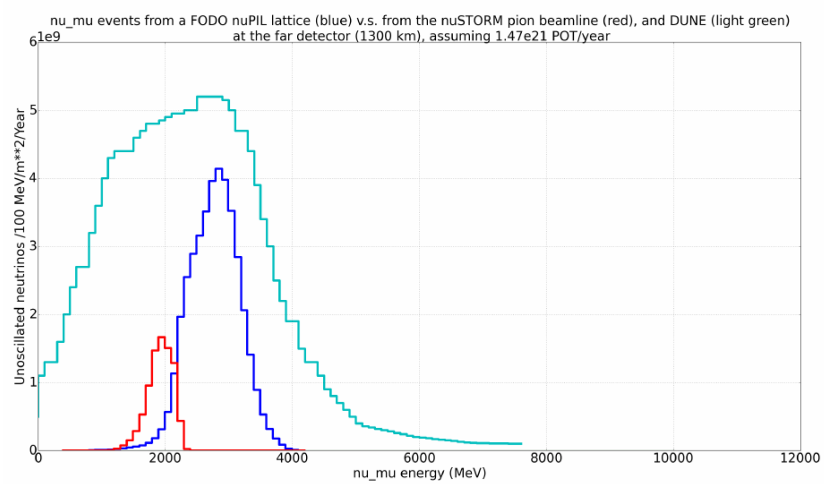




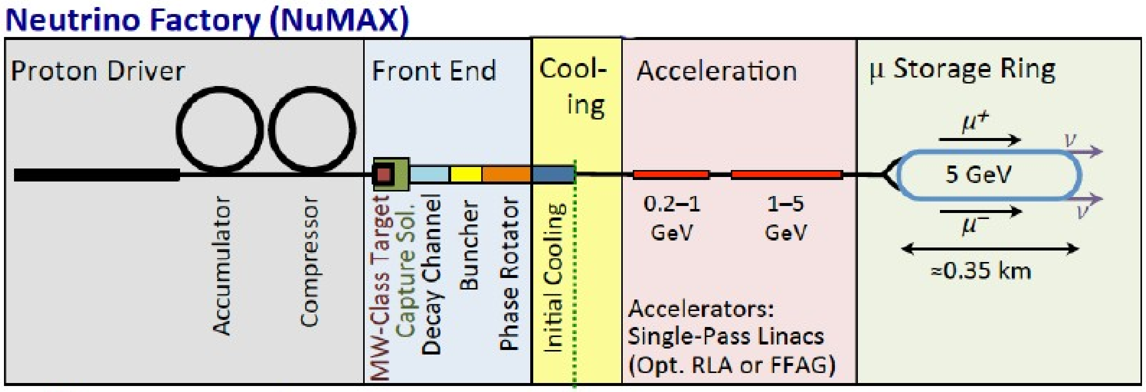
nuPIL

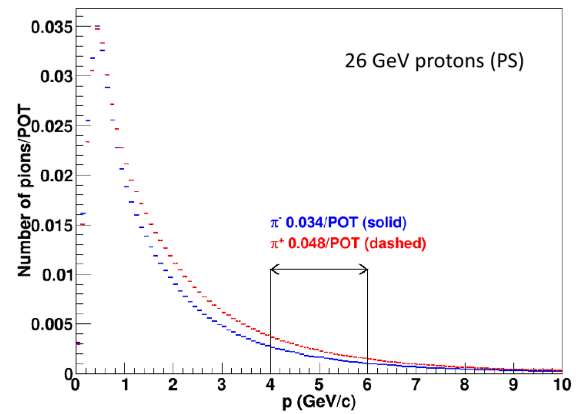
- Take ENUBET concept to production beam
- Add momentum selection chicane after the target
  - Remove kaons
  - Reduce required shielding
    - Protons are taken to dedicated beam dump
  - Pion charge/momentum selection





Neutrino Factory

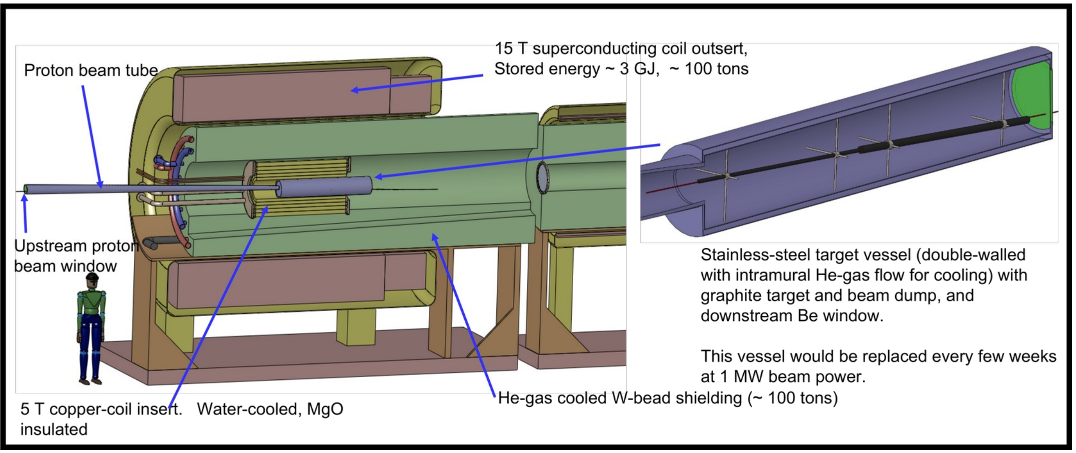


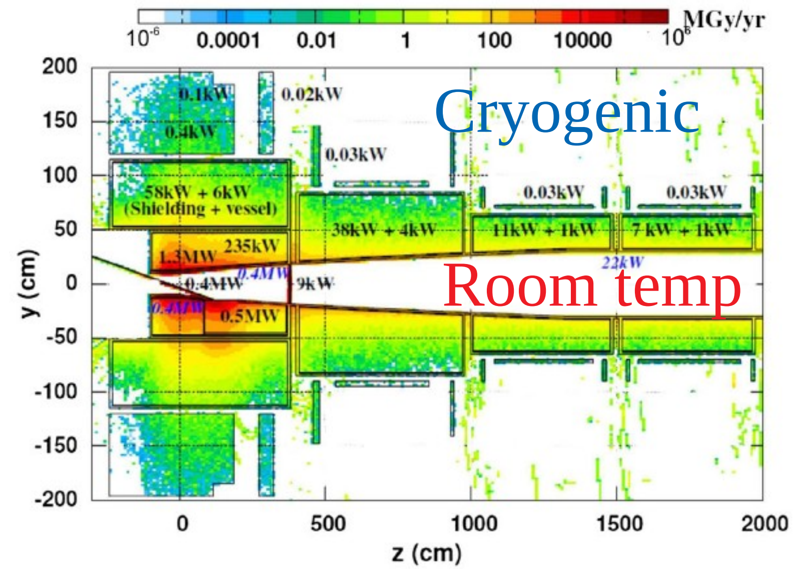


- How to improve precision further?
- Take the nuSTORM concept further
  - Enhanced muon capture
    - Use solenoid
  - Accelerate muons in a linac
  - Storage ring

Neutrino Factory - target

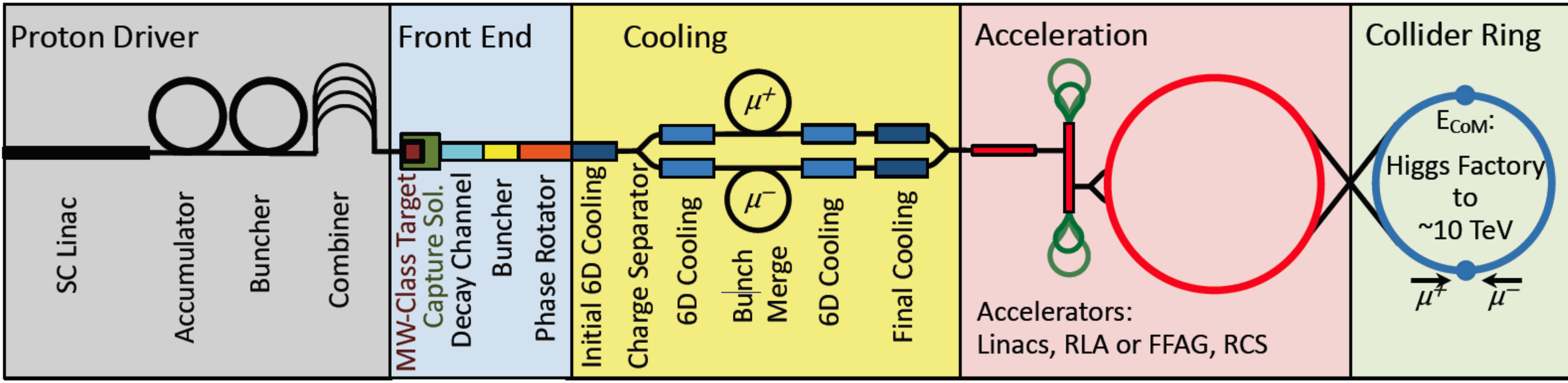
Neutrino factory, Bogomilov et al, PRSTAB 17 (2014)





- Proof-of-principle solenoids under study
  - Fusion machines operate in similar parameter space
- Targetry is the power limit for neutrino beams anyway
  - Need to do *something*
- 10-20 year R&D programme

Muon Collider Facility



- Proton based Muon Collider (MC) facility
  - Protons on target → pions, muons et al.
  - Transverse and longitudinal capture and cooling
  - Acceleration
  - Collider ring
- Challenges
  - High current radioactive beam passing active components
  - Containment of tertiary beam (i.e. muons)

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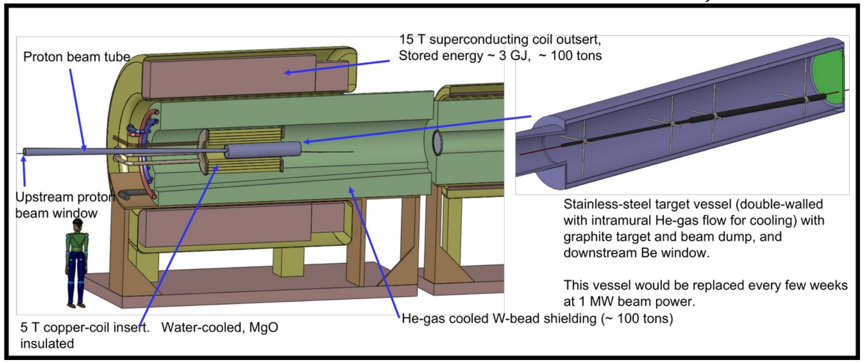
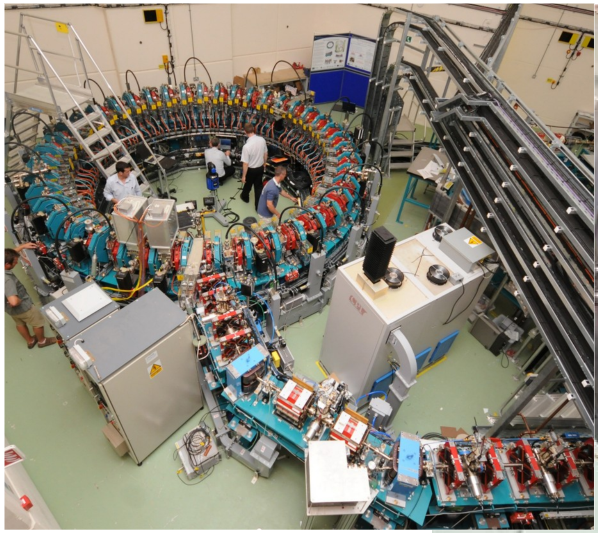
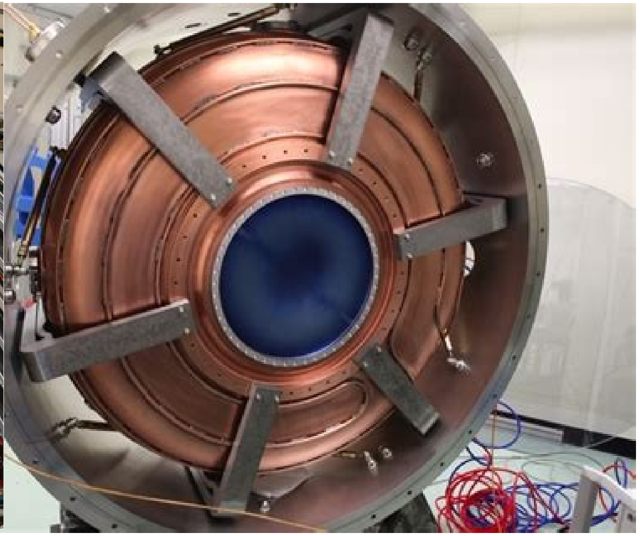
Technologies

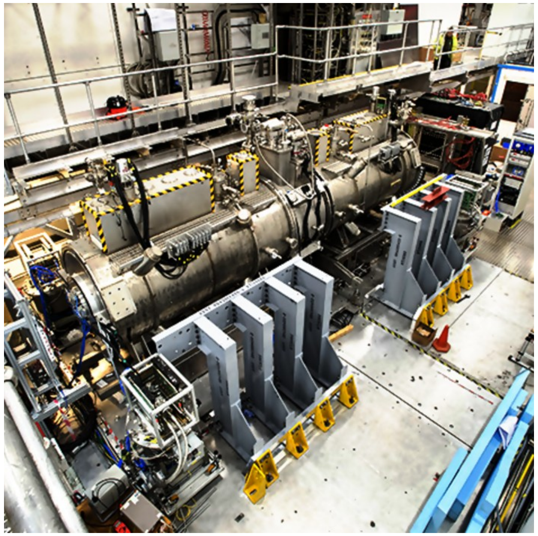
- High power dual-sign ($\mu^+\mu^-$) target
- Capture and ionisation cooling
- Acceleration and storage
  - Either conventional FODO-based Rapid Cycling Synchrotron
  - Or novel FFA

X. Ding et al, Carbon and Mercury target system for muon colliders and neutrino factories, IPAC16

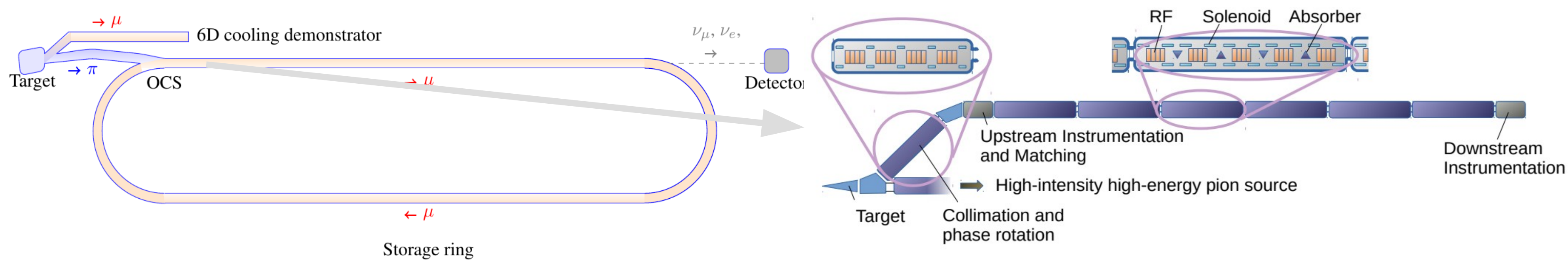


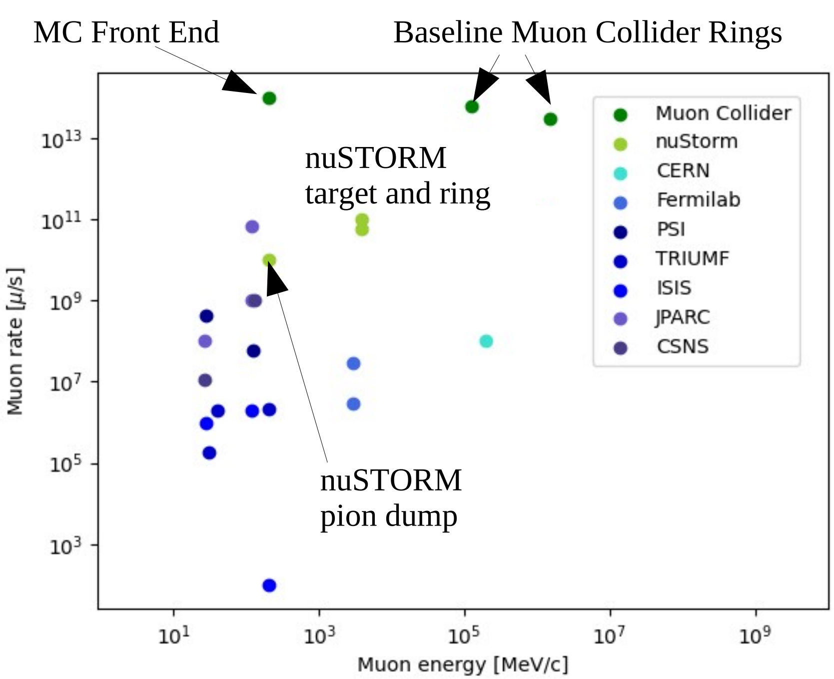






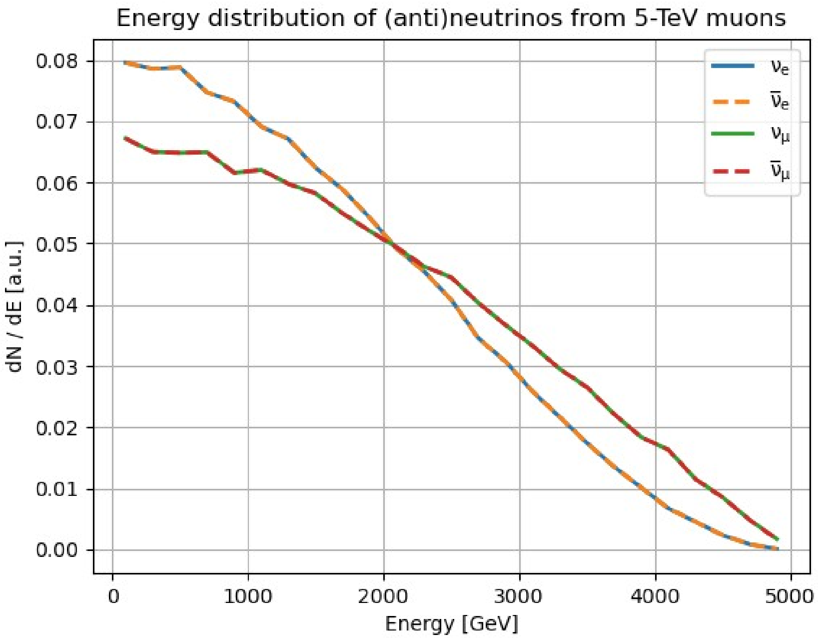
nuSTORM as a muon test bed

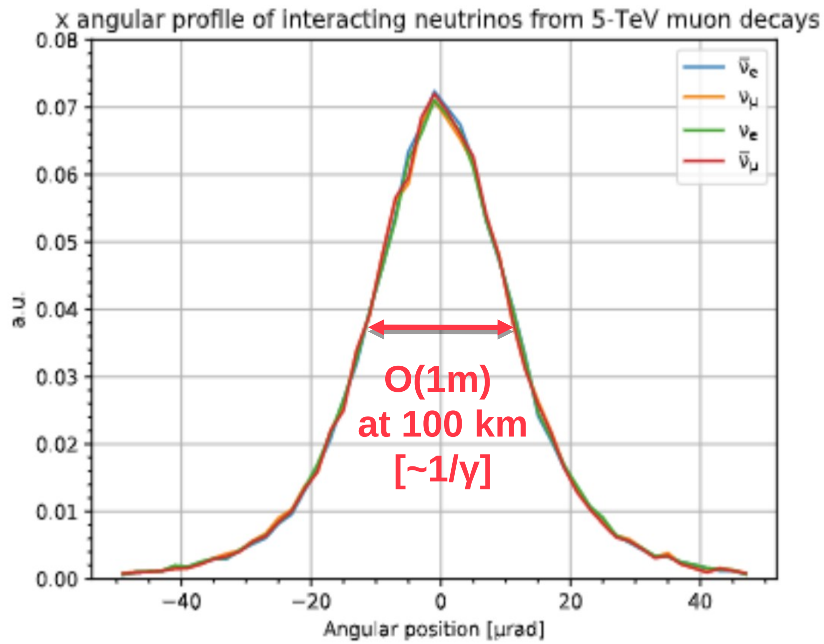




- NuSTORM would make an excellent test facility
  - One of the highest current high energy muon beams
- Target/irradiation test area
- Muon beam physics tests

Neutrinos from Muon Collider





- Muon collider **is** a neutrino factory
  - O(1e13) muons per second
  - Decay straight O(1e-3) of the ring
  - Neutrino beam is narrow

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Final thoughts

- Neutrino source is crucial part of the experiment
- Exciting current/next generation of superbeam experiments
  - Approaching the systematic limit
  - Target is probably the bottleneck
- To beat down the systematics, probably need novel source
  - Interesting ideas for source characterisation
  - Enables proper characterisation of the scattering
- To develop a new source technology
  - Lead times are longer than you think
  - Don’t end up without an upgrade path

Backups

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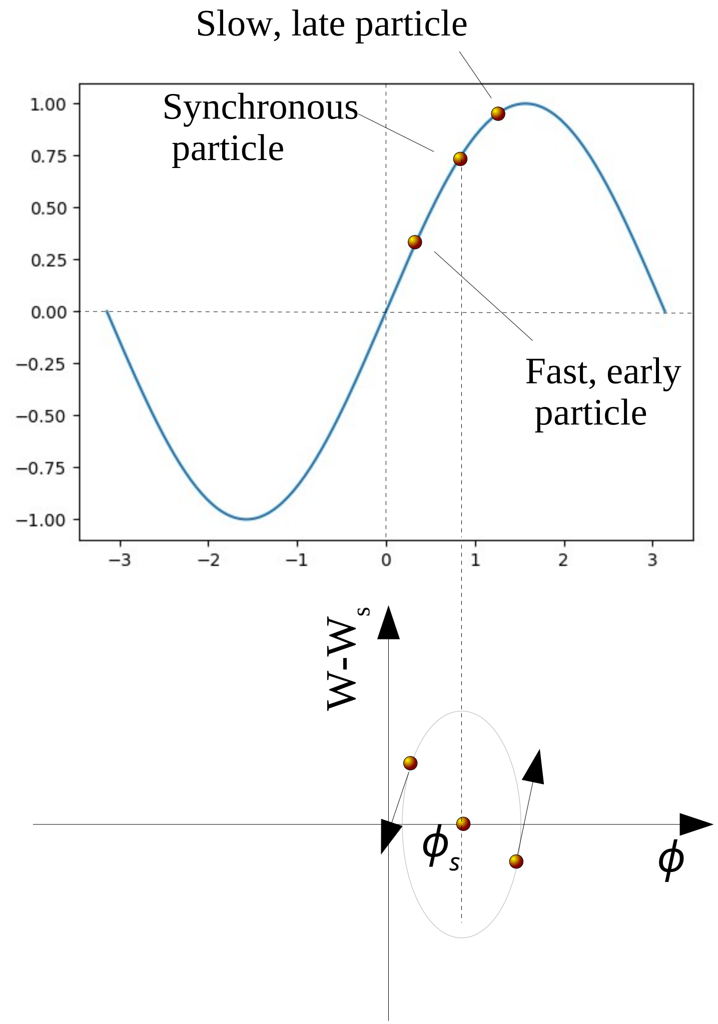
Phase stability

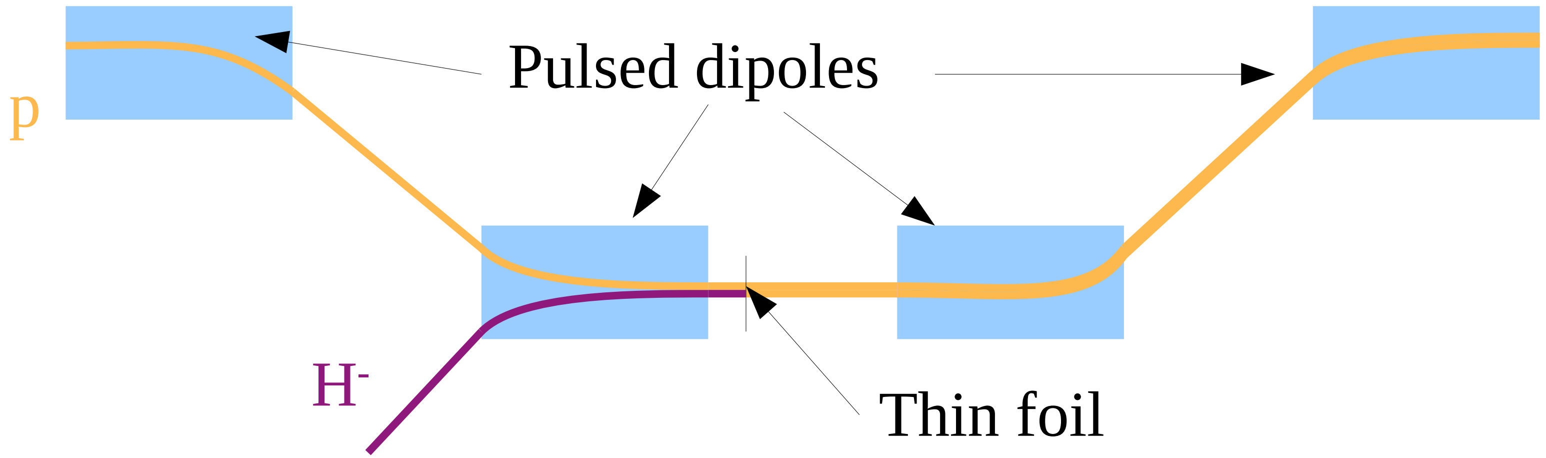
- Particle crossing at phase ϕ relative to synchronous particle

$$\delta W = q\,T\,g\,E_0 \sin(\phi + \phi_s)$$

- Particle arriving early
  - Fast
  - t negative
  - Gets smaller energy kick
  - Ends up relatively slower
- Particle arriving late
  - Slow
  - t positive
  - Gets bigger energy kick
  - Ends up relatively faster
- Phase stability!



Charge Exchange Injection



- High current → accumulate beam over many turns
  - Charge exchange injection of H^- ions through a thin foil
  - Foil removes electrons
  - Issues: Scattering and energy loss of protons in foil
- Painting of beam into synchtron acceptance using fast “bumper” magnets
  - Move recirculating beam around in horizontal and vertical phase space
  - Fill a much larger acceptance