High Intensity Neutrino Beams

A.K.Ichiawa, Kyoto University

09:00 - 11:30

Present Long-Baseline Neutrino Oscillation Experiments from Accelerators

Convener: François Vannucci (University of Paris Diderot)

09:00 **Status of NOvA** *20′*
Speaker: Andrew Norman (Fermilab)

09:20 **Results from ICARUS** *20′*
Speaker: Christian Farnese (INFN Padua)

09:40 **Results from OPERA** *20′*
Speaker: Stefano Dusini (INFN Padua)

10:00 **Results from MINOS/MINOS+** *30′*
Speaker: Alex Sousa (University of Cincinnati)

10:30 **Coffee Break** *30′*

11:00 **Results from T2K** *30′*
Speaker: Chris Walter (Duke University)

14:30 - 15:20

Future Long-Baseline Neutrino Oscillations from Accelerators (part 1)

Convener: Stanley Wojcicki (Stanford University)

14:30 **High Intensity Neutrino Beams** *25′*
Speaker: Atsuko Ichikawa (Kyoto University)

14:55 **Neutrino Factories** *25′*
Speaker: Paul Soler (Universtiy of Glasgow)
Material: Slides

15:20 - 15:50 Tea Break

15:50 - 17:30

Future Long-Baseline Neutrino Oscillations from Accelerators (part 2)

Convener: Ettore Fiorini, (University of Milan Bicocca)

15:50 **Future Long-Baseline Neutrino Oscillations: View from Asia** *25′*
Speaker: Yoshinari Hayato (The University of Tokyo)

16:15 **Future Long-Baseline Neutrino Oscillations: View from North America** *2*
Speaker: Robert Wilson (Colorado State University)

16:40 **Future Long-Baseline Neutrino Oscillations: View from Europe** *25′*
Speaker: Thomas Patzak (University of Paris Diderot)

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Reality

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Slides

How to achieve the volume?

...Yoshinari Hayato (The University of Tokyo)

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Slides

Speake

16:40 Future

Speake

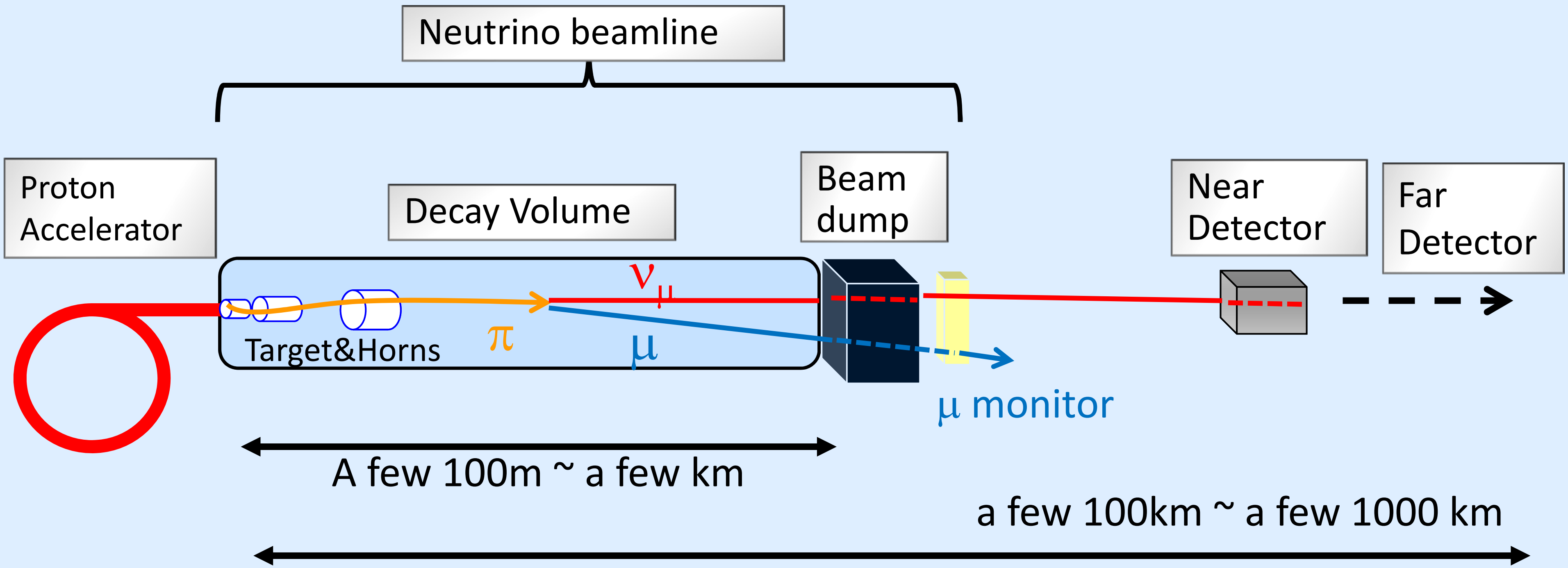
How to achieve the volume?

Won't talk about the taste (=physics sensitivity)

Contents

- focus on ‘conventional superbeam’: ν_μ beam from meson decay
- focus on on-going or future project
  - ✓ Can’t cover great achievement by FNAL Booster ν and CERN CNGS
- Talk about challenges in
  - ✓ High intensity Accelerator
  - ✓ ν beam facility

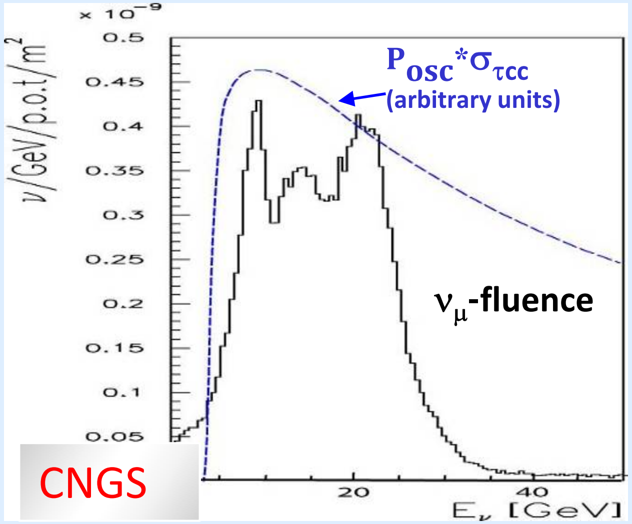
Components of the Long Baseline Neutrino Experiment

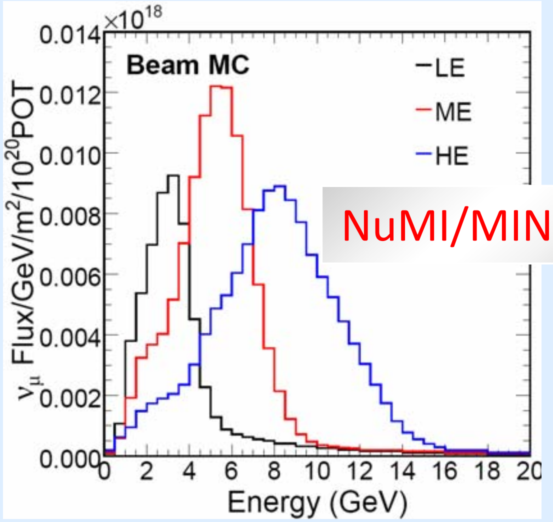


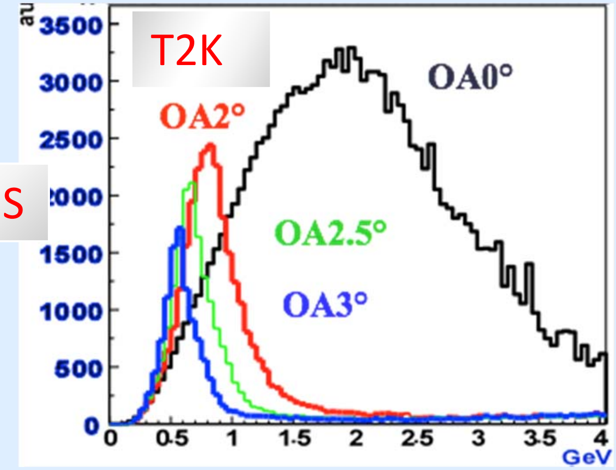
Example:
~1ν/cm²/s at T2K Far detector(295km away)
(@750kW proton beam power)
among which 10^{-10} interact.

Feature of Superbeam ν flux

- Wide band, but can be narrowed by
  - target-horn distance (NuMI)
  - off-axis method (T2K, NOvA)
- ~10% uncertainty with p-nucleus hadron production measurement (e.g. NA61, MIPP)+beamline error
- a few % ν_e contamination from the decay of Kaons and muons
- ν beam or anti-ν beam depending on the horn current polarity
  - Yield difference is modest (~10%), but ν-nucleus cross section is different:$\sigma_{\nu}:\sigma_{\bar{\nu}}$=2~3:1







Proton Machine Intensity Frontier

	Energy	Power		
		Current	Planed	Future
J-PARC/KEK	30 GeV	~0.25MW T2K	0.75MW T2K	~2MW
FNAL	120 GeV	~0.36MW MINOS	0.7MW NOvA	~2MW LBNE/LBNF
CERN	400 GeV/c	0.3MW~0.5MW OPERA/ICARUS	(0.2MW for short baseline: CENF)	0.7~2MW (CN2PY)

BEAM POWER

= (Energy) x (#Protons-per-pulse) x (acceleration-rep-rate)

Achieved = < 0.5 MW

Desired > 1 MW

What limits the intensity of proton accelerator?

Space Charge Effect

cause blow up of beam
Larger at lower energy
effect increase **non- linearly** with beam intensity

There can be many reasons. But here, let's highlight Space Charge Effect

Space charge effect $\rightarrow$ beam loss $\rightarrow$ problem on shielding's and maintenance

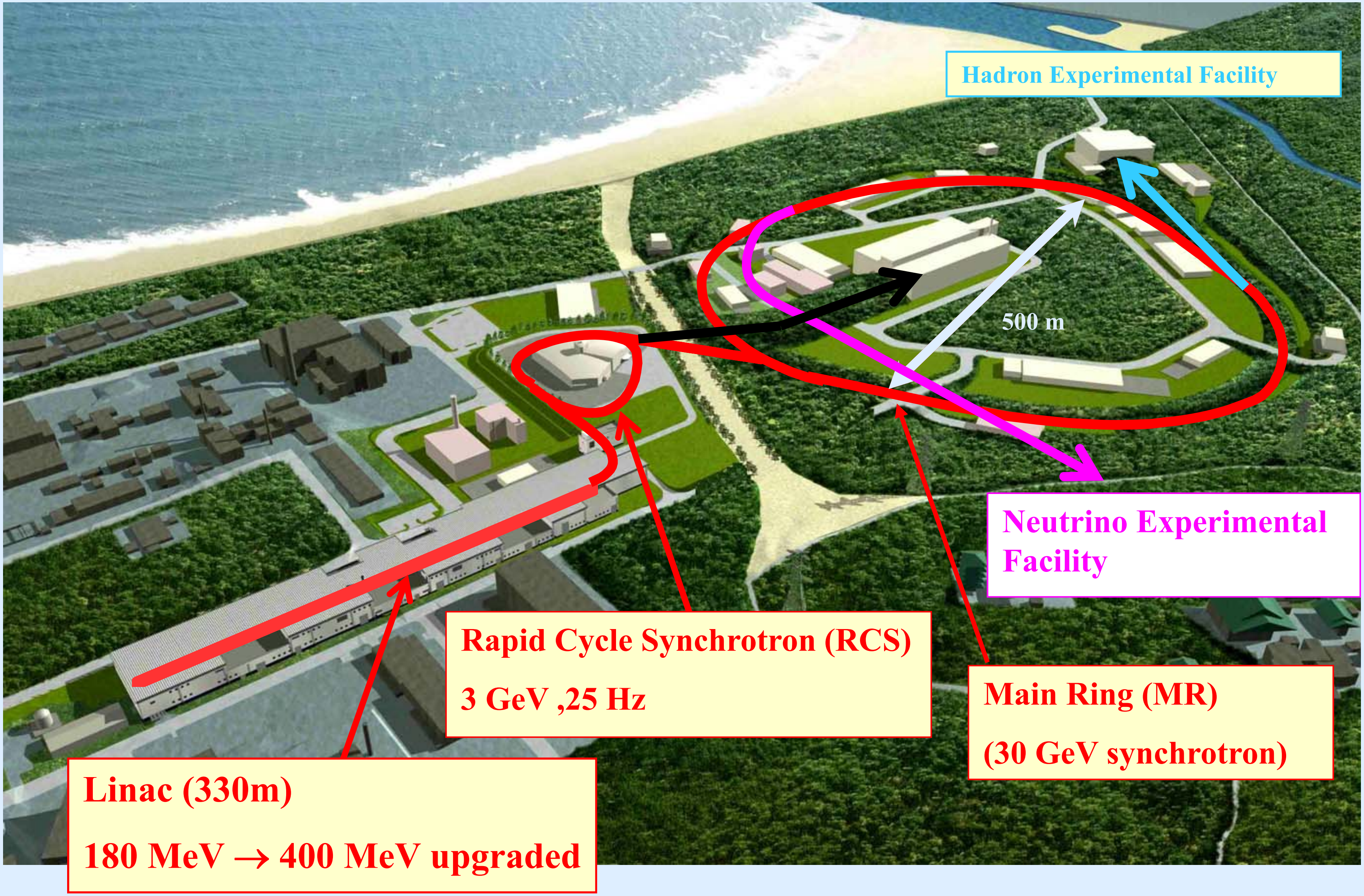
Bottle-neck of existing facility

- NuMI : Injection at booster, J-PARC: Injection at Main Ring,   see later slides

Possible solutions

- Increase repetition rate , not increasing protons-per-pulse(PPP)
- Increase injection energy
- use Linac = one path accelerator (, but difficult to go to high energy)

J-PARC


Hadron Experimental Facility
500 m
Neutrino Experimental Facility
Rapid Cycle Synchrotron (RCS)
3 GeV ,25 Hz
Main Ring (MR)
(30 GeV synchrotron)
Linac (330m)
180 MeV → 400 MeV upgraded

J-PARC power upgrade plan

JFY	2013	2014	2015	2016	2017
power(kW)	200-240	200-300	→	→	750
	Linac 180MeV→400MeV	Linac Front-end current 30mA→50mA	Main Ring rep. cycle 2.5s→1.3s w/ new Magnet Power supplies and new high Impedance RF		

- ➢ Current bottleneck

  beam loss at injection to MR

  → can't increase ppp (already world-highest)

  → go higher rep. rate → 0.75 MW

  ✓ New RF R&D completed

  ✓ Small prototype of 1 Hz PS is working.

- ➢ Long-term possibility under study

  ✓ New 8 GeV Booster

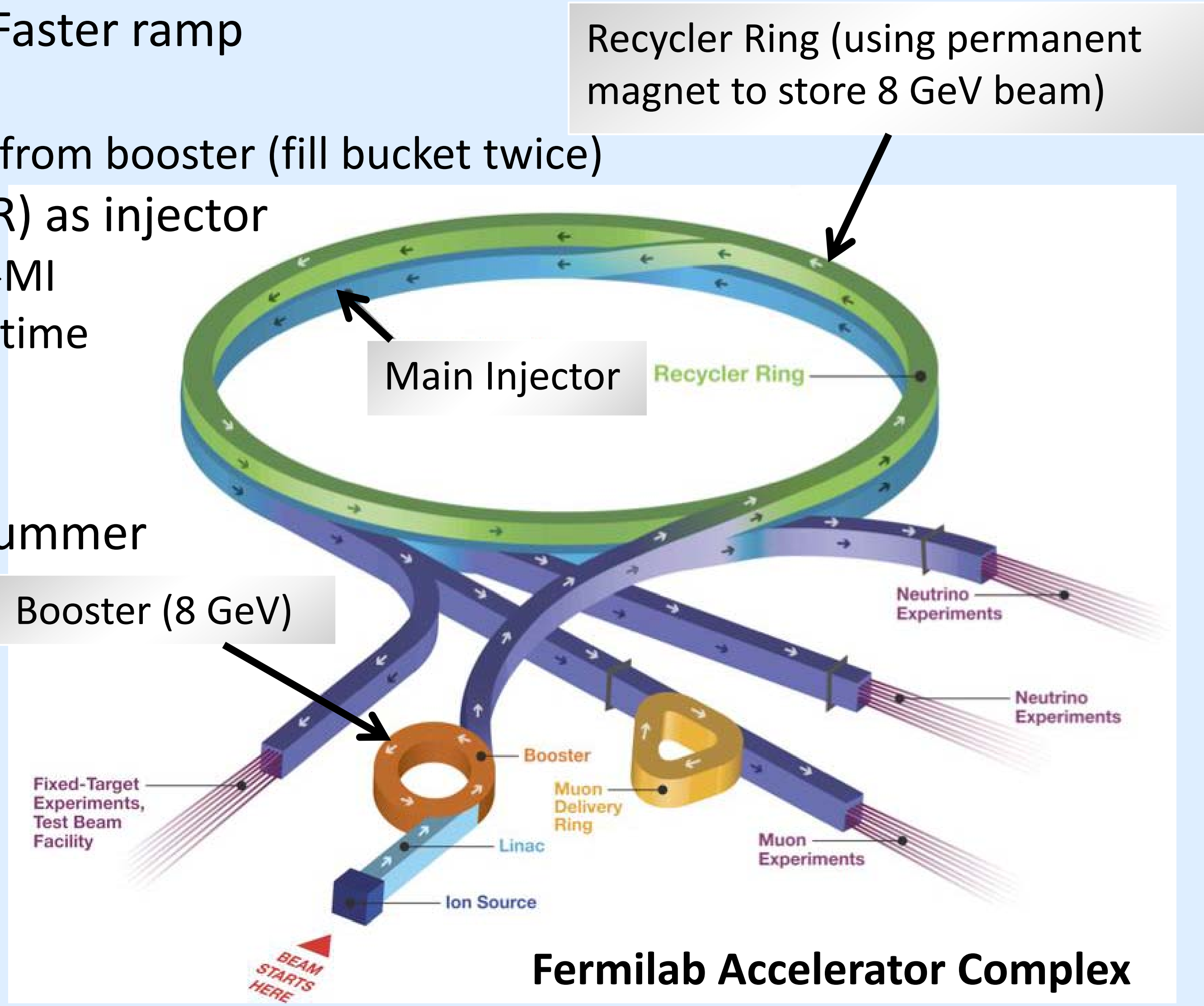
  ✓ Target > 1~3MW

New high impedance RF

FNAL power present upgrade plan

Booster is the current primary bottleneck.

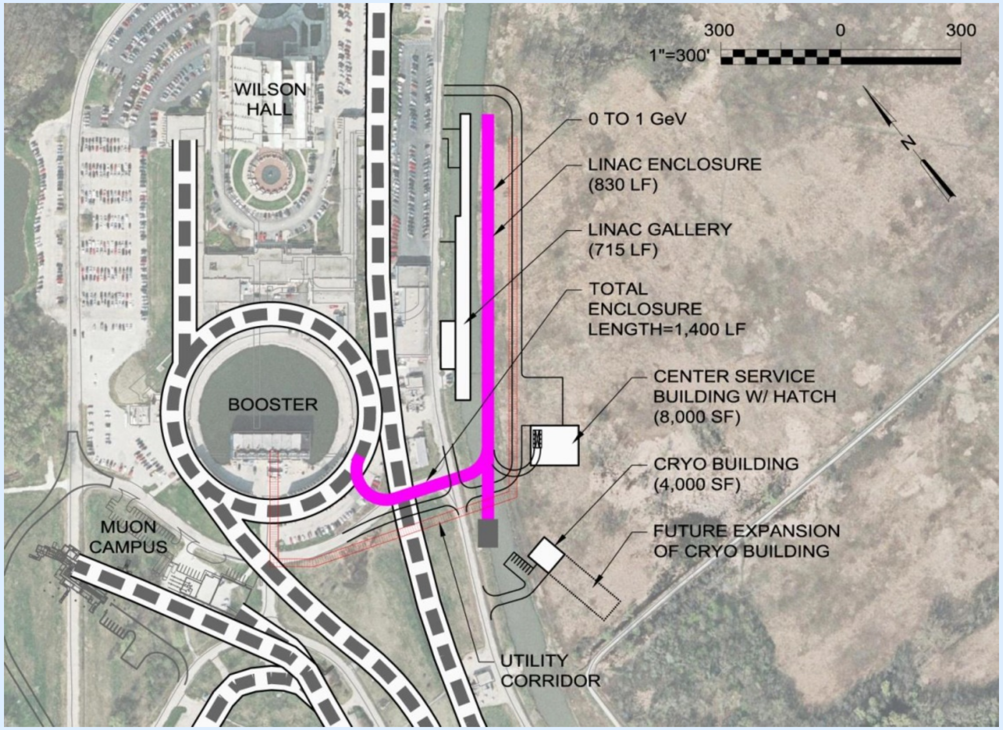
- Main Injector (MI) Faster ramp
- Slip stack
  - ✓ Put two batches from booster (fill bucket twice)
- Use recycler ring(RR) as injector
  - ✓ booster $\rightarrow$ RR $\rightarrow$MI
  - ✓ reduce injection time
- 280 kW $\rightarrow$350kW $\rightarrow$450kW by the end of this summer
- 700 kW in 2015



Fermilab Accelerator Complex

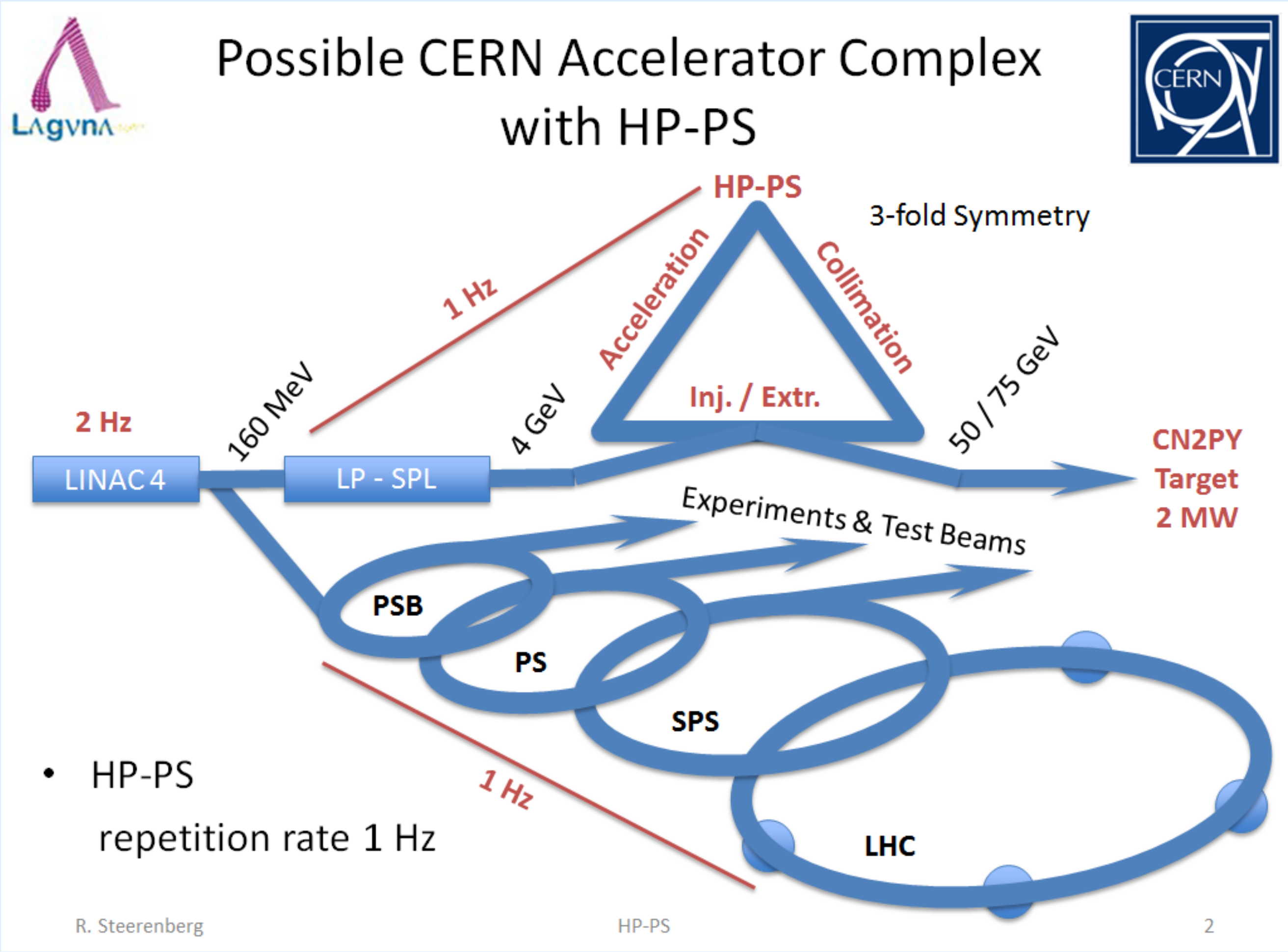
FNAL future power upgrade plan
-Proton Improvement Plan(PIP) II-

- goal > 1MW (~2025)
- Linac 400 MeV →New 800 MeV super conducting pulsed linac
- Higher energy injection to Booster will reduce beam loss

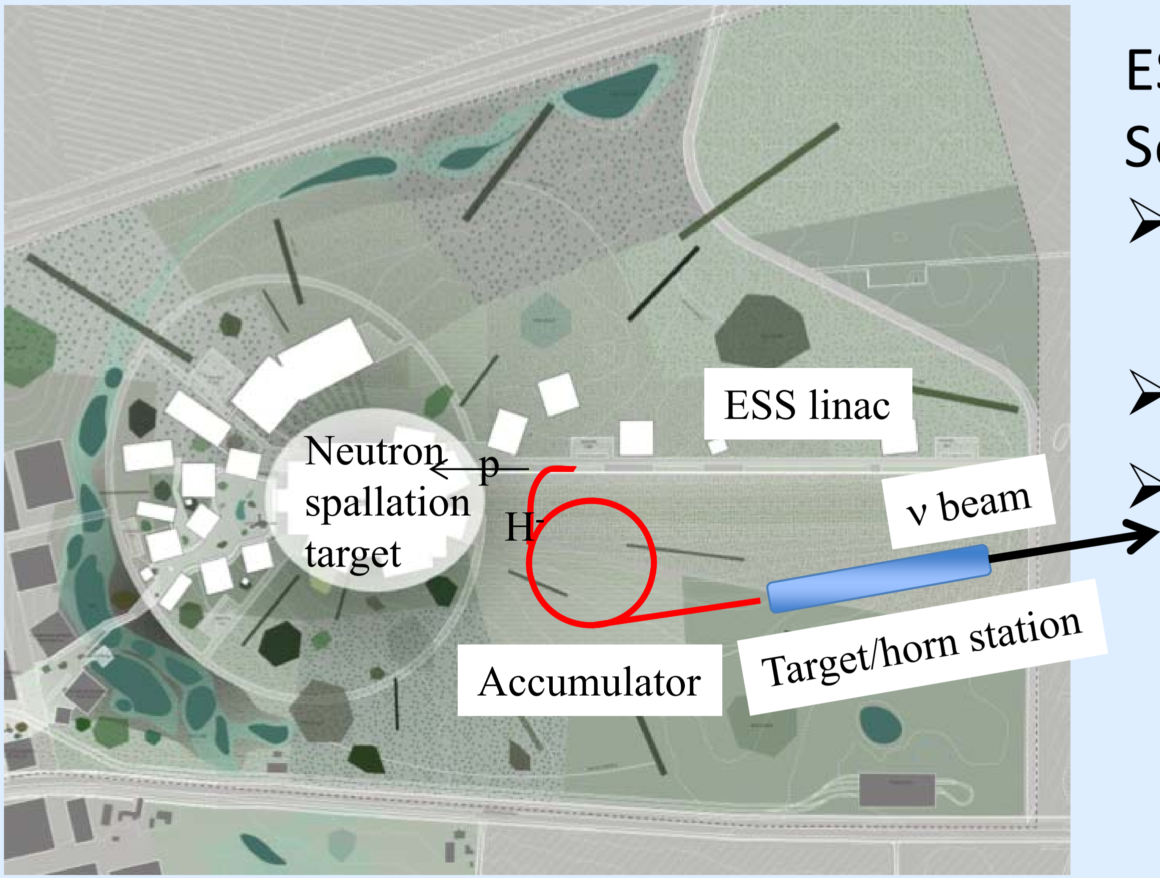


CN2PY (CERN-to-Pyhasalmi)

- Initial beam from SPS(+) 400 GeV/750 kW
- Phase II: LP-SPL(Superconducting Linac) to HP-PS 50 GeV/2 MW



ESS 2 GeV linac as proton driver for a neutrino Super Beam (proposal)



ESS: European Spallation Source in Sweden

- **2 GeV 5 MW** superconduction linac
- First beams 2019
- **Full power 2022**

Proposal

rise frequency from 14 Hz to 28 Hz.

(duty 4.0% → 8.0%, RF power 5 MW → 10MW)

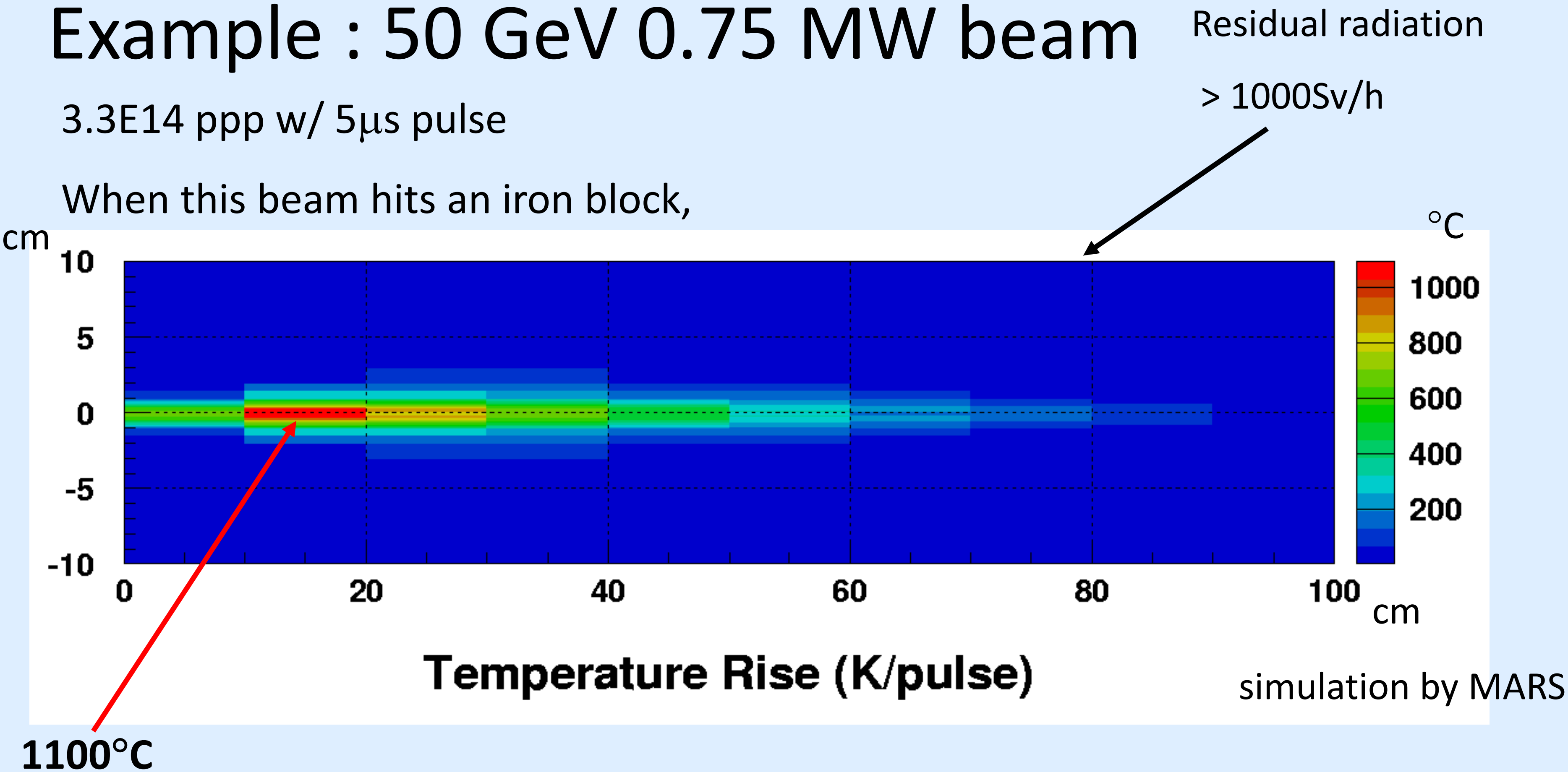
What limits the intensity of beamline?

- ✓ Beam loss (same as accelerator)
- ✓ Thermal shock
- ✓ Radiation damage
- ✓ Cooling power
- ✓ Dirty product in air(NOx) and water(Tritium,H_2,Acid)
- ✓ Radiation shield

Example : 50 GeV 0.75 MW beam

3.3E14 ppp w/ 5μs pulse

When this beam hits an iron block,



(cf. melting point 1536°C)

- ✓ Material heavier than iron would melt.
- ✓ Thermal shock stress

  (cf. strength ~300 MPa)

  Material heavier than Ti might be destroyed.
- ✓ Target and beam window have to withstand the thermal shock.

Radiation damage

- Any high molecular material cannot withstand. Only metal and ceramics.
- 25% of carbon atom in target will be displaced by beam hit in 1 year T2K 0.75MW operation.
- The material properties are changed.
  - ✓ Dimension change

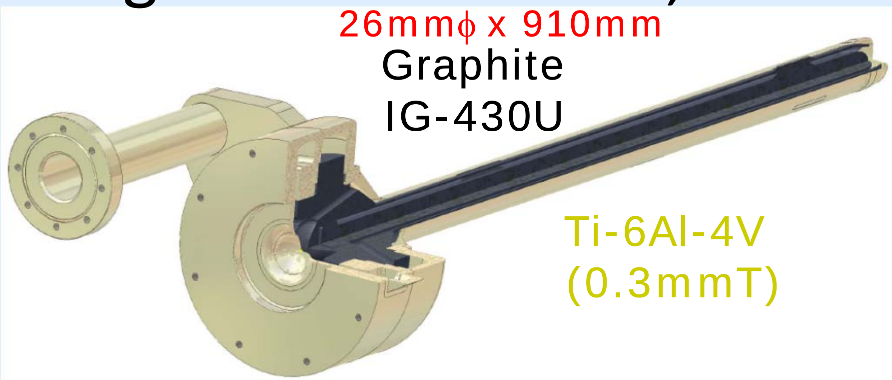
    shrinkage by ~5mm in length in 5 years at max for 90cm long target
  - ✓ Degradation of thermal conductivity

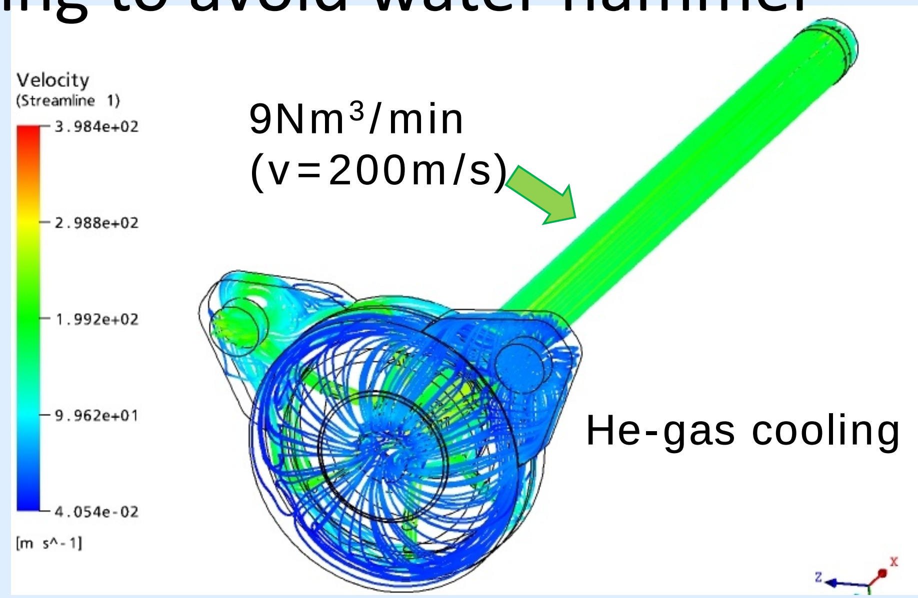
    decreased by 97% @ 200 ° C, 70~80% @ 400 ° C

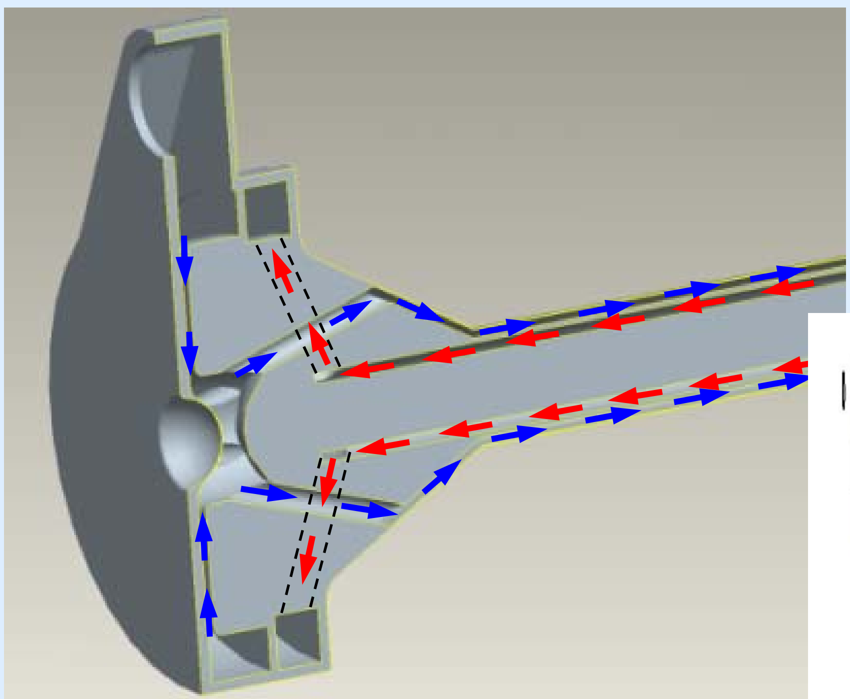
PSI fluence 10^{22} p/cm2

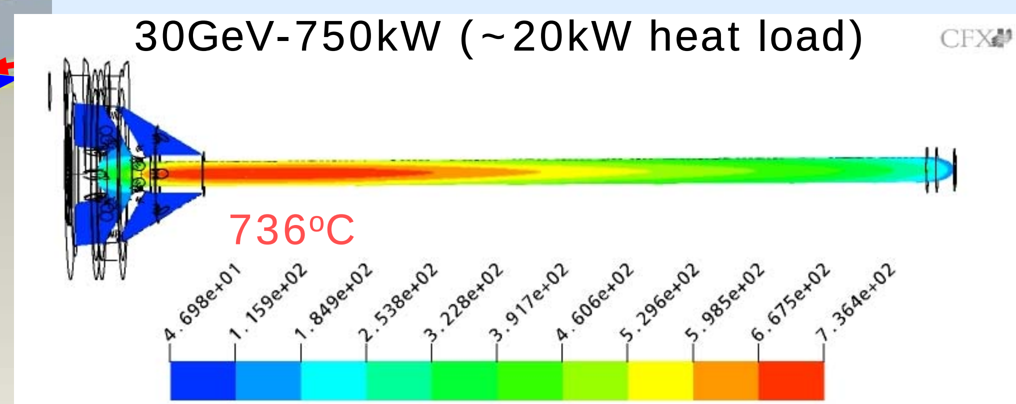
T2K Target

designed for 0.75 MW, He-cooling to avoid water hammer





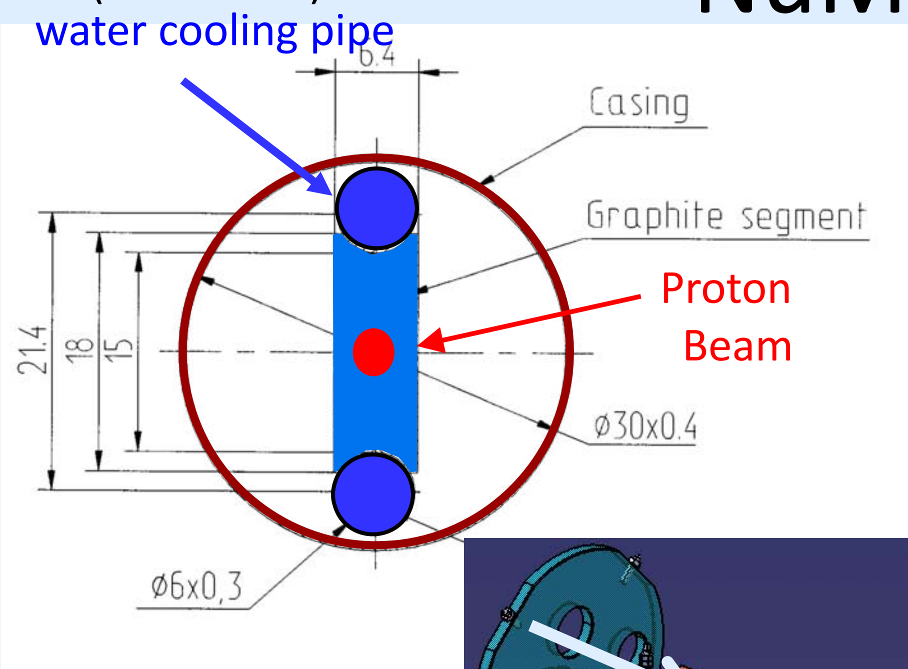




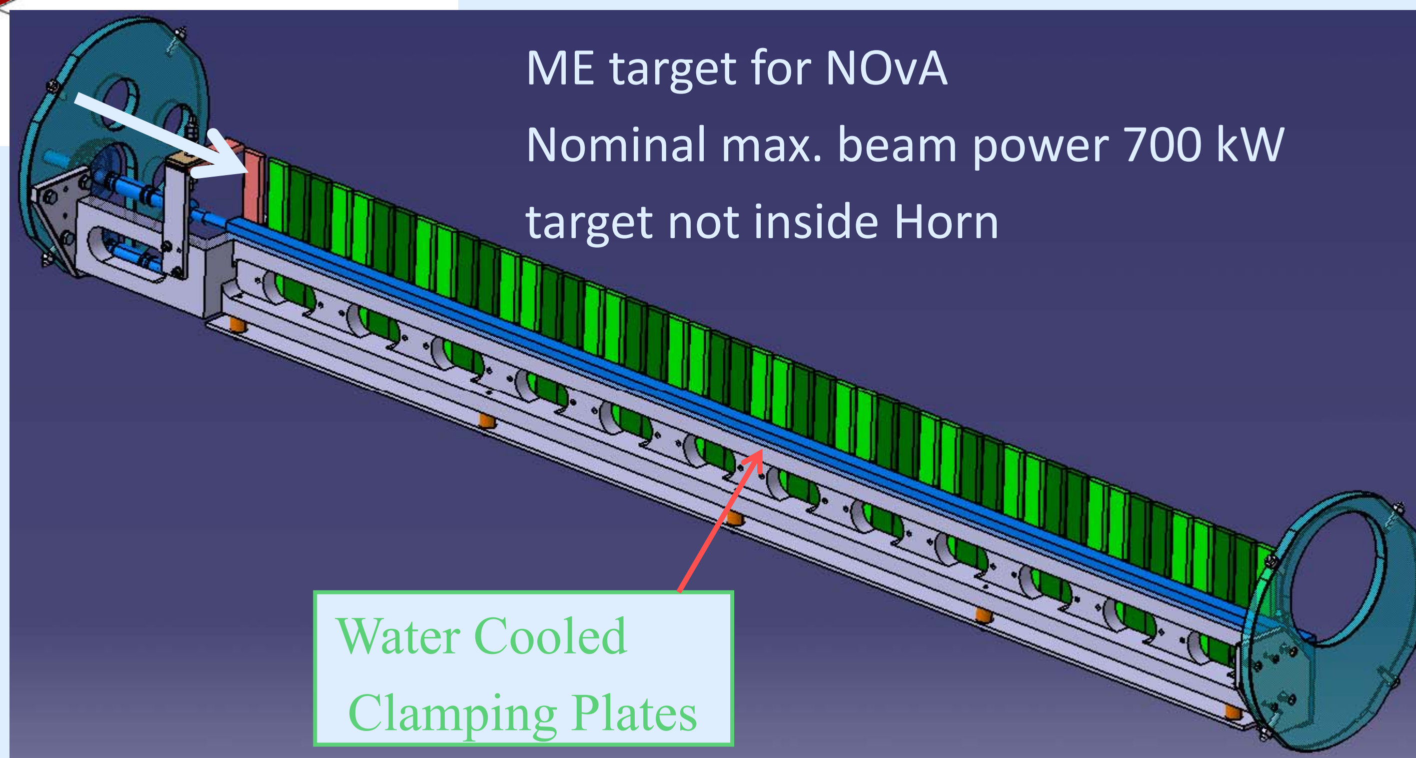
ΔT~200K ~7MPa (Tensile strength 37MPa)

NuMI target

LE target for MINOS
(for 400kW)



LE target : inserted into horn1
ME target: upstream of horn1



LBNE/LBNF target ideas

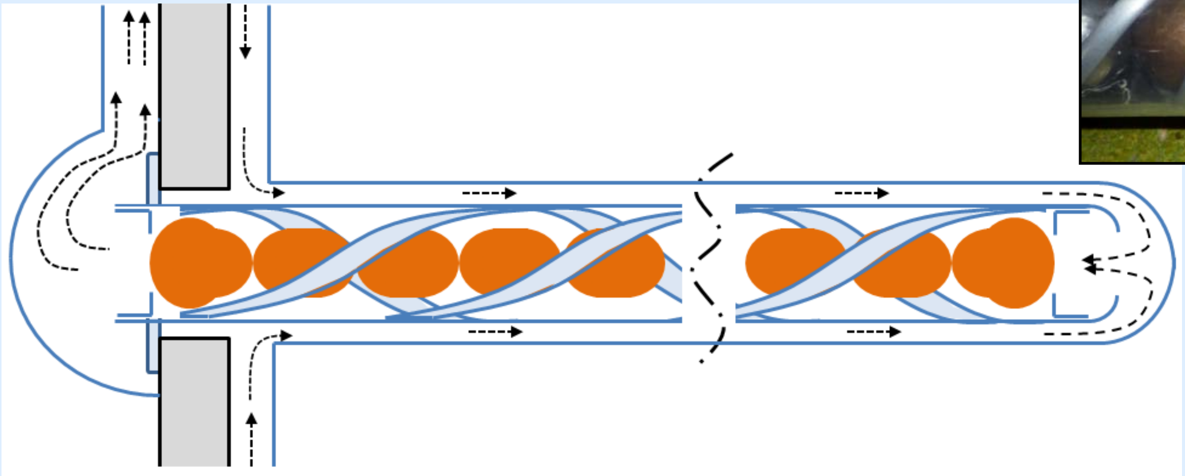
Minimal change from NuMI LE target

✓width: 6.4 mm → 10mm, beam spot:1.1 mm→ 1.7mm

✓ aimed for 1.2 MW

Pressurized helium cooled beryllium sphere (RAL idea)

✓ aimed for 2.3 MW

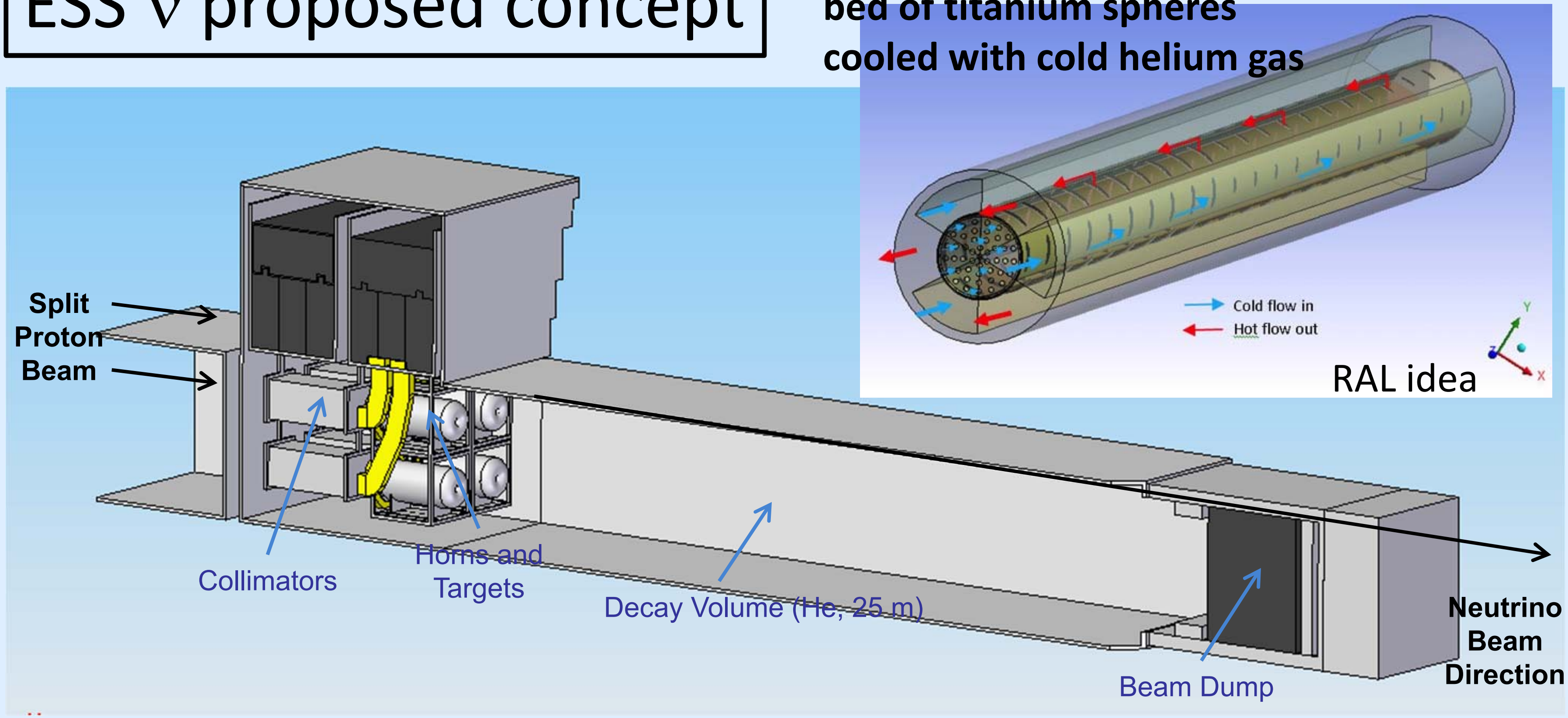


CN2PY target study

- ✓ Phase-I (400 GeV, 0.75 MW) : evolved version of the CNGS graphite target
- ✓ Phase-II (50 GeV 2 MW) : packed bed target (RAL idea)

ESS ν proposed concept

packed bed of titanium spheres cooled with cold helium gas

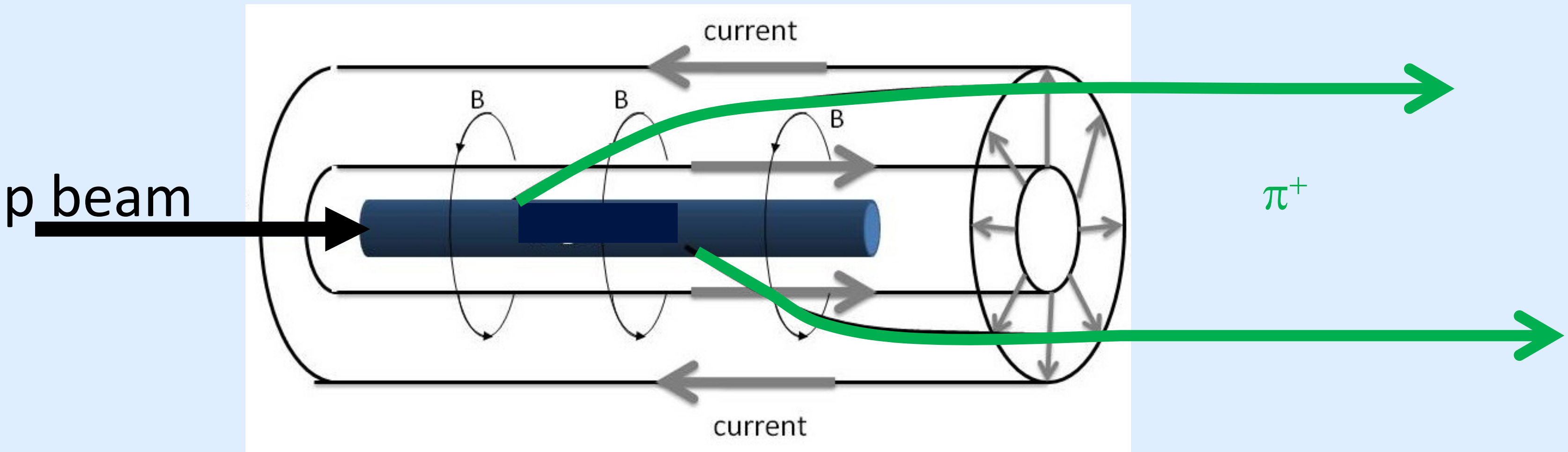


four systems to reduce the load

What limits the intensity of beamline?

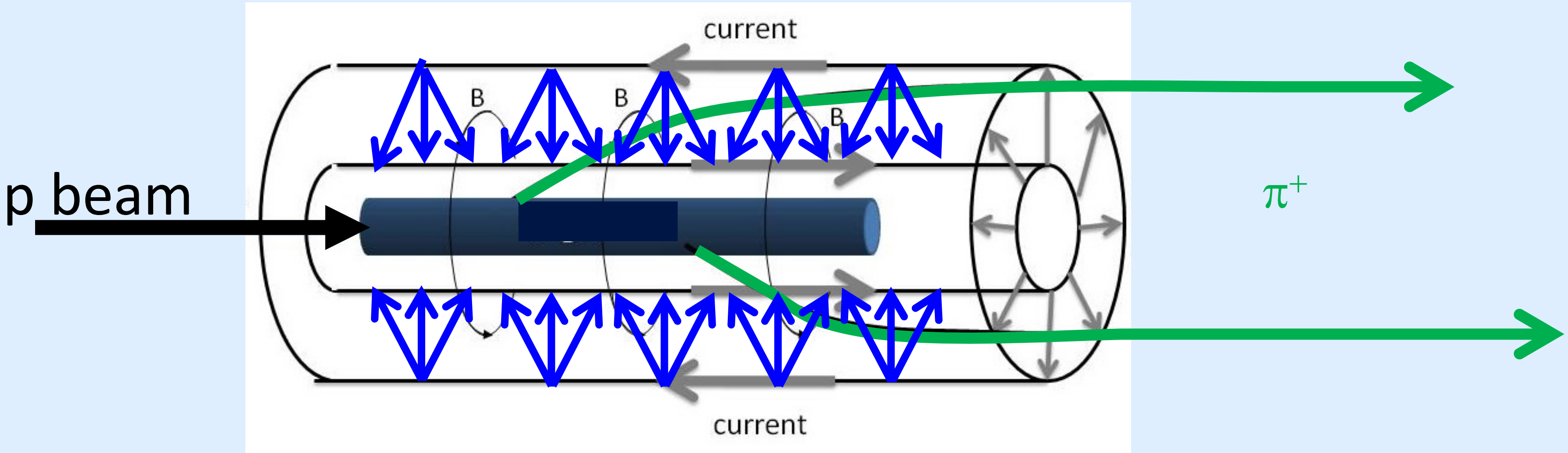
- ✓ Beam loss (same as accelerator)
- ✓ Thermal shock
- ✓ Radiation damage
- ✓ Cooling power
- ✓ Dirty product in air(NOx) and water(Tritium,H_2,Acid)
- ✓ Radiation shield

Magnetic Horn



- Toroidal Magnetic field $B[T] = \frac{I[kA]}{5r[mm]}$
- Usually operated at 100~300 kA
  e.g. 1.8T @ $r = 28mm, I = 250kA$
- a few ms pulsed current
- designed for ~700kW so far
- Radiation and Joule's heating
- Recent horns are cooled by spray water
  Issue on hydrogen, tritium NOx productions

Magnetic Horn



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- Recent horns are cooled by spray water
  Issue on hydrogen, tritium NOx productions

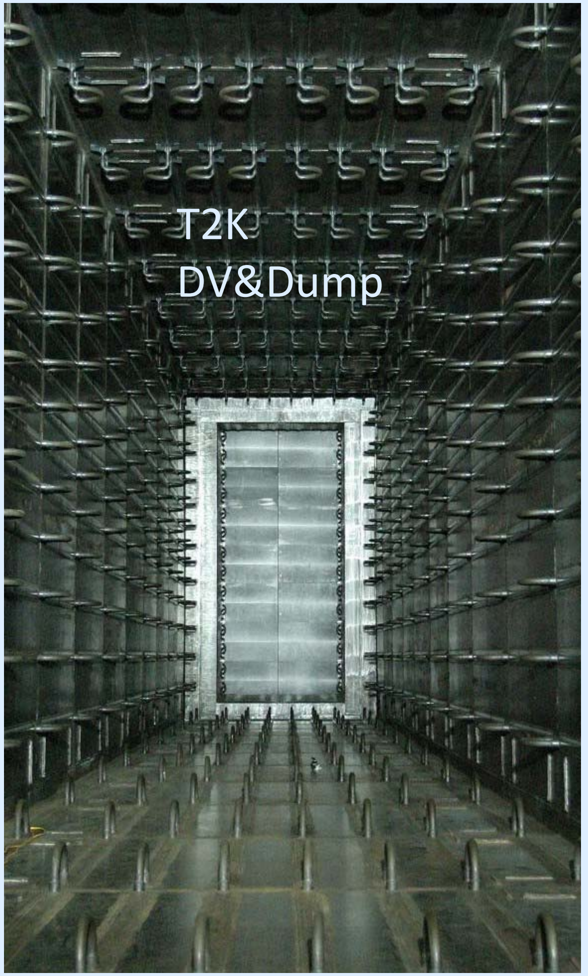
Decay Volume & Beam Dump

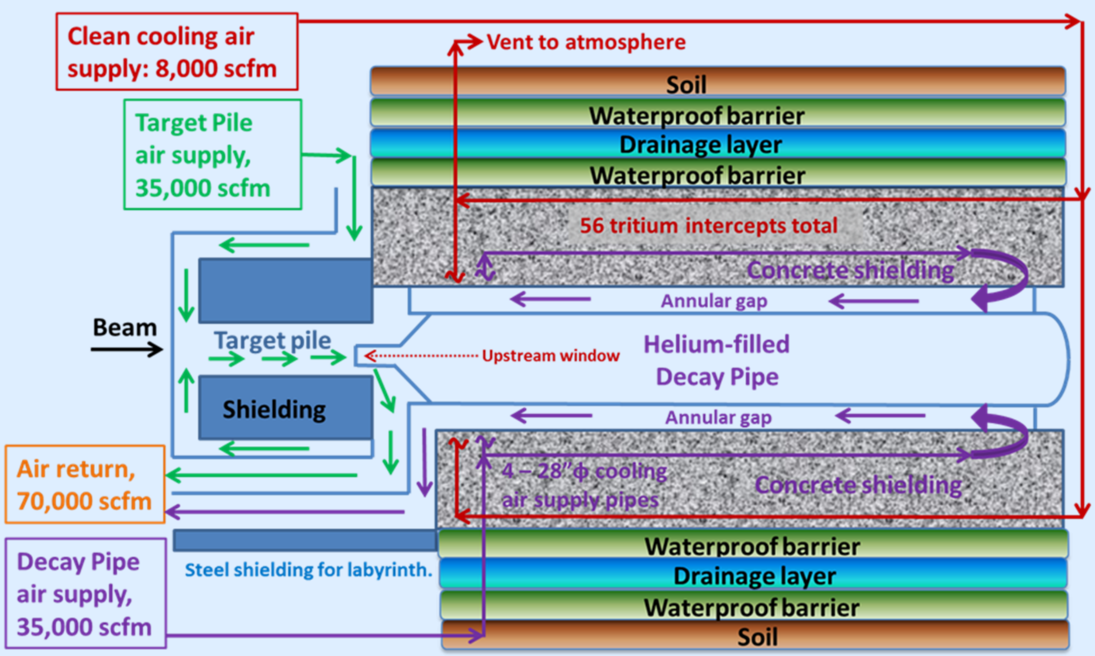
T2K (aimed for 3 MW)

- Decay pipe: iron walls are water-cooled
- Beam dump: Graphite-core
- filled with Helium

LBNE current design (aimed for 2.3 MW)

- Target chase: air filled, air/water cooled
- Decay pipe: helium filled/air cooled
- Beam dump: Aluminum core/ water cooeld





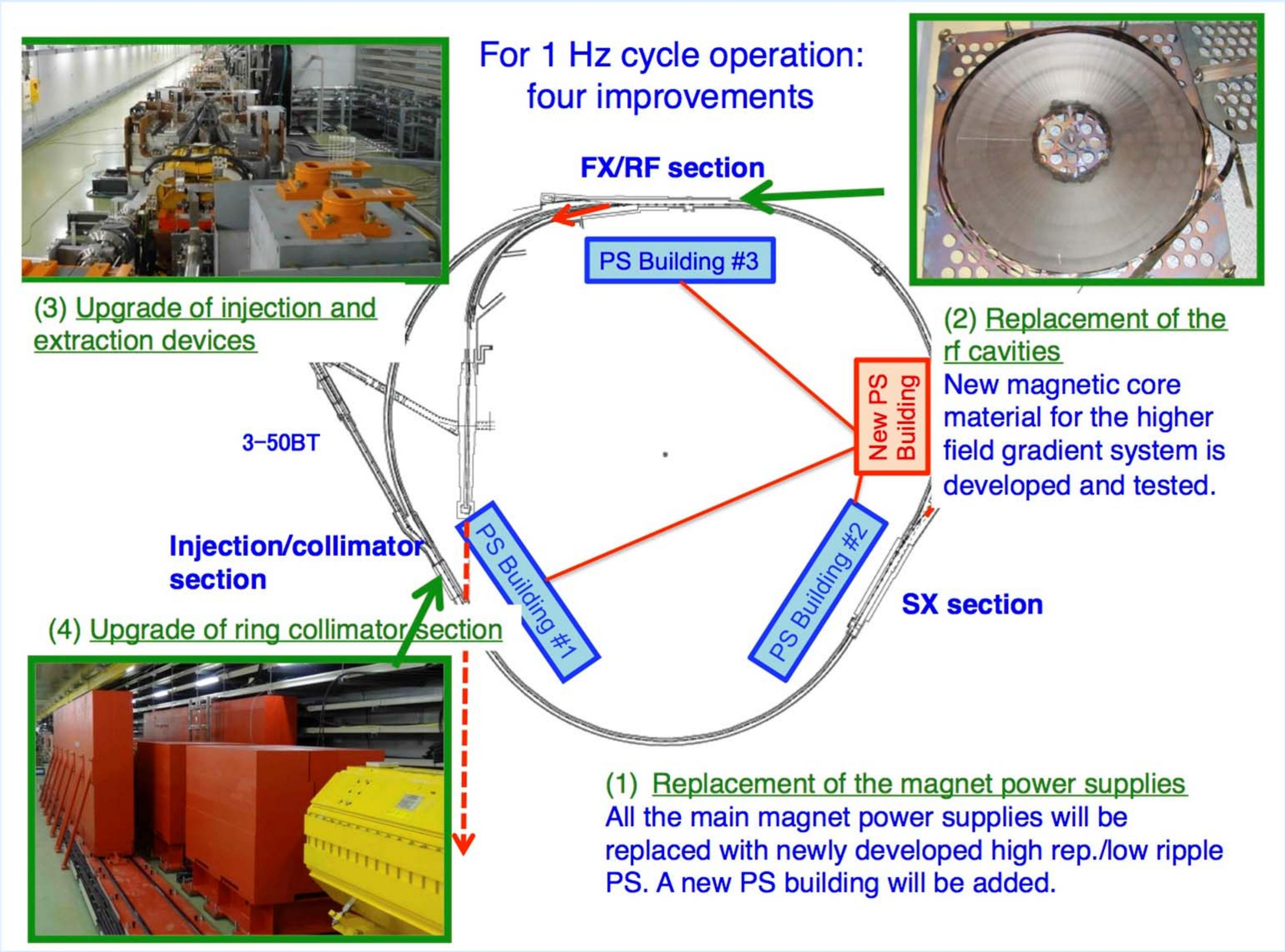
LBNE Decay pipe concept example

Summary

	Energy	Power		
		Current	Planed	Future
J-PARC/KEK	30 GeV	~0.25MW T2K	0.75MW T2K	~2MW
FNAL	120 GeV	~0.36MW MINOS	0.7MW NOvA	~2MW
CERN	400 GeV/c	0.3MW~0.5MW OPERA/ICARUS	(0.2MW for short baseline: CENF)	0.7~2MW (CN2PY)

Achieved = < 0.5 MW
Desired > 1 MW
Need tough works to go beyond 0.5 MW
Many innovative works are necessary for power beyond ~0.7 MW

MR Upgrade



2kW → 3.5kW

J-PARC power upgrade plan

JFY	2013	2014	2015	2016	2017
power(kW)	200-240	200-300	→	→	750
	Linac 180MeV→400MeV	Linac Front-end current 30mA→50mA	Main Ring rep. rate 2.5s→1.3s w/ new Magnet Power supplies and new high Impedance RF		

- ➢ Current bottleneck

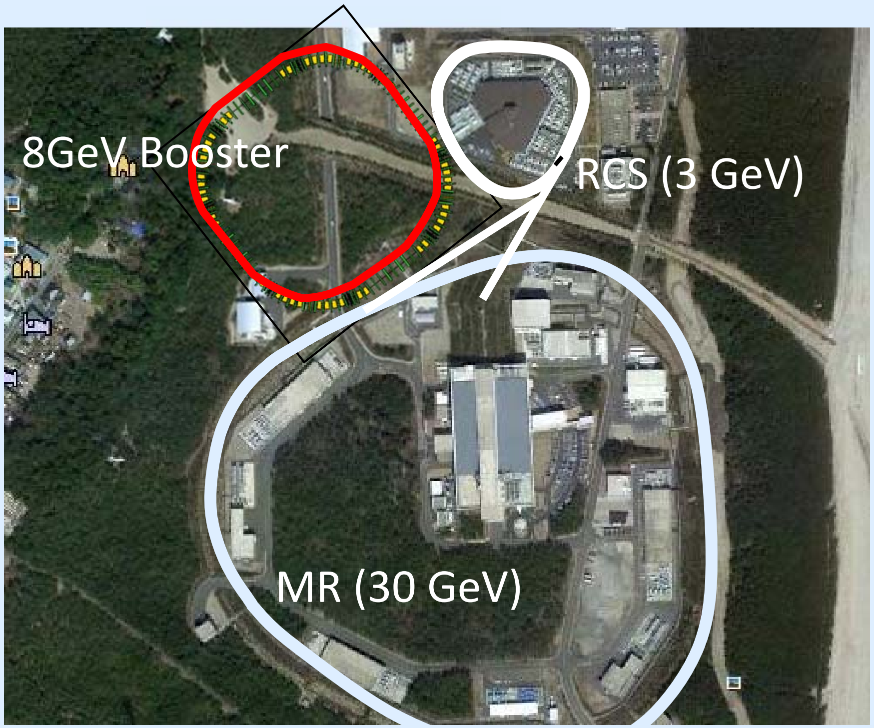
  beam loss at injection to MR

  → can't increase ppp

  → go higher rep. rate → 0.75 MW

  R&D of components succeeded.

- ➢ Long-term possibility under study
  - ✓ New 8 GeV Booster
    - ✓ reduce emittance and space-charge effect at MR injection
  - ✓ Target > 1~3MW



Accelerator complex status and plans

- **Presently running with Main Injector only, 6 Booster batches**
  - 2.5E13, 1.67 s cycle time, 280 kW peak power
- **Commissioning of Recycler ring (~ 4 months)**
  - peak power ≥ 500 kW in 2014
  - at ~ 700 kW in 2015
- **Project X ( ) is a complete design concept for**
  - 3 GeV CW superconducting H- linac with 1 mA average beam current
  - 3-8 GeV pulsed linac with 43 mA average beam current
  - Recycler and Main Injector upgrades to provide ≥ 2 MW to the long baseline neutrino target at 60-120 GeV
- **Fermilab plans to reorient the Project X program to have a goal of delivering > 1 MW from Main Injector to the neutrino program by 2025**
  - 800 MeV srf linac injecting into existing Booster

    ⟶ 6.6E12 protons per batch @ at 12 batches/1.2 sec

    ⟶ 12 batch slip-stacking in Recycler, providing 1.2 MW
  - or 400 MeV srf linac appended to existing 400 MeV linac ("afterburner")

Target
'Divide and Rule' for increased power

Dividing material is favoured since:

- ✓ Better heat transfer
- ✓ Lower static thermal stresses
- ✓ Lower dynamic stresses from intense beam pulses

Helium cooling is favoured (cf water) since:

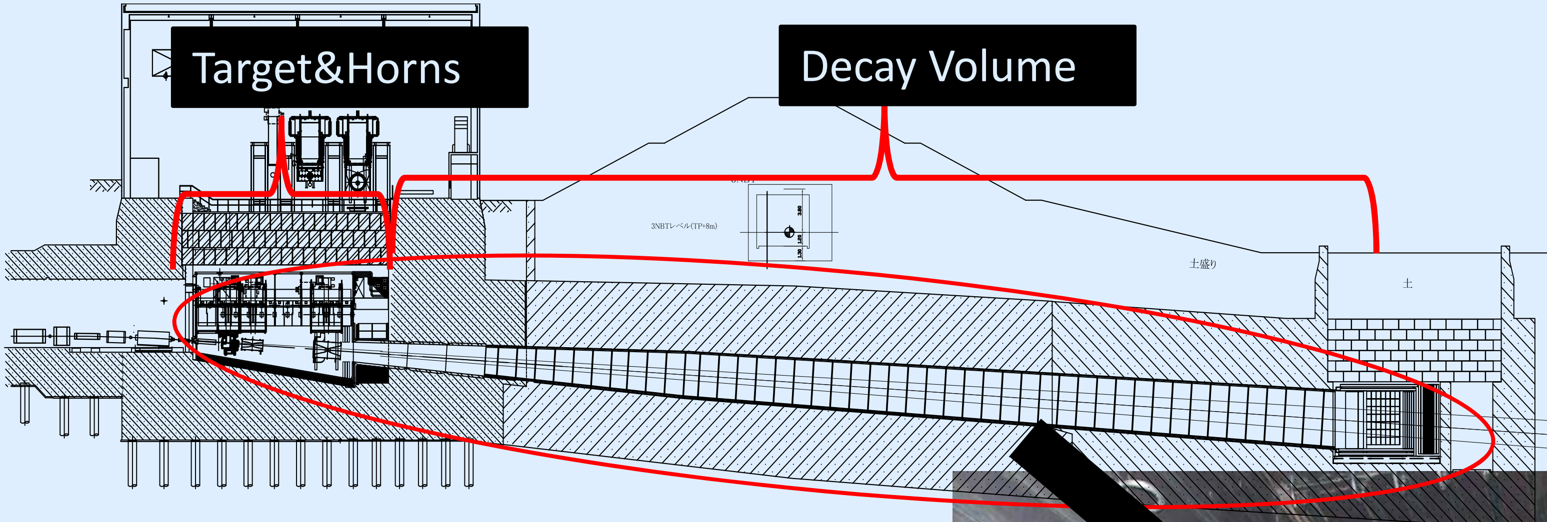
- ✓ No 'water hammer' or cavitation effects from pulsed beams
- ✓ Lower coolant activation, no radiolysis
- ✓ Negligible pion absorption – coolant can be within beam footprint
- ✓ For graphite, higher temperatures anneal radiation damage

Low-Z target concepts preferred (static, easier)

What limits the intensity of beamline?

- ✓ Beam loss (same as accelerator) : NOT LOSS but full power.
- ✓ Thermal shock
- ✓ Radiation damage
- ✓ Cooling power
- ✓ Dirty product in air(NOx) and water(Tritium,H_2,Acid)
- ✓ Radiation shield

Fight w/ the production of Nox, Tritium, acid etc.



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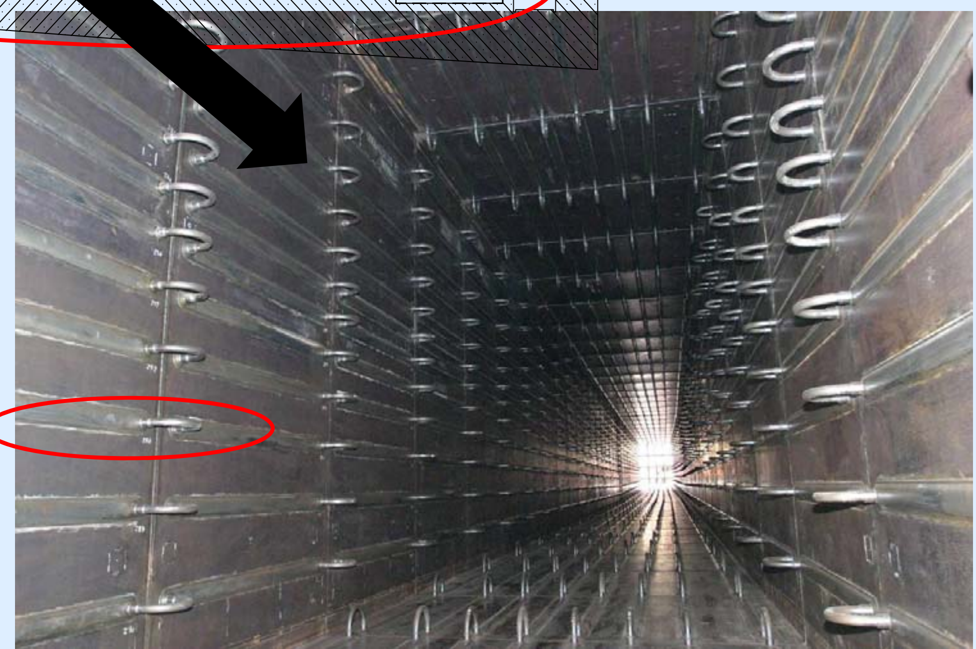
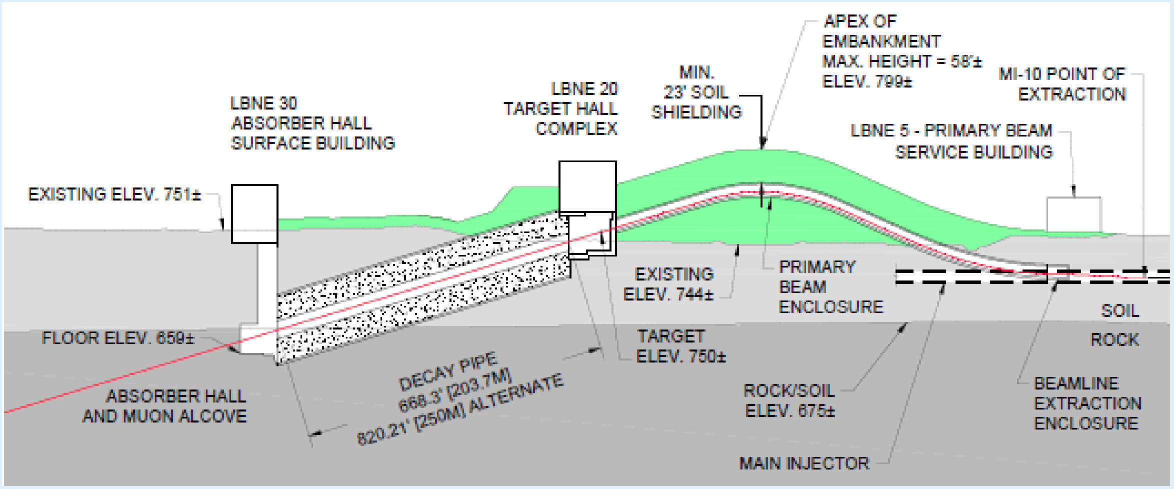
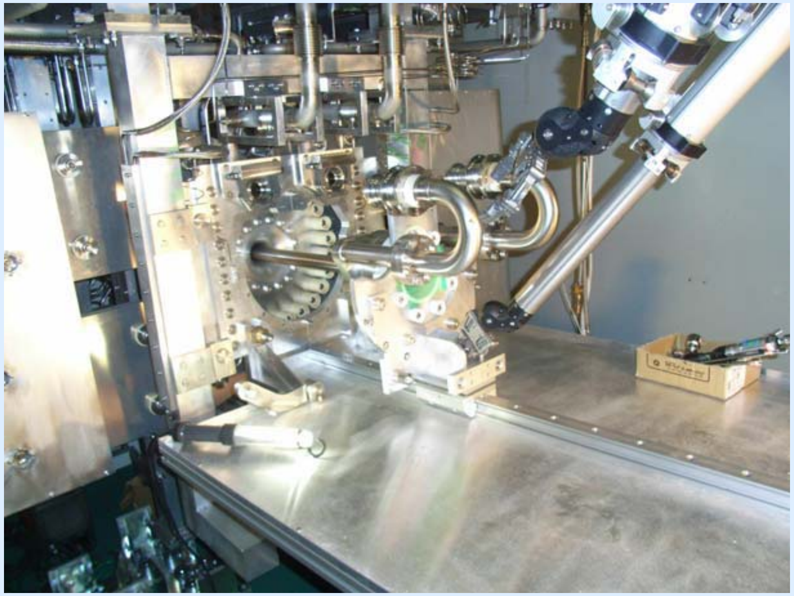
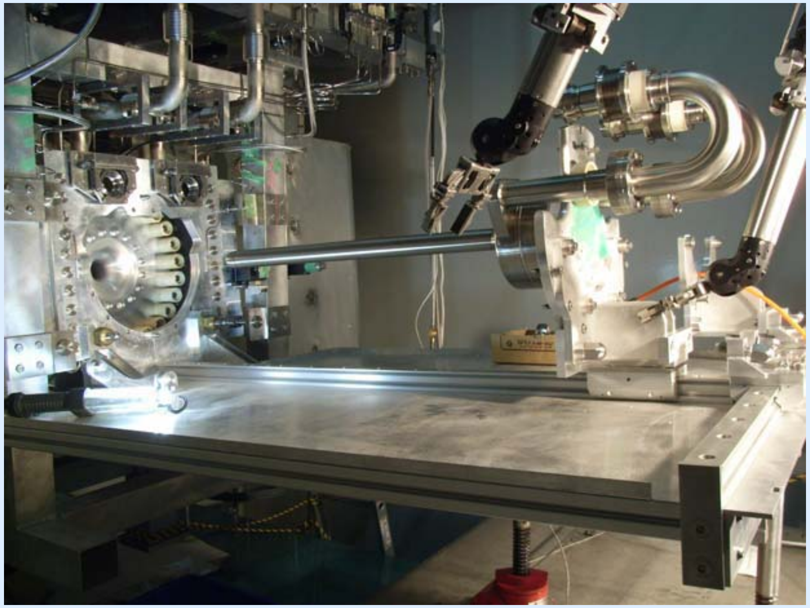




APEX OF
EMBANKMENT
MAX. HEIGHT = 58'±
ELEV. 799±
MIN.
23' SOIL
SHIELDING
MI-10 POINT OF
EXTRACTION
LBNE 20
TARGET HALL
COMPLEX
LBNE 30
ABSORBER HALL
SURFACE BUILDING
LBNE 5 - PRIMARY BEAM
SERVICE BUILDING
EXISTING ELEV. 751±
EXISTING
ELEV. 744±
PRIMARY
BEAM
ENCLOSURE
SOIL
ROCK
FLOOR ELEV. 659±
TARGET
ELEV. 750±
DECAY PIPE
668.3' [203.7M]
820.21' [250M] ALTERNATE
ABSORBER HALL
AND MUON ALCOVE
ROCK/SOIL
ELEV. 675±
BEAMLINE
EXTRACTION
ENCLOSURE
MAIN INJECTOR

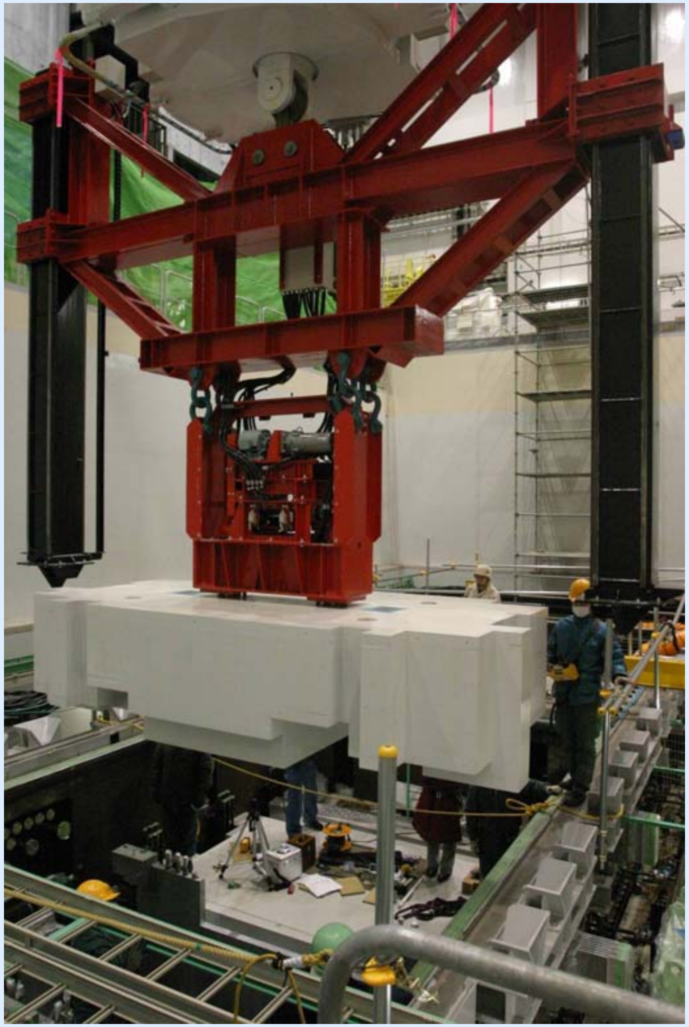
Remote maintenance



Radiation shieldings

2.2m thick iron shields remotely installed



1mm thick concrete block.

On top of them, another 3~4 m thick concrete