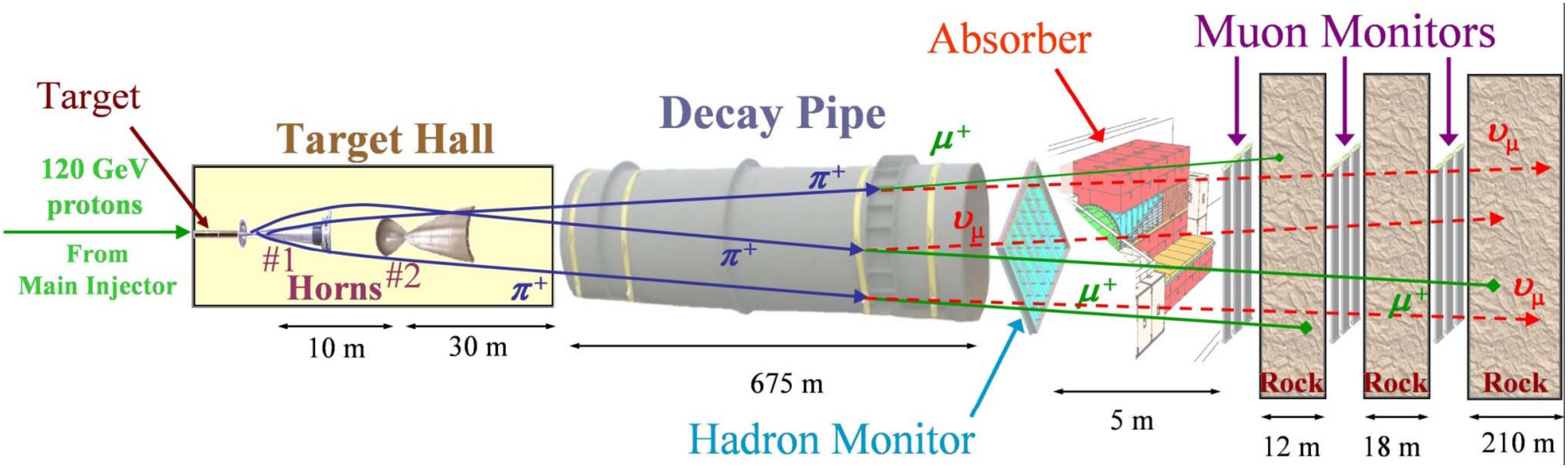
How to build a Superbeam



Definition of Neutrino Superbeam:

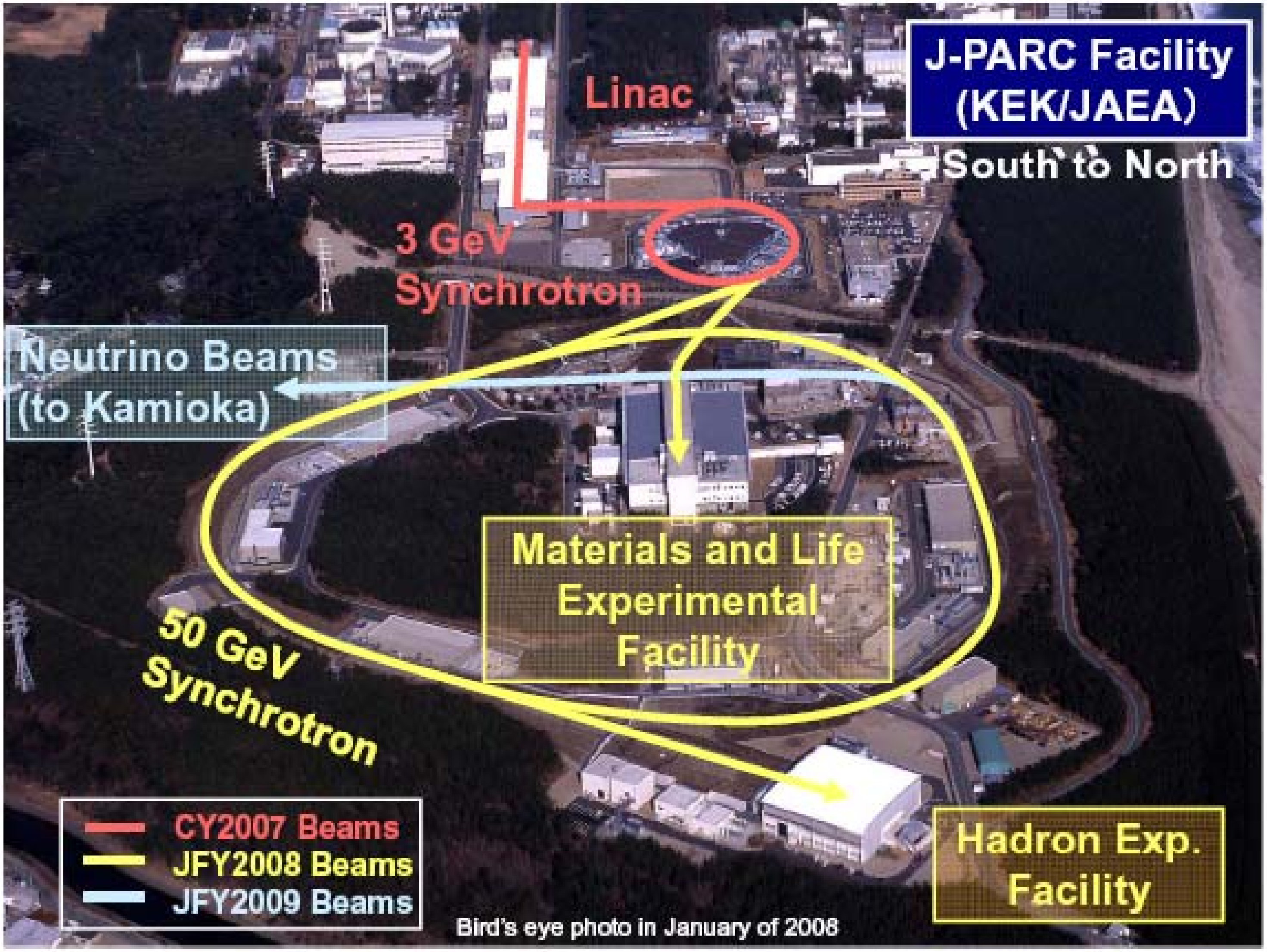
Conventional neutrino beam (protons on target produce pions/kaons, decay to neutrinos) with > 1 MW proton beam power

Superbeam step 1: Lots of protons

Three high-power neutrino facilities are now operational,
could get close to a Mega-watt in a few years,
and all three regions are drafting plans for superbeams

	Operational	Next ? “semi-superbeams ?”	Planning
CERN	CNGS 0.3 MW	CNGS “ultimate” 0.75 MW	SPL to new ν-beam 4 MW
FNAL	NuMI for MINOS 0.3 MW	Upgrade for NoVA 0.70 MW 2013	Proj.X to DUSEL =“LBNE” 2.1 MW
JPARC	T2K 0.1 MW next fall	T2K 0.75 MW ~ 2011…	Roadmap plan T2K 1.7 MW

JPARC



Bird's eye photo in January of 2008

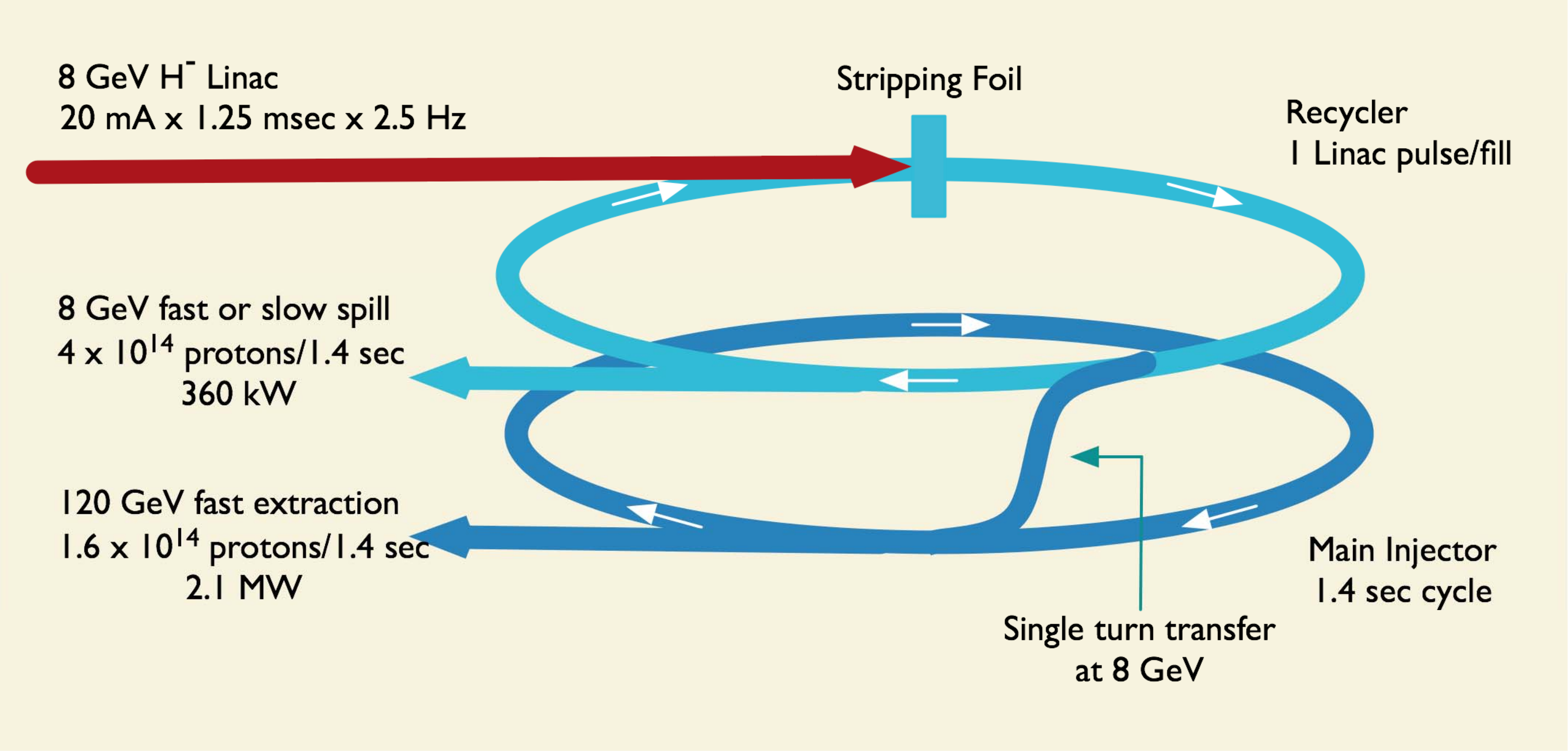
Accelerator enclosures all exist (along with superbeam target hall)

Several upgrades in power, stability, beam loss control needed to get from current 0.1 MW to > 1 MW

FNAL upgrade Project X

Add 8 GeV front end to existing Recycler and Main Injector

Costed Configuration can provide 2 MW between 60 to 120 GeV:

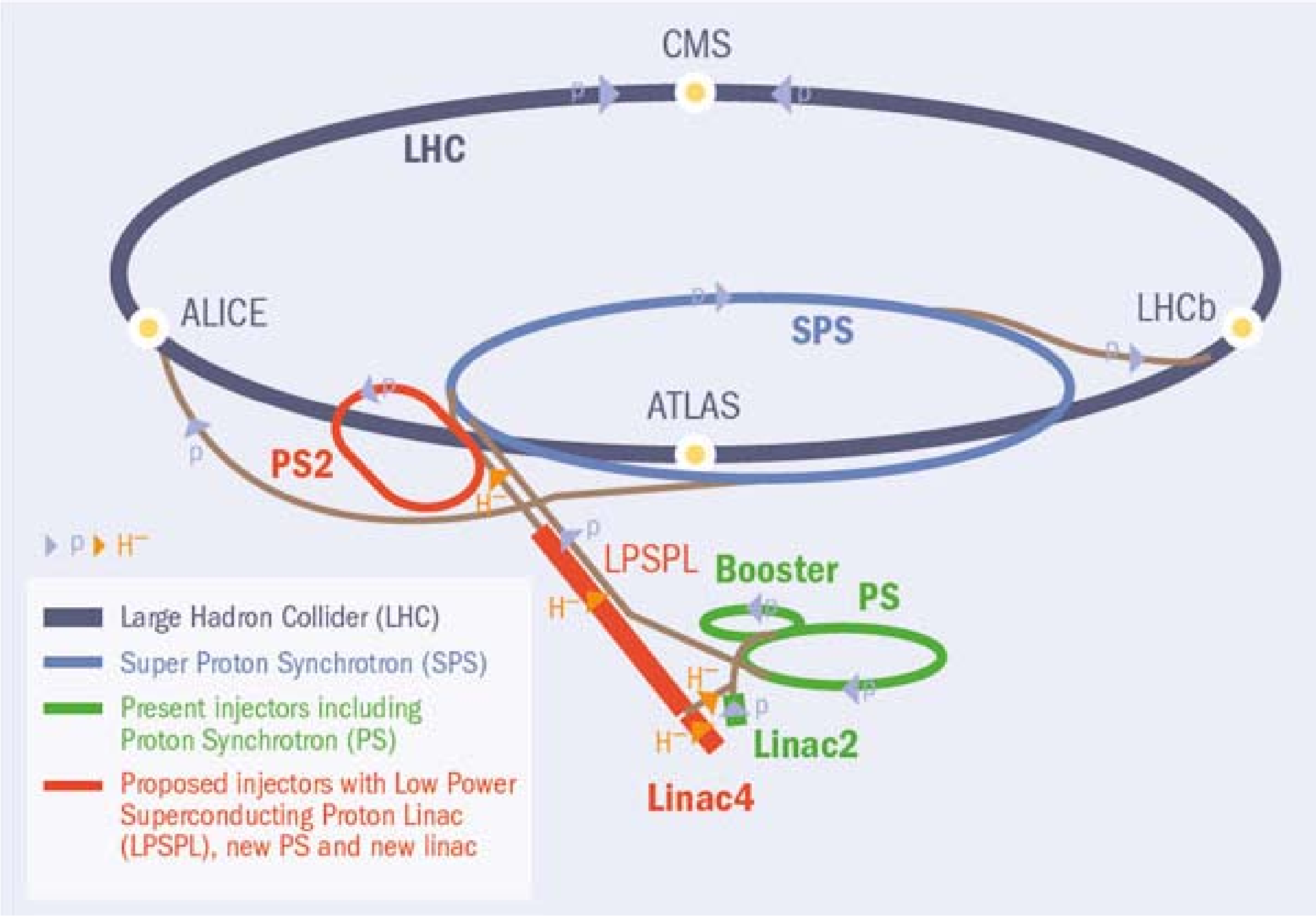


Alternate Configuration (2 GeV C.W. S.C. linac + synchrotron to 8 GeV) gives same structure 2 MW output for neutrino beam

a CERN path to superbeam

New injectors

- Linac4 (2013)
  - → 160 MeV
- LPSPL (2017)
  - → 4 GeV
- PS2 (2017)
  - → 50 GeV



Then upgrade LPSPL
to 4 MW Superconducting Proton Linac (SPL)

Spill structure table

	Proton energy	Protons per spill	Repetition rate	Beam power
JPARC “roadmap”	30 GeV	$6.7\text{x}10^{14}$	0.5 Hz	1.7 MW
FNAL Project X	120 GeV (60 GeV ?)	$1.6\text{x}10^{14}$	0.7 Hz (1.4 Hz ?)	2.1 MW
CERN SPL	3.5 GeV	$1.4\text{x}10^{14}$	50 Hz	4 MW

In all cases, fast-extract a huge number of protons, maximizing stress waves in target (factor of 4 above current NuMI POT/spill)

Public Relations

Open and early involvement of public

THE NEW YORK TIMES **SCIENCE** TUESDAY, JANUARY 23, 1996

'Neutrino Bombs' Idea Expands Debate on Human Extinction

"Neutrinos killed the dinosaurs" was publicized while NuMI/MINOS was seeking approval to send neutrinos through Wisconsin and Minnesota

State No. 1 in tritium spills

Illinois leads nation in leaks over decade

have been reported.

Tritium leaked in at least 10 sites across the country in the last 10 years, according to watchdog lists. Four, includ-

mined none of the leaks pose a threat to human health, but the NRC nonetheless set up a task force last month to probe the issue.

"We need to conduct an in-

year of the first Braidwood leak, until now.

By Aug. 31, it will consider potential public health effects, how the NRC responded and how the leaks were publicly

Illinois power plant tritium leaks caused public uproar just when NuMI discovered greater-than-expected tritium levels

NuMI survived these partly because of good relations with public

Environment, Safety & Health

If real estate is location, location, location
Superbeam technical design is ES&H, ES&H, ES&H

Decay pipe: physics says area π (2 m radius)**2,
but ES&H says shielding area π (5 m radius)**2
mining and installing shielding drives cost
Physics doesn't change,
but regulations/guidelines over the course of a long project can. *Risk:*
will allowable levels of tritium release be the same in the future ?

Radiation protection and hot handling considerations consume much of the design time

Oxygen Deficiency Hazard
Hazards specific to Underground Excavations
Nitric acid, ozone, sodium hydroxide in air (chemical effects of radiation)
Stored energy: even helium decay pipe has huge stored energy (because not 1 atm)
…

The secondary beam line

So you already have operating neutrino beams at high power, what's the big deal with going another order of magnitude ?

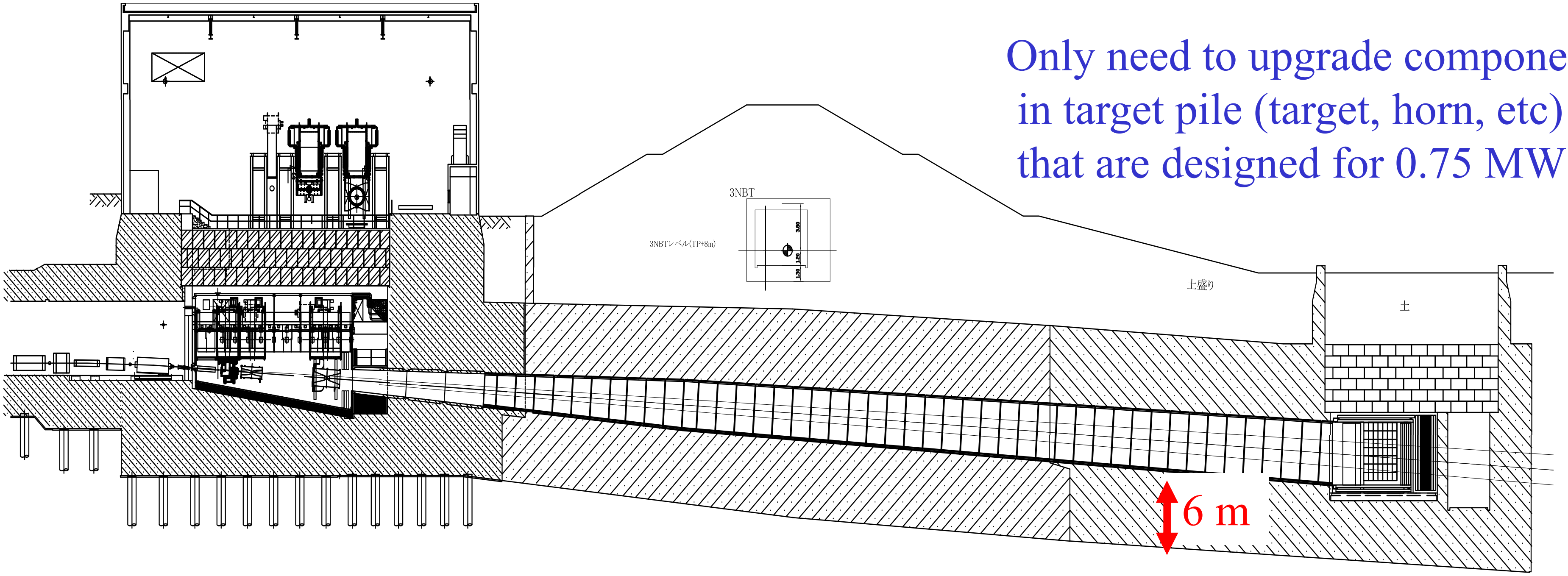
It IS an advantage of superbeams that we have experience with the technology that we can extrapolate, and it is not a huge step

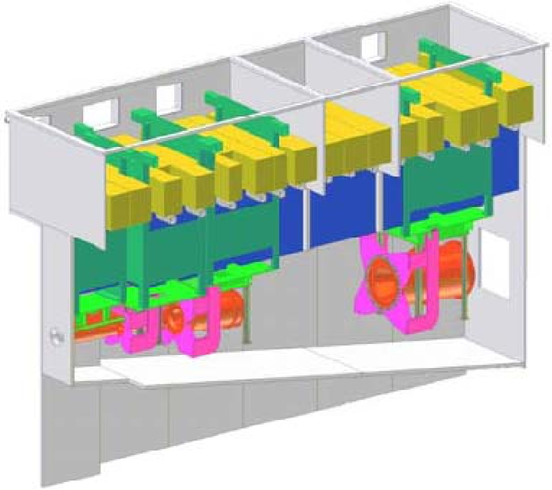
but there are some challenges:

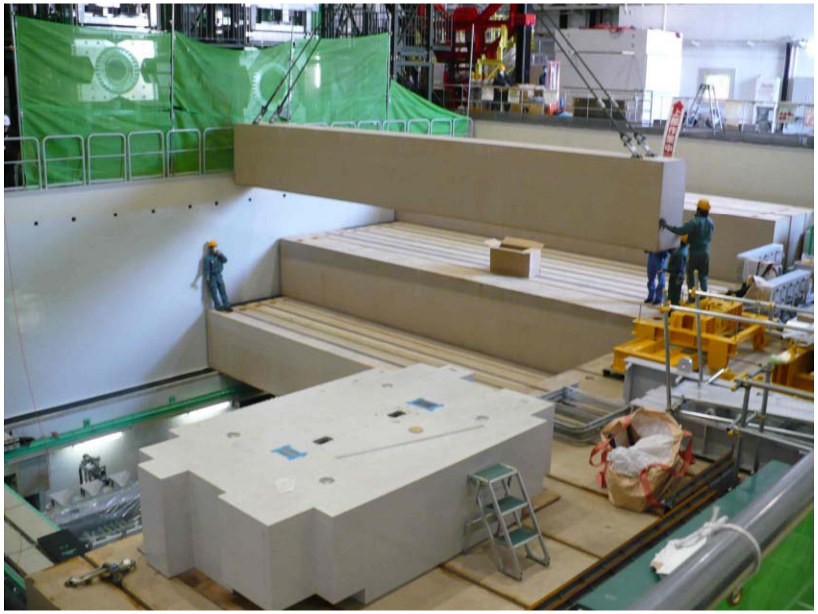
1) Higher profile (At FNAL, LBNE referred to as "flagship")
– consider before taking the same level of risk as in previous beamlines with non-repairable systems *what happens if decay-pipe cooling or absorber fails?*
2) Target is problematic due to (i) worse stress wave from fast beam spill (ii) higher thermal load (iii) faster radiation damage. *Also true for beam windows.*
3) Primary beam can do substantially more damage in a single pulse
4) Residual radiation levels cross point where hands-on repair becomes impossible, much more emphasis on remote handling. *(100 techs x 1 second each – NOT!)*
5) Increased heat load → e.g. target pile shielding probably needs water cooling
6) Another order of magnitude problem with corrosive air,
or else deal with system to enclose everything an inert atmosphere
7) Don't spend order of magnitude more money on order of magnitude more power

Target pile, Decay pipe, Absorber at T2K already built for 4 MW Superbeam !

Only need to upgrade components in target pile (target, horn, etc) that are designed for 0.75 MW







What neutrino spectrum does the experiment want ?

In general, desire neutrino flux at oscillation maximum, so want E_ν = 2 GeV L/1000 km

What base-line is desired ? 250 to 1700 km (LBNE longer L to see matter effects)

Narrow band beam (reduce backgrounds from ν outside oscillation max.)
or wide band (see both 1st and 2nd oscillation peaks to resolve ambiguities) ?

Can detector do event sign selection,
or does beam need to switch between ν and $\bar{\nu}$?

Balance between higher ν statistics and background reduction ?

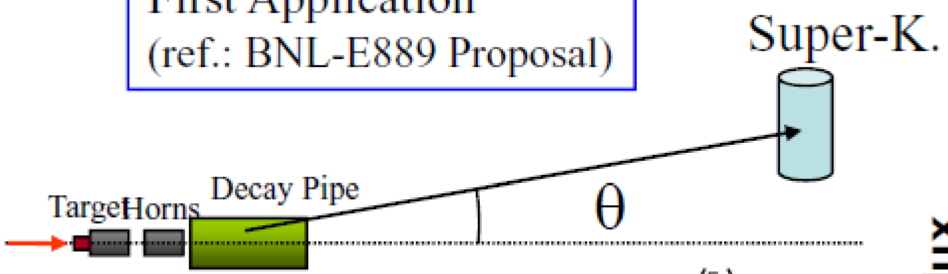
Focusing system choices for conventional neutrino beams:

- Horns, on or off-axis
- Solenoid
- Lithium lens
- Plasma lens
- Magnetic spokes
- Quadrupole triplet
- Dichromatic
- Hadron hose

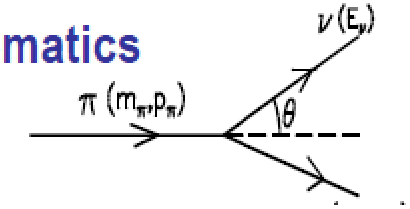
Nice review in Phys. Rep. 439, 3 (2007), Sacha Kopp

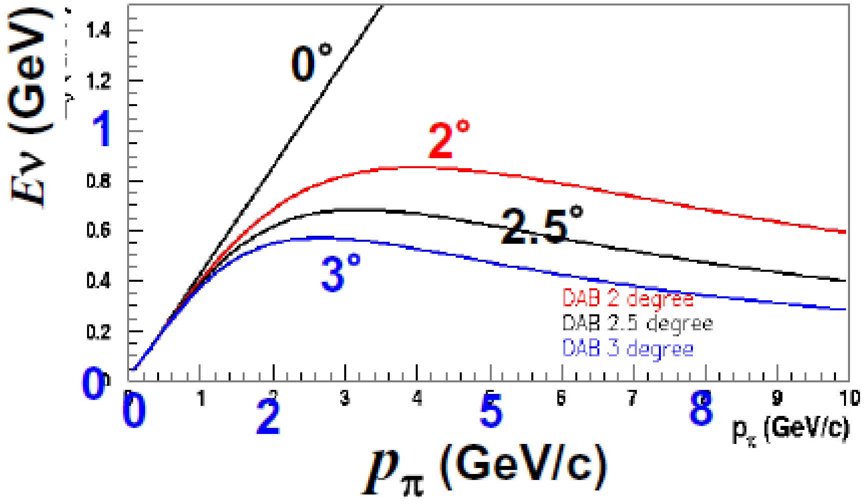
T2K off-axis beam

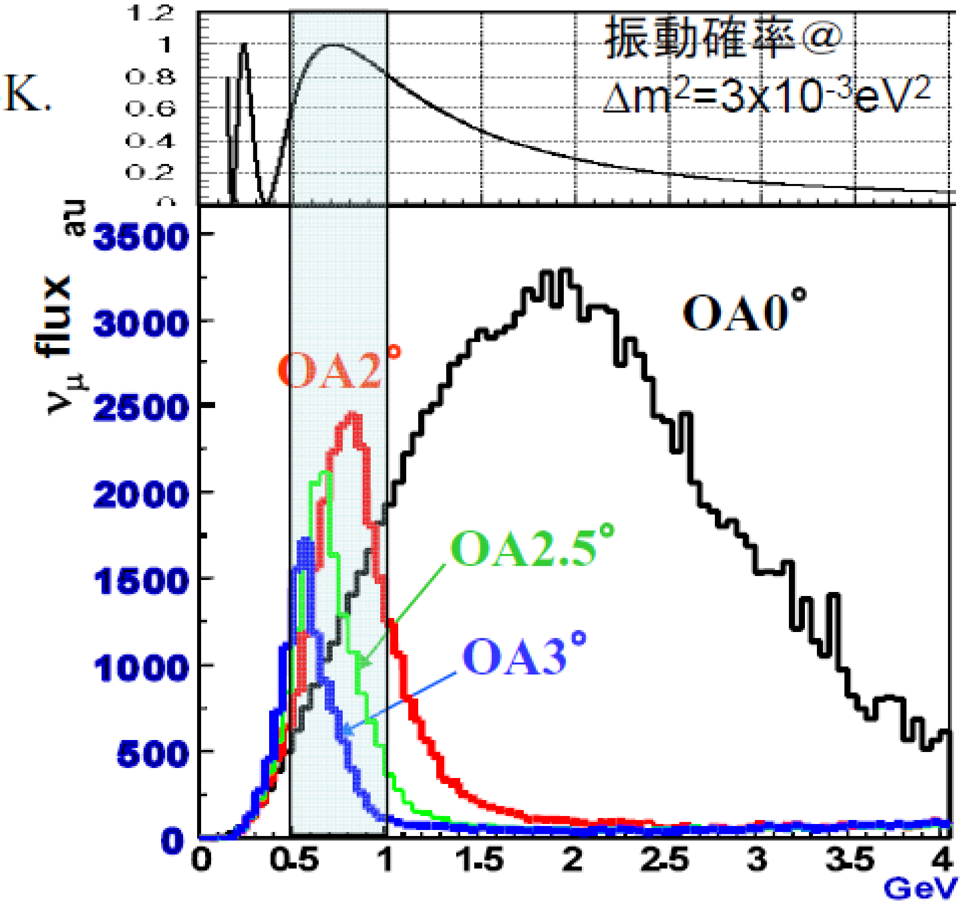
First Application
(ref.: BNL-E889 Proposal)



π decay Kinematics







- Quasi Monochromatic Beam
- x 2~3 intense than NBB
- Tuned at oscillation maximum

T.Kobayashi (KEK)

Statistics at SK

(OAB 2.5 deg, 1 yr, 22.5 kt)

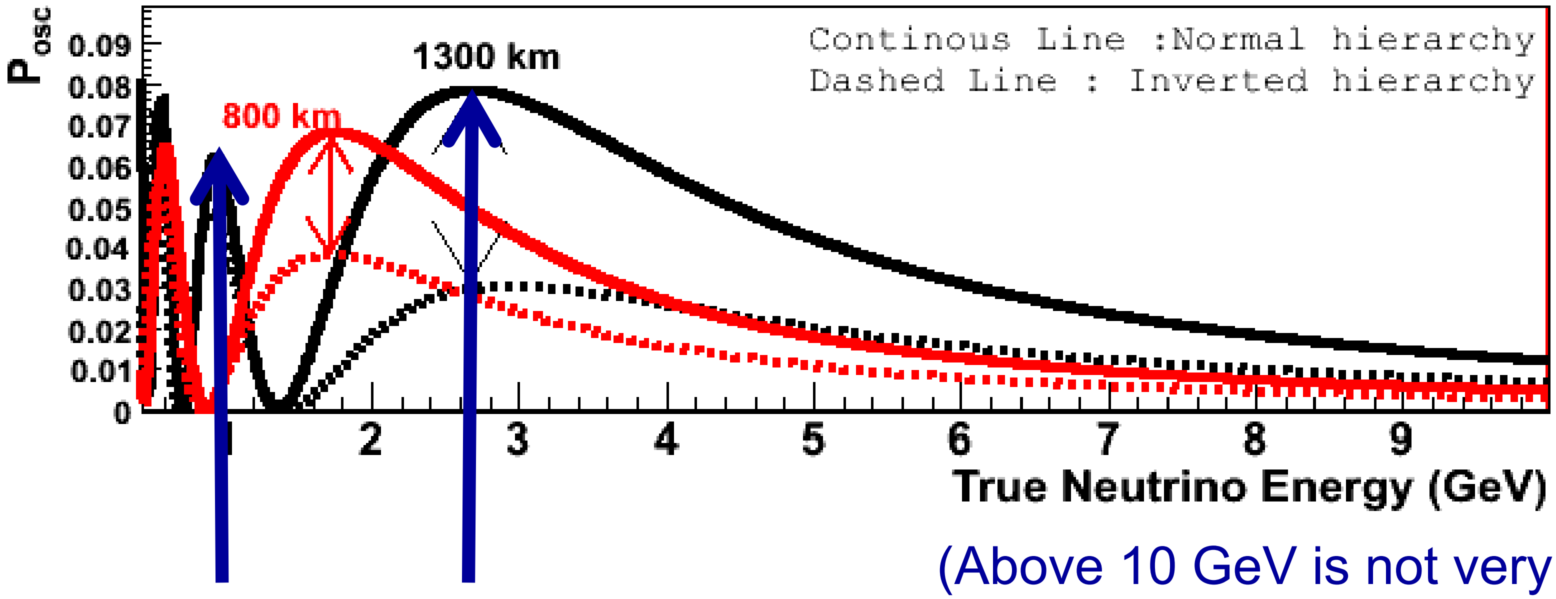
~ 2200 ν_μ tot

~ 1600 ν_μ CC

ν_e ~0.4% at ν_μ peak

LBNE (FNAL to DUSEL)
Beam Design Requirements

Want a wide band beam, cover the 1st and 2nd oscillation maximum



(Above 10 GeV is not very useful)

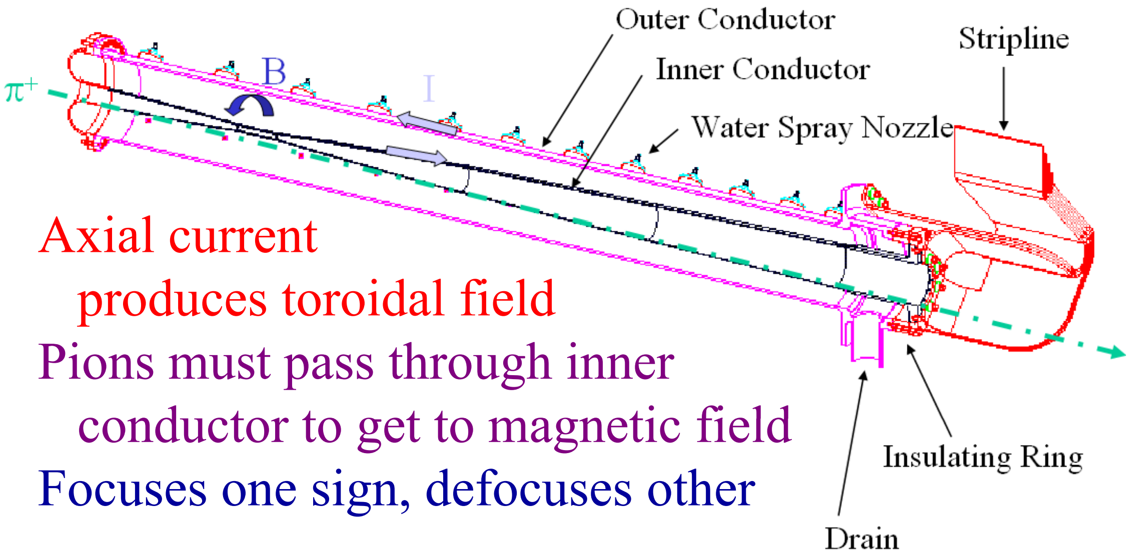
0.8 GeV   2.7 GeV

1st round detectors don't do ν sign selection

Implication is probably an on-axis horn focusing beam,
with target shoved into the first horn   (π angle from target ~ 0.1 GeV / E_ν)

Horn focusing

used by all current high power ν beams



Axial current
produces toroidal field

Pions must pass through inner
conductor to get to magnetic field

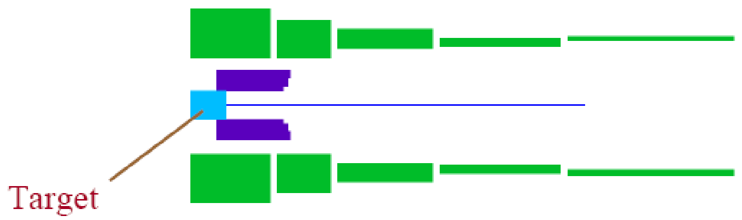
Focuses one sign, defocuses other


NUMI horn inner conductor


T2K

Solenoid focusing

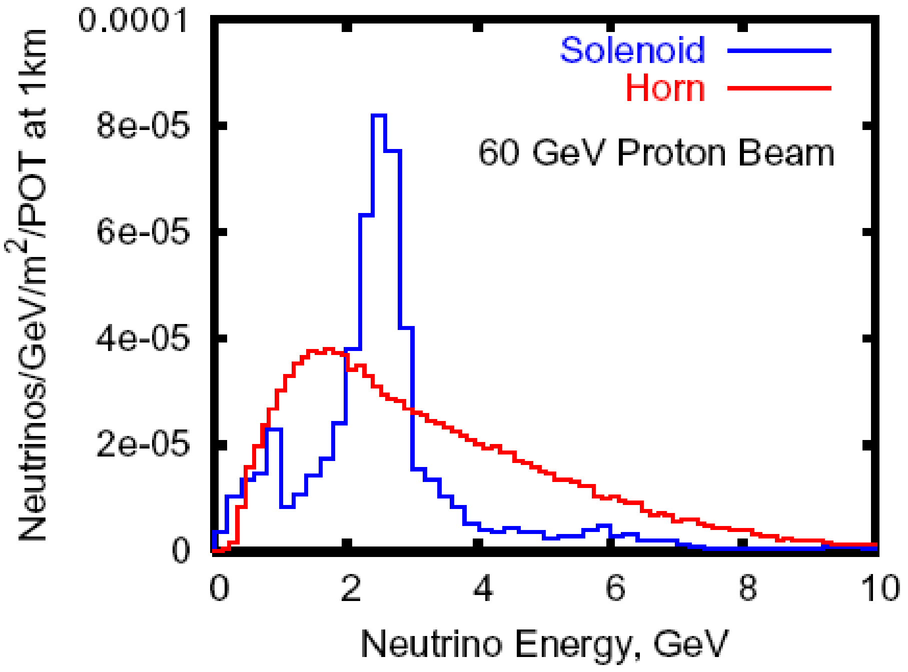
Harold G. Kirk / NUFACT06



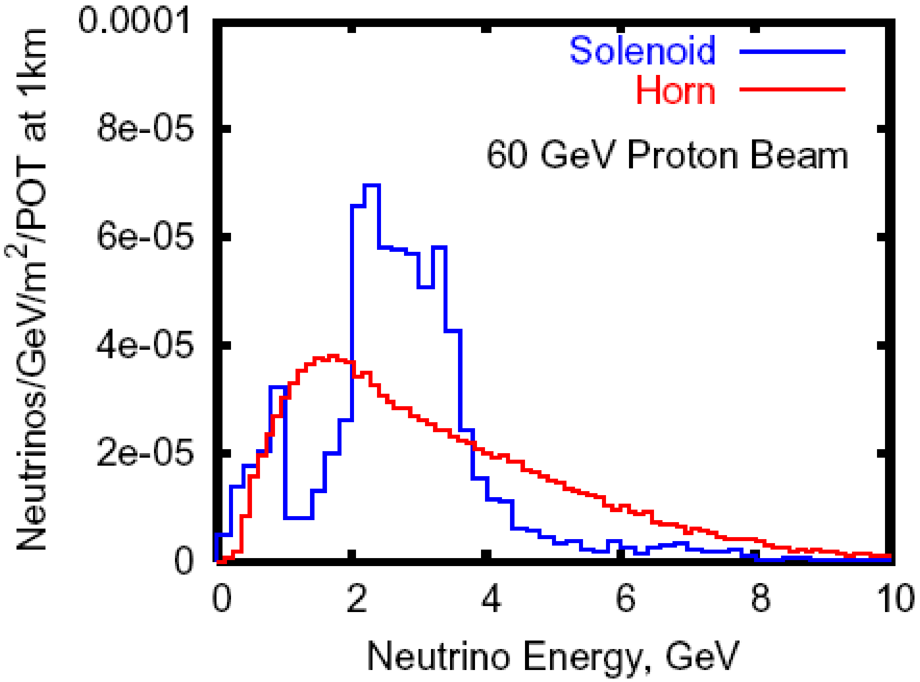
It's the fringe field that bends pions parallel to beam axis

Solenoid can give higher peak, lower tails than horn focusing

But ν and $\bar{\nu}$ both at same time, detector must have sign I.D. capability



3m Solenoid



3m-30m Solenoid

Target 101

Long enough (2 interaction lengths) to interact most protons

Dense enough that 2 λ_{int} fits in focusing system depth-of-field

Radius: R_{target} = 2.3 to 3 R_{beam} (minimize gaussian tails missing target)

Narrow enough that pions exit the sides without re-absorption

(but for high E_{proton} and low E_{ν}, secondary shower can help)

High pion yield (but to first order, ν flux α beam power)

Radiation hard

Withstand high temperature

High strength (withstand stress from fast beam pulse)

Low density (less energy deposition density, hence less stress; don’t re-absorb pions)

Low dE/dx (but not much variation between materials)

High heat capacity (less stress induced by the dE/dx)

Low thermal expansion coefficient (ditto)

Low modulus of elasticity (less stiff material does not build up stress)

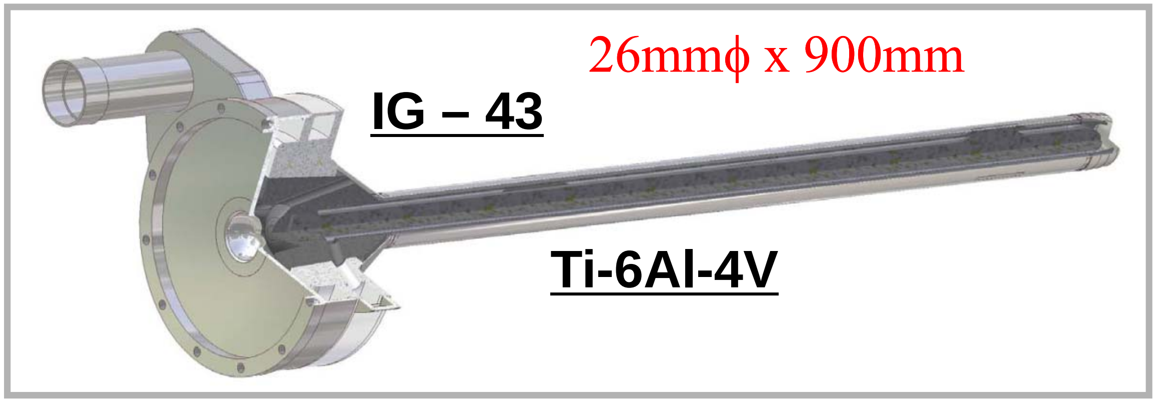
Reasonable heat conductivity

Reasonable electrical conductivity (monitor target by charge ejection)

CNGS, NuMI, T2K all using graphite

T2K Target for 0.75 MW

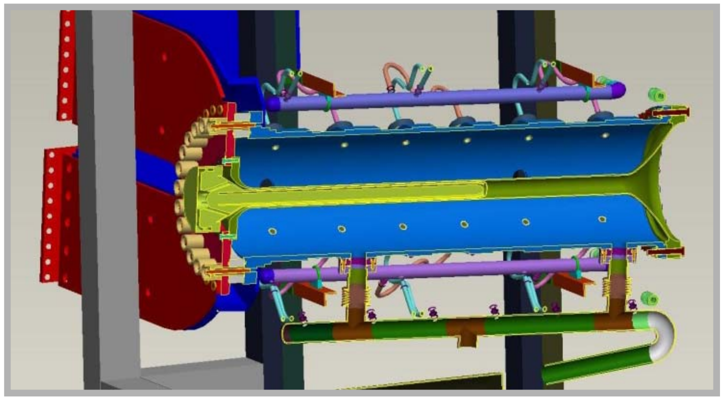
Helium-Cooled Graphite Target in the 1st Horn



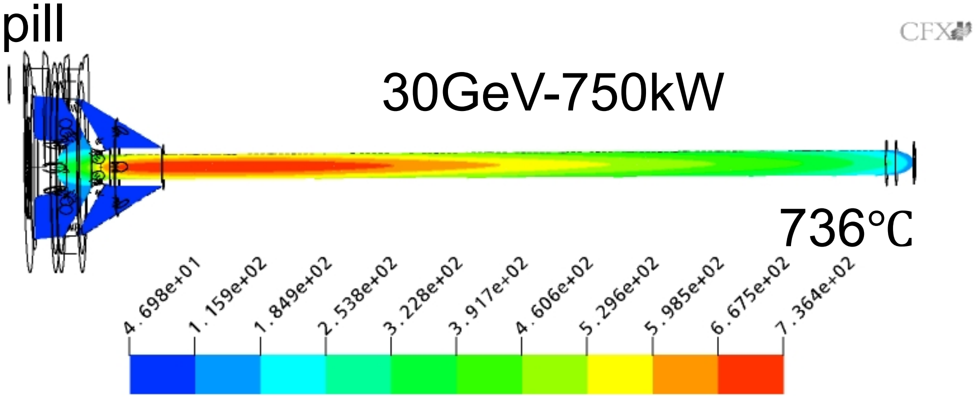
26mmϕ x 900mm

IG – 43

Ti-6Al-4V



58kJ/spill



30GeV-750kW

736°C

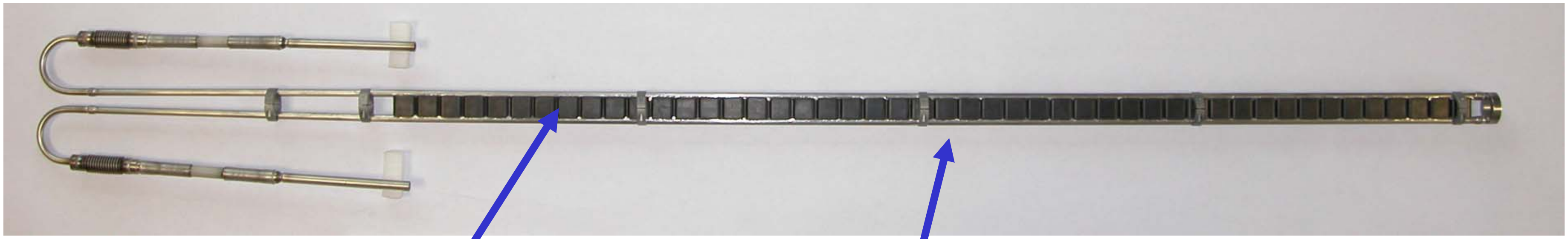
ΔT~200K ~7MPa(Tensile 27MPa)

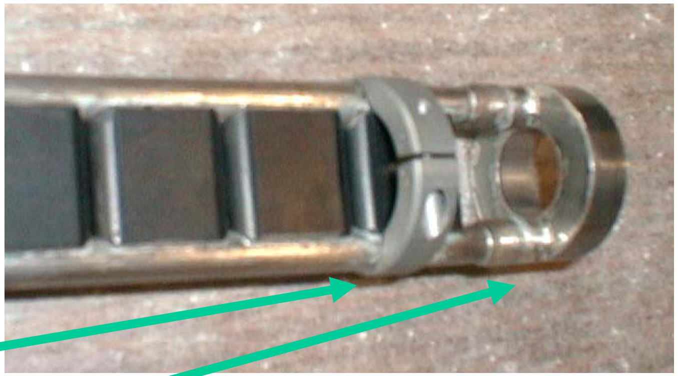
Helium flow is already aggressive - will helium cooling work at 2 MW ? Windows ?

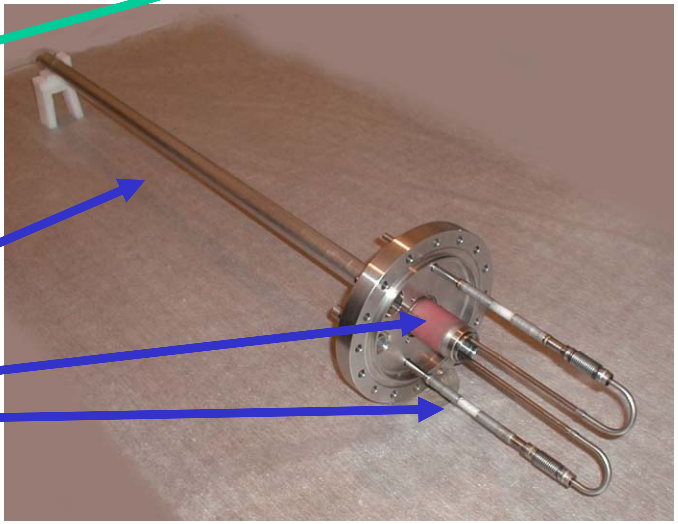
Hopefully T2K target group will figure this out and let us know

NuMI Target

long, thin, slides into horn without touching







Graphite Fin Core, 2 int. len.

(6.4 mm x 15 mm x 20 mm) x 47 segments

Water cooling tube also provides mech. support

(steel soldered to graphite)

Anodized Al spacer (electrical insulation)

Water turn-around at end of target

0.4 mm thick Aluminum tube *(He atmosphere, Be windows at U.S. and D.S. ends)*

Ceramic electrical isolation

Target 102

stress wave, thermal load, radiation damage

NuMI target was designed with stress safety factor ~ 1.6
To adjust design for higher superbeam intensities:

Spread out the beam spot to reduce stress, radiation damage:

Stress wave at target center α $(R_{beam})^{-2}$ 4 * POT/spill => 2 * R

Radiation damage at center α $(R_{beam})^{-2}$ 9 * beam power => 3 * R

Heat deposition α R (because path length = R/sin(θ))
Surface area of rod to carry away heat α R
→heat transfer coefficient required independent of R

Maximum temperature increases with R (conduction path length)
Maximum temperature of R=7.5 mm water-cooled graphite @2MW ~ 430 C, graphite OK at very high temperatures, as long as in inert atmosphere

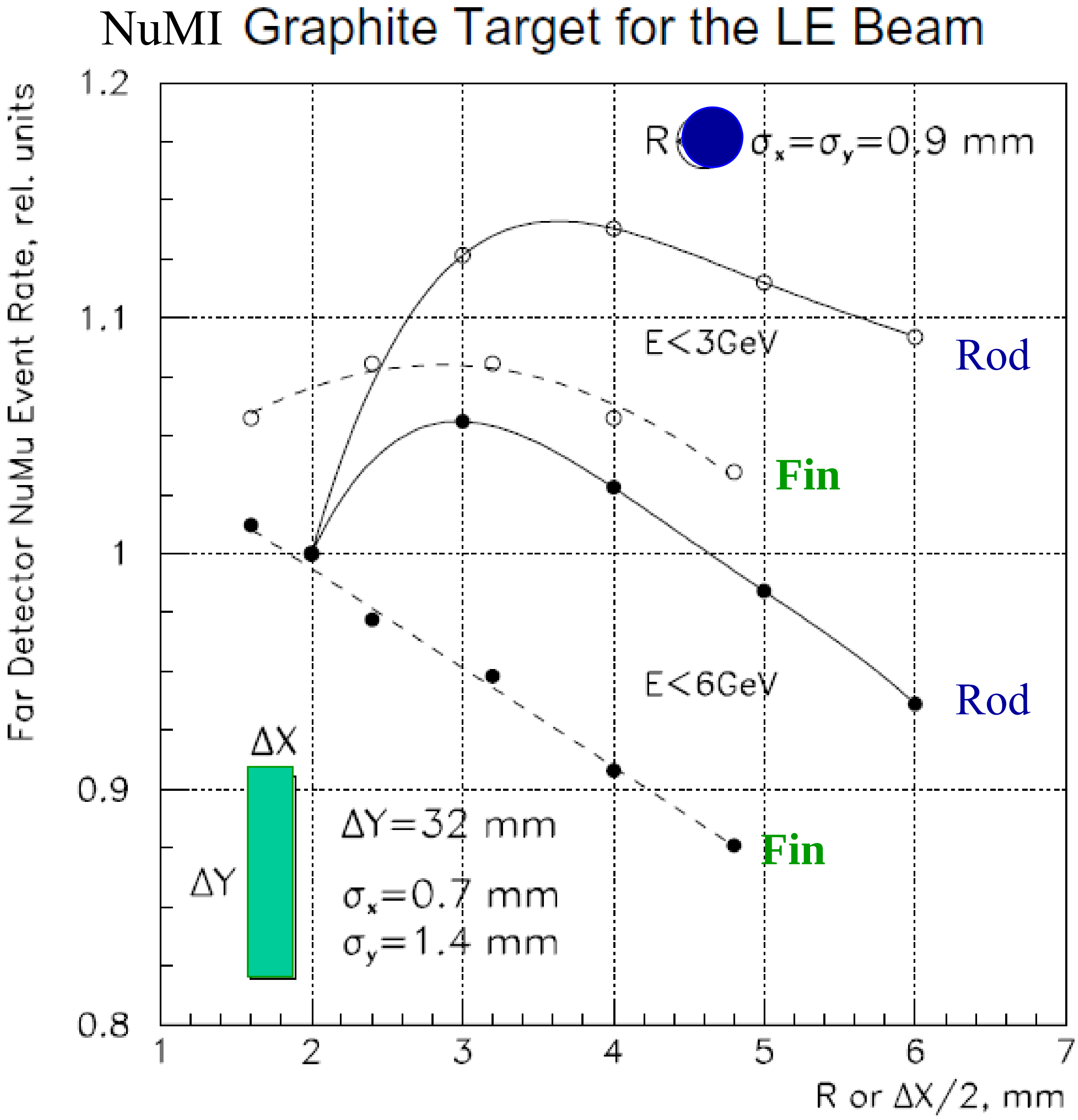
ν yield versus target radius

High E_ν => narrow target

For E_ν ~ few GeV,
optimum R_{target} ~ 3 mm

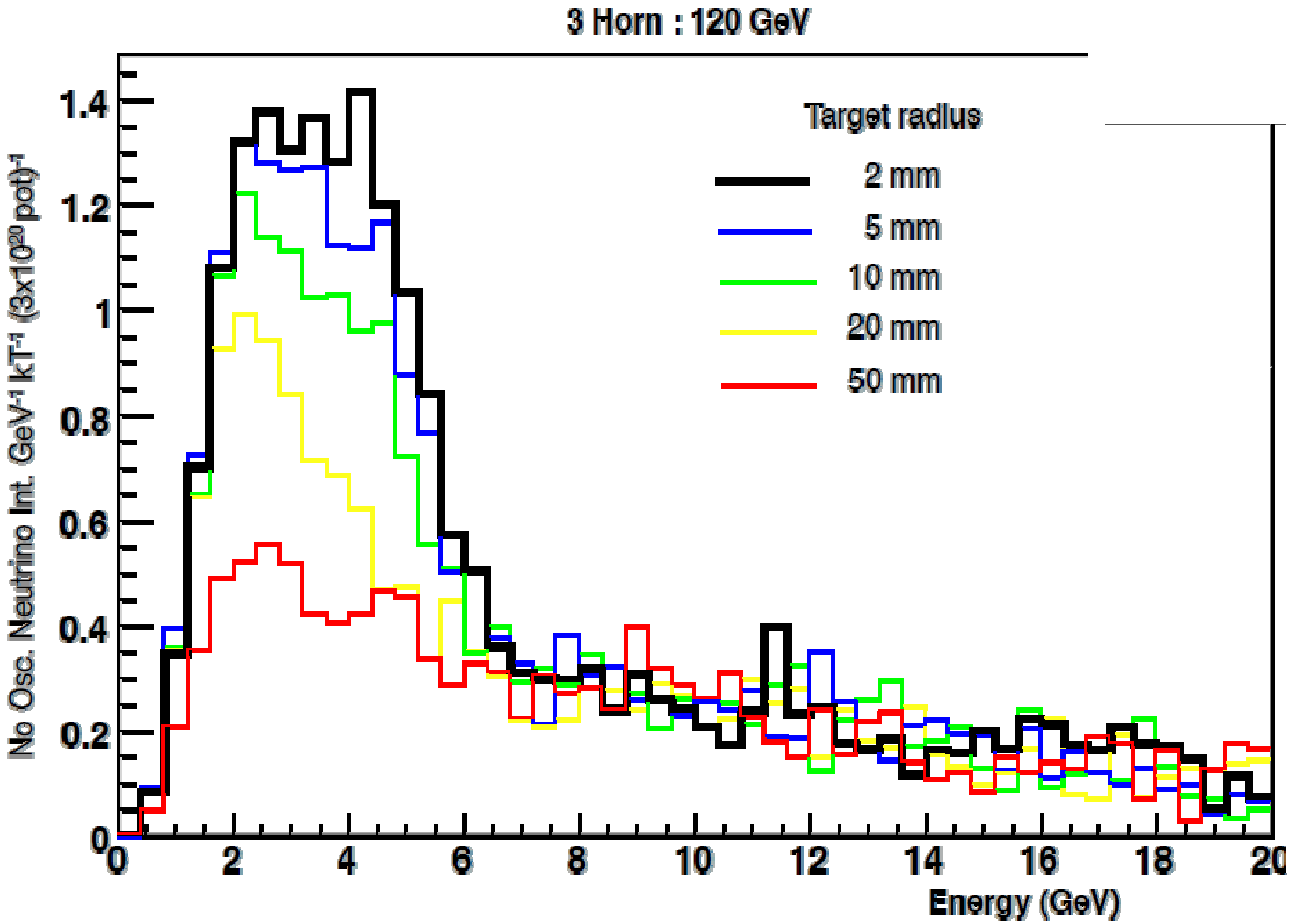
but fall-off at larger R
not horribly fast

Double target radius
cost ~ 10% of ν flux



LBNE

3 horn (T2K style) focusing but on-axis, horn radius changing with target radius



Similar conclusion:

$R_{target} < 10$ mm for LBNE

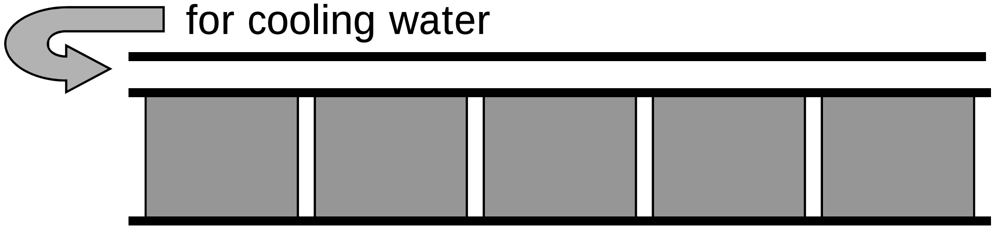
Less impact at lower E_ν

IHEP NOVA-Project X 2MW target

From 2005 study of graphite encapsulated in Al or steel sheath, with water cooling, graphite target stress and temperature were OK for 1.5e14 PPP 2 MW beam.

Remaining issues were:

- Hydraulic shock in cooling water (150 atm.) *(suggested using heat pipe to solve)*
- Radiation damage lifetime *(est. at 1 year but not well known)*
- Windows

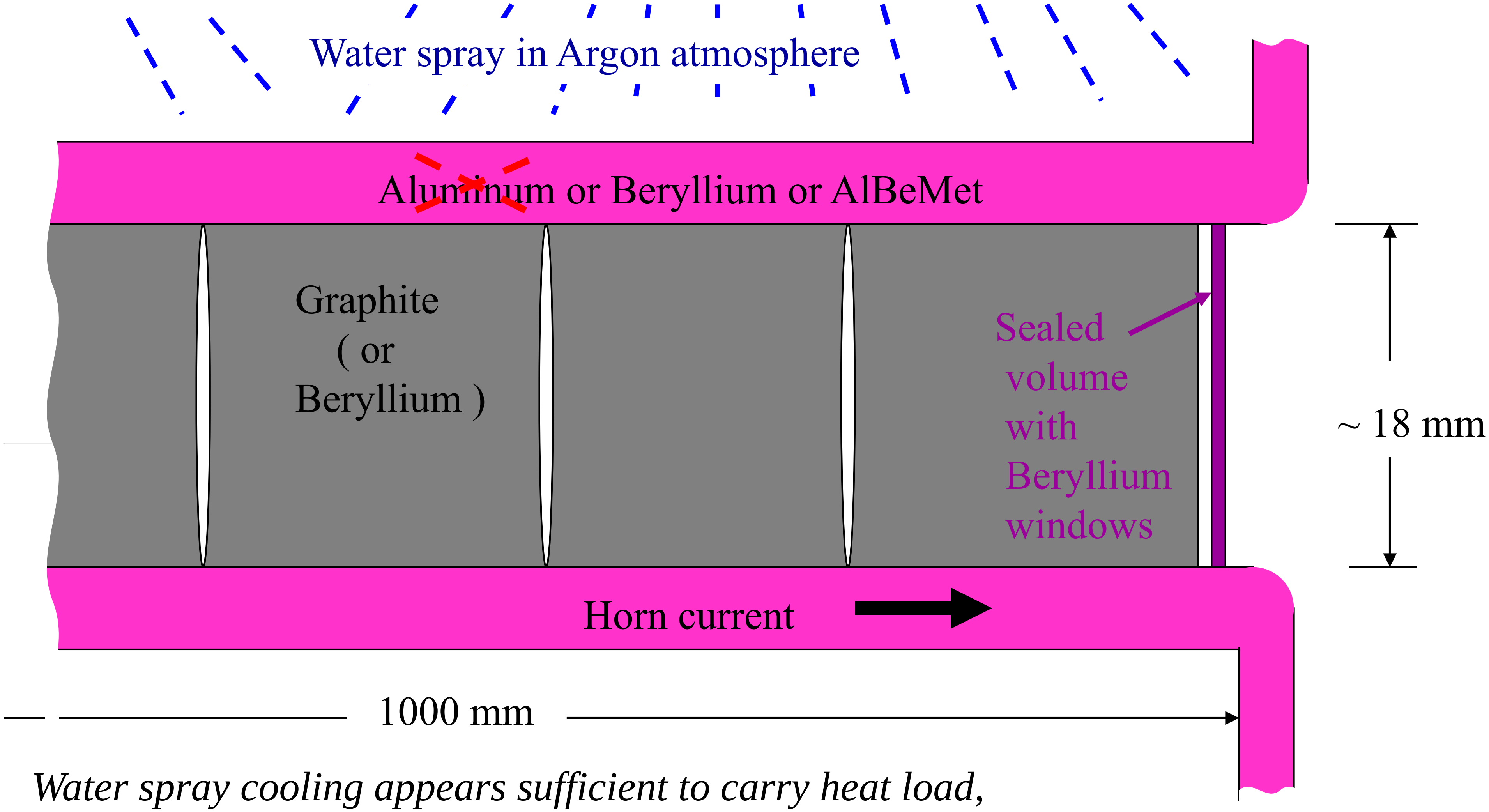


Annular channel (4 mm)
for cooling water

0.3 mm thick stainless
steel pipe

NUMI Target for 2 MW upgrades (IHEP, Protvino)

A concept of target encapsulated by horn inner conductor - *no hydraulic shock*

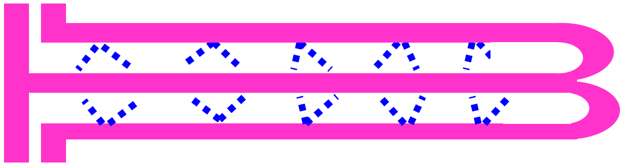


Water spray cooling appears sufficient to carry heat load, but beyond that we have not done engineering study.

Training a target ?

With single beryllium rod as combined target/horn-I.C.,
no target windows, no extra inert gas volume,
only 1 spray water cooling system…

K2K design (but was Al)



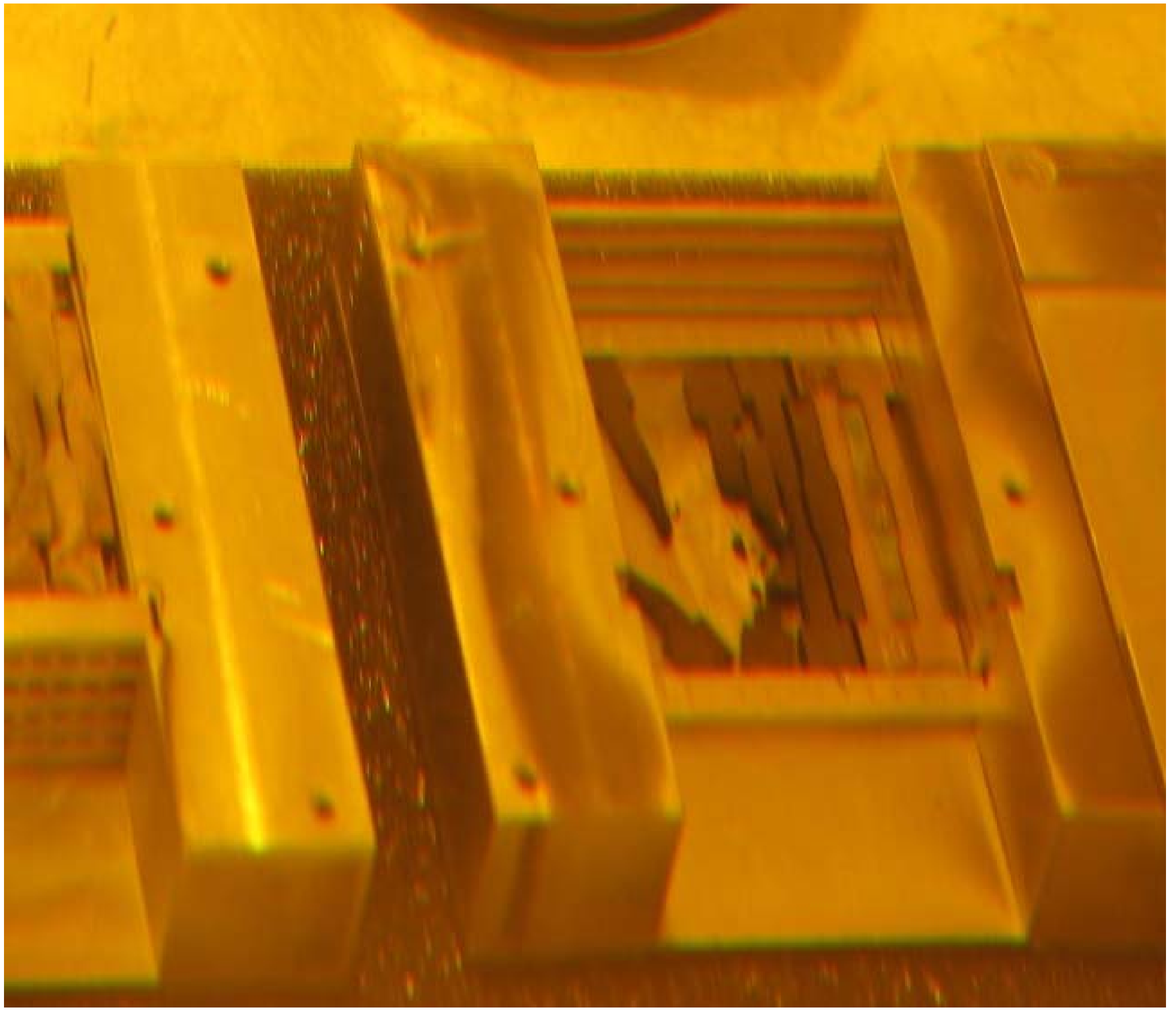
ANSYS model of 3 mm RMS, 2 MW beam
on 27 mm diameter beryllium tube
(combined target + horn inner conductor) indicates:

Stress from beam pulse exceeds yield point - - -

--- leaves target with a residual stress when it cools down from the beam pulse,
but perhaps this produces a target that is now appropriately pre-stressed,
and ready for subsequent running ?

The simplicity of a single beryllium (or AlBeMet) rod with water spray cooling
serving as both target and horn inner conductor is attractive enough
that perhaps we should not abandon the concept yet…

Radiation Damage test in IG43 Graphite - *data from Nick Simos, BNL*



200 MeV proton fluence

~10^21 p/cm^2

Scary, this is about how many p/cm^2 NuMI gets in a couple months

Note it falls apart even without high beam-induced stress

Latest from Nick:

IG430 may be better !

Important to continue testing with variety of graphites in different conditions !

NuMI target experience

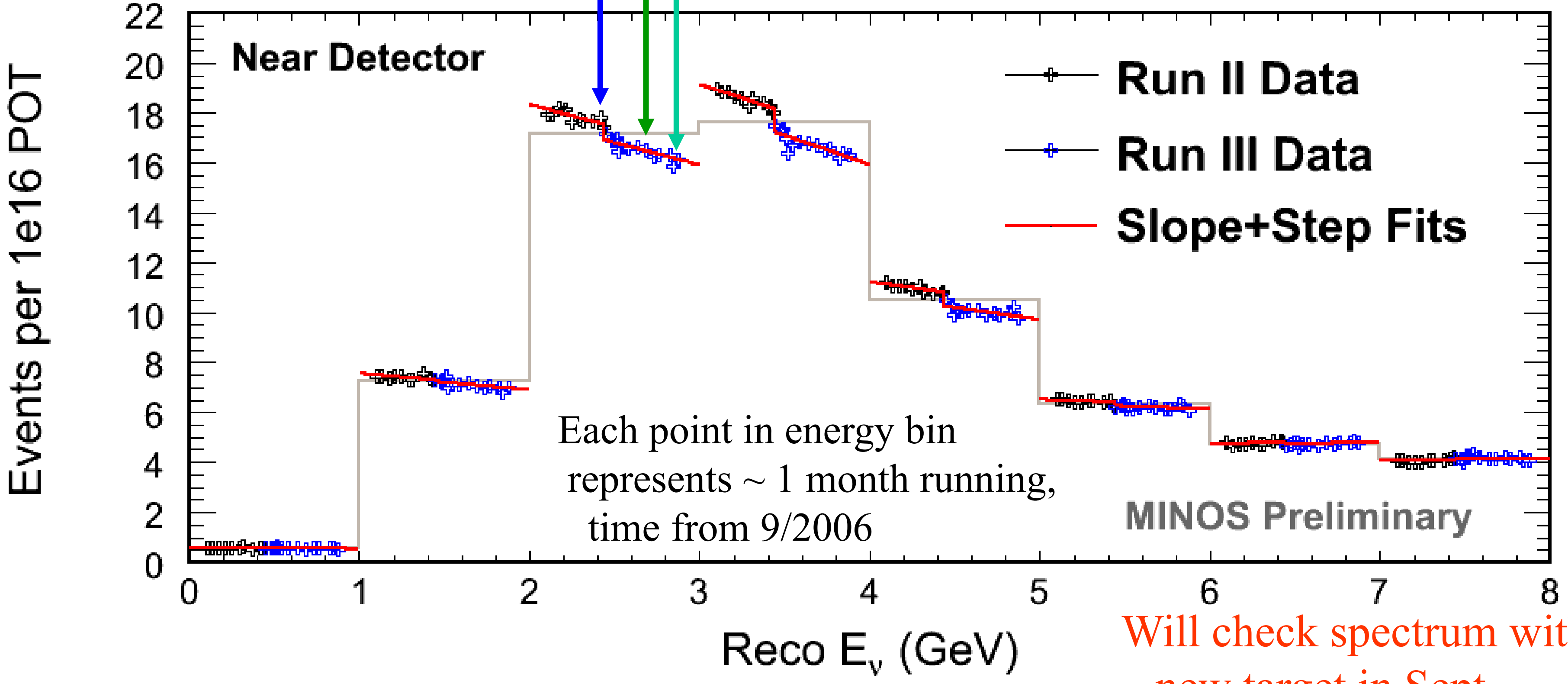
(ZXF-5Q amorphous graphite)

Gradual decrease in neutrino rate attributed to target radiation damage

Decrease as expected when decay pipe changed from vacuum to helium fill

No change when horn 1 was replaced

No change when horn 2 was replaced



Each point in energy bin represents ~ 1 month running, time from 9/2006

Will check spectrum with new target in Sept.

Extrapolate NuMI target lifetime to Project X

3 years running on this target, beam power 0.1 to 0.3 MW
NuMI accumulated 6 10^{20} POT @ 120 GeV → 4.44 MW-month

Assume Project X 2.3 MW @ 70% uptime → 4.4 targets / year

Similar to anti-proton production target, but couple shifts/change compared to NuMI couple weeks/change

NuMI used 1.1 mm RMS beam spot
so integrated flux at center is 8 10^{21} POT / cm^2

If Project X target uses 3 mm spot size (9 mm radius target)
and radiation damage scales by $(\text{beam-radius})^{-2}$ → 0.6 targets / year

Save many $M on rapid change-out capability ???

Caveats:

- Is 10% neutrino rate degradation considered acceptable?
- Will encapsulation of the graphite reduce the density decrease?
- Will higher temperature reduce the radiation damage?
- Would another grade of graphite do better?
- Will radiation damage really scale by $(\text{beam-radius})^{-2}$?
- Radiation damage probably twice as fast for 60 GeV protons at same power

Scaling not so cheerful for CERN SPL with 30x more protons, so more later …

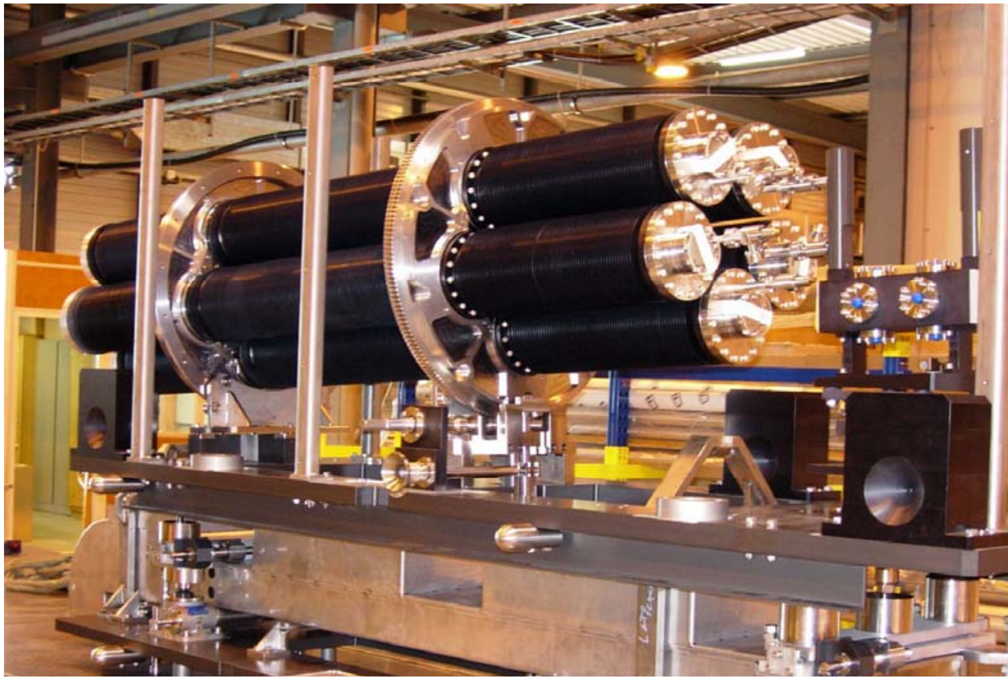
Alternate target material: CNGS experience

CNGS has carbon-carbon target in beam

- much lower thermal expansion coefficient than NuMI graphite
  reduces stress waves from fast beam spill
- CNGS target also operates at higher temperature
  slowing down radiation damage?

Although a solution to radiation damage for CNGS or NOVA, Gatling gun target doesn't fit in horn for T2K, LBNE

Accumulated flux at center is ~10^{21} protons/cm^2,
(~ 1/7 that of NuMI target) with no obvious sign of deterioration



Will be very interesting to see how this target does with increased exposure !

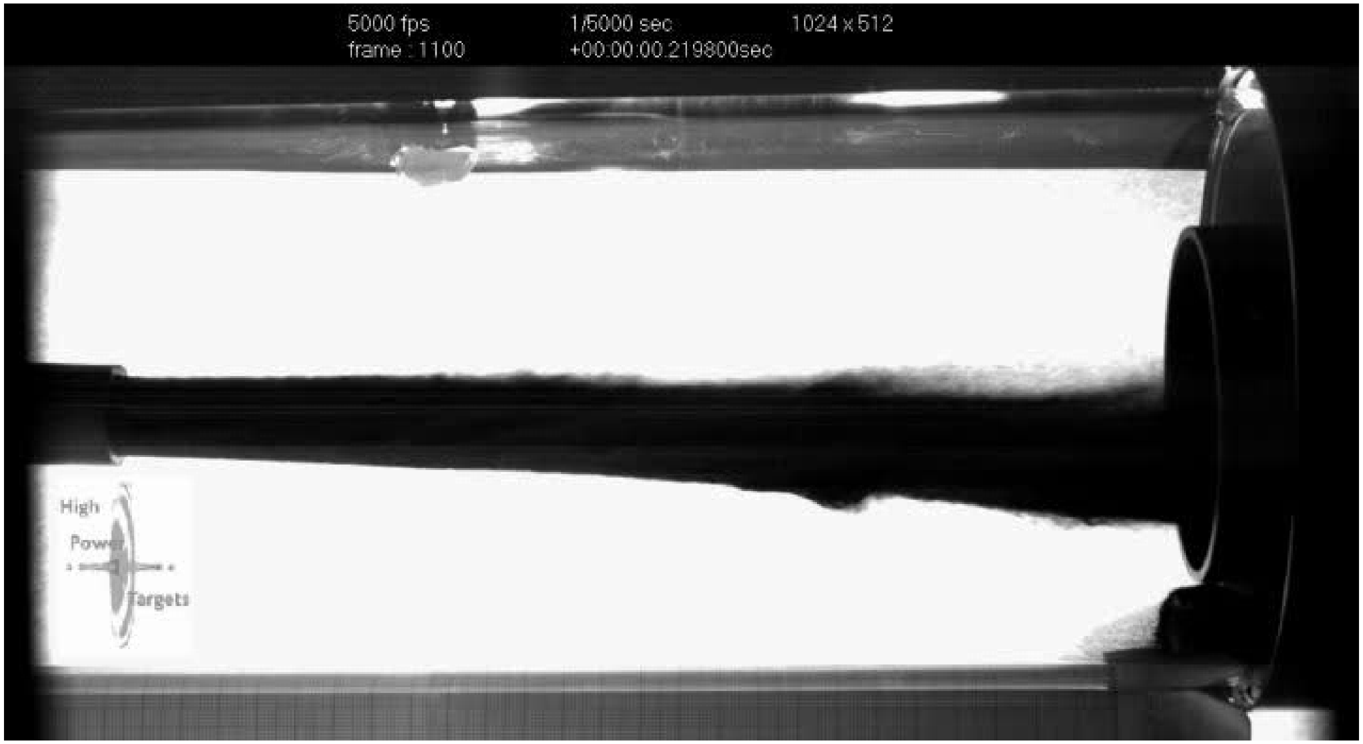
Caveat: Lack of neutrino near detector may make it hard to see subtle changes ?

Powder Jet Target

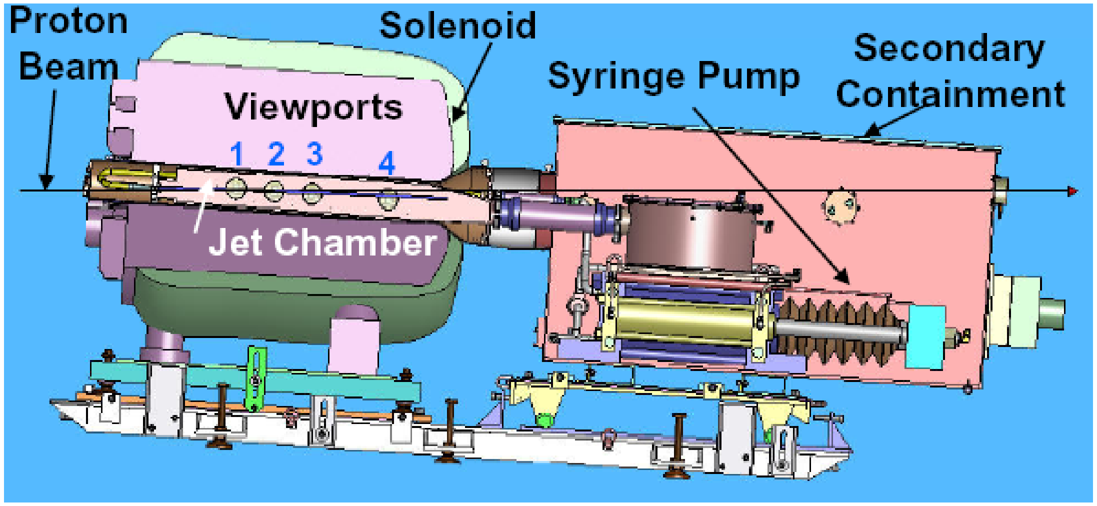
Very interesting R&D being done by RAL

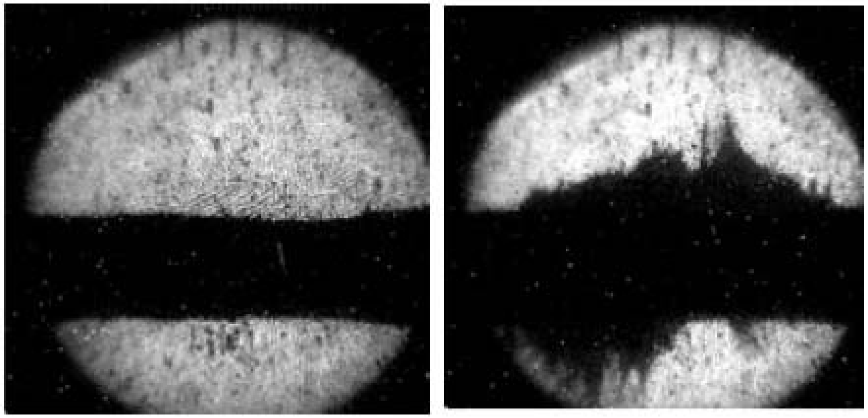
Jet can solve:
- Stress
- Rad. Damage
- Cooling

Some issues:
- Erosion
- Horn/beam integration
- Reliability



Liquid Mercury Jet Target





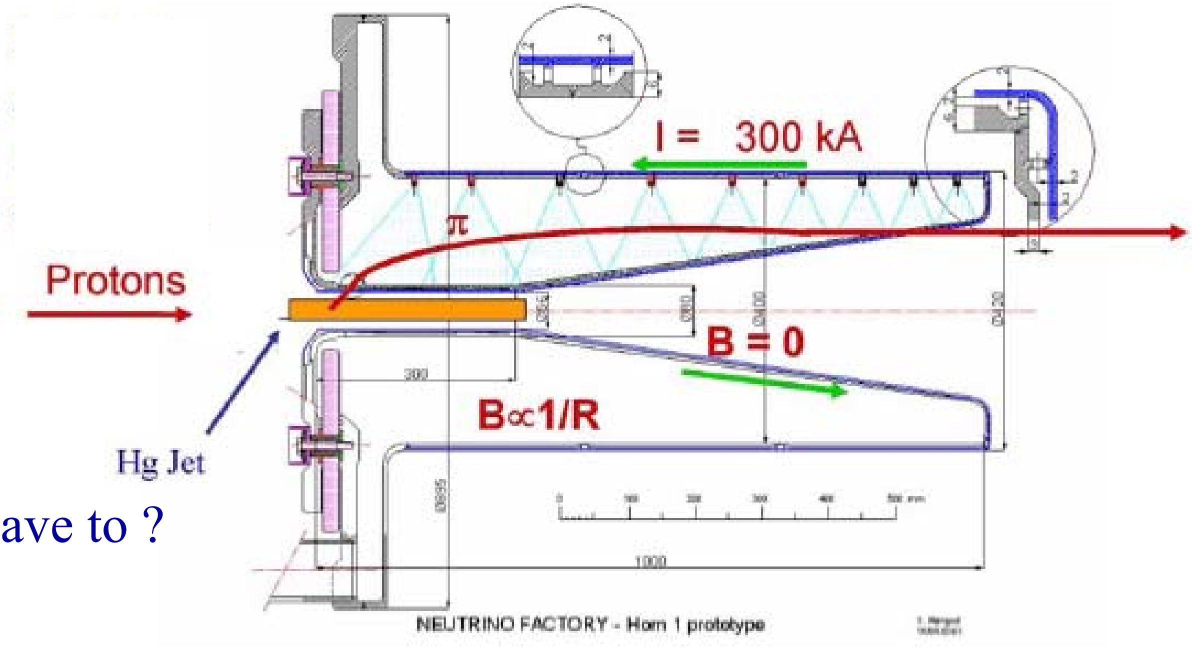
CERN MERIT Experiment (Nov 2007)

Demonstration of a mercury jet target
3×10^{13} protons/spill

Possible to apply this to horns
to circumvent 10^{22} p/cm^2 limit
on target lifetime, so matches to SPL

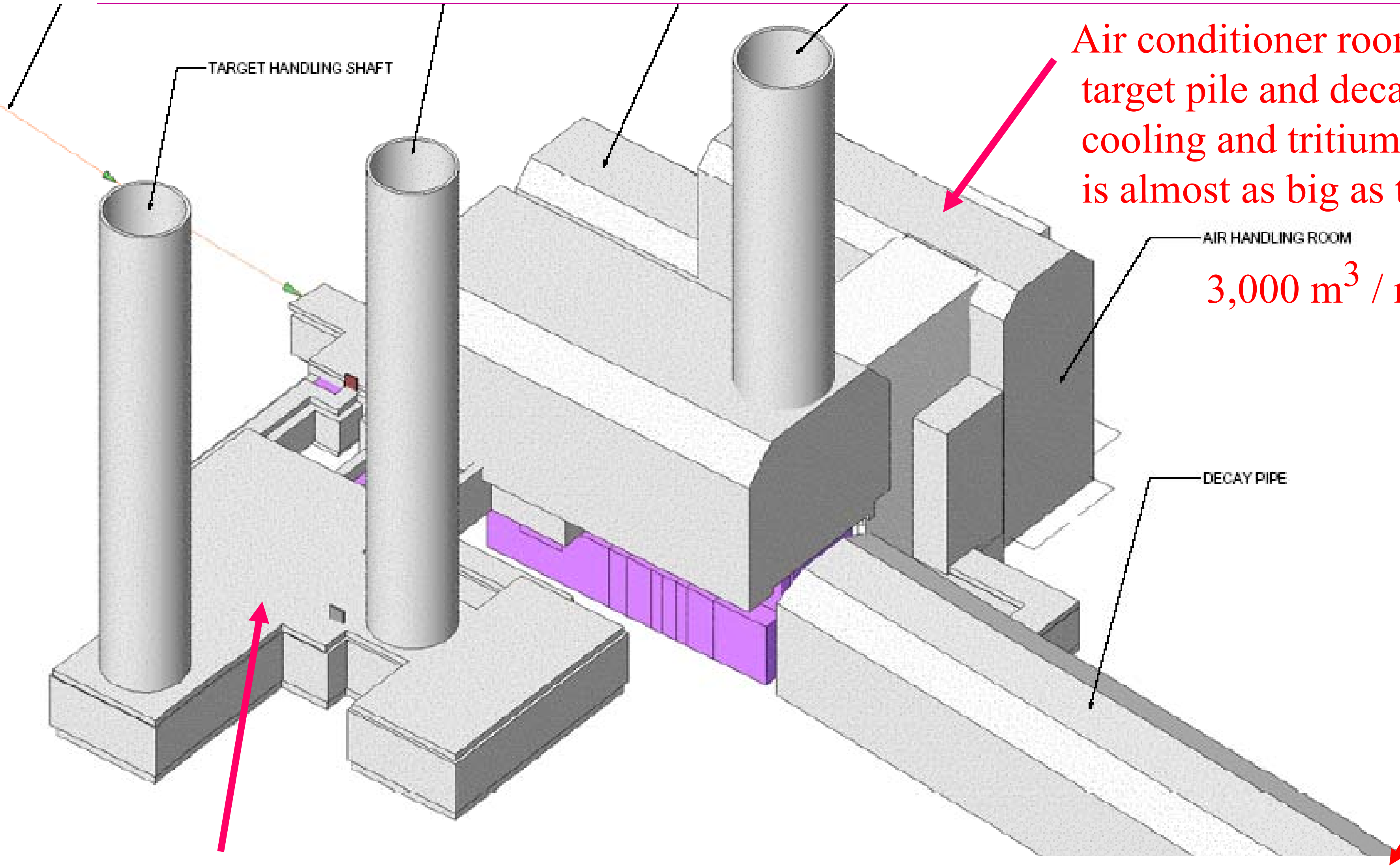
ES&H harder, don't use Hg until you have to ?

Mercury jet target (CERN SPL study):



One concept of LBNE Target-hall

target is ~50 m below ground



Air conditioner room for target pile and decay pipe cooling and tritium collection is almost as big as target hall !

3,000 m^3 / minute

$

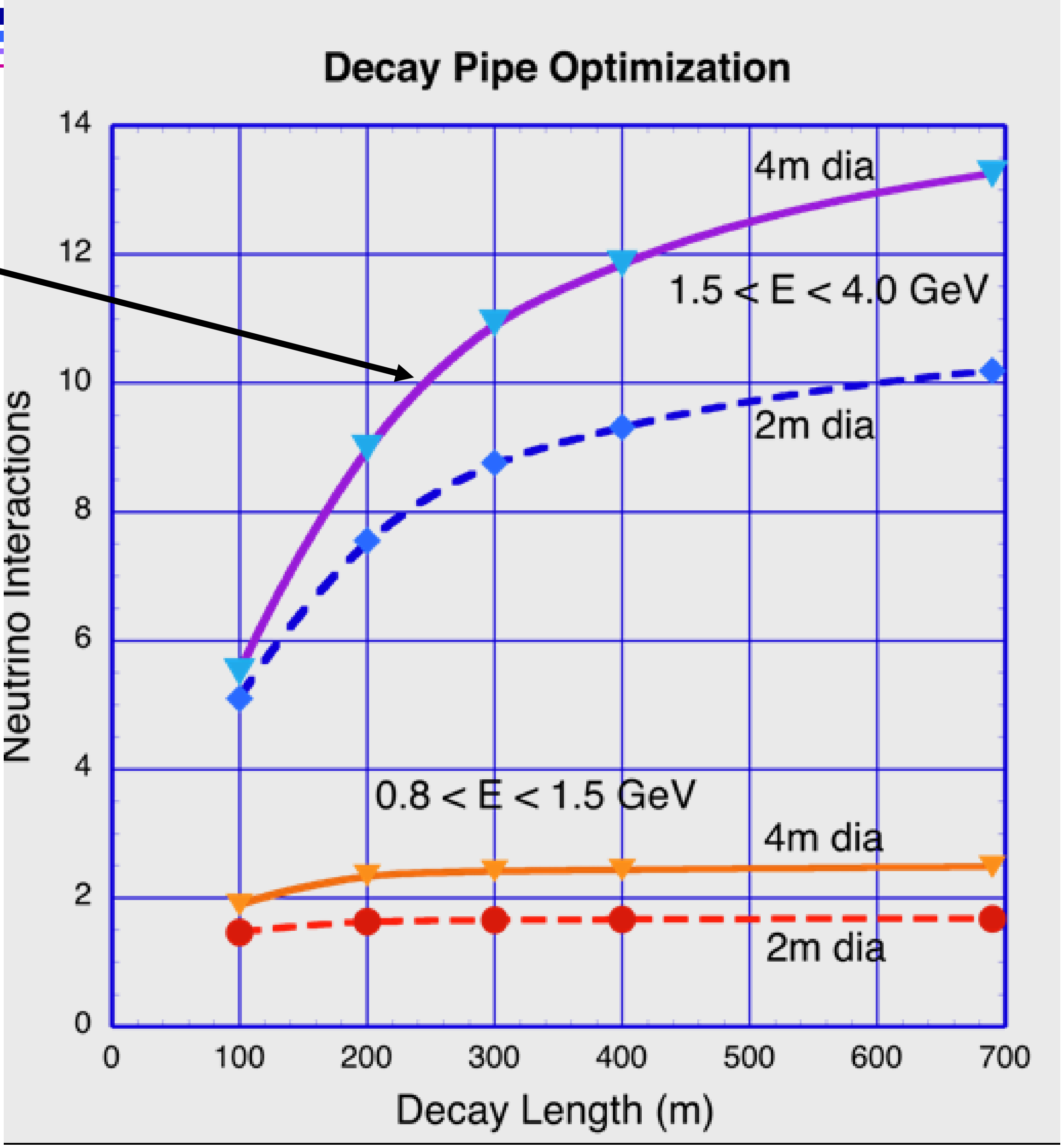
Staging and rapid exchange of target + horn 1 through side of target pile

LBNE Decay Pipe

Working design:

4 m diameter

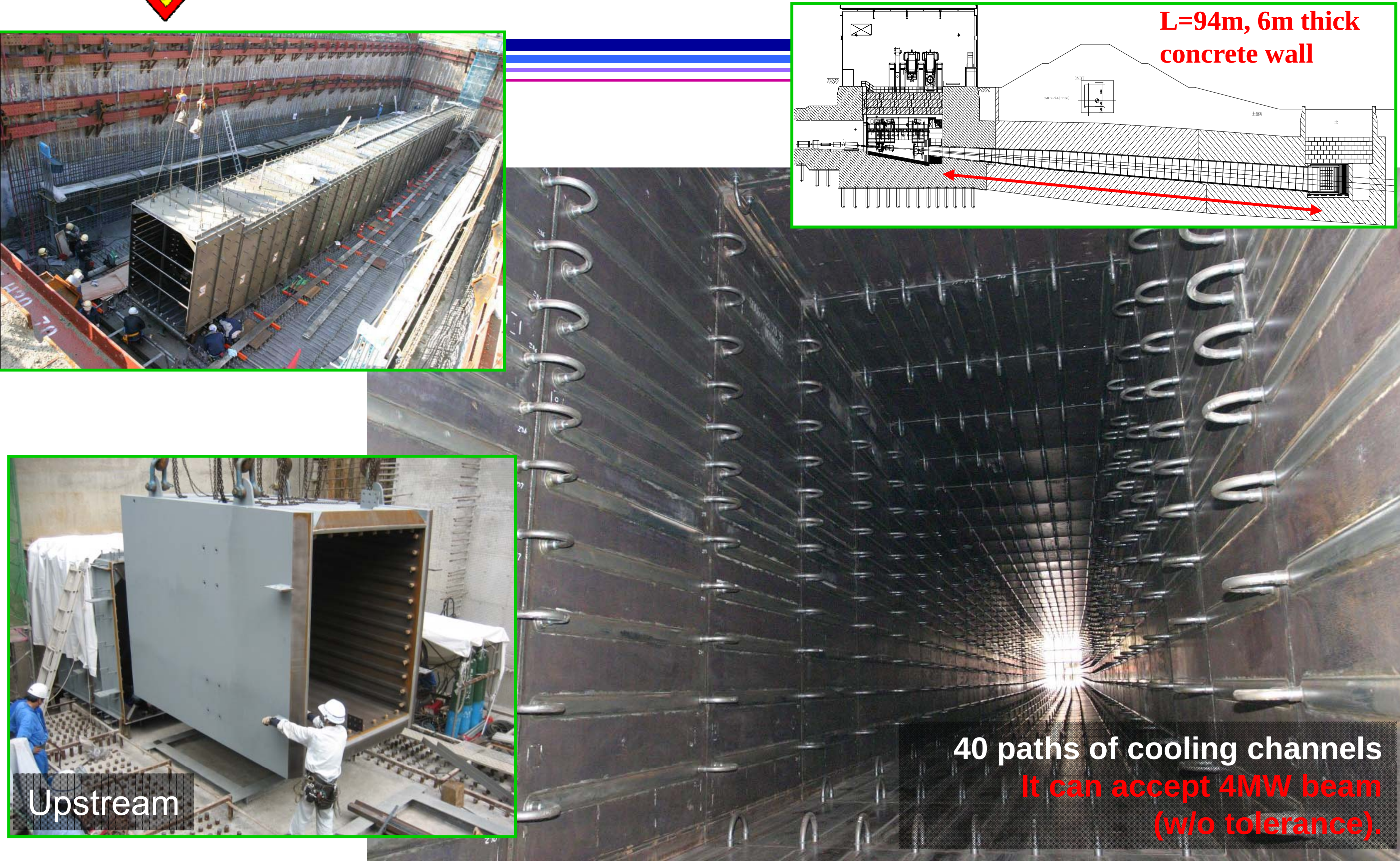
250 m length



Energy deposited
in decay pipe:
0.4 to 0.5 MW
for 2 MW beam

Requires active cooling

T2K Decay Volume for 4 MW



L=94m, 6m thick concrete wall

40 paths of cooling channels

It can accept 4MW beam (w/o tolerance).

T2KK07: 3rd International Workshop on a Far Detector in Korea for the J-PARC Neutrino Beam · Sep 30,'07 · Tokyo Japan

Decay Pipe Risk

After a mere 30 days running LBNE at 2 MW:

Cool-down time:	1 day	1 month	1 year
Residual radiation:	150 mSv/hr	35 mSv/hr	9 mSv/hr
(U.S. units)	15,000 mrem/hr	3,500 mrem/hr	900 mrem/hr
Time an FNAL worker could be there:	0.1 minute	1 minute	3 minutes

Decay Pipe is almost immediately un-accessible for repair due to residual radiation

Decay Volume Options?

NuMI has 5 miles of un-accessible water pipes

Vacuum + water cooling:

- Yields most neutrinos
- Large thin window at upstream end is a headache
- Stored energy is a bomb waiting to go off
- Repair of vacuum or water cooling is problematic (low prob. high consequence)

Sealed helium volume + water cooling:

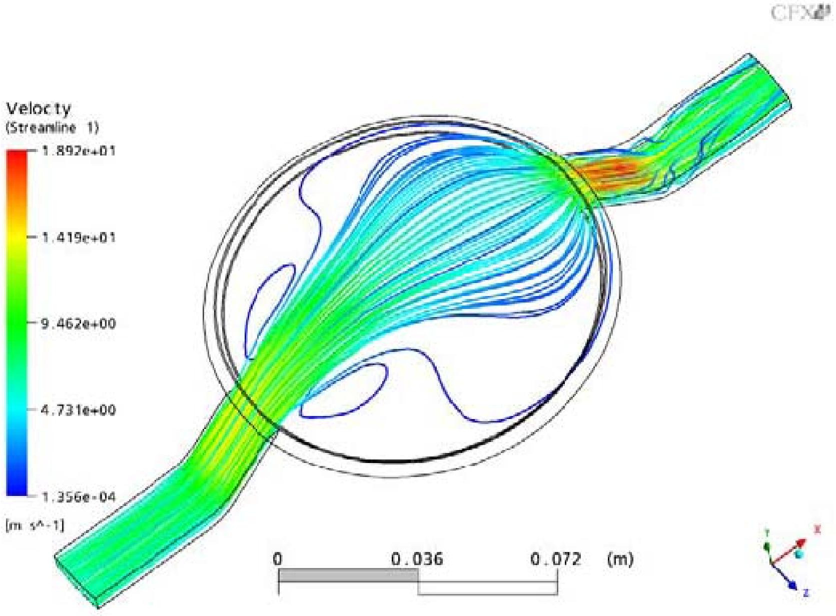
- Helium-filled gives few % fewer neutrino yield than vacuum
- T2K eliminated upstream window by putting target pile in helium volume
  - Reduces corrosion of components
  - Evacuate before putting new helium in? → still want vacuum vessel integrity
  - Dump helium inventory for access
- Repair of vacuum or water cooling is problematic (low prob. high consequence)

Air filled + re-circulating air cooled: *flow ~ 1,500 m^3 / min. (+ similar for target hall)*

- Air-filled gives 10% less neutrino yield than helium-filled
- All air equipment is external, where it can be maintained, no buried water lines
- Air exchange system, ready for access in a few hours
- Air provides system to collect substantial fraction of tritium before it goes somewhere else
- Air needs external space for decay of radio-activation before release *~ 10,000 m^3*
- Have to make sure air doesn't go in unwanted directions (easier underground)

T2K Proton Beam Window

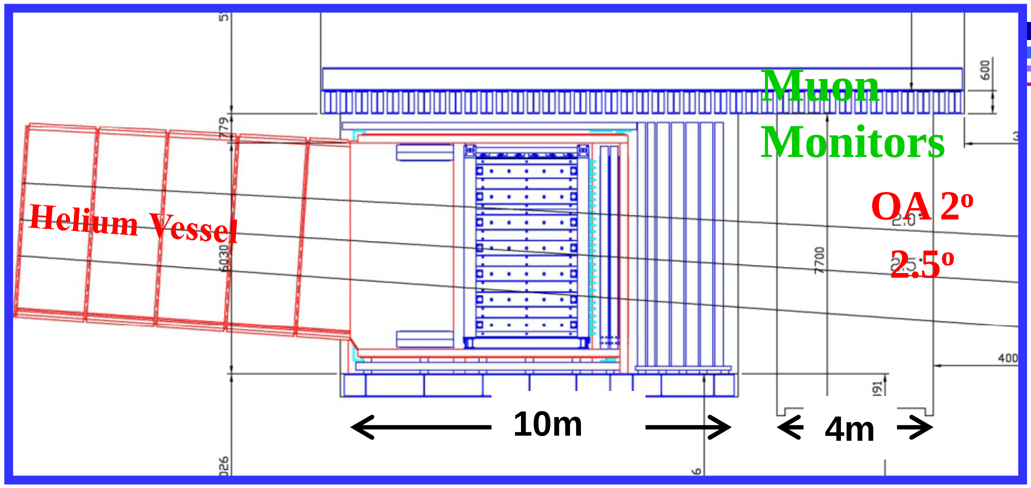
Helium cooled
Gas operated pillow seal for remote installation

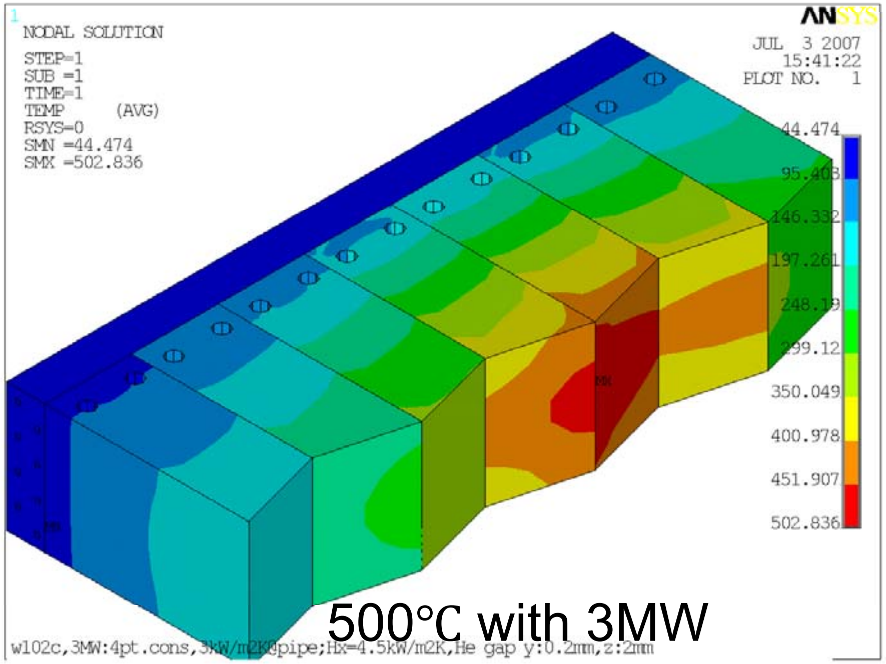


Depending on beam structure,
may need some modification
for superbeam

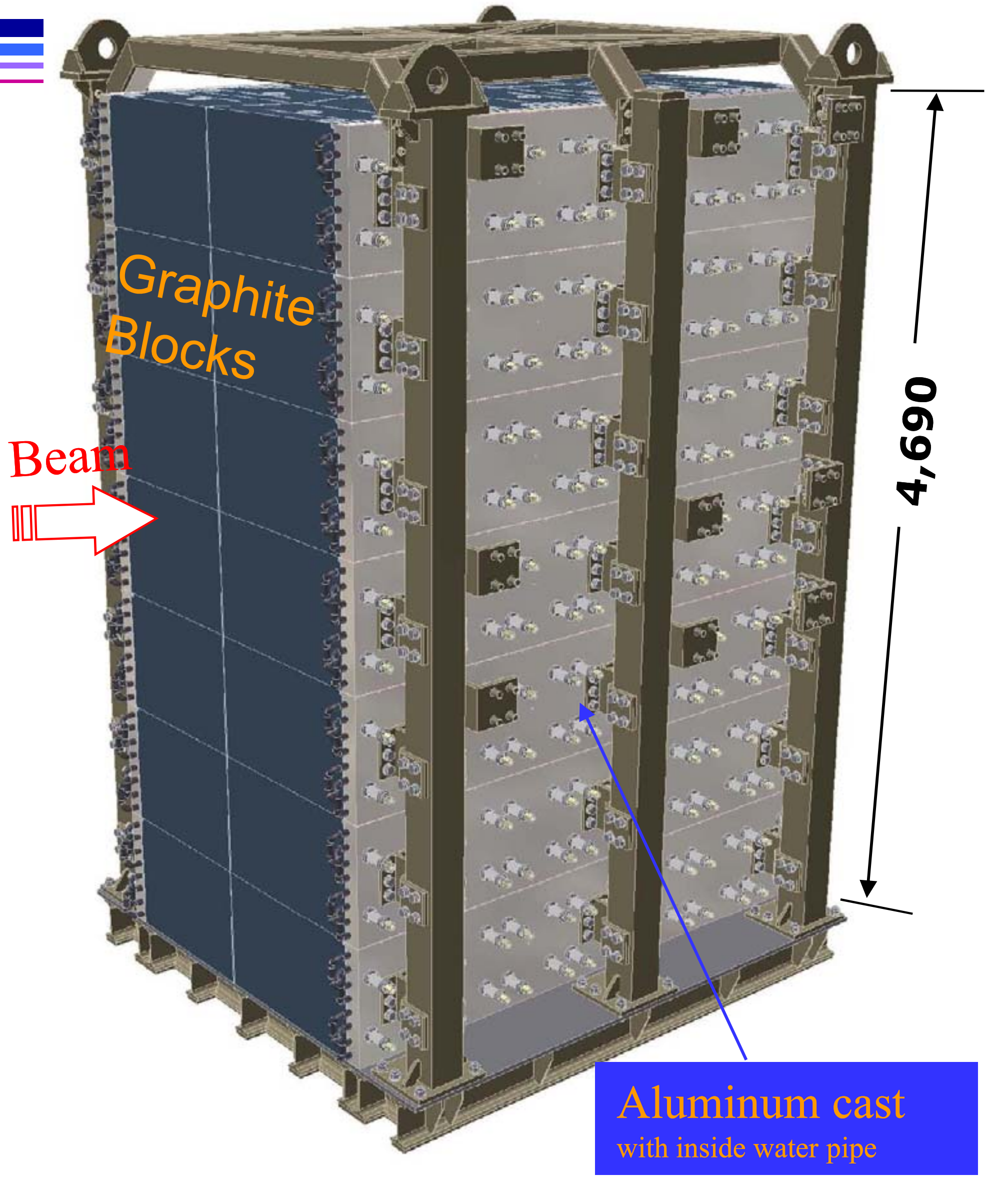
For your superbeam, buy beg borrow or steal one of these !

A Superbeam Beam Dump already exists at T2K





500°C with 3MW
[Assuming phase-I target]



Aluminum cast
with inside water pipe

T2K Hadron Absorber

Feb. 12, 2009

T2K 4 MW absorber exists!
For other future superbeams:
consider carefully repair scenarios

Tritium 101

Tritium is produced in hadronic showers, proportional to beam power, not hugely sensitive to material choice, hence mostly embedded in the radiation shielding.

NuMI produces few hundred Ci/yr. Superbeam will produce few thousand Ci/yr.

Tritium is super-mobile, penetrates concrete, even solid steel

NuMI has found about 10% of the tritium produced in the shielding ending up in the dehumidification condensate each year.

And it is the gift that keeps on giving, long after the beam turns off.

Drinking water limit (U.S.) is 20 micro-Ci of HTO per liter of H2O.

There are a lot of micro-Ci in a Ci. (Exercise for the reader)

Putting tritium in the water is not good public relations,
even if below drinking water standards.
Also, standards for tritium may change.

Tritium 102

Half-life of Tritium is 12.3 years, so eventually it takes care of itself.

Beta emission from tritium will not penetrate skin.
Do absorb some HTO from breathing vapor; excreted from body in about 10 days.
But drinking HTO is the main hazard.

When elevated Tritium levels were discovered in NuMI sump water,
we installed air dehumidification equipment.

This reduced tritium in ~1000 liter/minute sump water stream by an order of magnitude, and put the tritium in ~ 0.2 liter/minute waste stream.

Originally, waste stream was barreled, solidified and sent to waste facility.
Now condensate is evaporated, and is small component of FNAL overall air emissions.

This system could work even better in a facility designed for it rather than retro-fitted.

Tritium is not a show-stopper for superbeam, but needs to be carefully considered in design.

Systematics
beam designers need to know

For superbeam, unlike neutrino factory,
target station can affect experiment systematics.

For low-statistics appearance experiment, beam systematics is less problematic.

For high-statistics disappearance, projecting far detector spectrum from near detector can depend on state of radiation damage of solid target, pulse-to-pulse jitter of a jet target, shower of particles off decay pipe walls, horn alignment, etc.

One solution: put near detector far enough away (~ 10 km instead of < 1 km) to make decay pipe look like point source. Such near detector is deep and expensive.

Affects:
- construction and alignment tolerances
- needed knowledge of fringe magnetic fields
- needed accuracy of shower Monte Carlos

Need to know experimental systematics requirements going into beam hardware design.

Corrosive air

The Mini-Boone intermediate absorber came crashing down,
even though there was a design strength safety factor of four on the chain
and the chain was not in the beam.

Radiation in humid air creates nitric acid (and Ozone …)

High strength steel does not like hydrogen (embrittlement)

NuMI has also had problems with radiation induced accelerated corrosion
(stripline clamp failure, target positioning drive, decay pipe window corrosion)

More resources should be applied to general studies of air + radiation, etc
-- we are in rather unusual environmental conditions !

I have skipped many important topics

Proton beamline

Beam Monitoring

Horn design

Remote Handling

Collimator

Instrumentation

Beam based alignment

Timely design resources

Target pile cooling

Shielding

Access

Cranes

Utilities

Projects

Decommissioning

NuMI Lessons Learned

Closing

Planning for Mega-watt proton sources for superbeams is underway

superbeams could exist in about a decade

What each superbeam looks like depends on the physics one wants to do

Once built, will have limited flexibility (unless pre-designed and paid for)

The target is the component where materials properties are on the edge

For JPARC and FNAL beams, by scaling from current targets,
conventional solid targets appear plausible,
detailed design and engineering remains to be done

For T2K, the target hall / decay pipe / absorber for superbeam already exist

For others, significant design choices still remain