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.

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

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<th>Protons per spill</th>
<th>Repetition rate</th>
<th>Beam power</th>
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<td><strong>JPARC “roadmap”</strong></td>
<td>30 GeV</td>
<td>$6.7\times10^{14}$</td>
<td>0.5 Hz</td>
<td>1.7 MW</td>
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<tr>
<td><strong>FNAL Project X</strong></td>
<td>120 GeV</td>
<td>$1.6\times10^{14}$</td>
<td>0.7 Hz</td>
<td>2.1 MW</td>
</tr>
<tr>
<td></td>
<td>(60 GeV ?)</td>
<td></td>
<td>(1.4 Hz ?)</td>
<td></td>
</tr>
<tr>
<td><strong>CERN SPL</strong></td>
<td>3.5 GeV</td>
<td>$1.4\times10^{14}$</td>
<td>50 Hz</td>
<td>4 MW</td>
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In all cases, fast-extract a huge number of protons, maximizing stress waves in target (factor of 4 above current NuMI POT/spill)
Open and early involvement of public

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

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

Decay pipe: physics says area $\pi (2 \text{ m radius})^{2}$,
but ES&H says shielding area $\pi (5 \text{ m radius})^{2}$

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 $E_\nu = 2 \text{ GeV L}/1000 \text{ km}$

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

Narrow band beam (reduce backgrounds from $\nu$ 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 $\nu$ and $\bar{\nu}$?

Balance between higher $\nu$ 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*
How to build a Superbeam
Jim Hylen / NUFAC09
July 21, 2009
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T2K off-axis beam

First Application
(ref.: BNL-E889 Proposal)

Super-K.

π decay Kinematics

ν (νe)

π (mπpπ)

θ

ν flux (au)

Eν (GeV)

0°

2°

2.5°

3°

DAB 2 degree
DAB 2.5 degree
DAB 3 degree

Statistics at SK
(OAB 2.5 deg, 1 yr, 22.5 kt)
~ 2200 νμ tot
~ 1600 νμ CC
νe ~0.4% at νμ peak

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

TKobayashi (KEK)
Want a wide band beam, cover the 1\textsuperscript{st} and 2\textsuperscript{nd} oscillation maximum

(Above 10 GeV is not very useful)

0.8 GeV  2.7 GeV  1\textsuperscript{st} round detectors don’t do $\nu$ sign selection

Implication is probably an on-axis horn focusing beam, with target shoved into the first horn  ($\pi$ angle from target $\sim 0.1$ GeV / $E_{\nu}$)
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
Solenoid focusing
Harold G. Kirk / NUFAC06

Solenoid can give higher peak, lower tails than horn focusing

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

It's the fringe field that bends pions parallel to beam axis
Target 101

Long enough (2 interaction lengths) to interact most protons
Dense enough that $2 \lambda_{\text{int}}$ fits in focusing system depth-of-field
Radius: $R_{\text{target}} = 2.3$ to $3 \, R_{\text{beam}}$ (minimize gaussian tails missing target)
Narrow enough that pions exit the sides without re-absorption

(but for high $E_{\text{proton}}$ and low $E_{\nu}$, secondary shower can help)
High pion yield (but to first order, $\nu$ flux $\propto$ 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

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
How to build a Superbeam  
Jim Hylen / NUFAC'T09  
July 21, 2009  
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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 $\propto (R_{beam})^{-2}$  
$4 \times \text{POT/spill} \Rightarrow 2 \times R$

Radiation damage at center $\propto (R_{beam})^{-2}$  
$9 \times \text{beam power} \Rightarrow 3 \times R$

Heat deposition $\propto R$ (because path length = $R/\sin(\theta)$)  
Surface area of rod to carry away heat $\propto R$  
→ 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
How to build a Superbeam
Jim Hylen / NUFACT09
July 21, 2009

ν yield versus target radius

High $E_\nu$ => narrow target

For $E_\nu$ ~ few GeV, optimum $R_{\text{target}}$ ~ 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:

$R_{\text{target}} < 10 \text{ mm}$ for LBNE

Less impact at lower $E_{\nu}$
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

**NUMI Target for 2 MW upgrades (IHEP, Protvino)**
A concept of target encapsulated by horn inner conductor
- no hydraulic shock

Water spray in Argon atmosphere

Aluminum or Beryllium or AlBeMet

Graphite (or Beryllium)

Sealed volume with Beryllium windows

Horn current

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 $6 \times 10^{20}$ POT @ 120 GeV $\rightarrow$ 4.44 MW-month

Assume Project X 2.3 MW @ 70% uptime $\rightarrow$ 4.4 targets / year

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

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

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?

Accumulated flux at center is \( \sim 10^{21} \text{ protons/cm}^2 \),

\((\sim 1/7 \text{ that of NuMI target})\) 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
CERN MERIT Experiment (Nov 2007)

Demonstration of a mercury jet target
3x10^{13} protons/spill

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

ES&H harder, don’t use Hg until you have to?
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
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).
### Decay Pipe Risk

After a mere 30 days running LBNE at 2 MW:

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

*Decay Pipe is almost immediately un-accessible for repair due to residual radiation*
Decay Volume Options?

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? \(\rightarrow\) 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: \(\text{flow} \sim 1,500 \text{ m}^3 / \text{min.} \) (+ 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 \(\sim 10,000 \text{ m}^3\)
Have to make sure air doesn’t go in unwanted directions (easier underground)

NuMI has 5 miles of un-accessible water pipes
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

- Helium Vessel
- Muon Monitors
- OA 2°

500°C with 3MW

[Assuming phase-I target]

Aluminum cast with inside water pipe

Graphite Blocks
T2K Hadron Absorber

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

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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*