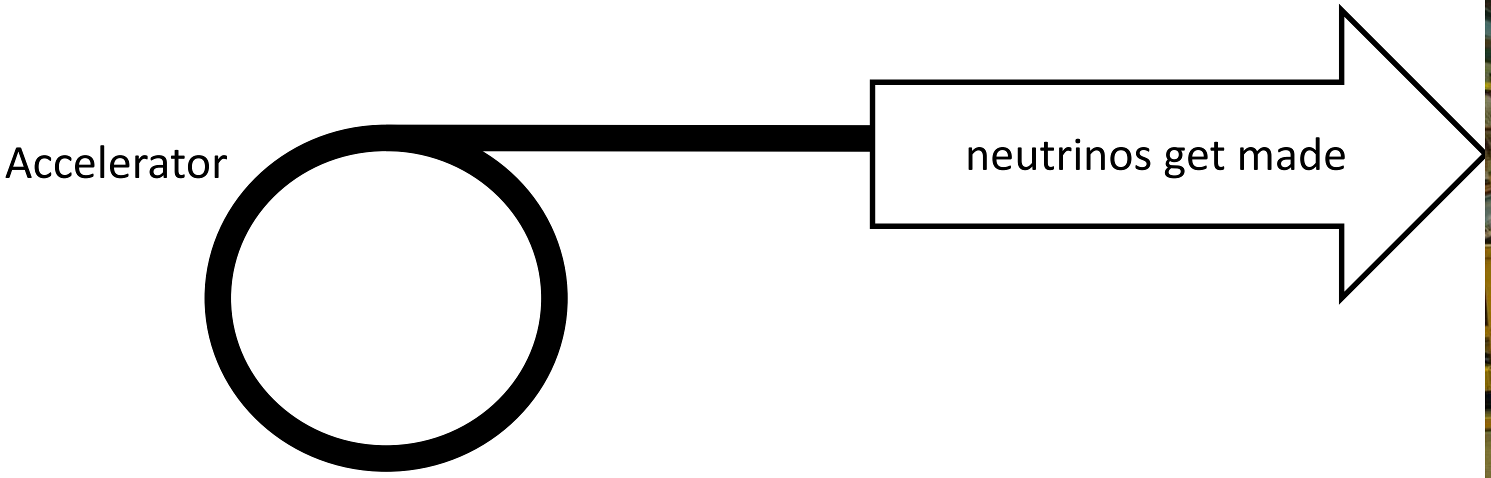
Neutrino Production at Accelerators

How the Sausage is Made

Neutrino University 2018

Tom Kobilarcik – External Beams Department, Fermilab

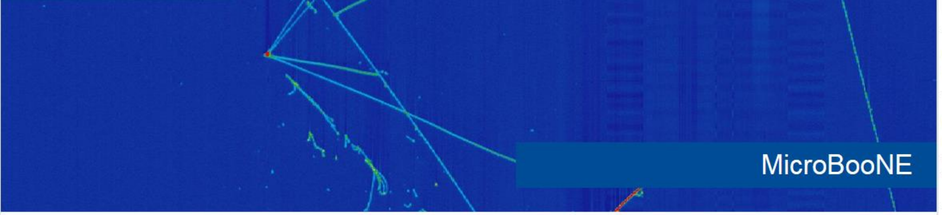


By Jon 'ShakataGaNai' Davis, CC BY 3.0,
https://commons.wikimedia.org/w/index.php?curid=3146809

Fermilab

Home | About | Science | Jobs | Contact | Phone Book

Newsroom | LBNF/DUNE | Come visit us | Resources for



MicroBooNE

About MicroBooNE

- Physics
- Detector
- Collaboration
- R&D Program
- Documents and Publications
- Images and videos
- In the News
- Contact

For Collaborators

µBooNE

Search this site... Search

Related Experiments

MicroBooNE is a large 170-ton liquid-argon time projection chamber (LArTPC) neutrino experiment located on the Booster neutrino beamline at Fermilab. The experiment first started collecting neutrino data in October 2015.

MicroBooNE will investigate the low energy excess events observed by the MiniBooNE experiment, measure a suite of low energy neutrino cross sections, and investigate astro-particle physics.

MicroBooNE is also contributing crucial input towards the construction of massive kiloton scale LArTPC detectors for the future Deep Underground Neutrino Experiment (DUNE) and is the first detector in the Short-Baseline Neutrino (SBN) program at Fermilab.

The MicroBooNE spokespeople are Bonnie Fleming (Yale University) and Sam Zeller (Fermilab). The international collaboration consists of over 170 scientists from 31 institutions.

MicroBooNE physics

Learn about the MicroBooNE physics program.

MicroBooNE detector

Learn about the MicroBooNE Time Projection Chamber (TPC).

Facebook

MicroBooNE
Like Page

MicroBooNE
on Thursday

You have to check this out!

Symmetry magazine
Magazine · 21,462 Likes
· July 12 at 8:04 AM

For the first time, scientists have traced an ultra-high-energy cosmic neutrino back to its source. #blazarneutrino

MicroBooNE liquid-argon time projection chamber

Detector design

The 40-ft long MicroBooNE detector is a 170 ton (total volume) liquid-argon (LAr) time projection chamber (TPC). It is currently the largest LArTPC operating in the U.S.

The liquid argon serves as the neutrino target. This is desirable since it is dense (40% denser than water), inert, and relatively cheap compared to other noble liquids. The argon must be kept extremely cold (87K) to remain in liquid form and be extremely pure for the ionization electrons to drift across the TPC volumes so that their signals can be recorded.

The TPC consists of a cathode plane on one side, a field-shaping cage around the drift perimeter, and three planes of wires on the opposite end to record the signals from the drifting ionization electrons. The cathode plane is powered to a very high voltage (roughly -100 kV) to create an electric field

Rotation of MicroBooNE cryostat at DZero Assembly Hall

Documents and Publications

Public Notes

See the Public Notes page for a list of notes with results made public by the MicroBooNE collaboration.

Presentations

See the Talks page for copies of slides and posters presented at conferences and workshops.

MicroBooNE DocDB

MicroBooNE uses DocDB as a documents database. Much of the contents of the DocDB are restricted to members of the collaboration, but some items are public. Use the link below to enter the public portions of the MicroBooNE DocDB.

- MicroBooNE Public DocDB

Publications/Documents by the MicroBooNE Collaboration

- MicroBooNE collabo ... E Model Predictions", ...
- MicroBooNE collabo ... and Performance in Micr...
- MicroBooNE collabo ... Quantitative Evaluati ... /09/18)
- MicroBooNE collabo ... and Neutrino Events in th...
- MicroBooNE collabo ... mall External Cosmic Ray...
- MicroBooNE collabo ... NST 12, P08003 (2017), ...
- MicroBooNE collabo ... arXiv:1704.02927, JI...
- MicroBooNE collabo ... tiple Coulomb Scattering"...
- MicroBooNE collabo ... Chamber", arxiv:1611 ... 7)
- MicroBooNE collabo...

- MicroBooNE Data M...
- MicroBooNE TDR fro...
- Experiment Proposal...
  - Initial experiment proposal, October 2007

The TPC as the field cage is being assembled.

MicroBooNE Physics

MicroBooNE is the first large liquid-argon time projectio... With its superb capabilities in tracking, vertexing, calori... represents a major advance in detector technology for n... oscillation phenomena. These capabilities lead to objec... ...-term technological innovations.

The experiment primary scientific objectives are to to re... measure a suite of neutrino cross sections, to search for astrophysical phe... live, when a SNEWS alert is received, data will be saved to study neutrino bu... ...BooNE lies in the area of detector development. MicroBooNE will provide enorm... ...nd analysis of a large LArTPC. This experience will directly inform the design of very large LArTPC detectors envisioned for DUNE and beyond.

Construction on the Liquid Argon Test Facility

The MiniBooNE Low Energy Excess

The MiniBooNE experiment performed a short baseline search for the $\nu_\mu \rightarrow \nu_e$ oscillation signature suggested by the Liquid Scintillator Neutrino Detector (LSND). MiniBooNE observed an unexpected $>3\sigma$ (statistical and systematic combined) excess of neutrino interactions producing final state electrons or photons at lower energies. This result generated substantial theoretical interest. Proposed explanations for the source of these events predict either a single electron track or a single photon produced at the neutrino interaction vertex. MiniBooNE cannot discriminate between these two possibilities, as Cherenkov detectors cannot distinguish an electron from a photon converting near the interaction point.

Cross Section Measurements

MicroBooNE proposes to make the first measurement of exclusive final states from neutrino scattering on argon.

Four cross section measurements in particular attract great interest from the neutrino community. These measurements stress the value of:

- Excellent efficiency for triggering on low ... th a kinetic energy above 40 MeV;
- Excellent resolution in position and mo... get;
- Ability to observe and reconstruct comp...
- Sufficient statistics to reduce statistical uncertainties to the same order as systematic effect for rare processes.

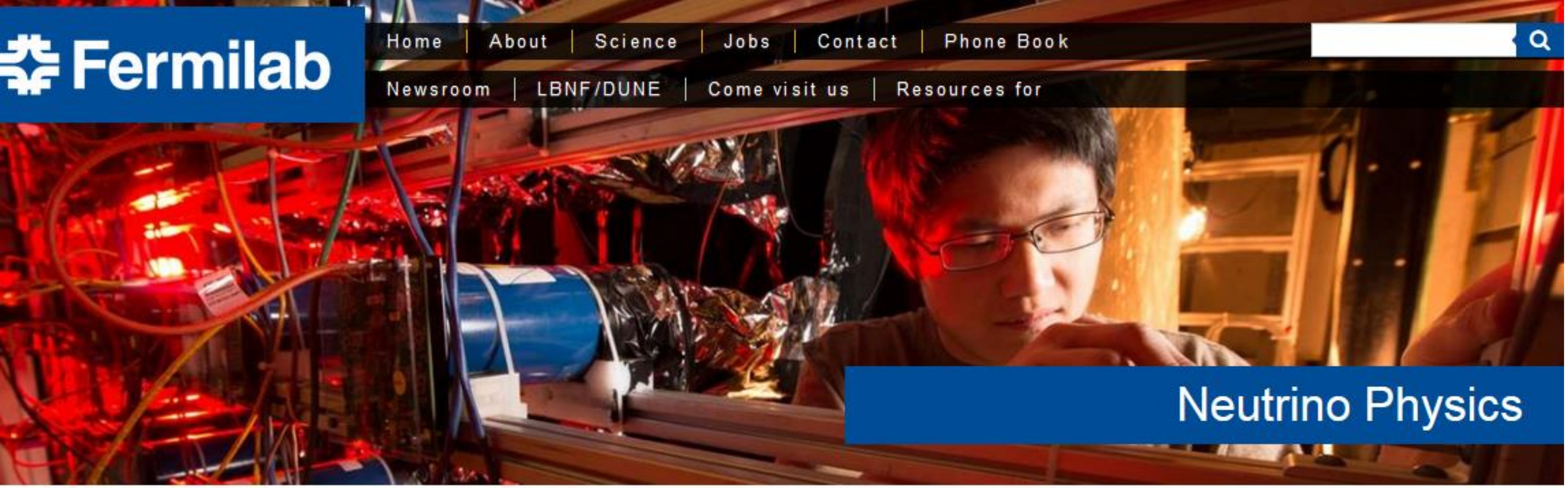
See MicroBooNE web site
microboone.fnal.gov

These four features constitute the design drivers for the MicroBooNE detector that arise from the cross section physics.

Precision Cross-Sections Measurements

MicroBooNE is carrying out an extensive cross section physics program that will help to probe current theories on neutrino-nucleon interactions and nuclear effects. Cross section measurements will also be relevant for oscillation analyses.

Many cross-section analyses are currently underway within the MicroBooNE collaboration:



Fermilab support for neutrino experiments and associated infrastructure.
(Need a lot of people for this, too, but I could not find a group photo.)

http://neutrinophysics.fnal.gov/neutrino-division/

Neutrino Physics

- Experiments
- DOE Science Highlights
- Neutrino Physics Center
- Question of the week
- Events
- Fellowships

Neutrino Division

- Organizational chart
- Who is who
- Facilities >
- How do I...
- Division events
- Postdoc supervision

Detector R&D Facilities

The Neutrino Division hosts several facilities for new detector research and development. These facilities are open to the neutrino community. The facilities include test stands for developing liquid argon time projection chambers, areas exposed to charged particle beams, and areas exposed to neutrino beams.

Learn more about the Fermilab Neutrino Detector R&D facilities:

- Liquid Argon Facilities
- Neutrino Beam Facilities
- Charged Particle Beam Facilities

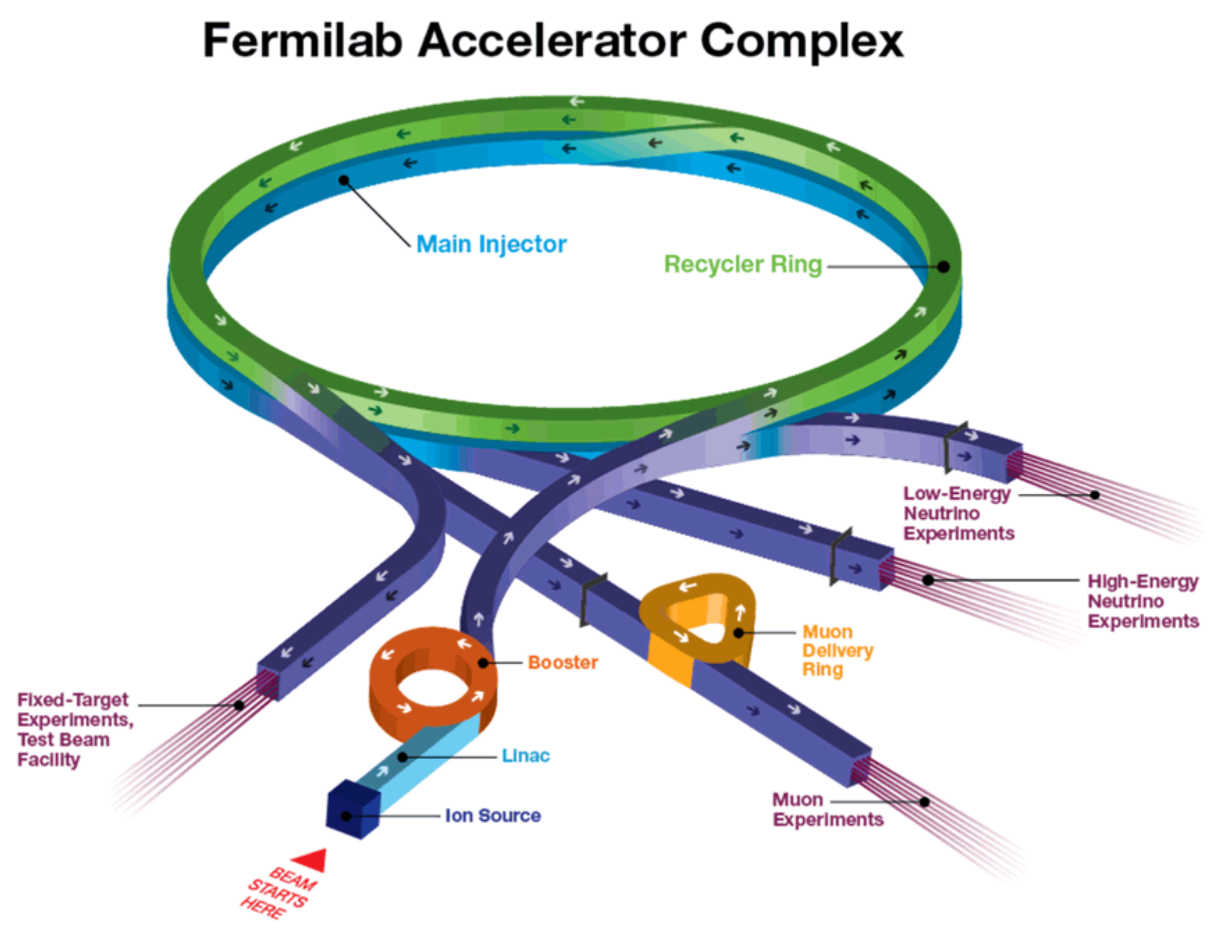
Contact

General inquiries may be sent to the Neutrino Division R&D Coordinator, Alan Hahn.

The Neutrino Division is home for Fermilab scientists and staff, and users from academic institutions around the world, operating and analyzing neutrino experiments and designing new ones.

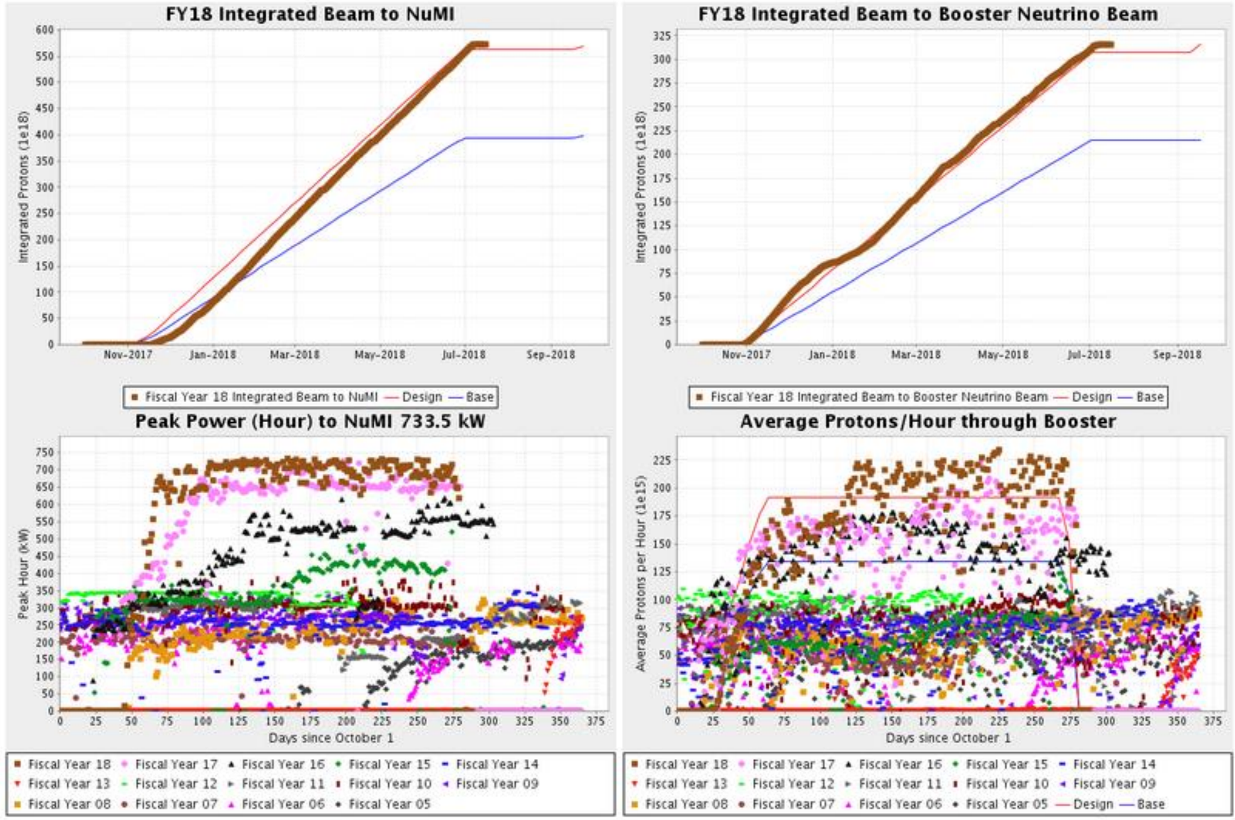
Mission Statement

- Host a world-leading program of neutrino experiments
  - Operate the current program : NOvA, MicroBooNE, Minerva
  - Coordinate and execute a new international program of short and long-baseline neutrino experiments
- Provide support to the neutrino user community to participate in all aspects of this program
  - Ranges from technical expertise in design, project management, operations, etc. to arranging office and meeting spaces



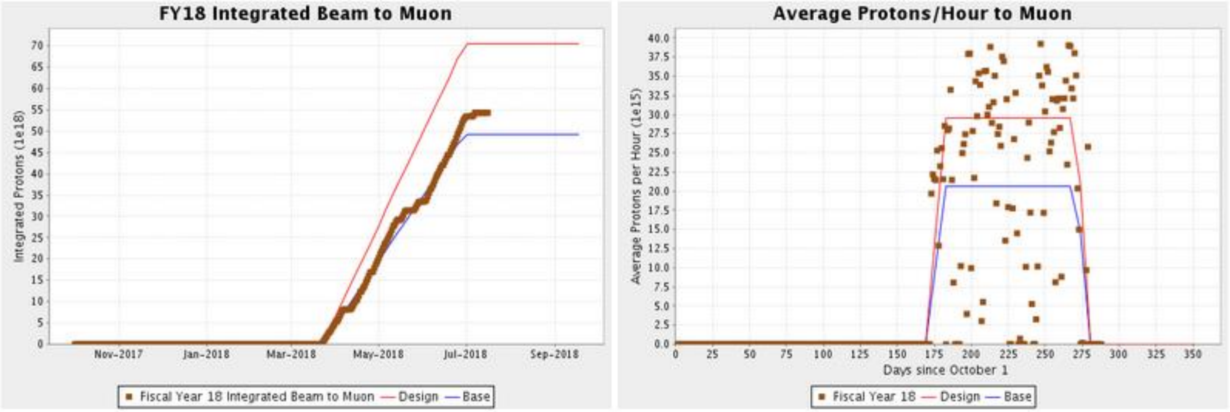
http://www.fnal.gov/pub/science/particle-accelerators/images/accel-complex-animation.gif

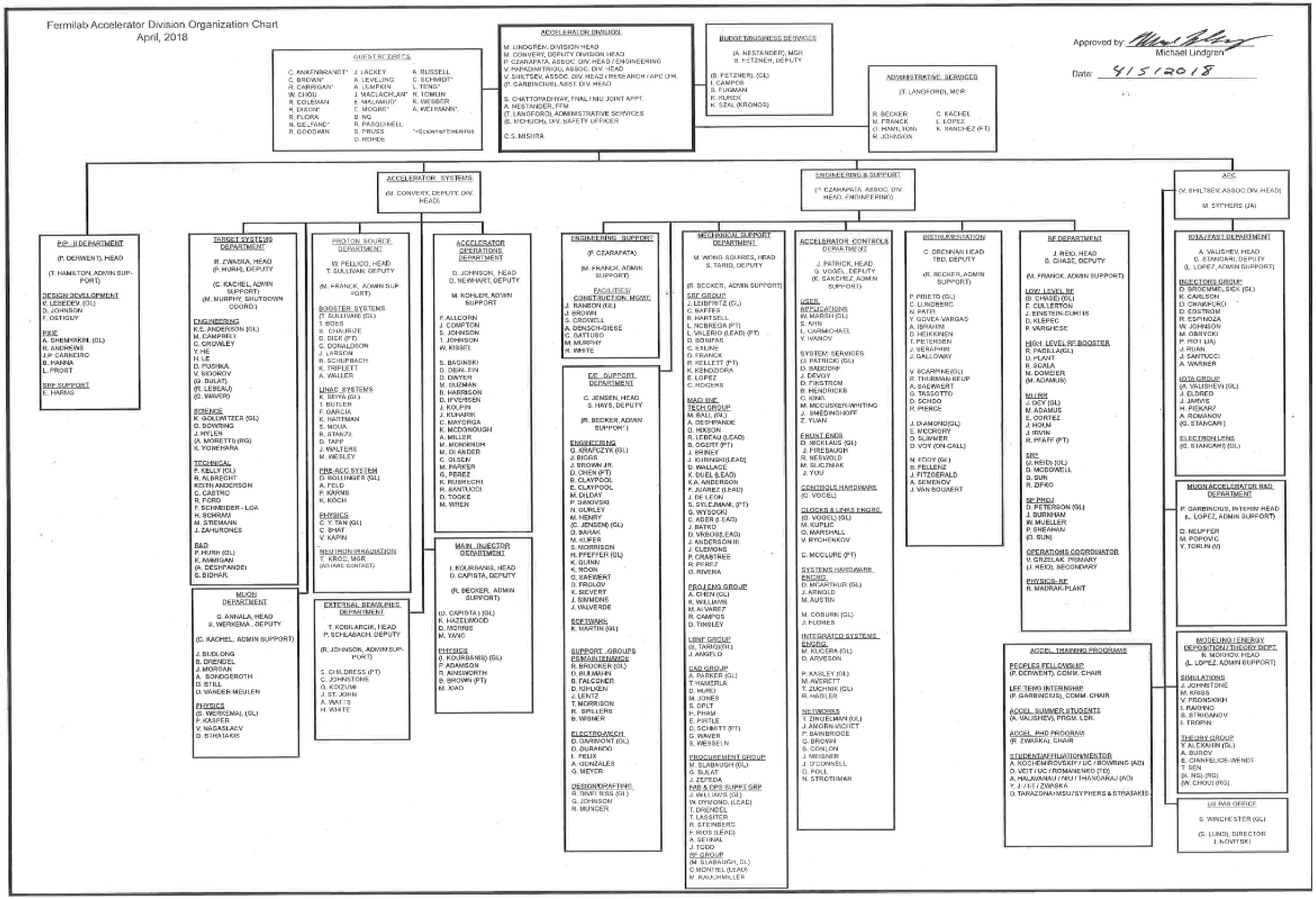
Performance: Neutrino beam from MI and Booster Neutrino Beam



Performance: Protons on target for g-2

https://www-bd.fnal.gov/accSystems.html





Boring org chart. But there is a face associated with each name!

We do not have any good group photos, either.

I am going to start at the target

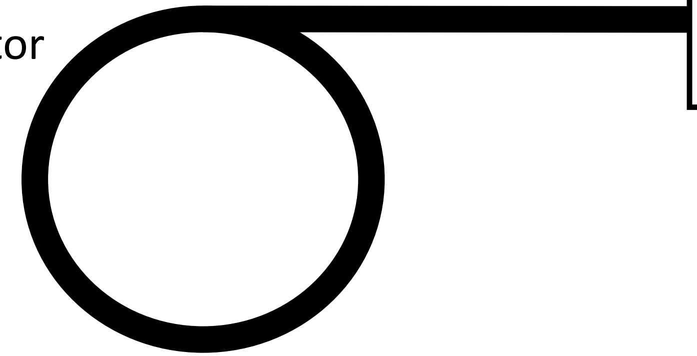
- This is at the “end of the line” from the accelerator’s point of view; it is where the protons end up (sort of).
- This is at the “beginning of the line” from the neutrino beam’s point of view; it is where the neutrinos begin (sort of).

“Sort of”?

- Not all the protons interact, so you have to do something with them.
- The neutrinos come from the decay of pions (and kaons) produced in the target.

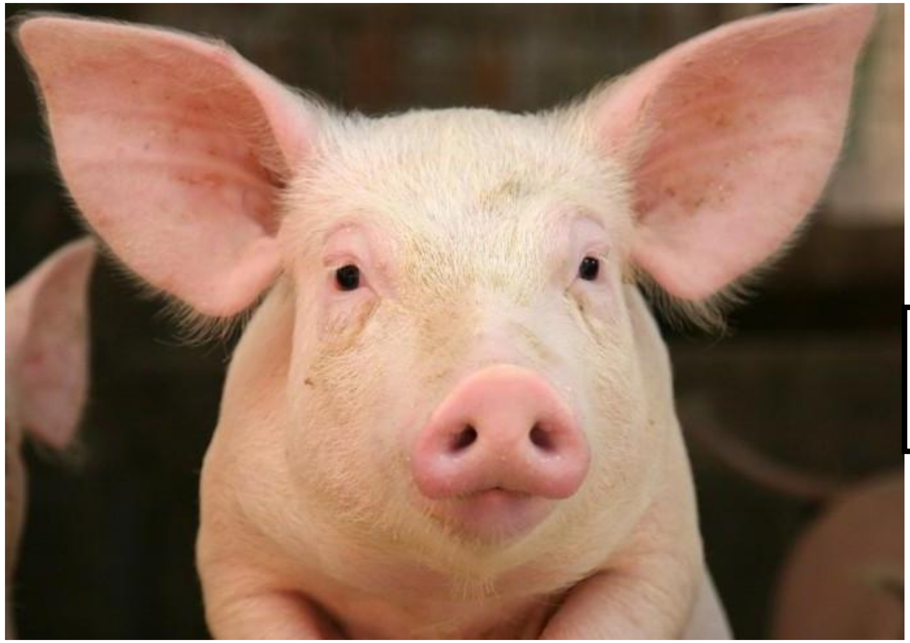
The secondary beamline – target, focusing system, and absorber – determine the neutrino beam. After all, once you produce a bunch of neutrinos, you are stuck with them!

Accelerator



neutrinos get made

By Jon 'ShakataGaNai' Davis, CC BY 3.0,
https://commons.wikimedia.org/w/index.php?curid=3146809



https://kids.nationalgeographic.com/animals/pig/#pig-young-closeup.jpg

(best not to go into details)

http://www.spam.com/varieties

I am going to focus on Fermilab, and mostly on the Booster Neutrino Beamline.

Feel free to interrupt and ask questions, especially if I use jargon.

How Do You Make Your Neutrino Beam?

Ideally:
Collect all the pions (and kaons?) from target.
“Straighten them out” (so they are all parallel, and point to detector).
Let them all decay into neutrinos.

How Do You Make Your Neutrino Beam?

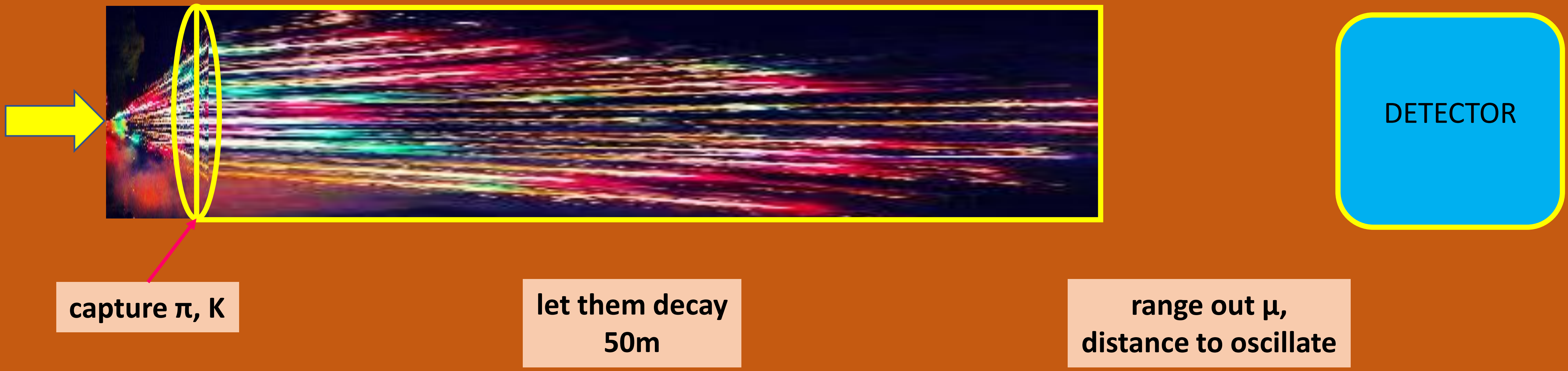
Ideally:
Collect all the pions (and kaons?) from target.
"Straighten them out" (so they are all parallel, and point to detector).
Let them all decay into neutrinos.

How hard can it be?

8GeV protons hit a two interaction length beryllium target.
Lots of stuff (mostly pions, some kaons) shoots out.

How do you get a neutrino beam from this?

http://yourlastrites.com/Files/Articles/1098/7557717814_9988d35415.jpg



Idealized Target

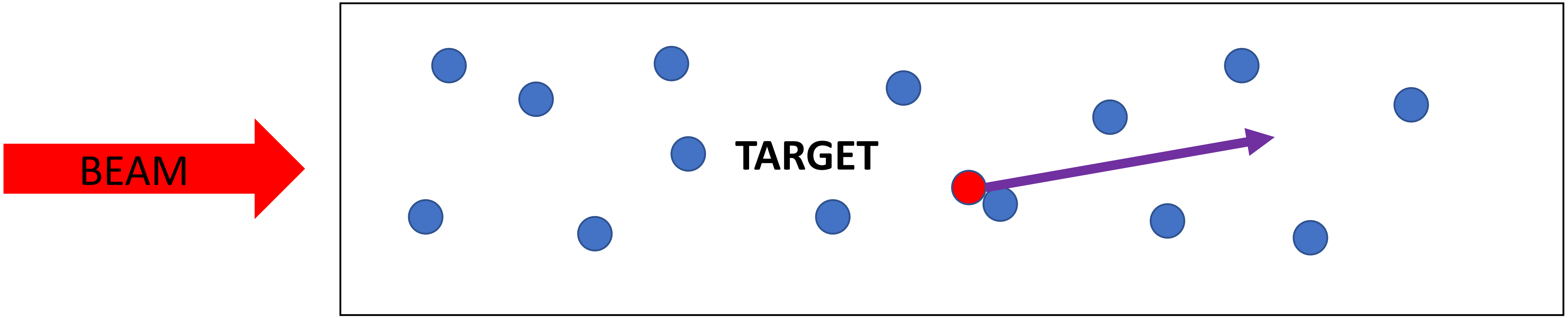
You can put as much beam on the target as you want to.
All the beam interacts (and no secondary interactions?).
Point like.
Floats in space.

There it is! →

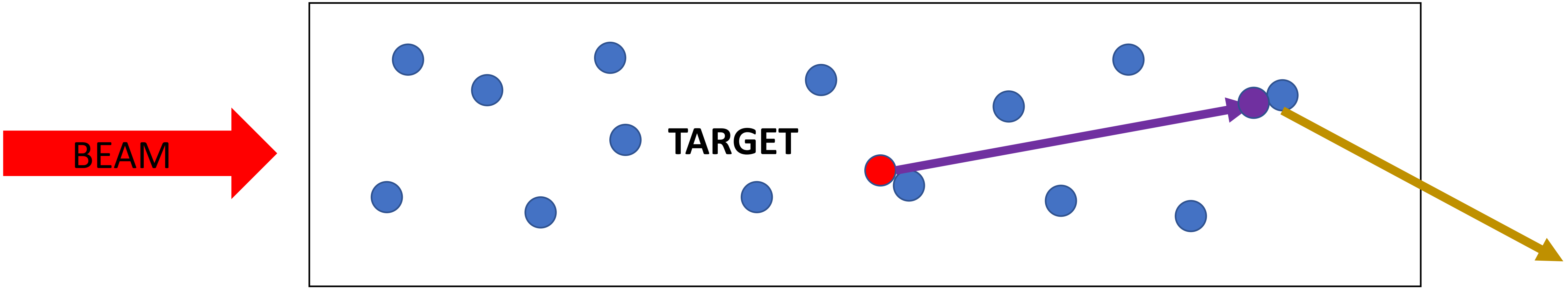
Idealized Target

You can put as much beam on the target as you want to.
All the beam interacts (and no secondary interactions?).
Point like.
Floats in space.

That's just not realistic. Real targets have mass, size, get hot, etc.

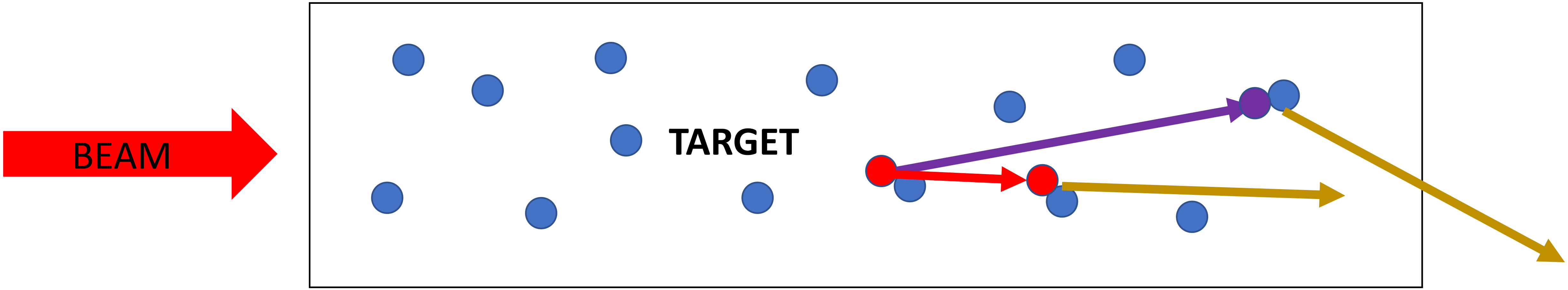


Target is mostly empty space (so is the proton beam).
If you want more interactions, make the target longer.



Target is mostly empty space (so is the proton beam).
If you want more interactions, make the target longer.

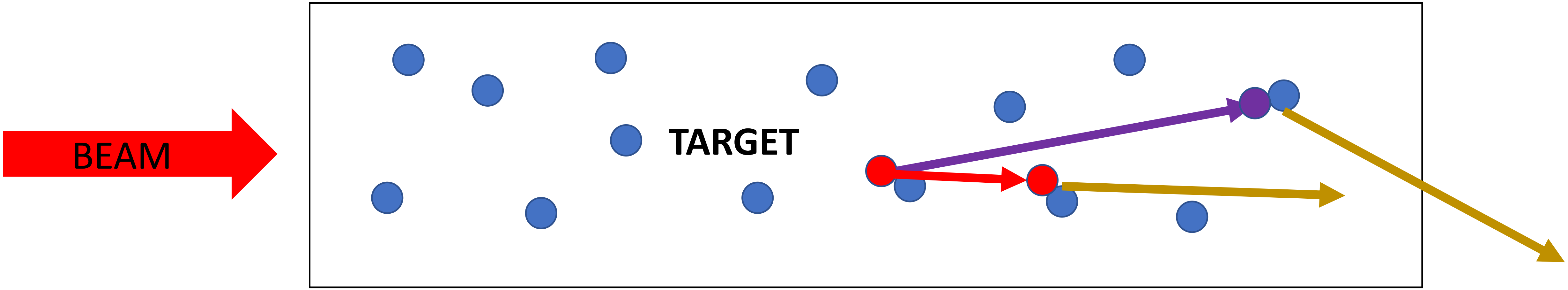
But as the target length increases, the chance of a pion re-interacting in the target increases.
(this is a secondary interaction)



Target is mostly empty space (so is the proton beam).
If you want more interactions, make the target longer.

But as the target length increases, the chance of a pion re-interacting in the target increases.
(this is a secondary interaction)

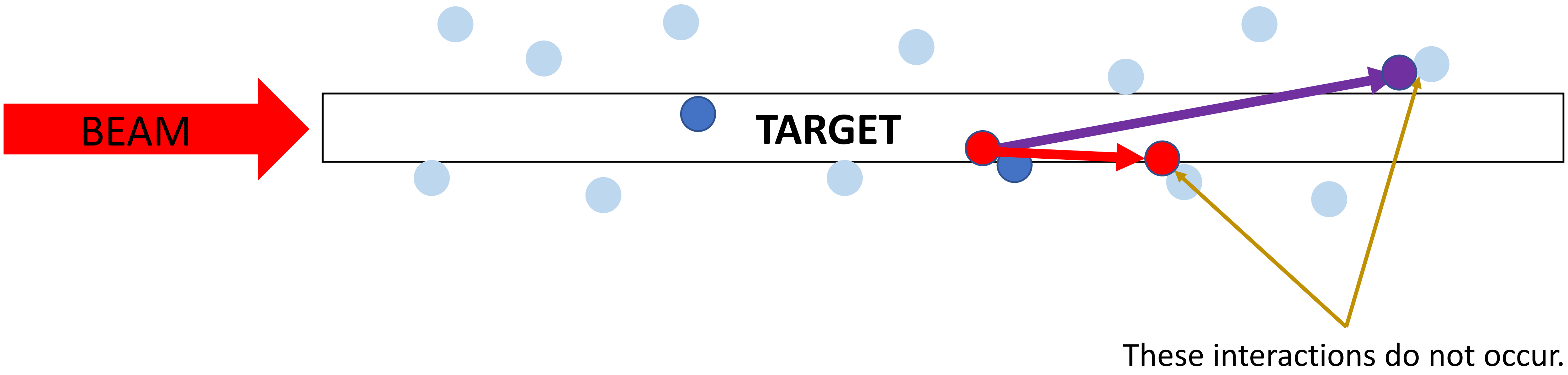
There is also a chance of the primary proton undergoing a secondary interaction.



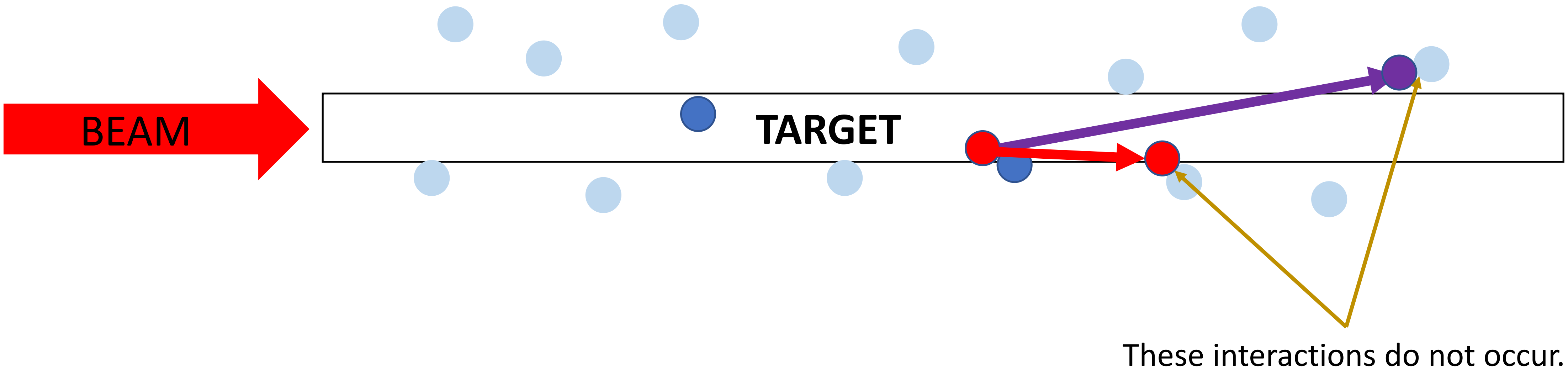
All this is hard to model.

Well, … if it were easy, if would have been done by now … ☺

Affects the energy spectrum. You are not going to produce a particle with more energy than the initial particle, and every time you have an interaction the particle looses energy.



One can also decrease the radius of the target. Instead of everything coming out the downstream face, the pions "leak out the sides".



One can also decrease the radius of the target. Instead of everything coming out the downstream face, the pions “leak out the sides”.

But you would need to make the beam smaller – which is another other talk …

How do you choose a target material?

A small, dense, target would act like a point source. Point sources are easy to model.
Steel is reasonably dense, and people make things out of steel all the time.
But steel is an alloy, I do not know the exact composition, so I will choose iron (close enough).

Yes, this is just a wild guess. Even worse, I know it is wrong. But it is useful to illustrate a point.

Let's choose a 2 interaction length, 0.5 cm radius, iron rod, and hit it with 1 MW NuMI beam.

Properties of iron from the Particle Data Group:
Specific gravity: 7.874 g cm-3
Nuclear interaction length: 16.77 cm
Melting point: 1811 K

From Wikipedia:
Atomic weight: 55.845 g mol-1
Heat capacity: 25.10 J (mol K)-1

So the target is 208 g, or 3.7 mol.
86% of the beam interacts,
so let's assume 0.86 MW (or 0.86x10^6 J/s) of energy is deposited,
which would raise the temperature by 9300 K in one second.

Properties of iron from the Particle Data Group:
Specific gravity: 7.874 g cm-3
Nuclear interaction length: 16.77 cm
Melting point: 1811 K

From Wikipedia:
Atomic weight: 55.845 g mol-1
Heat capacity: 25.10 J (mol K)-1

So the target is 208 g, or 3.7 mol.
86% of the beam interacts,
so let's assume 0.86 MW (or 0.86x10^6 J/s) of energy is deposited,
which would raise the temperature by 9300 K in one second.

Properties of iron from the Particle Data Group:
Specific gravity: 7.874 g cm-3
Nuclear interaction length: 16.77 cm
Melting point: 1811 K

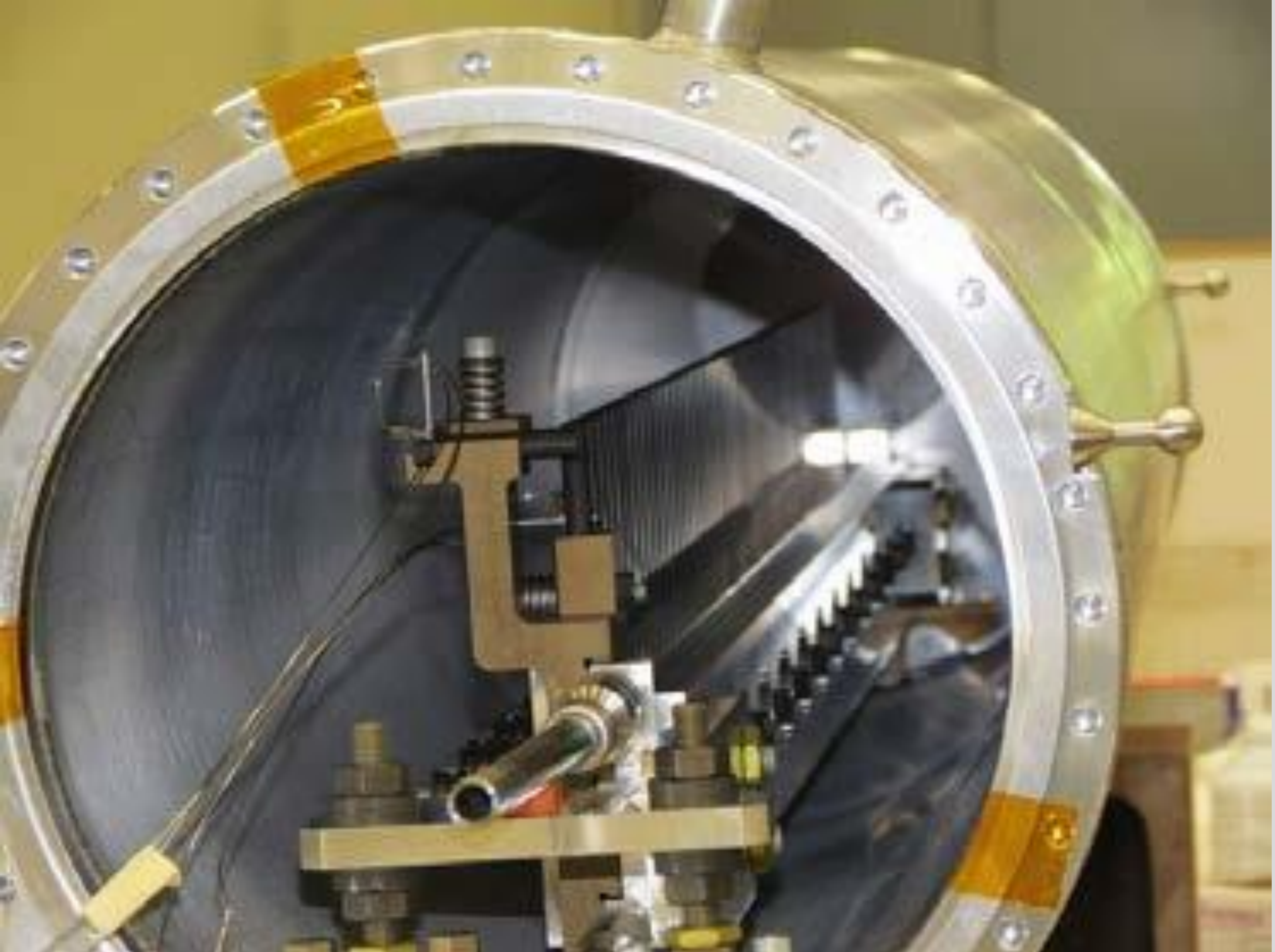
So the target is 208 g, or 3.7 mol.
86% of the beam interacts,
so let's assume 0.86 MW (or 0.86x10^6 J/s) of energy is deposited,
which would raise the temperature by 9300 K in one second.

Apologies to Walt Disney

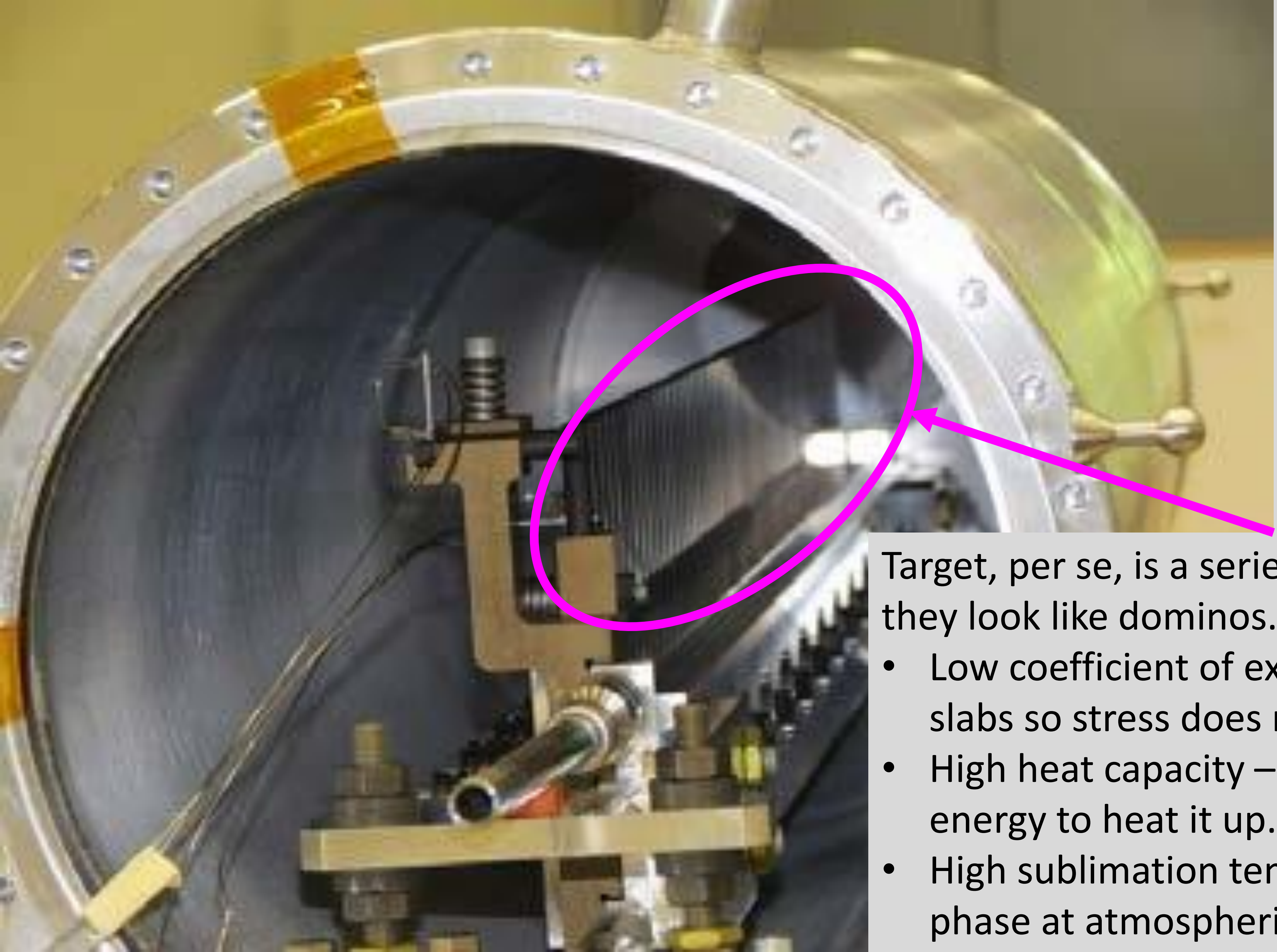
Two major flaws in the previous “analysis”:

1. All the energy is not deposited in the target.
    - If we use the minimum ionization value, the heating is reduced by a factor of ~1000.
    - But that would still melt the target in less than 5 minutes.
2. Heat will be transferred from the target.
    - What mechanism (conduction, convection, radiation)?
    - How quickly?

Also, how quickly is heat deposited into target, and what is the distribution? Most materials expand when heated …

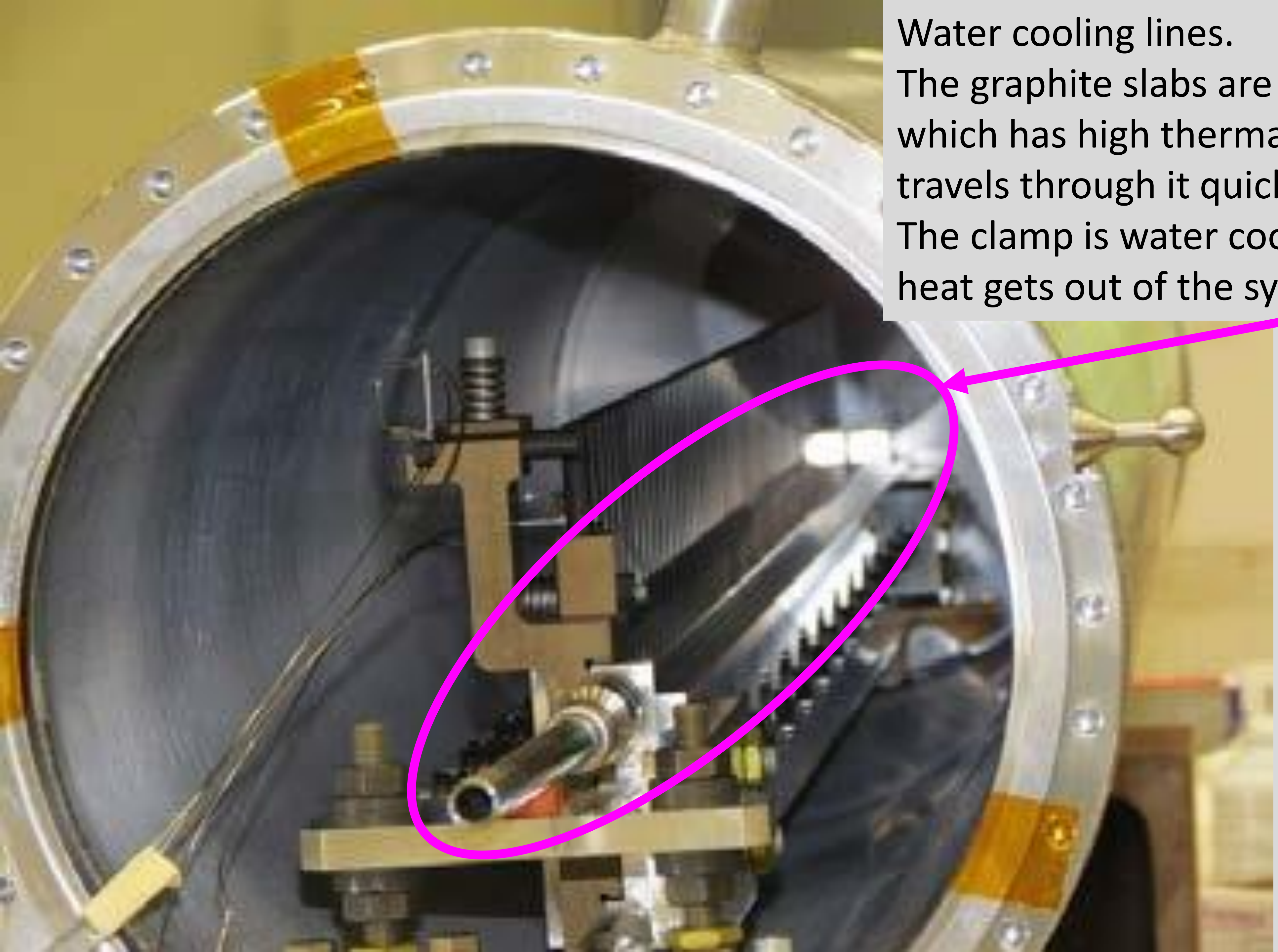


NuMI Target

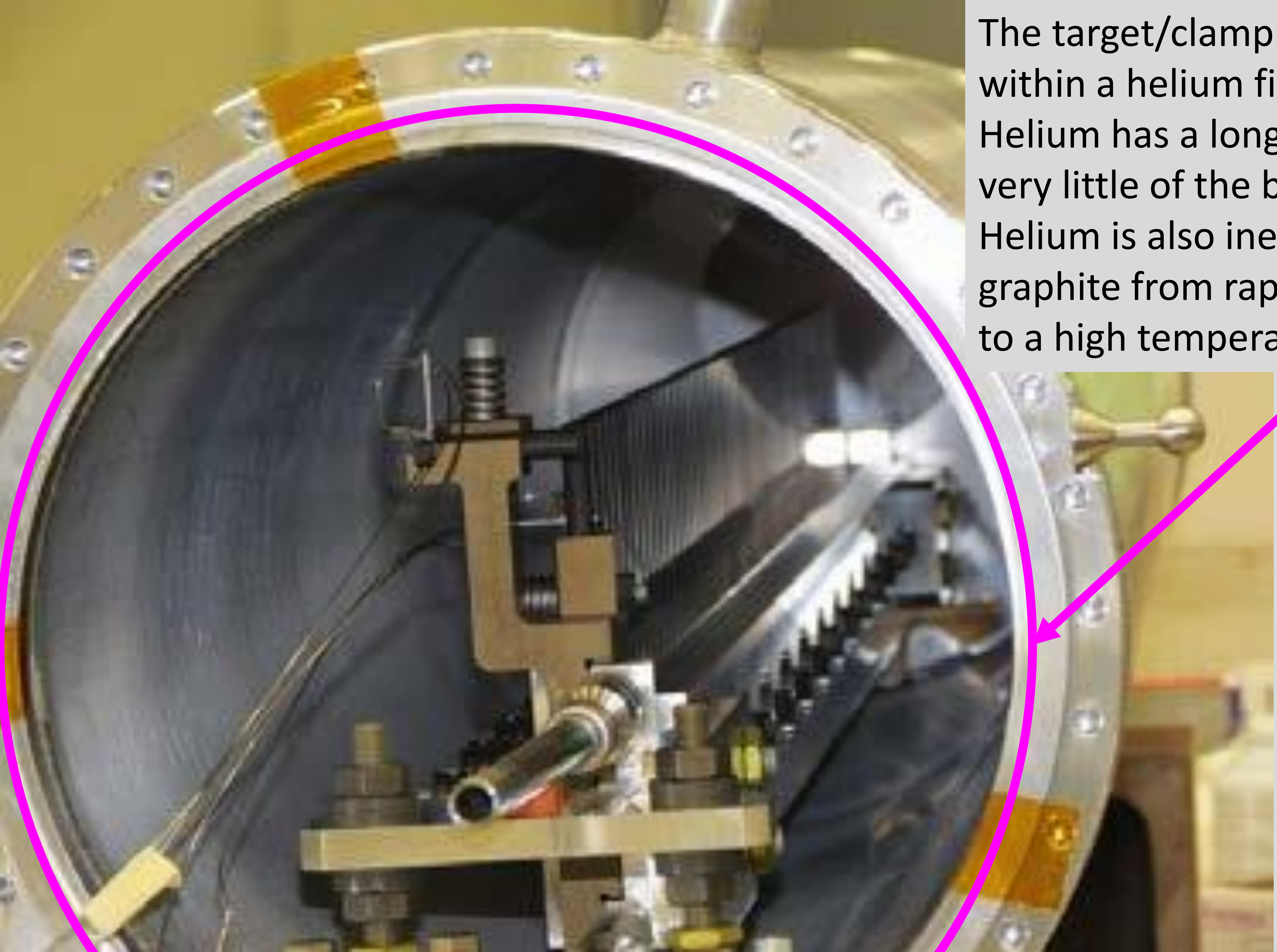


Target, per se, is a series of graphite slabs – they look like dominos.

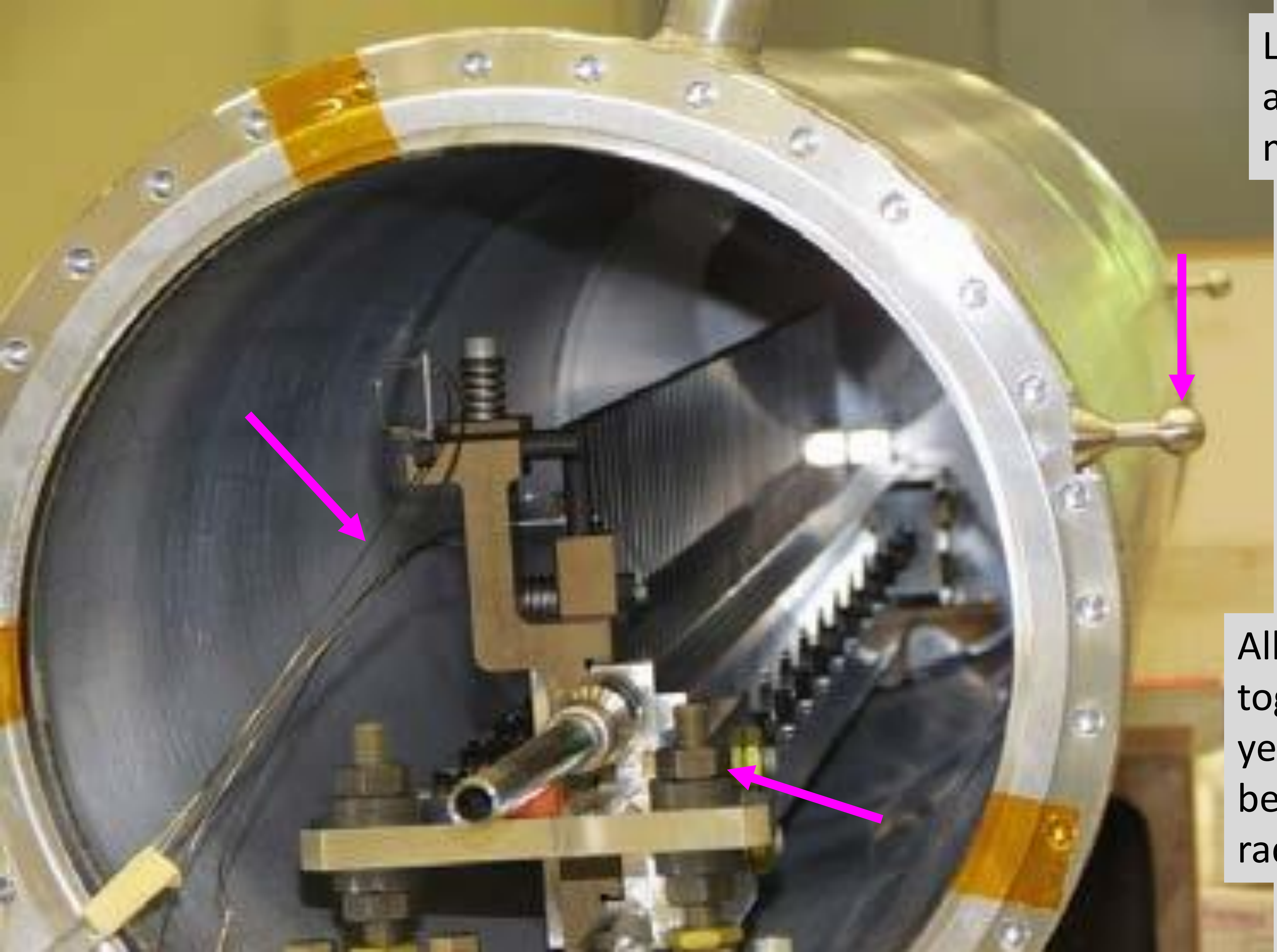
- Low coefficient of expansion; split into slabs so stress does not build up.
- High heat capacity – takes a lot of depsited energy to heat it up.
- High sublimation temperature (no liquid phase at atmospheric pressure).



Water cooling lines.
The graphite slabs are held in a metal clamp, which has high thermal conductivity (heat travels through it quickly).
The clamp is water cooled – that is how the heat gets out of the system.

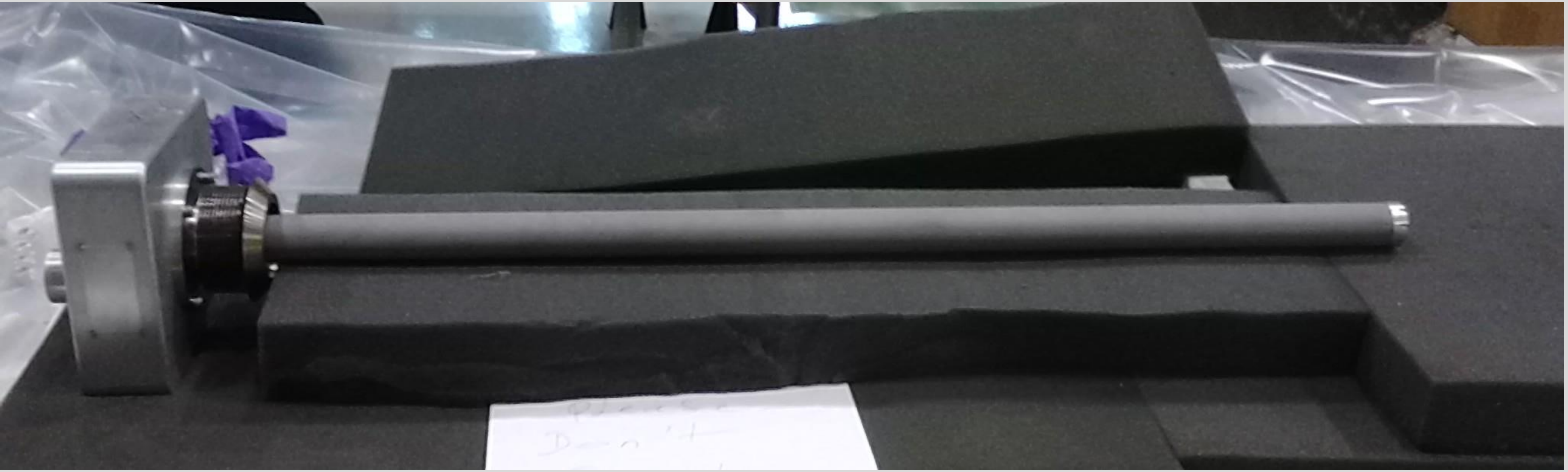


The target/clamp assemble is housed within a helium filled vessel.
Helium has a long interaction length, so very little of the beam interacts with it.
Helium is also inert, which prevents the graphite from rapidly oxidizing if it gets to a high temperature.



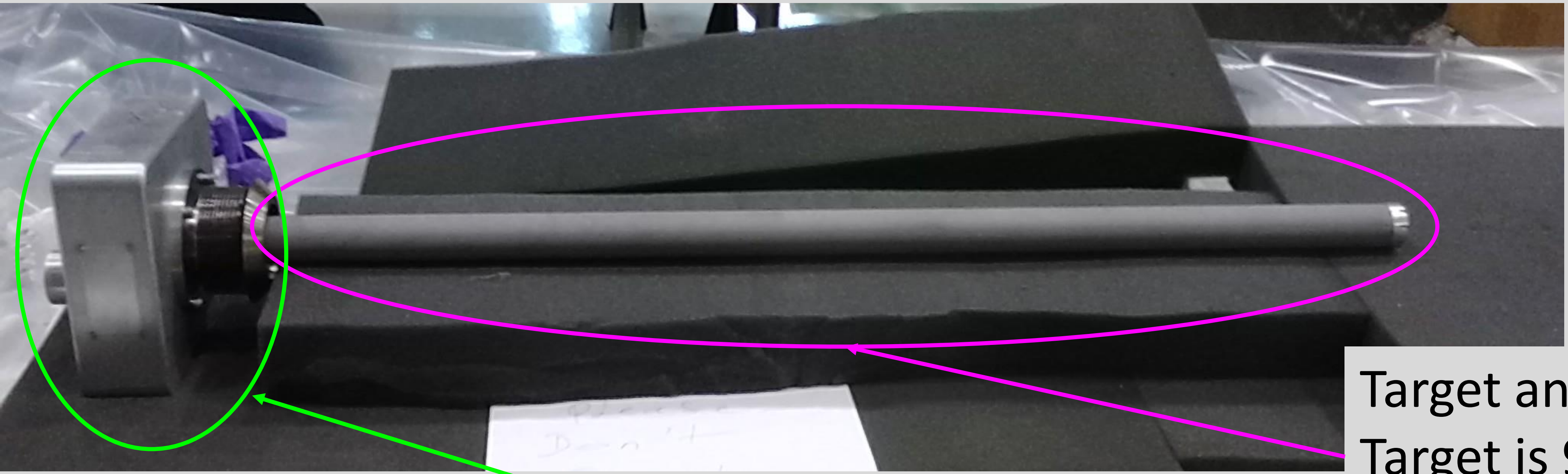
Lots of other stuff for alignment, monitoring, mechanical stability.

All this has to be put together and last for years. Once it is in the beam, it becomes too radioactive to work on.



BNB Target

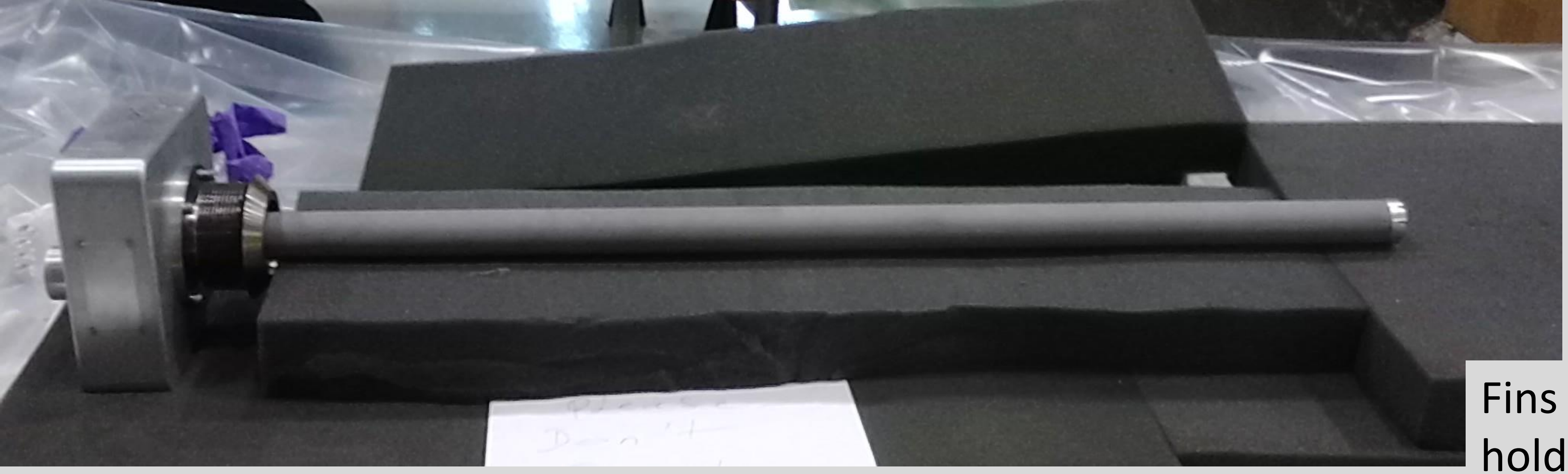
Air cooled, Beryllium target.



Target and target tube. Target is 9 mm diameter and 70 cm long (aprox.)

“Other Stuff” to direct cooling air, and hold target in place.

The BNB target is inside the focusing device, and in electrical contact with it. The bellows keeps it pressed in place, which prevents arcing.

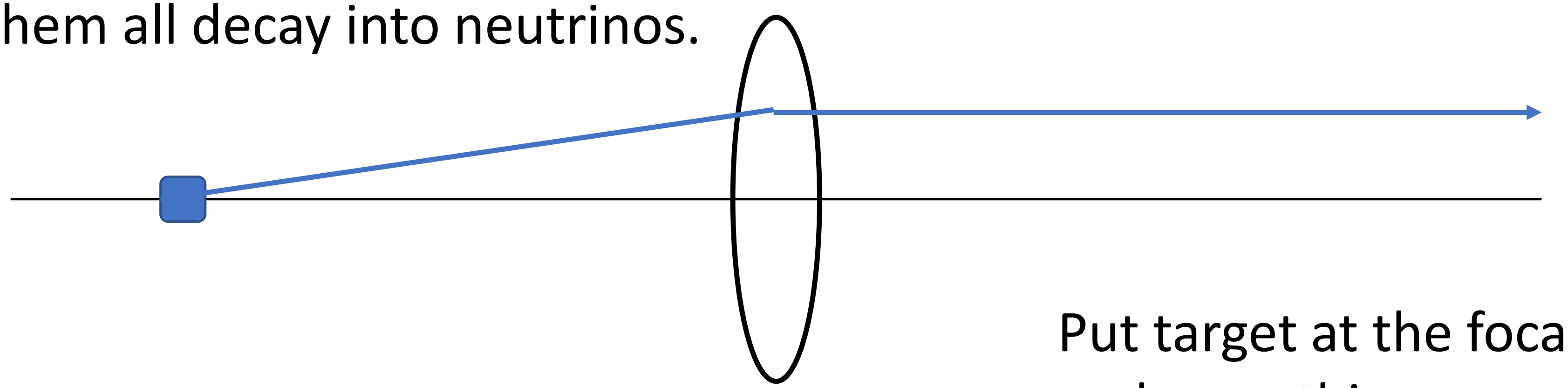


Beryllium has good mechanical properties -- it will not shatter when heated rapidly, and does not corrode quickly. The target is segmented to relieve stress.

Fins on the target hold it in place (so air can flow around it), and increase surface area which helps heat transfer.

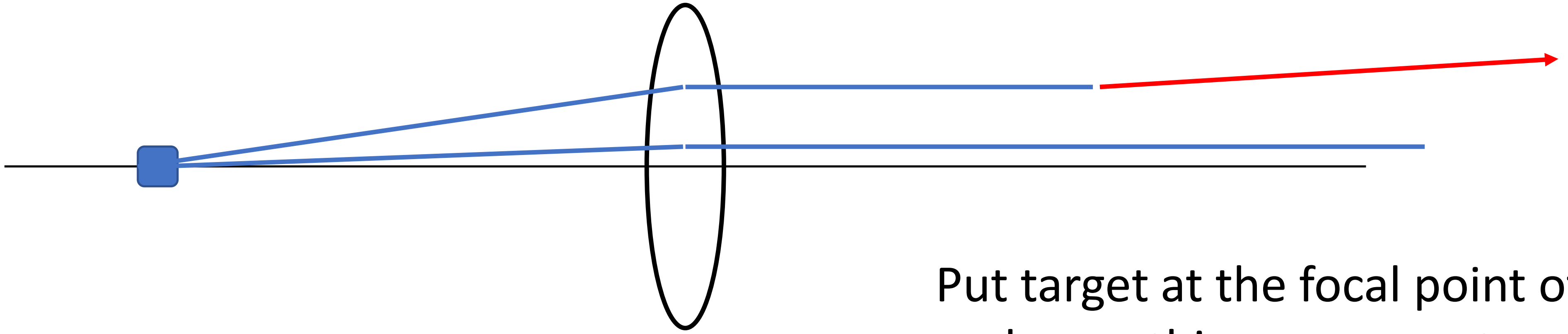
How Do You Make Your Neutrino Beam?

Ideally:
Collect all the pions (and kaons?) from target.
"Straighten them out" (so they are all parallel, and point to detector.
Let them all decay into neutrinos.



Put target at the focal point of a lens,
and everything comes out parallel.

How Do You Make Your Neutrino Beam?



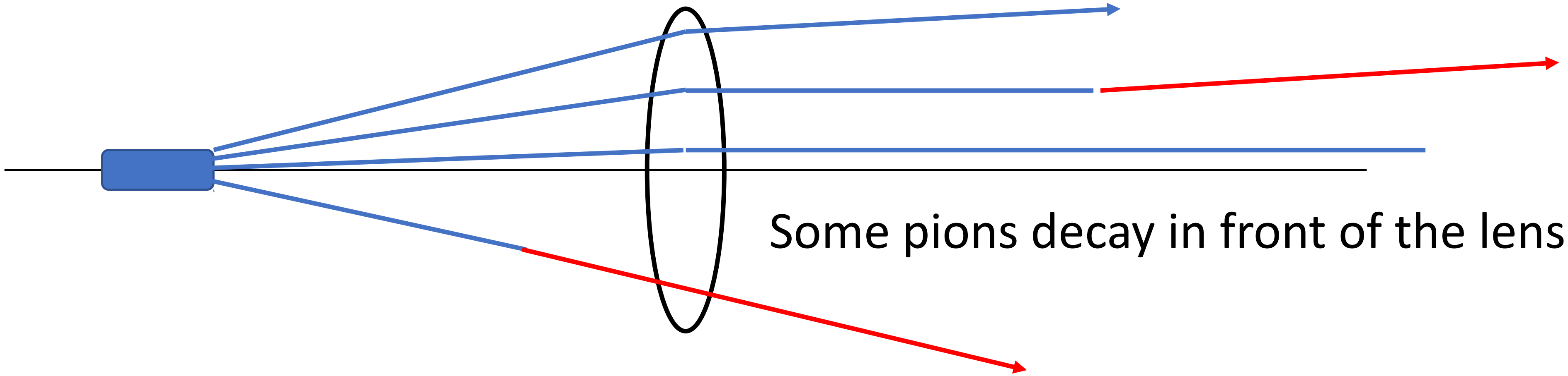
Put target at the focal point of a lens, and everything comes out parallel.

That is too easy:
Pions have a lifetime, so not all of them will decay.
Neutrinos will not decay parallel to pion.

How Do You Make Your Neutrino Beam?

Even Worse!

Target has finite length and radius → aberrations.



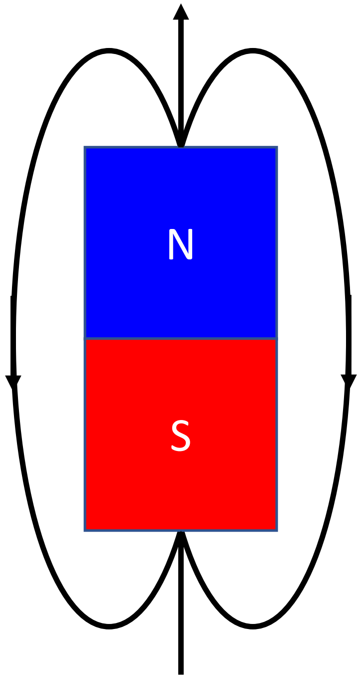
Some pions decay in front of the lens.

That is too easy:

Pions have a lifetime, so not all of them will decay.

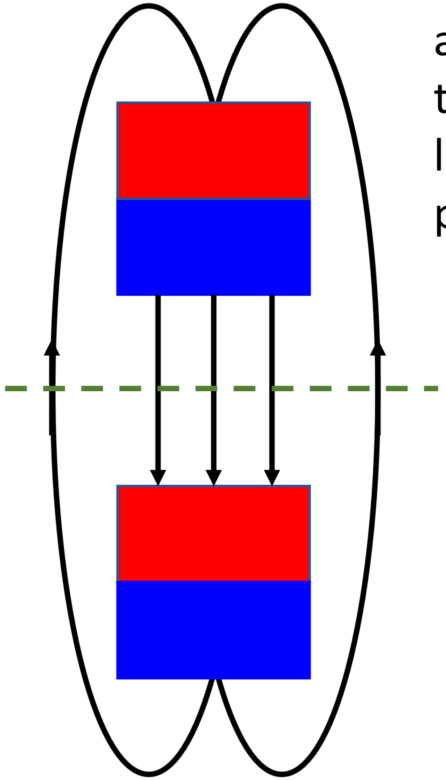
Neutrinos will not decay parallel to pion.

Focus pions with a magnetic field



Do not want to send pions alongside a magnet, the field is all bulgy.

Besides, this just changes the direction of the beam, like a prism. It does not focus, like a lens.

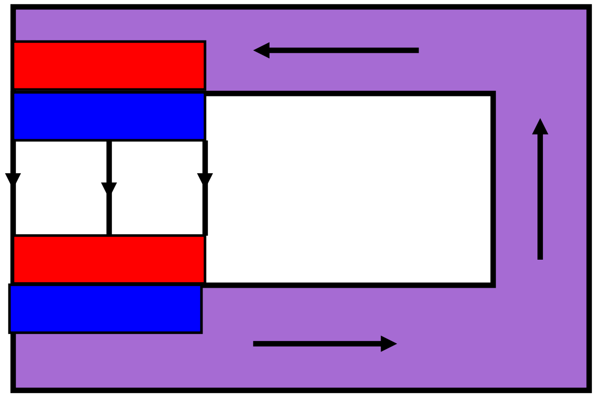


Dipole Magnet

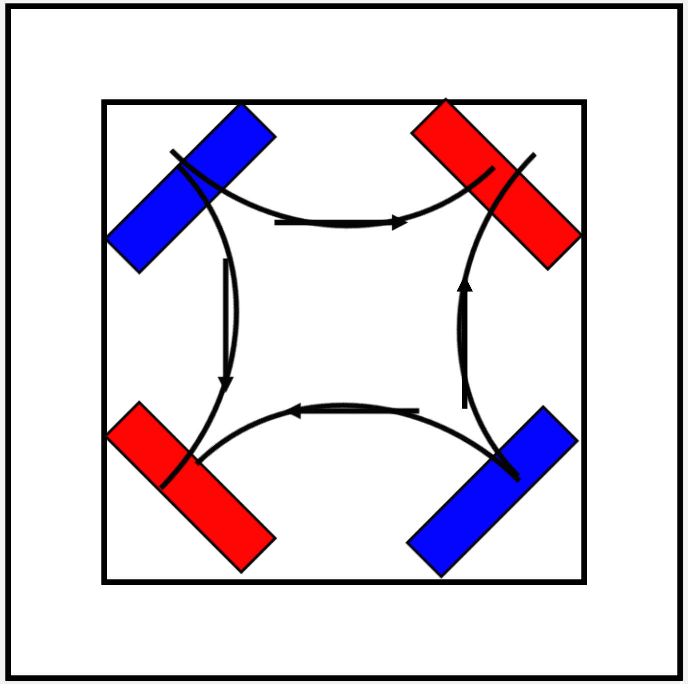
Can have two magnets, and as long as the gap is larger than the width, the field lines should be pretty parallel.

And looking from midplane, you go through both signs. (Draw on board)

Can add a “return yoke” to manage the field.



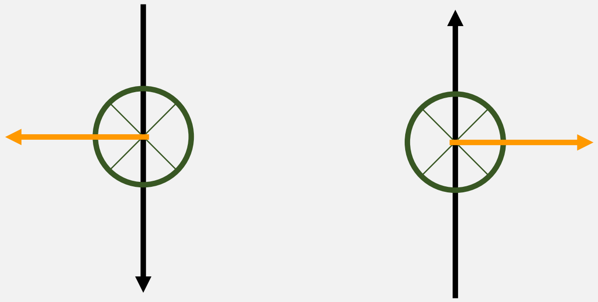
What happens when the beam whacks into the magnet?



Beam going through the top or bottom of the magnet is steered *toward* the center – it is "focused". That is what we want!

☺

Quadrupole Magnet



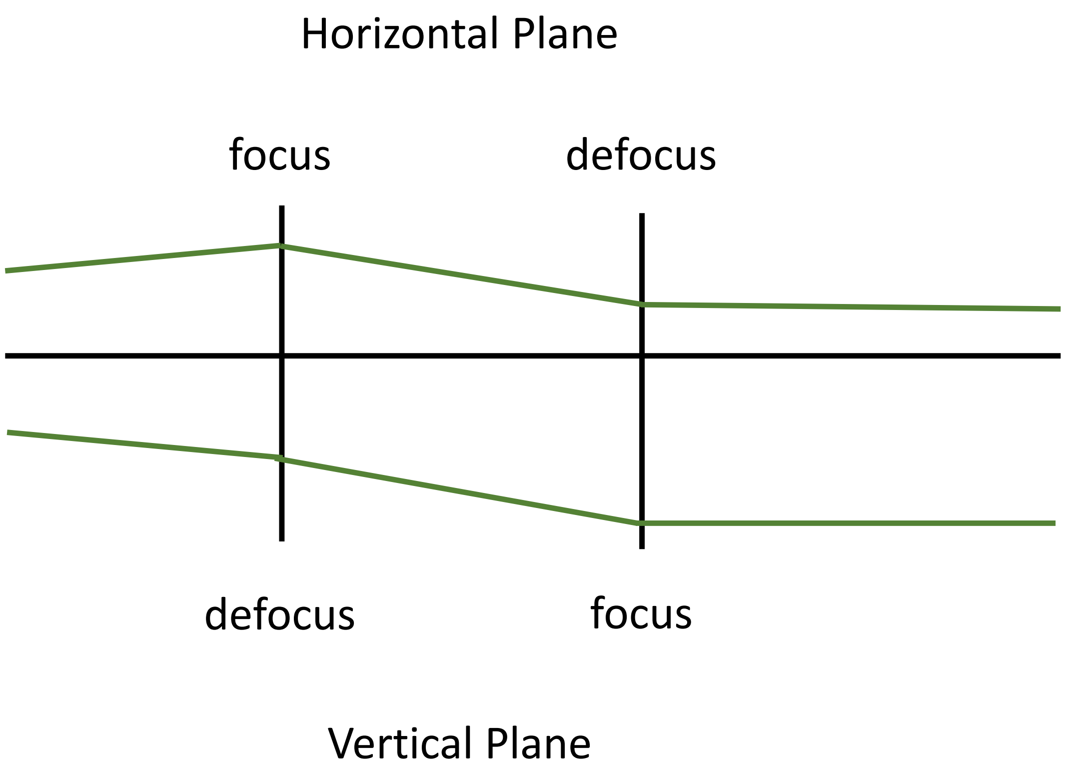
But beam going through the side of the magnet is steered *away from* the center – it is "defocused". That is NOT what we want!

☹

Maybe two Quadrupoles?
(double the confusion!)

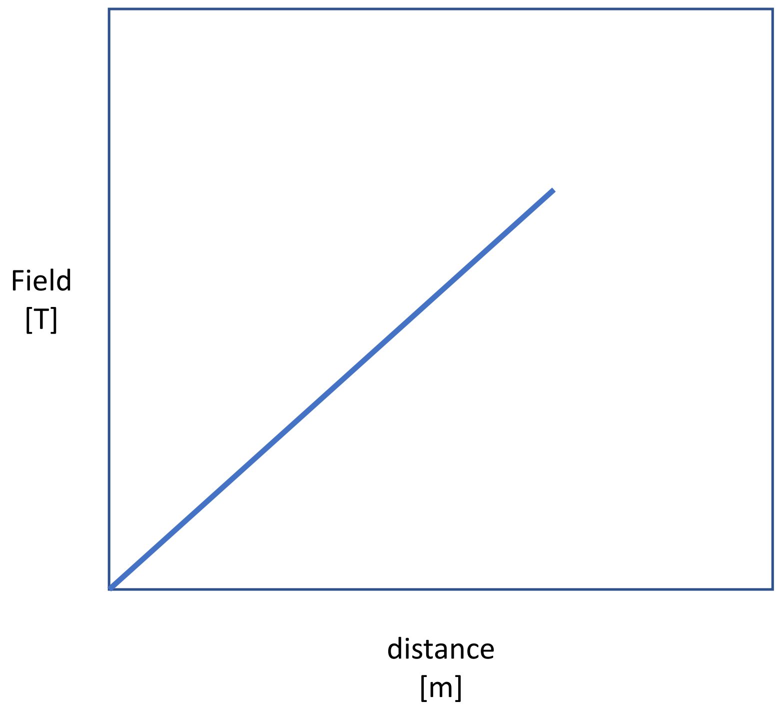
It can be shown that …
Given the initial conditions of the secondary beam (at one position), one can arrange two quadrupoles to have a net focus in both planes.

(three work even better)



Not a bad solution:

- The magnetic field in a (perfect) quadrupole varies linearly with distance from center.
- When you integrate the equations of motion (because a quadrupole has a finite length), it behaves reasonable like a thin lens. This means it is easy to get a first pass at a design.
- For a physical quadrupole, the “imperfections” are well categorized, and the math to get a handle on them is not too bad – it is very similar to aberrations in an optical system.

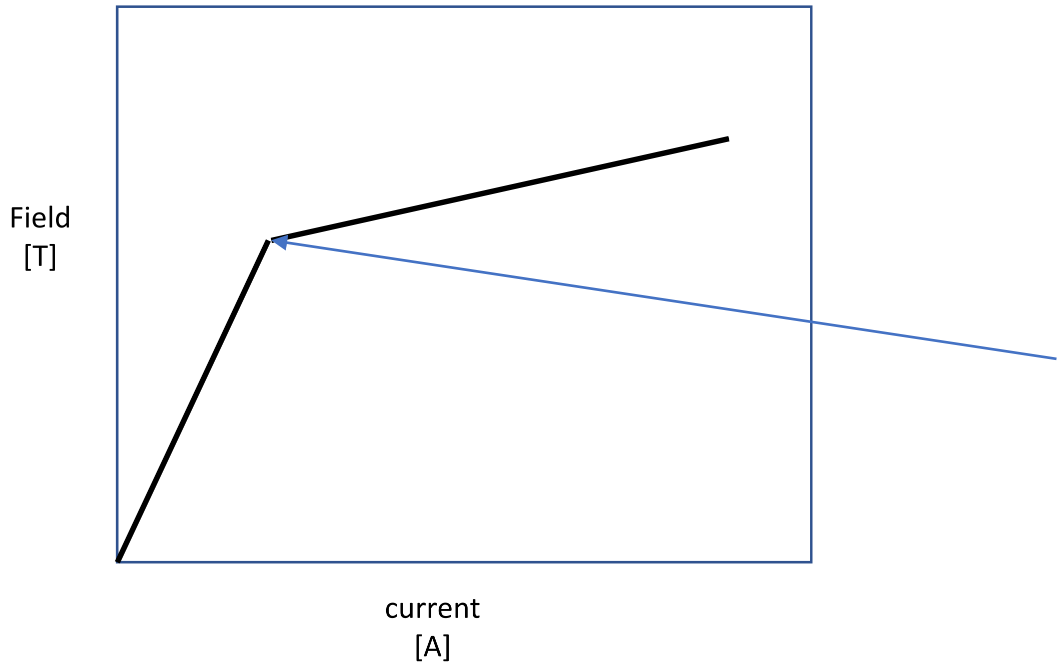


But there are some problems:

- You need electric current to magnetize the steel, so you need wire to carry the current. The more current, the more field, but the wire gets hot (good old Joule heating).

But there are some problems:

- You need electric current to magnetize the steel, so you need wire to carry the current. The more current, the more field, but the wire gets hot (good old Joule heating).
- Steel (what the magnet is made of) “saturates” – after a while, it acts like the steel is not there, and you are just getting the field from the current.



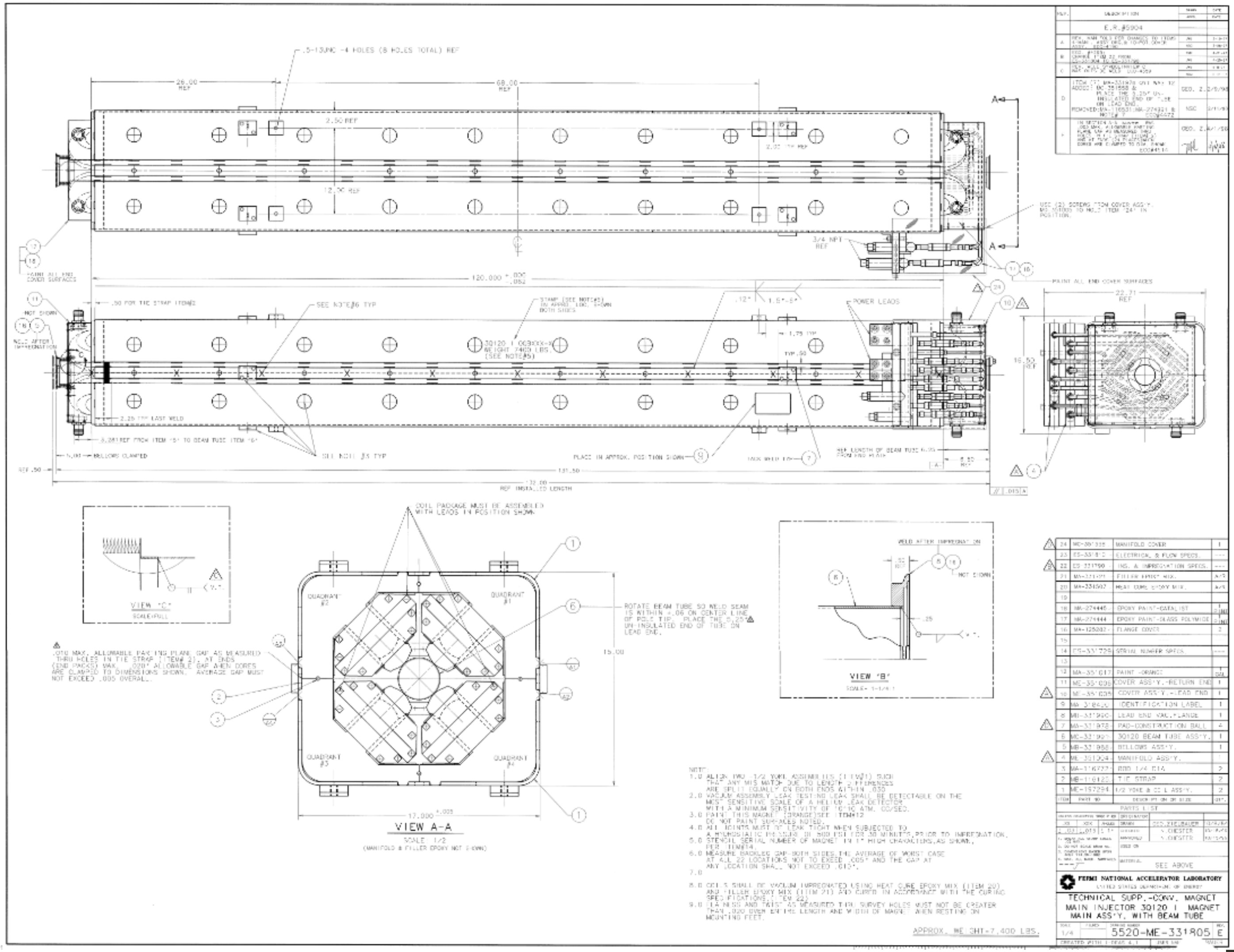
steel “saturates”
(actual transition is smoother)

But there are some problems:

- You need electric current to magnetize the steel, so you need wire to carry the current. The more current, the more field, but the wire gets hot (good old Joule heating).
- Steel (what the magnet is made of) “saturates” – after a while, it acts like the steel is not there, and you are just getting the field from the current.
- You could keep the magnet cool(er) by pulsing it, but the coils around the steel give cause inductance. You can get around that to some degree by increasing the voltage, but then the insulator gets thick.
- Because the focusing depends on the gradient (field/radius), the larger the aperture, the smaller the gradient (and weaker the focusing). Remember, you want a large aperture to collect the pions.

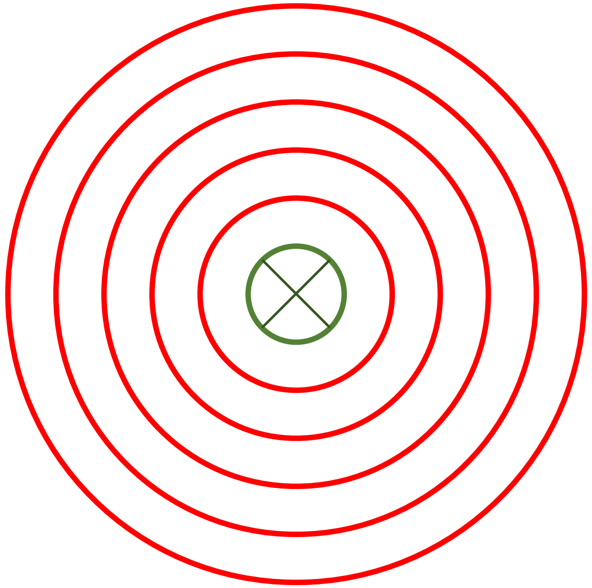
Last one is a real issue – want a high magnitude, short duration, field

This is getting complicated …

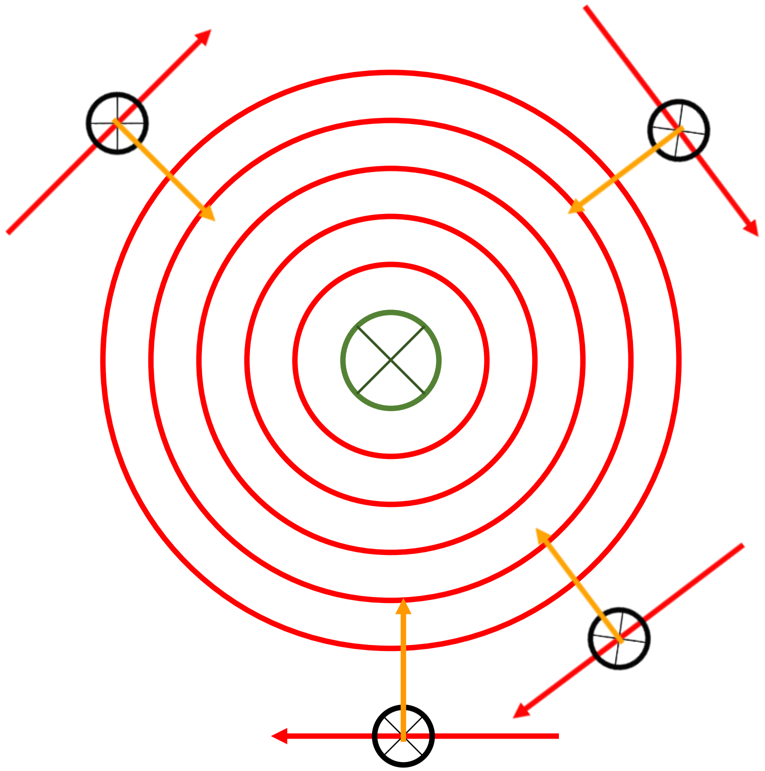


Typical magnet used in beamlines. This is a "3Q120", which has a (nominal) 3" aperture, is a Quadrupole, and is 120" long.
Can run about 100 A, gradient of 5 kG/in., need 700 l/hr. cooling.

Drawing, photos, and information, from FNAL technical division

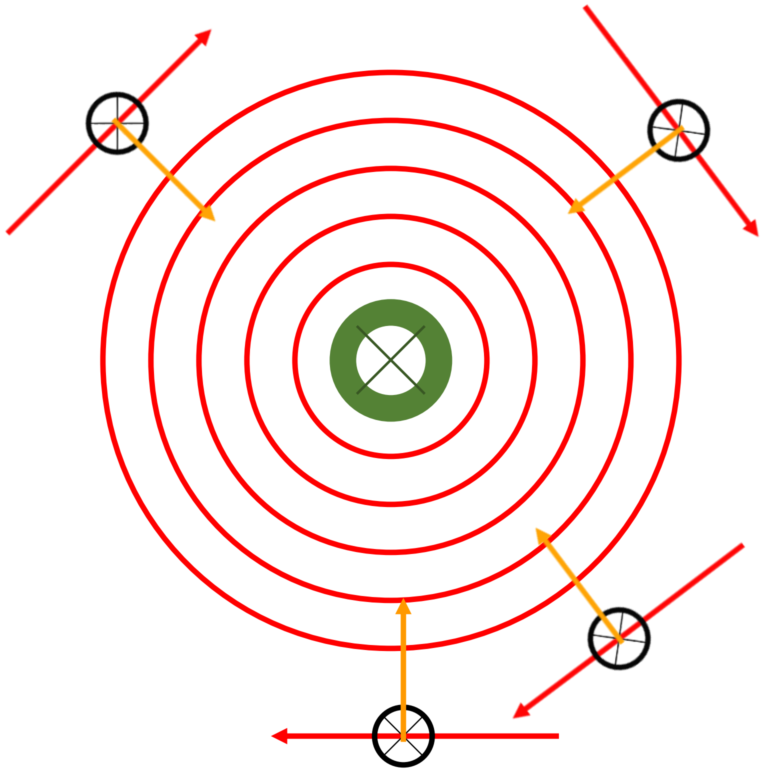


How about a toroidal field?



How about a toroidal field?

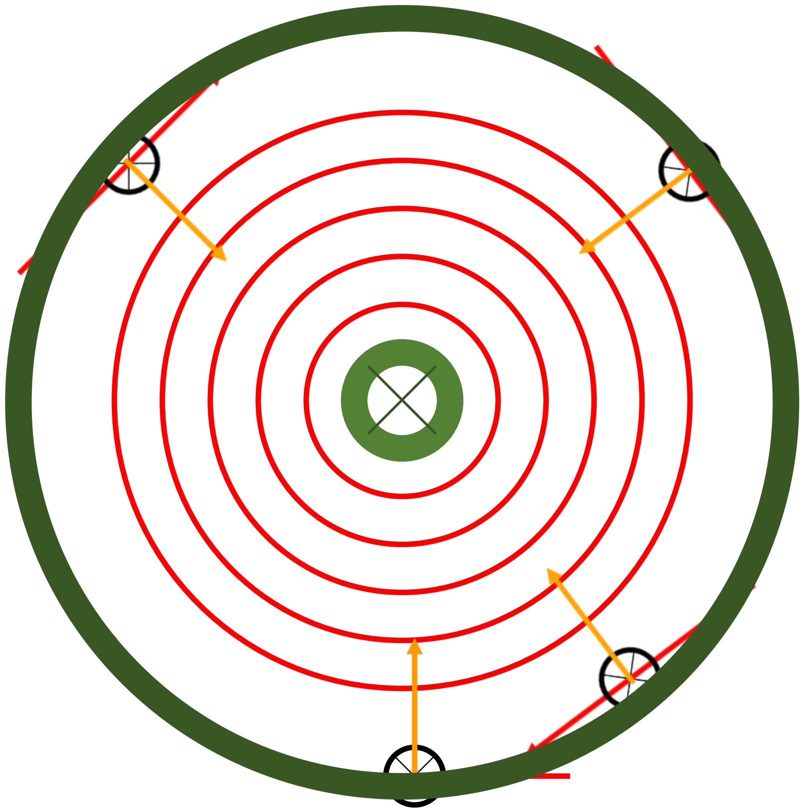
This will focus in all directions.



How about a toroidal field?

Need to get current “down the center” – can run a wire. But the beam would hit it. So make it hollow.

However, anything going down the center sees no field …



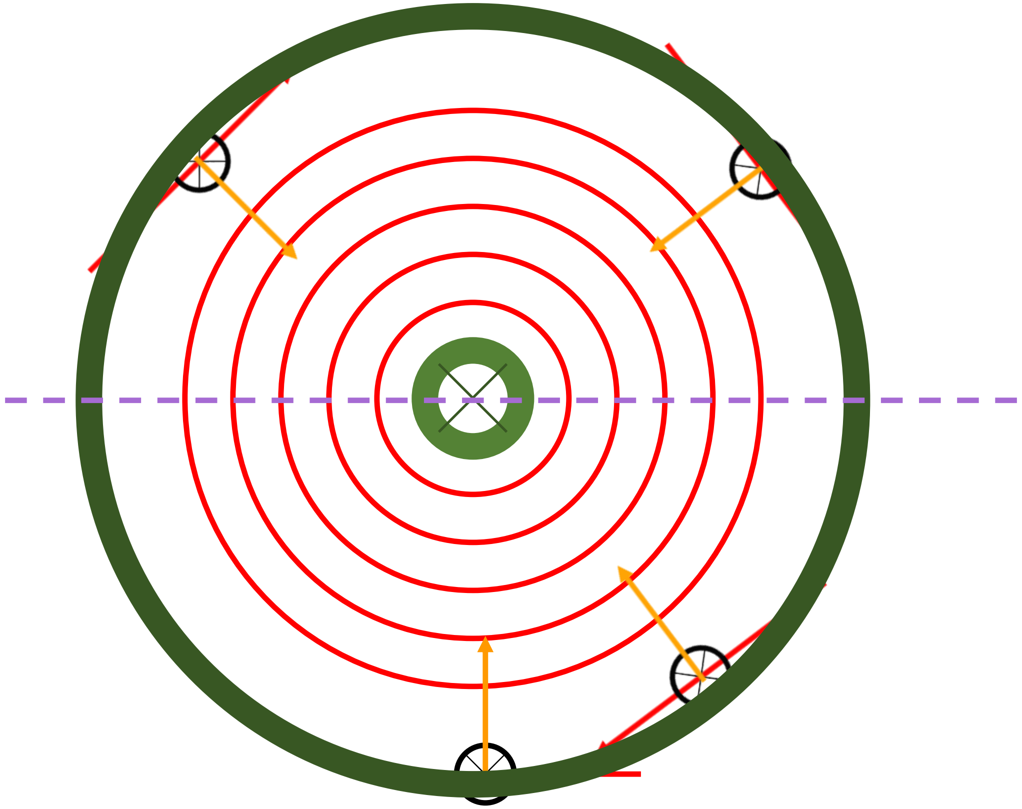
How about a toroidal field?

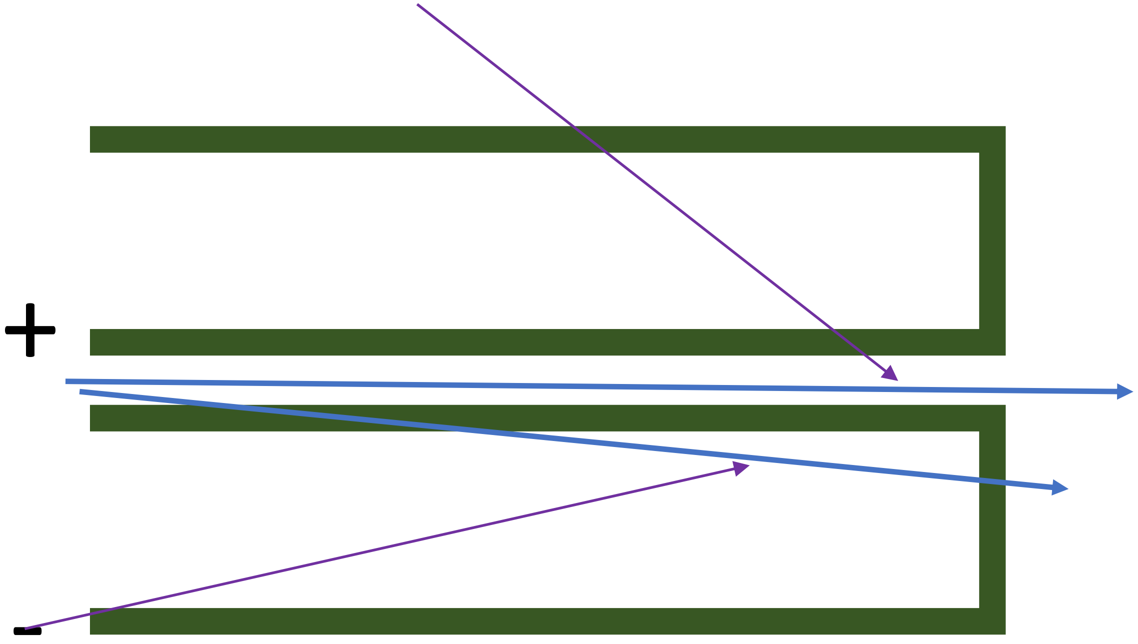
The current needs to “get back”, so put a return conductor around it.

This cuts off any field outside the outer conductor (no net current enclosed). No stray fields.
But the inner and outer conductors have to join, so beam will go though end.

How about a toroidal field?

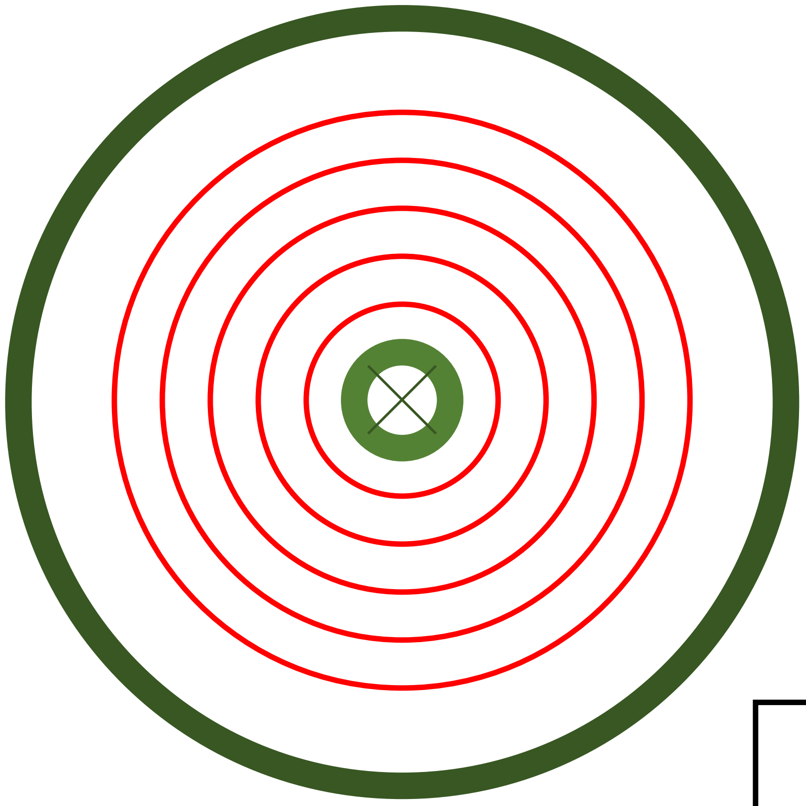
This pion is not deflected.





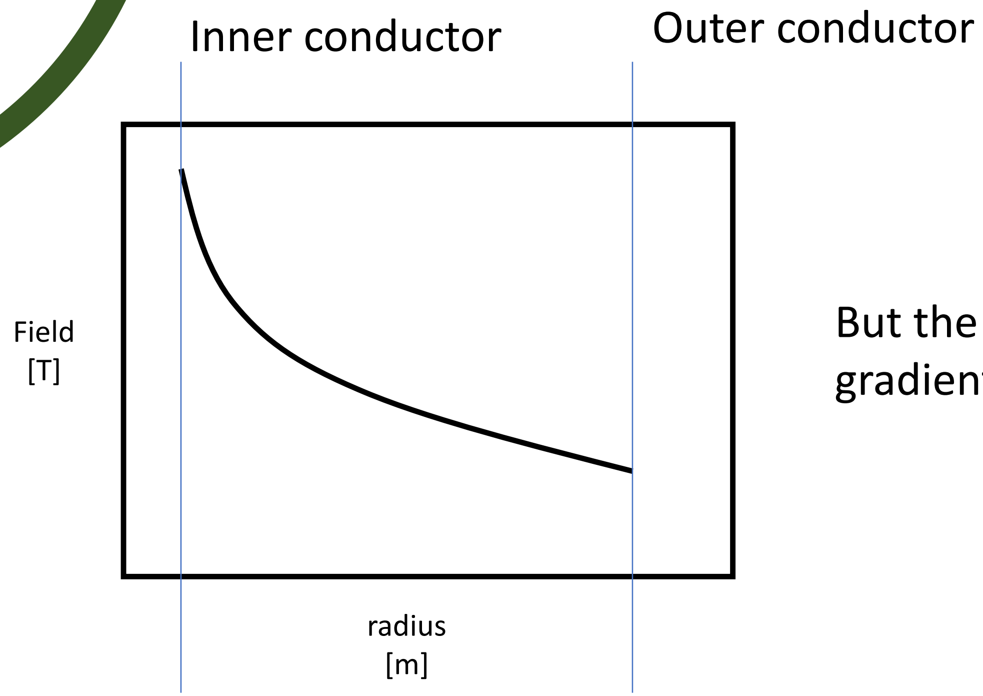
This pion goes through wall twice.
(trajectory is curved between conductors)
Can be a source of wrong-sign contamination.

Side view



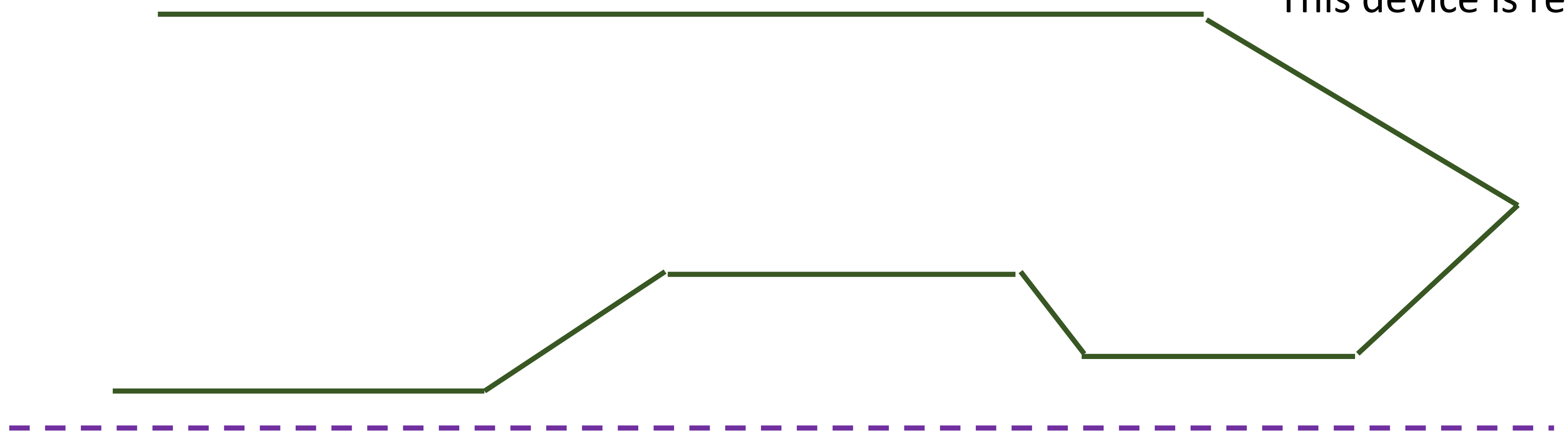
How about a toroidal field?

No steel to shape field, so low inductance.
Essentially a dead-short.
In the Booster Neutrino Beamline, this device carries 180,000 Amps for a few microseconds.



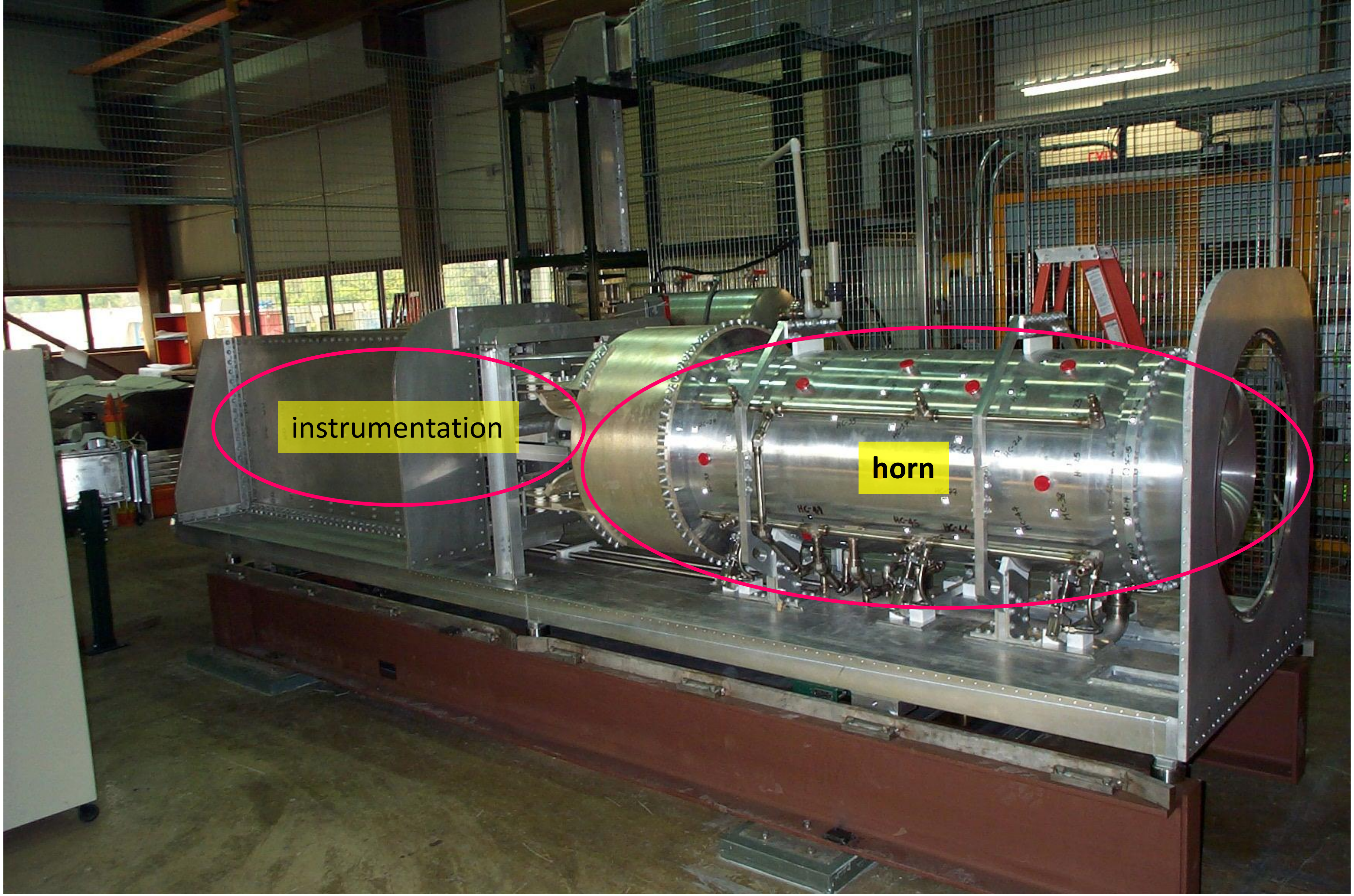
But the field is the wrong shape – gradient is not constant.

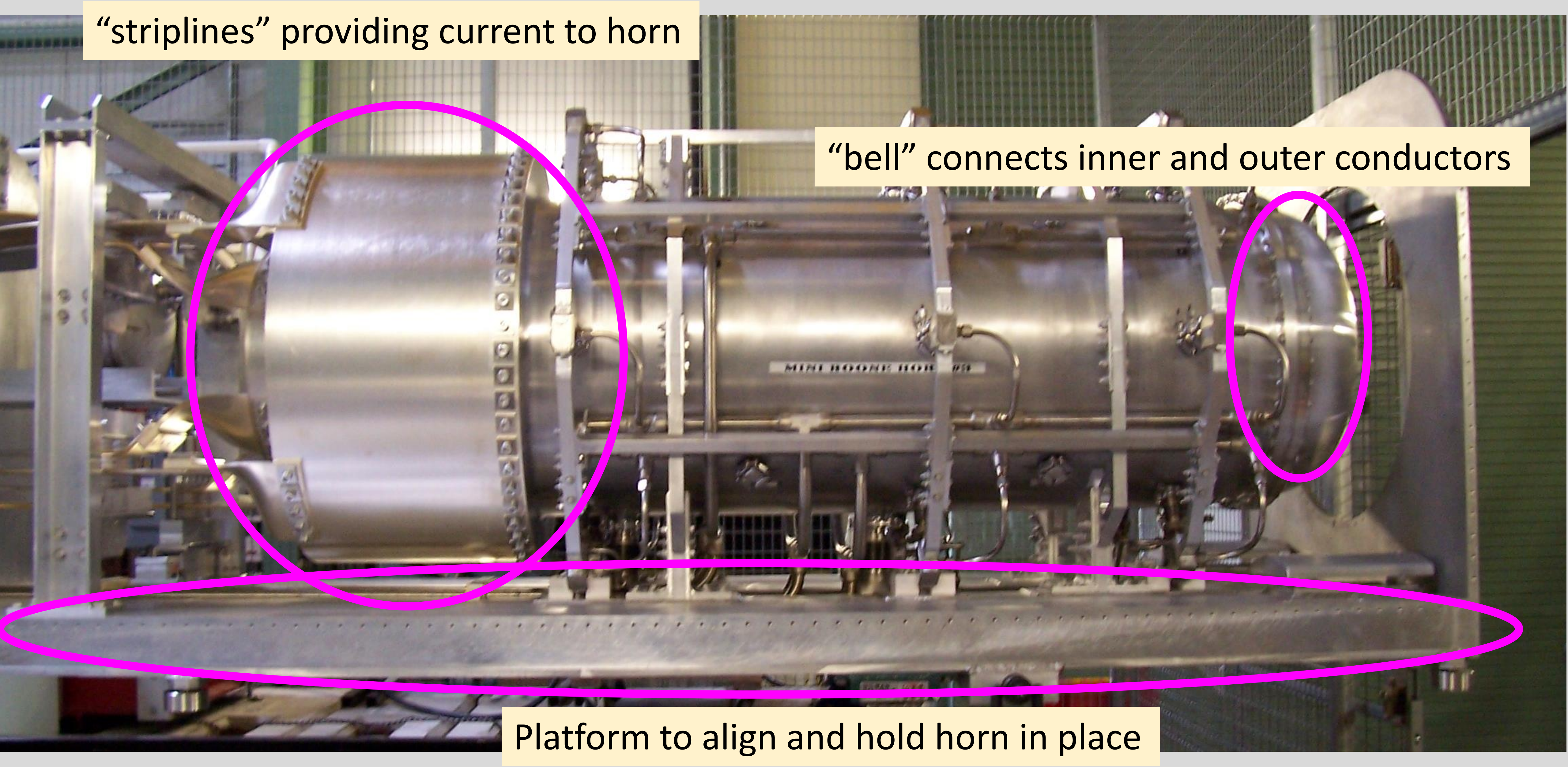
This device is referred to as a “Neutrino Horn”



However, one can shape the conductor so pions see the appropriate amount of field. This may mean a pion crosses conductor more than twice.

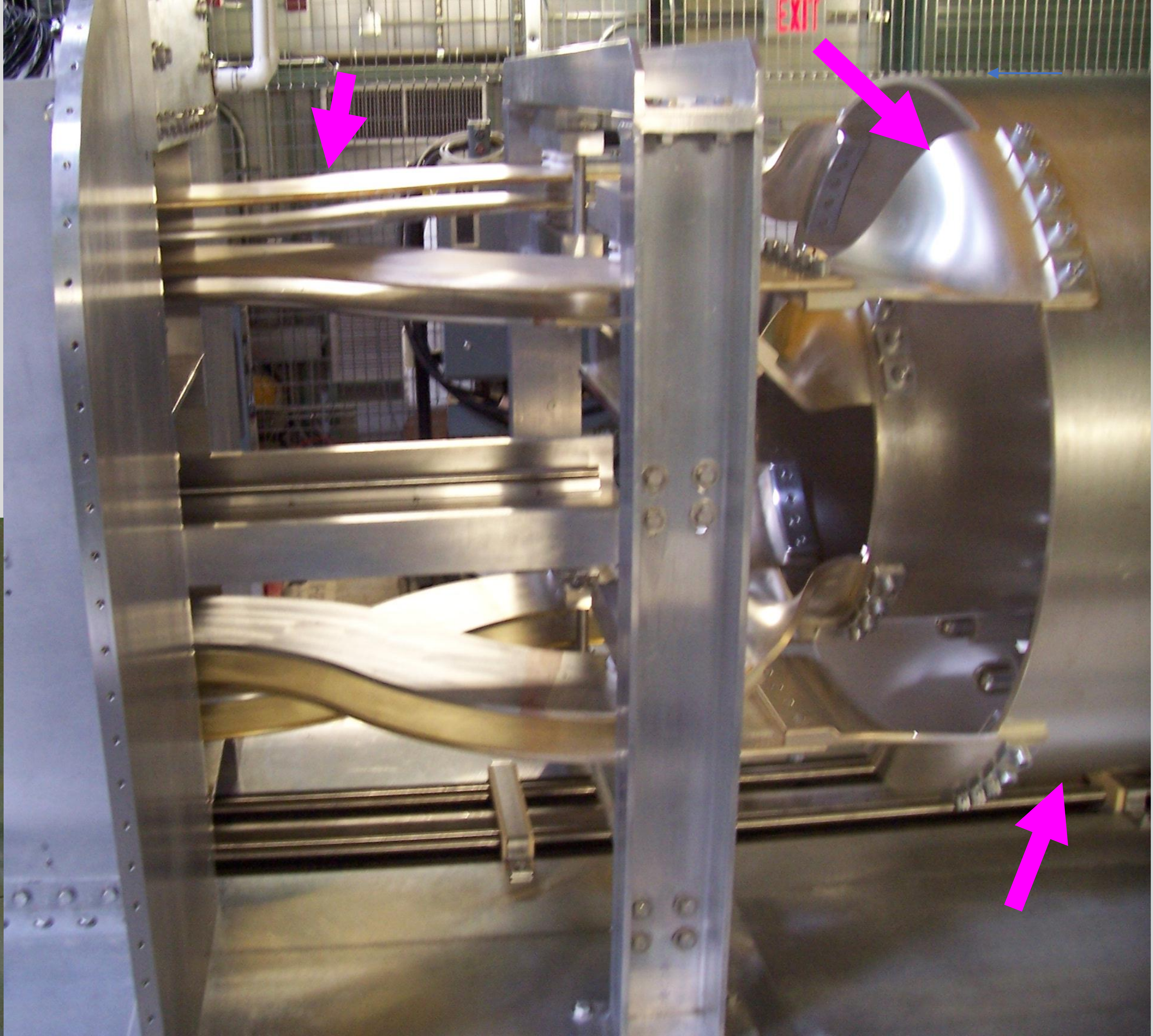
Make the walls thin, but still need to hold up to mechanical stress, joule heating, and heating due to energy deposition.


instrumentation
horn

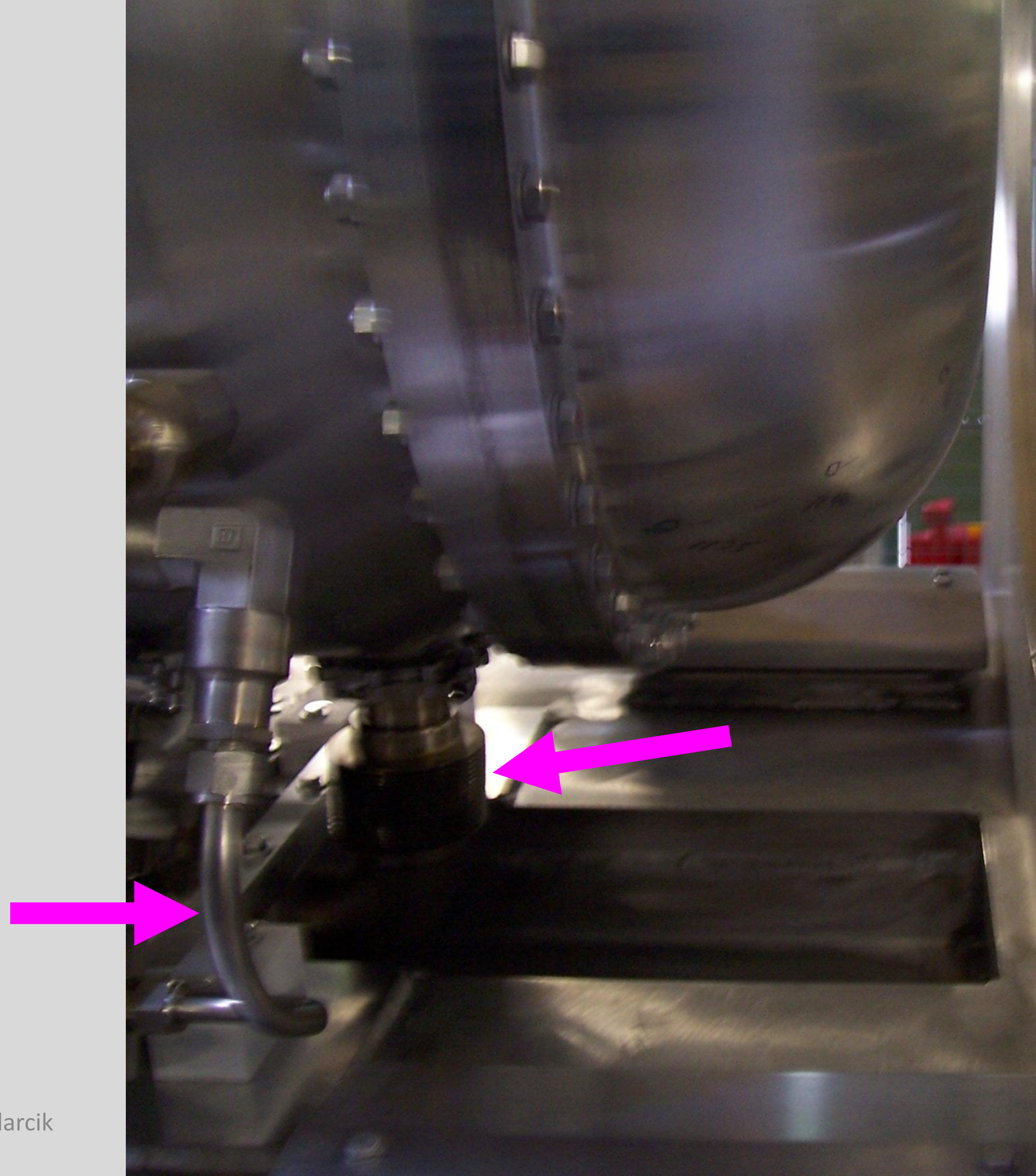

"striplines" providing current to horn
"bell" connects inner and outer conductors
Platform to align and hold horn in place

Closeup of striplines, which bring current to inner and outer conductors.

Striplines bolt to “twist transitions”, which in turn bolt to cylindrical transitions which allow current to “even out” before reaching the conductor.



Closeup showing bell, water spray line, and water drain line



This shows the BNB target assembly fitted into horn. A lot of details is shown, such as twist transitions, corona caps, and ceramic isolators.

Decay Pipe

How wide do you make the pipe?

- If it is too small, secondary beam may interact with it.
- Larger diameter implies higher cost.

How long do you make the pipe?

- The longer the pipe, the more pions will decay, but muons will decay, also.
- Excavation cost money.

Evacuated or gas-filled (what gas, and what pressure)

- A large, evacuated, volume posses a life-safety risk. How do you keep people from being injured if the window ruptures? Injury can range from being sucked in, to rapid decompression, to shrapnel.
- Any gas in pipe is a source of particle production. Can lead to residual radiation, energy deposition in walls of pipe, and beam systematics.
- If it is filled with other than air, a rupture can displace oxygen and lead to an oxygen deficiency hazard.

More Decay Pipe

The BNB decay pipe is open to the atmosphere.

- Beam does interact with the air in the pipe. This has to be accounted for in beam simulations. Also, when changing the horn, the air can be a (potential) source of radionuclides – proper precautions need to be taken.
- Approximately 10%-15% of the beam power is deposited in the pipe and surrounding soil – a cooling system can remove excess heat.

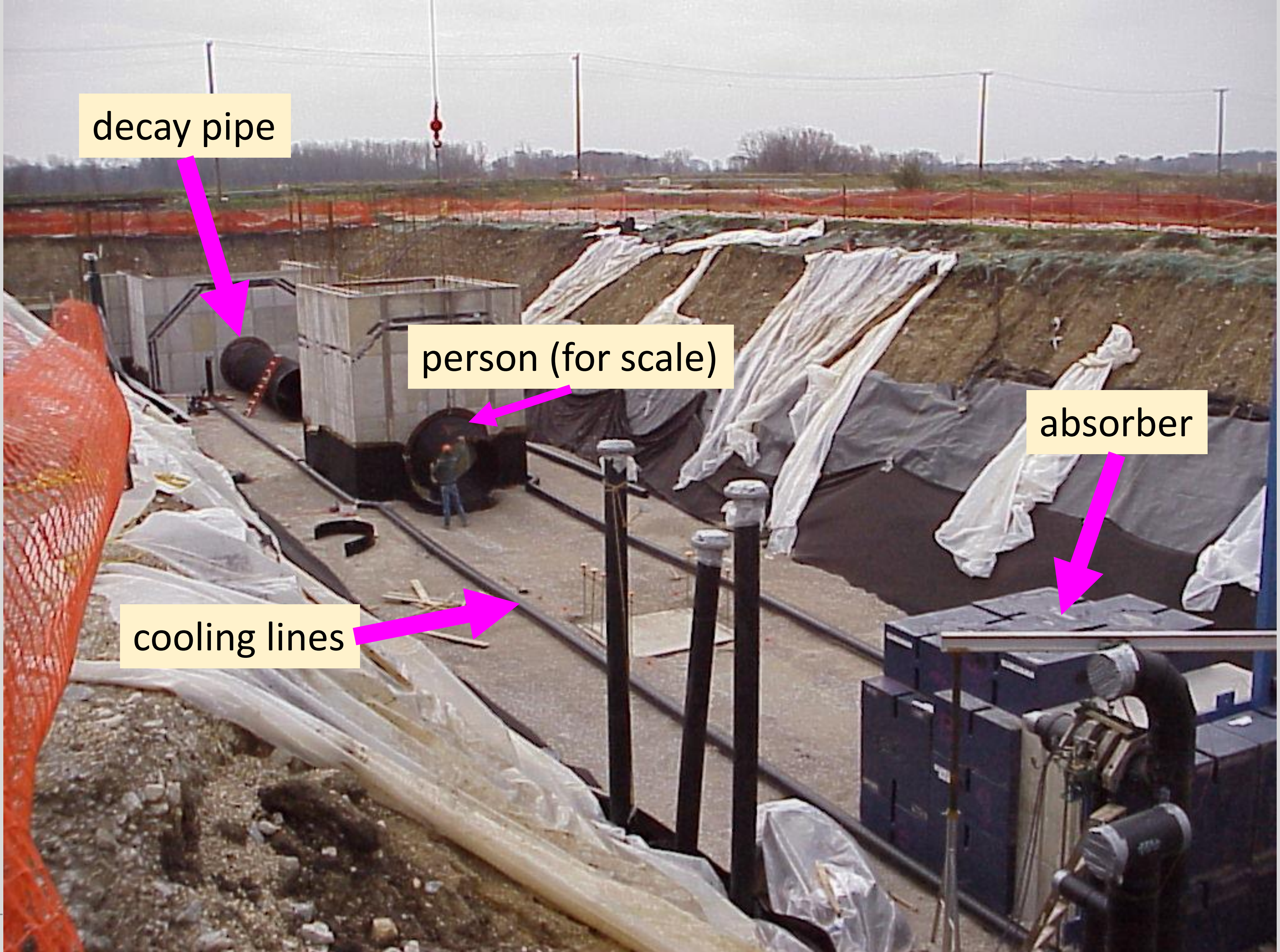
The NuMI decay pipe is filled with helium.

- Interaction length of helium is longer than that of air (but the decay pipe is longer).
- In some running modes, up to 1/3 of beam power is deposited in the pipe and surrounding concrete – a cooling system removes excess heat.

Uninteracted Proton Beam and Pion Beam

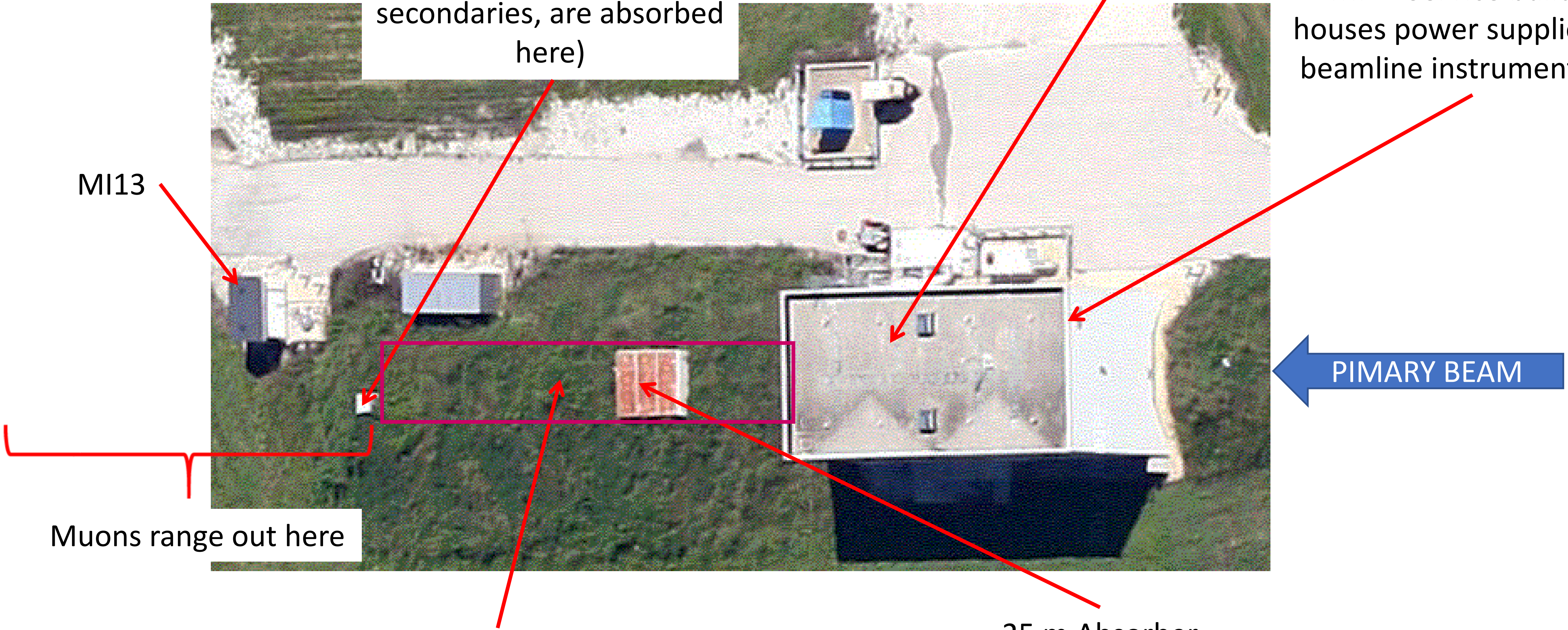
All that energy has to go somewhere! BNB can operate up to ~38 kW, and NuMI ~720 kW. That adds up!

Both beamlines have an “absorber” at the end of the decay pipe. The BNB absorber is cooled by conduction through the surrounding fill; NuMI has a dedicated water cooling system.



decay pipe
person (for scale)
absorber
cooling lines

Location


50 m Absorber
(uninteracted protons,
and undecayed
secondaries, are absorbed
here)
Target is sited here, about 10 m underground
MI12 Service building
houses power supplies and
beamline instrumentation
MI13
PIMARY BEAM
Muons range out here
Decay pipe, about 10 m underground,
2 m diameter, air filled
25 m Absorber
(not used)

Booster Neutrino Beamline and Detector Facilities

SB-FD

MiniBooNE

LArTF

Booster

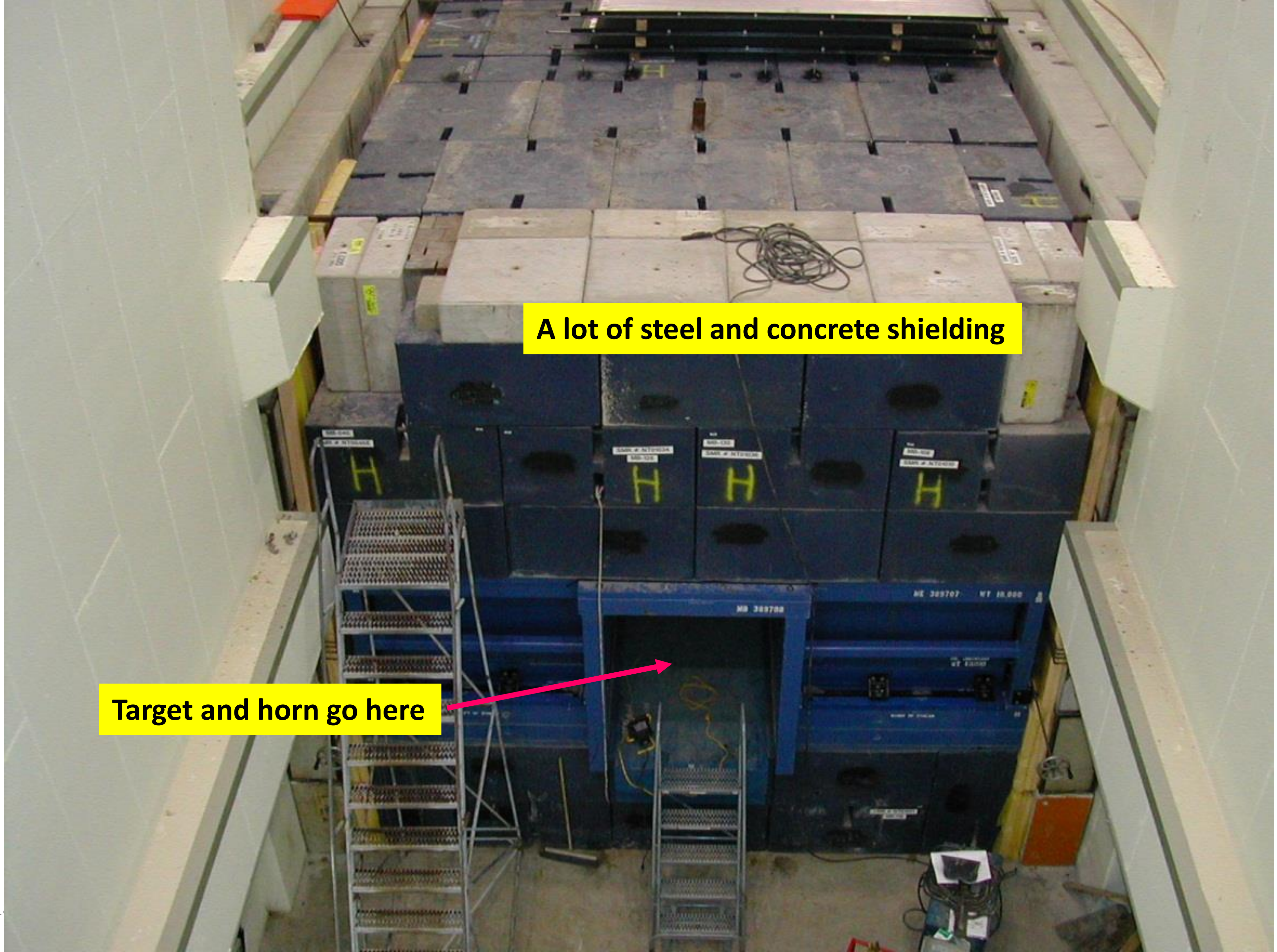
SB-ND

SciBooNE

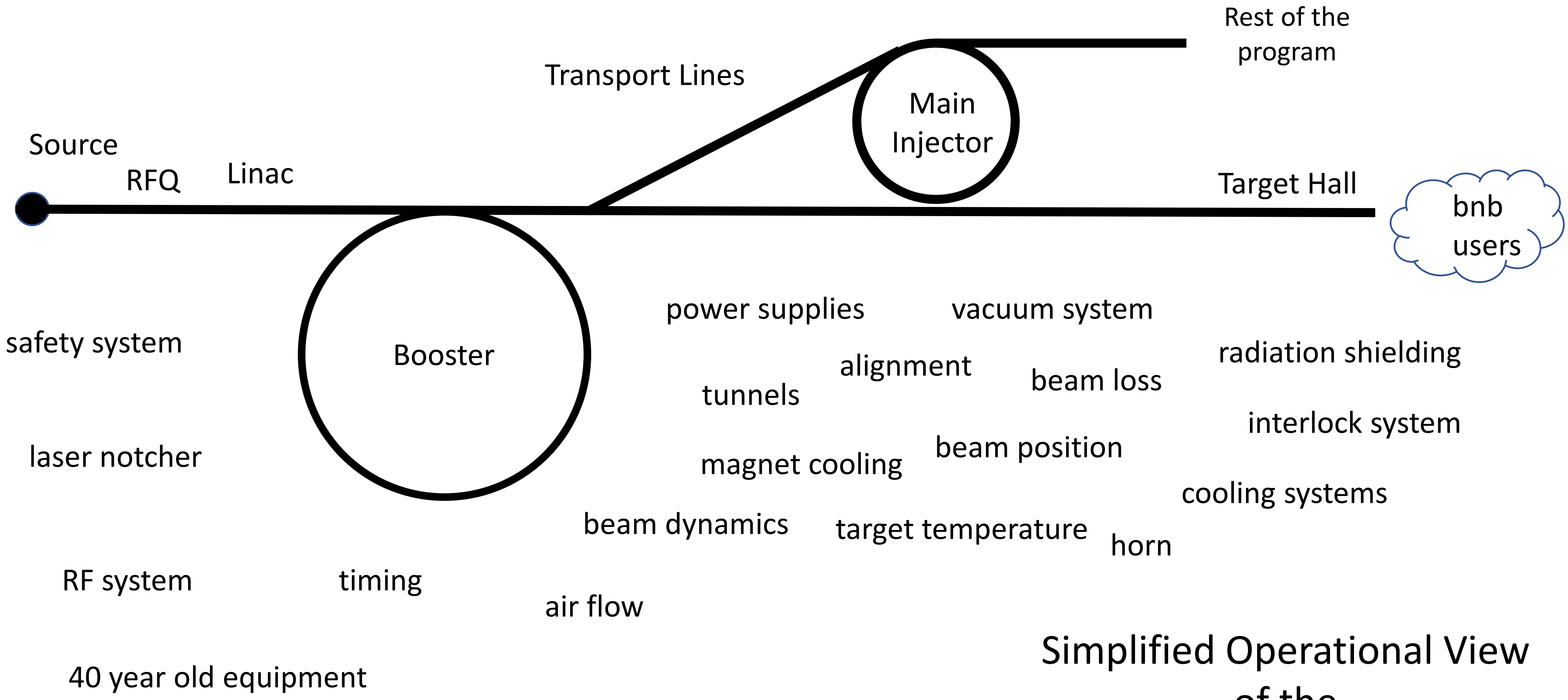
Booster Neutrino Beamline

END

BACKUP


A lot of steel and concrete shielding
Target and horn go here


Primary
Beamline



Simplified Operational View of the Booster Neutrino Beamline