C^3, the Cryomodule and Cryogenics

Martin Breidenbach, Emilio Nanni, Marco Oriunno, Caterina Vernieri

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Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Plan

- C^3 concept from very high altitude
- C^3 Cryomodule
- C^3- 550
- C^3 - Quarter Cryo Module
- C^3 Demonstrator

C3 Strategy

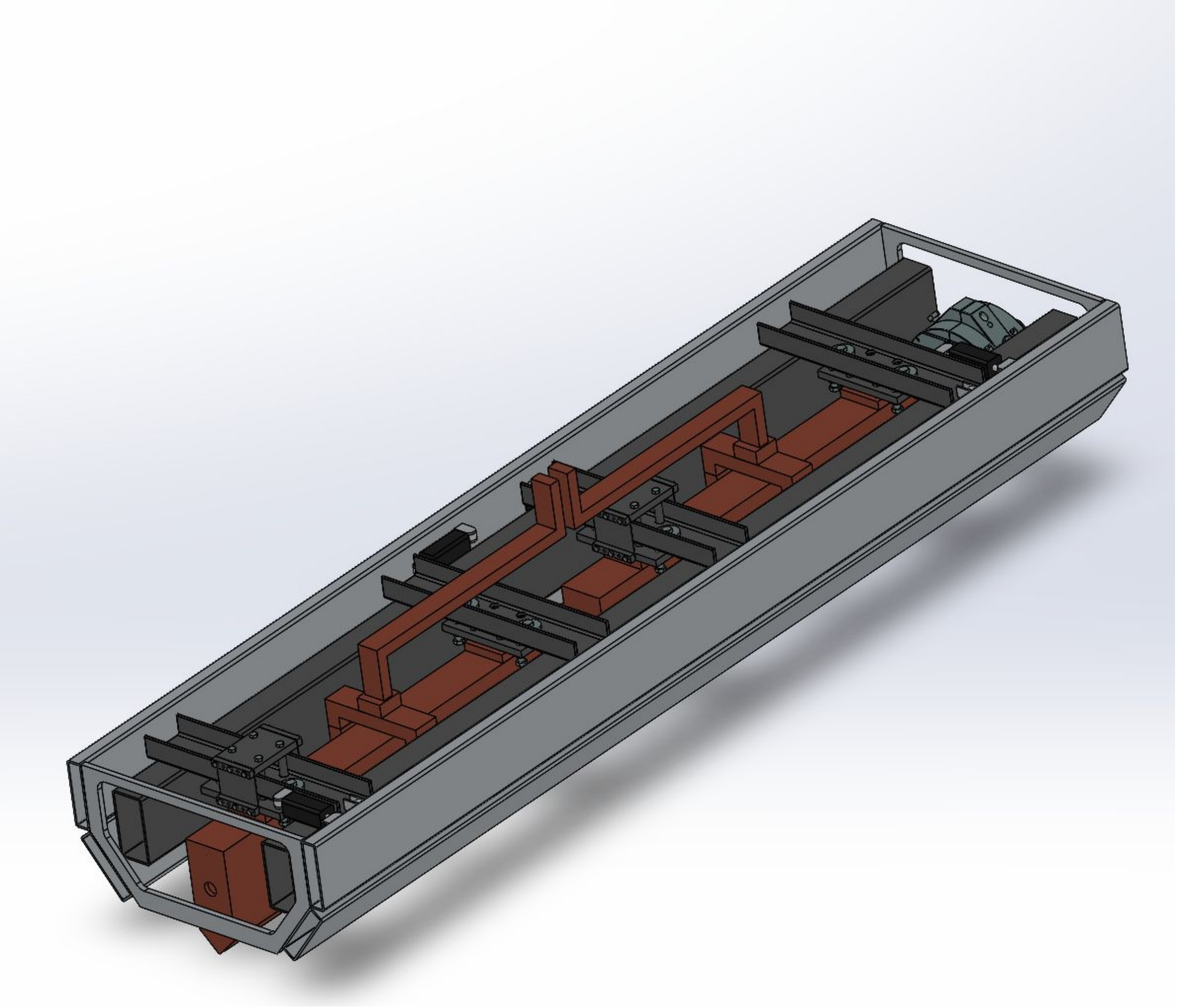
- C^3 will be built for 550 GeV com operation, but will initially run at 250 GeV com.
- At 250 GeV, the gradient will be 70 MeV/m, and will require ~¼ the RF sources required for 550 GeV.
- The transition to 550 GeV entails the addition of more RF sources. During the next 20 years, there will be intensive R&D for cheaper, more efficient RF sources.
- This talk will focus on the 550 GeV C^3.

Basic Cryogenic Concept

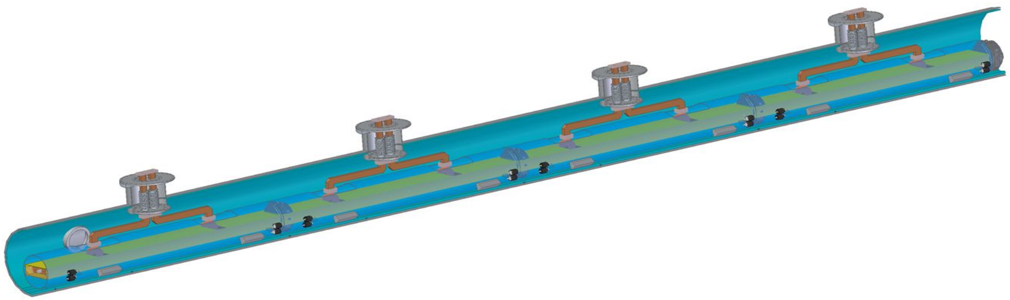
- C3 is based on a radically new linac technology optimizing the accelerating gradient, breakdown rate, and linac cost. The accelerator runs at 80K.
- The accelerator structures are normal conducting and milled from OFHC copper to make up a block 10 x 20 x 106 cm^3. Each structure dissipates 2500 watts.
- The structures are submerged in an LN pool and are cooled by nucleate boiling on the surfaces, with a power density of ~0.4 $watts/cm^2$
- The cryomodule is 75 cm ID, with LN flowing 300-400 m, and LN vapor counterflowing to be re-liquified.

First brazed C-Band module

C^3 Raft



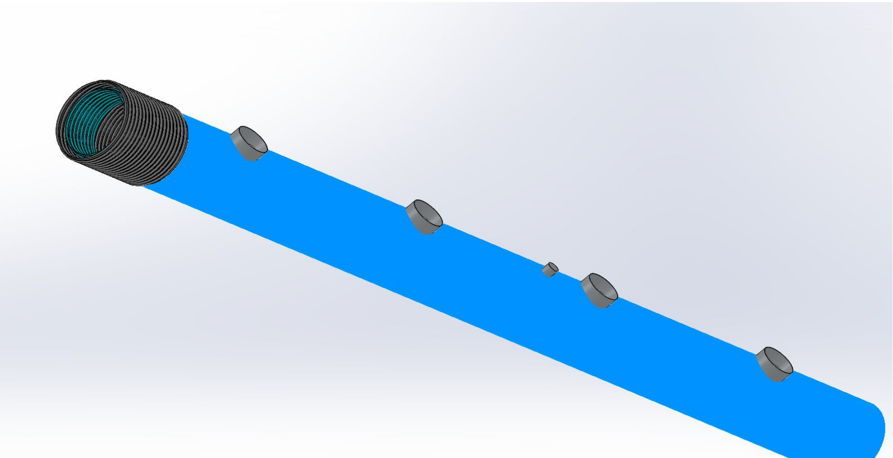
The Cryomodule



4 rafts per Cryomodule

Inner cryostat (probably) 304 Stainless
Outer cryostat might be mild steel, but 304 for now.
Only 4 ports for waveguides and a few other cables.

Plan (hope?) to have only welded joints in cryostat - no bolted flanges or other connectors. Weld preps designed for “can opener” removal.



Model used to get budgetary cost estimate

Note that Cryomodule fits in standard 40’ ISO container for transport.

Thermal Contraction

Integrated contraction from room temperature to 77K:

Cu -0.31%   SS 304   -0.29%

- So ΔL between 1 meter of Cu and 1 meter of SS 304 is ~200 μm
  - Accelerator is pinned in Z to raft at its midpoint
  - Accelerator sections separate by 200 μm
  - ΔL is taken by bellows

- 10 m SS inner cryostat contracts ~3 cm. Outer steel shell stays warm, so sliding support needed.
  - SS inner cryostat pinned in Z to outer shell at midpoint by G10 standoffs.
  - Cryomodules cold sections separate by 3 cm at ends.
  - ΔL is taken by bellows

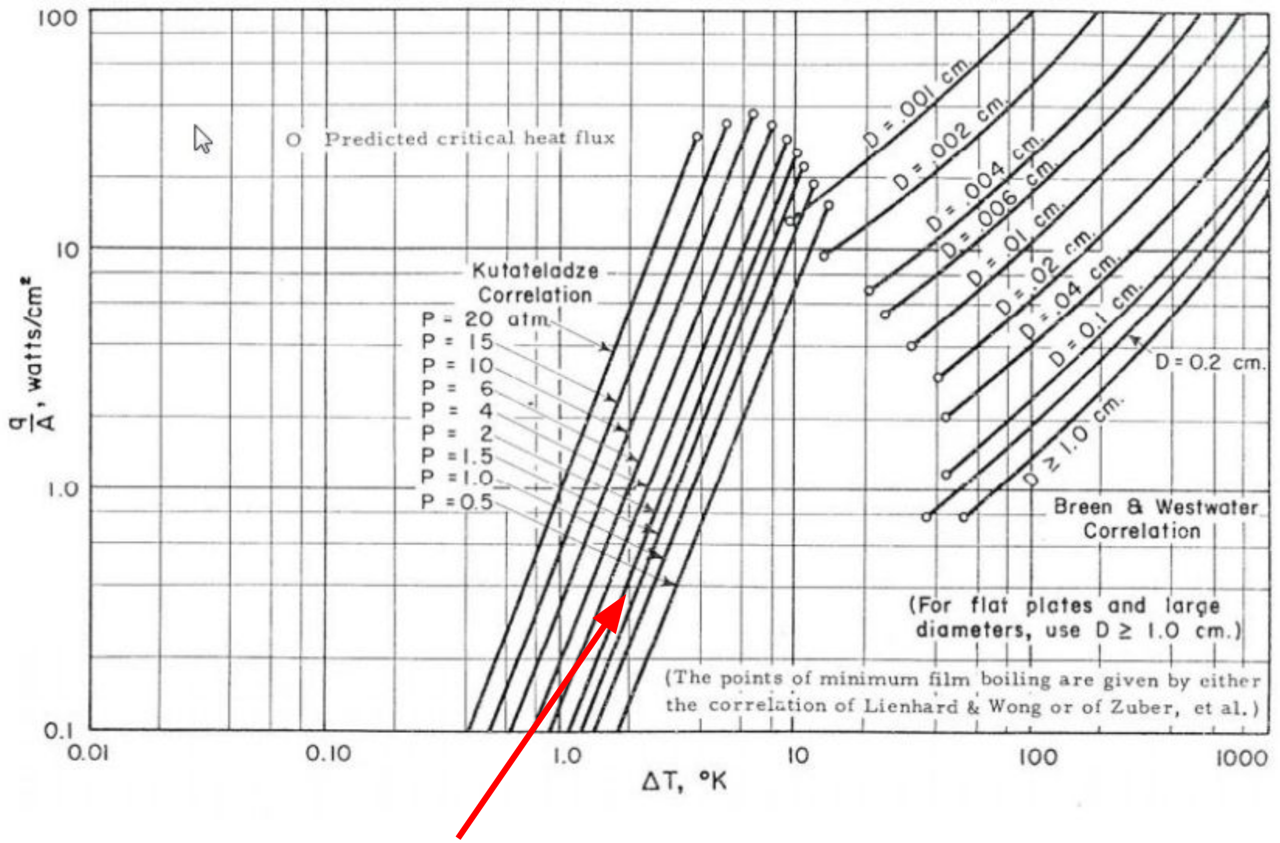
Thermal Loads

Gradient (Mev/m)	Power Dissipation (W)	RF Flat top pulse length (ns)	Pulse Compression	Comments	Power/Area W/cm^2	Delta T Cu-Bulk LN (K)
70	2500	700	N	C^3-250	0.393	2.3
120	2500	250	N	C^3-550	0.393	2.3
150	3900	250	N	C^3-550 in 7 km	0.614	2.5
120	1650	250	Y	C^3-550	0.259	2.1

Nucleate boiling regime, assuming entire area participates, but…

Dominant Cooling Mode

Prediction of Nucleate/Film Boiling for Nitrogen



Nucleate Boiling on bottom??

This needs study because of probable large bubble formation on underside. Possible mitigations:

- “Vertical” accelerator on axis - *accepted*
- Contour bottom of accelerator - *accepted, details tbd*
- Surface treatment *awaiting simulation and experiments*

Bubbling Induced Vibrations

- Initial study at SLAC with Cu slab ~accelerator size in open LN bath on pneumatically isolated table.
- Fitted with cryogenic accelerometers for x, y, z, table y
- Just beginning when COVID stopped everything.
- First measurements with 1700 W internal heater.

- *This effort now continuing!!!!*
- Will move to a real accelerator structure with 2500 watt tungsten wire on axis.
- Will be in the Quarter CryoModule with window looking up to bottom of accelerator.

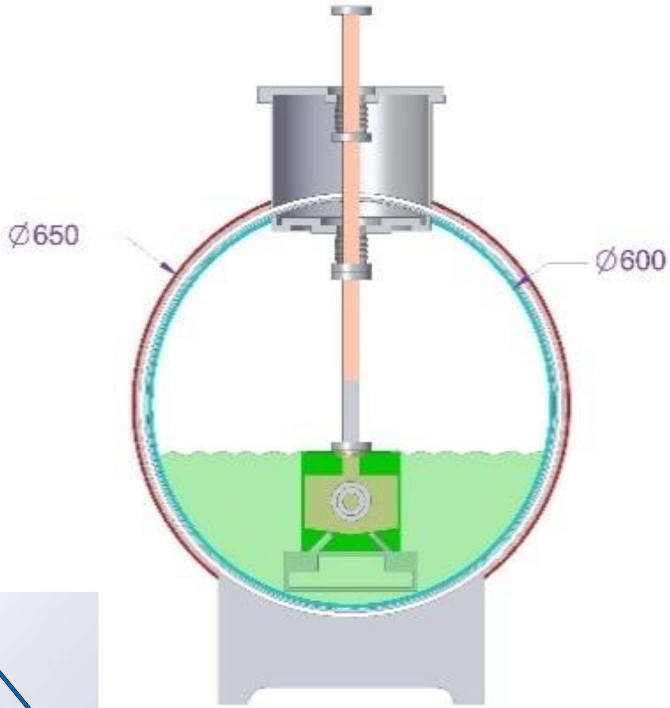
Alignment

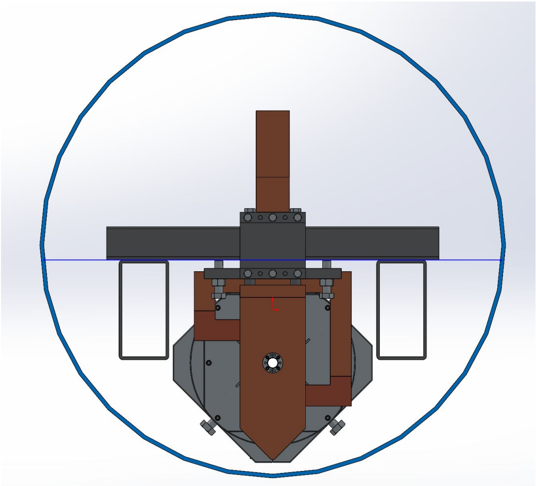
- Raft (2 accelerators + quad) are pre-aligned on bench to ~5 μ.
- Rafts are pre-aligned cold to <500 μ.
  - Considering RASNIK laser alignment system from NIKHEF. Almost optical version of stretched wires.
  - Stretched wires seem plausible if RASNIK will not work under LN.
  - RASNIK talk next!

- Beam Based alignment takes over.

LN distribution concepts

- Accelerator is under LN in a vacuum insulated cryostat
- LN flows into page
- Nitrogen vapor counterflows
- Gravity drives LN flow
- Pressure difference drives vapor flow
- Distributed re-liquifiers condense the cold vapor.





SuperSectors

- The reliquification plant feeds two “CryoRuns” going in each direction from a “SuperCross”.
- For 550 GeV baseline, each CryoRun is ~445 m.
- The end of each CryoRun (furthest from the SuperCross) is closed, and the beamline between CryoRuns is warm.
- So for C^3-250 and C^3-550, each linac has 3 SuperSectors

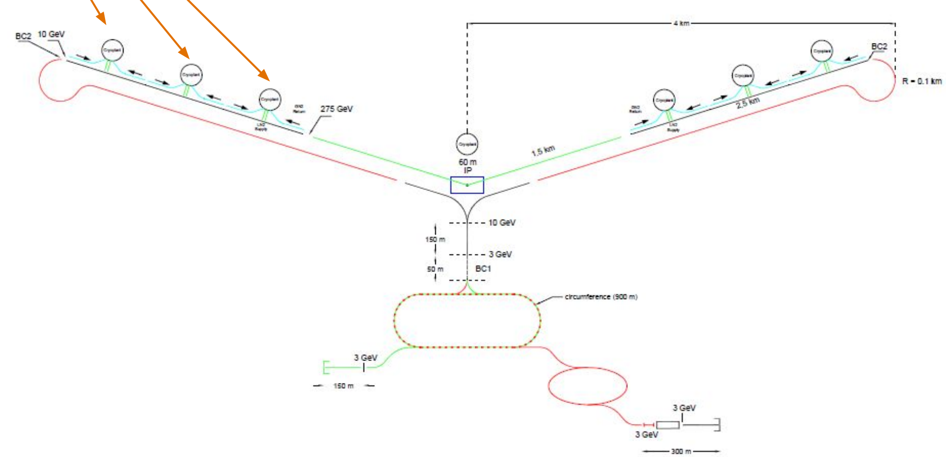
Gravity

- SuperSectors are laser straight, normal to earth radius at midpoint (SuperCross).
- Sagitta is 15 mm.
- Bend angle between SuperSectors is ~100 microradians.
- Required dipole strength is ~0.1 T-m for 0.25 TeV beam, ok for emittance growth. Located in warm section between SuperSectors.

Concentrate on C^3-550

Each 265 GeV linac:

- Linac Length 2668 m
- Linac Cooling Power 5.4 MW
- 3 Re-liquification plants
- 6 "Cryo-Runs", each 445 m
- 0.9 MW/Cryo-Run
- LN mass flow/Cryo-Run = 4.5 kg/sec
- LN Volume flow = 5.6 l/sec
- LN flow velocity = 0.03 m/sec = 0.1 km/hr
- LN Inventory ~7.4 x 10^5 kg (both linacs)



Length Comments

- Favored concept is to install enough cryomodules for 550 GeV @ 120 MeV/m, but initially provide RF power for ~70 MeV/m to run at 250 GeV.
- This complete structure is 8 km long, exceeding the FNAL site by 1 km.
- Could get to 550 GeV on FNAL site with ~ 150 MeV/m, but getting aggressive. Cooling is fine.
- Certainly no expansion to TeV class on FNAL site.
- Hanford site is big enough for most anything.

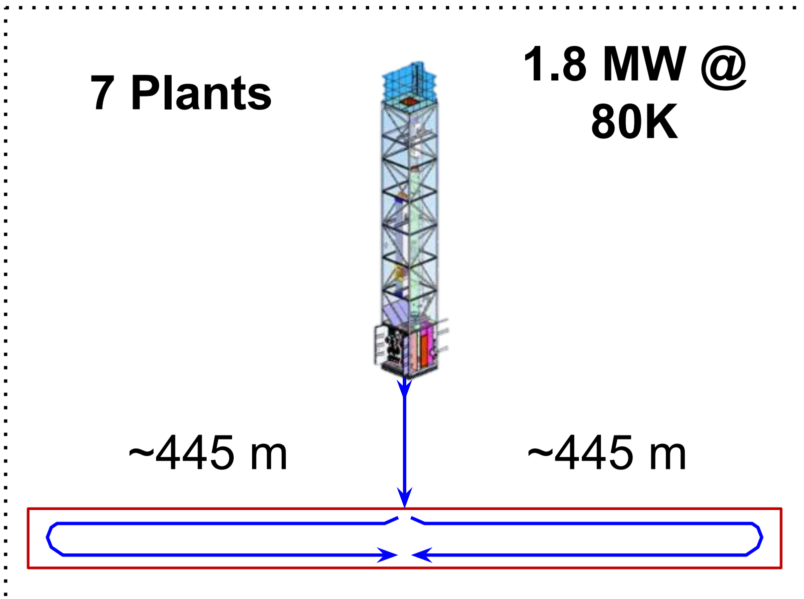
Gas Phase Pressure Drop

Using FNAL method and nominal C3-250 parameters:

- Mass flow at Reliquifier = 4.5 kg/sec
- Flow length of ½ total since flow goes to 0 at midpoint
- Then gas velocity = 4.0 m/s   (OK????)
- And Pressure drop ~3 mBar   (Probably OK)

CRYOGENIC Process

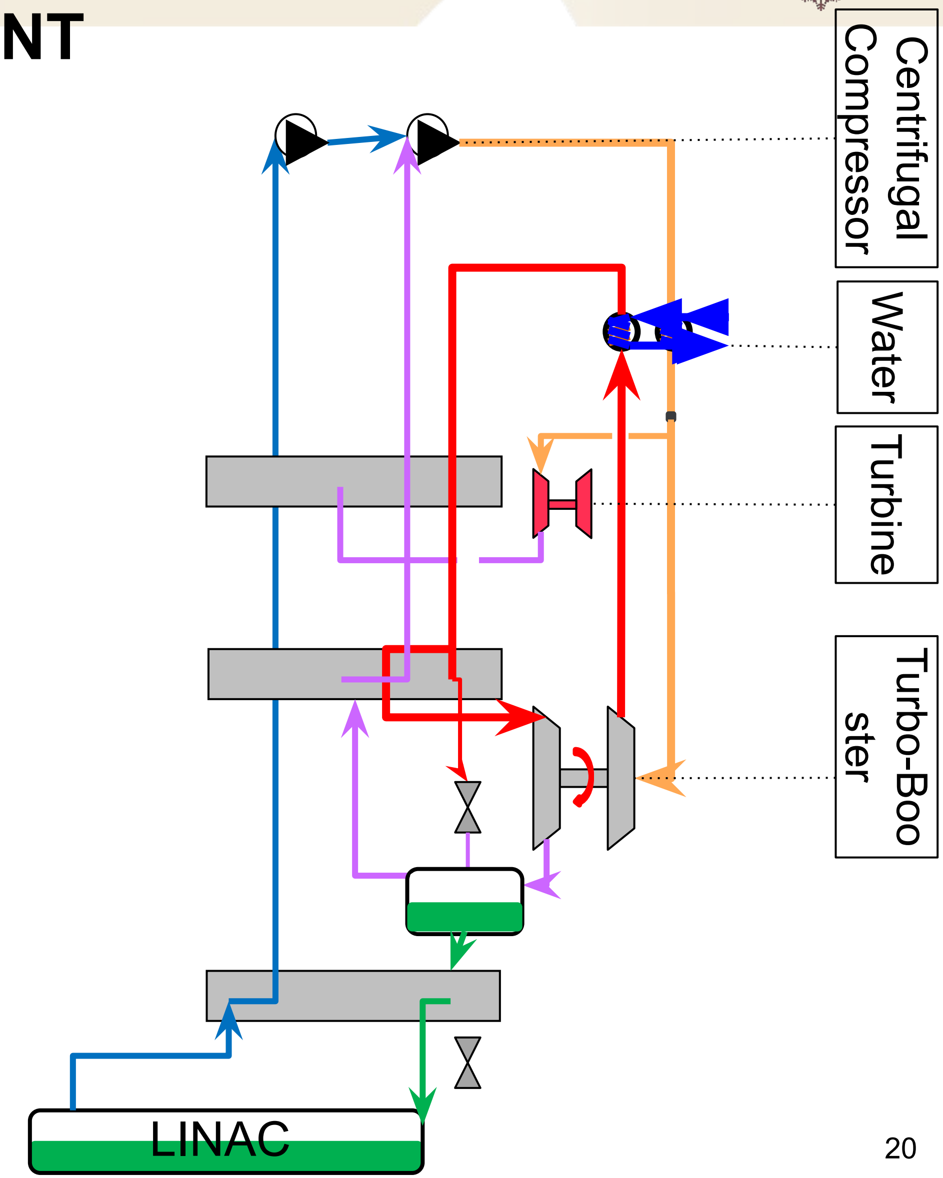
- **LN2 REFRIGERATION PLANT**



EFFICIENCY

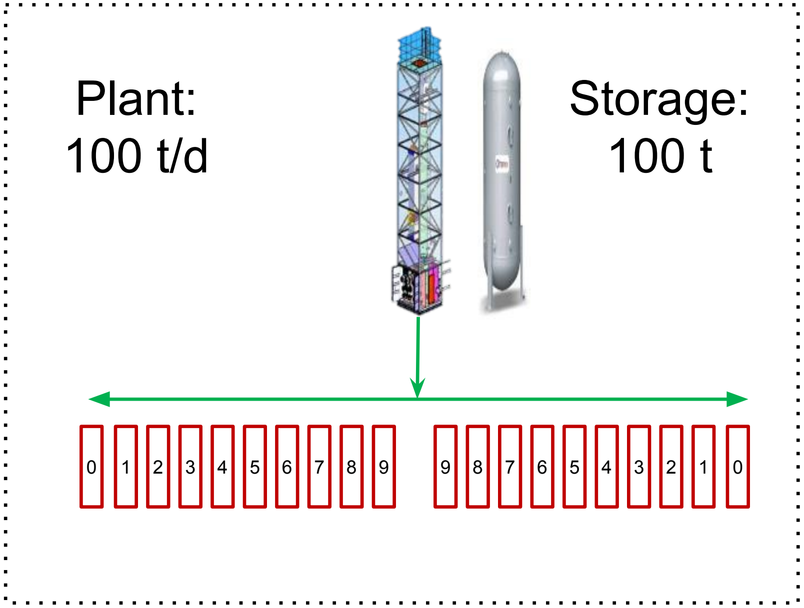
- Carnot: 30%
- Machine: 50%
- Overall: **15%**

- 12 MW Elec. / plant
- 60 MW Elec. cooling
- 40 MW Elec RF
- **150 MW Elec. Total site for C3-250**
- **175 MW Elec. Total site for C3-550**



CRYOGENIC Process

- **LN2 PRODUCTION AND STORAGE**



LN2 Plant function: (Air Separation Unit)

- Process LN2 Inventory from Air
- Compensate Leaks from Plants
- Limit Impact of the Loss of 1 Plant

LN2 Storage Function:

- Allow storage of partial LINAC Inventory

LN2 Lines:

- ~4 km to distribute LN2 to each plant

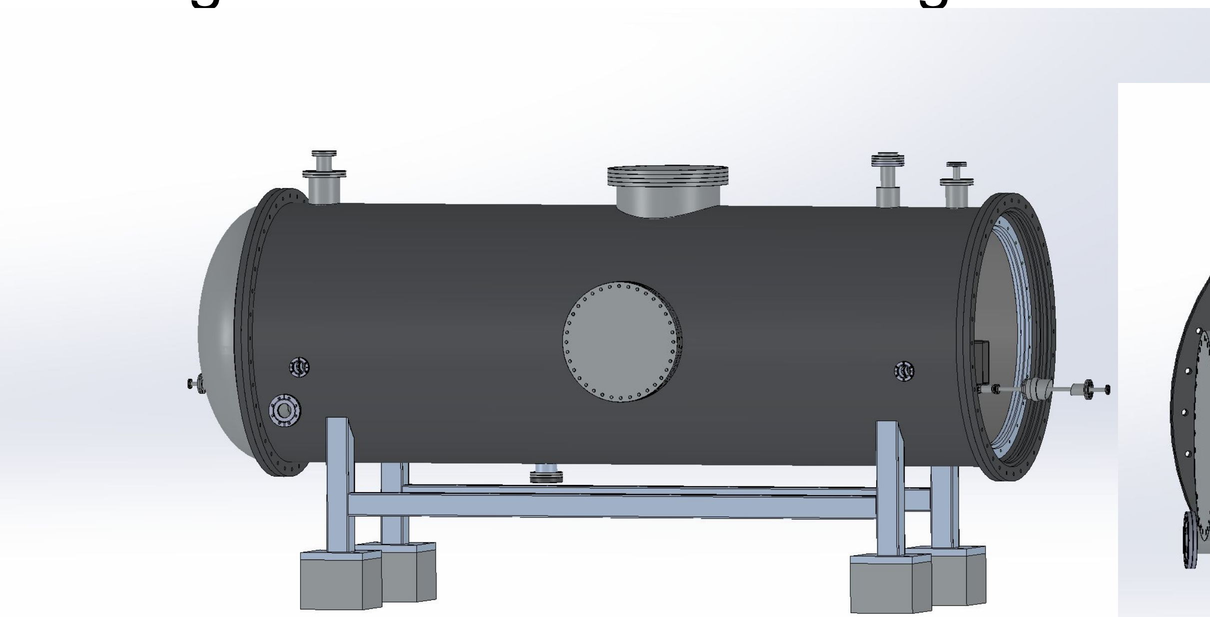
Note: LINAC Inventory ~740 tonnes Liquid.

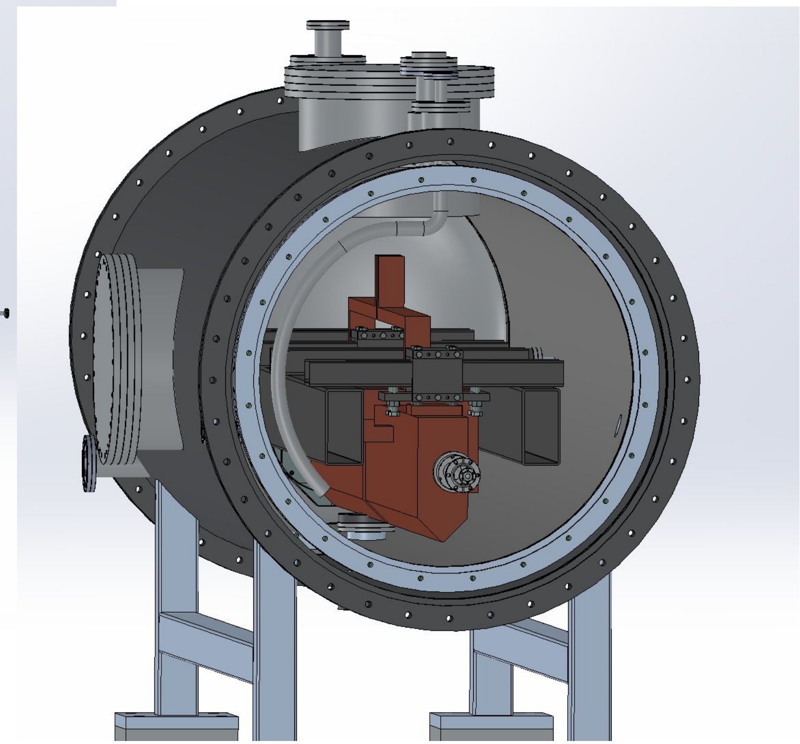
Quarter CryoModule (QCM)

Raft Alignment when cold

Bubble testing

Single Raft Accelerator testing?





Model & description detailed design almost done
Expect PO for QCM by July

Demonstrator Functionality

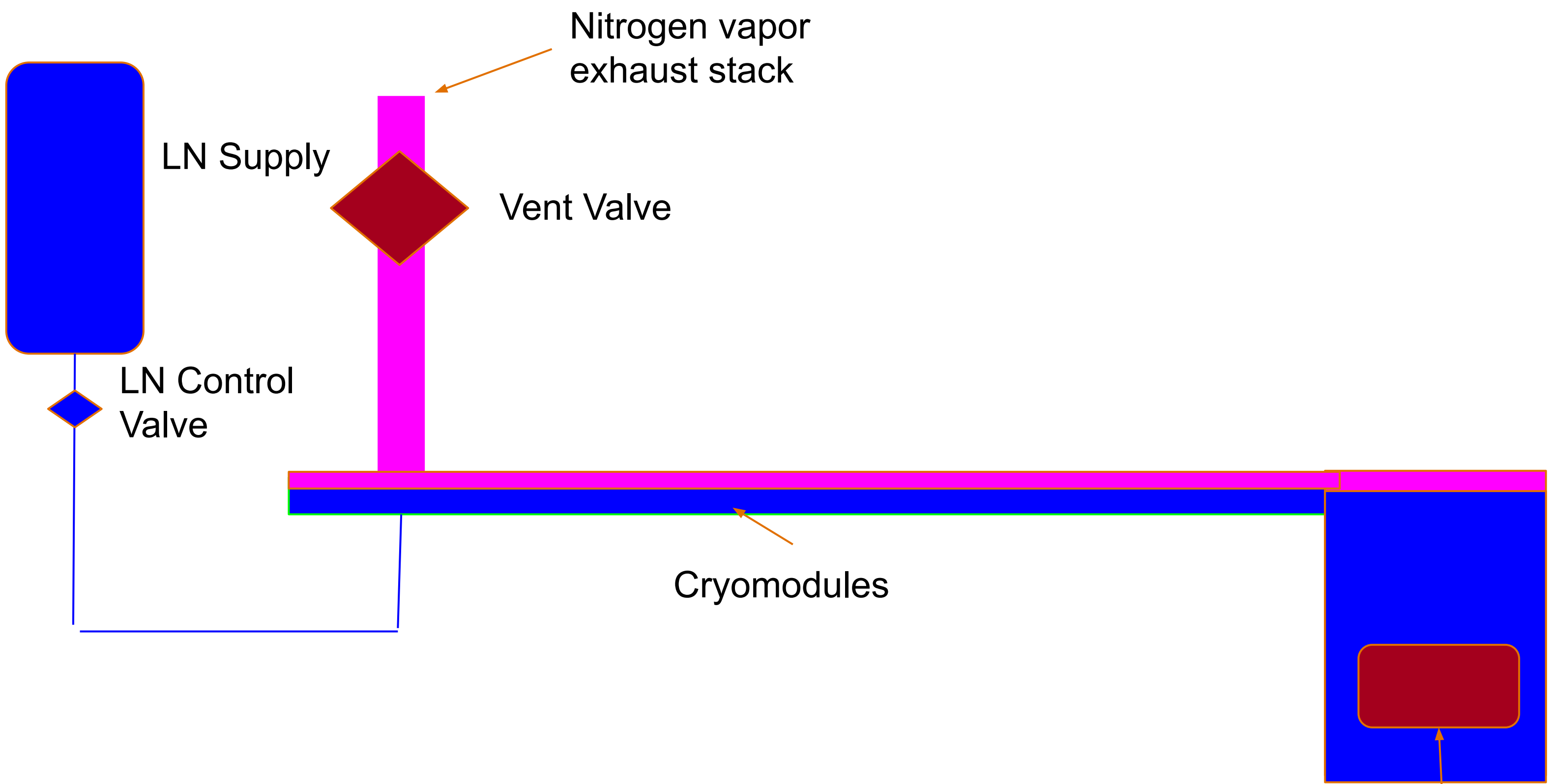
- Overall Goals
  - Reduce C3 Technical risks
  - Reduce C3 Cost Risks
  - Reduce C3 Schedule Risks

- First step in a baseline design for the Demonstrator Cryogenics
  - Mode 1 - Normal Accelerator development
    - LN at nominal height above accelerator sections
    - low LN flow
  - Mode 2 - High flow for vibration testing etc, up to 10 kg/sec

Demonstrator Linac

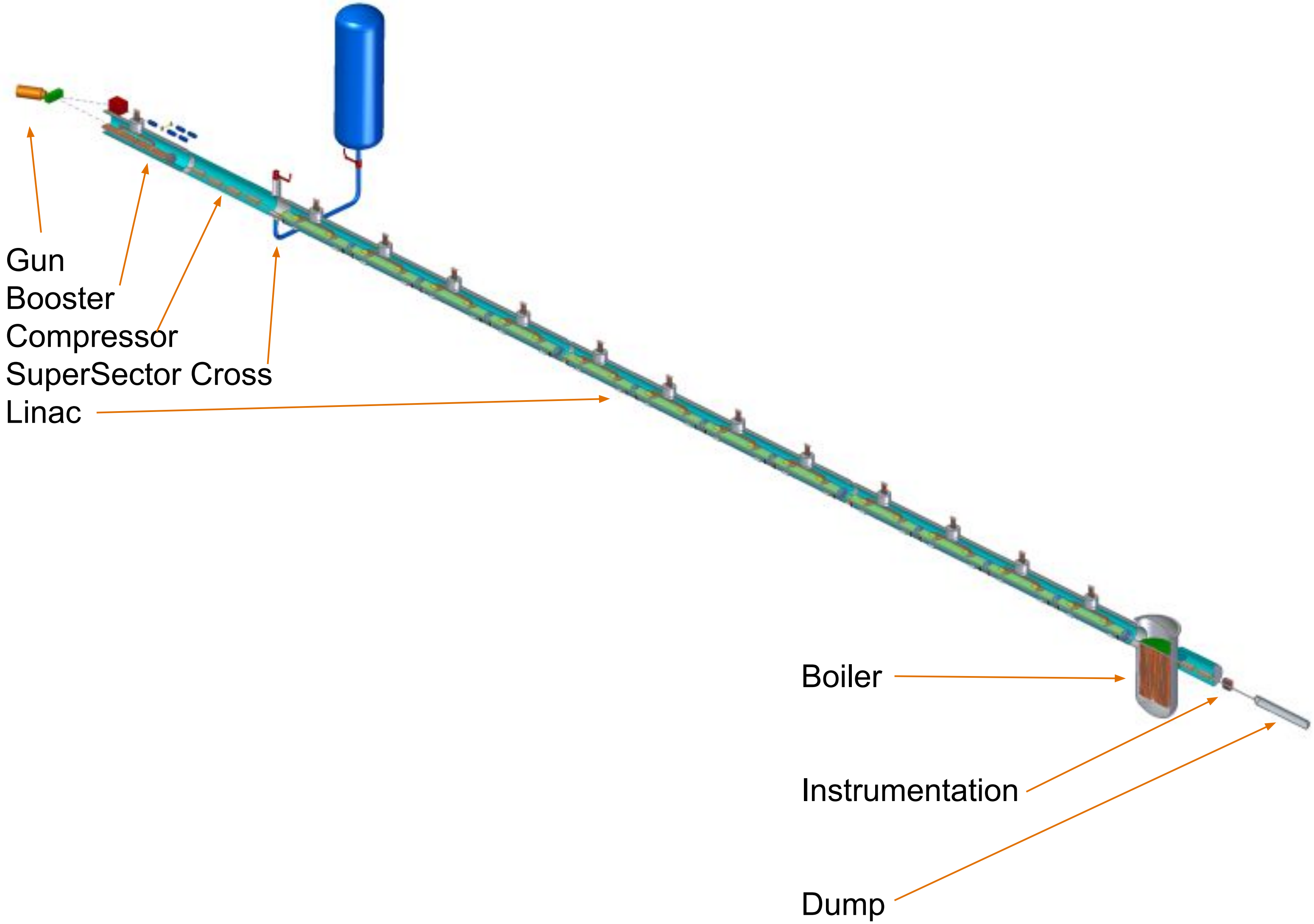
- The linac proper will consist of 3 cryomodules
  - Each cryomodule will have 4 rafts, each raft having 2 accelerator sections -
  - But only 18 accelerator sections will be powered
- This will permit demonstration of full fluid flow over the rafts including cryomodule transitions.
- The accelerator sections will be nominally powered for C^3-250 gradient (70 MeV/m), but also tested at the C^3-550 gradient (120 MeV/m), and the stretch gradient of 150 MeV/m. Operating margins will be explored.

Simplified Cryogenic Layout

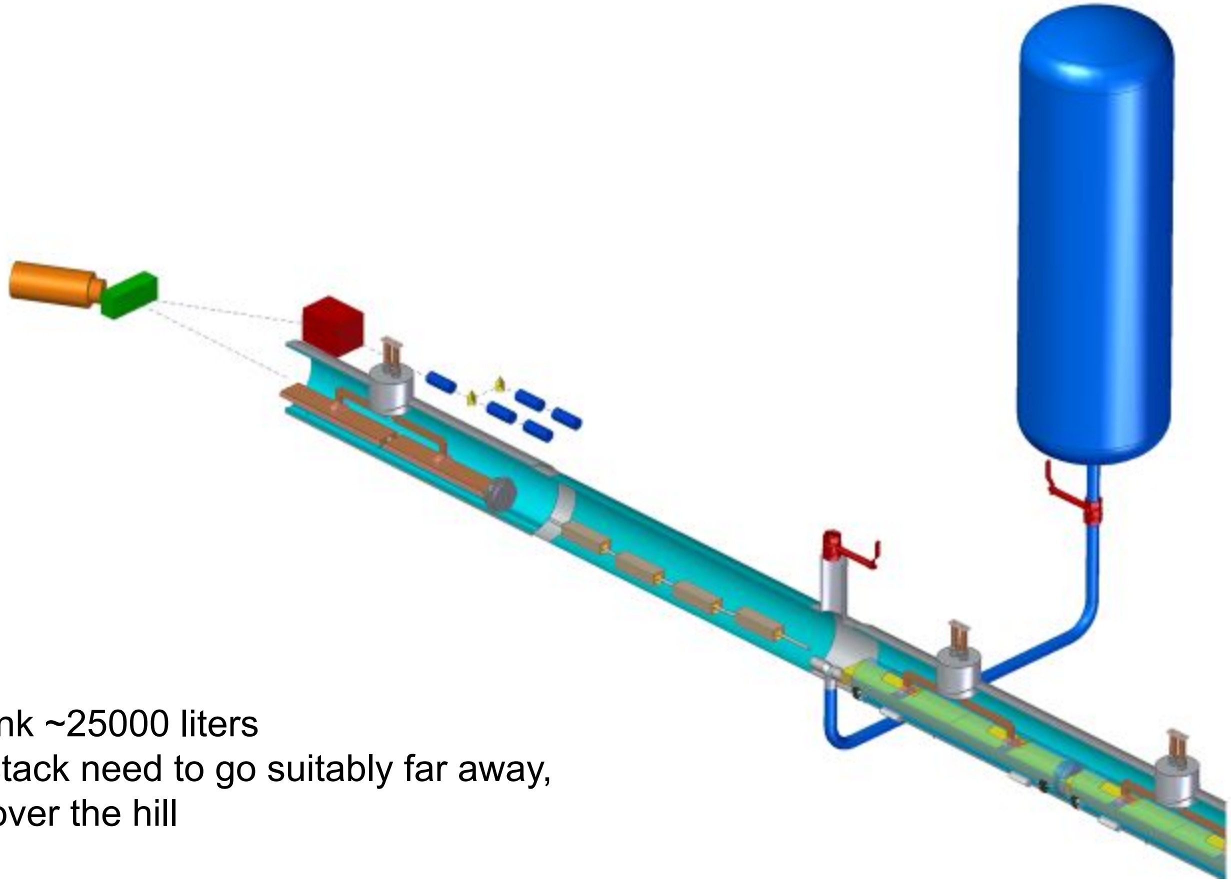


LN Supply ~25000 liters. Adjust T ~80K
LN Control Valve regulates on LN height in cryomodules
Vent Valve regulates on nitrogen vapor pressure ~T

Demonstrator Layout

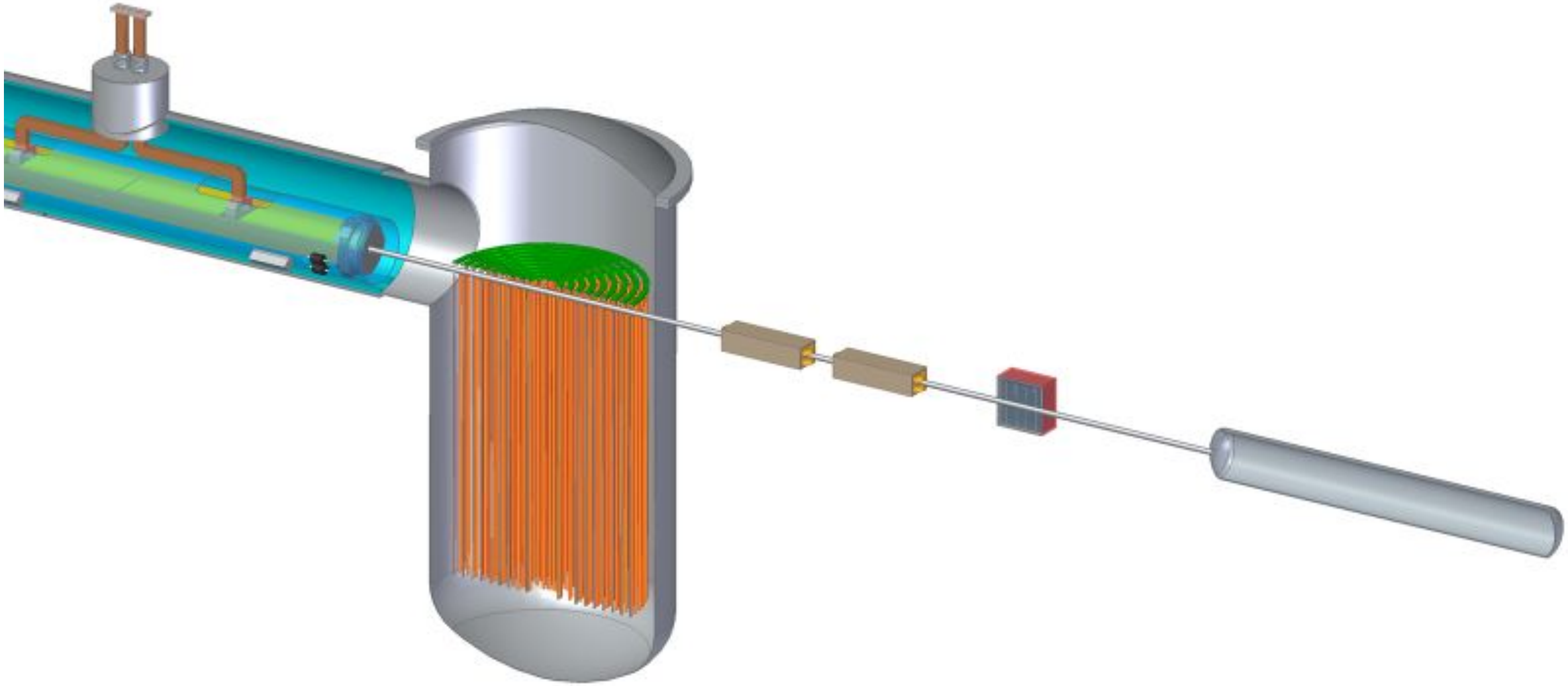


LN in, vapor out at “SuperSector Cross”



LN Tank ~25000 liters
Vent stack need to go suitably far away,
as in over the hill

Boiler

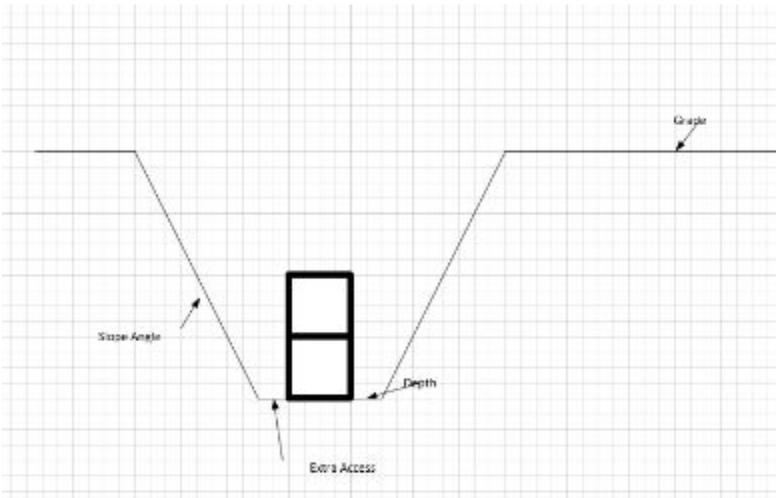


900 Calrods, 4 W/cm^2 , ~2 MW total.
LN in boiler at same level as in cryomodules, covering Calrod array.

And a little civil engineering….

For Cut & Cover:

Total excavated volume (including experimental hall) ~ 2E6 m^3
Total concrete ~200,000 m^3



Conclusions

- C3 will operate under LN to improve accelerator properties with net gain of efficiency.
- The cryostats for C3 are simple compared to those required for LHe.
- Important tests of the raft concept for maintenance of alignment will be tested with the QCM.
- Important tests of vibrations of an accelerator section dissipating 2500 watts will be tested in the QCM.
- Full liquid and vapor flow will be tested (with x2 margins) in the Demonstrator using the boiler.