Horns: new and improved

Photo: Stephen Coleman

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Snowmass NF04 workshop
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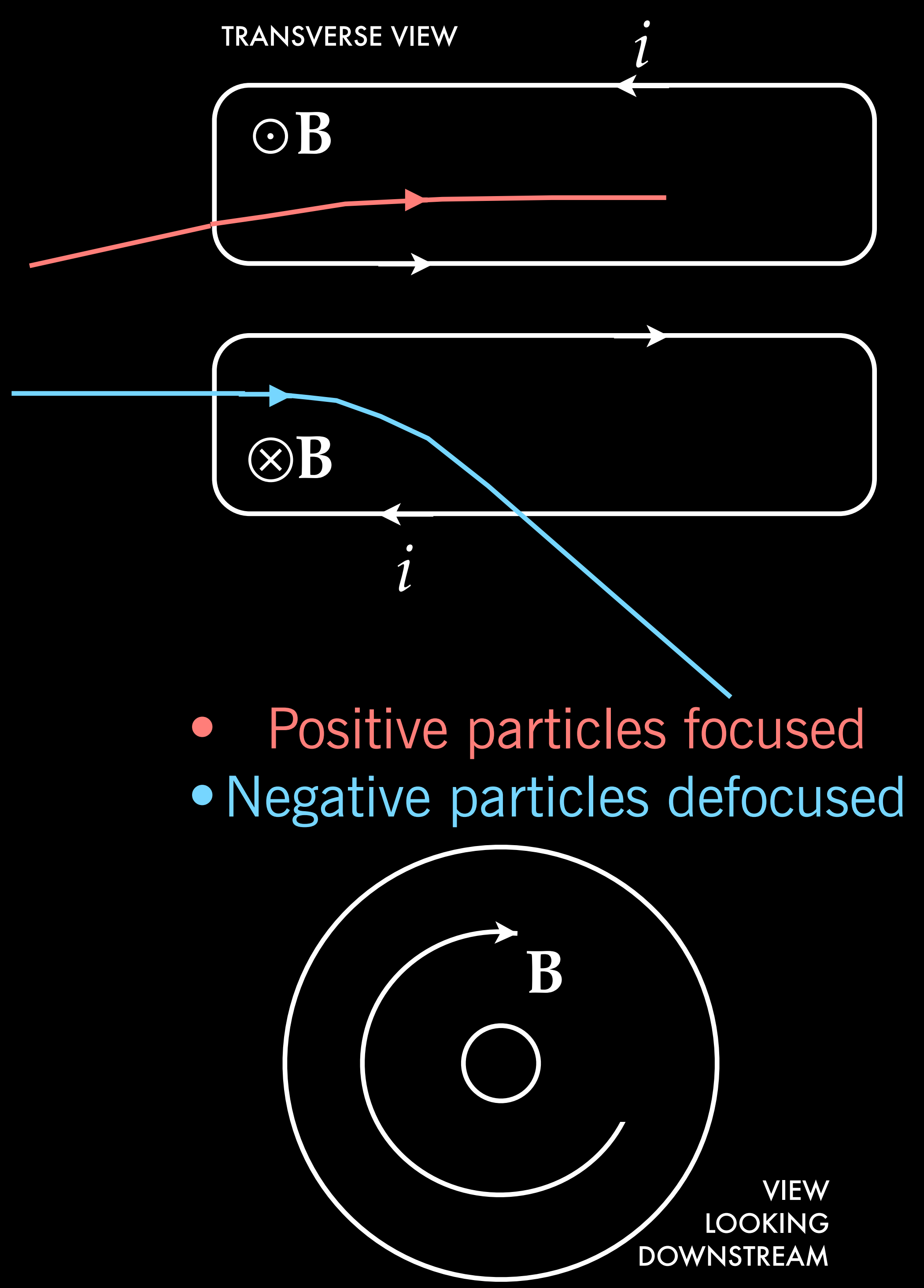
Horns: new and improved

- Horns
- High-power horn systems and their successors
- Developments at KEK
- Developments at FNAL
- Extreme horns! Slides by T. Sekiguchi

Horns

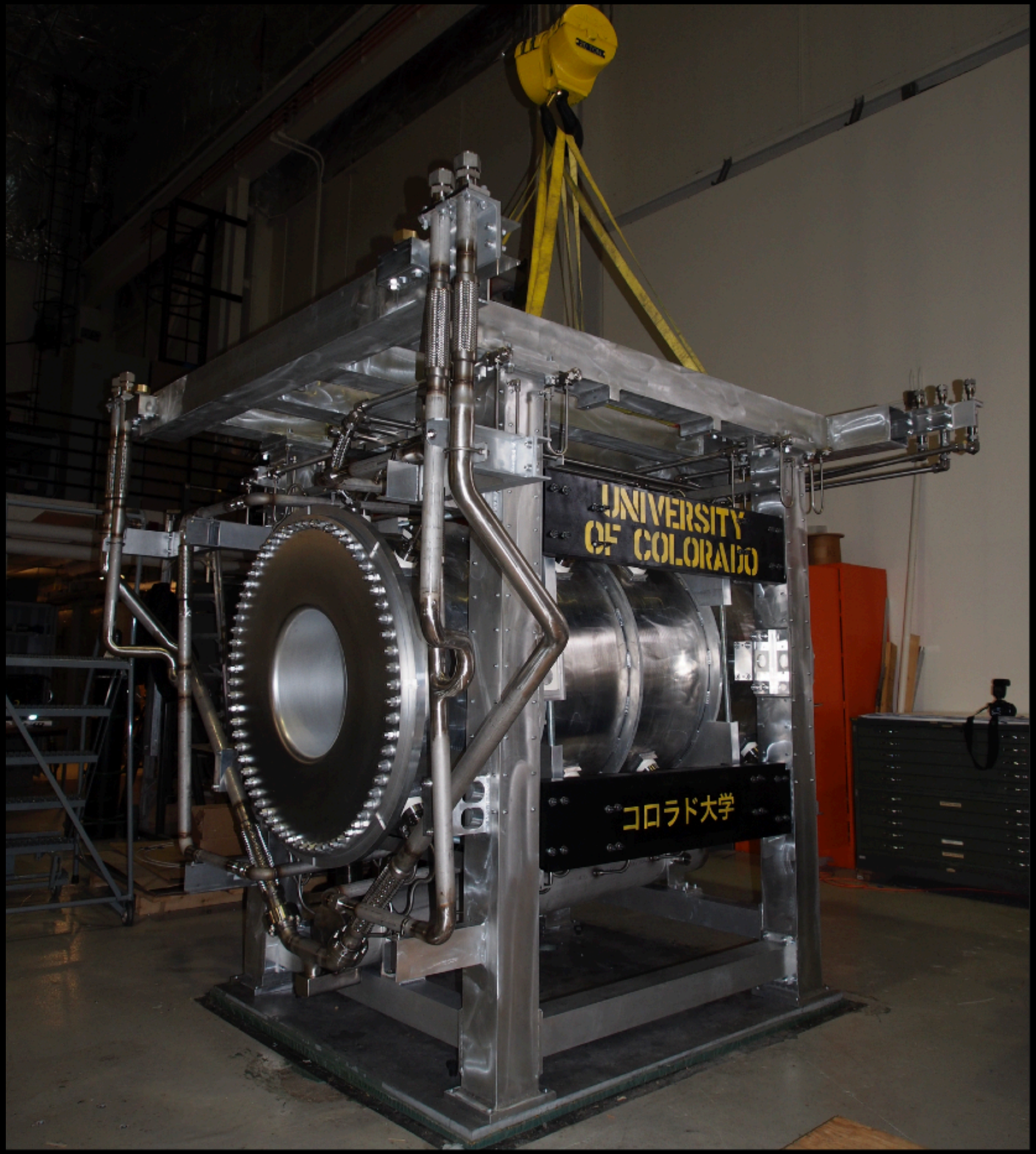
- Horns first proposed by Van der Meer (1961)
- At the most basic level:
  - Two coaxial conductors: a toroidal field exists in the region radially between inner and outer conductors
  - Inner conductor is thin enough (2-3 mm) for most pions to pass through
  - Conductor currents are 100-300 kA so water cooling, pulsed operation necessary to prevent melting
  - Generally made of aluminum alloy



Horns

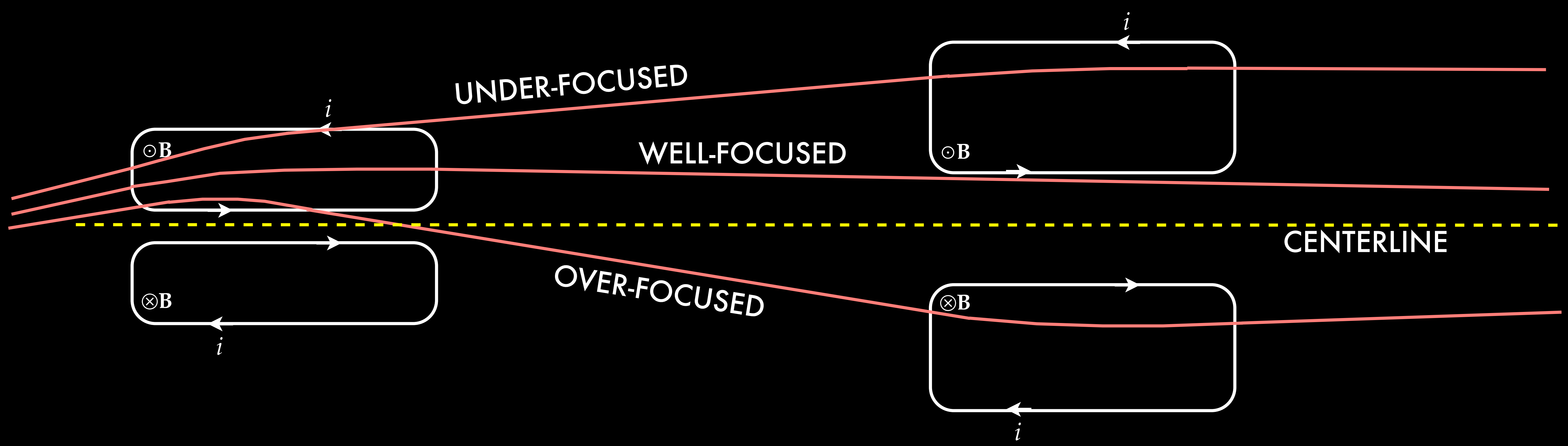
1960s

2010s

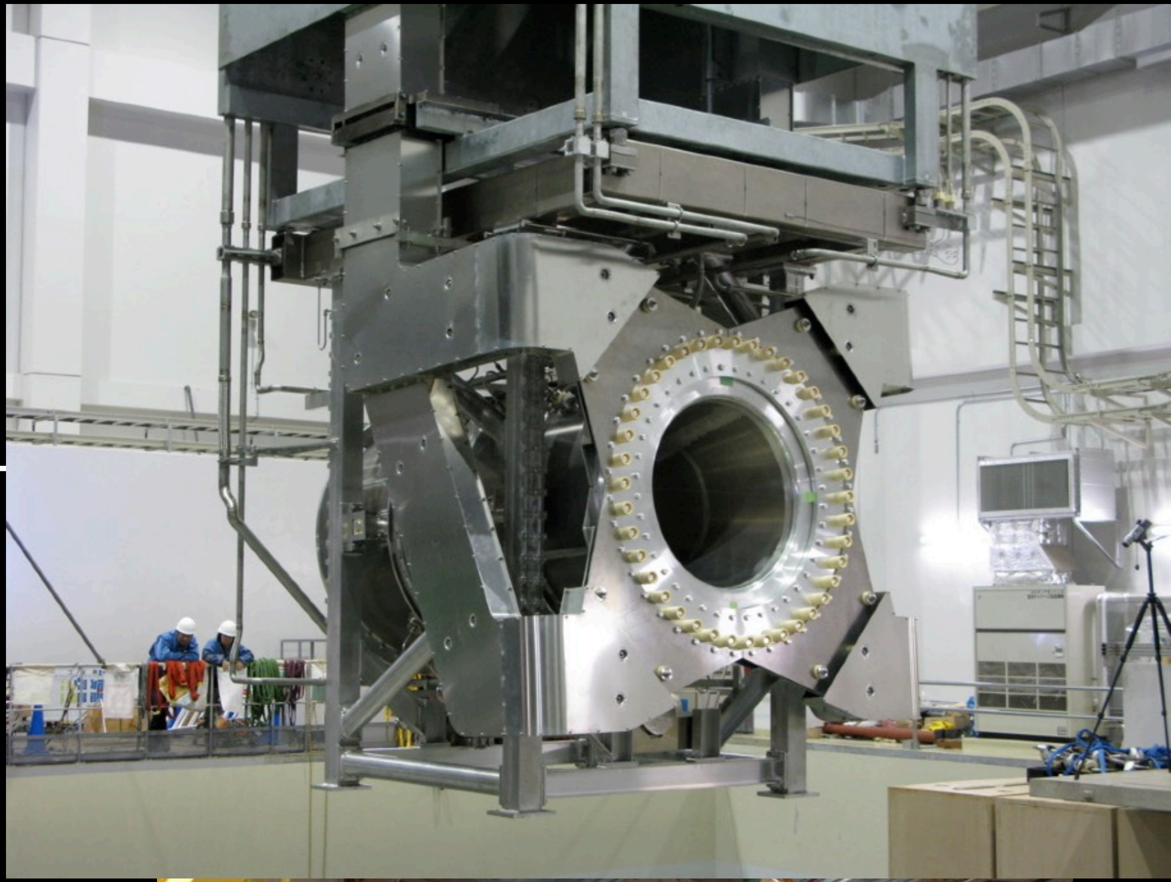


Multi-horn systems

- A single horn generally reduces the angular spread of the beam by a factor of ~2. The resulting beam, observed from far enough downstream, looks again like a point source of pions with an angular spread ⇒ it can be focused further by adding another horn.
- Common for beams to be designed with two (or even three) horns in series. The downstream horns allow correction of both under- and over-focused particles:



Current horn systems



- T2K, NuMI
- Both see beam power around 500-700 kW at present
- Similar type of installation geometry:
  - Vertical installation with shielding, striplines (current-carrying plates) water cooling inside support modules
  - Rather different designs for the horns themselves, partially due to different energy/baseline.

High-power horn systems

- Two multi-hundred-kW beams exist now:
  - T2K
    - >500kW now, planning upgrade to 1.2 MW
  - NuMI
    - >700kW now, planning 1 MW
- One under construction:
  - LBNF, planning 1.2 MW, eventually 2.4 MW
- Probably the biggest difference between J-PARC, FNAL approaches to high-power horns is that T2K will continue upgrading existing facility in place, while FNAL will transition to a new facility with new geometry

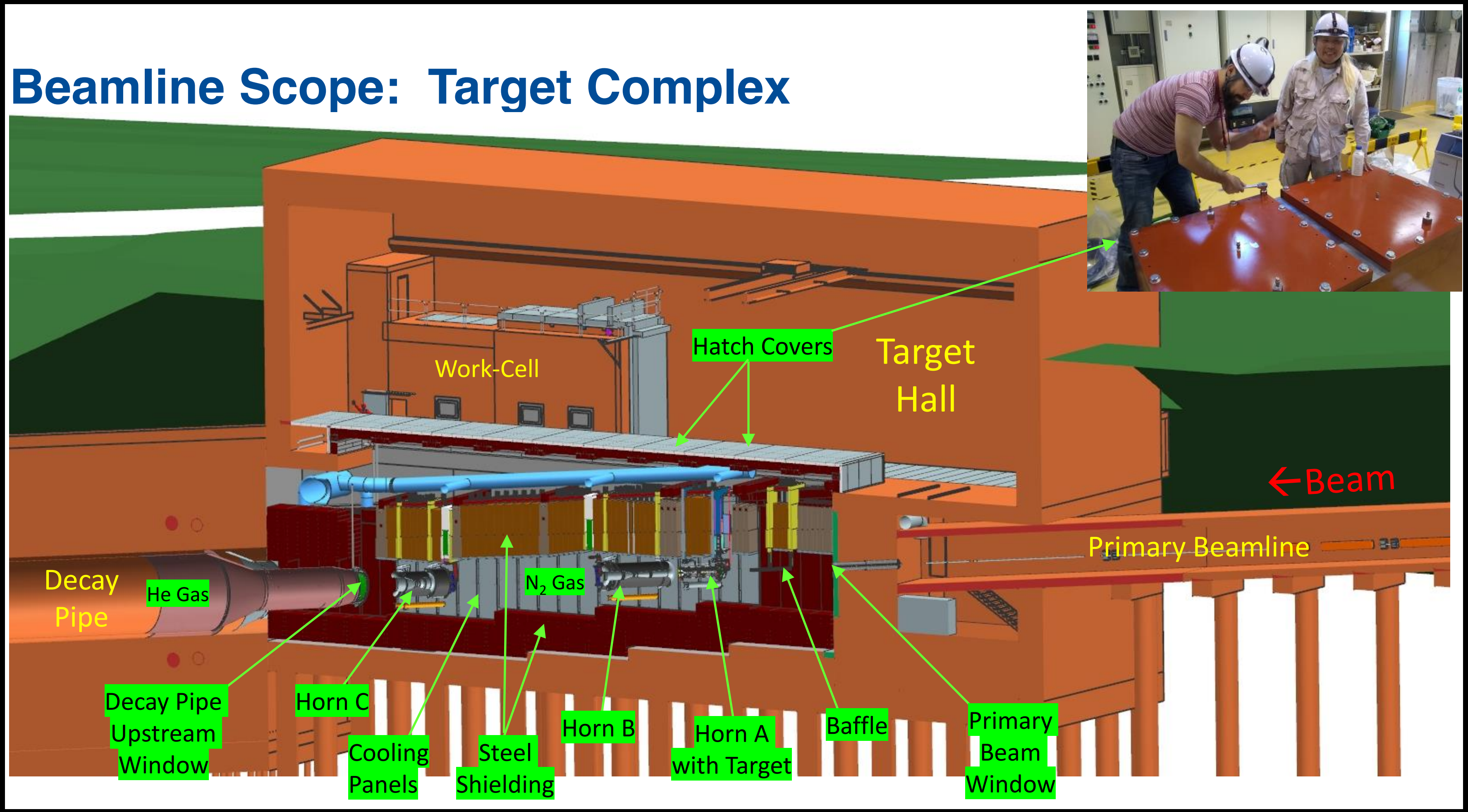
(A few) qualitative changes needed for horns in megawatt-class beams

- Beam heating starts to become dominant in all horns (Joule heating in inner conductors used to be more important)
- Cycle time is shorter: more fatigue, more heating
- Beam heating isn’t just for conductors: striplines need water cooling
- Hydrogen accumulation in horn volumes mean active gas exchange is needed
- Extensive use of friction-stir welding

LBNF horn system

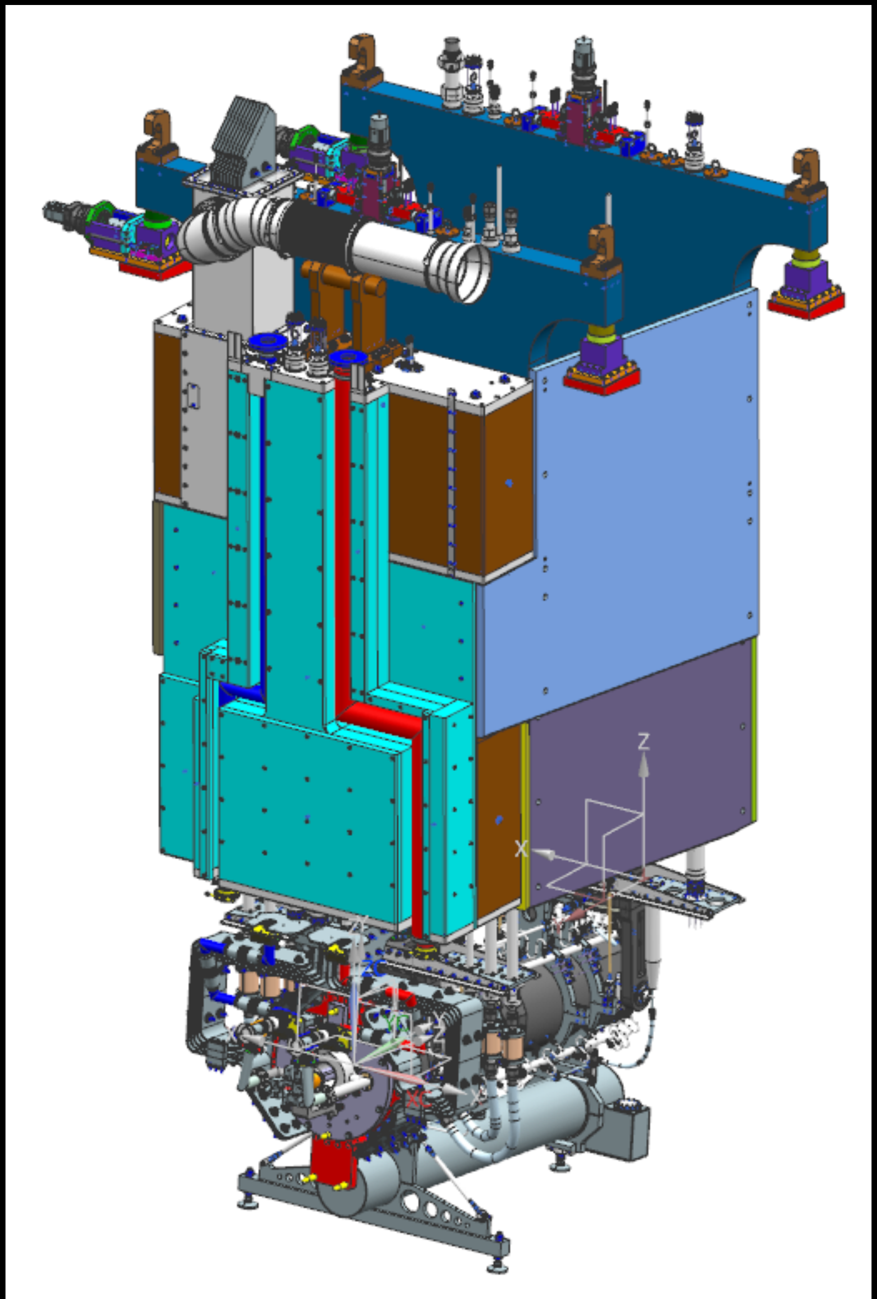
- 3-horn system
- Similar vertical installation geometry
- Horns labeled A, B, C

S. Tariq, NBI2019



LBNF horn requirements

- First-generation LBNF horn A inner conductor will have 7.4 kW deposited in it
  - Most of this is beam heating (5.2 kW), not Joule heating (1.8 kW) — very different from historic horn systems
  - Total power deposited in all horns is 169 kW: all this has to be removed by cooling!
- Total cooling water flow 44 GPM (166 l/m) for horn A, 115 and 70 GPM for horns B, C



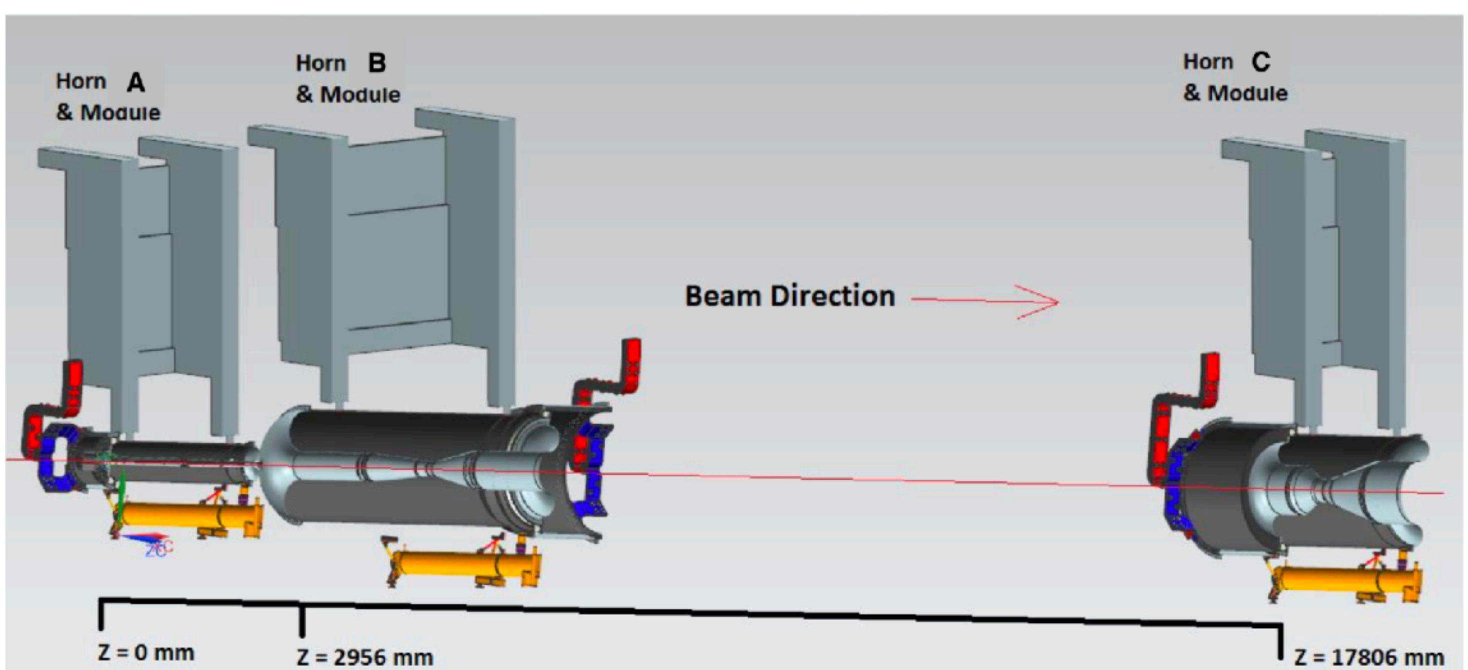
LBNF horn design features

- Ceramics & stripline design for 5kV operation, 300kA, .8ms half sine pulse, & 9 layer force balanced geometry
- The outer conductor has no welding required before assembly
- Each horn now must be actively purged with Argon to flush out dissociated Hydrogen / Oxygen:
    - Horn A/B/C: 9/4/1 L/min

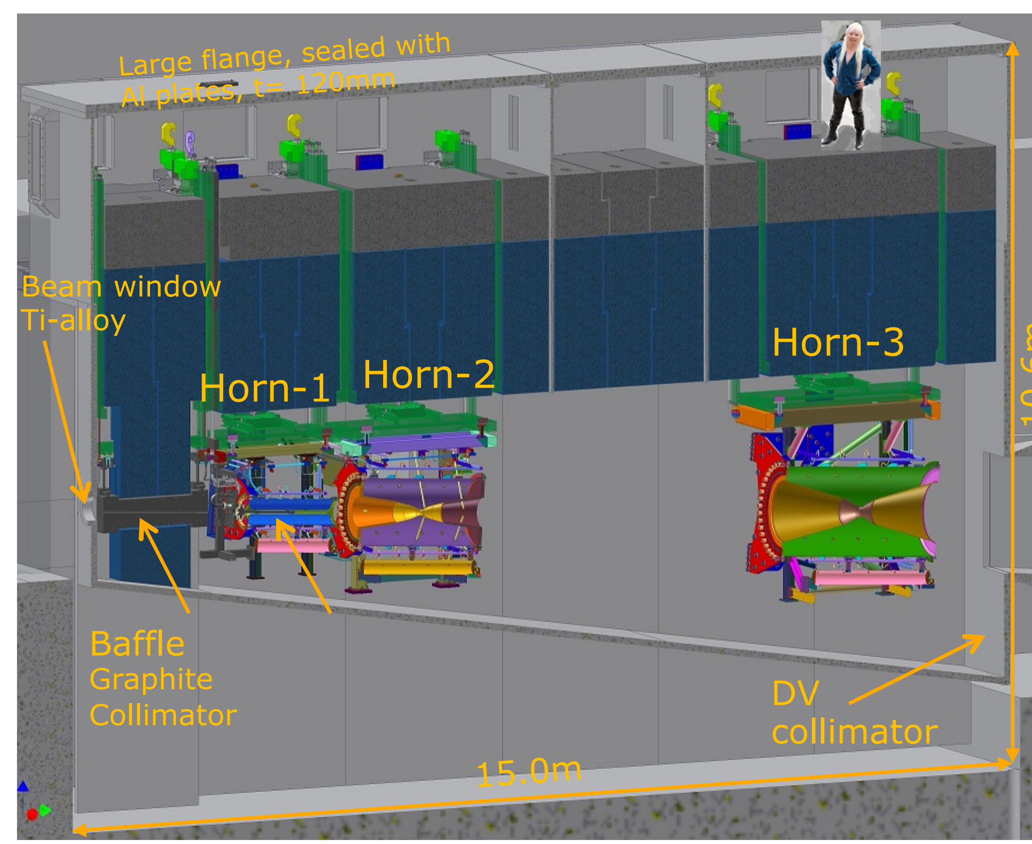
Next Generation Horns

- Requirements
  - Next gen. horns will be used for >1MW beam power
  - Operated at ~300kA at 1 Hz
  - Higher heat load by both beam and Joule heating
- Key issues
  - High current and high cycle operation
  - Higher cooling performance to accommodate higher heat load

NuMI 1MW → LBNF 1.2 MW



J-PARC upgrade 0.75 MW → 1.3 MW



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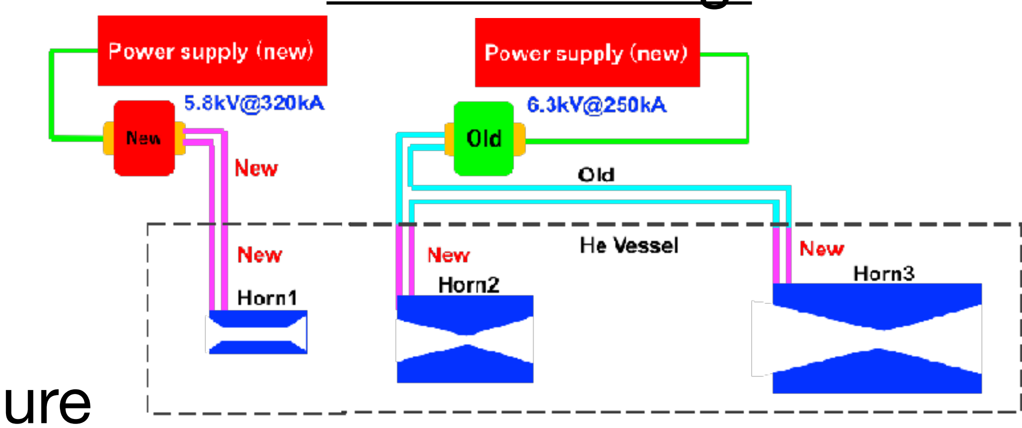
J-PARC Horn Upgrade

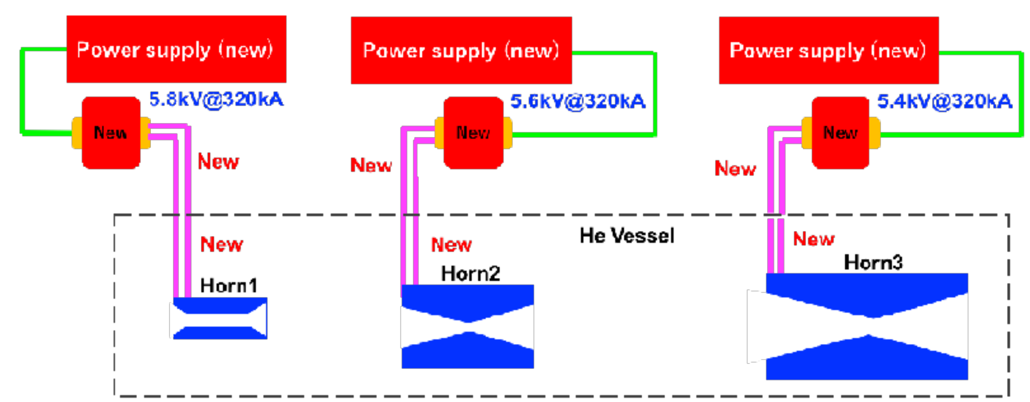
Horn electrical system upgrade for 320 kA at 1 Hz

- Horn current 250 kA → 320 kA (design)
  - ~10% flux gain for right-sign neutrinos
  - 5~10% flux reduction for wrong-sign neutrinos
- Requirements
  - Lower voltage operation is desirable to reduce a failure risk at semi-conductor devices → lower input load
  - Shorter charging time → energy recovery and low Joule loss
- Solution = one-by-one operation (one PS ↔ one Horn)
  - Three power supplies to drive three horns
    - New PS with energy recovery
    - New transformers for 320 kA operation
    - New low impedance striplines

Current config.



Proposed config.



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J-PARC Horn Upgrade

Horn cooling for 1.3 MW

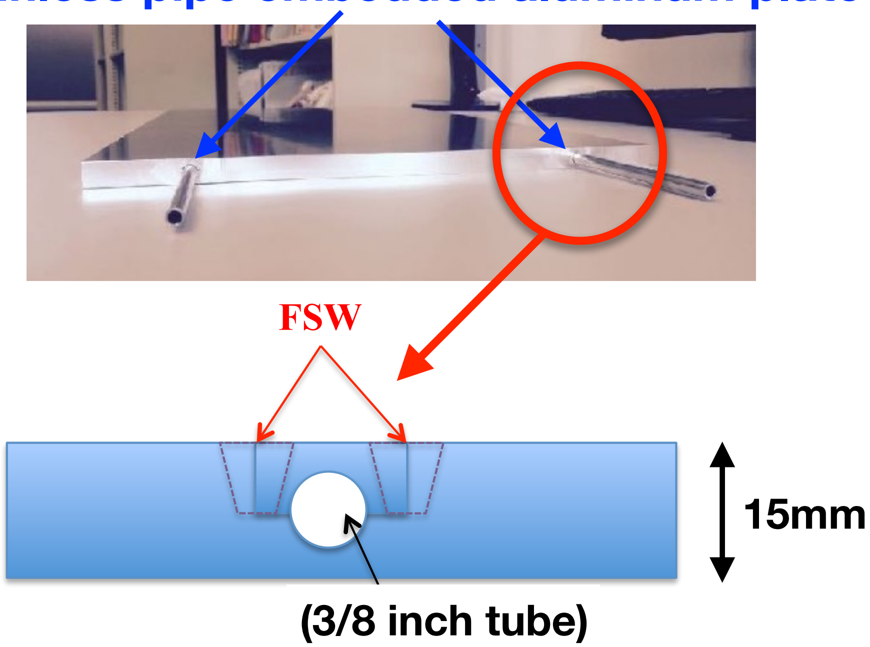
- Inner conductor cooling sufficient up to 2 MW
- No forced cooling at outer conductor so far → Need forced cooling

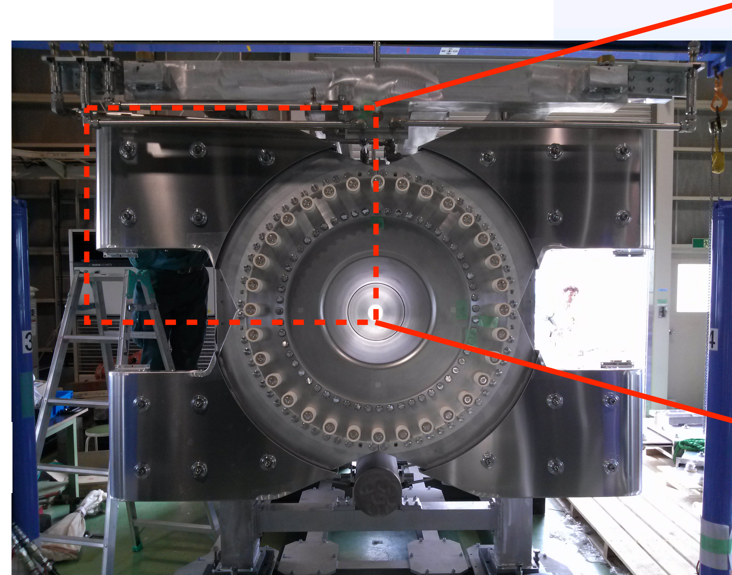
High heat load at upstream part of horn2 due to defocussed particles by horn1

→ Horn2 upstream conductor cooling improvement

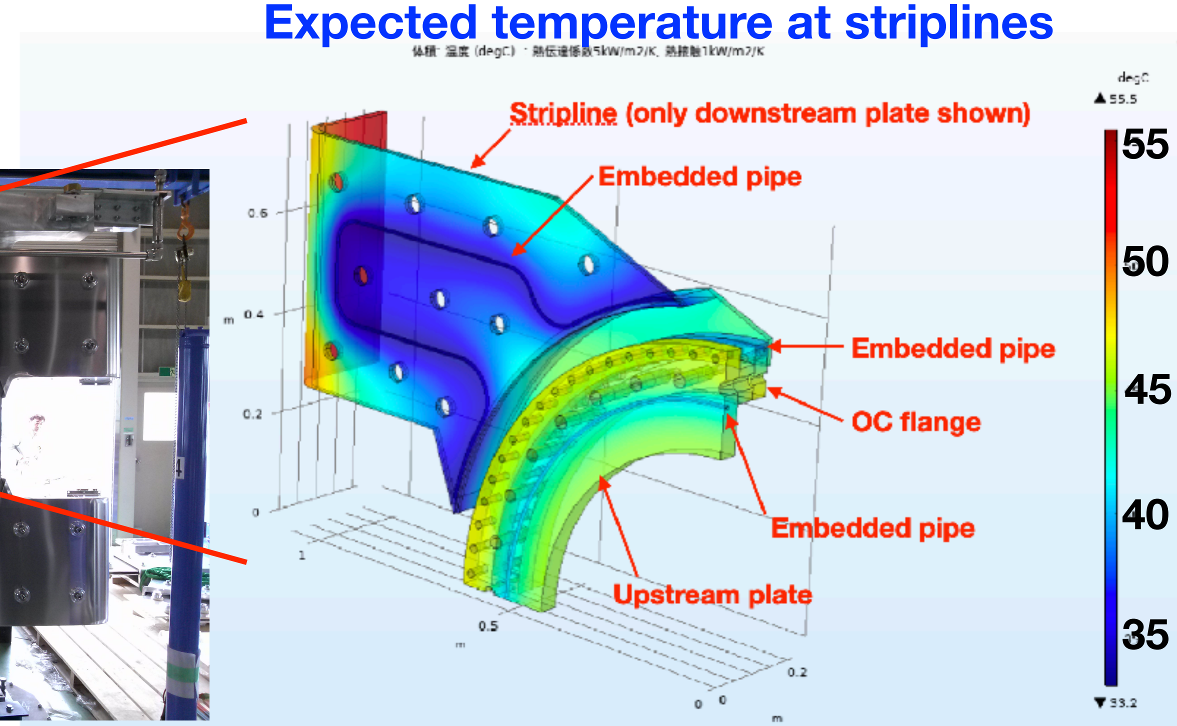
- Stripline cooling
  - Current forced He flow scheme not enough for 1.3 MW
  - New water-cooling method established
    - Stainless pipe embedded inside thin aluminum plate using Friction Stir Welding (FSW)
- Upstream conductor cooling
  - Stainless-pipe-embedded conductors adopted
- Expected <50°C at upstream conductors → Sufficient cooling at 1.3 MW

Stainless pipe embedded aluminum plate





Expected temperature at striplines



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Next to Next Generation Horns

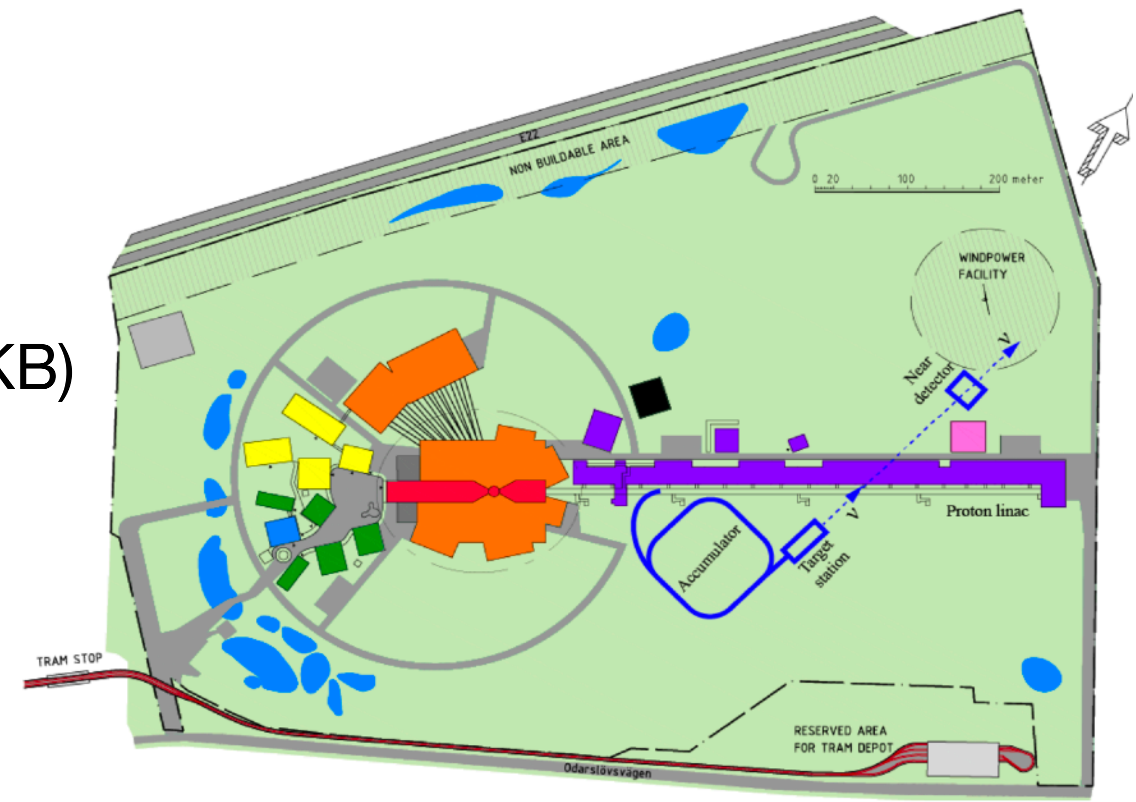
Multi-MW proton drivers

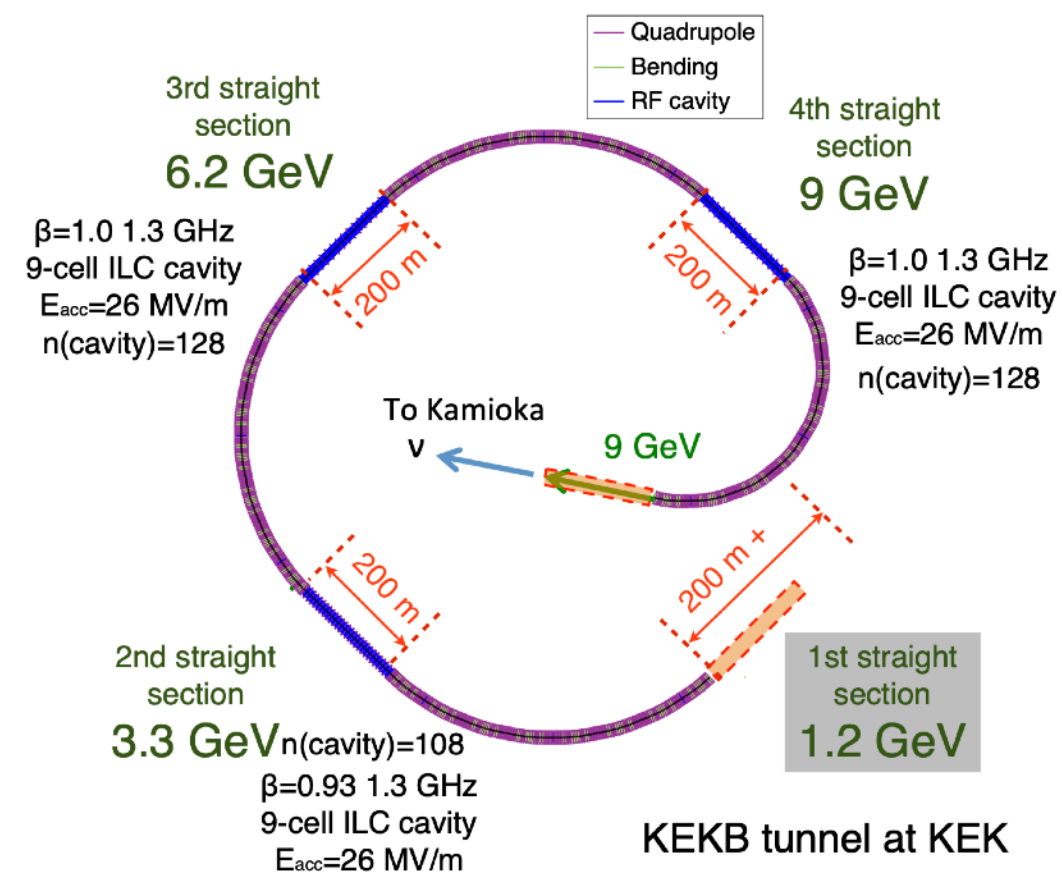
- Possible candidate = Superconducting proton linac
  - ESS ν SB (5MW SC linac)
  - A proposed proton driver at KEK (post-SuperKEKB)
    - 9MW beam (9GeV, 1mA)
- High cycle (>10Hz) with O(1) ms wide pulse

Challenge for high cycle horns

- Wide pulse O(1) ms and high cycle O(10) Hz

  → How do we accommodate such a large heat load?
  - Narrow pulse solution with accumulator ring → ESS ν SB
    - Good for horn operation, but huge construction cost needed for accumulator ring
  - Is it feasible to improve horn cooling performance by one order?
    - If so, no additional ring is needed → Worth considering on this possibility



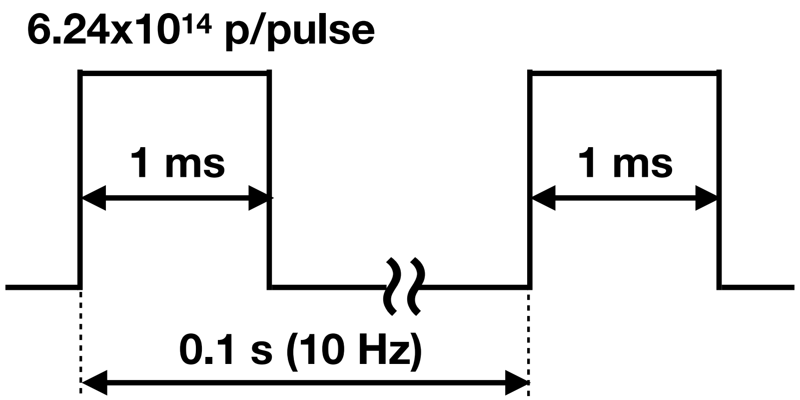


KEKB tunnel at KEK

Consideration on High Cycle Horn

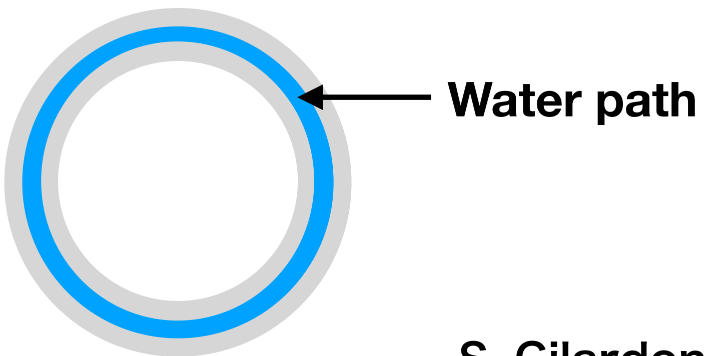
- **A big challenge is to achieve a high cooling performance**
- **9 MW proton driver**
  - 9GeV, 1mA, 1ms (duty factor = 1%), 10Hz
- **Heat load： 185 kW ↔ 28 kW (J-PARC1.3MW)**
  - Beam heating： 83 kW, Joule heating：102 kW
  - Horn operation at 320kA, 10Hz, 1ms squire wave pulse
- **Consideration on cooling**
  - Water-spray cooling with 3.5 kW/m^2/K (@T2K horn)
    → Conductor temperature will reach ~280°C (ΔT~250°C)
    - Need >20 kW/m^2/K to keep the temperature < 80°C
  - Forced water flow for much higher heat transfer
    → "Double skin horn" concept
    - Dual aluminum layers at inner conductor → forced water flow between two layers
      - Flow rate 100 L/min in 2 mm gap
        ⇒ Heat transfer coefficient ~36 kW/m^2/K can be achieved
    - Past R&D of this scheme at CERN for Neutrino Factory (S. Gilardoni)
- **Many other considerations needed (of course)**
  - 9MW target, flux optimization (target/horn geometry optimization) Horn electrical design, horn mechanical design, etc

Beam time structure

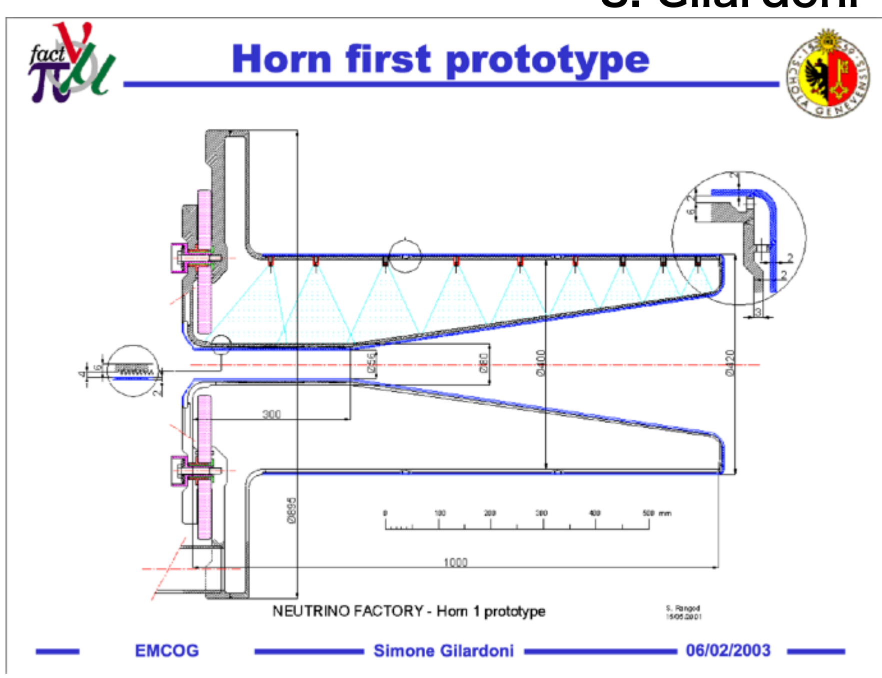


"Double skin horn" concept

Cross-section of horn IC



S. Gilardoni



Best source of information on horns (and neutrino beams in general)

- The Neutrino Beams and Instrumentation (NBI) workshops
- Most recent was at Fermilab in 2019.
  - https://indico.fnal.gov/event/21143/
- Next is scheduled for the UK in September 2021 (first time away from FNAL/CERN/Japan!)