WG2 (Design, Fabrication, Assembly) Summary

- Design of corrugated tube well advanced (SF 4-5 accounted for)
  - Advanced modelling available for the CE-ET community (parametric study/equivalent 1D model)
- Thick wall straight tube viable provided passivation surface (carbon steel).
  - Innovative design based on counter-spiral reinforcement stiffeners well advanced (ferritic steel)
- Conical scarf fillet weld appears promising for the circumferential welding
- For leak testing, a trade off between cost and risk relies on time constants and cycle times. It entails a very significant component level leak testing.
- Extensive weld testing of sleeve has validated the design and fabrication
- MACBETH program is a significant project development for industrialization and full validation of ET beam tube requirements
- Cork+bio-phenolic appears as a promising solution for thermal insulation at a reduced cost (1/2 cost)
- Significant progress for induction heating system for baking that looks scalable.

WG2 Open Issues

- Better requirements definition of modal frequencies and damping
- Better requirements on particle contamination (particles falling from beam tube)
- How to manufacture corrugated tubes
- How to manufacture a more robust joint for circumferential weld (tolerances, dust control)
- How deep to dig at the end of the CE?? To avoid Newtonian noise !

Additional Summaries

WG#2 Summary

- Design specifications & tube design overview for CE Dennis Coyne
  - Emphasized reliability is far more important than minimizing cost; Must comply with ASCE, ASME codes with high margins to ensure 50 yr life
  - Proposes requirement < 1 UHV leak per 10 years (@ 10^-9 Torr-L/s)
  - Tube and/or baffle seismic isolation could be a significant cost driver; need better requirement definition
  - Proposed support arrangements for configurations with and without bellows
  - Points out that we have 4 viable tube options from a structural stand-point:
    - Thick-walled, unstiffened (carbon steel)
    - Thin-walled, ring stiffened
    - Thin-walled, continuously corrugated (U-profile)
    - Thin-walled, sparsely corrugated (sine-profile)
  - All designs are stiffness critical (for buckling margin and acceptable sag), and all materials of interest have similar elastic modulus, so design for lowest yield material (304/304L) and choose material on the basis of other considerations

WG#2 Summary

- Vacuum Tube Design for the Einstein Telescope (Alexandre Lacroix, CNRS LAPP)
  - Welded external stiffening helix with low helix angle
  - Joining 2 tubes with reverse chirality (counter-wound stiffener) with a bellows
  - Bellows is supported with a “sliding support” with rotationally unclamped rings
  - Elegant design, but suggest flextural arrangement of bellows support to avoid unclamping for bake and then reclamping after bake
- Overview of ET pilot sector circumferentially corrugated design (Marco Marrone)
  - Column stability for hanging structure (Aramid fiber suspension supports)
  - Helical corrugation drawbacks (buckling, ext-torsion coupling)
  - 1D simplified beam model for computational efficiency
- Optimized corrugated tube design for CE (Alberto Franco)
  - Explained why sinusoidal corrugation is preferred
  - Explained how to perform the parametric analysis in Ansys (I/O parameters)

WG#2 Summary

- Circumferential Joint (Dennis Coyne)
  - Stress intensity of radial lip joint could exceed threshold for type I crack initiation
  - Recommend conical scarf joint
- UHV Leak risk of convolutions (Dennis Coyne)
  - LEP operational expansion joint failure rate is unacceptably high
  - Speculations of cyclic fatigue or stress corrosion cracking explanation
  - If real argues for corrugated tube rather than discrete bellows
- Design proposal of tube supports, end caps, and pump port spools for CEBEX/CE (Anna Iudintseva)
  - Parametric design
  - Proposed support design, welded spools, bolted end caps
  - Dig a 10m hole under the end of the BT to mitigate Newtonian noise?

WG#2 Summary

- Beamtube Principal Cost Factors (Dennis Coyne)
  - Presented Rai Weiss's breakdown of CBI/LIGO costbook for the LIGO BT
  - Used the underlying CBI cost data to show that CBI's design was close to minimum cost
  - (Alberto also ran an Ansys parametric analysis of ring-stiffened BT and found CBI's design near optimal)
- MACBETH (Fabien Quinten, NIKHEF)
  - MAnufacturing and Cleanliness of Beampipe for ET in High-vacuum
  - Industrialize, cost-efficient, production & installation facility
  - 5 companies involved + Nikhef
  - ~1.5 mm, circumferentially corrugated BT, AISI 441 (ferritic)
  - Robotic, in-tube RGA sampling for surface contamination

WG#2 Summary

- Leak detection of the ET Pilot Sector beam tubes (Purnalingam Revathi, CERN)
  - He bagging around each weld joint for pilot, for each tube segment
  - Component, sub-sector, sector level leak testing
  - Outlined Max, Mid, Min selective testing strategy vs risk & cost
  - Adopting “mid strategy”, but dynamically change test frequency as program evolves
  - Based on LIGO experience, encouraged to consider the long time constants and cycle times for sub-sector & sector testing, for clearing out He after testing, as well as the unacceptability of more than 1 leak per volume
  - Also encouraged to consider robotic testing

WG#2 Summary

- Weld design to join chambers (Roxane Misler, CERN)
  - Sleeve (open & closed, 4 & 2 mm thick) installed with manual TIG fillet welds on 441 test chambers
  - Monitored airbourne (generally ISO 7 to 8 during steps) & surface dust contamination
  - LIGO will share cleanliness protocols & surface test procedures (may have some applicability)
  - Metallographic qualification of sample welds
  - Vacuum test & check for virtual leak – found leak & successfully repaired
  - Closed 2 mm thick sleeve with 1 mm gap better, used on ET pilot sector

WG#2 Summary

- Welding Techniques (Roxane Misler, CERN)
  - Butt, fillet, lip welds – auto, manual – repairability
  - Roundness tool clamped to the end of each tube
  - (LIGO used hydraulic tool to expand and circularize tube ends)
  - Presented various joint geometries for the circumferential joint designed to minimize contamination, some of which can be merged with the bellows or stiffener, with a single field weld
  - (Discussed the observation by the light baffling group that the particulate contamination problem is over-specified/stated)
  - Plan to use orbital TIG welder for testing lip weld geometry – eventually can orbitally weld fillet for ET

WG#2 Summary

- Thermal insulation for GWDs beam pipe vacuum systems (Carlo Scarcia, Karl Owens; CERN)
  - ~20M euro for mineral wool is the default/baseline but dirty
  - Aerogel alternative is expensive and not durable
  - Polyurethane foam is durable, lightweight, but off gasses and has a lower operating temperature (80 to 120C)
  - Initiated project to develop a new, sustainable insulation for ET
    - Cork+bio-phenolic (~10M euro)
    - Fire retardant modified PIR
    - Sheep wool is also being explored
    - Installation in ET-PS in 2026 Q3
  - Deliverable includes disclosure of additives, chemical composition – must evaluate potential corrosive risk to tube

WG#2 Summary

- Overview of Potential Manufacturing Techniques for Corrugated Beamtube (Peter van der Heijden, VDL)
  - CERN has experience with corrugated pipe, comprised of 441 ferritic
  - Working on a prototype of > 3m length
  - Three basic methods:
    - Slip roll in short lengths limited by coil width
    - Form from 2 coils with 2 longitudinal welds
    - Helically weld with skelp width equal to coil width (preferred)
  - Then either weld on stiffeners, or form circumferential corrugations by hydroforming (expensive); rolling forming has contamination & thinning risks
  - Focused on process control and industrialization (QA, measurement after each process step)
  - Orbital TIG welding, K-TIG welding, Vacuum laser welding
  - Possible methods for sealing end caps for tube segment leak testing

WG#2 Summary

- Induction Bakeout Experiment at LIGO Caltech (Melina Fuentes-Garcia, LIGO)
  - Particularly good method for carbon steel (highly magnetically permeable and resistivity too low for practical ohmic heating through the tube)
  - RF System translated on a rail system along technology demonstrator tube
  - System baked @150C, then vented to atm, then 80C bake recovers UHV with DR modeling; will be tested in LTREX system
  - Translating (zone heating) works (10^-10 mbar)
  - LTREX experiment planed with purging with dry gas (ppb H2O) using integrated circuit foundry filters
  - Design for full scale (in particular getting around “obstacles” (pumps, supports, etc.) is needed for CE
  - The pipeline industry has full-scale systems that can navigate around obstacles
  - (Note that oil/pipelne industry uses Heat Trace Systems capable of 150C with long circuit lengths - up to 50 km)

WG#2 Summary

- Alternative Method for Large Vacuum Systems Bakeout (Freek Molkenboar, TNO)
  - Prototype plasma system (RF+DC, 0.3m dia) to test effectiveness vs length to ~4m
  - Intent is to permanently install behind baffles (at upto 50m spacing?) and use to remove water