CO2 Footprint of the CLIC Main Linac
A very first look

Benno List

CLIC Module Meeting 18.1.2023

Introduction

Ultimate Goal: Quantify the environmental impact of a whole accelerator project, i.e., CLIC

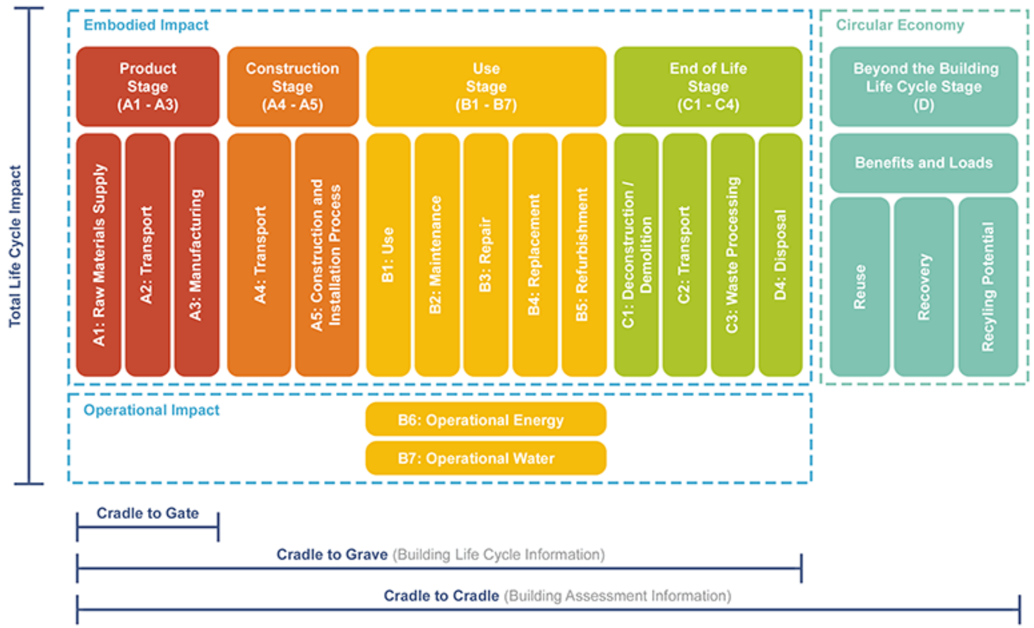
Accepted method:
LCA = Life Cycle Assessment

Define Scope:

- **System Boundaries**
- **Lifecycle Stages**

As a starting point:

- **consider a subsystem (Main Linac), focus on tunnel and accelerator components**
- **Consider Production (A) stage, focus on raw materials (A1)**



Materials and their Carbon Footprint

Material	Density (g/cm3)	GWP (kg CO2-eq/kg)
Cement	1.4	1.0 [3]
Concrete	2.5	0.1 [3]
Mild Steel	7.85	1.7
Stainless Steel (18%Cr, 10%Ni)	7.85	3.7 [1]
Copper	8.96	2.5
Aluminium	2.70	8.2 [2]
Titanium	4.5	8.1 [2]
Silicon Carbide	3.2	--

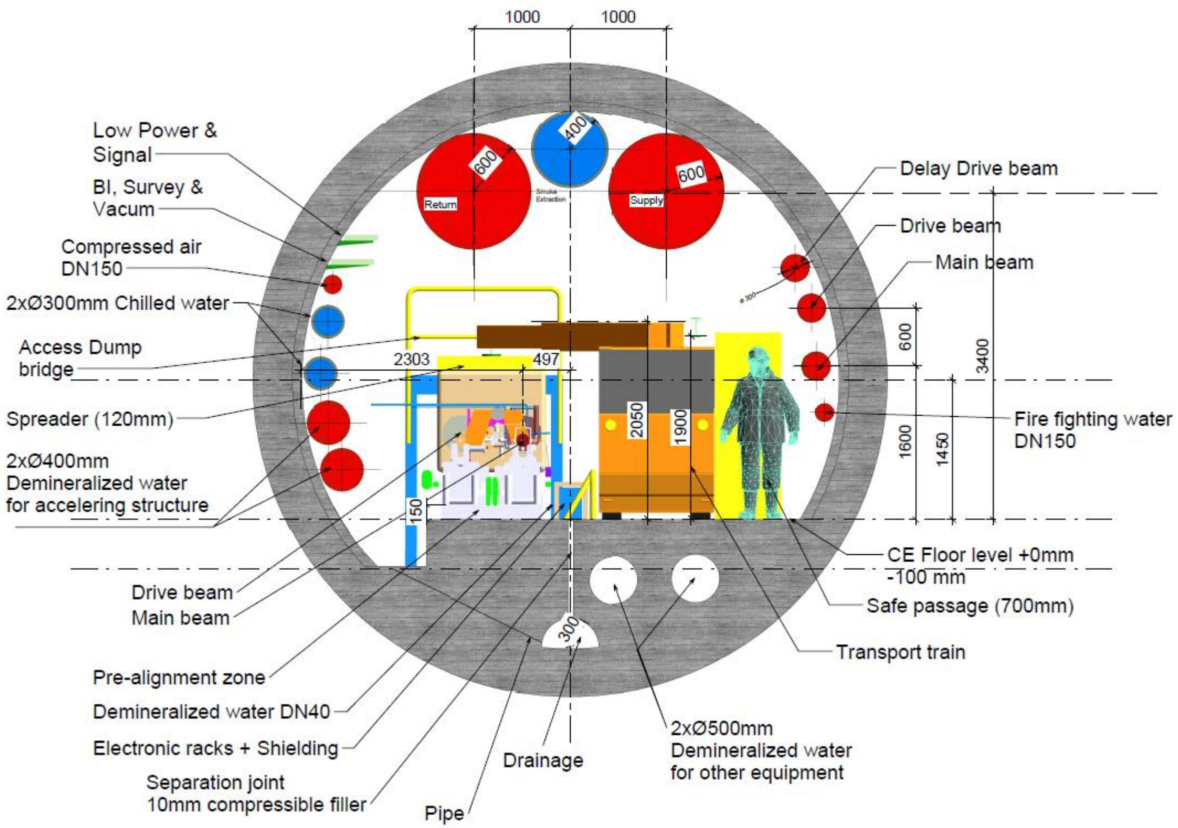
1. Eurofer LCI for 316 cold rolled coil steel
2. Nuss and M. J. Eckelman, PLoS ONE 9 (2014) e101298. DOI:10.1371/journal.pone.0101298. CC-BY
3. T. Hottle et al., *Environmental life-cycle assessment of concrete produced in the United States*, J Cleaner Prod. 363 (2022) 131834, DOI:10.1016/j.jclepro.2022.131834

Notes

1. GWP: Global Warming Potential (over 100 years), expressed in kg CO2 eqivalent
2. All numbers for GWP vary by factors of 2 or more, depending on country of origin, production method, energy mix, transport ways etc

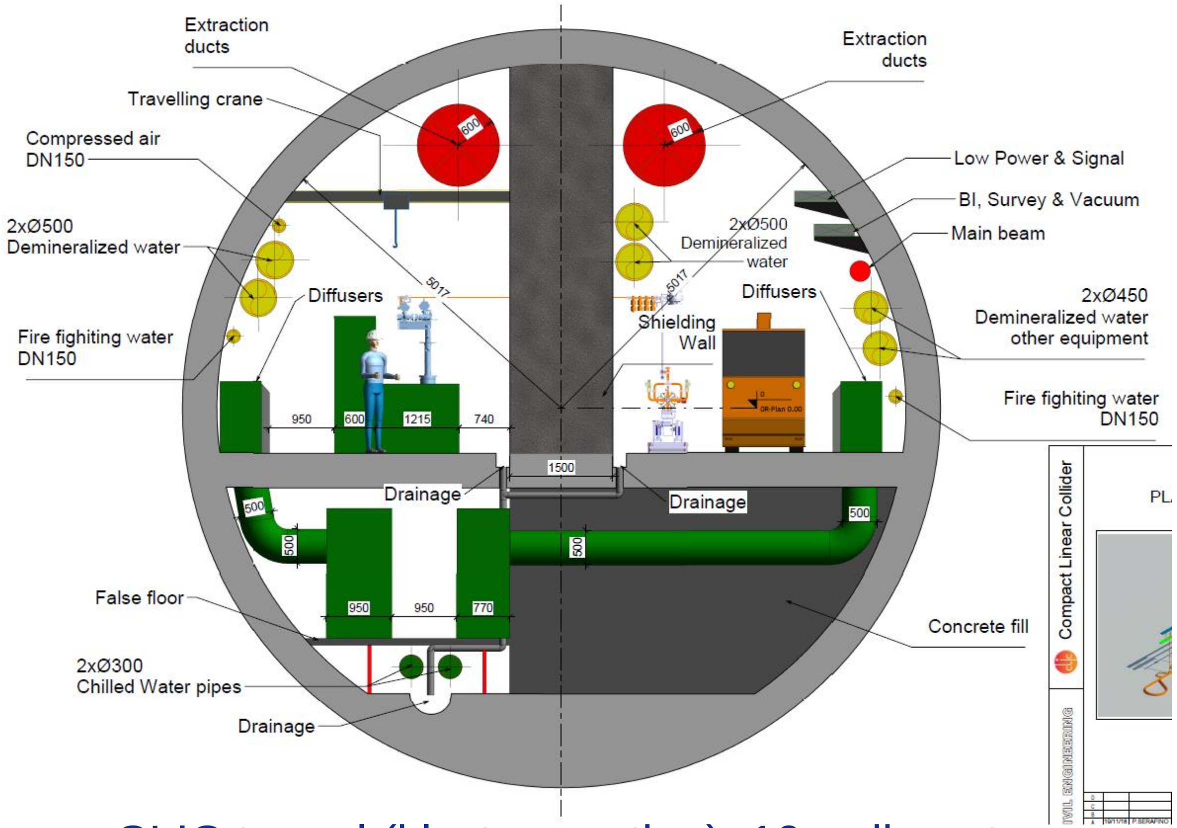
The Tunnel

Tunnel Cross Sections



CLIC tunnel (drive beam option), 5.6m diameter

My estimate: 12.4m^2 concrete
-> 31t/m concrete



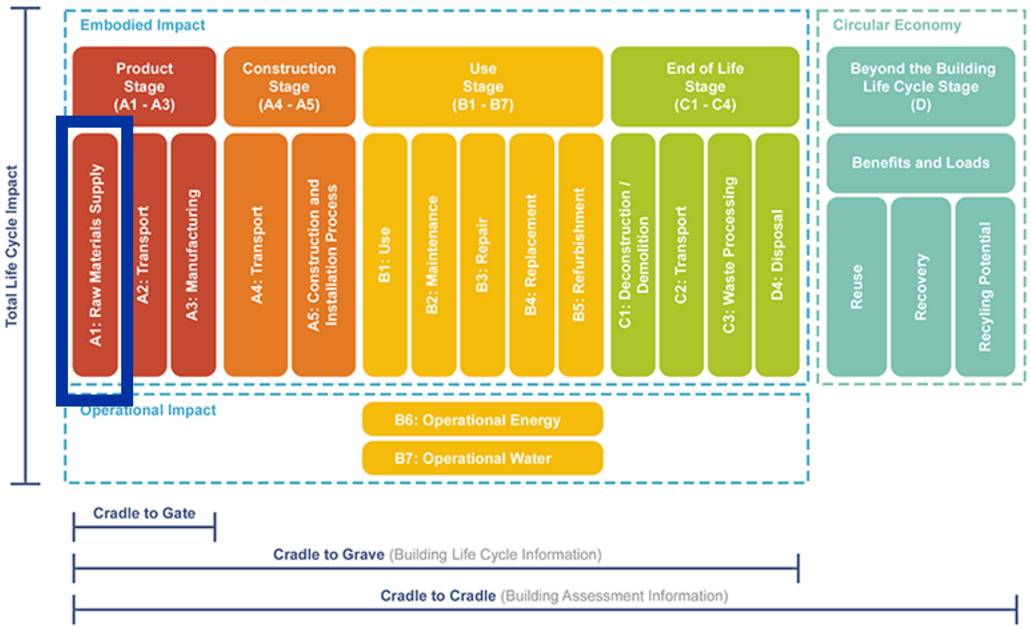
CLIC tunnel (klystron option), 10m diameter

My estimate: 44.8m^2 concrete
-> 112t/m concrete

Tunnel GWP (CO_2 Impact) from Materials

Quantity	DB	Klys.
Inner Diameter [m]	5.6	10
Tunnel Cross Section [m^2]	25	79
Lining / Grouting [cm]	30 / 10	45 / 15
Concrete Area [m^2]	12.4	44.8
Lining&Floor Area [m^2]	8.2	19.7
Concrete per m [t/m]	31	129
Steel per m [t/m]	0.95	2.3
Concrete GWP [t CO2-eq/m]	3.1	12.9
Steel GWP [t CO2-eq/m]	1.6	3.8
Material GWP [t CO2-eq/m]	**5**	**17**
Total GWP (25% overhead)	**6**	**21**

Lifecycle stages according to EN 15978



https://browningday.com/news/lca-stages-matter-when-tracking-embodied-carbon/
https://www.buildingenclosureonline.com/blogs/14-the-be-blog/post/89547-lca-stages-matter-when-tracking-embodied-carbon

Only A1 considered here!

Comparison to Road Tunnels

Survey of Road Tunnels (Drill and Blast) in Spain

CO_2/m: 5-15 t/m
for Cross Sections 50 – 140m^2

Materials make up 66 – 88% of emissions

Assuming 25% overhead:

- **5.6m CLIC tunnel: 6 t /m for 25m^2**
- **10m CLIC tunnel: 21 t/m for 79m^2 (with 1.5m shield wall!)**

Table 3
Summary of emissions rates (kgCO_2/m).

Tunnel	RMR	Excavation Method used (%)			Length (m)	Cross Section (m^2)	Emissions rate (kgCO_2/m)
		D&B	RH	HBH			
Somao	25–45	10	0	90	466	142.5	15,284
Fresno	25–45	0	0	100	940	125	14,417
Fabares	30–55	18	72	10	1922	92.1	10,276
Padrún	25–55	98	0	2	1762	88.5	10,261
Santiuste	25–65	60	0	40	500	113.7	8,710
Peñaflor	21–50	44	0	56	695	99.4	8,260
Folledo	35–70	100	0	0	2021	54	4,293

Table 4
Most relevant contributions to the CO_2 emissions.

Tunnel	Materials used (concrete and steel) KgCO_2/m (%)	Auxiliary facilities KgCO_2/m (%)	Advancing activities KgCO_2/m (%)
Fabares	9,087 (88%)	473 (5%)	423 (4%)
Folledo	3,533 (82%)	243 (6%)	252 (6%)
Fresno	11,747 (81%)	1303 (9%)	904 (6%)
Padrún*	6,809 (66%)	458 (4%)	264 (3%)
Peñaflor	6,304 (76%)	1166 (14%)	492 (6%)
Santiuste	7,531 (86%)	555 (6.5%)	560 (6.5%)
Somao	12,801 (85%)	1257 (8%)	993 (7%)
Average value	10,753 (83%)	832 (8%)	604 (6%)

*Methane emissions in this tunnel (27% of the total) make the % values lower than the rest. Not considered for the average value.

Rodríguez and Pérez, Tunn. Undergr, Space Techn. **108** (2021) 103704,
DOI:10.1016/j.tust.2020.103704

Comparison to a Recent Publication

Snowmass Paper "Climate impact of particle physics": estimate for FCC tunnel (5.5m inner diameter)

- **2.37 t CO2-eq /m from concrete**
- **5 – 10 t CO2-eq /m top-down estimate**

This estimate for 5.6m tunnel: 6 t CO2-eq /m

arXiv:2203.12389v1 [physics.soc-ph] 23 Mar 2022

Climate impacts of particle physics

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Abstract. The pursuit of particle physics requires a stable and prosperous society. Today, our society is increasingly threatened by global climate change. Human-influenced climate change has already impacted weather patterns, and global warming will only increase unless deep reductions in emissions of CO_2 and other greenhouse gases are achieved. Current and future activities in particle physics need to be considered in this context, either on the moral ground that we have a responsibility to leave a habitable planet to future generations, or on the more practical ground that, because of their scale, particle physics projects and activities will be under scrutiny for their impact on the climate. In this white paper for the U.S. Particle Physics Community Planning Exercise ("Snowmass"), we examine several contexts in which the practice of particle physics has impacts on the climate. These include the construction of facilities, the design and operation of particle detectors, the use of large-scale computing, and the research activities of scientists. We offer recommendations on establishing climate-aware practices in particle physics, with the goal of reducing our impact on the climate. We invite members of the community to show their support for a sustainable particle physics field [1].

Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

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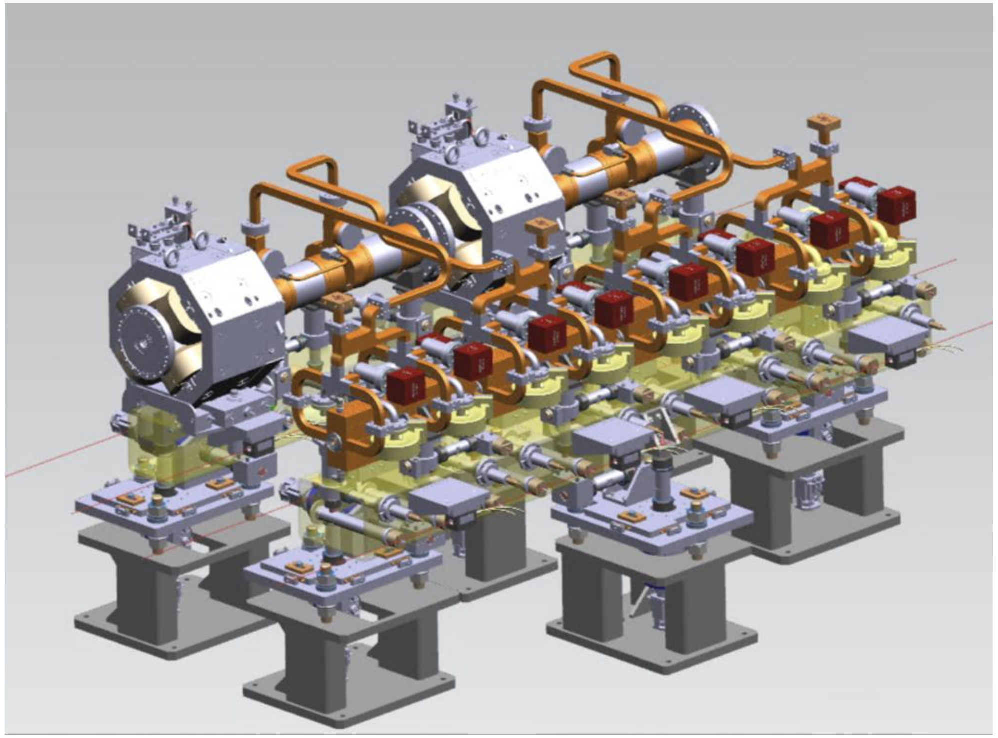
The Accelerator

Evaluating the GWP of the Accelerator: The T0 Two Beam Module

For Accelerator: Start with Two Beam Module

Attempt a bottom-up calculation of total material budget

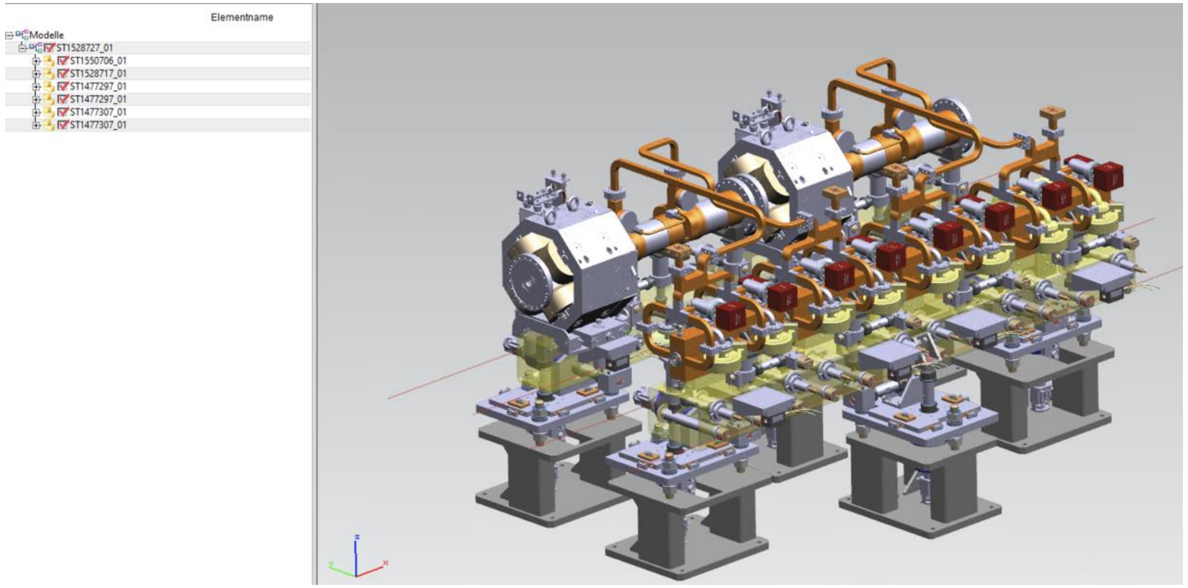
- **Decompose system to level of individually manufactured pieces**
- **Collect info on**
  - Material
  - Mass (net and gross = net + scrap)
  - Manufacturing method (machining/turning, welding, extruding, casting) -> input to scrap estimate
- **From material, estimate LCA quantities**



Creating the MBOM

MBOM: Manufacturing BOM
-> hierarchical product structure,
focus on manufacturing / mounting,
and project organisation / responsibilities,
i.e. work packages (magnet, RF, vacuum…)

Starting Point: CAD Model structure, i.e.
EBOM (Engineering BOM)

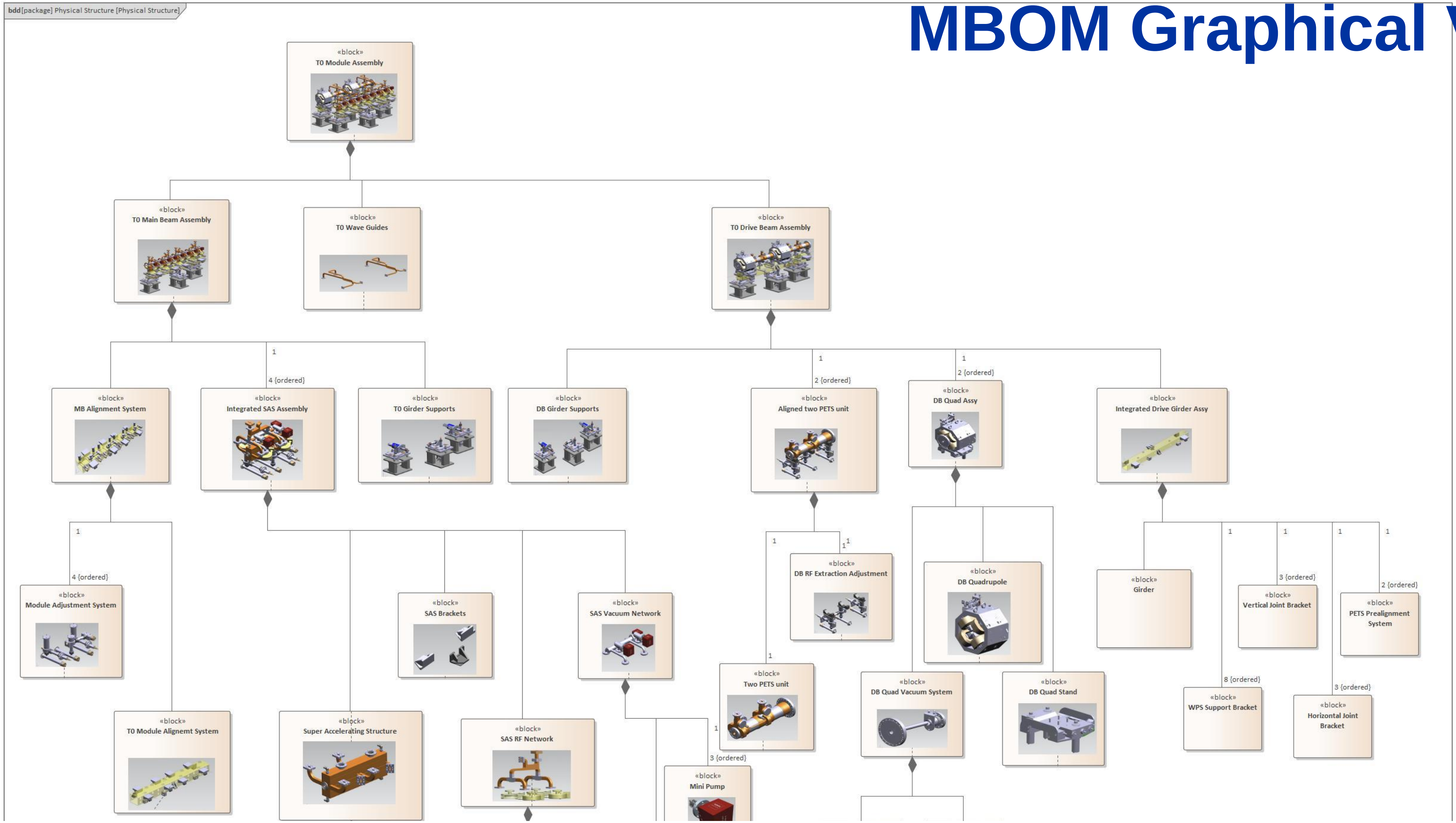


The T0 Module Data

	Component Tree							Number	PBS Code	PBS Text	Quantity / A	Q / Tot	Material	Densit	Mass	Manufacturing
	Level 0	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6									
5	T0 Module Assembly							ST1528727	3.1.1.	Two-Beam Module Type 0 e+	1	1	Mixed		1710	
6		T0 Main Beam Assembly						ST1550706			1	1	Mixed		950	
7			Integrated SAS Assembly								4	4	Mixed		63	
8				Super Accelerating Structure				ST1378439	3.1.1.1.1.	Super-accelerating Structures	1	4	Mixed		47	
9					Rectangular Disk Assy			ST0790069			56	224			0.7	
10						Rectangular Disk		ST0787907			1	224	Copper	8.85	0.51	Machined
11						Absorber left		ST0798602			2	448	Silicon Carbide	3.21		
12						Absorber right		ST0798631			2	448	Silicon Carbide	3.21		
13					Coupler Disk			ST1378544			2	8	Copper	8.85	1	Machined
14					Structure Connecting Disk			???				0	Copper	8.85	1	Machined
15					SAS Interconnect Bellow			ST0347489			4	16	Stainless Steel	7.85	0.1	Fabricated
16					Input Waveguide						2	8			0.5	Extruded
17						Input Waveguide Arm		ST1437145			1	8	Copper	8.85		Extruded
18						Waveguide Flange		ST0666851			1	8	Stainless Steel	7.85		
19					Output Waveguide						2	8			0.5	
20						Output Waveguide Arm		ST1393409			1	8	Copper	8.85		Extruded
21						Waveguide Flange		ST0666851			1	8	Stainless Steel	7.85		
22					SAS Vacuum Flange			ST0396788			8	32	Stainless Steel	7.85	1	Turned
23					SAS Water Connector			ST1358471 + ST0295539			4	16	Stainless Steel	7.85	0.1	
24				SAS Bracket Set				ST1556884 + ST1556973 +							9	Machined
25					SAS Bracket 1									.85	3	Machined
26					SAS Bracket 2									.85	3	Machined
27					SAS Bracket 3									.85	3	Machined
28				SAS Vacuum Network											12	
29					Vacuum Manifold										1.5	Fabricated
30						Vacuum Manifold								.85		Fabricated
31						Pumping port								.85		Fabricated
32					Mini Pumps										2	
33				SAS RF Network											1	
34					SAS Input Waveguides										1	Extruded
35						SAS Input Wavegu								.85		

- 6 Level deep MBOM (Manufacturing BOM)
- Based on CAD model (not identical)
- 114 lines
- Includes multiplicity, mass, material as far as available
- Linkage to overall CLIC PBS where I could identify it

MBOM Graphical View



Result for a T0 Module

	Sum	Copper	Stainless Steel	Mild St	Titan	Alum
Main Beam Module & WG	906	155	114	583	45	9
T0 Drive Beam Assembly	871	159	22	686	0	5
Total mass (kg)	**1777**	**314**	**135**	**1269**	**45**	**14**
GWP/kg		2.5	3.7	1.7	8.1	8.2
Main Beam Module & WG: GWP (kg CO2-eq)	**2237**	388	421	991	363	74
T0 Drive Beam Assembly: GWP (kg CO2-eq)	**1681**	398	80	1167	0	37
Total GWP (kg CO2-eq	**3918**	**786**	**501**	**2158**	**363**	**111**
scarp mass estimate (kg)		242	128	532	45	5
scrap GWP (kg CO2-eq) (at 50%)	**1191**	303	236	452	181	18
total GWP with scrap (kg CO2-eq)	**5109**	**1089**	**737**	**2610**	**544**	**129**

Breakdown according to Material

“Mild Steel”: Mostly Support System

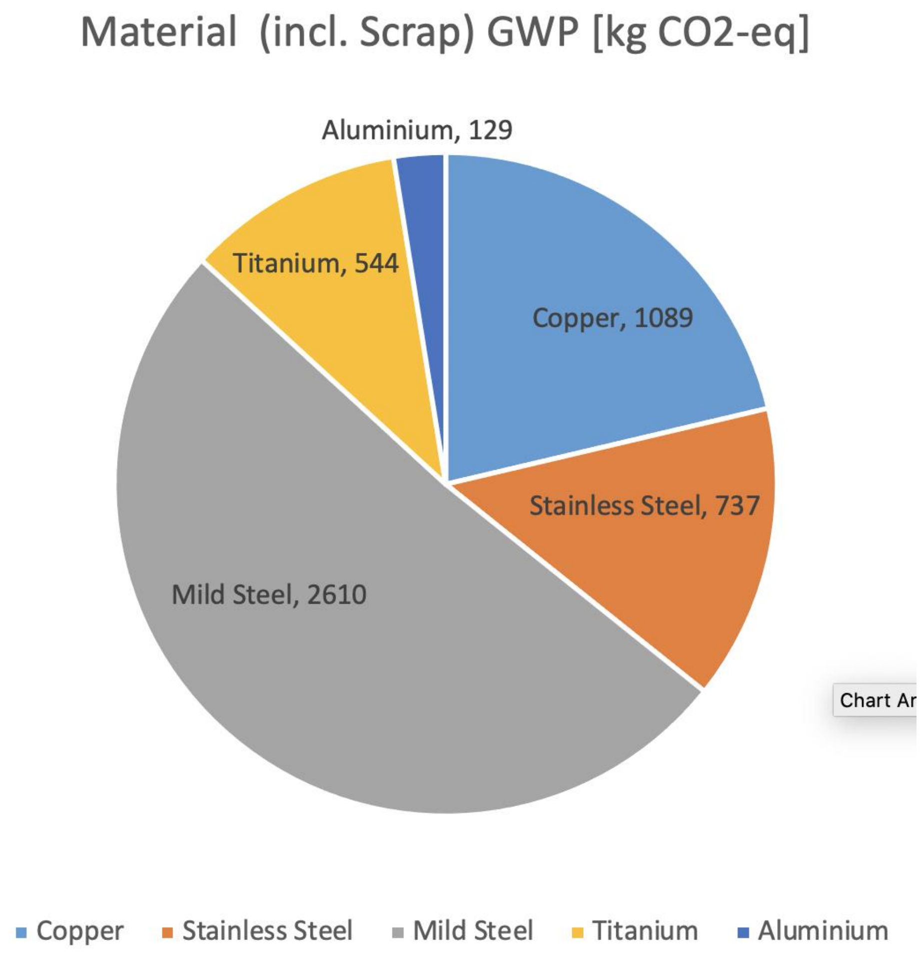
Conclusion here:

Supports have a large impact on CO_2 just from the sheer mass
-> a good place to start

For large scale production:

Cast iron may be interesting

- **Reduced material carbon footprint**
- **Less scrap, less machining**



Summary

Tunnel (per 2.01m module):

- **12 t CO_2-eq for two-beam**
- **42t CO_2-eq for klystron**

Accelerator (T0 module)

- **5 t CO_2-eq for two-beam**

A lot of things missing:

- **Transport, fabrication, installation stages**
- **Tunnel infrastructure (heating/ventilation, cooling pipes, cable trays)**
- **Magnet cables, power supplies**
- **Magnets for T1-T4 modules**

Conclusion so far:

- **Civil engineering (tunnel) is dominant so,urce of CO_2**
- **Accelerator non-negligible, even in absence of large magnets**
- **Accelerator supports are more important that RF structures**

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