



# Lifecycle Inventory Input to an LCA for ILC and CLIC

Steffen Doebert on behalf of the CLIC/ILC Sustainability Team

LCWS 2024, Tokyo, Japan, 8-11 of July

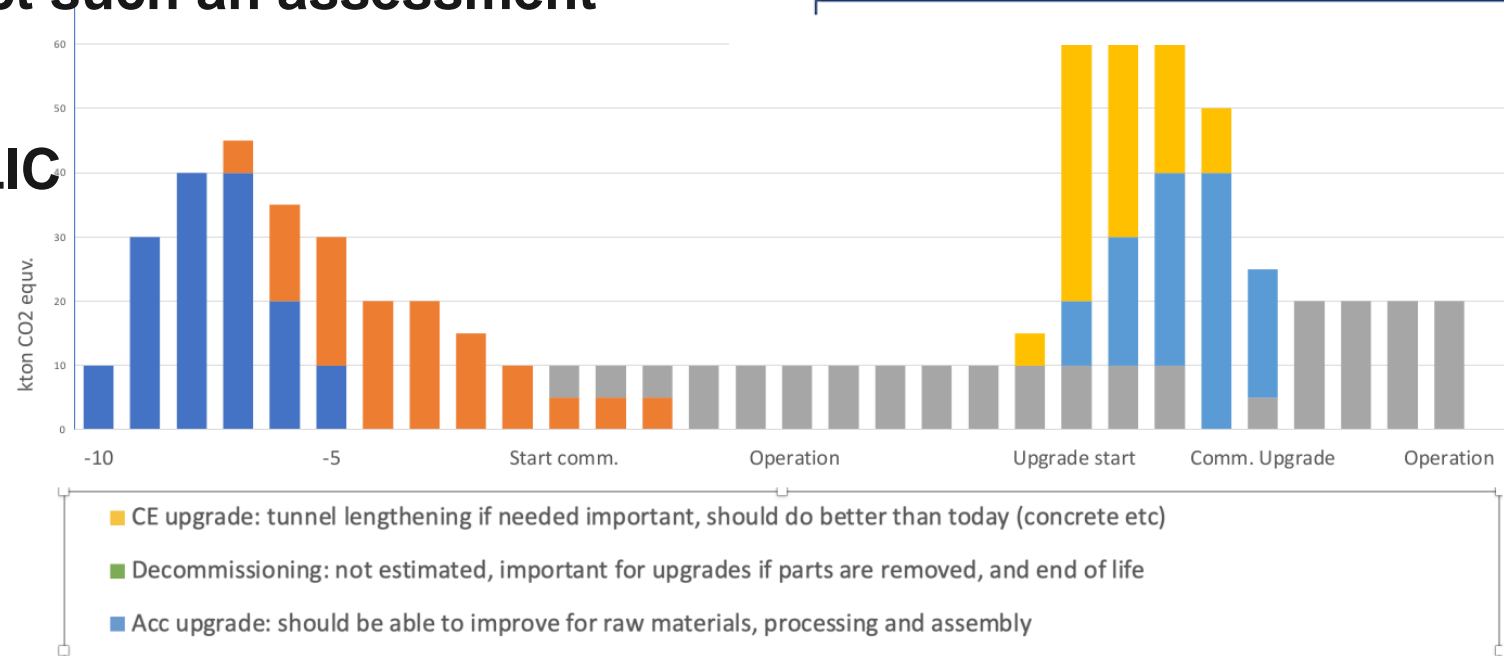
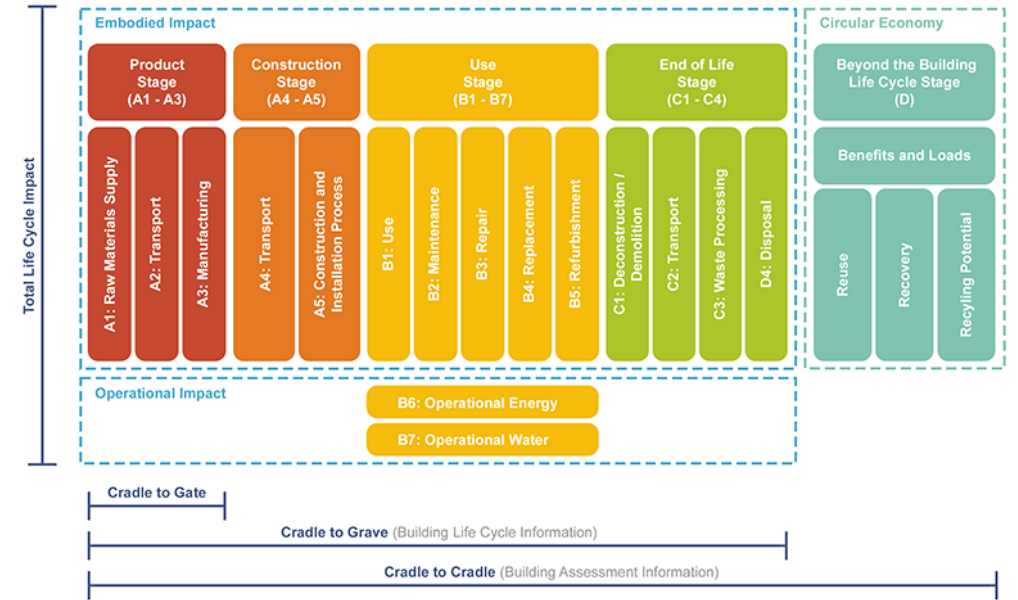
# Introduction

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

**Accepted method:**  
**LCA = Life Cycle Assessment**

**CLIC and ILC will conduct such an assessment together with ARUP**

**Will talk mainly about CLIC**

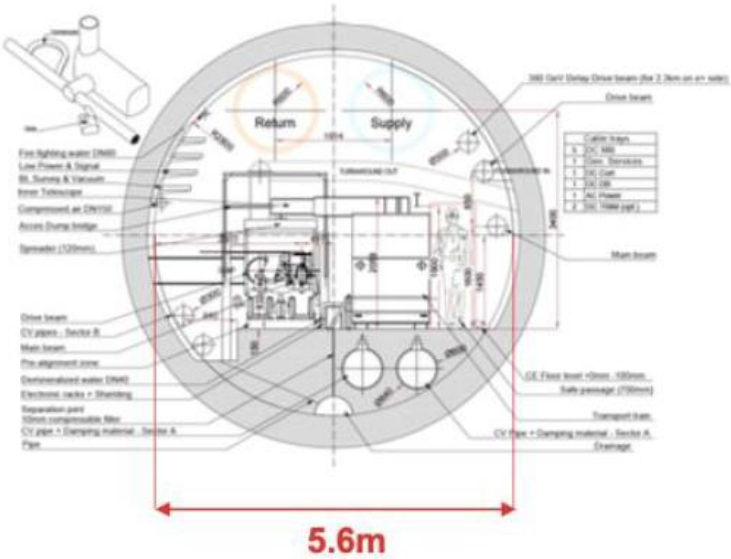


# The Tunnel

# LCA study for the accelerator tunnel

## 1. CLIC Drive Beam

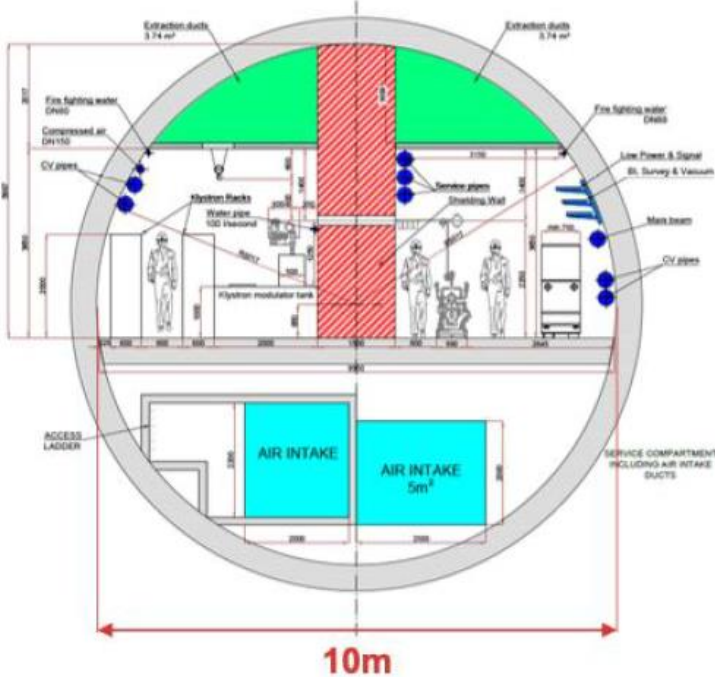
5.6m internal dia. Geneva.  
(380GeV, 1.5TeV, 3TeV)



Reference: CLIC Drive Beam tunnel cross section, 2018

## 2. CLIC Klystron

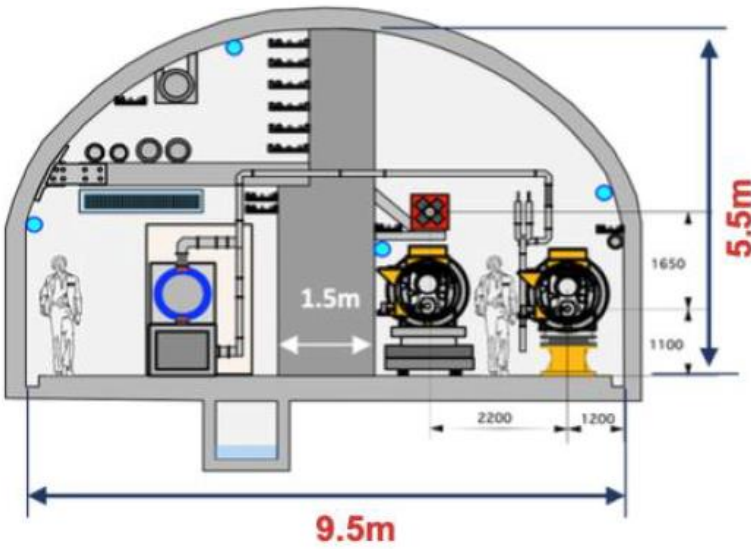
10m internal dia. Geneva.  
(380GeV)



Reference: CLIC Klystron tunnel cross section, 2018

## 3. ILC

Arched 9.5m span. Japan.  
(250GeV)

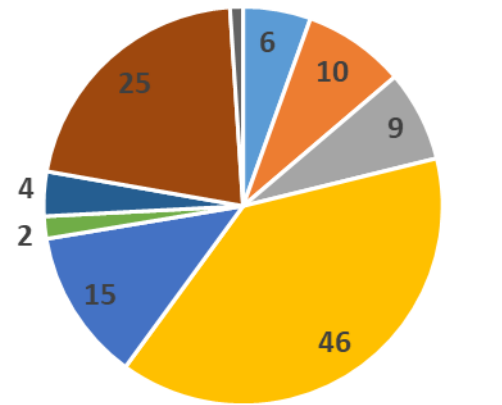


Reference: Tohoku ILC Civil Engineering Plan, 2020

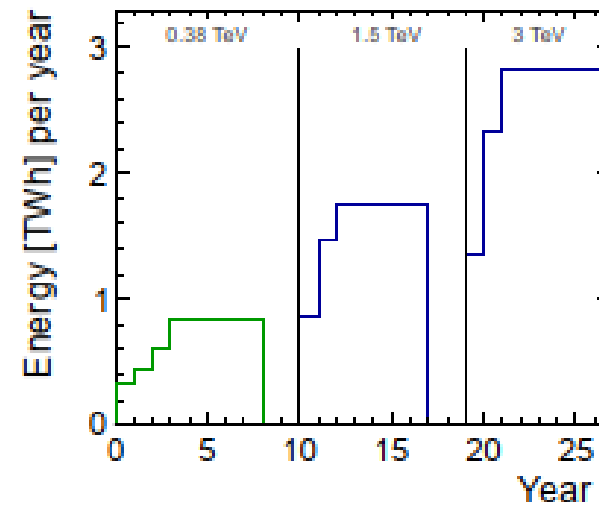
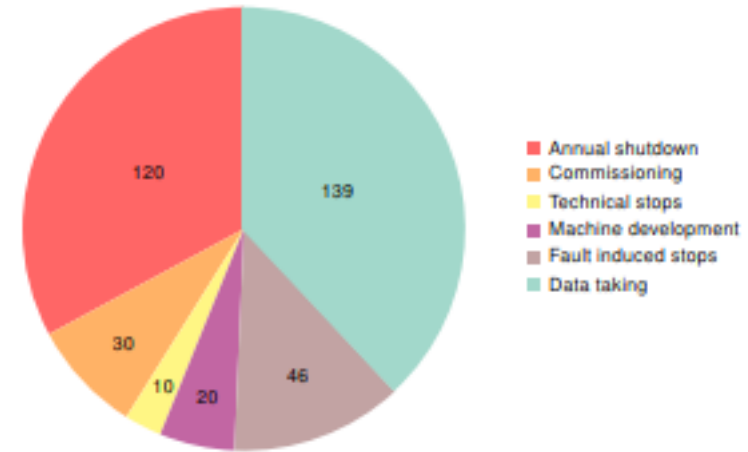
# Energy consumption during operation

# CLIC power and energy consumption

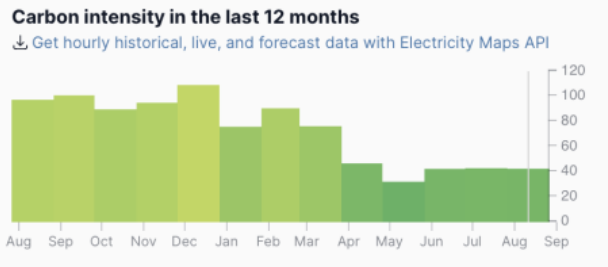
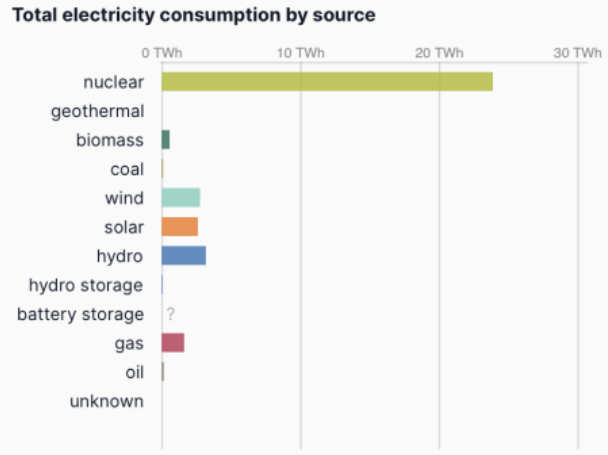
Drive beam option: 118 MW



- MB Injectors
- MB Damping Rings
- MB booster & Transport
- DB Injectors
- DB Frequency Multiplication & Transport
- Two-beam accelerators
- Interaction Region
- Infrastructure and Services
- Controls and Operation



# From energy to CO2 – in 2040-50

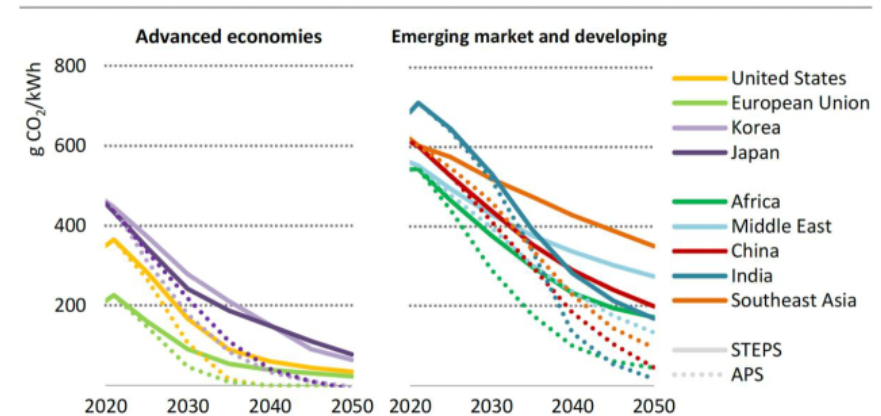


From: <https://app.electricitymaps.com/zone/FR>  
Contains also g/kWh per source

What is the carbon intensity of energy in ~2050 (operation):

- 50% nuclear and 50% renewable give ~10-15g/kWh
- France summer-months are today ~40g/kWh
- ILC has a green implementation concept including compensation and contracting renewable energy
- Reductions predicted ([LINK](#))

**Figure 6.14** ▶ Average CO<sub>2</sub> intensity of electricity generation for selected regions by scenario, 2020-2050



IEA, CC BY 4.0.

CO<sub>2</sub> intensity of electricity generation varies widely today, but all regions see a decline in future years and many have declared net zero emissions ambitions by around 2050

Different strategies to offset or reduce the energy consumption with higher efficiencies, sustainable sources and running when energy production peaks

# The Accelerator



# Materials and their Carbon Footprint

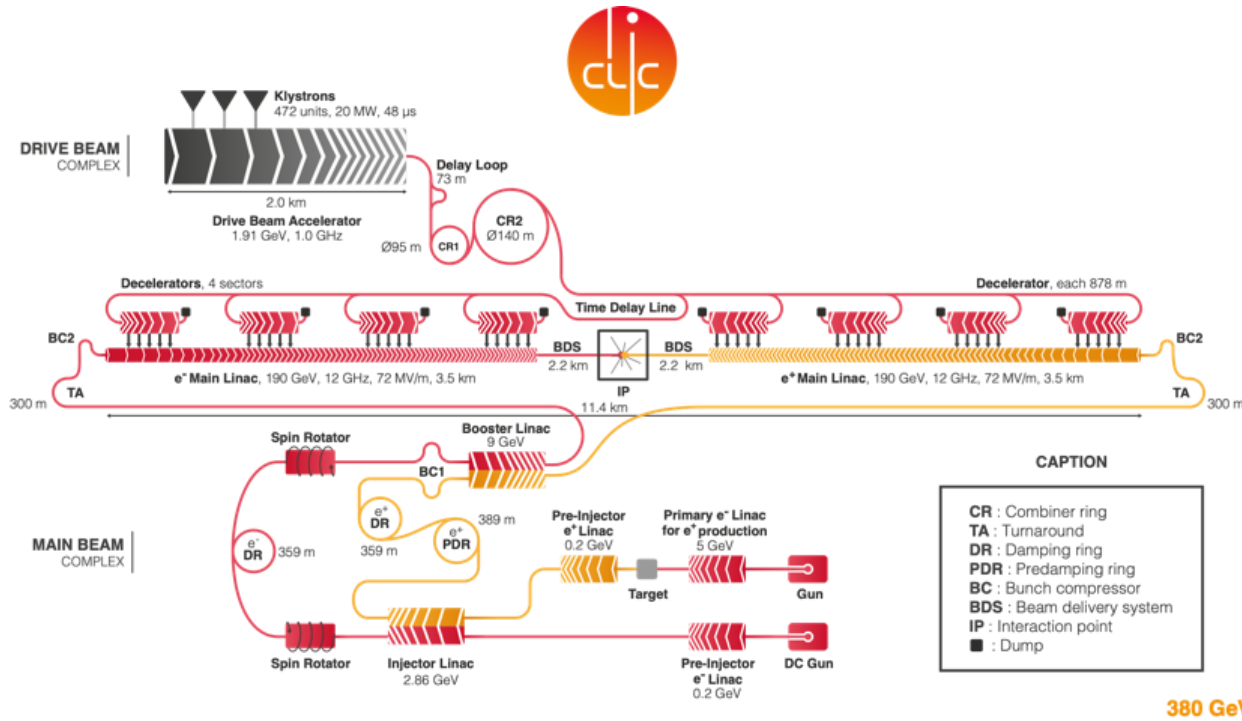
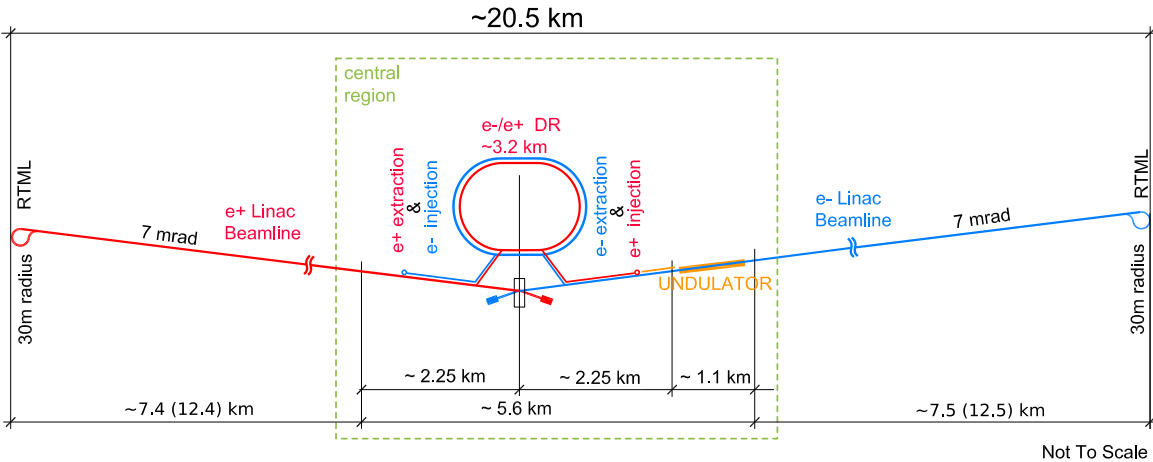
Material	Density (g/cm <sup>3</sup> )	GWP (kg CO <sub>2</sub> -eq/kg)
Cement	1.4	1.0 [3]
Concrete	2.5	0.1 [3]
Mild Steel	7.85	1.7
Stainless Steel (18%Cr, 10%Ni)	7.85	3.7 [1]
Copper	8.96	2.5
Aluminium	2.70	8.2 [2]
Titanium	4.5	8.1 [2]
Silicon Carbide	3.2	--

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](https://doi.org/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](https://doi.org/10.1016/j.jclepro.2022.131834)

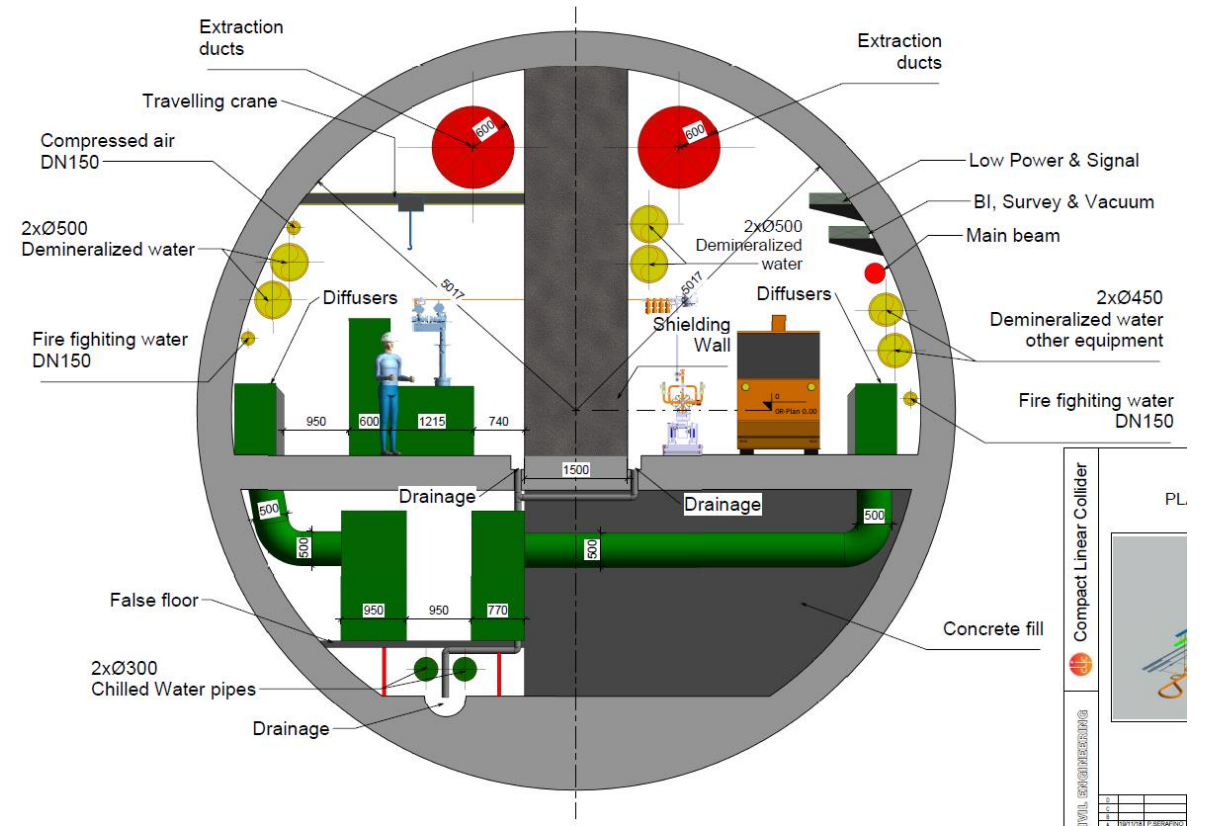
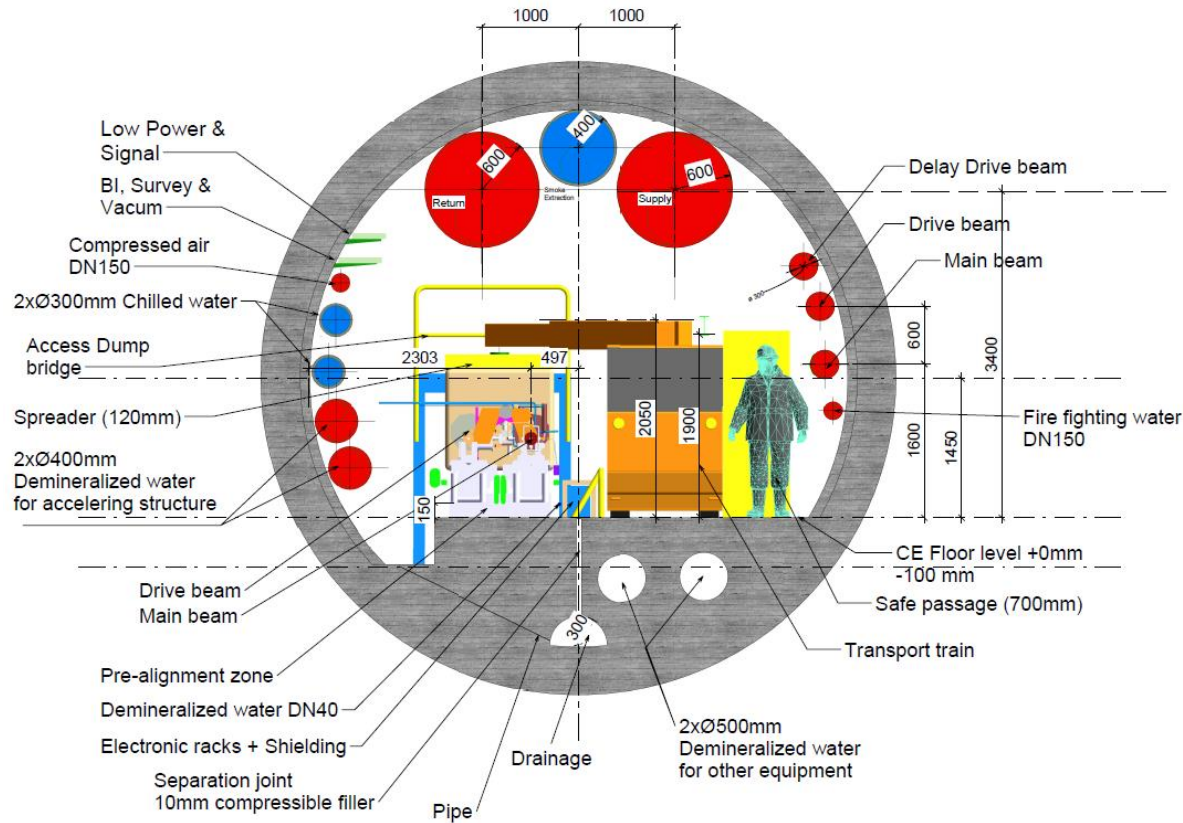
## Notes

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

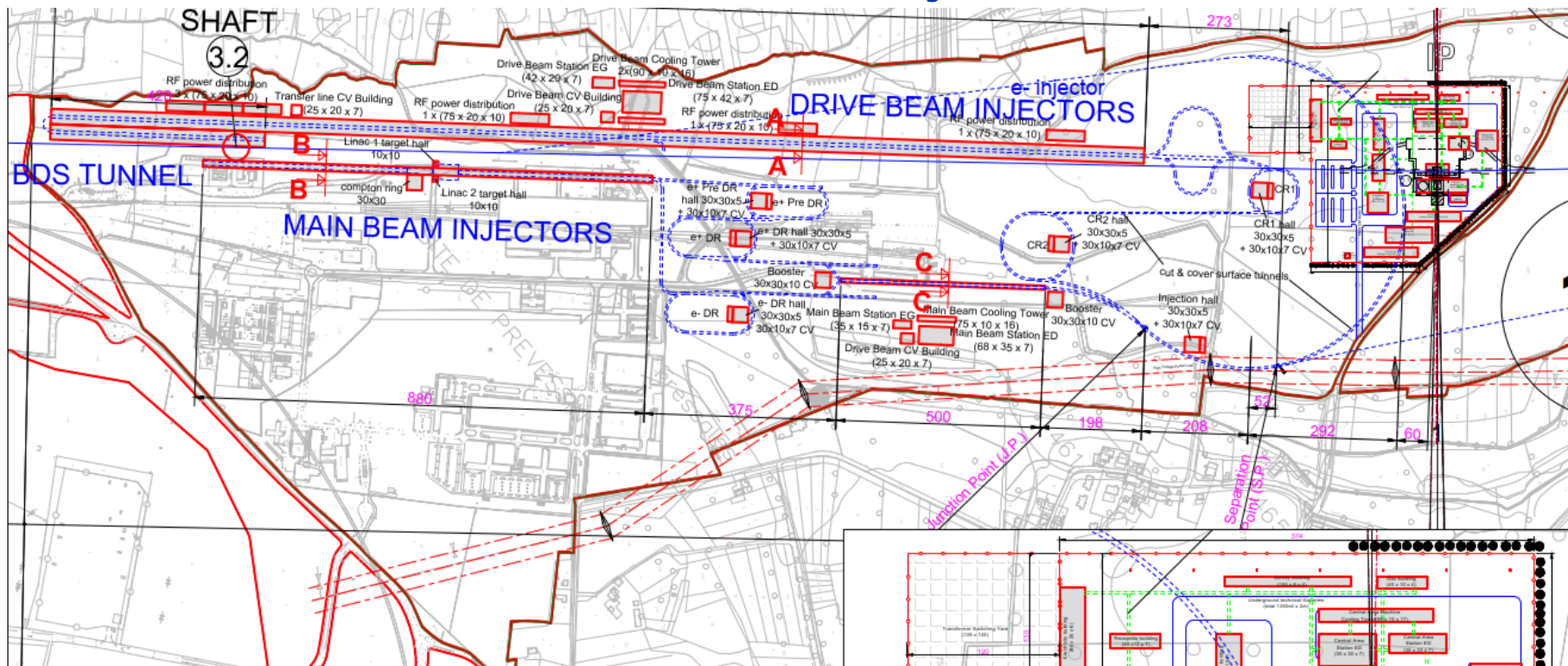
# CLIC and ILC layouts



# Tunnel Cross Sections

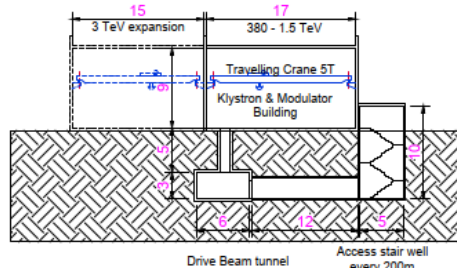


# Zoom into the injectors

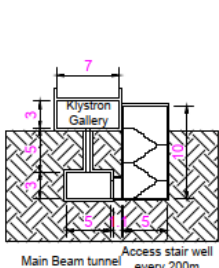


Main Beam & Drive Beam Injector Cross Sections

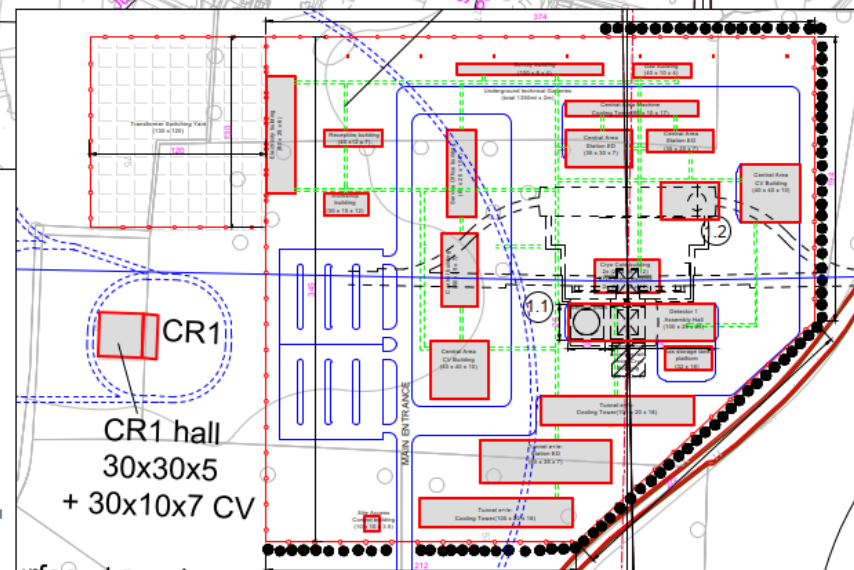
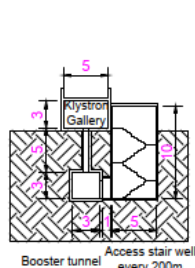
Section A-A



Section B-B



Section C-C



CLIC- MAIN / DRIVE BEAM INJECTORS AND EXPERIMENTAL AREA  
SURFACE BUILDINGS LAYOUT

	GROUP : G3-2E	SCALE : 1/7500(A3_FORMAT)	DATE : 10-JUL-2017
	CIVIL ENGINEERING	CLIC.CE-1.1799.0005	
	SUPERVISOR : JOSBORNE DESIGNER : P.SERAFINO		
			SIZE INDICES 3 E





# CLIC 380 GeV Two beam area breakdown

Sub-system	Components
Drive beam injector complex and transfer to ML tunnel	DB linac module (supports,diag,vacuum) DB linac waveguide system DB linac magnets DB linac Modulator/Klystron Delay Loop and Combiner Rings CV infrastructure
Main beam injector complex	Injector module (supports, vaccum, diag, modulator,klystron, waveguides) Injector magnets Injector CV infrastructure Damping ring (DR)
Transfer to main linac, RTML, main and drive beam	RTML vacuum, diagnostics, support RTML magnets RTML CV infrastructure
Main Linac (ML)	Main linac modules drive beam Main beam magnets Post decelerators/dumps CV infrastructure drive beam
Beam delivery and post collision lines	Beam delivery system (BDS) Post collision lines/dumps CV infrastructure
Central area	Detector Infrastructure

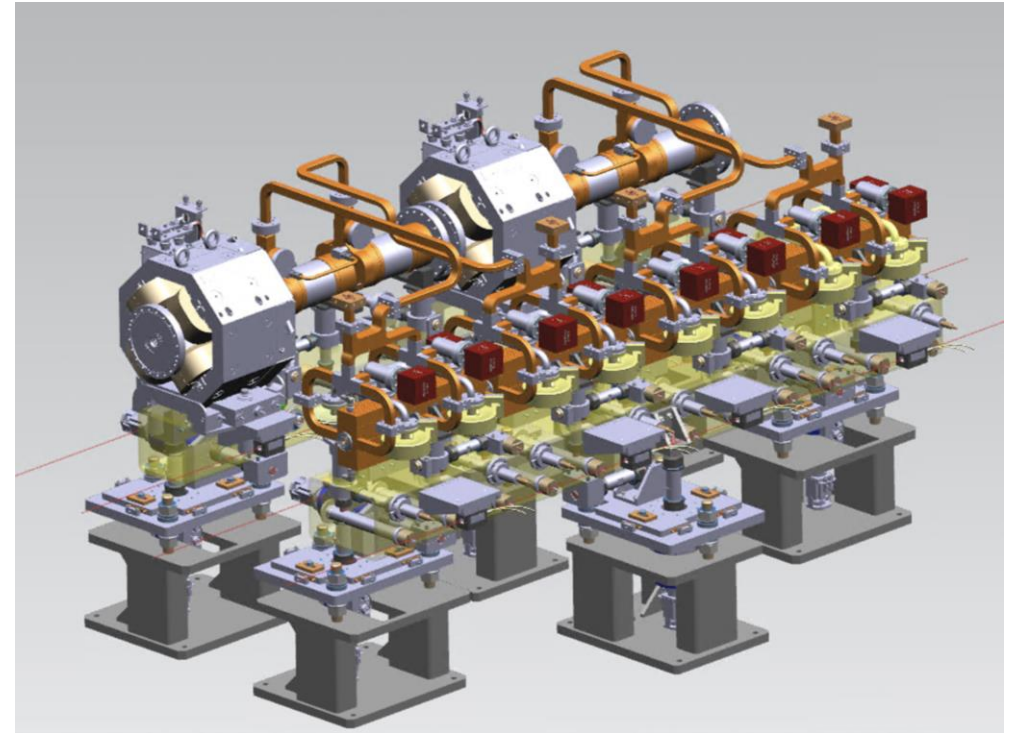
# ILC area breakdown

Sub-system	Components
ES: Electron Source	Magnets with Power supplies and stands Vacuum system Cryomodules HLRF (Klystrons, Modulators) Cryogenics Area Specific: NC Accelerating Structures, Gun
PS: Positron Source	Magnets with Power supplies and stands Vacuum system Cryomodules HLRF (Klystrons, Modulators) Cryogenics Dumps and Collimators Area Specific: NC Accelerating Structures, Target
DR: Damping Rings	Magnets with Power supplies and stands Vacuum system Cryogenics Dumps and Collimators Area Specific: Cryomodules, Klystrons, Wigglers
RTML: Ring to Main Linac	Magnets with Power supplies and stands Vacuum system Cryomodules HLRF (Klystrons, Modulators) Cryogenics Dumps and Collimators
ML: Main Linac	Magnets with Power supplies and stands (warm magnets) Vacuum system (warm vacuum) Cryomodules HLRF (Klystrons, Mmodulators) Cryogenics Dumps and Collimators
BDS: Beam Delivery System	Magnets with Power supplies and stands Vacuum system Cryomodules HLRF (Klystrons, Modulators) Cryogenics Dumps and Collimators Area specific: Crab cavities
Detectors	ILD SiD Infrastructure

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

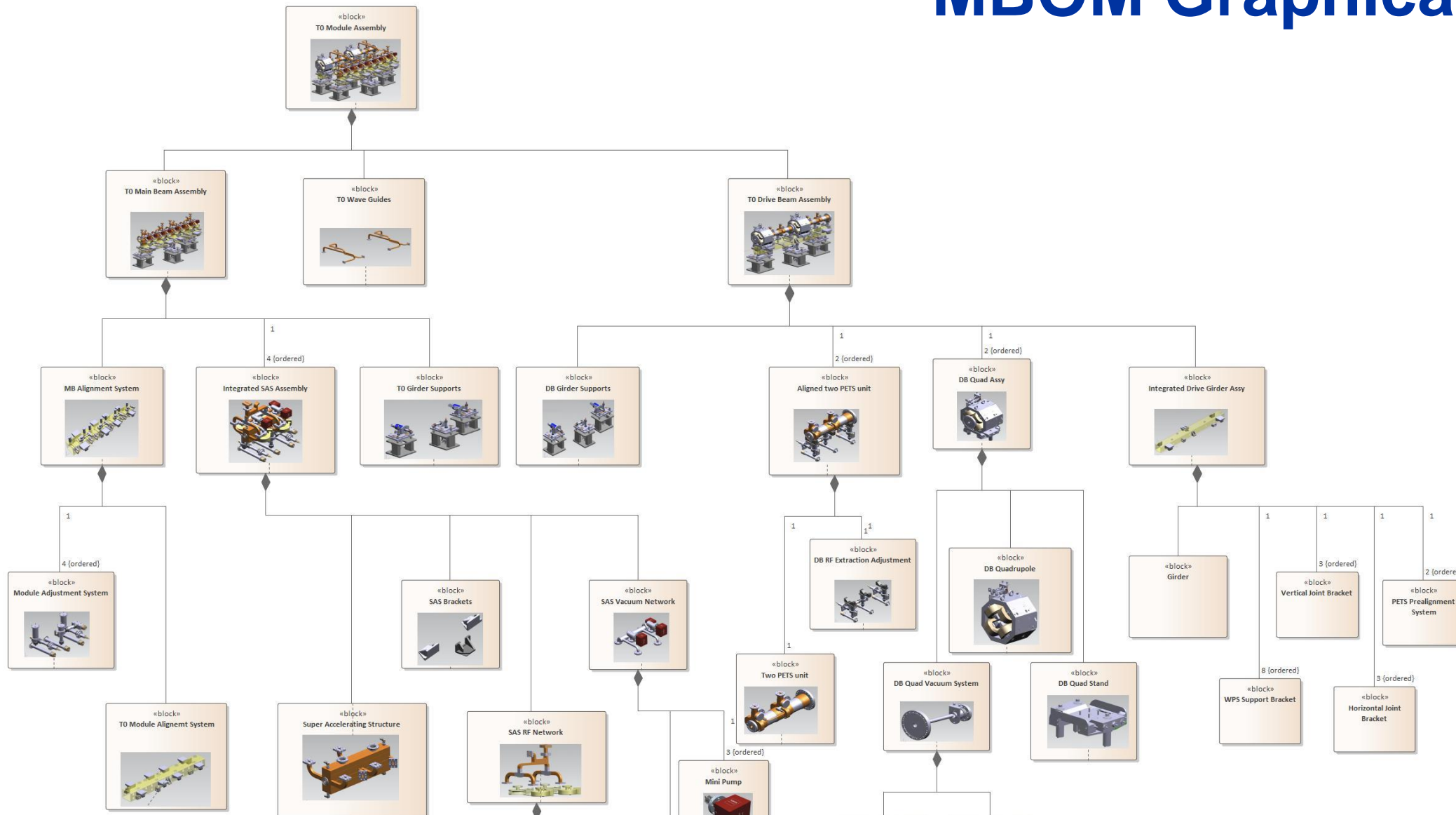
Attempt a bottom-up calculation of total material budget

- Decompose system to level of individually manufactured pieces
- Start with CAD model and create MBOM
- 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



# MBOM Graphical View

bdd[package] Physical Structure [Physical Structure]



# Breakdown according to Material

## “Mild Steel”: Mostly Support System

### Conclusion here:

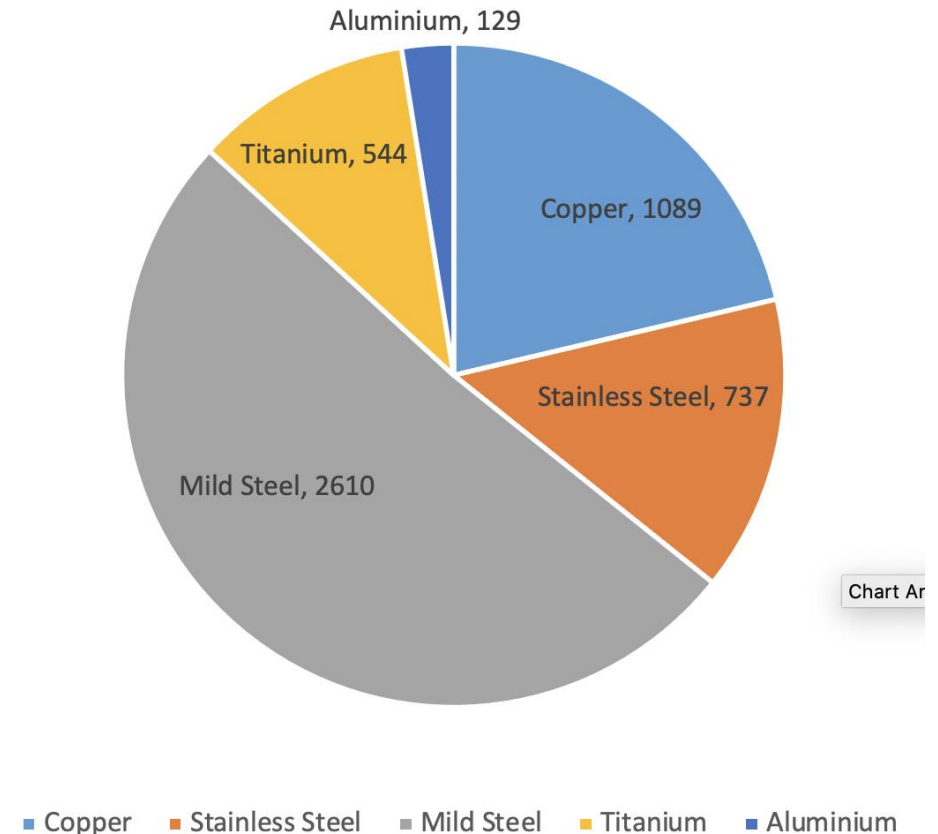
Supports have a large impact on CO<sub>2</sub> just from the sheer mass  
-> a good place to start

### For large scale production:

Cast iron may be interesting

- Reduced material carbon footprint
- Less scrap, less machining

Material (incl. Scrap) GWP [kg CO<sub>2</sub>-eq]





# Cryomodule Production Steps

## Half Cell Deep Drawing

Click to add text

- Unknown: Value of scrap, how is scrap recycled
- One sheet of niobium used to produce one half-cell: mass 1.09kg
- > 68 kg CO2-eq per half cell, dominated by CO2 from electricity for Nb refinement

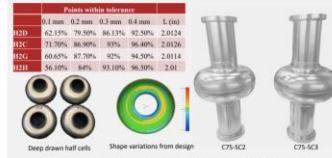
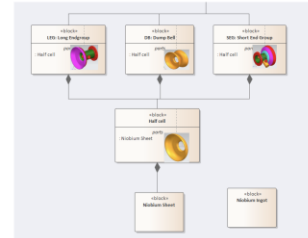


Fig. 6: Fabrication of two single cell cavities labeled C75-SC2 and C75-SC3.

## Dump Bells and End Groups

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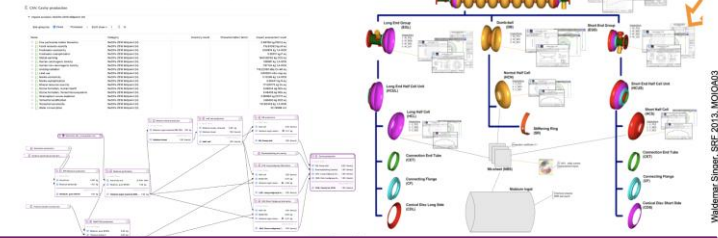
- 2 half cells plus stiffening ring welded to form a "dump bell"
- End groups: half cells plus tube and other stuff
- Unknown: Energy of Electron Beam Welding
- Unknown: Material efficiency for the other parts



## Cavity Production

Click to add text

- Unknown: Electron Beam Welding
- Prelim. Result: 1641kg CO2-eq per cavity



## Cavity Treatment

Click to add text

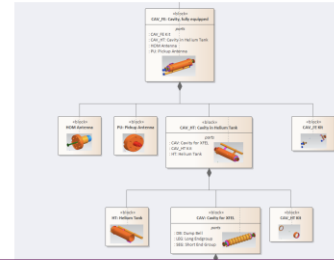
- Cavity treatment consists of
  - Heat Treatment
  - Electropolishing
  - HPR
- Needs chemicals (phosphorous acid), water, electricity
- Currently not taken into account!



## Cavity with Helium Tank and Fully equipped

Click to add text

- Cavity is jacketed with helium tank (made from Titanium) -> CAV\_HT
- Cavities are tested, possibly sent to rework, or rejected
- Energy consumption of test stand not taken into account
- Rejection quota (yield) not considered
- Transport from vendor (RI or Zanon) to DESY, transport to CEA after testing -> not yet included



## Assembly in the XFEL Village

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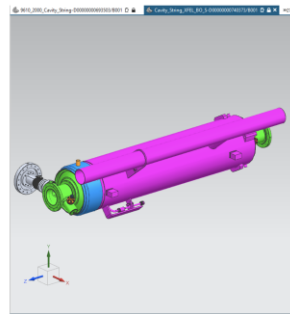
- Assume final throughput: 1.25CM / week -> 7/1.25 = 5.6 days per CM
- Assign operating resources (power) to work stations according to area
- Distinguish "general assembly area" and ISO4 cleanrooms
- Unknown:
  - electricity usage for lighting, heating, ventilation
  - Other resources (water, alcohol, LN2)



## Cold Coupler Assembly in clean room

Click to add text

- First step: Cold coupler part mounted on cavity
- Done in "CC" (Cold Coupler) area



DESY, Benno List | Cryomodule LCA

## STR: String Production

Click to add text

- String assembly done in cleanroom area



DESY, Benno List | Cryomodule LCA

## Integration with vacuum vessel, warm coupler mounting

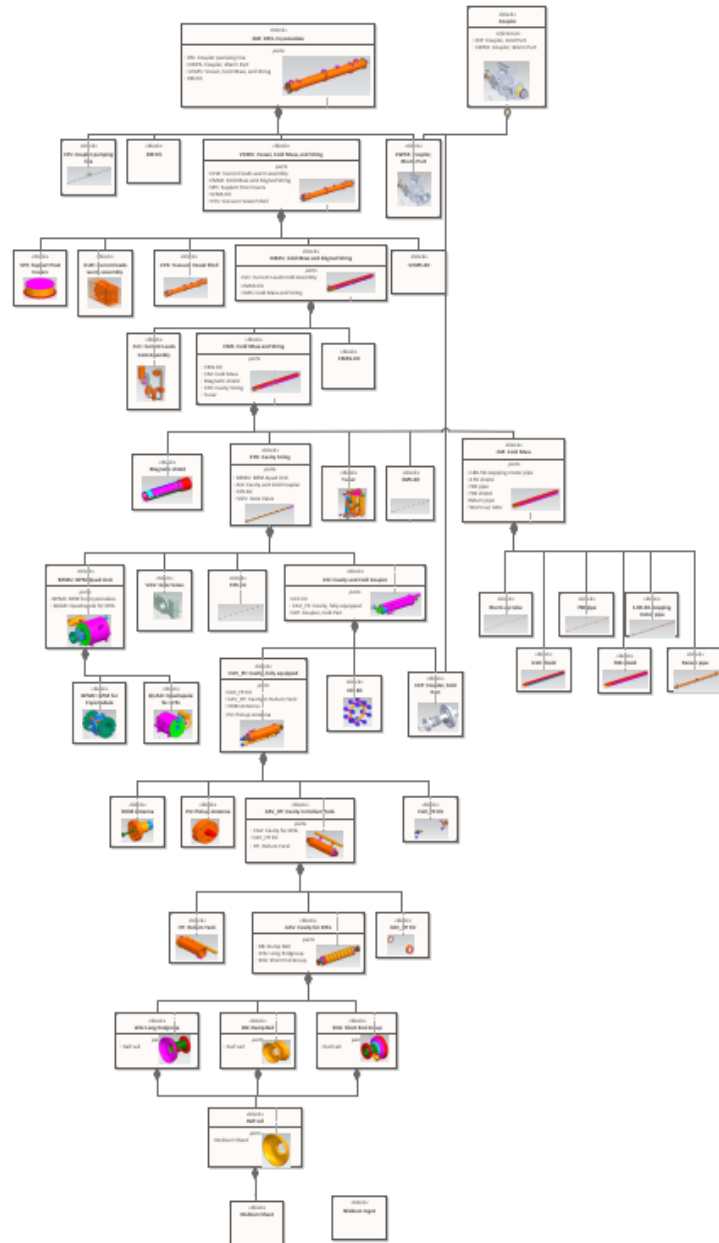
Click to add text

- Combine aligned cold mass and string with vacuum vessel in cantilever area
- Mount warm couplers in checkout area
- Final inspection in shipping area
- Vacuum vessel: 3500kg steel



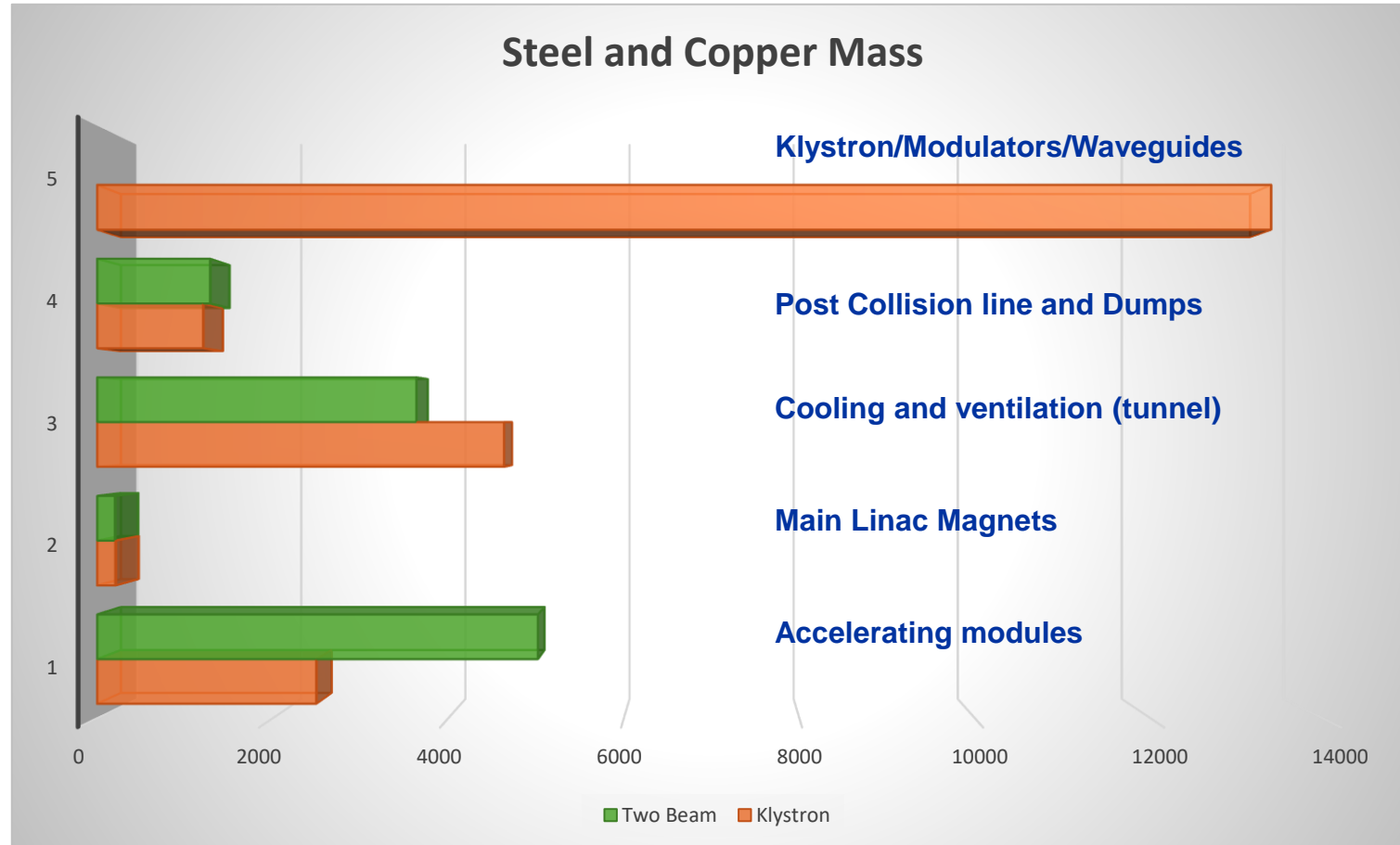
DESY, Benno List | Cryomodule LCA

# MBOM Graphical View



**Particular challenge here for the LCA:  
Niobium material  
No impact assessment exists yet  
On Nb RRR300 material**

# Preliminary findings for the CLIC machine



# Difficulties and Remarks

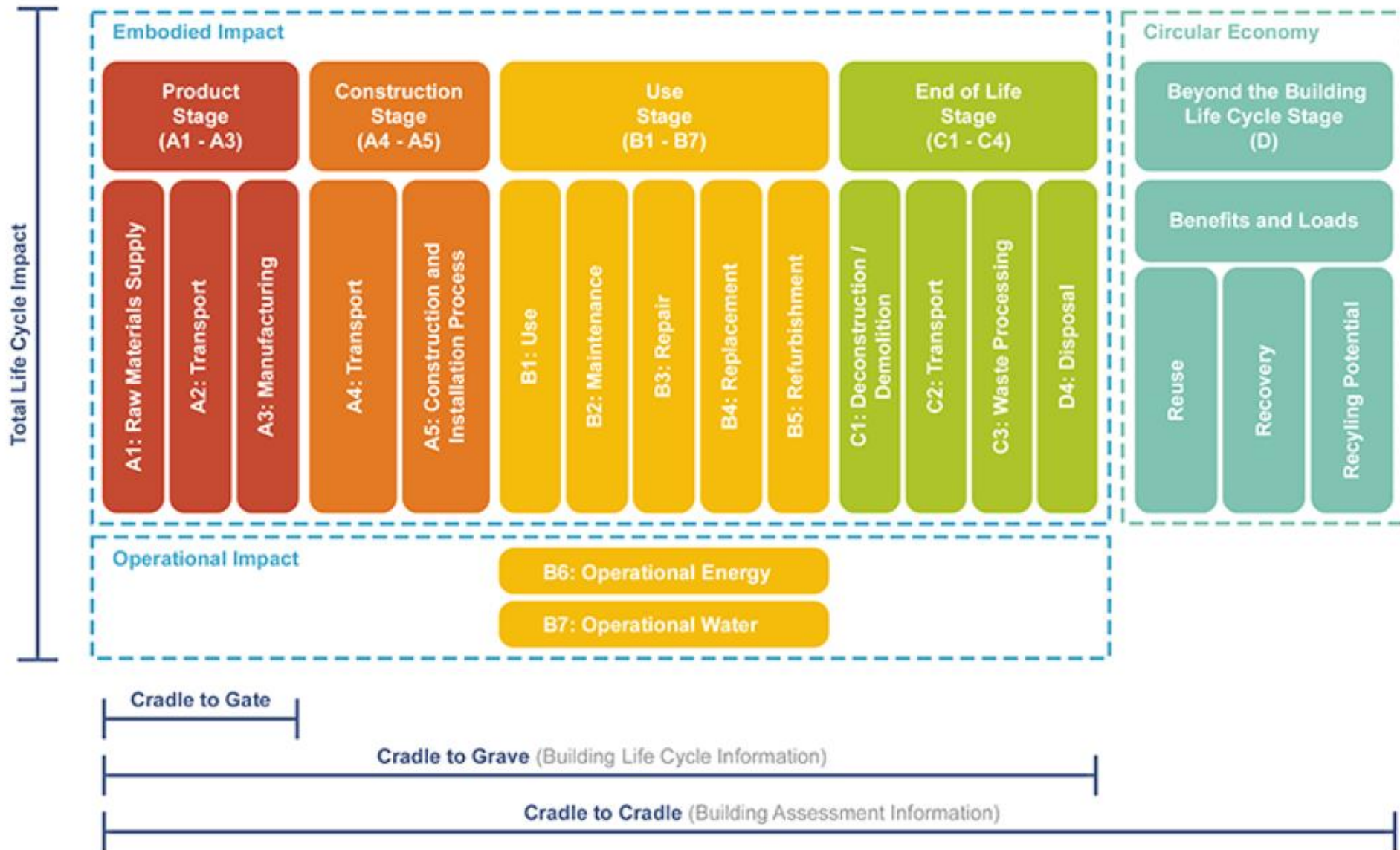
- Where detailed 3D designs of components existing, a detailed and accurate material breakdown is relatively straight forward
- Knowledge about fabrication processes is needed to evaluate correctly scrap metal amounts
- Very little knowledge or none of resources needed during production in industry at this stage
- Averaging assumptions about origin of goods and related transport impact
- Some systems needs educated guessing and scaling (for example klystrons and modulators)
- Often no detailed data from commercial products
  
- Will give an indication of the true environmental impact, likely good for comparisons but still with large error bars
- Will help identifying hot spots and making engineering decisions

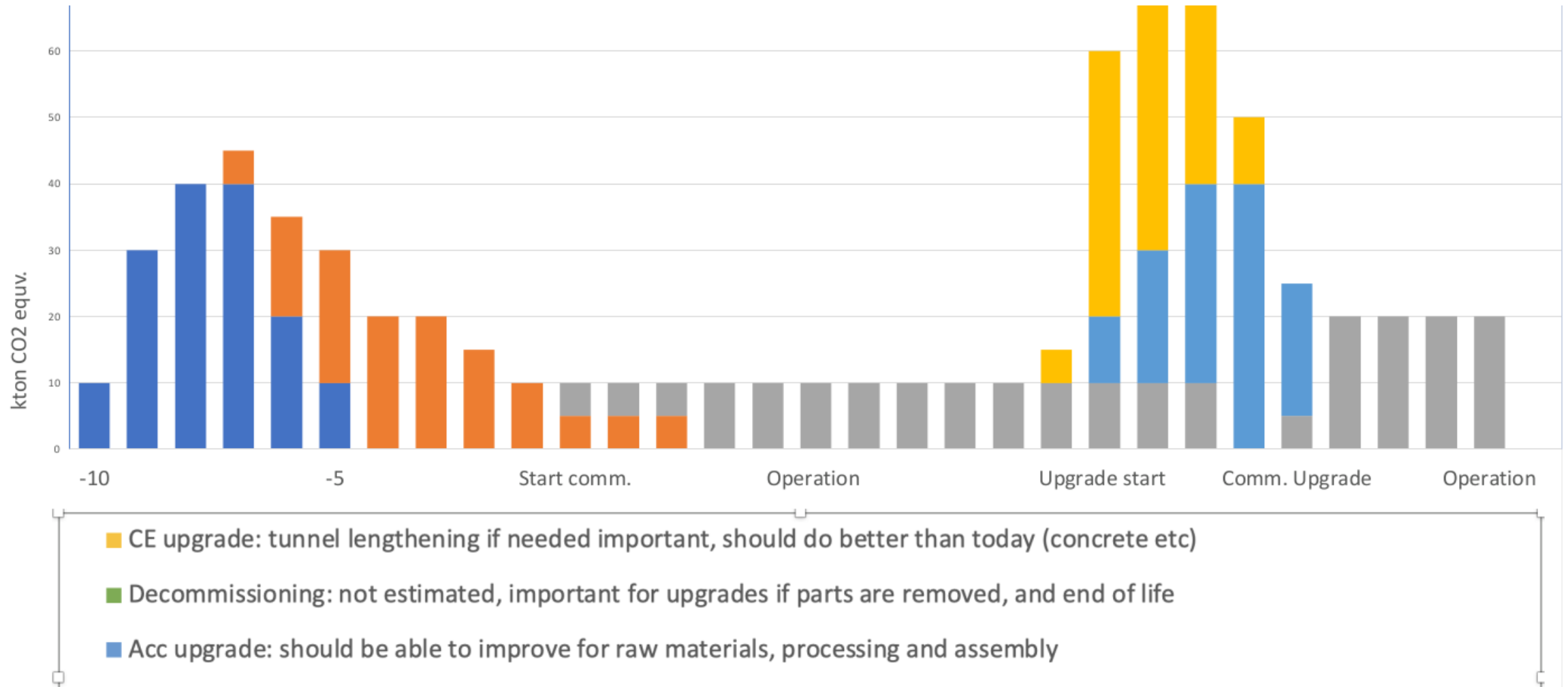
# Preliminary conclusions

- **Still a lot to do !**
- **CV infrastructure comparable to accelerator components**
- **Accelerator comparable to tunnel construction**
- **Accelerator supports are more important than RF structures**
- **Still a lot of items missing, details on cabling, transport, packaging, decommissioning/recycling**
- **For CLIC: Klystron version is significantly worse in terms of GWP**



[home.cern](http://home.cern)







# The T0 Module Data

Level 0	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Number	PBS Code	PBS Text	Quantity /	Q / Tot	Material	Densit	Mass	Manufacturing	
TO Module Assembly							ST1528727	3.1.1.	Two-Beam Module Type 0 e+	1		1 Mixed		1710		
TO Main Beam Assembly							ST1550706			1		1 Mixed		950		
Integrated SAS Assembly										4		4 Mixed		63		
Super Accelerating Structure							ST1378439	3.1.1.1.	Super-accelerating Structures	1		4 Mixed		47		
Rectangular Disk Assy							ST0790069			56		224		0.7		
Rectangular Disk							ST0787907			1		224 Copper	8.85	0.51	Machined	
Absorber left							ST0798602			2		448 Silicon Carbide	3.21			
Absorber right							ST0798631			2		448 Silicon Carbide	3.21			
Coupler Disk							ST1378544			2		8 Copper	8.85	1	Machined	
Structure Connecting Disk							???					0 Copper	8.85	1	Machined	
SAS Interconnect Bellow							ST0347489			4		16 Stainless Steel	7.85	0.1	Fabricated	
Input Waveguide										2		8		0.5	Extruded	
Input Waveguide Arm							ST1437145			1		8 Copper	8.85		Extruded	
Waveguide Flange							ST0666851			1		8 Stainless Steel	7.85			
Output Waveguide										2		8		0.5		
Output Waveguide Arm							ST1393409			1		8 Copper	8.85		Extruded	
Waveguide Flange							ST0666851			1		8 Stainless Steel	7.85			
SAS Vacuum Flange							ST0396788			8		32 Stainless Steel	7.85	1	Turned	
SAS Water Connector							ST1358471 + ST0295539			4		16 Stainless Steel	7.85	0.1		
SAS Bracket Set							ST1556884 + ST1556973 +								9	Machined
SAS Bracket 1													0.85	3	Machined	
SAS Bracket 2													0.85	3	Machined	
SAS Bracket 3													0.85	3	Machined	
SAS Vacuum Network														12		
Vacuum Manifold														1.5	Fabricated	
Vacuum Manifold													0.85		Fabricated	
Pumping port													0.85		Fabricated	
Mini Pumps														2		
SAS RF Network														1		
SAS Input Waveguides														1	Extruded	
SAS Input Waveg														0.85		

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

# Typical injector modulator/klystron system



Contacted company for input to this study  
( Integrated system value or material breakdown )

# CLIC klystron base module

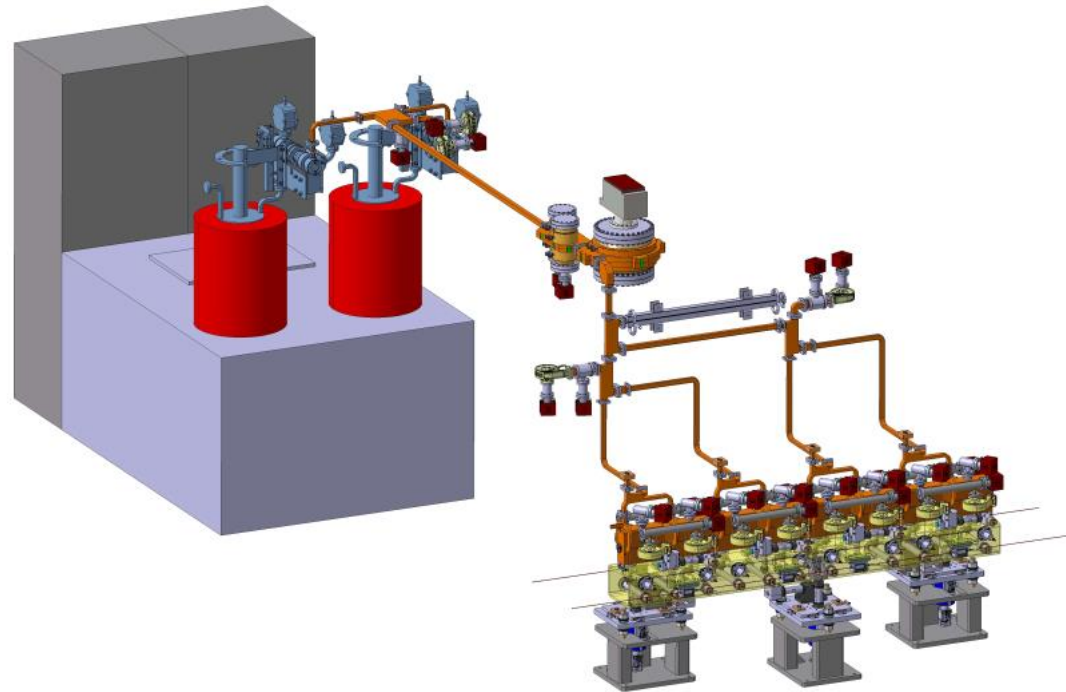


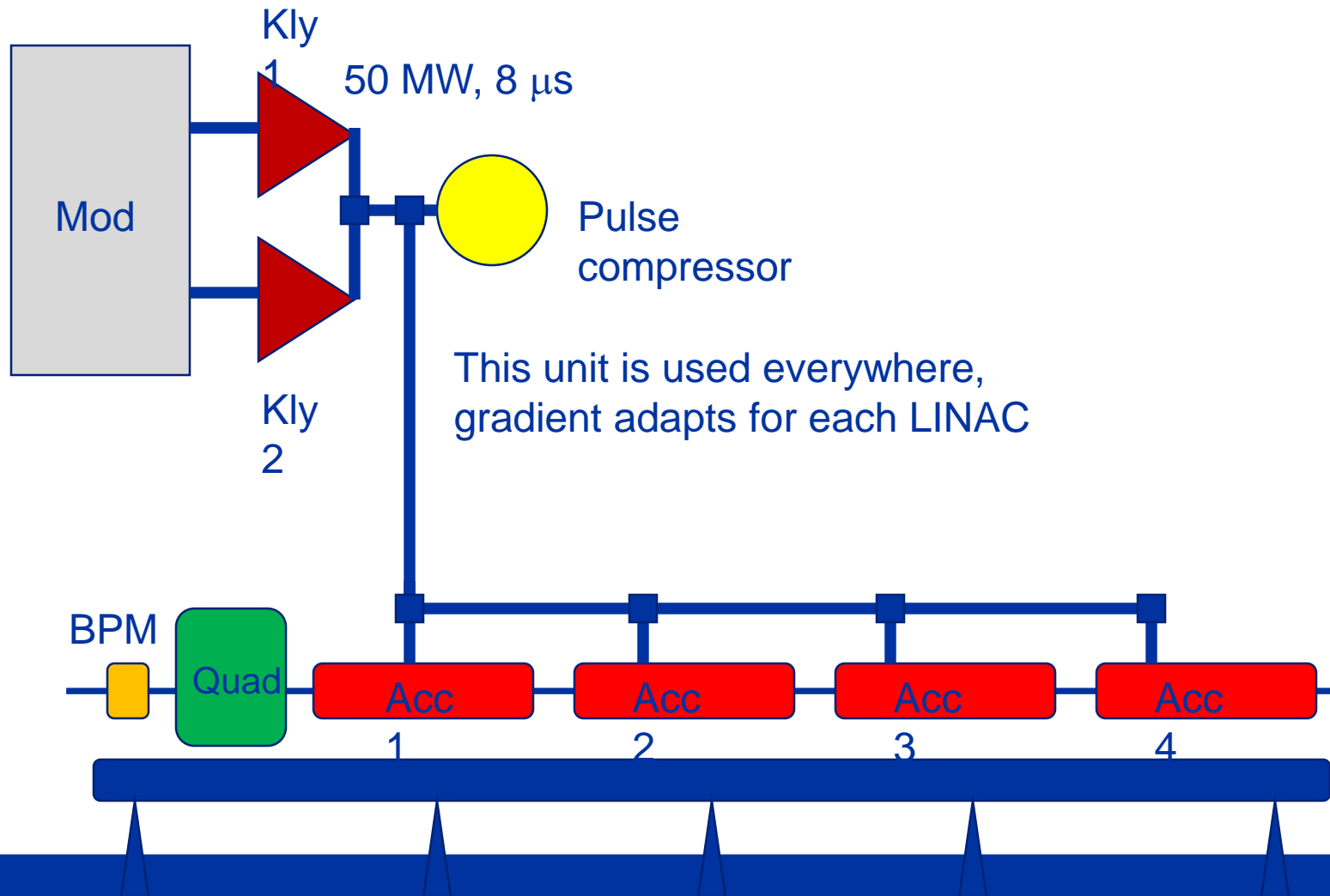
Figure 3: A CLIC Klystron Module



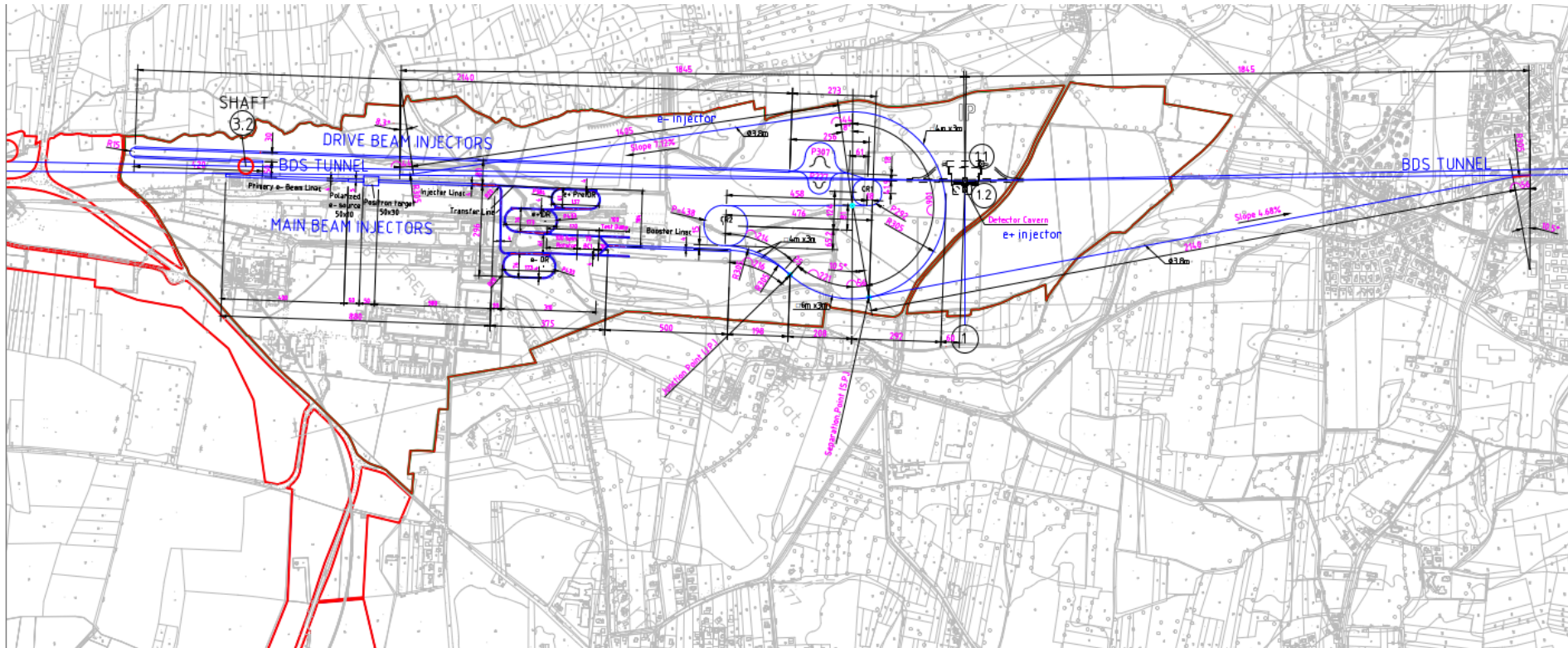
# Rf-module cost model



Typical 2 GHz rf module including accelerators and beam line



# Injector infrastructure



INJECTORS TUNNELS	DRIVE BEAM INJECTORS COMPLEX							MAIN BEAM INJECTORS COMPLEX									COMMON TRANSFER TUNNEL J.P. to S.P.	FINAL TRANSFER TUNNELS ((From Separation Point))		
	LINAC	DL1	DL2	CR 1	CR 2	Transfer Lines	TT to Junction Point	Preliminary e- beam LINAC	Polarized e- source	Positron Target	Transfer Lines	e+ Pre DR	e+/e- DR	SpinRotator +BC1+TD	Booster LINAC	TT to Junction Point		e- TT	e+ TT	
Length (l) m	2140 +48+420	227	307	292	438	518	239	400	50	50	482	384	2x433	2 x 313	500	216	277	945	1449	2196
Section (w x h) m	6 x 3	4 x 3	4 x 3	4 x 3	4 x 3	4 x 3	4 x 3	4 x 3	5 x 3	30 x 3	4 x 3	4 x 3	4 x 3	4 x 3	4 x 3	4 x 3	6 x 3	4 x 3	∅ 3.8	∅ 3.8
Surface Buildings (l x w x h) m	2560 x 30 x h 9	-	-	30x30 x h 5	30x30 x h 5	-	-	400 x 7 x h 3	Compton R. 30x30 x h 3	Linac1+2. 30x30xh5(x2)	-	30x30 xh5(x2)	30x30 xh5(x2)	-	500 x 5 x h 3	-	Inject.Hall 30x30xh5	delta e-/e+ = 198m		

CLIC- MAIN / DRIVE BEAM INJECTORS AND EXPERIMENTAL AREA LAYOUT



GROUP : GS-SE  
CIVIL ENGINEERING  
SUPERVISOR : J.OSBORNE  
DESIGNER : P.SERAFINO

SCALE : 1/8000(A3\_FORMAT) DATE : 02-JUN-2017

CLIC.CE-1.1799.0002 3 | L





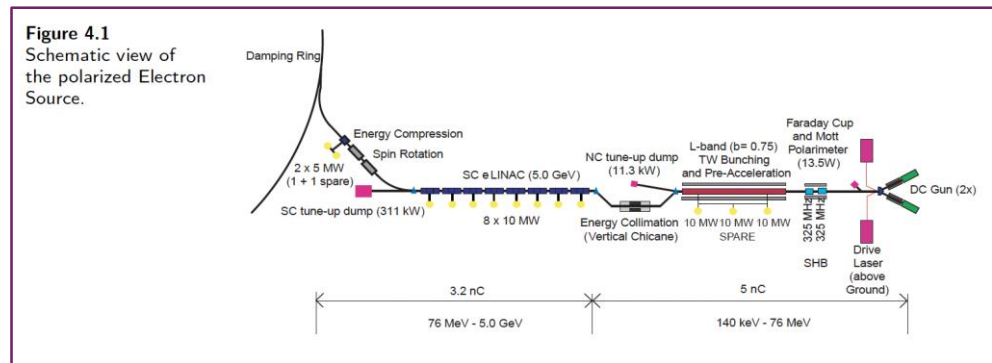
# Result for a T0 Module

	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
<b>Total mass (kg)</b>	<b>1777</b>	<b>314</b>	<b>135</b>	<b>1269</b>	<b>45</b>	<b>14</b>
GWP/kg		2.5	3.7	1.7	8.1	8.2
Main Beam Module & WG: GWP (kg CO2-eq)	<b>2237</b>	388	421	991	363	74
T0 Drive Beam Assembly: GWP (kg CO2-eq)	<b>1681</b>	398	80	1167	0	37
<b>Total GWP (kg CO2-eq)</b>	<b>3918</b>	<b>786</b>	<b>501</b>	<b>2158</b>	<b>363</b>	<b>111</b>
scrap mass estimate (kg)		242	128	532	45	5
scrap GWP (kg CO2-eq) (at 50%)	<b>1191</b>	303	236	452	181	18
<b>total GWP with scrap (kg CO2-eq)</b>	<b>5109</b>	<b>1089</b>	<b>737</b>	<b>2610</b>	<b>544</b>	<b>129</b>

# Sources (Electron & Positron)

## Electron Source:

- ~ 300m of beamline
- Laser & target
- 76MeV pre-accelerator
- **5 GeV booster** (superconducting linac)  
-> ~identical to 5GeV section of ML
- Injection line into DR  
-> vacuum tube and **magnets**



ILC TDR, Vol III.2

## Positron source

- In electron main beamline:
  - 1150 m of beamline (vacuum, **magnets**), incl.
  - 230m of superconducting undulators
  - Photon beampipe
- Positron source proper
  - Target station
  - 400MeV preaccelerators
  - **5 GeV booster**

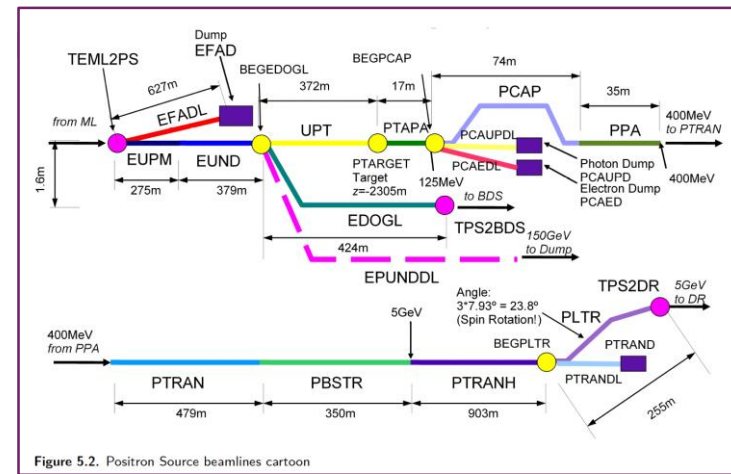
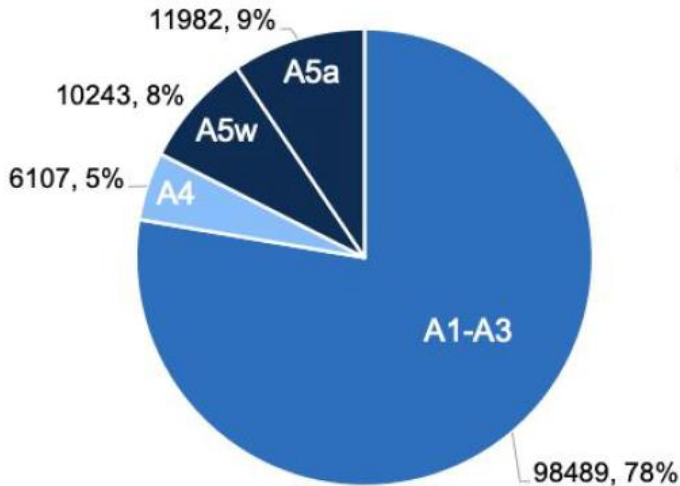


Figure 5.2. Positron Source beamlines cartoon

# LCA study for the accelerator tunnel

## 1. CLIC Drive Beam 380GeV

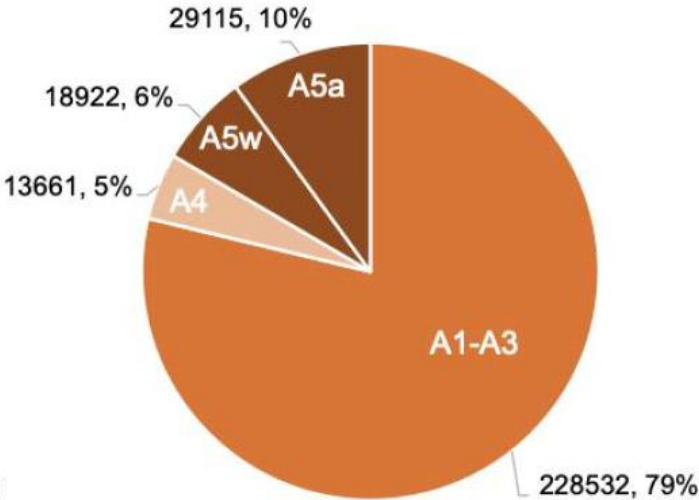
5.6m internal dia.  
Geneva



Total A1-A5 GWP: 127000 tCO<sub>2</sub>e

## 2. CLIC Klystron 380GeV

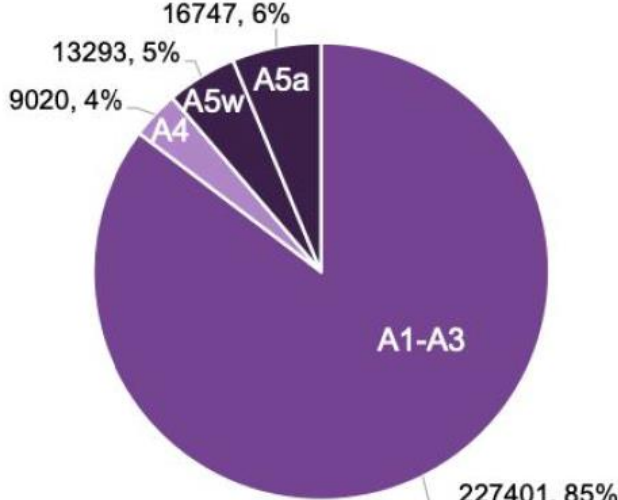
10m internal dia.  
Geneva



Total A1-A5 GWP: 290000 tCO<sub>2</sub>e

## 3. ILC 250GeV

Arched 9.5m span  
Japan

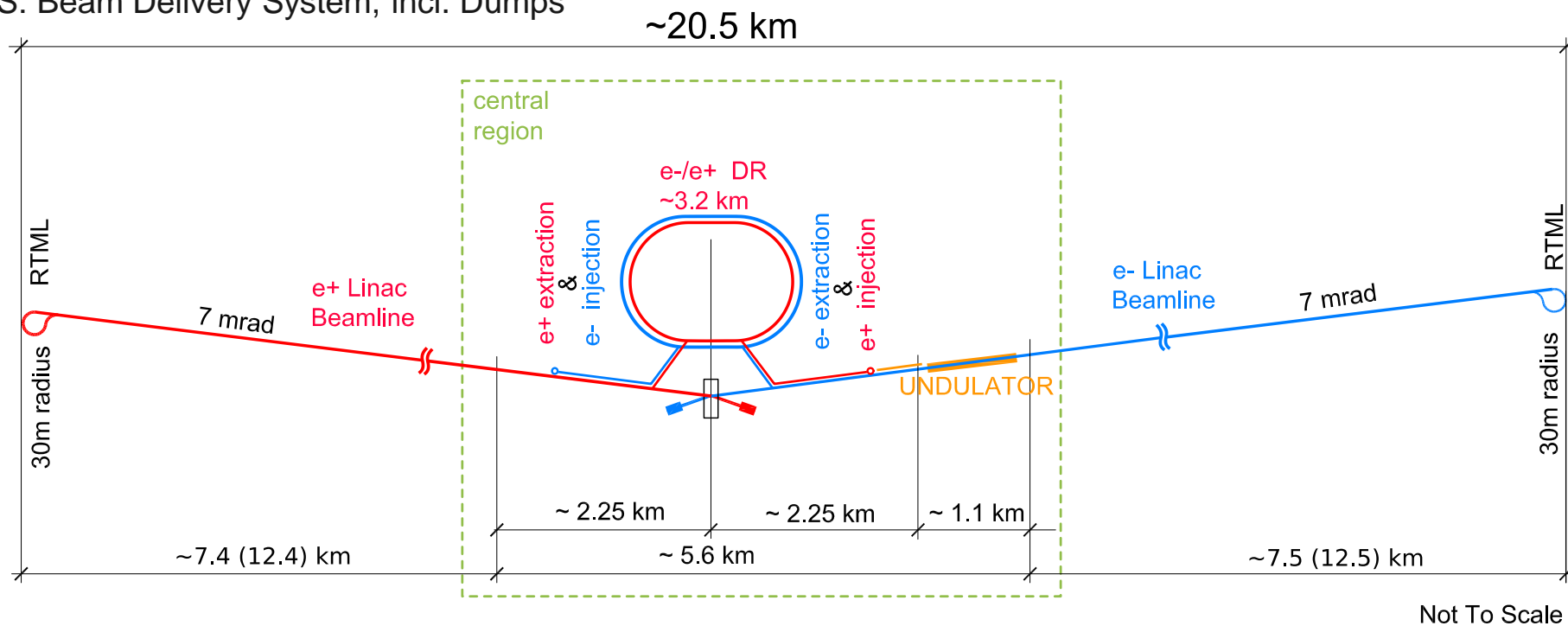


Total A1-A5 GWP: 266000 tCO<sub>2</sub>e



# Accelerator Areas

- ES: Electron Source
- PS: Positron Source
- DR: Damping Rings
- RTML (Ring to Main Linac, i.e. transport line)  
incl. Bunch Compressors
- ML: Main Linac
- BDS: Beam Delivery System, incl. Dumps



# Niobium Material

## Niobium Mining

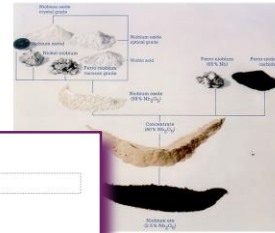
- Yearly production (2021): 75 kt [1]
- Known reserves (2021): > 17 Mt [1]
- > lasting > 226y
- Biggest Supplier: Brazil (90%)
  - CBMM, Araxá mine
- Products: 90% NbFe, 10% Nb<sub>2</sub>O<sub>5</sub>



[1] USGS 2022, <https://pubs.usgs.gov/periodicals/mcsa2022/mcsa2022-niobium.pdf>

DESY: Benno List | Cryomodule LCA

## Niobium



- Raw material production:
  - Ore (~2.5% Nb<sub>2</sub>O<sub>5</sub>) to FeNb or Nb<sub>2</sub>O<sub>5</sub>
  - FeNb: used as alloy component for steel
  - Nb<sub>2</sub>O<sub>5</sub>: used in glass for optical lenses and starting point for Nb metal production
  - Reduction of Nb<sub>2</sub>O<sub>5</sub> with aluminum to get pure Niobium

Page 4

## ATR Niobium Production

Click to add text

- ATR: Aluminothermic Reaction: Reduce Niobium Pentoxide to pure Niobium
- LCA of Nb<sub>2</sub>O<sub>5</sub> available: L. Da Silva Lina et al., J. Clean. Prod. 348 (2022) 131327, DOI:10.1016/j.jclepro.2022.131327
- Aluminothermic reaction: from stoichiometry: 0.484kg Al + 1.431kg Nb<sub>2</sub>O<sub>5</sub> -> 1kg Nb
- Unknown: efficiency of process
- Assuming 16.8kg CO<sub>2</sub>-eq from Al results in 14.9 kg CO<sub>2</sub>-eq per kg ATR-Nb



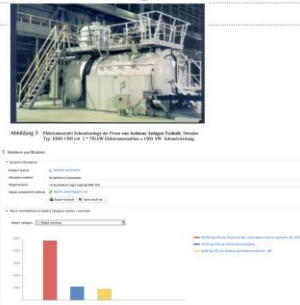
CAVEAT: Aluminum GWP very uncertain

DESY: Benno List | Cryomodule LCA

## Niobium Refinement by Electron Beam Melting

Click to add text

- Production of RRR300 material: Remelting of ATR-Niobium in electron beam oven
- Typical procedure: remelt 6 times -> 67kWh of electric power per kg of final product, 75.2% overall efficiency (AIP CP 927(2007)165)
- > assuming a German electricity mix, this results in 68.0kg CO<sub>2</sub>-eq per kg of final RRR-300 Niobium!



CAVEAT: Uses unrealistic dirty electricity mix for Germany with 719g CO<sub>2</sub>-eq / kWh -> about 3 times too high

DESY: Benno List | Cryomodule LCA

## Niobium Refinement by Remelting

- Pure niobium:
  - aluminothermic reduction of Nb<sub>2</sub>O<sub>5</sub> -> "ATR niobium"
  - Carbon footprint of Nb dominated by aluminium needed here
  - My estimate: ~11 kg CO<sub>2</sub>-eq / kg Nb
  - Niobium is refined by remelting in vacuum electron beam furnace
  - Takes ~10kWh/kg per step



FIGURE 1. CBMM electron beam furnace 1 and 2.

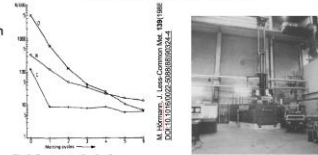


Fig. 3. Gas contents, C, O, Si, Cu, as a function of the number of melting cycles.



Fig. 4. Electron beam melting furnace: -160x160x160mm, 3000-30000VA

DESY: Benno List | Cryomodule LCA

Problem for this work:

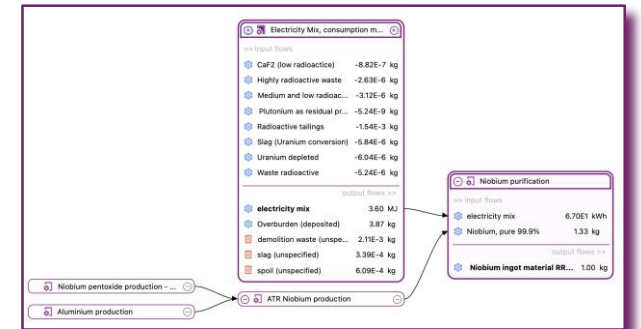
LCA data for some materials does not exist -> here: niobium

No impact assessment data for high-purity ("RRR300") niobium available (?)

Even for 99% pure niobium, data seems not exist? – could not check ecoinvent

Research reveals good description of niobium processing

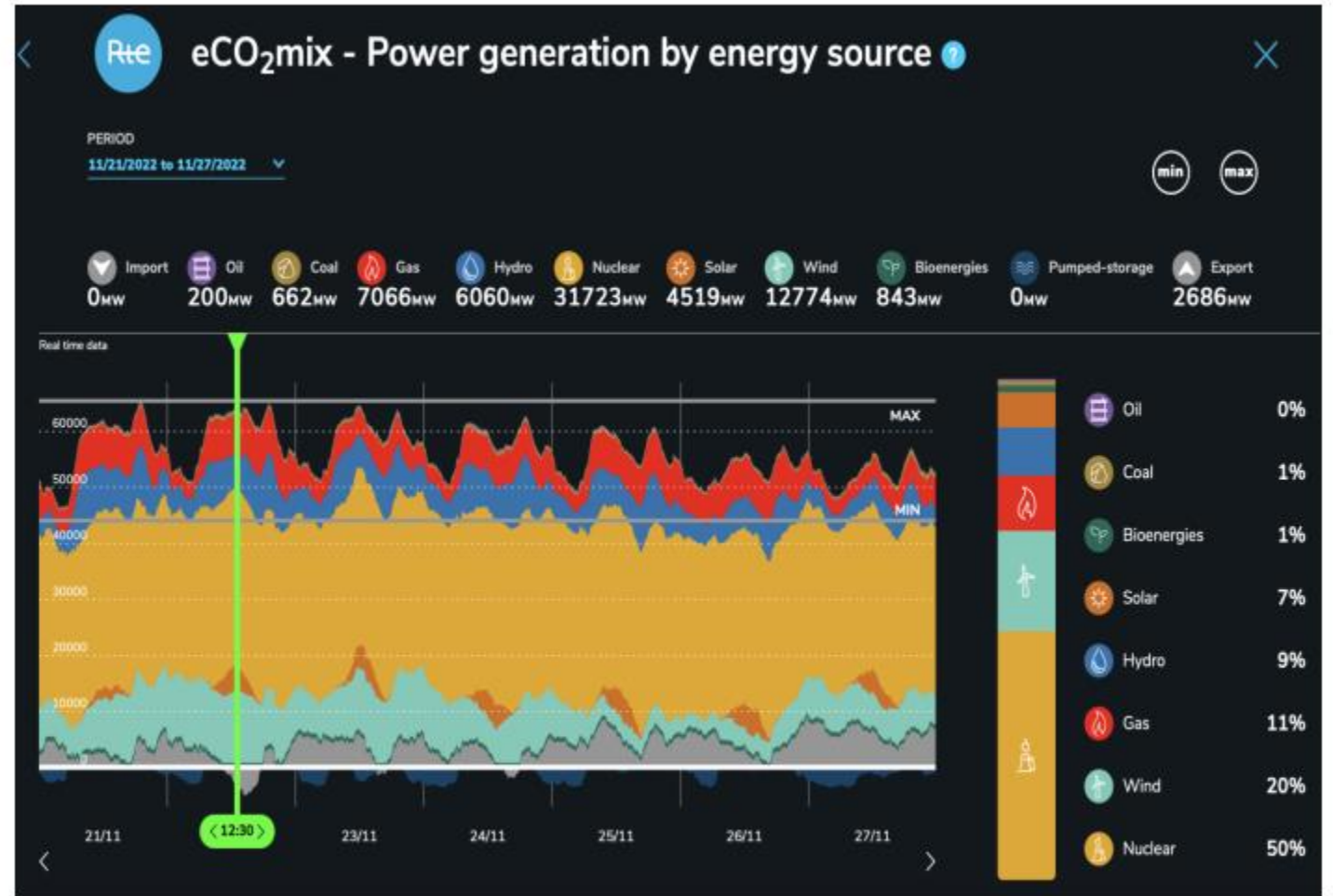
-> has been implemented in OpenLCA



ILC center futuristic view



# Sustainable Operation



Different strategies to offset or reduce the energy consumption with higher efficiencies, sustainable sources and running when energy production peaks