Lifecycle Inventory Input to an LCA for ILC and CLIC

Steffen Doebert on behalf of the CLIC/ILC Sustainability Team

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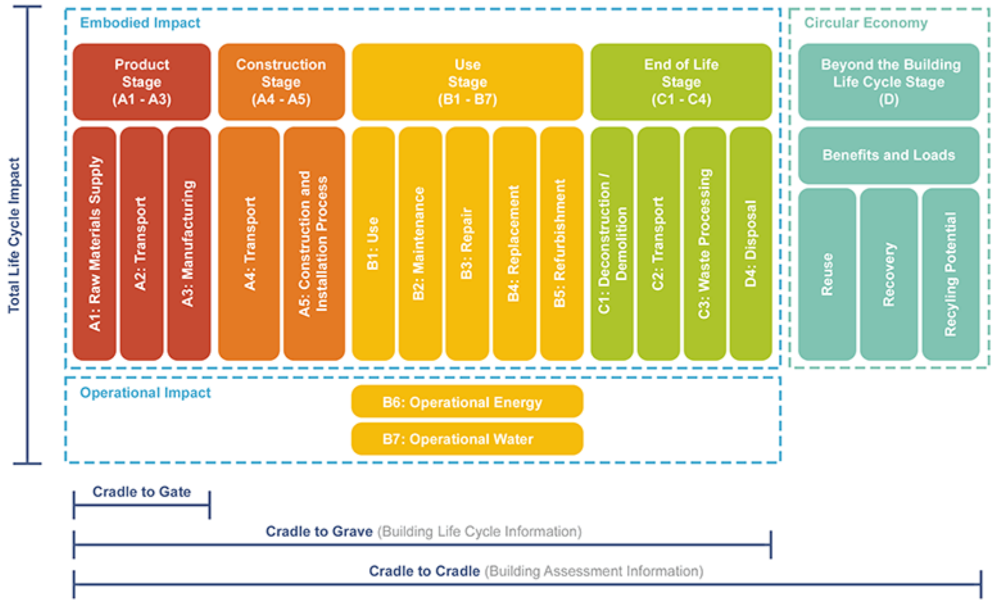
Introduction

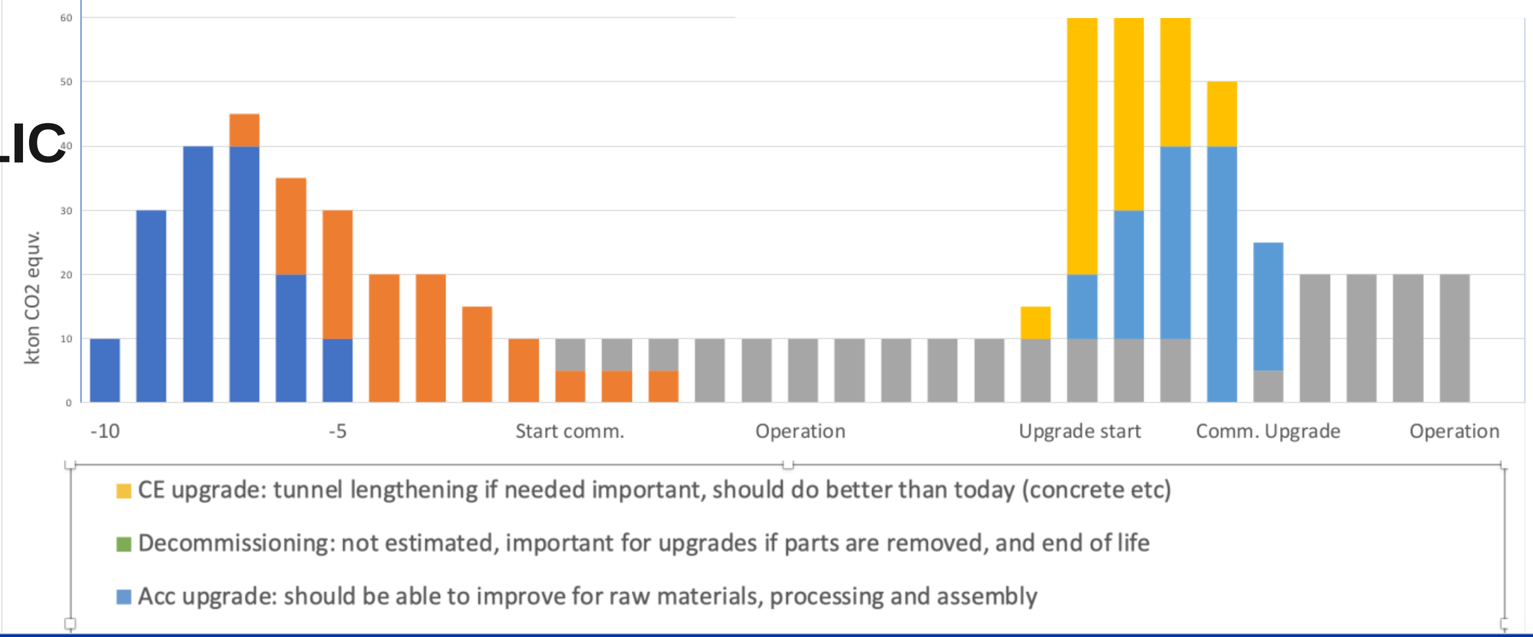
Ultimate Goal:
Quantify the environmental impact of a whole accelerator project, i.e., CLIC and ILC

Accepted method:
LCA = Life Cycle Assessment

CLIC and ILC will conduct such an assessment together with ARUP

Will talk mainly about CLIC



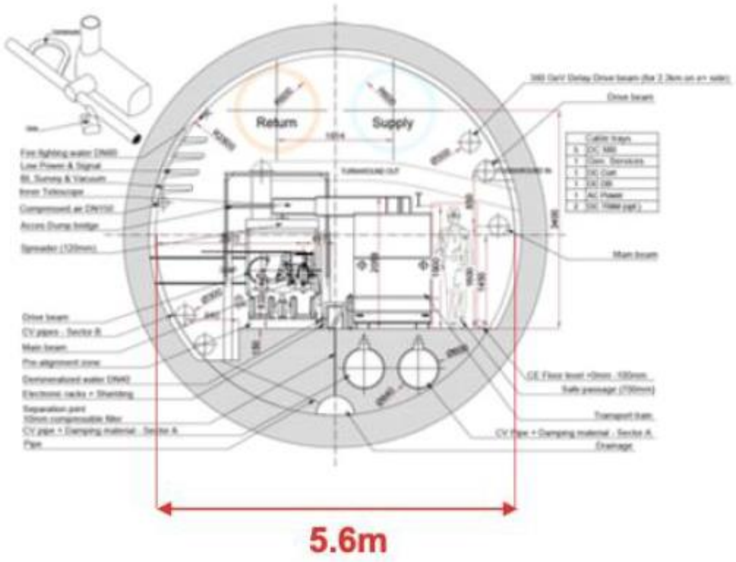


The Tunnel

LCA study for the accelerator tunnel

1. CLIC Drive Beam

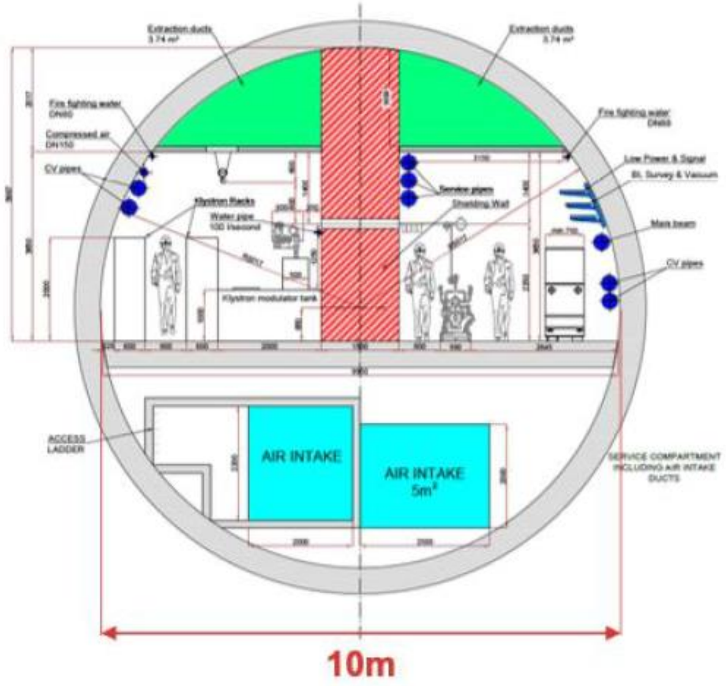
5.6m internal dia. Geneva.
(380GeV, 1.5TeV, 3TeV)



Reference: CLIC Drive Beam tunnel cross section, 2018

2. CLIC Klystron

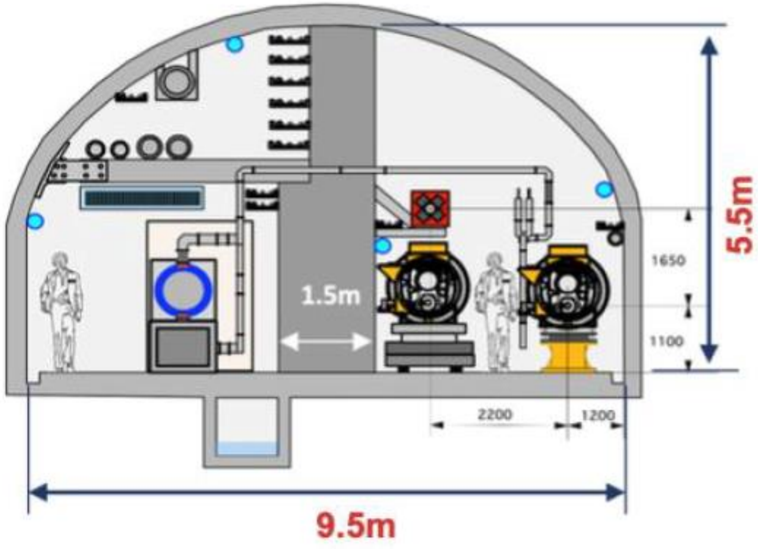
10m internal dia. Geneva.
(380GeV)



Reference: CLIC Klystron tunnel cross section, 2018

3. ILC

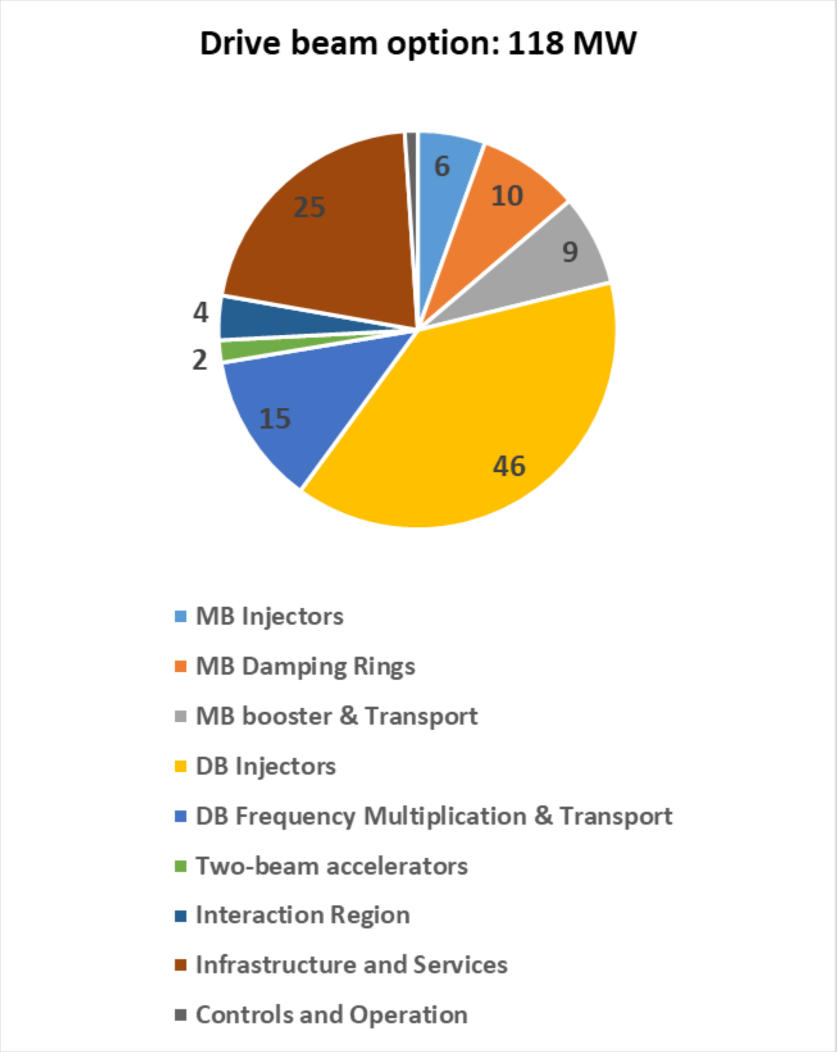
Arched 9.5m span. Japan.
(250GeV)

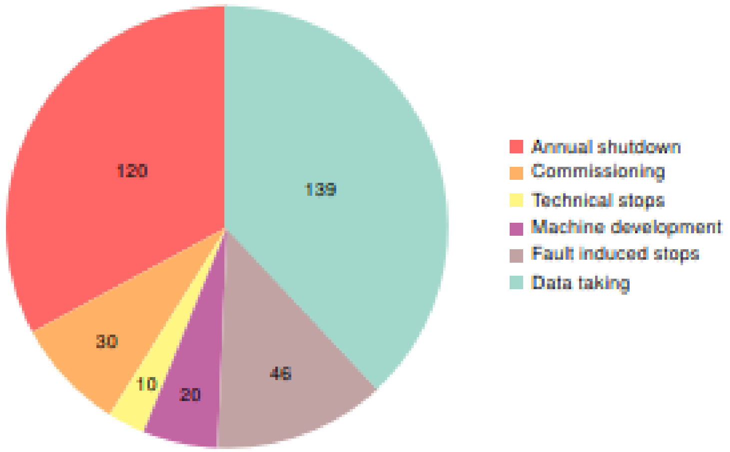


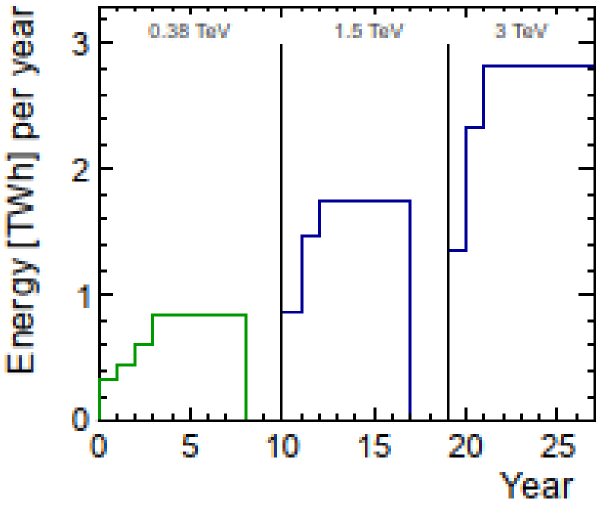
Reference: Tohoku ILC Civil Engineering Plan, 2020

Energy consumption during operation

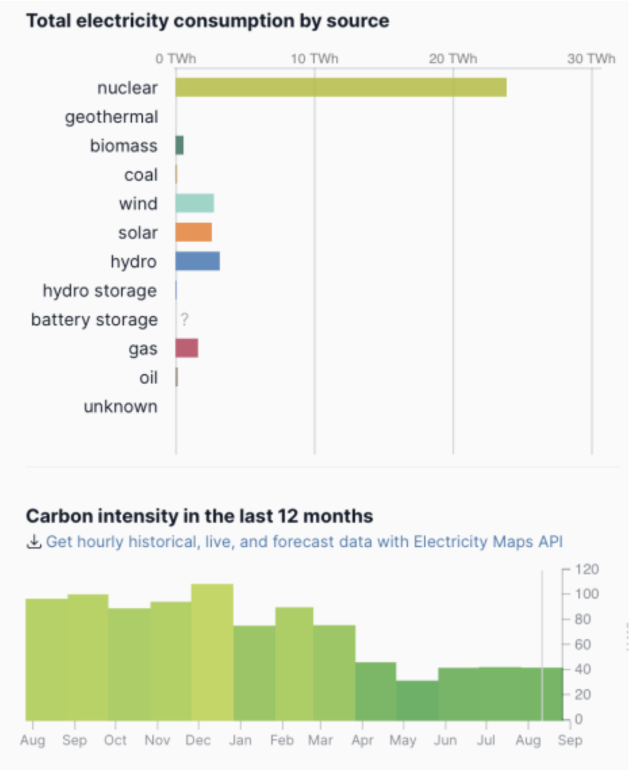
CLIC power and energy consumption







From energy to CO2 – in 2040-50

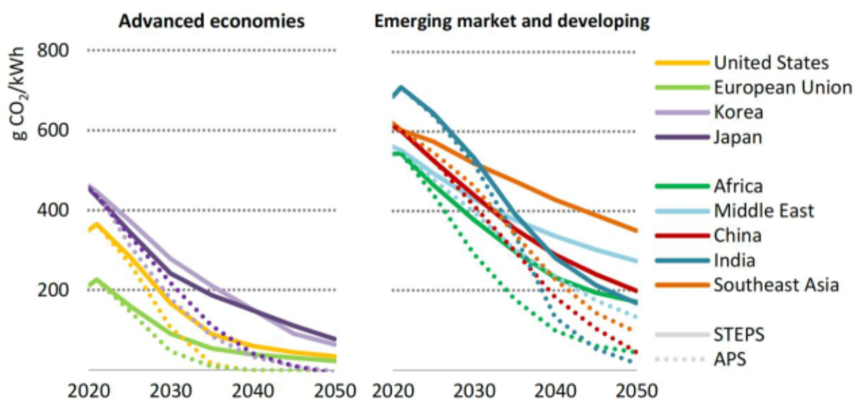


From: https://app.electricitymaps.com/zone/FR
Contains also g/kWh per source

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_2 intensity of electricity generation for selected regions by scenario, 2020-2050



IEA. CC BY 4.0.

CO_2 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

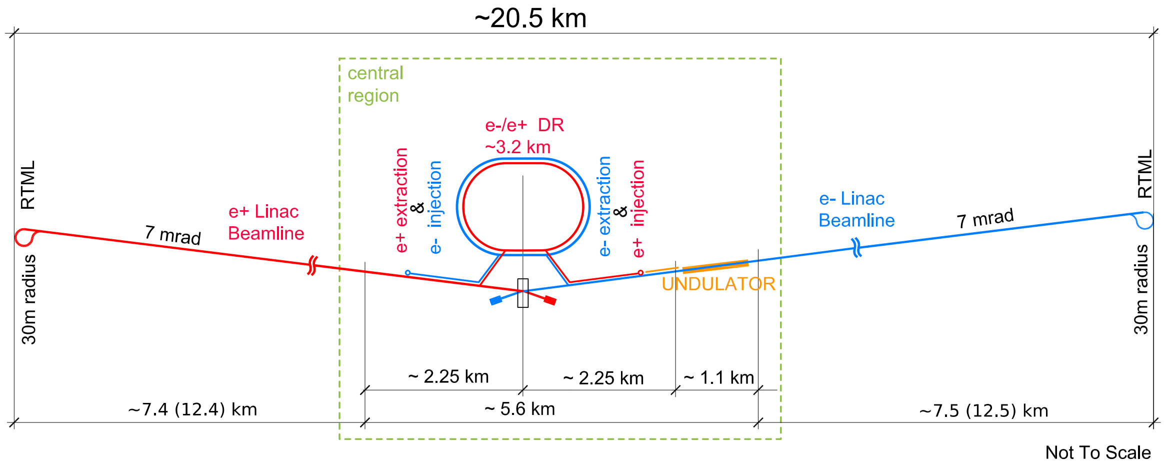
Material	Density (g/cm3)	GWP (kg CO2-eq/kg)
Cement	1.4	1.0 [3]
Concrete	2.5	0.1 [3]
Mild Steel	7.85	1.7
Stainless Steel (18%Cr, 10%Ni)	7.85	3.7 [1]
Copper	8.96	2.5
Aluminium	2.70	8.2 [2]
Titanium	4.5	8.1 [2]
Silicon Carbide	3.2	--

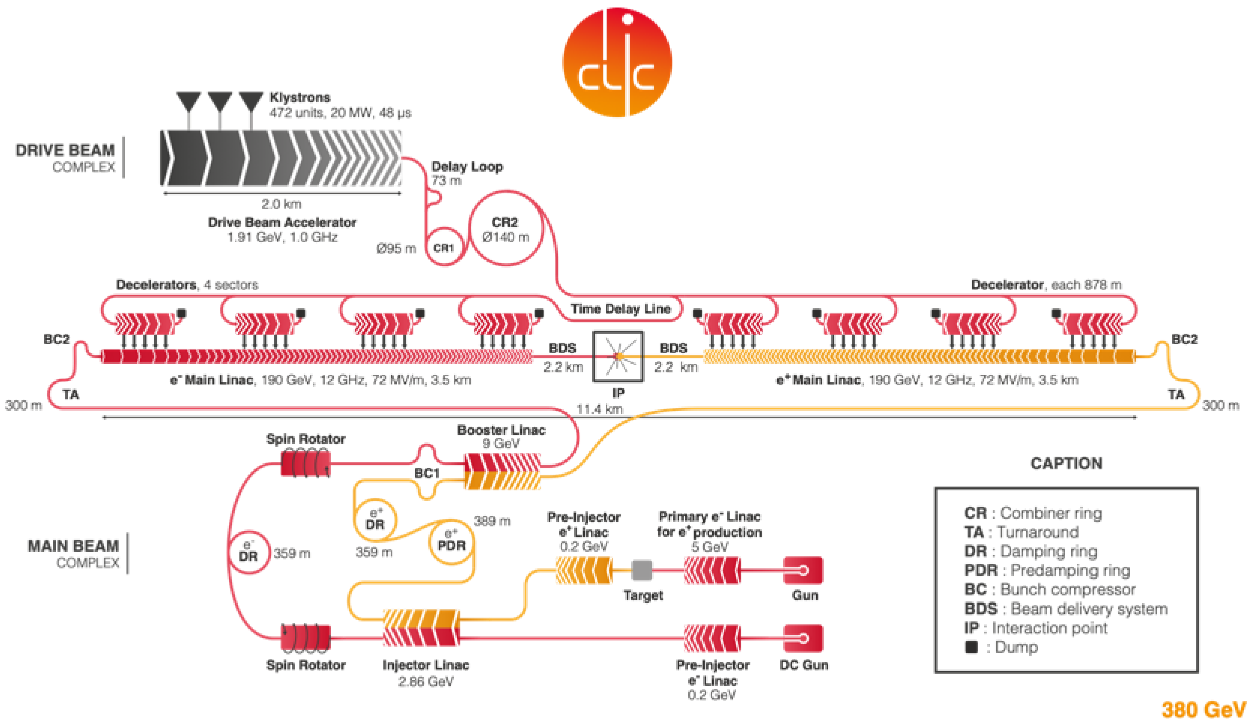
1. Eurofer LCI for 316 cold rolled coil steel
2. Nuss and M. J. Eckelman, PLoS ONE 9 (2014) e101298. DOI:10.1371/journal.pone.0101298. CC-BY
3. T. Hottle et al., *Environmental life-cycle assessment of concrete produced in the United States*, J Cleaner Prod. 363 (2022) 131834, DOI:10.1016/j.jclepro.2022.131834

Notes

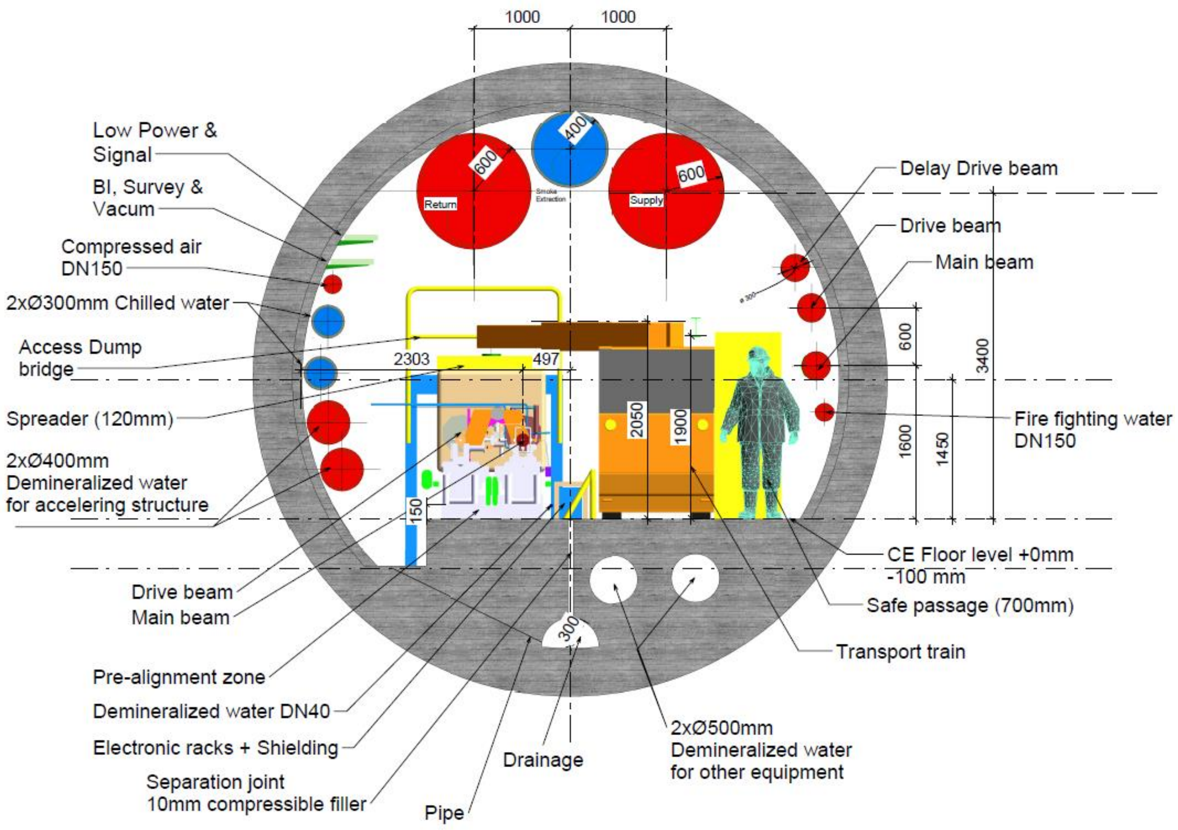
1. GWP: Global Warming Potential (over 100 years), expressed in kg CO2 eqivalent
2. All numbers for GWP vary by factors of 2 or more, depending on country of origin, production method, energy mix, transport ways etc

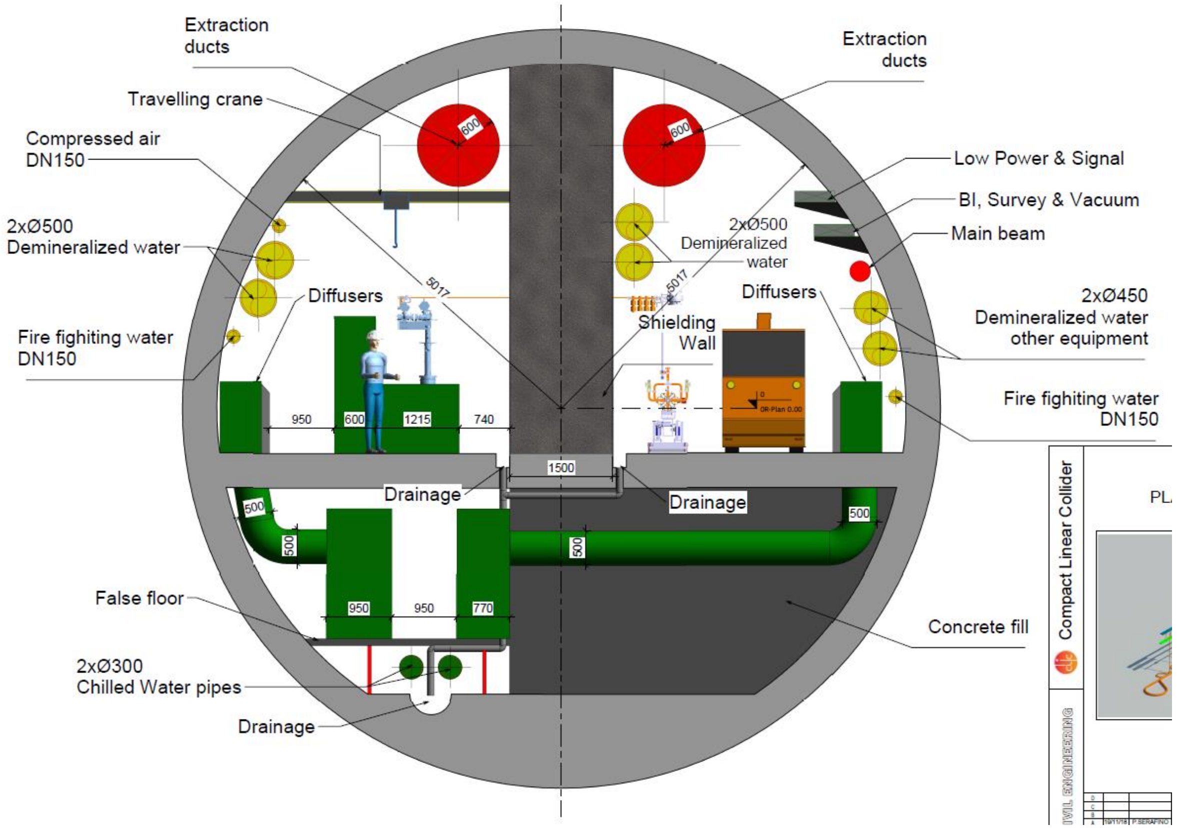
CLIC and ILC layouts



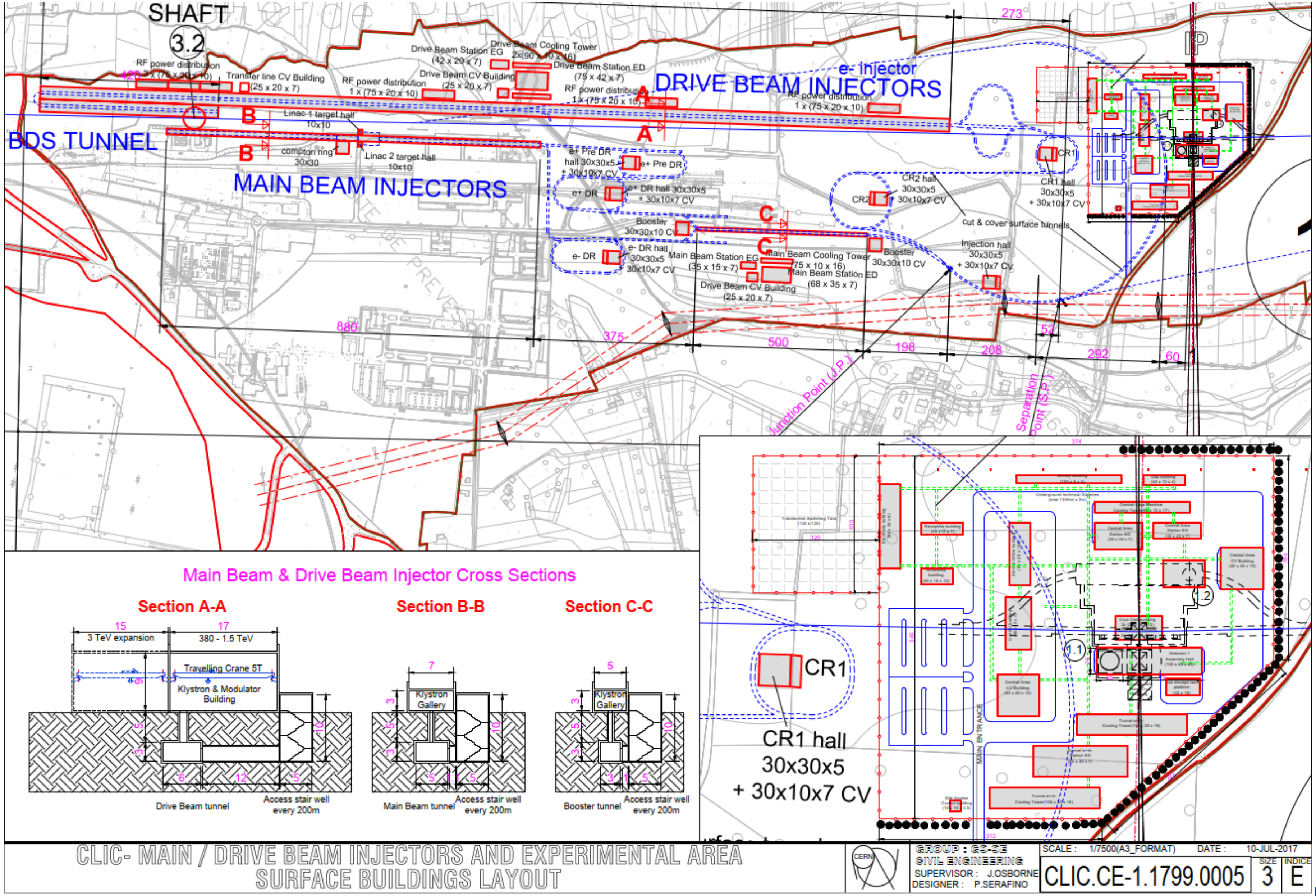


Tunnel Cross Sections





Zoom into the injectors



CLIC 380 GeV Two beam area breakdown

Sub-system	Components
Drive beam injector complex and transfer to ML tunnel	
	DB linac module (suppports,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 decelrators/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

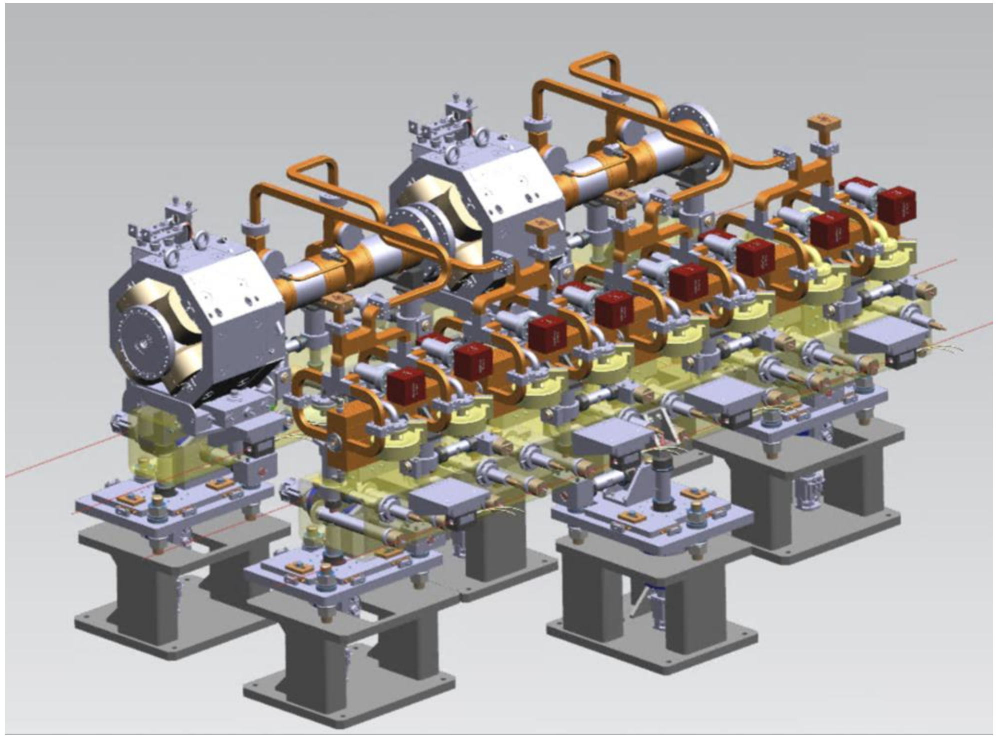
ILC area breakdown

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

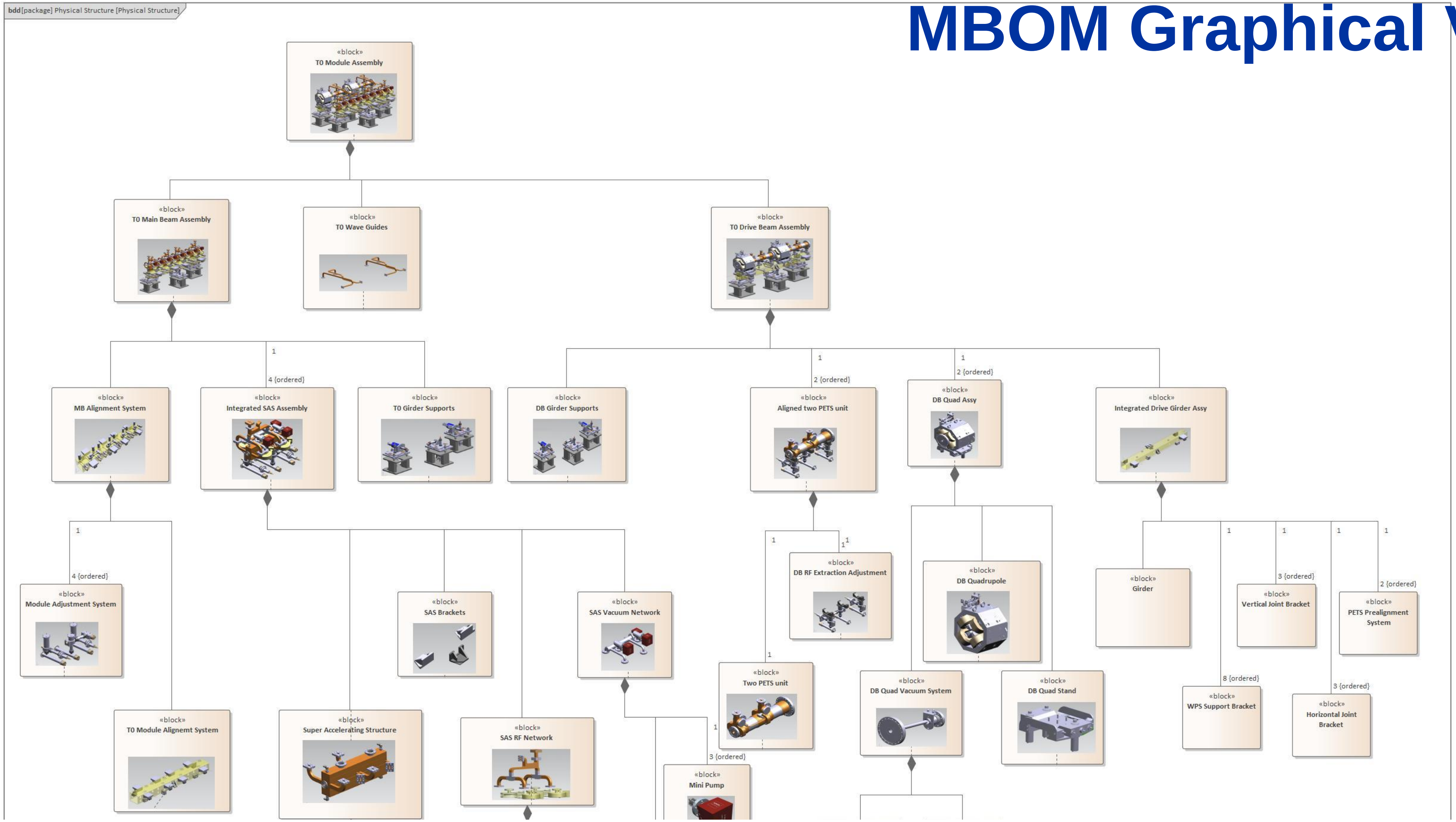
Evaluating the GWP of the Accelerator: The Two Beam Module

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



Breakdown according to Material

“Mild Steel”: Mostly Support System

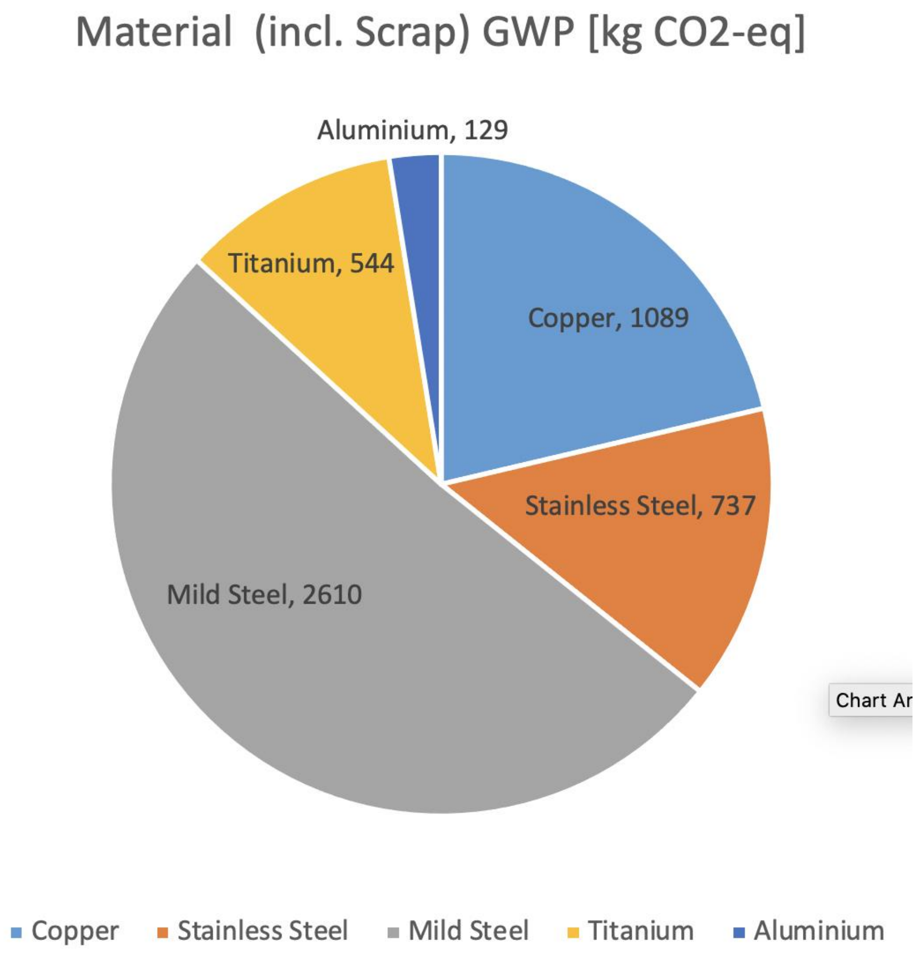
Conclusion here:

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

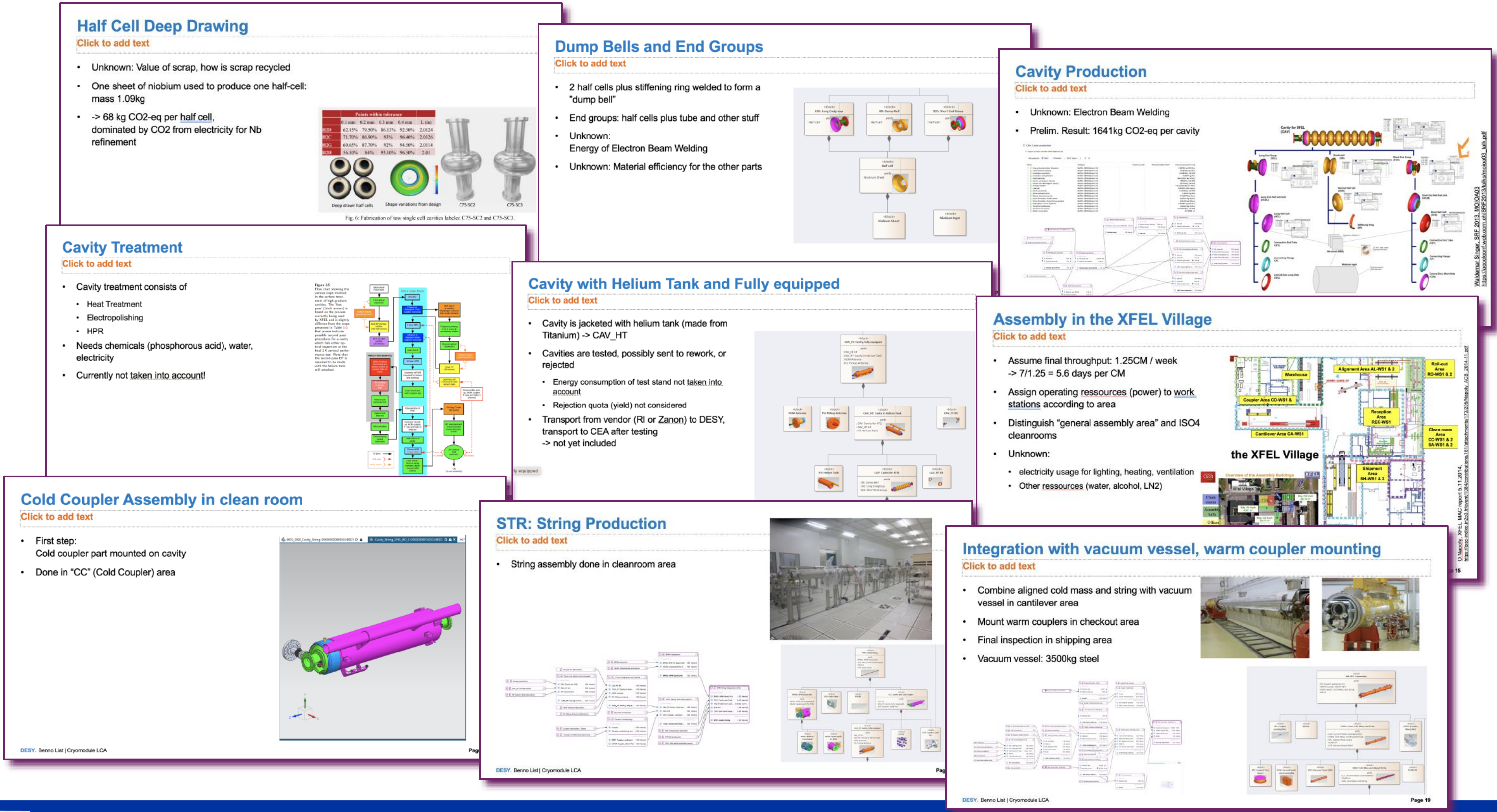
For large scale production:

Cast iron may be interesting

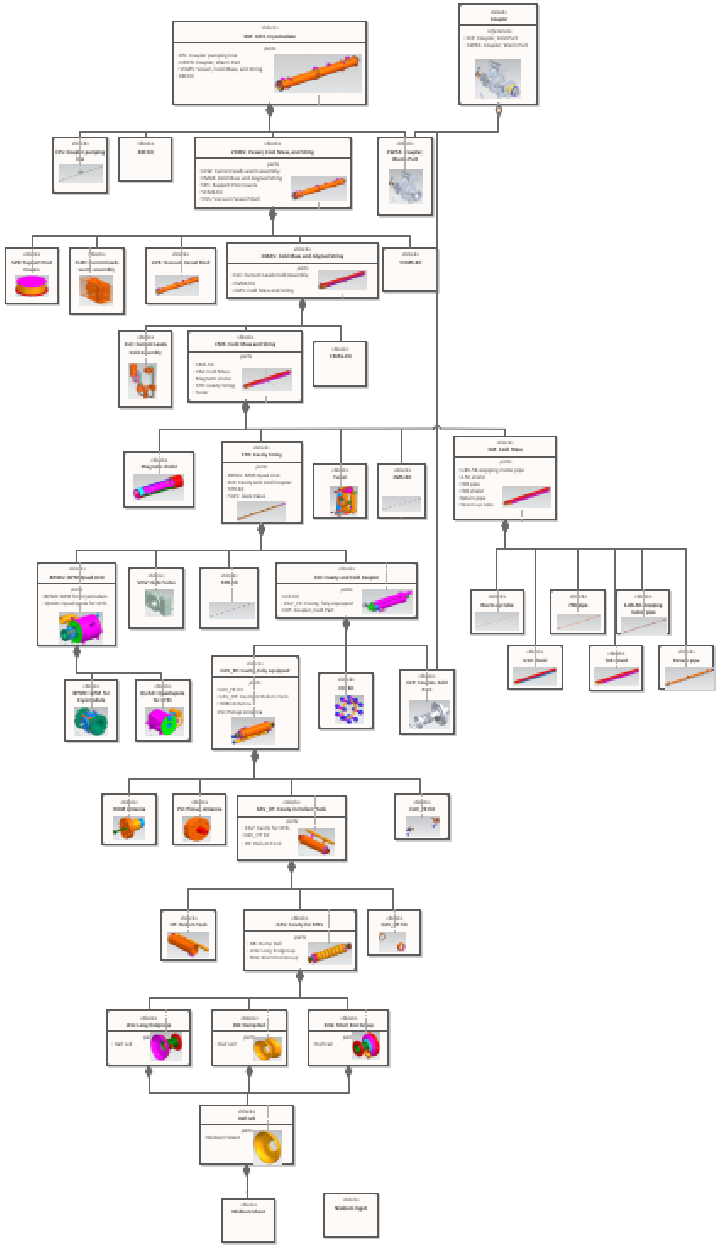
- **Reduced material carbon footprint**
- **Less scrap, less machining**



Cryomodule Production Steps

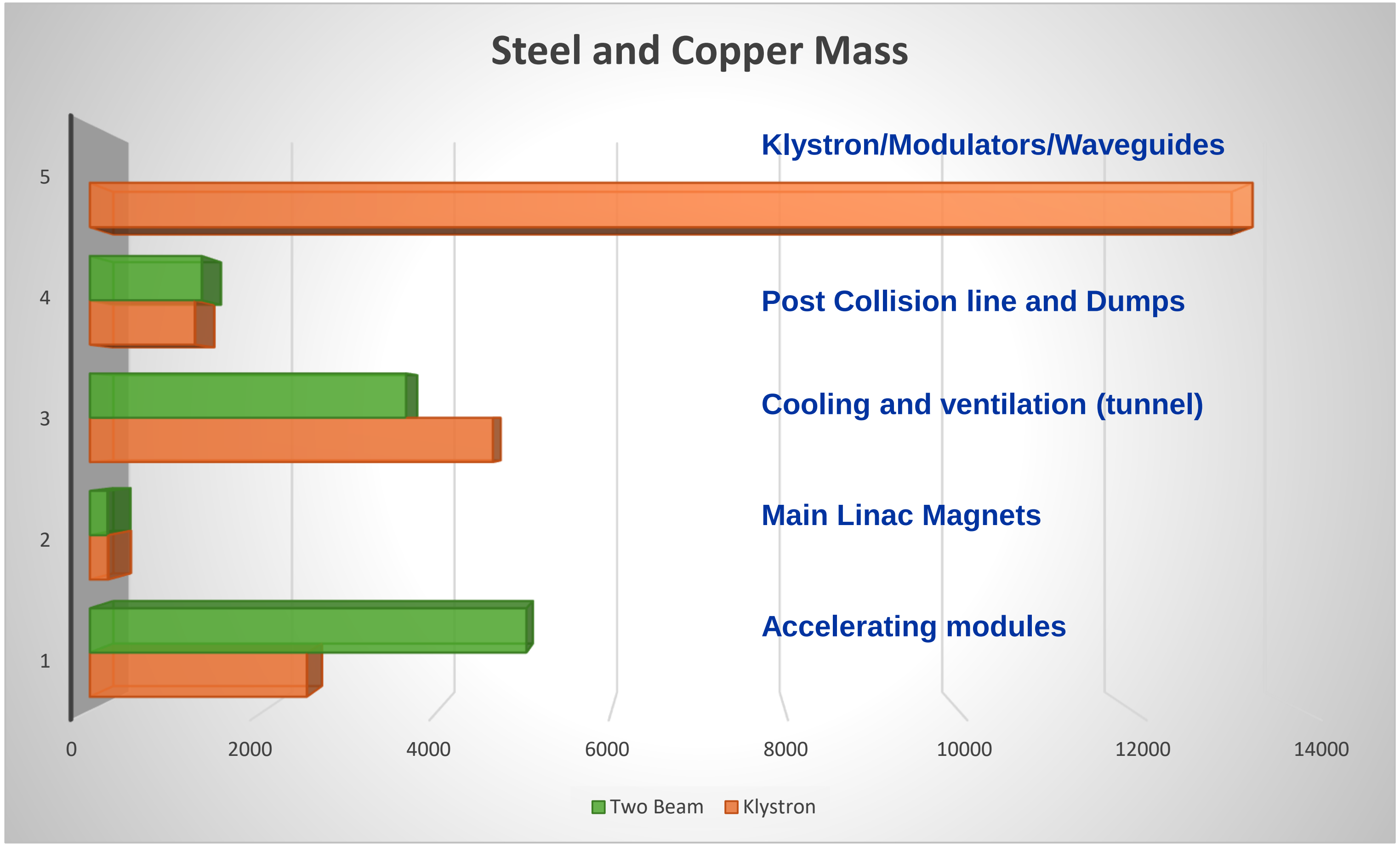


MBOM Graphical View



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

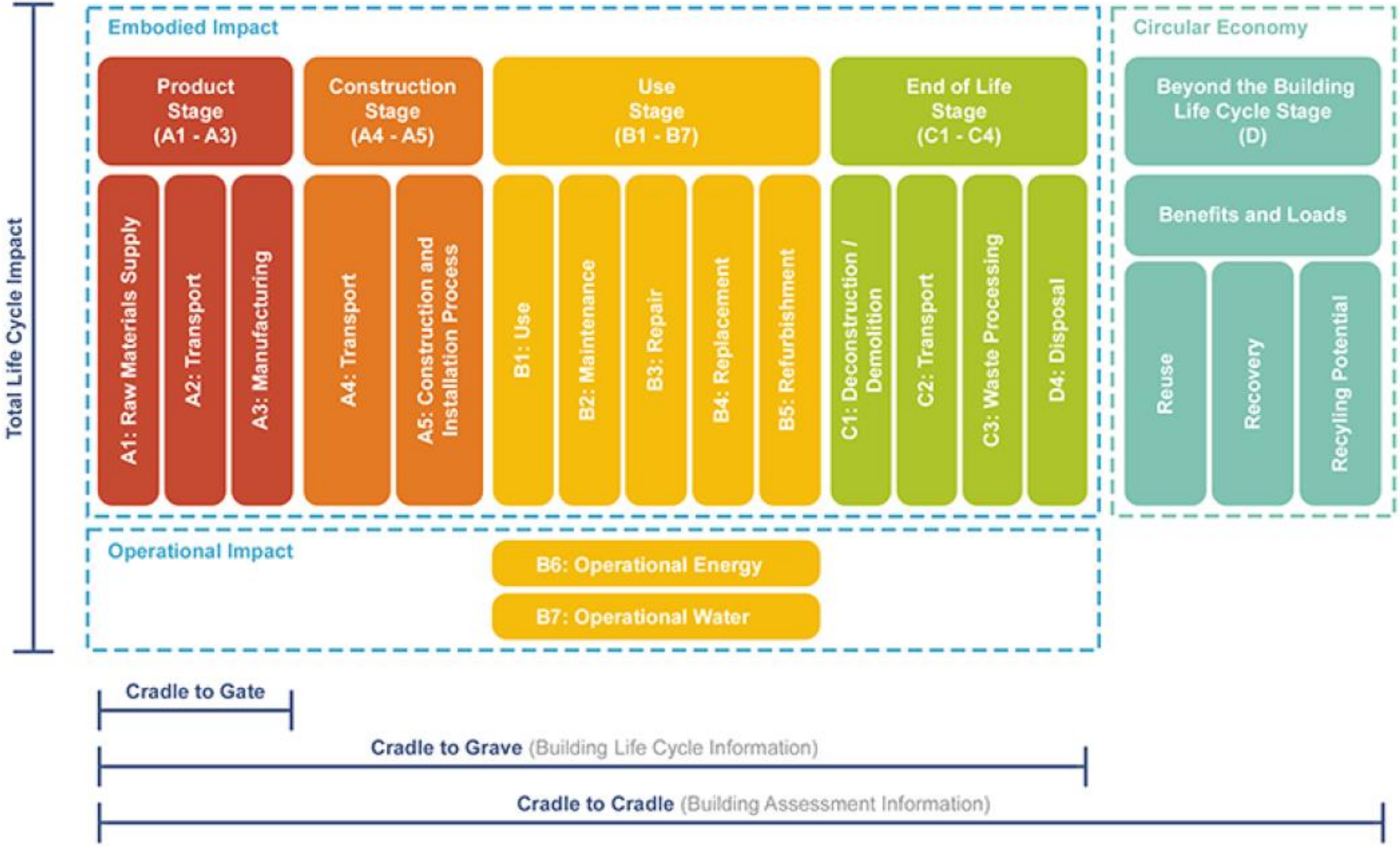
- Will give an indication of the true environmental impact, likely good for comparisons but still with large error bars
- Will help identifying hot spots and making engineering decisions

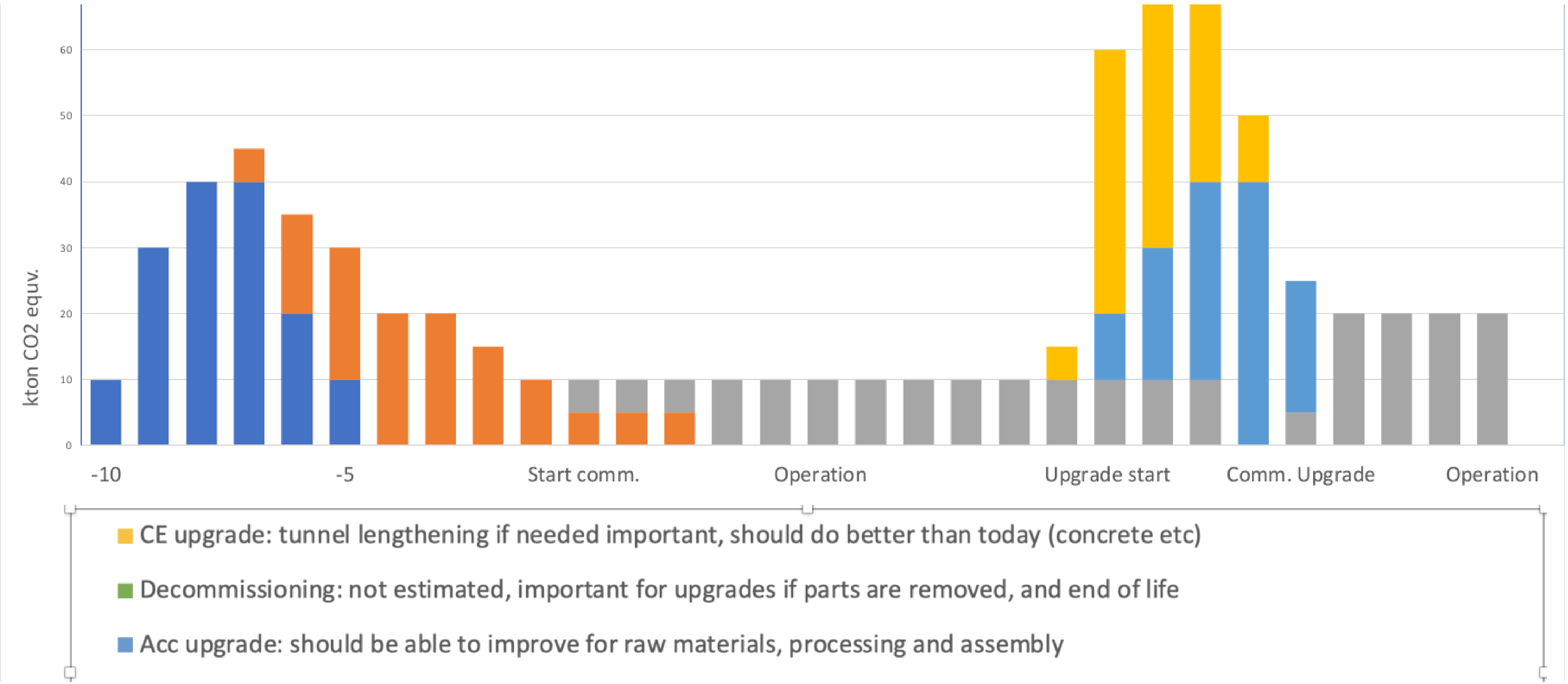
Preliminary conclusions

- Still a lot to do !

- CV infrastructure comparable to accelerator components
- Accelerator comparable to tunnel construction
- Accelerator supports are more important that 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


Total Life Cycle Impact
Embodied Impact
Product Stage (A1 - A3)
A1: Raw Materials Supply
A2: Transport
A3: Manufacturing
Construction Stage (A4 - A5)
A4: Transport
A5: Construction and Installation Process
Use Stage (B1 - B7)
B1: Use
B2: Maintenance
B3: Repair
B4: Replacement
B5: Refurbishment
End of Life Stage (C1 - C4)
C1: Deconstruction / Demolition
C2: Transport
C3: Waste Processing
D4: Disposal
Circular Economy
Beyond the Building Life Cycle Stage (D)
Benefits and Loads
Reuse
Recovery
Recyling Potential
Operational Impact
B6: Operational Energy
B7: Operational Water
Cradle to Gate
Cradle to Grave (Building Life Cycle Information)
Cradle to Cradle (Building Assessment Information)


kton CO2 equv.
60
50
40
30
20
10
0
-10
-5
Start comm.
Operation
Upgrade start
Comm. Upgrade
Operation
CE upgrade: tunnel lengthening if needed important, should do better than today (concrete etc)
Decommissioning: not estimated, important for upgrades if parts are removed, and end of life
Acc upgrade: should be able to improve for raw materials, processing and assembly

The T0 Module Data

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

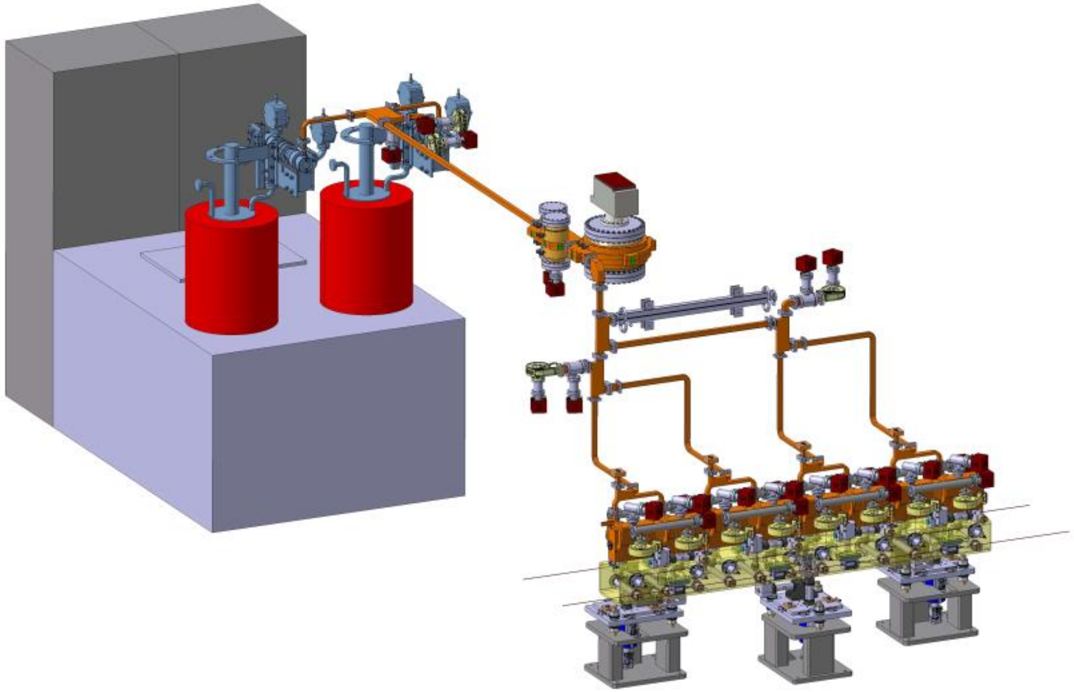
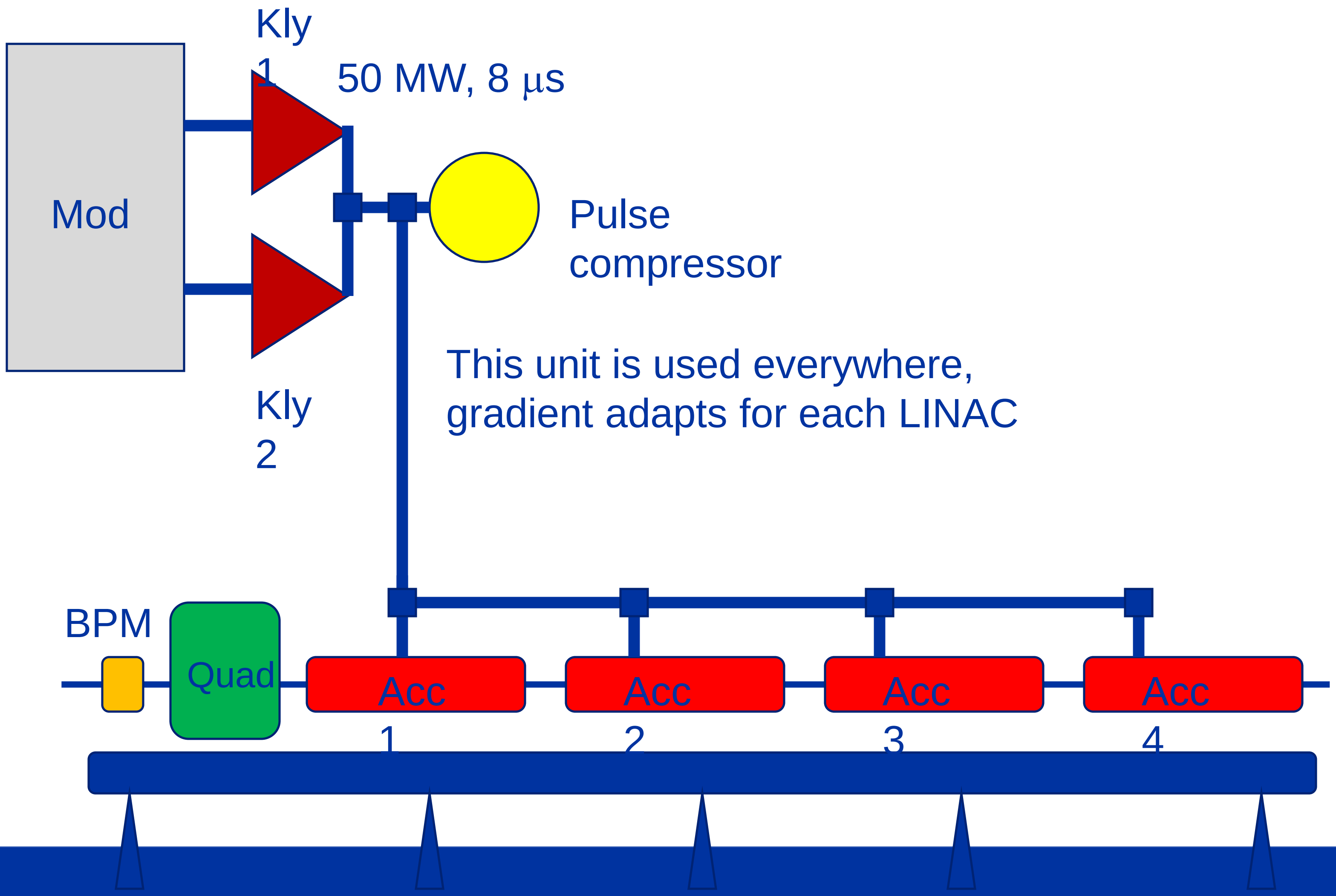


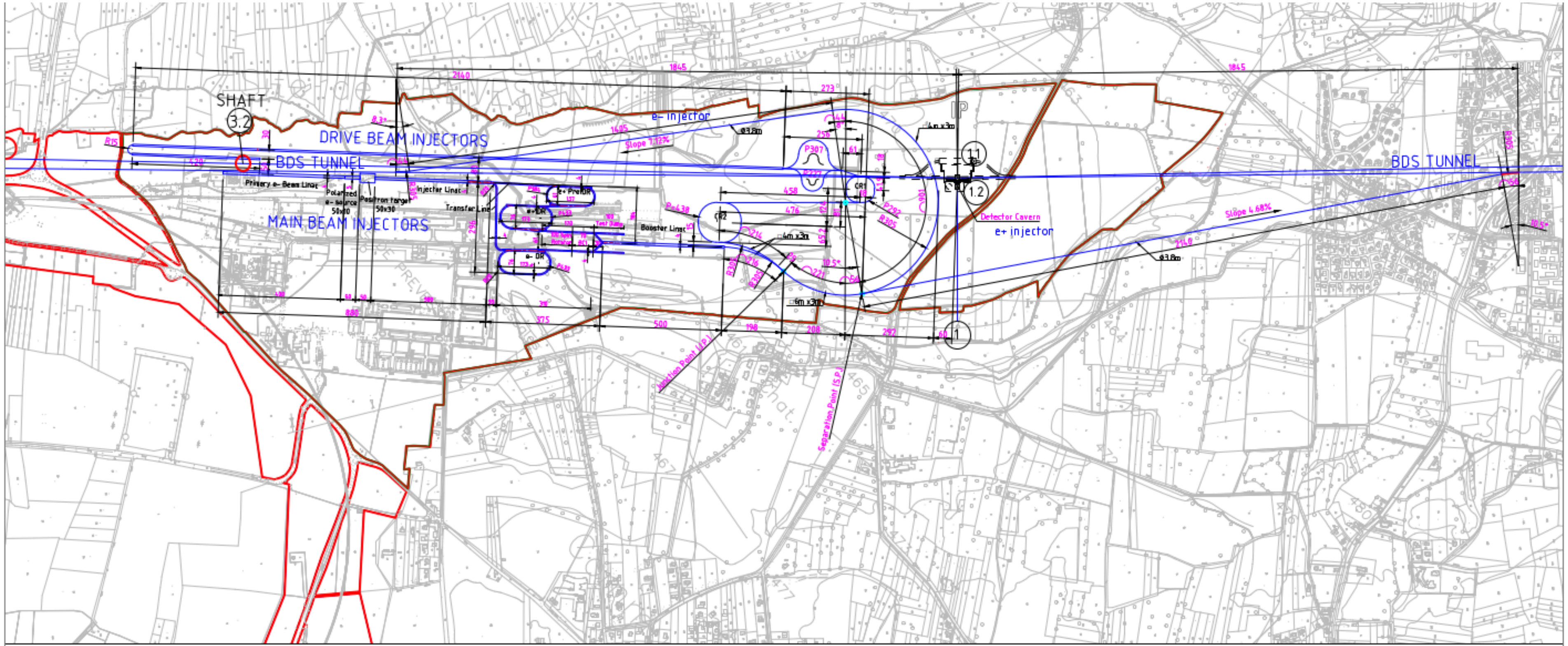
Figure 3: A CLIC Klystron Module

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	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	J.P. to S.P.	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	4x 3	4 x 3	4 x 3	6 x 3	4 x 3	ϕ 3.8	ϕ 3.8
Surface Buildings (l x w x h) m	2560 x 30 xh 9	-	-	30x30 x h 5	30x30 x h 5	-	-	400 x 7 x h 3	ComptonR. 30x30x h3	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

CERN

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 | SIZE 3 | INDICE L

CERN

Result for a T0 Module

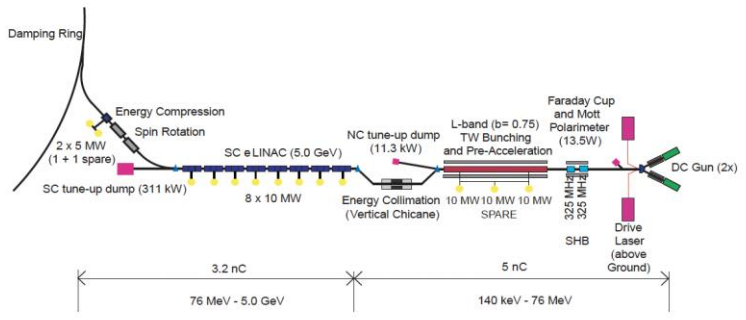
	Sum	Copper	Stainless Steel	Mild St	Titan	Alum
Main Beam Module & WG	906	155	114	583	45	9
T0 Drive Beam Assembly	871	159	22	686	0	5
Total mass (kg)	**1777**	**314**	**135**	**1269**	**45**	**14**
GWP/kg		2.5	3.7	1.7	8.1	8.2
Main Beam Module & WG: GWP (kg CO2-eq)	**2237**	388	421	991	363	74
T0 Drive Beam 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**

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**

Figure 4.1
Schematic view of the polarized Electron Source.



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**

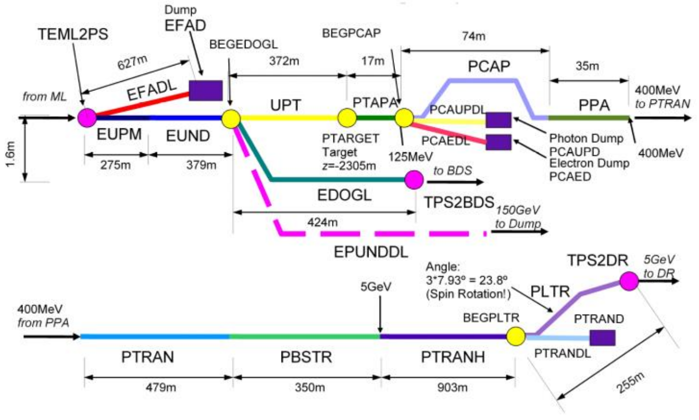
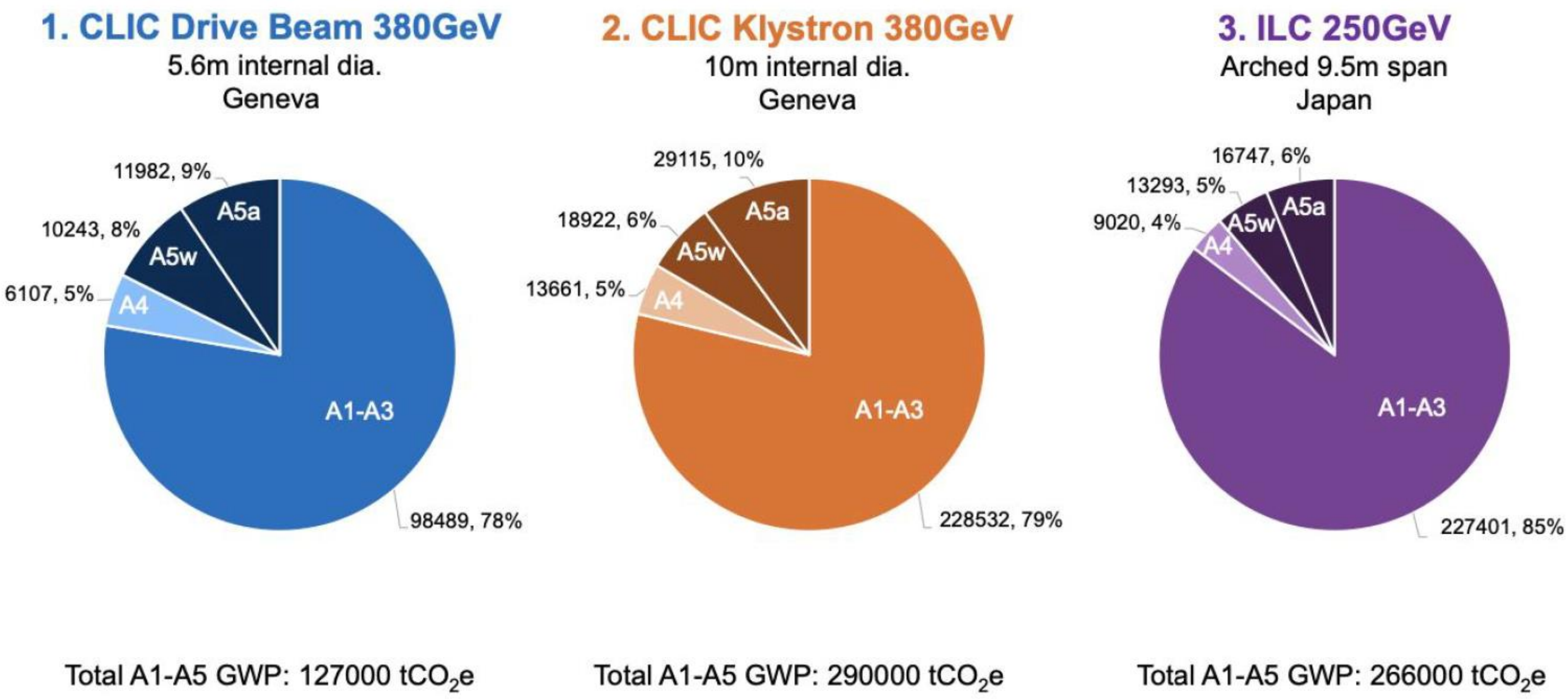


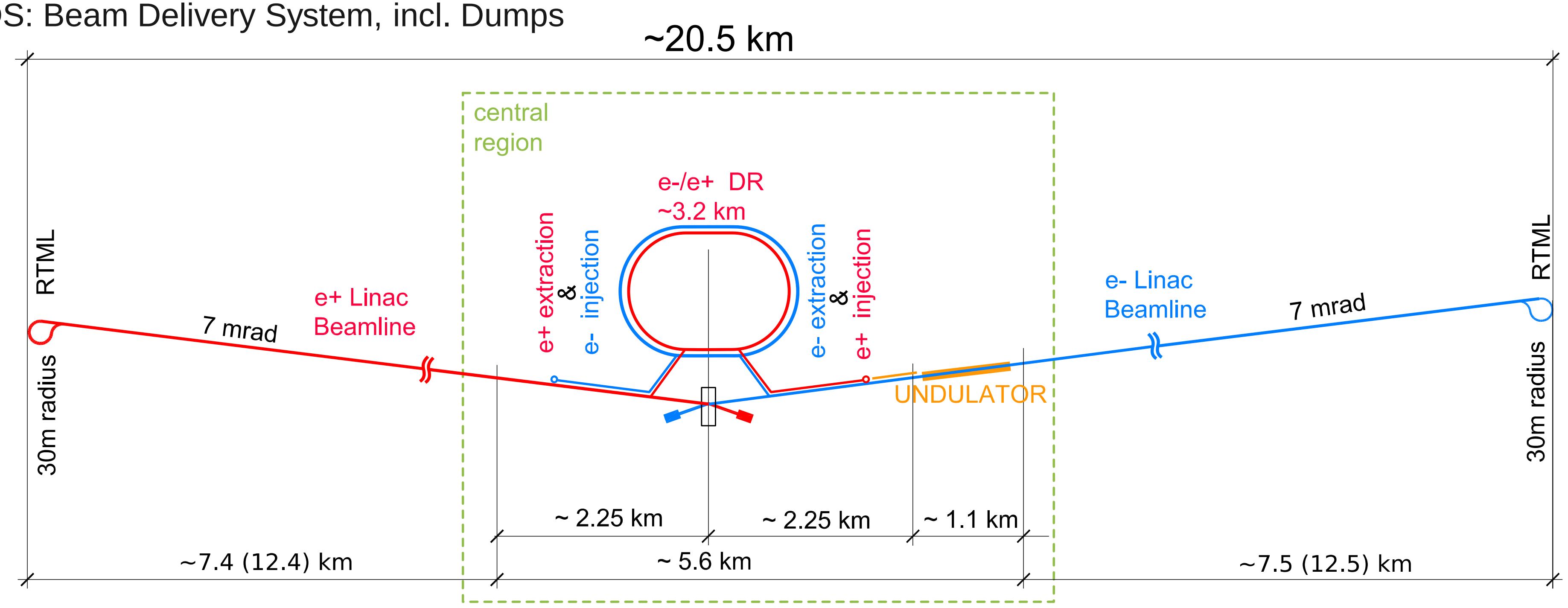
Figure 5.2. Positron Source beamlines cartoon

LCA study for the accelerator tunnel

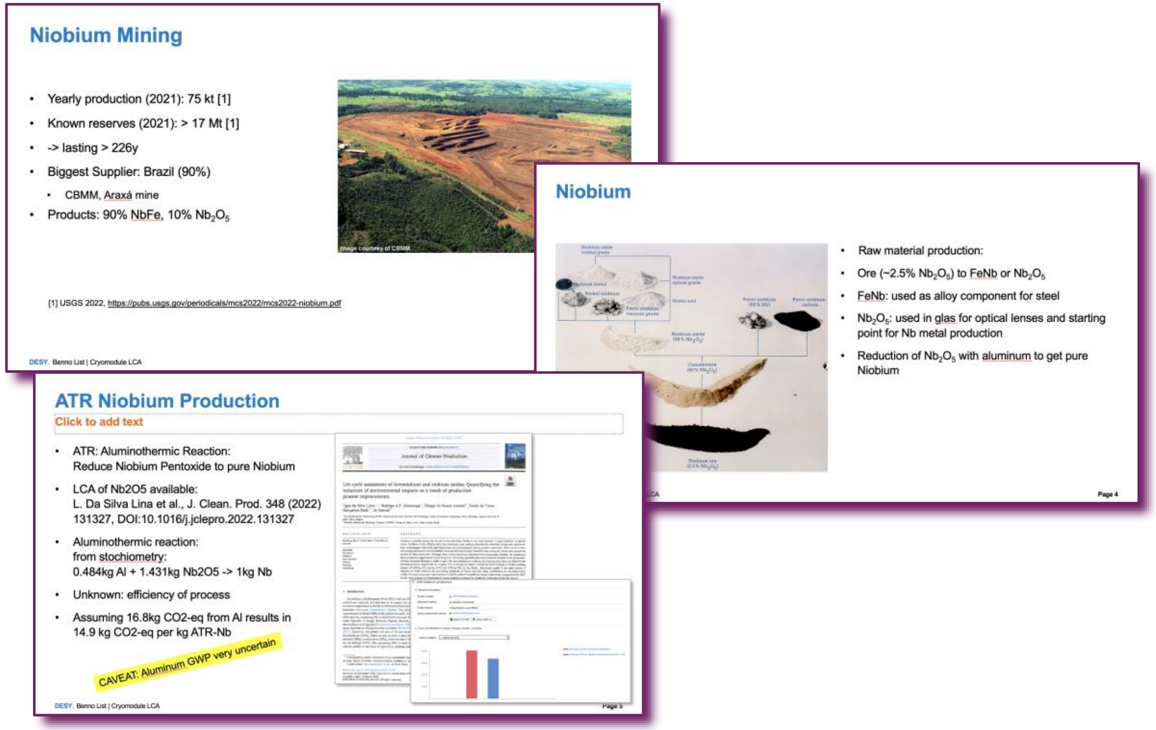


Accelerator Areas

- 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

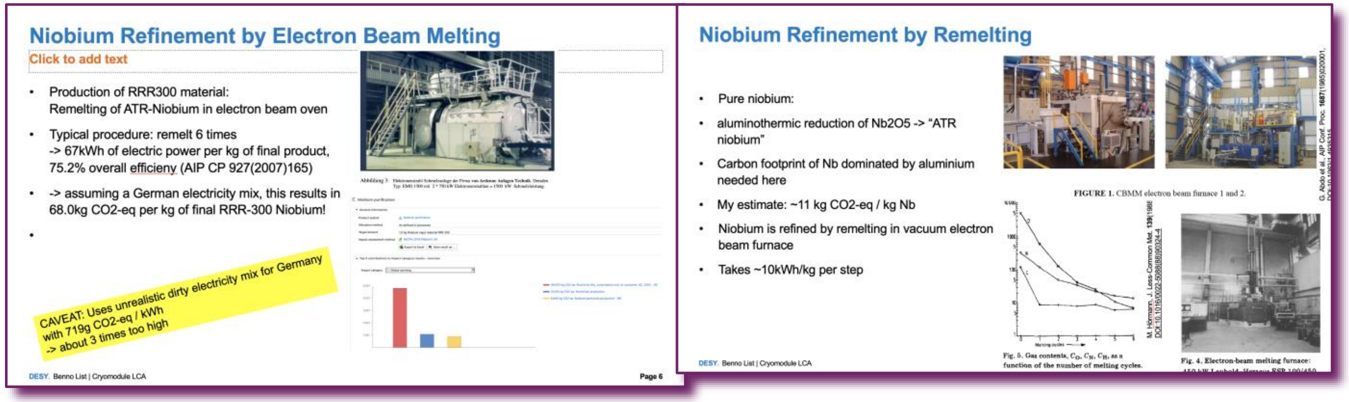


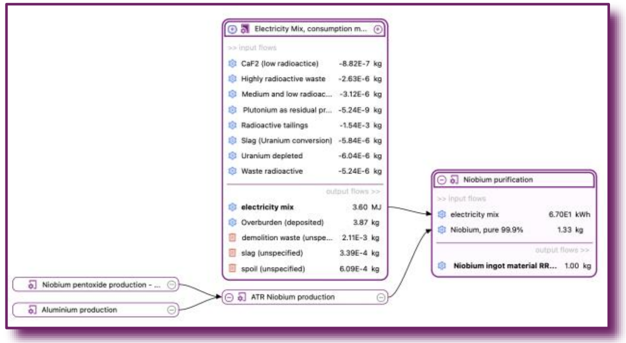
Problem for this work:
LCA data for some materials does not exist
-> here: niobium

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

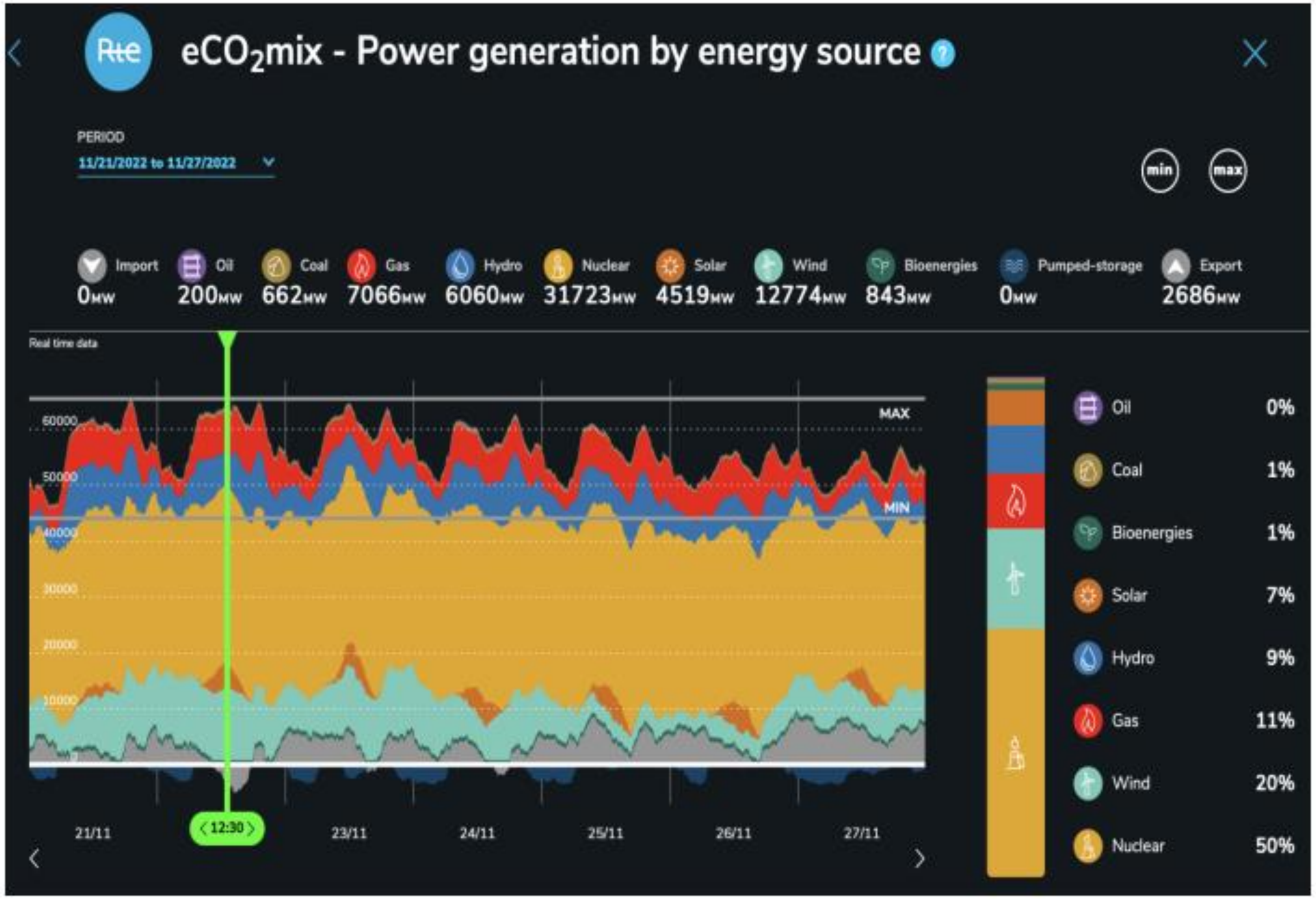
Even for 99% pure niobium, data seems not exist? – could not check ecoinvent

Research reveals good description of niobium processing
-> has been implemented in OpenLCA





Sustainable Operation



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