International Development Team

LCI Input to LCA Studies for ILC/CLIC

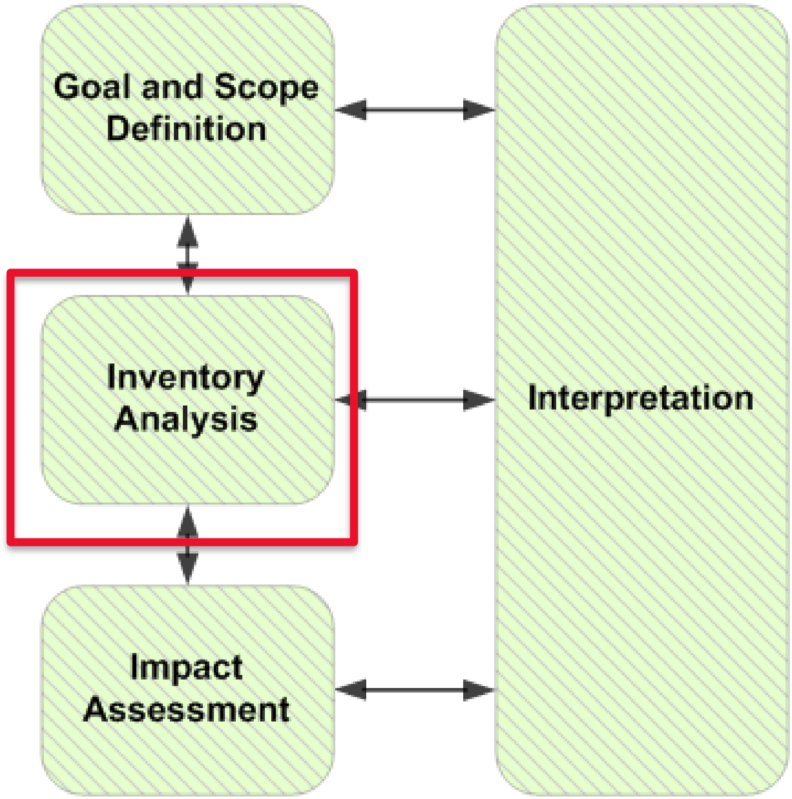
Benno List, DESY

LCA Phase 2 Workshop

Apr 9, 2024

Life Cycle Assessment Structure

- Inventory Analysis:
  Materials, Energy, waste, production process -> domain specific
  -> input from accelerator, detector and CFS experts, i.e. **us**
  - Tunnel/cavern/shaft dimensions & type
  - component types and numbers
  - Production of components
- Impact Assessment:
  -> ARUP



LCA Framework according to ISO 10040
Public Domain, https://commons.wikimedia.org/w/index.php?curid=40862556

ILC Overall Structure (towards a PBS)

- 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

- In TDR, costs and rollups were done in a matrix approach, with all technical systems for each accelerator area
- For TDR, no formal PBS was established
- Obvious approach:
  - 1st level – accelerator area
  - 2^{nd} level – technical system

- Technical Systems:
  - Civil Engineering
    - Civil Construction (“concrete2)
    - Technical infrastructure – water, power, HVAC
  - SCRF Cavities & Cryomodules (1.3GHz)
  - HLRF (High-Level RF: Klystrons, modulators…)
  - Other RF Systems (DR 650MHz system)
  - Cryogenics
  - Magnets and (magnet) Power Supplies (includes magnet stands / girders)
  - Vacuum
  - Instrumentation
  - Dumps & Collimators
  - “Area specific” (e.g. positron source target)
  - Controls & Computing
  - Installation

Accelerator Areas

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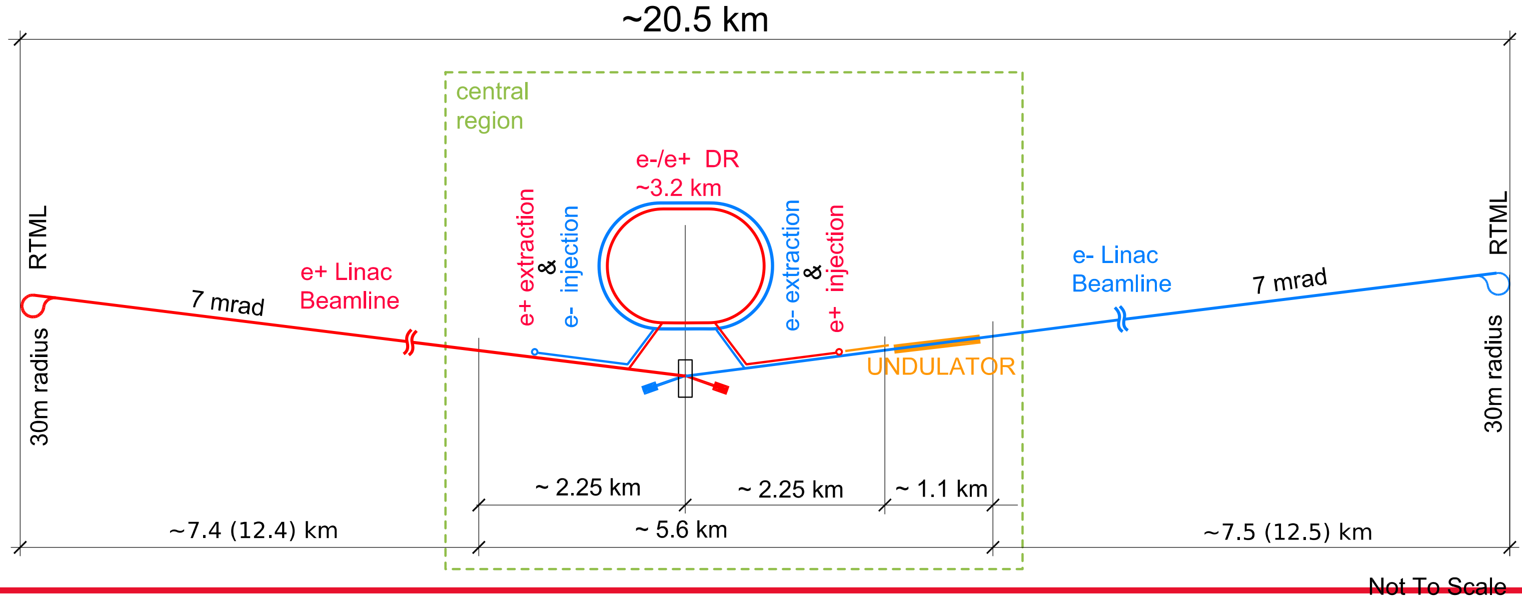


Sources (Electron & Positron)

- 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**

- 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**
    - Injection line into DR -> vac & **magnets**

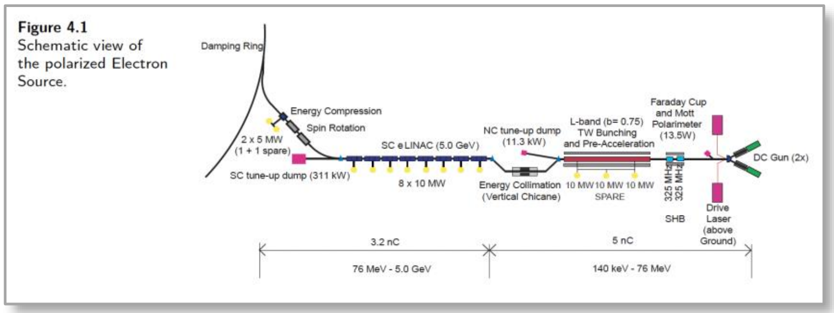


Figure 4.1 Schematic view of the polarized Electron Source.

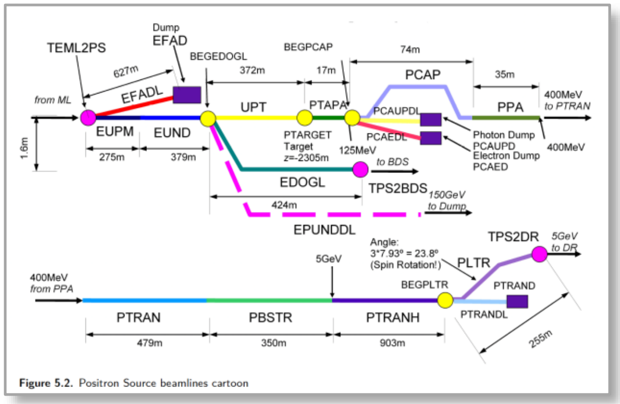
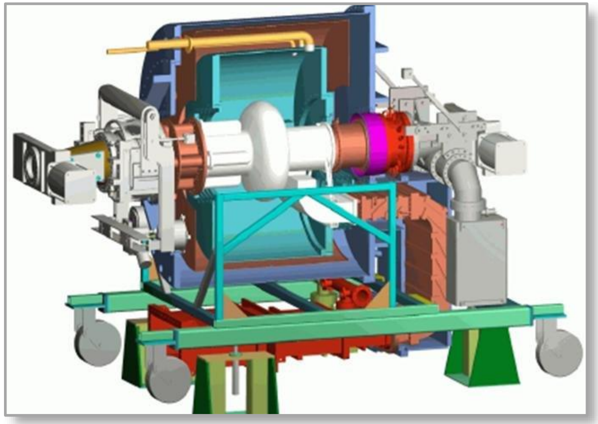


Figure 5.2. Positron Source beamlines cartoon

ILC TDR, Vol III.2

Damping Rings

- Two accelerators (electron, positron) in one tunnel, 3.2km circumference (3rd ring is upgrade)
  - **Magnets,** mounted on girders
  - **Vacuum System**
  - RF system: 650MHz superconducting Rf system, 2-3.8MW power to beam
  - Area specific: Superconducting wigglers



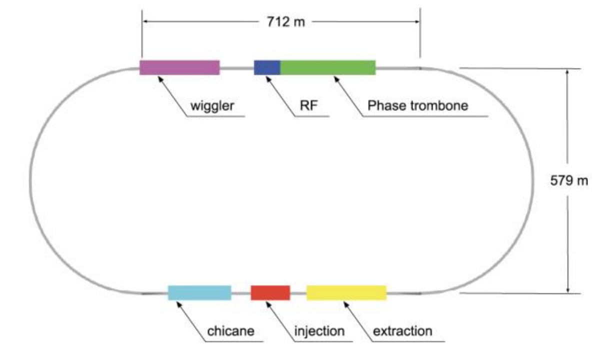


Figure 6.1
Damping-ring layout: the circumference is 3238.7 m; the length of each straight is 710.2 m.

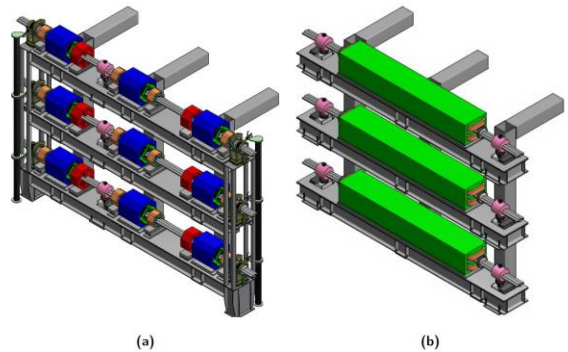


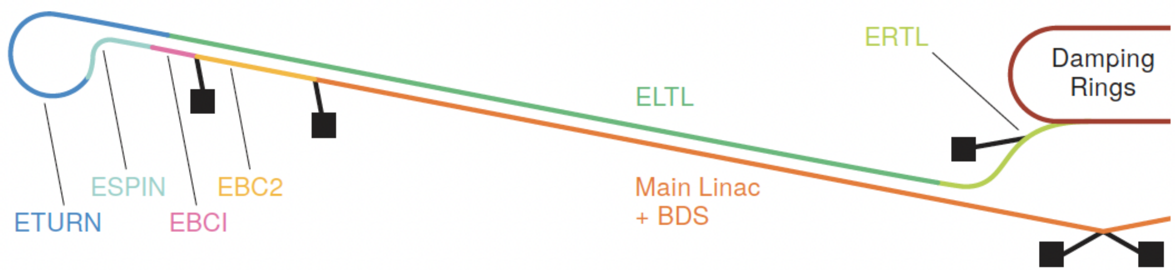
Figure 6.2
Damping-ring arc magnet layout with positron ring at the bottom and electron ring directly above. A second positron ring would be placed above the electron ring if required: (a) quadrupole section layout and (b) dipole section layout.

https://www.researchgate.net/publication/230794961_Science_Requirements_and_Conceptual_Design_for_a_Polarized_Medium_EnergyElectron-Ion_Collider_at_Jefferson_Lab

RTML: Long Transfer Line, Turn Around, Bunch Compressors

- 2 (e-, e+) long transfer lines from DR to start of Main Linac; include turn around loop and bunch compressors
  - LTL (long transfer line): 2x10km beamline: **vacuum system, magnets**
  - Turn around: vacuum, magnets
  - Bunch compressors: long wiggler (magnet) sections, plus SC accelerators, same cryomodules as in Main linac
    -> **vacuum, magnets**
    - 51 cryo modules (same as ML)

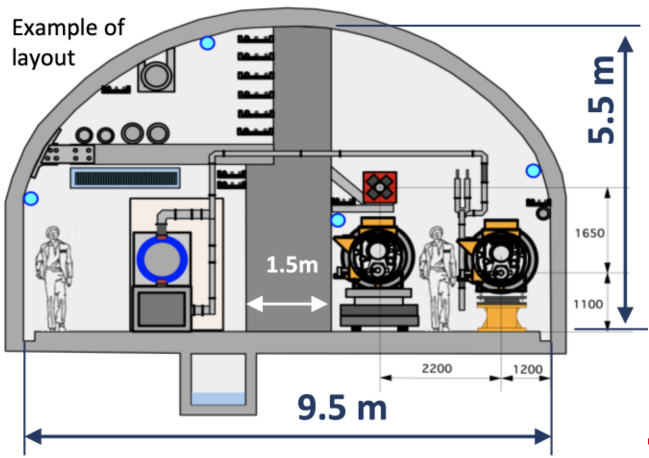
Figure 7.1 Schematic of the RTML, indicating the various functions described in the text.

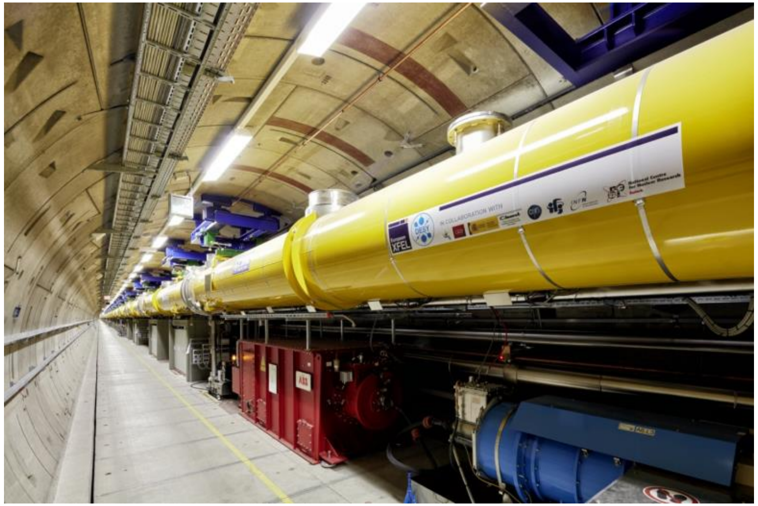


Each of the key functions of the RTML listed in Section 7.1 is supported by several of the sub–beamlines shown in Fig. 7.1.

Main Linac

- 2 x 5km long linacs
  - **Cryomodules**
  - **Cryogenics: ~6 cryo plants** (commercial, ~19kW eq at 4.5K, 2K op, temp)
  - **HLRF:** ~250 10MW pulsed klystrons, with modulators and wave guide distribution
  - Instrumentation: BPMs within cryomodules, plus electronics
  - Magnets: SC magnet package in CM, plus power supplies



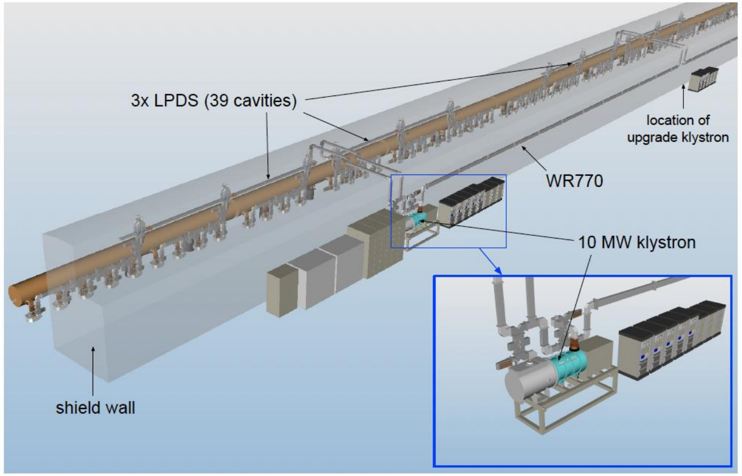


Tunnel of European XFEL at DESY with Cryomodules
Blue klystrons below

Main Linac Components

- Per “RF Unit”:
  - 1 klystron
  - 1 modulator
  - Waveguide system
  - -> supplies 4.5 cryo modules, i.e. unit of 9 cryomodules (1 short string) has 2 RF units

Figure 3.42
The DKS arrangement in the main-linac tunnel for the mountainous topography. One DKS unit (39 cavities) is shown.



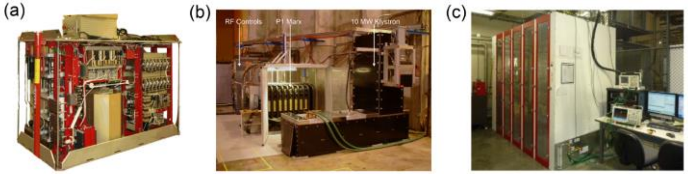


Figure 3.28. (a) DTI Marx modulator, (b) SLAC P1 Marx modulator and (c) SLAC P2 Marx.

Figure 3.30
Thales TH1801 (left) and the horizontally mounted Toshiba E3736.

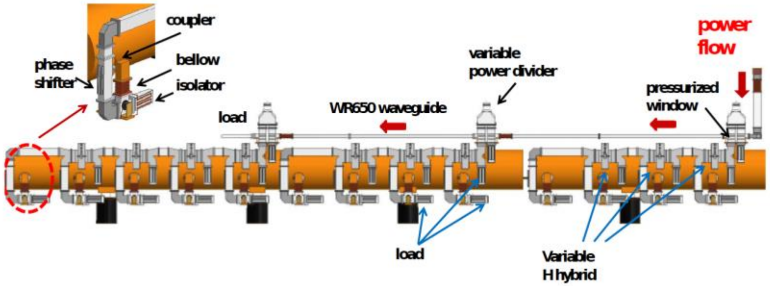


Figure 3.33. CAD model of a 13-cavity local power-distribution system (LPDS)

ML Configuration

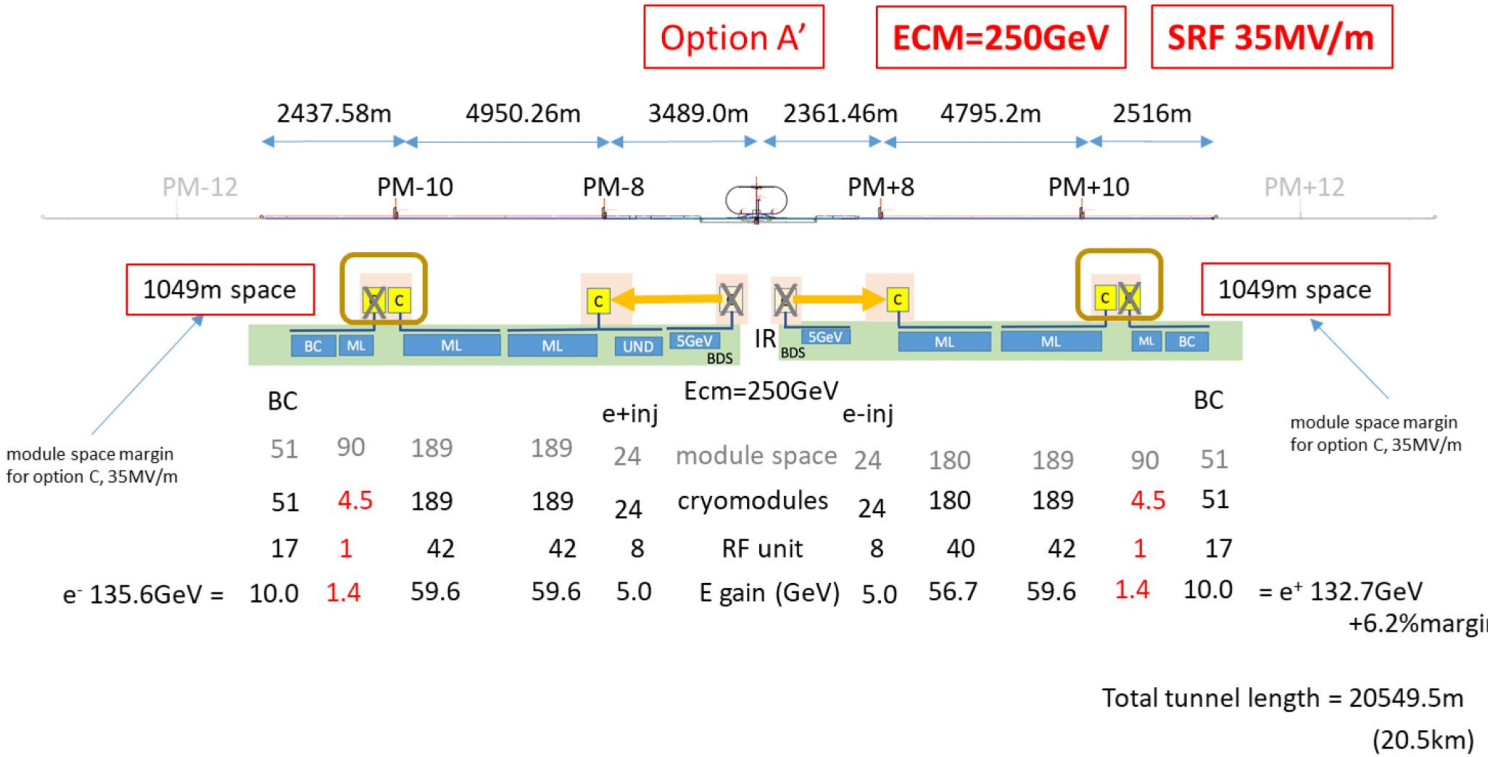


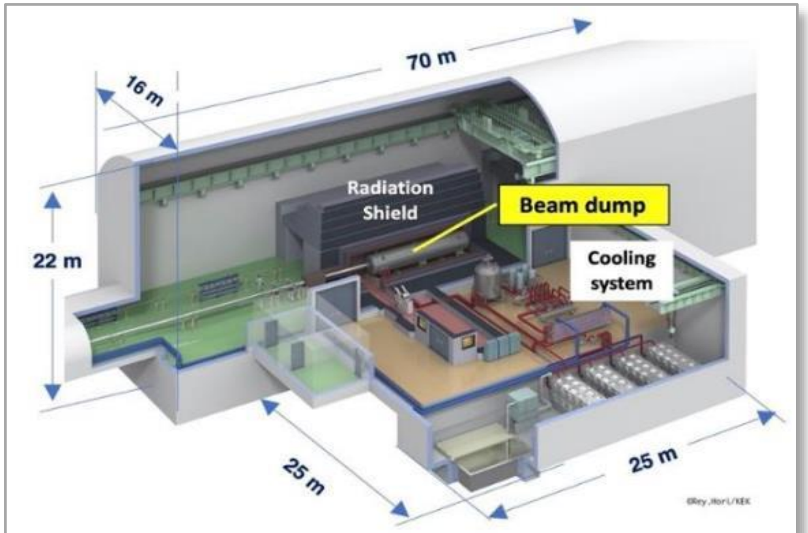
Figure 3-7 Option A' configuration.

ILC Staging report, arXiv:1711.00568

Beam Delivery System and Dumps

- 2 beamlines (e-, e+), ~2.5km long
- **Magnets** (large, because high energy)
- **Vacuum system**
- Beam dumps: 4 dumps overall, rating 17MW, water vessel, with radiation shielding and tritium treatment
- **Muon deflectors**: Large iron slabs

https://agenda.linearcollider.org/event/9718/



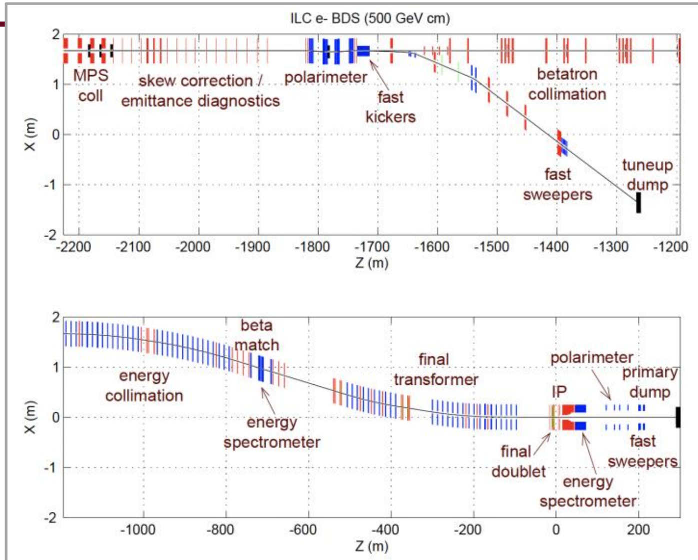
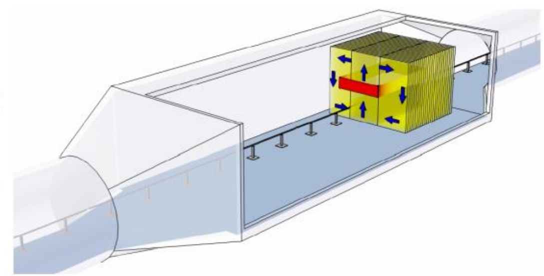


Figure 8.1. BDS layout showing functional subsystems, starting from the linac exit; X – horizontal position of elements, Z – distance measured from the IP.

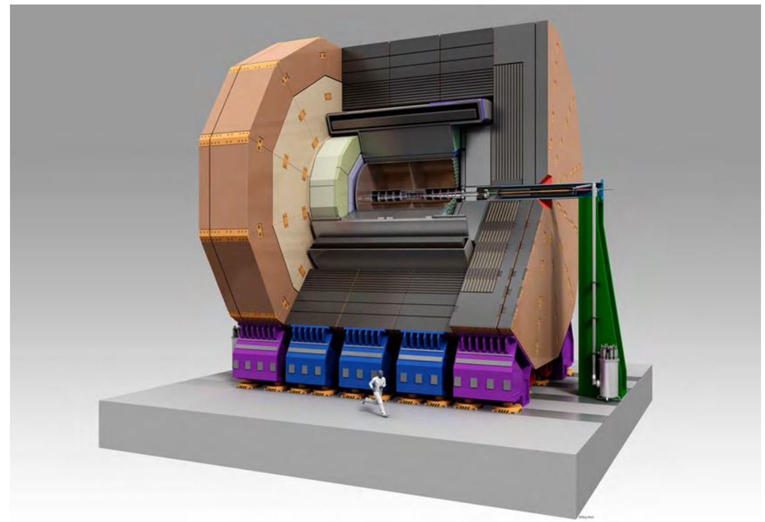
Chapter 8. Beam Delivery System and Machine Detector Interface

Figure 8.2
Schematic of the 5 m-long magnetised muon shield installed in a tunnel vault which is configured to accommodate a possible upgrade to a 19 m-long shield. The coil is shown in red, and blue arrows indicate the direction of the magnetic field in the iron.



Detectors

- Two concepts: ILD (International Large detector) and SiD (Silicon Detector)
- Biggest components of ILD:
  - Flux return yoke (iron)
    ~13499 tonnes of steel (ILD)
  - Calorimeters:
    ECAL: 109 tonnes steel
  - HCAL: 1154 tonnes tungsten(!)
  - Superconducting coil
- -> Detailed, up-to-date information available from detector collaborazions



ILD

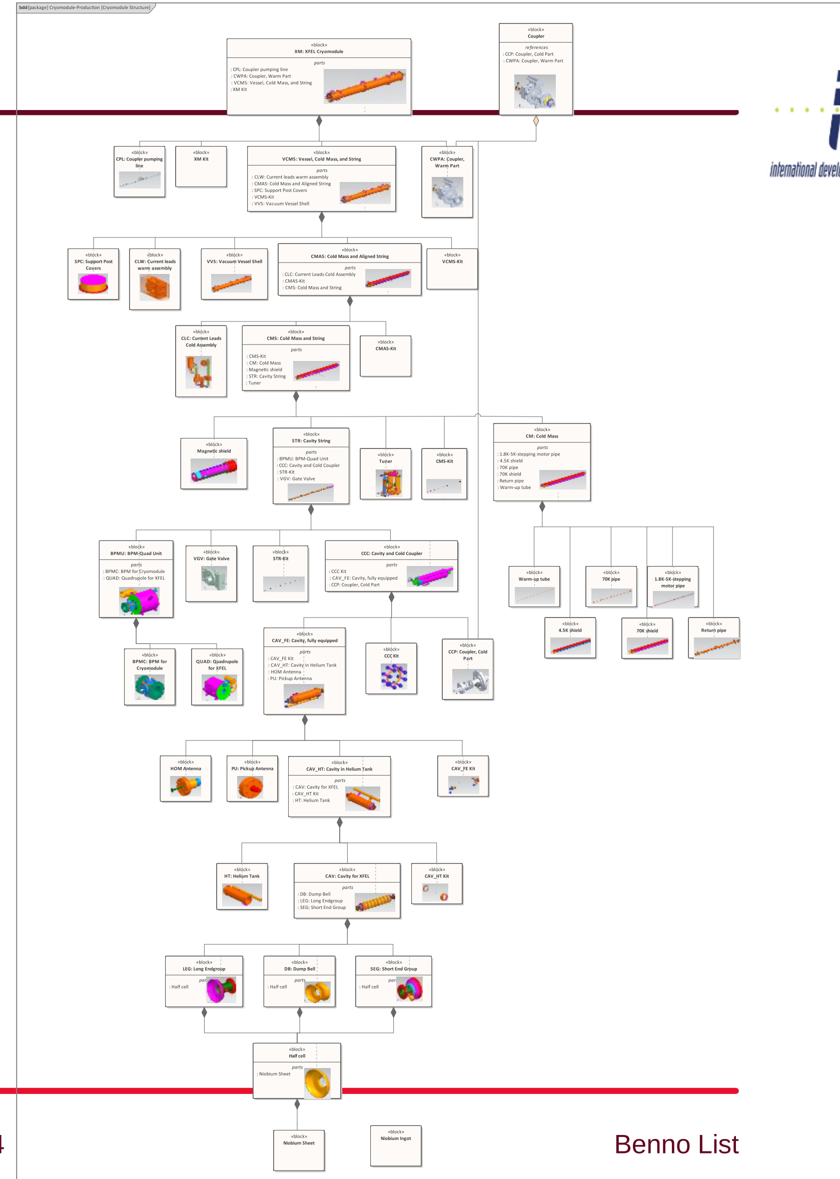
ILC: LCI Data for Cryomodules

- ILC cryomodules are very similar to XFEL cryomodules
- Production of XFEL modules has been industrialized and is meticulously documented
- I prepared a detailed model of an XFEL cryomodule for a LCA
- Cryomodule: ~12.5 m long, mass 6.5ton

K. Jensch, https://mks.desy.de/sites/sites_desygroups/sites_extern/site_mks/content/e83094/e127519/infoboxContent127521/2019_10_07_XFELmodules_ECD_Jensch_ger.pdf

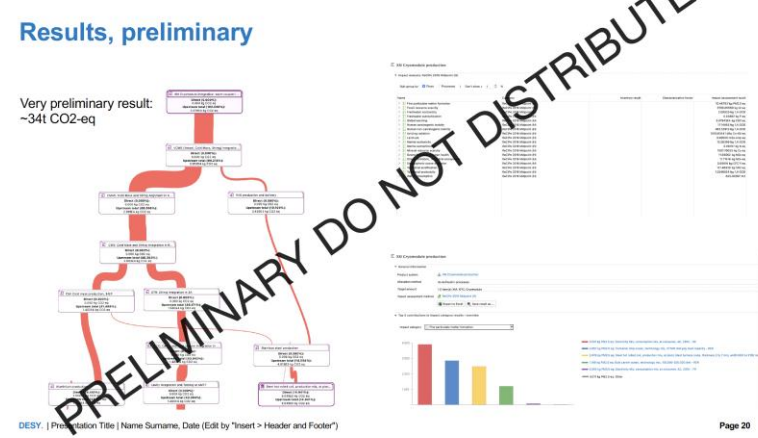
Cryomodule MBOM

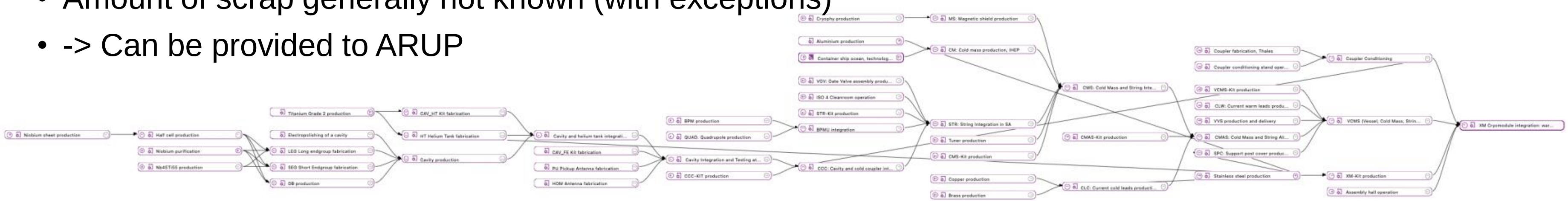
- Detailed MBOM, starting from Niobium sheet up to complete cryomodule
- Mass and material of components is known
- For some important steps, amount of scrap is known (production of half cells from sheets)



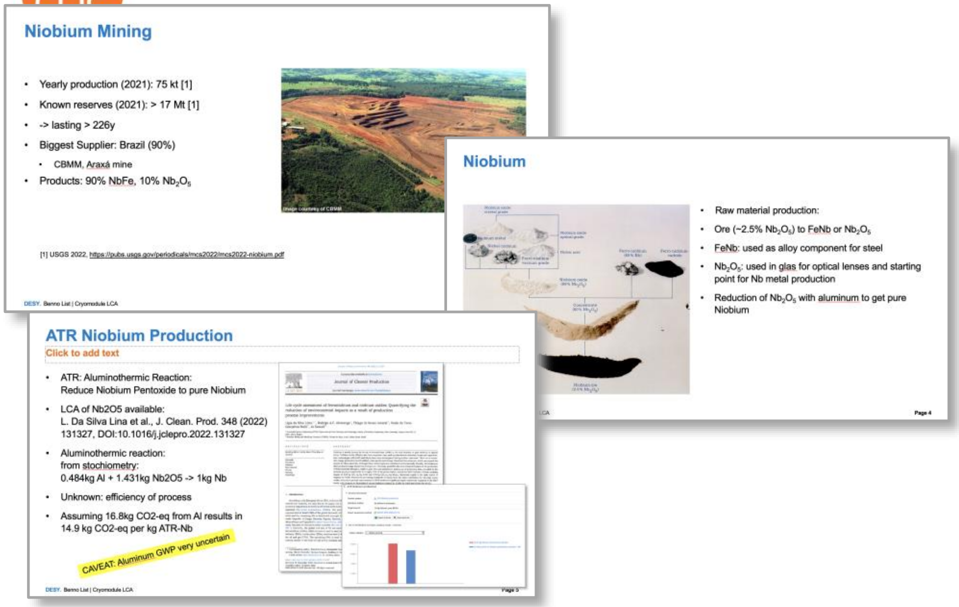
LCI Implementation of Cryomodule

- Manufacturing has been implemented in an OpenLCA model
- LCI is expressed in terms of
  - Kg of high purity (RRR300) niobium – also scrap
  - Kg of Nb45Ti55
  - Kg of titanium Grade 2
  - Kg of Cryophy (shielding metal, 60%Fe, 28%Mn, 10%Cr, 2%Ni)
  - Kg of stainless steel, brass, aluminium, high-purity (oxygen-free) copper
  - Km*t of transport (sea, road)
  - M2*day of cleanroom operation
  - Kg Usage of chemicals (phosphoric acid) – not yet
  - Minutes of electron beam welding time – not yet
- Amount of scrap generally not known (with exceptions)
- -> Can be provided to ARUP



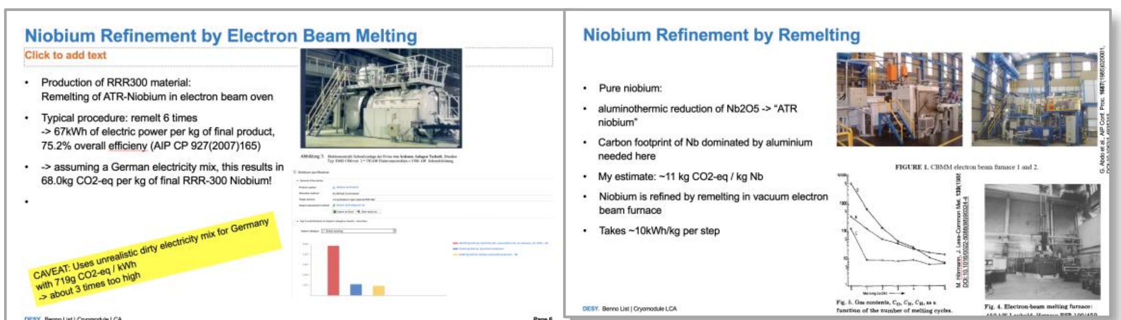


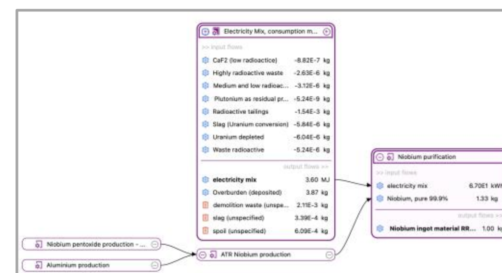
Niobium Material



- 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





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

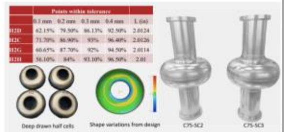
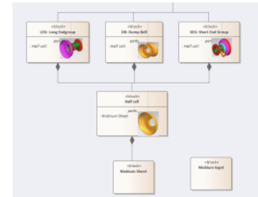


Fig. 6: Fabrication of tow single cell cavities labeled C75-SC2 and C75-SC3.

Dump Bells and End Groups

Click to add text

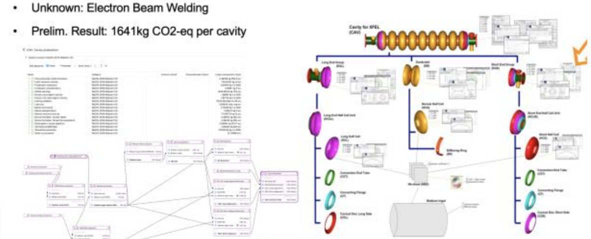
- 2 half cells plus stiffening ring welded to form a "dump bell"
- End groups: half cells plus tube and other stuff
- Unknown:
  Energy of Electron Beam Welding
- Unknown: Material efficiency for the other parts



Cavity Production

Click to add text

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

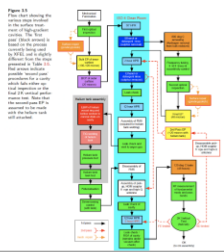


Waldemar Singer, SRF 2013, MOIOA03
https://accelconf.web.cern.ch/SRF2013/talks/moioa03_talk.pdf

Cavity Treatment

Click to add text

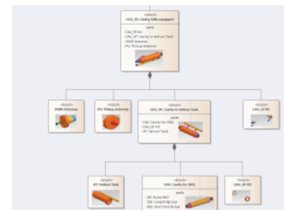
- Cavity treatment consists of
  - Heat Treatment
  - Electropolishing
  - HPR
- Needs chemicals (phosphorous acid), water, electricity
- Currently not taken into account!



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

Click to add text

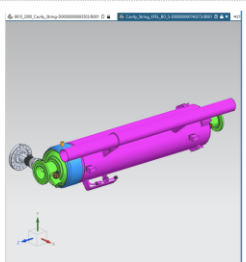
- Assume final throughput: 1.25CM / week
  -> 7/1.25 = 5.6 days per CM
- Assign operating ressources (power) to work stations according to area
- Distinguish "general assembly area" and ISO4 cleanrooms
- Unknown:
  - electricity usage for lighting, heating, ventilation
  - Other ressources (water, alcohol,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

O.Napoly, XFEL MAC report 5.11.2014

Cold Coupler Assembly in clean room

Click to add text

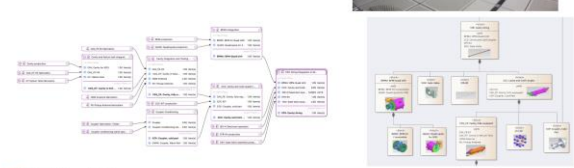
- First step:
  Cold coupler part mounted on cavity
- Done in "CC" (Cold Coupler) area



STR: String Production

Click to add text

- String assembly done in cleanroom area



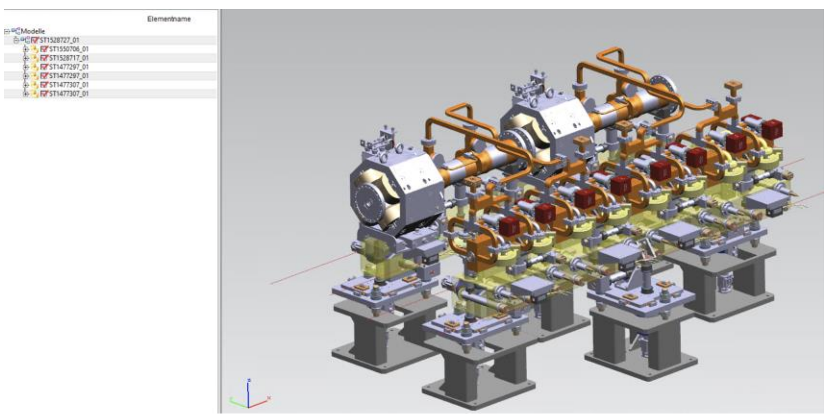
Integration with vacuum vessel, warm coupler mounting

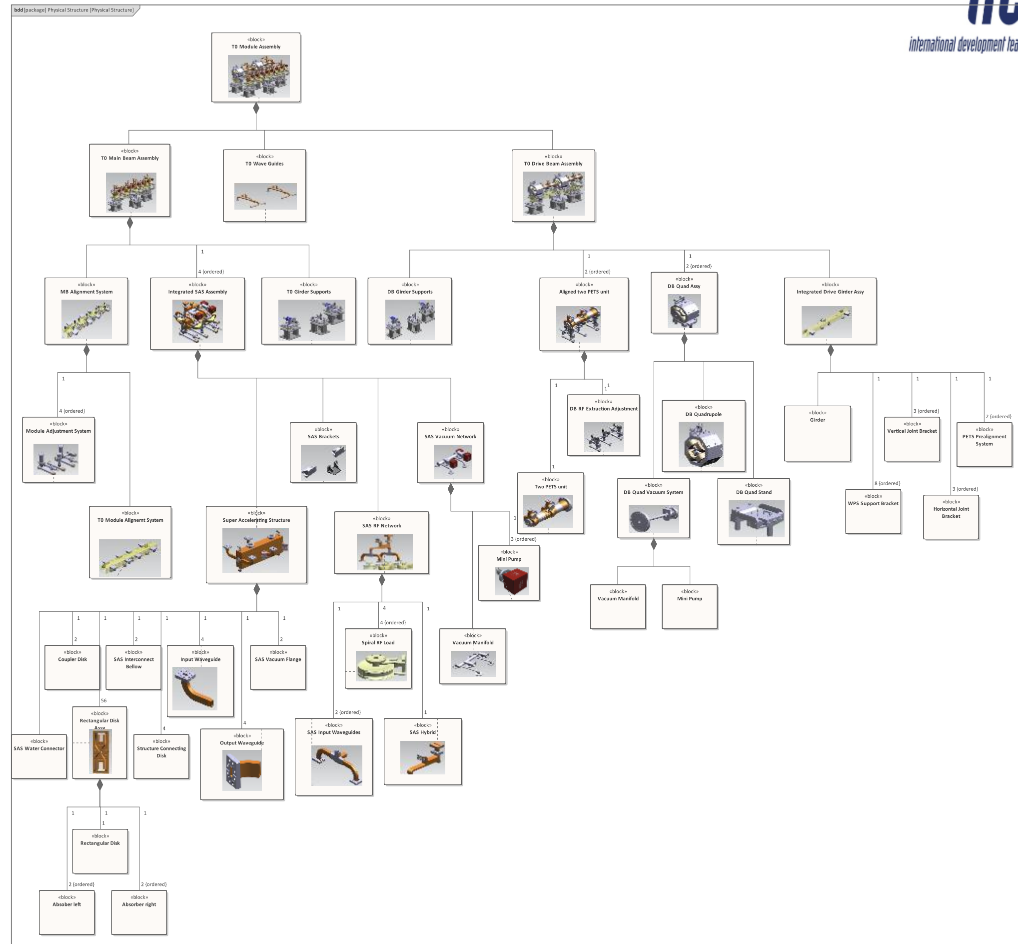
Click to add text

- 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

CLIC: 2-Beam Module

- CLIC 2-beam module: The fundamental building block of the CLIC main linac
- Similar approach, based on existing CAD model



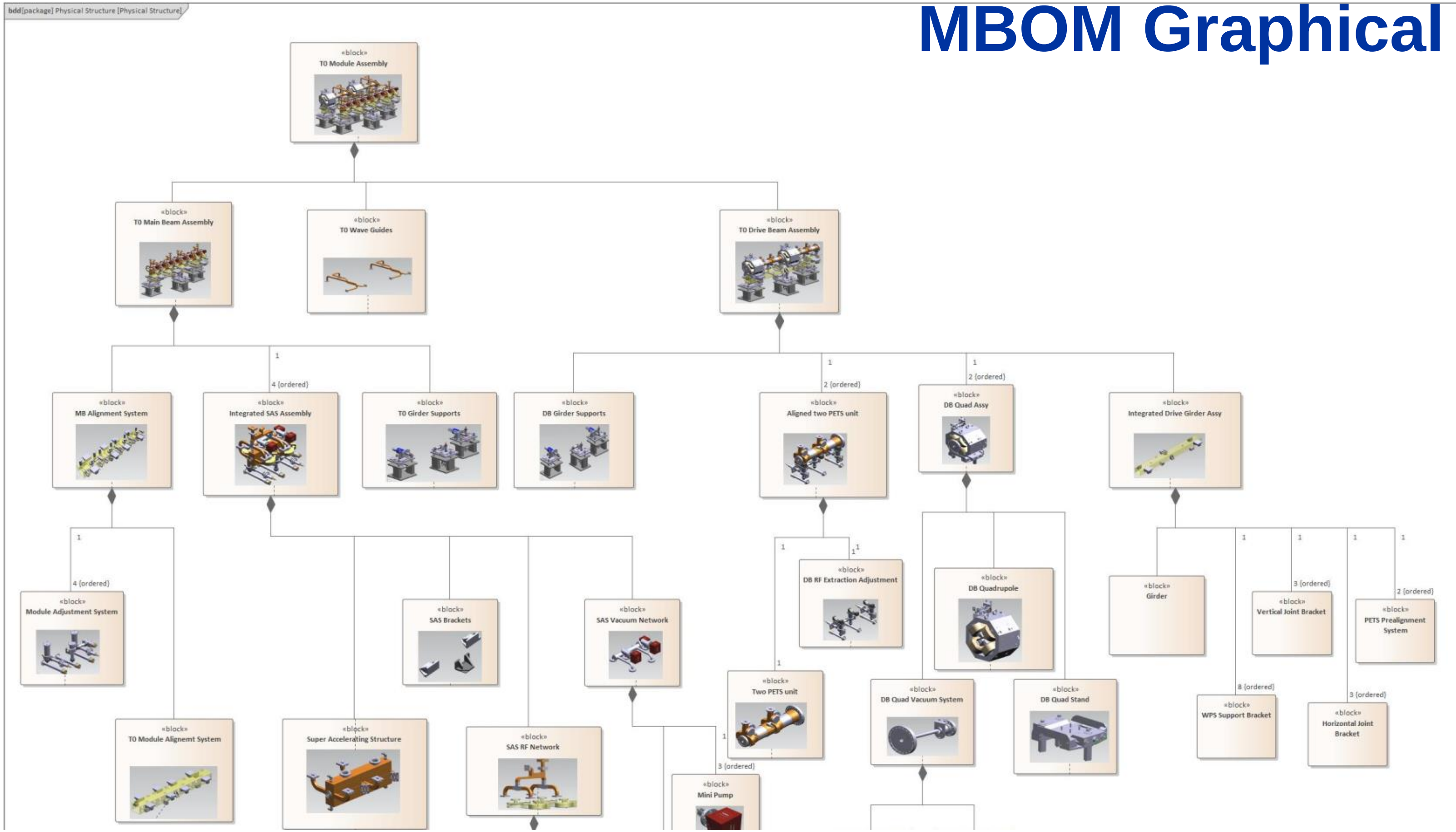


The T0 Module Data

1																
2	Com	nen	ree					Number	PBS Code	PBS Text	Quantity / A	Q / Tot	Material	Densit	Mass	Manufacturing
3	Level 0	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6									
4																
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

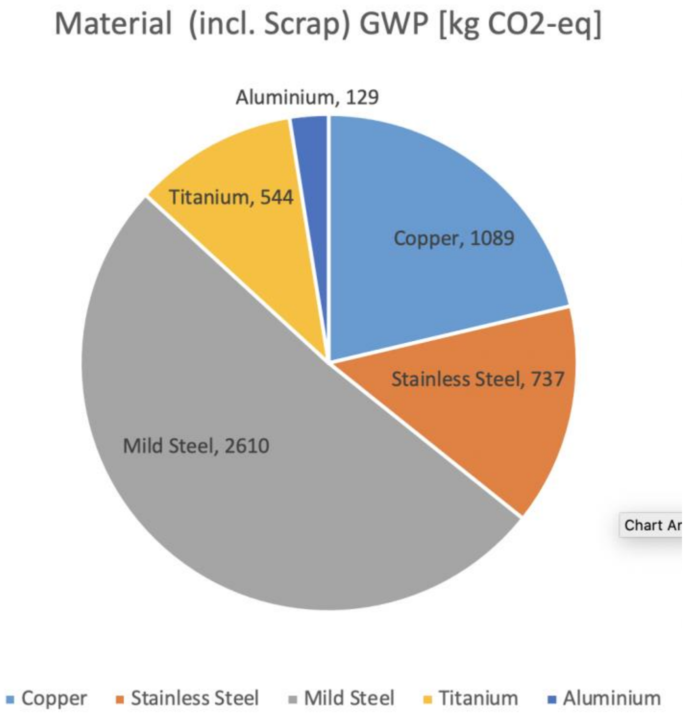
Conclusion here:

Supports have a large impact on CO2 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**



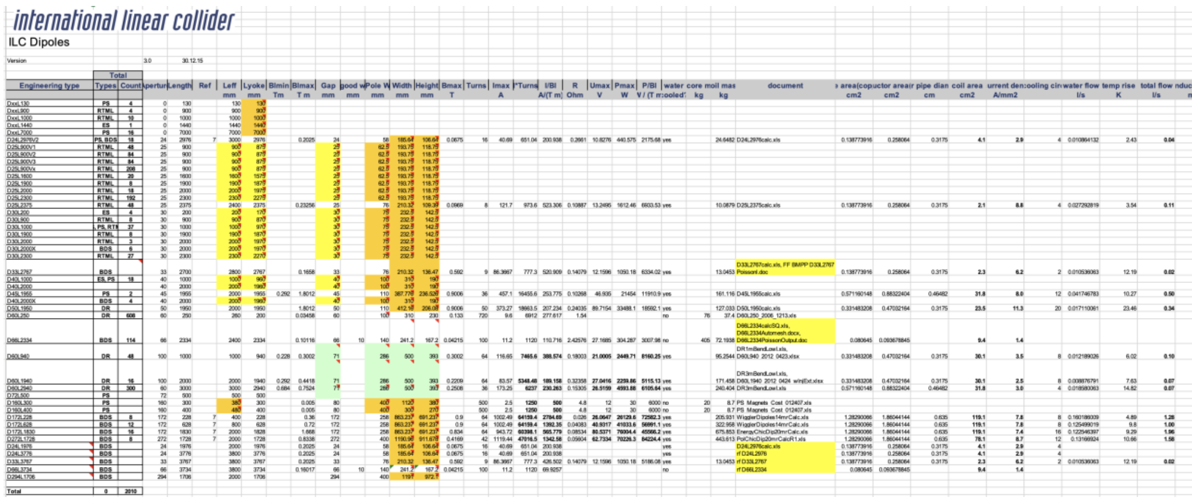
Magnets

- Resistive Electromagnets are a big contributor to LCA, because of large mass
- Many different types: dipoles, quadrupoles, sextupoles …
- 2 Parts:
  - Yoke: Iron / magnetic steel, often made from stamped laminations
  - Coil: Copper conductor, extruded, insulation: epoxy resin
- Yoke and coil net weights are known
- Yoke gross weight can be estimated from overall cross section
- Coil:
  - extruded profile has probably little scrap
  - Insulation (potting) – neglected so far
- Not to be forgotten: Stands! Here, data is often scarce…

Magnets in an accelerator

Magnet Catalogue: ILC

- List with magnet types, cross sections data, masses, number is available for ILC
- Need some consolidation, but basically is ready to use



Magnet Catalogue: CLIC

- Magnet catalogue exists
- All types have preliminary designs, documented in a set of CLIC notes
- Summary table of types with properties exists as well

Index	System	Type	Magnet type	Generic type name	Shape family	Total	Total 380	Effective Length [m]	Aperture H/V [m]	Shape	Strength	unit	Range [%]	Rel. Field Accuracy	Higher harmonics [Tm]	Type	PBS Items	Full Aperture	St
1	DB	MBTA	Dipole	D53L1470	D53	576		1.5	0.04/0.04	circular	1.6	T	10-100	1.00E-03	1.00E-04	MBTA	2.3.5.5, 2.3.6.5	53	
2	DB	CF_CR1	Combined Function				24												
3	DB	CF_CR2	Combined Function				32												
4	DB	CF_CR3	Combined Function				24												
5	DB	MBCOTA	Dipole CO	DC53L170	DC53	1872		0.2	0.04/0.04	circular	0.07	T	-1	1.00E-03	1.00E-03	MBCOTA	2.2.5.5, 2.3.6.5	53	
6	DB	QTA	Quadrupole	Q53L480	Q53	1872		0.5	0.04/0.04	circular	14	T/m	10-100	1.00E-03	1.00E-04	QTA	2.3.5.5, 2.3.6.5	53	
7	DB	SXTA	Sextupole	SX53L185	SX53	1152		0.2	0.04/0.04	circular	85	T/m2	10-100	1.00E-03	1.00E-03	SXTA	2.3.5.5, 2.3.6.5	53	
8	DB	MB1	Dipole	D93L1448	D93-1	184	342	1.5	0.08/0.08	circular	1.6	T	10-100	1.00E-03	1.00E-04	MB1	2.2.1.5, 2.2.6.5	93	
9	DB	MB2	Dipole	D93L648	D93-1	32	352	0.7	0.08/0.08	circular	1.6	T	10-100	1.00E-03	1.00E-04	MB2	2.2.1.5, 2.2.6.5	93	
10	DB	MB3	Dipole	D93L150	D93-2	236	15	1	0.08/0.08	circular	0.26	T	10-100	1.00E-03	1.00E-04	MB3	2.3.2	93	
11	DB	MBCO	Dipole CO	DC93L150	DC93	1061	1342	0.2	0.08/0.08	circular	0.07	T	-1	1.00E-03	1.00E-03	MBCO	2.2.1.5, 2.2.6.5, 2.3.2	93	
12	DB	Q1	Quadrupole	Q93L460	Q93	1061	501	0.5	0.08/0.08	circular	14	T/m	10-100	1.00E-03	1.00E-04	Q1	2.2.1.5, 2.2.6.5, 2.3.2	93	
13	DB	Q1++	Quadrupole				180									Q1++			
14	DB	SX	Sextupole	SX93L170	SX93-1	416	202	0.2	0.08/0.08	circular	85	T/m2	10-100	1.00E-03	1.00E-03	SX	2.2.1.5, 2.2.6.5	93	
15	DB	SX2	Sextupole	SX93L470	SX93-2	236	511	0.5	0.08/0.08	circular	360	T/m2	10-100	1.00E-03	1.00E-04	SX2	2.3.2	93	
16	DB	SX2++	Sextupole				11									SX2++			
17	DB	QLINAC	Quadrupole	Q100L210	Q100	1638	655	0.25	0.087/0.087	No data	17	T/m	No data	No data	No data	QLINAC		100	
18	DB	QLINAC--	Quadrupole				8									QLINAC--			
19	DB	MBCO2	Dipole CO	D213L881	DC213	880	223	1	0.2/0.2	circular	0.008	T	-1.00E+00	2.00E-03	2.80E-05	MBCO2	2.3.1, 2.3.4	213	
20	DB	Q4	Quadrupole	Q213L905	Q213	880	223	1	0.2/0.2	circular	0.14	T/m	10/100	0.002	2.80E-05	Q4	2.3.1, 2.3.4	213	
21		Data from ATS Note 2011-044 / CLIC-Note 873 / EDMS 1139561														Data from ATS Note 2011-044 / CLIC-Note 873 / EDMS 1139561			
22	MB-BT	D1	Dipole	D30L970	D30-1	6	6									D1	1.3.13	30	
23	MB-BT	D2 Type 1	Dipole	D30L1470v1	D30-2	12	29									D2 Type 1	1.3.4, 1.3.5, 1.3.8, 1.3.9	30	
24	MB-BT	D2 Type 2	Dipole	D30L1970	D30-2	666	659									D2 Type 2		30	
25	MB-BT	D3	Dipole	D30L1470v2	D30-3	16	16									D3	1.3.1, 1.3.2, 1.3.10, 1.3.11	30	
26	MB-BT	D4	Dipole	D30L1470v3	D30-4	8	8									D4	1.3.10, 1.3.11	30	
27	MB-BT	Q1	Quadrupole	Q30L290v1	Q30-1	268	292									Q1	1.3.4, 1.3.5, 1.3.8, 1.3.9	30	
28	MB-BT	Q2	Quadrupole	Q30L290v2	Q30-2	223	144									Q2	1.3.4, 1.3.5, 1.3.8, 1.3.9	30	
29	MB-BT	Q3 Type 3	Quadrupole	Q30L290v3	Q30-3	202	280									Q3 Type 3	1.3.4, 1.3.5, 1.3.8-1.3.11, 1.3.13	30	
30	MB-BT	Q3 Type 2	Quadrupole	Q30L190v1	Q30-3	75	34									Q3 Type 2		30	
31	MB-BT	Q3 Type 1	Quadrupole	Q30L140v1	Q30-3	316	89									Q3 Type 1		30	
32	MB-BT	Q4 Type 3	Quadrupole	Q30L190v2	Q30-4	230	354									Q4 Type 3	1.3.1-1.3.5, 1.3.8-1.3.12	30	

Vacuum Parts (ILC)

- Some data on length of chambers, number of flanges etc is available
- Can be used to evaluate a rough number of material per average meter of beamline
- Do separately for DR, RTML and BDS (different requirements)

Damping Ring Vacuum Chambers	
Chamber Name	**Number Req (2 Rings)**
Arc Cell Chambers	
3m Dipole Chamber	300
Quad Vacuum Chamber	300
Arc Drift Chamber	600
Wiggler Cell Vacuum Chambers	
Wiggler Chamber	60
Wiggler Quad Chamber	60
Wiggler Drift Chamber	60
Wiggler Photon Stop	60
Chicane Cell Vacuum Chambers	
Chicane Quad Chamber	32
Chicane Drift Chamber 1	16
Chicane Drift Chamber 2	16
Chicane Drift Chamber 3	16
Chicane Drift Chamber 4	16
Chicane Dipole Chamber 1	16
Chicane Dipole Chamber 2	16
RF Cell Vacuum Chambers	
RF Drift Chamber 1	24
RF Drift Chamber 2	12
RF Drift Chamber 3	24
Straight Cell Vacuum Chambers	
Straight Quad Chamber	262
Straight Drift Chamber	250
Non-Repeating Components	
2m Dipole Chamber	16
Wiggler Straight End Photon Stop	2
Circular - Antechamber Transition	8
Wiggler - Arc Transition	2
Other Components	
Ion Pump + Plenum	1250
Sliding Joint + BPM	962
Gate Valves	64
Specialty Gate Valve	32
RGAs	64
Turbo Cart	10
Solenoid Power Supplies	520

RTML		Jo
vacuum_RTML_transport_		
Transport lines		
Chambers	length	qu
beam pipe	15000	
bellows		
crosses		
pumps		
controller		
Valves		
gate		
interlock		
right angle		
Stands		
Hardware		
gaging		
gaskets		
cable		
bolts		
racks		
pumpcart		
Total M&S		
EDI		
EDI hours		
Contingency		
Vacuum calculations		
length	unit length	ur
15000	2	
pipe cost	passivate	fal
38	17	
unit prices		
pipe unit cost		
gasket		
pump cost		
controller		
iso valves		
vlv intlk		

Item
Chambers, 2m long
Chambers, 2m long, with flanges
Gaskets, 5 per chamber
Bolts, 6 per chamber
Stands, 1/2 per chamber
Pumps, every 19m
Pump
Cross
Controller (1/2 per pump)
Right angle
Bellows (2 per pump)
Cable
Bolts (9 per pump)
Stands
Racks (1 per 6 pumps)
Valves, every 100m
Gate
Interlock
Gaging
Pumpcarts
Total (per meter)

Specific Issues I have encountered

- Treatment / Estimation of gross raw material amount / scrap:
  - For milled and turned parts, net weight of final product is a bad estimator for total material
  - Detailed evaluation of raw material size typically hard to impossible
  - Designs from tubes, sheet metal, extruded material much more efficient
  - -> does it make sense to introduce “pseudo-materials” such as “milled/turned steel” (not “mild”) and assume e.g. 1kg of milled steel uses 1.5kg steel and produces .5kg scrap?
- Impact assessment of special materials encountered in accelerator component fabrication:
  - High-purity (RRR300) niobium
  - Ni45Ti55, Ti grade 2
  - Oxygen-free copper
  - Cryophy (shielding metal)
  - Magnetic steel (various qualities), with Co
  - -> hopefully, ecoinvent to the rescue
- Treatment of operation of production facilities: example XFEL village, with clean rooms
  -> assume some overall power consumption (lighting, heating, ventilation), calculate rate for area*time?
- Special production methods
  - Electro polishing
  - Electron beam welding

End of Life - Disposal

- Inclusion of decommissioning & disposal of accelerator components and civil infrastructure in LCA up to now unsolved
- Missing quantitative data
  - How much waste is produced
  - Amount of scrap that can be sold for recycling
  - Amount of activated material, impact of its treatment / storage / disposal
- Not all projects end in dismantling:
  ILC or CLIC based higgs factory will probably evolve into higher energy facility

IAEA, Decommissioning of particle accelerators,
https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1854_web.pdf

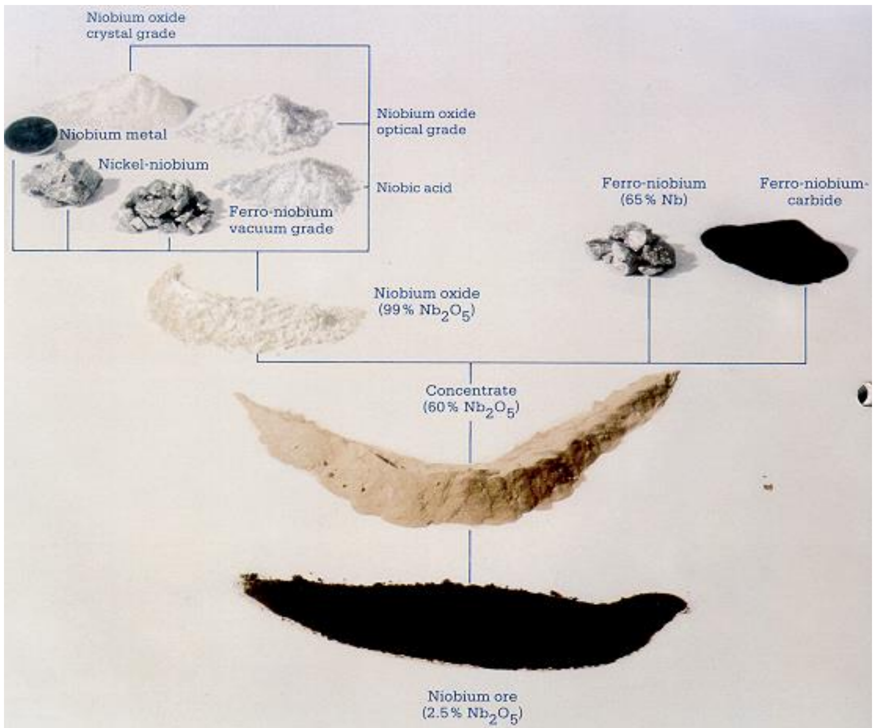
Thank You

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_2O_5

[1] USGS 2022, https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-niobium.pdf

Niobium



- Raw material production:
- Ore (~2.5% Nb_2O_5) to FeNb or Nb_2O_5
- FeNb: used as alloy component for steel
- Nb_2O_5: used in glas for optical lenses and starting point for Nb metal production
- Reduction of Nb_2O_5 with aluminum to get pure Niobium

ATR Niobium Production

- ATR: Aluminothermic Reaction:
  Reduce Niobium Pentoxide to pure Niobium
- LCA of Nb2O5 available:
  L. Da Silva Lina et al., J. Clean. Prod. 348 (2022) 131327, DOI:10.1016/j.jclepro.2022.131327
- Aluminothermic reaction:
  from stochiometry:
  0.484kg Al + 1.431kg Nb2O5 -> 1kg Nb
- Unknown: efficiency of process
- Assuming 16.8kg CO2-eq from Al results in 14.9 kg CO2-eq per kg ATR-Nb

CAVEAT: Aluminum GWP very uncertain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Life cycle assessment of ferroniobium and niobium oxides: Quantifying the reduction of environmental impacts as a result of production process improvements

Lígia da Silva Lima[a,*], Rodrigo A.F. Alvarenga[a], Thiago de Souza Amaral[b], Paulo de Tarso Gonçalves Nolli[b], Jo Dewulf[a]

[a] Sustainable Systems Engineering (STEN), Department of Green Chemistry and Technology, Faculty of Bioscience Engineering, Ghent University, Coupure Links 653, B, 9000, Ghent, Belgium
[b] Brazilian Mining and Metallurgy Company (CBMM), Córrego da Mata, Araxá, Minas Gerais, Brazil

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ABSTRACT

Niobium is mostly known for its use as ferroniobium (FeNb) in the steel industry or pure niobium in special alloys. Niobium oxides (Nb_2O_5) also have important uses, such as piezoelectric materials, lenses and capacitors. New technologies with FeNb and Nb_2O_5 have been investigated having positive outcomes. Their use in renewable energy production (wind turbines, solar panels) and storage (batteries) has advanced, which can expand the market for these materials. Although these technologies are considered environmentally friendly, the burdens at their production stage should not be forgotten. This study quantifies the environmental impacts at the production of these materials through a cradle-to-gate life cycle assessment, making use of production data, provided by the niobium producer responsible for roughly 75% of the global market. Results for 2019 indicate a Global warming impact of 5.09 kg CO_2 eq./kg FeNb and 4.70 kg CO_2 eq./kg Nb_2O_5. Aluminum supply is the main source of impacts for FeNb, whereas the processing chemicals of Nb_2O_5 have the main contribution for the high purity oxides. Production process improvements in 2019 resulted in significant impact reductions compared to the 2017 levels, with impacts on Stratospheric ozone depletion reduced by 55.8% for FeNb and 65.6% for Nb_2O_5.

1. Introduction

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Available online 12 March 2022
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Niobium Refinement by Electron Beam Melting

- 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 efficieny (AIP CP 927(2007)165)
- -> assuming a German electricity mix, this results in 68.0kg CO2-eq per kg of final RRR-300 Niobium!
-

CAVEAT: Uses unrealistic dirty electricity mix for Germany
with 719g CO2-eq / kWh
-> about 3 times too high

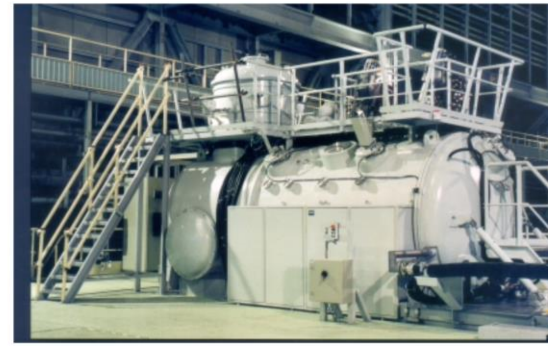
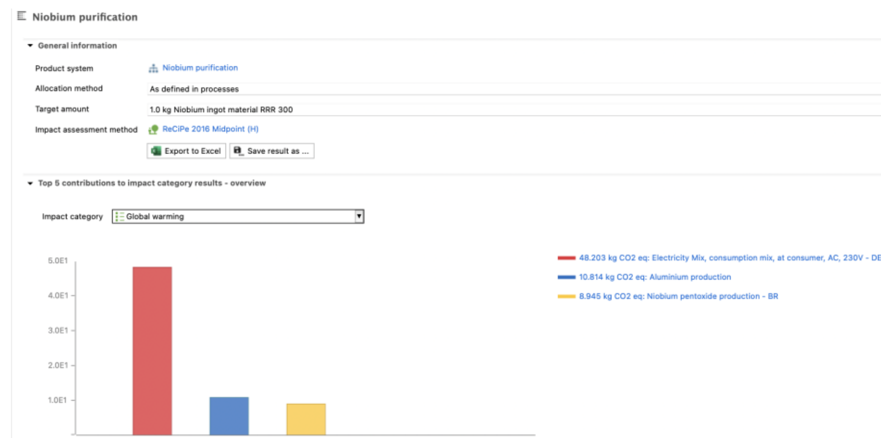


Abbildung 3: Elektronenstrahl Schmelzanlage der Firma **von Ardenne Anlagen Technik**. Dresden
Typ: EMO 1500 mit 2 * 750 kW Elektronenstrahlen = 1500 kW Schmelzleistung.



Niobium Refinement by Remelting

- Pure niobium:
- aluminothermic reduction of Nb2O5 -> “ATR niobium”
- Carbon footprint of Nb dominated by aluminium needed here
- My estimate: ~11 kg CO2-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.

G. Abdo et al., AIP Conf. Proc. **1687**(1985)020001, DOI:10.1063/1.4935315

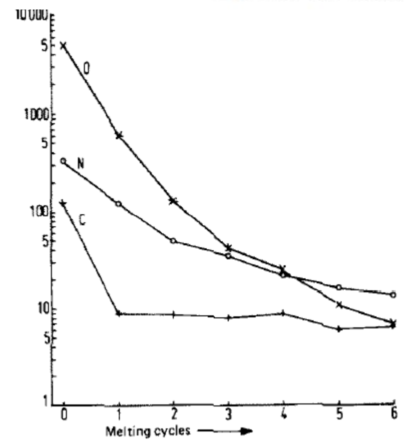


Fig. 5. Gas contents, C_O, C_N, C_H, as a function of the number of melting cycles.

M. Hörmann, J. Less-Common Met. **139**(1988) DOI:10.1016/0022-5088(88)90324-4

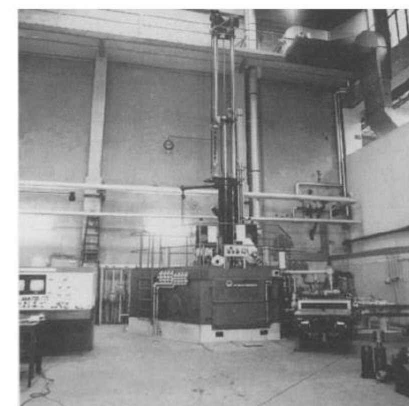


Fig. 4. Electron-beam melting furnace: 450 kW Leybold–Heraeus ESP 100/450.

The Magnet Catalogue

Comprehensive data sheets for many magnet types

- CN 863 (MB PCL): 5 Types
- CN 864 (DB): 14 Types
- CN 865 (MB DR): 11 Types
- CN 873 (MB BT): 17 Types
- CN 984 (MB BDS): 55 Data sets;
  - 45 distinct types
  - could be further consolidated
  - Not included in cost estimate document

QLINAC

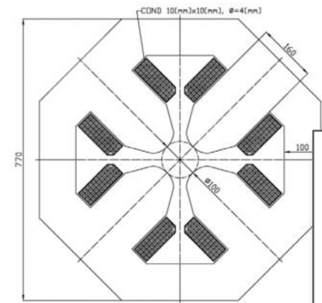


Fig 24. Quadrupole QLINAC Cross-section

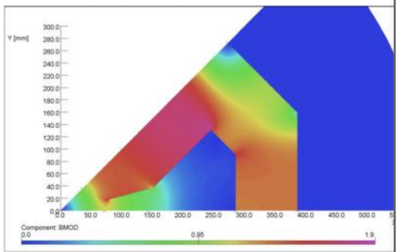


Fig 25. Quadrupole QLINAC OPERA 2D model view

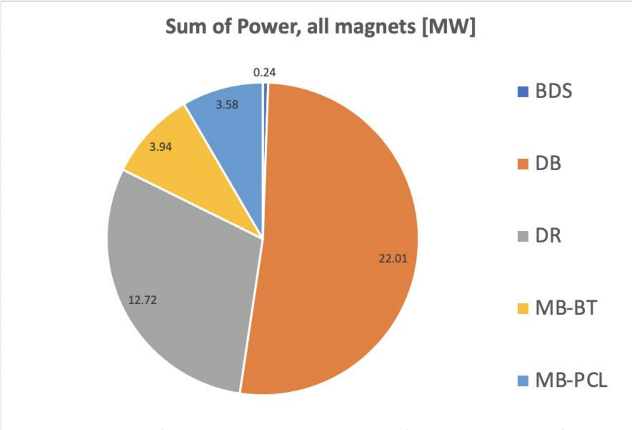
Parameters	UNITS	
Magnet type		Quadrupole QLINAC
Full aperture	[mm]	100
Good field region diameter	[mm]	10×2=20
Effective length	[mm]	250
Strength	[T/m]	17
Pole field	[T]	17[T/m]×(100mm/2)=0.85
	YOKE	
Yoke length	[mm]	210
Yoke cross section area	[m^2]	0.363
Yoke mass	[kg]	600
	USED STEEL	
Steel block size **H×S×L**	[mm×mm×mm]	770×770×210
Used steel mass	[kg]	980
	COIL	
Conductor type	"Luvata"[ID number- 8237]	10[mm]×10[mm], Ø=4[mm]
Conductor mass per 1 m	[kg/m]	0.77
Number of turns per coil		43
Number of pancakes/coil		1
Average turn length	[m]	1
Total conductor length	[m]	1×43×4=172
Total conductor mass	[kg]	132.5
	Electrical parameters	
Ampere turns per pole	[A]	17'800
Current	[A]	414
Current density	[A/mm^2]	4.8
Total resistance	[mOhm]	37
Total inductance	[mH]	27.3
Voltage	[V]	15.3
Power	[kW]	6.3
	COOLING	
Cooling circuits per magnet		4
coolant velocity	[m/s]	1.77
cooling flow per circuit	[l/min]	1.33
Pressure drop	[bar]	5.3
Reynolds number		10100
Temperature rise	[K]	17

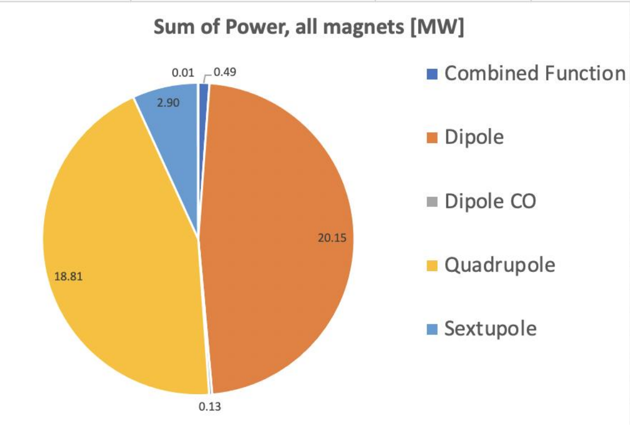
Some plots from the magnet catalogue

Power of all magnets

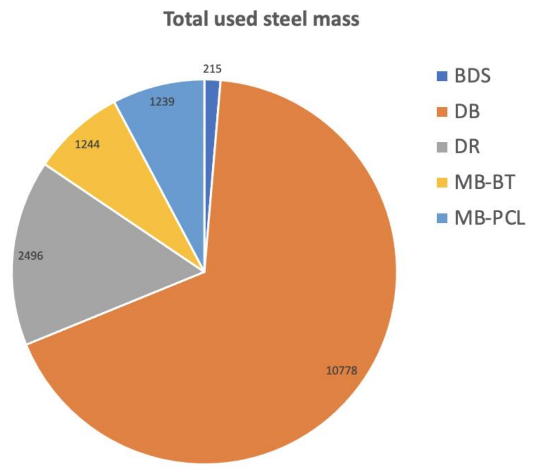
Some assumptions here:

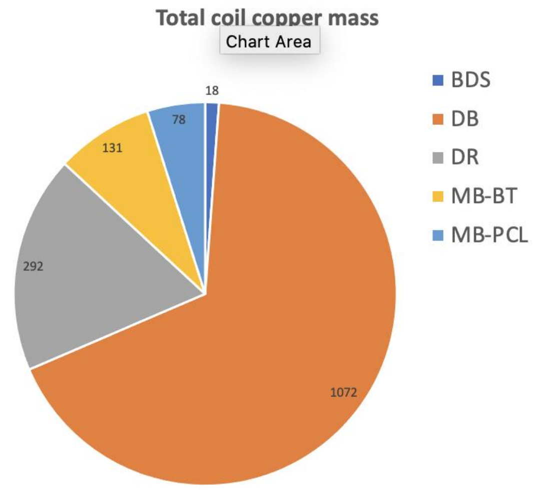
- For dipole correctors, assume 5% of nominal power
- For DB magnets, assume 50% of nominal power -> needs to be consolidated!
- This is NOT a reasonable estimate of magnet power per subsystem, important magnets missing (Main Beam!), settings not consolidated

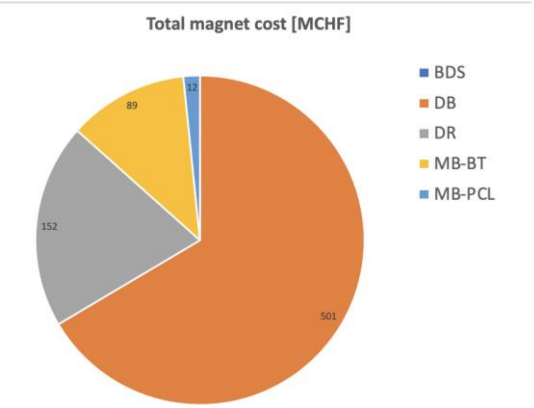




Material Budgets and Cost







BDS magnets not costed

Used steel: estimate of steel mass before stamping
Total amount: 15971 t
At 2 CHF / kg: 32 MCHF (only material!!!)
At 1.7 kg CO2-eq / kg: 27000 t CO2-eq

Total coil copper mass: 1591 t
At 20 CHF/kg: 32 MCHF material cost
At 2.5 kg CO2-eq/kg: 4000 t CO2-eq

Global Warming Potential GWP from Raw Material

GWP from steel and copper alone:
31000 tonnes CO2

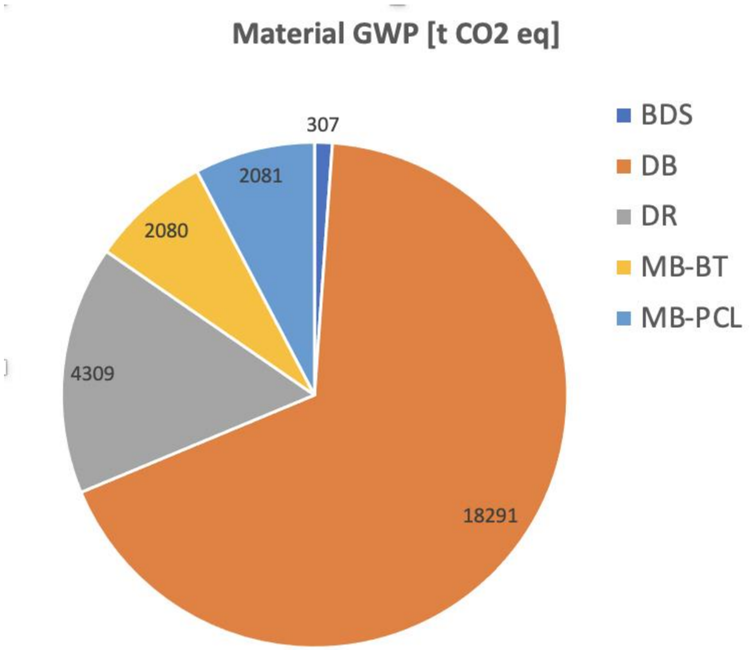
How much is that?

arXiv:2203.12389 quotes 5000-10000 tons per km of tunnel

-> this corresponds to 3-6 km of tunnel (a very very rough estimate)

Missing here: CO2 impact of fabrication, cables, power supplies; material CO2 may be higher for special (pure) copper, cobalt steel etc

But most important: GWP from el. Power!



Total: 31129 tons CO2-eq