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INDUSTRIALIZATION STUDY FOR 12 GHZ ACCELERATING STRUCTURES FOR CLIC 380

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Abstract

The Compact Linear Collider (CLIC) is a multi-TeV electron-positron machine under development by the CLIC accelerator collaboration for few decades. To be compact, the design aims to provide a very high accelerating gradient (100 MV/m) achieved by incorporating normal conductive radiofrequency (RF) cavities operating in X-band range (12 GHz). Each accelerating structure is a challenging component involved ultra-precise machining and diffusion bonding techniques. The first stage of CLIC operates at collision energy of 380 GeV for a site length of 11 km. It demands about 21630 accelerating structures. The present number of qualified suppliers for both machining and joining techniques is limited. Therefore, an industrialization study was done through a technical survey with qualified hi-tech companies. The aim is to evaluate capabilities of the current suppliers, to ensure the necessary manufacturing yield, schedule, and cost for mass production. Moreover, the strategy for ramping-up the production volume is individual to each supplier. The study will be followed by preparing an implementation strategy, which includes organization of the supply among different companies and quality assurance scheme. This note presents the results of the industrialization study for 12 GHz accelerating structures for CLIC 380 GeV, highlighting the principal challenges towards mass production.

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Contents

1. Introduction..3
2. State of the art..4
2.1. Production flow 4
2.2. Material flow 6
2.3. Accelerating structures cost estimation 6
3. Motivation..7
3.1. Research questions..8
4. Similar study 8
5. General framework 9
6. Data collection 10
6.1. Participants 10
7. Manufacturing strategies 11
7.1. Production volume..12
7.2. Ramp-up and ramp-down 13
7.3. Project timeline 16
7.4. Afterwards use of the production space..16
7.5. Delivery strategy..17
7.5.1. Traceability 19
7.5.2. Packing 19
7.5.3. Transport..20
7.6. Investment and manufacturing cost 20
7.6.1. UP machining 20
7.6.2. Assembly 21
7.6.3. Sub-contracting operations 24
7.7. Quality and process yield..25
7.7.1. Communication..26
7.8. Production process and production layout. Automation..26
8. Discussion..28
8.1. R&D from companies' perspectives..29
9. Conclusion 29
10. Acknowledgement 30
11. Raw data 30
REFERENCES 31
Annex 2 Documentation list 32
Annex 3 Drawings and 3D models list 32

1. Introduction

The LHC will continue its operation for approximately 20 years. Simultaneously, diverse studies are conducted for the design of a future large-scale machine. One of the options is the Compact Linear Collider (CLIC) [1]. CLIC is a multi-TeV electron-positron machine under development by the international accelerator collaboration. For the optimal exploitation of its physical potential the accelerator is designed for three consequent phases with the collision energies of 380 GeV, 1.5 TeV and 3 TeV respectively and with the length range of two linacs from 11 to 50 km. To be compact, the design aims to provide a very high accelerating gradient (100 MV/m) achieved by incorporating normal conductive radiofrequency (RF) cavities operating in X-band range (12 GHz). Each accelerating structure is a complex component implicated ultra-precise machining and diffusion bonding techniques [2]. The manufacturing tolerances, driven by achieving the required RF performance, and time constraints make the supply of the components challenging. Thus, accelerating structures production is one of the cost-drivers for the CLIC project. As of the project implementation plan (PiP) from 2018, procedure and steps needed to reliable manufacturing large quantities still need to be developed [3].

The construction of the first CLIC energy stage is proposed to start by 2026 with the first beams to be available by 2035, see Figure 1. Accordingly, a six years' preparation phase is foreseen prior to the construction start. At that time an industrial procurement preparation and pre-series studies have to be accomplished.

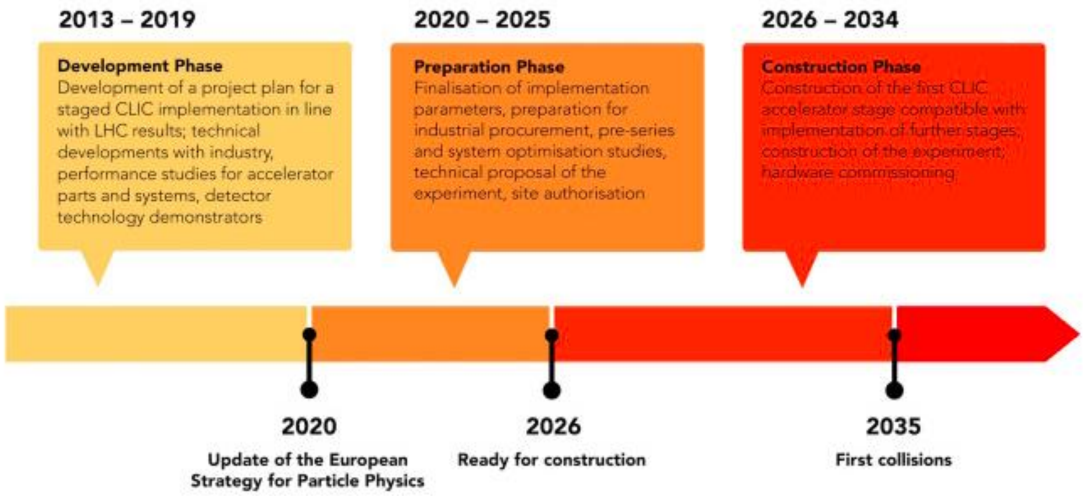

Figure 1. CLIC implementation schedule

Based on the technology-driven schedule shown on Figure 2 the first phase takes seven years, dividing into five years for construction, installation, and two years for commissioning of the machine. Considering, complicity of the machine and given number of components, it is a challenging task for all stakeholders of the project.

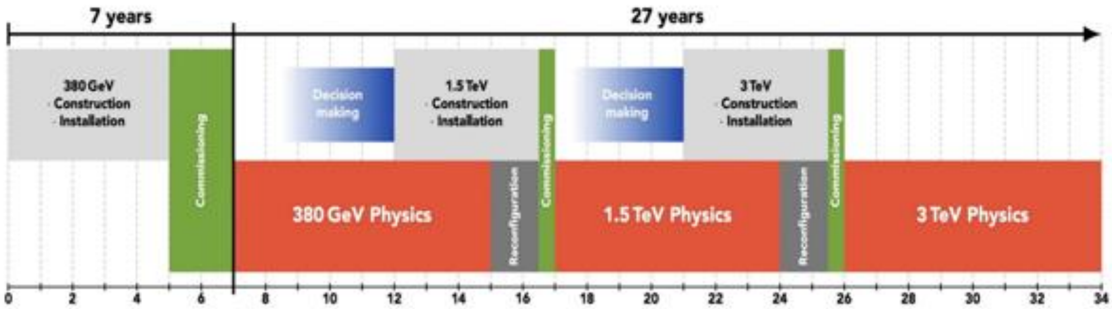

Figure 2. Technology and construction-driven CLIC schedule

Only the first stage of CLIC operating at collision energy of 380 GeV for a site length of 11.4 km [3] demands around 21000 of assembled accelerating structures. Nowadays the prototypes procurement and machining require from six months to one year, depending on the company experience in the ultra-precise machining and years of collaboration with CLIC. Moreover, assembly time is also depending for the moment on the companies' experience, particularly on the collaboration with CLIC for accelerating structures bonding and brazing. Thereby, a company who has produced or assembled prototypes faced already diverse problems in almost every stage of manufacturing, starting from 3D models converting, CNC machine's programming, raw material properties, milling cutters selection, fixation tooling, achieving tolerances and choosing the right and effective machining or assembly strategy and quality control. Furthermore, supplier's location can be crucial for problem solving and consulting. The previous experience demonstrated that close by location of production premises reduces the problem-solving time and allows to interact more often and more efficient.

2. State of the art

Firstly, to have an overview on the state of the art a literature review has been done. The large part of found scientific publications is related to the general term of industrialization as a process of economy transformation from a traditional to an industrial development stage. The process is linked with new technologies development. Industrialization is considered as a more global process of economy revolution, while for the purpose of the current study industrialization is considered as transformation from a lab prototype to industrial mass production. The process includes knowledge and technology transfer from a big research infrastructure (RI) to industrial partners, along with consortium establishment to meet quality requirements and the time constraints. In the context of the present study, industrialization includes development and building a reliable production system. Thus, industrialization activities final goal is to make the product possible to produce in required volume to the customer [4]. Authors discussed two other concepts – product introduction and methods planning as synonymous to industrialization. They distinguish three main industrialization aims: (1) manufacturable products; (2) selection and design of production process and (3) secure production. Furthermore, two critical components of an industrial study are cost-saving and timing. Thus, according to [5], those two factors can be consider in the framework of:

(1) The reduction in manufacturing labor hours, connected to the workers training and learning to correctly perform tasks.
(2) Rethinking the production process (if possible) and implementation of automation.
(3) Removing unnecessary constraints (tight tolerances).
(4) Improving in logistic.
(5) Advantage of the scale factor – bigger order, better conditions, and price.

Finally, the results of an industrialization study have to include a defined achievable limit on the cost saving, determined the upper limit of production scale up. Furthermore, the authors [5] suggest to quantify the learning slope, based on the real manufacturing data, and compare this value to other advanced industries. Similar studies are discussed below in the present document in a separate chapter.

2.1. Production flow

TD26 accelerating structure is used as a baseline for the study. The prototype contains 29 discs from oxygen free copper (Cu-OFE). Discs are joint together by diffusion bonding at a vacuum oven under protective atmosphere as Hydrogen partial pressure.

The production flow of X-band accelerating structures has been established and demonstrated by assembling various CLIC prototypes [2], see Figure 3. Currently, ultra-precise (UP) machining and heat treatment (HT) operations are provided by two different categories of

suppliers with intermediate acceptance tests at CERN. The whole workflow cycle is from ten to twelve months. The current production rate depends significantly on the previous experience of supplier, whether the company has already delivered parts or assemblies to CLIC.
However, for mass production several operations are suppressed such as the final tuning. Eventually it eliminates the step of the tuning studs brazing. Furthermore, numerous HT jobs can be done simultaneously, such as brazing of couplers and cooling circuits. Additionally, further optimization of production must include determination of a batch size, represented by the number of structures which can be brazed as a group at the same heating cycle. The latter requires assessment of vacuum furnace dimensions, electricity and space consumption, risk evaluation in case of the failure.

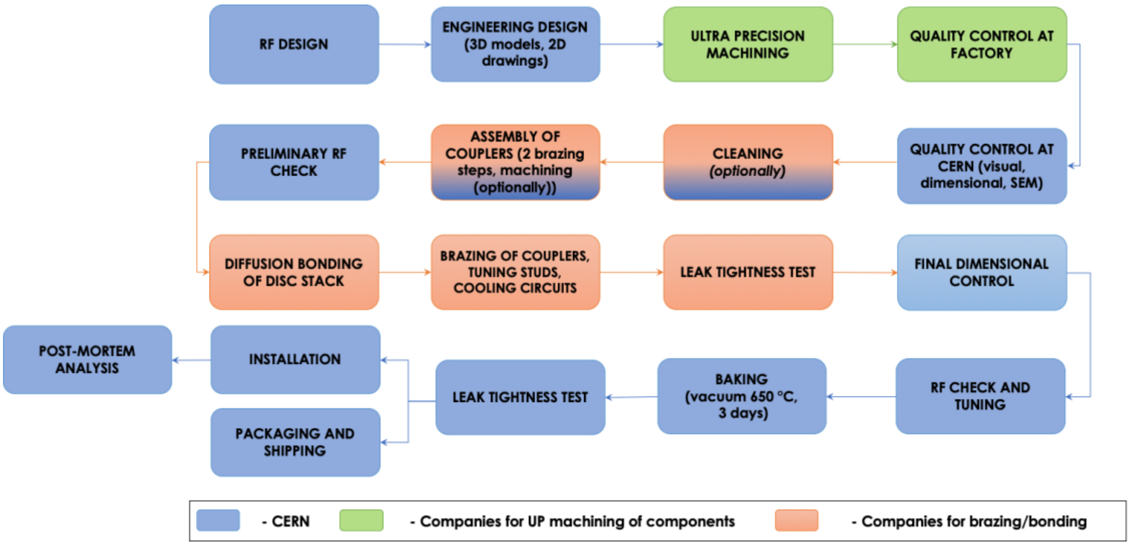

Figure 3. Production flow for CLIC AS prototypes

Thereby, one of the objectives of the industrialization and later of the CLIC preparation phase is to take all constraints into account and to scale fabrication from the current prototype to mass production rates, see Table 1: by sharing production volume between two suppliers the manufacturing rate for discs increases from one to 251 discs per day; for the assembly – from 0.1 to 8.65 assemblies per day, counting 20 and 250 working days per months and per year respectively.
Furthermore, currently, UP machining and HT operations are provided by two different categories of suppliers with intermediate acceptance tests at CERN. For the mass production intermediate steps between concerns need to be negotiated and set up together with strategies for quality control, store, and delivery.

Table 1. Prototype vs Mass production

Operation	**Prototype**			**Mass production (100%)**	
				Number of structures	*21630*
				Number of discs	*627270*
	Responsible	*Time*	*Rate*	*Responsible*	*Rate*
UP machining	Company 1	6 months	*1 disc/day*	Company 1/ Consortium	502 discs/day
Acceptance tests	CERN	3 months		Company 1,2/ Consortium	
Assembly	Company 2	1-2 months	*0.1 as/day*	Company 2/ Consortium	17.3 ass/day
Machining of couplers	CERN	1 months		Company 2/ Consortium	
Acceptance test	CERN	0.2 months		CERN	
Full production		10-12 months			5 years

2.2. Material flow

Material flow represents movement of raw material, parts, assemblies during the product lifecycle. Following the production flow in the previous section, the material flow splits into three: material flow (1) in an UP-machining workshop (Company 1/consortium), (2) in a HT operations workshop (company 2/consortium) and (3) in acceptance test facilities (CERN). The intermediate steps between concerns need to be negotiated and set up together with strategies for quality control, store, and delivery. Particularly, the links between three main actors, Copmany1, Company 2 and CERN, needs to be established. Figure 4 represents the existing condition where CERN is responsible for the quality of raw material, intermediate controls between two suppliers and for final acceptance tests. Whereas for the mass production several roles of CERN can go to one of the two stakeholders. CLIC management must identify the level of interference and responsibility of each participant for raw material, machined parts, and final assemblies.

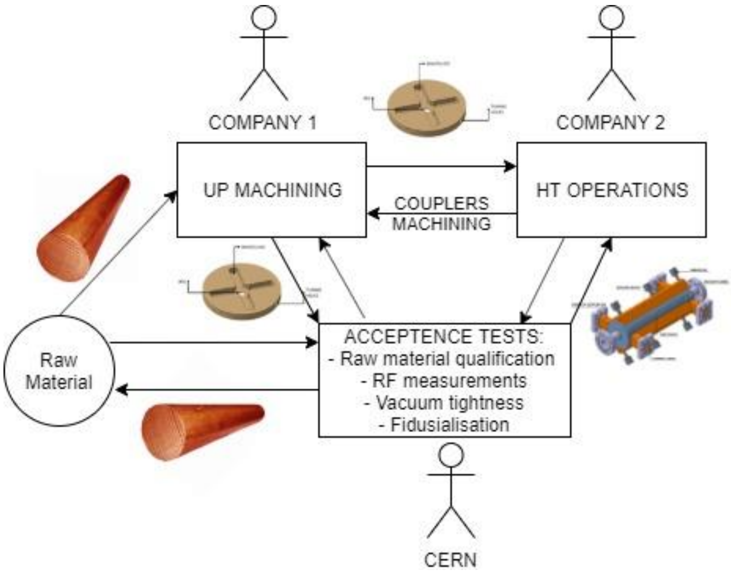

Figure 4. Material flow

2.3. Accelerating structures cost estimation

Accelerating structures are one of the cost-drivers of CLIC accelerator, considering its complexity, limited number of qualified suppliers and price estimation. Therefore, during an active development phase of the project from 2013 – 2019 one of the objectives was to demonstrate cost-effective series production of X-band accelerating structures. More than twenty of 12 GHz accelerating structure prototypes have been fabricated and tested to prove scientific concept and study feasibility and price formation. According to CLIC PiP [3] Main Linac Modules represent about 22.6% of the total CLIC 380 GeV cost.

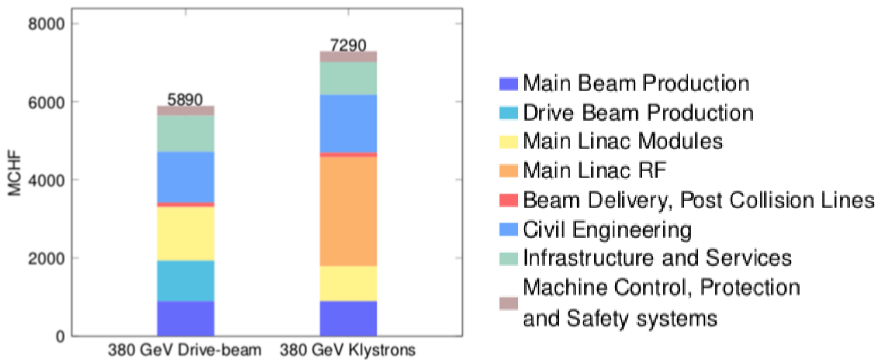

Figure 5. Cost breakdown for the 380 GeV stage of CLIC accelerator, for the Drive-beam and for the Klystron options [3].

The cost of accelerating structures is estimated at about 37% of a two-beam module cost which arrives to about 8% of the total cost of the accelerator. Therefore, the reduction of accelerating structures cost has significant impact on the cost of the whole accelerator. The final prototype cost of an assembled structure is calculated and represents in the range between 75 to 95 kCHF. The prototype cost depends on the complexity of the disc shape, experience, and reliability of a supplier. Based on the learning curve for repetitive machining [6] and used learning percentage for the LHC dipoles [5] of 85% - 90% the cost of the structures for the series production goes down by factor three. In terms of the manufacturing rate: machining has to be scaled from one disc to 502 discs per day, while the total assembly has to be scaled from 0.1 cavity to 17.3 cavities per day. For the study purpose a rough estimation of the total number of 21630 accelerating structures for the first CLIC stage of 380 GeV is applied. Construction time estimated to seven years where five years is assigned for production.

3. Motivation

The CLIC is an international study of the large-scale particle accelerator, representing similar implementation scale to existing Large Hadron Collider at CERN. The number of hi-tech components to be fabricated for CLIC is large. Therefore, a collaboration with industrial partners is essential. In the meantime, technology transfer is a complicated and time-consuming task. To encounter the challenge, the CLIC production team has launched an industrialization study. This paper describes the study and summarizes the main findings by describing industrialization approach and foreseen strategy for the mass production of accelerating structures by industrial partners.

During the last decades CLIC production team has tested diverse prototypes of 12 GHz X-band accelerating structures. Firstly, production of this kind of components requires an interest from companies to collaborate with RI. Since in the most cases initial investments in in-house R&D from a firm are demanded for manufacturing a qualification part. Moreover, benefits and outcomes of the university-industry collaboration often are unobvious and intangible. Secondly, a firm must be keen and able to develop a technology until the required level if it is not yet developed. For normal conductive CLIC accelerating structure, the technologies are represented namely by (1) ultra-precise single-diamond machining and (2) diffusion bonding in a vacuum oven under hydrogen partial protective atmosphere. Even though the ultra-precise machining technology has been existing already for more than 70 years (Yuan et al., 2017) the World market of providers for 12 GHz accelerating structure discs is extremely narrow. Thus, it challenges the manufacturing full volume of accelerating structures in limited time, in case of the CLIC project approval and receiving a green light for realization. Therefore, for the purpose of the study, industrialization strategies of other international scientific projects such as LHC [7], ILC [8] and XFEL [9] are examined. Based on their experience an industrial survey among qualified suppliers for machining and assembly of 12 GHz accelerating structures for CLIC was launched.

The industrialization study reflects interests of different stakeholders of the international study: a study team, CLIC management and industrial partners. Consequently, research questions are developed for two concerned groups: companies and the CLIC team.

Thus, industries participate in an imagination exercise: companies are asked to think about a situation where they need to produce 21630 accelerating structures in five years. Potential suppliers are guided through critical questions for preparation to mass production by a provided technical questionnaire, as a .doc or .pdf format file. The document contains questions about required investments, efficient production process, quality assurance, yield etc.

In turn, the CLIC team and management of RI serves the industrialization study to evaluate capabilities of the current suppliers, take corrective actions if required, to optimize and to

improve the cost model, to prepare a project implementation strategy. The latter includes organization of the supply among main stakeholders, quality assurance and delivery.
Finally, the study is driven by several critical factors, playing an essential role for industrialization: (1) short list of the qualified suppliers; (2) even shorter list of the qualified suppliers who are ready to cooperate for the project realization, considering required initial investments; (3) time constraints of the project.
The accelerating structures supply in time should become a common aim of the industry and RI. To achieve the goal main actors must establish sustainable relationship clearly defined responsibilities. Moreover, the findings of the industrialization study can be of interest for the scientific community, highlighting important steps and complexities in a project implementation phase of similar nature developments.

3.1. Research questions

The abovementioned derives us to the following research questions:
RQ1: Does CLIC have enough suppliers?
RQ2: How should the supply be organized among different companies?
RQ3: What is the most efficient production process?
RQ4: What kind of investment will be needed and how this will affect cost?
RQ5: What is the ramp-up and ramp-down production time?
RQ6: What quality assurance needs to be put in place? How does it affect the cost?
RQ7: What yield is expected?
Hence, the technical questionnaire is directed to response to those questions. The results of the study are presented in the subsequent sections.

4. Similar study

Similar studies were conducting for other accelerator machines and facilities, summarized in the Table 2. Comparing to the ILC study [10] where the detailed scenario was established only by one company the present study combines a comprehensive view on the strategy by different suppliers from different operational fields. The demanded production rate of accelerating cavities for CLIC 380 GeV phase is quite high, even in comparison to other projects.
The benchmarking studies for XFEL and ILC are using superconducting technologies and therefore they focus on the production of cryomodules [10]. Consequently, the fabrication involves slightly different production technologies and dimensions. Whereas SwissFEL and CLIC are using normal conducting (warm) accelerating structures, SwissFEL in C-band range while CLIC in X-band [11]. In contrary to CLIC and ILC, XFEL and SwissFEL are operational machines, constructed and commissioned recently. SwissFEL together with many other prototype assemblies proved feasibility and the concept of technologies used in CLIC. The technology is mature and ready for industrialization.

Table 2. Relevant studies

Project	Technology	Numbers of cavities	Production sharing	Cavity production	Production period (years)	Production rate (cavities/day) (at 250 work-days/yr)
XFEL	Superconducting	800	50%	400	2	0.8
ILC	Superconducting	7800	33%	2600	9	1.15
SwissFEL	Warm C-band	104	100%	104	2	0.2
CLIC 380 GeV	Warm X-band	21630	100% 50% 33%	21630 10815 7210	5	17.3 8.65 5.77

The XFEL cavity production was contracted to two companies. The industrialization experience of one of them is presented in [12]. The company had to ensure the delivery rate of up to five cavities per week, required initially from the XFEL project management. The requirement on the initial rate was slightly relaxed during setting up production. Finally, the manufacturing was ramped up to four cavities per week. The series production was released only after completion and successful testing of four set-up and eight pre-series cavities. Four reference cavities were used to set up infrastructure, personnel training and verify process flow, afterwards eight pre-series cavities were tested. ILC having larger and more challenging application of superconducting RF accelerator technology, is incorporating the XFEL industrial experience in its own industrialization strategy [8], [13]. Moreover, one of the parts of global industrial exploration is possible cost savings of the fabrication process. ILC considers that they can use the same learning percentage reached between 85% and 90% after 45 produced units as in LHC superconducting magnet production [5]. The LHC main dipoles are delivered by three suppliers. All three companies were asked to fabricate a pre-series of 30 magnets and then prepare an offer each for 386 magnets of the main production. The production is considered to have reached industrial maturity, showing the high learning percentage similar to aerospace and complex machine tools industries. The high learning percentage, evaluated for the first period of series production, was achieved due to extensive process setting up for the first unit, introduced automation and strict inspections by a resident CERN specialist. Thus, LHC project can be used as benchmarking for other comparable-scale scientific projects. Moreover, there are other industrialization studies for LHC critical components, a few examples of them are the interconnections of the LHC cryomagnets [7] and activities related to CMS coil winding [14].

5. General framework

CLIC industrialization study consists of series of technical visits, meetings, and information collected through a technical survey. The framework is built on the literature review of the previous studies. The questionnaire is designed to facilitate to industrial partners to go through main milestones and obstacles of the industrialization process and as a result to allow to develop a first draft of manufacturing strategy for CLIC accelerating structures. A baseline configuration of a tapered damped (TD) accelerating structure, so-called TD26, is used for the study,

Figure 6. Companies studied the provided technical documentation to evaluate the best production strategy in terms of time, cost, manufacturing volume etc.

TD26 structure is chosen due to several important aspects: (1) the RF design is confirmed; (2) the assembly procedure is well defined and proved not only by CLIC but also by collaborators for different in-kind projects; (3) easy to scale to the final CLIC module structure. CLIC 380 GeV stage requires about 21630 structures.

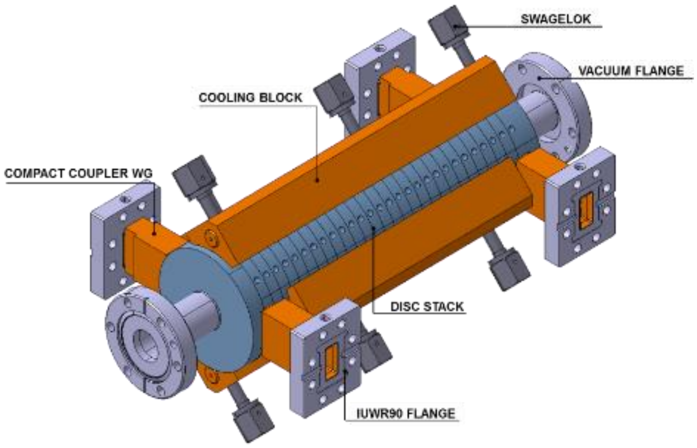

Figure 6. CLIC accelerating structure prototype - TD26

The questionnaire is divided into three sections according to the preferable production case: manufacturing discs, manufacturing halves or full assembly supply. Manufacturing of discs or halves includes ultra-precise machining (UP) while a full assembly supply includes both UP machining and heat treatment (HT) operations. Companies are asked to study the provided technical documentation (see Annexes 1-3) and to choose a more reasonable scenario in terms of investments, time, and risks. Required production volume showed below in Table 3.

Table 3. Accelerating structures production volume

	Fraction of total no of structures	**Discs (type A)**	**Halves (type B)** ***Optional***	**Assembly (discs)**	**Full assembly (disc version)** ***Optional***	**Production period**
Scenario 1	100%	627 270	43 260	21 630	21 630	5 years
Scenario 2	50%	313 635	21 630	10 815	10 815	5 years
Scenario 3			*% proposed by company*			5 years

To accomplish the production of discs and full assemblies in five years, in case of scenario 1, 100% volume, the production rates are 502 discs/day and 17.3 structures/day, respectively. Corresponding production rates for 100% and 50% of the supply are presented in Table 4. However, the scenario 1 is unrealistic and unsafe since CLIC management would not take so high risk to give supply only to one company. The scenario 1 is mainly considered for the evaluation reason as the most extreme case.

Table 4. Accelerating structures production rate

Fraction of total no of structures	**Production rate (discs/day) at 250 work-days/yr**	**Production rate (halves/day) at 250 work-days/yr**	**Production rate (cavities/day) at 250 work-days/yr**
100%	501.82	34.62	17.3
50%	250.91	17.3	8.65

The technical survey leads companies-suppliers through questions on the full manufacturing cost, required investments, production curve, comprising ramp up and ramp down phases etc. The answers have been treated and summarized in the ensuing sections of this document.

6. Data collection

The data collection is done via technical visits, meetings, and the technical questionnaire. The industrial survey was distributed among qualified potential CLIC suppliers accompanied by the technical specification, technical drawings, and fabrication procedures. The provided documents are listed in Annexes 1-3.

6.1. Participants

Twelve qualified suppliers have been contacted for the aim of the study. The firms provide either UP machining or HT operations or both service sectors. The companies are classified with respect to their continent or to provided service. For the further evaluation the company codes ECx and JCx for European and Japanese companies accordingly are introduced. Seven current European CLIC suppliers EC1 to EC7 have been asked to fill the technical questionnaire: four UP machining companies and three companies for HT operations. The study was extended to the Asian market via our Japanese collaboration, who had already established contacts for CLIC accelerating structures manufacturing. Consequently, five Japanese companies were included in the survey JC1 to JC5: four UP machining and one company for both services. In the past the mentioned Asian firms had already demonstrated the quality by producing several CLIC prototypes. In addition, two Japanese companies JC1 and JC4 had already a direct contact with CLIC team for qualification and supply of prototype structures.

Approaching an Asian market brings numerous perspectives for the research. Firstly, Japanese companies are well known for quality and time respect. Secondly, by increasing the sample group an additional data for the evaluation is accumulated. And thirdly, but one of the most important for the CLIC management, by involving more companies the list of CLIC suppliers is enlarged. The sample group of contacted industrial partners is presented in the Table 5. The companies are from seven countries, see Figure 7. Any identifiers or information which allow to recognize firms or to link with given records are avoided for confidential purpose. Two suppliers JC4 and EC5 were excluded for the further estimation: EC5 is not interested to participate; JC4 data is partial. Consequently, the industry evaluation is realized for ten companies.

Table 5. List of companies

Nr	Company code	Operational Field	Experience	Technology for CLIC	Desirable volume
1	JC 1	UP machining	One structure	UP machining	8.6%
2	JC 2	UP machining	With a collaborator	UP machining	100%
3	JC 3	UP machining	With a collaborator	UP machining	100%
4	JC 4	Moulding	Qualification part	UP machining	ND
5	JC 5	Assembly	With a collaborator	Full supply	100%
6	EC 1	Assembly	One structure	Assembly	50%
7	EC 2	UP machining	Structures	Assembly	12.3%
8	EC 3	UP machining	Structures	Full supply	30%
9	EC 4	UP machining	With a collaborator	UP machining	100%
10	EC 5	UP machining	Structures	UP machining	ND
11	EC 6	Assembly	Structures	Assembly	100%
12	EC 7	Assembly	One structure	Assembly	19.3%

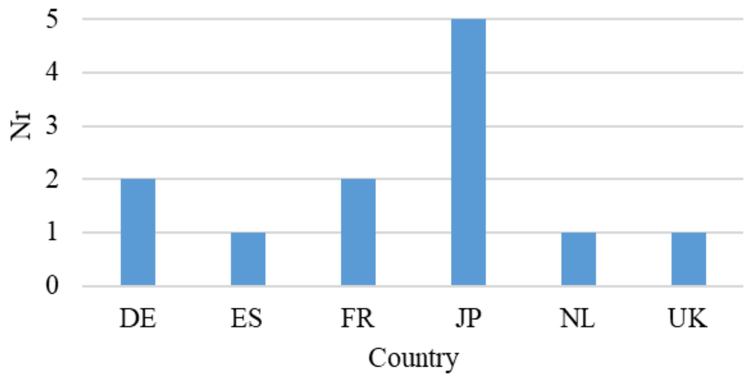

Figure 7. Companies per country

7. Manufacturing strategies

This section summarizes the results and main outcomes from the industrialization study. Companies' strategy to approach manufacturing of 21630 accelerating structures with their opinion on the consortium and further use of the developed production facilities as well as time and investment required for the ramp up, regular production capacity and ramp down phases are described. Objectives for a production system are usually expressed in terms of cost, quality, flexibility, and deliverability [4]. In the findings three out of four factors are discussed: cost, quality, and deliverability. Since the aim of the current study to analyze production systems for manufacturing the same component (TD26 accelerating structure) repetitively or continuously flexibility of the process is not discussed.

7.1. Production volume

Companies were asked to specify the production volume up to which they consider reasonable to scale their production. There are three scenarios: 100%, 50% or their own value. Obviously, not only for companies but also for the management of the project it is quite risky to have only one supplier of the product. Therefore, the companies choose the desirable volume taking into consideration, required investment, time limits, and afterwards use of new production premises once the project is completed.

The first study outcome showed that the CLIC study has enough suppliers for manufacturing and assembly of 21630 accelerating structures. The distribution of the chosen production percentage is not homogeneous, but it covers the CLIC needs. Based on the technical survey five companies are interested in manufacturing discs, three companies are interested in heat treatment operations supply and two companies are interested in the full assembly supply, see Table 6. Five companies demonstrated an interest in 100% production. No information received on halves manufacturing. JC3 showed an interest in the halves production and supplying a full assembly but the firm requires prior research to provide any data on the process.

Table 6. Chosen scenario and fraction.

N	**Code**	**Desirable volume (%)**	**Production volume discs**	**Production volume assemblies**	**Current capacity discs/day ass/day**	**Technology for CLIC**	**Required capacity discs/day or ass/day**	**Scaling coefficient**
1	EC2	12.3	77000		12	UP machining	72	6
2	EC4	100	628000		0.42	UP machining	502.4	1196
3	JC1	8.6	54000		7.5	UP machining	45	6
4	JC2	100	627270		ND	UP machining	501.8	ND
5	JC3	100	627270		4.04	UP machining	501	124
6	EC1	50		10815	0.1	HT operations	8.65	86.5
7	EC6	100		21630	0.1	HT operations	17.3	173
8	EC7	19.3		4000	1.6	HT operations	3.2	2
9	JC5	100	627270	21630	8	Full supply	501	63
10	EC3	30	188181	6489	6.25	Full supply	167.3	27

Graphically representation of companies' distribution based on different production cases and the market location is illustrated on Figure 8.

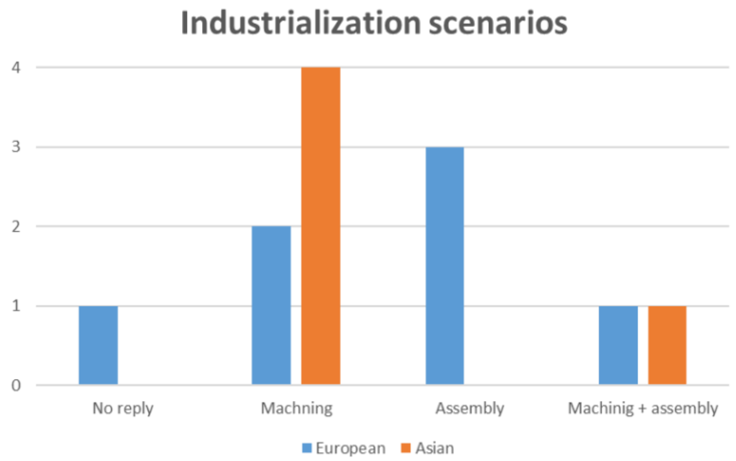

Figure 8. Industrialization scenarios

The comparison of the scaling coefficients depending on the chosen manufacturing strategy for CLIC is shown in the Table 6. The graph Figure 9 demonstrates the overall range of the production scale and highlights an extreme case of EC4. The scaling coefficient for production differs depending on the desirable volume and existing facilities, and experience with CLIC.

EC4 demonstrates a high scaling coefficient, which can be explained by low volume of the current production for CLIC. The company is qualified, but it has supplied few orders due to the cost-formation policy. Otherwise, two medium-size machining companies JC1 and EC2 intend to scale their current capacity by factor six with similar proposed production contribution to CLIC, around 10%.

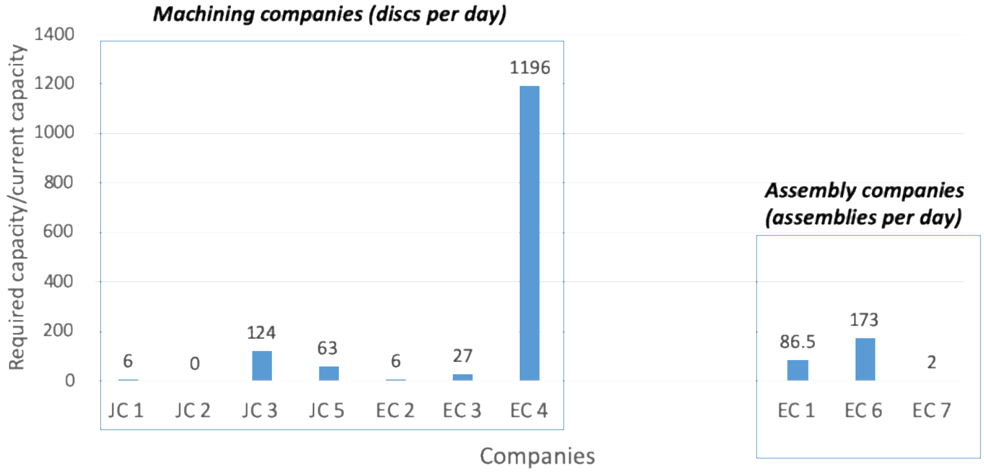

Figure 9. Scaling coefficients

Increasing the production capacity is resource consuming. Companies need to prepare new facilities and to hire new workers. Therefore, the next sections are focused on the demanded investments and duration of main production curve phases (preparation or ramp-up, stable production and ramp down). Critical for CLIC is a ramp-up phase of companies manufacturing plans since it impacts the CLIC construction schedule. The ramp-down phase is more essential for involved firms since they ought to slow down the production to have as less as possible idly premises.

7.2. Ramp-up and ramp-down

The production is organized in three main sections: ramp-up, regular production and ramp-down, see Figure 10. A preparation phase including installation and set-up is prior to the ramp-up, but for the purpose of the present study the both are joint and represented by one – ramp-up phase. A strategy for ramping-up the production volume is individual to each supplier. Therefore, firms are asked to specify the parameters of their production curve.

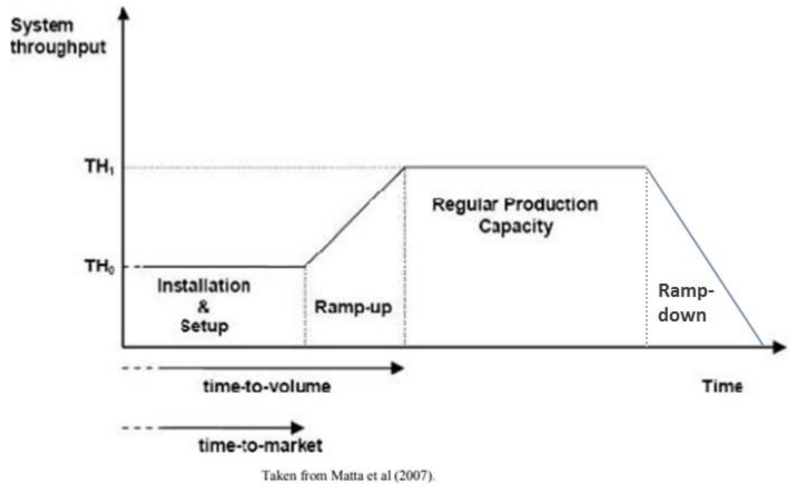

Figure 10. Production curve

Figure 11 reveals preparation phase with respect to a chosen production volume per a company. The ramp up phase incorporates all steps necessary to start the regular production. Mainly five years and two to three years of the preparation and the ramp-up were indicated for UP machining and HT operations companies accordingly. Two companies JC3 and EC4 did not specify the time required to arrive to the regular production. The ramp down phase is suggested between two and ten months (Figure 12). Additionally, the ramp down phase will depend on the future scientific strategy for CLIC, especially in case of extending to the further energy level of 1.5 TeV. It follows that the regular production phase is longer, and it postpones the ramp-down of manufacturing.

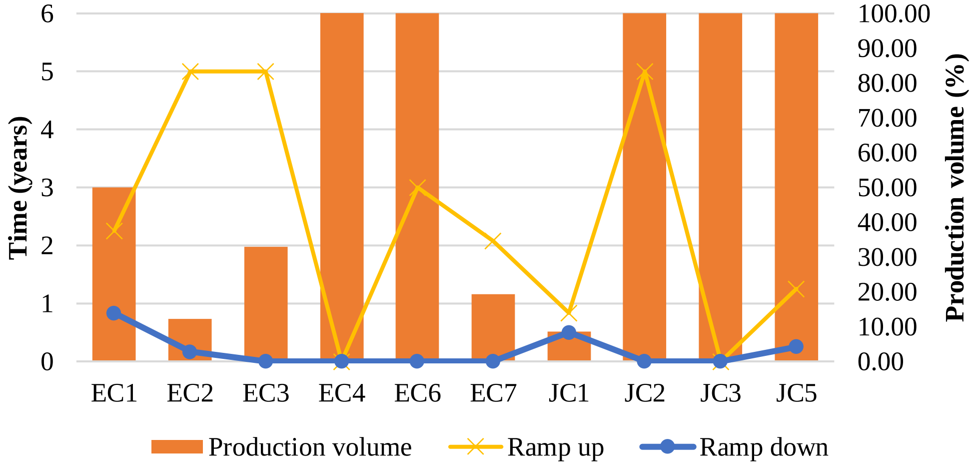

Figure 11. Production volume vs ramp-up and ramp-down

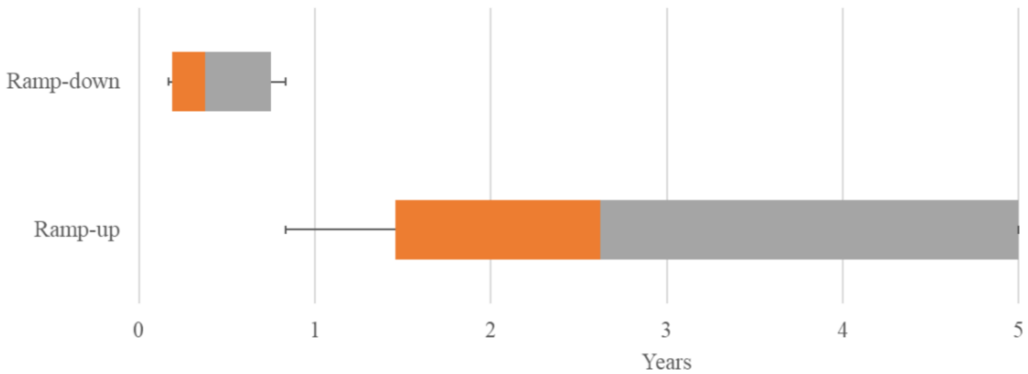

Figure 12. Ramp-up and ramp-down (whisker)

Table 7. Production schedule

Code	Technology for CLIC	%	Scale coef.	Ramp (months) up	Ramp (months) down	UP machines
EC 2	UP machining	12.3	6	60	2	Self-developed
EC 4	UP machining	100	1196	ND	ND	Self-developed
JC 1	UP machining	8.6	6	10	6	Commercial
JC 2	UP machining	100	ND	60	ND	Commercial
JC 3	UP machining	100	124	ND	ND	Customized
EC 1	HT operations	50	86.5	27	10	
EC 6	HT operations	100	173	36	ND	
EC 7	HT operations	19.3	2	25	ND	
JC 5	Full supply	100	63	15	3	Commercial
EC 3	Full supply	30	27	60	ND	Customized

A detailed representation of the ramp-up phase with respect to the preferred production volume is shown in Figure 13. The companies form four clusters: (1) who did not specify the duration

of the ramp-up phase (EC4, JC3), (2) who plan to use commercial machines (JC1, JC5), (3) who plan to use self-developed machines (JC2, EC2, EC3), and (4) who supply HT operations (EC1, EC6, EC7).
JC1 and JC5 companies plan to use commercial machines, machines presented already on the market. Those firms specify between 10 to 12 months of the time to regular production. Comparing to the manufacturing companies who plan to use self-developed machines and they ask for five years of the ramp-up since the new development is time-consuming. Three HT companies are found in concordance and ask about two to three years of preparation until the stable production.
Therefore, to summarize:

- Difference in ramp-up is explained by a choice of different machining strategies: customised, commercial, or self-developed machines.
- Consequently, less preparation time for companies who supposed to use commercial machines.
- Suppliers of HT operations need less preparation time.

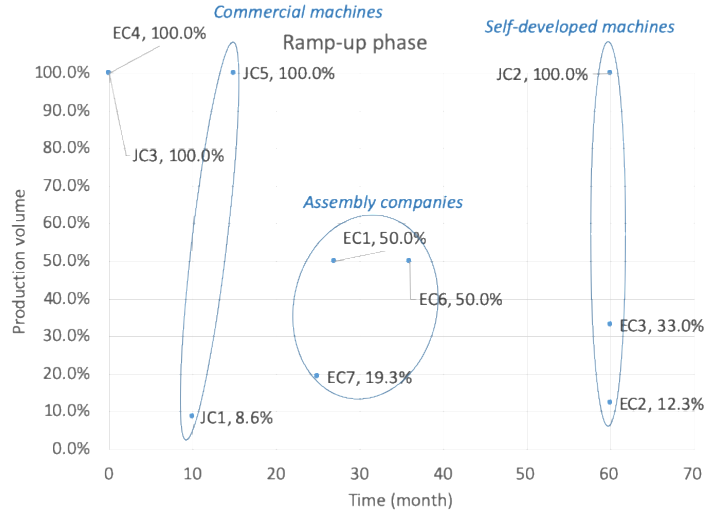

Figure 13. Ramp-up

Figure 14 reviews production curves of involved suppliers, measuring by numbers of assemblies per month for both UP and HT providers. The graph is built on the companies' estimations submitted via the survey. Six out of ten potential suppliers offered these data to the CLIC management.

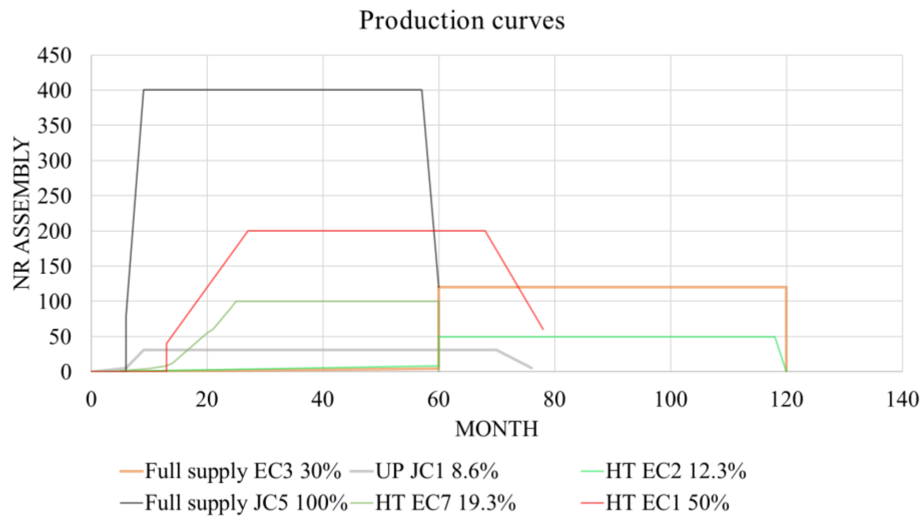

Figure 14. Production curves

7.3. Project timeline

Ramp-up phase specified by UP machining companies is between two and five years and for HT operations supplier is between two and three years. Therefore, the length of the production curve including the preparation phase not considering ramp-down (from ten to twelve months) arrives to 6.5 and 10 years for discs manufacturing and to five and 6.5 years for HT assembly. In the meanwhile, CERN has to be ready for performing acceptance tests: RF measurements, leak tightness check and fiducialisation[1]. Thus, a project timeline can be drawn as indicated in Figure 15. Initially disc manufacturing companies launch preparation of the production, secondly in two-three years HT operations suppliers organize the assembly premises, simultaneously CERN establishes acceptance test facilities. The delivery strategy is discussed lately in the present documents.

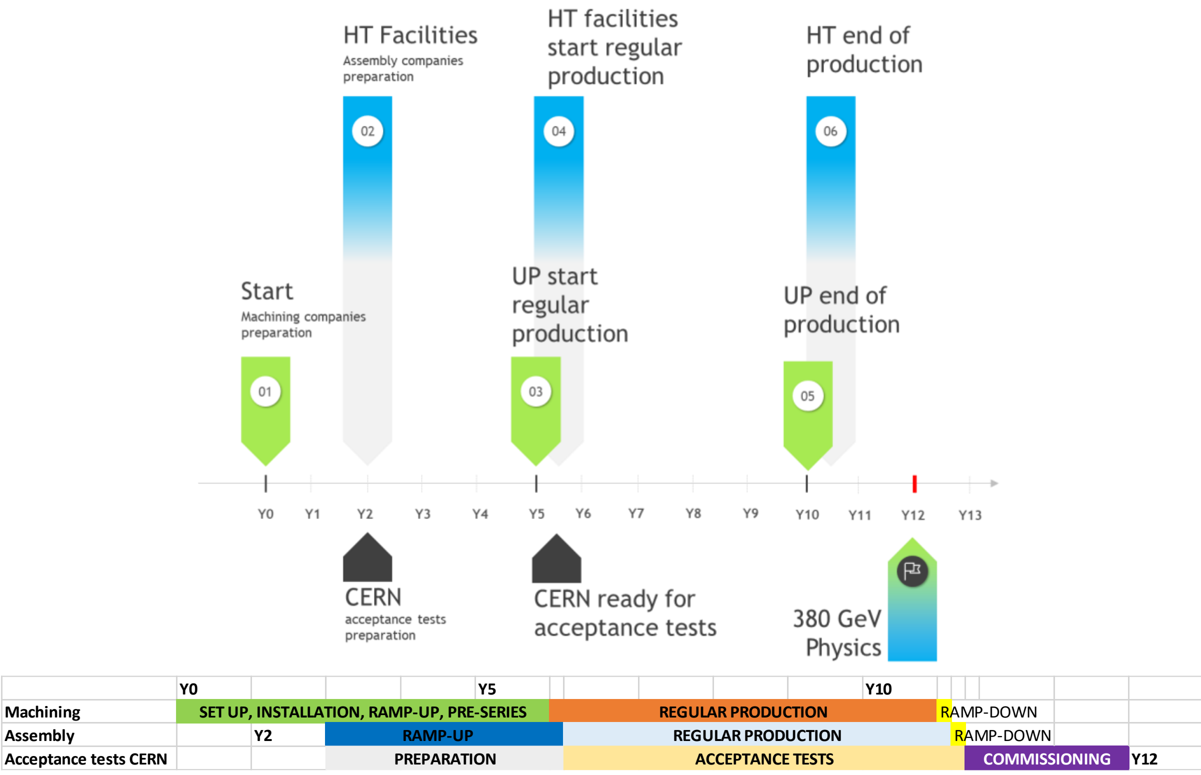

Figure 15. Timeline of CLIC 380 GeV

7.4. Afterwards use of the production space

The suppliers could encounter idle capacities after completing the mass production for CLIC, since they need to ramp down the manufacturing. Moreover, the investments are quite excessive for the preparation of premises to the mass production. Therefore, companies are asked to reflect on the further use of the fabrication sites. This consideration is also important for contractors to take a decision on the reasonable share of the CLIC accelerating structures production volume. However, the post-production strategy highly depends on the next step in the CLIC scientific program. Meanwhile companies believe to participate in the construction of the next energy stage of the experiment. Otherwise, industrial partners study to exploite the new premises or the part of them for other business lines. UP machining and vacuum furnaces as core technologies can be set up for processing of different parts and products. Few companies, as machine builders indicated a possibility of a minor modification of some UP

[1] Fiducialisation is the process of determining the position of component's reference axis with respect to external benchmarks, called fiducials, which will allow the component's alignment. The role of fiducialisation is to geometrically link the zero of a component to fiducials [17].

machines for wider production range. New CMM is a worthy supplement to companies' quality control department, which also creates an additional service for other clients. Additionally, CLIC-related spin-off and other high precision-related projects can profit from the new capabilities of the suppliers but in significantly less volume. However, the idea is to inform companies about the discussed problem that they can take it into account for the production organization.

7.5. Delivery strategy

Delivery strategy is one of the key points for maintaining continuous supply and schedule. Synchronization of deliver is important considering several stakeholders engaged in production flow. Thus, the material flowchart for manufacturing CLIC accelerating structures is presented in Figure 16. The smooth links between main production steps are essential. A company performing HT operations must receive in time the raw material (discs, cooling system, brazing material) to assemble parts and do not stop the production. It means that a machining company has to send their supply (copper discs) on schedule. In its turn, the latter must receive the raw material (copper bars) from CERN or from a firm-supplier to start the UP machining of discs.

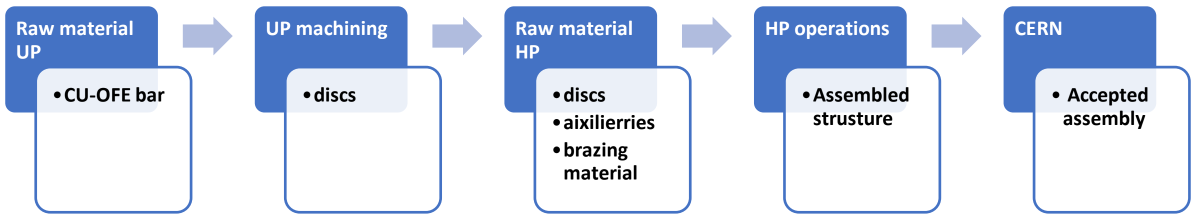

Figure 16. Material flowchart

Therefore, deliveries have to be organized between UP machining companies, HT operation providers and CERN. All stakeholders must establish a storage according to a chosen manufacturing and delivery strategy. For this purpose, in the framework of the present study companies-participants need to reflect on the delivery frequency and the storage place. A warehouse has to be arranged in a way to ensure constant supply and to prevent any delays, damages and other concerned risks.
Moreover, companies are asked to specify a schedule for raw material and final product supply. The results shown in the Table 8 demonstrate that the production can be organised uninterrupted based on the consistency in the suppliers' preferred delivery strategy.

Table 8. Material flow

Delivery frequency	**Raw material UP**	**UP discs**	**Raw material HT**	**HT assembly**
Monthly	70%	14%	60%	
Once a few months		14%		20%
4 times per year		14%		
Every 6 months	10%		40%	
Every year	20%			
Depending on the CERN assembly strategy		29%		40%
Weekly				30%
Bi-weekly				10%
ND		29%		

60% HT operation companies choose the monthly delivery frequency and 14% of machining companies are ready to meet this requirement. Additionally, 28% companies are ready to organise the supply of the discs once a few months and four times per year. The assembled structures will be delivered more often on weekly or bi-weekly basis. The latter allows to coordinate the acceptance tests at CERN in more efficient and reasonable manner.

The chosen industrialization scenario and delivery plans affect the dimensions of the storage and its location. UP machining companies specify their estimation on the raw material requirements varying for the chosen manufacturing scenario for CLIC, see Figure 17. JC5 indicates factor 1.5 more material than companies JC2 and JC3. Nevertheless, JC2 and JC3 companies' requirements are consistent with the rest of the suppliers, JC1, EC2 and EC3 and proportional to the chosen manufacturing scheme.

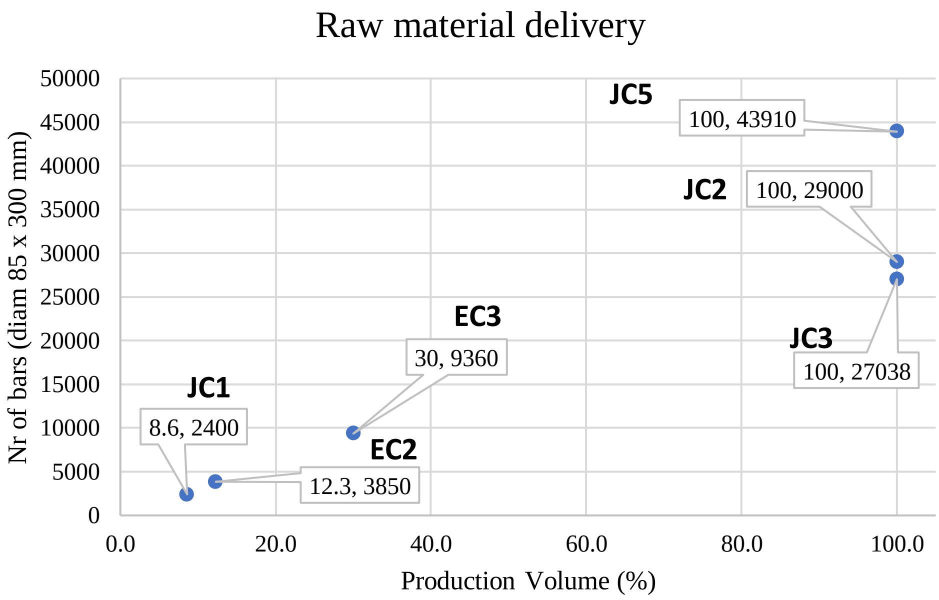

Figure 17. Raw material delivery. UP companies

Based on the raw material estimation in case of 50% fraction of the total production volume, CLIC demands to provide, and a disc manufacturing company needs to store monthly about 484 bars of the diameter 80 mm and the length 300 mm. Moreover, for the same fraction of 50%, the machining company requires to store about 5228 fabricated discs. Considering the dimensions (the height of 8 mm and the diameter of 80 mm) kept in a plastic frames of 10 cm x 10 cm x 3 cm, which gives the poor volume of 1.5 m^3. Table 9 shows an approximate volume and mass estimation for the warehouse in case of 50% production fraction for monthly and weekly deliveries. The table does not include the storage of auxiliary parts, such as brazing material, tooling, waveguides, flanges etc. However, the packing system discussed later in the present document is intended for the storage, as it diminishes manual manipulations with the final discs and assemblies.

Table 9. Storage estimation for every month for 50% CLIC volume

Part	Production fraction	Delivery strategy	Quantity	Dimension (mm)	Mass per unit (kg)	Box dimensions (mm)	Box mass (kg)	Poor volume (m^3)	Total mass (kg)
Disc	50%	Monthly	5228	Ø80 x 8	0.3	100 x 100 x 30	0.1	1.5	2091
Assy	50%	Monthly	181	362 x 186	16.6	330 x 540 x 300	30	9.7	8435
Disc	50%	Weekly	1307	Ø80 x 8	0.3	100 x 100 x 30	0.1	0.4	523

Assy	50%	Weekly	46	362 x 186	16.6	330 x 540 x 300	30	2.5	2109

7.5.1. Traceability

Traceability in production is ability to track every aspect of manufacturing and distributing a product. In the present study a product is either a machined disc or a final assembly. The companies-participants proposed few different approaches for traceability: (1) a unique engraved QR code per disc; (2) an ID per each part, engraved by a laser marker; (3) a serial number per each part, using barcoding system.

1. QR code: based on the large quantity, engraving strategy is proposed and must be aligned with CERN, as a unique QR code per disc.
2. ID: each part has own id and id is marked on the product using laser marker. Material id shall be corresponded to the parts id. Before id is marked on the product, intermediate processing products are always handled with special document which describes parts id and other required information.
3. Serial number: on each part will be written down in an assembling report and a test protocol. Parts will be supplied with a batch and serial no., these will be electronically logged using a barcoding system through the complete assembly process, including the final assembly being serialized. The data will be accessible through the SharePoint data base.

The parts should be marked during the machining process, for instant by CNC engraving, avoiding any hand manipulation. Moreover, a supplier proposed to manage production by lots with work sheets, indicating clearly involved workers, work machines, raw materials, and tools used for each production lot.

As an example, the bar code identification has been already applied for SwissFEL caps manufacturing, allowing to employ automatic stacking by a robot picker arm [15].

7.5.2. Packing

The companies, current active suppliers of accelerating structures, specified to use the current system of packing, developed by CLIC production team (see Figure 18). A transportation box is a custom metallic container, designed for two delivery missions: transport of machined parts and transport of assembled structure.

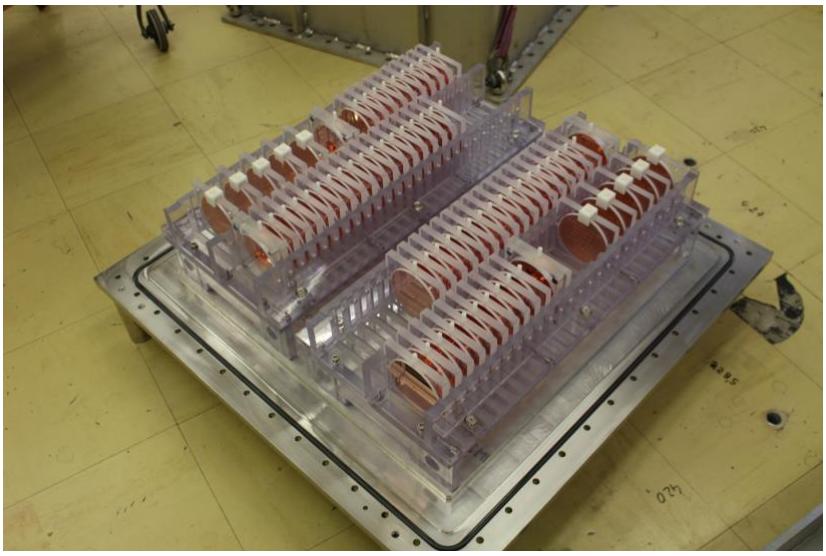

Figure 18. Transportation box

Each disc is installed in an individual thermoplastic (Makrolon®) frame and fixed inside by special pins. Once a disc is mounted in the frame, the frame protects it during further manipulations up to the delivery to heat treatment operation workshop, where the discs are dismounted and aligned for the bonding. Otherwise, the acceptance tests, such as visual inspection, dimensional control, SEM, and cleaning have to be performed without disassemble the frame. Thus, a disc cannot be damaged due to handling manipulation. Furthermore, the support is modified for fitting an assembled structure in the same metallic box. Transportation of parts and of assemblies are done under Nitrogen.

7.5.3. Transport

The final product transport will be selected in consideration of suppliers' location, cost and the most protective method. Thus, the involved companies propose the transport (1) by company's driver, (2) a ship for overseas shipping, (3) onto vehicle transported via sea ferry, (4) by a transporter vehicle.

7.6. Investment and manufacturing cost

7.6.1. UP machining

Companies requires certain funds to scale the production capacity to fulfil CLIC manufacturing needs. This chapter is focused on UP machining firms. They provided approximate evaluation of the necessary investments by main categories, manufacturing costs and UP machining cost breakdown of the supply unit, in this case of the copper disc, see Figure 19. The manufacturing cost in addition to investment breakdown includes the actual cost of supporting the production facility, considering electricity and maintenance. While the disc cost breakdown is more precisely focus on each single operation during the UP machining.

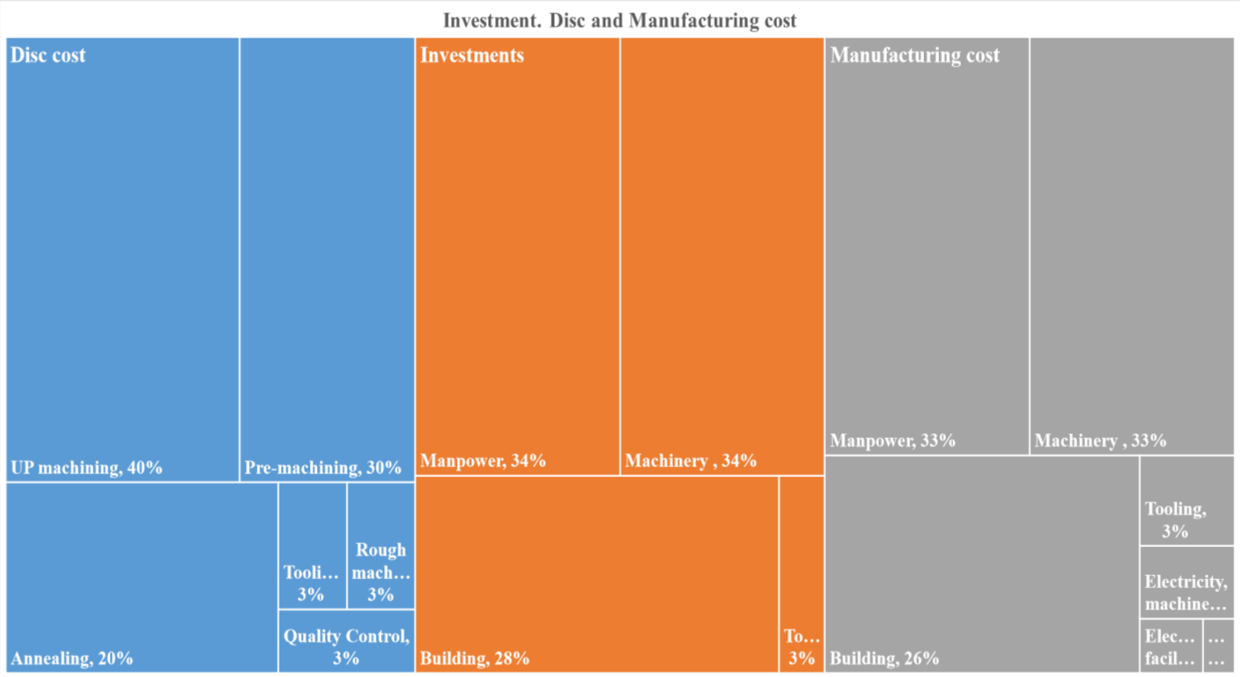

Figure 19. Investment and cost breakdown

The most part of disc manufacturing cost is manpower and machinery classes (see Figure 20). Consequently, these two are considering for bigger investments for both European and Asian suppliers. The investment has to be discussed with CERN in order to decide main stakeholders' contributions.

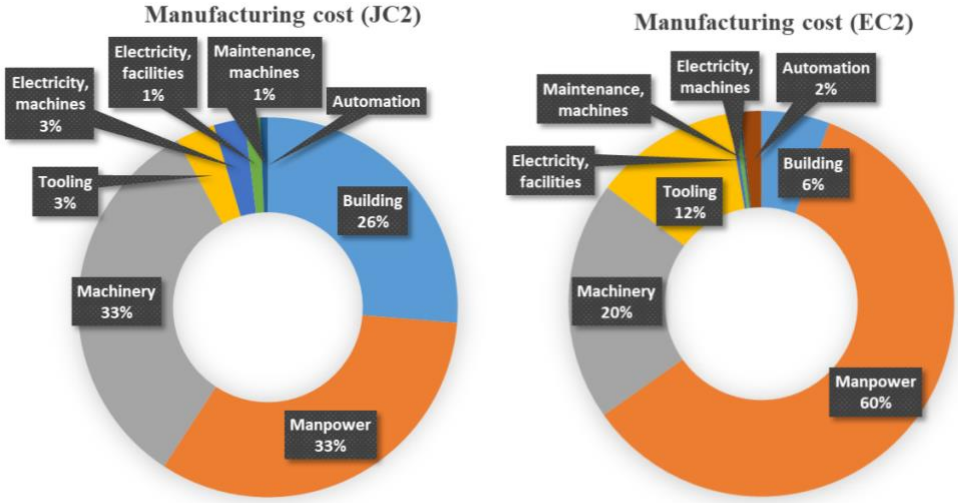

Figure 20. Manufacturing cost of discs

Based on the feedback from the machining companies, in the most optimistic scenario the cost of the disc decreases from the prototype by factor 4 (JC2), for the 100% supply. Whereas two current main suppliers indicate the drop of the cost by factors 1.5 (EC2) to 1.8 (EC3) for 12.3% and 30% respectively. For the final price of the manufacturing CLIC management needs to clarify contribution from main stakeholders on initial investments and carrying the manufacturing cost. The cost reduction according to the companies derives from shortening the end machining time, see Figure 21. To do the end machining including annealing and metrology in a range of 160 – 360 minutes. The latest can be achieved either (1) by pallet manufacturing, or (2) by using automated process, or (3) by reducing the number of measured parts, or (4) by using a self-developed machine.

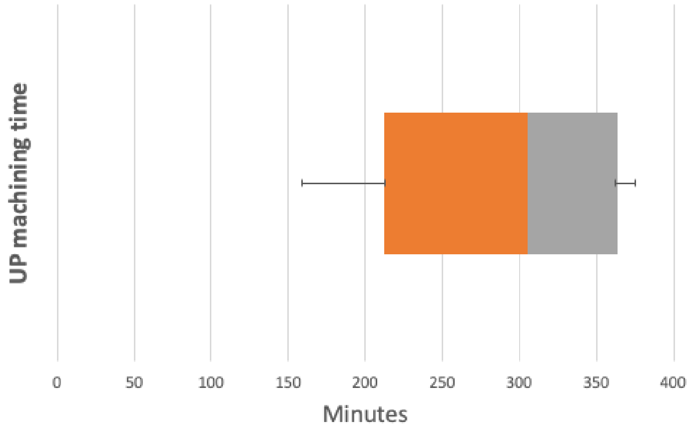

Figure 21. End machining time

7.6.2. Assembly

The assembly cost is evaluated by three companies, who have already had experience to assemble prototype structures and one company who is specialized on UP machining for CLIC and has an experience of assembling only mock-up structures:

EC1 – one assembled prototype.

EC3 – four assembled mock-up structures (supplier specialized on UP machining for CLIC).

EC6 – more than twenty assembled prototypes.

EC7 – one assembled prototype.

The cost estimation from companies providing assembly and including the quality control showed lower cost than for a prototype production. The cost of the assembly from mass production goes down by factor 2.5 for EC3 (30% supply), factor 4 for EC1 (50% supply) and EC6 (100% fraction), and by factor 7.5 for EC7 (19.3% supply). Companies EC6 and EC7 specified the batch size of eight structures. The reduction factors with respect to the appropriate contribution to CLIC are summarized in the Table 10. An average cost, for the disc and for the prototype assembly were used for comparison to mass production values. For the final price of the manufacturing CLIC management needs to clarify contribution from main stakeholders on initial investments and carrying the manufacturing cost.

Table 10. Reduction factors from prototype to mass production

Code	Desirable volume (%)	Production volume discs	Production volume assemblies	Technology for CLIC	UP Mass production (reduction factor)	HT Mass production (reduction factor)
JC1	8.6%	54000		UP machining	1.1	
JC2	100%	627270		UP machining	4	
JC3	100%	627270		UP machining	ND	
JC5	100%	627270	21630	Full supply	ND	ND
EC1	50%		10815	Assembly		4.1
EC2	12.3%	77000		UP machining	1.5	
EC3	30%	188181	6489	Full supply	1.8	2.5
EC4	100%	628000		UP machining	1.2	
EC6	100%		21630	Assembly		4.1
EC7	19.3%		4000	Assembly		7.5

Figure 22 indicates the cost dispersion for a single disc manufacturing and for an assembly construction. There is a notable price variation in both cases, only the cost level is different. The disc price varies from -44% to 62% from an average value, while for the assembly the cost varies from -60% to 55% from an average. An average factor between a disc cost and an assembly cost is around 7 (min factor 2 and max factor 30).

Figure 22. Disc and assembly cost (mass production)

According to the detailed estimation of EC1 company expected for 50% CLIC production share, the most part of HT assembly operations cost is manpower, furnaces and braze material classes (see Figure 23).

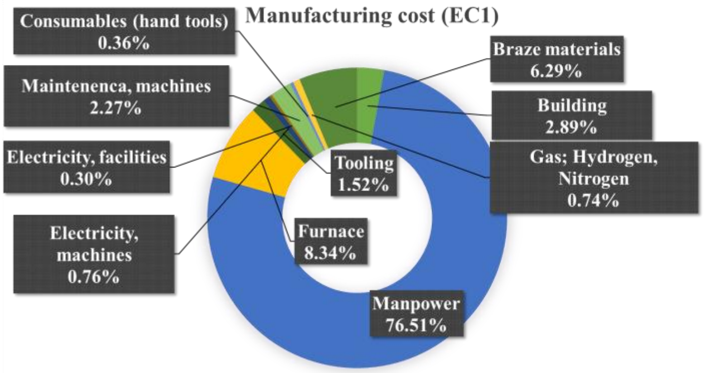

Figure 23. HT operations assembly cost breakdown

The evaluation is in line with the data provided by other HT operations supplier, who indicate a major part of investments in furnaces 85% for EC6, expected for 100% CLIC production and 47% for EC7, expected for 19.3% CLIC production share (see Figure 24). The investment has to be discussed with CERN in order to decide main stakeholders' contributions, the same as it was discussed previously for preparation to UP machining of discs.

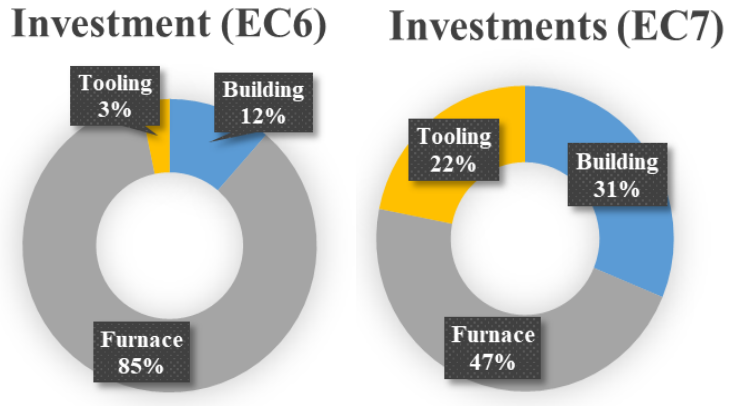

Figure 24. Investment categories

Thus, the radar plot of required investments reveals a shift for UP and HT suppliers towards the top-right quarter, which includes additional building, manpower, machinery, furnaces (see Figure 25). A considerable part of the manufacturing cost adduces manpower, and therefore the training will be also one of the major parts of preparation expenses.

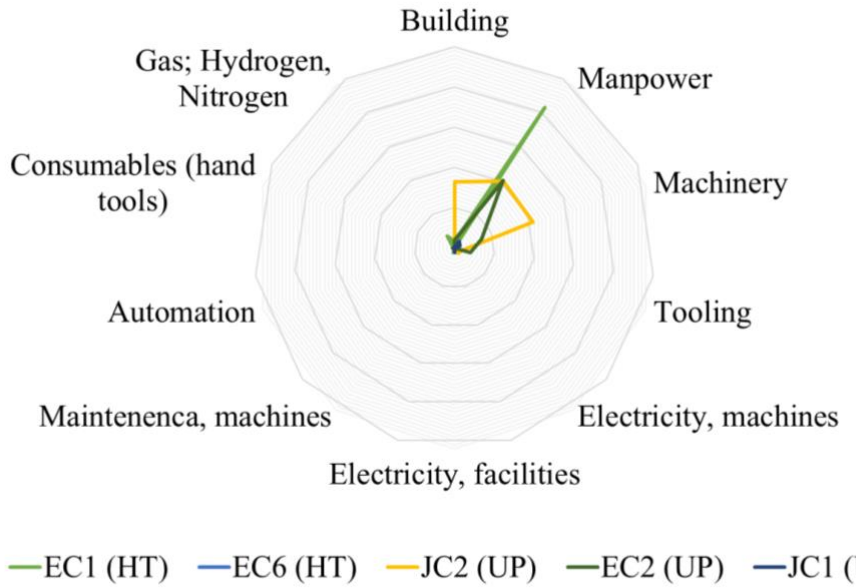

Figure 25. Investment. UP and HT suppliers

Companies-participants provide information on numbers of new equipment and personnel to be invested for the mass production, see Figure 26. The quantities differ because of diverse current manufacture capabilities and the desirable CLIC production volume. Thus, the data is included mainly for an overview and cannot drive to any crucial conclusion. Simply, that implementation of new machines and people is required time and money. Hence, based on the collected replies, the quantity of new employees differs from four to 100 people. Moreover, suppliers consider investing into one up to five new coordinate-measuring machines (CMM); into one up to 20 new vacuum furnaces and into three up to 60 new UP machines. To house new capacities six out of ten companies indicated a need for the new premises' construction with the surface between 600 and 3000 m2, Figure 27.

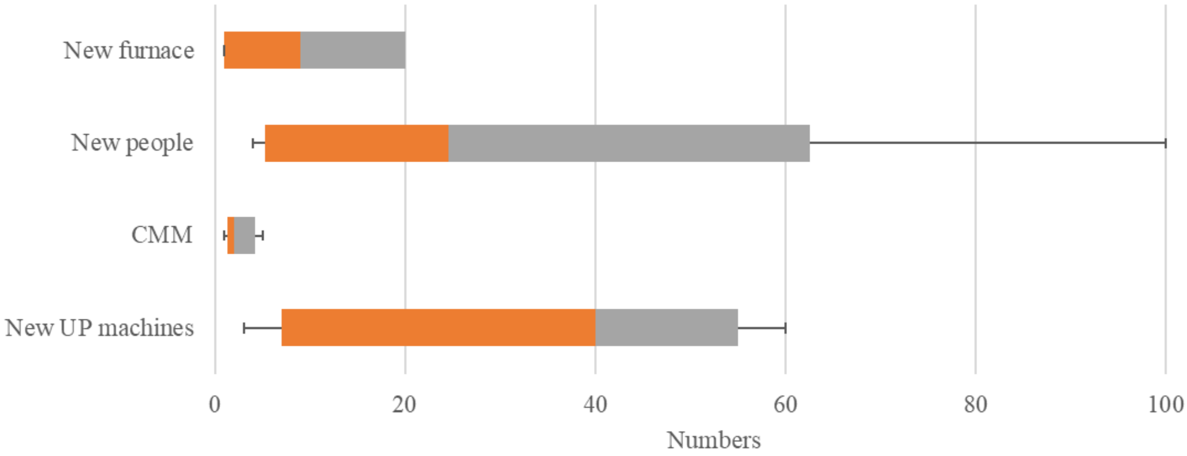

Figure 26. Investments. Equipment and personnel

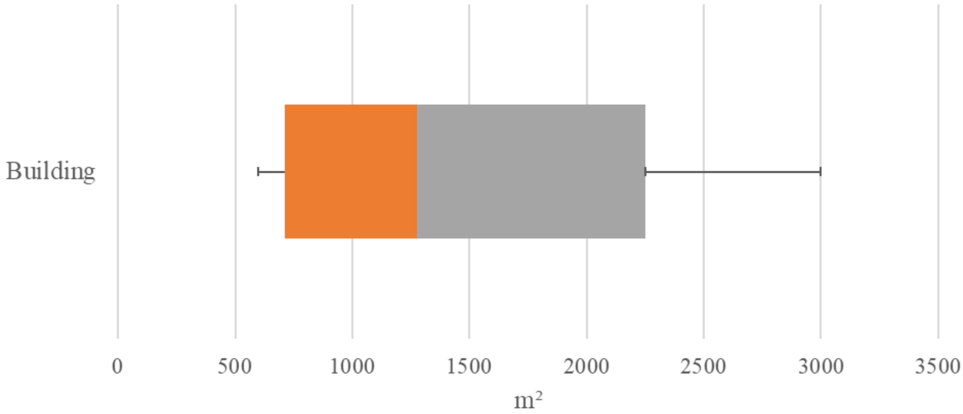

Figure 27. Investments. Buildings

7.6.3. Sub-contracting operations

Some companies consider to sub-contract cleaning, annealing and rough-machining operation. Table 11 presents the summary. Thus, three UP machining companies take into consideration to contract out some operations such as rough machining, annealing, and cleaning. Other participants either indicate no-subcontracting (NA) or do not specify their needs of subcontracting operations.

Table 11. Sub-contracting operations

Code	Desirable volume (%)	Technology for CLIC	Sub-contracting operation	Percentage	Country
JC1	8.6%	UP machining	Annealing	5%	Origin
JC2	100%	UP machining	Rough machining, cleaning	100%	Origin
JC3	100%	UP machining	ND		
JC5	100%	Full supply	ND		
EC1	50%	Assembly	NA		
EC2	12.3%	UP machining	Rough machining	100%	Origin
EC3	30%	Full supply	ND		
EC4	100%	UP machining	NA		
EC6	100%	Assembly	ND		
EC7	19.3%	Assembly	ND		

Note: NA – not applicable, ND – not determined

7.7. Quality and process yield

Quality refers to an ability to meet customer needs and expectations [4]. Producing with good quality often means achieving specification and producing with less defects.
Companies are asked to provide expected or aimed value for the process capability index Cpk or process yield. Cpk is one of the important parameters and targets of the production. The index is a statistical measure of the capacity to produce parts within the specification. Firms-participants specify the target process yield between 90% and 99.99%.
Meanwhile, to maintain the production quality suppliers need to choose and to stick to a control strategy for a mass production. The survey demonstrated that seven industrial partners want to do a 100%-parts control, one firm proposes 25% control for machining parts and 100% for assemblies, and two suppliers consider 10% parts for the full control but including statistical process control, see Table 12. Providers of HT operations prefer to do a 100% quality control check of a full assembled structure as its final product. Eventually, the beginning of pre-series production will require to measure every product to align the production. Then the related control strategy will be implemented.

Table 12. Quality assurance strategy

N	Code	Desirable volume (%)	Technology for CLIC	QA (discs)	QA (assembly)	Process yield (%)	QA/QC documentation
1	EC2	12.3	UP machining	10% 100%		99.99	ND
2	EC4	100	UP machining	100%		90	ND
3	JC1	8.6	UP machining	100%		ND	Work procedure, inspection method of each process
4	JC2	100	UP machining	100%		ND	QC process chart
5	JC3	100	UP machining	100%		ND	ND
6	EC1	50	HT operations		10% 100%	98	Certificate of conformity
7	EC6	100	HT operations		100%	98	Delivery note, inspection report, thermal cycle record
8	EC7	19.3	HT operations		100%	99.99	Leakage protocol, metrology report
9	JC5	100	Full supply	NTD	100%	ND	Inspection report, FAT report
10	EC3	30	Full supply	25%	100%	95	Metrology report, RF performance report

Note: NTD – need to be discussed, ND – not determined

EC2 company considers the 100% control of critical values for each disc, including geometry by CMM, roughness control by white light interferometer and visual inspection, and only 10% parts the control of all values.
Two companies claimed for the full supply: JC5 company thinks important to measure the first and the last batches in the series production of discs, and EC3 company proposes the metrology of discs once per shift, three times per day, one disc out of four. Opposite to the control of assemblies, where both firms indicate the need of 100% check of the supply including metrology (the length and straightness of disc stack, angular orientation of discs) and RF performance test, providing FAT (factory acceptance test) and corresponding reports.
Another important aspect in achieving the target process yield is well-defined intermediate control steps. Thus, machining companies introduce intermediate measuring during UP machining operation on milling machine. HT providers specify intermediate measuring steps during assembly after each brazing step, which include 100%-visual inspection and 100%- or 10%-dimensional control depending on complexity and functionality of sub-assemblies and

assemblies. Furthermore, machining companies consider critical to perform a tool monitoring, since it is responsible for the dimensional accuracy and the final surface quality of a piece.
Beside the above-mentioned QA/QC documentation, companies specify a leakage report, a thermal cycle record, a certificate of conformity.
Chosen quality strategies for achieving the quality target need to be investigated further during the preparation phase of production. Moreover, knowing that metrology represents about 10% from the total disc manufacturing cost, an appropriately selected strategy may result to a significant cost reduction. However, the later should not cause any prejudice of quality. Thus, the right balance has to be found between the price and the quality.

7.7.1. Communication

The companies contemplate communicating the progress to CERN in one of the following ways (or in combination):

- Via standard reports, regularly meetings and on-site acceptance process.
- By monthly submission of a document such as a progress report.
- Regularly updated project schedule and phone or video calls.
- Sharing monthly reports on deliveries and WIP (work in progress) through the SharePoint portal.
- Weekly reports, production indicators.
- Emails and process charts.
- Monthly status by email, immediate email in case of problem.

Most companies prefer to use SharePoint as a knowledge sharing database to use.
Nevertheless, the QA/QC documentation and communication schedule (frequency, emergency contacts, interaction mode etc.) have to de clearly determined prior to a contract establishment.

7.8. Production process and production layout. Automation

The organization of the production includes definition of the production process and the layout. Thus, potential suppliers were asked to specify the process type – batch, repetitive or continuous and describe the layout of fabrication facilities – functional (a), cellular (b), line-based layout (c) (Figure 28) or a combination of the different layouts.

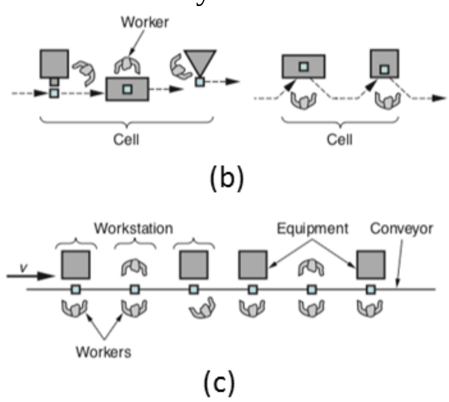

Figure 28. Production layout

Table 13 and Figure 29 provide the summary of firms' preferences for production organization. Hence, 50% companies specify the batch process which allows to maintain moderate volume and moderate flexibility. The batch size is to be determined by examining the achievement of

the required process yield. The batch size is also influenced by the replacement cycle of tools, cutting fluids, etc. to keep machining conditions within an acceptable range. Likewise, 50% suppliers prefer to organize a facility functionally (process oriented), when equipment of the same type is collocated. Other 40% companies consider a combination of different layouts.
The series production of accelerating structures considered in the industrialization will require some level of automation which allows to suppress several manual manipulations, to decrease the production price and time, to reduce human mistakes, to increase the quality. But at the same time, implementation of automation is time- and money- consuming. Nine companies employ automatic and semi-automatic production means.

Table 13. Production process

N	Code	Desirable volume (%)	Technology for CLIC	Process	Layout	Automation
1	EC2	12.3	UP machining	Batch	Combination	Semi-automatic
2	EC4	100	UP machining	Continuous	Combination	Automatic
3	JC1	8.6	UP machining	Job shop	Combination	Automatic
4	JC2	100	UP machining	Repetitive	Functional	Semi-automatic
5	JC3	100	UP machining	Batch	Functional	Semi-automatic
6	EC1	50	HT operations	Batch	Functional	Semi-automatic
7	EC6	100	HT operations	Batch	Combination	Semi-automatic
8	EC7	19.3	HT operations	Repetitive	Cellular	Semi-automatic
9	JC5	100	Full supply	Job shop	Functional	Manual
10	EC3	30	Full supply	Batch	Functional	Semi-automatic

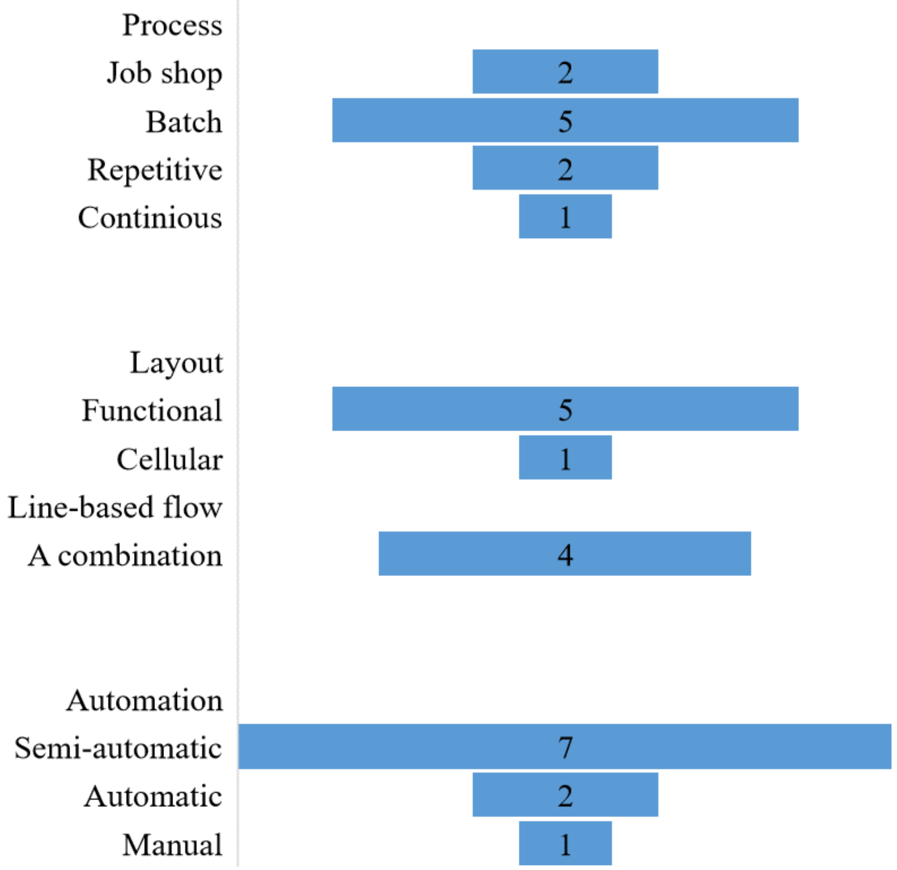

Figure 29. Production process

8. Discussion

The presented study gives a first estimation and an overview about the industrialization of CLIC accelerating structures. The questionnaire allowed to check the readiness of potential suppliers to scale manufacturing to the mass production, going through critical organizational milestones. One part of the survey investigates the investments required for the production scaling. Still, it rises a few questions for the future discussion. Partners have to accord on the investors: (1) who will carry out the necessary expenses; (2) what is the volume share between; (3) how the source of investment does affect the final production cost. In the present study required investment, manufacturing cost and a product cost were discussed separately. The values indicated by every single supplier are stored confidentially as raw data files and summary tables and can be accessed by the CLIC team management.
Additionally, a further complement to the study should be an analysis of unnecessary engineering constraints by reviewing the mechanical design, including tolerance requirements, and assembly process. Thus, the specified accelerating gradient of CLIC structures is 100 MV/m, while the prototypes built and tested in the last ten years tend to achieve up to 120 MV/m (REF). If for the prototyping phase a higher gradient is a prove of the concept and understanding the limits, then for the mass production a higher gradient presents an over constrained product resulting to an excessive cost and time. Therefore, we highly recommend reviewing the workflow process and reinforcing it by several manufacturing tests which will allow to either reduce the tolerances and therefore machining time and/or review the assembly process. At least, a link between required performance and specified tolerances needs to be studied more for making any reasonable conclusions.
Furthermore, for the purpose of the industrialization study TD26 CC design of accelerating structure is employed, which does not correspond completely to a CLIC module accelerating structure. Therefore, the collected data relates to this configuration and needs to be scaled to the final design.
Moreover, responsibles for required intermediate control steps, such as discs and other parts acceptance tests, together with involved QA documentation must be defined between main stakeholders: CERN, machining firms and assembling companies. Who is doing the control and when? A supply model has to be developed, taking into account all important variables such as the production strategy, the production volume and the delivery scheme, the logistic between countries and the quality control.
Additionally, the study should be followed by discussion with potential industrial partners about proposed capacities and building a consortium. Thus, the survey demonstrates that 50% companies are agree and 40% are neutral about creation of the partnership, see Figure 30. The bigger part of "neutral" (three out of four) and one "not determined (ND)" opinions is Japanese companies. One "neutral" company is an European HT operation company who selected 19.3% production volume.

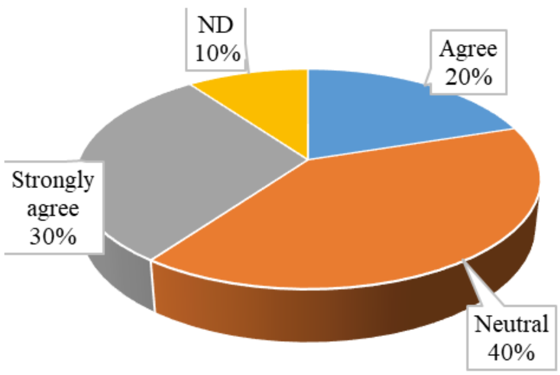

Figure 30. Interest in partnership creation

8.1. R&D from companies' perspectives

Furthermore, companies indicate some R&D programs and other activities essential to prepare for the mass production. Hereafter is a summary of several suggestions.

1. To carry out a production study with the CERN team on the CLIC structure to enable the most efficient manufacture: design of tooling, jigs, fixtures, and minor mechanical redesign of the structure can ease manufacture and ensure greater repeatability. This work results in reducing manufacturing times, higher yields, and greater repeatability between structures. Investigation of the potential for automated assembly is also beneficial to improve repeatability and reduce hand assembly requirements.
2. To redesign from bonding to brazing assembly, reproducibility of the brazing process and 12 GHz X-band RF (high power) test knowledge. Moreover, to launch activities for getting experience with high power RF test requirements.
3. To test a possibility to use a vacuum blazing without hydrogen for assembly of CLIC accelerating structures.
4. To do a process qualification for series production of assembly, employee training, establishing series process.
5. To do research on selection of UP machine, CMM, additional production area for the new machines.
6. To do a R&D project to increase automation of manufacturing to increase the production speed.

9. Conclusion

Thanks to the performed study the CLIC management has an evaluation of capabilities of the potential suppliers for manufacturing one of the most challenging components – accelerating structure. Meanwhile five companies demonstrated an interest to build consortium to cooperate with other industrial partners. However, the study is limited to Japanese and European companies and can be further enforced by firms from other continents through CLIC collaborators.

The survey examines investments required for the production scaling. Furthermore, this part has to be discussed individually with each company. Agreement on sharing the investments needs to be negotiated and considered in the context of its impact on the final cost of the product.

There are four main conclusions:

1. Enough suppliers are interested and qualified for 21630 CLIC accelerating structures production.
2. Companies are interested to build a consortium.
3. There is a possible cost reduction for discs from factor 1.1 to 4 and for TH assembly from factor 2.5 up to 7.5.
4. The estimation of the ramp-up for discs differs depending on involved UP machines, one year with commercial machines and five years for self-developed machines. HT operation companies require about 2-3 years for the ramp-up. Ramp down is from 2 to 10 months. As a result, the full production for discs is estimated between 6.5 and 10 years, for HT assembly is between 5 and 6.5 years.

Finally, the study allowed to answer some of the posed research questions and some of them still need additional investigation, see Table 14.

Table 14. Research questions

Research question	**Answer**	
RQ1: Does CLIC have enough suppliers?	Yes. Out of 12 contacted suppliers, 10 demonstrate an interest to collaborate: 5 companies for UP, 3 companies for HT and two for a full supply. Based on the desirable volume, those companies are enough to produce the required quantity of accelerating structures.	☑
RQ2: How should the supply be organized among different companies?	The supply should be organised based on the material flow between main stakeholders, taking into account intermediate controls. This has to be discussed in details at one of the next steps, depending on responsibilities of main partners, the shared production volume, their location and main roles in the supply.	TBD
RQ3: What is the most efficient production process?	The companies consider the most efficient production process the batch process, at the functional or combination layout and prefer semi-automatic process.	☑
RQ4: What kind of investment will be needed and how this will affect cost?	Companies provides the data on the foreseen investments. The main investment fields are manpower, machinery and furnaces. However, its link and effect on the cost require additional study	TBD
RQ5: What is the ramp-up and ramp-down production time?	**<u>Ramp-up:</u>** UP machining (commercial machines) 10-15 months; UP machining (with self-developed machines) is around 5 years; HT about 2-3 years. **<u>Ramp down</u>** from 2 to 10 months.	☑
RQ6: What quality assurance needs to be put in place? How does it affect the cost?	70% industrial partners specify a 100%-part control, 10% propose 25% parts control and 20% consider 10% parts for the full control but including statistical process control, see chapter 7.7. The most part of the suppliers providing the HT operations, the result of which is a full assembled structure, prefers to do a 100% quality control check. Effect of the QC on the final cost has to be investigated.	TBD
RQ7: What yield is expected?	The companies specify the target process yield between 90% and 99.99%.	☑

10. Acknowledgement

We would like to thank all industrial partners for valuable contribution to this study and fruitful collaboration.

11. Raw data

The raw data is stored confidentially and can be accessed only by the CLIC study management for the purpose of the further investigation. The data includes detailed information on the numbers of required personal, total cost of production, recycling policy etc.

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Annex 1 Questionnaires

Nr	Reference	Description
1	EDMS 2082307	Technical Questionnaire for CLIC suppliers
2	EDMS 2082307	Technical Questionnaire for Industrialization study of CLIC 380 GeV accelerating structures production
3	EDMS 2082307	Technical Specification for the Industrialization study of CLIC 380 GeV accelerating structures production

Annex 2 Documentation list

Nr	Reference	Description
1	EDMS 1827101	Procedure for ultra-precision manufacturing companies' qualification for accelerating structure discs production
2	EDMS 1961959	Procedure for ultra-precision manufacturing companies qualification for accelerating structure halves fabrication
3	EDMS 2082324	Technical specification Assembly and supply of a RF Accelerating Structure TD26 R1 CC type
4	EDMS 1534673	Procedure for vacuum furnace qualification for brazing/bonding of accelerating structures and RF components
5	EDMS 1313413	Procédure de dégraissage avec la machine aux solvants MEG
6	EDMS 1421001	Procedure for couplers assembly for x-band accelerating structures
7	EDMS 1237642	Alignment procedure of the RF Accelerating structure disc stack
8	EDMS 1237642	Procedure for bonding of copper discs for x-band accelerating structures
9	EDMS 1421006	Procedure for assembly of cooling circuits for x-band accelerating structures
10	EDMS 1421002	Procedure for brazing of disc stack with couplers and tuning studs
11	EDMS 1278313	Procedure for leak tightness test for RF Accelerating Structure

Annex 3 Drawings and 3D models list

Nr	Reference	Description
	TD26 CC disc version	
	CLIAAS110332.v0	11 GHZ ACCELERATING STRUCTURE COOLING CAP

	CLIAAS110351.v0	TUNING STUD
	CLIAAS110373.v0	DN 40 – UHV CF ROTAT. FLANGE (TD24)
	CLIAAS120106.v0	12SWV18026-01CSCC - DN40 - UHV CF FIXED FLANGE (TD26)
	CLIAAS120107.v0	BEAM PIPE TD26 12SWV18026-__01CSCC
	CLIAAS120228.v0	12SWV18026-01CSR1CC - EXTREMITY DISC A_TD26_R1_CC
	CLIAAS120229.v0	12SWV18026-01CSR1CC - COMPACT COUPLER DISC A_TD26_R1_CC
	CLIAAS120230.v0	12SWV18026-01CSR1CC - DISC 1_TD26_R1_CC
	CLIAAS120231.v0	12SWV18026-01CSR1CC - DISC 26_TD26_R1_CC
	CLIAAS120232.v0	12SWV18026-01CSR1CC - COMPACT COUPLER DISC B_TD26_R1_CC
	CLIAAS120233.vAA	12SWV18026-01CSR1CC - STANDARD DISC_TD26_R1_CC
	CLIAAS120234.v0	12SWV18026-01CSR1CC - TD26_R1_CC_BONDING
	CLIAAS120235.v0	12SWV18026-01CSR1CC - COOLING BLOCK_ D83_L192_SWAGELOK
	CLIAAS120236.v0	12SWV18026-01CSR1CC - COOLING SYSTEM_D83_L192_SWAGELOK
	CLIAAS120237.v0	COOLING BLOCK D83 L245.7
	CLIAAS120238.v0	COOLING SYSTEM D83 L245.7
	CLIAAS120239.v0	12SWV18026-01CSR1CC - BRAZING_SHIM_CS_D83_L245.7
	CLIAAS120240.v0	12SWV18026-01CSR1CC - BRAZING_SHIM_CS_D83_L192
	CLIAAS120241.v0	WAVEGUIDE COVER TD26R1CC
	CLIAAS120242.v0	WAVEGUIDE BODY-TD26R1CC
	CLIAAS120243.v0	WAVEGUIDE TD26R1CC-FIRST BRAZING AND MACHINING
	CLIAAS120244.v0	WAVEGUIDE TD26R1CC-SECOND BRAZING
	CLIAAS120245.v0	12SWV18026-01CSR1CC - TD26_R1_CC_FULL ASSEMBLY
	CLIAVACU0189.vAE	UHV RF SYSTEM INTERNATIONAL - UNIVERSAL WR90 FLANGE (COATED)
	TD26 CC half version	
	CLIACTD260001	CLIC-HDS-A (QUALIFICATION PART)
	CLIACTD260002	CLIC-HDS-A (W/O SIC)
	Bonding tooling	
	CLIATOOL0001.vAB	WEIGHT APPLICATION TOOL - DISK DIA. 280, FOR HOLDING WEIGHT
	CLIATOOL0003.vAB	WEIGHT APPLICATION TOOL - BASE PLATE DIA. 300 X 40
	CLIATOOL0005.vAB	WEIGHT APPLICATION TOOL - BAR DIA 20 X 20 FOR SUPPORTING THE TOOL
	CLIATOOL0006.vAB	WEIGHT APPLICATION TOOL - PAD, DIA. 20 X 20 FOR LEVELLING
	CLIATOOL0007.vAB	WEIGHT APPLICATION TOOL - THREADED ROD, M10 X 500

		FOR HOLDING THE WEIGHTS
	CLIATOOL0008.vAC	ACCELERATING STRUCTURE BRAZING - WEIGHT APPLICATION TOOL
	CLIATOOL0175.v0	V-SHAPED BASEMENT
	CLIATOOL0228.v0	WEIGHT APPLICATION TOOL - DISK DIA. 280, FOR APPLYING WEIGHT
	CLIATOOL0317.v0	WEIGHT APPLICATION, 10 KG WEIGHT APPLICATION TOOL TOP APPLYING WEIGHT, 10 KG
	CLIATOOL0318.v0	WEIGHT APPLICATION TOOL BASE PLATE
	CLIATOOL0319.v0	WEIGHT APPLICATION TOOL - APPLYING WEIGHT 10 KG
	CLIATOOL0320.v0	WEIGHT APPLICATION TOOL - APPLYING WEIGHT 10 KG (CUT)
	CLIATOOL0321.v0	WEIGHT APPLICATION TOOL - APPLYING WEIGHT 5 KG (CUT)
	CLIATOOL0322.v0	BONDING TOOLING ASSY ACCELERATING STRUCTURE BONDING