ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB416

INDUSTRIALIZATION STUDY OF THE ACCELERATING STRUCTURES FOR A 380 GeV COMPACT LINEAR COLLIDER

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Abstract

The LHC at CERN will continue its operation for approximately 20 years. In parallel, diverse studies are conducted for the design of a future large-scale accelerator. One of the options is the Compact Linear Collider (CLIC) who aims to provide a very high accelerating gradient (100 MV/m) achieved by using normal conducting radio-frequency (RF) cavities operating in the X-band range (12 GHz). Each accelerating structure is a challenging component involving ultra-precise machining and diffusion bonding techniques.

The first stage of CLIC operates at a collision energy of 380 GeV with an accelerator length of 11 km, consisting of 21630 accelerating structures. Even though the prototypes have shown a mature and ready to build concept, the present number of qualified suppliers is limited. Therefore, an industrialization study was done through a technical survey with 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 a quality assurance scheme. This paper presents the results of the industrialization study for 12 GHz accelerating structures for CLIC 380 GeV, highlighting the principal challenges towards mass production.

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 a multi-TeV electron-positron machine under development by an international collaboration known as the Compact Linear Collider (CLIC) [1]. For the optimal exploitation of its physical potential the accelerator is designed for three consequent phases with collision energies of 380 GeV, 1.5 TeV and 3 TeV respectively and with a length range of 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 involving ultra-precise (UP) machining and heat treatment (HT) operations, mostly diffusion bonding and vacuum brazing techniques [2]. The manufacturing tolerances, driven by: i) achieving the required RF performance; ii) the time constraints; and iii) a limited list of the qualified suppliers complicates the supply of the structures [3]. Furthermore, accelerating structures are one of the cost-driver components and represent about 8% of the total cost of the CLIC accelerator.

Already the first CLIC stage operating at collision energy of 380 GeV for a site length of 11.4 km [4], demands around 21630 assembled accelerating structures in five years' time. Based on the technology-driven schedule shown on Fig. 1, the initial phase requires seven years, split up into five years for construction and installation, and two years for commissioning of the machine. The construction of the first CLIC energy stage is proposed to start by 2026 with the first beams to be available by 2035.

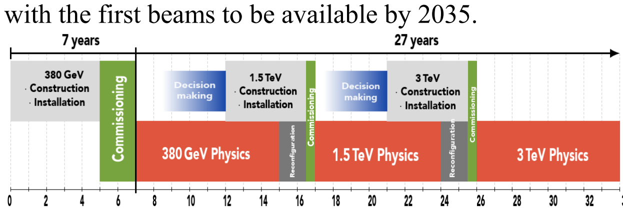

Figure 1: Technology and construction-driven CLIC schedule.

Considering the complexity of the machine and given the number of components, well-scheduled delivery is a challenging task for all stakeholders of the project. Based on the project implementation plan (PiP) from 2018, a procedure and steps necessary to reliably produce large quantities still needs to be developed [4]. Therefore, an industrialization study has been launched to evaluate current capabilities of the CLIC suppliers and to ensure the necessary manufacturing yield, schedule, and cost for mass production.

PRODUCTION OF CLIC ACCELERATING STRUCTURES

The tapered, damped (TD) accelerating structure, 26 regular cells with integrated compact couplers (CC), so-called TD26 CC, is used as a baseline for the study [5], and can be seen in Fig. 2.

The prototype contains about 30 discs machined from Oxygen Free Electronic copper (Cu-OFE). Discs are joint together by diffusion bonding in a vacuum oven under hydrogen protective atmosphere. There are several key aspects which suggest the selection of the TD26 CC structure for the industrialization study: the RF design and the production flow of the structure had been established and demonstrated by assembling various prototypes not only

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ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB416

by CLIC production team but also by collaborators for different in-kind projects. The study outcomes are easy to project and to scale to the final CLIC module structure [2]. Full workflow cycle for the prototype fabrication is from 10 to 12 months. The current production rate depends significantly on the previous experience of the supplier, specifically on whether the company has already delivered parts or performed operations for CLIC.

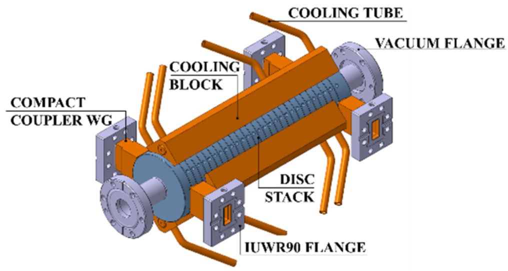

Figure 2: CLIC accelerating structure TD26 CC.

Nevertheless, for mass production several operations will be suppressed such as the final tuning and numerous operations can be done simultaneously. Moreover, further optimization of production must include determination of the batch size – number of structures to be brazed as a group at the same heating cycle. The latter requires assessment of vacuum furnace dimensions, electricity, and space consumption as well as risk evaluation in case of failure.

Table 1: Prototype vs. Mass Production

Prototype	
UP machining rate	1 disc/day
HT operations/assembly rate	0.1 ass/day
Full fabrication cycle	10-12
Mass production (100%)	
Number of structures	21 630
Number of discs	627 270
UP machining rate	502 discs/day
HT operations/assembly rate	17.3 ass/day
Full production period	5 years

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: the manufacturing rate for discs increases from one to 502 discs per day; for the assembly – from 0.1 to 17.3 assemblies per day, counting 20 and 250 working days per months and per year respectively.

At present 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 each step need to be negotiated and set up together with strategies for quality control, storage, and delivery.

INDUSTRIALIZATION STUDY

The industrialization study consisted of a series of technical visits, meetings, and a technical survey. The survey was designed to guide industrial partners through the main milestones and obstacles of scaling to mass production. Companies studied the provided technical documentation to establish the best production strategy in terms of time, cost, production volume etc. Thus, the study contributes to help companies to prepare a manufacturing strategy for 21630 accelerating structures in five years' time by asking for an "imagination" exercise. For the CLIC study team and management, the survey evaluates (1) the current suppliers' capabilities, (2) the list of corrective actions if required, (3) possible optimization and improvement of the cost model, together with (4) preparing an implementation strategy, which includes organization of the supply among different companies, quality assurance, yield etc.

Data Collection

Twelve qualified suppliers were contacted for the aim of the study: seven current European CLIC suppliers (EC1 to EC7) and five Japanese companies (JC1 to JC5). However, companies JC4 and EC5 had to be excluded for the further evaluation: EC5 declined the invitation and JC4 provided incomplete data. Thus, the study results are presented by the data from 10 companies.

Manufacturing Strategies

Based on the questionnaire, companies specified the production volume up to which they considered it reasonable to scale their fabrication. They took into consideration the required investment, time limits, and the potential use of new production premises after completing the work for the CLIC project. Suppliers had a choice between three scenarios: 100%, 50% or their own value. 100% was used as an extreme case, evidently understanding risks for the CLIC management to have only one supplier of the product or the service.

Table 2: Summary Table

Code	**Technology for CLIC**	**%**	**Scale coef.**	**Ramp (months)**	
				up	**down**
EC 2	UP machining	12.3	6	60	2
EC 4	UP machining	100	1196	ND	ND
JC 1	UP machining	8.6	6	10	6
JC 2	UP machining	100	ND	60	ND
JC 3	UP machining	100	124	ND	ND
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
EC 3	Full supply	30	27	60	ND

Table 2 summarizes the collected data for designing mass production: the desirable volume, manufacturing scaling coefficient, ramp-up and ramp-down phases duration. Five companies showed interest in taking over 100% of the production. Six suppliers consider building a consortium. Machining companies showed the will to invest to

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manufacture the discs and felt confident in achieving this large number of discs. Overall, these results indicate that CLIC have enough suppliers for manufacturing and assembly of 21630 accelerating structures.

Ramp-up

Each firm specified the parameters of the production curve. Mainly five years and two to three years of the preparation and the ramp-up were indicated for UP machining and HT operations companies, respectively. A detailed representation of the ramp-up phase with respect to the preferred production volume is shown in Fig. 3. The companies form four clusters of companies: (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).

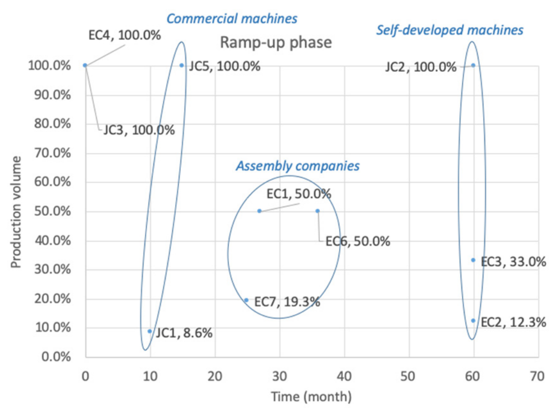

Figure 3: Ramp-up phase.

Therefore, the difference in ramp-up appears firstly because of different machining strategies: customized, commercial, or self-developed machines, secondly, we can assume that assembly premises will need less preparation time.

Cost Breakdown

The larger part of disc manufacturing cost is manpower and machinery investment, see Fig. 4. Consequently, these two are considering for bigger investments for both European and Asian suppliers.

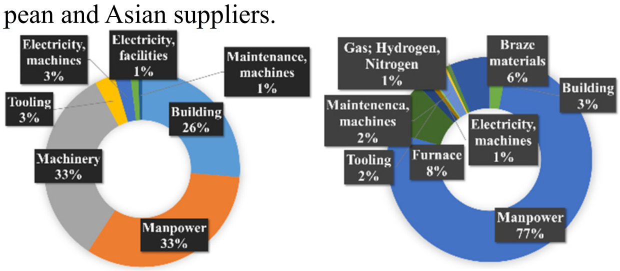

Figure 4: UP machining disc (left) and HT operations (right) cost breakdown.

Production Cost

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), when assuming 100% of the 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. The cost reduction according to the companies derives from shortening the end machining time. The latest can be achieved by: (1) pallet manufacturing, (2) using automated process, (3) reducing the number of measured parts, (4) using a self-developed machine. 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% supply), and by factor 7.5 for EC7 (19.3% supply). Companies EC6 and EC7 specified the batch size of eight structures. The cost reduction factors with respect to the appropriate contribution to CLIC are summarized in the Table 3. An average cost, for the disc and for the prototype assembly were used for comparison to mass production values. For the final price of manufacturing the CLIC management needs to clarify contributions from main stakeholders on initial investments and carrying the manufacturing cost.

Table 3: Cost Reduction Factors

Code	**%**	**Technology for CLIC**	**Mass production (cost reduction factor)**	
			UP	**HT**
EC2	12.3	UP machining	1.5	
EC4	100	UP machining	1.2	
JC1	8.6	UP machining	1.1	
JC2	100	UP machining	4	
JC3	100	UP machining	ND	
EC1	50	Assembly		4.1
EC6	100	Assembly		4.1
EC7	19.3	Assembly		7.5
JC5	100	Full supply	ND	ND
EC3	30	Full supply	1.8	2.5

DISCUSSION AND CONCLUSION

Thanks to the current study, the CLIC management has now a better insight on the strategy of the potential industrial partners for manufacturing one of the most challenging components – the accelerating structure. Meanwhile six companies demonstrated an interest to build a consortium to cooperate with other industrial partners. However, the study is limited to Japanese and European supplier and can be further enforced to firms from other continents of CLIC collaborators. The survey examines investments required for the production scaling. Furthermore, this part needs to be discussed individually with each company. Agreements about sharing the investments needs to be discussed and the impact on the final cost to be reviewed.

ACKNOWLEDGEMENT

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

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