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CONCEPTUAL DESIGN OF THE VACUUM SYSTEM OF CSTART

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Abstract

The Karlsruhe Institute of Technology operates research accelerator facilities for the development of new technologies for future compact light sources at the Institute for Beam Physics and Technology. Within the cSTART project (compact STorage ring for Accelerator Research and Technology), the Very Large Acceptance compact Storage Ring will be realized to combine a compact storage ring (SR) and a laser-plasma accelerator (LPA). The new design, based on a DBA lattice with two 45° bending angle magnets, is suitable to store a wide momentum spread beam. Good vacuum conditions are essential for the successful operation of such an accelerator system. In our case, a final pressure of 1×10^{-8} mbar is required. For cSTART, special care was taken to find a compact (43 m circumference), space- and cost-saving, yet efficient vacuum system design that fulfils this requirement.

This article presents the vacuum concept that will be used at cSTART. This includes the design of the vacuum chamber, vacuum simulations and the selection of vacuum components.

INTRODUCTION

LPAs can produce ultra-short, high-current electron bunches within compact setups, making them promising candidates as injectors for next-generation light sources [1]. Their ability to emit intense coherent radiation in the THz regime stems from the extremely short bunch durations. However, challenges such as large energy spread, high divergence, and low repetition rates (typically a few Hz) so far hinder practical applications. The cSTART project addresses these limitations by developing a compact storage ring (SR) with very large momentum acceptance, designed to store sub-picosecond electron bunches, see Fig. 1. Acting as a repetition rate multiplier, the ring boosts the effective repetition rate from a few Hz to MHz levels by storing each bunch for ca. 100 ms and performing swap-out injection. Two injectors are foreseen: an LPA delivering ~20 pC bunches at 50 MeV with < 20 fs bunch lengths and ~2% energy spread [2]; and the linac-based FLUTE (Far-infrared Linac and Test Experiment) accelerator, which offers broader beam parameters from 1 pC to 1 nC, 40 MeV to 90 MeV energy, and bunch lengths down to a few femtoseconds [3]. The relatively low energies involved ensure negligible incoherent

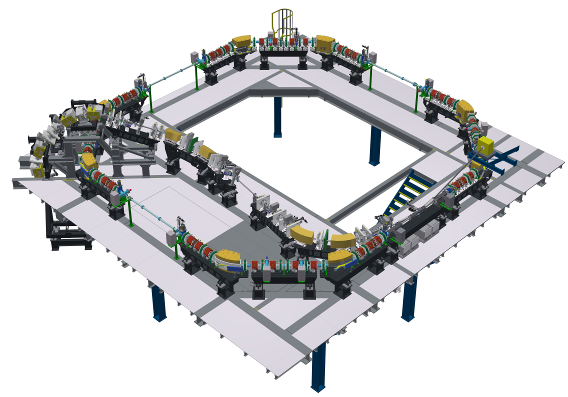

Figure 1: Rendered view of the compact SR. The SR will be mounted on a steel-frame platform elevated 3.5 m above ground level. The individual magnets are highlighted in colour. Not shown is the LPA that will be at the same height. The FLUTE injector is connected via a complex injection line (IL), partly seen on left side.

synchrotron radiation losses, with beam dynamics remaining in a non-equilibrium state throughout the storage period. To accommodate a wide range of beam properties, the ring lattice is fully tunable and supports various optics configurations, including double-bend achromat, reduced-momentum compaction, and quasi-isochronous optics [4, 5]. To enable the required lattice flexibility across the 40 MeV to 90 MeV energy range, all magnets are designed as fully tunable electromagnets [6]. In addition to the criteria mentioned above, the vacuum concept of SR and IL (injection line) faces further challenges due to the requirement for compactness (only 43 m diameter for many different devices) on the one hand and cost-saving combined with efficiency on the other. In the next section, general vacuum requirements and conceptual realization are presented.

VACUUM SYSTEM REQUIREMENTS

The vacuum system of cSTART represents a central interface within the overall project, as its role extends beyond ensuring sufficient vacuum quality. It must also account for interactions with other system properties and requirements, such as beam dynamics (e.g., impedance [7]) and magnetic field behaviour (e.g., magnetic permeability). Beam dynamics calculations and simulations conducted at the beginning of the project showed that a final pressure of 1×10^{-8} mbar is sufficient, both in the compact SR and in the IL, to carry

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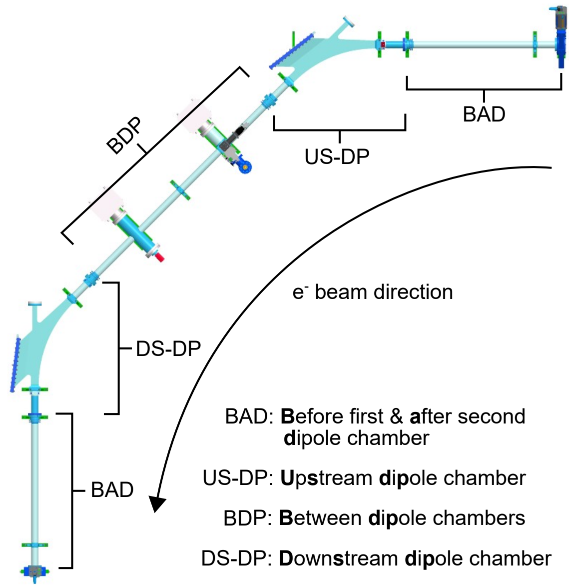

Figure 2: The arc section of the SR is divided into 5 parts.

out the desired physics investigations. It should be noted that the following list summarizes the key requirements.

- oil-free and polymer-free for all vacuum equipment
- materials with a magnetic permeability $\mu_r < 1.01$
- materials such as austenitic/non-magnetic stainless steel (e.g. EN 1.4429 for flanges) or aluminium alloys
- no vibrations during operation
- full-metal valves, vacuum shutters RF shielded
- edge welded bellows with RF fingers at inner surface
- flange design with low inner gap at connection (< 0.2 mm) by spigot or chamfer design
- vacuum pipe SR is round DN 63 (d_{in} = 56.3 mm, d_{out} = 60.3 mm), IL is round (d_{in} = 38.4 mm, d_{out} = 42.4 mm)
- vacuum chamber inside dipoles is rectangular (h_{in} = 36.4 mm, w_{in} = 64.0 mm, h_{out} = 42.4 mm, w_{out} = 70.0 mm)

In accordance with these requirements, the design of the vacuum system was carried out by RI Research Instruments GmbH and FMB Feinwerk- und Messtechnik GmbH, leveraging their expertise in precision engineering and accelerator technology.

TECHNICAL DESIGN OF THE VACUUM SYSTEM

The compact SR consists of four almost identical arc sections and four different straight sections; see Fig. 1. During the commissioning period, up to three straight sections are empty and reserved for future experiments; the fourth section is the injection straight for the anti-clockwise injection of the electron beam generated within FLUTE. An exemplary arc section is shown in Fig. 2. Starting from the top right, the first part of the arc is the so-called before and after dipole chamber (BAD) . It consists of a straight tube-like vacuum pipe that connects the gate valve on the beam position monitor (BPM) assembly to the dipole chamber on the opposite side, see Fig. 3. A total of 8 larger vacuum chambers with light ports are integrated in the dipoles (US-DP and DS-DP) of the storage ring, 2 in each corner, see Fig. 4. The light ports allow the outcoupling of broadband THz radiation, which means they need to have a very large opening. Therefore, a standard flange cannot be used, and a large custom rectangular flange is foreseen. Between the two dipole chambers is a vacuum tube (BDP) shown in Fig. 5. The entrance and exit of the chamber have incorporated bellows assemblies that follow the same design as in Fig. 3, as well as the BPM assembly. The pump-cross tube is optimized to maintain the maximum possible pumping speed. The arc section ends with a BAD part.

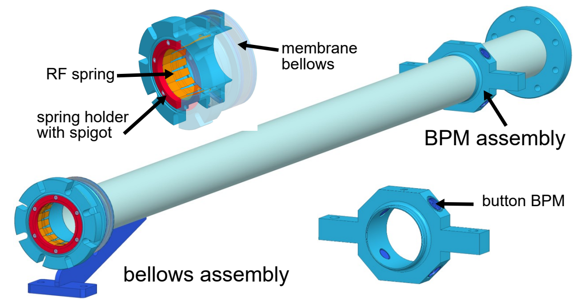

Figure 3: Before and after dipole chamber (BAD). The button-BPM is a stainless-steel (1.4429) body with welded BPM buttons, for more information [8]. The bellows assembly compensates for length changes during ring assembly to account for production tolerances and temperature fluctuations. Due to space constraints the BPM and bellows assembly are welded to the vacuum pipe on one side. The total length is approx. 1310 mm.

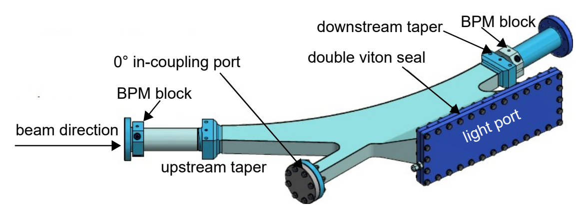

Figure 4: Design of the dipole magnet chamber with light port. The dimensions ($l \times w \times h$) are approx. 1200 mm × 700 mm × 170 mm. Additionally, two sets of BPM and taper are located at the entrance and exit of the dipole chamber. The taper generates a smooth transition between the rectangular profile of the dipole chamber body and the round profile of the connecting vacuum tubes.

In each straight section are two ion pumps, so a total number of 16 200 L s^{-1} ion pumps is foreseen for the SR and twelve 75 L s^{-1} ion pumps for the IL. Regarding pressure control, PKR 361 vacuum gauges are chosen; 8 for the SR and 3 for the IL. Table 1 gives an overview of the vacuum components.

Based on this design and components, the next section presents the vacuum simulations for the SR and the IL.

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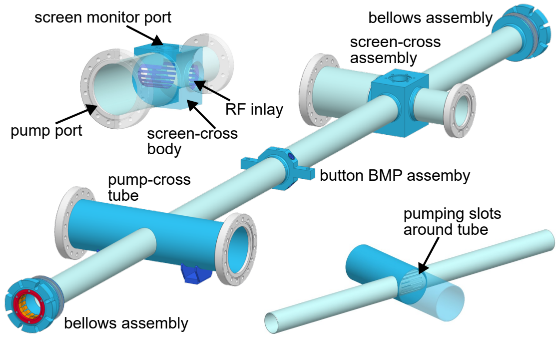

Figure 5: Between upstream and downstream dipole chamber (BDP). The screen-cross contains a CF100 flange for a 200 L s^{-1} ion pump, a CF63 valve port flange. In addition, the screen-cross contains a retractable screen monitor for diagnosing the beam position. The pump-cross tube is equipped with a CF100 flange for a 200 L s^{-1} ion pump and on the opposite site a PKR 361 pressure gauge is connected. The electron channel tube is designed with integrated pumping slots that are evenly distributed around its entire circumference.

Table 1: Selected vacuum components for the SR and the IL. Pumps and their controller are from Gamma Vacuum and the vacuum gauge from Pfeiffer Vacuum.

#	Product	Article Number
16	Titan pump 200 L s^{-1}	200L-CV-6S-SC-N-N
12	Titan pump 75 L s^{-1}	75S-CV-6S-SC-N-N
7	19” controller	QPC-4-P-S-1-EC230-S-S-N
11	PKR 361	PT T03 350 010
2	TPG 366	PT G28 770

VACUUM SIMULATIONS AND BAKEOUT CONCEPT

Water as the remaining residual component dominates the out-gassing of the walls of the inner chamber. Therefore, to reach the final target pressure of 1×10^{-8} mbar, the vacuum chambers are subjected to a preconditioning bake-out process. Due to its compactness, there is no space for an in-situ bake-out of the components. The vacuum chambers will be baked for at least two days at 200 °C at the manufacturer. For assembly and installation, nitrogen overpressure will be applied. Table 2 lists the parameters used for the vacuum simulation with Molflow+ and the resulting final pressure accordingly. The simulations are based on three different

Table 2: Parameter Settings for the Vacuum Simulation With Molflow+

Pump	Pumping Speed L s^{-1}	Duration d	Final Pressure mbar
Rough	3	0.5	$< 1 \times 10^{-4}$
TMP	10	2 - 3	$< 1 \times 10^{-6}$
Ion	SR: 200, IL: 75	10	$< 1 \times 10^{-8}$

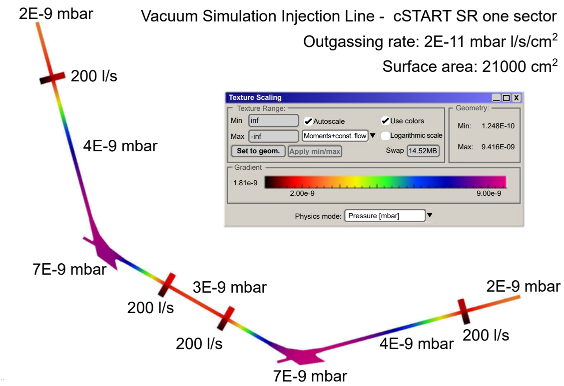

Figure 6: Vacuum levels (mbar) achieved after 10 days of pumping with 200 L s^{-1} ion pumps.

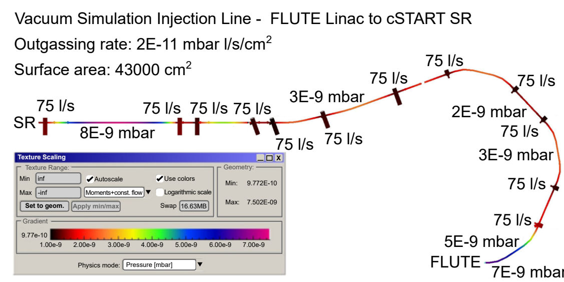

Figure 7: Vacuum levels (mbar) achieved after 10 days of pumping with 75 L s^{-1} ion pumps.

phases, starting with rough pumping, followed by the use of turbo-molecular pumps and finally the ion pumps. The outgassing rate is assumed to be 3×10^{-9} mbar L/s/cm^2 at the beginning and drops to 2×10^{-11} mbar L/s/cm^2 after baking. Figs. 6 and 7 display the simulation results after 10 days of pumping for the SR and the IL, respectively. According to the simulation, the final pressure will be achieved. Test particles that leave upstream enter the system downstream and vice versa (periodic boundary conditions). Based on the bake-out concept and the corresponding vacuum simulations, it can be shown that a required pressure of 1×10^{-8} mbar will be achieved for the developed vacuum design. Furthermore, the design meets all the required specifications.

STATUS AND CONCLUSION

The challenge with cSTART lies in the interplay between limited space, a final pressure of 1×10^{-8} mbar, and the goals of energy efficiency and cost savings. Based on the technical design and corresponding simulations, it has been demonstrated that the target final pressure can be achieved. The technical design of the vacuum components has been completed and the final design report is expected by the end of 2025. In addition, key vacuum components such as ion pumps, sensors, and controllers have been delivered.

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