VACUUM DESIGN AND PRESSURE MODELLING OF THE AWAKE Run 2c BEAMLINES

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Abstract

The Run 2c upgrade of the Advanced Proton Driven Plasma Wakefield Acceleration (AWAKE) Experiment at CERN introduces complex integration requirements for its vacuum infrastructure due to the coexistence of multiple new beamlines. This contribution presents the proposed vacuum architecture, detailing tailored pumping strategies, hardware choices, and the remote-control system, collectively designed to ensure operational reliability and minimize maintenance across diverse pressure regimes (down to 10^{-10} mbar). The baseline layout, established with analytical dimensioning, is validated through Molflow+ 3D simulations to guarantee meeting the pressure requirements in critical interaction regions.

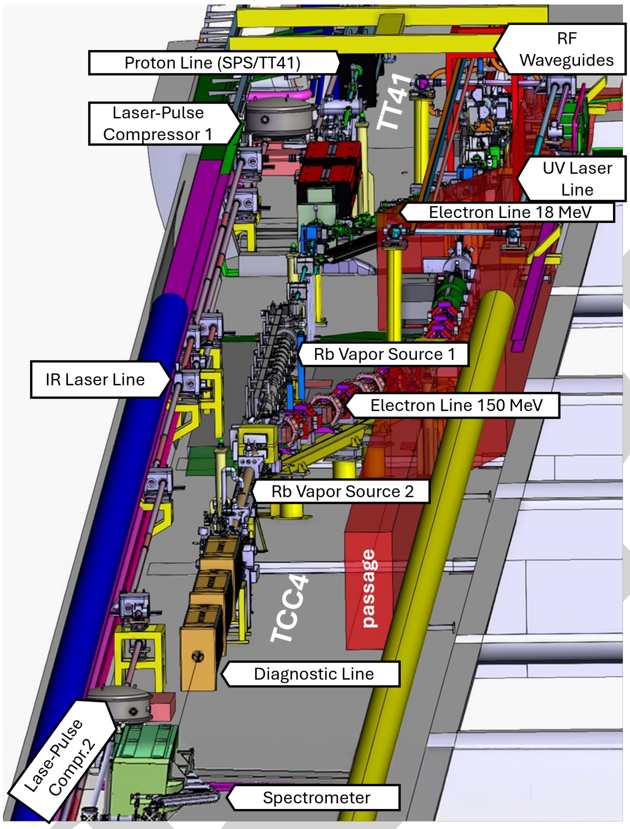

Figure 1: 3D CAD model illustrating the high-density integration of the AWAKE Run 2c experimental area.

INTRODUCTION

The Advanced WAKE-field Experiment (AWAKE) at CERN investigates proton-driven plasma wakefields to achieve gigavolt-per-meter accelerating gradients [1]. The Run 2c phase (from 2029) aims to achieve 10 GeV electron acceleration by physically decoupling the proton self-modulation and electron acceleration stages using a two-plasma-source configuration [2]. Integrating these systems in the experimental area significantly increases vacuum complexity and demands a high-density layout. The upgrade introduces a 150 MeV electron beamline alongside the existing, relocated 18 MeV system. Optical transport requirements expand with ~150 m of in-vacuum infrared (IR) laser lines for the Rb vapor ionization and an ultraviolet (UV) laser driving two electron guns. Furthermore, the electron source RF waveguides transition from sulfur hexafluoride insulation to vacuum operation. Integrating these diverse systems—spanning primary to ultra-high vacuum regimes—within the spatial constraints of the experimental area dictates a new architecture. This contribution outlines the resulting vacuum design and operational choices.

VACUUM ARCHITECTURE

Strict spatial constraints (Fig. 1) and coexisting beamlines dictate a modular vacuum architecture covering a range from 10^{-3} to 10^{-10} mbar, organized by operational needs, gas loads, and restricted accessibility in a radiation environment (Table 1). Proton, diagnostic, and electron beamlines rely entirely on robust, low-maintenance, Sputter Ion Pumps (VPI). To manage periodic venting, each sector includes a fixed Turbomolecular Pumping Group (VPG) repurposed from Run 2b. To maximize lifespan, VPGs remain unpowered during beam operation, activated remotely only for pump-downs or dealing with unexpected transient gas loads. Electron sources and RF waveguides foresee minimal venting, hence they are initially evacuated to 10^{-5}–10^{-6} mbar via mobile groups before NEG cartridge activation and ion pump flashing. The ultra-high vacuum required for the e-guns is provided by a space-optimized mix of legacy and new pumps consisting of NEG cartridges, VPIs, combined NEG-ion pumps (VPN), and Titanium Sublimation Pumps (VPS). RF Waveguides rely exclusively on VPIs. UV and IR laser transport lines rely on a single permanent pump per line and require strict vibration mitigation. The IR laser line (> 150 m, 10^{-2} mbar) traverses a radioactive zone where standard dry scroll pumps could degrade, therefore it utilizes a single vibration-damped VPG, relying on the turbomolecular stage to block hydrocarbon backstreaming from its rotary vane backing pump. The UV line uses a single dry scroll pump (VPP) housed in an adjacent gallery to protect the tip seals from radiation and decouple vibrations. High-vacuum laser lines connecting pulse compressors to merging chambers do not share this vibration sensitivity. In-

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Table 1: Operational Parameters and Pumping Architecture for AWAKE Run 2c Sub-systems

System	P_{target} (mbar)	**Gas Load Source**	**Pumps**	**Gauges**
Proton Beamline	$5 \cdot 10^{-8}$	Beam instruments	VPI, VPG	VGR, VGP
Diagnostic Beamline	$1 \cdot 10^{-7}$	Beam instruments	VPI, VPG	VGR, VGP
Electron Beamline (18 & 150 MeV)	$1 \cdot 10^{-8}$	Beam instruments	VPI, VPG	VGR, VGP
Electron Gun 1 & Acc. Cavity	$1 \cdot 10^{-10}, 1 \cdot 10^{-9}$	RF thermal desorption	VPI, VPS, VPN	VGI, VGR, VGP
Electron Gun 2 & Acc. Cavities	$1 \cdot 10^{-8}$	RF thermal desorption	VPI, VPN	VGR, VGP
RF Waveguides	$1 \cdot 10^{-7}$	RF thermal desorption	VPI	Full-range
UV Laser Transport Line	$1 \cdot 10^{-2}$	Optical boxes	VPP	VGR
IR Laser Transport Line	$1 \cdot 10^{-2}$	Optical boxes	VPG	VGR
IR Laser Delivery Lines 1 & 2	$1 \cdot 10^{-6}$	Laser pulse compressors	VPG	VGR, VGP
Rb Vapor Source Interfaces*	$1 \cdot 10^{-2}$	Rubidium vapor	VPG	VGR, VGP

* When sources are filled with Rb for plasma generation

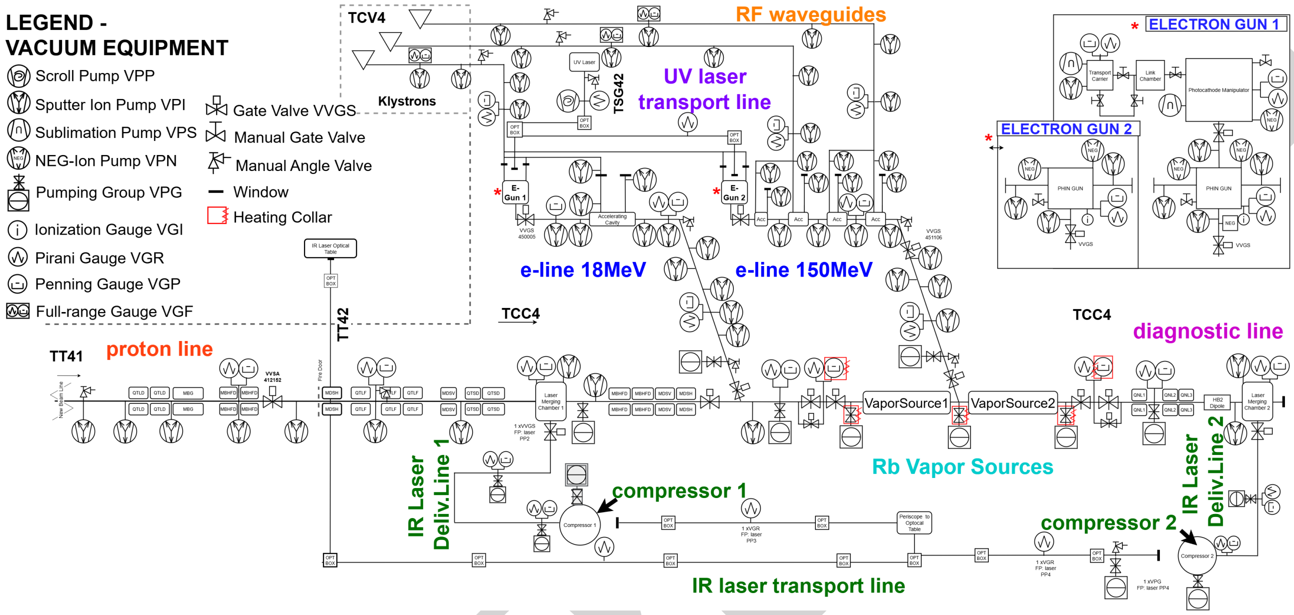

Figure 2: Preliminary vacuum equipment layout for AWAKE Run 2c, detailing the pumping architecture, diagnostic gauges, and strategic sectorization via gate valves (VVGS).

stead, they require continuous, high-pumping-speed VPGs specifically to mitigate substantial dynamic outgassing from the pulse compressors. Similarly, the three interface volumes for the two vapor sources (officially designated as Expansion Volumes) feature continuous VPGs to actively manage localized rubidium (Rb) gas loads. Monitoring relies on radiation-hard passive Pirani (VGR) and Penning (VGP) gauges, active full-range combined Penning/Pirani for RF waveguides (< 1 Gy/year radiation environment) and Bayard-Alpert (VGI) gauges for Electron Gun 1. Gauges in the Rb expansion volumes are equipped with external heaters to prevent Rb condensation.

Figure 2 illustrates these choices and the gate valve (VVGS) sectorization, critical for operational flexibility and Rb containment. Acronyms follow CERN nomenclature (see layout legend). The control system is based on a WinCC OA supervisory SCADA application coupled to a Siemens S7-1500 master PLC. Distributed S7-1200 PLCs are employed for the control of the pumping groups, while passive vacuum gauges are interfaced using Pfeiffer TPG500 controllers with Profinet fieldbus. A custom bakeout prototype has been developed to thermally condition the vapor source components.

ANALYTICAL PRESSURE MODELLING

First-order dimensioning relied on an analytical periodic pumping model. Assuming uniform specific outgassing q and specific conductance c, the parabolic pressure profile between two pumps separated by distance L yields a maximum pressure P_{max} at the midpoint [3]:

$$P_{\text{max}} = AqL\left(\frac{L}{8c} + \frac{1}{S_{\text{eff}}}\right) \tag{1}$$

where A is the specific surface area and S_{eff} is the effective pumping speed. Conductances were estimated using standard molecular flow formulations [3, 4]. The model assumes water vapor as the dominant residual gas for unbaked austenitic stainless steel, assigning a baseline specific outgassing rate q of $3 \cdot 10^{-11}$ mbar·l/s·cm^2 after 100 hours

Table 2: Simulation Parameters and Results at 100 h Pumping

Line	**Suppl. Gas Loads**	Q_{H_2O} (mbar·l/s)	S_{eff} **(Pump)** (l/s)	P_{target} (mbar)	P_{max} (mbar)
Proton	Laser Merging Chamber	$3 \cdot 10^{-6}$	75 (VPI)	$5 \cdot 10^{-8}$	$4.8 \cdot 10^{-8}$
	BPM (DN63), BCTF	$8 \cdot 10^{-8}, 3 \cdot 10^{-7}$			
Electron	BTV1, BTV2, Beam Stopper	$3 \cdot 10^{-7}, 1 \cdot 10^{-7}, 3 \cdot 10^{-7}$	75 (VPI)	$1 \cdot 10^{-8}$	$8.8 \cdot 10^{-9}$
	F-Cup, BCT, BPM (DN40)	$3 \cdot 10^{-8}, 1.5 \cdot 10^{-8}, 5 \cdot 10^{-8}$			
IR Laser	Compressor, Optical Boxes	$1.2 \cdot 10^{-4}, 2 \cdot 10^{-6}$	685, 260 (VPG)	$1 \cdot 10^{-6}$	$4.5 \cdot 10^{-7}$

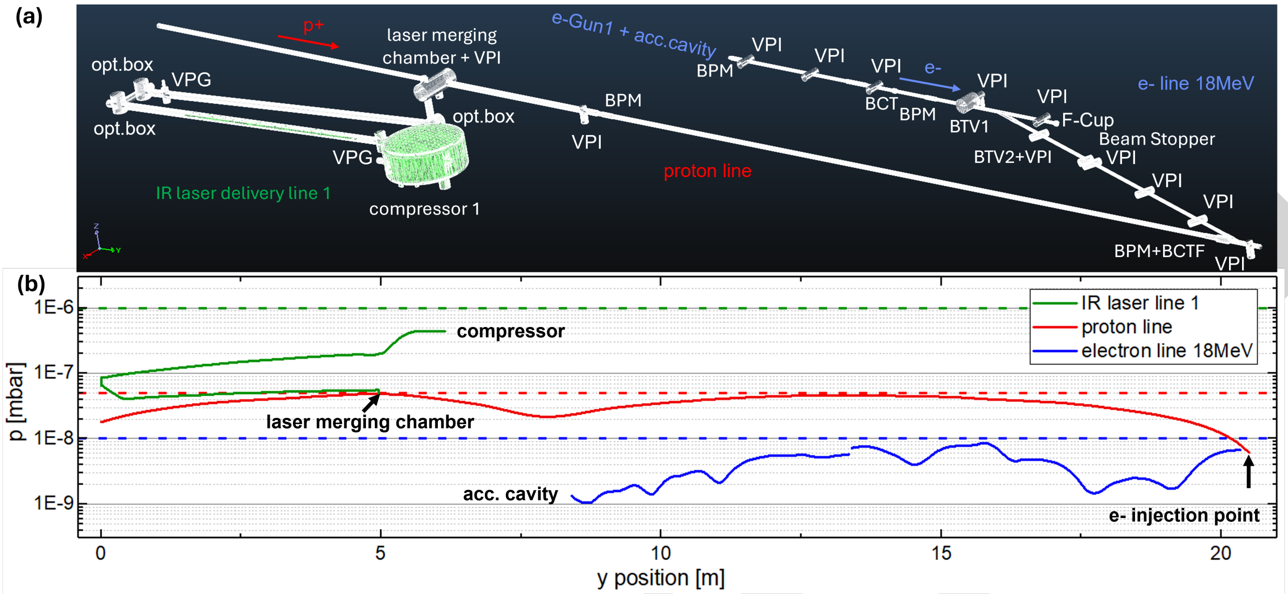

Figure 3: (a) Molflow+ 3D geometry detailing the merging regions of the IR laser delivery line 1 and the 18 MeV electron beamline with the proton beamline.(b) Simulated pressure profiles along the longitudinal axis for the respective beamlines.

of pumping [5]. To accommodate supplementary localized outgassing from beam instrumentation, the ideal spacing L_{ideal} was calculated targeting a conservative design pressure 20% below the operational thresholds (P_{target}) listed in Table 1. This baseline distribution was adapted to physical constraints and validated via 3D simulations.

3D NUMERICAL MODELLING

To validate the analytical pressure estimates, 3D pressure profiles were simulated using the Molflow+ test-particle Monte Carlo code [6, 7]. For brevity, only a critical subsection is presented here. This model (Fig. 3) features two key merging points: the intersection of the first high-intensity laser line with the proton beamline and the injection point of the 18 MeV electron beamline into the proton line. The simulation accounts for the realistic 3D geometry and varying conductances, incorporating specific pipe diameters (DN100 for the HV laser line, DN40 for the electron line, and DN63 for the proton line, with a 2.3 m DN80 section downstream of the merging chamber). The numerical model directly applies the aforementioned water vapor outgassing baseline q. Additional total outgassing loads Q were assigned to discrete components based on historical acceptance tests and expertise from the CERN Vacuum Group (TE-VSC). These values (Table 2) are indicative, as the official vacuum acceptance test campaign for Run 2c components has not yet commenced. The simulation confirms that predicted maximum pressures (P_{max}) match or fall below the target thresholds (P_{target}). The 100-hour outgassing assumption provides a conservative upper limit. Operational pressures are expected to progressively improve as the system continues to pump down.

CONCLUSION

The AWAKE Run 2c vacuum architecture effectively addresses the high-density integration constraints and diverse pressure regimes of the upgraded experimental area. The rationale for the vacuum system dimensioning is confirmed by both analytical calculations and 3D numerical modelling.

ACKNOWLEDGEMENTS

The authors thank the AWAKE Collaboration for their support.

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