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Title: MEBT Bunchers: System Design Document (SDD)

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LANSCE MODERNIZATION PROJECT

MEBT Bunchers: System Design Document (SDD)

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Component Overview

The LAMP Medium Energy Beam Transport (MEBT) transfers bunched beam at the energy 3 MeV from RFQ to the Drift-Tube Linac (DTL) entrance. The beam particles (protons or H^-) in the LAMP MEBT have velocity $\beta = v/c = 0.08$, where v is the beam velocity, c is the speed of light. The MEBT bunchers keep beam bunches from spreading longitudinaly as they propagate through the MEBT, where some unwanted bunches are removed by a chopper to create a required beam pattern. The MEBT bunchers are RF cavities operating at the frequency 201.25 MHz; possible design options were considered in [1].

Requirements

The requirements for the LAMP MEBT bunchers are determined by the MEBT beam dynamics design. The main requirements are listed in Table 1.

Table 1. Requirements for the LAMP MEBT Bunchers.

Identifier	**Requirement**	**How met**
Effective voltage $V_{\mathrm{eff}} = VT$	Should be sufficient to prevent bunch longitudinal spreading	MEBT beam dynamics design; buncher electromagnetic design
Buncher length L	Should be minimized	Buncher electromagnetic design
Buncher aperture a	Should allow the beam to pass without scraping	MEBT beam dynamics design

Relevant Parameters

The preliminary LAMP MEBT design [2] includes four bunchers at RF frequency of 201.25 MHz with the beam aperture radius $a = 1.8$ cm and effective voltage $V_{\mathrm{eff}} = 90$ kV [2]. The main parameters are listed in Table 2.

Table 2. Parameters of the LAMP MEBT Bunchers.

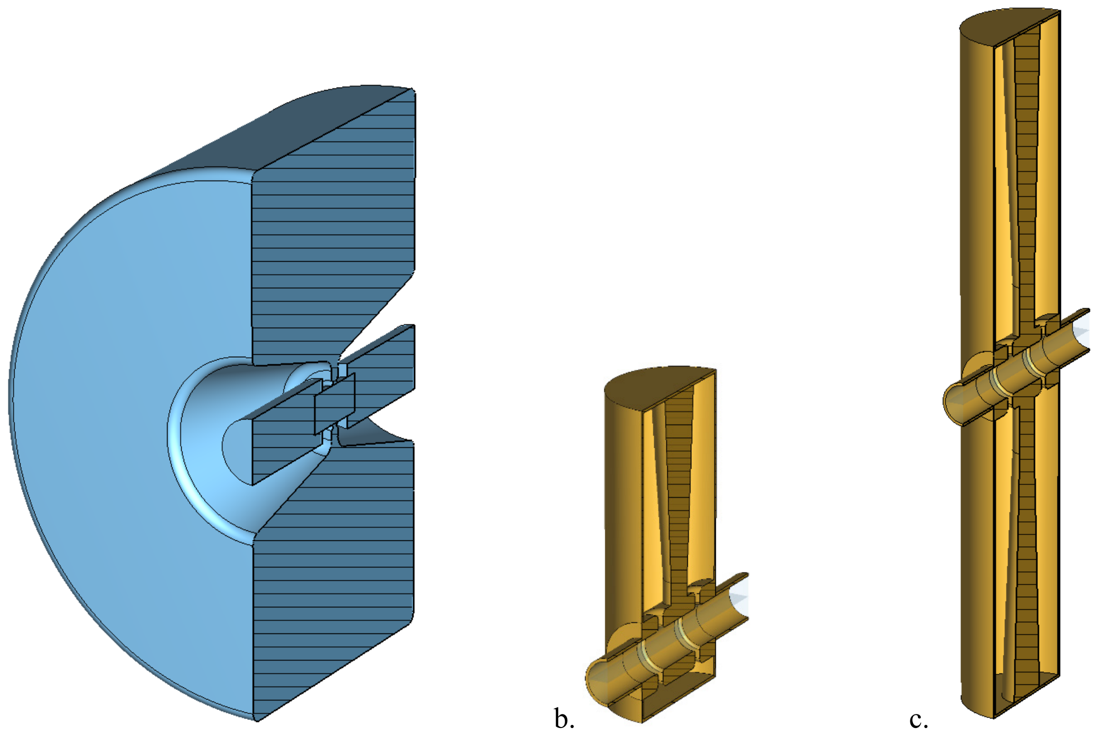
Parameter	**Value, units**	**Design**
RF frequency	201.25 MHz	[2]
Effective voltage $V_{\mathrm{eff}} = VT$	90 kV	[2]
Buncher aperture radius a	1.8 cm	[2]

The buncher length (or its footprint on the beam line) should be as short as possible while meeting the other requirements. The buncher transverse size is less important. In addition, it is important to keep maximum surface electric field below E_K, where E_K = 14.77 MV/m is the Kilpatrick field at 201.25 MHz

Design Decisions

Buncher cavity options.

In Ref. [1], three cavity design options – reentrant single-gap, quarter-wave (QW), and half-wave (HW) resonators – for the 201.25-MHz beam bunchers at 3 MeV (β = 0.08) in the LAMP MEBT were considered. The CST models of these bunchers are shown in Fig. 1. The image size of each cavity approximately reflects the relative cavity size.



a. b. c.

Figure 1: CST models of the LAMP MEBT buncher cavities [1]: vacuum volume of re-entrant cavity (a), quarter-wave resonator (b), and half-wave resonator (c).

While these buncher cavities can be further optimized, the results [1] provide a base for design comparison and selection. Main parameters for comparison are presented in Table 3, assuming for all bunchers the beam aperture radius 1.8 cm and total effective voltage V_{eff} = 90 kV. For two-gap bunchers (QW, HW), it means 45 kV/gap. The values in green are better, in red worse.

Table 3. Main Dimensions and Electromagnetic Parameters of LAMP MEBT Bunchers.

Parameter	**Re-entrant cavity**	**Quarter-wave cavity**	**Half-wave cavity**
Length along beam line, cm	28	12	12
Max transverse size, cm	55	27	64
Quality factor Q*	24,300	5,800	6,350
Transit-time factor T	0.78	0.84	0.84

Max electric field E_{max}, MV/m (E_K)	14 (0.95)	9.8 (0.66)	9.5 (0.64)
Wall power loss P, kW*	2.5	4.7	5.7
Max surface power density, W/cm^2*	1.3	33	8.8

* Assuming copper walls with conductivity σ = 5.8·10^7 Sm/m and 100% duty.

With account of additional considerations such as the cavity mechanical stability, ease of its water cooling, and the buncher field quality, the half-wave resonator seems the best option. The HW cavity vertical size is large but likely will not present any challenges in the MEBT 3D layout. The HW cavity voltage can be increased if needed, though that will influence the RF power requirements.

RF systems.

From CST simulations in [1], the required RF power of about 10 kW at 201.25 MHz is sufficient for any of the buncher options above.

Other systems.

Mechanical.

Each of the three proposed buncher designs will require water cooling. A conservative heat load is about 2 kW. The flow required for the estimated heat load is 0.76 gpm. The current J01 water system that will supply cooling to the bunchers is adequate. Each design will require unique cooling passages, once the optimal design is chosen a pressure drop calculation will be required to ensure the system is not pressure limited.

The mechanical structure of the cavity is required to be vacuum-tight with a He leak rate at or below 1x10^-9 atm-cc/sec. Internal surfaces of the cavity require a material that is both thermally and electrically conductive. An obvious choice for this is copper. However, to increase the structural integrity the chamber should be fabricated from 304 SST and internal surfaces copper plated. The plated surfaces are also required to be smooth for the RF conductance.

To compensate for fabrication tolerances, welding distortion and thermal expansion a mechanical tuner will be mounted to the cavity. The tuner will act as a plunger traveling in and out of the cavity to maintain appropriate resonance. The plunger will be driven by a stepper motor remotely controlled by a combination of LLRF and IC as described in the subsequent section.

Controls / LLRF.

The bunchers need to be synchronized with the accelerator timing system. To accomplish this, a timing event link will be provided by the master timer system to the LLRF buncher control system. This will be accomplished by adapting timing event receiver IP provided by Micro-Research Finland, who developed the master timer system used at LANSCE and many other accelerator facilities, to the LLRF field control module's FPGA processor board. This requires the LLRF board to include a fiber SFP interface with lanes routed to the FPGA. A system design update will be undertaken between LLRF and AOT-IC teams for the LLRF buncher interface, using the existing LANSCE LLRF field control module system as a starting point. Upgrades are necessary as the current system as the cPCI single board computer and event receivers are no longer available, and we see VPX as a sustainable platform replacement.

Buncher resonance control tuning slug motion control is also required and will be accomplished using LANSCE-standard quad actuator controller (QAC) motor driver and EPICS interface. Phase and amplitude and digitized forward and reflected power signals will interface to the LLRF field control module (FCM) and HPM systems. Additional temperature and phase and amplitude indications will interface into AOT-IC NI Compact RIO (cRIO) industrial controllers.

The cavity-field control subsystem maintains the field amplitude and phase in the MEBT buncher cavities. This is accomplished using a feedback control system to maintain the overall phase and amplitude at the desired set points and provides a low power signal to high power RF. The feedback control system obtains phase and amplitude via RF pickup loops from the cavity. It obtains the RF phase reference from the 201.25 MHz RF Reference Line.

The frequency control system for the MEBT Buncher portion of the accelerator will use slug tuners within the water-cooled cavity to maintain the cavity resonant frequency. The slug tuner system on the MEBT bunching systems will be activated by either a phase detector between the forward and cavity signals or an amplitude detector on reflected power signal. These detection functions will be implemented digitally in the LLRF FPGA-based control system.

The LLRF systems interfaces with the timing and EPICS systems from AOT-IC, the fast protect and run permit systems from AOT-OPS and water, vacuum and tuner systems from AOT-MDE. In Fig. 2, the blue outline represents the entire LLRF system, and the purple outline represents the LLRF Control System.

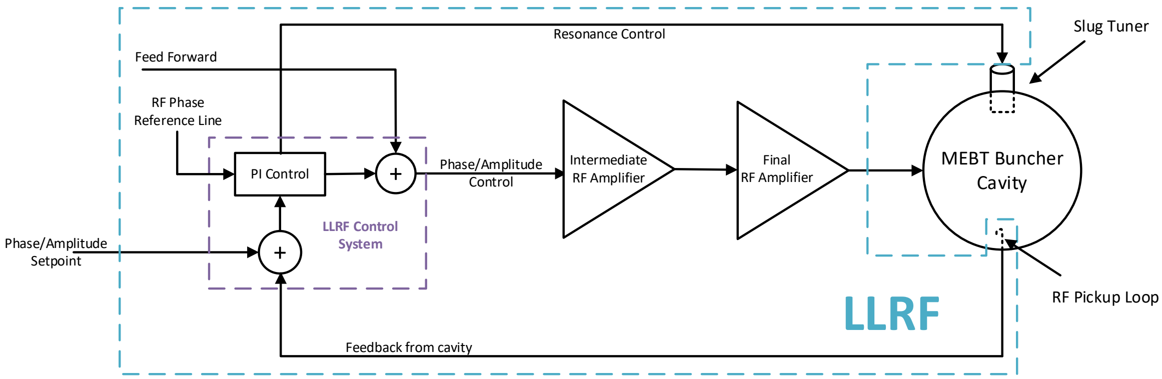


Figure 2: LLRF MEBT Buncher System Block Diagram

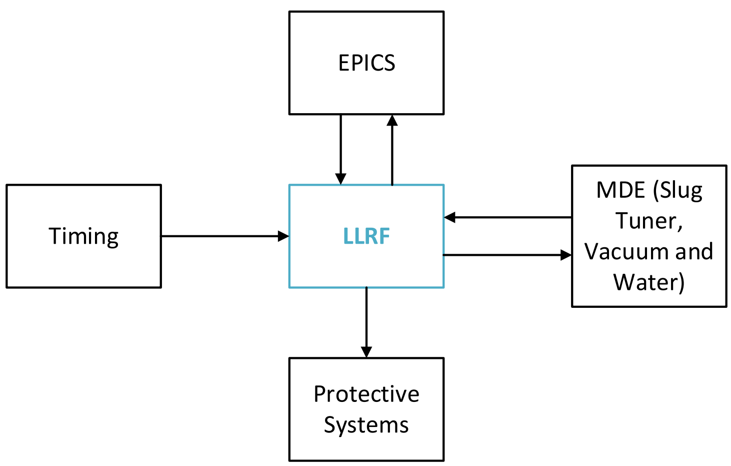


Figure 3: LLRF MEBT Buncher System interaction with other systems

Table 1 LLRF 201-MHz MEBT bunchers RF systems	
Peak amplitude error	± 0.1%
Peak phase error	± 0.2°
Amplitude control margin	15% min

Phase control margin	± 45°
Cavity operating frequency	201.25 MHz
RF Peak Power (Maximum)	10 kW
Cavity Resonance Control	
Peak Operational Resonance Error	± 3 kHz from 201.25 MHz

Design Decisions

The LAMP MEBT Low Frequency Buncher LLRF system will be developed from the current digital LLRF systems to a new MEBT digital LLRF system. Due to technology advancements, the hardware can now support direct RF and frequency conversion will no longer be needed, direct RF at 201.25 MHz will be used. Additionally, the cPCI currently in use by LLRF will not be used as they obsolete and parts can no longer be obtained. A VPX-based direct RF system will need to be developed.

The choice of VPX as the primary system architecture is based on the experience over the last two decades of using compact PCI based system and the experiences at other accelerator facilities. Two telecommunication standards, Advanced TCA and MicroTCA, are viable alternative to VPX and are used at many accelerator facilities around the world and have the appropriate features we require in a system architecture. VPX was chosen by DOD as their system standard with the expectation that it would have a service lifetime of 35 to 50 years in support of DOD systems. Both of the telecommunication standards are expected to have a viable lifetime of 8-12 years. VPX offers a system lifetime and extension that meets the long-term requirements of LANSCE.

RF Phase Reference Line

The current RF Phase Reference Line will need to be modified, or a new reference line designed. The current reference line doesn't have enough pickup points for the two new additional DTL tanks and will not be long enough for the MEBT bunchers or the RFQ. The exact requirements for this extension have not been determined, however this will need to be looked at closely as this will require a large design effort. As the RFQ is before the "butt line zero" wall, the RF Phase Reference Line may need to be extended through the wall. This is a major change from the current RF Phase Reference Line, as the current line does not extend past DTL tank 1.

Protection.

The present H^- configuration provides Fast Protect with one input to TBFP1 for the LEBT buncher. This input is tethered to the LFPE gate. A new MEBT buncher would more than likely require similar monitoring circuitry with a similar output to Fast Protect, supplied by the equipment owner. TBFP1 has ample spare input channels to accommodate the new input. It also has spare gate capacity to tether the new input to a new gate if needed.

Any additional interlocks required will be integrated into the PLC-based Run Permit system, similar to the cavity temp interlocks.

References

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2. S.I. Sosa Guitron. Private communications, Oct. 2024.
3. CST Studio, Dassault Systèmes: www.3ds.com/products-services/simulia/products/cst-studio-suite/