KlyLac CONCEPTUAL DESIGN FOR BOREHOLE LOGGING*

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Abstract

Linac-based system for borehole logging exploits KlyLac approach combing klystron and linac sharing the same electron beam, vacuum volume, and RF network. The conceptual design tailors delivering 3.5-4 MeV electrons within 3.5 inch borehole at ambient temperatures 150 degrees C to replace ^{137}Cs, >1 Ci source used in borehole logging. The linac part is based on a very robust, high group velocity, cm-wave, standing wave accelerating structure. The design concept features i) self-oscillation analog feedback that automatically provides modal stability; ii) ferrite-free isolation of the klystron; and iii) long accelerating section with large (0.3%) frequency separation between adjacent modes; and iv) low-voltage klystron.

INTRODUCTION

Borehole logging tools utilize high-activity ^{137}Cs or ^{60}Co radionuclide sources for densitometry and lithology among other applications. These sources are always “on” imposing significant concerns to radiation safety during handling and transport, potential environmental pollution in case of loss downhole, and security/terrorism activity. The borehole depth of geophysical interest typically exceeds 3000 ft. The X-ray detectors generally operate at ambient temperatures ranging from below 0°C (up-hole calibration) to 175°C or even higher. Borehole tool diameter is usually a fraction (<75%) of a borehole size varying from less than 4” to 10”. For a prospective logging tool diameter is limited by a ~3.5”.

The first linac development for well logging was performed in late 70s in Soviet Union [1]. Extensive work has been done over the past few decades in attempting to adapt linacs for this application, understanding how to characterize and monitor its output [2], and to develop and design a detection system accommodated to a linac with entire tool, including detectors, power conditioning and communications electronics to aid in research into downhole measurements with an intense radiation source [3]. Feasibility of the linac was tested [2] using S-band linac deployed on the ground. The electron beam was transported in the borehole and the corresponding technique for the geological density measurement was developed. In late 80s Haimson Research Corporation made a considerable adaptation of the linac technology to design a linac for logging [4].

RF linacs using conventional technology remain too large and sensitive to background to operate remotely in harsh environment of deep borehole wells at temperatures as high as 150°C and in presence of vibrations (with accelerations 2G and above). The conventional linacs with their automatic frequency control (AFC) system, ferrite-based circulator, and magnetron are not suitable.

KlyLac concept [5,6,7,8] offers an alternative, rugged approach to this problem. Both KlyLac and KlyNac [9,10] concepts are based on a combination of klystron and linac sharing the same vacuum envelop and electron beam source.

The goal of the development is to conceptually design a linac-based source equivalent to ~1-2Ci of ^{137}Cs and capable to operate in a harsh environment as a borehole logging tool at 150°C and cross-section of the housing down to 3.5” without any cooling means. Below we discuss some of the initial developments related to a ~3.8 MeV KlyLac with emphasis made to performance of a ~1.3 m long “jungle-gym” accelerating structure revisited recently [11].

THE TOOL CONCEPT

A KlyLac-based concept of the tool illustrated in Fig. 1 employs RF linac in a standing wave (SW) mode. It allows eliminating RF window, circulator, linac electron gun, and classical AFC. Instead, a simple low-level RF (LLRF) feedback loop may provide automatically adjusted RF self-oscillation [12,13] of the KlyLac at temperature-independent, self-tuned phase and magnitude of accelerating field keeping it optimal without temperature-limited solid state electronics and ferrites. However, such a significant flexibility is possible only if stability conditions are satisfied and a wide enough bandwidth is enabled by both the klystron and linac section.

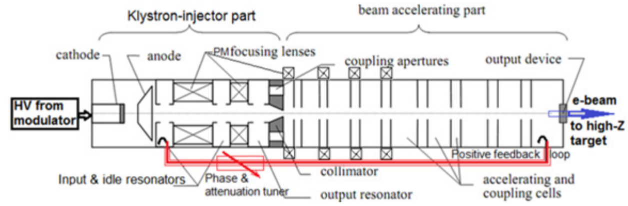

Figure 1: Simplified schematics of the compact X-ray source for borehole logging using “KlyLac” concept enhanced with a positive feedback loop.

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MBK AS THE LINAC DRIVER

A wideband, multi-beam klystron (MBK) has been pre-designed here for ~9.4 GHz central frequency to study feasibility of the "source" part of the tool. Only a small fraction of central beamlet (~0.5%) of a seven-beam MBK is required for injection into the linac. Six cavity klystron is modelled with 1D code AJDisk as shown in Fig. 2 with the following parameters: active length: ~16 cm; efficiency: η=30%; output power: 7×100kW; voltage: 38 kV; cathode beam loading: <15A/cm2; beamlet current and diameter: 9.4 A and 5 mm. The klystron cavities are detuned to provide sufficiently wide bandwidth simulated in Fig. 3.

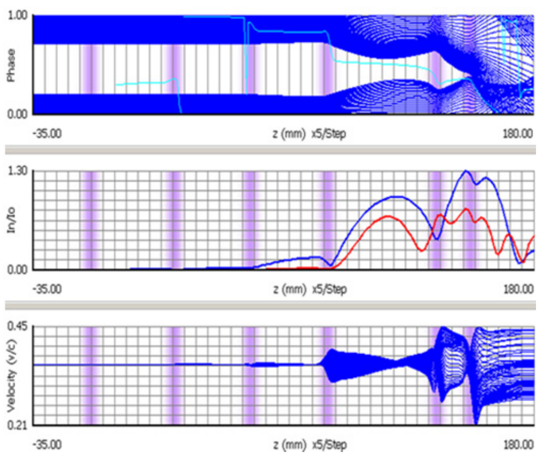

Figure 2: AJDisk simulations for a single beamlet of six-cavity, 7-beam X-band MBK for KlyLac with phase (a), bunching factors for fundamental and next harmonic (b), and particle velocities plotted along the klystron.

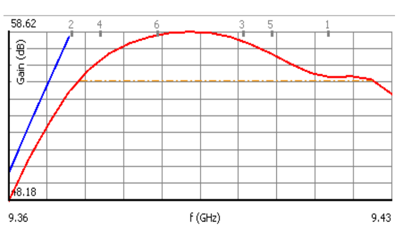

Figure 3: Gain [dB] simulated (red) and computed analytically (blue) plotted vs. frequency [GHz] for MBK.

In designing the bunching cavities (see Fig. 4) we focused on uniformity of interaction between beamlets at sufficient coupling and tunability of the frequency. That was successfully addressed using the approach [14] at the following parameters: aperture: 7.68 mm; R/Q=110 Ω at 0.2% non-uniformity; gap=1.23 mm; coupling coefficient: M=0.49 at 11% non-uniformity; and Qo≈1600 Q-factor.

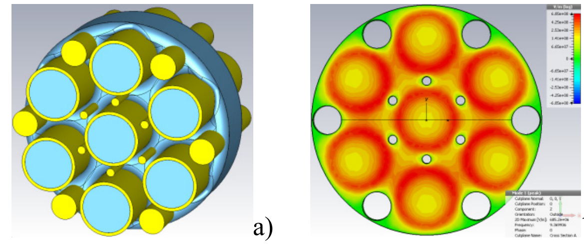

Figure 4: MBK bunching cavity design (a) where drift tubes and rods are given in yellow and vacuum volume in blue. Contour plot of the field distribution in median plane (b). The outer dimension is ∅34 mm (1.3").

Design of the output cavity presents the most challenging task as it requires addressing simultaneously frequency, external Q-factor ~117 found from AJDisk, and uniformity of gap-to-gap beamlet coupling. We managed to approach the solution for the output cavity with three output ports and three stubs as shown in Fig. 5.

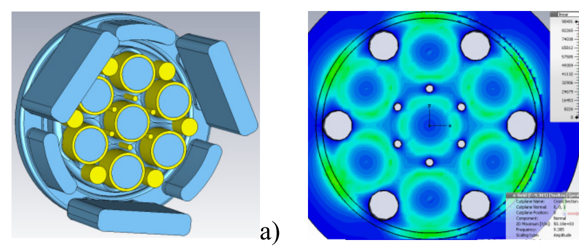

Figure 5: Upstream view (a) of the output MBK cavity. Contour plot of the field distribution in median plane (b).

CROSS-ROD SINGLE-SECTION LINAC

The linac part of the tool should accept both RF power and the central part of the beam with energies ~(12-20) kV (see Fig. 2c) in a compact configuration to accelerate ~5 μA beam to ~(3.5-4) MeV energies. Besides, frequency separation between adjacent resonances of the linac section to be larger than the change of difference between central frequency of the klystron and the resonant frequency of the section caused by environment (temperature and/or vibrations). This frequency difference is generally caused by difference in geometry between the klystron and acceleration cavities as well as gradient of temperature and deformations along the tool. On the other hand, limited RF power implies large number of cells resulting in reduction of frequency separation. What is why we have chosen a cross-rod type of a ~100 cell structure enabling as large as 0.24c group velocity at still substantial shunt impedance [11].

We consider here two variants of the cross-rod linac section shown in Fig. 6: a) with three RF ports to be connected directly to the MBK; and b) with two ports using the scheme of Fig. 7 to reduce reflections seen by MBK.

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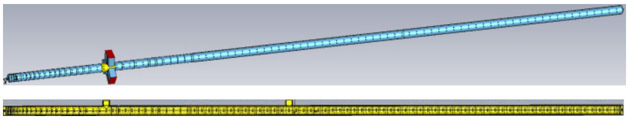

Figure 6: 1.3 m long SW section with three ports (top, "negative" volume view) and two ports (cut-view on the bottom).

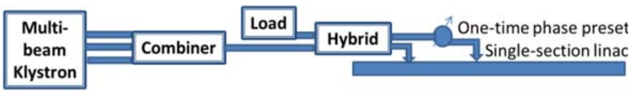

Figure 7: Partial isolation of three-port MBK from a two-port SW linac cavity.

The RF fields and S-parameters shown in Fig. 8 and Fig. 9 respectively have been simulated in time domain using simultaneous excitation of the multi-port cavities of Fig. 6. One can see that the modal separation is ~31 MHz that can be compared to 30 MHz frequency walk-off found for a cross-rod cell at βph=0.9 and temperature change from 20°C to 150°C.

We have adopted brazing technology for fabrication of a 6-cell tapered mock-up of the cross-rod structure (see Fig. 11). The measurements showed unloaded Q-factor 3064 vs. 3259 simulated. Field profile measured with bead-pull technique showed excellent agreement with simulations (see Fig. 12) without any tuning.

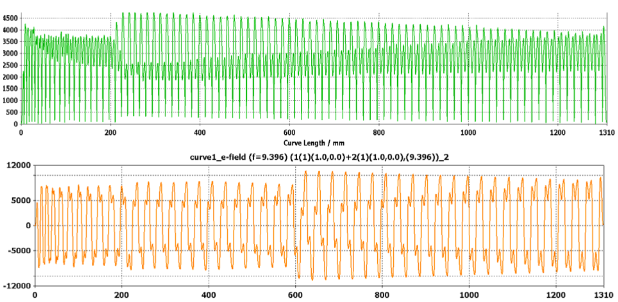

Figure 8: Ez field profiles along the 3-port (magnitude on the top) and 2-port (bottom) configurations of Fig. 6.

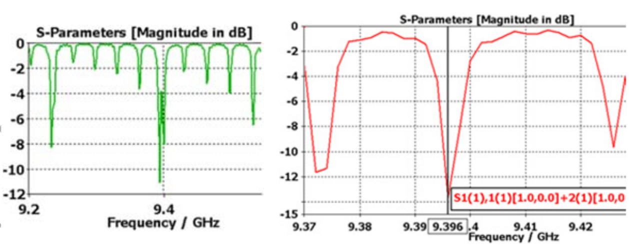

Figure 9: S11 parameter for 3-port (left) and 2-port (right) configurations of Fig. 6 at simultaneous excitation.

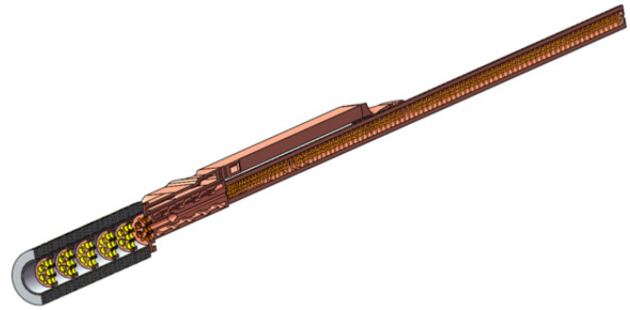

Figure 10: Rendering of the ∅3.5" KlyLac design with MBK and 2-port linac section (see Fig. 7). MBK cathode and linac focusing are not shown.

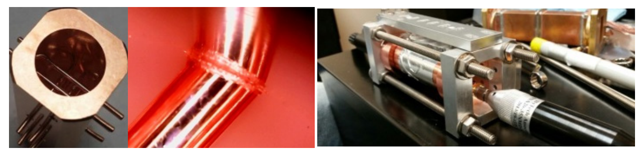

Figure 11: Brazed mock-up elements and test setup.

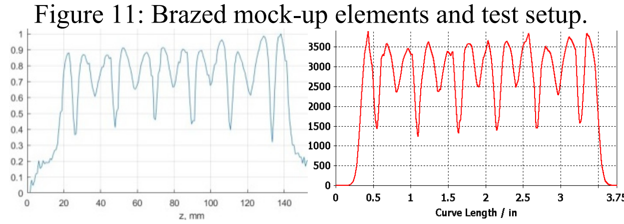

Figure 12: Field magnitude profile measured (left) and simulated (right) along a cross-rod 6-cell tapered mockup.

Energy gain is simulated with ASTRA code [15] for the two-port configuration using the same focusing used in Ref. [11].

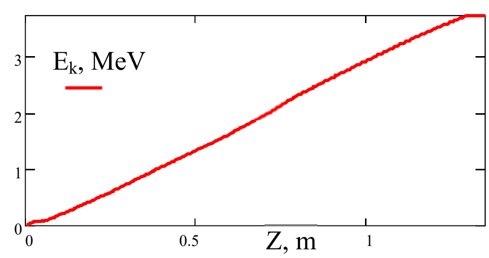

Figure 13: Beam energy gain [MeV] along the structure for the field profile of Fig. 8 (bottom) for RF power ~600 kW.

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