RFQ DRIFT-TUBE PROTON LINACS IN IHEP

Yu.A. Budanov#, O.K. Belyaev, S.V. Ivanov, A.P. Maltsev, I.G. Maltsev,
V.B. Stepanov, S.A. Strekalovskyh, V.A. Teplyakov, V.A. Zenin
IHEP, Protvino, Moscow Reg., 142281, Russia

Abstract

The major RFQ Drift-Tube proton Linacs (RFQ-DTL) of IHEP-Protvino are described. The unique feature inherent in these accelerators is use of spatially periodic quadrupole RF focusing. Prospects are outlined for a further progress in R&D of this brand of linacs in IHEP.

PREAMBLE

Stability of a particle motion in a linear accelerator can be attained via choosing a dedicated geometry for accelerating gaps such as to force transverse components of accelerating field to exert the RF quadrupole focusing effect. Primary feasibility studies for this kind of focusing were, mostly, theoretical and foresaw either a weak focusing effect, or an unacceptably low accelerating rate.

A proposal by V.A. Teplyakov [1] to supplement an accelerating gap with a spacer electrode (or, generally, with a few of them), charged under an intermediate potential, has allowed for a noticeable upgrade in performance of the focusing mechanism at issue. Careful tailoring the period geometry allows to attain nearly the same minimal transverse frequency for all phases along bunch which improves beam quality [2].

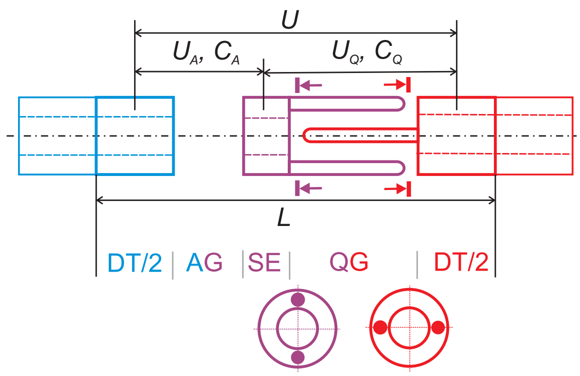

Figure 1: Schematic layout of accelerating cell.

Fig. 1 sketches such an accelerating cell with one spacer electrode SE (AG and QG are accelerating and quadrupole gaps, U_A and U_Q are voltages across them, total $U = U_A + U_Q$, and DT/2 is half of a drift tube, $L = \beta\lambda/2$). It is this structure that is employed in the first sections of URAL-30 and URAL-30M linacs of IHEP (URAL is a Russian acronym for **a**ccelerator **r**esonant **a**uto-focusing and **l**inear — a local code name for the machines).

Since then, a comprehensive R&D program has been pursued in IHEP to manufacture and run RFQ-DT linacs in which accelerating & focusing structure is driven at π-mode by a standing-wave cavity oscillating at a longitudinal-magnetic-field fundamental mode (an *H*-cavity).

In what follows, a 20-year long experience of IHEP-Protvino in R&D of RFQ-DTLs is reviewed.

RFQ-DTL FACILITIES

URAL-30

In 1968, the first experimental model of a linac based on the RFQ principle was assembled [3]. This event has encouraged feasibility studies for implementing RF focusing at lower energies. In 1969, I.M. Kapchinsky (ITEP-Moscow) and V.A. Teplyakov (IHEP-Protvino) put forward the concept of spatially uniform (smooth) quadrupole RF focusing (RFQ). By 1972, initial testing was accomplished, and the first accelerated beam was obtained [3].

The URAL-30 proton linac was commissioned in 1977. It applies a through front-to-end RFQ-focusing up to the top energy of 30 MeV. For a few years to follow diverse and instructive experimental studies of the machine were performed, and a sound practical experience acquired.

Since 1985 till now, this facility routinely operates as an injector to booster proton synchrotron, thus feeding the entire accelerator complex of IHEP (see Fig. 2).

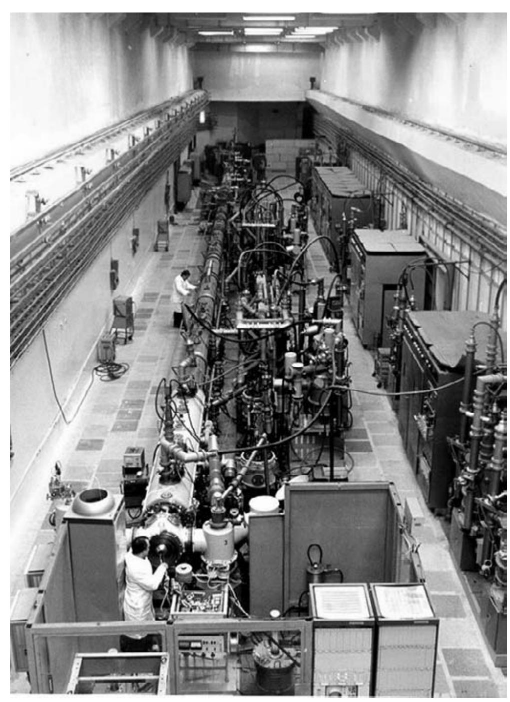

Figure 2: URAL-30 linac in the machine hall. Direction downstream of beam — away from the viewpoint.

#budanov51@mail.ru

Table 1 specifies major parameters of URAL-30. Its RFQ-DTL part comprises two segments, either being divided into two sections, four in total.

Table 1: Parameter list of URAL-30

Parameter	RFQ	RFQ-DTL	
	S # 0	S # 1,2	S # 3,4
Beam energy, in, MeV	0.1	1.98	16
Beam energy, out, MeV	1.98	16	29.99
Max. current, mA	100	100	100
Voltage, kV	150	304	352
Max. E-field on surface, kV/cm	225	380	370
Momentum spread, %	±1.5	±0.47	±0.42
Bunch width, deg	45	20	12
Stable phase angle, deg	–(90-30)	–30	–30
Gap efficiency	0.002–0.3	0.63–0.87	
Number of cells	136	65	57
Phase advance, μ	0.96	1.5–1.38	
Acceptance, πcm·mrad	1.12	0.85	
Emittance @ 90% and 100 mA, π cm·mrad	0.18	0.26	0.32

Beam pulse length is 10 μs. Pulse repetition rate is 25 Hz inside a packet, packet-to-packet recurring frequency being 0.2 Hz. Operating radio frequency is 148.5 MHz. Length of accelerator is 25.3 m. Tank shell is manufactured of steel, copper-coated from inside. Electrodes are wholly tooled of OFC-grade copper.

The operational experience gained by now tells that, given careful manufacturing and accurate tuning, the RFQ-DTL is well commeasurable to a conventional Alvarez DTL in reliability and physical parameters yielded.

On putting URAL-30 into operation, a few more advanced models of RFQ and RFQ-DTL accelerators are being developed and assembled in IHEP.

URAL-30M

By now, many parts and subsystems of URAL-30 no longer comply with up-to-date requirements and thus call for replacement. A-few-year-long scientific research efforts and computer simulations ([5], [6], [7] etc) allowed to launch design of a novel, upgraded machine intended to yield far a better functionality than URAL-30.

This accelerator, URAL-30M (**m**odernized), is currently being manufactured in IHEP. For the time being, a conventional (smooth) RFQ and two of four RFQ-DTL sections (up to 15 MeV) are assembled and subjected to pre-commissioning tests. Others are being fabricated.

In this machine, measures are foreseen to facilitate a better section-to-section matching of beam. The particular attention is paid to interface between RFQ and RFQ-DTL. To this end, accelerating rate at exit from RFQ approaches that at entry to RFQ-DTL. Longitudinal emittance of beam is minimized. A more regular transverse focusing pattern is foreseen — FD periodicity is applied in both, RFQ and RFQ-DTL sections. On the contrary, the RFQ-DTL section of URAL-30 relied on the FFDD layout.

To ensure the improved stability of operation, maximum E-field on the surface tips of electrodes is lowered down to ≤ 350 kV/cm. Voltage jumps in between sections are reduced noticeably. Vane-to-vane voltage U is now ramped along the cavity length, downstream of beam motion. This allows to compensate for a descent in accelerating rate $\propto 1/\beta$ inherent in an invariable-voltage option (e.g., that of URAL-30).

The accelerating structure itself diverges essentially from that of URAL-30. Both, cavity and tanks are manufactured of a copper-plated aluminum alloy; which eliminates corrosion problems and lowers outgassing rate. Electrodes are tooled of bulk OFC copper. An old-fashioned *H*-cavity (refer to Fig. 3) is used only in the first section of URAL-30M. Other sections employ the so-called sector *H*-cavity (an *SH*-cavity). These exhibit a higher shunt impedance and enable much an easier assembly of the electrodes. The latter procedure is not a trivial task since it should yield the prescribed partition of overall voltage U in between accelerating (U_A) and focusing (U_Q) gaps. To this end, support stems of intermediate (spacer) electrodes must be installed at a well-controlled angle with respect to the vertical plane of the cavity symmetry. The design goal is to provide constant voltage U_Q across quadrupole gaps, while keeping the voltage across accelerating gaps ramped along beam path, $U_A \propto \beta$. Contrary to URAL-30, URAL-30M has lengths of accelerating gaps varying along the cavity section.

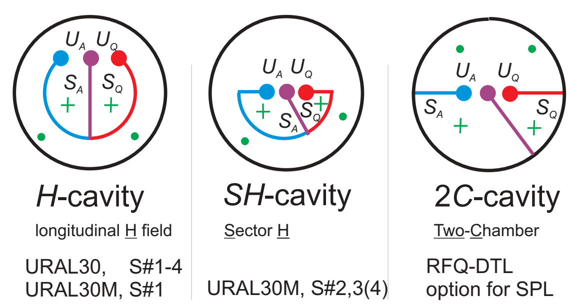

Figure 3: Three *H*-cavity options for the RFQ-DTLs.

Preliminary testing of the first two RFQ-DT sections of URAL-30M indicates that emittance growth is now significantly lower, as compared to its predecessor. All the more, URAL-30M has a shorter length of 23.4 m.

Tuning the accelerator

This procedure is of crucial importance for the facility in question. It must provide: (i) the prescribed partitioning of the net cell voltage $U = U_A + U_Q$ through a distributed series capacitive divider,

$$U_A / U_Q = C_Q / C_A ,$$

(ii) a proper ramp of U longitudinally along beam axis, and (iii) ensure ultimate tuning the entire loaded cavity to the preset operating radio frequency.

In URAL-30M, the capacitive tuners for $C_{A,Q}$ are placed onto the cavity vanes. Since, generally, $U_A \neq U_Q$, one has to install support stem of an intermediate (spacer) electrode so as to cancel out electrical current from the stem to the cavity body. This demand is met by obeying the ratio

$$\int_{S_A} H_A dS \Big/ \int_{S_Q} H_Q dS = C_Q \big/ C_A ,$$

which dictates inclination angle of stem with respect to vertical. Here, S_A and S_Q are cross-areas in between respective vanes and the spacer electrode (see Fig. 3). First, this angle is calculated theoretically. Then, its value is subjected to bench verification. If required, proper stem position is adjusted iteratively, Fig. 4.

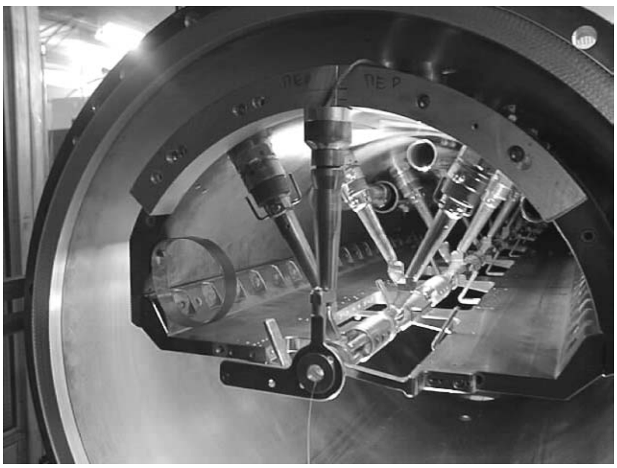

Figure 4: Open *SH*-cavity in a tuning process.

A smaller-scale *H*-cavity has a rather low stored energy, about an order of magnitude less as compared to its Alvarez counterpart. Therefore, on the one hand, tolerances on the field stability under beam in RFQ-DTLs get tougher. To handle this problem, two quite novel automatic control systems were developed and implemented in IHEP [8]. On the other hand, lower stored energy alleviates aftermaths of electrical breakdowns, which is crucial for a heavy-duty-factor regime.

Dedicated long-life-time (of 4 years ca) ion sources for URAL-30 and URAL-30M were custom-made in situ [9].

Other activities with RFQ-DTLs

During the recent years, there was an apparent trend observed word-wide towards R&D of new ion linacs to be operated at higher radio frequencies, under heavier duty-factors, and having decreased geometrical dimensions.

At the moment, IHEP is getting involved into R&D and manufacture of a prototype first section for 40 MeV RFQ-DTL at 352.2 MHz — the intended RFQ-DTL option for the warm front-end part of the CERN SPL project. It is a tri-lateral endeavor of CERN-Geneva, IHEP-Protvino and RFNC-VNIIEF-Sarov, supported by the Moscow-based International Science and Technology Center (ISTC) [10].

A tentative parameter list of the prototype to be manufactured is specified in Table 2. The cavity option proposed is the so-called 2*C*-cavity (refer to Fig. 3).

Table 2: Parameter list of 352.2 MHz RFQ-DTL

Beam energy, MeV	3.0–11.27
Beam current, mA	40
Length of accelerating channel, mm	3243.6
Voltage across cell, kV	170–219.7
Voltage across accelerating gap, kV	80–129.7
Voltage across quadrupole gap, kV	90
Max. E-field on surface, kV/cm	325
Acceptance, π mm·mrad	5.5
Focusing pattern	FFDD
Phase advance, μ	0.6
Min. transverse frequency, minν	0.46
Stable phase angle, deg	–30
Gap efficiency	0.68–0.85
Normalized transverse r.m.s. emittance @ 40 mA, π mm·mrad	0.33–0.34
Normalized longitudinal r.m.s. emittance @ 40 mA, π deg·MeV	0.25–0.26
Aperture radius, mm	4.5
Number of cells	65

CONCLUSION

The concept itself of accelerating protons to 30-40 MeV with RFQ-DTL has not yet exhausted itself. Further activity in that direction is well promising and can result in new effective facilities.

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