REVIEW ON TRENDS IN NORMAL CONDUCTING LINACS FOR PROTONS, IONS AND ELECTRONS, WITH EMPHASIS ON NEW TECHNOLOGIES AND APPLICATIONS

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Abstract

In recent years superconducting (SC) cavities seem to rise in popularity. While these cavities can save operating costs and shorten the length of linacs, there are many applications and circumstances where normal conducting (NC) cavities are superior. This talk reviews some of the NC Radio Frequency (RF) linacs, which have been either recently commissioned, or which are currently under construction or in the design phase. Focus will be given to the choice between NC and SC cavities and to emerging normal conducting technologies and their applications.

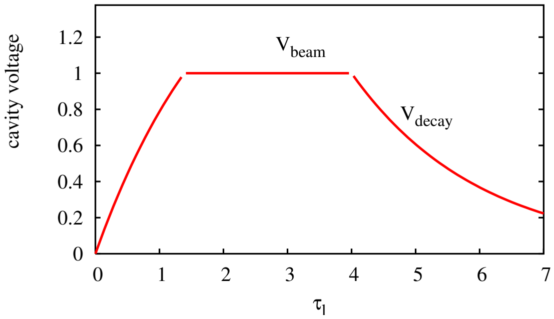

Figure 1: Voltage profile in a pulsed cavity.

PARAMETER RANGE FOR NC LINACS AND THEIR APPLICATIONS

The choice between NC and SC linacs is made according to power efficiency, real estate gradient, capital investment, maintenance/ running cost, local expertise, and the interest in “doing something new”. While the last one may not sound very scientific, engineers are often more attracted to work on SC cavities, which are perceived as challenging and innovative, while NC linacs are considered as not very high-tech.

The above mentioned criteria depend very much on operational parameters such as beam pulse length, bunch current, final energy, duty cycle, and final energy, which also determine the transition energy between NC and SC cavities in the case of hadron linacs.

Parameters

Beam pulse length The filling time t_{fill} of a cavity together with the beam pulse length t_{pulse} determines the RF duty cycle and therefore the RF power consumption. For the cryogenic duty cycle of SC linacs one has to add not only t_{fill} but also the decay time t_{dec} [1] in order to calculate the power consumption of the cryogenic system (see Fig. 1). The filling time is generally proportional to Q/f with Q being the quality factor of the cavity and f the RF frequency. In case of TW NC structures t_{fill} is determined by the group velocity of the RF wave and the structure length, yielding very small values in the <1 µs range. SW NC structures typically need 10 s of µs until the reflected RF waves have stabilised and in SC SW structures one is typically in the range of 100 s of µs or even ms. It is therefore clear that the combination of short µs-range pulses and SC cavities is not very efficient.

Bunch current The power dissipated in the surface of NC SW structures is determined by its accelerating voltage V_{acc}, effective shunt impedance ZT^2, and its length L according to

$$P_d = \frac{V_{acc}^2}{ZT^2 L}. \tag{1}$$

For high currents (e.g. > 100 mA) the beam power $P_b = I \cdot V_{acc}$ can be larger than P_d and then the power efficiency of a NC linac can often be better than a SC alternative. High beam currents may also require to operate SC cavities at a modest gradient in order to protect the power coupler from too high peak power values, which is another argument against SC cavities at high bunch current.

Accelerating gradient/final energy A high-energy linac needs high accelerating gradients in order to limit its length and cost. For short pulses in the µs range NC TW or SW structures are usually the most efficient choice. For longer pulses in the ms range one can choose SC structures. NC TW structures are used routinely at ≈ 30 MV/m for the acceleration of electrons. Even though much higher gradients (60-70 MV/m) can be operated reliably they are rarely used because of the increased cost of high peak power RF systems. SC structures also approach usable gradients of around ≈ 30 MV/m with a good example being the XFEL cryomodules, which achieved an average 27.9 MV/m during testing [2]. More R&D may push the gradients of SC cavities higher but also here the cost of high peak power RF systems may put a natural limit to the gradients being used in operational machines.

TW NC cavities for proton acceleration are so far not used in low-energy linacs, mostly because of the need to adapt the structures to the different energies. However, several projects [3, 4] are working on this option and the coming years may see the first NC linacs operating routinely with 50 MV/m.

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In order to define suitable transition energies between NC and SC sections of a hadron linac one has to consider: i) the operating cost, ii) the cost of the associated RF systems, iii) the engineering effort to adapt the structures to changing particle velocity, iv) the need to maintain the cavity gradients at their exact nominal level in order to maintain the synchronism between the particle velocity and the geometrical gap distances, and v) the needs for transverse focusing. High-current low-energy beams require strong and regular transverse focusing, which means either to integrate the focusing into cryomodules or to loose significant real-estate length by having many cold-warm transitions to fit NC quadrupoles, which increases the footprint.

Duty cycle High duty cycles are more difficult to handle in NC structures, as the heat removal via water cooling is only possible up to a certain threshold. For high duty cycles also the RF efficiency becomes more important as it directly translates into a high operational cost.

SC and NC linacs A detailed comparison of SC versus NC cavities can be found in [5]. In summary (see Table 1) we can see that NC linacs are mostly used for high-current low-duty-cycle operation. For duty cycles in the percent range, NC linacs are usually used as proton injectors for SC linacs or circular machines.

Table 1: Parameter Space for NC and SC Linacs

	NC TW	NC SW	SC
t_{pulse}	$\leq n\times1\,\mu s$	$n\times10\,\mu s$	$n\times100\,\mu s$
I_{beam}	high	high	low
$d.c.$	low	low	high
$E_{electrons}$	high	low	high
$E_{hadrons}$	low	low	high

EXAMPLES/OVERVIEW OF RECENT NC LINAC DESIGNS

Proton/Ion Linacs

Most recent ion linac projects have decided to use low-beta SC structures like half- or quarter-wave resonators followed by spoke cavities. As ion linacs typically operate with very low currents there is a clear economic advantage to use SC structures as the RF system becomes very cheap and the running costs will be low. For this reason we will focus here on recent NC proton injector linacs, which are used as front-ends of larger SC linacs, or as injectors into circular machines.

Proton/H$^-$ injectors Linacs which inject into circular machines usually accelerate H$^-$ to enable charge-exchange injection. As one can see from Table 2 all of these machines start with a Radio Frequency Quadrupole (RFQ), followed by an Alvarez-type or Cross-bar H-mode Drift Tube Linac (DTL, CH-DTL). RFQs have become the standard accelerating structure after the source that: i) bunches the continuous source beam, ii) provides the first few MeV of acceleration (typically 1-5 MeV), and iii) focuses the beam transversely. After an RFQ proton beams are often still space charge dominated, requiring strong and regular transverse focusing to prevent the degradation of the transverse emittance. As the classic Alvarez DTL can accommodate quadrupole magnets in each drift tube, it is ideally suited for low-energy acceleration of space charge dominated beams. Most H-mode DTLs use very small drift tubes to maximise shunt impedance and therefore often use quadrupole triplets between a certain number of accelerating cells. As a result and due to the inherently lower surface losses of H-mode cavities H-type DTLs have a much higher shunt impedance at low energy (see Fig. 2). This comes at the cost of a less regular transverse focusing than in the case of an Alvarez DTL. KOMAC, CSNS, SNS, and ESS use DTLs up to an energy of ≈ 100 MeV. From this energy onwards typically higher frequency $\pi/2$ or π-mode structures are employed due to their higher shunt impedance in this energy range. LINAC4 for instance uses a Pi Mode Structure (PIMS) between 100 and 160 MeV (at the same frequency at the DTL), SNS switches to a $\pi/2$-mode Side Coupled Linac (SCL) at twice the DTL frequency and covers an energy range between 90 and 160 MeV, and ESS makes its transition to SC structures at 90 MeV. Some projects use variations of the Alvarez DTL between 50 and 100 MeV, or even beyond 100 MeV. One example is J-PARC, which uses a Separate-type DTL (SDTL) from 50 to 190 MeV, comprised of short, independently powered DTL tanks. CERN's LINAC4 uses a Cell Coupled DTL (CCDTL) from 50 to 100 MeV, which also uses short DTL tanks but in this case 3 small tanks are coupled in the $\pi/2$-mode via coupling cells to a common RF power supply. Both structures use the fact that from 50 MeV onwards, the space charge forces in the beam are low enough to lengthen the transverse focusing periods. That means that the quadrupoles can be taken out of the drift tubes and be placed between the short tanks, which significantly eases their installation, alignment, and cooling and which reduces

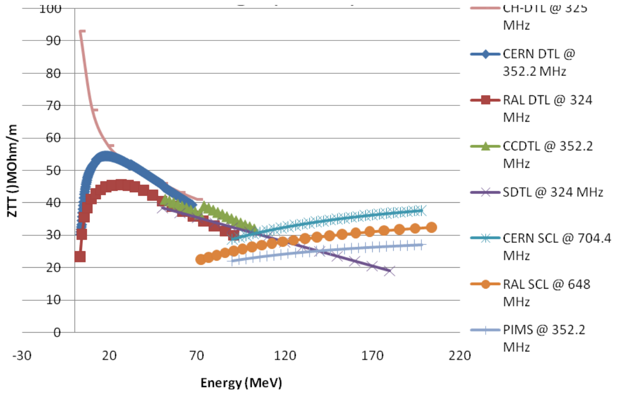

Figure 2: Effective shunt impedance per unit length of various NC SW cavities [6].

Table 2: Examples of Recent NC Linacs under Design (Status D), Construction (Status CN), Commissioning (CM), or Operation (OP)

Linac	t_{beam} [ms]	I^*_{peak} [mA]	$d.c.$ [%]	f_{rep} [Hz]	E_{beam} [MeV]	f_{RF} [GHz]	E_{acc} [MV/m]	P_{beam} [kW]	structures	application	status
					H^- linacs						
LINAC4† [7]	0.8	32	0.08	1	160	0.352	4	2.6	RFQ, DTL, CCDTL, PIMS	p-injector	CM
JPARC† [8]	0.5	30	1.3	25	400	0.32/0.97	4	133	RFQ, DTL, SDTL, ACS	p-injector	OP
SNS NC† [9]	1	26	6	60	186	0.4/0.8	4	288	RFQ, DTL, SCL	p-injector	OP
CSNS† [10]	0.4	15	1	25	80	0.324	2.5	6	RFQ, DTL	p-injector	CM
					Proton linacs						
KOMAC [11]	1.33	20	8	60	100	0.35	2	160	RFQ, DTL	multi-purpose	OP
ESS NC [12]	3	62.5	4.2	14	90	0.352	3.2	236	RFQ, DTL	neutron source	D
FAIR PI [13]	0.2	70	0.1	4	70	0.325	6	4	RFQ, CH-DTL	p-injector	CN
TULIP [4]	0.02	0.3	0.4	200	230	0.8/3	30/50	0.3	RFQ, IH, DTL, BTW	hadron therapy	D
					Carbon linacs						
CABOTO [14]	0.0035	?	0.1	300	400/u	12	30	?	CCL	carbon therapy	D
ACCIL [3]	?	?	?	?	450/u	2.86	50	?	CCL	carbon therapy	D
					Electron linacs						
ILU-14 [15]	0.42	500	2.1	50	10	0.176	1.8	100	bi-per. CCL	industrial	OP
KIPT [16]	0.0027	600	0.17	625	100	2.856	7.5	100	TW	neutron source	CN
ELI-NP [17]	0.0005	1425	0.005	100	720	5.7	33	13	TW	γ-ray	CN
FERMI [18]	n.a.	1500	n.a.	50	1500	3	30	< 0.1	BTW	FEL	OP
SWISSFEL [19]	n.a.	1000	n.a.	100	5800	5.7	28.5	0.2	TW	FEL	CN
PAL-XFEL [20]	n.a.	570	n.a.	60	10000	2.86	20	0.1	TW	FEL	CM
MAX IV [21]	n.a.	300	n.a.	100	3000	3	20	< 0.1	TW	e-injector	OP
CLIC [22]	156 ns	1000	0.0008	50	1.5 TeV	12	100	14000	TW	collider	D

* peak currents are averaged over one RF period

† these linacs have a sub-pulse structure, which reduces the average pulse current

the tolerances on alignment of the drift tubes. The NC section of the J-PARC linac continues after the SDTL with an Annular Coupled ring Structure (ACS) at 3× the DTL frequency up to 400 MeV, which is probably the highest energy of any recently built NC proton linac.

Medical linacs For medical linacs NC structures are attractive for various reasons: i) the needed energy for proton therapy is relatively modest (< 250 MeV), ii) the duty cycle is generally low, iii) the complication of maintaining a cryogenic cooling plant is avoided. So far all operating hadron therapy facilities are based on cyclotrons and synchrotrons but technological advances of recent years have made the linac option more interesting. In the case of ACCIL and CABOTO for Carbon therapy the bulk of the acceleration is made with a SW CCL operating in S-band and X-band with 50 or 30 MV/m, respectively. High gradients and therefore the high peak power from the RF system were chosen in order to keep the footprint of the 400/450 MeV/u machines small, which in the case of ACCIL is only 40 m for the complete linac. Another approach is taken for TULIP (Fig. 3), were a proton beam is pre-accelerated to 60 MeV (5 MeV with a 750 MHz RFQ, 20 MeV with a 750 MHz IH DTL, and up to 60 MeV with a 3 GHz DTL) and then boosted to 230 MeV by a low-beta Backward Travelling Wave (BTW) structure [23], which is directly mounted on the gantry for patient treatment. Also here, high gradients of 50 MV/m are necessary to keep the linac structure short. First test results of the BTW structure are expected this year.

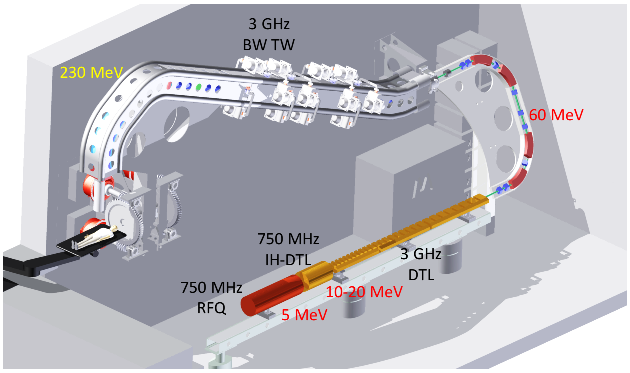

Figure 3: Layout of TULIP.

Electron Linacs

Light/neutron sources Certain Free Electron Lasers (FEL) are built to achieve extremely short pulse lengths, using just one or two bunches/pulse. SC linacs would be extremely inefficient for this purpose because of their long cavity filling time and the very small duty cycle. They are used, however, at higher energies and with longer bunch trains as in the case of the European XFEL [24] or even in CW mode [25]. Table 2 has three examples of NC linac used for FELs: FERMI@Elettra in Italy [18], which is undergoing various upgrades, SWISSFEL [19], which is under construction at PSI in Switzerland, and PAL-XFEL in Korea [20], which is presently being commissioned. They span final energies from 1.5 to 10 GeV and are working in S-band or C-band (SWISSFEL). They all accelerate highly charged bunches, in the order of 1 kA (when averaged over one RF cycle) and they all use travelling wave structures with accelerating gradients in the order of 30 MV/m. With repetition rates between 50 and 100 Hz the final beam power is in the 100 W range.

TW cavities are also used in full-energy injector linacs for synchrotron light sources of the newest generation, as for instance at MAX IV in Sweden [21]. There only 3 bunches are needed per pulse for injection or top-up operation, yielding again a negligible duty cycle and very small beam power.

The 720 MeV electron beam, which will be produced at the Extreme Light Source (ELI-NP) interacts with laser light to produce a gamma-ray beam via Compton backscattering. While the linac is very similar to the afore mentioned FEL's ELI-NP uses short trains of bunches resulting in 13 kW of beam power. An even higher beam power of 100 kW at an even lower beam energy of 100 MeV will be produced at the KIPT neutron source in Ukraine [16], where the gamma radiation of the electron beam produces neutrons via irradiation of uranium or tungsten targets. These neutrons will then be multiplied in a subcritical assembly and used for nuclear physics, solid state physics, biology, medical isotopes, and radionuclide transmutations. Also at KIPT S-band TW structures are used.

Linear collider The most active design study for a NC collider is the Compact Linear Collider (CLIC) study based at CERN [22]. It aims at collision energies of up to 3 TeV and at accelerating gradients of 100 MV/m in 12 GHz TW structures [26] (Fig. 4). The RF power for the accelerating structures is created by a drive beam, which is decelerated in special Power Extraction and Transfer Structures (PETS). The drive beam itself is accelerated in 1 GHz cavities, powered by klystrons. Breakdowns in the accelerating structures are limited by using only short pulses in the order of 150 ns and by employing extensive power conditioning, which lasts 2-3 months per accelerating structure [27].

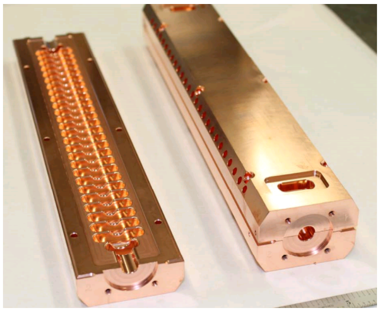

Figure 4: CLIC-G T24OPEN prototype.

Industrial and medical machines Low energy electron linacs are since many years produced commercially and used for radiotherapy, cargo screening, radiography, and radiation processing [28]. X-ray or electron beams produced by small electron linacs remain a workhorse in the treatment of various cancers. Due to their low energy of 10-20 MeV these machines typically integrate the accelerator in the gantry, which is used to treat the patient from various angles. SW and TW structures between S- and X-band are employed and often driven by cheap magnetron RF sources.

Progress on the intensity frontier was recently made using lower frequency accelerating structures. BINP, Novosibirsk succeeded in constructing a 10 MeV electron linac (ILU-14) [15] providing a 100 kW beam for industrial applications.

TRENDS AND NEW TECHNOLOGIES IN NC LINAC TECHNOLOGIES

Proton/H$^-$ Linacs

Proton and H$^-$ linacs, which are designed to deliver several per cent of duty cycle all rely on a RFQ/DTL front-end. The Alvarez DTL remains the most popular low-energy structure and despite it's 70 year age, it has seen some improvements in recent years.

RFQ Several improvement have been made in recent years in the design of RFQs. One example is the use of trapezoidal cells, which was pioneered at IHEP, Russia [29] and recently used for instance at Argonne, USA [30]. Compared with the sinusoidal vane modulation, the trapezoidal one increases the transit time factor and therefore gives higher acceleration efficiency, higher effective accelerating gradients and can yield a better longitudinal matching into subsequent accelerating structures.

Progress has also been made in the field of high duty cycle, or CW NC RFQs, which require elaborate cooling schemes. Due to past successful CW operation of 4-vane RFQs, new devices [31] are designed with heat loads up to around 100 kW as for instance the FRIB RFQ [32]. Building 4-rod RFQs for high duty cycles remained somewhat challenging as illustrated by the SARAF RFQ, which reached reliable CW operation up to a heat load of $\approx$ 60 kW/m [33]. However, recent progress with the cooling of 4-rod RFQs seems to push the limits. A prototype of the FRANZ RFQ [34] has been successfully CW tested with a heat load above 100 kW/m and a new CW 4-rod RFQ is under design for GSI [35].

Another innovation is the construction of a 750 MHz RFQ at CERN, which will be the highest frequency RFQ built so far [36, 37]. One of the applications is a high-frequency front-end for medical linacs, allowing for more compact and cost efficient machines.

DTL quadrupoles In order to raise the DTL shunt impedance an effort has been made to reduce the size of the drift tubes and therefore to shrink the size of the quadrupoles, which are housed inside. SNS and Linac4 chose permanent magnetic quadrupoles (PMQs), relying therefore on precise beam dynamics simulations and a good prediction of the beam characteristics out of the source. J-PARC and CSNS reduced the size of electric quadrupoles by using reverse copper electro-forming to make very compact coils. While this solution is more expensive than PMQs it offers more adjustment possibilities for the DTL operation. Both approaches have been validated during operation at SNS and J-PARC. Another trend that can be seen is to use focusing schemes, which do not use every drift tube for quadrupoles. Leaving for instance every 2nd drift tube empty only slightly increases the beam radius but offers space for beam position measurements and corrector magnets.

DTL post coupler adjustment Post coupler stabilisation of DTLs was patented 50 years ago and is used since then for basically every Alvarez type DTL that has been put into operation. The adjustment of the coupler length, however, has either been subject to a certain trial-and-error approach, or involved a complicated modelling of the coupled resonant circuitry inside a DTL. With the construction of Linac4 at CERN a new method was derived, which has considerably streamlined the adjustment process and which allows a simple stabilisation without the extraction of the circuit model itself [38].

Medium beta structures With the goal to optimize the shunt impedance and to simplify construction and magnet alignment for proton energies above 50 MeV, the Linac4 project at CERN has decided to revive the Cell-Coupled DTL (CCDTL), which was conceived at LANL for CW operation [39]. However, the large heat load of CW operation made it difficult to keep the coupled resonator chain on tune. The Linac4 CCDTL was re-engineered for a maximum duty cycle of 10% and constructed in collaboration with BINP, Novosibirsk and VNIITF, Snezhinsk in Russia [40]. It has recently been commissioned successfully [7] and will be the first CCDTL to be used in an operational machine.

The ACS at J-PARC (190-400 MeV) has been concieved [41] to minimise field distortion at the beam axis, which can be caused by non-symmetric coupling slots. This yields slightly larger transverse dimensions, which have been compensated by tripling the frequency from 324 MHz (DTL) to 972 MHz. A good comparison of some NC medium beta structures is given in [42].

The PIMS at CERN is according to our knowledge the first pi-mode structure, which is used for medium-energy protons. The goal was to have a simple structure that maintains the same frequency as the section up to 100 MeV in order to simplify the RF system. For this purpose the Pi-mode NC structure, which was used at LEP, was scaled for lower velocity and re-engineered for pulsed operation with 7 cells instead of 5. The first PIMS structure of Linac4 has recently seen beam and the following 11 structures will undergo beam commissioning before the end of 2016.

The choice how many different structures and which structure types to use after a DTL, is usually influenced by local experience and the local capacity to engineer and build different structure types. The ability to "make it work" is a strong function of local knowledge and interest and therefore it is often justified to choose a certain structure type even if it is slightly less efficient than another.

Hadron therapy linacs TULIP [4] plans to introduce several innovative technologies in its proton therapy linac: i) high-frequency (750 MHz) RFQ, ii) Backward Travelling Wave structure for low energy protons with gradients up to 50 MV/m, iii) proton linac structure on the gantry. Bundled together these may result in a significant cost and size reduction of such a facility. Carbon linac projects, like CABOTO [14] and ACCIL [3] also count on high-gradient NC structures (30/50 MV/m) to reduce the footprint and cost for carbon-based therapy.

Electron Linacs

High gradient travelling wave structures, which were originally developed in the frame of linear colliders find more applications. Specifically for FEL's with short bunch trains, containing just a few or even just one bunch per pulse, but also as full energy injectors to synchrotron light sources. Also higher power applications, like KIPT [16] are planning to use TW structures, though at lower accelerating gradients. Even though gradients of 60-70 MV/m are considered feasible, most projects limit themselves to around 30 MV/m as higher gradients would significantly increase the cost of RF power generation.

Unless very high beam power is needed, as for ILU-14 [15], electron linacs mostly deploy TW structures.

SUMMARY

NC linear accelerators have very well defined applications and significant R&D is being done on many different NC structure types. Research that was done for NC linear colliders is now being used in light sources and other user facilities. Travelling wave structures are being adapted for low-energy protons to reduce the footprint of medical linacs. Even the classic Alvarez DTL received a modern day theory for post-coupler stabilisation.

For short pulses, high beam currents, and low duty cycles NC linacs usually offer unparalleled energy efficiency, simplicity, and accelerating gradients.

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