The Low Energy Part of High Intensity Accelerators*

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Abstract

The interest in high intensity particle beams has been pushed by high energy physics needs as well as by applications like neutron sources, military material testing, and inertial and confinement fusion. Based on development in High Energy Labs the work on ions sources and accelerator structures have increased the pulse as well as the average current significantly. Especially the development of the RFQ-structure changed the designs of high intensity accelerators. A survey of the status of low beta linac parts of high intensity proton beam installations is given together with results of test stand work and properties of proposed future machines.

1. Introduction

Preinjectors, a combination of an ion source, a low energy beam transport line (LEBT), a preaccelerator, mostly a Cockroft Walton Cascade or a RFQ, and an intermediate matching section (IMS) which matches the beam to a following structure e.g. an Alvarez accelerator. Despite being relativly short, this preinjector defines the phase space density for the following stages in which the effective emittance can only grow. For light ion beams the emittance can be made smaller only by losses, that means cutting out the core of the beam, or by cooling, which is not suitable for high intensity beams. Emittance and beam current are optimized in the design of a high intensity accelerator.

The increase of beam intensity has been a major part of machine development efforts starting mostly just after the comissioning of high energy accelerators. The efforts lead to the improvements in high current beam dynamics, ion sources and accelerator structures. The classical low energy part was a combination of a proton source, a static 500-750kV Cockroft Walton preinjector and a 200 MHz Alvarez-Linac. First modification of this first accelerator stage have been the use of H^--sources together with stripping injection into the (first) synchrotron ring, which requires relativly low linac currents with higher pulse lengthes. The bottleneck than mostly was the space charge limit in this first ring, which could be cured by a higher injection energy like at FNAL [1].

The development of the RFQ-structure was a major step for the improvement of preinjectors. It replaced C.W. Cascades in most old and all new high intensity accelerator designs giving the option for higher overall transmission and reduced emittance growth in the preinjector. It also made it possible to design and operate injectors with up to 100% duty factor.

For special ion sources like for polarized protons and for heavy ions with high charge states (and eventually also high duty factors), it allows the use of complicated bulky sources, which are installed on "low" voltage platforms (20-100kV), which at least facilitates the maintenance of such systems.

While the injectors for synchrotrons work at low duty factors of 10^{-6} to $5*10^{-3}$ the high power linacs like used at LAMPF and ISIS (duty factors 10^{-1} and $2.5*10^{-2}$-) still employ C.W. injectors, but plans for modifications and improvement by use of RFQs are in progress.

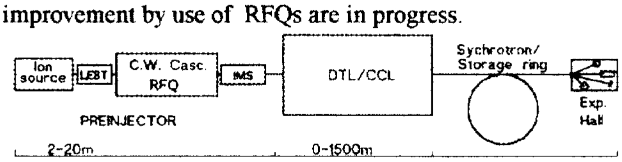

Fig. 1 Scheme of a high intensity accelerator system

2. Ion Sources

Up to now there is no generally accepted solution for the choice of an ion source for a high intensity preinjector. Depending on the operational requirements the current brightness requirement might lead to a choice which differs from proven performance in reliability, operational stability and life time or efficiency [2,3].

The development in source performance is slow if a common basis of judgement is applied. Therefore operational accelerators might get more pessimistic results and extrapolations[4]. Proton sources are "simpler" than H^--sources. CERN is using a Duoplasmatron and reaches well over 200mA in pulsed (appr. 100μsec, 1Hz) operation, while a cw-ECR source developed in Chalk River [5] provided up to 100mA with 100% duty factor.

The injectors at BNL, FNAL and DESY routinely work with magnetron sources for H^- and get very good results for their regime of currents and duty cycles, especially with respect to operational stability, because their sources last up to a complete run of several months.

The Penning ion sources are similar, because they also use surface ionisation process to generate H^- and a very dense discharge with a strong magnetic field across the extraction area [6]. The Penning is better suited for high duty factors and the ISIS injector (RAL) operates very succesfully with a duty factor of 2.5%, H^- currents between 25mAand 45mA [4]. LANL has developed and operated for ATS and GTA a Surface Penning source which they scaled up (4x,8x) for better thermal properties and life time, planned to be applied

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at the LANSCE upgrade of LAMPF [7]. The power density of the discharge is a limiting factor, which for the Penning source has still development potential. At present for H⁻ operation and injection into PSR at LAMPF a surface converter volume source is being used with currents up to 7mA.

The volume source for H^- has been developed at LBL, BNL, Culham, Palaiseau, and KEK. LBL has a special development of a rf-driven source, without the lifetime restriction given by the filaments and without Cs supply, which was successfully tested at the SSC injector [3]. For higher currents Cs is drastically improving the performance.

Taking the scaling laws of ion sources and the corresponding extraction systems for a high density plasma, an increase in current goes along with a larger emittance and a change of the optimum geometry. By applying higher voltages or increasing the extraction aperture only, beam quality will be worsened. The complex interference of plasma parameters and beam optics parameters makes simple scaling and comparison difficult. Generally for a high brightness beam a small extraction voltage, a quiet plasma with small ion temperature, and a high plasma resp. current density must be chosen.

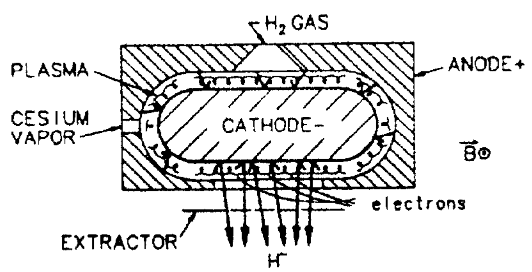

Fig. 2 Basic magnetron source configuration

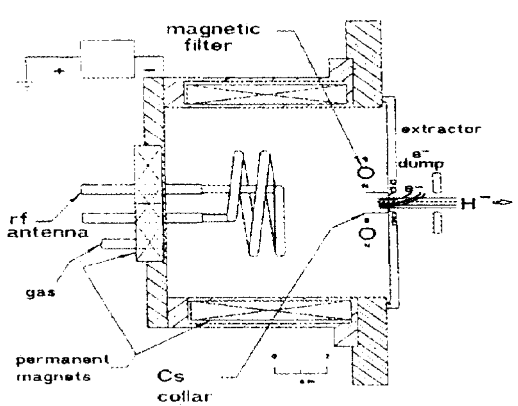

Fig. 3 Rf-driven Volume-Source

3. Low Energy Beam Transport

The LEBT section connects the ion source with the following accelerator and must allow beam optics matching, diagnostics, some steering and sufficient pumping to avoid breakdowns in the high gradient structures. It should provide these properties without significant emittance growth and losses. The beam transport is done with combinations of electrical and magnetical lenses, which will influence the beam neutralization of high current beams in a difficult way, such that losses are unavoidable.

In case of matching into a RFQ-structure normally a round converging beam is required. Two Einzel-Lenses or two solenoids are mostly used. More complicated but stronger are triplet arrangements. For lower currents a single lens can give sufficient results, while for slit extraction system a good matching requires more degrees of freedom.

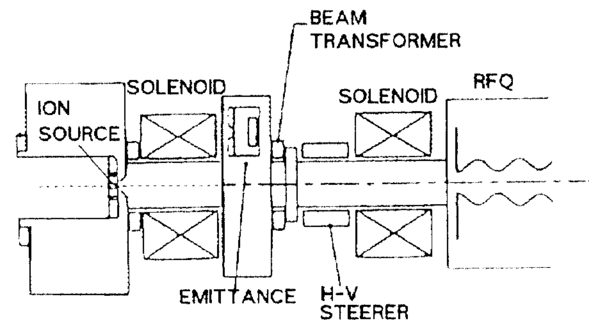

Fig. 4 LEBT with two Solenoids

Fig. 4 shows the scheme of a system which is used at CERN, BNL, DESY and in some heavy ion injectors as well. The space between the solenoids can be used for pumping, diagnostics and also for chopping, to produce voids (e.g. 250nsec each 800nsec) in the beam for ring injection or extraction. The rise time of the deflector voltage leads to transients in such a chopper, which results in beam losses. Deneutralisation by the deflector is more severe because it leads to mismatch.

BNL had successfully operated a chopper in the LEBT but has shifted the chopper position to the IMS between RFQ and Alvarez [8]. The deflector voltages are higher and the system is bigger but the beam is well bunched and fully decompensated.

Chopping can be done in a system shown schematicly in fig. 5. For high current applications the losses have to be minimized which makes a smaller RFQ frequency favourable. Splitting the RFQ one can optimize the chopper energy and reduce loss power and ease the focusing gradient requirement at the Alvarez input at the same time

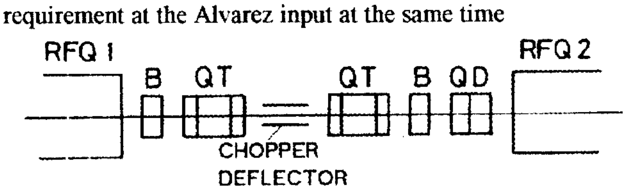

Fig .5 Scheme of a chopping line

4. Radio Frequency Quadrupoles

The possibilities of the RFQ structure to bunch and accelerate low energy high current ion beams opens new parameter spaces for accelerator designs [9,10].

The variety of RFQ-accelerators covers the full ion mass range from H to U, frequency range from 5-500MHz and duty factors up to 100% [11,12]. The physics of transport and acceleration of high current ion beams in RFQs have been solved to such extend, that the best beams, which can be produced by ion sources and tranported in a LEBT, can be captured and transmitted with very small emittance growth by RFQs as shown schematically in Fig.6 [13].

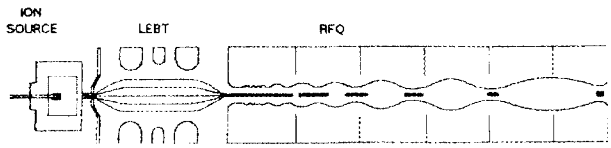

Fig. 6 Scheme of a RFQ injector

The optimum frequency can be determined by many factors. In smaller projects it is the availability of transmitters or a postaccelerator to match. Lower frequencies give stronger focusing, less difficulties with power density and mechanical tolerances and generally a higher current limit. Higher frequencies, for which 4-Vane RFQ structures are employed, are favourable for compact designs with highest brillance e.g. because the charge per bunch is smaller and the frequency jump to a final linac stage is smaller. Fig.7 shows the current limit in proton-RFQs considering a maximum phase advance σ per cell and V=2Kilp. as sparking limit, for proton beams from 50keV to 2MeV.

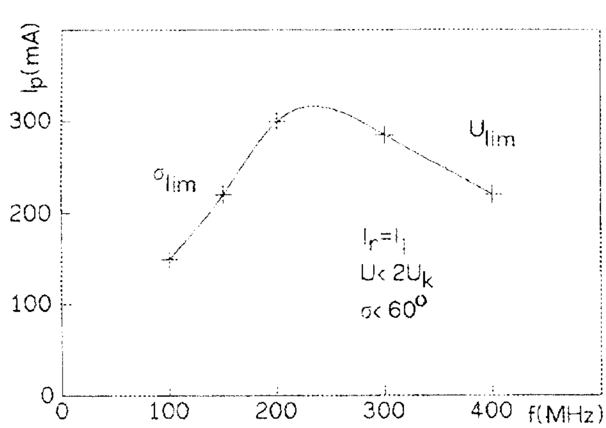

Fig. 7 Proton Current as function of the operating frequency

The parameters of existing RFQs fit into this curve, assuming that the operational current is normally 50% of the current limit.

Generally, the rf-power N needed is independant of the frequency while the acceptance and the max. ion current are proportional to the electrode voltage resp. N^2, which is not a big issue in pulsed injectors with low average power. High duty factor operation is the actual area of development. A first class of structures, which might be used as SNS-linac injectors with duty factors of up to 10%, are being designed now, still more difficulties can be expected for cw-RFQs.

One way to solve the power density problem are cryogenic structures, like at the GTA project at LANL where a 2.5MeV RFQ was operated successfully at 20K temperature [14]. The technology developed for this NPB program (electroformed, one block, 425 MHz 4-vane-RFQs, as show in fig.8) was also applied for Grummans CWDD RFQ [15] and the (room temperature) SSC injector.

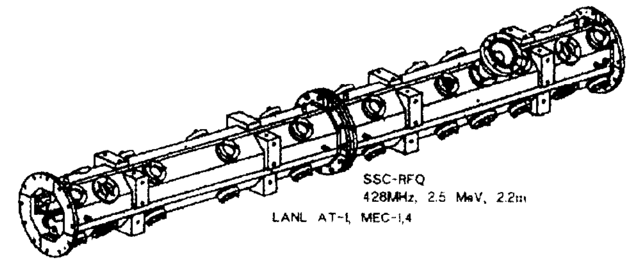

Fig. 7 The SSC-RFQ cavity

5. Intertank Matching Section

Matching between the RFQ and an Alvarez can be done by directly attaching the RFQ and radial matching with the first few quadrupoles in the linac as has been done at DESY. Higher currents, like for the new CERN RFQII, requires an IMS section with rebunchers and additional quads and will change the periodicity of the focusing only adiabatically. Very compact systems have been built for GTA and SSC[16], while BNL has an IMS line of several meters allowing chopping and inflection of a second (polarized) beam.

If the perveance of the ion source or the transport capability of the accelerator system are not sufficient, two beams can be combined into a single beam with same emittance, if the frequency of the accelerator is doubled at the same time, as shown schematically in fig.9

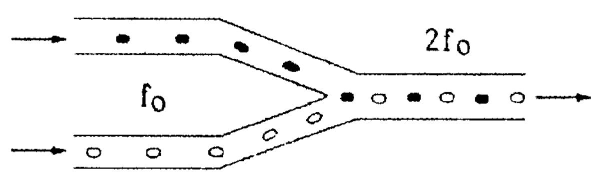

Fig. 9 Funneling scheme

The current limit for RFQs is proportional to the velocity β, so at higher energies the beam current can be multiplied easily. Funneling, proposed first by Montague and Bongardt[17,18], makes use of this fact, but has to be done with a well bunched beam, which is needed for low emittance growth in a system of dipoles, quadrupoles, rebunchers and a deflecting (funneling) rf-cavitiy (fig.10).

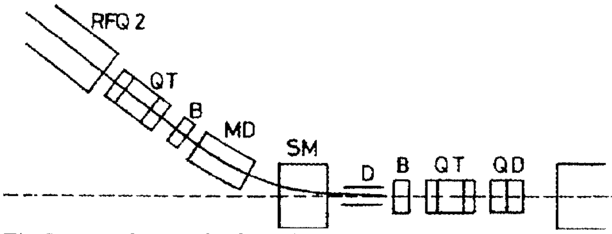

Fig 8 scheme of a funneling line

A successful experiment has been made at LANL with a single leg (one branch) of a funneling systen with a 5MeV H^-

beam [19]. A smaller experiment splitting a RFQ beam with a rf-deflelctor has been done at Frankfurt[20].

6. Applications

The standard application is the operation as preinjector for an Alvarez linac feeding a synchrotron. These systems are comfortably matched to ion source and RFQ designs, because they have a low duty factor, which allows pulsed, high power density operation.

BNL was the first outside Russia to use a RFQ based preinjector for an operational machine, the DESY linac was the first to be designed with an RFQ only (202MHz, 4-Rod RFQ structure, as shown in fig.11).

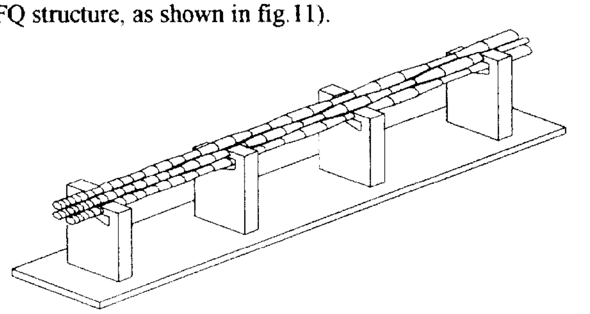

Fig. 11 Scheme of the DESY 4-Rof RFQ structure

CERN replaced its LinacII injector by an RFQ in 1994 (shown in fig.12 with harmonic bunchers in the IMS), with peak currents of 230mA, more than the linac can digest at the moment [22]. FNAL, ISIS and LAMPF don't have an RFQ (yet). Table II summarizes some parameters of these high current linacs. The first group are operational machines, the second group summarizes smaller systems, test stand results and accelerators which operate for shorter periods.

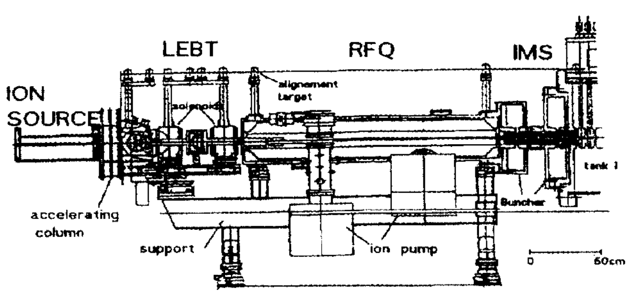

Fig.12 Layout of the CERN RFQII injector

The Loma Linda Synchrotron is a smaller system for medical applications [23]. It employs a 2MeV RFQ (built by AccSys) injecting into a 250MeV synchrotron.

Some of the smaller linacs make use of the properties of light targets for the efficient production of neutrons and PET isotopes. Accelerators like PL/7 of AccSys [24] and the Linac at ICR Kyopto are examples of the increasing use of linac technology for these applications [25].

A big push was given by the defense funded development of high brilliant beams for ATS, GTA and CWDD. To achieve high duty factors with very compact "light" system design cryogenic operation was chosen, the

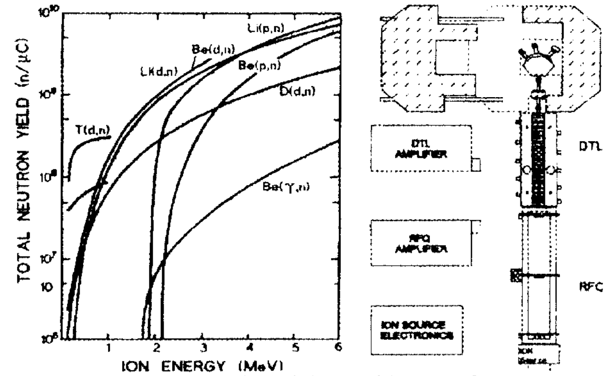

Fig. 13 Neutron production yields and layout of a compact linac as proton source

RFQ structures were electroformed 4-vane cavities with stabilizers, which achieved very good flatness and field stability. On this basis structures for the LANSCE upgrade of LAMPF will be built [26,27].

The CWDD project being set up at ANL, for which Culham did built the dc-injector and Grumman the cryogenic for a RFQ (350 MHz), was designed for a 2MeV, 80mA D^- RFQ beam [15]. The RFQ has been set up and tested. ANL is now converting that accelerator to AWCL, a room temperature linac for neutron a radiography [28], which will adopt some designs from the CRNL RFQ1 project[11]. This RFQ1 project, which was startet as injector for ZEBRA[29], has achieved a great success by accelerating a 1.2MeV, 70mA 100% duty factor beam. At first a "grand piano injector" with a duopigatron, later a ECR proton source was used [30]. The hardware is now being set up at LANL where the continuation of this work is planned.

Actual work is concerned with development of linacs for future hadron facilities [31] and spallation sources, e.g. to upgrade LAMPF and to built a European Spallation source ESS [32], both with a beam power of 5MW. For this beam power and use of H^- for storage ring or RCS injection, the injectors use funneling and must have choppers for a 200nsec beam void. Fig14 shows a scheme of an ESS-injector.

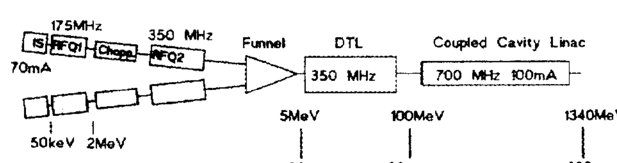

Fig.14 Scheme of a high current ESS-injector linac

For smaller installations like possible upgrades of ANS ISIS and Austron a single injector is sufficient.

Proposals for cw proton accelerators are made for waste transmutation, Tritium- and fuel-bredding [33]. These linacs are designed for 200-400 mA and include funneling after the first DTL linac (LANL), a single RFQ injector (JAERI)[34], and a new high current injector design (MRTI) which has a superconducting solenoid like a manifold over a compact classical DTL[35].

Another proposal is IFMIF, a fusion material irradiation accelerator for 35 MeV deuterium to generate neutrons [36].. The injector parameters are similar to the FMIT experiment, but with a funnel section. The resulting current of one unit is 250mA. Groups from Europe, Japan, USA and Russia are involved in this study.

7. Acknowledgements

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Table 1
Proven H^- Source Performance

	Type	Current [mA]	Duty Cycle [%]	Voltage [kV]	e^-/H^-
LAMPF	SC	5	6	80	1
RAL	P	40	2.5	18	1
FNAL	M	50	0.1	35	0.8
BNL	M	65	0.25	35	0.8
TRIUMPF	V-X	5	100	25	12
LBL	V rf-X	30	0.25	35	10-40
BNL	V	30	0.25	35	40
KEK	V	20	1	40	
LANL	PS	60	2	35	1.5
INP	SPI	100	2.5	25	1
CWDD	V,D^-	20	100	200	
H^+ sources:					
CERN	DP	200	0.1	70	
CRNL	ECR	70	100	50	

Table 2
Performance of High Current Linacs

	Type		Ion Energy [MeV]	Beam Current [mA]	Pulse Length [μsec]	Duty Cycle [%]
CERN	DP/RFQ	H^+	50	150	110	0.01
Saclay	DP/vdG	H^+	20	20	500	0.1
BNL	M/RFQ	H^-	200	50	500	0.25
FNAL	M/CW	H^-	400	35	50	0.1
Sepukhov	DP/RFQ	H^+	30	100	10	0.001
LAMPF	P/CW	$H^{+,-}$	800	24	500	6
RAL	P/CW	H^-	70	35	500	2.5
DESY	M/RFQ	H^-	50	20	250	0.01
KEK	V/CW	H^-	40	10	80	0.16
BPL	D/CW	H^+	35	60	50	0.01
ITEP	DP/RFQ	H^+	10	250	10	0.001
ICR	V/RFQ	H^+	7	20	50	0.25
SSC	PM/RFQ	H^-	2.5	30	100	0.1
ATS	P/RFQ	H^-	2.0	100	1000	0.1
GTA	P/RFQ	H^-	5	35	1000	100
KEK	V/RFQ	H^-	3	10	80	0.16
JAERI	V/RFQ	H^+	2	50	1	10
FMIT	DP/RFQ	H_2^+	2	45	cw	100
CRNL	EC/RFQ	H^+	1.2	70	cw	100
CWDD	V/RFQ	D^+	2.5	20	20 sec	100*
PL2/7	DP/RFQ	H^+	2/7	15/35	250	0.25
Proposals:						
ASNS	P/V/RFQ	H^-	1300	2x50	500	5-10
AXY	EC/RFQ	H^+	1600	2x125	cw	100
IFMIF	EC/RFQ	D^+	35	2x125	cw	100