Review of Continuous Beam Electron Machines

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1. INTRODUCTION

CW electron accelerators are mainly used for nuclear physics. However a project will be reported below on an application for transmutation of wastes coming from nuclear reactors. Accelerators able to deliver continuous, or nearly continuous electron beams can be separated in two main classes.

In the first one, one takes benefit of a usually existing pulsed electron linac to which one adds a pulse stretcher ring (PSR), used either with an internal target or with an extracted beam obtained with a slow extraction system. Starting from the initial duty factor of the order of one percent one reaches something like 80 % for the extracted beam and almost 100 % when using internal targets. It must be noted that this sort of accelerator usually delivers on external targets low intensity beams, not really continuous, but intensity modulated for a number of reasons ranging from non homogeneously filled rings to ripples in power supplies.

In the second one, the accelerator is designed from the beginning to get a continuous beam. The basic component is a piece of linear accelerator with a beta equal one structure. Bending magnets oblige the beam to pass several times through this linac. Depending on the bending magnet technology, one will speak of microtrons (or polytrons) or of race-tracks. In the latter the returning beams are treated separately, while in the former the magnets are common to all the returning beams. In both cases, the linear accelerator may be either a room temperature machine, or a superconducting one. Due to the high price of accelerating gradients at room temperature, the quest for an optimum overall budget results in choosing a few passes in the linac for the superconducting structures, and much more for microtrons.

2. PULSE STRETCHER RINGS

2.1. SSTR, Tohoku [1] [2] [4] [5]

The Laboratory of Nuclear Science at Tohoku, Japan, is equipped with a 300 MeV linac and a 150 PSR (SSTR) whose parameters are given in table 1. The ring has been used for coincidence and tagging gamma ray experiments for about 10 years since it was constructed as a prototype for an other stretcher ring, at higher energy, which is being proposed now. The project consists in raising the linac energy from 300 MeV to 500 MeV, recirculate the beam to get 1 GeV, add a stretcher-booster ring to reach 1.5 GeV. This ring, which is intended to work with an internal target, would be used also as an injector for a 1.5 GeV storage ring, used as a synchrotron radiation source.

(Extracted beam)	
energy(MeV)	129.1
duty factor(%)	80
average current(μ A)	1.0
energy width(%)	0.2
emittance (x)(π mm.mr)	4
(y)(π mm.mr)	2

Table 1. The TOHOKU accelerator parameters.

2.2. EROS, Saskatoon [1] [2] [6]

The University of Saskatchewan, Canada, is currently using its linac plus PSR at a maximum energy of 296 MeV, for a systematic study of few body physics. Table 2 gives PSR extraction achievements (goals and results to date). The experimental equipments use tagged photons and two 4π detectors. Beam has been available during 2910 hours in 1991. A new spectrometer will be put into operation in 1992. It requires high beam current with a small beam emittance. For this, the closed orbit must be better controlled, and the injected beam must be better matched to the PSR during injection. So a development of improved stripline monitors and fast synchrotron light cameras is underway.

Goals	
Energy range	50-300 MeV
Maximum c.w. current	70 μA
Energy spread	± 0.01 %
Vertical emittance	0.3 mm-mrad
Horizontal emittance	0.3-0.6 mm-rad
Duty factor	→ 100 %
Results to date	
Energy range	114-293 MeV
Maximum c.w. current	8 μA
Extracted energy spread	± 0.02 %
Vertical emittance	< 1 mm-mrad
Horizontal emittance	< 1 mm-mrad
Duty factor	> 65 %
(Maximum stored current)	80 mA
(Minimum c.w. current)	<1 nA

Table 2. The Saskatchewan accelerator parameters.

2.3. BATES, MIT [1] [2] [7] [8]

The Bates Linear Accelerator Center is now completing its so-called "South Hall Ring". A recirculated electron linac injects in a PSR (2 turns injection), where the beam can be used either with an internal target or can be extracted to be sent to an external target. The commissioning of the beam and physics start-up are scheduled for 1993, while the full research program is due for 1994. The ring will be operated at a maximum energy of 1 GeV, with polarized electrons. Future experiments on spin-dependent electron scattering will be performed with polarized internal targets and a large magnetic spectrometer, BLAST (Bates Large Acceptance Spectrometer Toroid). Expected characteristics of the beam are given in table 3. The experimental equipment will consist of large out of plane spectrometers (OOPS) and a one hundred inch proton spetrometer (OHIPS) with polarimeter.

$E \leq 1$ GeV	
Internal current :	80 mA
Extracted current :	50 μA
Duty factor	~ 85 %
$\Delta E/E$	~ 0.04 %
Emittance	$0/\pi$ mm.mr
Polarization	~ 0.40

Table 3. The BATES accelerator parameters.

2.4. NIKHEF, Amsterdam [9] [10] [20]

The AmPS ring project entered its installation phase at the end of 1990. This phase covers a period until April 1992. It will be followed by a commissioning period. First physics experiments with a stretched beam are scheduled in summer 1992. Starting from an existing electron linac, "MEA" (Medium Energy Accelerator), the project consisted in upgrading the linac and adding a stretcher ring. The linac energy has been raised from 500 MeV to 900 MeV and the beam peak intensity from 10 mA to 80 mA. An energy spectrum compressor has been added. At the present time, the beam has been successfully guided through the injection line , including the narrow septum channel. All four curved sections and 80 % of the straight sections have been installed. The project was initially approved for physics using an extracted beam (electron scattering experiments), but the ring may also be used in a storage mode, with polarized electrons and a polarized internal target : it is the SPITFIRE project (Spin Physics with an Internal Target Facility for International Research). Table 4 gives the beam specifications for both stetcher and storage mode.

		Former	Stretcher	Storage
E max @ i=0	[MeV]	580	910	910
Beamloading	[MeV/mA]	2.8	2.6	2.6
Linac pulse length	[μsec]	40	2.1	2.1
Rep. rate	[Hz]	300	400	-
Beam d.f.	[%]	1.2	> 90	100
i peak linac	[mA]	10	80	10
I average on target	[μA]	100	67	200. [mA]

Table 4. The NIKHEF accelerator parameters.

2.5. ELSA, Bonn [1] [11] [12]

ELSA, at Bonn University, is a stretcher ring which has been built to improve the duty factor of an existing synchrotron, and not a linac as in the cases discussed above. ELSA provides electron beams at energies between 0.5 and 3.5 GeV. ELSA is able to operate in three different modes : at energies between 0.5 and 2.0 GeV the "stretcher mode" is applied ; for energies above 2.0 GeV the "post-accelerator mode" is used ; in the third mode ELSA can be operated as a dedicated synchrotron radiation source.

ELSA is now operated mainly in the pure "stretcher mode" at energies up to 1.6 GeV. Injection from the synchrotron is done at full energy at a repetition rate of 50 Hz. Experiments with real photons use a 0.02 nA extracted beam (the electrons are converted to photons in a tagging facility which limits the instantaneous intensity). For the electron scattering experiment a current of up to 40 nA is extracted (limited by radiation background problems). The extracted beam shows a macroscopic duty factor of more than 90 %, but the microscopic duty factor is limited to about 50 % due to the fact that the circumference of the stretcher is not homogeneously filled.

About 15 % of the ELSA operation time is given to users of synchrotron radiation. For them ELSA is operated in a storage ring mode with injection of about 60 mA of circulating beam and ramping up of the energy to 2.3 GeV. The life-time of the beam is about 80 minutes.

The main project for modification and improvement is the acceleration of polarized electron beams. For this purpose a GaAs source has been set up and tested. Polarized beams at high energies will be available at the end of 1992.

3. ACCELERATORS BASED ON CW LINACS

3.1. MAMI, Mainz [1] [3] [13] [14] [15]

The third stage of the cascaded race-track microtron has been delivering its first 855 MeV beam at Mainz in 1990. This remarkable achievement placed MAMI in a leading position for delivering high intensity CW electron beams at energies a little under 1 GeV. One could say that MAMI uses classical accelerator technology since the linacs work at room temperature, but there is obviously a lot of innovation and technical skill in the design and construction of this third stage microtron, the biggest in the world to date.

Energies available from MAMI are : 855 MeV - n*15 MeV (n = 0, 1,...45). Proved : n = 0, 42, 45. The stability is better than $3*10^{-5}$.

The maximum CW beam current is currently 40 μA (delivered only for a few seconds because of safety problems). 300 μA have been obtained in 10 ns long pulses. The minimum CW beam current has been 10^{-12} A when performing detector tests.

The beam emittance is below 0.04 π mm*mrad in both planes at 1 μA and 850 MeV.

Electrons from the polarized source have been accelerated at the beginning of 1992 for the fist time at full energy.

The operation time from January 1991 to March 1992 amounts to 1900 hours of beam on target.

The experimental areas include :

New A1-Hall : 3 spectrometers to be put into operation in about 2 month.
A2-Hall : experiments with tagged photons ; first beam in April 1991.
A3-Hall : experiments with polarized electrons ; first non-polarized beam in June 1991.
A4-Hall : future installation for polarized beam.

Details on MAMI will be found in the H. Herminghaus' article, this conference.

3.2. HEPL, Stanford [1] [2]

This superconducting 40 MeV CW linac operates at 1.8 K at 1.3 GHz. It has been using a recirculating system to reach 70 MeV, the accelerator being essentially used for FEL research. The recirculation has now been dismounted since FEL users are working in the infra-red for which a single pass is sufficient. An improvement program is underway, consisting in changing the injector. A new high voltage gun, harmonic bunchers and magnetic compression will allow to get a more intense laser beam.

3.3. S-DALINAC, Darmstadt [1] [2] [16] [17] [18] [19]

The recirculating superconducting Darmstadt linac (3 passes) is now routinely operated. The cavities are made of niobium working at 2 K, at a frequency of about 3 GHz. The average operating gradient is 4.4 MeV/m, with $Q = 3*10^9$. The cavities are rather long : ten 20-cell cavities and one 5-cell cavity. It must be noted that during the construction of this accelerator, the Darmstadt Institute for Nuclear Physics acquired about the behaviour of niobium a lot of knowledge which has been very useful for the whole community. For instance the importance of niobium quality characterized by the so-called RRR parameter is clearly demonstrated : S-DALINAC is presently using niobium with 3 different qualities ; the average gradient goes from 3.0 to 5.4 MeV/m when the RRR is improved.

The CW beam intensity is of the order of 3 μA. The injector, able to deliver a 10 MeV beam, injects at 6 MeV in the main linac. Available energies are 29, 52, 75 MeV respectively after first, second and third pass in the linac. The beam is used either at 10 MeV (injector alone) or in the range 30 to 50 MeV for channeling experiments, or up to 75 MeV with a so called "QCLAM" large acceptance, high resolution spectrometer. In addition FEL tests are being made.

3.4. CEBAF, Newport News, Virginia [25] [26] [24]

It out of question to give here a general desciption of the 4 GeV accelerator being built in Virginia, to become the largest multi-GeV CW electron facility when it will be put into operation. Machine characterics will be found in table 5 while the general lay-out of the accelerator is shown in figure 1. However it may be worthwhile to give some details on the experimental halls :

. Hall A (53 m diameter) will be equipped with high resolution spectrometers (electron or hadron arm). Start of physics : summer 1995.
. Hall B (30 m diameter) will house a large acceptance spectrometer. Start of physics : summer 1995.
. Hall C (46 m diameter) will receive a short orbit spectrometer and a medium resolution spectrometer. Start of physics : spring 94.

CEBAF is the first accelerator to use superconducting cavities on a very large scale for nuclear physics. Developped at Cornell and CEBAF cavities are produced by industry. Cavity pairs are assembled and tested at CEBAF, where the cryounits are also fabricated. Four cryounits are then assembled to become a full cryomodule (8 cavities). Performances in terms of gradients and Q values have been excellent : cryomodule gradients are from 1 to 1.4 over the 5 MeV/m specification and cryomodule power dissipation is from 32 % to 100 % of specifications (Q specification is $3\ 10^9$ for one cavity). Some tchnical problems resulted in a production halt between June and November 1991 (vacuum leaks of indium seled HOM flanges and RF window flanges, bad performance of HOM loads, excessive defects in ceramic RF windows). Problems have been solved and cavity pair production restarted in November 1991.

CEBAF construction started in 1987. Today the "Front End" has been extensively operated. "Front End" covers the 500 keV room temperature injector and the first 18 superconducting cavities, the central helium liquifier and the machine control center. So it has been verified that field amplitude and phase are controlled to the required tight tolerances in the presence of microphonics and beam loading, and that one can meet beam quality objectives. The design energy of 45 MeV has been reached, and the CW design current of 200 µA exceeded. One can say that the project is well on cost and schedule. A commissioning plan in place calls for almost continuous running in parallel with installation. In late 1993, when the whole accelerator is installed, the two linac segments and one arc will have been operated at 800 MeV. Through 1994 all 5 passes to 4 GeV will be commissioned and the RF 3-way distribution implemented.

The energy potential of CEBAF has been recently reviewed. It has been concluded that the accelerator which is being built is basically a 6 GeV machine provided cavity performances remain as good as they are. Moreover, quite evolutionary changes that can be accomodated in a few month long shut-downs would allow to reach the 8 to 10 GeV range. For the more immediate future it is planned to incorporate a second injector for high charge bunches to drive an IR and a UV free electron laser. This program may be funded in 1993 or 1994.

Energy:	.5-4 GeV
Current:	200µA
Duty Factor:	cw
Emittance:	$\varepsilon \sim 2 \times 10^{-9}$ m·rad
Energy Spread:	$\frac{\sigma_E}{E} \sim 2.5 \times 10^{-5}$

Table 5. The CEBAF accelerator parameters.

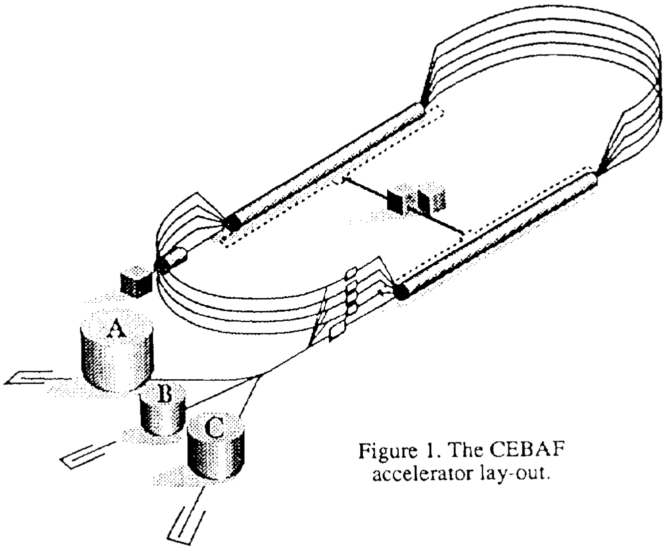

Figure 1. The CEBAF accelerator lay-out.

3.5. LISA, Frascati [28]

LISA is a superconducting electron which is being built at Frascati for FEL applicatins. The nominal energy will be 25 MeV, and could reach 49 MeV with recirculation. The superconducting cavities are 4-cell cavities working at 500 MHz and 4 K, the nominal gradient being 5 MeV/m. First 25 MeV beam is scheduled in one year from now.

3.6. MACSE, Saclay [29]

MACSE is a pilot accelerator built at Saclay in order to develop the technology of superconducting electron linacs. The working frequency is 1.5 GHz. A 10 MeV beam has been obtained in 1991. Up to now MACSE has been using 5-cell solid niobium cavities. The main topics studied have been cavity vibrations, RF feed-back loops, niobium surface treatments. The program will continue with new 3-cell cavities. It is also intended to feed 4 RF cavities with a single klystron.

4. ULTRA HIGH POWER LINACS

A trend to study very high power proton linear accelerators can be observed in the USA, Japan, and to to a lesser extent Europe, for the transmutation of high level radioactive wastes recovered from the plants reprocessing the spent fuel of nuclear power plants. These proton linacs essentially produce by spallation reaction neutrons suitable to treat transuranium elements ; they may be used with reactor plants of the hybrid type, that is subcritical reactors driven with the accelerator. But there are also long lived fission products among which Strontium-90 and Cesium-137 play a major role. Their neutron reaction cross-section are small, and they can not be effectively transmuted by fast neutrons. So studies are under way to transmute these fission products by photo nuclear reactions. It appears that a one ampere, 100 MeV electron linac would be required for that purpose.

Japan has started a 3 steps development program in this direction [27]. The first step is the "Elementary Technology Development", aiming at a 10 MeV, 100 mA CW linac. A 1.2 MW CW klystron is being developped at a frequency of 1.25 GHz. Presently 330 kW were obtained in the CW mode, while the klystron was able to deliver 780 kW in the pulsed mode (50 ms pulse, once per second). Beam tests at full power are expected in 1995. In the second step ("Engineering Test") the energy will be raised up to 100 MeV, while in the third step (Pilot Scale Test") the intensity will be raised to 1 A.

5. A EUROPEAN PROJECT [21] [22] [23]

The Nuclear Physics European Collaboration Committee (NuPECC) published at the end of 1991 a report on the future of nuclear physics in Europe. Among other things, NuPECC recommanded that "a major initiative be launched now to develop a proposal for a European CW electron accelerator in the 15 GeV region". To follow this recommandation, several European countries are now engaged in studies to propose an optimum design for the accelerator. The machine specifications are shown in table 6. One can see that the machine must be designed in such a way as to be opened to future extensions up to an energy of 30 GeV, although with a relaxed energy dispersion. The required current is rather low as compared to CEBAF, due to the fact that the beam power becomes very large at these high energies. Even if the project is still in its "conceptual design" stage, a report being due at the end of 1992, one may give here some general remarks, and indicate some trends.

First, clearly such an accelerator must use one or several long superconducting (SC) linacs and a recirculation system. There seems to be a general agreement that for such a project, the design accelerating gradient must be 10 MeV/m, considered as a value industrially achievable in the years to come where such a machine could be built. Higher gradients, when available, would contribute to raise the energy of the 15 GeV machine. The working frequency is not very critical ; it will probably be chosen in the range of 1.3 to 1.5 GHz. To stay in a reasonable budget, one will have to reduce by a substantial factor the price per meter of SC cavities as well as the price of the kW of RF power. It is hoped to take benefit of the developments made by the TESLA group for other purposes. It turns out that since the beam current is rather low, and since the number of passes in the linacs will be small (see below), beam break up problems are not critical ; so there is no need to use short cavities. One may use 9 cells cavities, a large number of them being packed in a single cryomodule, which is one of the options considered by TESLA. The study group is working on a design with room temperature quadrupoles every 10 meters, which means that one could stay cold for length as long as 10 meters.

Energy : 15 GeV

with the possibility of increasing the energy up to 30 GeV in natural steps depending on budget and construction schedule.

Current : > 10μA at 15 GeV

Resolution : $\frac{\Delta E}{E} \leq \underline{3.10^{-4}}$ FWHM at $\underline{15\ \text{GeV}}$

$\leq \underline{10^{-3}}$ FWHM at $\underline{30\ \text{GeV}}$

Duty cycle : ~ 100 %

Emittance : $\left(\frac{\varepsilon}{\pi}\right) \leq 10^{-8}$ at 15 GeV (m.rad at 95 %)

$\leq 3\ \ 10^{-7}$ at 30 GeV

Numbers of beams : 3 (time-shared with different energies and intensity)

Polarized beams : P > 80 %, I maximum

Table 6. The 15 GeV accelerator specifications.

Second, there is the problem of how to recirculate the beam. Two possible schemes can be considered : a race-track *à la* CEBAF or a machine belonging to the microtron family. Preliminary cost optimization showed that a 15 GeV race-track accelerator must be limited to a small number of passes : at the present stage of the studies 3 passes seems to be the right choice. The microtron solution was considered for a while as impracticable for such energies, essentially because of the its $\mathcal{H}$ fonction (see table 7). But H. Herminghaus [23] showed that this was not the case if one consider a new type of microtrons, the polytrons, where there would be for instance 24 pairs of magnets in a triangular

For a 180° turn through an arc, the average energy loss $\overline{\Delta E}/E$ and the induced relative energy spread σ_E/E are classically given by :

$$\overline{\Delta E}/E = 5.9\ 10^{-15}\ \frac{\gamma^3}{\rho(m)}$$

$$\sigma_E/E = 6.72\ 10^{-14}\ \frac{\gamma^{5/2}}{\rho(m)}$$

γ being the Lorentz factor and ρ (in meters) the dipole bending radius.

Using the circular machine results, the transverse emittance growth is traditionally supposed to be given by :

$$\sigma\left(\frac{\epsilon_x}{\pi}\right) = 4.52\ 10^{-27}\ \frac{\gamma^5}{\rho^2(m)}\langle\mathcal{H}\rangle$$

where $<\mathcal{H}>$ is a lattice function defined as :

$$\langle\mathcal{H}\rangle = \frac{1}{L_{dip}} \int_{arc} \frac{ds}{\beta_x} \left[D^2 + (\alpha_x D + \beta_x D')^2\right]$$

D, D' being the dispersion function and its slope.

Table 7. Basics of synchrotron radiation effects.

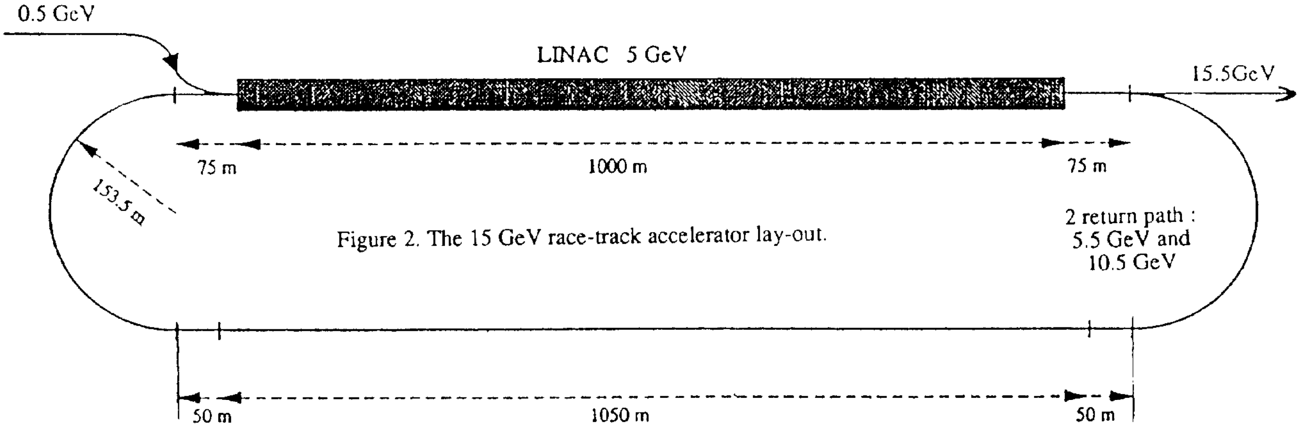

Figure 2. The 15 GeV race-track accelerator lay-out.

configuration, with 3 linacs and 8 magnet pairs per arc (details are given in the H. Herminghaus' article, this conference). In this case the cost optimum seems to to be reached for 5 passes. Polytrons are rather insensitive to phase and amplitude errors in the SC cavities. This may result in a simpler, hence cheaper RF control. However the polytrons require a slightly higher RF voltage, to provide for a phase angle which is not at the top of the wave. The argument is still not conclusive if one considers that race-track machines can also be operated in the same manner [24]. There may be a financial advantage for polytrons since the bending is made with the same magnets for all the return passes. However these rather complicated magnets would require detailed technological studies before their price could be stated with enough confidence. This is the reason why it was decided to base the proposal on the race-track scheme, while keeping on working on the polytron magnets technology.

Third, there is the choice of the size of the reciculating arcs. It is well known (see table 7) that bending high energy electron beams produces synchrotron radiation which has three effects from the point of view of accelerator physics :

1. A loss in the average energy of the beam. This effect which is of most importance for storage rings is not the worse for recirculating machines since it can be easily compensated for.
2. An increase in beam emittance, which is not the most critical point in this project, when choosing a suitable lattice.
3. An increase in energy dispersion, which depends only on the magnets radius of curvature.

The latter point is what determines the radius of the arcs. Of most imporance of course is the energy of the last turn (or half turn). So for a 15 GeV accelerator it was found that ones reaches the optimum with the last arc at 10 GeV, with only one 5 GeV linac, and 3 passes. Due to the fact that the required maximum energy spread is larger at 30 GeV than at 15 GeV, it turns out that a magnetic radius of 60 meters (hence a physical radius of about 150 meters) is suitable for both energies. The general lay-out of the accelerator is shown in figure 2.

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