APPLICATIONS OF MEV PROTON AND DEUTERON LINEAR ACCELERATORS

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ABSTRACT

There are a number of applications, either proposed, currently under development or already reduced to practice, that utilize proton or deuteron beams in the 1-10 MeV energy regime. These applications have been reviewed and the accelerator requirements summarized. In terms of the beam time-structure, nearly all of the applications fall into three broad categories. (1) Beams that utilize nanosecond pulses at low duty factors (<0.5%) are required for a variety of material composition interrogation concepts using neutron time-of-flight techniques. (2) Pulsed beams, in the microsecond regime, are also used for material characterization utilizing (non-time-of-flight) characteristic nuclear signatures, where a low duty factor is used to suppress backgrounds. (3) High duty factor and continuous beams are needed for several applications, including neutron radiography (NR) and boron neutron capture therapy (BNCT), in which a high total current is required, or for which the time structure of the beam is unimportant. Linear accelerators of various types can meet most of the requirements for each category, but the high average power machines of the last category of applications require further development. The primary results of this review are presented, and an assessment of the current development status of radiofrequency accelerators to meet the high-duty-factor requirements is given.

I. CLASSIFICATION OF APPLICATIONS

To put different applications into the perspective of potential accelerator technologies, it is useful to classify the applications in terms of their accelerator requirements. There are a number of important accelerator parameters that need to be considered in developing a classification scheme. Previous authors have reviewed the requirements for particular application areas [1-3], or for a specific accelerator technology [4,5]. Beam energy and beam current play a major role in defining appropriate accelerators for a given application. The required time structure of the beam can be equally important. In terms of the beam time structure, nearly all of the applications fall into the three broad categories defined in the abstract. Figure 1 summarizes the accelerator requirements, classified using these key parameters, for the applications reviewed for this work. Each of the applications is described briefly below.

In addition to the beam current, energy and time structure, other accelerator requirements must be considered for most practical applications. The site requirements of an application, for example, location in a hospital or at a remote test site, or a requirement for a mobile system, can impact accelerator specifications. It is also useful to distinguish applications according to whether or not they require the production of neutrons. Applications for which the accelerator beam is used to provide a neutron source have certain common elements: targets that use (p,n) or (d,n) reactions, moderators to customize the neutron spectrum, frequently with collimators to localize the neutron flux, and detectors or imaging systems for measuring neutron or associated particle, yields or spectra.

II. NANOSECOND PULSE APPLICATIONS

Beams that have nanosecond pulses at low duty factors are required for a variety of material interrogation concepts using neutron time-of-flight (TOF) and/or coincidence techniques. Prominent among the applications of this category are those involved with the detection of contraband, primarily explosives or narcotics [6]. Two primary approaches are being investigated: pulsed fast neutron analysis (PFNA) and fast neutron spectroscopy (FNS).

To detect and measure the relative concentrations of oxygen, carbon and nitrogen, FNS utilizes a broad white spectrum of neutrons in the 0.75-4 MeV region [7]. TOF measurements are used to determine the neutron attenuation, as a function of neutron energy, by comparing the target-in to target-out spectra. PFNA utilizes the delayed coincident measurement of the gammas produced by the inelastic scattering of fast neutrons [8]. A monoenergetic pulsed beam of neutrons is used and the spatial distribution of oxygen, carbon, nitrogen, and chlorine can be measured. PFNA can be useful in characterizing the condition of nuclear weapons [9] and these techniques may also have applicability to non-proliferation and other inspection needs.

Compact tandem Van de Graaffs, Pelletrons, and other electrostatic linacs provide sufficient beam energy, and can be pulsed to produce the required beam time structure. However, the high current required for most FNS applications is pushing the state of the art for electrostatic machines.

III. MICROSECOND PULSE APPLICATIONS

Pulsed beams in the microsecond regime are also used for material interrogation utilizing (non-time-of-flight) characteristic signatures. A low duty factor is used to suppress backgrounds.

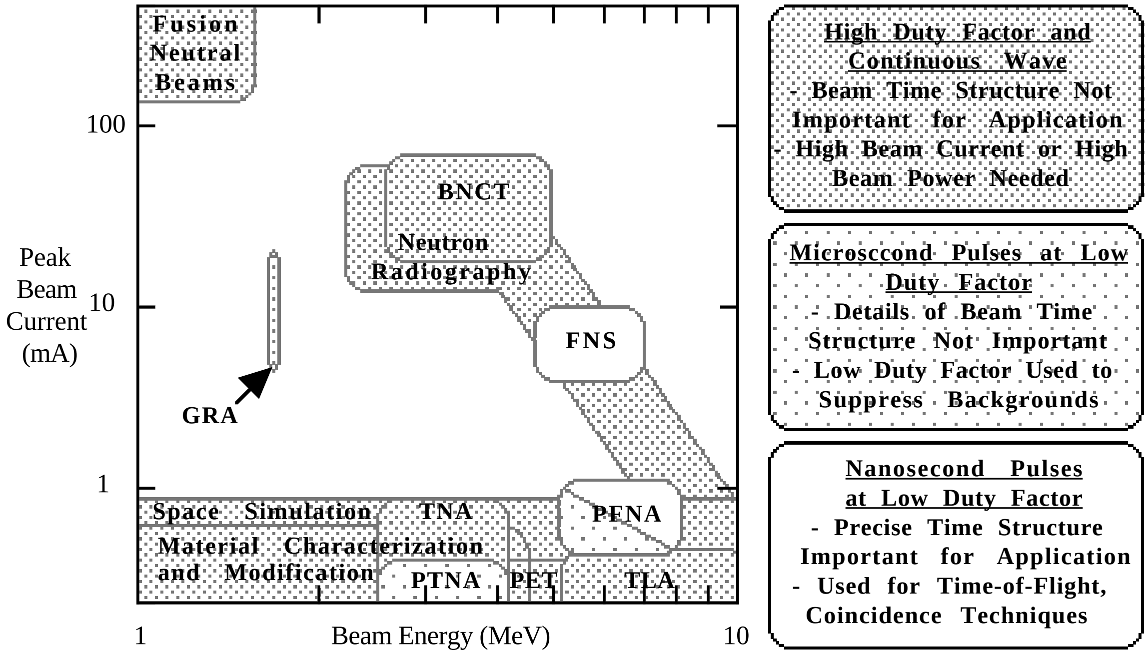

Figure 1. Scheme for classification of applications, using 1-10 MeV proton and deuteron beams, according to the accelerator requirements. Applications plotted in the central region of the vertical axis, the high current regime (1 mA ≤ I ≤ 100 mA), use a logarithmic scale for peak beam current. The moderate (0 < I < 1 mA) and very high (100 mA < I < ∞) current regimes are approximate, and the plots are only intended to suggest a rough measure of the relative scale.

Pulsed thermal neutron activation (PTNA), as well as a variation of PFNA, use a pulse of fast neutrons injected into the sample to be interrogated. In PTNA, the neutrons are allowed to thermalize, and the delayed gamma rays from the thermal (n,γ) reactions are examined to determine the composition of the sample. The pulse length, typically 10-50 µsec, is not critical, but the time between pulses needs to be of the order of the neutron capture time, typically a few 100 µsec. The pulsing technique suppresses the background from prompt gammas produced by inelastic collisions of the fast neutrons during the pulse on-time. The prompt gammas can be used in a non-TOF variant of the PFNA technique (see Section III). By selecting different time gates for the gamma detectors, PTNA and PFNA may be combined [6]. In addition to detecting contraband in luggage [8,10], PTNA can be used for measuring the pollutant constituents of bulk coal and determining the composition of other solids [11].

Electrostatic linacs can meet the needs of these applications, as can radiofrequency quadrupole (RFQ) linacs. Pulsed, high current RFQs have also found a number of specialized, one-of-a-kind applications [3,4] not shown in Fig. 1.

IV. HIGH DUTY FACTOR APPLICATIONS

High duty factor, including continuous, beams are important for several applications. Neutral beams for heating fusion plasmas require very high currents. The International Thermonuclear Experimental Reactor (ITER), if the designers decide to use neutral beam heating, would need several tens of amperes (CW) of 1-1.5 MeV deuterons. This is a formidable amount of power and will likely require an approach using multiple beams in an electrostatic quadrupole linac.

There are a number of applications that utilize beams of less than a milliampere. Materials characterization and modification encompass several applications in this energy regime, as well as at lower energies. Ion implantation [12], surface hardening [13], lifetime killing of minority charge carriers [2], and the alteration of surface chemical properties [2], are representative examples of materials modification applications. In this energy region, and higher, the production of radioisotopes [14], for positron emission tomography (PET), and thin layer activation (TLA), for corrosion and wear analysis [15], are finding increased application. Simulation of the space radiation environment [16] spans the energy regime considered. Electrostatic or RFQ linacs can provide most required beams.

Among the high-duty-factor applications illustrated in Figure 1, three require relatively high beam current: gamma resonance absorption (GRA) for explosives detection [10], neutron radiography (NR) for a variety of uses [17], and boron neutron capture therapy (BNCT) for cancer treatment [18]. A high current is required for these applications in order to meet practical, operational needs associated with the total doses desired (high through-put or short exposure times). The time structure of the beam is not important, and the duty factor may be selected to optimize the performance of the system.

BNCT offers a promising hope in the treatment of certain cancers, and initial clinical trials at reactor facilities, especially in Japan, are encouraging. While the BNCT prospects are good, a large investment in accelerator technologies to optimize the delivery of the neutrons may be premature. In contrast, the utility of NR is established for several applications. Reactor-based facilities are used for examining aircraft parts. Ordinance inspection is of current interest, but requires remote siting and has hazards for reactor-based approaches. Transportable, low-fluence NR systems, based on radioactive sources, D-T tubes and cyclotrons, have been developed. Other applications are waiting for better mobile systems.

Electrostatic linacs may be able to meet the requirements of BNCT and NR, but the high currents required are a challenge. RFQs probably offer the best approach for both BNCT and NR. One RFQ-based system of modest duty factor (1 mA average current) has been built to further explore practical NR uses [5]. However, development work will be required to make economic, portable RFQs, with the 10-60 mA continuous beams needed for many applications. The target, moderator and collimator assemblies for these high-duty-factor systems will also require development [19]. The Argonne Continuous Wave Linac (ACWL) can provide a 2 MeV continuous beam, of over 20 mA of deuterons [20]. With modifications, 3.5 MeV protons at the same current and duty factor could be produced. The ACWL offers a unique facility to develop and test technology for both NR and BNCT.

V. SUMMARY

Applications that utilize proton or deuteron beams in the 1-10 MeV energy regime have been reviewed and the accelerator requirements summarized. The beam energy, peak beam current requirements, and the beam time structure, all impact the appropriate selection of accelerator technologies. Linear accelerators can meet most of the requirements. However, the high current ($1 \text{ mA} \leq I \leq 100 \text{ mA}$) and high-duty-factor applications challenge the state-of-the-art. Both neutron radiography and boron neutron capture therapy and fall into this category. RFQs offer the potential to meet the requirements, although developments are needed in several areas. The ACWL offers a unique test bed for developing a number of key technologies needed for NR and BNCT.

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