POWER DENSITY AND BEAM QUALITY AS APPLIED TO LOW ENERGY, HIGH BEAM CURRENT ACCELERATORS.

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POWER DENSITY AND BEAM QUALITY AS APPLIED TO LOW ENERGY, HIGH BEAM CURRENT ACCELERATORS - A SURVEY

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INTRODUCTION

The saturation yield of a nuclear reaction, apart from scaling factors, is given by

$$Y = I\, N\sigma(E)\, dE$$

with:

N: density of target atoms
I: particle beam current
σ(E): interaction cross section

Integration goes from zero (or threshold) energy to the maximum energy of the particle entering the target sample.

From the equation above, Y seems to be a linear function of the particle flux or beam current I. This would mean that deficits in the available energy and hence in the yield function (E)dE could be compensated for by higher beam currents. With respect to gaseous or liquid targets at least we had to learn that N can be a strong function of I:

$$N = N(I) \text{ and hence: } Y / I.$$

N is affected by the heat produced in the target sample from its interactions with the particle beam even at currents as low as a few micro-Amperes. The effects can be dramatic and are always negative. Nevertheless, to optimize yields we have do use maximum available beam currents.

Availability and Needs

Low energy charged particles, i.e. low Z ions with energies up to, say, 70 MeV are being used for radionuclide production, activation analysis, as well as for the production of fast neutrons and protons for radiation therapy.

The analytical methods of charged particle activation analysis (CPAA), induced X-ray emission (PIXE) and proton therapy require only low currents in the μA or even sub-μA range. As such, these fields are beyond the scope of today's subject and will be excluded from further consideration.

20 - 50 μA of beam current are adequate to supply local or regional diagnostic departments and PET centers with short-lived radionuclides.[1,2]

200 -300 μA are currently in use by commercial radionuclide producers. Even higher beam loads will be welcome when available in the near future.[3]

30 - 60 μA of protons on Be-targets from 50 to 65 MeV proton accelerators give adequate dose rates (around 50 cGy/min at 150 cm source skin distance) for radiation therapy with fast neutron beams. Deuteron and 3He-beams of up to 100 and 200 μA, respectively, on Be-targets were in use until the early 80's. They have since been given up in favour of protons: cyclotrons commonly deliver protons of double the energy of deuterons yielding approximately twice the average energy of the neutron beam. The higher energy neutrons provide superior penetration in tissue and skin sparing.

In this field, d-T neutron generators with low energy (200 keV) but high currents (up to 200 μA) are still being used for radiotherapy.[4,5] Despite their low dose rate (10-15 cGy/min) limited by the cooling capacity of the tritium/deuterium loaded target they remain a serious competition to cyclotron neutron sources because the costs of their installation are lower; their operation is relatively easy and their compactness allow direct mounting on a rotating gantry. They will most probably be replaced in not too distant future by new dedicated devices of comparable costs, e.g. superconducting cyclotrons[6] or linear accelerators.

Table I summarizes the capacities of low energy high power accelerators in use for applications in medicine and radiochemistry including those new designs presented at this meeting either as dedicated systems or as a spin-off from other fields of research and development.

Table I: Applications and Implications of Low Energy High Current Accelerators

Field of Application [a]	Type of Accelerator	Proton Energy (MeV)	Beam current Available (μA)	Beam current Needed (μA)	Beam Power Available (kw)	Power Density Acceptable (kW/cm²)
RP	cyclotron	11-17 (H^+,H^-)	100-200	20-50	2	0.3-0.5
RP [b]	cyclotron	26-35 (H^+,H^-)	300-580	≥300	15	2 (?) [c]
RP,NT	cyclotron	50-65 (H^+)	60-100	30-60	5	0.3-2.0
NT	d-T gener.	0.2 (D^+,T^+)	200 μA	200 μA	40	0.6 (ScDT)
		0.5 (D^+)	8 μA	"more"	4	≤0.1(WT)

New devices:[d]

						Power Density available (kW/cm²)
RP	RFQ+LINAC	11(H^+)	650		7	≈100
RP (limited)	RFQ ($3He^{++}$)	8	150		1.2	≈ 20
	TCA	4 (H^+,D^+)	1000		4	≈ 1
	cyclotron	3.2 (D^+)	500		1.6	0.2
NT	SC cycl.	50 (D^+)	?		50 int.	?
	RFQ+LINAC	66 (H^+)	350		25	≥300
NCT (?)	RFQ	2 (H^+)	300		≤1	≈ 10
		3 (D^+)	300		≤1	

[a] RP = radionuclide production, NT = fast neutron therapy, NCT = neutron capture therapy (with epithermal neutrons)
[b] for commercial large scale production
[c] very rough estimate. Exposed target areas vary from 0.8 to 3.8 cm², no data are available from commercial producers (industrial secret)
[d] RFQ = Radio Frequency Quadrupole, LINAC = linear accelerator, TCA = tandem cascade accelerator

Constraints

As shown in Table I, the acceptable current of ion beams is usually not limited by the capacity of the accelerator, but rather by detrimental effects of the high power density imparted to the target sample or system. Density reduction in gas targets adversely affects the yield of radioisotopes or fast neutrons.[3,7-9,12-16,17,19,22-24,26,27] In a similar fashion, vapor voids in fluid targets,[2,10,17,20,21,25,26,46] melting of the solid sample in radionuclide targets,[11] melting or sputtering of Beryllium neutron targets also diminish output.[4,30,31] This loss in yield and in the durability of target operation can be modified by reducing the spacial density of the electric power imparted by the beam i.e. the heat burden to the surface exposed and to the inside of the target. This may be achieved by:

- beam handling, i.e. defocusing or moving the beam spot and
- optimizing the target system design with respect to:
    - foil material and thickness
    - target material and surface preparation
    - cooling, pressure, circulation
    - by increasing the target surface exposed to the beam (conus, grazing incidence)
    - by rotation of the target or
    - by building a vertical beam line

The frontiers in handling high beam current density are still being pushed back. At present, the state of the art is as follows:

0.5 kW/cm^2 for medium scale RP
0.6 kW/cm^2 for d-T generator targets
2 kW/cm^2 for cyclotron fast neutron targets
> 2 kW/cm^2 for large scale RP (exact data not available)

Beam characteristics

Emittance, essentially the integral over the dimensions and divergences in one direction perpendicular to the beam (usually quoted for the horizontal x-axis), is of relevance as a design feature of an accelerator and for beam matching, but is of limited importance in relation to power density. Not too small an emittance may even be an advantage in the case of bright beams emerging from linear accelerators. Modelling the current density across the beam by defocusing or sweeping at the time it hits the target surface is an easy and accepted way to optimize yield and reliability of high power target operation.

Current density within the beam cross section depends on the actual tuning of many parameters of the accelerator and beam line operation. For cyclotrons the tuning and hence the beam shape are not perfectly reproducible. Before every bombardment the homogeneity of the density distribution should hence be checked by a beam viewer.

Energy transfer: An appreciable portion of the heat load imparted to the sample occurs in the region of maximum stopping power near the end of the particle tracks at a point where the radioisotope yield is very low. In a gas target it should be possible to optimize the yield by adjusting the length of the target to exclude the region of maximum density reduction as indicated (Figure 1).

To summarize: modern cyclotrons - with the exception of those for commercial radionuclide production - usually exceed the demands from even high beam current applications. For fast neutron therapy, compact low cost accelerators for protons or deuterons of about 50 MeV would seriously compete with d-T generators.

New Concepts

Cyclotrons: negative ion acceleration and extraction by foil stripping besides reducing the risks of radiation burden and malfunction by not having an electrostatic deflector, deliver external (proton) beam currents well above 100 μA.[3,39-42] In addition, negative ion cyclotrons are capable of extracting more than one beam thus permitting two or more different simultaneous applications with minimum interference, e.g. RP and NT or RP for PET and other diagnostic procedures.

The compact, superconducting and rotating positive ion cyclotron for 50 MeV deuterons designed

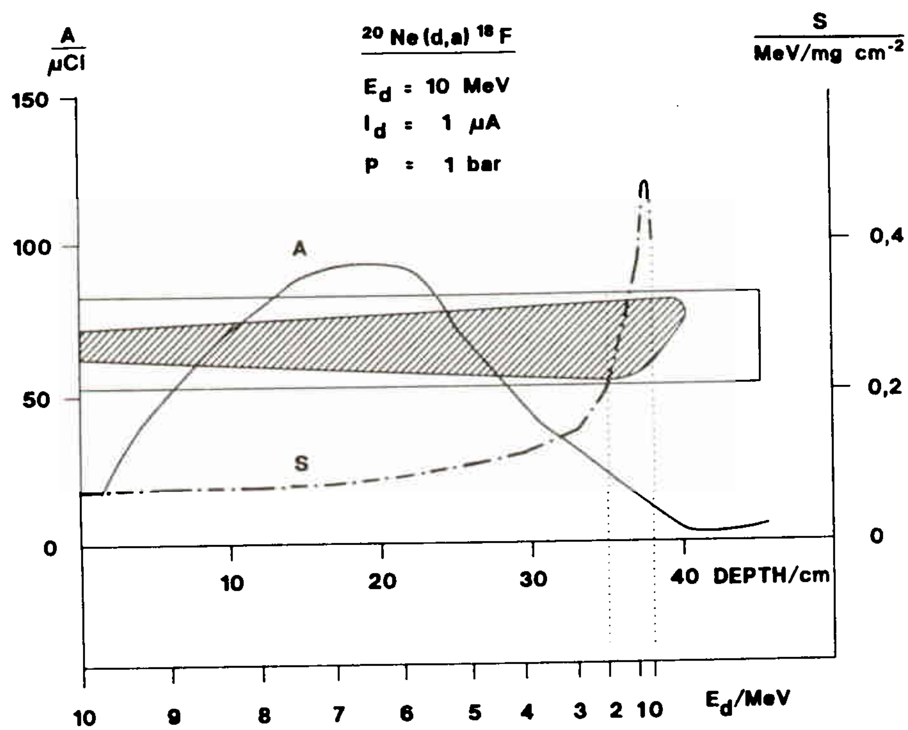

Figure 1: As the regions of maximum yield and maximum electronic heating (maximum stopping power) are separated in space, there is an optimum length of containment where the density reduction is minimized without significantly affecting the yield.

by Henry Blosser and coworkers[6] has become an interesting alternative to d-T neutron generators. However, the dosimetric quality and operational reliability of this new device remain to be proven.

RFQs: radiofrequency quadrupoles are compact and powerful sources of charged particles.[35-37,45] Originally designed as injectors, RFQs are limited to low energies. This reduces the spectrum of applications to special cases of RP like zero threshold nuclear reactions, e.g. $^{18}O(p,n)^{18}F$, $^{16}O(^{3}He,p)^{18}F$, $^{14}N(d,n)^{15}O$. The ^{3}He RFQ[45] is not able to deliver carrier- free ^{11}C and ^{15}O. The combination with a linac can compensate for the deficiency in energy but increases size and cost.

The TCA[44] represents as a light weight and relatively inexpensive device for PET radioisotope production. However, it has to be shown if enduring operation is as uncritical as compared to a small cyclotron.

The high brightness of linear accelerators has to be adapted to manageable power densities. The compensation of low energy by high beam currents, as stated, has its limitations in the quality of target design.

RFQs and TCA as well as the very small cyclotron cyclone-3D[43] may be useful for reducing load of a busy main accelerator and may have an important role as specialized secondary radionuclide production systems.

SUMMARY AND CONCLUSIONS

In general, high current low energy accelerators deliver surplus beam power in view of most of today's local needs within a research or hospital setting. The demands of commercial radionuclide production for proton beam currents higher than 300 μA will soon be met by H^- cyclotrons.

The crucial point in compensating low energies by high beam currents is the suitable design of targetry to withstand the high loads. Extending the beam spot decreases power density and helps to preserve long term reliable operation so necessary for all clinical or commercial applications.

New types of compact accelerators will become effective only in combination with intelligent design of specialized target systems and, of course, if they are competitive with respect to dimensions and weight as well as costs both for purchase and operation.

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