SYSTEMS ANALYSIS OF ACCELERATOR AND STORAGE RING SYSTEMS FOR INERTIAL FUSION

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Summary

A computerized systems model is being developed to help assess the relative merits of the various accelerator systems that appear able to meet the requirements for inertial fusion with high energy heavy ion beams. Assessment involves calculating the total cost and parameters that are critical to technical feasibility. Current results showing cost trends and important technical parameters for rf linac/storage ring systems using ions of different mass, charge state, and kinetic energy are presented.

Introduction

Conceptual design work during the past two years has resulted in widespread agreement that a number of accelerator systems involving a large range of parameters are available for a high energy ion beam fusion system for power production. Candidate systems include rf linacs with storage rings, synchrotrons with or without storage rings, and linear induction accelerators with or without storage rings. The best values of atomic weight, peak energy per particle, and charge state are likely to be different for each of the possible systems and selection of the best system requires a common method of evaluation. The situation suggests a need for a computerized systems analysis that would yield the values for figures of merit such as dollar cost and technical reliability. This systems analysis should evolve in time as additional information is made available from experiment and theoretical work. For example, although higher charge states are cheaper to accelerate, a quantitative and continuous assessment is necessary to indicate just how much effort should go into overcoming the attendant technical difficulties. A systems analysis would provide a picture of the interrelation of target chamber, storage rings, high- and low-beta accelerators, and sources as their designs unfold.

Description of the Computer Model

The Systems Model

An ion beam fusion accelerator system is composed of the subsystems shown in Fig. 1. Listed in the boxes representing the various subsystems are a number of the items that are considered in the equations describing the systems. Proceeding from the pellet to the ion source, the most important considerations for the various systems are the following.

Pellet Values are input for the total energy, power and energy deposition density (energy/mass) needed for ignition of fusion fuel pellets. These values reflect the current predictions of the inertial fusion target designers¹. The ion range is calculated from the integral of the dE/dx formula² with the atomic number replaced by the charge state calculated for a thick stripping foil³. The target diameter is then determined.

Final Focus The lens aperture and focal length together with the target diameter determine the maximum targettable beam emittance. To date, values of the lens bore and chamber radius assumed in Ref. 1 have been used.

Final Transport The number of beam lines is decided by an optimization procedure that involves the costs of transport and bunching. For this procedure, the minimum number of beam lines is the larger of the number of quadrupole lines needed to transport the total power required for ignition or the number of storage rings. The maximum number of beam lines is

the smaller of the maximum number of targettable beams or an arbitrary, practical number (100). The minimum required may turn out to be larger than the maximum allowed. This disqualifies the set of parameters but registers the usefulness of an invention or other means to change the limits if the cost for the set of parameters is particularly attractive.

Storage Rings The number of rings required to store the total energy needed for pellet ignition is based on the space charge limit (assuming a tune shift of $1/4$). Usually, the ion energy is optimized for least cost and several values of the charge state are run so the parameters can be inspected. Initially, the emittance used in this calculation is the maximum targettable emittance or an arbitrary value regarded as a practical limit for extraction (20 mrad-cm). To allow even comparison between systems using different particle energies and charge states, the emittance is subsequently reduced to make all rings have the same bunching factor since the emittance is and the bunching factor is not directly involved in costing.

The radius of the rings is increased from the radius of curvature of the bending magnets by the maximum of the amount needed to a) accommodate bunch compression cavities or b) reduce the average electric beam current to an imposed upper limit (100 amperes). The bunch compression model assumes that the differential velocity from front to rear is caused by repeated passes through rf cavities. The calculation includes the effect of the longitudinal space charge force. Larger numbers of bunches reduce the voltage requirement. However, the number of bunches is assumed to be equal to the number of beams and the maximum number of bunches is found by minimizing the combined cost of bunch compression and final transport subject to the limitations of targetting or practicality applied to the number of beams.

The number of turns of injection (N) is calculated using the final linac current. The emittance is increased by $\sqrt{N}$ and it is verified that the result does not exceed the allowed maximum emittance.

Synchrotron The space charge limit is evaluated at injection. Since the injection energy affects the required acceptance and therefore the cost of the synchrotron magnet, the injection energy is selected by minimization of the combined costs of the synchrotron and the linac injector. The synchrotron systems studied so far accelerate all particles in a single pulse which takes 0.1 sec. It is believed that this time will prove short enough to avoid serious beam loss due to charge exchange between beam ions. The risetime is used to calculate the accelerating rf voltage requirements. The parameters for bunch compression are treated the same as for storage rings.

Linac The ion energy exiting the linac is an input parameter for linac/storage ring systems but is determined by cost optimization for synchrotron systems as explained above. The total linac voltage depends on the charge state. Where $q > 3$, it is assumed that $q = 1$ before a stripper to find the total required voltage. Limitation on the maximum current is checked at the beginning of the pre-stripper and again at the beginning of the post-stripper where the particle current is always less (20 percent of original) but the electrical current may be more than before stripping.

Preaccelerator An assumed voltage drop is used in calculating the limitation on the current in the beginning of the rf linac as noted above.

Ion Source The source is assumed to produce sufficient current to allow 50 mA (particle) to be trapped in the rf linac as was concluded to be feasible in Ref. 1 for a normalized beam emittance of 0.02 mrad-cm.

Cost Assumptions

Cost assumptions are made as follows.

1. The cost of magnets is proportional to the product of the magnetic rigidity and the area of the bore. The bore area is assumed to be proportional to $a + bc$. The coefficients, a and b , are derived from cost estimates for the Fermilab main ring and booster synchrotrons⁴. With cost in dollars, emittance in mrad-cm, and $B\rho$ in Gauss-cm, $a = 0.0124$ and $b = 0.00634$.
2. The entire cost of linacs is assumed to be a constant times the total voltage. Values of 50 and 100 k\$/MV are used as representative of high current linacs.
3. Buildings are priced at 300 \$/m².
4. The cost of synchrotron rf cavities is assumed to be a constant times the voltage gain per turn. The constant used is 6M\$/MV, derived from the cost estimate for the rf cavities in the Fermilab booster⁴.
5. The cost of bunch compression is assumed to be proportional to the total voltage required. A cost factor of 30 k\$/MV was derived from the breakdown of the cost estimate for the Fermilab linac⁴.
6. The cost of final transport is assumed to be proportional to the total length times the bore of the transport tubes. The length of the lines is equated to the radius of the storage rings or synchrotrons and the radius is taken to be the maximum of a) an assumed minimum, b) $\sqrt{\beta E}$ (β = betatron oscillation length, assumed to be 10 meters), or c) the minimum radius for which the electric field at the tube surface due to the beam is below the field emission limit (assumed to be 500 kV/cm). The cost factor derived from the Fermilab quadrupoles is 600 k\$/m³.
7. A fixed cost of 1 M\$ is assumed for the pre-accelerator.

Order of Calculations

Set default values

Read in input values. (Loop over cases begins here.)

Calculate quantities simply dependent upon the inputs, e.g., B -min, ion energy (T)-min, T -max

Optimize: Total cost(T), T -min $< T < T$ -max

Calculate beam and target parameters that depend only on T and quantities directly derivable from the inputs, e.g., γ , β , range (β , A , Q , (β , Z), and A , Z , and the average ionization potential for the target material)

Calculate remaining target and targetting specifics starting with either an input energy deposition value (preferred at this time) or a maximum emittance.

Calculate parameters and unit costs for:

Source(s)

Pre-accelerator(s)

Linac(s)

Calculate storage ring parameters that are not dependent on the number of bunches.

Sub-optimize: (cost of transport + cost of rf in rings) versus # bunches

bunches-min $< \#$ bunches $< \#$ bunches-max

Calculate bunching dependent quantities that affect the cost of transport and cost of rf in storage rings

End sub-optimization

Calculate remaining quantities of interest, final costs, and total system cost.

End optimization

Print out summary of results for optimum
End case loop or branch back for more input data.

Discussion

The model of linac/storage ring systems is most developed at present. Data for such systems which give minimum cost with xenon and uranium for a range of charge states are shown in Figures 2 and 3 and Table 1. Column 4 of the table differs from the plotted cases in that the linac cost factor was changed to 100 k\$/MV. The main indications of these data are:

1. Xenon appears to be as economical as uranium for rf linac/storage ring systems.
2. An intermediate charge state gives the best economics. Figure 2 shows the component cost trends that give this result. A major cause for the minimum is the higher prestripper linac voltage for the highest charge states.

A previously recognized technical question is underscored by the number of turns of injection required for the systems shown in Table 1. The large number of turns needed for the least cost systems for all charge states for both xenon and uranium (with the greatest requirement for +1) highlights the importance of the linac current and injection technique questions.

Future Work

Many additions and improvements to the computerized model are needed. As soon as possible, the costing assumptions should be checked with sufficiently elaborate conceptual designs of components such as bunch compression cavities.

Thin lens formulas are being incorporated to assess the problems and cost of lens systems. Spot calculations of the length of quadrupole triplet systems indicate that the requirements may be excessive for some cases, especially the highest energy, heaviest, and most lightly charged ions.

The practicality of the bunch compression requirements must be analyzed and the importance of voltage linearity and rf frequency on cost studied. The feasibility of rapidly crossing resonances during compression also needs to be studied.

The synchrotron model will be augmented by including systems with storage rings and systems with one or more synchrotrons at one or more intermediate energy level as well as one or more synchrotrons for the peak energy.

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FIGURE 1

FIGURE 2. XENON

FIGURE 3.

	XENON			URANIUM		
LINAC COST FACTOR (k\$/MV)	50			100		
CHARGE STATE	+1	+3	+35	+35	+1	+50
TOTAL COST (M\$)	512	409	258	387	680	281
TARGET DIAMETER (cm)	1.5	0.79	0.22	0.25	1.9	0.31
STORED EMITTANCE (mrad-cm)	19	12	3.2	3.8	18	4.6
LINAC CURRENT (mA)	50	50	10	10	50	10
URNS OF INJECTION	820	390	300	298	750	210
NUMBER OF BEAMS	22	25	136	227	10	103
COST OF TRANSPORT (M\$)	14	6	6	7	11	6
COMPRESSION VOLTAGE (MV/RING)	35	10	0.6	0.6	75	0.9
COST OF COMPRESSION (M\$)	9.5	7	2.3	3.7	7	2.8

TABLE 1. PARAMETERS FOR RF LINAC & STORAGE RING SYSTEMS
TOTAL ENERGY = 10 MJ, ENERGY DEPOSITION DENSITY = 30 MJ/gram
TOTAL BEAM POWER = 600 TW