IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

TELESCOPING BEAMS FOR HEAVY ION FUSION*

Robert J. Burke†

Abstract

In addition to the strong longitudinal compression and multiple beams now used in all designs for heavy ion fusion drivers, attaining the required beam power could be helped by telescoping bunches of different ion species. Telescoping is here defined as the overtaking and interpenetration of bunches consisting of ions of different species but whose velocity, mass, and charge state have been selected so that the typical ions in the various bunches have the same ratio of momentum to charge, or magnetic rigidity, and, therefore, the same single particle dynamics in transport and focussing lines. With velocities differing by 10% or more, the highest powers would only arise close to the end of the transport lines. Telescoping also increases the total available phase space of the different species. This can be translated to a smaller final momentum spread or a means to accommodate greater phase space dilution.

Introduction

The concept of heavy ion beam fusion (HIF) was established by the recognition that multiple beams[1] and strong bunch compression[2] could be used to achieve the high beam power needed to ignite fusion pellets. Since these techniques are fully compatible with each other, the standard approach to conceptual designs of HIF systems is to use some of each to avoid impractical, overreliance on either. Telescoping beams is an additional mechanism for pushing the power to very high levels. It is also compatible with the two previously established mechanisms and can be used to further reduce the extent to which any one mechanism must be used. Since it appears practical to achieve the requisite beam parameters using only the compression and multiple beam concepts, however, an equally important consideration is the effect such an additional concept has on the system cost. In this respect also, in spite of some additional complexity, telescoping appears to be valuable.

In the telescoping beam concept, bunches of different species ions are switched into a common beam line. The mean velocity of the ions in a bunch is higher than that in preceding bunches, but the ratio of momentum to charge (magnetic rigidity or stiffness) is identical for all bunches. Consequently, trailing bunches will telescope into leading bunches and all species will have a common focal spot. An obvious result is that a system may use a number of bunches that is larger than the number of beams by a factor equal to the multiplicity of telescoping. Since each bunch may use the maximum volume in six-dimensional phase space permitted by the focussing requirements and the total number of particles is not changed, the larger number of bunches translates to a reduction of the required particle density in phase space.

Telescoping also introduces an additional means to shape the power pulse to increase the efficiency of pellet implosion. When pulse shaping is achieved with telescoping, the beam in every line has the power profile, in contrast to constructing a pulse shape at the pellet by sequencing the arrival of simple bunches from a number of parallel beam lines. This pulse shaping method can also be extended to regulating the penetration of the beam into the pellet during the pulse by exploiting the capability of a telescoping beam pulse to comprise ions that have different ranges in the target material.

Telescoping could also increase the power that can be transported in each beam line. The parameters for telescoping can be chosen to give a bunch-to-bunch ratio of velocities large enough for telescoping to occur over a short final section of the beam line. Augmented by collapsing of the individual bunches, this could prevent possible instabilities during transport in the lines from becoming important by not giving enough time for them to grow. In addition, the power-limiting space charge forces are reduced during the final portion of the beam line due to the larger beam size used there in preparation for tight focussing and neutralization is also relatively feasible in that section, as the vacuum requirement there is least.

Basic Requirements

The stiffness of a charged particle is proportional to $\beta\gamma A/q$, where β and γ are the relativistic parameters, A is the atomic mass number, and q is the electrical charge state. Thus, ions with different velocities will have the same stiffness if a difference in their $\beta\gamma$ products is compensated by an equal difference in their q/A ratios. Many different bunch velocities may be used by providing the means to accelerate ions with different charge states, ions of different elements, or ions of different isotopes of the same element.

To accelerate different ions for HIF, the voltages on the drift tubes of an RF linac would need to be changed within a millisecond and a variable energy gain section would be needed at the high energy end. Accelerating a variety of ions may also affect the requirements for ion sources, preaccelerators, and prestripper linac. Switches to feed bunches of different species into common beam lines would also be required. Using different elements would require different sources, possibly separate preaccelerators, and additional features in the prestripper linac and stripper sections. The accelerator for ions of the same mass but different charge states would need no special features up to the stripping section, which could also be simple if a number of charge states used were small enough to allow adequate stripping efficiency for all with stripping at only one kinetic energy. Large velocity differences in the telescoping bunches could be realized in accord with charge state ratios substantially different from unity, but the variability needed in the linac would be correspondingly large. The third possibility, isotopes of the same element, would minimize the special features demanded of the accelerator because of the small differences involved in the velocities and masses of the different species. However, the small velocity difference limits the uses of telescoping (e.g., the ranges of all species are very nearly equal) and may pose some problem due to the relatively long drift distances required for telescoping.

Examples

Regardless of the reason for its use, realizing a benefit from telescoping is likely to depend on there being some advantage of a system that is inextricably related to a need for a large number of bunches. This situation is created, for instance, by using a short linac so that a large number of rings are needed to

---

*Work supported by the U.S. Department of Energy

†Argonne National Laboratory, Argonne, IL 60439, USA

0018-9499/79/0600-3092$00.75 © 1979 IEEE

store the total beam energy and each ring produces at least one bunch. Economies from making many small storage rings could make such a system cost effective. The need to handle a large number of bunches is also created by the use of beam splitting. In this concept, the beam in the rings has an emittance larger than the emittance that will be targeted. The energy per ring is increased relative to the case where only the targeted emittance is stored, but the beam must be split after extraction into a number of lower emittance beams. If splitting is carried out in both transverse phase planes, the multiplicity is the square of the ratio of the emittances of the stored and targeted beams. With several rings, the number of beams can easily be larger than desirable and telescoping becomes useful.

One application of beam splitting is to synchrotron systems, in which the space charge limit tends to be low. Using splitting and telescoping, the compounding problems of low space charge limit, large RF bucket area, and complicated manipulations of rapid cycling synchrotron systems can be avoided. In this way, some synchrotron systems can be described that are interesting in their use of short linac injectors.

Some parameters of a relatively simple system that uses telescoping and beam splitting are given in Tables I and II. This system uses four-fold beam splitting to achieve greater energy storage per ring, and telescoping is based on accelerating the four abundant isotopes of mercury. A useful aspect of this particular example is that it permits an assessment of the potential for cost reduction of the novel concepts by comparing the hardware requirements to those of the HEARTHFIRE Reference Concept #2 (HRC #2) system that was studied at the HIF workshop held last September at Argonne.[3] Most of the advantages indicated in the tables are due to the novel techniques, although the example uses an ion kinetic energy that is lowered by dropping the charge state as well as by the shortening of the linac that is possible because of the increased energy storage per ring. This choice reflects current trends in pellet designs. Besides the main effects of shortening the linac and reducing the number of storage rings, the estimated net 30% cost reduction is achieved with an important contribution from the long beam lines, which are reduced in number from 18 to 2. In this regard, the combination of telescoping and splitting is especially favorable as the number of long lines is less than the number of rings by the telescoping multiplicity and also less than the number of final lenses by the splitting multiplicity.

Uses of Dilution

Although numerous HIF system designs have been worked out using only multiple beams and compression to achieve the needed high power levels, important questions persist about some technical issues. Chief among these for linac systems is multiturn injection, involving trade-offs between linac current, number of turns, injection efficiency, and phase space dilution. In HRC #2, these considerations led to avoiding multiturn injection altogether in favor of a system of delay lines and delay rings to take advantage of the fact that beams can be merged using septum magnets with a dilution factor of only 1.4 in each transverse plane and no loss.[4] If more dilution were allowable, these additional cost elements could be avoided.

The dilution allowed in six-dimensional phase space due to all operations on the beam between the time it leaves the linac and hits the pellet is

$$D_6 = \frac{\text{Allowable 6D Volume/Bunch x No. Bunches}}{\text{Minimum 6D Volume/Ring x No. Rings}}$$

The allowable volume/bunch is $(\varepsilon_{tp})^2\,\varepsilon_{\ell p}$, where the subscript p stands for pellet and the subscripts t and ℓ stand for transverse and longitudinal. Both are determined primarily by focussing considerations.

The minimum six-dimensional volume/ring is set by the space charge limit of the ring together with the parameters of the beam from the linac: current, transverse and longitudinal emittances (ε_{tL} and $\varepsilon_{\ell L}$), and the bunch frequency. The linac current determines the multiplicity of transverse stacking; and the longitudinal emittance of the entire stored beam is given by the product of h, the linac bunch frequency times the revolution period in the ring, and the longitudinal emittance of each linac bunch.

The allowable dilution may then be written

$$D_6 = \frac{(\varepsilon_{tp})^2\,\varepsilon_{\ell p}\ \mathrm{NB}}{(\varepsilon_{tL})^2\ \mathrm{NT}\ \varepsilon_{\ell L}\ h\ \mathrm{NR}}$$

This expression may be simplified by using the following additional constraints on the comparison we want to make. For beams of comparable stiffness (such as the example telescoping system and HRC #2), the condition for transverse focussing is comparable focussing angles, Θ. Using the often assumed relation between pellet radius and ion range, $r_p \sim (\text{range})^{-\frac{1}{2}}$, and a dependence of range $\sim T$, we obtain $\varepsilon_{tp} \sim \Theta\, r_p \sim T^{-\frac{1}{2}}$.

The longitudinal emittance at the pellet may likewise be simplified for this comparison by using $\varepsilon_{\ell p} \sim \Delta T \cdot \Delta t$ and noting that the pulse length, Δt, is fixed for systems with the same total beam energy and power. The energy spread, ΔT, is constrained by spot enlargement due to chromatic aberrations, which may be assumed to be proportional to $\Delta T/T$ over our range of parameters. The allowable enlargement, however, increases the pellet radius, so the appropriate criterion is $\Delta T/T \sim r_p \sim T^{-\frac{1}{2}}$, and $\varepsilon_{\ell p} \sim \Delta T \sim T^{\frac{1}{2}}$.

The linac bucket area ($\sim \varepsilon_{\ell L}$) and normalized transverse emittance ($\beta\gamma\,\varepsilon_{tL}$) are constant. The number of turns of injection is

Table I. Variability in Telescoping Example ($\beta\gamma A$ = Constant)

	A = 198	A = 200	A = 202	A = 204
$\beta\gamma$	0.3397	0.3363	0.3330	0.3297
Kinetic Energy (GeV)	10.346	10.248	10.152	10.058
$\beta = v/c$	0.3216	0.3188	0.3159	0.3131
$\Delta\beta/\beta$	0.027	0.018	0.009	
Distance to Telescope 1 ns (m)	3.5	5.2	10.4	
Kinetic Energy from Fixed β Linac (GeV)	10.048	10.149	10.251	10.352
ΔT (GeV)	+0.298	+0.099	-0.099	-0.294
Trimmer Linac Voltage (GV)	0.050	0.017	-0.017	-0.049

$$NT = \frac{\text{Energy Stored/Ring}}{\text{Linac Beam Power x Revolution Time in Ring}}$$

$$\sim \frac{Q/NR}{V_L I_L (R/\beta)}$$

where R is the ring radius. After dropping Q, I_L, and f_L because they are fixed for this example, substituting gives

$$D_6 \sim (\beta\gamma)^2 T^{1/2} V_L NB \quad \text{or} \quad T^{3/2} q^{-1} NB$$

Thus, the allowed dilution in six-dimensional phase space is about 3.4 times larger for the telescoping example than for HRC #2. In addition, the telescoping example uses more longitudinal phase space per ring because more linac bunches fit into each. However, since the criteria for the longitudinal and transverse focussing are independent, dilution in the transverse space needs to be considered by itself.

The dilution in the transverse space may be written

$$D_4 = \left(\frac{\varepsilon_{ts}}{\varepsilon_{tL}}\right)^2 \frac{1}{NT}$$

Here the transverse emittance used with splitting is

$$\varepsilon_{ts} \sim \frac{NS}{T^{1/2}}$$

where NS is the splitting multiplicity in each transverse plane. Since the energy per ring is proportional to $T^2 \varepsilon_{ts} q^{-2}$ and the ion revolution time is $\sim 1/q$, the number of turns may be written

$$NT \sim \frac{T^2 \varepsilon_{ts}}{q I_L V_L}$$

After dropping the fixed linac current and emittance, we obtain

$$D_4 \sim \frac{NS}{T^{1/2}}$$

Thus, the maximum increase in D_4 for the telescoping example compared to HRC #2 is about $4\sqrt{2}$. Together with other options such as increasing the linac current and the radius of the rings, this additional dilution should obviate the need for the delay lines and rings. Thus, the cost of HRC #2 could be reduced by an additional 12%, raising the total savings to 40%.

Conclusion

The telescoping concept offers advantages for the practicality of the accelerator system (phase space, power transport), the efficiency of pellet implosion (pulse shaping, range stepping), and system cost (shorter linacs, fewer long beam lines), with modest off-setting demands.

The concept may be validated with the Accelerator Demonstration Facility[5] under consideration by the U.S. Department of Energy.

Table II. Comparison with HRC #2

	HRC #2	Teles. Example	Total Cost Effect
Kinetic Energy (GeV)	20	10	
Charge State	+8	+6	
Linac Voltage (GV)	2.5	1.67	-14%
Trimmer Linac (GV)		0.05	+1%
Target Radius (mm)	1.1	1.6	
Beam Emittance (mrad-cm)	5	6	
Stored Emittance (mrad-cm)	5	24	
Ring Aperture (cm)	15	<15	
Magnetic Rigidity (T-m)	37	35	
No. Rings	18	8	-13%
No. Beam Lines	18	2	-9%
Splitter Sections		30	+3%
Focussing Half-Angle (mrad)	45	38	
No. Lenses	18	32	+3%

References

1. R. Arnold and R. Martin, "Ion Beam Pellet Fusion as a CTR Neutron Test Source," Proceedings of the International Conference on Radiation Test Facilities for the CTR Surface and Materials Program, Argonne National Laboratory Report ANL/CTR-75-4, p. 436 (July 1975).

2. A. Maschke, "Relativistic Heavy Ions for Fusion Applications," IEEE Transactions on Nuclear Science, NS-22, No. 3, p. 1825 (June 1975).

3. Proceedings of the 1978 Heavy Ion Fusion Workshop, Argonne National Laboratory, September 19-26, 1978, to be published.

4. J. Delahaye, "Etude des Modifications de la Ligne de Transfert BR-PS Pour Assurer la Recombinaison 10 ou 5 Paquets," CERN Report PS/BR/Note 76-20 (July 13, 1976).

5. T. Godlove, "Recent Progress and Plans for Heavy Ion Fusion," to be published this conference.