ITEP-7-94

Fermilab Library
0 1160 0033467 6

INSTITUTE OF THEORETICAL
AND EXPERIMENTAL PHYSICS

ITEP-7-94

12

D.G.Koshkarev

FERMILAB
APR 8 1994
LIBRARY

Driver with Neutralized Beams for Heavy Ion Fusion

RETURN TO FERMILAB LIBRARY

NAME	ID No	MS

MOSCOW 1994

UDK 621.384.664 M-16

DRIVER WITH NEUTRALIZED BEAMS FOR HEAVY ION FUSION: Preprint ITEP 7-94/

D.G.Koshkarev - M., 1994 - 12p.

A concept and main parameters of driver for Heavy Ion Fusion (HIF), based on ion beam neutralization, has been considered. The advantage of this driver scheme is considerable current limit increase in the beam transport channel and, therefore, allows to upgrade the specific power deposition into the thermonuclear target up to 10^{16} W/g. To profit from the neutralization idea more completely, a family of ions with different masses should be used. The optimal choice of ions has been also discussed.

Fig. - 3, ref. - 6

© Институт теоретической и экспериментальной физики, 1994

1 Driver Conception

An indirect (radiation) target is a practictical solution of one of two serious problems in the heavy ion fusion - a problem of perfectly symmetric illumination on a spherical shell of a target. However, a heavy-ion driver to be used with an indirect target should provide an essentially higher specific power deposition up to $\geq 10^{16}$ W/g. Such a high specific power deposition ensures the heating of a target up to 500 eV, that allows to convert $\approx 90\%$ of beam energy into soft X-ray radiation.

The second problem is focusing of the intensive beam of charged heavy ions, for the indirect target, becomes more complicated. The focusing onto the small thermonuclear pellet is techically attainable, when the beam phase volume is small as well. But, the small phase volume means small beam current and, therefore, the unsufficient beam power.

The value of the total power deposition P into the thermonuclear target, can be written as the following:

$$P = J \cdot U \cdot m \tag{1}$$

where J is ion current through one individual beam line, U is linac potential and m is beam lines number.

There are three different ways to increase P value. The first one is to multiply the beam lines number, however because of simple engineering considerations m magnitude should not be over than ≈ 30. We should remember that the rate of ions range in the matter grows faster than ions energy, so the particles with too high energy become ineffective in achieving target ignition. In addition, high-voltage linac becomes too expensive. Thus, the linac potential about $U \approx 10^{10}$ V is quite acceptable. The third possibility to enhance P value, is to increase the beam current J. In the meantime, the experimental, theoretical and numerical studies have pointed out that space charge effects can complicate the driver design (especially within its final focusing system).

A promising way to overcome these limitations, imposed by space charge, is to consider a new concept of accelerator driver, based on space charge neutralization scheme. So far as some heavy metals give stable enough negative ions,

we propose a charge-symmetric driver, which provide acceleration, transport and focusing both for positive ($q = +1$) and negative ($q = -1$) ions with the same atomic mass A (q is ion charge state).

Negative and positive beams are to be spatially separated during the acceleration through the linac. On leaving the linear accelerator, beams should be accumulated separately in two corresponding accumulating rings. Being ejected from these rings, both beams are to be directed into their transport lines. Note, that current growth takes place during this process and when its value achieves the desirable level, lines funneling occures: both beams are merging into one. As a result we obtain a zero average current in any cross section. At the same time, one should remember, that quasi-neutral beams can be transported only along a straight line, so any bends after neutralization become impossible. This drawback should be taken into account in the driver final stage design.

One can see, that due to the strong focusing in the transport channel, the difference between $(+q)$ and $(-q)$ envelopes will produce the additional quadrupole focusing. Fig.1 shows the dependence of σ (phase advance per one focusing period) on beam current for different external focusing strengths. Instead the beam current we now use a new dimensionless variable

$$\Lambda = \frac{4JLq}{AJ_p \cdot \epsilon(\beta\gamma)^3} \tag{2}$$

where J_p is Alfven current for protons ($J_p = 3.1 \cdot 10^4 kA$), $\pi\epsilon$ is beam phase volume, L is the focusing period length, β and γ are relativistic factors. Beam current increase (see Fig.1) leads to corresponding σ value increase (solid line), in contrast to mono-charged beam, when space charge suppresses σ magnitude (dashed line). One can see, that big envelopes oscillations in the strong focusing channel deteriorate the neutralization effect (neutralization can be ideal only for smooth envelopes). Nevertheless, the Λ value in our charged-compensated scheme can be enhanced to $20 \div 30$, whereas in frames of the conventional scheme (mono-charged beam) one get only $\Lambda \approx 3 \div 4$. Evidenly, the relative gain factor is between $5 \div 7$, so the total gain for both beam components ($q = +1$ and $q = -1$) becomes $\eta \approx 10$ at least.

At the same time, the energy $\mathcal{E} = J \cdot U \cdot t$, stored in one accumulating ring, must not be too high (t denotes the time of target illumination). The maximal value $\mathcal{E}_{max}$, accumulated in a single ring is restricted by

$$\mathcal{E}_{max} \leq 2\pi\Delta Q \cdot \epsilon B\gamma(\gamma+1) \cdot U^2 \tag{3}$$

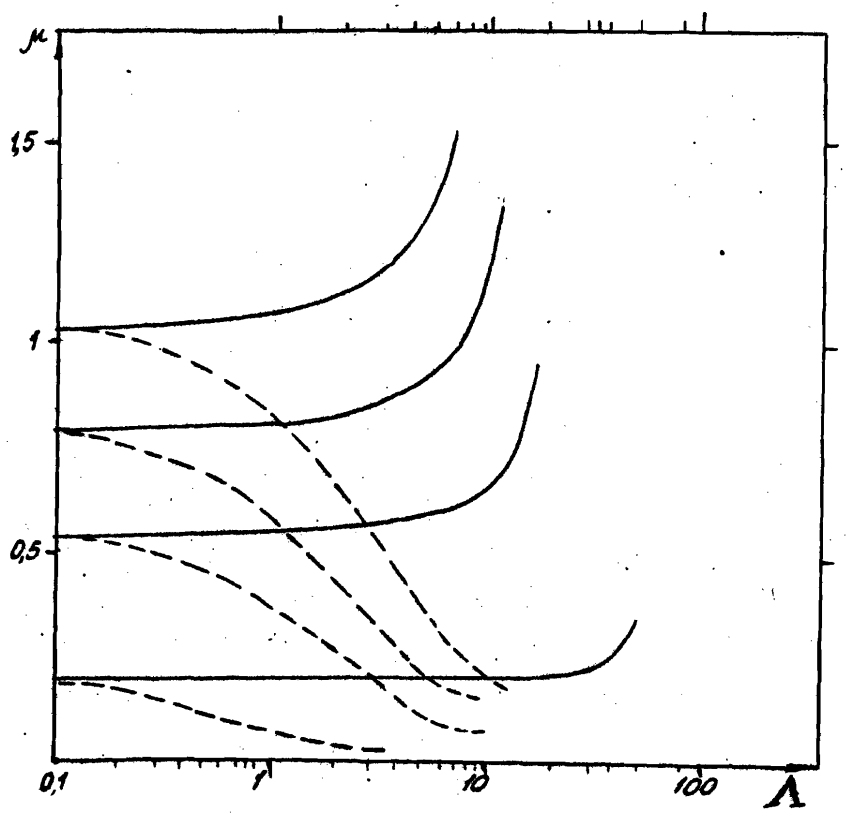

Fig 1

where ΔQ is an incoherent tune shift admitted, B is the bunching factor ($B = 1$ for the coasting beam).

Trying to avoid the limitation (??), we may multiply the accumulating rings number, but this is not a good decision in frames of Liuville's theorem. We propose, therefore, to deal with ions (when we are not restricted by Liuville's theorem), having the different atomic masses $A_i, i = 1, 2, ..., k$ and actual k can be determined by the desirable current gain per a single focusing channel. It has been found that $k = 4 \div 6$ is sufficient for our purposes. The masses difference must be rather small to accelerate them with the same velocities in the one main linac ($\beta_i = \beta_k$ see Fig.2). However, this difference must be sufficient enough to separate beams after the acceleration through the main linac and further handling. The acceptable mass dispersion should be about $\Delta A_i/A \approx 1\%$. On leaving main linac, the ions should be separated, owing to the difference in momenta $p_i = A_i\beta_i\gamma_i$ and then, we should arrange the coincidense of all ions momenta by means of auxiliary linacs. After that, every ion family will compress and store in it's own rings system. On attaining the required parameters (current level, etc.), we eject every family and provide funneling in accordance with Fig.2 ($A_1 < A_2 < A_3 < A_4$, and $\beta_i \neq \beta_k$).

2 The Choice of the Ions

The ions, used in the proposed scheme, must be stable enough: their total losses must not be over than $\sim 1\%$ during the acceleration, accumulation and beam transport. There are three main reasons, resulting in ion losses: ions scattering on residual gas, an intra-beam scattering and so-called "tunnel-effect". Let us consider these phenomena.

Scattering cross-sections on residual gas are practically the same both for negative and positive ions (under the assumption that the ions charge state is far from equilibrium state), so there are no particular limitations for gas pressure within driver's vacuum system.

As regards to intra-beam scattering, we have a preliminary experimental data (see ref.[?]) for the following charge-exchange reactions:

$$1).\ \mathbf{Bi}^{+1} + \mathbf{Bi}^{+1} \rightarrow \mathbf{Bi}^{+2} + \ldots \quad . \quad (\textit{beam accumulation})$$

$$2).\ \mathbf{Au}^{-1} + \mathbf{Au}^{-1} \rightarrow \mathbf{Au}^{0} + \ldots \quad (\textit{beam accumulation})$$

$$3).\ \mathbf{Bi}^{+1} + \mathbf{Au}^{-1} \rightarrow \mathbf{Bi}^{0} + \mathbf{Au}^{0} \quad (\textit{final beam transport})$$

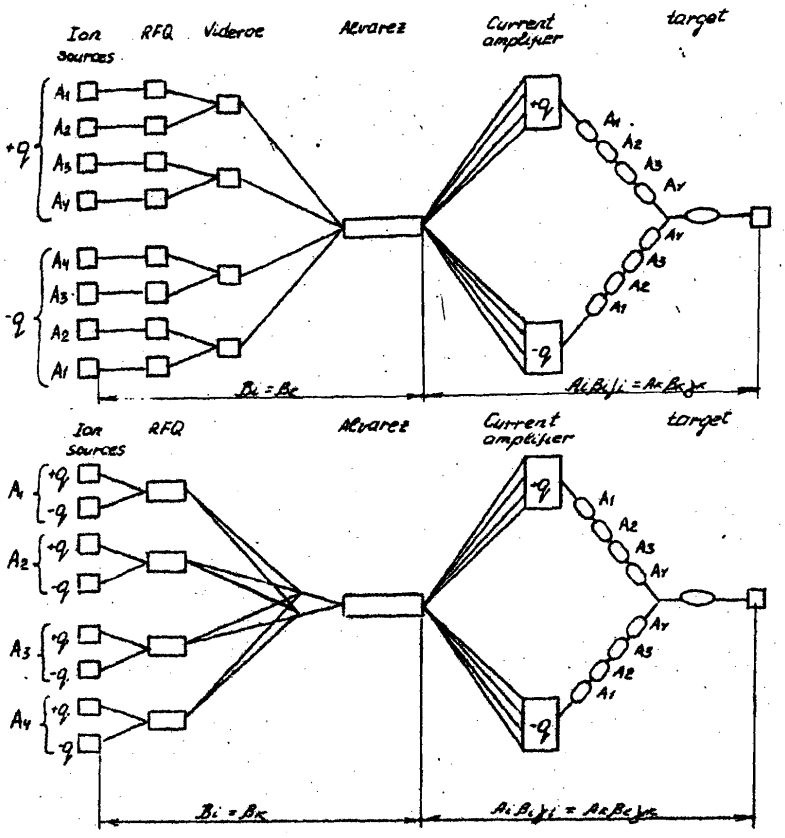
Ion sources
RFQ
Videroe
Alvarez
Current amplifier
target
+q
-q
A1
A2
A3
A4
Bi = Bc
AiBiji = AkBkjk
Ion sources
RFQ
Alvarez
Current amplifier
target
Bi = Bk
AiBiji = AkBkjk

Fig 2

The cross-section for the above processes are approximately related, as 1, 20 and 20. In the third case, the losses will not be essential owing to the duration of this process is about 10^{-5} s, whereas the accumulation processe durate about $1ms$. Thus, the third reaction does not deteriorate the design, and we must pay particular attention to the second case abovementioned, which gives the most part of ions losses. Nevertheless, it could be proven, that even for the second reaction (with a cross-section about $\approx 4 \cdot 10^{-15}\ cm^2$), we can arrange such characteristics of accumulating rings, when the corresponding losses will not be over, than 1%.

The third phenomenon — the spontaneous losses of electrons due to strong external electric fields, goes according to the following reaction:

$$\mathbf{Au}^{-1} \rightarrow \mathbf{Au}^{0} + e$$

The acceptable losses are due to the sufficient long life time τ_i. At the same time, the magnetic fields H in the laboratory system corresponds to the electric field E in ion's rest system. The relation between H and E values can be written as

$$H(T) = (3\beta\gamma)^{-1} \cdot E(MV/cm) \tag{4}$$

and the corresponding electric fields E_i for the $i-th$ negative ion can found [?] from

$$\lg \tau_i = -13.17 - \lg g_i + \frac{1}{2} \lg E_i + 29.67 \cdot E_i^{3/2} \cdot g_i^{-1} \tag{5}$$

where τ_i is measured in seconds; E_i in (MV/cm) and g_i in eV. Having introduced an auxiliary variable x, we can reduce the Eq.?? to a couple of simple equations:

$$E_i = g_i^{3/2} \cdot x^{-1} \quad , \quad \tau_i = g_i^{-1} \cdot Y(x) \tag{6}$$

where $Y(x) = x \cdot 10^{29.67x-13.17}$ is plotted in Fig.3.

We can accept $\tau_i = \tau^* = 1sec$ for all i, that is quite sufficient for acceleration and accumulation; the total losses are less than 1%. The corresponding E^* can be calculated from Eq.?? and H^* could be found from (??), under the assumption that kinetic energy 10 GeV for all ions.

The acceptable chemical elements and their parameters can be taken from the paper [?]. One can see in the Table ??, that heavy elements (with atomic masses $A_i > 120$), posessing the high electron-affinity energy g_i, are the most preferable. The high enough energy g_i means that without essential ions

Table 1:

	Z	A	%	g_i	E^*	H^*		Z	A	%	g_i	E^*	H^*
Au	**79**	197	100	2.31	7.5	7.5	**Te**	**52**	130	34.5	1.97	6.0	4.7
Pt	**78**	198	7.2	2.13	6.67	6.66			128	32.0			
		196	25.3						126	18.7			
		195	33.8						125	7.0			
		194	32.9						124	4.6			
		192	.78						123	.9			
Ir	**77**	191	37.3	1.56	4.25	4.25			122	2.5			
		193	62.7						120	.09			

losses we can use a high magnetic field within the current amplifier (transfere, storage and compression rings).

Final results are collected in the Table 1 and we can choose now three families of ions:

$$\mathbf{1.}\ \mathbf{Pt}^{78}_{198}\ \mathbf{Pt}^{78}_{196}\ \mathbf{Pt}^{78}_{194}\ \mathbf{Pt}^{78}_{192} \qquad (H^* = 6.66T)$$

$$\mathbf{2.}\ \mathbf{Au}^{79}_{197}\ \mathbf{Pt}^{78}_{195}\ \mathbf{Ir}^{77}_{193}\ \mathbf{Ir}^{77}_{191} \qquad (H^* = 4.25T)$$

$$\mathbf{3.}\ \mathbf{Te}^{52}_{130}\ \mathbf{Te}^{52}_{128}\ \mathbf{Te}^{52}_{126}\ \mathbf{Te}^{52}_{124}\ \mathbf{Te}^{52}_{122}\ \mathbf{Te}^{52}_{120} \qquad (H^* = 4.7T)$$

Taking into account the above considerations, we can state that the first family (platinum ions) is the best one. In the meantime, we must note, that the necessity to deal with isotopes complicates the practical operating.

3 Discussion

Note, that the dependence $\sigma(\Lambda)$ (Fig.1) has been found in frames of linear transversal motion (K-V equations) and hence all nonlinear effects were out of consideration. Generally speaking, we may expect, that two beams with opposite charge states can generate a certain coherent instabilities, which might emerge under such resonance conditions: $n[\sigma(+q) + \sigma(-q)] = 2\pi$, where n is the order of resonance and for quadrupole resonance we take $n = 2$. However, the undesirable resonance phenomena might be significantly suppressed owing to the working point will move accross the resonance grid due to gradual current increase during the transportation. Thus, the numerical simulation, using super-particles algorithm is the only reliable way to estimate the beam

behaviour in the driver.

Beside that, in practice, σ depends on Λ as well as beam amplitudes, however this effect will result in additional suppression (Landau damping) of beam-beam resonances and some of coherent instabilities [5]. These considerations increase our confidence that the presense of non-linearities is rather positive than negative. The more detailed studies are in a progress now.

Eq.5 has been derived under the assumption, that the affinity potential function is represented by δ-function, that can violate the validity of the above formula for some ions. The preliminary studies have shown, that the validity range τ^* and E^* values, are sufficiently reliable, though the best way, obviously, is to measure ions life-time directly, and the corresponding experimental programm is under consideration now.

The Fig.2 shows two possible schemes of the proposed driver and the main driver parameters for both cases are given in Table 2.

Table 2

Total energy, $\mathcal{E}$	$9\ MJ$	Total power, P	$600\ TW$
Specific power deposition	$10^{16}\ W/g$	Ion energy	$10\ GeV$
Channels number m	6	Maximal current in	
Target number	2	single beam line, J	10 kA
Target sizes (H/D)	1/3.4 mm/mm	Time of illumination	15 ns
Linac length	4 km	Momentum spread	$\pm 2 \cdot 10^{-5}$
Maximal current for		Maximal current for	
each component	125 mA	all components	1 A
Emittance, ϵ	$0.2\pi cm \cdot rad$	Pulse duration	0.9 ms
Transfere rings	8	Radius	350 m
Multiturn injection	7	Mean magnetic field	$0.57T$
Emittance horizontal	$2\pi\ cm \cdot mrad$	Tune shift	0.07/0.21
Emittance vertical	$0.2\pi cm \cdot mrad$	Maximal current	875 mA
Storage rings	8	Radius	50 m
Multiturn injection	7	Mean magnetic field	$4T$
Emittance horizontal	$2\pi\ cm \cdot mrad$	Tune shift	0.07/0.07
Emittance vertical	$2\pi\ cm \cdot mrad$	Maximal current	6.25 A
Compression rings	48	Radius	100 m
Initial momentum spread	$\pm 2 \cdot 10^{-5}$	Mean magnetic field	$2T$
Final momentum spread	$\pm 4 \cdot 10^{-3}$	Bunching RF	0.6 MV
Tune shift $(\Delta Q_i/\Delta Q_f)$	0.14/0.42	RF harmonic	1

By the contrast with conventional schemes (see ref.[?]), the presented schemes have that specific features, that any ion source produces the unique ions family with different masses and charge states. Both schemes have the different design in the initial part of the linear accelerator. According to the upper variant every ion source supplys ions for the corresponding beam channel. The lower variant shows, that the sources, producing the ions with different charge state ($+q$ and $-q$) and the same mass, are coupled and we profit from neutralization in the initial stage of acceleration (as well as in the final transport). The advantage of the neutralization will be significant evidently only for the low rate of acceleration.

In the both schemes all ion fractions have the same velosities (mean values), but the mean momenta of each fraction will be different due to the mass diffences. So, the beam hanling (merging and separation) are facilitated. Note, the above procedure could be realized under the assumption, that the momentum spread in each fraction is less, than the momentum difference between fractions.

On ejecting from the linear accelerator the beam must be separated by fraction and every fraction will be additionally accelerated in its own linac, in order all fraction will have the same momenta (and different velocities owing to the mass difference). After that the fractions are accumulated and compressed in the family of storage rings (in the Fig. 2 we denotes it, as a current amplifier).

The total compression for every beam channel will be achieved due to the following factors:

multiturn injection in the transversal phase space gives:	$7 \times 7 = 49$ times
longitudinal compression presents	200 times
usage of the both positive and negative ions gives	2
usage of four beam fractions gives factor	4
As a result we obtain the gain factor	8×10^4.

Thus, taking the ion source current 0.125 A, we attain for every transport channel 10 kA, that corresponds to 100 TW – the transmitted power in one channel. On taking the time of target illumination 15 ns, the energy transmitted in one channel will be 1.5 MJ. One can see, that the total energy deposition can be increased by the factor m. If we assume, that the total energy 9 MJ is sufficient for the reliable target ignition, we should take $m = 6$

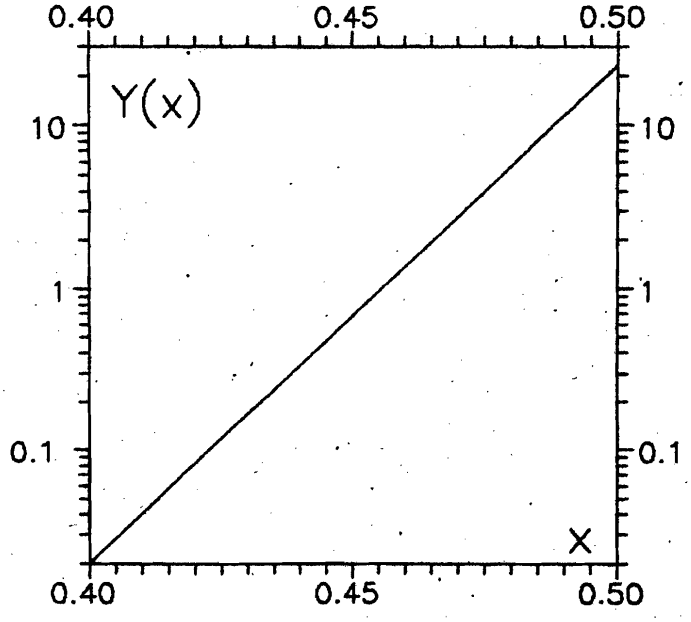

Fig.3

in our schemes.

4 Conclusions

We can summarize the benefits of the driver with neutralized beams:

- Transversal charge forces compensation by means of negative ions allows to transfer very high power beam through a single channel with $P \geq 100TW$.
- The application of ions families with different masses but the same momenta allow us to have within final focusing system high spread velocities ($\pm 1.9\%$) , while the momentum spread is low ($\pm 0.4\%$).
- In contrast to conventional schemes, the beams funneling takes place for the different q/A ratios, that facilitates the design of funneling system. As the result, the longitutinal phase volume dilution becomes considerably less.
- The compression factor in the developed scheme can be substantionally increased (≥ 200) simultaneously with the decreasing of the RF electric field, owing to the small longitudinal phase volume and longitudinal space charge forces compensation.

Acknowledgements

The author wish to that Dr. Yu.N.Cheblukov for fruitful discussions, concerning the optimal choice of ions family, and wish to thank A.V.Barchudarian and Dr. L.G.Vorobiev for their help in numerical calculations.

References

[1] A.V.Barchudaryan, D.G.Koshkarev, P.R.Zenkevich, Proceedings of International Symposium on HIF, Frascati, 25-28 May 1993.

[2] A.N.Balabaev, E. Salzborn and F.Melchert. Private communication, 1993.

[3] H.Hotop and W.C.Lineberger, J. Phys. Chem. Ref. Data, Vol.14, N 3, 1985.

[4] Y.N.Demkov, G.F.Drukarev, Sov. J.T.E.P. v.47, 3(9), pp.918-924, 1964.

[5] I.Hofmann, L.J.Laslett, L.Smith and I.Haber. Particle accelerators, **13**, 145, 1983.

[6] "HIBALL-II An Improved Conceptual Heavy Ion Beam Driven Fusion Reactor Study", KfK 3840, FPA-84-4, UWFDM-625, Kernforschungszentrum, Karlsruhe, 1985.

Д.Г.Кошкарев

Драйвер с нейтрализованными пучками для тяжелоионного термоядерного синтеза.

Подписано к печати 25.01.94 Формат 60x90 1/16 Офсетн.печ.
Усл.-печ.л.0,75. Уч.-изд.л.0,5 Тираж 95. Заказ 7.
Индекс 3649

Отпечатано в ИТЭФ, 117259, Москва, Б. Черемушкинская,25