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by

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A Conceptual Design of Transport Lines for a Heavy-Ion Inertial-Fusion Power Plant

by
David L. Judd

Commentary by Edward Lee
April 2011

David Judd's last project was a conceptual layout of beam lines leading from an induction linac driver to a fusion chamber, including the final focus system. This work was essentially complete and he left a draft report (1998-attached) that he thought had some errors to be corrected. I have worked through this draft and believe it is a useful contribution to HIF science and system design and that it should be made generally available. There are some errors in analysis (mostly unimportant), but significant assumptions and parameters are omitted. I have tried to cover these points in this commentary. However the main value of Judd's work is not in its extensive algebraic detail but rather in his approach and conclusions. Essentially he accepts a set of system parameters (from W. Meier) and then does his best to make a consistent layout without changing any parameters. For example the length of the final focus system is fixed at 20m. Such restrictions are not completely necessary, but they force potential issues into the open and motivate modifications and innovation. Judd's most important contribution is his observation that velocity tilt must be applied to the ion beams well beyond the linac to avoid premature stagnation of compression (for his system layout and by implication for most others with two-sided illumination).

Topics covered in the draft include:

- drift compression
- large bends
- small final bends
- packing of final focus magnets
- timing of pre-pulse vs. main pulse
- application of tilt
- compression stagnation

Topics not covered include:

- quadrupole transport
- dispersion from bends
- neutralization
- final focus details
- steering

I Introduction

Some major system features are not stated but can be inferred. For example this is probably an engineering test facility, not a power plant driver, because the standoff from target to final magnet is only 5.0m (W. Meier can't recall).

The fusion target takes two-sided illumination with indirect drive using a total of 60 beam pulses: 10 pre-pulses (3.0GeV) +20 main pulses (4.0GeV) from each side. On pg. 12 it is stated that the charge per beam pulse is 26.8 μC, so we calculate

pre-pulse: 20x3GeVx26.8 μC=1.608MJ
main pulse: 40x4GeVx26.8 μC =4.288MJ
total beam energy 5.896MJ

The beam ion mass is 200amu, so the species is Hg^+. Therefore the mid-pulse velocities are

pre-pulse v =.1773c=5.316x10^{7}m/s
main pulse v=.2040c=6.114x10^{7}m/s

On page (12) it is stated that the pre-compression pulse length is L_0=10.0m, and compression is by a "factor of order 20". We infer a final pulse length of about .5m and final durations

$$\text{pre-pulse}\ \tau \approx \frac{.5}{5.316x10^7} = 9.4ns$$

$$\text{main pulse}\ \ \tau \approx \frac{.5}{6.114x10^7} = 8.2ns$$

The magnetic rigidity of the beam ions is

$$[B\rho] = \gamma m v/e = \begin{Bmatrix} 112.0T - m & prepulse \\ 129.5T - m & mainpulse \end{Bmatrix}$$

II The Approach to a Cone of Final Focus Arrays

The length of the four-quadrupole final focus system is 20m plus 5.0m standoff to the target, for a specified d=25m total. The array figure shows unspecified magnet lengths of about $\ell = 2.5m$ each. We can estimate the quadrupole magnet gradient since for this type of focus the focal length must be approximately f$\approx$standoff=5.0m:

$$B' \approx \frac{(B\rho)}{\ell \mathrm{f}} \approx \begin{Bmatrix} 8.96\,{}^{T}\!/\!{}_{m}\,\text{prepulse} \\ 10.36\,{}^{T}\!/\!{}_{m}\,\text{mainpulse} \end{Bmatrix}$$

Quadrupole wire fields are less than 2.5T, modest compared with $B_0 = 4.0T$ assumed for all bend magnets. The final focus quadrupole windings must fit into spaces with square cross sections of side s=.70 (specified by Judd for a rough intuitive optimization (??)), so there appears to be room for return flux paths and shielding from neutrons/gammas. If the final magnet aperture radius is .10m then convergence angles up to .1/5=20mr can be contemplated. A safely factor of 1.5 reduces this to 1.3mr, typical of HIF design.

Judd stresses the importance of transverse packing of final focus magnets; the transverse size of the beam bundle scales linearly with bundle half angle θ and length d, so bundle volume scales as $\theta^2 d^3$. See the second figure on pg (3). Indirect drive permits minimization of θ, consistent with packing, but the bundle volume is large anyway.

On page (2) the relations among lengths and angles for the packing geometry are correct, but the symbol d (denoted by dp below) has a new meaning. Also φ means ϕ.

All bends (magnetic dipoles) have assumed longitudinal field occupancy $\eta = .4$, so the mean bend field in an arc is $B = .4x4.0 = 1.6T$ in this study.

The transverse angle ψ defined on pg (2) is not the same as the longitudinal geometry angle ψ defined on pg (3) and denoted here by ψp.

On pg (4) the initial displacement of a beam from the system axis is assumed to be e=2.55 s without explanation. This is not important since e is small and $\psi p \rightarrow \theta$ as $e \rightarrow 0$.

The essential algebraic relations used in section II are correct and displayed in the Mathematica© output below. Given Parameters are {N, d, s, η, $B0$, P/q=$B\rho$}. Derived Parameters {ψ, r, θ, B, ρ, t, e, ψp, h, Δp, ϕ, a, b, c, dp}

On pg. (4) the calculated total longitudinal length h should be 145.1m not 141.3m for the assumed magnet box diameter s=.7m.

Untitled-1 1

```
In[613]:=
 (*layout of final focus and final bends*)

 (*input main pulse final focus and final bend parameters*)

 NN = 20.;
 d = 25.;
 s = .7;
 eta = .4;
 B0 = 4.;
 Brho = 129.5;

 (*output Final focus and final bend parameters*)

 ψ = Pi / NN
 r = s / 2 * (Cot[ψ] + 1)
 θ = ArcSin[5 * r / d]
 B = eta * B0
 rho = Brho / B
 t = d * Sin[θ] + rho * (1 - Cos[θ])
 e = 2.55 * s
 ψp = ArcCos[1 - (t - e) / 2 / rho]
 h = rho * (2 * Sin[ψp] + Sin[θ]) + .5 * r * Cot[θ]
 ΔP = d + rho * (2 * ψp + θ) - h
 ϕ = ArcCot[2 + Cot[ψ]]
 a = s / 2 / Sin[ψ]
 b = s / 2 / Sin[ϕ]
 c = s / 2 * Cot[ψ]
 dp = s / 2 * Cot[ϕ]
```

Out[619]=	0.15708	ψ
Out[620]=	2.55981	r
Out[621]=	0.537468	θ
Out[622]=	1.6	B
Out[623]=	80.9375	ρ
Out[624]=	24.2106	t
Out[625]=	1.785	e
Out[626]=	0.532652	ψp
Out[627]=	145.115	h
Out[628]=	9.60887	Δp
Out[629]=	0.119708	ϕ
Out[630]=	2.23736	a
Out[631]=	2.93079	b
Out[632]=	2.20981	c
Out[633]=	2.90981	dp

III & IV Main Pulse Two-Sided Illumination and Pre-pulse Path Parameters

The geometry of the large bend/drift system is specified, with emphasis on minimum length given the fixed values of h and ρ derived above. The total main pulse path is actually 600m, not 592.5m.

A somewhat innovative feature is the “cut across the corner” path for the pre-pulses to allow then to catch up with the main pulses. The algebra is correct.

V Connection Between Compression and Distance in Free Drift

Judd solves the drift compression equation with space charge included. This feature is vital since compression must stagnate near the middle of the final focus system. The equation for pulse length L(t) is the (very approximate)

$$\frac{d^2L}{dt^2} = \frac{12g}{4\pi\varepsilon_0\gamma^5}\frac{qeQ}{M_0L^2}$$

with g factor (from W. Meier) having the constant value g= 1.234.
This is probably

$$g = \frac{1}{2} + Log\left(b/\bar{a}\right)^2,$$

with pipe to beam aspect ratio $b/\bar{a} = 1.443$, a major (and suspect) model simplification. Judd uses initial pulse length $L_0 = 10.0$m and needs total compression factor C=20. This requires initial velocity tilt $\Delta v/v = .041$, a large but not crazy value. Unfortunately, he finds the stagnation distance is found to be only 240m, much less than the ~600m consistent with the layout. If we increase the initial pulse length to 24.5m stagnation works out ok at 600m, but the initial tilt is the larger value $\Delta v/v$ =.082. Judd takes note of the problem and proposes to add tilt along the beam lines nearer the fusion chamber rather than in the linac. This is either a major innovation or reinvention of an old idea.

VI There is no section VI in Judd’s draft

VII Distances and Pulse Lengths with External Compression Fields

With motivation from section V, Judd adds a constant term to the rhs above of the described pulse length equation. This models the application of tilt by additional induction modules, and greatly complicates the mathematics. It appears that sign errors are made in several equations on pg (14), and subsequent results are therefore suspect. Fortunately the details of the model are not important at this point and the general idea is clear. Also, I am unable to follow the derivation beyond the apparent sign errors.

VIII Achieving the Required Final Compression

Here Judd calculates an optimal zone for application of tilt to the main pulses and pre-pulses. He does not want to change the layout of bends and drifts described in sections. I-IV; in particular he states that adding additional drifts between the final (small) bends and large bends would increase “the bunch length and the tilt further”. I don’t understand this assertion. Anyway, the result is that the tilt modules are located largely in large (180° and 156°) bends! Not a good idea in my opinion. He opts for a gradient $\pm 250\, kV/m$ applied over 400m for the main pulse and $\pm 140\, kV/m$ over 360m for the pre-pulse. The calculation uses results from section VII and may be inaccurate … I can’t follow the calculation. However, the main message is that it will be difficult to apply tilt near final focus without some modification in layout design. The details of drift geometry will depend on assumptions about the operation of the tilt modules.

IX Tolerances

Judd correctly points out that path lengths must be controlled to about 10.0cm. However, his assertion that to do this the bend field must be controlled to $\sim 10^{-3}$T out of 4.0T appears to be incorrect. Quadrupole transport magnets will maintain a low maximum orbit dispersion in the bends and eliminate this particular sensitivity.

X & XI & XII Thoughts on Improved Design, Comparison of the Present Design with One-Sided Illumination and Summary

Judd points out that a target with single-sided illumination would have “the greatest benefit” YES! He finds that the added tilt modules can be eliminated.