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ACCELERATOR AND FINAL FOCUS MODEL FOR AN INDUCTION LINAC BASED HIF SYSTEM STUDY*

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ABSTRACT

An overview of the assumptions and models incorporated in the ongoing Induction-Linac-based, HIF System Assessment is presented. Final transport, compression and final focus pose constraints which form a critical link between the accelerator and target requirements. A recent analysis has shown that system costs may be considerably reduced by the use of multiply charged ions. The assumptions underlying this direction are described.

1. INTRODUCTION

Inertial confinement fusion (ICF) requires very high power irradiance and energy deposited on the fusion target which are nearly independent of the driver type. In addition, the depth of deposition must be small (typically $\sim .1 \text{ gm/cm}^2$ in a stopper material) to produce the high fusion yields required for an economically attractive power plant. The range condition can be met in principal by any ion species, accelerated sufficiently to match the range-energy relation, as well as by short wave-length ($\lesssim 300 \text{ nm}$) photons. For the heavy-ion driver approach to ICF two conventional but very high current accelerator technologies are being explored. These are the rf linac/storage ring system now studied in W. Germany and Japan, and the induction linac approach of the USA. For both accelerator types the combined considerations of space charge limits and range in dense matter lead to the use of heavy ions of high kinetic energy.

A typical set of final beam parameters suitable for a power reactor, which was adopted in the HIBALL II study,¹ applies equally well to either of the two heavy ion driver types (see Table I). It must be emphasized that cost tradeoffs among the many components of a complete power plant allow a broad range of system parameters (such as repetition rate) to be considered with minor effect on final cost of electricity (COE). Some cost data for HIBALL II are also included in Table I. It should be noted that, although its 47.9 mill/kWh COE is about double that available from existing, on-line coal or fission plants, it is comparable with the estimates from other fusion system studies (e.g. 59.1 mill/kWh for the STARFIRE tokamak in 1984 dollars using current costing methods.) The primary concern at present is not so much the COE, but the magnitude of generating capacity and capital investment of the plant. A 500-1000 MWe fusion plant with this COE is of considerable interest, but it is difficult to achieve, primarily because of the economy of scale associated with all nuclear electric plants. Both the rf linac/storage ring and the induction

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Table I - Selected HIBALL II Parameters

Pulse Energy	5.0 MJ
Particle Energy	10 GeV
Particle Type	B_i^+ ($A = 209$)
Pulse Power	250 TW
Pulse Length	20 ns
Rep. Rate per Reactor	5 Hz
Number of Beams per Reactor	20
Net Pulse Charge	500 μ C
Relativistic Factor ($\beta\gamma$)	.325
Emittance (unnormalized)	3×10^{-5} m-r
Momentum Width	$\pm 1\%$
Spot Radius	4 mm
Range in Pellet (Pb+Li layers)	.19 gm/cm ²
Convergence Half Angle	≈ 10 mr
Standoff to Final Magnet	8.5 m
Target Gain	87
Net Electric Power (4 Reactors)	3.784 GW
1984 Cost of Electricity (4 Reactors)	47.9 mil/kWh
Direct Cost of Entire Plant	5.1 G\$
Direct Cost of Driver	2.432 G\$

linac drivers provide a substantial fraction of total direct capital costs of a plant and scale poorly for lower net electric power. The HIBALL II driver cost is "only" about 48% of total direct capital cost largely because the high rep. rate capability of the accelerator has been exploited in a large (multi-GW) plant with four reactors. Magnetic fusion systems are also very large for reasons of economy of scale as well as physical constraints imposed by the use of low density plasma.

A goal of the ongoing Heavy Ion Fusion Systems Assessment² is to find ways of reducing the cost of the driver and other plant components to

the point where 500-1000 MWe plants are attractive. Another, related, goal of Heavy Ion Fusion, not covered by the Assessment, is to find a path of development which will lead from the current research to a fusion plant with a minimum of risk and expense. Cost reductions can be achieved in several directions:

- a. Reduced cost of materials
- b. Innovative use and manufacture of components
- c. Optimized match of major system components (e.g. high rep. rate reactor to high rep. rate accelerator)
- d. Changes in design limitations resulting from improved understanding of physical constraints.

The present paper addresses only the last of these directions, where there have been significant new developments in the understanding of limits of high current transport in the accelerator system.

2. INDUCTION LINAC SYSTEM

An induction Linac driver is now envisioned as a multiple beamlet transport lattice consisting of (N) closely packed parallel FODO channels. Surrounding the lattice are massive induction cores of ferromagnetic material and associated pulser circuitry which apply a succession of long duration, high voltage pulses to the N parallel beamlets. Longitudinal focussing is also achieved through the detailed timing and shape of the accelerating waveforms (with feedback correction of errors). A multiple beam source of heavy ions operates at 2-3 MV, producing the net charge per pulse required to achieve the desired pellet gain. Initial current (and therefore initial pulse length) are determined by transport limits in the lattice at low energy. The use of a large number of electrostatic quadrupole channels ($N \sim 16 - 64$) appears to be the least expensive focal option at low energies (below ~ 50 MV). This is followed by a lower number of superconducting magnetic channels ($N \sim 4-16$) for the rest of the accelerator. Merging of beams may therefore be required at this transition. Furthermore, some splitting of beams may be required after acceleration to stay within current limits in the final focus system.

The rationale for the use of multiple beams is that it increases the net charge which can be accelerated by a given cross section of core at a fixed accelerating gradient. Alternatively a given amount of charge can be accelerated more rapidly with multiple beams since the pulse length is shortened and a core cross section of specified volt-seconds per meter flux swing can supply an increased gradient. However, an increase in the number of beamlets increases the cost and dimensions of the transport lattice and also increases the cost of the core for given volt-sec product since a larger core volume is required. For a given core cross section ($\propto$ volt-seconds/m), the volume of ferromagnetic material increases as its inside diameter is increased. Hence there is a tradeoff between transport and acceleration costs with an optimum at some finite number of beamlets. The determination of this optimum is a complex problem

depending on projected costs of magnets, core, insulators, energy storage, pulsers and fabrication. The induction linac design code LIACEP³ is used for this purpose.

The choice of superconducting magnets for the bulk of the linac is mandated by the requirement of system efficiency; this must be at least ~ 10% in an ICF driver and ideally > 20% to avoid large circulating power fractions (which result in a high COE). Induction cores are most likely to be constructed from thin laminations of amorphous iron, which is the preferred material due to its excellent electrical characteristics and flux swing. At a projected cost of ~ 4 \$/lb (insulated and wound) this is a major cost item for the first 2-4 GV of a typical linac. At higher voltage the cost of pulsers and fabrication of the high gradient column with insulators dominates.

Results from about 400 LIACEP runs, spanning a selected range of beam parameters suitable for a driver, have been fit with a polynomial expression and incorporated into the HIFSA system code. The fitted data are accelerator cost, efficiency and length.

3. FINAL TRANSPORT AND FOCUS

Between the accelerator and the fusion reactor the beamlets are separated and also, if necessary, split. The drift lines leading to the final focus area are 200-600 m in length and used for ballistic compression as well as to match to the final focus configuration of the reactor. The transport lattice is composed of cold bore superconducting quadrupoles, bends, and possibly higher order elements needed to control dispersion. As the beamlets compress, the transport of the high current becomes increasingly demanding, with the large apertures and the close packing of elements especially pronounced immediately before the final focus train.

The final focus system itself has parameters determined largely by the requirements of spot size on target, reactor size, and the neutron, x-ray, and gas fluxes from the reactor. The final focus triplets described by R. Martin⁴ are well suited as the basic beam line components. HIBALL II uses magnet trains consisting of a pair of triplets separated by a pair of weak bends used to remove line-of-sight neutrons from the beam transport line. A detailed discussion of shielding requirements for this system is also presented in the HIBALL II Study.

Transport within the reactor vessel has, in most studies, been assumed to take place in near vacuum ($P \leq 10^{-4}$ torr Li) to avoid disruption by the two-stream instability, or in a high pressure window ($P \sim 10^{-1}$ -10 torr), where the beam is also thought to be stable⁵. HIBALL specifies $P < 10^{-5}$ torr Pb vapor to avoid stripping of beam ions, which would lead to reduced irradiance due to the beam's electric field. Unfortunately, several attractive reactor concepts (CASCADE,⁶ HYLIFE⁷) have residual gas pressures in the range 10^{-2} - 10^{-3} torr Li at reasonable rep. rates; this pressure must be taken into account both for transport in the reactor and in maintaining vacuum in the final focus lines. Recent calculations⁸ show that the two stream mode is benign at these pressures due to the detuning effects of beam convergence. The control of gas flux into the beamlines, and the process of stripping and neutralization in the reactor have not yet been examined in necessary detail, and are dealt with by plausible assumptions in the Heavy Ion Fusion System Assessment.

To produce a small radius (r) on the target, the beamlet emittance (ϵ) must, satisfy

$$\epsilon < r\theta$$

where θ is the beamlet convergence cone half-angle. For HIBALL ($r = 4$ mm, $\theta = 10$ mr) this condition is $\epsilon < 4 \times 10^{-5}$ m-r, which is 33% larger than the design value of 3×10^{-5} m-r. Allowance must also be made for the effect on spot size of momentum dispersion, various forms of jitter, and space charge induced blow up. A final focus system comprised of quadrupoles and weak bends has dispersion at the target which leads in a practical design based on a pair of triplets to increase spot radius:

$$\Delta r \approx 8 L \theta \frac{\Delta P}{P},$$

where L is the distance from pellet to the center of the final quadrupole. Without compensation by higher order elements it is desirable to keep $\Delta P/P \leq 10^{-3}$. This is a severe requirement to be met by the accelerator system.

In summary, the requirement of small spot size on target is met by small specified emittance and a set of other focal and reactor constraints which are not currently well understood. The cone half angle θ is set at a value which is determined by a trade-off between factors which drive it towards a low value and those which drive it to a high value. In the first category are dispersion, aberrations, magnet costs, reactor constraints, shielding and beamline vacuum. In the second category are the emittance limit, space charge effects, and jitter control. The range $\theta = 10$ -20 mr is the result of compromises among these factors. Aside from the spot size condition, it is economically desirable to make the emittance large, since the limit on transport of high current is found to vary as $\epsilon^{2/3}$.

4. SCALE LAWS FOR TRANSPORTABLE CURRENT

A simple set of formulas relating transportable current to lattice properties were originally derived by A. Maschke.⁹ Since these serve as a good framework for the discussion of recent developments in high current transport they are rederived here. The continuous limit approximation for alternate gradient focussing is adopted. Let (σ_0) be the phase advance of a single ion per lattice period of length ($2L$), η is the lens occupancy factor, (B') or (E') is the pole field gradient, [$B\rho$] the particle rigidity, and v is its velocity. Then we have approximately

$$\sigma_0 = \frac{\eta(B', E'/v)L^2}{[B\rho]} \quad (1)$$

The depressed tune (σ), which is the actual phase advance per period in the high current beam [mean edge radius (a) and electric current (I)], is given by

$$\sigma^2 = \sigma_0^2 - \frac{2I}{(\beta\gamma)^2 [B\rho]} \left(4\pi\epsilon_0 c^2 \right)^{-1} \left(\frac{2L}{a} \right)^2 \quad (2)$$

Normalized emittance ($\epsilon_n = \beta\gamma\epsilon$) is related to depressed tune and radius by

$$\epsilon_n = \beta\gamma \frac{\sigma}{2L} a^2 . \quad (3)$$

In addition to these three relations we have the definitions

$$[B\rho] = \frac{\beta\gamma M c}{qe} , \quad (4)$$

$$\beta\gamma = \left[\left(\frac{E}{Mc^2} \right)^2 + 2 \left(\frac{E}{Mc^2} \right) \right]^{1/2} ,$$

where $M = M_0A$ is ion mass, M_0 is the atomic mass unit, q is charge state and E is kinetic energy. Values of β are generally less than about .33 for conceptual drivers, so with $\lesssim 1\%$ error we set

$$\beta\gamma = \sqrt{\frac{2 qeV}{M_0 A c^2}} , \quad (5)$$

where V is the cumulative accelerating voltage experience by an ion. The magnetic field or electric potential of the quadrupoles, evaluated at the beam radius, are respectively

$$B = B'a \lesssim 3.0 \text{ T} \quad (6)$$

$$\phi = E'a^2/2 \lesssim 50 \text{ kV} . \quad (7)$$

In the original treatments of high current transport equations (1)-(3) were solved for I , a , and L as a function of the other parameters; this gave for magnetic lenses:

$$I = (2.89 \text{ MA}) \left(1 - \frac{\sigma_0^2}{\sigma^2} \right)^{4/3} \frac{\sigma_0^2}{\sigma^{2/3}} (\beta\gamma)^{5/3} \left(\frac{A}{q} \right)^{1/3} (\eta B \epsilon_n)^{2/3} , \quad (8)$$

$$a = (2.32 \text{ m}) \left(\frac{\sigma_0^2 \epsilon_n^2 A}{\eta B \sigma^2 q \beta\gamma} \right)^{1/3} , \quad (9)$$

$$L = (2.68 \text{ m}) \left(\frac{\sigma_0^2 \epsilon_n^2 A^2 \beta\gamma}{\eta^2 B^2 \sigma q^2} \right)^{1/3} , \quad (10)$$

with B given in Tesla, ϵ_n in meter-radians, and the tunes in radians.

In the earlier application of these formulas there was little sound basis for fixing the values of σ_0 and σ . The assumptions, $\sigma_0 \leq 90^\circ$ and $\sigma/\sigma_0 \geq 1/\sqrt{2}$ were made somewhat arbitrarily, although the factor $1/\sqrt{2}$ does correspond to an equal split between emittance and charge related forces in an envelope equation. For the HIBALL II parameters ($\beta\gamma = .325$, $A = 209$, $\epsilon = \epsilon_n/\beta\gamma = 3 \times 10^{-5}$ m-r), and setting $nB = 1.0$ T, we get $I = 1.29$ kA, which is close to the value reached by a beamlet in final focus (≈ 1.25 kA). In fact the current limit [Eq. (8)] does not actually apply in final focus, where the beamlets are expanded to large radii for the last 180° of phase advance before the reactor chamber is reached. However, it does apply, along with Eqs. (9) and (10) in the transport lines prior to final focus and the induction linac transport lattice. Several developments relating to the use of these transport limits since 1976 are described here:

- a. A near exact treatment of the matched envelope was obtained numerically and more recently, analytically.¹⁰ This is incorporated into the optimization code LIACEP.
- b. The stability of transverse beam modes, which depends on the values of σ_0 and σ , and the consequences of mode growth were examined with analytical calculations and PIC simulation.
- c. Experiments with the Single Beam Transport Experiment (SBTE) at LBL explored the consequences of a broad range of values of σ and σ_0 .
- d. Scaling laws for the continuous limit formulas point to possible large cost reductions for the driver linac.

5. SCALE LAWS FOR INCREASED CHARGE STATE

Heavy ion driver studies have for several years concentrated on the use of charge state $q = 1$ and the highest available mass ($A \geq 200$), however it has been noted that increased charge state may be desirable in order to lower linac cost and length.¹¹ It is clear that increased q or decreased A decreases the final cumulative acceleration potential required to reach a final given ion velocity, but it is less clear that, given the constraints of transportable current and range in the target, this is a useful path to take. Examination of Eqs. (5)-(10) shows that increased q and decreased A are equivalent as regards transport for given V . The differences are in the availability of good sources and range in the target at fixed final velocity.

For ion range in the target the situation is clear: at $\beta \approx .3$ an ion of mass number $A = 100$ has about twice the range as an ion of mass number 200. Other things being equal the doubled range would halve the specific energy deposition, and to achieve equal target gain the spot radius would need to be decreased approximately by $\sqrt{2}$.

The only heavy ion sources available at present which can be readily adapted to driver requirements are the contact ionization of Cs and the Mercury vapor arc. However, the metal vapor vacuum arc (MEVVA),¹²

where we assume $\sigma_0 = 90^\circ$, $\sigma \ll \sigma_0$, and $\eta = 1/2$. Hence electric current increases only as $q^{1/2}$, and we are lead to consider a large number of beamlets of small radius, which are merged for the magnetic transport lattice.

The high energy transport and final focus lines may have reduced costs per line for increased charge state since rigidity varies inversely with q . However, this savings is likely to be offset by an increase in the number of lines required to avoid exceeding space charge limits in the final focus and reactor. A rough measure of the minimum number of beamlines is obtained from an examination of the beam envelope equations in vacuum, neglecting all effects except that due to space charge:

$$\frac{d^2 a}{ds^2} = \frac{Q}{a} , \quad (13)$$

where Q is the dimensionless perveance:

$$Q = \frac{2I(4\pi\epsilon_0 c^2)^{-1}}{(\beta\gamma)^2 [B\rho]} . \quad (14)$$

The minimum radius resulting from Eq. (13) is

$$r = a_{\text{lens}} \exp(-\theta^2/2Q) . \quad (15)$$

where $a_{\text{lens}} = L\theta$. For a power reactor we expect $L \sim 5\text{-}10\text{ m}$, $\theta \sim 10\text{-}20\text{ mr}$, and 2-4 mm spot size. To make the influence of space charge negligible we therefore require, in the absence of neutralization,

$$Q \lesssim (.1) \theta^2 , \quad (16)$$

This condition leads to unacceptably large numbers of beamlets when the charge state exceeds $q = 2$ or 3, so some degree of neutralization must be invoked in general. The figure adopted in the HIF System Assessment is 90% neutrality, either from ionization of residual gas or co-injected electrons. We then have the condition

$$Q \lesssim (2.25 \times 10^{-4}) (\theta/15\text{ mr})^2 . \quad (17)$$

HIBALL II, with $Q = 1.1 \times 10^{-5}$ and $\theta = 10\text{ mr}$ easily meets this condition without invoking neutralization. In general for fixed total power P (summing over N beamlets), perveance per beamlet varies as

$$Q \propto \frac{Pq^2}{N(\beta\gamma)^5 A^2} , \quad (18)$$

so the condition (17) becomes very restrictive for $q \gtrsim 4\text{-}5$.

which produces copious ions of high brightness in a range of charge states for all metals, is undergoing an impressive development and may be considered as a possible future driver source. The main problem in adaptation appears to be the removal of unwanted charge states from the beam pulse before introduction into the induction linac.

We assume here that the highest mass ions will be used due to their short range, and that charge state can be increased arbitrarily until some transport or focal limit is reached. If σ/σ_0 is small, so that the factor $(1-\sigma^2/\sigma_0^2)$ in Eq. (8) can be replaced by unity, then the following scale relations are found for $q \rightarrow q'$:

At each value of voltage V ,

$$q \rightarrow q' \quad \alpha q, \quad (11)$$

$$V \rightarrow V, \quad a \rightarrow a, \quad nB \rightarrow nB, \quad \epsilon_n \rightarrow \epsilon_n, \quad \sigma_0 \rightarrow \sigma_0,$$

$$I \rightarrow \alpha I, \quad \tau_p \rightarrow \tau_p,$$

$$E \rightarrow \alpha E, \quad B\gamma \rightarrow \alpha^{+1/2} B\gamma,$$

$$\sigma \rightarrow \alpha^{-3/4} \sigma, \quad L \rightarrow \alpha^{-1/4} L,$$

$$\text{volt-sec/m} \rightarrow \text{volt-sec/m}.$$

The significance of this transformation is that the transported power is increased by the factor α at given V with very little change in the transport lattice. Only the half period has been decreased by the small factor $\alpha^{-1/4}$. The big change is that the depressed tune σ is decreased by the factor $\alpha^{-3/4}$. A discussion of tune limits is given in Section 6.

There are many possible linac configurations for a given value of q ; the low cost optimum is found by LIACEP. One attractive possibility (not optimal) is found by simply applying the transformation [Eq. (11)] to a known configuration with $q = 1$, raising its charge to $q = \alpha$ and eliminating the high voltage portion of the linac so that the final kinetic energy is unchanged. This procedure is expected to yield incremental cost savings for the main portion of the linac of $\sim 28\%$ for each doubling of q , and in fact LIACEP verifies this approximate cost scale. A five Megajoule induction linac driver with output similar to HIBALL II is predicted to cost ~ 1.5 G\$ accelerating charge state +1 and $\sim .8$ G\$ accelerating charge state +4 (1986 dollars). This price does not include the first 50 MV or the final transport and focus lines. The cost of these components is not expected to improve with higher charge state.

At low voltage ($V < 50$ MV) the current that can be conveniently transported with superconducting quadrupoles is low, and the use of electrostatic quadrupoles is preferred. Unfortunately, the scale law for increased charge state is not attractive for this form of transport. It is found that the electric line charge density per meter is limited by the value¹⁰

$$\lambda \lesssim \left(.6 \frac{\mu C}{m} \right) \frac{\phi(a)}{50 \text{ kV}}, \quad (12)$$

6. LIMITS ON TUNE

As mentioned, in the early work on transport limits Maschke adopted the values $\sigma_0 = 90^\circ$ and $\sigma/\sigma_0 = 1/\sqrt{2}$. In fact, it is not immediately apparent from Eqs. (8)-(10) that a higher allowed value of σ_0 and lower allowed σ will result in lowered accelerator costs since the beam radius is also increased as the current increases. If the half period is eliminated between Eqs. (1) and (2) we get the suggestive result

$$I = \frac{(\beta\gamma)^2}{8} 4\pi\epsilon_0 c^2 a \sigma_0 n B, \quad (19)$$

which shows current to be independent of σ and proportional to σ_0 for fixed a , n , and B . Hence it is good to raise σ_0 as high as possible. The corresponding value of depressed tune is given by

$$\sigma = \frac{2\epsilon_n}{a^{3/2}} \left(\frac{Mc\sigma_0}{\beta\gamma q e n B} \right)^{1/2}, \quad (20)$$

and a lower allowed value for σ permits either a lower normalized emittance or increased q/M .

Since the work of Maschke there have been several developments in the understanding of tune limits, which now stand at the values $\sigma_0 \leq 80^\circ$, $\sigma/\sigma_0 > .1$; a brief summary of part of this work is given here:

- a. Analytical calculations¹³ showed that the Kapchinsky-Vladimirsky (K-V) distribution of phase space variables is unstable in stop bands depending on σ and σ_0 . Perturbations of order n in the radial coordinate are potentially unstable for $\sigma_0 > 180^\circ/n$. Simulation studies^{13,14} supported this point by demonstrating the onset of the third order and second order (envelope) modes with characteristic phase space distortions. To stabilize these modes the conditions $\sigma_0 \leq 60^\circ$, $\sigma \geq 24^\circ$ were adopted for driver studies during the period 1981-84.
- b. Simulation studies performed with realistic (non K-V) distributions [by I. Haber and C. Celata] have shown little evidence of unstable mode growth for $\sigma/\sigma_0 > .1$ and $\sigma_0 < 80^\circ$. The principle diagnostic is the growth of emittance. This empirical result may be the consequence of the detuning effect of the slightly rounded charge profile of the non-KV distributions, which could damp modes higher than $n = 2$ (the envelope equations and modes are nearly independent of distribution details).
- c. Recent simulation work¹⁵ has considered the effects of both images and higher order focal multipoles which are always present to some degree. For large amplitude oscillations of the beam's centroid, the image forces are

found to drive a coherent internal sextupole mode, resulting in emittance growth for $\sigma/\sigma_0 \lesssim .1$ and moderate values of σ_0 (60° - 72°). This effect can be largely cancelled by the addition of dodecapole elements of appropriate magnitude.

- d. High current transport experiments (SBTE) performed at LBL¹⁶ with a coasting 160 kV C_3^+ beam focussed by an electrostatic FODO lattice yield the phenomenological rule for stability (M. Tiefenback):

$$\omega_p \leq \frac{1}{3} \omega_L , \quad (21)$$

where ω_p is the plasma frequency within the pulse and

$$\omega_L = \frac{2\pi\sigma_0 v}{2L} \quad (22)$$

is the lattice frequency. This condition may be written

$$\sigma_0^2 - \sigma^2 < (85^\circ)^2 . \quad (23)$$

A plot of recent results from this experimental program is given in Fig. (1) along with the stability boundaries predicted for the envelope mode. Finite beam emittance prevents experimental conclusion being made for very low tune values ($\sigma \lesssim 8^\circ$ at $\sigma_0 = 60^\circ$). There is no really good theoretical understanding of this observed stability boundary at present, but simulation study continues to probe it.

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Experimental limits on beam stability in terms of σ and σ_0

Fig. 1. Zones of predicted and observed instability are depicted in the (σ, σ_0) plane). The cross hatched area corresponds to the unstable envelope mode predicted for the KV distribution. Data points (except for those on the lower broken line) indicate the onset of emittance growth or disruption as σ_0 is increased, with the phenomenological fit $\omega_p = \omega_L/3$ given by the dotted line. The zone below the lower broken line is inaccessible due to the nonzero emittance of the SBTE pulse. (Courtesy of M. Tiefenback)

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