Some Applications of the Kinetic Tandem Concept

Richard F. Post

Lawrence Livermore National Laboratory

In searching for better approaches to magnetic fusion there are important guidelines from past research

- Axially symmetric magnetic fields eliminate cross-field plasma transport effects that arise in non-symmetric fields from “resonant” particle drifts.
- Magnetic fields with positive field-line curvature suppress MHD instabilities.
- Open-ended systems can confine plasmas in turbulence-free states.
- In open-ended systems the radial boundary of the plasmas can be far from material surfaces, thereby eliminating turbulence caused by radial temperature gradients and plasma sheath effects.
- Axial confinement of ions and electrons by ambipolar potentials (as in the tandem mirror) is effective and is well understood theoretically.
- The feasibility of employing direct conversion to enhance the efficiency of open-ended fusion systems has been demonstrated in the laboratory.

Since earliest days open-ended systems have achieved plasma losses that agree closely with classical rates

- In early hot-electron plasmas in mirror systems radial transport five orders of magnitude slower than Bohm rates were observed.
- In long open-ended theta pinch experiments classical radial transport rates were observed
- In the 2XIIB experiment at Livermore stable high-beta plasmas were created that had particle losses that agreed with classical rates.
- In the Gamma 10 Tandem Mirror at Tsukuba, axial confinement times were observed in agreement with theory, and drift modes were suppressed by control of the radial distribution of the plasma potential
- In the the Gas Dynamic Trap (an axially symmetric mirror experiment) at Novosibirsk, stabilization of MHD modes in agreement with theory was observed, and the plasma containment agreed with classical theory.

Open systems can attain “infinite” confinement time for trapped particles in the absence of turbulence effects

- In axially symmetric open systems the existence of the adiabatic invariants μ and J (magnetic moment and longitudinal action integral) insures that trapped particles remain on closed drift surfaces, so that their cross-field diffusion is not enhanced *á priori* over Spitzer (classical) rates in the absence of turbulence
- The classic example of the power of these invariants was the ARGUS experiment of Christofilos that produced an artificial “Van Allen Belt” of trapped electrons, still detectable a decade later.

In “Table Top” at LLNL (1960) plasma radial diffusion rates were 5 orders of magnitude below Bohm rates*

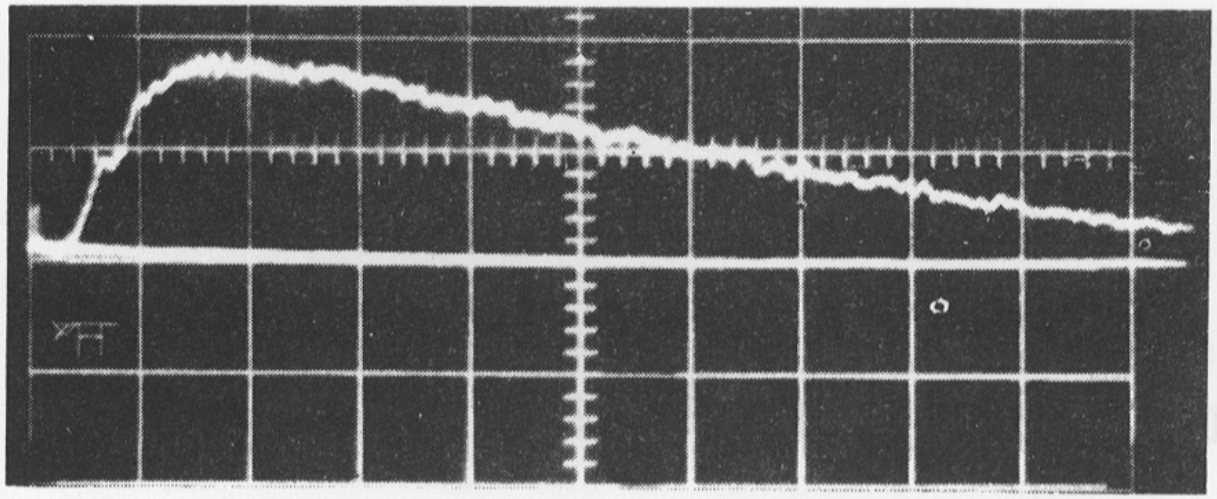


FIG. 1. Typical oscilloscope trace of a scintillator photometer signal – sweep time 5 milliseconds.

* R.F. Post, R. E. Ellis, F. C. Ford, M. N. Rosenbluth, “Stable Confinement of a High-Temperature Plasma,” Phys. Rev. Lett. 4, 166 (1960)

In the Table Top 20 keV “hot electron” plasmas there was no evidence of non-classical cross-field transport

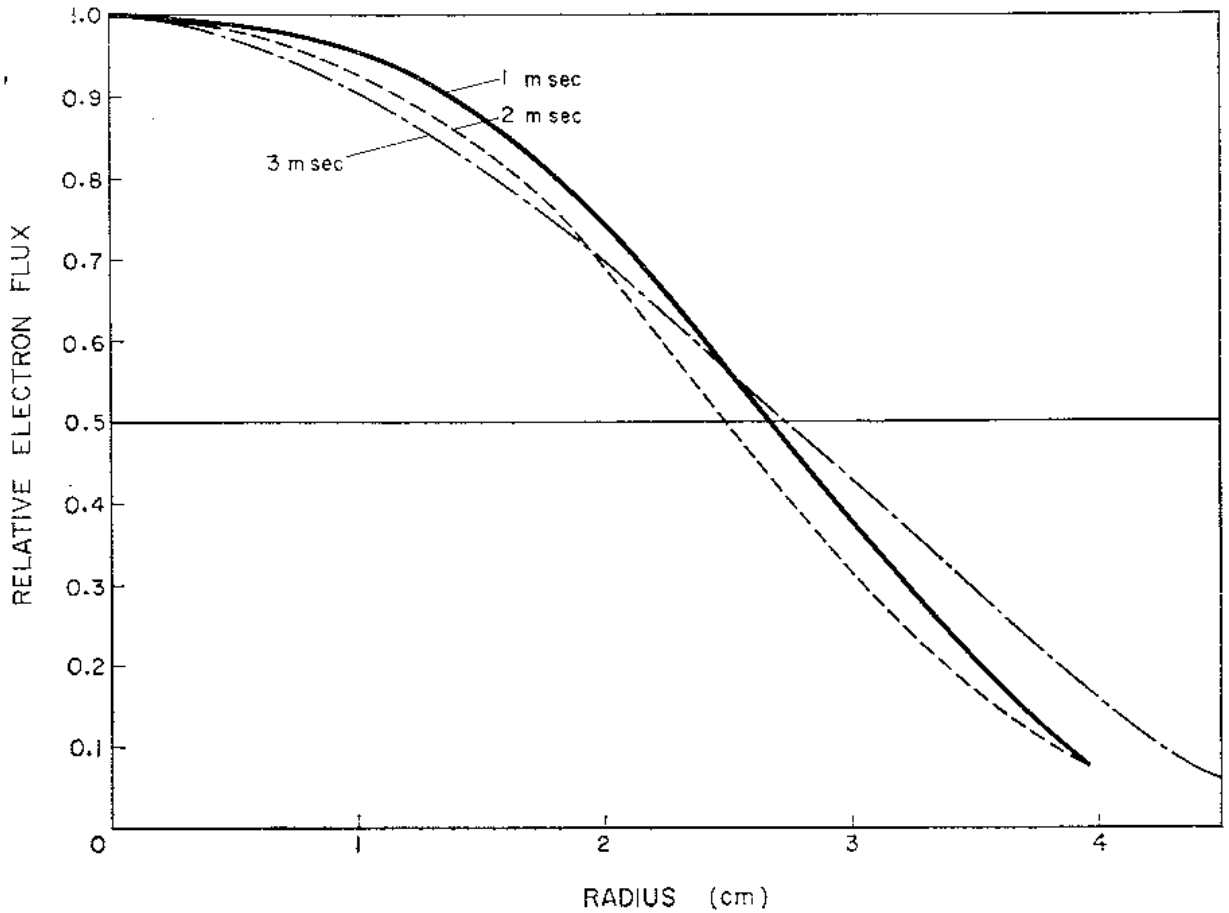
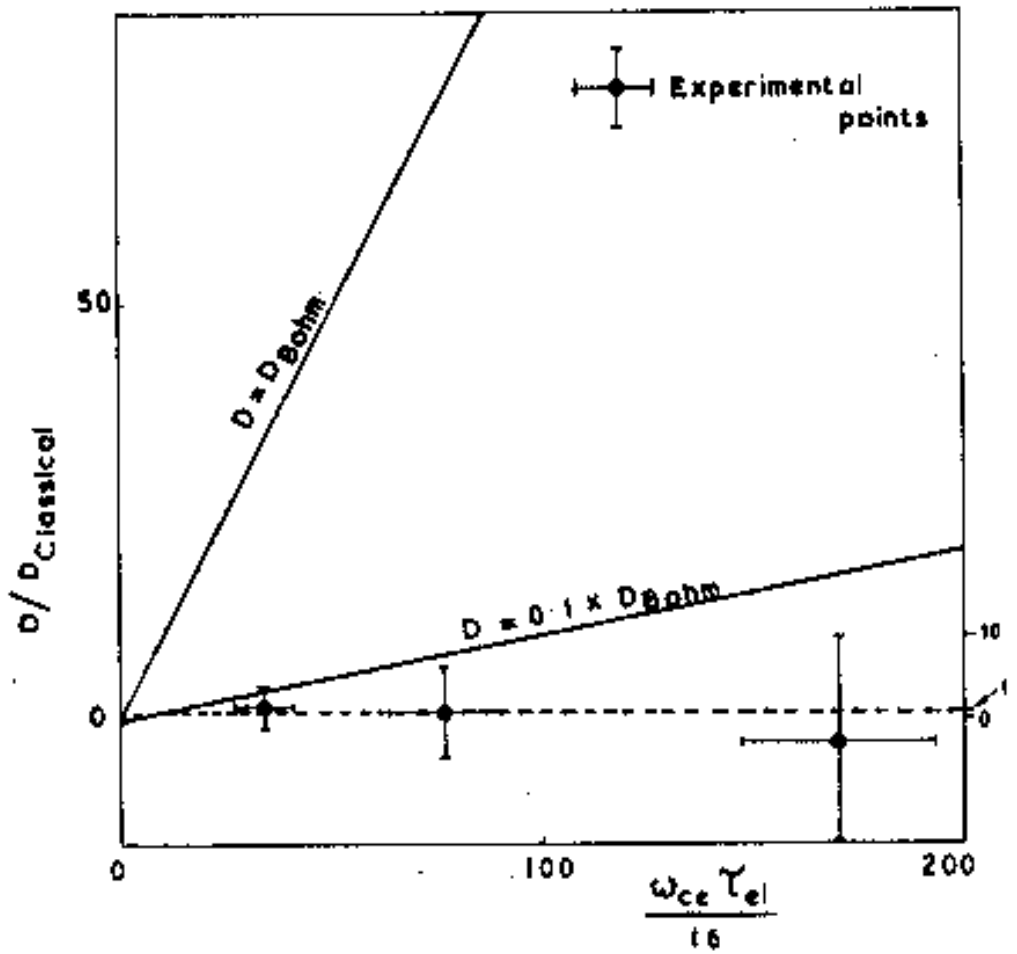


FIG. 11. Normalized radial distribution of plasma as a function of time.

Plasma parameters (approx.): kTe = 20 keV, B = 1.0 Tesla

In the 8-meter theta pinch experiment at Culham in 1968 classical cross-field diffusion was observed



In the Gas Dynamic Trap at Novosibirsk, plasma ion and electron containment agrees with classical theory

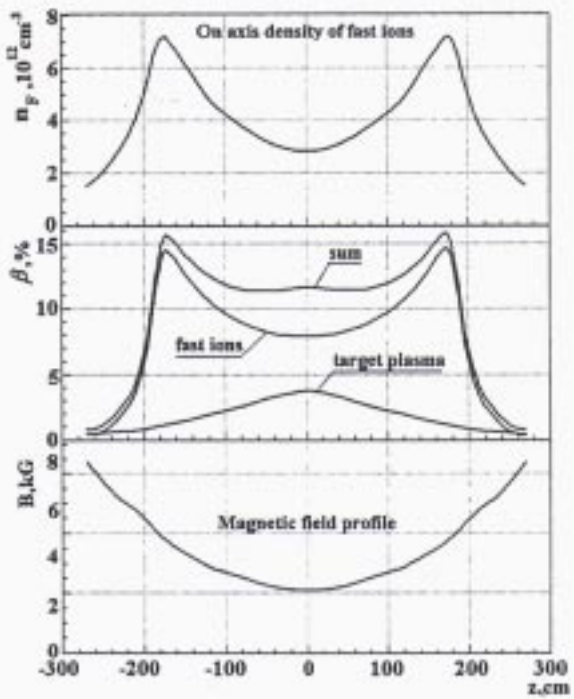
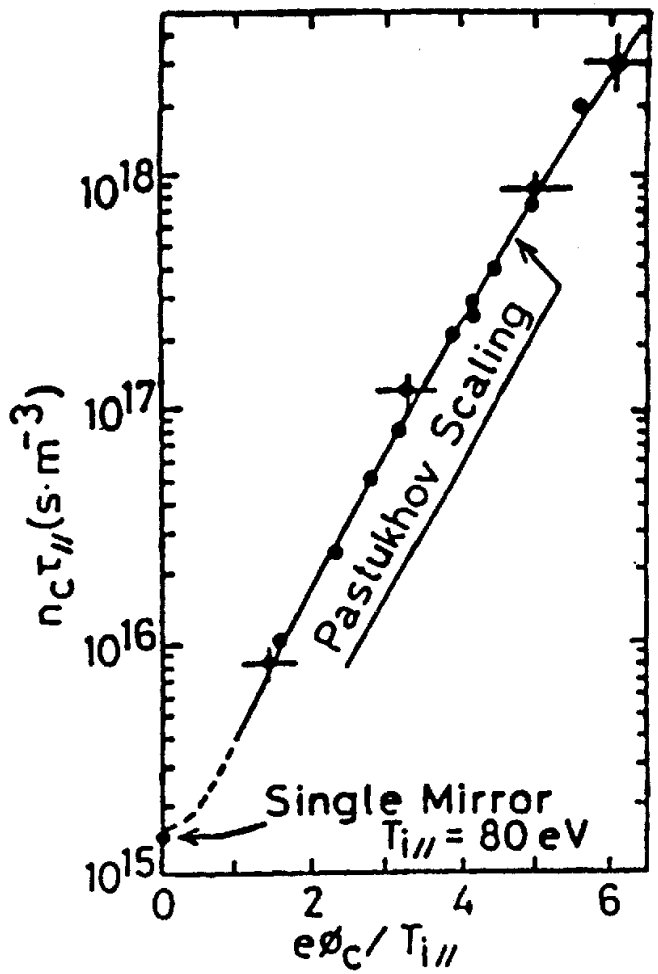


Fig. 4 Simulated longitudinal profiles of β and fast ion density

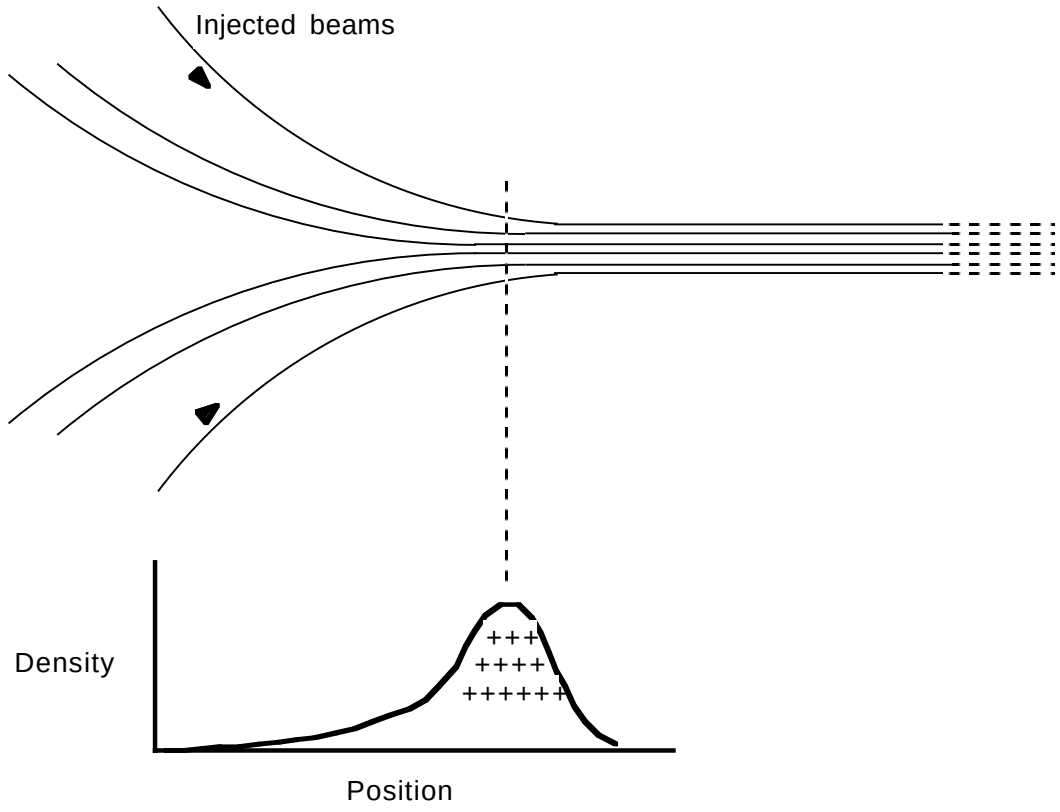
"The comparison between the measured and the calculated energy contents of the fast ions shows that within the accuracy of measurements the experimental and simulated data are identical."

P. A. Bagryansky, et. al., "Recent Results of Experiments on the Gas Dynamic Trap," Transactions of Fusion Technology, Vol. 35, p. 79 (January 1999)

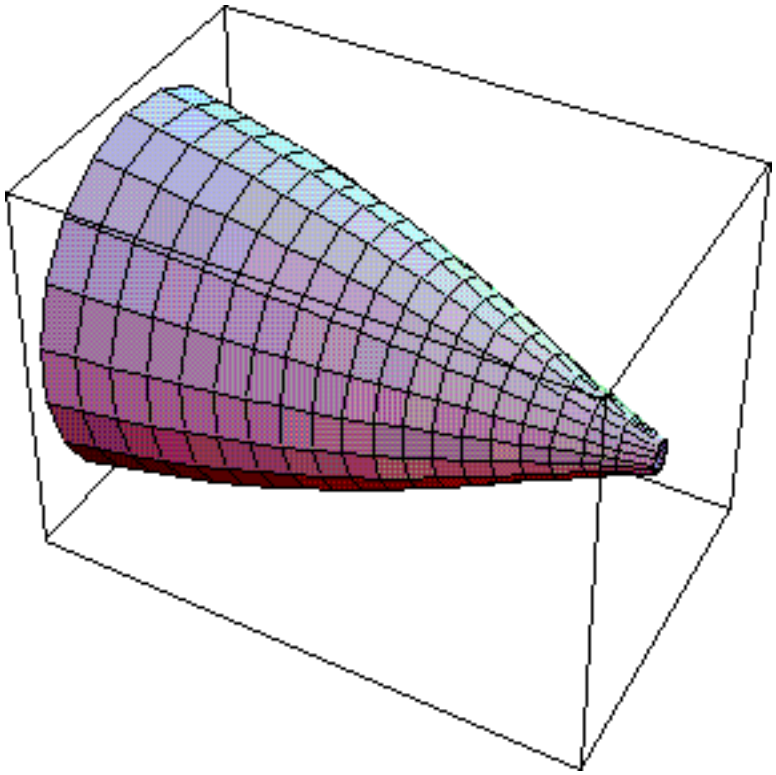
The axial confinement in the Gamma 10 tandem mirror agrees closely with Pastukhov/Cohen theory

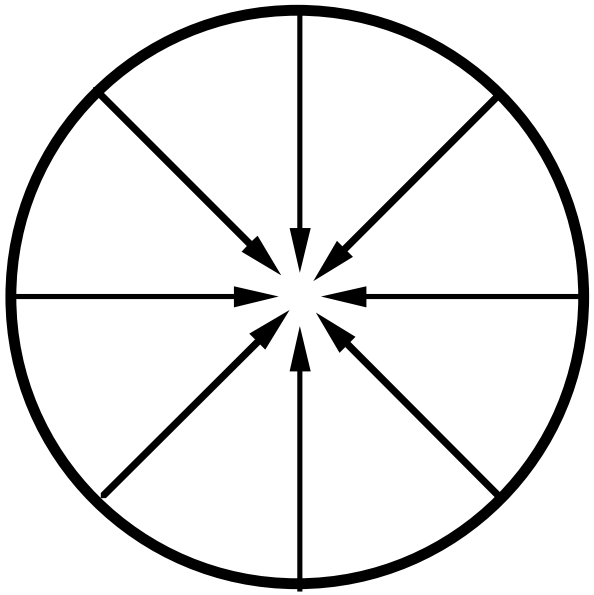


The potential barriers in the kinetic tandem are made by the magnetic compression and reflection of ion beams



Inward ion motion in a converging magnetic field is analogous to compression by spherical convergence

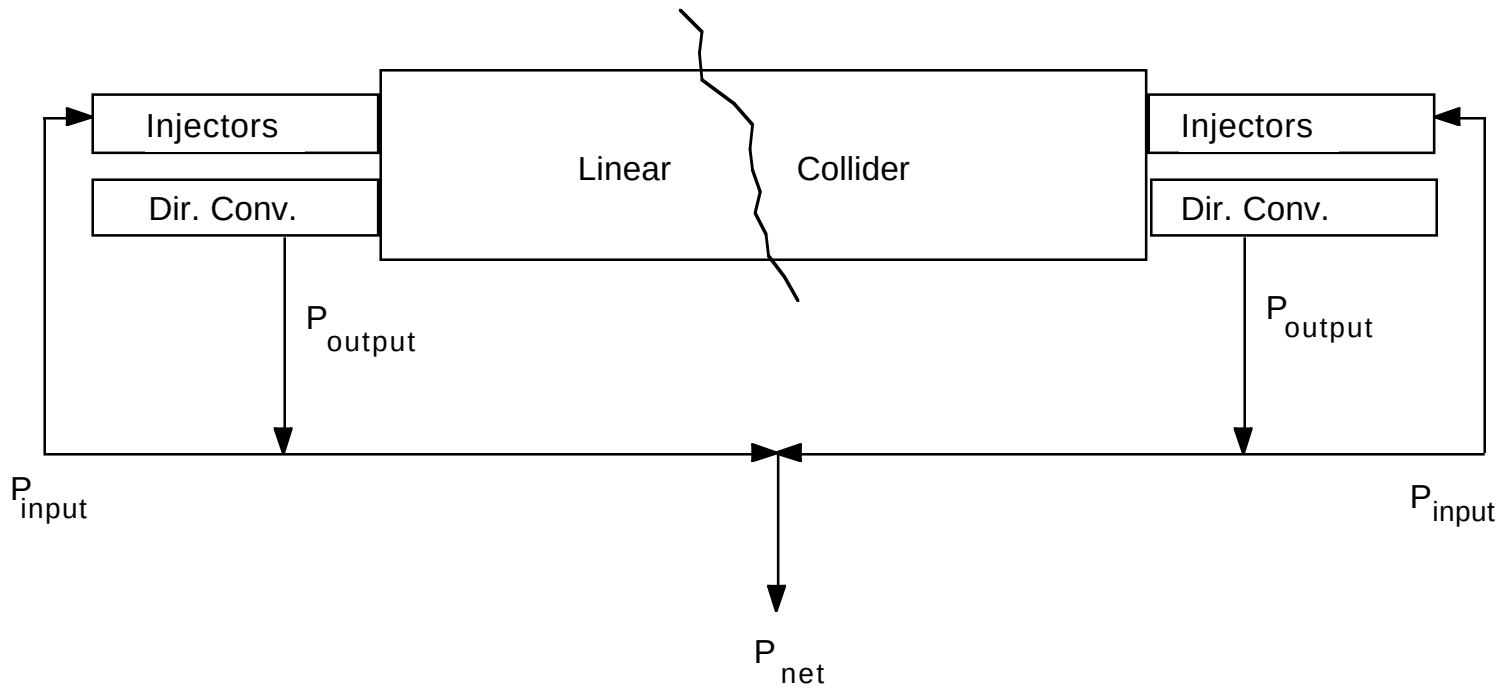




Our motivation for investigating the kinetic tandem: the need for simpler and less expensive fusion systems.

- Simplify the magnetic field geometry, at the same time assuring MHD stability of the confined plasma.
- Transfer as much as possible of the research burden from complex confinement and stability issues to well-defined technological goals.
- Take advantage of the well-documented physics of potential confinement in open-ended systems.
- Investigate systems that are open to innovative improvements.

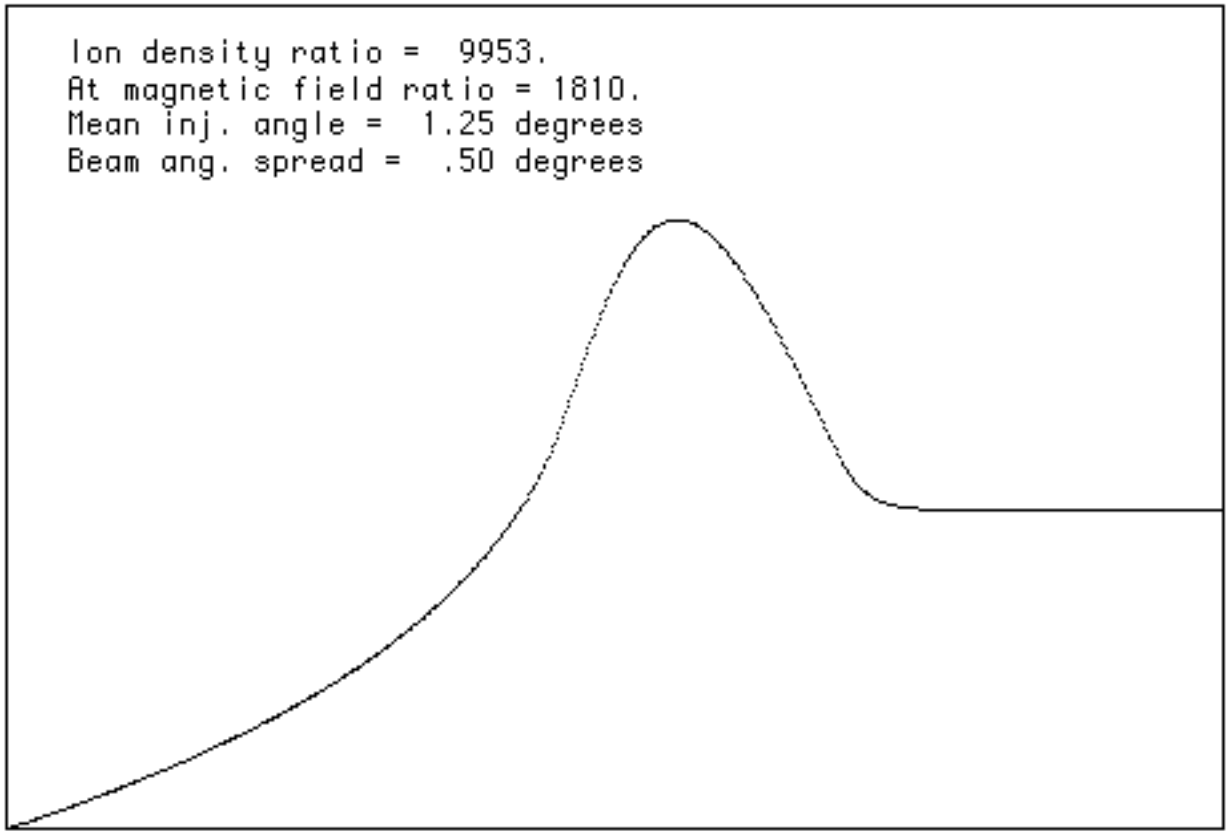
High-efficiency direct converters and ion injectors could be employed in fusion “linear colliders”



Achievement of high efficiency in the injectors and the direct converters would allow the production of net fusion power with minimal confinement requirements

The Large Electron Positron Collider (LEPC) at CERN is in a 27 kilometer tunnel 100 meters underground

Tandem mirror plug densities have been calculated analytically and simulated using the LLNL ICEPIC code



Density Ratio

Axial Position (on linearly increasing B field)

R. F. Post, “Mirror-Based Fusion: Some Possible New Directions,” Transactions of Fusion Technology, **35**, 40 (January 1999)

We have made preliminary studies of alternative forms of kinetic tandem fusion power systems

- High-beta systems would minimize the area of the flux-bundles to be plugged relative to the volume of the fusion plasma, thus improve the power balance.
- The power-balance scaling laws favor high plug densities and higher atomic number plugging ions, injected at lower energies.
- The kinetic tandem potential plugging concept may permit the practical implementation of a long-proposed field configuraton: the “cusp” magnetic field and its variants.

A long linear Kinetic Tandem open system could be used as a “two-ion-component” fusion power plant

- In the 1970’s studies were made of two-ion-component tokamaks and mirror systems predicting favorable fusion Q values.
- A long linear system with a moderate temperature “target” plasma into which magnetically compressed high-energy ion beams are injected represents another approach.
- The target plasma could be contained between the higher-density plugging plasmas in a Kinetic Tandem open-ended configuration.

A long linear Kinetic Tandem system could utilize axially symmetric fields with positive (stabilizing) field-line curvature throughout the containment region

The kinetic tandem plugs can sustain the parallel pressure of fusion-relevant plasmas

- Maximum parallel pressure of the plug:

$$P_{par}(\max) = \frac{1}{\sqrt{3\mu_0}}\left[j_0 M_i v_0\right]^{1/2} B(z) \quad N/m^2$$

- Example:

  Helium ions (A = 4)

  Current density, j_o = 3. A/cm^2

  Energy at injection: 20 keV

  B(z) = 10. Tesla

  p_{par} (max) = 1.8 x 10^5 N/m^2

This amount of parallel pressure is sufficient to balance the pressure of a 2.5 keV target plasma at an ion density of 2.0 x 10^{20} m^{-3}

In a sufficiently long kinetic tandem, the power needed for the plugs is small compared to the fusion power

$$\frac{P_{fusion}}{P_{plug}} = 2.02 \times 10^{-4} \left\{ \frac{G\alpha_T^{1/2}\,\eta Z A^{1/2} F}{\lambda_i^{3/2}\cos^2(\theta)} \right\} \left\{ \frac{\eta_{fus}}{(1/\eta_{inj}) - \eta_{dc}} \right\} L_0$$

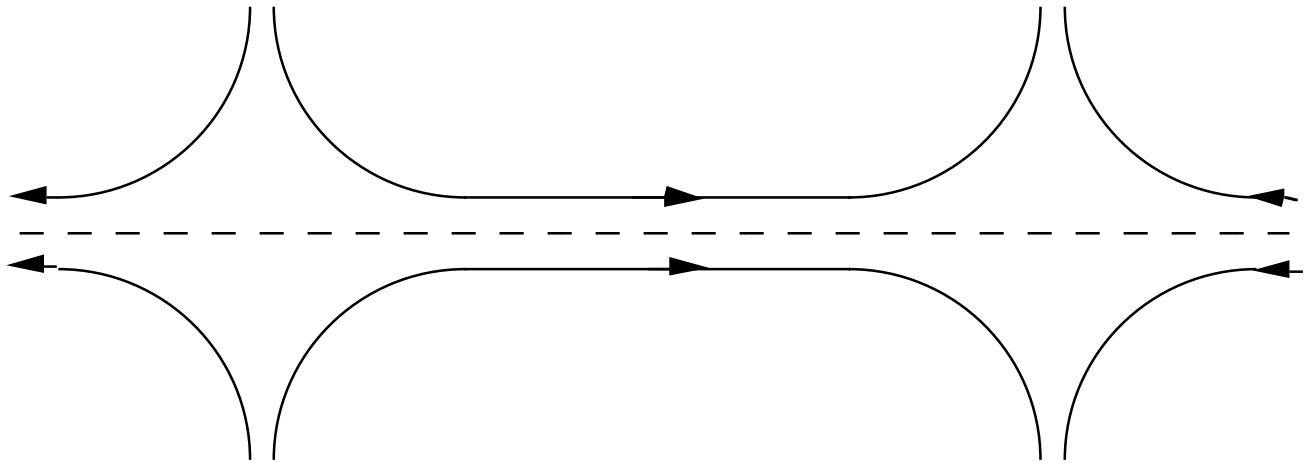
<u>Example</u>:

$\eta_{inj} = \eta_{dc} = 0.8$, $\eta_{fus} = 0.33$, $G = 0.5$, $\eta = 1.0$ (10 Tesla),

$Z = 3$, $A = 7$ (Lithium), $F = 4.0$, $\cos(\theta) = 0.5$, $\lambda_i = 1.0$ (10 keV)

At: $L_0 = 3 \times 10^4$ m., $\frac{P_{fusion}}{P_{plug}} = 70.4$

The kinetic tandem concept could be employed to plug the exiting flux lines of a double-cusp fusion system



High-beta kinetic tandem cusp systems could be a factor of ten or more shorter than long linear two-component kinetic tandems

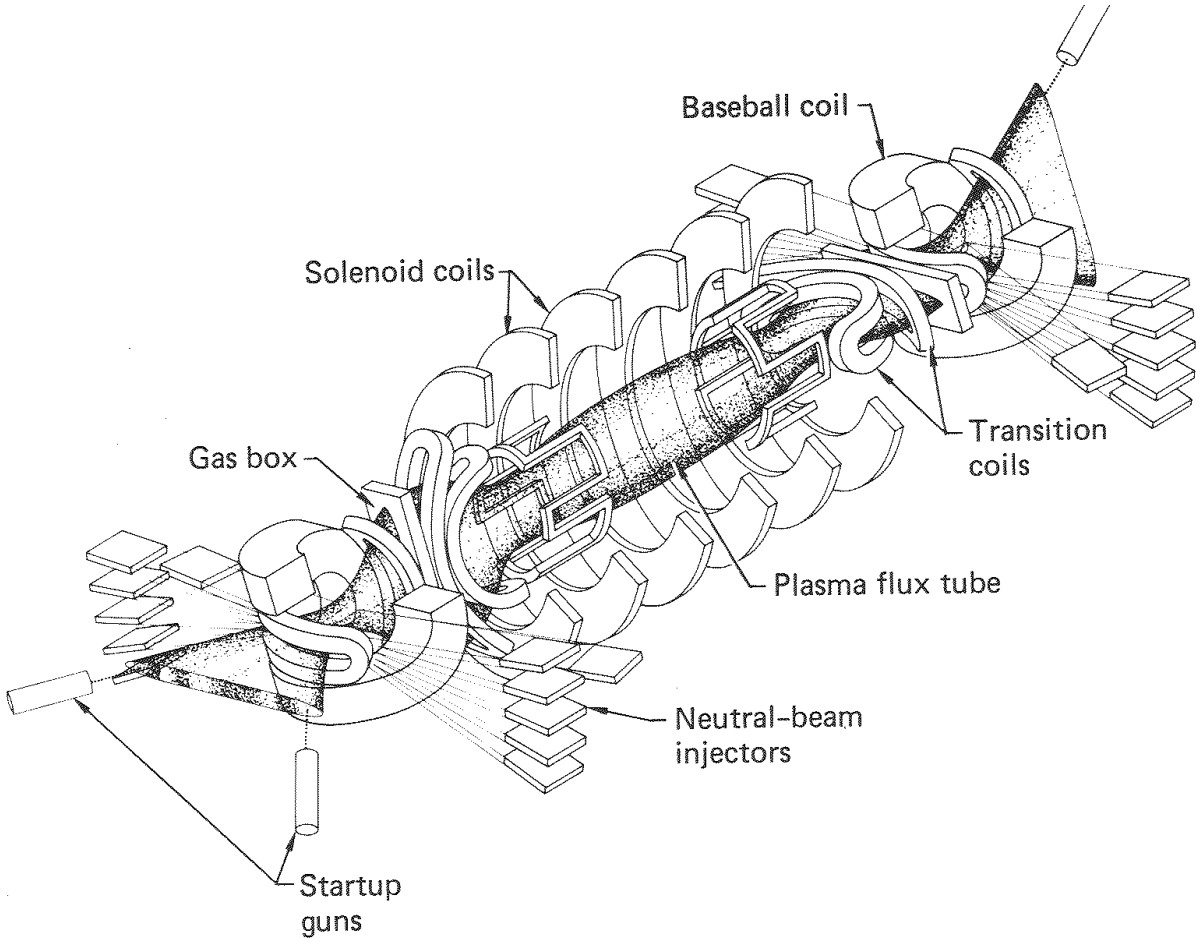
Kinetically produced potential peaks may have applications other than their use in a kinetic tandem fusion system.

- For the confinement of moderate-density plasmas to be used for "warm-plasma" stabilization of mirror-confined plasmas.
- To act as ionizers for neutral or molecular ion beams injected into the ends of mirror systems.
- To modulate the loss rates of ions from conventional tandem mirror systems as an aid to direct conversion or for use in ash removal.

Another possible use of the kinetic tandem plug concept is as an "MHD Stabilizer" for a T. M.

- Conventional Tandem Mirror systems require complex non-axisymmetric magnetic fields (with attendant particle losses) to insure MHD instability
- Theory (Ryutov, et. al.) predicts that in axisymmetric mirror fields a low-density plasma residing on the positive curvature field lines exterior to the mirrors can render an interior high-density plasma MHD stable.
- This theory has been confirmed experimentally in the axisymmetric Gas Dynamic Trap at Novosibirsk, for plasma pressures equivalent to $\beta = 30$ percent.

The original tandem mirror concept required non-axisymmetric magnetic fields to assure MHD stability

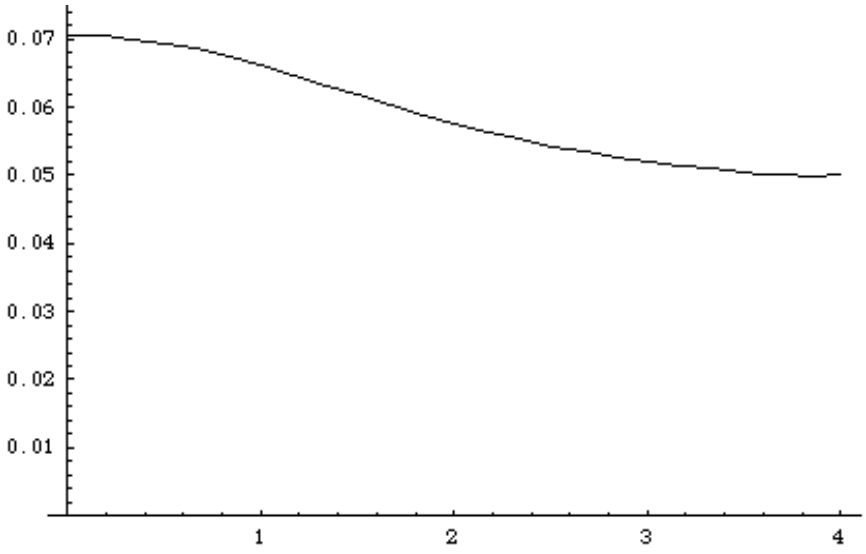


The quantitative requirement for MHD stabiliity of plasma in an axisymmetric mirror is given by the theory

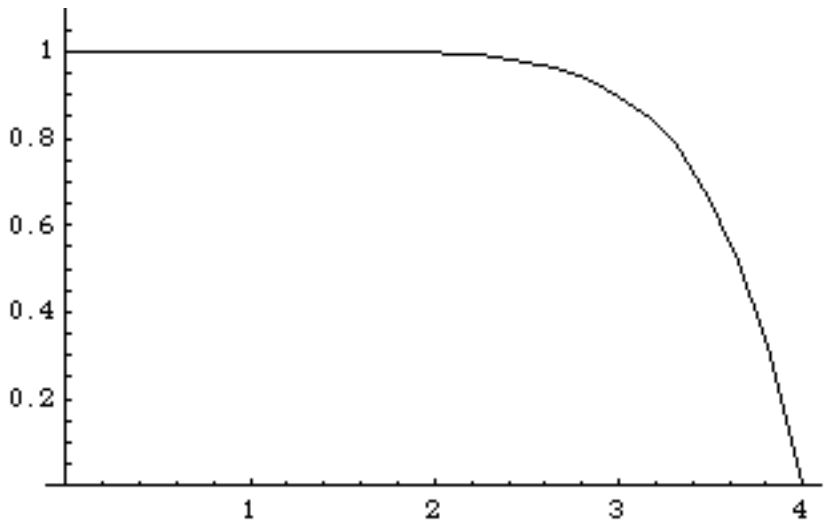
If the plasma boundary
is located at radius a, MHD
stability requires that

$$I = \int a^3 \frac{d^2a}{dz^2} \left[p_{/\!/} + p_{\perp}\right] dz > 0, \text{ stable}$$

As a first step we have evaluated the MHD stability integral for a plasma in an axisymmetric mirror field



Flux surface: Mirror ratio = 2.0



Plasma density distribution

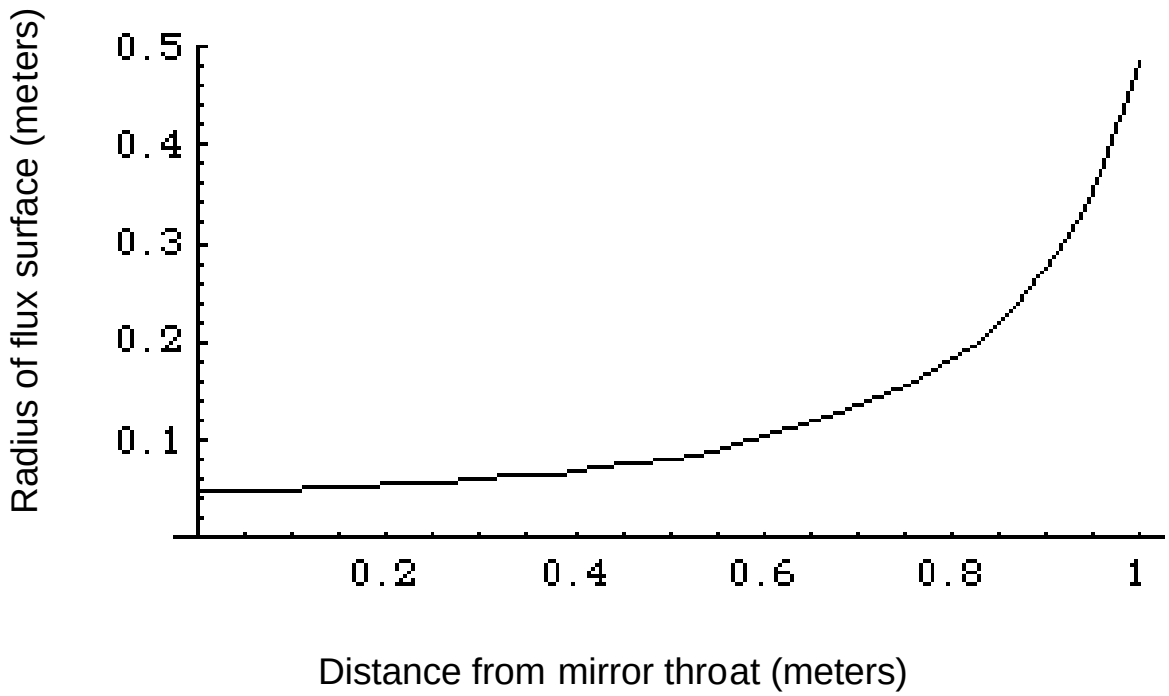
Stability integral for unit central pressure : $I = -1.730 \times 10^{-6}$

We have evaluated the MHD stability integral for a stabilizer plasma peaked outside the mirror throat

- Flux surfaces were calculated using the paraxial ray expansion of the fields
- The stabilizer plasma density peak was located on the flux surface in such a way as to maximize the value of the stability integral.
- Two different cases were considered:
  - Flux surfaces generated by a gaussian decrease of the field on axis
  - A conical flux surface followed by a transition to a curving flux surface defined by an arc segment

By locating the stabilizer plasma density peak optimally on the expanding field the stability integral is maximized

Flux surface for gaussian decay of field on axis



For a unit pressure plasma located between 0.9 and 1.0 m. I = +.1215

Based on Gas Dynamic Trap experimental results, stabilization of fusion plasmas at β = 0.30 is possible

Example of an axially symmetric tandem mirro fusion power system stabilized by end plasma

Plasma parameters

Central cell magnetic field: 5.0 Tesla

Plasma diameter: 14 cm., Plasma β = 0.3

D-T fuel: $T_i = T_e$ = 15 keV

$n_i = n_e = 6.2 \times 10^{20}\ m^{-3}$

Fusion power = 1.6 Megawatts/meter

The stabilizer plasma density is much lower than the central plasma, so that stabilizer beam power is low

<u>Stabilizer plasma parameters for the case of a gaussian flux expander</u>

$$\frac{nkT_{stab.}}{nkT_{central\ cell}} = \frac{1.73\times10^{-6}}{0.1215} = 1.42 \times 10^{-5}$$

Assume 1.0 keV Cs^{+} stabilizer plasma ions, $T_e << T_i$

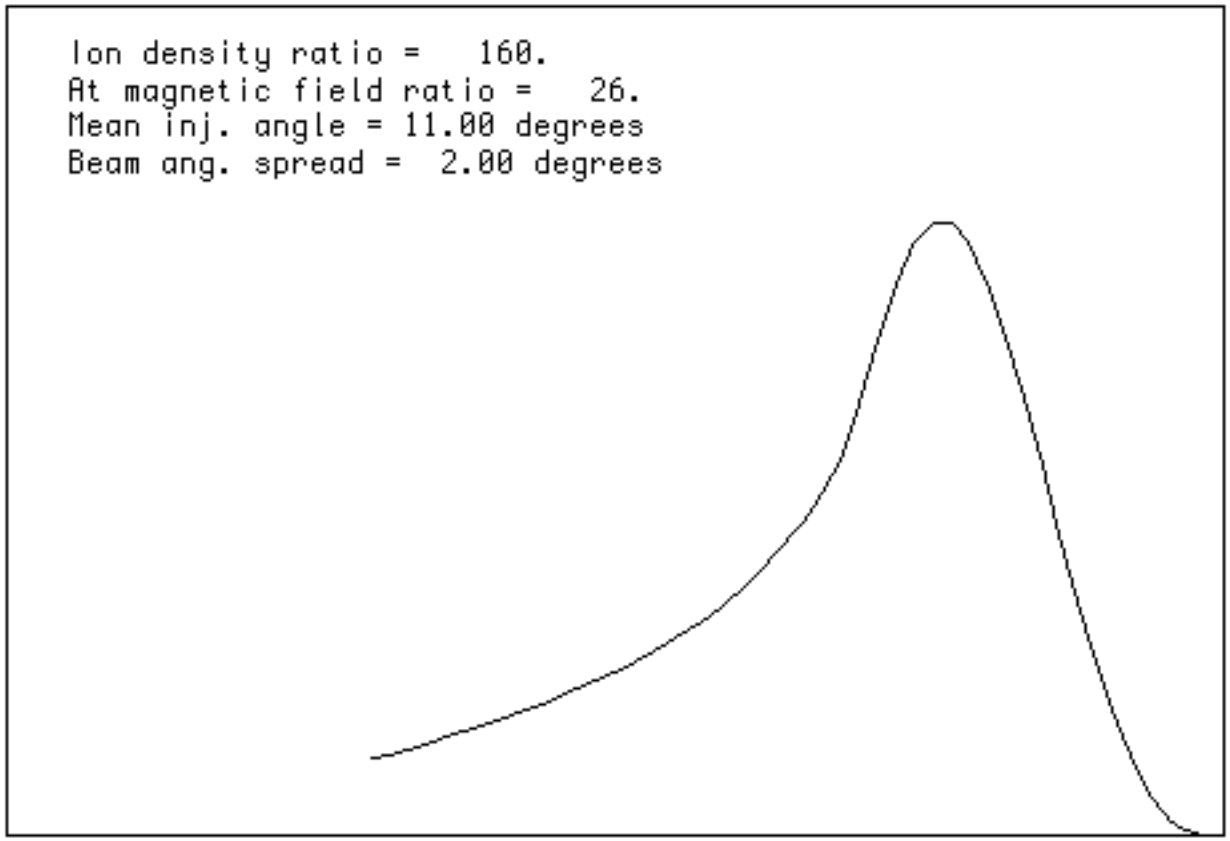
$$nkT_{stab.} = 1.42 \times 10^{-5} \times 2.98 \times 10^{6} = 42.4 \text{ Joules-m}^{-3}$$

$$n_{stab.} = 2.65 \times 10^{17}\ m^{-3}$$

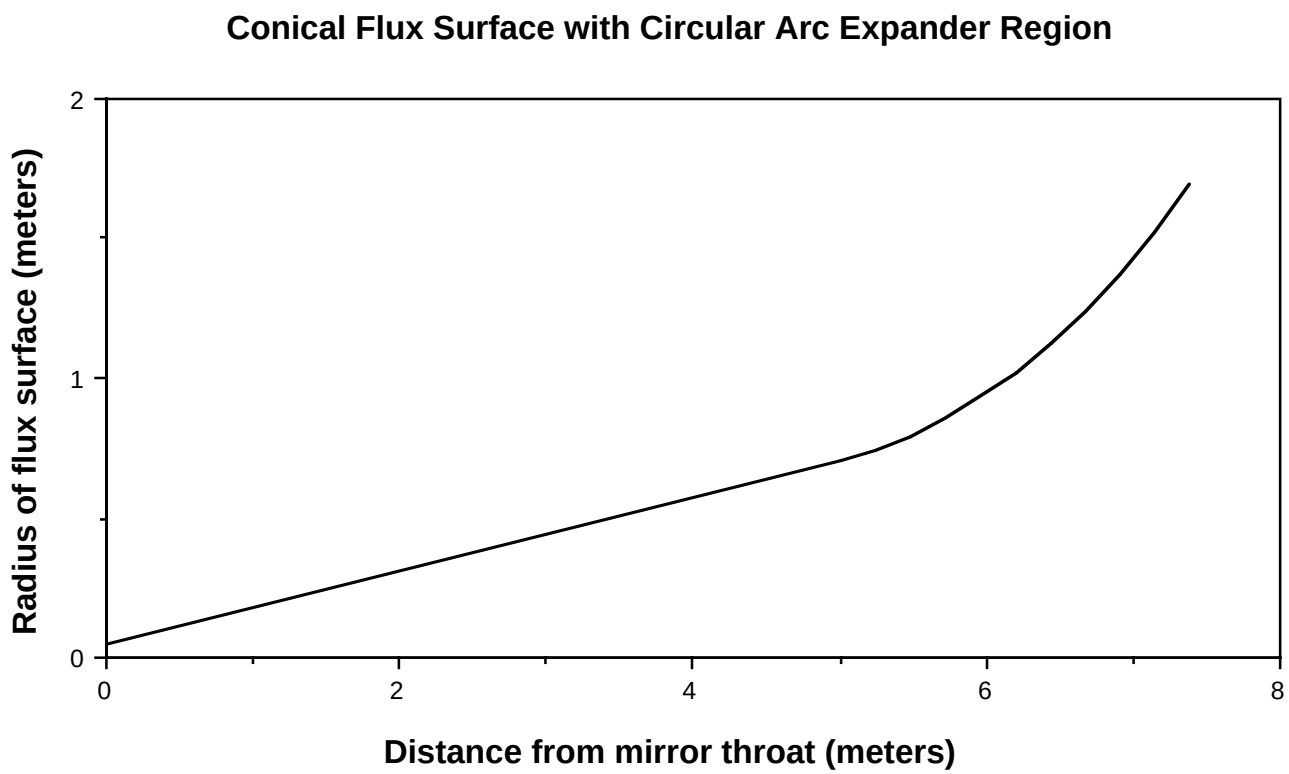
Beam density compression = 160 at $B/B_0 = 26$

Stabilizer beam power = 209 kW

Ions injected into the converging field at an angle to the field lines are compressed to form the stabilizing plasma



A conically expanding flux surface, followed by an outwardly curving surface,optimizes the stability integral



For a unit density plasma located between 5.0 and 7.4 meters I = +1.132

Summary and Conclusions

- The axisymmetric Gas Dynamic Trap experiment at Novosibirsk has demonstrated MHD stabilization of high-density central-cell plasmas at β values of 0.3 by low- density plasma in the positive curvature region of the magnetic field outside the mirrors.
- Mirror-reflected ion beams can be used to create potential plugs and/or to generate density peaks in field expanders to stabilize MHD interchange modes in axisymmetric mirror confining fields
- By optimizing the shape of the flux surface in the expanders, the density ratio between the central-cell plasma and the plasma in the expander can be made to be very large
- Fusion plasmas yielding Megawatts/meter can be stabilized with beams whose total power is of order 100's of kilowatts