Copy of Viewgraphs Presented on State of Tandem Mirror Physics – 1992

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Status of Tandem Mirror Research

-1992-

by

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December 17, 1992

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Tentative Schedule of Presentations on "The Status of Tandem Mirror Research-1992"

Thursday, Dec. 17, 1992

Time	Subject	Presenter
9:00 AM	General Comments and Introductions	Komarek
9:10	Introduction and Conclusions	Kulcinski
9:30	State of Art of TM Physics-1986	Santarius
10:15	Break	
10:30	Progress in Physics Since 1986	Santarius
11:00	Implications For TM Power Plants	Kulcinski
11:15	Critical Experiments For the 1990's	Emmert
11:40	Recommendations and Conclusions	Emmert
12:00	Open Discussion	
12:30	Lunch	
2:00-4:00	Open for Continuing Dialog	FPA Group
4:00	Depart KfK Lab	FPA Group

Tasks For Present Study:

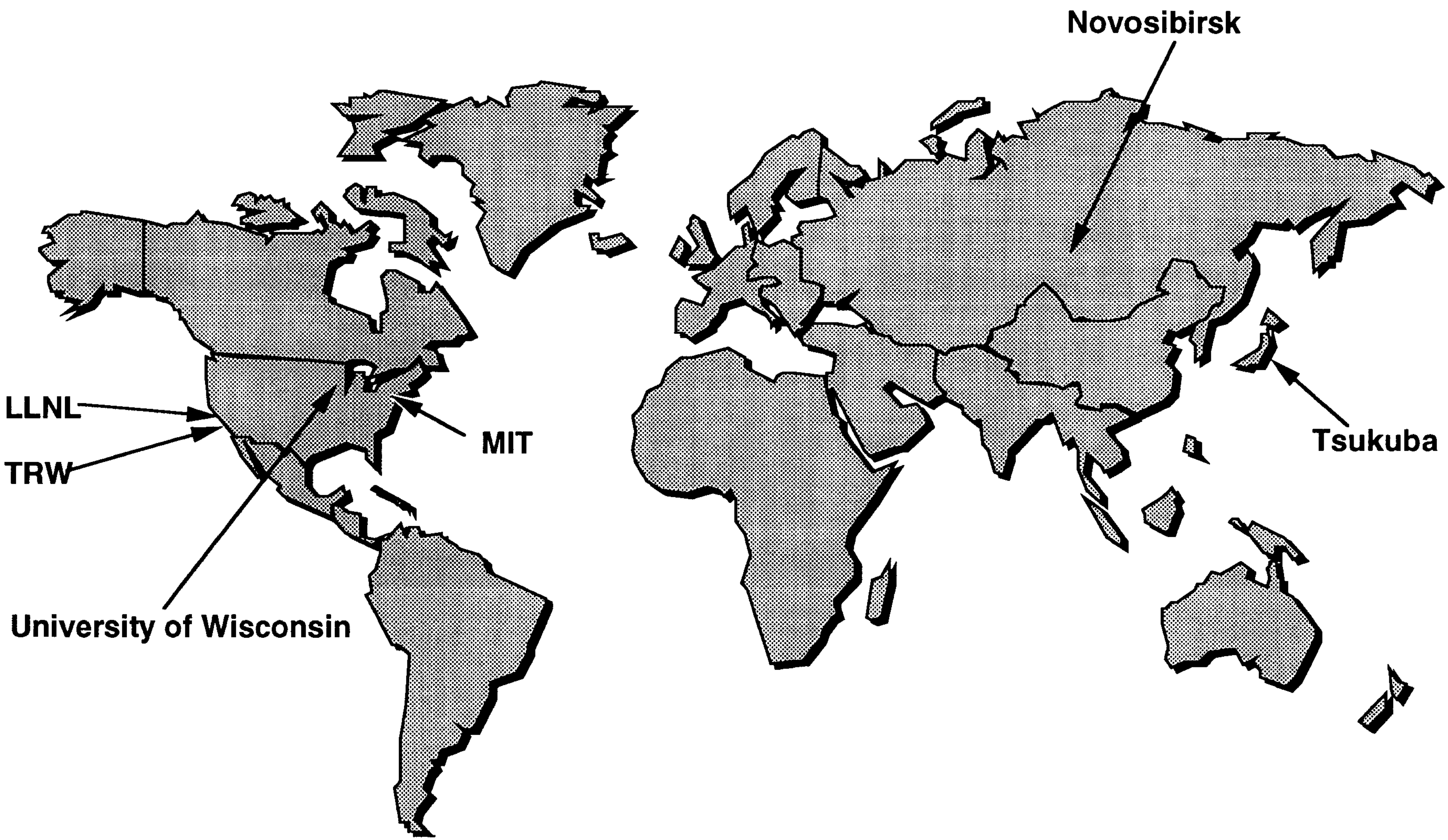
- An Assessment of the State of Tandem Mirror Physics at the Time of the MFTF-B Cancellation.

- Progress in Tandem Mirror Physics Since the MFTF-B Cancellation.

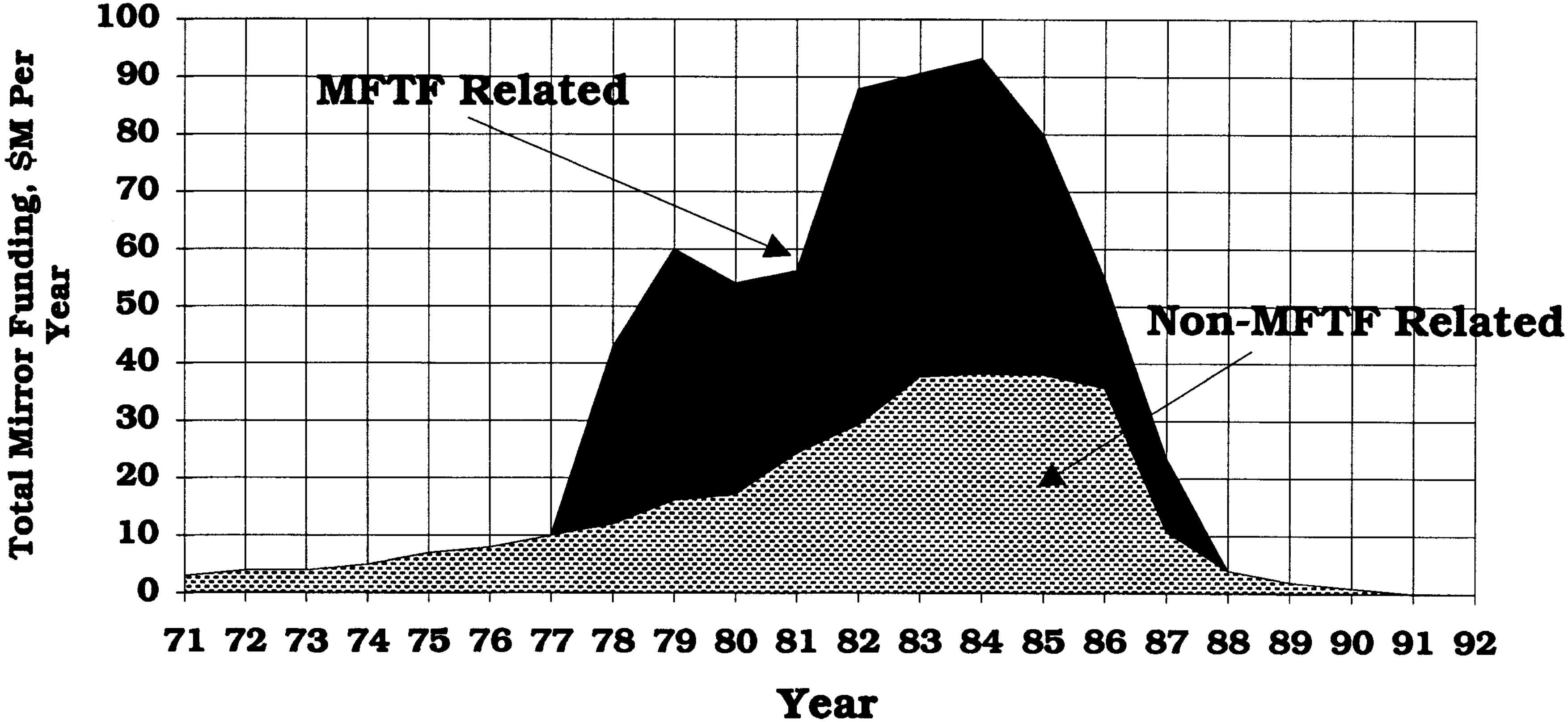
- What Would a Tandem Mirror Reactor Designed Today Look Like?

- What Critical Experiments Are Needed to Revive the Tandem Mirror Program?

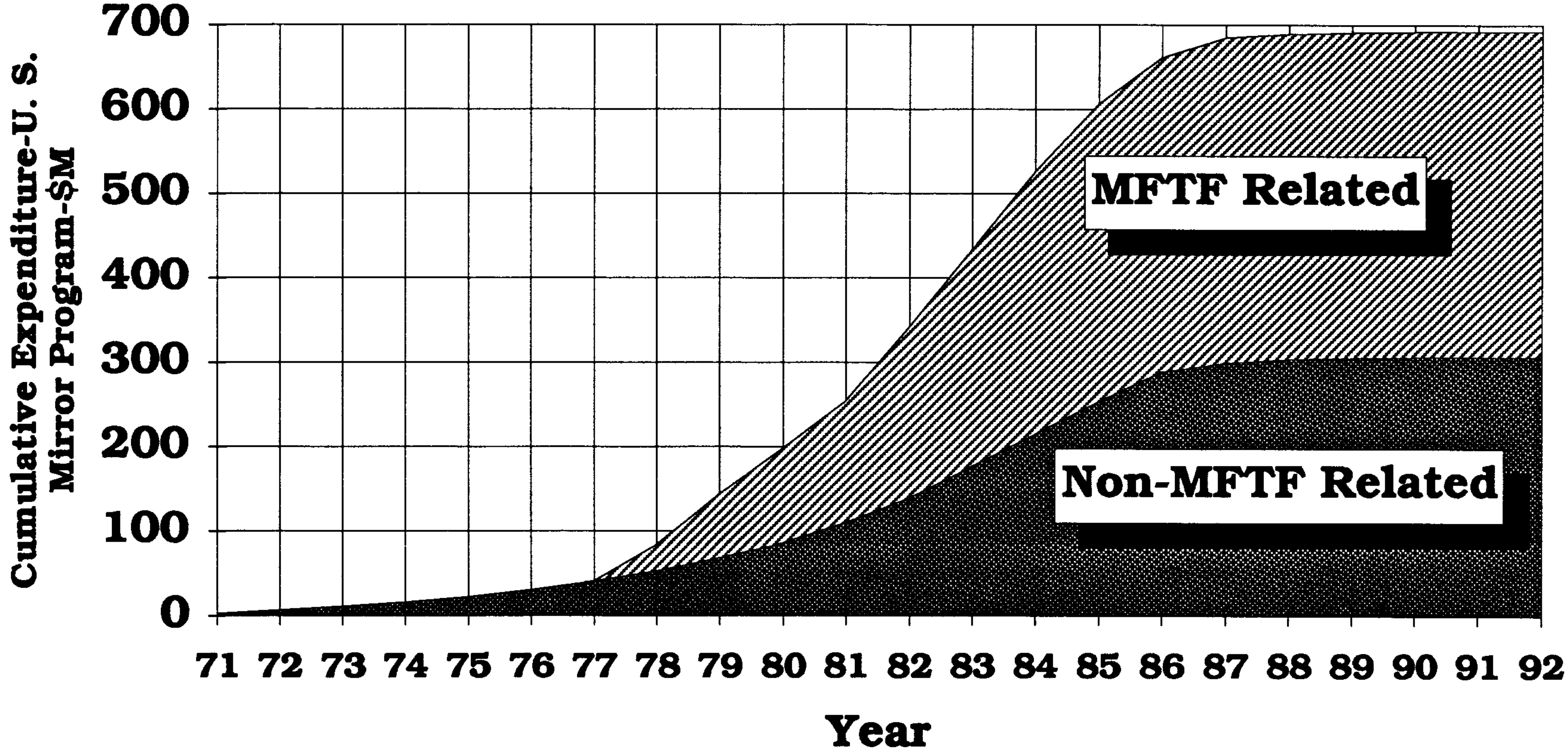
Major Tandem Mirror Programs - 1986



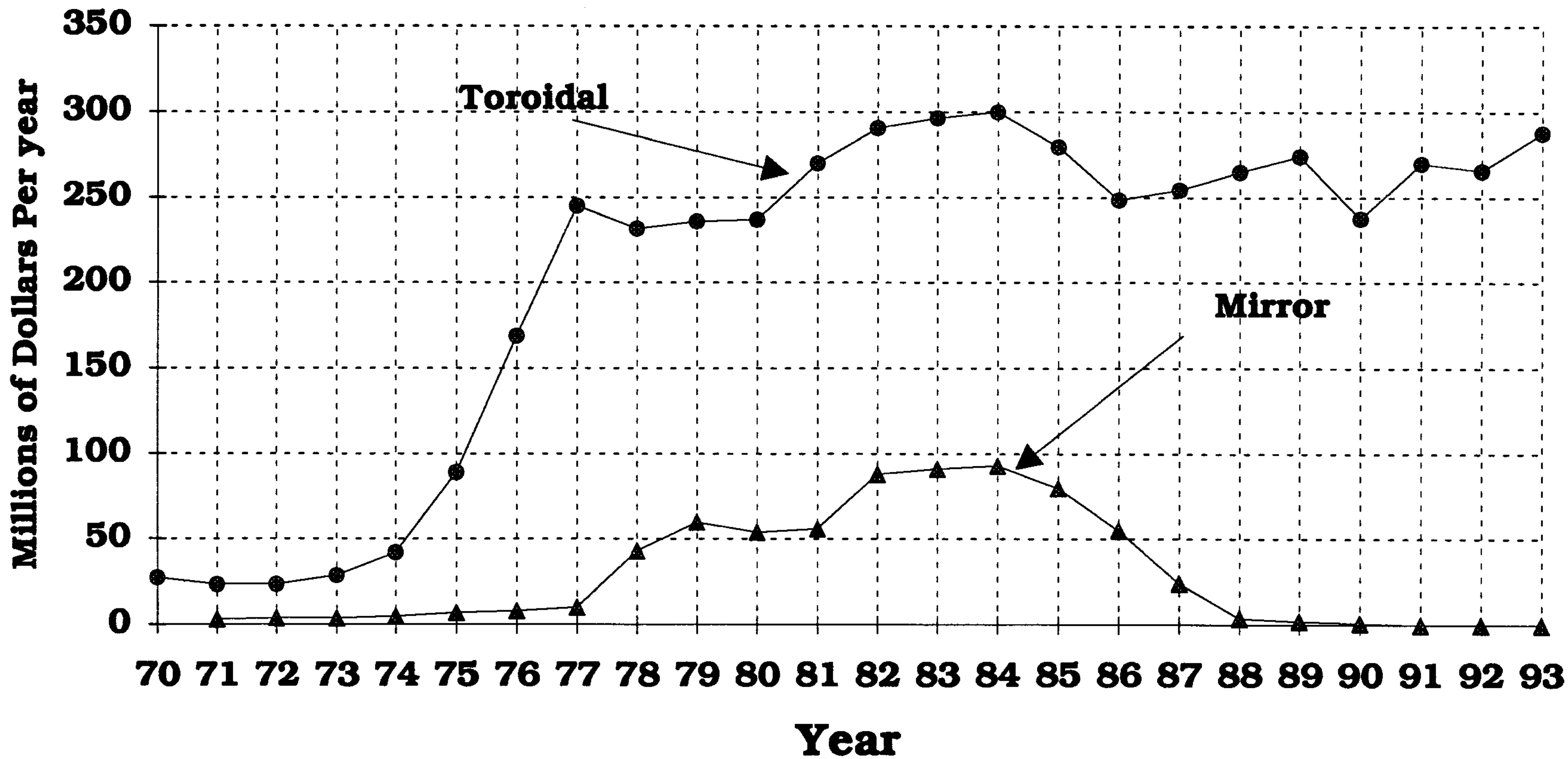
The Funding for MFTF Dominated the U.S. Tandem Mirror Program From the Late 1970's to the Late 1980's



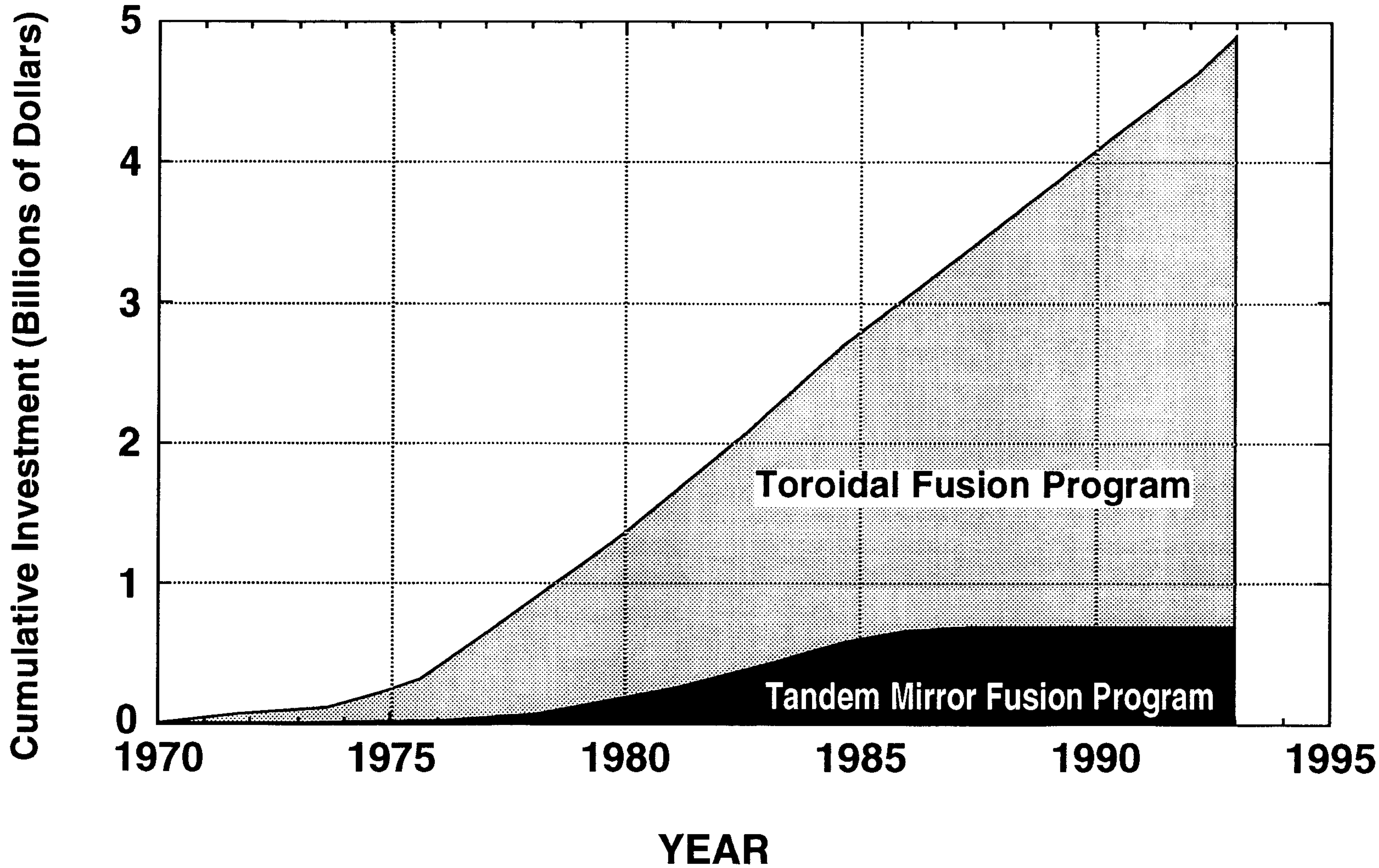
The MFTF Program Consumed 60% of the Resources Available to the Mirror Program Even Though it Never Operated



The Financial Support For the Toroidal Program in the U.S. Far Exceeds That For The Mirror Program



The Cumulative Investment in the U.S. Toroidal Fusion Program is 7 Times More Than Invested in Tandem Mirror Based Concepts



Tasks For Present Study:

- **An Assessment of the State of Tandem Mirror Physics at the Time of the MFTF-B Cancellation**

In 1986 there were 6 major experimental programs worldwide and they had demonstrated that Tandem Mirrors were stable against MHD & microinstabilities. It was also demonstrated that they could use thermal barriers to reduce end loss by several orders of magnitude.

However, financial pressure in the U.S. and the failure of TMX-U to meet its goals caused the U. S. to close its Mirror Program

Tasks For Present Study:

- **Progress in Tandem Mirror Physics Since the MFTF-B Cancellation**

Experimental programs in Japan, Russia, and the U.S.(UW and MIT) showed continued progress after 1986 in the areas of

- ***End plugging***
- ***Thermal barrier potentials***
- ***Corroboration of thermal barrier theory***
- ***Operation of axisymmetric end cells using RF stabilization***

Tasks For Present Study:

- **What Would a Tandem Mirror Reactor Designed Today Look Like?**

The main improvements that could be included in TM reactors designed in 1992 would be the inclusion of:

- ***Axisymmetric end cells***
- ***Compact toroid fueling***

Technology choices in TM power reactor designs made up to 1986 are still valid today demonstrating the robustness of the TM configuration

Tasks For Present Study:

- **What Critical Experiments Are Needed to Revive the Tandem Mirror Program?**

Key experiments needed at reactor relevant parameters include:

- ***Operation in purely axisymmetric mode with MHD stability***
- ***Demonstration of effective barrier pumping schemes***
- ***Understanding of the loss of plugging in TMX-U (and the success of GAMMA-10 in overcoming the problem)***

Status of Tandem Mirror Physics Through 1986

Tandem Mirror Physics Through 1986
Executive Summary

- Excellent experimental and theoretical progress had been made in most areas of tandem mirror research.
- Key exception was that TMX-U could not plug ion end loss above a central cell plasma density of 3×10^{18} m^{-3}.
- Solutions had been identified for all major physics issues related to attractive tandem mirror reactor design.

Major Topics

MHD Equilibrium and Stability

Microstability

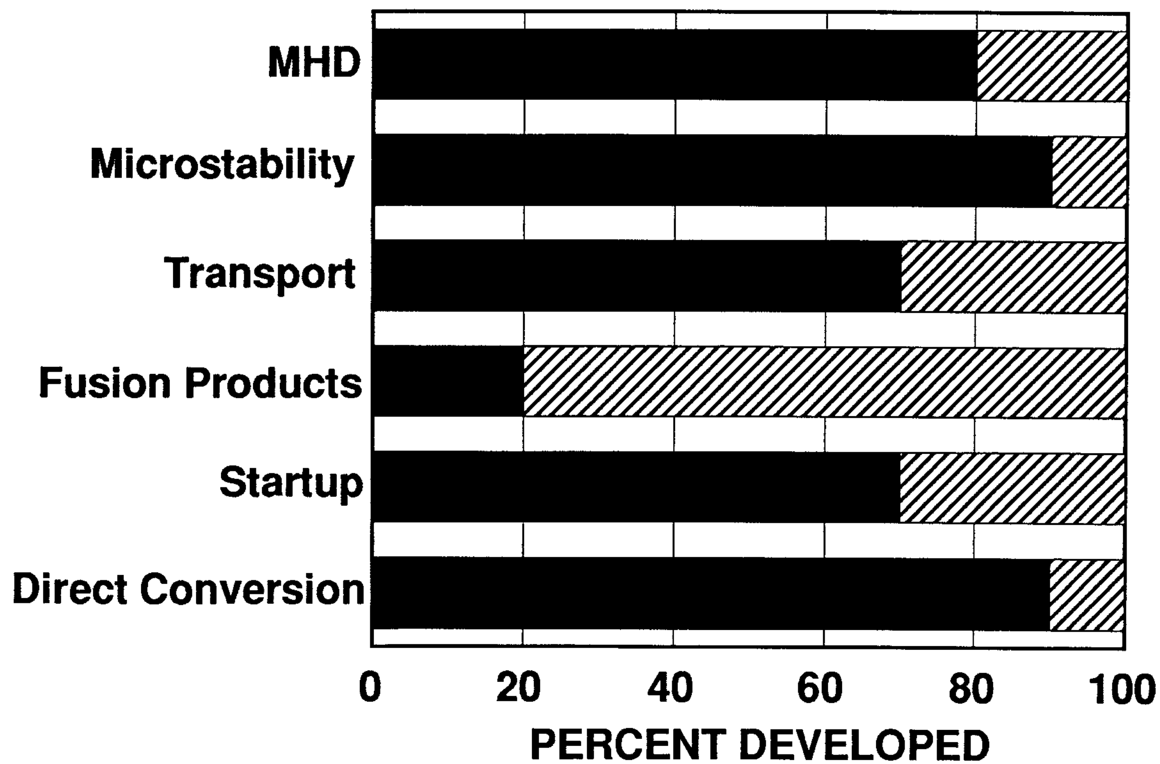
Transport

Fusion-Product Physics

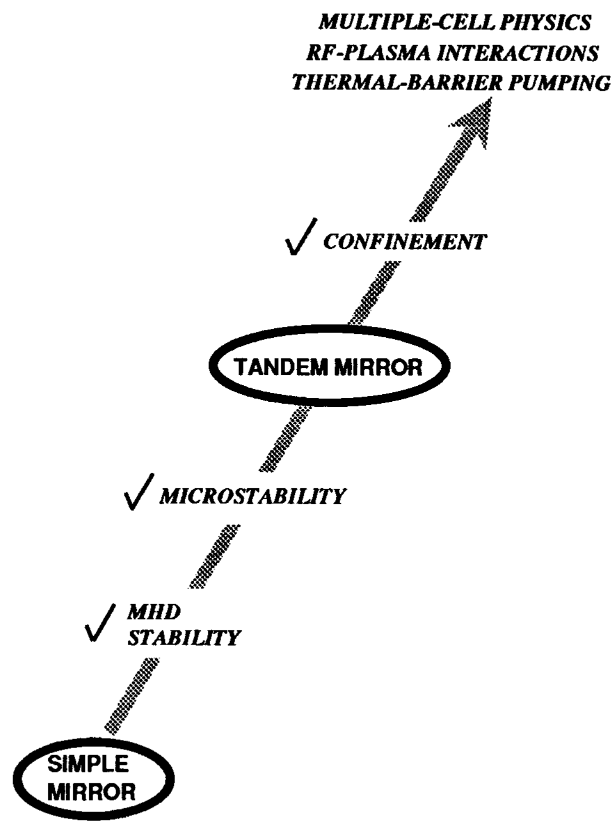
Startup

Direct Conversion

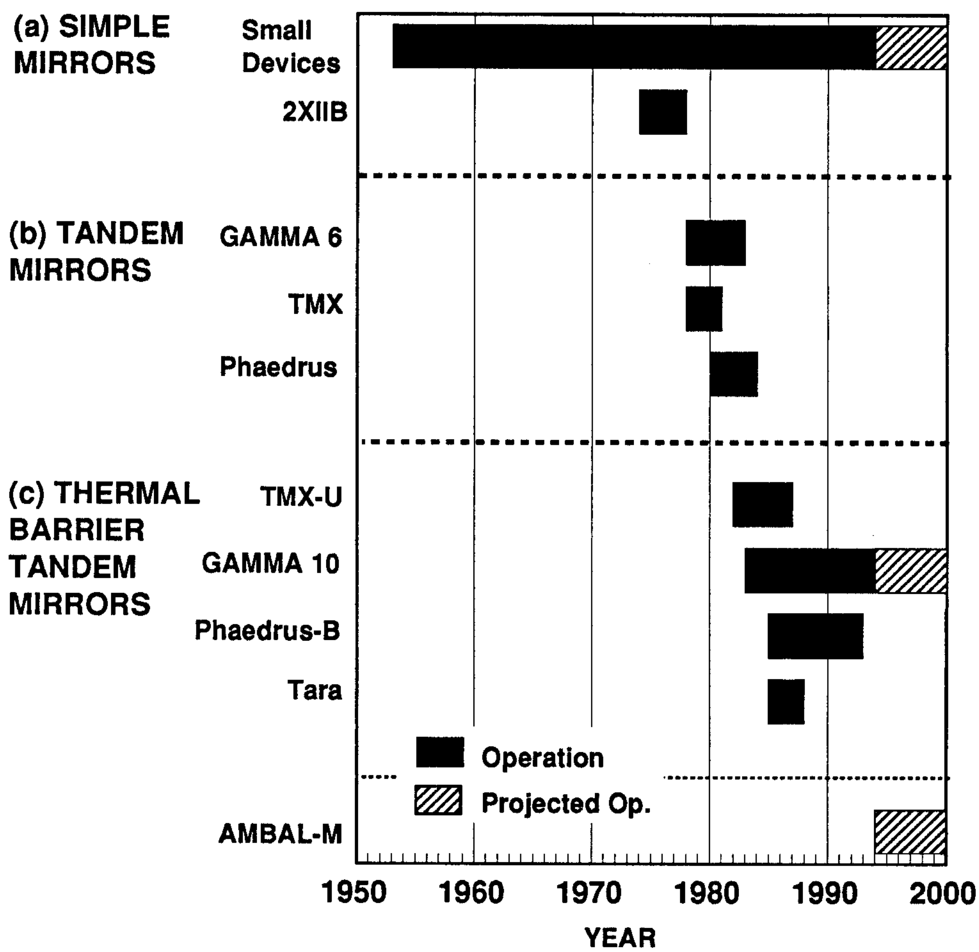
Tandem Mirror Physics is Reasonably Well Understood



Mirrors have Overcome Several Important Hurdles



Tandem Mirror Operation Has Been Limited



Tandem Mirrors Have Several Advantages Over Tokamaks

- The axisymmetric tandem mirror central cells have high β and a magnetic field on the axis that approaches the magnetic field on the coils.
  - ▷ Gives high leverage, because the fusion power density in the plasma scales as $\beta^2 B^4$.
- Open-field-line topology is amenable to the direct conversion of charged-particle fusion power to electricity
  - ▷ Increases the attractiveness of advanced fuel cycles in tandem mirrors.

Tandem Mirrors Have Several Advantages Over Tokamaks

- No equilibrium plasma current is required, so plasma disruptions do not occur.

- Linear, axisymmetric central-cell geometry greatly simplifies the engineering design in the region of highest radiation fluxes.

- Most of the transport energy loss is axial, so magnetic flux tube can be expanded to reduce the surface heat flux.

MHD Equilibrium and Stability

Equilibrium

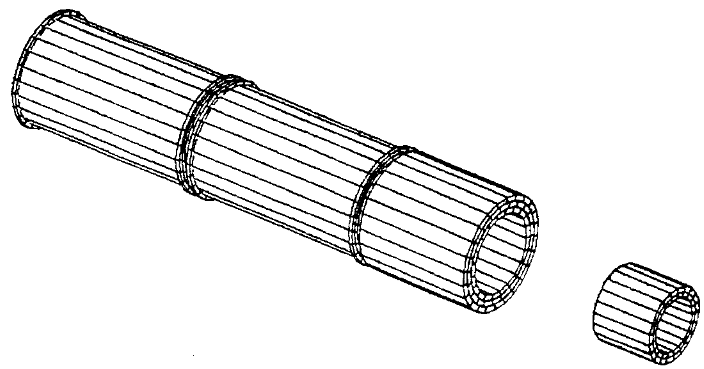
Minimum-B MHD Stability

Axisymmetric MHD Stability

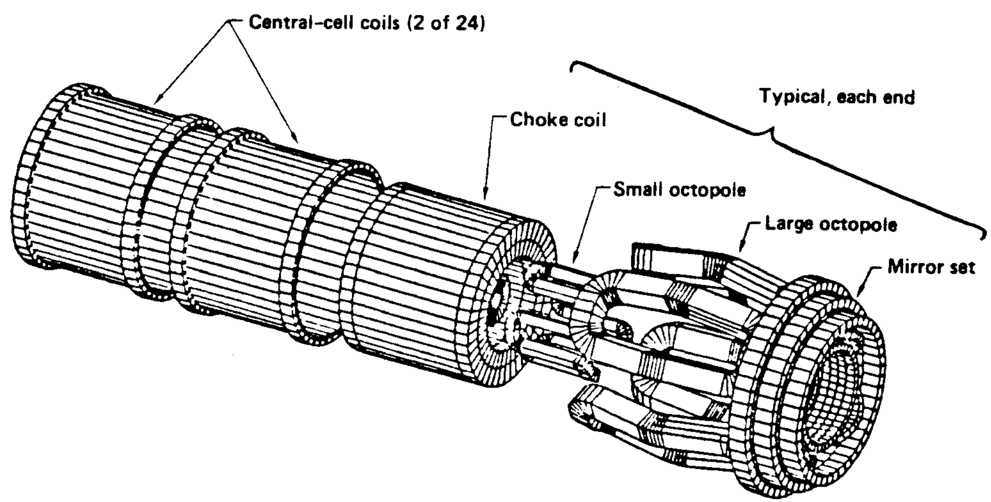
Trapped-Particle Modes

Axisymmetry Greatly Simplifies Fusion Engineering

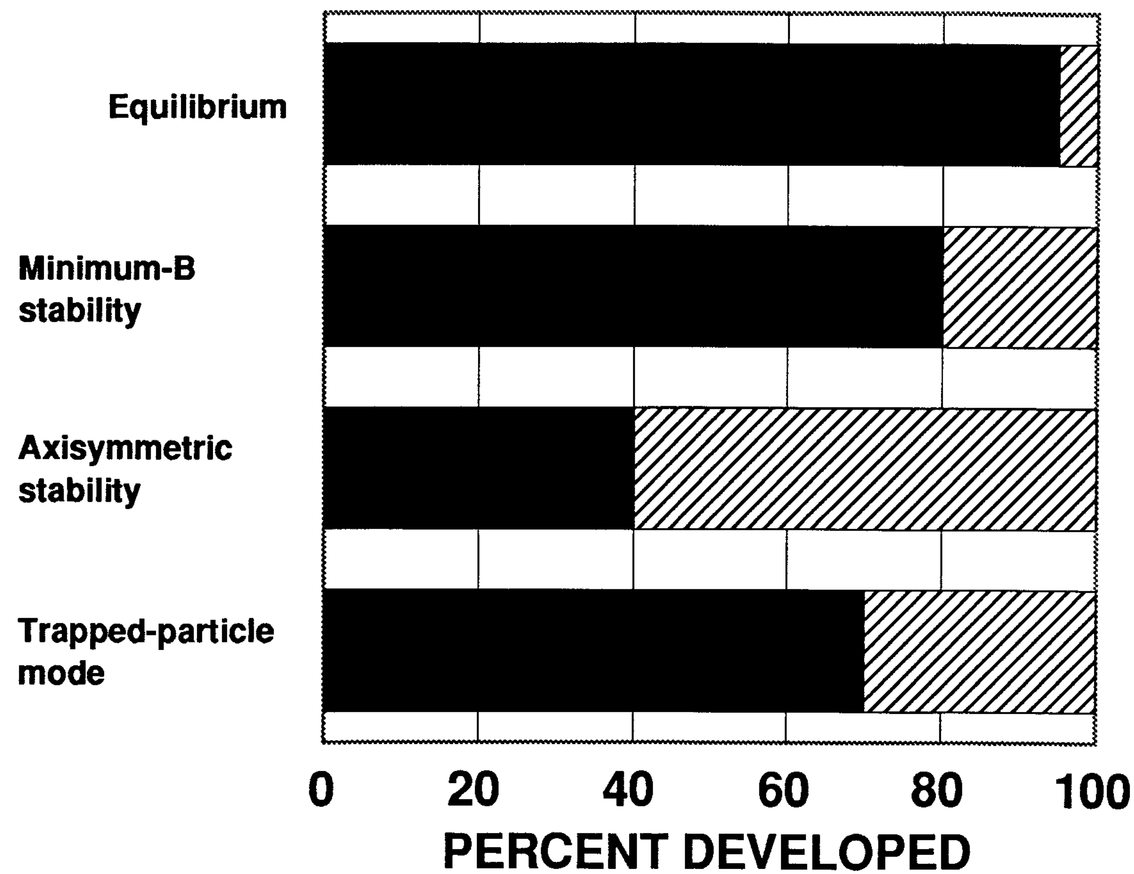
Axisymmetric Tandem Mirror



Octupole Tandem Mirror



Tandem Mirror MHD Understanding



Transport

Electron Thermal Conduction

Electrostatic Potentials

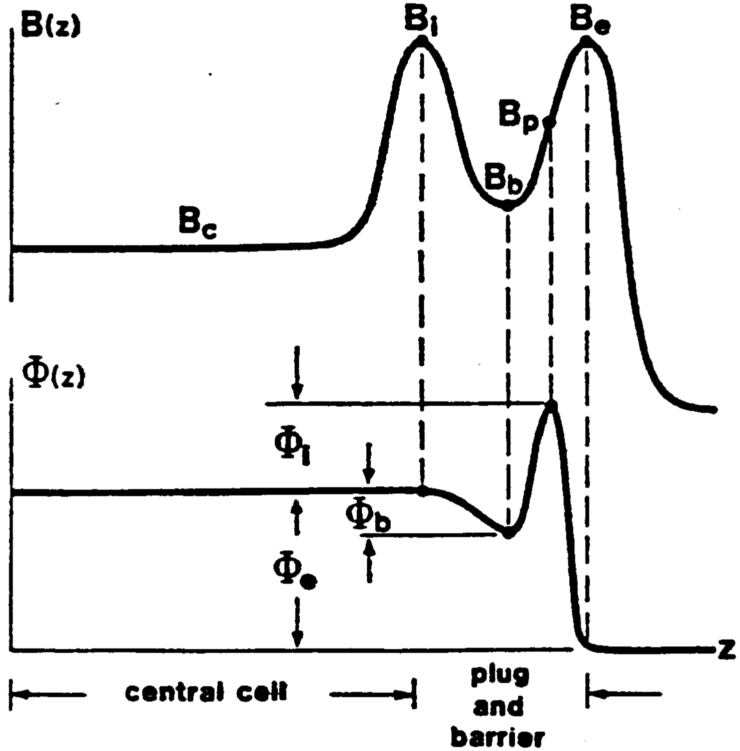
Thermal Barrier Physics

Axial Loss

Radial Transport

Thermal Barriers Can Be in the Same Cell or Separate

(a)



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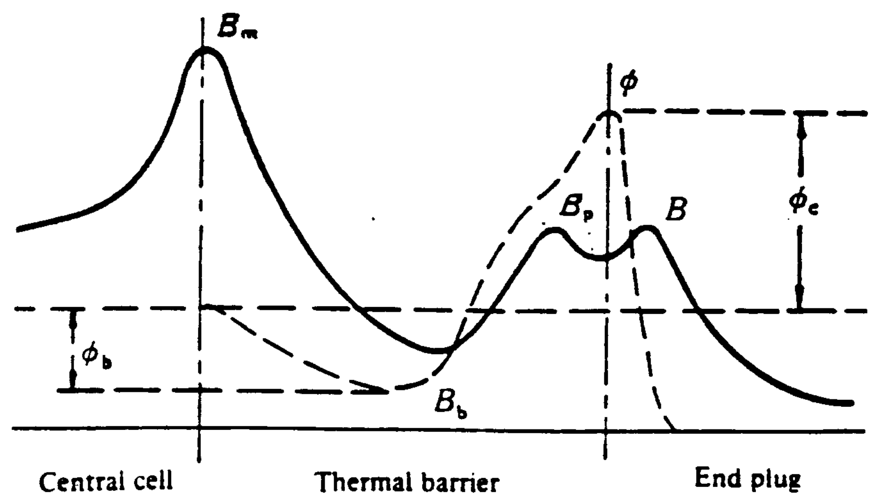
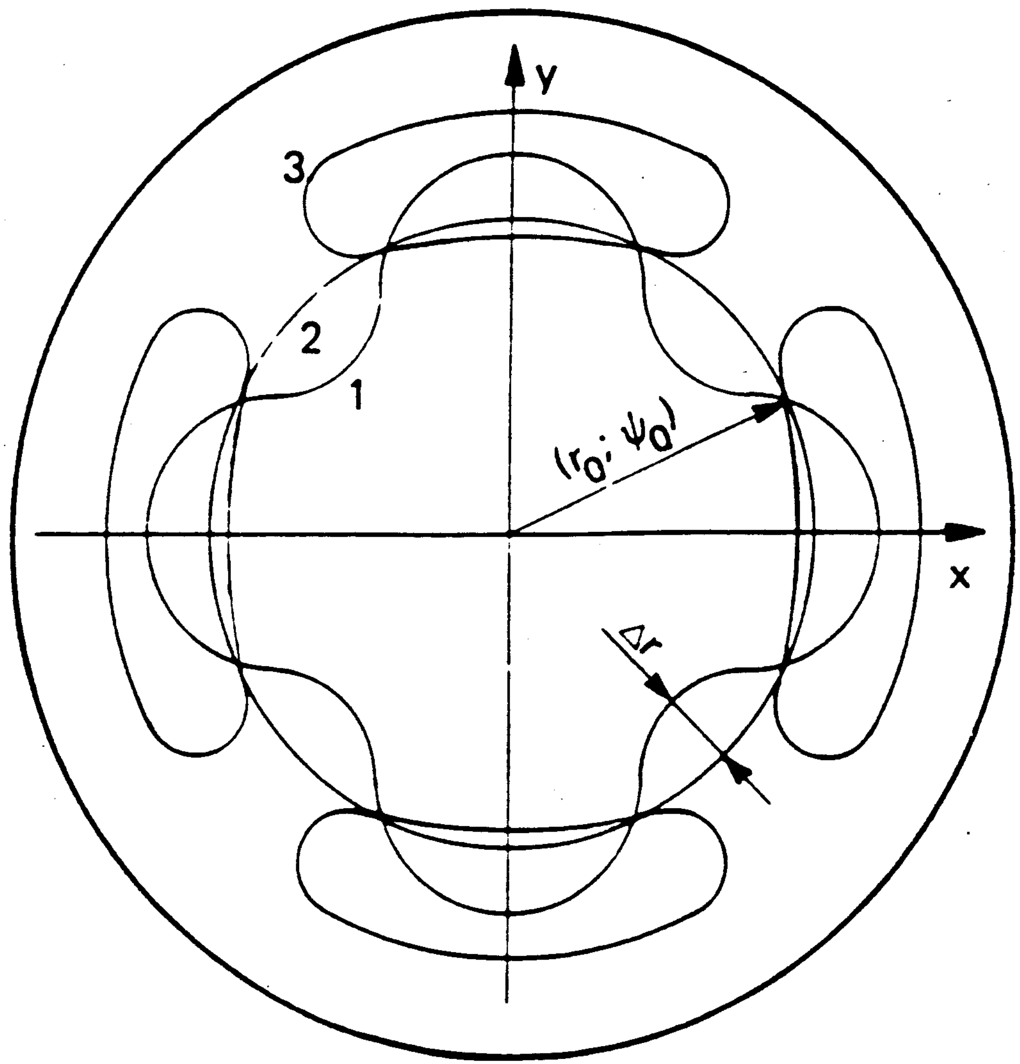
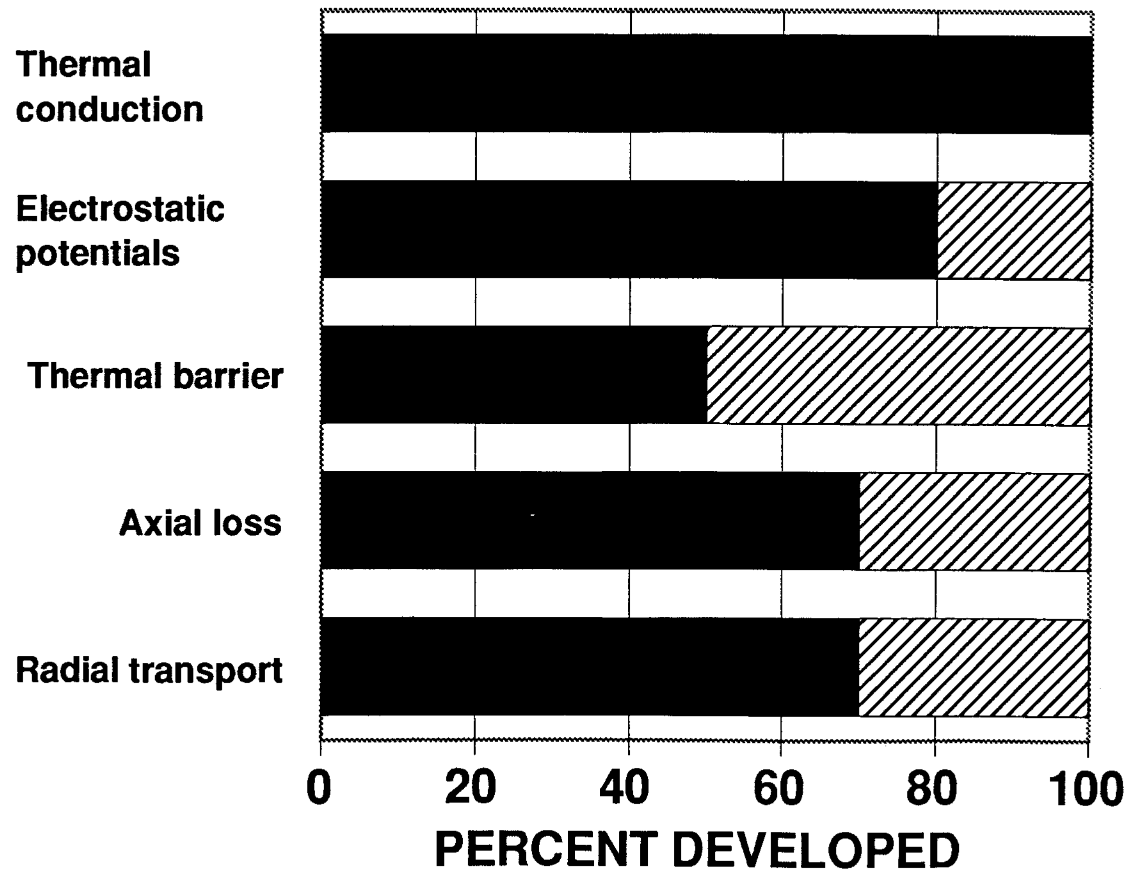


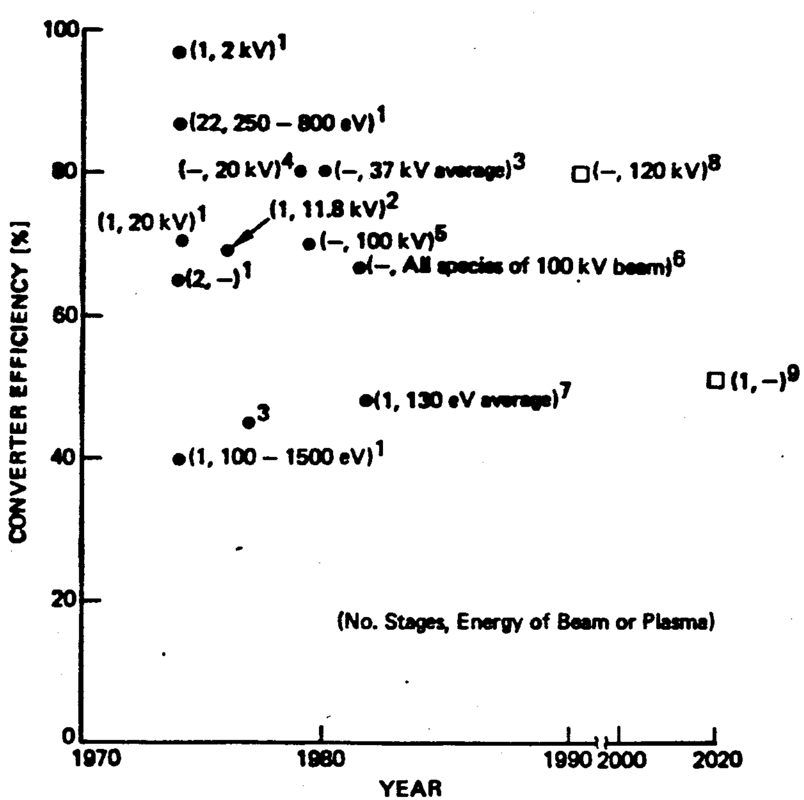
Minimum-B Tandem Mirrors Can Experience Transport Analogous to Tokamak Neoclassical Transport

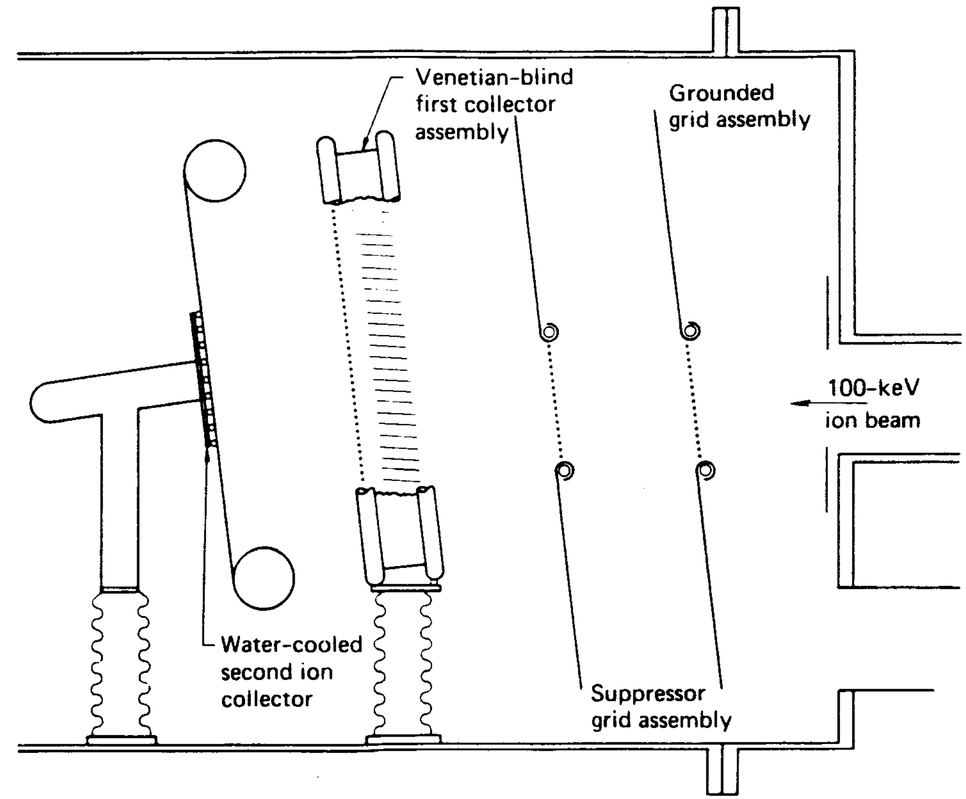


Tandem Mirror Transport Understanding



Direct Conversion has been Well Verified





Summary: Status of Tandem Mirrors Through 1986

- Good understanding existed for
  - ▷ MHD equilibrium and stability
  - ▷ Microstability
  - ▷ Transport
- However, only four thermal barrier tandem mirrors had operated.
- High β (15–20%) had been routinely achieved.
  - ▷ Theory predicted even higher values are accessible.
  - ▷ Methods for achieving axisymmetric operation were emerging.

Summary: Status of Tandem Mirrors Through 1986

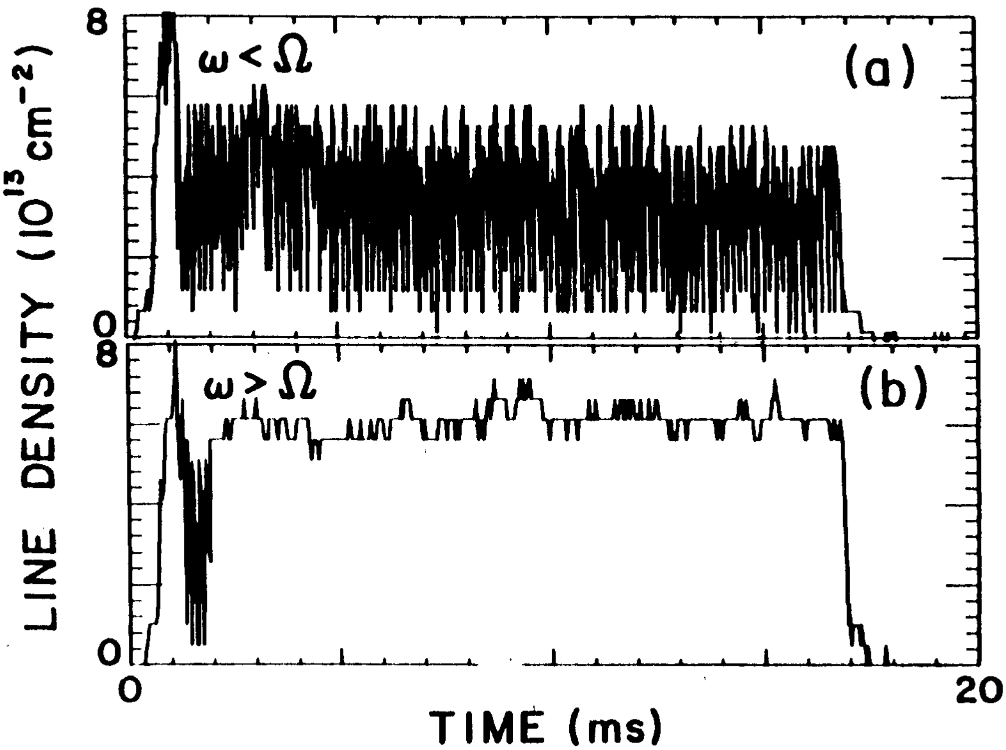
- Thermal barrier physics had reached fair understanding, but several issues remained.
  - ▷ Experimental test of collisional barrier filling.
  - ▷ Methods for thermal barrier pumping.
  - ▷ ECRF–plasma interactions in the barrier and plug.
- Axial end loss scaling had received preliminary verification.
  - ▷ TMX-U experienced loss of end plugging at a central cell plasma density of $3 \times 10^{18}\ m^{-3}$.

Summary: Status of Tandem Mirrors Through 1986

- Radial transport in minimum-B tandem mirrors was reasonably well understood.
  - ▷ Constrained design space.
  - ▷ Made end cell engineering and RF heating extremely complicated.
- Very little was known about fusion-product physics except the slowing down process.
- Startup of tandem mirrors had been accomplished successfully, but it required complicated programming of sources.

Progress in Tandem Mirror Physics Since 1986

RF Stabilization, Wall Stabilization, or Magnetic Limiter Stabilization Would Lead to Axisymmetric Operation

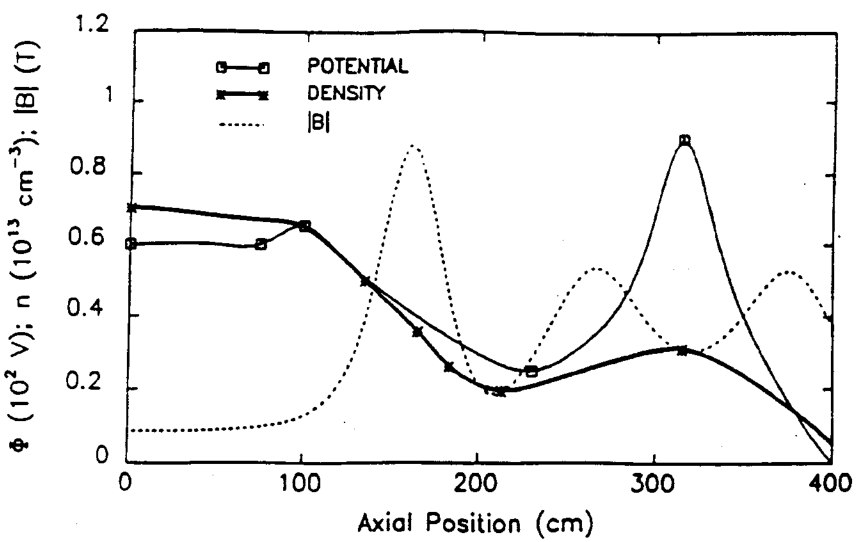


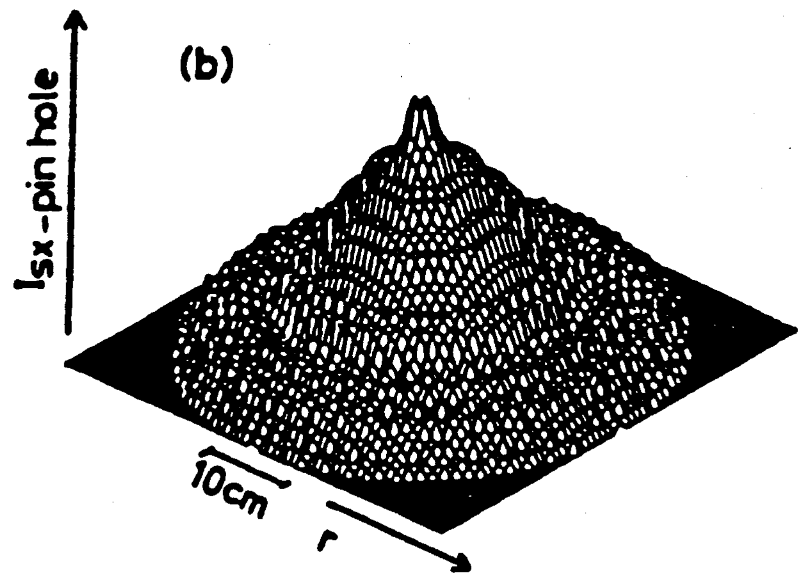
- Experimental ion cyclotron range of frequencies (ICRF) stabilization has been demonstrated on Phaedrus at the University of Wisconsin.

- Operating mode was completely axisymmetric.

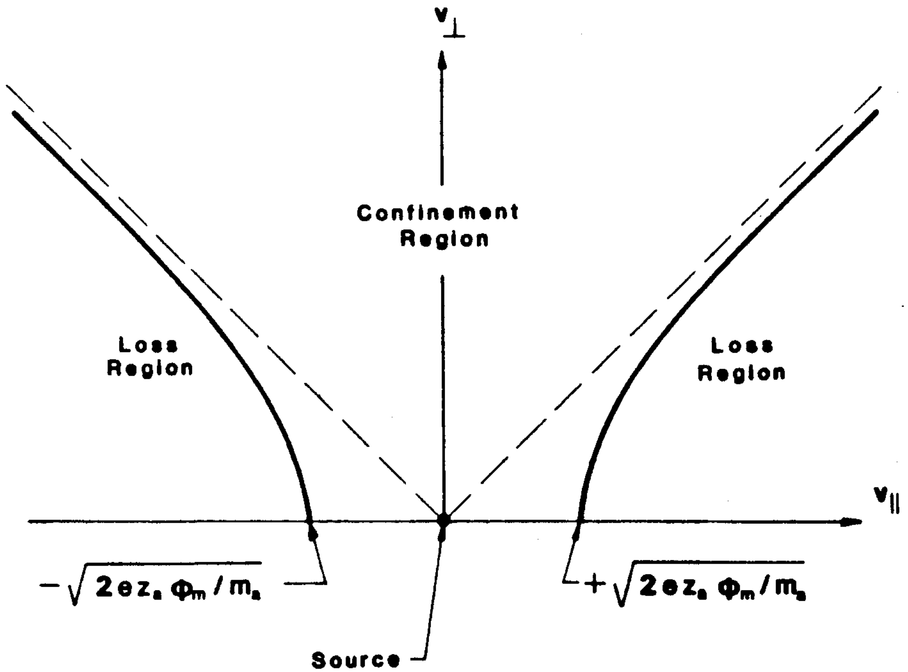
- Density greater than 10^{19} m^{-3} in Phaedrus and GAMMA 10.

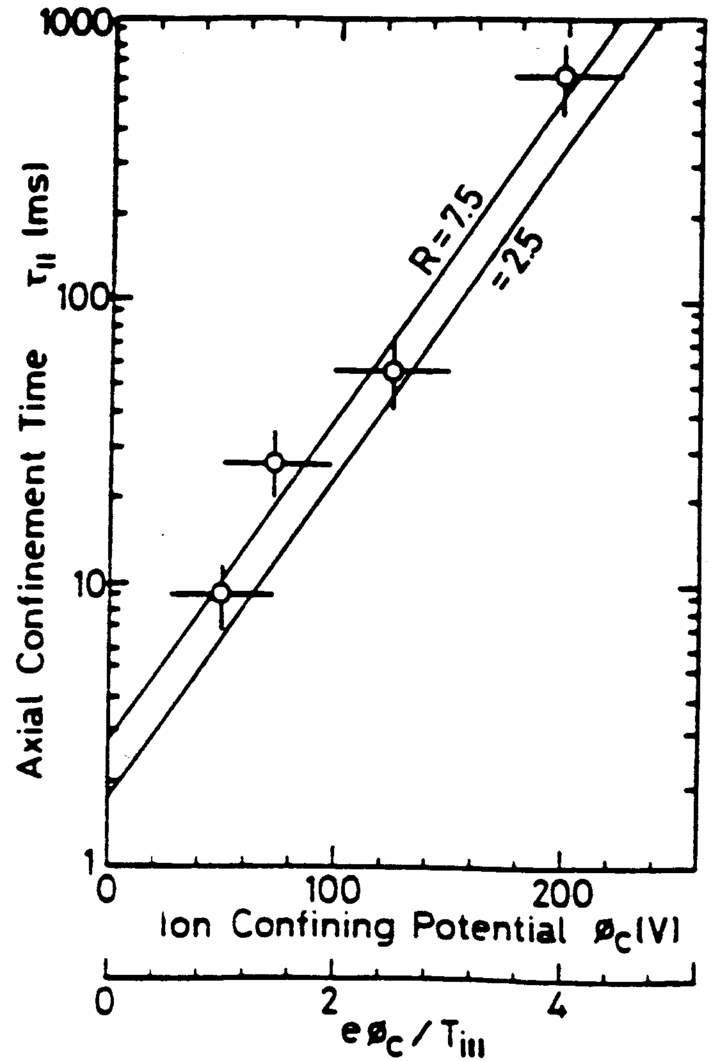
Thermal Barrier Electrostatic Potential Physics is Well Verified





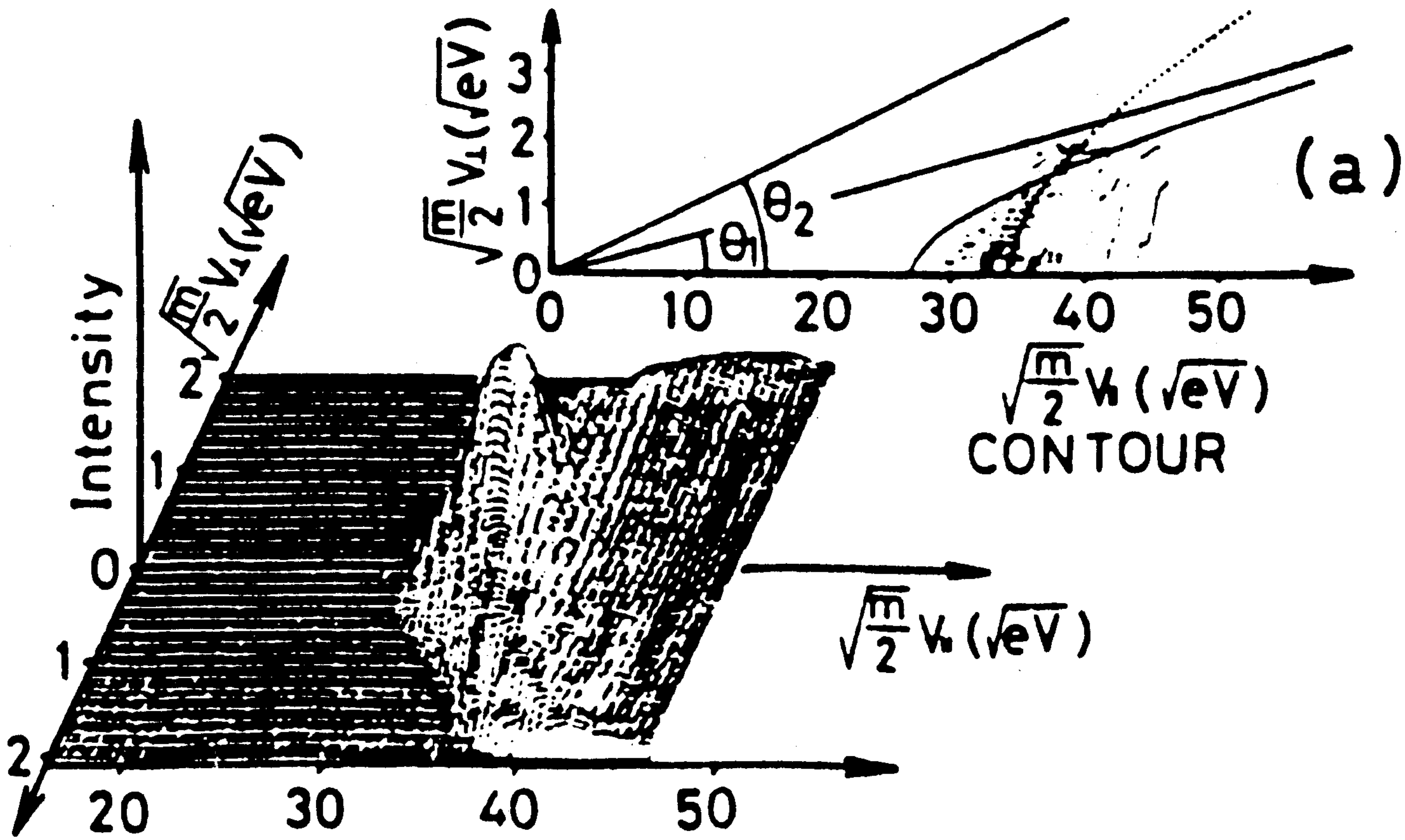
Pastukhov Loss has been Verified





Ion End-Loss Energy Spectrum in GAMMA 10 Matches Theory Very Well

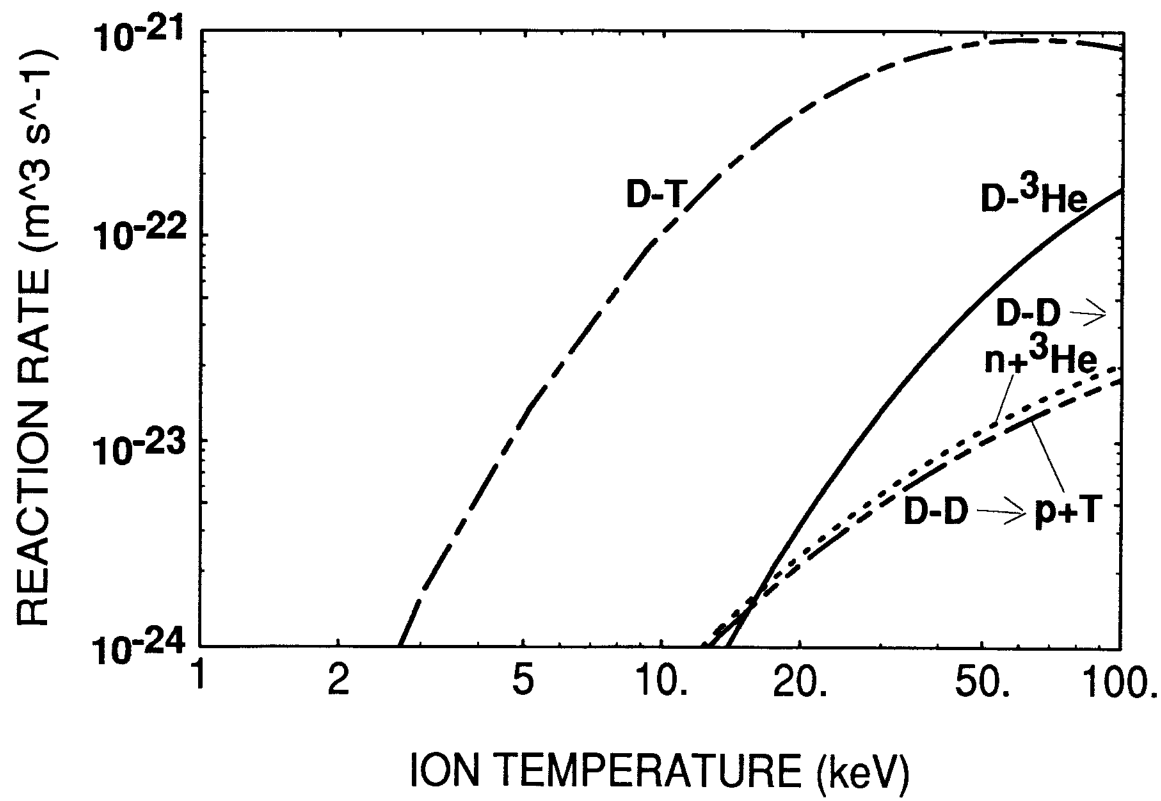
END-LOSS IONS IN VELOCITY SPACE



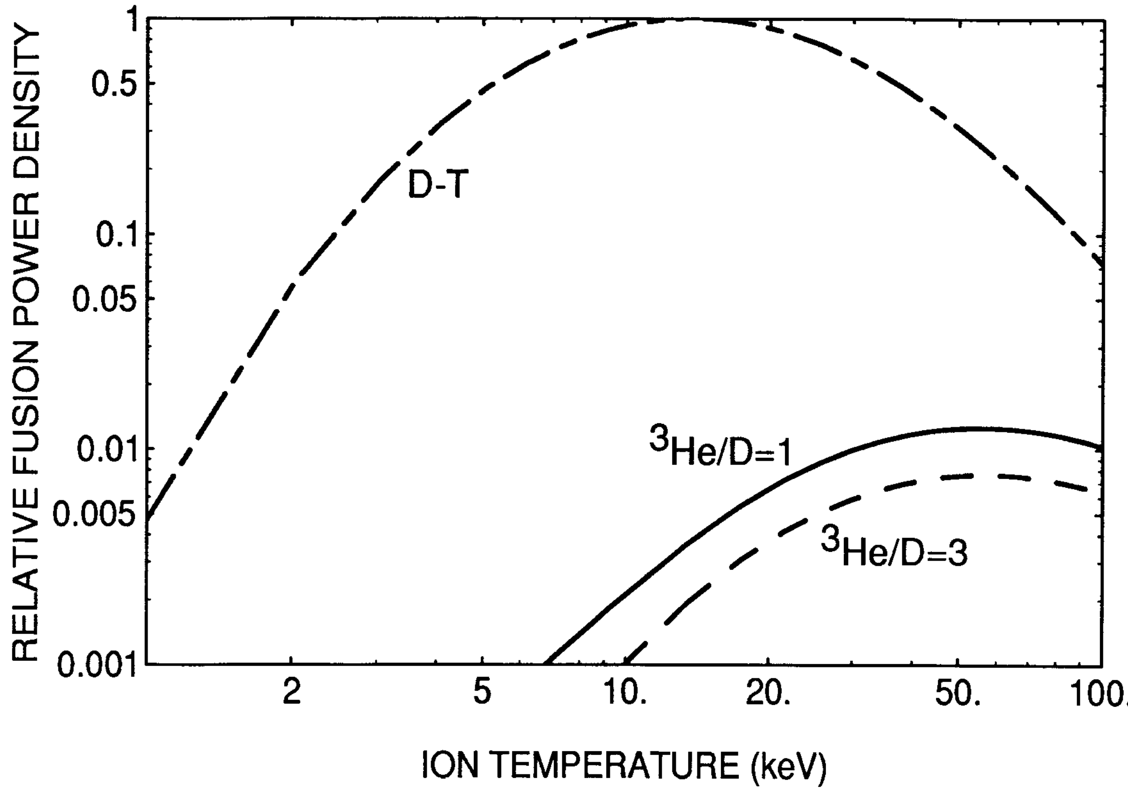
Fusion-Product Physics

- **Fusion-Product Particle Loss and Energy Deposition**
- **Fusion-Product Driven Instabilities**
  - ▷ **Alpha-Loss-Cone instability emerged as potentially important for tandem mirror reactors.**

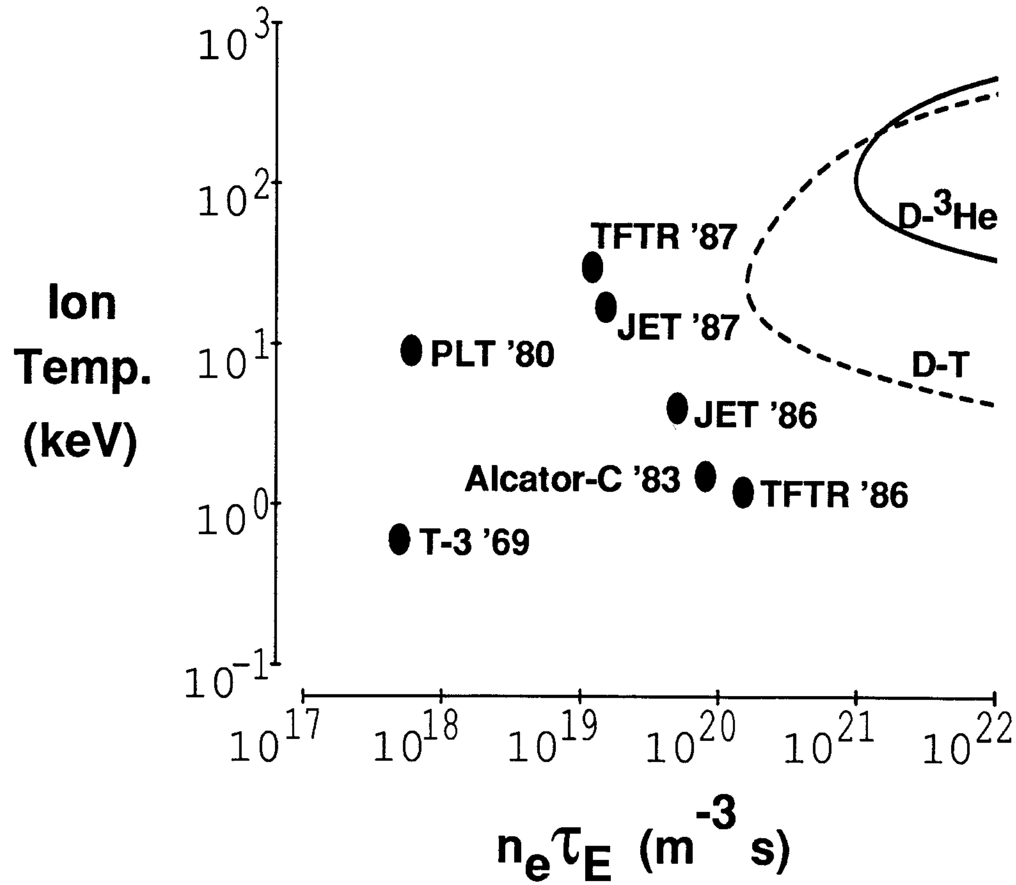
Maxwellian-Averaged Fusion Reaction Rates



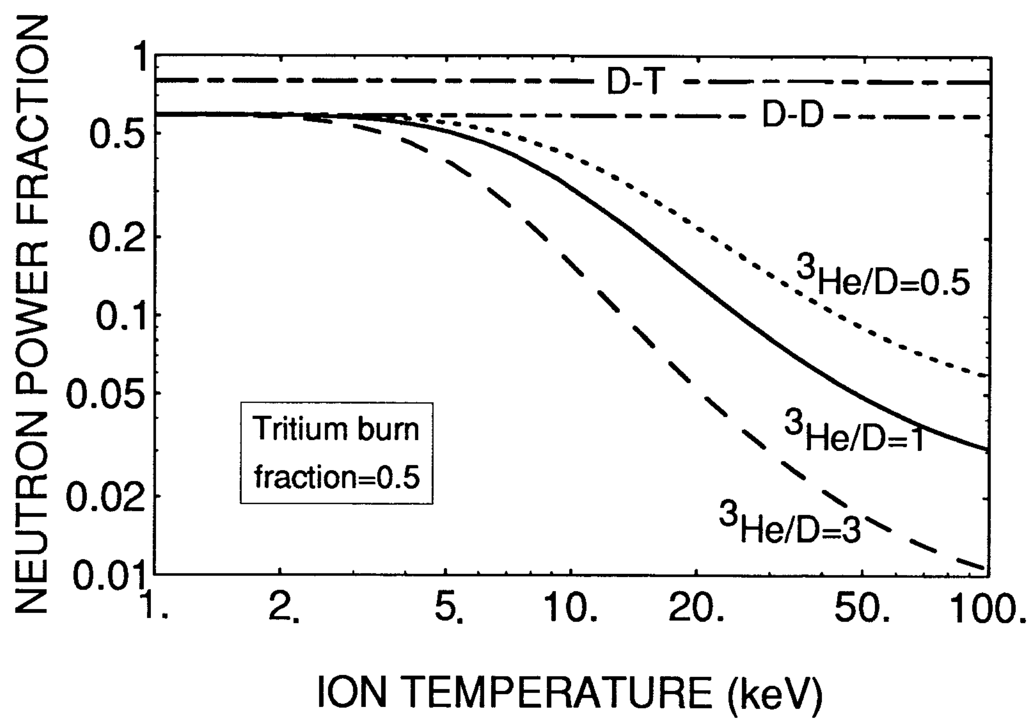
Fusion Power Density in the Plasma



Ignition $n\tau_E$ Values



Fraction of Fusion Power Produced as Neutrons



The D-^{3}He Engineering Power Density Can Be About the Same as that of D-T

AREA	D-T	D-^{3}He	Effect
Normalized fusion power density in plasma	1	0.013	0.013
Net Efficiency	0.35	0.7	2
Normalized blanket and shield volume	1	0.4	2.5
Central cell magnetic field	3.1 T	6.5 T	19
Total Effect on Engineering Power Density			1.2

Summary: Progress in Tandem Mirrors Since 1986

- **Axisymmetric tandem mirror operation became better understood and experimentally explored.**
  - ▷ **RF stabilization.**
  - ▷ **Wall stabilization.**
  - ▷ **Magnetic divertor stabilization.**
- **Trapped-particle modes were observed in Tara, where expected. Avoiding them should not be difficult.**

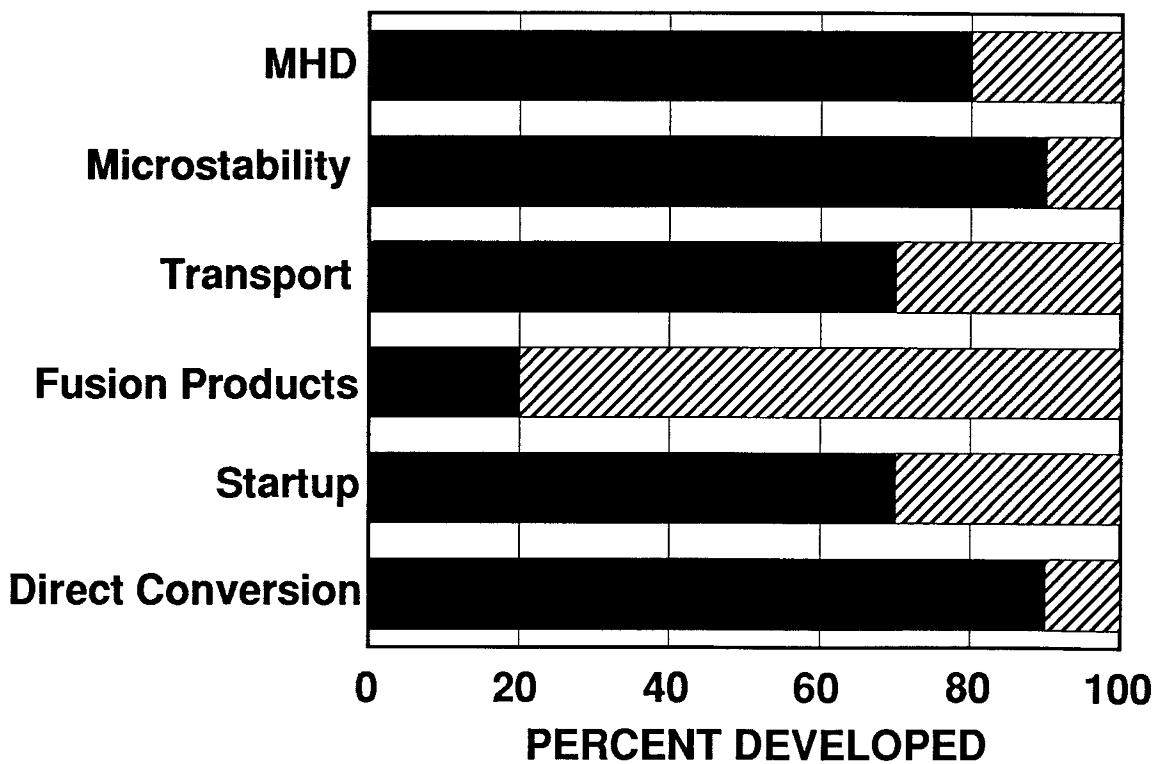
Summary: Progress in Tandem Mirrors Since 1986

- Thermal barriers were verified and understood in more detail.
  - ▷ Axial profiles, hot-electron distribution, and collisional filling wer all investigated.
  - ▷ Tests of thermal barrier pumping methods are still needed.
- GAMMA 10 and Phaedrus exceeded the density at which TMX-U lost end-plugging by factors of three to four.

Summary: Progress in Tandem Mirrors Since 1986

- TMX-U loss of plugging was interpreted as due to asymmetric ECRF heating in a highly elliptical magnetic flux tube.
- Pastukhov end-loss scaling was verified more completely.
- Tandem mirrors emerged as key devices for burning D-^{3}He fuel.
  - ▷ Direct conversion.
  - ▷ Thinner blankets.
  - ▷ Low central cell magnetic field.

Tandem Mirror Physics is Reasonably Well Understood

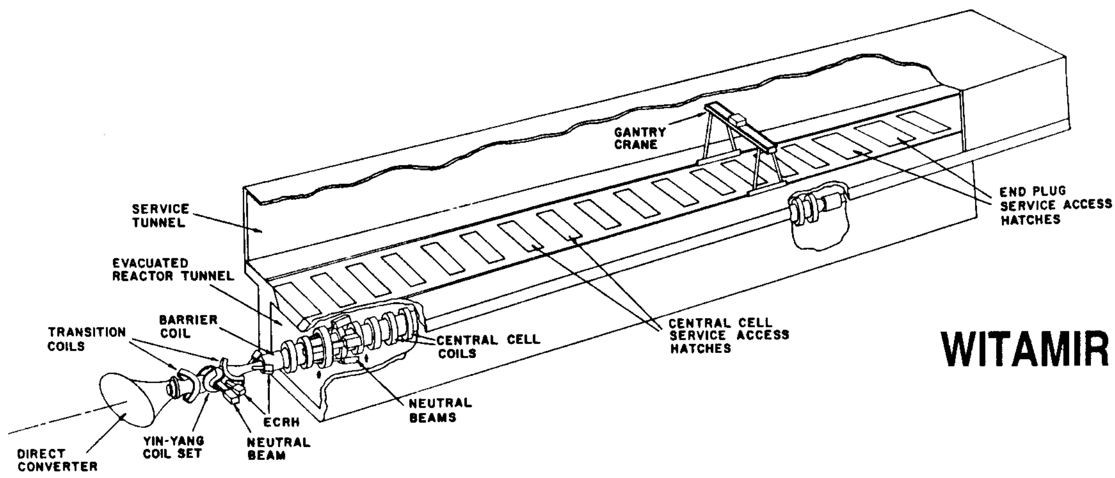


Conclusions

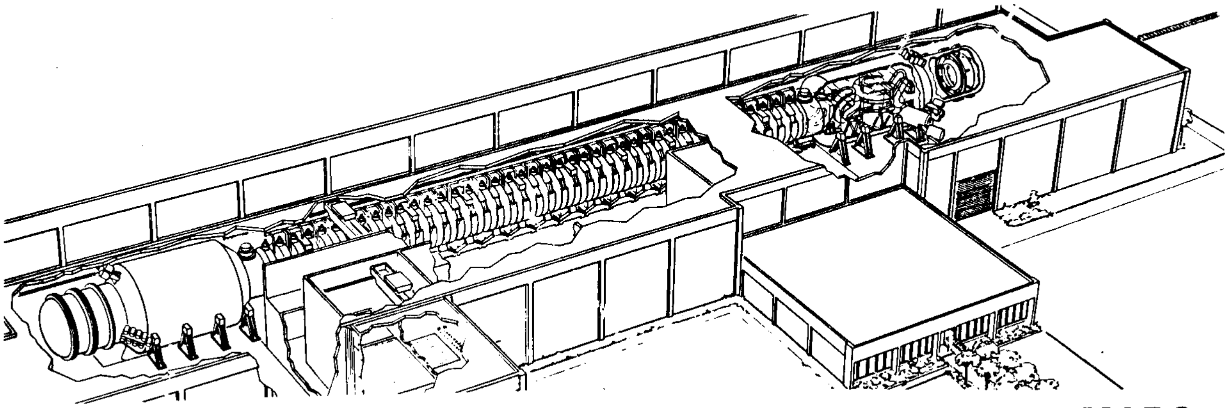
- **Tandem mirror physics had made good progress by 1986.**
- **TMX-U loss of end plugging appears to be reasonably understood and overcome.**
- **With the solution of a few, key remaining problems, tandem mirrors would be very attractive reactors with either D-T or D-^{3}He fuel.**
  - ▷ **Thermal barrier pumping.**
  - ▷ **Axisymmetric operation.**
  - ▷ **Demonstration of reactor-relevant parameters.**

Implications for Tandem Mirror Power Plants

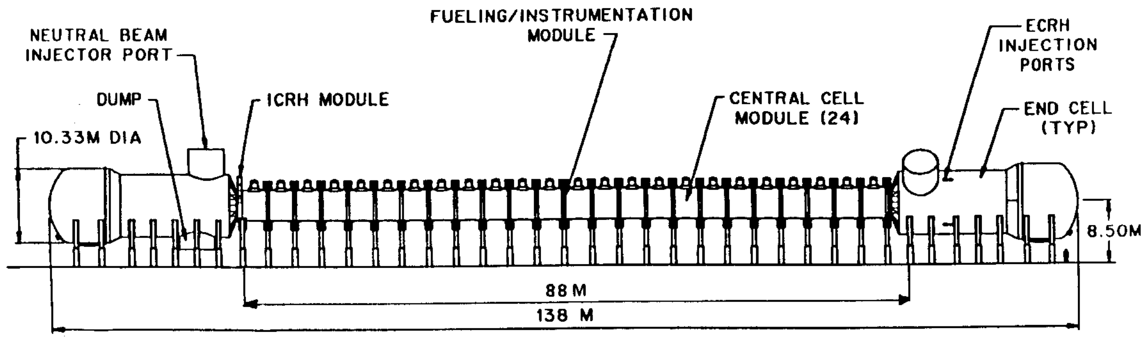
Tandem Mirror Power Reactor Overall Configuration



WITAMIR

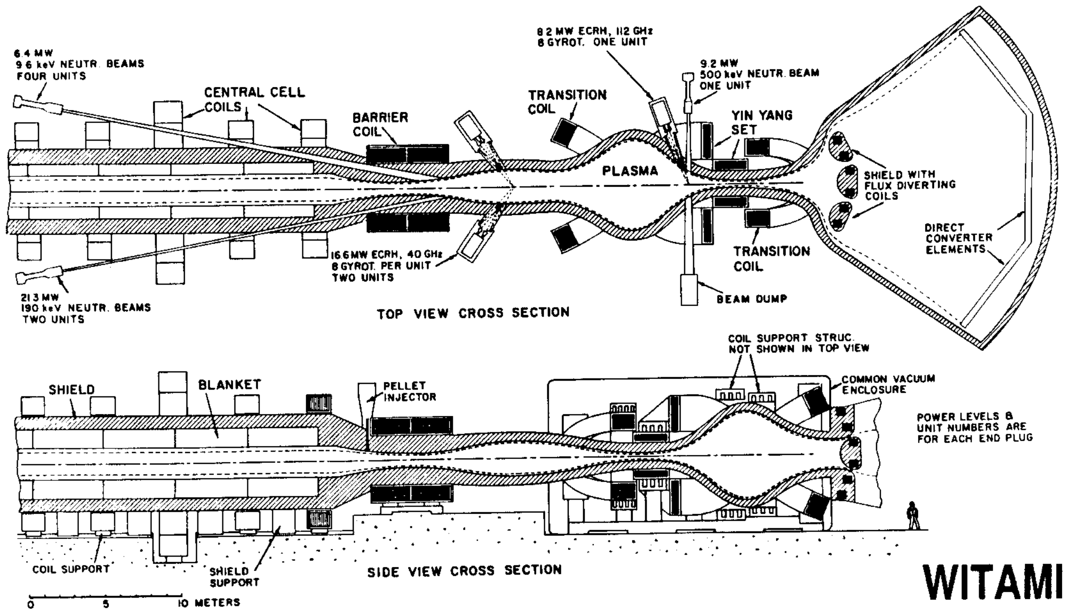


MARS

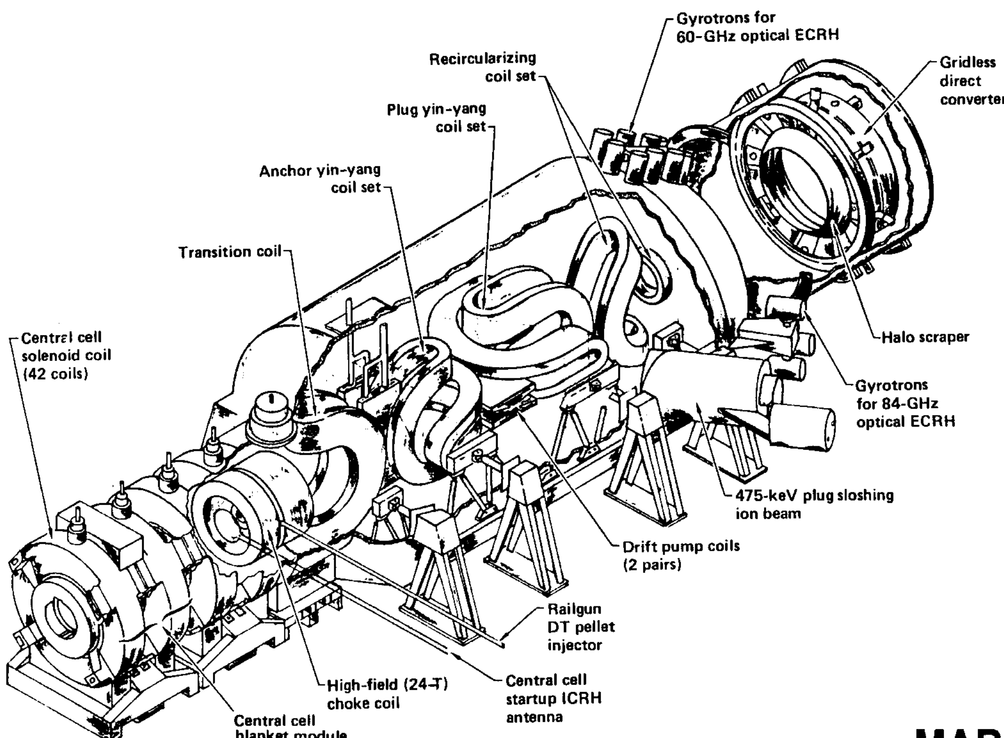


MINIMARS

Tandem Mirror Power Reactor End Cells

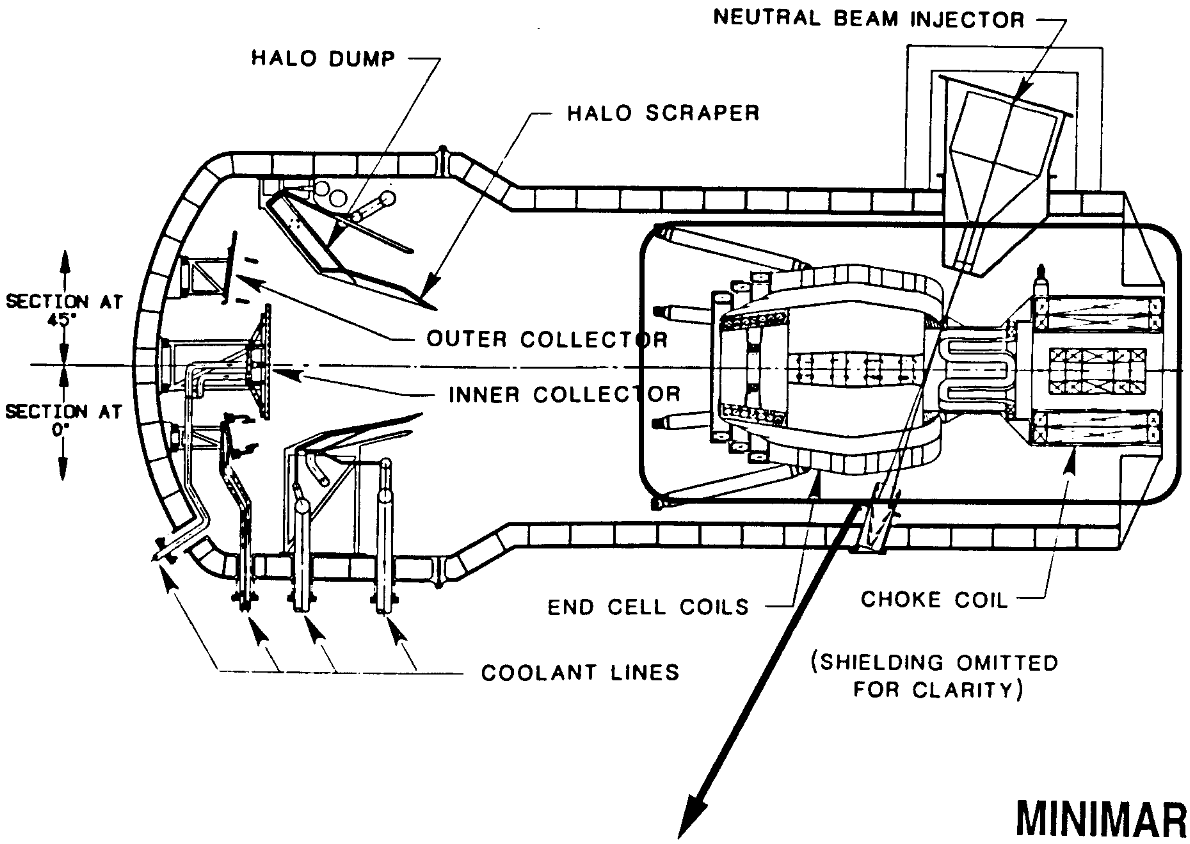


WITAMIR



MARS

MINIMARS Tandem Mirror Power Reactor End Cell



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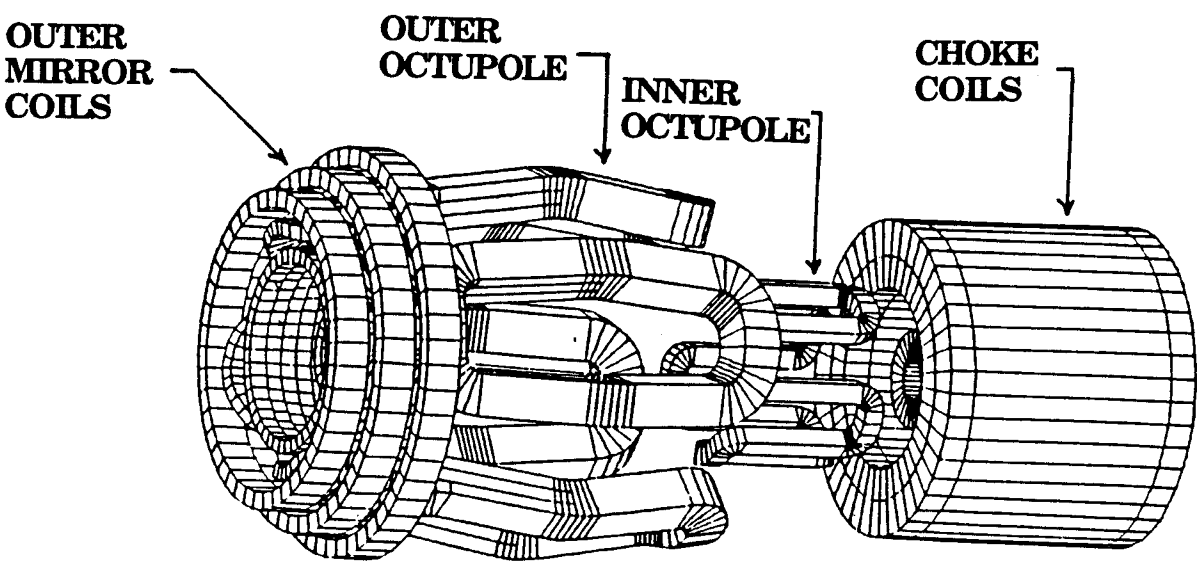
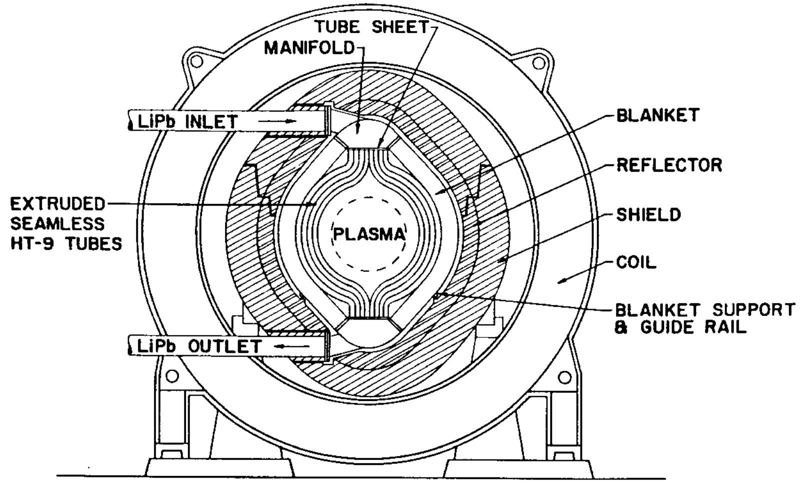


Tandem Mirror Power Reactor Central Cells



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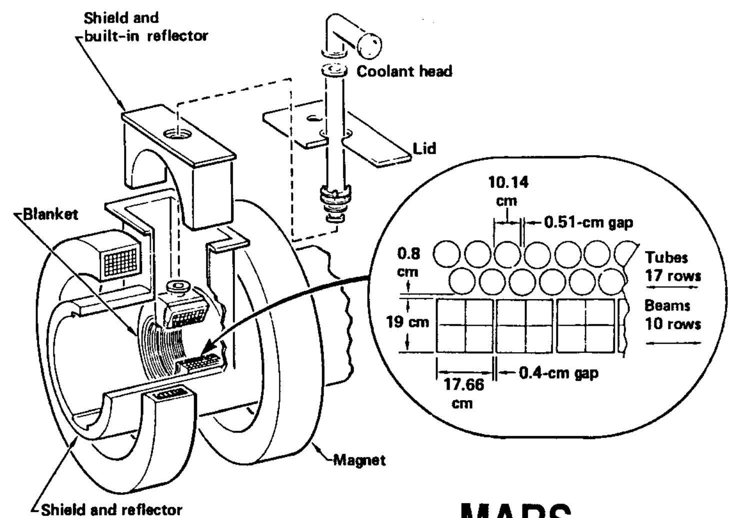
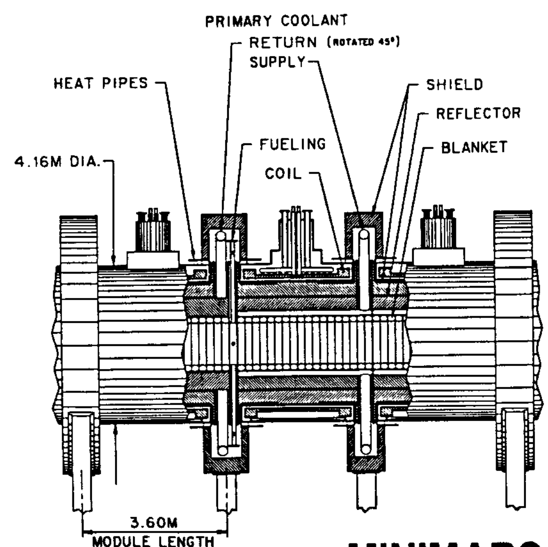


MARS



MINIMARS

Summary of Past Tandem Mirror Power Reactors

Overall Reactor

Parameter	Units	WITAMIR	MARS	MINIMARS	Ra	Current View DT Reactor	Current View D^3He Reactor
Year Published		1980	1984	1986	1987	1992	1992
Fuel		DT	DT	DT	D^3He, 3:1	DT	D^3He, 1:1
Fusion Power	MWt	3000	2600	1290	1227	1290	990
Net Electric Power	MWe	1530	1200	600	600	600	600
Net Efficiency	%	39	34	35	49	35	53
Reactor Length (CC+EP)	m	207	194	104	109	98	90
Overall Length (CC+EP+DC)	m	250	220	138	158	132	140

Summary of Past Tandem Mirror Power Reactors

Central Cell

Parameter	Units	WITAMIR	MARS	MINIMARS	Ra	Current View DT Reactor	Current View D^3He Reactor
CC Length	m	165	131	88	100	88	81
ID Plasma Chamber	m	1.94	1.2	1.08	1.18	1.08	1.18
Max. CC Mag. Field	T	3.6	4.7	3.08	6.5	3.08	6.5
Ion Density	$10^{14}/cm^3$	1.51	3.3	3.96	1.26	3.96	3
Ion Energy	keV	32.5	28	24.7	83	25	100
n Wall Loading	MW/m^2	2.4	4.3	3.3	0.05	3.3	0.1
Beta	%	40	28	60	73	60	73
Fueling		Beams/ Pellet Injection	Pellet Injection	Laser Propel. Pellets	Undeter-mined	Compact Toroid	Compact Toroid

Summary of Past Tandem Mirror Power Reactors

Parameter	Units	WITAMIR	MARS	MINIMARS	Ra	Current View DT Reactor	Current View D^3He Reactor
End Cell							
Type		Inboard Thermal Barrier with Yin Yang Coils	Inboard Thermal Barrier with Yin Yang & "C" Coils	Single Cell Thermal Barrier with Octupole Plug	Axisymmetric with RF Stabilization	Axi-symmetric	Axi-symmetric
Max. Choke Mag. Field	T	14.1	24	24	24 (16+8)	24	24
‹ Ion Energy›	keV	905	690 (anchor)	≈500	880	≈500	880
‹ Barrier›	keV	270	820	297	434	297	434
‹ Plug›	keV	123	123	277	336	277	336
End Cell Heating							
Hot Ion NBI Beams	MWe/keV	37/500	14/475	12/412	8/2000	12/412	8/2000
Anchor ICRF	MWe/keV	–	25/55	–	–	–	–
RF Stabilizing RF	MWe/keV	–	–	–	38/196	–	38/196
Mantle ECRF	MWe/GHz	–	–	33/110	–	–	–
Warm-Electron Plug ECRF	MWe/GHz	33/112	9/71	4/70	11/195	4/70	11/195
Hot-Electron Barrier ECRF	MWe/GHz	67/40	110/60	23/110	25/13	23/110	25/13
Barrier Pumping							
Mechanism		Neutral Beams	Ion bounce frequency drift pumping	Ponderomotive drift pumping	Ponderomotive drift pumping	Ponderomotive drift pumping	Ponderomotive drift pumping
Low Energy NBI	MWe/keV	12/10	–	–	–	–	–
High Energy NBI	MWe/keV	85/190	–	–	–	–	–
RF System	MWe/MHz	–	20/0.05–0.6	50/46	25/144	50/46	25/144

Summary of Past Tandem Mirror Power Reactors

Parameter	Units	WITAMIR	MARS	MINIMARS	Ra	Current View DT Reactor	Current View D^3He Reactor
Central Cell Materials							
Structural		HT-9	HT-9	HT-9	SS	HT-9	Low Activation SS
Max. Temp. of Structure	^{o}C	530	550	525	300	525	550
Neutron Damage	dpa/FPY	40.5	60	46	0.5	46	1
He Production	appm/FPY	281	500	380	< 3	380	< 6
Neutron Multiplier		None (Pb)	None (Pb)	Be, Pb	None	None (Pb)	None
n Energy Multiplication		1.37	1.362	1.46	2.4	1.36	2.4
Coolant							
Type		$Li_{17}Pb_{83}$	$Li_{17}Pb_{83}$	He@8 MPa	water	$Li_{17}Pb_{83}$	Pb
T(in)/T(out)	^{o}C	330/500	350/500	275/575	218/300	350/500	350/500
Breeder							
Type		$Li_{17}Pb_{83}$	$Li_{17}Pb_{83}$	$Li_{17}Pb_{83}$	None	$Li_{17}Pb_{83}$	None
TBR		1.07	1.15	1.067	None	1.07	None
Blanket T_2 Inventory	g	101 (8)	7	6	None	6	None
Direct Converter							
Type		Venetian Blind	Venetian Blind	Gridless	Venetian Blind	Gridless	Venetian Blind
Net Electric Power from Direct Conv.	MWe	302	292	82	400	82	375
Coolant		H_2O	H_2O	H_2O	H_2O	H_2O	H_2O
Economics (in Year of Publication)							
Unit Capital Costs	%/kWe	2130	2437	2740	2283	2600 (1986)	1850 (1987)
Cost of Electricity	mills/kWh	36	46	41	34+ fuel	39 (1986)	27+ Fuel (1987)

Common Performance Characteristics of Past DT Tandem Mirror Reactor Designs

- Modest magnet fields in CC coils-(3-5 T)
- Pellet fueling
- Radiation damage resistant ferritic steels
- Use of $Li_{17}Pb_{83}$ to achieve high n energy multiplication, high T, and adequate TBR.
- Peak n wall loading, 2-4 MW/m^2
- Low T_2 inventory in breeder
- Credible maintenance of CC

Common Performance Characteristics of Past D^3He Tandem Mirror Reactor Designs

(Compared to DT)

- Lower n energy & higher direct conversion
- Axisymmetric end cells with RF stabilization
- Water cooled, low activation austenitic steel, permanent life.
- Very low n wall loading, 0.05-0.1 MW/m^2
- No T_2 breeding
- 2 MeV NBI's and 195 GHz heating

Recommended Improvements From Past Tandem Mirror Power Reactor Studies

DT

- Compact toroid fueling
- Axisymmetric end cells
- Optimize HT-9/$Li_{17}Pb_{83}$ blanket to avoid using Be

D^3He

- Change 3He/D ratio from 3:1 to 1:1
- Compact toroid fueling
- Use Pb coolant to raise overall thermal efficiency

Overall Conclusions
-Tandem Mirror Power Reactors

- Robustness of tandem mirror configuration makes previous technology choices still valid today.

- Physics improvements (e.g., axisymmetry, compact toroid fueling, etc.) will make the tandem mirror reactor even more attractive from the COE and maintenance standpoint.

I. ***Critical Physics Issues for Tandem Mirrors***

II. ***What Experiments Should Be Done Next?***

III. ***Summary and Conclusions***

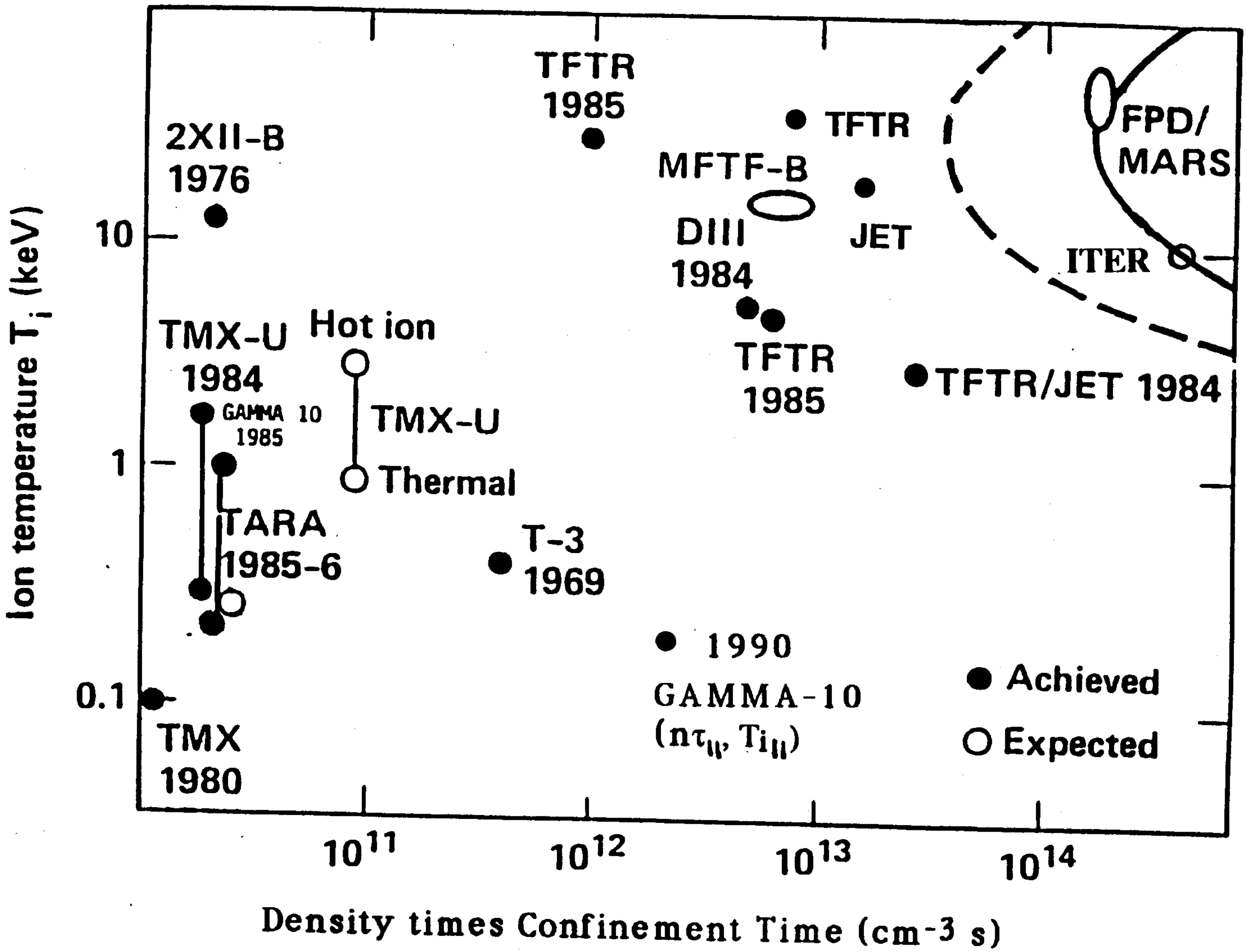
Critical Physics Issues for Tandem Mirrors

- Understand loss of plugging in TMX-U

  TMX-U: $n_c < 3 \times 10^{18}\ m^{-3}$
  Why?

- Achieve reactor relevant parameters in a microstable plasma

Lawson Diagram for Tandem Mirrors and Tokamaks



Tandem Mirror Parameters Achieved and Required

Parameter	Best Achieved* (as of 1992)	Reactor
Central Cell		
Density (m^{-3})	1.1×10^{19}	4×10^{20}
Ion temperature (keV), $T_{i\perp}$	5.6	25
Ion temperature (keV), $T_{i\parallel}$	0.3	25
Electron Temperature (keV), T_{ec}	0.28	20
Beta (%)	13	60
$n\tau_p$ (m^{-3} s)	1×10^{19}	1×10^{21}
End Plug or Anchor		
Plug-to-Central cell Density Ratio	0.4	
Beta (%)	15	25
Ion confining potential (kV), ϕ_c	2.0	148
ϕ_c/T_{ic}	5.5	7.4
Thermal Barrier		
Barrier Potential (kV)	1.1	126
Hot Electron Energy (keV)	50-100	297

*- Not achieved simultaneously, nor in the same machine

Critical Issues - continued

- Purely axisymmetric end cells with MHD stability

  Encouraging results with RF stabilization
  Encouraging results with the magnetic divertor
  Other ideas - not yet tested

- Thermal barrier pumping

  Neutral beam pumping is too expensive.

  RF ponderomotive drift pumping has been proposed as an alternative-no experiments as yet.

Critical Issues - continued

- Impurity Control

  The thermal barrier is an electrostatic potential well; fusion product ash and impurities tend to settle there.

  Need a thermal barrier pumping scheme which removes ash and impurities.

What Experiments Should Be Done Next?

GAMMA 10 Size Device

- Build an experiment the size of GAMMA-10, but with axisymmetric end cells.
- Develop effective thermal barrier pumping

MFTF-B Size Device

- Build an experiment the size and magnetic field strength of MFTF-B, but with axisymmetic end cells and an improved thermal barrier pumping concept.
- Goals for the central cell plasma:

Density	$3 \times 10^{19}\ m^{-3}$
Ion Temperature	15 keV
Electron Temperature	6 keV
$n\tau p$	$6 \times 10^{19}\ m^{-3}\ s$

What Experiments? - continued

This set of parameters, if achieved, would:

- produce a plasma roughly equivalent to that achieved to date in tokamaks (TFTR, JET),

- test
    - microstability
    - MHD stability
    - axisymmetric end cells
    - thermal barrier physics
    - thermal barrier pumping
    - impurity control

  in reactor-relevant plasma conditions,

- provide a basis for constructing an ignition device.

Summary and Conclusions

The total world investment in mirrors is about a factor of 20 less than that in tokamaks.

Summary and Conclusions - continued

At the termination of the major U.S. tandem mirror experiments in 1986, the primary research achievements were:

- demonstration of the basic tandem mirror concept,
- reduction of the end-loss by at least a couple of orders of magnitude compared with that in a simple mirror,
- establishment of thermal barriers in TMX-U and GAMMA 10,
- demonstration that tandem mirrors can be made stable against microinstabilities,
- operation with MHD stability using pressure-weighting of regions of good magnetic curvature.

Summary and Conclusions - continued

TMX-U did not meet all of its goals.

- Loss of plugging restricted to the central cell density to less than 3×10^{18} m^{-3}; the goal was 2×10^{19} m^{-3}.
- Electron temperature in TMX-U was no higher than that in TMX.

Summary and Conclusions - continued

Continued progress after 1986, although at a slower rate.

- Further improvement of thermal barrier potential and end cell potential
- Experimental corroboration of much of tandem mirror theory
- Operation with axisymmetric end-cells using RF stabilization and magnetic divertors

Summary and Conclusions - continued

- Technology choices made in 1986 for tandem mirror reactor studies would remain largely valid today.
- The physics of axisymmetric end cells and compact toroid fueling would be welcome additions to contemporary tandem mirror reactor designs.

Summary and Conclusions - continued

Critical plasma physics issues which need to be addressed are:

- understanding loss of plugging in TMX-U,
- achieving reactor relevant plasma parameters,
- achieving purely axisymmetric operation with MHD stability,
- developing alternative means of pumping thermal barriers,
- demonstrating adequate impurity control in a steady-state tandem mirror plasma.

Summary and Conclusions - continued

A possible experimental program leading to an ignition tandem mirror facility has been identified.