Innovative Confinement Concepts

Concept Exploration Experiments

Bick Hooper

Lawrence Livermore National Laboratory

Presented at the
Office of Fusion Energy Sciences Budget Planning Meeting
Gaithersburg, MD
March 18-19, 2003

Concept Exploration Experiments:

- Are carried Out By a Wide Range of PIs and Institutions
- Involve many collaborations across institutions
- Are highly Effective Scientifically
- Educate Many Undergraduate and Graduate Students

Number of experiments and supporting theory projects (ICC funded)	26
Number of PIs and co-PIs:	30
Number of Universities	11
Number of National Labs (includes 1 non-DOE)	4
Number of Industries	1

Number of refereed papers in past 2 years	82
Number of undergraduate students (part time) in past 2 years	58
Number of graduate students in past 2 years	61
Number of recent PhDs awarded	12

Concept Exploration ICCs can be summarized into Confinement Optimization and Physics Optimization Categories

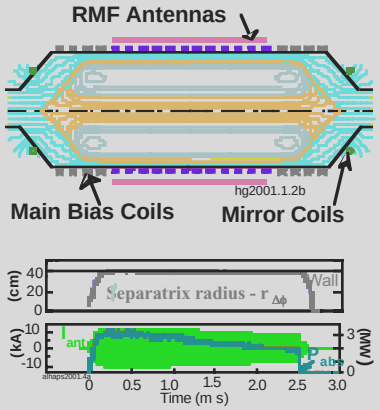
All Concept Exploration experiments have a strong component of Fundamental Understanding, and several contribute to Burning Plasma Physics

Category	Number of Expts and supporting Theory Proj.	Total Budget FY03 ($K)
Strong Stabilizing Field Experiments: stellarator (not incl. QPS), floating ring, tokamak, ST	5	6,307
Field-Reversed Configurations	6	2,880
Spheromak and Helicity Injection	3	3,798
Magnetized Target Injection	4	1,989
Other Confinement Optimization	4	1,162
Physics Optimization	4	1,722
TOTAL	26	17,858

Funding for individual projects varies from $35k to $2630k

Detailed information is available for the CE experiments in the CD file accompanying the talk – Example: FRC (below)

ICC Project Summary - FRCs



FRC Flux Build-up and Steady-State Maintenance

PI: Alan L. Hoffman

Thrust area: Configuration & Fundamental Understanding

IPPA Goal: 2.4 Resolve key issues for attractive steady-state FRC configuration

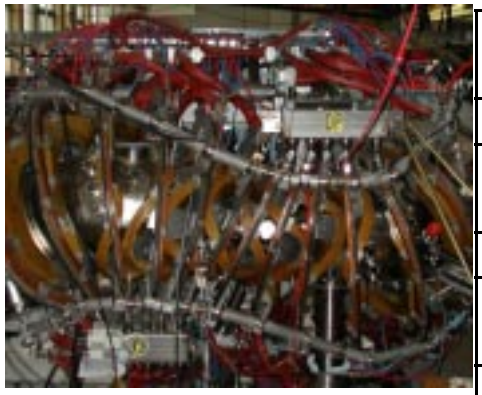
Objective is to produce higher temperatures and confinement fields for Rotating Magnetic Field (RMF) sustained FRC and determine confinement properties, while maintaining excellent stability.

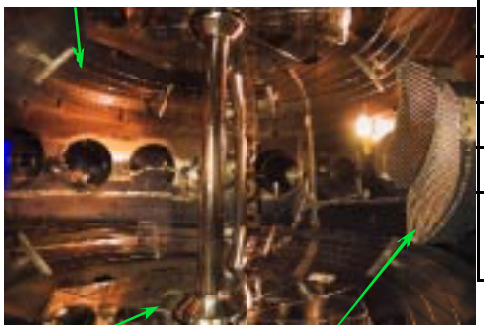
Next Review: 2005

	Base Program					Impacts	
FY	**Budget Guidance (requested)**	**FTE (Staff)**	**FTE (Tech)**	**Students/ PostDocs**	**Milestones /Tasks**	**+ 10%**	**- 10%**
03	$1640	4.5	4	5/2	Modify TCS for bakeout & wall conditioning	Faster & better construction & staff retention	3 month const. delay (-1 staff, -1 PD)
04	$1624 ($1673)	4.5	4	4/2	Run with low impurity level	Build complete multi-point TS (+.5 staff, 1 student)	No Thomson scattering (-.5 staff)
05	$1640 ($1706)	5	4	4/1	Produce > 100 eV temperatures & good confinement	Add soft x-ray tomography (+2 students, +1 PD)	Reduce to half-time ops. (-1 staff)

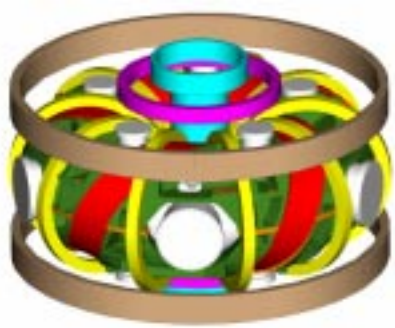
- **The following viewgraphs include information from these summaries**

ICC/CE — Strong stabilizing field experiments





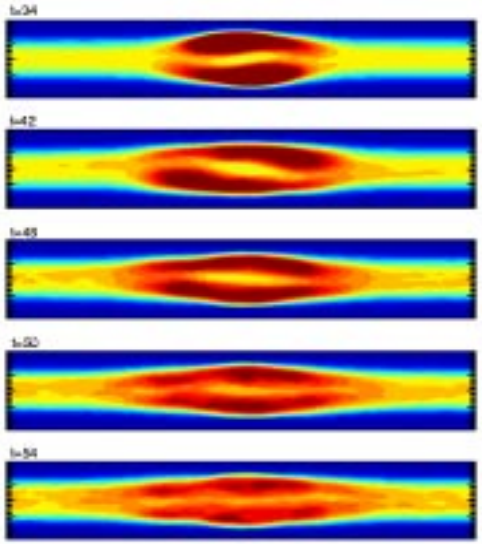
EXPERIMENT	PI	LAB/UNIV.	BUDGET FY03 (k$)	NEXT REVIEW
HSX: Quasi-Helically Symmetric Stellarator	David Anderson	U. Wisc./ UCLA	1,674	FY05
CTH: Compact Toroidal Hybrid Stellarator	Steve Knowlton	Auburn U.	515	FY04
LDX: Levitated Dipole Experiment	Jay Kesner/Mike Mauel	MIT/ Columbia	1,356	FY03
ET: Electric Tokamak	Bob Taylor	UCLA	1,906	FY03
Pegasus: Ultra Low Aspect Ratio Toroid	Ray Fonck	U. Wisconsin	856	FY05



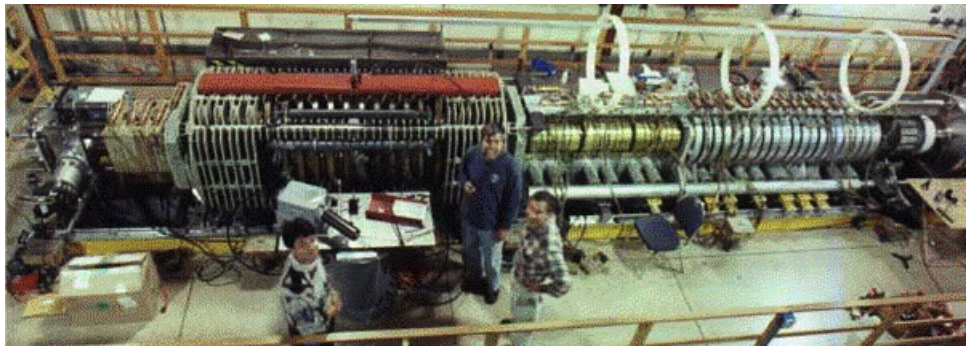
Goals and Opportunities — Strong stabilizing field exp.

EXP.	3-YEAR GOALS	OPPORTUNITES / FUNDING NEEDS (FY04, FY05)
HSX	Operate ECH at full pwr; study flow drive/damp. B=1T operation with profile diagnostics; meas. χ 53 GHz ECH @ 350 kW; low ν, high T_e	Fluctuation studies; improve diagnostics ($110K) Increased diagnostics ($160K)
CTH	3-D equilibrium reconstruction using MSE Study disruptions & magnetic islands	Fluctuation studies; improve diagnostics ($60K) Accelerate MSE diagnostic for internal B measurement ($60K)
LDX	Complete assembly; first plasma in months Eval. MHD stability, pressure profiles (hot electrons) Examine energy & particle confinement Measure convective flows	Install advanced diagnostics & profile control ($140K) Install 100kW ion heating; explore higher density ($140K)
ET	Apply 4 MW ICRH + ICCD, HHFW Demonstrate bootstrap driven profile + mag well High Beta + Stability Control	1 Post-Doc, Thomson Scattering ($200K) 1 Post-Doc, 20 keV CX diagnostic ($200K)
Pegasus	Complete facility rebuild & upgrade Suppress internal MHD Access High-field utilization Stability studies at low-q, high-beta	Grad Student, Diagnostic Neutral Beam (DBN) profile measurements ($140K) DNB profile measurements ($100K)

ICC/CE — Field-Reversed Configurations



EXPERIMENT	PI	LAB/UNIV.	BUDGET FY03 (k$)	NEXT REVIEW
TCS: Translation, Conf., and Sustainment Exp.	Alan Hoffman	U. Wash.	1,640	FY05
RMF (Rotating Magnetic Field) Collaboration	Glen Wurden	LANL	178	FY05
Num. and Theoretical Stability Properties	Ron Davidson/ Elena Belova	PPPL	208	FY03
Rotating Magnetic Field Sustainment	Sam Cohen	PPPL	277	FY03
SSX-FRC: (Swarth. Spher. Exp. – FRC)	Mike Brown	Swarthmore	171	FY03
Ion Ring Experiment	John Greenly	Cornell	406	FY03

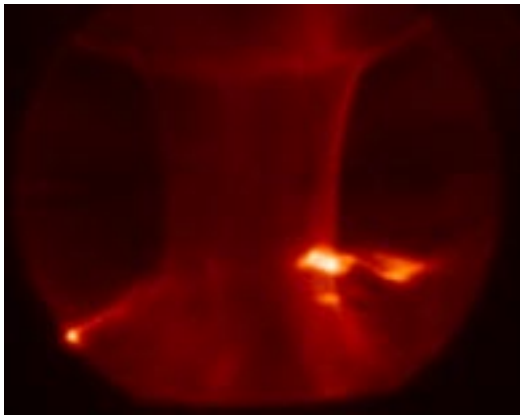


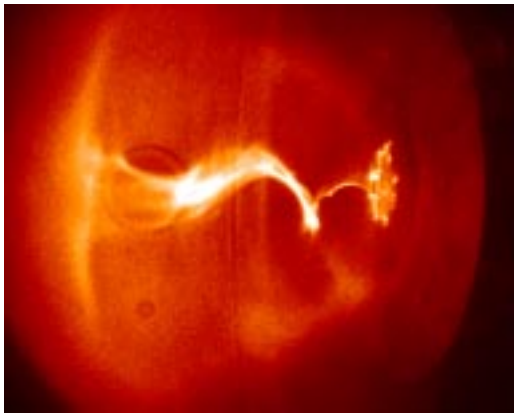
Goals and Opportunities — Field-Reversed Configurations

EXP.	3-YEAR GOALS	OPPORTUNITES / FUNDING NEEDS (FY04, FY05)
TCS	Modify TCS for bakeout & wall cond. Run with low impurity level Produce > 100 eV temperature & good confinement	Build complete multi-point TS (+.5 staff, 1 student) ($170K) Add soft x-ray tomography (+2 students, +1 PD) ($160)K)
RMF Collab	Build, install, operate 20-channel bolo. Conduct radiation balance studies	Buy VME bus digitizers ($20K) Install second 20-channel bolometer view ($20K)
Stab. theory	Characterize stabilization and sustainment of FRCs by energetic ion beams Study oblate stability for non-Max. ions Incorporate add. electron physics (e.g., trapped electrons) and investigate stability properties	Develop prelim. physics design - parameter study for ion-beam-sustained/ stabilized FRC ($40K, $40K)
RMF Sust.	Evaluate τ_E at 1 kW Evaluate τ_E at 10 kW, pulse > 1 ms Determine T_e vs density	T_e diagn. ($140K) 100 kW RMF ($140K)
SSX-FRC	Complete FRC studies Analyze data / upgrade experiment Measure ion heating and flow by Doppler spectroscopy	Fast imager ($20K)
Ion Ring	Inject ion ring into reversed field Form high-flux FRC with injected ring Study FRC-ring stability	Partially support student to completion of PhD ($40K) Capital for diagnostic equipment ($80K)

ICC/CE — Spheromak and Helicity Injection

EXPERIMENT	PI	LAB/UNIV.	BUDGET FY03 (k$)	NEXT EVIEW
SSPX: Sustained Spheromak Physics Experiment	Dave Hill	LLNL	2,630	FY05
Physics of Magnetic Helicity Injection	Paul Bellan	Cal Tech	367	FY03
HIT: Helicity Injected Torus	Tom Jarboe	U. Wash.	801	FY04



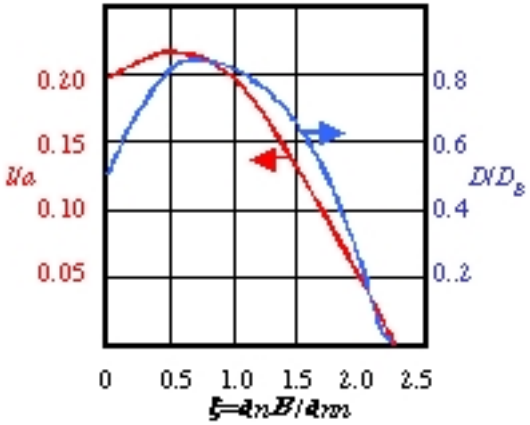


Goals and Opportunities — Spheromak and Helicity Injection

EXP.	3-YEAR GOALS	OPPORTUNITES / FUNDING NEEDS (FY04, FY05)
SSPX	Improve understanding of energy confinement and flux/current amplification; increase both Install & operate new small-radius injector to test flux amplification hypotheses Install modular bank to improve sustainment efficiency, extend pulse length, and provide injection flexibility	Increase operations & install modified bank prototype ($675K) Complete modified bank & increase operations ($815K)
Magnetic Helicity Inj.	Resolve details of kink-to-spheromak trans. Study flow processes and convection of magnetic flux Determine dependence of formation on gas injector arrangement Determine spatial and temporal properties of energetic particle formation Determine dominant transport processes	Resolve spheromak detachment process at x-point using *soft x-ray imaging and energy-resolved soft x-ray detector* ($40k) Modify spheromak to become a high-ripple ST, where ripple disappears due to strong MHD pumping effect (identified in ongoing experiments) ($80K)
HIT	Mix CHI and Ohmic on HIT-II Finish const. HIT-SI Plasma Experiment Move HIT-SI to HIT exp. Achieve I_p=100kA, t = 5ms on HIT-SI	+1 student, +0.3 FTE, increase rate of progress, add soft x-ray diag. ($80K, $80K))

ICC/CE — Magnetized Target Fusion

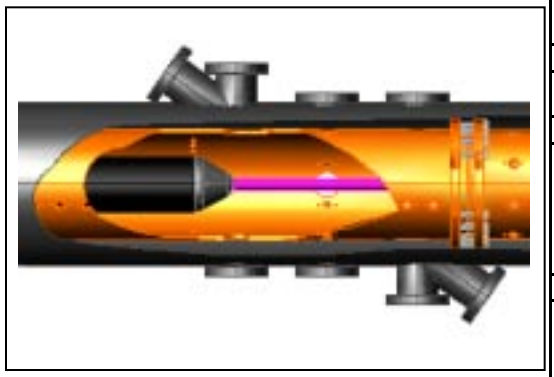
EXPERIMENT	PI	LAB/UNIV.	BUDGET FY03 (k$)	NEXT REVIEW
MTF: Magnetized Target Fusion	Glen Wurden/ Tom Intrator	LANL	1,399	FY03
Imploding Liner for MTF	Jim Degnan	AFRL	515	FY03
Theory of Strongly Collisional MTF Plasma	Dmitri Ryutov	LLNL	40	FY03
MTF Theory: Eq., stabil., comp.	Paul Parks	GA	35	FY03



Goals and Opportunities — Magnetized Target Fusion

EXP.	3-YEAR GOALS	OPPORTUNITES / FUNDING NEEDS (FY04, FY05)
MTF	Characterize in-situ FRC; Raise fields to increase performance. Translate and measure FRC in liner Construct integrated plasma/liner experiment at Shiva Star. Model plasma/liner implosions	Start integrated design. Expand theory support. Add university collaborations. ($1M) Construct integrated plasma/liner experiment. Model implosions ($1M)
Imploding Liner	Improve FRC n, T, τ Pulse Power O&M, diagnostics & analysis Construct & use more crowbar switches, FRC-liner translation hardware; Conduct FRC purity experiments FRC injection, start deformable contact liner experiments for FRC injection	Perform deformable contact liner experiments at AFRL ($500K) Construct & start liner-FRC experiments at AFRL ($500K)
Theory: Strong. Coll.	Analyze anomalous transport in collisional plasma Eval. current-driven microinstab in collisional FRC and estimate diffusion coefficients Deter. collisional effects in gross stability	Analyze stability of the plasma liner as standoff driver; begin numerical studies of compression ($115K) Optimize the plasma liner ($115K)
Theory: Equil. stability, compress.	Continue support of MTF program by modeling equilibria, stability, and compression of FRCs	Extend modeling support ($25K)

ICC/CE — Other Confinement Optimization

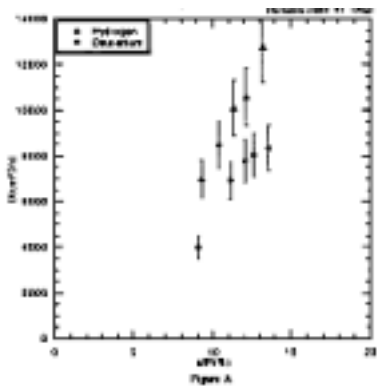


EXPERIMENT	PI	LAB/UNIV.	BUDGET FY03 (k$)	NEXT REVIEW
ZAP: Flow Z-Pinch	Uri Shumlak	U. Wash.	285	FY03
MCX: Maryland Centrifugal Experiment	Rick Ellis/ Adil Hassam	U. Maryland	453	FY03
POPS: Oscillating Inertial Electrostatic Confinement Exp.	Rick Nebel	LANL	274	FY03
Magneto-Bernoulli Confinement	Roger Bengtson	U. Texas – Austin	(150) Not funded as of 3/03	FY05

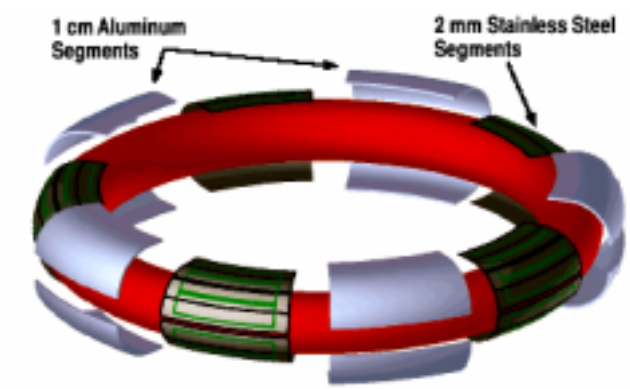
Goals and Opportunities — Other Confinement Optimization

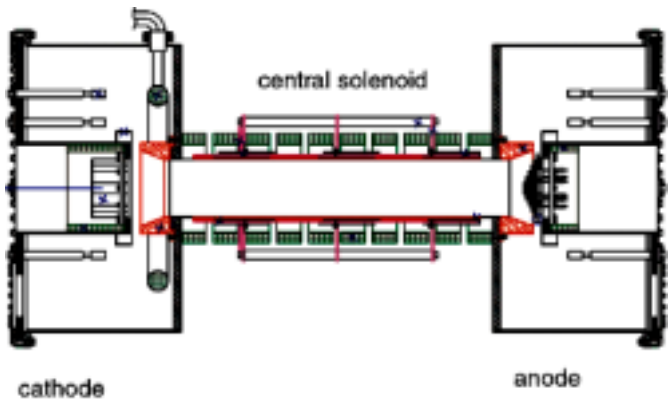
EXP.	3-YEAR GOALS	OPPORTUNITES / FUNDING NEEDS (FY04, FY05)
ZAP	Measure int. B; double plasma length; increase I_p duration; extend plasma life Measure v(r) evolution and correlate with stability; raise T; investigate limits to shear stabilization Approach quasi-steady state	Hire postdoc to begin TS development; add diagnostics (filtered diodes, bolometer) ($230K) Tomography for axial mode structure; refine Zeeman splitting diagnostic; develop multipoint TS ($230K)
MCX	Obtain supersonic rotation Implement advanced diagnostics Optimize operating regimes Extend pulse length, preionize Assess centrifugal confinement Assess MHD stability and V' shear	Replace technician with engineer ($45K, $50K)
POPS	Evaluate virtual cathode stability Demonstrate POPS mode of operation Determine virtual cathode uniformity	Study kinetic stability ($60K) Operate at high voltage ($60K)
Mag.-Bern. Confine.	Demonstrate centrifugal confinement/ Increase voltage and density Show critical rotation/ improve diagnostics Seek bifurcated states/ compare with simulations	Add student ($30K)

ICC/CE — Physics Optimization



EXPERIMENT	PI	LAB/UNIV.	BUDGET FY03 (k$)	NEXT REVIEW
HBT–EP: High Beta Tokamak – Extended Pulse	Jerry Navratil/ Mike Mauel	Columbia U.	950	FY05
Tokamak Transport and Feedback Control	Amiya Sen	Columbia U.	246	FY03
Stabilization of RWM Using Rotating Metal Walls	Cary Forest	U. Wisconsin	232	FY03
CTIX: Compact Toroid Injection Experiment	David Hwang	UC Davis	294	FY04





Goals and Opportunities — Physics Optimization

EXP.	3-YEAR GOALS	OPPORTUNITES / FUNDING NEEDS (FY04, FY05)
HBT-EP	Resistive Wall Mode Control at Ideal Limit Control with DSP Combine RWM & Tearing Mode Control	Add postdoc; multi chord rotation ($100K) Add student; data system upgrade ($100K)
Transport-Feedback Control	Establishment of the basic physics of isotope scaling of tokamak transport Production, identification and parametric signature of ETG modes Neural network for adaptive, learning control of plasma instabilities	Increase operations by 30% to explore further the key physics of isotope scaling and seek the ETG mode ($50K) Seek definitive identification of ETG modes; explore electron transport ($50K)
Rotating Metal Walls	Study properties of RWM and Ferromagnetic WM in linear pinch Stabilize RWM with rotating mechanical shell Perform experiments with flowing liquid metal walls	Add postdoc ($70K, $70K)
CTIX	Optimize Spheromak-CT formation, increase gas efficiency Study SCT interaction with external field Design, test rep-rated injector for hi-beta plasma devices Initial operation of rep-rated new fueler	Initial design of MTF target vessel. Construct new fueler ($30K) Initial injection into MTF target ($30K)

What is working and what is not?

STUDENTS

"The revival of ICC-level experiments on campuses is helping us recruit more and better graduate students, as well as attract over-achieving undergraduates into the field. The main significant issue is the chronic underfunding of the experiment. Presumably, we are not alone."

"The constraints on our program have been a lack of interest by prospective graduate students in fusion – they all seem to be going into nano-technology or biophysics."

MANPOWER AND DIAGNOSTICS

"The programmatic lesson is that it is a good idea to set up an experiment dedicated to revealing as clearly as possible what actually occurs in a plasma, rather than starting out being prejudiced with the predictions of some theoretical model. . . . We are also extremely limited in diagnostics. Any significant additional diagnostic really requires at least half a person, and we just do not have the manpower."

"[A major constraint is] lack of manpower, especially to build, operate, and interpret diagnostic and RF systems."

"Collaborations with 'lab xyz' scientists have been extraordinarily informative."

"At the suggested funding levels we will continue to be in a constantly-shrinking manpower mode, with essentially no fabrication or capital money."

MODELING

"More support is needed for advanced modeling/code development in ICC area – unique codes are required, because standard tokamak's codes are not applicable (for example, for FRC, the full kinetic ion description is needed, and large-beta effects must be included, and etc)."

Good News / Bad News!

Good News:

- **The ICC/CEs are achieving significant scientific results**
- **Theory and modeling has helped guide and interpret some experiments**
- **Results are being published in the best scientific journals**
- **Coupling with other areas of science – e.g. astrophysics – is occurring**
- **There are many, strong inter-institutional collaborations**
- **There is progress towards the goals stated in the proposals**
- **Students are learning about fusion and coming into the program**

Good News / Bad News!

Bad News:

- **Results – and their scientific quality – are severely constrained by inadequate diagnostics**
- **There is insufficient manpower on all the experiments**
- **Theory and modeling could contribute considerably more**
- **Many experiments take 3 or more years to construct, and many years to complete, because the funding levels do not match the sophistication and complexity necessary for a state-of-the-art fusion experiment**
- **No experiments even approach the $5M level called for when the ICC program was established**
- **Tight funding – and consequential slow progress – makes it difficult to turn-over the portfolio of projects for new ideas**

Recommendation: Funding for the ICCs, and for the CEs in particular, should be increased both in absolute dollars and as a fraction of the program.

- **A ramping of the CE funding from $17.8M to $25M in FY05 would bear significant scientific benefits for MFE.**