The Path to Fusion Energy for Concepts Currently at the Concept Exploration Level

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General comments on CE experiments and fusion energy

These [CE] programs are aimed at innovation and basic understanding of relevant scientific phenomena. [*FESAC Report on Alternate Concepts*]

- Innovation — search for a better fusion reactor
- Coupling to other sciences — e.g. self-organized plasmas to reconnection physics and space plasmas
- Education — The young scientists and engineers who will develop fusion energy

We now have examples of PoP experiments to guide our planning

- NSTX — Followed from success of START, a CE-level experiment
- MST — Upgrade path from CE-level MST
- NCSX — Built on theory and a strong international data base but no CE experiment

The portfolio approach is being applied in a flexible and pragmatic way

The path forward for each concept can take advantage of its unique attributes

Three types of CE programs

There is a large variation in the maturity and nature of CEs — Thus it is useful to consider 3 examples

Toroidal confinement concepts

- **Spheromak**
- **FRC**

Concepts operating in a very different parameter space

- **Magnetized Target Fusion (MTF)**

Non-toroidal concepts — generally in early exploratory stage

- **Flow Z-pinch ("ZAP")**
- **Electrostatic confinement**
- **Others**

Development plan for toroidal confinement – spheromak

Status:

- One moderate-sized experiment (SSPX) and one supporting experiment (HIT-SI)
- Diagnostics on SSPX from several University groups
- Small theoretical effort, including simulations with NIMROD resistive MHD code
- Synergy with RFP physics

SSPX: Focused on energy confinement and buildup of magnetic flux and current

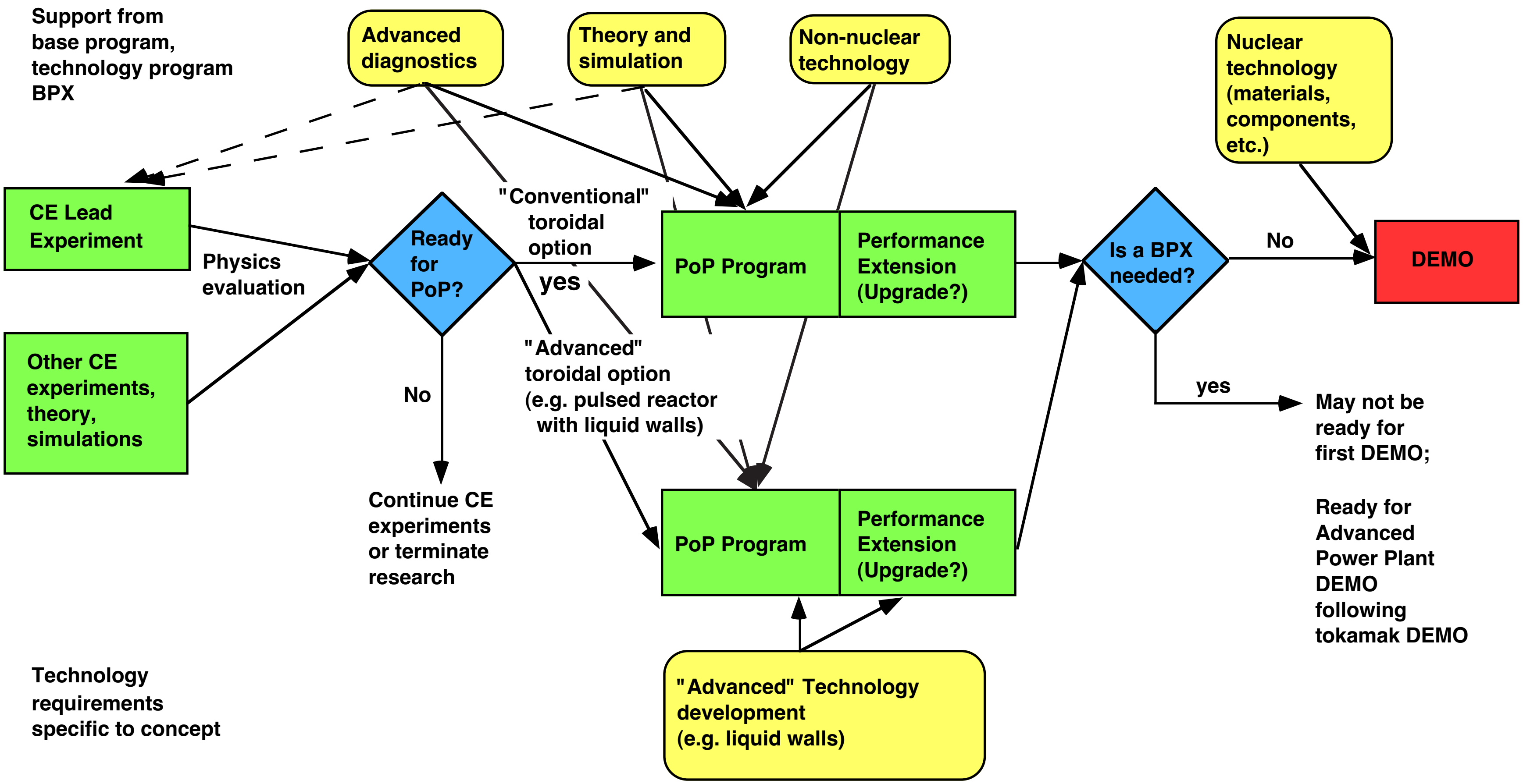
- $T_e > 250$ eV
- Magnetic fluctuations ~ 1%
- χ_e(core) $< 30\ m^2/s$

Reactor visions:

- "Tokamak-like" reactor with no toroidal-field coils
- "Boiling-pot reactor"
- Steady-state reactor with flowing liquid lithium or salt walls
- Pulsed reactor with liquid-lithium protecting the wall
- Reactor sustained by repetitive merging of spheromaks

This wide range of reactor visions offers opportunities for a better reactor, but the development plan will have several decision points as the concept progresses towards application to fusion energy

Timeline to develop a CE Toroidal Configuration



Start operation	+5 to 10 years	+ 20 years	+ 30 years	+ 40 years
1998	2007	2017	2027	2037

(Possible dates for spheromak development)

Note: In the present program, rate of progress is limited by funding;
development would be accelerated if sufficient resources were available.

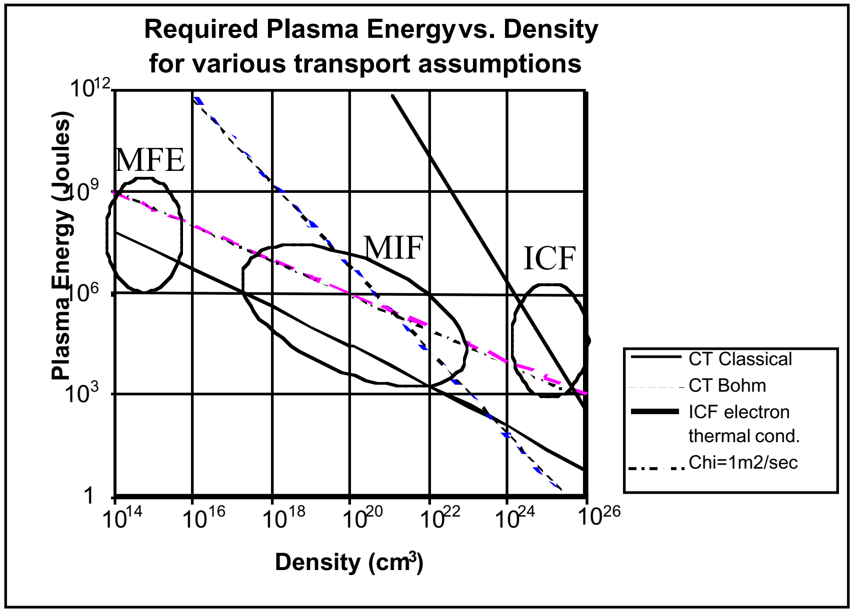
EBH 1/13/03

Budget for a program, not just an experiment

Possible cost of development to DEMO for a CE toroidal concept using IPPA guidelines. Estimates are based on costs in the tokamak (PE) and ICC-PoP programs and are rough. Not included are costs such as nuclear materials development, supported by the lead program.

Cost Category	Cost/year ($M)	Duration (years)	Total Cost ($M)
Concept Exploration (2 experiments and supporting research)			
Exp. #1			
Construction	1	2	2
Operations	3 – 5	8	24 – 40
Exp. #2			
Construction	1	2	2
Operations	3 – 5	8	24 – 40
Theory & Sim.	0.3 – 0.5		2.4 – 4
Proof of Principle (1 PoP and 1 CE experiment and supporting research)			
PoP exp.			
Construction	5 – 7	4	20 – 30
Operations	20 – 30	10	200 – 300
CE exp.			
Construction	1	2	2
Operations	3 – 5	8	24 – 40
Theory & Sim.	2 –3		20 – 30
Technology	5		50
Performance Extension			
Const./upgrade	7 – 12	4	30 – 50
Operations	50	10	500
Theory & Sim.	10		100
Technology	10		100
Total		38	1100 – 1300

Development plan for MTF



Imploding liner compresses target plasma to fusion density and temperature

Operates in plasma-density regime intermediate to MFE and IFE

Much less sensitive to confinement than MFE

Confine. time ≈ dwell time = 0.1-1 μs

Alpha particles contribute little to plasma heating, so insensitive to alpha physics

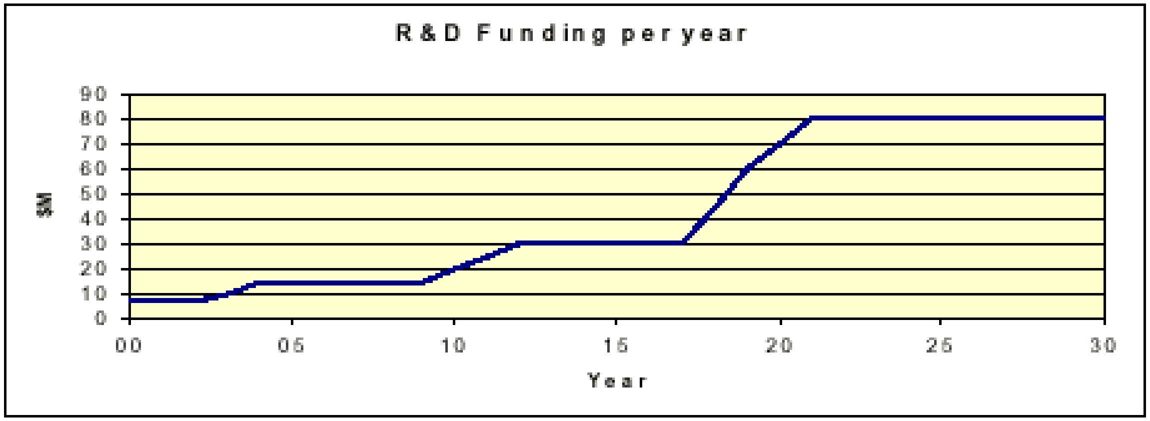
Status:

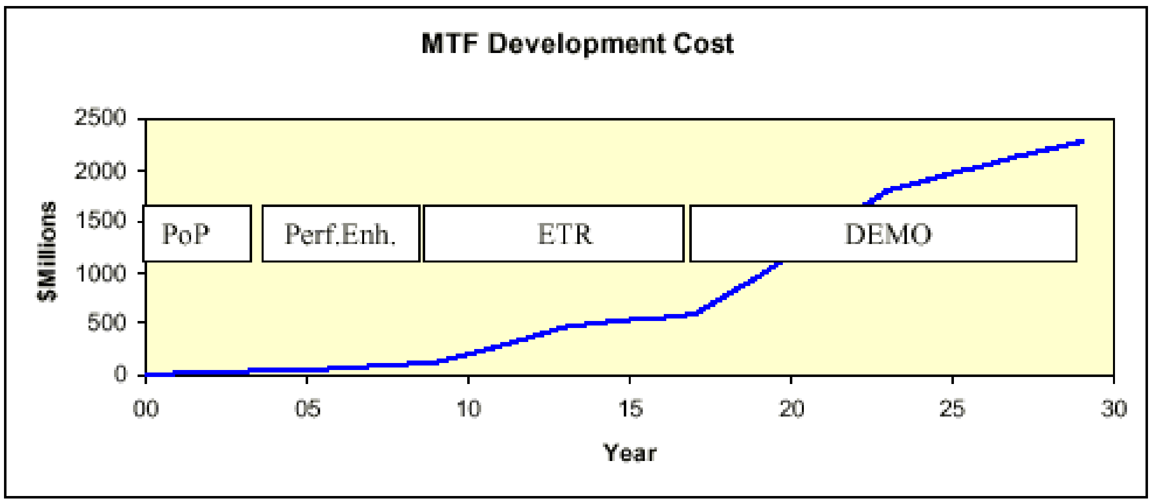
- Target: FRC in required density range (> 10^{16} cm^{-3}) developed, T ≈ 60 eV; experiments to increase T to 200 eV underway
- Imploding liner experiments on Shiva Star compressed plasma quasi-spherically to 1 MBar and magnetic field cylindrically by factor of 11

Reactor visions:

- Fast liner with disposable solid electrode and liquid blanket of FLIBE
- Slow liner (“LINUS”) with liquid metal liner to compress plasma

Timeline and costs to develop MTF





Assumptions

***PoP stage*:**
Shiva Star at Phillips Laboratory – FRC heating to keV temperatures by liner implosion, with Q_{equiv} = 0.01-0.10. 3 years at $7M./year

***PE stage*:**
Optimize plasma targets. ATLAS at the Nevada Test Site – single-pulse mode obtains Q_{equiv} = 0.1-1.0 in ~ 2 years. Optimization and assessment ~ 7 years at ~ $20M/year.

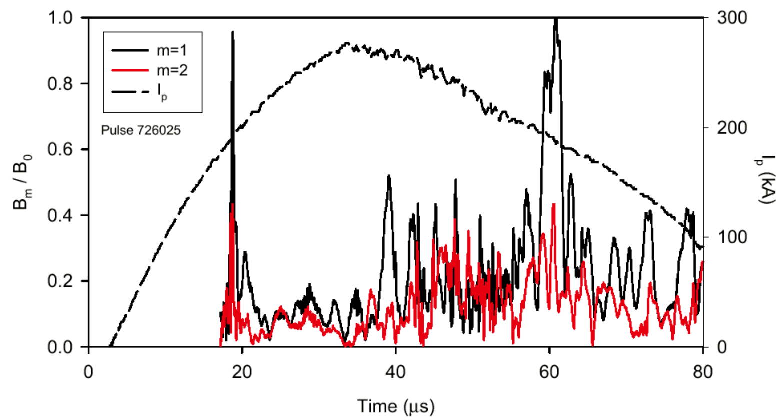
***ETR stage*:**
Choose fast or slow liner approach. Test rep-rated power supply in finite burst mode. 8 years at ~ $30M/year. ($250M facility.)

***DEMO*:**
250-MW unit; 1-10 GJ yield; 0.1-1 Hz; Reliable rep-rated containment. Nuclear materials and tritium handling. 12 years at $80M/year. ($800M facility.)

Development of Flow Z-pinch

Status: An experiment, not yet a program

- **MHD calculations indicate stabilization with sufficiently sheared flow**
  - **Unsettled differences on the flow velocity required**
- **Experimental results: Z-pinch with steep velocity shear at edge had m=1 and m=2 fluctuation amplitudes < 10% for 17 μs. After that time, the shear became small and fluctuations became > 20%**



Reactor vision:

- **Reflex geometry for power reactor or for neutron source**
  - **Issues of recycling of magnetic energy, electron thermal conduction, enthalpy loss remain to be settled**

Because of the physics status and because of the low funding of the Flow Z-pinch, there has been no attempt to quantify a timeline or costs

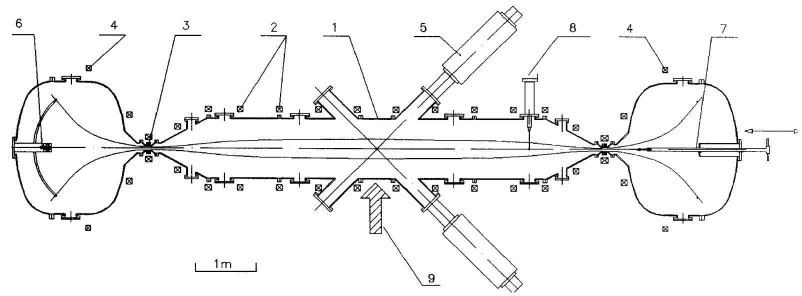
If a reactor is possible, the simplicity of the concept should allow significantly reduced costs from the tokamak or toroidal ICCs

The Gas Dynamic Trap – Neutron Source (GDT-NS) is ready to move to the PoP/PE level

In the GDT-NS, sloshing ions from neutral beam injection form two intense neutron sources near the ion turning points (close to the mirrors)

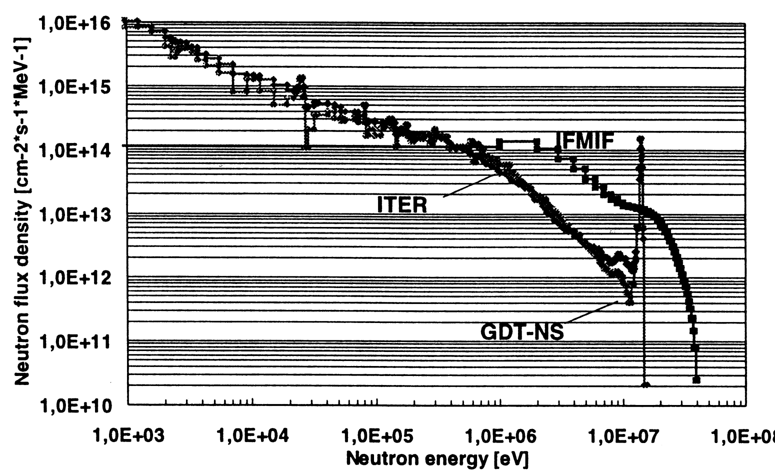
GDT experiments at Novosibirsk have demonstrated the critical physics, e.g.:

- $T_e \approx 150$ eV and scaling to high temperatures by flux-expansion in end tanks
- MHD stability in agreement with theory
- Microstability of sloshing ions



Extensive design studies have been made of a GDT fusion neutron source

- High neutron fluxes are localized near sloshing-ion turning points, so damage to machine components is limited
- The neutron spectrum is predicted to be very close to that in ITER



Criteria for PoP decision

IPPA:

- "Physics shown to be promising; energy vision attractive"
- PoP experiments have sufficient resources to "develop an integrated understanding of the basic science of a concept
- "Well diagnosed and controlled experiments are large enough to cover a fairly wide range of plasma parameters and some dimensionless parameters in the power plant range

A caveat to the IPPA definition: It calls for temperatures of "a few keV." It is clear from the MST experience that there may be a learning process necessary to achieve this, and that initially temperatures may be limited to about 1 keV

Peer review is an essential part of the process to determine when an experiment is ready to move to PoP status

- Is the physics well enough understood to warrant the additional resources?
- Is the reactor vision attractive enough to warrant the additional resources?

The review must recognize that the limited resources at the CE level will limit the physics base being reviewed

For many experiments the appropriate step will be to a larger experiment; for others, the MST route of evolution through upgrades and new diagnostics will be appropriate

Resource requirements

- **None of our CE experiments are at the $5M level — the IPPA "maximum"**
  - **This slows progress and lengthens the duration of the CE experiments**
  - **More seriously: Low funding limits scientific results through constraints on experiment upgrades and diagnostics — *A stretched-out program may never have sufficient resources to test important ideas***

- **Concepts which show significant progress also need:**
  - **Experiments on specific issues**
  - **Theory**
  - **Computational simulations**

The present funding of the ICC/CE program is less than needed to make rapid progress towards the energy mission.

- **A doubling of CE funding would generate a significant increase in the rate-of-progress**
- **This would still be less than the funding — extrapolated to today's dollars – of the equivalent experiments in the 1970-80 time frame**