Cost effective path to DEMO

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To

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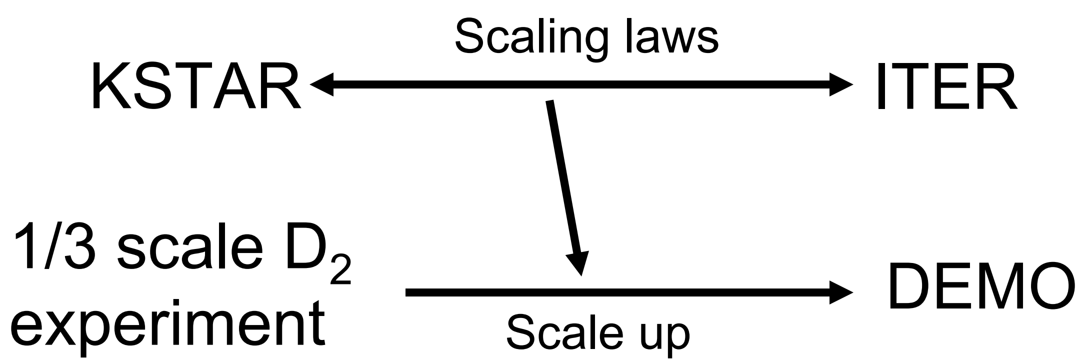
Outline

- Maximizing the development-cost benefit from ITER knowledge
- Getting on cost effective path
- Requirements of smaller scale experiment
- Cost problems are helped with efficient current profile sustainment
- Discovery of a new current drive method with profile control potential
- Summary

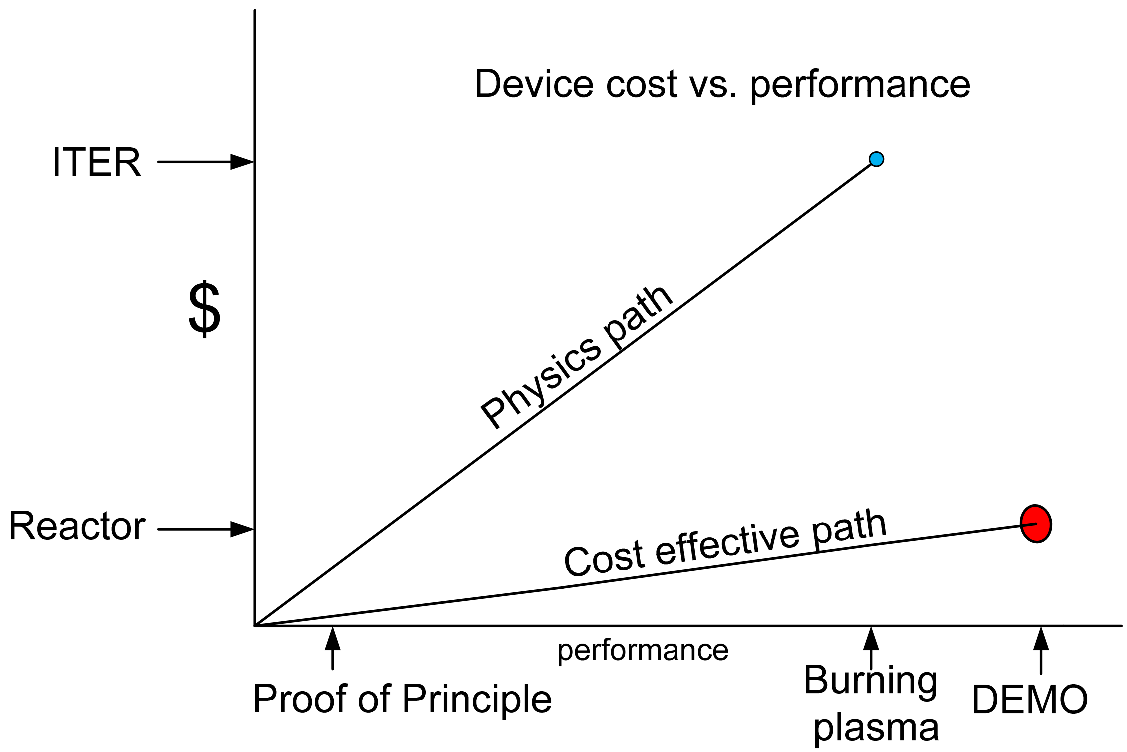
Cost benefit of scaling results from ITER must be maximized

- Scaling studies will allow us to predict the performance of the DEMO using data from a smaller scale experiment.



- Future fusion physics experiments only need to be ~1/3 the size of DEMO.

Need to get on a cost effective path to DEMO



- Have to get on cost effective path someday.
- Development costs are less if we do it now.

Scaling from ITER sets DEMO-PoP cost

• Cost of ITER	$ 20 B
• Cost of KSTAR	$ 330 M
• Cost scaling: 1/3 size without blanket and shield is 1/60 the cost. About $(1/3)^3/2$	
• Total cost of ARIES AT power plant	$2.8 B
• Half of direct cost is the reactor	$ 1.4 B
• Similar 1/3 scale size of DEMO can cost	$1.4B/60 = $ 23 M
• First of a kind credit (60%)	$ 37 M

Some specification of 1/3 scale PoP based on ARIES-AT

- Machine cost $37 M
- R 1.7 m
- Aspect ratio 4
- Beta > 9%
- Exceed Greenwald 60%
- Coil-1st wall space 0.25 m
- Boot strap frac. > 90%
- Plasma performance depends on scaling laws, perhaps like DIII-D

- High temperature super con. coils
- High temperature structure material
- Control temperature gradient modes
- Scalable divertor
- Scalable fueling
- Steady state current drive
- Solenoid free startup
- Prevent disruption
- Control ELMs

- Has to be the next experiment (s).

Efficient current drive with profile control solves many problems for 1/3 scale PoP

- Machine cost $ 37M
- R 1.7 m
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- High temperature super con. Coils
- High temperature structure material
- Control temperature gradient modes
- Scalable divertor
- Scalable fueling
- Cost and power efficient steady state current drive with profile control
- Solenoid free startup
- Prevent disruption
- Control ELMs

Most of the remaining issues are addressed if the control is sufficient for removal of the TF coil

- Machine cost $37M
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- High temperature super con. Coils
  $\Rightarrow$Normal conductors
- High temperature structure material
- Control temperature gradient modes
- Scalable divertor
- Scalable fueling

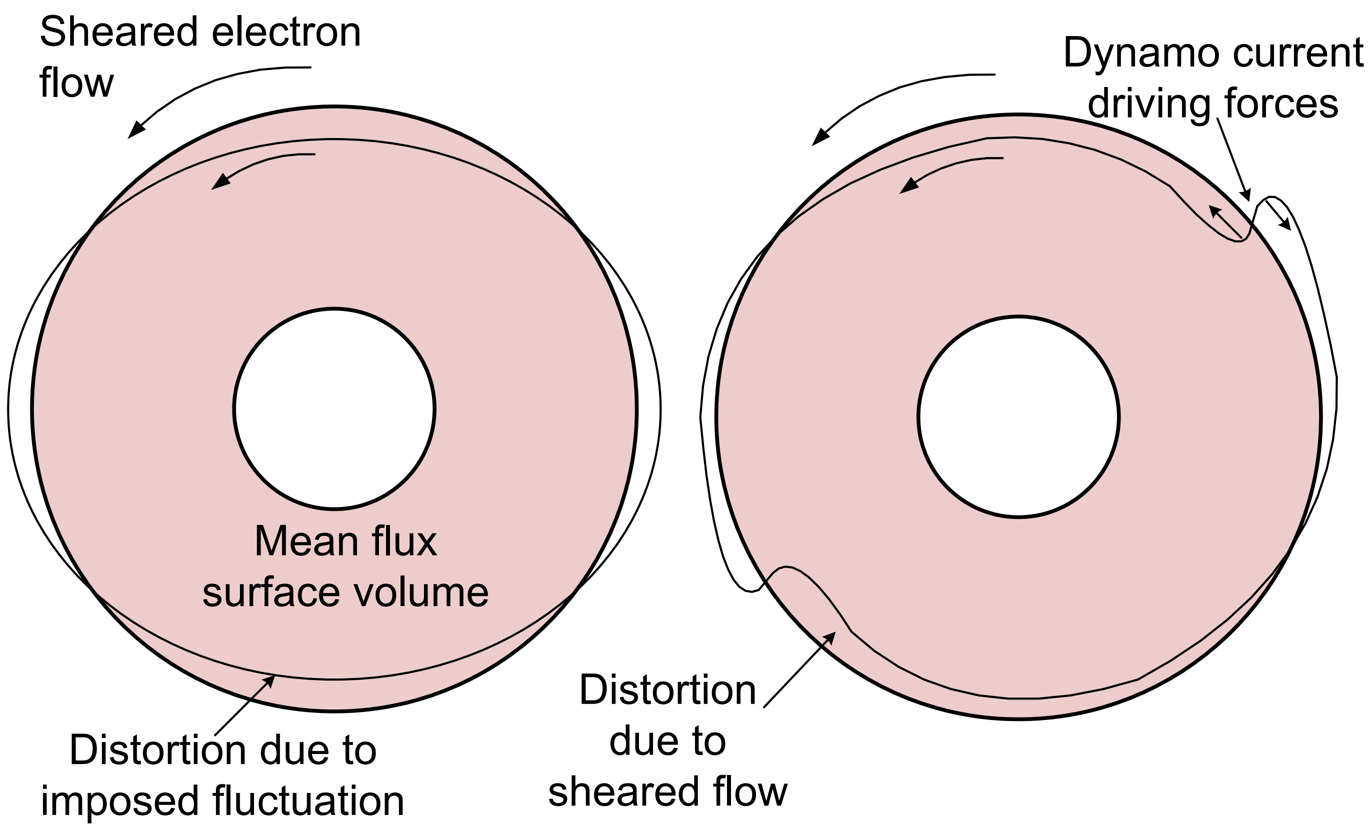
- With efficient current drive and profile control external toroidal field may not be necessary for stable well-confined equilibria with acceptable beta

- Cost may be low enough that very high temperature nuclear materials are unnecessary

Newly discovered Imposed-Dynamo Current Drive might give the control

- Observed to do current drive and should allow profile control.
- Similar to the way magnetic perturbations cause a force in a plasma rotating next to a resistive wall, perturbations also produce a force on differential flows in the electron fluid giving current drive.
- Sheared electron flow distorts almost any perturbation into cross-field current driving force. (B-field is frozen in the electron fluid.)
- Imposed perturbation profile $\Rightarrow$ defined current drive profile
- Only requires $\delta B/B \cong 10^{-4}$ in a reactor.

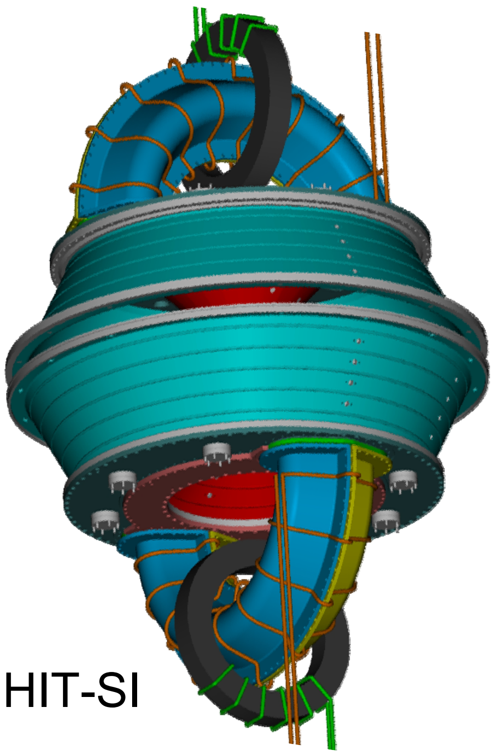
Imposed Dynamo Current Drive needs high electron fluid velocity at the edge and imposed fluctuations



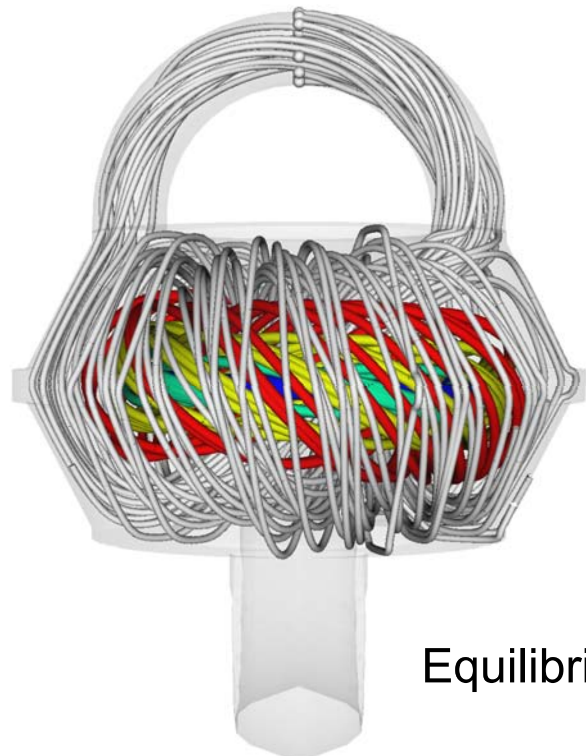
Maxwell stress on mean flux surface = current driving force inside flux surface

$$\int \frac{\delta B_{\perp} \delta B_{\parallel}}{\mu_o} da = \int ne(\eta j_{\parallel} - E_{\parallel})dvol$$

HIT-SI meets the requirements for imposed dynamo



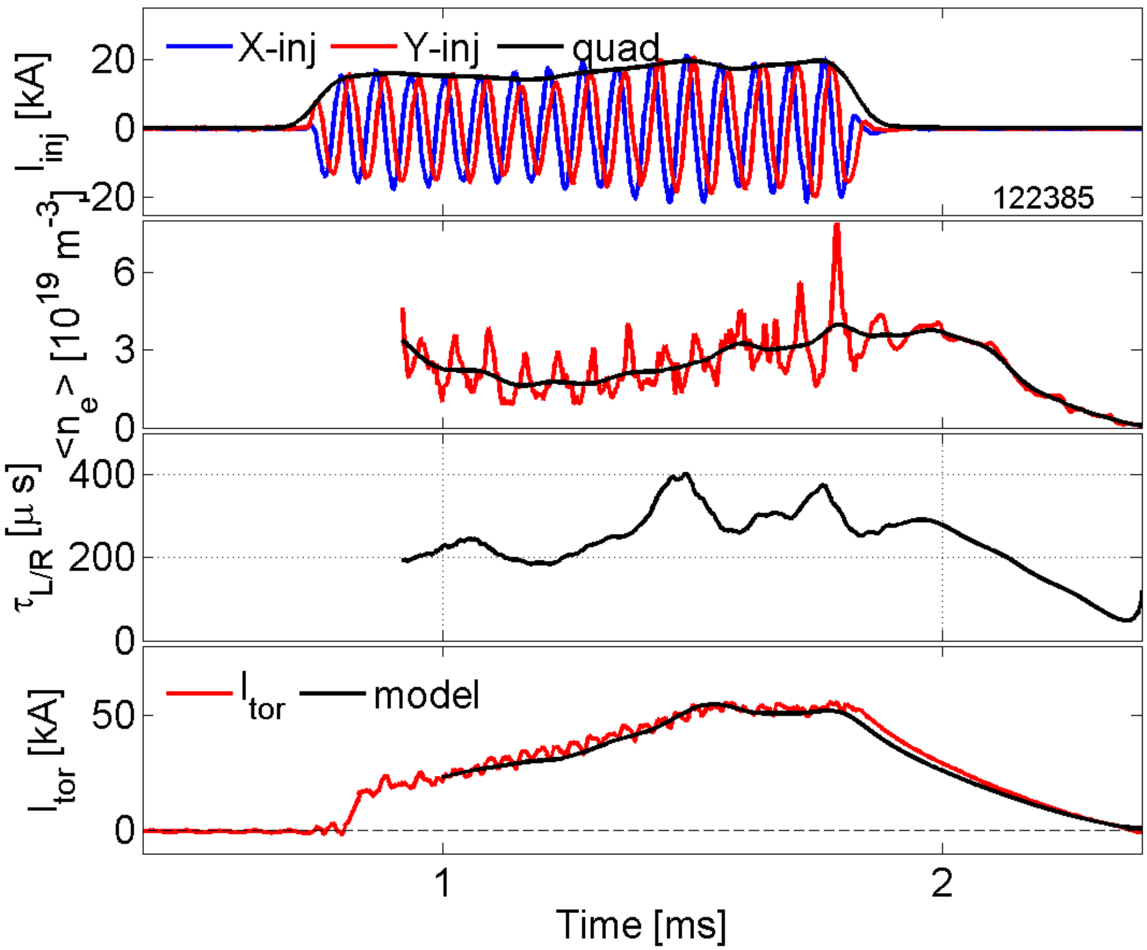
HIT-SI



Equilibrium Produced

- Injectors take turns driving edge current and imposing perturbations.
- Imposed dynamo was discovered on this first experiment to meet both requirements.

Imposed dynamo predicts current vs time



$$\int \frac{\delta B_{\perp} \delta B_{\parallel}}{\mu_o} da = \int ne(\eta j_{\parallel} - E_{\parallel}) dvol$$

$$\dot{I}_{tor} = \frac{C_3}{n} I_{inj}^2 - \frac{I_{tor}}{\tau_{L/R}}$$

- δB from I_{inj}.
- η from helicity decay time.
- Calculation starts at 1ms.
- Imposed dynamo accurately predicts current drive in edge flux surface.

Appling imposed dynamo to all flux surfaces $\Rightarrow$ Imposed current profile

A good goal is to learn the physics and control needed to eliminate the TF coil

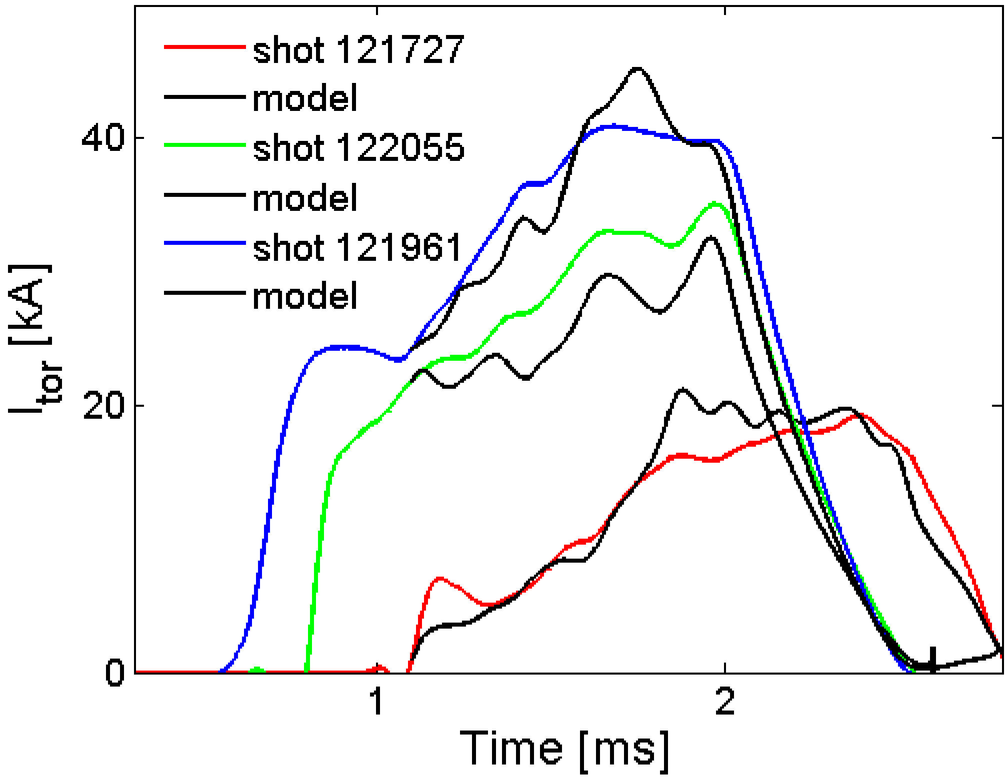
- May be only way to get on a cost effective path to DEMO.
- Private investment is only in TF-coil free ideas, demonstrating the cost point.
- Confinement has been demonstrated in transient low TF operation.
- The way to efficient formation and sustainment with profile control is now well lighted.
- In case we cannot afford the luxury of a TF-coil in a reactor, we must develop the profile control needed to eliminate it.
- Better control is valuable even with a TF-coil.

Summary

- Scaling data from ITER is extremely valuable.
- We need to get on a cost path that leads to DEMO NOW.
- Imposed dynamo may provide the control needed to solve many cost problems including the TF-coil.

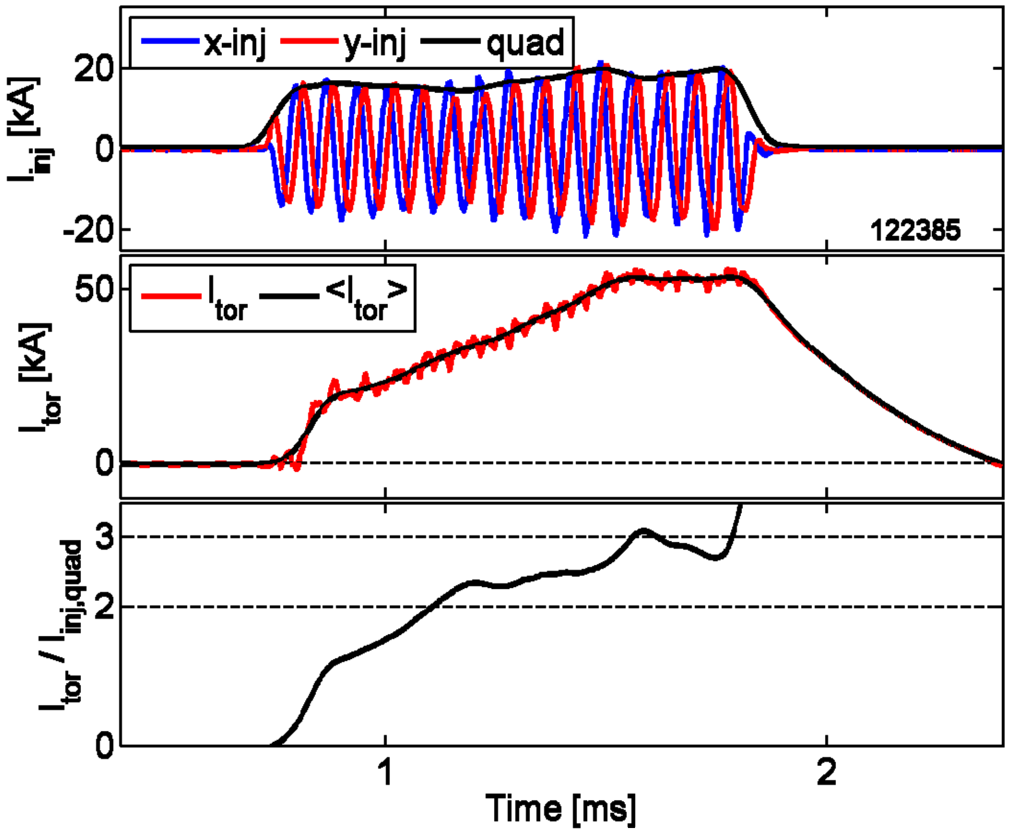
Data over wide range of parameters agrees with model

- Applying theory to more shots



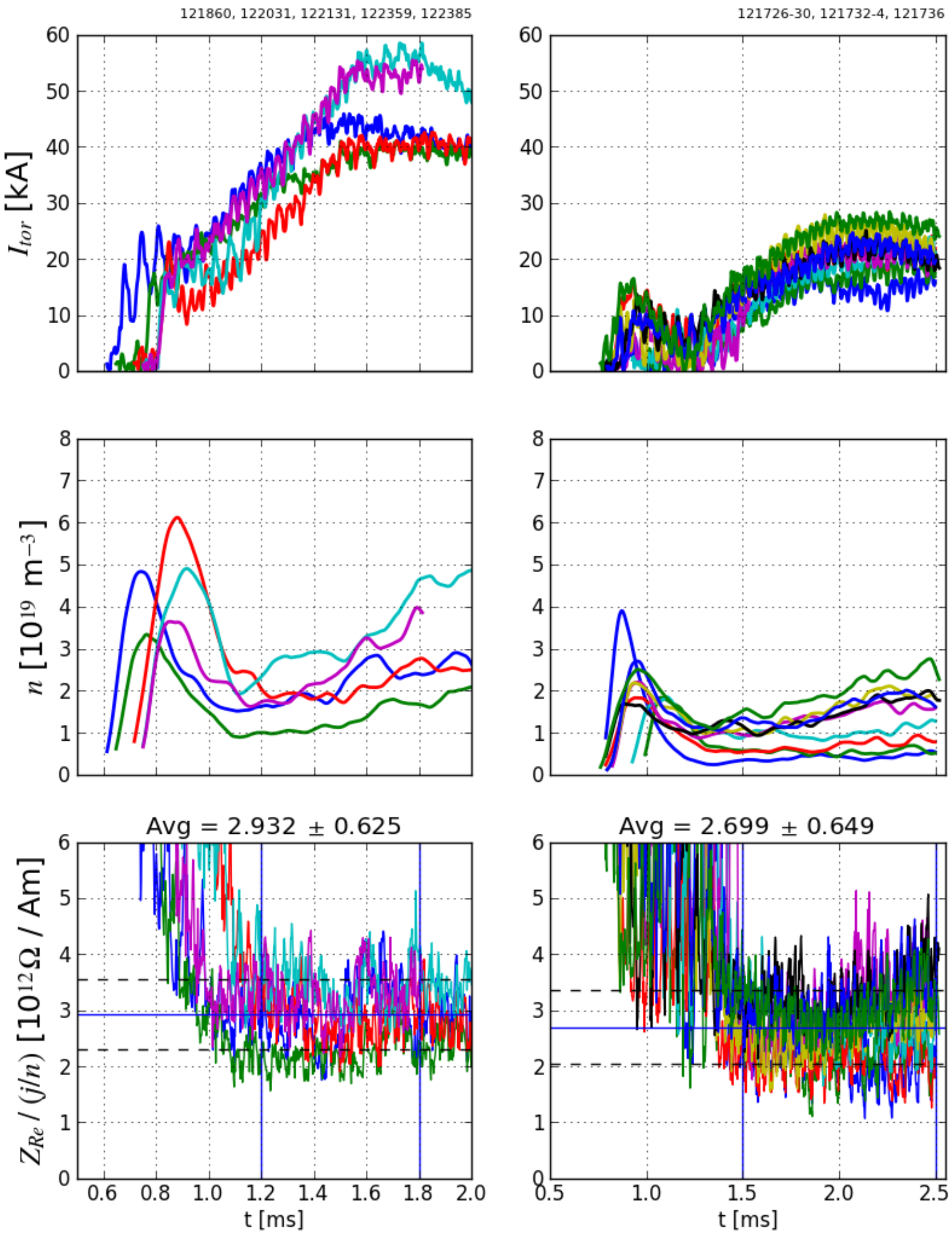
Using $C_3 = 1.5 \times 10^{19}$ for all data

Current amplification of 3 is a spheromak record



- The injector currents are added in quadrature and smoothed over an injector cycle
- The toroidal current is smoothed over an injector cycle
- Shows a sustained current amplification greater than 2 with a peak value of 3
- Up to 0.65 ms toroidal current persistence

Model predicts injector impedance



- IDCD model predicts

$$\frac{V_{inj}}{I_{inj}} \propto \frac{j}{n}$$

- Measurements show

$$\frac{V_{inj}}{I_{inj}} = (2.8\times10^{-12} \pm 0.7\times10^{-12})\frac{j}{n}$$

- Amazing agreement

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- Measurements show

$$\frac{V_{inj}}{I_{inj}} = (2.8\times10^{-12} \pm 0.7\times10^{-12})\frac{j}{n}$$

- Shows agreement

Model predicts I_{tor} vs time

$$\int \frac{\delta B_\perp \delta B_{||}}{\mu_o} da = \int ne(\eta j_{||} - E_{||}) dvol$$

- For a mean flux surface of minor and major radii of r and R this can be approximated as:

$$\frac{\delta B_{rms}^2}{2\mu_o} 2\pi R 2\pi r = (\eta j_{||} - E_{||}) ne\pi r^2 2\pi R$$

Using: $\frac{B\lambda}{\mu_o} = j_{||};\ \tau_{L/R} = \frac{\mu_o}{\eta\lambda^2};\ B = \frac{C_1 \mu_o I_{tor}}{2\pi a};\ E_{||} = -\frac{\dot{B}}{\lambda};\ \delta B_{rms} = \frac{\mu_o I_{inj}}{C_2 a};\ r = a$

Yields: $$\frac{\delta B_{rms}^2}{\mu_o} = C_1 \frac{\mu_o ne}{2\pi\lambda} \left(\frac{I_{tor}}{\tau_{L/R}} + \dot{I}_{tor} \right)$$

Solving for dI_{tor}/dt yields: $$\dot{I}_{tor} = \frac{C_3}{n} I_{inj}^2 - \frac{I_{tor}}{\tau_{L/R}}$$

Where $C_3 = \pi\lambda / C_1 C_2^2 a^2 e$. Using a = 0.22 m, $\lambda = 10.3\ m^{-1}$ from for HIT-SI and estimating $C_1 = 2$ and $C_2 = 4\pi$ gives $C_3 = 2.6 \times 10^{19}$ in SI units.

Future Plans

HIT-SI3

- Place three injectors on one side.
  - Drives plasma rotation for stability
  - Injectors have same preferred direction
  - Injectors easy to shield from DC spheromak fields
- Thicker plate gives better injector opening
- Using higher power surface treatment
- Try perforated plate backed by a pumped chamber for density control

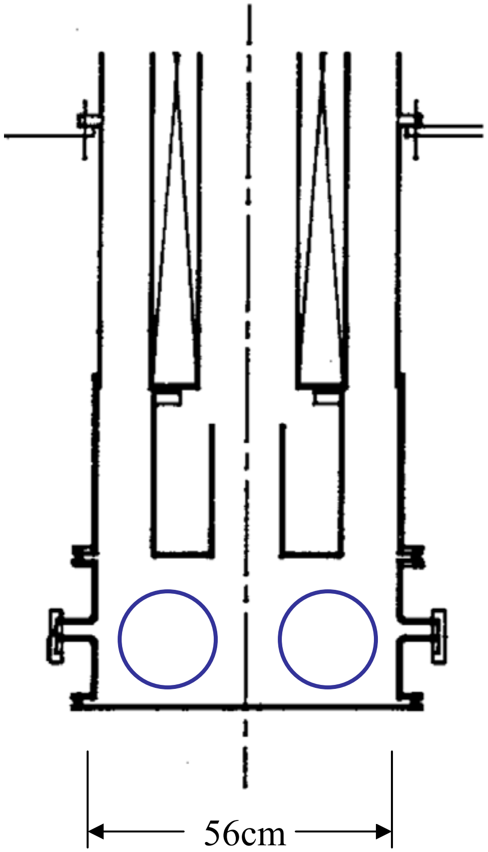
Office of Nuclear Energy is developing ARIES-AT relevant materials

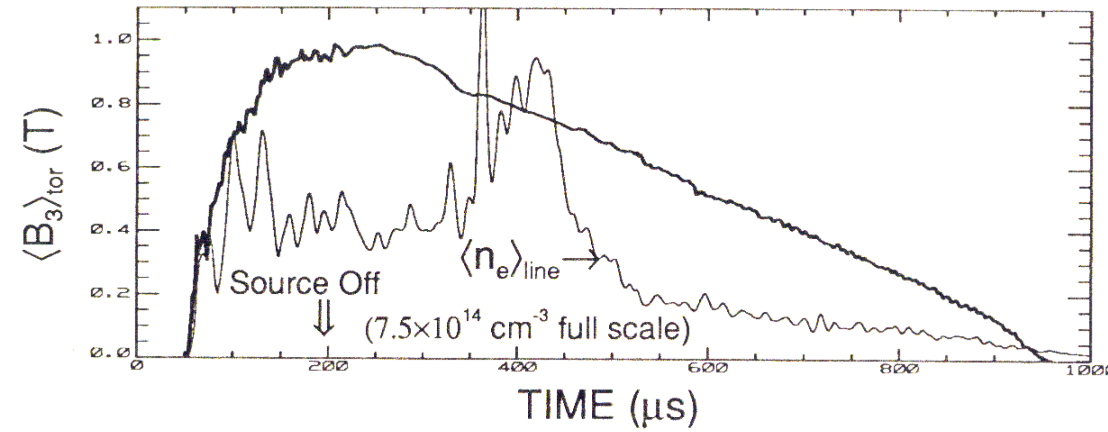
- Very High Temperature Reactor (VHTR) concept
- Developing high temperature structural material that can tolerate the nuclear environment.
- The temperature (1000^{o} C) and DPA requirements are similar to the most difficult materials demands of ARIES-AT
- We need to keep abreast with these developments in NE
- It is not cost effective for us to do it

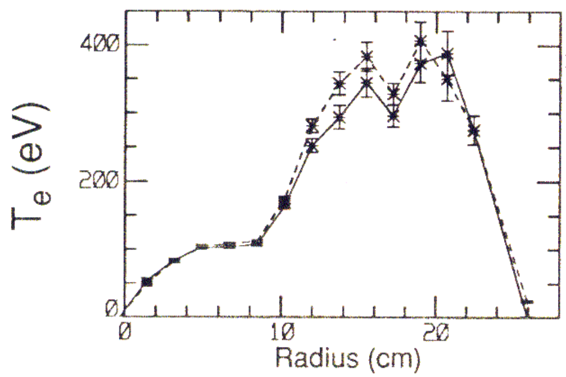
Specification of 2/3 scale CTF based on ARIES-AT

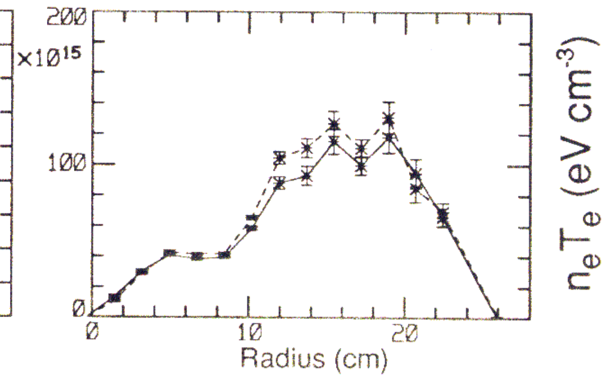
- $415 M machine cost
- CTF requirements
- Tritium gain
- Many blanket modules
  - High temperature nuclear certified materials
  - Do 14 MeV R & D (try top candidates)
- Pre-DEMO
- R = 3.4 m
- 0.5 m thick blanket and shield

Small CTX Spheromaks achieved 400eV temperatures **[Jarboe 90]**



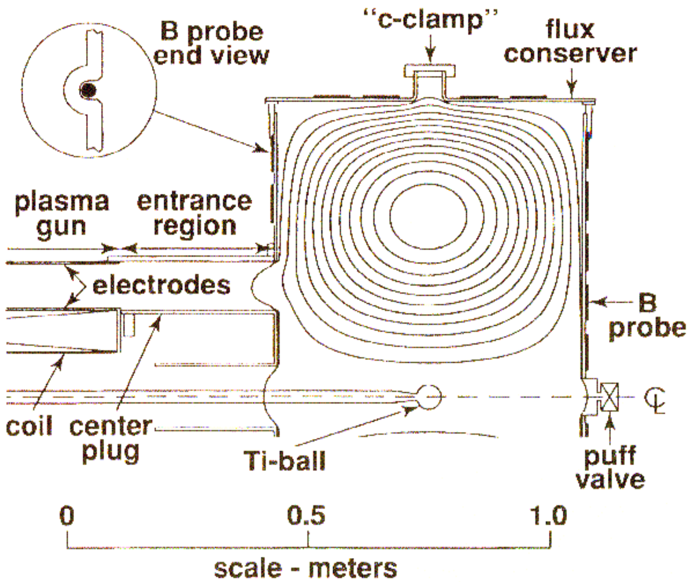


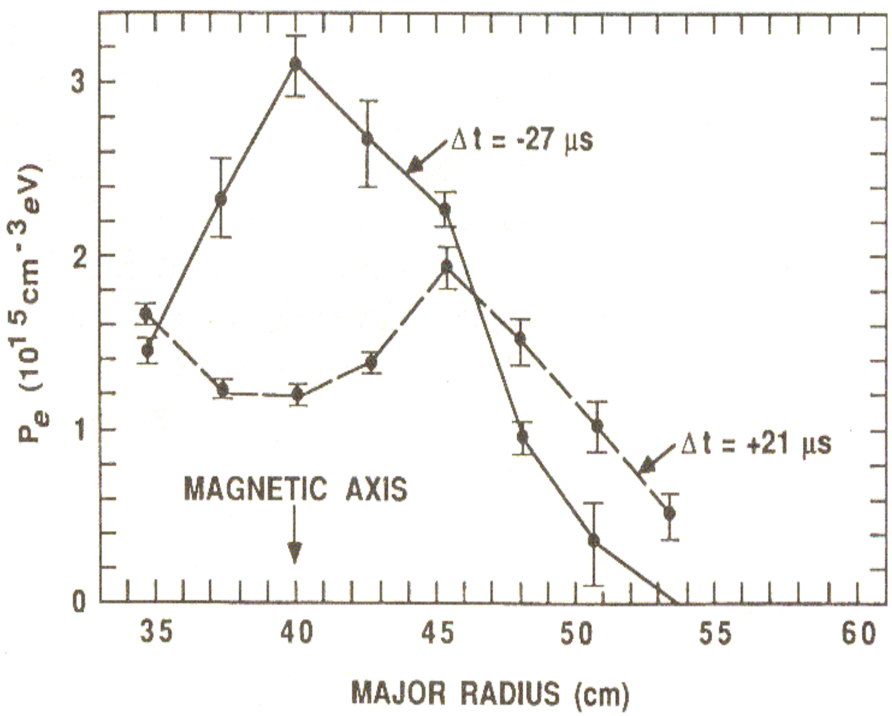




- •Temperature is taken at 310 μs.
- • MeV runaway electrons observed [Chrien 91]
- •Ohmically heats to beta limit –Best it can do.

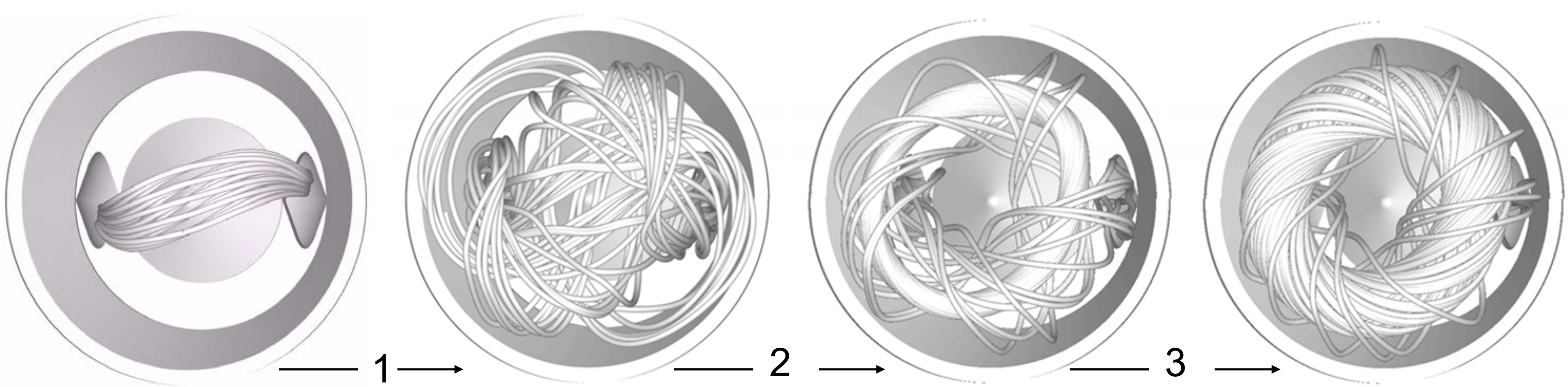
Goal of ohmically heating to the β-limit was achieved in the CTX large solid flux conserver experiment. **[Wysocki 88]**





- Results are from Multi-point Thomson scattering. Peak temperature was 150eV.
- With $T_e = T_i$ peak local $\beta \approx 60\%$, ($\beta_{tor} = \infty$)
- Δt is time the relative to a rapid loss of density at the magnetic axis (from the instability)
- If resistivity and confinement scale as Spitzer, result independent of size and T.
- Confinement cannot get any better than this and should be sufficient for reactor.

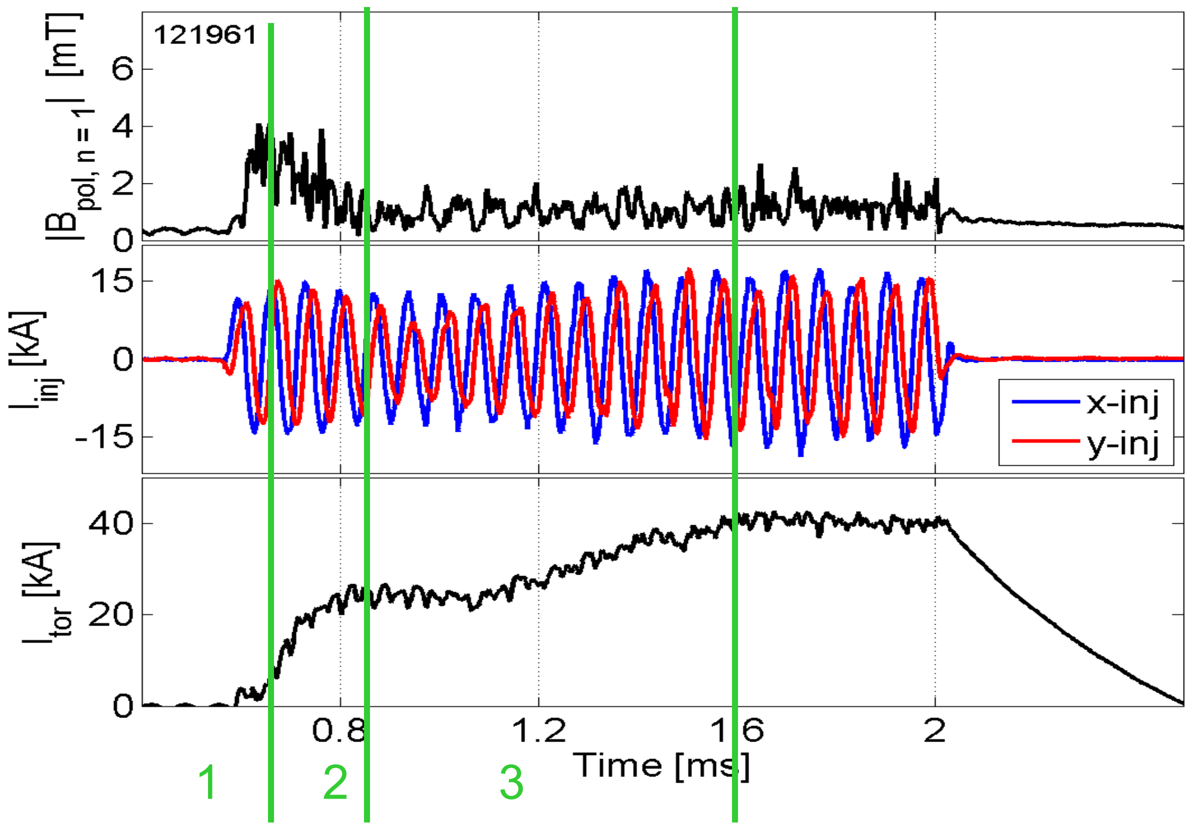
Achieving large separatrix region is a three step process



1. A large non-symmetric configuration is formed (matches injector symmetry)
2. A self-organizing reconnection event forms separatrix
3. Separatrix current is increased by imposed dynamo current drive

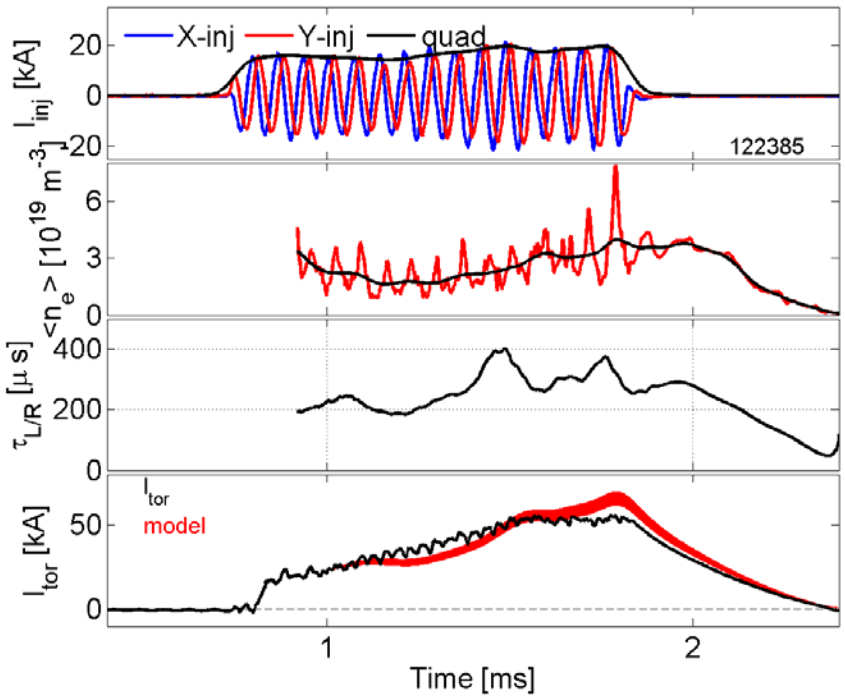
[Calculations performed by George Marklin *(Plasma Science and Innovation Center)*]

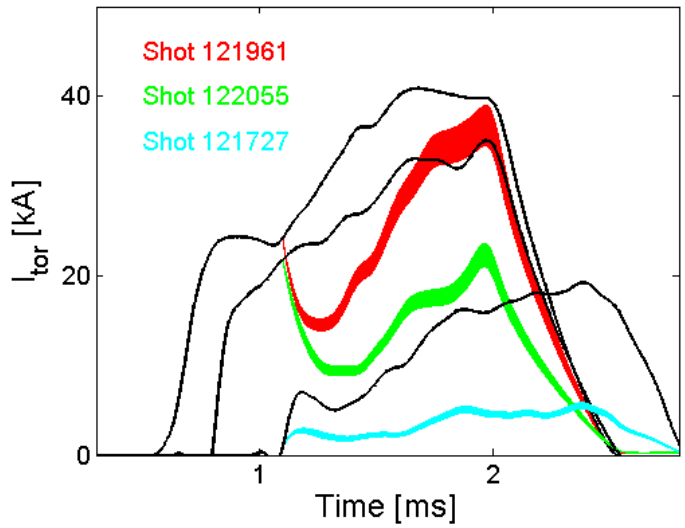
Data show three step process



1. A large non-symmetric configuration is formed (injector symmetry)
2. A self-organizing reconnection events forms separatrix
3. Separatrix current is increased by imposed dynamo current drive (IDCD)

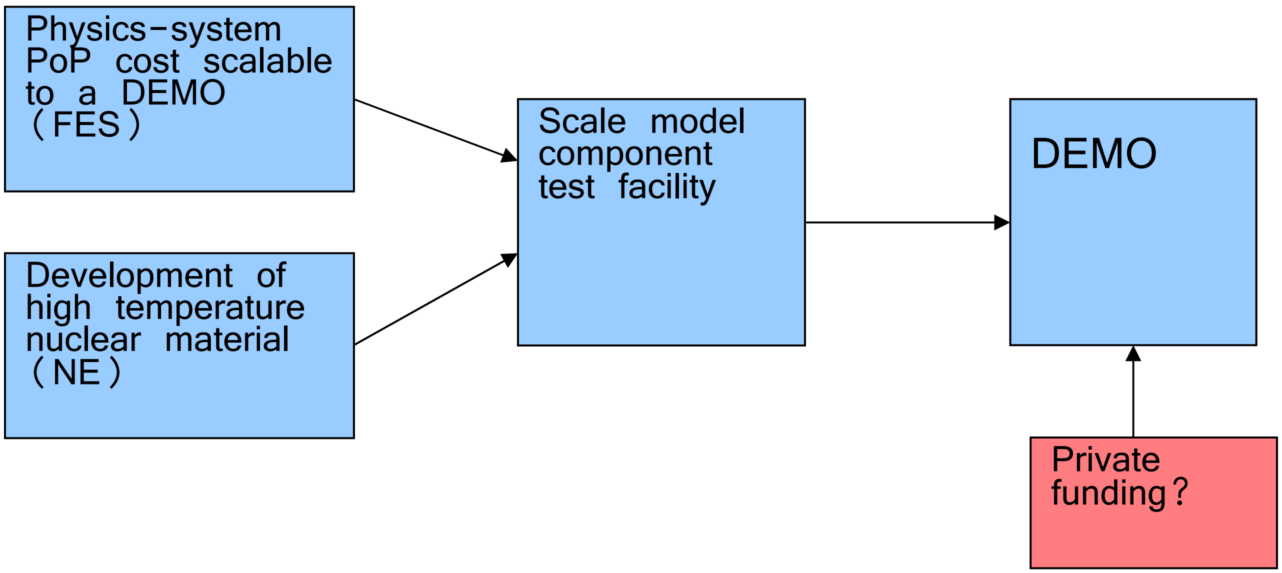
Equation without density fails to fit





$$\dot{I}_{tor} = C_3 I_{inj}^2 - \frac{I_{tor}}{\tau_{L/R}}$$

Simple roadmap to DEMO



- Cost and science scalable CTF might entice private funding.

referencs

F. Najmabadi et al. / Fusion Engineering and Design 80 (2006) 3–23

KSTAR: Nuclear Engineering International 10 August 2009