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1 Dec 2010

Pulsed Power Inertial Fusion Energy

Fusion Power Associates

31st Annual Meeting and Symposium

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Pulsed Power Sciences Center, Sandia National Laboratories
in collaboration with our colleagues at Sandia National Laboratories

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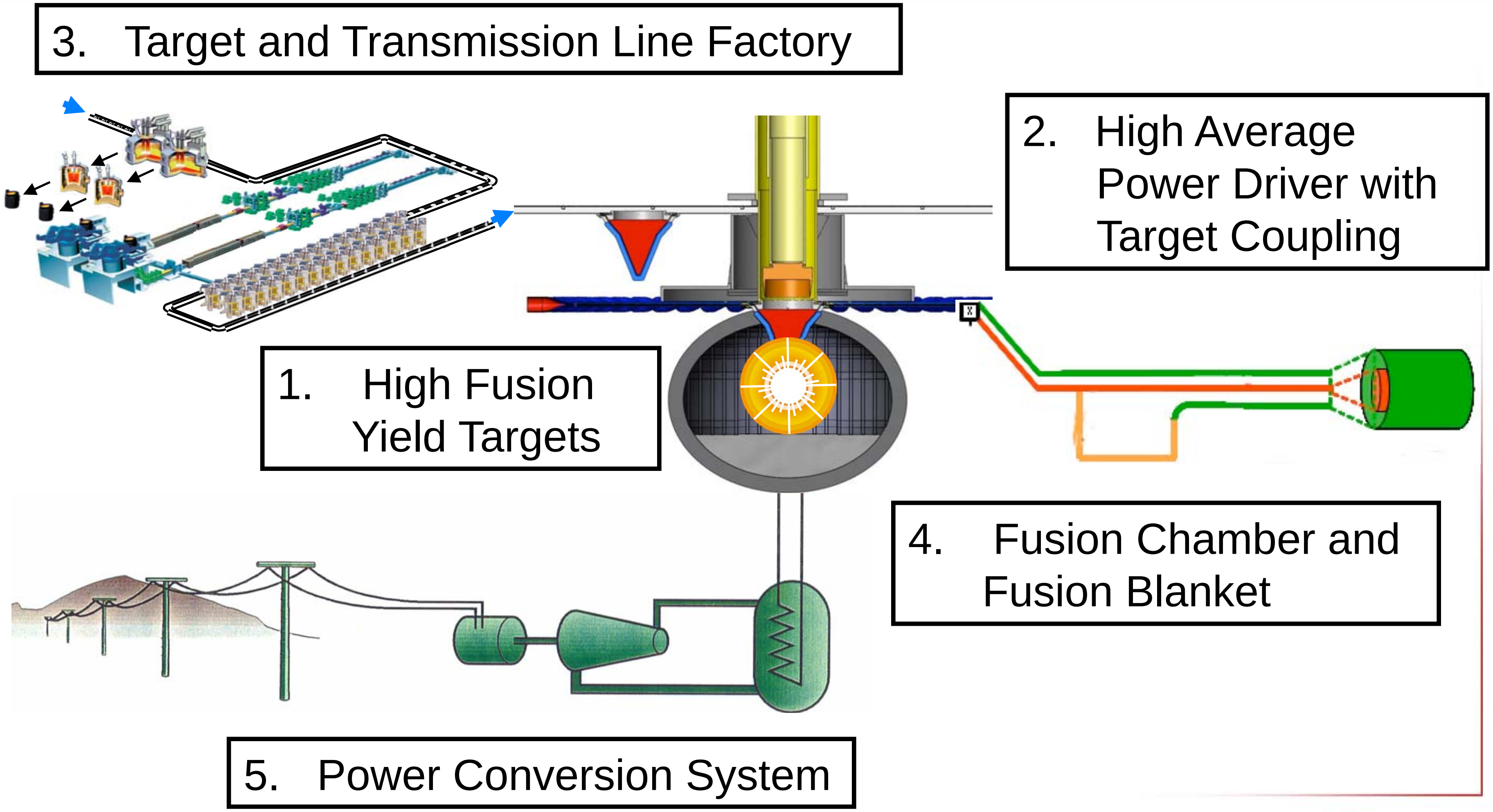
At a high level, all IFE power sources have five major elements



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The diversity of drivers, targets, coupling methods, chamber technologies requires *close scrutiny* of systems interface/integration issues

Drivers
Pulsed power magnetic pressure
Pulsed power x-rays
Fast Ignition Laser
Heavy Ion Accelerator
DPSSL Laser
KrF Laser

Coupling
Conductor transport-conductor recycling
Beam transport-inverse diode
Beam transport-space-charge-neutralization
Photon transport-target-injection-tracking

Targets
Direct-drive fast-ignition
Direct-drive hot-spot ignition
Indirect-drive fast-ignition
Indirect-drive hot-spot ignition
Other advanced concepts

Chamber and Blanket
Thick liquid wall
Vaporizing blanket
Wetted wall
Dry wall with gas fill

- IFE has separability built into it from the start (attractive compared to MFE)
- System integration is not trivial
- It is imperative to optimize at a system level, *not just* at a sub-system level
- Efficient coupling needs to be demonstrated and is hard for all options

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Pulsed power concepts allow thick liquid wall for long lifetime but require recyclable transmission lines

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- Direct connection of driver-target
  - simple in concept for low rep-rate, can it be engineered, can yield be high enough?
  - needs to economic, thus recyclable, is this feasible?
  - longer lifetime chamber designs with larger yields?

This system of systems must meet a large number of demands

Performance	Cost/Schedule	System Engineering	Policy and Politics
Energy rich	Low cost	Reliability	Ease of licensing
High gain	Credible, rapid, development path	Availability	Public acceptance
Efficient	Affordable development path	Maintainability	Acceptabilty of local or global environmental impact
Scalable/flexible	Credible, rapid, deployment path to mass production	Inspectability	No evacuation plan
Robust	Affordable deployment path to mass production	Manufacturability	No high-level waste
Closed, on-site fuel cycle	Management of R and D risk	Disposability	Financing
Sufficient rep-rate		Usability	Safety analysis
Handling of high fusion yields		Mass-producability	Infrastructure development
		Suppliability	

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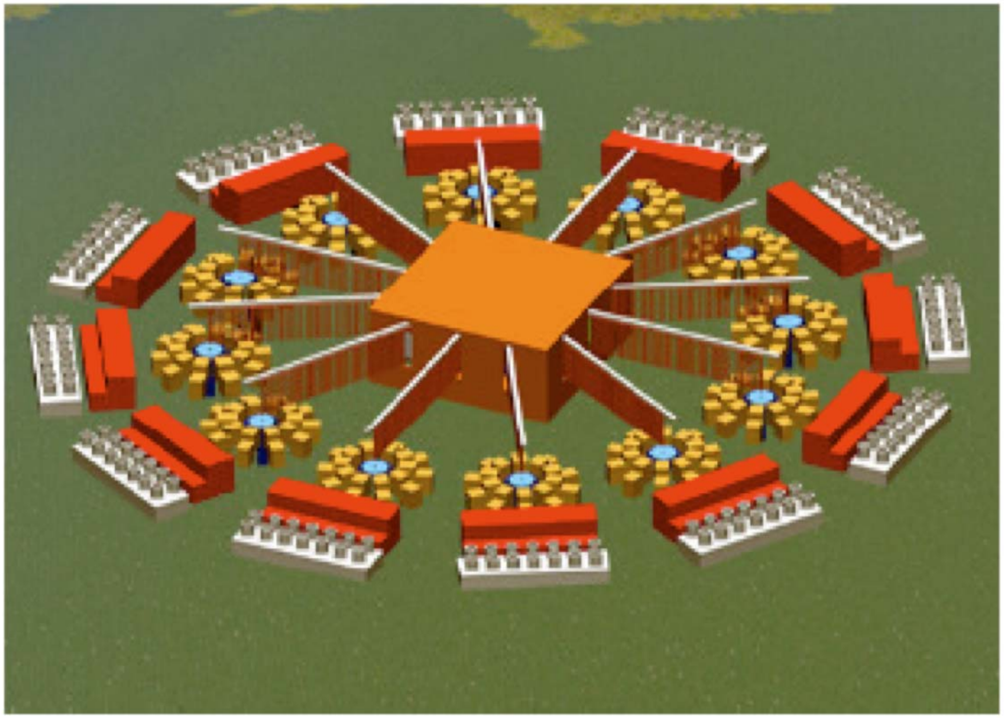
The first IFE z-pinch study (2004-2006) proposed 10 target chambers at 100 MWe per chamber



3 GJ yield per chamber
RR = 0.1 Hz per chamber
300 MWth, 100 MWe/chamber
RReff = 1 Hz
Total power = 1 GWe

31,560,000 RTL's & targets/year

- C.L. Olson et al identified the science issues of repetitive drivers, recycled transmission lines, thick liquid wall target chambers
- We concluded 10 units are not practical or economic – too much steel for RTL's, need higher target yield, system efficiency, and wall plug gain

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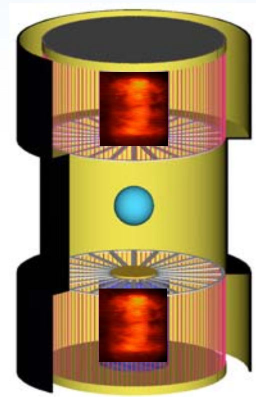
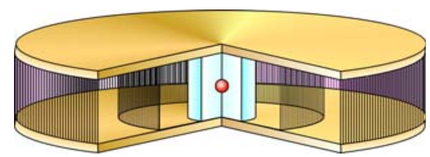
What is new?

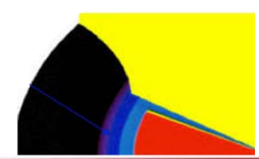
'Out with the old'





- Indirect drive targets:
  - Gwall ~1 (400 MJ yield) required two 60 MA, 60 ns drivers
  - IFE would require >3 GJ yields at RR = 1 Hz
  - Required 7.2 to 8.6 MJ absorbed at capsule
  - Required 40 to 100 MJ z-pinch x-ray sources
  - Gave 4.6 GJ yields
  - But required a 100 MA or two 150 MA drivers

'In with the new'



- Direct drive targets:
  - Higher efficiency target concepts (25X)
  - Higher efficiency driver concepts (2X)
  - 5-10 MJ absorbed energy in target with single 60 MA driver
  - Possibly quite compact Z-sized (7800 ft^2) to 10 *x* Z (85,000 ft^2)
  - Higher thermal efficiency cycles (Brayton or Brayton-Rankine)
  - Require G = 500 – 1500, RR = 0.1 Hz for economic IFE
  - 1/10th number of RTL's and targets at 0.1 Hz

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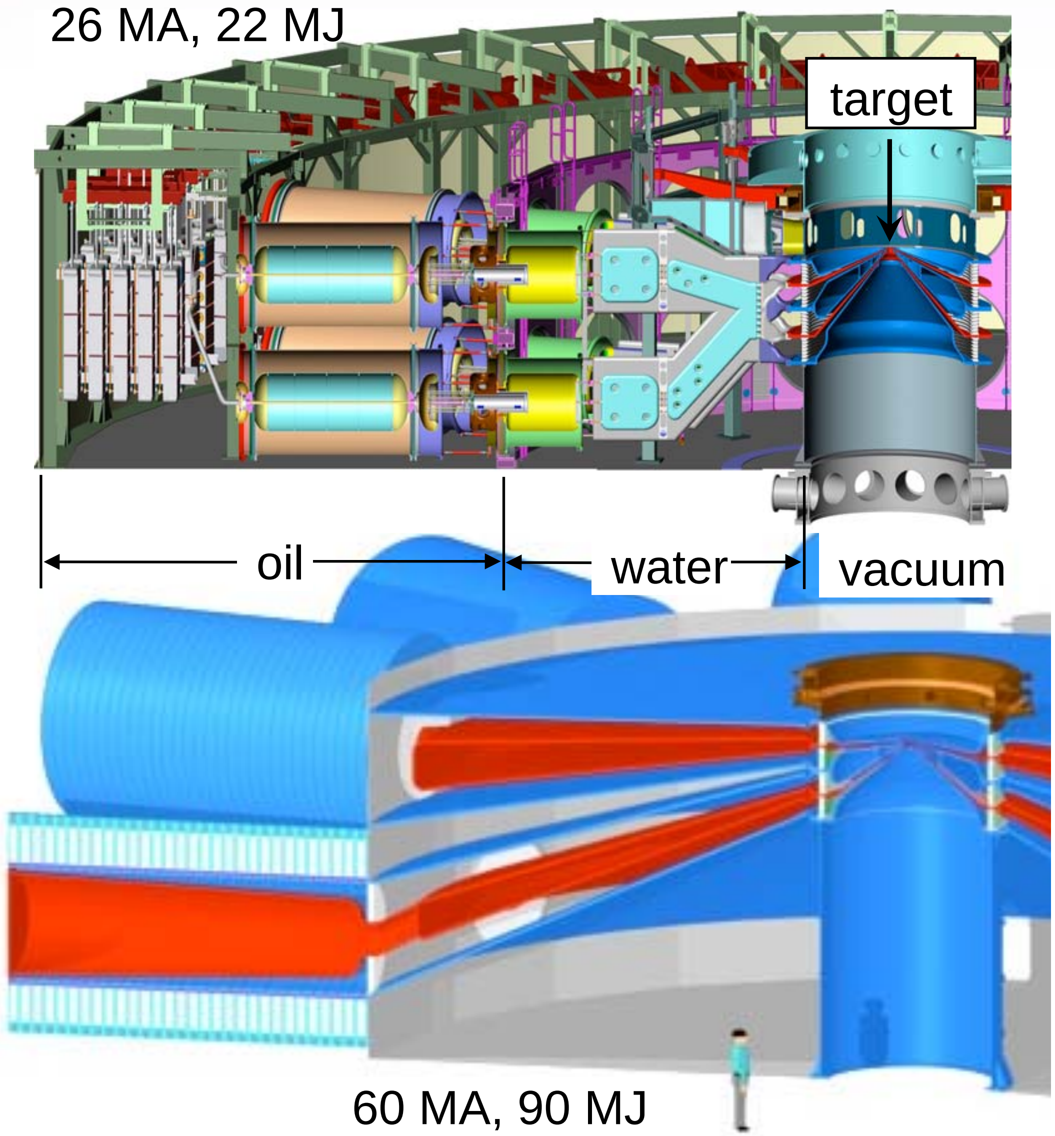
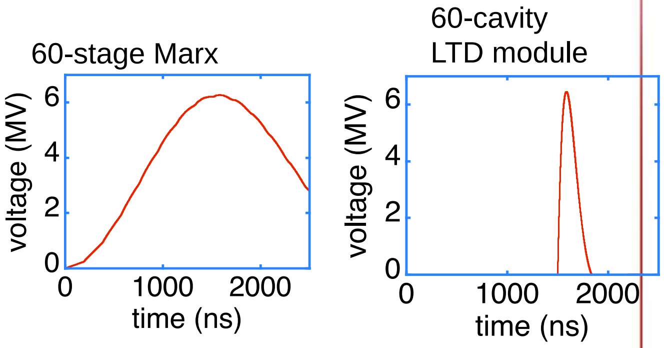
LTDs (Linear Transformer Drivers) are the greatest advance in prime power generation since the invention of the Marx (1924)



LTD cavity

Single step pulse compression



Doubles electrical efficiency

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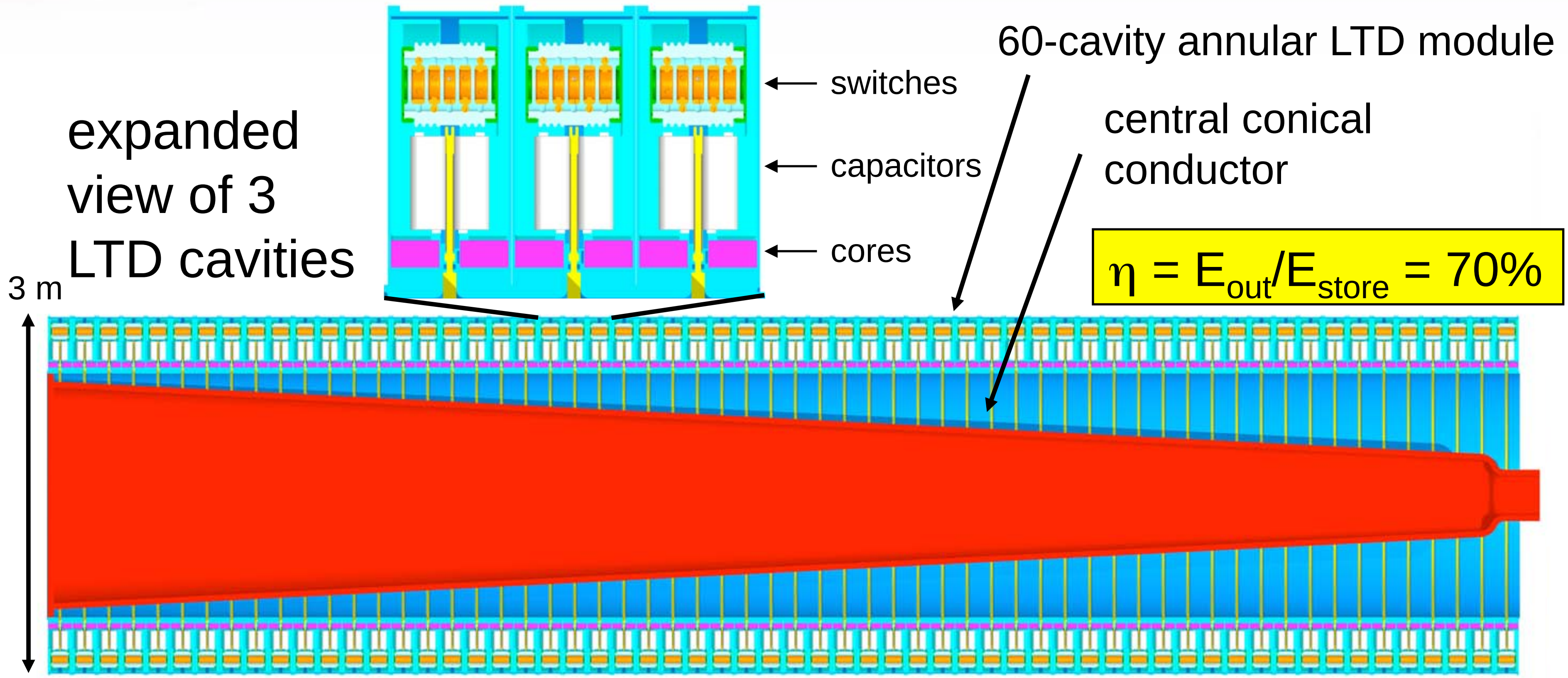
W. Stygar *et al.*, (2007)

Rep-rate generator designs use Linear Transformer Driver (LTD) modules have economy of scale mass production



- Double electrical efficiency of conventional architecture (70%)
- Random failure rate of low voltage switches is better than 7 x 10^{-6}
- Components have shown 13,000 to 37,000 shots (1.5 to 4.3 days) with no failure

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M. Mazarakis, W. Stygar *et al.*, (2010)

Tests of a 1 TW rep-rate module are planned at 0.1 Hz at the required energy and technology scale

MYKONOS LTD Driver Test Bed

Prototype costs are:
$11/Joule
~10^{-4} cents/peak watt

- 1 MA, 0.2 TW, 25 kJ, two cavity tests planned in FY2011
  - Fire 40,000 shots (= *1,600,000 switch firings*) at 6 shots/minute with resistive load
  - Engineer and test a replaceable transmission line system
  - 1 MA, 1 TW, 125 kJ, 10 cavity test planned to follow
- ZR was built for 4$/J. This technology scales more favorably.
- Gen 3 LTD designs have 80% peak current with 50% cavity radius

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W. Stygar *et al*., Phys. Rev. ST– AB (2007)

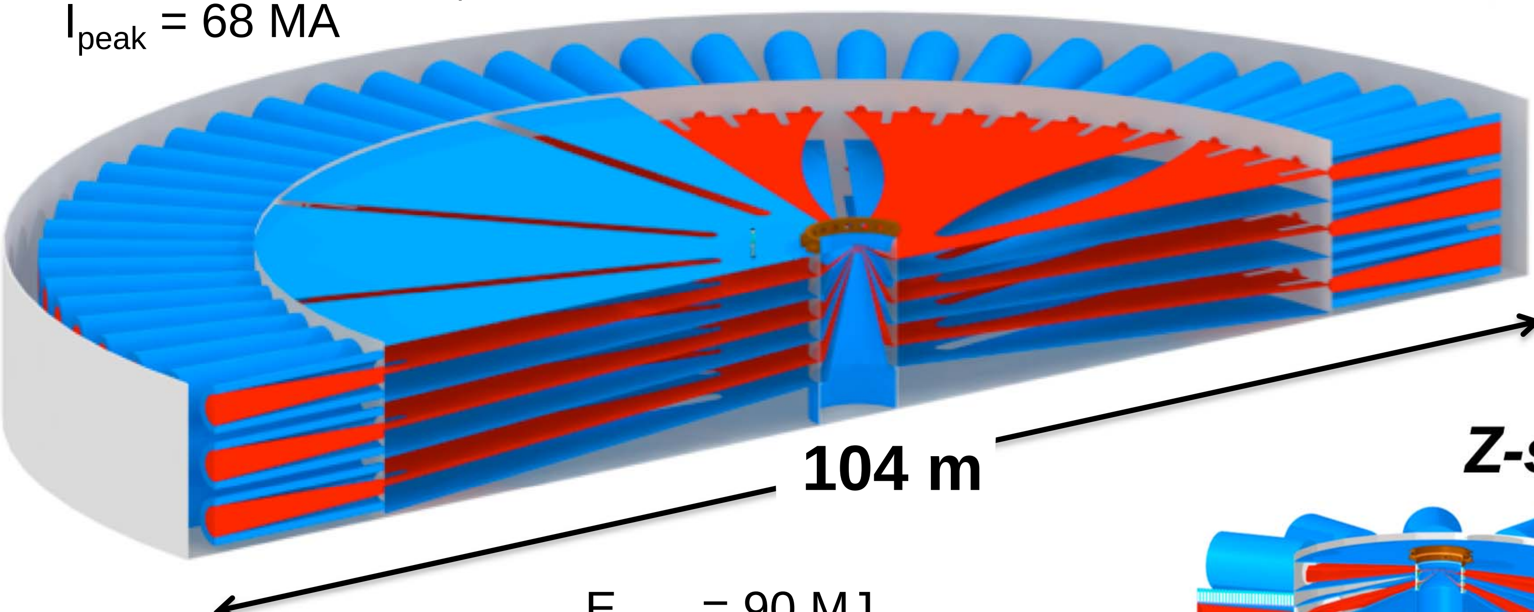
LTD modules are integrated into efficient, low cost, compact, high yield scale pulsed power systems

E_{store} = 180 MJ

I_{peak} = 68 MA

τ_{imp} = 100 ns

Patent: US 7,679,297 B1 Stygar *et al.*

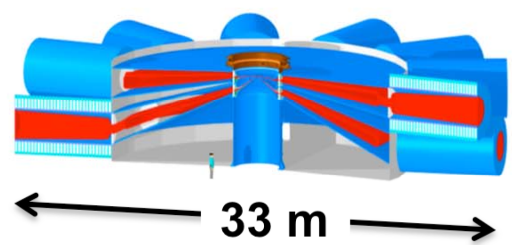


Z-sized

E_{store} = 90 MJ

I_{peak} = 60 MA

τ_{imp} = 300 ns



- **Both systems can deliver 10 to 20 MJ to target regions**

These accelerators consist of capacitors, switches, oil, water, plastic, stainless steel, and air

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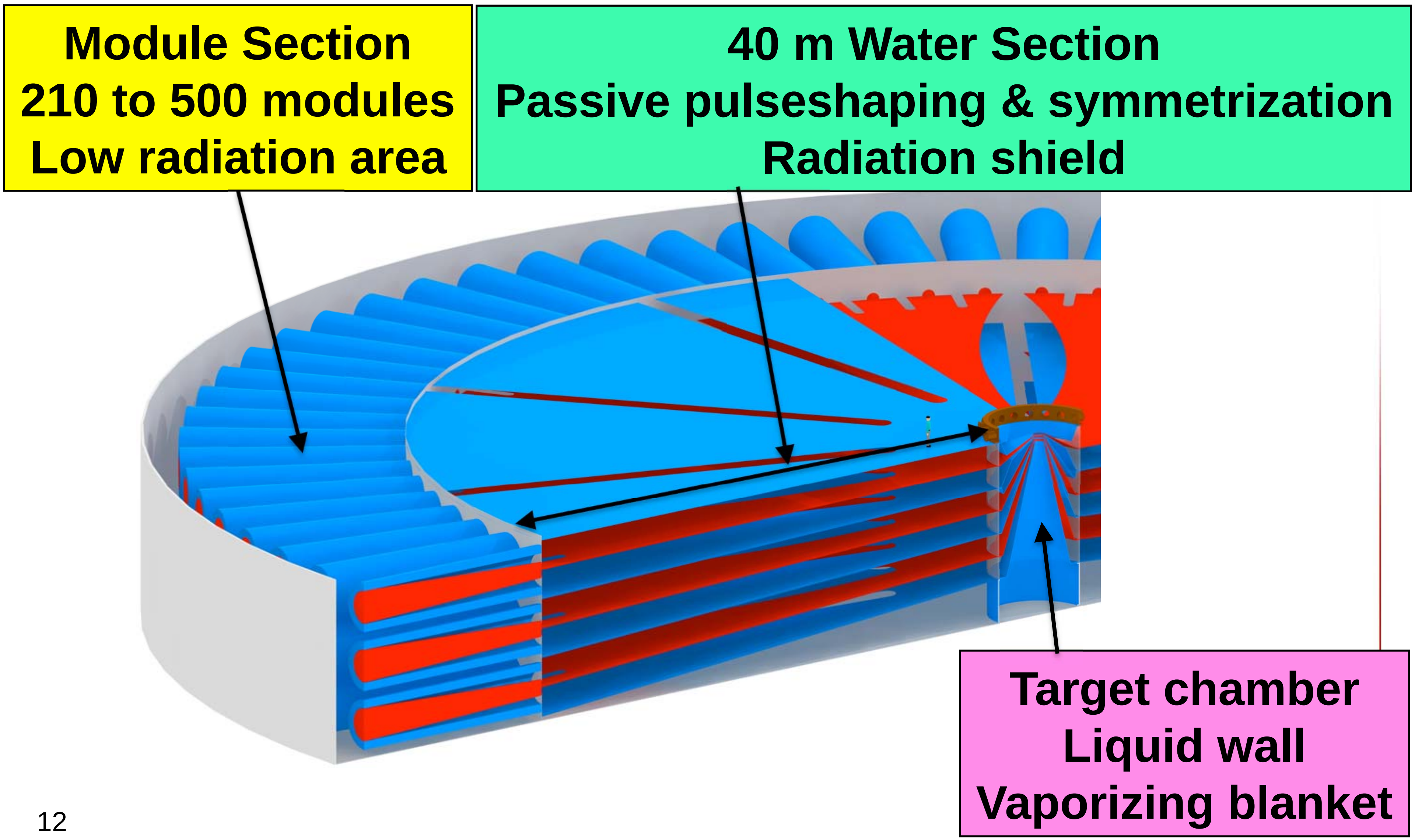
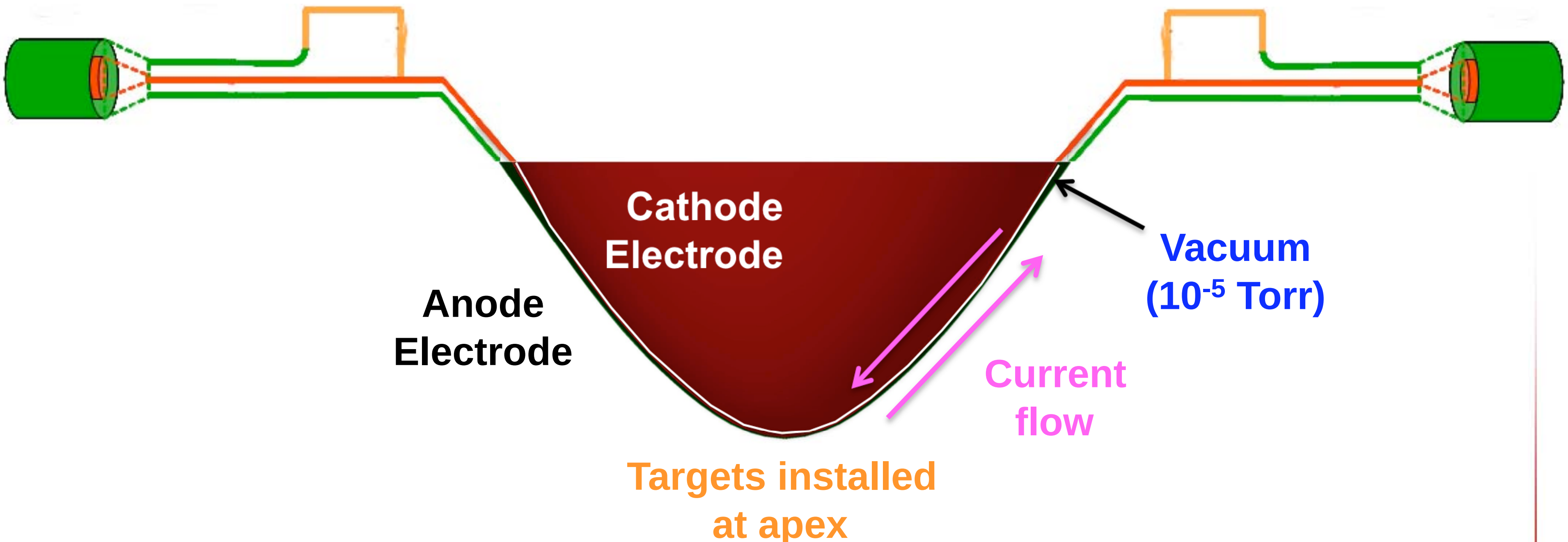
Concept of operations would allow module replacement during continuous high yield operation



S. Slutz *et al.*, Phys. Plas. (2003) and C. Olson *et al.*, FST, (2005)

Repetitive connection of driver and target is achieved by replacing a Recyclable Transmission Line (RTL) at 0.1 Hz



- RTL and the targets are a low mass (<50 kG), low cost, portable vacuum system
- Recyclable so the process can be economic.
- RTL provides coupling of driver and target even with chamber debris from previous event; chamber clearing not required
- RTL can be shaped to shield direct line of sight to driver

There are a number of science and engineering challenges for RTL driver-target coupling

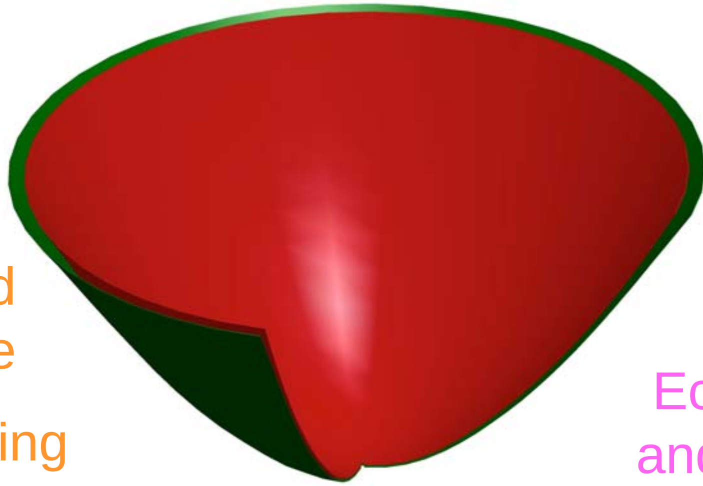
Inductance

RTL recovery and waste handling

Electron flow

Assembly, staging, and operational issues

Ohmic dissipation



Mechanical integrity

Plasma formation and gap closure

Economic recycling and mass fabrication

Driver shielding from blast

Driver/RTL pulsed power integration

Driver/RTL engineering repetitive connection

- An applied science and technology R and D program is needed
- The “ilities”: manufacturability, maintainability, reliability, affordability, disposability, usability, availability

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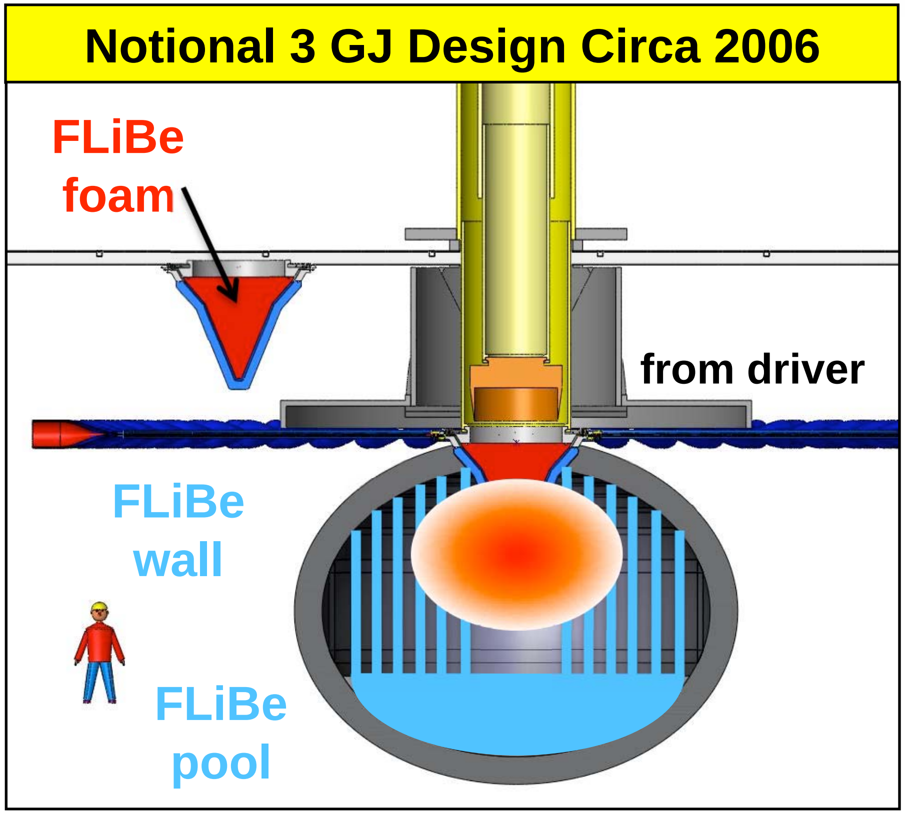
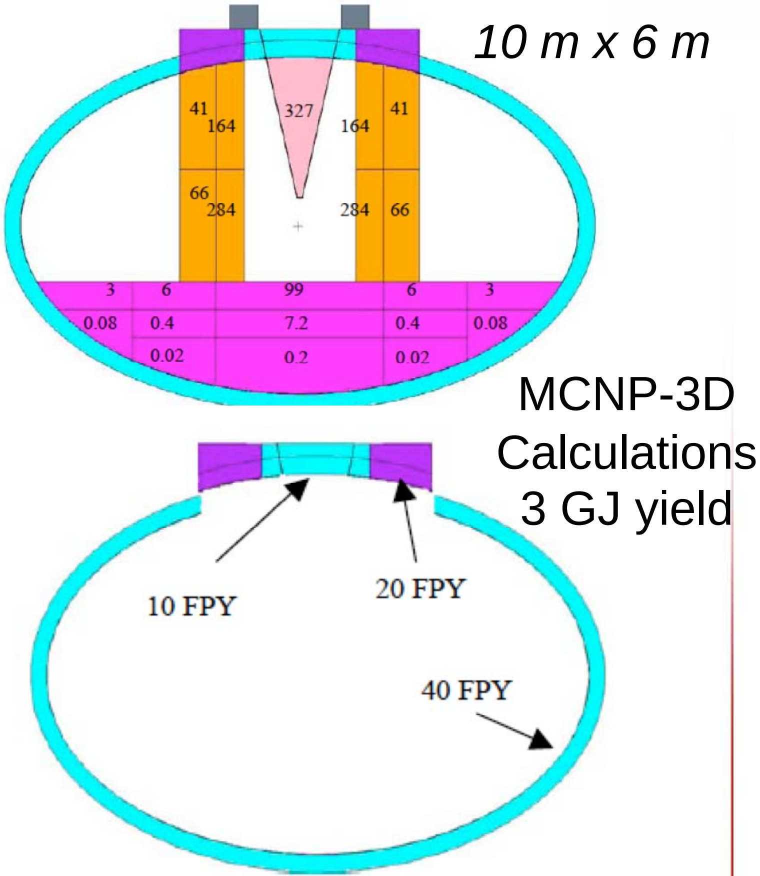
M. Sawan, L. El-Guebaly *et al.*, FST (2007)

Liquid walls and vaporizing blankets could drastically reduce the materials issues that a fusion power plant will face





- Direct connection with pre-pumped, mechanically-rigid RTL allows thick liquid wall
- Ongoing calculations to determine optimal shielding configuration
- Neutronics: 40 year lifetime chamber
- Initial point design: cyclic material fatigue: 7 year lifetime

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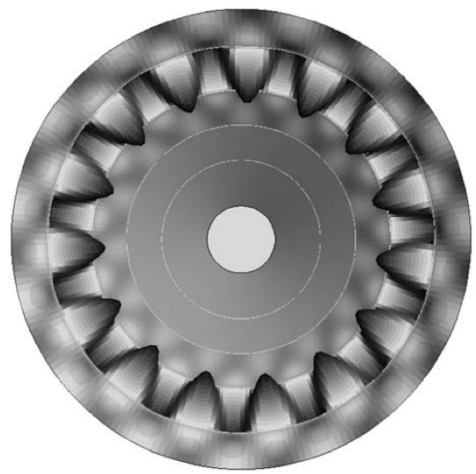
M. Barkey, *et al.*, Experimental Mechanics, (2008)

Prototype RTL's were manufactured by metal spinning and buckling strengths were measured and modeled

Prototype | **FEM Simulation** | **Experiments**

ASTM 1008 low carbon steel
Thickness = 0.620 ± 0.02 mm (25 mils)
Buckling ~ 8.3 psi



Buckling ~ 26 psi

- Outer RTL electrode is susceptible to the buckling instability
- Stiffening rings increase buckling pressure by 3X
- Thicker RTL's for higher gain and lower rep-rate
- Other materials, other fabrication techniques

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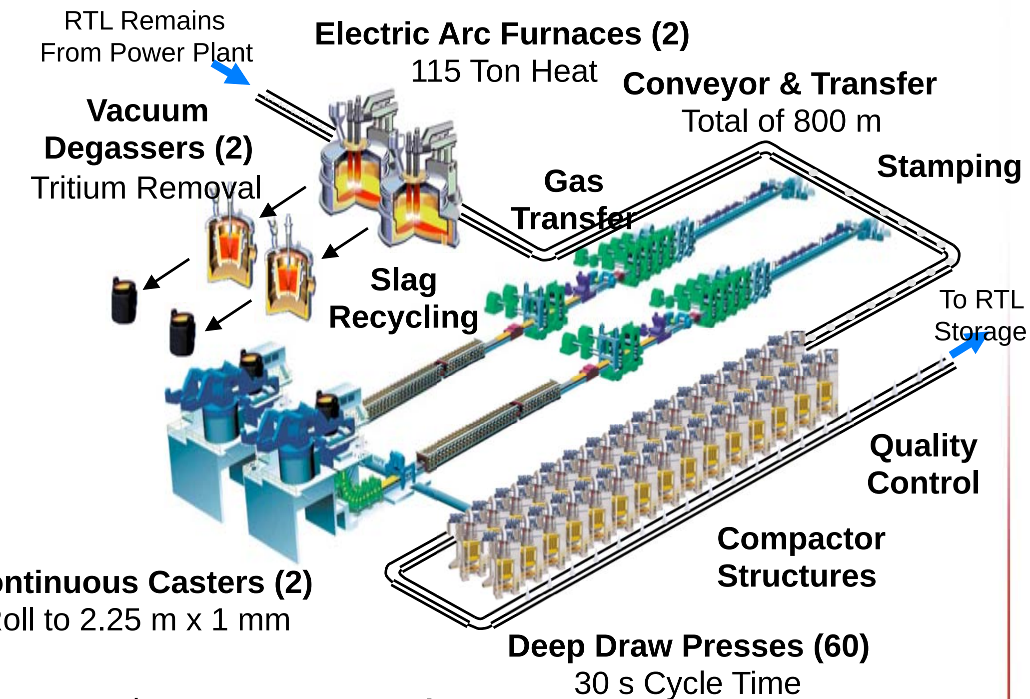
B. Cipiti *et al*. SAND-2006-7399P (2006)

RTL's can be fabricated economically – up to \$15/shot can be spent on RTL's and targets at >10 GJ and 0.1 Hz

@1 GW_e, 0.1 Hz, 3.1e6/yr

RTL Type	RTL unit cost (\$)	Cost/ $MWhr_e$ (\$)
Stamped steel (25 kG)	5.30	1.90
Cast FLiBe (76 kG)	1.00	0.36

OCC RTL stamping plant: 160 million



- Nuclear plants raw fuel costs ~ \$3.50 to \$5.50 per $MWhr_e$
- Coal ~ \$10 to \$13.20 \$/$MWhr_e$
- Only 5 to 10% of COE results from RTL and target costs
- 2 week inventory (3000 metric tons), yearly throughput (<190,000 metric tons)
- Need to develop design of full scale production line with industry (SCHULER)

We will manage IFE R and D with Technology Readiness Levels

System	TRL level completed	Achievement (by 2014)
LTD Cavity	5	Prototype module costs ~ 11$/Joule
Switches	5	3,000,000 to 9,000,000 shot lifetime (1 to 3 years)
Driver Module	5	1 TW sub-scale module testing complete at 2-6 shots/min 40,000 shots with no failure (~ 5 days)
RTL's	4	Prototype system demonstrated on sub-scale module at sub-speed for 100 shots Conceptual designs for economic RTL mass production factory
Target	5	Q ~ 0.5 to 1 DT implosions on Z Cryogenic implosions High gain target designs (>5 GJ) and validated simulations
Chamber	4	Preliminary thick-liquid wall designs Scaled hydrodynamic shielding experiments
Breeding	3	Preliminary design of tritium recovery system
Balance of Plant	5	Preliminary design of Brayton cycle system for inertial fusion energy with primary loop of molten salt
Net TRL	4	

- Subsystems mature enough to integrate into a viable IFE system have a TRL of 6

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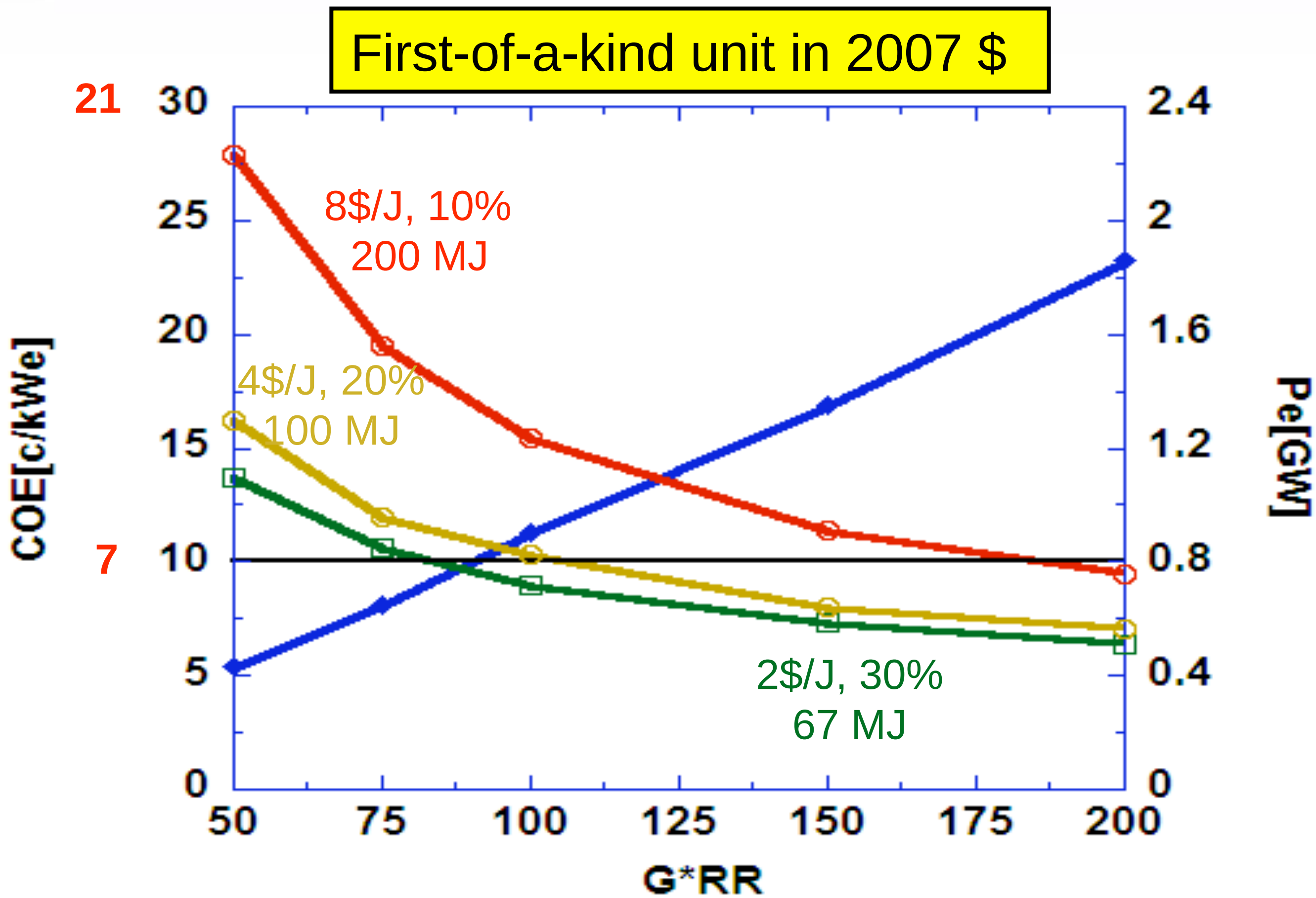
W. Meier *et al.*, FST (2006)

Cost of electricity models put requirements on the product of target gain and rep-rate (*G*RR)*



- Escalate TCC = 2 *x* based on MIT nuclear study
- Cost of $ = 7.8% based on MIT nuclear study
- Learning curves and 10th-of-a-kind units for fusion power economy could lower COE by 30%

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Large yields and low rep-rate may be an attractive path for Inertial Fusion Energy

The logic of the integrated system is compelling

- **Compact, efficient, low cost, long-lifetime, repetitive driver**
- **Advanced, efficient, low cost, robust targets, that are simple to fabricate**
- $\Longrightarrow$ **Very large absorbed target energies**
- $\Longrightarrow$ **Very large fusion yields**
- $\Longrightarrow$ **Allows low rep-rate**
- $\Longrightarrow$ **RTL coupling is feasible, engineering development required**
- $\Longrightarrow$ **Thick-liquid-wall and vaporizing blanket for long lifetime chamber**
- $\Longrightarrow$ **Shielding of line of sight to the driver**

Key enabling physics: magnetically-driven-targets
Key enabling technologies: LTD's and RTL's

IFE diversification

- Many possible IFE systems (1000’s)

- Don’t up-select too early:
  - Magnetically-driven implosions and pulsed power could be a breakthrough
  - Diversify the risk portfolio for national IFE plan. Diversification is in the national interest.

- Diversification, formally: for a given level of expected return, a portfolio minimizes total variance by diversifying amongst assets with poorly correlated risks.

- Technology adoption lifecycles require 40 years for significant market penetration (25% market share)