Design Point for a 1MW Fusion Neutron Source

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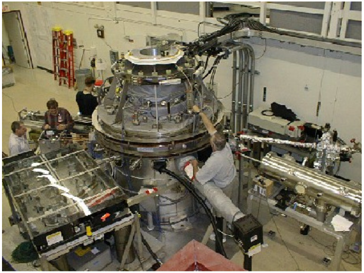
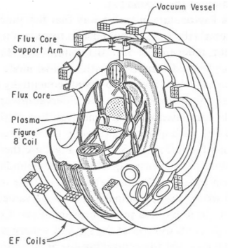
Work completed as part of the IAEA CRP on Compact Fusion Neutron Sources

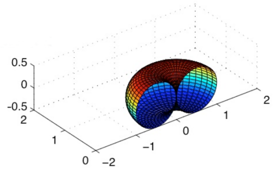
Motivation: IAEA CRP Compact Fusion n-Sources

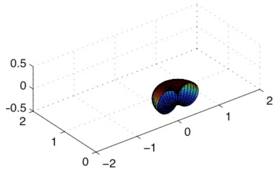
- CRP 2014-1016 aiming for P_n=1-100MW ($10^{17} - 10^{19}$n/s) design points for waste transmutation, fuel reprocessing.
- Tokamak, mirror, ST and other DT concepts considered.
- Ours: magnetically compressed Spheromak with convergence C_R ($=R_0/R_f$) < 3.
- Based on prior results from SSPX [2] and S1 [3].
- Could readily fall into the ARPA-E IDEAS or ALPHA programs.

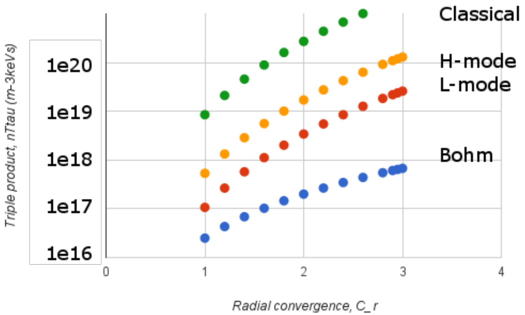




Motivation: high nTτ adiabatically with 1m system







- Historical: ATC [4], TUMAN-3M[5]
- Current: ARPA-E, private (FRCs, spheromaks and STs)
- Adiabatic means faster than τ_E.

Method: 0D, 2D and 3D time-dependent simulation

Tools:

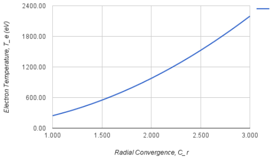
- 0D analytic modeling
- 3D resistive MHD [6] analysis of compression to compare with 0D analytic modeling
- CORSICA 2D equilibrium and stability code [7]
- Engineering design (CAD and force/stress analysis)
- ARIES-like systems code written for Matlab [1]

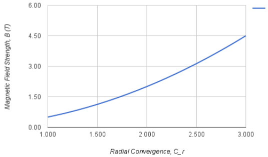
Method:

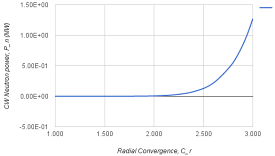
1. A 0D design point is defined
2. A CORSICA model is defined with coil positions to support equilibrium, and for formation.
3. NIMROD is used to test for stability, examine dynamics
4. Given coil currents from CORSICA, a bank design is developed.
5. Knowing the size of bank and coils, an engineering design point is developed.
6. With all components defined, a cost analysis is produced.

Results: 0D modeling for adiabatic compression

- P . V = N . R . T
- For processes that are adiabatic, (γ=5/3): $P_0 \,.\, V_0^\gamma = P_f \,.\, V_f^\gamma$.
- If the compression is adiabatic, then $PV^{5/3}$ = const.
- and for self-similar compression ($C = a_0 \,/\, a_f$)
- $P_0 {V_0}^\gamma = P_f {V_f}^\gamma$ and since $V_f = V_0 C^3$ then: $P_f = P_0 \,.\, C^5$ and since $P \sim n.T$ and $T_f = T_0 \,.\, C^2$





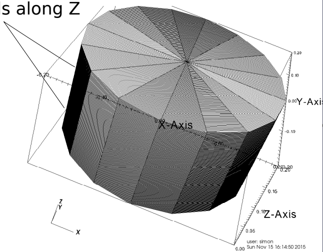


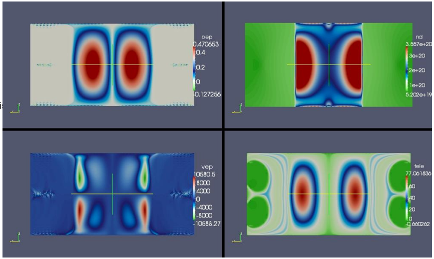
Results: Device design point from 0D modeling

Parameter	Symbol	Value	Units
Radial Convergence	C_r	3	
Volumetric Convergence	C_V	27	
Initial Plasma Radius	r_0	0.5	m
Final Plasma Radius	r_f	0.166	m
Initial Volume	V_0	0.55	m^3
Converged Volume	V_f	0.16	m^3
Initial Beta	β_0	15	%
Initial Density	n_0	2	$\times 10^{20} m^{-3}$
Initial Magnetic Field	B_0	0.5	T
Initial Temperature	T_0	244	eV
Final Temperature	T_f	2196	eV
Final Density	n_f	54	$\times 10^{20} m^{-3}$
Final Magnetic Field	B_f	4.5	T
Initial plasma current	I_0	0.75	MA
Final plasma current	I_f	6.75	MA
Final Beta	β_f	45	%
Final Magnetic Energy	U_f	1.37	MJ
Steady State Fusion Power from neutrons	P_n	1.27	MW
Steady State Neutron Rate	Γ_n	5.7E+17	n/s

Results: 3D MHD simulations of compression in cylindrical geometry

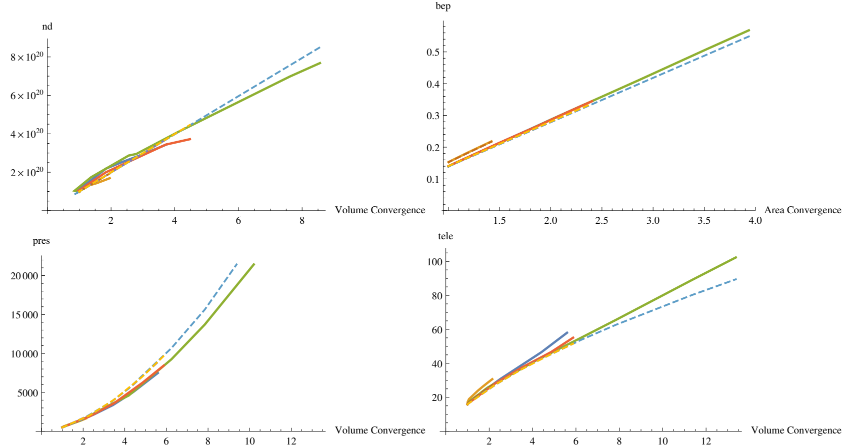
E_tan applied
in bands along Z



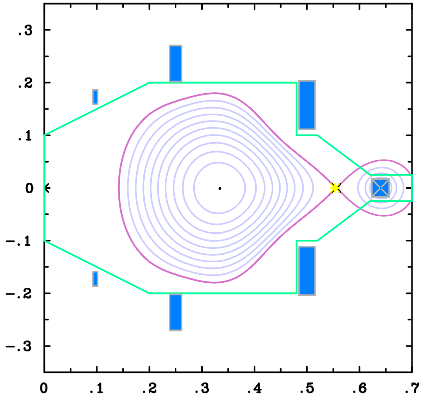


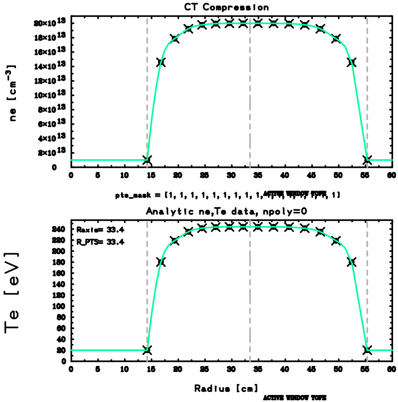
- NIMROD simulation campaign with broad range of ICs, 20cm radius can, 5μs compression
- Full Braginskii (T-dependent) 2 fluid transport model calibrated to SSPX

Results: 3D MHD results follow 0D adiabatic scaling



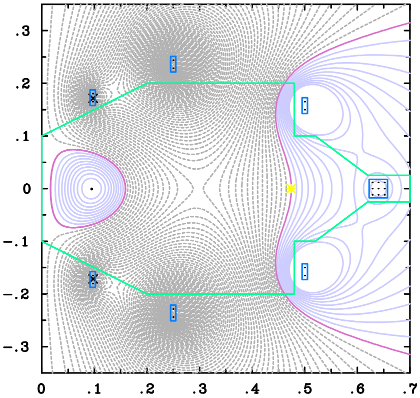
Results: CORSICA uncompressed, radial formation

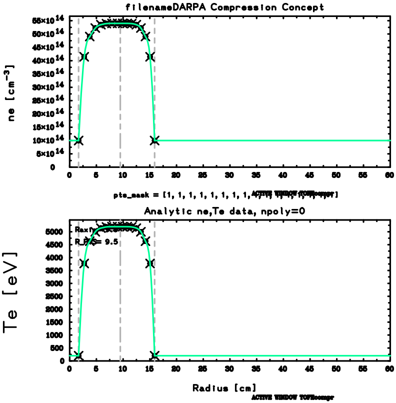




- Injection from outboard side using solenoid and conical annular electrodes (somewhat like S1)
- $T_0 = 200$eV, and $n_0 = 1e20 m^{-3}$.

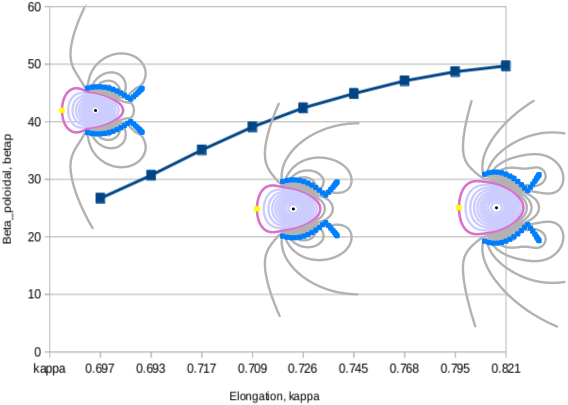
Results: CORSICA peak compression





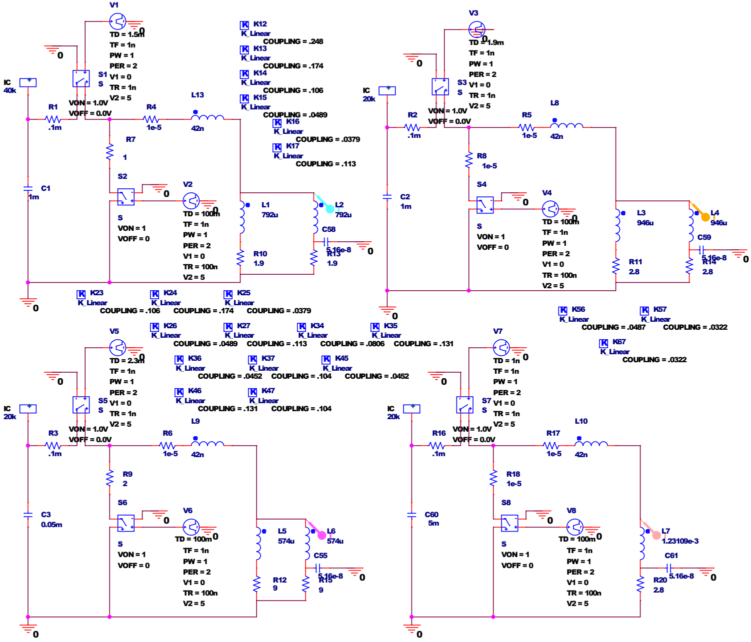
- Plasma current increases to 6.75MA
- Fusion power of 1.3MW at 5keV

Results: Pressure optimization with shaping



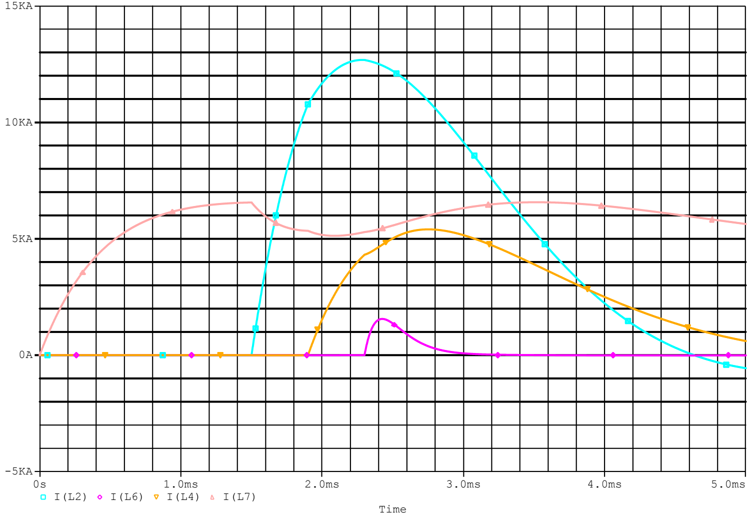
- At peak compression, the shape of the plasma dictates the attainable beta (stable to Mercier (pressure-driven) modes).

Results: PSpice design point for coil banks



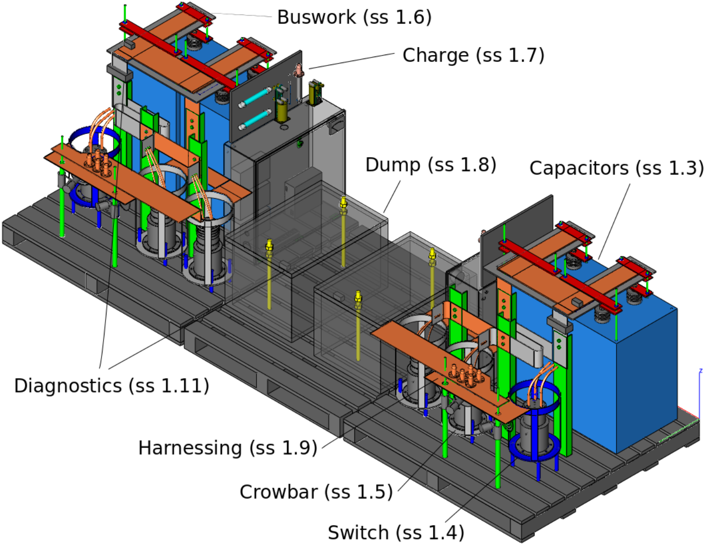
Results: PSpice design point for banks

- Fast compression: 1ms rise for coils



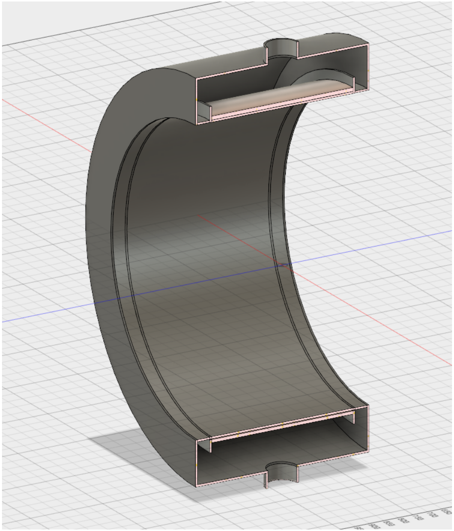
Results: Engineering design point for banks

- Bank engineering point design based on WSI prior design [8]
- Shown are two 120kJ modules, 20kV caps. $200k per set.



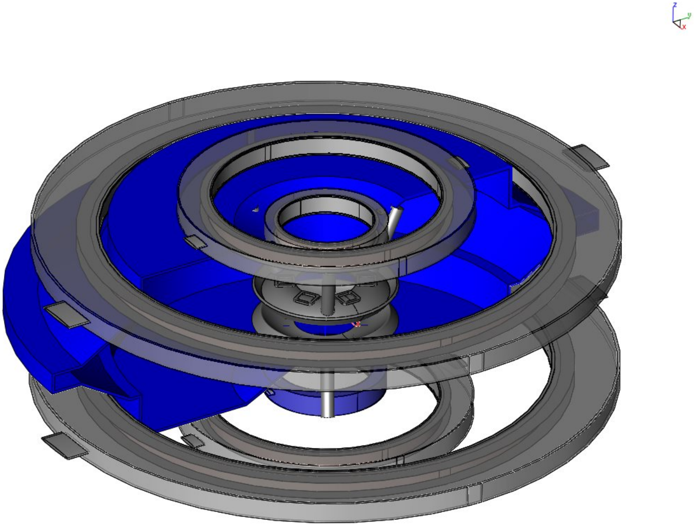
Results: Engineering design coils

- Coils to be actively cooled in vacuum.
- Design point current for copper at 20C, although cooling will allow bank to be reduced in size.
- Outer-most coil will use HT superconducting tape (REBCO), since it remains energized.



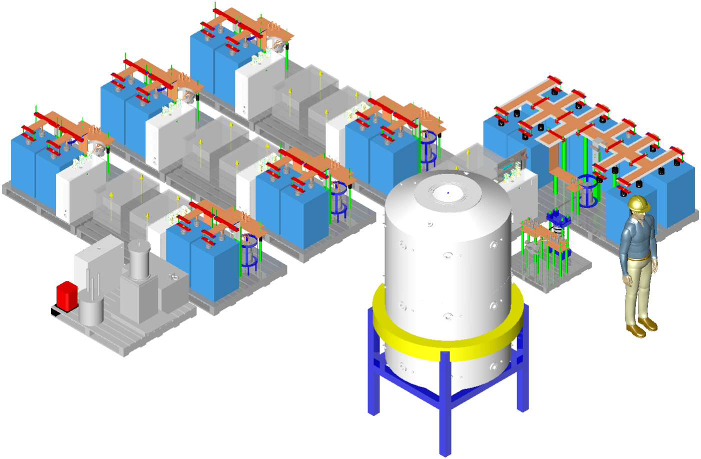
Results: Full assy for in-vacuum components

- Coil casings, windings, support for in-vacuum operation.



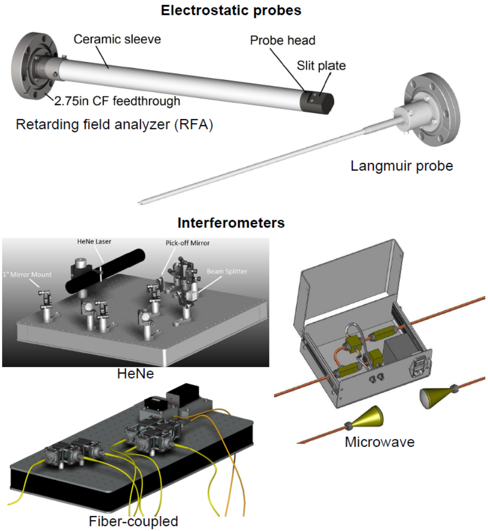
Results: full system engineering design point

- Test compression and optimize neutron production
- Banks, chamber and diagnostics would fit in a 2000sqft lab



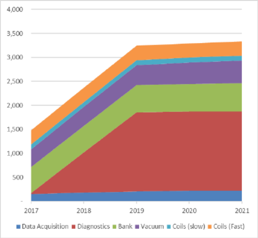
Results: Diagnostics requirements for system

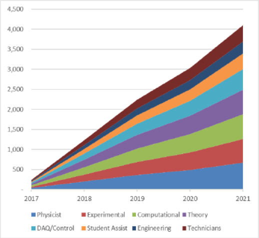
- Thomson, interferometry, magnetics, electrostatic probes.
- Engineering design points completed as part of Phase II SBIR

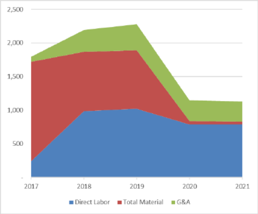


Results: costing for n-Source prototype over 5 years

- Forecast costs by category (materials, labor and overhead), based on experience at WSI.
- Build-out over Y1-Y3.
- Labor Y3-Y5.
- Prototype costs are $10M
- Full neutron source: $50M







Further Work

- Neutronics analysis with MCNP6 awaits - coming up in September.
- Design point can be further optimized for efficiency, and for rep-rate.
- CORSICA analysis can be performed to address transport and shape optimization during run-in - this would form part of a SBIR proposal.
- Concept fits into ARPA-E IDEAS program, seeking to use fusion to resolve fission issues.

Summary

- Design point for a n-Source prototype has been examined analytically and numerically, using state-of-the-art tools (2D and 3D time-dependent MHD).
- A full engineering point design has been developed, based on physics design point.
- Cost of prototype source would be $10M, full source likely $50M.

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