STELLARATOR REACTOR OPTIMIZATION CODE

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TOPICS

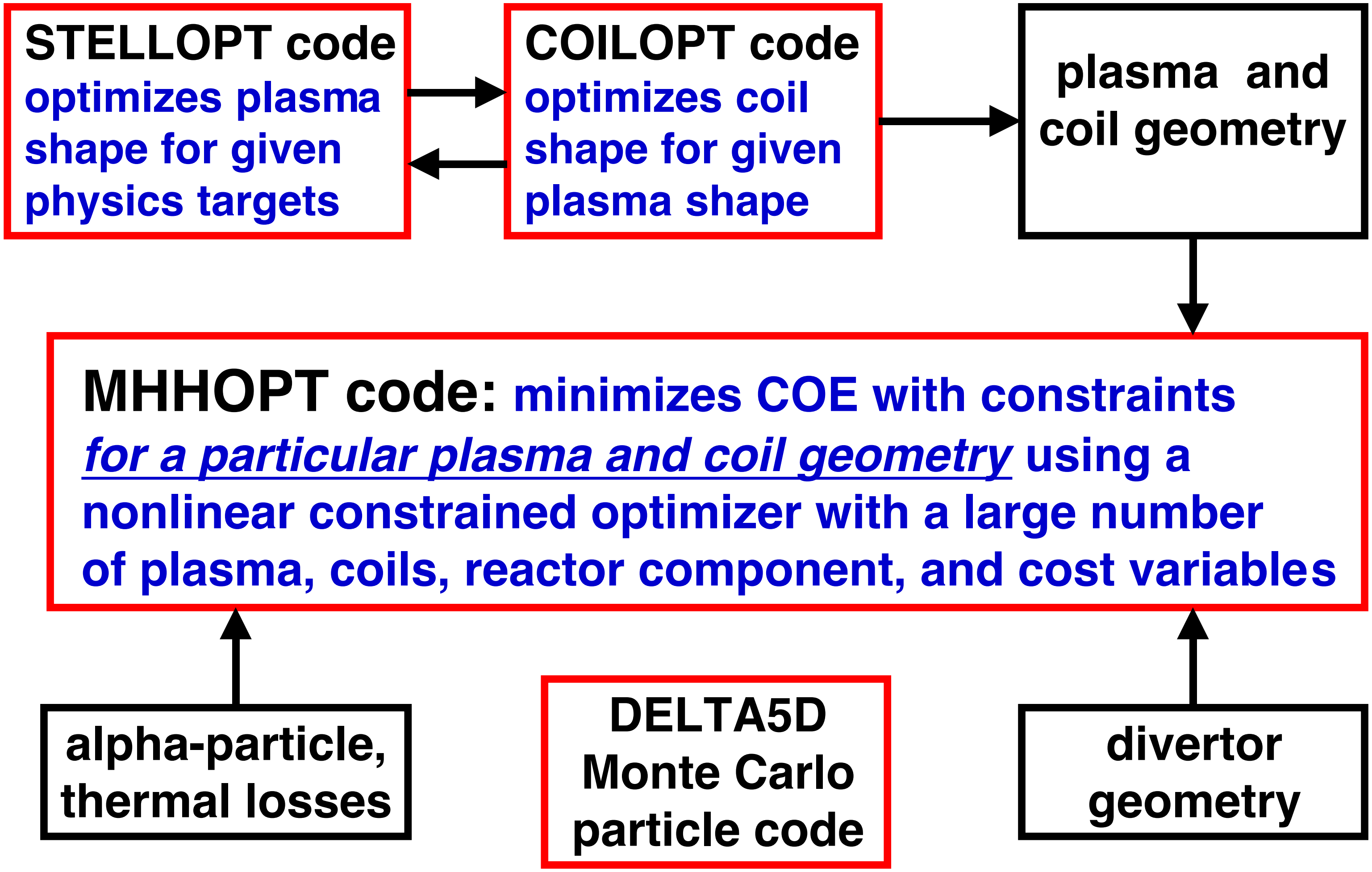
- 0-D Spreadsheet Reactor Optimization
- Present 1-D Optimization Approach
- Alpha-particle Losses and Patterns
- Next Steps

0-D Spreadsheet Calculations

- **Fixed plasma and coil geometry**
  - R/a, $\iota(2/3\ a)$, R/Δ, B_{max}/B_0
- **Input parameters**
  - max H-ISS95, max β, max $T(0)$
  - max B_{max}, target P_{fusion}, max neutron wall loading ($\Gamma_{n,\ max}$)
- **Minimize *R* for target P_{fusion} by varying *n* and H-ISS95 with constraints: parameters ≤ max. allowed values**
  - H-ISS95, β, $T(0)$, n/n_{Sudo}
  - plasma-coil distance, j_{coil}, Γ_n
- **Calculated quantities**
  - R, a, n, T, β, ν^*, H-ISS95
  - plasma-coil distance, coil j, coil thickness, P_{fusion}, Γ_n
- **Useful for size scaling for *fixed* plasma and coil geometry and comparing reactor configurations**

Present Reactor Optimization Approach

- presently uses separate ORNL codes
  (VMEC-STELLOPT/COILOPT, DKES, DELTA5D)



STELLOPT code
optimizes plasma shape for given physics targets

COILOPT code
optimizes coil shape for given plasma shape

plasma and coil geometry

MHHOPT code: minimizes COE with constraints *for a particular plasma and coil geometry* using a nonlinear constrained optimizer with a large number of plasma, coils, reactor component, and cost variables

alpha-particle, thermal losses

DELTA5D Monte Carlo particle code

divertor geometry

MHHOPT Optimization Approach

- Minimizes core cost or size or COE with constraints for a particular plasma and coil geometry using a nonlinear constrained optimizer with a large number of variables
- Large number of constraints allowed (=, <, or >)
  - ignition margin, β limit, ISS-95 multiplier, radial build, coil *j* and B_{max}, plasma-coil distance, blanket and shielding thicknesses, TBR, access for divertors and maintenance, etc.
- Large number of fixed parameters for plasma and coil configuration, plasma parameters and profiles, transport coefficients, cost component algorithms, and engineering model parameters
- Calculates (and iterates on) a large number of variables
  - plasma: $T_e(r)$, $T_i(r)$, $n_e(r)$, $n_e(r)$, $E_r(r)$, β, Z_{eff}, power components (coronal and bremsstrahlung radiation, $\alpha \rightarrow i$, $\alpha \rightarrow e$), α losses, etc.
  - coils: components volumes and costs, *j*, B_{max}, forces
  - reactor variables: blanket volumes, TBR, neutron wall loading, $P_{electric}$, divertor area, access between coils, radial build, etc.

Systems Code Integrates Physics, Materials, Cost Models

- **1-D Stellarator transport with different models for χ_i, χ_e, D_i, D_i and electric-field-dependent terms**
  - (a) 1-D evaluations with fixed profiles
  - (b) solve for $T_e(r)$ and $T_i(r)$ with fixed $n_e(r)$ and $E_r(r)$
  - (c) solve for $T_e(r)$, $T_i(r)$, $n_e(r)$ and $E_r(r)$ with fixed particle source
- **Detailed physics models for**
  - alpha-particle heating and losses (Fokker-Planck with losses)
  - radiation (coronal line radiation, bremsstrahlung, synchrotron)
- **ARIES magnet and reactor material assumptions**
  - multi-region blanket and shield (except for divertor regions)
  - B_{max} vs. j in coil from ARIES studies
  - allowable stresses, reactor safety penalties, etc. from ARIES
- **ARIES costing algorithms based on masses and cost per kg**
  - Uses all ARIES-RS algorithms and accounts

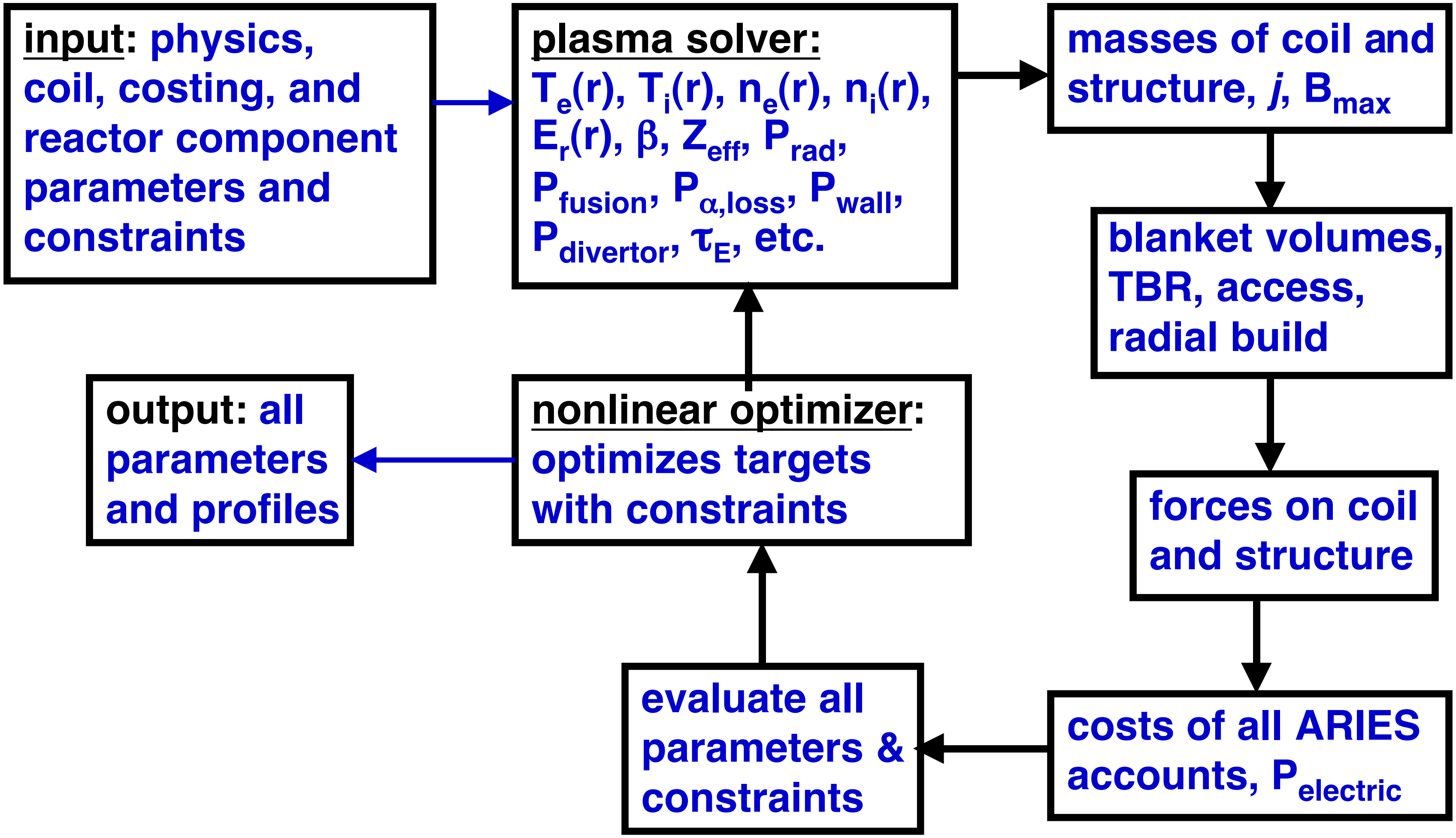
1-D Transport in Systems Code

- Steady-state 1–D integral-differential equations for the heat and particle fluxes for the ions (D,T) and electrons are solved for $n_e(r)$, $n_i(r)$, $T_e(r)$, $T_i(r)$, and $E_r(r)$:

$$\rho q_j(\rho) = a_p \int p_j(\rho^*)\rho^* d\rho^* \ , \quad \rho \Gamma_j(\rho) = a_p \int s_j(\rho^*)\rho^* d\rho^* \ ; \quad \mathrm{j = ions, electrons}$$

- Heat flux $q_j = -n_j \chi_j^T \nabla T_j - T_j \chi_j^n \nabla n_j - Z_j n_j \chi_j^\phi \nabla \phi$
- Particle flux $\Gamma_j = -n_j D_j^T \nabla T_j - T_j D_j^n \nabla n_j - Z_j n_j D_j^\phi \nabla \phi$
- The electric field is determined from the ambipolarity condition. The electric field *E* enters both through an *E*/*B* drift term in the denominators of χ and D, and directly through the sign-dependent $\nabla \phi$ term.
- The volumetric heat sources (and sinks) are the usual alpha-particle heating and losses, electron-ion heat transfer, and radiation terms.
- Profiles for $n_e(r)$ and impurity fraction can be chosen or a particle source rate (*s*) to represent shallow or deep fueling of the plasma.

MHHOPT Reactor Optimization Code



input: physics, coil, costing, and reactor component parameters and constraints

plasma solver: $T_e(r)$, $T_i(r)$, $n_e(r)$, $n_i(r)$, $E_r(r)$, β, Z_{eff}, P_{rad}, P_{fusion}, $P_{\alpha,loss}$, P_{wall}, $P_{divertor}$, τ_E, etc.

masses of coil and structure, *j*, B_{max}

blanket volumes, TBR, access, radial build

forces on coil and structure

costs of all ARIES accounts, $P_{electric}$

evaluate all parameters & constraints

nonlinear optimizer: optimizes targets with constraints

output: all parameters and profiles

Input Parameters

- Configuration geometry
  - *present:* plasma aspect ratio, surface area, coil aspect ratio, closest approach aspect ratio, β_{limit}, $\iota(r)$, ripple$_{effective}(r)$, etc.
  - will upgrade to more realistic plasma geometry
- Reactor component parameters
  - inside & outside shield thickness; coil width and depth
  - blanket thickness inside & outside, under and between coils
  - coil case & dewar thickness inside, outside, top & bottom for modular coils and VF coils; scrapeoff thickness
  - first wall and reflector thickness; coil to cryostat gap
  - allowable nuclear heating in coil; $j_{max}(B)$
  - blanket energy multiplication
- Cost assumptions
  - modular and VF costs /kg
  - cost multipliers for blanket and shield
  - duty factor, inflation, safety assurance

Optimization Parameters

- **Plasma assumptions**
  - profiles for $T_e(r)$, $T_i(r)$, $n_e(r)$, $n_e(r)$, $n_{Fe}(r)$, $n_O(r)$, $E_r(r)$ *if* not calculated
  - B_0, $\langle R \rangle$, $\langle n \rangle$, $\langle T \rangle$, α loss; expressions for different $\chi_e(r)$, $\chi_i(r)$
  - 0-D *or* 1-D with fixed *or* calculated n(r) and $E_r(r)$
- **Reactor optimization target**
  - minimum $\langle R \rangle$, equipment cost, $|\phi_0/T_{e0}|$, $P_{electric}$
- **Constraints** (=, <, or >)
  - equipment cost, annual operating cost, total project cost
  - $\langle \beta \rangle$, n_{max}, ISS-95 factor, ignition margin, electric power, TBR
  - radial build, max. & min. width/depth of coils, clearance between coils
  - max. *j* in coils, B_{max}, tensile stress in coils & structure
- **Iteration variables**
  - $\langle R \rangle$, B_0, n_i, T_i, ϕ/T_e, modular & VF coil width & depth, case thickness, blanket thickness, ISS-95 factors

Output

- **Plasma parameters and profiles**
  - <R>, B_0, W_{plasma}, τ_E, H factors, <β>, β*, n_{Fe}/n_e,n_O/n_e, Z_{eff}
  - <T>, T_{i0}, $T_{i,edge}$, T_{e0}, $T_{e,edge}$, ϕ_0/T_{e0}, <n>, n_{i0}, n_{e0}, $<n>/n_{Sudo}$, n_{DT}/n_e,
  - ignition margin, P_{fusion}, $P_{electric}$, $P_{neutron}$, $P_{charged}$, $P_{divertor}$, components of P_{rad} and P_{wall}, P_{loss}
- **Coil parameters**
  - modular & VF coil dimensions, currents, forces, inductance, stored energy, *j*, B_{max}, case thickness
- **Reactor parameters**
  - blanket area accessible and blocked, inboard and outboard shield thickness, cryostat gap, access between coils

Output (cont.)

- Cost elements
  - land & structures; power supplies; impurity control; heat transport; power conversion; startup power
  - blankets & first wall; shields; modular & VF coils; structure; vacuum vessel
  - turbine plant equipment; electric plant equipment; misc. plant equipment; special materials; total direct cost
  - construction; home office; field office; owner's costs; project contingency; construction interest; construction escalation; total capital cost
  - unit direct cost; unit base cost; total unit cost; capital return; O&M costs; blanket/first wall replacement; decommissioning allowance; fuel costs; cost of electricity
- Summary of all component masses & mass utilization
- Dimensions of each element in the radial build

Alpha Particle Confinement Issues

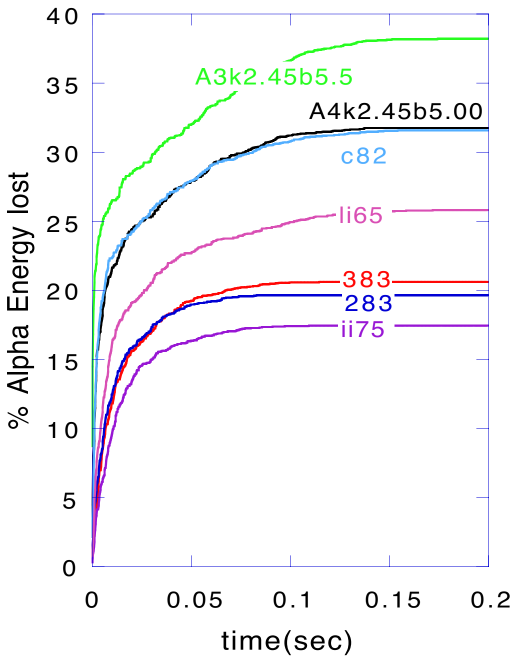
- Alpha energy losses during slowing down
  - Impact on power balance
- Alpha power deposition on first wall
  - Sputtering, impurity generation
  - Wall protection against high localized heat loads
- Improved alpha confinement optimization target
  - Should be specific to phase space regions with high loss rates
  - New noise reduction techniques under development
    - Monte Carlo splitting
    - Back-averaging over optimization cycles
  - Longitudinal adiabatic invariant, J
    - New method under development to target direct losses rather than local radial drifts

Alpha Losses Were Studied With Monte Carlo (DELTA5D) Code for Different QA Configurations

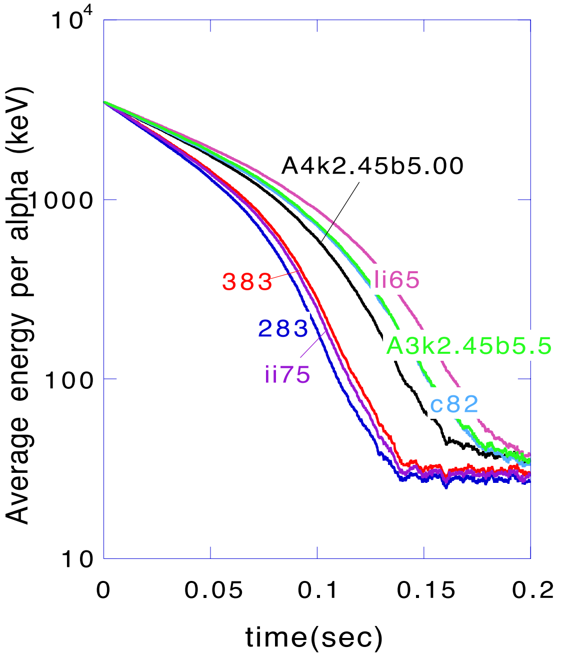
- **Parameters chosen for constant fusion power (2.2 GW) - Zarnstorff**
- **ARIES-RS magnetic field strength**

device	R0	B (T)	n0 (10**14)	T0 (keV)	% alpha losses
c82	5.91	7.98	2.11	30.1	31.6
283	6.11	7.98	2.45	23.9	19.7
383	6.91	7.98	2.45	26.5	19.7
ii75	7.44	7.98	2.45	25.8	17.45
Ii65	7.34	7.98	2.05	30.9	25.8
A3k 2.45b5.5	4.4	7.98	2.45	35.5	37.2
A4k2.45b5.00	5.68	7.98	2.45	32.3	31.8

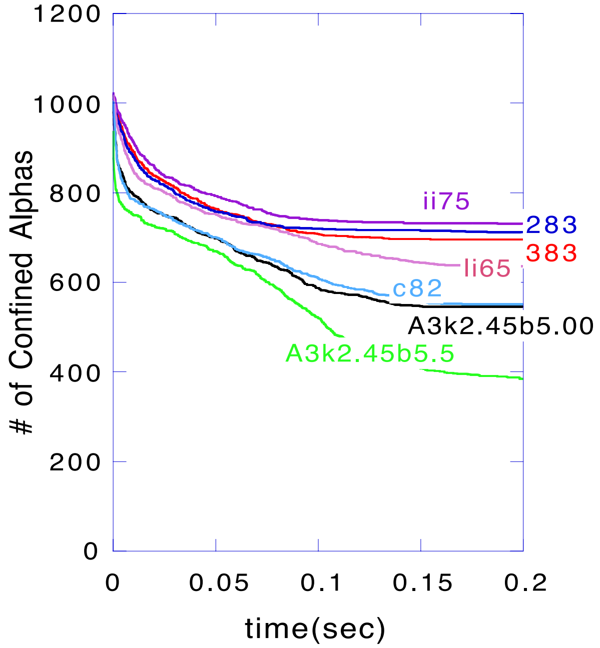
Cumulative alpha energy loss



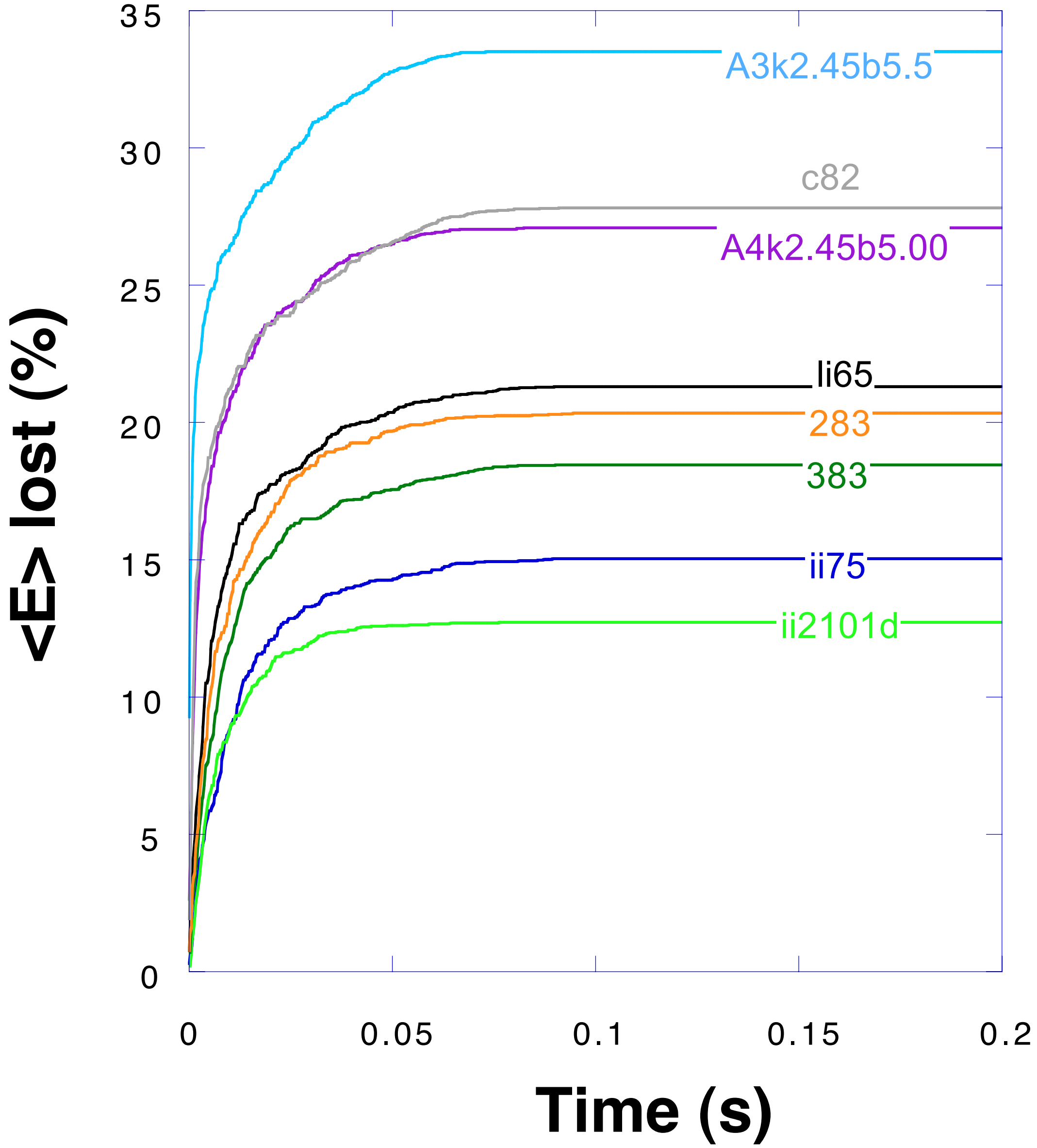
Alpha slowing-down timescale



Reduction of confined alphas during slowing-down



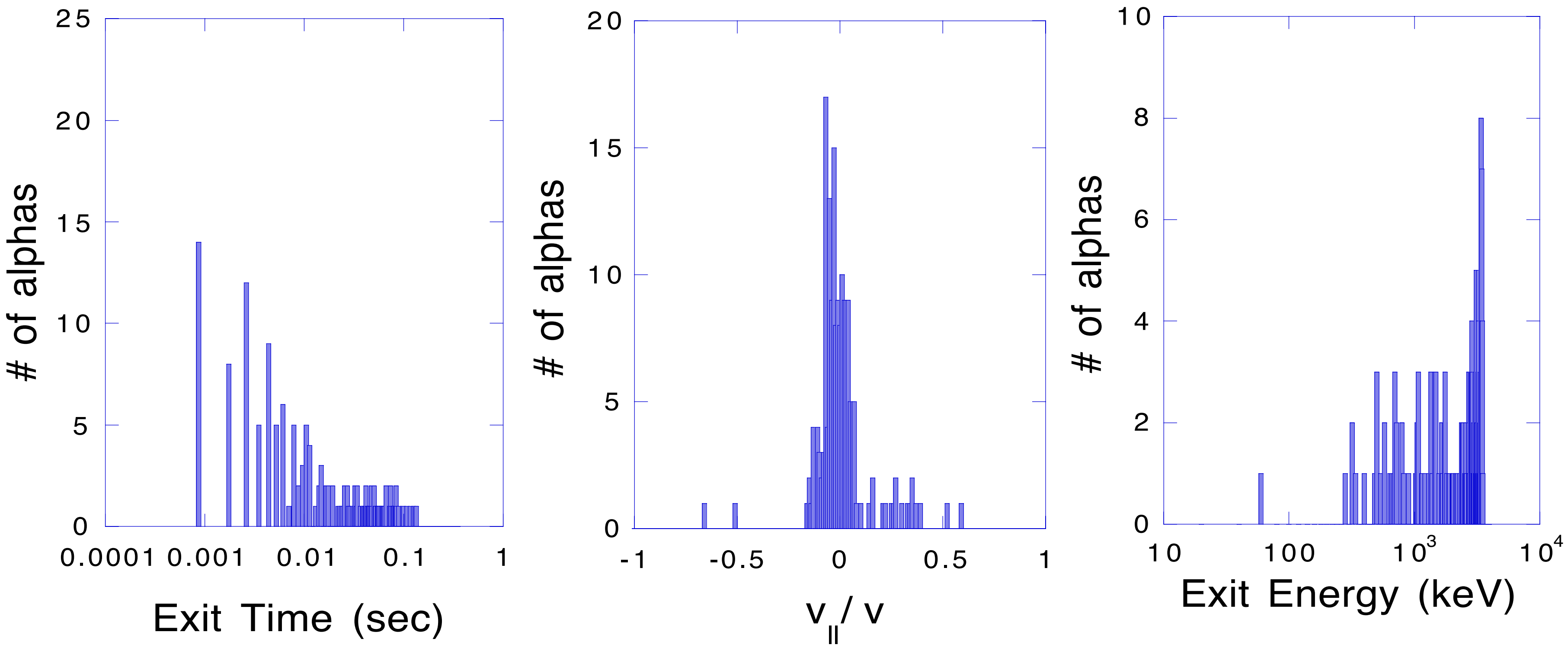
Alpha Losses in the Same Devices at Fixed Electron Temperature and Varying Fusion Power Output



$n(0) = 2.5 - 3.7 \times 10^{14}\ \mathrm{cm}^{-3}$
$T(0) = 23.65$ keV
$\langle B \rangle = 7.98$ T
$\langle R_0 \rangle = 4.4$ to 7.4 m
$p_\alpha \propto (1-\psi)^5$
$n \propto (1-\psi)^{1/2}$
$T \propto (1-\psi)^2$

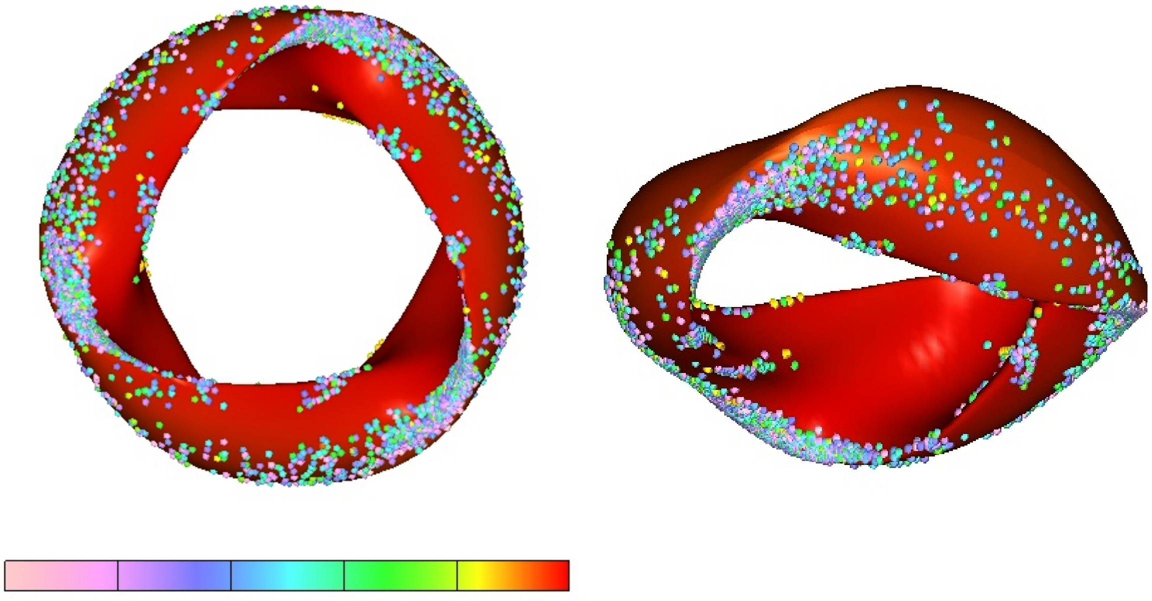
Histograms of Escaping Alpha Parameters for the Reactor-Size LI383 Device

- Significant prompt losses above 1 Mev
- Most exiting alphas are trapped particles



DELTA5D Shows Fast Ions Exit Last Closed Flux Surface Near Ridges at Toroidal Angles = π/3, π, and 5π/3

- These figures are based on neutral beam losses for NCSX, but alphas show similar patterns
- Power deposition can be calculated
- Exits are at $\max\left(\vec{B}\times\vec{\nabla}B\right)$
- Can be extended to vacuum region



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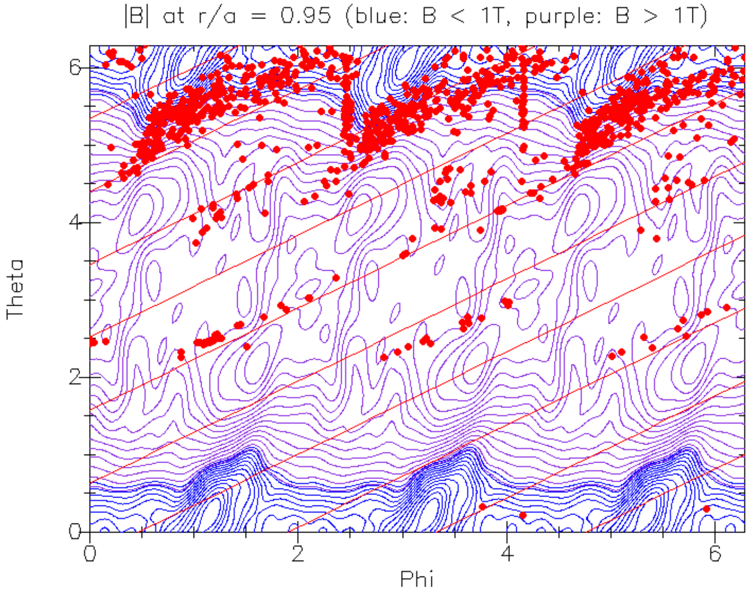

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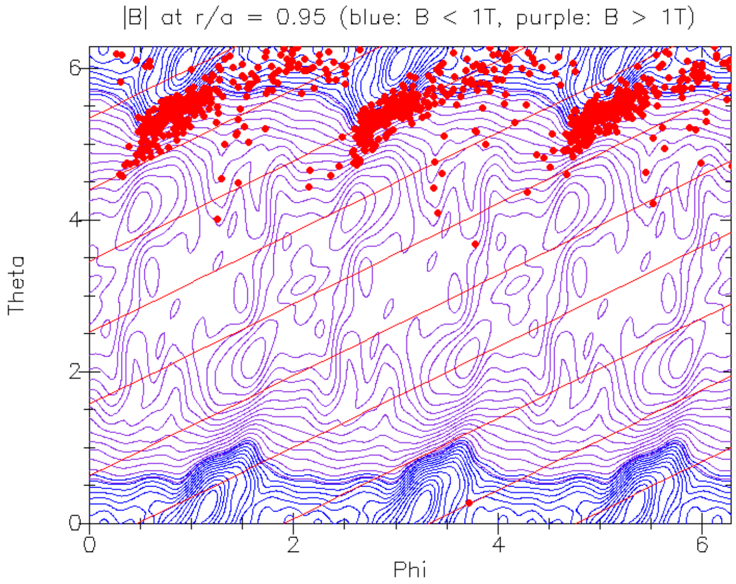
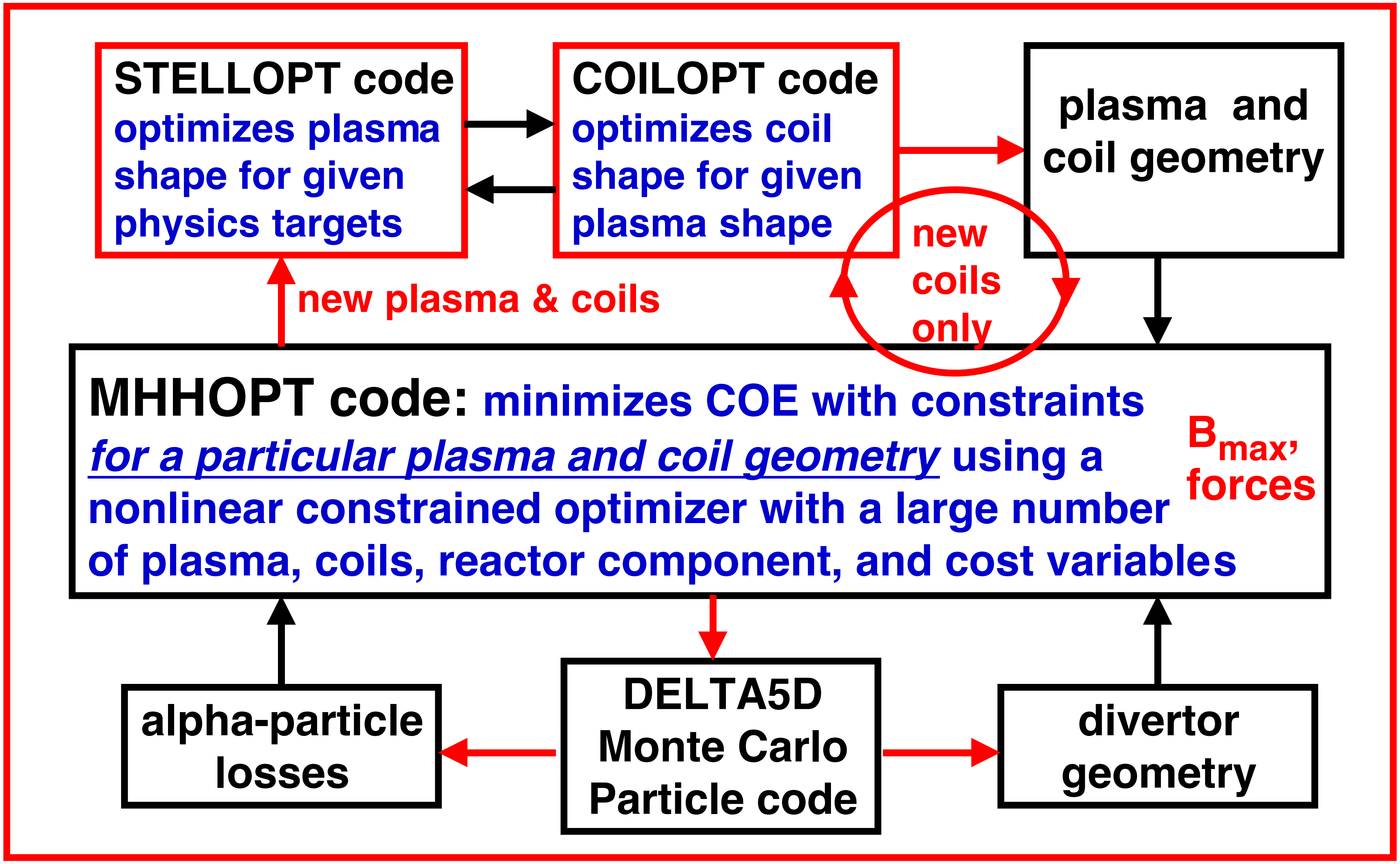


Can Construct New Alpha Confinement Targets for Reactor Optimization Studies

- Tailor particle launch points to phase space regions that are known to have high losses
  - Transitional orbits near trapped/passing boundary
  - i.e., $v_{||}/v = 0$, distributed on constant $B = B_t$ locations, with $B_t = \varepsilon/\mu$, and $B_t = B_{max} \pm \delta$
  - Use Monte Carlo splitting techniques to emphasize alphas with poor confinement
- Smoothing for derivative-based optimization methods
  - e.g., Levenberg-Marquardt or VMCON
  - Back average over preceeding optimization cycles
  - Or non-derivative methods (differential evolution, genetic algorithm)
- First wall heat loads might be smoothed out by targeting reduced variation of $\vec{\nabla}\psi \cdot \left(\vec{B} \times \vec{\nabla}B\right)$ on outer flux surfaces
- Follow non-local variation bounce-averaged orbits near transitional layer using J (longitudinal adiabatic invariant)
  - Previous methods based on J only attempted to reduce local radial drifts

Desired Reactor Optimization Approach

- integrate existing codes



STELLOPT code
optimizes plasma shape for given physics targets

COILOPT code
optimizes coil shape for given plasma shape

plasma and coil geometry

new coils only

new plasma & coils

MHHOPT code: minimizes COE with constraints *for a particular plasma and coil geometry* using a nonlinear constrained optimizer with a large number of plasma, coils, reactor component, and cost variables

B_{max}, forces

alpha-particle losses

DELTA5D Monte Carlo Particle code

divertor geometry

Next Steps

- Upgrade to current math libraries and operating system
- Incorporate plasma and modular coil geometry
  - plasma shape, plasma-coil separations, B_{max}, forces, etc.
- Upgrade costing algorithms
- Incorporate alpha-particle loss regions and divertor areas
- Integrate COILOPT/STELLOPT in optimization