# Inertial Confinement Fusion (ICF) $\varphi$-Spaced Pulse Shaping with Symmetry-Ledger Optimization and Certificate-Gated Deployment

Provisional Patent Draft

## Field

This disclosure relates to drive-pulse synthesis and deployment for inertial confinement fusion (ICF) targets in direct-drive and indirect-drive (hohlraum) configurations. It provides: (i) a construction of *$\varphi$-spaced sub-pulses* in a multi-subpulse train, (ii) minimization of a *symmetry ledger* formed from normalized mode-amplitude ratios $|a_{\ell m}|$, (iii) a *certificate* (audit surface) enforcing symmetry and performance thresholds, and (iv) a *geometric convergence* property of residual asymmetry as a method feature.

## Background

Conventional ICF pulse shaping optimizes shock timing and implosion symmetry via ad-hoc objectives (e.g., least-squares on select modes) and heuristic spacing of pickets and ramps. Existing methods do not (a) enforce golden-ratio timing that desynchronizes low-order coupling across dominant hydrodynamic/RT modes, (b) use a convex, dimensionless ledger over normalized symmetry ratios, or (c) gate shot deployment by a formal certificate that prevents out-of-tolerance symmetry.

## Summary

A drive pulse $P(t) = \sum_{k=1}^{K} A_k\, s(t - t_k)$ is constructed from sub-pulses with *$\varphi$-commensurate* inter-pulse spacings. Symmetry diagnostics yield spherical-harmonic coefficients $a_{\ell m}$; their normalized magnitudes $r_{\ell m} := |a_{\ell m}|/a^\star_\ell$ feed a convex *symmetry ledger* $\mathcal{L}_{\text{sym}}$ via the cost $J(x) = \frac{1}{2}(x + 1/x) - 1$. An optimizer selects $\{A_k, t_k\}$ under energy and plant constraints to minimize $\mathcal{L}_{\text{sym}}$. A certificate (audit surface) with fixed thresholds authorizes or blocks shot deployment. Within the admissible regime, the residual ledger exhibits *geometric convergence* as the sub-pulse count $K$ increases, up to saturation.

## Definitions

**$\varphi$-spaced sub-pulses.** Let $\varphi = \frac{1+\sqrt{5}}{2}$. A $K$-subpulse train has inter-pulse spacings

$$\Delta t_k := t_{k+1} - t_k, \qquad \frac{\Delta t_{k+1}}{\Delta t_k} \in \{\varphi, \varphi^{-1}\}, \quad k = 1, \dots, K-2,$$

with $\sum_{k=1}^{K-1} \Delta t_k = T_{\text{win}}$ meeting a declared drive window. Sub-pulses share a bounded shape $s(\cdot)$ (e.g., raised-cosine, Gaussian, spline); amplitudes $A_k$ obey energy and slew limits.

**Symmetry coefficients.** From x-ray self-emission, radiography, backlighter, or equivalent diagnostics, compute spherical-harmonic coefficients $a_{\ell m}$ on a reconstruction window.

**Recognition ratios and symmetry ledger.**

$$r_{\ell m} := \frac{|a_{\ell m}|}{a_\ell^\star}, \qquad J(x) := \tfrac{1}{2}\left(x + \frac{1}{x}\right) - 1, \quad x > 0, \qquad \mathcal{L}_{\text{sym}} := \sum_{\ell \in \mathcal{S}} w_\ell \sum_{m=-\ell}^{\ell} J(r_{\ell m}),$$

with declared mode set $\mathcal{S}$ (e.g., $\{2,4,6\}$), targets $a_\ell^\star > 0$, and positive weights $w_\ell$.

**Certificate (audit surface).** Pass/Fail criteria with fixed thresholds, e.g.,

$$\mathsf{Pass} \iff \mathcal{L}_{\text{sym}} \le \Lambda, \quad |a_{20}| \le \tau_2, \quad |a_{4m}| \le \tau_4, \quad \text{shock timing/bang-time within bands, adiabat bounds,}$$

Only *Pass* pulses are authorized for shot deployment.

# Detailed Description of Embodiments

## Pulse Synthesis and Optimization

Given energy budget $E_{\text{tot}}$ and plant constraints, choose $\{A_k, t_k\}_{k=1}^{K}$ to minimize $\mathcal{L}_{\text{sym}}$ subject to: (i) $\varphi$-spacing constraints on $\{\Delta t_k\}$, (ii) amplitude/slew bounds, (iii) total energy $\sum_k A_k \int s(t)\, dt \le E_{\text{tot}}$, and (iv) facility timing and pointing limits (cone, ring, quad assignments). The optimizer may be model-based (hydrodynamics surrogate) or data-driven, provided constraints are enforced.

## Multi-Beam and Geometry

In direct drive, per-beam sub-pulse phases inherit the scalar $\{t_k\}$ with optional per-ring micro-delays that preserve $\varphi$-commensurability. In indirect drive, laser entrance holes, cone fractions, and hohlraum wall coupling are accommodated via transfer functions used in the objective prediction; the ledger remains unchanged.

## Certificate-Gated Deployment

Prior to a high-energy shot, predicted symmetry (or low-energy surrogate shot data) must satisfy the certificate thresholds. At shot time, on-shot symmetry proxies are checked online; violation blocks subsequent sub-pulses or aborts the sequence, per safety policy.

## Geometric Convergence Feature

For fixed $E_{\text{tot}}$ and within the weakly nonlinear regime, adding one $\varphi$-spaced sub-pulse permits a best-response update that reduces residual ledger by at least a fixed fraction, i.e., $\mathcal{L}_{\text{sym}}(K) \le \eta\, \mathcal{L}_{\text{sym}}(K-1) + \xi$, with $0 < \eta < 1$ qualitative and $\xi$ a higher-order remainder; convergence persists until mode-coupling saturation.

# Advantages

The approach (i) regularizes timing via $\varphi$-spacing to avoid low-order modal reinforcement, (ii) uses a convex, dimensionless ledger aligned to physical symmetry, (iii) gates deployment with certificate thresholds for safety and repeatability, and (iv) achieves monotone, at-least-geometric reduction of residual asymmetry with sub-pulse count, up to saturation.

# Claims

## Independent Claims

1. **(Method)** A method of driving an inertial-confinement-fusion target, comprising:

   (a) constructing a multi-subpulse drive $P(t) = \sum_{k=1}^{K} A_k\, s(t - t_k)$ whose inter-pulse spacings $\Delta t_k = t_{k+1} - t_k$ satisfy $\Delta t_{k+1}/\Delta t_k \in \{\varphi, \varphi^{-1}\}$ for $\varphi = (1+\sqrt{5})/2$ and $\sum_{k=1}^{K-1} \Delta t_k$ equals a declared drive window;

   (b) acquiring symmetry diagnostics and computing spherical-harmonic coefficients $a_{\ell m}$ and normalized ratios $r_{\ell m} = |a_{\ell m}|/a_\ell^\star$ for a set of modes $\ell \in \mathcal{S}$;

   (c) minimizing a symmetry ledger $\mathcal{L}_{\text{sym}} = \sum_{\ell\in\mathcal{S}} w_\ell \sum_{m=-\ell}^{\ell} J(r_{\ell m})$ with $J(x) = \frac{1}{2}(x + 1/x) - 1$, subject to energy and facility constraints, by selecting amplitudes $A_k$ and times $t_k$ consistent with the $\varphi$-spacing;

   (d) evaluating a certificate comprising fixed thresholds on $\mathcal{L}_{\text{sym}}$ and mode-specific bounds and authorizing shot deployment only upon satisfaction of the thresholds; and

   (e) executing the authorized pulse on target while monitoring symmetry proxies and enforcing the certificate during the shot.

2. **(System)** A pulse-shaping system for inertial confinement fusion, comprising:

   (a) a scheduler that generates $\varphi$-spaced sub-pulse times $\{t_k\}$ for a declared drive window and enforces $\Delta t_{k+1}/\Delta t_k \in \{\varphi, \varphi^{-1}\}$;

   (b) an optimizer that selects amplitudes $\{A_k\}$ to minimize $\mathcal{L}_{\text{sym}}$ over predicted $r_{\ell m}$ subject to energy and facility constraints;

   (c) a symmetry-estimation module that computes $a_{\ell m}$ and $r_{\ell m}$ from diagnostics; and

   (d) a certificate module that evaluates thresholds on $\mathcal{L}_{\text{sym}}$ and mode bounds and authorizes or blocks deployment accordingly.

3. **(Non-transitory medium)** A non-transitory computer-readable medium storing instructions that, when executed, cause a system to perform the method of claim 1.

4. **(Method feature: convergence)** The method of claim 1, wherein, for fixed total drive energy and within an admissible operating regime, the residual symmetry ledger decreases

at least geometrically with the number of sub-pulses, characterized by a qualitative constant $0 < \eta < 1$ up to saturation.

## Dependent Claims (Method of Claim 1)

5. The method of claim 1, wherein $s(\cdot)$ is a bounded sub-pulse template selected from raised-cosine, Gaussian, spline, or programmable waveform families, and amplitudes satisfy bounds and slew limits.

6. The method of claim 1, wherein the facility constraints include per-beam energy, cone fraction, ring assignment, pointing, bandwidth, and minimum inter-pulse separation.

7. The method of claim 1, wherein the mode set $\mathcal{S}$ includes at least quadrupole and hexadecapole terms.

8. The method of claim 1, wherein the certificate thresholds comprise: $\mathcal{L}_{\text{sym}} \le \Lambda$, $|a_{20}| \le \tau_2$, $|a_{4m}| \le \tau_4$, shock timing and bang-time windows, adiabat bounds, and preheat limits.

9. The method of claim 1, wherein the optimizer is model-based using a hydrodynamics surrogate with declared error bounds, or data-driven provided the $\varphi$-spacing and certificate are enforced.

10. The method of claim 1, further comprising low-energy surrogate shots for parameter identification and updating the prediction model while keeping $\mathcal{L}_{\text{sym}}$, $\varphi$-spacing, and certificate thresholds fixed.

11. The method of claim 1, wherein direct-drive embodiments apply per-ring micro-delays that preserve $\varphi$-commensurability across beams.

12. The method of claim 1, wherein indirect-drive embodiments model hohlraum transfer via a coupling operator and minimize $\mathcal{L}_{\text{sym}}$ on capsule-mode predictions.

13. The method of claim 1, wherein online monitoring enforces the certificate during the shot and blocks or truncates remaining sub-pulses upon threshold violation.

## Dependent Claims (System of Claim 2)

14. The system of claim 2, wherein the scheduler exposes an interface that verifies $\varphi$-spacing compliance and logs timing for certification.

15. The system of claim 2, wherein the symmetry-estimation module fuses x-ray self-emission, radiography, and backlighter channels to compute $a_{\ell m}$.

16. The system of claim 2, wherein the certificate module provides operator reports summarizing $\mathcal{L}_{\text{sym}}$, per-mode ratios $r_{\ell m}$, and pass/fail decisions.

### Dependent Claims (Medium of Claim 3)

17. The non-transitory computer-readable medium of claim 3, wherein the instructions implement a safety filter that rejects candidate pulses not satisfying the $\varphi$-spacing constraints or the certificate thresholds.

## Exemplary Embodiments

Without limitation, the method is applied to (i) direct-drive capsules with multi-ring beam phasing and $\varphi$-spaced pickets and ramps, and (ii) indirect-drive hohlraums with cone-fraction management; in both, the symmetry ledger is minimized under fixed energy and facility constraints, and deployment is certificate-gated.


## Abstract

A pulse-shaping method for inertial confinement fusion constructs $\varphi$-spaced sub-pulses and minimizes a convex, dimensionless symmetry ledger over normalized spherical-harmonic mode amplitudes, subject to energy and facility constraints. A certificate with fixed thresholds authorizes shot deployment. The residual asymmetry decreases at least geometrically with the number of sub-pulses within an admissible regime, up to saturation. Systems and software for implementing the method are also disclosed.