

Cross Resolution

December 11, 2025

```
[21]: from __future__ import annotations

import copy
import math
import random
from dataclasses import dataclass
from typing import Tuple, Dict, List

import matplotlib.pyplot as plt
import numpy as np
import torch
import torch.nn as nn
```

```
[22]: def set_seed(seed: int = 1337) -> None:
    """Ensure reproducible pseudo-randomness across numpy, torch, and python."""
    random.seed(seed)
    np.random.seed(seed)
    torch.manual_seed(seed)
    torch.cuda.manual_seed_all(seed)

@dataclass
class BurgersConfig:
    """Configuration bundle for the Burgers' cross-resolution benchmark."""
    grid_size: int = 64
    viscosity: float = 0.05
    horizon: float = 1.0
    time_step: float = 5e-4
    modes: int = 5
    samples: int = 50

    # Data splits
    batch_size: int = 10
    train_frac: float = 0.6
    val_frac: float = 0.2 # test_frac = 1 - train_frac - val_frac

    # Training budget control (fairness)
```

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fair_total_updates: int = 6000 # approximate target gradient updates per model

# OLFM-style training config
olfm_fm_epochs: int = 300
olfm_finetune_epochs: int = 100
olfm_patience: int = 20

# Seeds (overridden per outer seed in main)
dataset_seed: int = 1337
split_seed: int = 1338
model_seed: int = 1339

# Multi-seed experiment
num_seeds: int = 3

# Hyperparameter search
hp_trials_per_model: int = 1

# Cross-resolution target grid
cross_grid_size: int = 128

DEVICE = torch.device("cuda" if torch.cuda.is_available() else "cpu")
set_seed(1337)

```

0.1 Data generation

```
[23]: def generate_initial_condition(
    nx: int,
    num_modes: int = 5,
    rng: np.random.Generator | None = None,
) -> np.ndarray:
    """Sample a smooth periodic initial condition with unit amplitude on [0, 1]."""
    x = np.linspace(0, 1, nx, endpoint=False)
    u0 = np.zeros_like(x, dtype=np.float64)
    if rng is None:
        rng = np.random.default_rng()
    for k in range(1, num_modes + 1):
        decay = 1.0 / (k ** 2)
        a_k = rng.normal(0.0, decay)
        b_k = rng.normal(0.0, decay)
        u0 += a_k * np.cos(2 * np.pi * k * x) + b_k * np.sin(2 * np.pi * k * x)
    u0 -= u0.mean()
    max_amp = np.max(np.abs(u0))
    if max_amp > 1e-8:
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        u0 /= max_amp
    return u0

def simulate_burgers(
    u0: np.ndarray,
    *,
    horizon: float,
    dt: float,
    nu: float,
) -> np.ndarray:
    """Integrate viscous Burgers' equation using a pseudospectral explicit-Euler scheme."""
    nx = u0.size
    omega = 2 * np.pi * np.fft.rfftfreq(nx, d=1.0 / nx)
    u_hat = np.fft.rfft(u0)
    nsteps = int(horizon / dt)
    cutoff = nx // 3

    for _ in range(nsteps):
        u_phys = np.fft.irfft(u_hat, n=nx)
        u_x_phys = np.fft.irfft(1j * omega * u_hat, n=nx)
        conv_hat = np.fft.rfft(-u_phys * u_x_phys)
        conv_hat[cutoff:] = 0
        diff_hat = -nu * (omega ** 2) * u_hat

        u_hat = u_hat + dt * (conv_hat + diff_hat)
        u_hat[cutoff:] = 0

    return np.fft.irfft(u_hat, n=nx)

def build_dataset(cfg: BurgersConfig) -> Tuple[np.ndarray, np.ndarray]:
    """Generate paired initial/final states for the Burgers benchmark."""
    initials: List[np.ndarray] = []
    finals: List[np.ndarray] = []
    rng = np.random.default_rng(seed=cfg.dataset_seed)
    for _ in range(cfg.samples):
        u0 = generate_initial_condition(cfg.grid_size, cfg.modes, rng=rng)
        uT = simulate_burgers(
            u0,
            horizon=cfg.horizon,
            dt=cfg.time_step,
            nu=cfg.viscosity,
        )
        initials.append(u0)
        finals.append(uT)

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    return np.asarray(initials), np.asarray(finals)

def make_splits(
    cfg: BurgersConfig,
    initials: np.ndarray,
    finals: np.ndarray,
):
    """Train/val/test split with fixed random seed."""
    N = initials.shape[0]
    rng = np.random.default_rng(seed=cfg.split_seed)
    indices = rng.permutation(N)

    n_train = int(cfg.train_frac * N)
    n_val = int(cfg.val_frac * N)
    n_test = N - n_train - n_val

    train_idx = indices[:n_train]
    val_idx = indices[n_train:n_train + n_val]
    test_idx = indices[n_train + n_val:]

    train_u0, train_uT = initials[train_idx], finals[train_idx]
    val_u0, val_uT = initials[val_idx], finals[val_idx]
    test_u0, test_uT = initials[test_idx], finals[test_idx]

    return train_u0, train_uT, val_u0, val_uT, test_u0, test_uT

```

0.2 Spectral encoder / decoder

```
[24]: def encode_field(u_phys: np.ndarray) -> np.ndarray:
    """Pack a real-valued field (shape [..., Nx]) into concatenated rFFT coefficients."""
    u = np.asarray(u_phys)
    if u.ndim == 1:
        u = u[None, :]
    batch, nx = u.shape
    fft_coeffs = np.fft.rfft(u, axis=1)
    halfM = fft_coeffs.shape[1]

    latent = np.zeros((batch, nx), dtype=np.float32)
    latent[:, 0] = fft_coeffs[:, 0].real

    if nx % 2 == 0:
        latent[:, -1] = fft_coeffs[:, halfM - 1].real
        max_freq = halfM - 1
    else:
        max_freq = halfM
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for k in range(1, max_freq):
    real_idx = 2 * (k - 1) + 1
    imag_idx = 2 * (k - 1) + 2
    latent[:, real_idx] = fft_coeffs[:, k].real
    latent[:, imag_idx] = fft_coeffs[:, k].imag

return latent if batch > 1 else latent[0]

def decode_latent(latent: np.ndarray) -> np.ndarray:
    """Recover a real-valued field from concatenated spectral coefficients."""
    z = np.asarray(latent, dtype=np.float32)
    if z.ndim == 1:
        z = z[None, :]
    batch, nx = z.shape
    halfM = nx // 2 + 1

    fft_coeffs = np.zeros((batch, halfM), dtype=np.complex64)
    fft_coeffs[:, 0] = z[:, 0].astype(np.float32) + 0j

    if nx % 2 == 0:
        fft_coeffs[:, halfM - 1] = z[:, -1].astype(np.float32) + 0j
        max_freq = halfM - 1
    else:
        max_freq = halfM

    for k in range(1, max_freq):
        real_idx = 2 * (k - 1) + 1
        imag_idx = 2 * (k - 1) + 2
        fft_coeffs[:, k] = z[:, real_idx] + 1j * z[:, imag_idx]

    u_reconstructed = np.fft.irfft(fft_coeffs, n=nx, axis=1)
    return u_reconstructed if batch > 1 else u_reconstructed[0]

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0.3 Spectral latent model

```
[25]: class TinyMLP(nn.Module):
    """Frequency / time modulator for spectral multipliers."""

    def __init__(self, hidden: int = 48) -> None:
        super().__init__()
        self.net = nn.Sequential(
            nn.Linear(2, hidden),
            nn.Tanh(),
            nn.Linear(hidden, hidden),
            nn.Tanh(),
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        nn.Linear(hidden, 2),
    )

def forward(
    self,
    kappa: torch.Tensor,
    t: torch.Tensor,
) -> Tuple[torch.Tensor, torch.Tensor]:
    """
    Args:
        kappa: normalized frequencies, shape [B, M, 1]
        t: times, shape [B, M, 1]
    Returns:
        Tuple of real/img multipliers (each [B, M]).
    """
    x = torch.cat([kappa, t], dim=-1)
    out = self.net(x)
    return out[..., 0], out[..., 1]

class SpectralOperatorInvariant(nn.Module):
    """Resolution-aware spectral vector field operating on packed latent
    vectors."""
    def __init__(
        self,
        nx: int,
        lip_cap: float = 1.5,
        hidden: int = 48,
    ) -> None:
        super().__init__()
        self.nx = nx
        self.halfM = nx // 2 + 1
        self.lip_cap = lip_cap
        self.A_mlp = TinyMLP(hidden)
        self.B_mlp = TinyMLP(hidden)
        self.sigma = nn.Tanh() # 1-Lipschitz non-linearity
        self.register_buffer("freq_mask", torch.ones(self.halfM, dtype=torch.
            float32))

    # ----- packing helpers
    #

    def _pack(self, z: torch.Tensor) -> torch.Tensor:
        """Pack real/img latent z [B, Nx] into complex FFT coeffs [B, halfM].
    """
    batch, _ = z.shape

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fft = torch.zeros(batch, self.halfM, dtype=torch.complex64, device=z.
device)
fft[:, 0] = z[:, 0].to(torch.complex64)

if self.nx % 2 == 0:
    fft[:, -1] = z[:, -1].to(torch.complex64)
    max_freq = self.halfM - 1
else:
    max_freq = self.halfM

for k in range(1, max_freq):
    real_idx = 2 * (k - 1) + 1
    imag_idx = 2 * (k - 1) + 2
    fft[:, k] = torch.complex(z[:, real_idx], z[:, imag_idx])
return fft

def _unpack(self, fft: torch.Tensor) -> torch.Tensor:
    """Unpack complex FFT coeffs [B, halfM] back to latent z [B, Nx]."""
batch, _ = fft.shape
z = torch.zeros(batch, self.nx, dtype=torch.float32, device=fft.device)
z[:, 0] = fft[:, 0].real

if self.nx % 2 == 0:
    z[:, -1] = fft[:, -1].real
    max_freq = self.halfM - 1
else:
    max_freq = self.halfM

for k in range(1, max_freq):
    real_idx = 2 * (k - 1) + 1
    imag_idx = 2 * (k - 1) + 2
    z[:, real_idx] = fft[:, k].real
    z[:, imag_idx] = fft[:, k].imag
return z

# ----- forward pass
# ----- #

def forward(self, z: torch.Tensor, t_scalar: torch.Tensor) -> torch.Tensor:
    """
Args:
    z: packed latent states [B, Nx]
    t_scalar: times in [0, 1], shape [B] or [1]
Returns:
    Spectral velocities with the same shape as the input latent.
    """
z = z.to(torch.float32)

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batch, _ = z.shape

Z = self._pack(z)

k = torch.arange(self.halfM, device=z.device).float()
denom = max(self.halfM - 1, 1) + 1e-8 # avoid divide-by-zero for tiny grids
kappa = (k / denom).view(1, self.halfM, 1).repeat(batch, 1, 1)

if t_scalar.ndim == 1:
    t = t_scalar.view(-1, 1, 1).to(torch.float32).repeat(1, self.halfM, 1)
else:
    t = t_scalar.to(torch.float32).view(-1, 1, 1).repeat(1, self.halfM, 1)

Ar, Ai = self.A_mlp(kappa, t)
Br, Bi = self.B_mlp(kappa, t)

cap = torch.tensor(self.lip_cap, dtype=torch.float32, device=z.device)
A = torch.complex(torch.tanh(Ar) * cap, torch.tanh(Ai) * cap)
Bm = torch.complex(torch.tanh(Br) * cap, torch.tanh(Bi) * cap)

linear = A * Z * self.freq_mask.view(1, -1)

u_phys = torch.fft.irfft(Z, n=self.nx, dim=1)
v_phys = self.sigma(u_phys)
nonlinear = Bm * torch.fft.rfft(v_phys, n=self.nx, dim=1) * self.freq_mask.view(1, -1)

return self._unpack(linear + nonlinear)

def lipschitz_penalty(
    model: SpectralOperatorInvariant,
    target_cap: float = 1.5,
    weight: float = 1e-3,
) -> torch.Tensor:
    """Penalty encouraging spectral multipliers to stay within the Lipschitz cap."""
    penalty = torch.tensor(0.0, device=next(model.parameters()).device)
    for mlp in (model.A_mlp.net, model.B_mlp.net):
        for param in mlp.parameters():
            penalty = penalty + torch.relu(param.abs().mean() - target_cap / 2.)
    return weight * penalty

```

```

def project_constraints_latent(z: torch.Tensor) -> torch.Tensor:
    """Enforce zero mean in physical space by zeroing the DC component."""
    z = z.clone()
    z[:, 0] = 0.0
    return z

def count_parameters(model: nn.Module) -> int:
    """Count trainable parameters."""
    return sum(p.numel() for p in model.parameters() if p.requires_grad)

```

0.4 Integration and train

```
[26]: def integrate_final_torch(
    model: SpectralOperatorInvariant,
    z0: torch.Tensor,
    steps: int = 100,
) -> torch.Tensor:
    """Integrate the learned latent ODE from t=0 to t=1."""
    model.eval()
    with torch.no_grad():
        z = z0.clone()
        dt = 1.0 / steps
        time = 0.0
        for _ in range(steps):
            t_tensor = torch.full(
                (z.shape[0],),
                time,
                dtype=torch.float32,
                device=z.device,
            )
            z = z + dt * model(z, t_tensor)
            z = project_constraints_latent(z)
            time += dt
    return z

def integrate_trajectory_numpy(
    model: SpectralOperatorInvariant,
    z0: torch.Tensor,
    steps: int = 100,
) -> np.ndarray:
    """Integrate the latent ODE and return the full trajectory as numpy array.
    ↵"""
    model.eval()

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z = z0.clone()
dt = 1.0 / steps
traj = [z.detach().cpu().numpy()]
time = 0.0
for _ in range(steps):
    t_tensor = torch.full(
        (z.shape[0],),
        time,
        dtype=torch.float32,
        device=z.device,
    )
    z = z + dt * model(z, t_tensor)
    z = project_constraints_latent(z)
    time += dt
    traj.append(z.detach().cpu().numpy())
return np.asarray(traj)

def train_flow_matching(
    model: SpectralOperatorInvariant,
    optimizer: torch.optim.Optimizer,
    z0: torch.Tensor,
    zT: torch.Tensor,
    epochs: int = 200,
    batch_size: int = 10,
) -> List[float]:
    """Pure flow-matching training."""
    model.train()
    n = z0.shape[0]
    losses: List[float] = []

    for epoch in range(epochs):
        perm = torch.randperm(n, device=z0.device)
        running_loss = 0.0
        n_batches = 0

        for start in range(0, n, batch_size):
            idx = perm[start:start + batch_size]
            z0_b, zT_b = z0[idx], zT[idx]

            t = torch.rand(len(idx), device=z0.device)
            t_col = t.unsqueeze(1)
            zt = (1.0 - t_col) * z0_b + t_col * zT_b
            target_v = zT_b - z0_b

            pred_v = model(zt, t)

            loss = F.mse_loss(pred_v, target_v)
            running_loss += loss.item()
            n_batches += 1

        losses.append(running_loss / n_batches)

    return losses

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        loss = torch.mean((pred_v - target_v) ** 2) + lipschitz_penalty(model)

        optimizer.zero_grad()
        loss.backward()
        optimizer.step()

        running_loss += loss.item()
        n_batches += 1

        avg_loss = running_loss / max(1, n_batches)
        losses.append(avg_loss)

        if (epoch + 1) == 1 or (epoch + 1) % 20 == 0:
            print(f"[Burgers-OLFM] FM Epoch {epoch + 1:03d}/{epochs},",
                  loss=[avg_loss:.4e"])

    return losses

def finetune_with_rollout(
    model: SpectralOperatorInvariant,
    optimizer: torch.optim.Optimizer,
    z0_train: torch.Tensor,
    zT_train: torch.Tensor,
    z0_val: torch.Tensor,
    zT_val: torch.Tensor,
    epochs: int = 100,
    batch_size: int = 10,
    steps: int = 20,
    patience: int = 20,
) -> Dict[str, List[float]]:
    """Fine tune OLFM with rollout loss and early stopping on validation MSE."""
    model.train()
    n = z0_train.shape[0]
    dt = 1.0 / steps
    mse_loss = nn.MSELoss()

    history: Dict[str, List[float]] = {
        "train_fm": [],
        "train_rollout": [],
        "val_mse": [],
        "best_val": [],
    }

    best_val = float("inf")

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best_state = {k: v.detach().cpu().clone() for k, v in model.state_dict().  

    ↪items()}
patience_counter = 0

for epoch in range(1, epochs + 1):
    permutation = torch.randperm(n, device=z0_train.device)
    running_fm = 0.0
    running_roll = 0.0
    n_batches = 0

    for start in range(0, n, batch_size):
        idx = permutation[start:start + batch_size]
        z0_b = z0_train[idx]
        zT_b = zT_train[idx]

        # Flow matching term
        t_batch = torch.rand(z0_b.shape[0], device=z0_b.device)
        t_col = t_batch.unsqueeze(1)
        zt_batch = (1.0 - t_col) * z0_b + t_col * zT_b
        target_velocity = zT_b - z0_b
        loss_fm = torch.mean((model(zt_batch, t_batch) - target_velocity)  

            ↪** 2)

        # Rollout term
        z_pred = z0_b.clone()
        time = 0.0
        for _ in range(steps):
            t_tensor = torch.full(
                (z_pred.shape[0],),
                time,
                dtype=torch.float32,
                device=z0_b.device,
            )
            z_pred = z_pred + dt * model(z_pred, t_tensor)
            z_pred = project_constraints_latent(z_pred)
            time += dt

        loss_rollout = torch.mean((z_pred - zT_b) ** 2)
        loss = loss_fm + 0.1 * loss_rollout + lipschitz_penalty(model)

        optimizer.zero_grad()
        loss.backward()
        optimizer.step()

        running_fm += loss_fm.item()
        running_roll += loss_rollout.item()
        n_batches += 1

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```

avg_fm = running_fm / max(1, n_batches)
avg_roll = running_roll / max(1, n_batches)
history["train_fm"].append(avg_fm)
history["train_rollout"].append(avg_roll)

# Validation MSE via full integration
model.eval()
with torch.no_grad():
    z_pred_val = integrate_final_torch(model, z0_val, steps=50)
    val_mse = mse_loss(z_pred_val, zT_val).item()
    history["val_mse"].append(val_mse)

if (epoch == 1) or (epoch % 10 == 0):
    print(
        f"[Burgers-OLFM] FT Epoch {epoch:03d}/{epochs}, "
        f"FM={avg_fm:.4e}, Roll={avg_roll:.4e}, val MSE={val_mse:.4e}"
    )

if val_mse < best_val:
    best_val = val_mse
    best_state = {k: v.detach().cpu().clone() for k, v in model.
state_dict().items()}
    patience_counter = 0
else:
    patience_counter += 1

if patience_counter >= patience:
    print(f"[Burgers-OLFM] Early stopping at epoch {epoch} with best_val MSE {best_val:.4e}")
    break

model.train()

model.load_state_dict(best_state)
history["best_val"].append(best_val)
return history

```

```
[27]: def train_spectral_model(
    cfg: BurgersConfig,
    train_u0: np.ndarray,
    train_uT: np.ndarray,
    val_u0: np.ndarray,
    val_uT: np.ndarray,
    hidden: int = 48,
    lr: float = 1e-3,
    fm_epochs: int | None = None,
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        finetune_epochs: int | None = None,
) -> Tuple[SpectralOperatorInvariant, Dict[str, List[float]]]:
    """Wrapper for Burgers spectral OLFM-style model."""
    if fm_epochs is None:
        fm_epochs = cfg.olfm_fm_epochs
    if finetune_epochs is None:
        finetune_epochs = cfg.olfm_finetune_epochs

    nx = cfg.grid_size
    z0_train = torch.tensor(encode_field(train_u0), dtype=torch.float32, □
    ↵device=DEVICE)
    zT_train = torch.tensor(encode_field(train_uT), dtype=torch.float32, □
    ↵device=DEVICE)
    z0_val = torch.tensor(encode_field(val_u0), dtype=torch.float32, □
    ↵device=DEVICE)
    zT_val = torch.tensor(encode_field(val_uT), dtype=torch.float32, □
    ↵device=DEVICE)

    model = SpectralOperatorInvariant(nx=nx, hidden=hidden).to(DEVICE)
    print(f"Burgers-OLFM params: {count_parameters(model)}")
    optimizer = torch.optim.Adam(model.parameters(), lr=lr)

    print("Training Burgers OLFM (flow matching stage)...")
    fm_losses = train_flow_matching(
        model,
        optimizer,
        z0_train,
        zT_train,
        epochs=fm_epochs,
        batch_size=cfg.batch_size,
    )

    print("Fine tuning Burgers OLFM with rollout and validation early stopping.."
    ↵.)
    history_ft = finetune_with_rollout(
        model,
        optimizer,
        z0_train,
        zT_train,
        z0_val,
        zT_val,
        epochs=finetune_epochs,
        batch_size=cfg.batch_size,
        steps=20,
        patience=cfg.olfm_patience,
    )

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history: Dict[str, List[float]] = {
    "fm_loss": fm_losses,
    "train_fm": history_ft["train_fm"],
    "train_rollout": history_ft["train_rollout"],
    "val_mse": history_ft["val_mse"],
    "best_val": history_ft["best_val"],
}
return model, history

def train_spectral_with_search(
    cfg: BurgersConfig,
    train_u0: np.ndarray,
    train_uT: np.ndarray,
    val_u0: np.ndarray,
    val_uT: np.ndarray,
    total_epochs: int,
) -> Tuple[SpectralOperatorInvariant, Dict[str, List[float]], Dict]:
    """Hyperparameter search for Burgers spectral OLFM under a fixed epoch budget."""
    search_space = [
        {"hidden": 48, "lr": 1e-3, "fm_frac": 0.5},
        {"hidden": 64, "lr": 1e-3, "fm_frac": 0.7},
        {"hidden": 64, "lr": 5e-4, "fm_frac": 0.5},
    ]
    num_trials = min(cfg.hp_trials_per_model, len(search_space))
    if num_trials < len(search_space):
        candidates = random.sample(search_space, num_trials)
    else:
        candidates = search_space

    best_val = float("inf")
    best_model: SpectralOperatorInvariant | None = None
    best_hist: Dict[str, List[float]] | None = None
    best_hps: Dict | None = None

    for trial_idx, hps in enumerate(candidates):
        print(f"\n[Burgers-OLFM] Hyperparam trial {trial_idx + 1}/{num_trials}, hps={hps}")
        set_seed(cfg.model_seed + 100 * trial_idx)

        fm_epochs = max(1, int(total_epochs * hps["fm_frac"]))
        ft_epochs = max(1, total_epochs - fm_epochs)
        model, hist = train_spectral_model(
            cfg,
            train_u0,
            train_uT,

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```

        val_u0,
        val_uT,
        hidden=hps["hidden"],
        lr=hps["lr"],
        fm_epochs=fm_epochs,
        finetune_epochs=ft_epochs,
    )
    current_val = hist["best_val"][-1]
    print(f"[Burgers-OLFM] Trial val MSE: {current_val:.4e}")
    if current_val < best_val:
        best_val = current_val
        best_model = model
        best_hist = hist
        best_hps = {**hps, "fm_epochs": fm_epochs, "ft_epochs": ft_epochs}

    assert best_model is not None and best_hist is not None and best_hps is not
    ↵None
    print(f"\n[Burgers-OLFM] Selected hyperparameters: {best_hps}, best val
    ↵MSE={best_val:.4e}")
    return best_model, best_hist, best_hps

```

0.5 Evaluation helpers

```
[28]: def pad_field_to(u_low: np.ndarray, n_tgt: int) -> np.ndarray:
    """Zero-pad a physical field in Fourier space to a target resolution."""
    fft = np.fft.rfft(u_low)
    m_src = fft.shape[-1]
    m_tgt = n_tgt // 2 + 1
    fft_tgt = np.zeros(m_tgt, dtype=np.complex64)
    fft_tgt[:m_src] = fft[:m_src] # copy existing modes
    return np.fft.irfft(fft_tgt, n=n_tgt)

def evaluate_low_resolution(
    model: SpectralOperatorInvariant,
    cfg: BurgersConfig,
    test_u0: np.ndarray,
    test_uT: np.ndarray,
    steps: int = 100,
) -> Tuple[np.ndarray, np.ndarray, np.ndarray]:
    """Evaluate learned mapping on the original resolution."""
    model.to(DEVICE)
    model.eval()

    z0_test = torch.tensor(encode_field(test_u0), dtype=torch.float32, ↵
    ↵device=DEVICE)
```

```

    with torch.no_grad():
        z_pred = integrate_final_torch(model, z0_test, steps=steps)

    pred_latent = z_pred.cpu().numpy()
    pred_phys = decode_latent(pred_latent) # [N, nx]

    mse_all = ((pred_phys - test_uT) ** 2).mean(axis=1)
    return mse_all, pred_phys, test_uT


def evaluate_cross_resolution(
    model_low: SpectralOperatorInvariant,
    cfg: BurgersConfig,
    test_u0_low: np.ndarray,
    steps: int,
    hidden: int,
) -> Tuple[np.ndarray, np.ndarray, np.ndarray]:
    """Evaluate cross-resolution transfer 64 -> 128 using spectral zero-padding.

    """
    nx_high = cfg.cross_grid_size

    # Instantiate a high-resolution operator and copy weights
    model_high = SpectralOperatorInvariant(nx_high, hidden=hidden).to(DEVICE)
    state_dict = model_low.state_dict()
    if "freq_mask" in state_dict:
        # Drop old freq_mask due to shape mismatch
        del state_dict["freq_mask"]
    model_high.load_state_dict(state_dict, strict=False)

    # Zero out new high-frequency modes to avoid noise
    m_src = model_low.halfM
    with torch.no_grad():
        model_high.freq_mask[m_src:] = 0.0

    # Build high-resolution test dataset
    N = test_u0_low.shape[0]
    test_u0_high = np.zeros((N, nx_high), dtype=np.float64)
    test_uT_high_true = np.zeros_like(test_u0_high)

    for i in range(N):
        u0_low = test_u0_low[i]
        u0_high = pad_field_to(u0_low, nx_high)
        test_u0_high[i] = u0_high
        test_uT_high_true[i] = simulate_burgers(
            u0_high,
            horizon=cfg.horizon,
            dt=cfg.time_step,

```

```

        nu=cfg.viscosity,
    )

latent_high = torch.tensor(encode_field(test_u0_high), dtype=torch.float32, □
device=DEVICE)
with torch.no_grad():
    z_pred_high = integrate_final_torch(model_high, latent_high, □
steps=steps)

pred_latent_high = z_pred_high.cpu().numpy()
pred_phys_high = decode_latent(pred_latent_high)

mse_all = ((pred_phys_high - test_uT_high_true) ** 2).mean(axis=1)
return mse_all, pred_phys_high, test_uT_high_true, test_u0_high

def h1_norm(u: np.ndarray) -> float:
    """Compute the H1 norm of a periodic function u."""
    nx = u.size
    u_hat = np.fft.rfft(u)
    omega = 2 * np.pi * np.fft.rfftfreq(nx, d=1.0 / nx)
    u_x = np.fft.irfft(1j * omega * u_hat, n=nx)
    return float(np.sqrt(np.mean(u ** 2) + np.mean(u_x ** 2)))

def spectral_error(u_pred: np.ndarray, u_true: np.ndarray) -> float:
    """Compute relative error in the spectral domain."""
    u_pred_hat = np.fft.rfft(u_pred)
    u_true_hat = np.fft.rfft(u_true)
    return float(np.linalg.norm(u_pred_hat - u_true_hat) / np.linalg.
norm(u_true_hat))

def get_spectrum_1d(u: np.ndarray) -> Tuple[np.ndarray, np.ndarray]:
    """Compute 1D energy spectrum."""
    u_hat = np.fft.rfft(u)
    k = np.arange(u_hat.size)
    E_k = np.abs(u_hat) ** 2
    return k, E_k

```

0.6 Diagnostics and plotting

```
[29]: def plot_training_curves(history: Dict[str, List[float]]) -> None:
    """Plot FM pretraining loss and fine-tuning metrics."""
    fm_loss = history.get("fm_loss", [])
    train_fm = history.get("train_fm", [])
    train_roll = history.get("train_rollout", [])
```

```

val_mse = history.get("val_mse", [])

if fm_loss:
    plt.figure(figsize=(8, 4))
    plt.plot(fm_loss, label="FM loss")
    plt.xlabel("Epoch")
    plt.ylabel("MSE")
    plt.title("Burgers OLFM flow-matching pretraining")
    plt.grid(True, alpha=0.3)
    plt.legend()
    plt.tight_layout()
    plt.show()

if train_fm and val_mse:
    plt.figure(figsize=(10, 4))
    plt.plot(train_fm, label="Fine-tune FM term")
    plt.plot(train_roll, label="Fine-tune rollout term")
    plt.plot(val_mse, label="Validation MSE")
    plt.xlabel("Fine-tune epoch")
    plt.ylabel("Loss")
    plt.title("Burgers OLFM fine-tuning and validation")
    plt.grid(True, alpha=0.3)
    plt.legend()
    plt.tight_layout()
    plt.show()

def plot_mse_summary(test_mses: Dict[str, np.ndarray]) -> None:
    names = list(test_mses.keys())
    means = [test_mses[k].mean() for k in names]
    stds = [test_mses[k].std() for k in names]
    x = np.arange(len(names))
    with plt.rc_context({
        "axes.spines.top": False,
        "axes.spines.right": False,
        "axes.grid": True,
        "grid.linestyle": "--",
        "grid.alpha": 0.2,
        "axes.edgecolor": "0.3",
        "xtick.direction": "out",
        "ytick.direction": "out",
    }):
        fig, ax = plt.subplots(figsize=(8, 4))
        ax.bar(
            x,
            means,
            yerr=stds,

```

```

        capsizes=4,
        width=0.6,
        linewidth=0.8,
        edgecolor="0.2",
        alpha=0.9,
    )
    ax.set_xticks(x)
    ax.set_xticklabels(names)
    ax.set_ylabel("Test MSE")
    ax.set_title("Test MSE (mean ± std)")
    ax.grid(axis="y")
    fig.tight_layout()
    plt.show()
fig, ax = plt.subplots(figsize=(8, 4))

bp = ax.boxplot(
    [test_mses[k] for k in names],
    labels=names,
    showmeans=True,
    meanline=True,
    patch_artist=True,
)
for box in bp["boxes"]:
    box.set(facecolor="0.9", edgecolor="0.3", linewidth=0.8)
for median in bp["medians"]:
    median.set(color="0.2", linewidth=1.0)
for whisker in bp["whiskers"]:
    whisker.set(color="0.4", linewidth=0.8)
for cap in bp["caps"]:
    cap.set(color="0.4", linewidth=0.8)
for mean in bp["means"]:
    mean.set(color="0.1", linewidth=1.0)

ax.set_ylabel("Test MSE")
ax.set_title("Test MSE distribution")
ax.grid(axis="y")
fig.tight_layout()
plt.show()

def plot_mse_summary_log(test_mses: Dict[str, np.ndarray]) -> None:
    names = list(test_mses.keys())
    means = [test_mses[k].mean() for k in names]
    stds = [test_mses[k].std() for k in names]

    plt.figure(figsize=(8, 4))
    x = np.arange(len(names))

```

```

plt.bar(x, means, yerr=stds, capsize=5)
plt.xticks(x, names, rotation=15)
plt.yscale("log")
plt.ylabel("Test MSE (log scale)")
plt.title("Test MSE summary (mean ± std, log scale)")
plt.grid(True, axis="y", alpha=0.3)
plt.tight_layout()
plt.show()

def plot_mse_summary_relative(test_mses: Dict[str, np.ndarray]) -> None:
    names = list(test_mses.keys())
    means = np.array([test_mses[k].mean() for k in names])
    stds = np.array([test_mses[k].std() for k in names])

    base = means[0]
    rel_means = means / base
    rel_stds = stds / base

    plt.figure(figsize=(8, 4))
    x = np.arange(len(names))
    plt.bar(x, rel_means, yerr=rel_stds, capsize=5)
    plt.axhline(1.0, linestyle="--", linewidth=1)
    plt.xticks(x, names, rotation=15)
    plt.ylabel("MSE / MSE(first)")
    plt.title("Relative Test MSE (lower is better)")
    plt.grid(True, axis="y", alpha=0.3)
    plt.tight_layout()
    plt.show()

def plot_field_comparisons_1d(
    cfg: BurgersConfig,
    test_u0_low: np.ndarray,
    test_uT_low: np.ndarray,
    pred_uT_low: np.ndarray,
    test_u0_high: np.ndarray,
    test_uT_high: np.ndarray,
    pred_uT_high: np.ndarray,
    sample_idx: int = 0,
) -> None:
    """Plot low-res and high-res true vs predicted fields for one sample."""
    x_low = np.linspace(0, 1, cfg.grid_size, endpoint=False)
    x_high = np.linspace(0, 1, cfg.cross_grid_size, endpoint=False)

    u0_low = test_u0_low[sample_idx]
    true_low = test_uT_low[sample_idx]

```

```

pred_low = pred_uT_low[sample_idx]

u0_high = test_u0_high[sample_idx]
true_high = test_uT_high[sample_idx]
pred_high = pred_uT_high[sample_idx]

plt.figure(figsize=(10, 4))
plt.plot(x_low, u0_low, "k--", label="Initial u0 (64)")
plt.plot(x_low, true_low, "b-", label="True u(T) (64)")
plt.plot(x_low, pred_low, "r--", label="Predicted u(T) (64)")
plt.xlabel("Spatial coordinate x")
plt.ylabel("u(x)")
plt.title("Burgers: true vs predicted final field (64-grid)")
plt.legend()
plt.tight_layout()
plt.show()

plt.figure(figsize=(10, 4))
plt.plot(x_high, u0_high, "k--", label="Initial u0 (128)")
plt.plot(x_high, true_high, "b-", label="True u(T) (128)")
plt.plot(x_high, pred_high, "r--", label="Predicted u(T) (128)")
plt.xlabel("Spatial coordinate x")
plt.ylabel("u(x)")
plt.title("Burgers: cross-resolution true vs predicted final field ↴(128-grid)")
plt.legend()
plt.tight_layout()
plt.show()

def plot_spectrum_comparison_1d(
    true_low: np.ndarray,
    pred_low: np.ndarray,
    true_high: np.ndarray,
    pred_high: np.ndarray,
) -> None:
    """Plot energy spectra for low-res and high-res true vs predicted fields."""
    k_true_low, E_true_low = get_spectrum_1d(true_low)
    k_pred_low, E_pred_low = get_spectrum_1d(pred_low)
    k_true_high, E_true_high = get_spectrum_1d(true_high)
    k_pred_high, E_pred_high = get_spectrum_1d(pred_high)

    plt.figure(figsize=(8, 4))
    plt.loglog(k_true_low[1:], E_true_low[1:], "b-", label="True (64)")
    plt.loglog(k_pred_low[1:], E_pred_low[1:], "b--", label="Pred (64)")
    plt.loglog(k_true_high[1:], E_true_high[1:], "r-", label="True (128)")
    plt.loglog(k_pred_high[1:], E_pred_high[1:], "r--", label="Pred (128)")
    plt.xlabel("Wavenumber k")

```

```

plt.ylabel("Energy |u_hat(k)|^2")
plt.title("Burgers: spectral comparison (64 and 128)")
plt.grid(True, which="both", alpha=0.3)
plt.legend()
plt.tight_layout()
plt.show()

```

0.7 Benchmark

```

[30]: def main():
    cfg_base = BurgersConfig()
    print(f"Device: {DEVICE}")
    print(f"Low-res grid: {cfg_base.grid_size}, high-res grid: {cfg_base.
    ↪cross_grid_size}")

    all_test_mses_low: List[np.ndarray] = []
    all_test_mses_cross: List[np.ndarray] = []

    history_first: Dict[str, List[float]] | None = None
    preds_low_first: np.ndarray | None = None
    test_u0_low_first: np.ndarray | None = None
    test_uT_low_first: np.ndarray | None = None
    preds_high_first: np.ndarray | None = None
    test_u0_high_first: np.ndarray | None = None
    test_uT_high_first: np.ndarray | None = None

    seed_values = list(range(cfg_base.num_seeds))

    for seed_idx, seed in enumerate(seed_values):
        print("\n" + "=" * 80)
        print(f"Outer seed {seed_idx + 1}/{len(seed_values)} (base seed_
    ↪{seed})")
        print("=" * 80)

        cfg = copy.deepcopy(cfg_base)
        cfg.dataset_seed = seed
        cfg.split_seed = seed + 100
        cfg.model_seed = seed + 200

        set_seed(cfg.model_seed)

        print("Generating Burgers dataset at low resolution...")
        initials, finals = build_dataset(cfg)
        print("Data shape:", initials.shape)

        (
            train_u0,

```

```

        train_uT,
        val_u0,
        val_uT,
        test_u0_low,
        test_uT_low,
    ) = make_splits(cfg, initials, finals)

    # Match training budget in number of gradient updates
    updates_per_epoch = math.ceil(train_u0.shape[0] / cfg.batch_size)
    total_epochs = max(1, cfg.fair_total_updates // max(1, ↵
    ↵updates_per_epoch))
    print(
        f"Using {total_epochs} epochs for Burgers-OLFM "
        f"({~{total_epochs} * updates_per_epoch} gradient updates)"
    )

    # Train OLFM-style spectral operator with hyperparameter search
    model_low, hist_olfm, best_hps = train_spectral_with_search(
        cfg,
        train_u0,
        train_uT,
        val_u0,
        val_uT,
        total_epochs=total_epochs,
    )

    # Evaluate low-resolution mapping
    print("\nEvaluating low-resolution mapping (64 -> 64)...")
    mse_low_seed, pred_low_seed, true_low_seed = evaluate_low_resolution(
        model_low,
        cfg,
        test_u0_low,
        test_uT_low,
        steps=100,
    )

    # Evaluate cross-resolution mapping
    print("\nEvaluating cross-resolution mapping (64 -> 128)...")
    mse_cross_seed, pred_high_seed, true_high_seed, u0_high_seed = ↵
    ↵evaluate_cross_resolution(
        model_low,
        cfg,
        test_u0_low,
        steps=100,
        hidden=best_hps["hidden"],
    )

```

```

    all_test_mses_low.append(mse_low_seed)
    all_test_mses_cross.append(mse_cross_seed)

    # Store diagnostics from first seed
    if seed_idx == 0:
        history_first = hist_olfm
        preds_low_first = pred_low_seed
        test_u0_low_first = test_u0_low
        test_uT_low_first = true_low_seed
        preds_high_first = pred_high_seed
        test_u0_high_first = u0_high_seed
        test_uT_high_first = true_high_seed

        print("\nTest MSE for this seed:")
        print(f"  Burgers 64->64:  mean={mse_low_seed.mean():.4e} ±"
              f"{mse_low_seed.std():.4e}")
        print(f"  Burgers 64->128:  mean={mse_cross_seed.mean():.4e} ±"
              f"{mse_cross_seed.std():.4e}")

    aggregated_test_mses: Dict[str, np.ndarray] = {
        "Burgers 64→64": np.concatenate(all_test_mses_low, axis=0),
        "Burgers 64→128": np.concatenate(all_test_mses_cross, axis=0),
    }

    print("\n" + "=" * 80)
    print("Aggregated test MSE over all seeds (per sample, concatenated):")
    print("=" * 80)
    for name, mse_vals in aggregated_test_mses.items():
        print(f" {name:15s}: {mse_vals.mean():.4e} ± {mse_vals.std():.4e}")

    # Training curves for first seed
    if history_first is not None:
        print("\nPlotting training curves for first seed...")
        plot_training_curves(history_first)

    # Aggregate MSE plots
    print("Plotting aggregated test MSE summary across resolutions (linear"
          "scale)...")
    plot_mse_summary(aggregated_test_mses)

    print("Plotting aggregated test MSE summary across resolutions (log scale)..
          ")
    plot_mse_summary_log(aggregated_test_mses)

    print("Plotting relative test MSE summary (normalised by low-res 64→64)...")
    plot_mse_summary_relative(aggregated_test_mses)

```

```

# Field and spectrum plots from first seed
if (
    preds_low_first is not None
    and test_u0_low_first is not None
    and test_uT_low_first is not None
    and preds_high_first is not None
    and test_u0_high_first is not None
    and test_uT_high_first is not None
):
    sample_idx = 0
    print(f"Plotting field comparisons for sample {sample_idx} (first seed).
    ↵...")
    plot_field_comparisons_1d(
        cfg_base,
        test_u0_low_first,
        test_uT_low_first,
        preds_low_first,
        test_u0_high_first,
        test_uT_high_first,
        preds_high_first,
        sample_idx=sample_idx,
    )

    print(f"Plotting spectral comparison for sample {sample_idx} (first seed...
    ↵seed)...")
    true_low = test_uT_low_first[sample_idx]
    pred_low = preds_low_first[sample_idx]
    true_high = test_uT_high_first[sample_idx]
    pred_high = preds_high_first[sample_idx]
    plot_spectrum_comparison_1d(true_low, pred_low, true_high, pred_high)

    print("\nDiagnostics (first seed, sample 0):")
    print(
        f"  Low-res H1(true)={h1_norm(true_low):.3f}, "
        f"H1(pred)={h1_norm(pred_low):.3f}, "
        f"spectral rel. error={spectral_error(pred_low, true_low):.3e}"
    )
    print(
        f"  High-res H1(true)={h1_norm(true_high):.3f}, "
        f"H1(pred)={h1_norm(pred_high):.3f}, "
        f"spectral rel. error={spectral_error(pred_high, true_high):.3e}"
    )

if __name__ == "__main__":
    main()

```

```
Device: cpu
Low-res grid: 64, high-res grid: 128
=====
Outer seed 1/3 (base seed 0)
=====
Generating Burgers dataset at low resolution...
Data shape: (50, 64)
Using 2000 epochs for Burgers-OLFM (~6000 gradient updates)

[Burgers-OLFM] Hyperparam trial 1/1, hps={'hidden': 48, 'lr': 0.001, 'fm_frac': 0.5}
Burgers-OLFM params: 5188
Training Burgers OLFM (flow matching stage)...
[Burgers-OLFM] FM Epoch 001/1000, loss=8.0190e+00
[Burgers-OLFM] FM Epoch 020/1000, loss=1.2373e+00
[Burgers-OLFM] FM Epoch 040/1000, loss=6.9596e-01
[Burgers-OLFM] FM Epoch 060/1000, loss=7.5711e-01
[Burgers-OLFM] FM Epoch 080/1000, loss=3.7235e-01
[Burgers-OLFM] FM Epoch 100/1000, loss=6.7884e-01
[Burgers-OLFM] FM Epoch 120/1000, loss=4.8783e-01
[Burgers-OLFM] FM Epoch 140/1000, loss=6.6494e-01
[Burgers-OLFM] FM Epoch 160/1000, loss=2.1593e-01
[Burgers-OLFM] FM Epoch 180/1000, loss=2.1949e-01
[Burgers-OLFM] FM Epoch 200/1000, loss=8.7127e-01
[Burgers-OLFM] FM Epoch 220/1000, loss=3.7953e-01
[Burgers-OLFM] FM Epoch 240/1000, loss=4.7310e-01
[Burgers-OLFM] FM Epoch 260/1000, loss=4.7243e-01
[Burgers-OLFM] FM Epoch 280/1000, loss=5.8282e-01
[Burgers-OLFM] FM Epoch 300/1000, loss=3.7968e-01
[Burgers-OLFM] FM Epoch 320/1000, loss=2.4750e-01
[Burgers-OLFM] FM Epoch 340/1000, loss=6.7843e-01
[Burgers-OLFM] FM Epoch 360/1000, loss=5.2503e-01
[Burgers-OLFM] FM Epoch 380/1000, loss=7.5851e-01
[Burgers-OLFM] FM Epoch 400/1000, loss=5.2142e-01
[Burgers-OLFM] FM Epoch 420/1000, loss=3.7357e-01
[Burgers-OLFM] FM Epoch 440/1000, loss=5.4264e-01
[Burgers-OLFM] FM Epoch 460/1000, loss=5.5546e-01
[Burgers-OLFM] FM Epoch 480/1000, loss=3.9626e-01
[Burgers-OLFM] FM Epoch 500/1000, loss=3.4025e-01
[Burgers-OLFM] FM Epoch 520/1000, loss=2.9156e-01
[Burgers-OLFM] FM Epoch 540/1000, loss=3.4873e-01
[Burgers-OLFM] FM Epoch 560/1000, loss=4.7503e-01
[Burgers-OLFM] FM Epoch 580/1000, loss=5.5972e-01
[Burgers-OLFM] FM Epoch 600/1000, loss=3.6481e-01
[Burgers-OLFM] FM Epoch 620/1000, loss=7.0467e-01
[Burgers-OLFM] FM Epoch 640/1000, loss=7.5834e-01
[Burgers-OLFM] FM Epoch 660/1000, loss=2.2931e-01
```

```

[Burgers-OLFM] FM Epoch 680/1000, loss=2.3501e-01
[Burgers-OLFM] FM Epoch 700/1000, loss=4.1365e-01
[Burgers-OLFM] FM Epoch 720/1000, loss=7.3802e-01
[Burgers-OLFM] FM Epoch 740/1000, loss=8.8033e-01
[Burgers-OLFM] FM Epoch 760/1000, loss=3.6000e-01
[Burgers-OLFM] FM Epoch 780/1000, loss=3.4350e-01
[Burgers-OLFM] FM Epoch 800/1000, loss=7.9589e-01
[Burgers-OLFM] FM Epoch 820/1000, loss=3.6268e-01
[Burgers-OLFM] FM Epoch 840/1000, loss=2.1163e-01
[Burgers-OLFM] FM Epoch 860/1000, loss=4.8793e-01
[Burgers-OLFM] FM Epoch 880/1000, loss=2.9367e-01
[Burgers-OLFM] FM Epoch 900/1000, loss=2.7482e-01
[Burgers-OLFM] FM Epoch 920/1000, loss=3.8755e-01
[Burgers-OLFM] FM Epoch 940/1000, loss=3.4709e-01
[Burgers-OLFM] FM Epoch 960/1000, loss=4.3726e-01
[Burgers-OLFM] FM Epoch 980/1000, loss=3.1419e-01
[Burgers-OLFM] FM Epoch 1000/1000, loss=3.8009e-01
Fine tuning Burgers OLFM with rollout and validation early stopping...
[Burgers-OLFM] FT Epoch 001/1000, FM=2.3880e-01, Roll=4.0088e-02, val
MSE=4.1397e-02
[Burgers-OLFM] FT Epoch 010/1000, FM=2.1519e-01, Roll=3.8852e-02, val
MSE=3.7351e-02
[Burgers-OLFM] FT Epoch 020/1000, FM=4.7691e-01, Roll=3.8293e-02, val
MSE=3.8075e-02
[Burgers-OLFM] Early stopping at epoch 23 with best val MSE 3.5011e-02
[Burgers-OLFM] Trial val MSE: 3.5011e-02

[Burgers-OLFM] Selected hyperparameters: {'hidden': 48, 'lr': 0.001, 'fm_frac': 0.5, 'fm_epochs': 1000, 'ft_epochs': 1000}, best val MSE=3.5011e-02

Evaluating low-resolution mapping (64 -> 64)...

Evaluating cross-resolution mapping (64 -> 128)...

Test MSE for this seed:
Burgers 64->64: mean=1.4526e-03 ± 9.3760e-04
Burgers 64->128: mean=4.0829e-04 ± 3.5495e-04

=====
Outer seed 2/3 (base seed 1)
=====
Generating Burgers dataset at low resolution...
Data shape: (50, 64)
Using 2000 epochs for Burgers-OLFM (~6000 gradient updates)

[Burgers-OLFM] Hyperparam trial 1/1, hps={'hidden': 48, 'lr': 0.001, 'fm_frac': 0.5}
Burgers-OLFM params: 5188

```

Training Burgers OLFM (flow matching stage)...

```
[Burgers-OLFM] FM Epoch 001/1000, loss=9.8153e+00
[Burgers-OLFM] FM Epoch 020/1000, loss=6.9797e-01
[Burgers-OLFM] FM Epoch 040/1000, loss=5.3497e-01
[Burgers-OLFM] FM Epoch 060/1000, loss=6.9539e-01
[Burgers-OLFM] FM Epoch 080/1000, loss=7.1956e-01
[Burgers-OLFM] FM Epoch 100/1000, loss=5.4589e-01
[Burgers-OLFM] FM Epoch 120/1000, loss=9.1110e-01
[Burgers-OLFM] FM Epoch 140/1000, loss=1.4618e+00
[Burgers-OLFM] FM Epoch 160/1000, loss=7.9682e-01
[Burgers-OLFM] FM Epoch 180/1000, loss=1.1418e+00
[Burgers-OLFM] FM Epoch 200/1000, loss=6.2168e-01
[Burgers-OLFM] FM Epoch 220/1000, loss=1.0804e+00
[Burgers-OLFM] FM Epoch 240/1000, loss=7.8963e-01
[Burgers-OLFM] FM Epoch 260/1000, loss=5.2680e-01
[Burgers-OLFM] FM Epoch 280/1000, loss=7.6103e-01
[Burgers-OLFM] FM Epoch 300/1000, loss=4.8300e-01
[Burgers-OLFM] FM Epoch 320/1000, loss=7.6823e-01
[Burgers-OLFM] FM Epoch 340/1000, loss=8.7033e-01
[Burgers-OLFM] FM Epoch 360/1000, loss=5.8097e-01
[Burgers-OLFM] FM Epoch 380/1000, loss=4.8346e-01
[Burgers-OLFM] FM Epoch 400/1000, loss=5.2214e-01
[Burgers-OLFM] FM Epoch 420/1000, loss=2.3410e-01
[Burgers-OLFM] FM Epoch 440/1000, loss=5.3845e-01
[Burgers-OLFM] FM Epoch 460/1000, loss=5.9759e-01
[Burgers-OLFM] FM Epoch 480/1000, loss=1.1540e-01
[Burgers-OLFM] FM Epoch 500/1000, loss=5.8937e-01
[Burgers-OLFM] FM Epoch 520/1000, loss=4.1220e-01
[Burgers-OLFM] FM Epoch 540/1000, loss=3.2923e-01
[Burgers-OLFM] FM Epoch 560/1000, loss=4.6775e-01
[Burgers-OLFM] FM Epoch 580/1000, loss=4.2985e-01
[Burgers-OLFM] FM Epoch 600/1000, loss=4.4210e-01
[Burgers-OLFM] FM Epoch 620/1000, loss=6.7034e-01
[Burgers-OLFM] FM Epoch 640/1000, loss=2.2246e-01
[Burgers-OLFM] FM Epoch 660/1000, loss=3.2835e-01
[Burgers-OLFM] FM Epoch 680/1000, loss=5.1549e-01
[Burgers-OLFM] FM Epoch 700/1000, loss=4.1610e-01
[Burgers-OLFM] FM Epoch 720/1000, loss=4.7145e-01
[Burgers-OLFM] FM Epoch 740/1000, loss=3.3016e-01
[Burgers-OLFM] FM Epoch 760/1000, loss=4.2591e-01
[Burgers-OLFM] FM Epoch 780/1000, loss=5.4675e-01
[Burgers-OLFM] FM Epoch 800/1000, loss=2.9127e-01
[Burgers-OLFM] FM Epoch 820/1000, loss=4.7642e-01
[Burgers-OLFM] FM Epoch 840/1000, loss=3.7480e-01
[Burgers-OLFM] FM Epoch 860/1000, loss=2.7207e-01
[Burgers-OLFM] FM Epoch 880/1000, loss=3.9161e-01
[Burgers-OLFM] FM Epoch 900/1000, loss=4.1950e-01
[Burgers-OLFM] FM Epoch 920/1000, loss=4.5309e-01
```

```
[Burgers-OLFM] FM Epoch 940/1000, loss=3.1336e-01
[Burgers-OLFM] FM Epoch 960/1000, loss=7.0457e-01
[Burgers-OLFM] FM Epoch 980/1000, loss=2.5087e-01
[Burgers-OLFM] FM Epoch 1000/1000, loss=1.6171e-01
Fine tuning Burgers OLFM with rollout and validation early stopping..
[Burgers-OLFM] FT Epoch 001/1000, FM=3.7701e-01, Roll=3.7822e-02, val
MSE=5.2226e-02
[Burgers-OLFM] FT Epoch 010/1000, FM=6.0183e-01, Roll=3.8815e-02, val
MSE=5.0299e-02
[Burgers-OLFM] FT Epoch 020/1000, FM=6.9715e-01, Roll=3.8414e-02, val
MSE=5.2588e-02
[Burgers-OLFM] FT Epoch 030/1000, FM=6.5440e-01, Roll=3.9848e-02, val
MSE=5.0152e-02
[Burgers-OLFM] FT Epoch 040/1000, FM=2.6256e-01, Roll=3.8346e-02, val
MSE=5.0015e-02
[Burgers-OLFM] FT Epoch 050/1000, FM=7.6040e-01, Roll=3.8609e-02, val
MSE=5.1776e-02
[Burgers-OLFM] Early stopping at epoch 53 with best val MSE 4.9916e-02
[Burgers-OLFM] Trial val MSE: 4.9916e-02
```

```
[Burgers-OLFM] Selected hyperparameters: {'hidden': 48, 'lr': 0.001, 'fm_frac': 0.5, 'fm_epochs': 1000, 'ft_epochs': 1000}, best val MSE=4.9916e-02
```

Evaluating low-resolution mapping (64 -> 64)...

Evaluating cross-resolution mapping (64 -> 128)...

Test MSE for this seed:

```
Burgers 64->64: mean=1.7280e-03 ± 1.2053e-03
Burgers 64->128: mean=5.0564e-04 ± 4.4048e-04
```

```
=====
Outer seed 3/3 (base seed 2)
=====
```

```
Generating Burgers dataset at low resolution...
```

```
Data shape: (50, 64)
```

```
Using 2000 epochs for Burgers-OLFM (~6000 gradient updates)
```

```
[Burgers-OLFM] Hyperparam trial 1/1, hps={'hidden': 64, 'lr': 0.001, 'fm_frac': 0.7}
Burgers-OLFM params: 8964
Training Burgers OLFM (flow matching stage)...
[Burgers-OLFM] FM Epoch 001/1400, loss=5.3680e+00
[Burgers-OLFM] FM Epoch 020/1400, loss=5.0038e-01
[Burgers-OLFM] FM Epoch 040/1400, loss=5.9146e-01
[Burgers-OLFM] FM Epoch 060/1400, loss=5.9185e-01
[Burgers-OLFM] FM Epoch 080/1400, loss=3.6544e-01
[Burgers-OLFM] FM Epoch 100/1400, loss=4.8749e-01
```

```
[Burgers-OLFM] FM Epoch 120/1400, loss=6.6554e-01
[Burgers-OLFM] FM Epoch 140/1400, loss=5.7316e-01
[Burgers-OLFM] FM Epoch 160/1400, loss=8.1581e-01
[Burgers-OLFM] FM Epoch 180/1400, loss=4.3837e-01
[Burgers-OLFM] FM Epoch 200/1400, loss=2.7344e-01
[Burgers-OLFM] FM Epoch 220/1400, loss=5.1995e-01
[Burgers-OLFM] FM Epoch 240/1400, loss=6.7230e-01
[Burgers-OLFM] FM Epoch 260/1400, loss=5.1583e-01
[Burgers-OLFM] FM Epoch 280/1400, loss=7.3579e-01
[Burgers-OLFM] FM Epoch 300/1400, loss=3.8326e-01
[Burgers-OLFM] FM Epoch 320/1400, loss=2.5117e-01
[Burgers-OLFM] FM Epoch 340/1400, loss=4.6945e-01
[Burgers-OLFM] FM Epoch 360/1400, loss=3.2538e-01
[Burgers-OLFM] FM Epoch 380/1400, loss=1.9269e-01
[Burgers-OLFM] FM Epoch 400/1400, loss=3.4312e-01
[Burgers-OLFM] FM Epoch 420/1400, loss=4.2863e-01
[Burgers-OLFM] FM Epoch 440/1400, loss=1.7064e-01
[Burgers-OLFM] FM Epoch 460/1400, loss=2.8013e-01
[Burgers-OLFM] FM Epoch 480/1400, loss=4.2185e-01
[Burgers-OLFM] FM Epoch 500/1400, loss=2.9467e-01
[Burgers-OLFM] FM Epoch 520/1400, loss=3.7119e-01
[Burgers-OLFM] FM Epoch 540/1400, loss=2.8284e-01
[Burgers-OLFM] FM Epoch 560/1400, loss=5.7814e-01
[Burgers-OLFM] FM Epoch 580/1400, loss=4.6702e-01
[Burgers-OLFM] FM Epoch 600/1400, loss=3.7808e-01
[Burgers-OLFM] FM Epoch 620/1400, loss=6.6469e-01
[Burgers-OLFM] FM Epoch 640/1400, loss=4.7747e-01
[Burgers-OLFM] FM Epoch 660/1400, loss=1.3271e-01
[Burgers-OLFM] FM Epoch 680/1400, loss=4.2561e-01
[Burgers-OLFM] FM Epoch 700/1400, loss=5.4678e-01
[Burgers-OLFM] FM Epoch 720/1400, loss=4.8491e-01
[Burgers-OLFM] FM Epoch 740/1400, loss=5.4619e-01
[Burgers-OLFM] FM Epoch 760/1400, loss=6.1607e-01
[Burgers-OLFM] FM Epoch 780/1400, loss=2.0379e-01
[Burgers-OLFM] FM Epoch 800/1400, loss=3.2220e-01
[Burgers-OLFM] FM Epoch 820/1400, loss=6.7641e-01
[Burgers-OLFM] FM Epoch 840/1400, loss=4.4853e-01
[Burgers-OLFM] FM Epoch 860/1400, loss=1.5084e-01
[Burgers-OLFM] FM Epoch 880/1400, loss=4.9735e-01
[Burgers-OLFM] FM Epoch 900/1400, loss=2.6470e-01
[Burgers-OLFM] FM Epoch 920/1400, loss=3.8399e-01
[Burgers-OLFM] FM Epoch 940/1400, loss=4.0580e-01
[Burgers-OLFM] FM Epoch 960/1400, loss=5.3973e-01
[Burgers-OLFM] FM Epoch 980/1400, loss=5.1632e-01
[Burgers-OLFM] FM Epoch 1000/1400, loss=2.3683e-01
[Burgers-OLFM] FM Epoch 1020/1400, loss=1.0811e-01
[Burgers-OLFM] FM Epoch 1040/1400, loss=5.1435e-01
[Burgers-OLFM] FM Epoch 1060/1400, loss=7.6293e-02
```

```

[Burgers-OLFM] FM Epoch 1080/1400, loss=4.6139e-01
[Burgers-OLFM] FM Epoch 1100/1400, loss=2.3193e-01
[Burgers-OLFM] FM Epoch 1120/1400, loss=4.3554e-01
[Burgers-OLFM] FM Epoch 1140/1400, loss=2.2494e-01
[Burgers-OLFM] FM Epoch 1160/1400, loss=1.7881e-01
[Burgers-OLFM] FM Epoch 1180/1400, loss=3.5902e-01
[Burgers-OLFM] FM Epoch 1200/1400, loss=3.1568e-01
[Burgers-OLFM] FM Epoch 1220/1400, loss=3.6440e-01
[Burgers-OLFM] FM Epoch 1240/1400, loss=3.5321e-01
[Burgers-OLFM] FM Epoch 1260/1400, loss=2.4177e-01
[Burgers-OLFM] FM Epoch 1280/1400, loss=5.3929e-01
[Burgers-OLFM] FM Epoch 1300/1400, loss=2.7126e-01
[Burgers-OLFM] FM Epoch 1320/1400, loss=3.2298e-01
[Burgers-OLFM] FM Epoch 1340/1400, loss=1.5160e-01
[Burgers-OLFM] FM Epoch 1360/1400, loss=1.8649e-01
[Burgers-OLFM] FM Epoch 1380/1400, loss=2.0438e-01
[Burgers-OLFM] FM Epoch 1400/1400, loss=2.4200e-01
Fine tuning Burgers OLFM with rollout and validation early stopping...
[Burgers-OLFM] FT Epoch 001/600, FM=3.1485e-01, Roll=3.7737e-02, val
MSE=6.2513e-02
[Burgers-OLFM] FT Epoch 010/600, FM=2.7441e-01, Roll=3.5344e-02, val
MSE=6.8187e-02
[Burgers-OLFM] FT Epoch 020/600, FM=3.3901e-01, Roll=3.9024e-02, val
MSE=6.4644e-02
[Burgers-OLFM] FT Epoch 030/600, FM=3.4186e-01, Roll=3.8722e-02, val
MSE=6.0806e-02
[Burgers-OLFM] Early stopping at epoch 31 with best val MSE 5.4564e-02
[Burgers-OLFM] Trial val MSE: 5.4564e-02

[Burgers-OLFM] Selected hyperparameters: {'hidden': 64, 'lr': 0.001, 'fm_frac':
0.7, 'fm_epochs': 1400, 'ft_epochs': 600}, best val MSE=5.4564e-02

Evaluating low-resolution mapping (64 -> 64)...

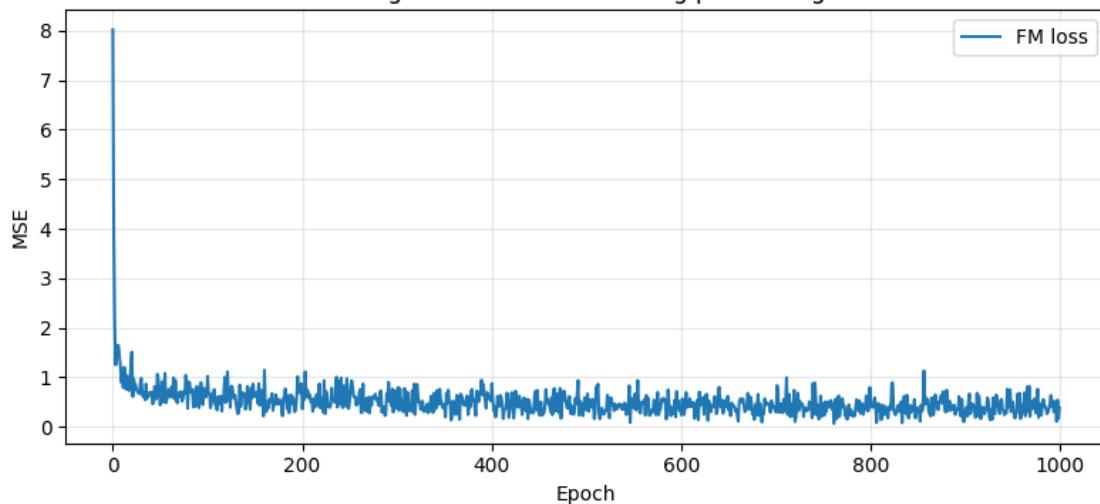
Evaluating cross-resolution mapping (64 -> 128)...

Test MSE for this seed:
Burgers 64->64: mean=9.6414e-04 ± 1.0202e-04
Burgers 64->128: mean=2.5624e-04 ± 5.9934e-05
=====
Aggregated test MSE over all seeds (per sample, concatenated):
=====
Burgers 64->64 : 1.3816e-03 ± 9.3835e-04
Burgers 64->128 : 3.9005e-04 ± 3.4409e-04

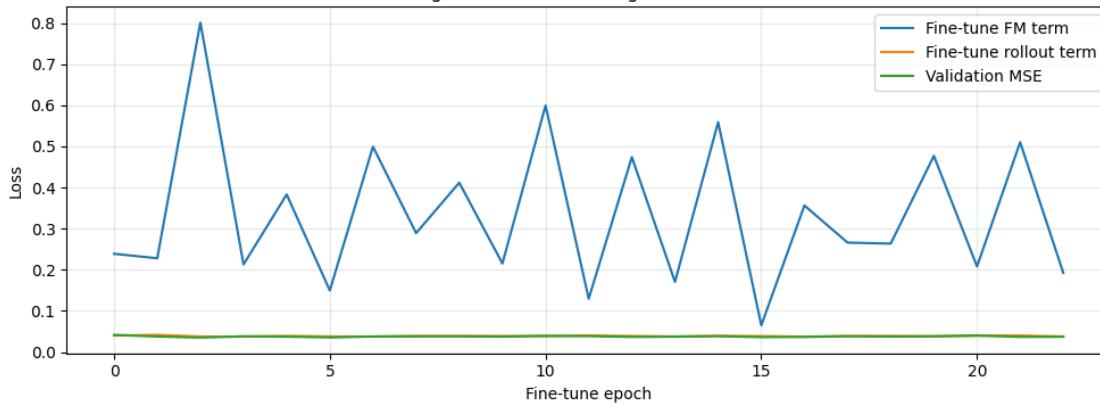
Plotting training curves for first seed...

```

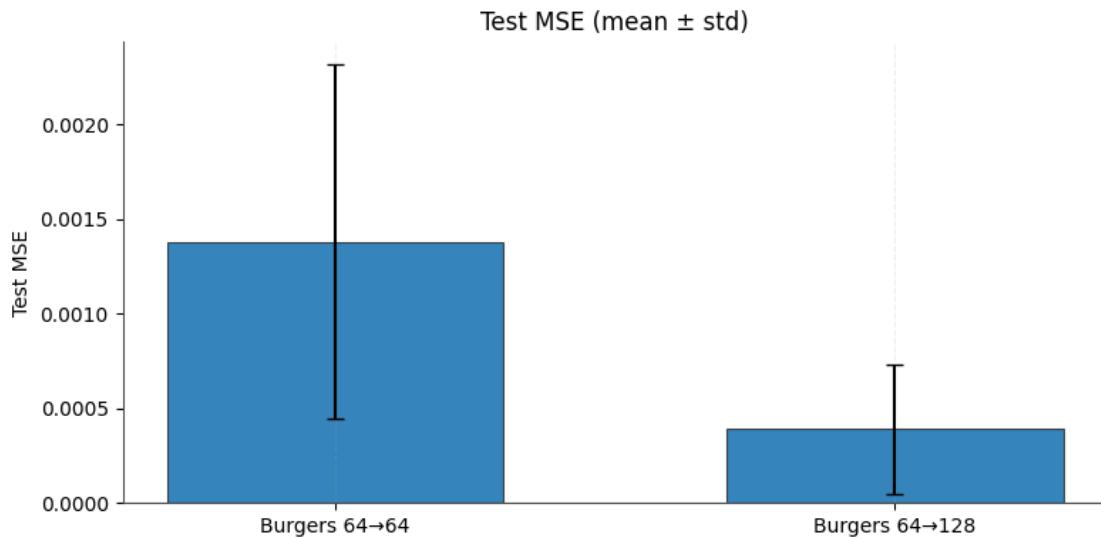
Burgers OLFM flow-matching pretraining



Burgers OLFM fine-tuning and validation

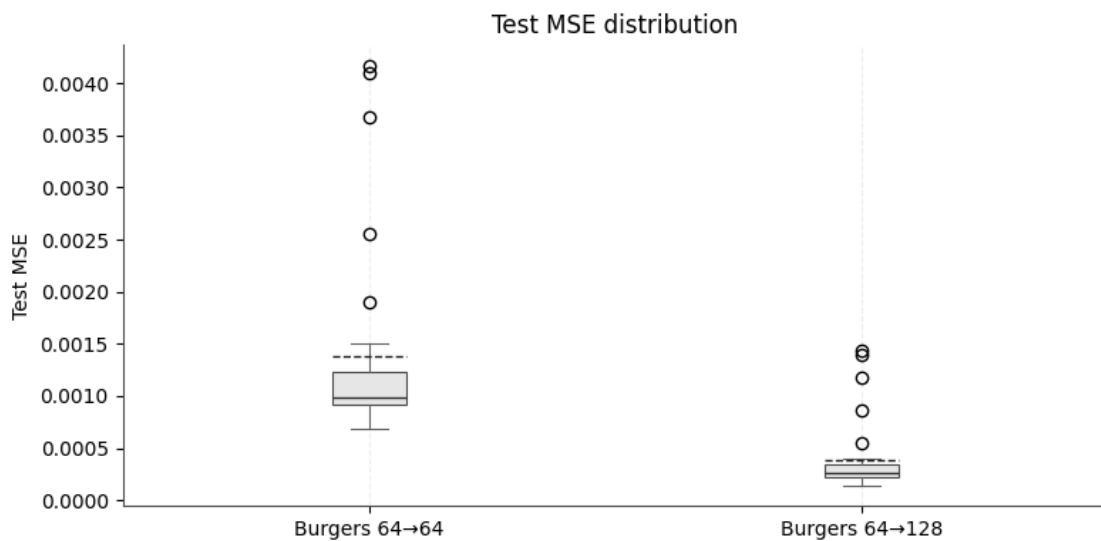


Plotting aggregated test MSE summary across resolutions (linear scale)...

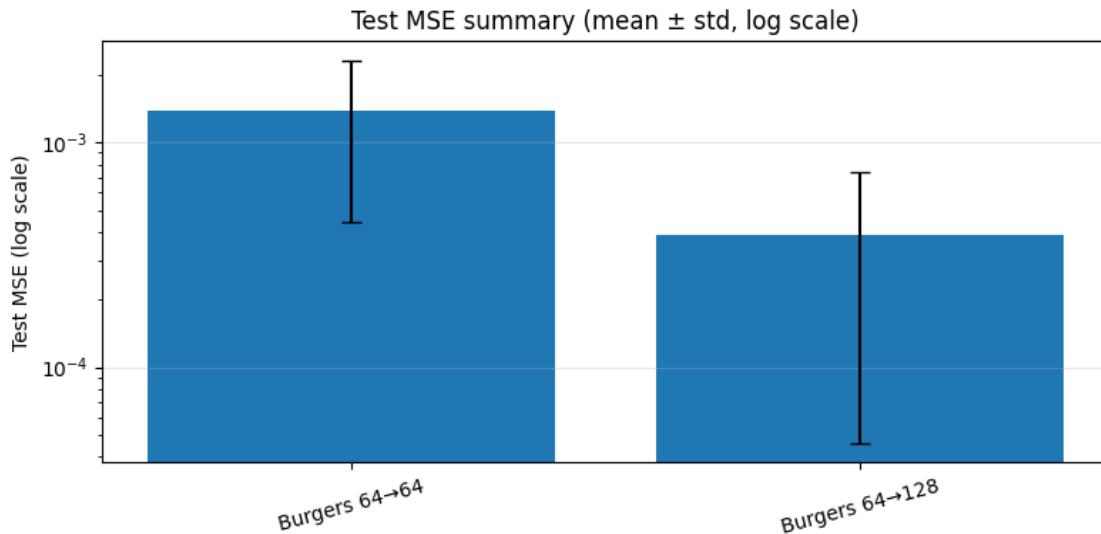


```
/var/folders/0s/bt69j7tj0pd5rl5dzc4n6bth0000gn/T/ipykernel_21079/4121282646.py:6
8: MatplotlibDeprecationWarning: The 'labels' parameter of boxplot() has been
renamed 'tick_labels' since Matplotlib 3.9; support for the old name will be
dropped in 3.11.
```

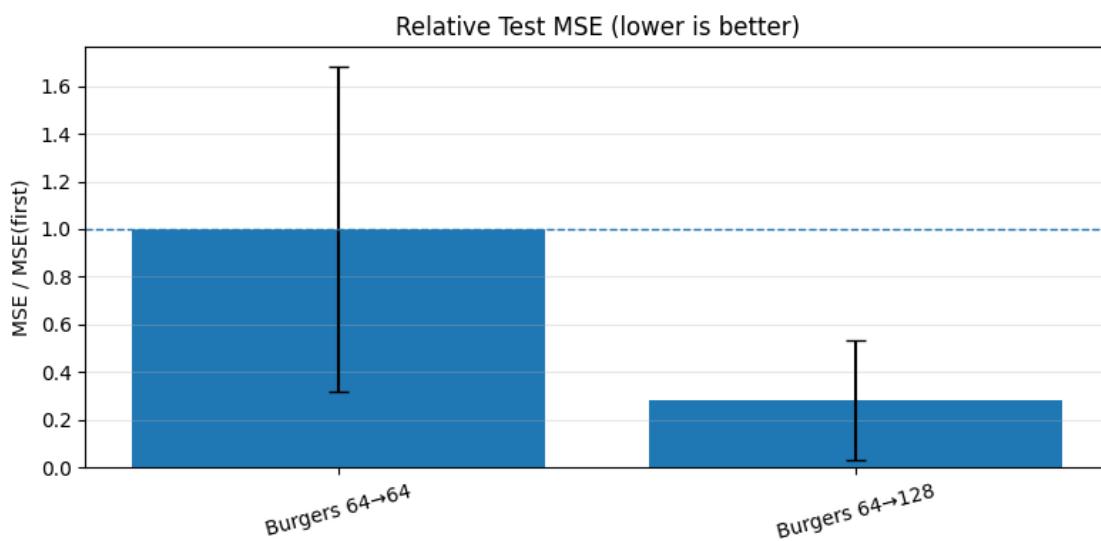
```
bp = ax.boxplot(
```



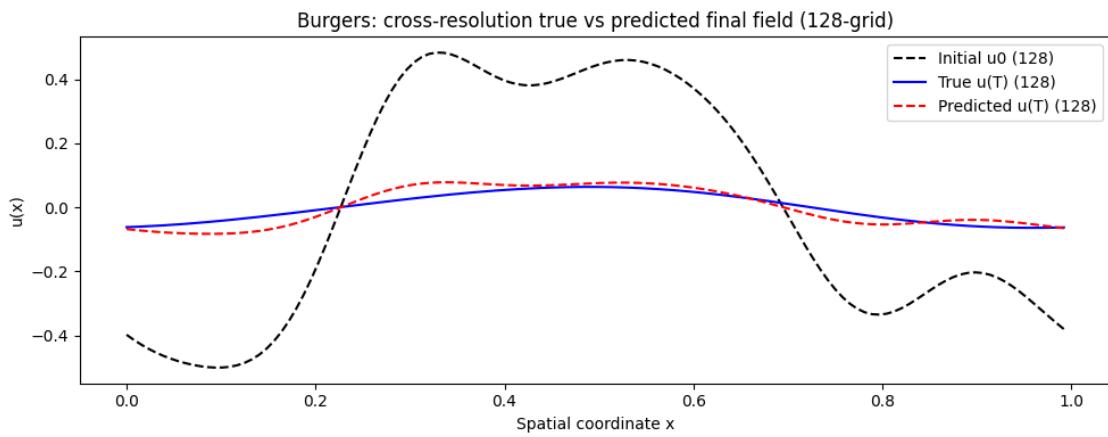
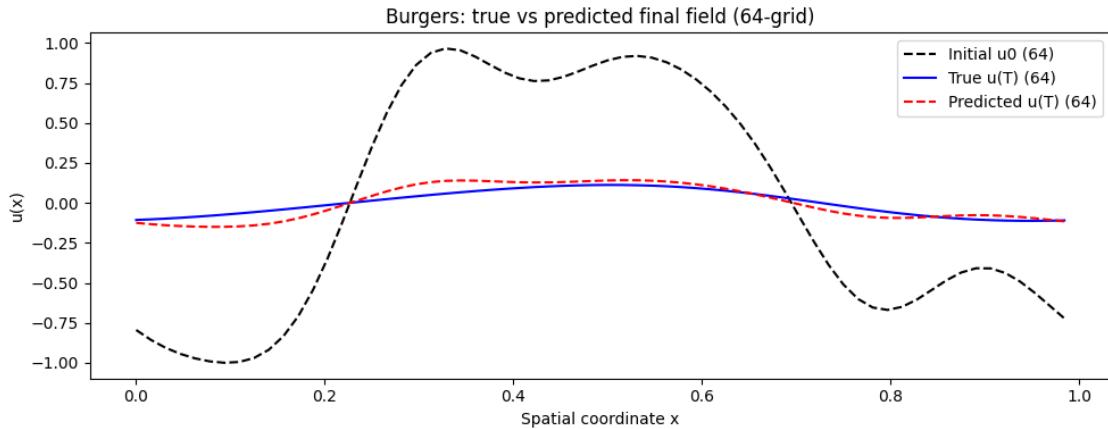
```
Plotting aggregated test MSE summary across resolutions (log scale)...
```



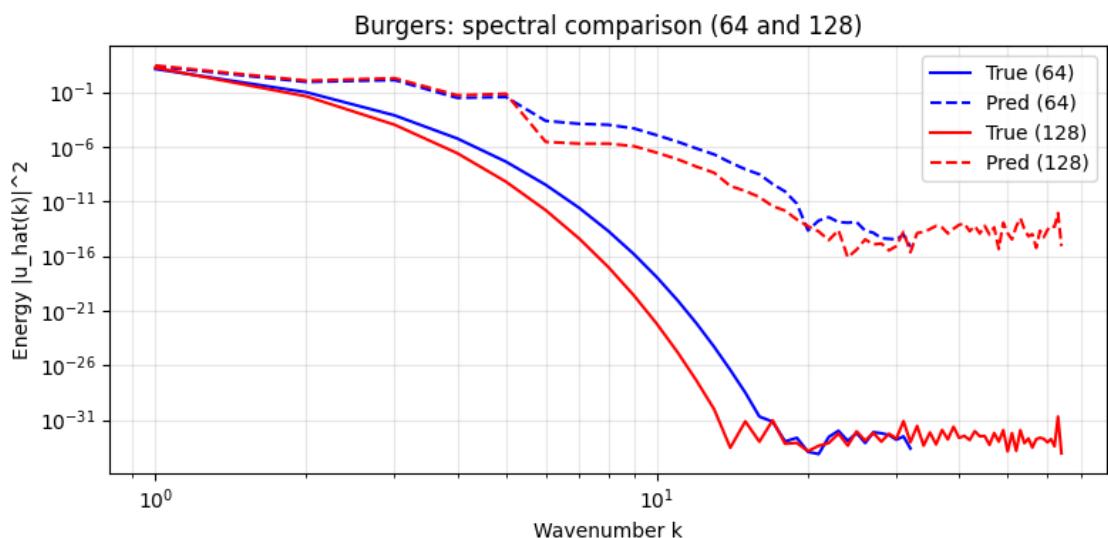
Plotting relative test MSE summary (normalised by low-res 64→64)...



Plotting field comparisons for sample 0 (first seed)...



Plotting spectral comparison for sample 0 (first seed)...



Diagnostics (first seed, sample 0):

Low-res H1(true)=0.509, H1(pred)=0.859, spectral rel. error=5.510e-01

High-res H1(true)=0.288, H1(pred)=0.492, spectral rel. error=5.189e-01