Optimizing minor machines for fame and glory

Phil Travis
APS DPP 2023 student dayyyy lmao

(Kunal technically helped with this project but any errors / emotional suffering caused by this talk is solely my own doing)

Mirror machines: old fusion concept, basis is conservation of μ

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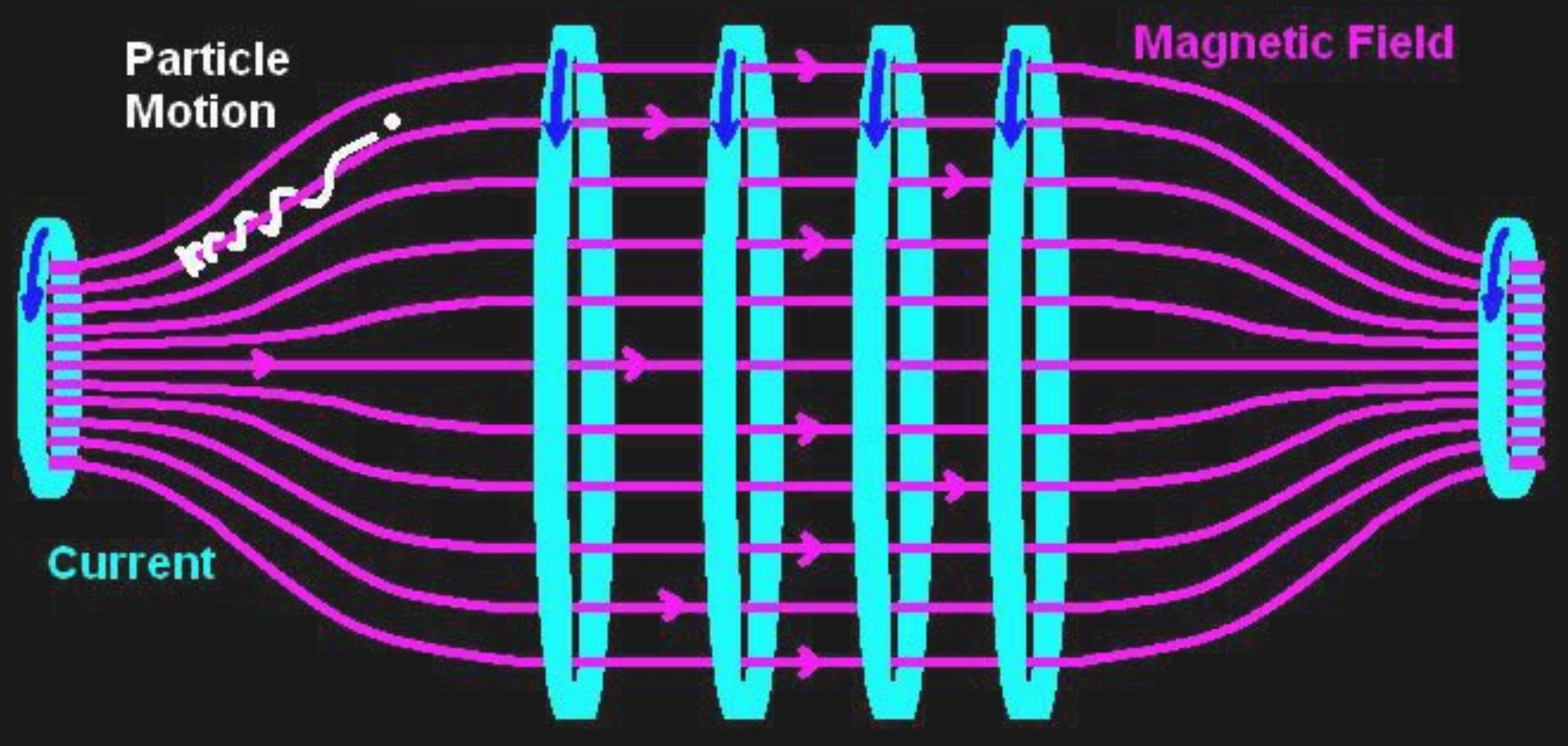

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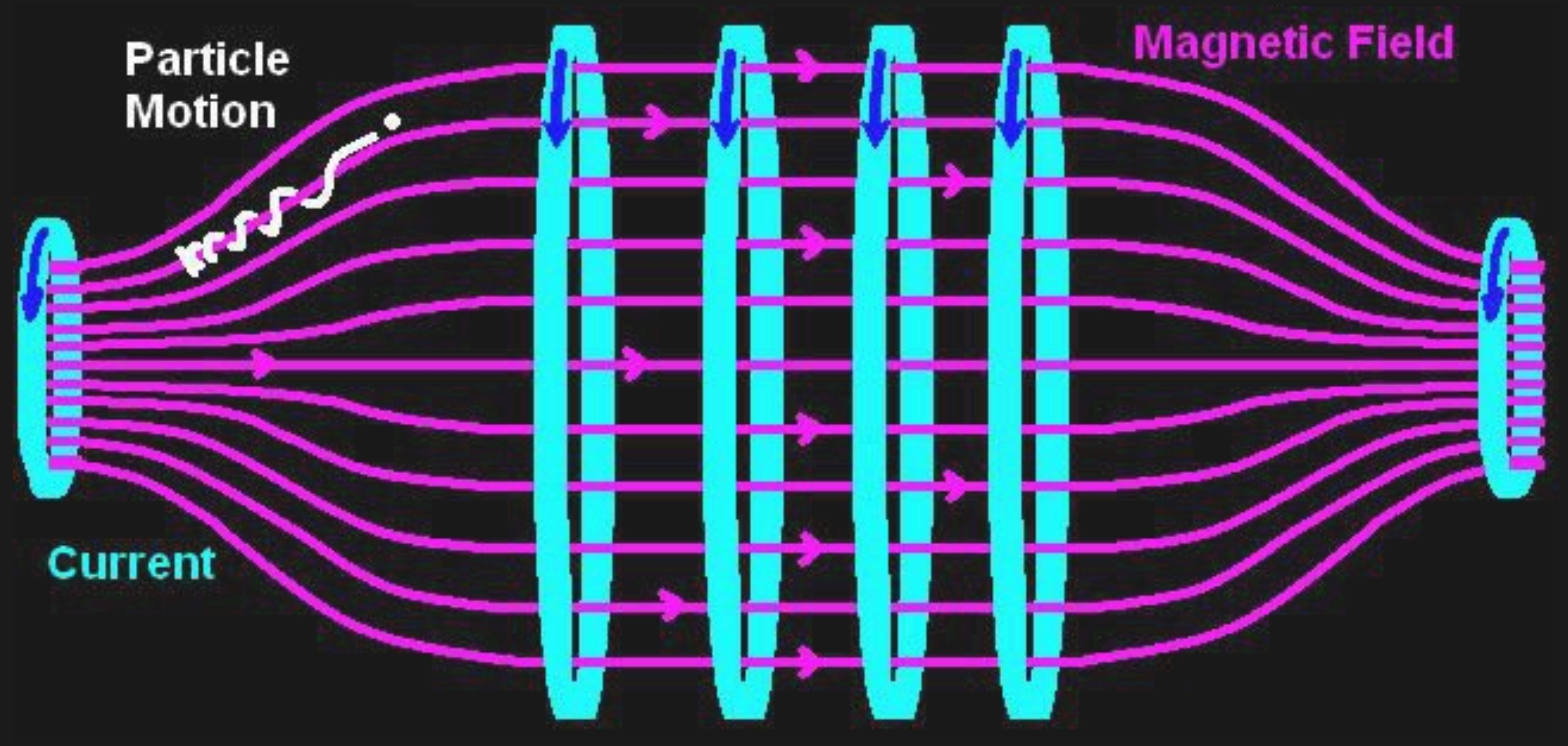
Mirror machines: old fusion concept, basis is conservation of μ



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Conservation of magnetic moment: $$\mu = \frac{W_\perp}{B}$$

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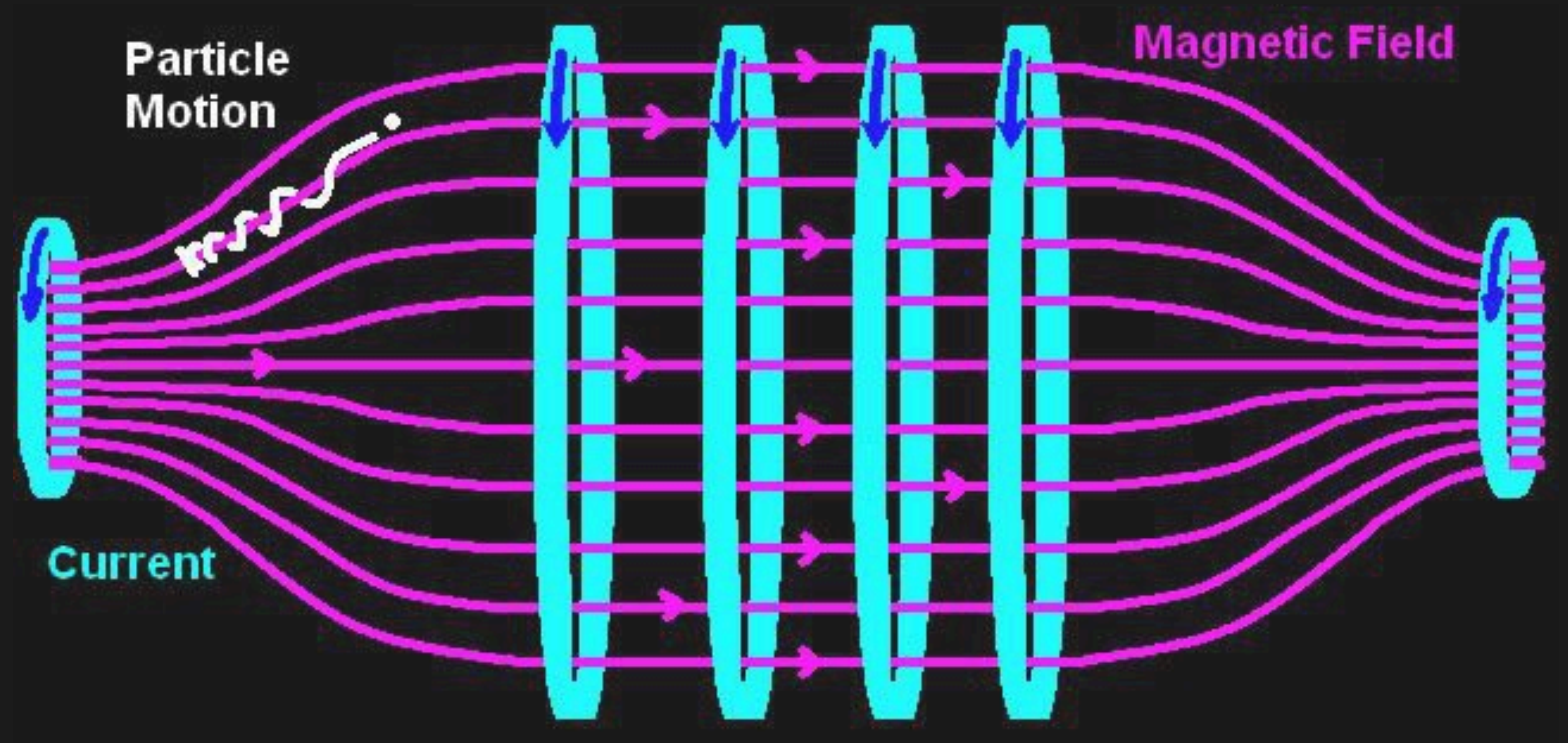

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Conservation of magnetic moment: $$\mu = \frac{W_\perp}{B} \uparrow$$

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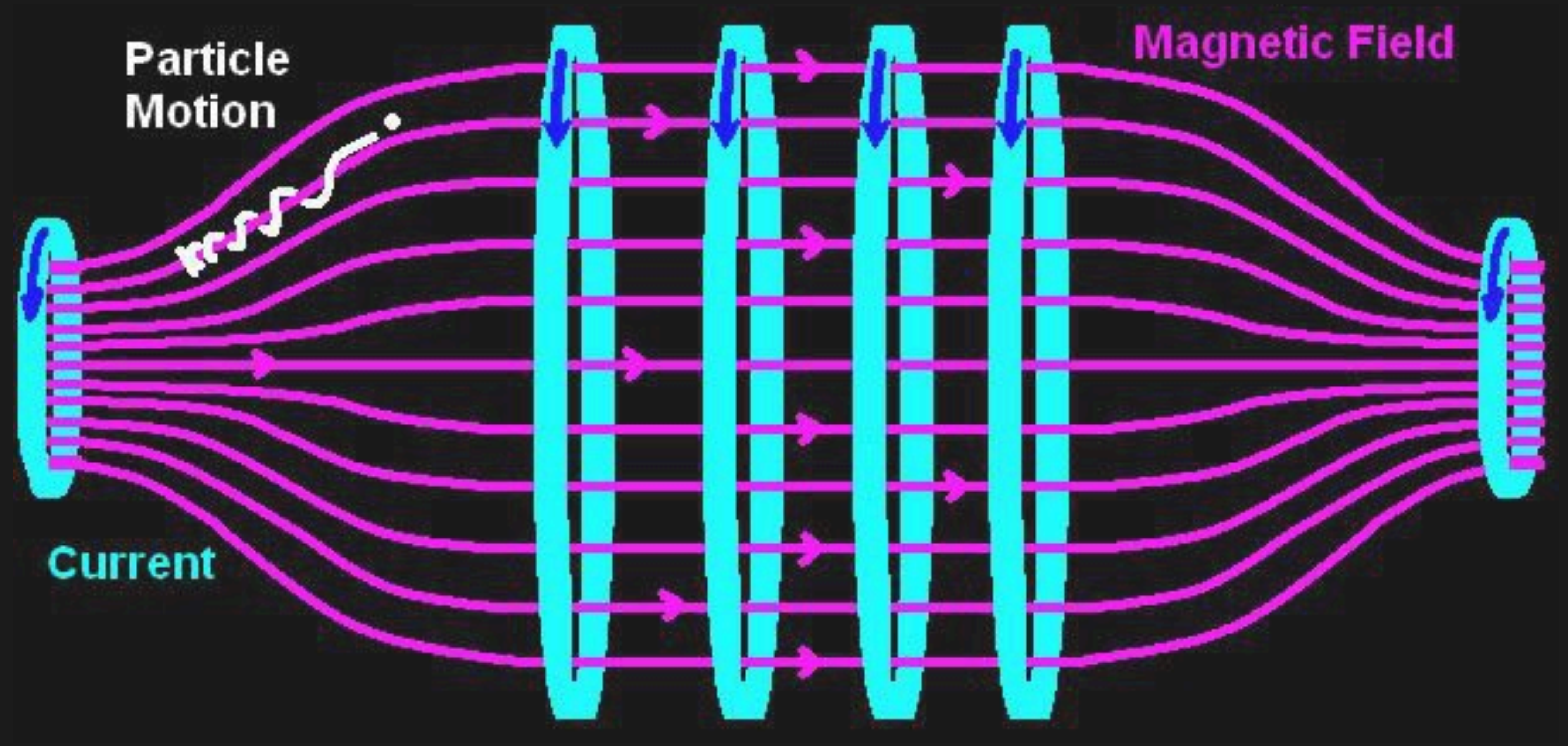

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Conservation of magnetic moment: $$\mu = \frac{W_\perp \uparrow}{B \uparrow}$$

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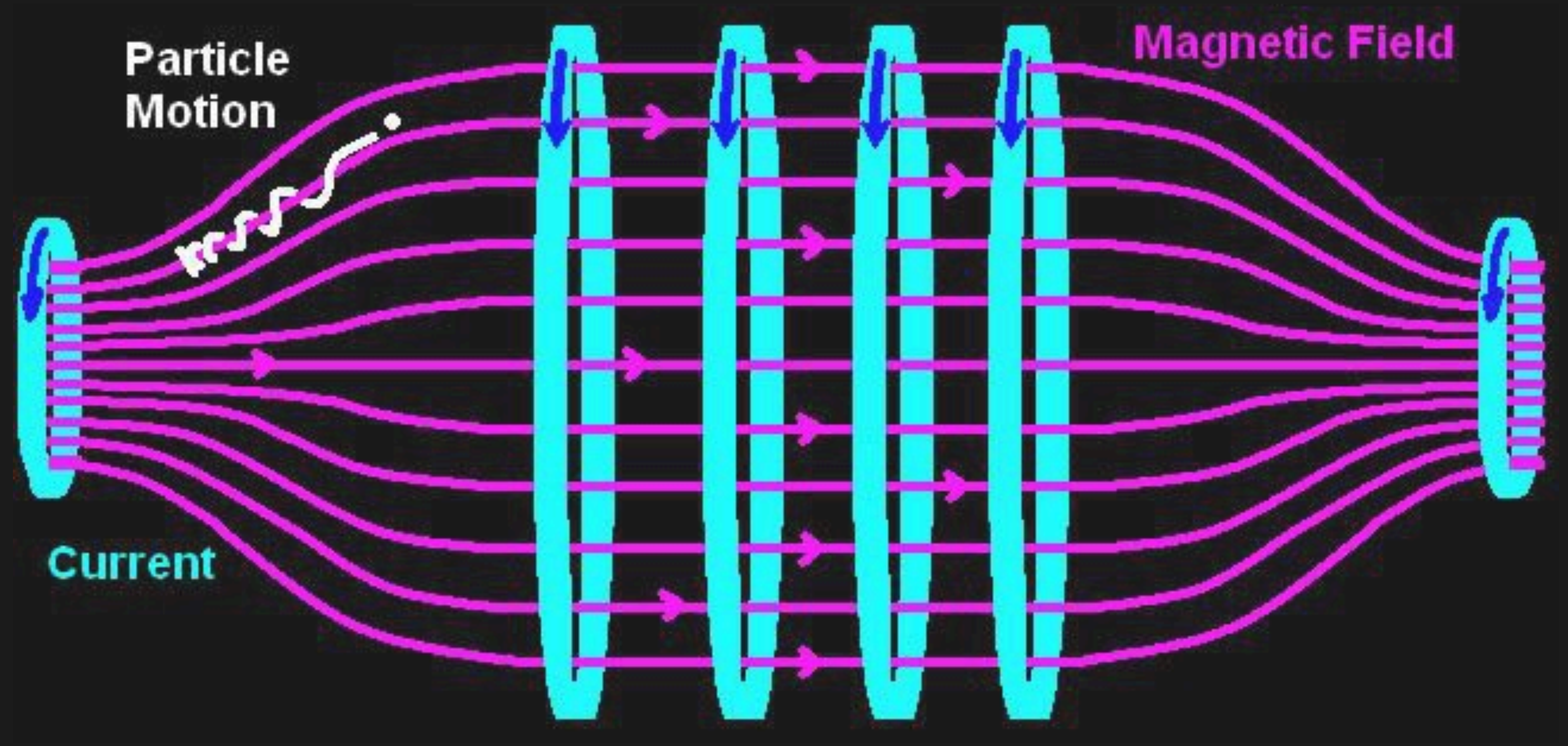

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Conservation of magnetic moment: $\mu = \frac{W_\perp \uparrow}{B \uparrow}$ ⟹ conservation of energy

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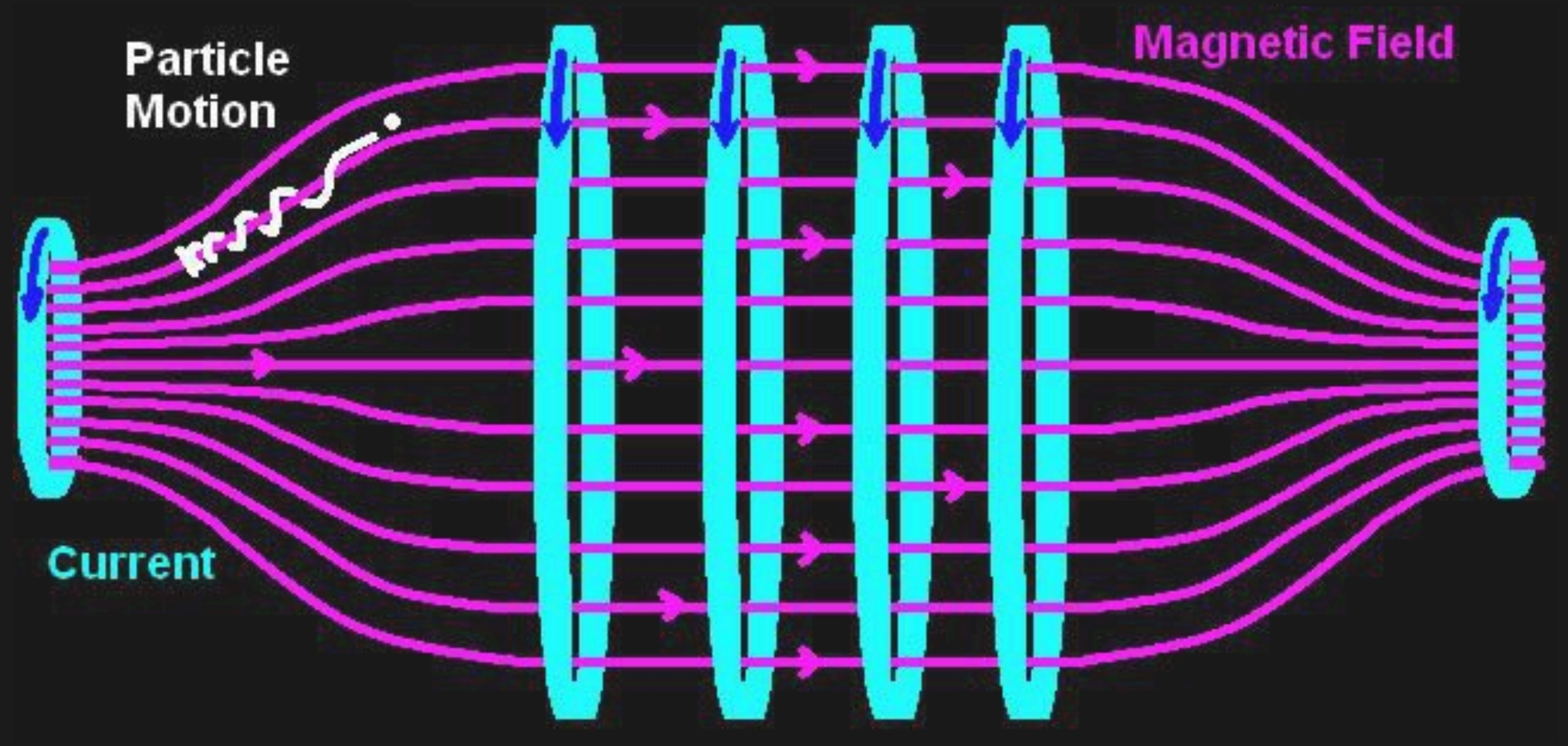

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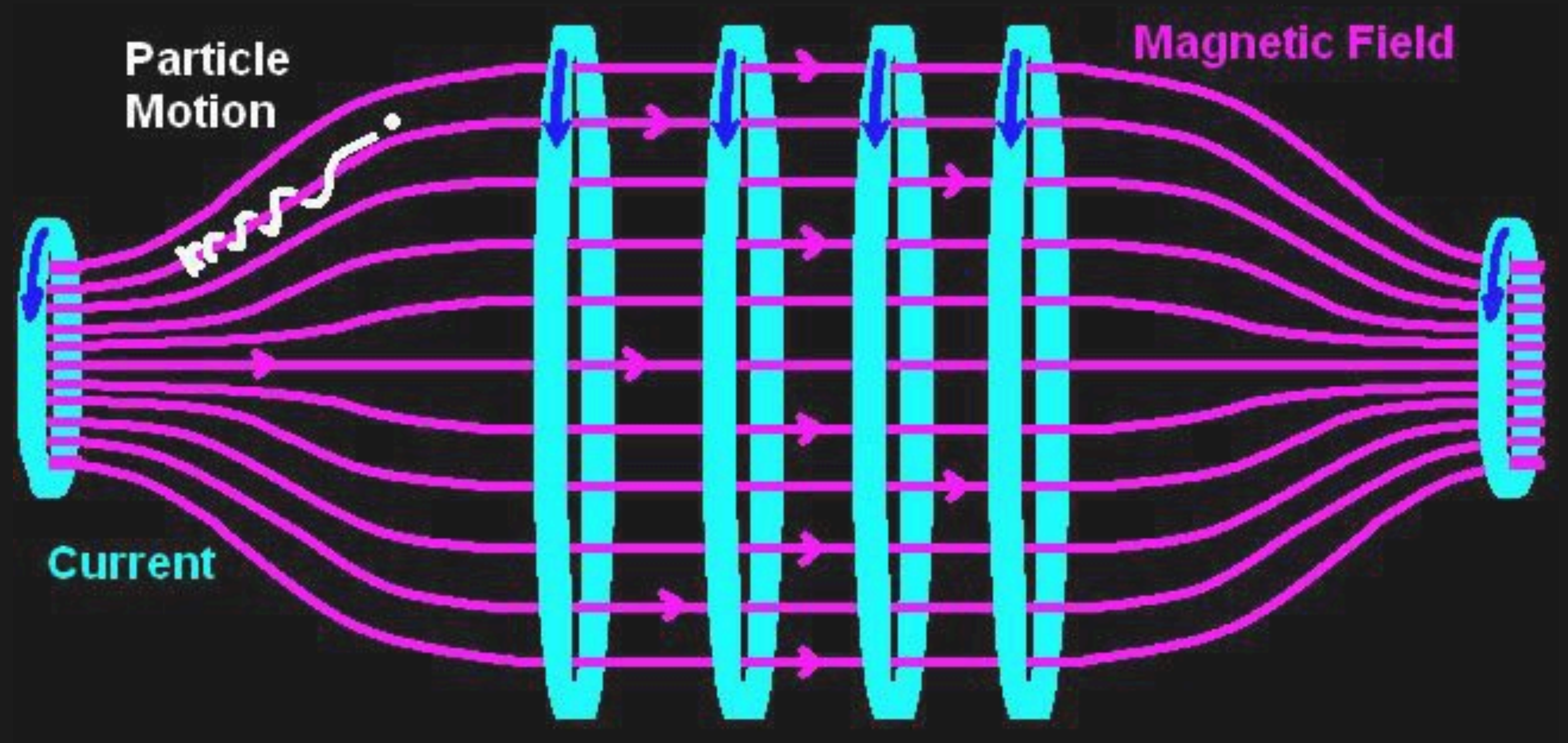
Conservation of magnetic moment: $\mu = \frac{W_\perp \uparrow}{B \uparrow} \Rightarrow W_{||} \downarrow$

conservation of energy

Mirror machines: old fusion concept, basis is conservation of μ



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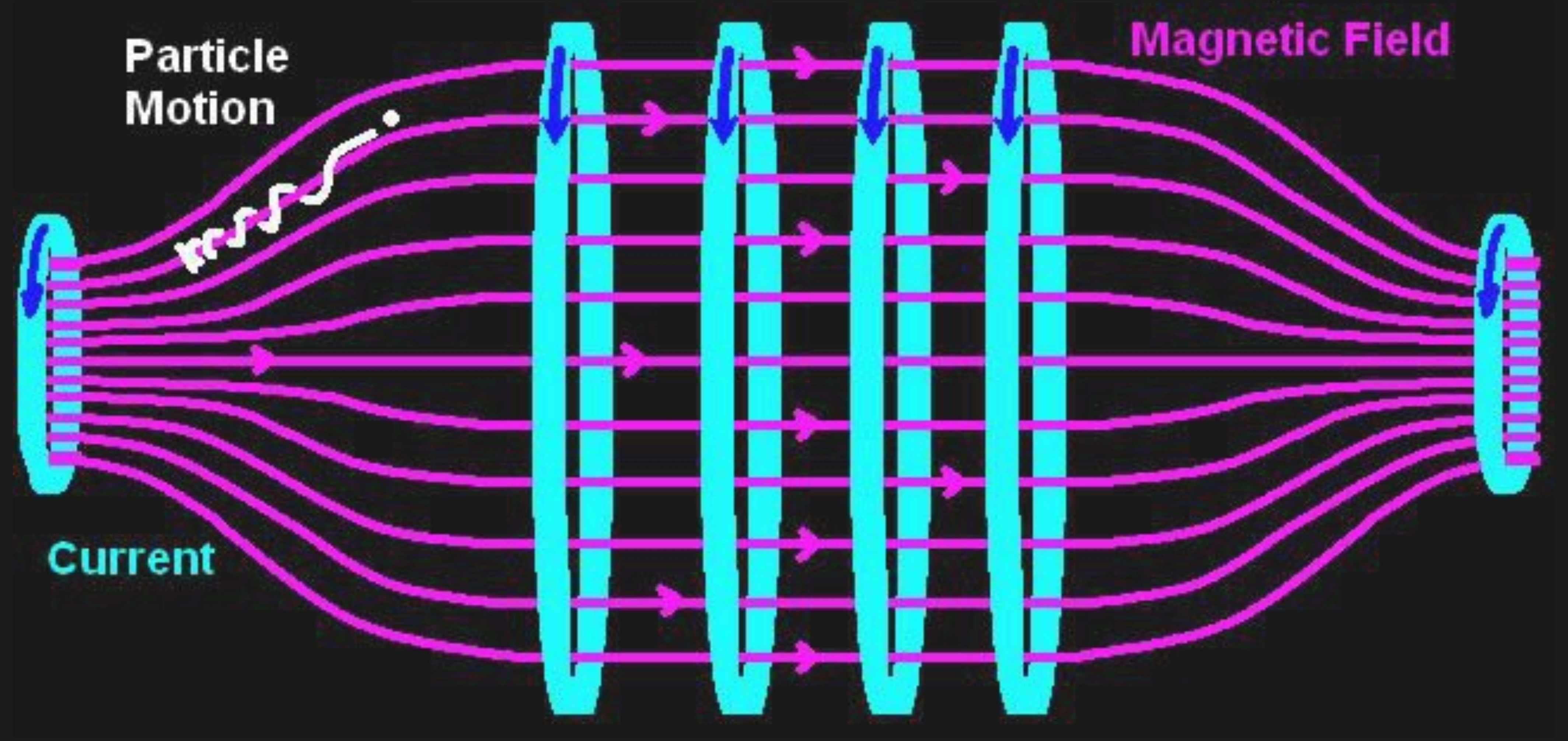
Conservation of magnetic moment: $\mu = \frac{W_\perp \uparrow}{B \uparrow}$ → $W_{||} \downarrow$ → particle reflected

conservation of energy

Mirror machines: old fusion concept, basis is conservation of μ



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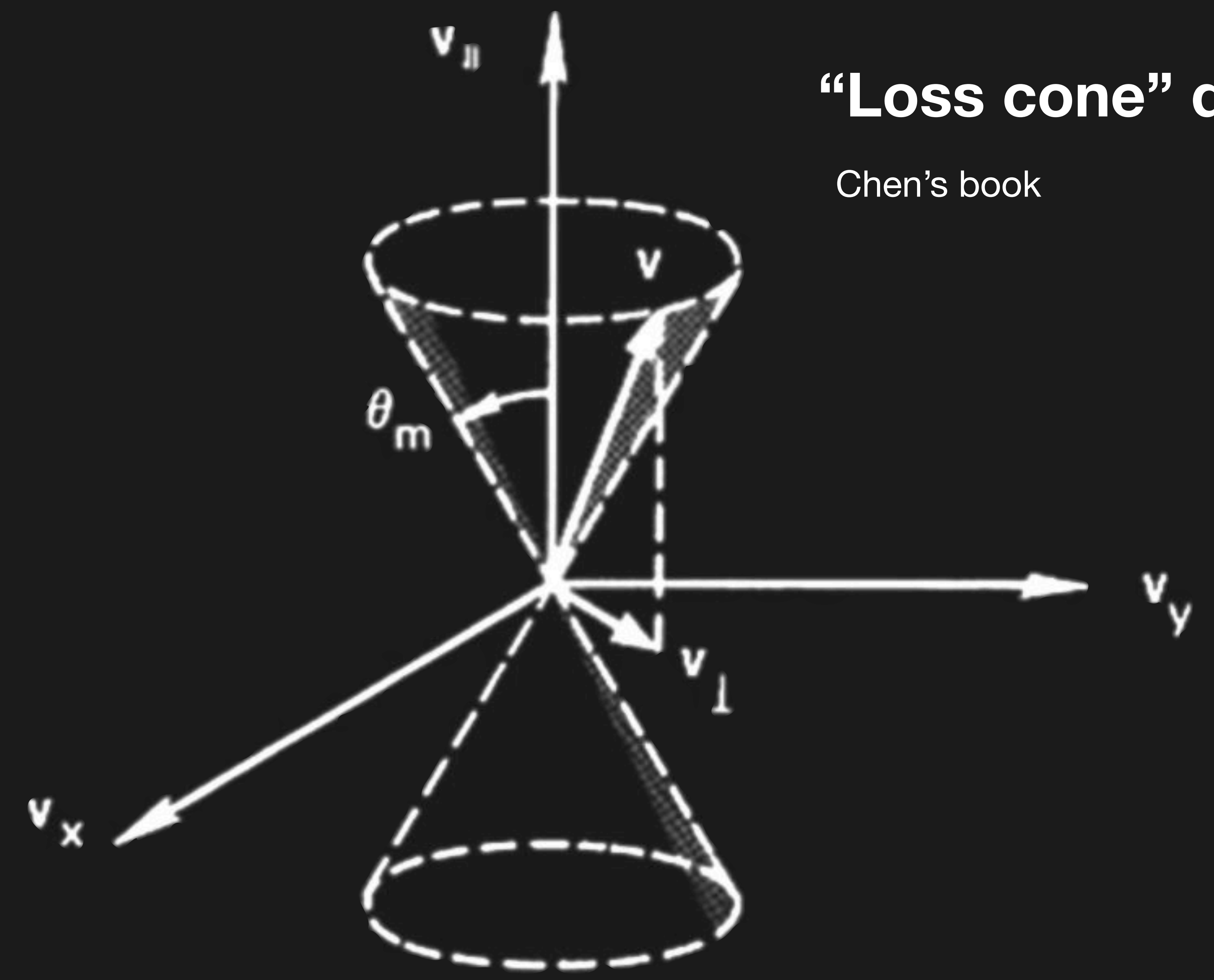


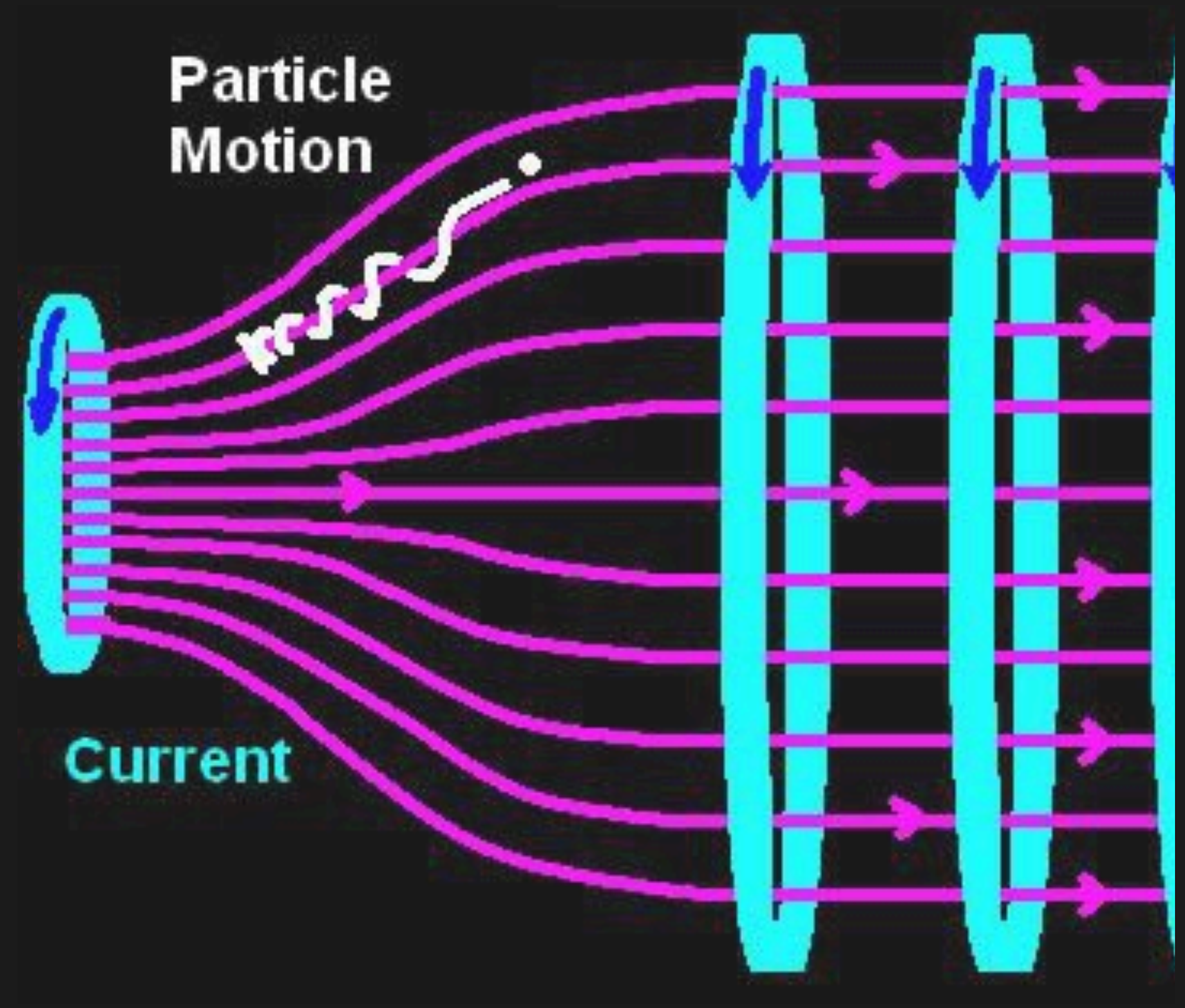
“Loss cone” distribution

Chen’s book

Conservation of magnetic moment: $\mu = \dfrac{W_{\perp} \uparrow}{B \uparrow}$ $\Rightarrow$ $W_{||} \downarrow$ $\Rightarrow$ particle reflected

conservation of energy

Mirror machines: old f ... of μ



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Conservation of magnetic moment

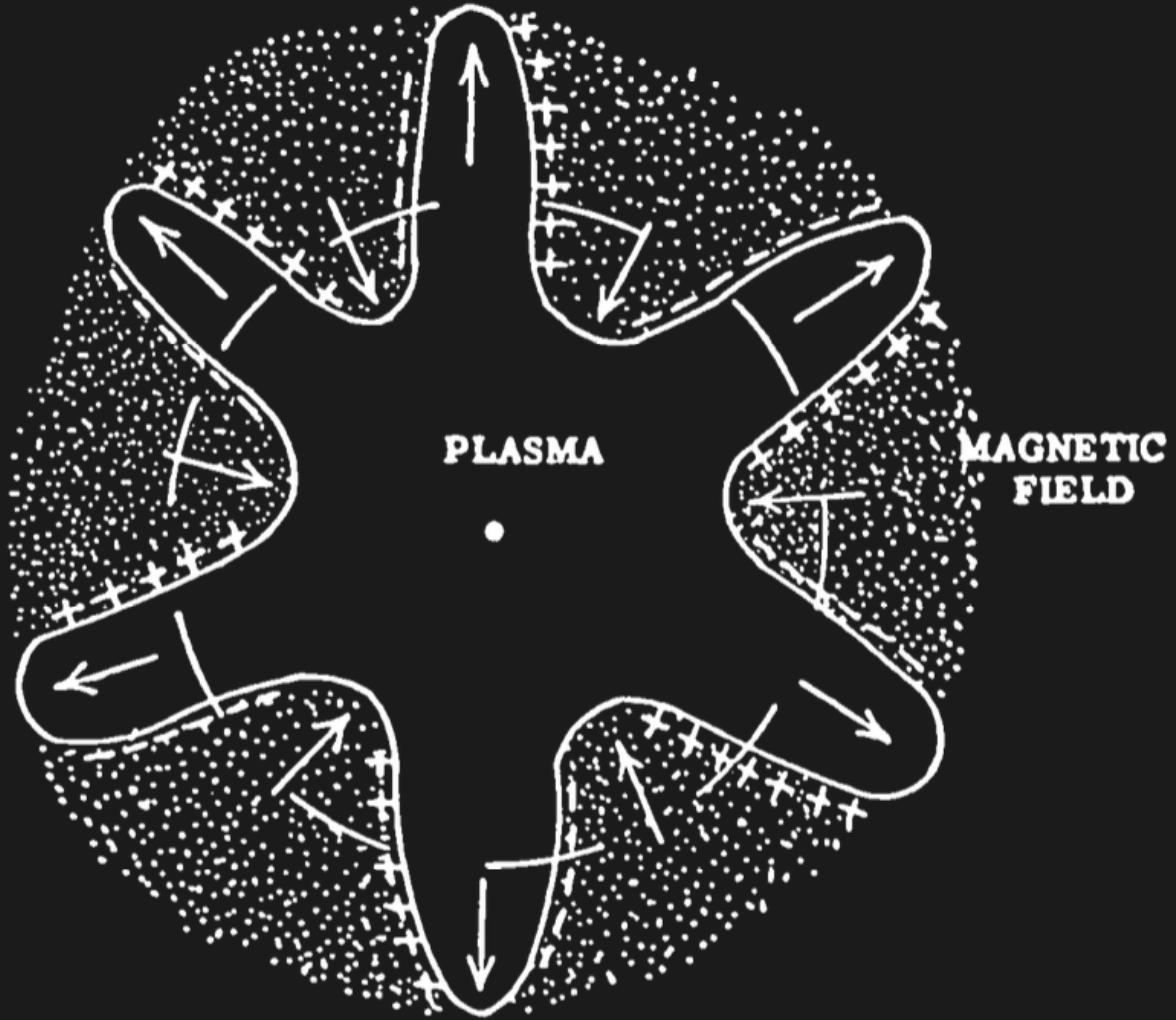


FIG. 30. Schematic illustration of the high-m flute instability in a simple mirror field, showing polarization fields and directions of unstable motion.

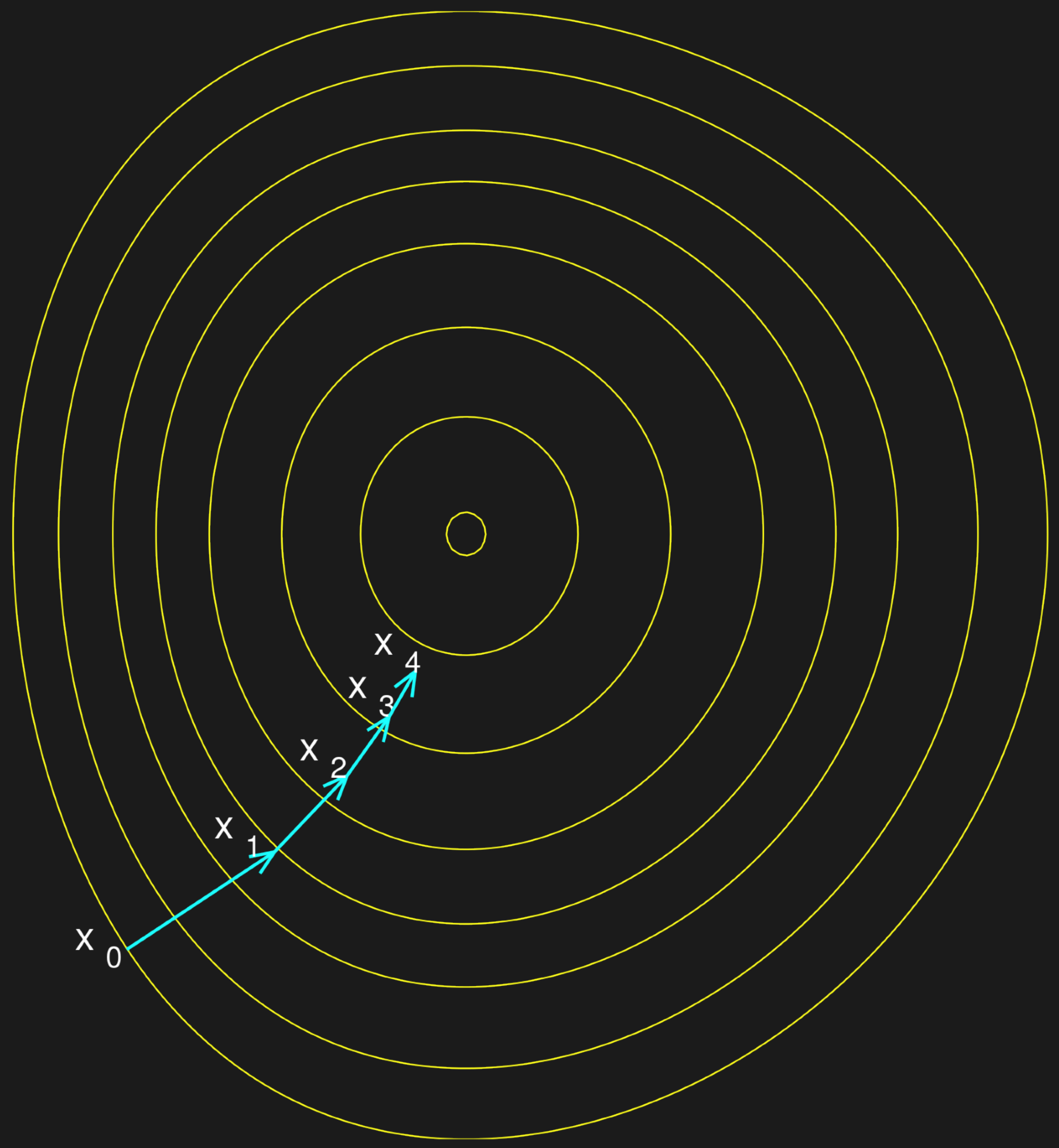
“Loss cone” distribution

Chen’s book

v_y

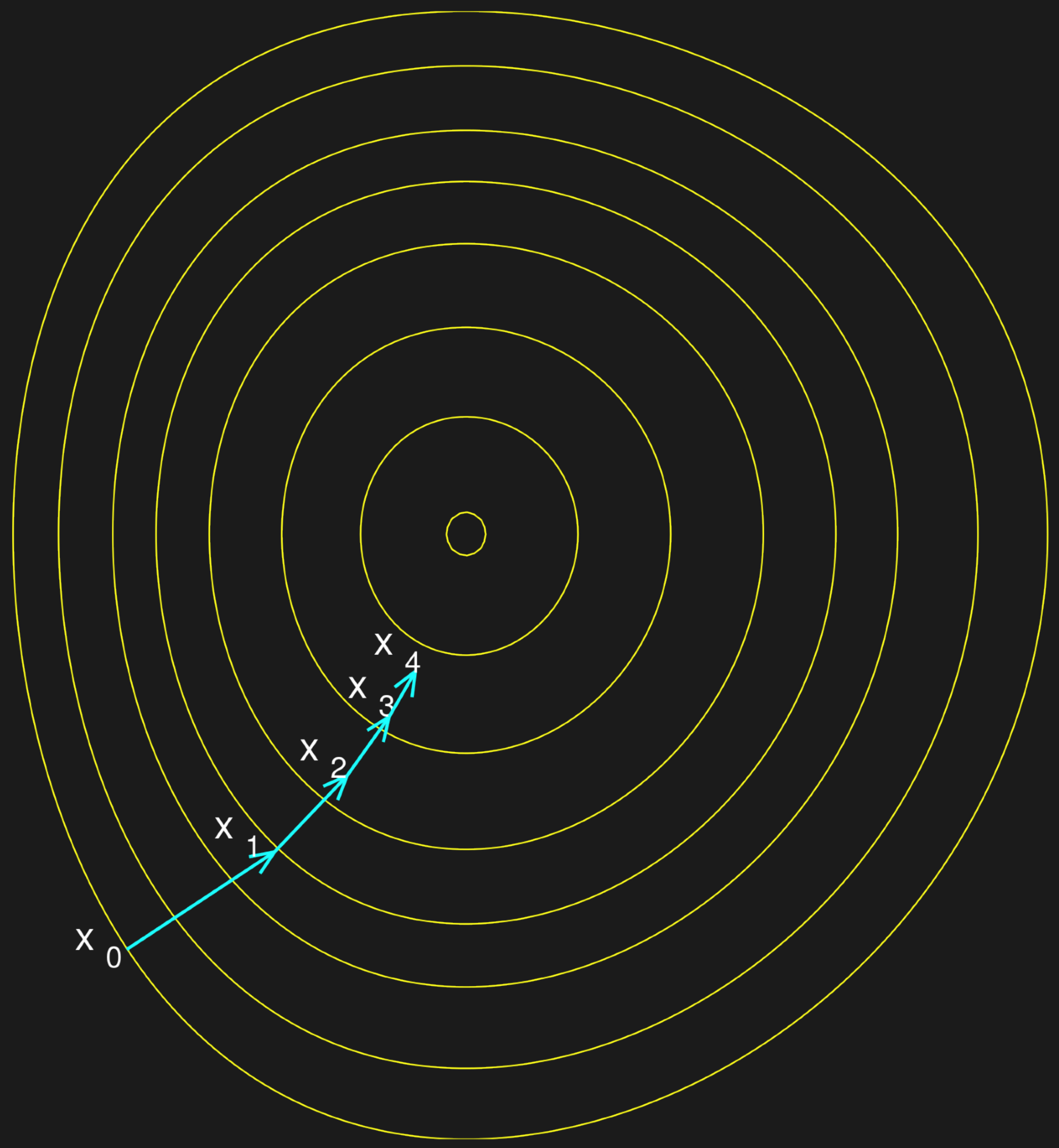
particle reflected

Optimization using gradient descent



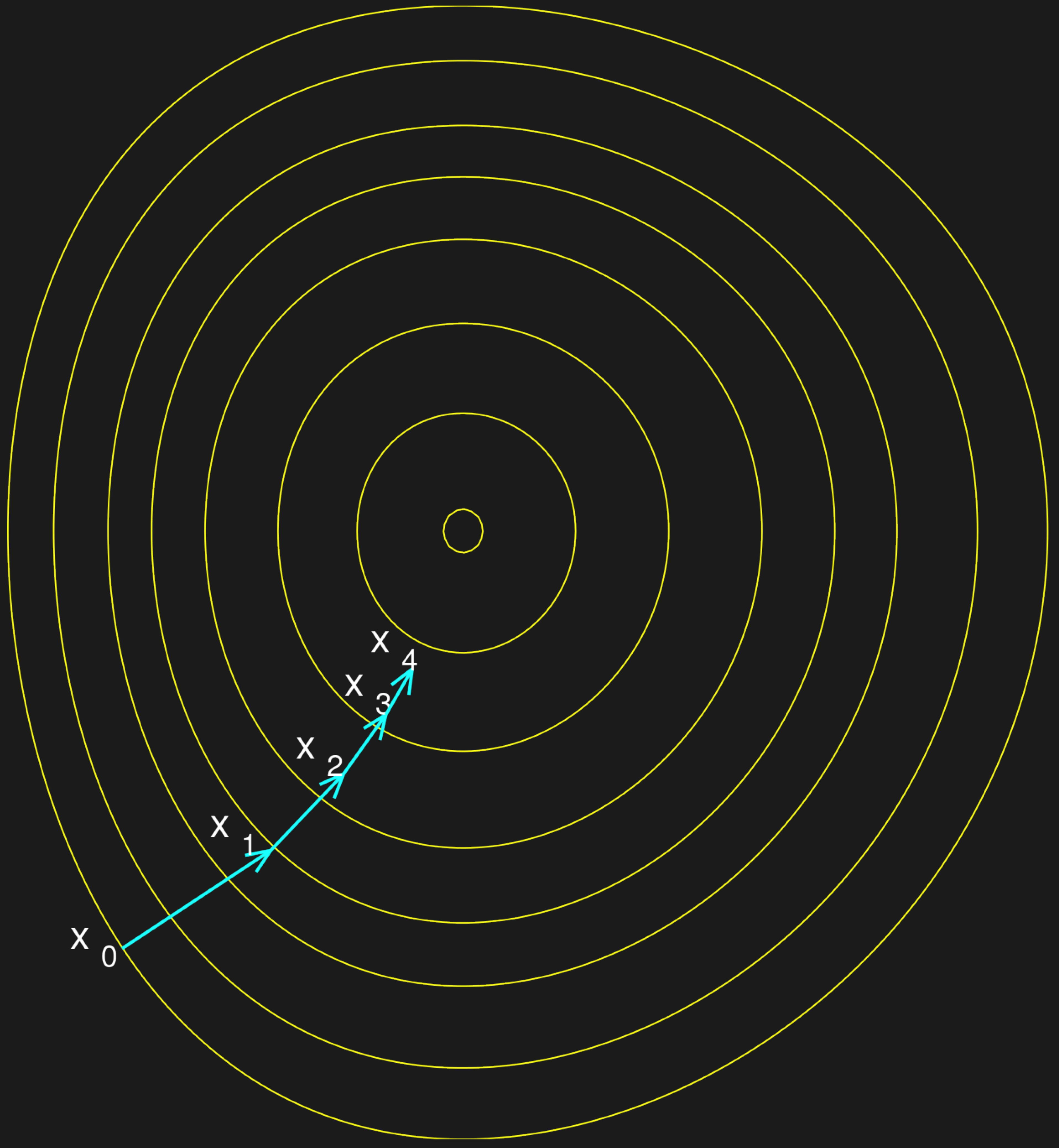
Optimization using gradient descent

- Update values based on gradient
  - $\vec{x} := \vec{x} - \nabla_{\vec{x}} \mathscr{C} \cdot \lambda$
  - $\mathscr{C}$ is the cost function (quantity to minimize)
  - λ is step size (chosen by trial-and-error in this case)



Optimization using gradient descent

you get there in the end



Optimization using gradient descent

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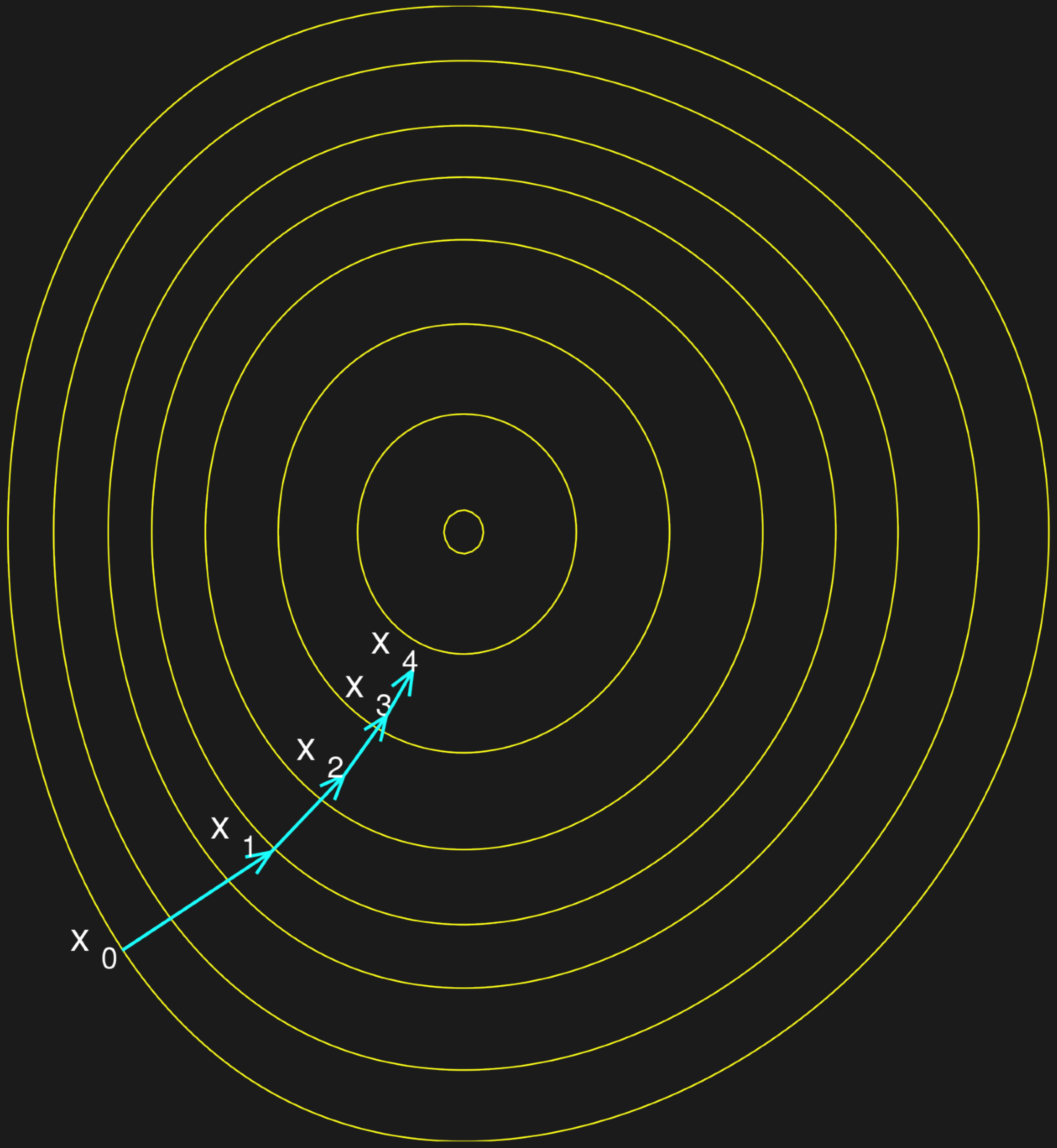
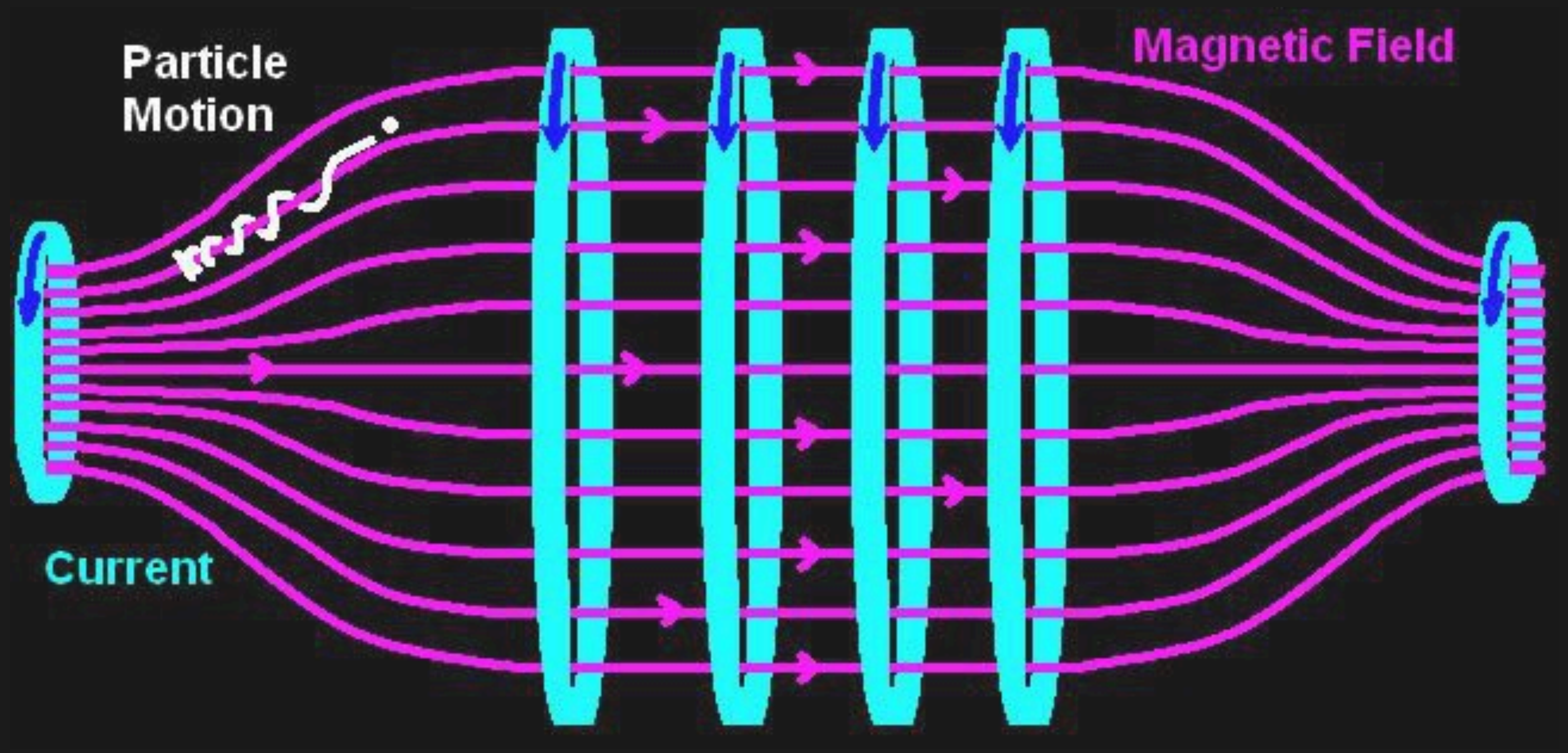


so lets optimize a simple mirror

so lets optimize a simple mirror



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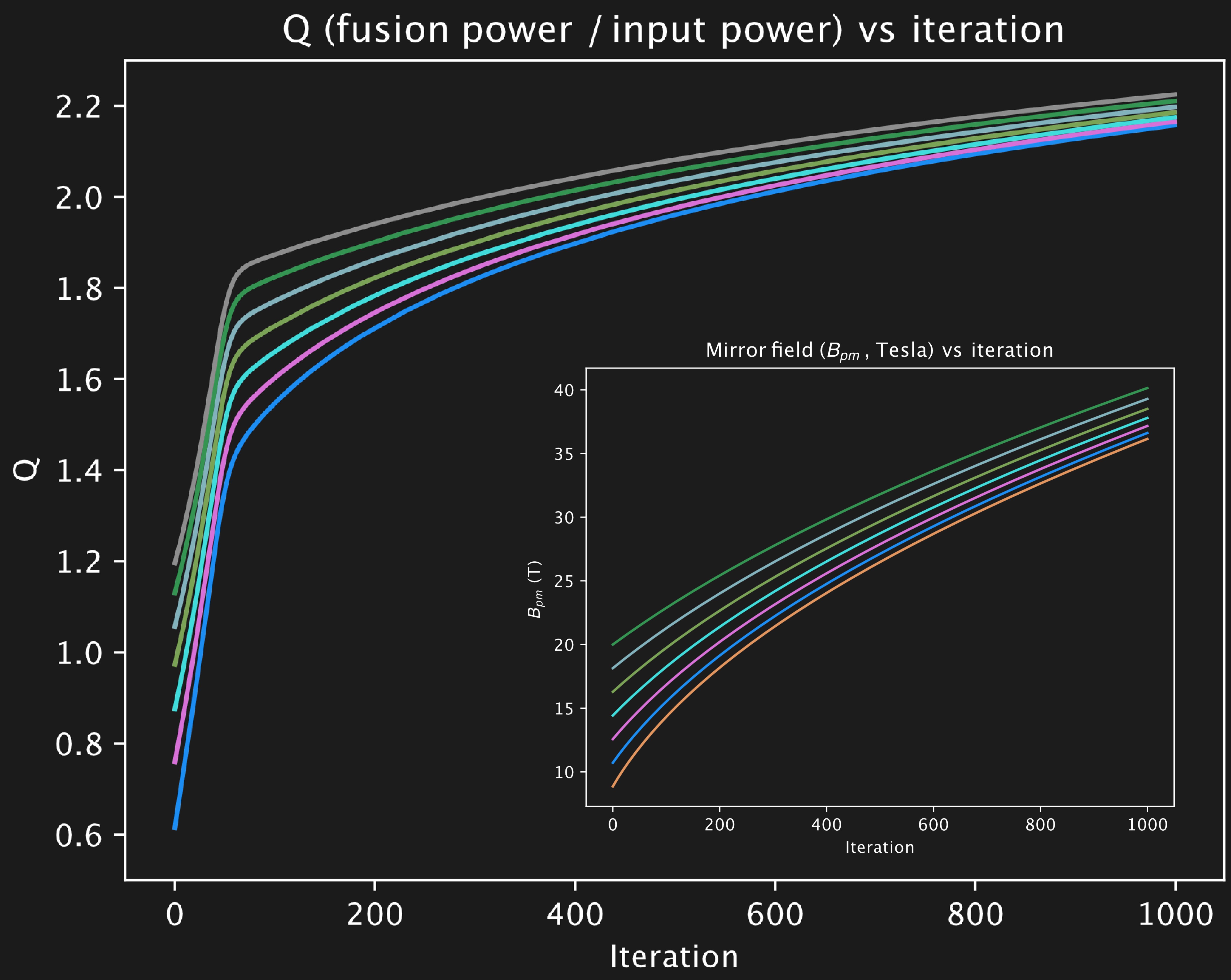
Fun fact: simple mirrors kinda aren't great



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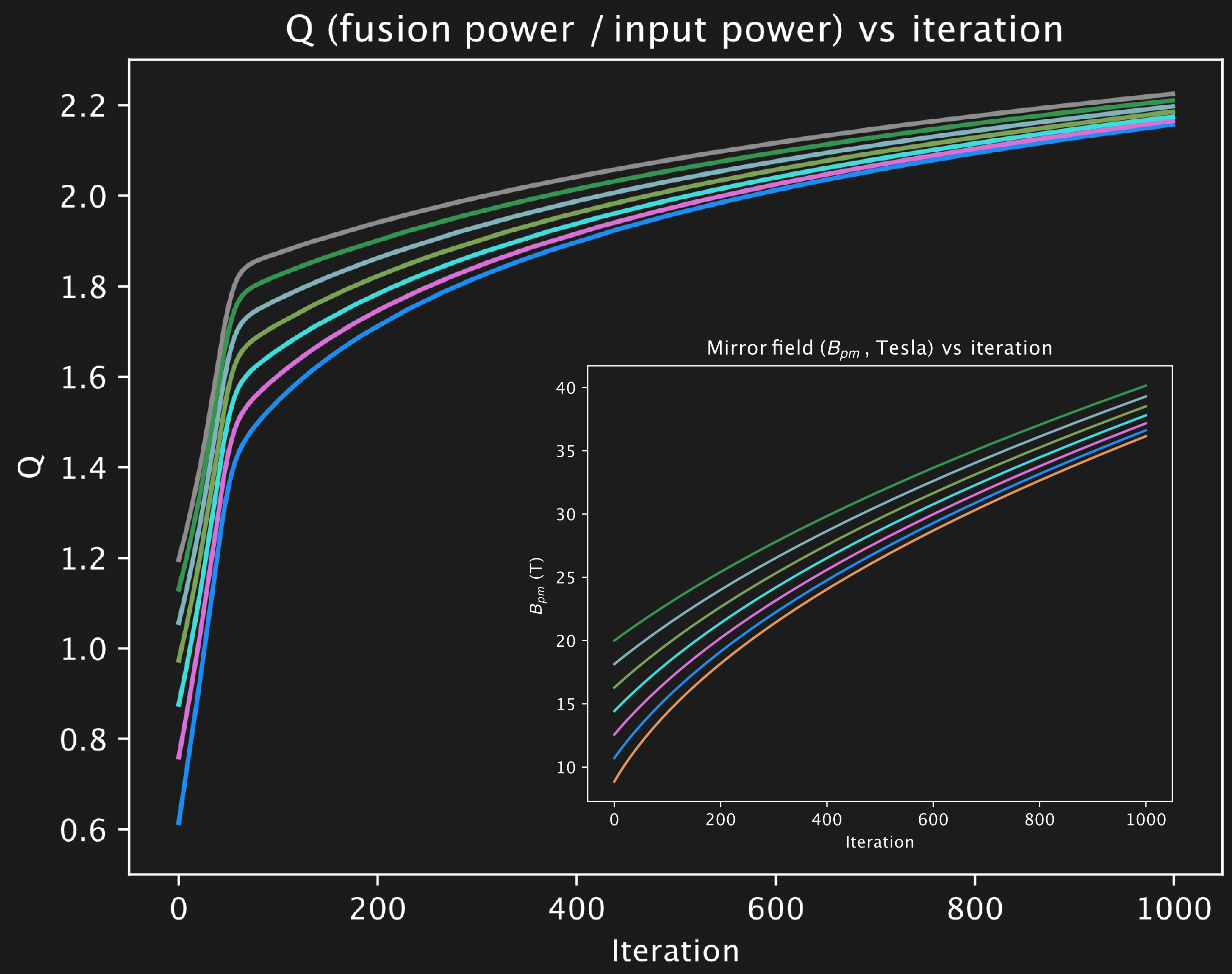
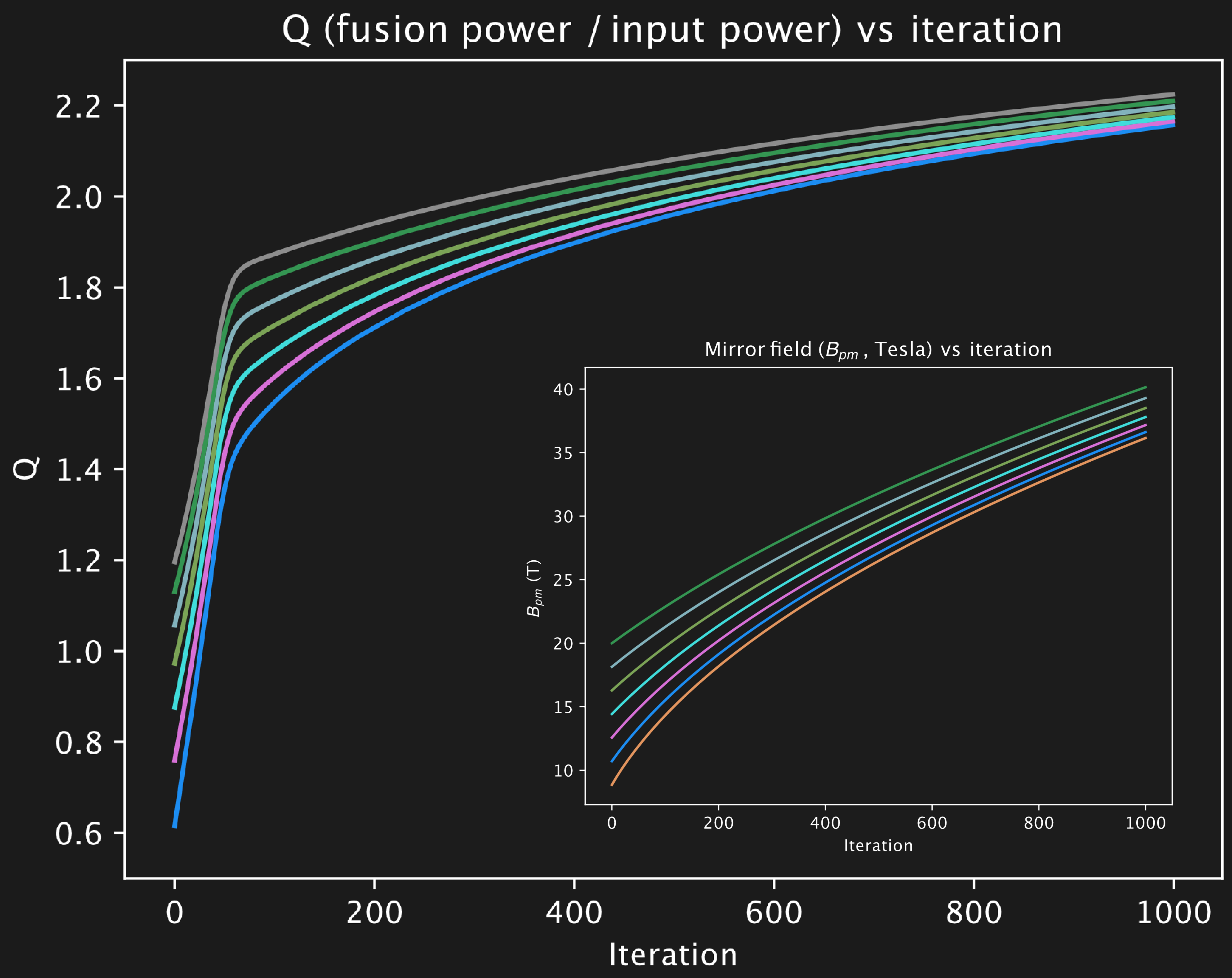


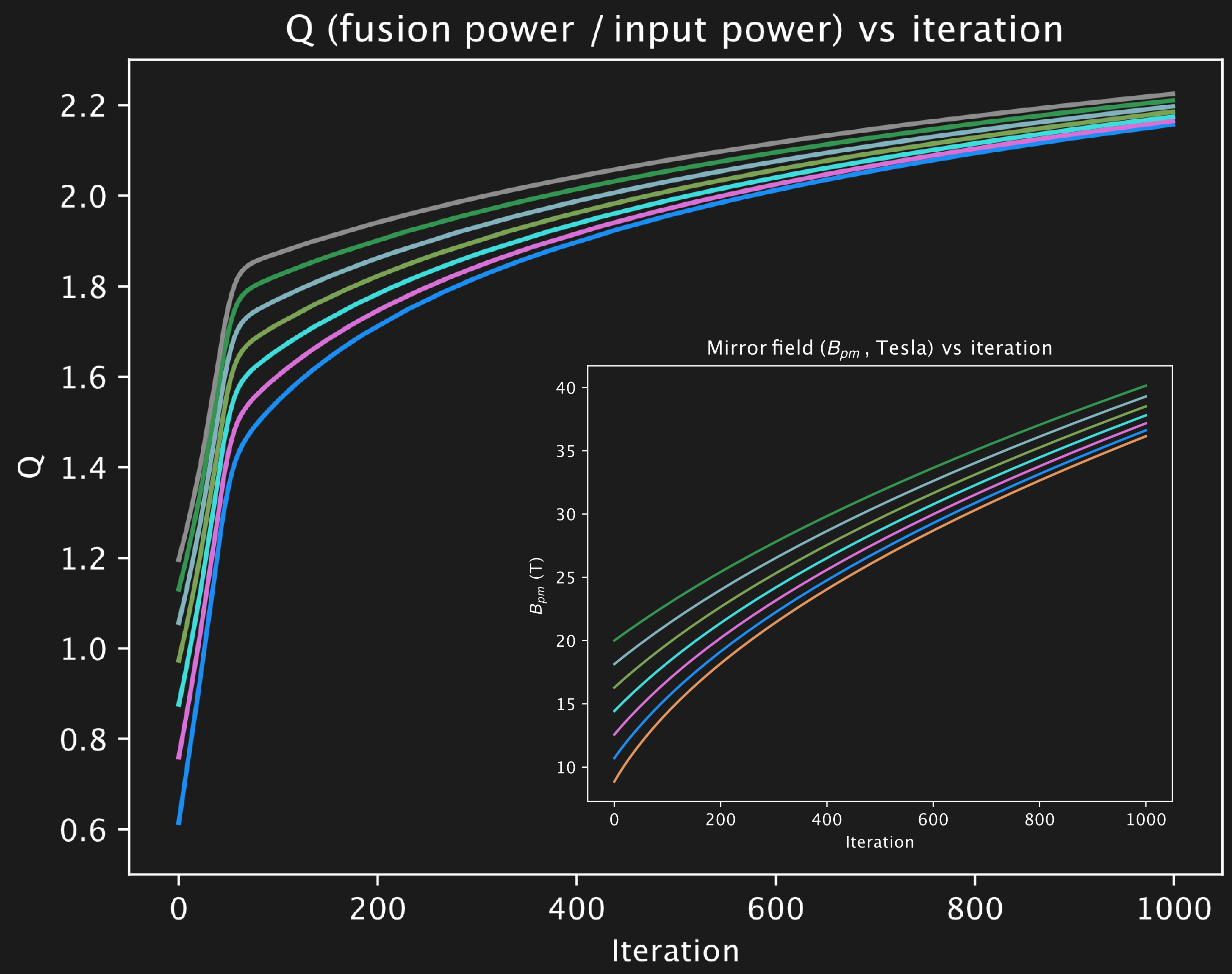
- Mirror field optimizes to 35+ T

Fun fact: simple mirrors kinda aren't great



- Mirror field optimizes to 35+ T
- Q optimizes to a little above 2

Fun fact: simple mirrors kinda aren't great



- Mirror field optimizes to 35+ T
- Q optimizes to a little above 2
- 1 MeV NBI

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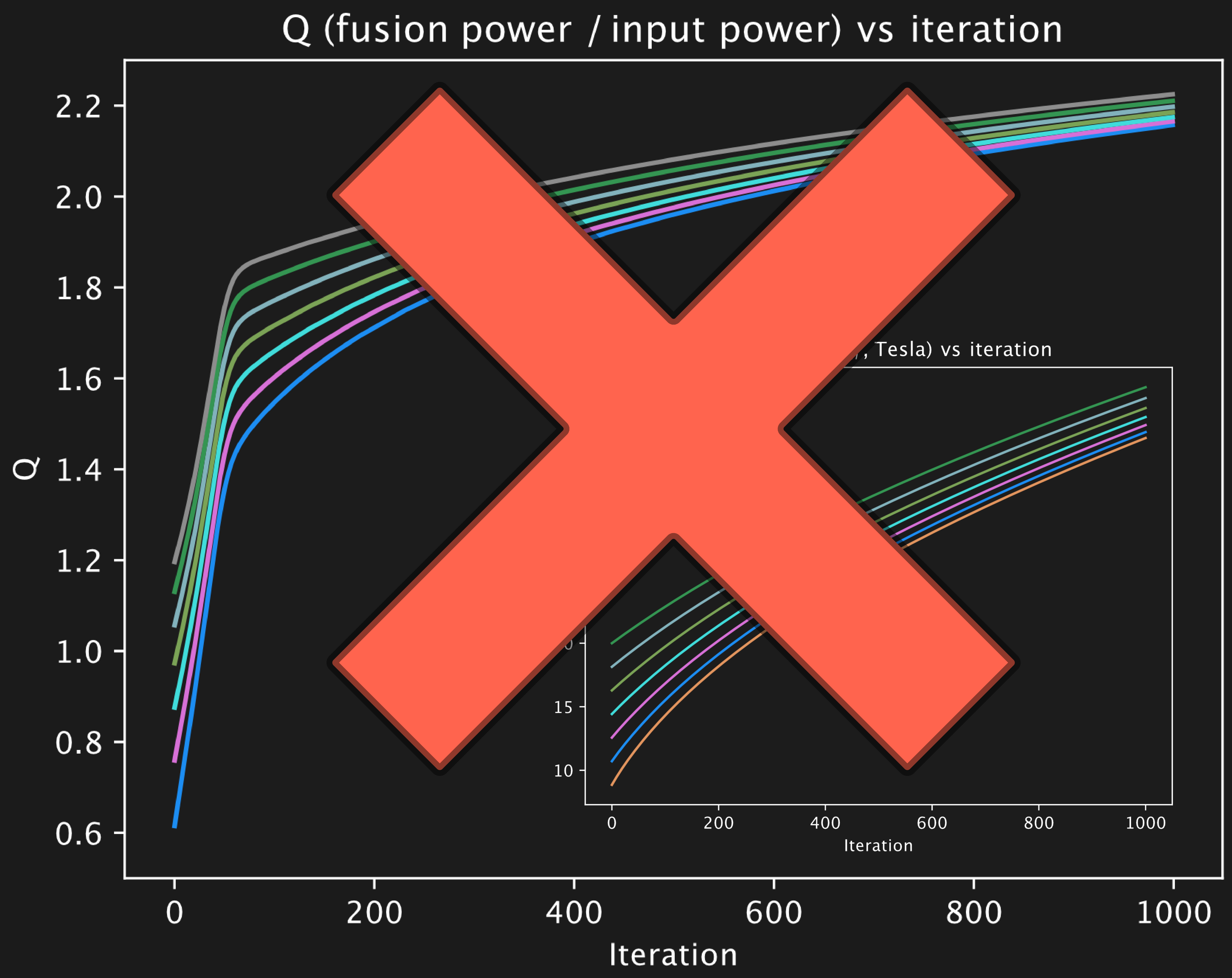

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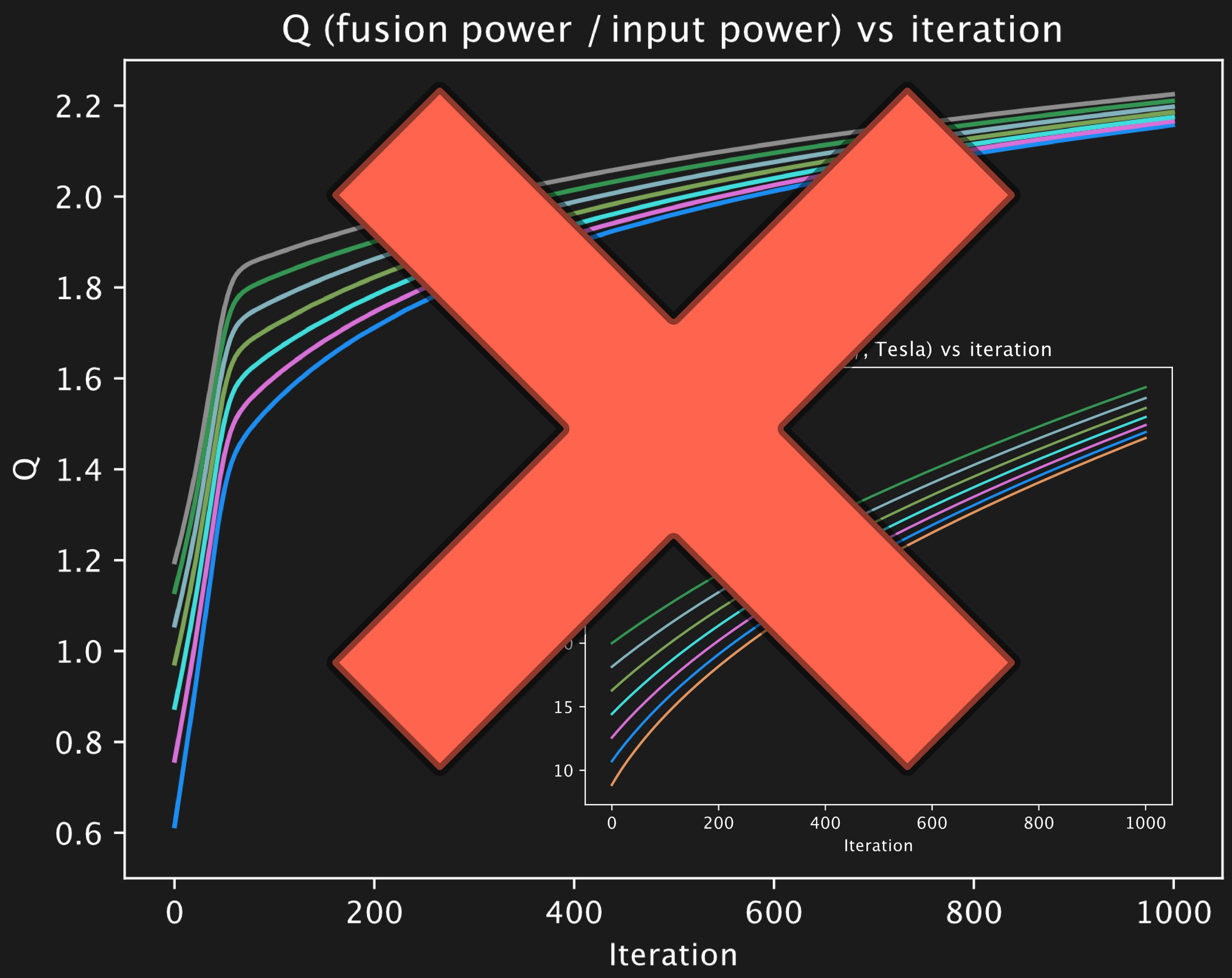
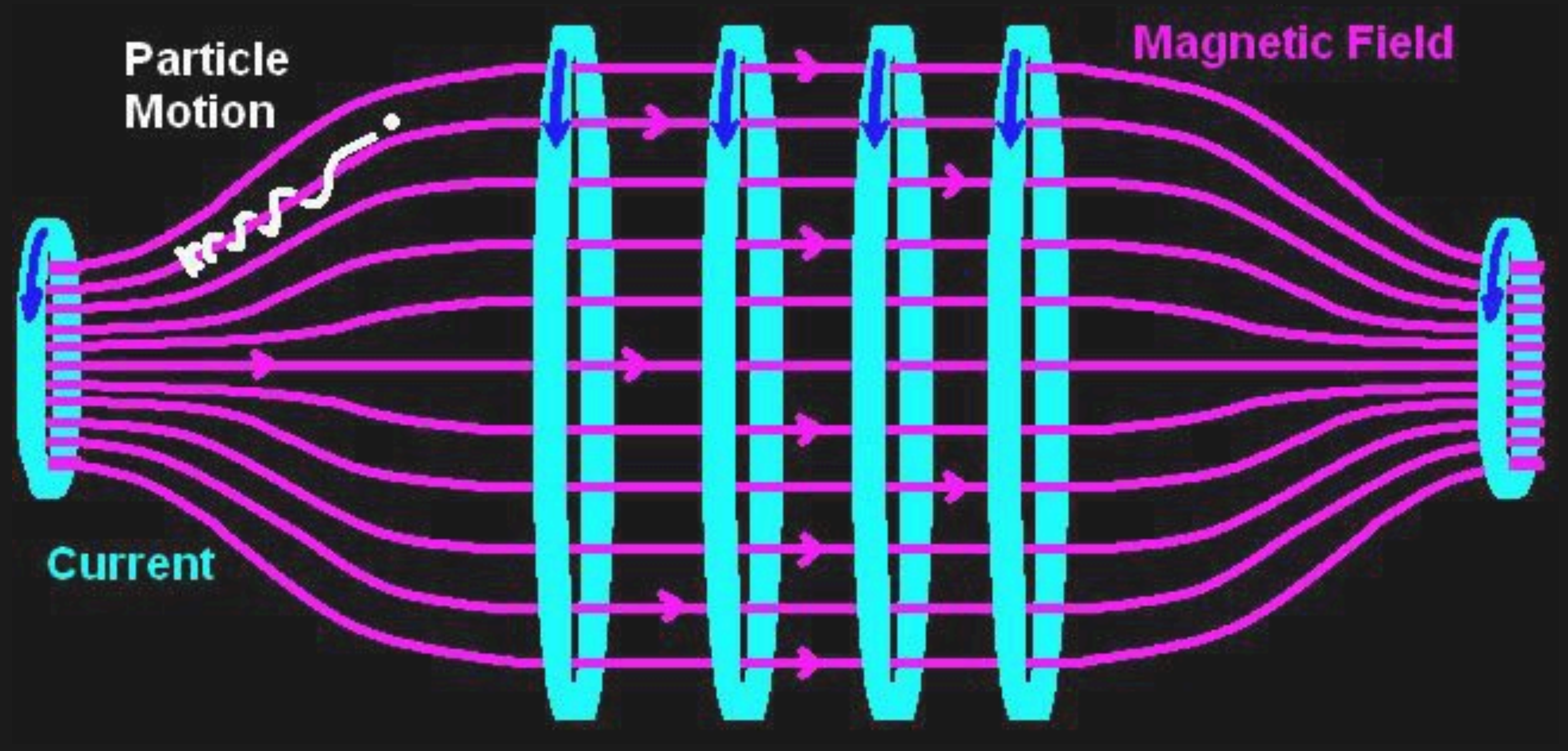


- Mirror field optimizes to 35+ T
- Q optimizes to a little above 2
- 1 MeV NBI
- Simple mirrors aint gonna work *

*** wellllll maybe we can use a gas-dynamic trap for a neutron source**



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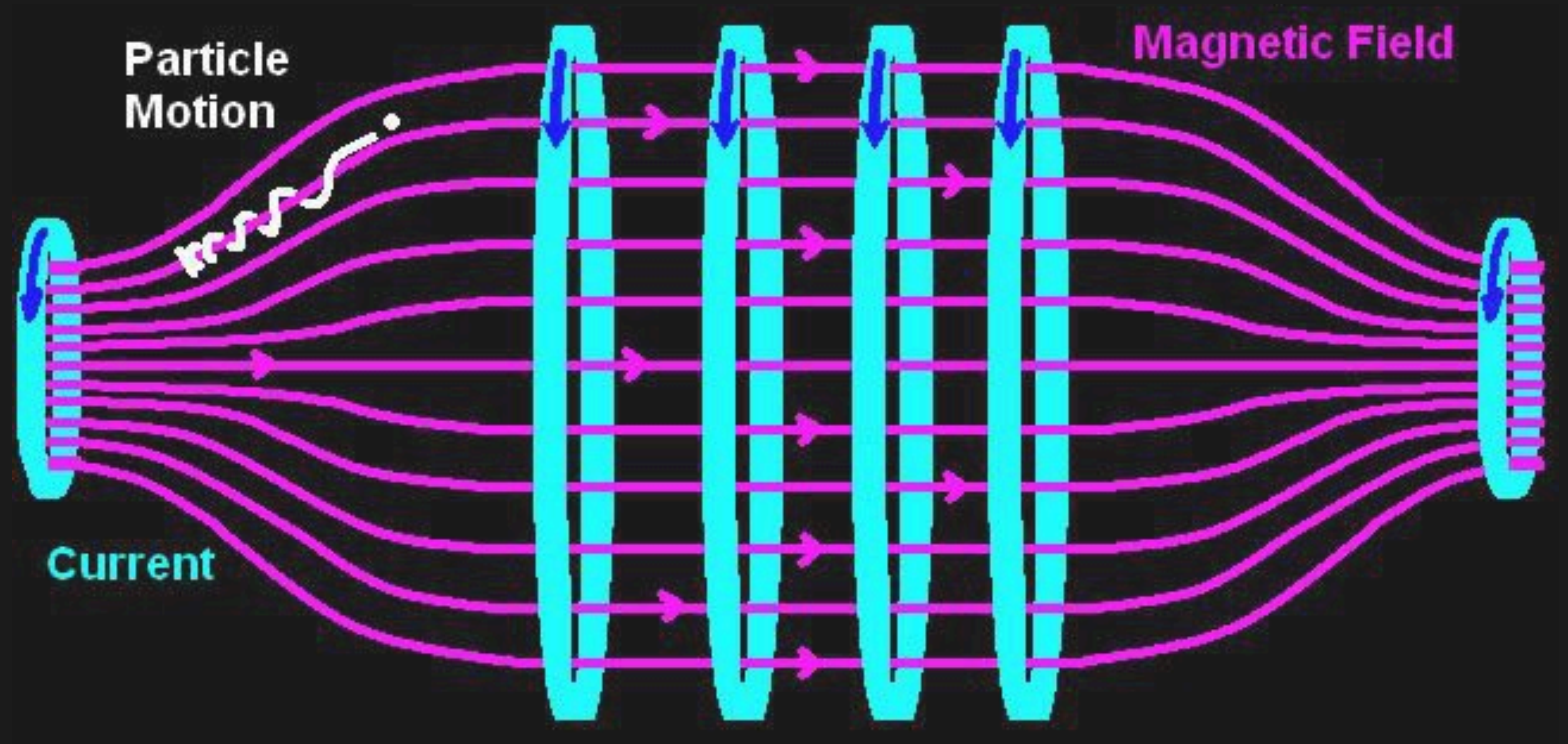
Particle
Motion
Magnetic Field
Current

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We have one yes. What about second mirror

so add more mirrors

"tandem mirror"

(okay it's actually 3 but you get the point)

so add more mirrors

"tandem mirror"

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“tandem mirror”

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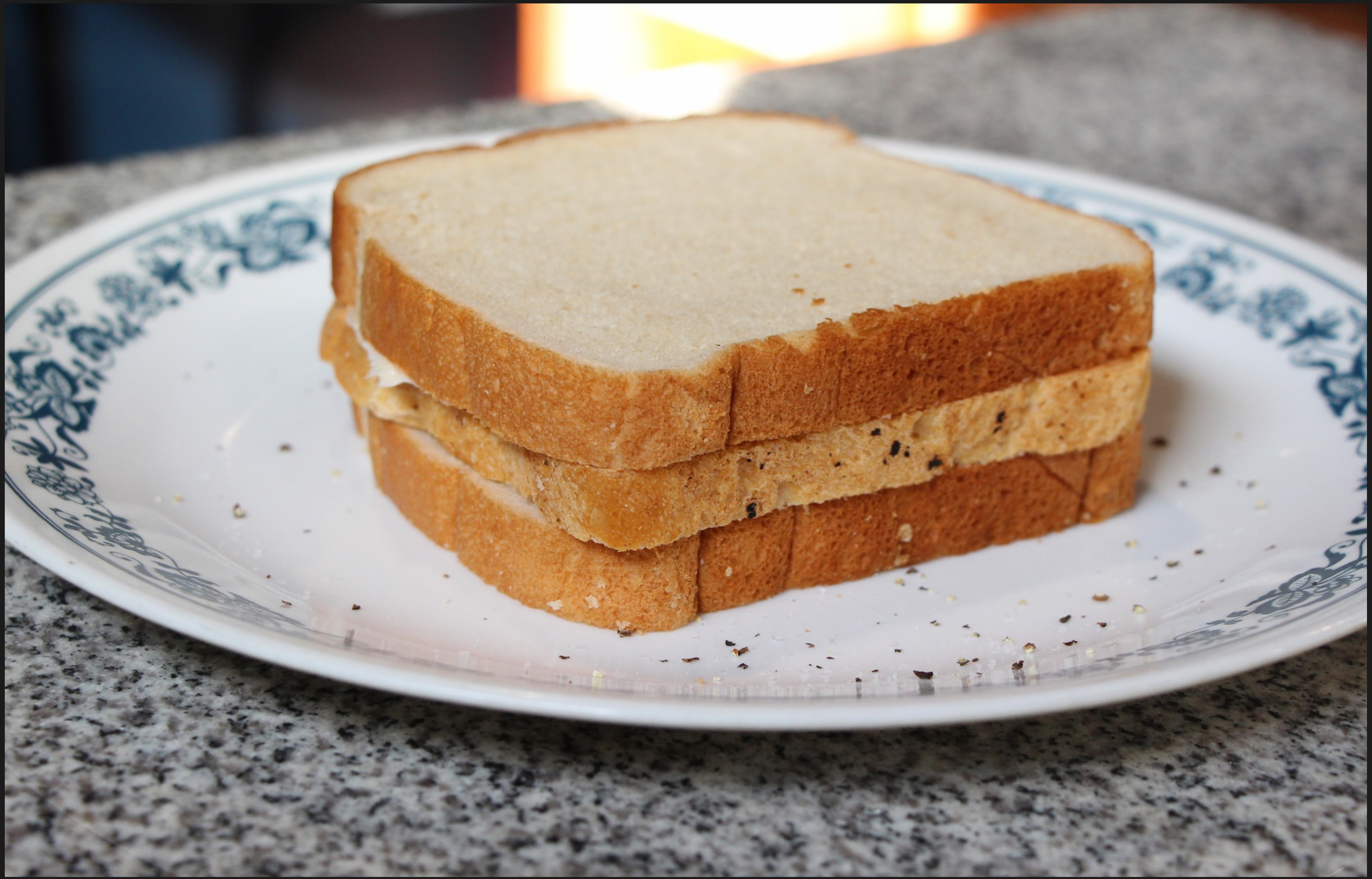

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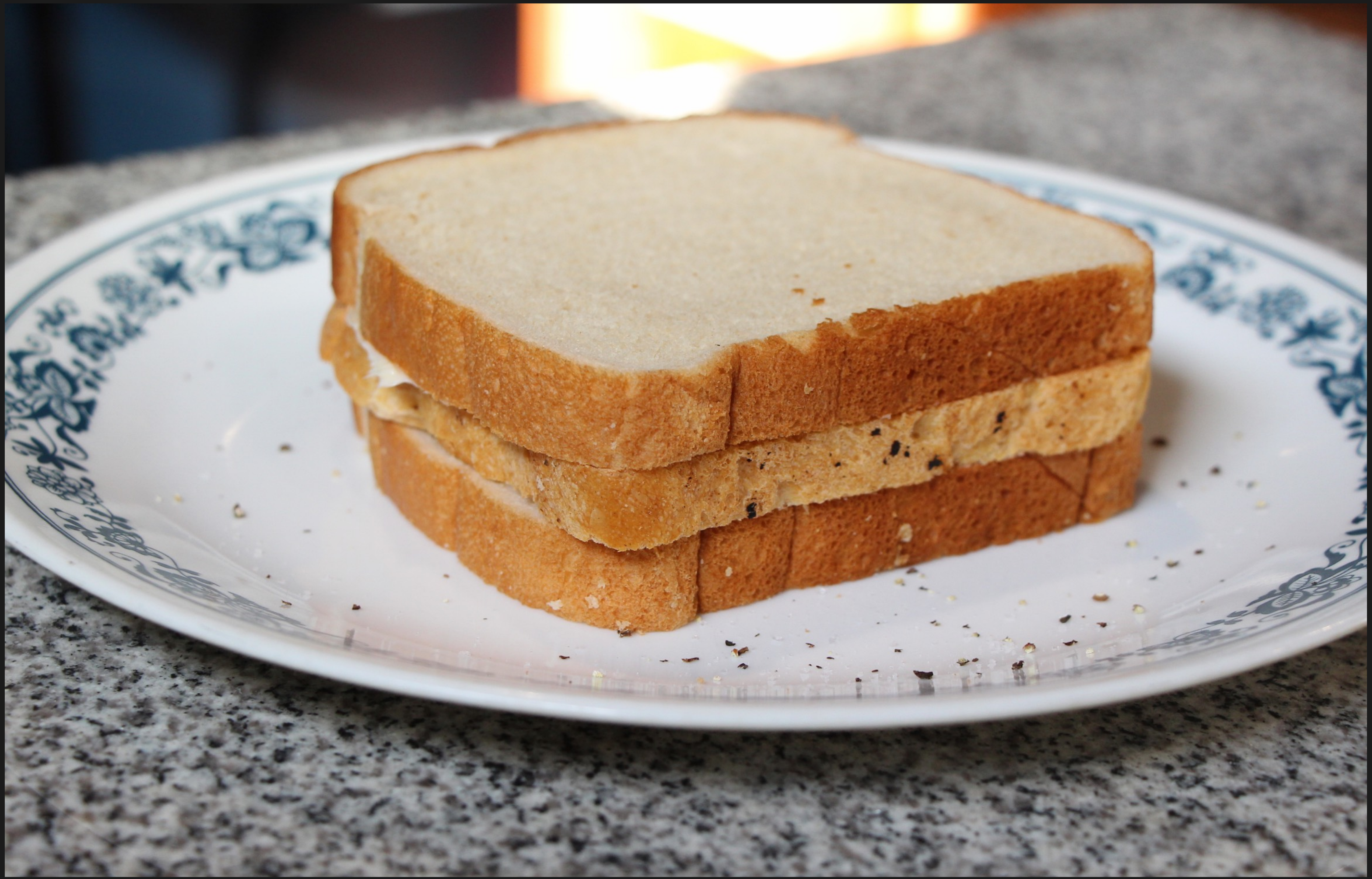

Fig 1. Toast sandwich / tandem mirror

so add more mirrors

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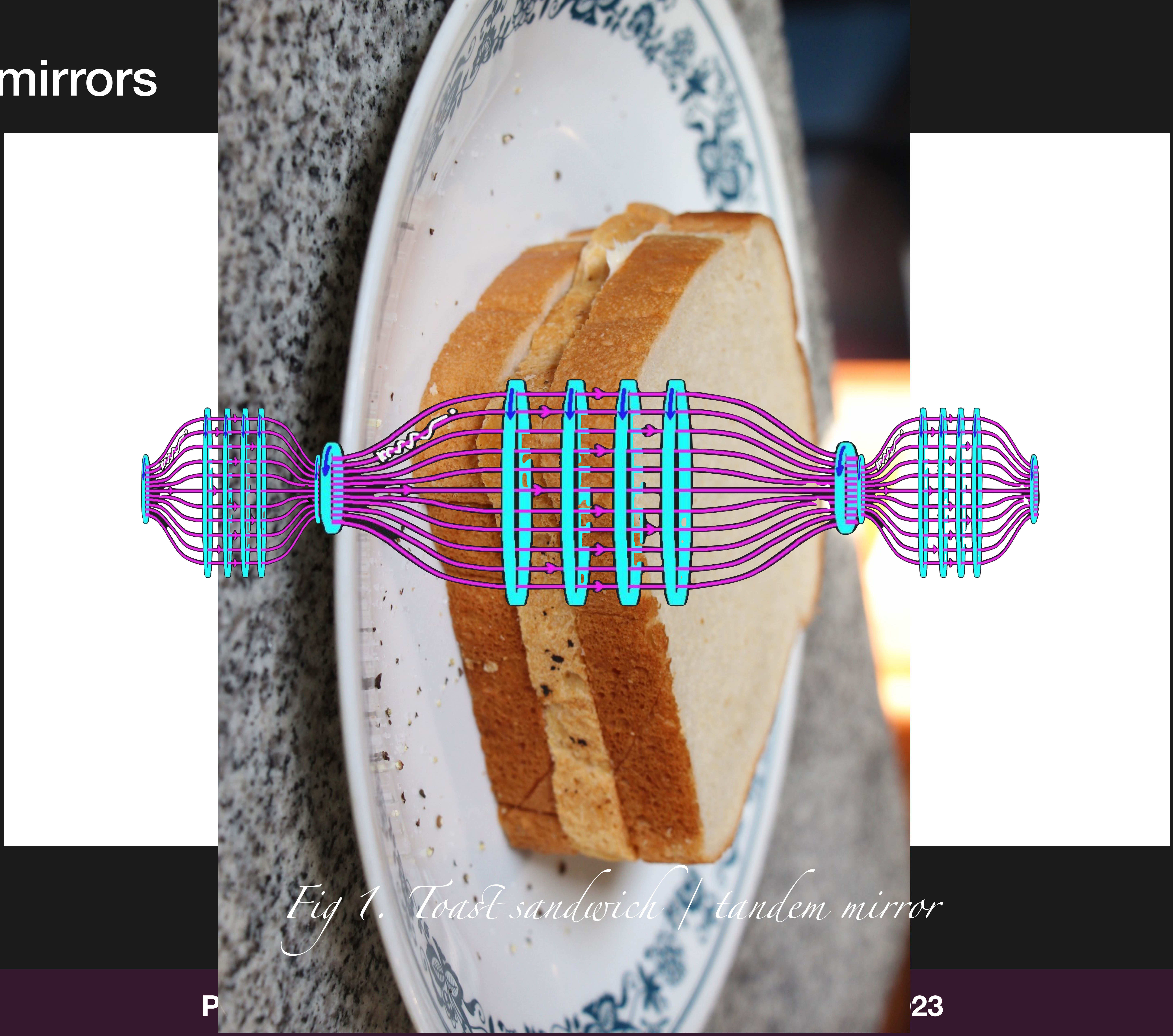

Fig 1. Toast sandwich / tandem mirror

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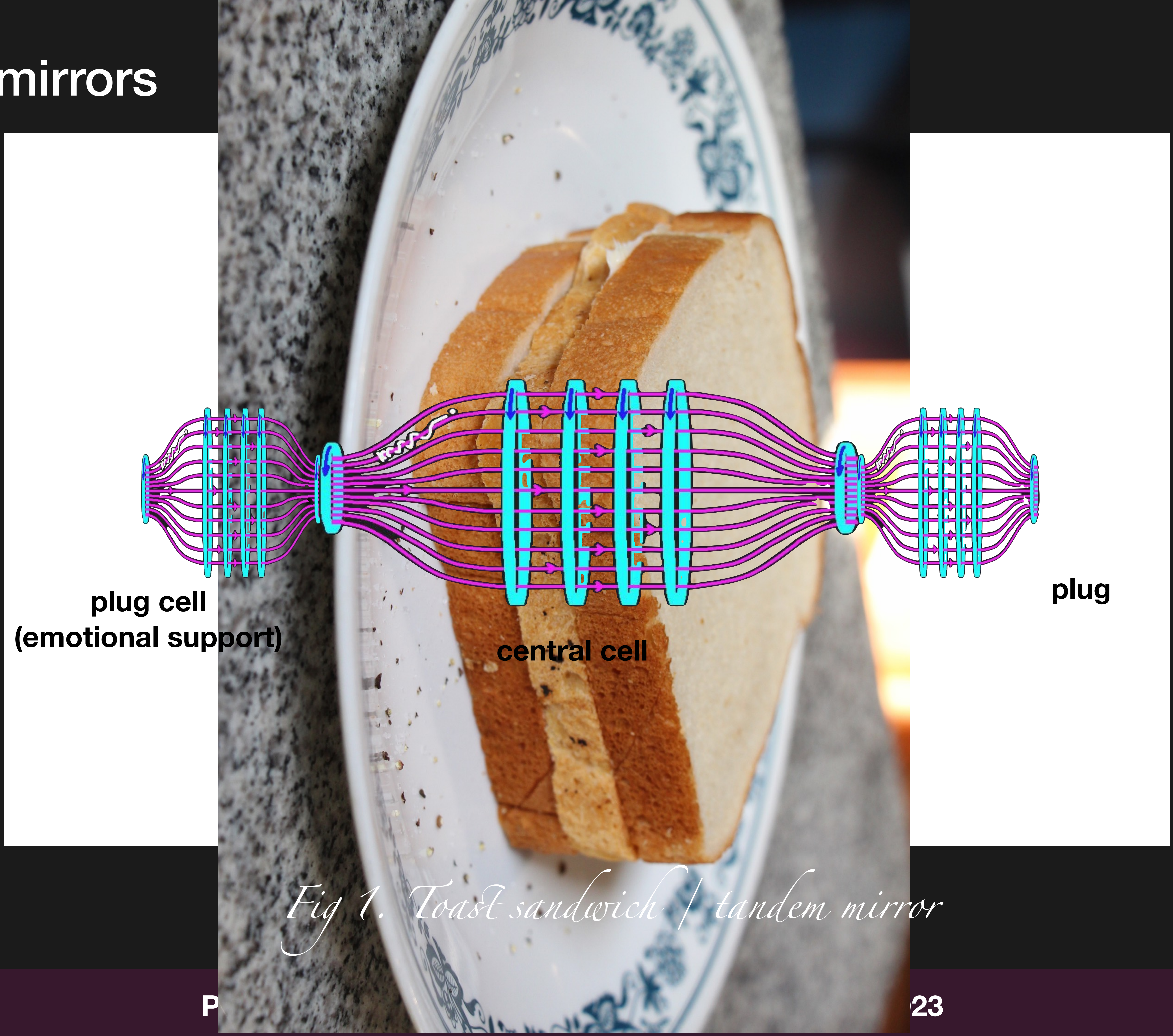

Fig 1. Toast sandwich / tandem mirror

Let’s optimize that tandem

It does okay

Let's optimize that tandem

Cost function:

```
(9.42477796076938e-17*B_cc*B_p**2*B_pm*L_cc*Te*beta*n_ccr*r_b**2*(1 - Te/511)/(4.02670907669414e-22*Te + 4.02670907669414e-22*Ti) +
795774715.026276*B_cc*L_cc*cost_HTS_kAm*(6.28318530717959*a_wall_r*r_b*sqrt(B_pm/B_cc) + 6.28318530717959*d_blanket + 6.28318530717959*d_vv)/
coil_spacing_cc + 32995390.6601843*pi*B_p**3*B_pm*L_p*sqrt(Te)*Z_eff*beta**2*r_b**2/(Te + Ti)**2 + 3.0e-17*pi*B_p**3*B_pm*L_p*Te*beta*r_b**2*(1 - Te/511)/
(4.02670907669414e-22*Te + 4.02670907669414e-22*Ti) + 8.01088317e-16*pi*B_p*B_pm*Eb*L_p*beta*r_b**2*(4.16666666666667e-17*B_p**2*beta*log(10)/
(Eb**1.5*(4.02670907669414e-22*Te + 4.02670907669414e-22*Ti)*log(B_pm/(B_p*sqrt(1 - beta)))) + 0.296691351241568*Te*sqrt(Ti)/(B_p*B_pm*r_b**2))/
(4.02670907669414e-22*Te + 4.02670907669414e-22*Ti) + 1591549430.05255*B_pm*cost_HTS_kAm*(a_wall_r*r_b + d_blanket +
d_vv)*(6.28318530717959*a_wall_r*r_b + 6.28318530717959*d_blanket + 6.28318530717959*d_vv) +
1591549430.05255*B_pm*cost_HTS_kAm*(a_wall_r*r_b*sqrt(B_pm/B_p) + d_blanket + d_vv)*(6.28318530717959*a_wall_r*r_b*sqrt(B_pm/B_p) +
6.28318530717959*d_blanket + 6.28318530717959*d_vv) + 103658076.90036*B_p**4*B_pm*L_cc*sqrt(Te)*Z_eff*beta**2*n_ccr**2*r_b**2/(B_cc*(Te + Ti)**2) +
7.55007951469143e-15*B_p**2*B_pm*L_cc*beta*n_ccr*r_b**2*(Te*Te_ccr + Te*Ti_ccr)*(8.0e-17*B_p**2*Z_eff**4*beta*n_ccr/
(sqrt(mu)*(Te*Ti_ccr)**1.5*(4.02670907669414e-22*Te + 4.02670907669414e-22*Ti)*(1/n_ccr)**(1/Ti_ccr)*log(1/n_ccr)*log(1 + 2*B_pm/(B_cc*sqrt(1 - Piecewise((0.9,
4.0267e-22*B_p**2*beta*n_ccr*(Te*Te_ccr + Te*Ti_ccr)/(B_cc**2*(4.02670907669414e-22*Te + 4.02670907669414e-22*Ti)) > 0.9),
(4.0267e-22*B_p**2*beta*n_ccr*(Te*Te_ccr + Te*Ti_ccr)/(B_cc**2*(4.02670907669414e-22*Te + 4.02670907669414e-22*Ti)), True)))))) +
0.296691351241568*Te*Te_ccr*sqrt(Te*Ti_ccr)/(B_cc*B_pm*r_b**2))/(B_cc*(4.02670907669414e-22*Te + 4.02670907669414e-22*Ti)))/
(-8.421040388304e-17*pi*B_p*B_pm*Eb*Ef_NBI*L_p*beta*r_b**2*(4.16666666666667e-17*B_p**2*beta*log(10)/(Eb**1.5*(4.02670907669414e-22*Te +
4.02670907669414e-22*Ti)*log(B_pm/(B_p*sqrt(1 - beta)))) + 0.296691351241568*Te*sqrt(Ti)/(B_p*B_pm*r_b**2))/(4.02670907669414e-22*Te +
4.02670907669414e-22*Ti) + 262800*Ef_DEC*(1.72921317451384e+24*pi*B_p**3*B_pm*DD_reac*L_p*beta**2*r_b**2*(1 - T_frac)**2/(Te + Ti)**2 +
6.91684313304943e+24*pi*B_p**3*B_pm*DT_reac*L_p*T_frac*beta**2*r_b**2*(1 - T_frac)/(Te + Ti)**2 + 82343.3706315408*pi*B_p**3*B_pm*L_p*beta**2*r_b**2*(Eb -
Te)*log(10)/(Eb**1.5*(Te + Ti)**2*log(B_pm/(B_p*sqrt(1 - beta)))) + 2.71624170277168e+24*B_p**4*B_pm*DD_reac*L_cc*beta**2*n_ccr**2*r_b**2*(1 - T_frac)**2/(B_cc*(Te
+ Ti)**2) + 1.08649517864105e+25*B_p**4*B_pm*DT_reac*L_cc*T_frac*beta**2*n_ccr**2*r_b**2*(1 - T_frac)/(B_cc*(Te + Ti)**2) +
6.04006361175315e-38*B_p**4*B_pm*L_cc*Z_eff**4*beta**2*n_ccr**2*r_b**2*(6.16736274022137e+42/(Te + Ti)**2)*(Te*Te_ccr + Te*Ti_ccr)/
(B_cc*sqrt(mu)*(Te*Ti_ccr)**1.5*(1/n_ccr)**(1/Ti_ccr)*log(1/n_ccr)*log(1 + 2*B_pm/(B_cc*sqrt(1 - Piecewise((0.9, 4.0267e-22*B_p**2*beta*n_ccr*(Te*Te_ccr + Te*Ti_ccr)/
(B_cc**2*(4.02670907669414e-22*Te + 4.02670907669414e-22*Ti)) > 0.9), (4.0267e-22*B_p**2*beta*n_ccr*(Te*Te_ccr + Te*Ti_ccr)/(B_cc**2*(4.02670907669414e-22*Te
+ 4.02670907669414e-22*Ti)), True))))))) - 262800*Ef_ECH*(9.42477796076938e-24*B_cc*B_p**2*B_pm*L_cc*Te*beta*n_ccr*r_b**2*(1 - Te/511)/
(4.02670907669414e-22*Te + 4.02670907669414e-22*Ti) + 6.59907813203687*pi*B_p**3*B_pm*L_p*sqrt(Te)*Z_eff*beta**2*r_b**2/(Te + Ti)**2 +
6.0e-24*pi*B_p**3*B_pm*L_p*Te*beta*r_b**2*(1 - Te/511)/(4.02670907669414e-22*Te + 4.02670907669414e-22*Ti) +
10.365807690036*B_p**4*B_pm*L_cc*sqrt(Te)*Z_eff*beta**2*n_ccr**2*r_b**2/(B_cc*(Te + Ti)**2) +
7.55007951469143e-22*B_p**2*B_pm*L_cc*beta*n_ccr*r_b**2*(Te*Te_ccr + Te*Ti_ccr)*(8.0e-17*B_p**2*Z_eff**4*beta*n_ccr/
(sqrt(mu)*(Te*Ti_ccr)**1.5*(4.02670907669414e-22*Te + 4.02670907669414e-22*Ti)*(1/n_ccr)**(1/Ti_ccr)*log(1/n_ccr)*log(1 + 2*B_pm/(B_cc*sqrt(1 - Piecewise((0.9,
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0.296691351241568*Te*Te_ccr*sqrt(Te*Ti_ccr)/(B_cc*B_pm*r_b**2))/(B_cc*(4.02670907669414e-22*Te + 4.02670907669414e-22*Ti))) +
262800*Ef_TE*(8.176696703712e+24*pi*B_p**3*B_pm*DD_reac*L_p*beta**2*r_b**2*(1 - T_frac)**2/(Te + Ti)**2 +
2.78649966217134e+25*pi*B_p**3*B_pm*DT_reac*L_p*T_frac*beta**2*r_b**2*(1 - T_frac)/(Te + Ti)**2 + (1 -
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+ 4.02670907669414e-22*Ti)), True))))))) + 1.28439251475068e+25*B_p**4*B_pm*DD_reac*L_cc*beta**2*n_ccr**2*r_b**2*(1 - T_frac)**2/(B_cc*(Te + Ti)**2) +
4.37702343395396e+25*B_p**4*B_pm*DT_reac*L_cc*T_frac*beta**2*n_ccr**2*r_b**2*(1 - T_frac)/(B_cc*(Te + Ti)**2)))
```

It does okay

Let’s optimize that tandem

- Cost function

$$\mathscr{C} = \frac{\text{Magnet cost} + \text{heating cost}}{\text{Electric energy produced}}$$

- No blanket / structure costs (yet)

It does okay

Future work: a one-man differentiable reactor design study. haha, jk… unless…?

- Near term
  - Add sanity checks (e.g., magnet structure loads, NBI shine-through)
  - Improve mirror cell particle + energy balance
  - Improve plug confinement time estimates
  - Include instability mitigation in optimization
    - DCLC, interchange (pretty much solved)
  - Incorporate better radial transport model (still an open question)
  - Implement thermal barrier tandem mirrors (enhances axial confinement)
  - Do a bunch of parameter scans (over things like Z_{eff})
- Long term: automating reactor design

thanks

- bottom text

not my dog but she's hella cute