Mitigation of the hose instability in plasma wakefield accelerators

3rd European Advanced Accelerator Concepts Workshop

September 27, 2017

Timon J. Mehrling[1,2,3]

A. Martinez de la Ossa[2], R. A. Fonseca[3], J. Osterhoff[1], J. Vieira[3]

[1] Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, 22603 Hamburg, Germany

[2] Universität Hamburg, Institut für Experimentalphysik, 22761 Hamburg, Germany

[3] GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, 1049-001 Lisboa, Portugal

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Content

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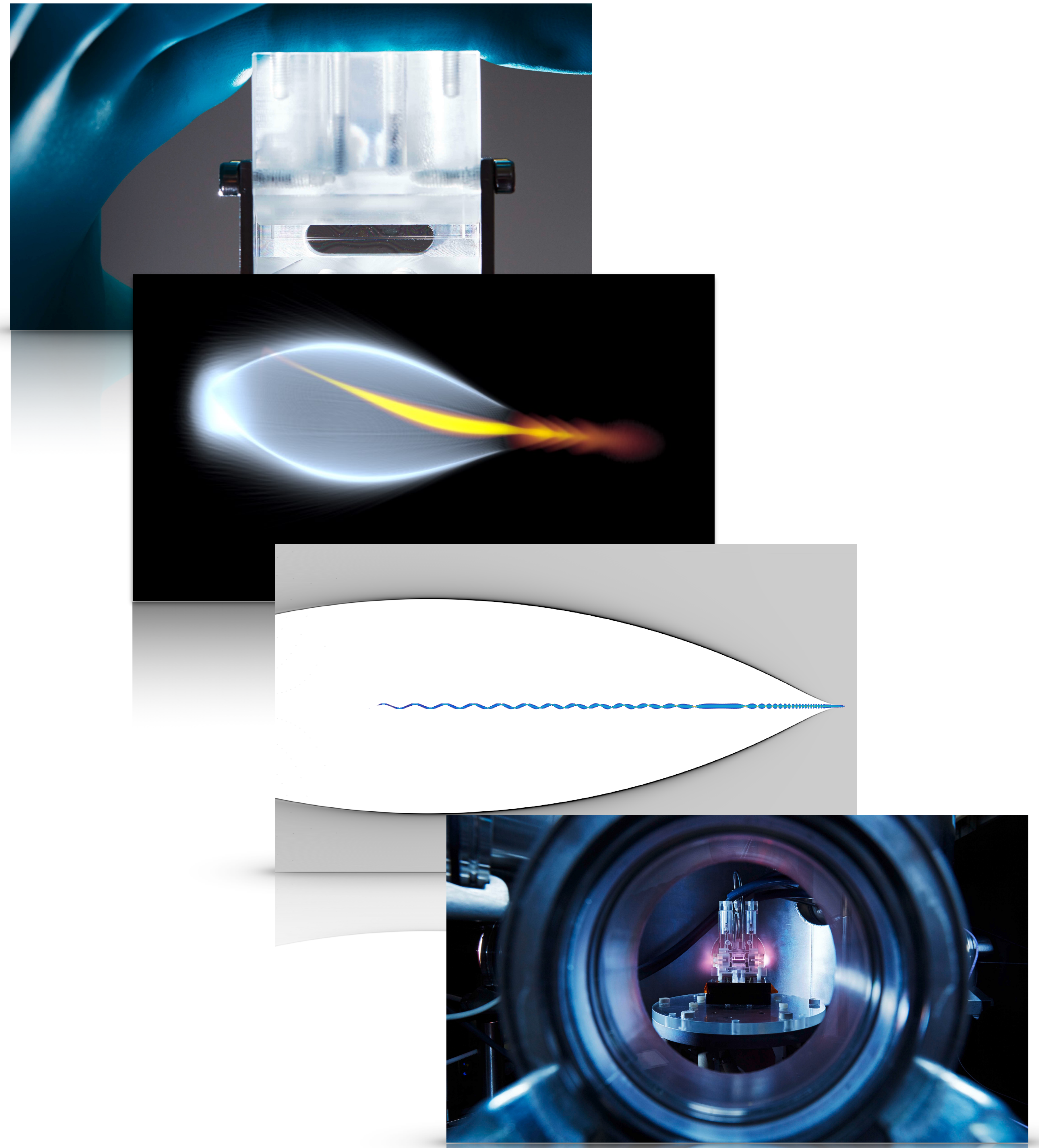
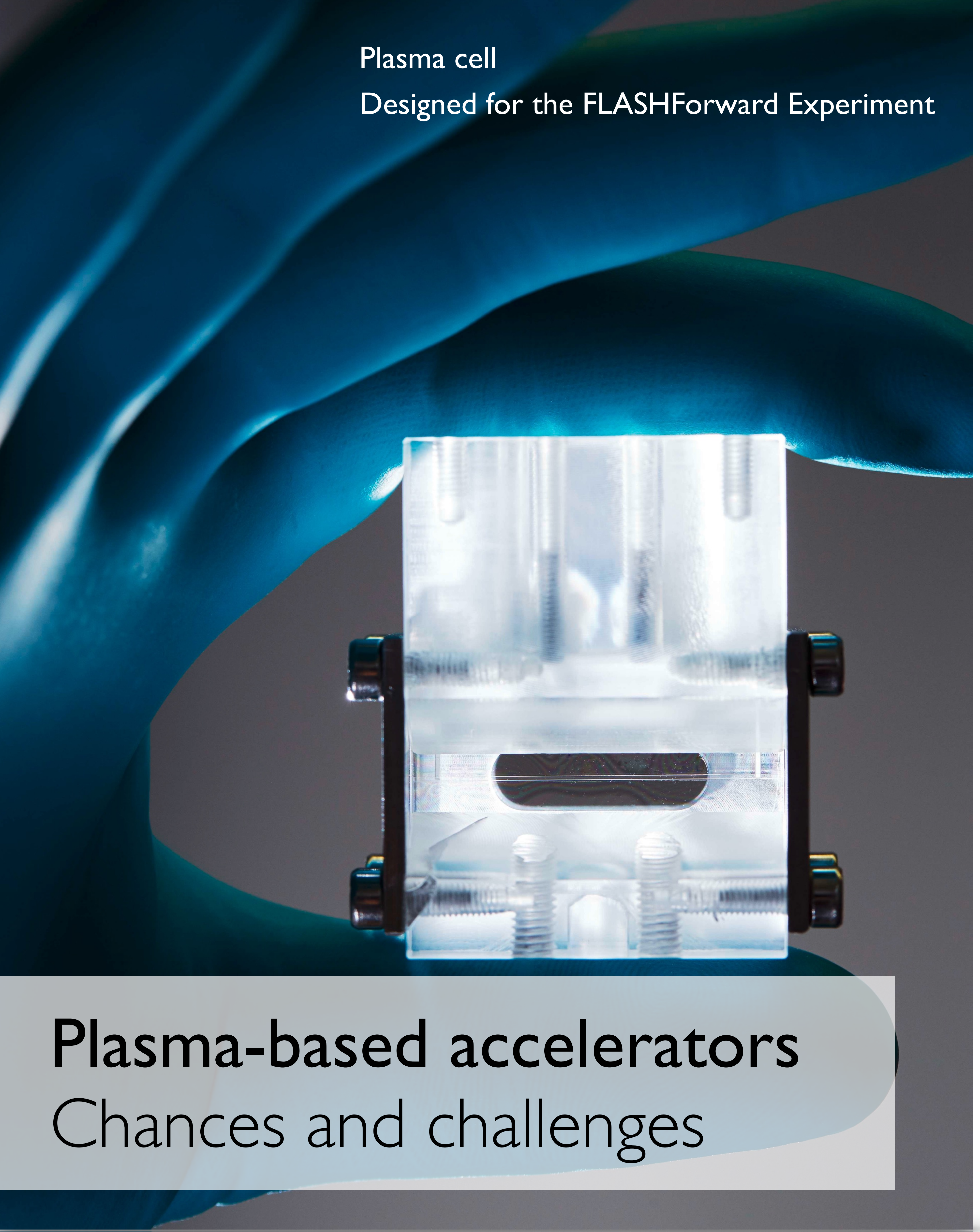


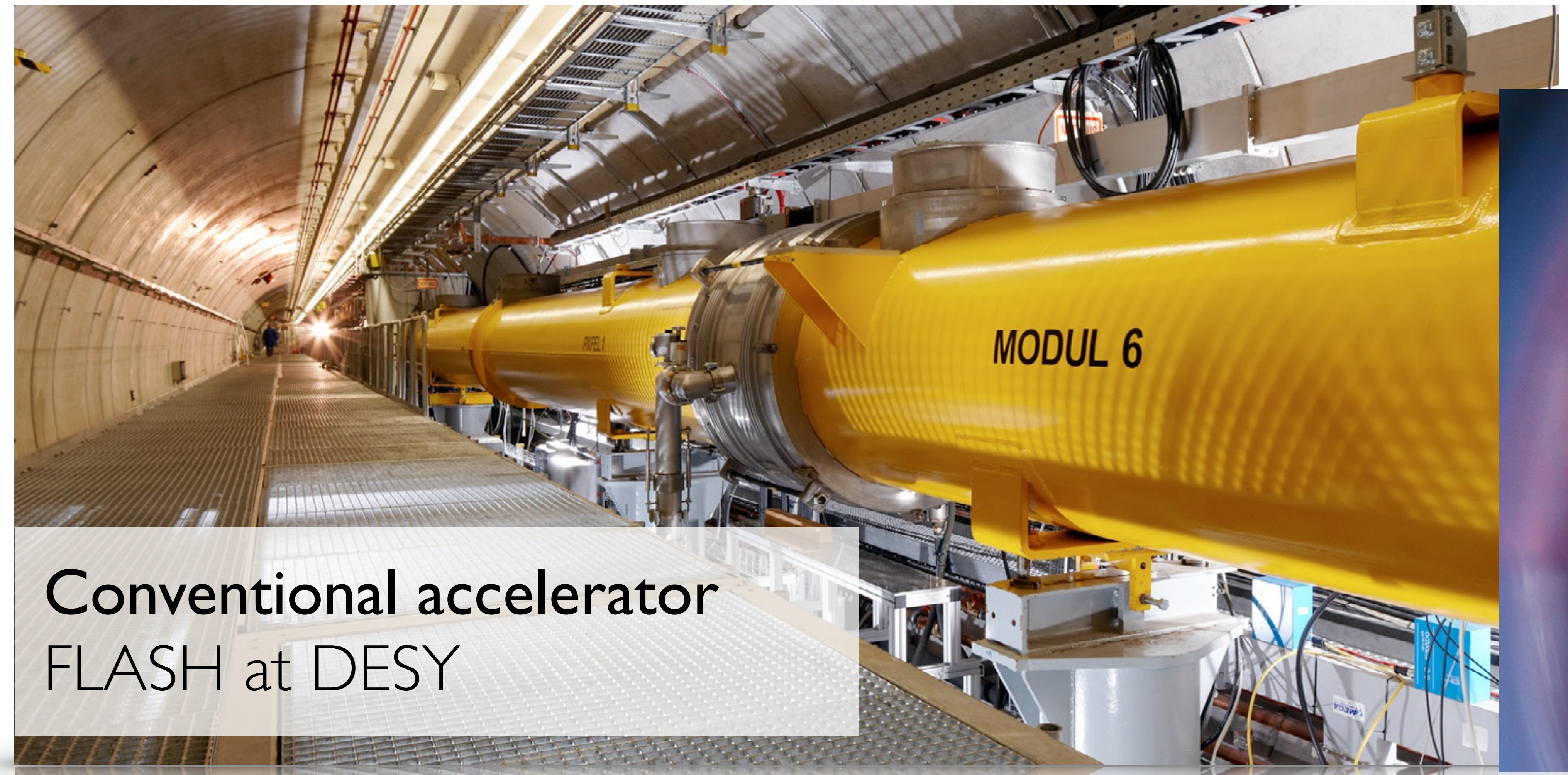
Plasma-based accelerators
Chances and challenges



Plasma cell
Designed for the FLASHForward Experiment

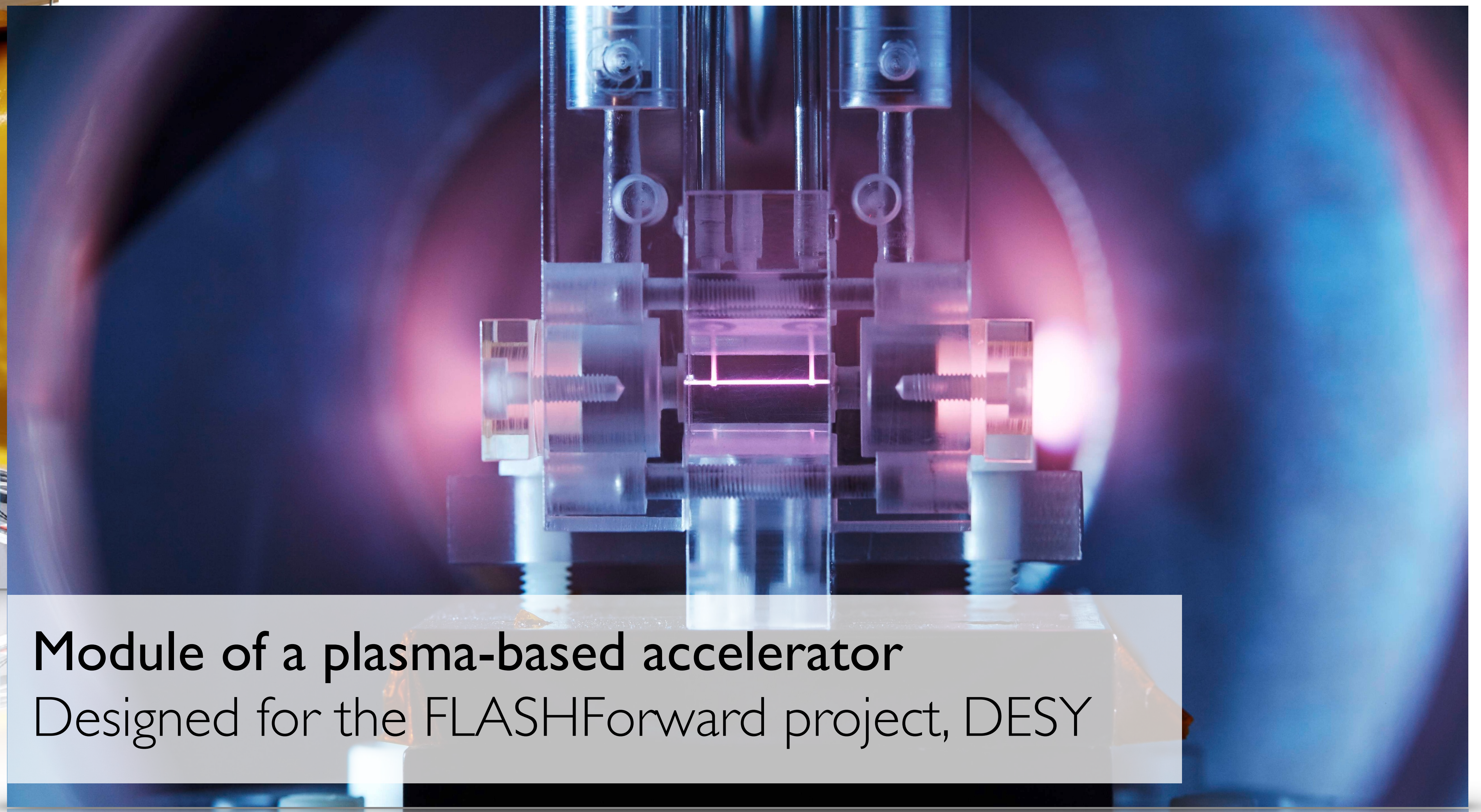
Miniaturisation with plasma-based accelerators

A key technology for future compact and affordable particle accelerators?



Conventional accelerator
FLASH at DESY

- Accelerating fields **~10-50 MV/m**
- Electrons accelerated to **~1GeV in ~80 m**

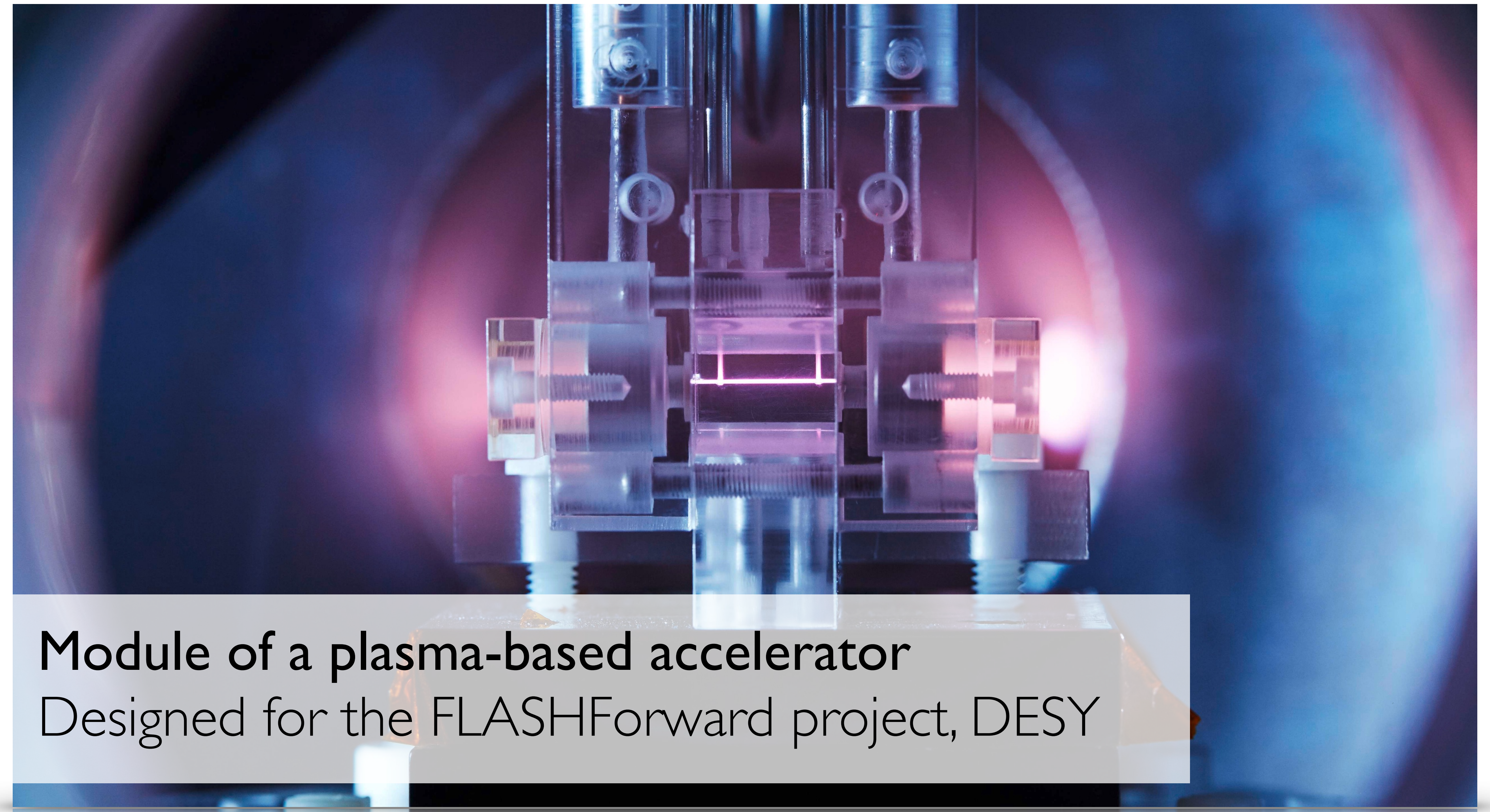


Module of a plasma-based accelerator
Designed for the FLASHForward project, DESY

- Accelerating fields **~10-100 GV/m**
- Electrons accelerated to **~1 GeV in ~1 cm**

Miniaturisation with plasma-based accelerators

A key technology for future compact and affordable particle accelerators?



Module of a plasma-based accelerator
Designed for the FLASHForward project, DESY

>> Accelerating fields **~10-100 GV/m**

>> Electrons accelerated to **~1 GeV in ~1 cm**

Chance: High energy gain on short distances

Plasma-based accelerators provide gradients > 10 GV/m

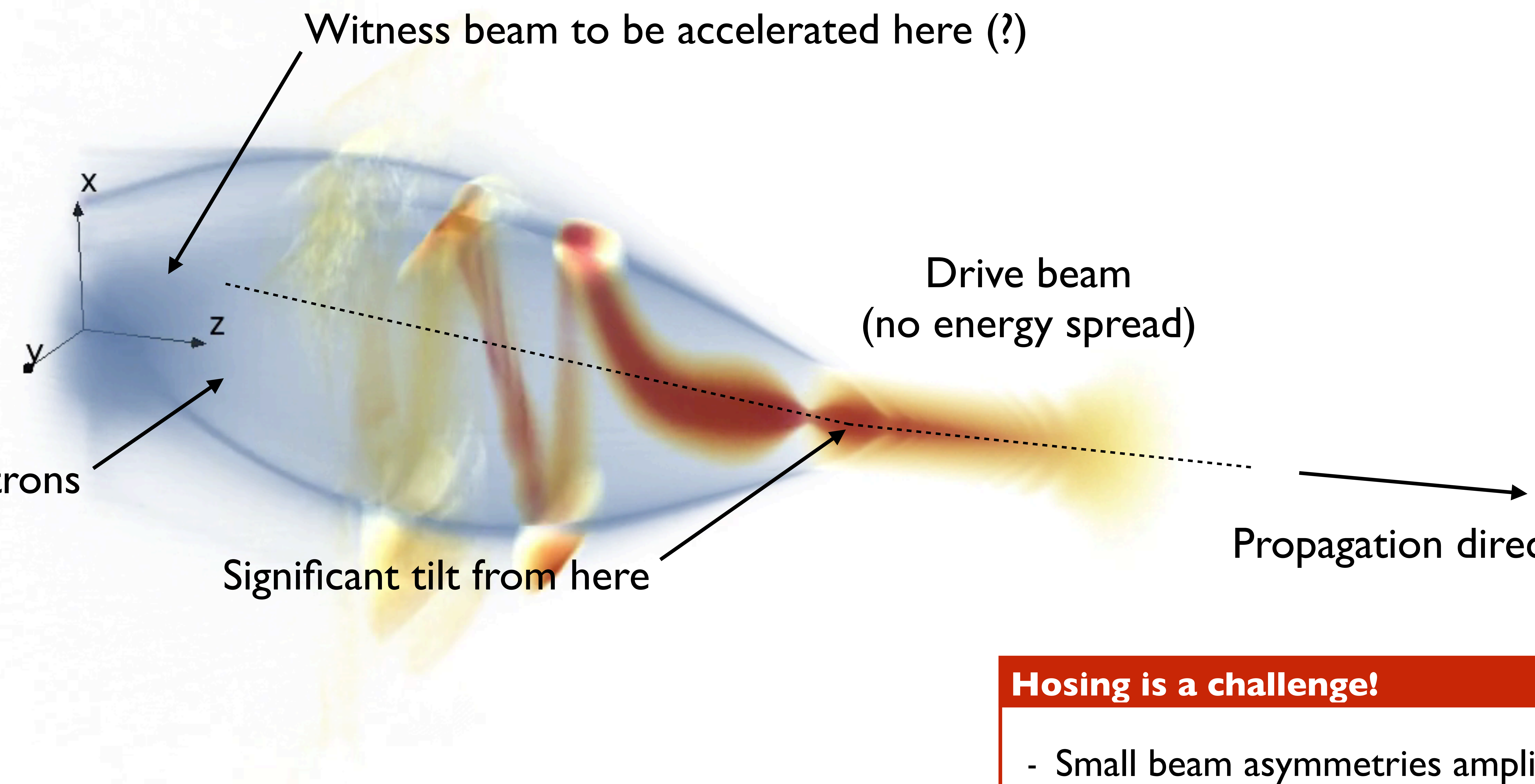
Challenge: Stability

Stability is of utmost importance for any application

Extreme focusing fields entail large growth rates for beam breakup instability!

Hose instability

Show-stopper for stable plasma wakefield accelerators?



HiPACE

Plasma wakefield acceleration with a tilted beam

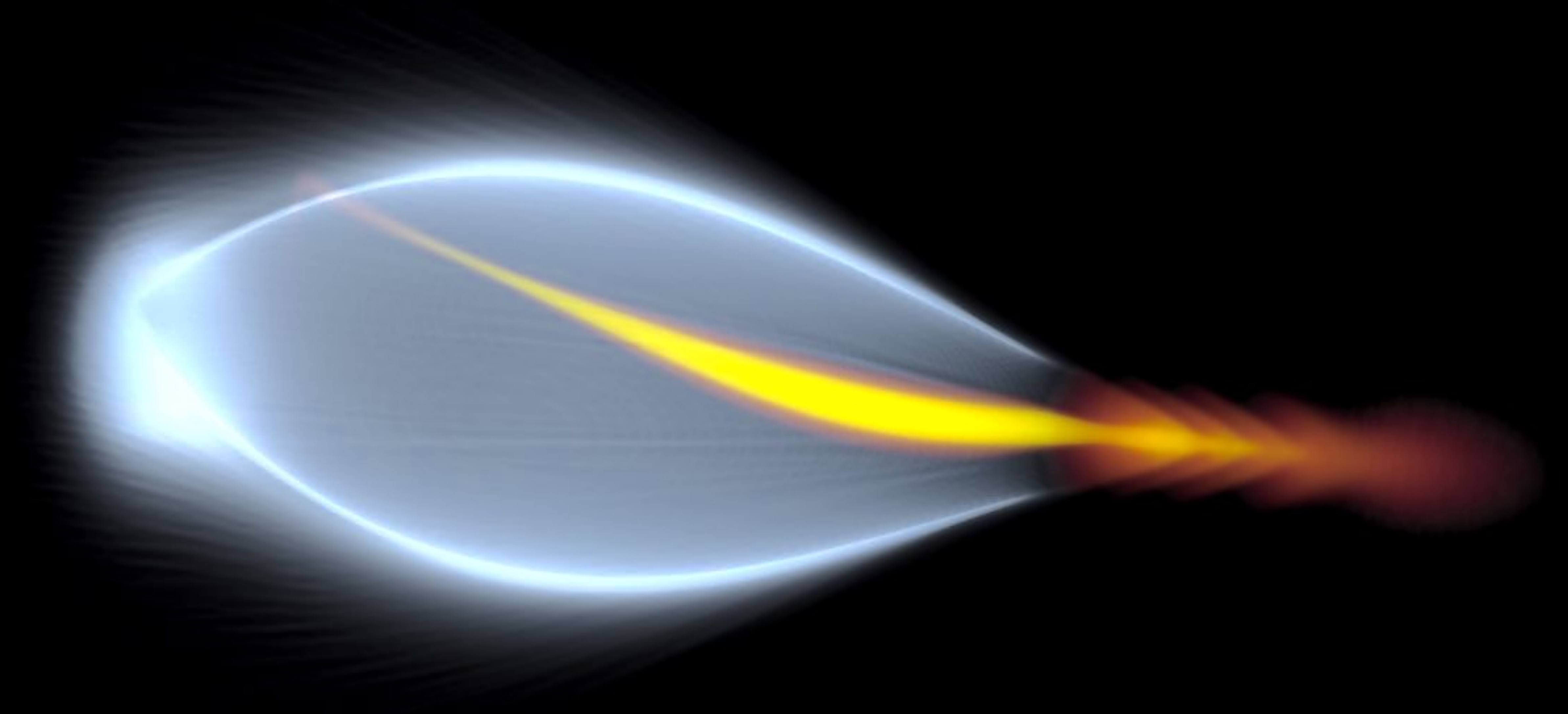
3D PIC simulation using the code HiPACE

Hosing is a challenge!

- Small beam asymmetries amplified $\Rightarrow$ Hosing
- Is beam breakup inevitable ?

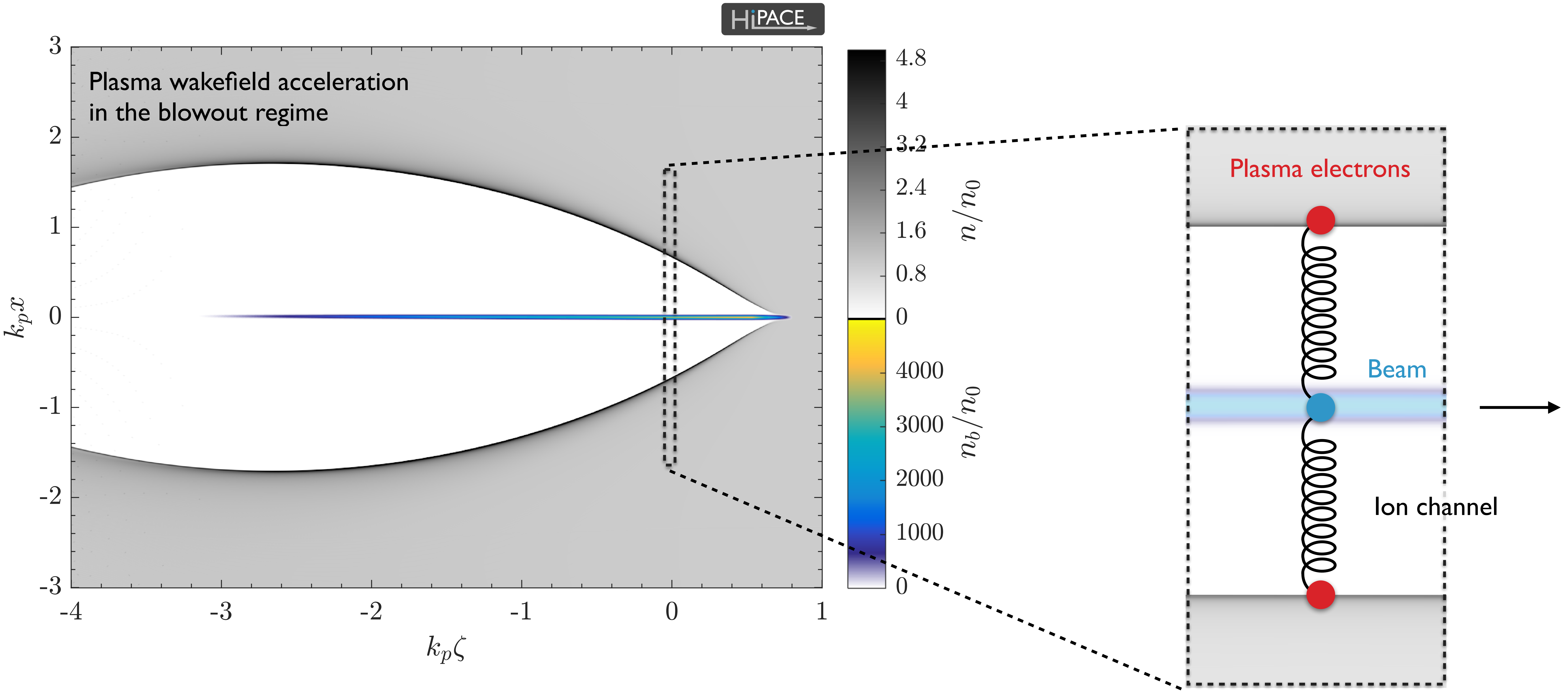
Hosing in Plasma Wakefield Acceleration

3D Simulation with the PIC code HiPACE



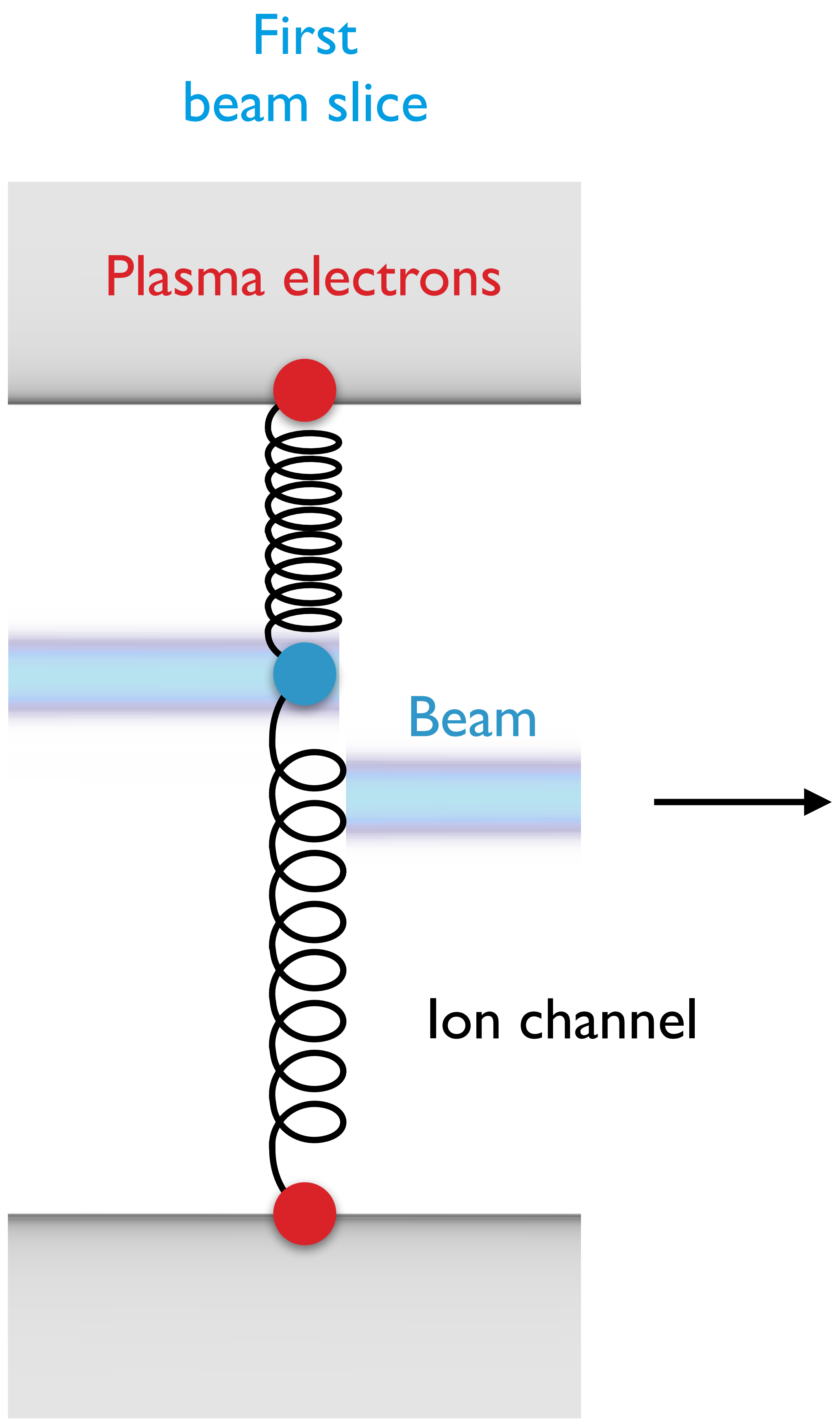
Hose instability
Show-stopper for stable plasma wakefield accelerators?

Basic mechanisms of hosing



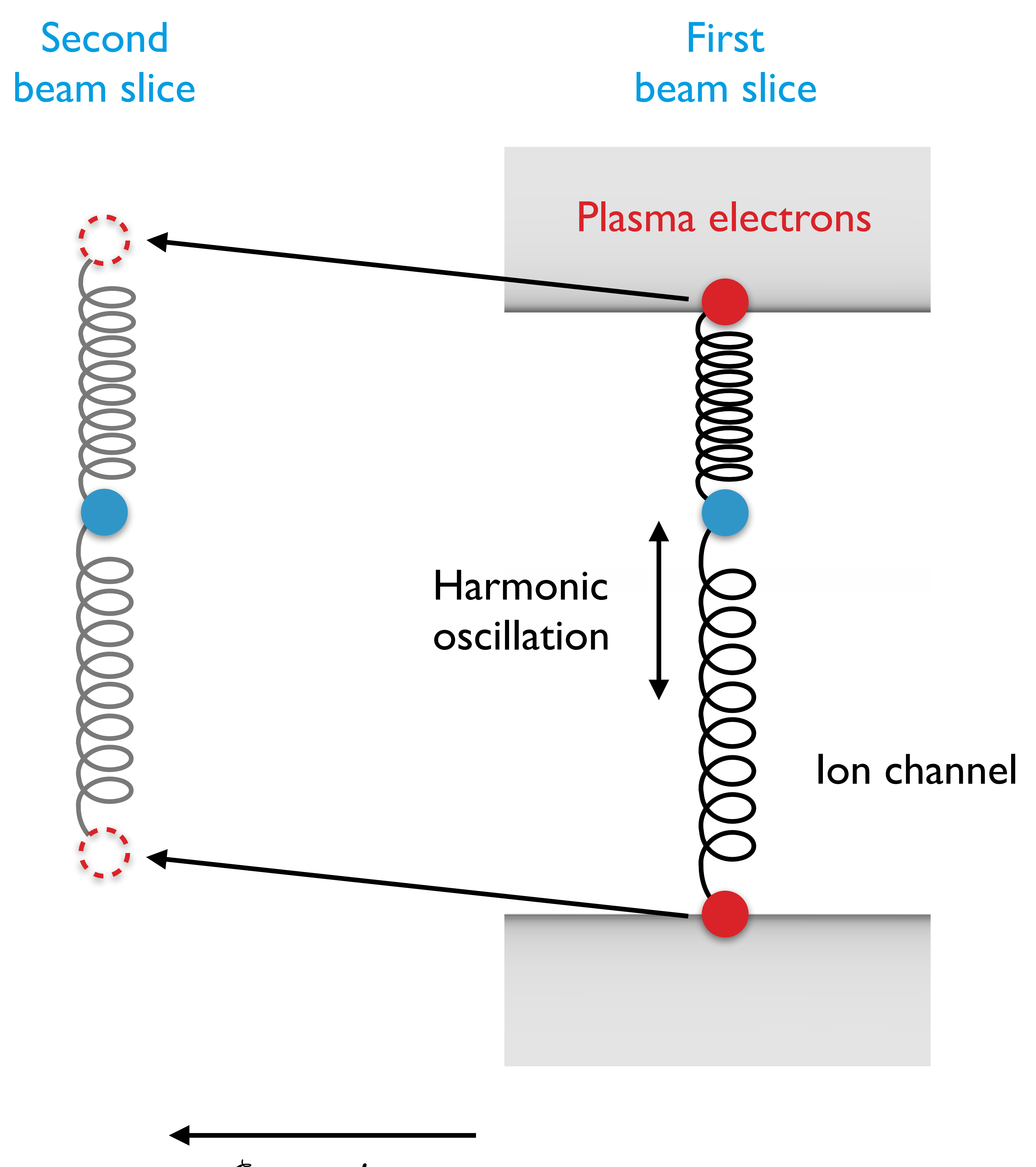
Basic mechanisms of hosing

Illustration with finite number of beam slices



Basic mechanisms of hosing

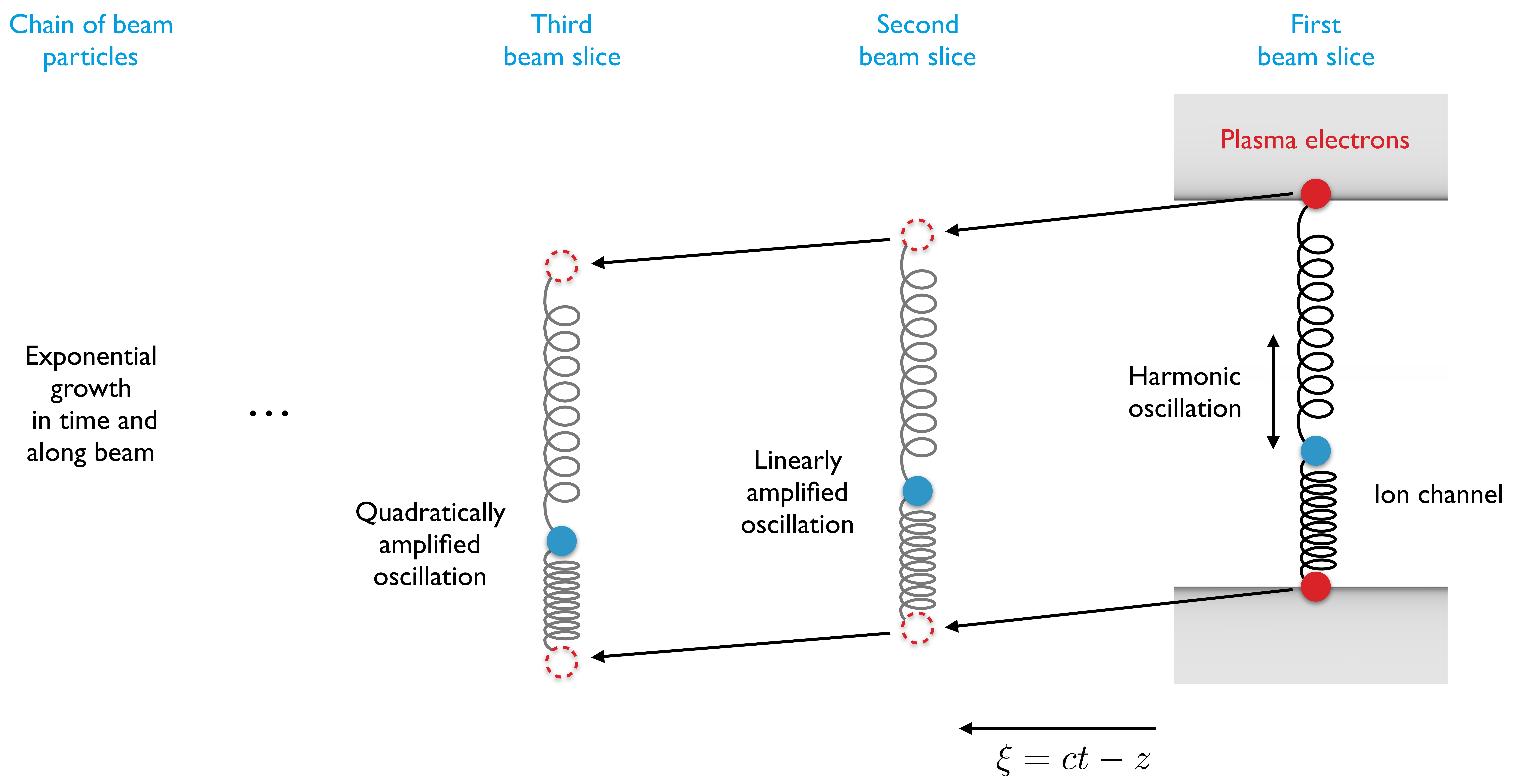
Illustration with finite number of beam slices



$\xi = ct - z$

Basic mechanisms of hosing

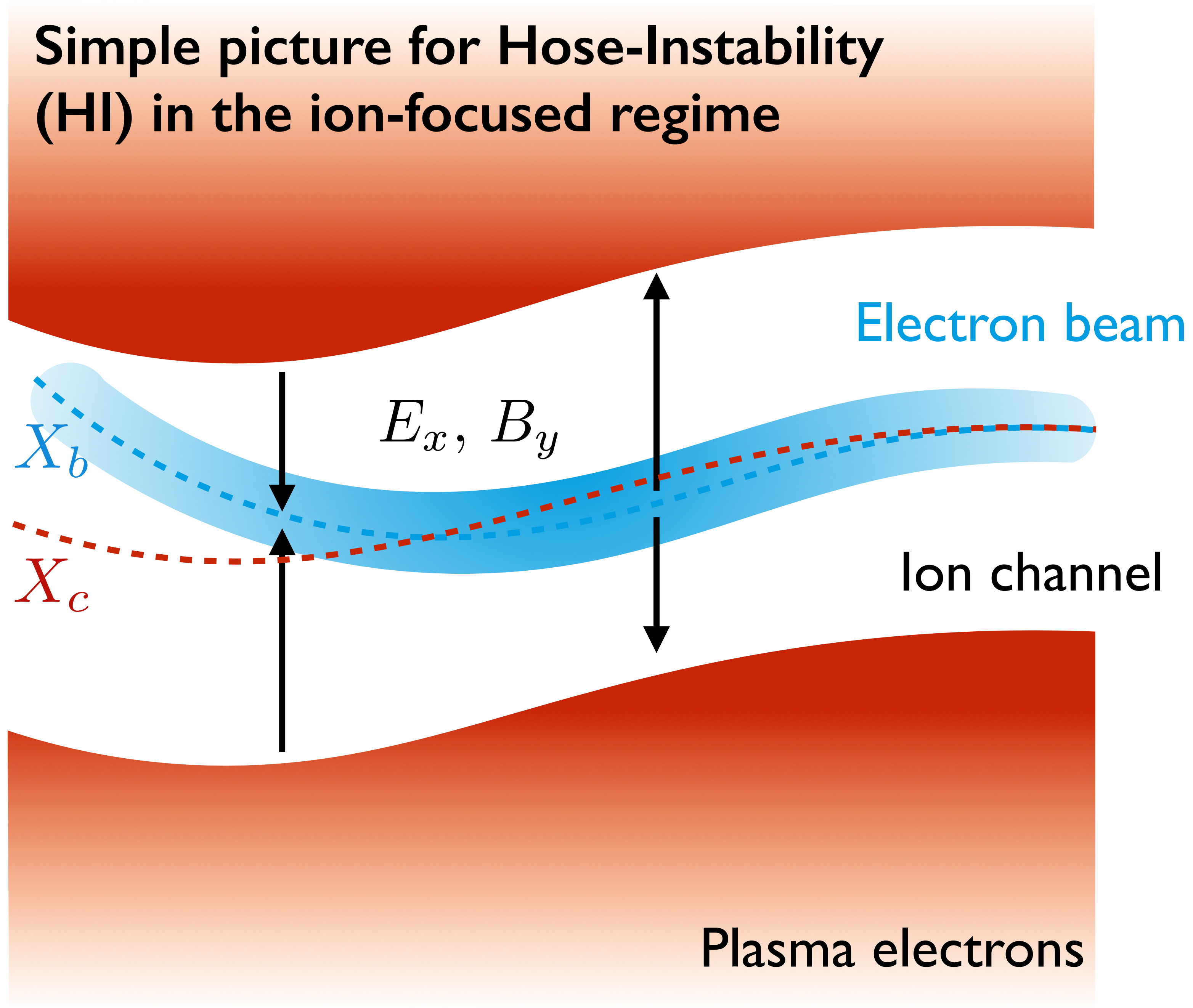
Illustration with finite number of beam slices



Hosing - a crucial challenge for PWFA

Seminal model predicts exponential growth of beam centroid deviations

Simple picture for Hose-Instability (HI) in the ion-focused regime



- Beam expels plasma electrons $\Rightarrow$ ion channel
- Beam centroid deviation X_b generates deviation of channel centroid X_c along beam
- X_c feeds back into temporal evolution of X_b

Centroid equations

Beam centroid equation

$$\frac{\partial^2 X_b}{\partial t^2} + \omega_\beta^2 (X_b - X_c) = 0$$

Betatron frequency in ion cavity:

$$\omega_\beta = \frac{\omega_p}{\sqrt{2\gamma}}$$

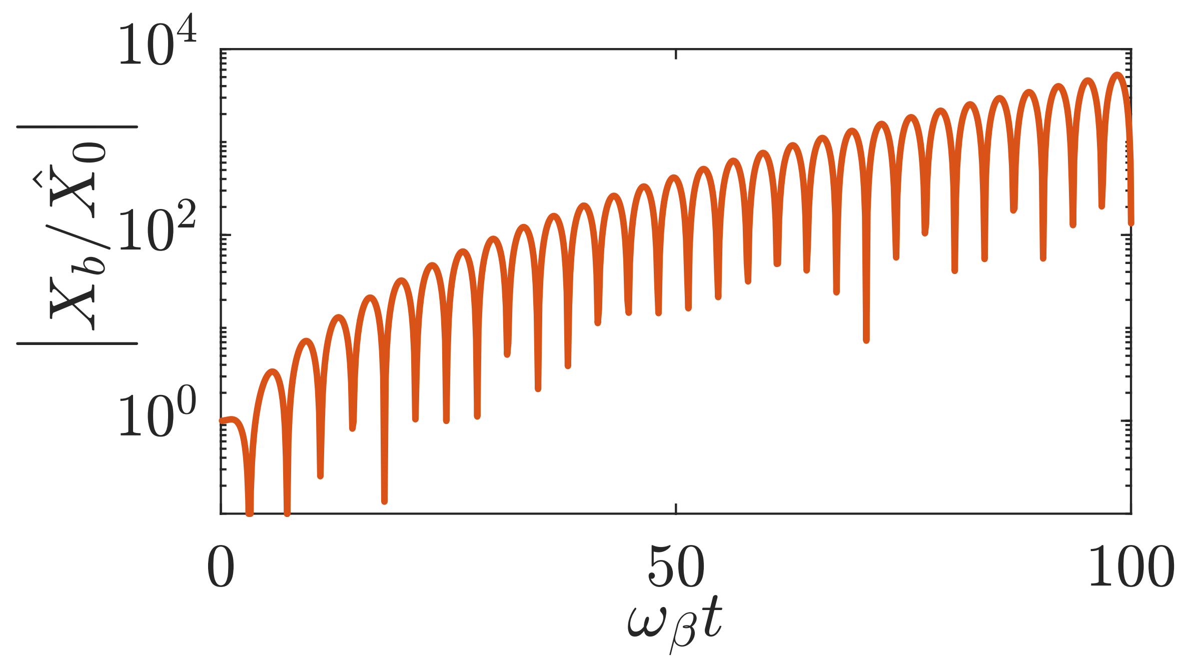
Channel centroid equation (adiabatic channel generation, non-relativistic)

$$\frac{\partial^2 X_c}{\partial \xi^2} + \frac{k_p^2}{2} (X_c - X_b) = 0 \qquad (\xi = ct - z)$$

D. H. Whittum, et al. Phys. Rev. Lett. 67, 991 (1991).

Seminal model: Dramatic implications for PWFA!

Whittum et al:
Centroid deviations amplified exponentially in time and along beam!



- Limited stable propagation
- Jitter of final beam parameters
- Emittance growth
- Beam breakup

Reviewing the basic mechanisms of hosing

Hose instability in a nutshell

In the hose instability,

transverse phase space

asymmetries

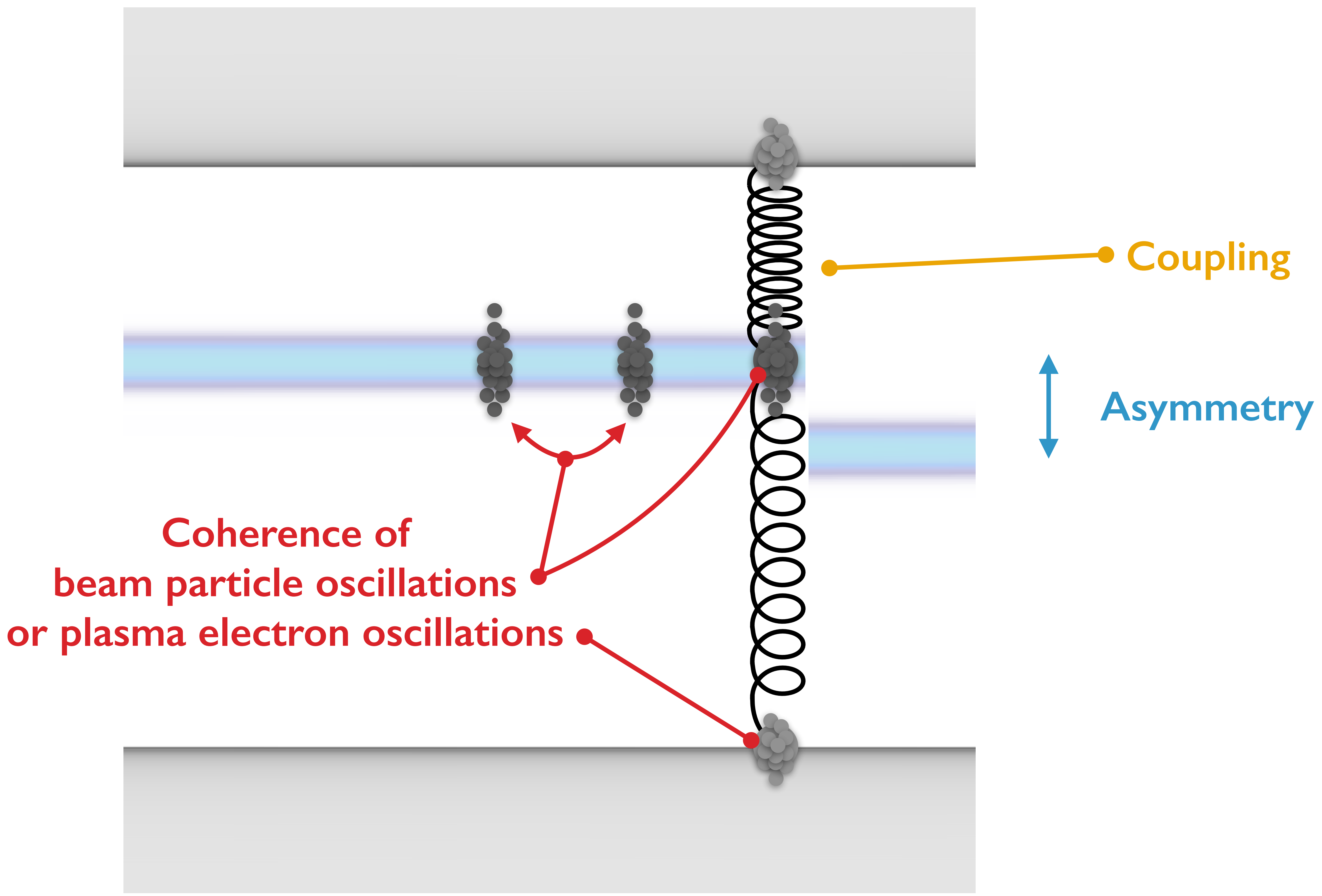
of beam particles

and plasma electrons are

coherently

coupled

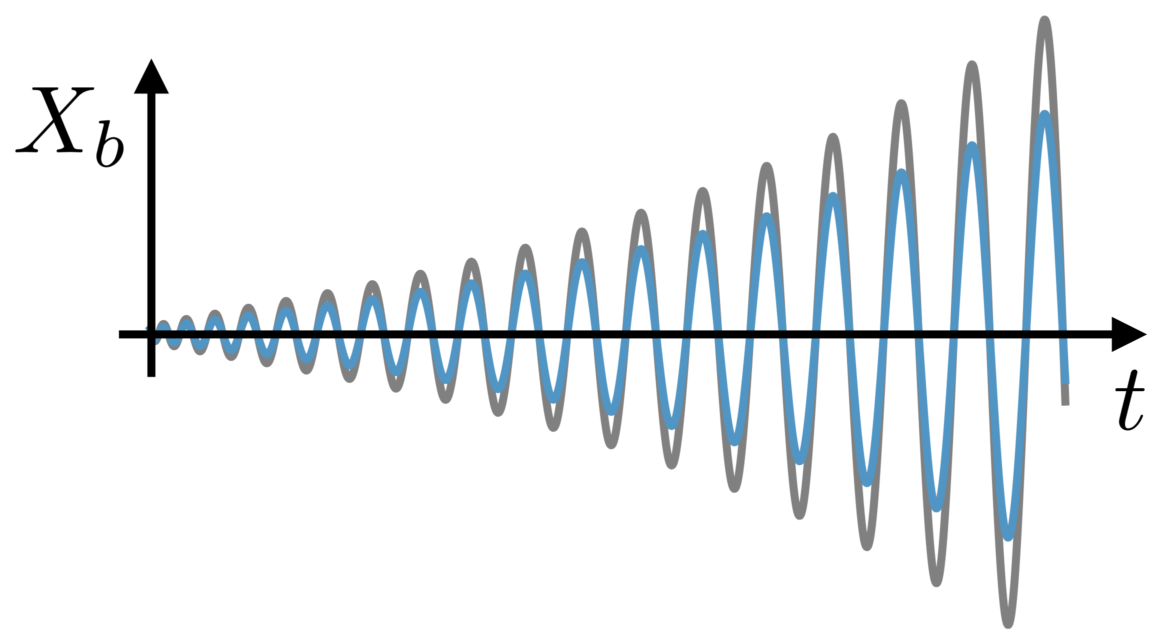
and thereby amplified.

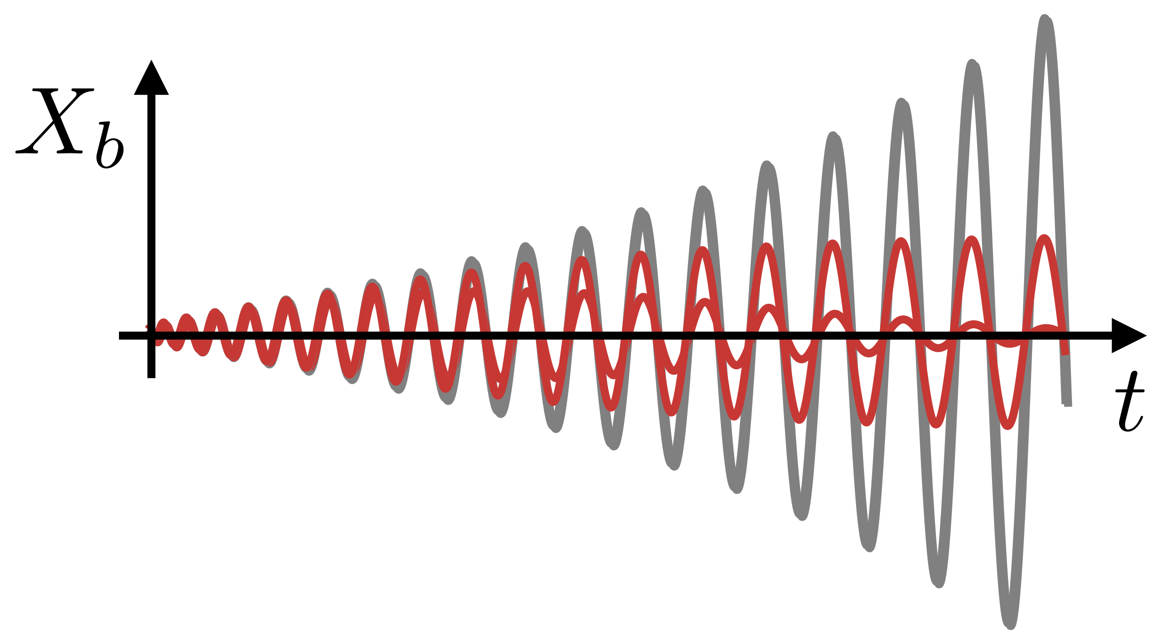


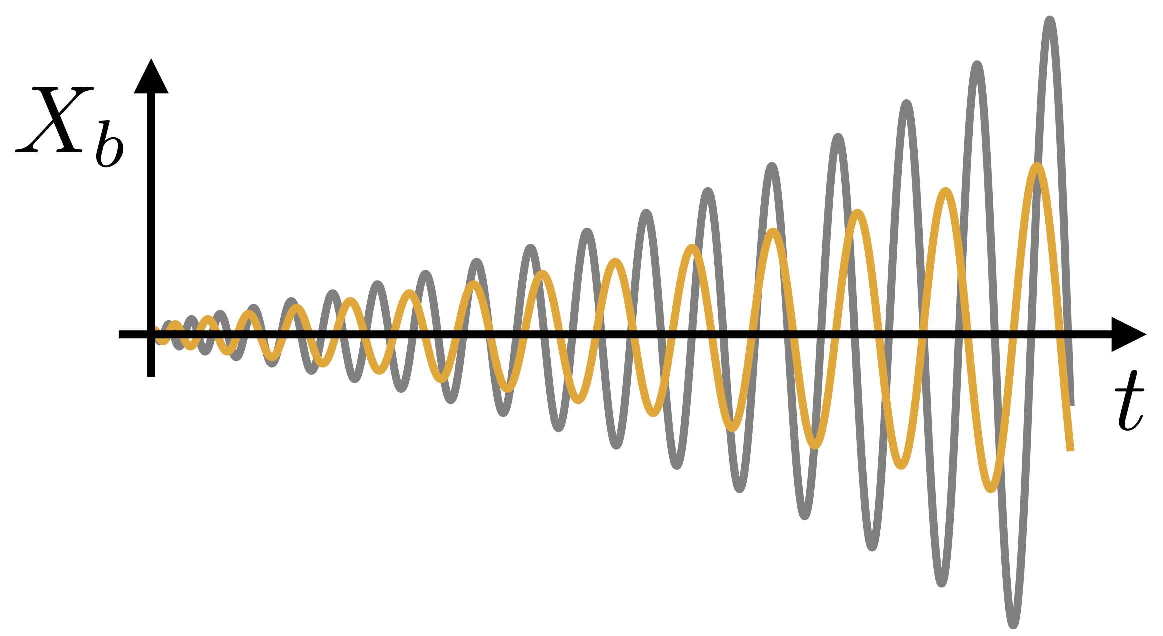
Hosing mitigation mechanisms

In the hose instability, transverse phase space asymmetries of beam particles and plasma electrons are coherently coupled and thereby amplified.

Mitigation mechanism	Effect
Reduction of seed	Reduced amplitude
Disrupting coherence	Stopping growth and/or damp oscillations
Reduction of coupling	Reduced growth rate







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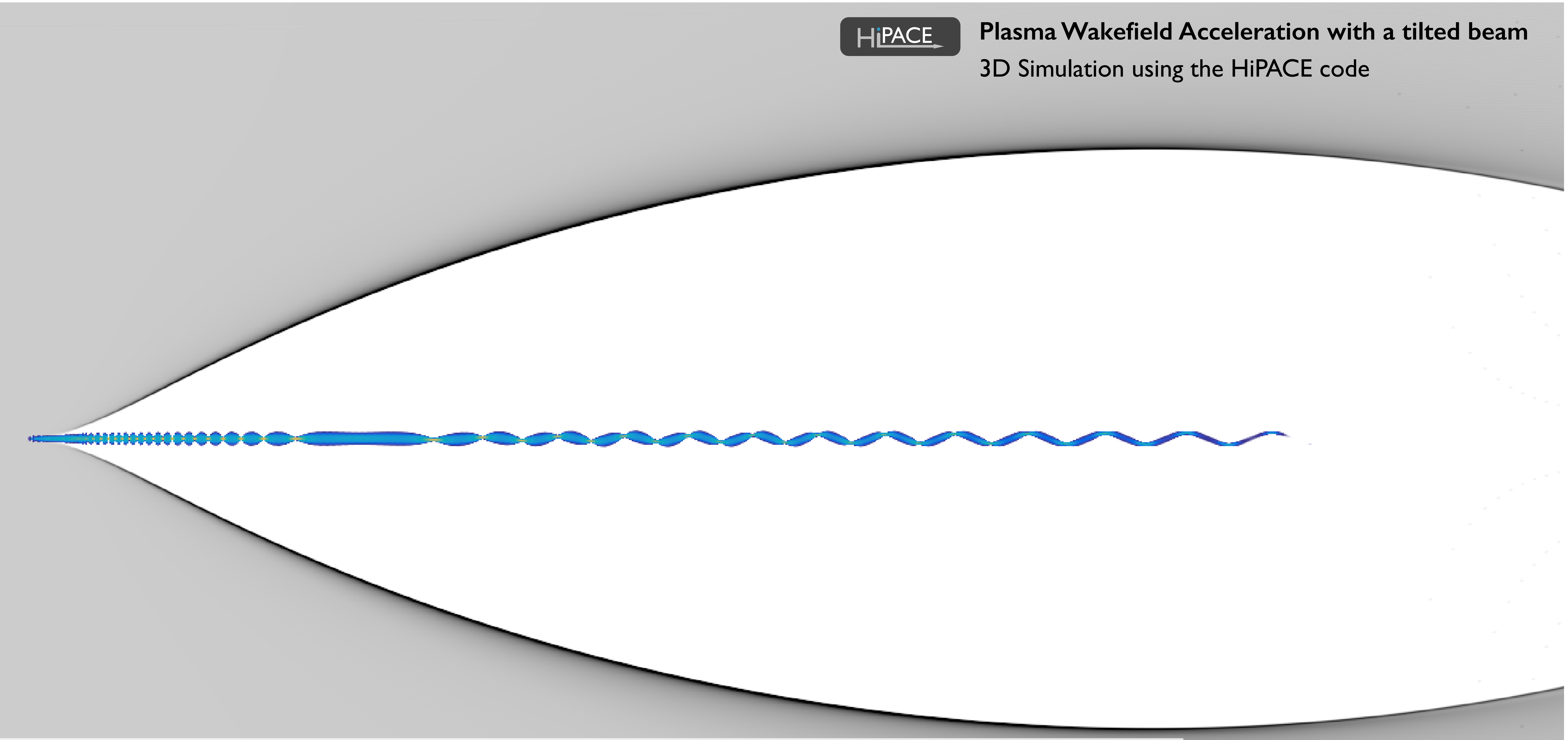


Mitigation of the hose instability

Reduction of coupling, coherence and seed

Coupling

Can coupling between plasma and beam be reduced?

$$\frac{\partial^2 X_b}{\partial t^2} + \omega_\beta^2 (X_b - X_c) = 0$$

$$\frac{\partial^2 X_c}{\partial \xi^2} + \frac{k_p^2}{2} (X_c - X_b) = 0$$

Reduction of coupling → **Plasma to beam** / **Beam to plasma**

Plasma to beam

In homogeneous ion-channel:

$$\omega_\beta = \frac{\omega_p}{\sqrt{2\gamma}}$$

Reducing density?

Accelerating field scales with E_0
$\Rightarrow$ Not an option!

Other possible approaches:

- Inhomogeneous channel/wide beam
- Linear regime

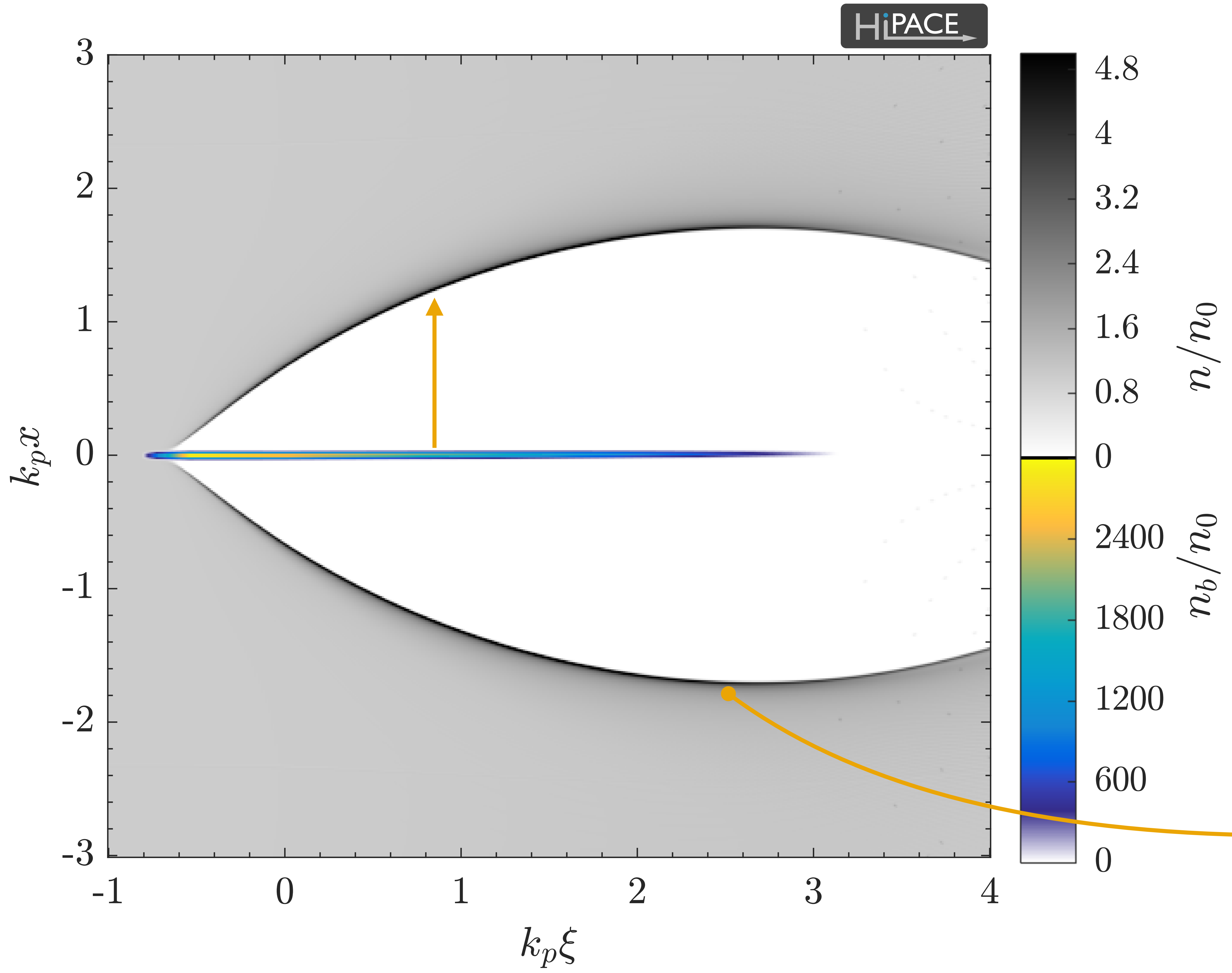
Beam to plasma

Is response of sheath electrons given by $k_p/\sqrt{2}$ in any kind of ion channel?

No!

Reduced coupling

Coupling between beam and plasma is reduced in the blowout regime



Beam to plasma

Is response of sheath electrons given by $k_p/\sqrt{2}$ in any kind of ion channel?

No!

In the nonlinear blowout:

- Force depends on beam current and blowout radius.
- Response depends on relativistic mass of sheath electrons

Reduced coupling

Coupling between beam and plasma is reduced in the blowout regime

Centroid equations - blowout regime (Huang)

Channel centroid equation in blowout regime

$$\frac{\partial^2 X_c}{\partial \xi^2} + \frac{k_p^2 c_\psi(\xi) c_r(\xi)}{2} (X_c - X_b) = 0$$

Beam centroid equation (same as Whittum)

$$\frac{\partial^2 X_b}{\partial t^2} + \omega_\beta^2 (X_b - X_c) = 0$$

C. Huang, et al. Phys. Rev. Lett. 99, 255001 (2007).

Beam to plasma

Is response of sheath electrons given by $k_p/\sqrt{2}$ in any kind of ion channel?

No!

In the nonlinear blowout:

- Force depends on beam current and blowout radius.
- Response depends on relativistic mass of sheath electrons

Mitigation of the hose instability

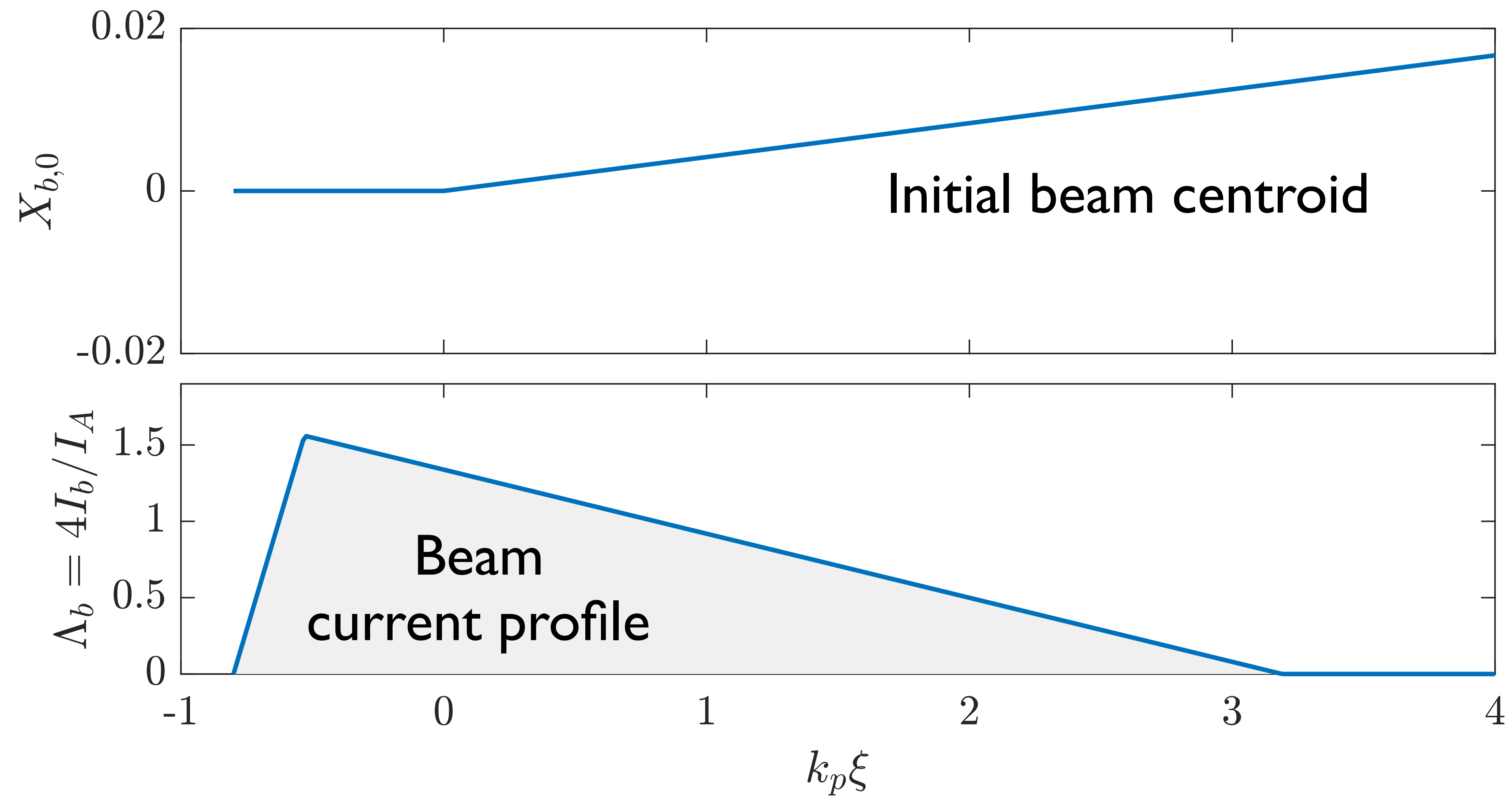
Investigated PWFA example

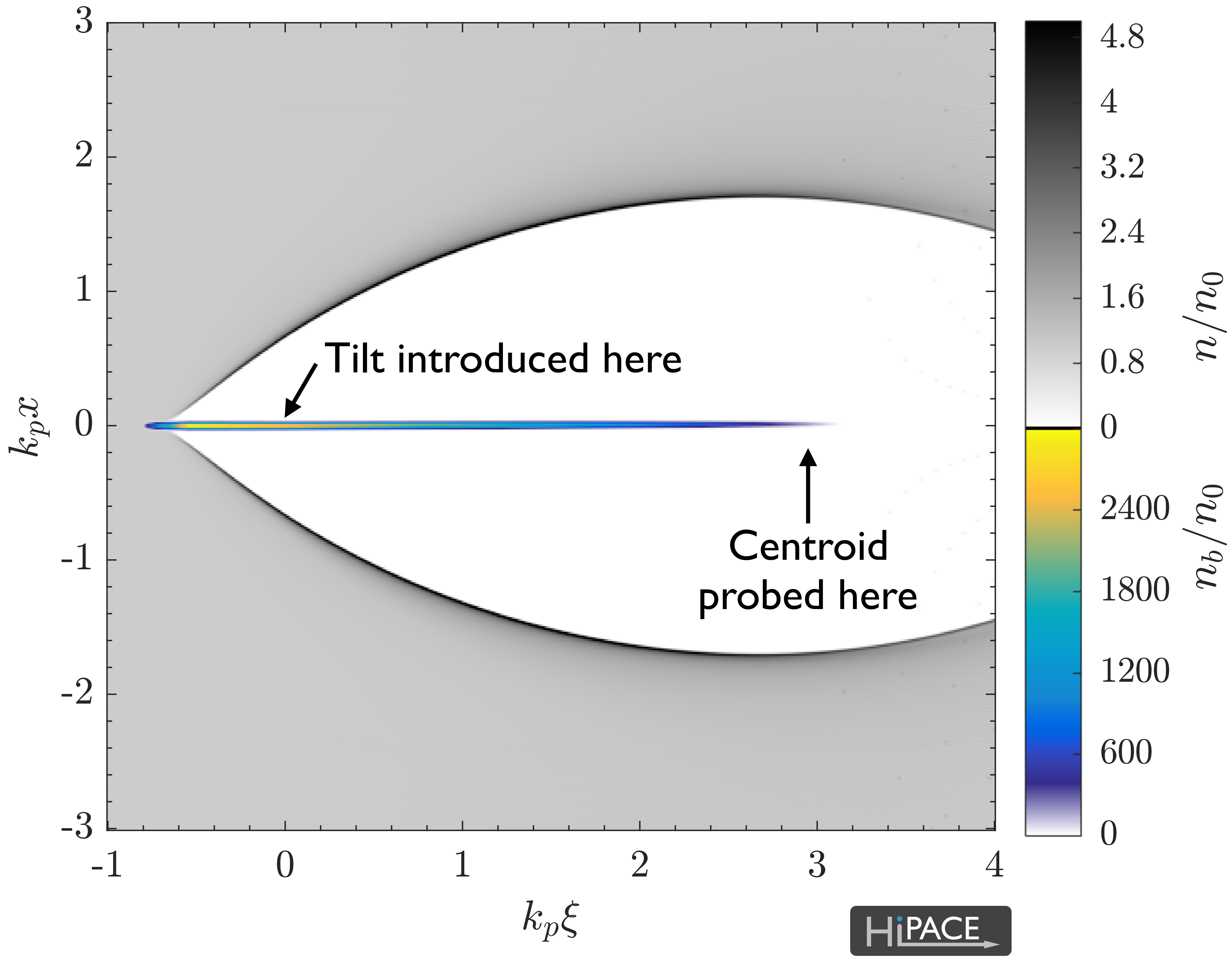
Tilted beam with triangular current profile

Init. centroid: $X_{b,0}(\xi) = 4.17 \times 10^{-3} \times \xi\, \Theta(k_p \xi)$

Energy: 28.5 GeV; Peak current: 6.65 kA

Setup as in C. Huang, *et al.* PRL **99**, 255001 (2007).





Reduced coupling

Growth rate is reduced in blowout regime but still exponential

Centroid equations - blowout regime (Huang)

Channel centroid equation in blowout regime

$$\frac{\partial^2 X_c}{\partial \xi^2} + \frac{k_p^2 c_\psi(\xi) c_r(\xi)}{2} (X_c - X_b) = 0$$

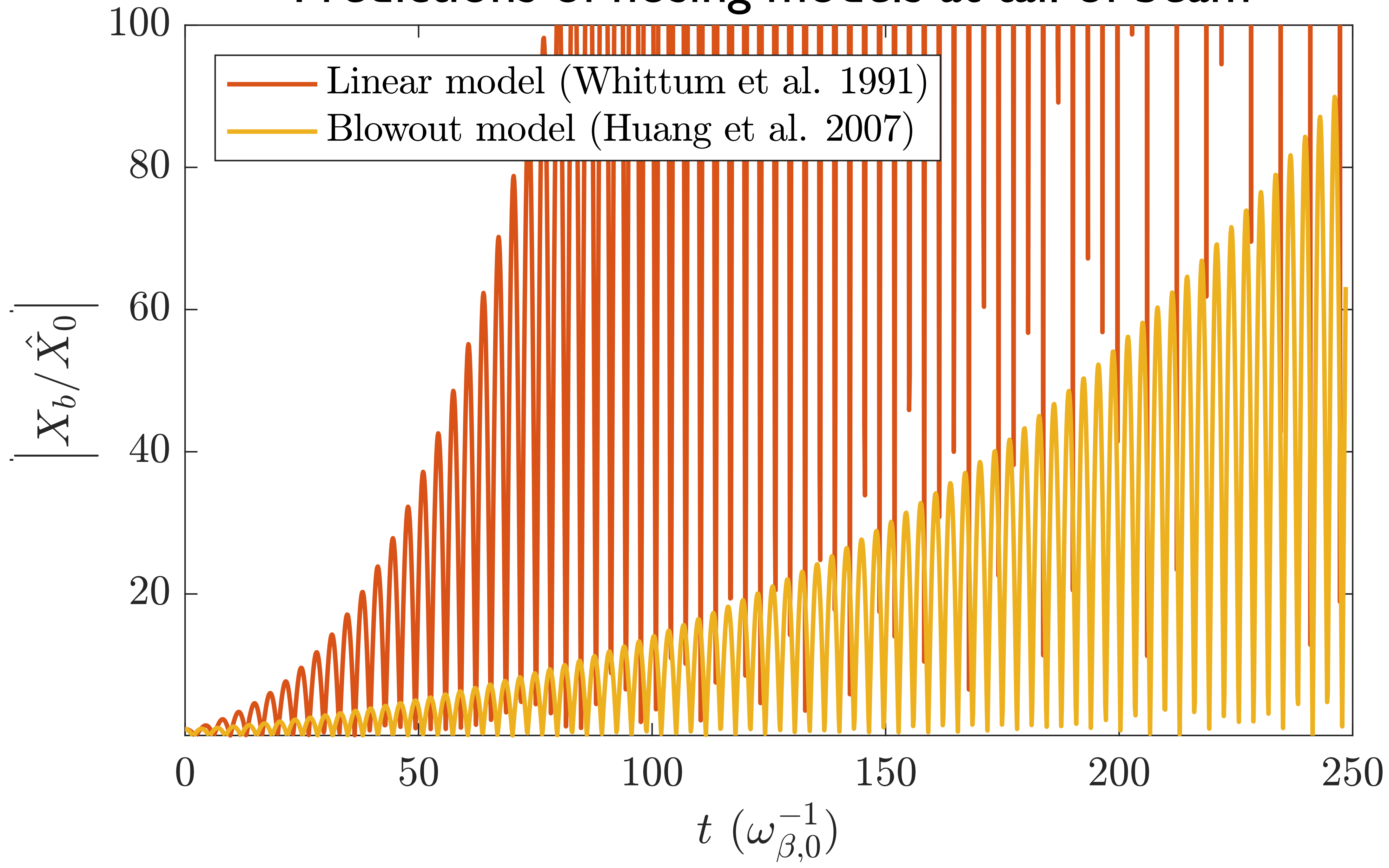
Beam centroid equation (same as Whittum)

$$\frac{\partial^2 X_b}{\partial t^2} + \omega_\beta^2 (X_b - X_c) = 0$$

C. Huang, et al. Phys. Rev. Lett. 99, 255001 (2007).

Assumption:
Beam is mono-energetic and energy does not evolve!

Predictions of hosing models at tail of beam



Growth still exponential

- Coupling and growth rate reduced
- But: Growth still exponential
- Small centroid deviations eventually lead to beam breakup!

Disrupting coherence along beam

Intrinsic beam energy change plays an essential role

Disrupting coherence of beam particles

Do beam particles with differing initial

x, p_x, ξ, γ

Oscillate coherently in time?

In homogeneous ion-channel: $\omega_\beta = \frac{\omega_p}{\sqrt{2\gamma}}$

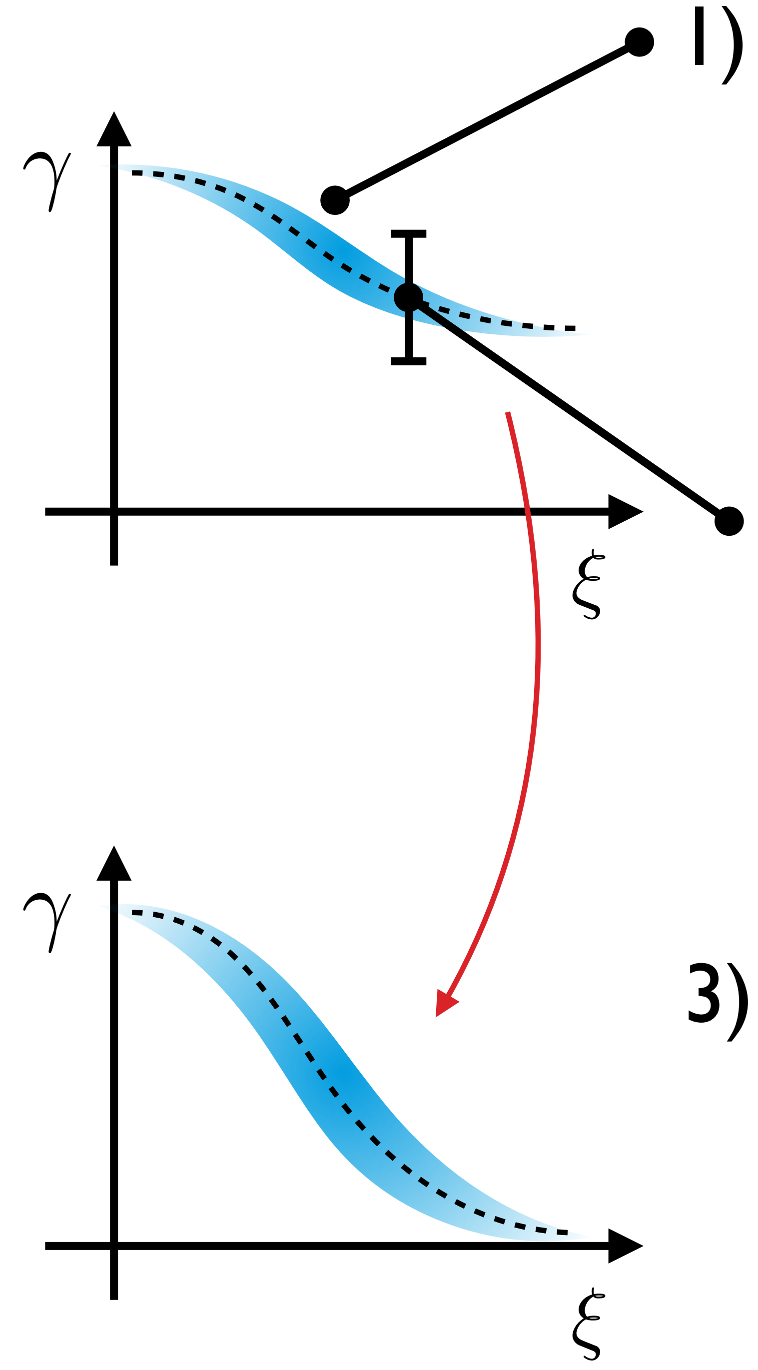
Different situation for:

- Inhomogeneous channel/wide beam
- Linear regime

Effects of beam energy spread and evolution

Betatron-frequency in ion channel: $\omega_\beta = \frac{\omega_p}{\sqrt{2\gamma}}$

Individual-electron energy: $\gamma = \gamma(\xi, t)$



1) Initial corr. energy spread (chirp)
- Betatron oscillations along beam are decoupled

2) Uncorrelated slice energy spread
- Betatron decoherence within beam slices

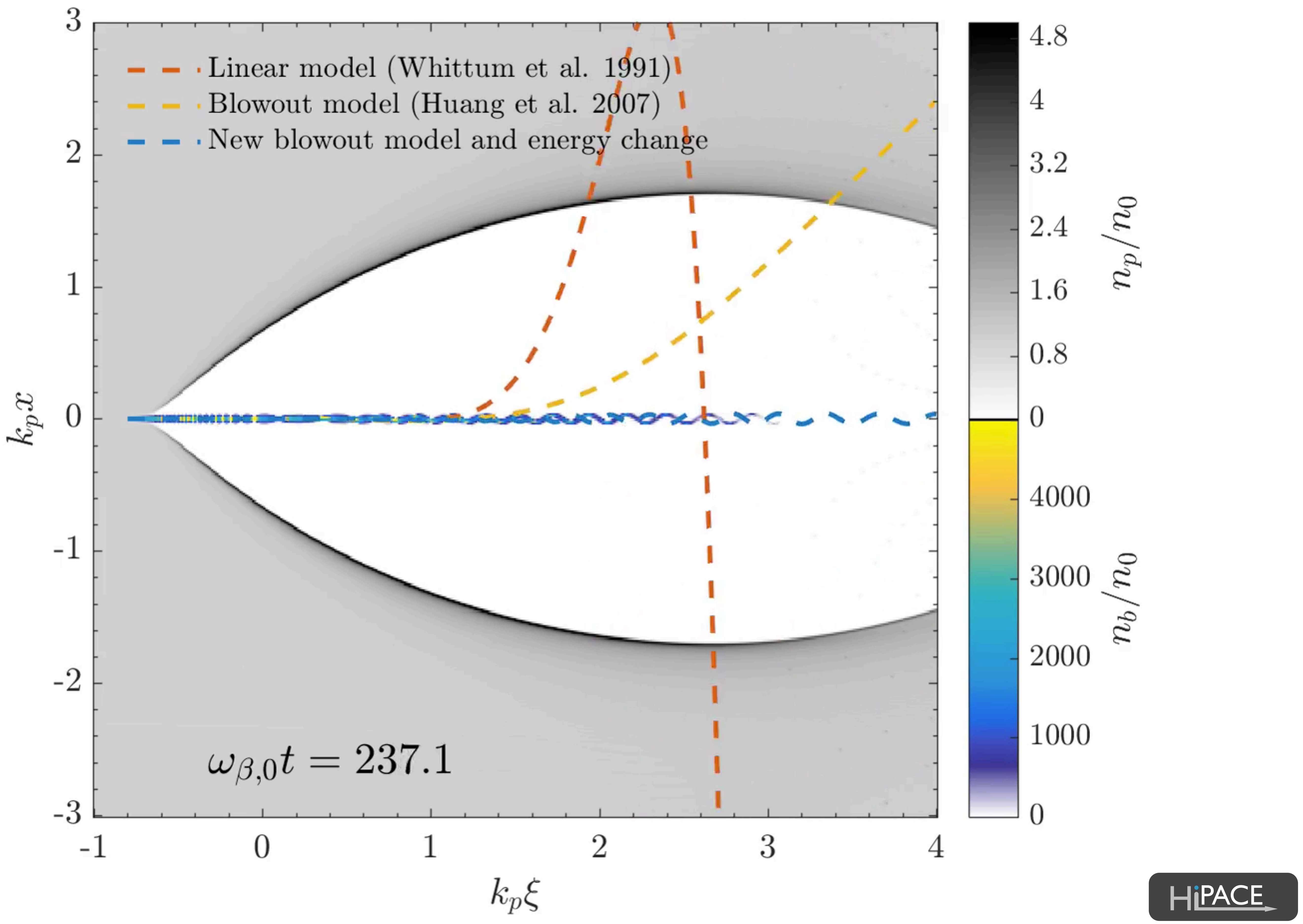
3) Evolution of energy chirp
- Betatron oscillations are detuned

Disrupting coherence along beam

Beam energy effects play an essential role

Demonstrating impact of intrinsic energy change on hosing

Beam with no initial energy spread: Comparison of PIC & different hosing models



Beam energy change plays an essential role

- Striking difference between PIC results and current models!
- Only accurately described when including self consistent energy change!

Disrupting coherence along beam

Beam energy evolution leads to saturation of hosing

Channel centroid equation, blowout regime**

$$\frac{\partial^2 X_c}{\partial \xi^2} + \frac{k_p^2 c_\psi(\xi) c_r(\xi)}{2}(X_c - X_b) = 0$$

**C. Huang et al., PRL 99, 255001 (2007).

Beam centroid equation incl. energy spread and change*

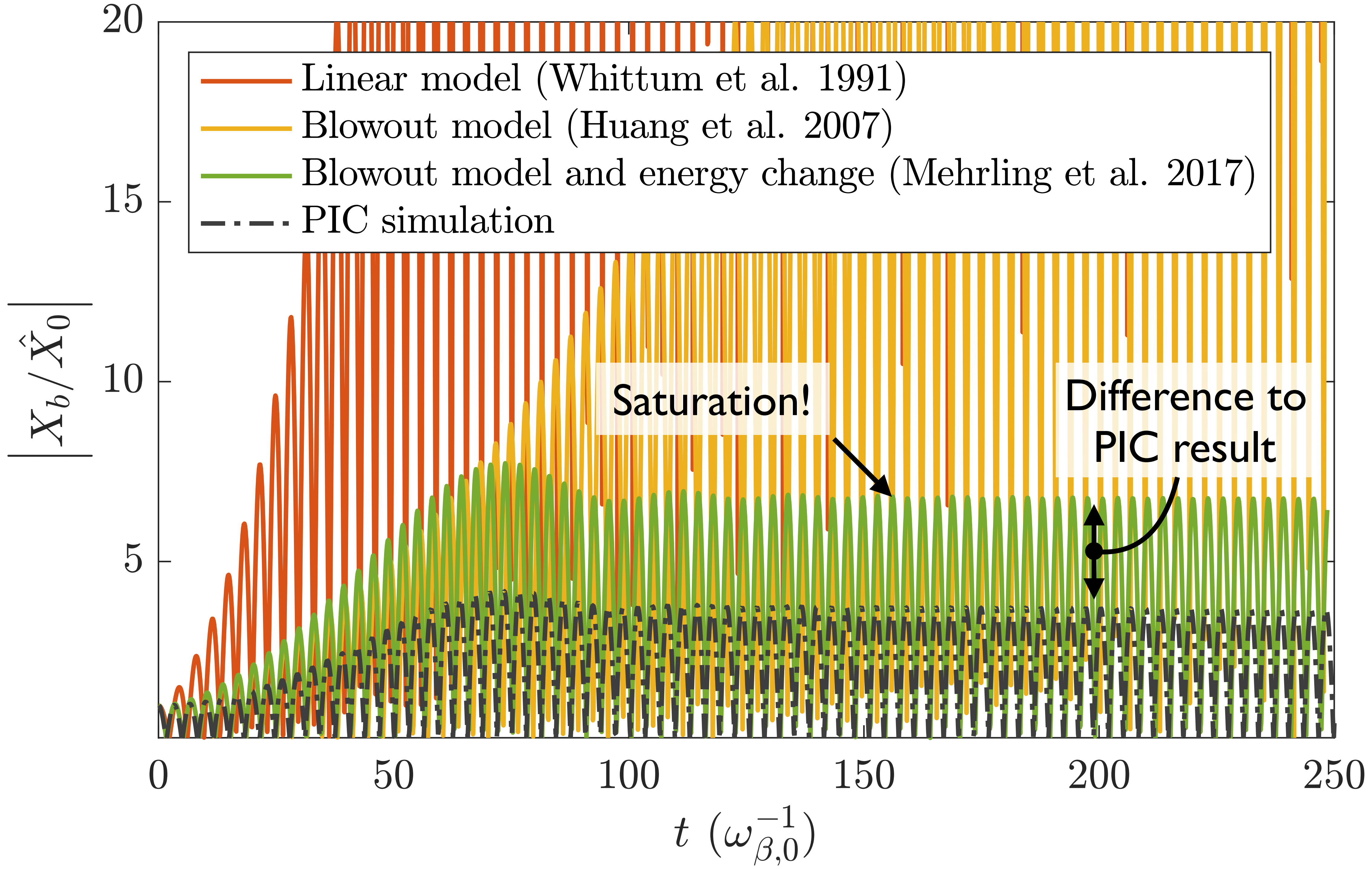
$$\frac{\partial^2 X_b}{\partial t^2} + \lambda(\xi,t)\frac{\partial X_b}{\partial t} + \Omega^2(\xi,t)(X_b - X_c) = 0$$

Acceleration rate-dependent frequency

"Friction" term for finite energy spread (and/or energy gain)

*T. Mehrling et al., PRL 118, 174801 (2017).

Predictions of different hosing models at tail of beam (without initial energy spread)



Saturation of hosing!

- Intrinsic energy evolution leads to decoupling of slice-betatron oscillations.
- Hosing stops when individual slices are decoupled.

Disrupting coherence along beam

New blowout model and energy change in excellent agreement with PIC simulations

Beam centroid equation incl. energy spread and change*

$$\frac{\partial^2 X_b}{\partial t^2} + \lambda(\xi, t)\frac{\partial X_b}{\partial t} + \Omega^2(\xi, t)(X_b - X_c) = 0$$

Acceleration rate-dependent frequency

"Friction" term for finite energy spread (and/or energy gain)

*T. Mehrling et al., PRL 118, 174801 (2017).

New channel centroid equation in blowout regime***

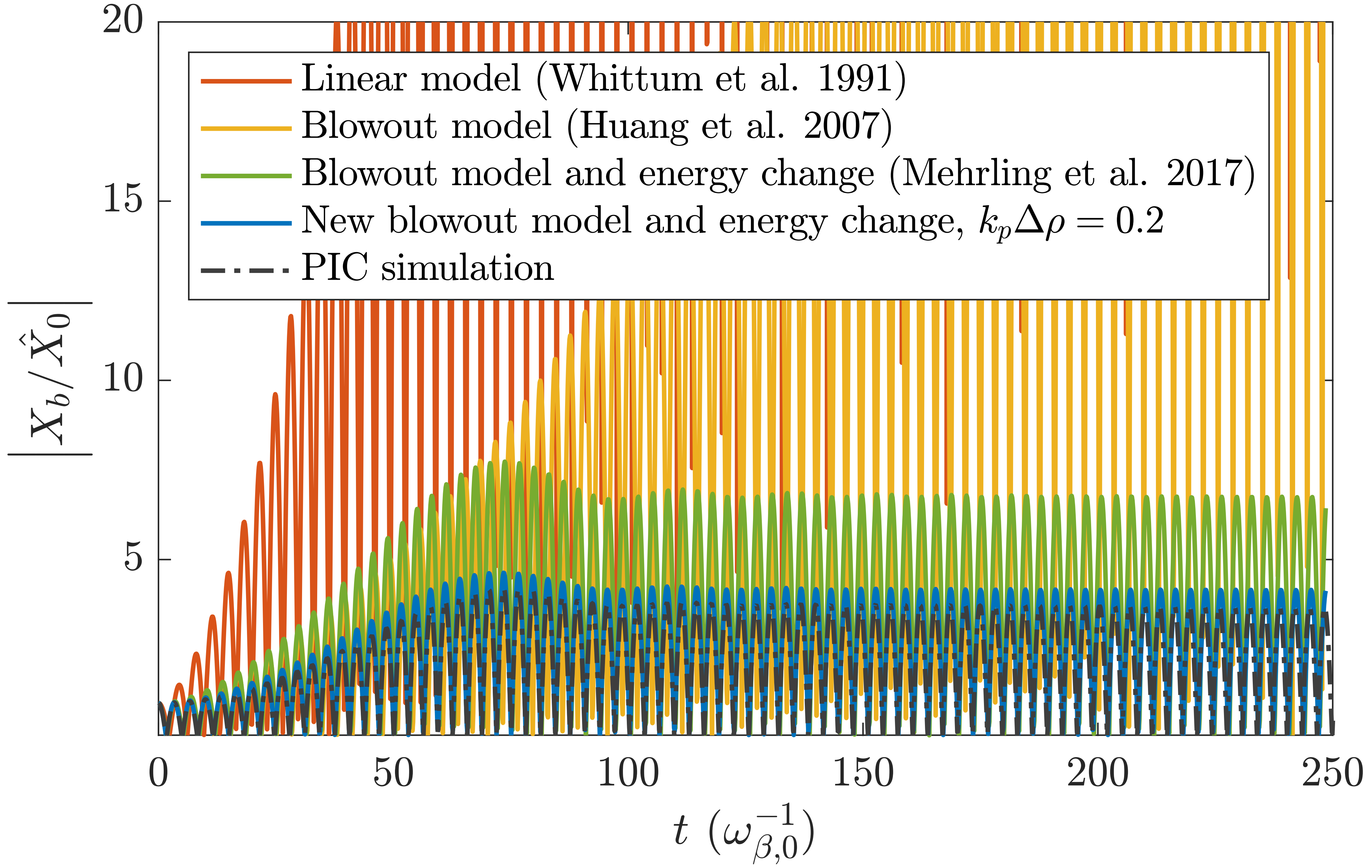
$$\frac{\partial^2 X_c}{\partial \xi^2} + \frac{k_p^2}{2}\left[c_c(\xi)X_c - c_b(\xi)X_b\right] = 0$$

Channel centroid for blowout regime including finite sheath thickness: $\Delta\rho$

***T. Mehrling et al., in preparation

Saturation mechanism generally effective ?

Predictions of different hosing models at tail of beam (without initial energy spread)



Excellent agreement

Excellent agreement between model & PIC

Disrupting coherence along beam

Hosing saturation from intrinsic energy evolution generally effective

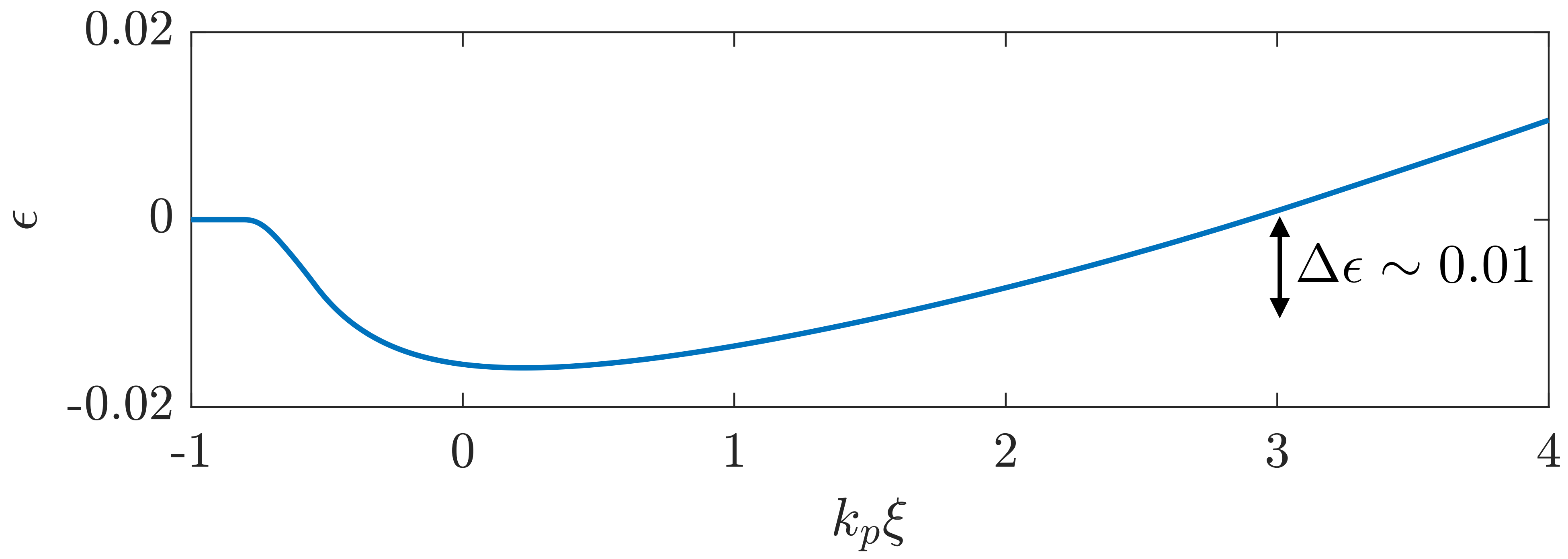
Interpretation using a two-particle model beam

Using a two-particle model beam:

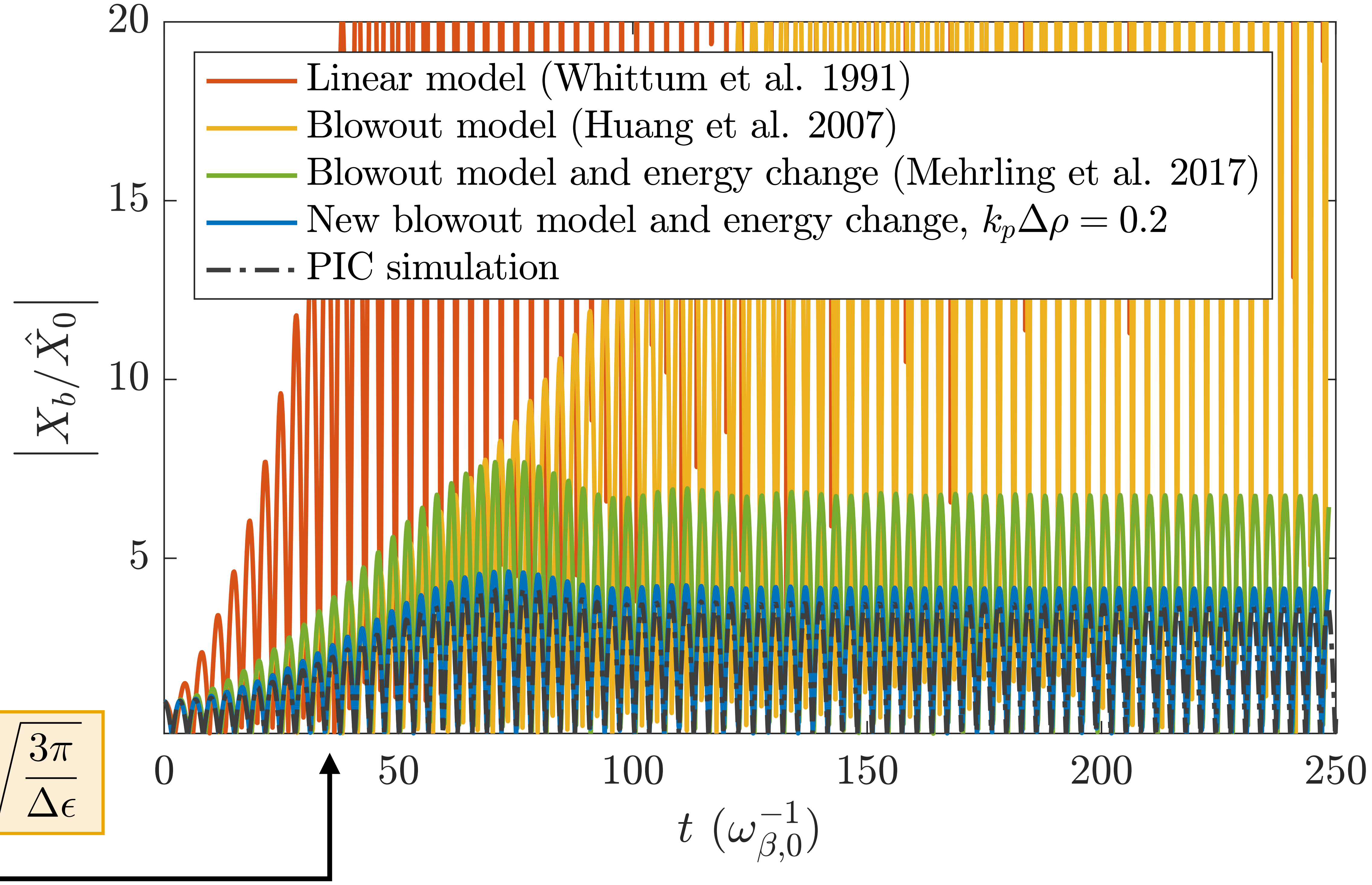
$$X_b(\xi,t) = X_{b,1}(\xi,t)\delta(\xi-\xi_1) + X_{b,2}(\xi,t)\delta(\xi-\xi_2)$$

One finds:

- Decoupling occurs at $t \simeq \overline{\omega_{\beta,0}}^{-1}\sqrt{\frac{3\pi}{\Delta\epsilon}}$
  where $\Delta\epsilon = |\epsilon(\xi_2) - \epsilon(\xi_1)|$
  and $\epsilon = -\sqrt{2/\overline{\gamma_0}}\, E_z/E_0$
- Decoupling generally occurs before depletion time, $t = [\overline{\omega_{\beta,0}}\min(\epsilon)]^{-1}$, if $\Delta\epsilon/\min(\epsilon) > 3\pi\min(\epsilon)$
- Since $0 \leq \Delta\epsilon/\min(\epsilon) \lesssim 1$ and $\min(\epsilon) \ll 1$



Predictions of different hosing models at tail of beam (without initial energy spread)



Hosing saturation generally effective

Hosing saturation from energy evolution generally effective before depletion of drive beam

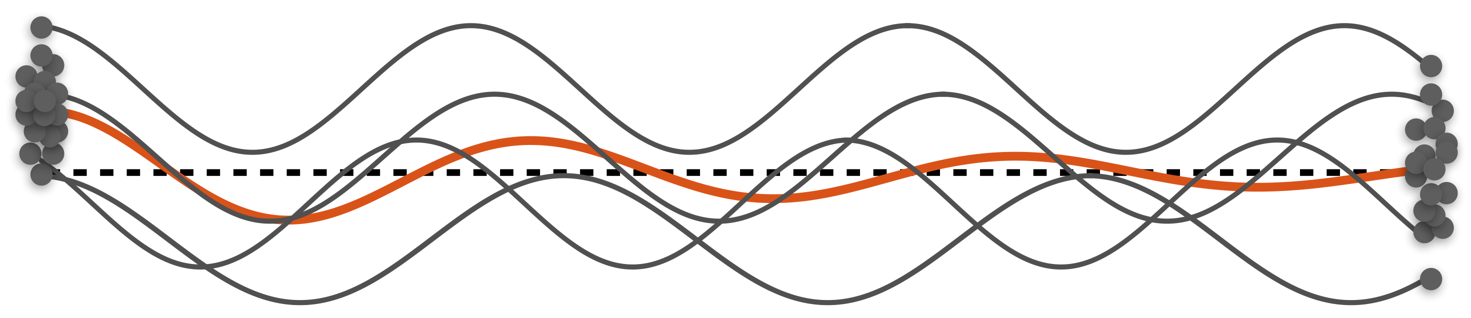
Disrupting coherence within a slice

Uncorrelated energy spread damps beam centroid oscillations

Damping from uncorrelated energy spread

- Slice energy spread causes betatron decoherence within individual slices

Incoherent oscillation



- Exponential damping of betatron oscillations!
- Damping dominates for times $t \gtrsim \frac{2\overline{\gamma_0}}{\omega_{\beta,0}\sigma_\gamma}$

Uncorrelated energy spread is relevant

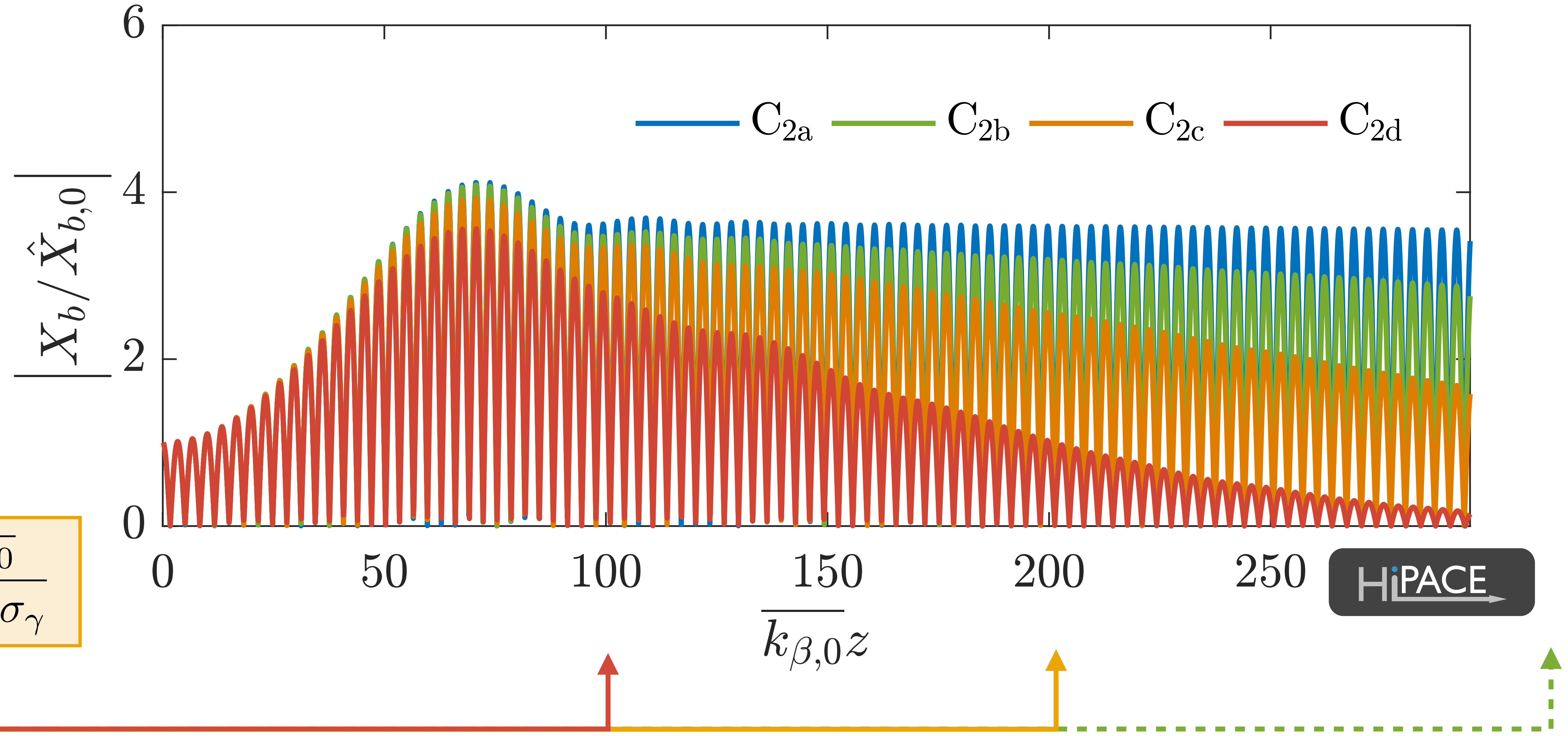
Damping of hosing can be effective for percent-level energy spreads!

Tilted beam with triangular current profile

Varying energy spread

C_{2a}: 0%, C_{2b}: 0.5%, C_{2c}: 1%, C_{2d}: 2%

$\frac{2\overline{\gamma_0}}{\omega_{\beta,0}\sigma_\gamma}$



But:
To be effective, mitigation mechanisms need to "kick-in" before beam-breakup!

Reducing hosing by plasma tapering

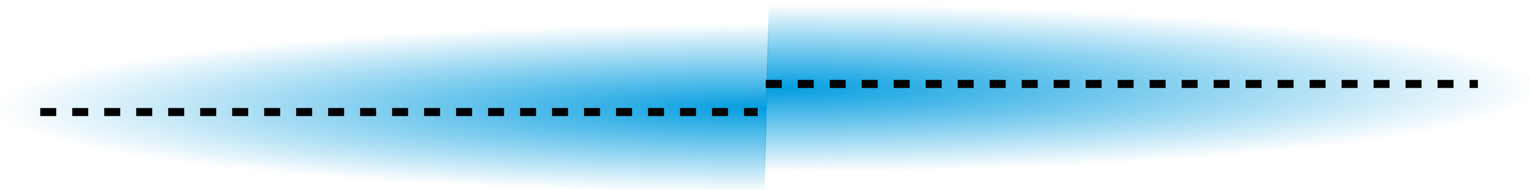
Reduction of the initial hose-seed by tailoring of vacuum-to-plasma transition

Reduction of seed

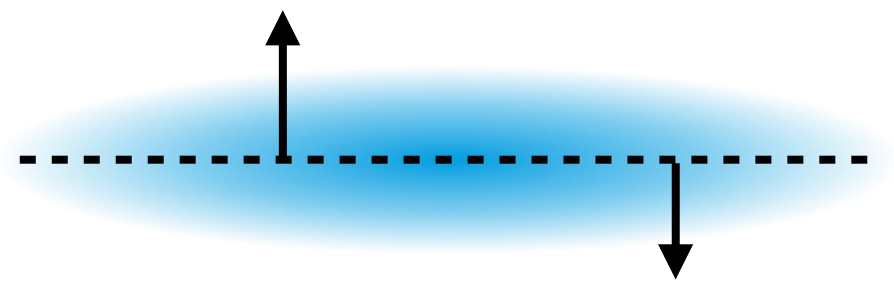
→ **Beam**

→ **Plasma**

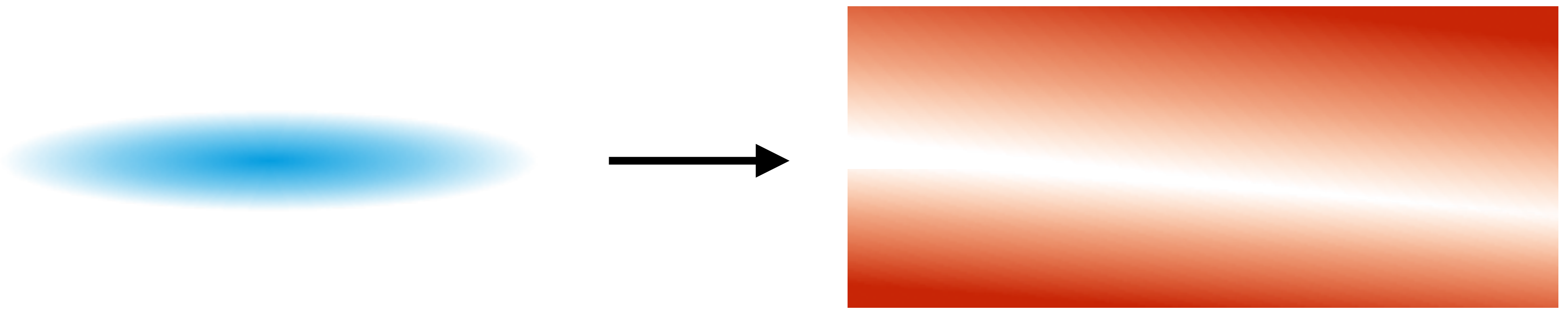
Reduction of beam centroid deviations



Reduction of initial momentum deviations



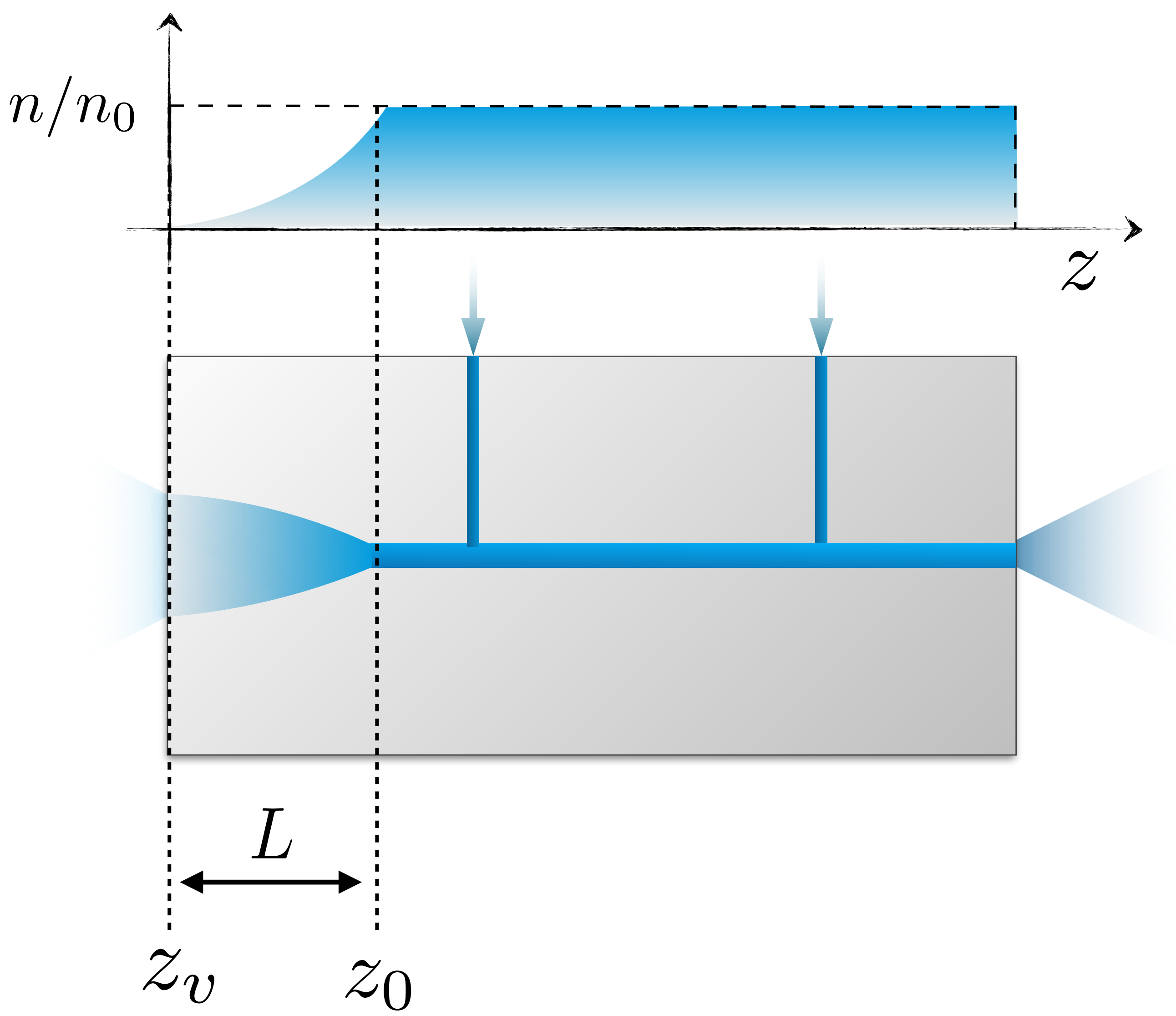
Reduction of transverse plasma density asymmetries



Mitigation of hosing by plasma tapering

Reduction of the initial hose-seed by tailoring of vacuum-to-plasma transition

Tailored density transition



Chosen functionality*:

$$n(z) = \begin{cases} 0 & \text{if } z \le z_v, \\ n_0(1-(z-z0)/\lambda)^{-4} & \text{if } z_v < z \le z_0, \\ n_0 & \text{if } z > z_0 \end{cases}$$

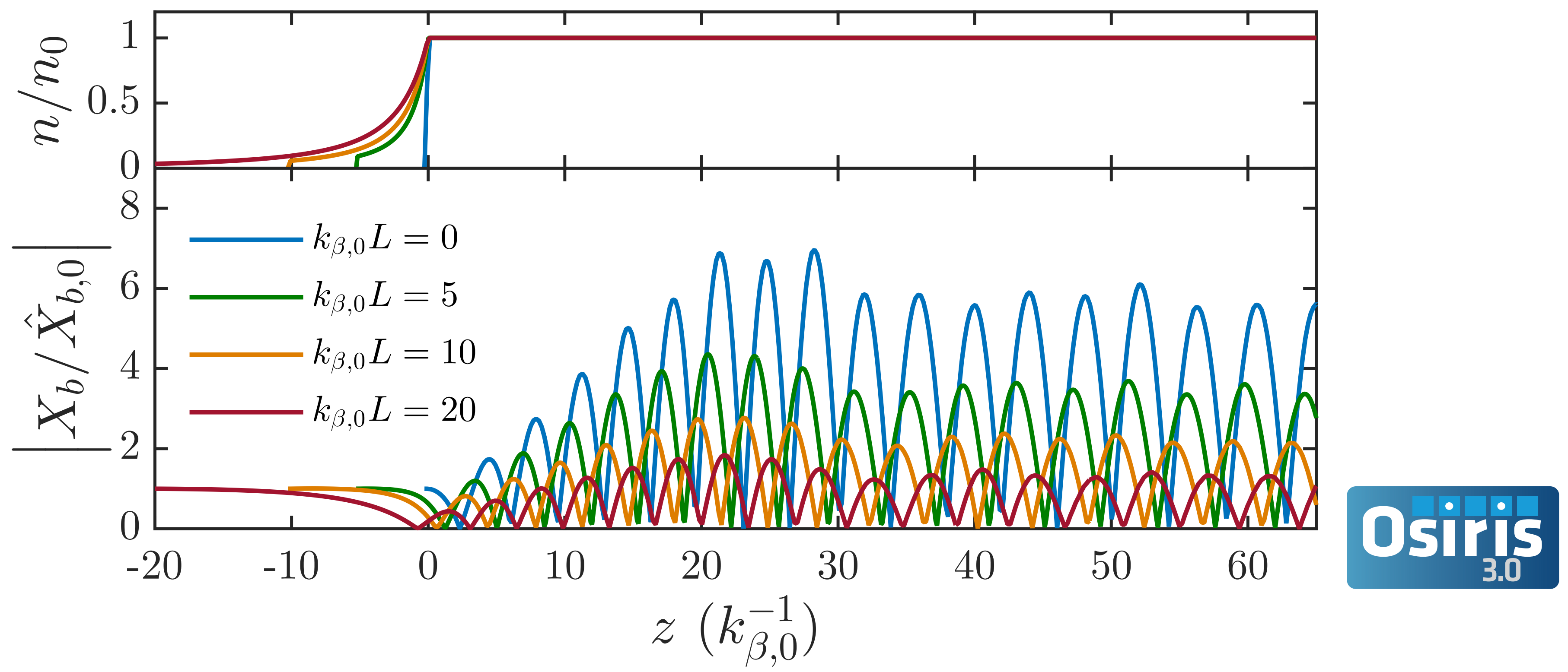
Betatron wavenumber: $k_\beta = k_{\beta,0}\sqrt{\frac{n}{n_0}}$

Beam centroid in transition

Differential equation
(neglecting hose and energy effects in taper profile)

$$\frac{d^2 X_b}{dz^2} + k_\beta(z)^2 X_b = 0\ .$$

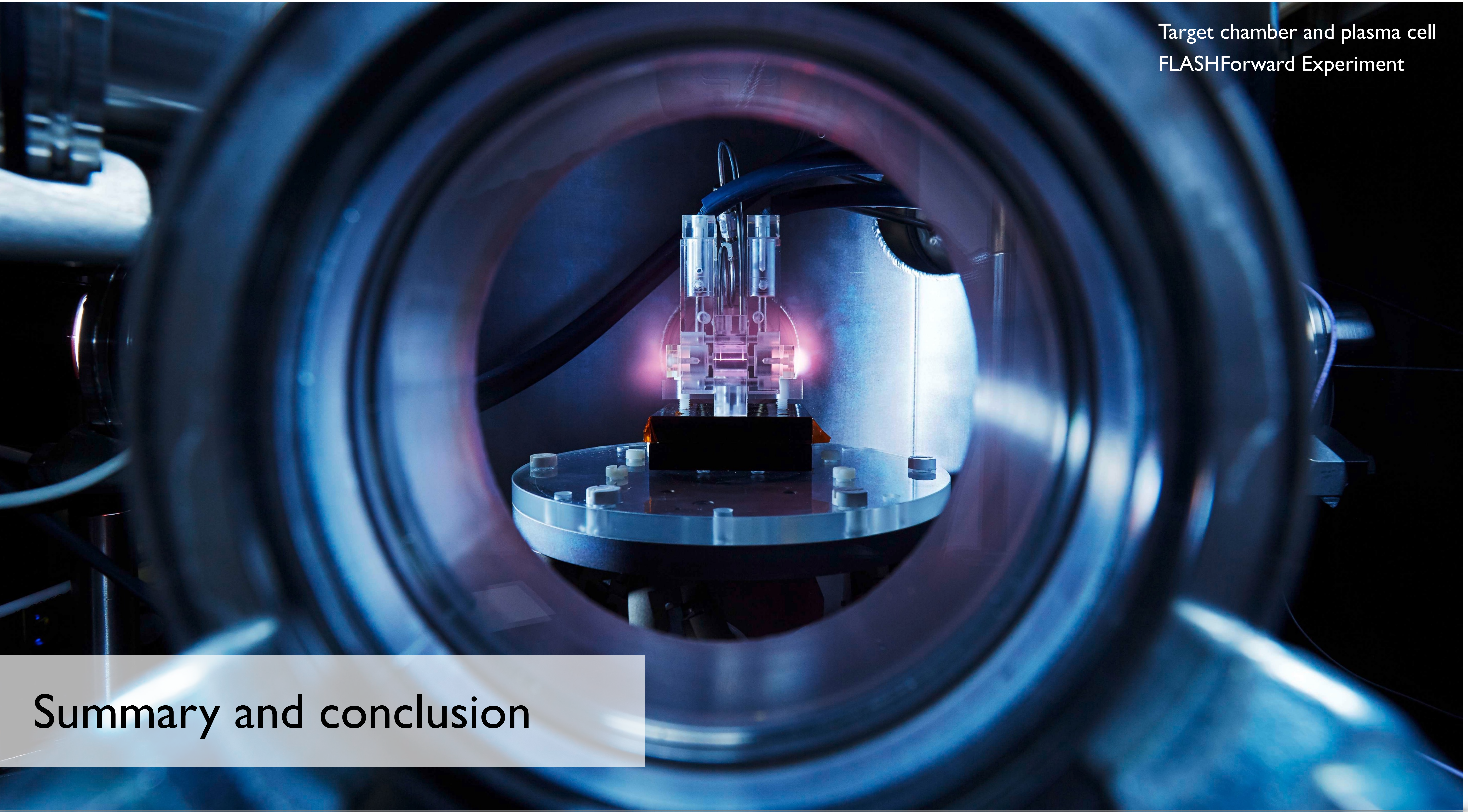
Harmonic oscillator with varying spring constant.



Density profiles and centroid oscillations for different λ

Significant reduction of the spatial hosing seed with appropriate tapers!

*Functionality used e.g. in K. Floettmann, Phys. Rev. ST Accel. Beams **17**, 054402 (2014); and X.L. Xu, *et al.* Phys. Rev. Lett. **116**, 124801 (2016) in the context of betatron-matching.



Target chamber and plasma cell
FLASHForward Experiment

Summary and conclusion

Summary

Mitigation of the hose instability in plasma wakefield accelerators
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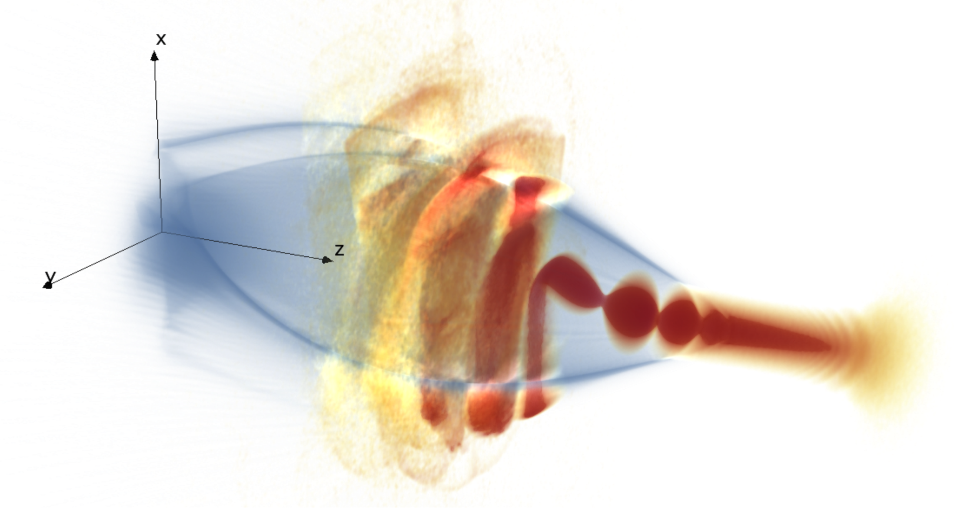
Current models: Hosing is fundamental impediment for stable PWFA

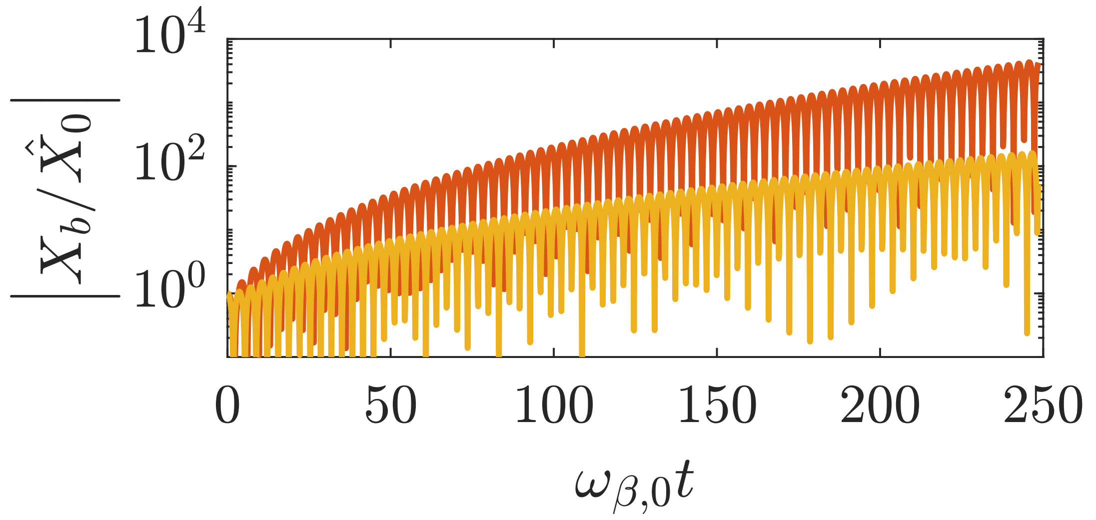
Initial deviations are exponentially amplified

Small asymmetries inevitably lead to beam deterioration or breakup



Coupling is / can be reduced

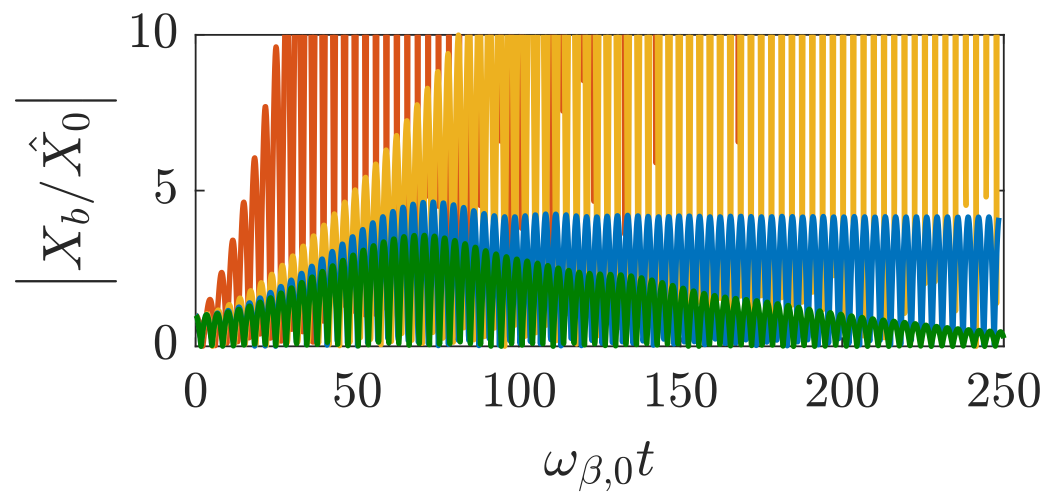
Reduced coupling in blowout $\Rightarrow$ smaller growth rate



Coherence is / can be disrupted

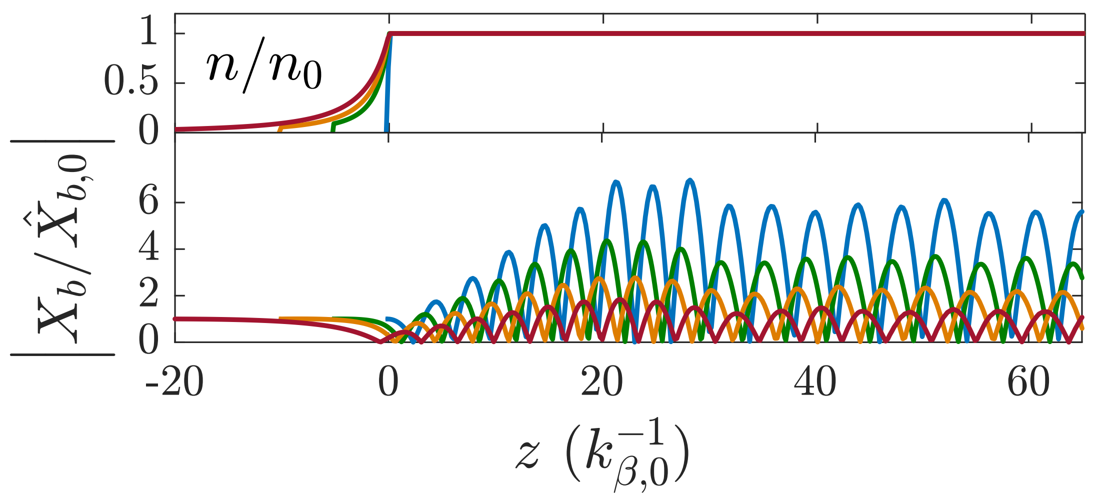
Inherent energy evolution decouples beam slices $\Rightarrow$ saturation of hosing

Decoherence from uncorr. energy spread $\Rightarrow$ damps centroid oscillations



Hosing seed can be reduced

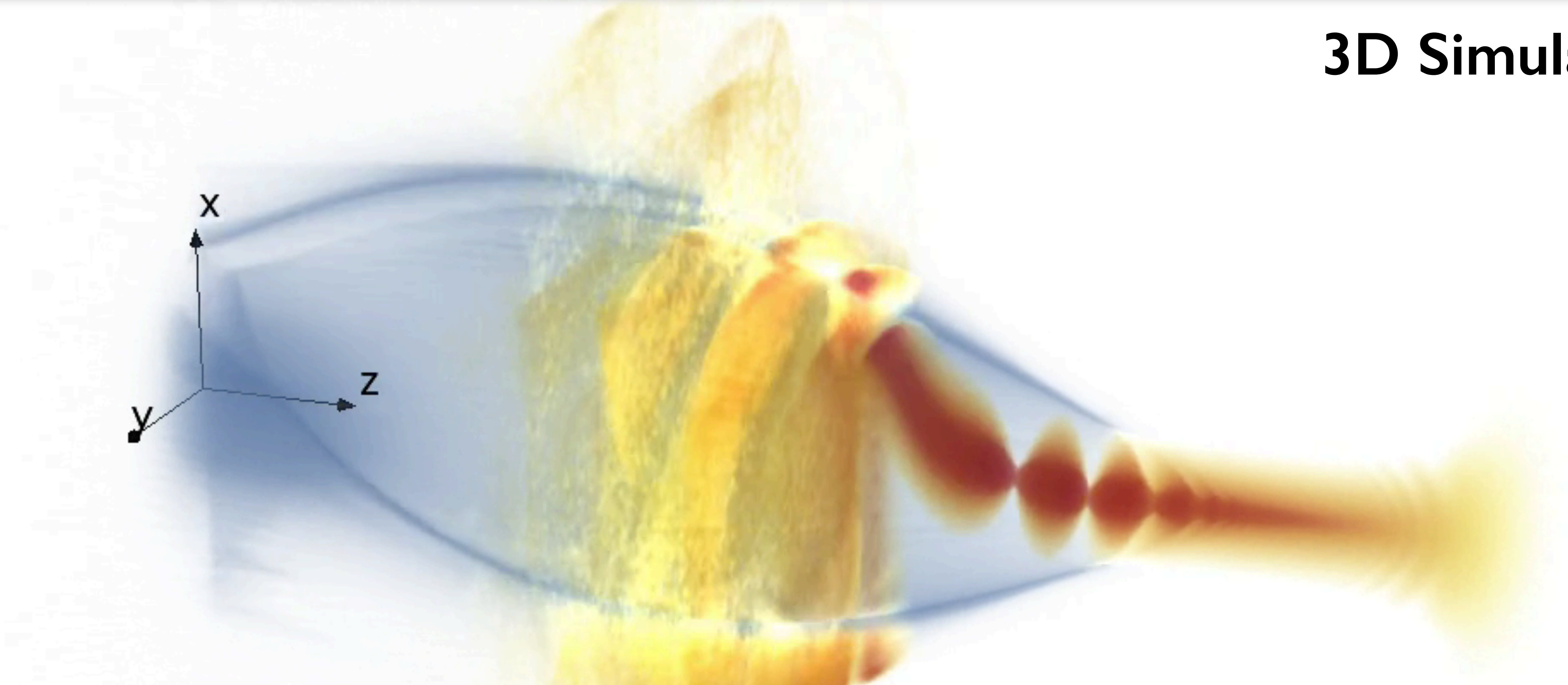
Tailored vacuum-to-plasma transitions $\Rightarrow$ reduce initial hosing seed



Conclusion

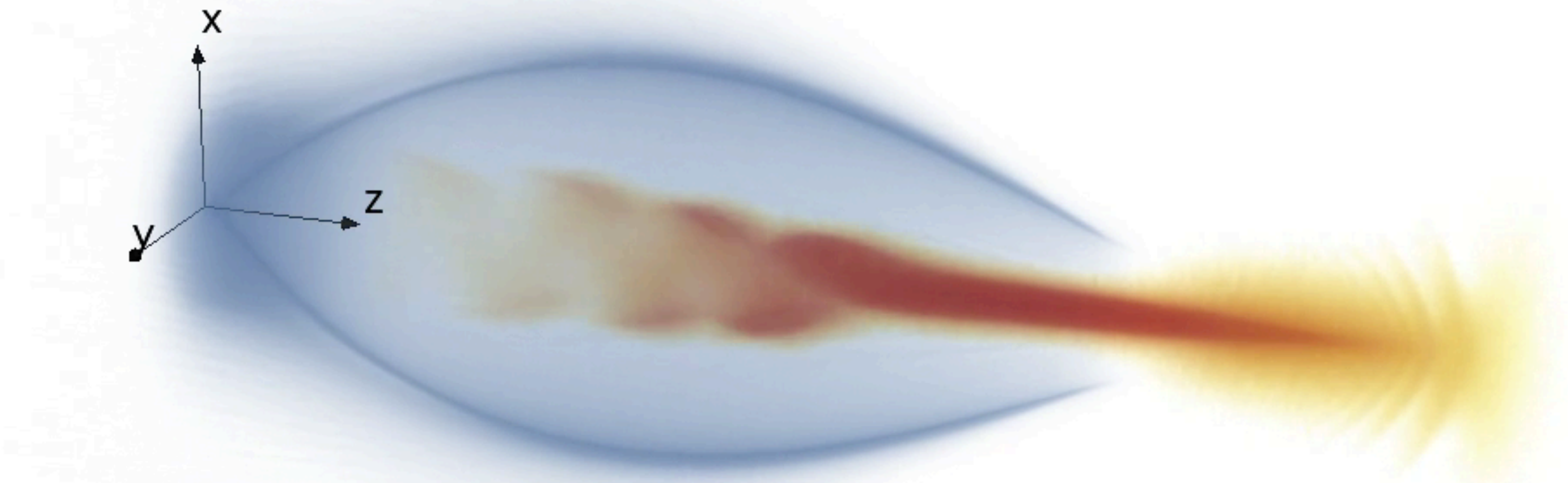
3D Simulations with tilted beams

HiPACE



No energy spread

No tapered vacuum-to-plasma transition



Energy spread

Tapered vacuum-to-plasma transition

Hosing is a challenge!

But it can be mitigated!

Other mitigation mechanisms exist: reduction of coupling, coherence and seed.

Stable acceleration of high quality beams possible over long distances in PWFAs!

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Timon J. Mehrling

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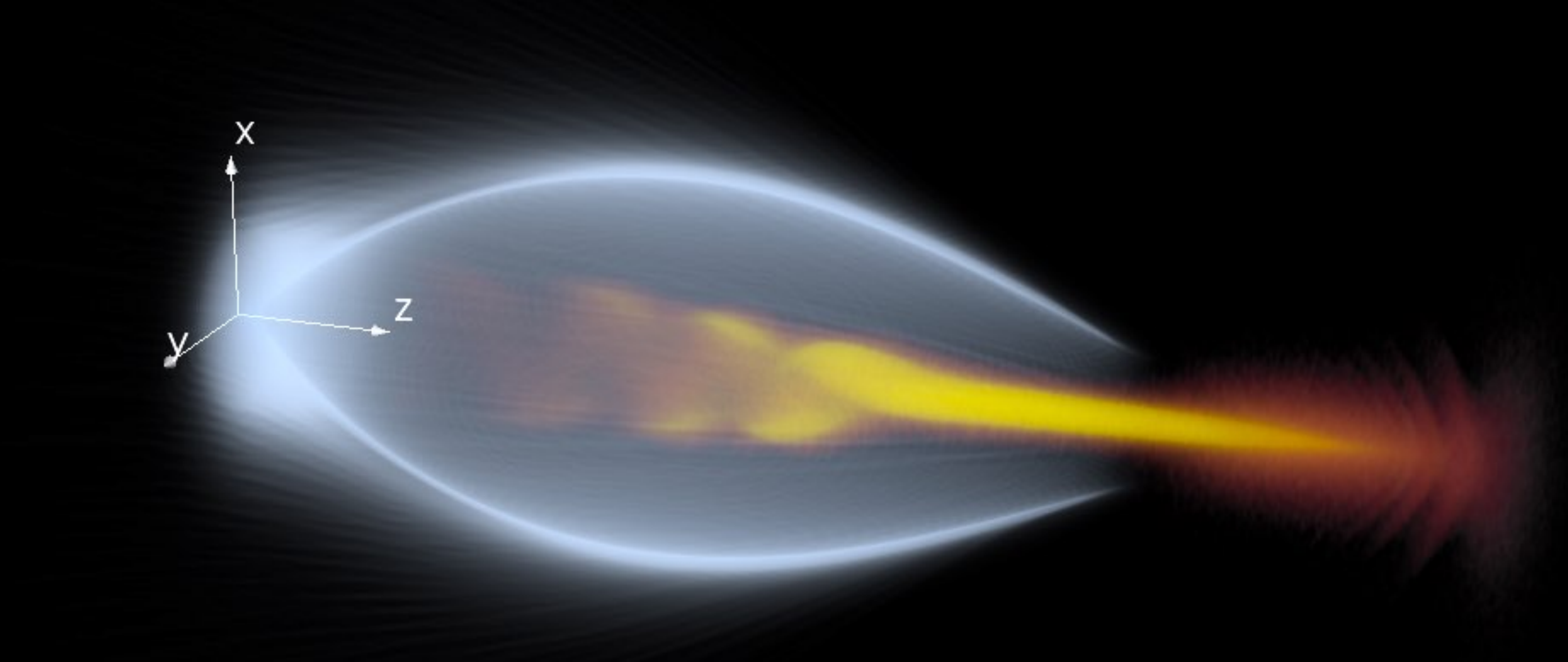

Thank you for your attention!