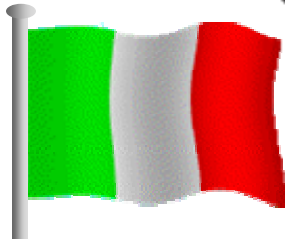


26TH INTERNATIONAL  
FREE ELECTRON LASER CONFERENCE  
& 11TH FEL USERS WORKSHOP



AUGUST 29 - SEPTEMBER 3  
*Fel* 2004  
Trieste, Italy

## The Harmonically Coupled 2-Beam FEL

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Mike Poole	- ASTeC & CCLRC Daresbury
Gordon Robb	- University of Strathclyde



# Outline:

- Quick review of seeded Vs unseeded FELs
- 2-Beam FEL concept
- 1-D model
- Analysis
- Numerical simulation
- Beam quality effects
- Summary & further possibilities

# Seeding Schemes:

## Benefits:

- Stable central wavelength
- Fourier transform limited
- Short pulse (20fs)
- Stable Intensity from shot to shot
- Narrow bandwidth

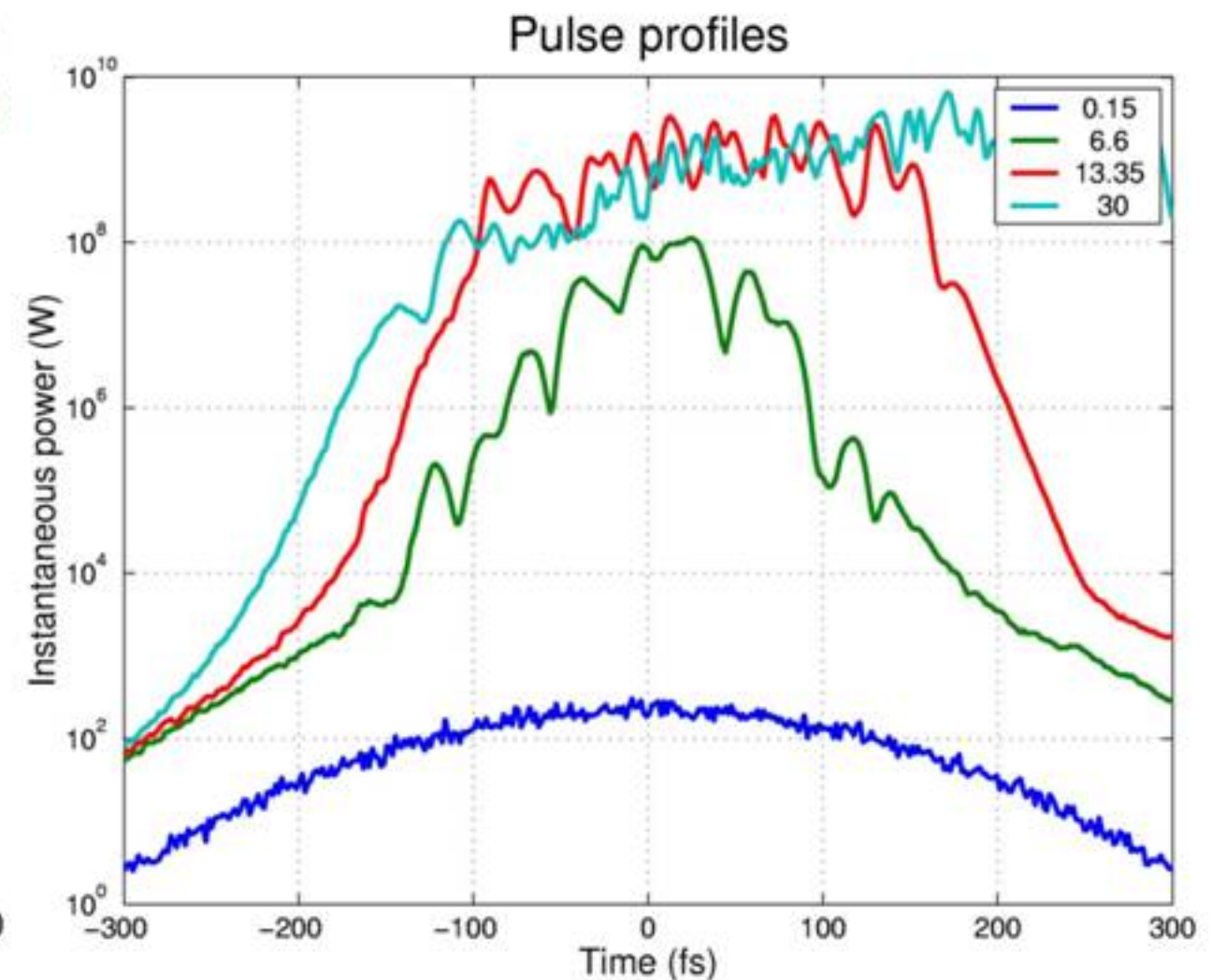
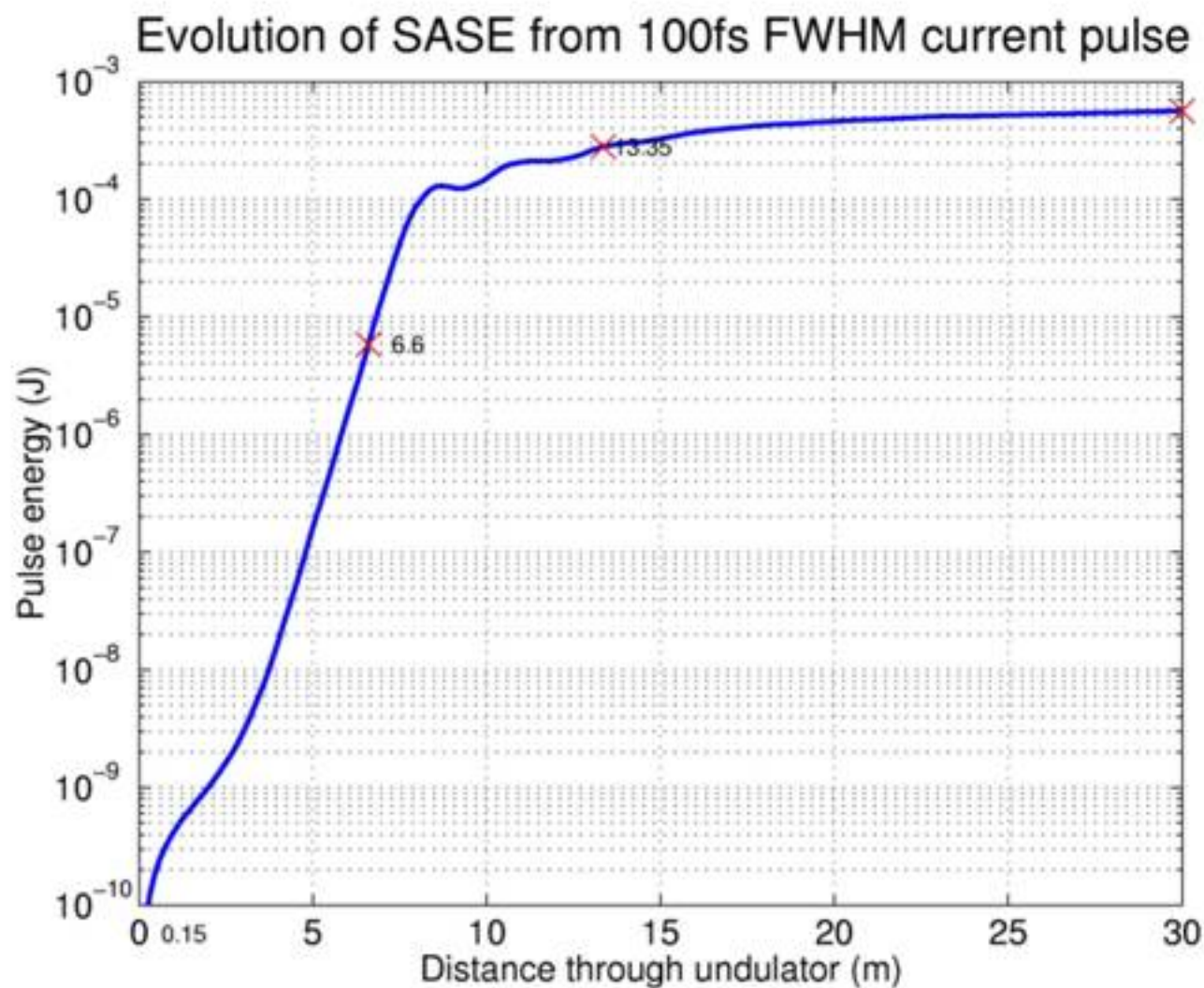
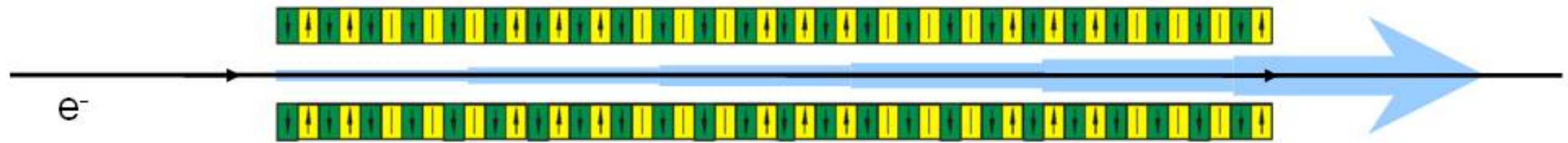
## Potential problems:

- Synchronisation
- Tunability

# Seeding Schemes:

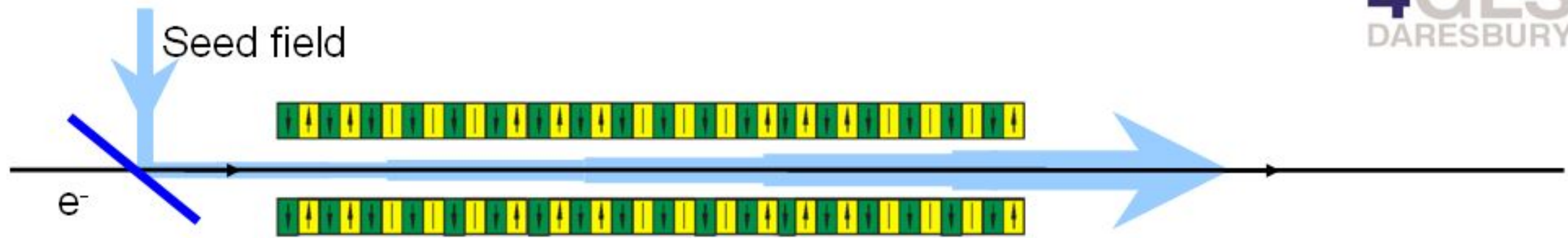
- Self seed of FEL (SASE)
- Direct seed of FEL (HHG as seed)
- 2-stage FEL (DESY)
- Seeded 2-wiggler schemes (HGHG - BNL)
- Low-Q cavity (RAFEL – LANL & DESY)
- Oscillator-Amplifier systems (ENEA)
- 2-beam FEL (Strathclyde/Daresbury)
- Seeding for broad-band FEL (4GLS)

# Genesis simulation of SASE – amplified noise

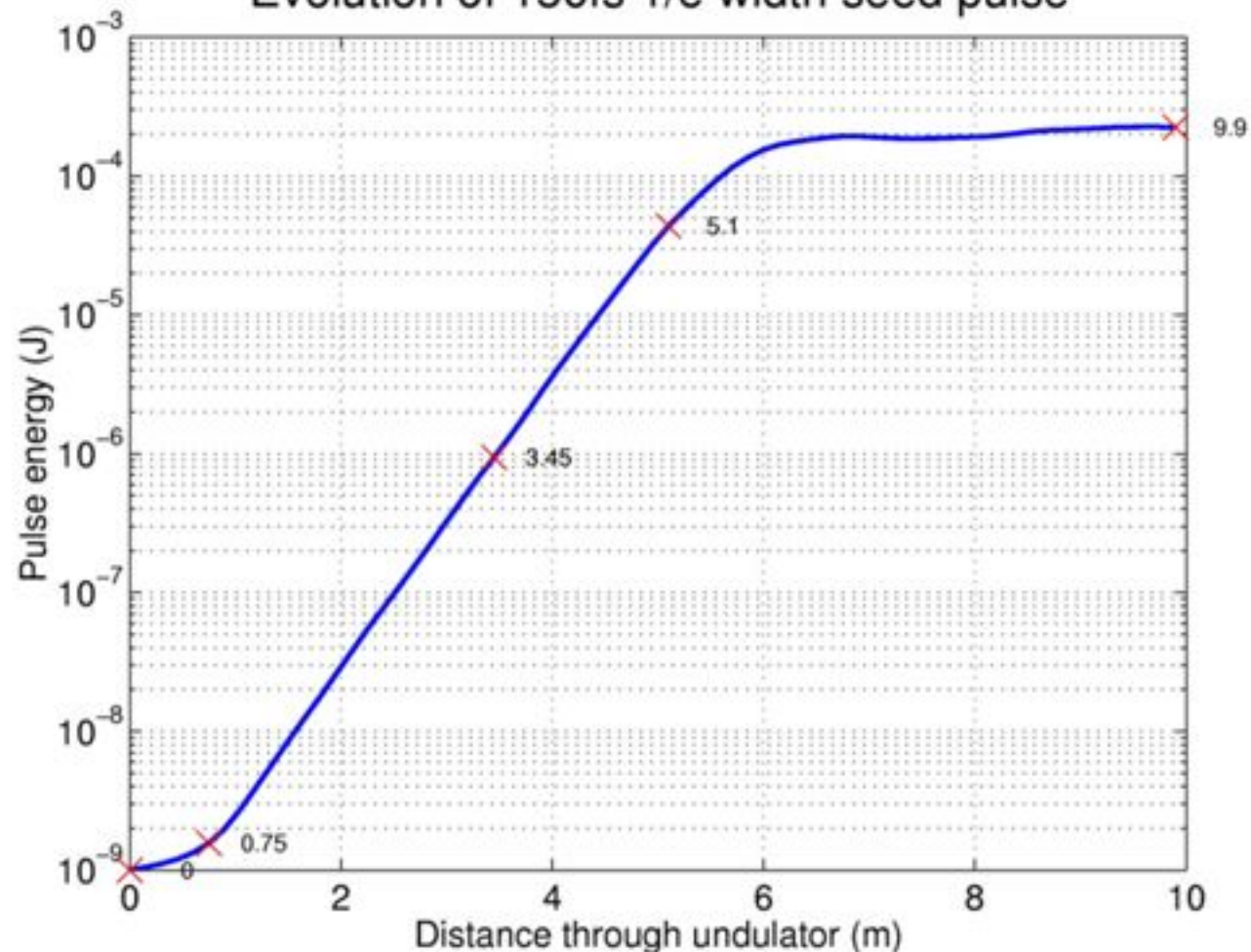




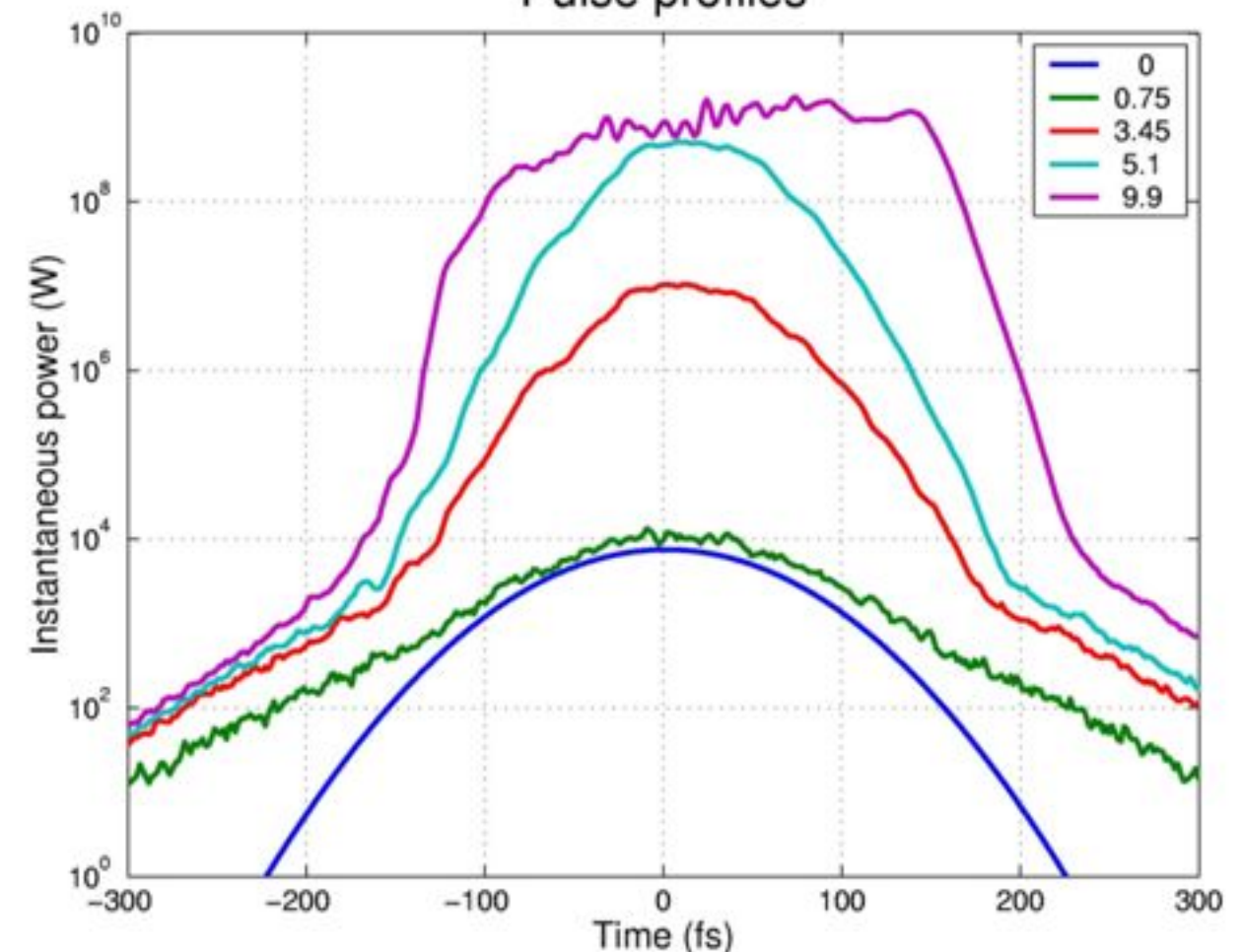
# Genesis simulation of FEL amplifier



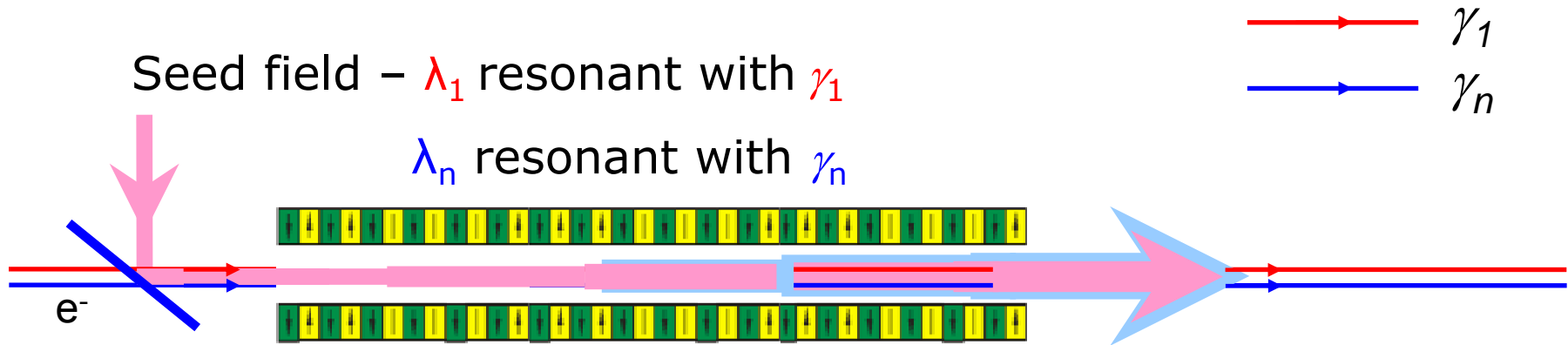
Evolution of 150fs 1/e width seed pulse



Pulse profiles



## 2-beam FEL amplifier\*



By choosing  $\gamma_n = \sqrt{n} \gamma_1$  the fundamental resonant wavelength of beam  $\gamma_n$  is the  $n^{\text{th}}$  resonant harmonic of beam  $\gamma_1$ .

The coherence properties of the seed field will be transferred to the higher energy interaction via the coupled harmonic interaction.

\*B.W.J. McNeil, M.W. Poole & G.R.M. Robb, Phys. Rev. E (in press)

# The Steady-State 1-D Model

$$\left. \begin{aligned} \frac{d\vartheta_j}{d\bar{z}} &= p_j \\ \frac{dp_j}{d\bar{z}} &= - \sum_{h, \text{odd}} F_h (A_h e^{ih\vartheta_j} + c.c.) \end{aligned} \right\} j = 1..N$$

Low energy  
electron motion

$$\frac{dA_h}{d\bar{z}} = F_h \langle e^{-ih\vartheta} \rangle \quad h = 1, 3, 5...$$

All radiation fields

$$A_n \Leftrightarrow A'_1$$

$$\left. \begin{aligned} \frac{d\varphi_j}{dz'} &= \wp'_j \\ \frac{d\wp'_j}{dz'} &= -F_1 (A'_1 e^{i\varphi_j} + c.c.) \end{aligned} \right\} j = 1..N$$

$$\gamma_n = \sqrt{n} \gamma_1$$

High energy  
electron motion

$$\frac{dA'_1}{dz'} = F_1 \langle e^{-i\varphi} \rangle$$

Highest harmonic  
radiation field

$F_k$  - Difference of Bessel function factor



# The Coupled Steady-State 1-D Model

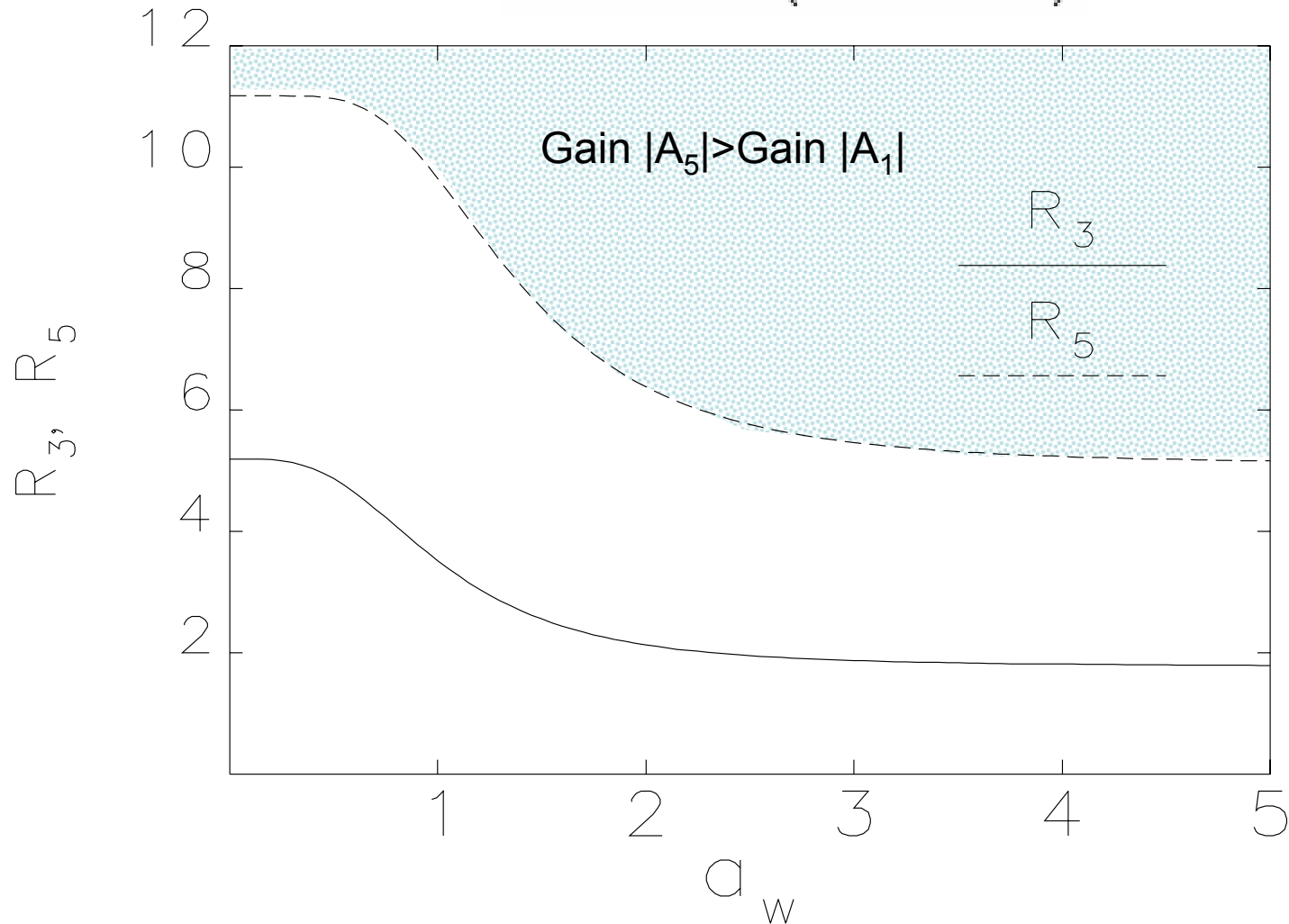
$$\begin{aligned}
 \frac{d\vartheta_j}{d\bar{z}} &= p_j \\
 \frac{d\varphi_j}{d\bar{z}} &= \wp_j \\
 \frac{dp_j}{d\bar{z}} &= -\frac{1}{c_1} \sum_{h, \text{odd}}^n F_h (A_h e^{ih\vartheta_j} + c.c.) \\
 \frac{d\wp_j}{d\bar{z}} &= -(F_1 A_n e^{i\varphi_j} + c.c.) \\
 \frac{dA_h}{d\bar{z}} &= S_{h\vartheta} \quad h < n \\
 \frac{dA_n}{d\bar{z}} &= S_\varphi + S_{n\vartheta},
 \end{aligned}$$

$$\begin{aligned}
 c_1 &= \frac{\sqrt{R_n}}{n} \\
 c_2 &= \frac{\sqrt{R_n}}{\sqrt{n}} \\
 R_n &\equiv I_n / I_1
 \end{aligned}$$

$$\begin{aligned}
 S_{k\vartheta} &\equiv \frac{1}{c_2} F_k \langle e^{-ik\vartheta} \rangle \\
 S_\varphi &\equiv F_1 \langle e^{-i\varphi} \rangle
 \end{aligned}$$

Constant of motion:  $\sum_{h, \text{odd}}^n |A_h|^2 + \frac{\langle p \rangle}{\sqrt{n}} + \langle \wp \rangle$

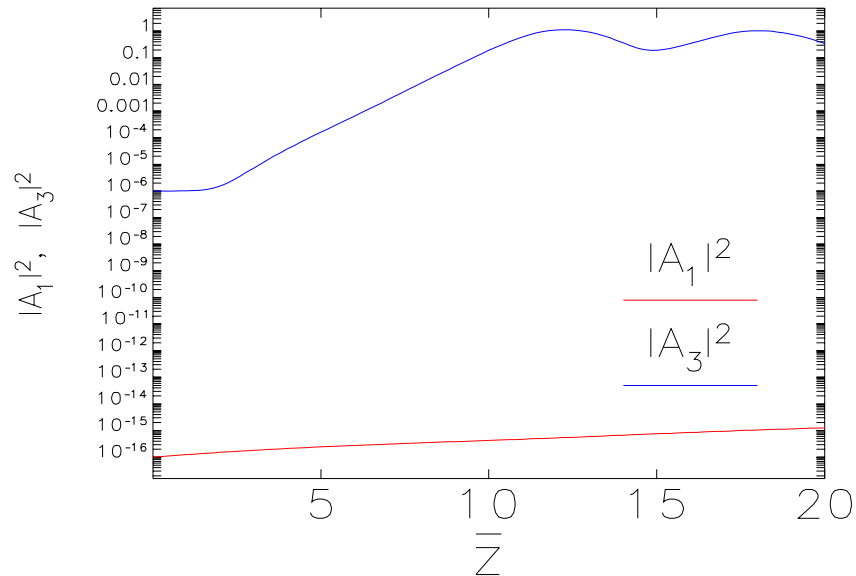
Linear theory:  $R_n > n\sqrt{n} \left( 1 - \frac{n|F_n|^2}{|F_1|^2} \right)$



# No low energy beam ( $R_n \gg 1$ ):

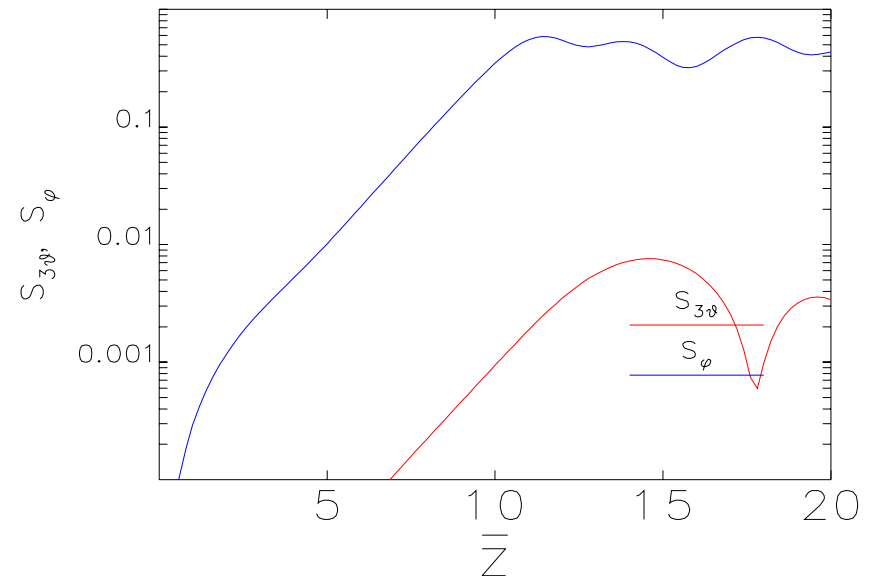
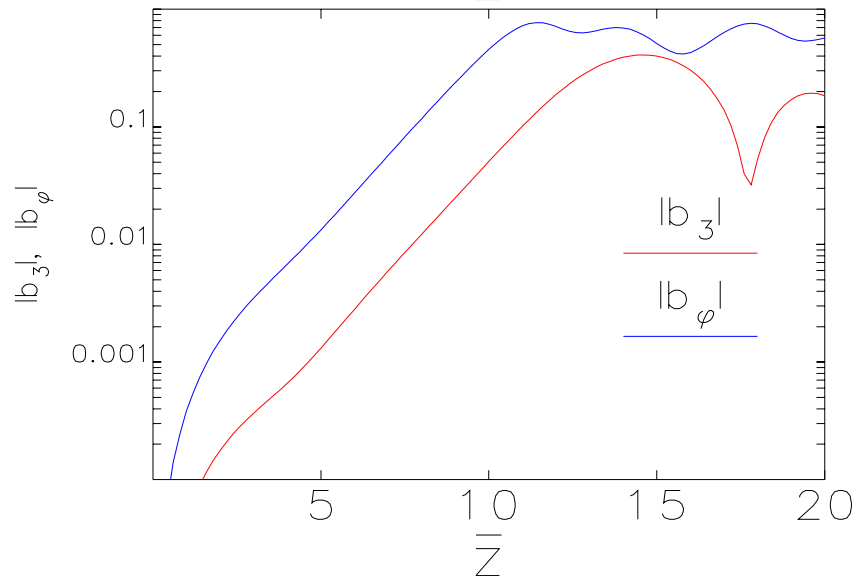


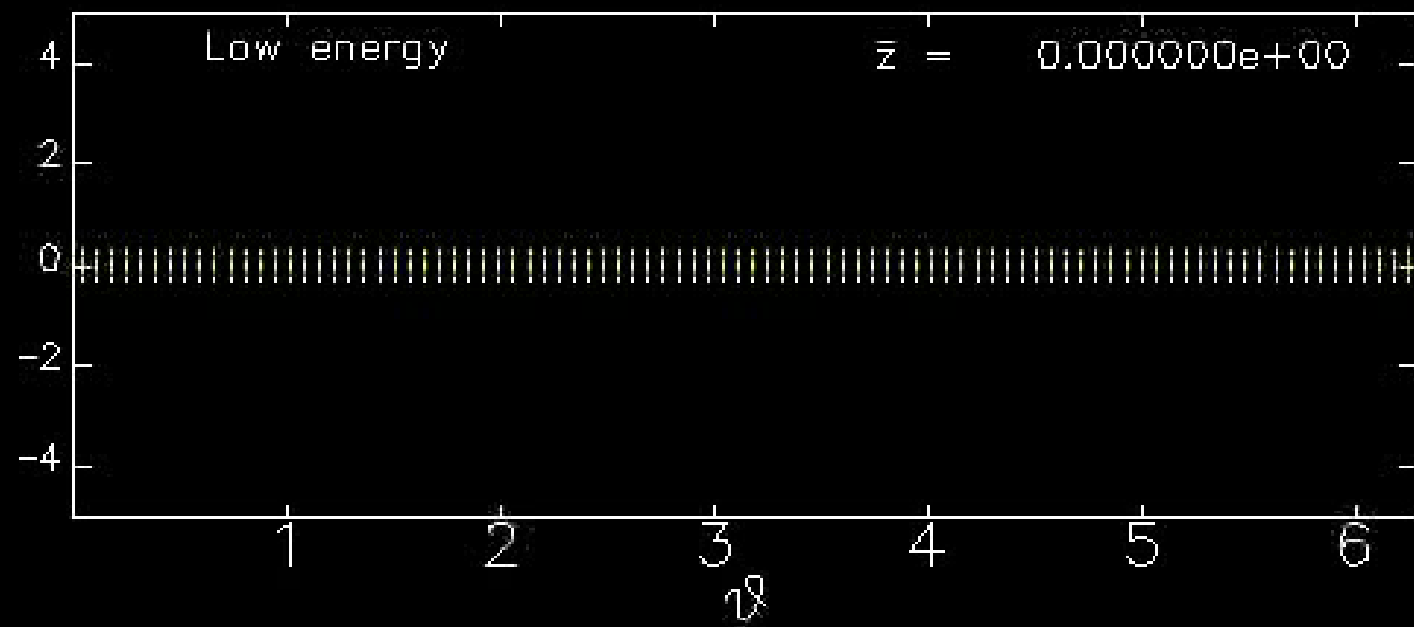
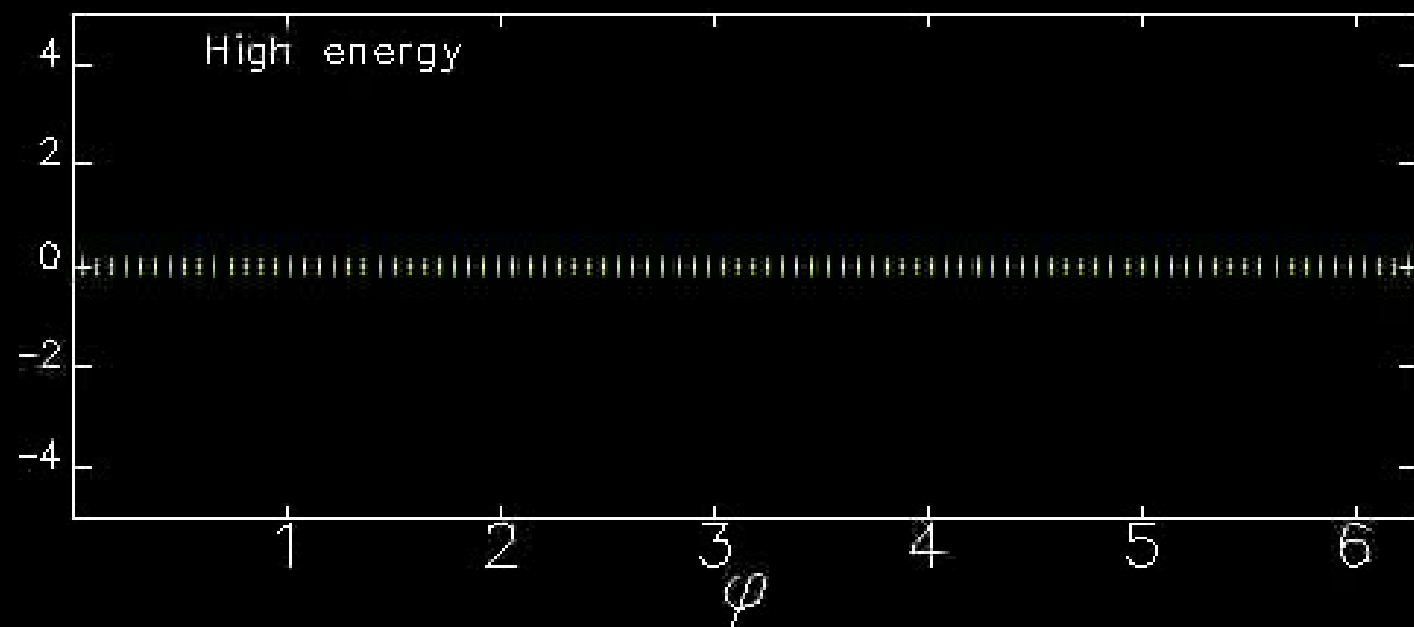
Here  $R_3 = 10^3$



$$S_{k\vartheta} \equiv \sqrt{\frac{n}{R_n}} F_k \langle e^{-ik\vartheta} \rangle$$

$$S_\varphi \equiv F_1 \langle e^{-i\varphi} \rangle$$



$\Omega$  $\Omega$ 

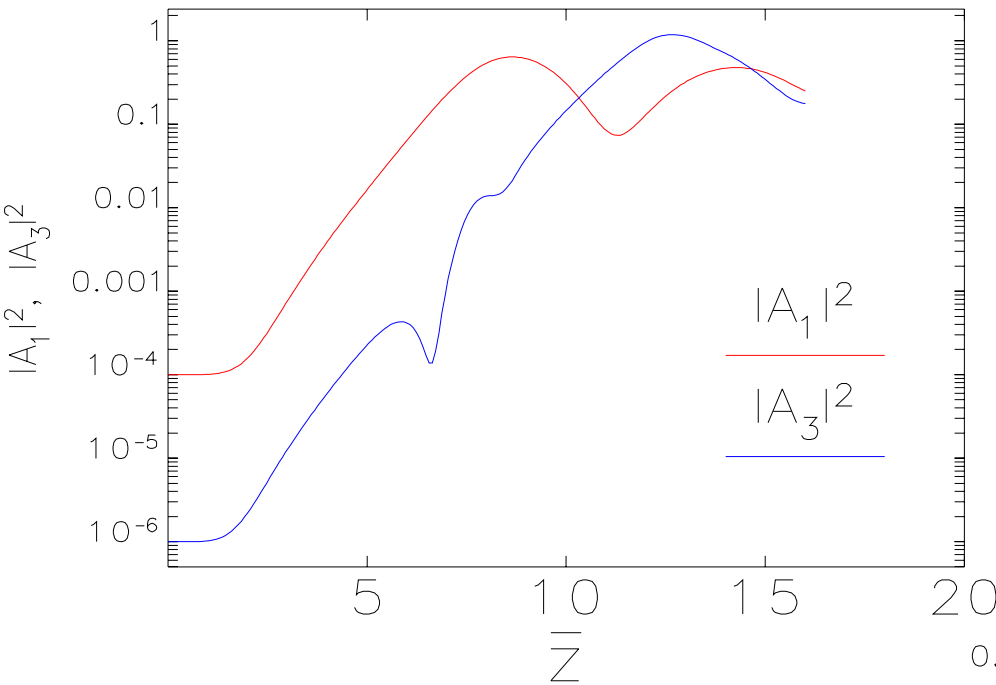
# The coupled 2-beam interaction



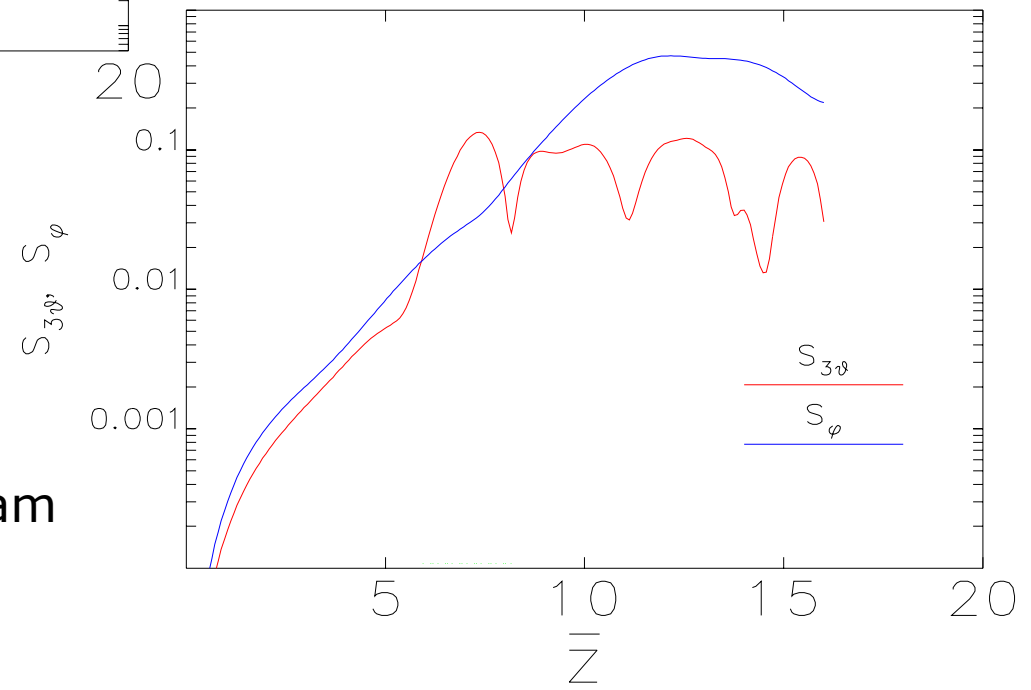
$$n = 3$$

$$R_3 = 5$$

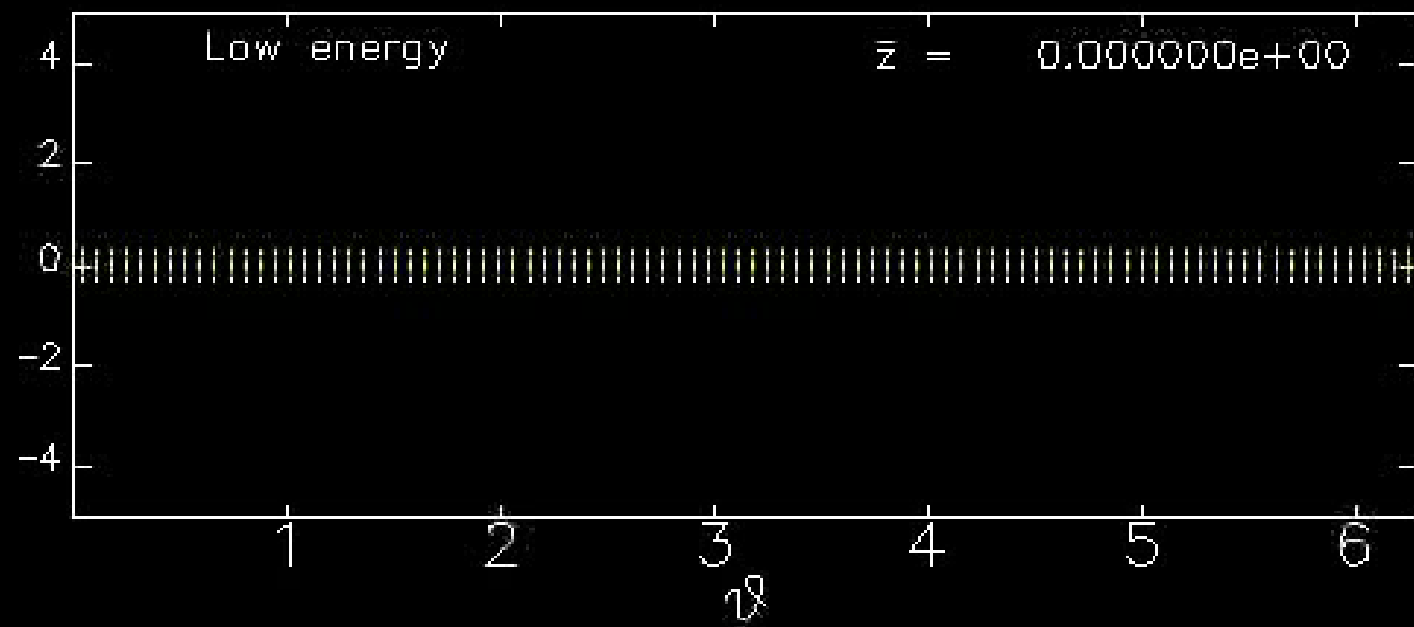
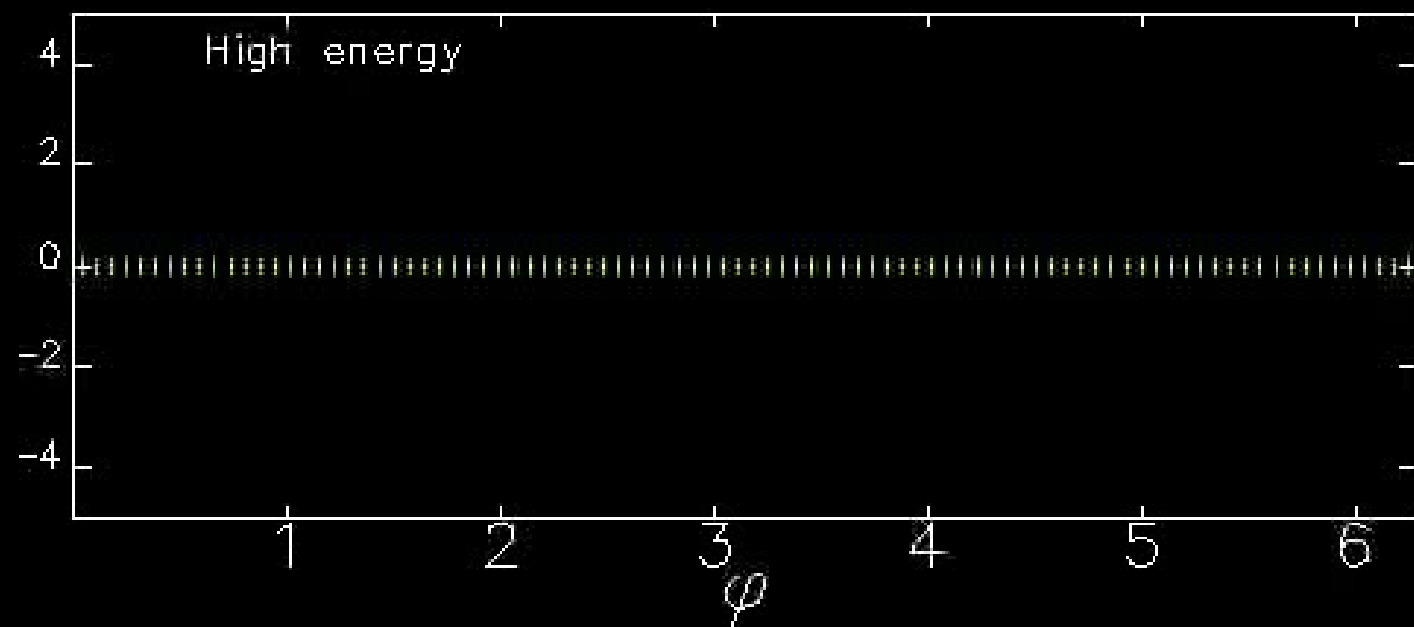
'Seeding phase'...



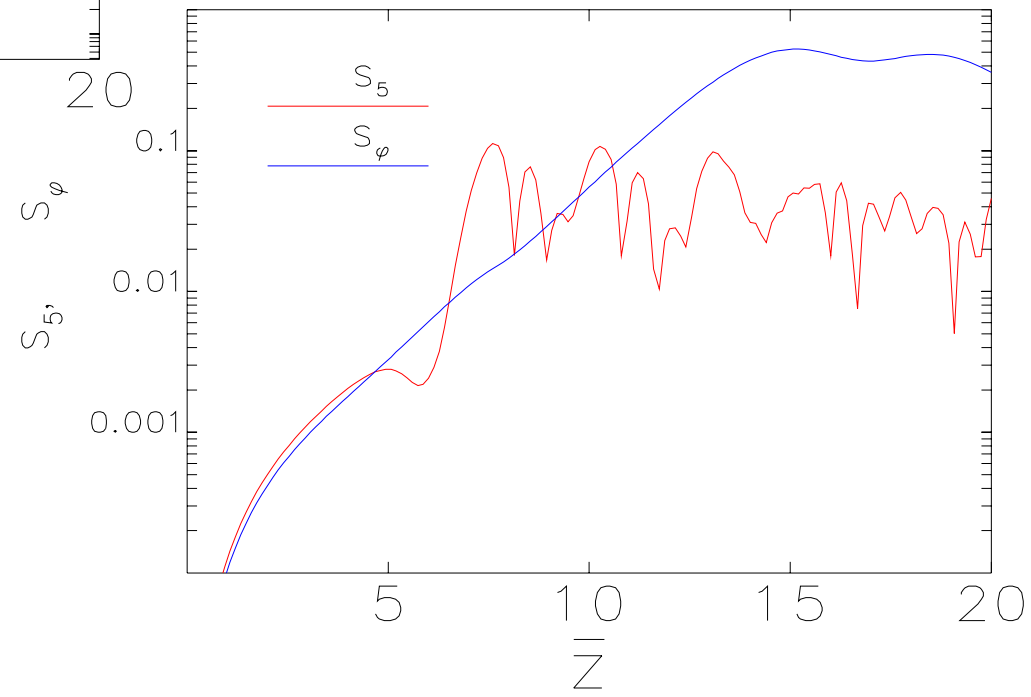
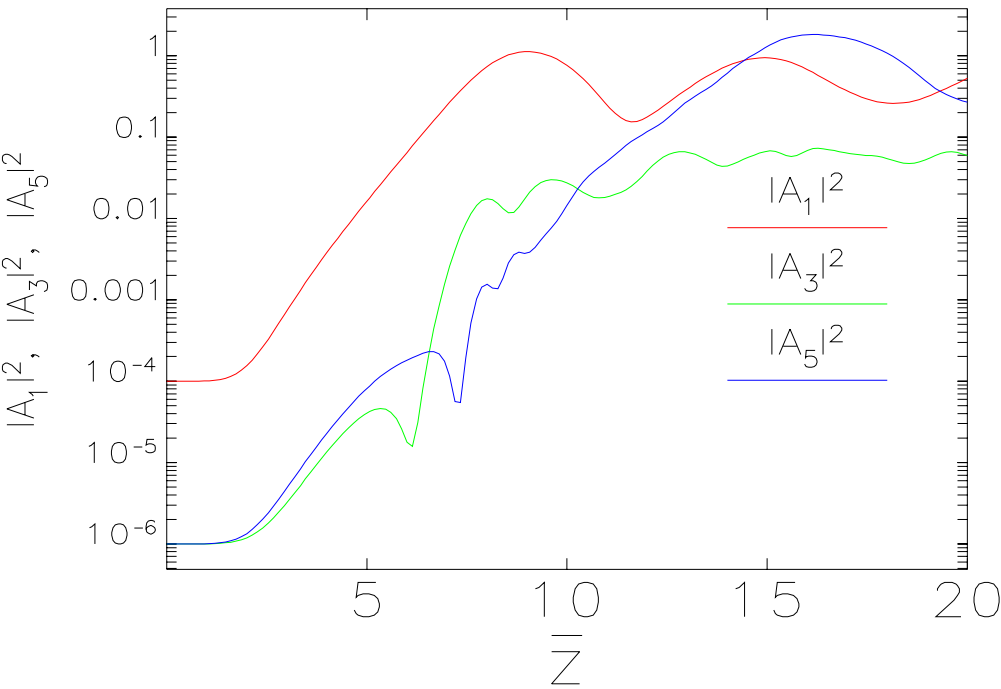
...driven by lower energy beam

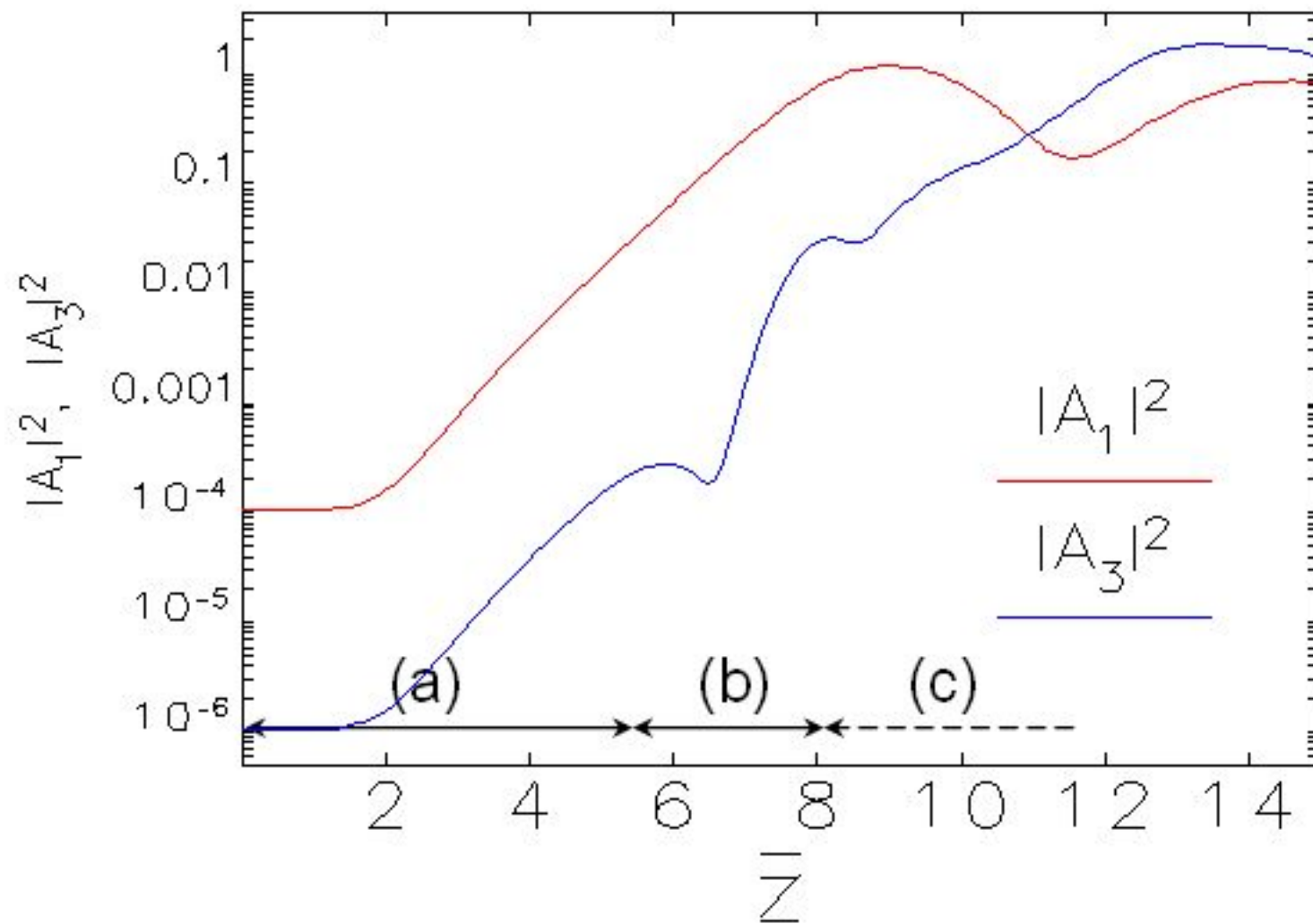




$\Omega$  $\Omega$ 

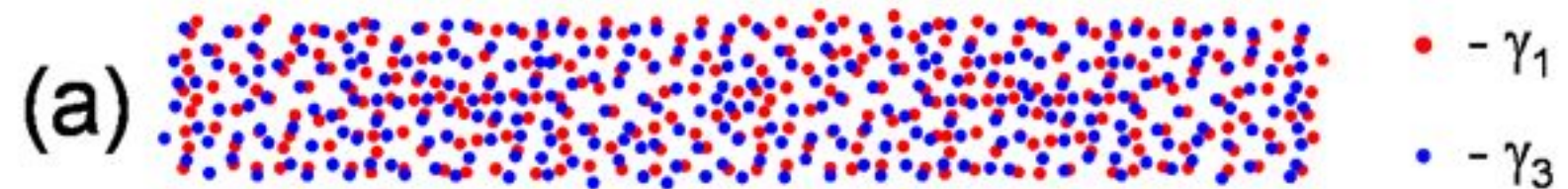
# The coupled 2-beam interaction (n=5)



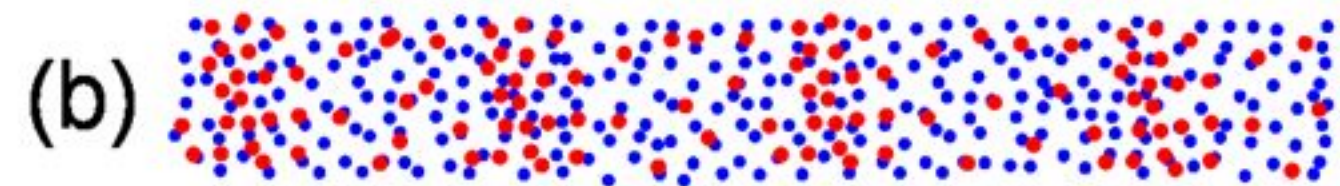


# Summarising

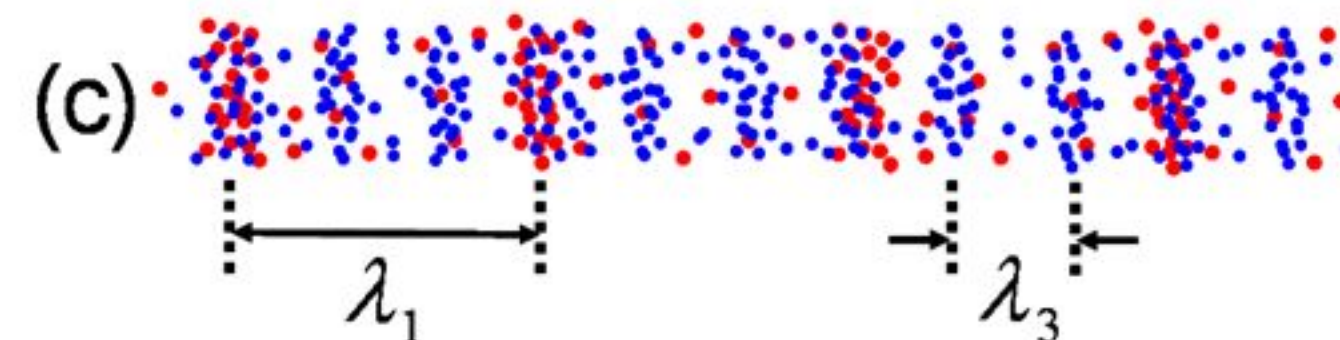
Linear regime – small bunching low energy beam driving  $|A_1|$  &  $|A_3|$



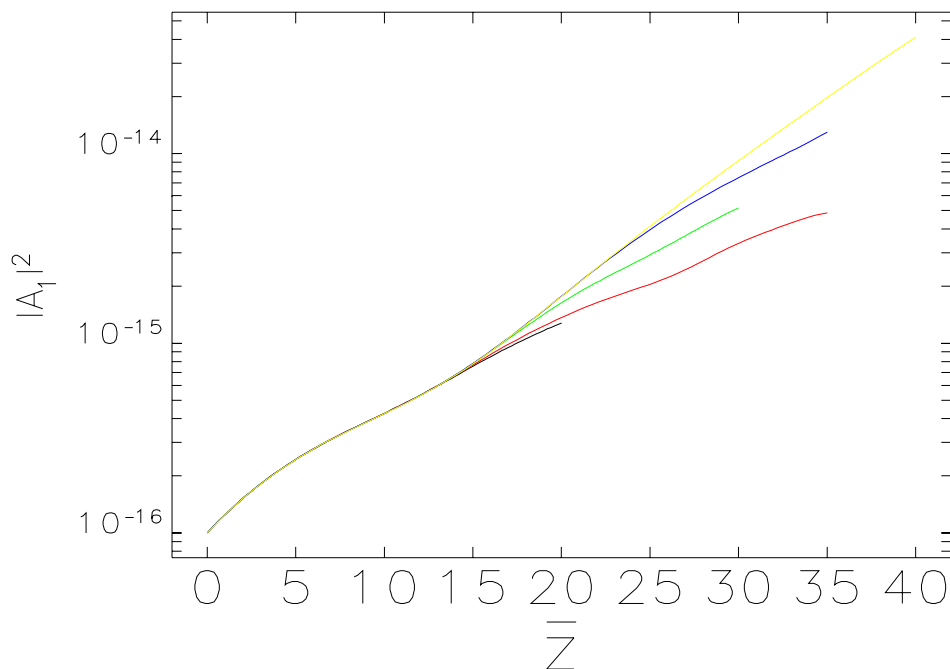
Nonlinear regime – larger bunching low energy beam driving  $|A_1|$  &  $|A_3|$



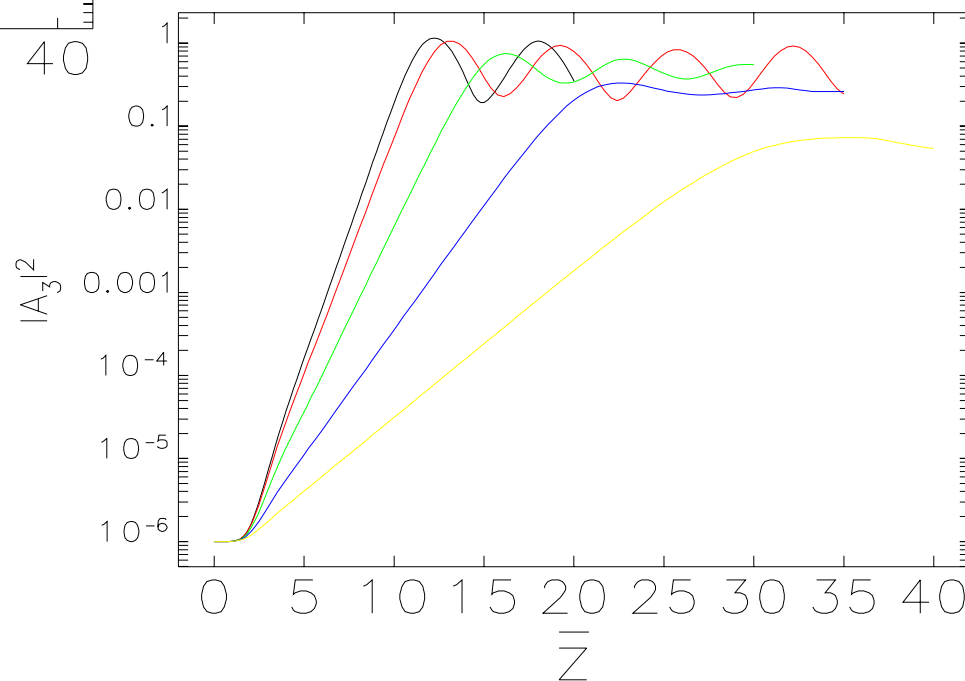
Nonlinear regime – larger bunching high energy beam driving  $|A_3|$



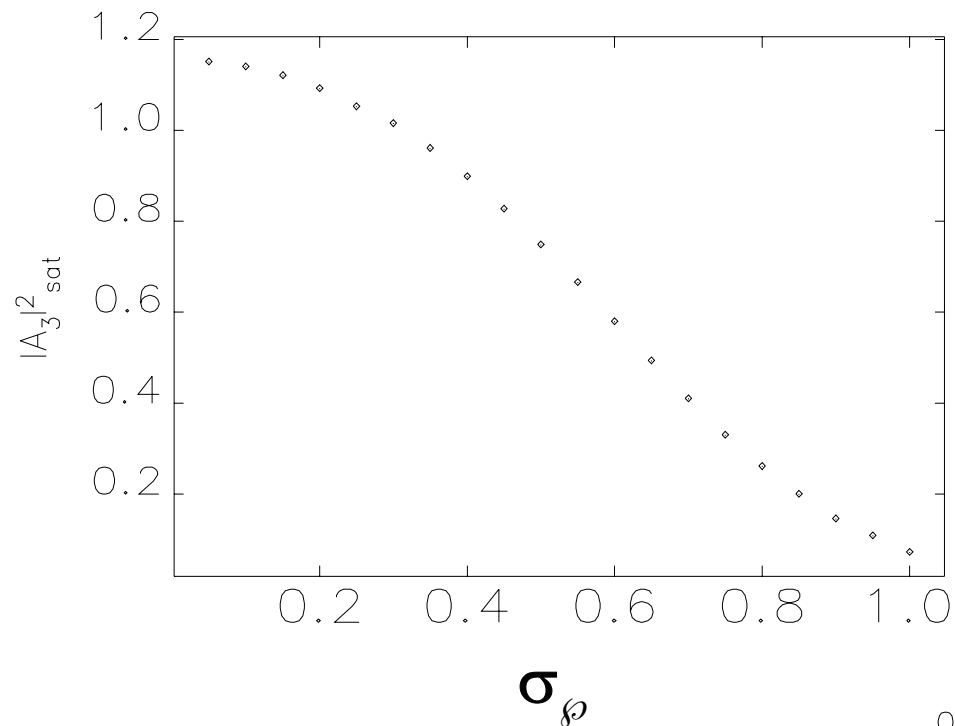
# Effects of energy spread ( $R_3=1000$ )



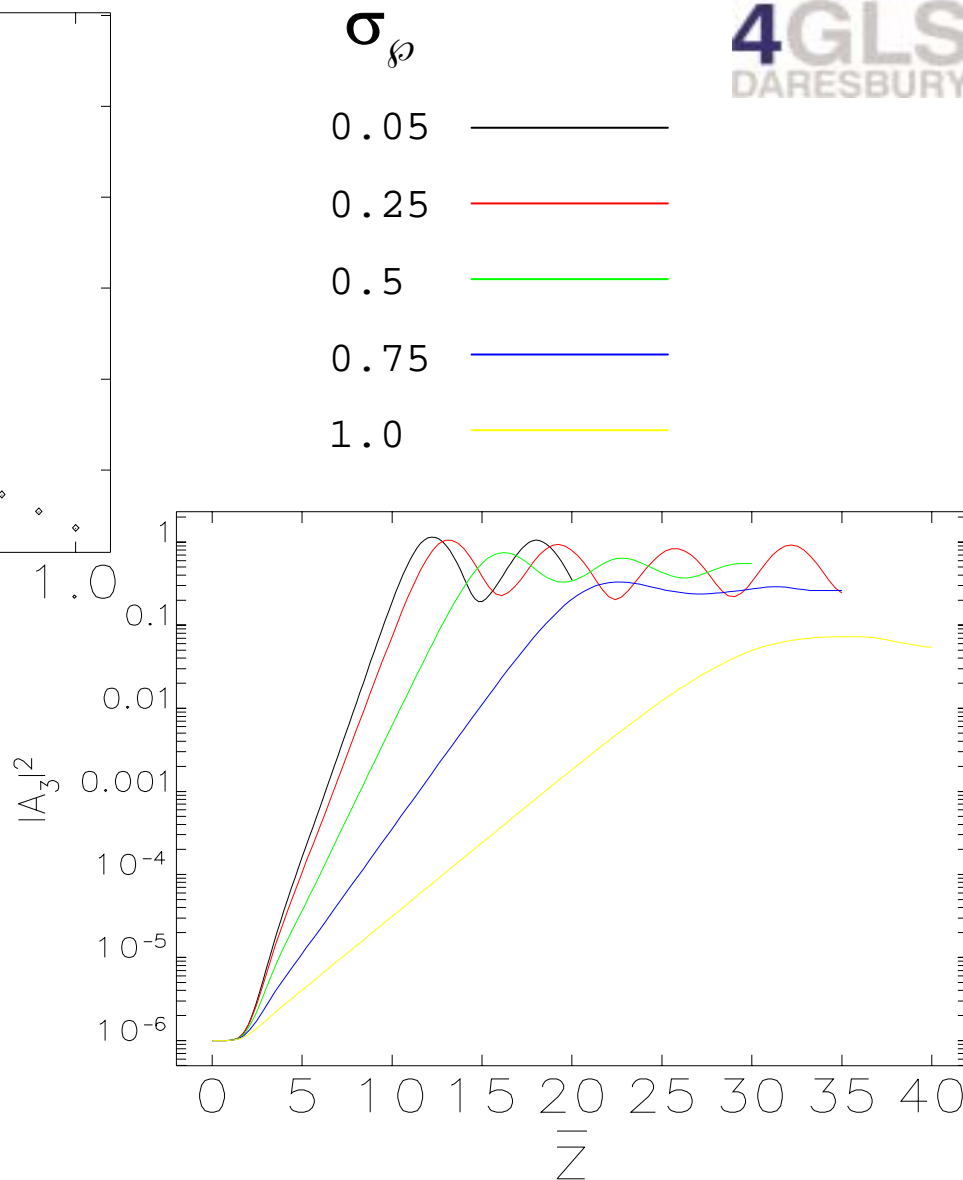
$$\sigma_p = 0.1$$



# Effects of energy spread ( $R_3=1000$ )

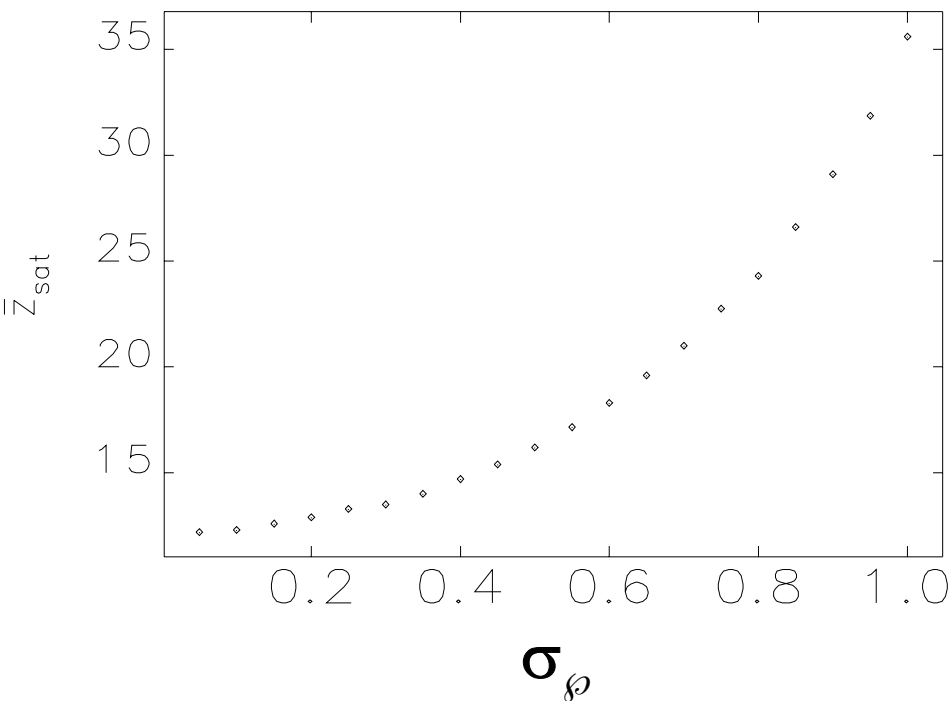


$$\sigma_p = 0.1$$

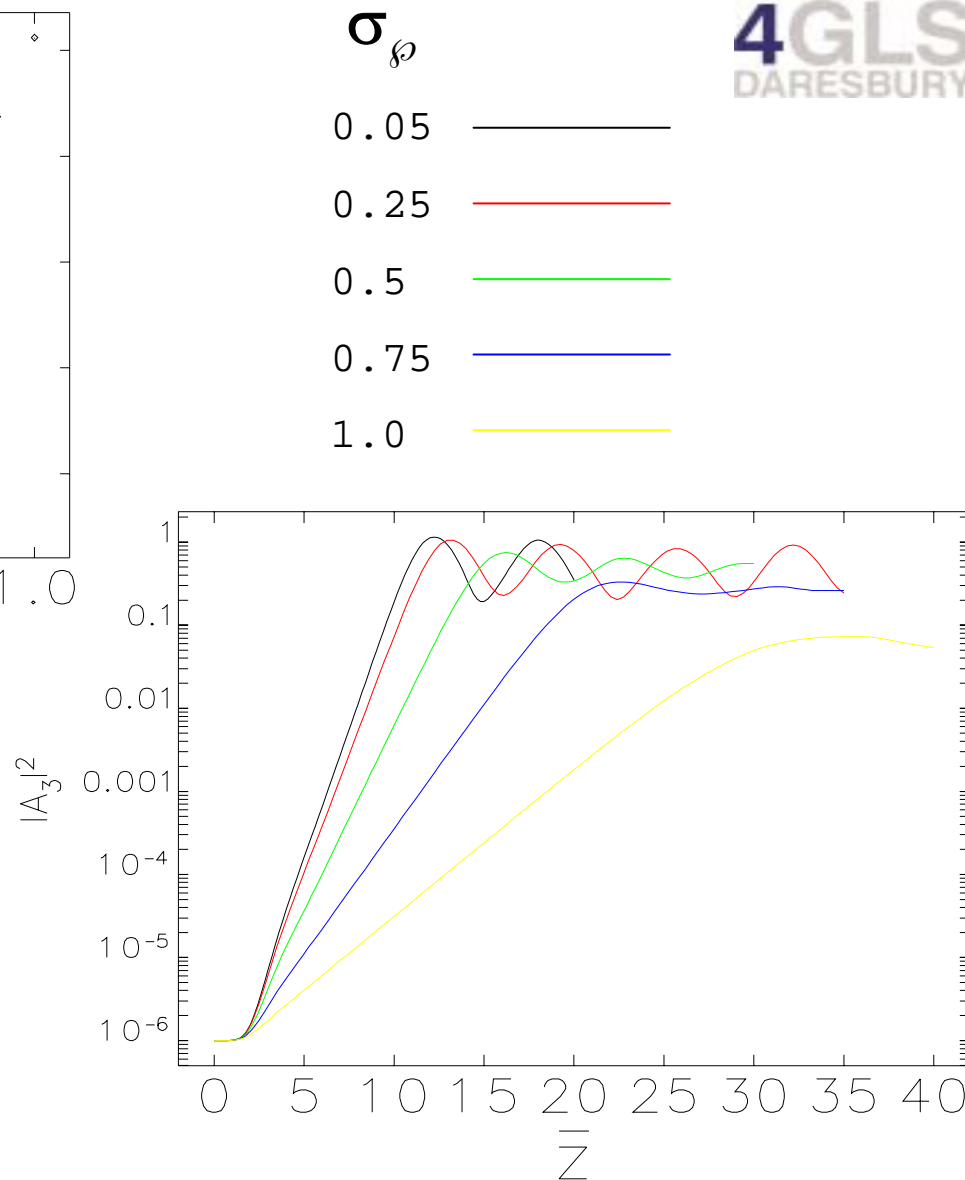




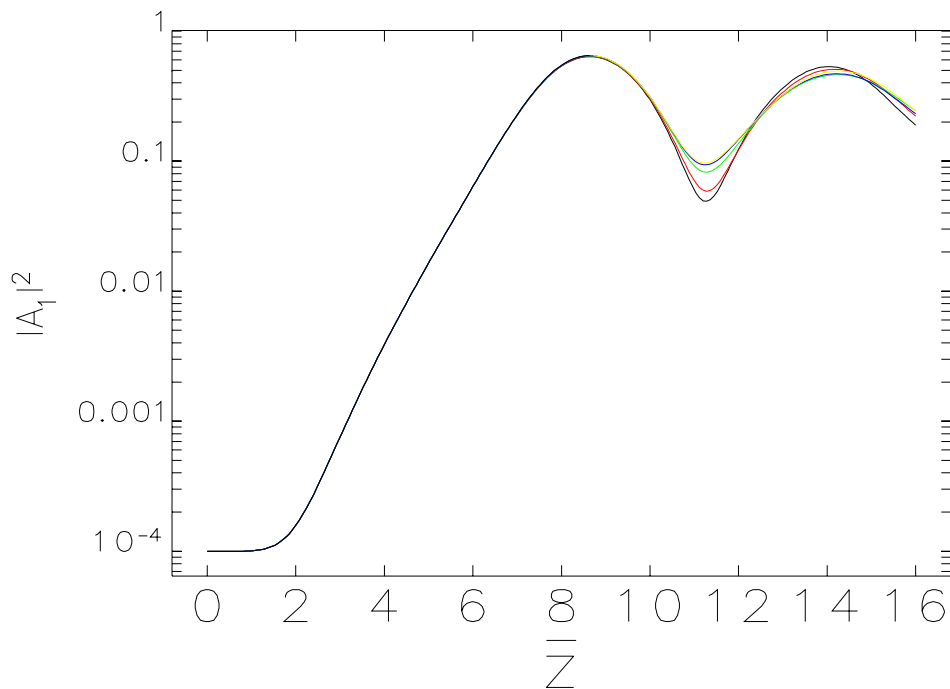
# Effects of energy spread ( $R_3=1000$ )



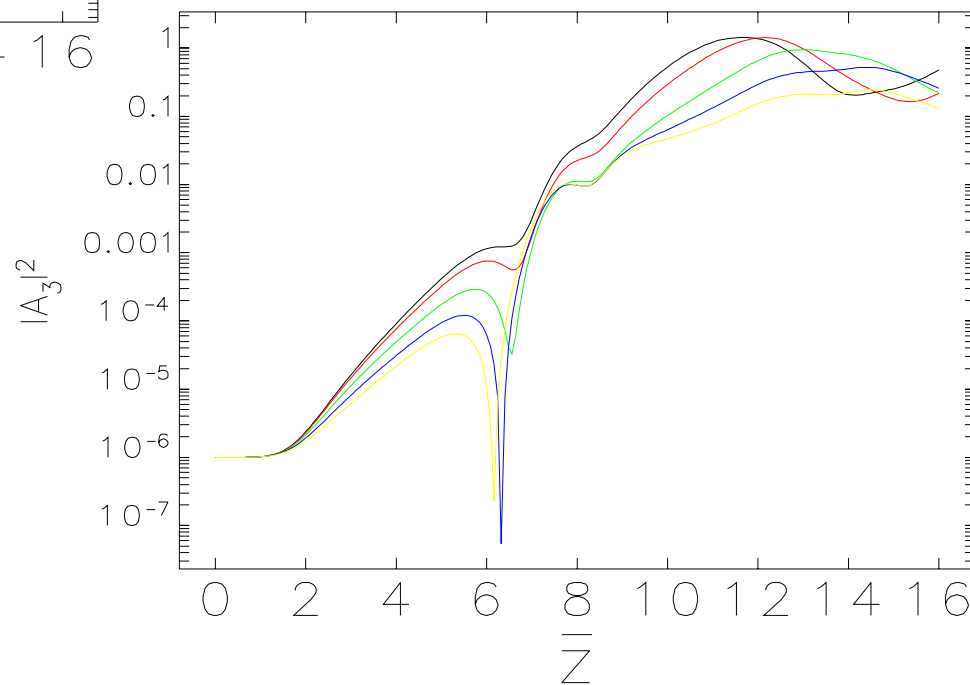
$$\sigma_p = 0.1$$



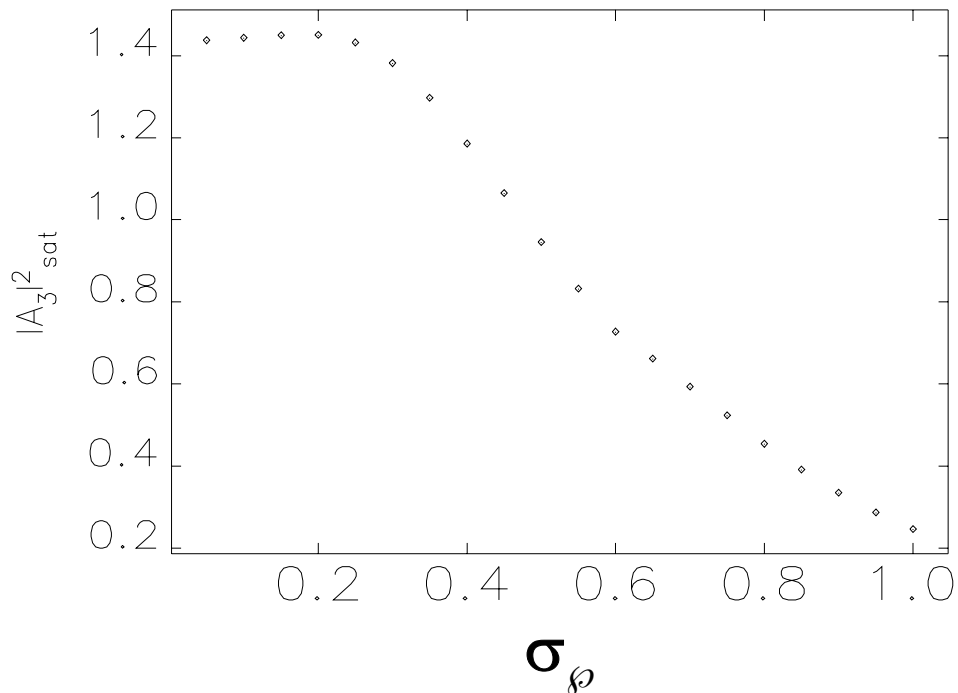
# Effects of energy spread ( $R_3=5$ )



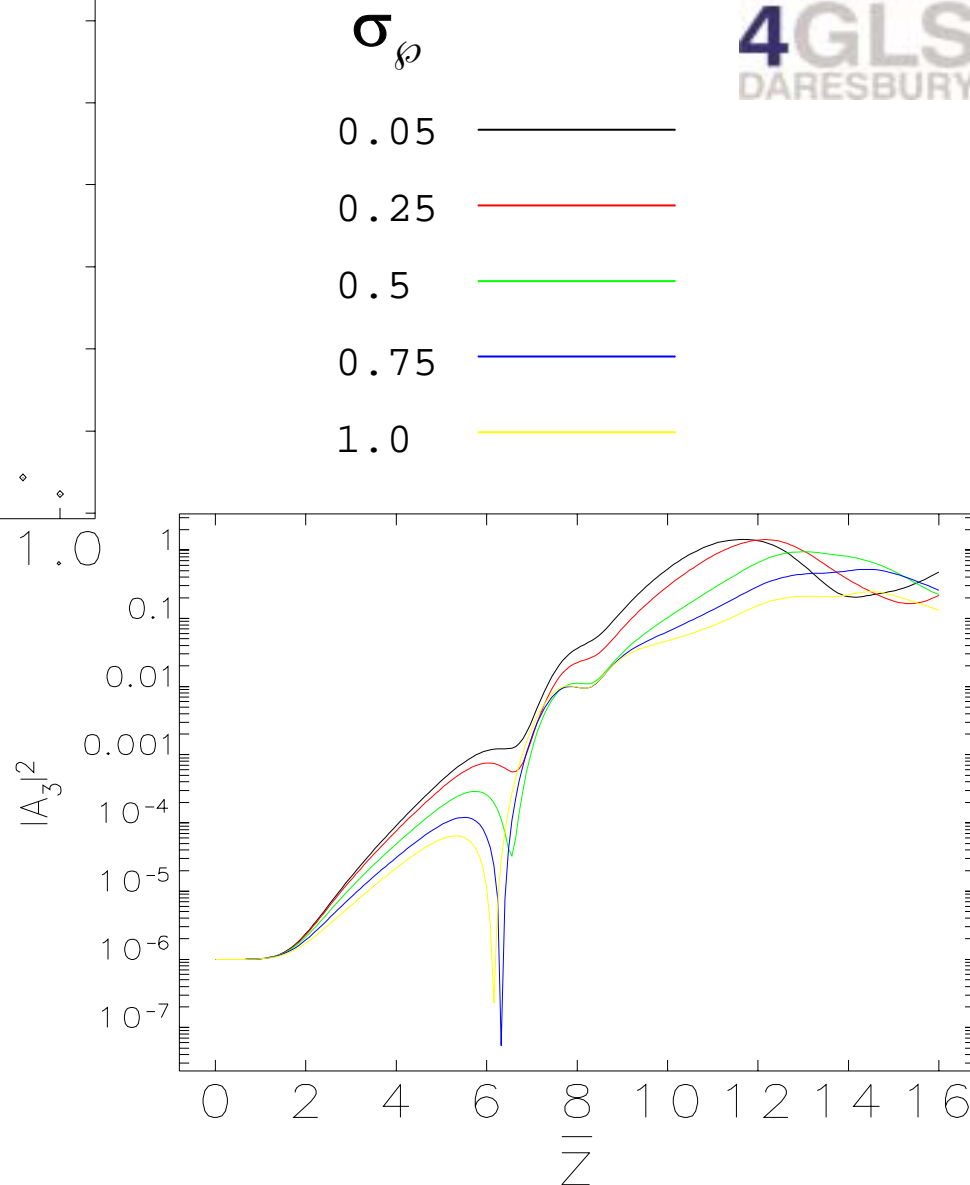
$$\sigma_p = 0.1$$



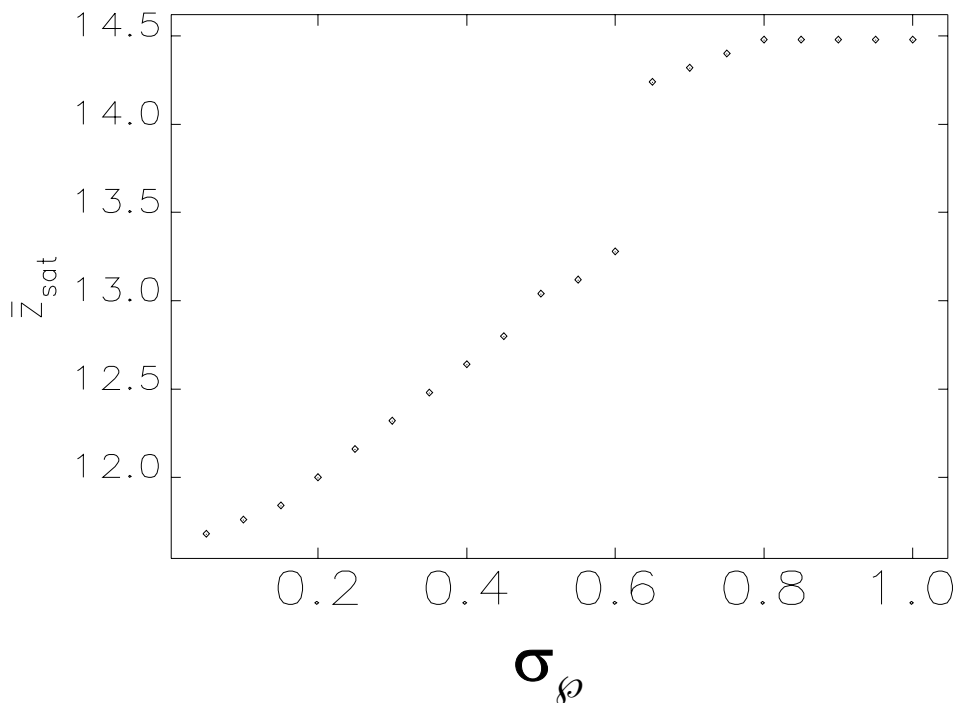
# Effects of energy spread ( $R_3=5$ )



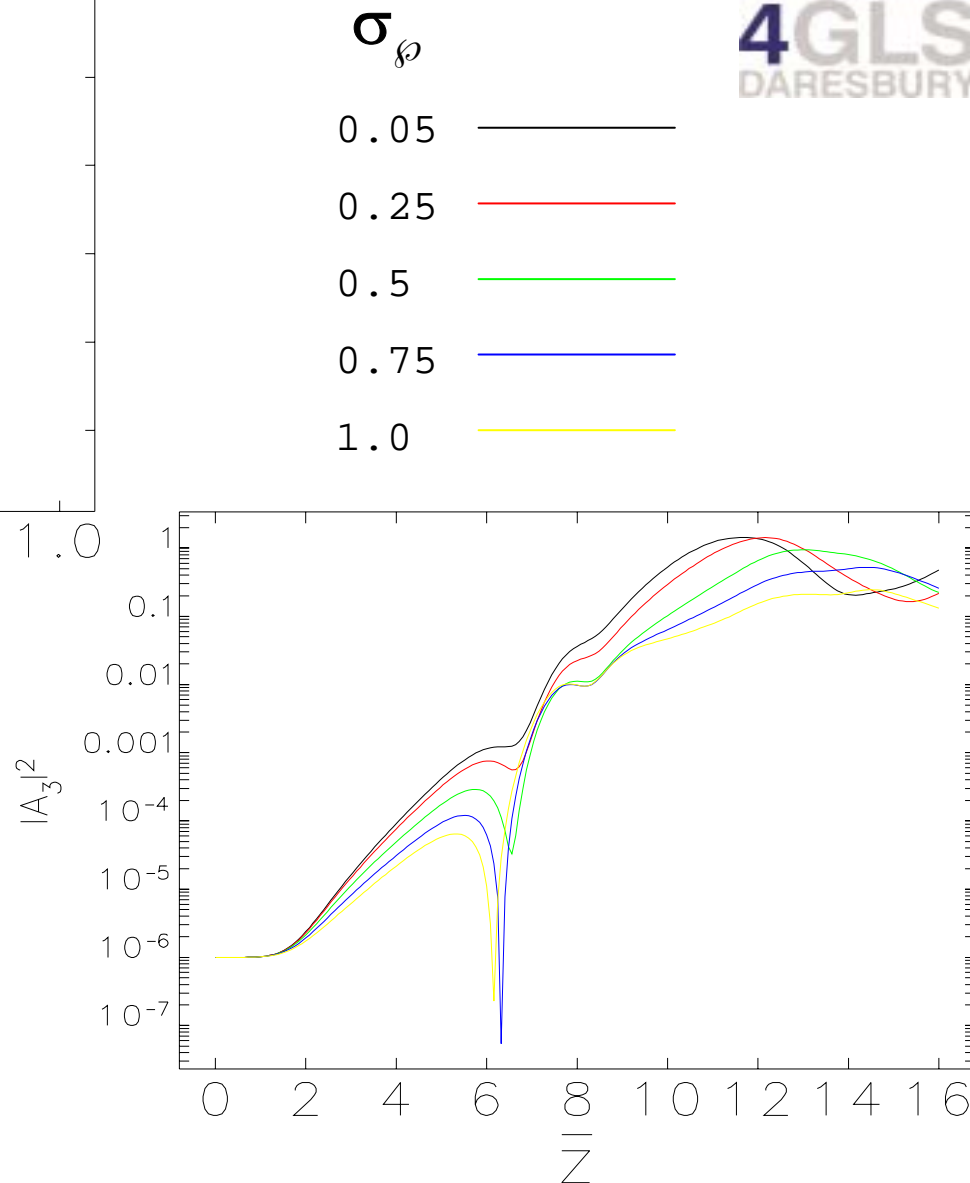
$$\sigma_p = 0.1$$



# Effects of energy spread ( $R_3=5$ )



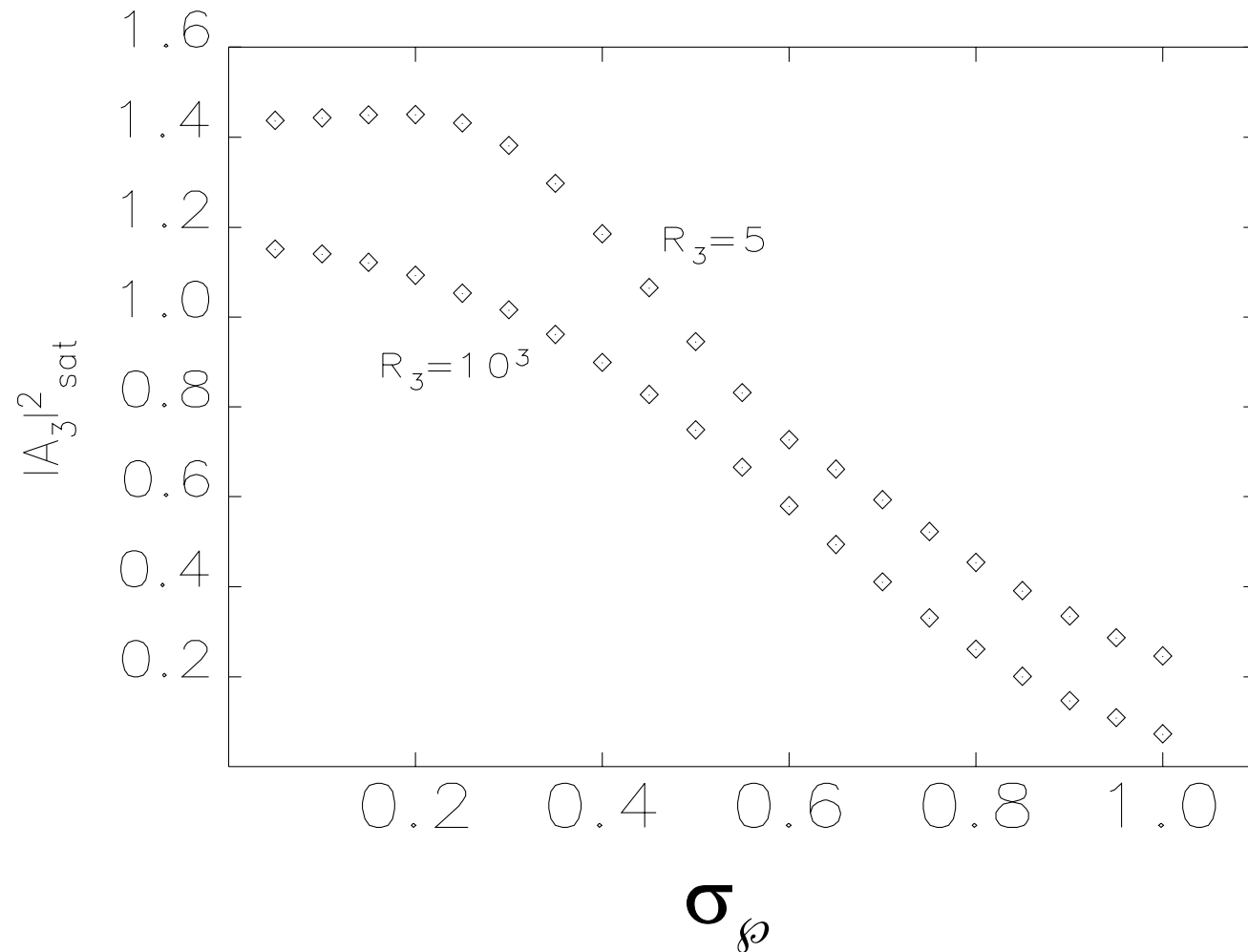
$$\sigma_p = 0.1$$



# Energy spread summary:



## Harmonic saturation intensity



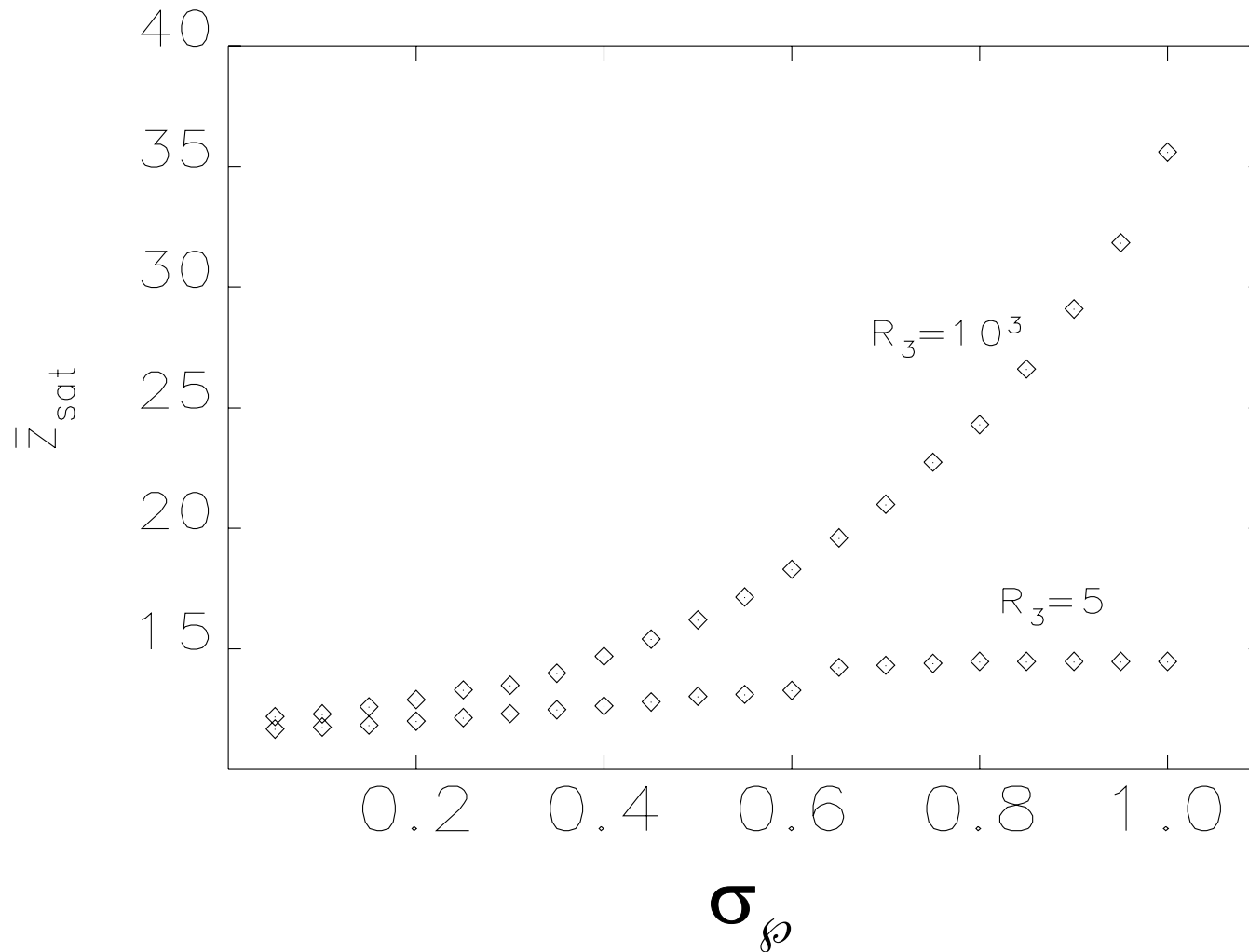


# Energy spread summary:

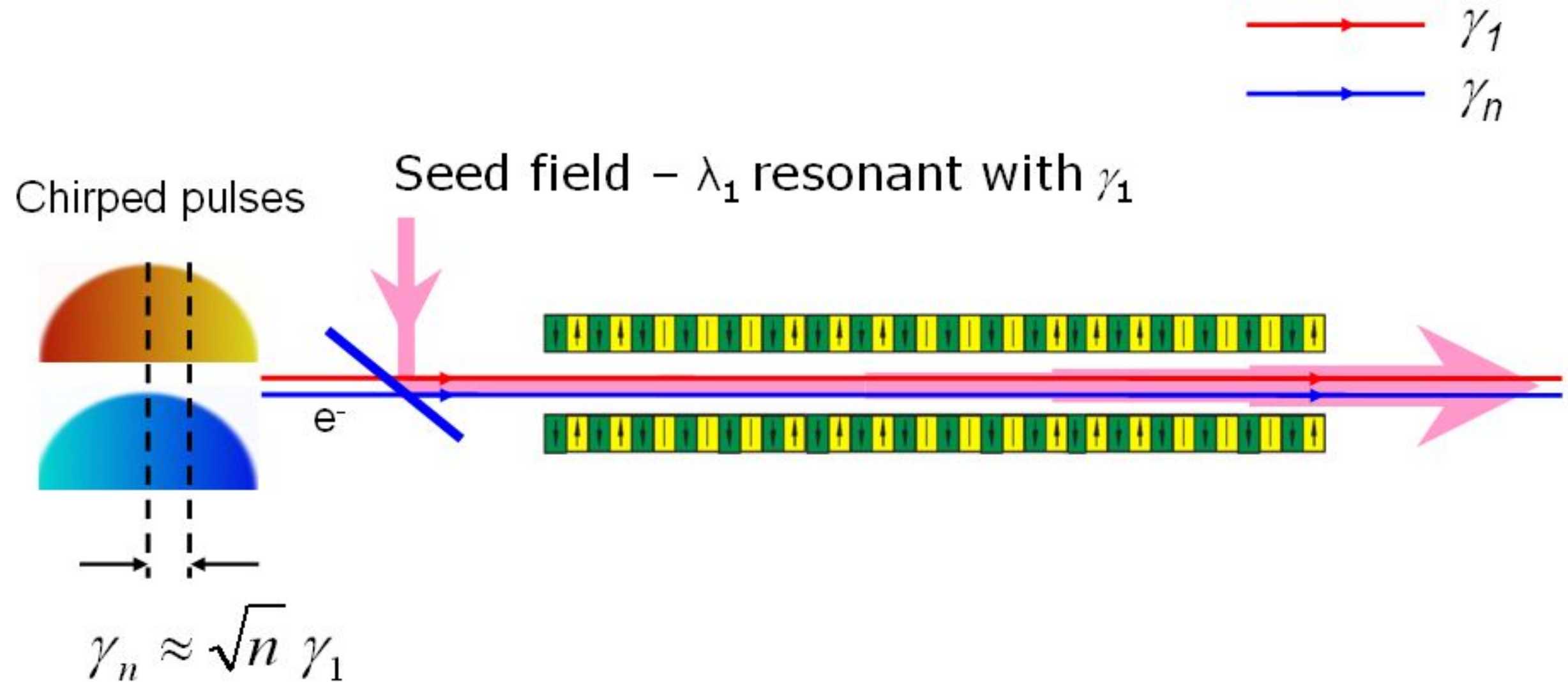


**4GLS**  
DARESBUY



## Harmonic saturation length



# 2-beam FEL pulses

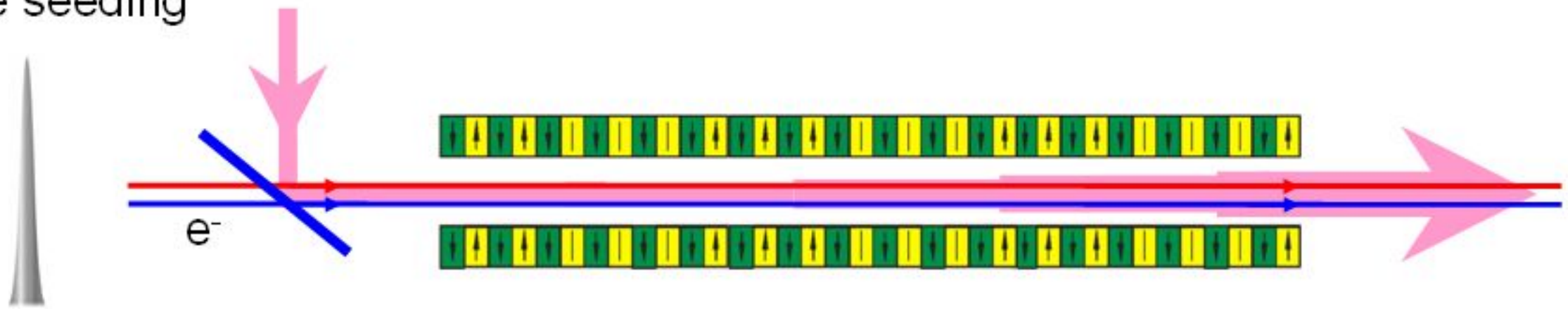


## 2-beam FEL pulses

  $\gamma_1$   
  $\gamma_n$

Effective short  
pulse seeding

Seed field –  $\lambda_1$  resonant with  $\gamma_1$



Note that relative slippage between electron pulses < slippage with respect to light

## Conclusions:

- First proof of principle numerical simulations of 2-beam FEL
- Potential seeding mechanism for shorter wavelengths
- Potential reduction in e<sup>-</sup>-beam quality requirements
- Added extra dimension to FEL physics:
  - Hybrid 'HGHG' schemes
  - Interactions with exotic wigglers...
- Feasibility?? – you tell me...