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**Conference on**
**Ultrafast Transmission Systems in Optical Fibres**

**13 - 17 February 1995**

# *Influence of Soliton Interaction on Soliton Transmission System Performance and Design*

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# Influence of Soliton Interaction on Soliton Transmission System Performance and Design

*Thierry GEORGES*

FRANCE TELECOM - CNET LANNION B

# Outlines of the talk

- Introduction
- Modelling
- Interaction reduction
- Influence on the jitter
- System design
- Conclusion

[redacted]

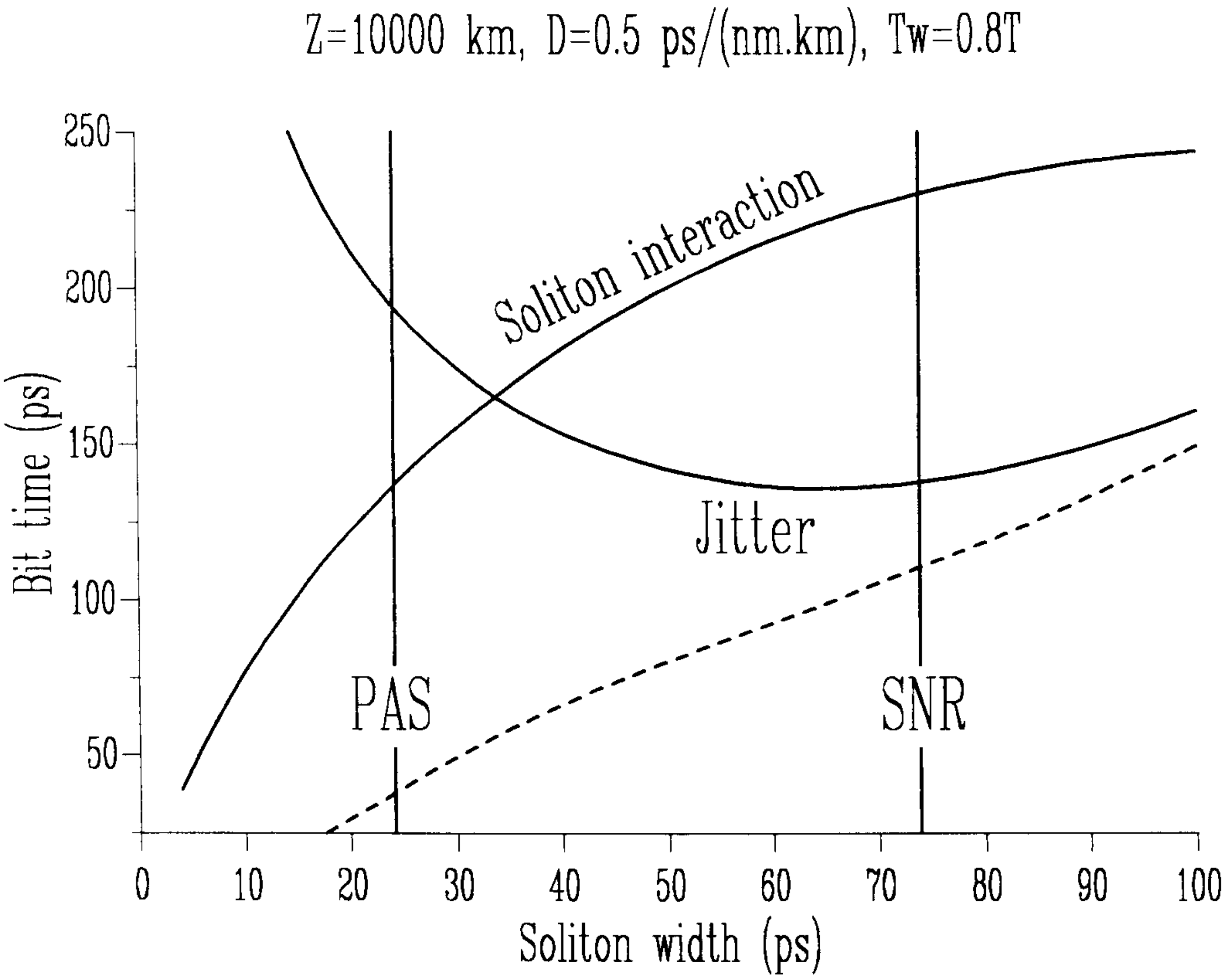
# Limits of soliton transmission systems

❶ Signal to noise ratio (SNR) $\tau<\tau_{max}$

❷ Path-averaged soliton (PAS) $\tau>\tau_{min}$

❸ Soliton interaction $T>f_{int}(\tau,Z,\ldots)$

❹ Jitter $T>f_{jit}(\tau,Z,\ldots)$


Z=10000 km, D=0.5 ps/(nm.km), Tw=0.8T
250
200
150
100
50
Bit time (ps)
0
10
20
30
40
50
60
70
80
90
100
Soliton width (ps)
Soliton interaction
Jitter
PAS
SNR

[redacted]

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# Normalization - 1 -

- **Time** **(ps) :** $\tau_c = \tau / 1.76$
- **Distance** **(km) :** $Z_c = 0.25\ \tau^2 / D$
- **Power** **(W) :** $P_s = 1.5\ D / \tau^2$
- **Energy** **(pJ) :** $E_c = 0.85\ D / \tau$

D in ps/(nm.km)

[redacted]

# Normalization - 2 -

- **Soliton separation :** $2\alpha=\alpha_1-\alpha_2=1.76\ T/\tau$

- **Distances :** $\Theta=|\rho|z$

$$\rho^2=4\exp(-2a-2i\Phi)+a^2 \quad \text{(after Gordon)}$$

$$2\Phi=\Phi_1-\Phi_2 \qquad 2a=A_1-A_2$$

# Theoretical studies

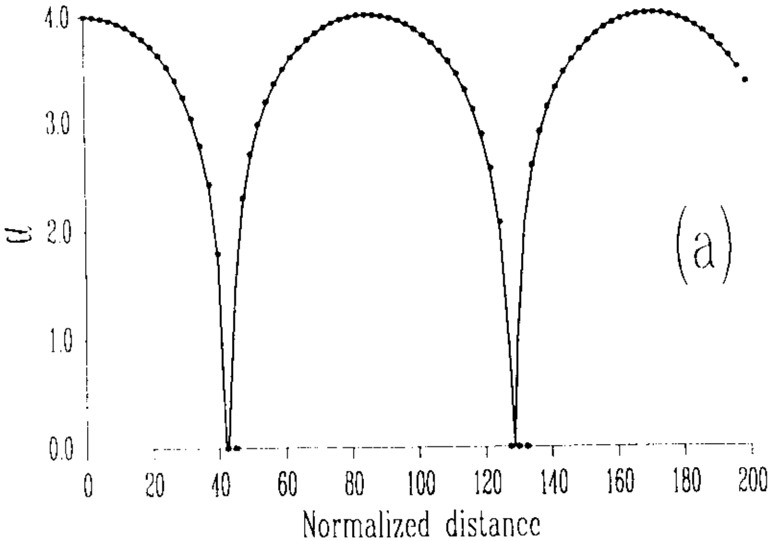
- Inverse Scattering Method

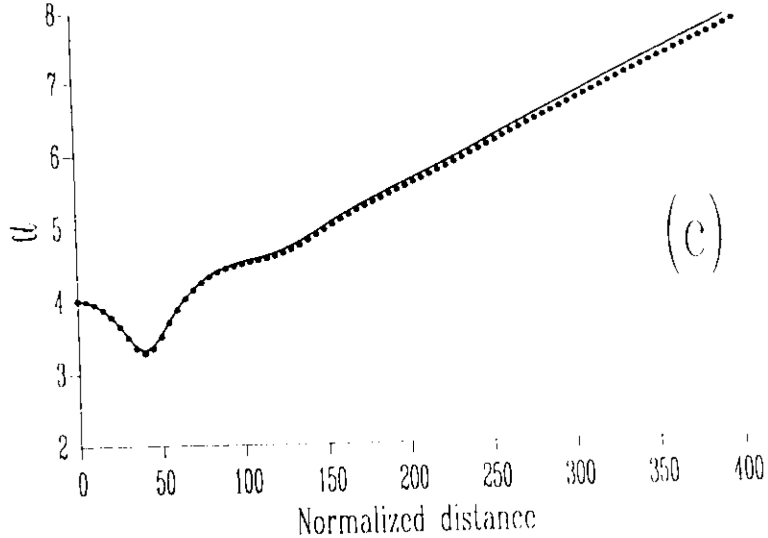
- Numerical simulations

- Perturbation Theory

[redacted]

# Comparison of ISM and Perturbation theory - 1

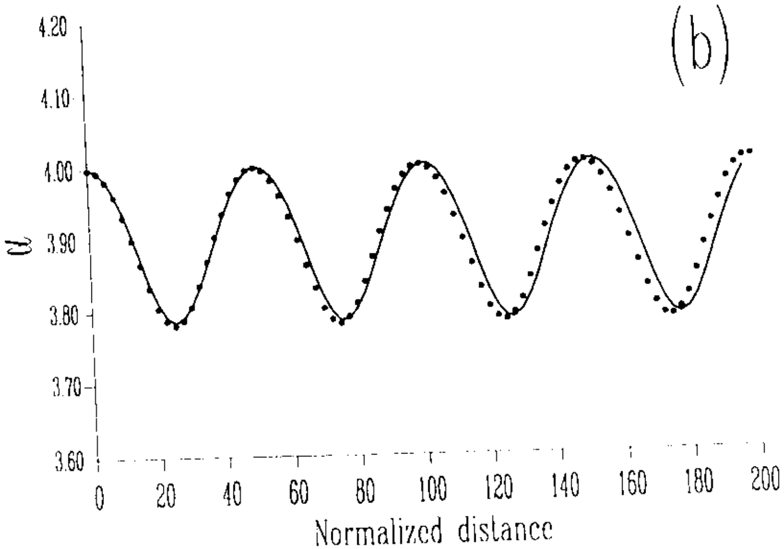



$(a)\quad \Phi_0 = 0$

$(b)\quad a_0 = 0.05$

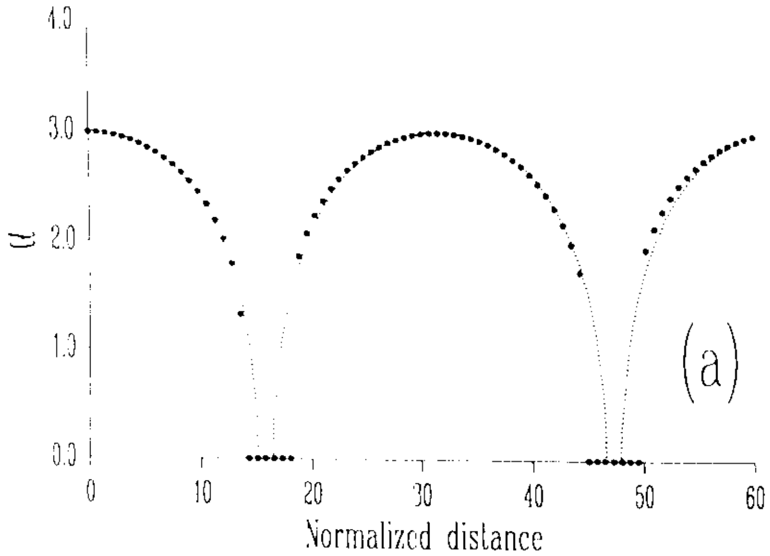
$(c)\quad \Phi_0 = 0.1\pi$

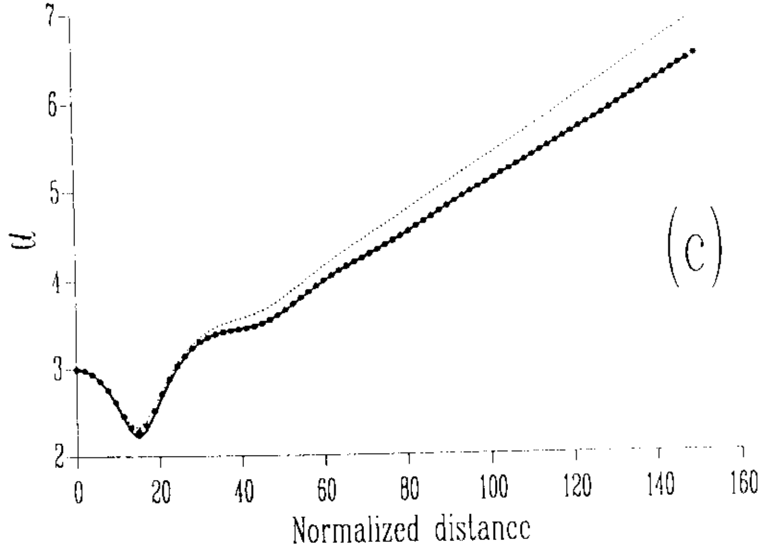



● ● ● *ISM*

⟶ *P.T.*

# Comparison of ISM and Perturbation theory - 2




$(a) \quad \Phi_0 = 0$

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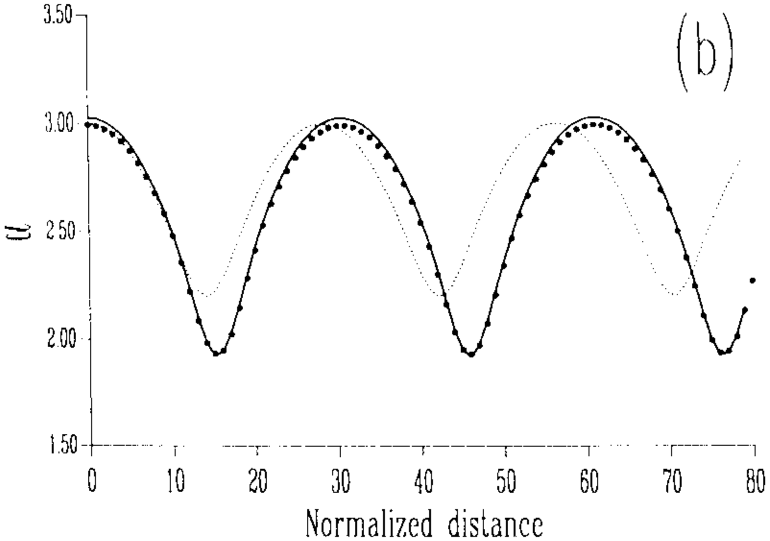


●●● *ISM*

$\cdots\cdots$ *P.T.*

$\longrightarrow$ *P.T.(m.p.)*

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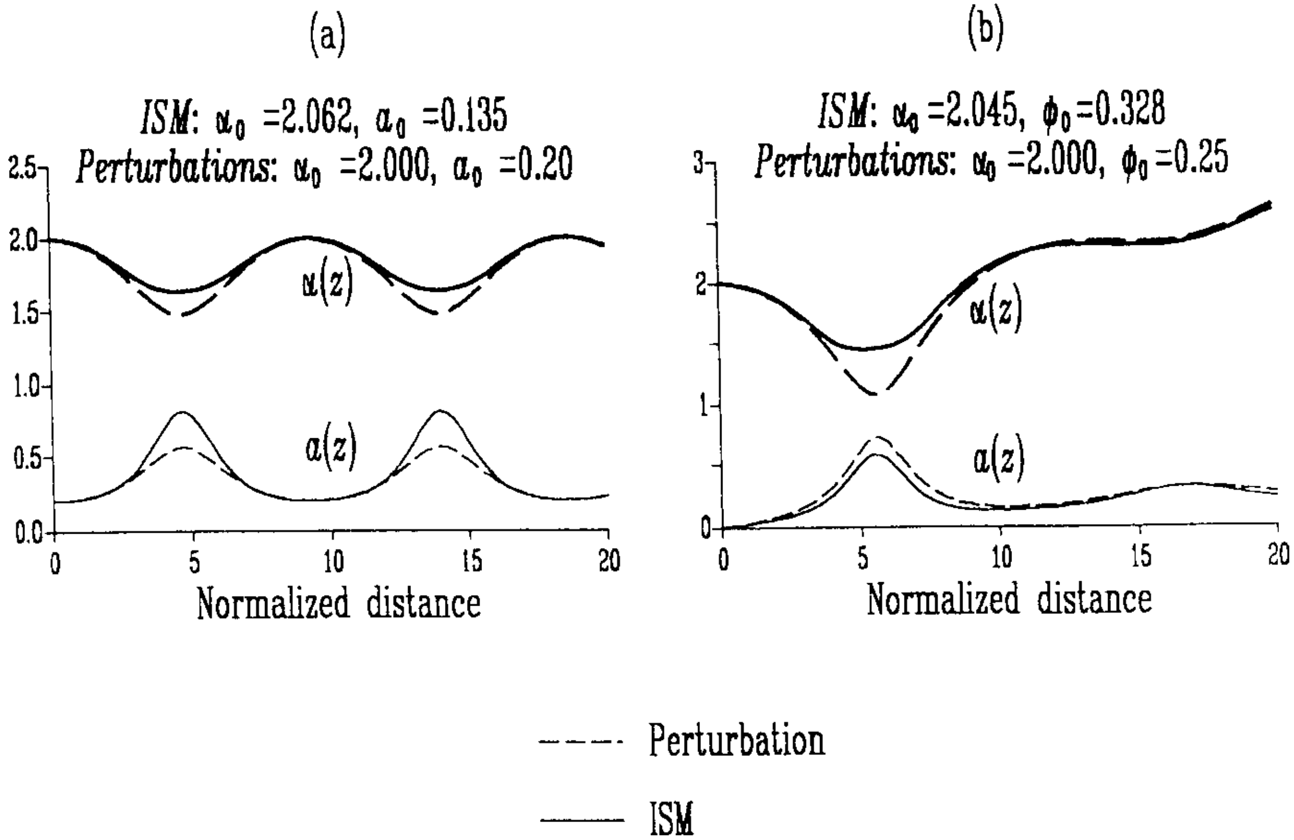
# Comparison of ISM and Perturbation theory - 3



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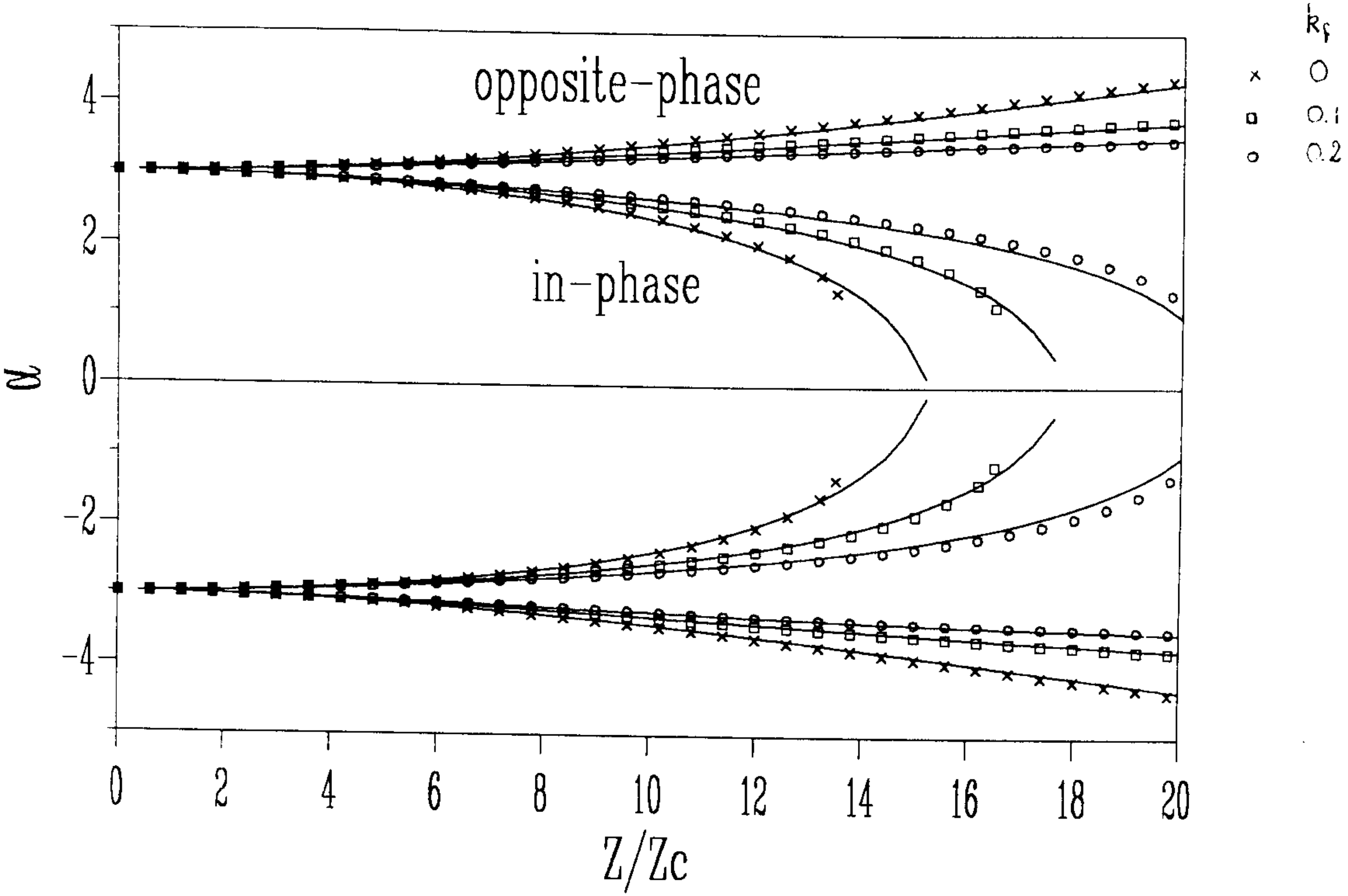
# Comparison of Numerical Simulations and P.T.



# Mechanical model of interaction

$\bullet \rightarrow \leftarrow \bullet \qquad . \qquad \bullet \rightarrow \leftarrow \bullet \rightarrow \leftarrow \bullet \rightarrow \leftarrow \bullet$

To first-order :

Forces are additive

Apply only to solitons in the neighbouring bit times

$\Rightarrow$ Consider only the behaviour of series of n consecutive solitons (characterized by a 4n component vector $x$ )

Integrating the equations leads $\quad x(z) = F\left(x_0, z - z_0\right)$

# Study of series of n consecutive solitons

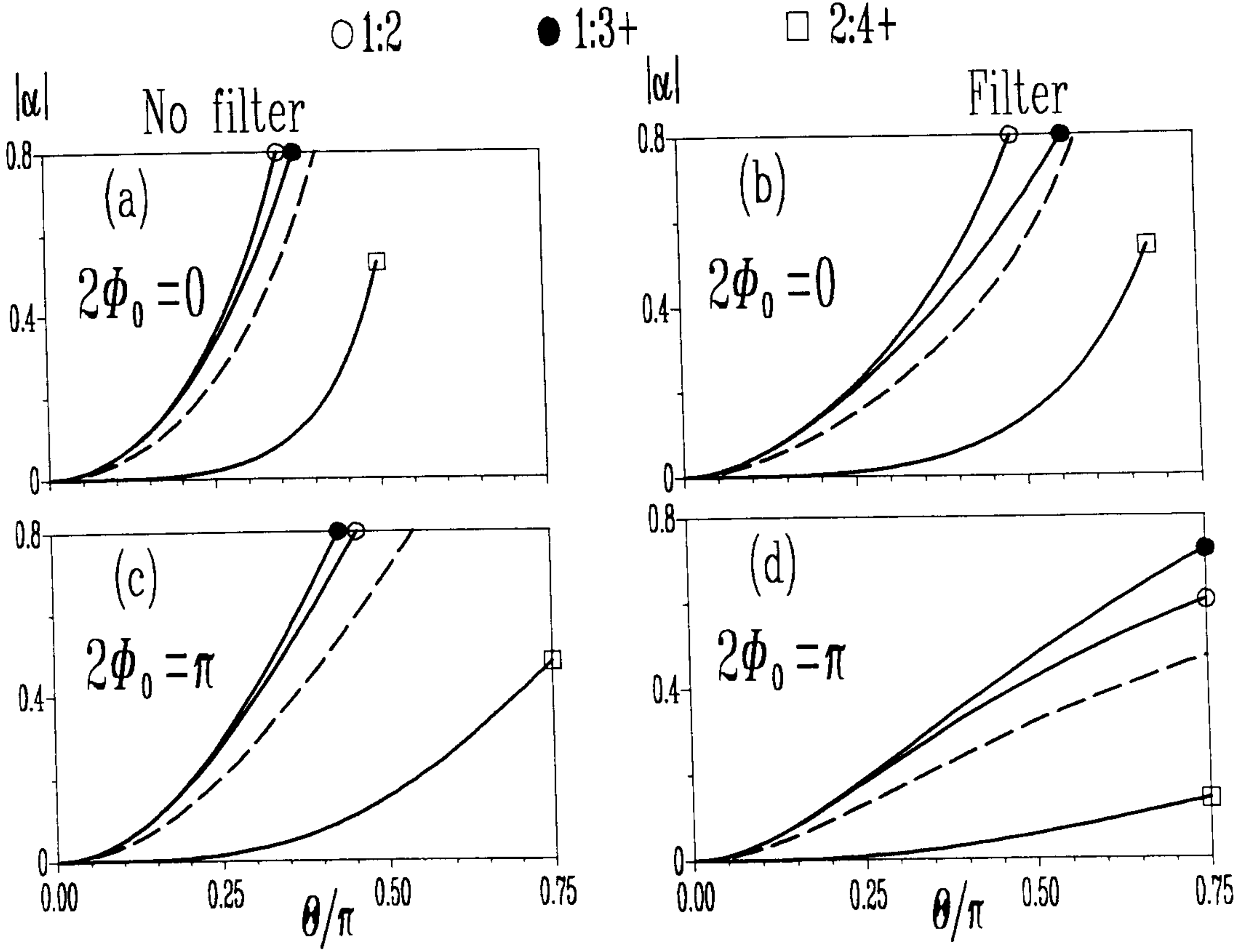
- Nomenclature

  → p:n is for $p^{th}$ or $(n\text{-}p)^{th}$ soliton in a series of n solitons

  → p:n+ is for $p^{th}$ soliton in a series of n solitons or more

- Conclusion

  → In most cases, the study of a series of 2 solitons is enough (or maybe 3 solitons)



○1:2
● 1:3+
□ 2:4+
|α|
No filter
Filter
(a)
(b)
(c)
(d)
2Φ₀ =0
2Φ₀ =π
0.8
0.4
0
0.00
0.25
0.50
0.75
θ/π

[redacted]

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# Types of soliton interaction control

- **Off-line control (emitter or receiver end)**
  - → Initial amplitude or phase modulation
  - → Polarization multiplexing
  - → Compensation fiber
- **Distributed in-line control**
  - → Filtering
  - → Synchronous modulation
  - → Raman effect, third-oder chromatic dispersion,...
- **Lumped in-line control**
  - → OPC, synchronous modulation,...

# Modelling of soliton interaction

| | Interaction | Filtering | IM | PM | Raman |
|---|---|---|---|---|---|
| $\omega'_z =$ | $4\exp(-2\alpha)\cos(2\Phi)$ | $-k_f(\omega+2\gamma a)$ | | $+k_\Phi(\alpha-\alpha_0)$ | $-8k_R a$ |
| $\gamma'_z =$ | | | | | $-k_R$ |
| $\alpha'_z =$ | $-\omega$ | | $-k_m(\alpha-\alpha_0)$ | | |
| $a'_z =$ | $4\exp(-2\alpha)\sin(2\Phi)$ | $-k_f(a+3\gamma\omega)$ | $+k_m a$ | | |
| $\Phi'_z =$ | $a$ | $-k_f\alpha\gamma$ | | $-\pi^2 k_\Phi a/12$ | |

$2\alpha$ : soliton separation  $\gamma$ : mean frequency

$2a$, $2\omega$, $2\Phi$ : amplitude, frequency and phase difference

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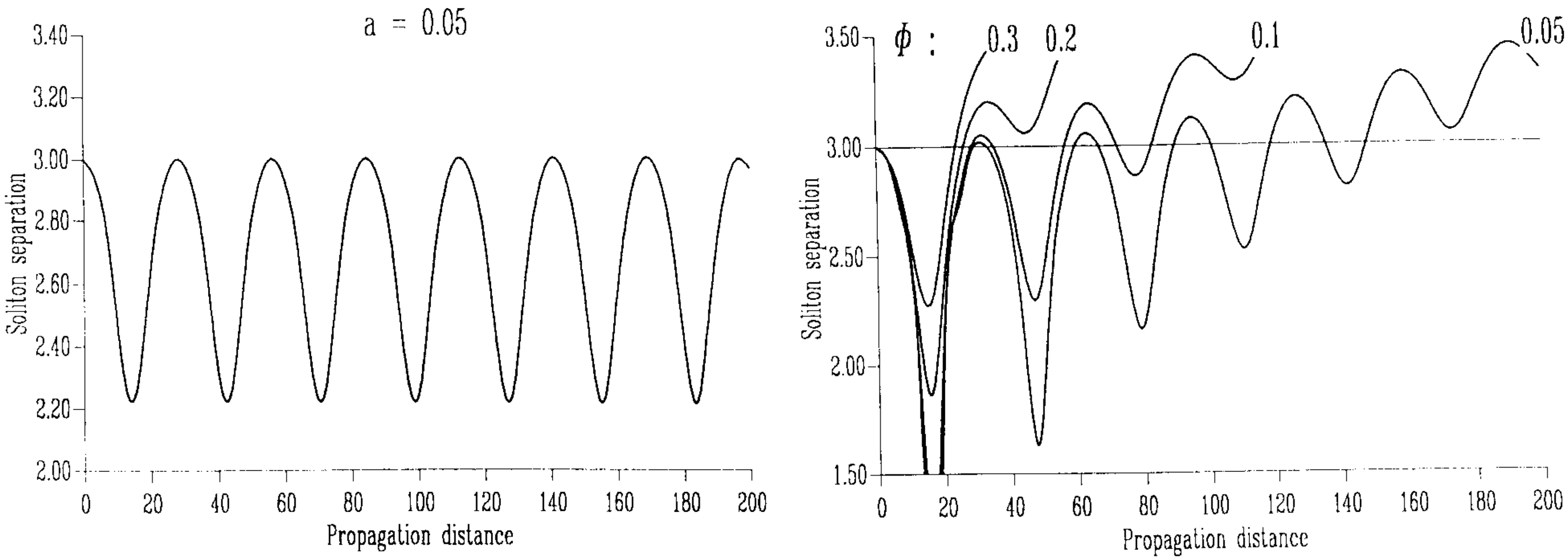
# Initial modulation



# Is the phase difference meaningful ?

- $\left\langle \sigma_{\Delta\Phi}^2 \right\rangle_{end} \approx \frac{n^3}{3} \left\langle \delta A^2 \right\rangle_{amplifier}$

- $\left\langle \sigma_{\Delta\alpha}^2 \right\rangle_{end} \approx \frac{n^3}{3} \left\langle \delta\omega^2 \right\rangle_{amplifier} \approx \frac{n^3}{9} \left\langle \delta A^2 \right\rangle_{amplifier}$

- **Real units:** $\sigma_{\Delta\Phi} \approx \frac{\sigma_{\Delta t}}{\tau}$

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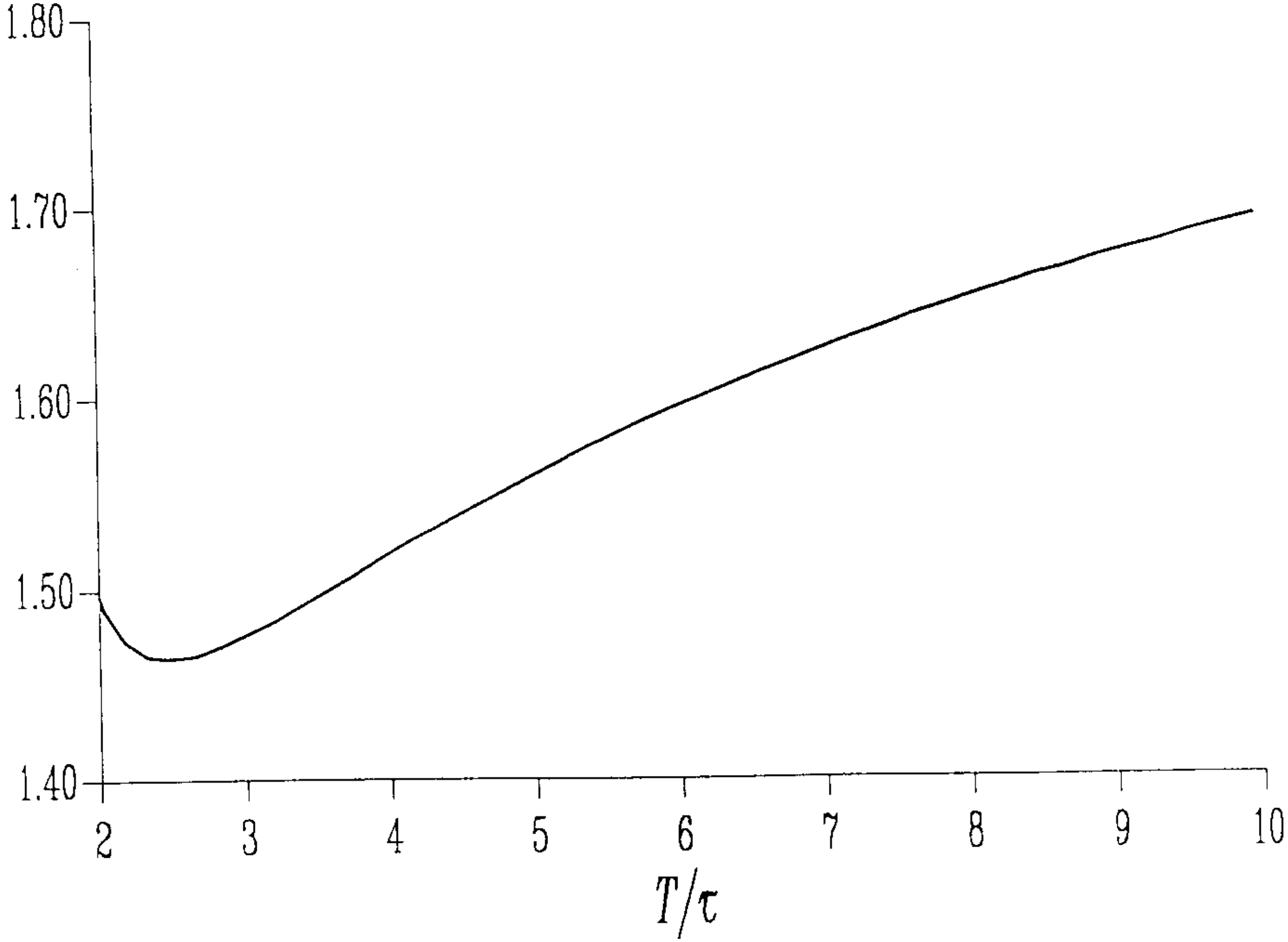
# Polarization multiplexing

Reduction factor of the bit time for polarisation multiplexing
only interaction is considered



# Limits -1-

***Criterion*** : $\Delta\alpha_{\max} = 0.1$

❶ **No control :** $z<0.45 \exp(\alpha_0)$

❷ **Polarization multiplexing :** $z<0.2 \exp(2\alpha_0)/\sqrt{(4\alpha_0-3)}$

❷ **Initial AM :** $a_0 \exp(\alpha_0)>4.3$

$\Rightarrow$ If $a<0.05$, then $\alpha_0>4.2$ ($T/\tau > 4.7$)

$\Rightarrow$ Independent of propagation distance z

❸ **Initial π-PM + CF :** $z<0.62 \exp(\alpha_0)$

Before CF, $\Delta\alpha = 0.63$

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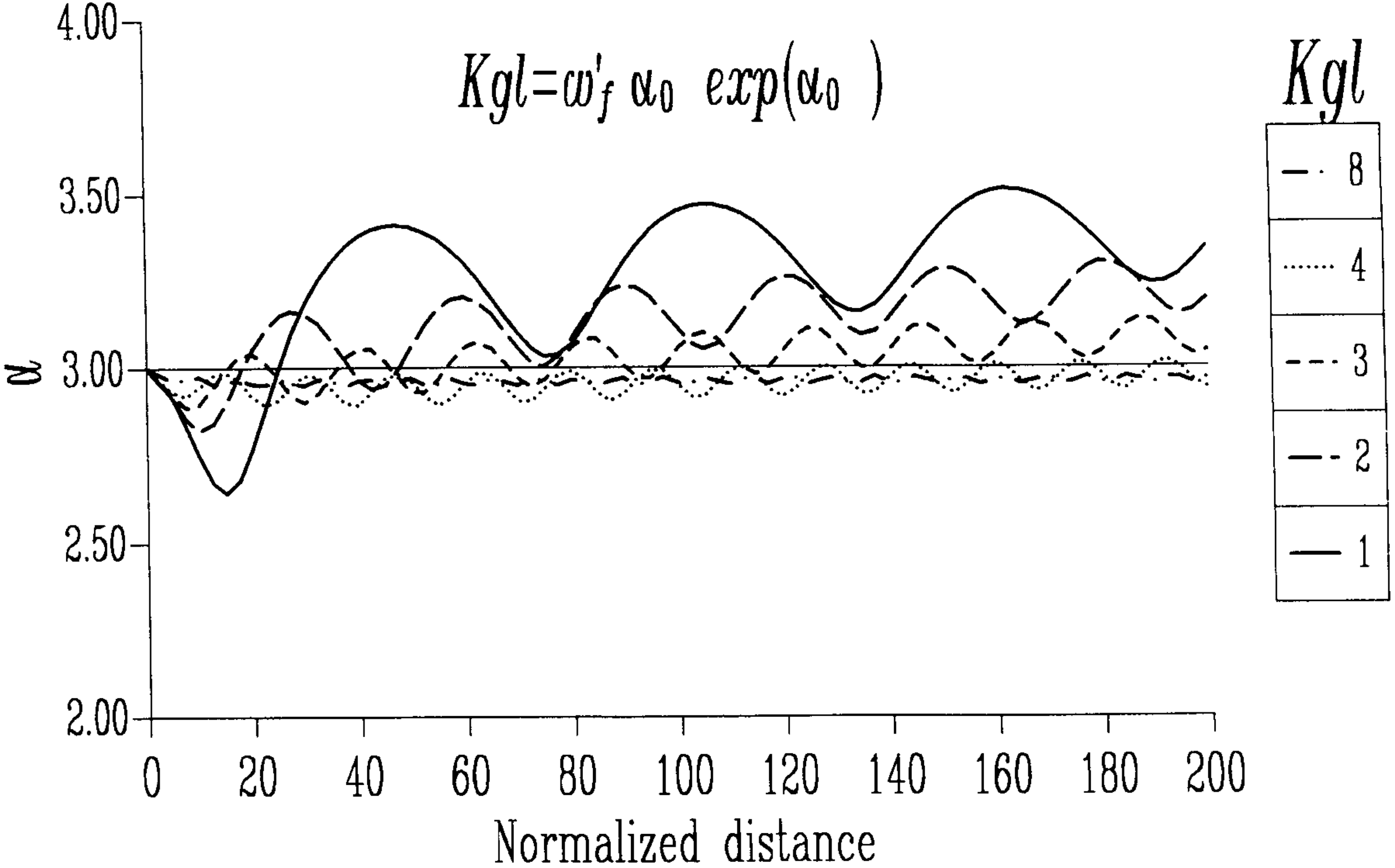
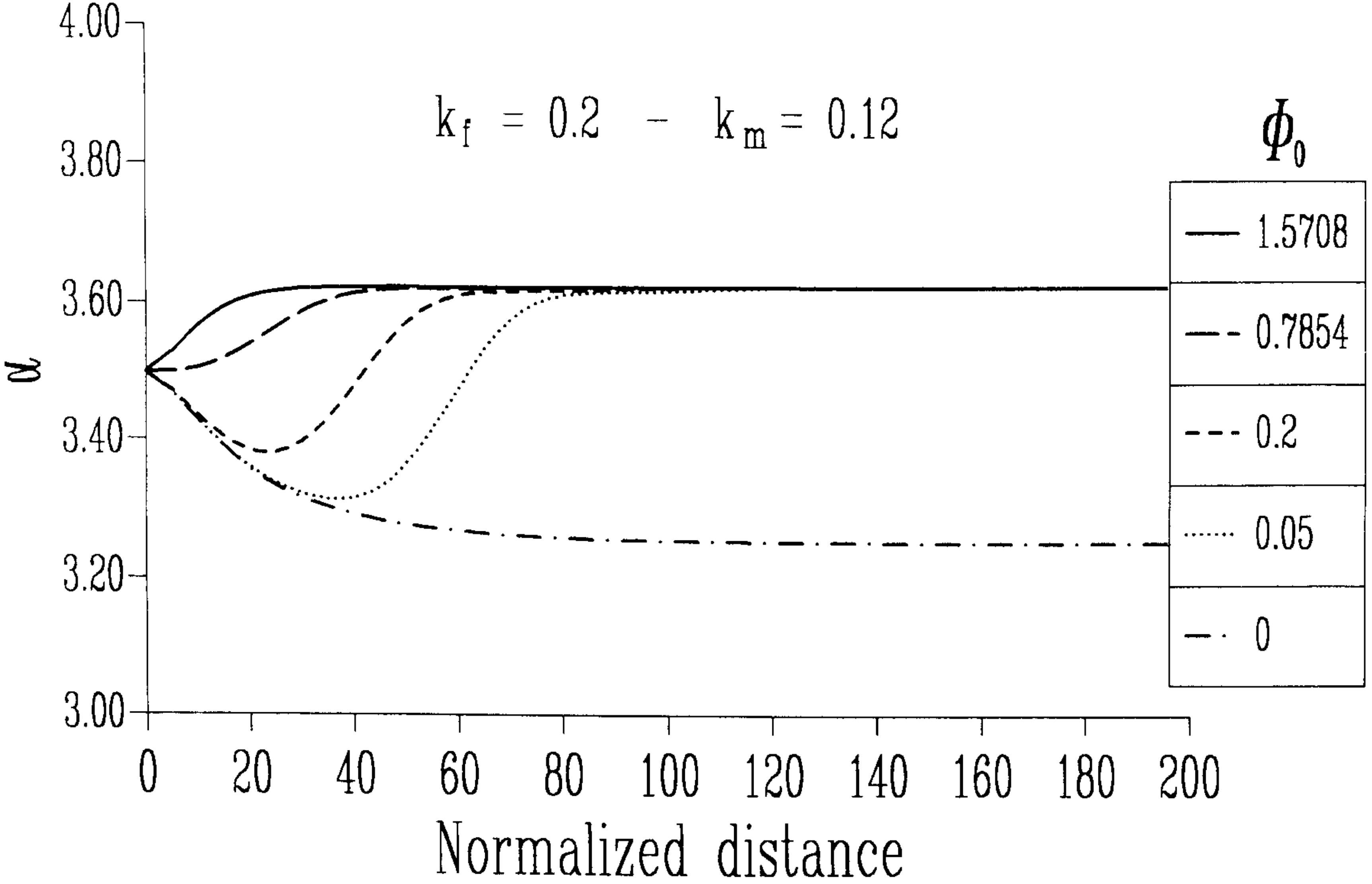
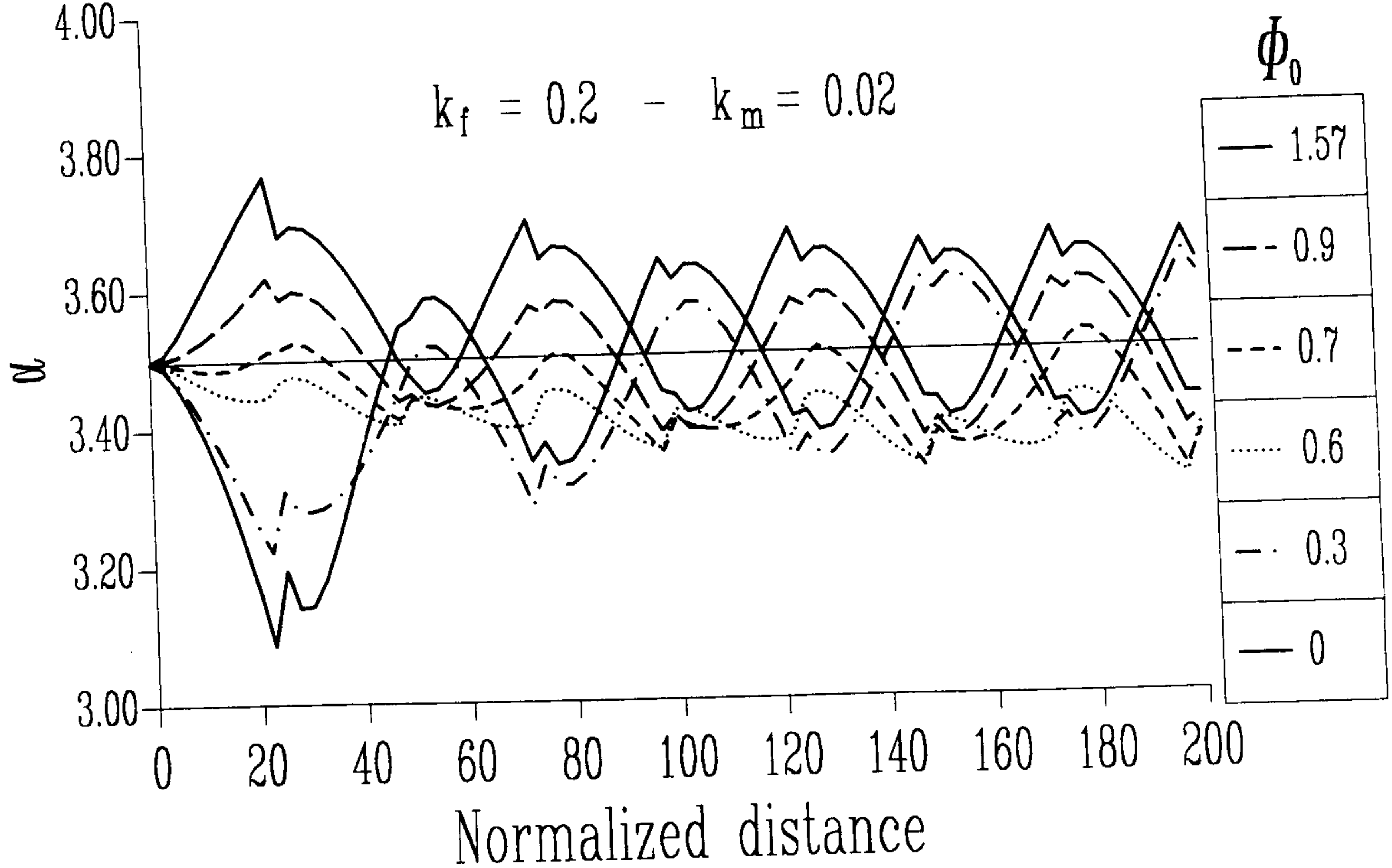
# Sliding frequency-guiding filtering



# Synchronous IM



# Synchronous AM



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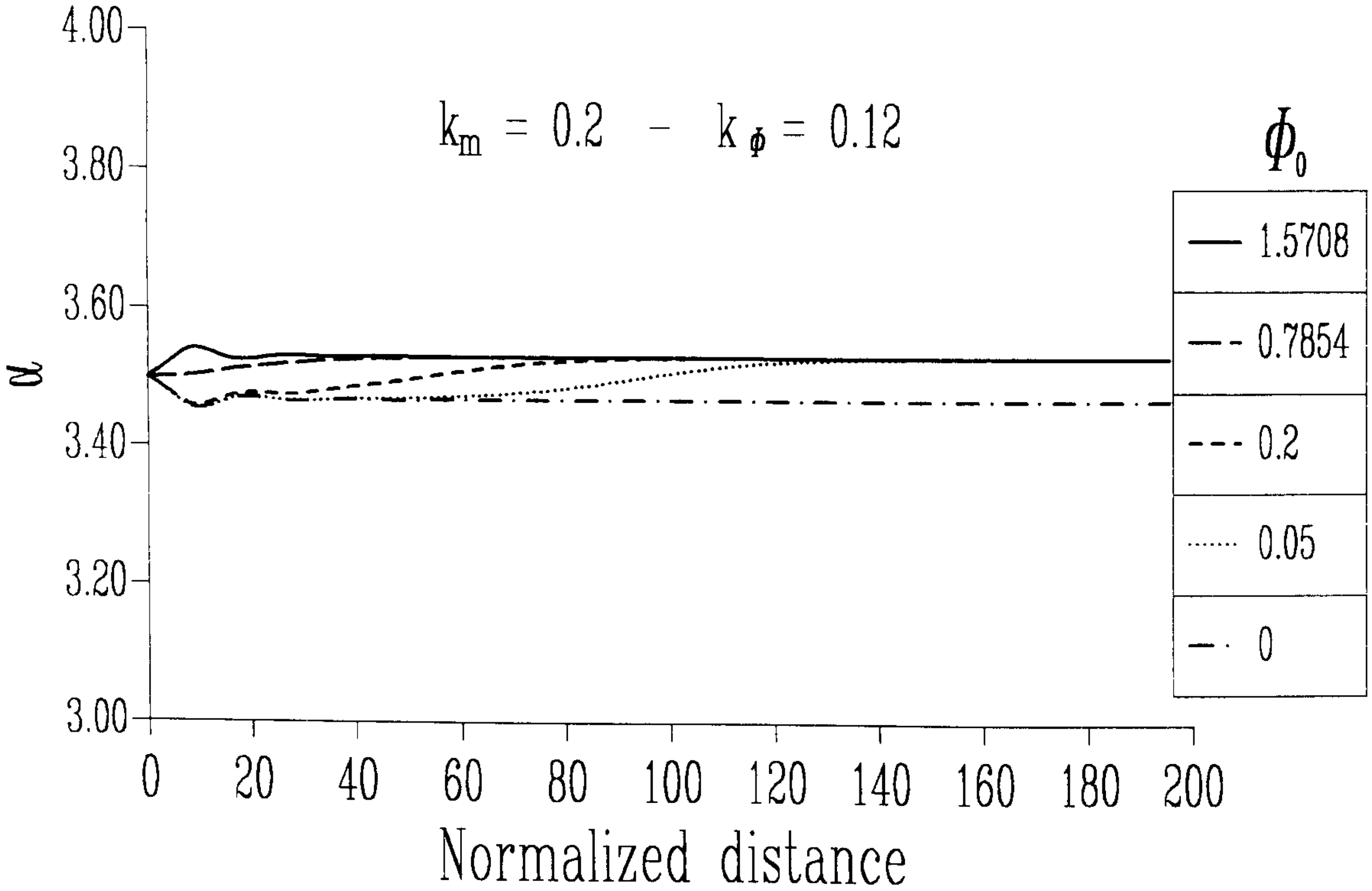
# Synchronous PM



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# Limits -2-

***Criterion*** : $\Delta\alpha_{max} = 0.1$

**❶ Sliding frequency F. :** $\omega'_f \alpha_0 \exp(\alpha_0) > 4$

$\Rightarrow$ Sensitive to initial mismatches (especially the frequency)

**❷ F + Synchronous IM :** $\sqrt{(k_f k_m)} \exp(\alpha_0) > 6.3$

**❸ F + Synchronous AM :** $\exp(\alpha_0) > 2.2\, z_m$

**❹ F + Synchronous PM :** $\sqrt{k_\Phi} \exp(\alpha_0) > 6.3$

# Soliton separation limits

| | $(T/\tau)_{min}$ | Conditions |
|---|---|---|
| Initial AM | 5.1 | $a=0.05$ |
| Sl. F | 3.1 | $\omega'_f=0.1$ |
| F + Sync. IM | 3.7 | $k_m=0.2$ - $k_f=0.3$ |
| F + Sync. AM | *1.7* | $z_m=2$ |
| F + Sync. PM | 2.8 | $k_\Phi=0.3$ |

[redacted]

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# Coupling of the 4 soliton parameters

- **Parameters at amplifier k :** $\overline{x_k} = \overline{F}\left(\overline{x_0}, z_k\right)$

- **To first order, fluctuations are**

$$\left\langle \overline{\delta x^2} \right\rangle_{end} = \sum_k \overline{\overline{B_k}} \cdot \left\langle \overline{\delta x^2} \right\rangle_{amp}$$

$$\overline{\overline{A_k}} = \partial_x \overline{F}\left(\overline{x_k}, z - z_k\right)$$

$\overline{\overline{B_k}}$ matrix of the squares of $\overline{\overline{A_k}}$

- **Effects of $\delta\omega$ still predominent (without in-line control)**

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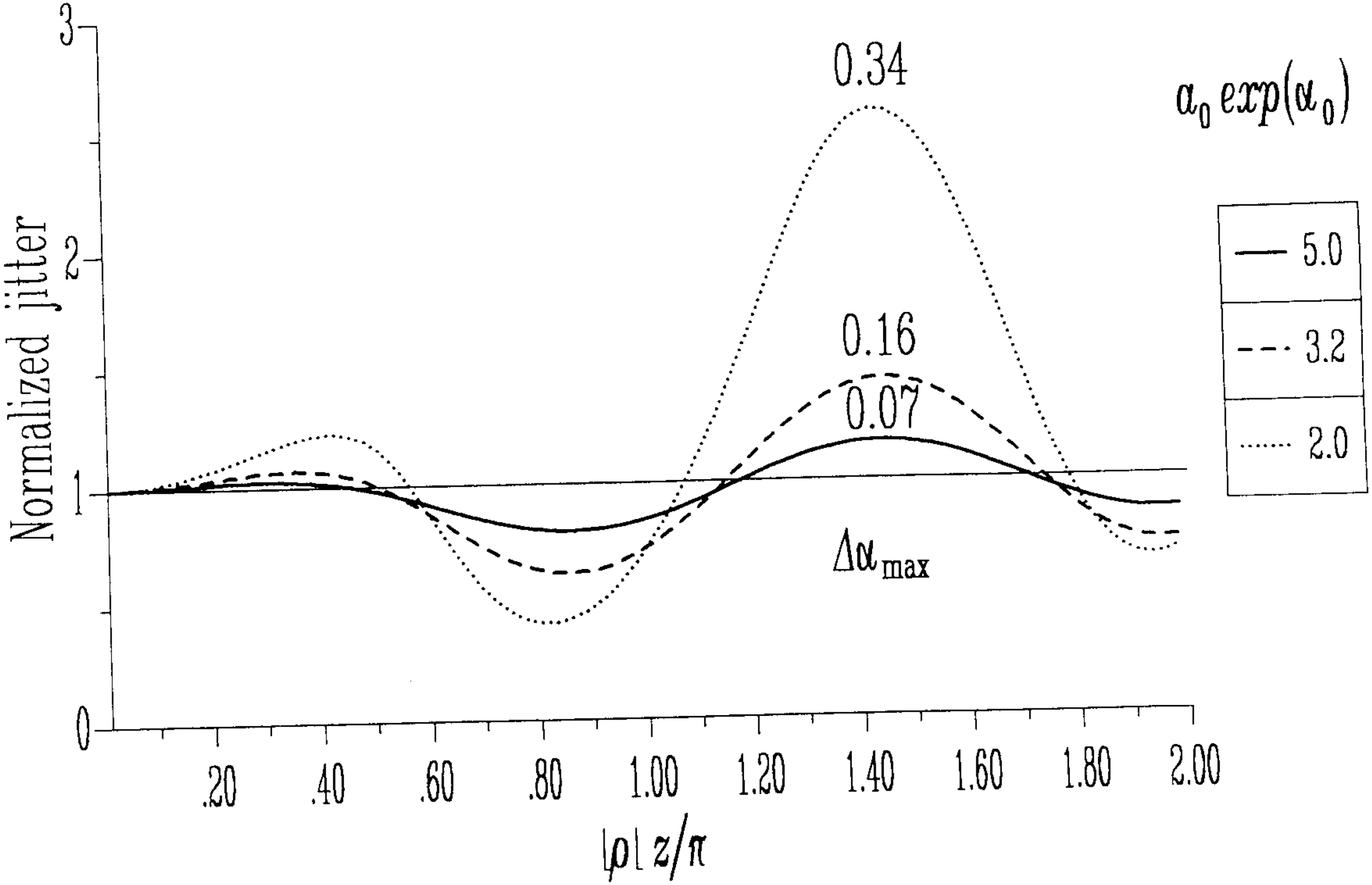
# Influence of interaction on jitter : IAM case



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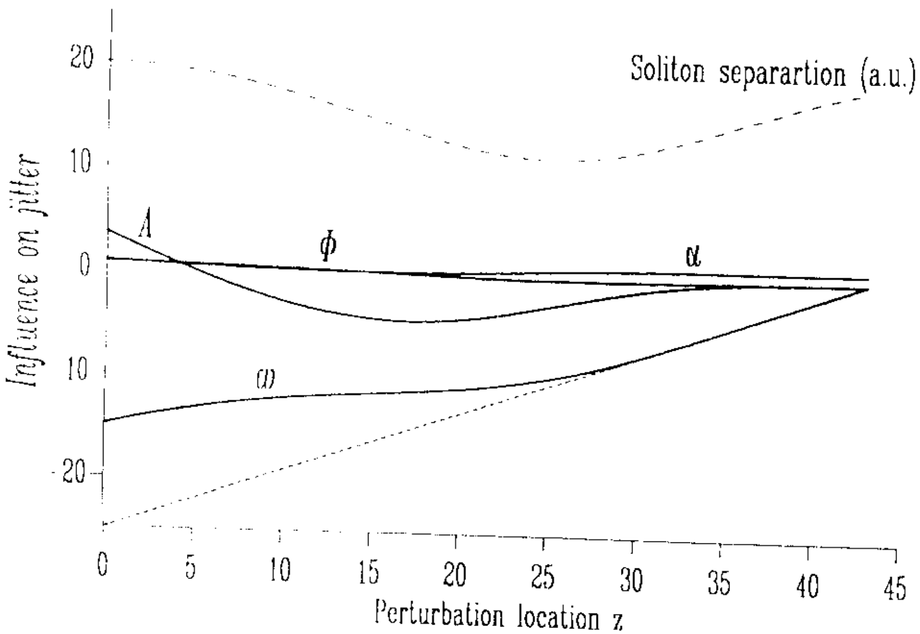
# Origin of jitter : IAM case

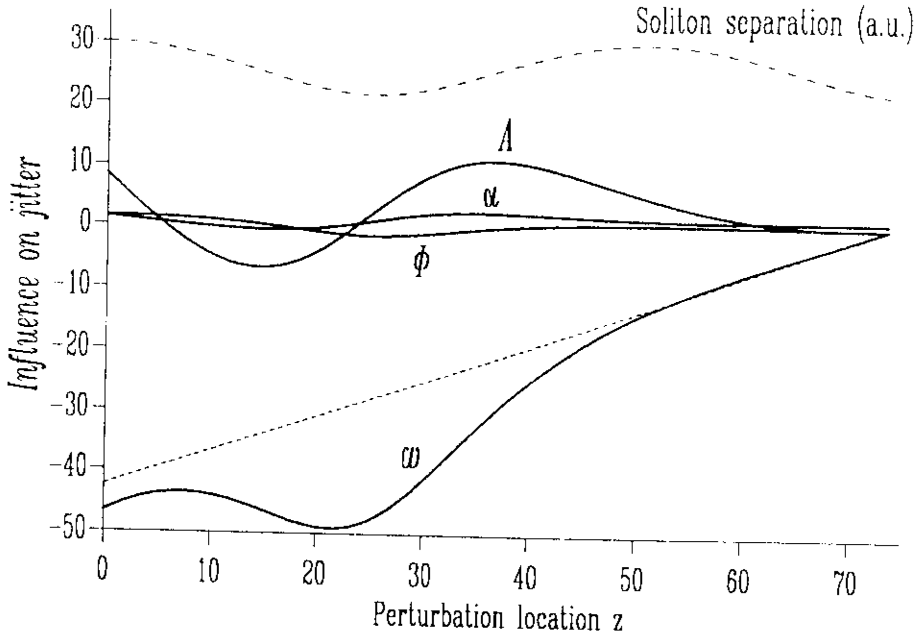
## Low jitter

$a=0.05$ - $\alpha=4.0$ - $\rho z=0.85\pi$




## High jitter

$a=0.05$ - $\alpha=4.0$ - $\rho z=1.45\pi$



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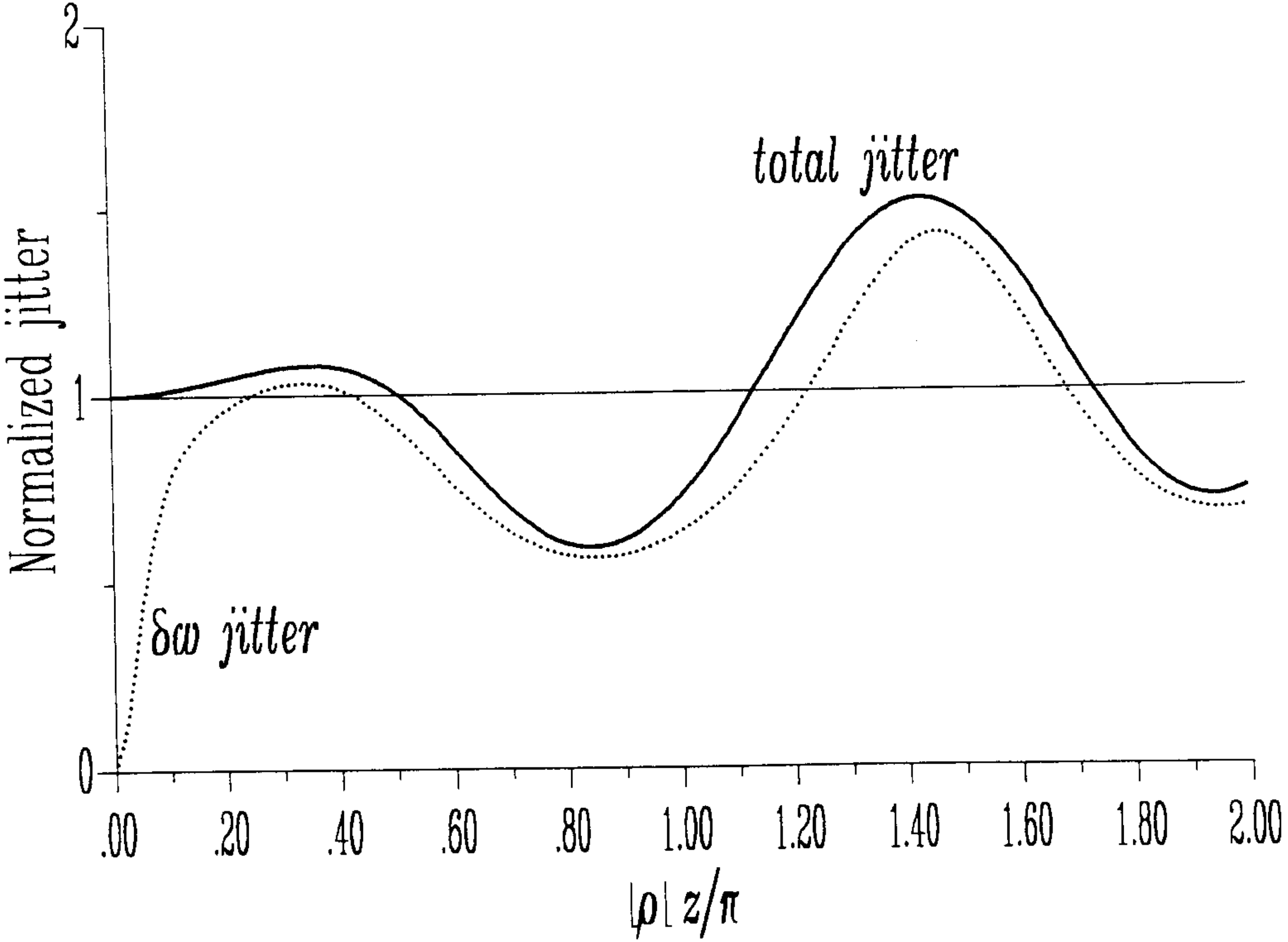
# Influence of frequency fluctuations



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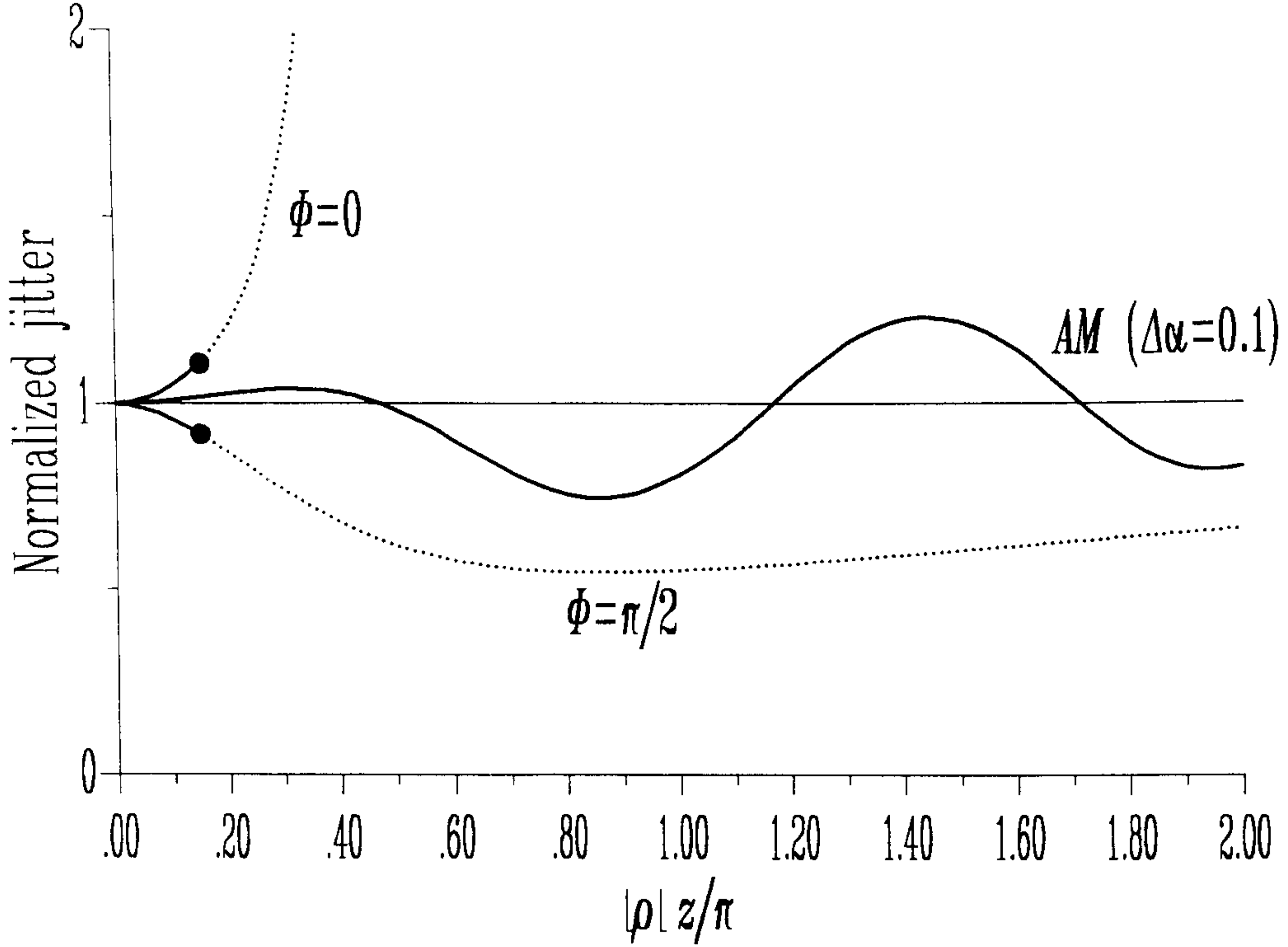
# Influence of interaction on jitter : IPM case



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# Nonlinearity of the interaction

- **Nonlinearity :** $\partial^2_{\overline{x}^2} \overline{F}\left(\overline{x_k}, z - z_k\right) \neq \overline{\overline{0}}$

**$\Rightarrow$ Statistic of jitter not Gaussian anymore**

**$\Rightarrow$ Contribution of second-order term may not be negligible in case of large fluctuations**

**$\Rightarrow$ Large fluctuations may be responsible for a collision $\Rightarrow$ catastrophic behaviour**

In-phase solitons for z=16 : $\Delta\alpha$=-0.18 if $\alpha_0$=4 and collision if $\alpha_0$=3

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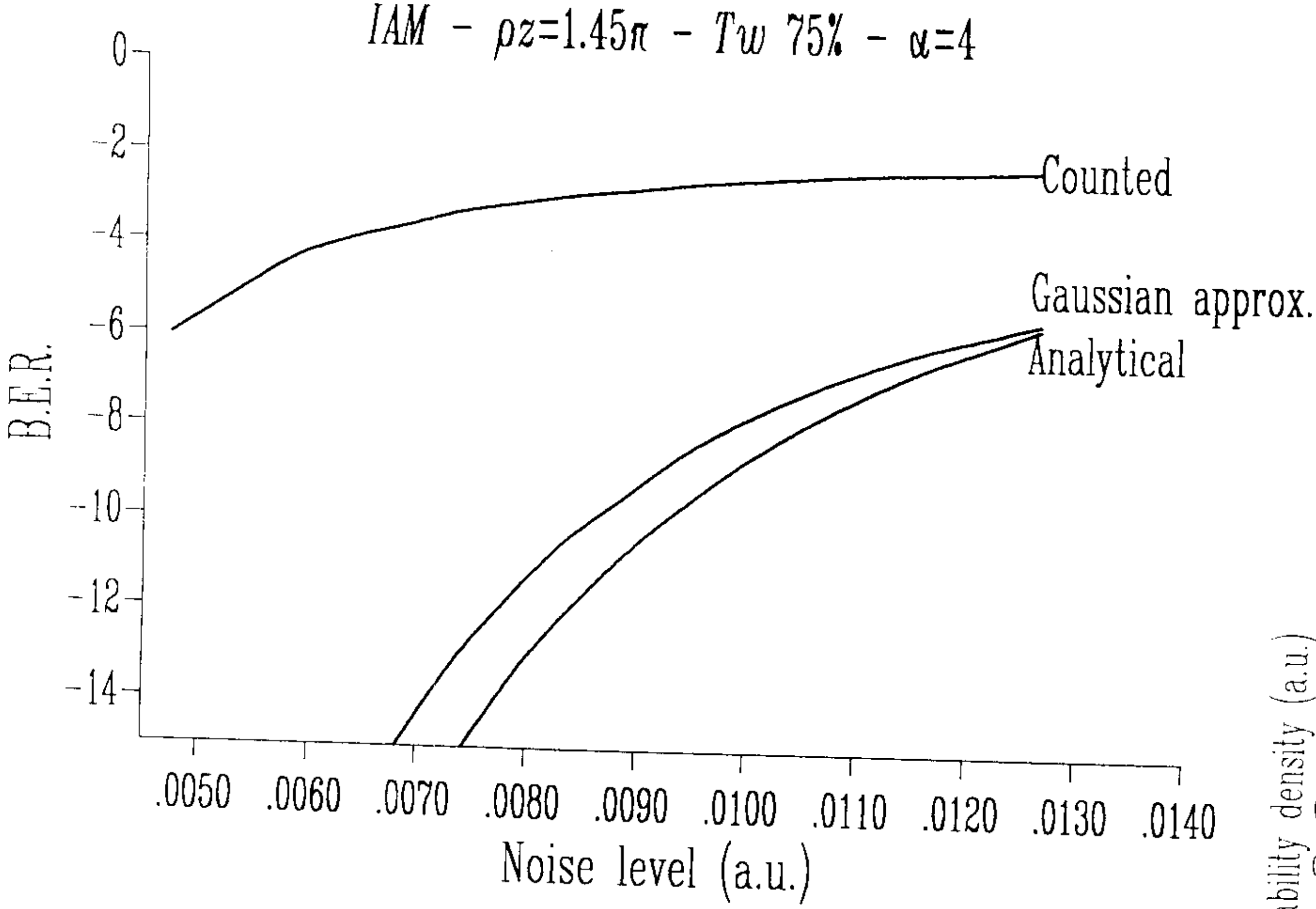
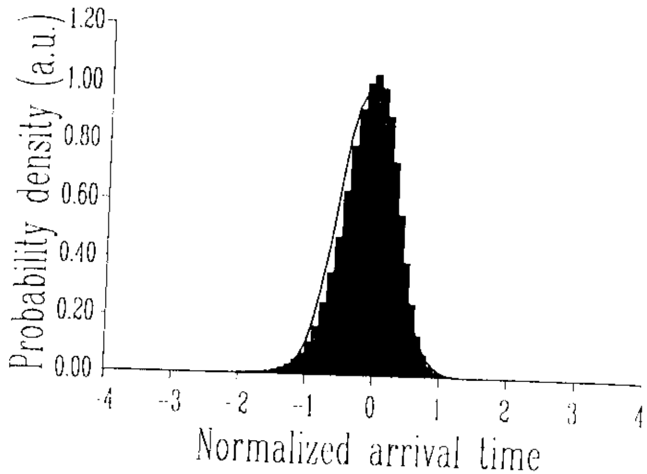
# Consequences on the B.E.R. - 1 -



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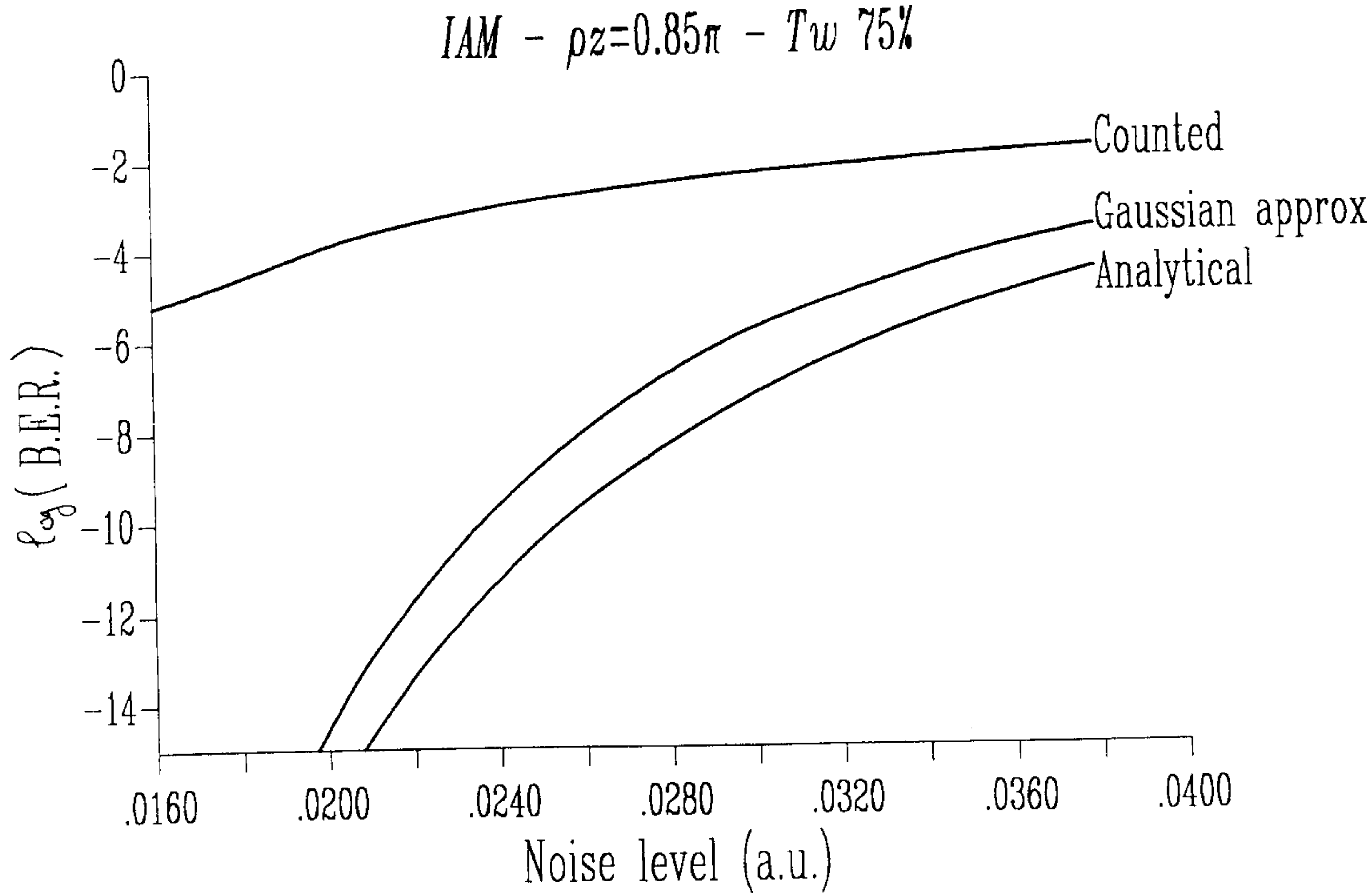
# Consequences on the B.E.R. - 2 -



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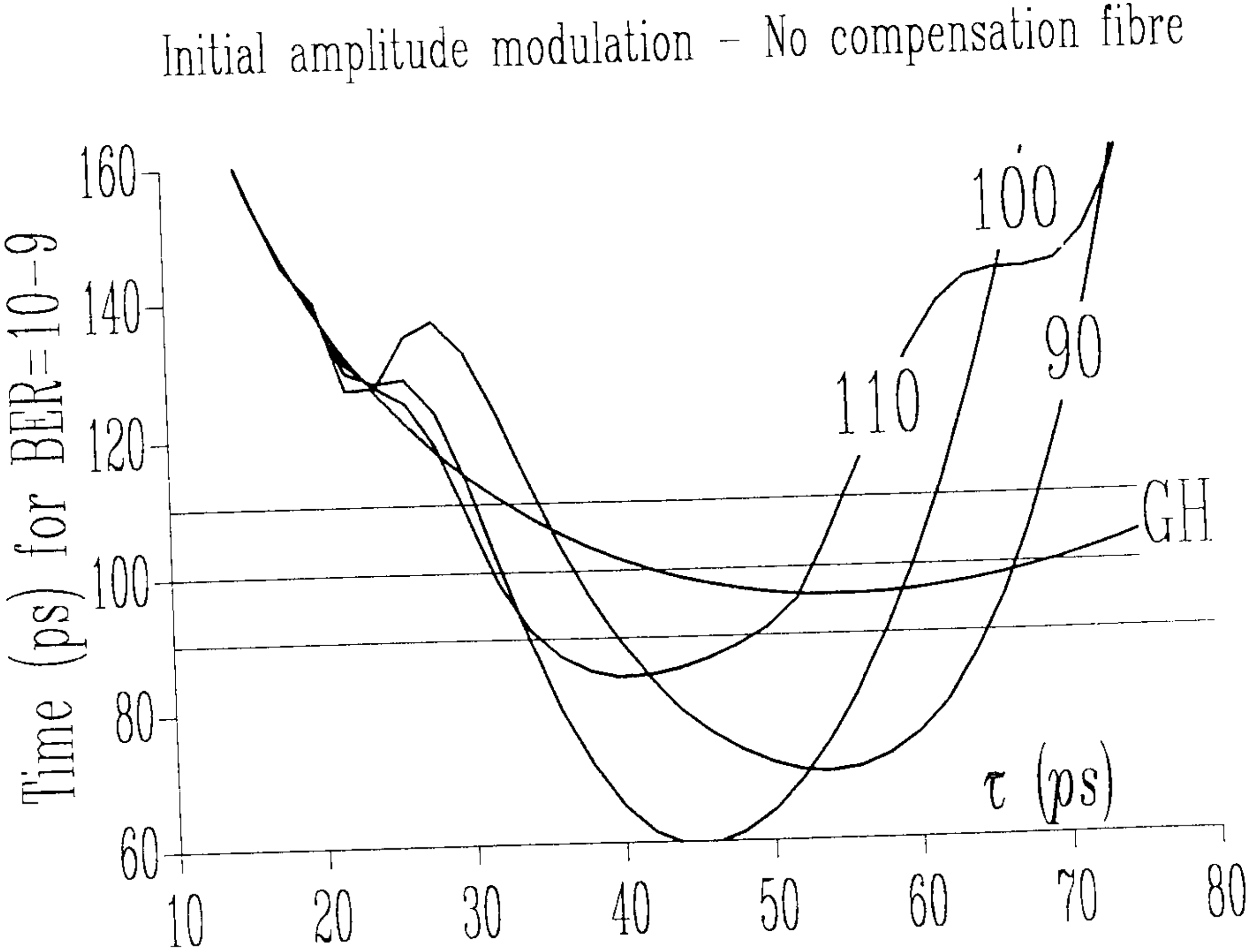
[redacted]

# Bit rate ultimate limits of a single channel -1-



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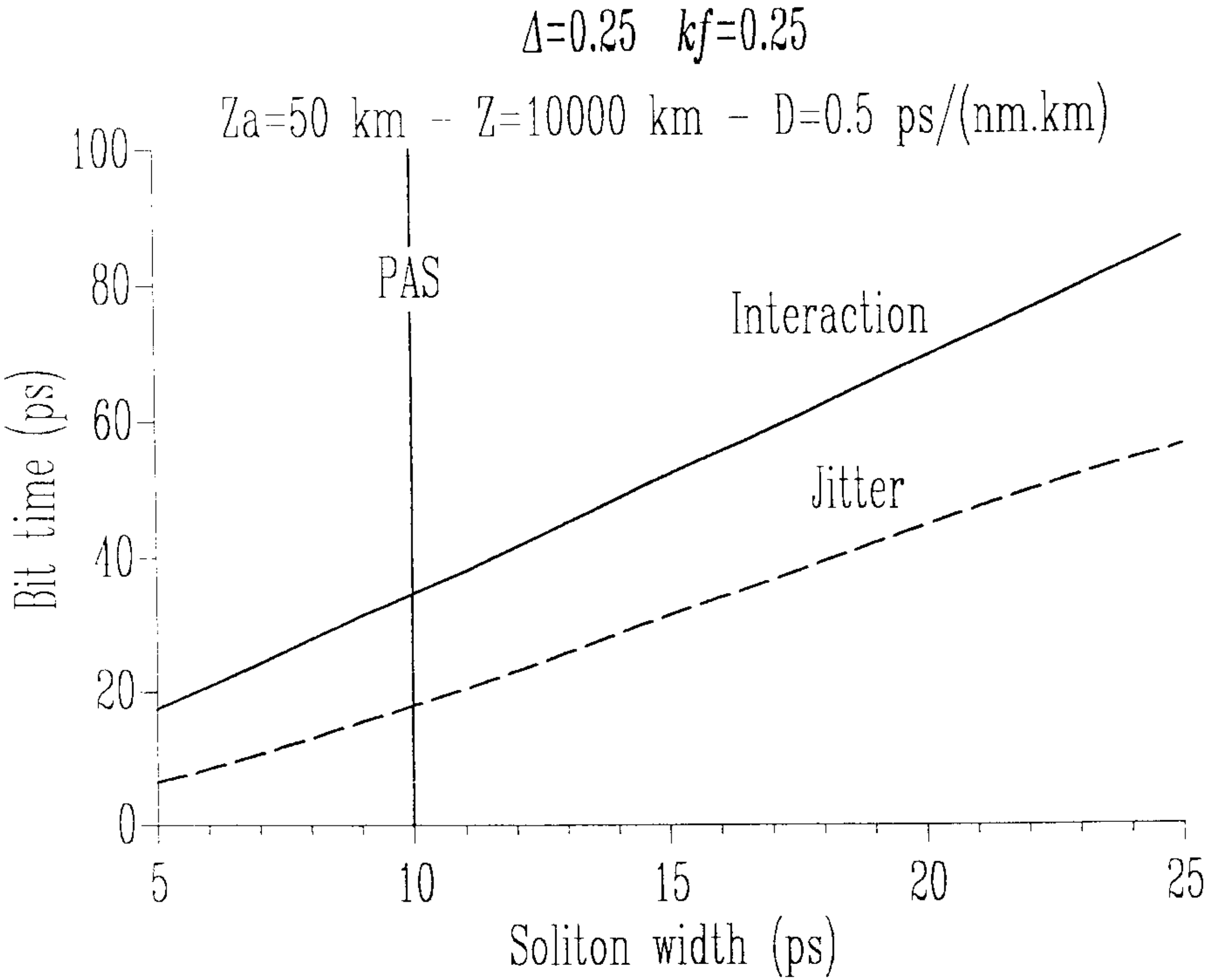
# Bit rate ultimate limits of a single channel -2-



# Conclusion

- **Validation of the perturbation theory**
- **Simple criteria for interaction reduction**
- **Calculation of interacting soliton jitter**
- **Effects of the non Gaussian statistics of jitter**
  Only P.T. can be used to estimate the right BER
- **10 Gbit/s - 10,000 km without inline control**
- **25 Gbit/s - 10,000 km with inline control**