

EM Structure-Based Optical Acceleration

Levi Schächter

Department of Electrical Engineering
Technion - Israel Institute of Technology
Haifa 32000, ISRAEL

Outline

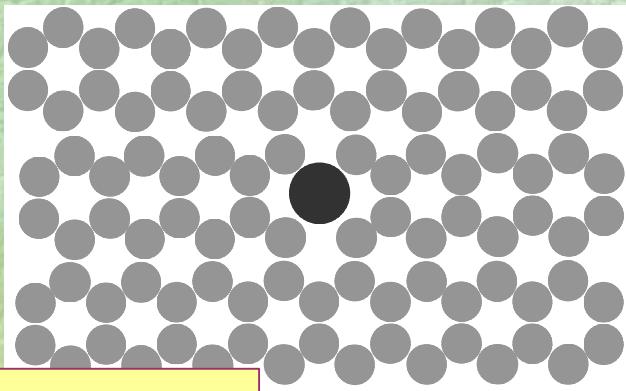
- *Constraints on optical structures*
- *Optical structures*
- *Four acceleration configurations*
- *Comments on luminosity & power*

Constraints

- ◆ **Gradient**: order of 1[GV/m] or higher.
- ◆ **Efficiency**: limited by radiation source and acceleration scheme
 - # Lasers anticipated efficiency of wall-plug to light $10\% \rightarrow 30\%?$!
 - # Efficiency of acceleration scheme – major **difficulty**
- ◆ **Breakdown**: at optical wavelengths **dielectrics** sustain higher fields comparing to metals.
- ◆ **Manufacturing** constraints favor planar structures – consistent with luminosity constraints.
- ◆ **Single Mode**: width of vacuum tunnel $0.3\lambda - 0.8\lambda$
- ◆ **Machining tolerance**: 1mm at 3 cm wavelength. Four orders of magnitude difference difficult to be preserved at $l=1\text{ mm}$ (**poster**).

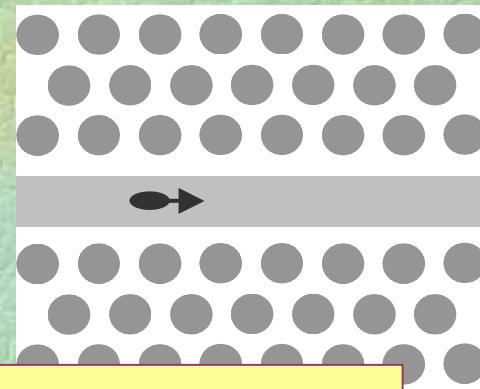
Optical structures

Transverse PBG



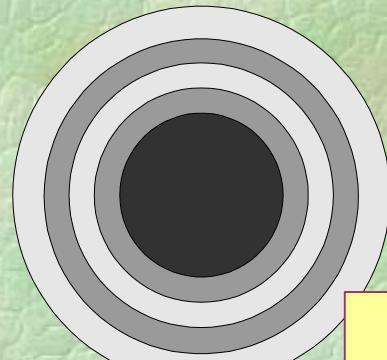
E. Lin, PR STAB, 2000

Longitudinal PBG



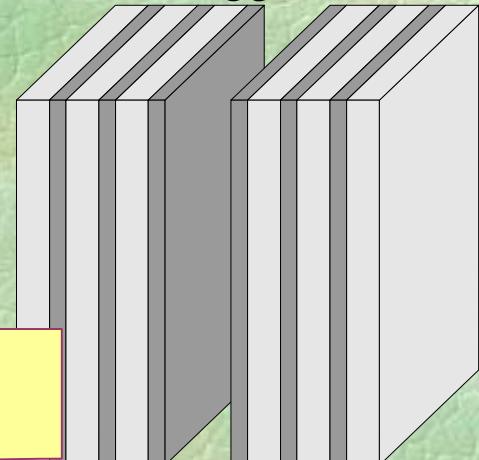
B. Cowan, PR STAB, 2003

Cylindrical Bragg Structure



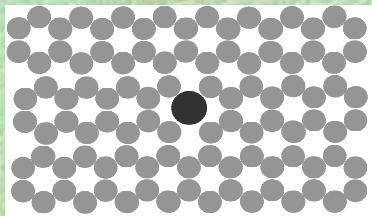
A. Mizrahi & L. Schachter,
Phys. Rev. E, 2004

Planar Bragg Structure



Structure parameters

Transverse PBG

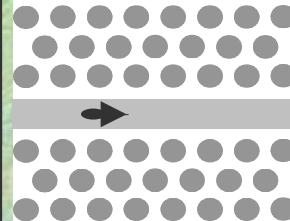


$$\frac{R_{\text{int}}}{\lambda} \square 0.68 \Rightarrow \begin{cases} Z_{\text{int}} \square 19.5[\Omega] \\ \beta_{gr} \square 0.58 \\ \frac{E_{\text{acc}}}{E_{\text{max}}} \square 0.5 \end{cases}$$

$\underbrace{\varepsilon=2.1, \lambda \square 1[\mu\text{m}]}$

E. Lin, PR STAB, 2000

Longitudinal PBG

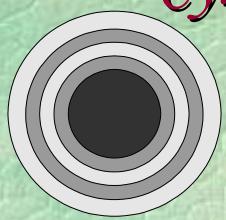


$$\frac{D_{\text{int}}}{\lambda} = 0.55 \div 1.25 \Rightarrow \begin{cases} Z_{\text{int}} \frac{\Delta_y}{\lambda} \square 250 \div 20[\Omega] \\ \beta_{gr} \square 0.2 \div 0.6 \\ \frac{E_{\text{acc}}}{E_{\text{max}}} \square 0.35 \div 0.15 \end{cases}$$

$\underbrace{\varepsilon=2.1, \lambda \square 1.5[\mu\text{m}]}$

B. Cowan, PR STAB, 2003

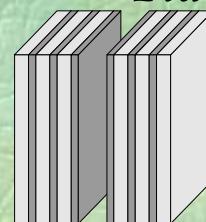
Cylindrical Bragg Structure



$$\frac{R_{\text{int}}}{\lambda} \square 0.3 \div 0.8 \Rightarrow \begin{cases} Z_{\text{int}} \square 268 \div 37[\Omega] \\ \beta_{gr} \square 0.41 \div 0.48 \\ \frac{E_{\text{acc}}}{E_{\text{max}}} \square 0.73 \div 0.37 \end{cases}$$

$\underbrace{\varepsilon_1=2.1, \varepsilon_2=4, \lambda=1[\mu\text{m}]}$

Planar Bragg Structure



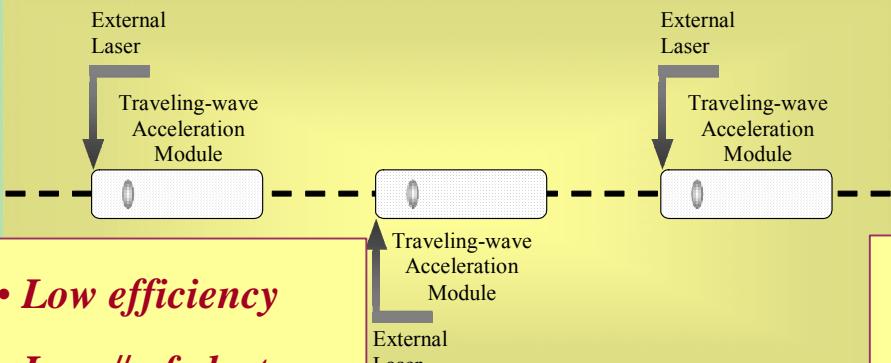
$$\frac{D_{\text{int}}}{\lambda} = 0.3 \div 0.8 \Rightarrow \begin{cases} Z_{\text{int}} \frac{\Delta_y}{\lambda} \square 147 \div 25.7[\Omega] \\ \beta_{gr} \square 0.42 \div 0.53 \\ \frac{E_{\text{acc}}}{E_{\text{max}}} \square 0.47 \div 0.20 \end{cases}$$

$\underbrace{\varepsilon_1=2.1, \varepsilon_2=4, \lambda=1[\mu\text{m}]}$

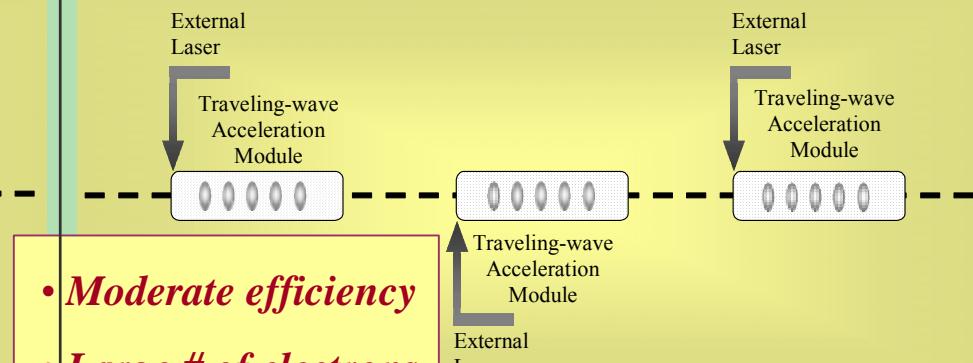
A. Mizrahi & L. Schachter, Phys. Rev. E, 2004

Configurations

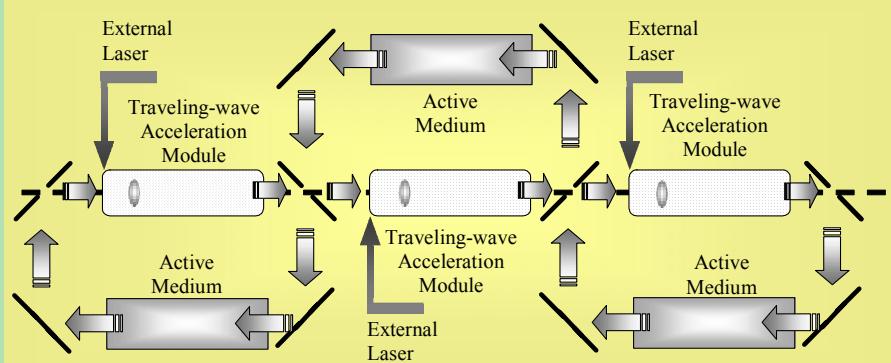
Single bunch & no feedback



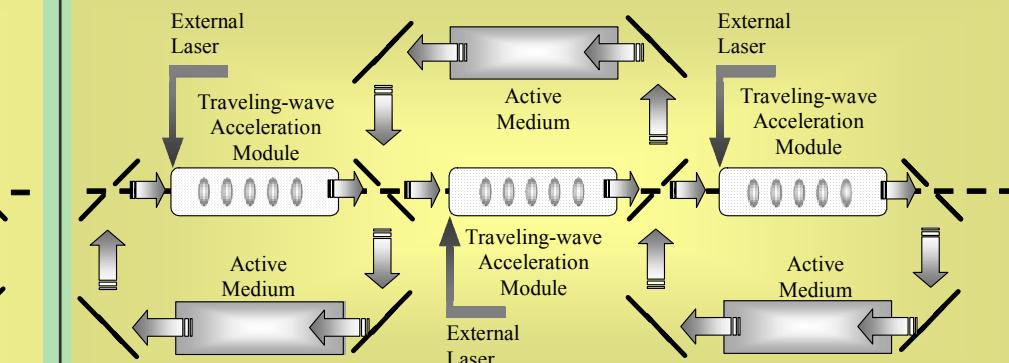
bunches & no feedback

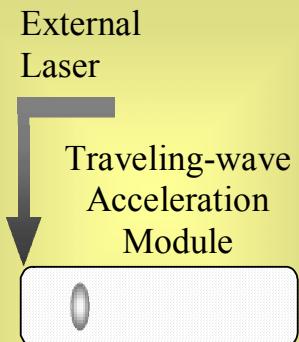


Single bunch & feedback



Train of micro-bunches & feedback





Single bunch & no feedback

- **Wake parameter:**

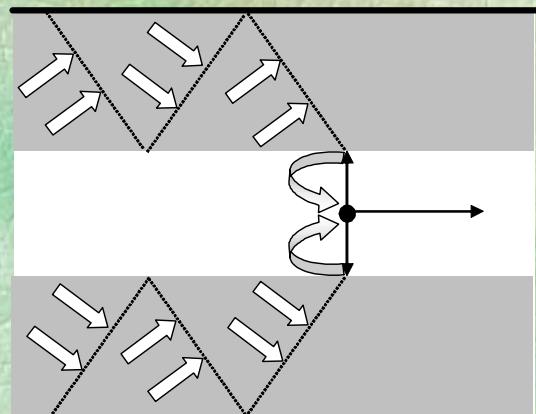
Decelerating field for a given charge

$$E_{\text{dec}} \equiv \kappa q$$

- **Beam-loading parameter:**

Beam-loading of the accelerating mode

$$E_{\text{dec}}^{(F)} \equiv \kappa_1 q$$



$$E_z(r=0, \tau = t - z/c) \square q\kappa \sum_{n=1}^{\infty} W_n \cos(\omega_n \tau) 2h(\tau)$$

$$\sum_{n=1}^{\infty} W_n = 1$$

$$\kappa_1 \equiv \kappa W_1$$

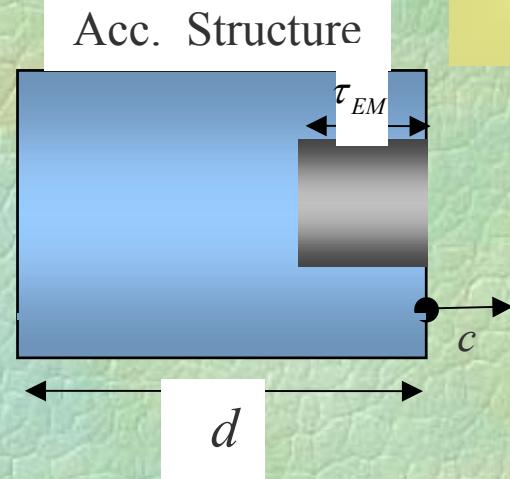
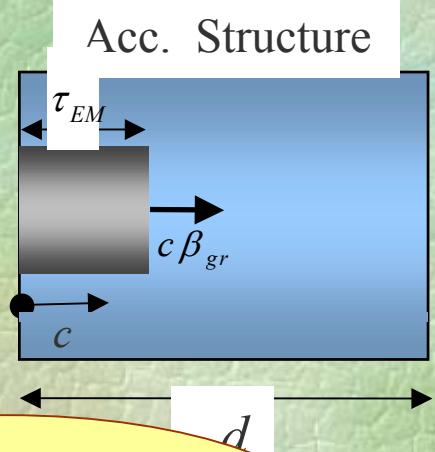
$$\kappa_1 = \frac{\beta_{\text{gr}}}{1 - \beta_{\text{gr}}} \frac{Z_{\text{int}}}{\sqrt{\mu_0 / \epsilon_0}} \frac{\pi}{4\pi\epsilon_0\lambda^2}$$

*Contribution of the fundamental
to the total deceleration*

Stupakov & Bane, PR STAB, 2003

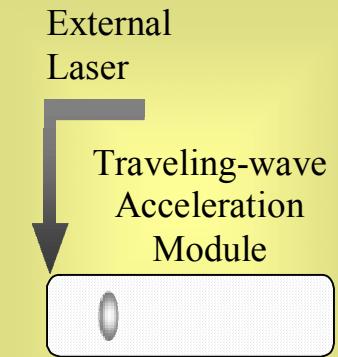
Single bunch & no feedback

Laser pulse length for full overlap

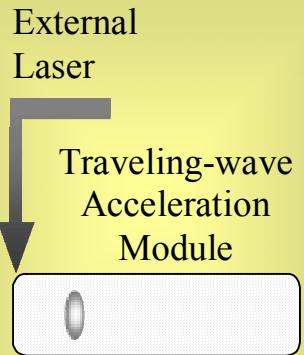


Time it takes the micro-bunch to traverse the structure

$$\frac{d}{c} = \frac{d - \tau_{EM} c \beta_{gr}}{c \beta_{gr}} \Rightarrow \tau_{EM} = \frac{d}{c} \left(\frac{1}{\beta_{gr}} - 1 \right)$$



Single bunch & no feedback



- Loaded gradient: $E_{\text{eff}} \equiv E_{\text{acc}} - E_{\text{dec}} = E_{\text{acc}} - \kappa q$

- Kinetic energy: $\Delta U_{\text{KIN}} \equiv q E_{\text{eff}} d$

- EM energy: $U_{\text{EM}} \equiv P_{\text{Laser}} \frac{d}{V_{\text{gr}}} (1 - V_{\text{gr}}/c)$

Zero force charge

$$\boxed{\eta \equiv \frac{\Delta U_{\text{KIN}}}{U_{\text{EM}}} = \eta_{\max} \frac{4q(q_0 - q)}{q_0^2}} \Rightarrow q_{\text{opt}} = \frac{1}{2} q_0 \equiv \frac{1}{2} \frac{E_{\text{acc}}}{\kappa}$$

$$\eta_{\max} = \frac{\kappa_1}{\kappa}$$

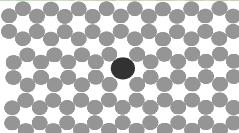
Maximum efficiency is set by the projection of the total deceleration on the fundamental !!

Single bunch & no feedback

Transverse PBG

$$\left. \begin{array}{l} R_{\text{int}} \square 0.68\lambda \\ \varepsilon = 2.1, \lambda \square 1.0[\mu\text{m}] \\ Z_{\text{int}} \square 19.5[\Omega] \\ \beta_{gr} \square 0.58 \\ E_{\text{max}} \square 2[\text{GV/m}] \end{array} \right\} \Rightarrow$$

$$\begin{aligned} P_{\text{Laser}} &\square 50[\text{kW}] \\ \eta &\square 6\% \\ q_{\text{opt}} &\square 7 \times 10^4 e \\ E_{\text{acc}} &\square 1[\text{GV/m}] \end{aligned}$$

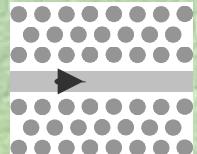


E. Lin, PR STAB, 2000

Longitudinal PBG

$$\left. \begin{array}{l} D_{\text{int}} \square 0.55\lambda \\ \varepsilon = 2.1 \\ \lambda \square 1.5[\mu\text{m}] \\ Z_{\text{int}} \Delta_y / \lambda \square 250[\Omega] \\ \beta_{gr} \square 0.2 \\ E_{\text{max}} \square 2[\text{GV/m}] \end{array} \right\} \Rightarrow$$

$$\begin{aligned} \bar{P}_{\text{Laser}} &\square 2.3[\text{kW}/\mu\text{m}] \\ \eta &\square 36\% \\ \bar{q}_{\text{opt}} &\square 5 \times 10^4 [e/\mu\text{m}] \\ E_{\text{acc}} &\square 0.6[\text{GV/m}] \end{aligned}$$

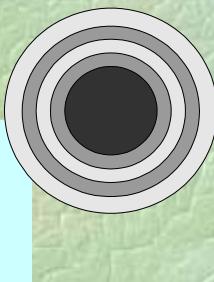


B. Cowan, PR STAB, 2003

Cylindrical Bragg Structure

$$\left. \begin{array}{l} R_{\text{int}} \square 0.68\lambda \\ \varepsilon_1 = 2.1, \varepsilon_2 = 4 \\ \lambda \square 1[\mu\text{m}] \\ Z_{\text{int}} \square 56.4[\Omega] \\ \beta_{gr} \square 0.58 \\ E_{\text{max}} \square 2[\text{GV/m}] \end{array} \right\} \Rightarrow$$

$$\begin{aligned} P_{\text{Laser}} &\square 18[\text{kW}] \\ \eta &\square 9\% \\ q_{\text{opt}} &\square 7 \times 10^4 e \\ E_{\text{acc}} &\square 1[\text{GV/m}] \end{aligned}$$

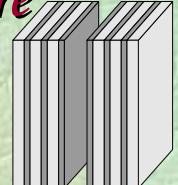


A. Mizrahi & L. Schachter, Phys. Rev. E, 2004

Planar Bragg Structure

$$\left. \begin{array}{l} D_{\text{int}} \square 0.55\lambda \\ \varepsilon_1 = 2.1, \varepsilon_2 = 4 \\ \lambda \square 1[\mu\text{m}] \\ Z_{\text{int}} \Delta_y / \lambda \square 57[\Omega] \\ \beta_{gr} \square 0.48 \\ E_{\text{max}} \square 2[\text{GV/m}] \end{array} \right\} \Rightarrow$$

$$\begin{aligned} P_{\text{Laser}} &\square 5.3[\text{kW}/\mu\text{m}] \\ \eta &\square 8\% \\ q_{\text{opt}} &\square 3.3 \times 10^4 [e/\mu\text{m}] \\ E_{\text{acc}} &\square 0.56[\text{GV/m}] \end{aligned}$$



Single bunch & no feedback

$$\eta_{\max} = \frac{\kappa_1}{\kappa}$$

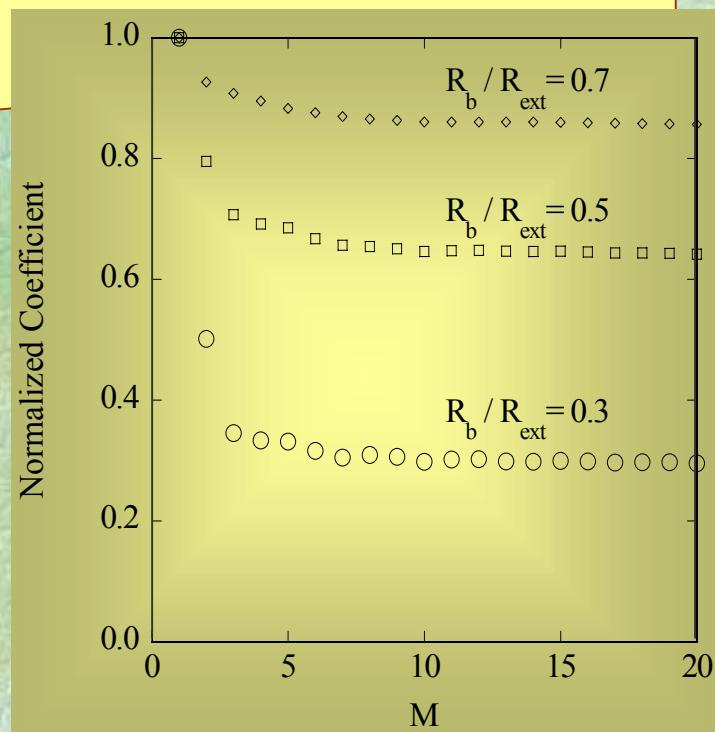
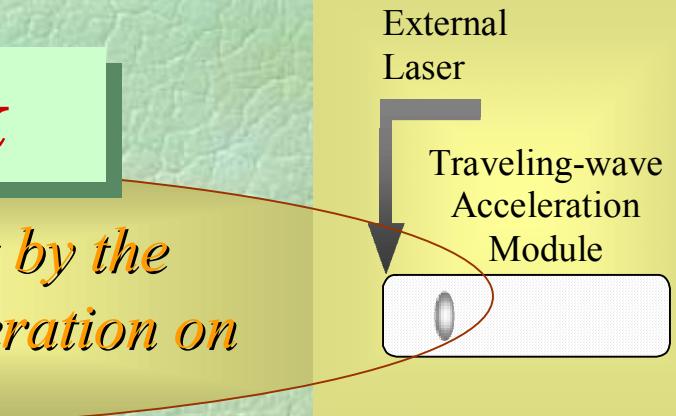
Maximum efficiency is set by the projection of the total deceleration on the fundamental

By splitting the bunch into a train of micro-bunches, the projection of the wake on the fundamental remains the same, but higher frequencies are suppressed

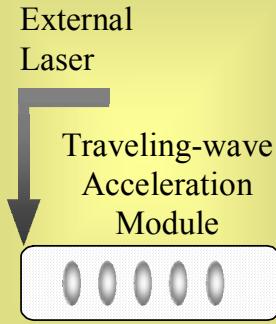
$$P(M) = q^2 c \kappa \sum_{n=1}^M W_n \left[\frac{\text{sinc}\left(\pi M \frac{\omega_n}{\omega_1}\right)}{\text{sinc}\left(\pi \frac{\omega_n}{\omega_1}\right)} \right]^2 = q^2 c \bar{\kappa}(M)$$

?? →

$$\eta_{\max} = \frac{\kappa_1}{\bar{\kappa}(M)} = \frac{\kappa_1}{\kappa_1 + \kappa_2(M) + \dots}$$



Train of bunches & no feedback

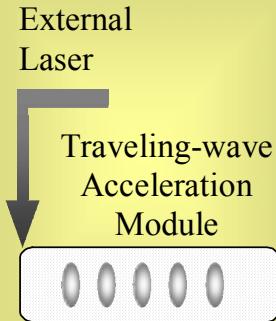


What is the efficiency in case of a train of micro-bunches?

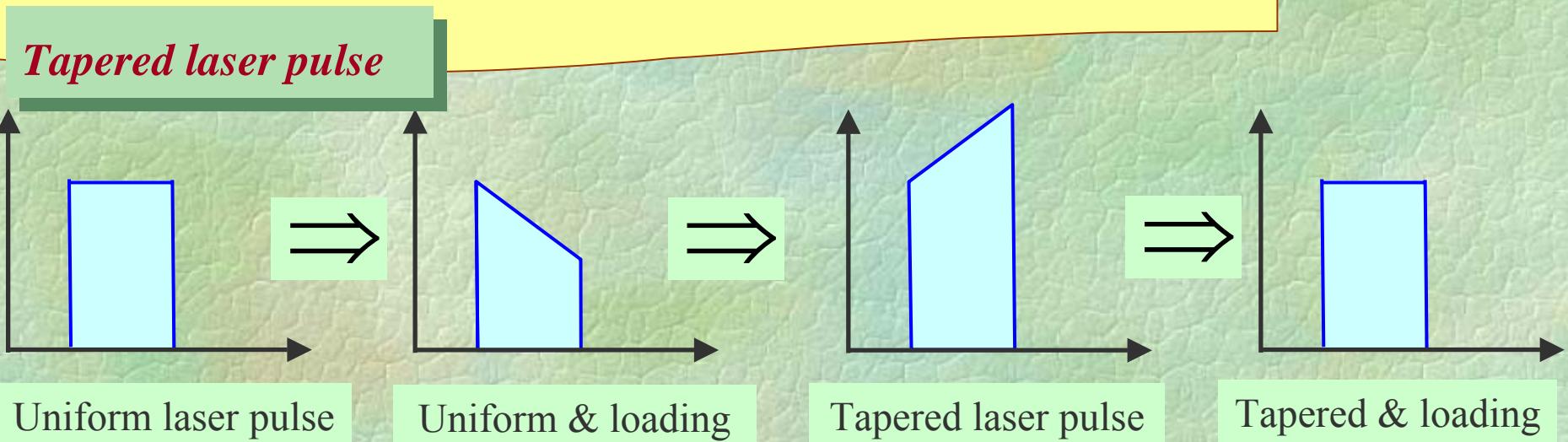
For an answer, one needs to make two observations:

- a) *The laser pulse duration ought to be **longer** in order to account for the macro-bunch length.*
- b) *The envelope of the laser pulse must be **tapered**, in order to compensate for beam loading.*

Train of bunches & no feedback

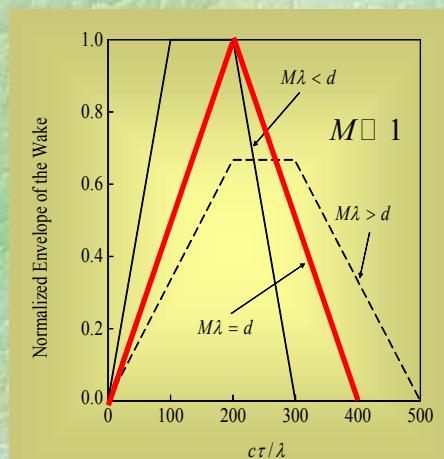


Laser **tapered pulse** necessary to **compensate** for the beam loading in order to ensure **uniform** acceleration of **all** micro-bunches



Still we have a problem: wake propagates at c whereas laser's envelope propagates at $c\beta_{gr}$.

Solution: $M\lambda = d$



Train of bunches & no feedback

$$\eta = \frac{\left[12(1 - \beta_{\text{gr}}) \frac{\kappa_1}{\kappa} \right] q (q_0 - q)}{3 \left[q_0 - q + q \frac{\kappa_1}{\kappa} \left(\frac{1}{M} + 1 \right) \right]^2 + \left[q \frac{1}{\beta_{\text{gr}}} \frac{\kappa_1}{\kappa} \right]^2}$$

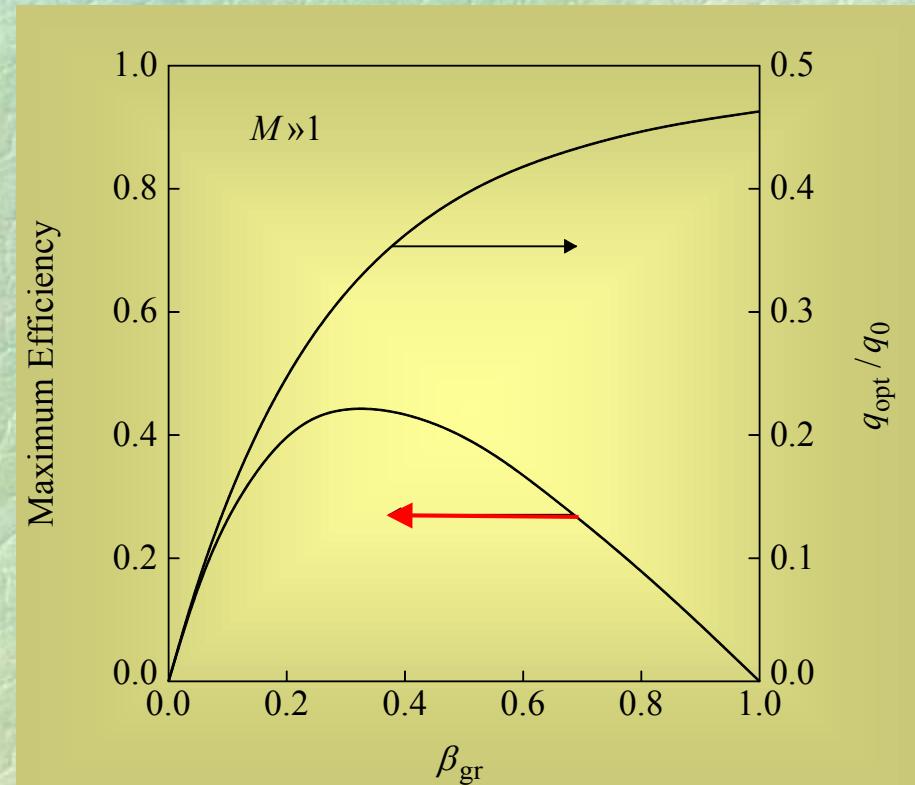
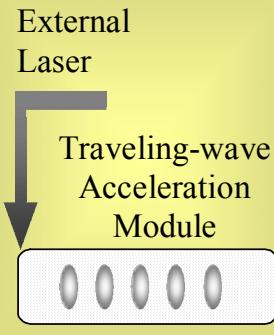
$\square 12(1 - \beta_{\text{gr}}) \beta_{\text{gr}}^2 \frac{q(q_0 - q)}{q^2 + 3q_0^2 \beta_{\text{gr}}^2}.$

$$M \square 1, \quad \frac{\kappa_1}{\kappa} \square 1$$

In spite of splitting the macro-bunch, there still is 50% waste of the laser energy → feedback loop.

$$\eta_{\max} \square 12(1 - \beta_{\text{gr}}) \beta_{\text{gr}}^2 \frac{\xi(1 - \xi)}{\xi^2 + 3\beta_{\text{gr}}^2}$$

$$q_{\text{opt}} \square 3q_0 \beta_{\text{gr}}^2 \left[\sqrt{1 + \frac{1}{3\beta_{\text{gr}}^2}} - 1 \right] \equiv q_0 \xi$$



Single bunch & feedback

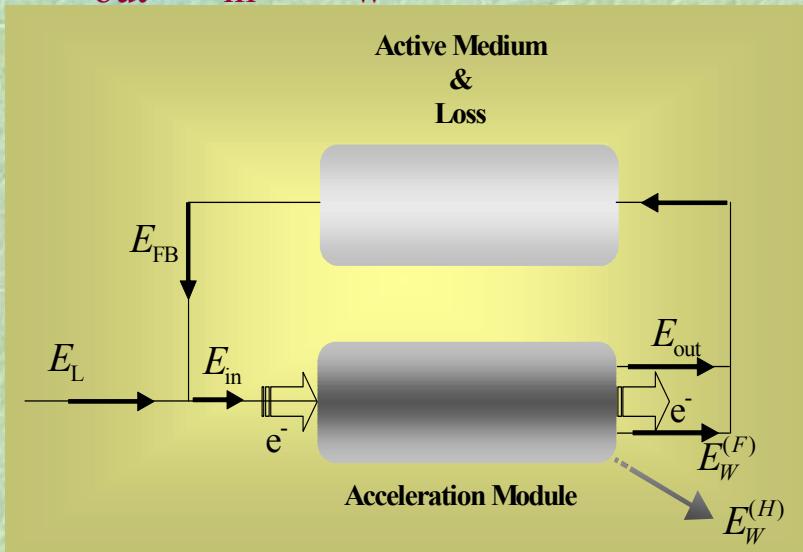
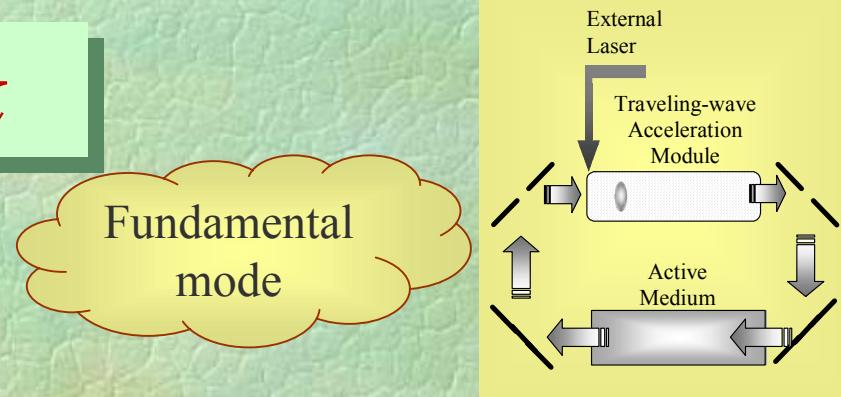
- External laser field: E_L
- Input to acceleration module : $E_{in} = E_L + E_{FB}$
- Output of the acceleration module : $E_{out} = E_{in} - \dot{E}_W$
- Feedback loop: $E_{FB} = \Gamma E_{out}$

$$\Gamma = g / (\text{gain loss coefficient})$$

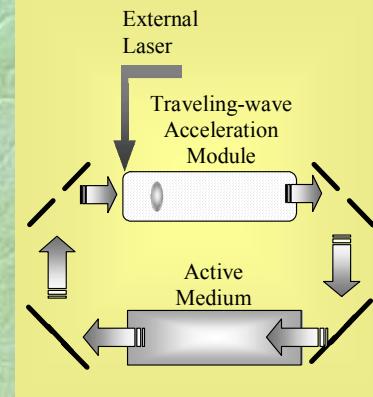
$$1 - e^{-2\psi} = 1/Q$$

- Dynamics:

$$E_{out}(t) = \Gamma E_{out}(t - T_{rr}) + E_L(t - d/c\beta_{gr}) - E_W^{(F)}(t - d/c\beta_{gr})$$



Single bunch & feedback



- External energy injected into the system:

$$U_{\text{Laser}} = \frac{(E_L \lambda)^2}{Z_{\text{int}}} \tau_{\text{EM}} \quad , \quad U_{\text{ACTIVE}} = (g^2 - 1) U_{\text{OUT}} = (g^2 - 1) \frac{[\lambda(E_{\text{acc}} - 2\kappa_1 q)]^2}{Z_{\text{int}}} \tau_{\text{EM}}$$

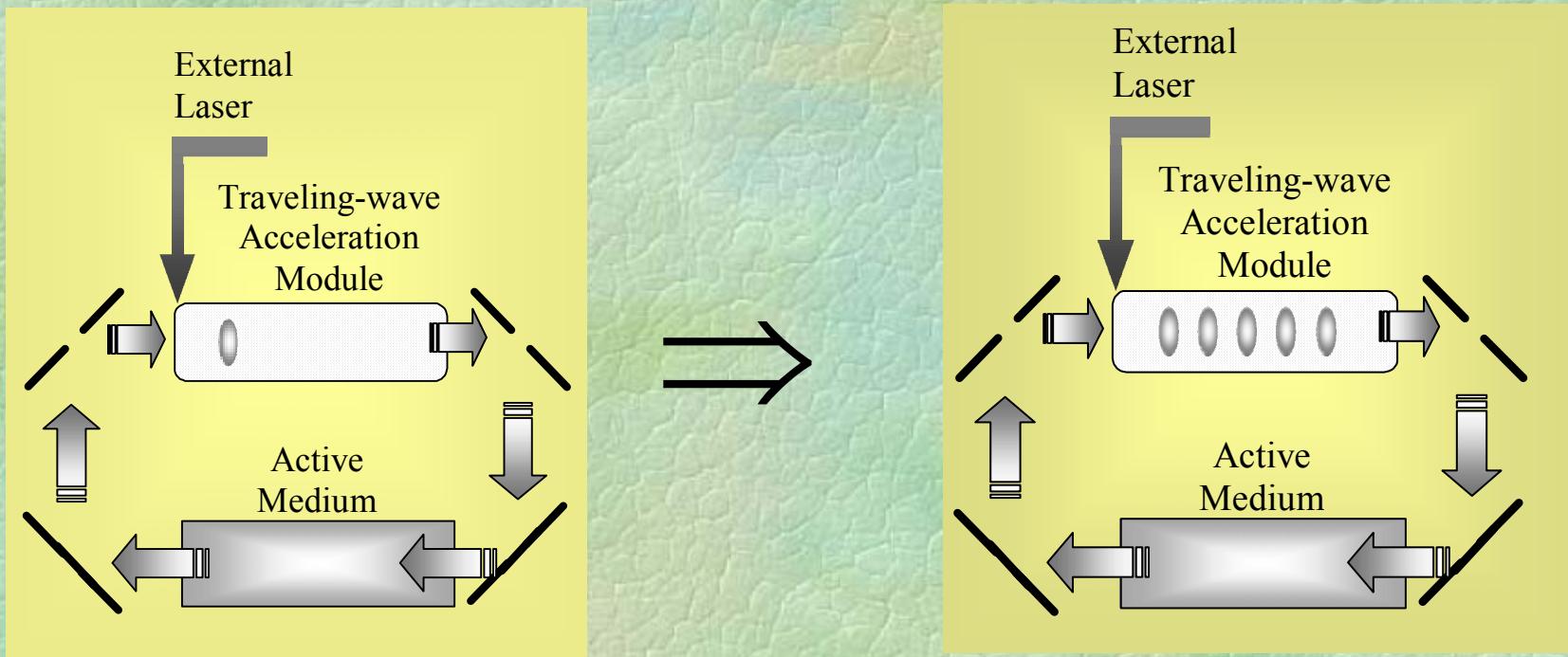
- In steady state it compensates energy which leaves: ΔU_{KIN} and $U_{\text{LOSS}} = U_{\text{OUT}}/Q$

$$\eta = \frac{\Delta U_{\text{KIN}}}{U_{\text{LASER}} + U_{\text{ACTIVE}}} = \frac{\Delta U_{\text{KIN}}}{\Delta U_{\text{KIN}} + U_{\text{LOSS}}} = \frac{1}{1 + \frac{1}{Q} \frac{U_{\text{OUT}}}{\Delta U_{\text{KIN}}}}$$

$$q_{\text{opt}} = \frac{1}{2} q_0, \quad \eta_{\text{max}} \square \frac{1}{1 + \frac{1}{Q \frac{\kappa_1}{\kappa}}} \square \begin{cases} 1 & Q \square 1 \\ \frac{\kappa_1}{\kappa} & Q \rightarrow 1 \end{cases}$$

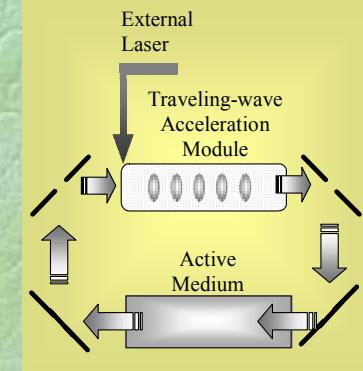
*High efficiency but,
small number of electrons →
train of bunches and feedback loop*

Train of bunches & feedback



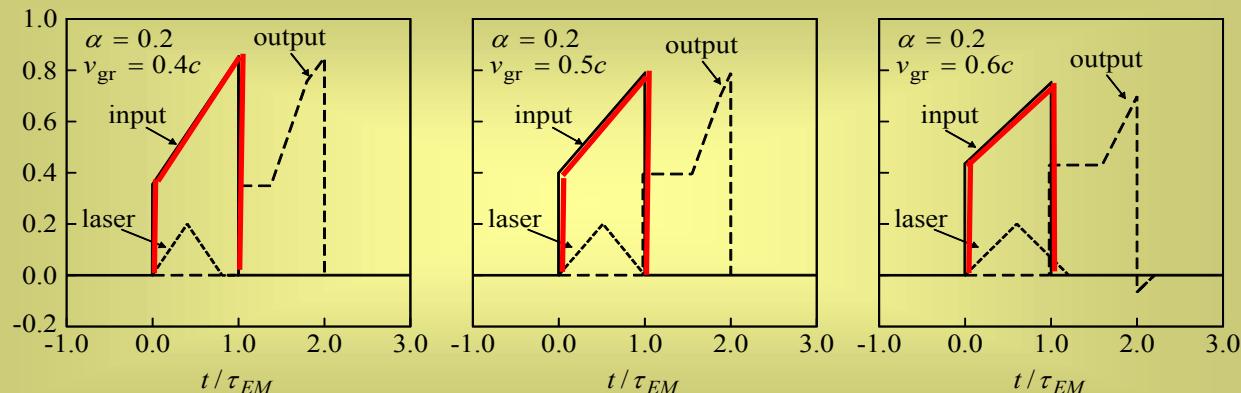
*Ensure that **output & feedback** are consistent with the necessary **input !!***

Train of bunches & feedback



Laser pulse shaping

$$\lambda M = d$$



Talk in Exotic schemes WG

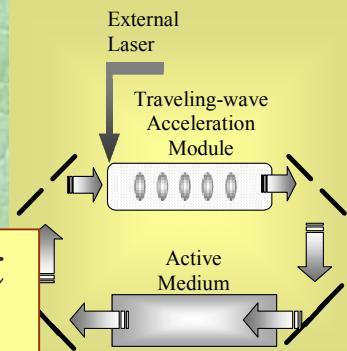
Active enhancement of the quality factor

Conditions for self-consistent field:

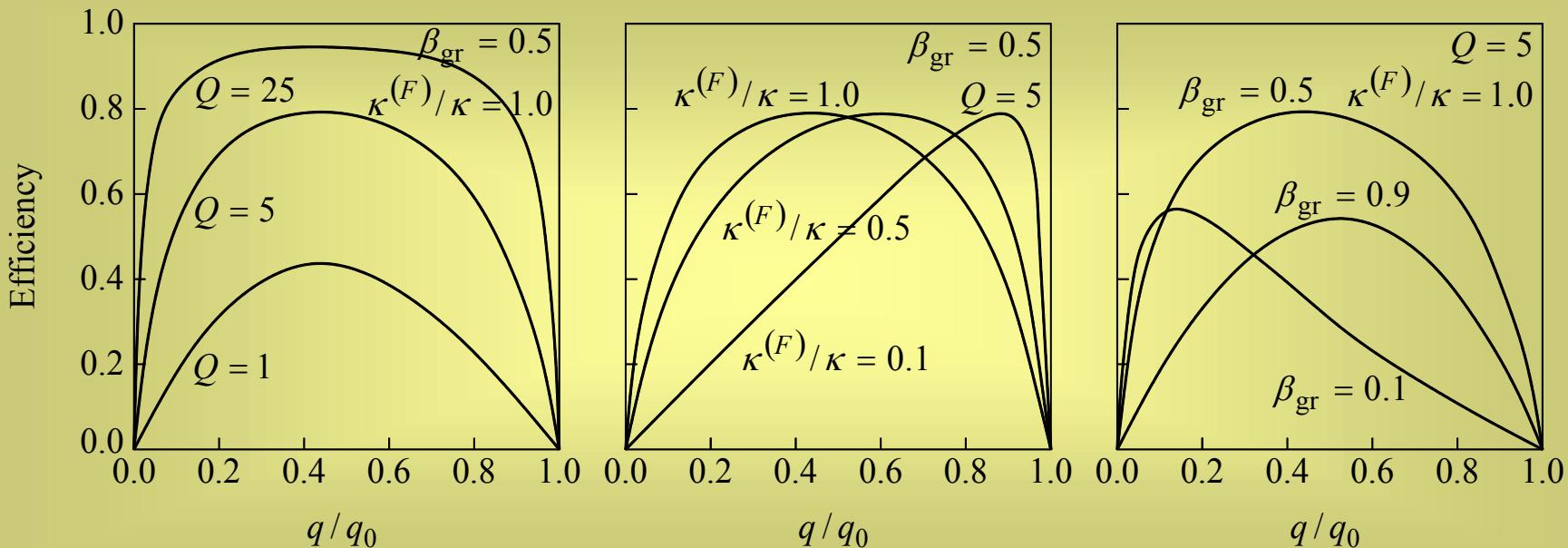
- (I) Amplifier compensates for all **radiation loss**
- (II) External laser compensates for **beam-loading**

$$\eta = \frac{\Delta U_{KIN}}{U_{LASER} + U_{ACTIVE}} = \frac{1}{1 + \frac{1}{Q} \frac{U_{OUT}}{\Delta U_{KIN}}}$$

Train of bunches & feedback



- Peak efficiency independent of κ_1/κ
- Sensitivity



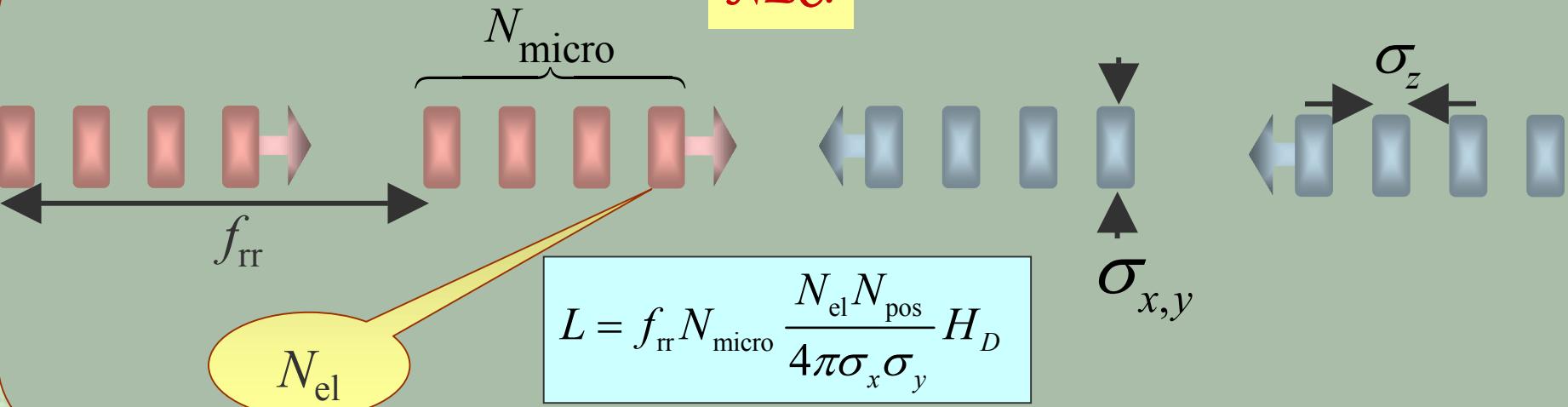
High Q :

- High efficiency
- Reduced sensitivity

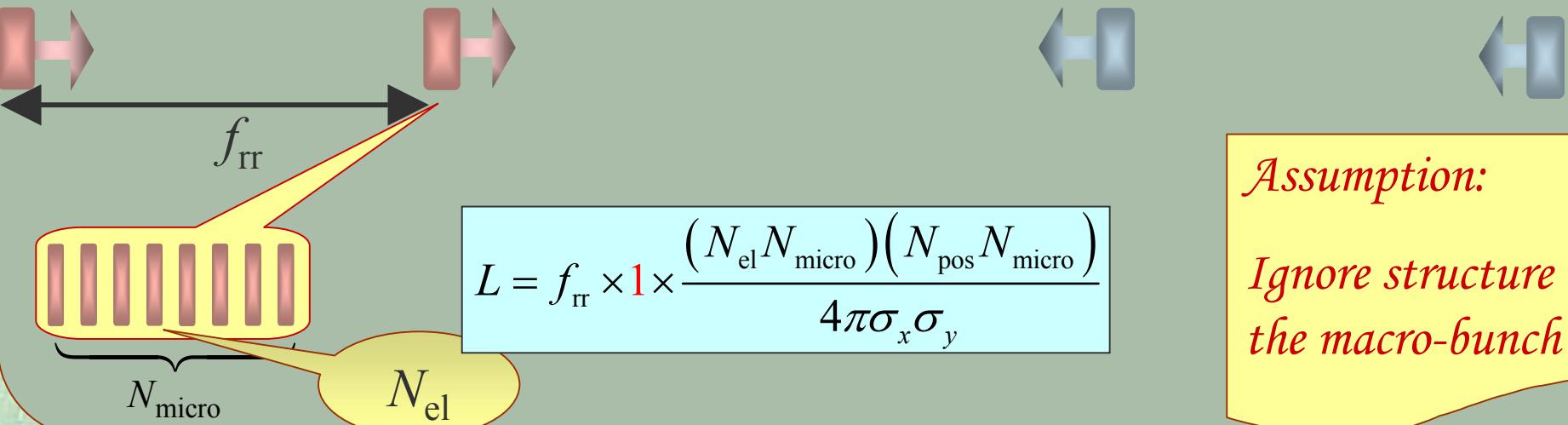
- Peak efficiency dependent on β_{gr}
- Sensitivity

Luminosity

NLC:



Optical Acc.:



Assumption:

Ignore structure of
the macro-bunch

Luminosity

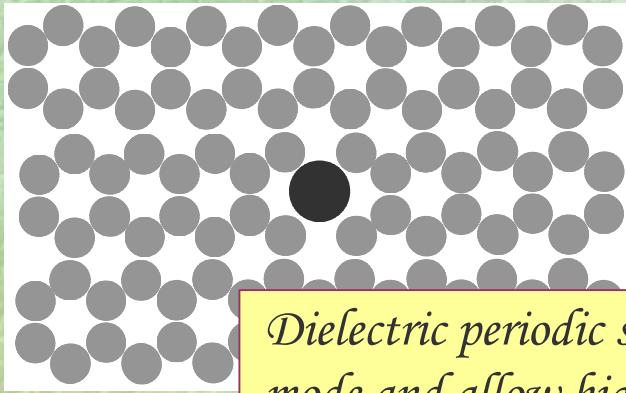
Fluence

	NLC	Single no FB	Single no FB	Train & FB	Train & FB
f_{rr} [Hz]	120	1(6)	1(9)	1(6)	1(6)
N_{micro}	190	1	1	1(3)	1(3)
N_{el}	0.75(10)	5(4)	5(4)	1(6)	1(6)
σ_z [nm]	0.11(6)	4	4	4	4
σ_x [nm]	245	245	24.5	245	24.5
σ_y [nm]	2.7	2.7	0.27	2.7	0.27
$n^{-1/3}$ [\AA]	2.1	3.8	0.8	1.4	0.3
H_D	1.4	1.0	1.0	1.0	1.0
L [$\text{cm}^{-2}\text{sec}^{-1}$]	2(34)	3(25)	3(30)	1.2(34)	1.2(36)
Beam power [MW]	13.7	4(-3)	4	80	80

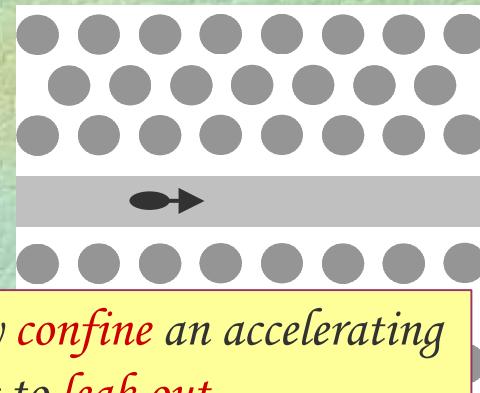
Density !

Summary: Dielectric Structures

Transverse PBG

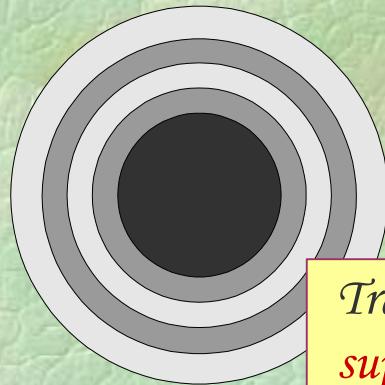


Longitudinal PBG

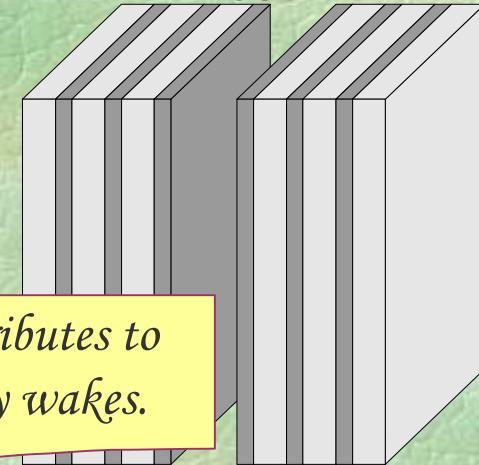


Dielectric periodic structures may *confine* an accelerating mode and allow high order modes to *leak out*.

Cylindrical Bragg Structure



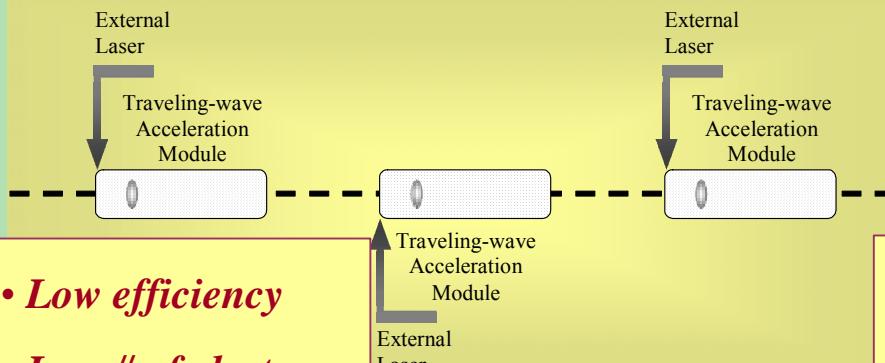
Planar Bragg Structure



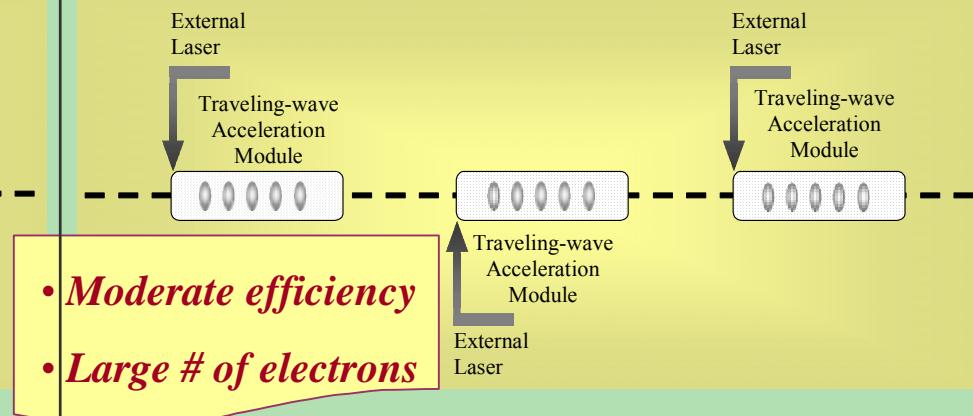
Train of micro-bunches contributes to suppression of high frequency wakes.

Summary: Configurations

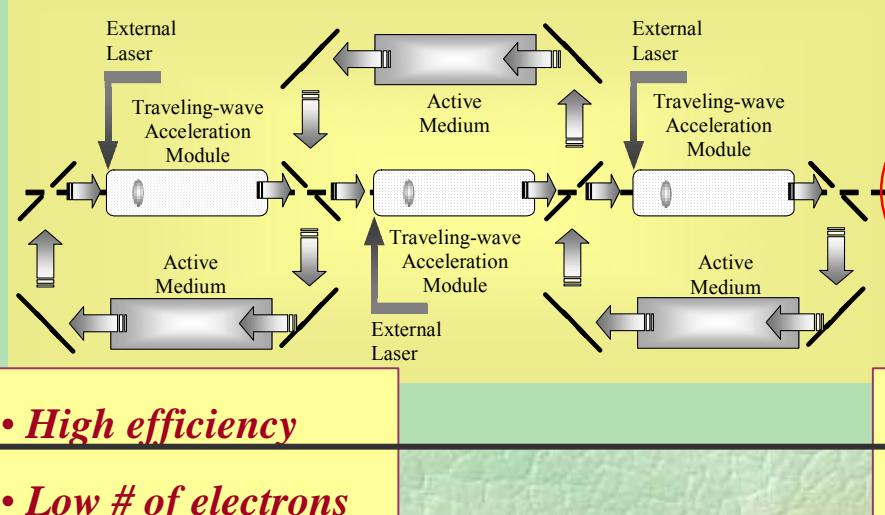
Single bunch & no feedback



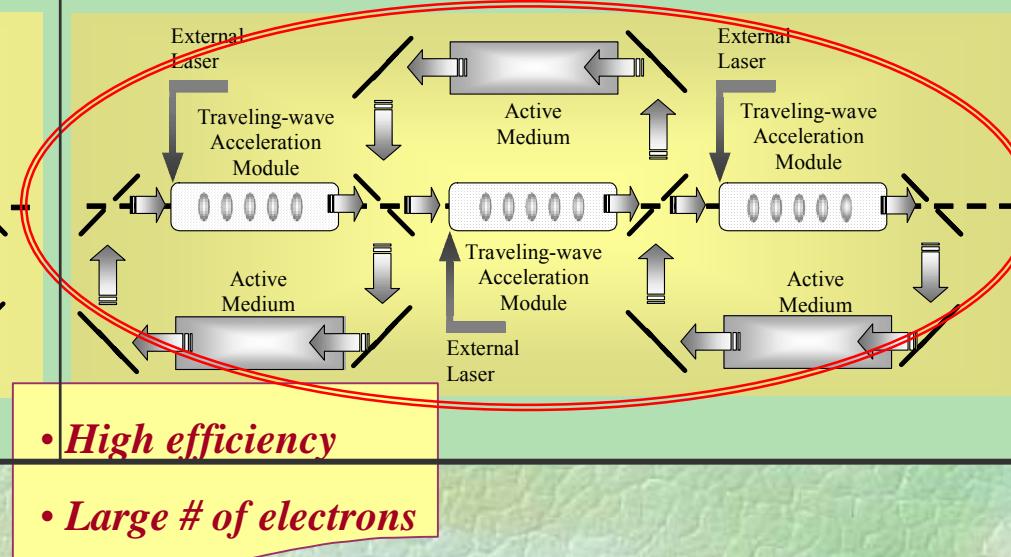
bunches & no feedback



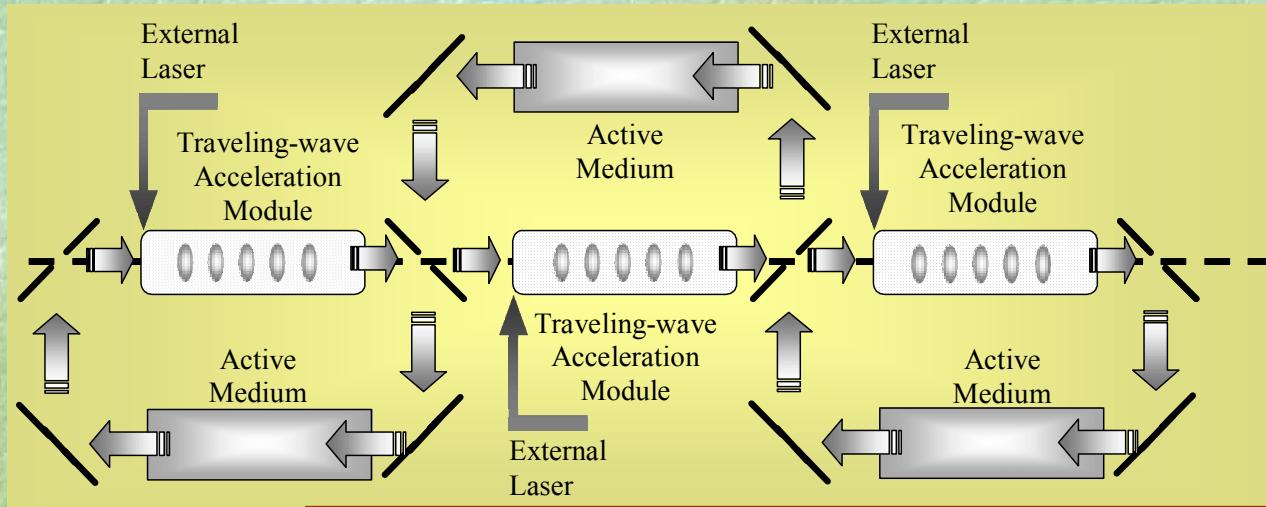
Single bunch & feedback



Train of micro-bunches & feedback



Summary: Efficiency & Luminosity



- (I) Amplifier compensates for all **radiation loss** (active enhancement of the Q—factor) facilitated by the wake being “quasi-coherent”
- (II) External laser compensates for **beam-loading** (tapered pulse)
- (III) Luminosity