EM Structures & Laser Acceleration

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Outline

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

Constraints

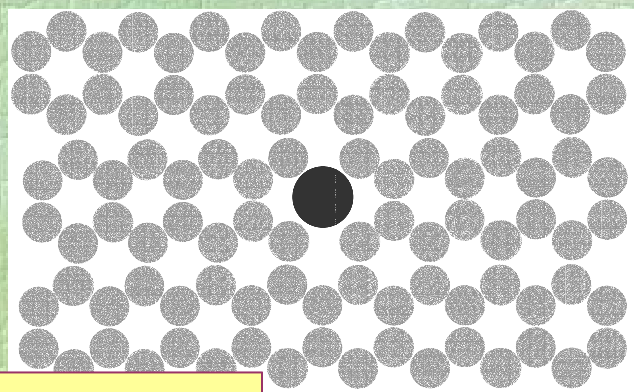
- ***Gradient***: order of 1[GV/m] or higher.
- ***Efficiency***: limited by radiation source and acceleration scheme

  # Lasers anticipated efficiency of wall-plug to light 10% → 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 0.3λ - 0.8λ
- ***Machining tolerance***: 1μm at 3 cm wavelength. Four orders of magnitude difference difficult to be preserved at λ=1μm (poster).

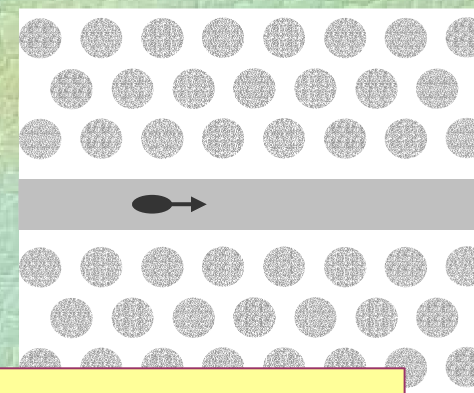
Optical structures

Transverse PBG



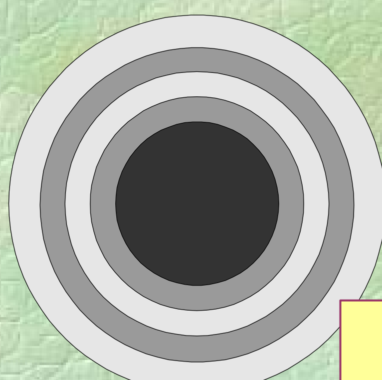
E. Lin, PR STAB, 2000

Longitudinal PBG

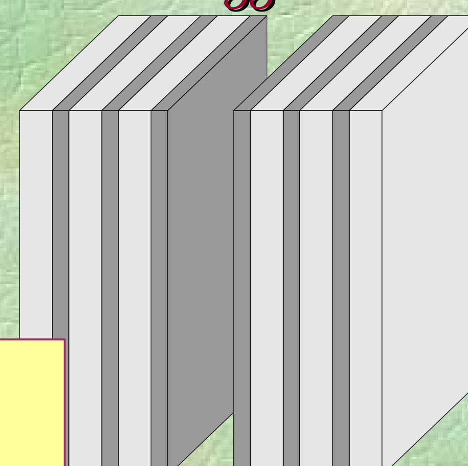


B. Cowan, PR STAB, 2003

Cylindrical Bragg Structure



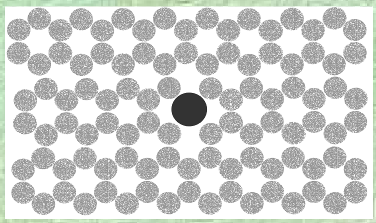
Planar Bragg Structure



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

Structure parameters

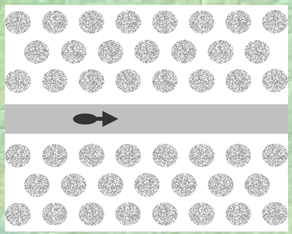
Transverse PBG



$$\underbrace{\frac{R_{\text{int}}}{\lambda} \simeq 0.68}_{\varepsilon=2.1,\ \lambda\simeq 1[\mu\text{m}]} \Rightarrow \begin{cases} Z_{\text{int}} \simeq 19.5[\Omega] \\ \beta_{gr} \simeq 0.58 \\ \dfrac{E_{\text{acc}}}{E_{\max}} \simeq 0.5 \end{cases}$$

E. Lin, PR STAB, 2000

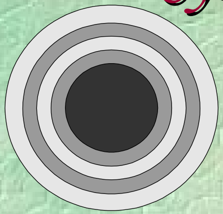
Longitudinal PBG



$$\underbrace{\frac{D_{\text{int}}}{\lambda} = 0.55 \div 1.25}_{\varepsilon=2.1,\ \lambda\simeq 1.5[\mu m]} \Rightarrow \begin{cases} Z_{\text{int}} \dfrac{\Delta_y}{\lambda} \simeq 250 \div 20[\Omega] \\ \beta_{gr} \simeq 0.2 \div 0.6 \\ \dfrac{E_{\text{acc}}}{E_{\max}} \simeq 0.35 \div 0.15 \end{cases}$$

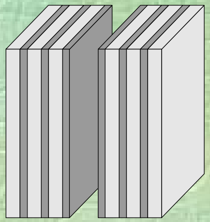
B. Cowan, PR STAB, 2003

Cylindrical Bragg Structure



$$\underbrace{\frac{R_{\text{int}}}{\lambda} \simeq 0.3 \div 0.8}_{\varepsilon_1=2.1,\ \varepsilon_2=4,\ \lambda=1[\mu m]} \Rightarrow \begin{cases} Z_{\text{int}} \simeq 268 \div 37[\Omega] \\ \beta_{gr} \simeq 0.41 \div 0.48 \\ \dfrac{E_{\text{acc}}}{E_{\max}} \simeq 0.73 \div 0.37 \end{cases}$$

Planar Bragg Structure

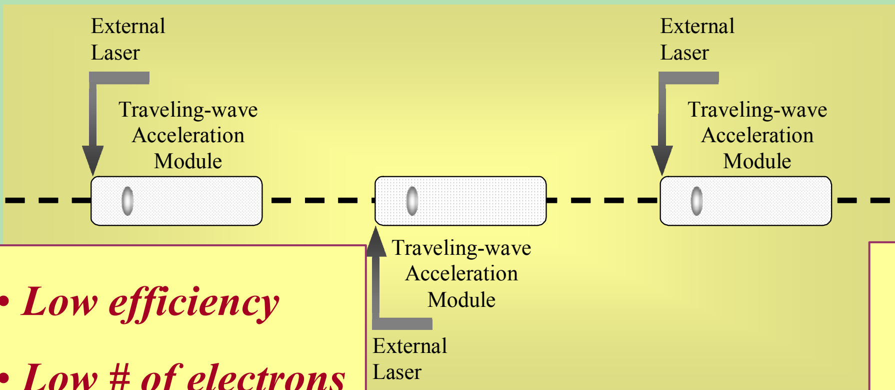


$$\underbrace{\frac{D_{\text{int}}}{\lambda} = 0.3 \div 0.8}_{\varepsilon_1=2.1,\ \varepsilon_2=4,\ \lambda=1[\mu m]} \Rightarrow \begin{cases} Z_{\text{int}} \dfrac{\Delta_y}{\lambda} \simeq 147 \div 25.7[\Omega] \\ \beta_{gr} \simeq 0.42 \div 0.53 \\ \dfrac{E_{\text{acc}}}{E_{\max}} \simeq 0.47 \div 0.20 \end{cases}$$

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

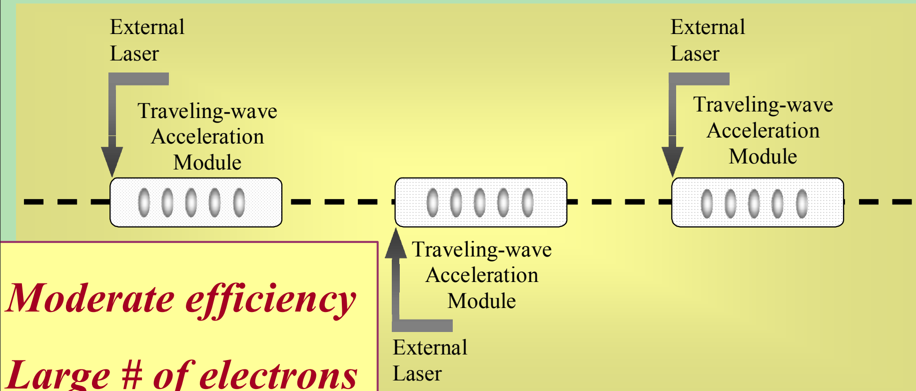
Configurations

Single bunch & no feedback



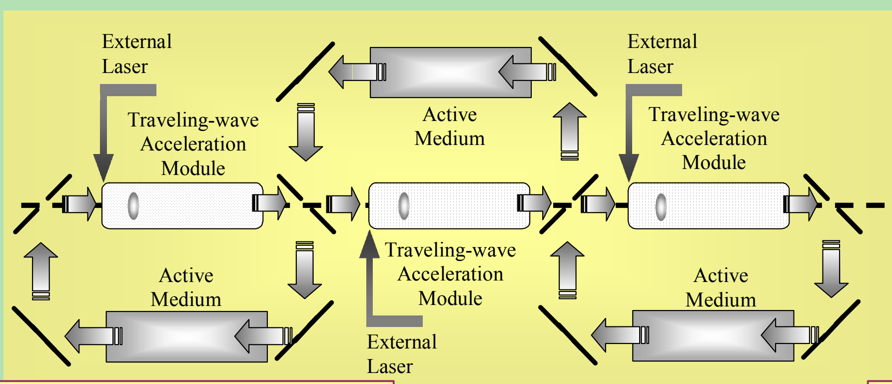
- Low efficiency
- Low # of electrons

bunches & no feedback



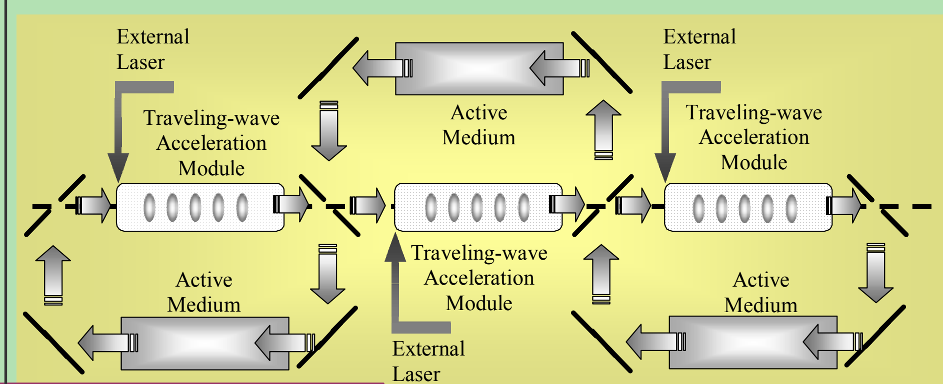
- Moderate efficiency
- Large # of electrons

Single bunch & feedback



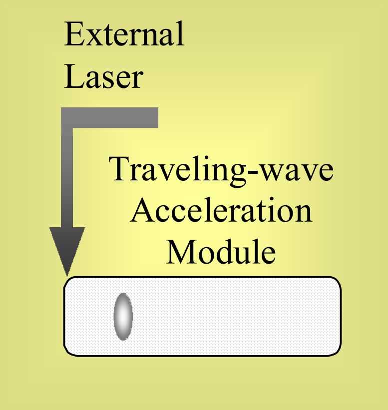
- High efficiency
- Low # of electrons

Train of micro-bunches & feedback



- High efficiency
- Large # of electrons

Single bunch & no feedback



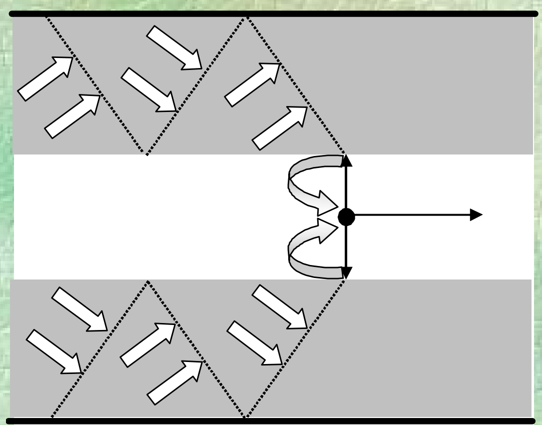
• ***Wake parameter:***

Decelerating field for a given charge ………… $E_{\mathrm{dec}} \equiv \kappa\, q$

$\kappa = 2 / 4\pi\varepsilon_0 R^2$

• ***Beam-loading parameter:***

Beam-loading of the accelerating mode ……….. $E_{\mathrm{dec}}^{(F)} \equiv \kappa_1\, q$



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

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

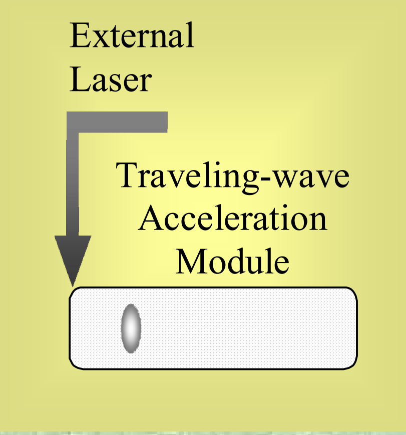
$\kappa_1 \equiv \kappa W_1$

$$\kappa_1 = \frac{\beta_{\mathrm{gr}}}{1-\beta_{\mathrm{gr}}} \frac{Z_{\mathrm{int}}}{\sqrt{\mu_0/\varepsilon_0}} \frac{\pi}{4\pi\varepsilon_0 \lambda^2}$$

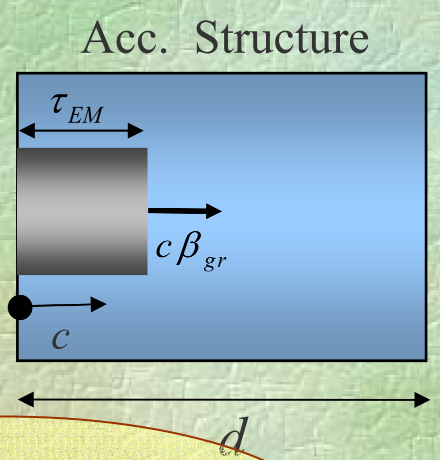
Contribution of the fundamental to the total deceleration

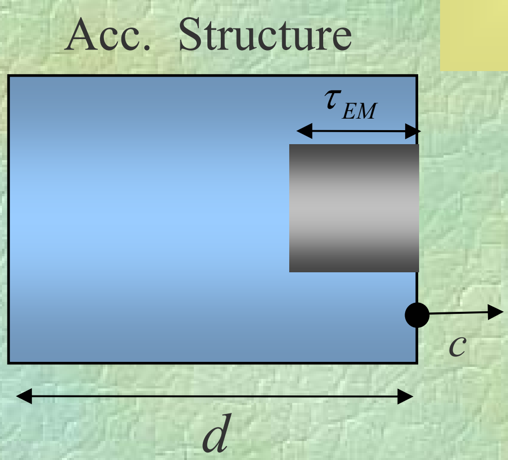
Stupakov & Bane, PR STAB, 2003

Single bunch & no feedback



Laser pulse length for ***full overlap***

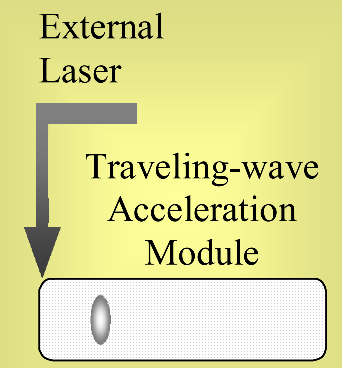




Time it takes the micro-bunch to traverse the structure

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

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

Zero force charge

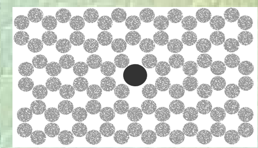
$$\eta \equiv \frac{\Delta U_{\text{KIN}}}{U_{\text{EM}}} = \eta_{\max} \frac{4q\left(q_0 - q\right)}{q_0^2} \Rightarrow q_{\text{opt}} = \frac{1}{2} q_0 \equiv \frac{1}{2} \frac{E_{\text{acc}}}{\kappa}$$

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

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

Single bunch & no feedback

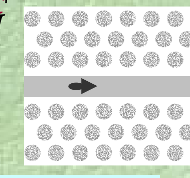
Transverse PBG



$$\left.\begin{array}{l} R_{\rm int} \simeq 0.68\lambda \\ \varepsilon = 2.1,\ \lambda \simeq 1.0[\mu{\rm m}] \\ Z_{\rm int} \simeq 19.5[\Omega] \\ \beta_{gr} \simeq 0.58 \\ E_{\max} \simeq 2[{\rm GV/m}] \end{array}\right\} \Rightarrow \begin{array}{l} P_{\rm Laser} \simeq 50[{\rm kW}] \\ \eta \simeq 6\% \\ q_{\rm opt} \simeq 7\times10^{4} e \\ E_{\rm acc} \simeq 1[{\rm GV/m}] \end{array}$$

E. Lin, PR STAB, 2000

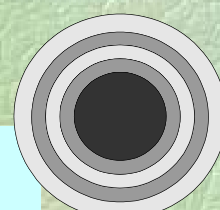
Longitudinal PBG



$$\left.\begin{array}{l} D_{\rm int} \simeq 0.55\lambda \\ \varepsilon = 2.1 \\ \lambda \simeq 1.5[\mu{\rm m}] \\ Z_{\rm int}\Delta_y/\lambda \simeq 250[\Omega] \\ \beta_{gr} \simeq 0.2 \\ E_{\max} \simeq 2[{\rm GV/m}] \end{array}\right\} \Rightarrow \begin{array}{l} \bar{P}_{\rm Laser} \simeq 2.3[{\rm kW}/\mu{\rm m}] \\ \eta \simeq 36\% \\ \bar{q}_{\rm opt} \simeq 5\times10^{4}[e/\mu{\rm m}] \\ E_{\rm acc} \simeq 0.6[{\rm GV/m}] \end{array}$$

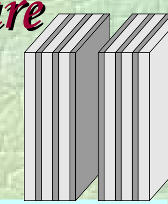
B. Cowan, PR STAB, 2003

Cylindrical Bragg Structure



$$\left.\begin{array}{l} R_{\rm int} \simeq 0.68\lambda \\ \varepsilon_1 = 2.1, \varepsilon_2 = 4 \\ \lambda \simeq 1[\mu{\rm m}] \\ Z_{\rm int} \simeq 56.4[\Omega] \\ \beta_{gr} \simeq 0.58 \\ E_{\max} \simeq 2[{\rm GV/m}] \end{array}\right\} \Rightarrow \begin{array}{l} P_{\rm Laser} \simeq 18[{\rm kW}] \\ \eta \simeq 9\% \\ q_{\rm opt} \simeq 7\times10^{4} e \\ E_{\rm acc} \simeq 1[{\rm GV/m}] \end{array}$$

Planar Bragg Structure



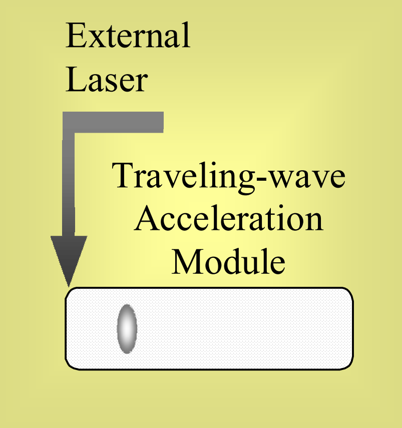
$$\left.\begin{array}{l} D_{\rm int} \simeq 0.55\lambda \\ \varepsilon_1 = 2.1,\ \varepsilon_2 = 4 \\ \lambda \simeq 1[\mu{\rm m}] \\ Z_{\rm int}\Delta_y/\lambda \simeq 57[\Omega] \\ \beta_{gr} \simeq 0.48 \\ E_{\max} \simeq 2[{\rm GV/m}] \end{array}\right\} \Rightarrow \begin{array}{l} P_{\rm Laser} \simeq 5.3[{\rm kW}/\mu{\rm m}] \\ \eta \simeq 8\% \\ q_{\rm opt} \simeq 3.3\times10^{4}[e/\mu{\rm m}] \\ E_{\rm acc} \simeq 0.56[{\rm GV/m}] \end{array}$$

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

Single bunch & no feedback

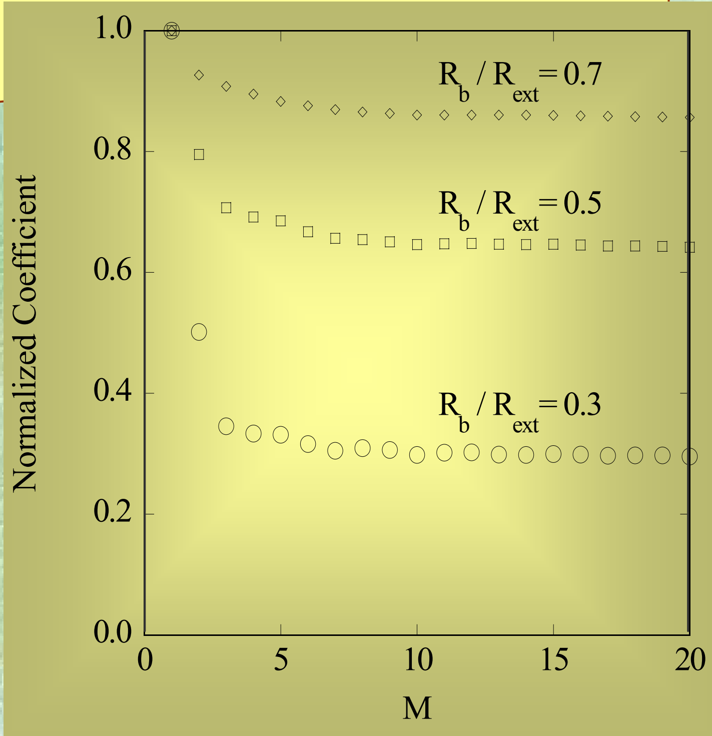
$$\eta_{max} = \frac{\kappa_1}{\kappa}$$

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

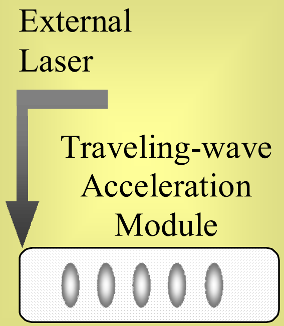
$$P(M) = q^2 c\kappa \sum_{n=1}^{M} W_n \left[\frac{\operatorname{sinc}\left(\pi M \frac{\omega_n}{\omega_1}\right)}{\operatorname{sinc}\left(\pi \frac{\omega_n}{\omega_1}\right)} \right]^2 = q^2 c\,\bar{\kappa}(M)$$



??

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

Train of bunches & no feedback



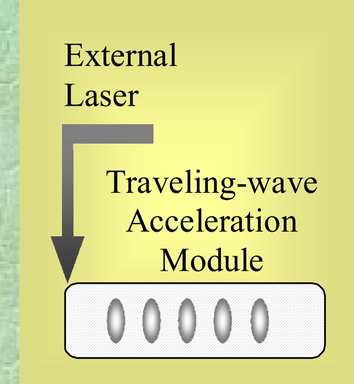
What is the efficiency in case of a train of micro-bunches?

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.*

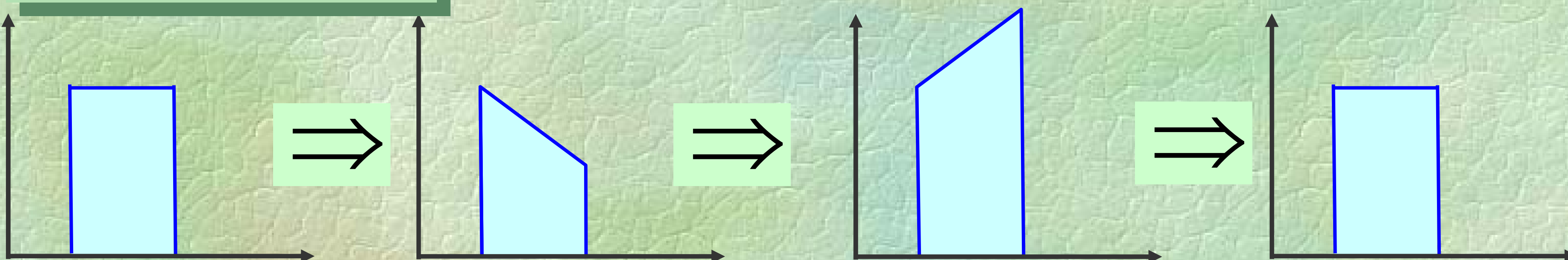
b) *The envelope of the laser pulse must be* ***tapered,*** *in order to compensate for beam loading.*

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

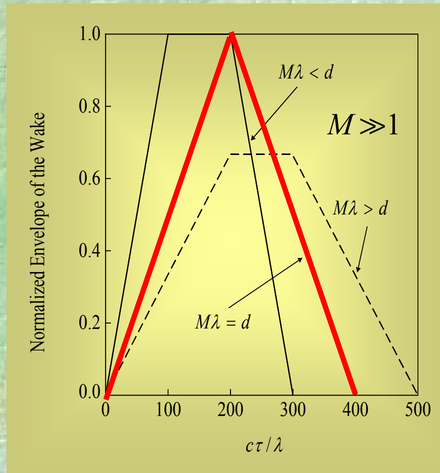
Tapered laser pulse



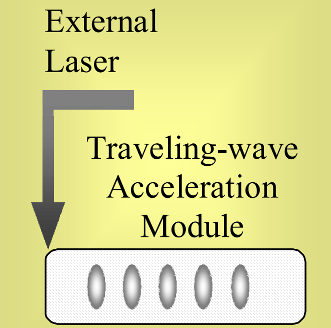
Uniform laser pulse | Uniform & loading | Tapered laser pulse | Tapered & loading

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



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

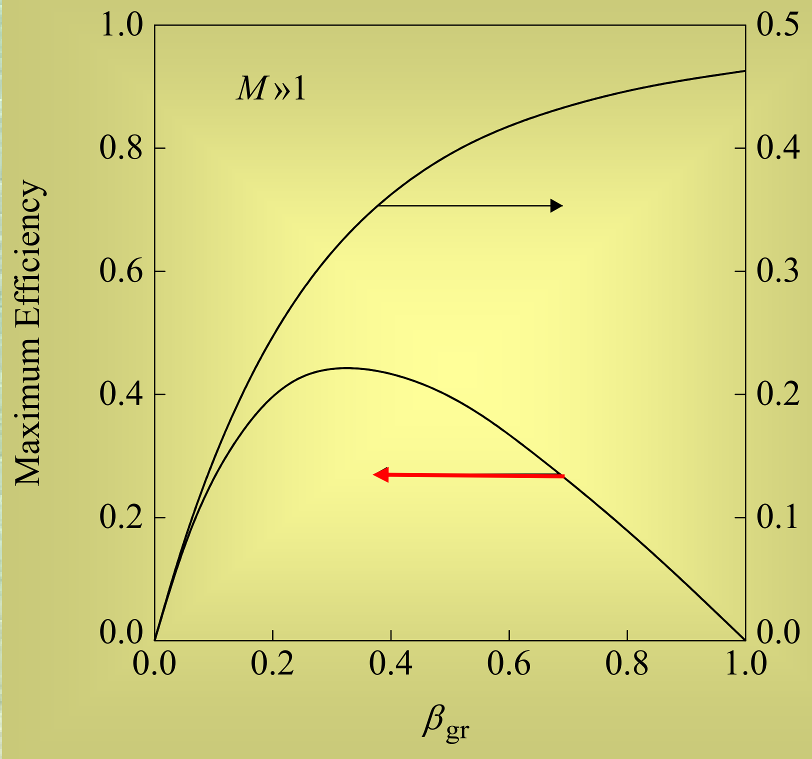
$$\simeq 12\left(1-\beta_{gr}\right)\beta_{gr}^2\frac{q\left(q_0-q\right)}{q^2+3q_0^2\beta_{gr}^2}.$$

$M \gg 1, \quad \frac{\kappa_1}{\kappa} \simeq 1$

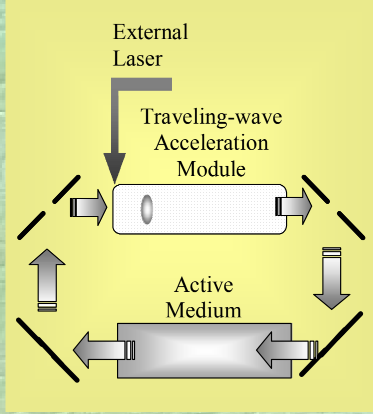
$$\eta_{\max} \simeq 12\left(1-\beta_{gr}\right)\beta_{gr}^2\frac{\xi\left(1-\xi\right)}{\xi^2+3\beta_{gr}^2}$$

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

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



Single bunch & feedback

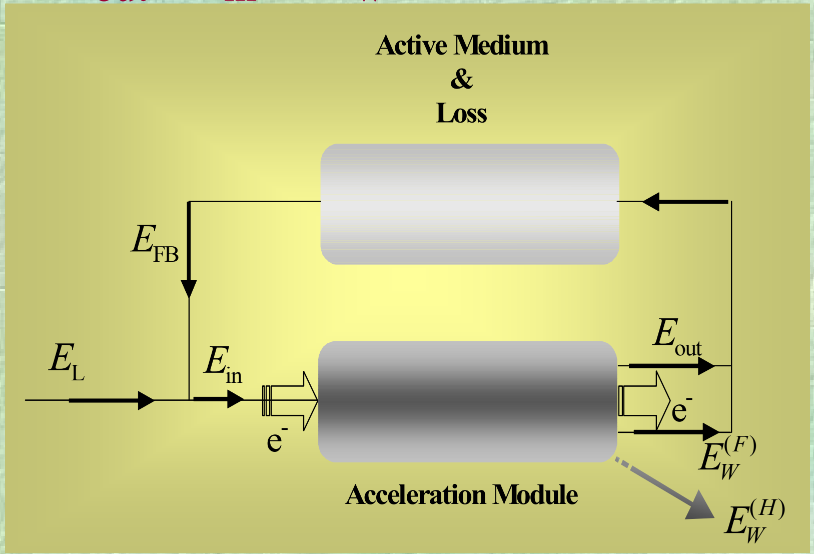


Fundamental mode

- External laser field: E_L
- Input to acceleration module : $E_{in}=E_L+E_{FB}$
- Output of the acceleration module : $E_{out}=E_{in}-E_w$

$2\kappa_1 q$

- Feedback loop: $E_{FB}=\Gamma E_{out}$



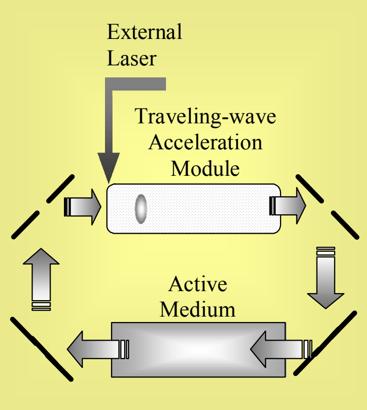
$$\underbrace{\Gamma}_{\text{overall gain}} = \underbrace{g}_{\text{gain}} \underbrace{e^{-\psi}}_{\text{loss coefficient}}$$

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

- Dynamics:

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

Single bunch & feedback



- External energy injected into the system:

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

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

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

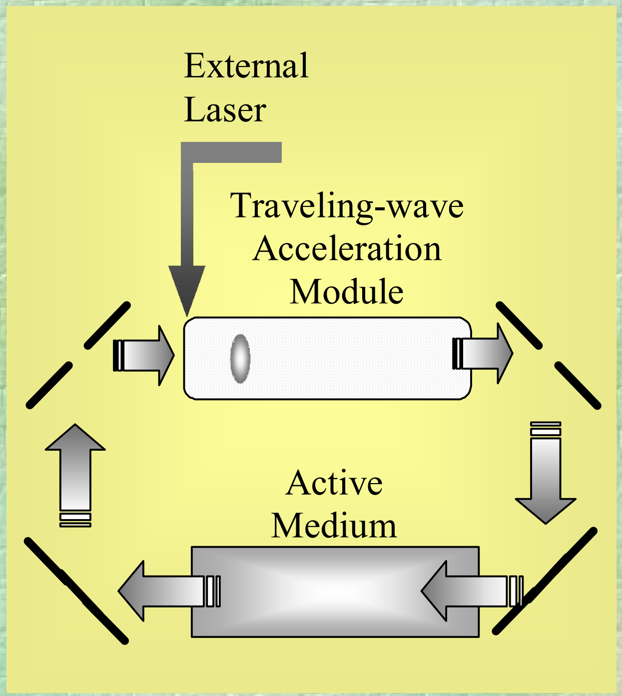
$$q_{\text{opt}} = \frac{1}{2}q_0, \quad \eta_{\max} \simeq \frac{1}{1+\frac{1}{Q\frac{\kappa_1}{\kappa}}} \simeq \begin{cases} 1 & Q \gg 1 \\ \frac{\kappa_1}{\kappa} & Q \to 1 \end{cases}$$

High efficiency but,

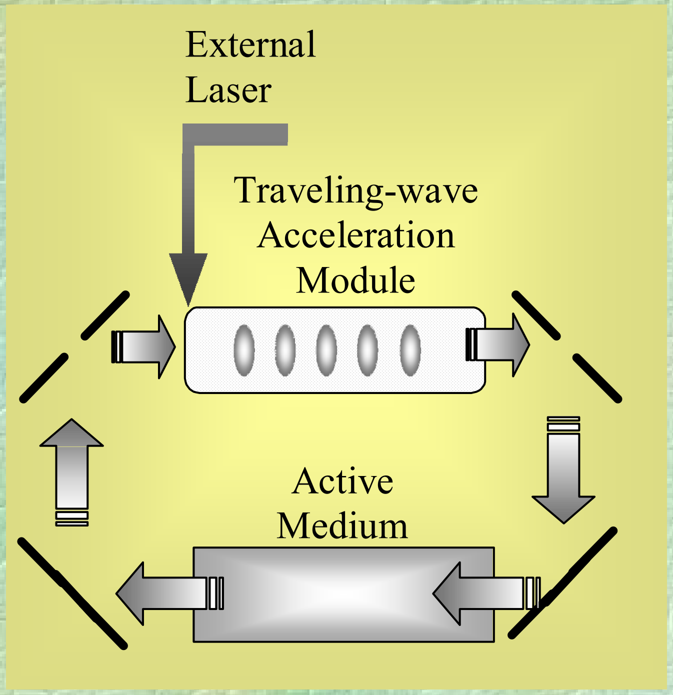
small number of electrons →

train of bunches and feedback loop

Train of bunches & feedback



$\Rightarrow$

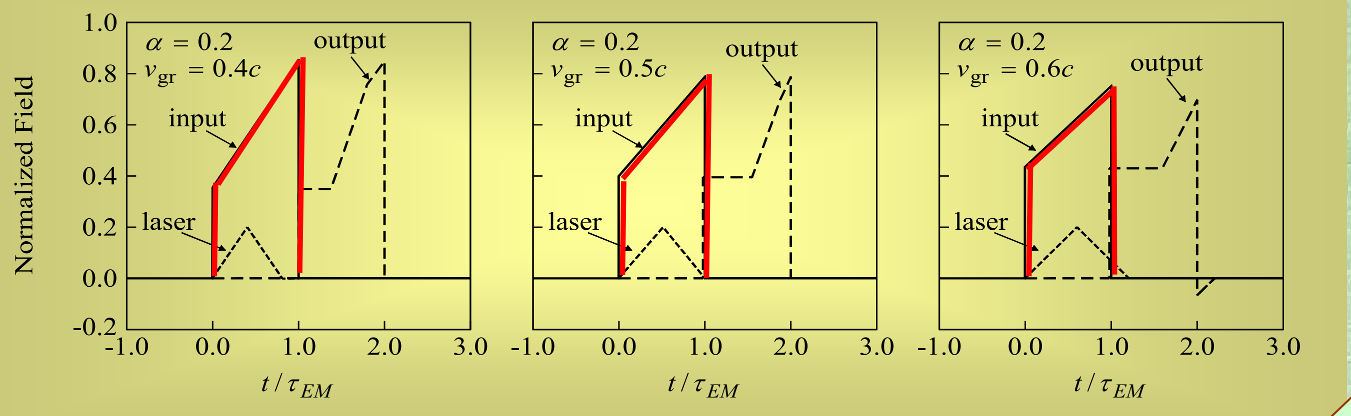


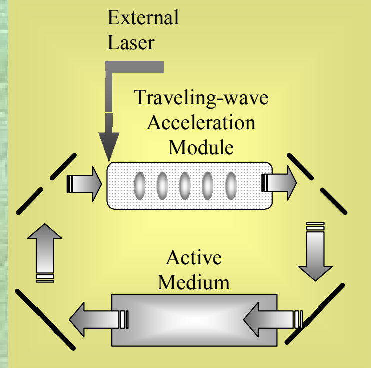
Ensure that output & feedback are consistent with the necessary input !!

Train of bunches & feedback

$\lambda M = d$

Laser pulse shaping





Talk in Exotic schemes WG

Active enhancement of the quality factor

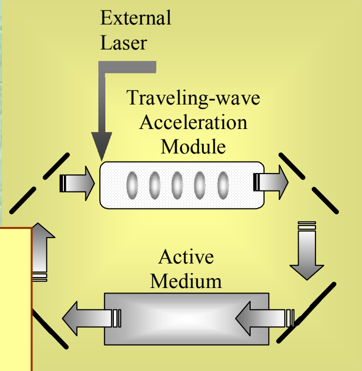
Conditions for self-consistent field:

(I) Amplifier compensates for all ***radiation loss***

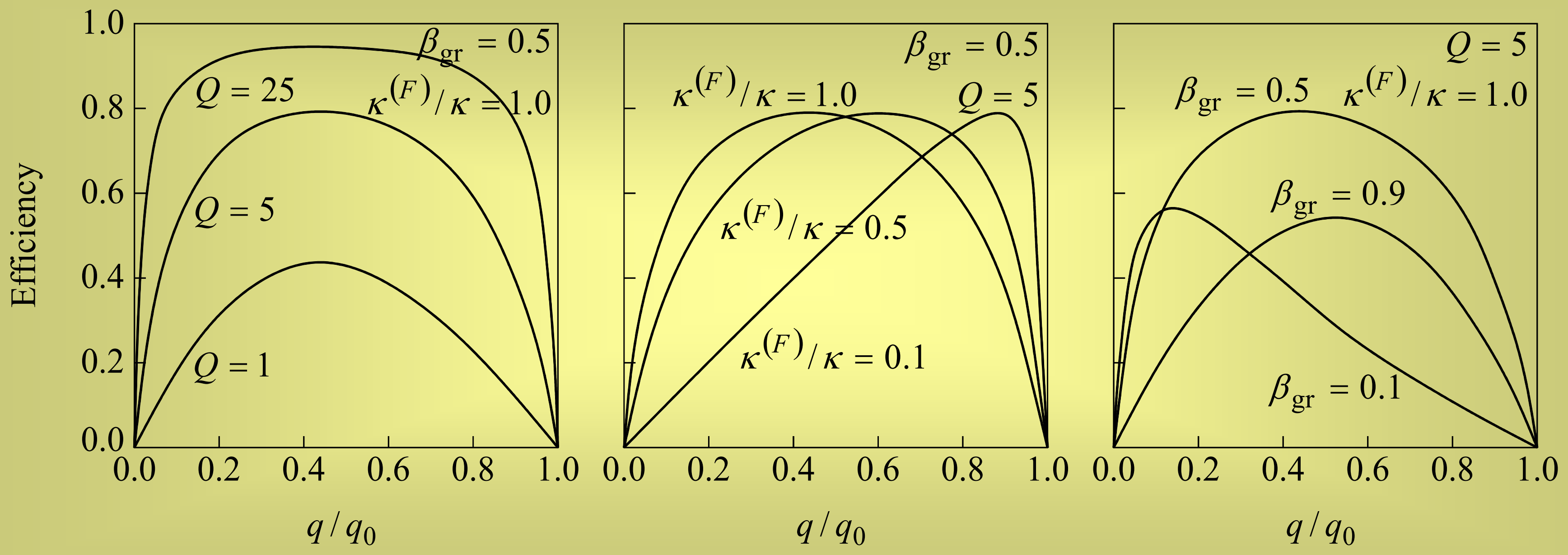
(II) External laser compensates for ***beam-loading***

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

Train of bunches & feedback



- Peak efficiency independent of κ_1/κ
- Sensitivity

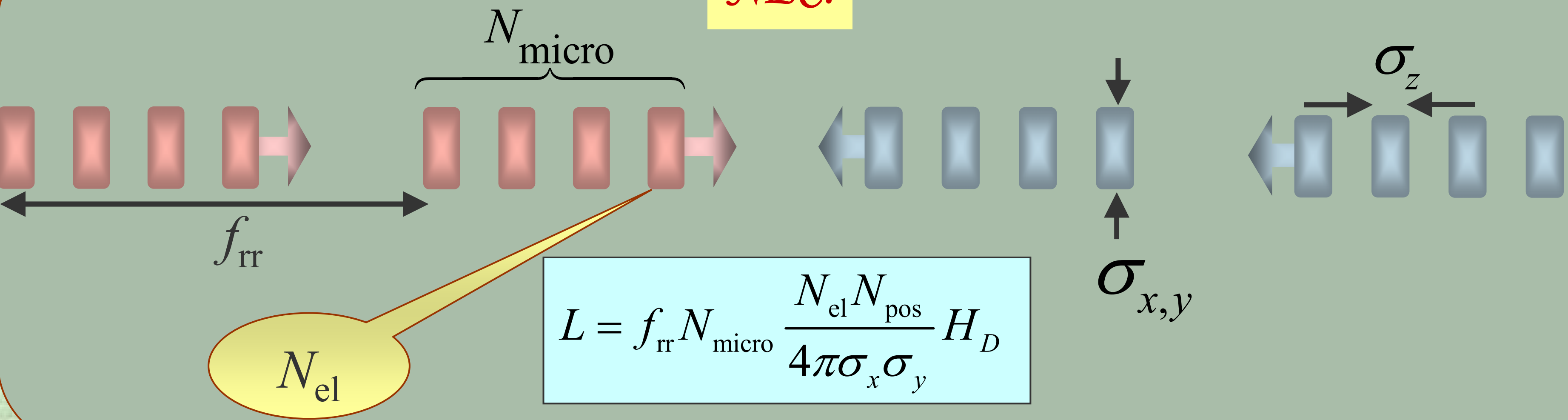


High Q:
(I) High efficiency
(II) Reduced sensitivity

- Peak efficiency dependent on β_{gr}
- Sensitivity

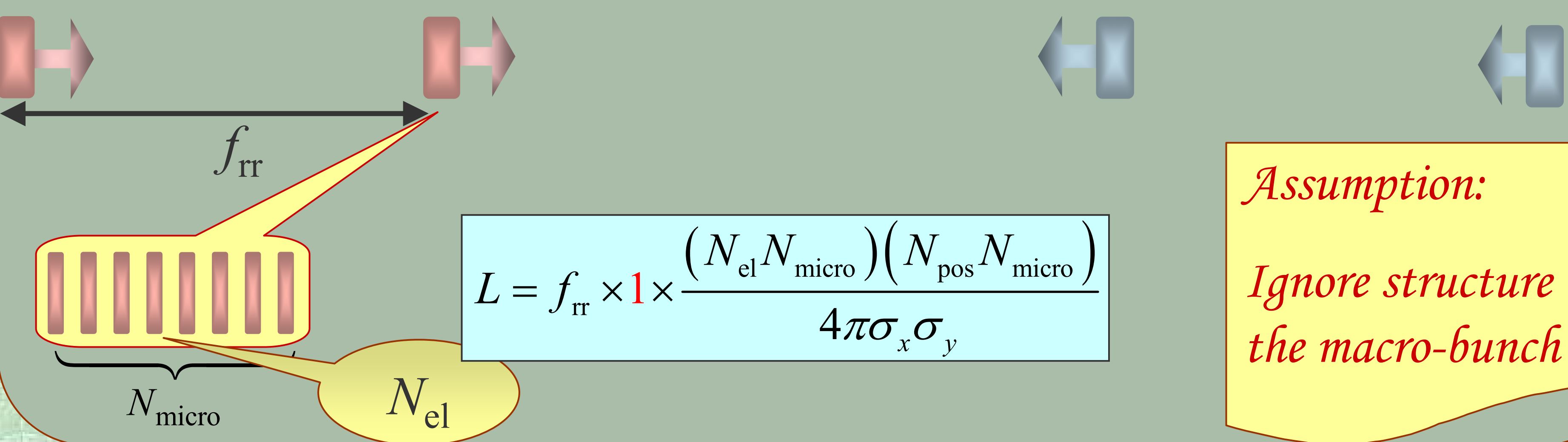
Luminosity

NLC:



$$L = f_{\text{rr}} N_{\text{micro}} \frac{N_{\text{el}} N_{\text{pos}}}{4\pi\sigma_x\sigma_y} H_D$$

Optical Acc.:



$$L = f_{\text{rr}} \times 1 \times \frac{\left(N_{\text{el}} N_{\text{micro}}\right)\left(N_{\text{pos}} N_{\text{micro}}\right)}{4\pi\sigma_x\sigma_y}$$

Assumption:

Ignore structure of the macro-bunch

Luminosity

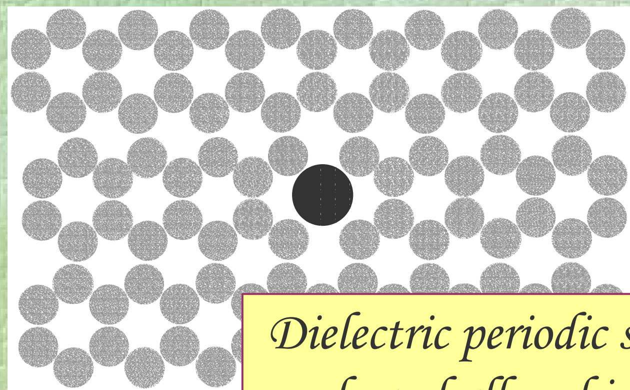
	NLC	Single no FB	Single no FB	Train & FB	Train & FB
f_{rr} [Hz]	120	1(6)	1(9)	1(6)	1(6)
N_{micro}	190	1	1	1(3)	1(3)
N_{el}	0.75(10)	5(4)	5(4)	1(6)	1(6)
σ_z [nm]	0.11(6)	4	4	4	4
σ_x [nm]	245	245	24.5	245	24.5
σ_y [nm]	2.7	2.7	0.27	2.7	0.27
$n^{-1/3}$ [Å]	2.1	3.8	0.8	1.4	0.3
H_D	1.4	1.0	1.0	1.0	1.0
L[$cm^{-2}sec^{-1}$]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

Fluence

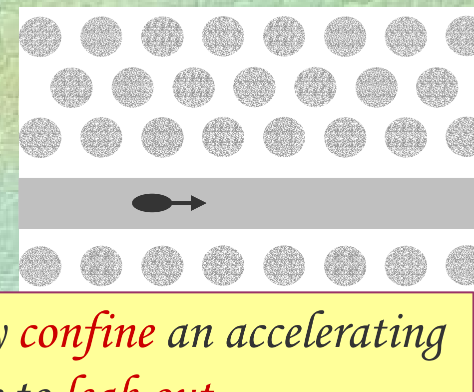
Density !

Summary: Dielectric Structures

Transverse PBG



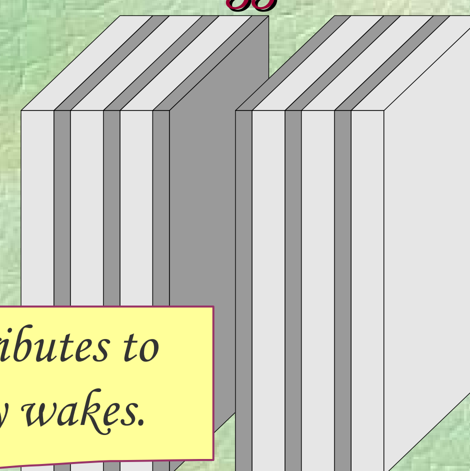
Longitudinal PBG



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

Cylindrical Bragg Structure

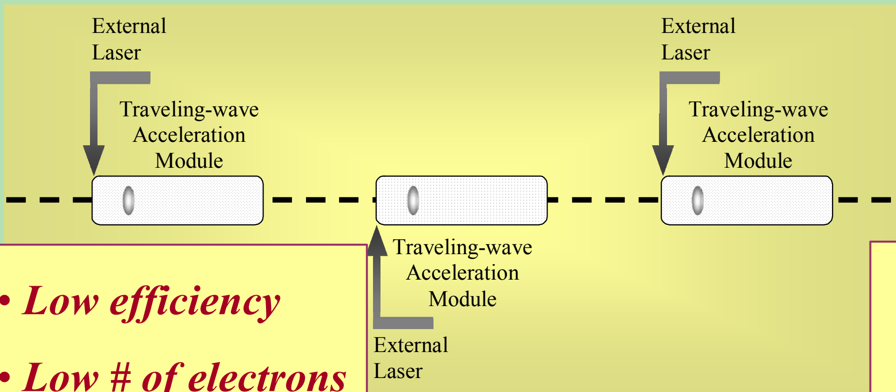
Planar Bragg Structure



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

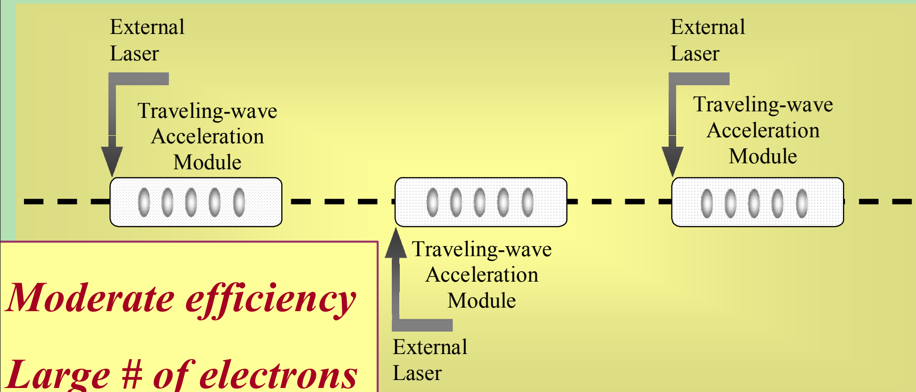
Summary: Configurations

Single bunch & no feedback



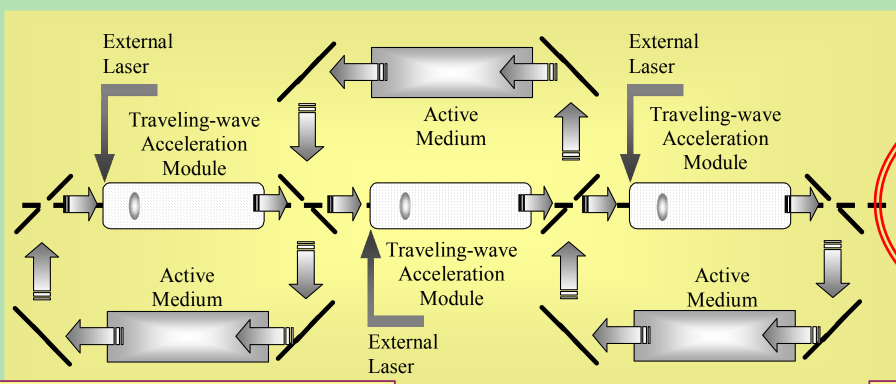
- Low efficiency
- Low # of electrons

bunches & no feedback



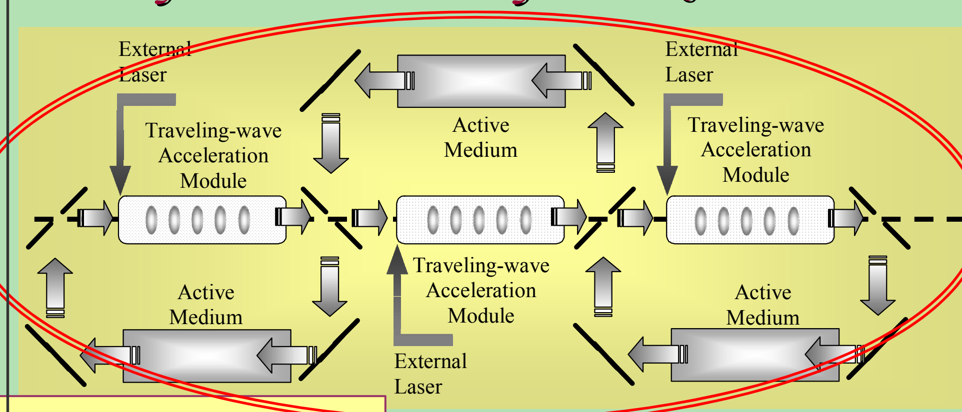
- Moderate efficiency
- Large # of electrons

Single bunch & feedback



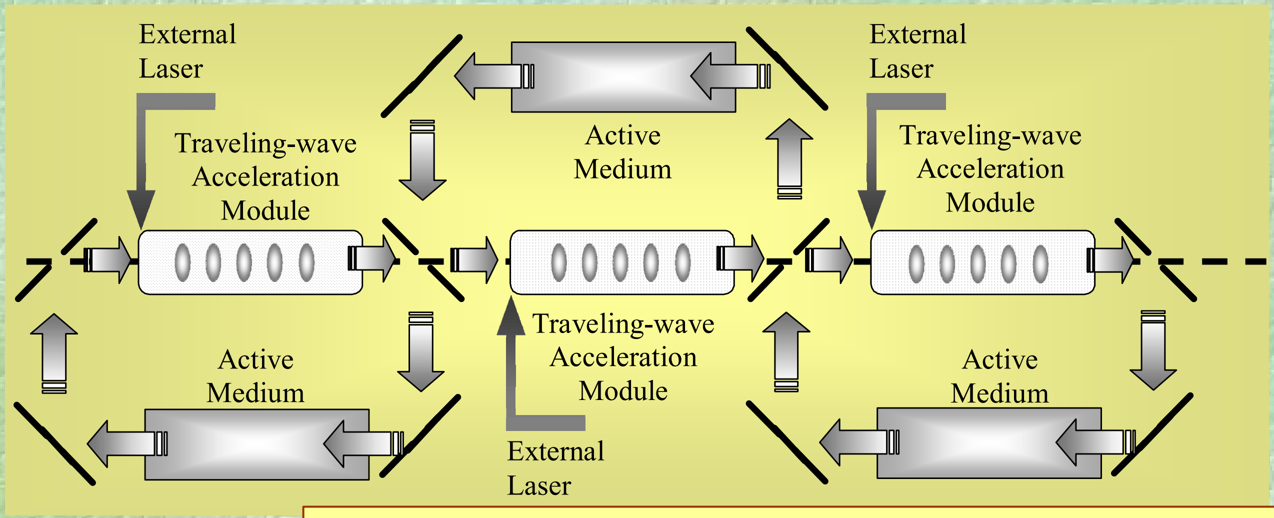
- High efficiency
- Low # of electrons

Train of micro-bunches & feedback



- High efficiency
- Large # of electrons

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