SPARC-BD-07/003

Laser Comb μ–Workshop

INFN-LNF May 14th, 2007

14.30 Introduction (M. Ferrario)

15.00 PARMELA Simulations (M. Boscolo)

15.30 Laser System(S. Cialdi)

16.00 Thz FEL (I. Boscolo)

16.30 FEL Simulations (V. Petrillo)

17.00 Discussion

International Journal of Modern Physics B

A TRAIN OF MICRO-BUNCHES FOR PWFA EXPERIMENTS PRODUCED BY RF PHOTOINJECTORS

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MOPCH025 Proceedings of EPAC 2006, Edinburgh, Scotland

LASER COMB: SIMULATIONS OF PRE-MODULATED E^- BEAMS AT THE PHOTOCATHODE OF A HIGH BRIGHTNESS RF PHOTOINJECTOR

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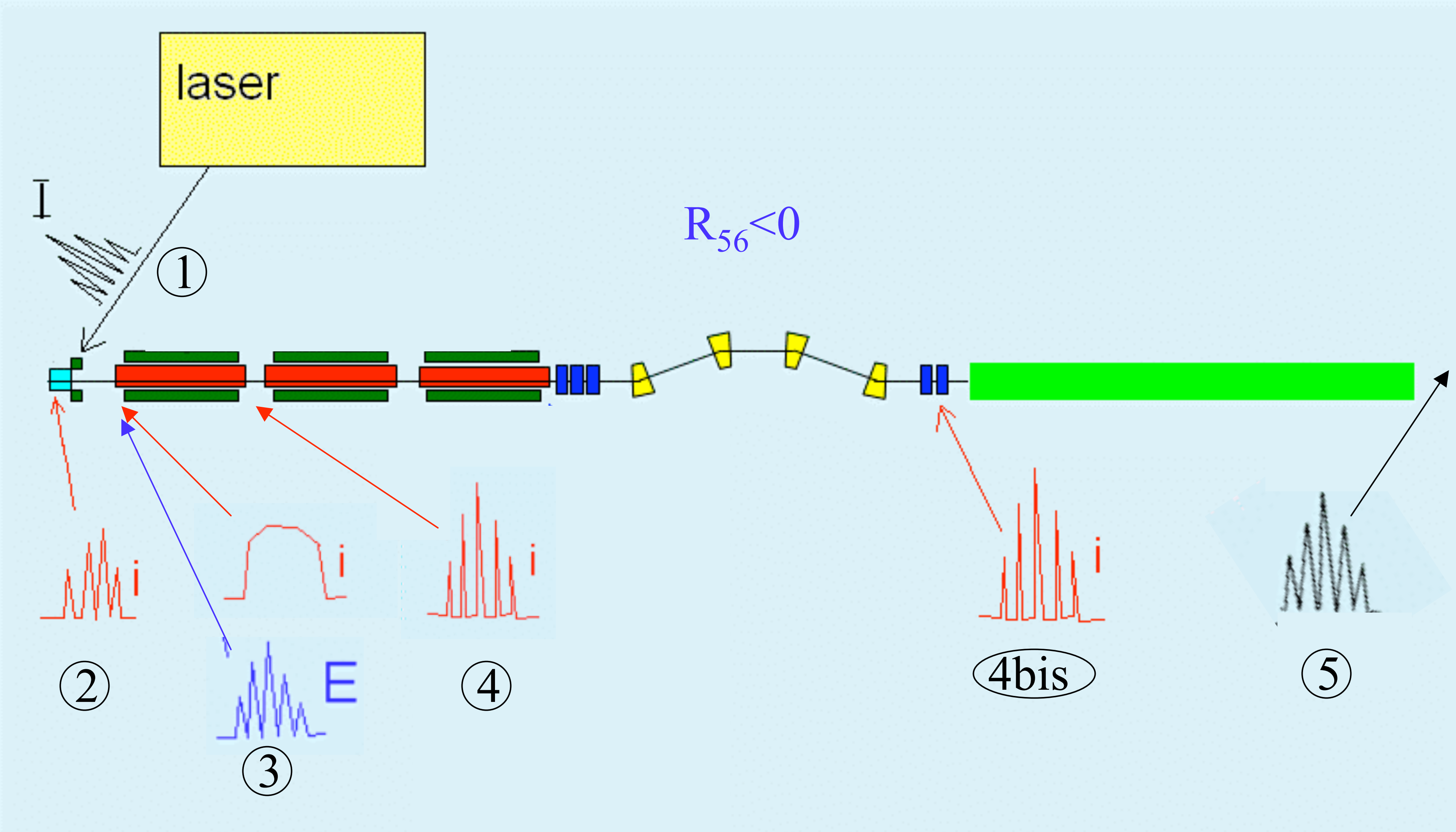
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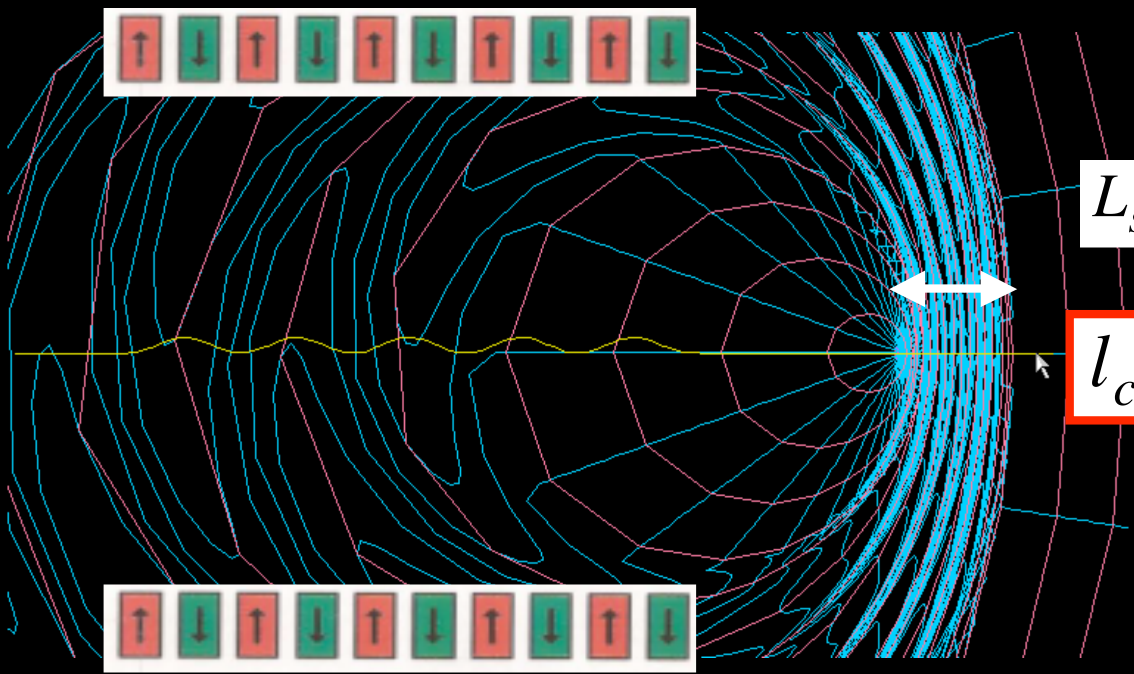
Possible applications

- Longitudinal Beam Dynamics studies @ SPARC
- Pump and Probe with FEL spike train, $l_{bunch} \sim l_{cooperation}$, @ SPARC
- THz Coherent Synchrotron Radiation
- Plasma Wakefield Acceleration Experiments @SLAC
- Pump and Probe wakefields measurements in high frequency rf structures (X-band) @ SPARC

FEL clean spike train



$$L_{slippage} = N_u \lambda_s$$

$$l_c = \lambda_s / 4\pi\rho$$

$$l_{bunch} \begin{cases} > l_c \Rightarrow & \textbf{\textit{Many Spikes}} \\ \leq l_c \Rightarrow & \textbf{\textit{Single Spike}} \\ < \lambda_s << l_c \Rightarrow & \textbf{\textit{Coherent Synchrotron Radiation}} \end{cases}$$

VOLUME 73, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JULY 1994

Spectrum, Temporal Structure, and Fluctuations in a High-Gain Free-Electron Laser Starting from Noise

R. Bonifacio,[1,2] L. De Salvo,[1] P. Pierini,[2] N. Piovella,[1] and C. Pellegrini[3]

$$\ell_c = \lambda_s/4\pi\rho$$

$$l_b \approx l_c$$

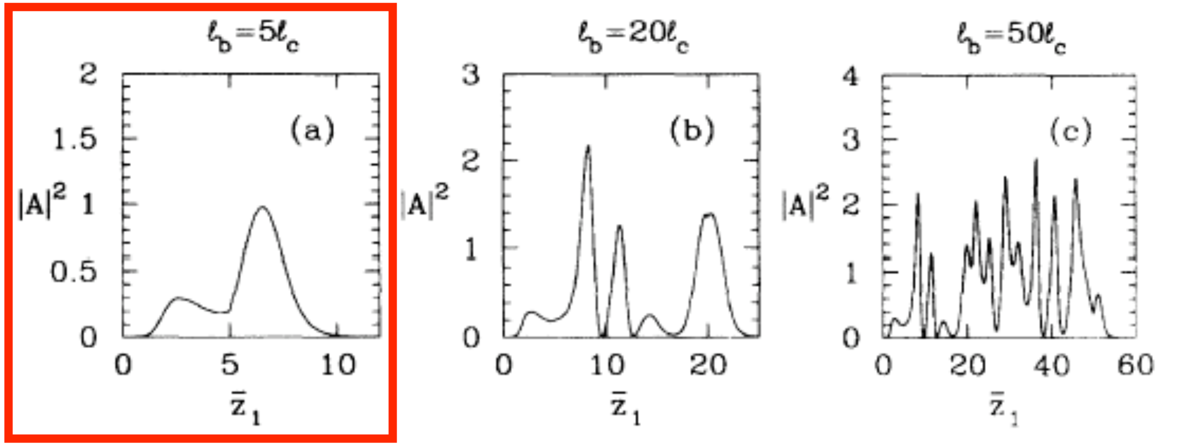


FIG. 1. Results of the numerical model: temporal structure of the radiated pulse, $|A|^2$ vs $\bar{z}_1$, at the first saturation, for

the initial noise pattern $b_0(\bar{z}_1)$. Each spike exhibits the superradiant scaling of intensity as the square density of the electron beam, as has been numerically tested. If the pulse is shorter than or of the order of $2\pi\ell_c$, only one "clean" spike occurs, as can be seen in Figs. 1 and 3.

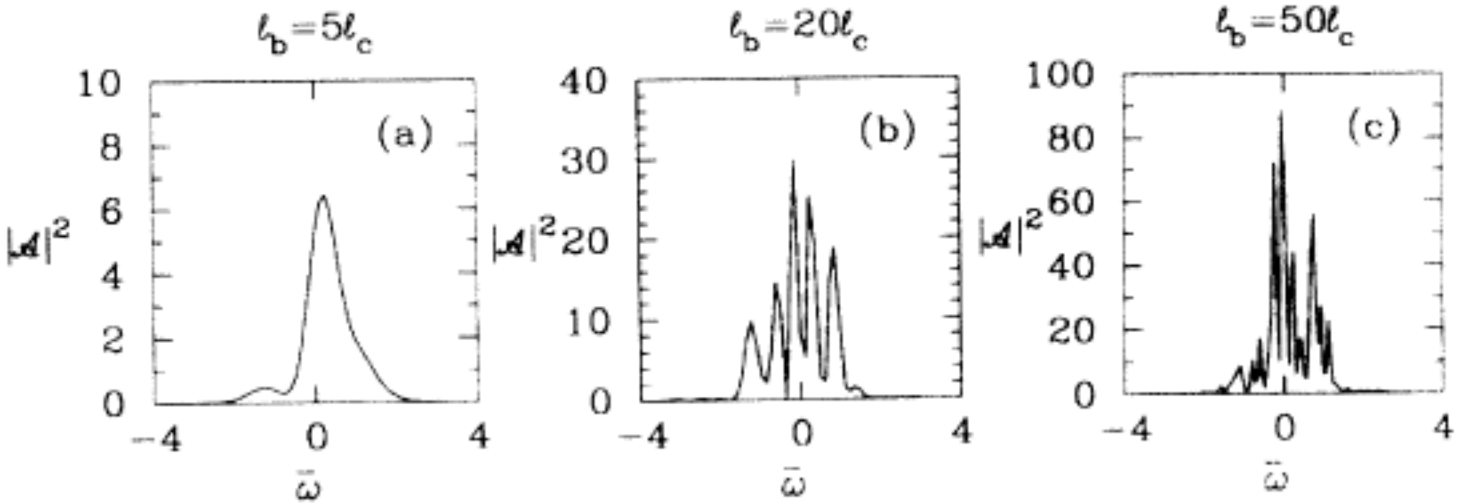


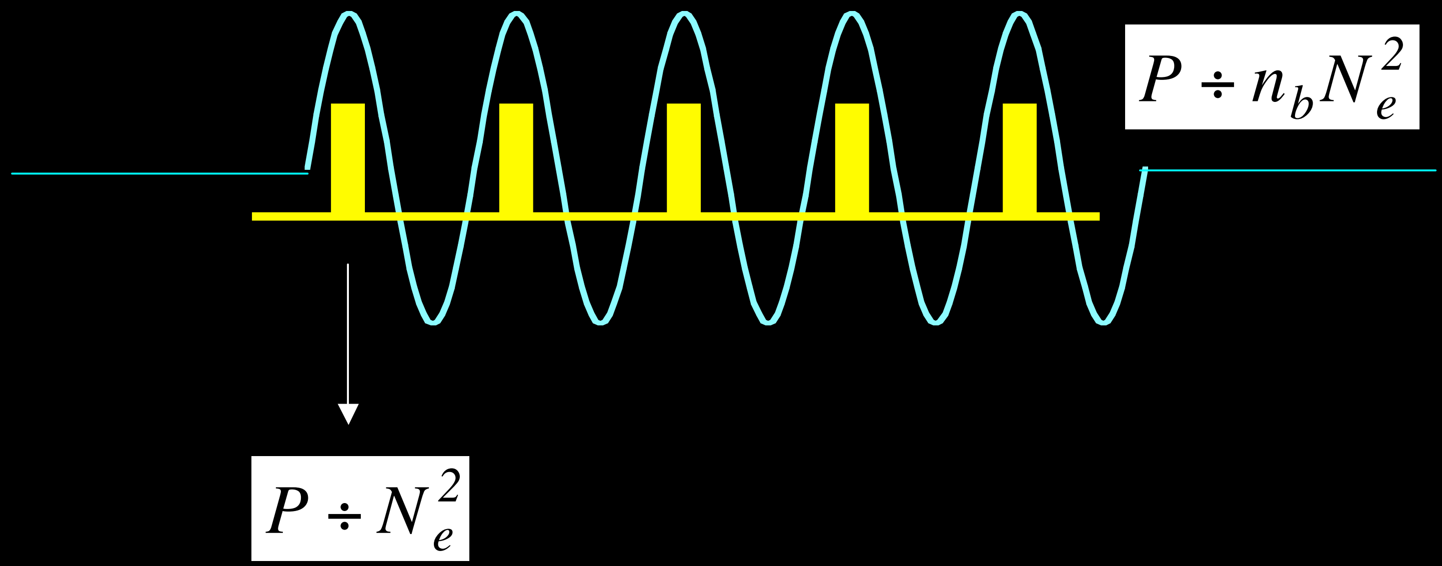
FIG. 3. Spectrum of the radiated pulses, for the same cases of Fig. 1; here $\bar{\omega} = \Delta\omega/2\rho\omega$.

THz Coherent Synchrotron Radiation

$$l_{bunch} < \lambda_s << l_c$$

$$W_{tot}(\omega) = W_1(\omega)\left(N_e + N_e(N_e - 1)f(\omega)\right)$$

$$f(\omega) = \left| \int d\vec{r}\, S(\vec{r})\, e^{i\frac{\omega}{c}\hat{n}\cdot\vec{r}} \right|^2$$



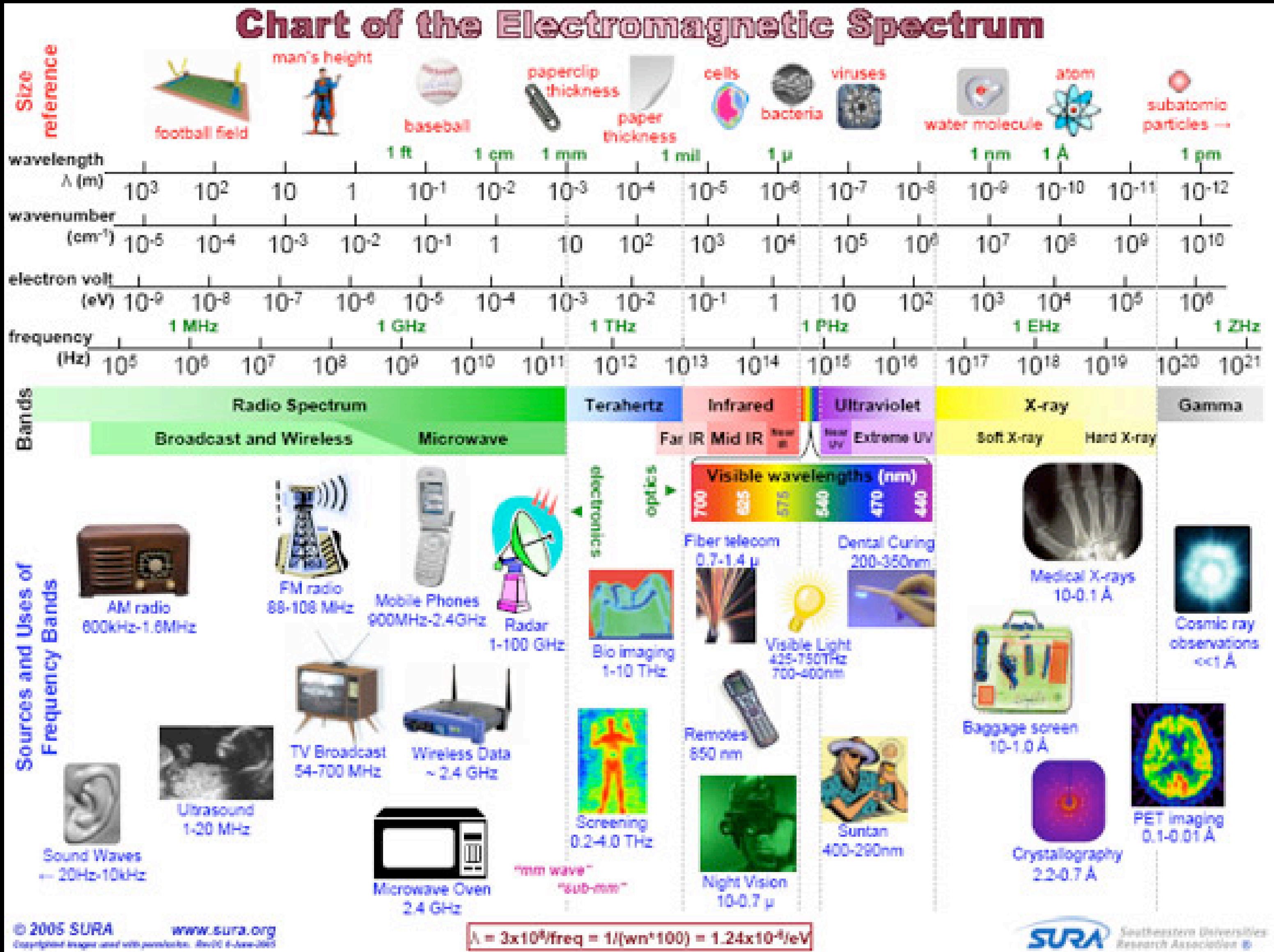


Chart of the Electromagnetic Spectrum
Size reference
football field
man's height
baseball
paperclip thickness
paper thickness
cells
bacteria
viruses
water molecule
atom
subatomic particles →
wavelength λ (m)
1 ft
1 cm
1 mm
1 mil
1 μ
1 nm
1 Å
1 pm
10^{3} 10^{2} 10 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}
wavenumber (cm^{-1})
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10}
electron volt (eV)
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}
frequency (Hz)
1 MHz
1 GHz
1 THz
1 PHz
1 EHz
1 ZHz
10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} 10^{21}
Bands
Radio Spectrum
Broadcast and Wireless
Microwave
Terahertz
Infrared
Far IR
Mid IR
Ultraviolet
Extreme UV
X-ray
Soft X-ray
Hard X-ray
Gamma
electronics
optics
Visible wavelengths (nm)
700
625
575
540
470
440
Sources and Uses of Frequency Bands
AM radio 600kHz-1.6MHz
FM radio 88-108 MHz
Mobile Phones 900MHz-2.4GHz
Radar 1-100 GHz
Bio imaging 1-10 THz
Fiber telecom 0.7-1.4 μ
Dental Curing 200-350nm
Medical X-rays 10-0.1 Å
Cosmic ray observations <<1 Å
Visible Light 425-750THz 700-400nm
TV Broadcast 54-700 MHz
Wireless Data ~ 2.4 GHz
Ultrasound 1-20 MHz
Sound Waves ← 20Hz-10kHz
Microwave Oven 2.4 GHz
Screening 0.2-4.0 THz
"mm wave"
"sub-mm"
Remotes 850 nm
Night Vision 10-0.7 μ
Suntan 400-290nm
Baggage screen 10-1.0 Å
Crystallography 2.2-0.7 Å
PET imaging 0.1-0.01 Å
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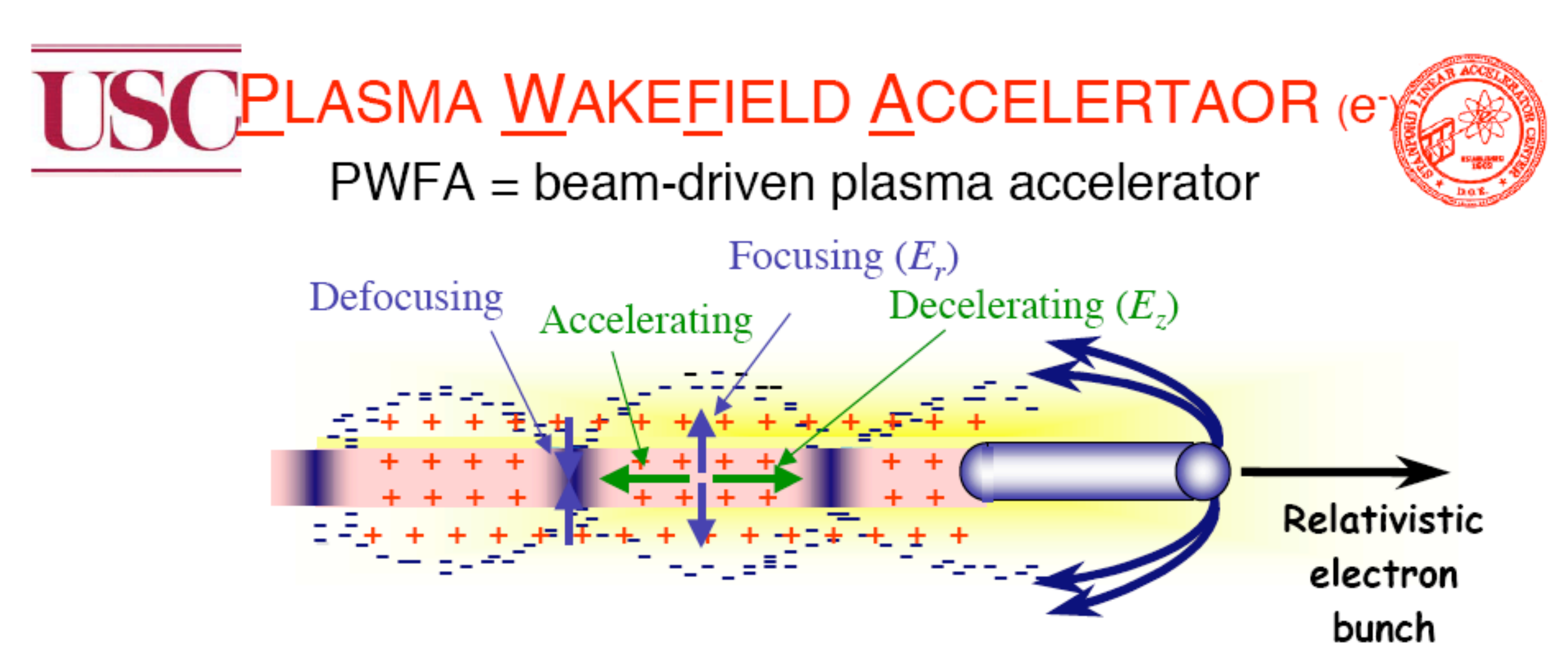
www.sura.org
λ = 3x10⁸/freq = 1/(wn*100) = 1.24x10⁻⁶/eV
SURA
Southeastern Universities Research Association

Plasma Accelerators $\boxed{l_{bunch} < \lambda_p}$



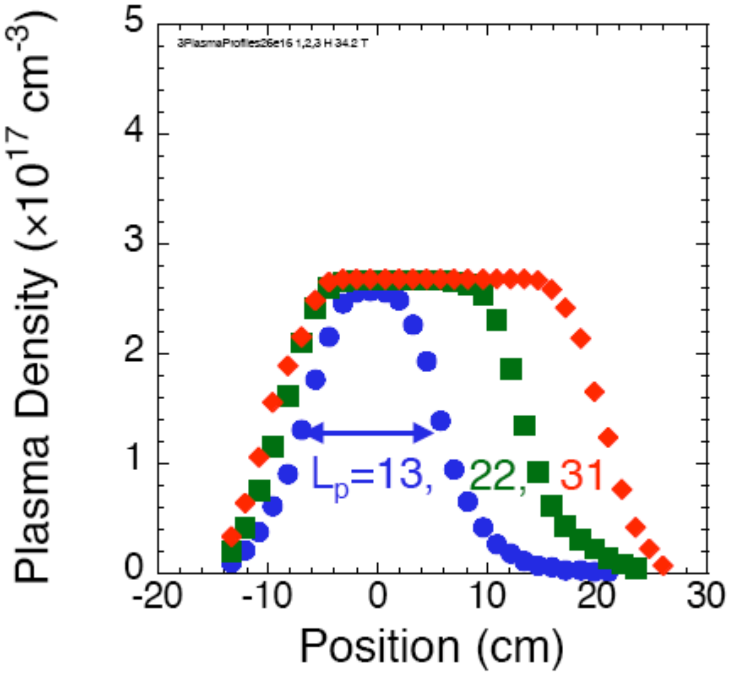
Plasma oscillation wavelength and longitudinal field value can be estimated to be

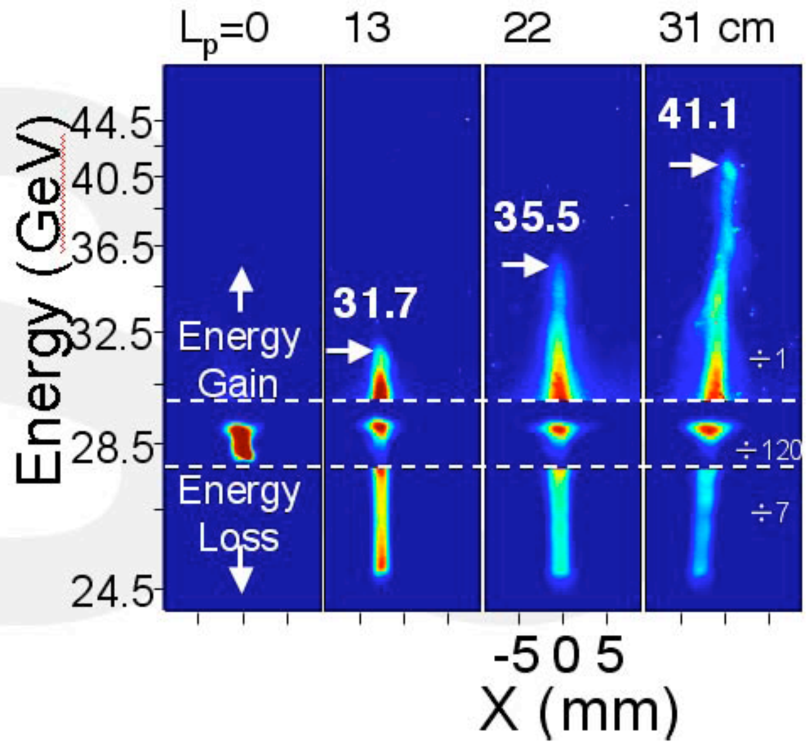
$$\lambda_p \approx \sqrt{\frac{10^{15}\,\mathrm{cm}^{-3}}{n_0}}\ (\mathrm{mm}) \qquad \text{and} \qquad E_z \approx 100\sqrt{n_0}\ (\mathrm{V\,m}^{-1}), \qquad (3.1.9)$$

respectively, n_0 being the plasma density. The equations show that bunches to be accelerated must be rather short: as an example, with $n_0 = 10^{14}\,\mathrm{cm}^{-3}$ one has $\lambda_p = 3.3\,\mathrm{mm}$ and $E_z = 1\,\mathrm{GV\,m}^{-1}$. Femto-second long bunches should thus be injected with sub-fs timing accuracy.

ENERGY GAIN VS. PLASMA LENGTH

E_0=28.5 GeV, n_e=2.7×10^{17}cm^{-3}

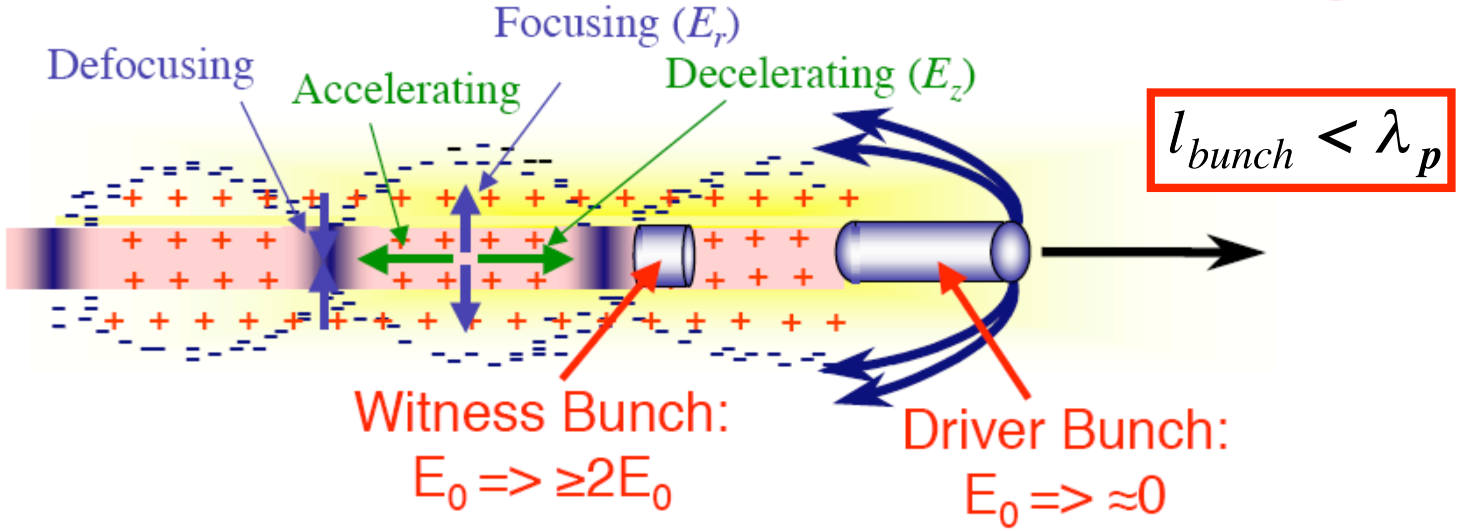




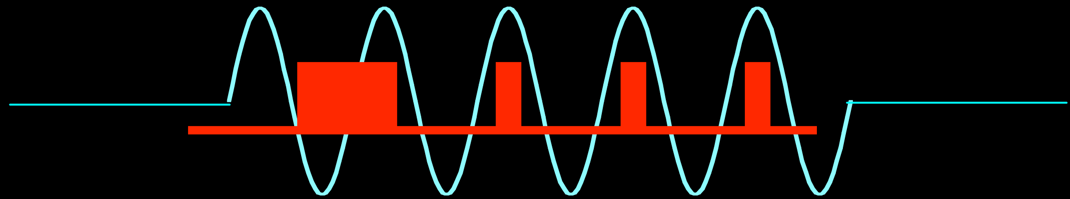
- Energy gain increases with plasma length (L_p)
- Energy gain reaches 13.6 GeV with L_p=31 cm!

FUTURE EXPERIMENT

- 2-Bunch PWFA



- Driver bunch: high-charge (*3N*), modest emittance, shaped?
- Witness bunch: lower charge (*N*), good emittance
  beam loading for $\Delta E/E \ll 1$
- Typical 2- bunch PWFA parameters:
  $n_e \approx 10^{16}$ cm^{-3}, $f_{pe} \approx 900$ GHz, $\lambda_{pe} \approx 300$ μm
  $G \approx 10$-20 GeV/m
  $N \approx 0.5 \times 10^{10}$ e^-
  $\sigma_D \approx 60$ μm, $\sigma_W \approx 30$ μm, $\Delta t \approx 150$ μm



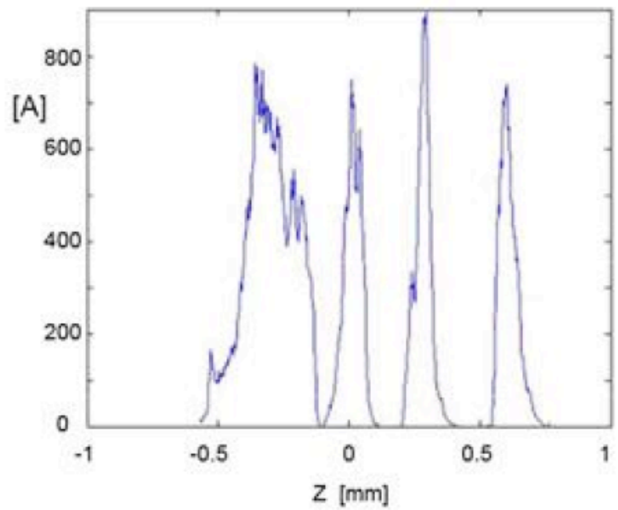


Fig. 7. Beam current at the end of three TW structures, 100 MeV energy.

three micro-bunches with σ_z 35 μm corresponding to 750 A peak current, with a population of 10^9 electrons, separated by 300 μm. The first three micro-bunches could excite coherently a λ_p=300 μm plasma wave corresponding to an plasma density of 10^{16} cm^{-3} producing hundreds of MV/m accelerating field probed by the fourth bunch. Transverse emittance has not been optimized in the simulations

Proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee

SIMULATIONS AND EXPERIMENTS OF ELECTRON BEAMS PRE-MODULATED AT THE PHOTOCATHODE*

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G. L. Carr, W.S. Graves[#], H. Loos[+] T. Shaftan, B. Sheehy, Y. Shen, Z. Wu,
BNL, Upton, NY 11973, USA

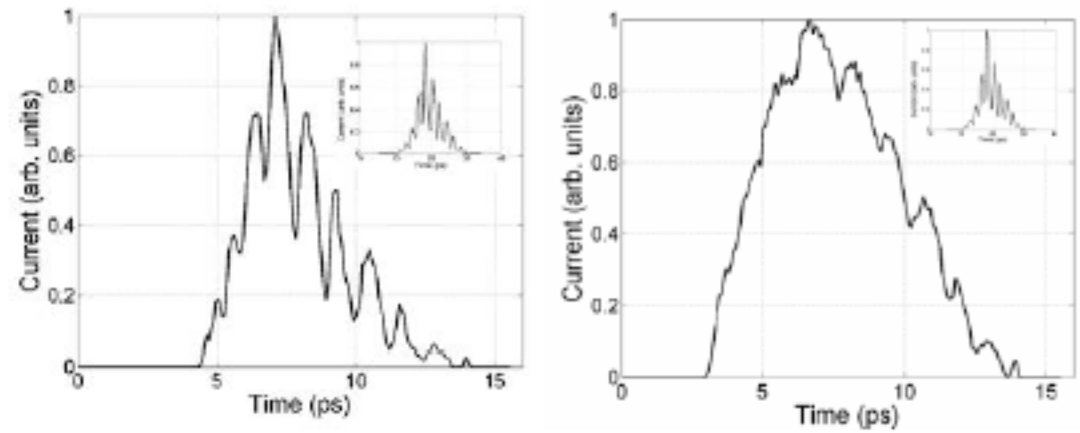


Figure 4: Electron beam longitudinal density after acceleration to 34 MeV for (left) 20 pC and (right) 200 pC.

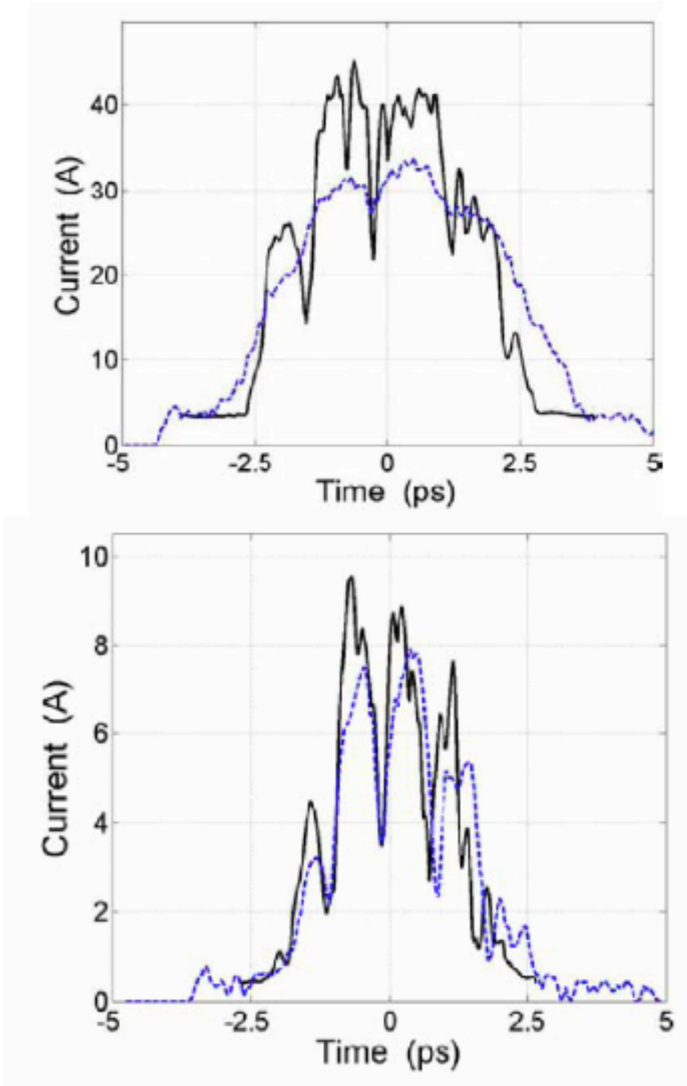


Figure 7: Longitudinal profile measurements (solid black) compared with simulations (dashed blue) for a 160 pC beam (top) and a 20 pC beam (bottom).

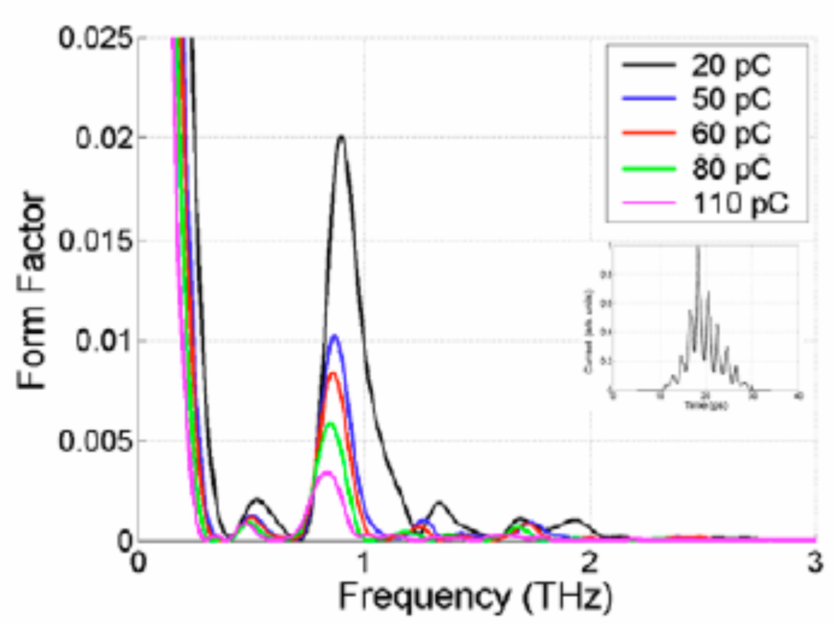


Figure 5: Variation of form factor with charge for pre-modulated electron beams accelerated to 34 MeV in the PARMELA simulation.

$$W_{tot}(\omega) = W_1(\omega)\left(N_e + N_e(N_e - 1)f(\omega)\right)$$

$$f(\omega) = \left| \int d\vec{r}\, S(\vec{r})\, e^{i\frac{\omega}{c}\hat{n}\cdot\vec{r}} \right|^2$$

Experimental investigation of the longitudinal beam dynamics in a photoinjector using a two-macroparticle bunch

P. Piot,[1,2,*] R. Tikhoplav,[3,†] D. Mihalcea,[1] and N. Barov[1,‡]
[1]*Northern Illinois University, Department of Physics, DeKalb, Illinois 60115, USA*
[2]*Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510, USA*
[3]*University of Rochester, Department of Physics & Astronomy, Rochester, New York 14627, USA*
(Received 21 March 2006; published 18 May 2006)

[redacted]

The photoemission electron source offers a convenient way of producing a two-macroparticle bunch: the photocathode drive-laser pulse is split into two and then recombined in such a way that a time delay is introduced between the two pulses. The delay can be remotely varied from ~7 to ~35 ps. A calibrated potentiometer provides a readout for the delay between the two pulses. An example of a double uv pulse is presented in Fig. 2. When such a double-pulse impinges the photocathode, it produces two electron bunches with a time separation much smaller than the rf period ($T_{\mathrm{rf}} = 769$ ps). Hence both macroparticles fall into the same rf bucket and can be treated as a single bunch.

[redacted]

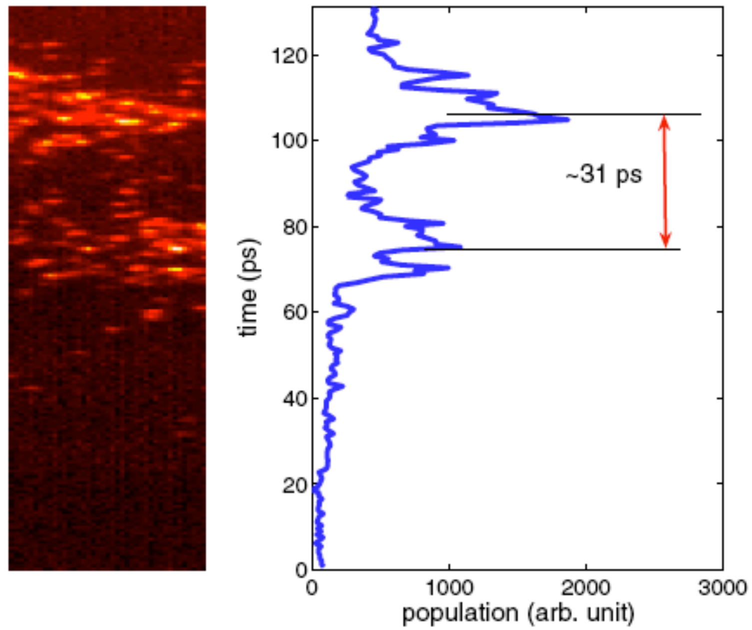


FIG. 2. (Color) Streak camera image (left) and corresponding time-profile (right) of a two-pulse laser. In this example the separation between the two pulses is approximately 31 ps. The apparent intensity difference between the two pulses (noticeable on the profiles) is an artifact of the measurement (slight misalignment of the second pulse on the streak camera entrance slit).

Generation of Short Bunch Trains in a RF Photoinjector- Beam Dynamics

M. Boscolo

Outline

- Description of the guiding idea
- Physics
- Simulations
- Perspectives , Open questions
- Tests at SPARC

Presentation based on:

- Nucl. Instrum. and Methods A

  M. Boscolo et al. “Generation of Short THz bunch trains in a RF Photoinjector” http://dx.doi.org/10.1016/j.nima.2007.04.129

- Intern. Journal of Modern Physics B vol. 21 nos.3-4 p.415:

  M. Ferrario et al. “A Train of micro-bunches for PWFA Experiments Produced by RF Photoinjectors”

- EPAC06:

  M. Boscolo et al.,”Laser Comb:Simulations pf pre-modulated e-beams at the photocathode of a high brightness RF photoinjector”

Introduction

trains of electron pulses
L~sub-ps; rep.freq.~THz; Q~100 pC;
interesting for
FEL experiments,
plasma accelerators and
efficient generation of THz radiation

Idea is to produce these pulse trains
in a RF photoinjector

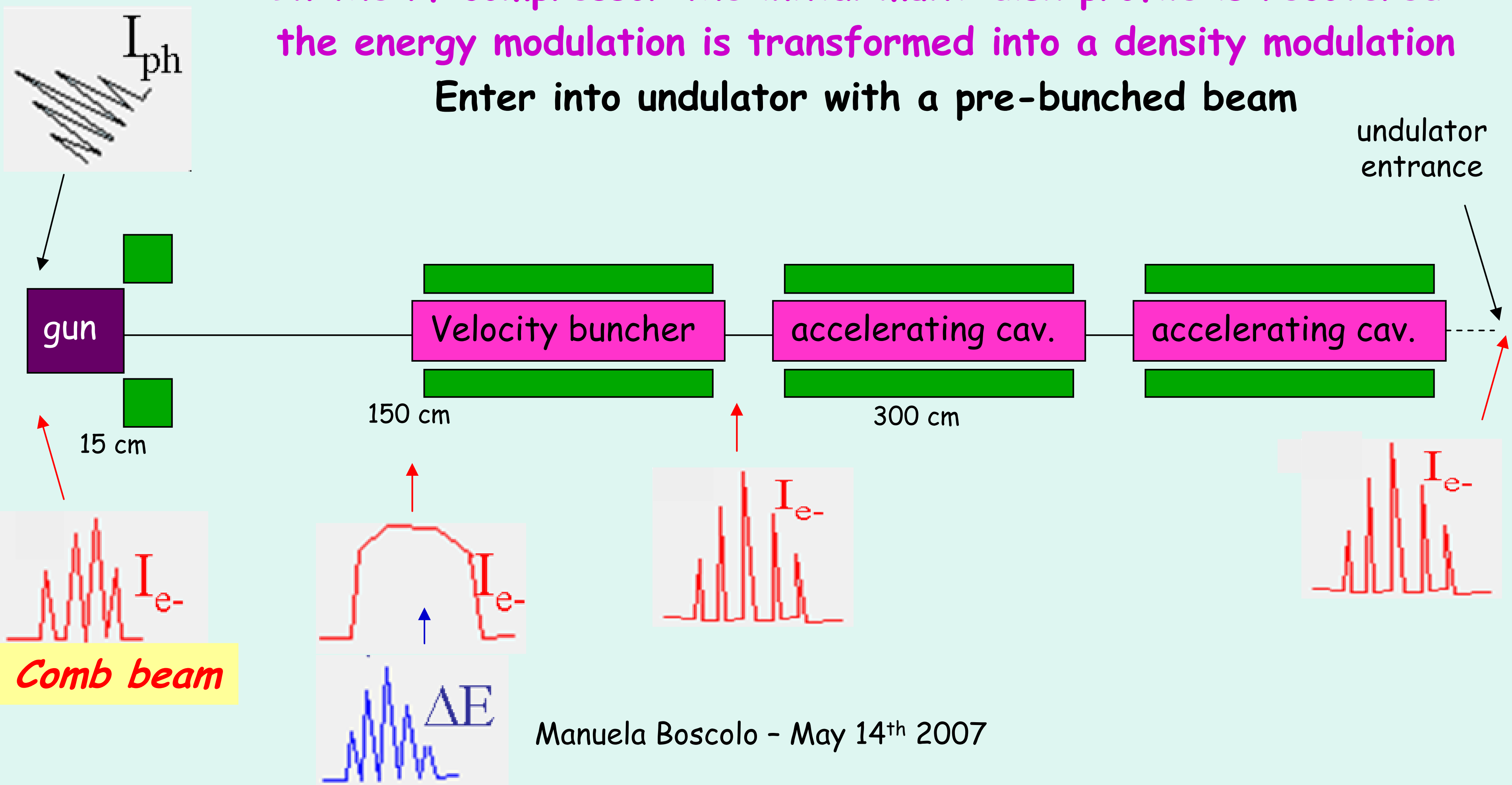
Experimental Scheme

Trains of subps e- pulses by illuminating the photocathode with trains of laser pulses

The disk train evolves toward a slug with a sawtooth energy modulation

In the rf compressor the initial multi-disk profile is recovered: the energy modulation is transformed into a density modulation

Enter into undulator with a pre-bunched beam



Challenging task:
see next talk by Simone

A comb-like laser pulse illuminates the cathode generating a comb-like electron pulse

Electrons in each disk experience a large longitudinal space charge

They expand longitudinally travelling along gun and drift

The work done by the space charge force produces an energy modulated e- beam with a sawtooth profile of energy modulation with $\Delta E \sim 0.4$ MeV

This energy modulation is transformed into a density modulation in a magnetic or rf compressor

SPARC as a reference injector

Nominal parameters RF GUN

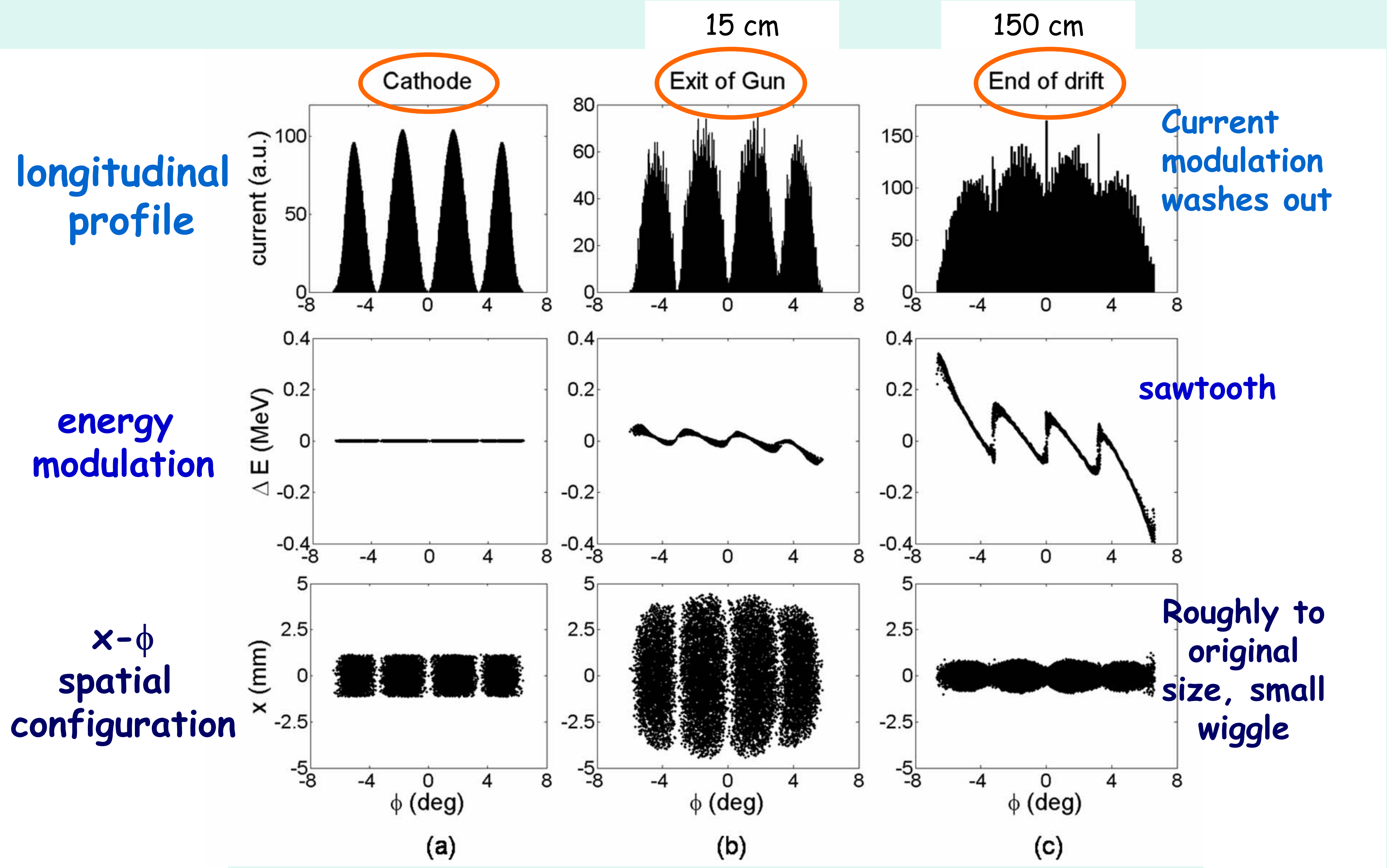
Gradient [MV/m]	**120**
Energy [MeV]	**5.6**
Phase ϕ [deg]	**32**
Solenoid field [G]	**2730**
length [cm]	**15**

Total macro-pulse length **10 ps**

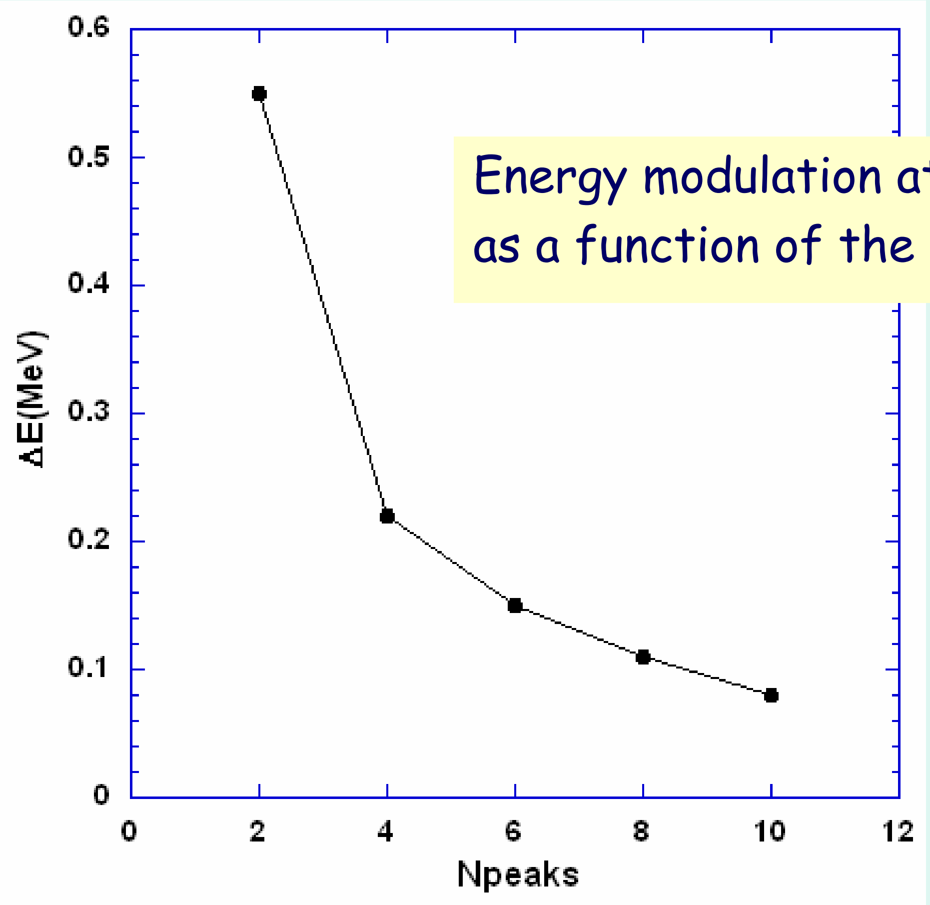
Total macro-pulse charge $\mathbf{Q_{tot} = 1.1nC}$

$Q_{micro\text{-}pulse} = Q_{tot} / N$
N=number of micro-pulses

Example of typical behavior: N = 4



The higher the number of micro-pulses the lower is the energy modulation



Energy modulation at the exit of the rf-gun as a function of the number of **sinusoidal** peaks

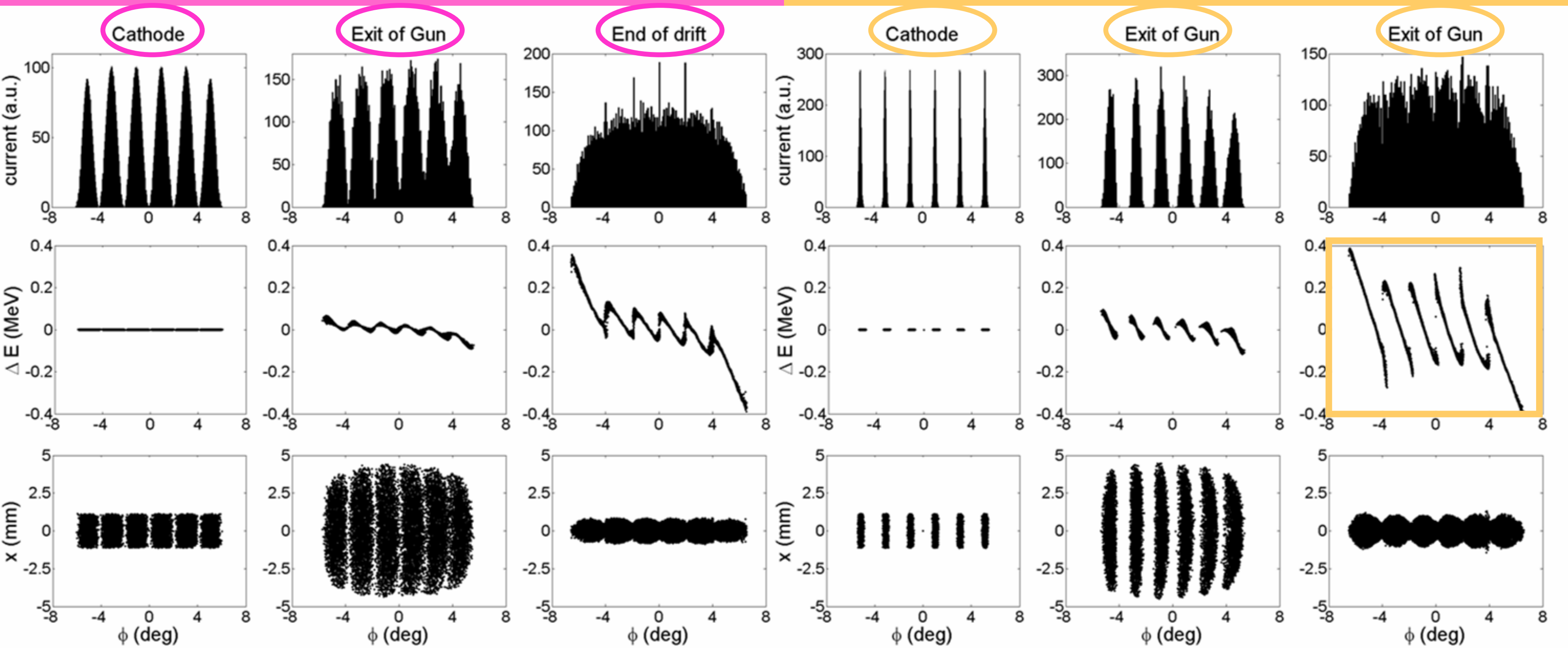
as the $N_{micro\text{-}pulses}$ increases

each micro-bunch has less charge and micro-bunches are closer

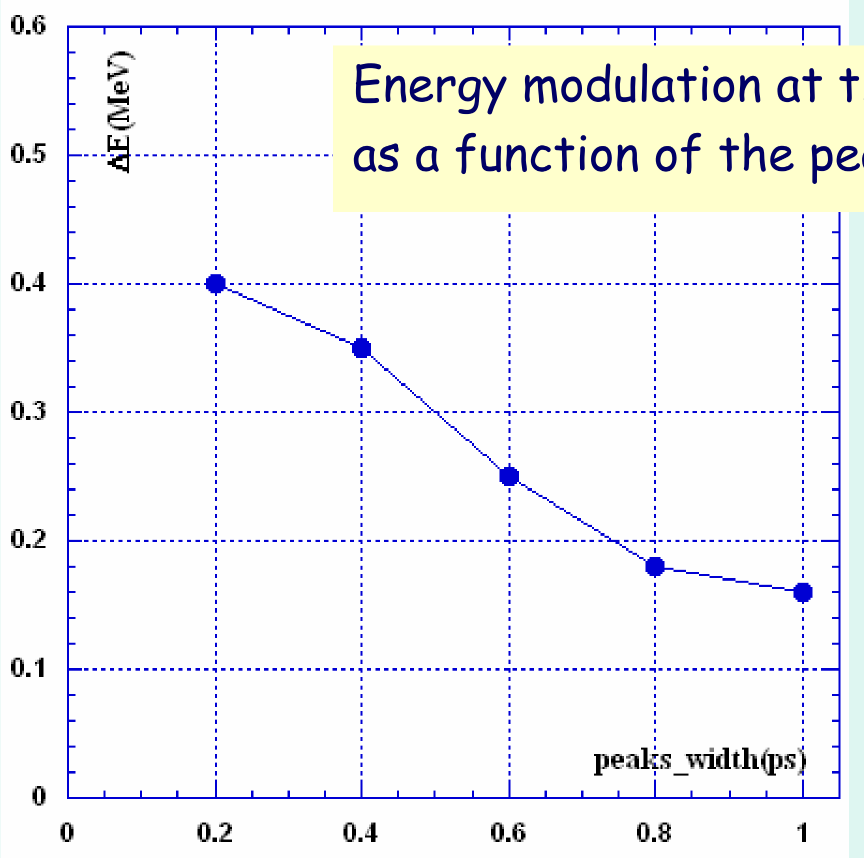
N = 6

The narrower the micro-pulses
the higher is the energy modulation
and the neater the energy separation between pulses

FWHM=1ps | **FWHM=0.2ps**



The narrower the micro-pulses the higher is the energy modulation and the neater the energy separation between pulses



Energy modulation at the exit of the rf-gun as a function of the peaks width for **N = 6**

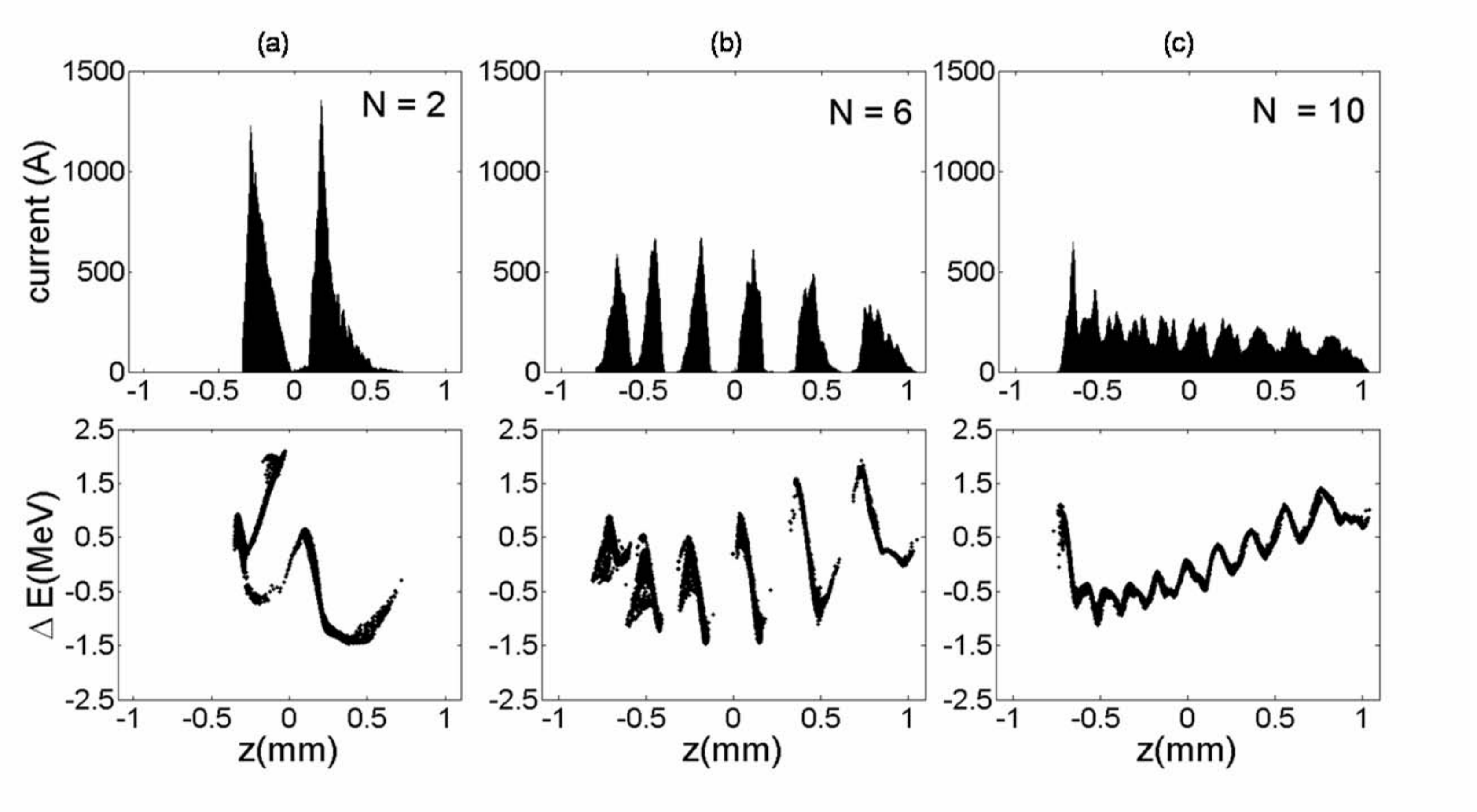
Evolution within the velocity buncher and accelerator

	Velocity buncher	II TW section	III TW section
Gradient [MV/m]	25	12.5	12.5
Energy [MeV]	17	55	88
Phase ϕ [deg]	-99/-101	on crest	on crest
Solenoid field [G]	615	0	0
length [cm]	300	300	300

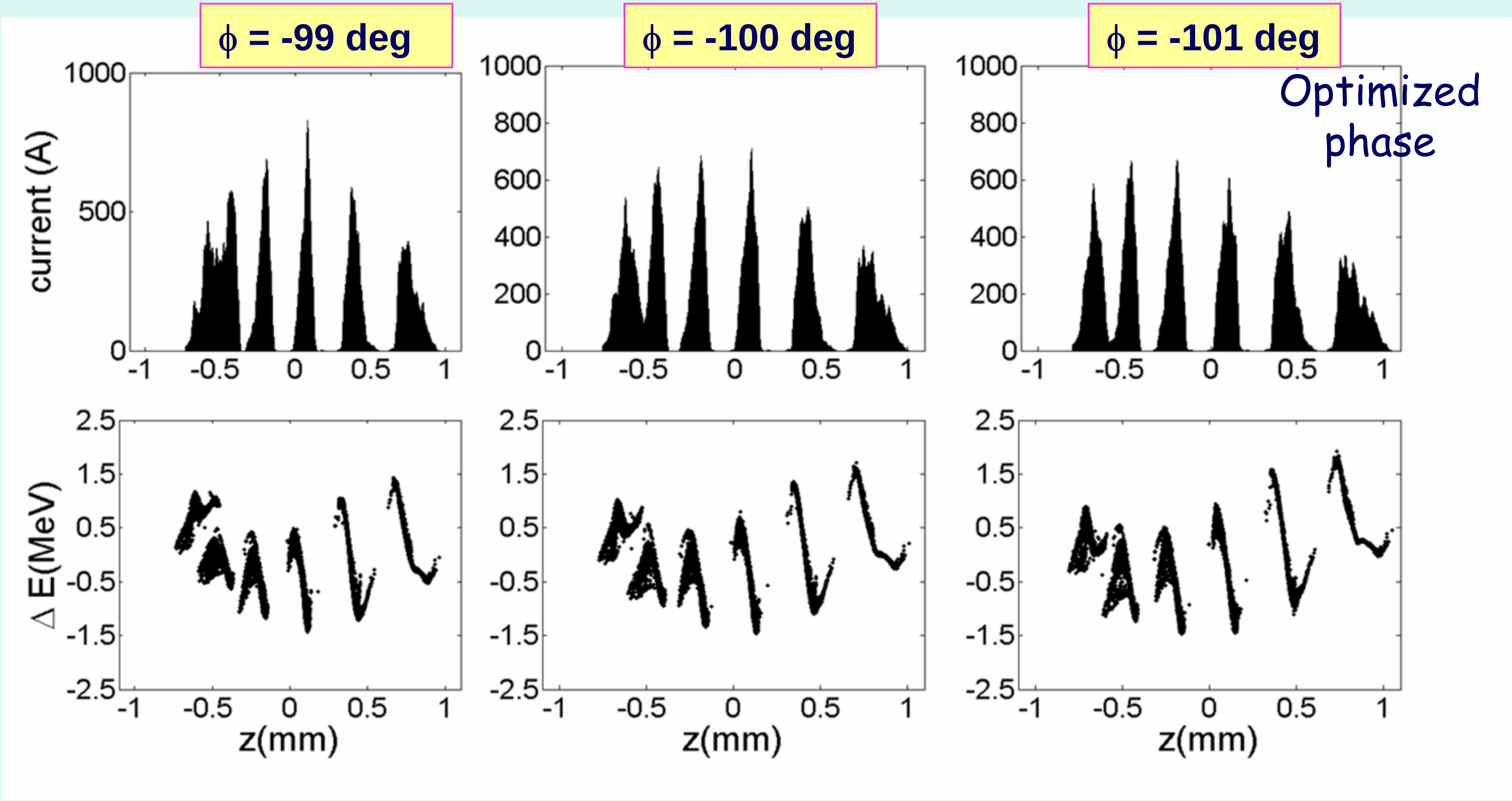
First investigations with magnetic compressor,

beam quality better preserved with rf compression

The intensity modulated electron comb beam at the end of the accelerator after velocity buncher and 2 TW cavities



Rf compression for N = 6 and FWHM=0.2ps

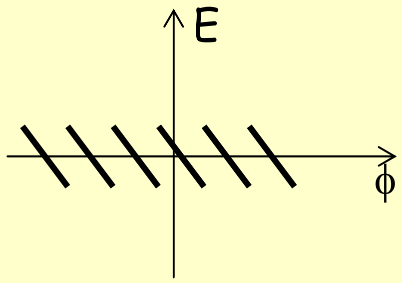


the two leading micropulses move from a partial overlap to a complete separation decreasing the phase of 2°

Proper rotation that recovers initial comb beam is in the over-compression region

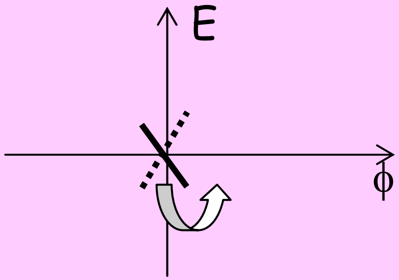
for ϕ=-101 deg

at the entrance of the rf compressor

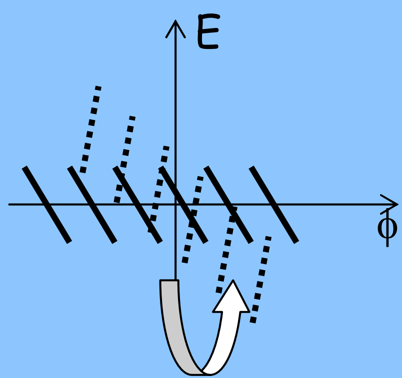


Comb beam : sawtooth

At exit of rf compressor:

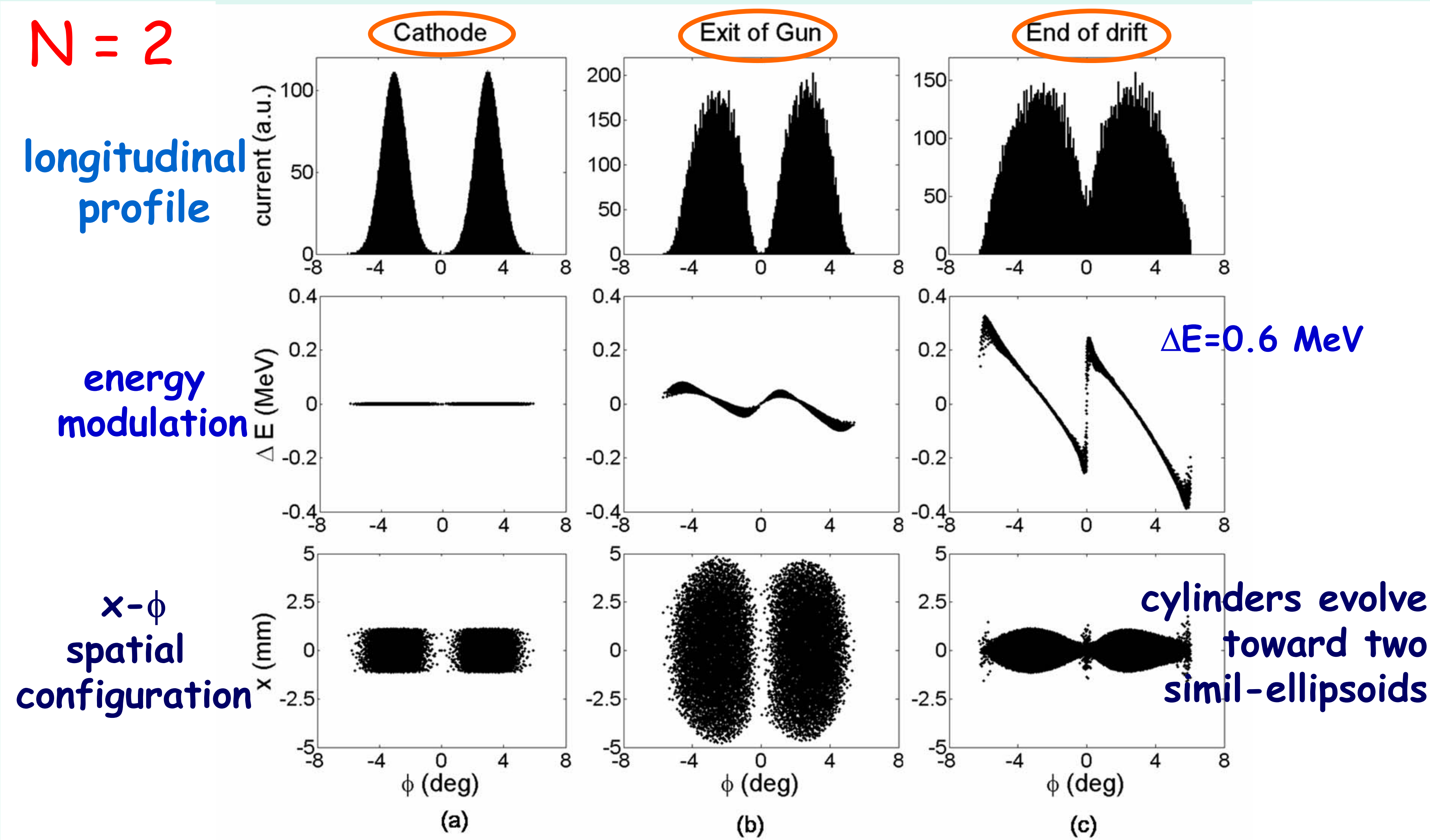


each segment:
rotation angle= (3/4)π



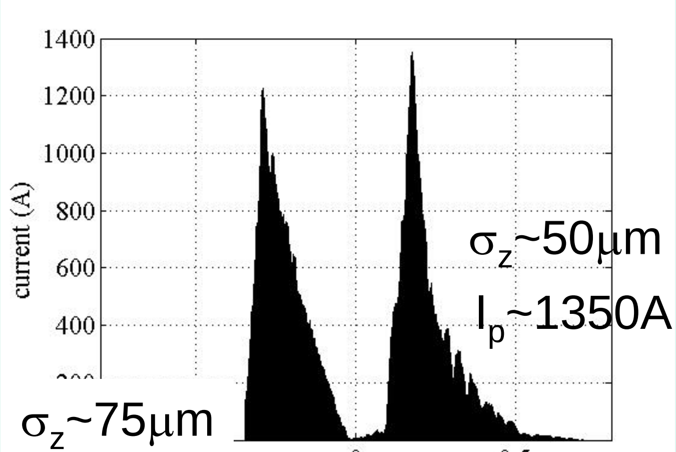
Entire train:
Rotation angle= (5/4)π

N = 2



Distance between 2 pulses can be set at any required value: interesting for pulse probe and in PWFA experiments

N = 2

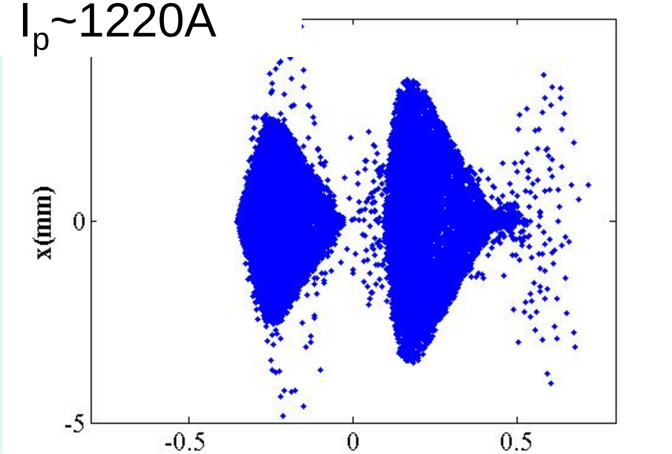


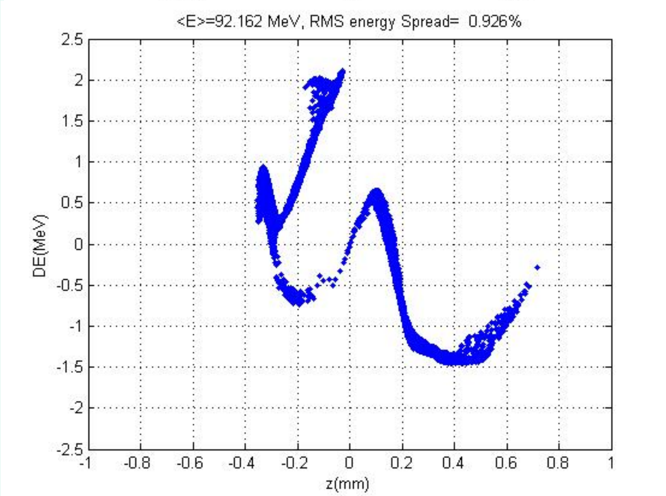
σ_z~50μm

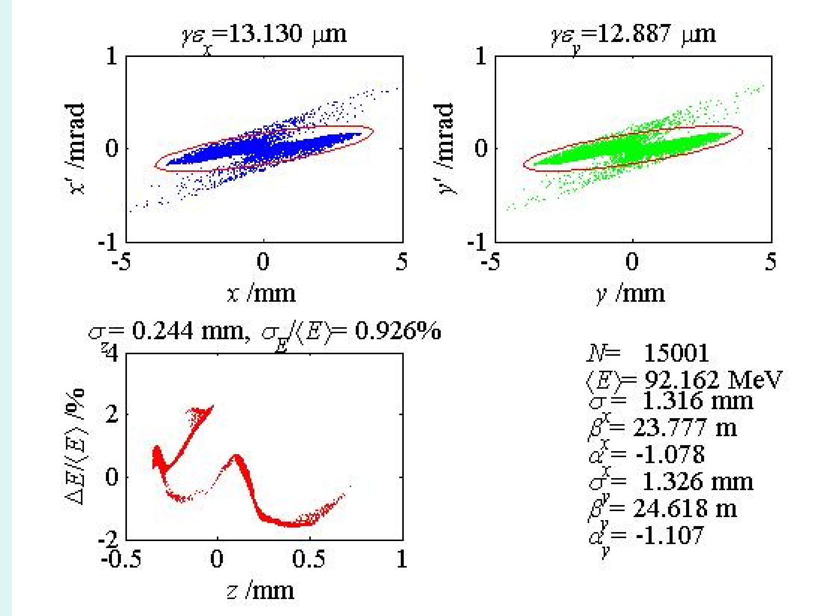
I_p~1350A

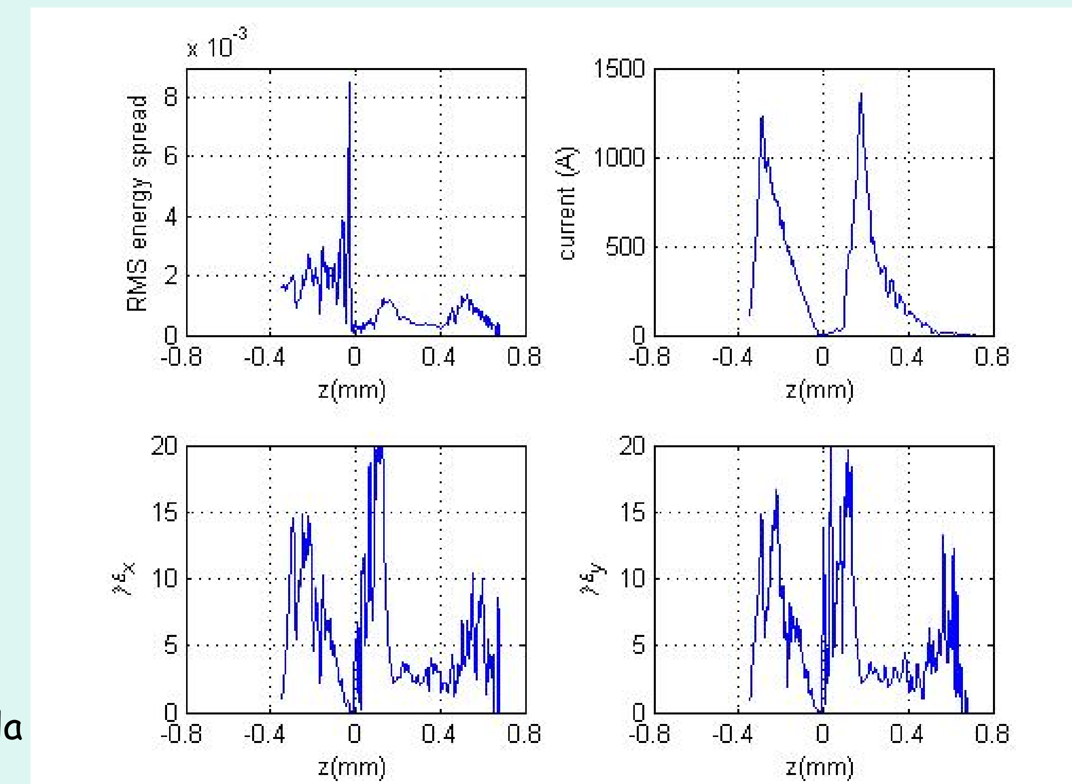
σ_z~75μm

I_p~1220A





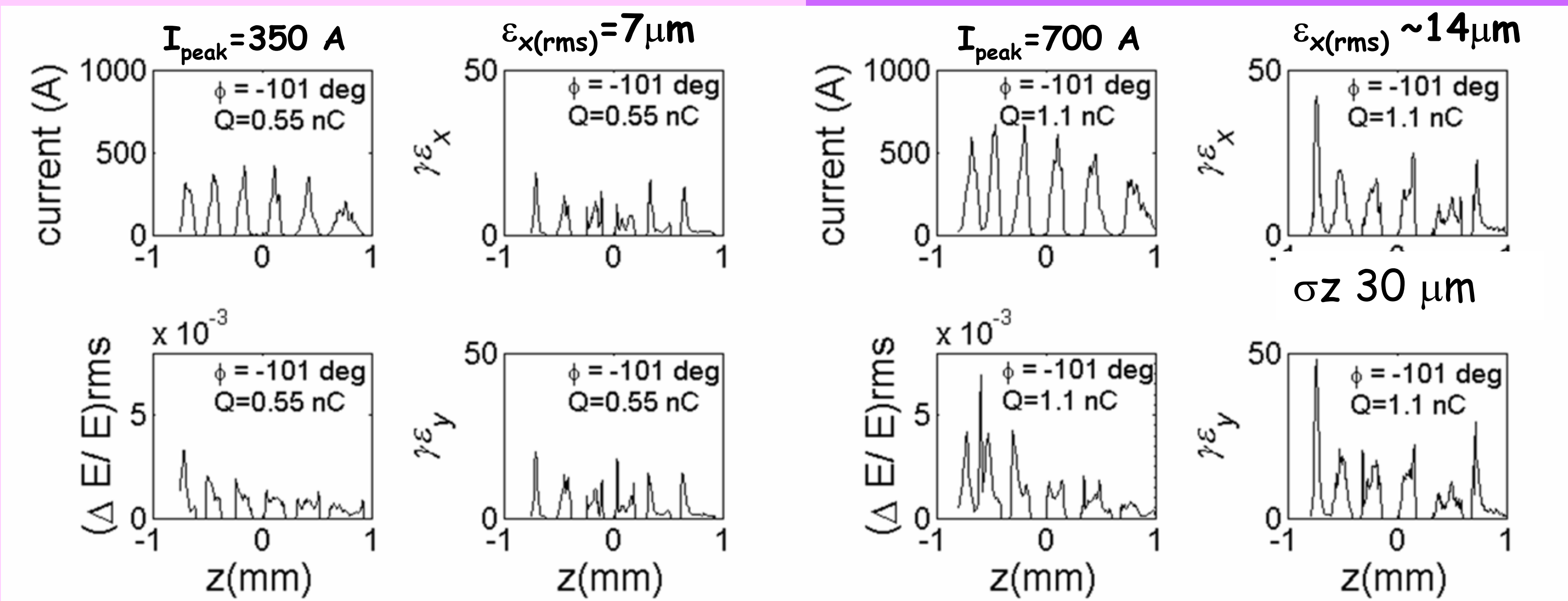




uela

Current and emittance follow the ratio between total charge

Half of nominal charge Q=0.55nC | **High nominal charge Q=1.1nC**



How to control emittance: there is a trade off between the amplitude modulation and emittance

Emittance is reduced switching on the TW solenoids

Example: ε_x =8μm Q=1.1nC with B(G) = 2720/ 1500/ 1600

but current modulation is lost

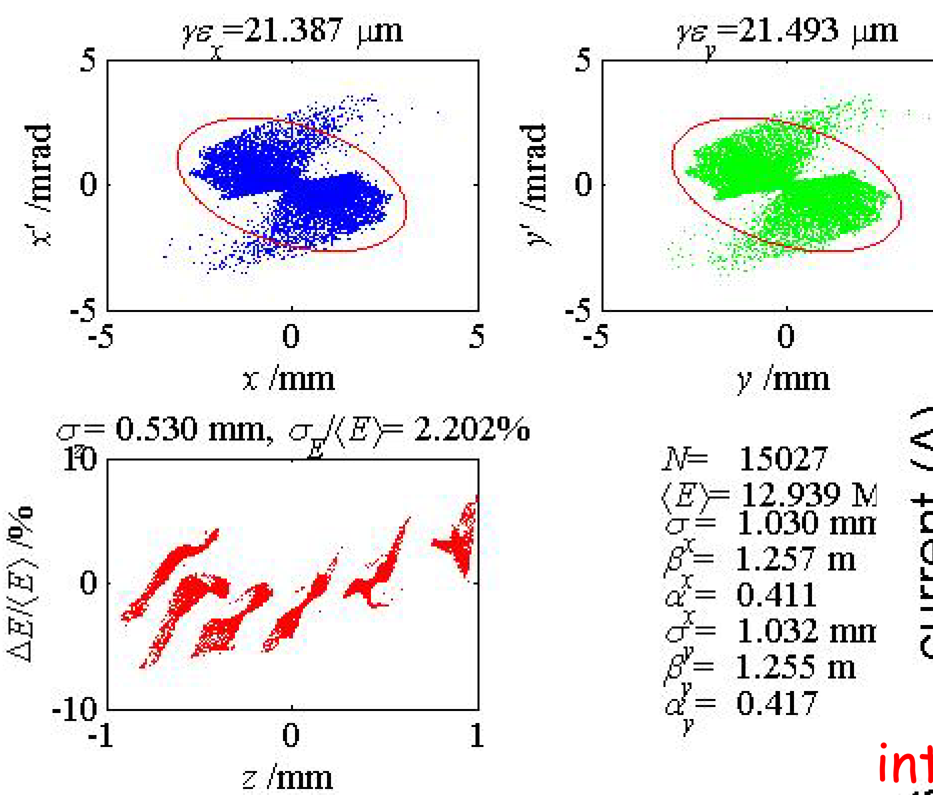
Example of interesting parameter sets

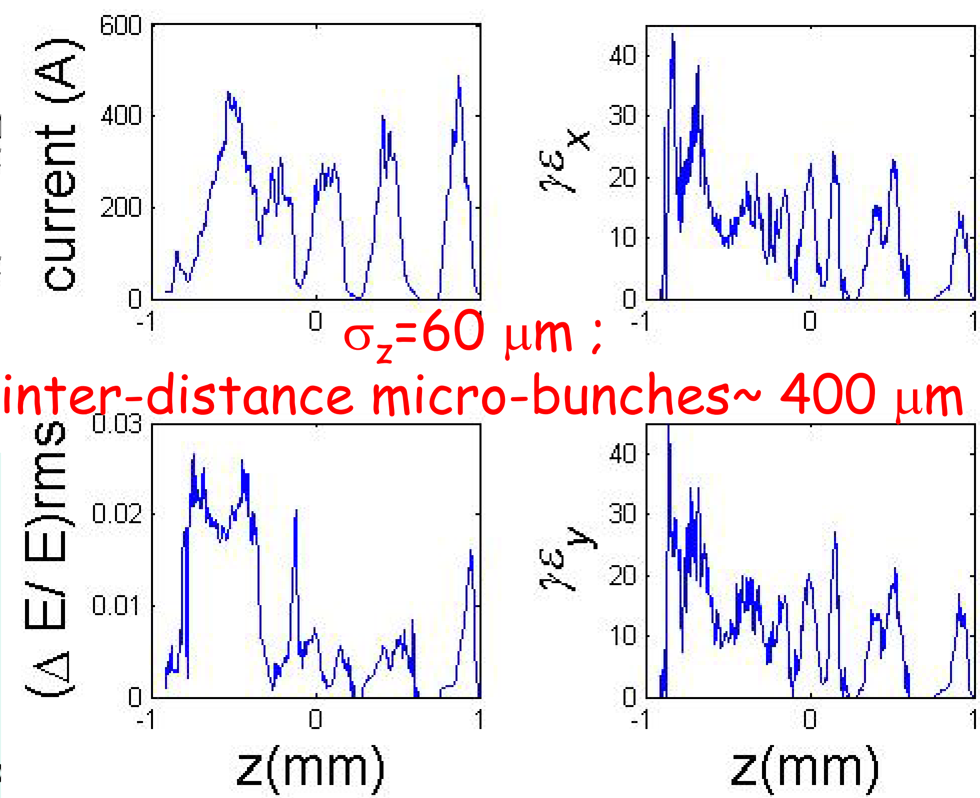
6 peaks 0.2 ps	Exit of 3 TW	Exit of rf compr.	Exit of rf compr
E(MeV)	90	18	13
γ	170	36	25
ε_x rms (μm)	14	17	21
$\Delta E/E$ rms(%)	0.8	6	2
Ipeak (A)	700	1000	450
Inter-distance λr (μm)	200	330	460

Exit from velocity buncher

γ= **25**

Gradient= 16MV/m





σ_z=60 μm ;

inter-distance micro-bunches~ 400 μm

Conclusions

The space charge force,
which is considered a destructive force,
in this case is turned into a constructive force:
it provides the turning of the density modulation into energy modulation.
This energy modulation by a dispersion system is again transformed into density modulation.
The simulation shows that the system is very efficient.
A comb beam accelerator relies on the capability of the laser which drives the rf gun to provide target light profiles by means of a versatile shaping system inserted in the laser system.

Open Questions

- Control emittance / energy spread
- Fix energy – inter-distance of peaks
- choose set of parameters to study in details and to optimize
- FEL process

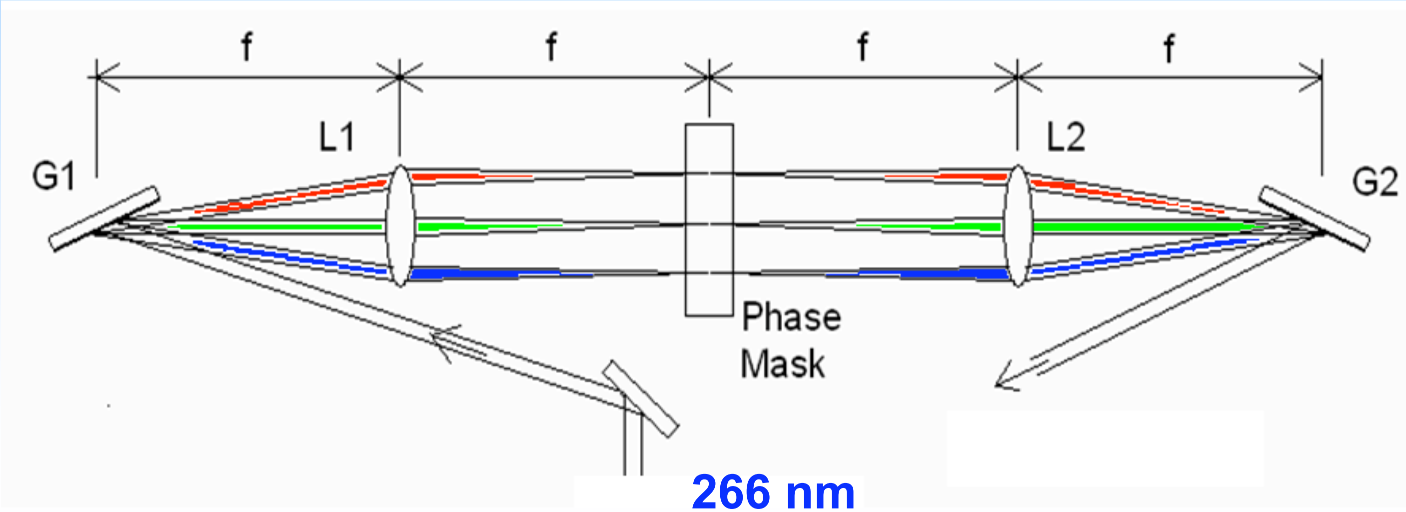
Apparati ottici per la generazione di treni di impulsi laser

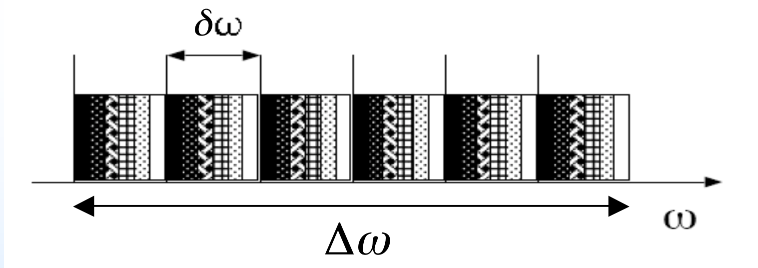
Simone Cialdi

Outline

- 4f + periodic phase modulation
  - Interference
- 4f-stretcher + amplitude modulation
  - Spectrum → Time
- 2f + spatial mask
  - Space → Time
- Beam splitters
  - Delay time
- Interferometer + stretcher
  - Interference → Time
- Considerations

4f + periodic phase modulation





$$I(t)=\left|\int d\omega\; A(\omega)e^{i\phi_p(\omega)}e^{i\omega t}\right|^2 =$$

$$=\left|\sum_{n=0}^{N-1}\int_0^{\delta\omega} d\Omega\, A\left(-\frac{\Delta\omega}{2}+n\delta\omega+\Omega\right)e^{i\phi(\Omega)}e^{i\left(-\frac{\Delta\omega}{2}+n\delta\omega+\Omega\right)}\right|^2$$

"microlithographically fabricated phase mask"

J. Opt. Soc. Am. B 5, 1563 (1988)

$$= \left| \sum_{n=0}^{N-1} \int_0^{\delta\omega} d\Omega \; e^{i\phi(\Omega)} e^{i\left(-\frac{\Delta\omega}{2} + n\delta\omega + \Omega\right)} \right|^2 = \left| \sum_{n=0}^{N-1} e^{in\cdot\delta\omega\cdot t} f(t) \right|^2 =$$

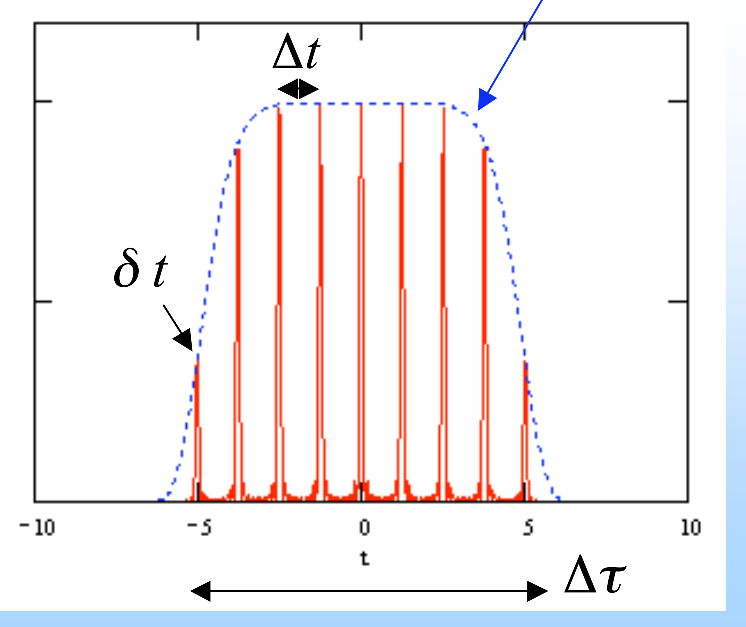
$$f(t) = \int_0^{\delta\omega} d\Omega \, e^{i\phi(\Omega)} e^{i\Omega t}$$

$$I(t) = \frac{\sin\left(\frac{N\delta\omega t}{2}\right)^2}{\sin\left(\frac{\delta\omega t}{2}\right)^2} |f(t)|^2$$

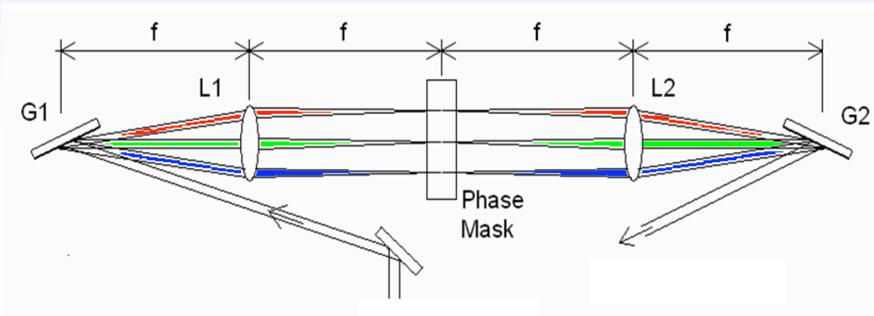
$$\Delta t = \frac{2\pi}{\delta\omega} \qquad \delta t = \frac{2\pi}{N\delta\omega} = \frac{2\pi}{\Delta\omega}$$

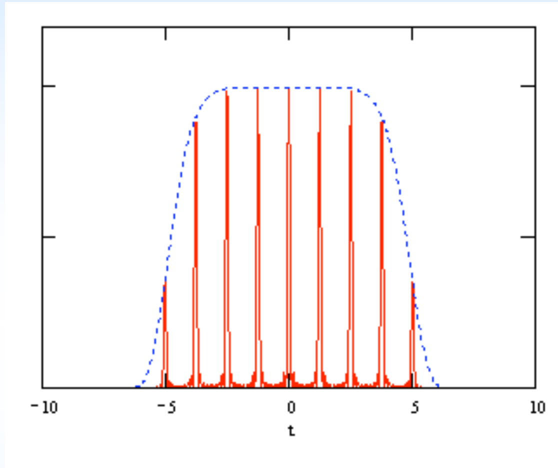
$$\Delta\tau = \frac{2\pi}{\delta\omega_{pixel}}$$

$|f(t)|^2$



4f + modulazione di fase periodica
(pregi e difetti)





pregi

•Il singolo impulso e' transform- limited

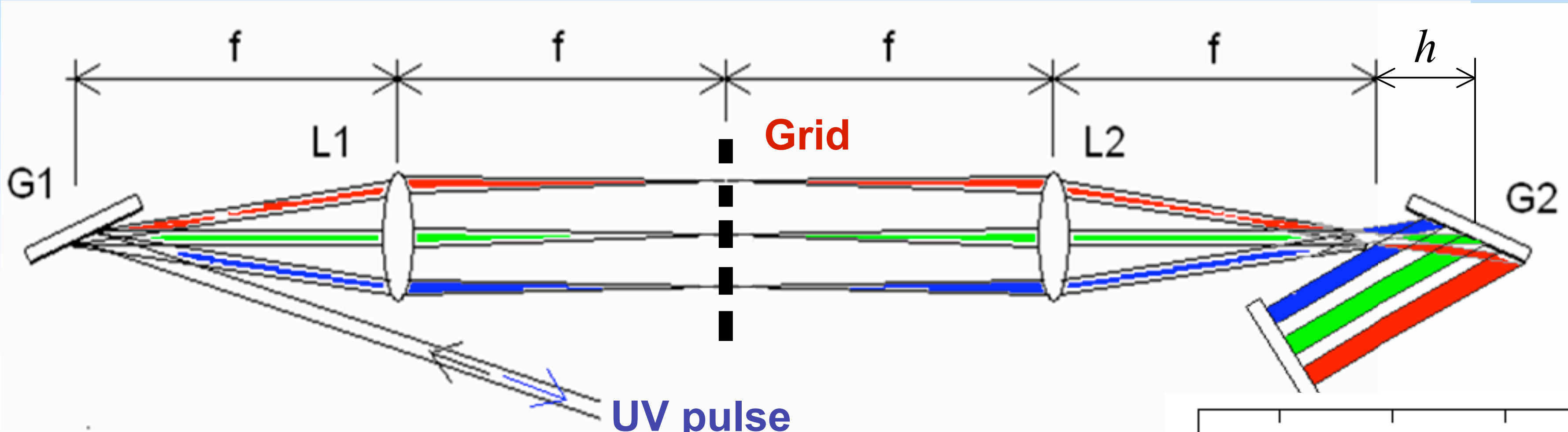
•Il profilo del treno e' libero

difetti

•Tutti gli impulsi stanno alla stessa distanza

•La diagnostica non e' single-shot

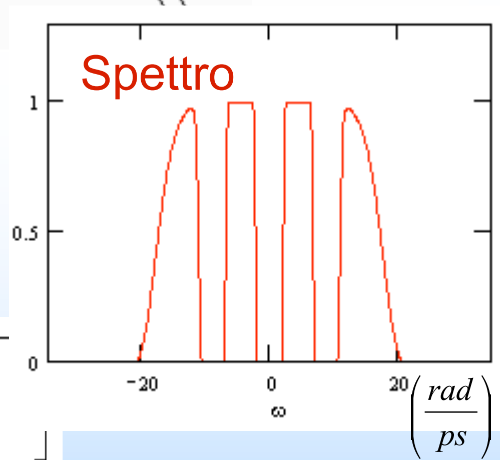
4f-stretcher + modulazione di ampiezza

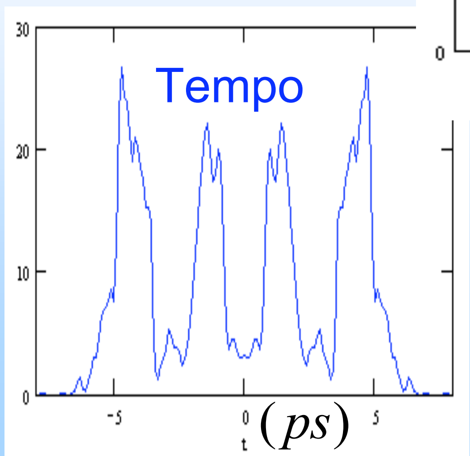


$$I(t)=\left|\int A(\omega)e^{i\frac{1}{2}\beta\omega^2}e^{-i\omega t}d\omega\right|^2 \approx \tilde{I}(\omega(t))$$

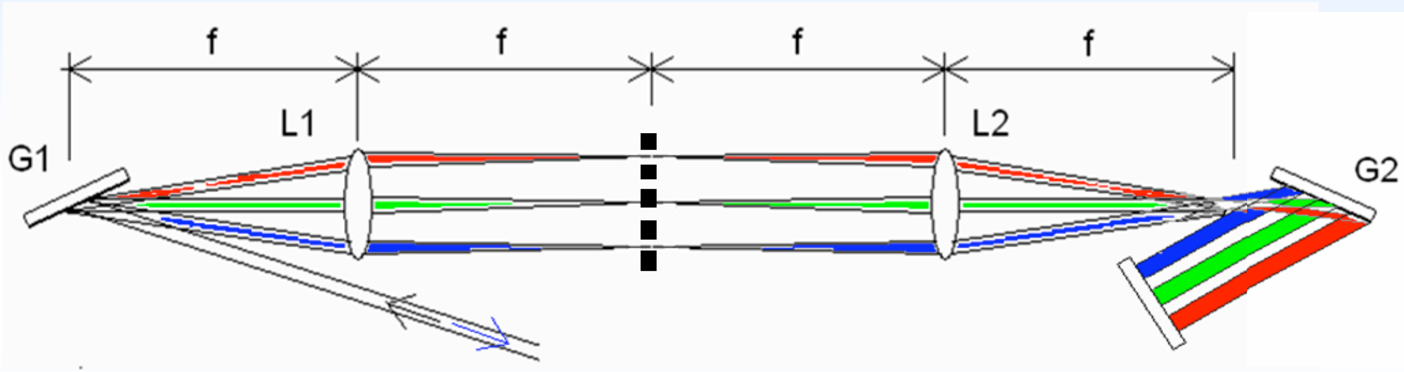
$$\omega(t)=\alpha\cdot t$$

$$\boxed{\begin{gathered}\delta t=\alpha\cdot\delta\omega\\ \delta t>\frac{1}{\delta\omega}\end{gathered}}$$





4f-stretcher + modulazione di ampiezza
(pregi e difetti)



pregi

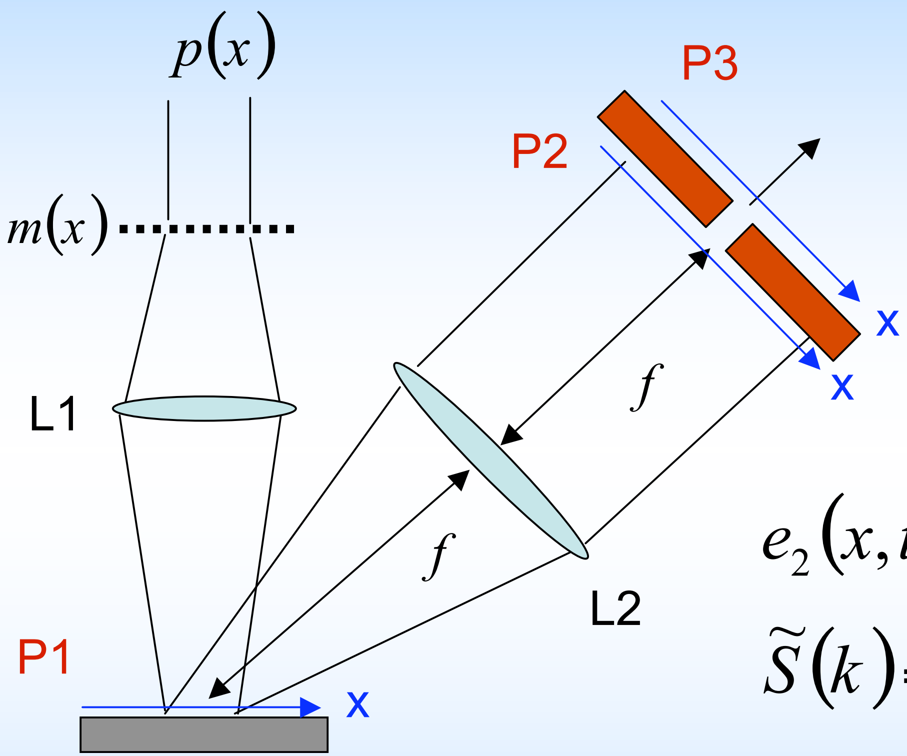
•La diagnostica e' single-shot

•La realizzazione della maschera e' semplice

difetti

•Il singolo impulso puo' essere minimo 1.5 ps

2f + maschera spaziale



$$e_1(x,t) = \int d\omega\, \tilde{E}_{in}(\omega) s(x) e^{i\omega \cdot t}$$

$$s(x) = p(x) \cdot m(x)$$

$$e_2(x,t) \propto \int d\omega\, \tilde{E}_{in}(\omega) \tilde{S}(\beta(x - \alpha\omega)) e^{i\omega \cdot t}$$

$$\tilde{S}(k) = FT(s(x))$$

$$k = \beta \cdot x$$

$$\beta = \frac{2\pi}{\lambda f} \frac{\cos(\theta_d)}{\cos(\theta_i)}$$

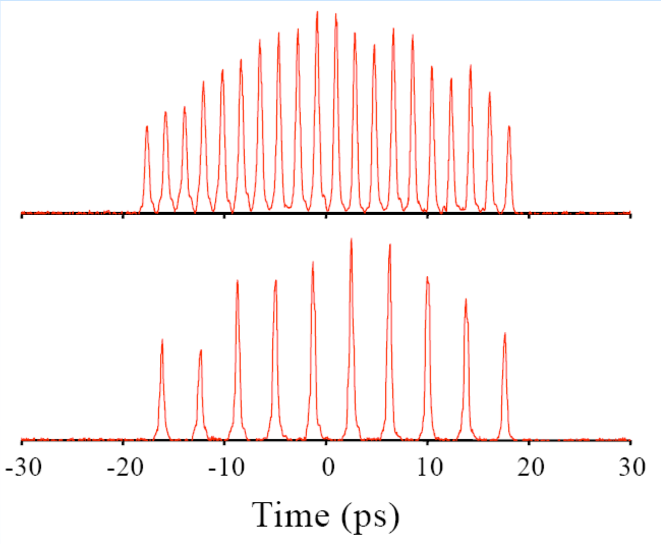
Scaling factor

$$\alpha = \frac{\lambda^2 f}{2\pi\, cd \cos(\theta_d)}$$

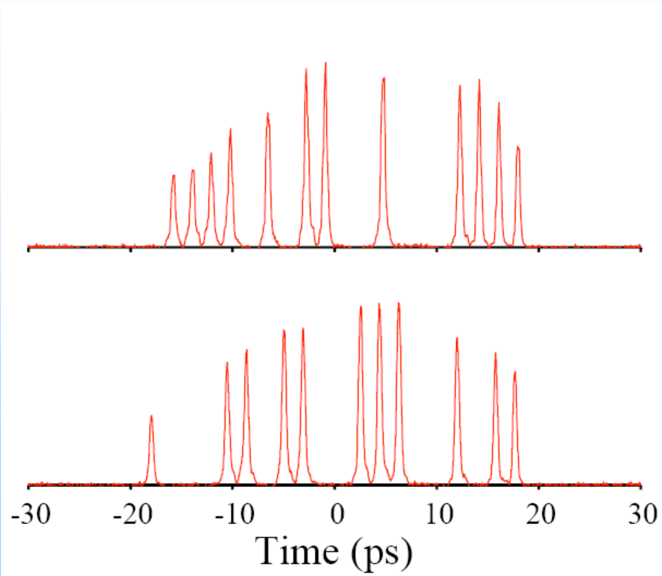
Spatial dispersion

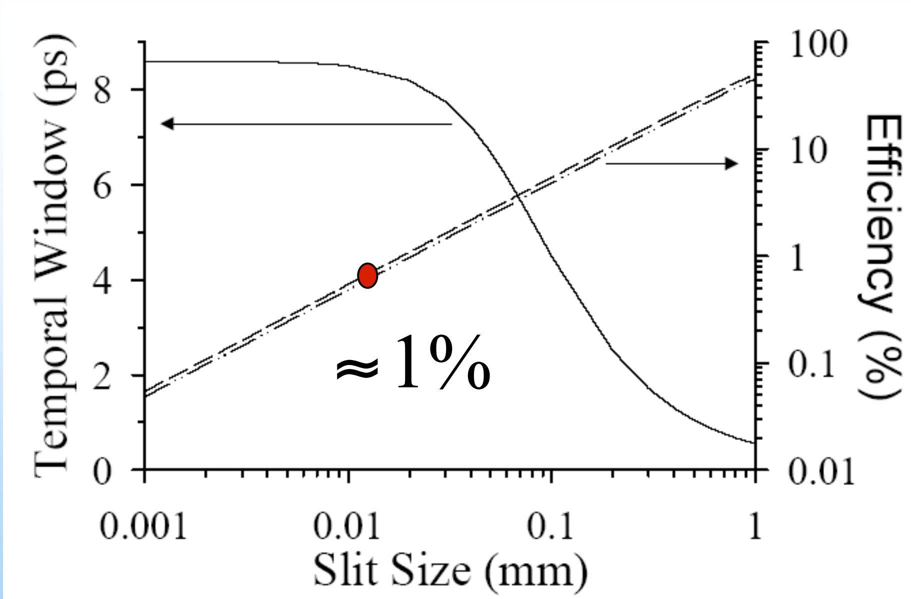
Opt. Lett. 24 (1999) 853

$$e_3(t) \propto \int d\omega\, \tilde{E}_{in}(\omega)\tilde{S}(-\alpha\beta\omega)e^{i\omega \cdot t} \propto e_{in}(t) \otimes s\left(-\frac{t}{\alpha\beta}\right) \approx s\left(-\frac{t}{\alpha\beta}\right)$$



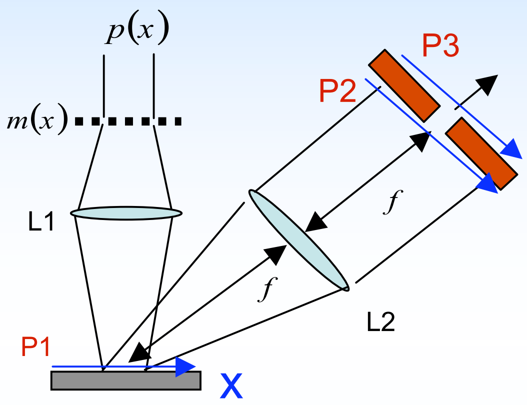
Spazio → **Tempo**





2f + maschera spaziale

(pregi e difetti)



$$e_3(t) \approx s\left(-\frac{t}{\alpha\beta}\right)$$

$$s(x) = p(x)m(x)$$

pregi

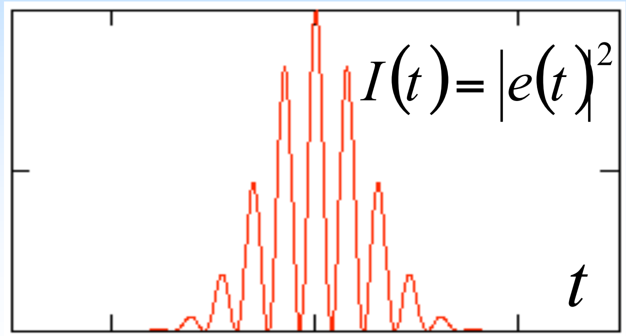
- La successione degli impulsi e' libera
- La diagnostica e' single shot (CCD)

difetti

- L'apparato deve essere collocato prima dell'amplificatore data la bassa efficienza

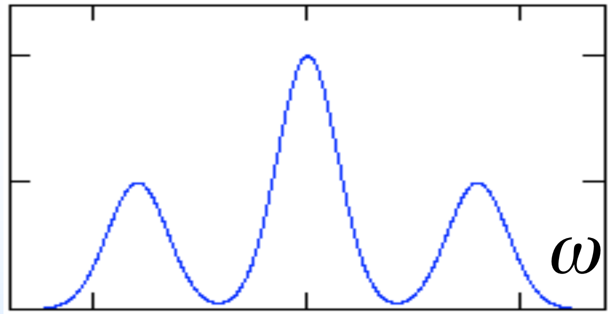
Propagazione del treno nell'amplificatore

$$e(t) = e^{-\frac{t^2}{\tau^2}}\left(1+\cos(\gamma t)\right) = e^{-\frac{t^2}{\tau^2}}\left(1+\frac{1}{2}e^{i\gamma t}+\frac{1}{2}e^{-i\gamma t}\right)$$



$$\downarrow FT$$

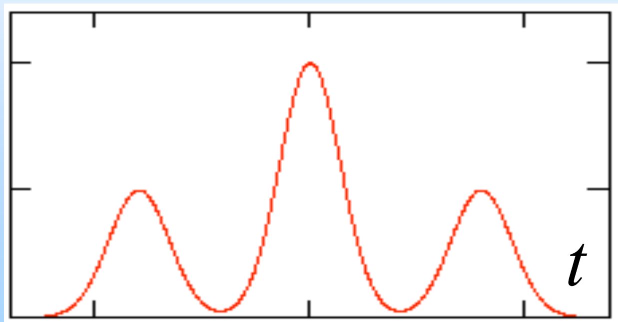
$$\tilde{e}(\omega) \propto \frac{1}{2}e^{-\frac{\tau^2}{4}(\omega+\gamma)^2} + e^{-\frac{\tau^2}{4}\omega^2} + \frac{1}{2}e^{-\frac{\tau^2}{4}(\omega-\gamma)^2}$$



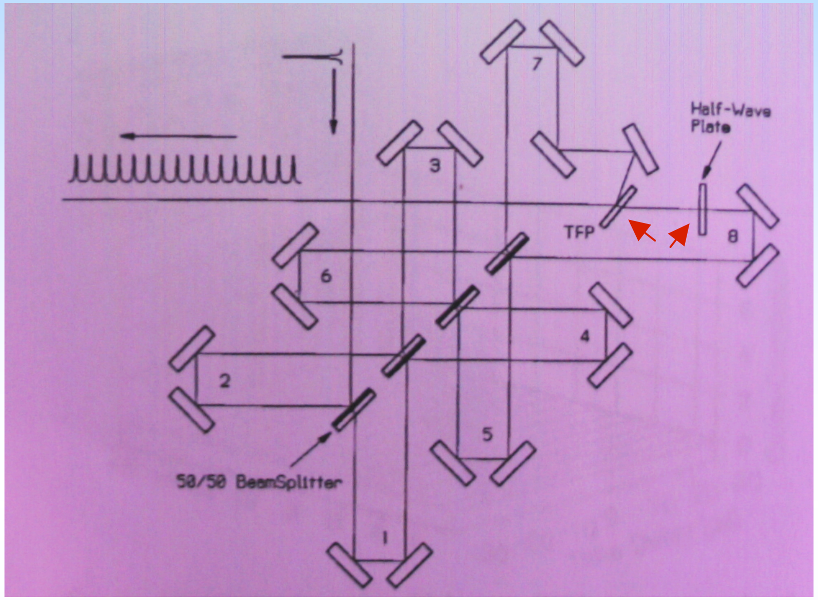
Stretcher $\downarrow$

$$I_{amp}(t) = \left|\tilde{e}(\omega(t))\right|^2$$

$$\omega(t) = \beta \cdot t$$



Beam splitters

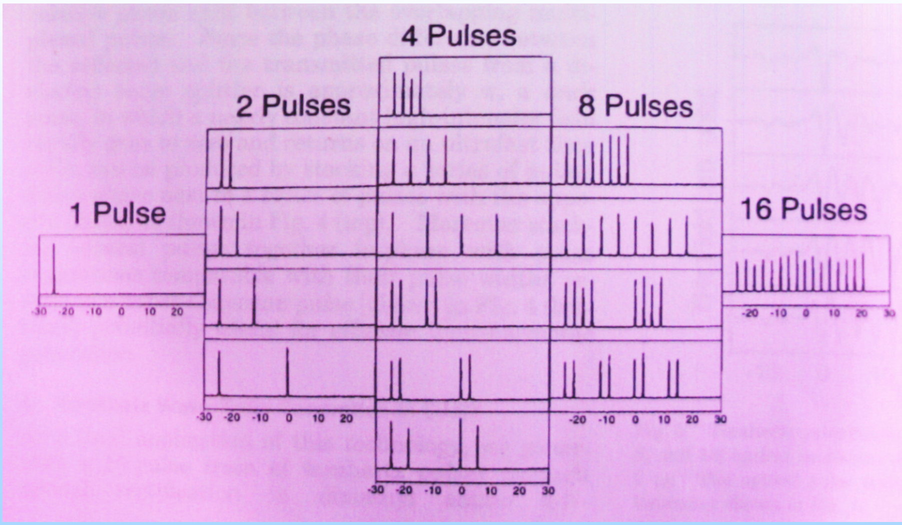


$$2^n \ \textit{pulse train}$$

$$\begin{cases} n \ \ \textit{beam splitters} \\ (4n+2) \ \textit{mirrors} \\ 2n \ \ \textit{linear traslators} \end{cases}$$

$$PBS \rightarrow E_{out} \approx E_{in}$$

$$BS \rightarrow E_{out} \approx \frac{1}{2} E_{in}$$



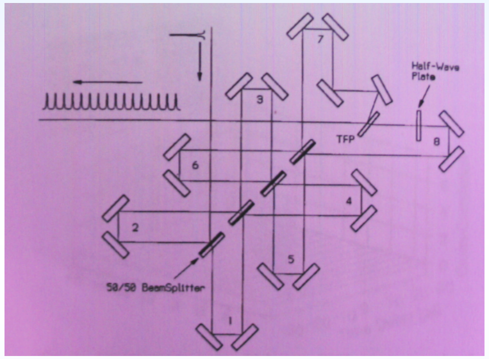
Appl. Opt. 37 (1998) 5302

Beam splitters

(pregi e difetti)

$$PBS \rightarrow E_{out} \approx E_{in}$$

$$BS \quad \rightarrow E_{out} \approx \frac{1}{2} E_{in}$$



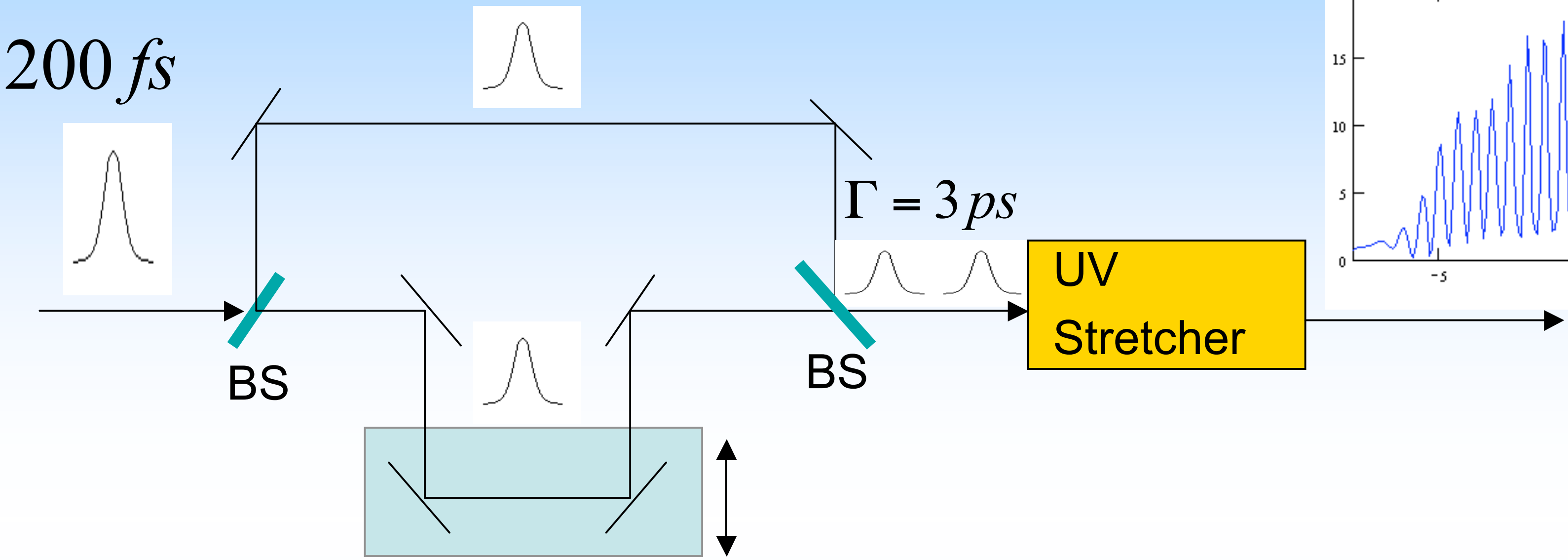
pregi

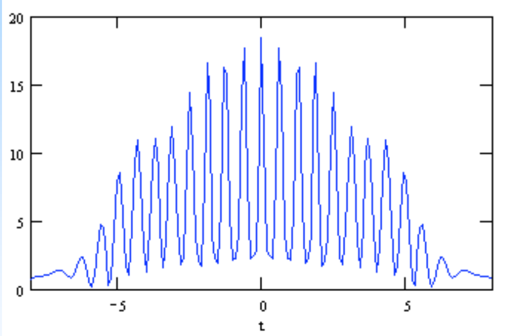
- La successione degli impulsi e' flessibile
- Alta eff. energetica

difetti

- Costo, allineamento e spazio

Interferometro + stretcher





$$A_{\text{int}}(\omega) = A_1(\omega) + A_2(\omega) = \frac{1}{2}A_{in}(\omega) + \frac{1}{2}A_{in}(\omega)\cdot e^{i\tau\cdot\omega}$$ **Interferometro**

$$A_s(\omega) = \frac{1}{2}A_{in}(\omega)e^{i\frac{1}{2}\beta\omega^2} + \frac{1}{2}A_{in}(\omega)\cdot e^{i\tau\cdot\omega}e^{i\frac{1}{2}\beta\omega^2}$$ **UV stretcher**

$$A_{in}(\omega) = e^{-\frac{\tau^2}{4}\omega^2}$$

$$A_s(\omega) = \frac{1}{2} e^{-\frac{1}{\gamma^2}\omega^2} + \frac{1}{2} e^{-\frac{1}{\gamma^2}\omega^2} e^{i\tau\cdot\omega}$$

$$\frac{1}{\gamma^2} = \frac{\tau^2}{4} - i\frac{1}{2}\beta$$

$$A_s(t) \propto e^{-\frac{\gamma^2}{4}t^2} + e^{-\frac{\gamma^2}{4}(t-\Gamma)^2} = e^{-\frac{\alpha^2}{4}t^2} e^{+i\frac{\eta}{2}t^2} + e^{-\frac{\alpha^2}{4}(t-\Gamma)^2} e^{+i\frac{\eta}{2}(t-\Gamma)^2} \approx$$

$$\approx e^{-\frac{\alpha^2}{4}t^2} e^{+i\frac{\eta}{2}t^2} \left(1 + e^{-i\eta\Gamma t}\right)$$

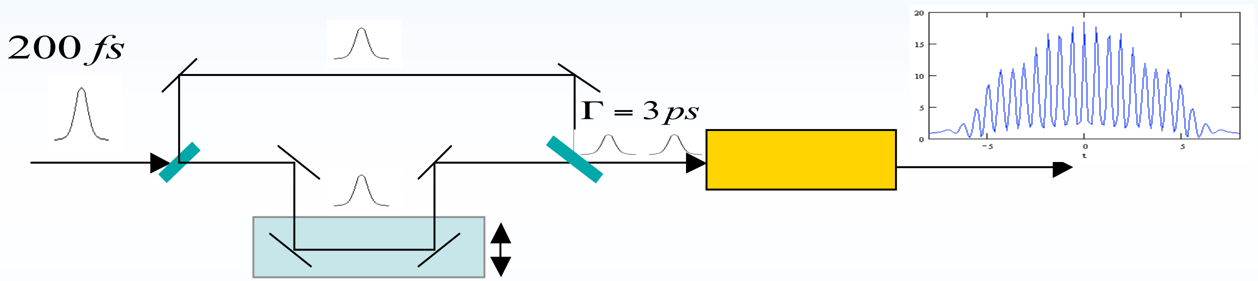
$$\Delta\tau_s >> \Gamma$$

$$I_s(t) \propto e^{-\frac{\alpha^2}{2}t^2} \cos\left(\frac{\eta\Gamma t}{2}\right)^2$$

$$\alpha^2 = \frac{\tau^2}{\frac{\tau^4}{4} + \beta^2} \qquad \eta = \frac{\beta}{\frac{\tau^4}{4} + \beta^2}$$

Interferometro + stretcher

(pregi e difetti)



pregi

- Semplice

difetti

- Modulazione cosinusoidale

Considerazioni finali

Apparato	Impulso Min	Distanza Impulsi	Profilo	λ
4f + PPM	T.L	Uguale per tutti	A piacere	266nm
4f-stretcher + AM	>1.5ps	Limitata	Flessibile	266nm
2f + SM	T.L.	A piacere	A piacere	800nm
BS	T.L.	Flessibile	Limitato	266nm
Interf. +stretcher	T.L.	**Uguale per tutti = 2* lunghezza impulso**	Flessibile	266nm

Emissione spontanea da fascio modulato

e
ricaduta sull'azione FEL

OUTLINE

- Introduzione
- Emissione spontanea da singolo elettrone
- Emissione incoerente da fascio omogeneo di elettroni
- Emissione coerente da fascio modulato
- Un esempio con i parametri di SPARC
- emissione spontanea ed emissione stimolata con un treno di microbunch
- Qualche commento

Introduzione

- IL problema di fare dei FEL con fasci modulati in densità è sempre stata considerata un'opzione molto interessante.

  In particolare io e il gruppo di collaboratori di Bari-Lecce abbiamo lavorato su questo problema con la configurazione che abbiamo chiamato TOK transverse Optical Klystron

- Nel FEL il fascio si modula in densità in tutta la fase di letargia che è impegna la parte maggiore della lunghezza del wiggler. Raggiunta la modulazione del fascio comincia il guadagno esponenziale ed in pochi passo di wiggler questo va in saturazione.

- Noi proponiamo di eliminare la fase di letargia con il sistema presentato da Manuela-Simone. Si capisce subito che vengono risparmiati tantissimi soldi

- Il sistema fascio modulato + wiggler emette una quantità interessante di radiazione spontanea coerente.

- Ma fascio modulato + wiggler naturamente provocano immediatamente l'azione FEL.

Vogliamo vedere un po' questo problema

1 Le leggi per il calcolo dell'emissione

- La legge che considera *la currente J*

  L'equazione dell'emissione di radiazione da una corrente J è (Jackson)

$$\frac{d^2 I}{d\omega d\Omega} = \frac{\omega^2}{4\pi^2 c^3} \left| \int dt \int d^3\, \vec{r}\, [\hat{n} \times (\hat{n} \times \vec{J}] \cdot exp\, [i\, \omega\, (t - \frac{\hat{n} \cdot \hat{r}}{c})] \right|^2 \tag{1}$$

- La legge che considera l'emissione dalla *singola carica accelerata*

  Il caso di moto non-relativistico ($\beta << 1$), la legge di Larmor

$$P_e = \frac{e^2}{6\pi\epsilon_0\, c^3} \ \cdot \dot{v}^2 = \frac{e^2}{6\pi\epsilon_0\, c^3} \ \cdot \ddot{x}^2 \tag{2}$$

$$= \frac{2}{3}\, r_0\, \frac{m_0}{c}\, \dot{v}^2$$

  Il caso generale (any β) ha la formula

$$P_e = \frac{1}{4\pi\epsilon_0}\, \frac{2e^2}{3m^2 c^3} \cdot \left(\frac{dp_\mu}{d\tau} \cdot \frac{dp^\mu}{d\tau} \right) \tag{3}$$

We have to calculate $\ddot{x}^2$ in undulator case

E' semplice fare i calcoli a partire dalla Eq. di Larmor, quindi seguiamo questo percorso

Assumiamo per comodità di calcolo il caso di undulatore, $K_w << 1$
Dobbiamo partire dall'Eq. oraria

$$x = a\ sin(k_w\, z) = a\, sin(k_w\, \beta_{||} ct) \simeq a\, sin(k_w\, \beta\, ct) \tag{4}$$

Ampiezza di oscillazione

$$a = \left[= \frac{K_w}{\gamma\, k_w}\right] = \frac{K_w}{\gamma}\,\frac{\lambda_w}{2\pi} \tag{5}$$

Parametro dell'ondulatore

$$K_w[= a_0] = \frac{e\, B_w \lambda_w}{2\pi m_0\, c} = \frac{e\, B_w}{m_0\, c\ k_w} \quad \propto B_w\, \lambda_w \tag{6}$$

2 Calcoli nel sistema in moto con gli elettroni

Il calcolo è immediato.

L'Eq. oraria è

$$x' = a\,sin(\omega'\,t') \tag{7}$$

per il calcolo di $\dot{v}^2$

$$\ddot{x}^2 = a^2\omega'^4\frac{1}{2} = 8\pi^4\,a^2\,\nu'^4 \tag{8}$$

La potenza dalla formula di Larmor, ($< sin^2 >= 1/2$)

$$P_e = \frac{1}{4\pi\epsilon_0}\,\frac{2e^2}{3c^3}\cdot(a\,\omega'^2)^2\frac{1}{2} \qquad\qquad \omega' = c\,\gamma\,k_w \tag{9}$$

In definitiva

$$P_e = \frac{1}{3}r_0 m_0 c^3\,[\gamma^2 K_w^2 k_w^2] \propto q^2\,\gamma^2 K_w^2 k_w^2 \tag{10}$$

The power is a Lorentz invariant quantity.

$$P_e \propto q^2\,\dot{v}^2 \propto q^2\,a^2\,\omega^4 \propto q^2\,\gamma^2 K_w^2 k_w^2 \qquad a^2 = \left[\frac{K_w^2}{\gamma^2 k_w^2}\right] \quad \omega^4 = [c^4 k_w^4 \gamma^4]$$

Il termine

$$q^2\,\gamma^2 K_w^2 k_w^2$$

contiene la fisica del moto dell'elettrone nell'ondulatore dentro nella formula di Larmor.

3 Calcolo nel Lab frame

Abbiamo fatto il conto per esteso nel Lab Frame

$$P_e = \frac{1}{6\,\pi\,\epsilon_0}\,\frac{e^2}{m_0^2 c^3}\,\dot{p}^2 \Rightarrow \frac{1}{6\,\pi\,\epsilon_0}\,\frac{e^2}{m^2 c^3} \cdot \left(-\frac{\partial p_\mu}{\partial \tau} \cdot \frac{\partial p_\mu}{\partial \tau}\right) \tag{11}$$

where $d\tau = dt/\gamma$ and p_μ is the momentum-energy tetravector of the electron.

In our case of wiggling motion and assuming $K_w < 1$, we get

$$\dot{\vec{\beta}} = \dot{\vec{\beta}}_\perp$$

therefore the equation becomes

$$P_e = \frac{e^2}{6\,\pi\,\epsilon_0\,c}\,\gamma^6\left[\dot{\beta_\perp}^2 - \beta^2\dot{\beta_\perp}^2\right]$$

Il risultato finale

$$P_e = \frac{e^2}{6\,\pi\,\epsilon_0\,c}\,\gamma^4\,\dot{\beta_\perp}^2 = \frac{e^2}{12\,\pi\,\epsilon_0\,c}\,\gamma^4\,c^2\frac{K_w^2}{\gamma^2}k_w^2 \tag{12}$$

Con il raggio classico dell'elettrone

$$P_e = \frac{e^2}{12\,\pi\,\epsilon_0\,c}\,\gamma^2\,c^2 K_w^2\gamma^2 k_w^2 = \frac{1}{3} r_0 c^3 m_0 \gamma^2 K_w^2 k_w^2 \tag{13}$$

OK

Se non è $K_w << 1$

$$P_e = \frac{1}{3} r_0 c^3 m_0 \gamma^2 \frac{K_w^2}{(1+K_w^2)^2} k_w^2 \tag{14}$$

4 Potenza spontanea emessa da un fascio di elettroni

è data dalla potenza

emessa dal singolo elettrone moltiplicata per il numero di elettroni che oscillano dentro all'ondulatore

$$P_I = P_e \cdot n = P_e \cdot \frac{Q_{oscill}}{e} = \frac{I\,\tau}{e}$$

Se ho un fascio infinito

$$\tau = \frac{L_w}{\beta_{||}c} \simeq \frac{N_w\,\lambda_w}{c}$$

e quindi

$$P_I = \frac{4\pi^2}{3} r_0\, m_0\, \gamma^2\, c^2\, \frac{K_w^2}{\lambda_w} \cdot \frac{I}{e}\, N_w \Longrightarrow \frac{4\pi^2\, r_0}{3\, e\, m_0\, c^2}\, E^2(energia)\, \frac{K_w^2}{\lambda_w}\, N_w \cdot I$$

Con la sostituzione

$$m_0\, \gamma^2\, c^2 = \frac{E^2(energy)}{m_0\, c^2}$$

Se ho un impulso di elettroni di lunghezza temporale τ

$$P_{e-bunch} = P_e \cdot \frac{I\,\tau}{e\,c} = \frac{1}{3} r_0 c^3 m_0 \gamma^2 K_w^2 k_w^2 \cdot \frac{I \cdot \ell_{e-bunch}}{e}$$

$$P_I \propto e\, K_w^2\, \gamma^2\, k_w^2\, (I N_w \lambda_w)$$

K_w = ampiezza oscillazione

γ^2 =energia

k_w = frequenza

IL_w = numero di singoli oscillatori incoerenti

5 Energia emessa da un elettrone

$$E_{rad} = \int P_e \, dt = P_e \cdot \Delta t = P_e \cdot \frac{L_w}{\beta_{||}\, c}$$

$$E_{rad} = \frac{1}{3} r_0 \, m_0 \, c^2 \, \gamma^2 \, K_w^2 \, k_w^2 \, L_w$$

Energia emessa da un e-beam

Se ci sono N elettroni dell'e-beam che attraversano l'undulatore

$$N = \frac{Q_w(charge)}{2}$$

$$E_{N-electrons-rad} = E_{rad} \cdot N = \frac{1}{3} r_0 \, m_0 \, c^2 \, \gamma^2 \, K_w^2 \, k_w^2 \, L_w \cdot \frac{I\tau}{e}$$

Da qualche parte sono partiti da questa formula per calcolare la emissione spontanea

6 Emissione <u>coerente</u> a partire dalla emissione del singolo elettrone

$$P_e = \frac{1}{3} r_0 m_0 c^3 \gamma^2 K_w^2 k_w^2$$

L'emissione da N_e coerenti/cooperativi elettroni è

$$q \Longrightarrow Q = e \cdot N_{e-coh} \qquad\qquad P_{coh} = P_e \cdot N_{e-coh}^2 \tag{15}$$

Il punto è: quanti elettroni sono cooperativi/coerenti?

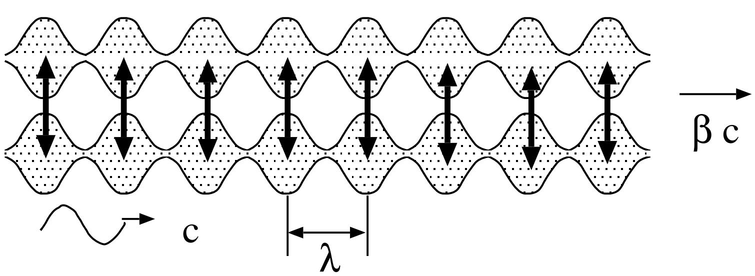
$$N_{e-cooperative} = N_{e-tot} \cdot A_1 = \frac{Q_{tot}}{e} \cdot A_1 = \frac{I \cdot \tau_{eb}}{e} \cdot A_1 \tag{16}$$

Ma

$$I \cdot \tau = I \cdot \frac{\ell_{e-bunch}}{\beta_{||} c} = I \cdot \frac{N_{eb} \cdot \lambda}{\beta_{||} c}$$

e

$$N_{eb} = \text{numero di picchi nel macrobunch} \qquad\qquad \lambda = \lambda_w / 2\gamma^2$$



Alla fine dei conti

$$P_{coh} = \frac{\pi}{12} \eta_0 K_w^2 \cdot I^2 \left(\frac{N_{eb}}{\gamma} \cdot A_1\right)^2 \simeq 10^2 \cdot K_w^2 \cdot I^2 \left(\frac{N_{eb}}{\gamma} \cdot A_1\right)^2 \tag{17}$$

The vacuum impedance $\eta_0 = 377$

$N_{eb} = N_w$ per un fascio più lungo del wiggler

7 Ilario formula del 1980

Partenza la formula del Jakcson

$$\frac{d^2I}{d\omega d\Omega} = \frac{\omega^2}{4\pi^2c^3}\left|\int dt\int d^3\,\vec{r}\,[\hat{n}\times(\hat{n}\times\vec{J}]\cdot exp\,[i\,\omega\,(t-\frac{\hat{n}\cdot\hat{r}}{c})]\right|^2 \quad (18)$$

Il beam di elettroni è modulato in densità

$$\vec{J} = e\,c\,\vec{\beta}\rho_0\sum_{m=0}^{\infty}A_m\,cos[m(kz-\omega t)] \quad (19)$$

facciamo uno sviluppo in serie di Fourier della corrente

con

$$\rho_0 = \frac{I}{e\cdot c}$$

$$\vec{\beta} = \beta_\perp\,\hat{x} + \beta_{||}\,\hat{z} = \frac{K_w}{\gamma}\,cos(k_wz)\,\hat{x} + \left[1-\left(\frac{K_w}{2\gamma}\right)^2 cos(2k_wz)\right]\,\hat{z} \quad (20)$$

Dopo paginate di conti molto incasinati, la potenza coerente sull'armonica m-esima per unità di angolo solido

$$\frac{dP_m}{d\Omega} = \left(\frac{dP_{spont}}{d\Omega_{spont}}\right)\frac{1}{4}\,\frac{\lambda_w}{(2\gamma^2)^2}\,\frac{1}{m}\,\frac{I}{e\cdot c}\,N_w\,A_m^2 \quad (21)$$

The spontaneous emitted power per unit solid angle in the forward direction by an homogeneneous beam (neglecting the oscillatory z-motion) is

$$\frac{dP_{spont}}{d\Omega_{spont}} = \frac{e^2}{2\epsilon_0}\,\frac{\gamma^4}{(1+K_w^2)^2}K_w^2\frac{1}{\lambda_w}\frac{I}{e}N_w^2 \quad (22)$$

Il calcolo dell'angolo solido da

$$\Delta\Omega \simeq \frac{\pi\,(1+K_w^2)}{2\gamma^2\,N_w} \quad (23)$$

e quindi

$$P_{spont} = \frac{dP_{spont}}{d\Omega_{spont}}\Delta\Omega \simeq \frac{\pi e}{4\,\epsilon_0}\,\frac{K_w^2}{1+K_w^2}\,\gamma^2\frac{1}{\lambda_w}\,I\,N_w \tag{24}$$

e per la potenza coerente

$$P_{m-coh}(W) = \frac{\pi}{8}\frac{K_w^2}{1+K_w^2}\eta_0\,I^2\,\left(\frac{N_w}{\gamma}\cdot A_m\right)^2\frac{1}{m} \tag{25}$$

Per un impulso di elettroni moto corto

N_w va nel numero di microbunches del e-beam $N_e b$

Questa procedura di calcolo permette di trovare

- la distribuzione angolare della radiazione
- la distribuzione in frequenza

Parametri per il nostro conto

energia MeV	5
γ	10
$\lambda_w \, m$	$2 \quad 10^{-2}$
$k_w \, m^{-1}$	$3.14 \quad 10^{2}$
N_w	10
current I (catodo) A	100
Q_{tot} C	10^{-9} [1 nC]
K_w	0.1
$\lambda = \lambda_w / 2\gamma^2$	100 μm
A bunching quote	0.5
P_e W	$2.3 \cdot 10^{-15}$
P_I spontanea	2 mW
P_{coh-1}	22 KW
$P_{coh-ilario}$	33 KW

$$P_e = \frac{1}{3} \cdot 2.82 \cdot 10^{-15} \cdot 0.91 \cdot 10^{-30} \cdot 27 \cdot 10^{24} \cdot 10^{2} \cdot 10^{-2} \cdot 10 \cdot 10^{4} = 2.3 \cdot 10^{-15} \, W = 2.3 \, femto{-}Wa$$

$$P_I = 0.07257 \cdot \frac{25 \cdot 10^{-6} \cdot 10^{-2} \cdot 10^{2} \cdot 10}{2 \cdot 10^{-2}} \sim 2 \, mW$$

$$P_{coh-1} = P_e \cdot N_{e-coh}^2 = P_e \cdot \left(\frac{Q_{tot}}{e} \cdot A_1 \right)^2 = 2.3 \cdot 10^{-15} \cdot \left(\frac{10^{-9}}{1.6 \, 10^{-19}} \cdot 0.5 \right)^2 =$$

$$2.3 \cdot 10^{-15} \cdot \left(0.31 \cdot 10^{10} \right)^2 = 22 \, kW$$

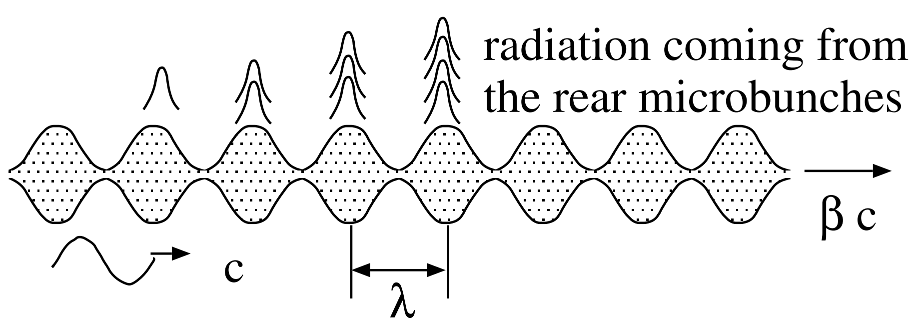
8 Qualche considerazione

- la emissione spontanea coerente da un fascio modulato in intensità ha un funzionamente indipendente dallo
  - spread di energia
  - dalla emittanza
  - dal detuning del FEL

  Non c'è, a prima vista, una condizione di risonanza da soddisfare, ma c'è una condizione di fase da soddisfare.

- Invece, la situazione è più complicata perchè la radiazione emessa dai microbunch di coda slippa in avanti e va ad agire sui pacchetti che sono più avanti secondo l'equazione

$$\frac{dmc^2\gamma}{dz} = eE_0\frac{K_w}{2\gamma}cos[(k+k_w)z-\omega t]$$



Questa è l'azione FEL di emissione stimolata.

Quindi è necessario mettere un wiggler taperato opportunamente per mantenere la risonanza.

- Noi non abbiamo qui la fisica del FEL SASE classico: in questo il fascio di elettroni si auto-organizza nello spezzone lungo quanto la lunghezza di cooperazione.

  Nel nostro abbiamo un fascio già organizzato e per questo emette una radiazione buona per essere amplificata (per stimolare la emissione) e quindi è più utile pensare al tapering.

9 Nota sul Thomson scattering

It is interesting to write down the sponteneous emitted power in the form

$$P_e = \frac{1}{3} r_0 \frac{e^2}{m_0} c\, B_w\, \gamma^2 \tag{26}$$

and introducing the Thomson cross section for a photon diffusion by an electron

$$\sigma = \frac{8\pi}{3} r_o^2 \qquad [= 0.665\, barn] \qquad\qquad (1\, barn = 10^{-24} cm^2) \tag{27}$$

and

$$c^2 = \frac{1}{\epsilon_0\, \mu_0}$$

the spontaneous power emistted by an electron in crossing an undulator

$$P_e = \frac{1}{2} \sigma\, c \frac{B_w^2}{\mu_0} \gamma^2 \tag{28}$$

The term

$$\frac{B_w^2}{2\, \mu_0}$$

is the energy density of the magnetic field and γ^2 is the relativistic compression of that energy (ona γ factor because of the electron sees the energy compressed and the second γ factor because of the electron does a second Doppler compression. Therefore P_e represents the scattered energy per unit time whose voume is Doppler compressed.

10 Thomson scattering con fascio modulato

Adesso la pseudoradiazione del wiggler vede dei centri diffusori ordinati in pacchetti risonanti con la pseudordiazione: i microbunch fanno da specchi di Bragg che avrà una sua efficienza.

Simulazioni FEL per laser comb

V. Petrillo

- Due possibili scenari

- Fasci a bassa energia ($\gamma \approx 10$), lunghezza d'onda di radiazione submillimetrica($\lambda \approx 100$ micron), modulazione di densità sulla lunghezza d'onda

- Fasci ad alta energia($\gamma > 100$), lunghezza d'onda ottica, modulazione sulla lunghezza di cooperazione

Simulazioni fatte con codice FEL

- Equazioni 1d (per cominciare)

Ampiezza lenta del potenziale

Fattore di bunching

$$\left(\frac{\partial}{\partial z}+\frac{1}{c}\frac{\partial}{\partial t}\right)A=\langle b\rangle$$

$$\left(\frac{\partial}{\partial z}+\frac{1}{v}\frac{\partial}{\partial t}\right)p_j=-(Ae^{i\theta_j}+cc)$$

$$\langle b\rangle=\frac{1}{N_{L_M}}\sum_{L_M}e^{-i\vartheta_j}$$

$$\left(\frac{\partial}{\partial z}+\frac{1}{v}\frac{\partial}{\partial t}\right)\theta_j=p_j$$

Lunghezza di media (non necessariamente λ)

Modulazione sulla lunghezza d'onda

- Un singolo pacchetto con $l_b \approx \lambda$
- $\gamma = 10$, λ_w=2cm , λ=200 micron, I=200 A, r_b=200 micron.

- Due pacchetti di dimensione minore della lunghezza d'onda al variare della distanza

- Dieci pacchetti

- Discussione sui problemi del modello

Dato che lb≈λ il bunching iniziale è vicino ad 1.

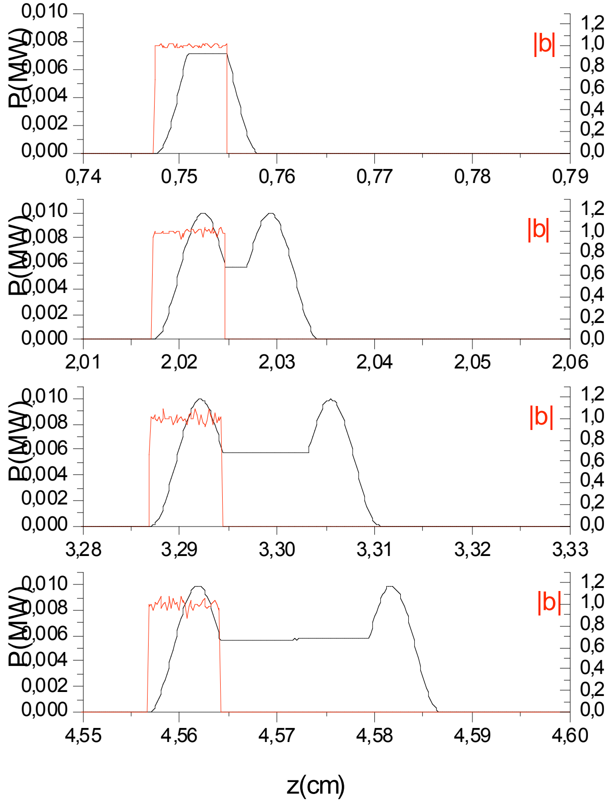
Singolo pacchetto prebunched : emissione spontanea coerente (superradianza debole)

$P<P_{beam}\,\rho$

Differenza rispetto alla emissione spontanea incoerente (Thomson Scattering): Invece di sommare le intensità si sommano i campi e si tiene conto dei termini di interferenza. Si tiene conto della deformazione (longitudinale) della traiettoria dovuta alla radiazione.

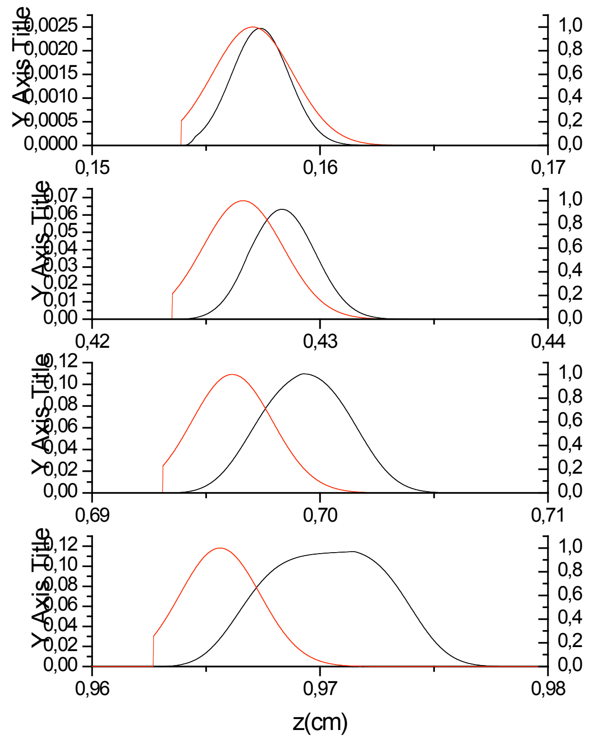
Simulazioni fatte con codice FEL 1d.

Fascio rettangolare

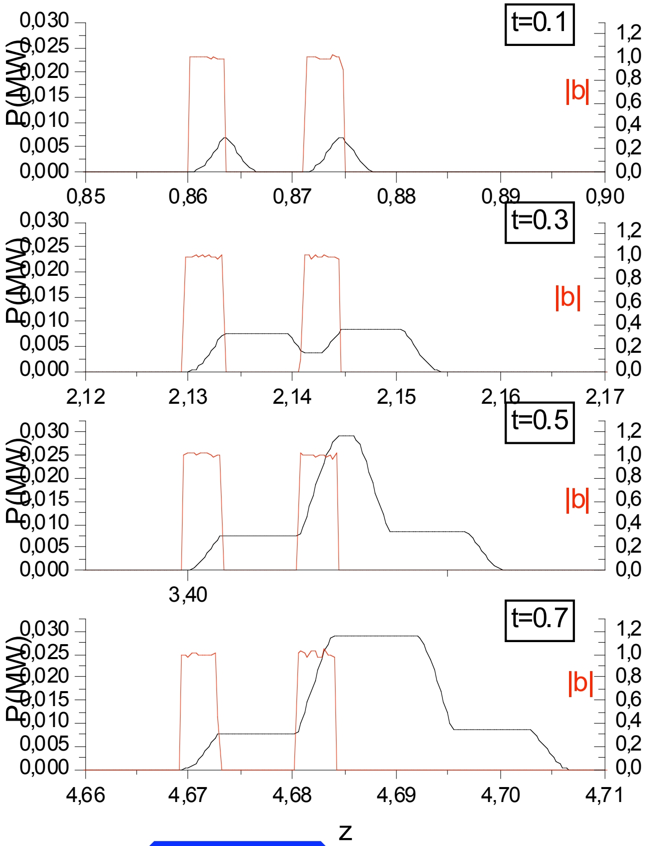


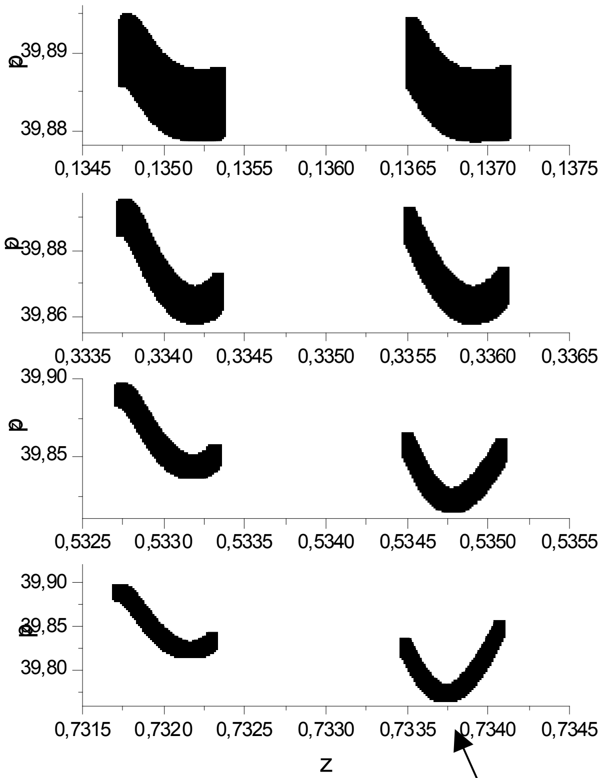
P

Fascio Gaussiano



Due pacchetti in fase



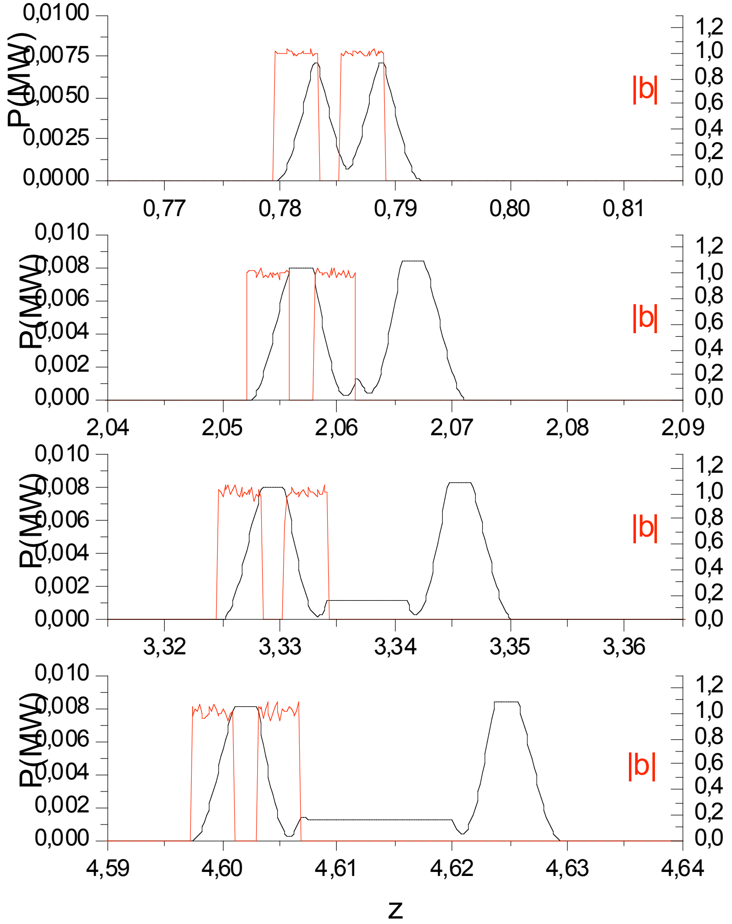


$$|E|^2 = \boxed{|E_1|^2 + |E_2|^2} + 2\mathrm{Re}(E_1^* E_2)$$

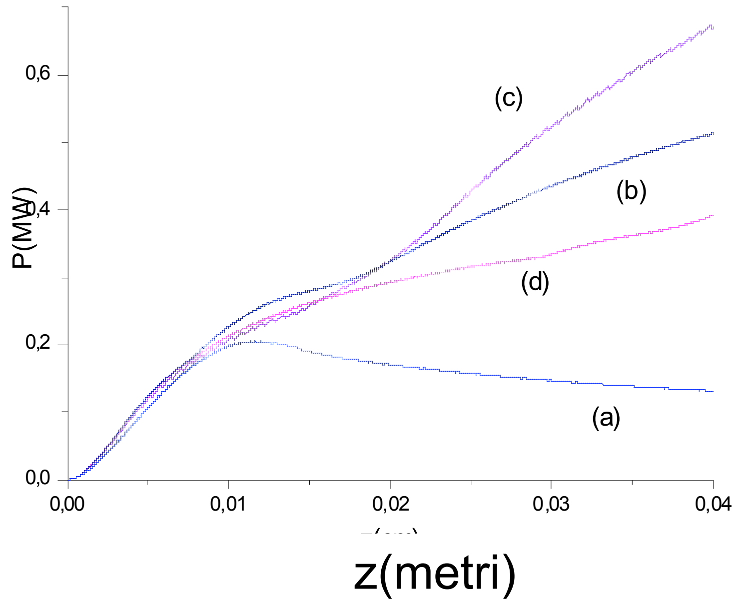
Termine incoerente

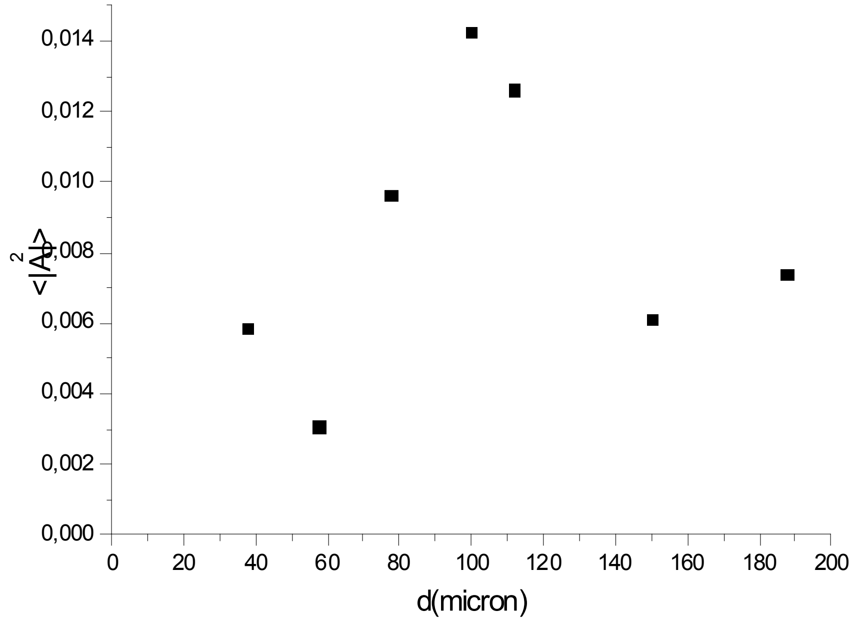
Effetto del moto longitudinale nell'onda ponderomotrice

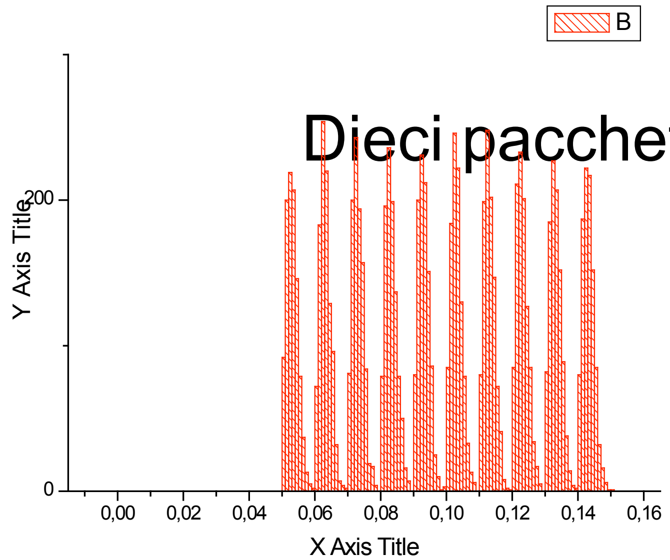
Due pacchetti in controfase

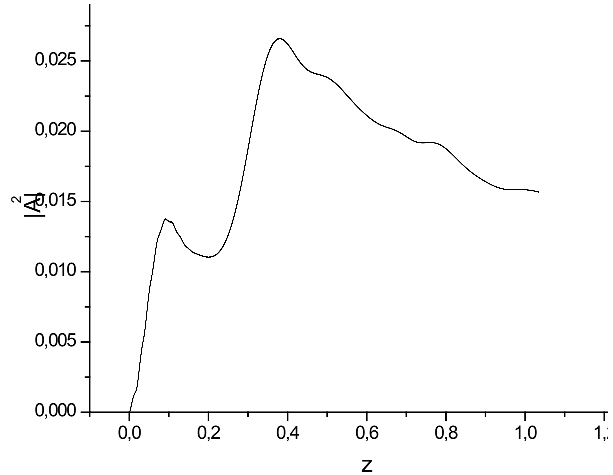


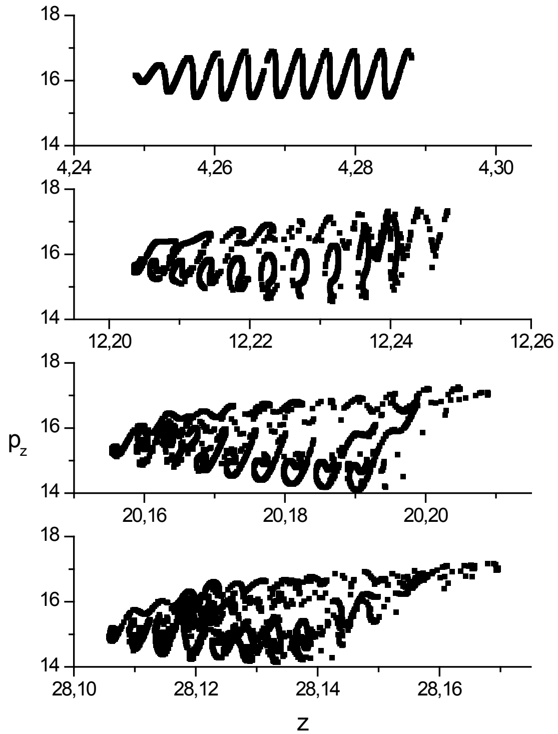
Radiazione al variare della distanza tra i pacchetti

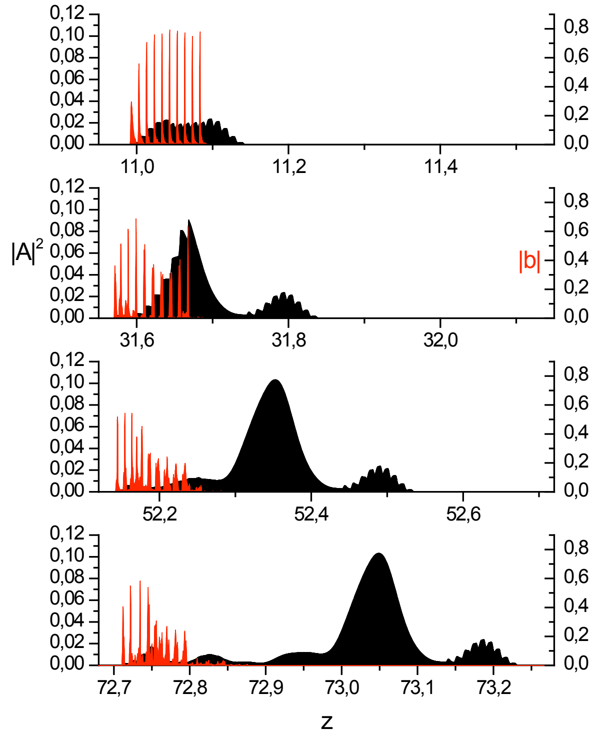





B
Dieci pacchetti
Y Axis Title
200
0
0,00
0,02
0,04
0,06
0,08
0,10
0,12
0,14
0,16
X Axis Title


0,025
0,020
0,015
0,010
0,005
0,000
$|A|^2$
0,0
0,2
0,4
0,6
0,8
1,0
z


18
16
14
4,24
4,26
4,28
4,30
12,20
12,22
12,24
12,26
p_z
20,16
20,18
20,20
28,10
28,12
28,14
28,16
z


0,12
0,10
0,08
0,06
0,04
0,02
0,00
0,8
0,6
0,4
0,2
0,0
11,0
11,2
11,4
$|A|^2$
|b|
31,6
31,8
32,0
52,2
52,4
52,6
72,7
72,8
72,9
73,0
73,1
73,2
z

- Problemi del modello

I parametri violano la Svea!!

Si possono scrivere e integrare equazioni FEL NON-SVEA

Si può utilizzare il codice RETAR

Gli effetti trasversi sono importanti!!

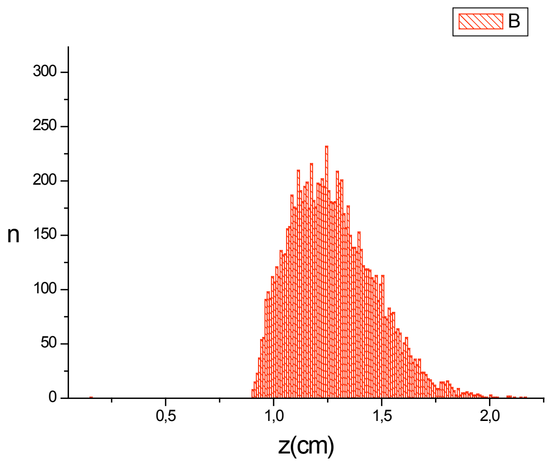
Soprattutto la diffrazione della radiazione

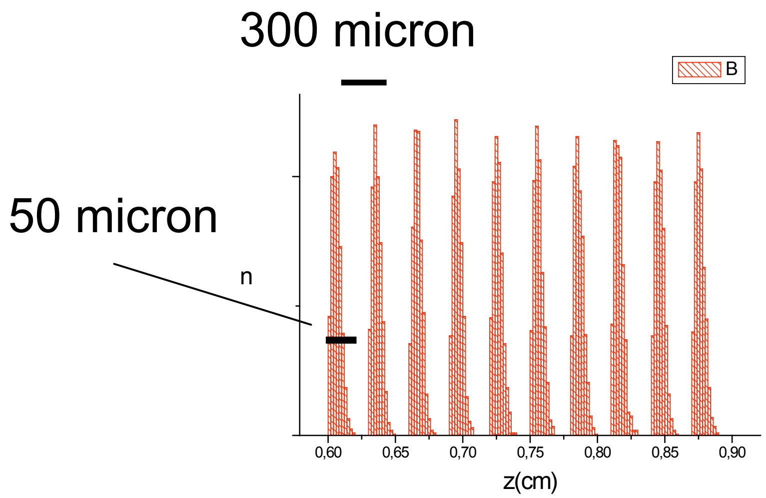
Stime di Ming Xie, codici tridimensionali

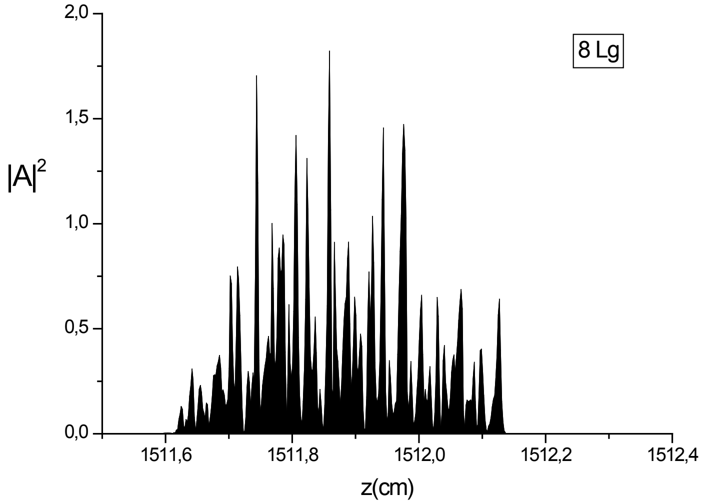
- ρ=0,015 L_g=61 mm L_R=5 mm

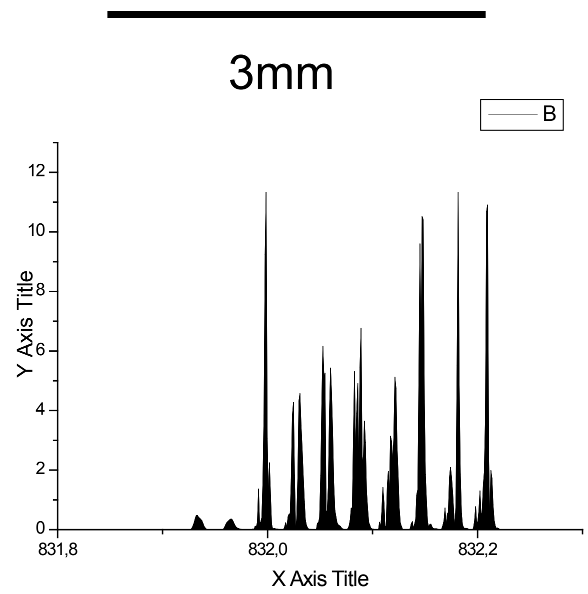
Per mantenere il più possibile i pacchetti in risonanza
si può taperare

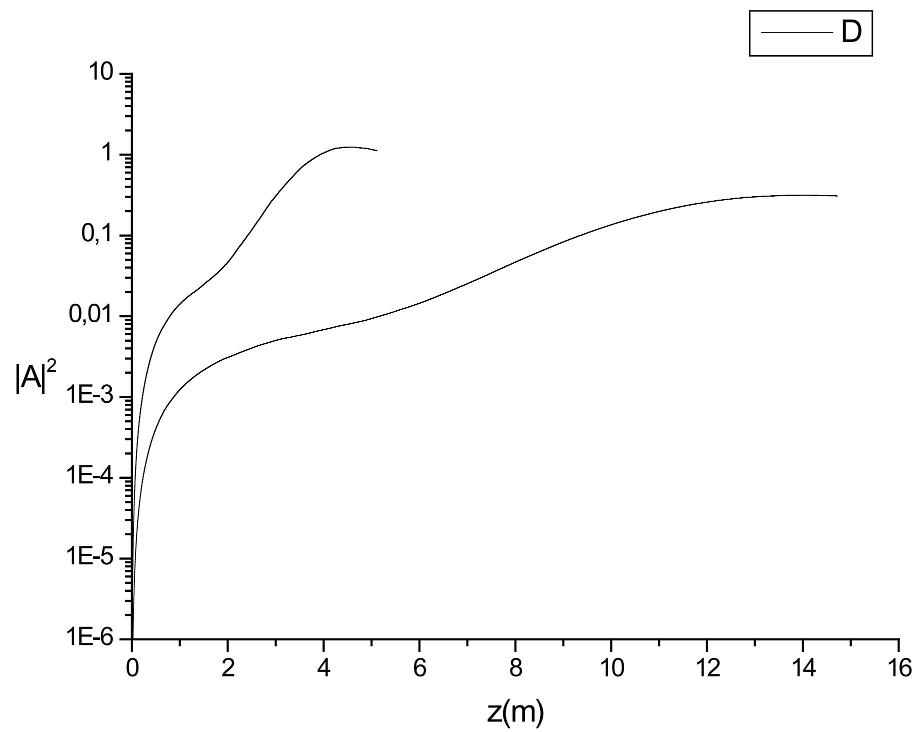
SPARC case aw0=1.4 γ=310, ρ=3.5 10-3, r=1.13 mm, lb=3 mm, λw=2.8 cm



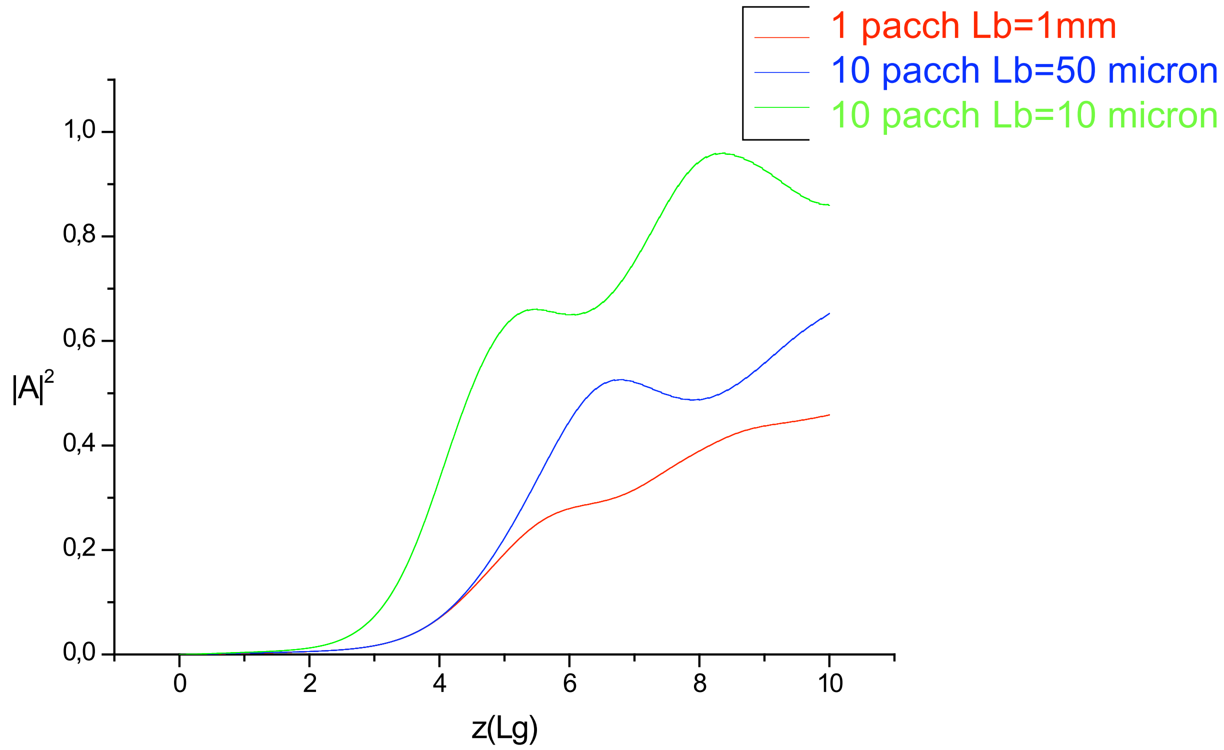


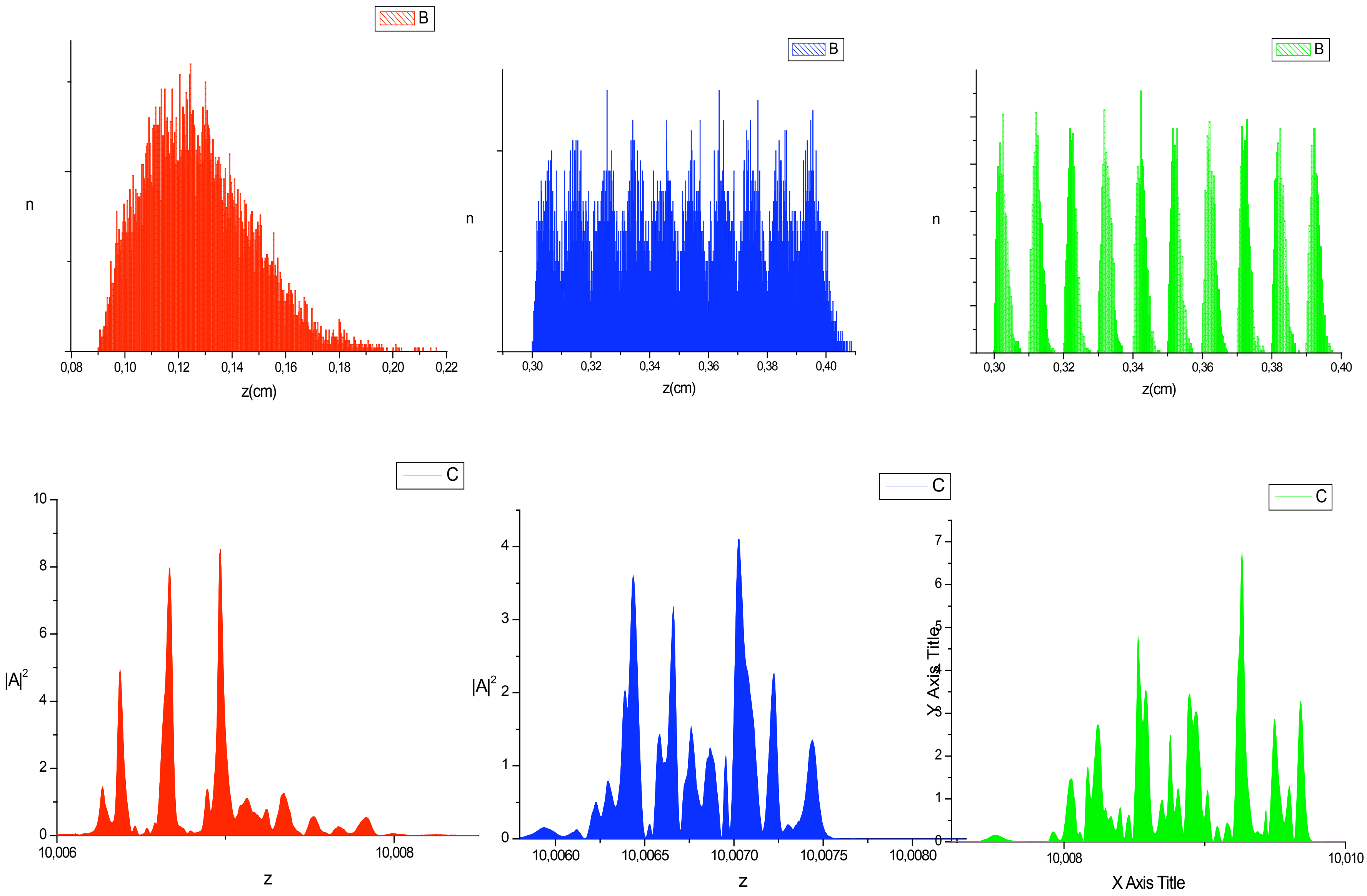





D
10
1
0,1
0,01
1E-3
1E-4
1E-5
1E-6
|A|²
0
2
4
6
8
10
12
14
16
z(m)

λ=0,69micron dens= 9.94E+012 ρ=3.56E-003 γ= 170. p0=280.4
Lg= 44.63 cm Lc=15.44micron Nspike=10.30
Dspike=97.05micron q=5.769E-006




B
n
0,08
0,10
0,12
0,14
0,16
0,18
0,20
0,22
z(cm)
B
n
0,30
0,32
0,34
0,36
0,38
0,40
z(cm)
B
n
0,30
0,32
0,34
0,36
0,38
0,40
z(cm)
C
10
8
6
4
2
0
|A|2
10,006
10,008
z
C
4
3
2
1
0
|A|2
10,0060
10,0065
10,0070
10,0075
10,0080
z
C
7
6
5
4
3
2
1
0
Y Axis Title
10,008
10,010
X Axis Title