SPARX NOTE 05
October 2001

CONTRIBUTIONS TO THE FEL MEETING ON Laser and photocathode iusses

1) L.Serafini: *Requisiti per Fotocatodi e Sistema Laser*

2) A Ghigo: *Il sistema LASER per l'iniettore del FEL*

3) I.Boscolo: *Generation of ps UV powerful pulses for FEL*

4) C. Vicario: *Pulse shaping*

Requisiti per Fotocatodi e Sistema Laser di un Linac ad alta brillanza che pilota un X-FEL SASE (L.Serafini)

- **Condizioni per brillanza massima nei fasci laminari** (leggi di scaling brillanza)
- **Alto Gradiente, Laser pulse rise-time** (catodi metallici)
- **Panoramica di performances** (BNL, UCLA, SLAC, Univ. Tokio)
- **Lista di Parametri**

Massimizzazione di brillanza nei fasci laminari

$$B_n = \frac{2I}{\varepsilon_n^2}$$

- Un fascio e' laminare quando

$$\gamma \le \frac{\left(I / I_0 \right)}{\varepsilon_{nth} \gamma' \sqrt{1 + 4\Omega^2}} \quad ; \quad \gamma_{lam} = 300 \;\; in \;\; LCLS$$

- La brillanza e' massima a $\gamma = \gamma_{lam}$ quando si ha matching sull'inviluppo invariante

$$\sigma_{INV} \;\; = \;\; \frac{1}{\gamma'} \sqrt{\frac{2I/I_0}{\gamma\left(1 + 4\Omega^2\right)}}$$

- Il che implica una condizione al fotocatodo

$$\frac{I}{\left(E_0^{RF} R_{cat}\right)^2} = \cos t \qquad \text{scaling nat.} \quad \begin{cases} R_{cat} \propto \lambda_{RF} \\ E_0^{RF} \propto \lambda_{RF}^{-1} \end{cases}$$

Come scalano l’emittanza e la brillanza a $\gamma = \gamma_{lam}$? Assumiamo Q=cost (1 nC)

- Le dimensioni rms del fascio scalano come λ_{RF}

$$\begin{cases} \sigma_r \propto \lambda_{RF} \\ \sigma_z \propto \lambda_{RF} \end{cases}$$

- Quindi la corrente cresce con la frequenza RF

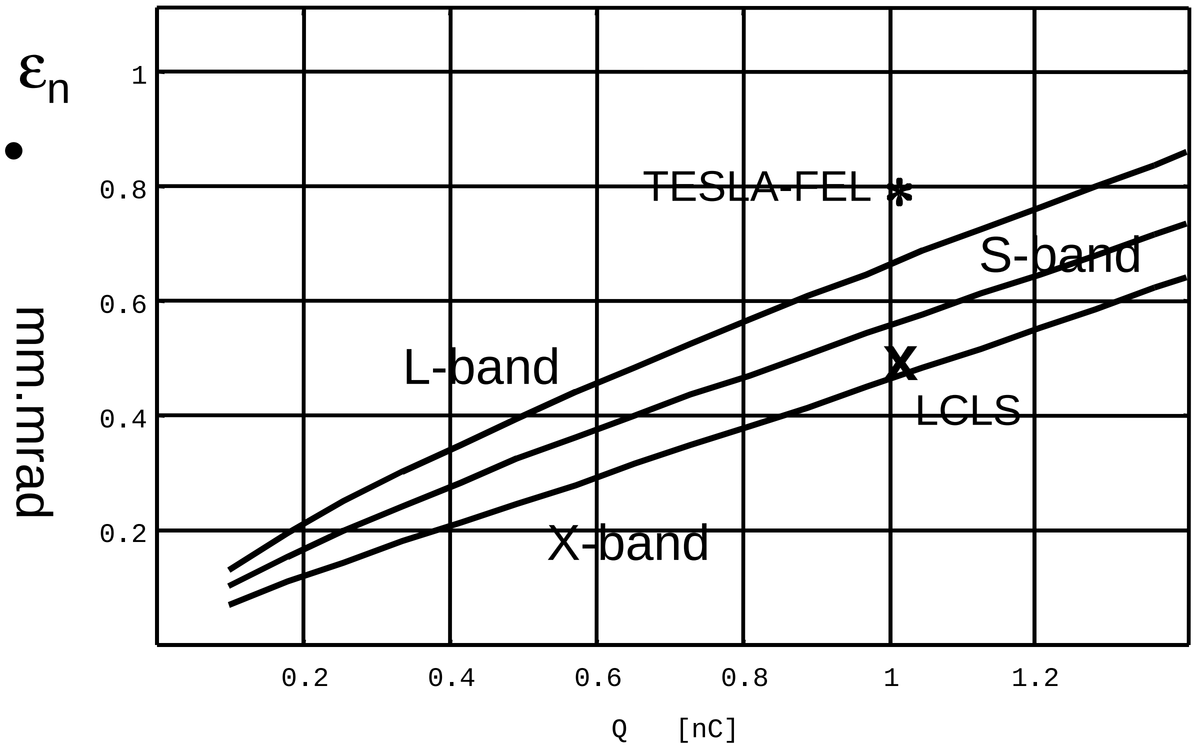
$$I \propto \frac{1}{\lambda_{RF}}$$

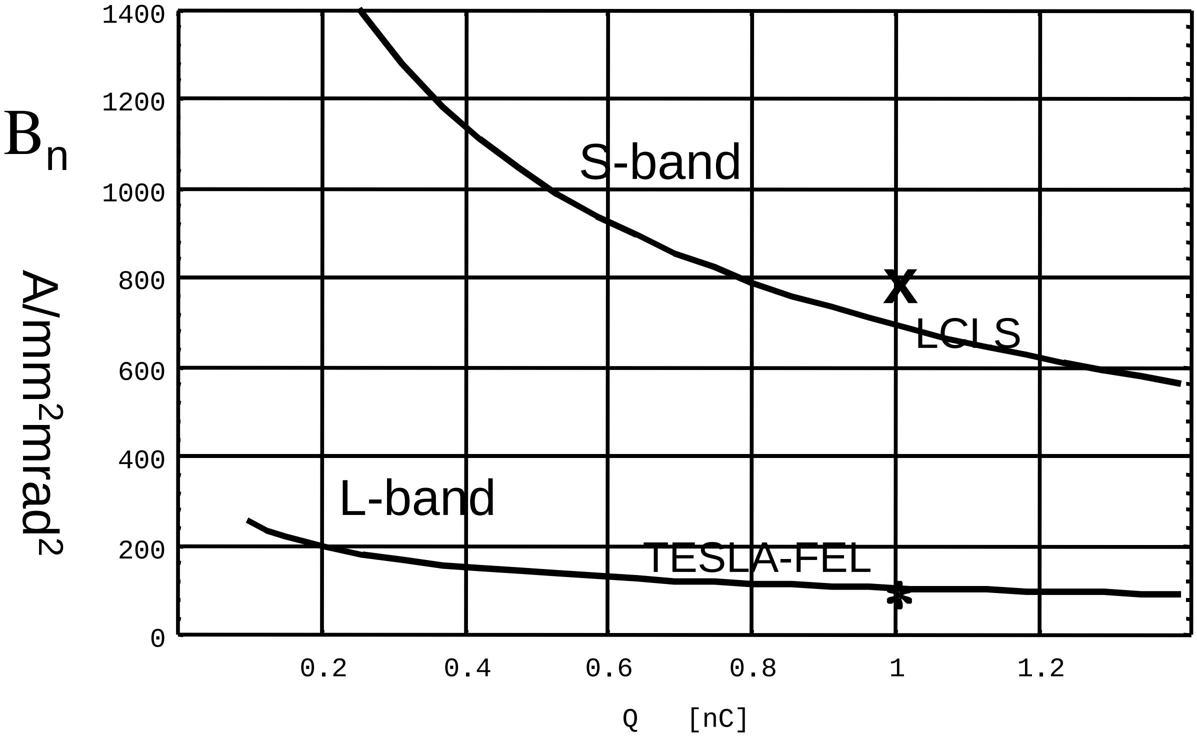
- L’emittanza scala come

$$\varepsilon_n = \eta \sqrt{0.2(Q/\eta)^{4/3} + 0.016(Q/\eta)^{8/3} + 0.09(Q/\eta)^2}$$

$$\eta \equiv \frac{2.856}{\nu_{RF}\ [GHz]} = \frac{\lambda_{RF}\ [cm]}{10.5}$$

Emittance and brightness scaling





Parametri

- Campo RF di picco sul fotocatodo: 140 MeV/m
  1) $R_{cat} = 1$ mm
  2) $T_{laser} = 10$ ps
  3) distribuzione trasversa intensita' laser : uniforme

- Rise-Time dell'impulso laser : < 1 ps minimizza non-linearita' longitudinali del campo di carica spaziale

- Jitters e stabilita'
  1) $\delta x_{cat} < 100\ \mu m$ (pointing stab.)
  2) $\delta\phi_{shot} < 1°$ RF = 1 ps (phase jitter)
  3) uniformita' spazio-temp. : 10%
  4) jitter di energia : $\delta W_l < 1\%$

Prestazioni in vari laboratori (S-band, catodi metall., QE < 10^{-4})

$$N_{el} = N_{ph} \cdot QE \quad ; \quad W_l \ [\mu J] = \frac{4.4 \cdot 10^{-3}}{QE}$$

- BNL record emittanza misurata
  0.8 mm.mrad @ 0.5 nC , catodo in magnesio, fissato per friction bonding nel back-wall della cavita' del gun RF
  $10^{-5} < QE < 10^{-4}$ (ottima uniformita')

- UCLA (Cu e single cristal Cu)
  $10^{-5} < QE < 5 \cdot 10^{-5}$
  (discreta unif. con single cristal, mediocre con policristallino)

Prestazioni in vari laboratori (S-band, catodi metall., QE < 10^{-4})

- **SLAC-GTF** risultati mediocri con Cu policristal. , dopo istallaz. di Cu single cristal QE < $3 \cdot 10^{-5}$

- Univ. of Tokio
  phase jitter 300 fs (design record)
  Cu policristallino, grande miglioramento dopo upgrade del vuoto (proc. Arcidosso 2000)
  QE da $4.5 \cdot 10^{-5}$ a $1.5 \cdot 10^{-4}$
  con 10^{-9} torr (RF on)
  7 nC estratti con 250 mJ (Ti:Sa 267 nm)

Il sistema LASER per l’iniettore del FEL (A.Ghigo)

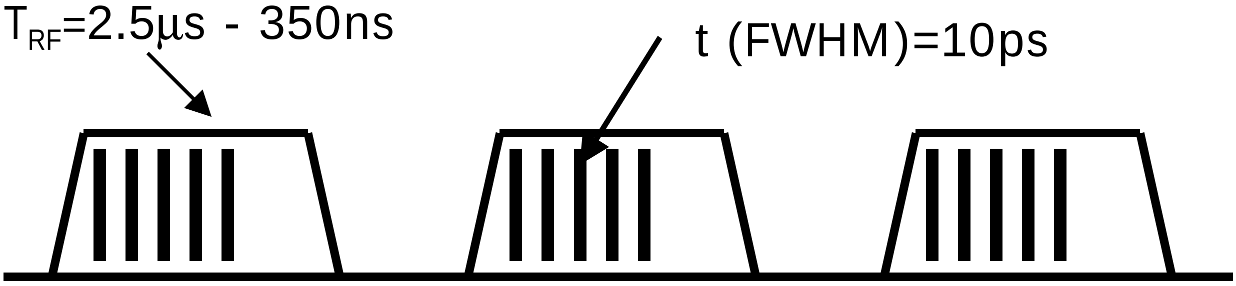
- Caratteristiche degli impulsi laser sul fotocatodo
- Struttura temporale
- Oscillatore del laser
- Amplificatore + laser di pompa dell’amplificatore
- Sistemi esistenti pseudo-commerciali
- Sistemi di manipolazione della distribuzione spaziale e temporale dell’impulso

Parametri

- L'utilizzo di un catodo metallico richiede, per avere 1 nC per pacchetto, un'energia per impulso del laser compresa fra 100 e 500 μJ (sul catodo) nella regione ultravioletta 250-270nm.
- Per il sistema iniettore + LINAC *normal conducting* la richiesta è quella di avere treni di impulsi di durata 350ns a massimo 3GHz di frequenza con rep.rate di 120 Hz.
- Per il sistema iniettore caldo + LINAC superconduttore CW la massima frequenza è 260 MHz e il rep.rate 1 KHz.
- La durata dell'impulso laser deve essere di 10 ps e la distribuzione temporale possibilmente squadrata (rise-time = fall-time = 1ps)

Struttura temporale

- La frequenza di ripetizione dei pacchetti singoli o dei treni di pacchetti di elettroni è governata dalle caratteristiche del Linac e del gun.
- Il numero di pacchetti nel treno è limitata dalla frequenza dell’oscillatore laser e dalla massima durata dell’impulso di pompa dell’amplificatore.
- Il desiderio di avere 1 KHz di impulsi singoli all’uscita del fotoiniettore è, dal punto di vista del laser, esaudito dai sistemi esistenti con i requisiti di stabilità di ampiezza e fase richiesti. Per quanto riguarda i treni di impulsi gli amplificatori esistenti non hanno le caratteristiche di durata temporale (max. 150 ns) e di uniformità di ampiezza richiesti.


T_{RF}=2.5µs - 350ns

t (FWHM)=10ps

Rep.Rate= 1KHz - 120Hz

Laser Oscillator

Tsunami

-Broadest pulse width coverage (< 35 fs to 100 ps) of any commercial mode-lockedTi:sapphire laser

-Power output > 2 W for high-power harmonic generation and OPO pumping

-New proprietary broadband optics

-Uses Millennia s series all-solid state pump lasers (5 to 10 watts)

-Long-term stability, prevention of pulse dropouts and broadest wavelength coverage

-Accessories include Lok-to-Clock synchronization, harmonic generators, OPOs, high-energy regenerative amplifiers, kHz regenerative amplifiers, OPAs and more

Spectra-Physics

COHERENT

The Mira 900 Modelocked Titanium:Sapphire(Ti:S) Laser System

-Simple, stable, KLM modelocking – ease of use and reliability

-GVD prism and GTI compensation

- soliton-like, nearly transform-limited pulses

-X-Wave optics – broadband, single optics set tuning 700-1000nm (femto and pico sets provided)

-Verdi-pumping (5W, 8W or 10W at 532nm) diode-pumped stability, reliability

-Optima system – advanced system monitoring and control

-Unique resonator design – ease of use, flexibility and stability

-Integrated pump steering optics – ease of pump alignment

-Simple femto/pico configuratuion changes

Auxiliary cw cavity for ease of alignment or configuration change

Mira

AMPLIFIER

The Hurricane Ti:sapphire amplifier, developed jointly by Positive Light and Spectra Physics, is the world's first all-diode-pumped, one-box Ti:sapphire oscillator-amplifier.

Amplified Output

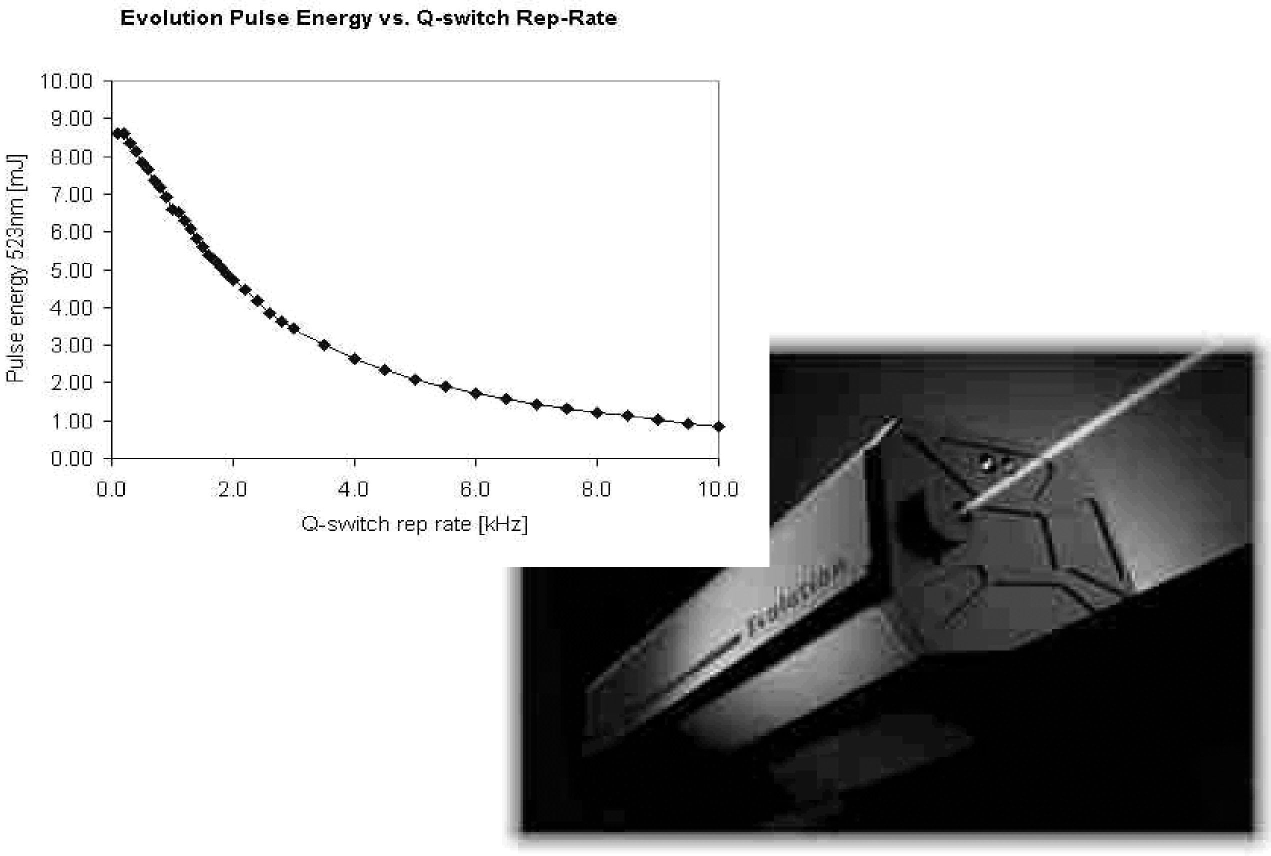
Wavelength [1]	780–800 nm
Repetition Rate [2]	1–5 kHz
Pulse Energy	750 µJ @ 1 kHz 200 µJ @ 5 kHz

Pulse Duration (FWHM, Gaussian) < 130 fs

PUMP LASER

The Evolution utilizes Nd:YLF as its gain medium. One ideal property of Nd:YLF is its 470 microseconds lifetime.

It is perfect as a pump for Ti:sapphire regenerative amplifiers. Producing over 30 Watts at 527 nm, and with pulse energies of greater than 20 mJ at 1 kHz



COHERENT

Corona

With over 75W of green power at repetition rates from 5 kHz to 30 kHz, the new Corona laser overturns all previous notions of speed and productivity. The Corona utilizes reliable diode pumping of Nd:YAG to generatehigh green power in a compact and rugged package, making it ideal for either Ti:Sapphire or dye pumping or material processing.

Generation of ps UV powerful pulses for FEL

I.Boscolo, S. Cialdi

The characteristics required to the laser for the I-RF-gun of 150 Mev are here listed

Wavelength	266 nm
Number of µpulse per pulse	No.1
Pulse length	10 ps
Rise time	<1ps
Energy per pulse	500 µJ
Laser to rf phase jitter	< 1ps
Pulse repetition rate	1 Hz

The single emitted pulse must be in synchronization with the RF of the electron gun. Let's say that the seeding oscillator must have a frequency of 110 MHz, with is the 24th subharmonic of the 3 GHz of the e-gun klystron. The block scheme of the system is shown in fig. 1.

The most critical point is the jitter between the phase of the laser pulse and the phase of the RF of electron gun below the ps means a timing stability of the laser system below the ps.

The jitter is usual large, let's say 10 ps, because many causes are present; the time and amplitude instability of the pump, environmental acoustic perturbations, table and mirror mount vibrations, cavity length instability, etc. The goal of 1 ps means a dedicated design of the laser system.

The pulse flatness is the other characteristic, which require a dedicated design. The laser pulses are gaussian, hence we must produce a transform limited very short pulse about 100 fs, so to can manipulate its shape in order to obtain the wanted flat pulse.

The energy of 500 µJ at 266 nm is not so much high for Ti:sapphire laser operating in 3° harmonics. This level of energy means an output from Ti:sapphire laser of about 20 times higher, that is 5-10 mJ. A lab apparatus in 1992 provided 0.45J[1].

The pulse is relatively long, 10 ps.

The oscillator

The oscillator capable to provide a femtosecond pulses is the Ti:sapphire oscillator. Our choose is then:

The self-starting self-mode-locked Ti;sapphire Ti:Al_2O_3 femtosecond oscillator.

The crystal for femtosecond pulses is Ti;sapphire because it has the largest gain bandwidth. The oscillator is passively mode-locked using *Kerr-Lens Mode Locking (KLM)* technique. The output mirror is slightly tape by a piezo so to initiate the mode locking.

The lock to the external Rf reference is done by tuning the length of the oscillator cavity. The length of the cavity is set up to match a fraction of the accelerator frequency, that is 110 MHz:

$$f_m(110MHz)=\frac{c}{2L} \tag{1}$$

A 110 MHz repetition rate means L=1.364 m.

From this relation we get the relation between the jitter and the cavity length variation:

$$\partial t=\frac{\partial L}{2\pi f_m L} \tag{2}$$

For the length variation of 0.1 mm we get 1 ps variation.

The output energy per pulse is 10nJ for 1 W average. The peak power in the pulse results in 100 kW. This is an high power, even if it is about a factor 2 less the record.

1.1 The laser cavity

The resonator is a stable non-linear resonator. It is has two internal lenses and two flat mirrors, forming a telescope with magnification one, see fig. 2.

The largest is the gain bandwith $\Delta\nu$ the higher is the number of modes excited within the cavity. The Ti:sapphire laser parameters are listed

Laser parameter of Ti:sapphire crystal	
Fluorescent lifetime	τ+ 32 μs
Fluorescent linewidth	$\Delta\lambda$~180 nm
Peak emission	λ_p~790 nm
Stimulated cross section	σ
Gain bandwidth	230 nm
Saturation fluence at 795 nm	I_{sat}=0.9J/cm^2

The larger the gain bandwidth __ the higher the number of modes excited within the cavity.

We remember the Free Spectral Range FSR (that is the distance between two adjaicent modes)

$$\nu_q=\frac{c}{2L} \tag{3}$$

The longer the cavity the more dense the modes. Our Ti:sapphire oscillator has a bandwidth of about $\Delta\nu$~400GHz for a number of modes in our cavity number of modes ~ $4*10^4$.

1.2 The laser pump of the Ti:sapphire oscillator

A CW-diode pumped doubled Nd:YAG laser pumps the Ti:sapphire crystal. It is CW operating, frequency doubled, 532 nm, powerful, 5 W.

2 Pulse stretching and square shaping before the amplification

The pulse produced by the Ti:sapphire oscillator is

-transform-limited, that is the pulse does not have chirp or other internal structure. It is such that the product of the bandwidth with the time of the pulse is ~ 0.5 (from a general Fourier theorem)

$$\Delta\nu\delta t \sim 0.5 \qquad (4)$$

-100 fs long

-10 nJ energy

This pulse must be stretched up to 500 ps before entering the two amplifiers. Besides it is squared. Before the pulse is temporally shaped and after it is stretched.

The procedure for the temporal shaping of the optical pulse is the following:

-the frequencies of the pulse are separated by a plane ruled grating;

-a spatially resolved amplitude mask allows the transmission of the frequencies such that their sum (Fourier composition) results in the requested shape.

-a second plane ruled grating set with its face and rulings parallel to the first grating re-joins the frequencies.

In principle, a square pulse with the pulse duration of the original pulse can be produced. The dispersion between the two gratings is avoided inserting a pair of lenses.

The power spectrum of the oscillator pulse is

$$I(\omega) = I_0 \, e^{-2\left(\frac{\omega-\omega_0}{\Delta\omega}\right)^2} \qquad (5)$$

where $\Delta\omega=2/\tau$ is the bandwidth of the pulse. The shorter the pulse the larger the spectral badwidth.

3 Signal Amplification

The pulse of the oscillator is stretched to 500 ps by a stretching system. This operation reduces considerably the energy, from 10 nJ up to 1nJ.

The two amplifiers proposed by LCLS are:

_four pass Ti:sapphire ampli_ers with an exponential gain of about 2000!

This multi-pass amplification system is very very critical. It seems that it operates in on/off.

Furthermore, the crystals operate in dramatic stressed conditions: the risks for damage are very high. The output power is estimated around 20 mJ/pulse. This level of power seems a bit in excess for final 0.5 mJ level at the third harmonics.

For a single pulse operation it could be advisable to have a regenerative amplifier as first amplifier and a multi-pass amplifier as the second. In this scheme the bandwidth of the oscillator pulse should be reduced of a factor ten, from 100 fs to 1 ps.

3.1 The pump of the amplifiers

The pump of the amplifiers is a Q-switched doubled Nd:YAG, delivering pulses of 8 ns and power of 160 mJ/pulse with a repetition rate of 120 Hz.
This laser system, called Infinity, is built by Spectra(?).

4 Pulse compressing

The pulse after the amplification is compressed and then it gets through the crystals for thefrequency multiplication.
In Fig. 3 the whole system is sketched.

5 Timing stabilization

The proposal of LCLS is proposing a two dynamical systems.

1. The stabilization of the oscillator output phase with respect to the acceleration rf phase. It is provided by the measurement of the laser and accelerator rf error, the down filtering of the error signal, the amplification of the error signal and finally its application to the oscillator piezo-stage. The length of the cavity is continuously adjusted to lock the phase the phase of the subsequent laser pulses to the rf.
2. The second stabilization system is put after the oscillator. A prism, mounted on a piezo stage with a fast motor (e.g., a picomotor from New Focus Inc.), is positional controlled
   by the error signal between the rf phase and the oscillator phase.
   The piezo and the motor would be computer controlled and would acount forthe slow drifs,in the laser optical path length ot timing drifts in the rf system.

A stabilization system similar to the described above has demonstrated the capability to fix the jitter up to 2 ps.

We must stress that we are willing a stabilization at 1 ps with some electronics which has the intrinsic time of the ns. This can say the challenge of this dynamical system. No dubt that a tigh temperature stabilization should be applied.

Riferimenti bibliografici

[1] A. Sullivan, et al. Opt. Lett. 16, 1406 (1991).

6 Le ditte e i costi

L'oscillatore e' costruito dalla Spectra Physics: e' il Tsunami.

Lo stesso oscillatore e' costruito dalla Coherent, il MIRA, ma non e' trackabile e non funziona.

Costo variabile pero' si puo' dire intorno ai 300 milioni

-Gli amplificatori sono costruiti dalla Quantronix. Costo 400 milioni cadauno.

-Il generatore di armoniche si potrebbe acquistare da Vilnius in Lituania.

Oscillatore	300 Milioni
Amplificatori (7)	800 Milioni
Generatore terza armonica	100 Milioni
Stretcher +compressore	100 Milioni
Elettronica per stabilizzatore	100 Milioni
TOTALE	~1.5 Miliardi

Le caratteristiche del laser per il progetto FEL-X sono:

No. impulsi	100
Rep.rate macro	100-200 Hz
No. impulsi/sec	10^4
Lunghezza impulso	τ~10 ps
Tempo di salita	t_{rt}<1 ps
Lunghezza treno	τ=350 ns
Rep.rate	110MHz
Energia impulso	500µJ
potenza	500 MW
ultravioletto	266nm
jitter	<1ps

Il microimpulso e' relativamente lungo, pero' deve essere flat-top, quindi con tempi di salita e di discesa ultracorti. Questo per problemi di emittanza.

La frequenza media e' 10 kH.

Oscillatore 100 Hz con 100 impulsi, 200 Hz con 40 impulsi. 100 Hz e' preferito perche' riduce il costo del modulatore.

Questi dati si riferiscono al progetto grande. Per il primo progetto, la macchina piccola, sara' sufficiente un impulso invece del treno di 40 impulsi.

Il laser proposto da SLAC nel progetto LCLS e' un titanio zaffiro.

Risultato discussione con Quanta System Ing. Malvicini.

Lo schema del laser deve essere oscillatore in continua-temporal pulse shaper- pulse strecher-2 amplificatori-pulse compressor-convertitore di armonica.

Perche' il titanio-zaffiro? perche' barretta corta e quindi sono evitati fenomeni non-lineari.

Il pulse shaping necessita di un impulso molto stretto dall'oscillatore, 0.1-0.15 ps. Questo e' possibile con il Titanio-Zaffiro perche' ha una banda molto larga.

il diametro della barretta deve essere abbastanza grande da permettere no. 8 passaggi separati:

si tratta quindi di un parallelepipedo. Quella energia (potenza) e' possibile.

Per ottenere quella energia per impulso e' necessaria una forte amplificazione. quindi due amplificatori con 8 passaggi. Per questo e' necessario

- impulso transformer limited : non _e un problema. Questo per poter fare bene lo streaching.

-streaching in e spansione dell'impulso all'uscita dall'oscillatore: da 1 ps a 60 ps. Questo serve per evitare tanti fenomeni non lineari nell'amplificatore. Questi fenomeni si hanno anche nel TiZr.

-ampli_catore a Ti:sapphire pompato YAG sotto il GW/cm^2 con multipasso, quindi con celle di Pockels. Queste ottiche interne richiedono un impulso lungo per evitare densita' di energia cosi' elevate che scatenano molti fenomeni non lineari nella cella.

-streaching in compressione dell'impulso in uscita dall'amplificatore. Lo streaching si calcola e si fa, una volta che l'impulso e' ben formato, cioe' transformer limited.

-multipulse operation: 40 pulses at 110 MHz.

-The microbunch separation is about 10 ns, which corresponds exactly to the length of the laser cavity. This means that the multibunch operation is obtained simply cutting trains of 350 ns.

-To alleviate any problem for multi-pulse operation, the laser amplifiers cannot be regenerative.

Compenation for gain depletion can be achieved by rumping up the power of the pump laser in the scale of 350 ns.

Il Titanio-Zaffiro opera a 800 nm, quindi la terza armonica e' 266 nm.

I punti cruciali-tecnologicamente delicati sono:

-time stability: $\Delta t_{rms} =$ 0:5 ps. The length of the oscillator cavity is continuously adjusted to lock the phase of the subsequent laser pulses to the rf.

A stable oscillator is essential.

-optical energy per pulse constant to the level f 1 % rms. This is difficult. The LCLS suggestions for the achievement of this goal are

- laser diode pumping
- careful control of beam mode

- Fourier relay imaging
- stabilization of the amplifier pumping

The oscillator is a Ti:sapphire because it has the large enough bandwidth to support rise times below 1 ps, as required. Besides, the desired wavelength can be obtained by frequency tripling of

Ti:sapphire

The amplifiers are Ti:sapphire because it supports the 120 Hz repetition rate requested.

Il sistema e' complesso ma fattibile, pero' e' tecnologimente challenging, pero' I vari componenti sono commerciali.

Un progetto di questo tipo richiede competenze precise, la Quanta non le ha e quindi bisogna prevedere una collaborazione con il Dipartimento di Fisica di Pavia, cioe' con Banfi.

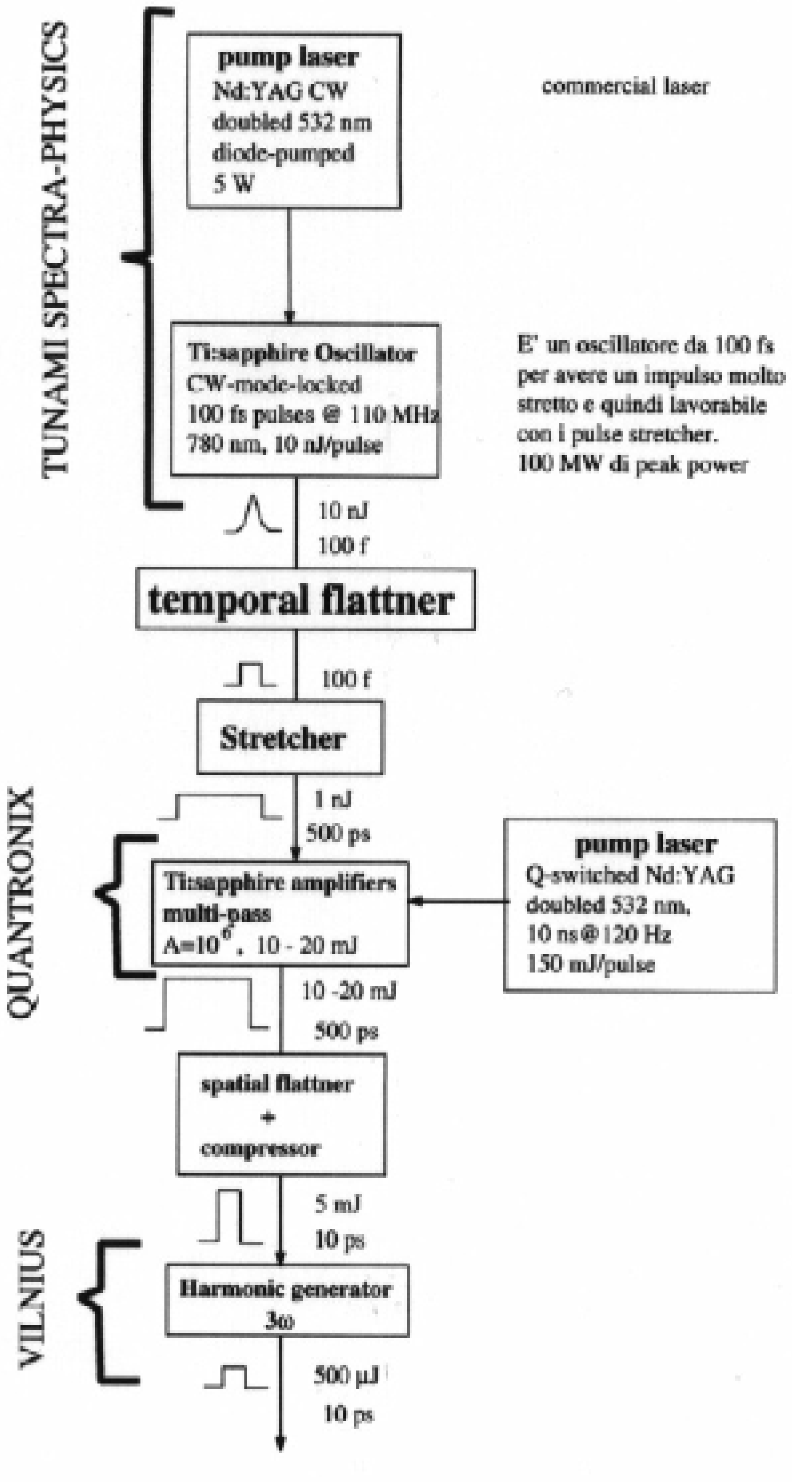


Figura 1: The Ti:sapphire oscillator is commercially available: MIRA by Coherent and Tsunami by Spectra-physics. The Ti:sapphire amplifier is sold by Quantronix.

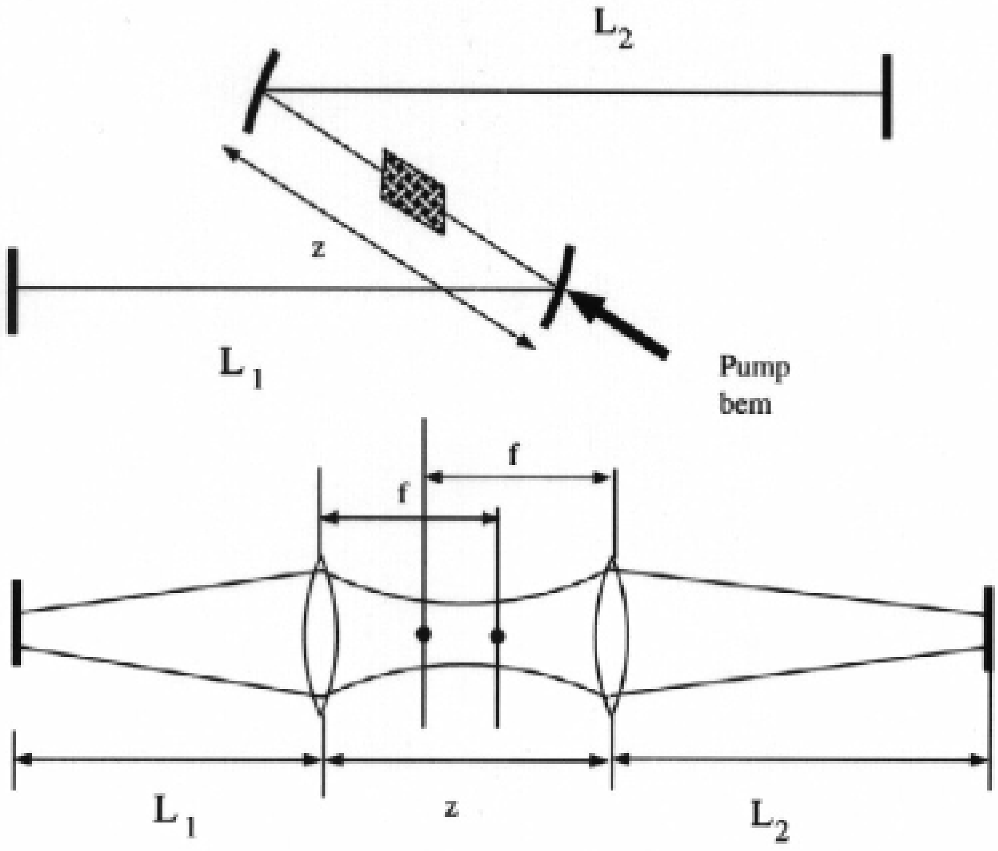


Figura 2: Typical resonator design used for Kerr lens mode locking, with the equivalent arrangement of the resonator.

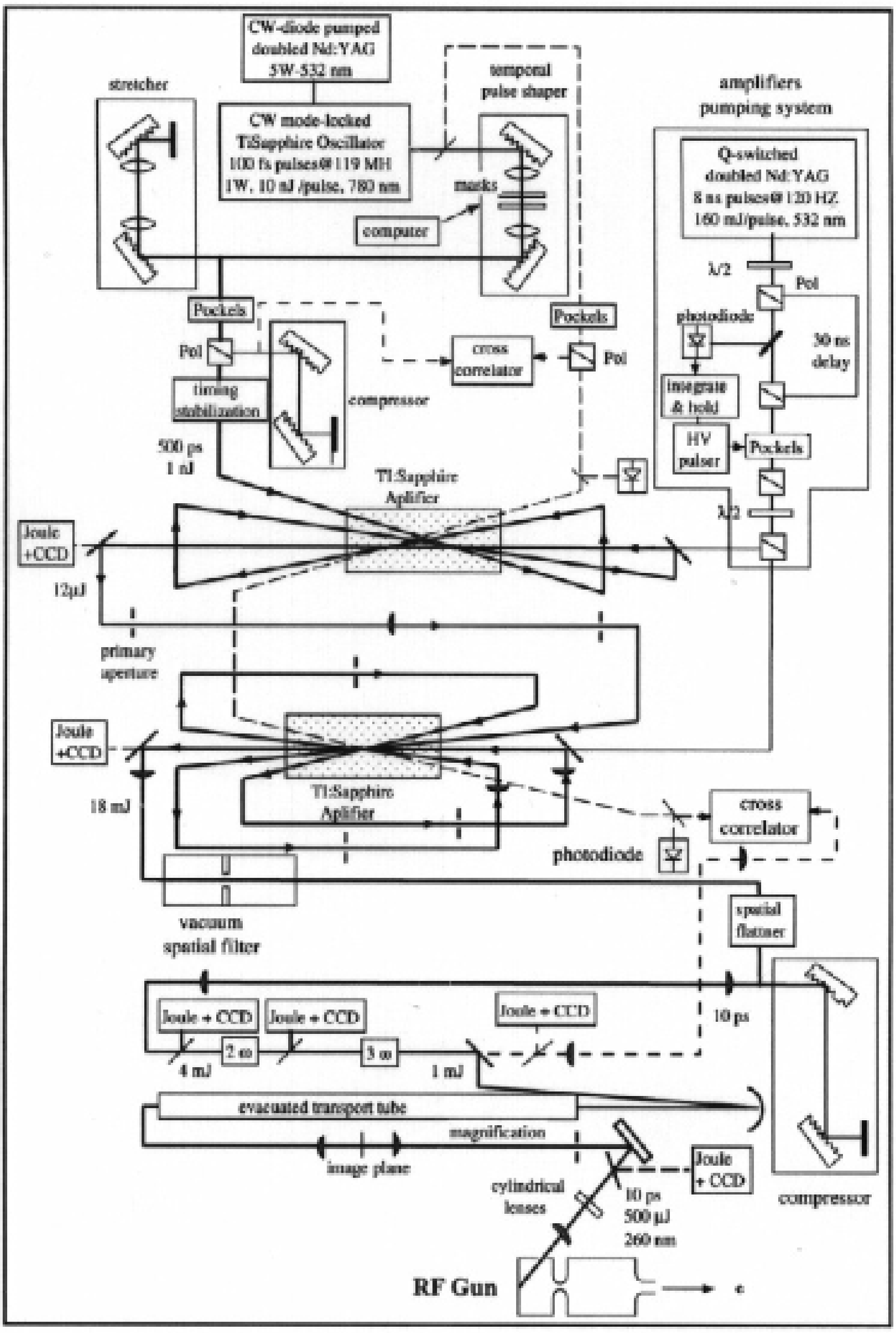


Figura 3: The drive laser for the RF photocathode electron gun of the LCLS. The thick lines show the main beam path, the dashed lines indicate diagnotist beams, the normal continuous line is the pump beam

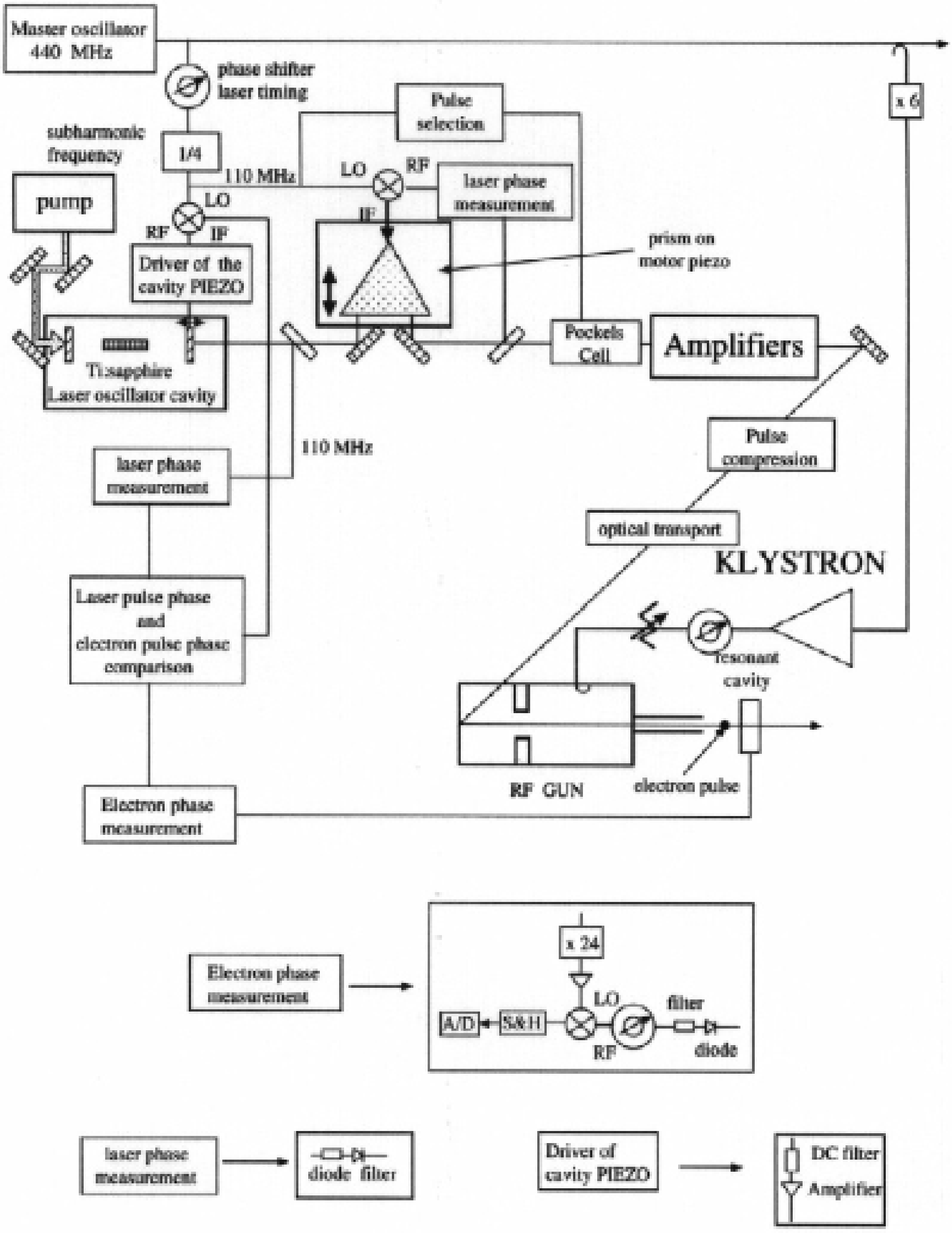
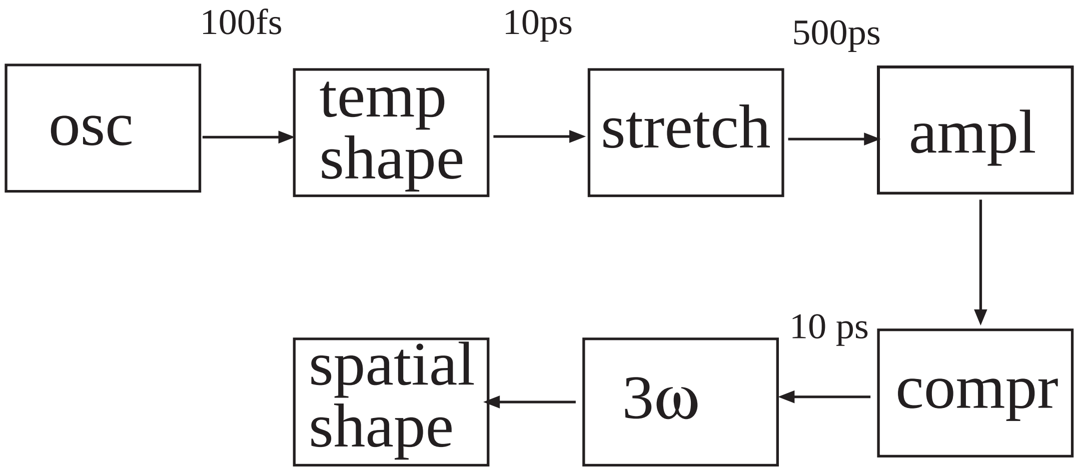


Figura 4: Timing stabilization schematic

Shaping temporale e spaziale

C.Vicario

Schema funzionale del laser



100fs

10ps

500ps

osc

temp shape

stretch

ampl

10 ps

compr

3ω

spatial shape

CPA (Chirped Pulse Amplification):

- Allungamento: dispersione velocita’ di gruppo
- Amplificazione
- Compressione: dispersione inversa della velocita’ di gruppo

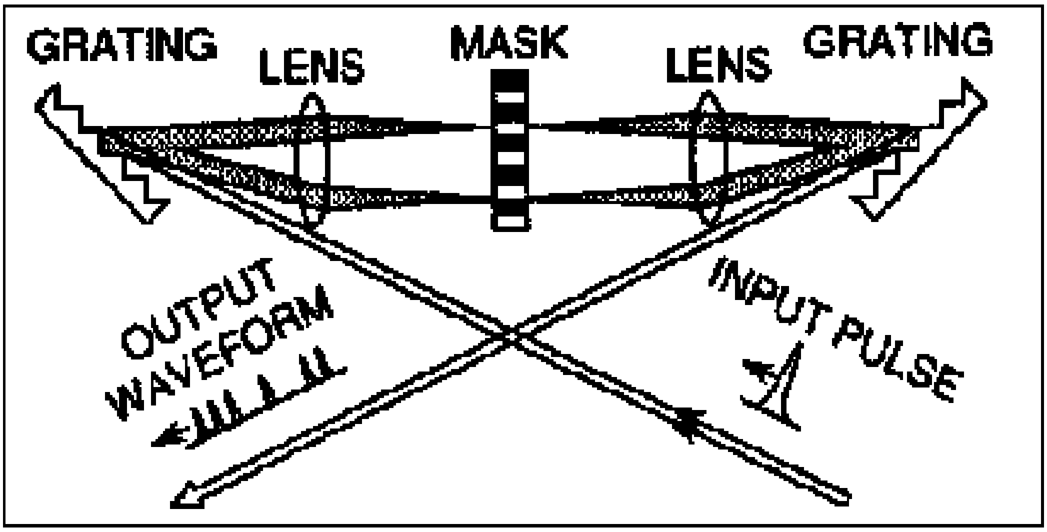
Temporal pulse shaping

Sistema non dispersivo con filtraggio spaziale delle frequenze

Maschera di fase e ampiezza per ottenere

$$E(f)=A\ \mathrm{sinc}(\pi f T)$$

Rise time ≤ durata impulso in ingresso



Posizionato prima dell’amplificatore

Soglia di danneggiamento

Perdite di inserzione 50-90%

! Distorsione negli elementi successivi

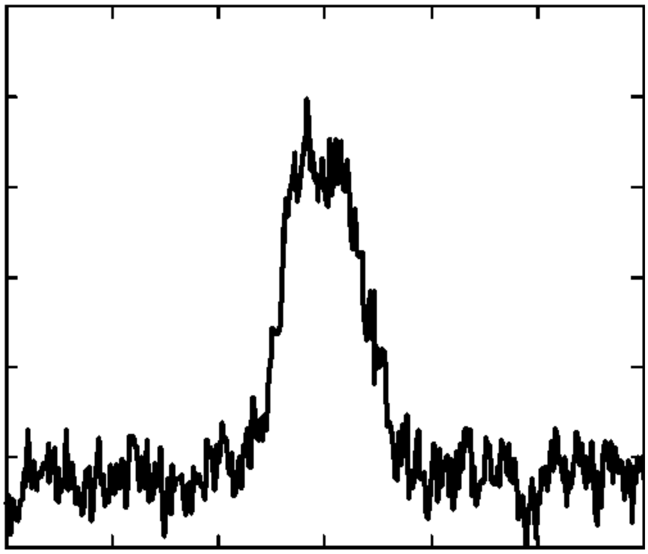
! Lo shaping riduce lo spettro del segnale

limitando la possibilita’ di stretching

Shaping con sola maschera di fase:

matrice a cristalli liquidi con pixel a indice di rifrazione controllato da tensione esterna.

Si e’ misurato, con risoluzione 1 ps, un impulso sagomato generato da un sistema Ti:Sa a 266 nm: :



<- 10 ps ->

Feedback dall’uscita e controllo automatico della maschera per ottimizzare la forma dell’impulso

Shaping spaziale

Filtro spaziale + attenuatore variabile

Perdite

Omogeneita’ attesa fino al 10% ptp per incidenza a 72° (LCLS)

Omogenizzatore tranfocale (ENEA)

Focalizza e collima su uno spot delle diverse porzioni di fascio con profilo arbitrario

Posizonabile fino a 1 m dal catodo

Omogeneita’ misurata 6% ptp