Technological challenges for high brightness photo-injectors

G. Suberlucq CERN

- High brightness
- Photo-injectors
- Photocathodes
- Lasers
- Guns
- Technological challenges: Top 10

High Brightness (1)

A high brightness means that the electron bunch has a high density in 6 phase space dimensions

High charge → Q — 1 nC → 100nC / pulse

Short pulse → τ_{FWHM} — 20 ps → 0.3 ps

$$\frac{Q}{\tau_{FWHM}}$$

High intensity — 100 A → 10 kA

$$B_n(A \cdot m^{-2} \cdot rad^{-2}) = \frac{2 \cdot I}{\sigma_{n(x)} \cdot \sigma_{n(y)}}$$

$10^{11} \rightarrow 10^{15}$ A.m^{-2}.rad^{-2}

Low emittances — 10^{-4} m.rad → 10^{-6} m.rad

High Brightness (2)

Some examples of source requirements

	I (A)	t_{FHHM} (ps)	e_n (mm.mrad)	B_n ($A.m^{-2}.rad^{-2}$)
Linear Collider	500	8	10	1.10^{13}
SASE-FEL	180	6	2	9.10^{13}
Energy recovery linac	50	3	1	10^{14}
Laser Wakefield Acc.	1000	0.2	3	2.10^{14}
Future Light Source ~ 2015 "GreenField" FEL (30 KeV)	500	< 1	0.1	10^{17}

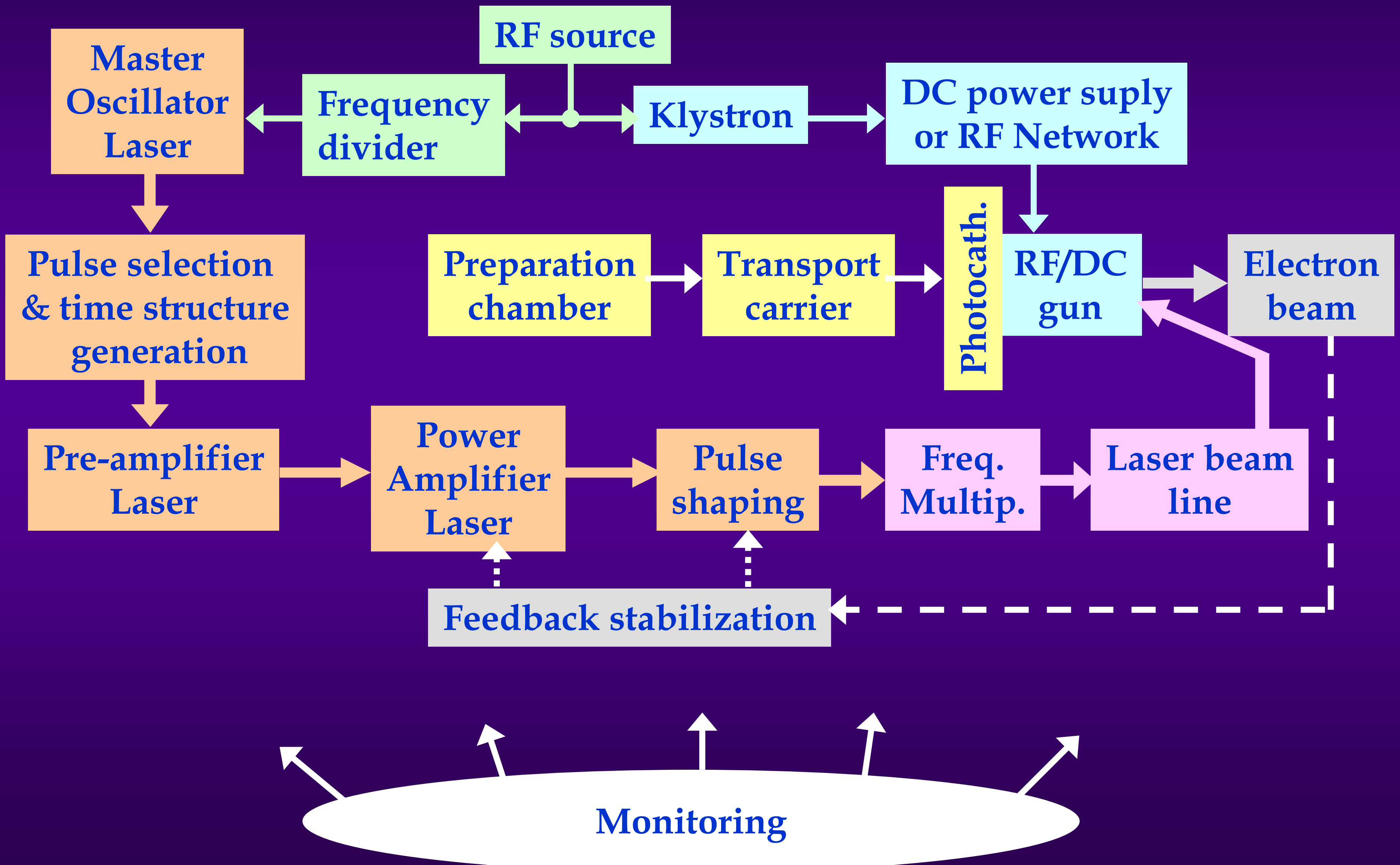
Photo-injector (1)

The photo-injector is a source, it must fulfill the specifications and it must be available and reliable

Typical expected behavior:

- Operation time : 2000 – 5000 h / year
- Availability > 95 %
- MTBF > 1000 h ; MTTR < 4 h
- 1 long annual shutdown (2 – 3 months)
- 2 or 3 short shutdowns / year (1 week)
- Total lifetime : ~ 10 years

Photo-injector (2)



Photocathodes

Three main sorts:

- Metallic photocathodes
- Activated Gallium-Arsenide photocathodes
- Alkali photocathodes
  - Cesium-iodide
  - Alkali-antimonide
  - Alkali-telluride

Weak part of photo-injectors

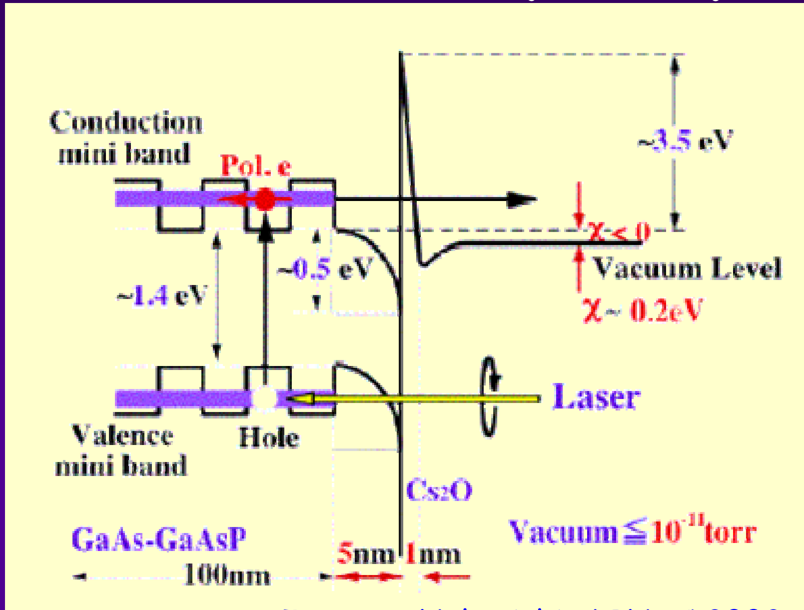
Metallic Photocathodes

- Require UV light and high laser power
- Special surface treatment for reasonable QE
- Well adapted for high electric field $\geq$ 100 MV/m
- Well adapted for "low" charge production, typically 1 to few nC per pulse and low mean current: few μA

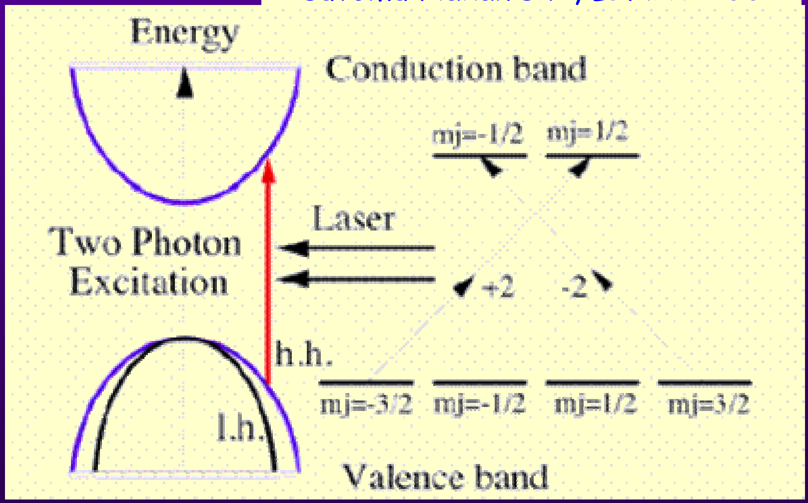
With QE ~ 10^{-3}, Mg seems to be the best metallic photocathode

Activated Ga-As photocathodes

Mandatory for polarized electron photo-injectors



Tsutomu Nakanishi , LINAC 2002



Requirements

- Strong cleaning by heating and/or with H^-
- NEA activation with $Cs+O_2$ or $Cs+NF_3$
- Very good vacuum < 10^{-11} mbar
- Low electric field < 5 MV/m
- NO breakdown
- Very low dark current

Best performances

- Polarization ~ 90 % ; QE ~ 0.5 % @ 780 nm
- Low thermal emittance ~ 25 meV)
- Shorter pulse length ~ 80 ps
- I_{max} ~ 8 A

Main limitations

- Surface Charge Limit (SCL)
- Lifetime
- Response time

Could be overcome with the two photon process

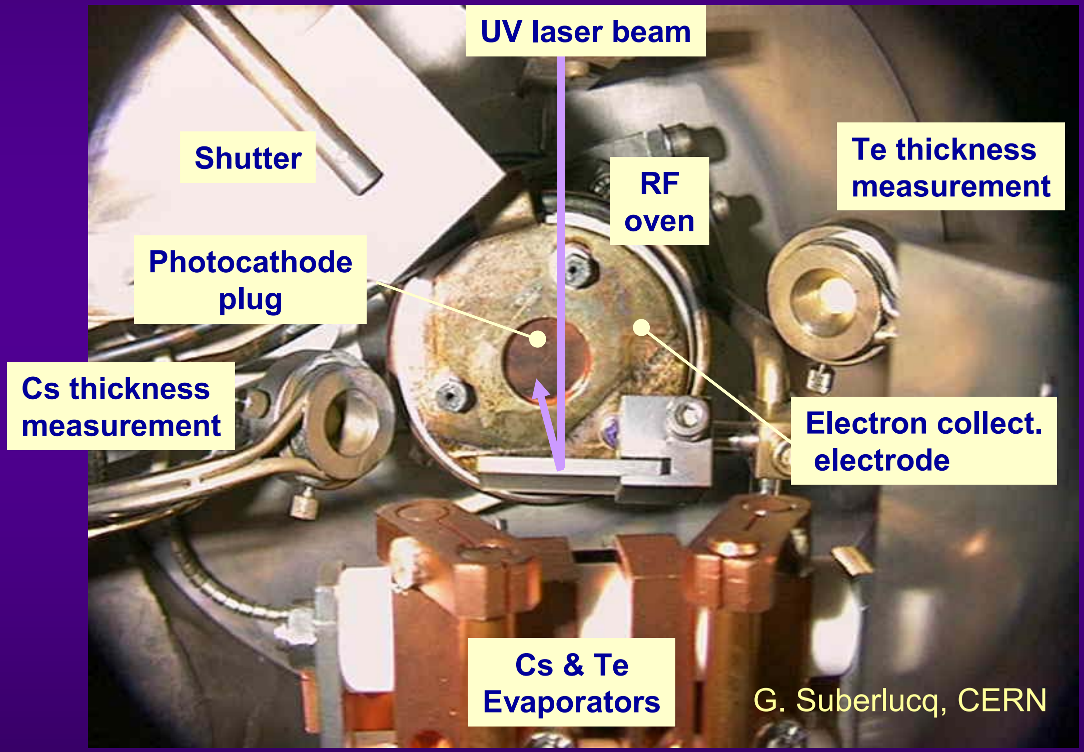
Alkali photocathodes

Photocathodes		λ (nm)	QE (%)	Lifetime	
Alkali iodide	CsI	< 200	20	years	Air transportable, Wavelength too short
	CsI+Ge	< 270	0.2	years	Air transportable, Delicate conditioning process
Alkali antimonide	K_2CsSb $Na_2K(Cs)Sb$	< 600	10	Days-hours	Lifetime too short, UHV required
Alkali telluride	Cs_2Te, RbCsTe	< 270	15	Months-weeks	Good lifetime and QE, UHV and UV light required

For the time being, Cs-Te photocathodes are the most used for high current and high charge production in operational photo-injectors

Improvement of alkali cathode preparation

Co-evaporation process

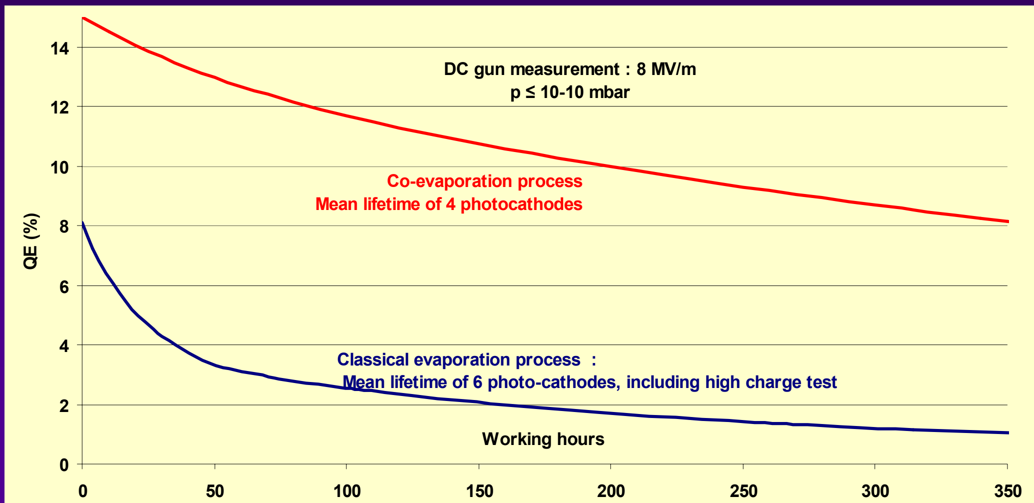


20 cath.	QE(%)	Cs/Te
Min	8.2	4
Average	14.9	5.1 (6.6 exp.)
Max	22.5	7.2

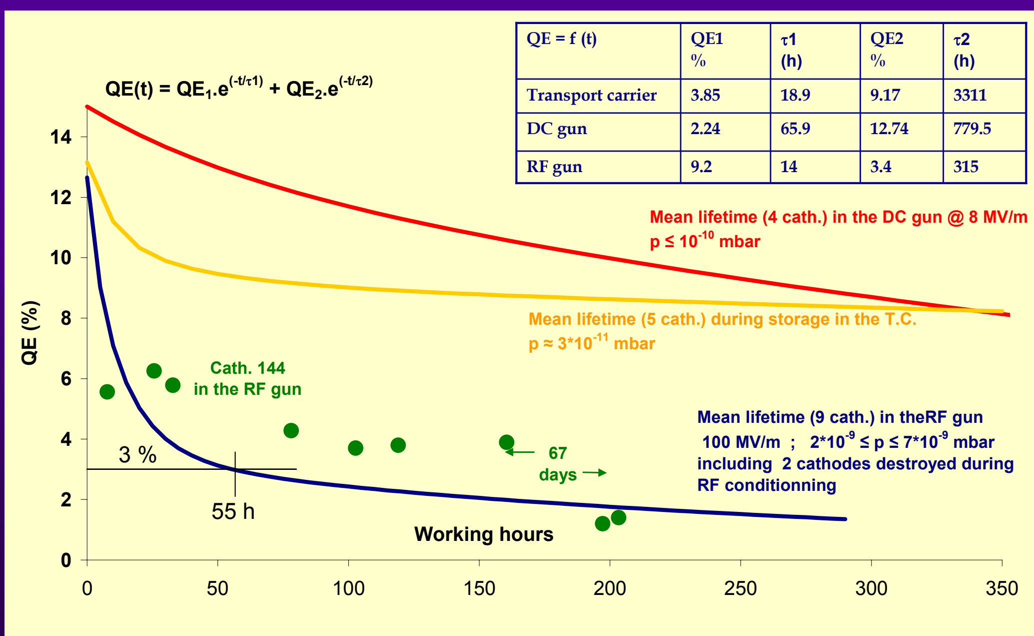
Difficult thickness measurements and poor reproducibility

Study supported by E.U. inside CARE - JRA - PHIN

Lifetime of Cs-Te photocath.



CERN measurements

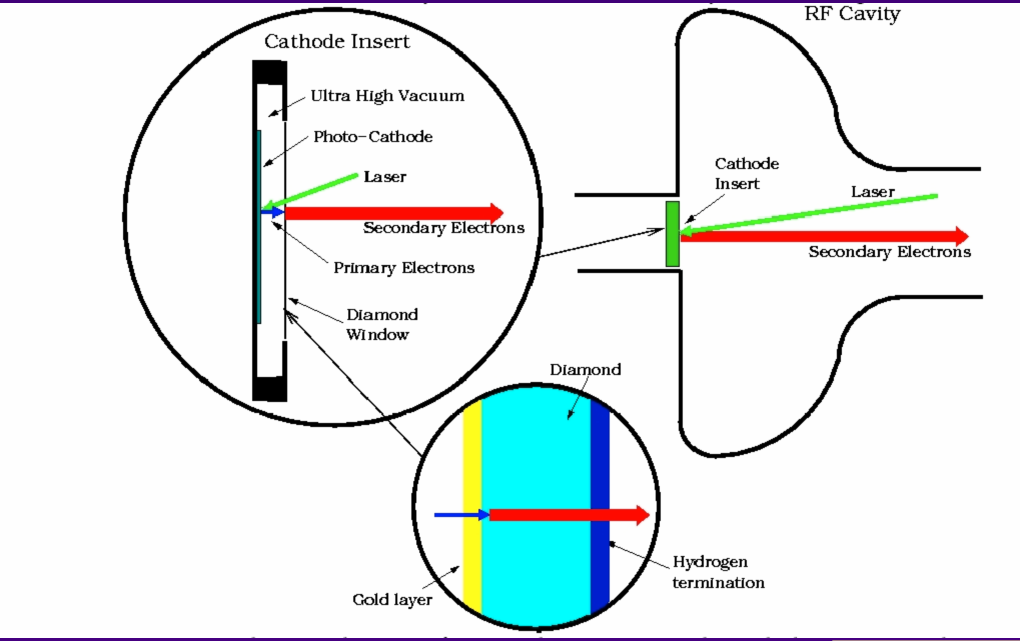


QE = f (t)	QE1 %	τ1 (h)	QE2 %	τ2 (h)
Transport carrier	3.85	18.9	9.17	3311
DC gun	2.24	65.9	12.74	779.5
RF gun	9.2	14	3.4	315

- Dramatic improvement of QE and lifetime of photocathodes produced by the co-evaporation process
- But photocathodes produced by co-evaporation seem to be more sensitive to the vacuum quality

Secondary Emission Enhanced photo-emitter

Proposal from I. Ben-Zvi et al. C-A/AP#149, April 2004, BNL



- The diamond window is transparent to photons and electrons
- Electrons are produced by a laser beam shooting an alkaline cathode
- Electrons are multiplied by secondary emission by the diamond window

- Cathode insert consist of :
- Alkali antimonide cathode
- A sealed diamond window (~10 μm thick)
- UHV in between

Expected advantages

- *Very high equivalent QE ~ 1000 % !*
- Low laser power
- Low thermal emittance (NEA surface)
- No mutual contamination between the gun and the photocathode
- Possible high mean current
- No load-lock system

Lasers

Master Oscillator Power Amplifier setup to allow ps synchronization

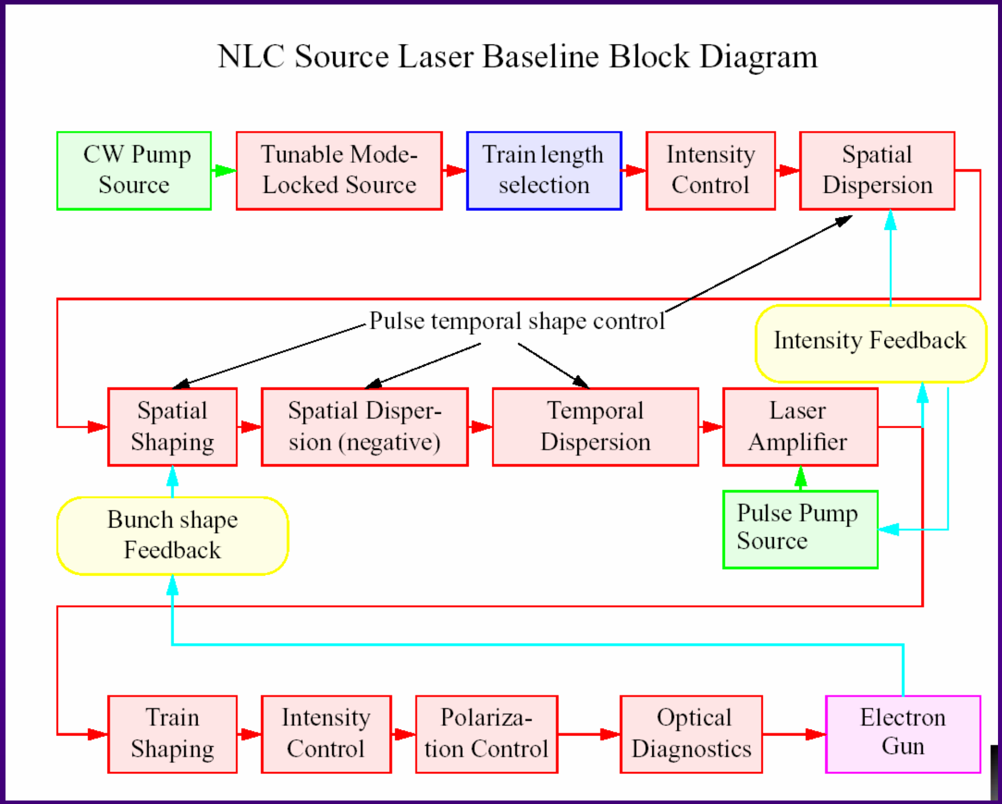
STRONG progress in optical pumping and in lasing medium

- Laser diode pumped solid state (LDPSS) lasers
- Nd:Vanadate lasers are replacing Nd:YAG lasers
- Thanks to InGaAs laser diodes emitting in the 900-980 nm, Ytterbium (Yb^{3+}) is the most promising doping material.
- Many new crystals : apatite (S-FAP, CLYPA, SYS, …), tungstate (KYW, KGW), sesquioxyde (Sc_2O_3, …) Yb^{3+} doped
- High power oscillator > 60 W
- Fiber laser (not yet actively mode-locked)
- High frequency mode-locked oscillator : 1.5 GHz commercially available
- Transversal and Longitudinal pulse shaping.

SMALL progress in frequency conversion

- 50-55 % IR to VIS ; 25-30 % VIS to UV

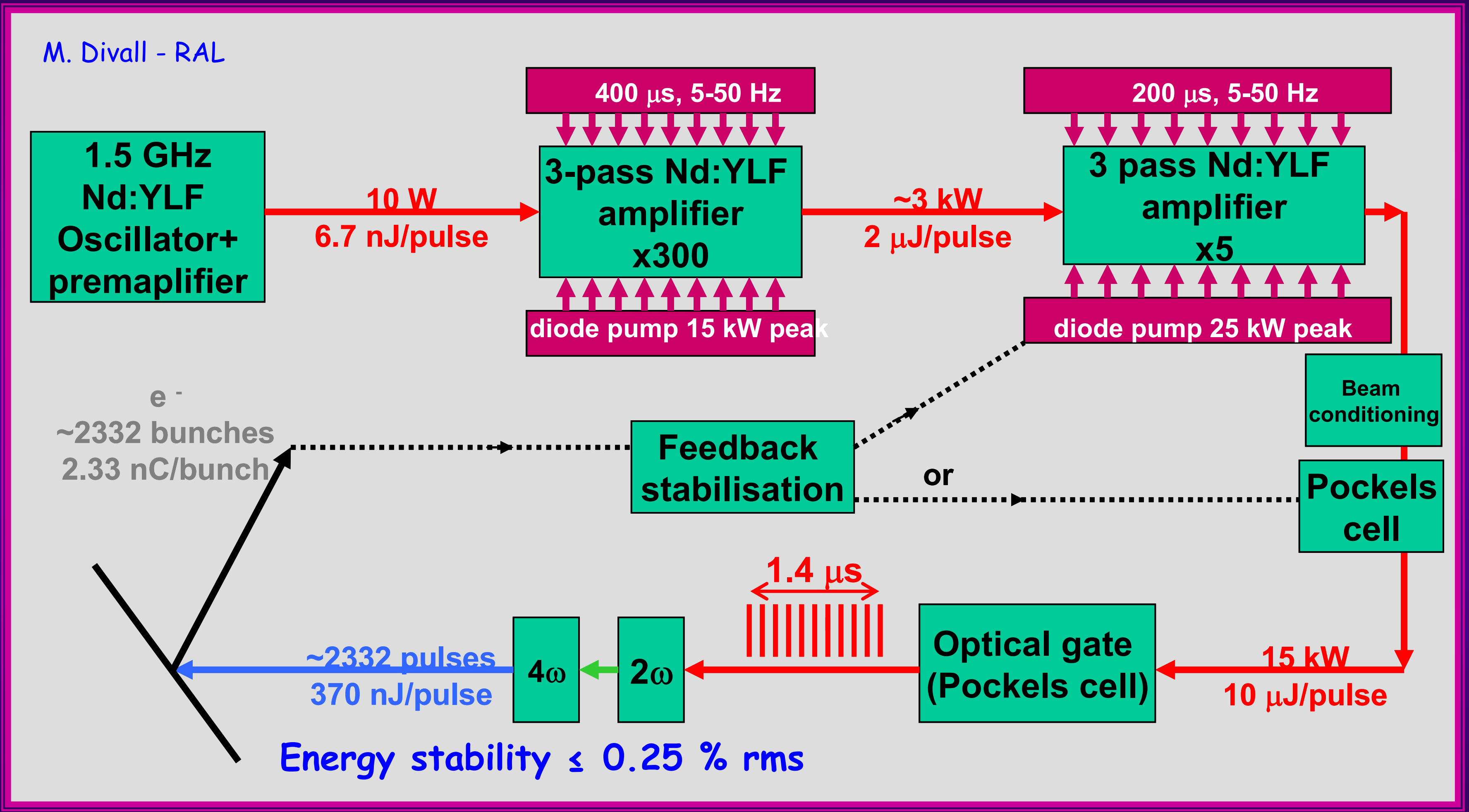
NLC Laser set-up proposal



http://www-project.slac.stanford.edu/lc/local/systems/Lasers/CombinedLaserSystem/laserr_d.pdf

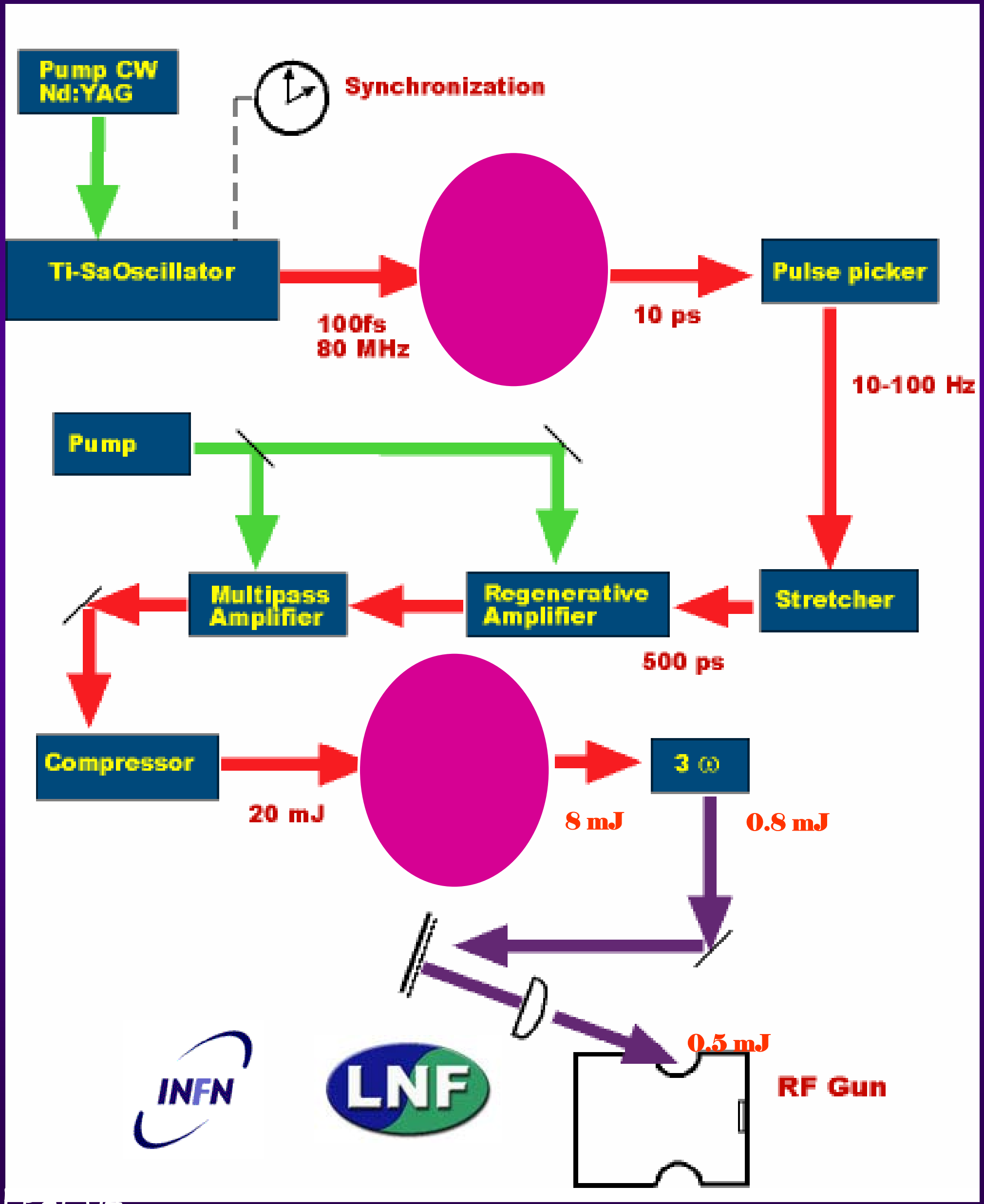
- Pulses per train 1 - 200 adjustable
- Pulse rate 357MHz or 714MHz
- **Pulse length 200psec to 700psec adjustable**
- **Pulse temporal shape Square, or adjustable with 100psec bandwidth**
- Train temporal shape Adjustable: 30 nanosecond time constant
- Wavelength range 750 to 870nm (with optics change)
- Wavelength tuning range +/- 5nm remote tuning
- Bandwidth <1 nanometer
- Pulse energy 5 - 30 micro Joules to photocathode maximum.
- Transverse profile TEM00
- Intensity Stability 0.5% RMS
- Position stability <1% spot radius RMS
- Wavelength stability 0.1 nanometers
- Bunch timing stability <10 picoseconds RMS
- **System MTBF >1000 Hours (Single laser)**
- **System MTTR <4 Hours (Single laser)**
- **System lifetime >50,000 Hours**

CERN - CTF3 Laser proposal



Design and construction supported by E.U. inside CARE – JRA - PHIN

SPARC Laser proposal



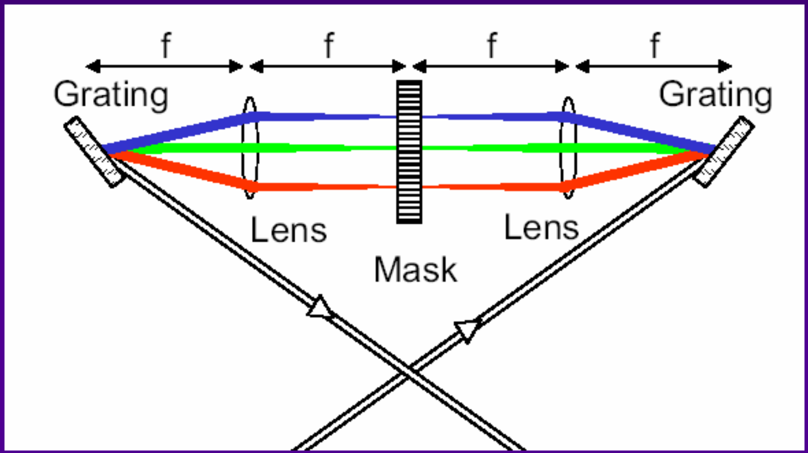
Operating wavelength	260-280 nm
Repetition rate	10-100 Hz
Number of micropulse per pulse	1
Pulse energy on cathode	500μJ (Q.E.=10^{-5})
Pulse rise time (10-90%)	< 1 ps
Pulse length	2-10 ps FWHM
Temporal pulse shape	Uniform (10% ptp)
Transverse pulse shape	Uniform (10% ptp)
Energy jitter (in UV)	1 % rms
Laser-RF jitter	< 1ps rms
Spot diameter on cathode	Circular 1 mm
Spot diameter jitter	1% rms
Pointing Stability	1% diameter rms

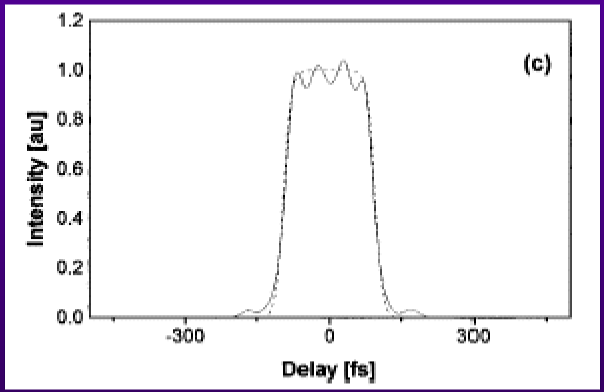
SPARC Laser group
C. Vicario, A. Ghigo,
F. Tazzioli, I. Boscolo,
S. Cialdi

Temporal pulse shaping

Liquid crystal spatial light phase modulator in Fourier plane

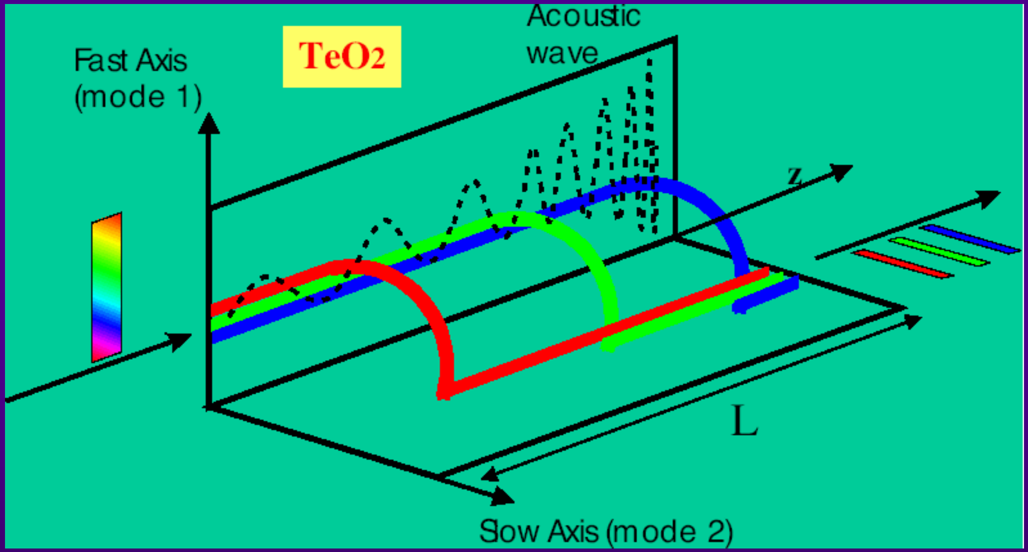
From L Serafini - INFN
2nd ORION Workshop - SLAC - Feb. 19th, 2003





D. Meshulach, D. Yelin, Y. Silberberge
J. Opt. Soc. Am., B 15 (1998) 1615

Collinear Acousto-Optic modulator (AOM)



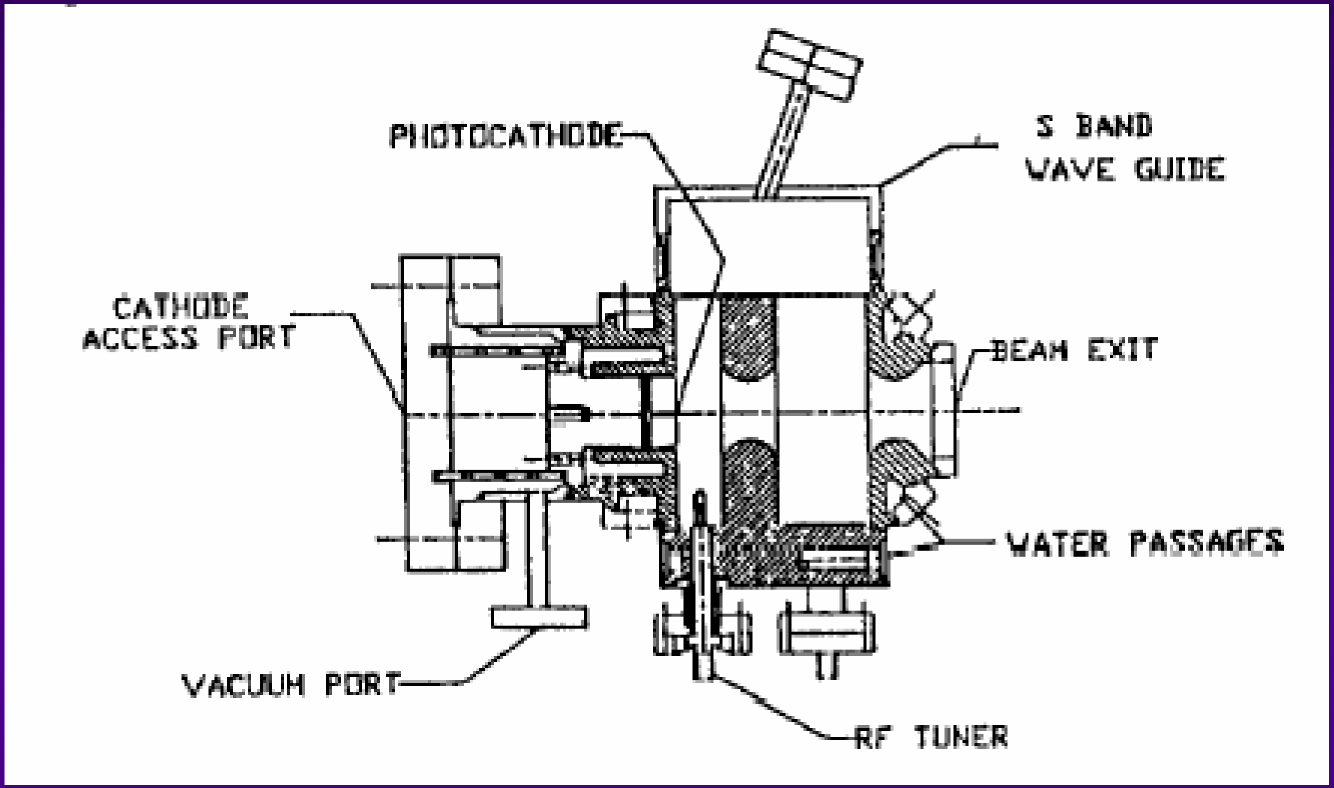
F. Verluise *et* al. Arbitrary dispersion control of ultrashort optical pulses with acoustic waves,
J. Opt. Soc. Am. B/Vol. 17, No 1/January 2000

Study supported by E.U. inside CARE – JRA - PHIN

Guns

Unpolarized e^-	high intensity, high electric field	→	RF gun
	High mean current	→	SRF gun
	Very good vacuum, low electric field	→	DC gun
	Medium I, medium electric field	→	PWT Under dev.
	Very high electric field (GV/m)	→	Pulsed DC gun Under dev.
Polarized e^-	Low electric field	→	DC gun
	Medium I, medium electric field	→	PWT Under dev.

RF guns : 1.5 cells BNL-type



1 + ½ cells , f = 2.856 GHz , Cavity Q = 11800 , $E_{cath.}$ = 100 MV/m , Beam energy = 4.85 MeV

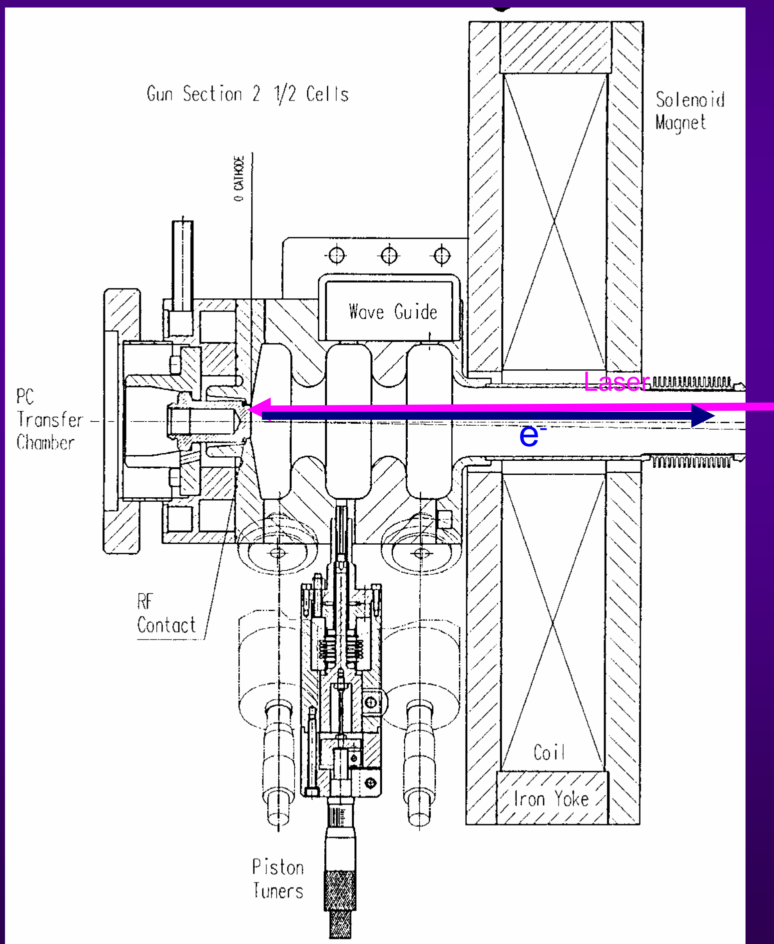
1 pulse , charge = 1 nC , Laser pulse width : σ = 2 psec.

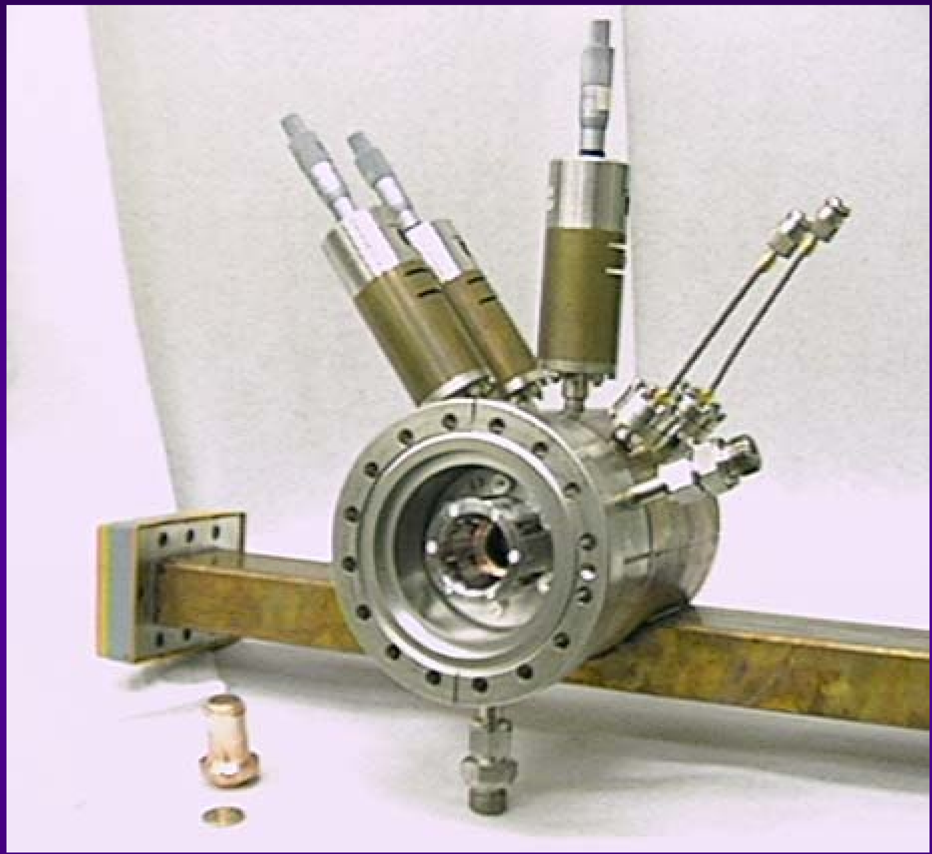
Emittance at the cathode : e_x = 3.5 mm.mrad , Emittance at exit : e_x = 7.3 mm.mrad

K. Batchelor et al. *Operational Status of the Brookhaven National Laboratory Accelerator Test Facility,* Proceedings of the 1989 IEEE PAC Conference,

CTF2 drive beam RF gun

RF gun optimized for high charge and high stored energy to minimize transient beam loading. Successfully operated since 1996 until 2002

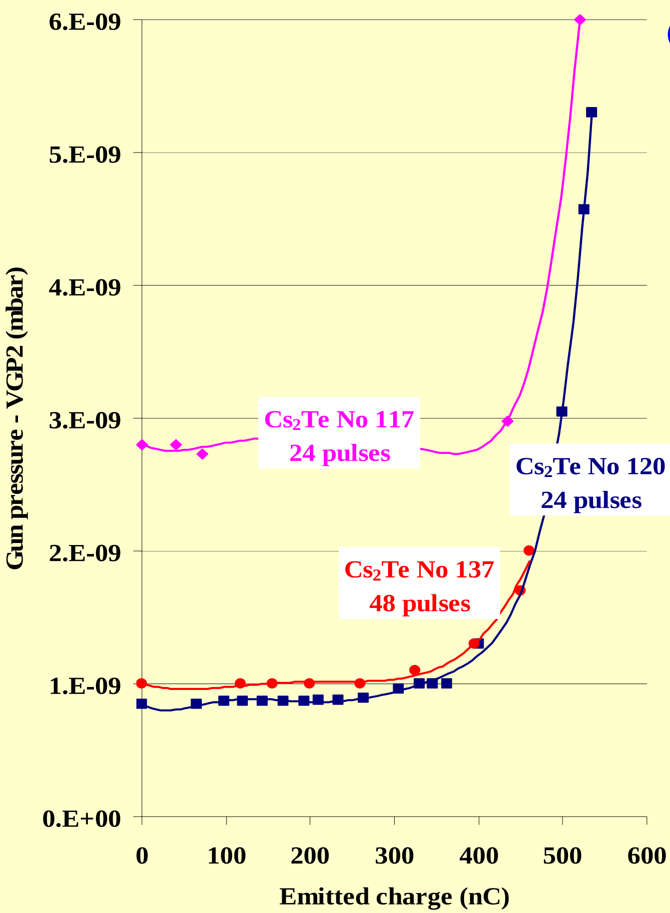




- 100-110 MV/m operational field at the cathode
- 16 MW input power at 100 MV/m
- Beam energy 7 MeV at 100 MV/m
- Maximum produced charge : 750 nC in 48 pulses
- Pulse width 10 ps FWHM
- Maximum single pulse charge : 100 nC
- Used photocathodes : Cs_2Te, Rb_2Te, Mg, Cu, Al

RF gun desorption

- Gun desorption is a potentially serious problem for high charge production
- Special attention must be paid to the pumping speed
- Low desorption material must be used



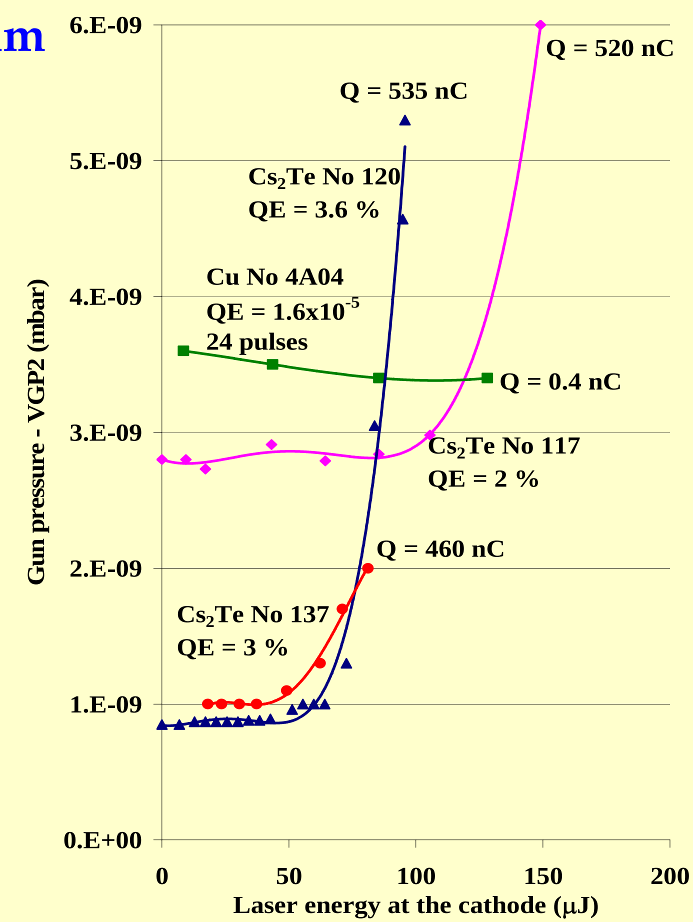
CTF2 Drive beam RF gun

f = 3 GHz

E = 105 MV/m

Δt = 333 ps

Rep. = 5 Hz



Superconducting RF gun (1)

T. Srinivasan-Rao et al. PAC 2003
Q. Zaho et al. PAC 2003

Superconducting RF gun under Development at BNL

½ cell Nionium cavity , 1.3 GHz

E_{max} = 45 MV/m

Niobium cath. QE ~ 5.10^{-5} at 262 nm with laser cleaning.

For high mean current, the requested laser power is too large :

P_L = 95 W / mA

J. Teichert et al. , SRF 2003, Lübeck

Superconducting RF gun at Rossendorf

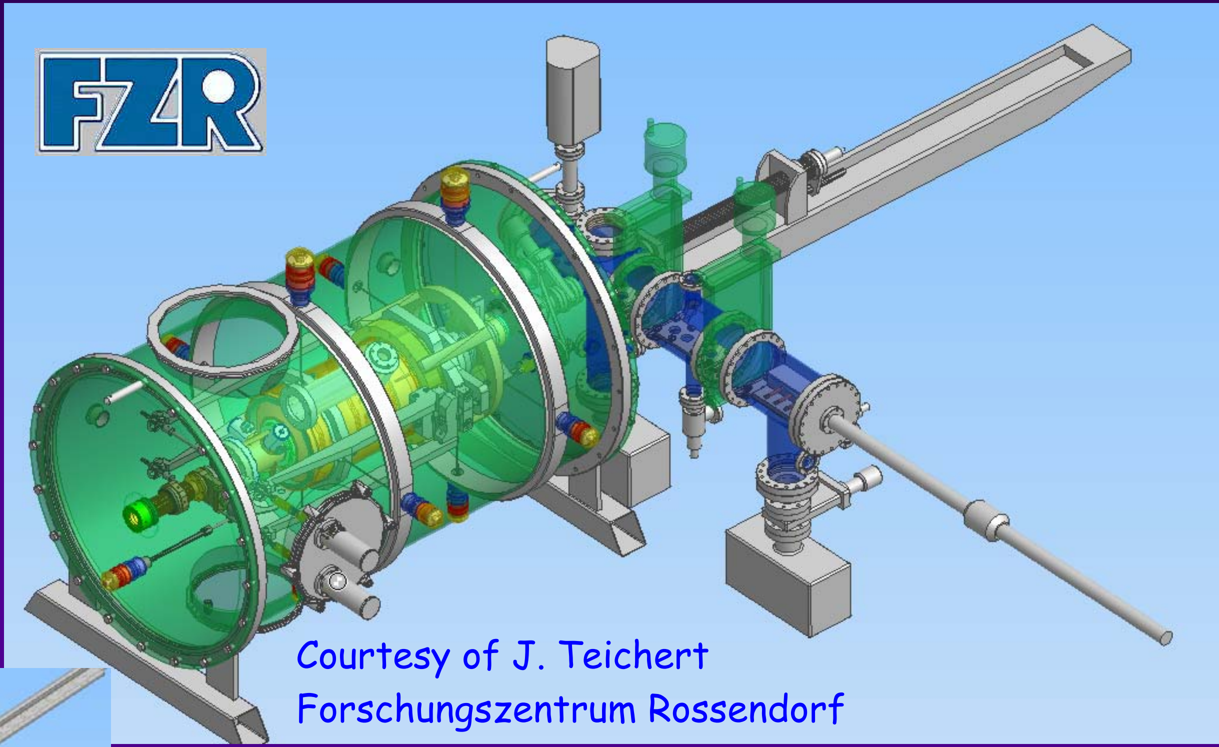
½ cell Nionium cavity , 1.3 GHz

Tesla geometry

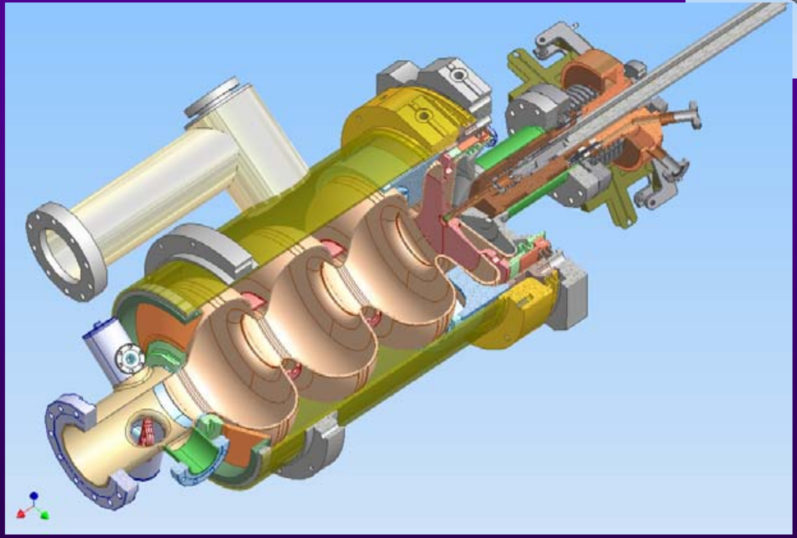
Normal-conducting Cs_2Te photocath. at LN_2 temperature and thermally insulated. Illuminated with 1 W laser at 262 nm

Superconducting RF gun (2)

1. 3 GHz, 10 kW optimized half cell & 3 TESLA $E_{z,max}$= 50 MV/m (T cells) = 33 MV/m (1/2 cell)	
77 pC	1 nC
I_{av}= 1 mA	
E = 9.5 MeV	
0.5 mm mrad	2.5 mm mrad



Courtesy of J. Teichert
Forschungszentrum Rossendorf



- Project under study
- $3\frac{1}{2}$-cell niobium cavity
- Will be operated at 2 K
- Cs_2Te cath. @ LN_2 temp. thermally insulated
- Expected QE ~ 5 %

Study supported by E.U. inside CARE – JRA - PHIN

DC guns

Advantages

- Very good vacuum : 10^{-12} mbar range
- Very low dark current : ~ 2 pA/cm^2 @ 30 MV/m
- High mean current

Disadvantages

- Limited current density : $J = \text{perv.}U^{1.5} \sim 200$ A/cm^2
- Limited electric field : $E \leq 30$ MV/m
- Limited potential : $U \leq 500$ kV

For the present time mandatory for GaAs photocathode applications

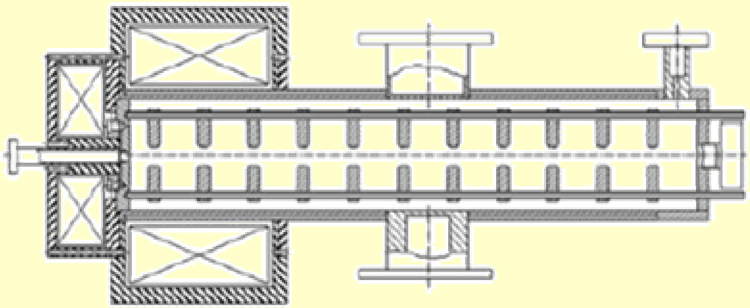
Other guns

Plane Wave Transformer RF gun

Large vacuum conductance and moderate electric field

THE UCLA PEGASUS PWT S-band gun

60 cm total length Tank diam. : 12 cm
11 cells Disk diam. : 4.2 cm

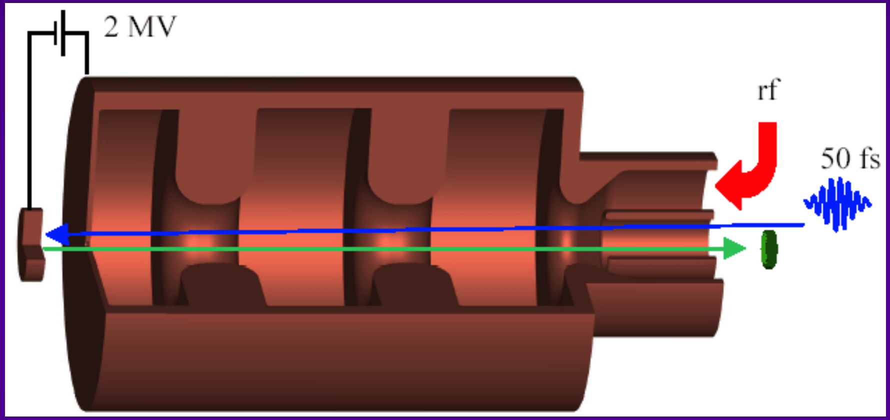


E_{peak} : 60 MV/m
Energy : 12 – 18 MeV
$Emittance_N$: 4 mm.mrad (rms)
Charge : 1 nC ; Bunch length : 1 – 10 ps

G. Travish *et al.* PAC 2003

Pulsed DC + RF gun

Alpha-X project DC/RF photo-injector
Strathclyde university and Eindhoven University of Technology



U_{DC} = 2 MV ; 1 ns
$E_{peak\text{-}DC}$: 1 GV/m ; Gap : 2 mm
S-band RF gun ; 100 MV/m
Output Energy : 10 MeV
$Emittance_N$: 1.π.mm.mrad
Charge : 100 pC
Bunch length : 50 - 200 fs
Peak current : 1 kA

M.J. de Loos *et al.* EPAC 2002
http://phys.strath.ac.uk/alpha-x/index.html

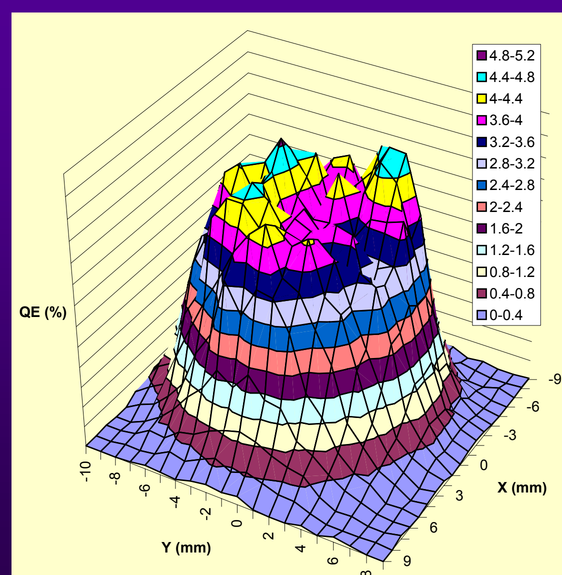
Cs-Te Layer behavior

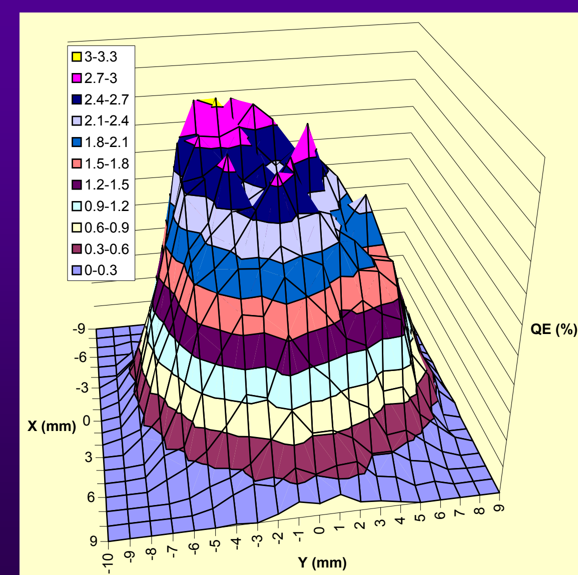
Fresh photocathode before use

Photocathode after 170 working hours in the DC gun @ 8 MV/m and 7nC/pulse
8 ns, 10 Hz, P ≤ 5×10^{-10}mbar
QE_{start} = 16.4 % ; QE_{end} = 4.2 %

Photocathode after 148 working hours in the RF gun @ 105 MV/m, 180 nC in 24 pulses , 10 ps FWHM
Rep. rate = 5 Hz , P ~ 2×10^{-9}mbar
QE_{start} = 11.4 % ; QE_{end} = 2.2 %

Cu photocathode destroyed at 85 MV/m during conditioning process





Technological challenges: top 10

(very subjective selection …)

- **Photocathodes :**
  - Secondary Emission Enhanced photo-emitter;
  - Polarized electron production with bulk GaAs photocathodes;
  - Co-evaporation process for alkali cathode production.
- **Lasers :**
  - High efficiency frequency conversion crystals ;
  - Mode-locked high power GHz oscillators;
  - Pulse shaping (longitudinal and transversal).
- **Guns :**
  - Very high voltage DC gun (DC/RF photo-injector);
  - High charge production without RF gun desorption;
  - SRF gun with high QE photocathode.
  - PWT gun with pressure $< 10^{-11}$ mbar