Photo-injectors

- Overview of a photo-injector
- Photocathodes
- Lasers
- Guns
- CTF3 Drive beam photo-injector
- CLEX Probe beam photo-injector
- Photocathode developments

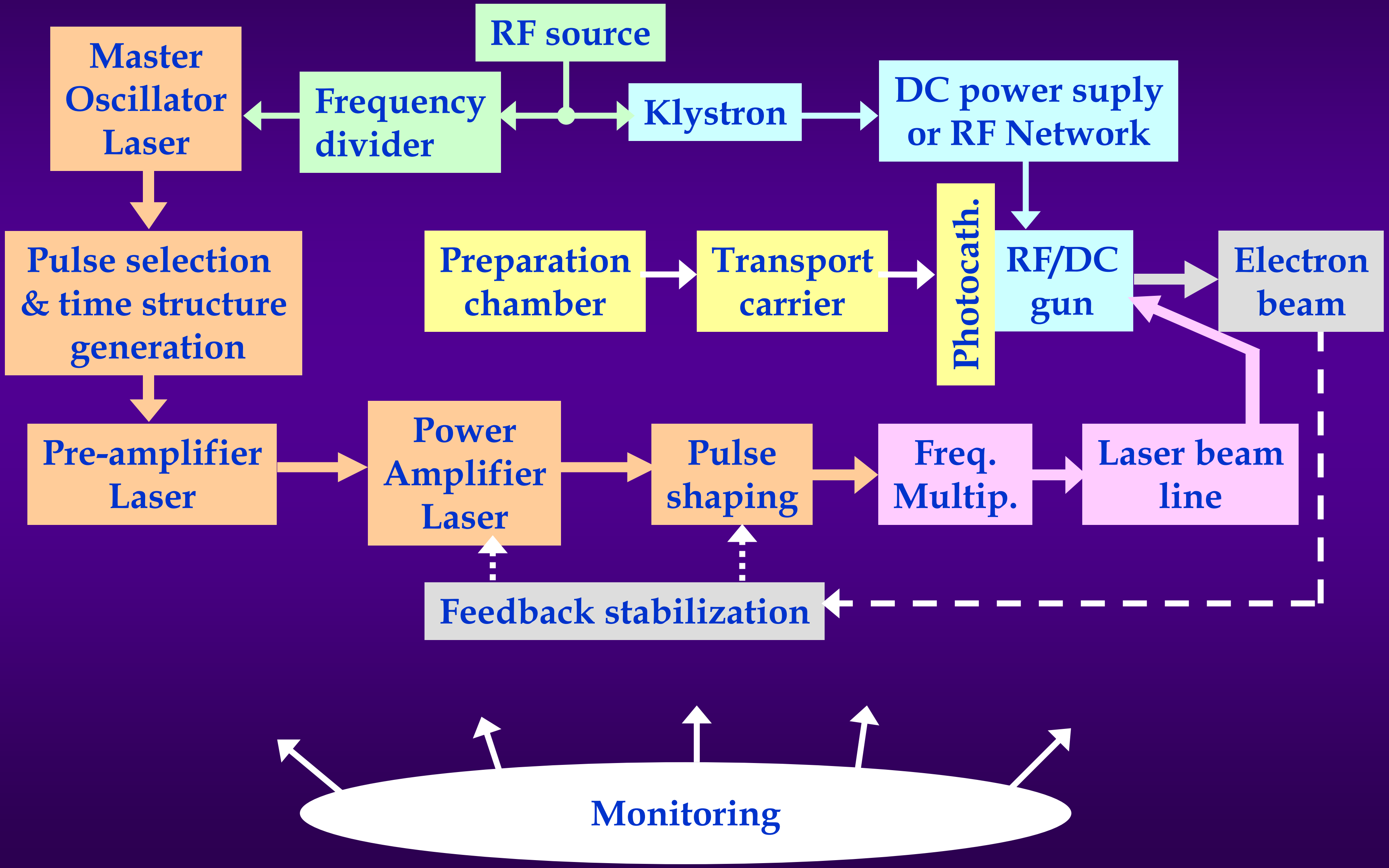
Photo-injector (1)

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)



G. Suberlucq

Photocathodes

Three main sorts:

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

Weak part of photo-injectors

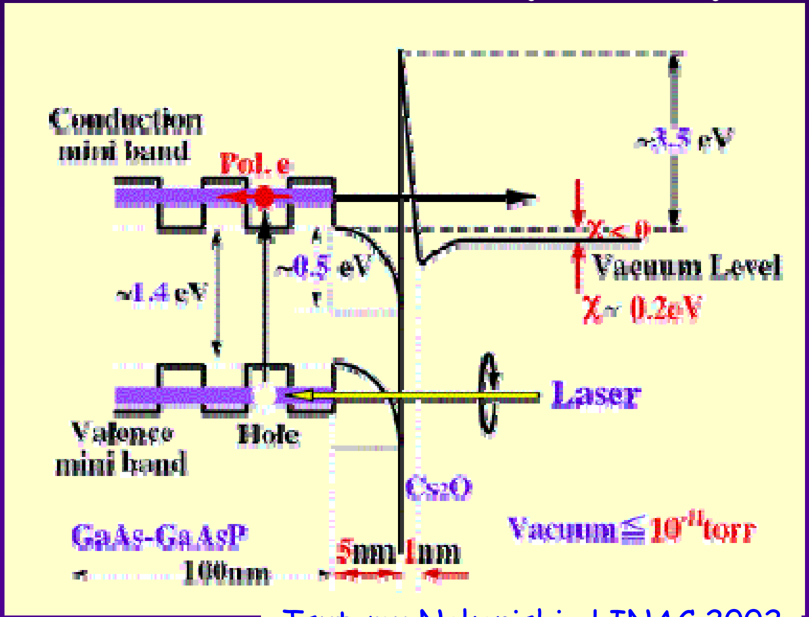
Metallic Photocathodes

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

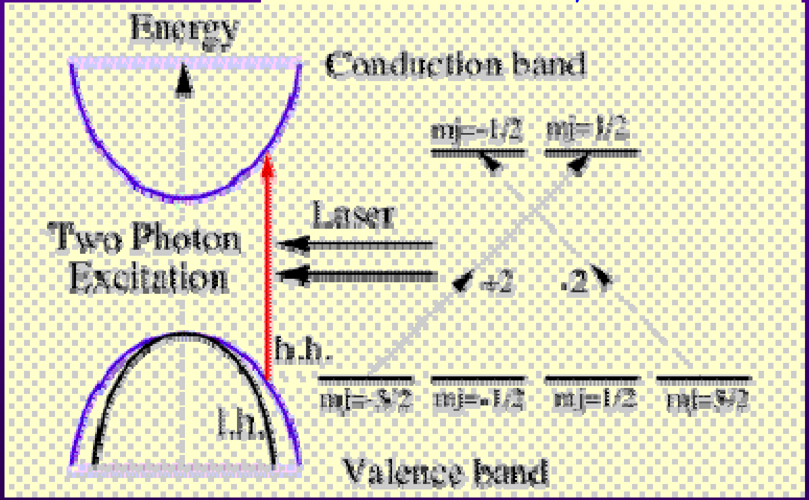
With QE ~ 10^{-3}, Mg seems to be the best metallic photocathode

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 output energy ~ 25 meV
- Shorter pulse length ~ 80 ps
- I_{max} ~ 8 A

Main limitations

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

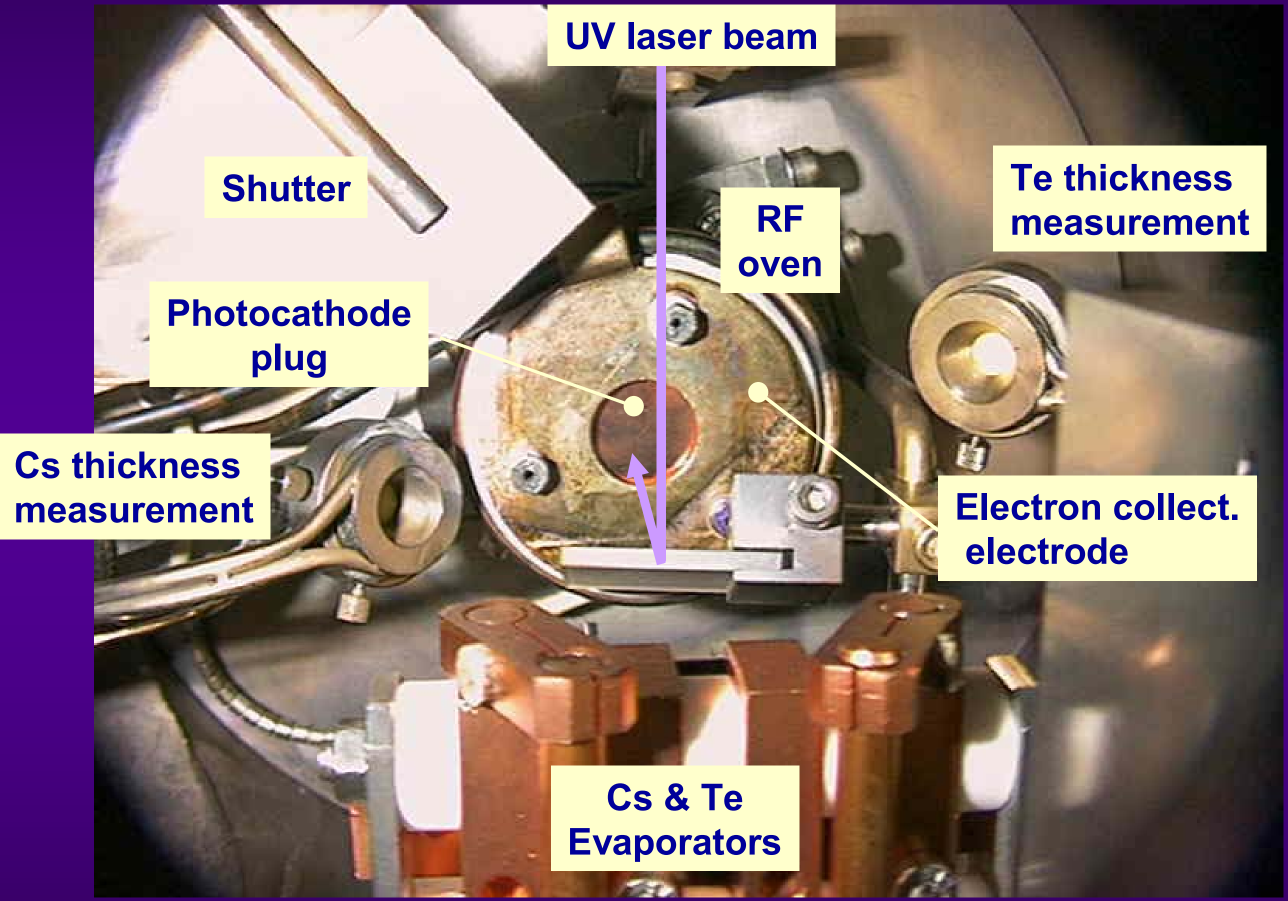
Could be overcome with the two photon process

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

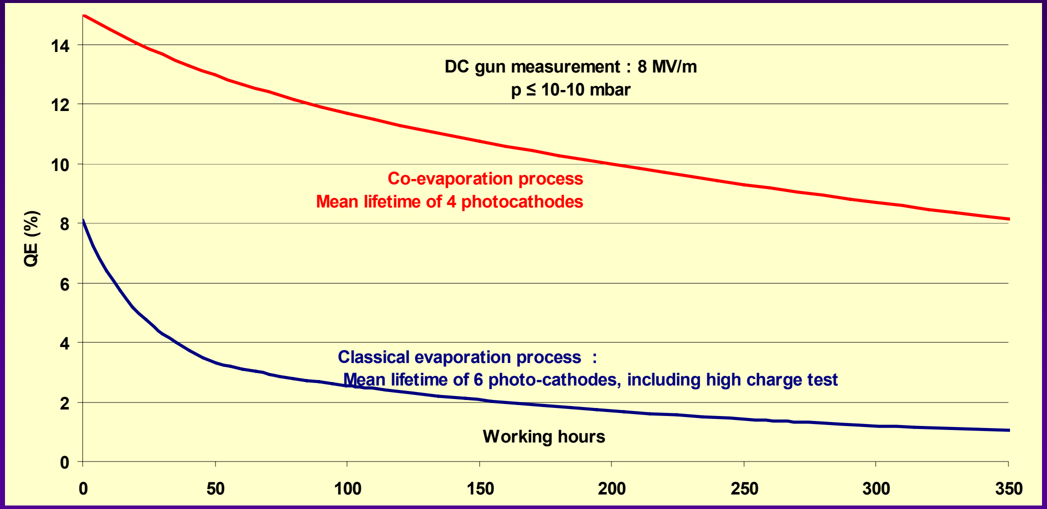
Improvement of alkali cathode preparation : Co-evaporation process



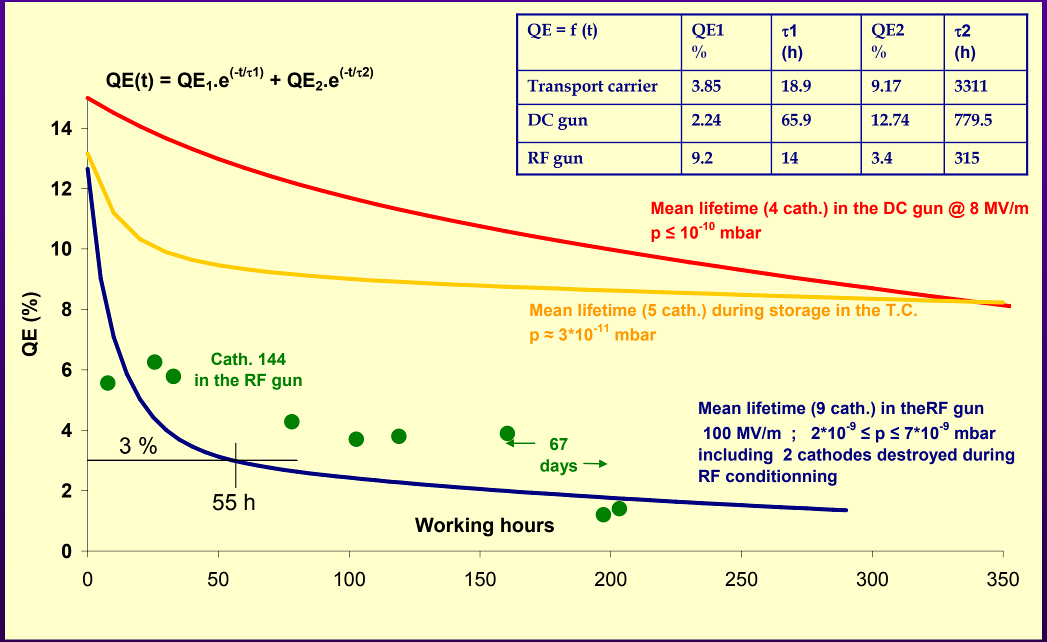
20 cath.	QE(%)
Min	8.2
Average	14.9
Max	22.5

Difficult thickness measurements and poor reproducibility

Lifetime of Cs-Te photocath.



CERN measurements



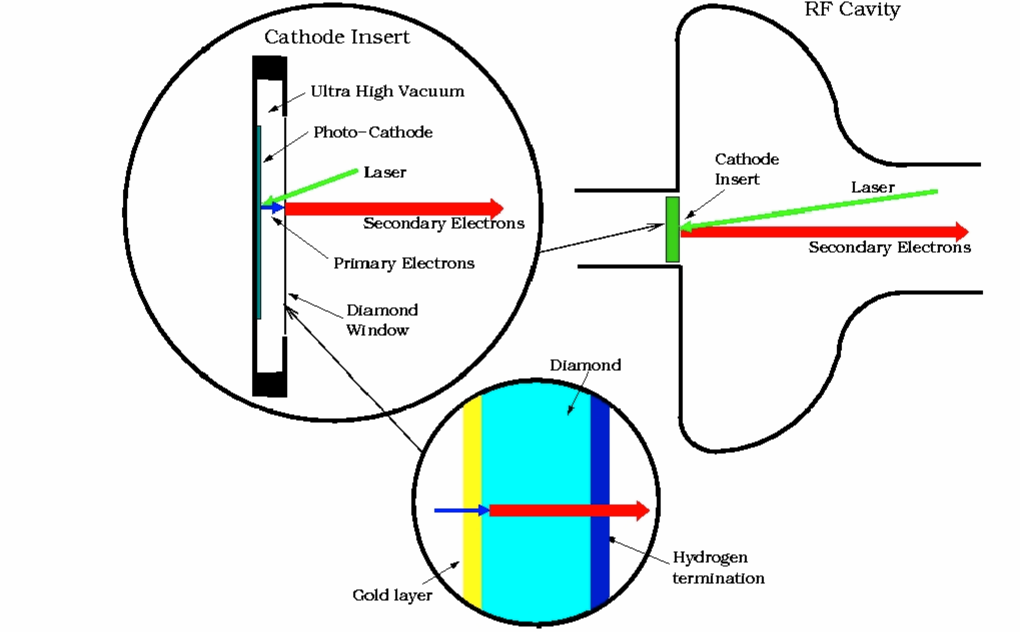
QE = f (t)	QE1 %	τ1 (h)	QE2 %	τ2 (h)
Transport carrier	3.85	18.9	9.17	3311
DC gun	2.24	65.9	12.74	779.5
RF gun	9.2	14	3.4	315

- 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

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

Cathode insert consist of :

- Alkali antimonide cathode
- A sealed diamond window (~10 μm thick)
- UHV in between

Lasers

Master Oscillator Power Amplifier setup to allow ps synchronization

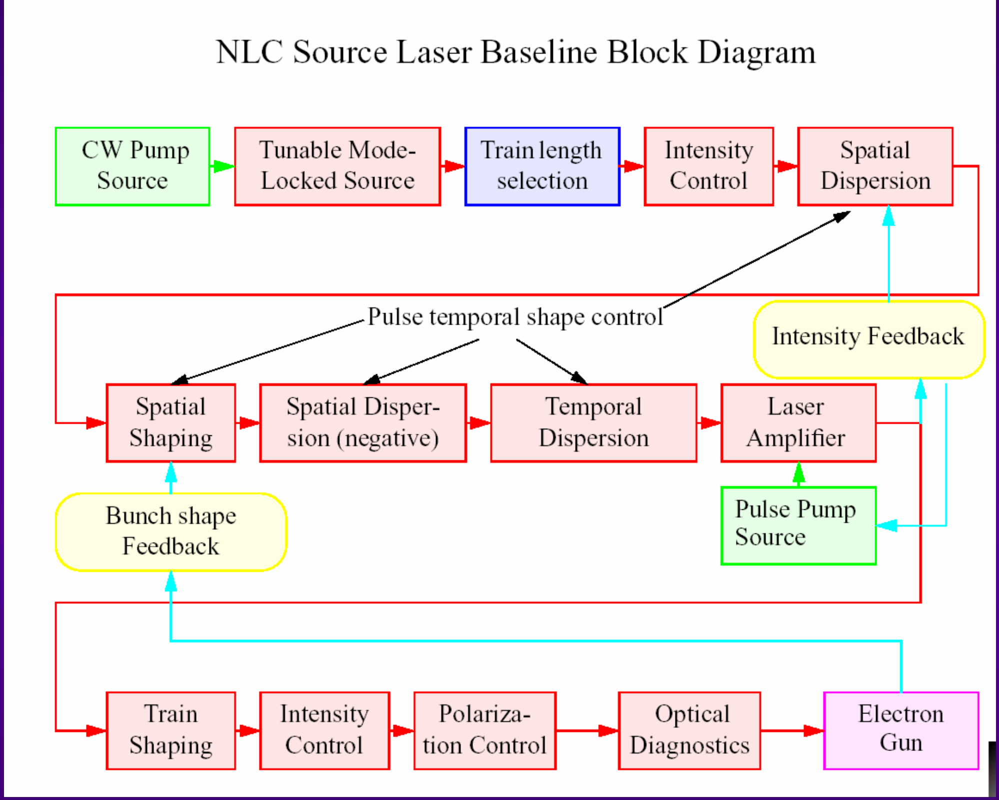
STRONG progress in optical pumping and in lasing medium

- 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



NLC Source Laser Baseline Block Diagram

CW Pump Source

Tunable Mode-Locked Source

Train length selection

Intensity Control

Spatial Dispersion

Pulse temporal shape control

Intensity Feedback

Spatial Shaping

Spatial Dispersion (negative)

Temporal Dispersion

Laser Amplifier

Bunch shape Feedback

Pulse Pump Source

Train Shaping

Intensity Control

Polarization Control

Optical Diagnostics

Electron Gun

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

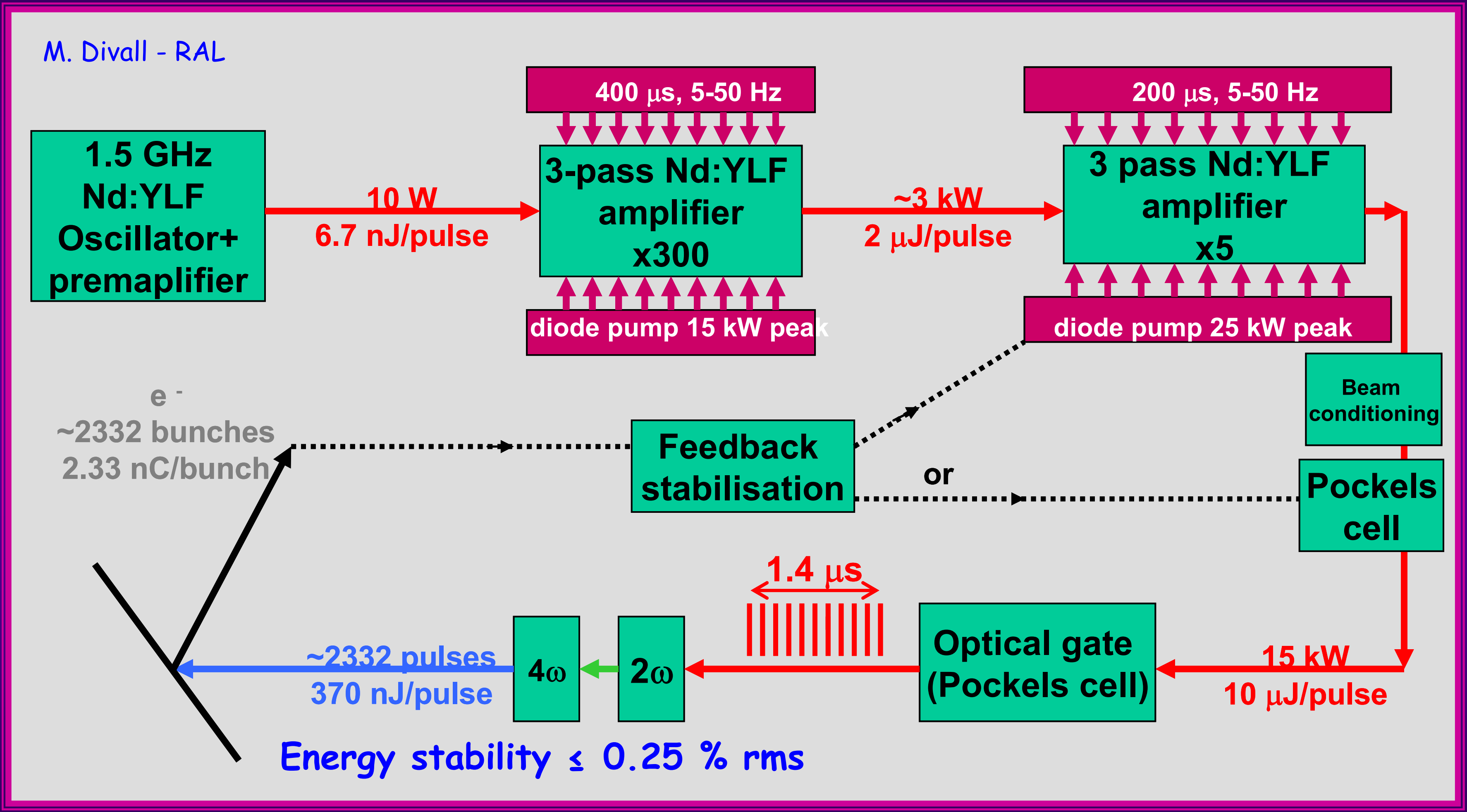
Bunch timing stability <10 picoseconds RMS

System MTBF >1000 Hours (Single laser)

System MTTR <4 Hours (Single laser)

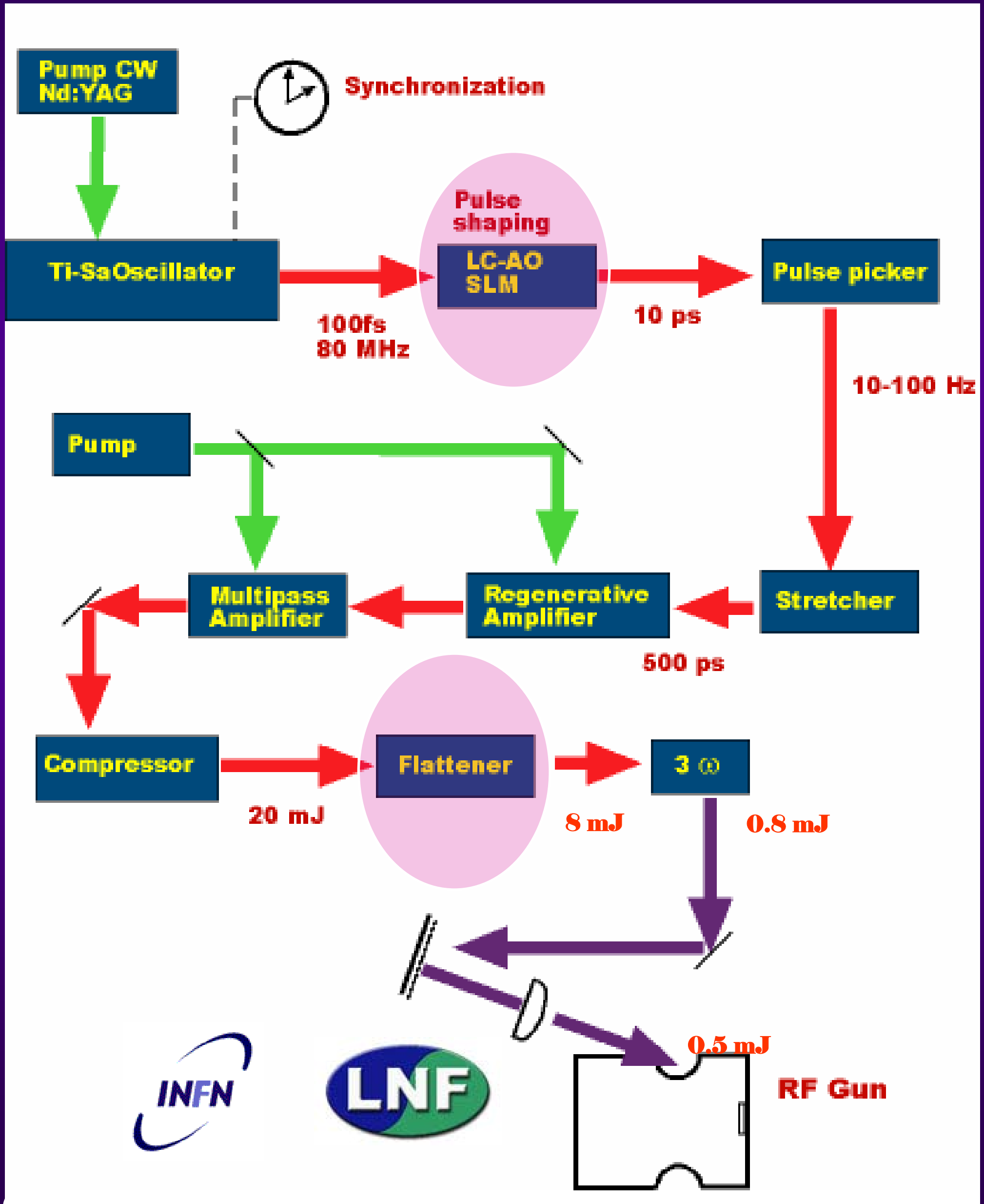
System lifetime >50,000 Hours

CERN - CTF3 Laser proposal



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

SPARC Laser proposal

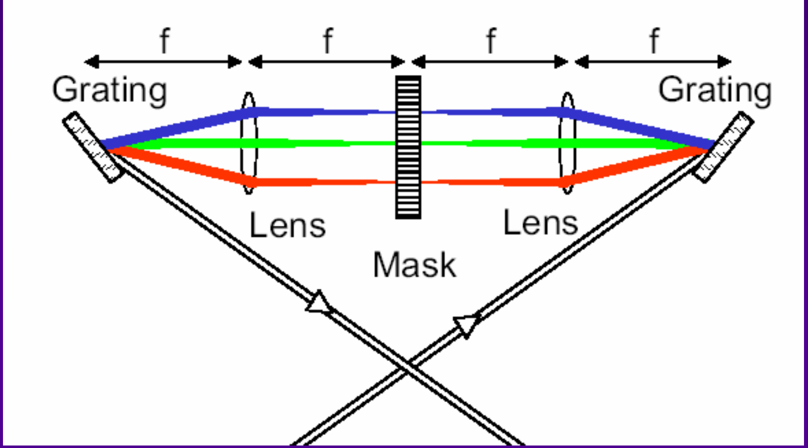


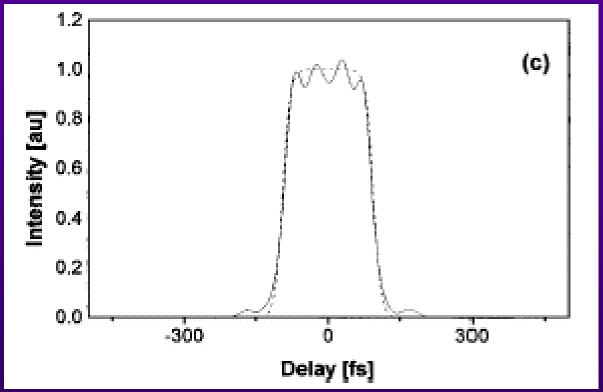
Operating wavelength	260-280 nm
Repetition rate	10-100 Hz
Number of micropulse per pulse	1
Pulse energy on cathode	500µJ (Q.E.=10^{-5})
Pulse rise time (10-90%)	< 1 ps
Pulse length	2-10 ps FWHM
Temporal pulse shape	Uniform (10% ptp)
Transverse pulse shape	Uniform (10% ptp)
Energy jitter (in UV)	1 % rms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

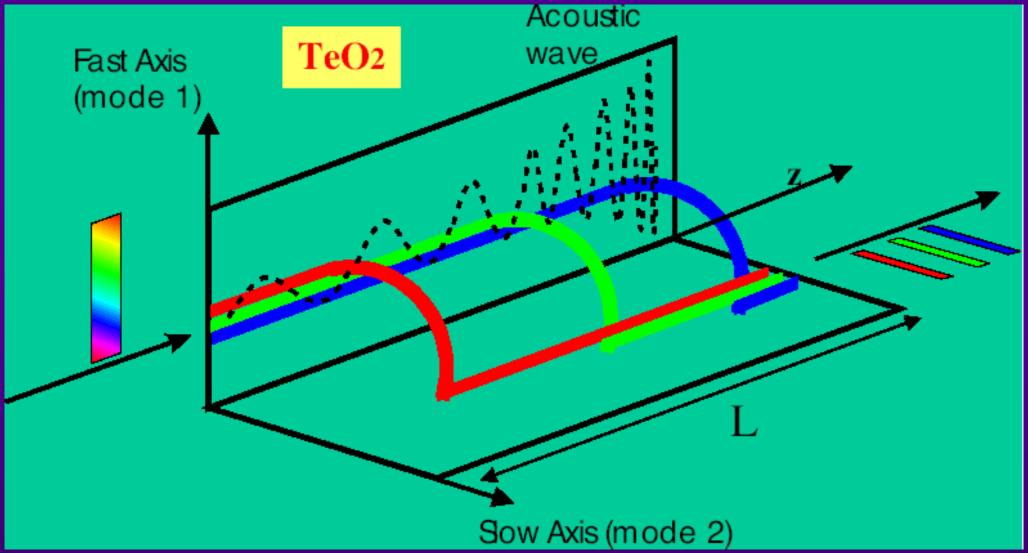




D. Meshulach, D. Yelin, Y. Silberberge
J. Opt. Soc. Am., B 15 (1998) 1615

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

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

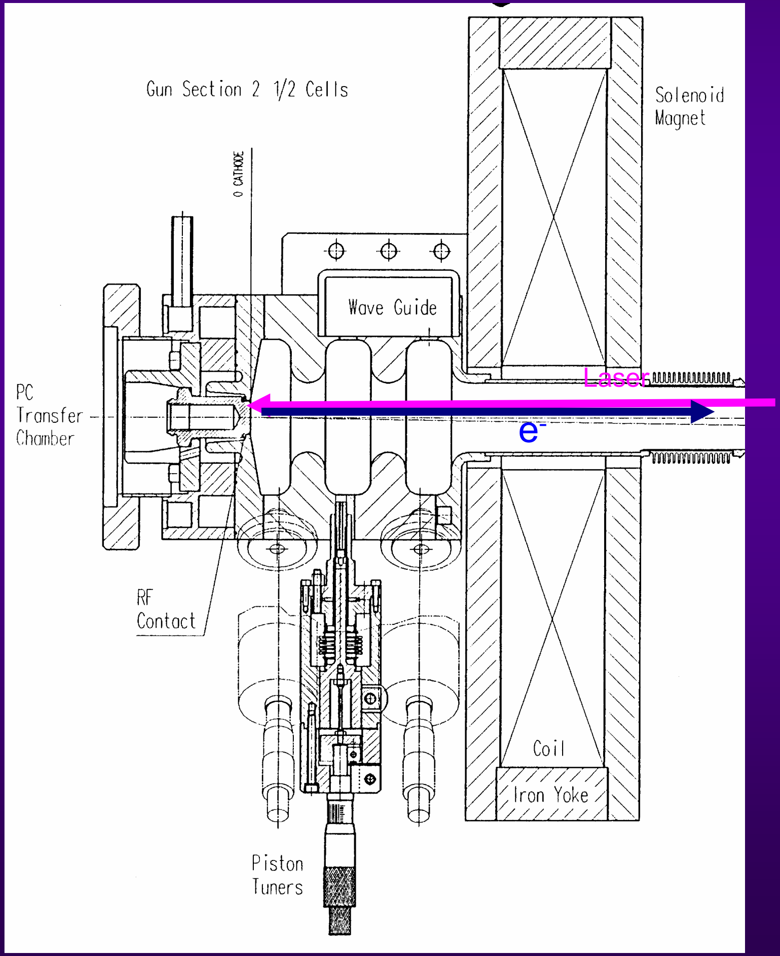
Study supported by E.U. inside CARE – JRA - PHIN

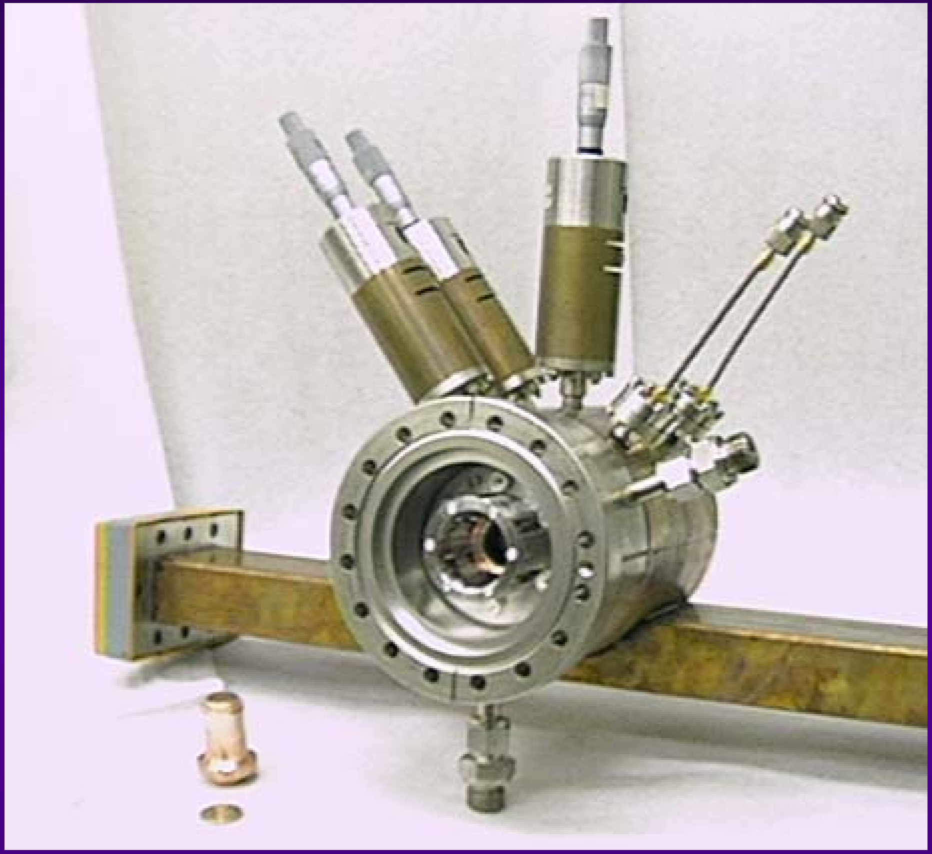
Guns

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.

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

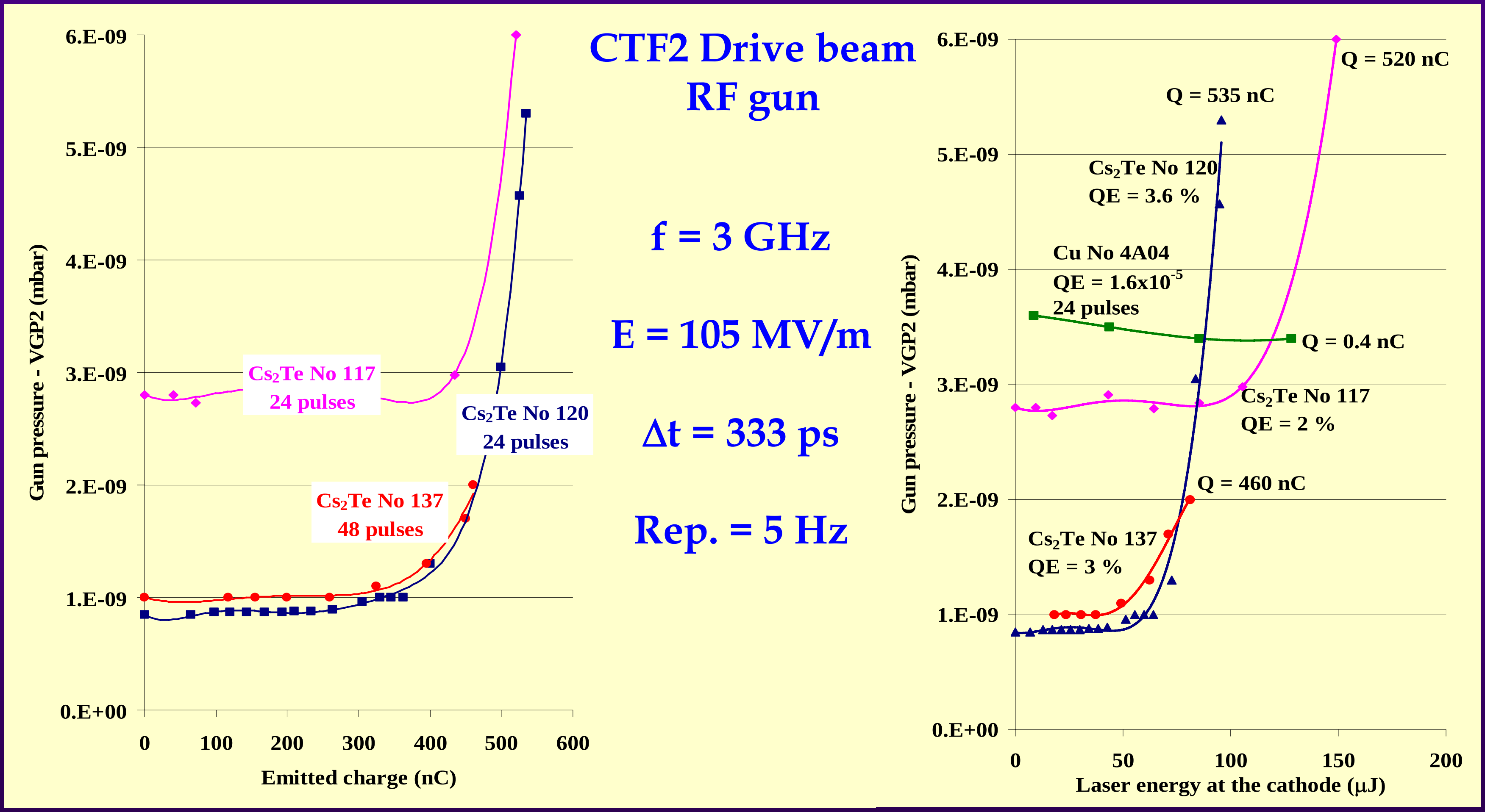




- 100-110 MV/m operational field at the cathode
- 16 MW input power at 100 MV/m
- Beam energy 7 MeV at 100 MV/m
- Maximum produced charge : 750 nC in 48 pulses
- Pulse width 10 ps FWHM
- Maximum single pulse charge : 100 nC
- Used photocathodes : Cs_2Te, Rb_2Te, Mg, Cu, Al

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 Niobium cavity , 1.3 GHz
E_{max} = 45 MV/m
Niobium cath. QE ~ 5.10^{-5} at 262 nm
with laser cleaning.

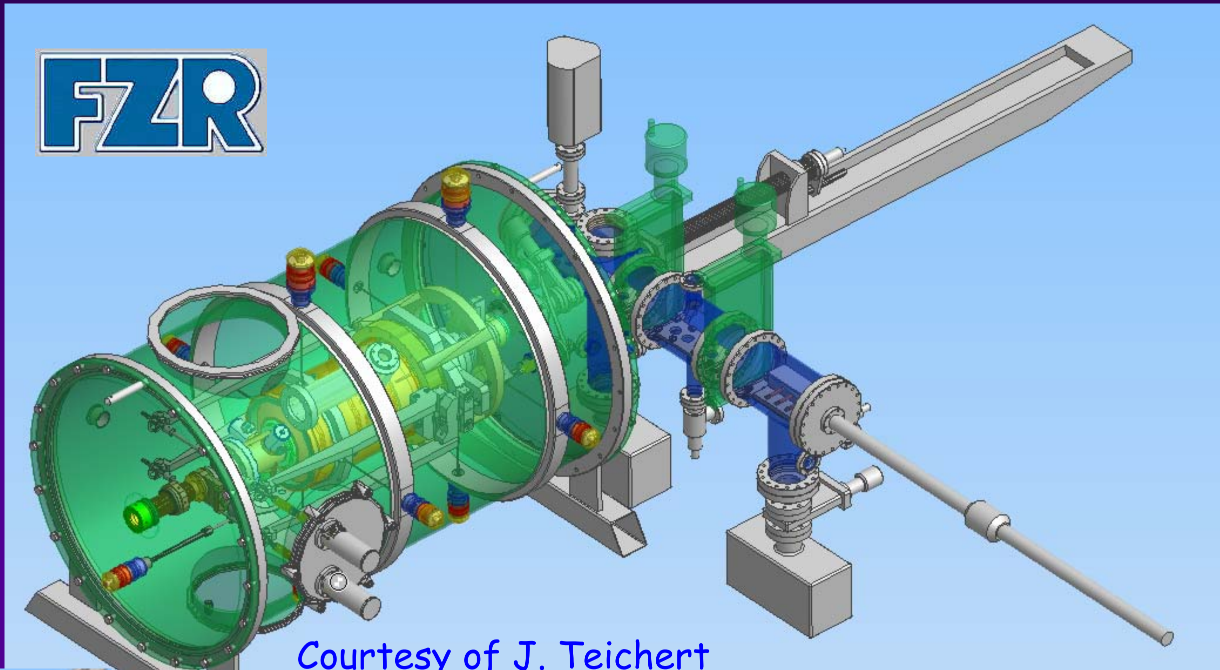
For high mean current, the requested laser power is too large :
P_L = 95 W / mA

J. Teichert et al. , SRF 2003, Lübeck

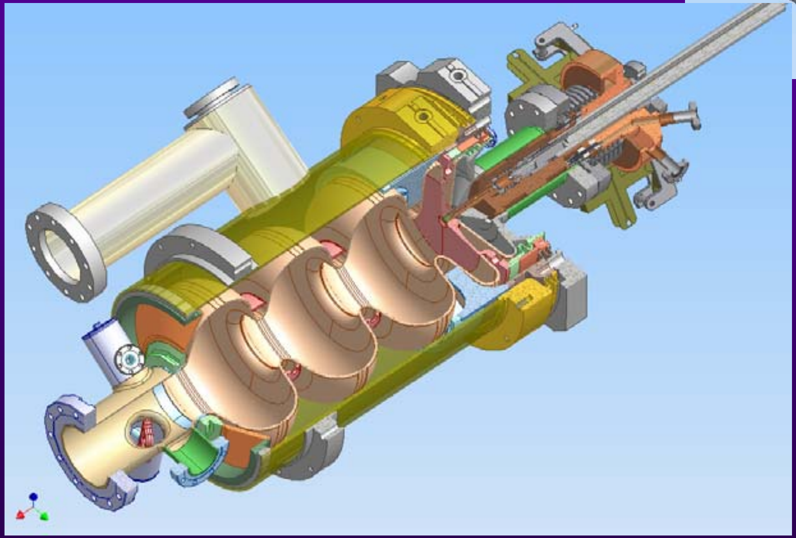
Superconducting RF gun at Rossendorf
½ cell Niobium cavity , 1.3 GHz
Tesla geometry
Normal-conducting Cs_2Te photocath.
at LN_2 temperature and thermally
insulated. Illuminated with 1 W laser
at 262 nm

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
- 3½-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 : $J = perv.U^{1.5} \sim 200\ A/cm^2$
- 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

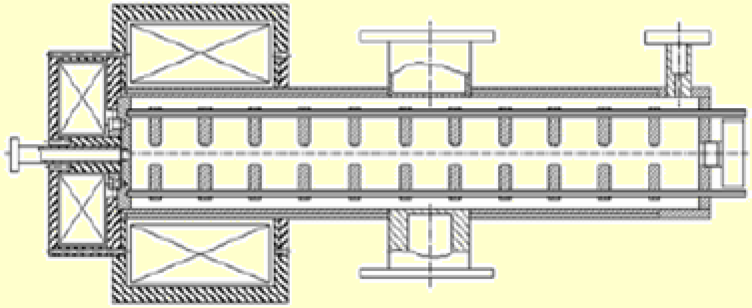
Plane Wave Transformer RF gun

Large vacuum conductance and moderate electric field

THE UCLA PEGASUS PWT S-band gun

60 cm total length
11 cells

Tank diam. : 12 cm
Disk diam. : 4.2 cm

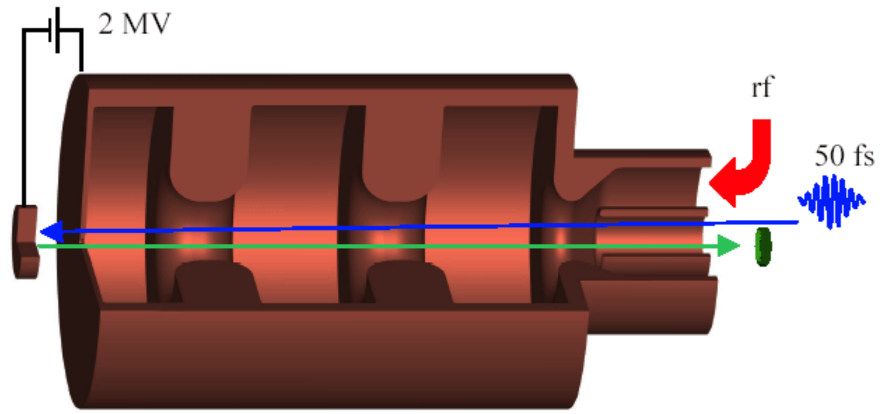


E_{peak} : 60 MV/m
Energy : 12 – 18 MeV
$Emittance_N$: 4 mm.mrad (rms)
Charge : 1 nC ; Bunch length : 1 – 10 ps

G. Travish *et al.* PAC 2003

Pulsed DC + RF gun

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

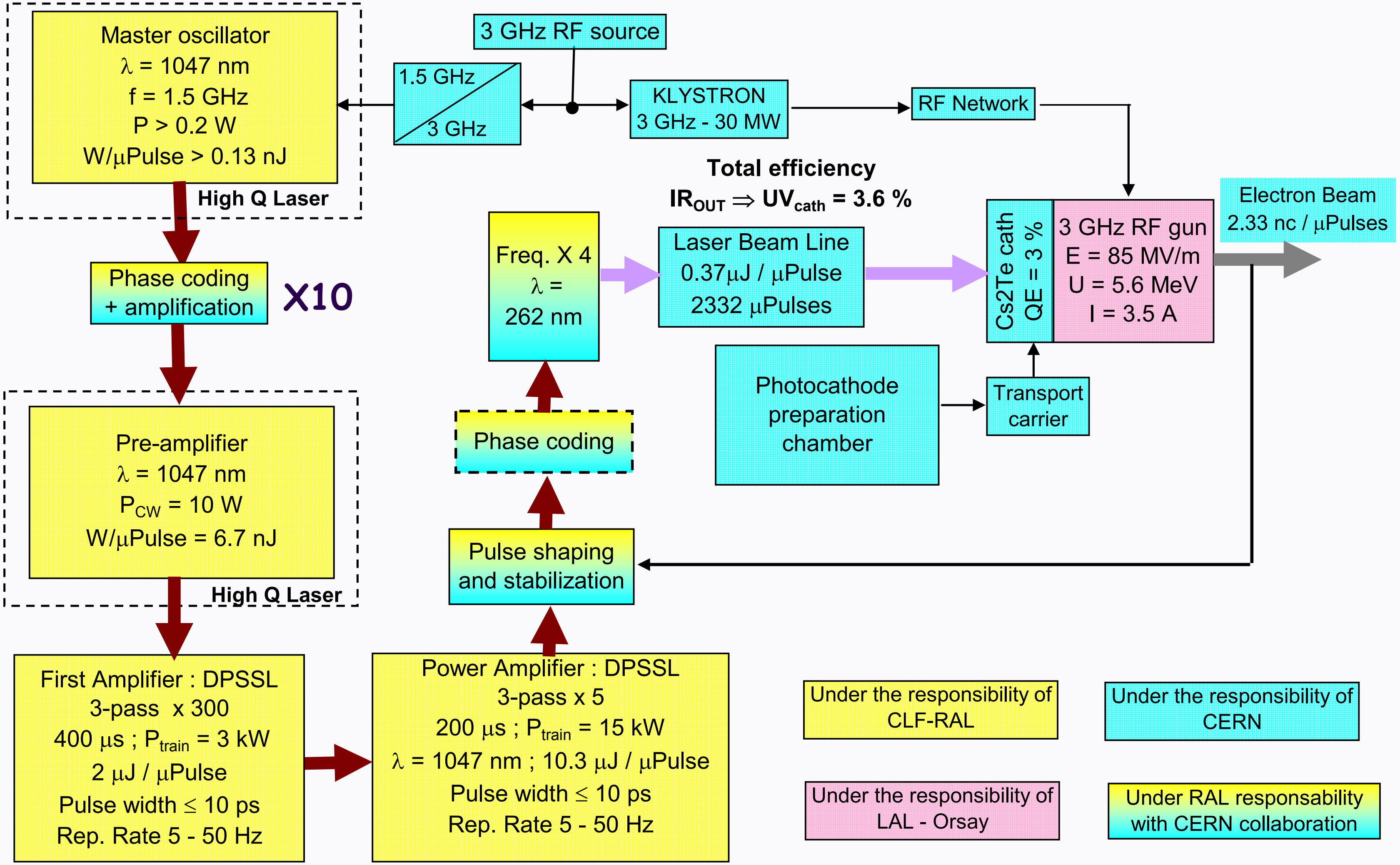


U_{DC} = 2 MV ; 1 ns
$E_{peak-DC}$: 1 GV/m ; Gap : 2 mm
S-band RF gun ; 100 MV/m
Output Energy : 10 MeV
$Emittance_N$: 1.π.mm.mrad
Charge : 100 pC
Bunch length : 50 - 200 fs
Peak current : 1 kA

M.J. de Loos *et al.* EPAC 2002

http://phys.strath.ac.uk/alpha-x/index.html

CTF3 Drive Beam photo-injector



Master oscillator
λ = 1047 nm
f = 1.5 GHz
P > 0.2 W
W/μPulse > 0.13 nJ

High Q Laser

1.5 GHz / 3 GHz

3 GHz RF source

KLYSTRON
3 GHz - 30 MW

RF Network

Total efficiency
IR$_{OUT}$ ⇒ UV$_{cath}$ = 3.6 %

Phase coding
+ amplification

X10

Freq. X 4
λ =
262 nm

Laser Beam Line
0.37μJ / μPulse
2332 μPulses

Cs2Te cath
QE = 3 %

3 GHz RF gun
E = 85 MV/m
U = 5.6 MeV
I = 3.5 A

Electron Beam
2.33 nc / μPulses

Photocathode
preparation
chamber

Transport
carrier

Pre-amplifier
λ = 1047 nm
P$_{CW}$ = 10 W
W/μPulse = 6.7 nJ

High Q Laser

Phase coding

Pulse shaping
and stabilization

First Amplifier : DPSSL
3-pass x 300
400 μs ; P$_{train}$ = 3 kW
2 μJ / μPulse
Pulse width ≤ 10 ps
Rep. Rate 5 - 50 Hz

Power Amplifier : DPSSL
3-pass x 5
200 μs ; P$_{train}$ = 15 kW
λ = 1047 nm ; 10.3 μJ / μPulse
Pulse width ≤ 10 ps
Rep. Rate 5 - 50 Hz

Under the responsibility of
CLF-RAL

Under the responsibility of
CERN

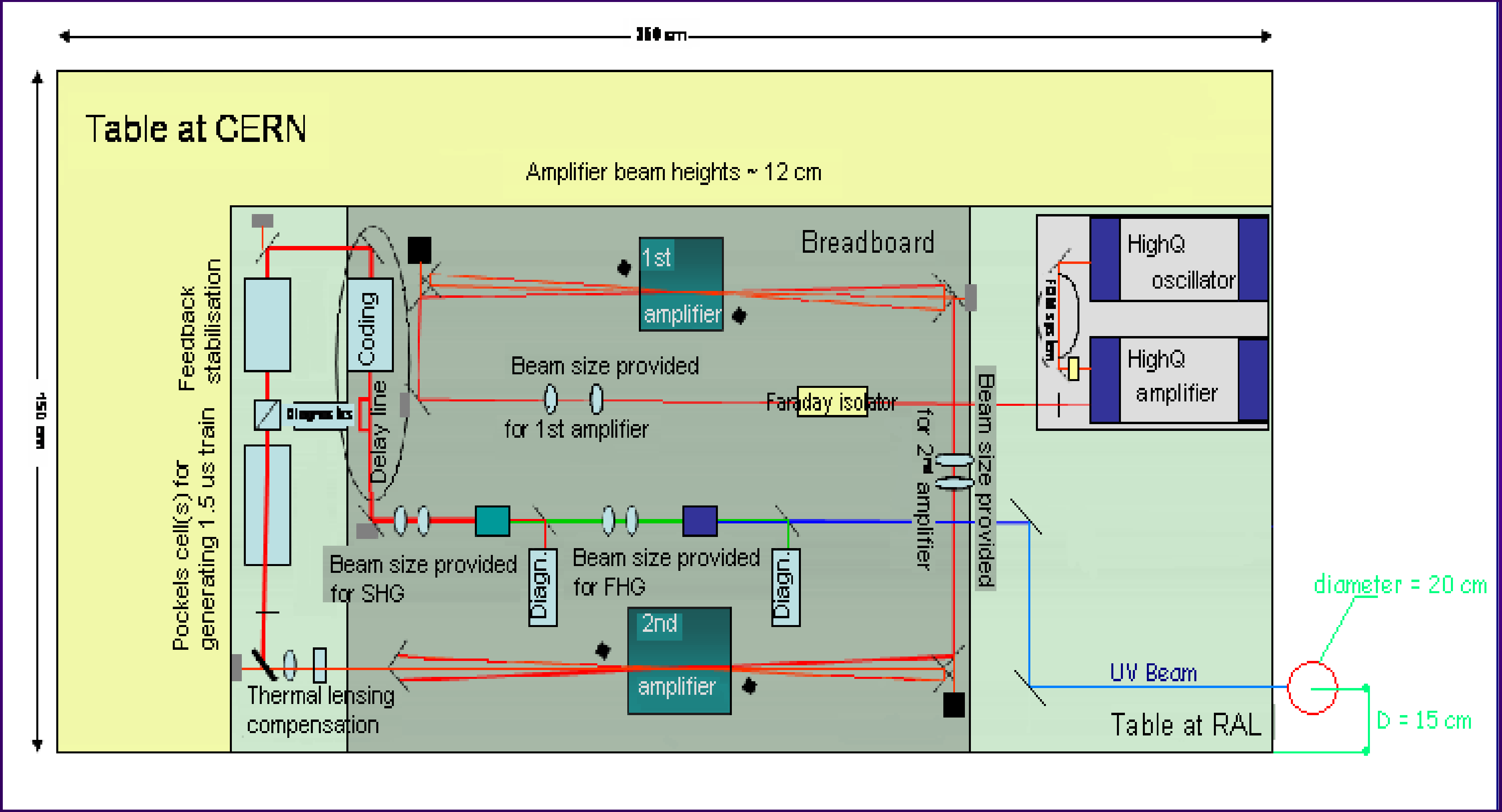
Under the responsibility of
LAL - Orsay

Under RAL responsability
with CERN collaboration

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

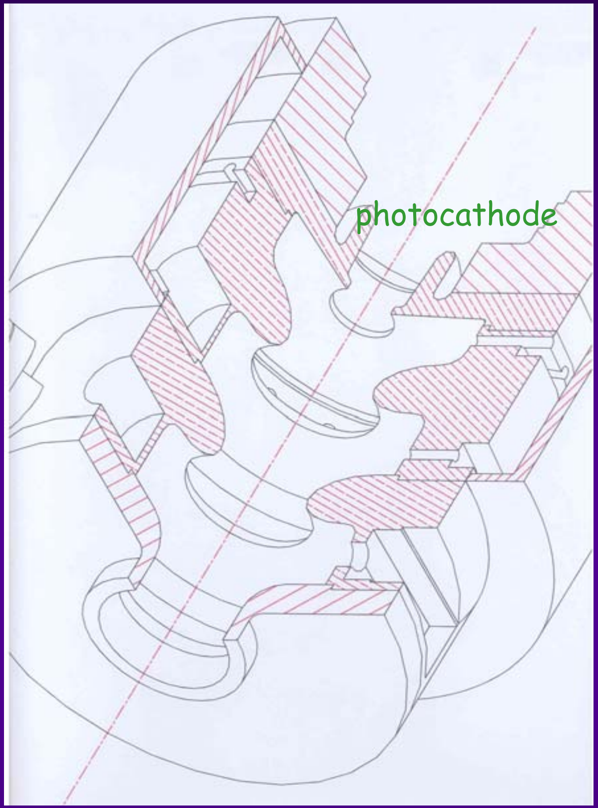
Laser layout

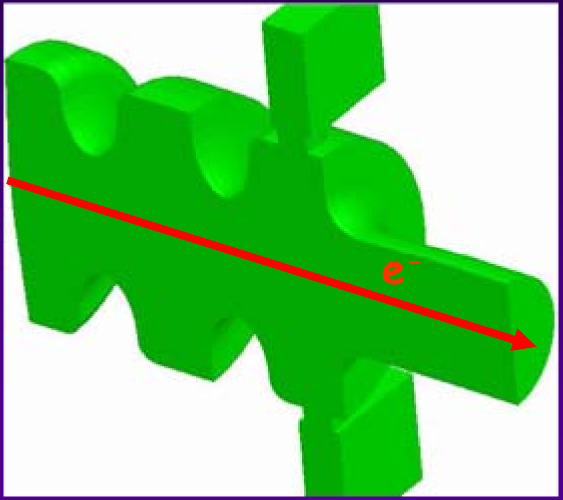
M. Divall *et al*, (RAL-GB)
N. Champault

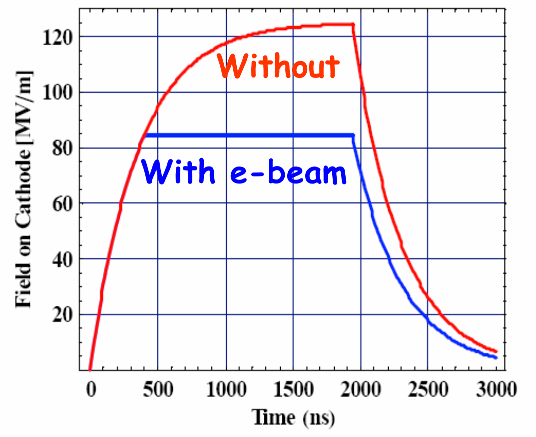


Will be presented in details during the next CTF3 collaboration meeting

CTF3 RF gun design







Four new improvements:

Elliptical iris → reduces the surface electric field

Race track coupler → Gives better field symmetry

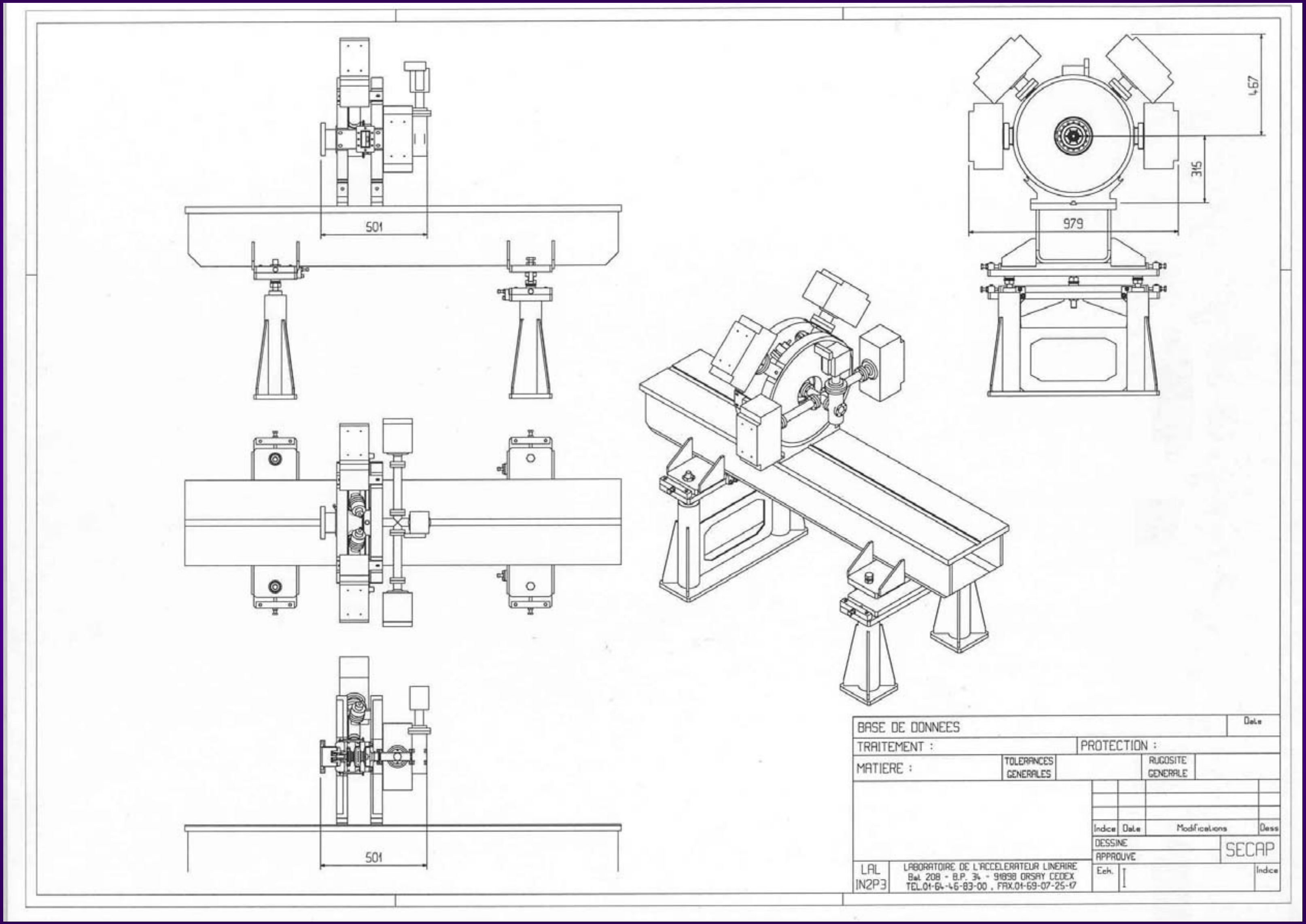
NEG & Ion pumping → Give better vacuum

Solenoids around the gun → Give lower emittances

RF frequency (GHZ)	**2.99855**
RF power (MW)	**30**
Acc. electric field (MV/m)	**85**
Beam energy (MeV)	**5. 6**
Beam current (A)	**3.5 - 5**
Charge/bunch (nC)	**2.33**
Bunch length (ps)	**10**
Energy spread (%)	**< 2**
Normalized emittance (π.mm.mrad)	**< 25**
Number of pulses	**~ 2332**
Pulse train duration (μs)	**1.548**
Coupling factor (β)	**2.9**
Vacuum pressure (mbar)	**2.10^{-10}**
Repetition rate (Hz)	**50**

G. Bienvenu, R.Roux, *et al*,
LAL-IN2P3 - Orsay

RF gun layout



Will be presented in details during the next CTF3 collaboration meeting

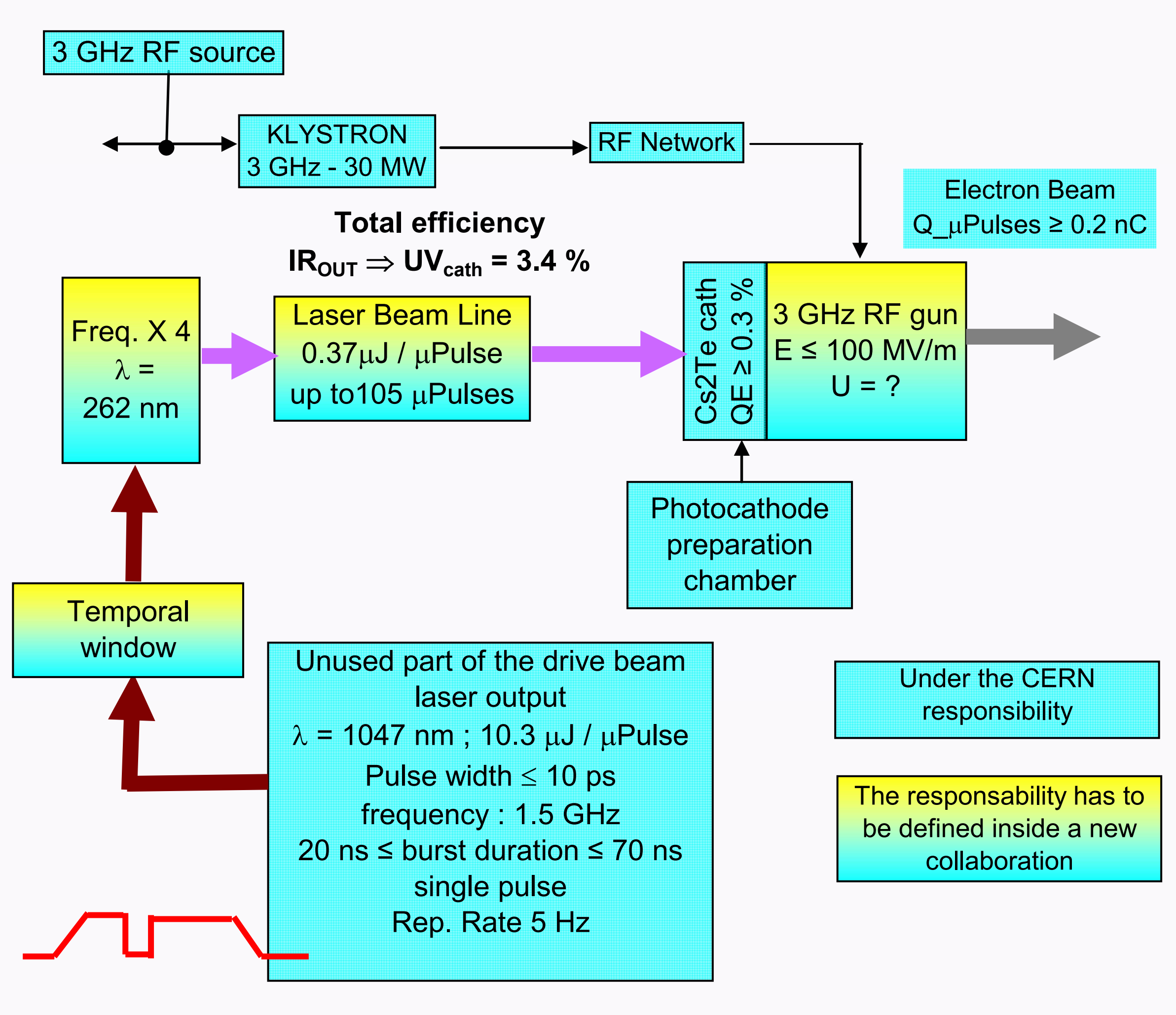
Photocathodes

Re-use of the former CTF2 equipment :

- Cs-Te photocathodes produced with an upgraded version of the present co-evaporation system
- Same Transport Carrier (TC)
- Same Manipulator of Photo Cathode (MPC) attached to the gun

Will be presented in details during the next CTF3 collaboration meeting

CLEX Probe beam photo-injector



3 GHz RF source

KLYSTRON
3 GHz - 30 MW

RF Network

Electron Beam
Q_µPulses ≥ 0.2 nC

Total efficiency
$IR_{OUT} \Rightarrow UV_{cath}$ = 3.4 %

Freq. X 4
λ =
262 nm

Laser Beam Line
0.37µJ / µPulse
up to105 µPulses

Cs2Te cath
QE ≥ 0.3 %

3 GHz RF gun
E ≤ 100 MV/m
U = ?

Photocathode
preparation
chamber

Temporal
window

Unused part of the drive beam
laser output
λ = 1047 nm ; 10.3 µJ / µPulse
Pulse width ≤ 10 ps
frequency : 1.5 GHz
20 ns ≤ burst duration ≤ 70 ns
single pulse
Rep. Rate 5 Hz

Under the CERN
responsibility

The responsability has to
be defined inside a new
collaboration

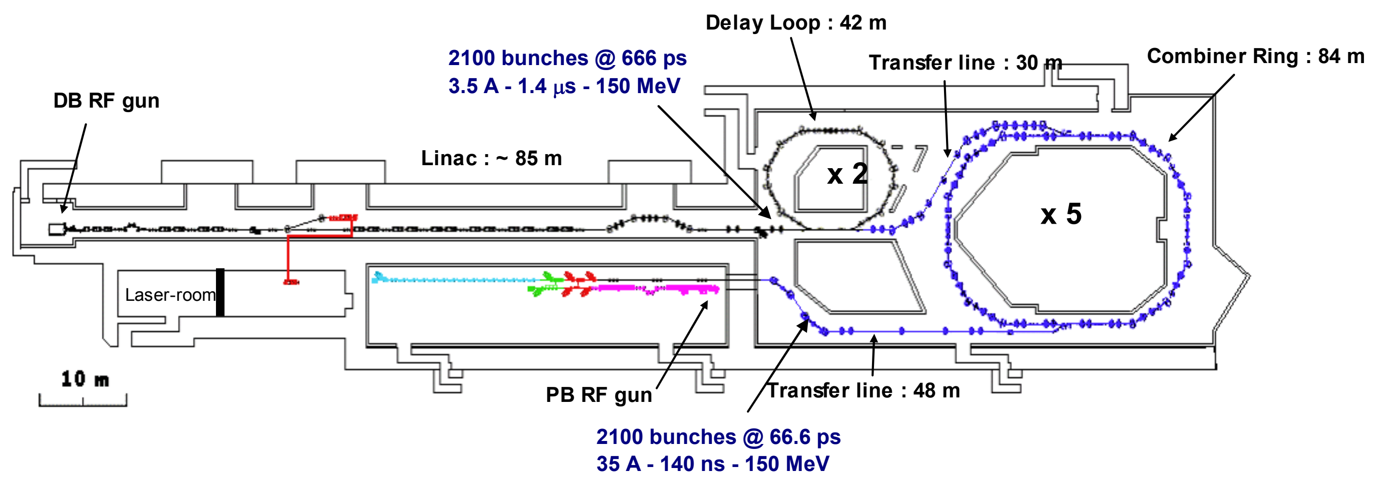
“Light” version

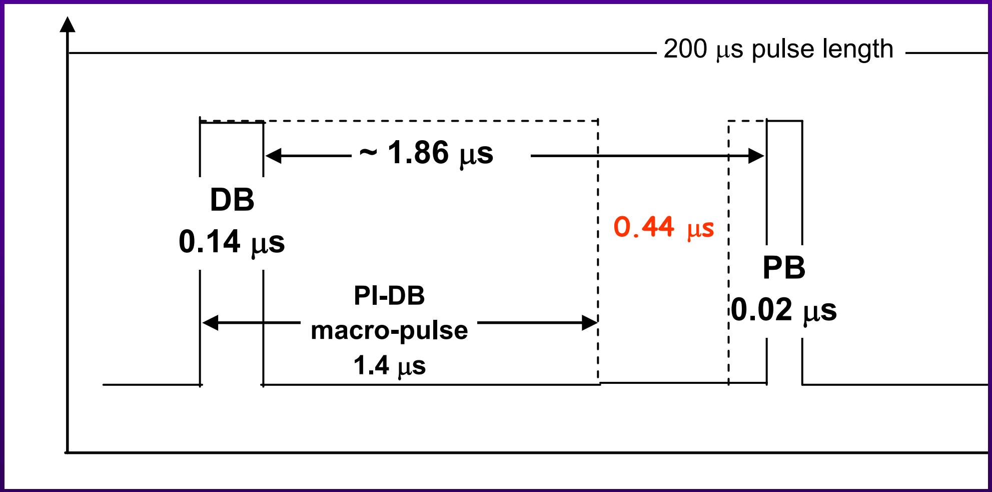
- Reduced frequency in the burst : 1.5 GHz
- Reduced charge per micro-pulse ~ 0.2 nC

↓

- **Re-use of the preparation chamber attached to the former CTF2 Probe beam RF gun. ➔ Not TC nor MPC**
- **Substantial simplification and economy in the laser system.**

Timing Drive - Probe beam

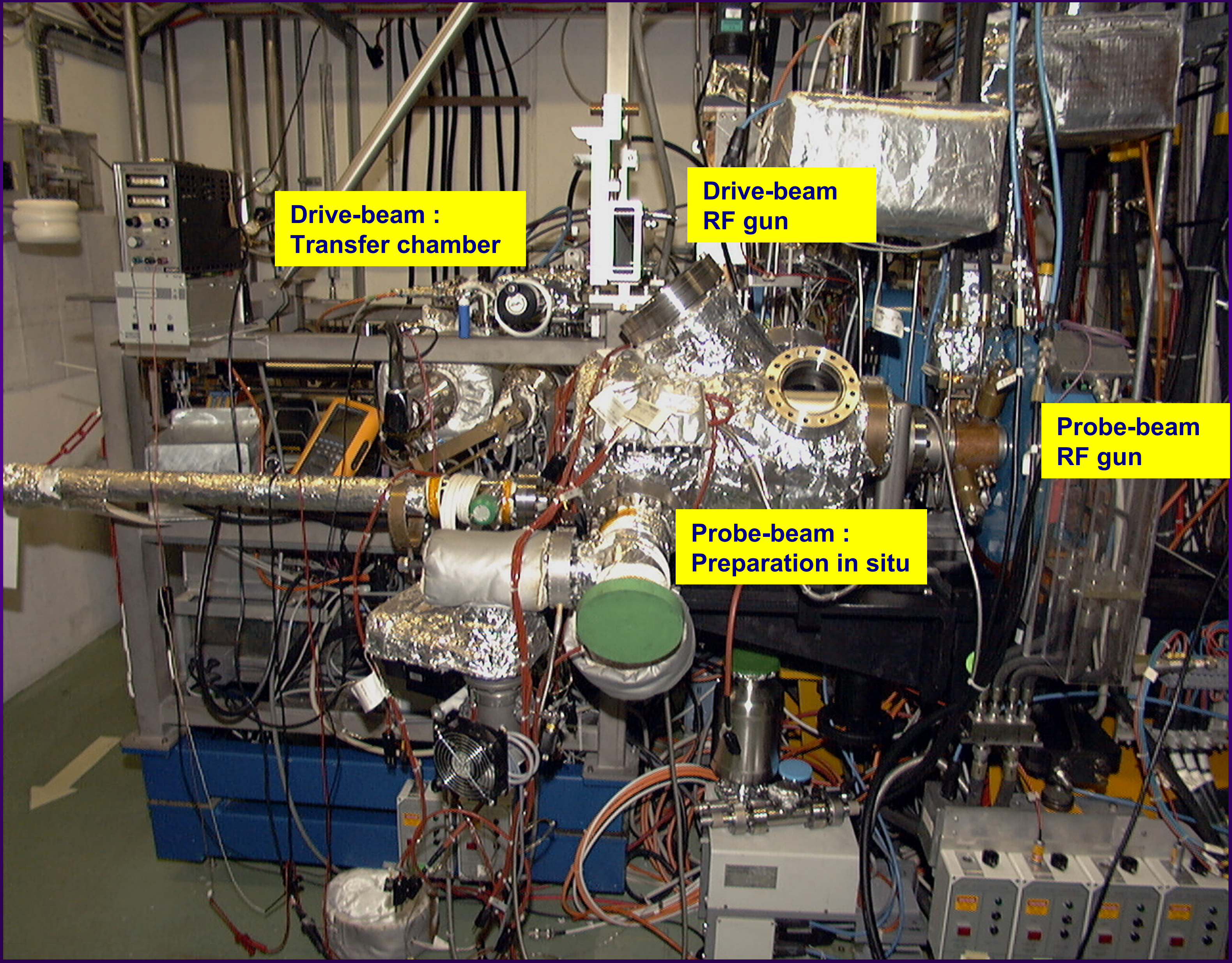




First pulse of the Drive beam		
Laser-room ➔ DB gun	15 m	0.05 µs
Photo-injector ➔ Delay Loop	85 m	0.2833 µs
Delay Loop	42 m	0.14 µs
TL Delay Loop ➔ Comb. Ring	30 m	0.1 µs
Combiner Ring	84 m	0.28 µs
TL Comb. ring ➔ Probe Beam	48 m	0.16 µs
Total with 1 DL and 4.5 C. Ring	598 m	1.9933 µs
Macro pulse length		0.14 µs
Filling time of PETS+Acc.		0.02 µs
TOTAL time		2.1533 µs

Probe Beam		
Laser-room ➔ PB gun	75 m	0.25 µs
PB macro-pulse length		0.021312 µs
TOTAL time		0.271312 µs
Conv. 1.5 GHz to 3 GHz		0.021312 µs

Probe beam preparation chamber



Photocathode developments

- **Co-evaporation process**

  Stochiometric ratio monitored with two different ways :

  - Separate thickness measurement with microbalances
  - Mass spectrometry

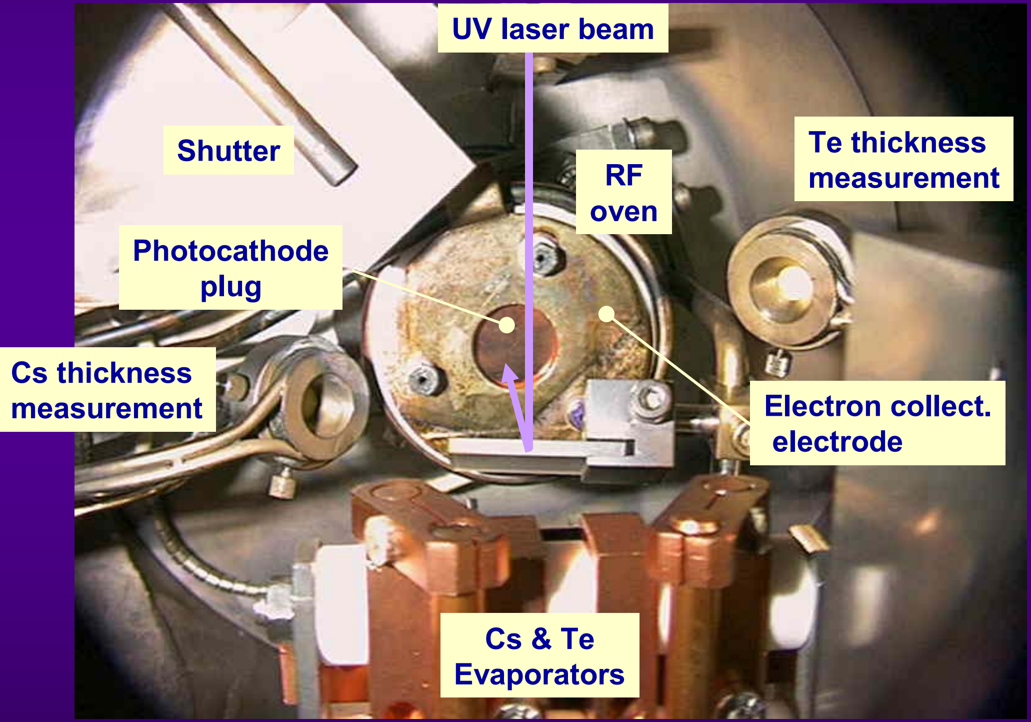
- **Photocathode poisoning study : mass spectrometry**

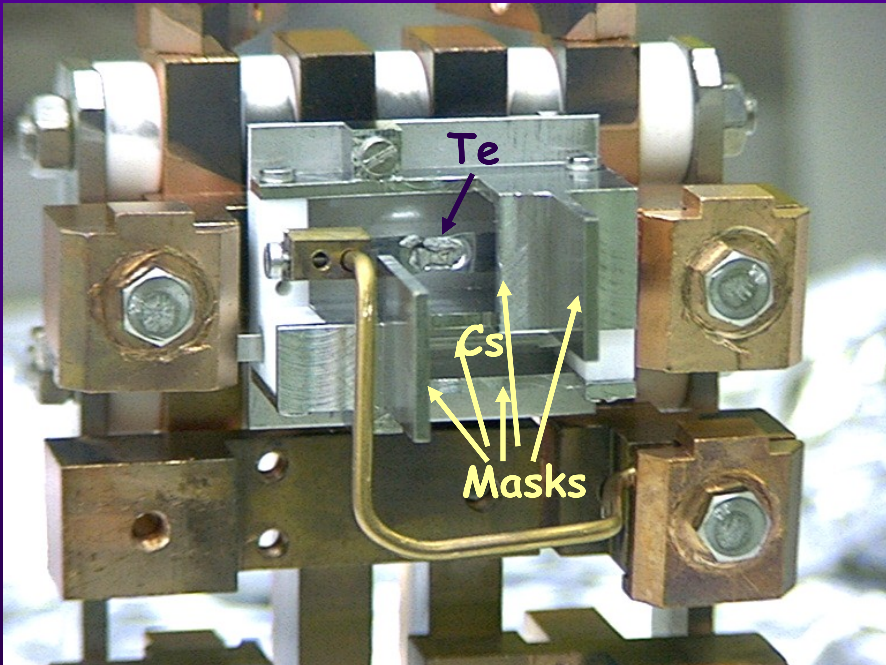
- **Alkali-antimonide photocathodes**

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

Co-evaporation process (1)

Evaporator prototypes allowing the monitoring of the evaporation rates



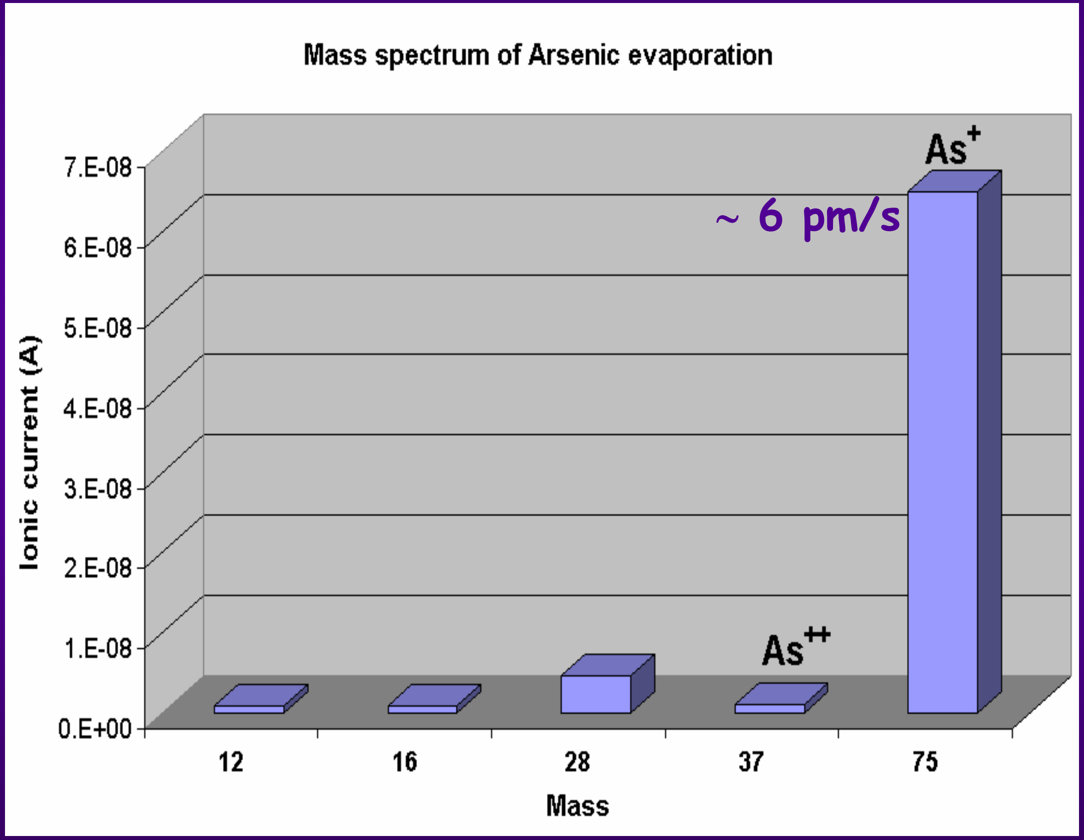


Every microbalance sees only a single product, while the cathode receives the 2 homogenously.

G. Suberlucq

Co-evaporation process (2)

Mass spectrometry



Ion current of the metallic vapor ∝ evaporation rate

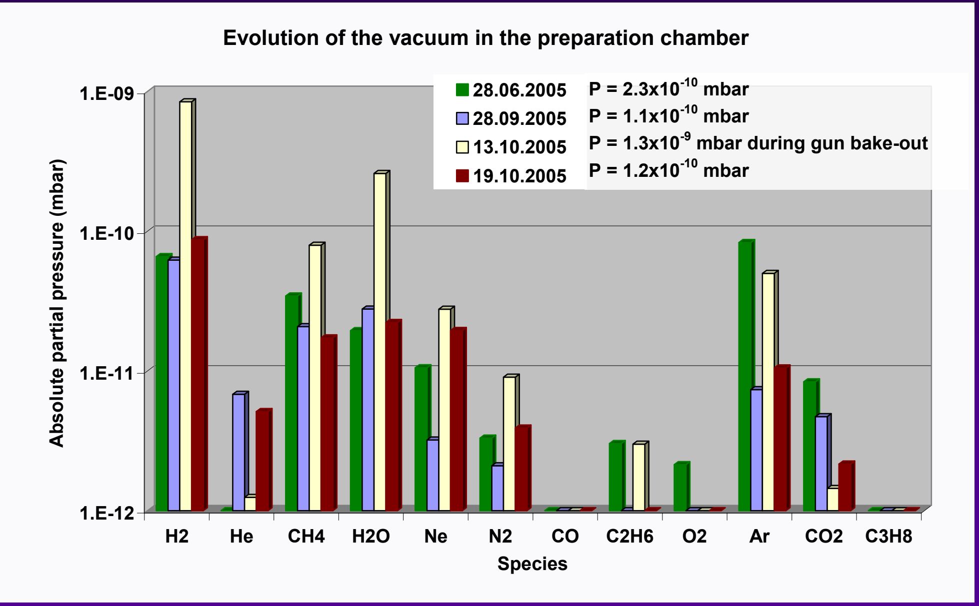
"Closed loop multi source evaporation rate control with a quadrupole mass spectrometer in an ultra high vacuum system", K. Wellerdieck et all.

Mass	Te (%)	Cs (%)
133		100
130	34.5	
128	31.8	
126	18.7	
125	7	

Thickness calibration program is current

Mass spectrometer upgraded to be able to scan masses up to 200

Photocathode poisoning study



Species	Cs-Te (L)	Cs-Te P (max) mbar	Cs-K-Sb (L)	Cs-K-Sb P (max) mbar
H_2O	?	?	?	?
O_2	15 300	6×10^{-12} 1×10^{-10}	0.1	4×10^{-14}
CO_2	1100	4×10^{-10}	1	4×10^{-13}

L = Langmuir, 1 L = 1.33×10^{-6} mbar.s

P (max) = absolute partial pressure to get QE_{max}/e after 1000 hours

- Calibration of species is achieved excepted for water vapor (soon)
- Compatibility with TS/MME for XPS analysis is current (vacuum transportation).
- Species analysis during electron production in DC and RF guns are foreseen.
- Study of water contamination
- Study of contamination by ion pump
- Effect of the stoichiometric ratio on the surface passivation
- Effect of the substratum on the contamination process

Alkali-antimonide photocathodes

- $QE_{(GREEN)} \sim QE_{(UV)}/8$
  $QE_{(GREEN)} \geq 0.4\ \%$ to produce the requested DB charge with the same IR power.

Two tests are foreseen

Co-evaporation process with a slight cesium deficit to improve the lifetime and the robustness at high electric field

Cathode/gun separate vacuum like SEE proposal from BNL

- Electron transparency of the window have to be checked
- Compatibility with the RF and high electric field should be demonstrated

Informal collaboration with CEA-SP2A

Don't forget (1)

- Ga-As photocathodes for polarized electron production

Today performances not directly compatible with CLIC specifications.

Don't forget (2)

A l'occasion de mon départ à la retraite, j'ai le plaisir de vous inviter à venir boire le verre de l'amitié

le lundi 31 octobre à 16h30

au "Glass Box" du restaurant n° 1

Guy Suberlucq