PHIN

CALIFES

The 2 CTF3 Photoinjectors

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CERN

…on behalf of CTF3 photoinjector community

CERN 22 April 2009

Outline

- CLIC & CTF3
- CTF3 electron sources
- Photoinjectors
  - Photoemission & cathode
  - Photoinjector laser
- PHIN photoinjector
- CALIFES photoinjector

CLIC

CLIC (“Compact” Linear Collider): is a study for a future **electron-positron collider**

goal: electron-positron collision with nominal center-of-mass energy of **3 TeV + “compact” machine**

high gradient → **100 MV/m**
high frequency (12 GHz)

+

Conventional high frequency RF sources
Klystron =
low frequency low power emitters

=

Two-beam acceleration concept:

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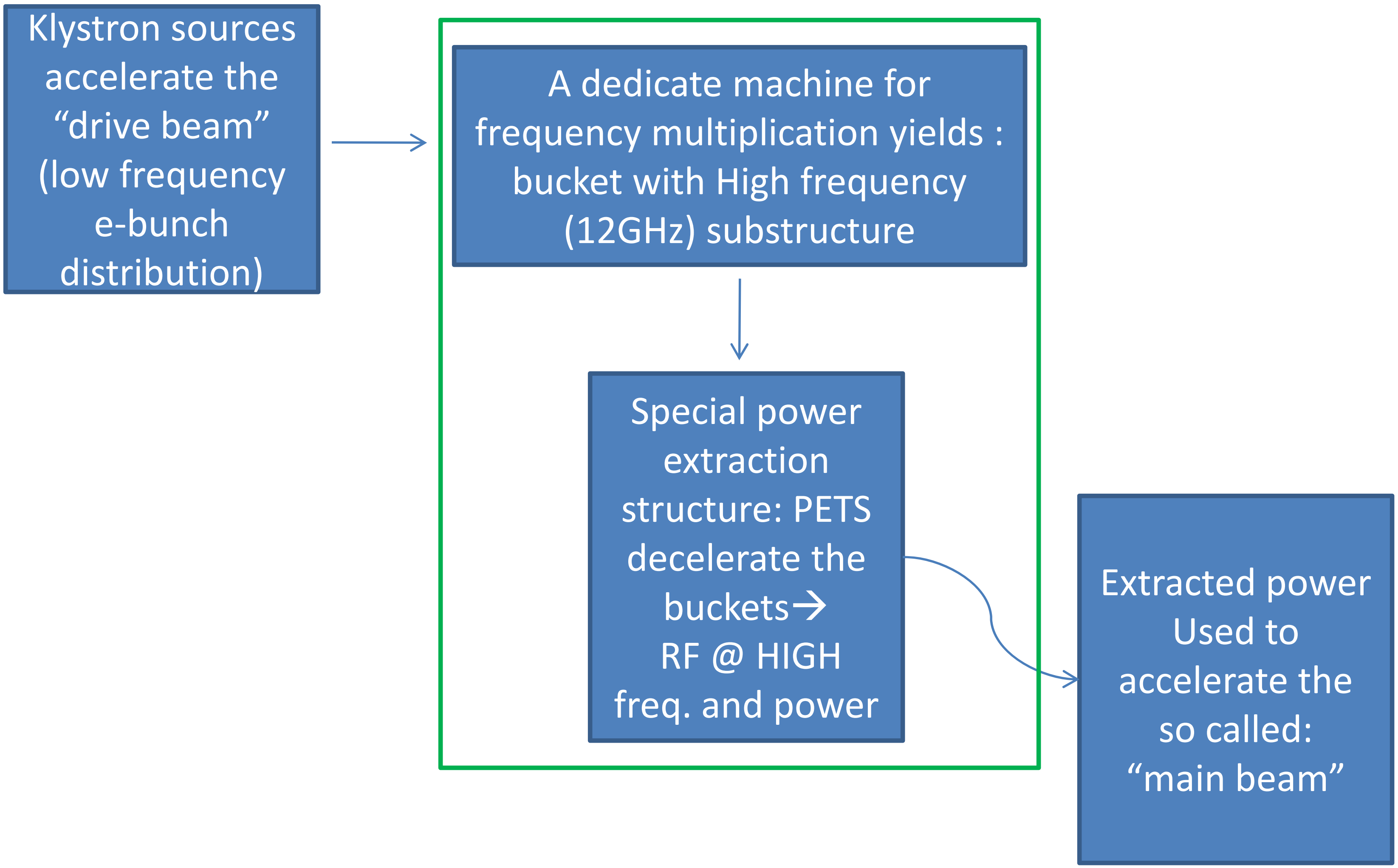
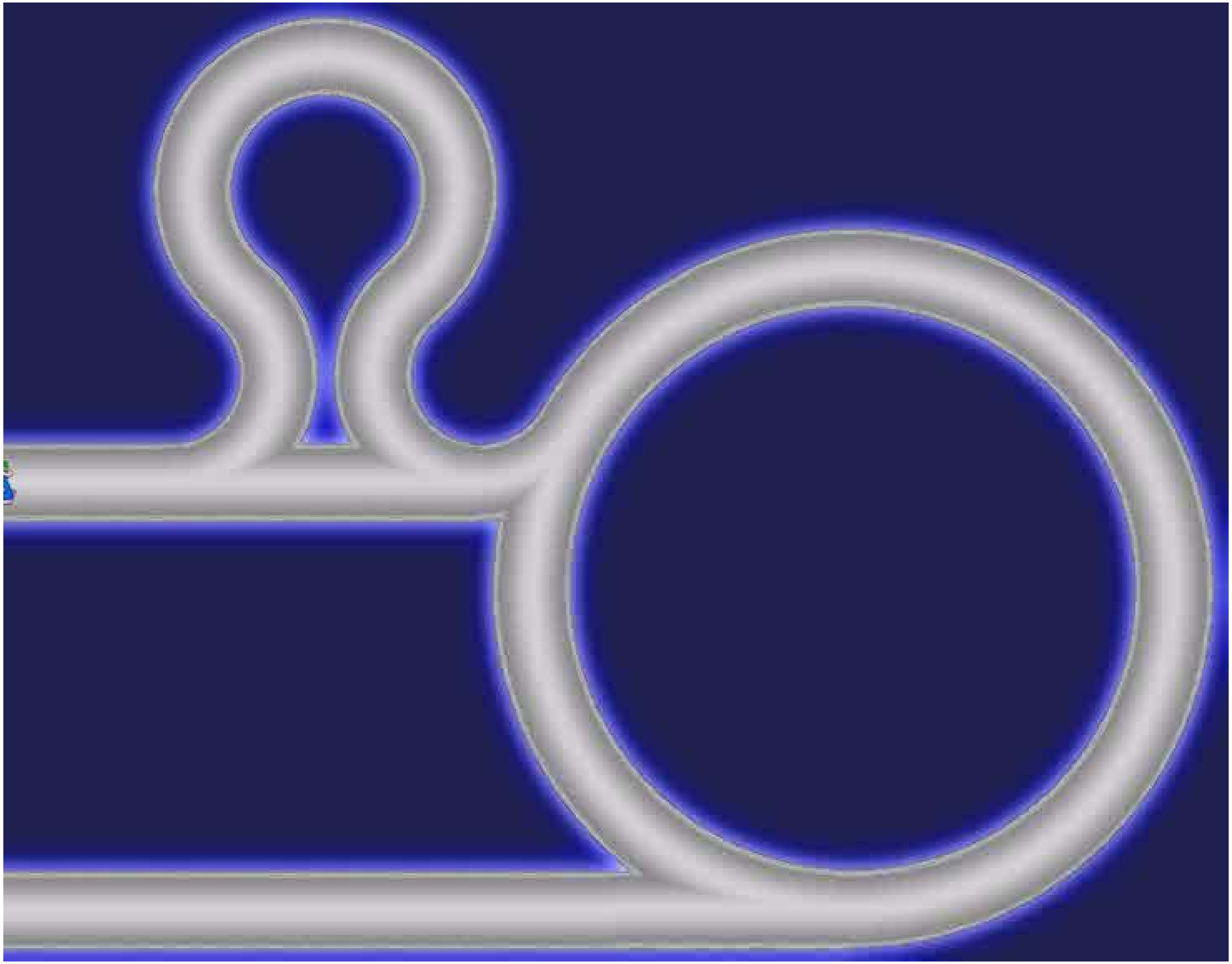
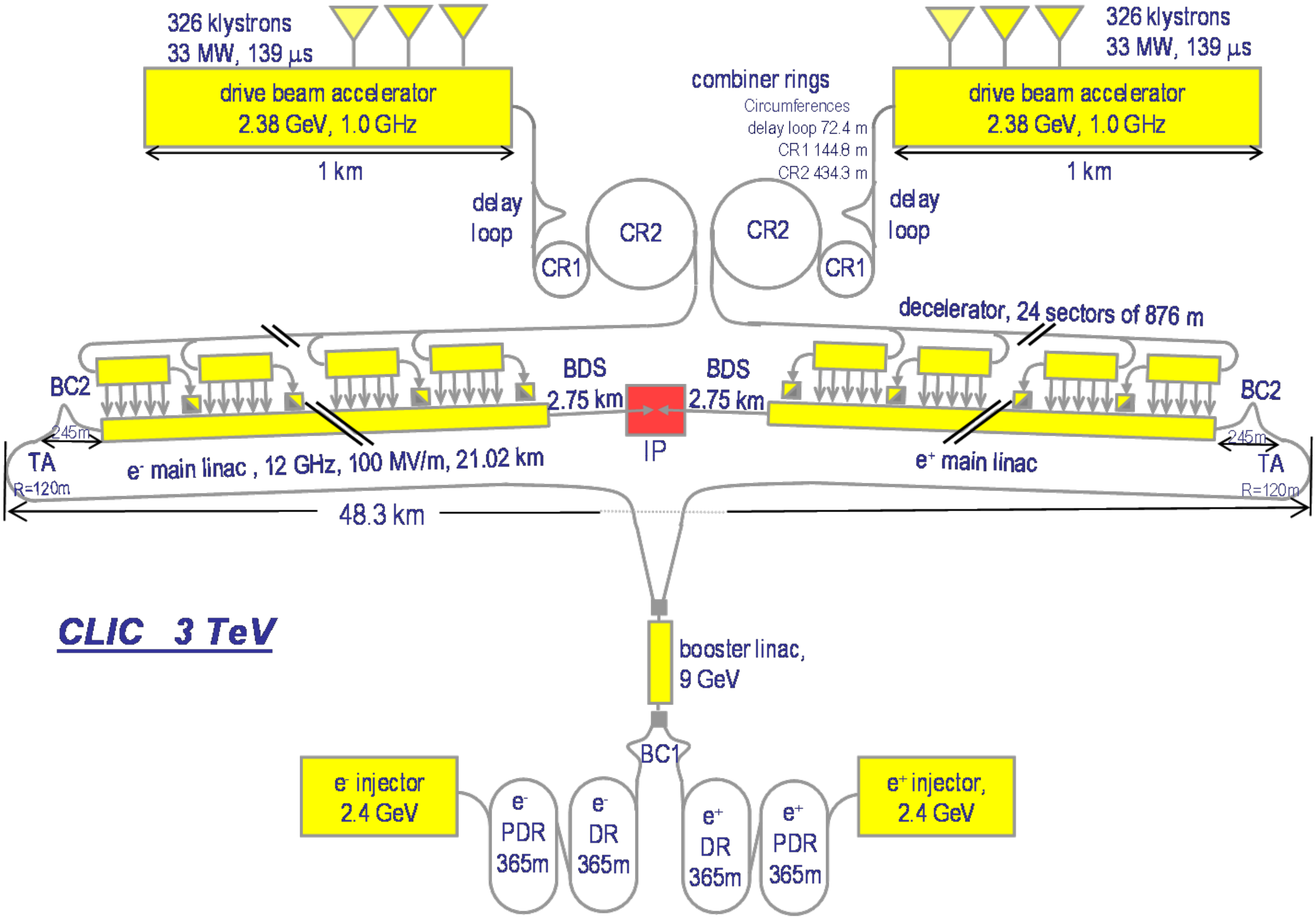


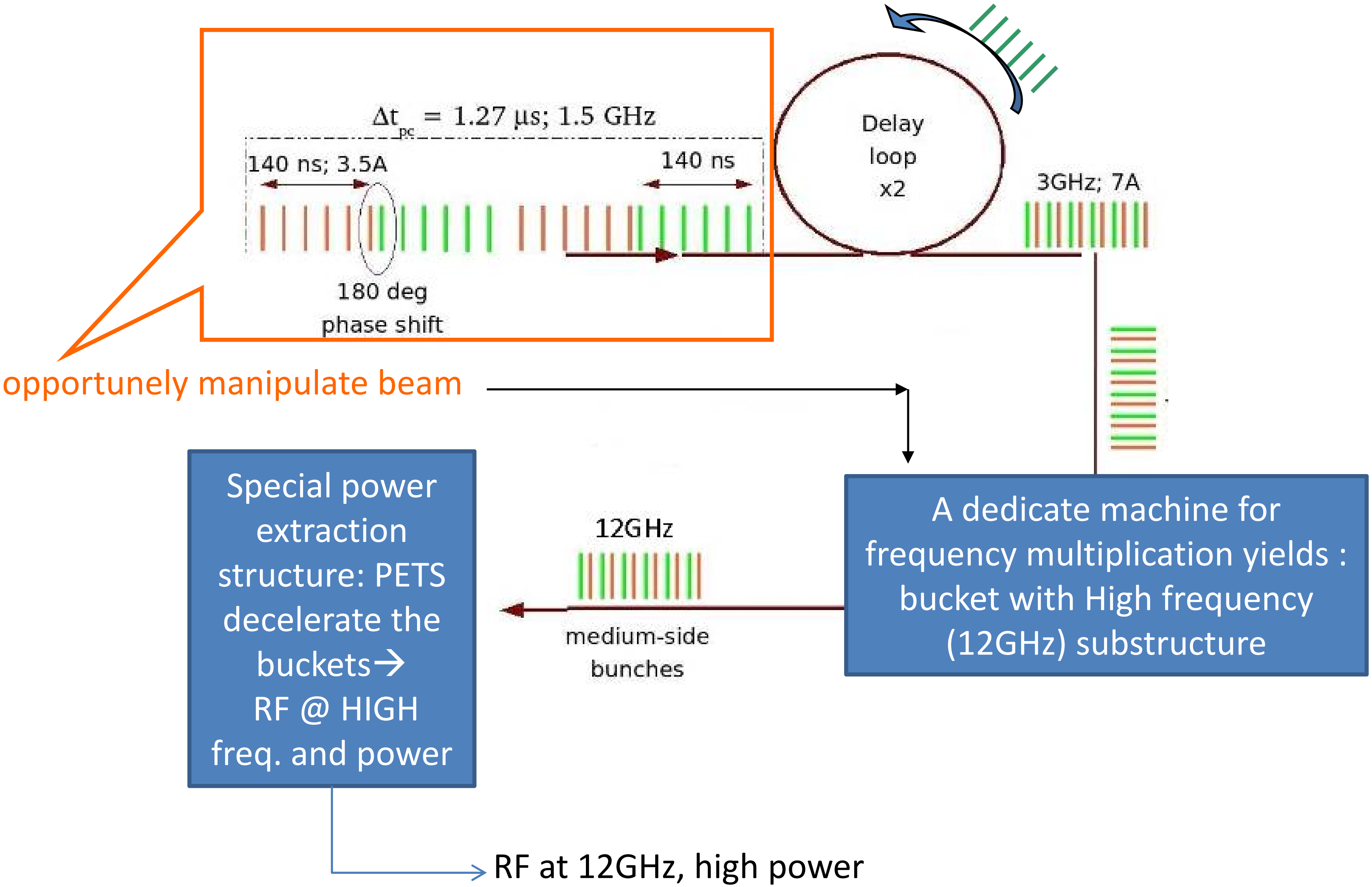


SPECIAL THANKS to Alexandra Andersson who produce the wonderful animation…

THANKS

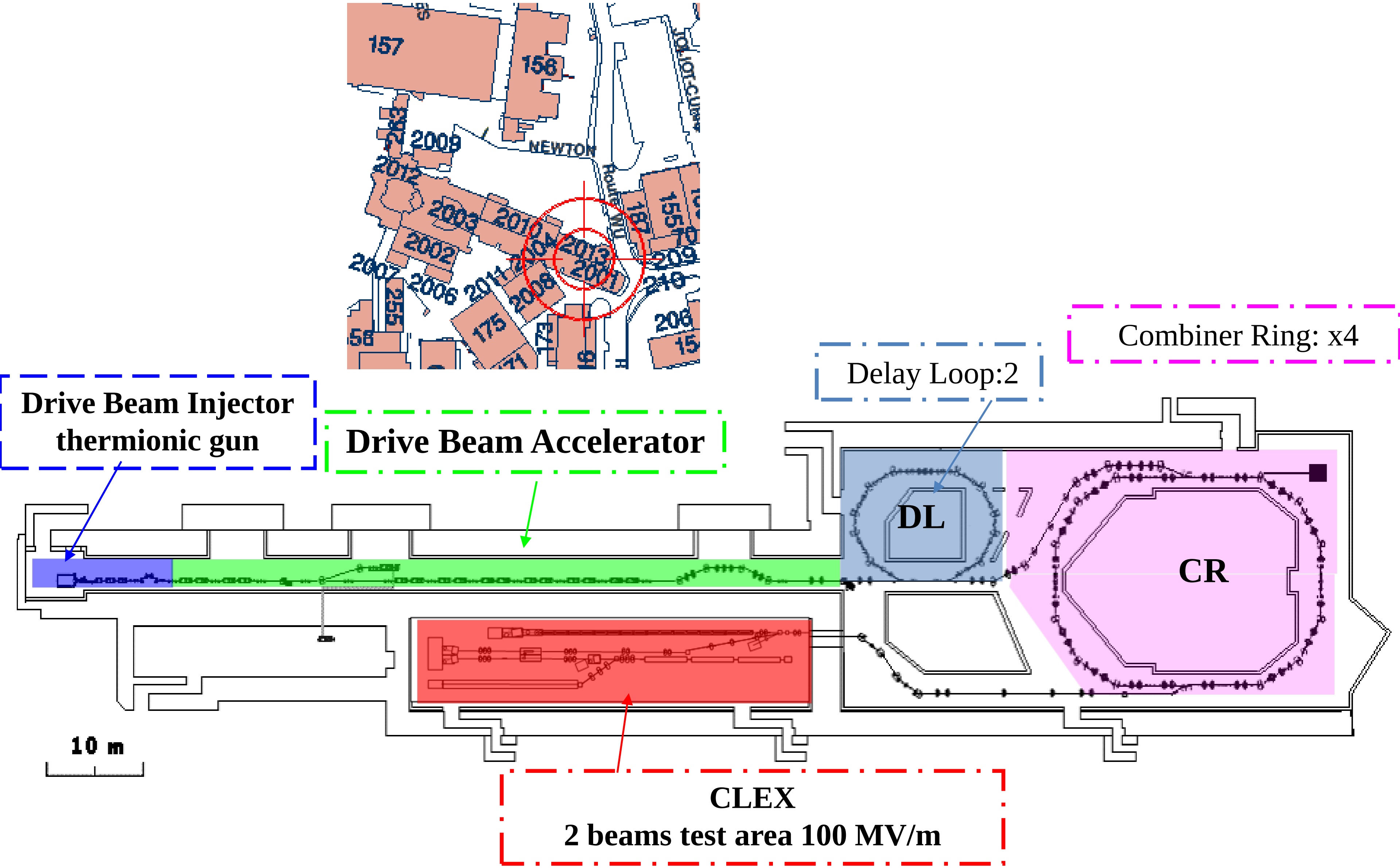


326 klystrons
33 MW, 139 μs
drive beam accelerator
2.38 GeV, 1.0 GHz
1 km
delay
loop
CR1
CR2
combiner rings
Circumferences
delay loop 72.4 m
CR1 144.8 m
CR2 434.3 m
326 klystrons
33 MW, 139 μs
drive beam accelerator
2.38 GeV, 1.0 GHz
1 km
delay
loop
CR2
CR1
decelerator, 24 sectors of 876 m
BC2
245m
TA
R=120m
BDS
2.75 km
IP
BDS
2.75 km
e- main linac , 12 GHz, 100 MV/m, 21.02 km
e+ main linac
BC2
245m
TA
R=120m
48.3 km
CLIC 3 TeV
booster linac,
9 GeV
BC1
e- injector
2.4 GeV
e-
PDR
365m
e-
DR
365m
e+
DR
365m
e+
PDR
365m
e+ injector,
2.4 GeV


Δt_pc = 1.27 μs; 1.5 GHz
140 ns; 3.5A
140 ns
180 deg
phase shift
Delay
loop
x2
3GHz; 7A
opportunely manipulate beam
Special power extraction structure: PETS decelerate the buckets→ RF @ HIGH freq. and power
12GHz
medium-side
bunches
A dedicate machine for frequency multiplication yields : bucket with High frequency (12GHz) substructure
RF at 12GHz, high power

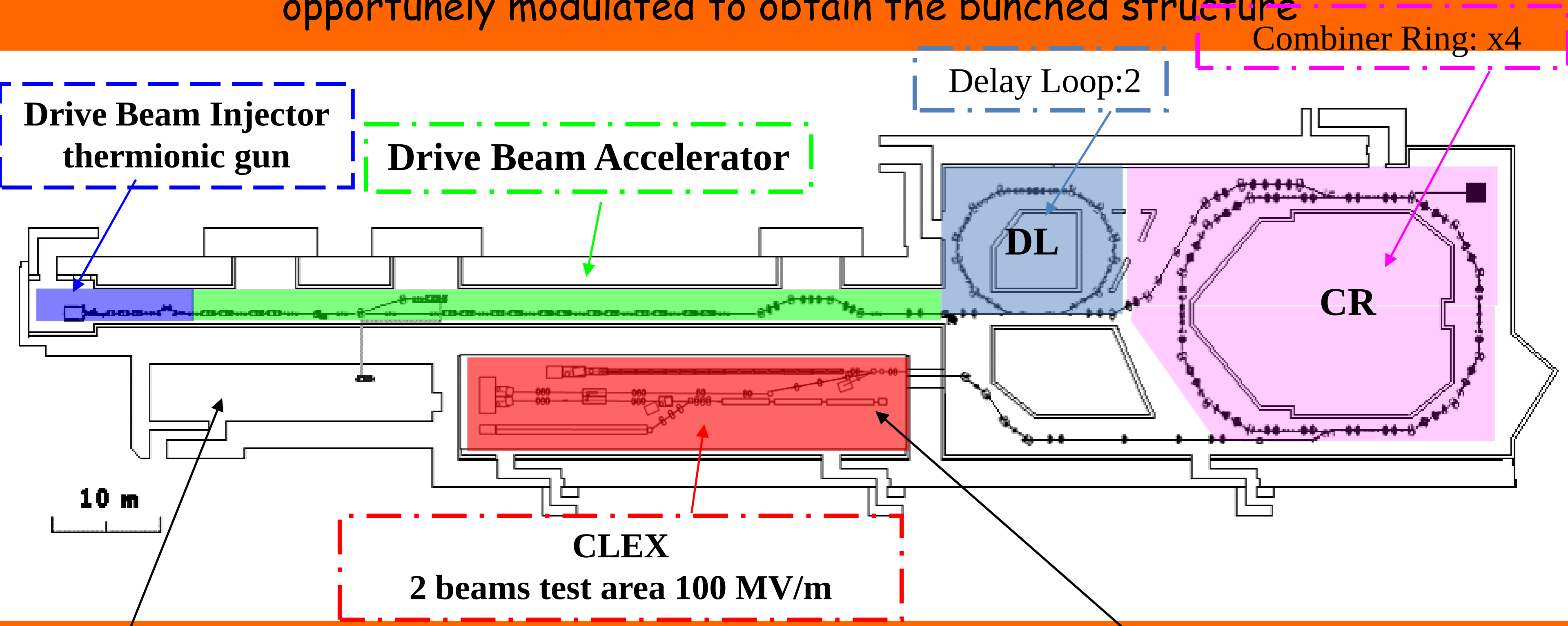
CTF3:

CTF3 (CLIC test facility 3rd) small version of CLIC power source



CTF3 electron sources:

Drive beam: thermionic gun produces a continuous e-beam which is opportunely modulated to obtain the bunched structure



Main beam: electron bunches produced by a laser based e-gun (generally named photoinjector) for the "CALIFES" "main" accelerator

A second photoinjector "PHIN" is under test: could it replace the Drive Beam thermionic gun ? → simplification of the drive beam generation scheme with reduction of losses <u>due to the already bunched structure generated by photoinjectors</u>

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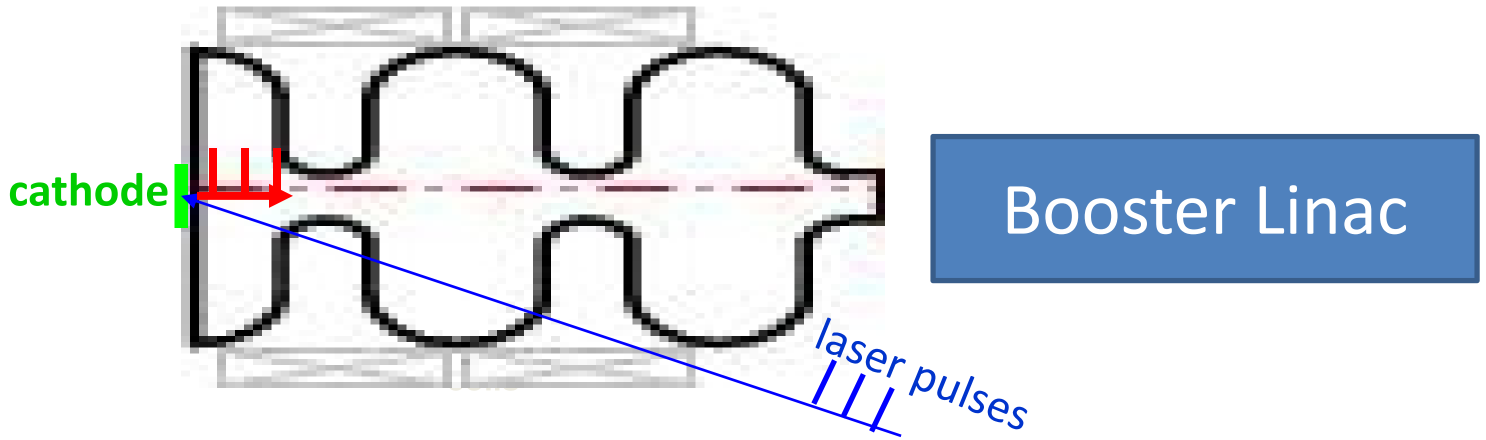
Photoinjectors

Since 1985 when the photoinjectors concept has been introduced their used grown exponentially!

They offer a good handle of the initial condition i.e. transverse and longitudinal distribution of the electron bunches.

Initial condition is controlled by the laser properties i.e. pulse length ,spot size energy

Principles:
laser pulses illuminate
a **photocathode** generating e-bunches by photoelectric process
The cathode is placed into an
accelerating structure to properly extract the electron bunches i.e
Multi-cell rf gun cavity with high peak electric field to reduce space charge effect



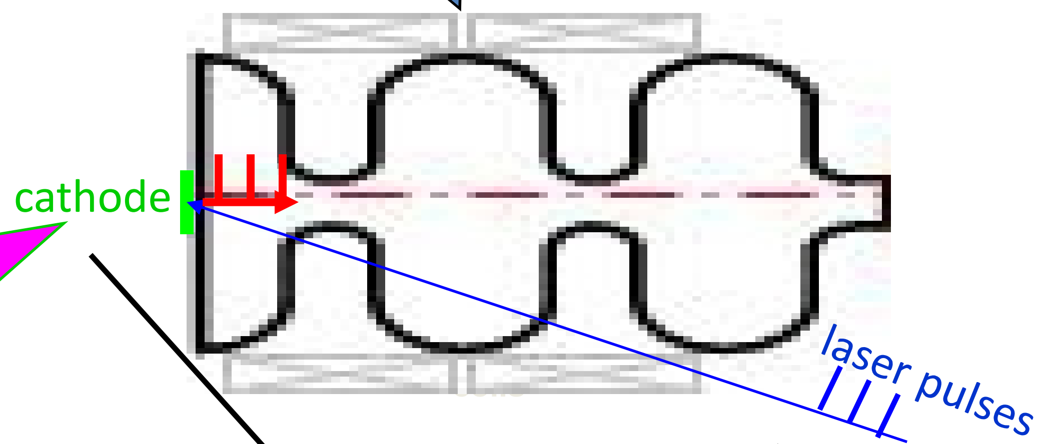
Choice of photoinjector elements

Gun is determined by: desired charge vacuum condition, rf frequency

Cathode is determined by:

charge per bunch

time response



The figure of merit of photocathode i.e. Quantum Efficiency

QE= #extracted electrons / # incident photons

Determines the laser pulse energy

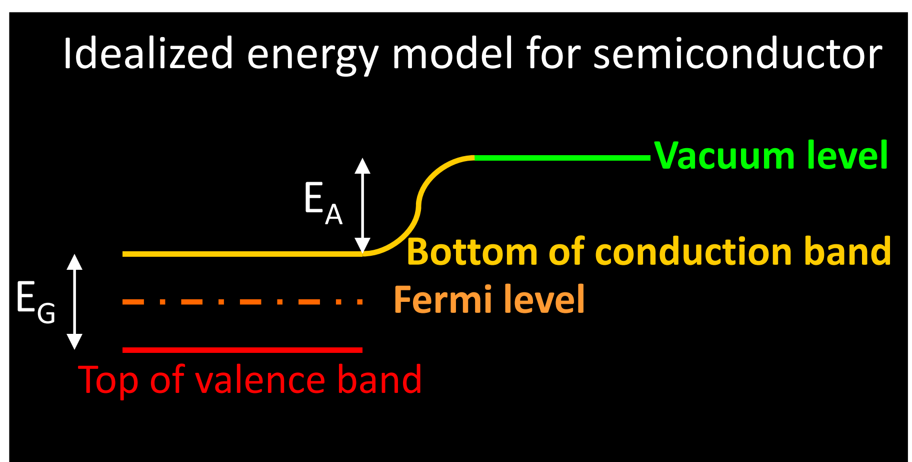
Photoemission

Photoemission process plays an important role in photoinjectors: the physics of *Metal and Semiconductor* puts constraints on the choice of the cathode to be used

Photoemission process:
- Absorption of photon
- Motion of "e" to vacuum interface
- Surface barrier

If hv > E_G, the photon can be absorbed and converted in free electron; to escape into vacuum e-energy > E_A (electron affinity)

Tot required energy: $E_G + E_A$.



Photoemission differences:

	Metal Mg, Copper….	Semiconductor GaAs,Cs_2Te (cesiumtelluride)
Summary	Low efficiency ~10^{-4} Fast response time ~10^{-15} , Resistant to contamination	High efficiency ~10^{-2} Slower time response ~10^{-12} , sensitivity to contamination, Response to visible and IR laser

	PHIN
number of bunches	1908
macro bunch beam current [A]	3.5
bunch spacing [ps]	666.7 (1.5GHz)
charge per bunch [nC]	2.3

Semiconductor cathode

Cs_2Te

Cern hosts a photoemission laboratory which is a dedicated facility to study different cathodes

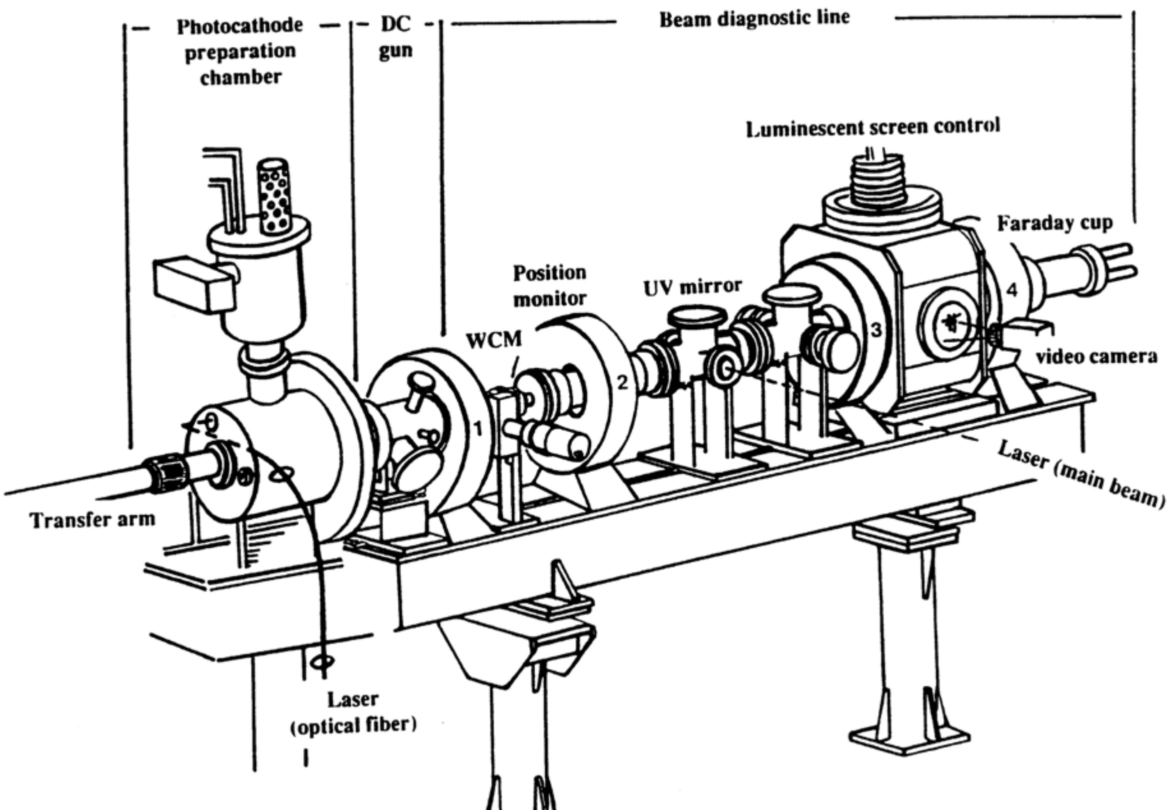


Figure 1: The DC test bench

- DC gun (8MV/m)
- Electrode gap:1cm
- $1x10^{-11}<p<1x10^{-10}$ mbar
- 4 mm laser spot

In the precedent years different cathodes have been tested:

metal cathode → rejected (low efficiency)

Alkali photocathode (semiconductor) has been studied in more details:

Table 4: Alkali photocathodes : QE = f(λ)

λ (nm) E (eV)	193 6.42	213 5.82	266 4.66	355 3.49	532 2.33	Ea + Eg eV
Cs_3Sb		3.5×10^{-2}	2.0×10^{-2}	1.8×10^{-2}	3.8×10^{-3}	2.0
K_3Sb		1.4×10^{-2}	1.6×10^{-2}	7.6×10^{-3}	2.3×10^{-4}	2.3
Na_2KSb		7.7×10^{-2}	6.1×10^{-2}	3.5×10^{-2}	2.0×10^{-4}	2.0
CsI	9.6×10^{-2}	6.8×10^{-2}	7.1×10^{-5}	1.9×10^{-6}		6.4
CsI + Ge		7.3×10^{-3}	1.3×10^{-3}	2.0×10^{-6}		5.0
Cs_2Te		6.0×10^{-2}	5.7×10^{-2}	2.0×10^{-4}		4.5

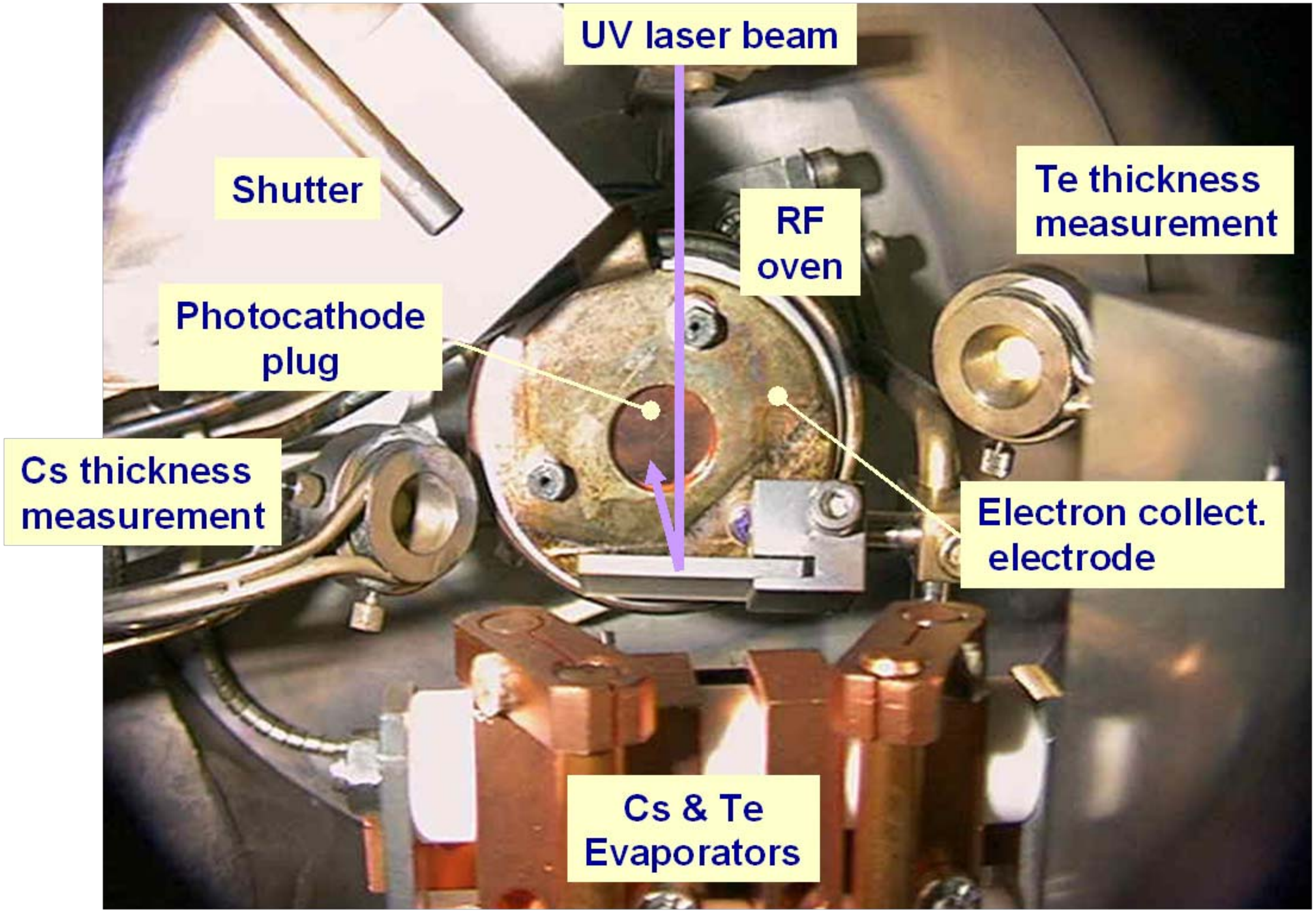
→ Ce2Te is so far the most useful cathode:

1) high quantum efficiency

2) acceptable life time: longer than the time needed to produce and make available 4 new cathodes → less than 4days

Tests in Rf gun at 100MV/m; pressure$2x10^{-9}$<P<$7x10^{-9}$ mbar, showed that after full 12 working hours per day after 4 days (~50h)→QE~ 3% within specification and it keeps this value over more than 100h. QE=3% reference value in project specification

The photoemission laboratory has been equipped for the production of Ce2Te:



Photocathode conclusion

- Ce_2Te semiconductor cathode has been selected for the commissioning of CTF3 photoinjectors due to its acceptable life time and high quantum efficiency
- A good vacuum condition ~10^{-10} mbar is required to preserve the cathode performance
- A transport carrier under vacuum (down to ~10^{-11} mbar) need to be used to transport the new cathode from the photoemission laboratory to the PHIN gun installation

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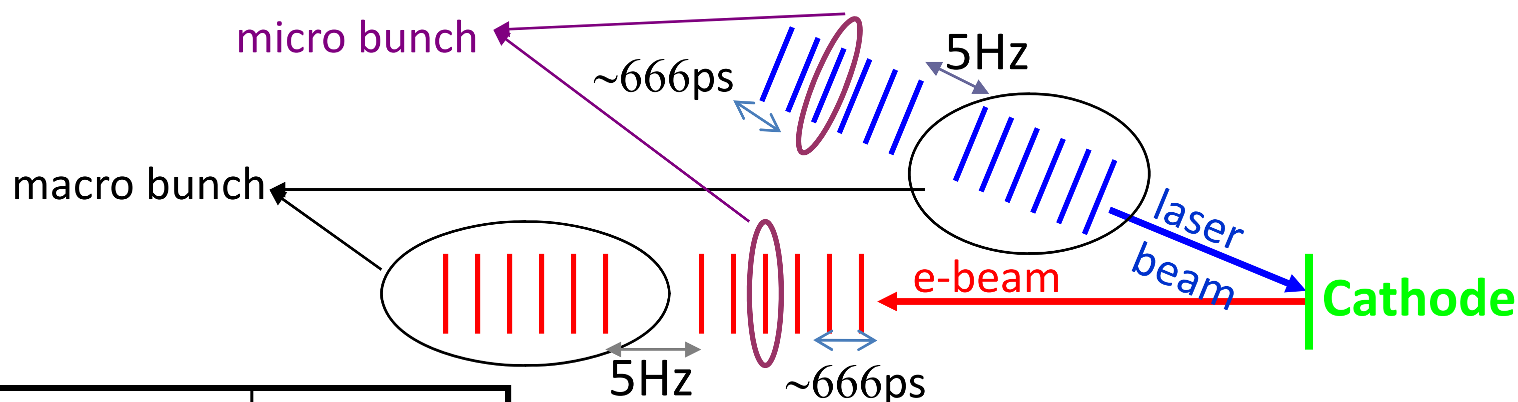
From laser to electron:

In photoinjectors the laser time structure is transferred into the electron time structure



	PHIN
number of bunches	1908
repetition rate [Hz]	5
bunch spacing [ps]	~666 (1.5GHz)
bunch length FWHM [ps]	< 10
charge per bunch [nC]	2.3

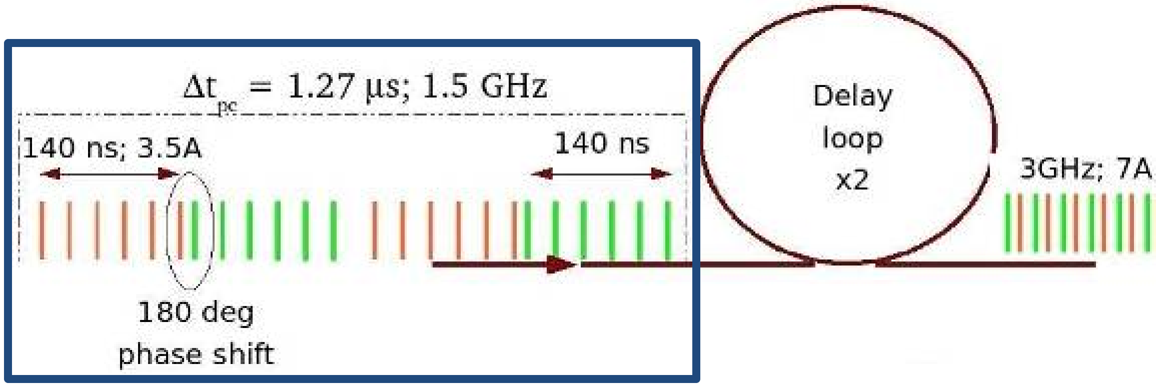
ir diode pumped amplifier (multi pass)

Laser r.r 1.5GHz → Mode locked

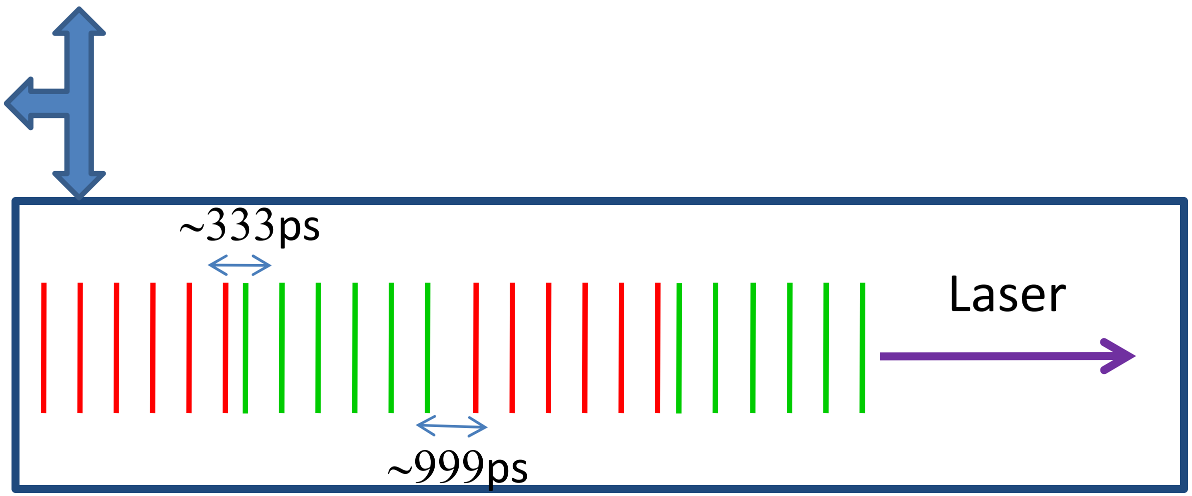
+ Cathode QE (3%) = 380nJ UV energy

Phase coding:

Being the laser time structure transferred into the electron time structure



The laser time distribution must have this profile



An optical device "Phase Coding" has to be implemented in the laser chain !!

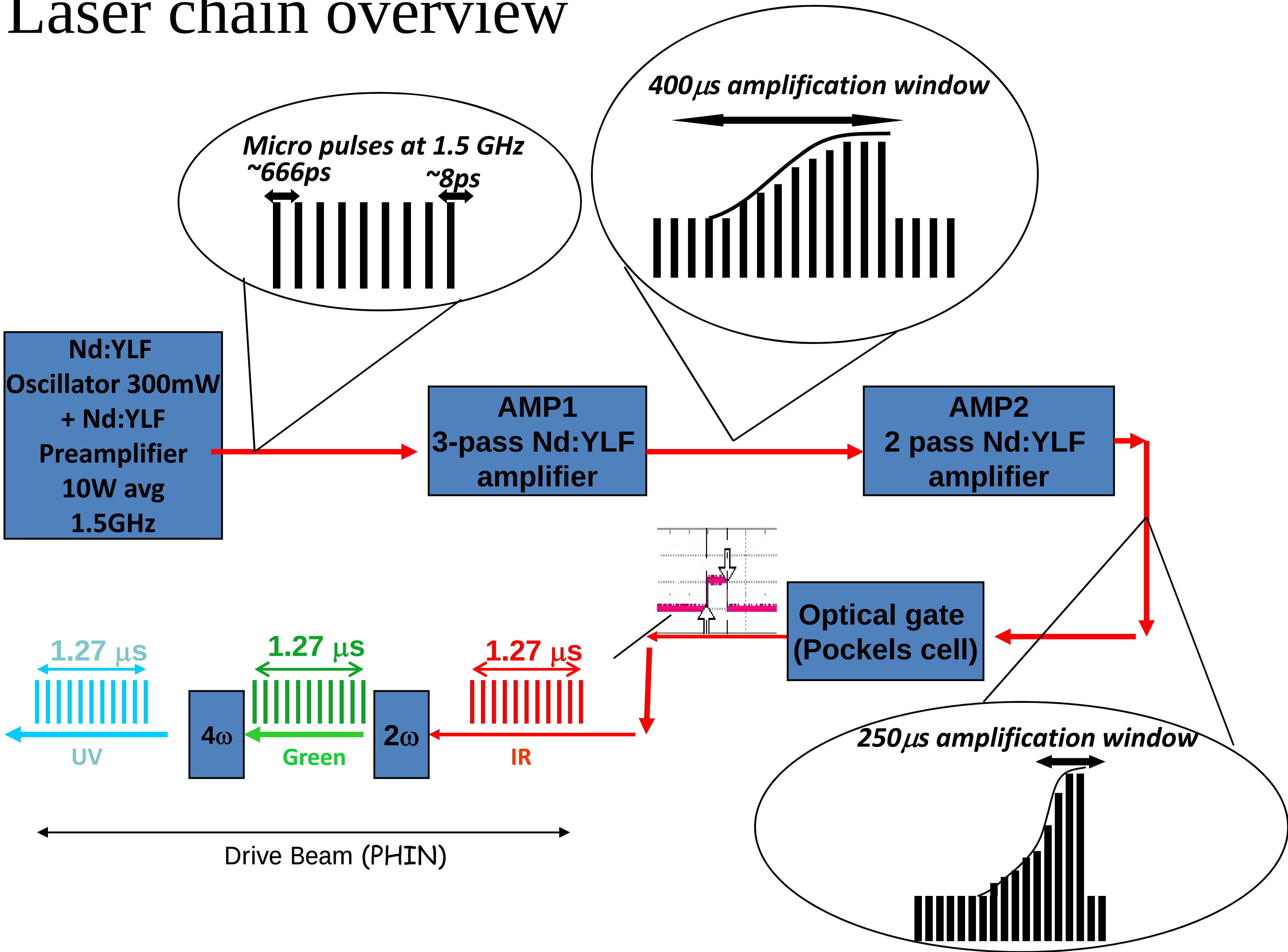
Device is not installed:

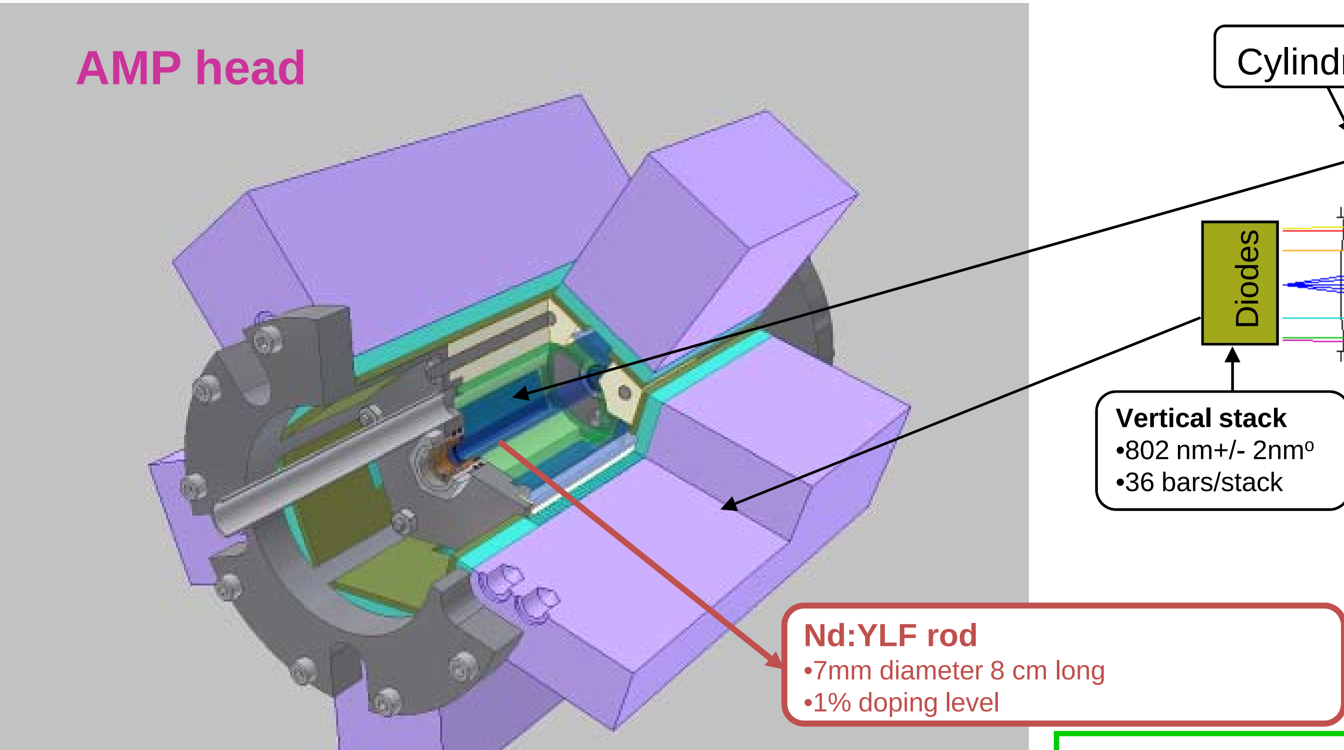
Losses too high → need a second booster amplifier.

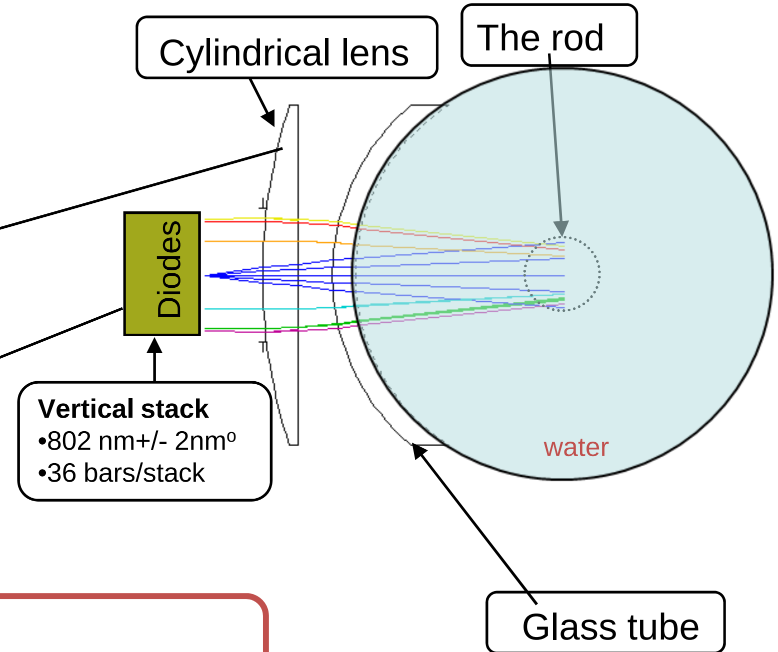
Feasibility study of the Phase Coding on the final laser must be performed

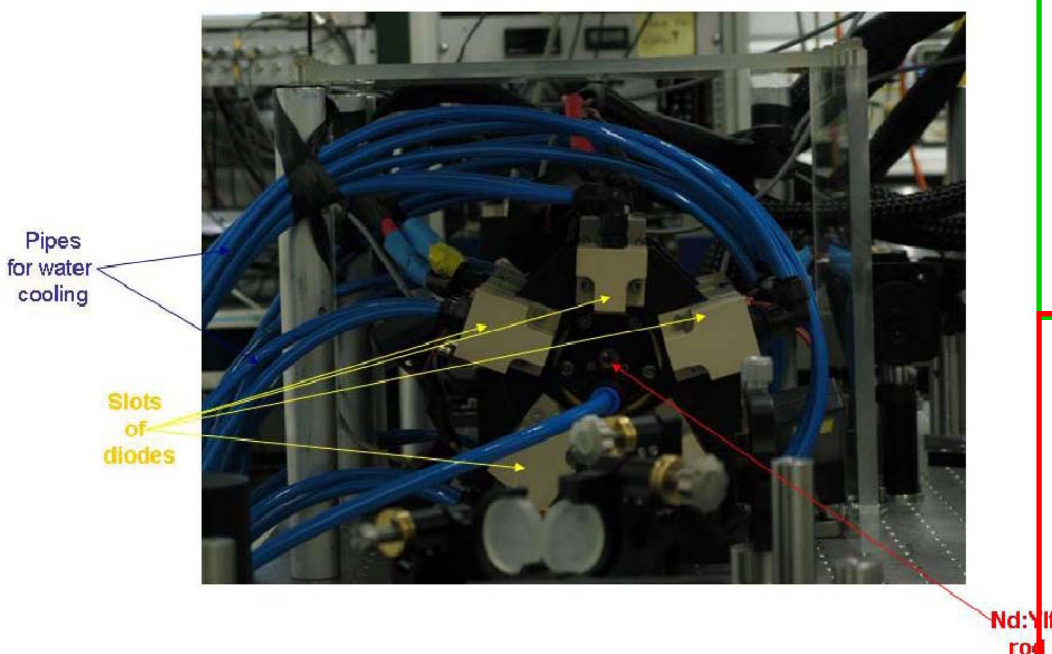
(It has been studied on a 100MHz laser Nd:Yag laser)

Laser chain overview









AMP1 pumping diode:

3KW peak power each (square pulse window 400µs long)

→15 KW total power

→Rod : 8cm long; 7mm diameter

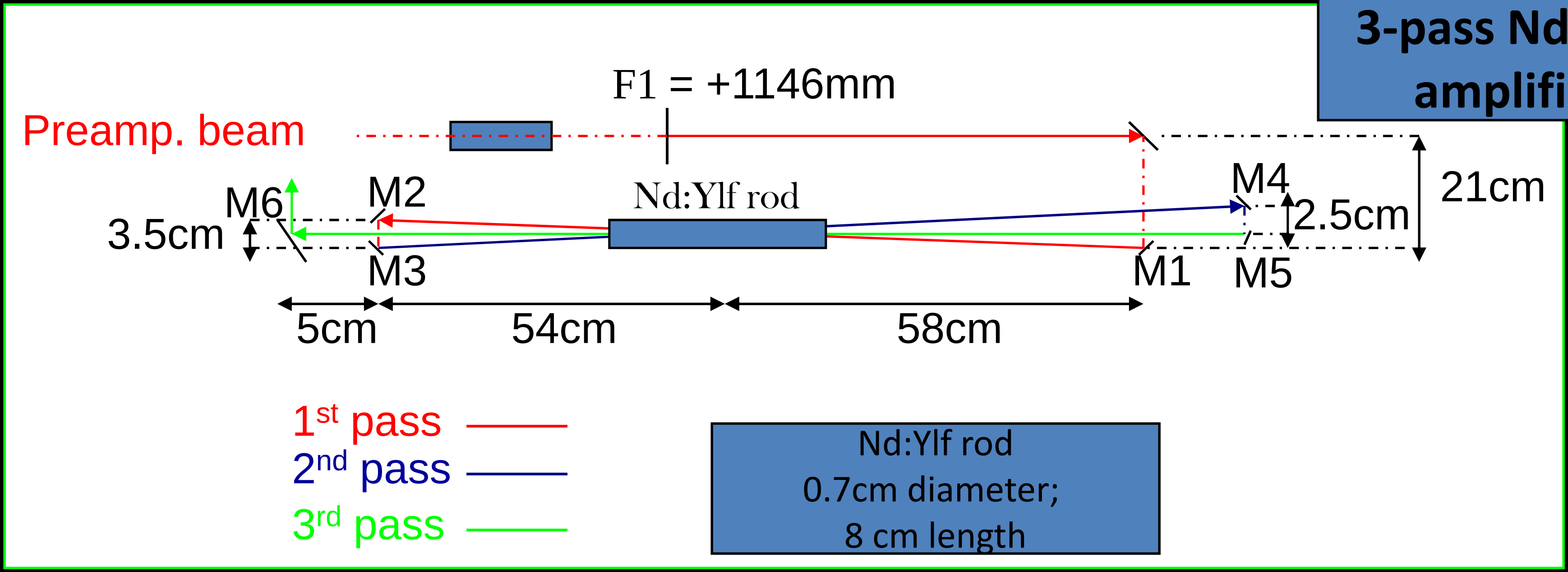
AMP2 pumping diode:

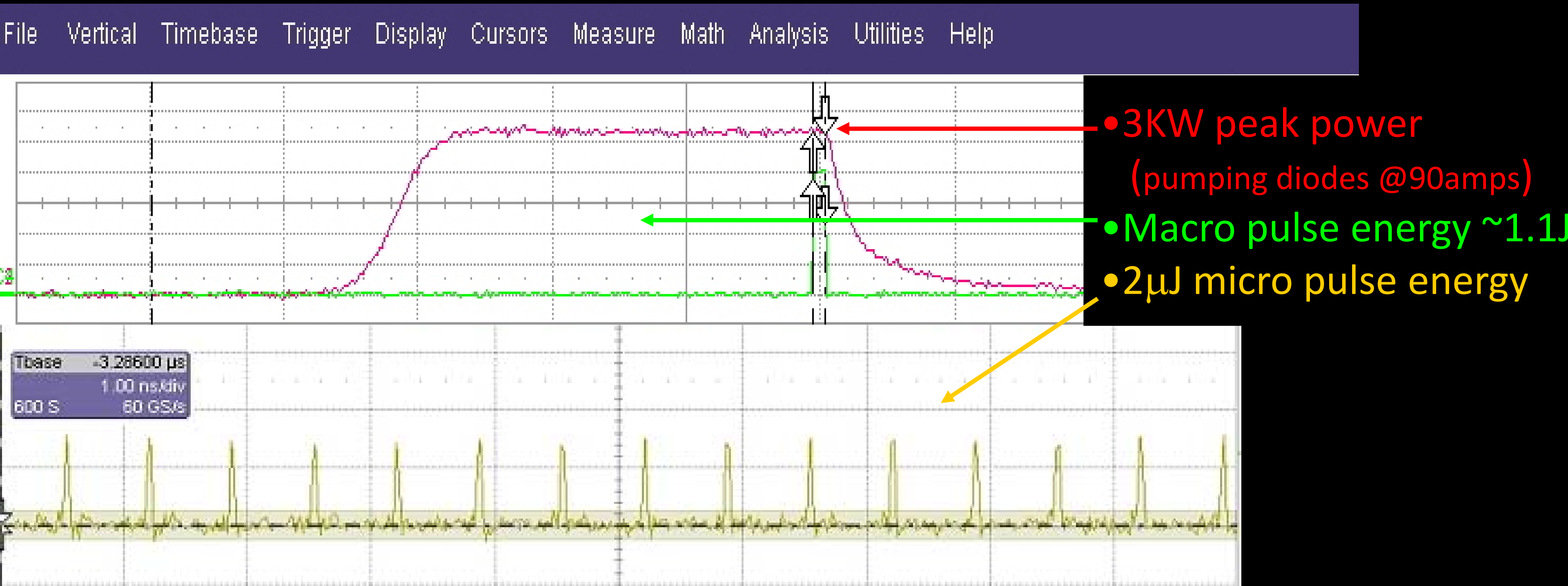
3.6 KW peak power each (square pulse window 250µs long)

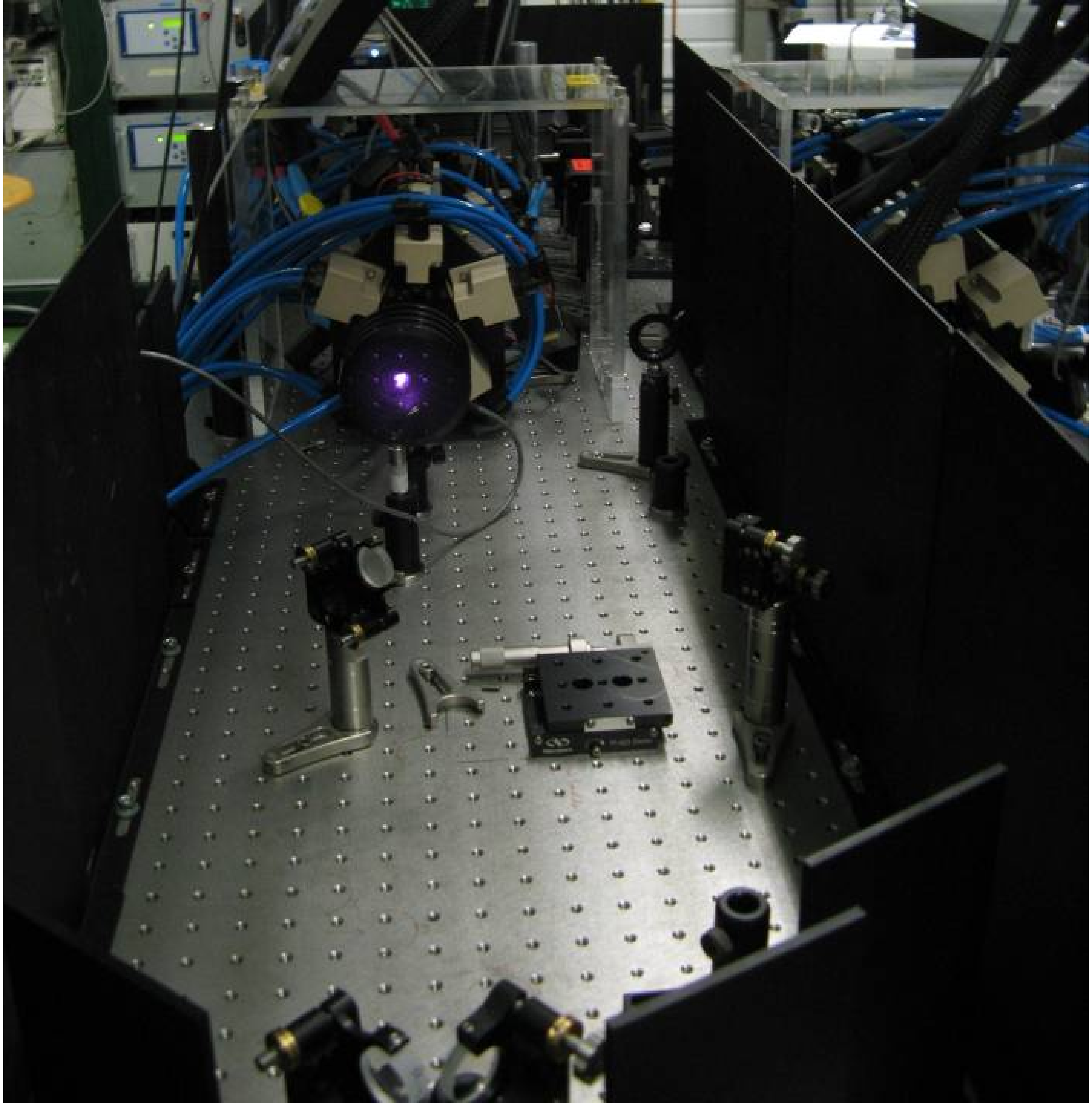
→18 KW total power

→Rod 12 cm long; 1 cm diameter

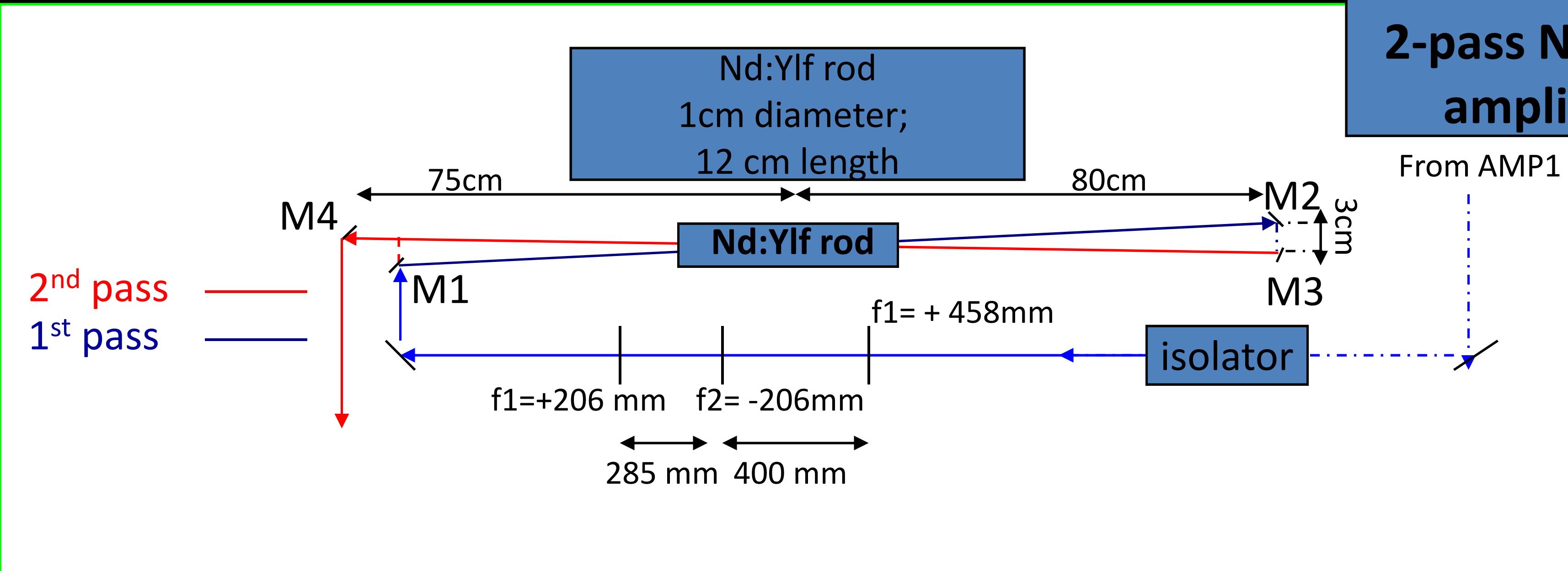
AMP1 3-pass Nd:YLF amplifier

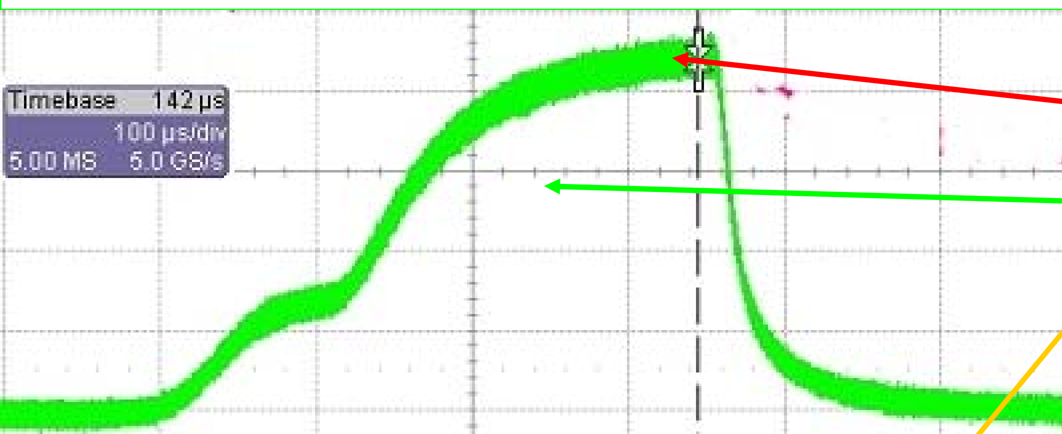




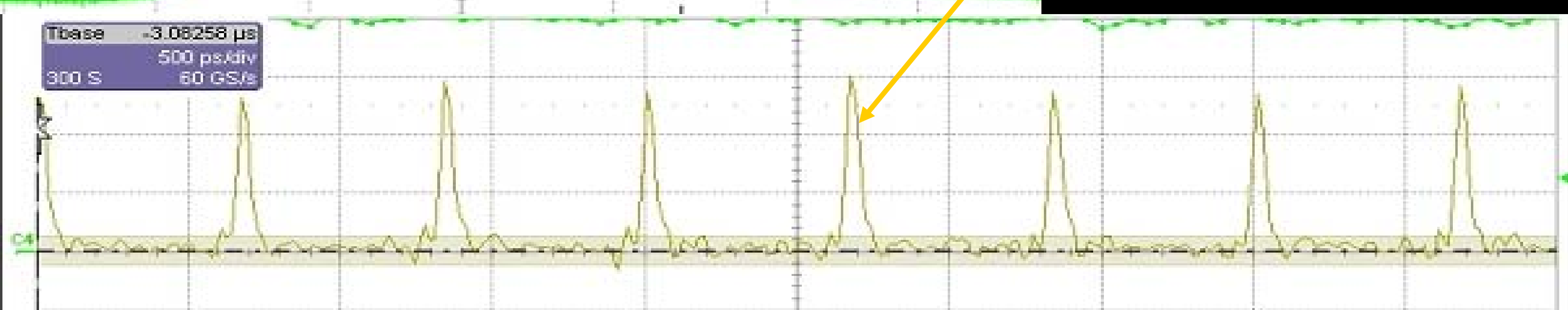


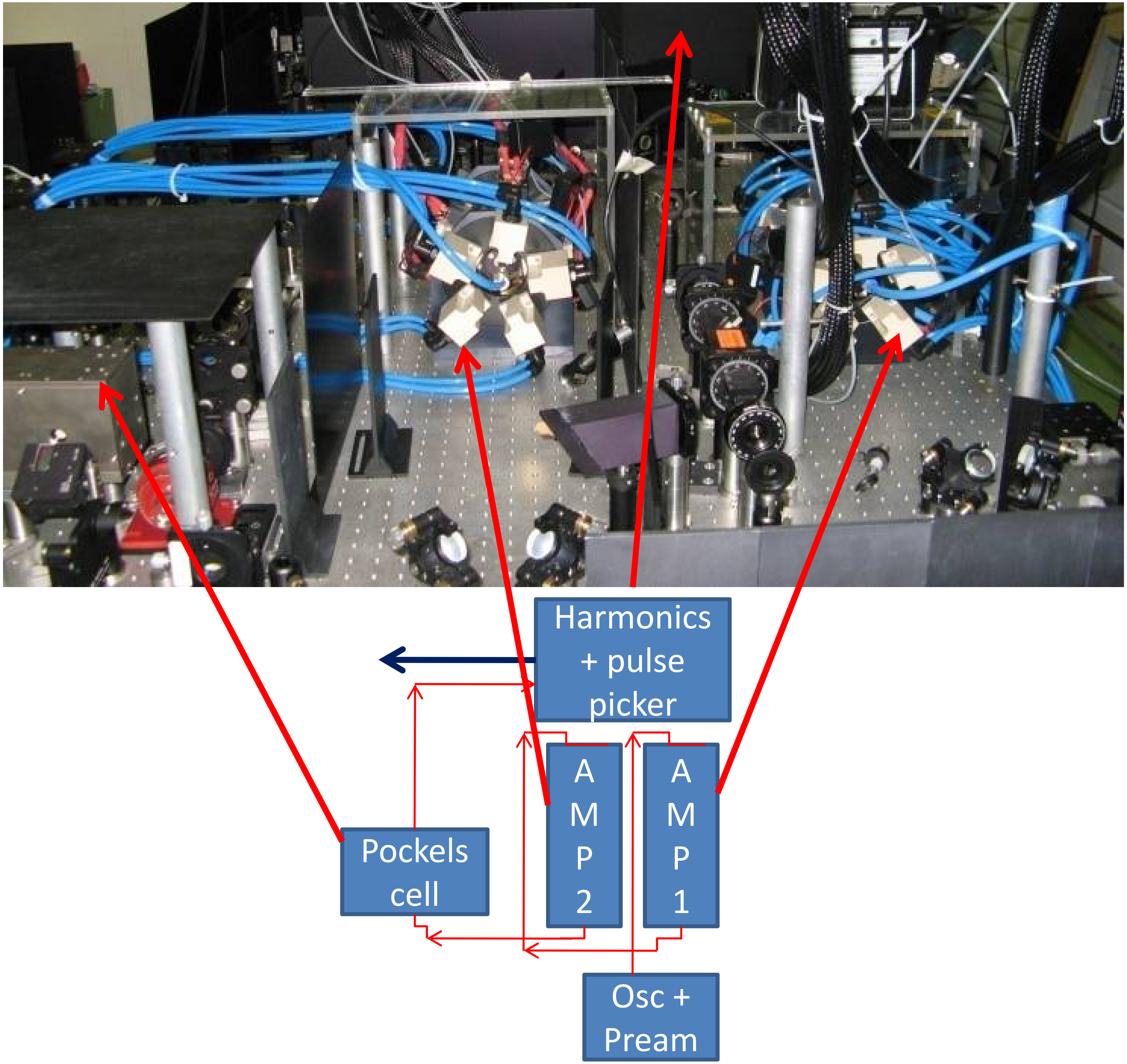
AMP2
2-pass Nd:YLF amplifier



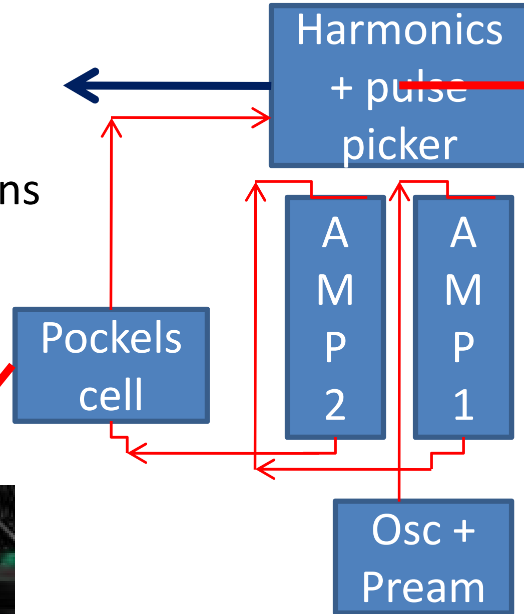


- ~8KW peak power (pumping diodes @90amps)
- Macro pulse energy ~1.7J
- ~6μJ micro pulse energy




Harmonics + pulse picker
A M P 2
A M P 1
Pockels cell
Osc + Pream

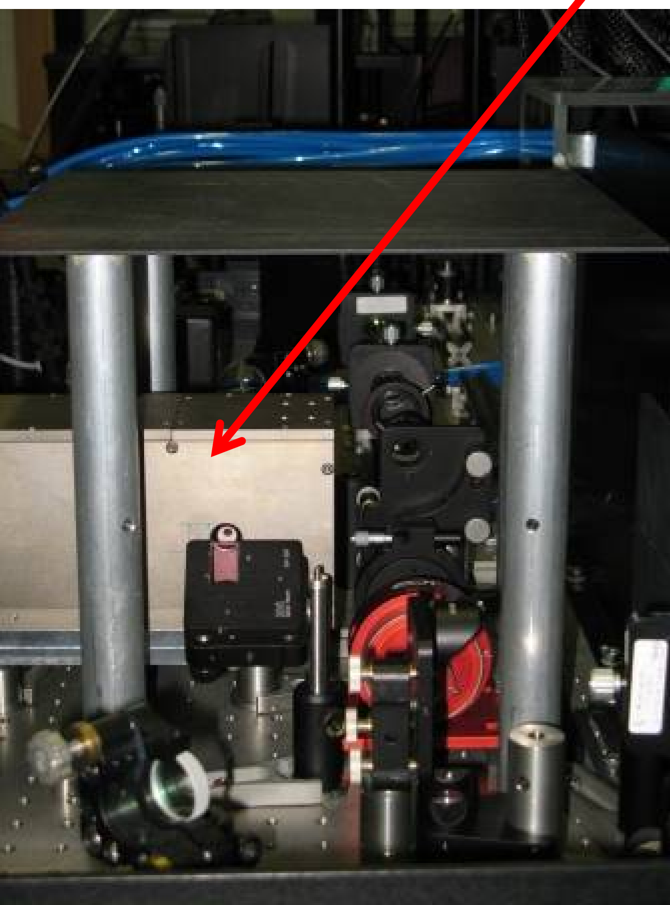
Optical gating system

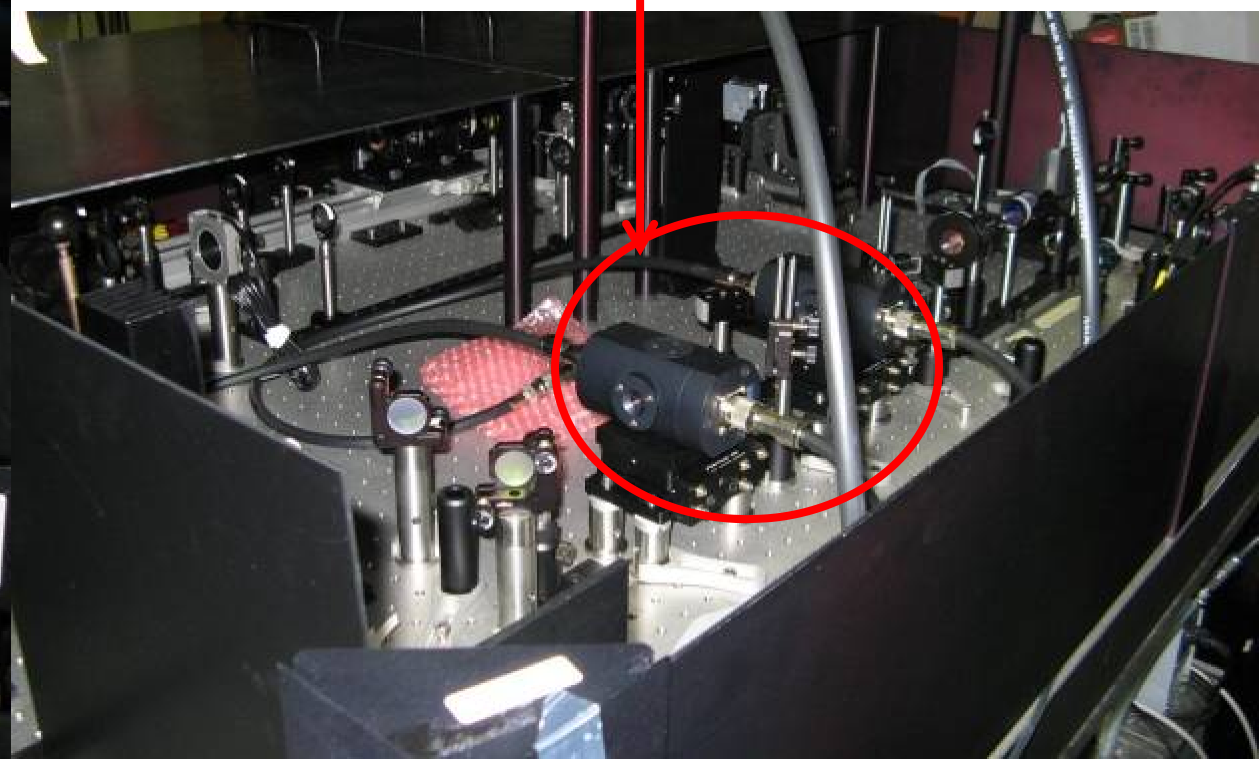


Pockels cell → down to 150ns (4ns rise & fall time)

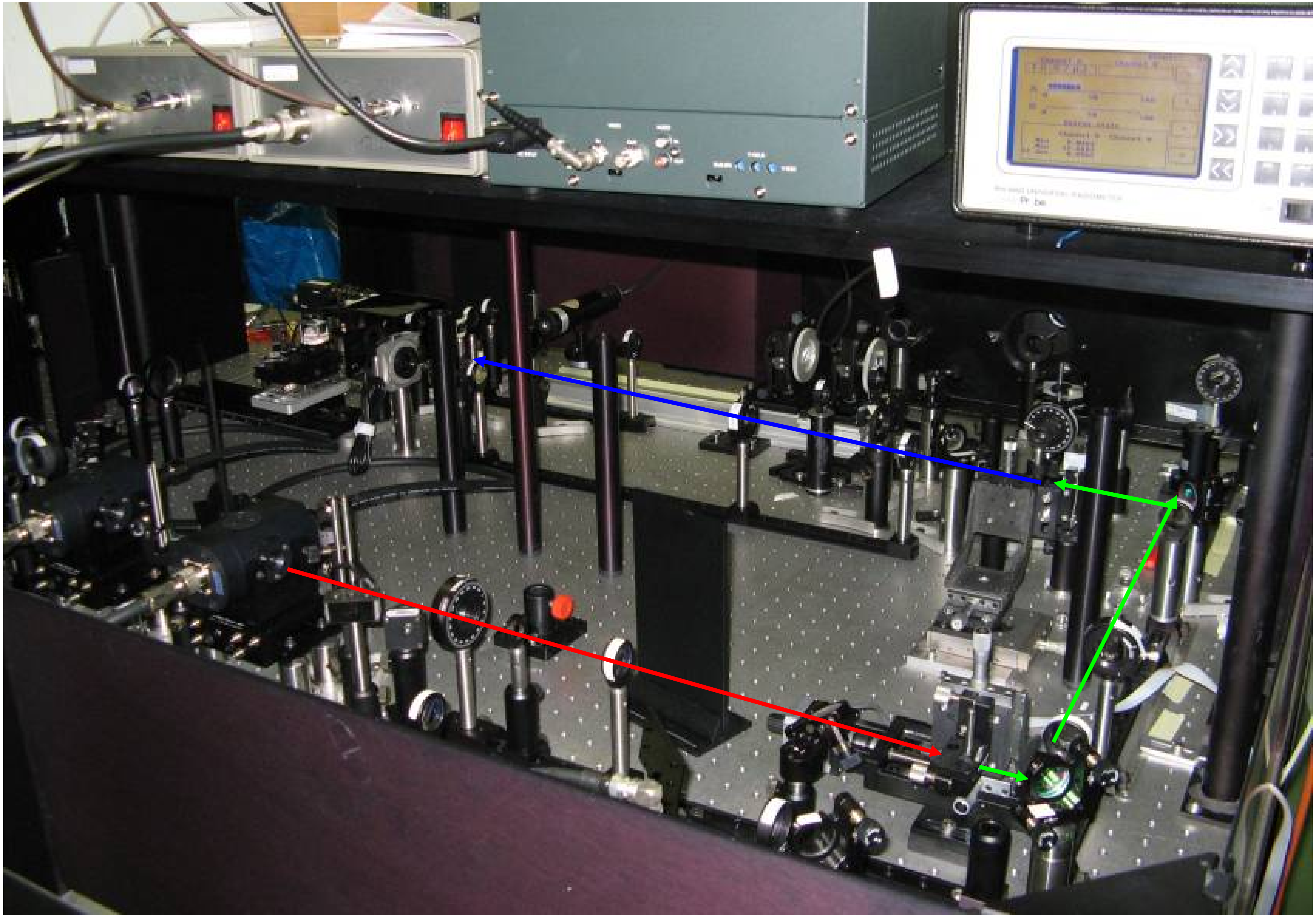
Pulse picker:

From 140 ns to <1ns for just one micro pulse selection





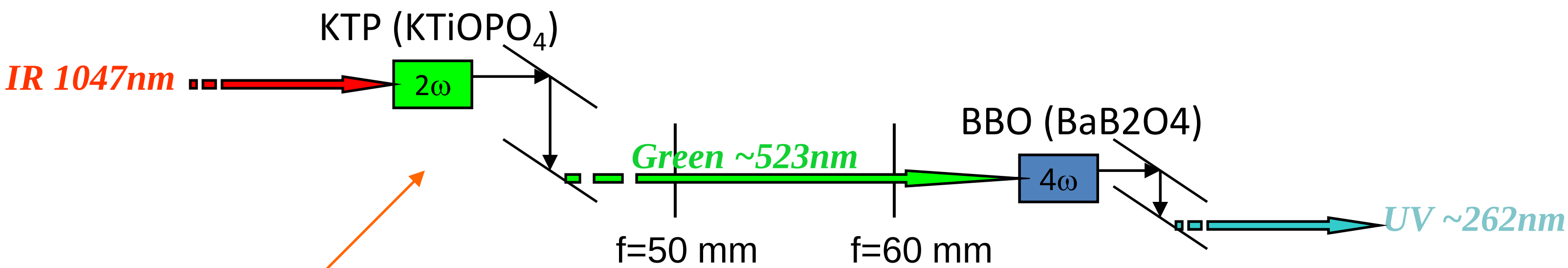
HARMONIC CONVERSION TABLE

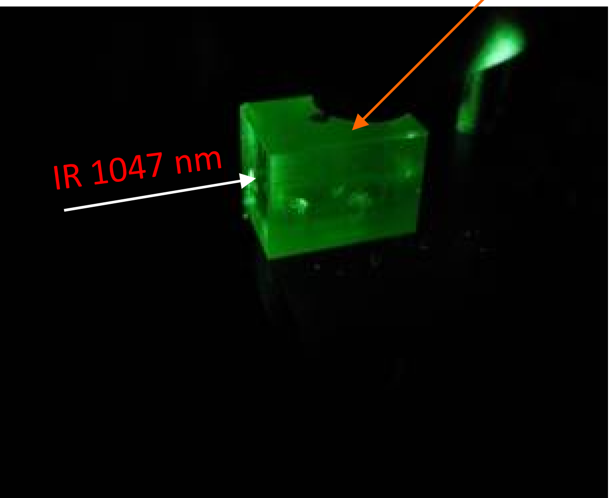


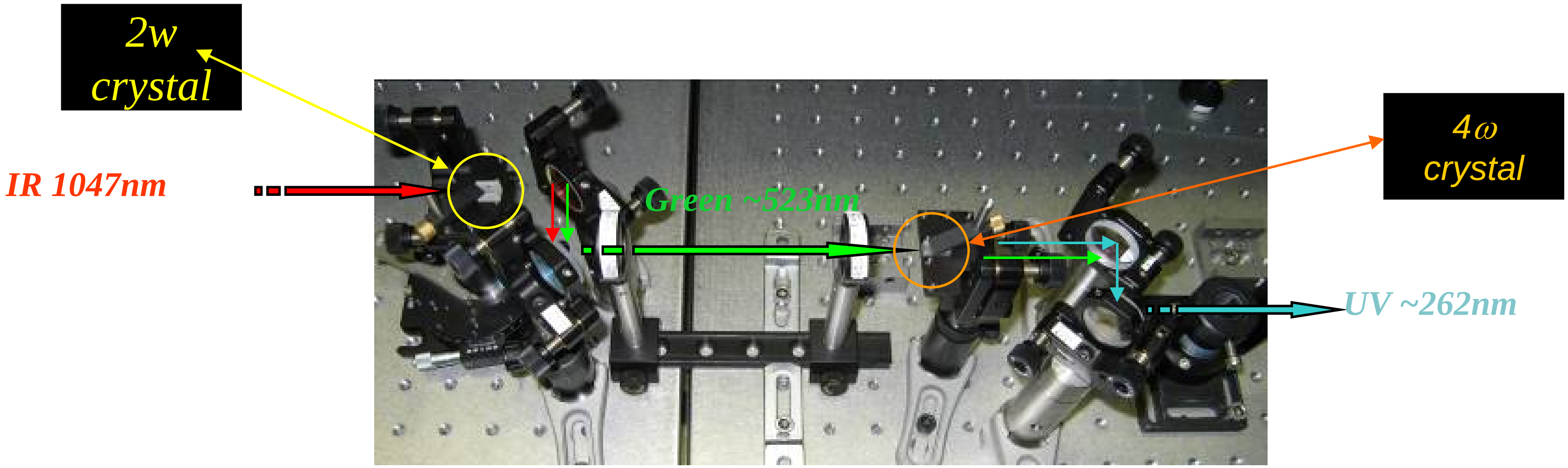
HARMONIC CONVERSION

Ce-Te cathode required laser wavelength λ ~262 nm

Nd:Ylf : λ~1047nm need to be converted in a two stages non linear process by crystals







	GREEN micro pulse energy	UV micro pulse energy
Amp1 + Amp2 @ full power	**1.3 μJ** **~29% conversion**	**->330nJ in a micro pulse** **~24%conversion** **~243nJ on cathode due to transport line** **~370nJ on specs**

With this beam the commissioning of both "PHIN" and "CALIFES" photoinjector has started and already showing satisfactory performance

Laser: Conclusion& Future

- A stable beam has been produced and it is being used in the two CTF3 photoinjectors. Nevertheless the UV laser energy has to be improved to reach the project specification:
  PHIN→ ~370nJ on cathode (~250nJ now); CALIFES→600nJ (~290nJ now)
- Modifications of the second amplifier & harmonic conversion scheme are under development
- A feedback system needs to be studied and implemented to increase the intensity stability <1% for UV (~2% now!)
- The phase coding = fiber based interferometer device to obtain the proper drive beam time structure is not yet installed; it requires detailed studies about how to it performs on our laser and how to be properly implemented in the system
- Laser to RF synchronization: jitter measured ~630fs-> satisfactory! (specs <1ps)

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Acknowledgements

- We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" programme (CARE, contract number RII3-CT-2003-506395).

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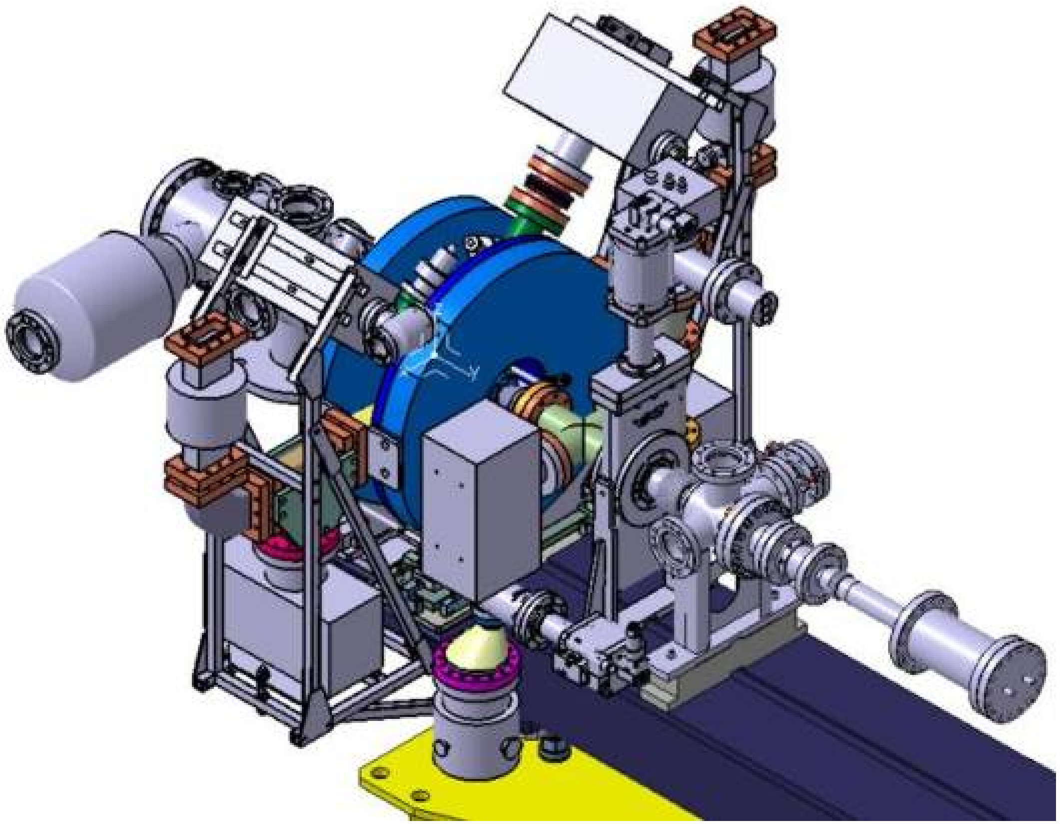
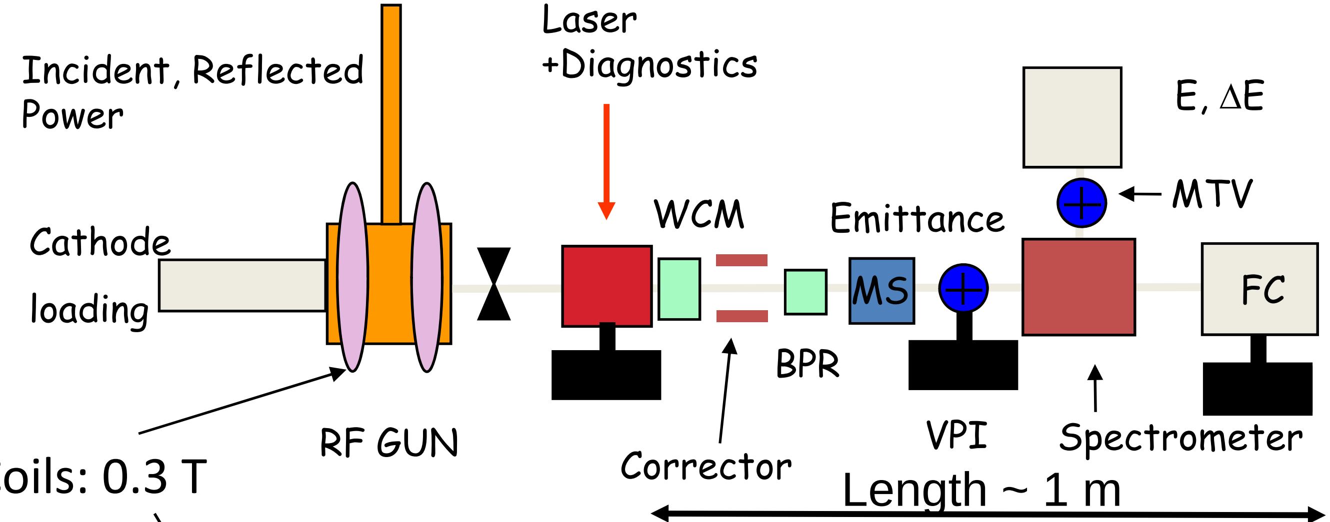
PHIN photoinjector



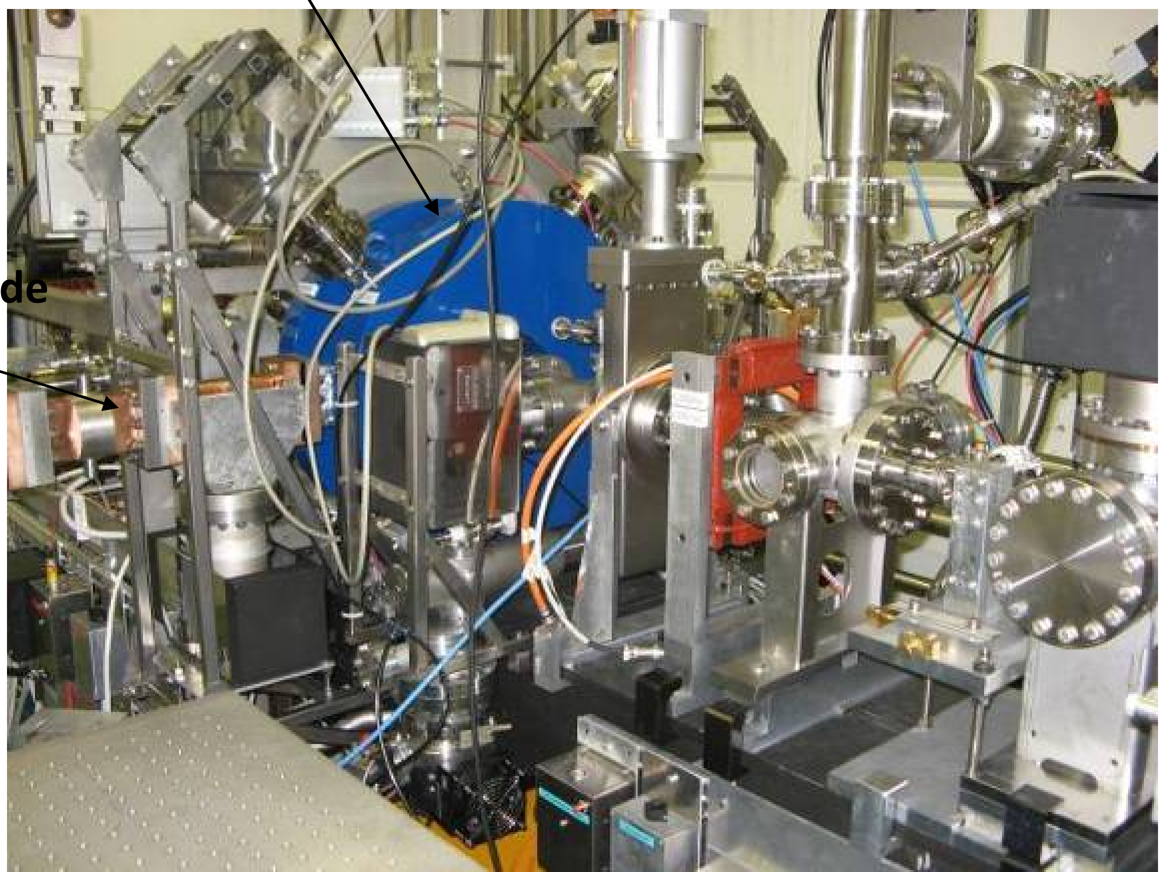
	PHIN
RF frequency [GHz]	2.9985
RF power [MW]	30
beam energy [MeV]	5-6
beam current [A]	3.5
number of bunches	1908
bunch spacing [ps]	666.7
charge per bunch [nC]	2.3
repetition rate [Hz]	5
bunch length FWHM [ps]	< 10
rms. energy spread [%]	< 2
n. emittance [π mm mrad]	< 25
vacuum pressure [mbar]	$< 2 \times 10^{-10}$

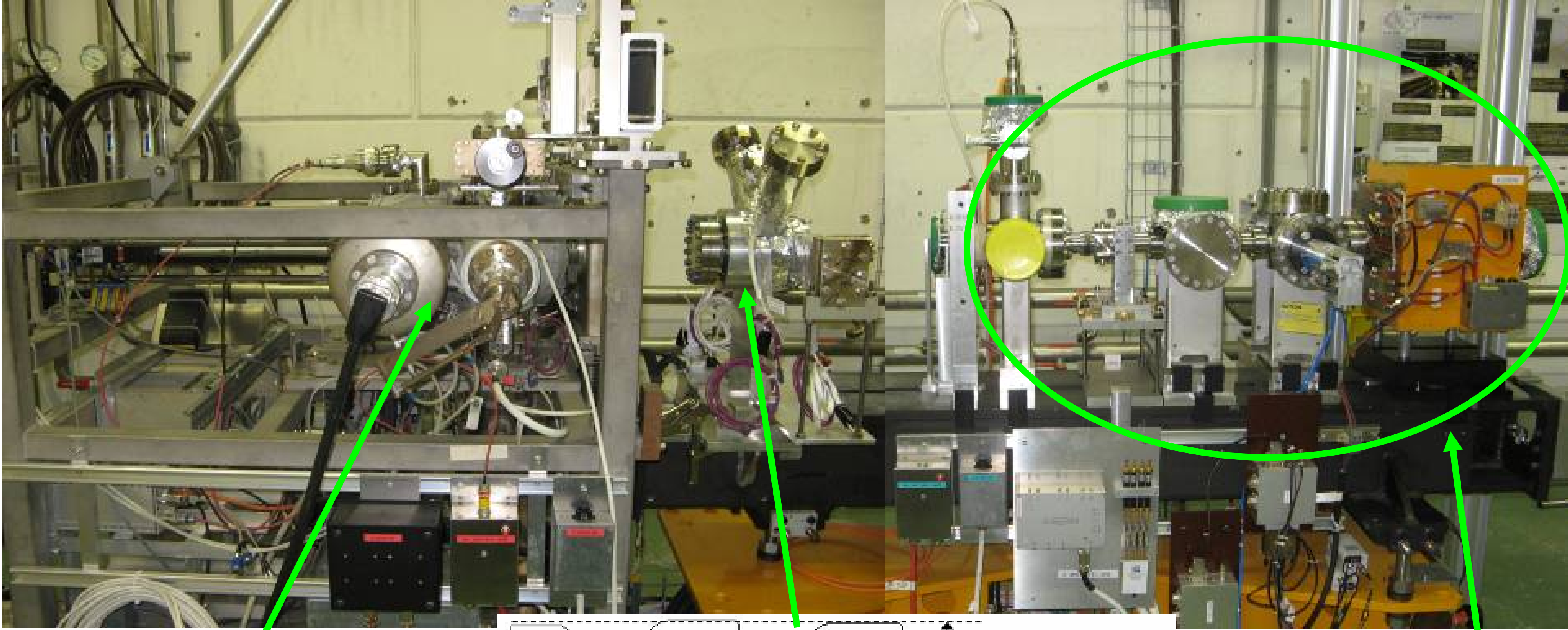
PHIN

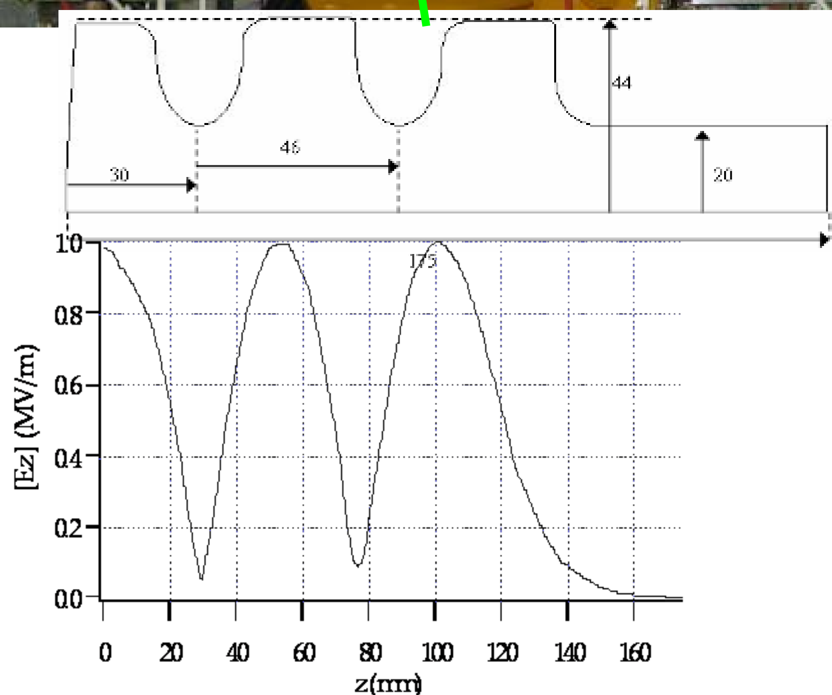


Solenoid Coils: 0.3 T

Rf wave guide







Propagation direction

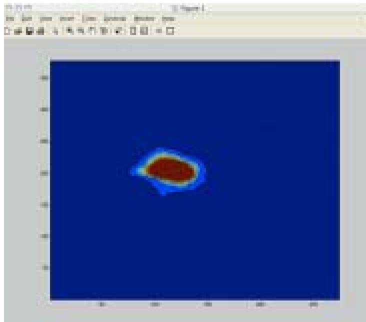
Cathode loader

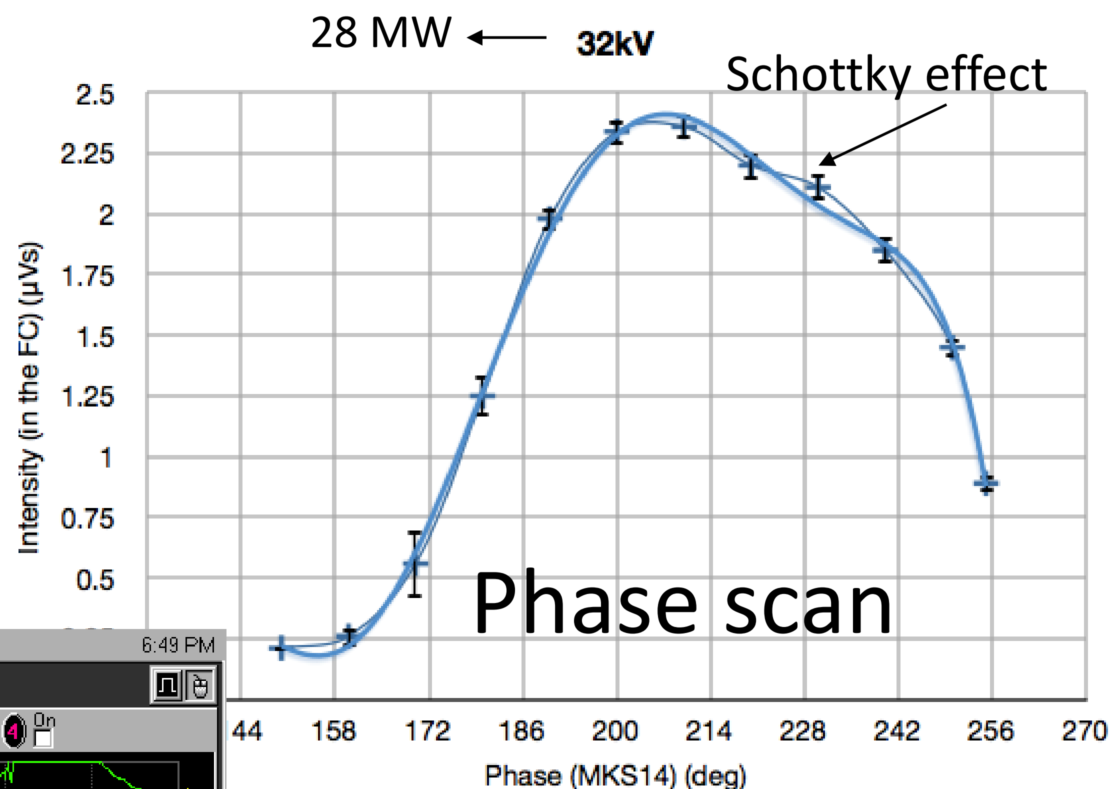
Important to install the Ce-Te cathode which require high vacuum to preserve its performance

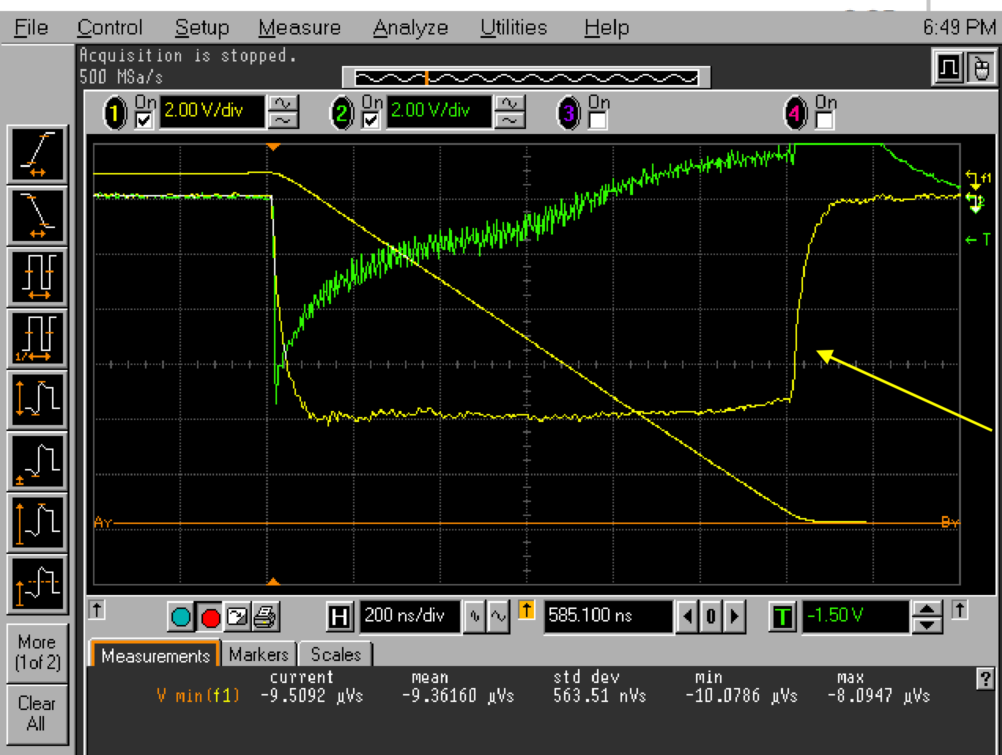
Beam diagnostic are:

charge; emittance; profile; energy

PHIN preliminary results



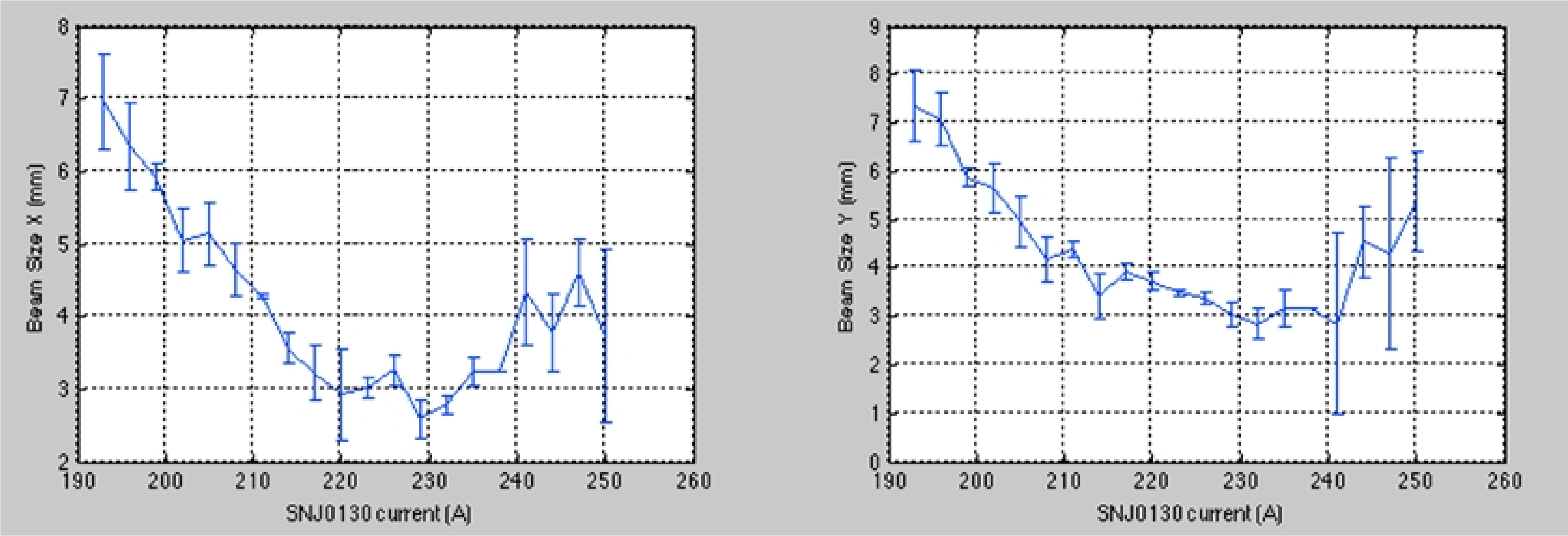




Faraday cup

PHIN preliminary results

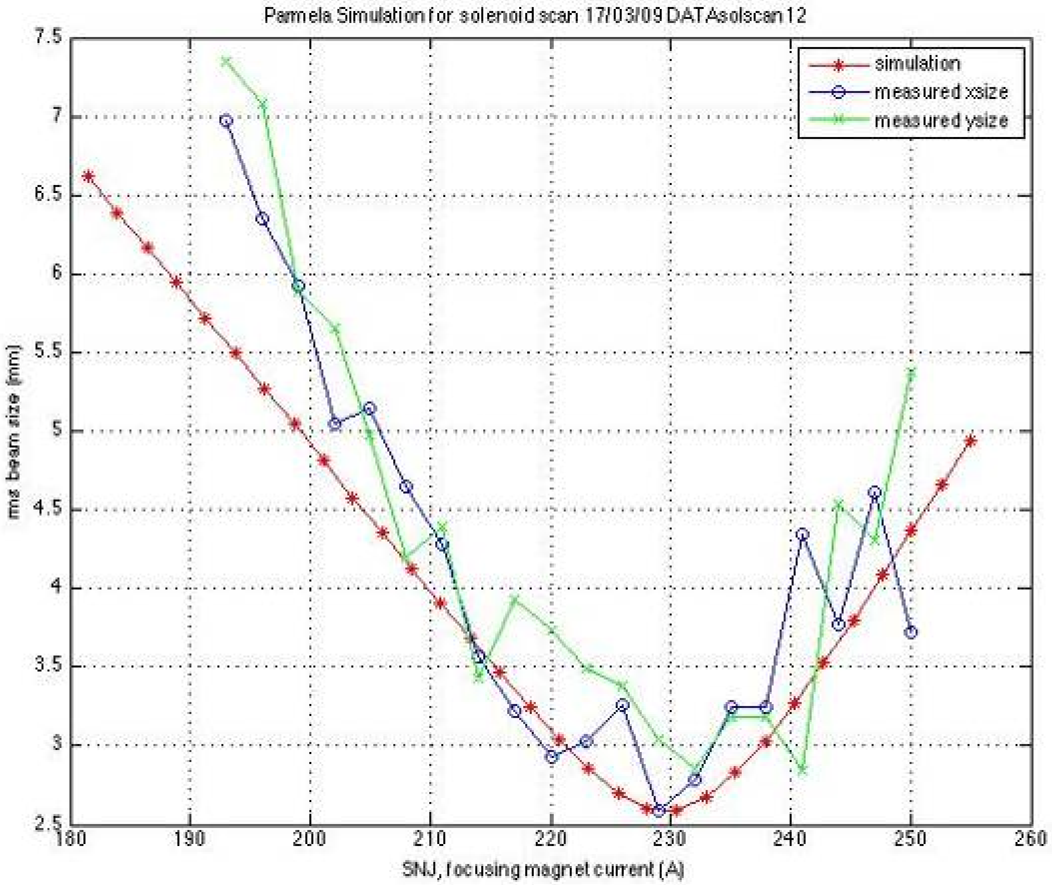
Envelope scan : Beam size vs Solenoid current



Charge: 1.5nC
Laser Spot Size: 2mm(FWHM)

PHIN preliminary results

Envelope scan : Beam size vs Solenoid current



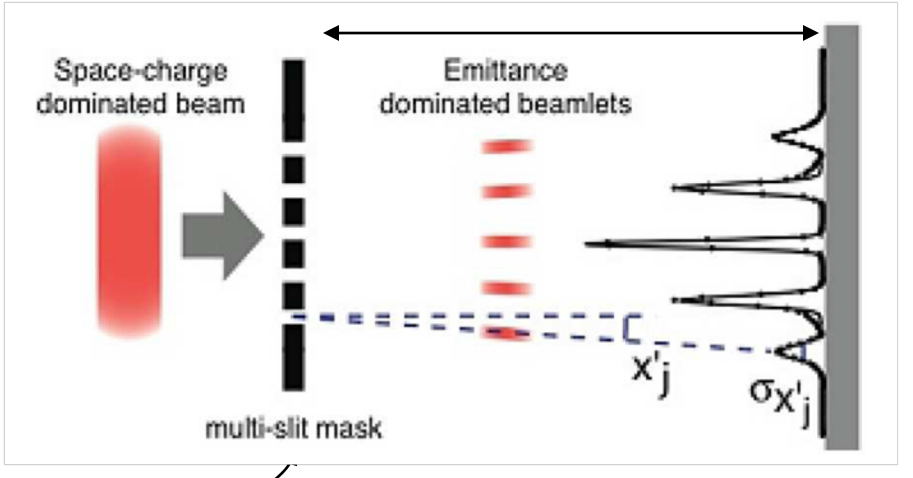
Charge: 1.086nC
Energy: 5.67 MeV
Laser Spot Size: 2mm(FWHM)

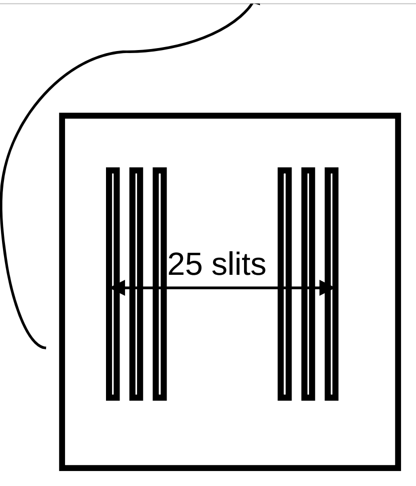
Emittance measurements & definition

Emittance : quality factor for electron beam

= transverse size x momentum angular divergence

It says how much the beam is collimated





<u>Tungsten slit mask:</u>

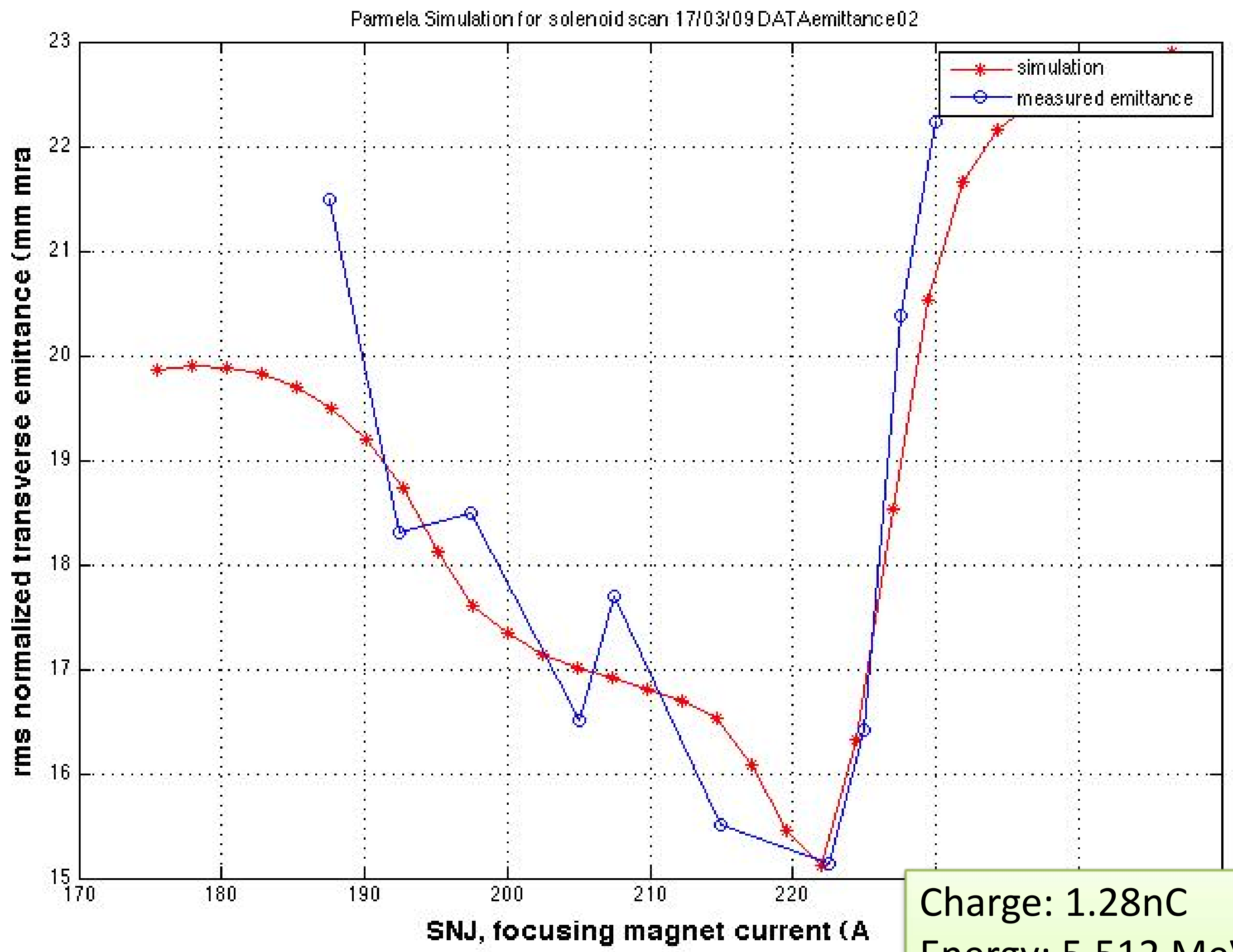
2 mm thick

0.1 mm slit width

0.8 mm distance

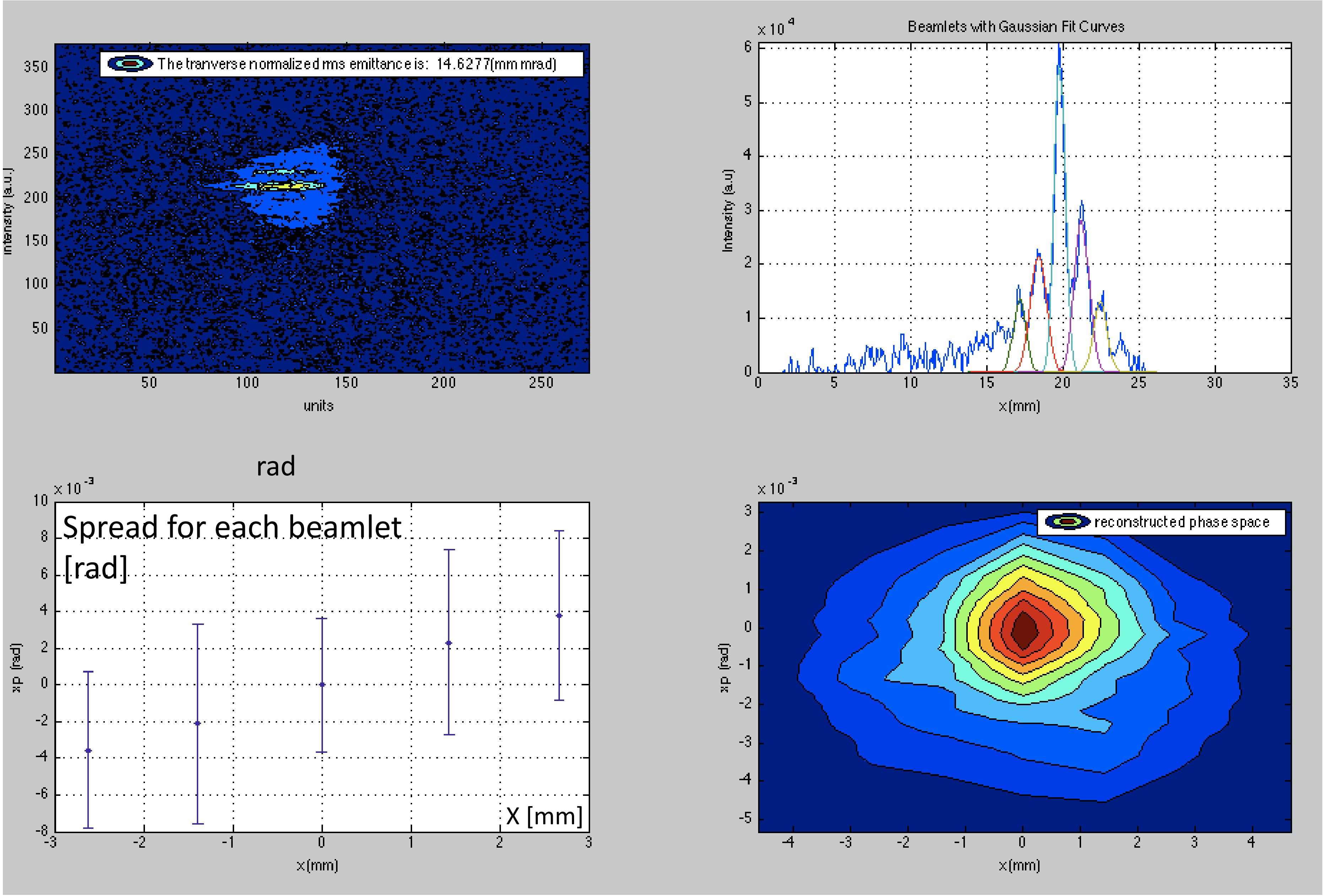
Scan Emittance vs Solenoid

PHIN preliminary results



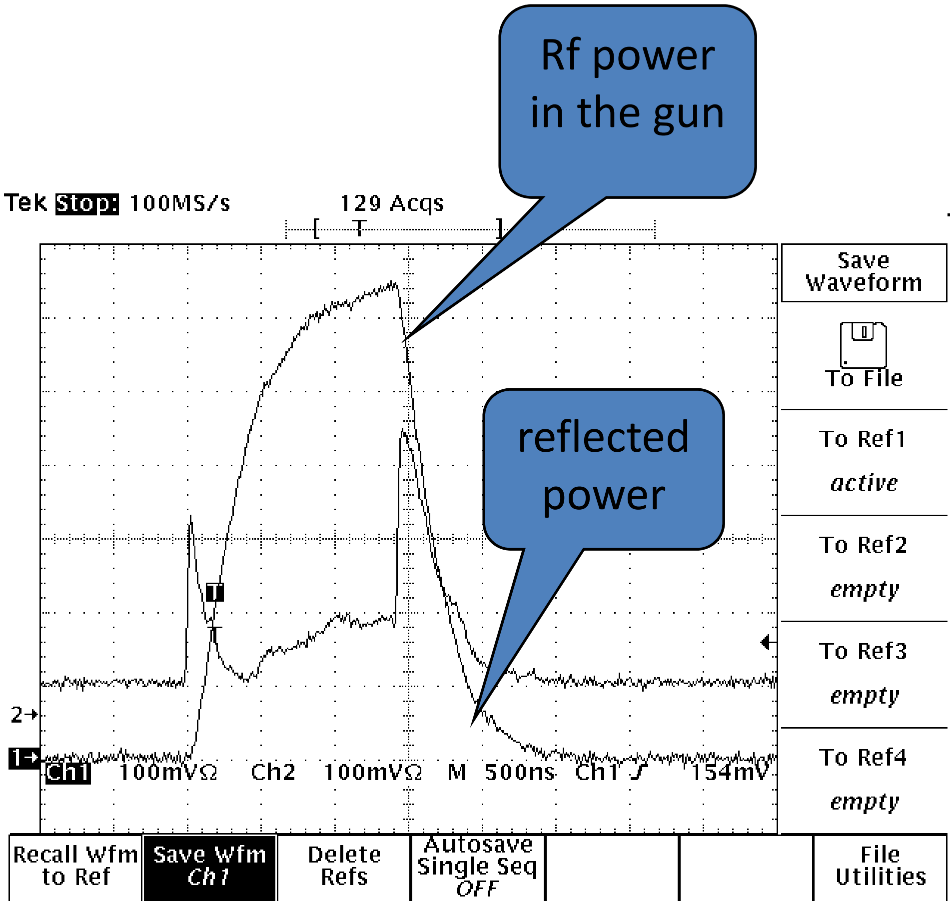
Charge: 1.28nC
Energy: 5.512 MeV
Laser Spot Size: 4mm(4sigma)

An Example of Emittance Measurement Analysis

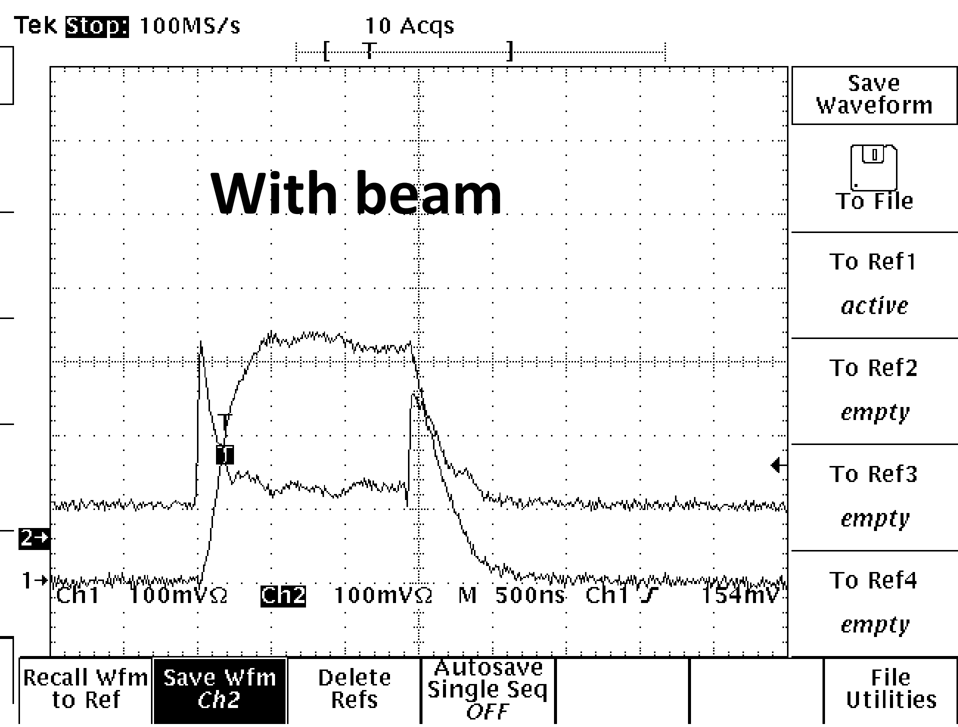


PHIN preliminary results

Beam loading effect



Without beam



PHIN photoinjector: Conclusion& Future

	PHIN design	February 2009	
RF frequency [GHz]	2.9985	2.9985	
beam energy [MeV]	5-6	5.3	
beam current [A]	3.5	~3.4	→ For 500ns macro bunch
		~2	→ For 1270ns macro bunch
number of bunches	1908	>1908	
charge per bunch [nC]	2.3	2.3	→ For 500ns macro bunch ; constant ~1.5nC
repetition rate [Hz]	5	0.8	
n. emittance [π mm mrad]	< 25	ok	
cathode QE	3%	3%<QE< 4%	
vacuum pressure [mbar]	$< 2 \times 10^{-10}$	$< 4 \times 10^{-9}$	

PHIN photoinjector: Conclusion& Future

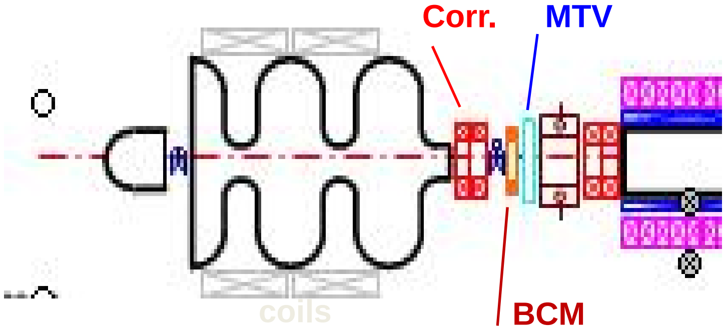
Preliminary measurement obtained in a week…..!!!

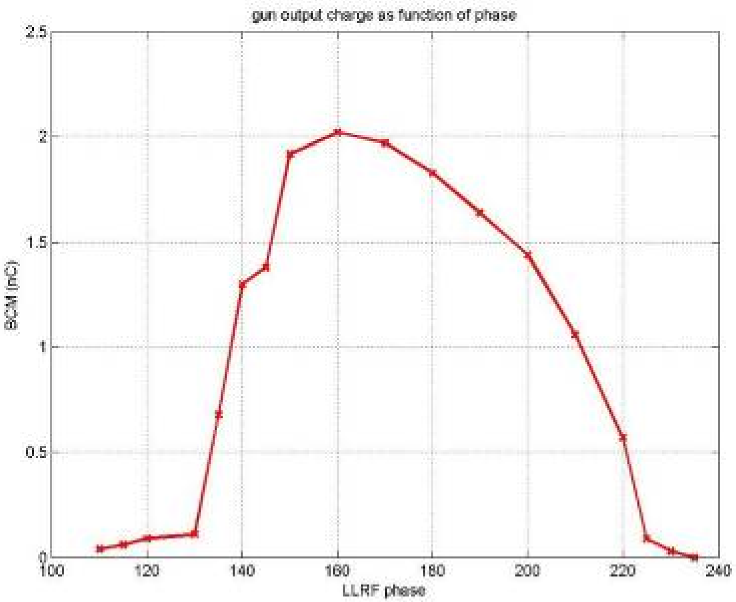
- Study of beam energy spread (improvement of diagnostic)
- Gas analysis
- Nominal charge @ nominal macro bunch length (~1270ns)
- QE map studies over many hour of working time
- Emittance measurement @ full current (2.3 nC for 1908 micro bunches)
- Phase coded beam

……….

CALIFES RF Gun

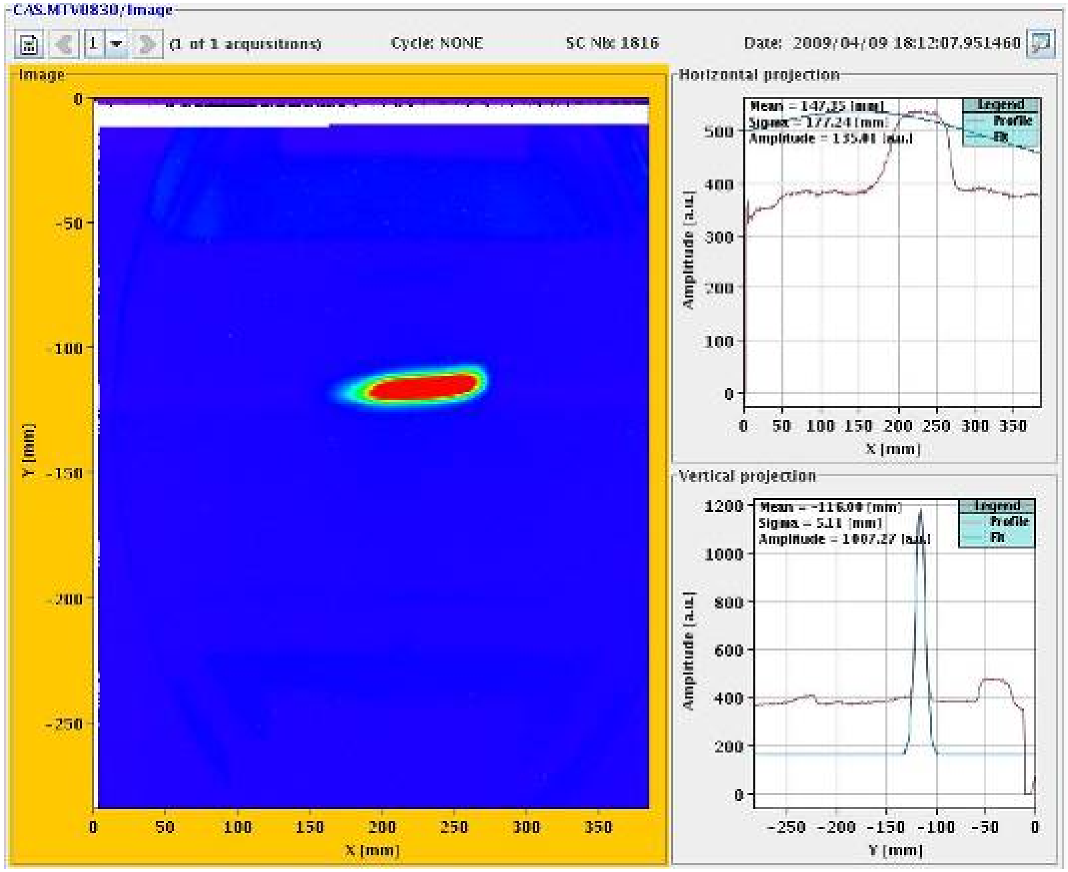
Measures of beam current, size, position, energy as function of phase, focusing coils field, laser spot position on photocathode…





- Laser pulses 7 ns (10 micro bunches)
- QE = 0.5%, 0.2 nC/bunch specs requires 0.6 nc
- UV Laser energy/bunch: 0.20 μJ (nominal 600nJ)

CALIFES beam reached for the first time the end of the TBTS line



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Valentine Fedosseev (STI/LPsection leader), Roberto Losito (EN/STI group leader)

……and all the people involved that I might not directly know but that made all this possible…THANK YOU

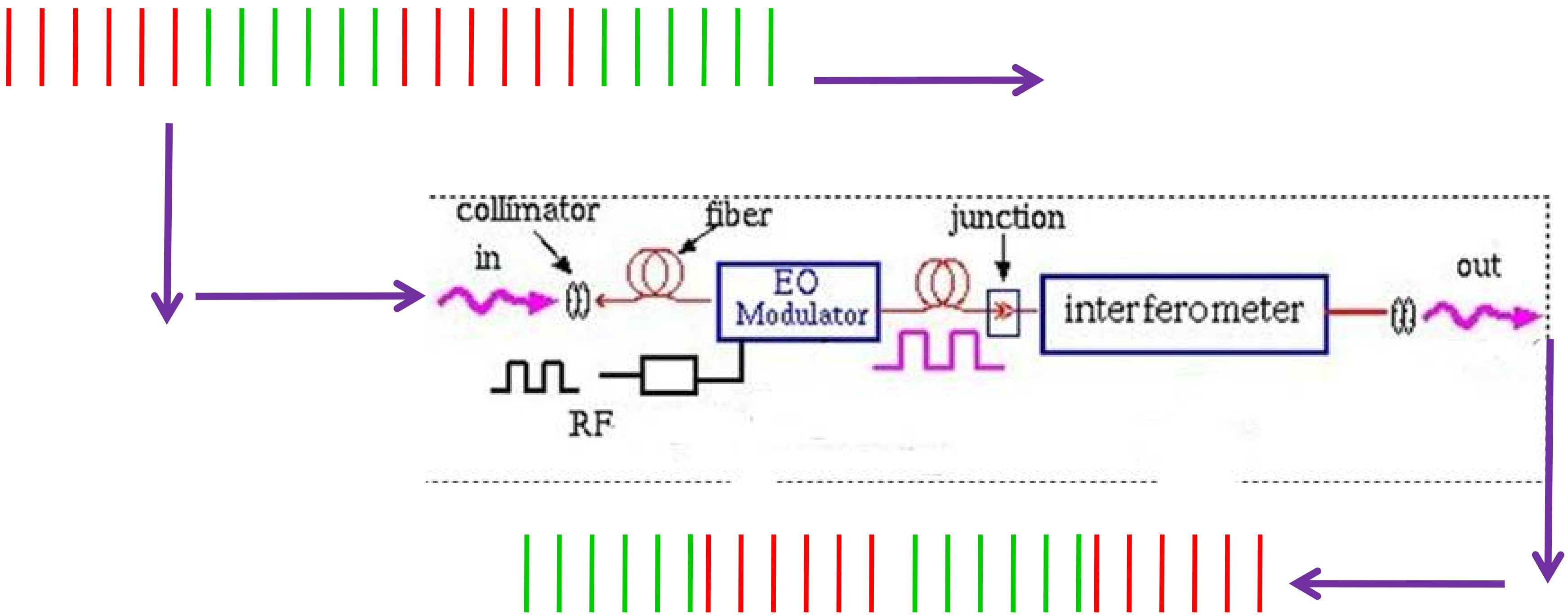

THE
END

Reserved Slides

Photoemission differences:

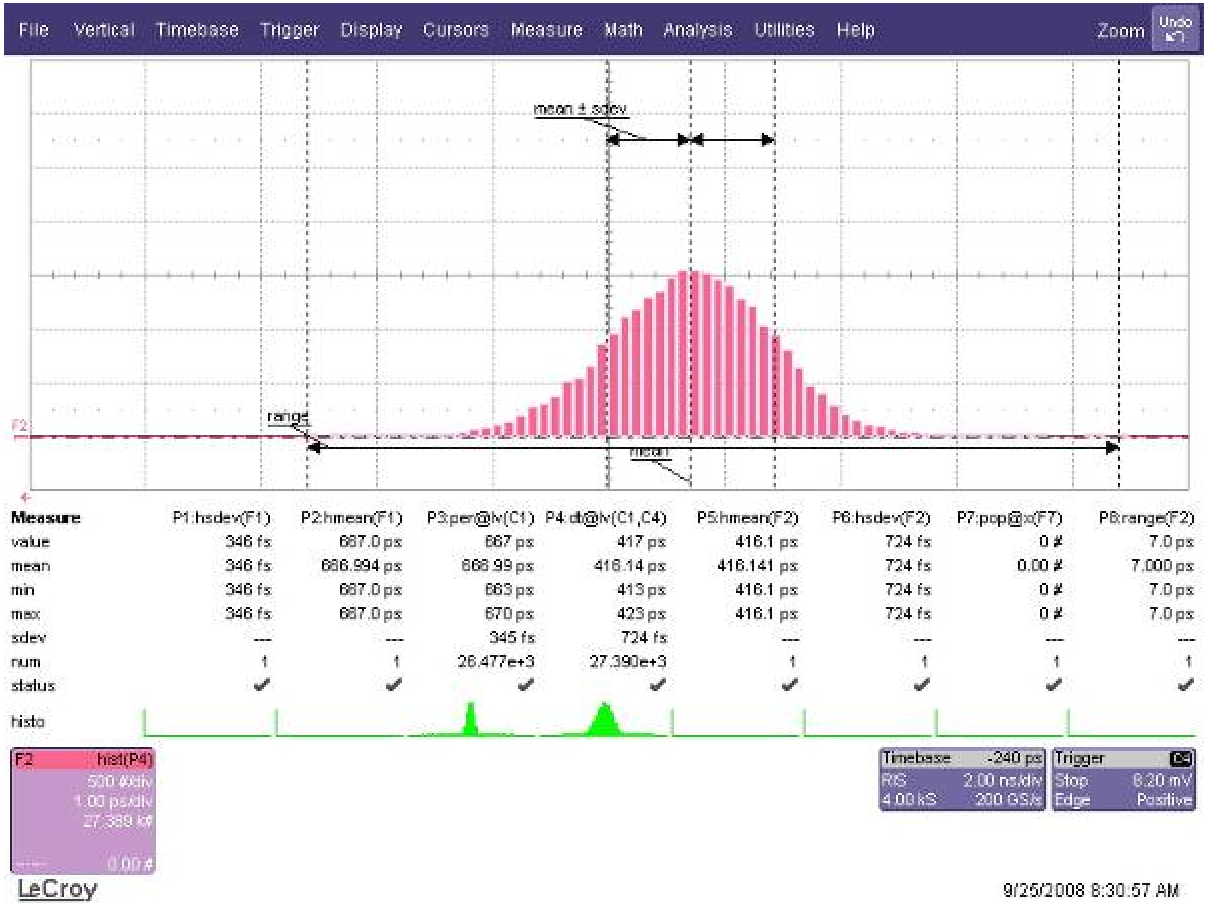
	Metal Mg, Copper….	Semiconductor GaAs,Cs2Te (cesiumtelluride)
Conversion photon→"e"	High optical reflectivity →Low efficiency	High efficiency for photon with energy > gap energy E_G (to obtain a free electron)
Motion through solid	"e"-"e" scattering →low efficiency	Loss for phonon scattering are low →High efficiency
Surface barrier	Determined by "work function" → >2eV	Determined by "e-affinity"
Summary	Low efficiency Fast time response, Resistant to contamination	High efficiency Slower time response, sensitivity to contamination, Response to visible and IR laser

Principle of operation:
An electro optical modulator produce 140ns macro pulse every 140ns.
A fiber based interferometer splits the beam and recombine it so that every 140 ns the gap between 2 successive beam is reduced by T/2 (being T the micro pulse period)



Synchronization:

Lecroy SDA (16GHz, 60GS/s+ NewFocus Photodetector25GHz)



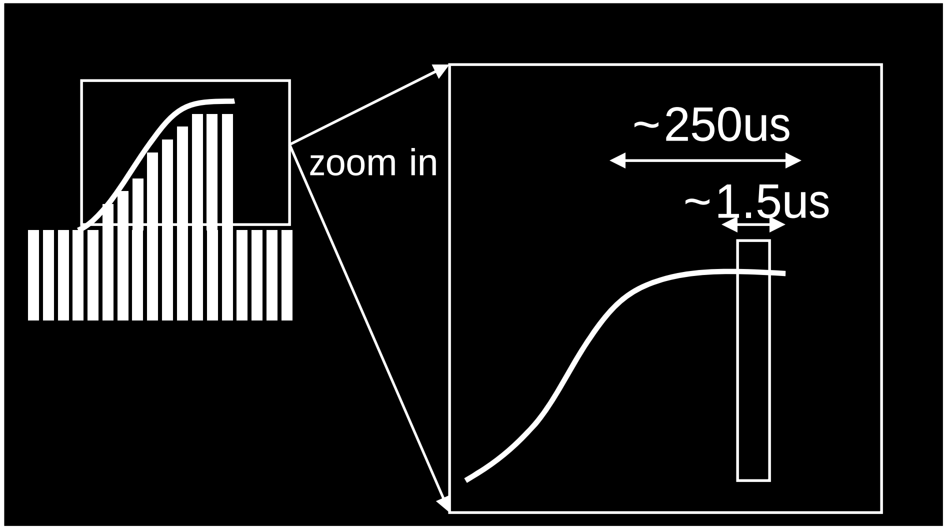
$$J_{real} = \sqrt{\left(J_{meas}\right)^2 - \left(JNF\right)^2}$$

JNF: jitter noise floor ~ 350 fs

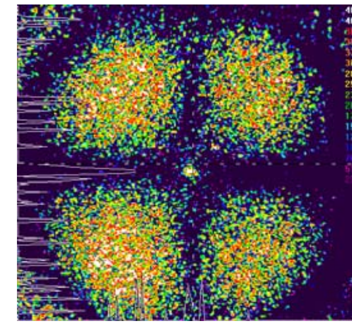
Jmeas: 724fs

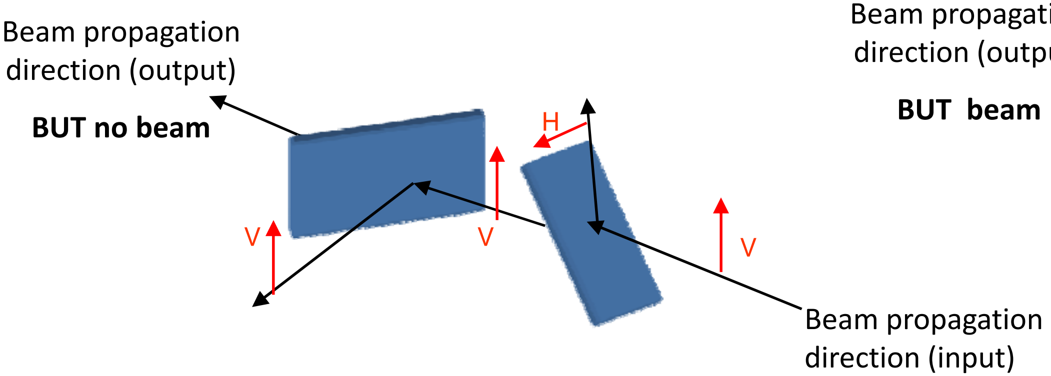
J_{real} ~ 634 fs (rms jitter required <1ps) → Satisfactory

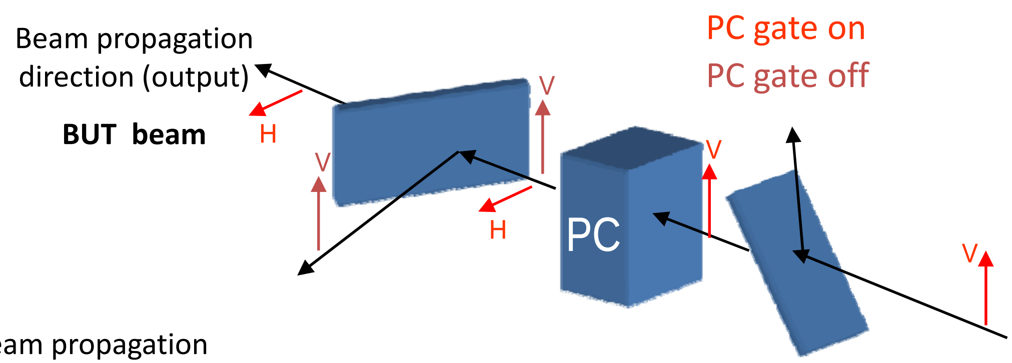
POCKELS CELL (PC)



ISOGYRE
pattern generated
By scattered light
Going trough the
2 Brewster plate
and the pc.
It shows the pc alignment

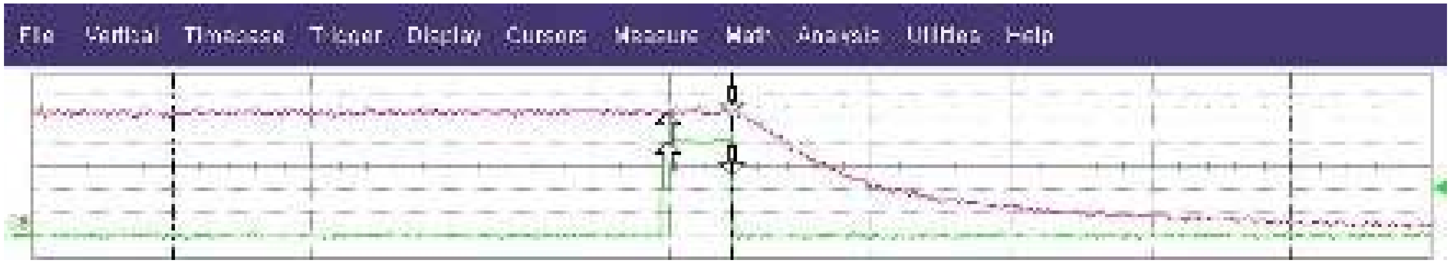




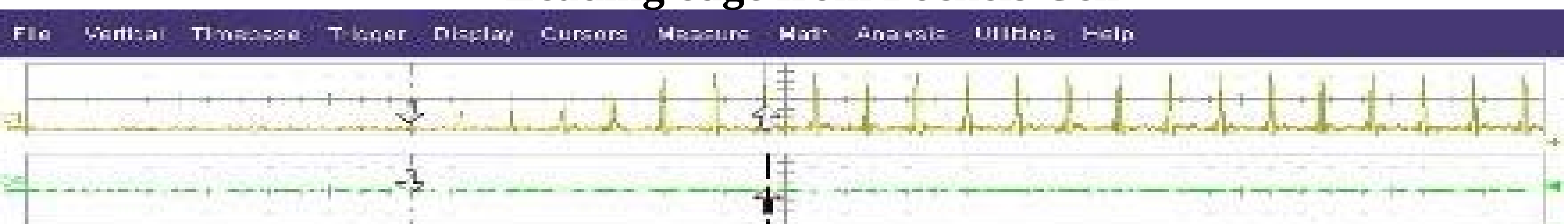


Temporal Profile after Gating system

Macro pulse window selection by Pockels Cell

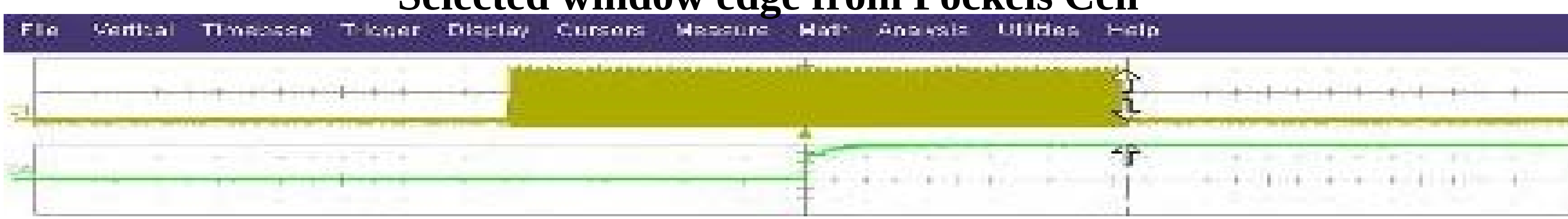


Leading edge from Pockels Cell

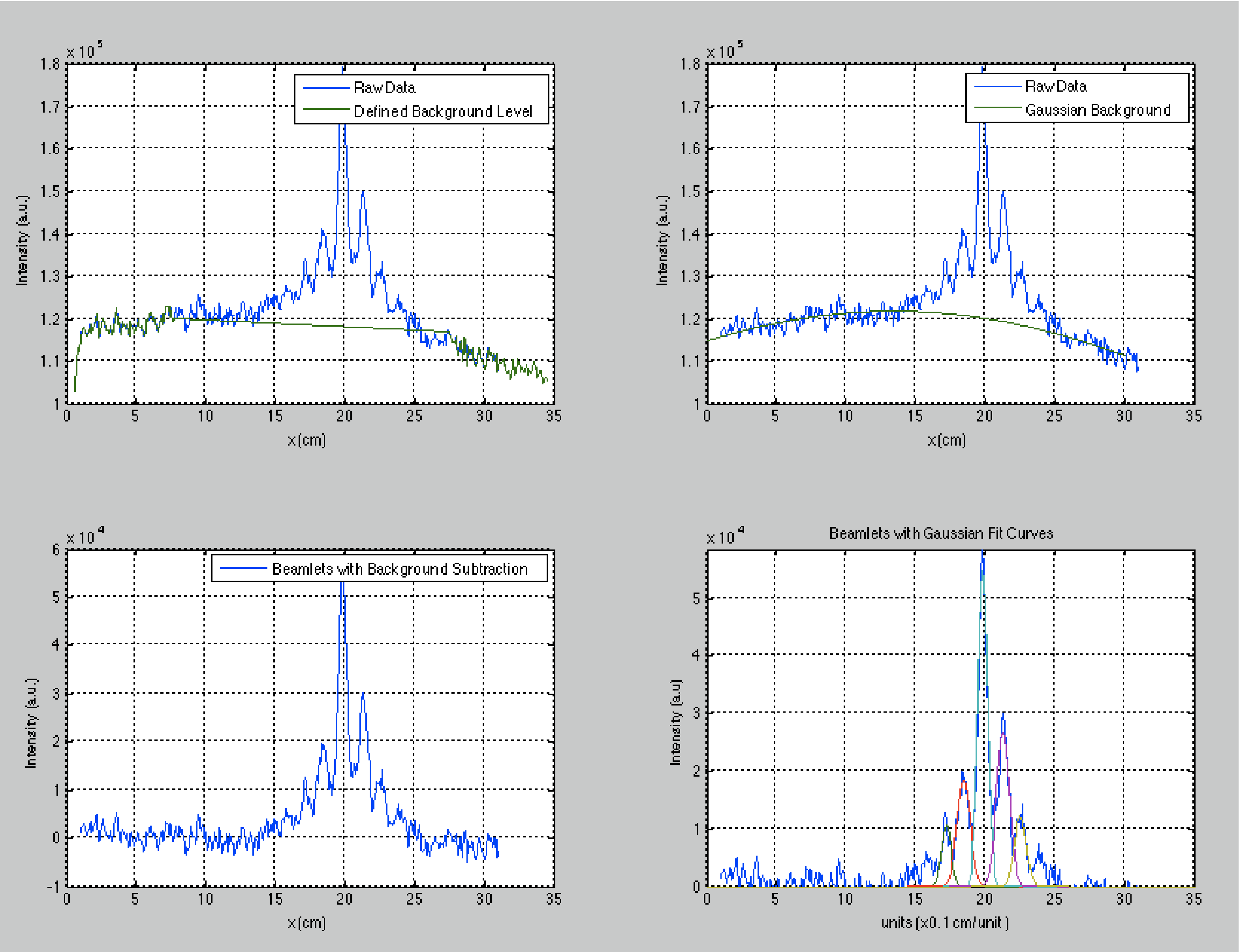


Trailing edge from Pockels Cell

Selected window edge from Pockels Cell



Analysis of beamlets from the slit mask



CLIC 3 TeV parameters

Center-of-mass energy	3 TeV
Peak Luminosity	$5.9 \cdot 10^{34}$ cm^{-2} s^{-1}
Peak luminosity (in 1% of energy)	$2 \cdot 10^{34}$ cm^{-2} s^{-1}
Repetition rate	50 Hz
Loaded accelerating gradient	100 MV/m
Main linac RF frequency	12 GHz
Overall two-linac length	41.7 km
Bunch charge	$3.72 \cdot 10^{9}$
Bunch separation	0.5 ns
Beam pulse duration	156 ns
Beam power/beam	14 MW
Hor./vert. normalized emittance	660 / 20 nm rad
Hor./vert. IP beam size bef. pinch	40 / 1 nm
Total site length	48 km
Total power consumption	389 MW

Comparison CLIC CTF3

CTF3 is scaled down from CLIC and uses existing infrastructure:
Main goals:
→ Demonstrate CLIC drive beam generation
→ Demonstrate 12 GHz rf structure with two beam acceleration
→ Demonstrate stable and efficient deceleration with test beam line

	CLIC	CTF3
Drive Beam energy	2.4 GeV	150 MeV
compression / frequency multiplication	24 (Delay Loop + 2 Combiner Rings)	8 (Delay Loop + 1 Combiner Ring)
Drive Beam current	4.2 A*24 → 101 A	3.5 A*8 → 28 A
RF Frequency	1 GHz	3 GHz
train length in linac	139 μs	1.5 μs
energy extraction	90 %	~ 50 %

CTF3 collaboration