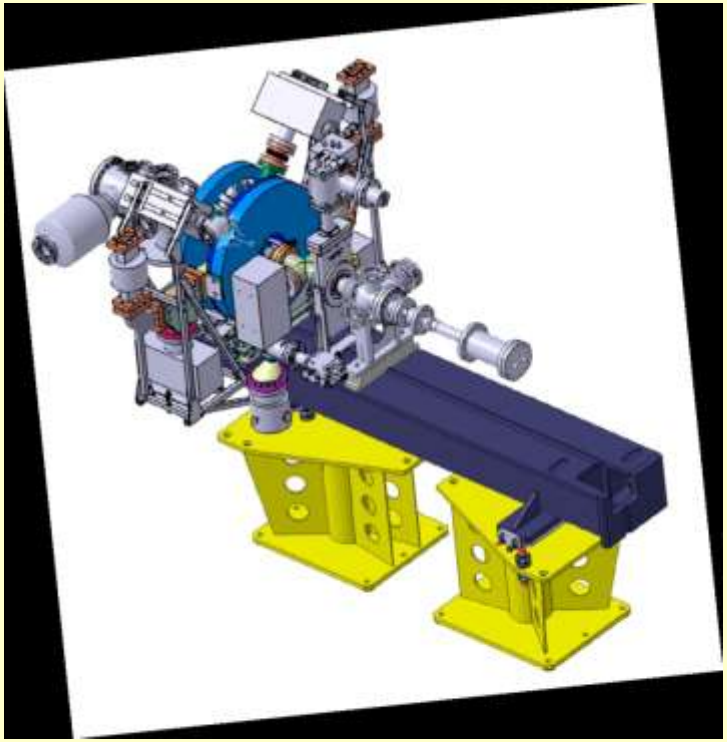
High average current photo injector (PHIN) for the CLIC Test Facility at CERN

- CLIC and CTF3 motivation
- Photo injectors, PHIN
- Emittance measurements
- Long pulse operation,
  time resolved measurements
- Cathode studies
- Stability
- Phase coding
- Conclusion and outlook



PHIN team

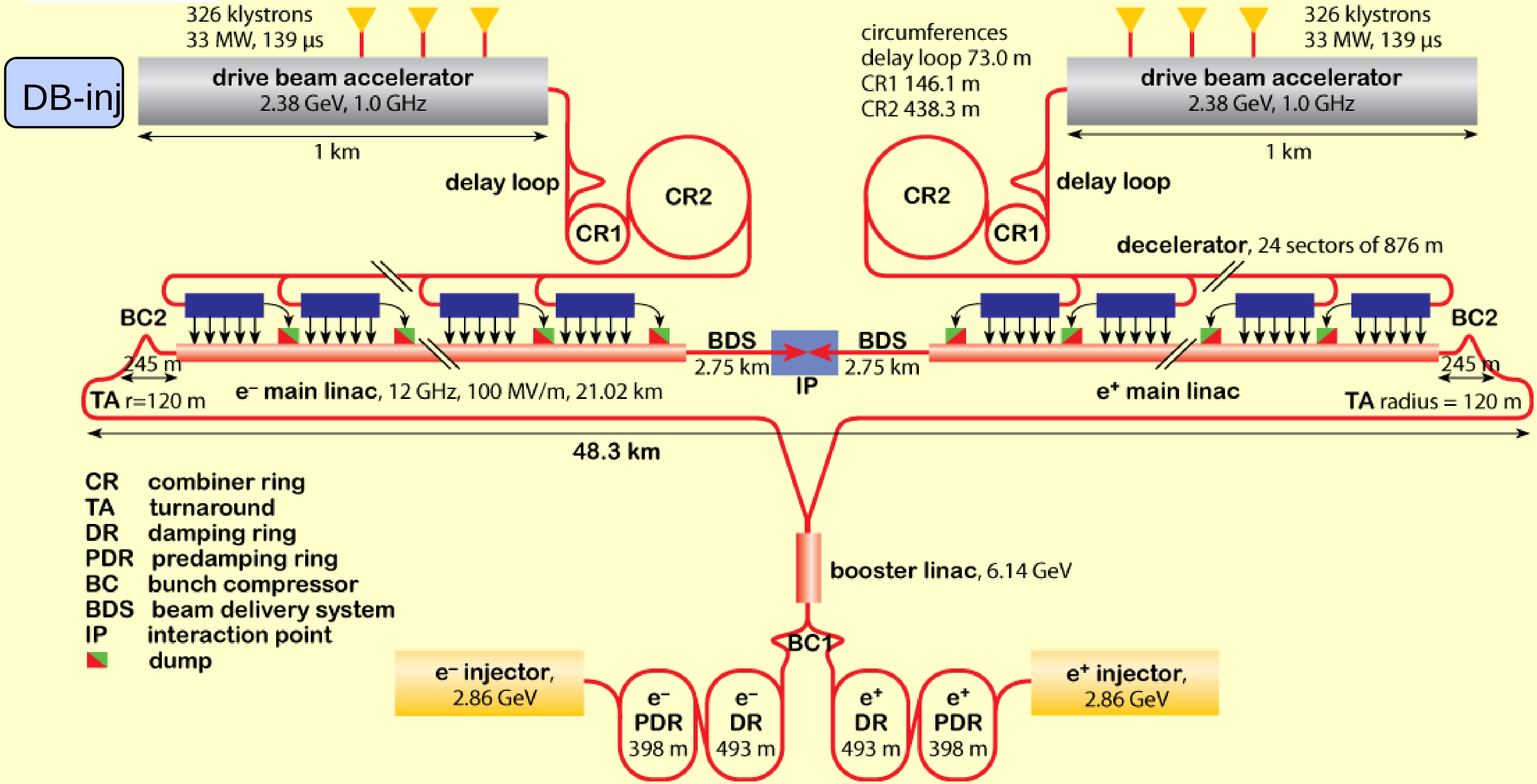
PHIN team and collaboration,
Joint venture within the European CARE program of:

LAL, rf-gun
RAL, laser
INFN, laser and phase coding
CERN, laser, cathodes, integration, commissioning

CERN people:

A. Andersson, B. Bolzon, E. Bravin, M. Csatari, E. Chevallay, S. Doebert, A. Drodzy, D. Egger, V. Fedosseev, C. Hessler, T. Lefevre, R. Losito, O. Mete, M. Olvegaard, M. Petrarca, A. Rabiller

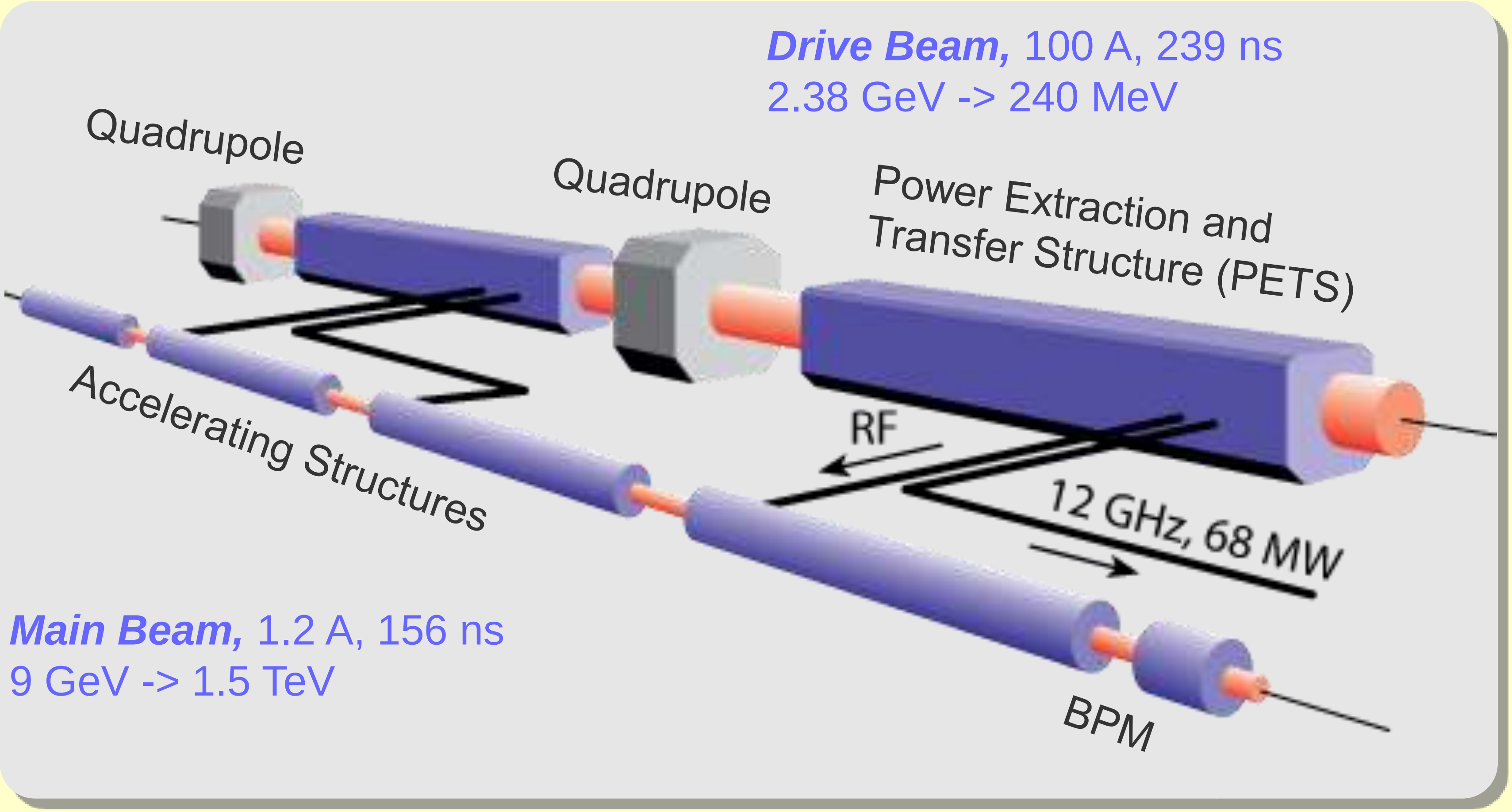
CLIC-layout



Compact Linear Collider for 3 TeV c.m., normal conducting, high-frequency, high-gradient, high efficiency, two beam acceleration, high-current drive beam

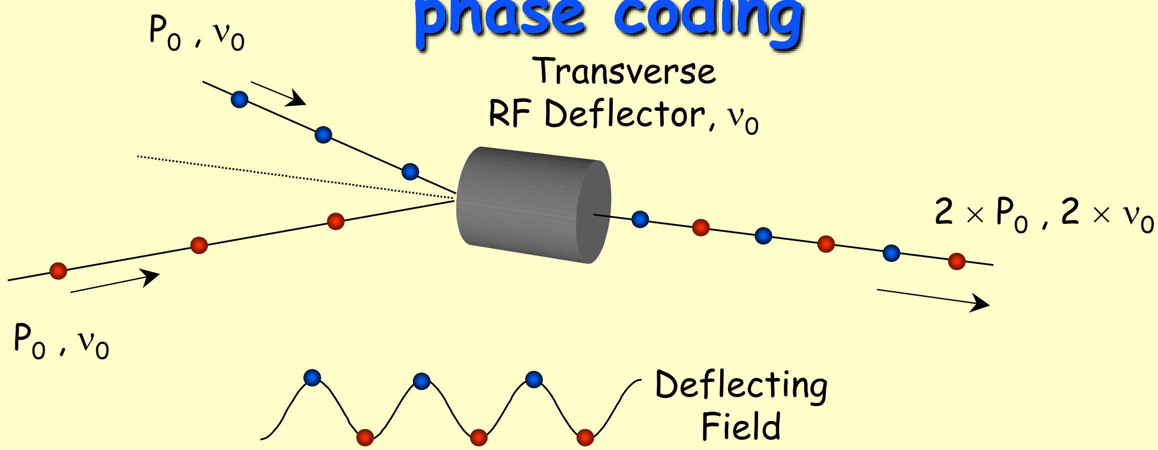
Two Beam acceleration

Transformer principle:
high-current low-energy drive beam to low-current high energy main beam



Bunch combination in CTF3

phase coding



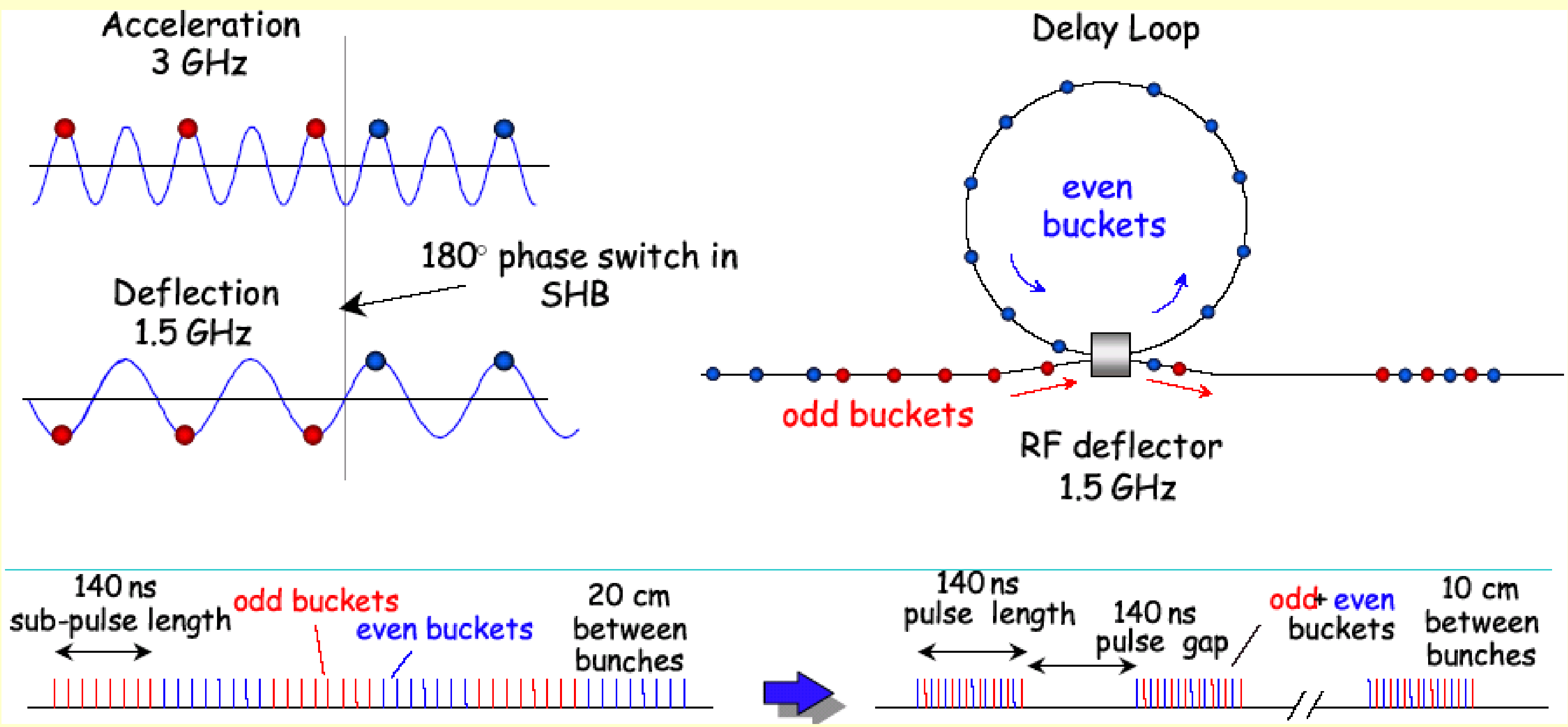
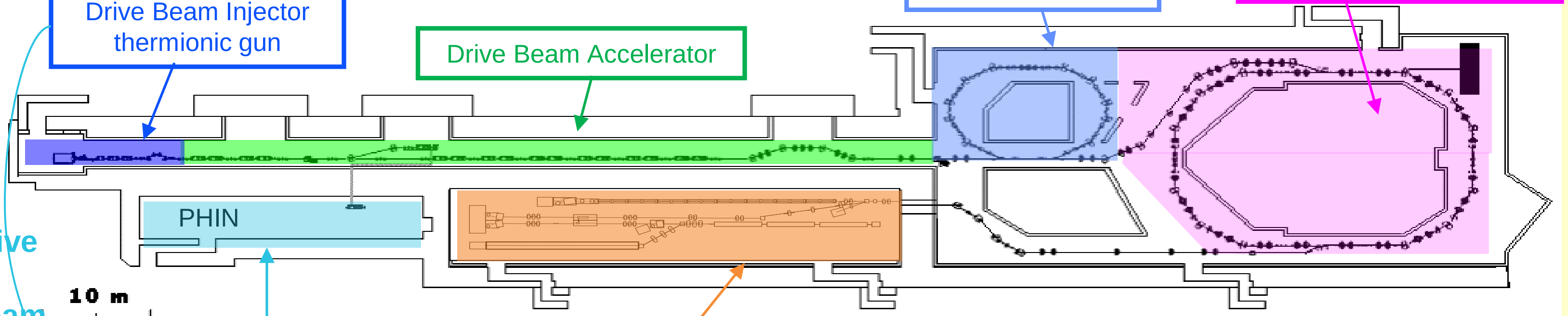
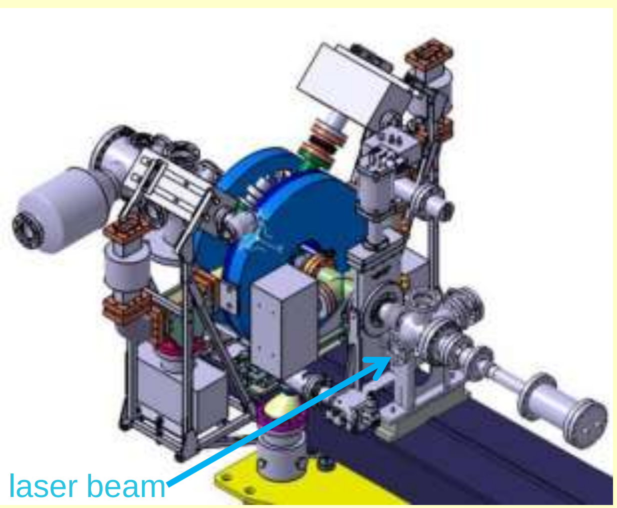


Photo-injectors for CTF3



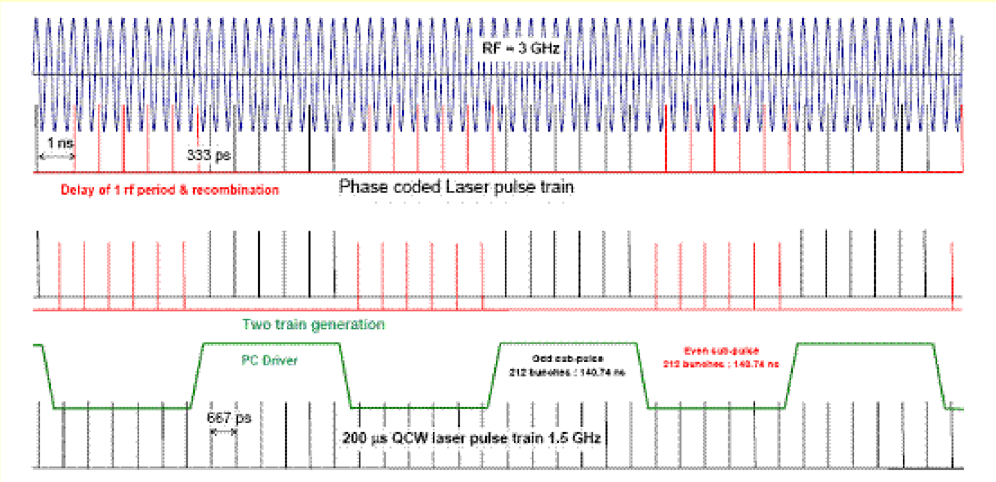
http://clic-study.web.cern.ch/clic-study/



		DRIVE beam	MAIN beam
Electrons		PHIN	CALIFES
	charge/bunch (nC)	2.3	0.6
	Number of subtrains	8	NA
	Number of pulses in subtrain	212	NA
	gate (ns)	1272	20-150
	bunch spacing(ns)	0.666	0.666
	bunch length (ps)	10	10
	Rf reprate (GHz)	1.5	1.5
	number of bunches	1802	32
	machine reprate (Hz)	5	5
	margine for the laser	1.5	1.5
	charge stability	<0.25%	<3%
	QE(%) of Cs2Te cathode	3	0.3

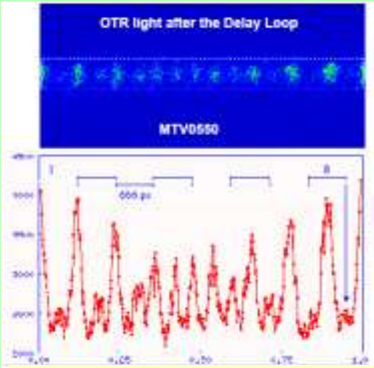
Machine parameters set the requirement for the laser

Time structure requirement

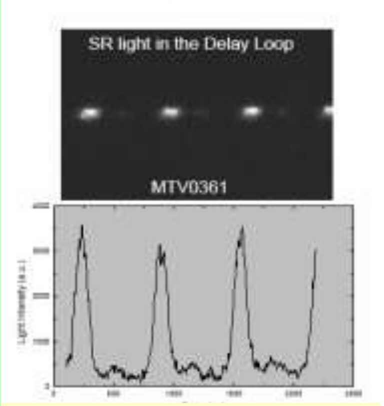


	PHIN
Micropulse repetition rate	1.5GHz
Macropulse repetition rate	1-5 Hz
Number of pulses	1900
Gate length	1254 ns
Number of subtrains	8
Length of subtrains	140.7ns

With thermionic gun



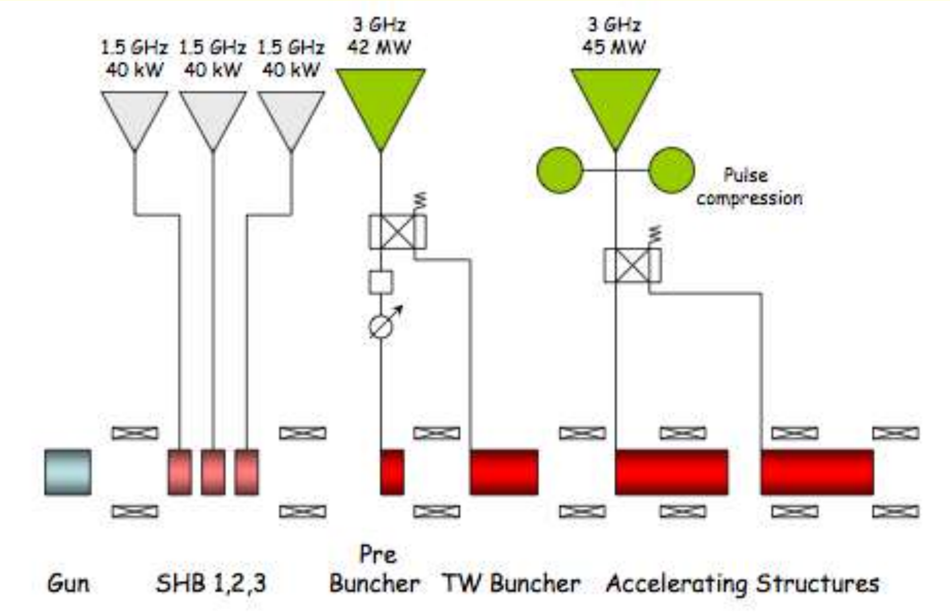
Phase switch is done within eight 1.5 GHz periods (~ 5 ns)



Satellite bunch population was estimated to ~ 7 %

Thermionic injector

The existing thermionic gun for the CLIC Test Facility 3

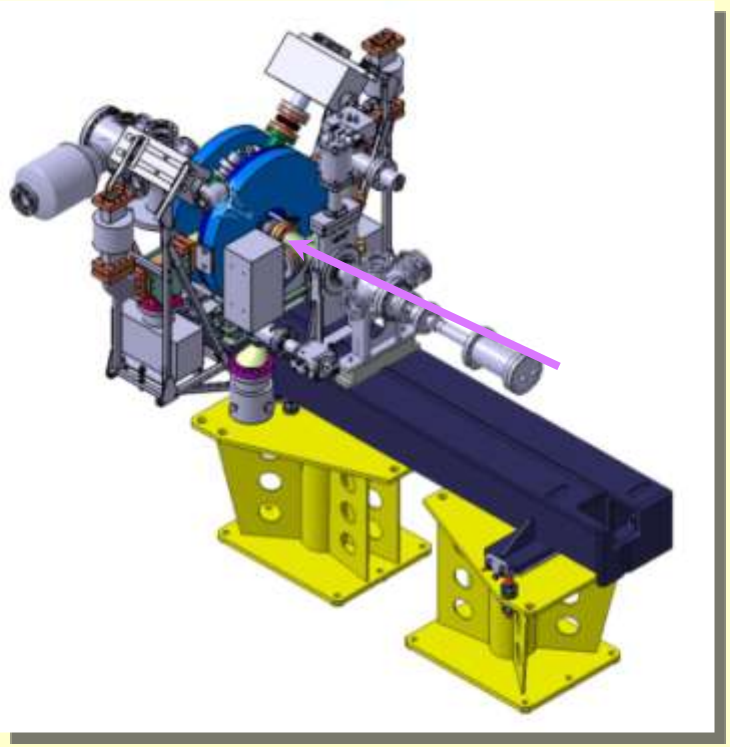


time structure is produced by

- **DC thermionic gun**
  - **three 1.5 GHz sub-harmonic bunchers**
  - **a S-band pre-buncher**
  - **a traveling wave buncher**

Drawback:
creation of satellites and beam quality degradation

What is a photo injector



- A photoinjector is an electron source that uses **laser** pulses in order to extract electrons from the surface of a metallic or semiconductor **cathode** by using the **photoemission** process.
- The electron beam resembles the temporal structure of the laser beam therefore it is **a compact system** without need for an additional bunching system.
- An **RF cavity** is used for rapid acceleration of the electrons after the emission.
- Solenoid magnets are placed in order to focus the space charge dominated beam and achieve the **emittance compensation**.

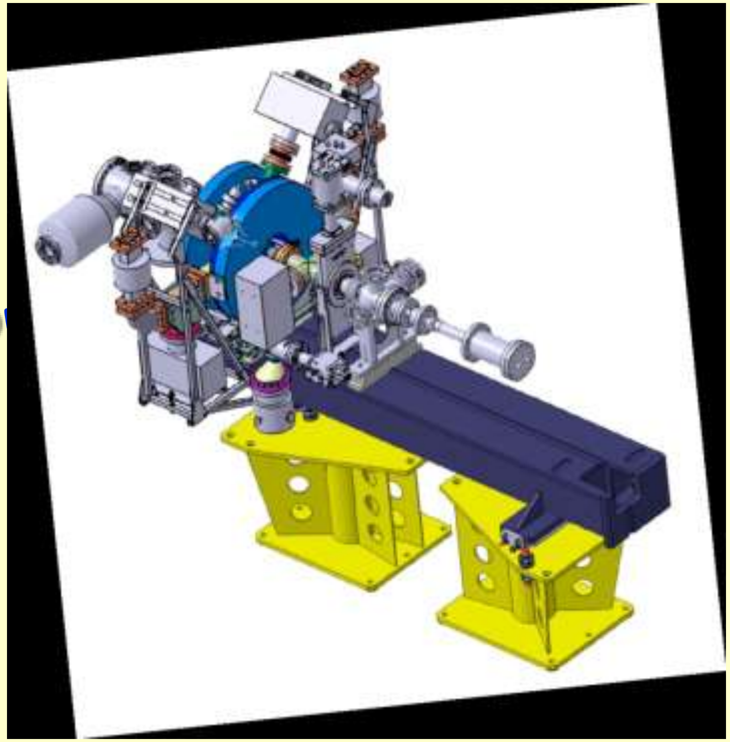
Photo injector option

Advantages

- No satellites or tails, phase coding on the laser side
- No or less bunching needed, possibly better emittance
- Flexible time structure

Concerns

- Cathode lifetime
- Challenging laser, peak and average po
- Intensity stability
- Maintenance and operation



PHIN parameters

Parameter	Specification	Achieved
RF		
RF Gradient (MV/m)	85	85
RF Frequency (GHz)	2.99855	
Electron Beam		
Charge per Bunch (nC)	2.33	9.2
Charge per Train (nC)	4446	> 5800
Train Length (ns)	1273	> 1500
Bunch Length (ps)	8	7
Number of Bunches / Train	1908	2250
Current (A)	3.5	13
Normalized Emittance (mm mrad)	<25	14
Energy Spread (%)	<1	0.7
Energy (MeV)	5.5	5.5
Charge stability, flat top and p. to p. (%)	0.25	0.8

PHIN is special due to the high average charge requirements and the emphasis on stability along the train

Photo injectors
from Öznur's thesis

PHIN research objectives

- Comprehensive **simulations** for the PHIN photo injector beam dynamics,
- Optimization of the **working point** providing the specifications,
- Full **experimental characterization** of the PHIN beam for short and long pulse trains,
- Development of a **single shot emittance measurement system** for space charge dominated beams,
- To measure the beam properties and their **stability along the bunch train** (time-resolved measurements),
- To compare the measurement results with the simulations,
- Eventually, to study the consequences of the findings to constitute a **preliminary RF gun design for CLIC-DB injector**.

A bit of theory
from C. Travier

- **Maximum gradient**

$$E_{0,max} = 8.47 + 1.57\sqrt{f[MHz]}$$

- **Bunch length**

$$\sigma_b[ps] \leq \frac{5 \times 10^4}{f[MHz]}$$

- **Maximum bunch charge, space charge limitations**

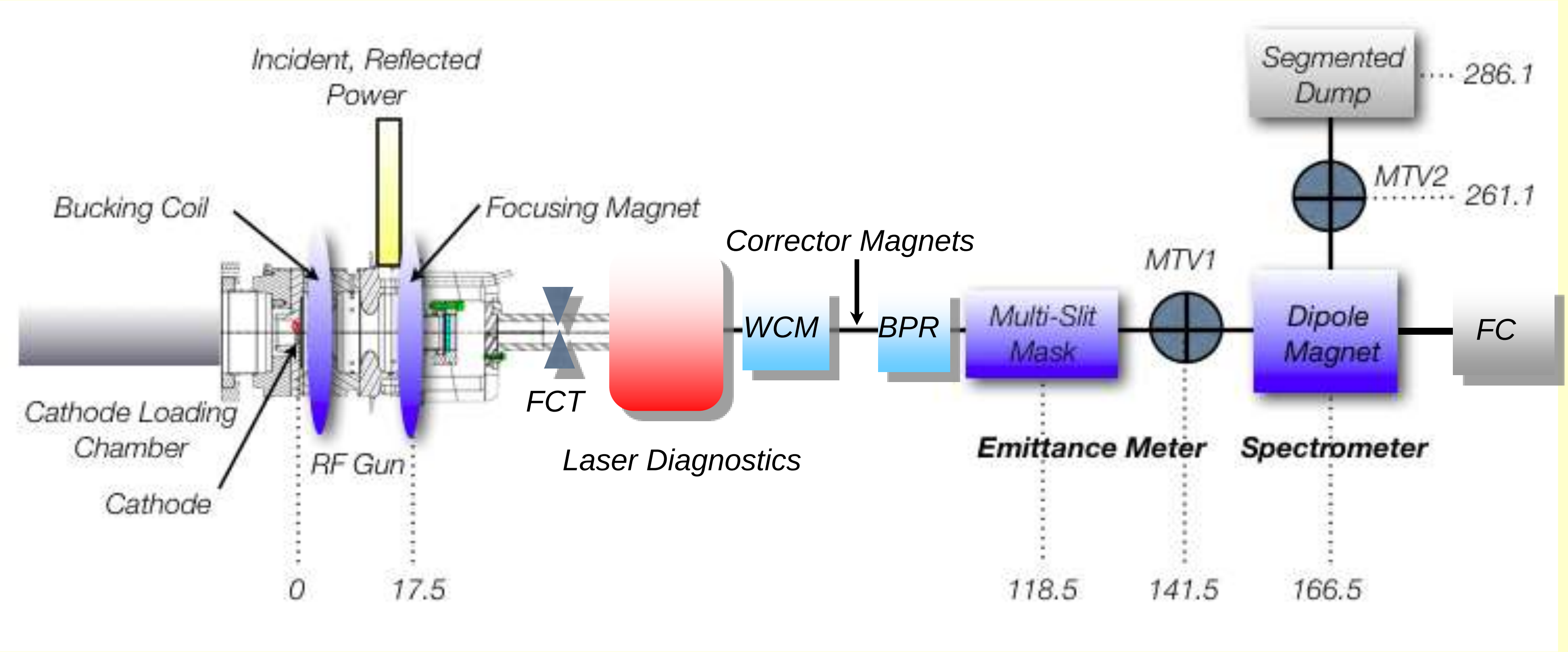
$$Q_{max}[nC] = \frac{E_{acc}[MV/m]\sigma_x^2}{18}$$

- **Emission phase, Energy, Energy spread, Emittance**

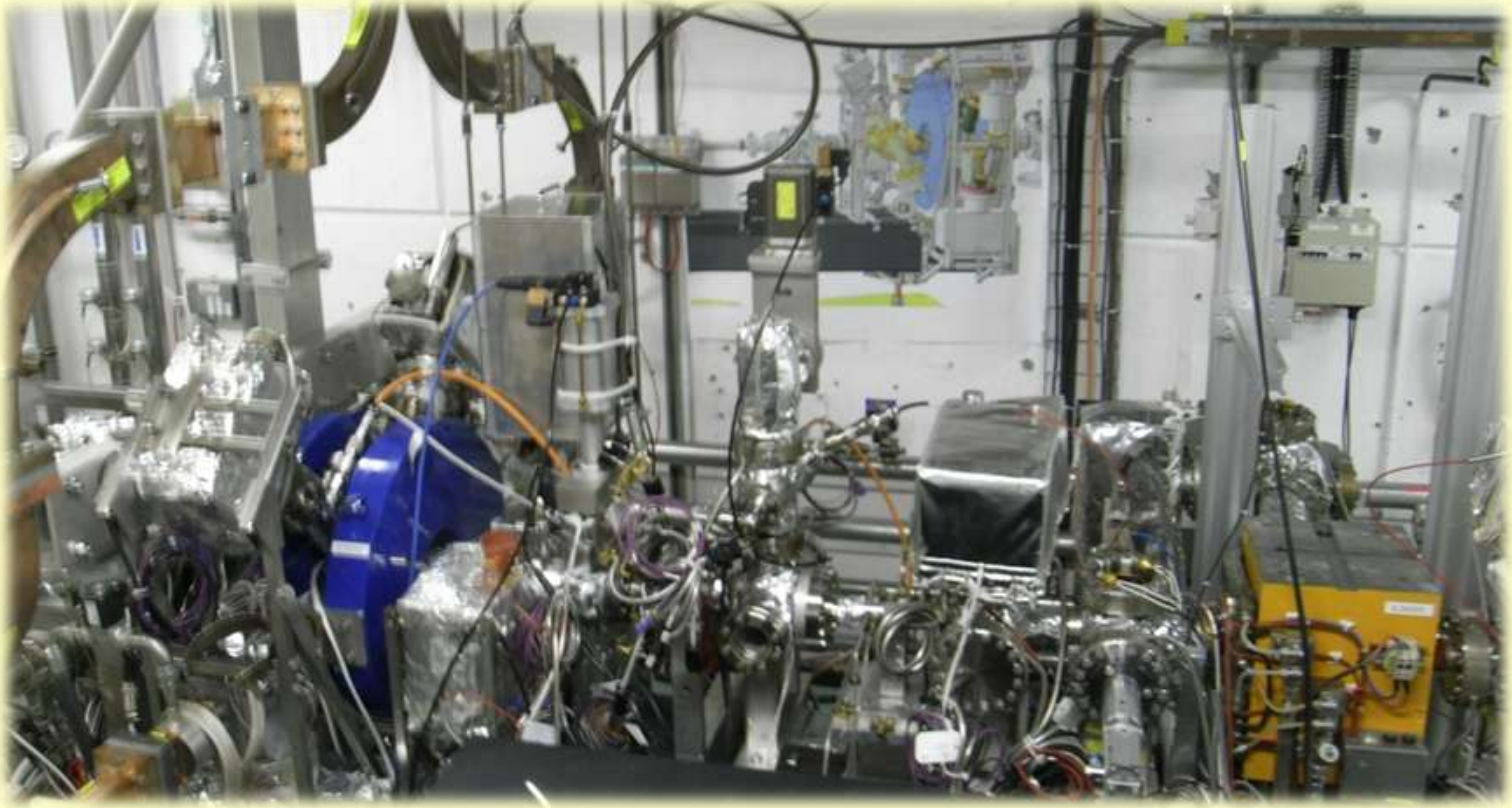
  Depends on rf- phase and focusing, phase < 90 deg (on crest)

$$\epsilon_{n,x,y,tot} = \sqrt{\epsilon_{rf}^2 + \epsilon_{sc}^2 + \epsilon_{th}^2}$$

PHIN Photo injector Layout

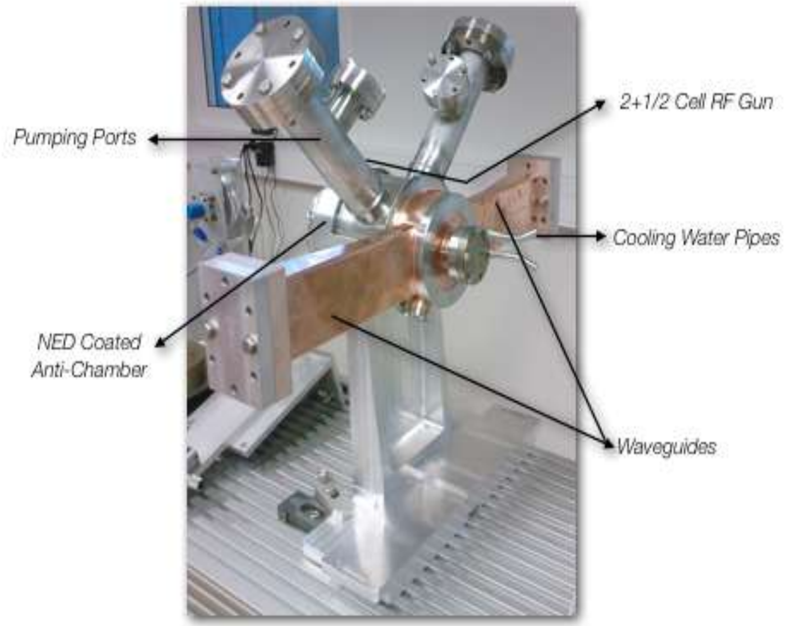


PHIN picture



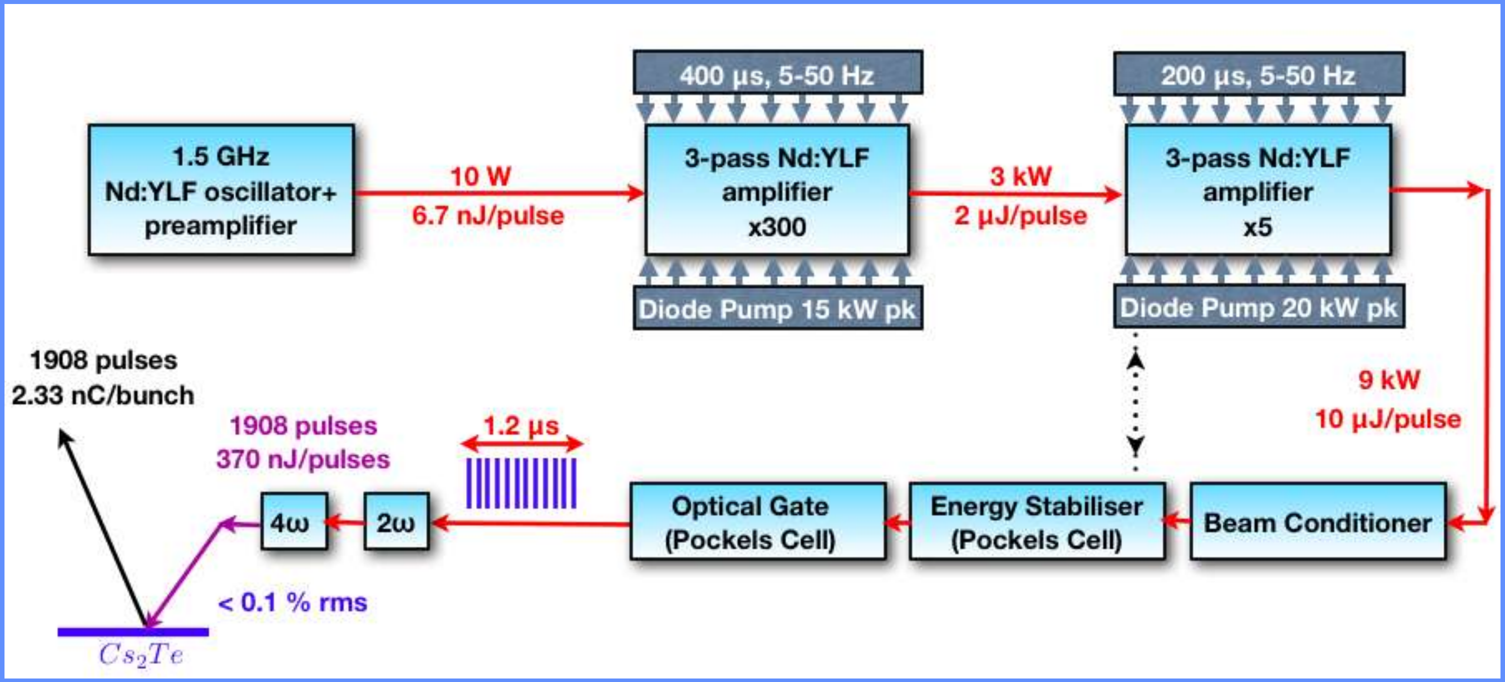
RF-GUN
developed by LAL

RF Gun



Laser
Developed by RAL

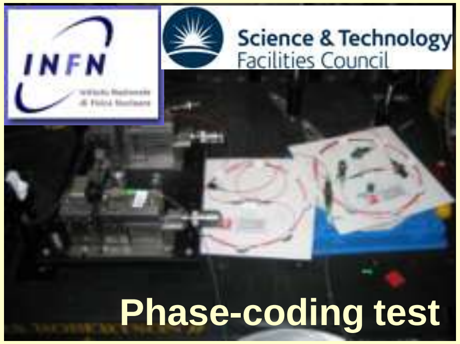
Laser

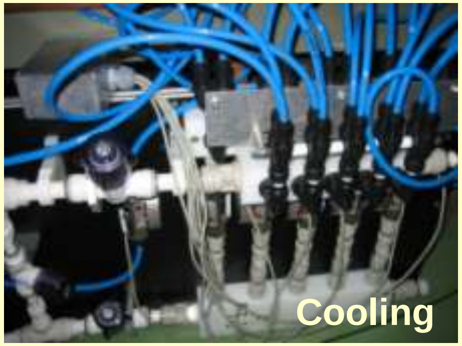


Dream Laser

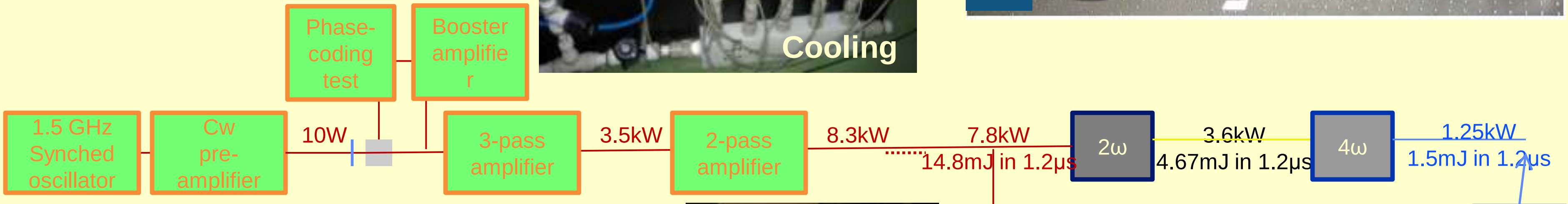

DreamLaser®
Wavelength
STOP
START
Pulse length
Energy/pulse
Train length
Rep. rate
Beamsize
Position

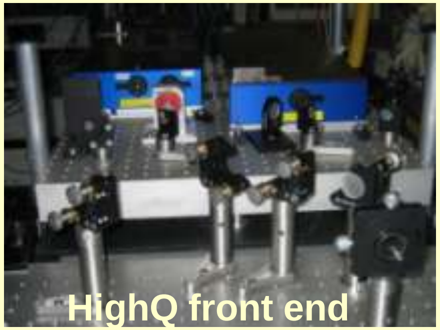
Laser setup

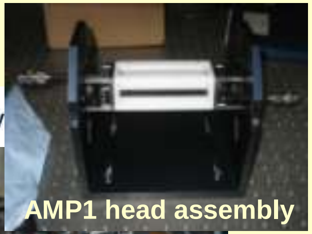

INFN
Science & Technology Facilities Council
Phase-coding test


Cooling

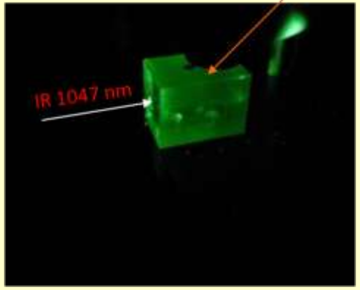

Harmonics


Phase-coding test
Booster amplifier
1.5 GHz Synched oscillator
Cw pre-amplifier
10W
3-pass amplifier
3.5kW
2-pass amplifier
8.3kW
7.8kW
14.8mJ in 1.2μs
2ω
3.6kW
4.67mJ in 1.2μs
4ω
1.25kW
1.5mJ in 1.2μs
Harmonics test stand
Feed-back stab.


HighQ front end


AMP1 head assembly

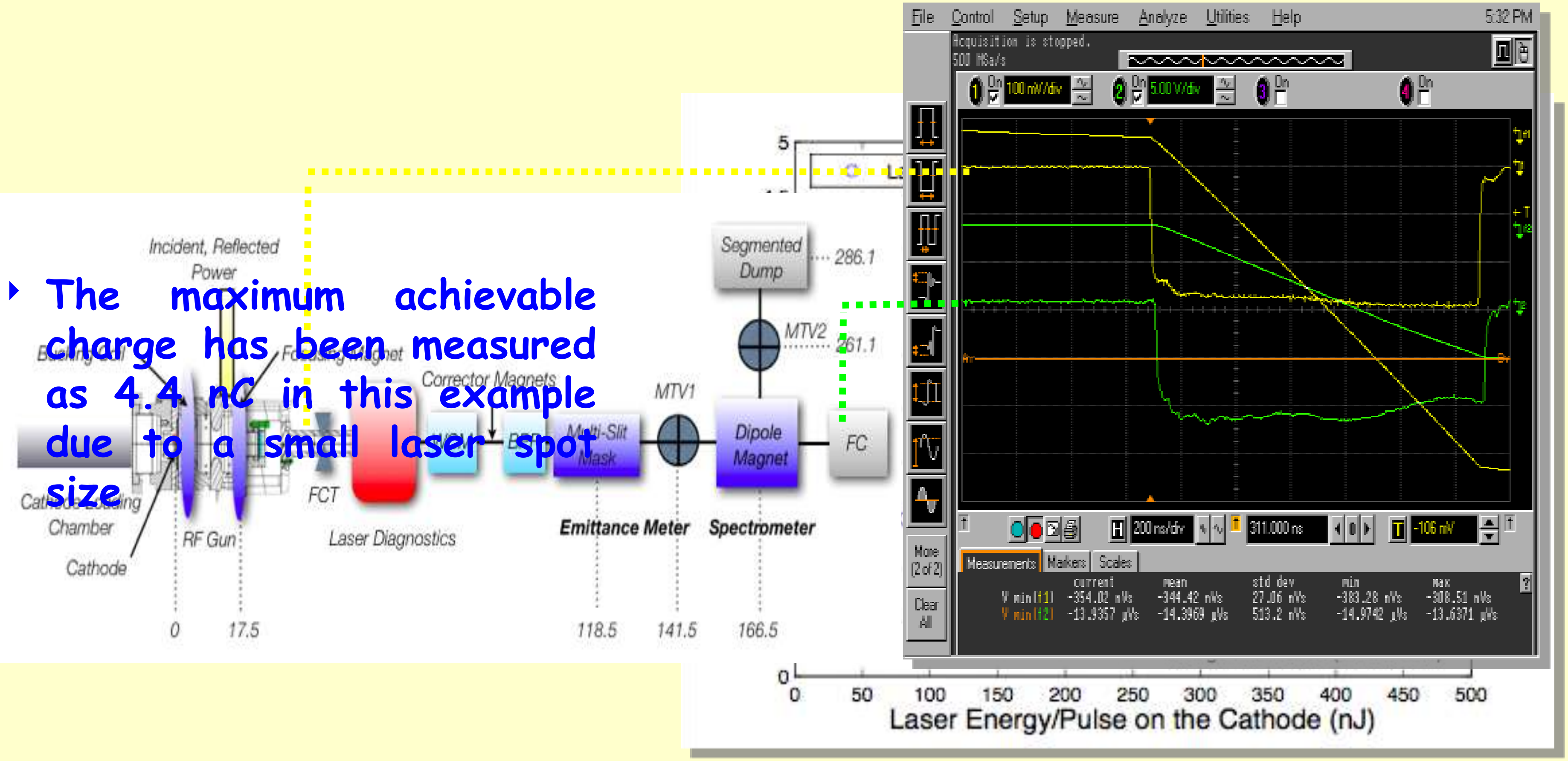

Science & Technology Facilities Council
AMP1 and AMP2


IR 1047 nm

Phin parameters

		DRIVE beam	
		PHIN	CLIC
Electrons	charge/bunch (nC)	2.3	8.4
	train length (ns)	1200	140371
	bunch spacing(ns)	0.666	1.992
	bunch length (ps)	10	10
	bunch rep rate (GHz)	1.5	0.5
	number of bunches	1802	70467
	machine rep rate (Hz)	5	100
	margine for the laser	1.5	2.9
	charge stability	<0.25%	<0.1%
	Cathode lifetime (h) at QE > 3%	>50	>150
Laser in UV	laser wavelegth (nm)	262	262
	energy/micropulse on cathode (nJ)	363	1988
	energy/micropulse laserroom (nJ)	544	5765
	energy/macrop. laserroom (uJ)	9.8E+02	4.1E+05
	mean power (kW)	0.8	2.9
	average power at cathode wavelength(W)	0.005	41
	micro/macropulse stability	1.30%	<0.1%
Laser in IR	conversion efficiency	0.1	0.1
	energy/macropulse in IR (mJ)	9.8	4062.2
	energy/micropulse in IR (uJ)	5.4	57.6
	mean power in IR (kW)	8.2	28.9
	average power on second harmonic (W)	0.49	406
	average power in final amplifier (W)	9	608

Charge measurement

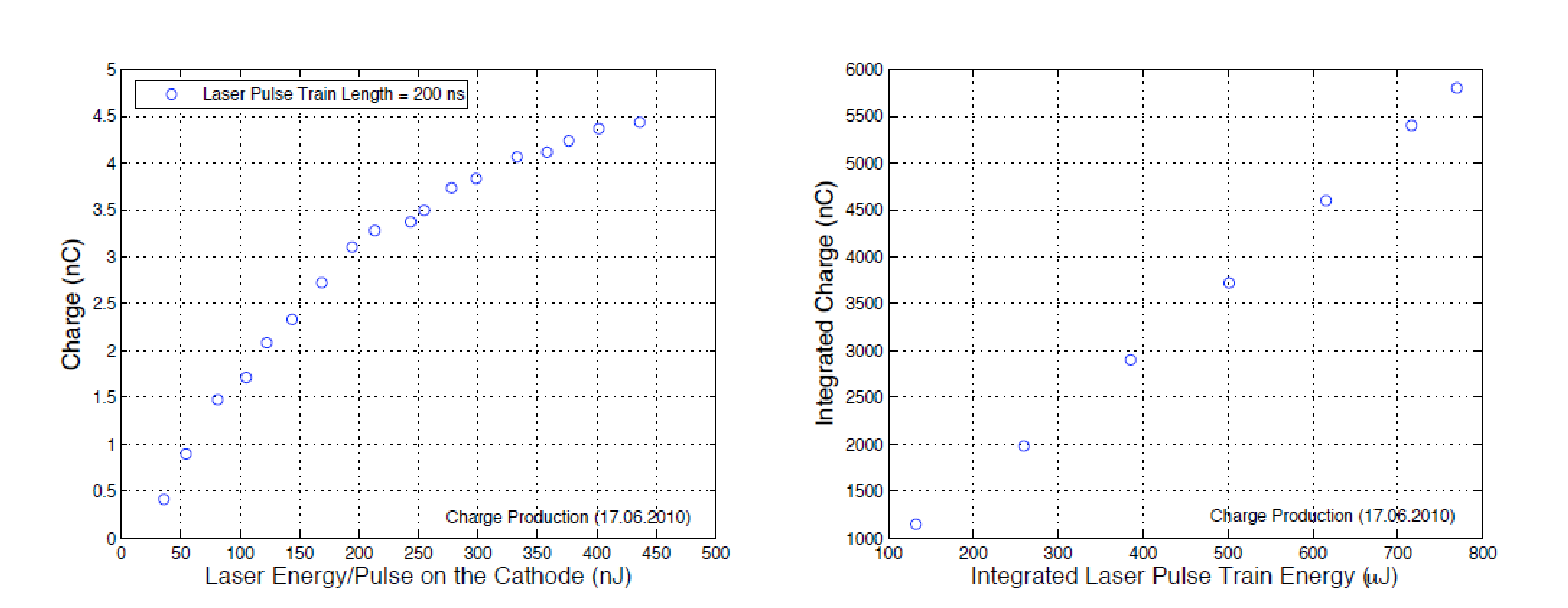


- The maximum achievable charge has been measured as 4.4 nC in this example due to a small laser spot size

$$Q_{max}[nC] = \frac{E_{acc}[MV/m]\sigma_x^2}{18} = \frac{85[MV/m](1[mm])^2}{18} = 4.7nC$$

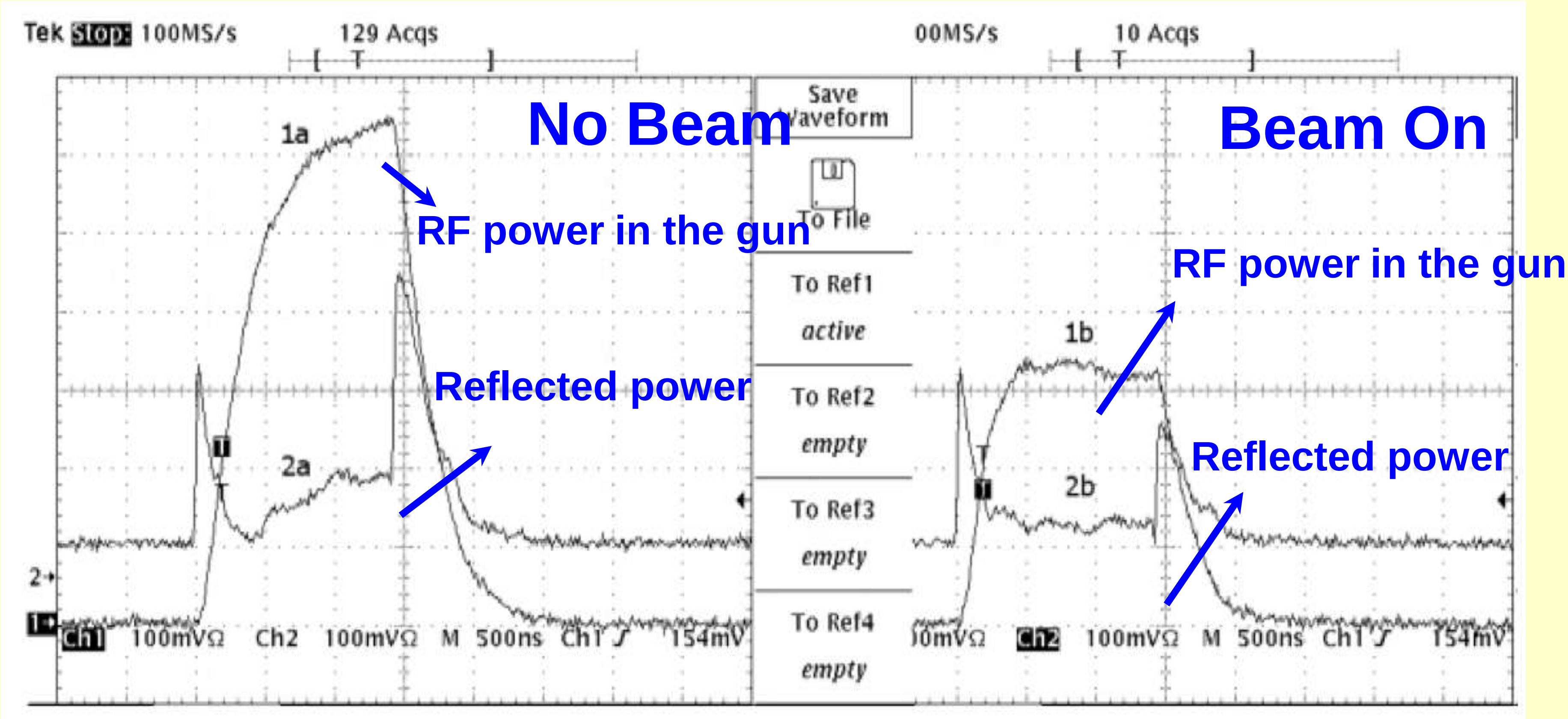
Charge production

Showed in CTF2 already the bunch charge needed (> 10 nC)
Total charge test performed in the cathode lab (> 1 mC)
460 h with 1.5% QE have been shown in excellent vacuum
Combination of those together has not yet been demonstrated
Cathode lifetime under this rough conditions is a big concern

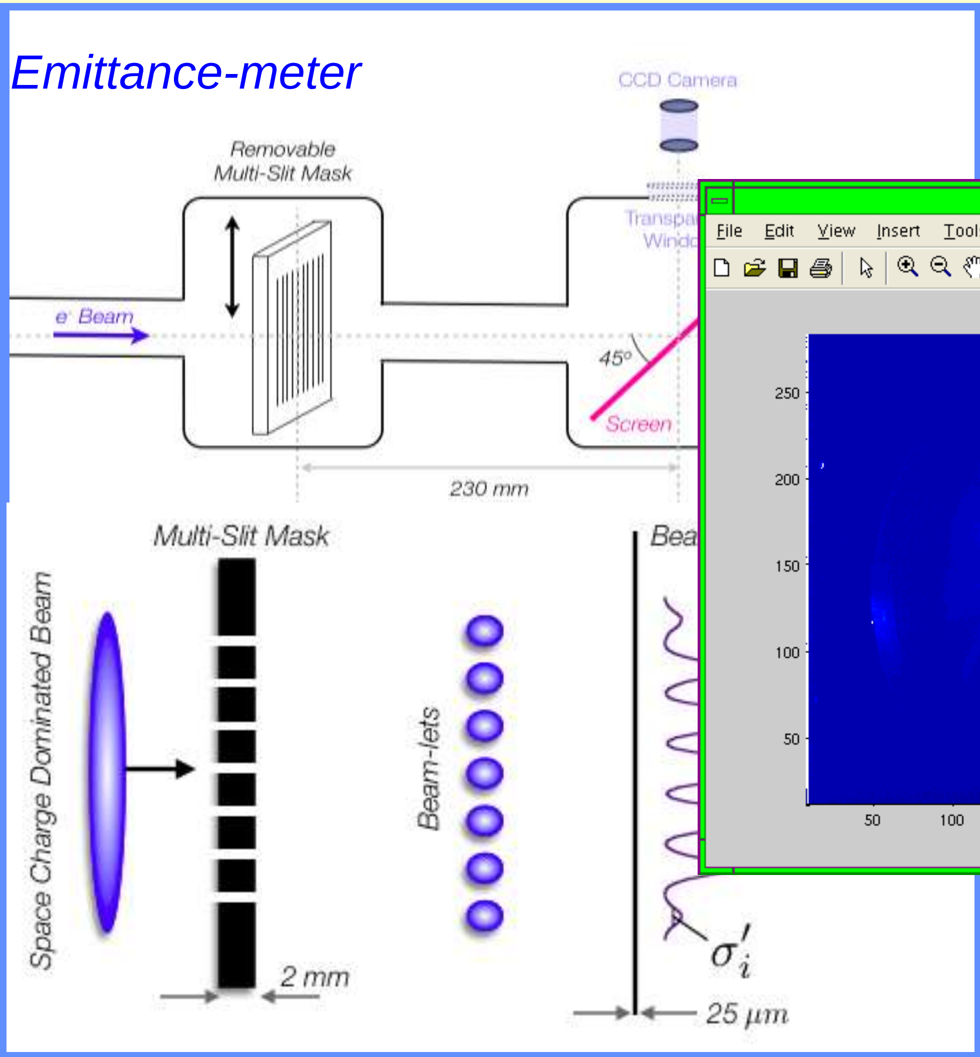


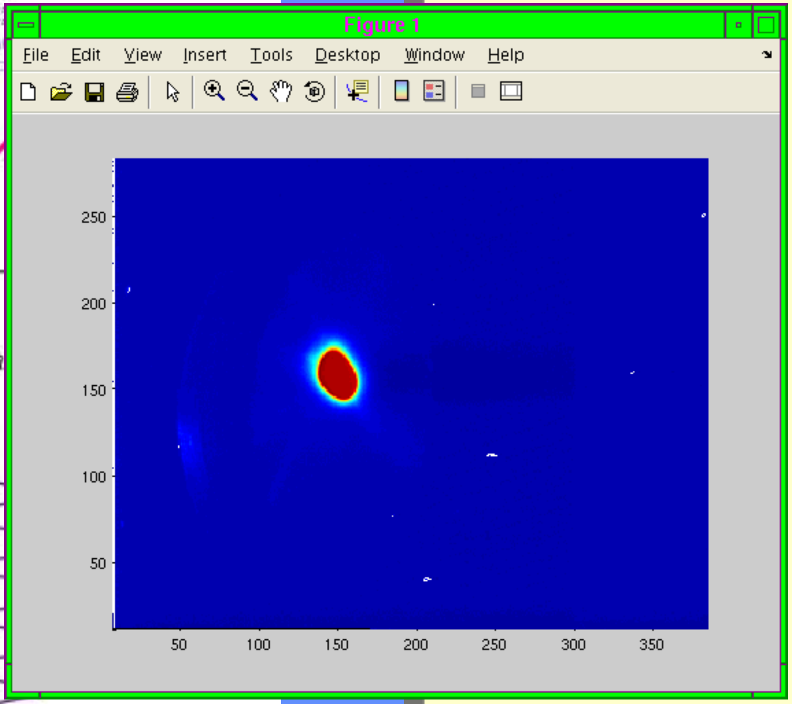
Charge production with PHIN

Beam loading compensation

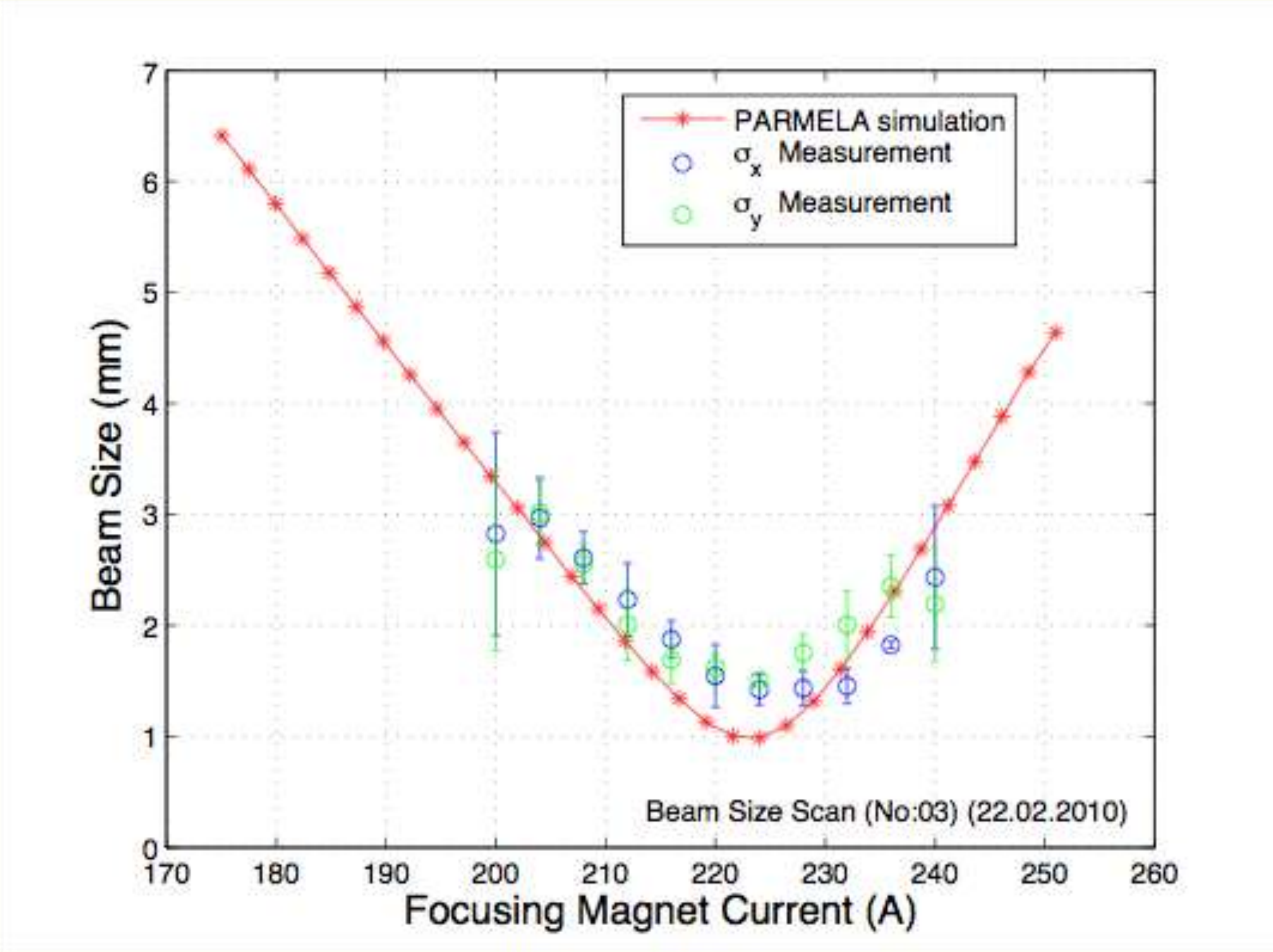


Beam size and Emittance

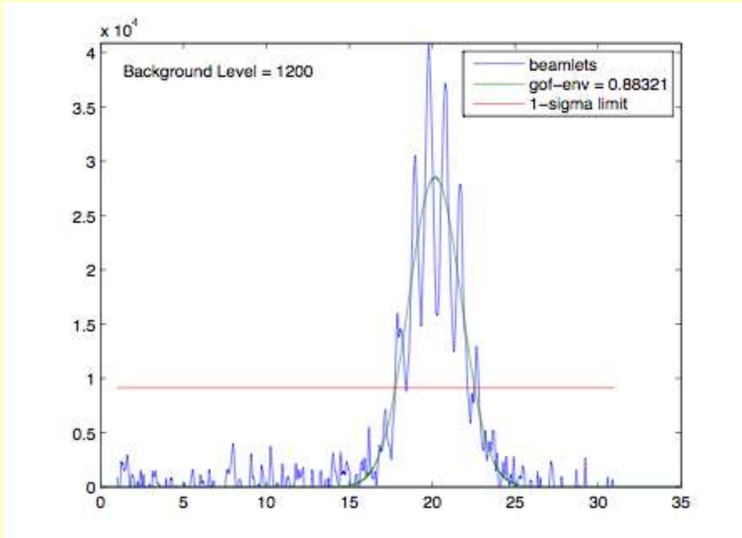


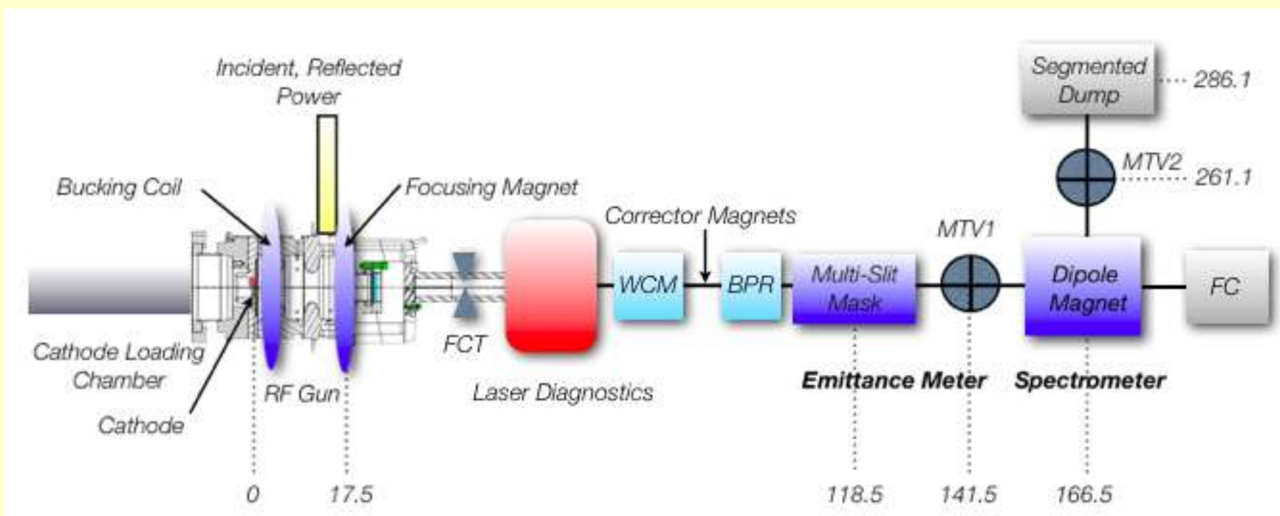


Transverse Diagnostics Solenoid scan



Multi slit emittance measurment

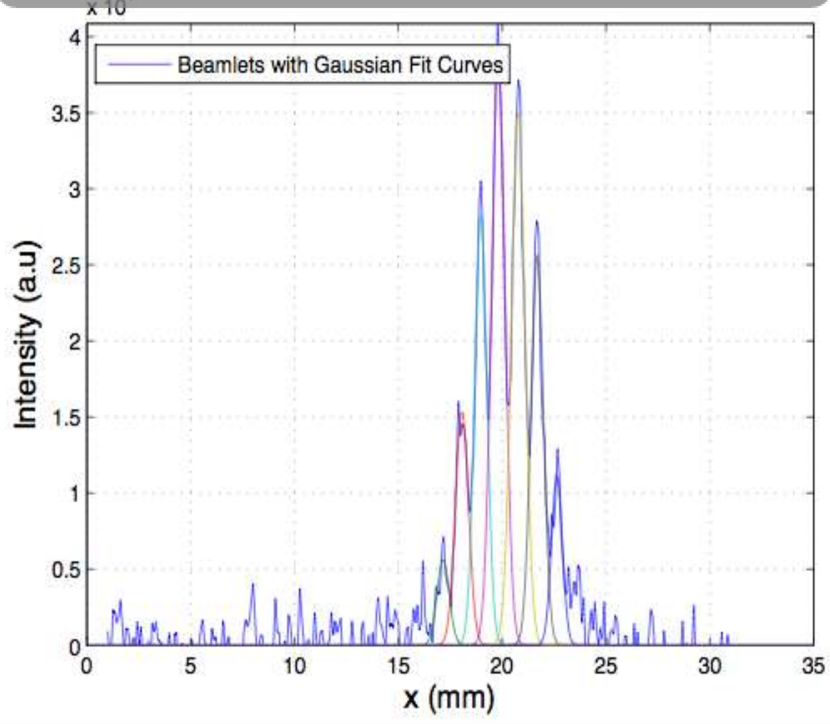




Multi slit emittance

ρ_i , intensity of individual beamlets.

$x_{i,c}$, mean positions of the beamlets.



$x'_{i,c} = < x_i - iw > / L$, divergences of the beamlets

σ'_i , spread on the divergences.

Emittance Calculation

The definition of the transverse geometric emittance.

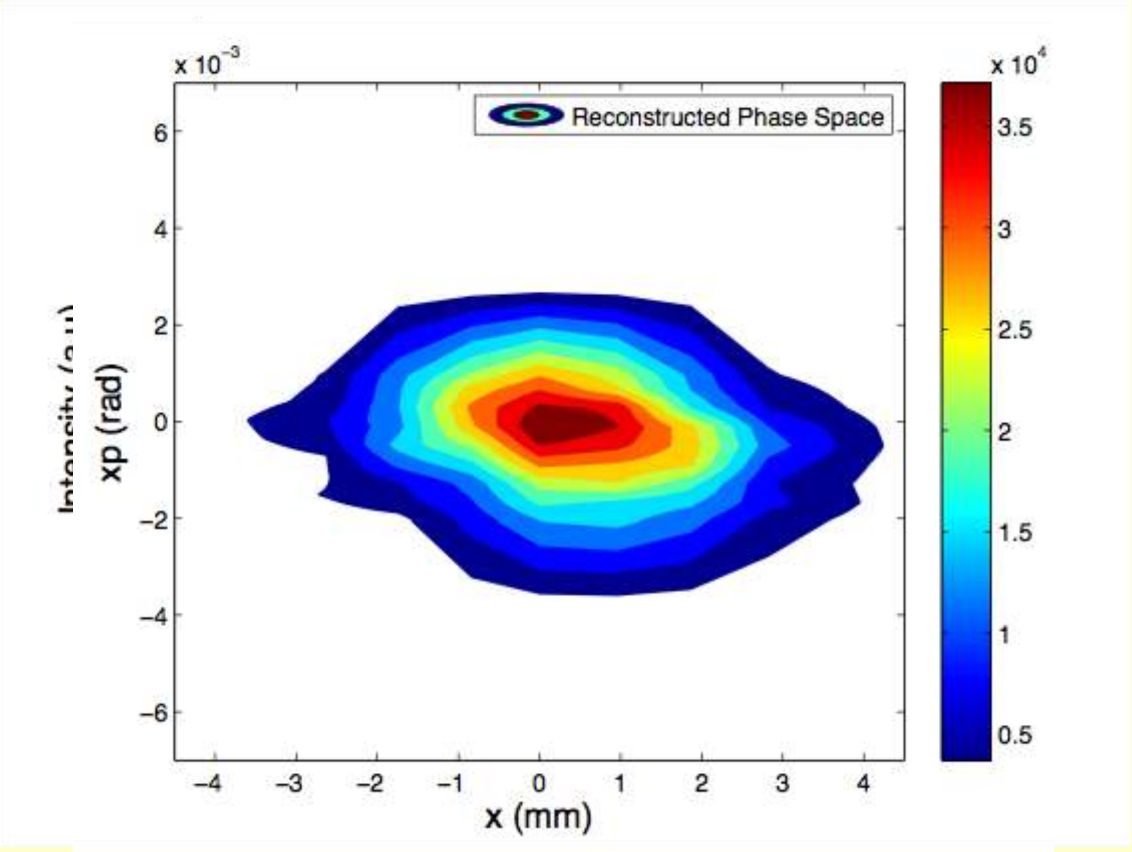
$$\epsilon_x \equiv \sqrt{< x^2 >< x'^2 > - < xx' >^2}$$

$$< x^2 >= \frac{\sum_{i=1}^{N} \rho_i x_{i,c}^2}{\sum_{i=1}^{N} \rho_i}$$

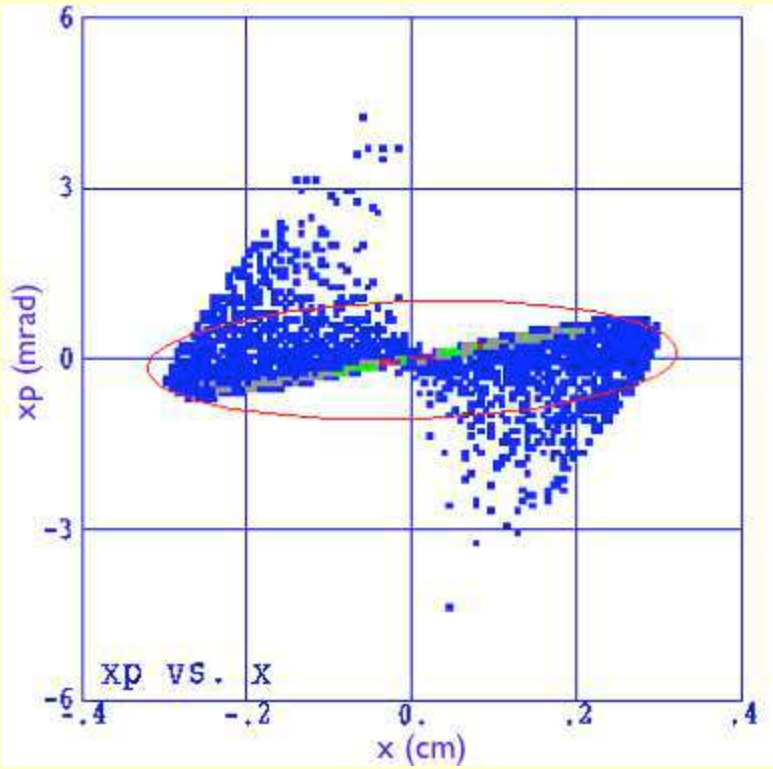
$$< x'^2 >= \frac{\sum_{i=1}^{N} \rho_i (x_{i,c}'^2 - \sigma_i'^2)}{\sum_{i=1}^{N} \rho_i}$$

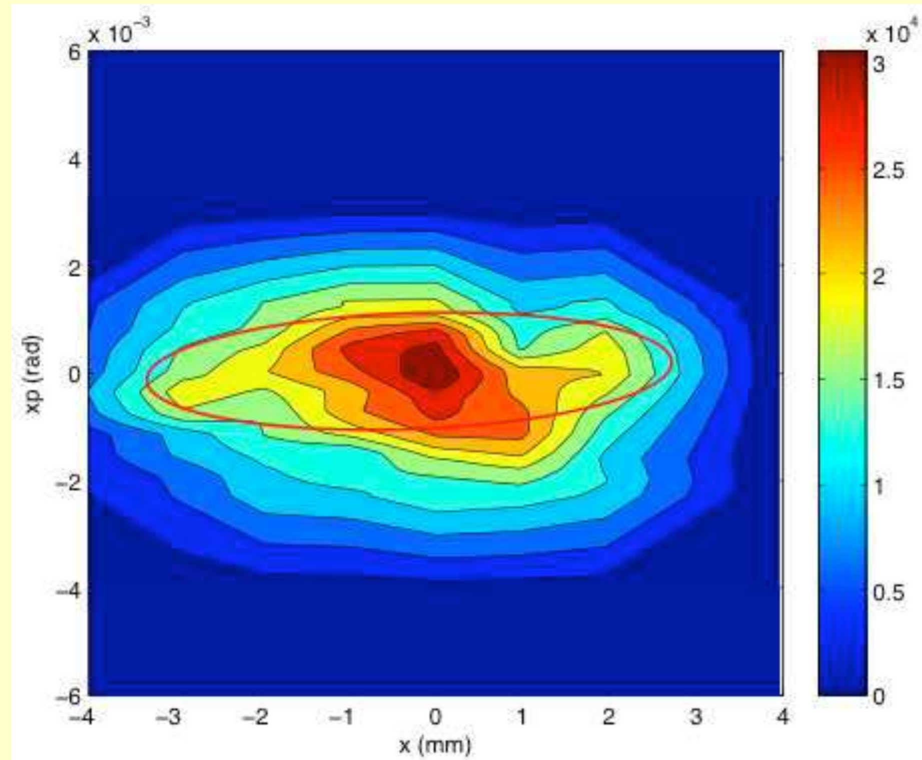
$$< xx' >= \frac{\sum_{i=1}^{N} \rho_i x_{i,c} x'_{i,c}}{\sum_{i=1}^{N} \rho_i}$$

Data analysis



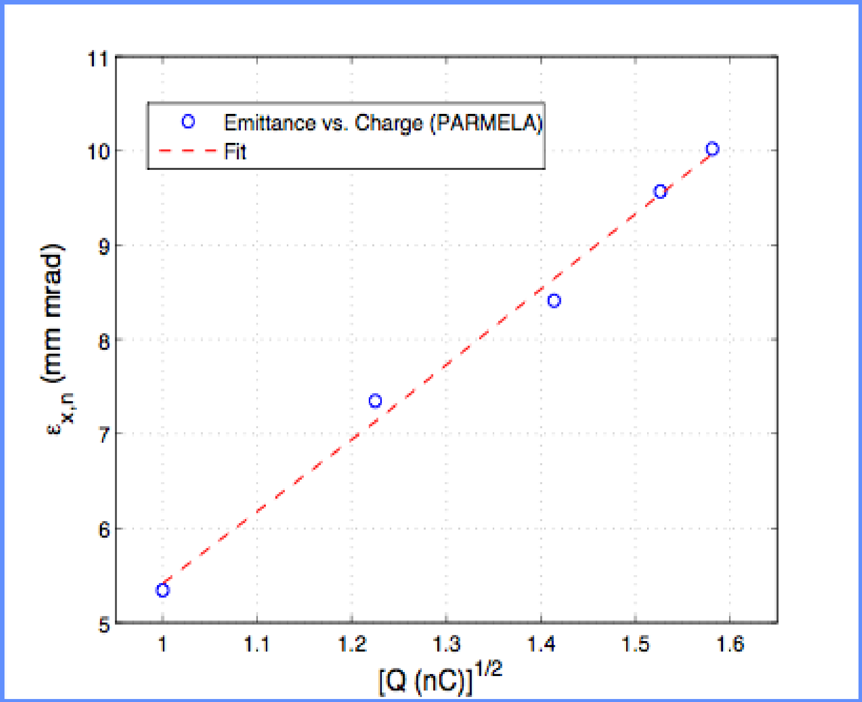
Example measurement vs simulation





Example: ε = 10.7 mm mrad for 1.28 nC beam at the energy of 5.5 MeV.
The measurement was performed with the laser spot size of 4 mm.

Emittance vs charge



$$\epsilon_n[mm\, mrad] \approx 1\mu m\sqrt{Q[nC]}$$

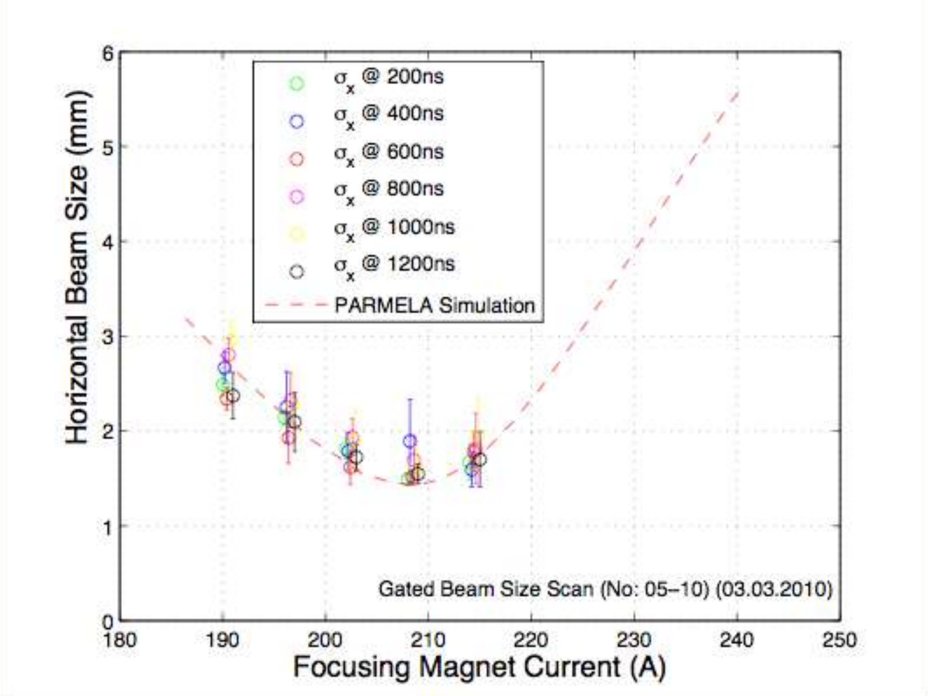
$$\epsilon_{n,x,y,tot} = \sqrt{\epsilon_{rf}^2 + \epsilon_{sc}^2 + \epsilon_{th}^2}$$

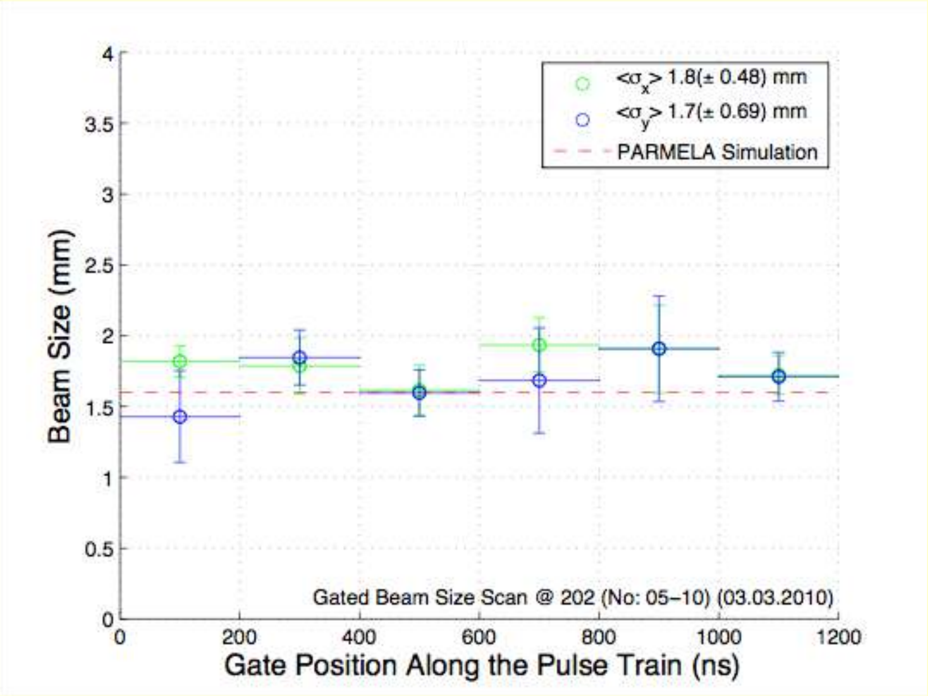
ε_{rf} ~ 1.4 mm mrad
ε_{th} < 1 mm mrad

It is all about the space charge distribution

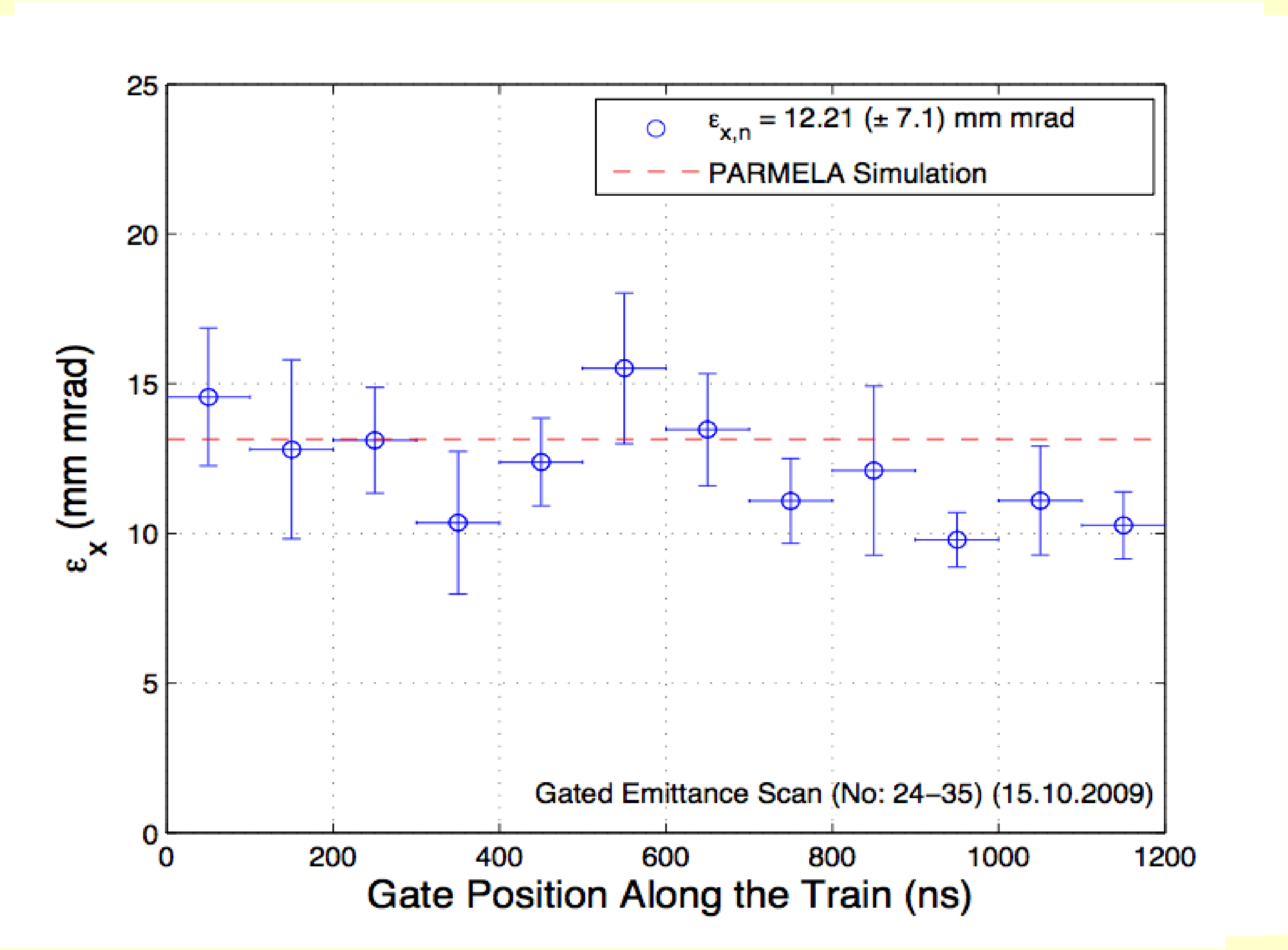
Can be optimized by laser shaping

Time resolved emittance measurements
Beam size

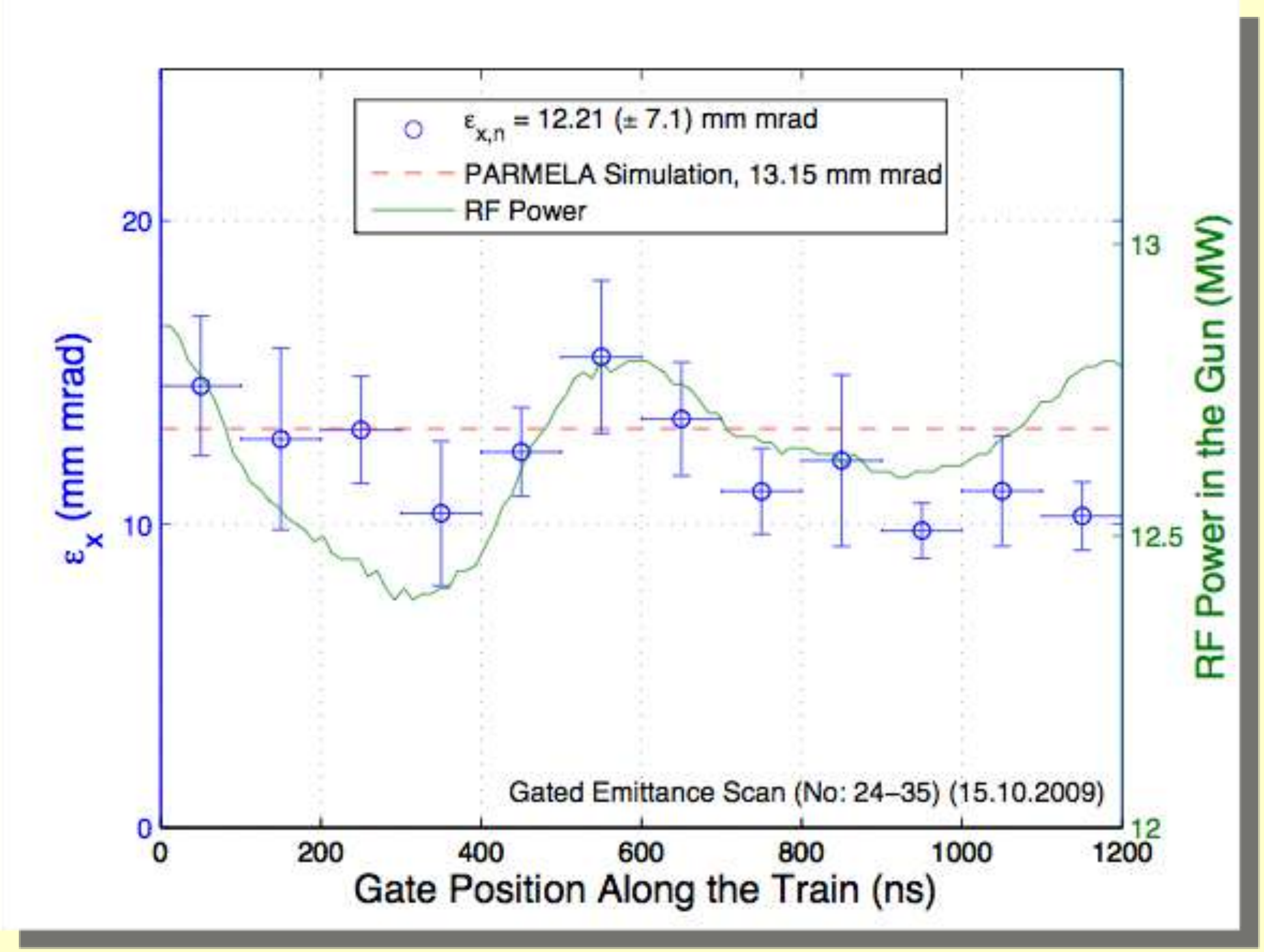




Time resolved emittance measurements

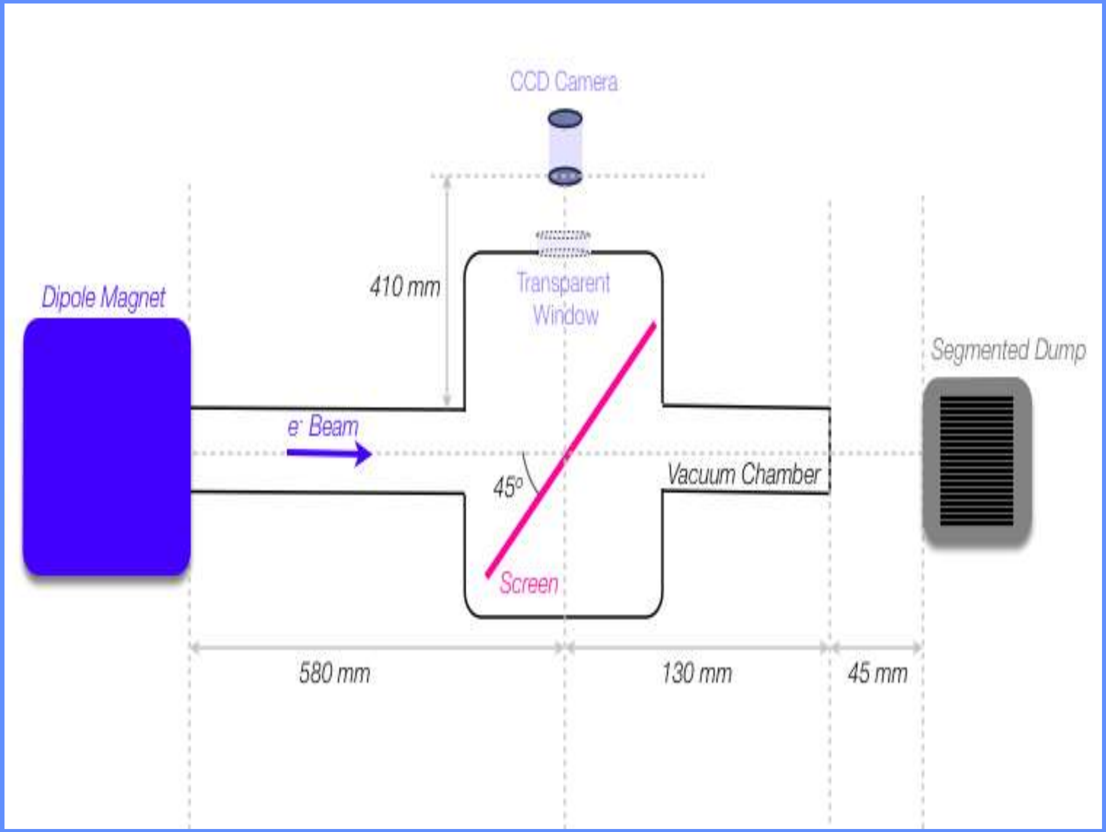


Correlation with rf power

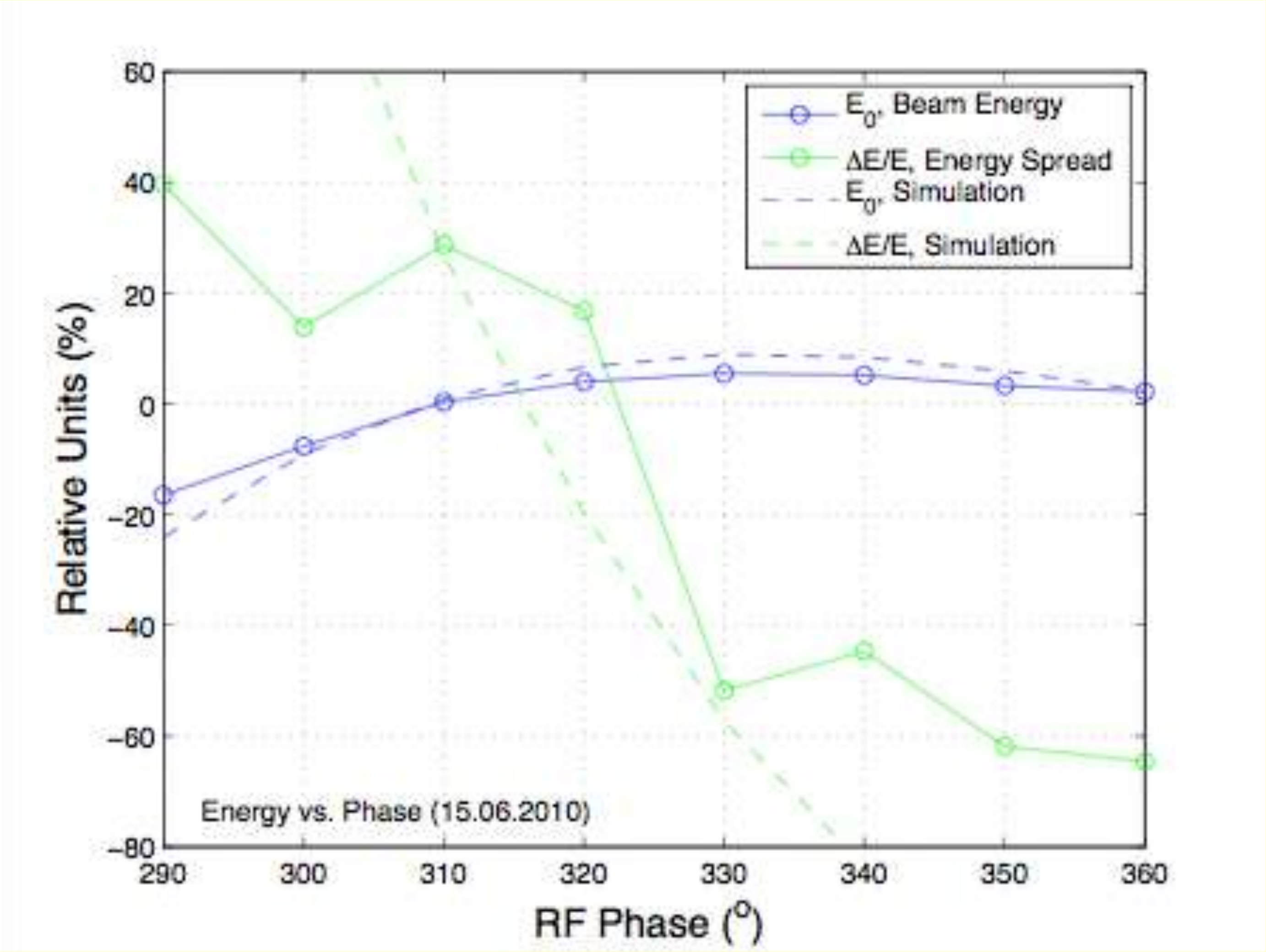


Spectrometer

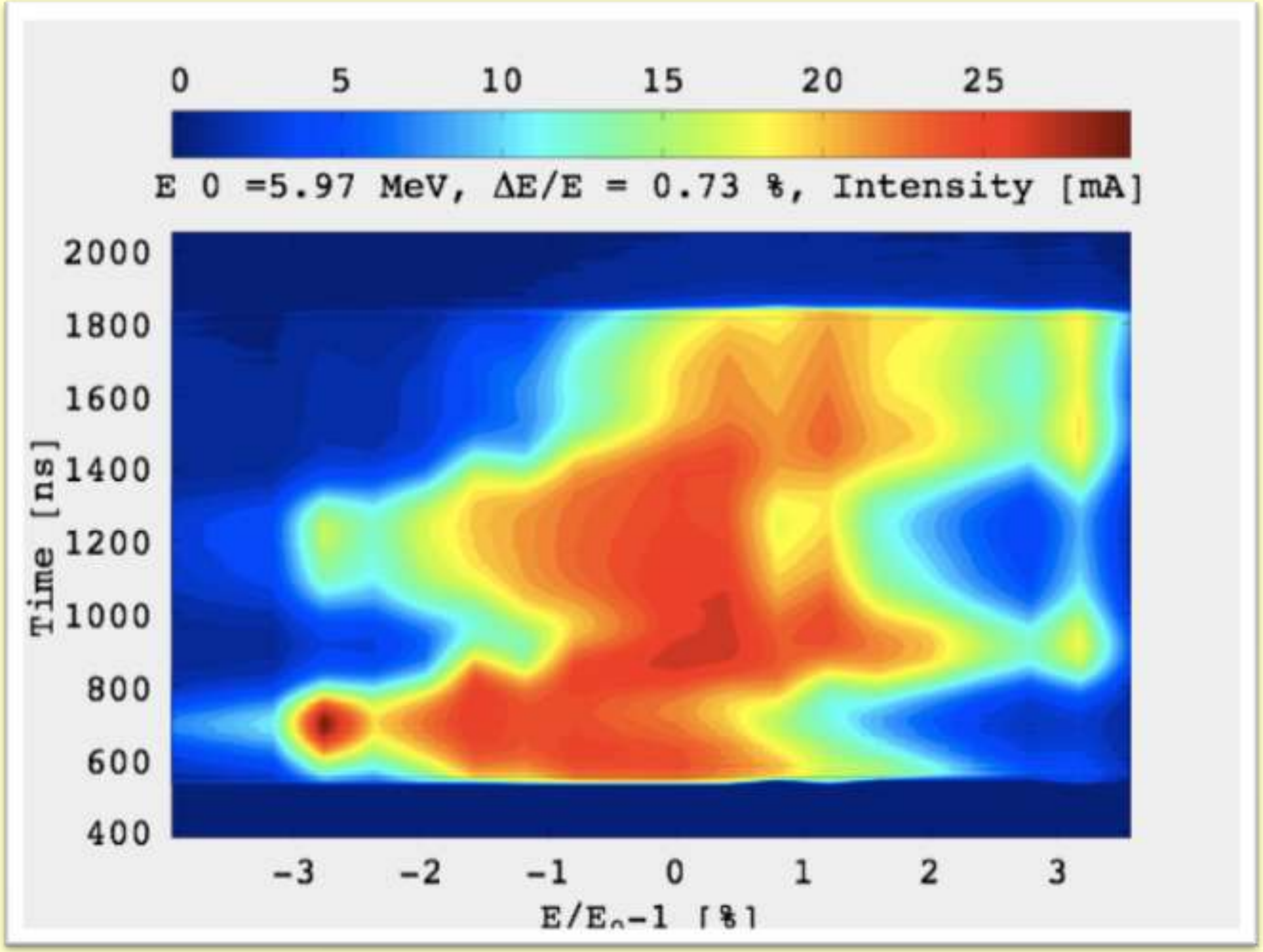
Spectrometer



Energy and energy spread

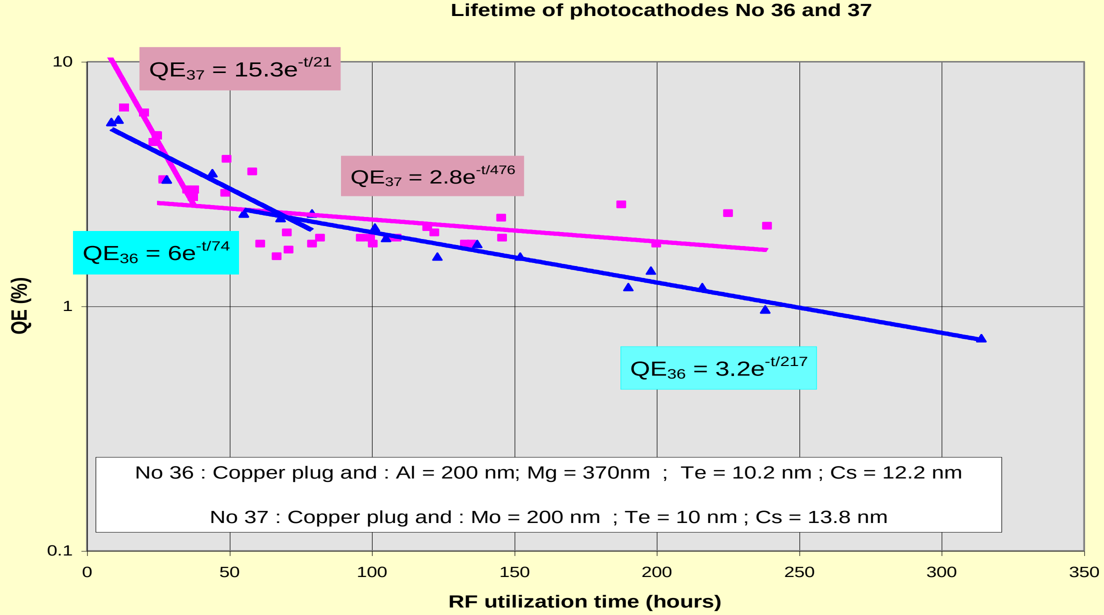


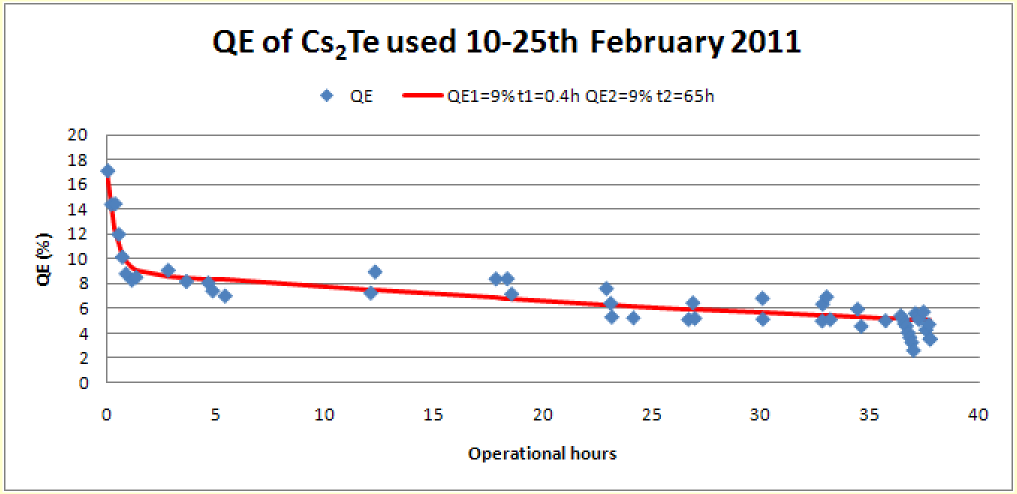
Time resolved energy spread
segmented beam dump



Cathode lifetime

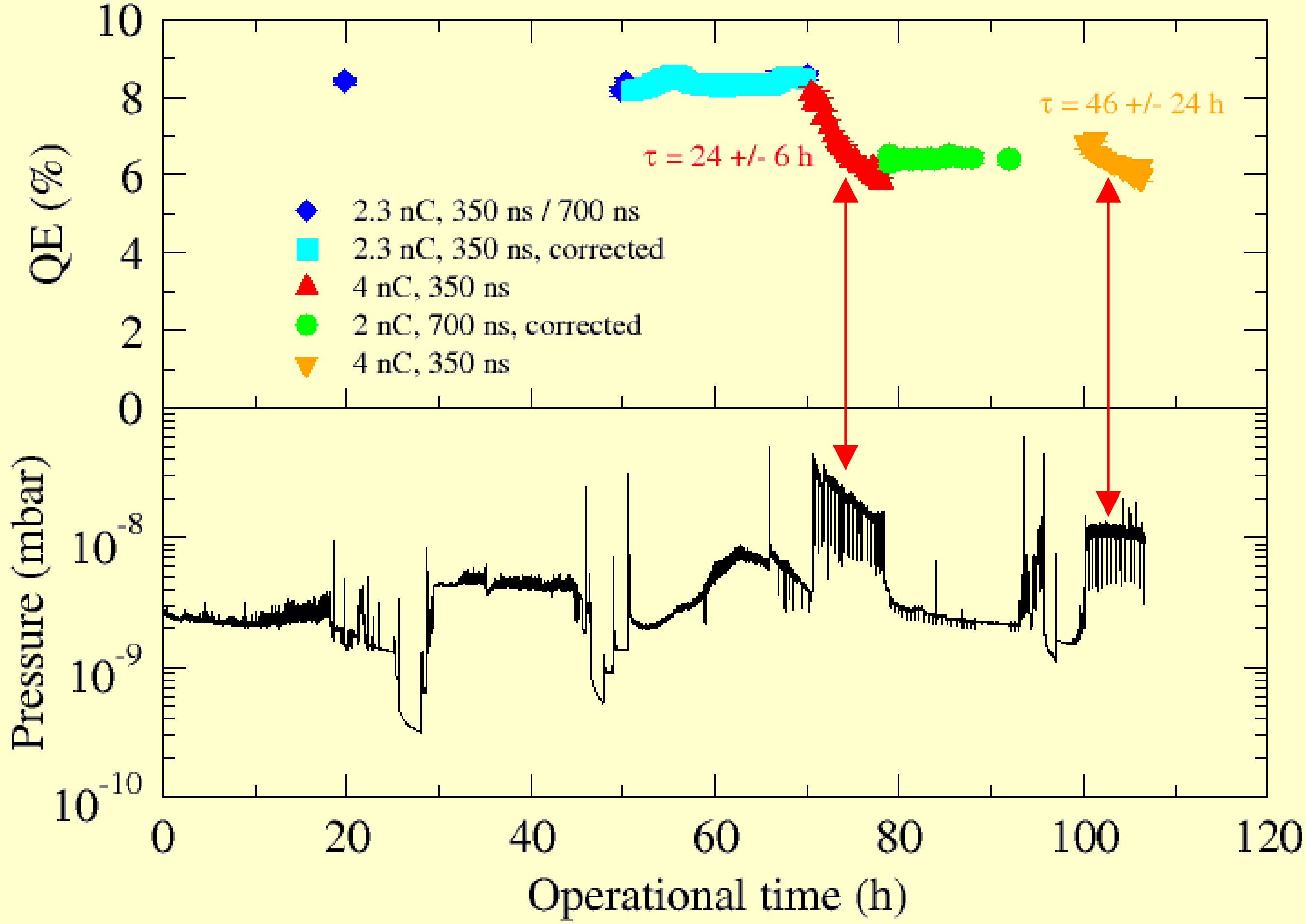
Measurements from 1996 for Cs2Te





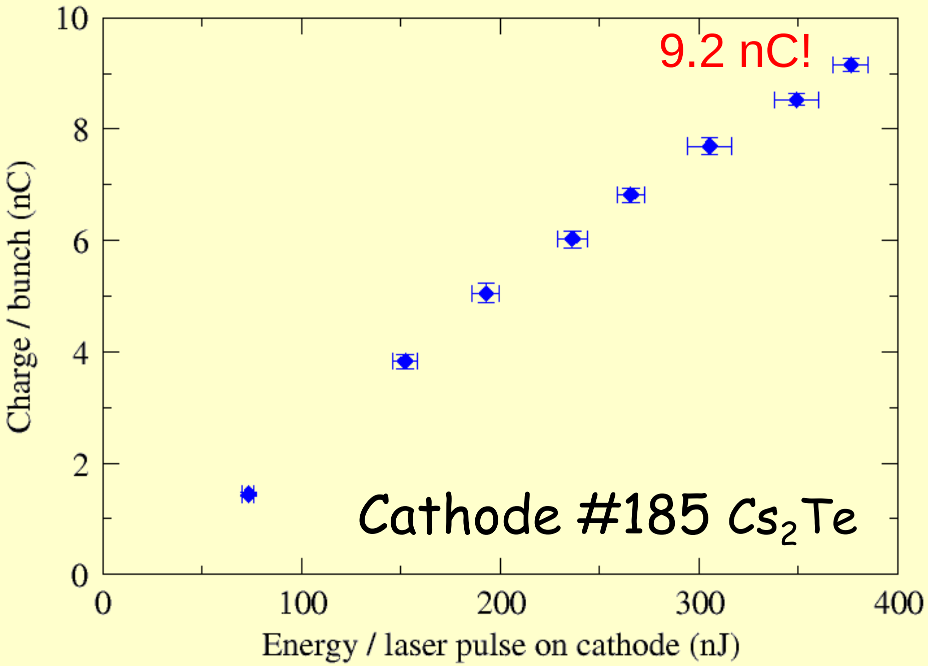
New software enables continuous Qe monitoring

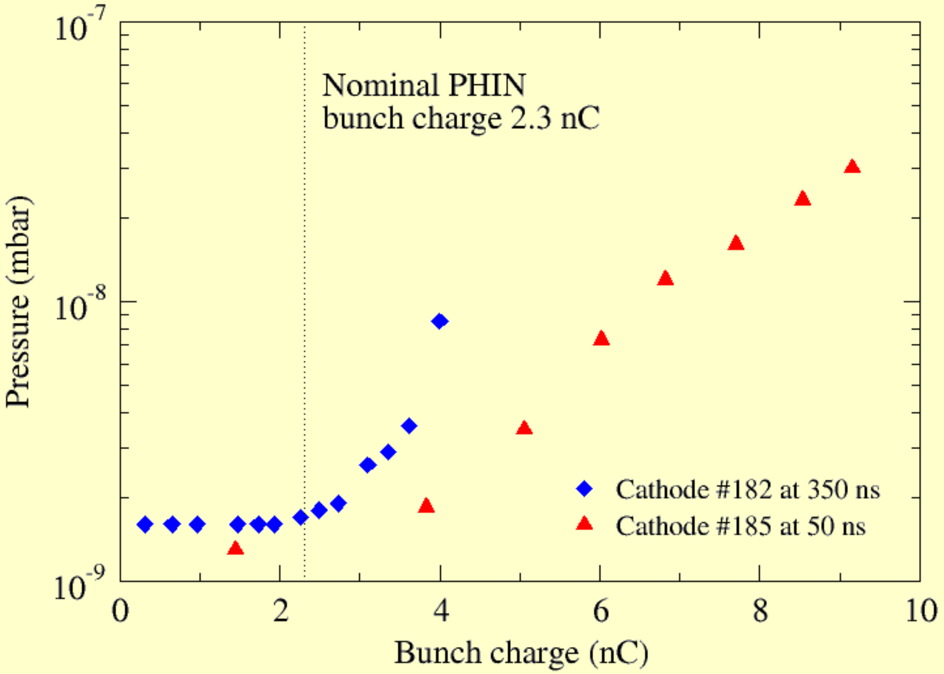
Cathode life time studies
Correlation with vacuum and bunch charge



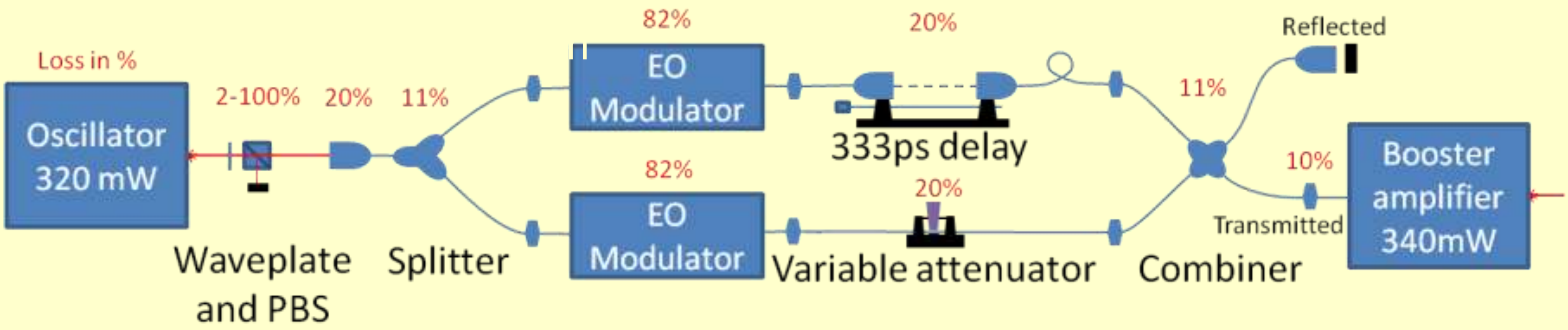
Cathode life time studies

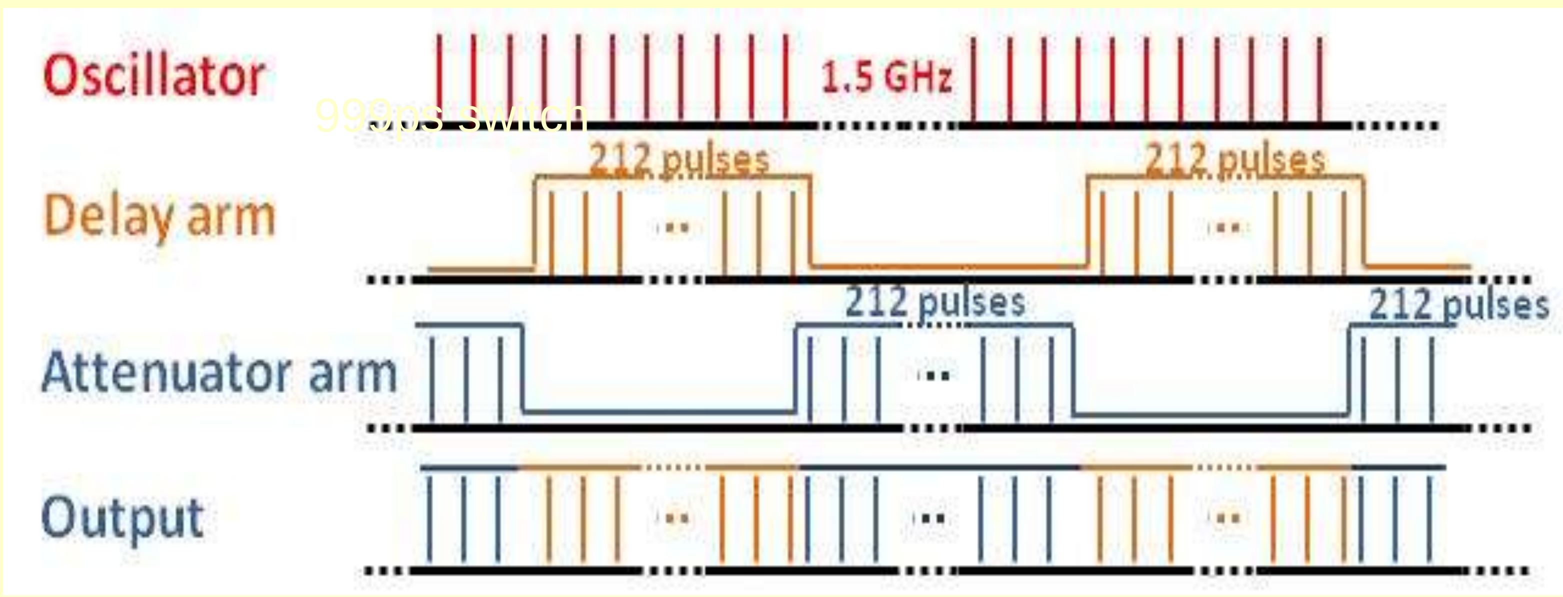
Again strong correlation with the pressure in the gun



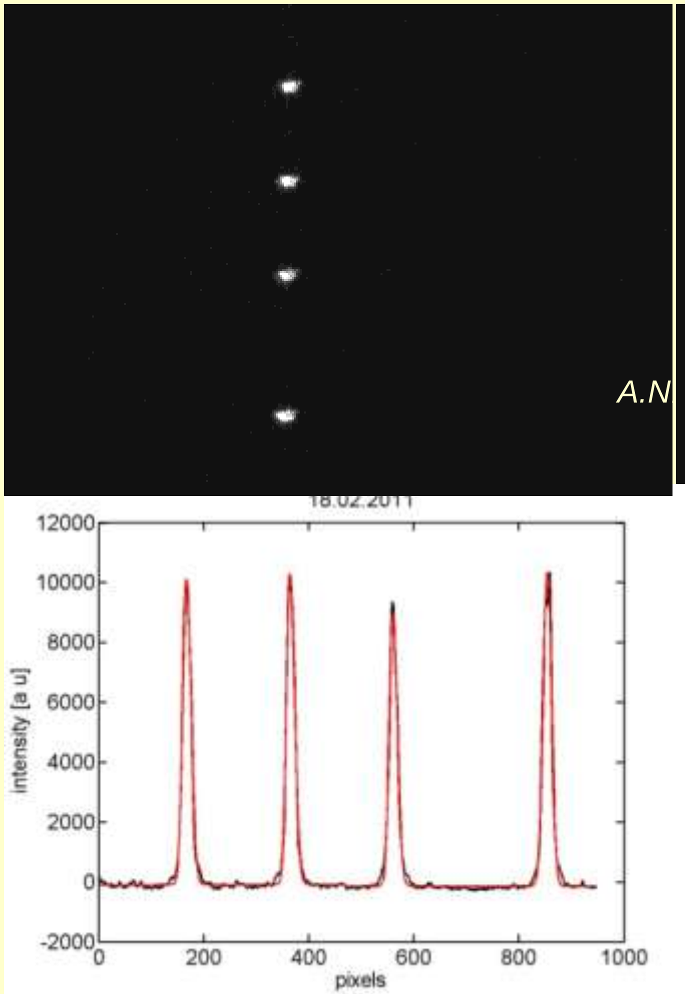


Phase coding



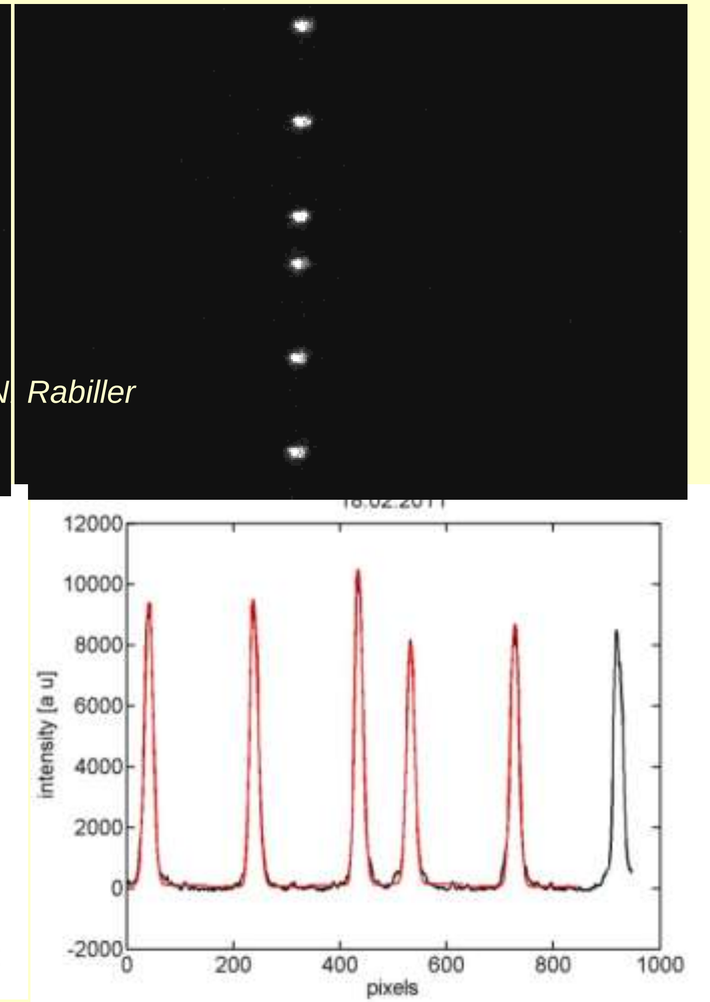


Streak measurements after AMP1&2



999ps switch

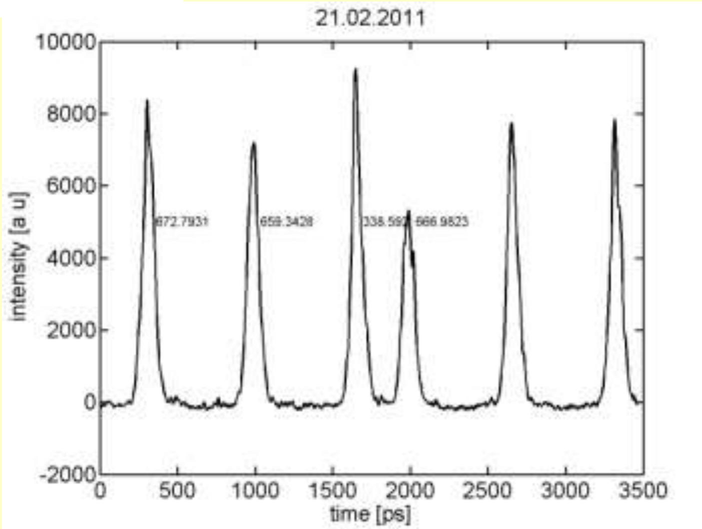
A.N. Rabiller

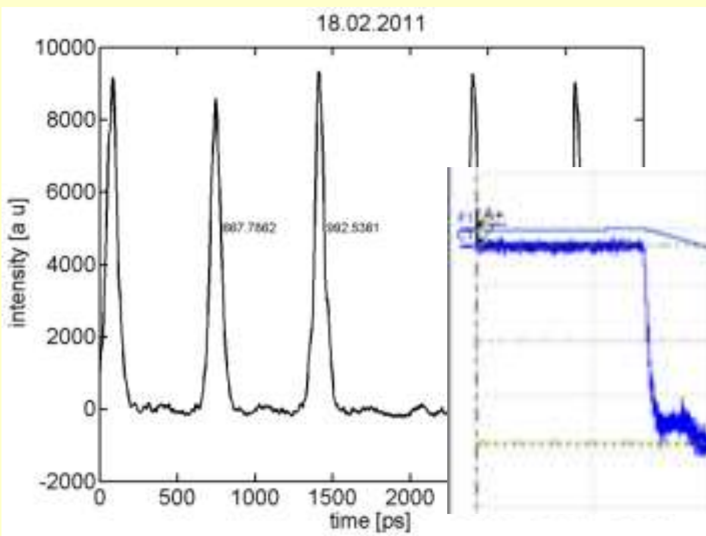


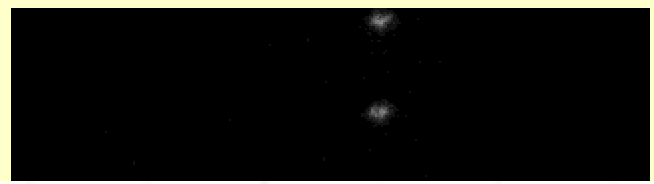
333ps switch

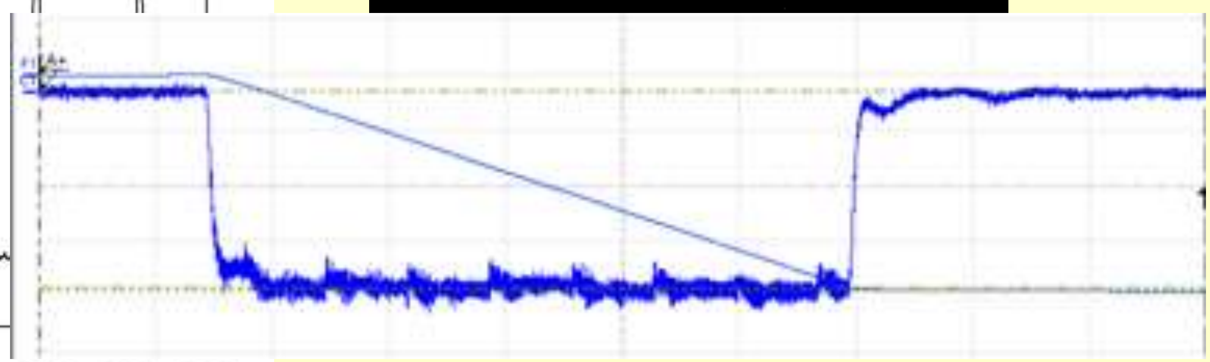
Using 523nm 2nd harmonic

Streak measurements with Cherenkov-line





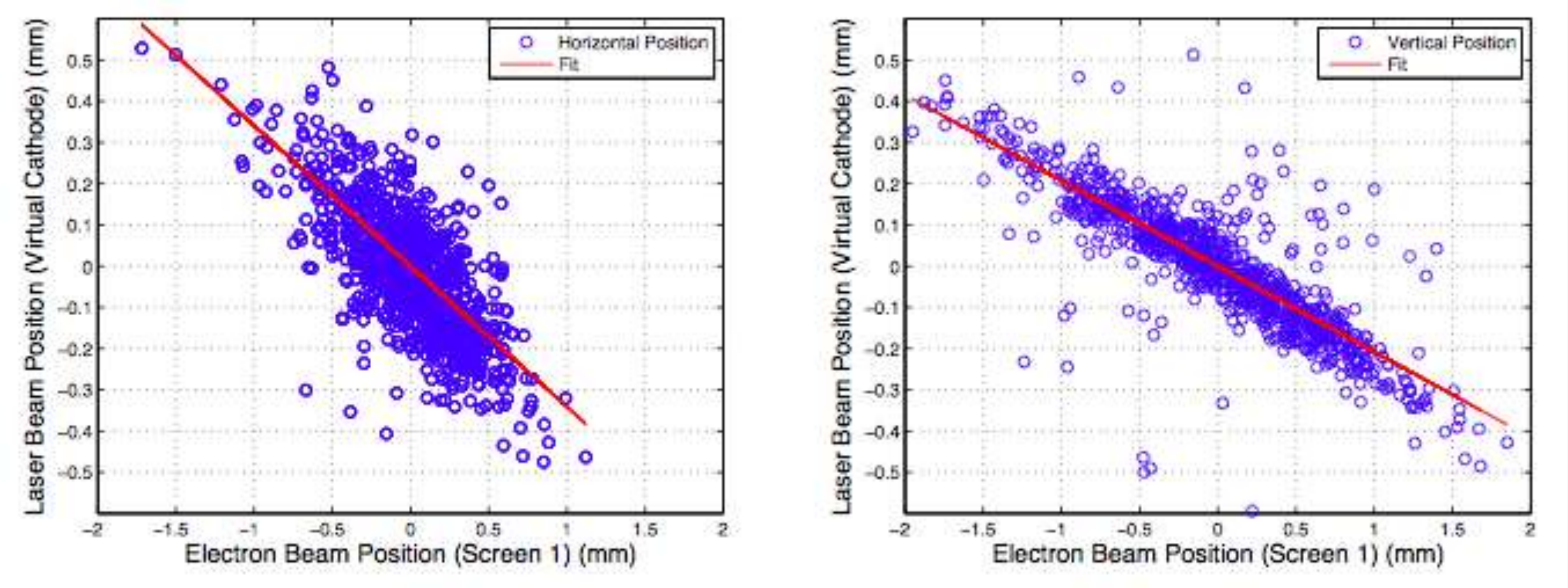


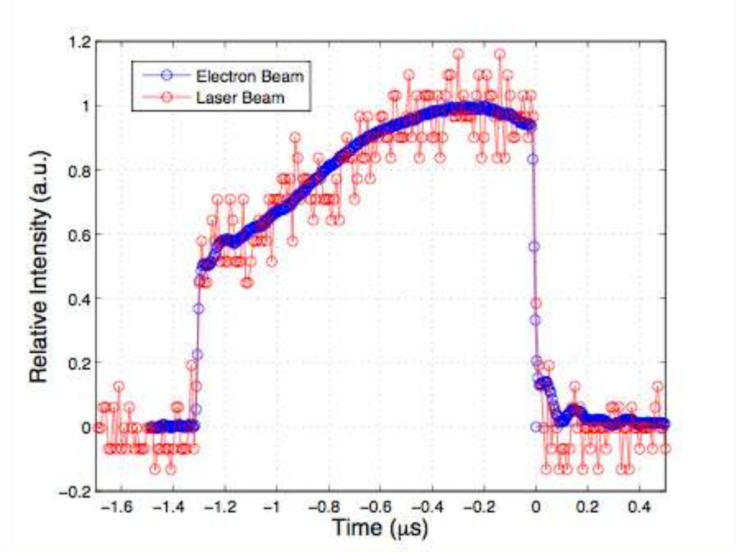


FCT signal with phase switching

A.N. Rabiller

Correlation Between the Laser and the electron Beam





Stability

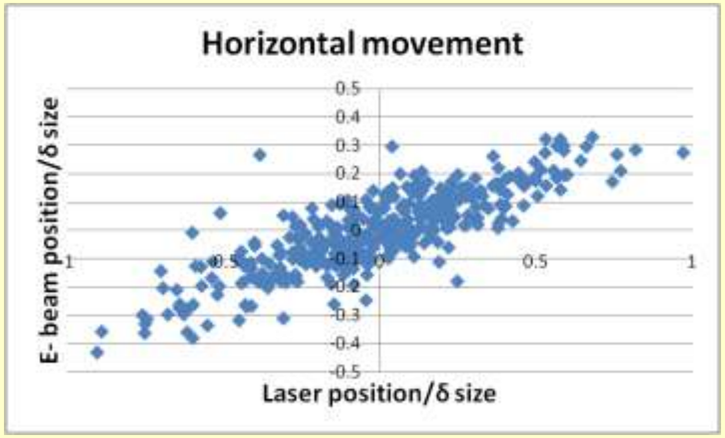
In laser room

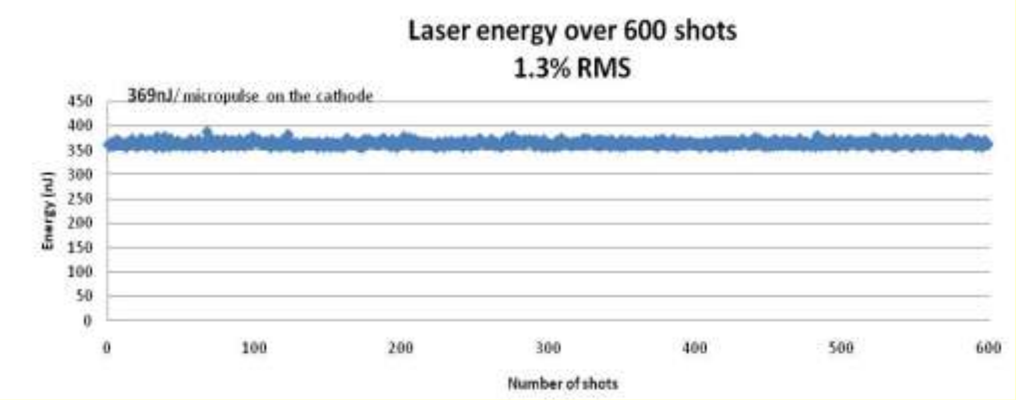
Macrop	IR	Green	UV
RMS stability	0.23%	0.8%	1.3%

Nonlinear conversion increases noise and causes amplitude variations along the train

In PHIN

Laser RMS	Current RMS	Train length(ns)	
1.3% RMS	**0.8% RMS**	1250	best
2.6%	2.4%	1300	worst

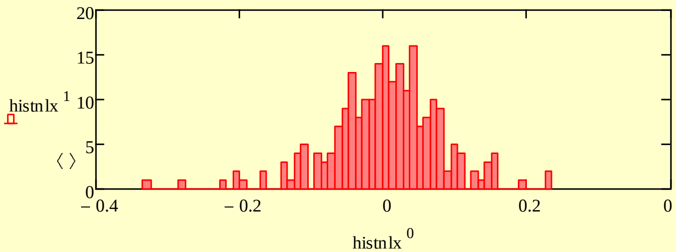




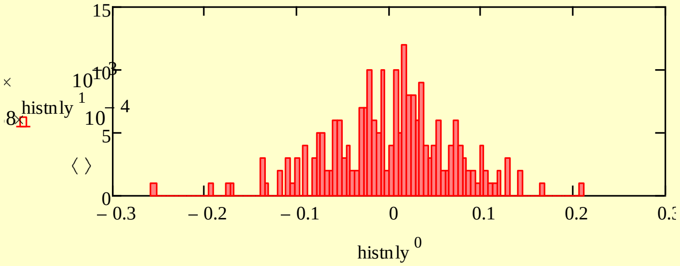
Beam stability seems almost entirely determined by laser stability
First tests of feedback system is encouraging

We need 0.1% RMS stability

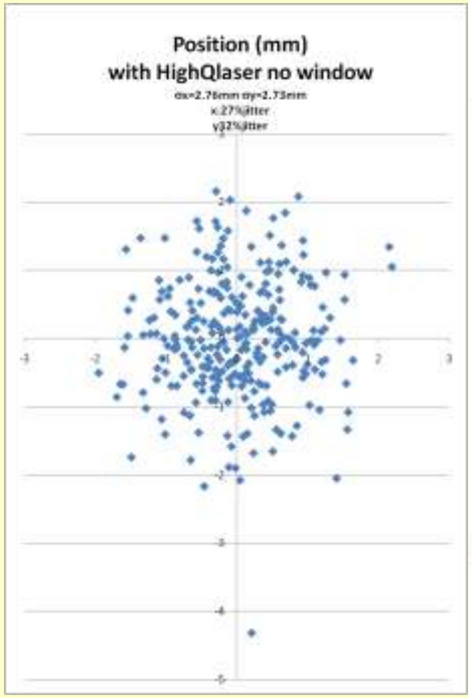
Beam pointing stability



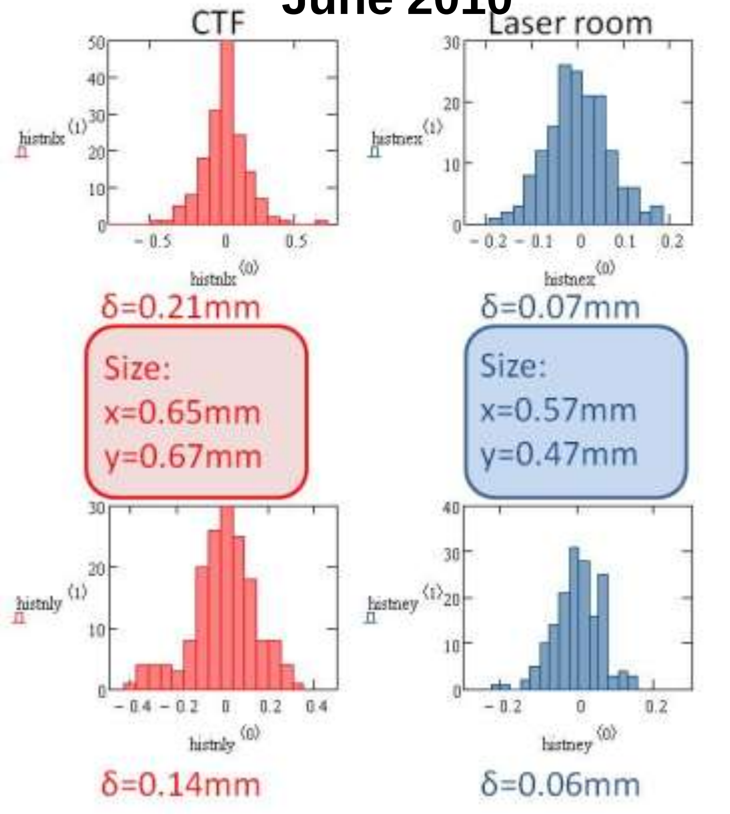
Beamposition X stdev=0.079mm sigmasize 0.522mm



Beam position Y stdev=0.067mm 0.34mmsigma



June 2010



mm	June 2010 no cover	Feb 2011 HighQ input & cover	Feb 2011 fiber input &cover
Size x	0.65	2.76	0.344
δ movement	0.21 (32%)	0.74 (27%)	0.067 (19%)
Size y	0.67	2.73	0.524
δ movement	0.14 (21%)	0.87 (32%)	0.079 (15.2%)

Continuing research program
Photo injector option

PHIN:
- study cathode lifetime:
  lifetime vs bunch charge (2-8 nC),
  total charge (0.5-4 μs pulse length),
  vacuum

- activate NEG chamber (partially done)
- test Cs_3Sb with green light (next run March 2012)
- study 8.4 nC beam dynamics, lower gradient ?

CLIC DB beam:
Design 1 GHz rf gun and investigate if full pulse length can be demonstrated

CLIC DB injector specifications

Parameter	Nominal value	Unit
Beam Energy	50	MeV
Pulse Length	**140.3** / 243.7	μs / ns
Beam current	4.2	A
Bunch charge	**8.4**	nC
Number of bunches	70128	
Total charge per pulse	**590**	μC
Bunch spacing	**1.992**	ns
Emittance at 50 MeV	100	mm mrad
Repetition rate	100	Hz
Energy spread at 50 Mev	1	% FWHM
Bunch length at 50 MeV	3	mm rms
Charge variation shot to shot	**0.1**	%
Charge flatness on flat top	**0.1**	%
Allowed satellite charge	< 7	%
Allowed switching time	5	ns

Challenges for the Photo injector option

- High single bunch charge 8.4 nC
- Extremely high total charge per pulse 590 μC
- Cathode life time, dynamic vacuum
- Extremely high average power for the laser
- Challenging stability requirements, laser, rf, …
- Challenging 1 GHz rf system, 140 μs long pulse
- RF design and engineering for the rf gun, gradient and cooling
- Budget situation

Conclusions

- PHIN completely constructed and commissioned
- Experimental characterizations agrees with simulations
- Design parameters for CTF3 demonstrated including phase coding and high average charge
- Pretty good beam and laser stability, needs to be improved for CLIC
- Working towards a photo injector option for the CLIC DB injector