PHIN Results

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Motivation for a CLIC Drive-Beam Photoinjector

- A conventional system (thermionic gun, sub-harmonic buncher, RF power sources) is not necessarily more reliable than a photoinjector. At CTF3 e.g. the availability of the CALIFES photoinjector is high.
- With a photoinjector in general a better beam quality can be achieved than with a conventional system.
- Conventional system (thermionic gun, sub-harmonic buncher) generates parasitic satellite pulses, which produce beam losses.
  - Reduced system power efficiency
  - Radiation issues
- These problems can be avoided using a photoinjector, where only the needed electron bunches are produced with the needed time structure. → Has been demonstrated for the phase-coding in 2011.

M.Csatari Divall et al., “Fast phase switching within the bunch train of the PHIN photo-injector at CERN using fiber-optic modulators on the drive laser”, Nucl. Instr. And Meth. A 659 (2011) p. 1.

Challenges for a CLIC Drive-Beam Photoinjector

- Achieve long cathode lifetimes (>150 h) together with high bunch charge (8.4 nC) and high average current (30 mA)

  → Vacuum improvement, new photoemissive materials, new cathode substrate surface treatment
- Produce ultra-violet (UV) laser beam with high power and long train lengths (140 µs)
  - UV beam degradation in long trains

    → Usage of Cs_3Sb cathodes sensitive to green light

    → New UV conversion schemes with multiple crystals
  - Thermal lensing and heat load effects?

    → Study the dynamics of laser system with full CLIC specs
- High charge stability (<0,1%)

  → Feedback stabilisation, new laser front end

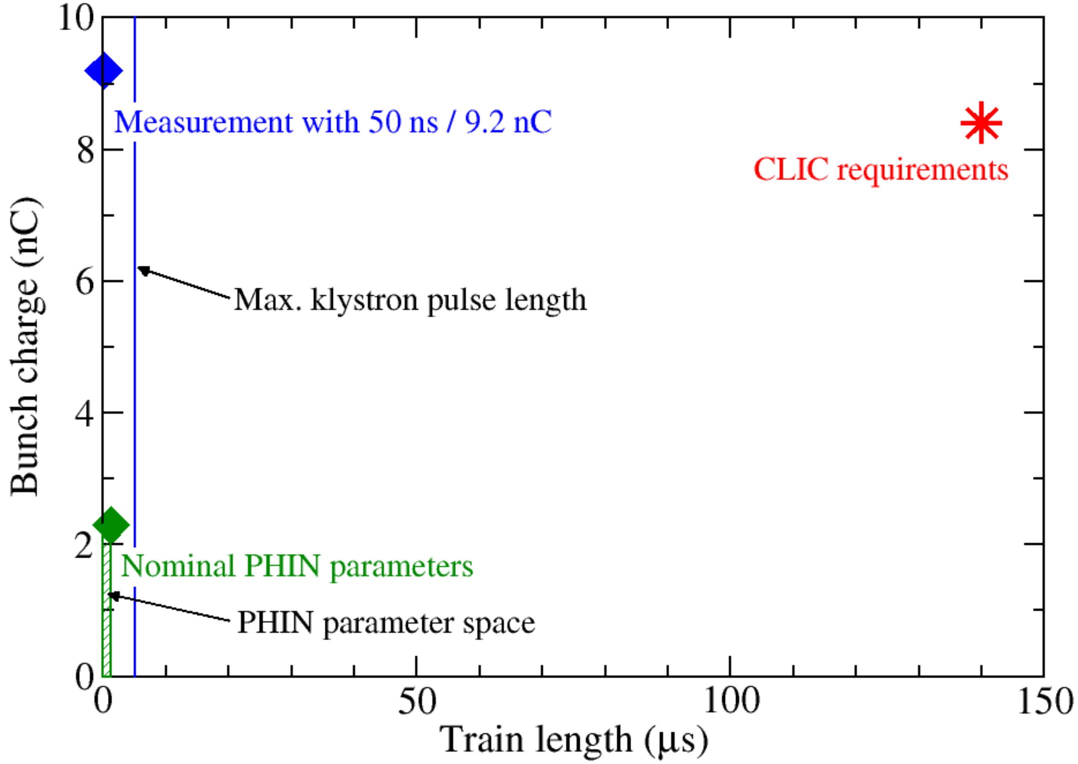
Photoinjector optimization and beam studies

Photocathode R&D

Laser R&D

Challenge to Verify Feasibility of Drive-Beam Photoinjector

- CLIC requirements far beyond PHIN specs:



Different macro-pulse repetition rates:
0.8 – 5 Hz (PHIN)
50 Hz (CLIC)

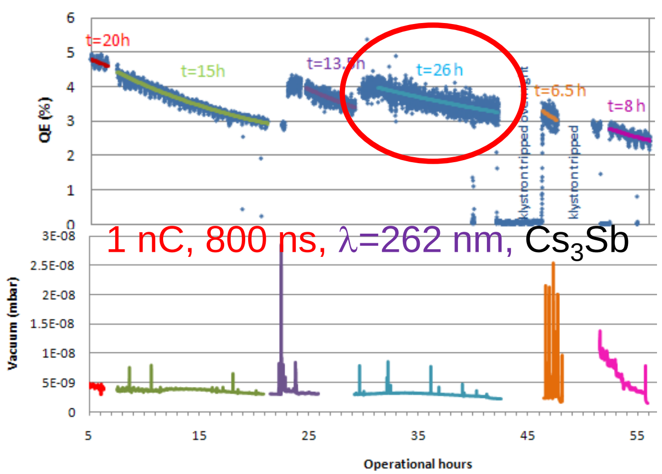
- One PHIN run per year with 3 cathodes to test.
→ No statistics possible under these conditions!
- Photocathode lifetime measurements require long measurement periods, which are in general not available to the extend as needed.

Recent R&D Activities at PHIN

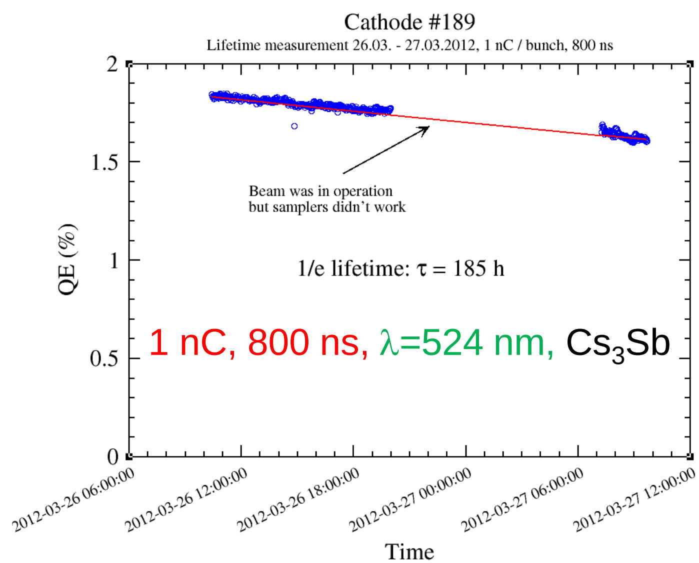
- Since a strong negative impact on vacuum level is expected for CLIC parameters, the vacuum level in PHIN has been improved and its impact on photocathode performance studied:
  - Lifetime studies with Cs_2Te cathode under improved vacuum conditions.
  - Lifetime studies with Cs_3Sb cathodes and green laser light under improved vacuum conditions.
- Focus on Cs_3Sb cathodes sensitive to green light:
  - Lifetime measurements.
  - RF lifetime measurements.
  - Dark current studies.
- Long-term measurement with Cs_2Te under nominal operating conditions (2.3 nC, 1.2 µs)
- Studies for AWAKE project:
  - Emittance measurement with low intensity beam to investigate PHIN's suitability for AWAKE.
  - QE measurement of copper cathode for defining QE requirements for AWAKE.

Improvement of Vacuum in PHIN

March 2011		March 2012		July 2013
Dynamic vacuum level: 4e-9 mbar	Activation of NEG chamber around gun →	7e-10 mbar	Installation of additional NEG pump →	<2e-10 mbar
Static vacuum level: 2.2e-10 mbar		1.3e-10 mbar		2.4e-11 mbar
1/e lifetime 26 h		1/e lifetime 185 h		1/e lifetime ?



1 nC, 800 ns, λ=262 nm, Cs_3Sb



1 nC, 800 ns, λ=524 nm, Cs_3Sb

Photocathodes Used during PHIN Run 2014

Number	Material	Age	QE in DC gun	QE in PHIN
#198	Cs_2Te	New cathode, produced 05.03.2014	14.8% after production	~10%
#199	Cs_3Sb	New cathode, produced 27.5.2014	5.2% after production	4.9%
#200	Cs_3Sb	New cathode, produced 7.8.2014	5.5% after production	3.9%
6A56	Cu	Copper plug (Diamond powder polished) used for RF conditioning	2e-4 after PHIN run	3e-4

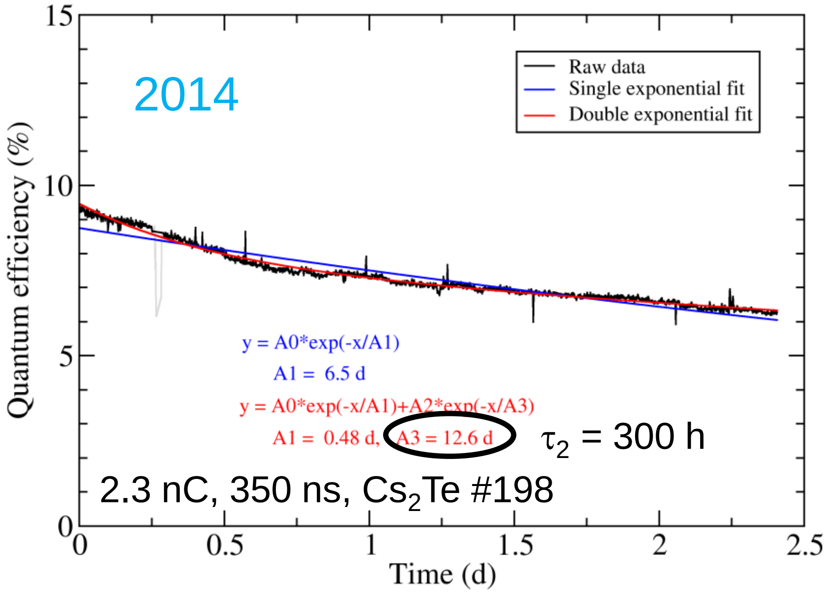
Test for AWAKE

- In 2014 the initial QE of Cs_2Te and Cs_3Sb cathodes in PHIN was in reasonable agreement with the measurements in the DC gun.
- QE of Cu cathode was too high compared with best literature values (1.4e-4) . Maybe contaminated with Cs.

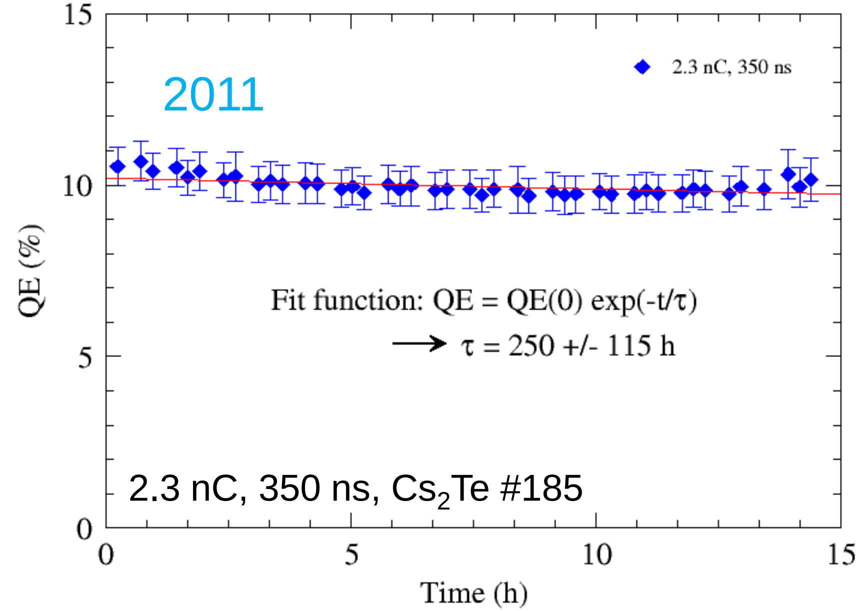
Lifetime Measurement with Cs_2Te Cathode

- Under improved vacuum conditions:

Dynamic pressure: 3e-10 mbar



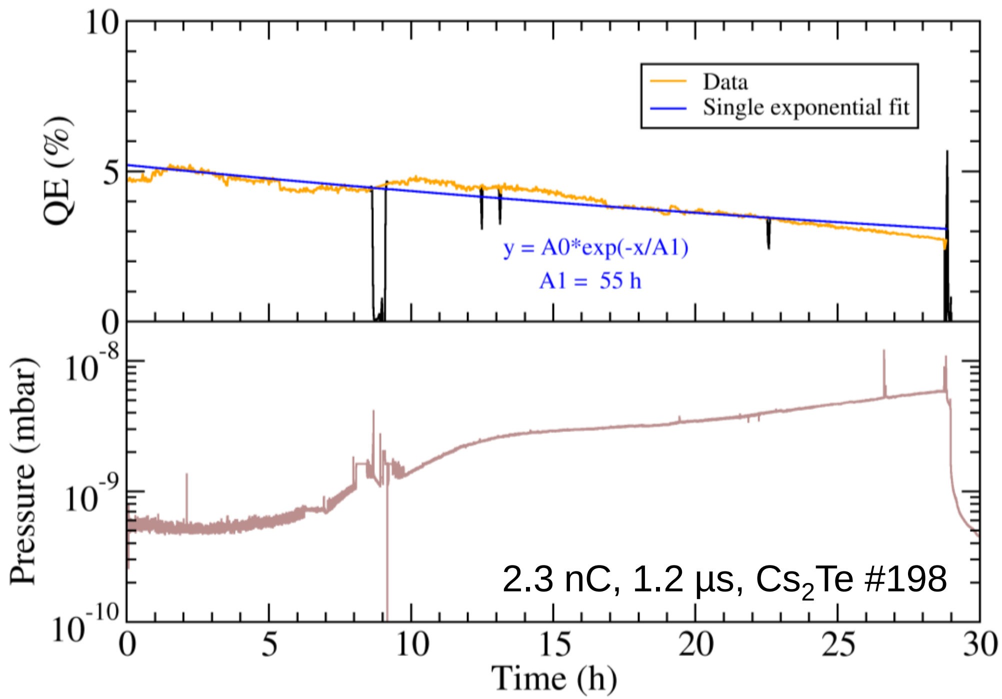
1.5e-9 mbar



- Double exponential fit represents well the data
- Lifetime similar to previous measurement.
- Cs_2Te is not ultra-sensitive against non-optimal vacuum conditions

Lifetime Measurement with Cs_2Te Cathode

- Under nominal operation conditions (2.3 nC, 1.2 µs)



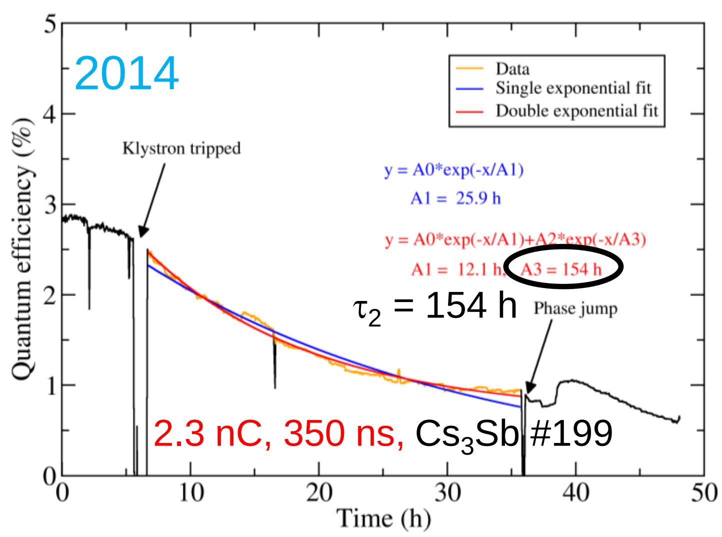
- Strong pressure increase. Heating of (uncooled) Faraday cup?
- 1/e lifetime still 55 h

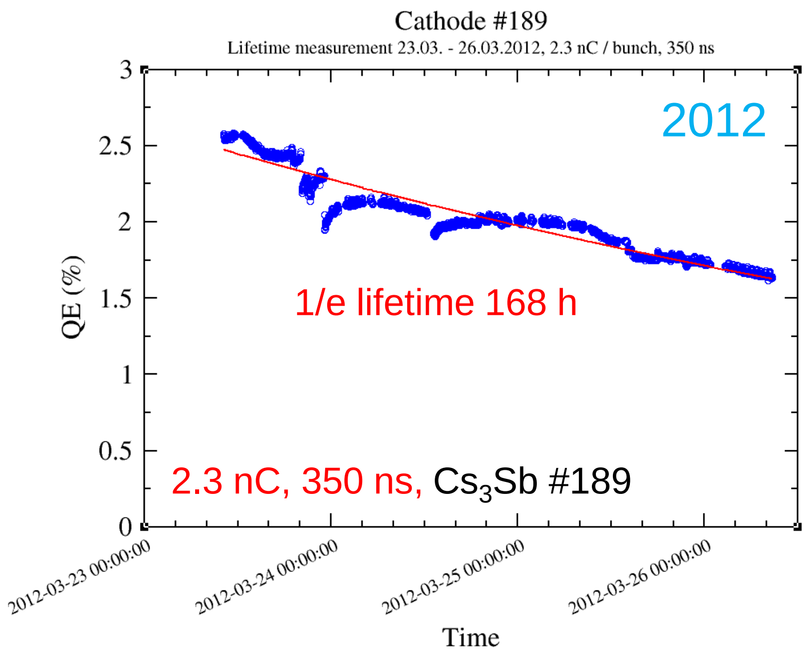
Lifetime Measurement with Cs_3Sb Cathodes

- Under improved vacuum conditions

Dynamic pressure: 2.5 - 5e-10 mbar

~9e-10 mbar



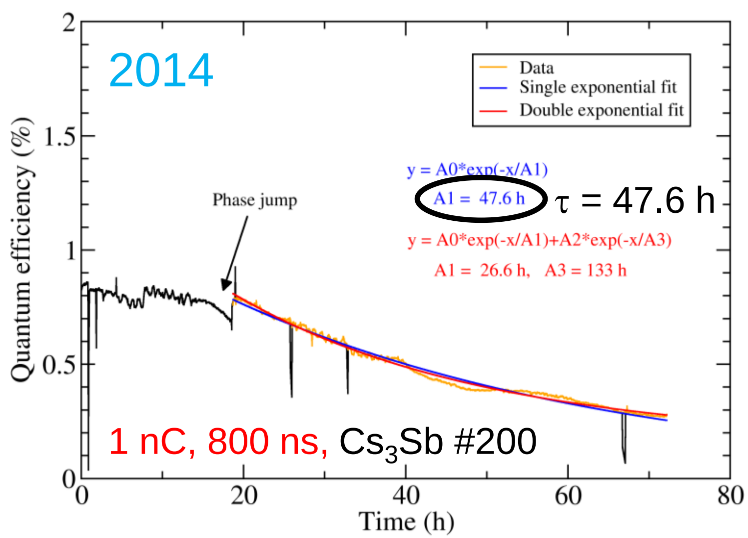


- Data can be partially fitted with a double exponential curve, with similar lifetime as 2012, however, measurement time is too short for reliable fit.
- Klystron trip and phase jump changed slope drastically.

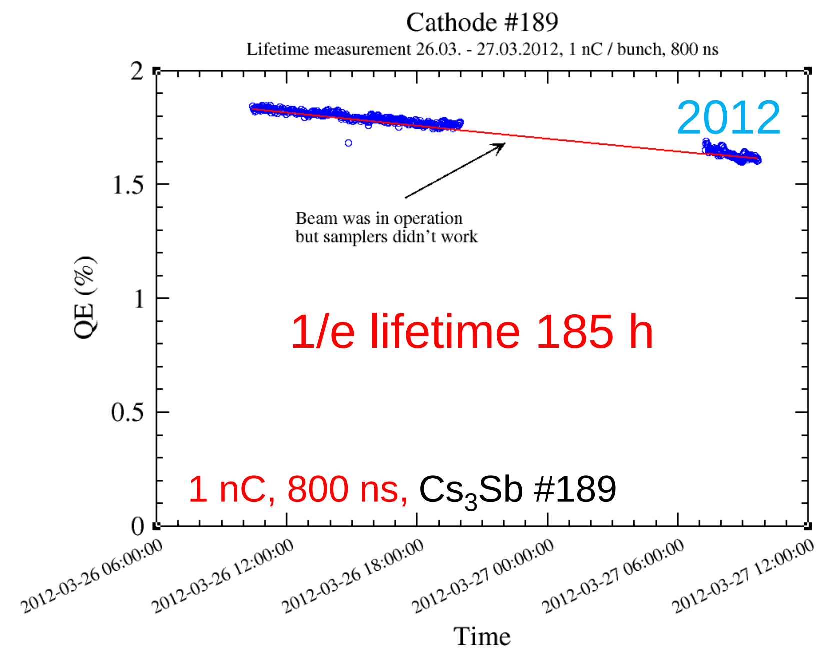
Lifetime Measurement with Cs_3Sb Cathodes

- Under improved vacuum conditions:

Dynamic pressure: 2.3e-10 mbar

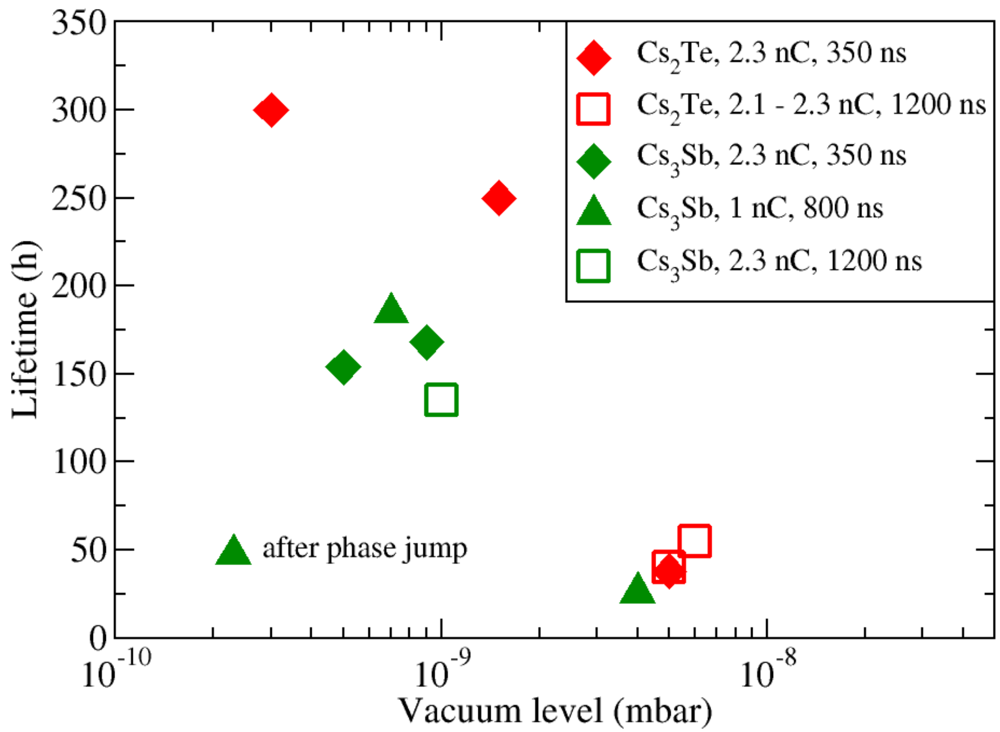


7e-10 mbar



- Despite better vacuum level the lifetime is significantly shorter.
- Strong QE decrease started after a phase jump.

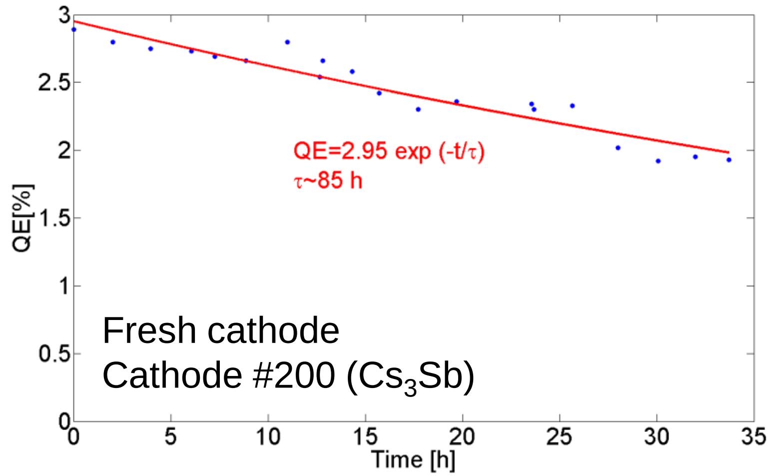
Lifetime Dependence on Vacuum



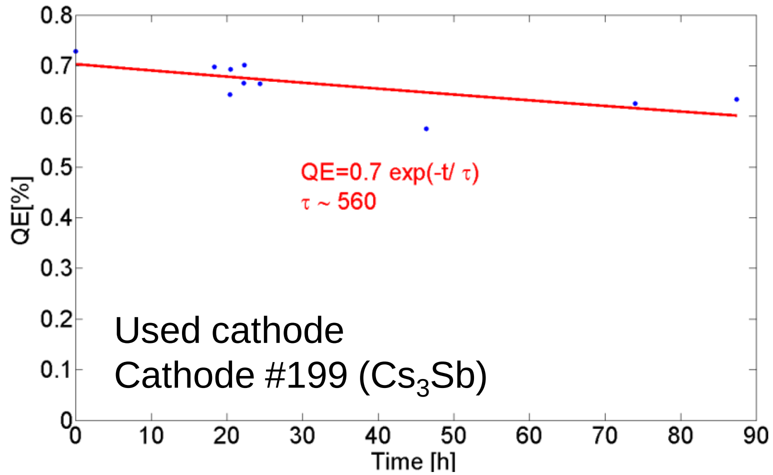
- Cs_2Te yields better than Cs_3Sb, but not drastically better.
- Measurements with different beam parameters but similar vacuum conditions yielded similar lifetimes.
  → It seems that lifetime is mainly determined by vacuum level. But the vacuum level is also a function of beam parameters.

RF Lifetime of Cs_3Sb Cathodes

Dynamic vacuum level: 3e-10 mbar

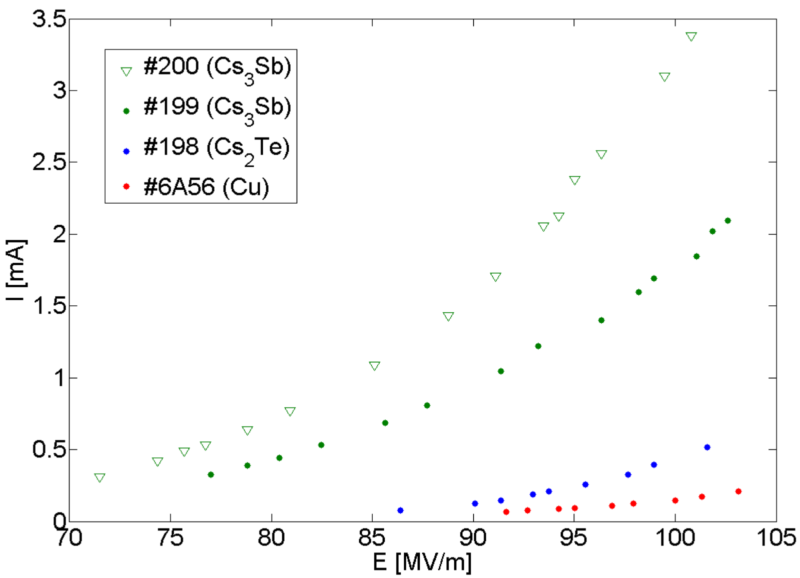


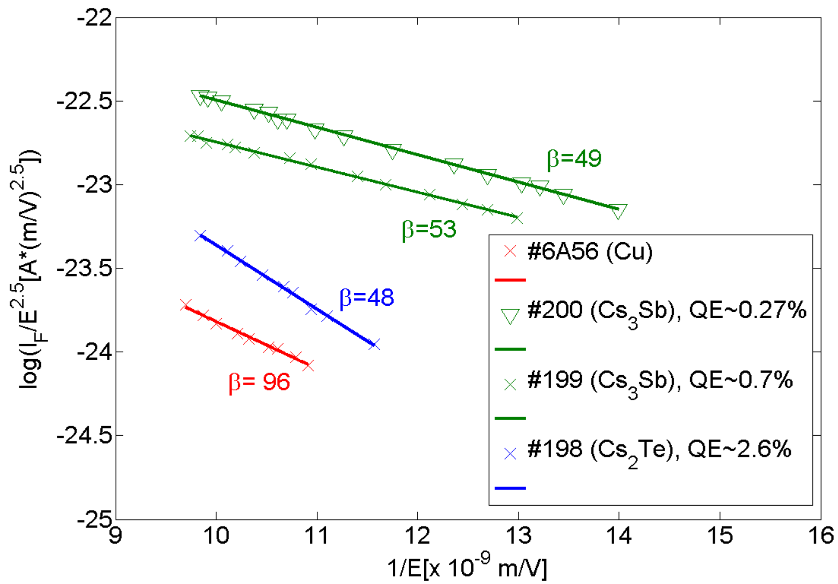
Dynamic vacuum level: 2.5e-10 mbar



- Fast and slow decay visible as during beam operation.
- In both cases longer lifetimes as during beam operation.
- Lower vacuum level than during beam operation.

Dark Current Measurements



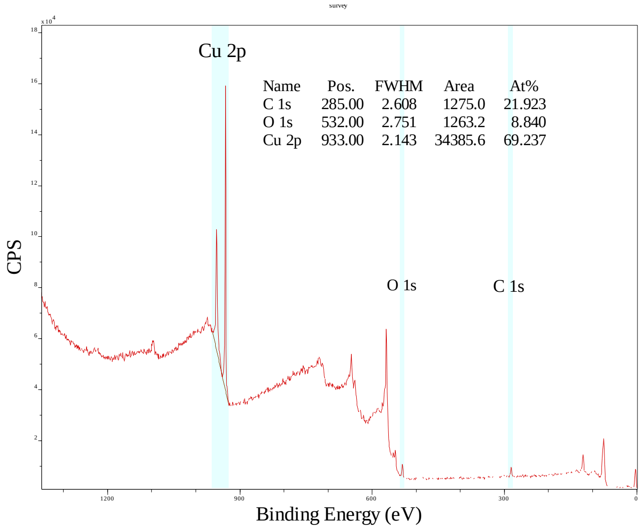


- Field emission contribution from gun cavity (Cu) and cathode.
- Cs_3Sb cathodes (Φ~2 eV) produce higher dark current than Cs_2Te (Φ~3.5 eV) and copper (Φ~4.5 eV).
  → Higher vacuum level for Cs_3Sb than Cs_2Te under same beam conditions.
- The low dark current measured with copper confirms that the major contribution is coming from the cathode.

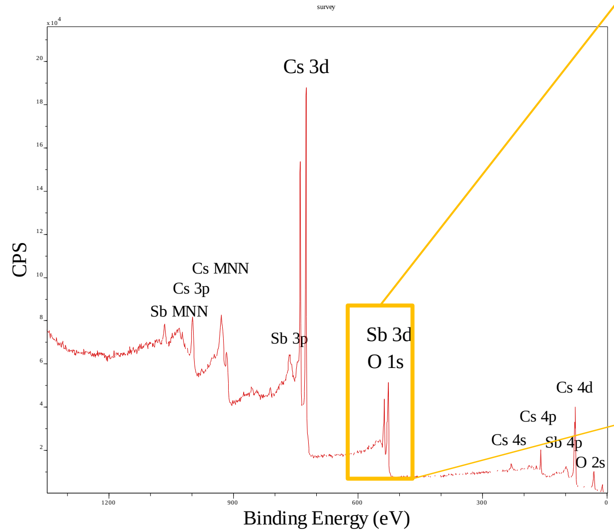
Cathode Surface Studies

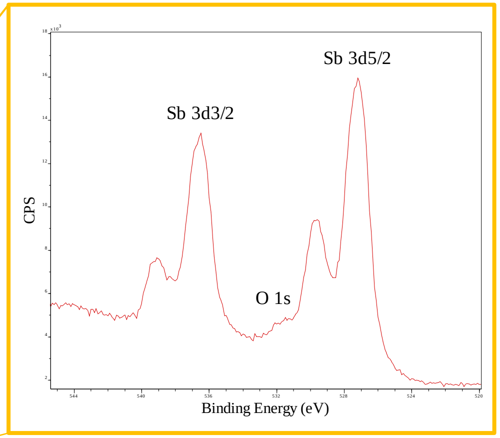
- Surface analysis of photocathode materials with XPS and their impact on the cathode performance in collaboration with TE/VSC has started.
  - New UHV carrier vessel was commissioned to transfer cathode from production laboratory to the XPS set-up:
  - XPS measurement allows material characterization of the surface. Together with qualitative elemental composition also chemical and quantitative information can be obtained (not straightforward):

Easy case: Cu (slightly oxidized)



Complex case: Cs_3Sb



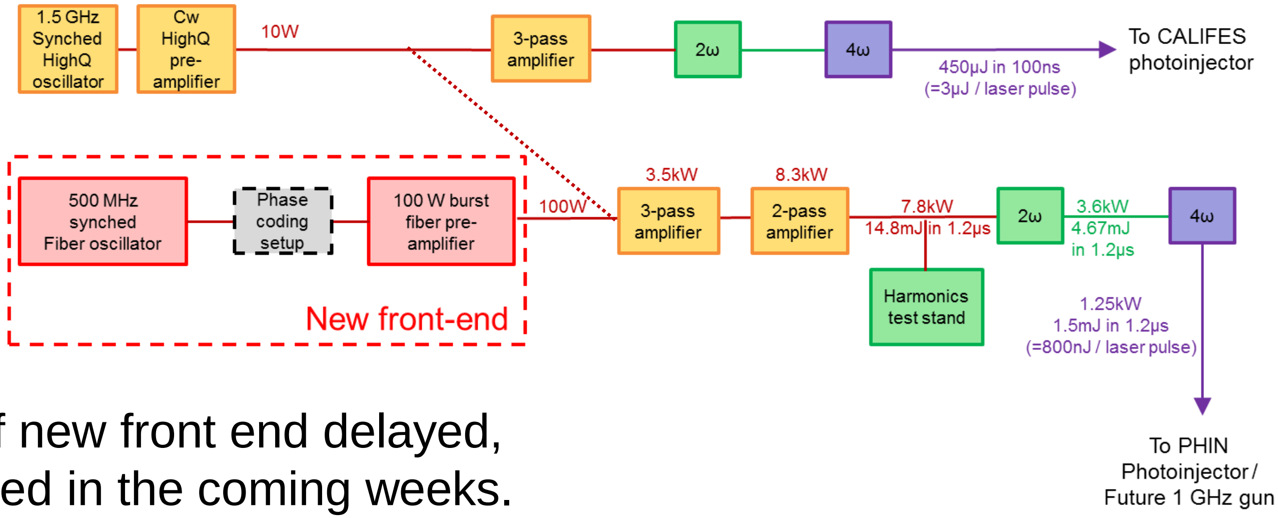


Peaks overlap!

Courtesy Irene Martini

Upgrade of Laser System

- Installation of new 500 MHz fiber front end with CLIC specs for PHIN. Decoupling PHIN and CALIFES laser systems, but keeping the possibility to switch back to the old front end for PHIN.



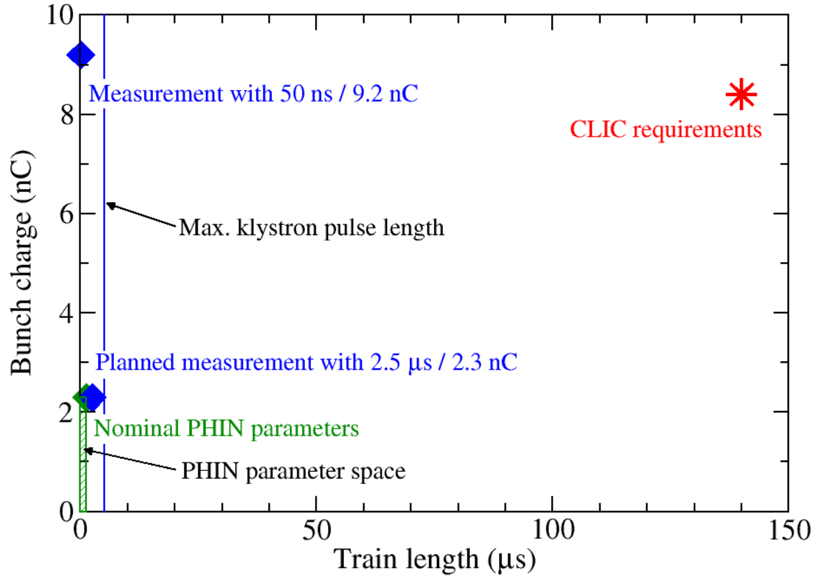
- Delivery of new front end delayed, but expected in the coming weeks.
- Preparation work (re-arrangement of current laser system) has started.
- Planned studies:
  - Stability studies with new front end with improved stability.
  - Studies of heat-load effects and thermal lensing in laser rods at 50 Hz rep rate.
  - In parallel further studies on new harmonics generation schemes with multiple crystals to solve problem with UV generation for 140 μs long trains.

Outlook: Plans and Ideas for PHIN

- Cathode lifetime studies with 2.5 µs long pulse trains (double of nominal PHIN train length) and tentatively 5 Hz repetition rate:
  → "old" 1.5 GHz time structure needed for obtaining conclusive results.
  → Vacuum window needed.
  → Long and probably painful RF conditioning required.
  → Using Cs_2Te cathodes.
- Measurement of RF lifetime of Cs_2Te cathode
- Study of impact of the longer bunch spacing with new laser front end on the photocathode lifetime.
  → Measurements with 1.05 µs (=3*350 ns) and 2.3 nC with Cs_2Te
- Study of charge stability with the new laser system.
- Study the effect of surface roughness on cathode lifetime (Electro-polished cathode plugs).
- Study the performance of three components cathodes in PHIN (e.g. K_2CsSb).
- Re-measure QE of uncontaminated copper cathode for AWAKE.

⇒ Many interesting ideas for a further PHIN run in 2015!

Ideas for Future CLIC Photoinjector Developments



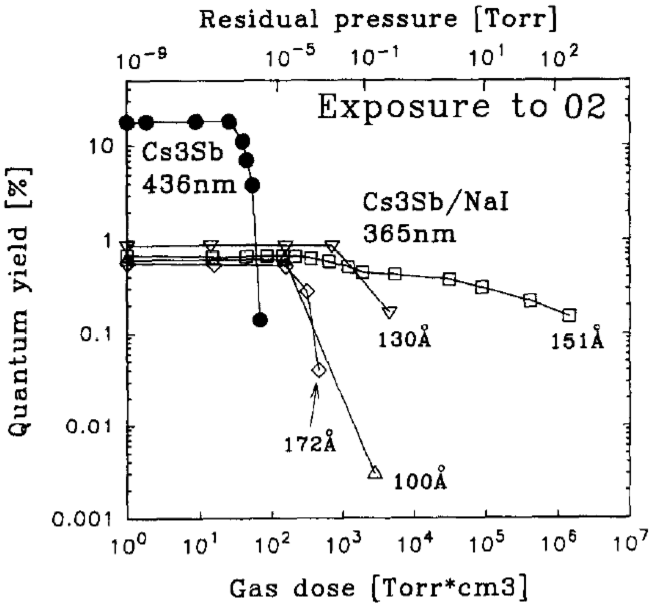
- The main concern about a CLIC drive beam photoinjector is:

  Will the high bunch charge and average current create conditions (e.g. vacuum level), which are deadly for the photocathode?

- It is clear that this question cannot be answered alone by extrapolating from PHIN experiments.
- To verify feasibility of photocathodes for CLIC specifications, at some point a RF gun with full CLIC specs must be built.
- If the environment will be not suitable for standard photocathodes, are there any fundamentally new ideas which could potentially solve the problem?

Protective Layers for Photocathodes

- Protective layer of alkali-halides (NaI, CsI, CsBr) can increase resistivity against oxidation:



A. Buzulutskov et al., Nucl. Instr. and Meth. A 387 (1997) 176

- Graphene (2D material, monolayer) as a chemically inert diffusion barrier to prevent oxidation:

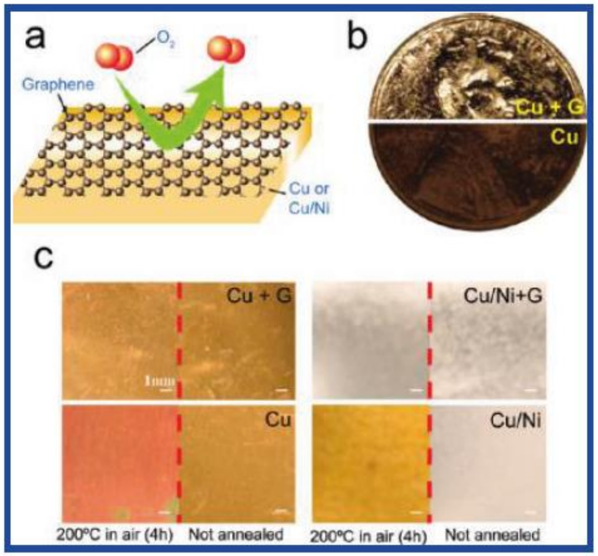


Figure 1. (a) Illustration depicting a graphene sheet as a chemically inert diffusion barrier. (b) Photograph showing graphene coated (upper) and uncoated (lower) penny after H_2O_2 treatment (30%, 2 min). (c) Photographs of Cu and Cu/Ni foil with and without graphene coating taken before and after annealing in air (200 °C, 4 h).

S. Chen et al., ACS Nano 5 (2011) 1321

- Works for metals. Is it also suitable for photocathodes?

Diamond Photocathodes

- Chemical stable photocathode
- Survives air-exposure
- High QE, however in the deep UV (<190 nm), not achievable with conventional laser sources.

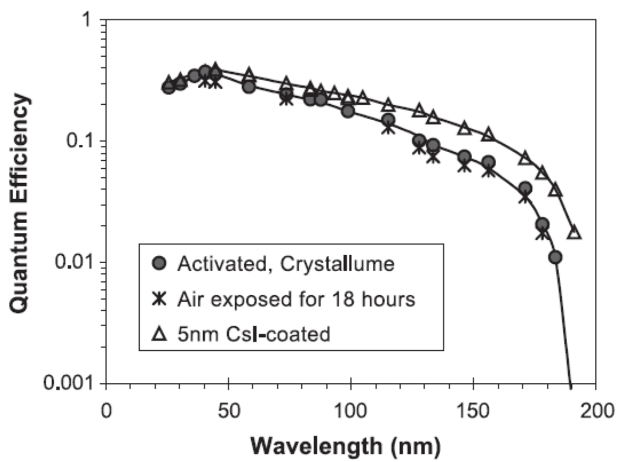


Fig. 2. The absolute quantum efficiency of hydrogen-activated (circles) and air exposed for 18 h (crosses) diamond photocathode. The efficiency of the same photocathode was increased by evaporation of a thin CsI film (4 nm thick), serving as an effective dipole layer lowering the electron affinity (triangles).

A.S. Tremsin, O.H.W. Siegmund,
Diamond & Related Materials 14 (2005) 48–53

- Potential solution (first proposed by H. Tomizawa et al (JASRI/SPring-8)): Z-polarized laser beam:

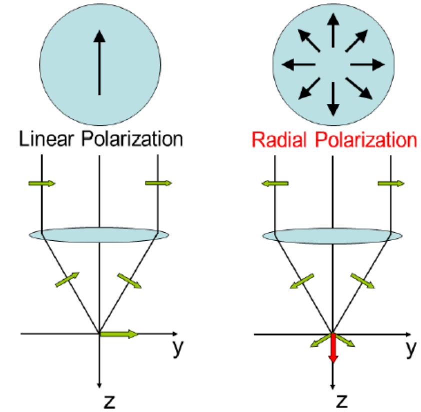


Figure 1: Principle of Z-polarization field on cathode surface generated from radial polarization

H. Tomizawa et al., Proc. LINAC2012, 996

- High Z-field (few GV/m) reduces work function due to Schottky effect.
- Excitation with longer wavelength could be possible.

Diamond-Amplified Photocathodes

- Concept developed at BNL: Diamond as a secondary electron emitter.

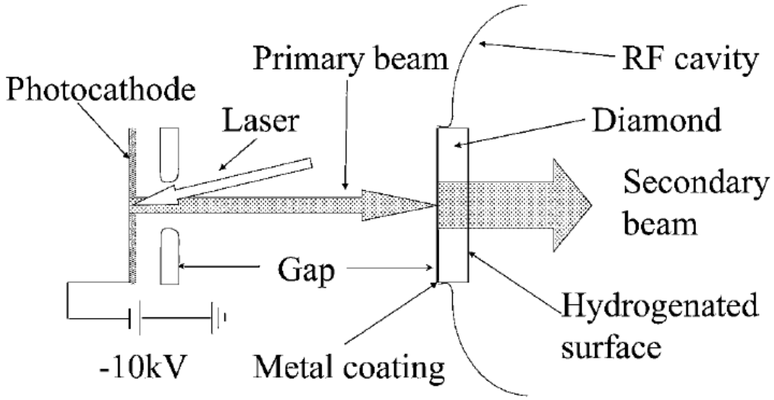


FIG. 1. DA in a rf cavity. The gap between the photocathode exit and the metal coating is roughly 5 cm.

[1] X. Chang et al., PRL 105, 164801 (2010)

- Due to robustness of diamond long lifetimes with high current seems to be reachable.
- In test setup at BNL a 35% probability of electron emission from the hydrogenated diamond surface was measured with an emission gain of 40 [1].
- However, slow charging of the diamond due to thermal ionization of surface states cancels the applied field within it.
  → Generation of long pulses might be problematic.
- Complicated setup (DC and RF acceleration)

Acknowledgement

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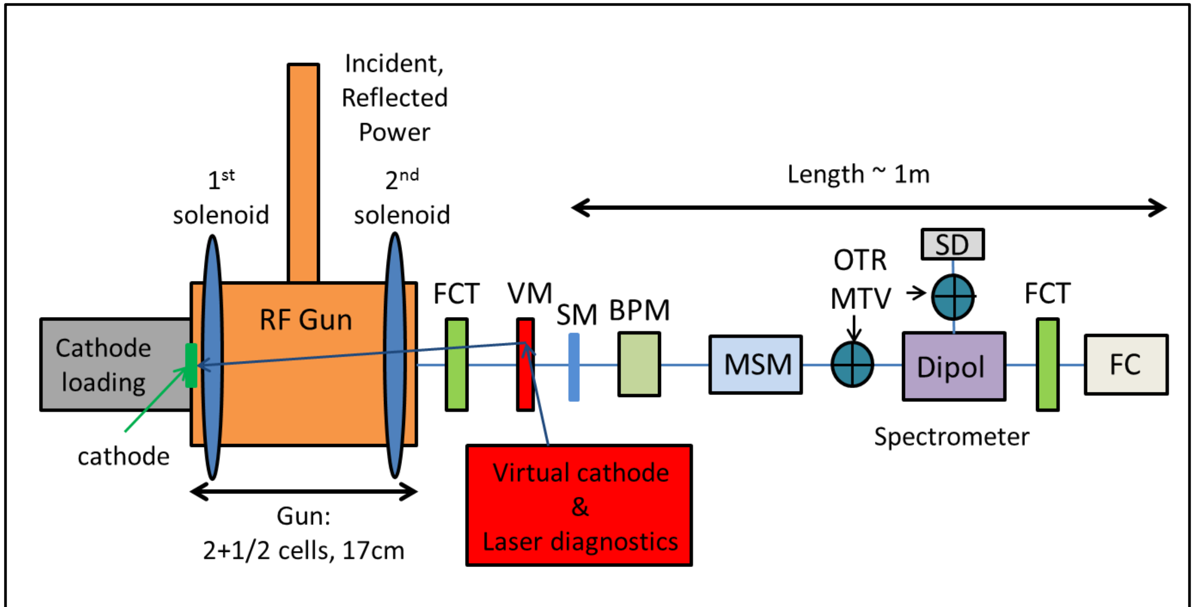
- Beam instrumentation: Thibaut Lefevre, Stephane Burger
- Vacuum: Berthold Jenninger, Esa Paju
- RF: Stephane Curt, Luca Timeo
- Wilfrid Farabolini
- CTF3 operators
- XPS studies: Holger Neupert, Valentin Nistor, Mauro Taborelli, Elise Usureau
- Collaborators at LAL and IAP-RAS
- … and many others

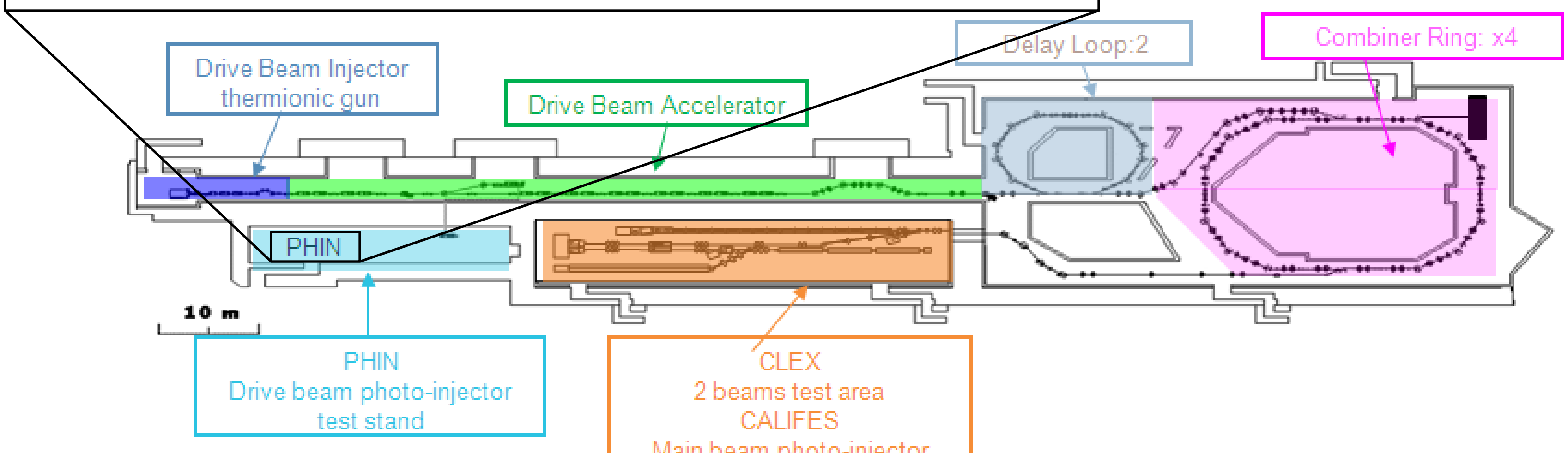
… and thank you for your attention!

Backup Slides

Layout of PHIN



FCT: Fast current transformer
VM: Vacuum mirror
SM: Steering magnet
BPM: Beam position monitor
MSM: Multi-slit Mask
OTR: Optical transition radiation screen
MTV: Gated cameras
SD: Segmented dump
FC: Faraday cup

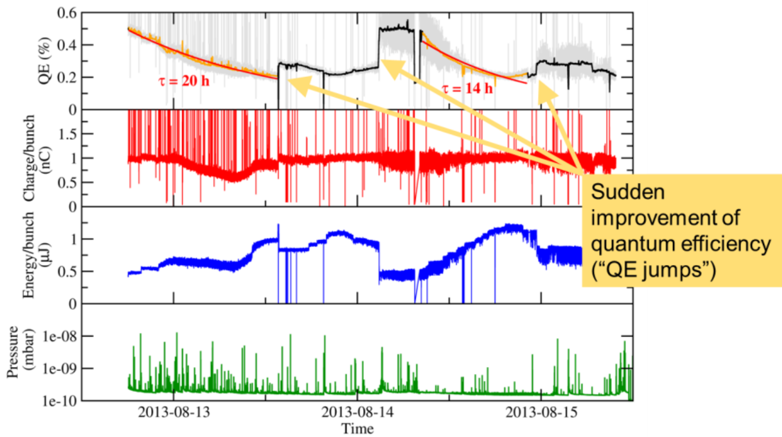


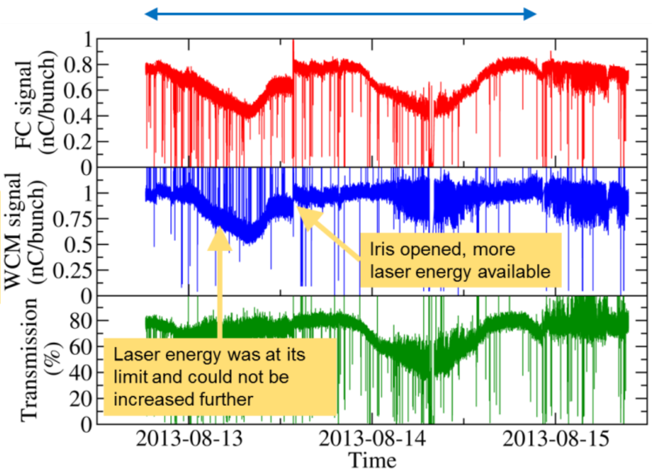
PHIN and CLIC Parameters

Parameter	PHIN	CLIC
Charge / bunch (nC)	2.3	8.4
Macro pulse length (μs)	1.2	140
Bunch spacing (ns)	0.66	2.0
Bunch rep. rate (GHz)	1.5	0.5
Number of bunches / macro pulse	1800	70000
Macro pulse rep. rate (Hz)	5	50
Charge / macro pulse (μC)	4.1	590
Beam current / macro pulse (A)	3.4	4.2
Bunch length (ps)	10	10
Charge stability	<0.25%	<0.1%
Cathode lifetime (h) at QE > 3% (Cs_2Te)	>50	>150
Norm. emittance (μm)	<25	<100

Photocathode Lifetime Studies 2013

- Lifetime studies under improved vacuum conditions were already planned for 2013, however due to many problems no comparable lifetime measurement could be performed at that time.
- Problems in 2013 among others: “unknown” beam instrumentation, low initial QE, fast QE decrease, QE jumps, 24h drifts.



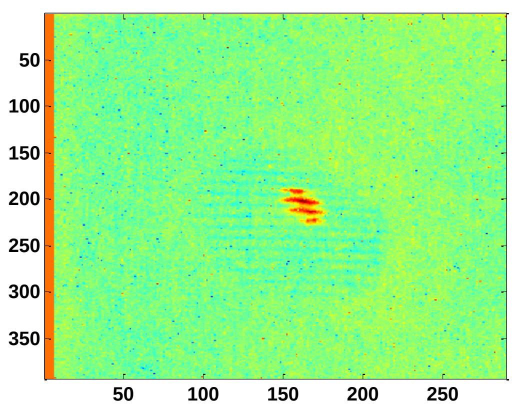


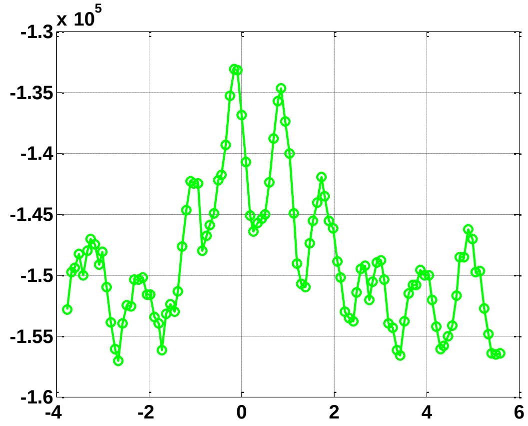
- Problems with photocathodes could be potentially traced back to a wrong surface finishing of the cathode substrates and have been solved in 2014.

Photocathode surface after usage

Emittance Measurements for AWAKE

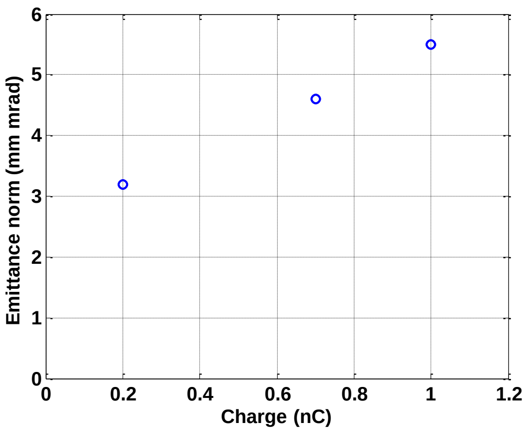
Laser beam size: ~ 1 mm sigma, charge 0.2, 0.7, 1.0 nC, energy 5.5 – 6 MeV





Normalized emittance for 0.2 nC:
3.2 mm mrad
(big errors !)

E_n(0.2 nC): 3.2 mm mrad
E_n(0.7 nC): 4.6 mm mrad
E_n(1 nC): 5.5 mm mrad



Charge dependence is roughly sqrt as it should be

QE Measurement for AWAKE

- Copper plug 6A56:
  - QE(DC-gun) = 2e-4
  - QE(PHIN) = 3e-4
- QE of Cu cathode was too high compared with best literature values (1.4e-4).
- Possible explanation: Contamination with Cs. The plug was located in photocathode preparation chamber during a bake-out.
- Copper plug 6A46 has not been in preparation chamber during bake-out and has a QE (DC gun) = 3e-5.
- It is planned to test 6A46 also in PHIN.