Experience on „polarized“ photocathodes

European Workshop on Photocathodes for Particle Accelerator Applications (EWPAA 2022)

September, 20, 2022

Presented by Kurt Aulenbacher

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through projects 05K19UMA (BETH) and 05K19UMB (CSBB)

Cluster of Excellence PRISMA+

MESA

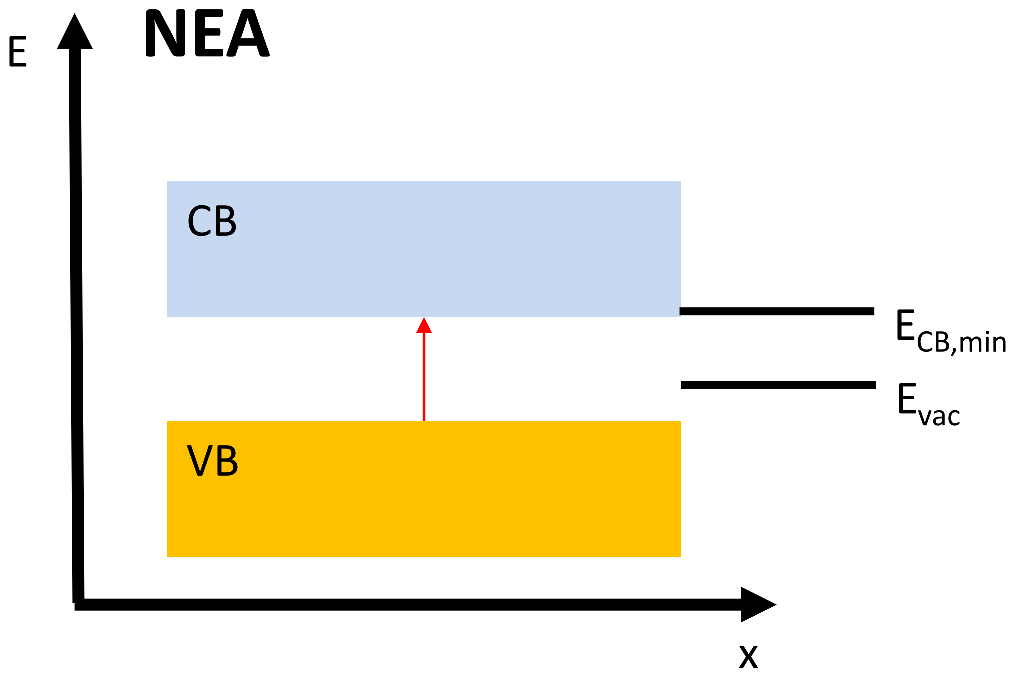
Outline

- "Polarized Photocathodes" - State of the art & development paths
- NEA-cathodes: technical limitations
- NEA-cathodes: physics limitations

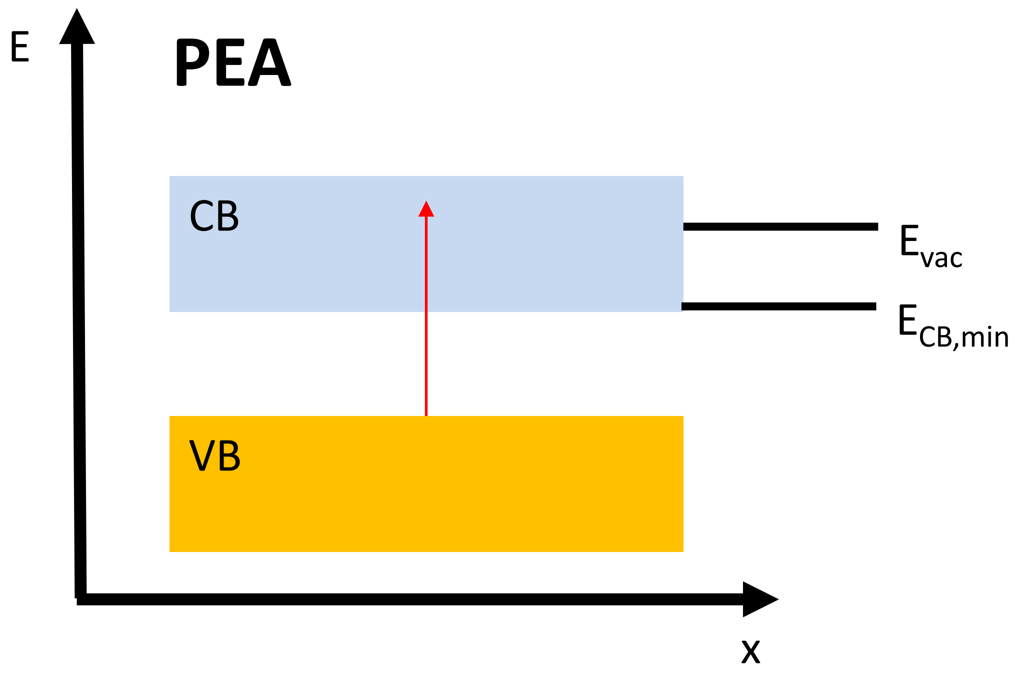
Electron affinity: NEA vs. PEA cathodes

- Electrons in S-states - i.e. high spin polarization - can be generated at the bottom of the conduction band !

The electron affinity is defined as : $\xi = E_{vac} - E_{CB,min}$



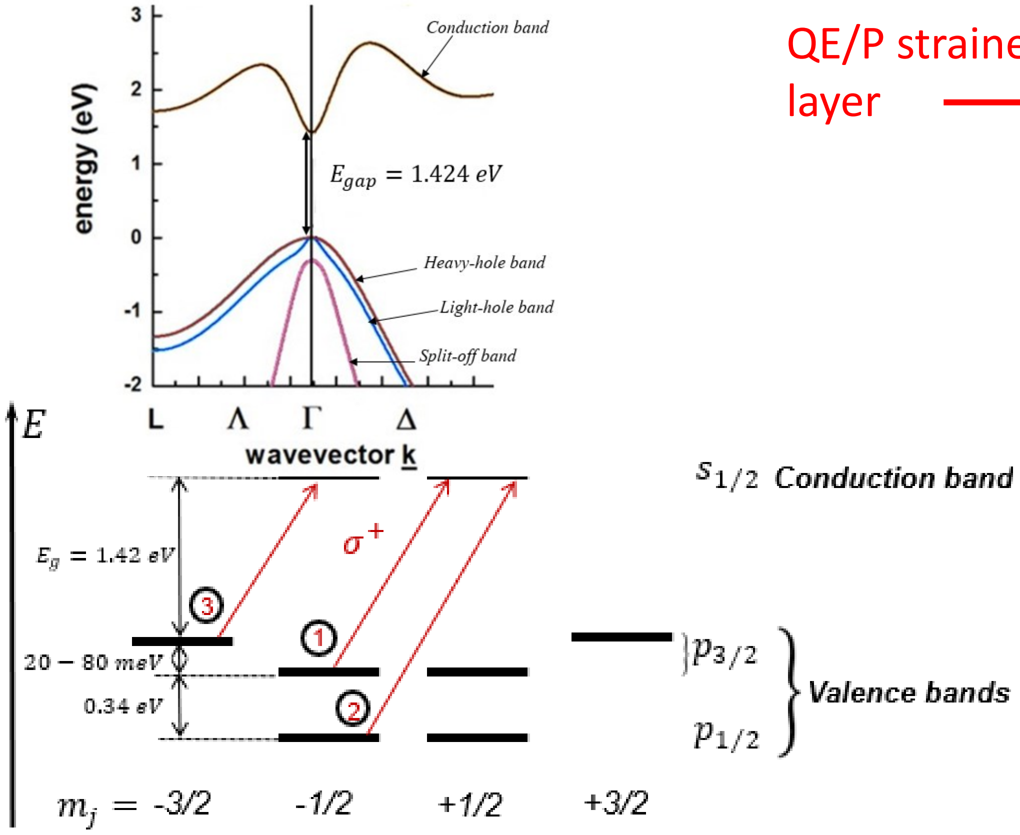
NEA-state: Photoemission possible from near band gap states



PEA-state: Photoemission only from states with sufficient energy above $E_{CB,min}$

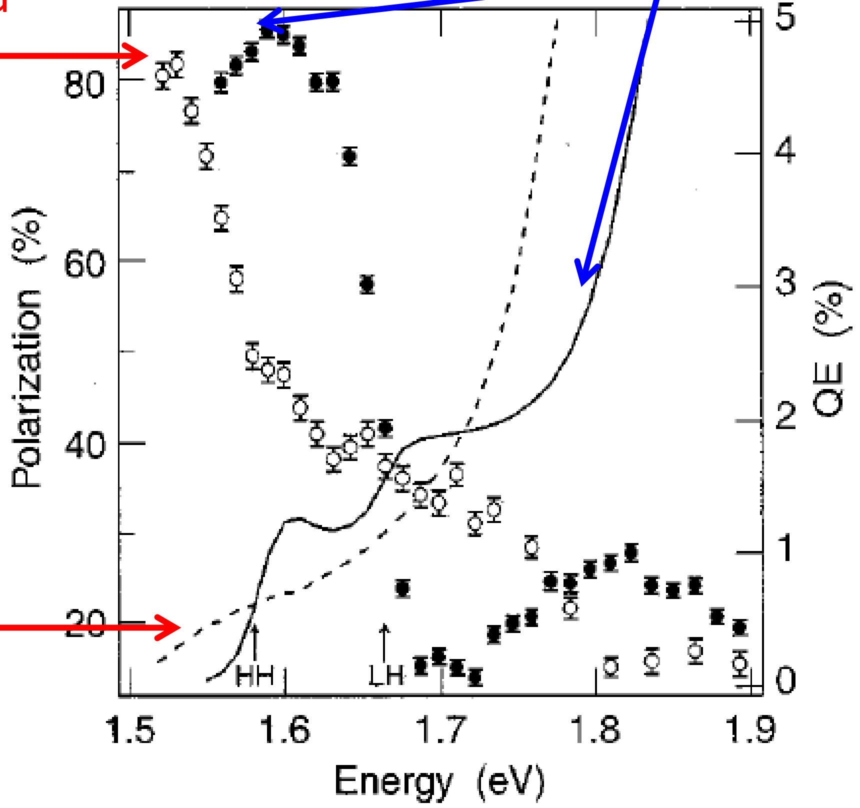
Band structure for high polarization

High spin orbit splitting is required → GaAs (cubic, fcc)
Lower symmetry ("tetragonal") → GaAs based strained layer or superlattice (SL)
SL causes shift of Band gap energy – depending on composition - wrt GaAs and removal of degeneracy
→ "Band structure engineering"



QE/P strained layer

QE/P Superlattice



(T. Maruyama et al. Appl. Physics. Lett. 85,13 (2004) 2640)

GaAs/GaAsP"Strained Superlattice" :
(T. Maruyama et al. Appl. Physics. Lett. 85,13 (2004) 2640)
SL causes shift of Band gap energy wrt GaAs and removal of degeneracy
: Gradient doping
- Matched to wavelength of frequency doubled telecommunication laser system.

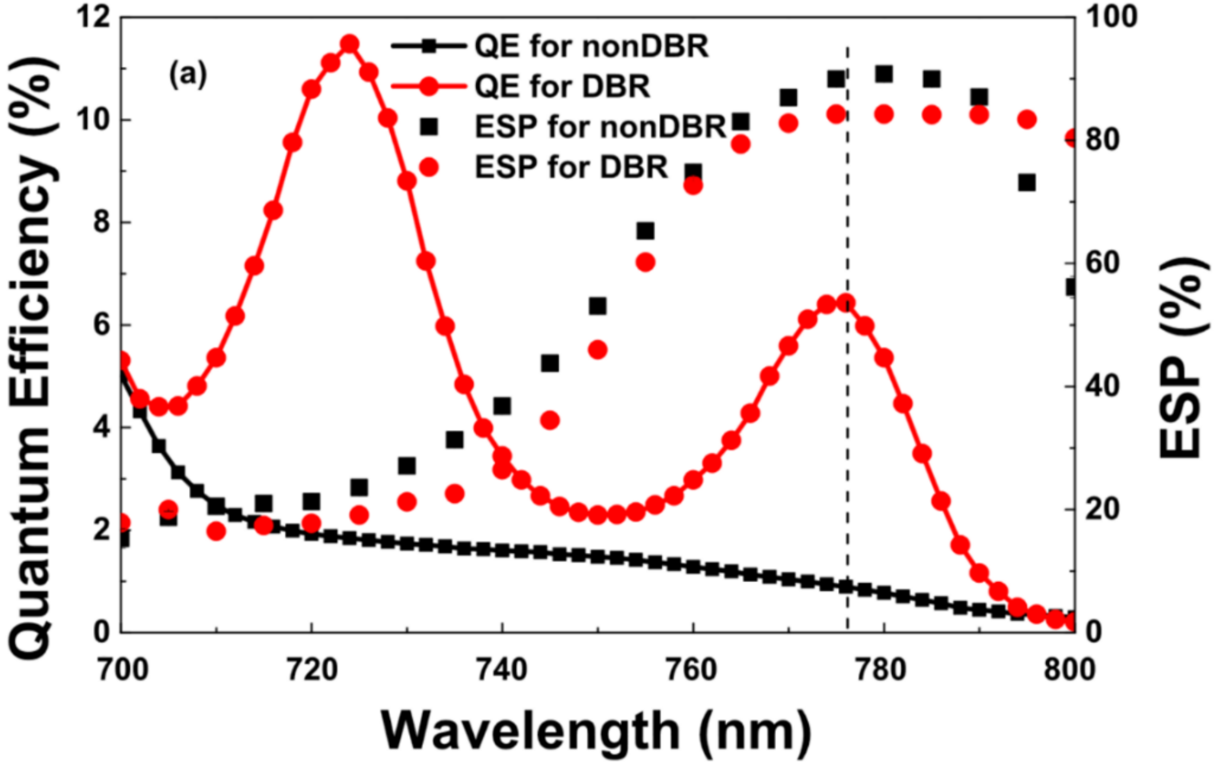
$SLAC/SVT - Superlattice$

GaAs	5 nm	p=5 $\times 10^{19}$ cm^{-3}
GaAs/GaAsP SL	(3.8/2.8 nm) ×14	p=5 $\times 10^{17}$ cm^{-3}
$GaAsP_{0.35}$	2750 nm	p=5 $\times 10^{18}$ cm^{-3}
Graded $GaAsP_x$ ($x = 0$~0.35)	5000 nm	p=5 $\times 10^{18}$ cm^{-3}
GaAs buffer	200 nm	p=2 $\times 10^{18}$ cm^{-3}
p-GaAs substrate (p>10^{18} cm^{-3})		

(T. Maruyama et al. Appl. Physics. Lett. 85,13 (2004) 2640)

“Resonant” Strained Superlattice-cathode

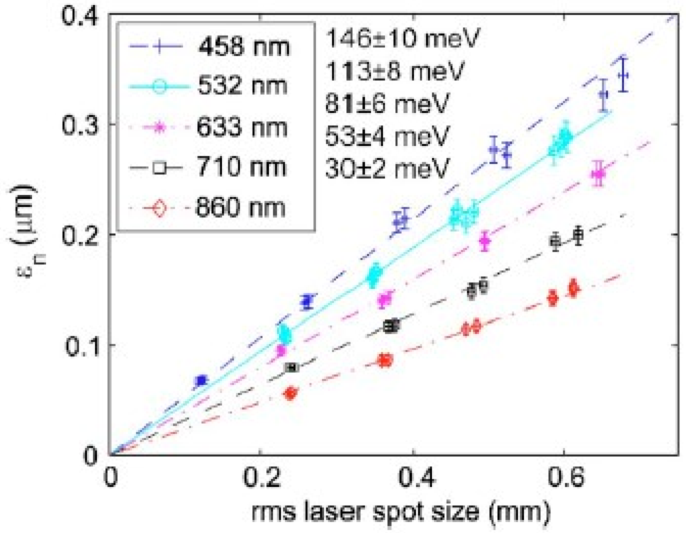
JLAB/$SVT - Superlattice$



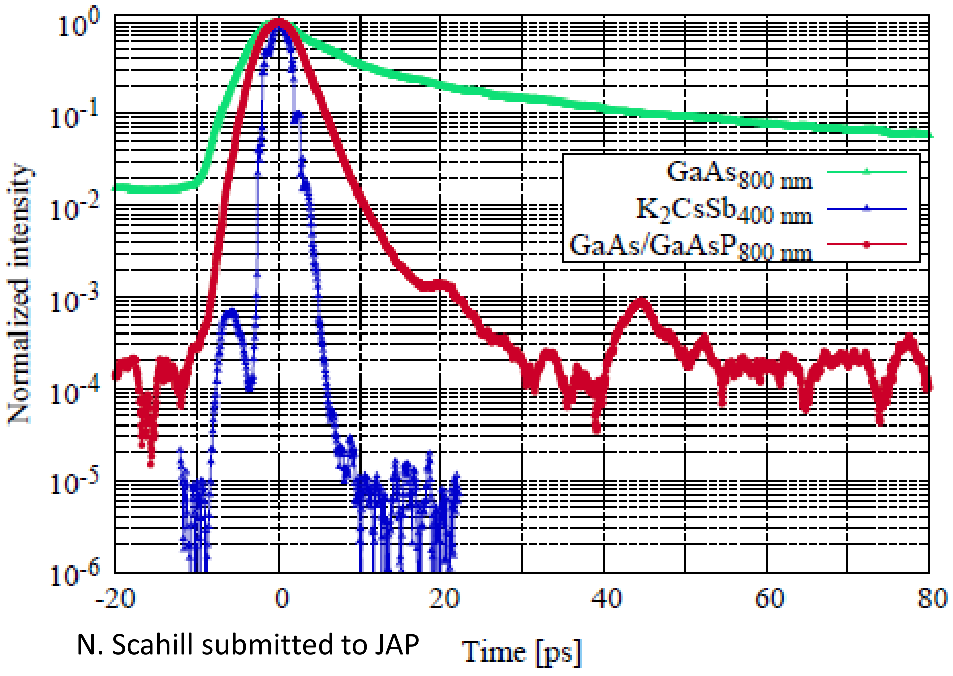
W. Liu et al. Appl. Physics. Lett. 109,252104 (2016) doi: 10.1063/1.4972180

Absorption enhanced by DBR-Reflector causing active region to be a cavity with enhanced absorption at resonance
→ increased QE. 6% @ 770nm (>30mA/Watt) @ >80% Pol.

1. Due to low doping in small active region: large mean free path $\lambda \approx d_{active}$
   → fast t<<5ps
2. almost 100% “sink” at surface
   → no tail
3. Huge “gradient” doping at surface
   → “high” current density and/or fluence possible in spite of “photovoltage”
   But “high” means Amps/cm^2 average current! (nC/cm^2 fluence in short pulses < 10ns)
4. (Quite) low transverse energy due to NEA-near band gap operation, typically
   $\varepsilon_{norm} < 0.3\ \mu m/mm$



I. Bazarov et al. J. Appl. Phys. **103**, 054901 (2008); https://doi.org/10.1063/1.2838209



N. Scahill submitted to JAP

Accelerators for polarized beam – nuclear & particle physics

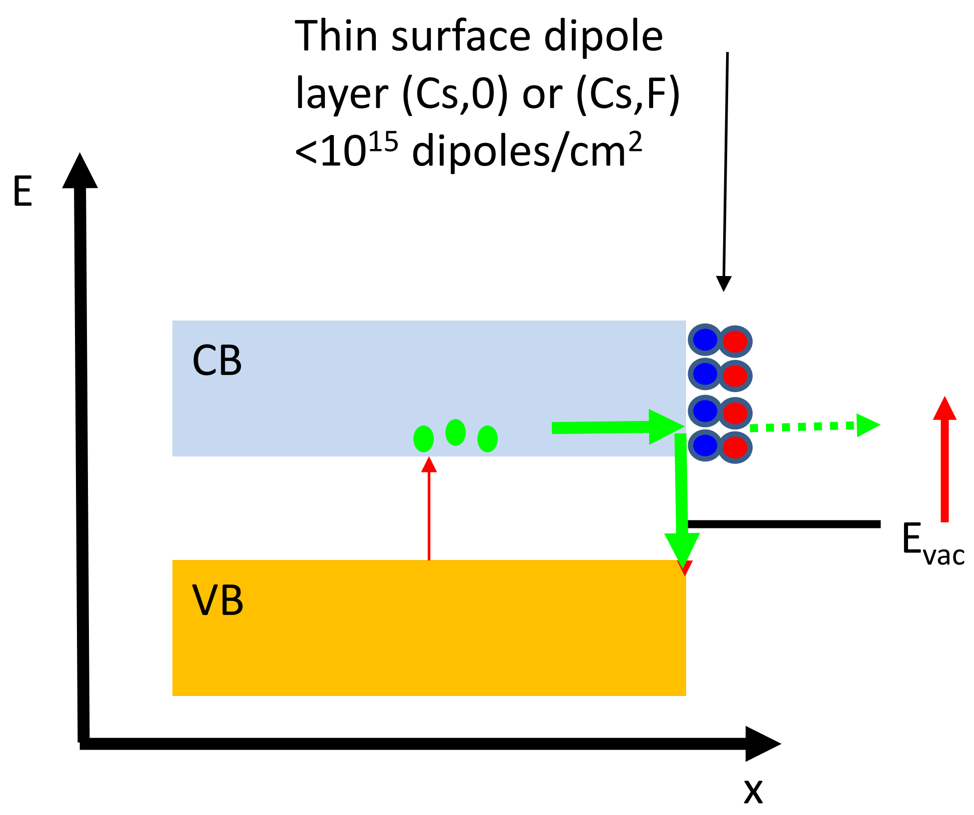
Project	Typcial Av. Current/mA	Bunch rep. Frequency/MHz	status
MAMI	0.02	2449	In operation
CEBAF	0.2	1500	In operation
MESA (ERL)	1	1300	upcoming
LHeC, (ERL)	20	40 (d.f.=0.05)	Future
…CERL, and others			

Note that the sustained operation of the upcoming and future projects will require extraction of charges in the order of 10-100 Kilocoulomb

Future projects may be challenged by **technical limits** and **physics limitations**

arxiv_2201.07895

Technical limits: research



Changes in surface layer will

- Increase electron affinity towards PEA
- Reduce emission probability of electrons

→ Low lifetime τ

Changes may be induced by:

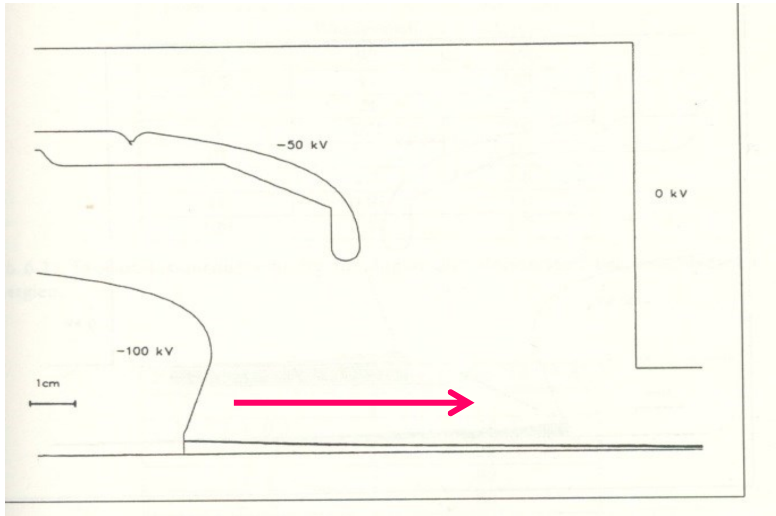
1. Chemical reactions
2. Sputtering by ions („ion backbombardment“)
3. Thermal decomposition

Necessary conditions for „reasonable“ lifetime:

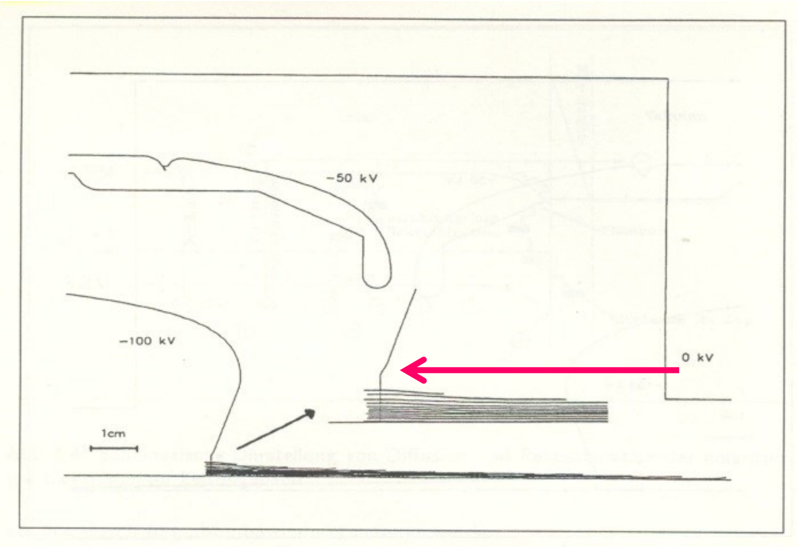
- Vacuum level 10^{-11} mbar or below
- Beam losses in source region only of nA scale
- Cathode Temperature below ~50 degree Celsius

Performance measure in real life is the „charge lifetime“ (charge that can be extracted until QE has dropped by 1/e)

Ion backbombardment in DC-guns



excentrically started
Electron-beam



causes back
traveling ions

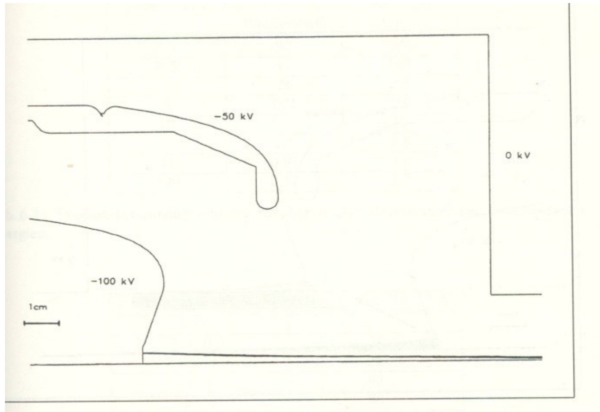
PhD thesis Kurt Aulenbacher
Mainz 1994, see also SLAC pub 432 p 1-13

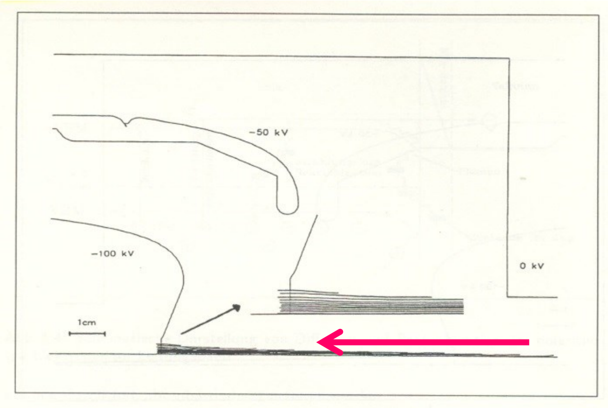
Superposition of several effects

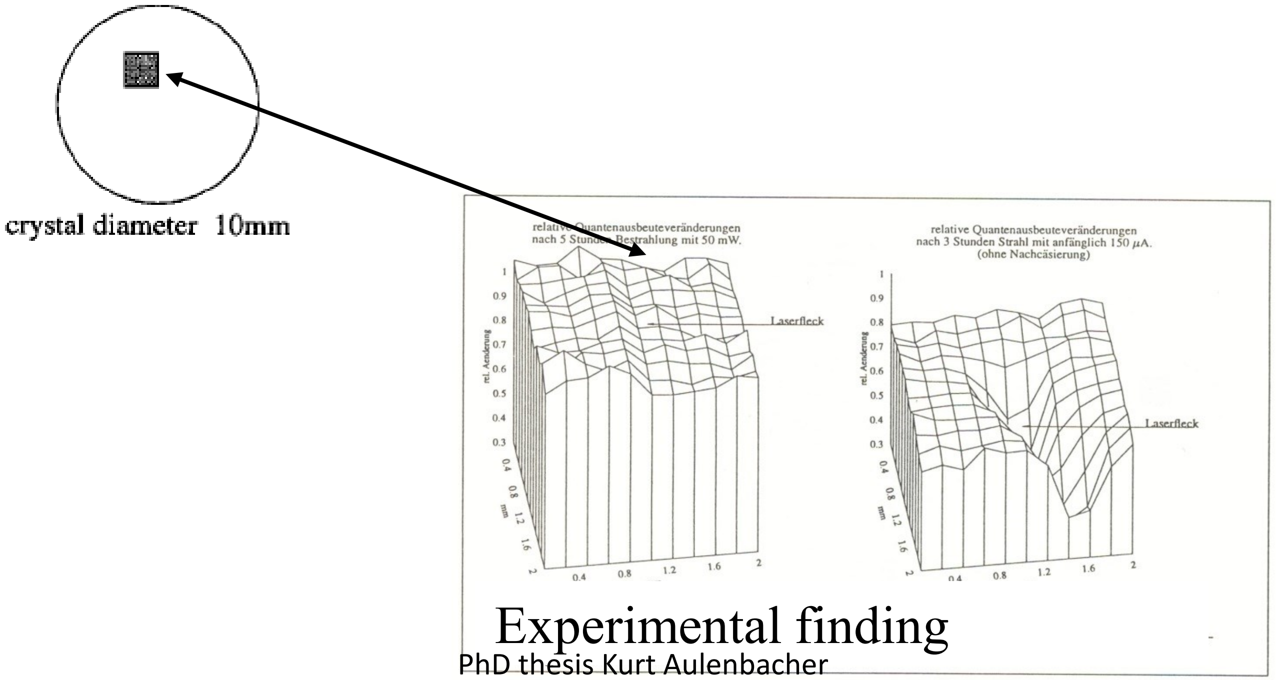
$$\frac{1}{\tau} = \sum_i \frac{1}{\tau_i}$$

If ion backbombardment is the ONLY cause of lifetime reduction, then $\boldsymbol{\tau^{-1} \propto pI}$.

- , i.e lifetime is reduced in proportion to the inverse of beam current times pressure.
- i.e the product of beam current times lifetime is constant (Charge lifetime)
- This requires that pressure and cathode temperature do not depend on the current
- Real life: Strongly interrelated many parameter problem



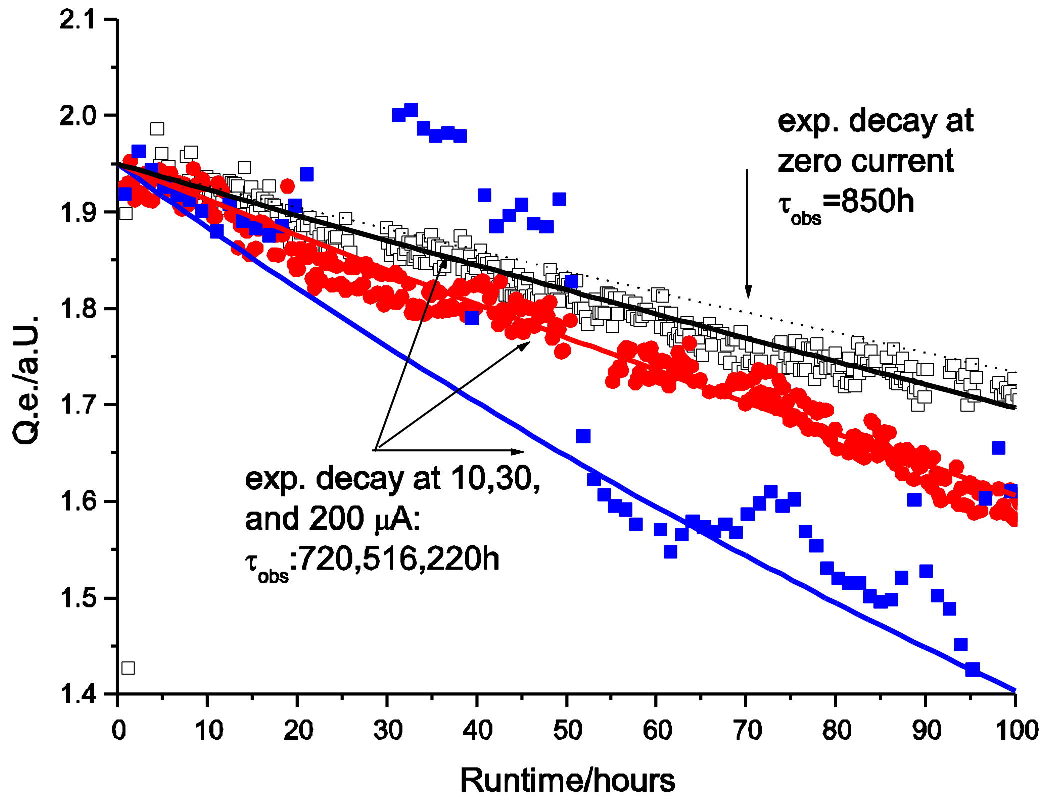




PhD thesis Kurt Aulenbacher
Mainz 1994, see also SLAC pub 432 p 1-13

$$\frac{1}{\tau} = \sum_i \frac{1}{\tau_i}$$

Besides the contributions already discussed there is **Ion backbombardment**. Example from MAMI-beam-times



Charge lifetime:

$C_\tau = I * \tau_{obs} = Q = const!$

Here ~200C !

Fluence lifetime:

$F = C_\tau / A_{beam} \sim 10^5\ C/cm^2$

Note: $\varepsilon_{norm} \sim 100nm$ in these experiments (150μm Laser spot rms)

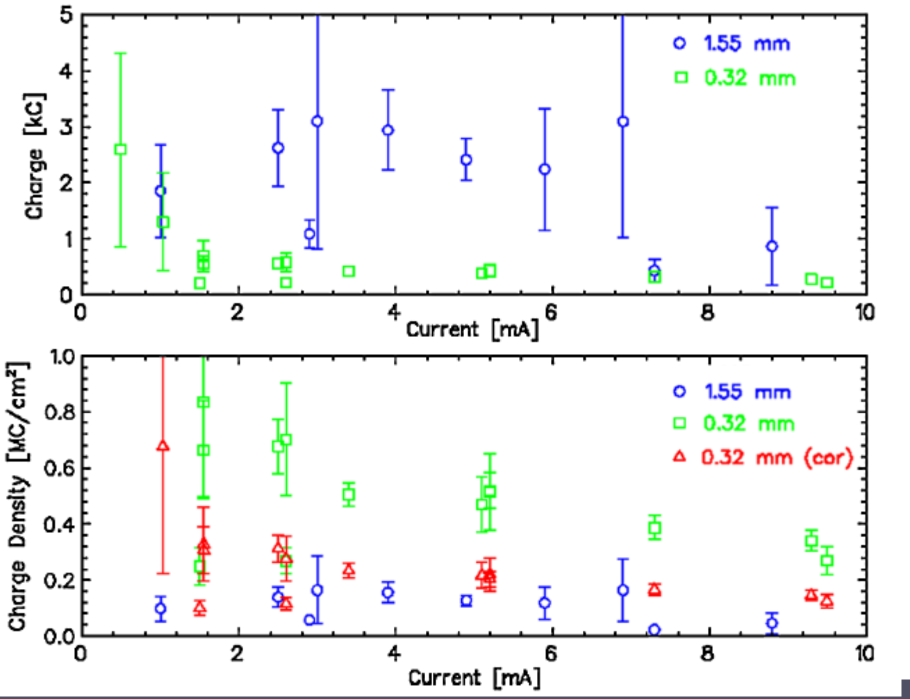
→ can Charge lifetime be increased to >>1000C at ε~1μm?

Careful experiments have been done at JLAB:
achieved >1000C with **green light** illumination at about 9mA current
Open question: other contributions become non negligible
(Heating, non-linear transmission loss?)

Note that (non-linear space charge may create halo…)

Charge lifetime

Fluence lifetime

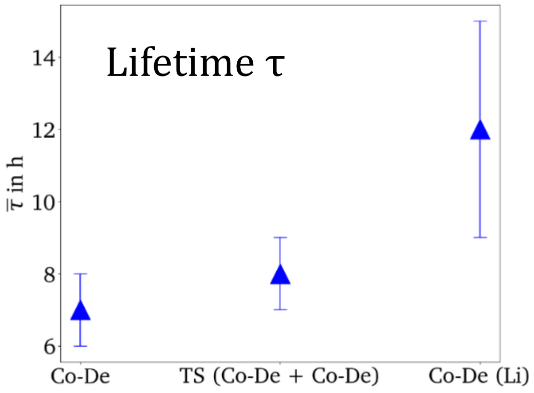


J. Grames et al.
PHYS. REV. ST.-AB 14, 043501 (2011

Exploring new paths

Modifying the surface layer

Changing the composition at the surface may „stabilize“ or protect it.
Examples Cs:F:Li (TU-Darmstadt & JLAB)and Cs:O:Sb (Cornell) and Cs_2Te (Cornell)



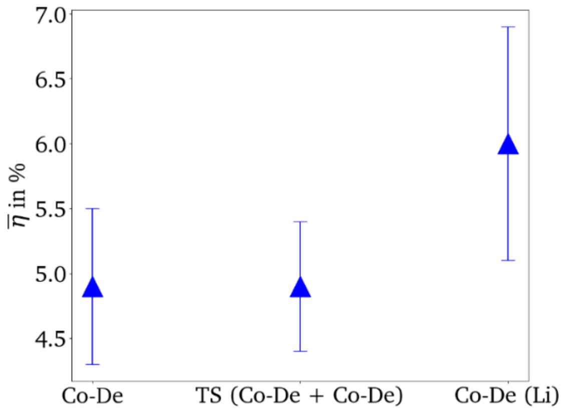
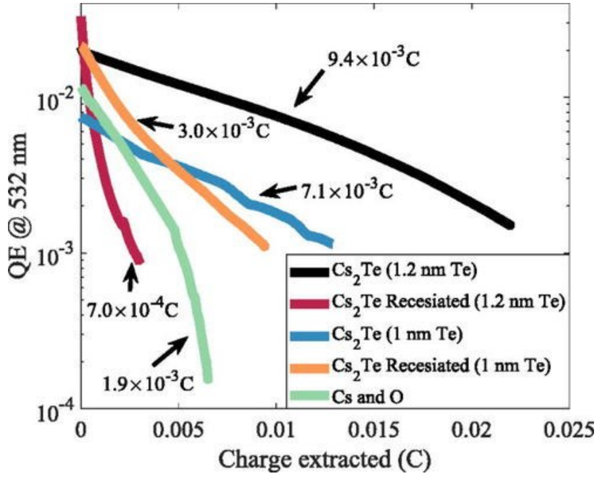


TABLE I. Lifetimes at 780 nm estimated by comparing initial QE and final QE after the QE degradation measurement in Fig. 5.

Activation method	Initial QE at 780 nm	Final QE at 780 nm	Lifetime estimate (h)	Improvement factor
$Cs{-}O_2$	3.3×10^{-2}	1.4×10^{-3}	15	×1
$Cs{-}O_2 + Cs{-}Sb$	9.5×10^{-3}	2.9×10^{-3}	41	×2.7
$Cs{-}Sb + Cs{-}O_2$	3.8×10^{-3}	1.1×10^{-3}	70	×4.6
$Cs{-}Sb{-}O_2$	1.0×10^{-2}	7.0×10^{-3}	104	×6.8

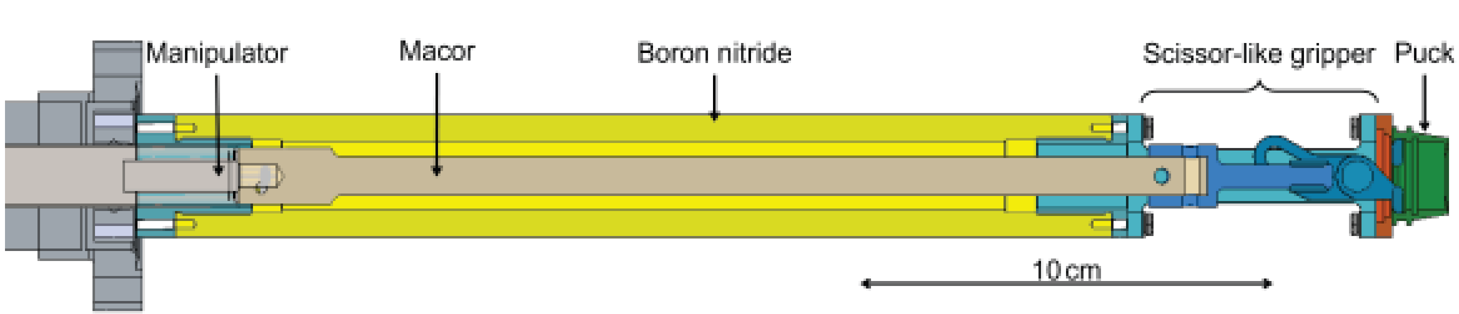
Jai Kwan Bae, Alice Galdi, Luca Cultrera, Frank Ikponmwen, Jared Maxson, and Ivan Bazarov
, "Improved lifetime of a high spin polarization superlattice photocathode", Journal of Applied Physics 127, 124901 (2020)
https://doi.org/10.1063/1.5139674



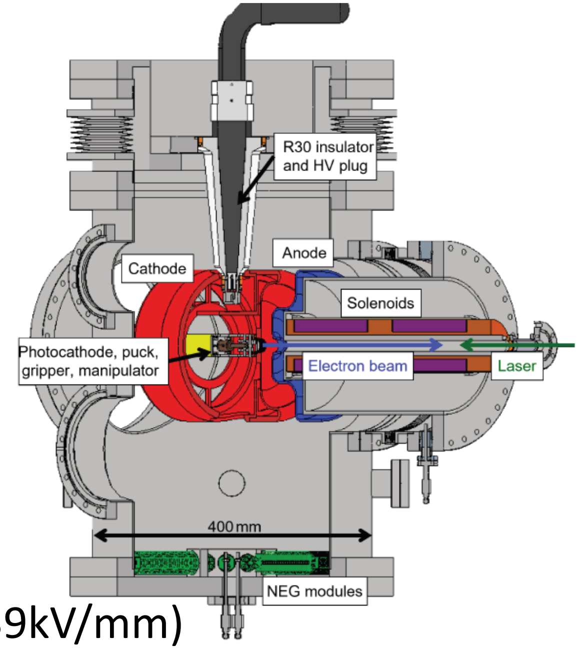
Though not useful for accelerator yet, these studies indicate that considerable improvements may be possible.

Cathode temperature control

- Within the „BETH“ project we investigate a new appoach. The cathode holder („Puck“) is pressed against an thermally conductive insulator (Boron nitride)
- This procedure is done „Outside“, the insulator is then moved into the electrode and stays there
- .A well defined small pressure can be used to provide electrical contact with the electrode



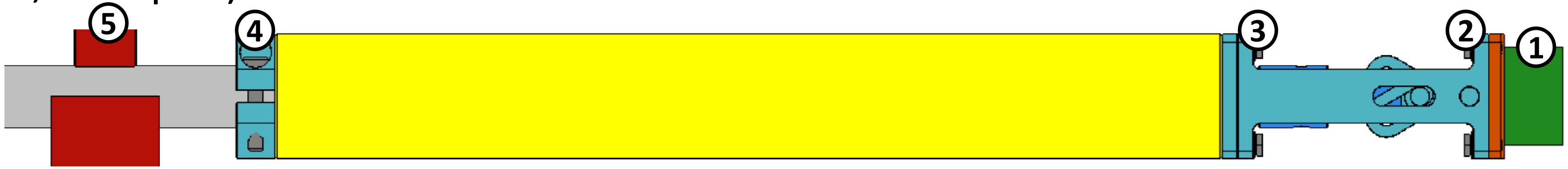
M.A. Dehn et al. IPAC-22 13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand
doi:10.18429/JACoW-IPAC2022-THPOPT024

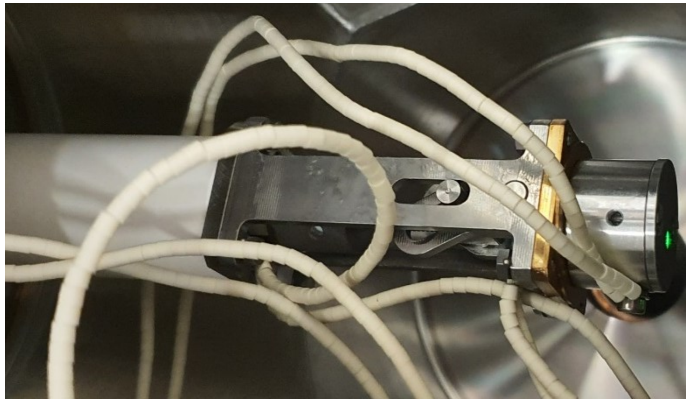


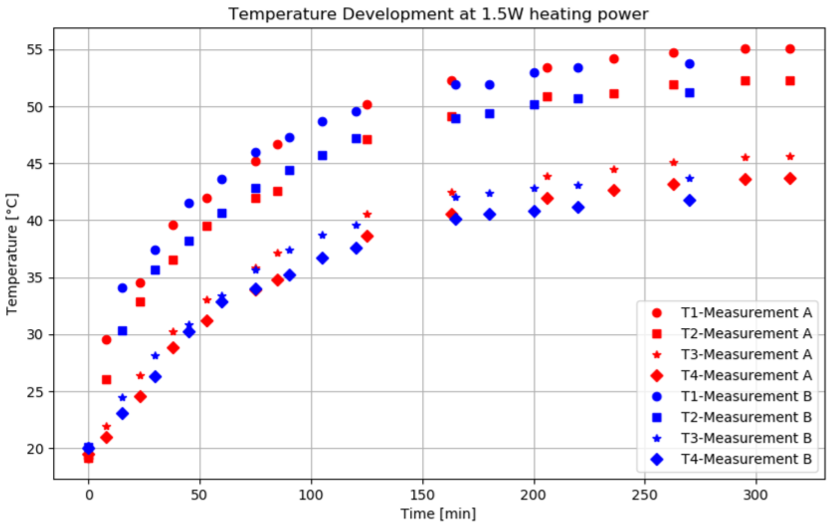
- The thermal conductivity Boron Nitride is large, about ¼ of Copper (1 W/(cm*K))..
- …whereas the resistance and discharge tolerance is very high (>10^{14} Ohm*cm and >39kV/mm)
- The pulling of the puck towards the stalk is done by marcor since the Boron nitride is not strong enough

Heating Experiment

- Heating power of 1.5W at 532 nm laser wavelength
- ΔT between “ground” (manipulator) and puck is <15 degree
- The Temperature of the manipulator can be controlled via cooling clamps
- Next step: Use cooling clamps to control the temperature (keep constant or even cool, if helpful)





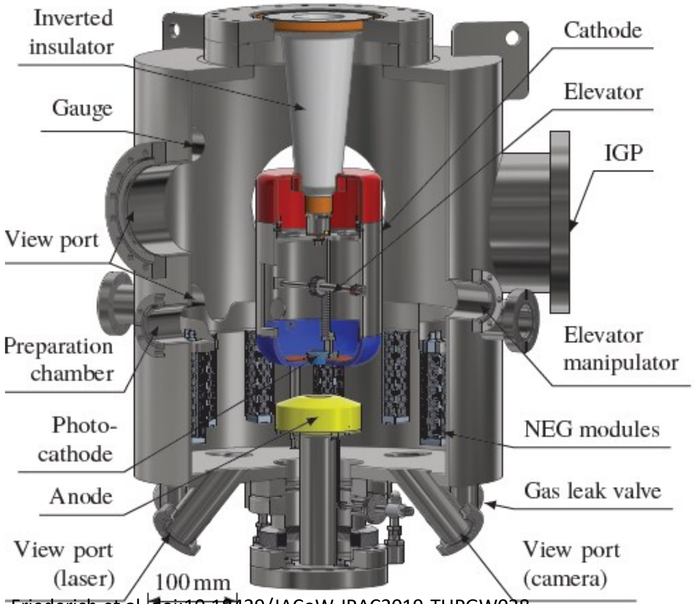


Promising, but a long way to go. Next: HV-test.

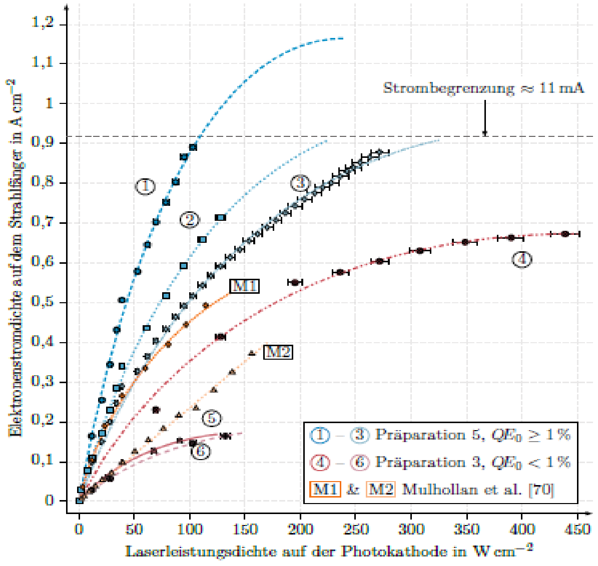
The brightness limiter: Surface Photovoltage

- Near band-gap excitation may provoque surface photovoltage at surface
  → leads to reduced QE because of modified NEA-state

Small „ThErmalized“ source At MAINZ (STEAM)- long pulse SPV



S. Friederich et al :doi:10.18429/JACoW-IPAC2019-TUPGW028



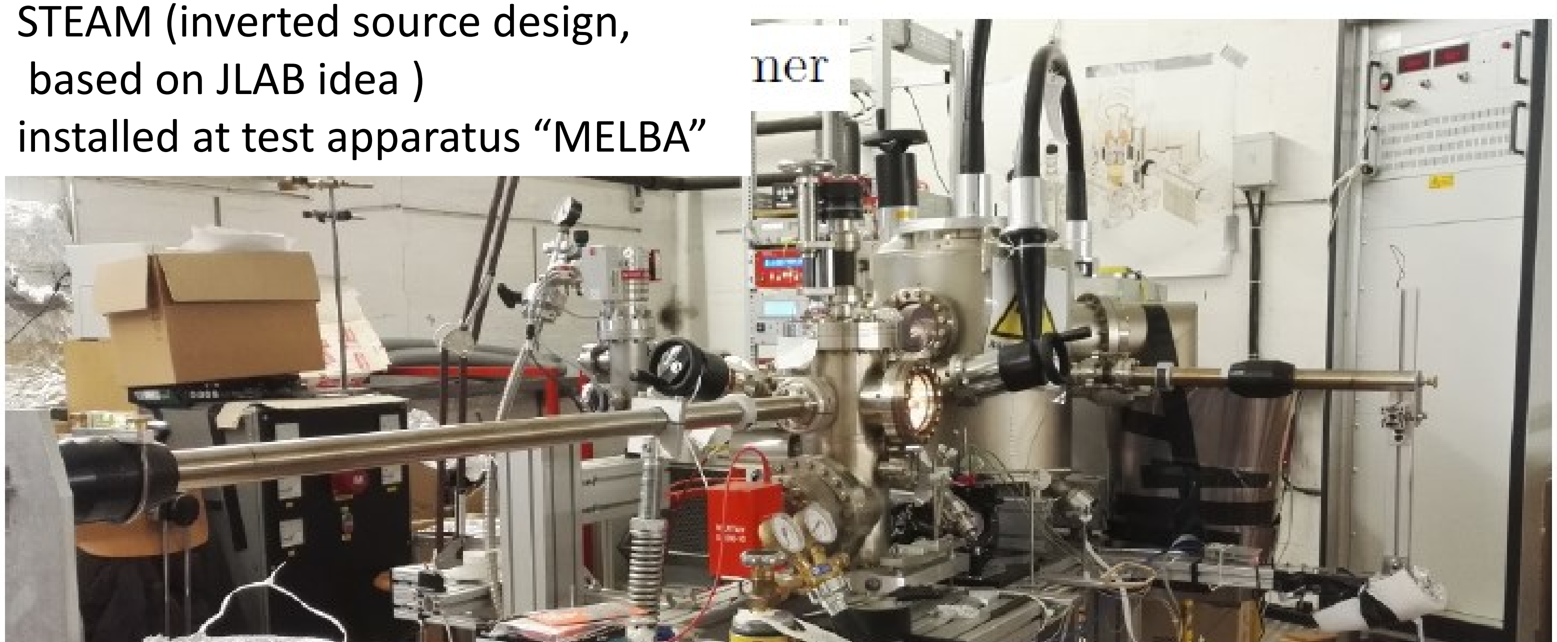
Operation with up to 150keVbeam and up to 10mA (400µs pulses)-

Surface photovoltage in NEA GaAs at 10mA leads to Q.E. dependend saturation current density in DC-operation

(400mus long pulses, 800nm excitation wavelength)

S Friederich-PhD thesis Mainz, 2019

STEAM (inverted source design, based on JLAB idea)
installed at test apparatus “MELBA”

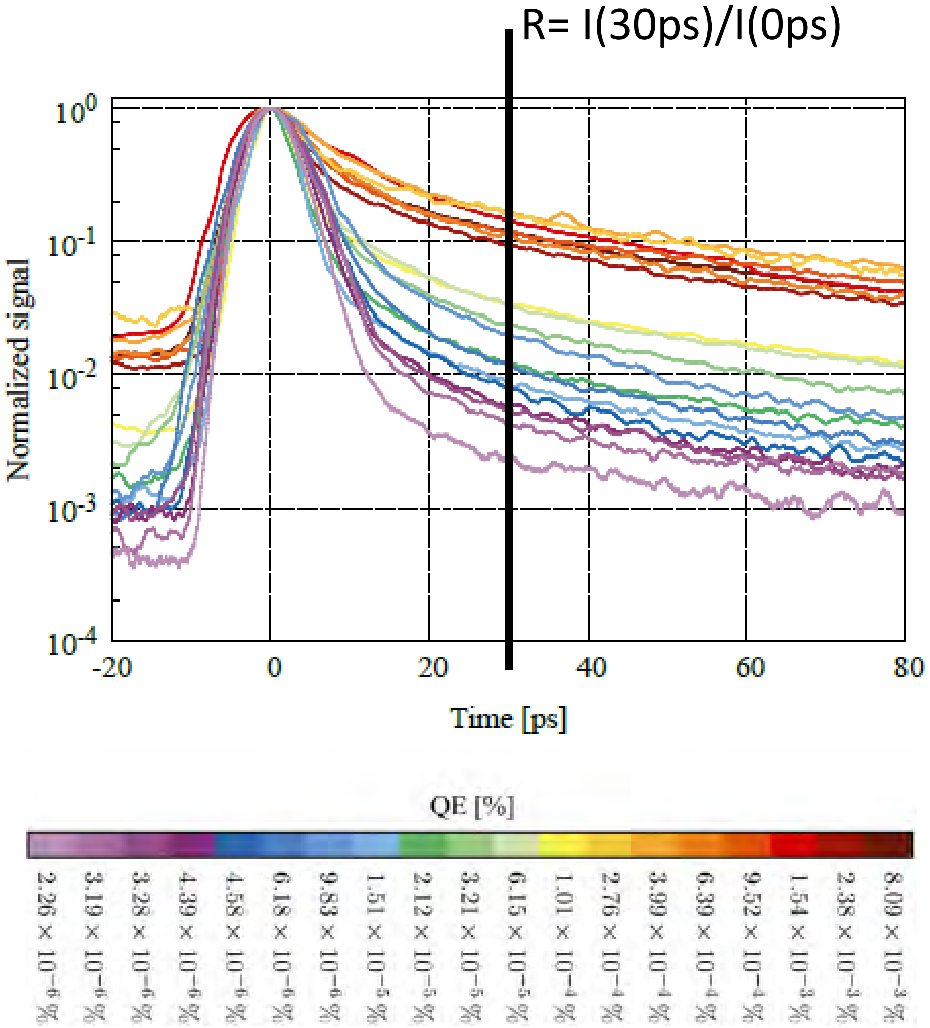


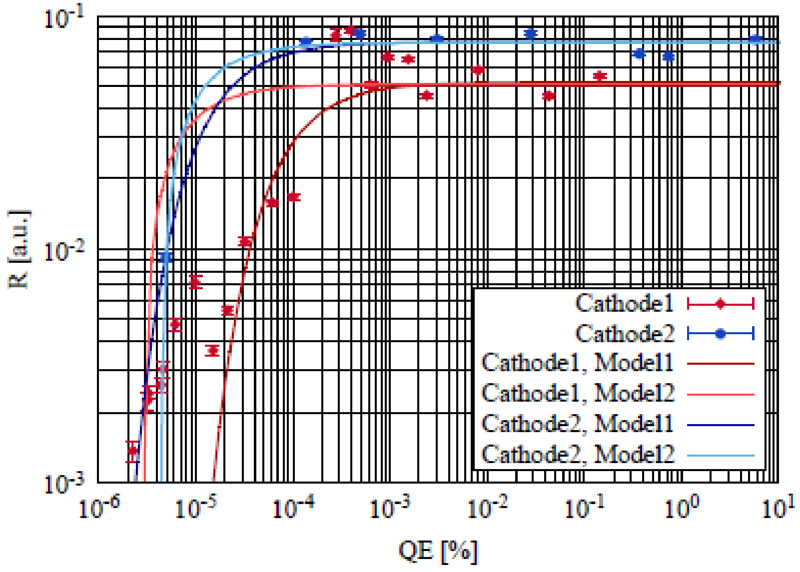
Commissioning of STEAM at MESA has started.

→ Commissioning of injector in 22/23

→ Beam operations for P2 (150muA average current, P>0.85) envisaged for end 2024.

Uni Mainz : Surface Photovoltage (shortpulse)





PhD thesis Nahid Scahill
-self modulation of picosecond pulses at very low QE?
Fits with models based on SPV (inspired by Mulhollan et al.)
Or PEA+thermionic emission

“Polarized” Photocathode acquisition problem

SLAC/SVT – Superlattice

GaAs	5 nm	p=5 $\times 10^{19}$ cm^{-3}
GaAs/GaAsP SL	(3.8/2.8 nm) ×14	p=5 $\times 10^{17}$ cm^{-3}
$GaAsP_{0.35}$	2750 nm	p=5 $\times 10^{18}$ cm^{-3}
Graded $GaAsP_x$ ($x = 0\sim0.35$)	5000 nm	p=5 $\times 10^{18}$ cm^{-3}
GaAs buffer	200 nm	p=2 $\times 10^{18}$ cm^{-3}
p-GaAs substrate (p>10^{18} cm^{-3})		

- Commercial supplier no longer available
- Due to absence of large-scale polarized accelerator activity in Europe liited interest in setting up infrastructure
- Investigating possible new suppliers and
- Help by government “applied” physics institutes (“Fraunhofer)?

Conclusion

- Upcoming (Planned/discussed) electron machines in Europe for nuclear/particle (N/P)-physics will need high average current from (probably) polarized photosources
  → large interest in progress but limited research activity so far
- “University scale machines” exist at Darmstadt and Mainz and there is high demand for improving conditions, in particular operational lifetime of spin polarized sources
- Research in this direction is feasible with university means and will also be used whereever such spin polarized beams are needed.

Thank you

Longitudinal Halo Study at Mainz

GaAs/GaAsP"Strained Superlattice" :
(T. Maruyama et al. Appl. Physics. Lett. 85,13 (2004) 2640)
Study of pulse response

SLAC/SVT – Superlattice

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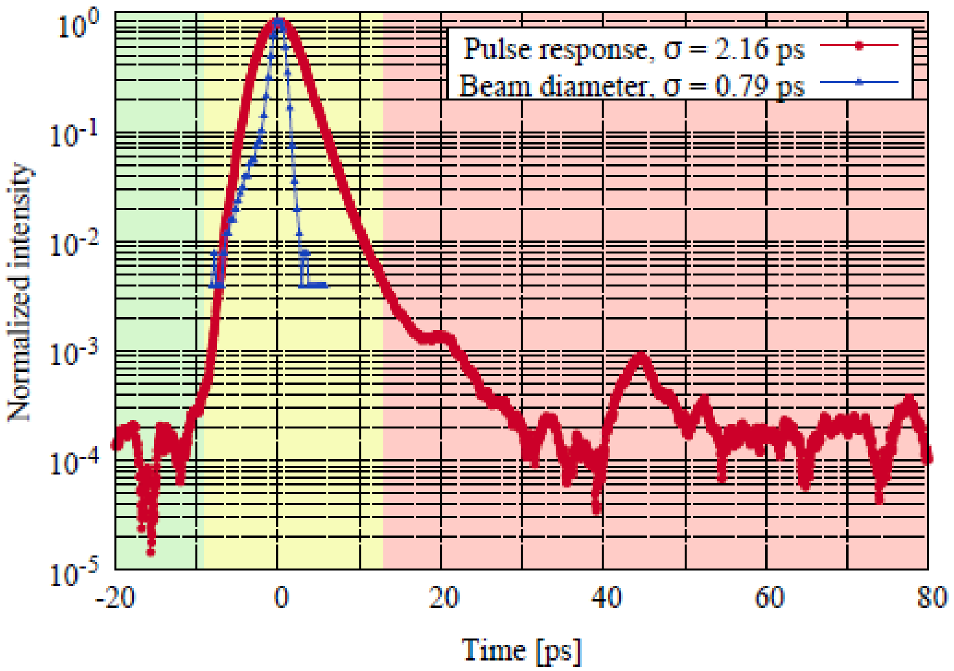

Peak width dominated by experimental resolution
As expected, Intensity drops into noise floor after a few picoseconds. Parasitic peaks due to double reflexes? (PhD Thesis Nahid Scahill)