

POLARIZED ELECTRON SOURCES IN LINACS

FCC week 2025 in Vienna
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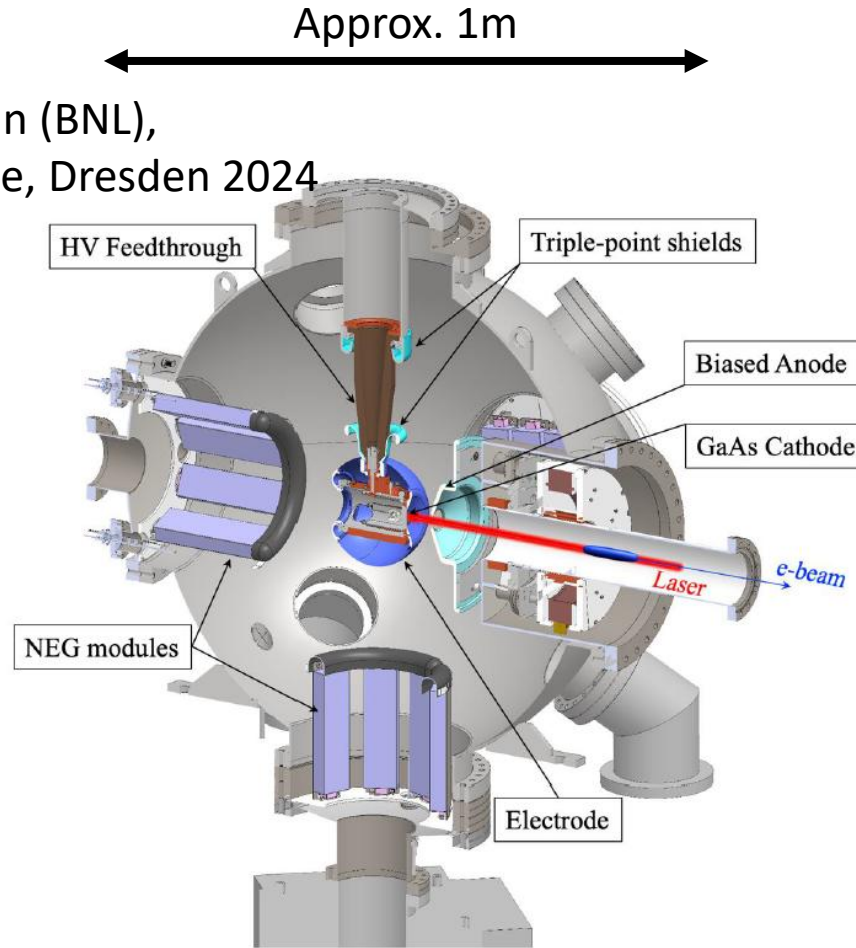


Outline-

- Basics of Spin-Polarized Photoemission
- Operating conditions and performance (lifetime limitations)
- Bunch fluence limitations
- Sustainable supply of photocathode epitaxial structures

Source – technical aspects

Taken from Omar Rahman (BNL),
Talk at EWPA conference, Dresden 2024

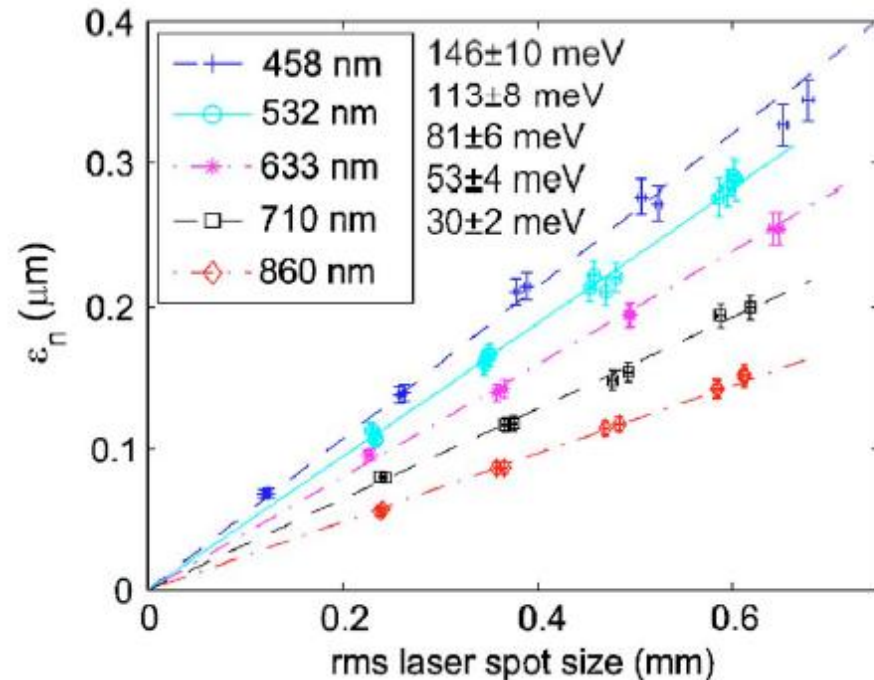


State of the art can be exemplified by the DC-source foreseen for the EIC-collider at BNL

- 300kV “inverted design”
→ Cathode field $< 10 \text{ MV/m}$
- Avoiding field emission by technical measures
- High pumping speed to achieve XHV conditions
- Load lock for reactivation or replacement of photocathode.
- HV conditioning with cathode removed
- **NC-RF-gun not compatible with vacuum/dark current requirements!**

PHYSICAL REVIEW ACCELERATORS AND BEAMS 25, 033401 (2022)

Beam emittance of (spin-polarized) photoemission



GaAs-“NEA“-photocathode

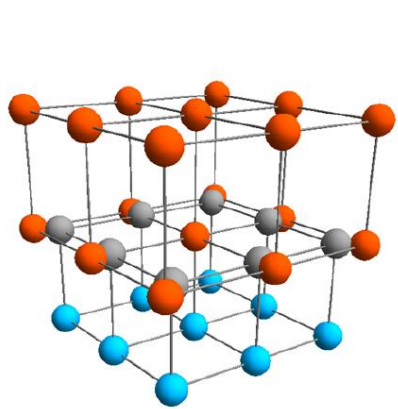
I.V. Bazarov et al. (Cornell Univ.)
J. Appl. Phys. **103**, 054901 (2008);

Best possible normalized emittance at near-IR photoexcitation (where spin-polarization can be expected)
→ After all accelerator physics/ technical aspects of the source have been solved,
the main task is to control/maintain properties of the photocathode, in particular spin-polarization

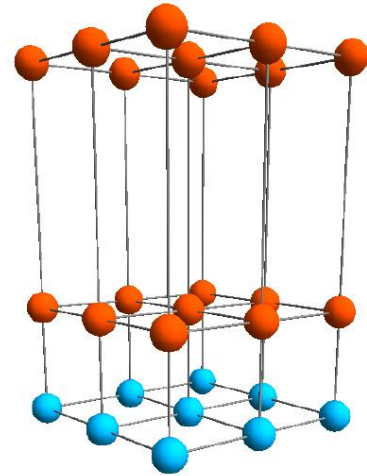
Spin-polarization Basics-1 (Atomic physics)

- Semiconductors with P-type symmetry in Valence band and S-type symmetry in Conduction band (approximation!) → III/V semiconductors (GaAs)
- Transfer of angular momentum from photon to electron spin during photo-absorption
- Reducing symmetry (similar to Stark effect)
 - Pure electron spin state in Conduction band („**100% spin-polarization**“)
- Wave function symmetry **only fulfilled in vicinity of absorption edge**

Crystal symmetry reduction



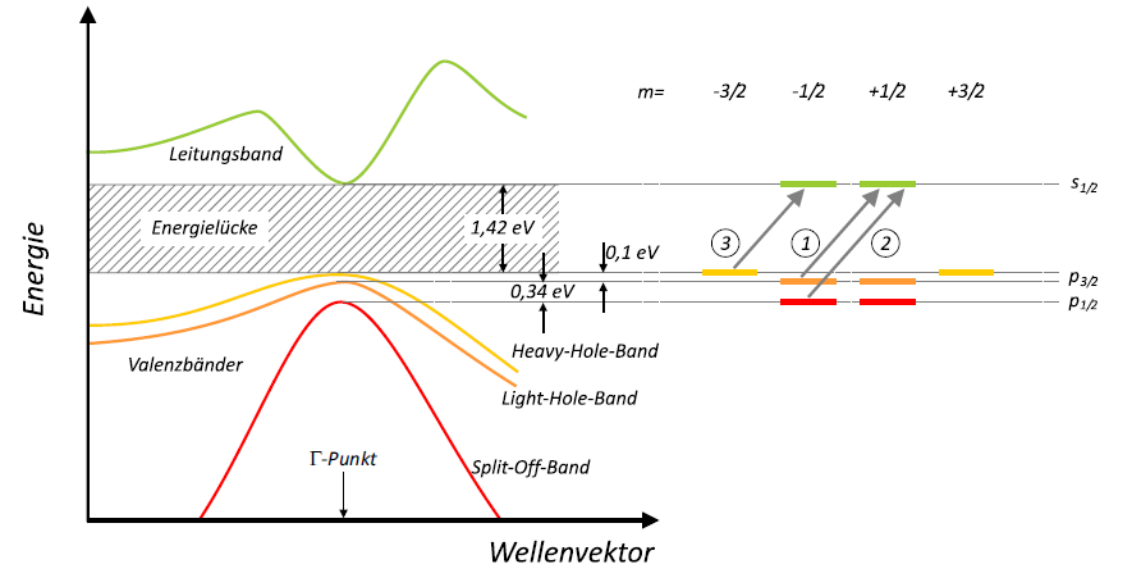
Epitaxial Layer growth with its natural lattice constant
 ①+③ transition degenerate → 50% Pol.



Better: Epitaxial Layer growth with lattice constant of substrate
 → tetragonal, 100% polarization

Epitaxial layer

Substrate



E. Riehn PhD thesis, Mainz 2013

- Fermis golden rule: Absorption $\alpha(E_\gamma)$ grows prop. to density of states i.e $\propto (E_\gamma - E_{gap})^{1/2} \rightarrow$ Quantum efficiency strongly depending on photon energy in vicinity of gap!
- But high polarization only available within $p_{3/2} - p_{1/2}$ Splitting!

Basics-3: Photoemission, NEA, QE and all that...

Quantum efficiency is probability to turn a photon into an electron in vacuum...

Three Step Model (Spicer, 1957): Quantum efficiency can be written as:

$$QE(E_\gamma) = P(1 - R) \frac{\alpha(E_\gamma)l_d}{1 + \alpha(E_\gamma)l_d}$$

GaAs is a very efficient photoemitter:

- l_d , the diffusion length is usually much larger compared to the absorption length $1/\alpha(E_\gamma)$
- The red factor determines the probability that an electron will reach the surface before it recombines to the valence band $\rightarrow 1$
- Whereas the reflectivity losses $(1 - R)$ are less important, the **surface escape probability P is ZERO** if the conduction band state is a bound state, i.e. has a **positive electron affinity (PEA)**

NEA Formation and technical challenges

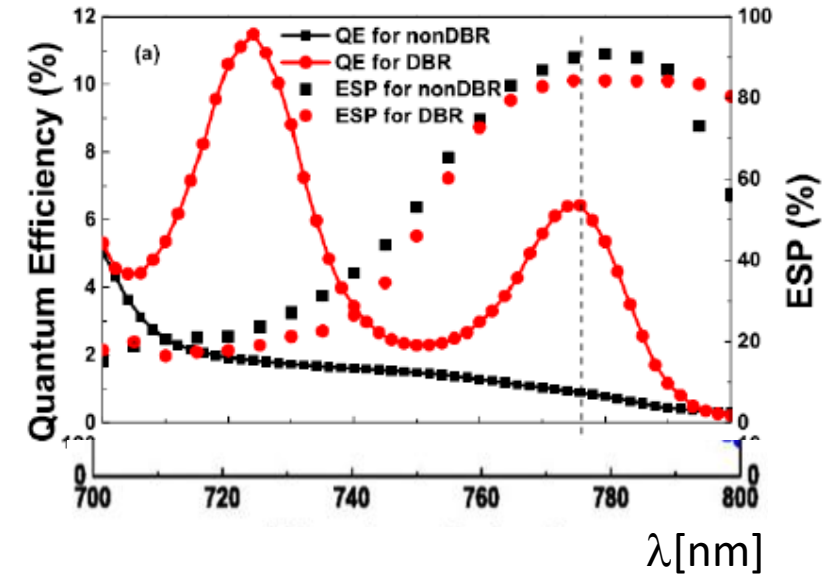
→ Trick: Reduce electron affinity at surface by **Cesium:Oxide monolayer** adsorption and band bending due to **high doping** („Fermi level pinning“ due to surface states). This creates **negative electron affinity (NEA)**

Resulting Challenges:

- 1.) Stability of Cs:O layer during operation → extreme sensitivity against „vacuum conditions“
- 2.) Doping reduces spin-polarization because of electron/hole scattering → only thin layers (ca 0.1 μm) can obtain highest polarization. → absorption/QE smaller compared to „bulk“
Also need to use „**gradient doping**“

State of the art: Superlattice cathodes

GaAs	5 nm	$p=5 \times 10^{19} \text{ cm}^{-3}$	GaAs	5 nm	$p=5 \times 10^{19} \text{ cm}^{-3}$
GaAs/GaAsP SL	(3.8/2.8 nm) $\times 14$	$p=5 \times 10^{17} \text{ cm}^{-3}$	GaAs/GaAsP SL	(3.8/2.8 nm) $\times 14$	$p=5 \times 10^{17} \text{ cm}^{-3}$
GaAsP _{0.35}	2750 nm	$p=5 \times 10^{18} \text{ cm}^{-3}$	GaAsP _{0.35}	750 nm	$p=5 \times 10^{18} \text{ cm}^{-3}$
Graded GaAsP _x (x = 0~0.35)	5000 nm	$p=5 \times 10^{18} \text{ cm}^{-3}$	GaAsP _{0.35} /AlAsP _{0.4} DBR	(54/64 nm) $\times 12$	$p=5 \times 10^{18} \text{ cm}^{-3}$
GaAs buffer	200 nm	$p=2 \times 10^{18} \text{ cm}^{-3}$	GaAsP _{0.35}	2000 nm	$p=5 \times 10^{18} \text{ cm}^{-3}$
p-GaAs substrate ($p>10^{18} \text{ cm}^{-3}$)			Graded GaAsP _x (x = 0~0.35)		
			5000 nm		
			$p=5 \times 10^{18} \text{ cm}^{-3}$		
			GaAs buffer		
			200 nm		
			$p=2 \times 10^{18} \text{ cm}^{-3}$		
p-GaAs substrate ($p>10^{18} \text{ cm}^{-3}$)					



JLAB cooperation with industrial partner

Table and plot taken from: Liu et al. Appl. Phys. Lett. **109**, 252104 (2016);

Resonant enhancement of absorption because of DBR mirror

(1%QE at 780nm ~ 6mA/Watt!)

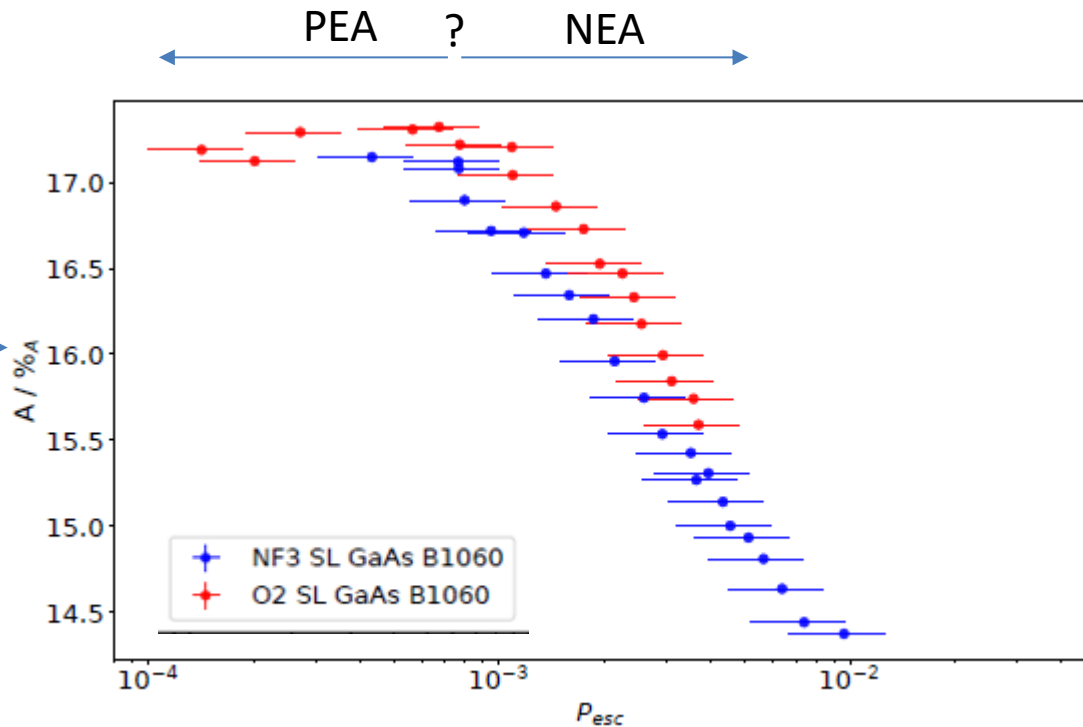
For high av. currents (>mA) scale DBR based superlattices are advisable (avoid laser heating!)

For lower av. currents at very „expensive“ machines it may be best to use the highest P!

Polarization is QE dependent...

Stable spin-polarization requires to maintain constant surface (NEA-) conditions....

Mott-Scattering asymmetry ($P=S*A$) Maximum P >90%

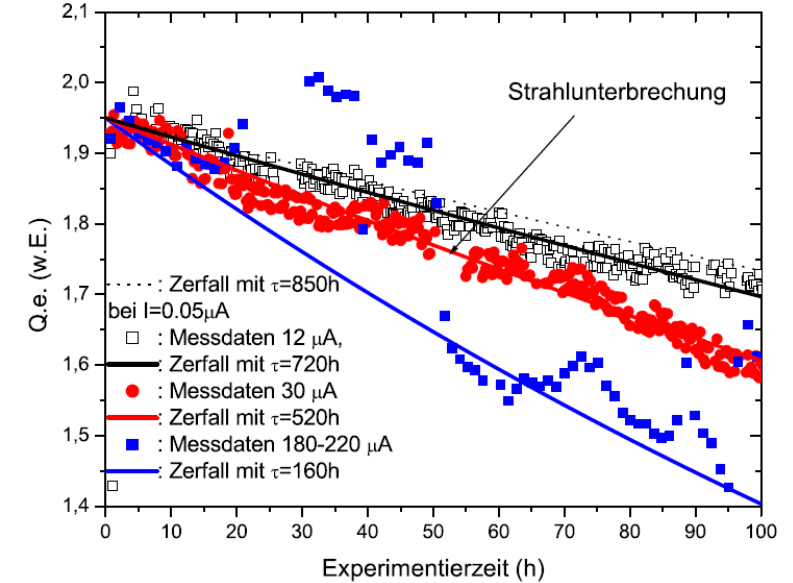
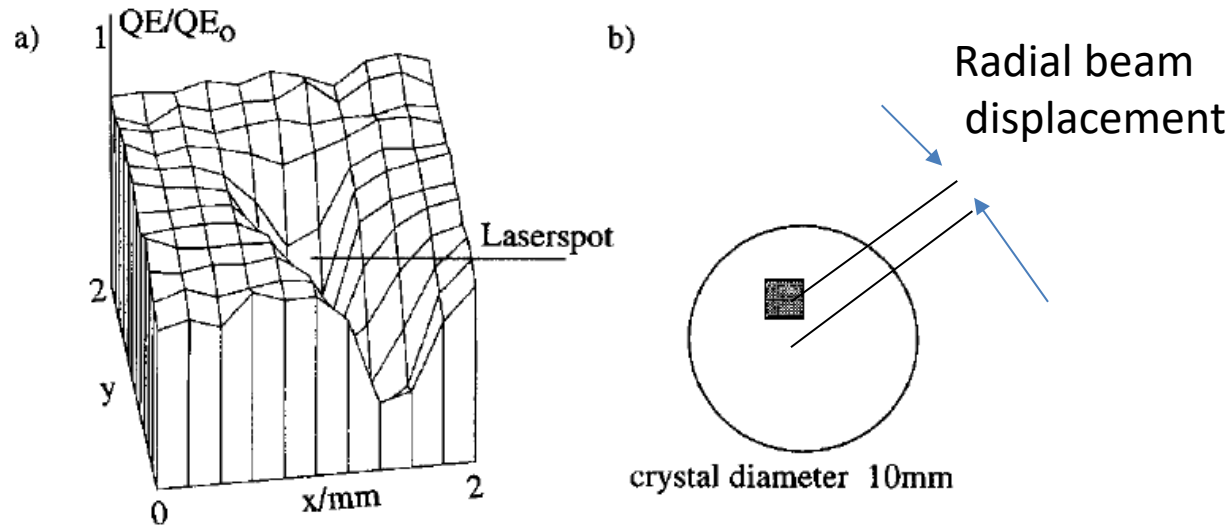


Jennifer Trieb, Dissertation, JGU Mainz, 2025

Example:
Change of escape probability (resp. QE) by $1/e$ after exposition to $1.5 \cdot 10^{-6}$ mbar*s oxygen \rightarrow partial pressure below 10^{-12} mbar in operation required.

\rightarrow Many effects reduce QE/P in practical life!

Technical problem: Ion backbombardment, Charge- and fluence-lifetime and all that...

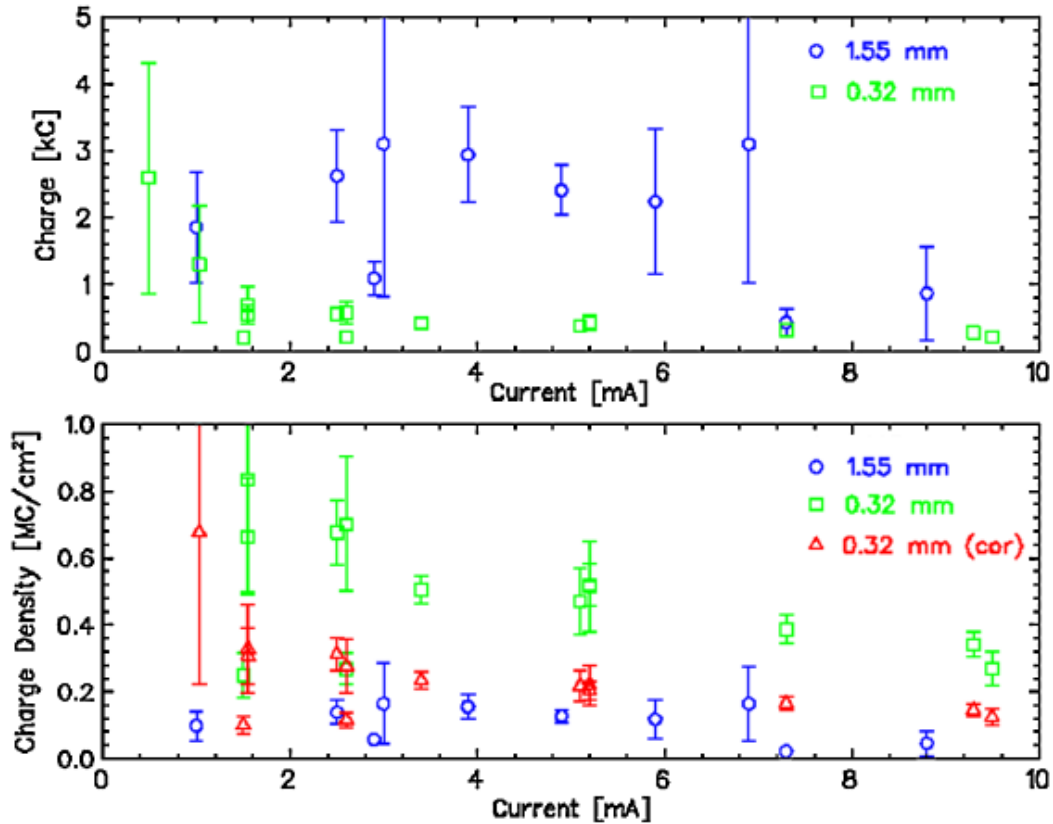


Finding: (PhD thesis K.A. , Mainz, 1994):
Ion backbombardment creates localized damage on crystal surface but there is also global damage!

Finding: (MAMI runtimes in 2000's):
Charge emitted during a lifetime is constant if current Exceeds several microampere
At low current: Effect of base vacuum and field emission

Note: „Charge lifetime“ $Q_\tau = I\tau$ is constant, once all other lifetime limitations are negligible, Q_τ of several hundred Coulombs possible

Scaling to fluence lifetime $F_\tau = \frac{Q_\tau}{A_{emission}}$ (order Mega-Coulomb/cm²) is not yet confirmed



A charge lifetime of 1800 Coulomb corresponds 50 hours of operation at 10mA

- More than enough for injection into synchrotrons
- Enough for conventional CW-Linacs and prototype ERL's (JLAB, MAMI, MESA)
- Not enough for future ERL's (even with automatized cathode regeneration)

Measurements from JLAB J. Grames et al. PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 14, 043501 (2011)

Surface photovoltage aka. „Surface charge limit“

314

G.A. Mulhollan et al. / Phys.

Results from SLAC G. Mulhollan et al.
Physics Letters A 282 (2001) 309–318

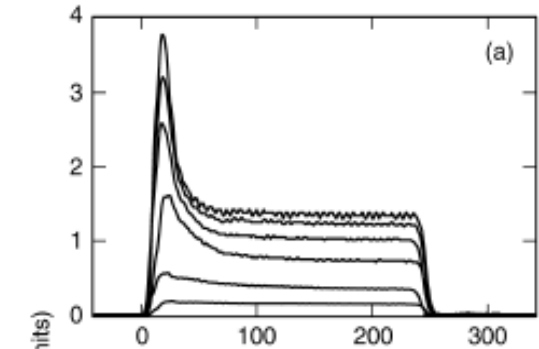
High doping reduces polarization →
gradient doping !

High field strength helps (Schottky effect)

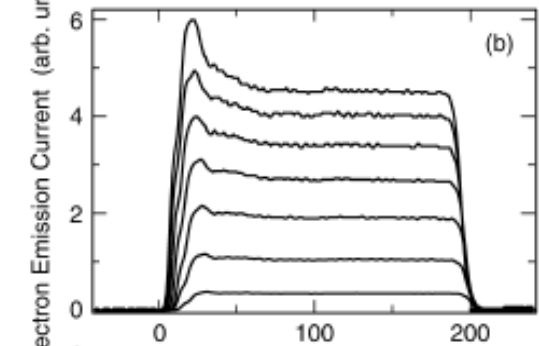
Lifetime of surface charges is ~10ns

- Bunch charge Limit for synchrotron injectors?
- And for pulsed for pol. Positron sources
(timing applications for materials science)

Low doping



Medium doping

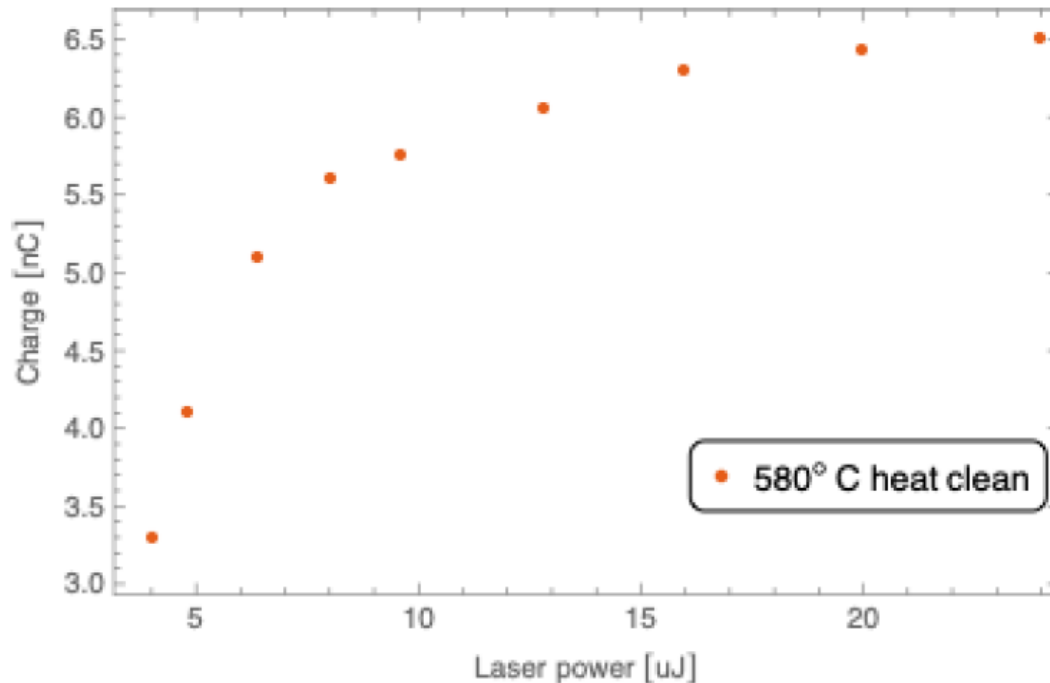


High doping



Fig. 3. The temporal profiles of the electron emission current using a long laser excitation pulse for (a) sample 1b, (b) sample 2a, and (c) sample 3. The laser intensity is varied from 1 to 150 W/cm².

State of the art...



Taken from: O. Rahman, Talk at
EWPAA conference, Dresden 2024
(Superlattice cathode with gradient
doping)

2025-04-25

- Clear surface charge limiting effect observed
- Laser spot size 8mm diameter
- **Charge starts to saturate at 5.5 nC**
- Increasing voltage to 320 kV did not help.
- Increasing spot size to 12 mm did not help
- Possible diffusion of the dopant due to high heat clean temperature (SIMS measurement confirmed)
- Retry with low temperature heat cleaning @ 450 C

Secure sustainable supply for fundamental research machines....

1. The old vendor does not want to deliver samples any more.
2. MBE-GaAsP not very attractive for mass fabrication (contrast to the 1990 „epitaxy“ peak)
3. Handling Phosphorus difficult and may block production of MBE machines
4. → an issue of „world wide“ interest. Stakeholders: Particle physicists (EIC, EICC, LHEC,..), e+ source developers ...and MAMI/MESA at Mainz.

Mainz/MESA has contacts to several national semiconductor research institutes (from the Fraunhofer and Leibniz institutes).

The issue with vendors....

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Mainz/MESA negotiates contract with national semiconductor research institutes (Fraunhofer ; Heinrich Hertz Institute) .

Production offer & services by federal lab:

Teil A - Fertigung des Puffers

Detailliertes Verfahren (Ausschreibung 3.2 a)

1. Epitaxieentwicklung auf p-leitenden GaAs-Substraten eines 5000 nm dicken Stufenpuffers (graded buffer) von GaAs hin zu GaAs_{0.65}P_{0.35}
2. inklusive Kalibrierung der Gasquellen-Regelparameter für As und P
3. inklusive Charakterisierung der Schichten mittels optischer Mikroskopie, hochauflösender Röntgenbeugung (HRXRD) und reciprocal space maps (RSM) sowie Sekundärionen-Massenspektroskopie (SIMS)
4. inklusive der Entwicklung und Analyse der in-situ-Messung der Substratkrümmung und Schichtverspannung (EZcurve) für den graded buffer
5. Epitaxieentwicklung metamorpher GaAs_{0.65}P_{0.35}-Puffer auf vorher entwickelten Stufenpuffer mit Variation der Wachstumstemperaturen für reduzierte AFM- (atomic force microscopy) Rauigkeit
6. inklusive Charakterisierung mittels Mikroskopie, AFM, EZcurve, HRXRD mit RSM
7. inklusive der Entwicklung und Analyse der in-situ-Messung der Substratkrümmung und Schichtverspannung (EZcurve) für den graded buffer
8. inklusive Charakterisierung mittels Transmissionselektronenmikroskopie (TEM) zur Bestimmung von Versetzungsdichten

The text on the left is only the number of steps required to make the buffer layer!

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p-GaAs substrate ($p>10^{18} \text{ cm}^{-3}$)		

Even if the production produces non-optimal results, the information about the growth will be transferred to us!

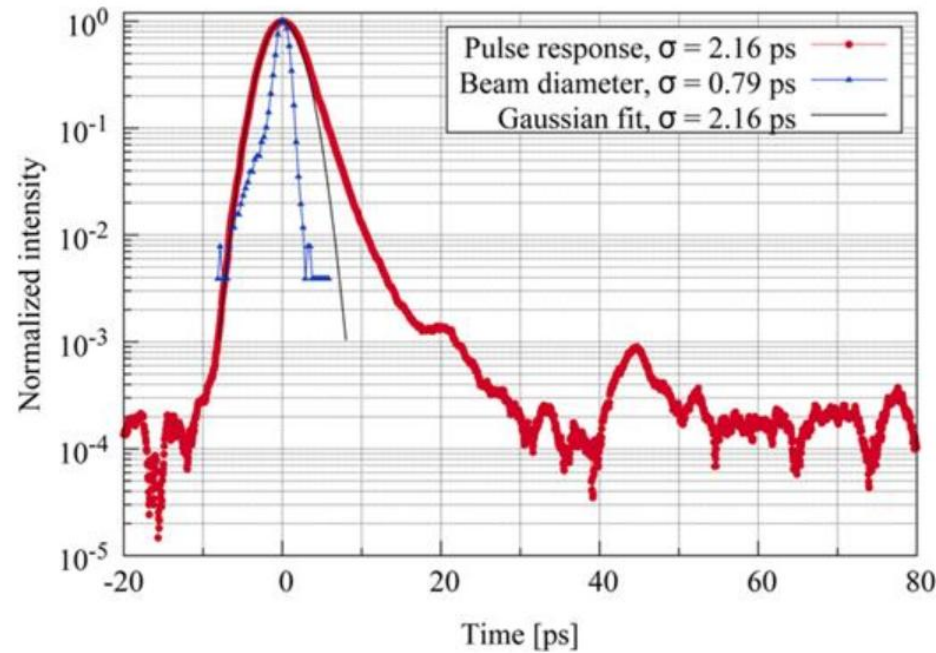
Conclusion and R&D outlook

- At LINACS high $P > 0.85$ is possible
- Ion backbombardment limits operational stability , but enough for conventional linacs (**not ERL**)
 - R&D high bandgap material GaN/GaAlN, CsSb₃:CsTe?
- NC RF-gun difficult
 - Superconducting RF-gun?
- Bunch charge in single acclerator bucket (bunch fluence) limited because of surface photovoltage
 - R&D on surface modifications , like CsTe coating.

Thank you

Spares

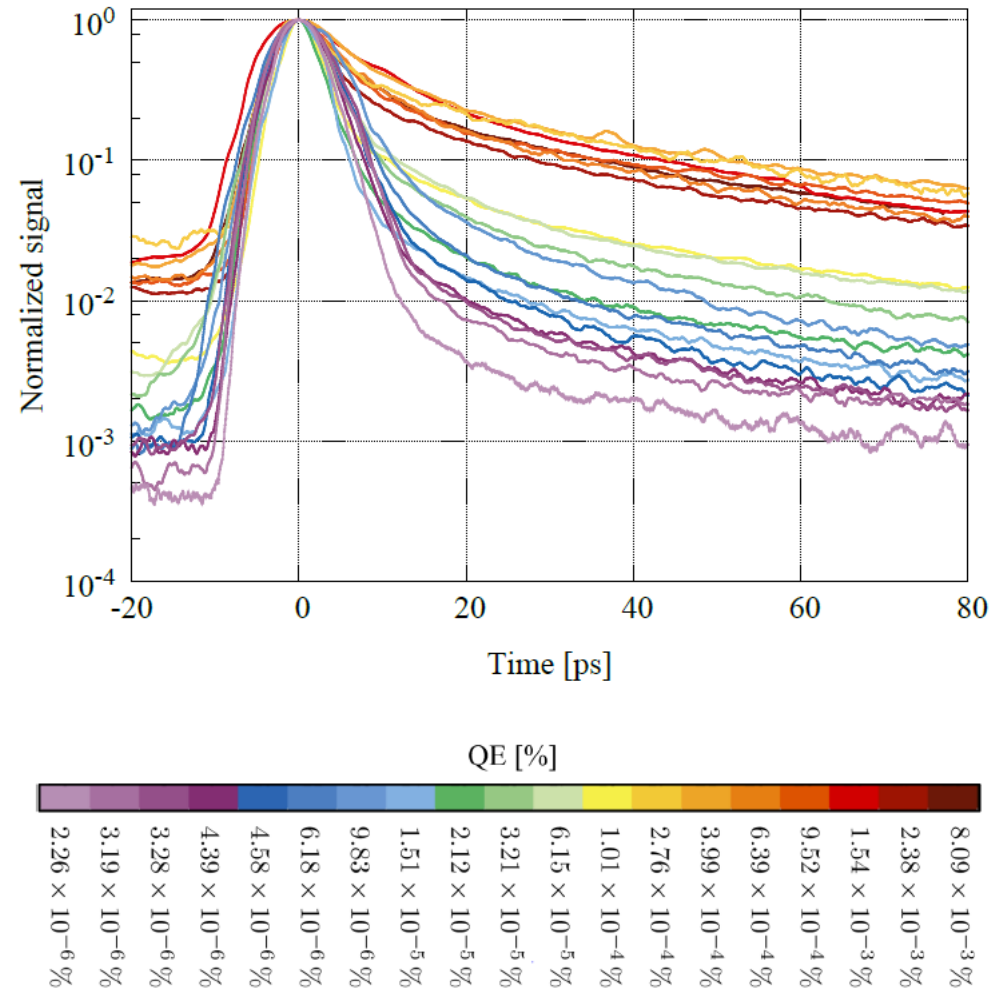
Time response/Superlattice



Resolution limited!

Response time measurement is resolution limited...(estimated RMS 0.7ps)
N. Scahill, K.A. , *J. Appl. Phys.* 132, 185702 (2022)

Time response bulk GaAs –QE-dependent! (self modulation by SPV?)



Dissertation N. Scahill,

JGU Mainz 2022