Record-level quantum efficiency from high polarization photocathodes

Wei Liu

Brookhaven National Laboratory

LCWS2021
International Workshop on Future Linear Colliders

BROOKHAVEN NATIONAL LABORATORY
Jefferson Lab
EXPLORING THE NATURE OF MATTER

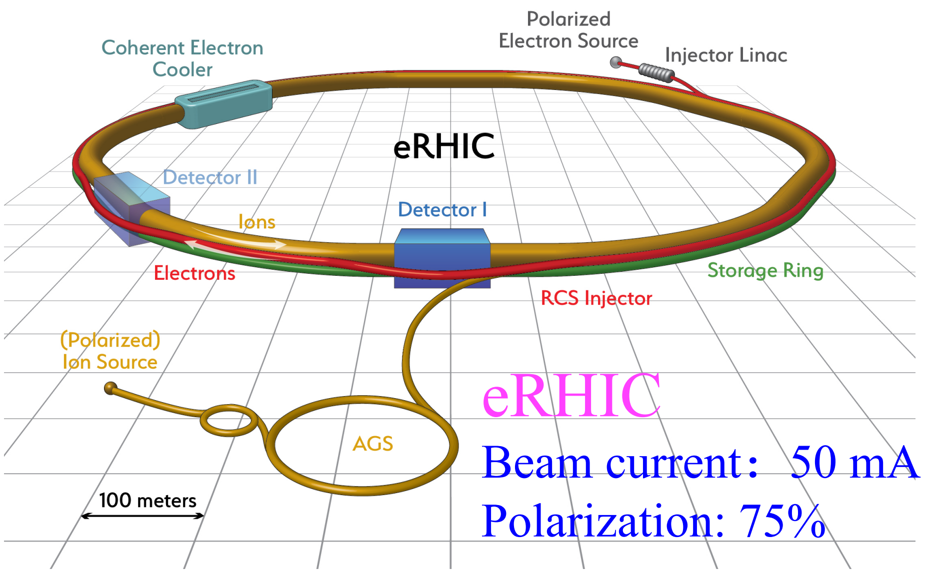
outline

1 **Motivation**

2 **Polarized photocathodes R&D, results**

3 **Summary**

High current polarized electron accelerators



eRHIC

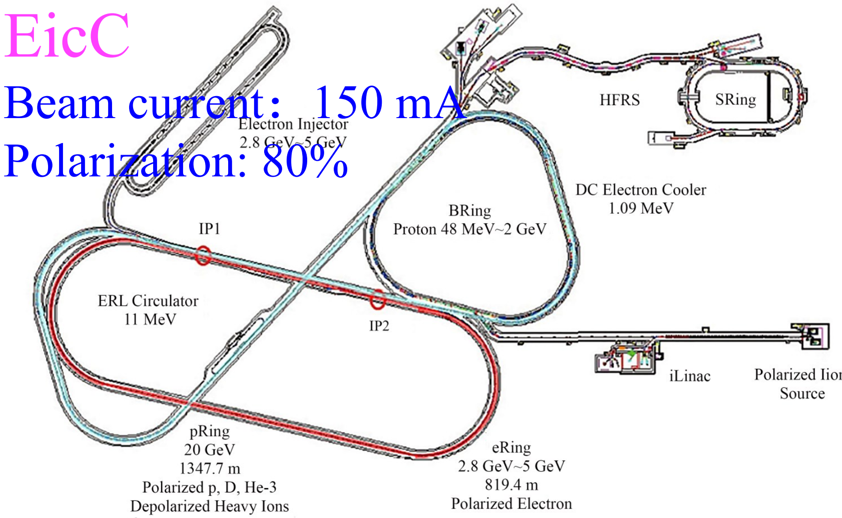
Beam current： 50 mA

Polarization: 75%

EicC

Beam current： 150 mA

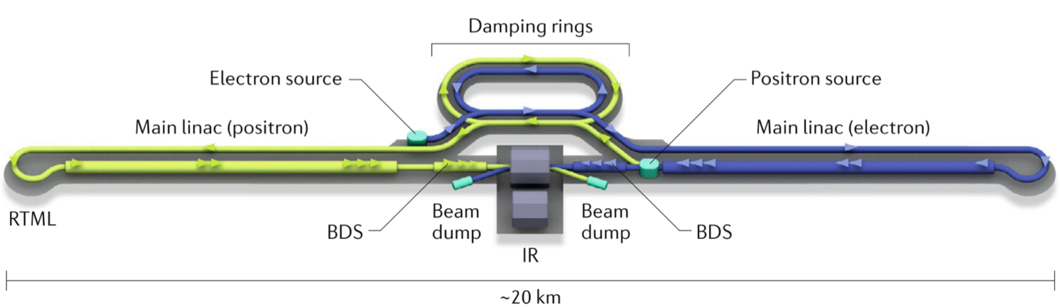
Polarization: 80%

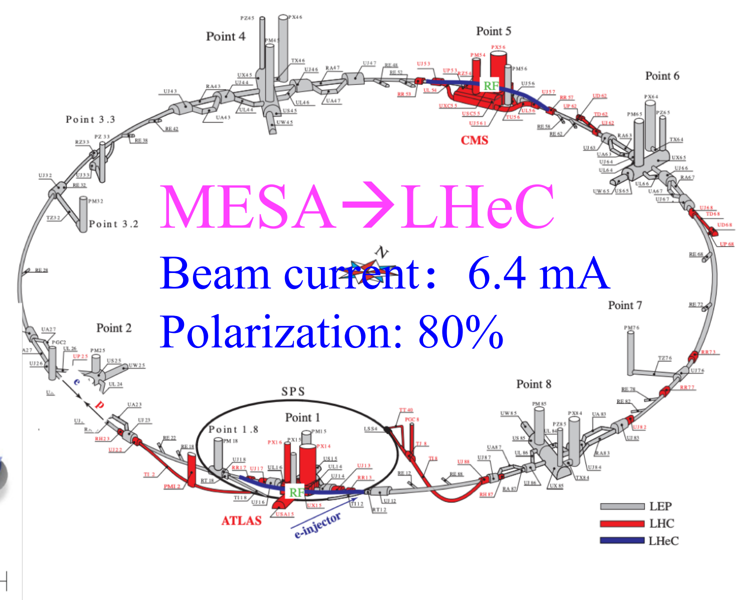


ILC

Beam current： 9 mA

Polarization: 90%





MESA→LHeC

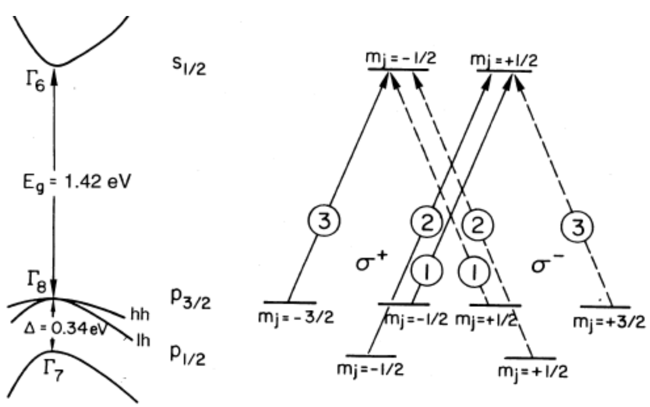
Beam current： 6.4 mA

Polarization: 80%

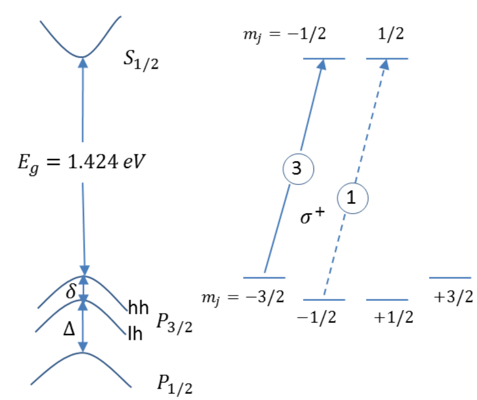
Existing polarized photocathodes

Structure	P (%)	QE (%)
Bulk GaAs	35	10
GaAs/GaAsP (strained well)	92	1.2
GaAs/GaAsP (strained compensated)	92	1.6
InGaAs/AlGaAs	77	0.7
AlInGaAs/GaAs	91	0.5
AlInGaAs/AlGaAs (with DBR)	92	0.85
AlInGaAs/GaAsP (with DBR)	92	0.6

- ❑ High polarization satisfies most accelerators' requirements
- ❑ Low QE only support sustained beam delivery at ~ μA level

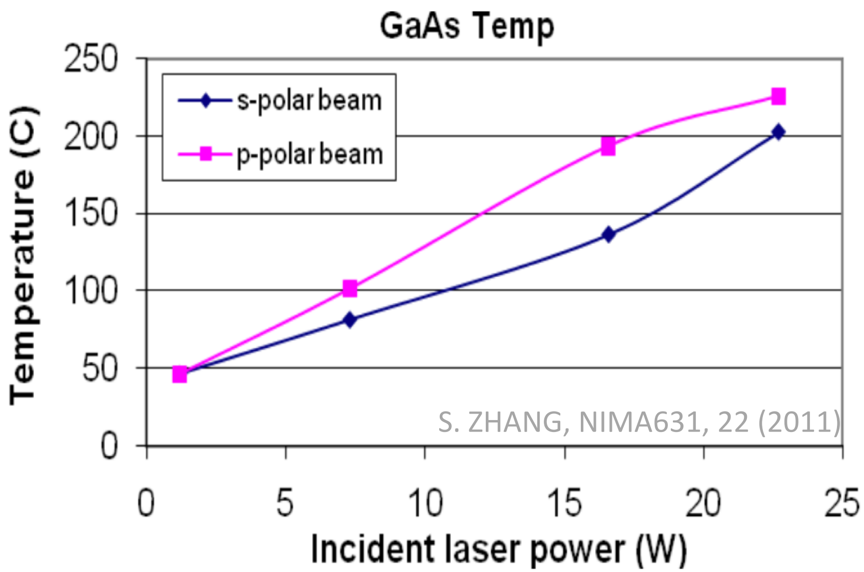


Unstrained GaAs: <50%



Strained superlattice GaAs: <100%

High QE requirement



- High current need high laser power for low QE photocathode
- Most of laser heats photocathode
  - Cs evaporation, QE degradation
  - Vacuum deterioration
- Cooling photocathode is required, which is complicated in HV photogun

QE = 0.5%, I = 10 mA

P = 3.18 W, T = 50°C

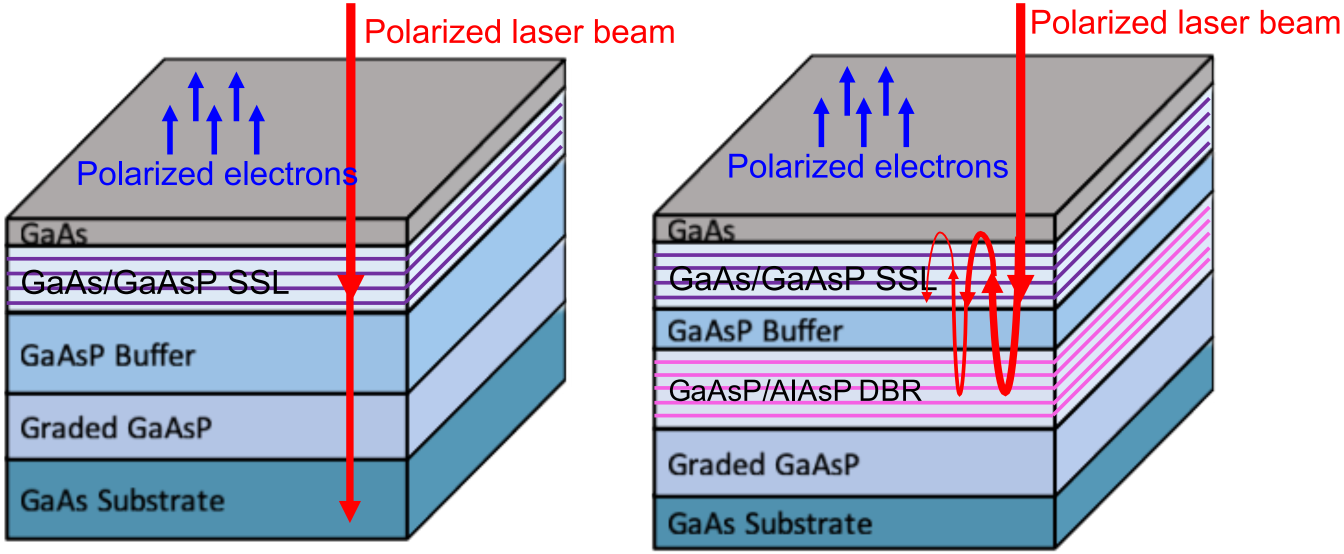
High polarization & QE ~ 10% is desired:

- simplify gun design
- reduce requirements on driven laser
- prolong operating lifetime

Solution: strained superlattice photocathodes with Distributed Bragg Reflector (DBR)

Benefits of DBR

- non-DBR Photocathode
  - Laser absorption in the GaAs/GaAsP superlattice < 5%
  - Most laser passes into the substrate and leads to unwanted heat
- DBR photocathode
  - Fabry-Perot cavity formed between DBR and top GaAs layer
  - Laser absorption in the GaAs/GaAsP superlattice >20%
  - Less laser required to make required beam, less laser means less heat



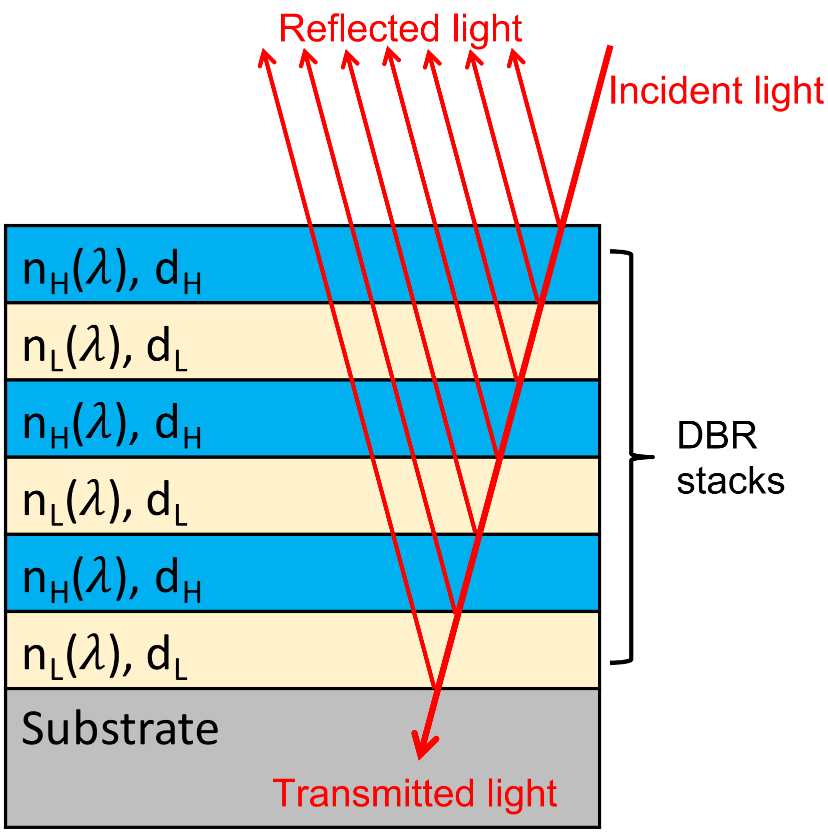
Standard strained superlattice (SSL) photocathode

Strained superlattice (SSL) photocathode with Distributed Bragg reflector (DBR)

Design of the DBR

To get high reflectivity for DBR stacks:

$$n_H(\lambda_{DBR})d_H = \frac{\lambda_{DBR}}{4} = n_L(\lambda_{DBR})d_L$$



Precise control of optical path length (nd) of each layer

Calculation for absorption of photocathode

Transfer matrix method:

$$\mathrm{M} = \begin{bmatrix} \mathrm{M}_{11} & \mathrm{M}_{12} \\ \mathrm{M}_{21} & \mathrm{M}_{22} \end{bmatrix} = \mathrm{J}_{\mathrm{m}-1\to\mathrm{m}} \mathrm{F}_{\mathrm{m}-1} \cdots \mathrm{F}_2 \mathrm{J}_{1\to 2} \mathrm{F}_1 \mathrm{J}_{0\to 1}$$

$$J_{i\to i+1} = \begin{bmatrix} \frac{k_{i+1}+k_i}{2k_{i+1}} & \frac{k_{i+1}-k_i}{2k_{i+1}} \\ \frac{k_{i+1}-k_i}{2k_{i+1}} & \frac{k_{i+1}+k_i}{2k_{i+1}} \end{bmatrix} \qquad F_i = \begin{bmatrix} e^{ik_i d_i} & 0 \\ 0 & e^{-ik_i d_i} \end{bmatrix}$$

Reflectivity, Transmission and absorption:

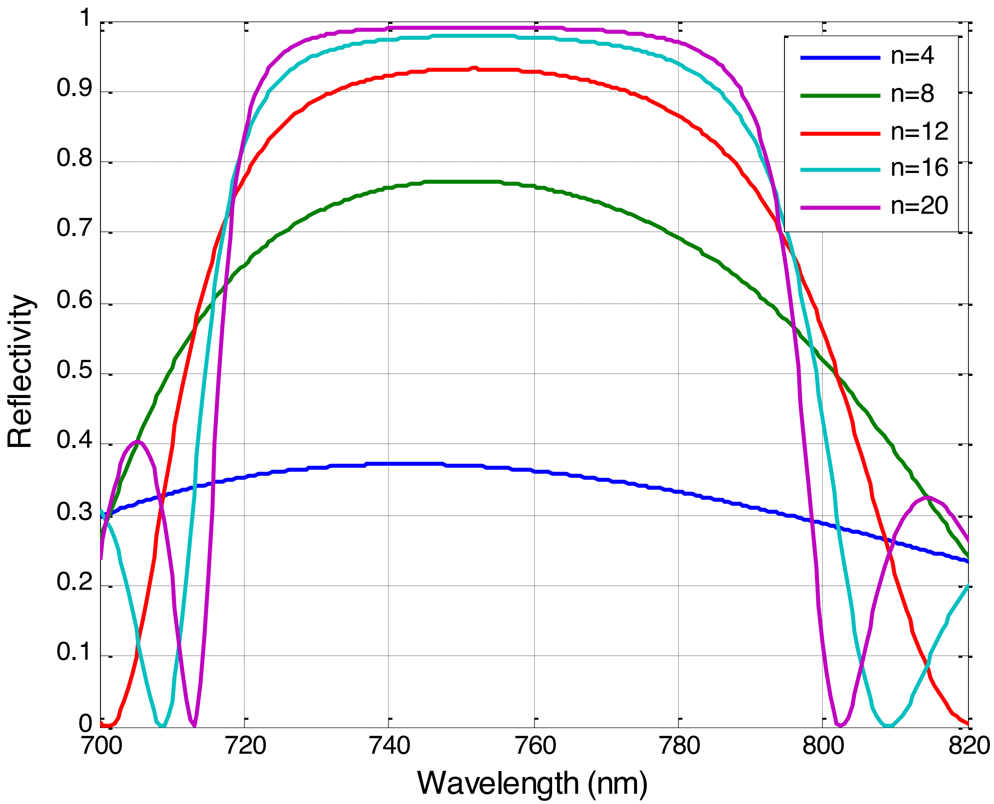
$$R = \left| -\frac{M_{21}}{M_{22}} \right|^2$$

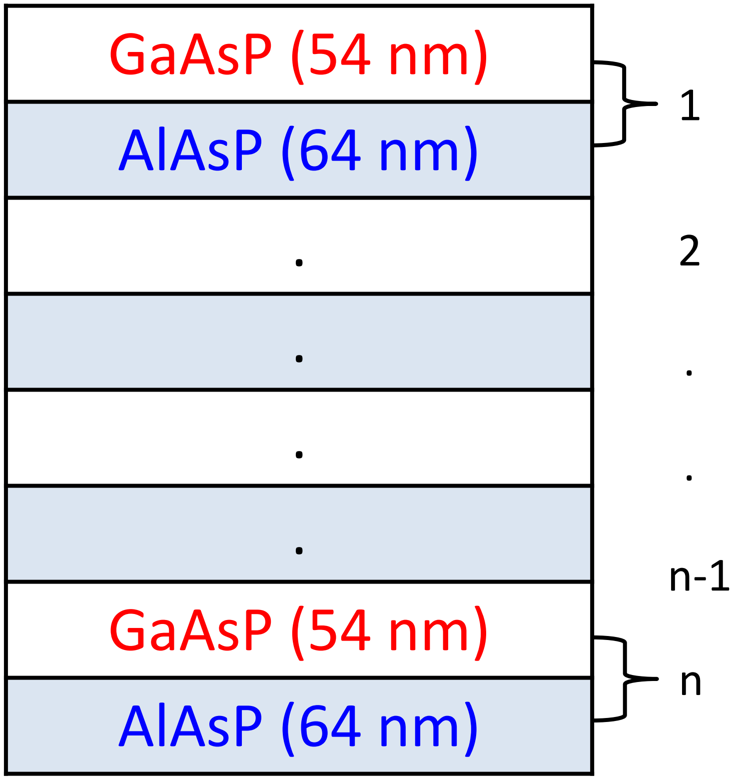
$$T = \left| M_{11} - \frac{M_{12} M_{21}}{M_{22}} \right|^2 \cdot \frac{n_m}{n_0}$$

$$A = 1 - R - T$$

Surface reflectivity of GaAsP/AlAsP DBR

- More layers, higher reflectivity, but more challenging
- 12 paired layers (our choice): highest reflectivity is 93.2%





DRB surface reflectivity vs. numbers of paired layers (n)

Schematic of photocathode structure

GaAs	5 nm	p=5E19 cm^{-3}
GaAs/GaAsP SSL	(3.8/2.8 nm) ×14	p=5E17 cm^{-3}
$GaAsP_{0.35}$ buffer	2750 nm	p=5E18 cm^{-3}
Graded $GaAsP_x$ ($x = 0 \sim 0.35$)	5000 nm	p=5E18 cm^{-3}
GaAs buffer	200 nm	p=2E18 cm^{-3}
p-GaAs substrate (p>1E18 cm^{-3})		

Standard SSL Photocathode

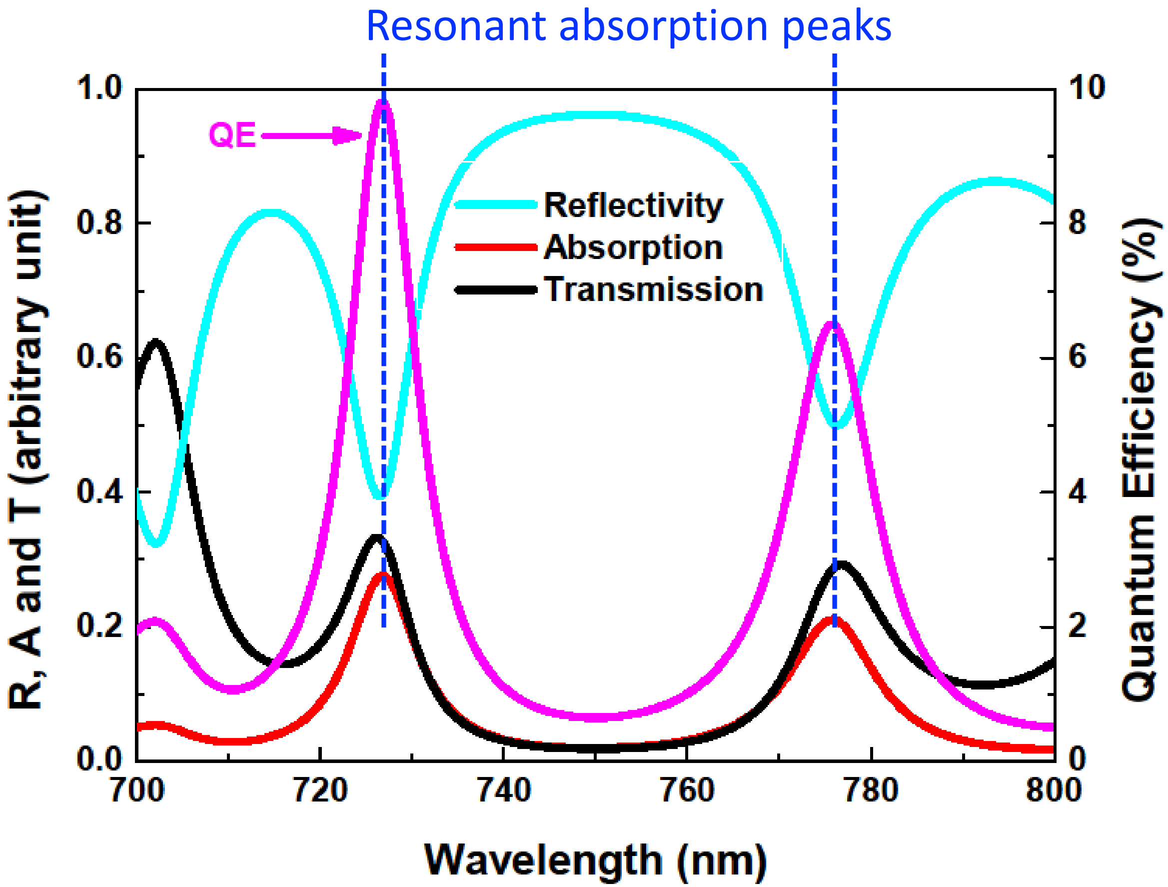
GaAs	5 nm	p=5E19 cm^{-3}
GaAs/GaAsP SSL	(3.8/2.8 nm) ×14	p=5E17 cm^{-3}
$GaAsP_{0.35}$ spacer	750 nm	p=5E18 cm^{-3}
$GaAsP_{0.35}$/ $AlAsP_{0.4}$ DBR	(54/64 nm) ×12	p=5E18 cm^{-3}
$GaAsP_{0.35}$ buffer	2000 nm	p=5E18 cm^{-3}
Graded $GaAsP_x$ ($x = 0 \sim 0.35$)	5000 nm	p=5E18 cm^{-3}
GaAs buffer	200 nm	p=2E18 cm^{-3}
p-GaAs substrate (p>1E18 cm^{-3})		

SSL photocathode with DBR

Key design consideration: optical path length

- ❖ Refractive index/Phosphorus content
- ❖ Layer thickness

Calculation results for DBR photocathode



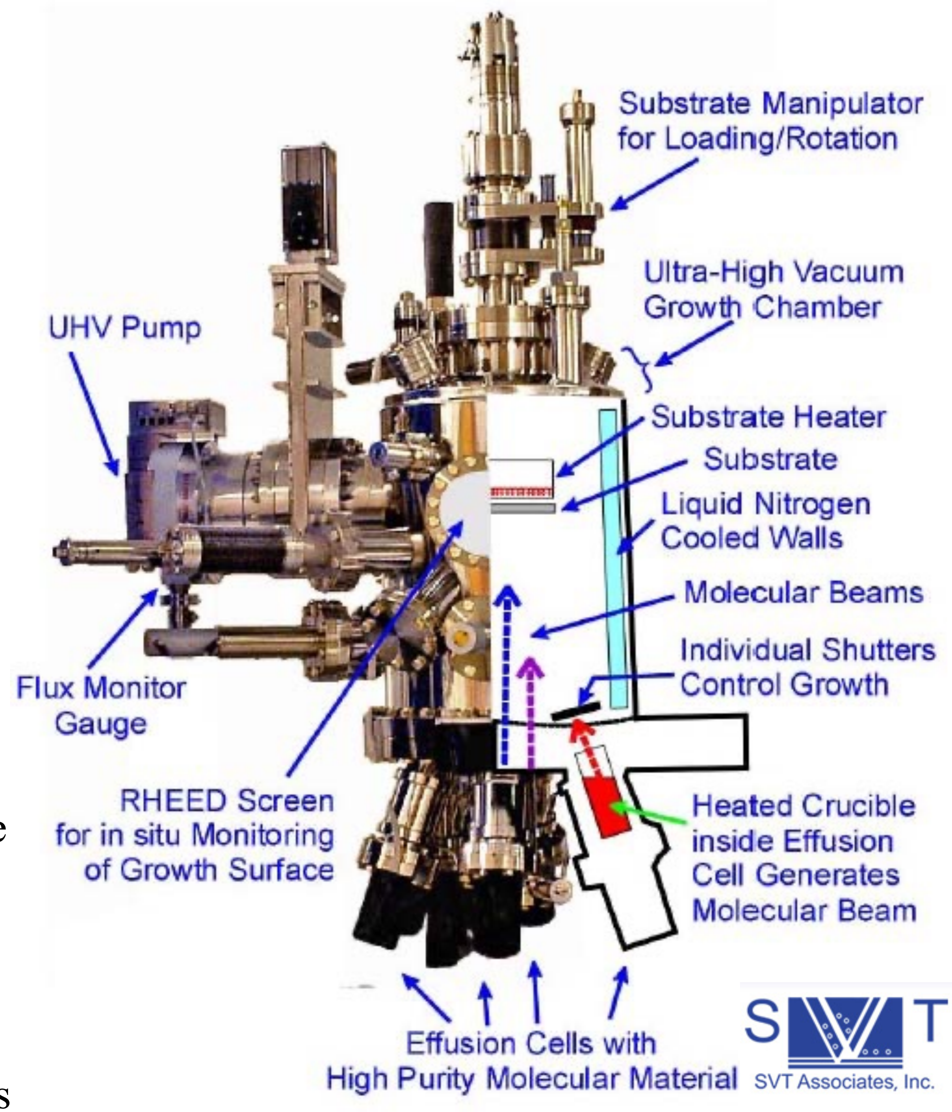
Calculated reflectivity, absorption, transmittance and QE of the DBR photocathode

Resonant absorption peak at 776 nm:

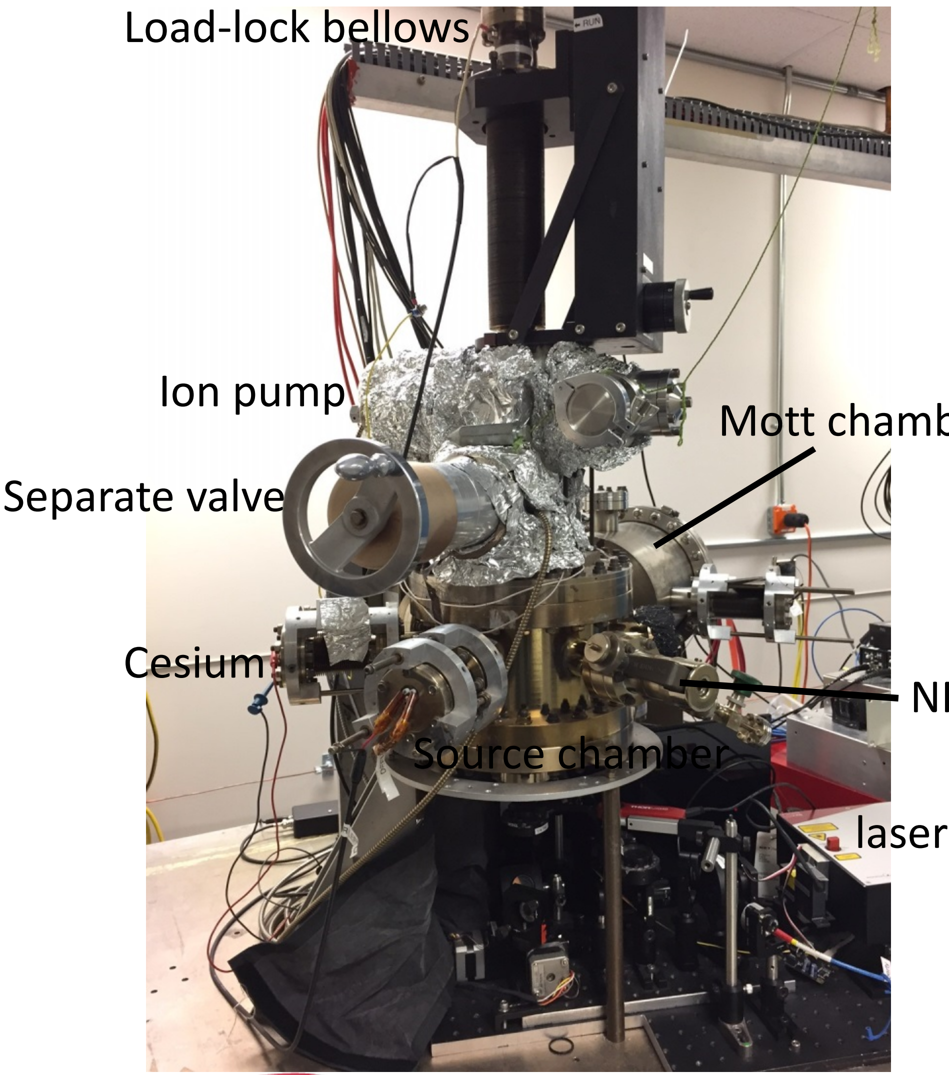
- Absorption: 21.03%
- QE: 6.4%

Growth of photocathode

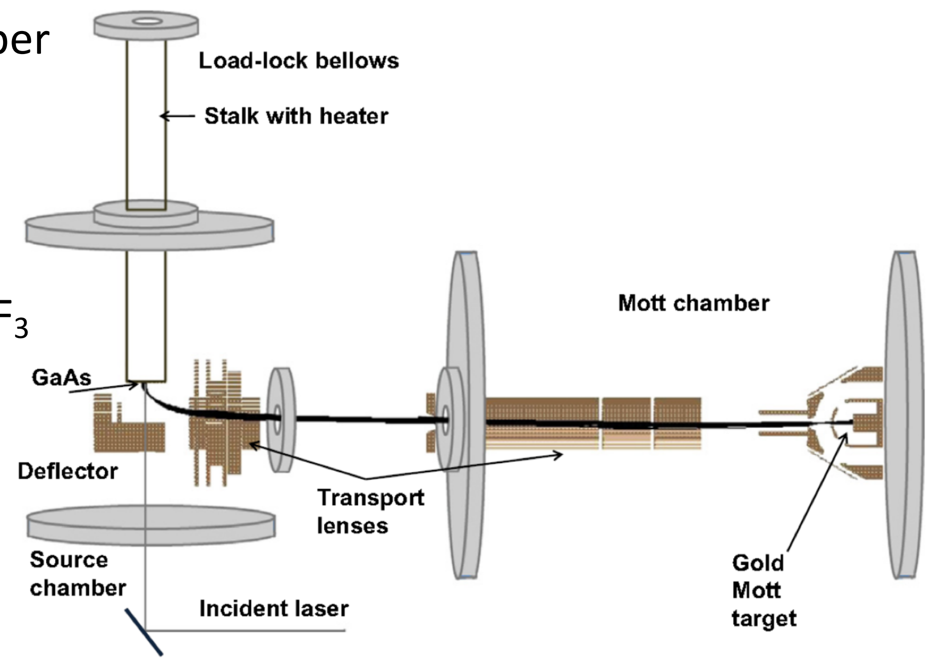
- Grown in a solid source molecular beam epitaxy (SSMBE) system
- Difficulties:
  - Large difference in best growth temperature for GaAsP (660-700°C) and AlAsP (700-750°C) layers
  - Large difference in the V/III flux ratios for the GaAsP (50) and AlAsP (3) layers
- Methods:
  - DBR layers waere grown at 700°C, and other layers were grown at 660°C
  - Growth temperature was monitored via an infrared pyrometer
  - The sample was characterized by reflective high energy electron diffraction (RHEED) during the MBE growth
  - Thickness and composition of each layer were verified using x-ray diffraction measurements and x-ray simulation models



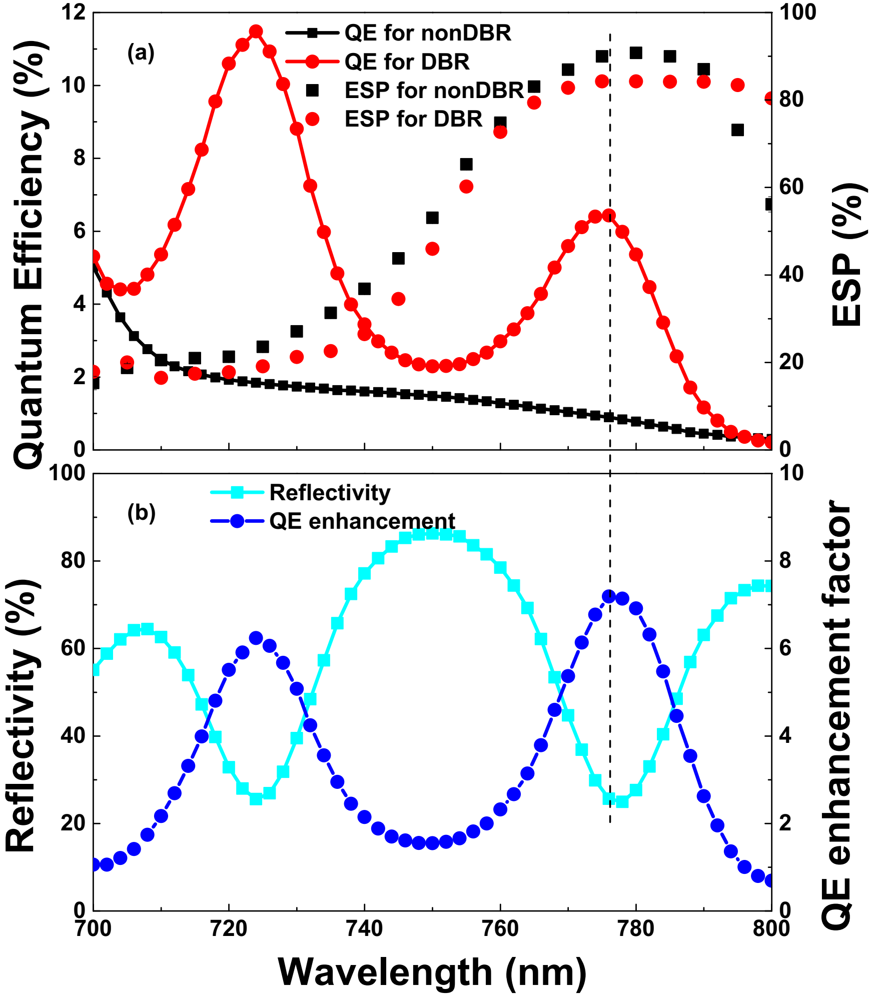
Experimental apparatus



- Activated with Cs and NF_3
- QE was evaluated in source chamber
- Polarization was evaluated by Mott polarimeter



Experimental results



	Non-DBR photocathode	DBR photocathode
QE	0.89%	6.4%
Polarization	92%	84%
Wavelength	776 nm	776 nm

QE Enhancement factor: 7.2

Performance of polarized photocathodes

Cathode	Ref.	P(%)	QE (%)	FOM (P^2QE)
$GaAs/GaAsP_{0.36}$ (no DBR)	SLAC/SVT	86	1.2	0.89
$GaAs/GaAsP_{0.38}$ (no DBR)	Nagoya	92	1.6	1.35
$Al_{0.19}In_{0.2}GaAs/Al_{0.4}GaAs$ (with DBR)	St. Peterburg	92	0.85	0.72
$GaAs/GaAsP_{0.35}$ (with DBR)	JLab/SVT	84	6.4	4.52

- Precise control over many layers is the biggest challenge
- Accurate modeling is helpful
- Optimized MBE growth recipe is helpful

Summary

- GaAs/GaAsP SSL photocathodes with DBR structure show QE enhancement of 7x, polarization over 80%
- Further work for the wavelength tuning of QE peak and increasing the peak QE
- High current photocathode for future polarized electron sources

Acknowledgement

- This work is performed when I was at Jefferson Lab
- I gratefully acknowledge Shukui Zhang, Matt Poelker, Marcy Stutzman, Joseph Grames, Carlos Hernandez-Garcia, John Hansknecht, Phil Adderley, Russell Mammei at CIS ground of Jefferson Lab
- I gratefully acknowledge Yiqiao Chen, Wentao Lu, Aaron Moy at SVT Associates, Inc.

Thanks for your attention