Record-level quantum efficiency from a high polarization strained GaAs/GaAsP superlattice photocathode with Distributed Bragg Reflector

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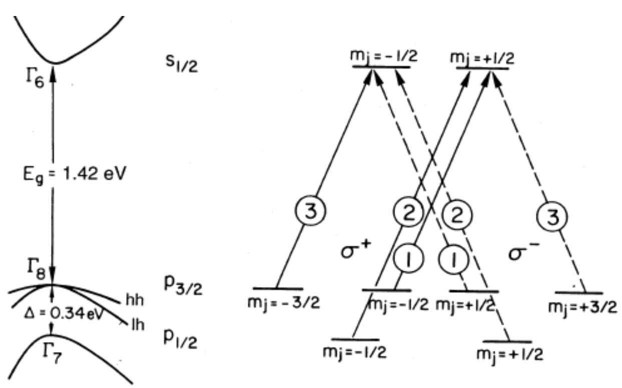
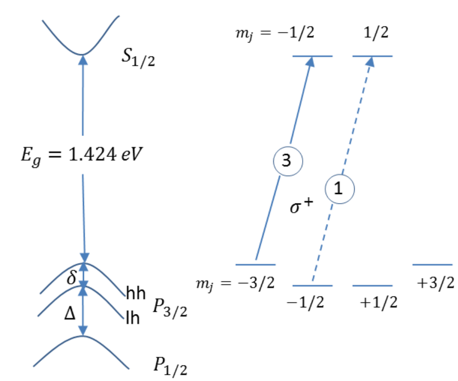
Existing polarized photocathodes

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

These QE values support sustained beam delivery at ~ uA levels



Unstrained GaAs



Strained GaAs

High Current Electron Accelerators

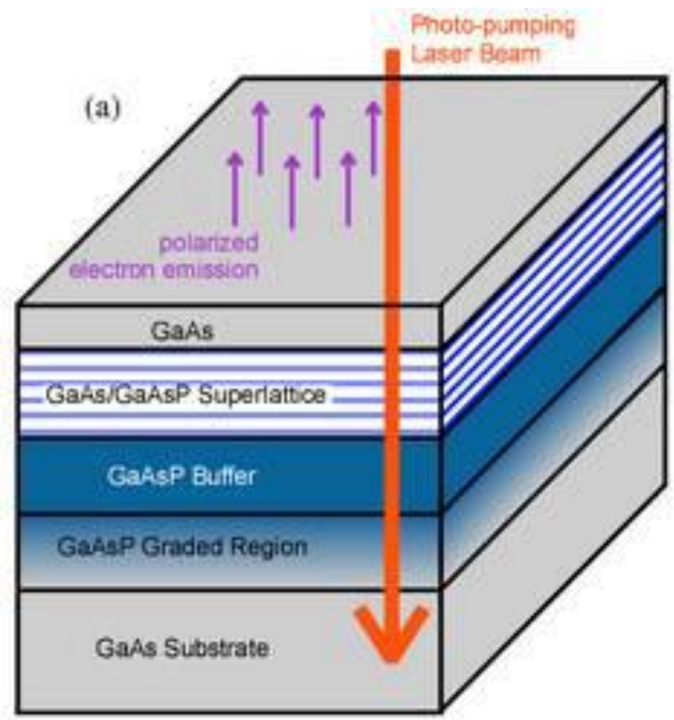
Accelerator	P	Current
eRHIC	75%	10 to 50 mA
Polarized positrons at CEBAF	90%	1 mA+

* See talk by Joe Grames

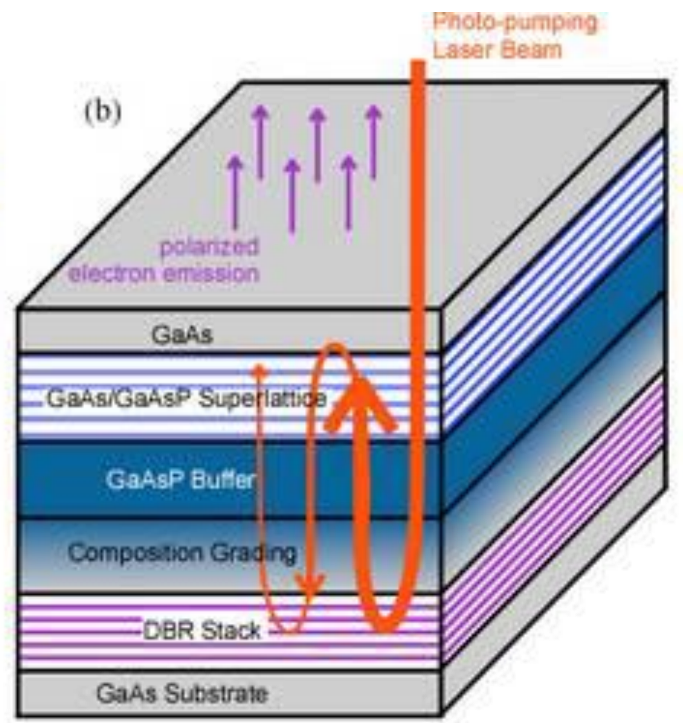
- Polarized electron beams at mA current will enable new physics experiments and new capabilities
- Most of the incident drive laser light simply heats the photocathode – photocathode cooling required, this is complicated at high voltage
- High polarization photocathodes with QE ~ 10% desired: simplify gun design, reduce requirements on drive laser, prolong operating lifetime
- Bulk GaAs has very high QE but low polarization
- Solution: High polarization photocathode with Distributed Bragg Reflector

Benefits of DBR

- non-DBR Photocathode : absorption in the GaAs/GaAsP superlattice < 5%
- Most light passes into the substrate and leads to unwanted heat
- DBR photocathode : absorption in the GaAs/GaAsP superlattice >20%
- Less light is required to make required beam, less light means less heat



Non-DBR photocathode



DBR photocathode

Schematic structure of photocathodes

GaAs	5 nm	p=5E19 cm^{-3}
GaAs/GaAsP SL	(3.8/2.8 nm) ×14	p=5E17 cm^{-3}
$GaAsP_{0.35}$	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})		

Non-DBR Photocathode

GaAs	5 nm	p=5E19 cm^{-3}
GaAs/GaAsP SL	(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}
$GaAsP_{0.35}$	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})		

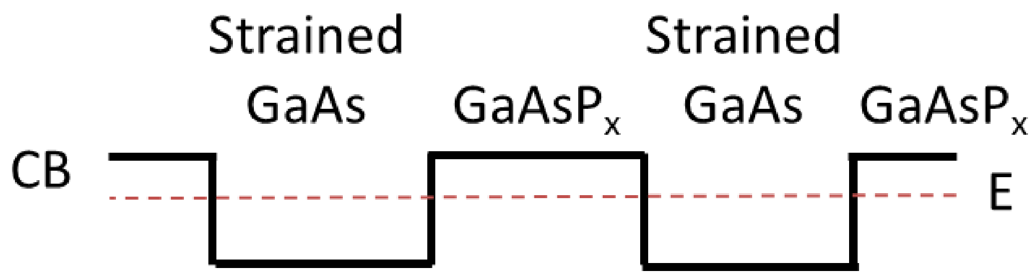
DBR photocathode

Phosphorus content influences the refractive index of each layer, and therefore the **optical path length** which is the key design consideration for this type of photocathode

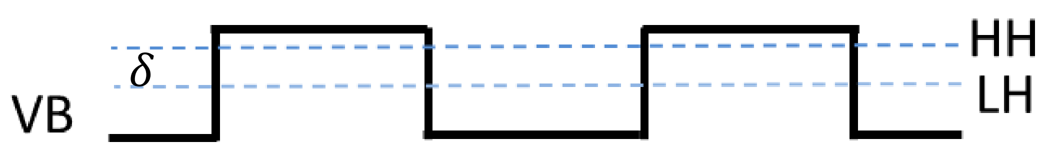
Energy level of strained GaAs/GaAsP superlattice

Heavy hole-Light hole splitting: $\delta \approx 0.24x - 0.02x^2$

High δ → High initial polarization, wide high polarization range



$$x = 0.35, \delta = 81.6\, meV$$



This part of the photocathode design was set in 2004, reported at PESP2004 (part of SPIN2004)

Design of the DBR photocathode

To get high reflectivity for DBR:

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

To get high absorption for photocathode:

$$2\sum_i n_i d_i = m\lambda_R \ \ (m: integer)$$

Precise control the optical path length of each layer!!!

Calculation for absorption of photocathode

Transfer matrix method:

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

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

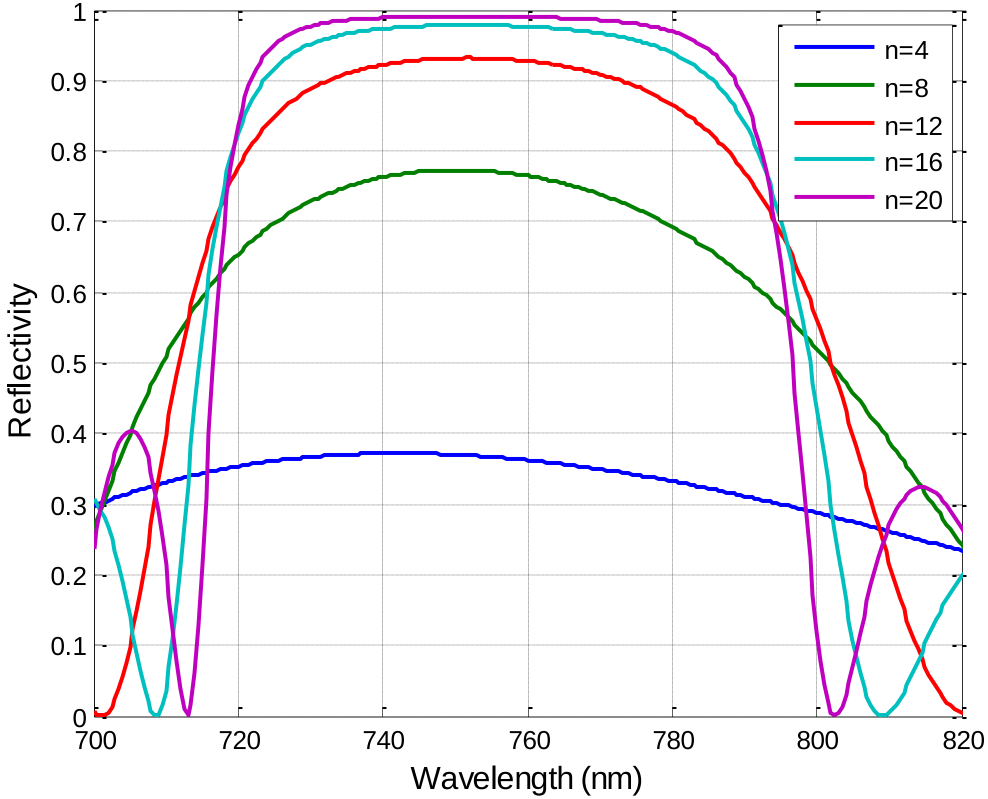
Reflectivity, Transmission and absorption:

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

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

$$A = 1 - R - T$$

Surface reflection of GaAsP/AlAsP DBR

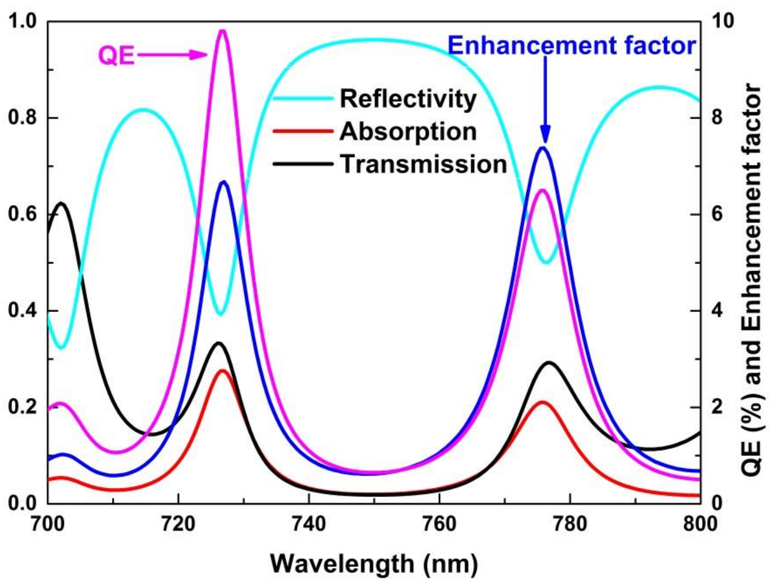


Surface reflection of DBR at different numbers of pair layers(n)

More pair layers, higher reflection.

For 12 pair layers: highest reflection is 93.2%

Calculation results for DBR photocathode



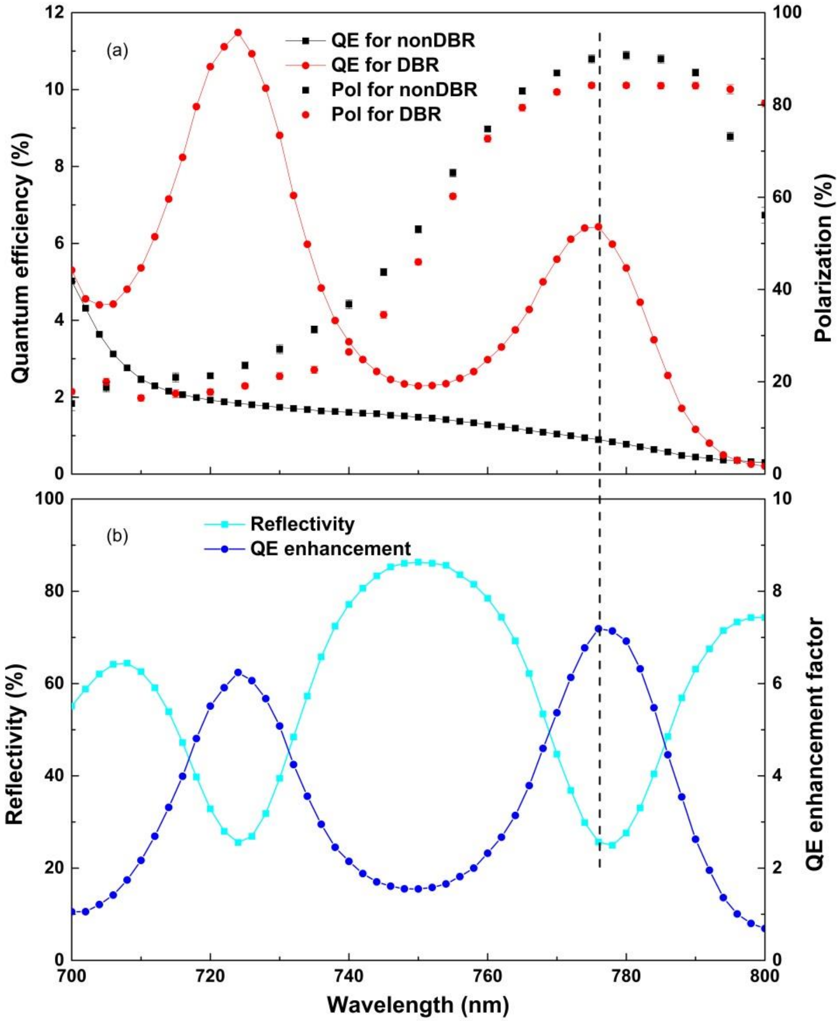
Calculated absorption, reflectivity and transmittance of the DBR photocathode, QE for the DBR photocathode, the absorption and QE enhancement factors compared to the photocathode without the DBR.

At 776 nm:

- Absorption: 21.03%
- QE: 6.4%
- Enhancement: 7.4

$$QE(\lambda) = \frac{P_L F_L A}{1+\frac{1}{\alpha_\lambda L_L}} + \frac{P_\Gamma \exp[k(-\frac{1}{1.42}-\frac{\lambda}{1240})]A}{1+\frac{1}{\alpha_\lambda L_\Gamma}}[F_\Gamma + \frac{F_L L_\Gamma}{\alpha_\lambda F_L (L_\Gamma + L_L)(1+\frac{1}{\alpha_\lambda L_L})}]$$

Experiment results



At 776 nm:

- For non-DBR: QE - 0.89% and Polarization - 92%
- For DBR: QE - 6.4% and Polarization - 84%
- QE Enhancement: 7.2, very close to predicted

(a) The QE and polarization for the strained GaAs/GaAsP superlattice photocathodes with and without DBR as a function of the wavelength; (b) Reflectivity and QE enhancement factor of photocathode with DBR as a function of the wavelength.

Figure of merit of polarized electron sources

Cathode	Ref.	P(%)	QE (%)	Figures of Merit (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

- The good result comes from precise control of many layers - the biggest challenge!
- Accurate modeling is necessary and very helpful.

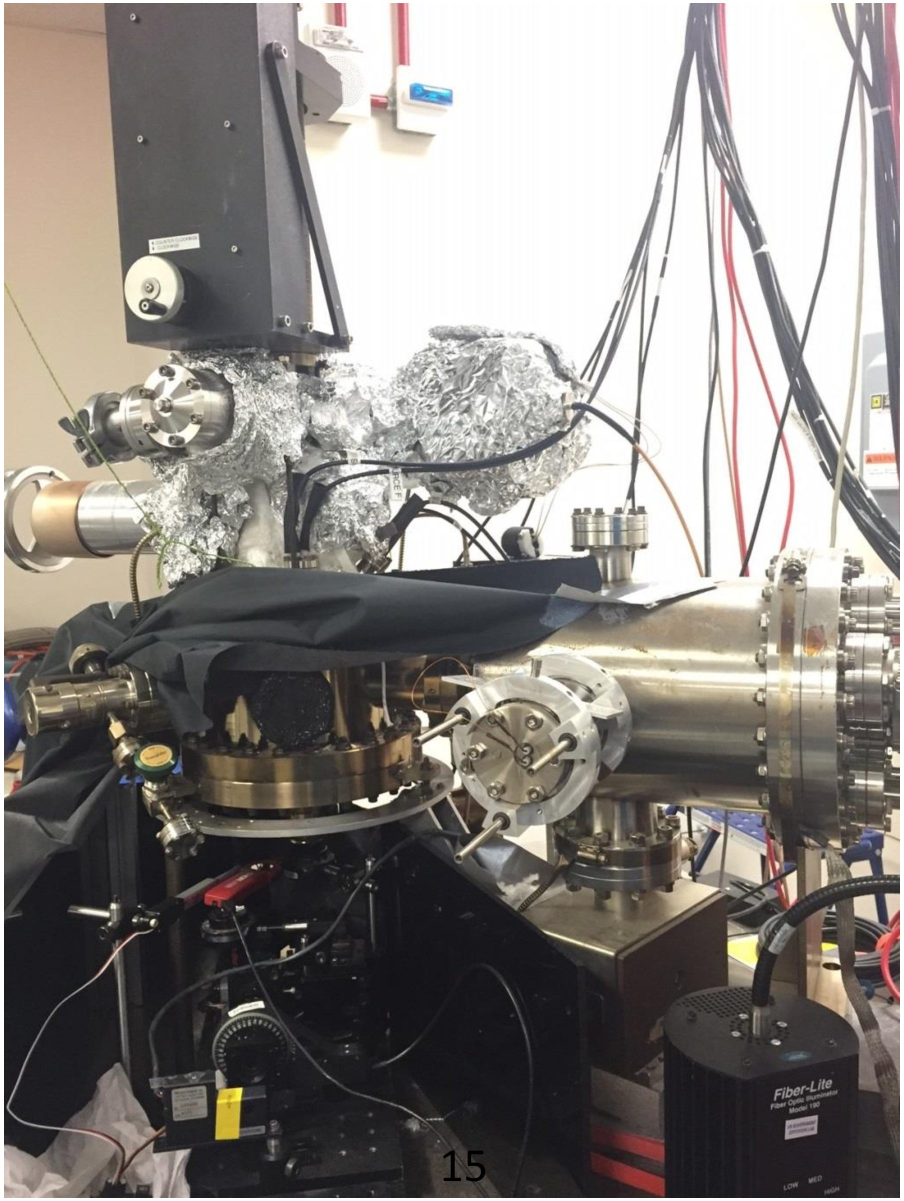
Conclusions

- Strained GaAs/GaAsP superlattice photocathodes with DBR show dramatic QE enhancement of 7x, polarization over 84%.
- Further work to tune the wavelength and increase the value of QE peak is going on. Expect higher values at SPIN2018!
- DBR photocathodes will be used to produce high current polarized electron beams soon in CEBAF

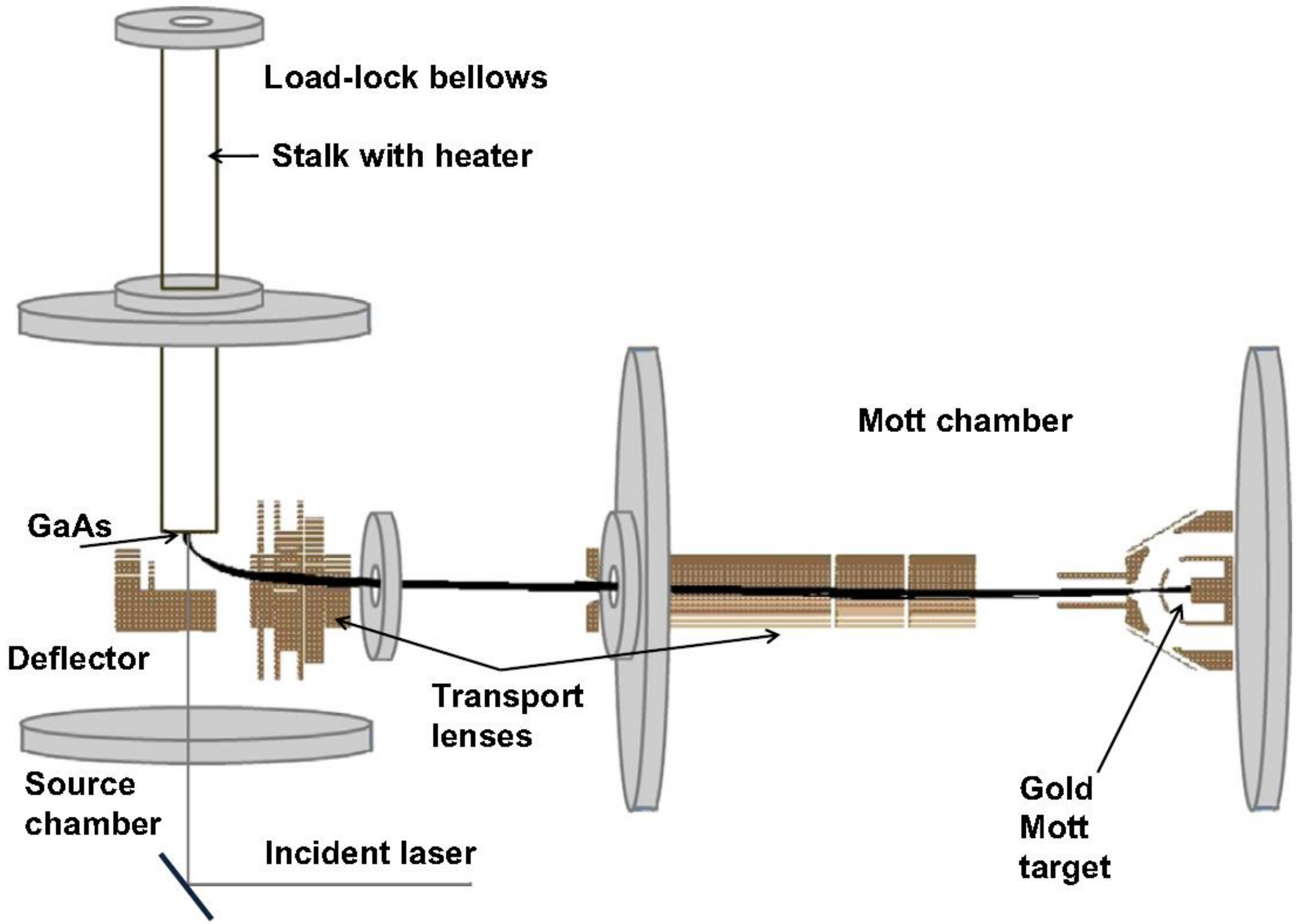
Thanks for your attention

1 2 3 Jefferson Lab EXPLORING THE NATURE OF MATTER 4 SVT Associates, Inc.

apparatus



Schematic of the experiment apparatus



Results shown in IPAC 2015