Development of high brightness high repetition rate electron injectors at Daresbury Laboratory

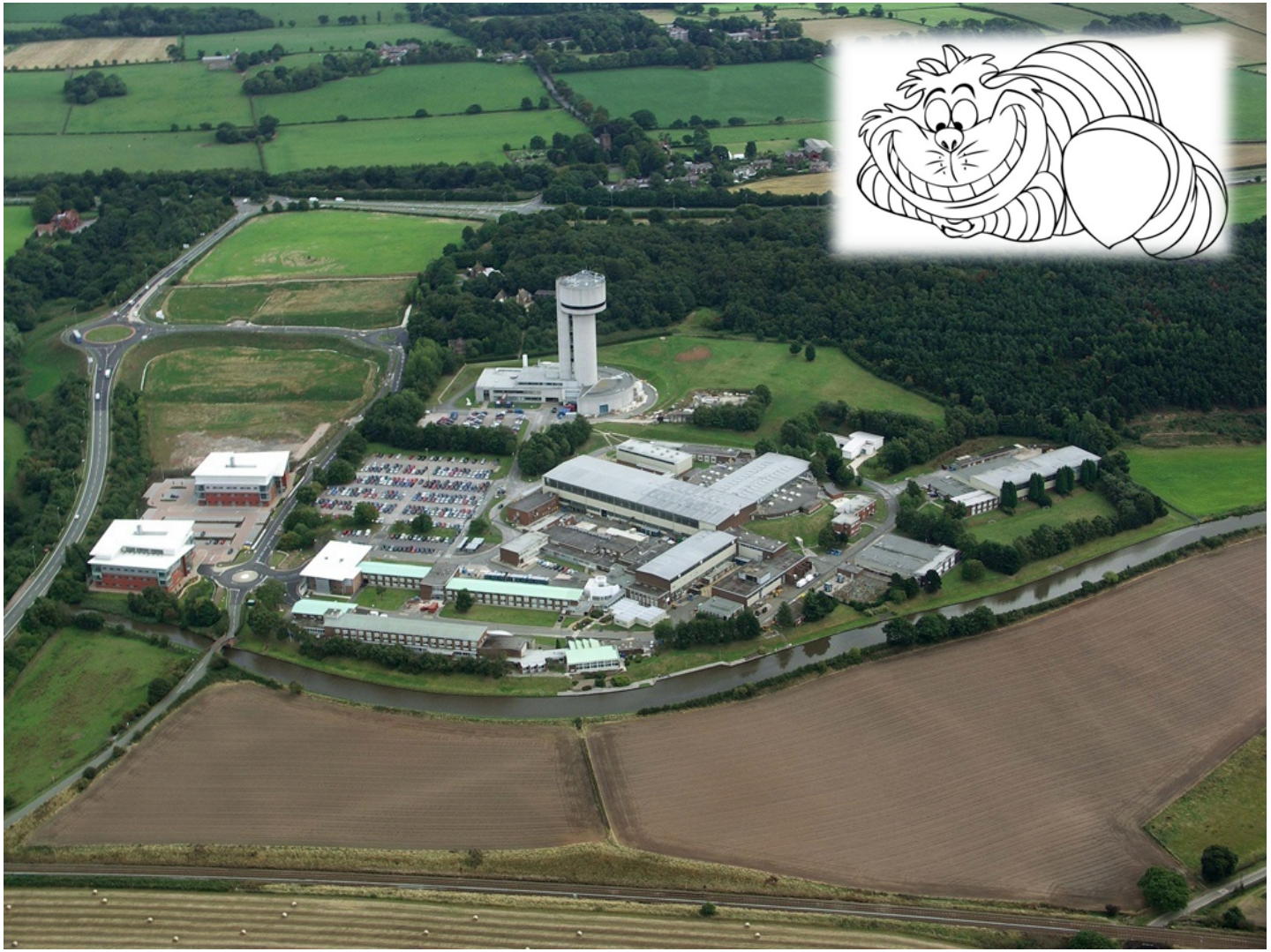
Boris Militsyn
ASTeC
STFC Daresbury Laboratory

Outline

- Daresbury laboratory
- (Photo)-injector activity at Daresbury Laboratory
  - Development of (photo)-injector for oncoming accelerator projects
  - Physics of the photoemission and photoemitters
  - Operation and upgrade existing installation
- Requirements to the modern electron injectors
- Ultimate achievable brightness of (photo)cathodes
  - Thermionic injectors
  - Photoinjectors
- High repetition rate high brightness photoinjector for the British Next Light Source (NLS)
- Daresbury Energy Recovery Linac
- Photoinjector of the ERL – operation and upgrade
- Conclusion

Daresbury Laboratory. Where we are?

Daresbury Laboratory, Daresbury, Cheshire, UK



Ultimate challenges to the modern electron injectors

Beam Parameter	**ERL (DL, Cornell, Berlin)**	**X-FELs (X-FEL,NLS)**	**Compact X-FELs (5GLS)**
Beam energy, *MeV*	1-10	1-10	1-10
Maximum bunch charge, *nC*	0.1	0.1-1	0.01-0.1
Bunch transverse emittance, *mm·mrad*	1.0	0.5-1	0.1-0.5
Maximum bunch repetition rate, *MHz*	1300	1	0.001
Average current, mA	100	1	0.001
Peak current of injector, *kA*	-	0.1	1
Bunch duration, *ps*	20	20	0.1-1

Electron emission

Ultimate emittance of the delivered beam

$$\varepsilon_{n,rms} = \sqrt{\overline{x^2}\,\overline{x'^2} - \overline{x \cdot x'}^2} = \sigma_\perp \sqrt{\frac{2E_i}{3mc^2}}$$

$$\sigma_\perp = \frac{1}{2}\sqrt{\frac{q}{\pi \varepsilon_0 E_c}}$$

$$E_i = 1 \quad eV$$

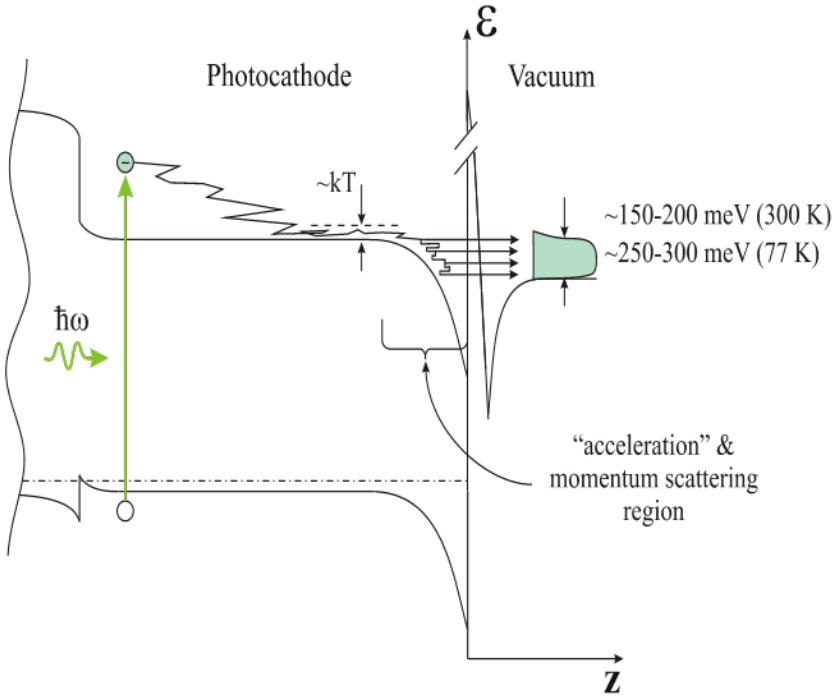
Field strengh	Technology	0.01 nC	0.1 nC	1.0 nC
10 MV/m	DC gun	0.11	0.34	1.08
20 MV/m	VHF gun	0.08	0.24	0.77
50 MV/m	L-band gun	0.05	0.15	0.48
100 MV/m	S-band gun	0.03	0.11	0.34

Photoemitters. GaAs family.

- Technology of the GaAs family photocathodes is well established and known in both academic and industrial communities
- Quantum yield of the photocathodes, defined as a ratio of the number of incident photons to the number of emitted electrons, is very high. Maximum reported value is 50%
- Technology of preparation is challenging and requires extreme high vacuum conditions
- This demands activation of the photocathodes directly in the gun on in a vacuum system adjacent to the gun
- Photocathode degradation modes in vacuum is not well understood and should be investigated

Photoemitters. GaAs family photocathodes.

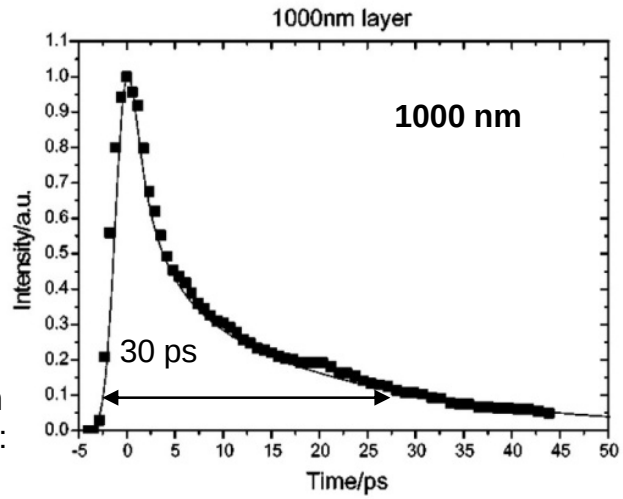
GaAs photocathodes on Mo substrate designed for the 4GLS project

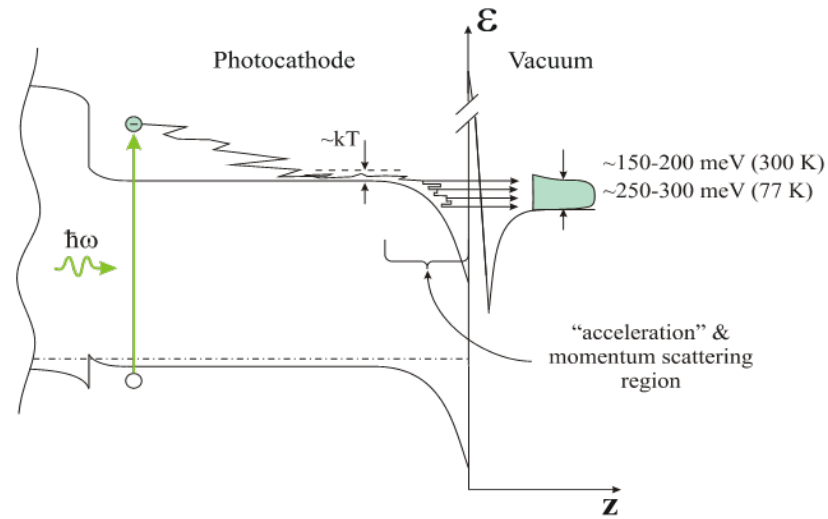


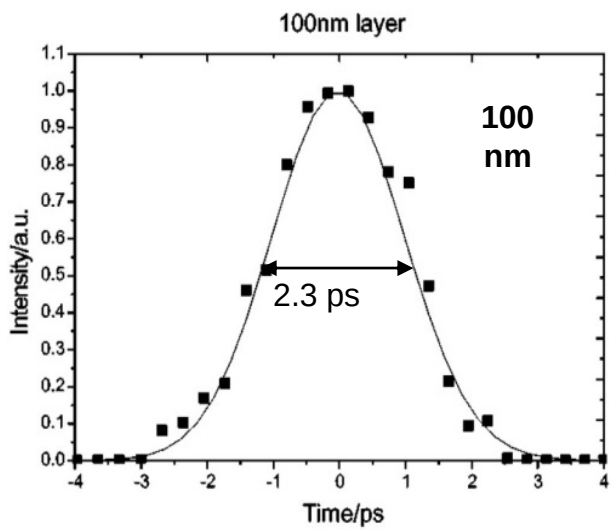
Photoemission from a GaAs photocathode activated to NEA state

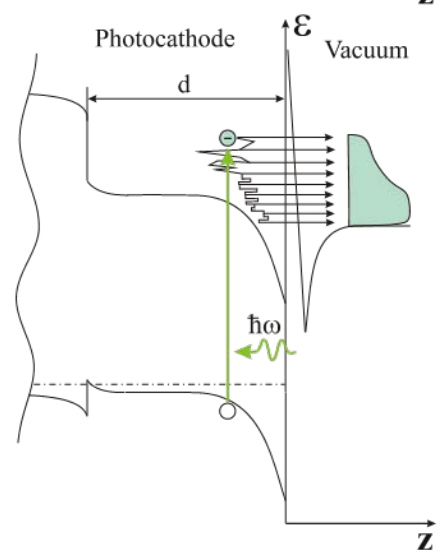
GaAs photocathodes. Response time

Experimental data from The University of Mainz: experiment, fitted with diffusion model

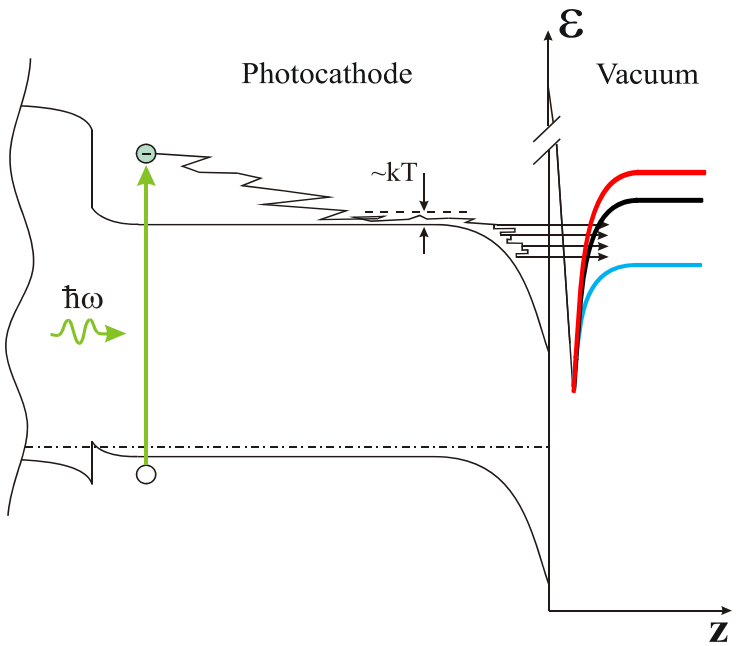








GaAs photocathodes. Intrinsic energy. Phenomenology.



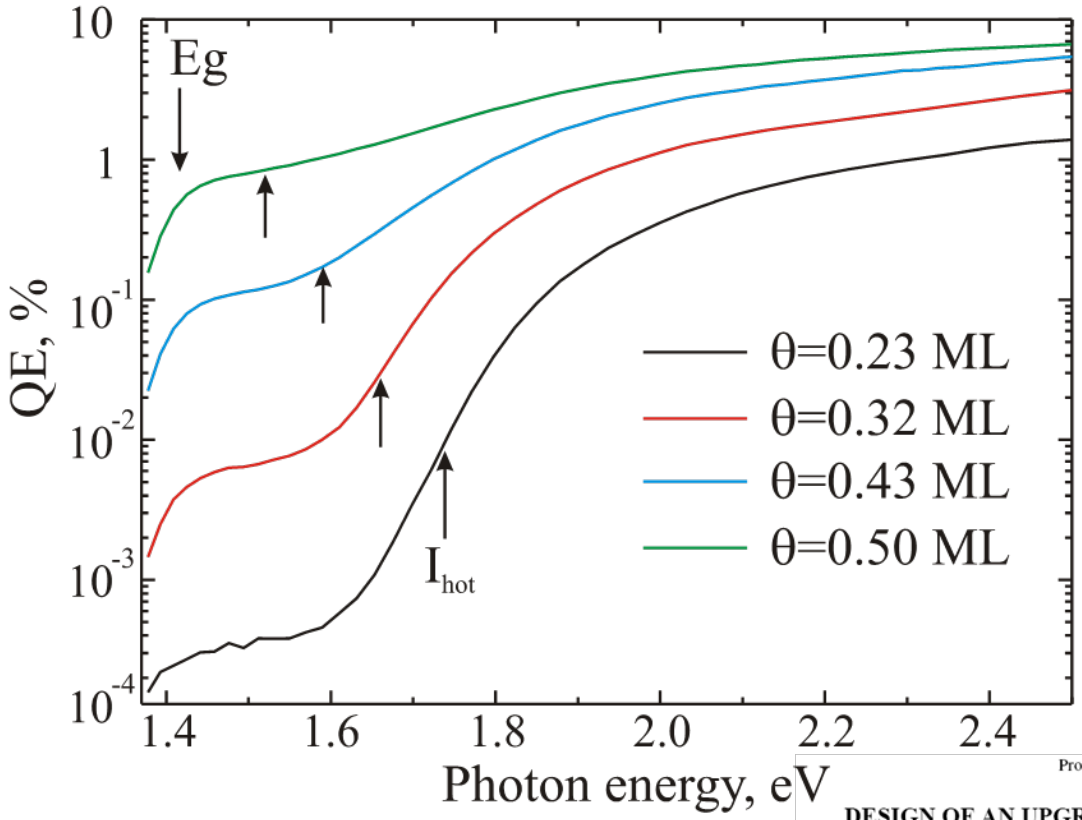
	DC	*Pulsed*
$\chi > kT$	$E_i = kT$	$E_i = h\nu - E_g - \chi$
$\chi < 0$	$E_i = kT - \chi$	$E_i = h\nu - E_g - \chi$

Varying electron affinity one can vary effective temperature of the emitted electrons.

Qe is the price for that!

GaAs photocathodes. Qe and electron affinity

Q.E. spectra and energy of emitted electrons spectra of GaAs photocathode activated to Positive Electron Affinity state.



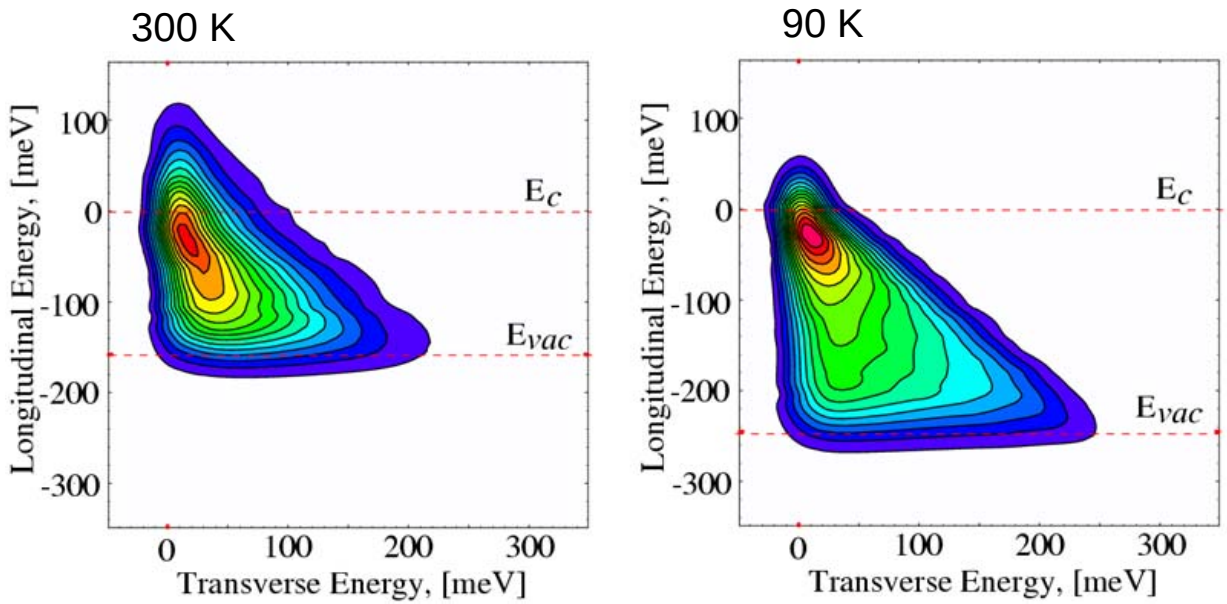
Proceedings of EPAC08, Genoa, Italy MOPC073

DESIGN OF AN UPGRADE TO THE ALICE PHOTOCATHODE ELECTRON GUN

B.L. Militsyn*, I. Burrows, R.J. Cash, B.D. Fell, L.B. Jones, J.W. McKenzie, K.J. Middleman, STFC Daresbury Laboratory, Warrington, WA4 4AD, UK
S.N. Kosolobov, H.E. Scheibler, A.S. Terekhov, ISP, Novosibirsk, 630090, Russian Federation

Intrinsic energy of NEA GaAs samples. Experiments

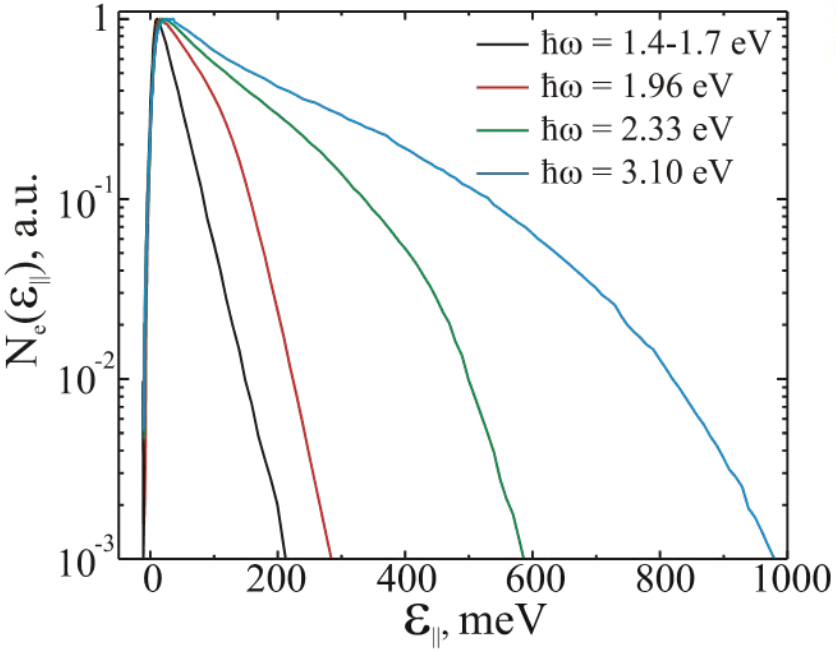
2D energy distributions of emitted photoelectrons



$$E_{\parallel} + E_{\perp} = E_i = \chi$$

D. A. Orlov et al., Appl. Phys. Lett. 78 (2001) 2721

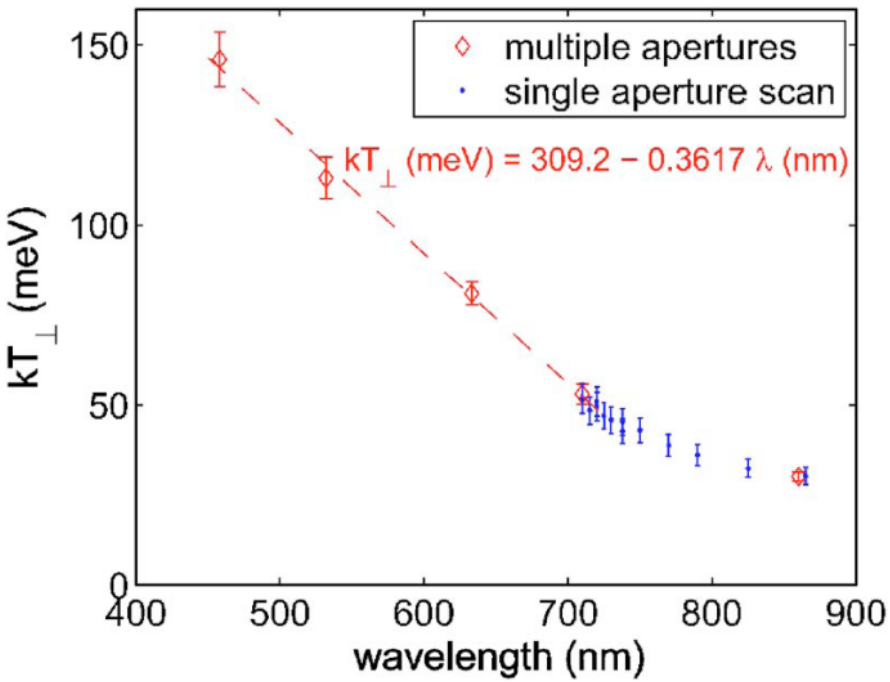
Intrinsic energy of GaAs. Experiment



JOURNAL OF APPLIED PHYSICS **103**, 054901 (2008)

Thermal emittance and response time measurements of negative electron affinity photocathodes

Ivan V. Bazarov,[1,a)] Bruce M. Dunham,[1] Yulin Li,[1] Xianghong Liu,[1] Dimitre G. Ouzounov,[1] Charles K. Sinclair,[1] Fay Hannon,[2] and Tsukasa Miyajima[3]
[1]*Laboratory of Elementary Particle Physics, Cornell University, Ithaca, New York 14853, USA*
[2]*Lancaster University, Lancaster, United Kingdom*
[3]*Photon Factory, KEK, Tsukuba, Japan*



Proceedings of EPAC08, Genoa, Italy MOPC073

DESIGN OF AN UPGRADE TO THE ALICE PHOTOCATHODE ELECTRON GUN

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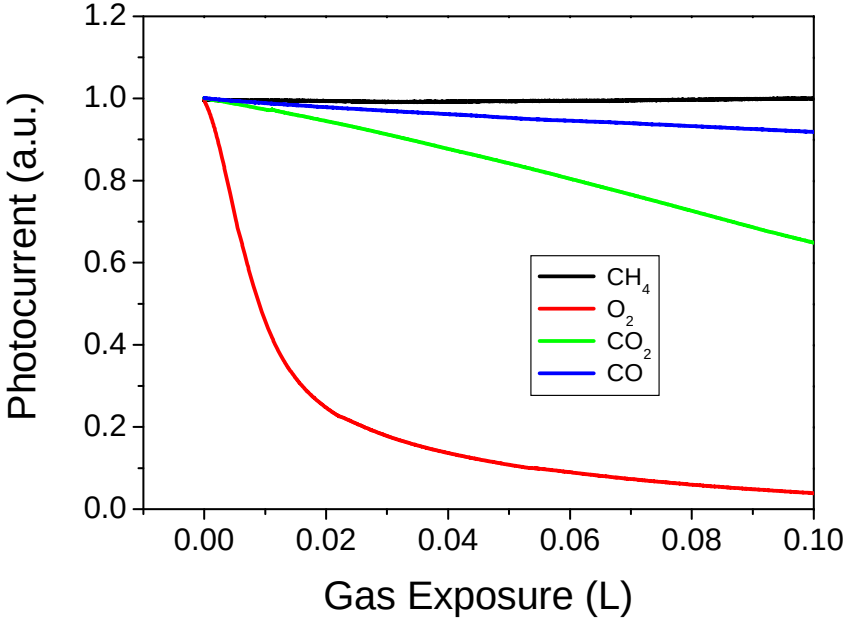
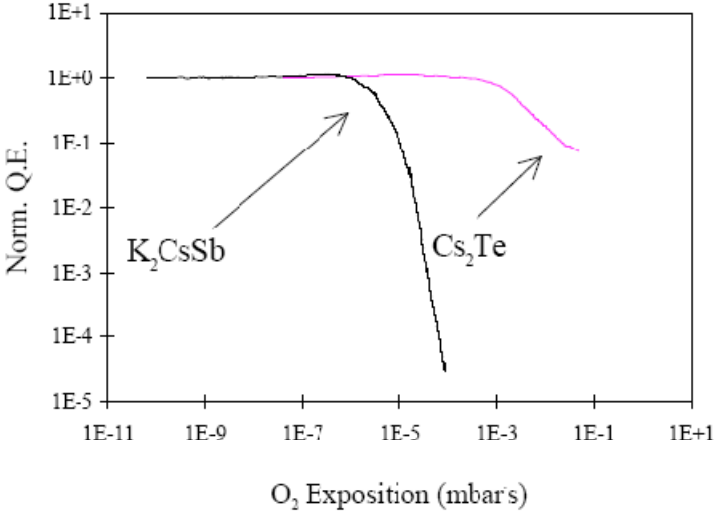
GaAs photocathodes. Life time

GaAs dark lifetime



K.J. Middleman et al., PESP2010

"...is GaAs the only photocathode we can use in DC photocathode guns?"



R & D ACTIVITY ON HIGH QE ALKALI PHOTOCATHODES FOR RF GUNS

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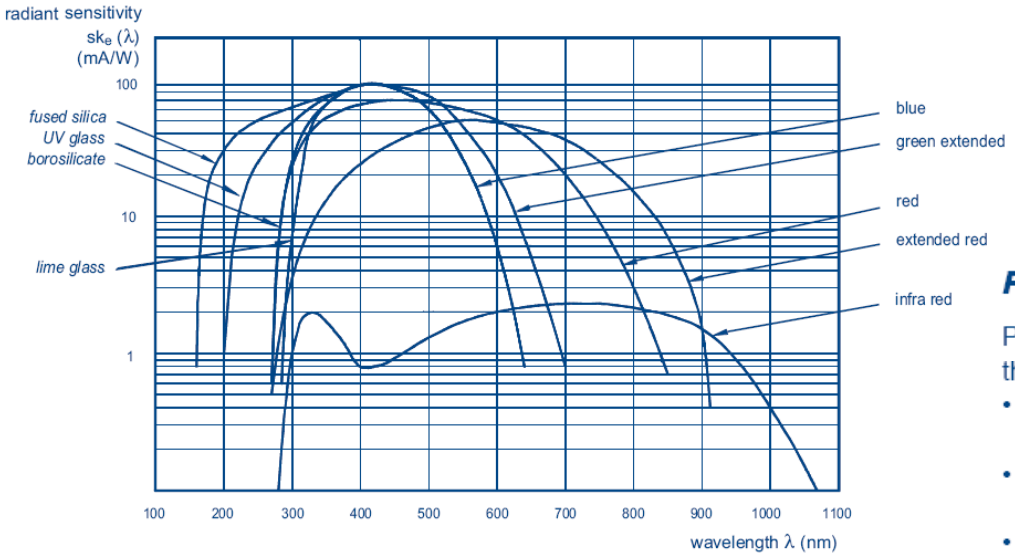
+INFN Milano - LASA, Via F.lli Cervi 201, 20090 Segrate (Milano), Italy.
#Dipatimento di Fisica and INFM, Via Campi 213/A, 41100 Modena, Italy.

Proceedings of PAC'1995

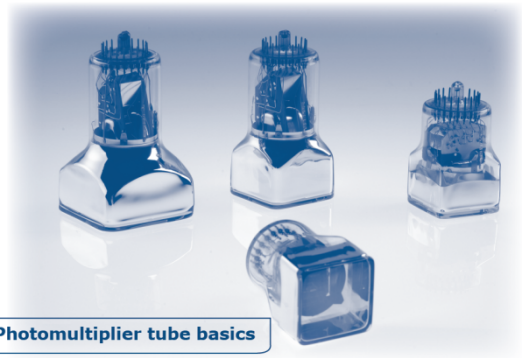
Alkali photocathodes.

- Technology of the alkali photocathodes is concentrated in industrial communities and only few academic groups are involved in the business
- Technology of preparation is very difficult and for multi-alkali photocathodes requires multi parametric optimisation
- Quantum yield of the photocathodes varies from moderate (1%) to high (10% and more)
- Alkali (telluride) photocathodes are robust enough and may be transported from the preparation system to the gun in a dedicated pumped transport vessel
- Modes of the photocathode degradation in vacuum is not well understood and should be seriously investigated
- Spectrum of the emitted electrons is not well investigated. Serious efforts in this field are required

Photoemitters. (Multi)alkali photocathodes



PHOTONIS

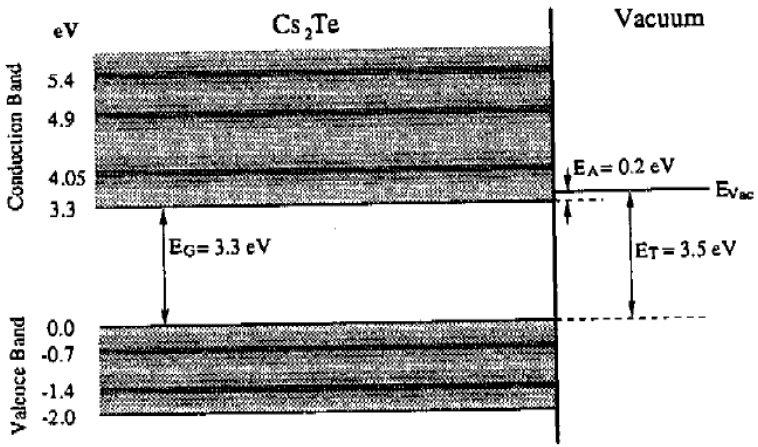


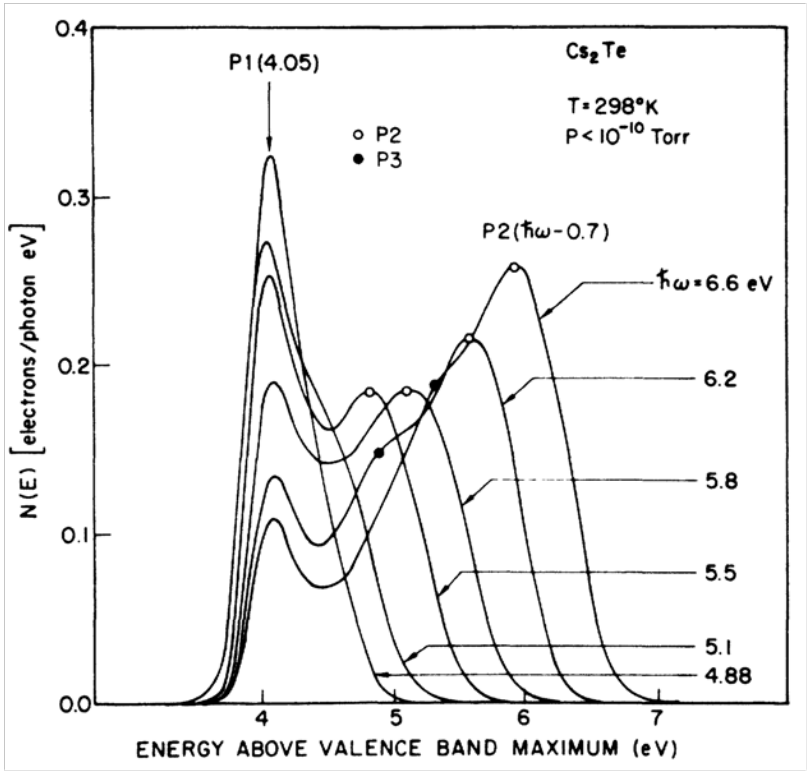
Photocathode material

PMT photocathodes are usually made of alkali antimonides, the most common being:

- **bialkali** (SbKCs): used to match light sources in the blue region of the visible spectrum,
- **green-extended bialkali** (GEBA): more sensitive than standard bialkali in the green region,
- **high-temperature bialkali** ($SbNa_2K$): less sensitive than the other bialkali cathodes; for prolonged use at temperatures above 60°C,
- **multialkali** ($SbNa_2KCs$): more sensitive than the bialkali types in the range 600 to 850 nm, but with correspondingly higher noise,
- **extended-red multialkali** (ERMA): a thicker multialkali cathode whose spectral response extends to 900 nm,
- **GaAs**, near infrared sensitive
- **RbCsSb**.

Alkali photocathodes. Caesium-Telluride.





$$\varepsilon_{n\,rms} = \frac{r}{2}\cdot\sqrt{\frac{2E_{kin}}{m_0c^2}}\cdot\frac{1}{\sqrt{3}}\cdot\sqrt{\frac{2+\cos^3\varphi_{max}-3\cos\varphi_{max}}{2\cdot(1-\cos\varphi_{max})}}$$

$$\varphi_{max} = \arccos\sqrt{\frac{E_A}{E_{kin}}}$$

Note on the thermal emittance of electrons emitted by Cesium Telluride photo cathodes

Klaus Flöttmann
DESY, Notkestr. 85, 22603 Hamburg, Germany

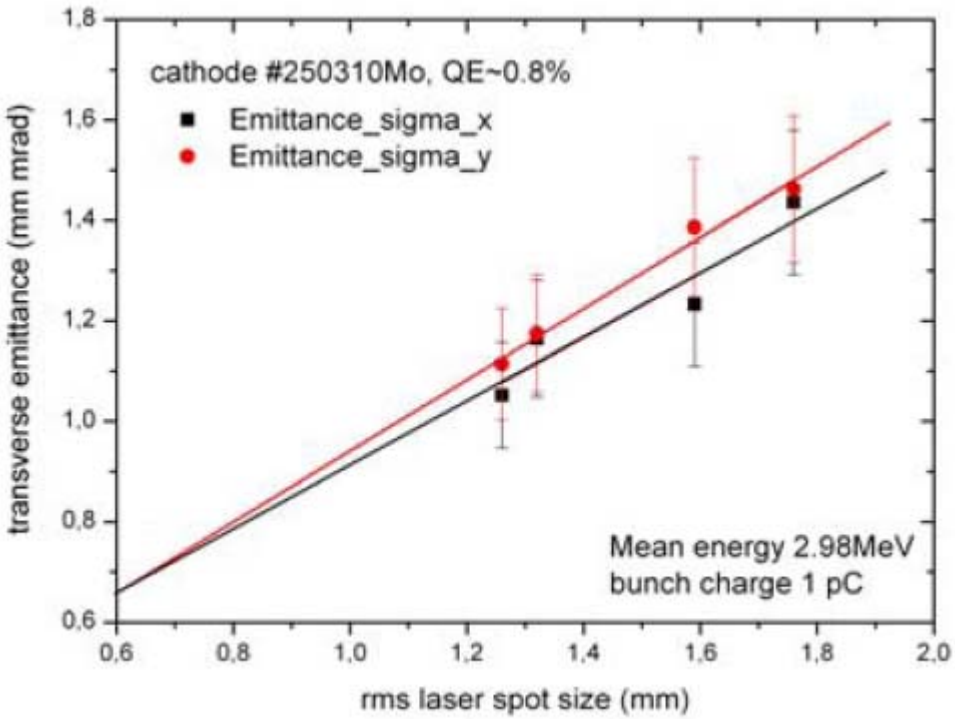
Feb. 1997, TESLA-FEL 97-01

PHYSICAL REVIEW B VOLUME 8, NUMBER 8 15 OCTOBER 1973

Photoemission Studies of Cesium Telluride*

R. A. Powell, W. E. Spicer, G. B. Fisher†, and P. Gregory
Stanford Electronics Laboratories, Stanford University, Stanford, California 94305
(Received 8 January 1973)

Alkali photocathodes. Evolution of the Cs_2Te vacuum level.



Jochen Teichert, FEL2010

For cathode #250310Mo in Fig. 4b, the slope of $\varepsilon_{rms,x}$ is 0.64 mrad, that of $\varepsilon_{rms,y}$ is 0.71 mrad. The average kinetic energy E_{kin} was 0.35±0.04eV; the electron affinity is E_A=0.40±0.04 eV, about 0.2eV higher than that of the fresh cathode.

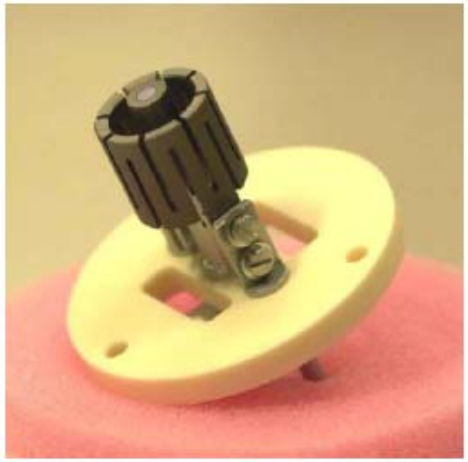
THERMAL EMITTANCE MEASUREMENT OF THE CS_2TE PHOTOCATHODE IN FZD SUPERCONDUCTING RF GUN *

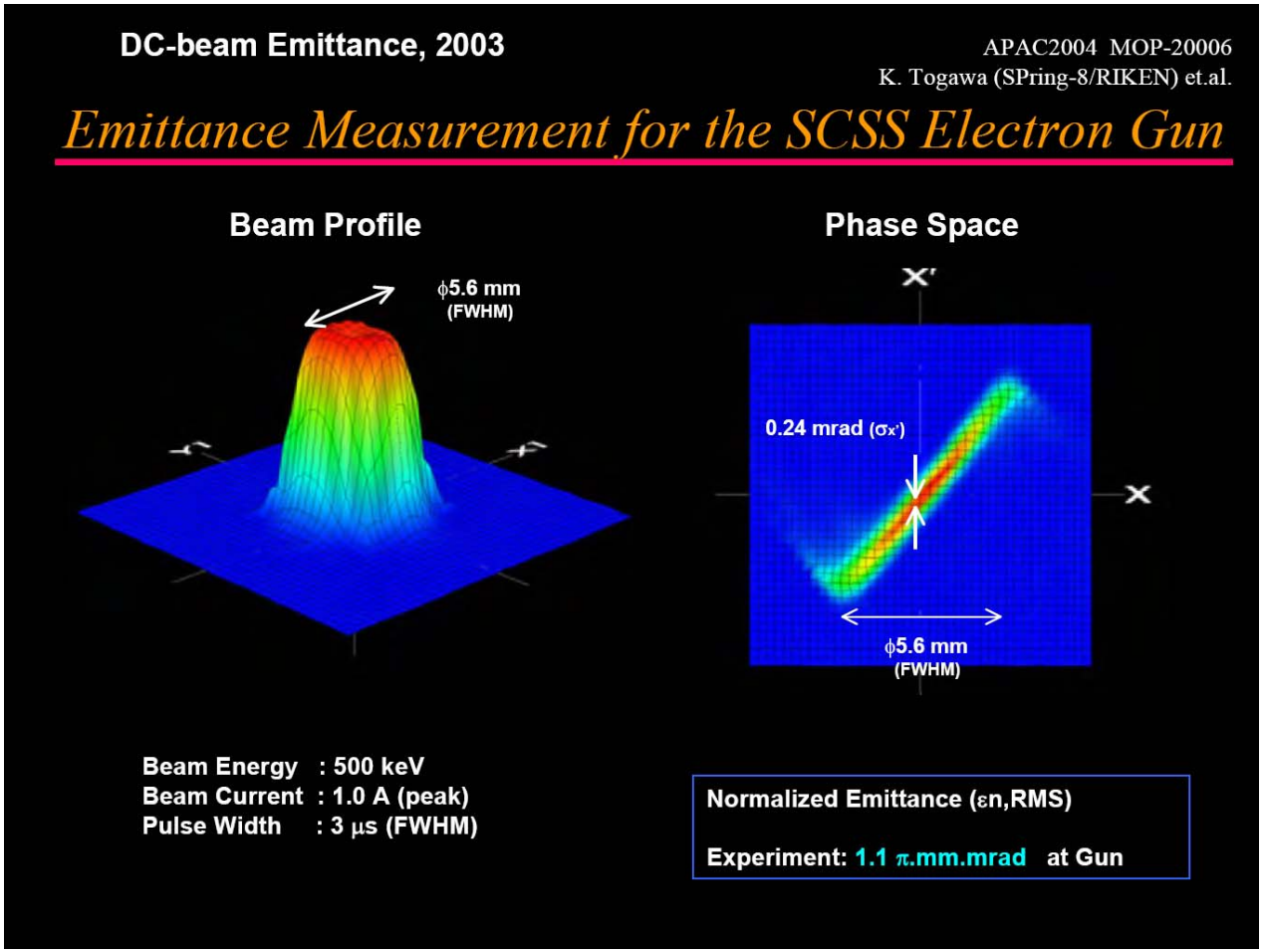
R. Xiang#, A. Arnold, P. Michel, P. Murcek, J. Teichert.

Research Center of Dresden-Rossendorf (FZD), 01328 Dresden, Germany.

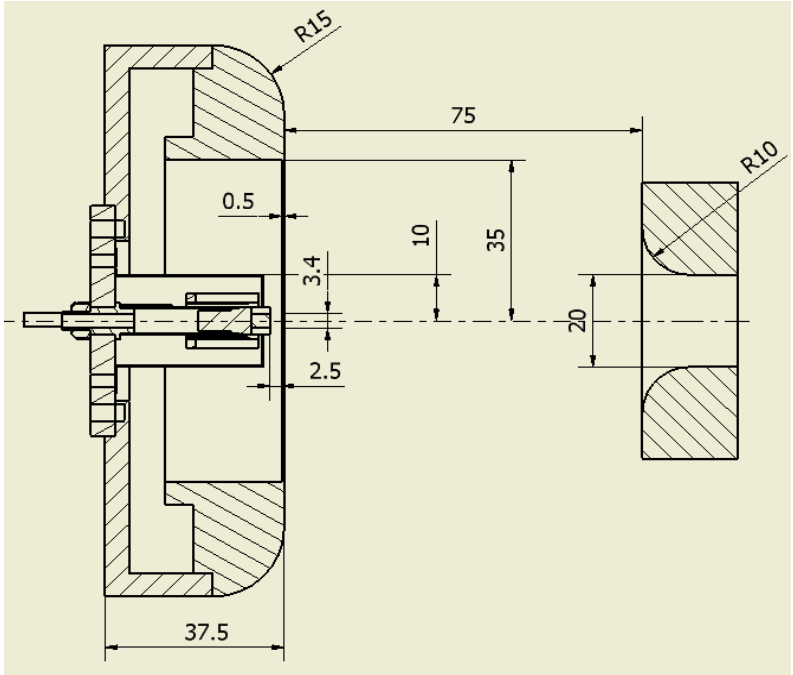
Thermionic emitters

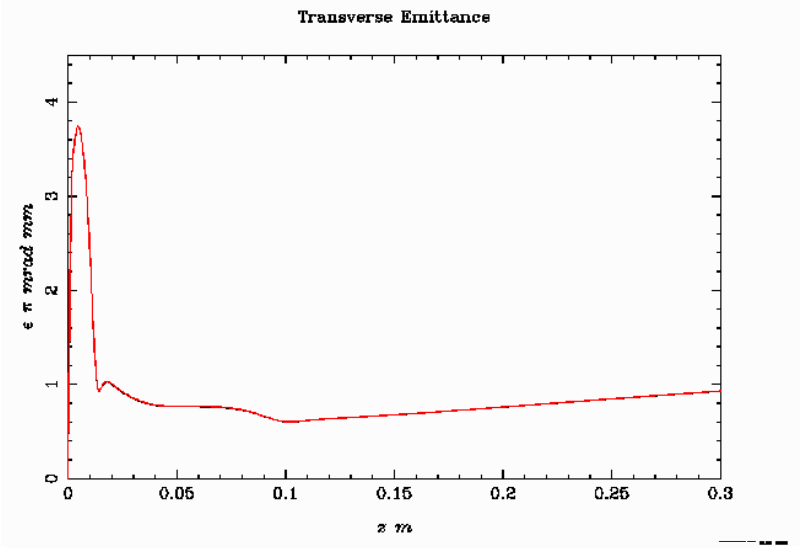
High voltage modulated single crystal CeB_6 emitter

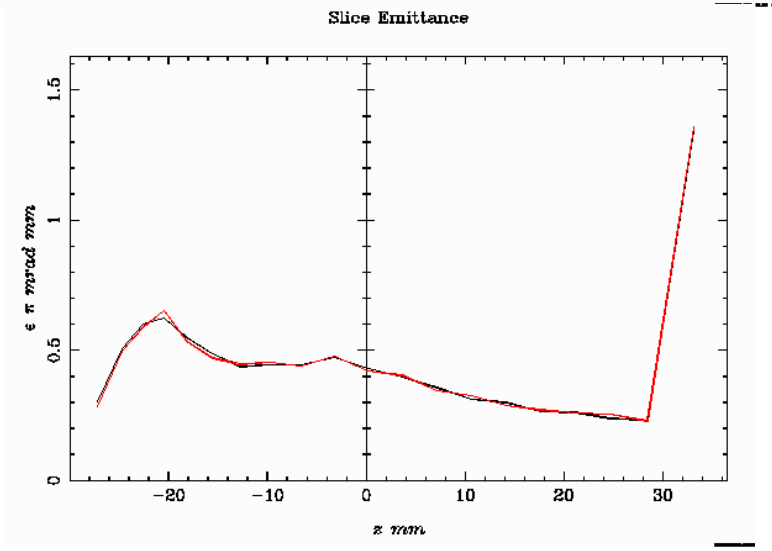




Gated thermionic gun. Preliminary results





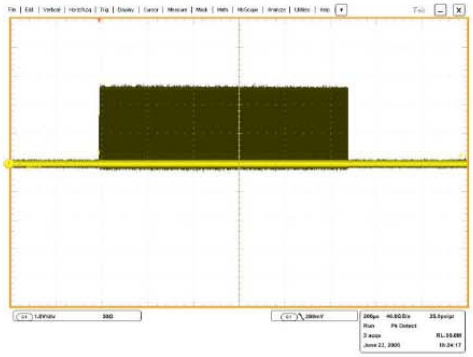


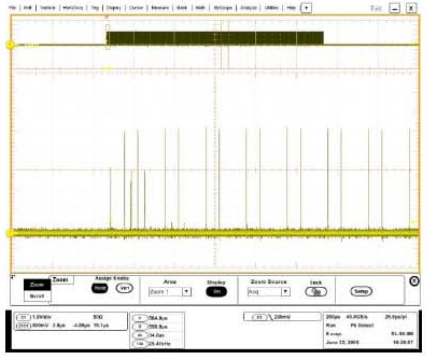
by the courtesy of Zhiqiang Yu

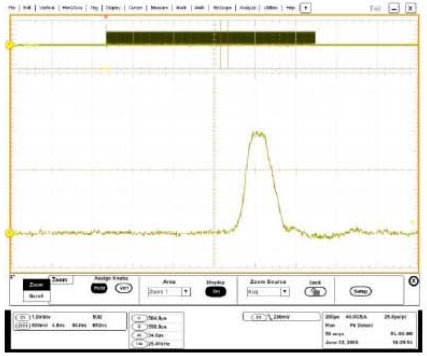
Gated thermionic gun. Gate driver

FID GmbH

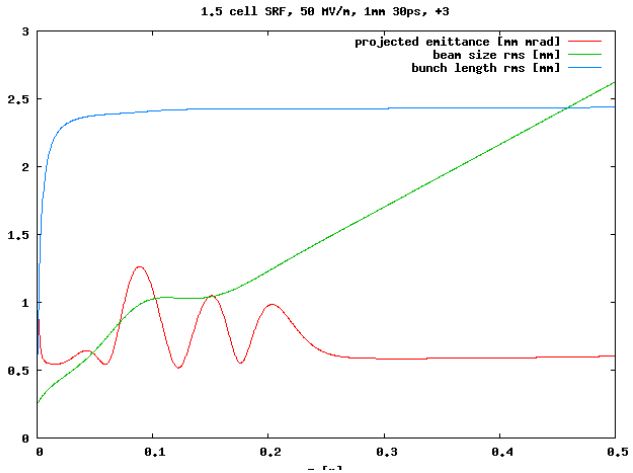
World Priorities of FID Tech – FPG 5-3000M
5 kV, 3 MHz, 2 ns

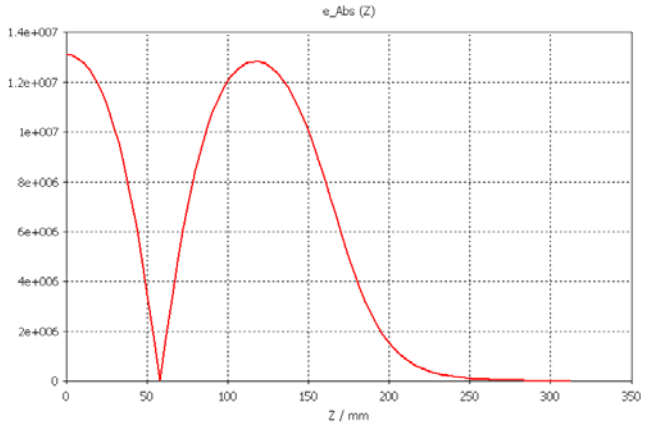






NLS injector. SRF gun concept. 1½ cell L-band



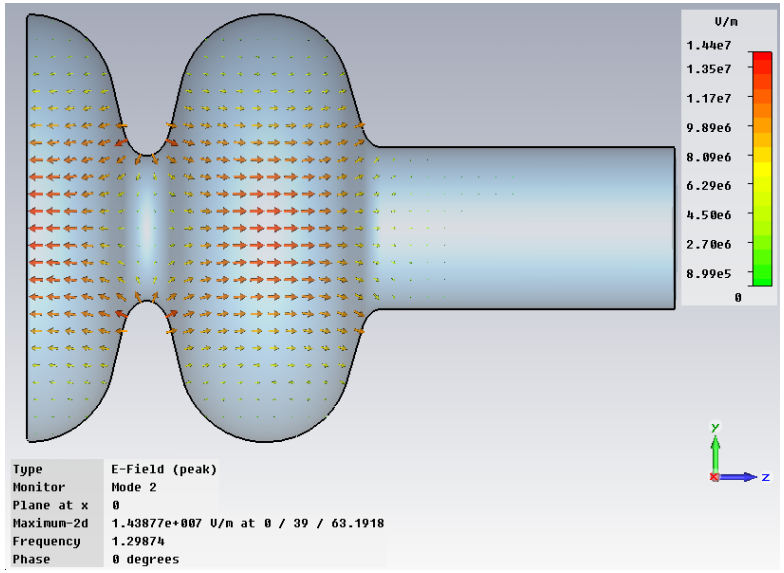


TUPEC016 Proceedings of IPAC'10, Kyoto, Japan

INITIAL DESIGN OF A SUPERCONDUCTING RF PHOTOINJECTOR OPTION FOR THE UK'S NEW LIGHT SOURCE PROJECT

J.W. McKenzie* & B.L. Militsyn, STFC Daresbury Laboratory, ASTeC & Cockcroft Institute, UK

1.5 Tesla cells at 50 MV/m → 4.5 MeV



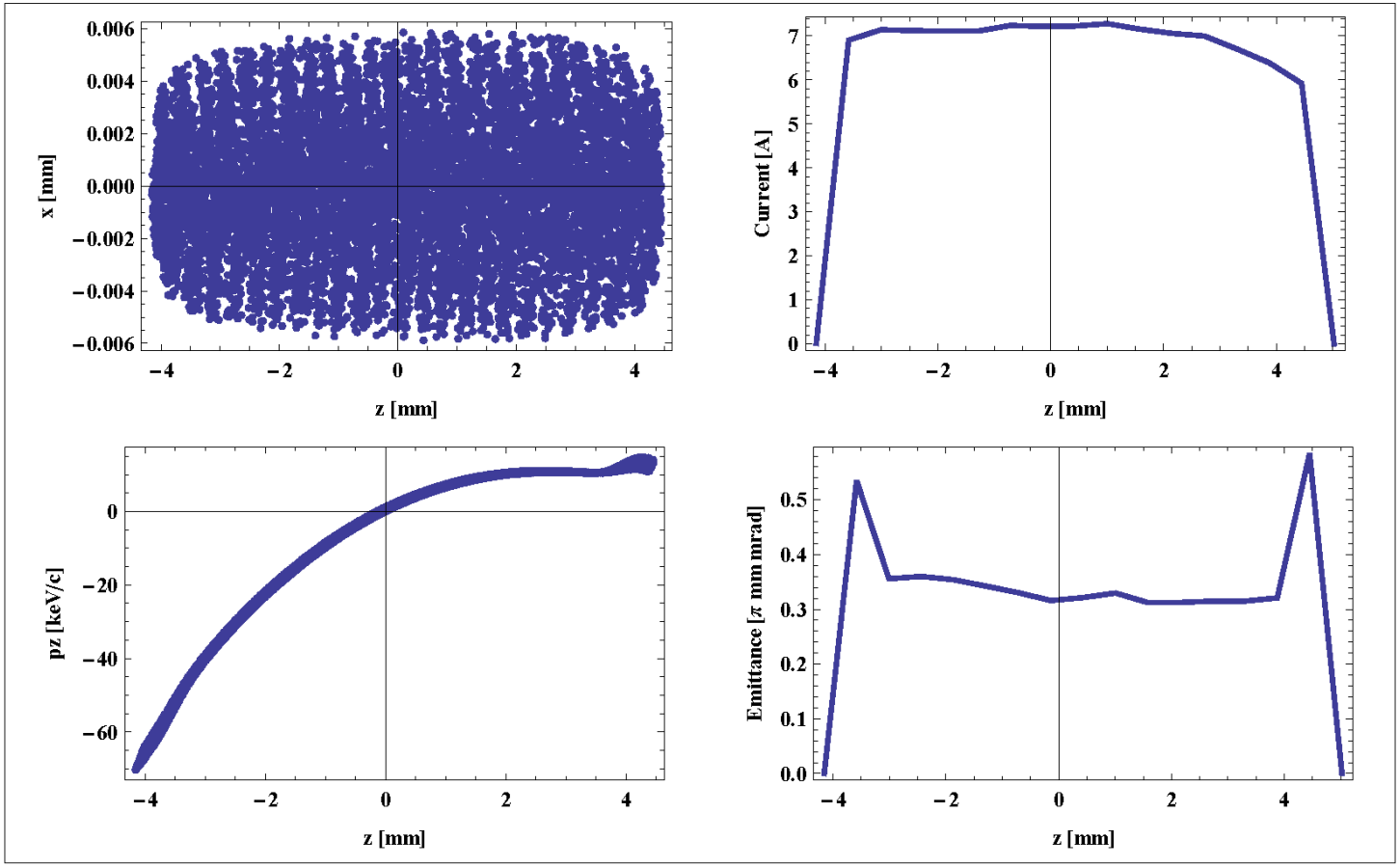
Laser:	
Pulse duration (full width)	30 ps
Spot diameter	1 mm
Gun:	
Launch phase	+3°
Initial thermal energy	0.7 eV (Cs_2Te)
Bunch charge	200 pC

NLS injector. SRF gun concept. Beam parameters

Average slice emit = 0.360332 mm mrad

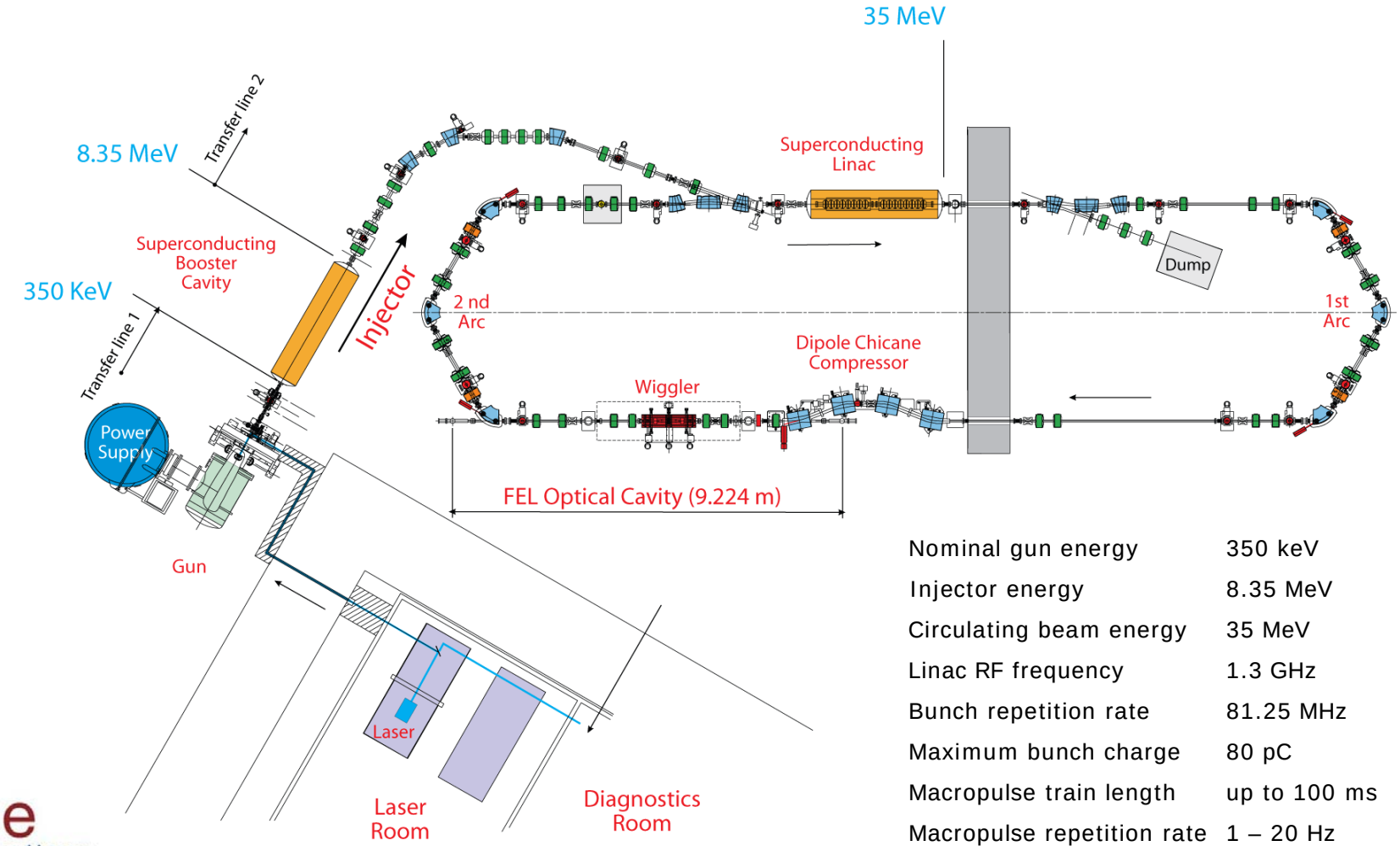
Peak current slice emit = 0.329664 mm mrad

full width = 28.688ps, rms 8.12827ps, FWHM 29.0677ps



Daresbury Energy Recovery Linac

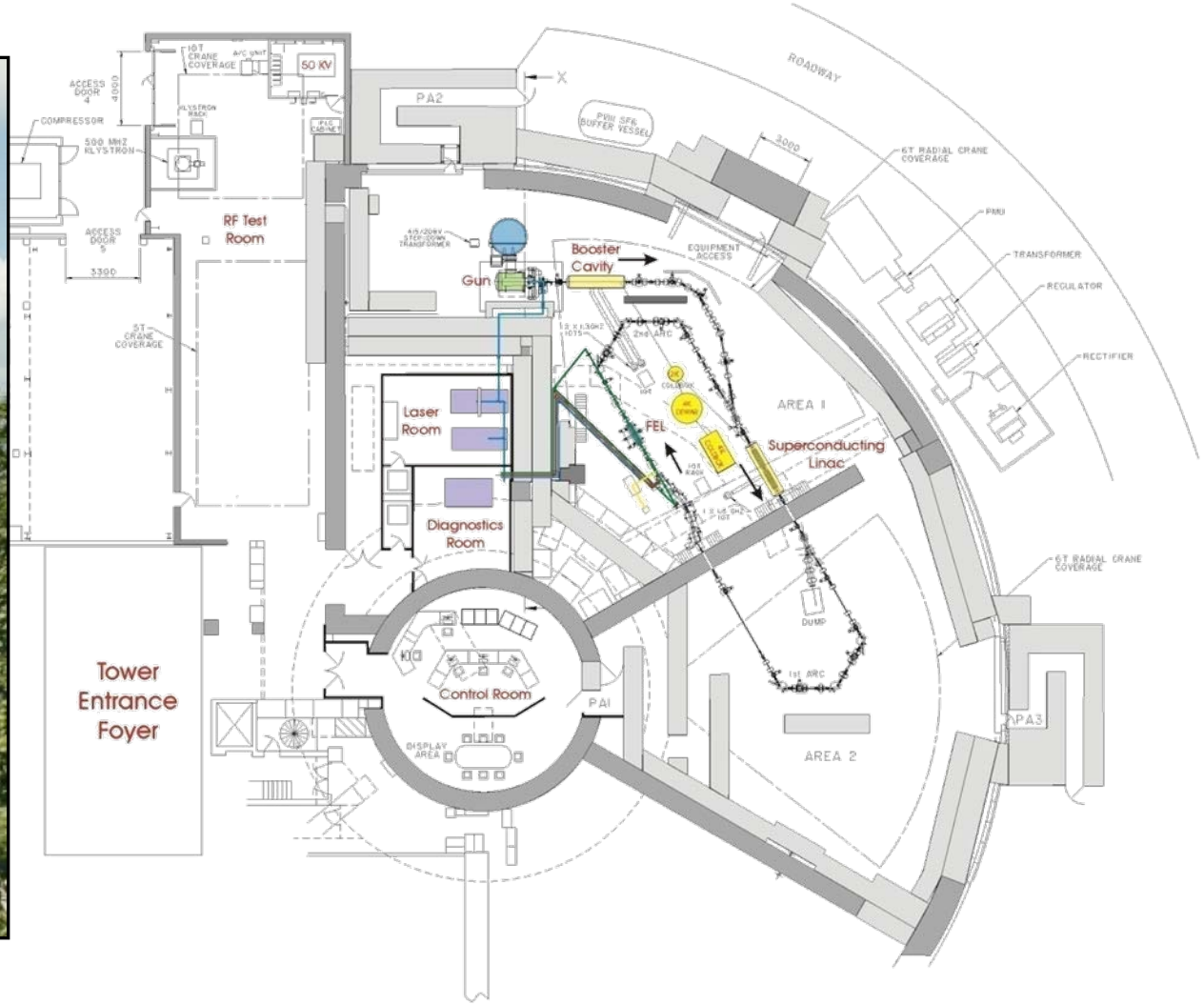
ALICE ERL. General Layout



Nominal gun energy	350 keV
Injector energy	8.35 MeV
Circulating beam energy	35 MeV
Linac RF frequency	1.3 GHz
Bunch repetition rate	81.25 MHz
Maximum bunch charge	80 pC
Macropulse train length	up to 100 ms
Macropulse repetition rate	1 – 20 Hz
Maximum average current	13 μA

Alice
Accelerators and Lasers In Combined Experiments

ALICE ERL. Location



ALICE ERL. Technical priorities

Primary Goals

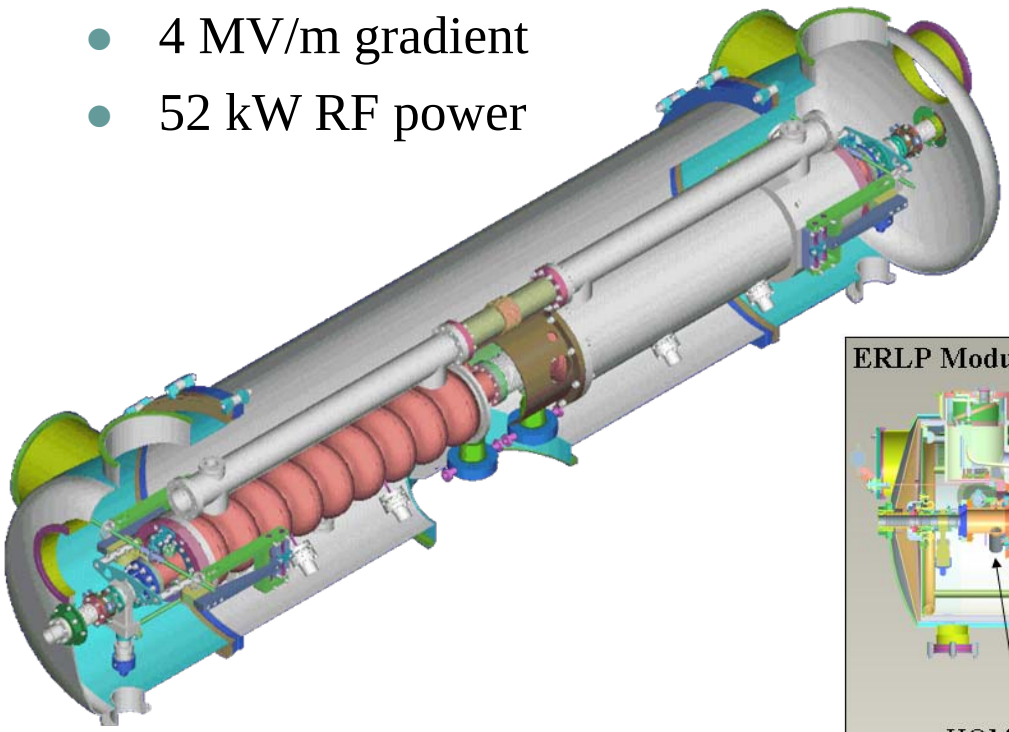
1. Foremost: ***Demonstrate energy recovery***
2. Produce and maintain bright electron bunches from a photoinjector
3. Operate a superconducting linac
4. Produce short electron bunches and drive a Free-Electron Laser (FEL)

Further Development Goals

1. Demonstrate energy recovery during FEL operation (with an insertion device that significantly disrupts the electron beam)
2. Develop a FEL programme suitable to investigate the expected synchronisation challenges and demands of a 4th generation light source
3. Build a photon science activity which capitalises on ALICE's capabilities
4. Produce simultaneous photon pulses from a laser and an ERL photon source which are synchronised at or below the 1 ps level

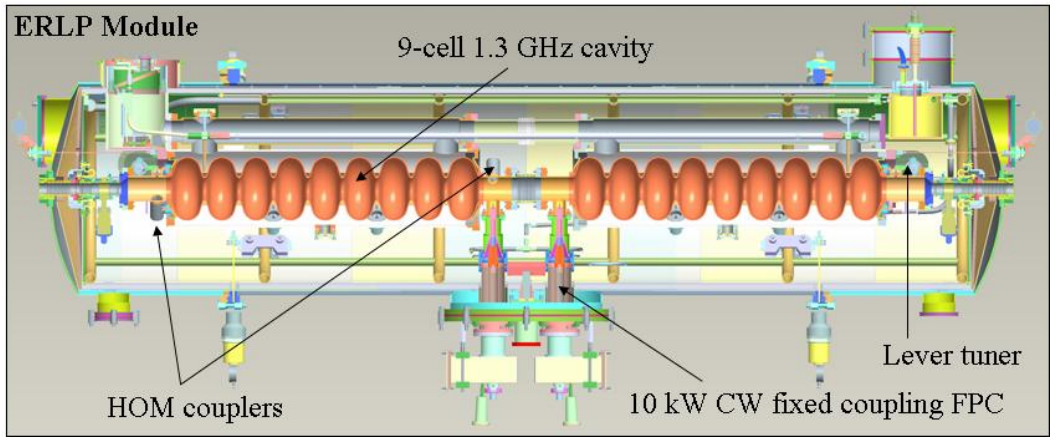
ALICE. SRF Accelerating modules

- 2 × Stanford/Rossendorf cryomodules, one configured as the ***Booster*** and the other as the ***Main Linac***, also using the JLab HOM coupler
- 2 × 9 - Cell 1.3 GHz cavities per module
- Booster module:
  - 4 MV/m gradient
  - 52 kW RF power

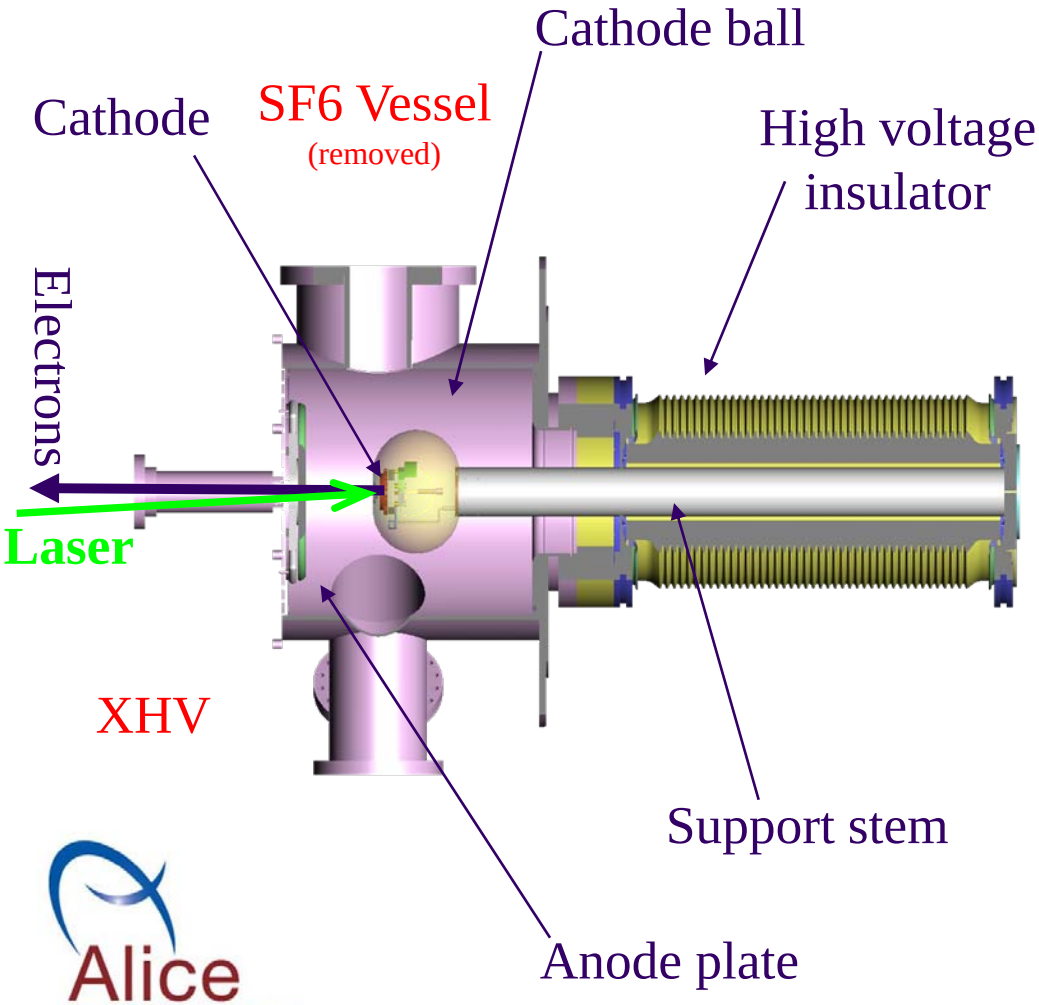


- Main Linac module:
  - 13.5 MV/m gradient
  - 16 kW RF power
- Quality factor, $Q_0 \sim 5 \times 10^9$
- Total cryogenic load:

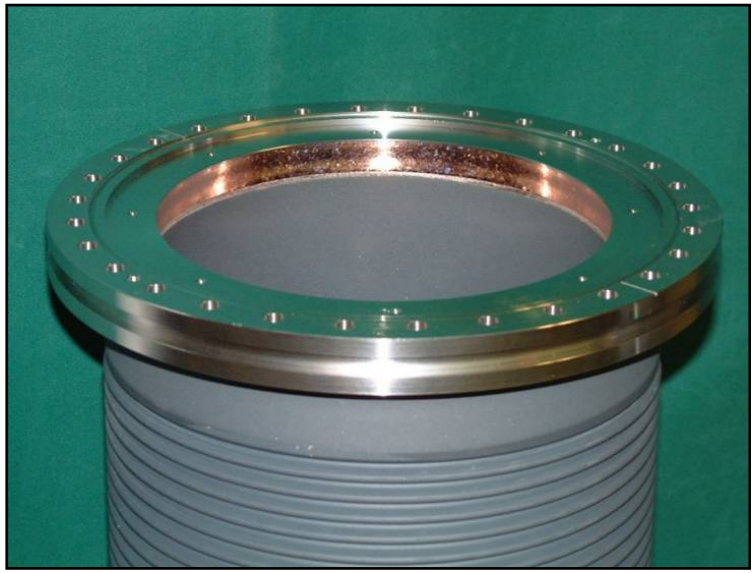
  ~ 180 W at 2 K



ALICE (TJNAF/DL) DC photocathode gun

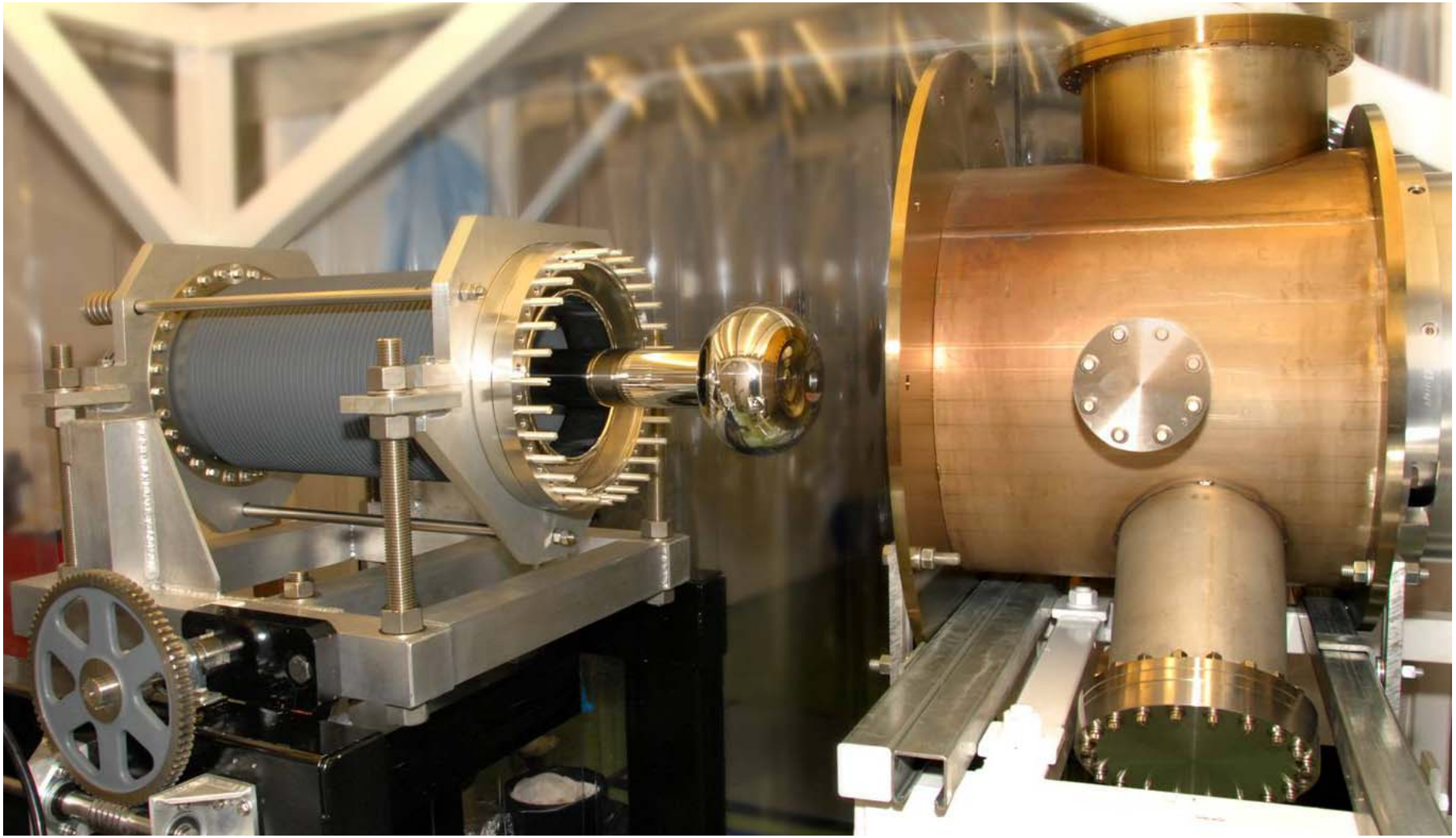


Operation voltage, kV	350/230
Beam operation mode	CW/Train-pulsed
Maximum bunch charge, pC	120/40



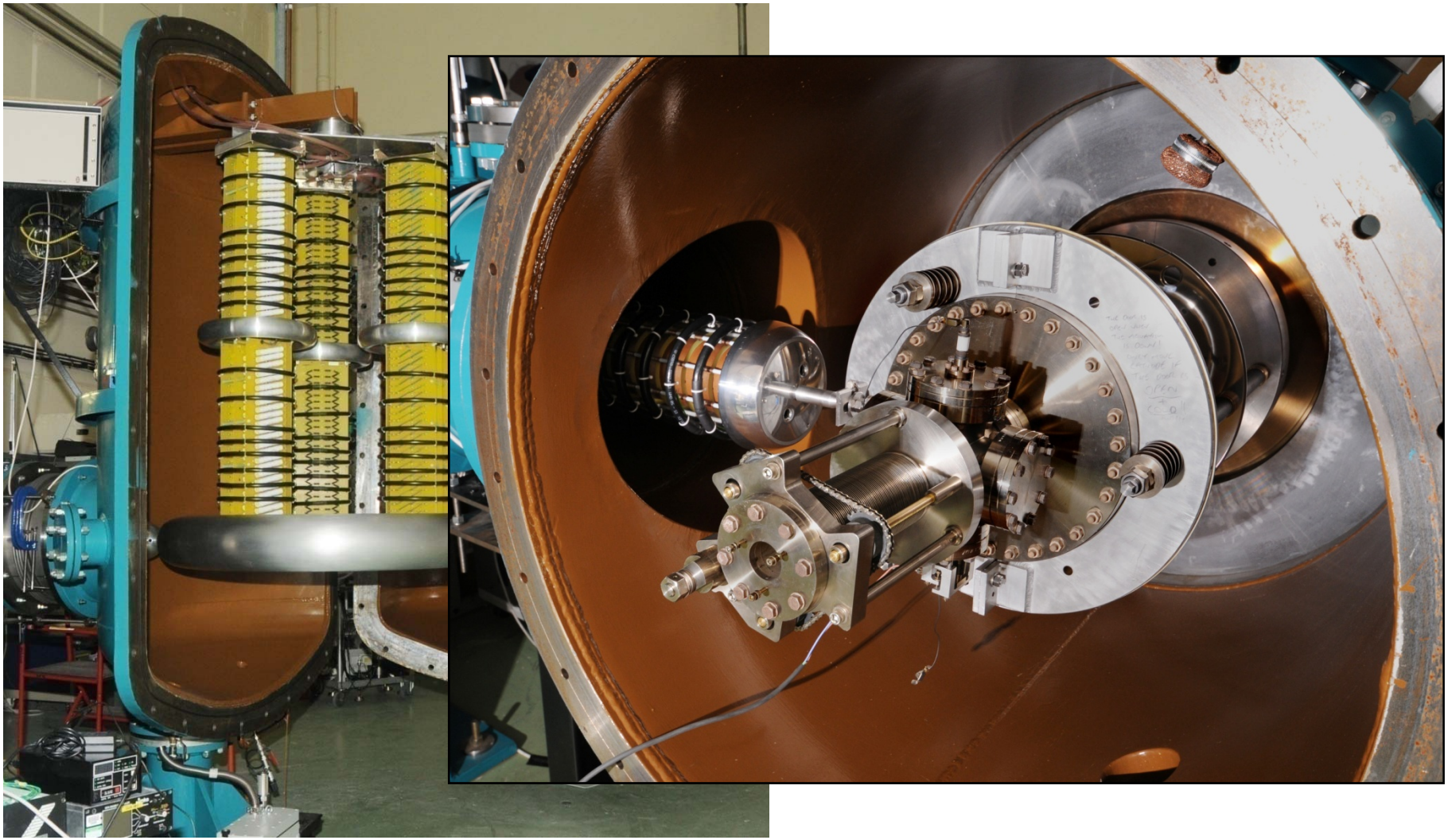
Alice
Accelerators and Lasers
In Combined Experiments

ALICE photocathode gun. Assembling stage.

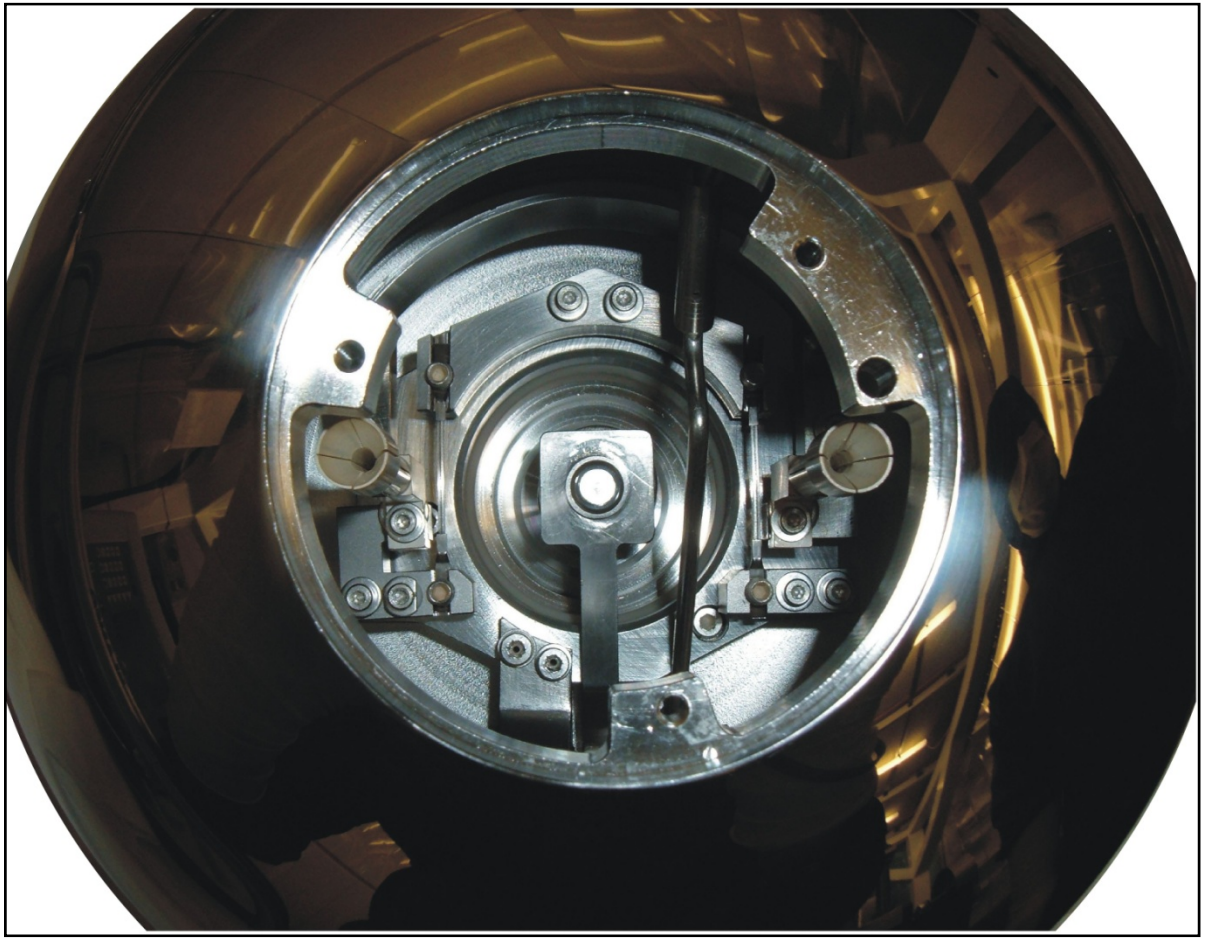


ALICE photocathode gun. 500 kV power supply I

ALICE photocathode gun. 500 kV power supply II

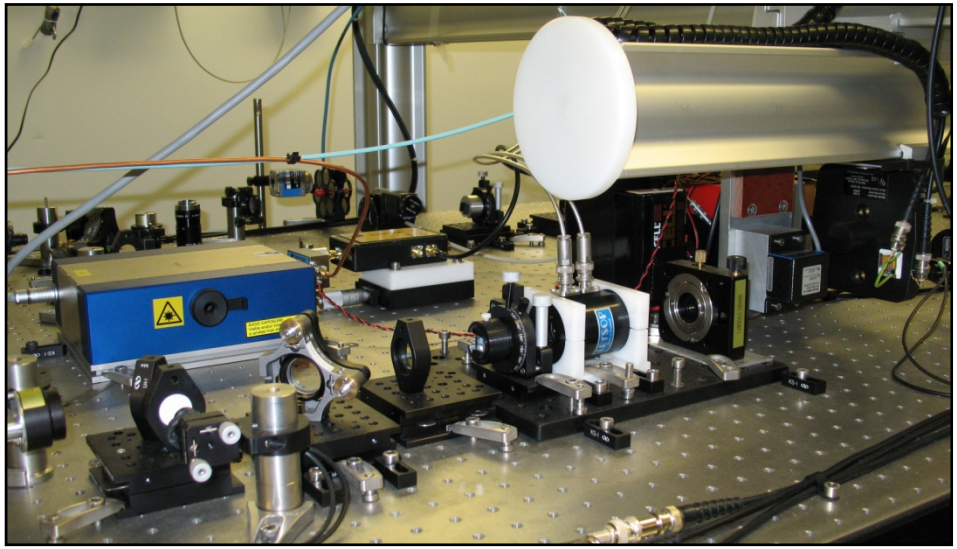


ALICE Photocathode gun. Photocathode stem.



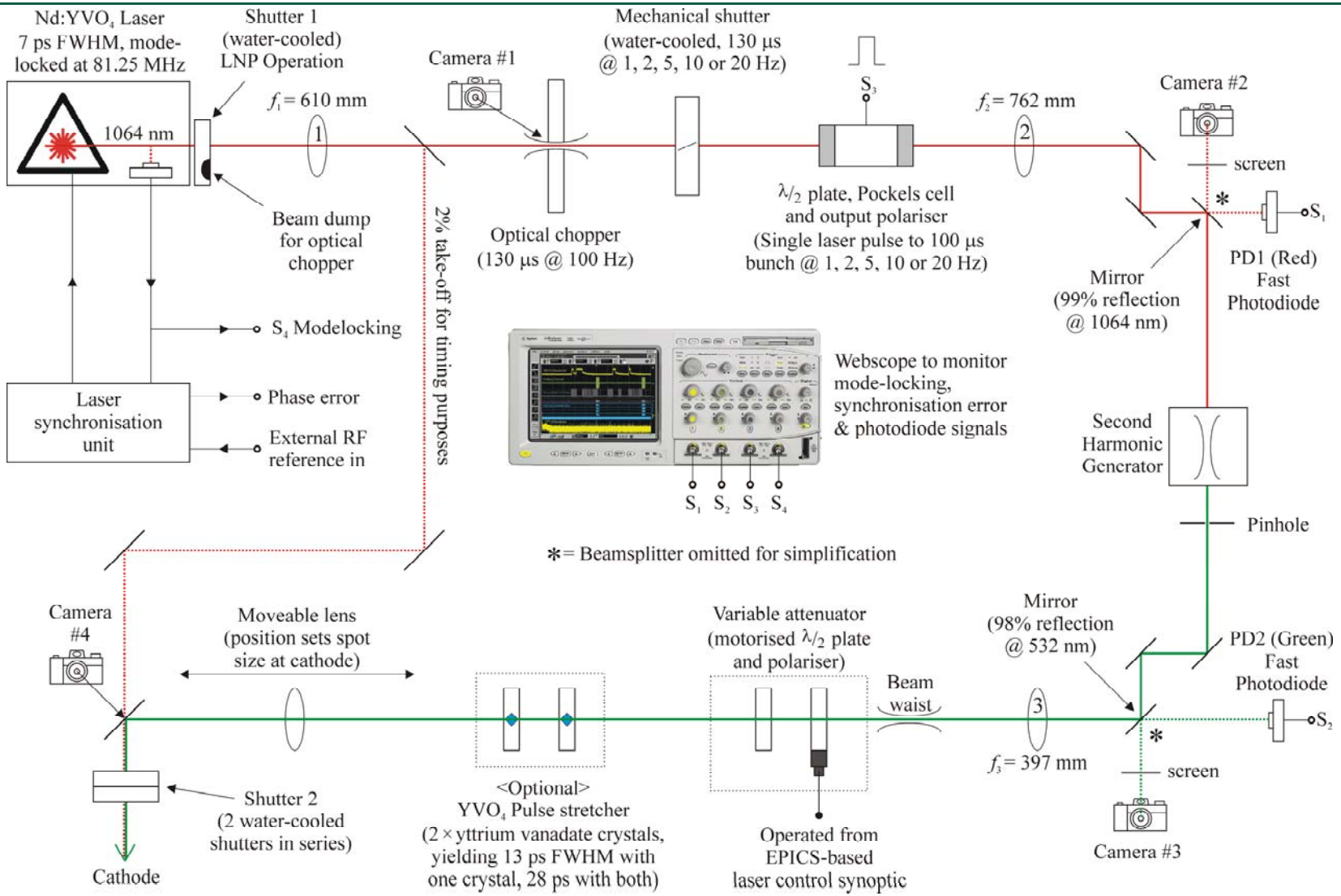
ALICE photoinjector. Drive laser system. Summary

- Diode-pumped Nd:YVO_4
- Wavelength: 1064 nm, doubled to 532 nm
- Pulse repetition rate: 81.25 MHz
- Pulse duration: 7, 13, 28 ps FWHM
- Pulse energy: up to 45 nJ (at cathode)
- Macropulse duration: 100 μs @ 20 Hz

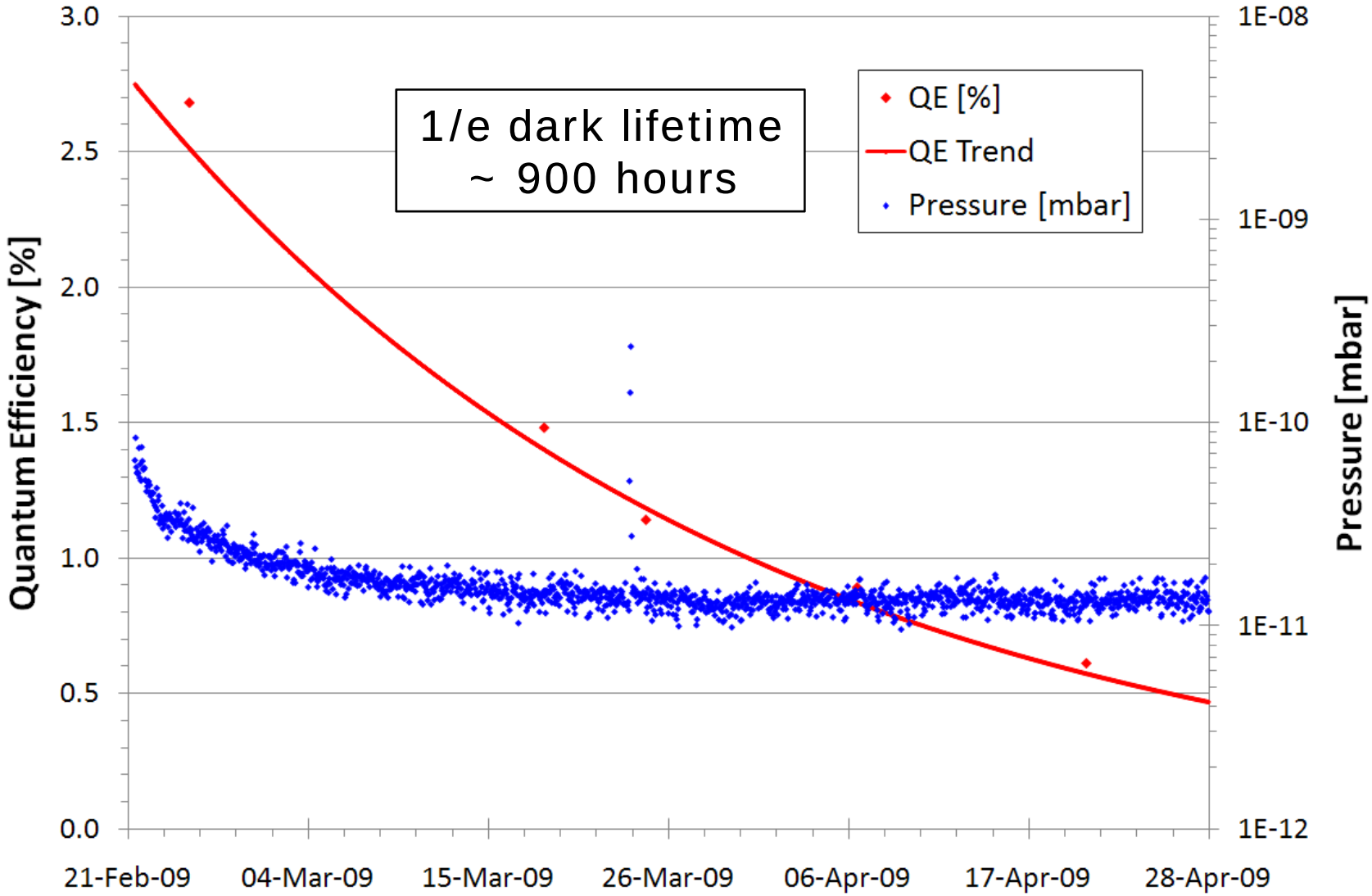


- Duty cycle: 0.2% (maximum)
- Timing jitter: < 1 ps (specified)
  < 650 fs (measured)
- Spatial profile: Circular top-hat on photocathode
- Laser system commissioned at Rutherford Laboratory in 2005, then moved to Daresbury Laboratory in 2006

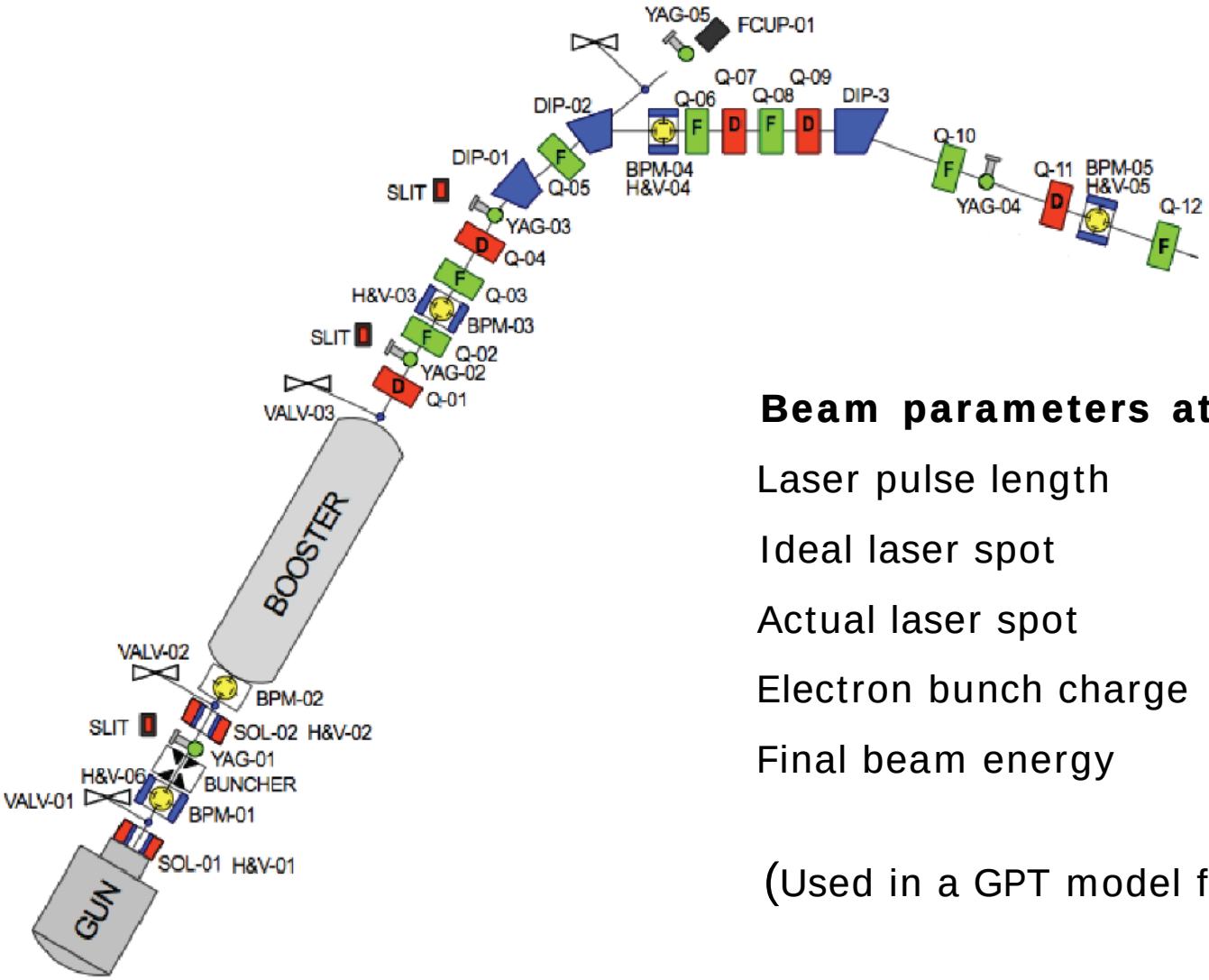
ALICE photoinjector. Drive laser system. General layout



ALICE photoinjector. Photocathode dark lifetime.



ALICE photoinjector. Emittance measurements

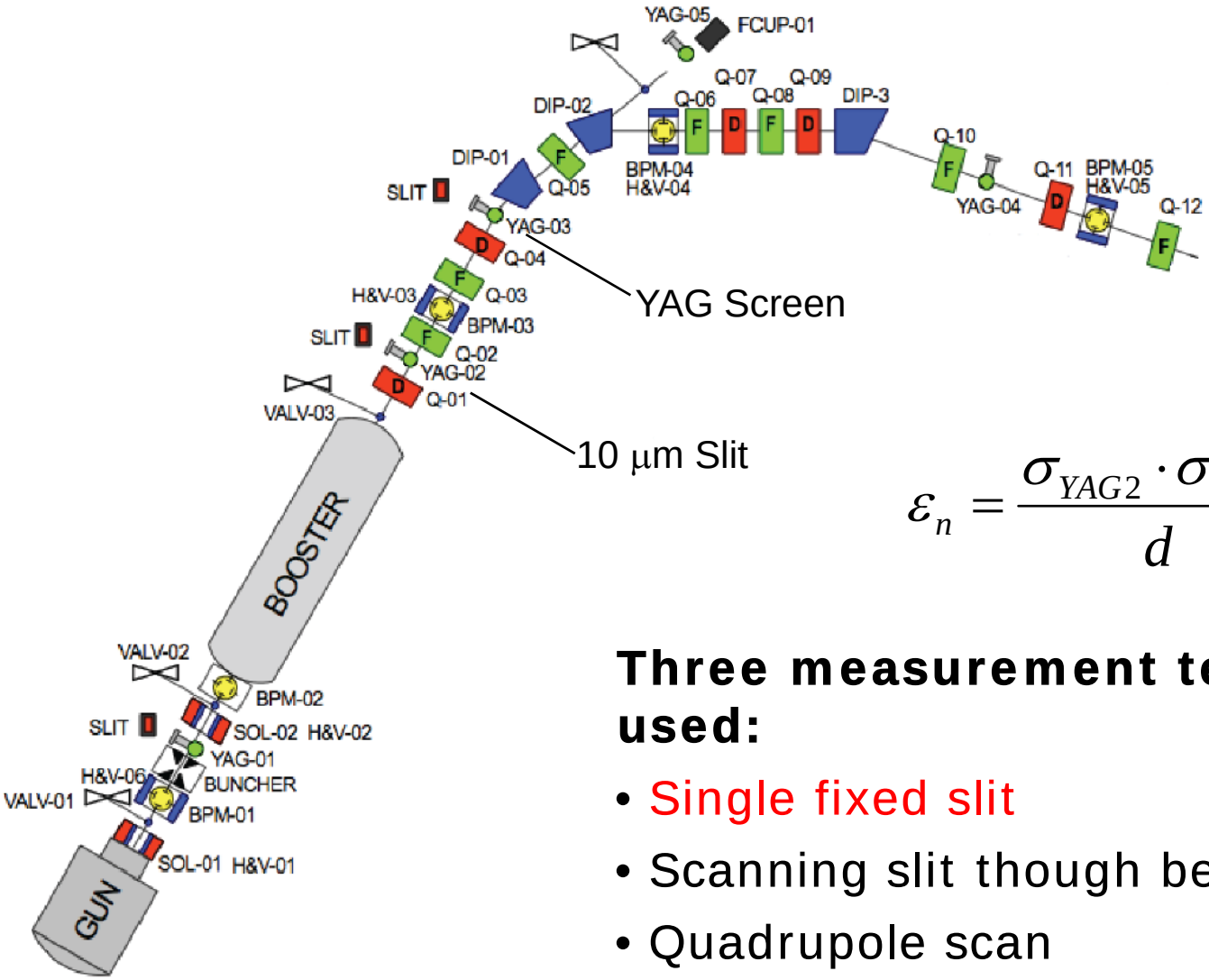


Beam parameters at the cathode

Laser pulse length	28 ps
Ideal laser spot	4 mm Ø
Actual laser spot	8 × 4 mm
Electron bunch charge	40 pC
Final beam energy	6.5 MeV

(Used in a GPT model for comparison)

ALICE photoinjector. Emittance measurements

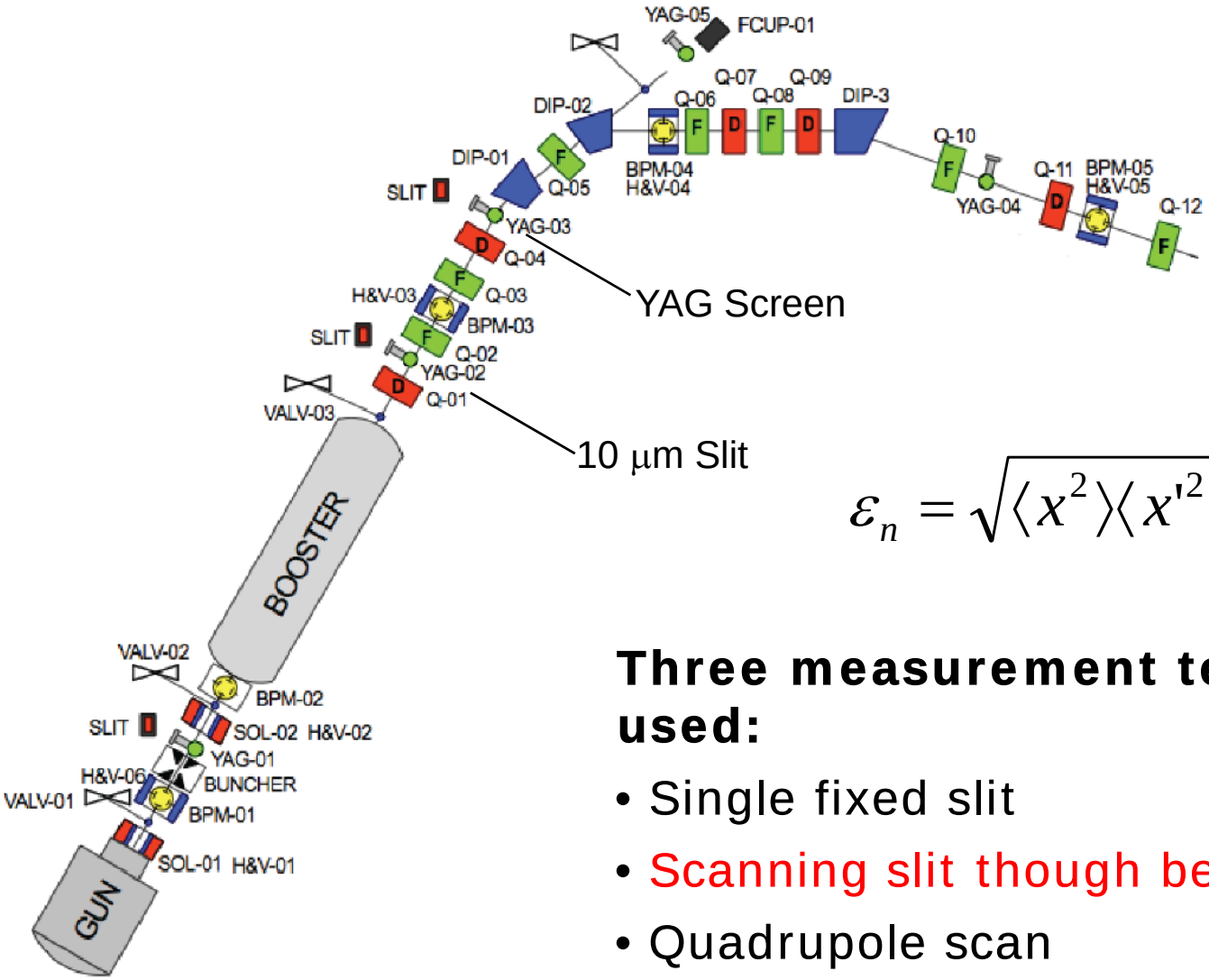


$$\varepsilon_n = \frac{\sigma_{YAG2} \cdot \sigma_{YAG3}}{d} \cdot \gamma$$

Three measurement techniques used:

- Single fixed slit
- Scanning slit though beam
- Quadrupole scan

ALICE photoinjector. Emittance measurements

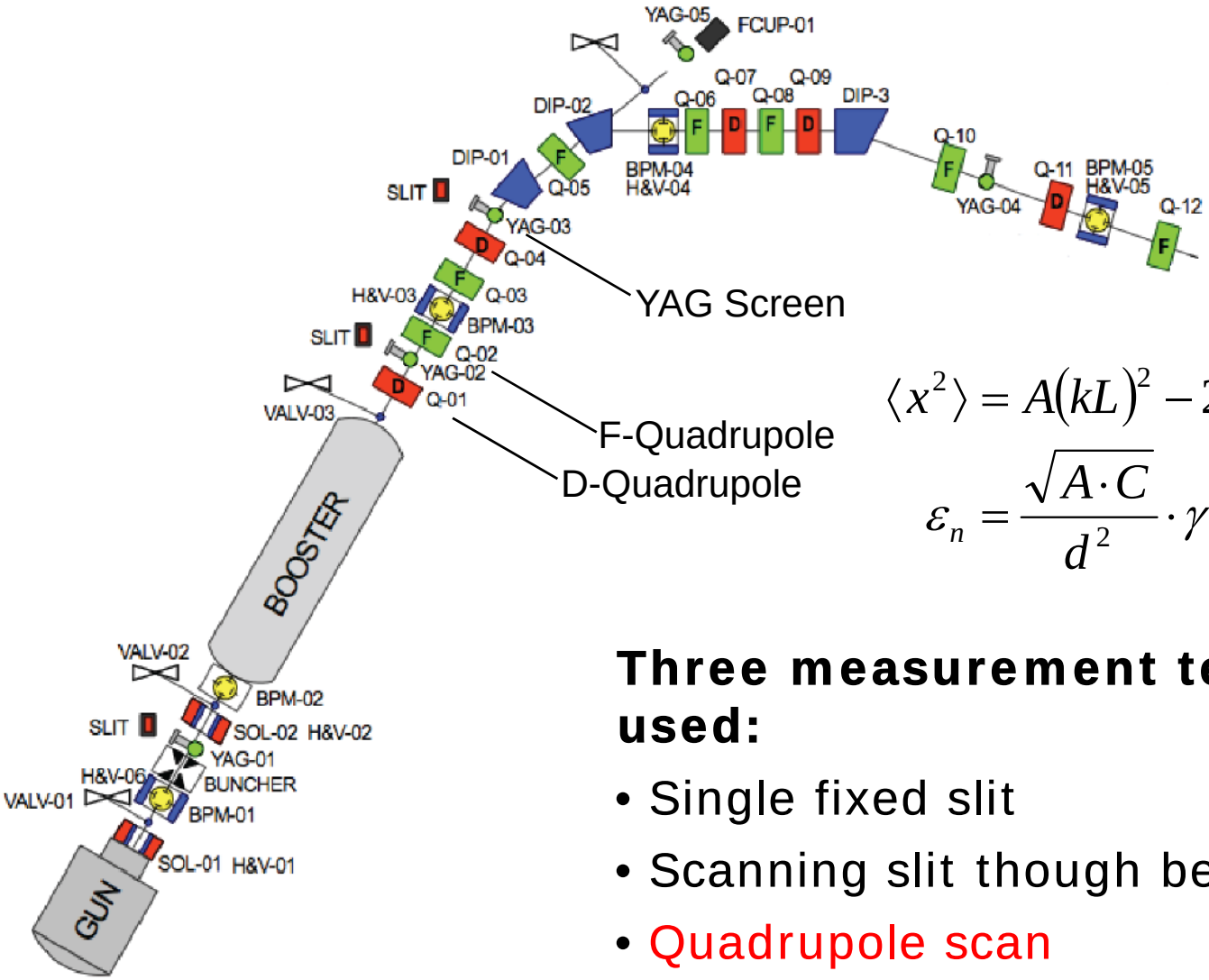


$$\varepsilon_n = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2} \cdot \gamma$$

Three measurement techniques used:

- Single fixed slit
- Scanning slit though beam
- Quadrupole scan

ALICE photoinjector. Emittance measurements



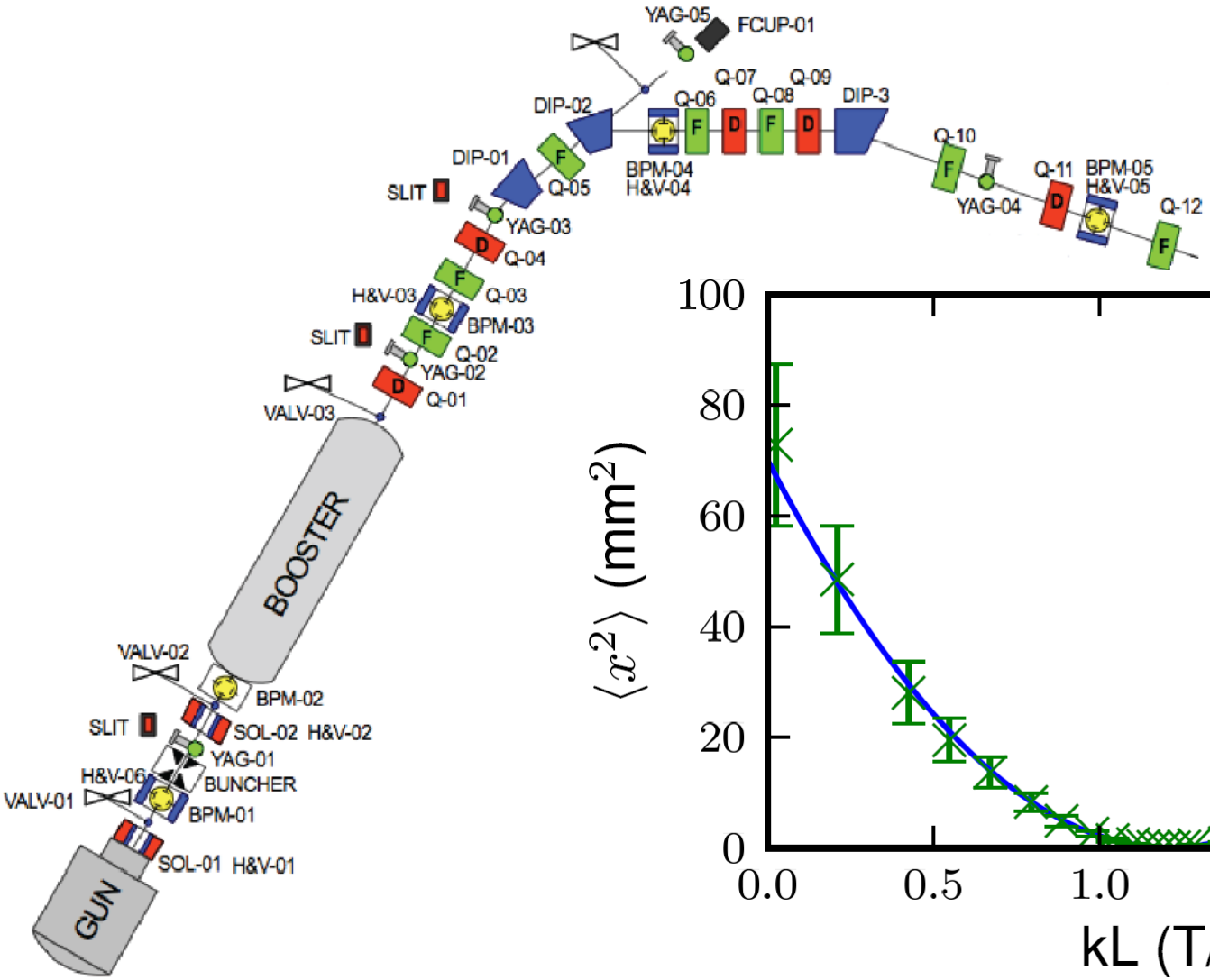
$$\langle x^2 \rangle = A(kL)^2 - 2AB(kL) + \left(C + AB^2\right)$$

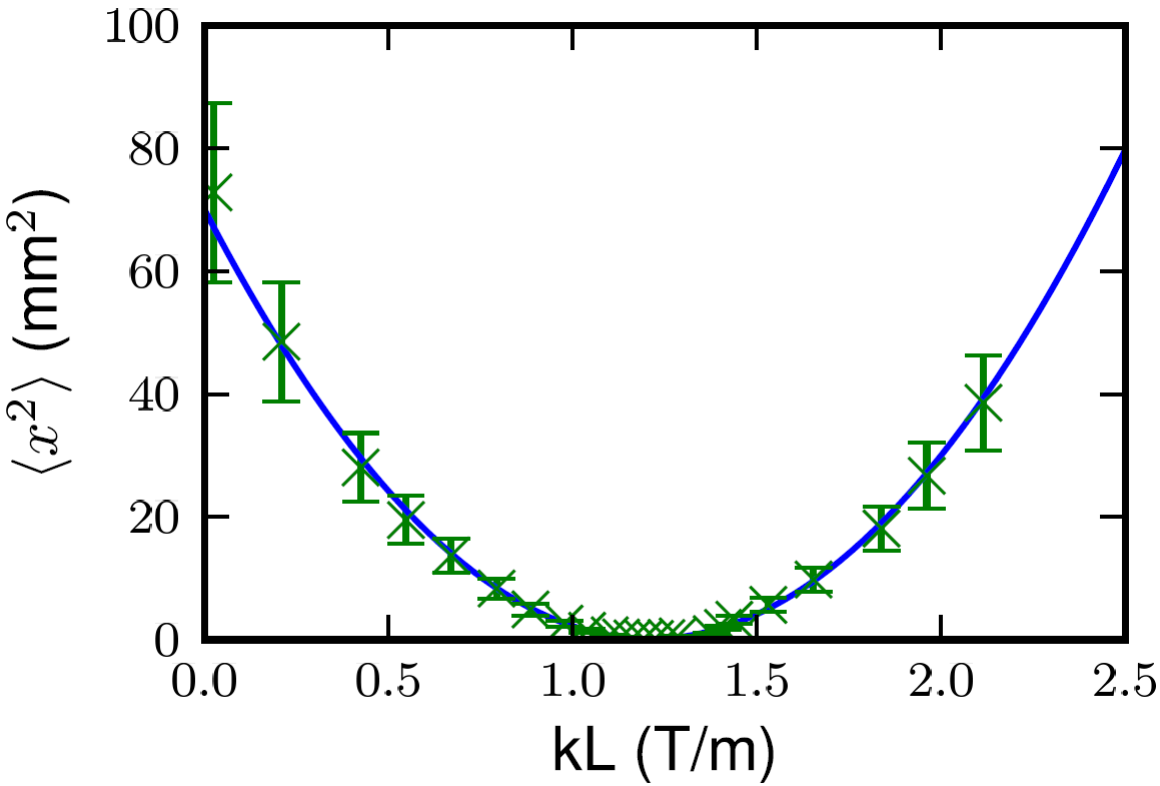
$$\varepsilon_n = \frac{\sqrt{A \cdot C}}{d^2} \cdot \gamma$$

Three measurement techniques used:

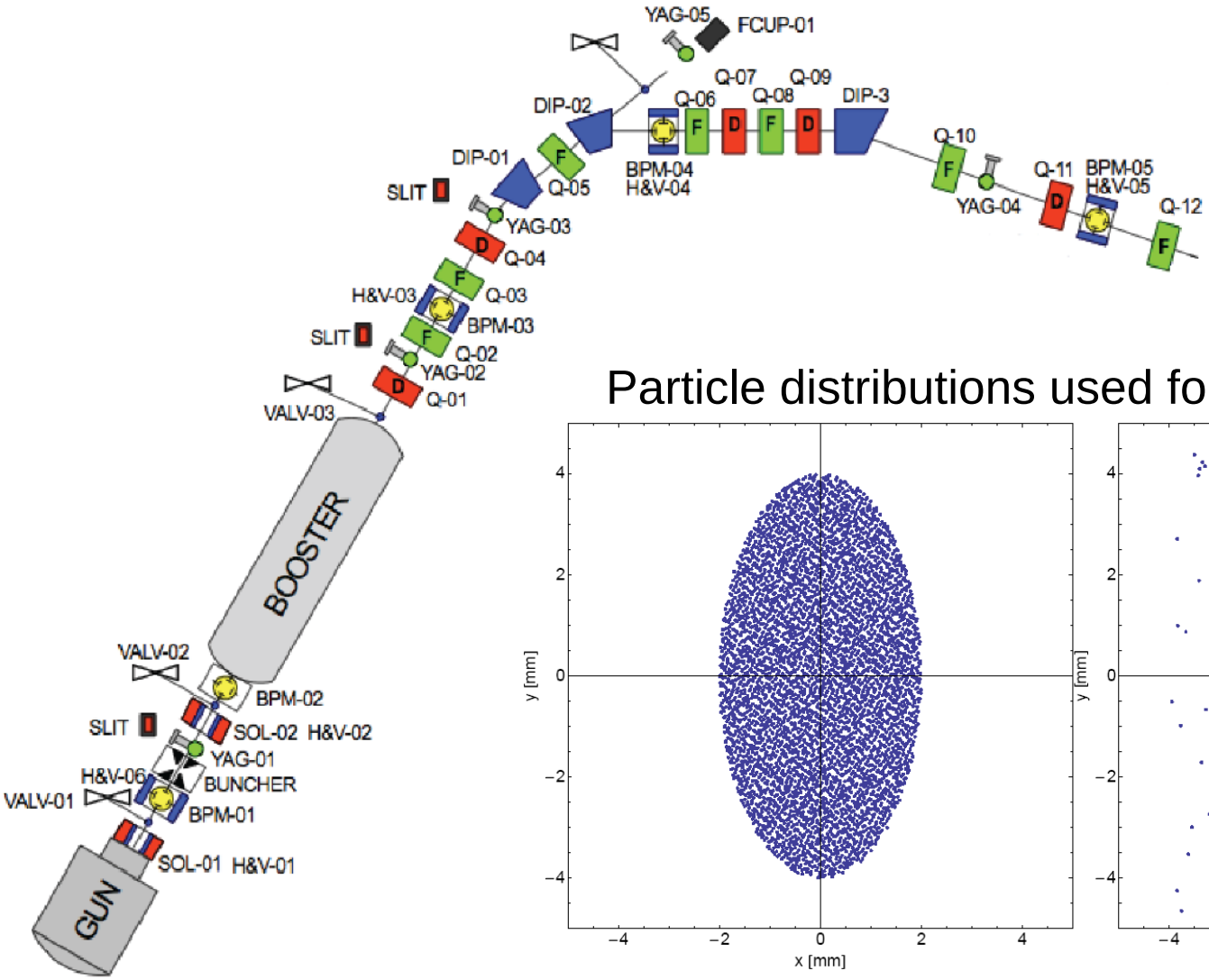
- Single fixed slit
- Scanning slit though beam
- Quadrupole scan

ALICE photoinjector. Emittance measurements

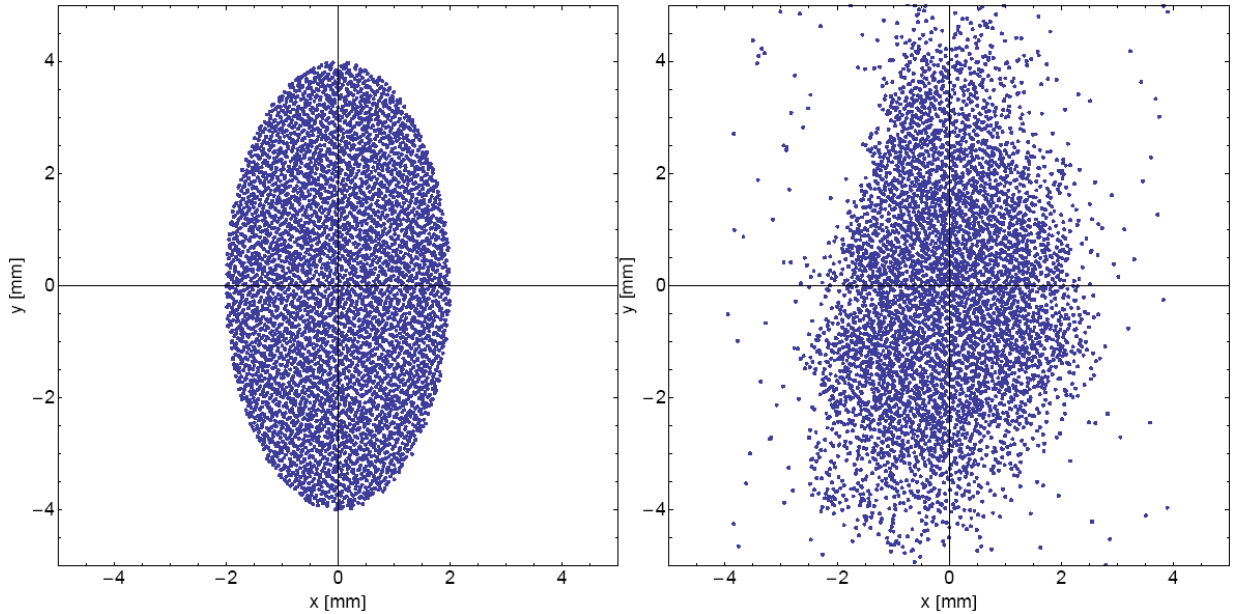




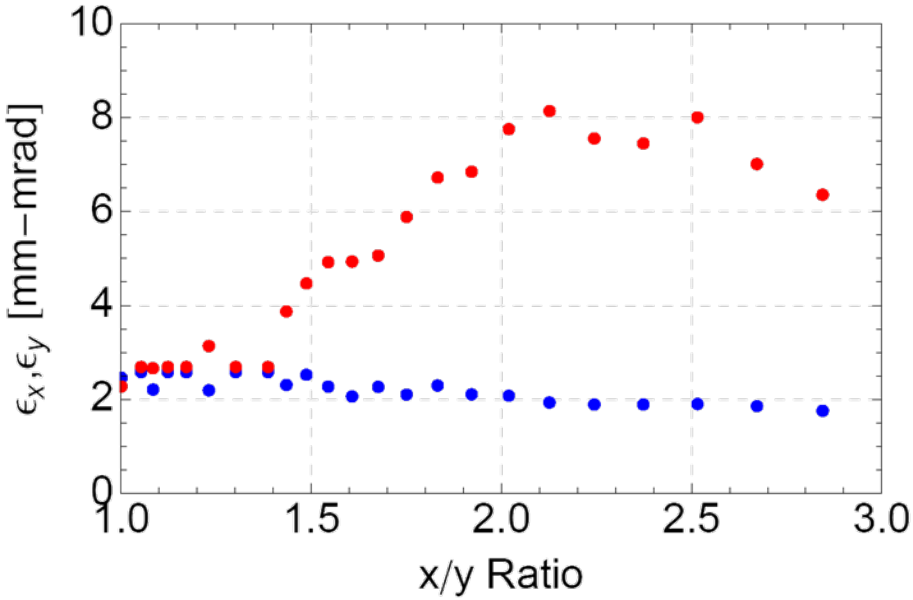
ALICE Photoinjector. Emittance measurements



Particle distributions used for GPT simulations



ALICE photoinjector. Emittance measurements



Result	ε_x	ε_y
Single slit	11.0	N/A
Scanned slit	9.1	N/A
Quadrupole scan	15.1	4.0
Measurement average	11.7	4.0
GPT (Elliptical)	9.5	1.9
GPT (Actual distribution)	17.7	3.8

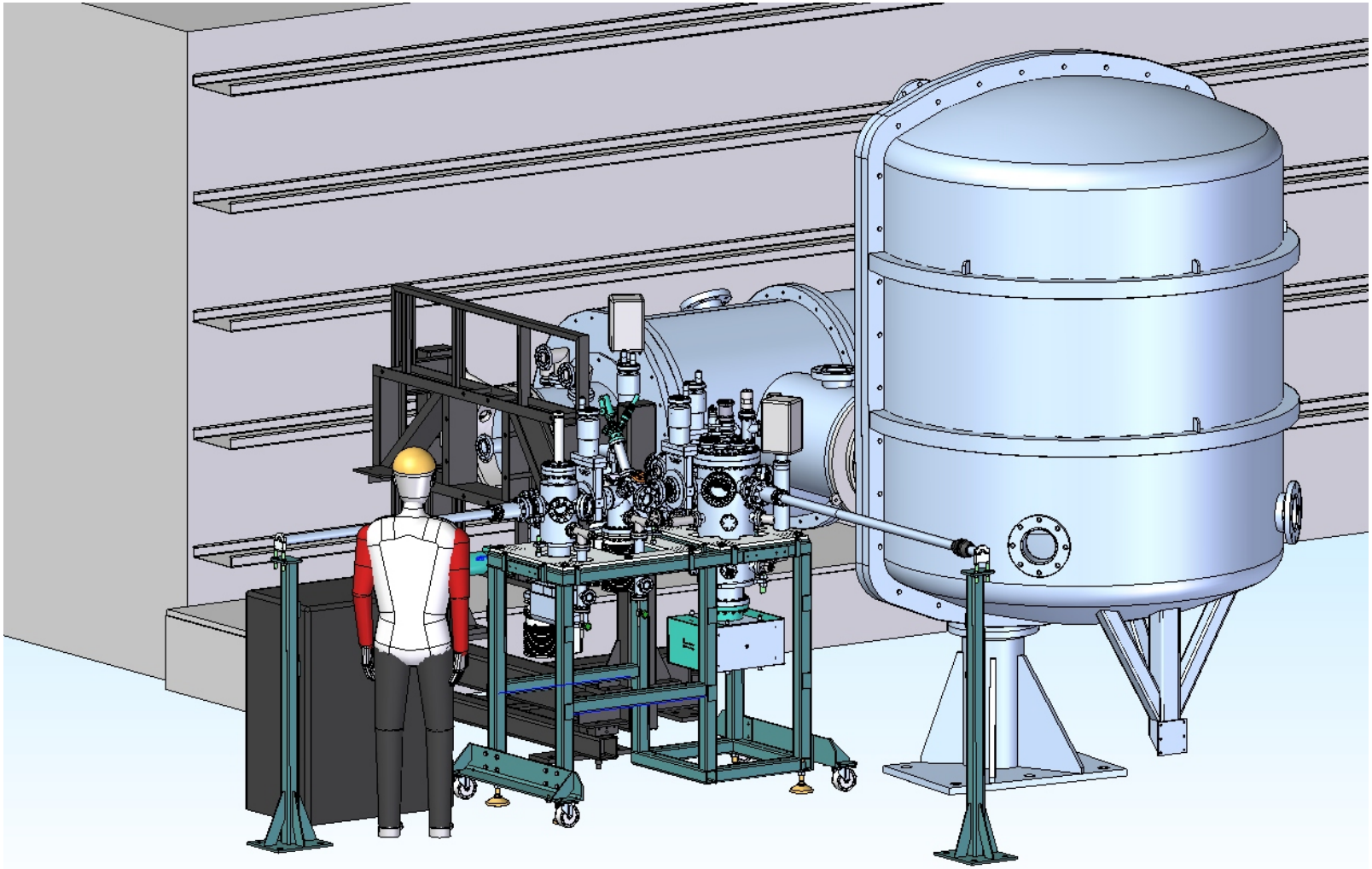
Courtesy J. Garland

ALICE. Design criteria demonstrated so far ……

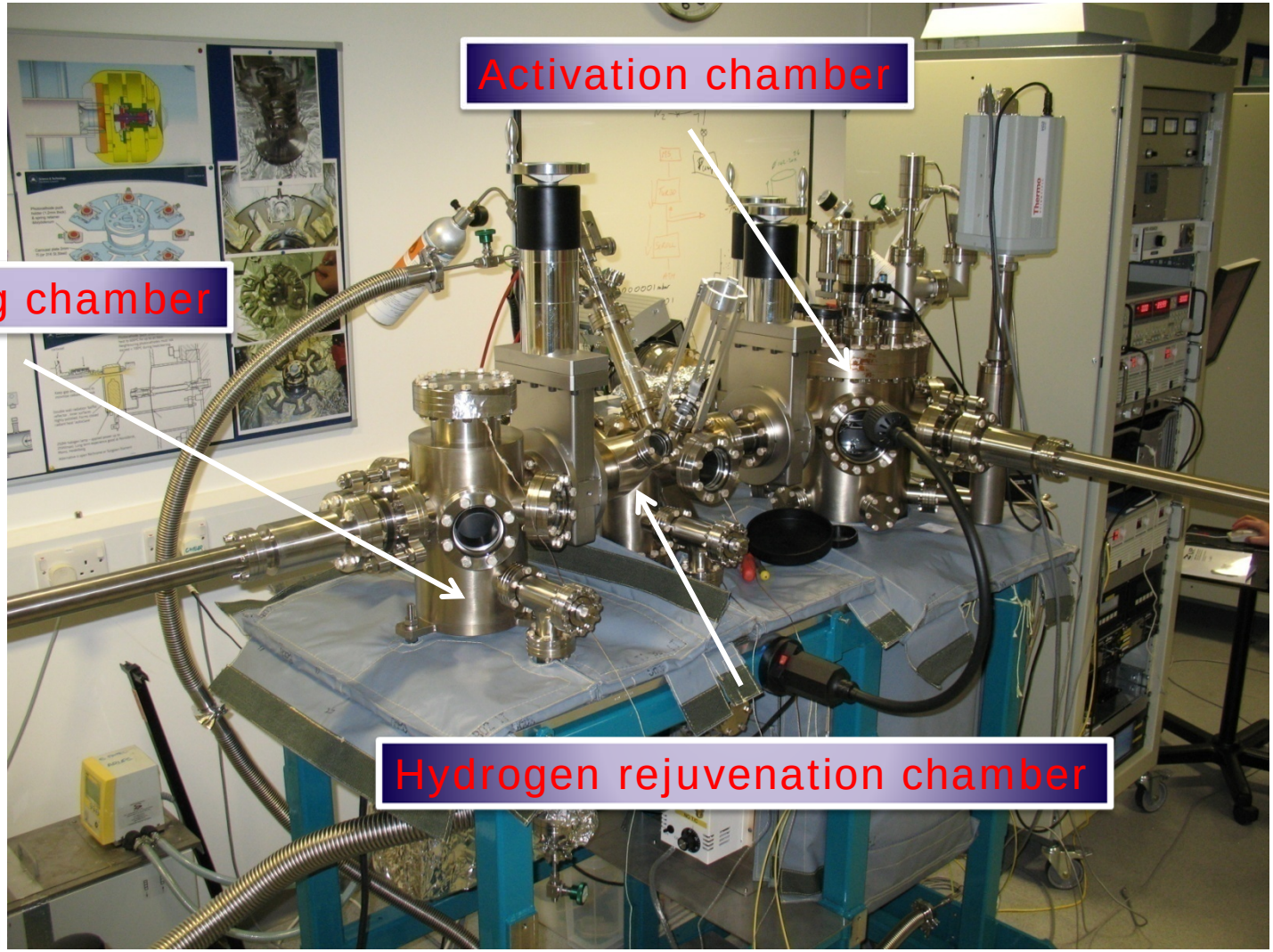
- Beam energy: **350 keV** ✓
- Bunch charge: **> 80 pC** ✓
- Quantum Efficiency ($Q.E.$):

  3.7 % with 1/e lifetime of ~ **900** hours ✓
- Bunch train length: **Single 7 ps pulse to 100 μs** ✓
- Train repetition rate: **Operated up to 20 Hz** ✓
- THZ radiation & CBS X-rays: **Achieved** ✓

ALICE gun upgrade. Artist's vew.

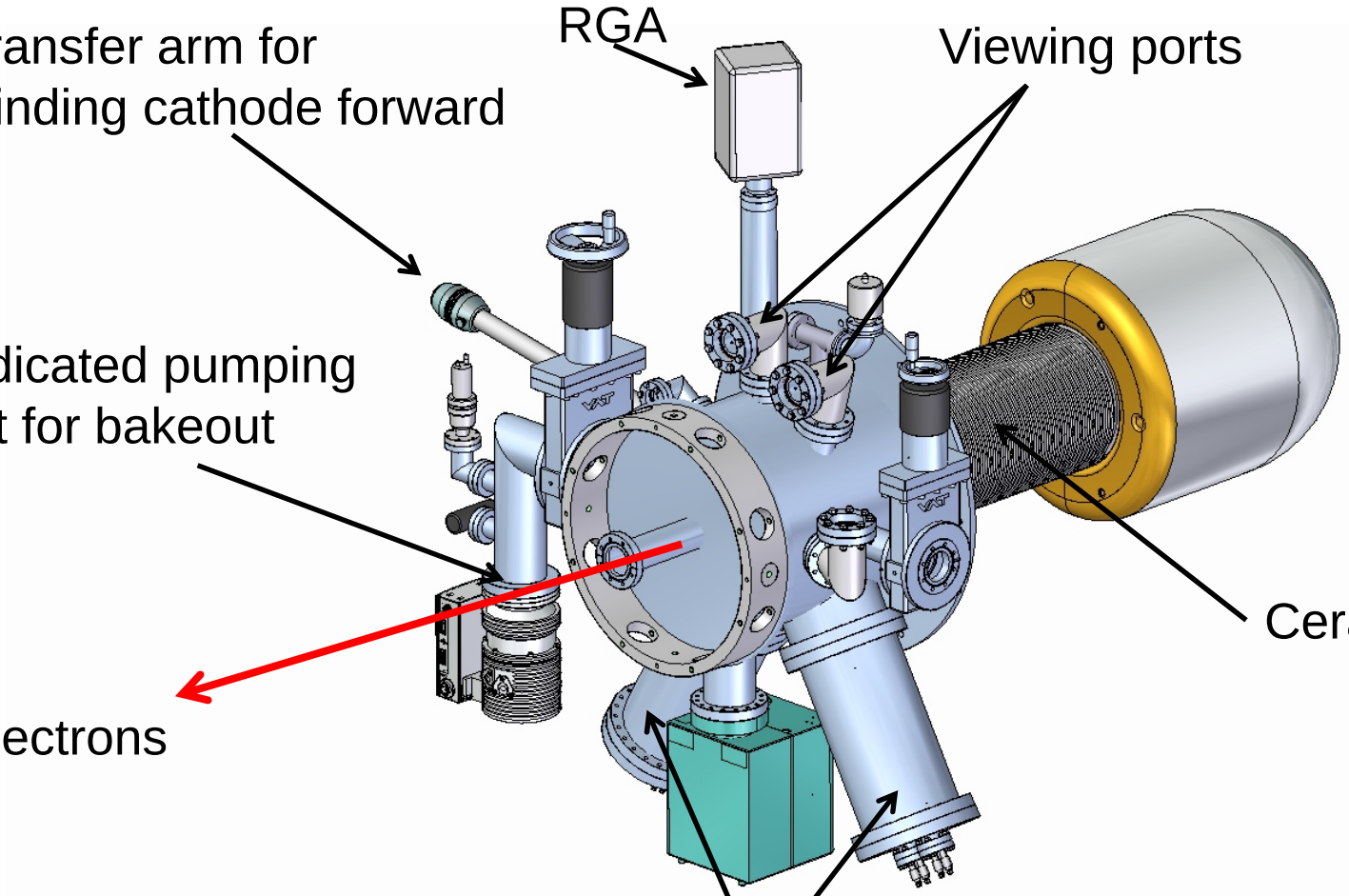


ALICE gun upgrade. Photocathode preparation facility.

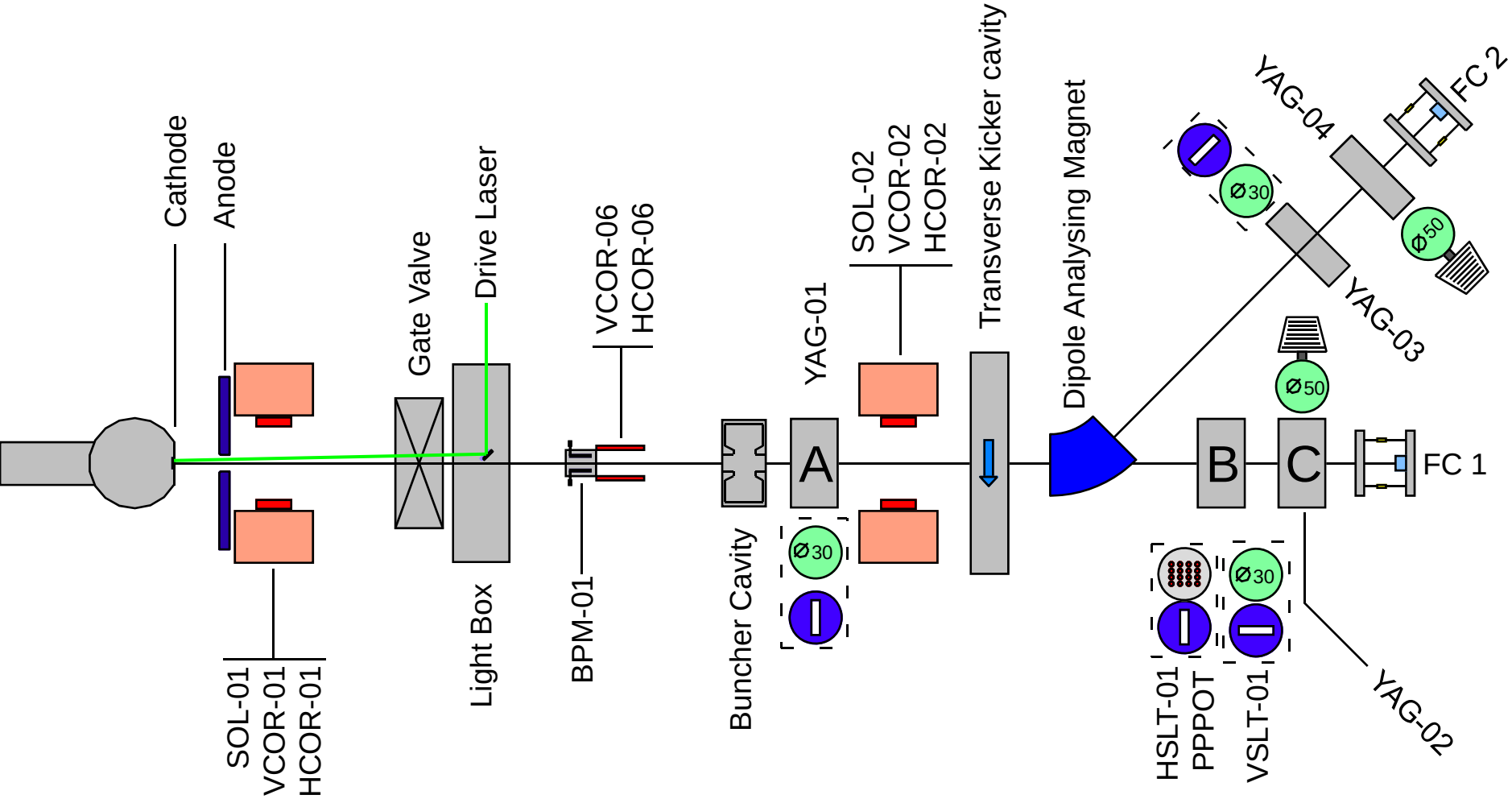


Alice
Accelerators and Lasers
In Combined Experiments

ALICE gun upgrade. New gun chamber

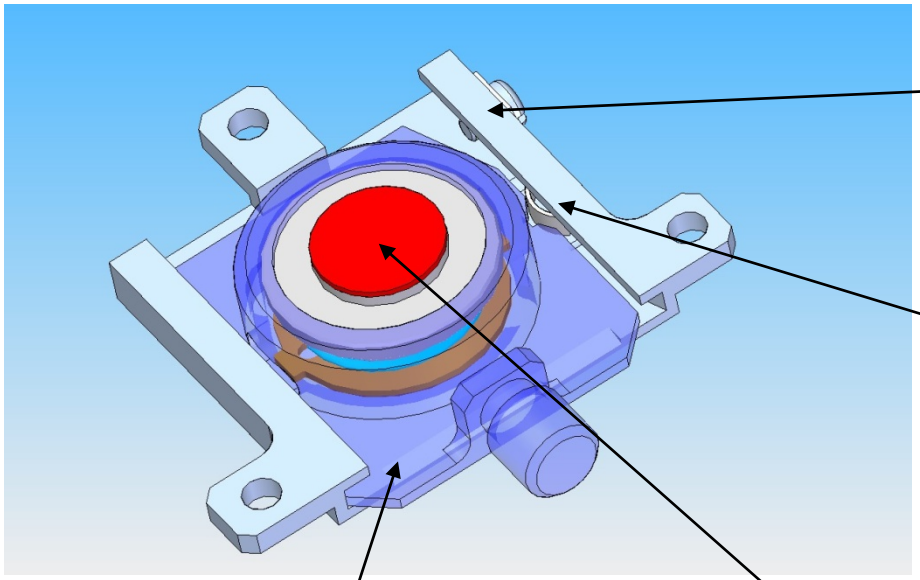


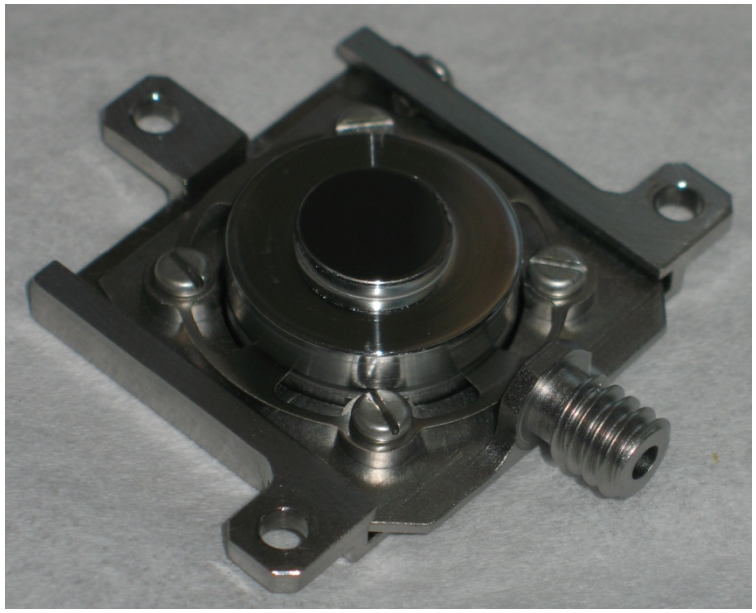
ALICE gun upgrade. Low energy beam diagnostic line



Courtesy Yu.M. Saveliev

ALICE gun upgrade. GaAs photocathode for ALICE/4GLS



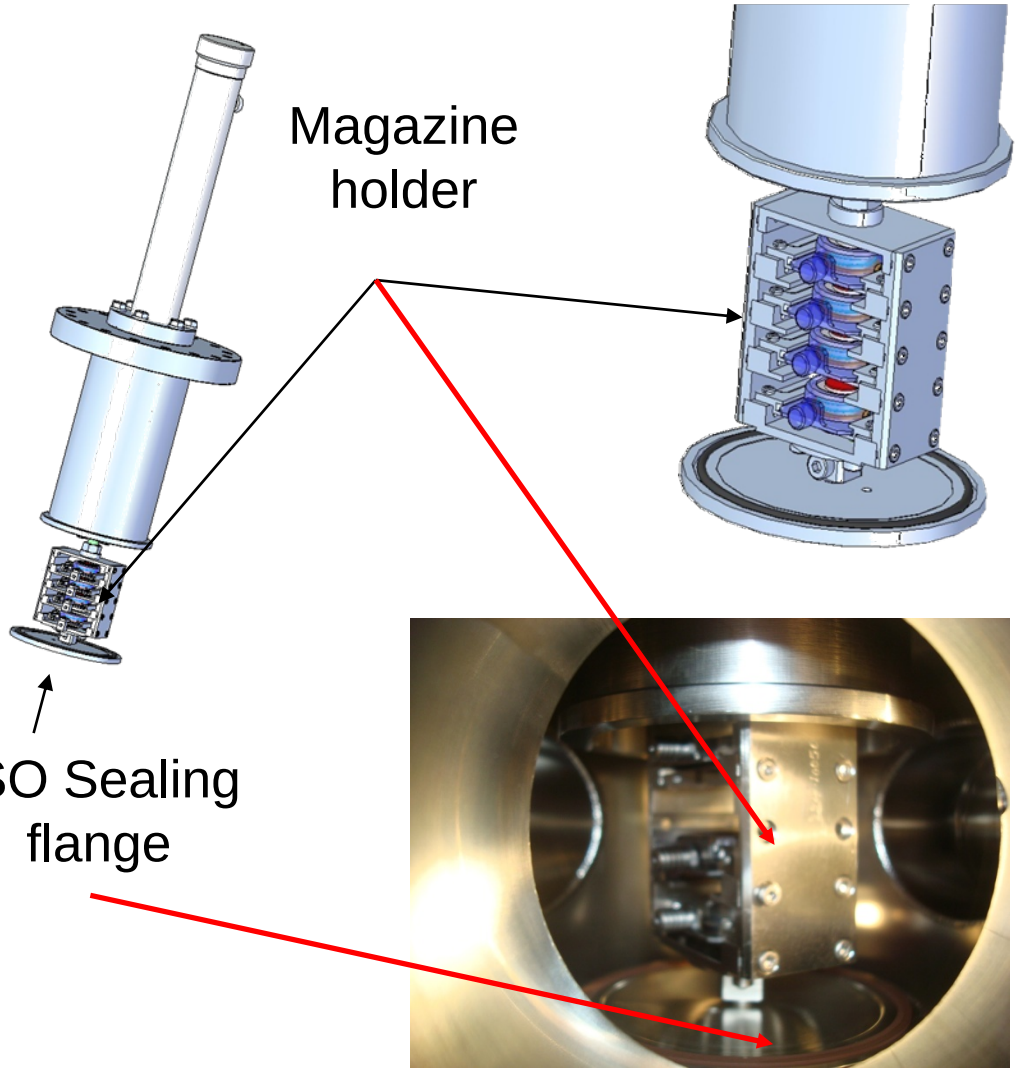


Alice
Accelerators and Lasers In Combined Experiments

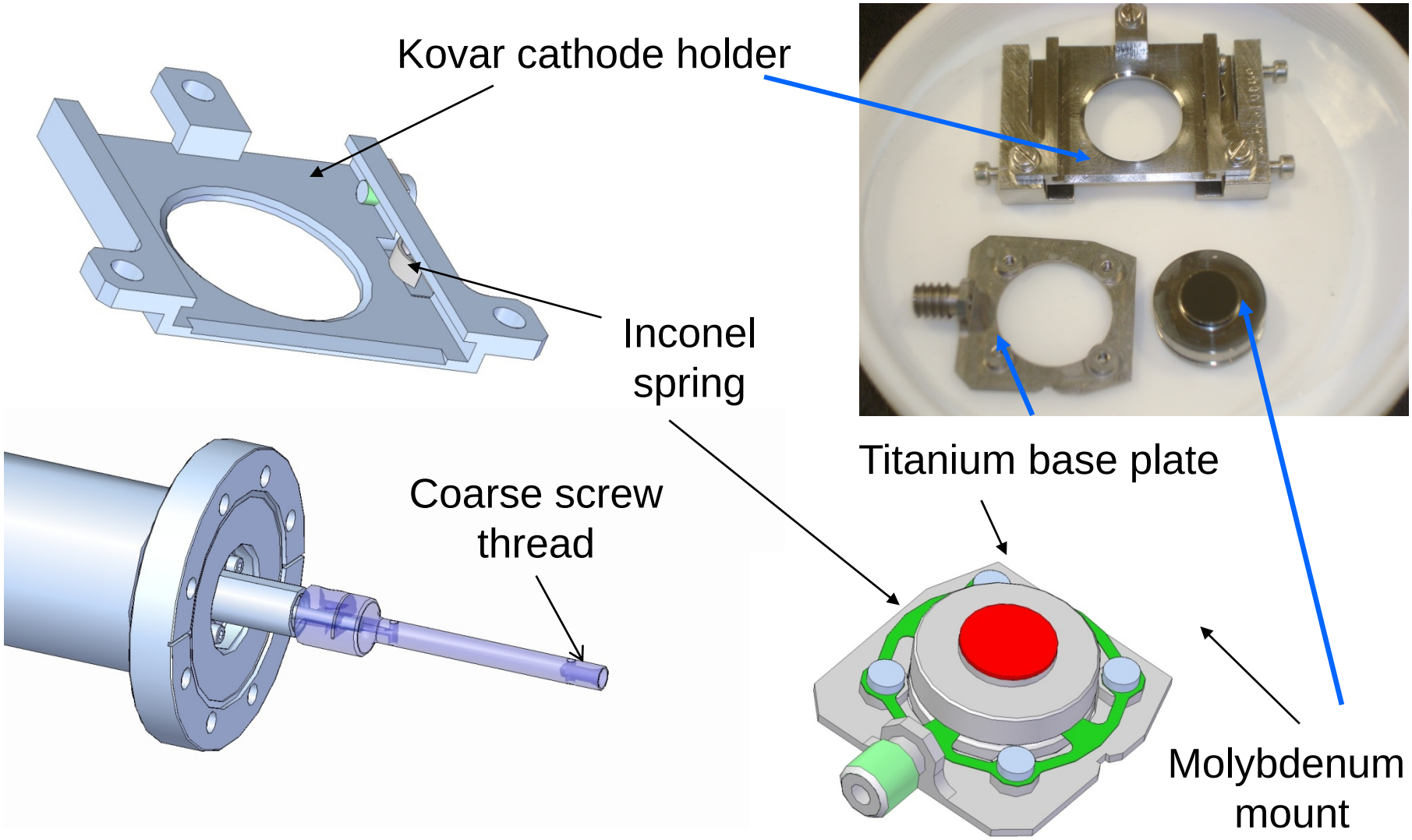
PPS. Photocathode chemical treatment

- Ensure photocathode holder is ‘clean’ and move into glove box without exposing to air
- Rinse with HCl + IPA solution (1:10 by volume) for 90 s
- Rinse with IPA for 60 seconds
- Remove solvent residue with dry nitrogen
- Load the photocathode into the transport vessel

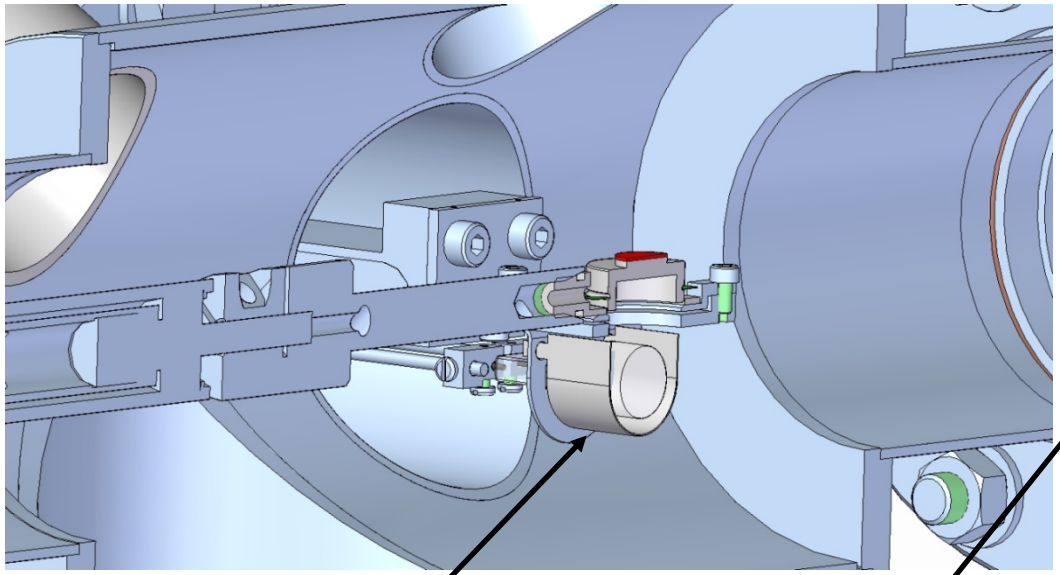
PPS. Transport vessel and loading chamber.

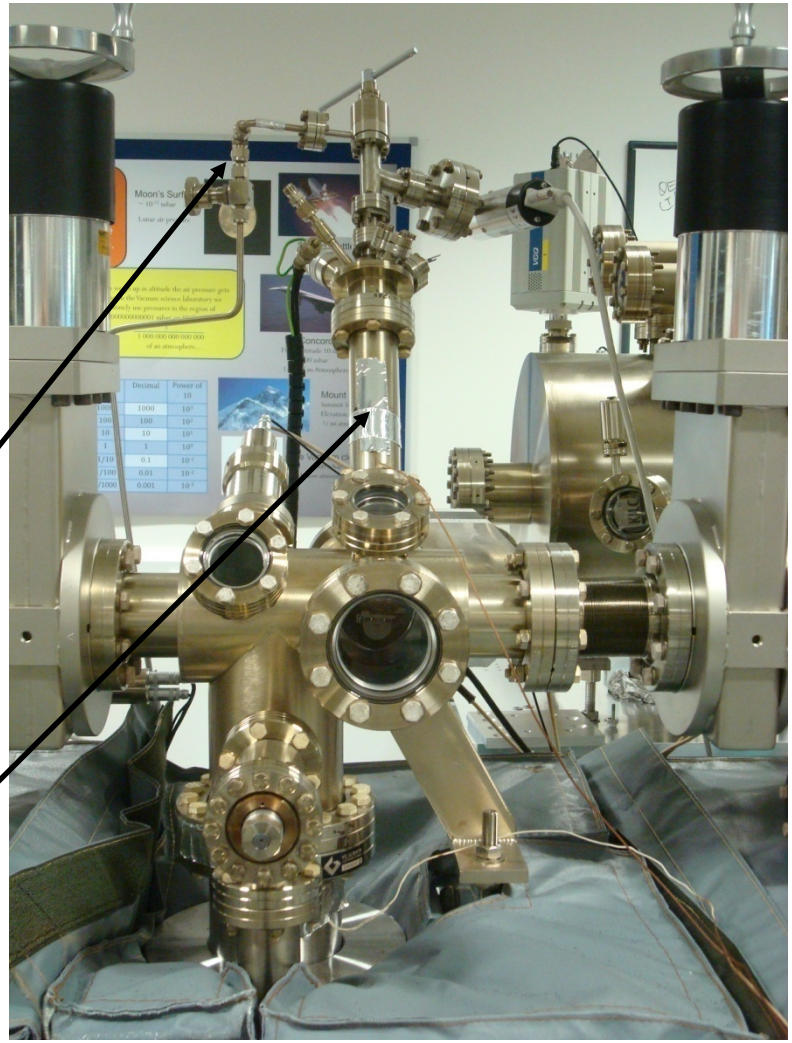


PPS. Transportation of the photocathodes within PPS



PPS. Atomic Hydrogen Cleaning Chamber



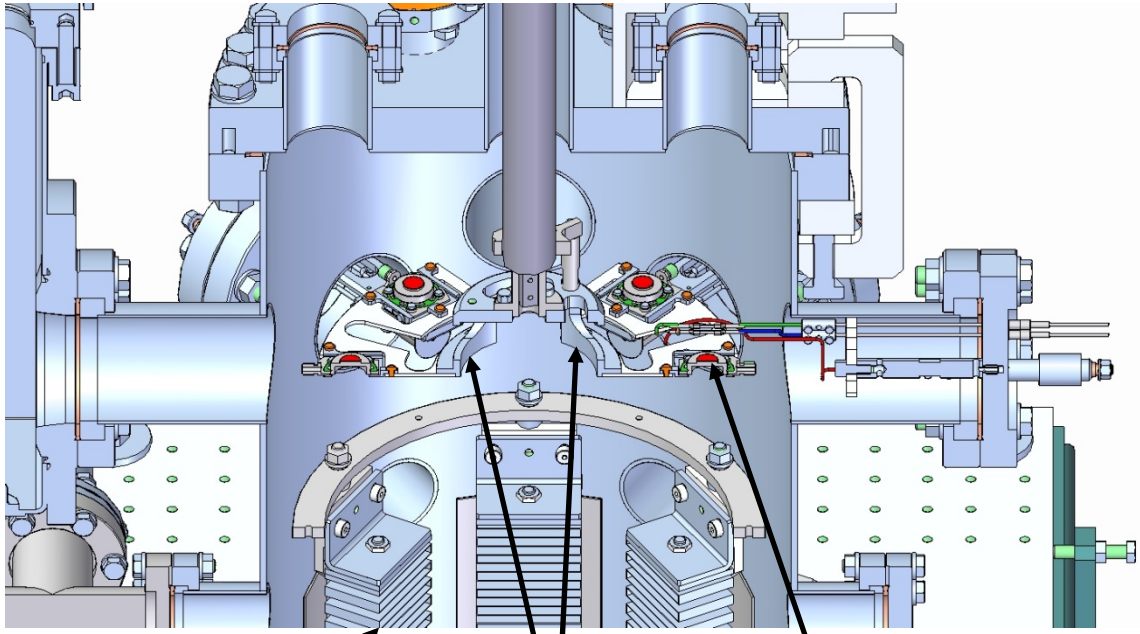


Photocathode heater

Hydrogen gas line

H_2 thermal gas cracker

PPS. Activation chamber



Heaters

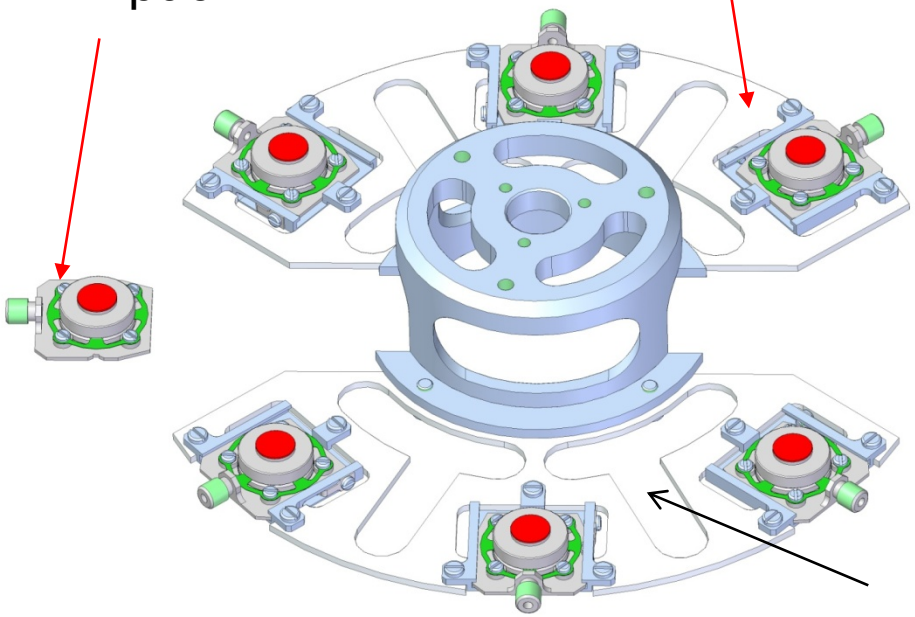
NEG Strips – ST707

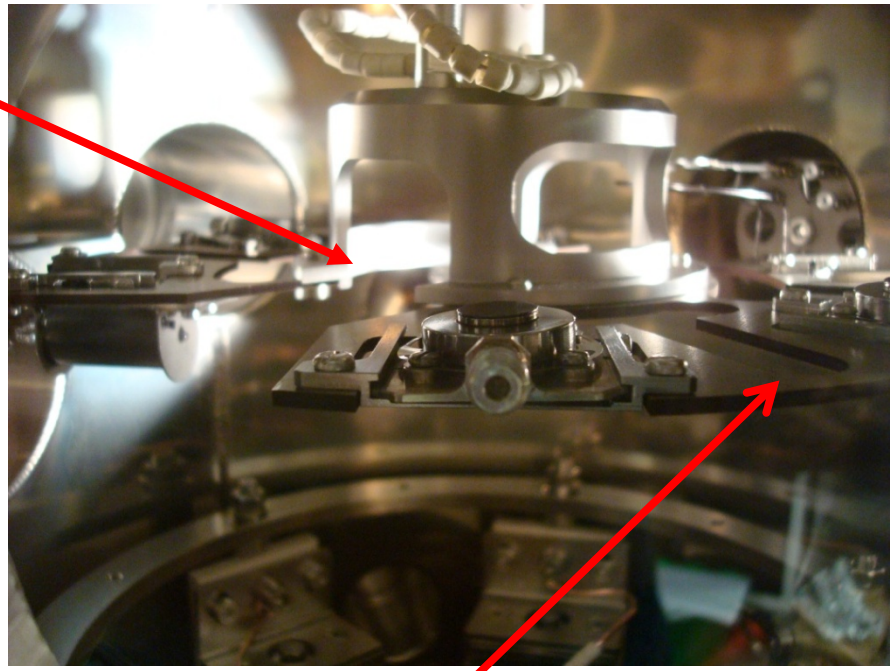
Activation position

PPS. Activation chamber. Cathode carousel

Ti Carousel

Photocathode puck

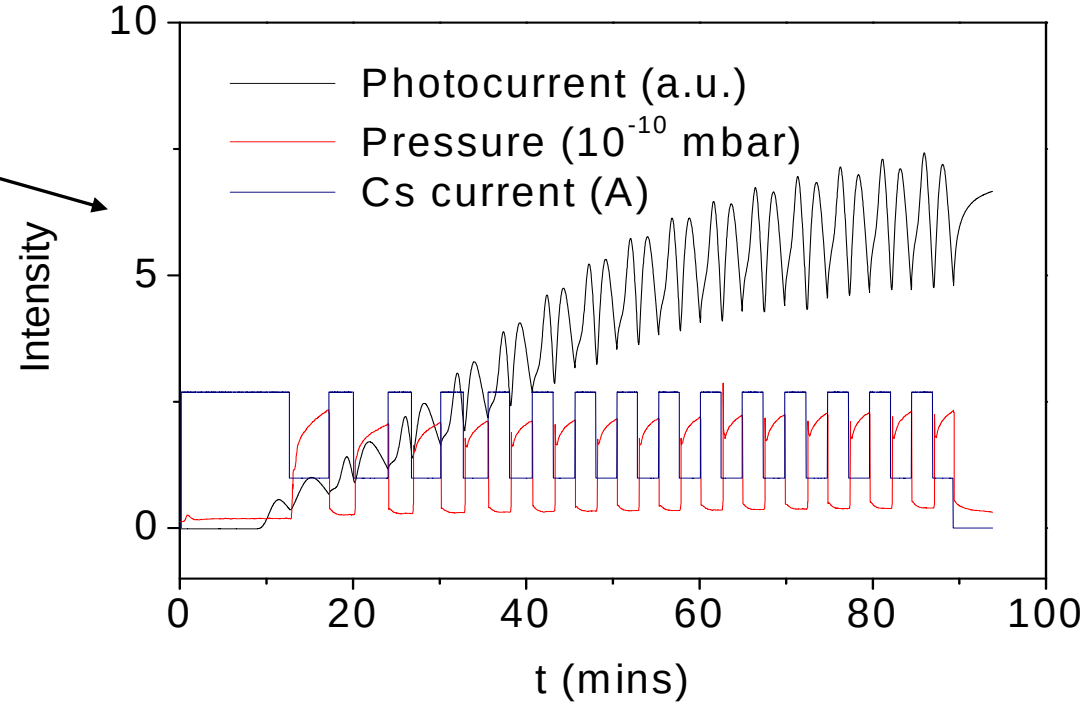


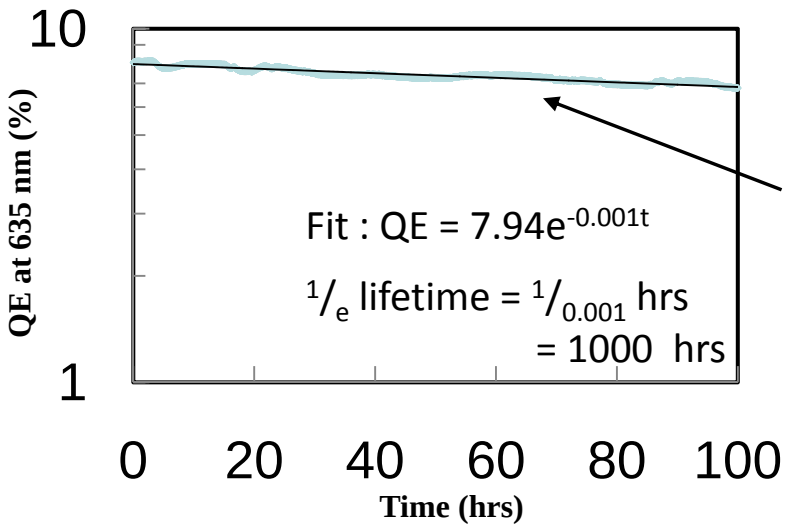


Radial slots & 2mm thin carousel plate limit in-plane heat conduction to neighbouring photocathodes during heating.

PPS. Photocathode activation and lifetime

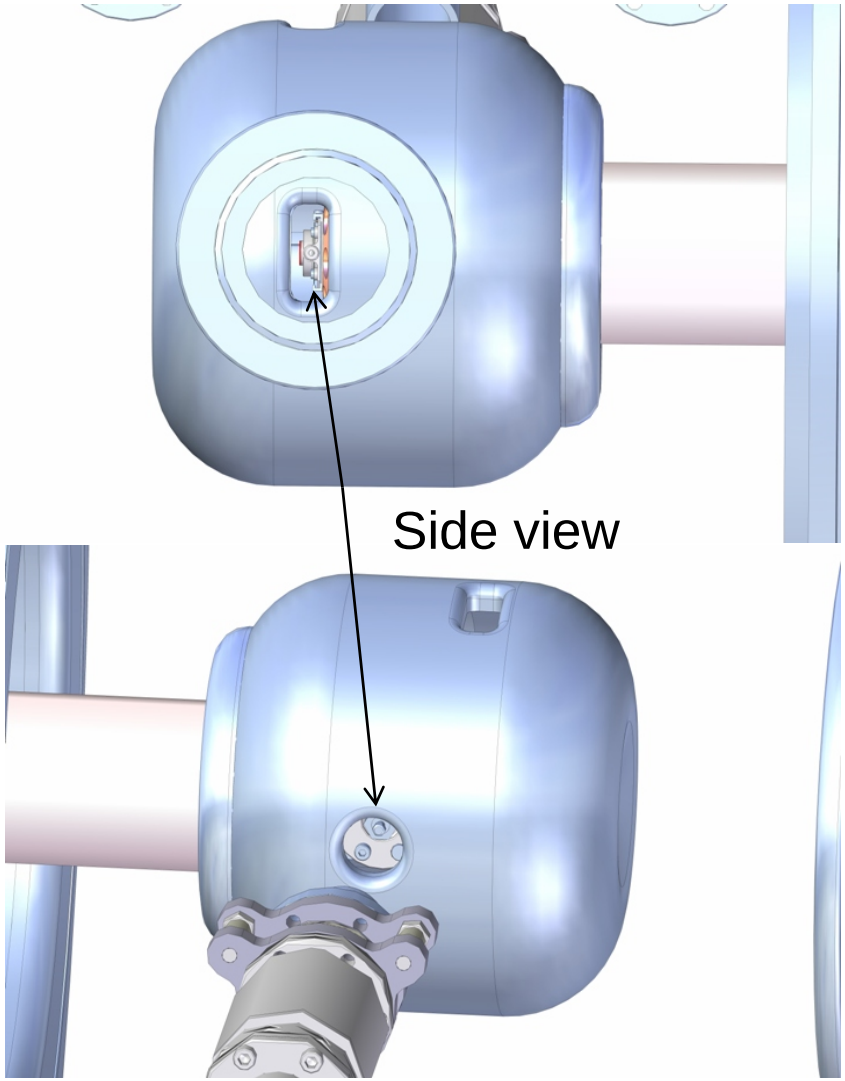
Computer controlled
Photocathode activation

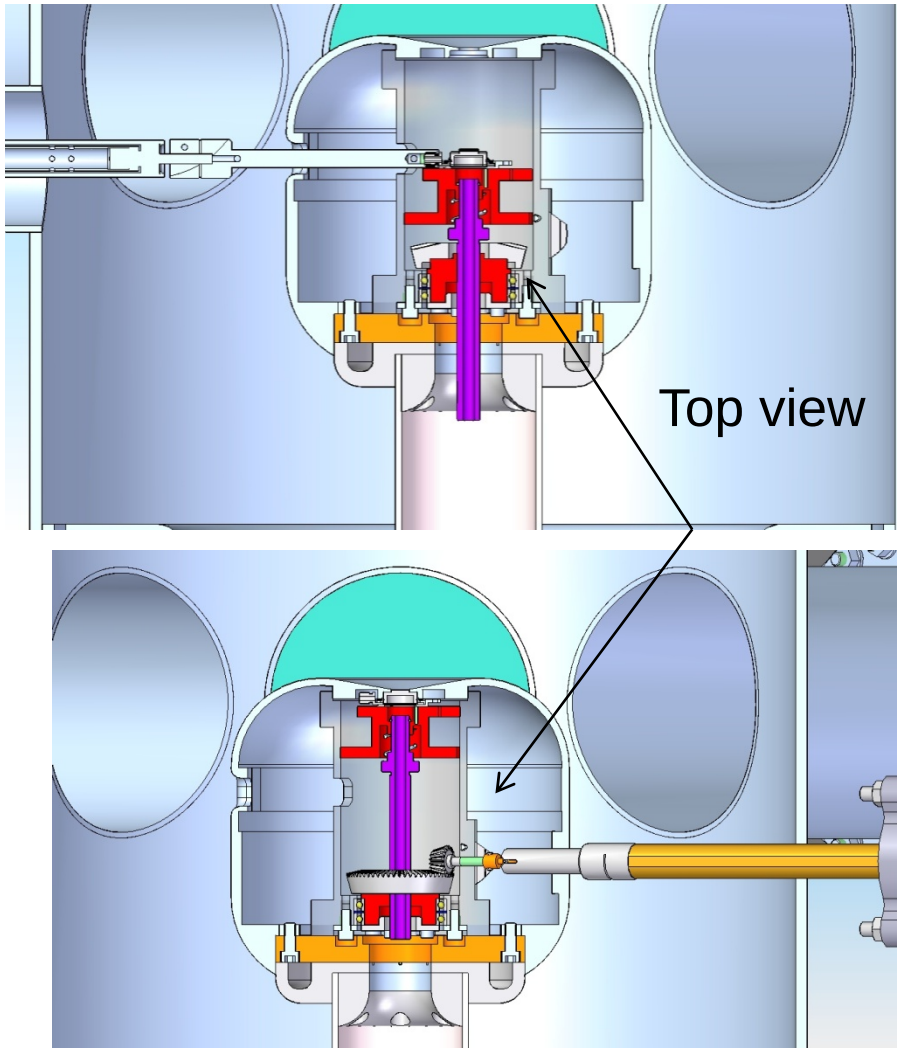




Photocathode lifetime
in the preparation chamber

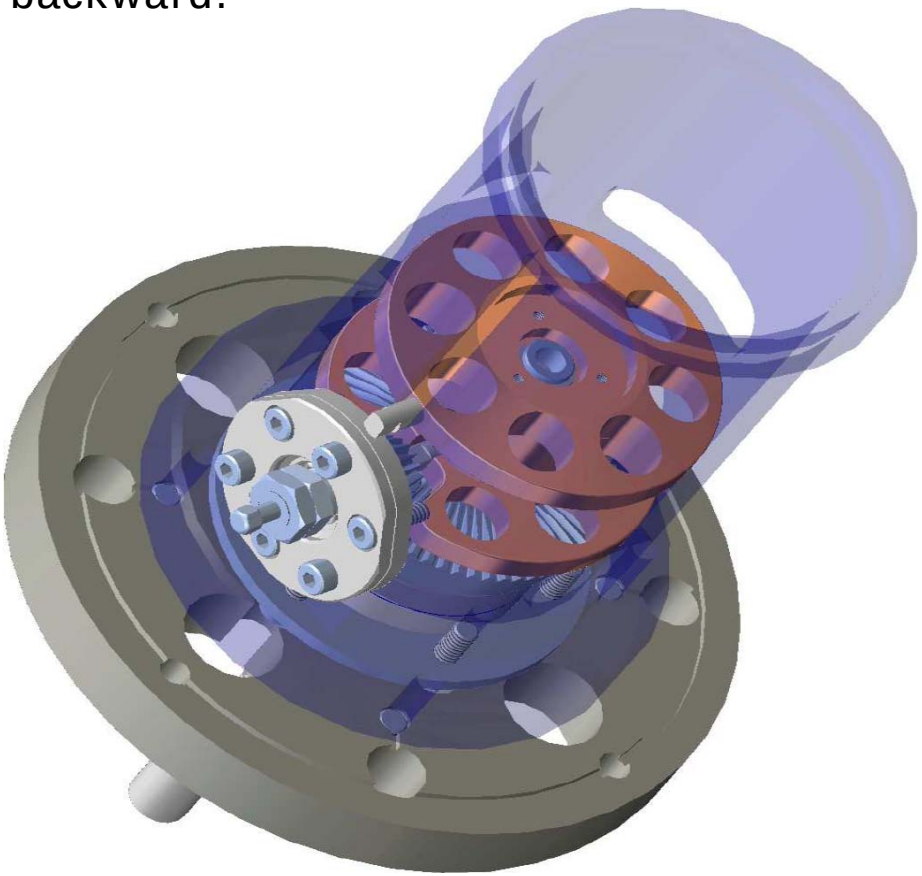
PPS. Side loading of the photocathode

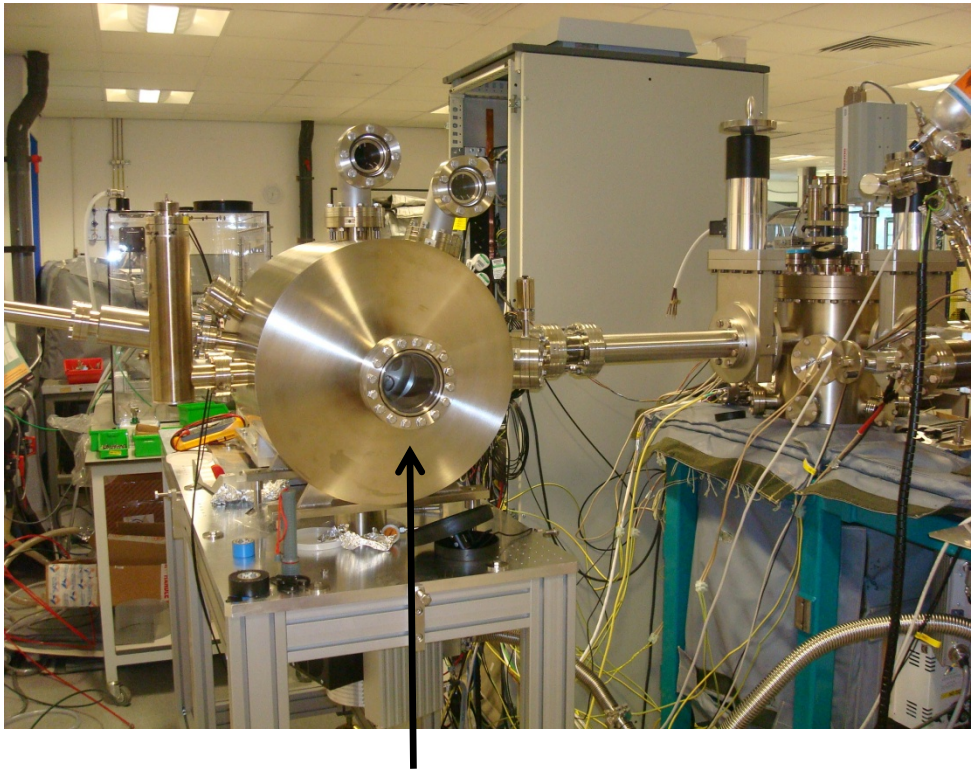




PPS. Ball Mechanism and Prototype Gun

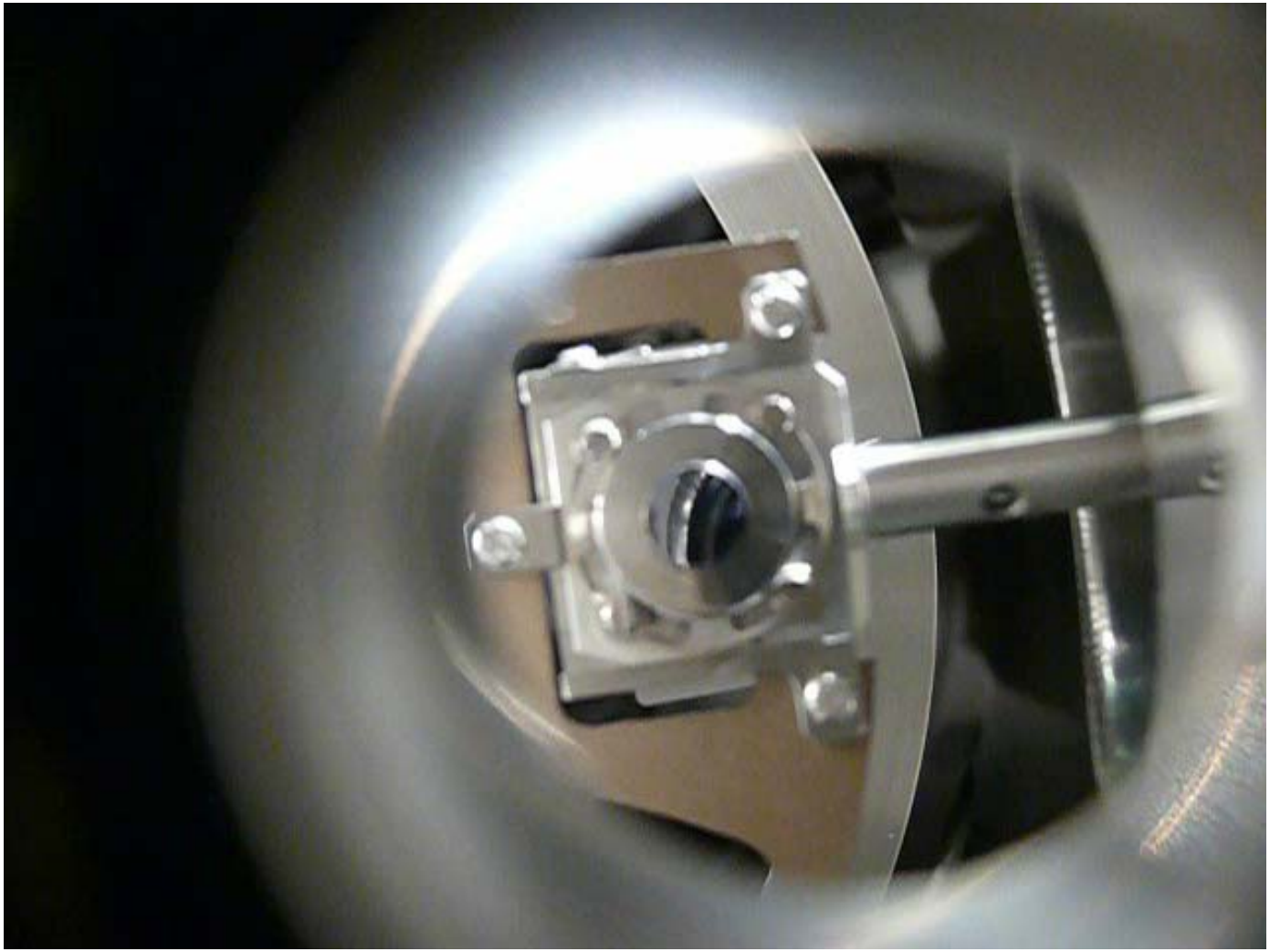
Cathode ball mechanism based a bevel gear for winding the cathode forward and backward.





Mock gun built to test the cathode transfer mechanism. Without bake out the system has worked well.

PPS. Photocathode transfer.



Conclusion

- High brightness high repetition rate electron injectors are the key component of modern accelerator systems which performance essentially defines the performance of the systems as a whole.
- At Daresbury laboratory the following projects are (and use to be) under development:
  - Medium charge, medium and high average current CW photoinjectors for Energy Recovery Linacs
  - Medium charge, high repetition rate thermionic injector for X-FELs
  - Low charge, low repetition rate short pulse photoinjector for compact X-FEL
- These project require solution of the following fundamental problems:
  - Development of semiconductor photocathodes (III-V and alkali) for accelerator application
  - Investigation of their ultimate brightness in different modes of operation
  - Test of the photocathodes in real operational conditions

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