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Dr. Lee Jones
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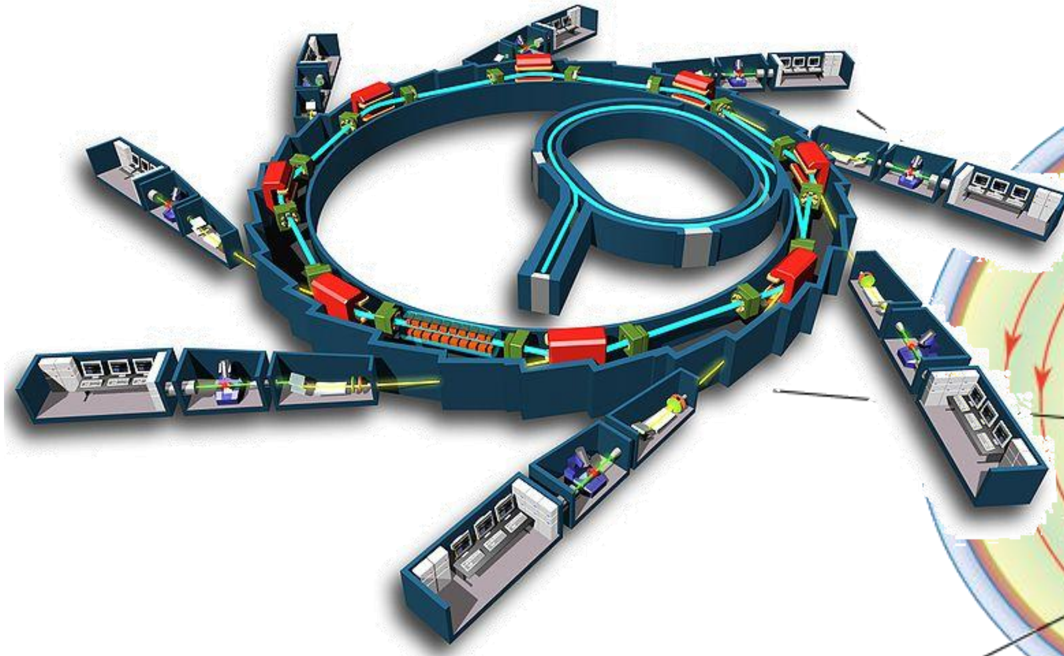
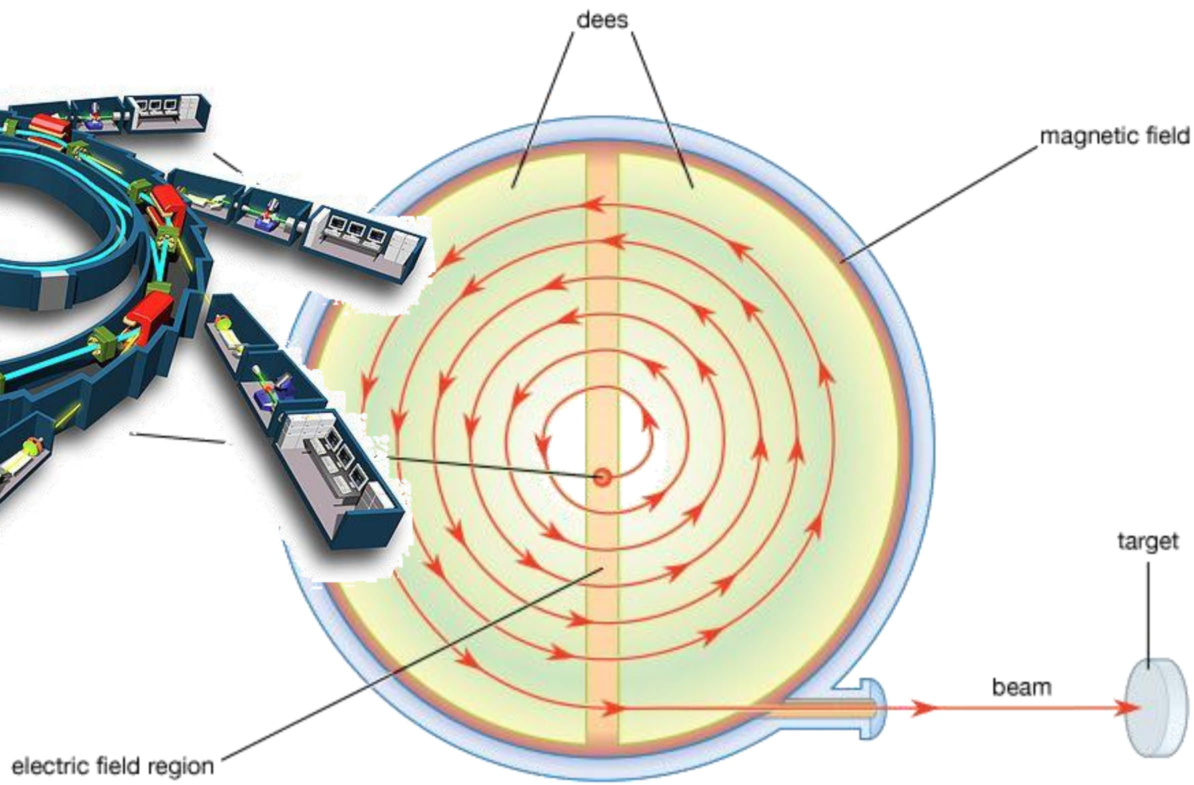
Accelerator Science and Technology Centre
STFC Daresbury Laboratory

Photoinjectors: A General Overview

Over the years ……

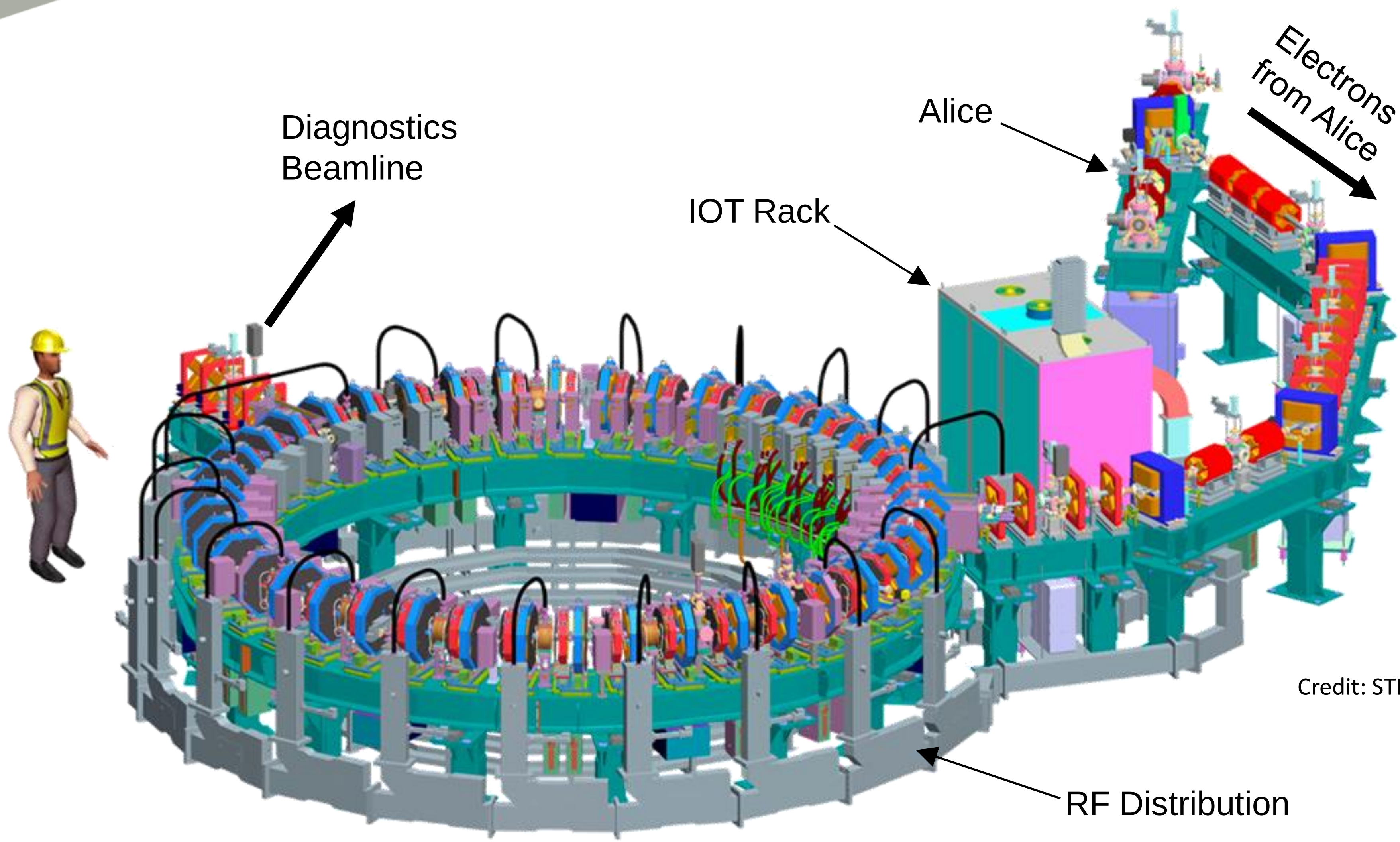




The *synchrotron*

The *cyclotron*

EMMA: The world's first non-scaling fixed-field alternating gradient accelerator (nsFFAG)



Credit: STFC

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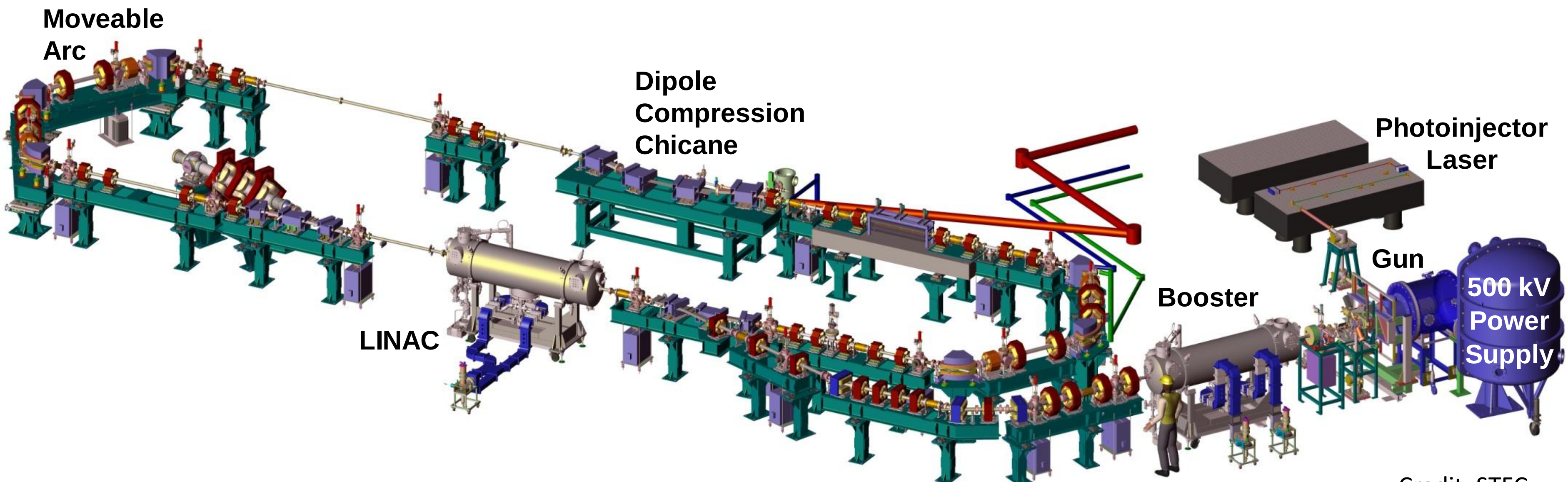
ALICE: Europe's first energy-recovery linear accelerator (ERL)

Single-pass machine ➔ dynamic aperture does not define beam brightness



Credit: STFC

Nominal Gun Energy: 350 keV | Injector Energy: 8.35 MeV | Final Beam Energy: 35 MeV

RF Frequency: 1.3 GHz | Rep. Rate: 81.25 MHz | Bunch Charge: 80 pC | Average Current: 6.5 mA

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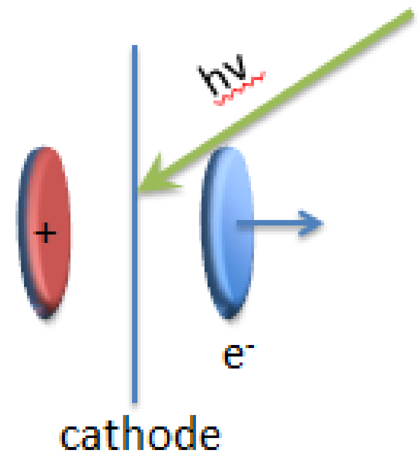
Ultimate beam brightness is now limited by photoinjector performance. Successful FEL operation requires ultra-short high-brightness electron bunches. Key parameters are:

- the photocathode surface electric field (E_{cath})
- the Mean Transverse Energy (MTE) of emitted photoelectrons
  - Difficult to measure – subject of much research

Joseph Liouville



$$B_{max} = \frac{\epsilon_0 mc^2}{2\pi} \frac{E_{cath}}{MTE}$$

$$\epsilon_{nxy,\mathrm{th}} = \sigma_{xy}\sqrt{\frac{\mathrm{MTE}}{mc^2}}$$

This means that Liouville's theorem applies from the photocathode surface

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- What is a an electron gun?
  - Combines electron source with beam conditioning and a high voltage for acceleration
- Possible electron gun technologies:
  - Hot filament
  - Field-emission nano tip array
  - Carbon nanotubes
  - Magneto-optical trap
  - Plasmonic surfaces & structures
  - Photoinjector
    - Photocathode
    - Illumination by pulsed laser
    - Emittance compensation + accelerating stage(s)

An electron gun ? …… No

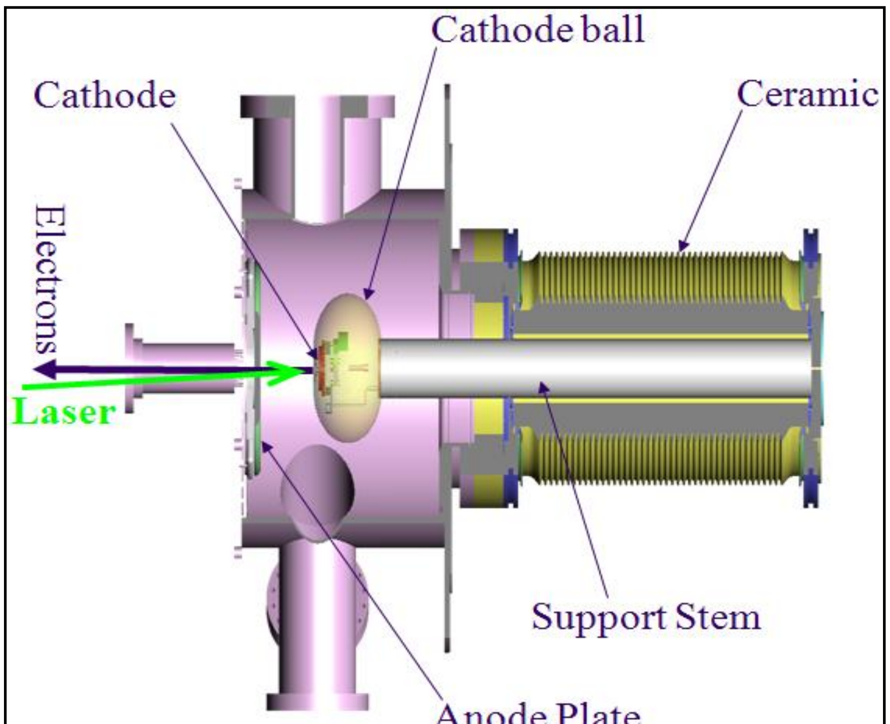
A ***high-performance electron machine gun*** !!!

Two general classes of photocathode electron sources have evolved to meet this challenge:

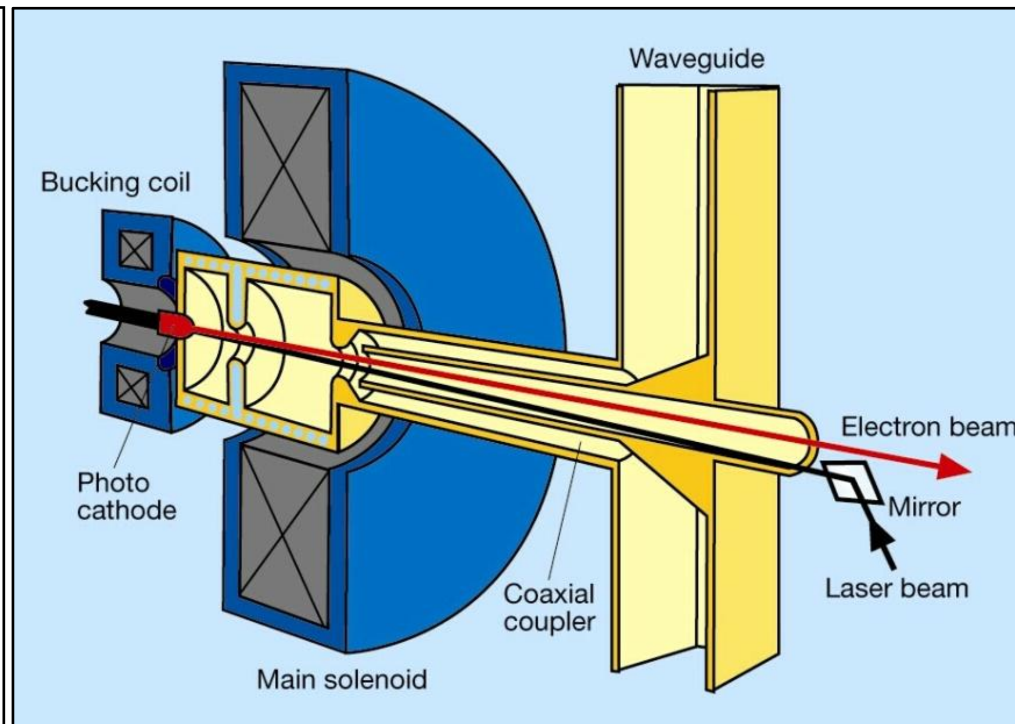
These differ primarily in terms of

- Cost – DC / RF / SRF
- Repetition rate

DC Gun



RF Gun



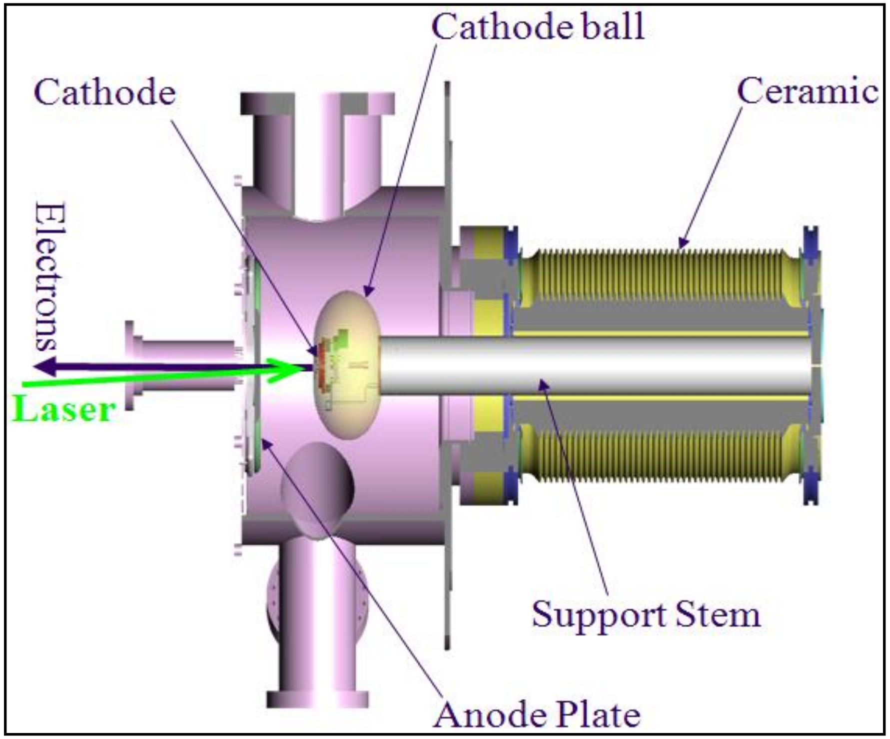
DC/RF Gun performance FOM:

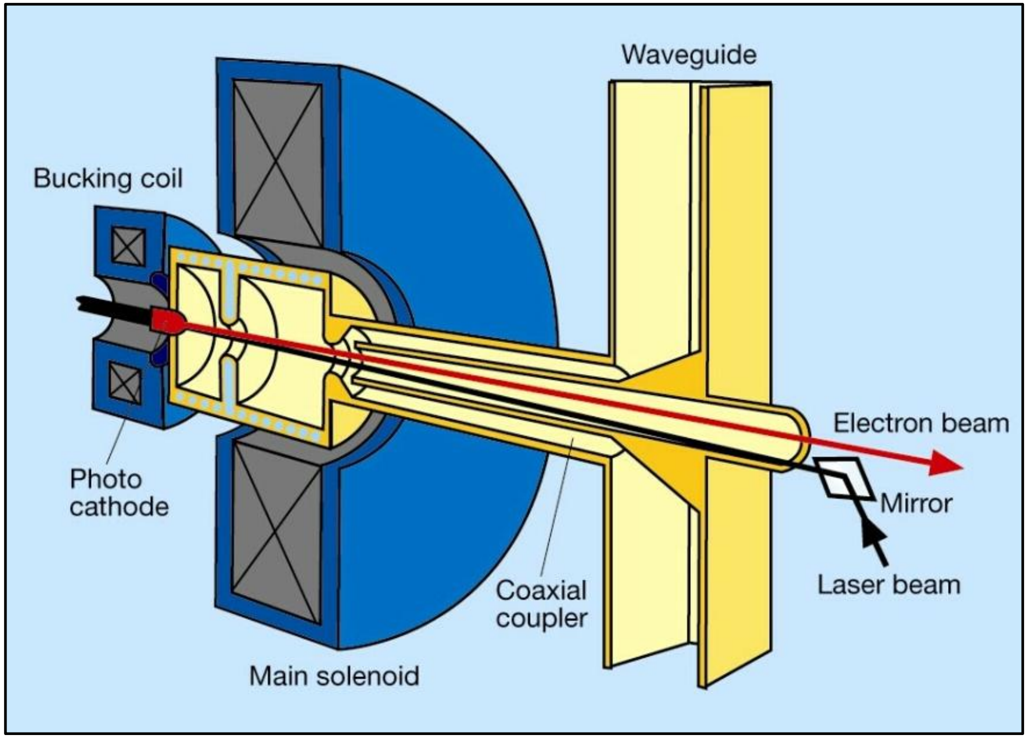
$$\varepsilon_{n,rms} = \frac{1}{2}\sqrt{\frac{2qE_i}{3\pi\varepsilon_0 E_{cath} mc^2}}$$

q = bunch charge [C]

E_i = initial energy [eV]

Field strength, E_{cath}	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





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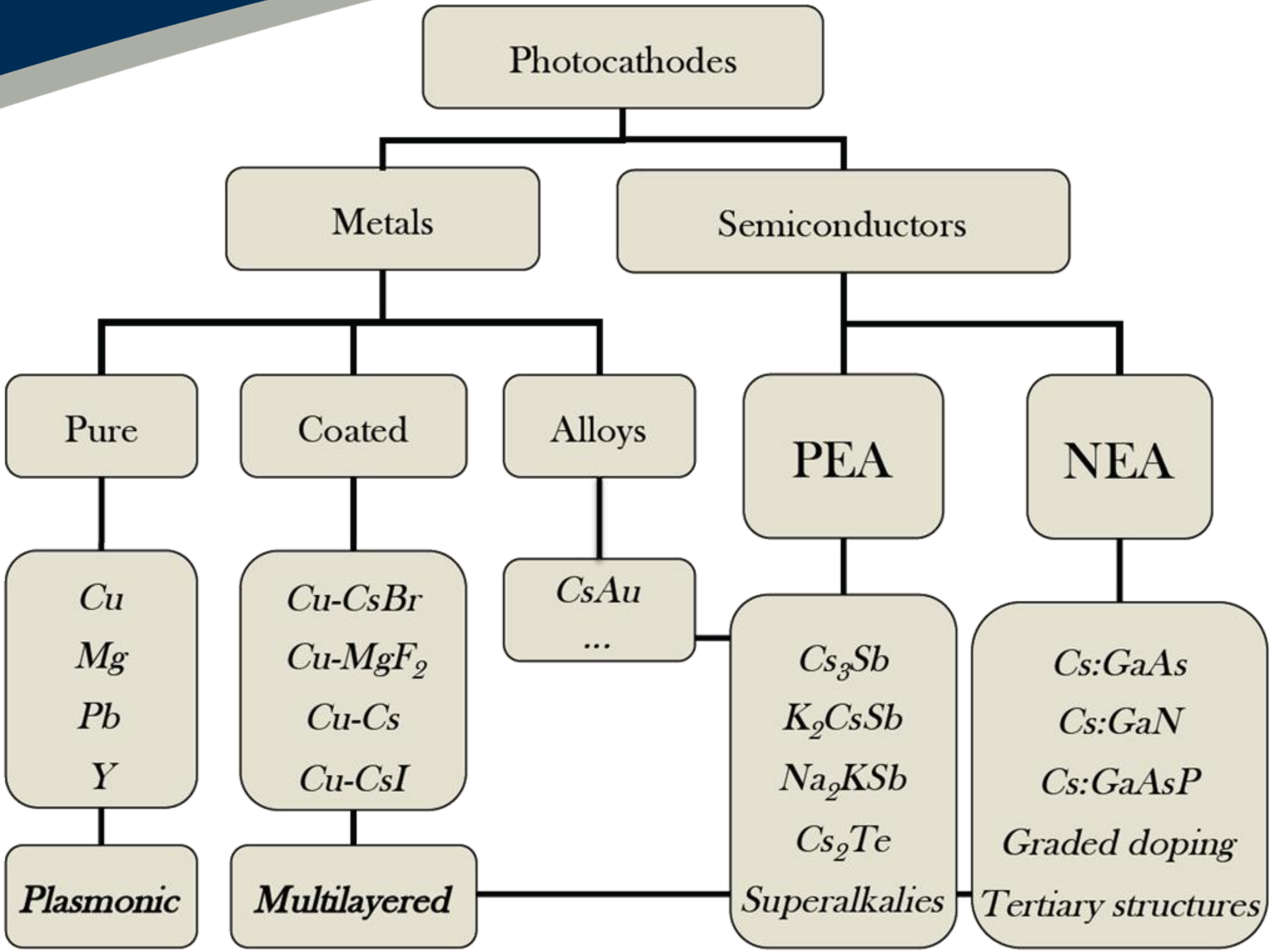
The photocathode family tree



DC Guns: Technical challenges

- Power supply ripple
- Vacuum requirements – dependent on cathode
- Back-ion bombardment
- Dark current / field emission
- HV Conditioning – use of He/Kr during processing
- Insulating ceramic – electrical and mechanical loading

DC Guns: Technical challenges

Power supply ripple

PSU ripple drives fluctuations in beam emittance, bunch shape, bunch arrival time, and average energy after full acceleration.

Phase change at a distance L away from the gun caused by gun voltage variation:

$$\Delta\varphi = 2\pi f \frac{L}{c} \frac{\gamma - 1}{(\gamma\beta)^3} \frac{\Delta V_{gun}}{V_{gun}}$$

where φ is in radians, f is the RF frequency, c is the speed of light, and $\Delta V_{gun}/V_{gun}$ is relative ripple of the gun voltage.

In terms of RF phase, variations of ± 1° are tolerable for low emittance beams.

At 1.3 GHz, ± 1° in phase is approximately ± 2 ps in arrival time, corresponding to a shift of ± 450 V (0.18 %) 1 metre from a 250 kV gun.

The voltage ripple needs to be specified over the **frequency ranges present in the power supply**, typically up to 60 kHz (or more) for switching power supplies.

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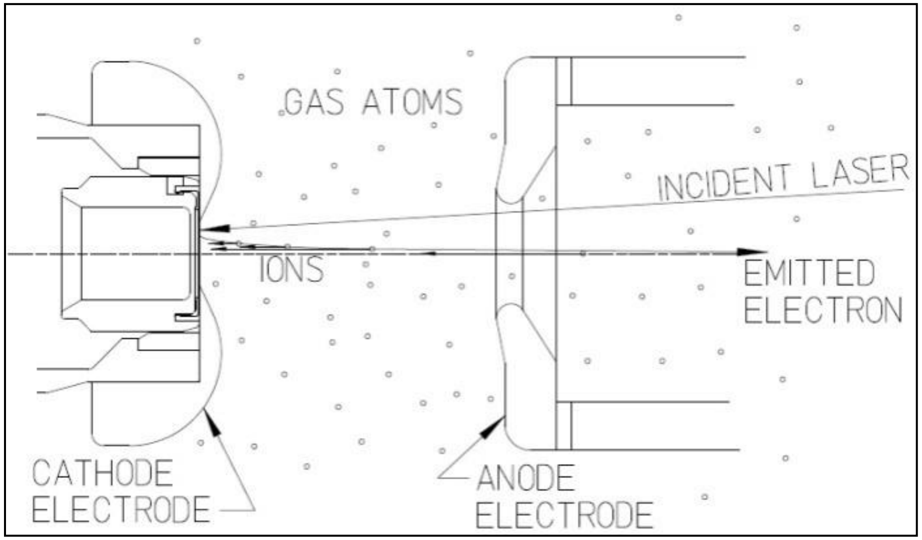
DC Guns: Technical challenges
Vacuum considerations

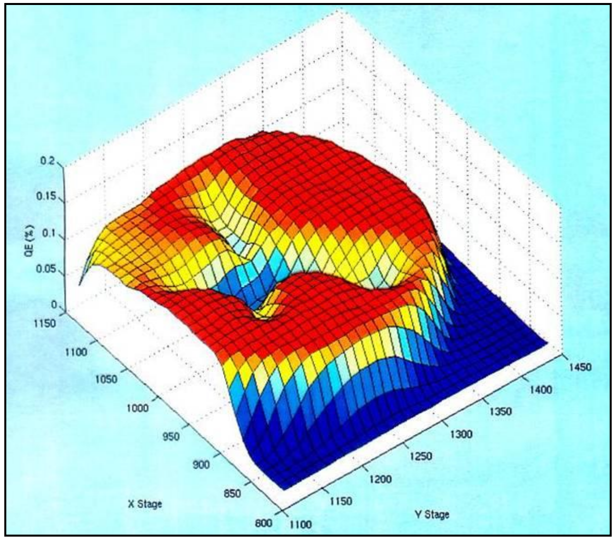
- Much easier to pump a DC gun chamber than an RF gun
- Photocathodes used in a DC gun generally have very high vacuum requirements
  - Requires use of high-quality materials and good engineering practices
  - Pumping to XHV achieved through use of large ion pumps and NEG coatings, and baking for a long time
- Vacuum degraded by gun operations, and in-situ photocathode preparation
  - Maintenance of good gun vacuum requires an external photocathode preparation facility (PPF)
- Poor vacuum leads to contamination of the photocathode, and thereby a drop in the Quantum Efficiency ($Q.E.$)
- Poor vacuum also increases the back-ion bombardment rate, reducing photocathode lifetime and the maximum achievable $Q.E.$

DC Guns: Technical challenges

Back-ion bombardment

- Back-ion bombardment is a major challenge in DC guns
- It degrades $Q.E.$ and damages the cathode surface
- Reduced by good vacuum, but fundamentally un-avoidable
- Worst effects occur within a few mm of the photocathode surface
- Positive bias on the anode suppresses back-ions from downstream



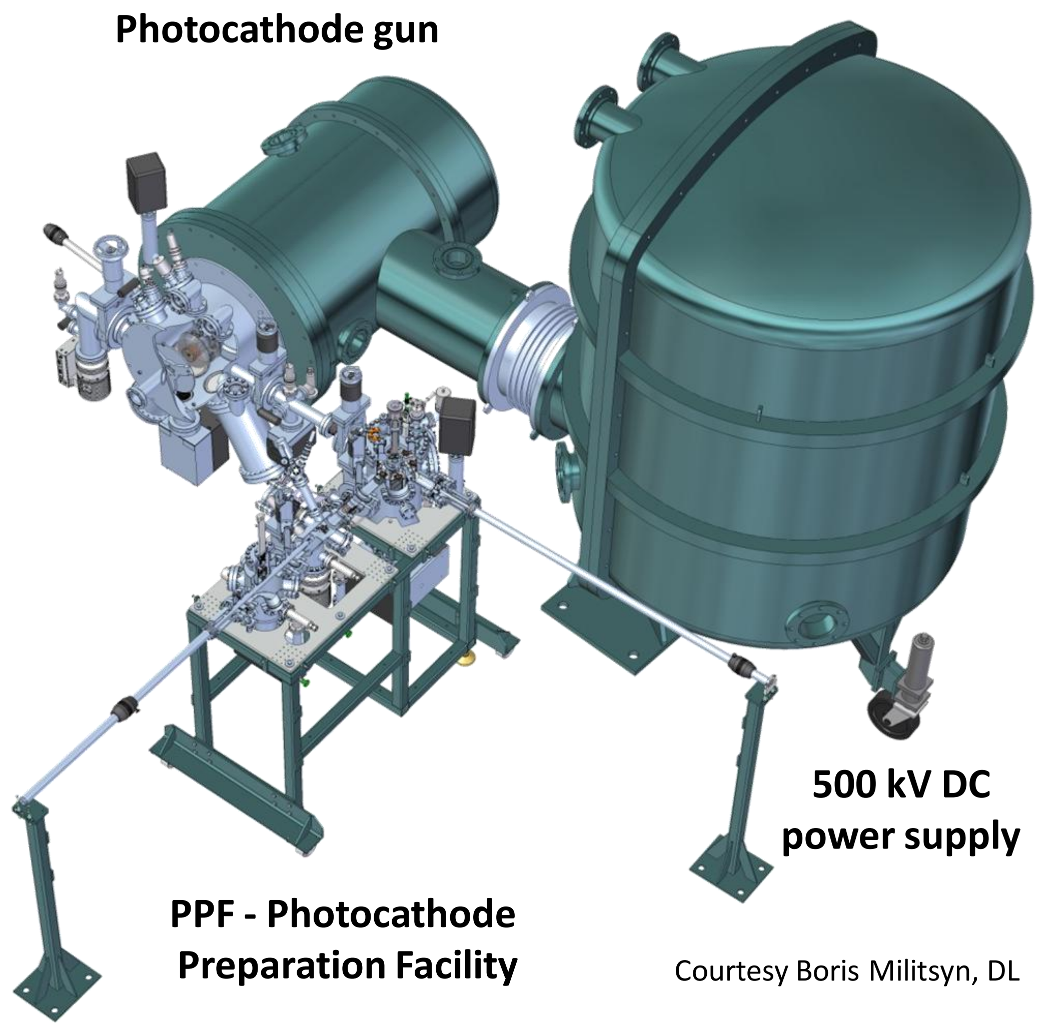


Courtesy Joe Grames, JLab

DC Guns: Technical challenges

The use of a PPF confers several *operational advantages*:

- Improved environment for photocathode activation
- Reduced accelerator down-time for photocathode activation, permitting operations with high bunch charge
- Improved gun operating environment
  - Better gun vacuum
  - Reduces contamination of the gun HV electrodes
- Permits accelerator operation with different types of photocathodes



Courtesy Boris Militsyn, DL

Photocathode Preparation Facility for the ALICE ERL DC photocathode gun

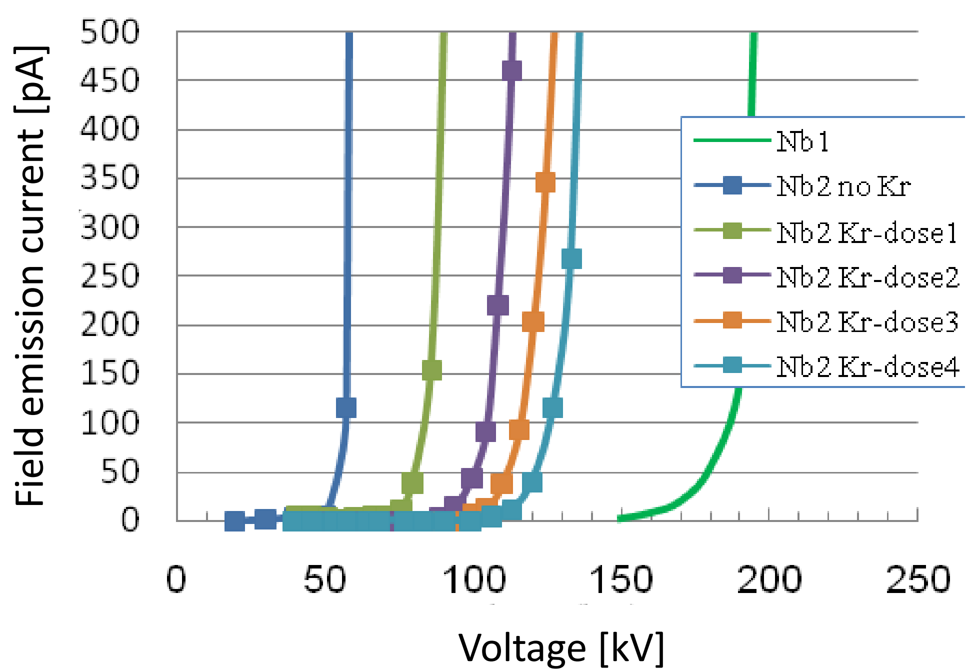
DC Guns: Technical challenges

High voltage conditioning

- Potentially dangerous, but essential for stable operation of a DC gun
- HV electrodes must be 'trained' to support high voltages
- Conditioning necessary to desired operating voltage + 10 % as a minimum
- Use of Kr during HV conditioning is beneficial for new HV electrodes

Right: Measurements of field emission between two single crystal niobium electrodes, polished with BCP process and HV conditioned using Kr.

Courtesy Matt Poelker, JLab



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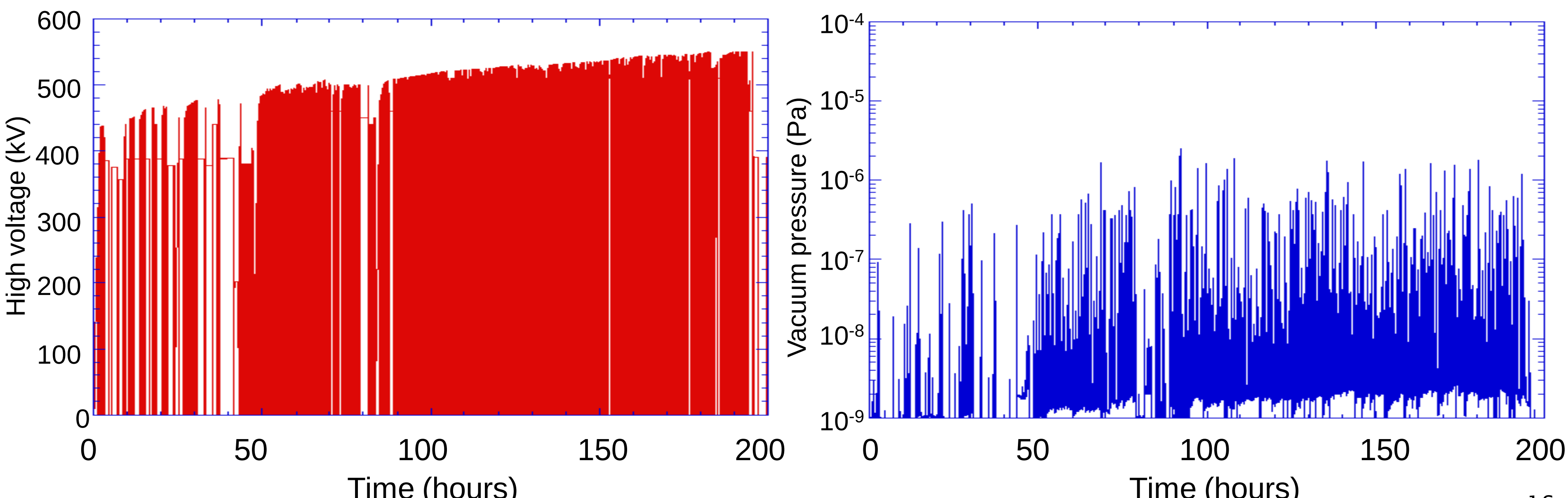
DC Guns: Technical challenges

High voltage conditioning

- Potentially dangerous, but essential for stable operation of a DC gun
- HV electrodes must be ‘trained’ to support high voltages
- Conditioning necessary to desired operating voltage + 10 % as a minimum
- Use of Kr during HV conditioning is beneficial for new HV electrodes
- Can be very time-consuming

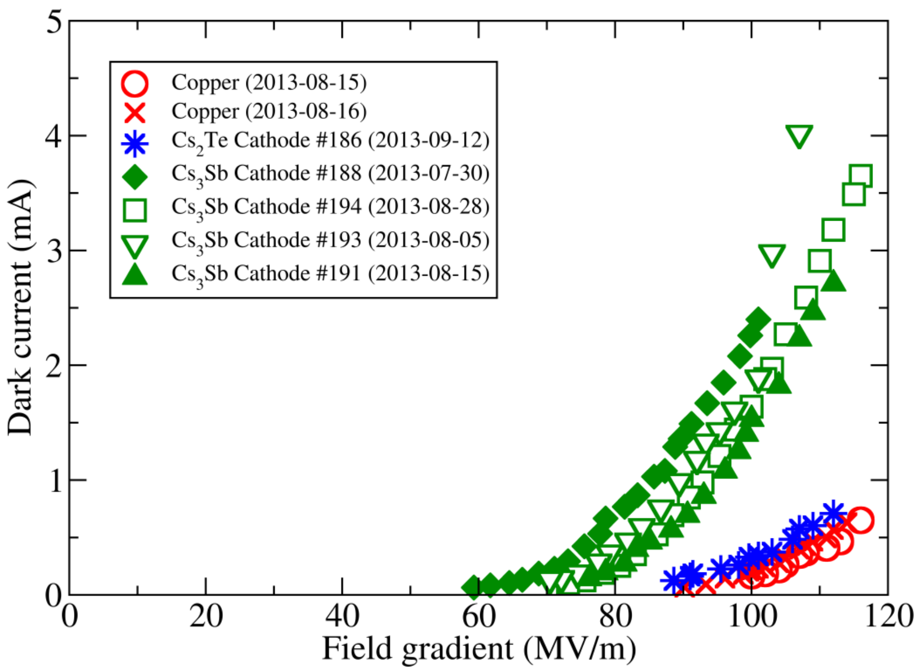


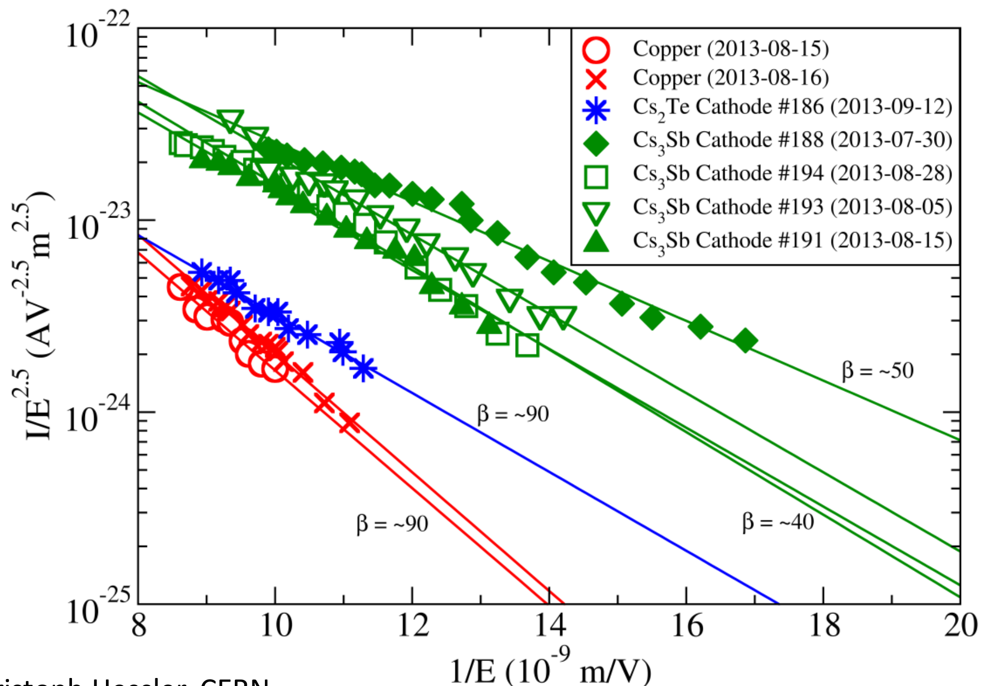
Courtesy Noboyuki Nishimori, JAEA

DC Guns: Technical challenges

Dark current & Field emission

- Some dark current is un-avoidable in *any* photocathode gun
  - Intrinsic property of the photocathode, affected by photocathode choice





Courtesy Christoph Hessler, CERN

Measurements show that Cu and Cs_2Te have similar levels of dark current emission, but Cs_3Sb exhibits much higher dark current levels.

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DC Guns: Technical challenges

Dark current & Field emission

- Some dark current is un-avoidable in *any* photocathode gun
    - Intrinsic property of the photocathode, affected by photocathode choice
- Low-level field emission is also unavoidable, but must be managed
    - Careful design of HV surfaces and maximum electric field strength
    - Clean conditions during assembly
    - Effective HV conditioning
- Intense or sudden field emission can be *catastrophic*
    - Tracking along ceramic – short circuit
    - Punch-through causing a leak
- Biased (floating) anode plate permits dark current measurements

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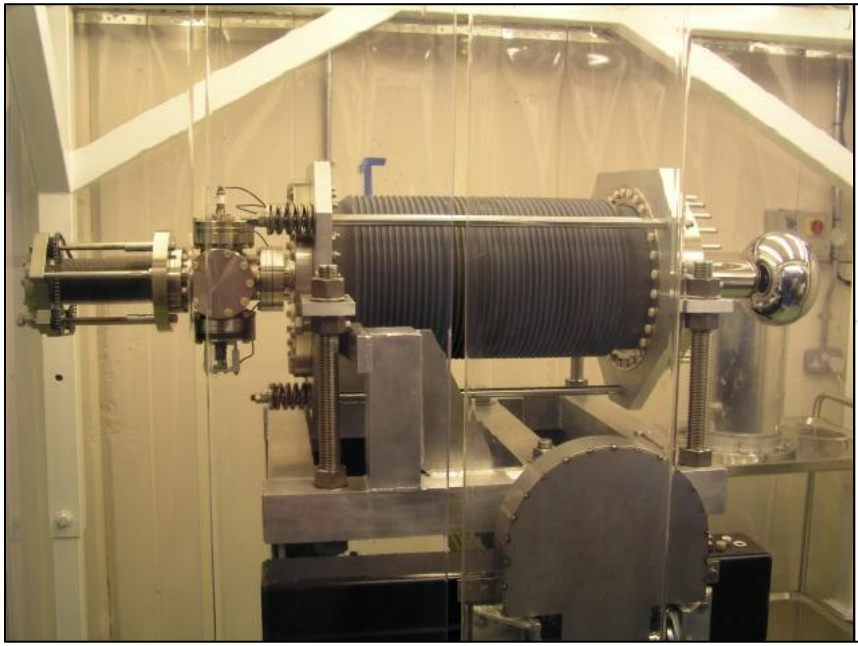
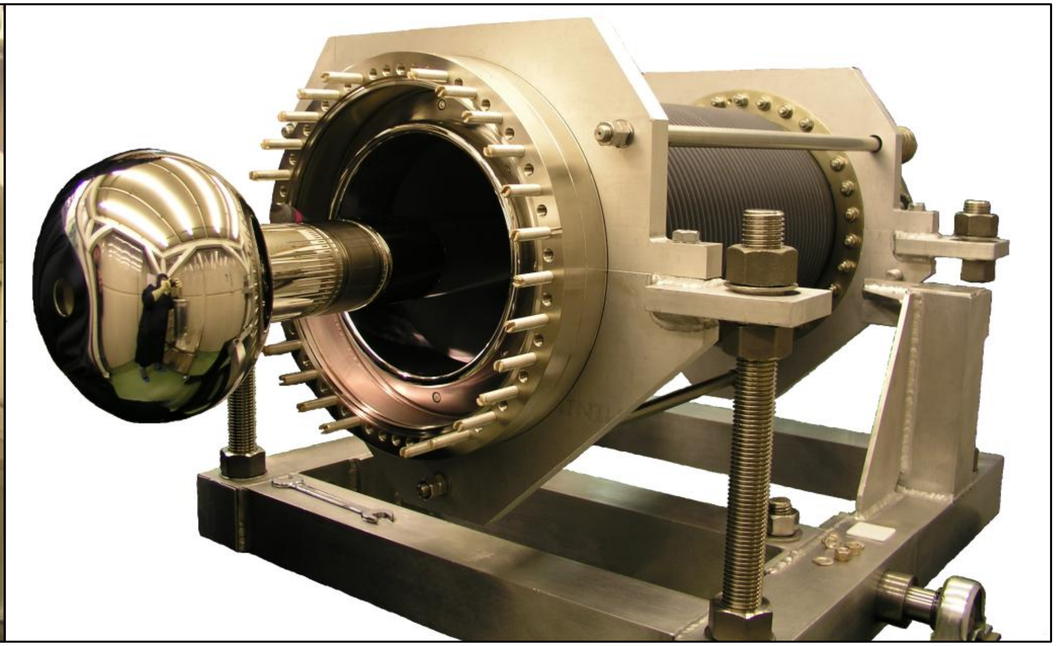
DC Guns: Technical challenges
Insulating ceramic

- Insulating ceramic must withstand extreme DC voltage and a large mechanical load whilst maintaining large pressure difference
- It should not be a perfect insulator !!!
- Surface coating or bulk doping for high resistivity





DC Guns: Technical challenges

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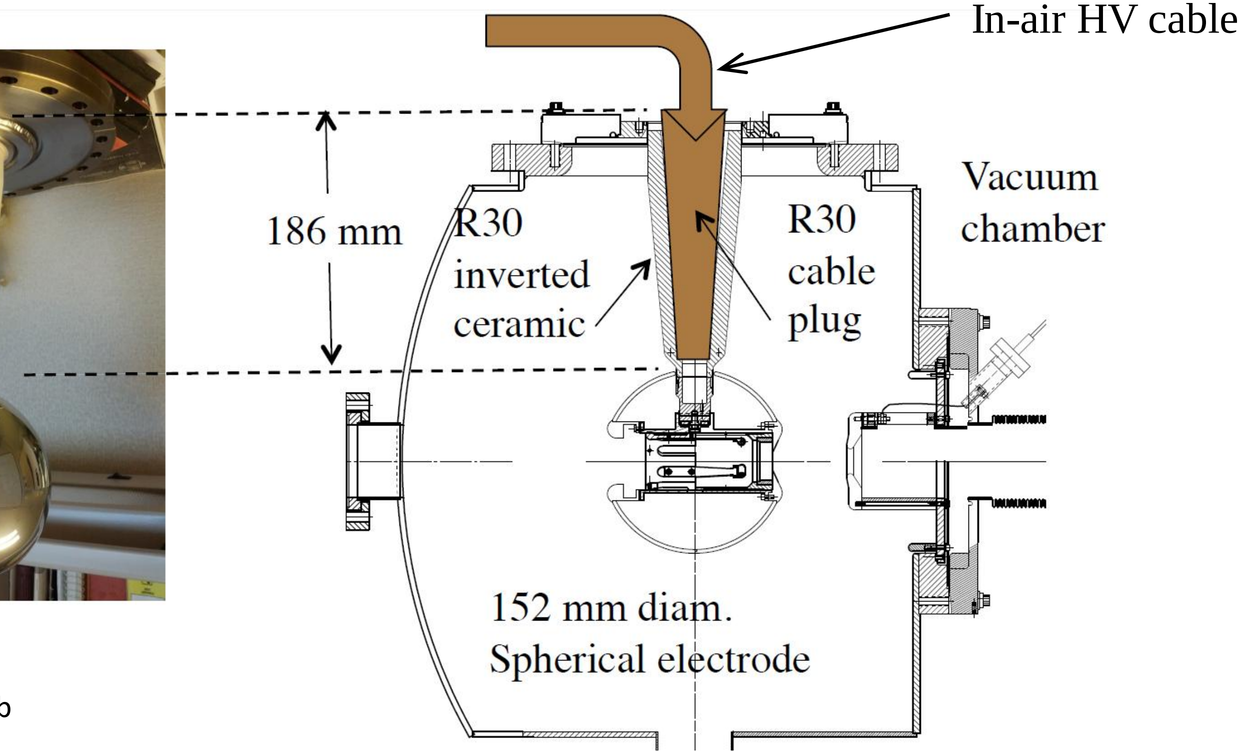
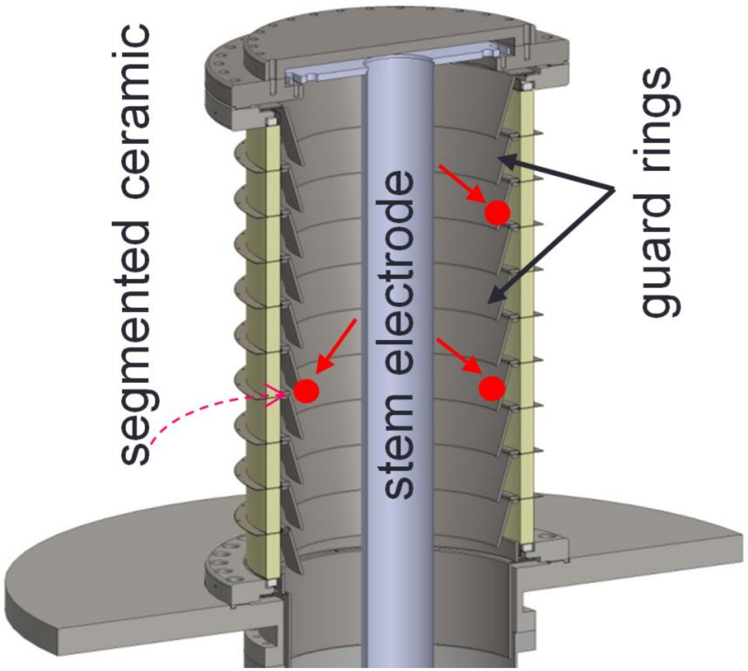


Courtesy Carlos Hernandez-Garcia, JLab

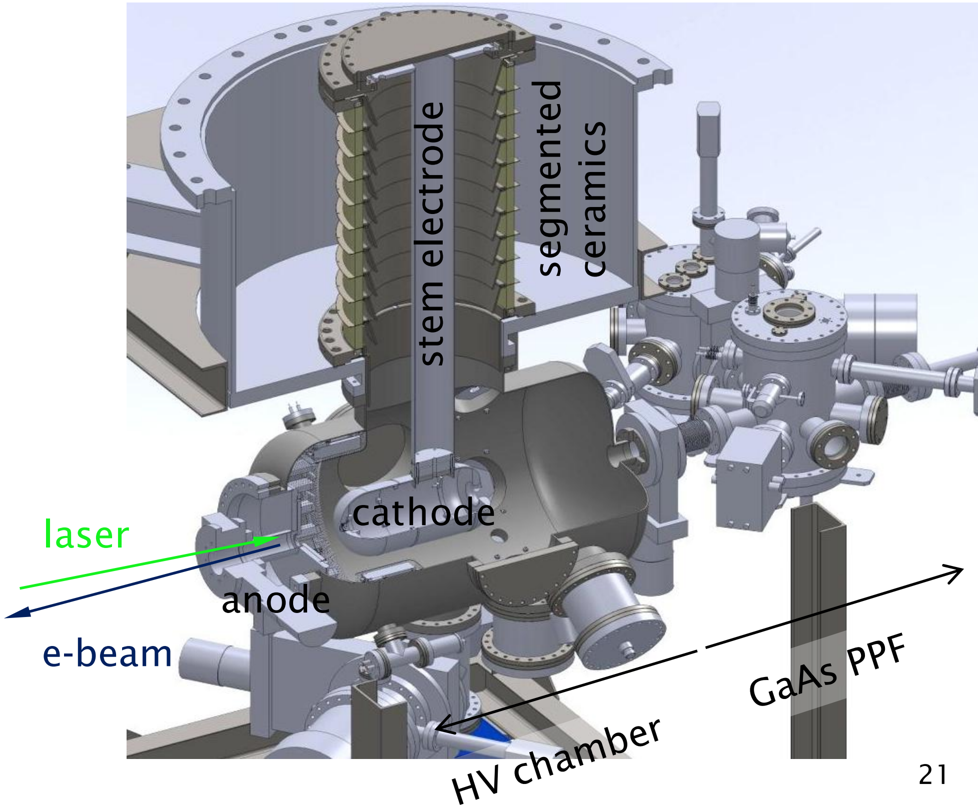
DC Guns: Technical challenges

Insulating ceramic

- Insulating ceramic must withstand extreme DC voltage and a large mechanical load whilst maintaining large pressure difference
- It should not be a perfect insulator !!!
- Segmented ceramic with guard rings



500 kV Photocathode gun at JAEA



Courtesy Noboyuki Nishimori, JAEA

RF Guns: Technical challenges

Some common ground

RF guns share some of the technical challenges described for DC guns:

- Photocathode integration
  - Vacuum environment & electric field disruption
  - Different photocathode ‘standards’
  - Collaborations difficult – vacuum suitcases needed
- DC Ripple / effective RF ripple – amplitude and timing
  - Cavity temperature stability
- Symmetric and uniform electric field
- Dark current / field emission
- Synchronisation of the photoinjector drive laser to the RF via a master clock
  - Use of optical clocks for distributed timing – Holgar Schlarb, DESY
  - Problems increase with the size of the facility

DC & RF Guns: Drive Lasers

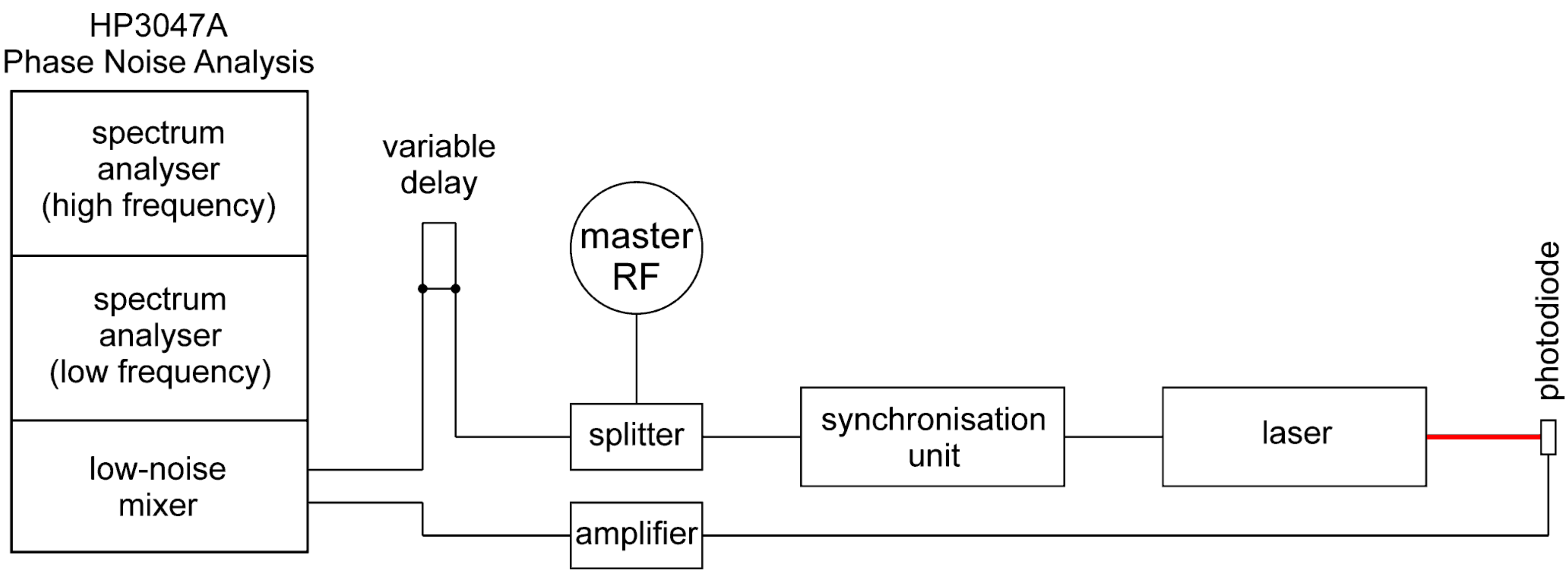
Synchronisation with the RF

- Arguably the most critical factor in a photocathode/photoinjector gun
- Very difficult to measure accurately !!!
    - Amplitude noise indistinguishable from phase noise
- Best-practice for phase noise measurements in lasers establish by Scott *et. al*: IEEE J. Sel. Top. Quan. Elec.; 7(4), 641, 2001

DC & RF Guns: Drive Lasers

Synchronisation with the RF

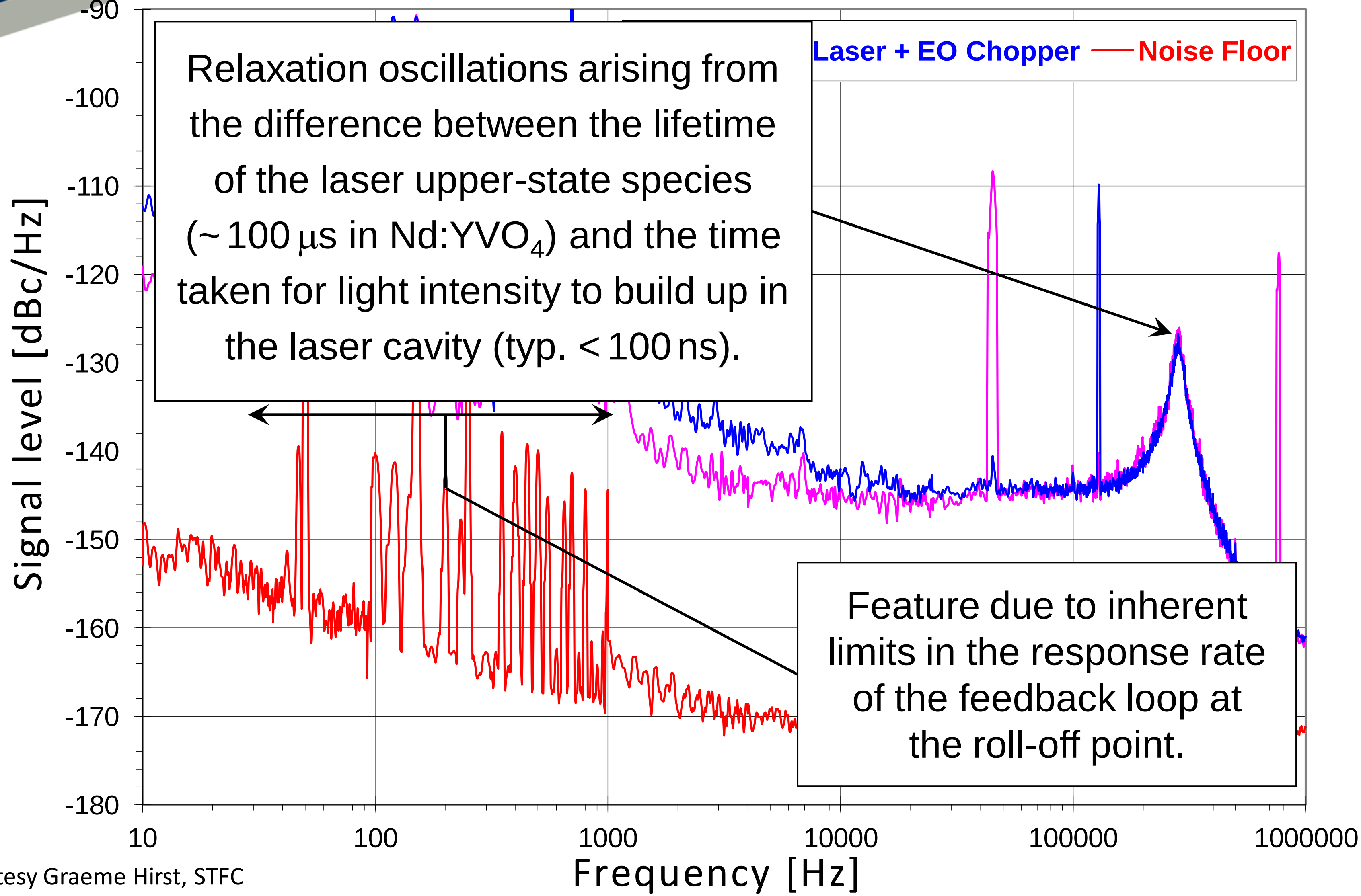
Measurements on ALICE: Initially, the noise floor of the HP3047A system was measured by feeding the same signal from a *Wenzel* low-noise 81.25 MHz RF oscillator into both inputs of the low-noise mixer in quadrature. The laser was then synchronised to the oscillator, and the laser output fed back to a low-noise mixer via a fast photodiode.



Courtesy Graeme Hirst, STFC

DC & RF Guns: Drive Lasers

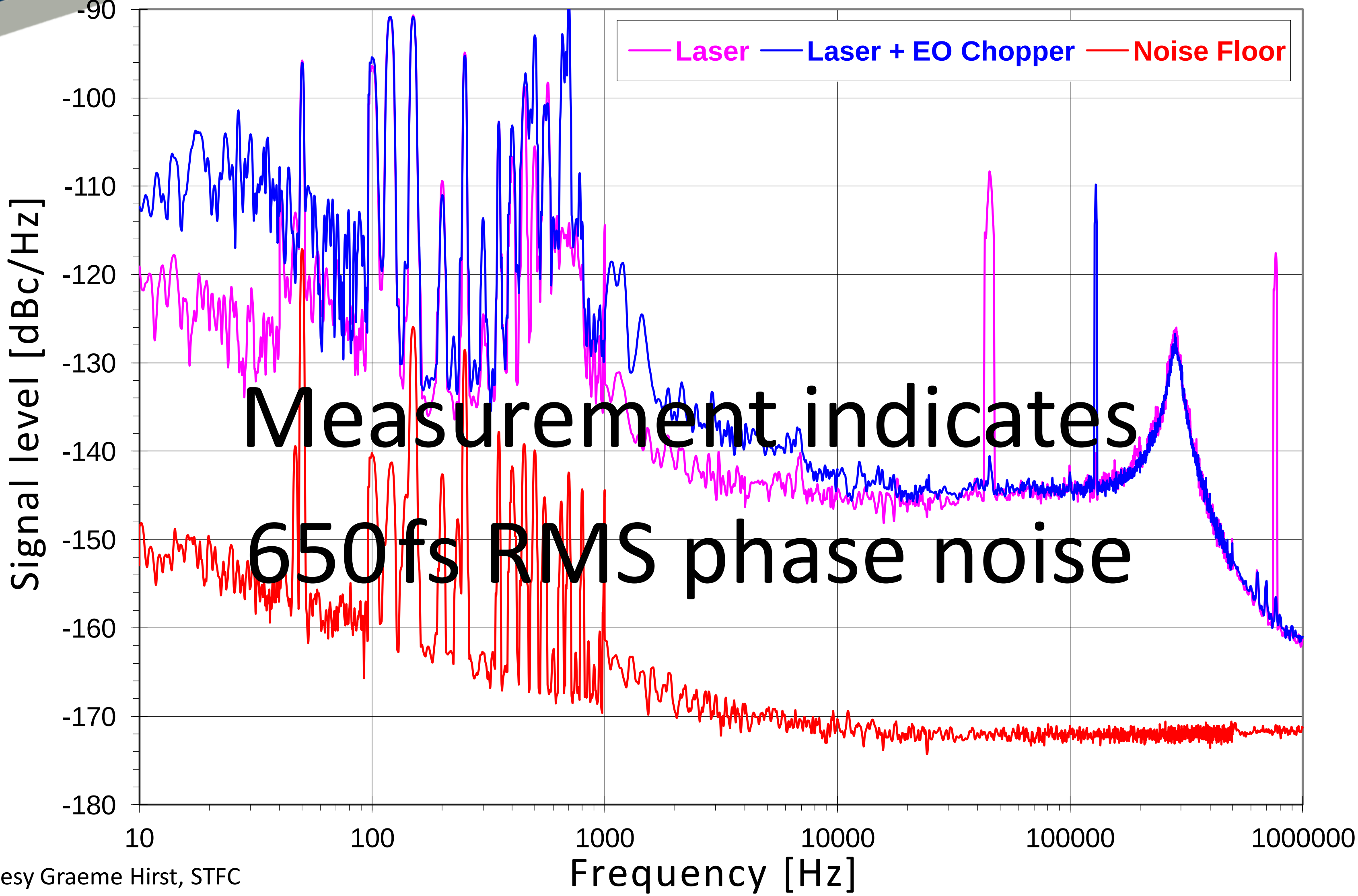
Synchronisation with the RF



Courtesy Graeme Hirst, STFC

DC & RF Guns: Drive Lasers

Synchronisation with the RF



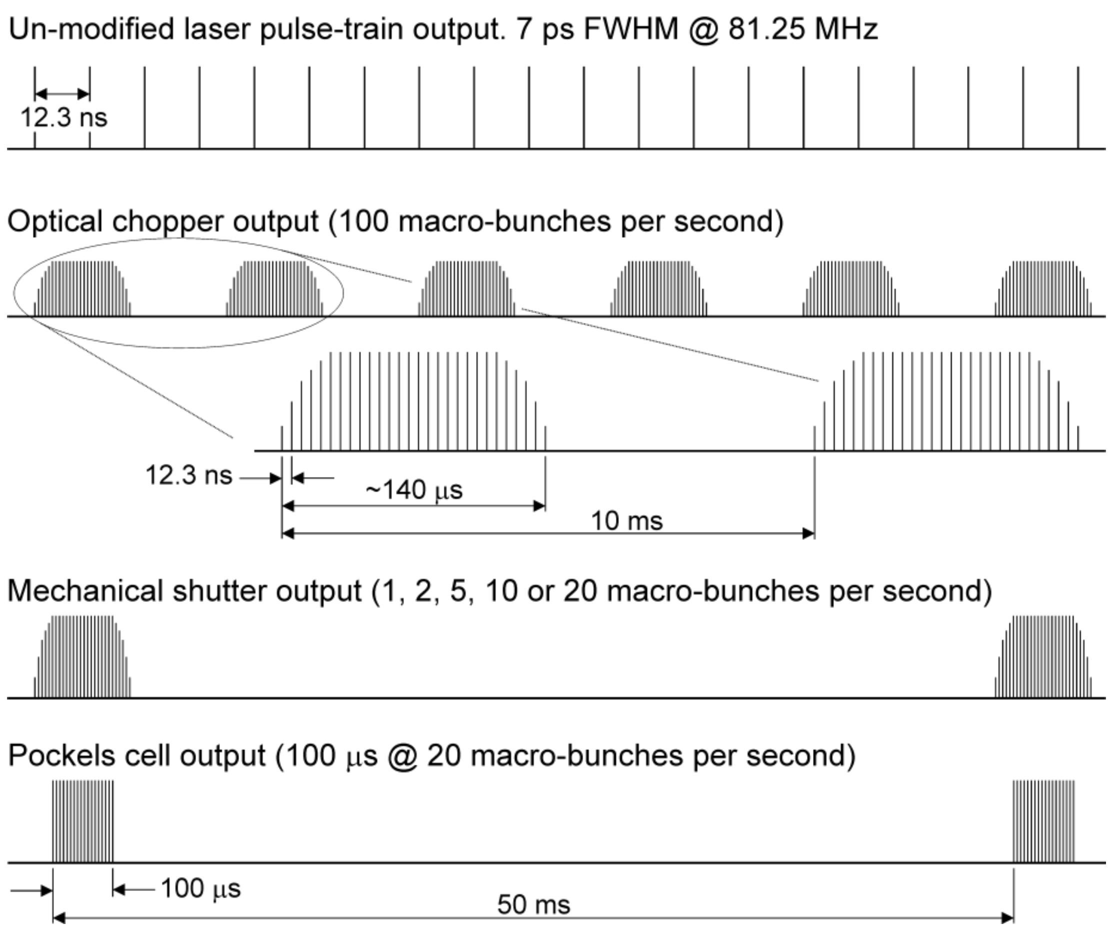
Measurement indicates 650fs RMS phase noise

Courtesy Graeme Hirst, STFC

DC & RF Guns: Drive Lasers

Extinction ratio

Extinction ratio is *critical* in a non-CW machine



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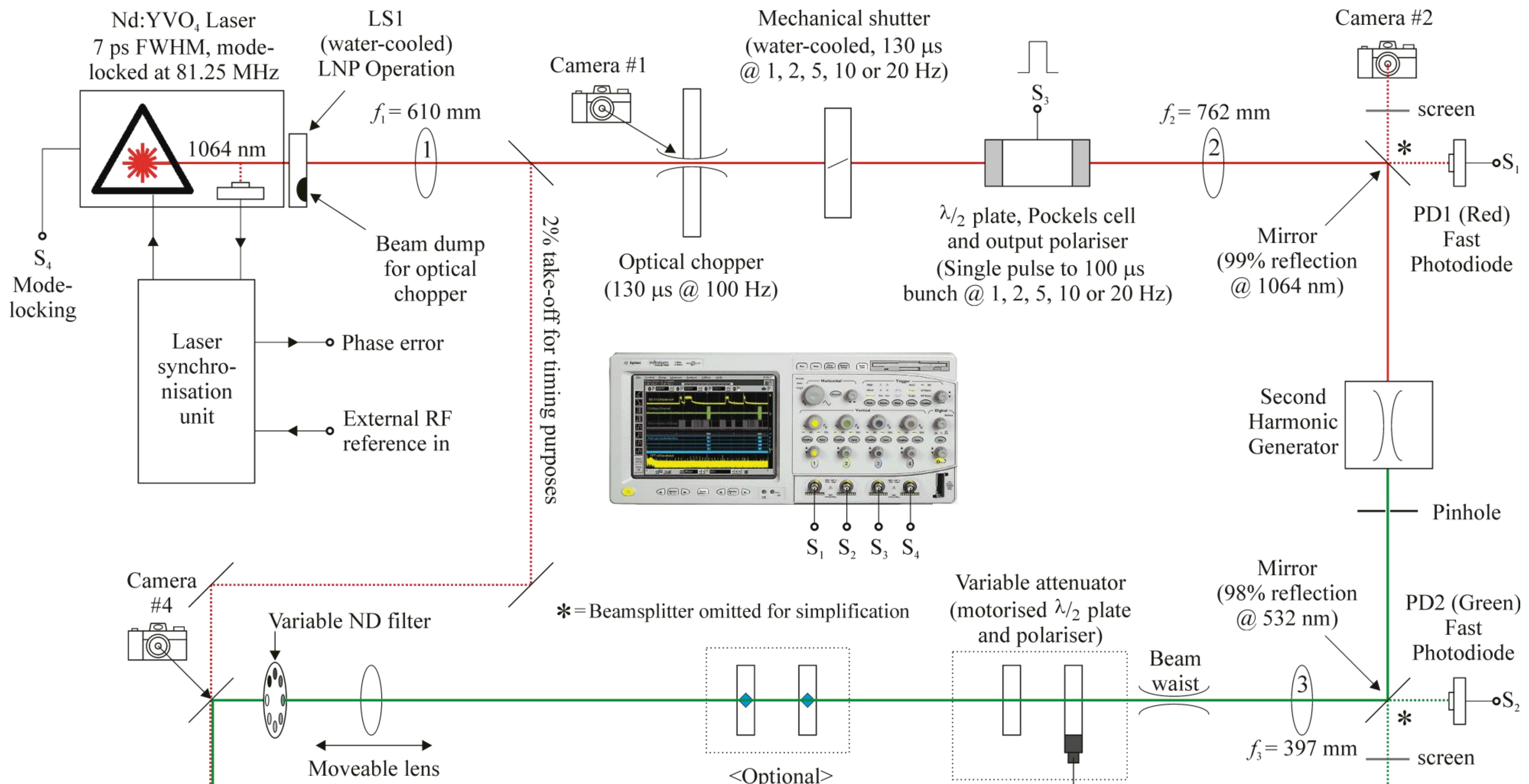
DC & RF Guns: Drive Lasers

Extinction ratio

Pulse chopping carried out at long λs, then frequency 2ω or 3ω applied



DC & RF Guns: Drive Lasers

Extinction ratio

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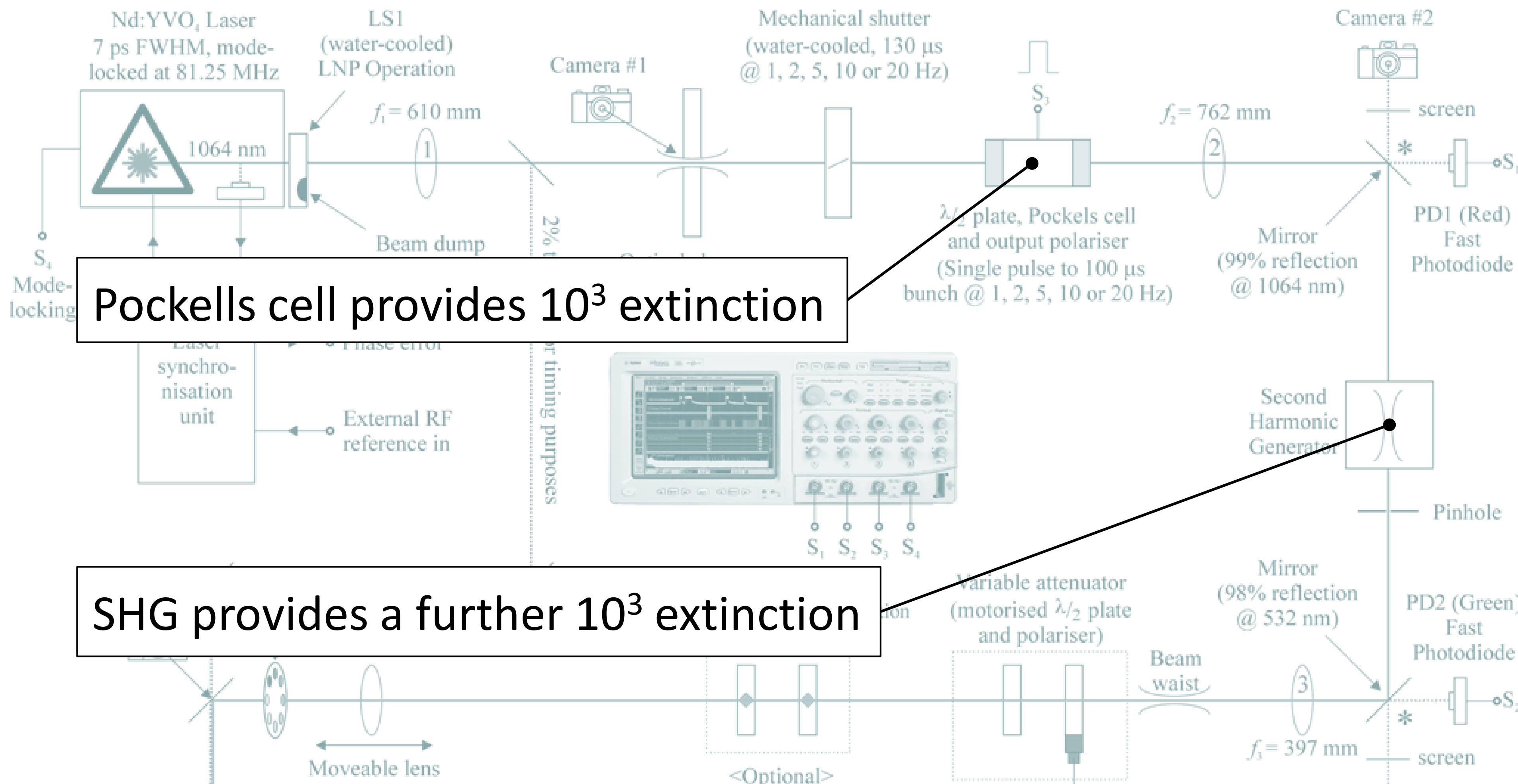

Pockells cell provides 10^3 extinction

SHG provides a further 10^3 extinction

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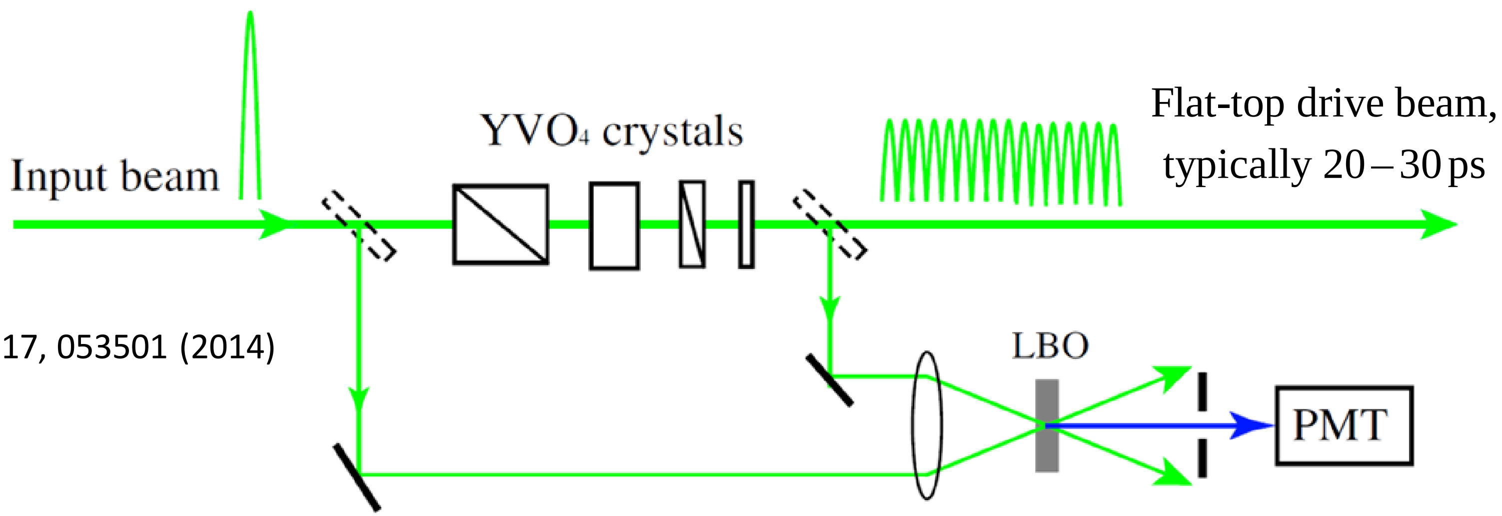
DC & RF Guns: Drive Lasers

Longitudinal & transverse shaping

- The 3D intensity distribution of the laser determines the 3D distribution of the photoemitted electrons
- The initial electron distribution has a significant effect on emittance in a space-charge-dominated beam
- Longitudinal and transverse laser spatial profiling can minimise emittance



PRSTAB 17, 053501 (2014)

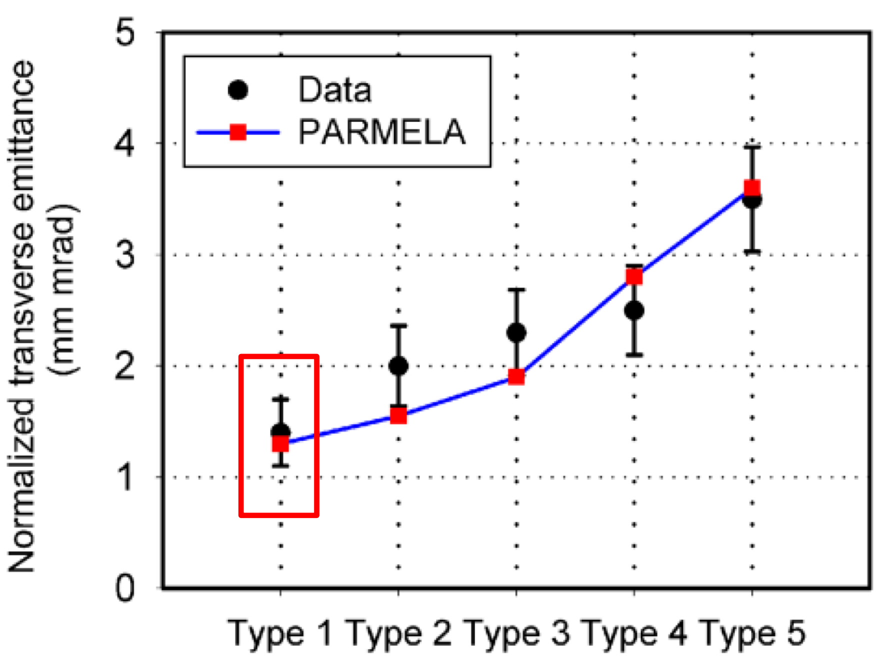
- Four YVO_4 crystals used in series to 'stack' copies of the incoming short laser pulse
- Cross-correlation measurement used to monitor overall pulse length

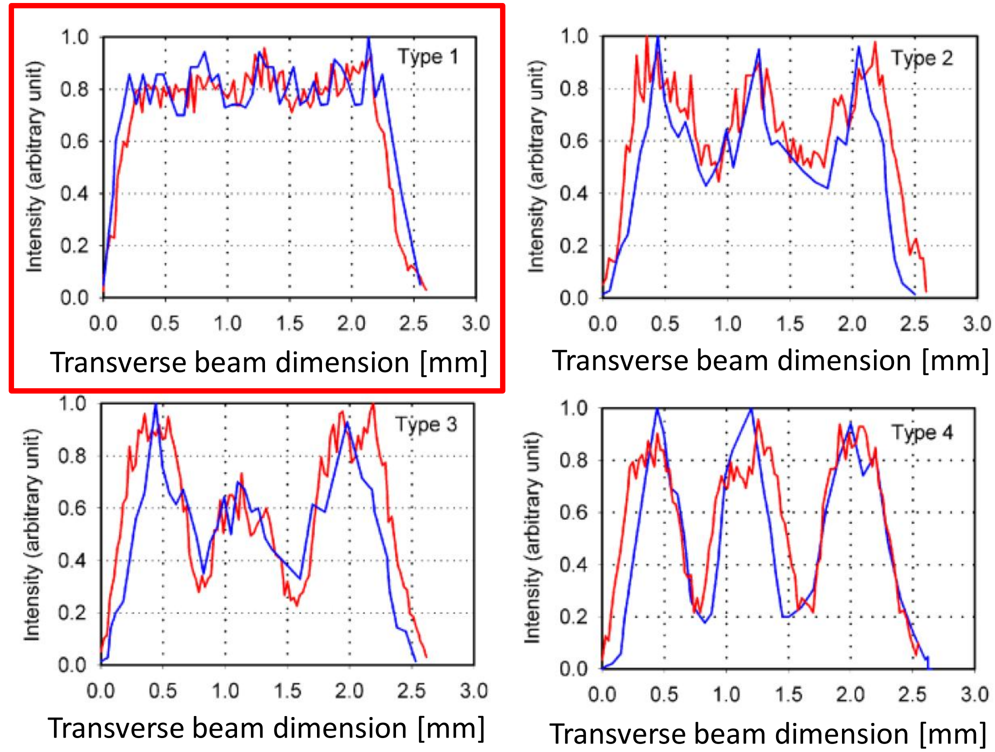
DC & RF Guns: Drive Lasers

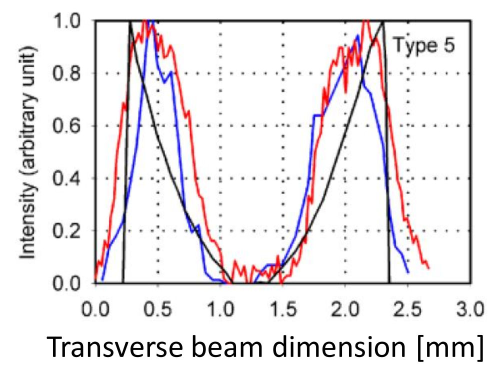
Longitudinal & transverse shaping

A non-uniform laser beam generates a non-uniform electron beam which expands at a rate linked to the plasma period.

The best electron beam is achieved with a *truncated Gaussian* transverse laser beam.







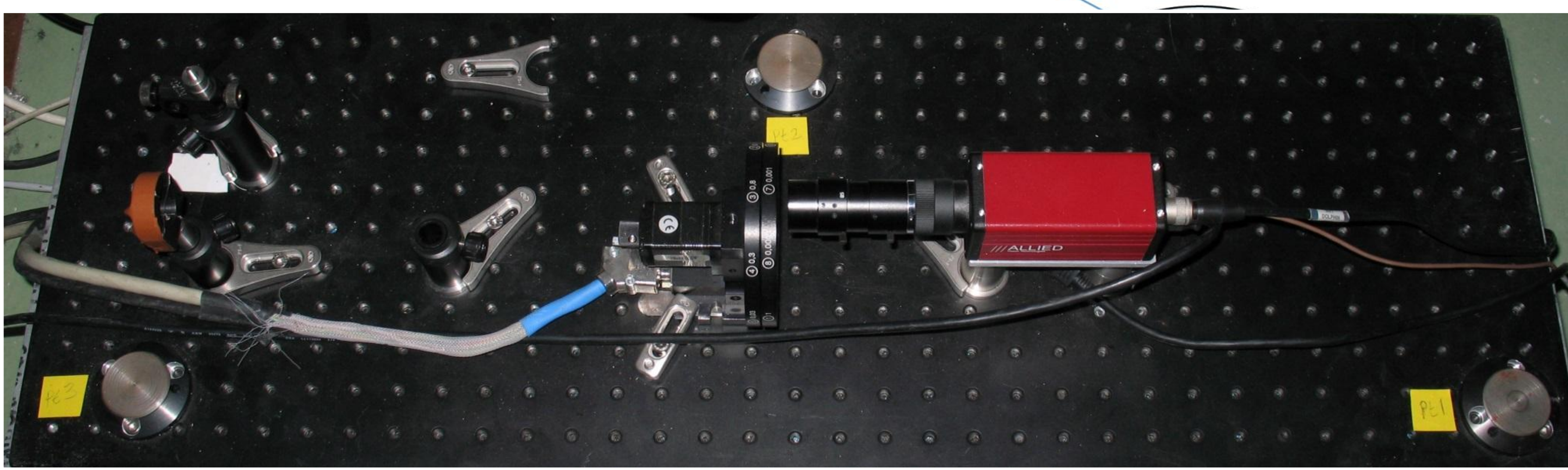
Emittance tests on various transverse laser beam profiles

PRSTAB 5, 094203 (2002)

DC & RF Guns: Drive Lasers

Good practice

- Off-centre illumination to avoid worst effects of back-ion bombardment
  - Cornell claim no detriment to emittance for a 0 – 4 mm laser offset
- Use of a virtual cathode
  - Concept inspired by DESY Zeuthen
  - Splits off small fraction of drive laser beam and images this on a screen



The Cornell 1.3 GHz, 1 ps rod fibre amplifier photoinjector drive laser

- **167 W IR laser power at 1.3 GHz (fibre amplifier)**
- **124 W green laser power at 1.3 GHz**
- **800 fs micropulses, stretchable to 80 ps ‘stacked’**
- **Further power increases possible**

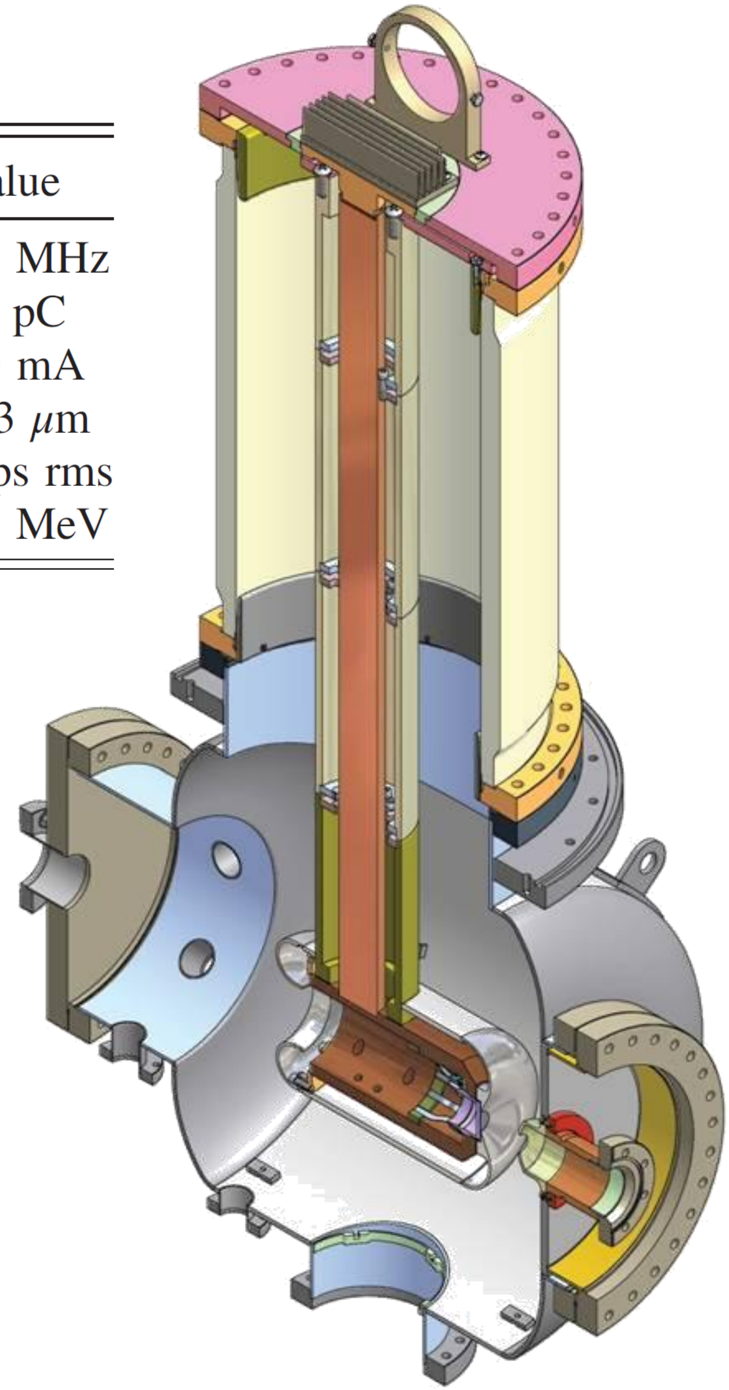
“Enabling next-generation high-current X-ray sources”

Courtesy Bruce Dunham, CHESS

The Cornell ERL Injector – DC Gun

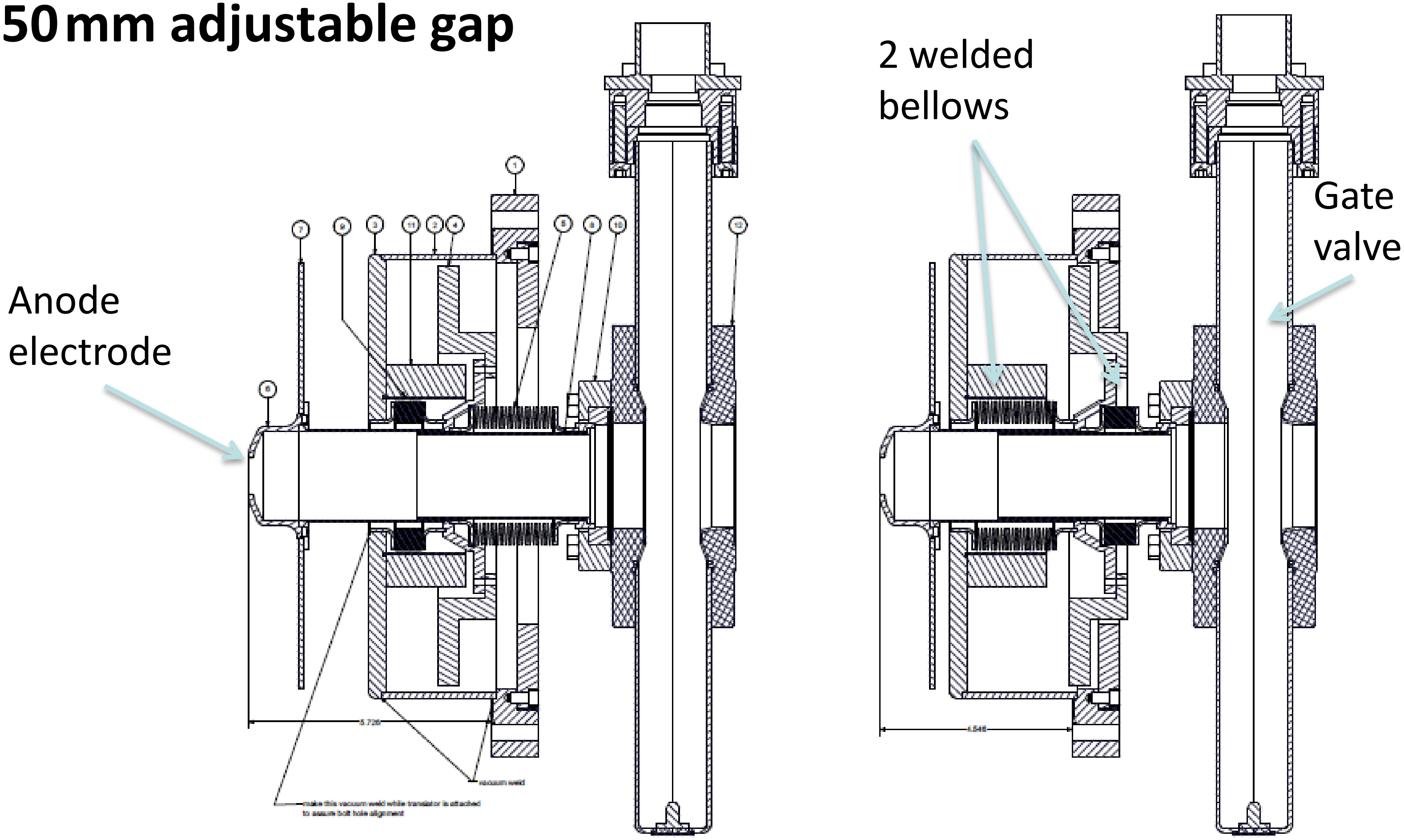
Parameter	Value
Frequency	1300 MHz
Charge per bunch	77 pC
Average current	100 mA
Normalized emittance	≤0.3 μm
Bunch duration	2–3 ps rms
Beam energy	4–15 MeV

- Demonstrated high-current operations at 65 mA using a Na_2KSb photocathode (2.6 day lifetime)
- Brief operation at 75 mA – *World Record*
- Low emittance beams (near thermal threshold)
- Extremely high DC voltages are not necessary



Courtesy Bruce Dunham, CHESS

- Gun originally designed for 750 kV operation
- *Cathode field* is crucial
- Translatable anode to tailor the cathode field strength
- **20 - 50 mm adjustable gap**



Small gap, 20 mm

Large gap, 50 mm

Courtesy Bruce Dunham, CHESS

The Cornell ERL Injector – DC Gun

Parameter	Value
Frequency	1300 MHz
Charge per bunch	77 pC
Average current	100 mA
Normalized emittance	$\leq 0.3\ \mu m$
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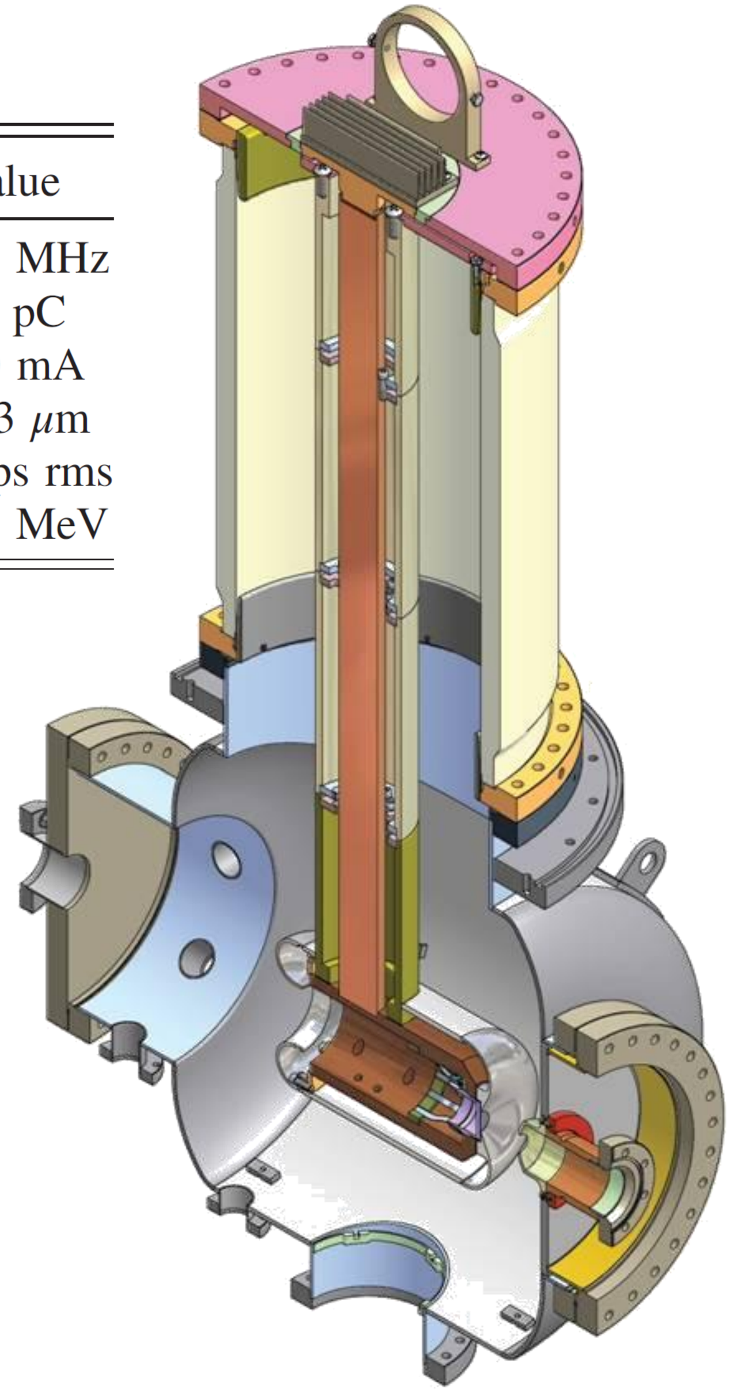
- Demonstrated high-current operations at 65 mA using a Na_2KSb photocathode (2.6 day lifetime)
- Brief operation at 75 mA – *World Record*
- Low emittance beams (near thermal threshold)
- Extremely high DC voltages are not necessary
- Simulations + optimisations match experiments
- Halo / beam loss can be maintained below 1 part in 10^7 to 10^8
- **Photocathodes are still the key challenge**



Courtesy Bruce Dunham, CHESS

Thank you for listening ☺

Credits to colleagues for material used in this presentation:

Dr. Bruce Dunham, Cornell

Dr. Joe Grames, JLab

Dr. Carlos Hernandez-Garcia, JLab

Dr. Christoph Hessler, CERN

Dr. Graeme Hirst, STFC (ret)

Dr. Boris Militsyn, STFC

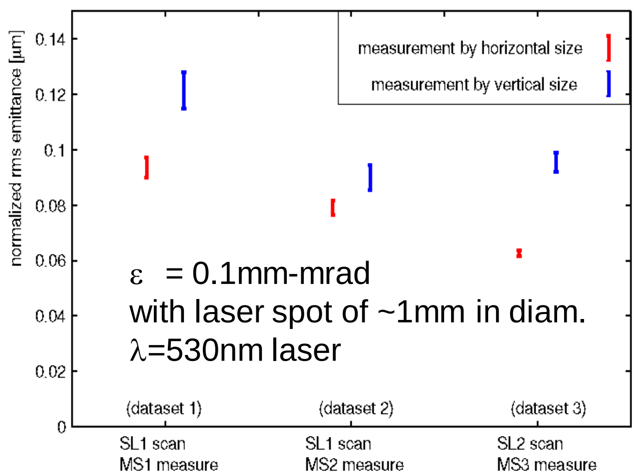
Dr. Noboyuki Nishimori, JAEA

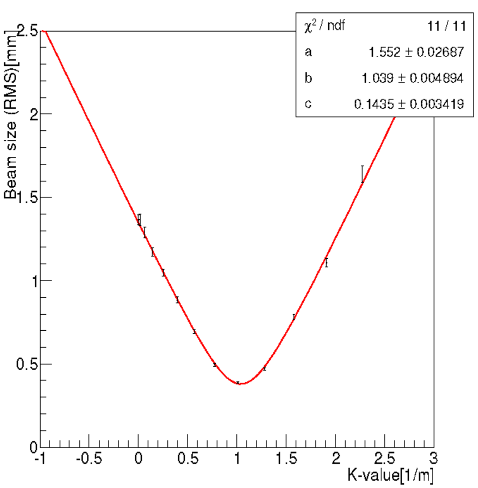
Dr. Matt Poelker, JLab

Preliminary emittance measurements

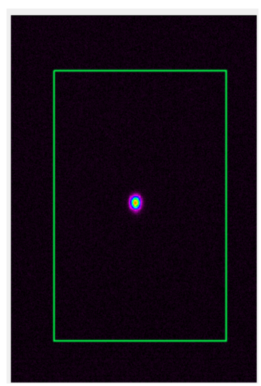
Y. Honda, T. Miyajima , et al., "Transverse Beam Performance Measurement at compact-ERL Injector", 10th Meeting of Particle Accelerator Society of Japan, SUP011, (2013).

Thermal emittance at the gun at E=390keV



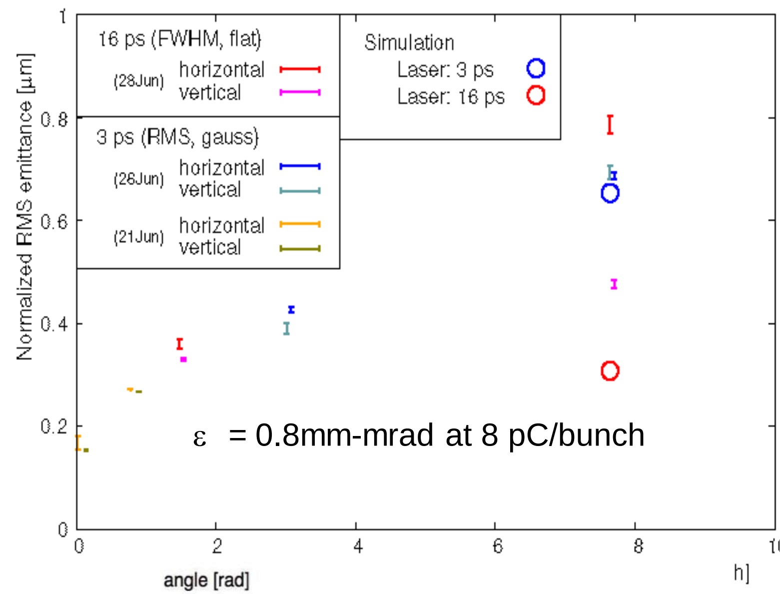


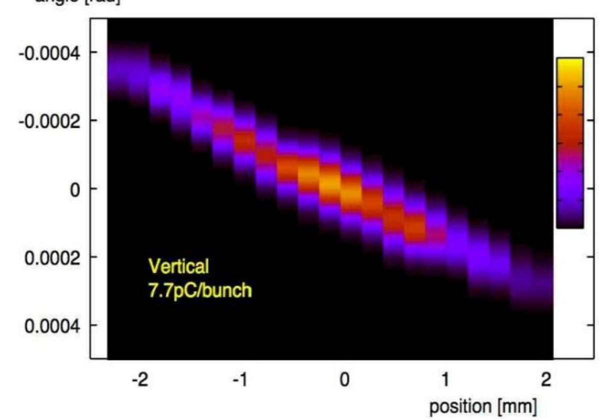
Solenoid scan



Beam profile on YAG screen

Emittance at the injector at E=5MeV





Phase space distribution measured with a slit scan

Science & Technology Facilities Council ASTeC

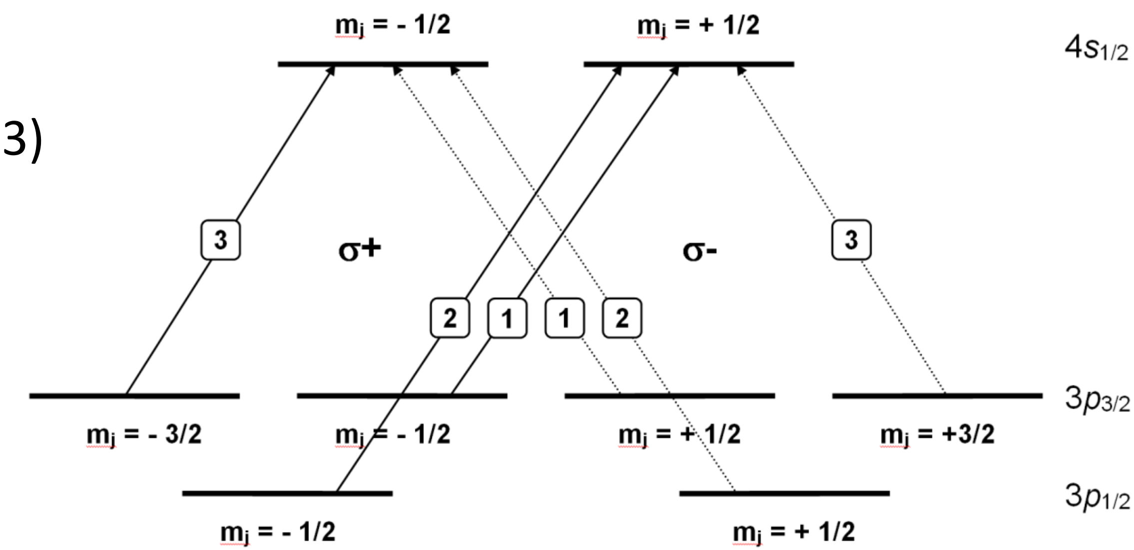
DC Guns: Drive Lasers

Polarised electrons

- Polarised emission from the $4s_{1/2}$ band when illuminating GaAs (100)
- λ ~ 800 nm ➔ RCP generates Δm_j = +1 and LCP generates Δm_j = -1
- Clebsch-Gordan coefficients give likelihood of transition
- Transitions from m_j = -3/2 state 3 times more likely than those from m_j = -1/2 state

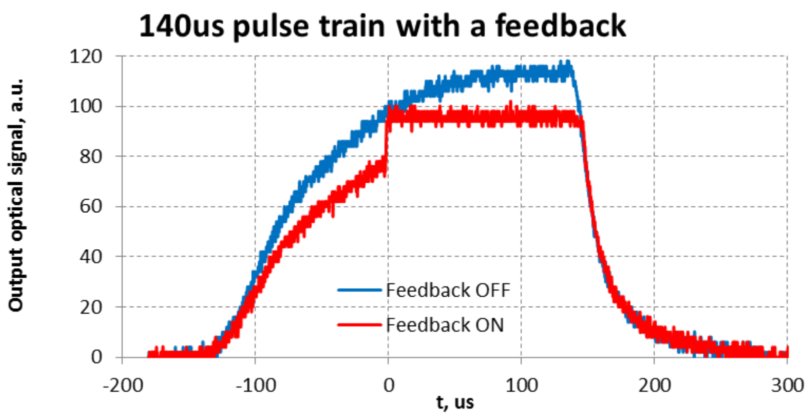
Polarisation, P = (1 – 3)/(1 + 3)

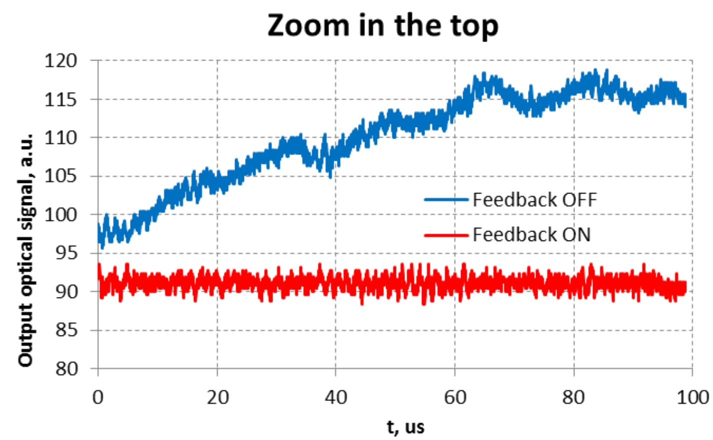
= -0.5

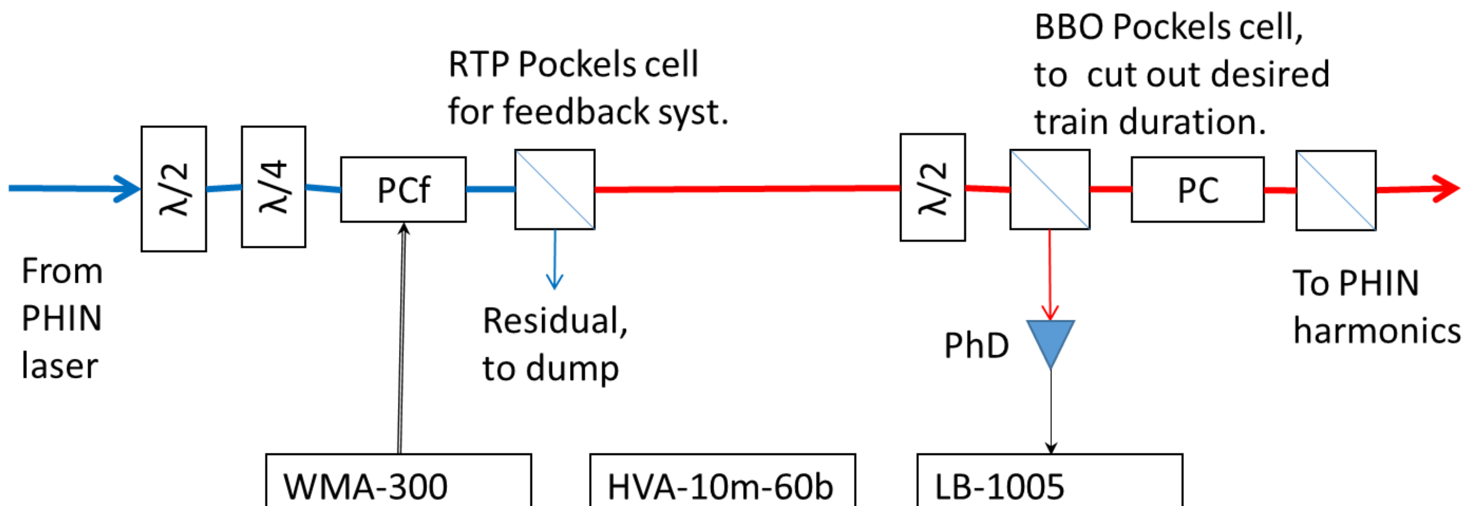


Courtesy Carlos A.E.R. Malins, STFC

Feedback Stabilization







Result: Improvement of intensity stability (laser beam) and charge stability (electron beam) by a factor of 3 down to 0.4% rms and 1% rms