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ALICE *Energy Recovery Linac Prototype*: DC Photocathode Electron Gun **Commissioning Results**

Dr. Lee Jones
Accelerator Physics Group
ASTeC and The Cockcroft Institute

Alice
Accelerators and Lasers In Combined Experiments

Science & Technology Facilities Council
Daresbury Laboratory

ALICE ERL Prototype: Technical priorities

Primary Goals:

1. Foremost: ***To achieve energy recovery with high efficiency***
2. Operate a photocathode electron gun and superconducting Linacs
3. Produce and maintain bright electron bunches from a photoinjector
4. Produce short electron bunches from a bunch compressor

Further Development Goals:

1. Achieve energy recovery during FEL operation (with an insertion device that significantly disrupts the electron beam)
2. Develop a FEL activity programme which is suitable to investigate the expected synchronisation challenges and demands of a UK XFEL
3. Produce simultaneous photon pulses from a laser and an ERL photon source which are synchronised at or below the 1 ps level

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In Combined Experiments

ALICE ERL Prototype: Location

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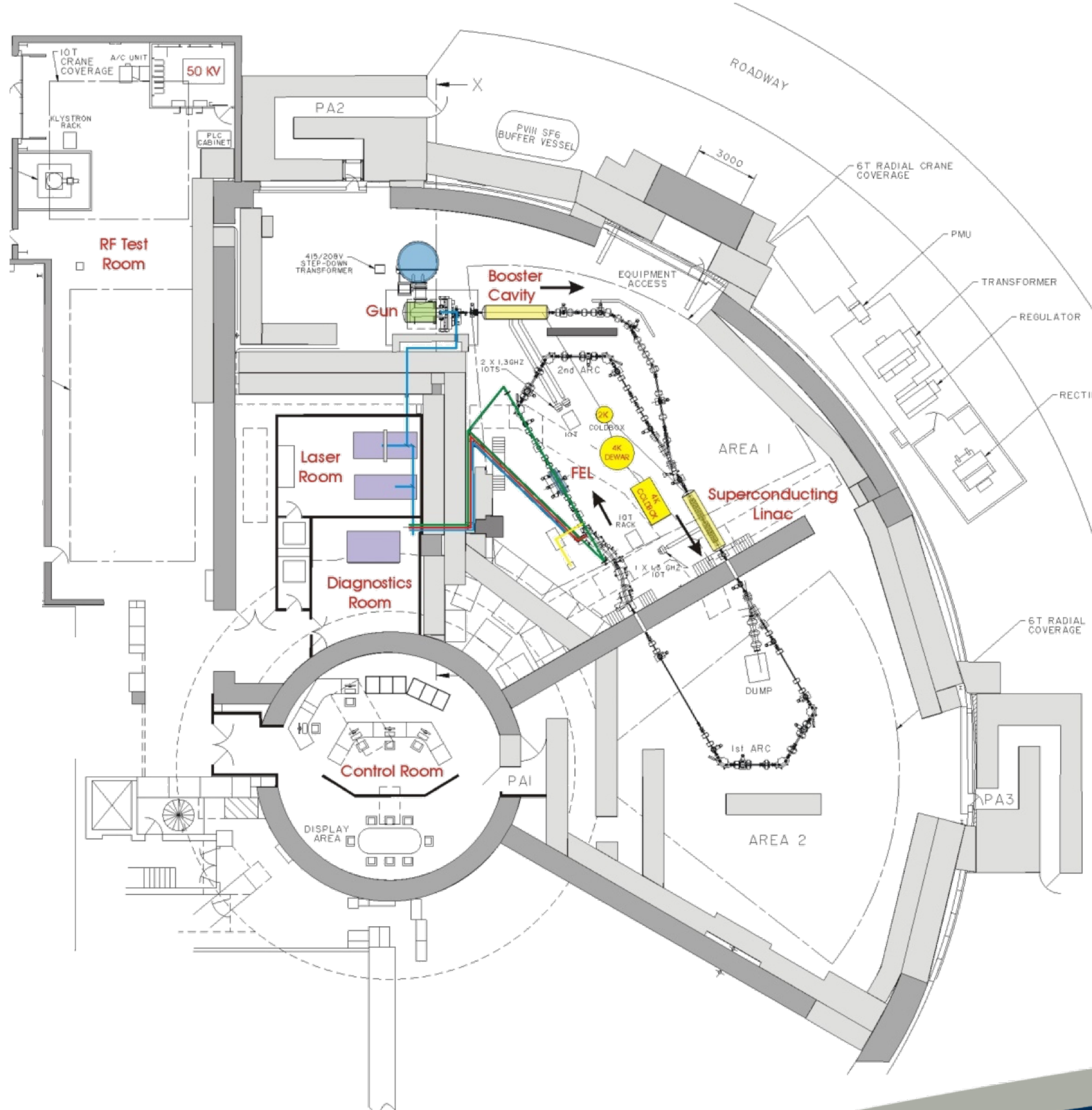
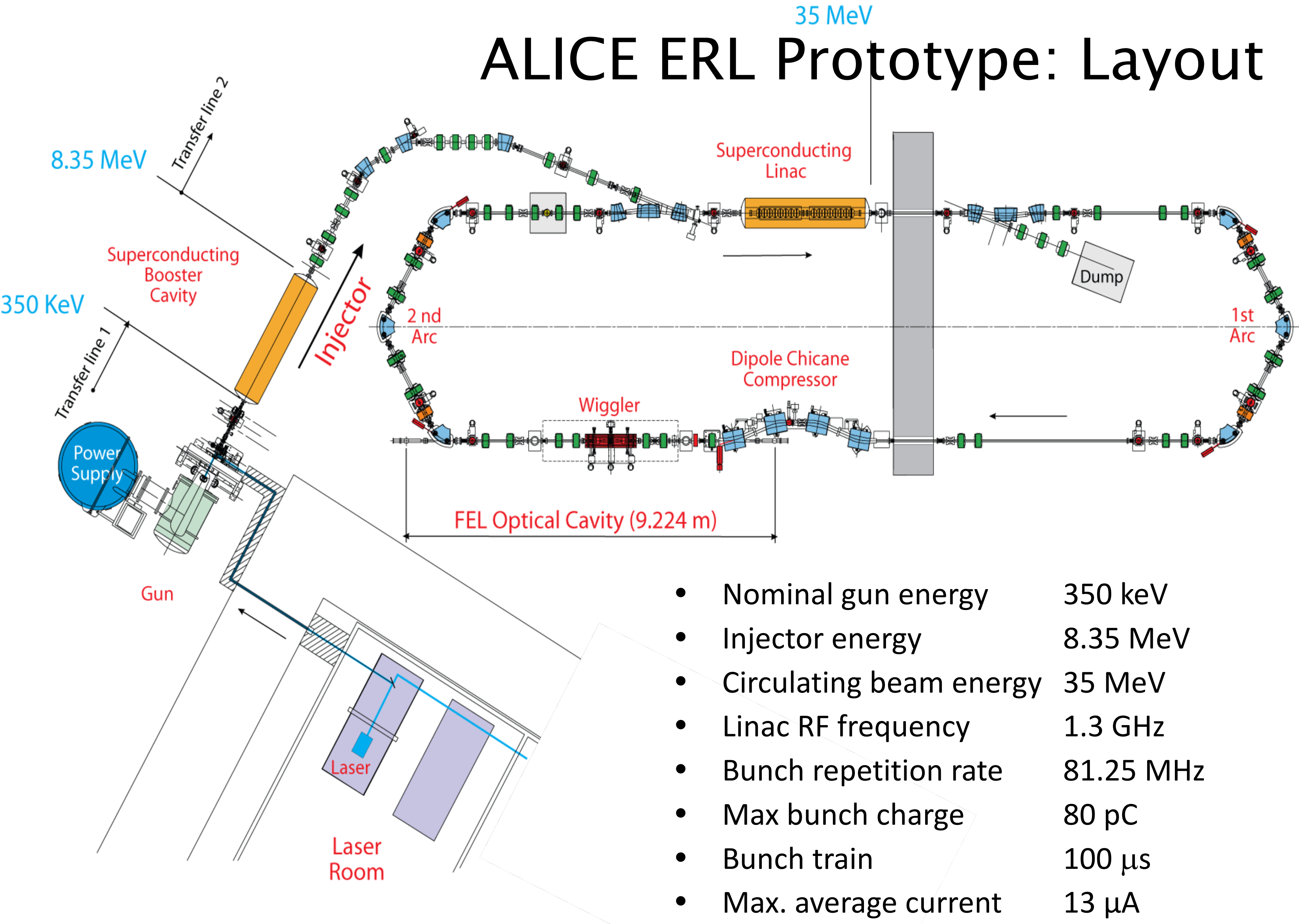

RF Test Room
50 KV
IOT CRANE COVERAGE
A/C UNIT
KLYSTRON RACK
PLC CABINET
PA2
PVIII SF6 BUFFER VESSEL
ROADWAY
3000
6T RADIAL CRANE COVERAGE
PMU
TRANSFORMER
REGULATOR
415/208V STEP-DOWN TRANSFORMER
Gun
Booster Cavity
EQUIPMENT ACCESS
2 X 1.3GHZ IOTS
2nd ARC
COLDBOX
4K DEWAR
4K COLDBOX
AREA 1
Laser Room
FEL
Superconducting Linac
IOT RACK
Diagnostics Room
DUMP
1st ARC
Control Room
PA1
PA3
DISPLAY AREA
AREA 2
6T RADIAL COVERAGE

ALICE ERL Prototype: 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
• Max bunch charge	80 pC
• Bunch train	100 μs
• Max. average current	13 μA

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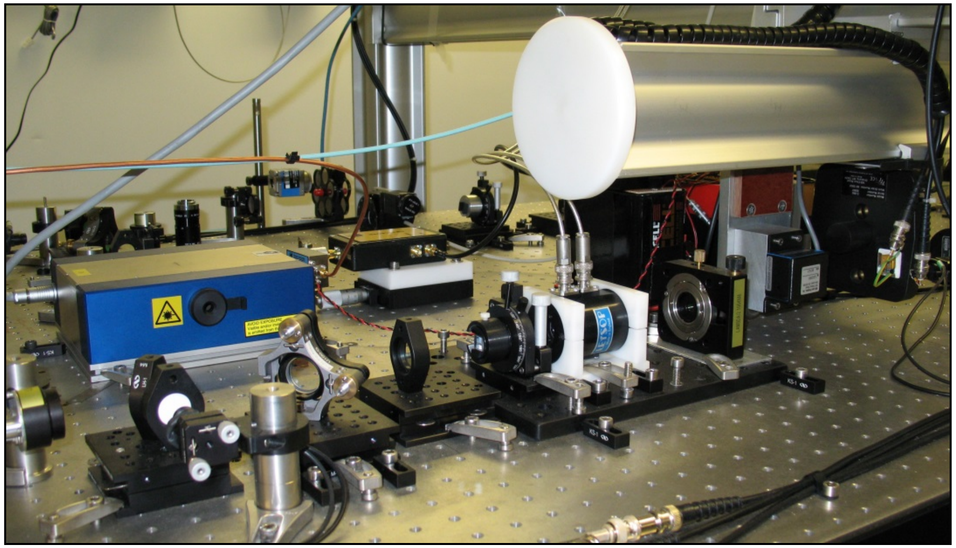
Drive Laser: Summary

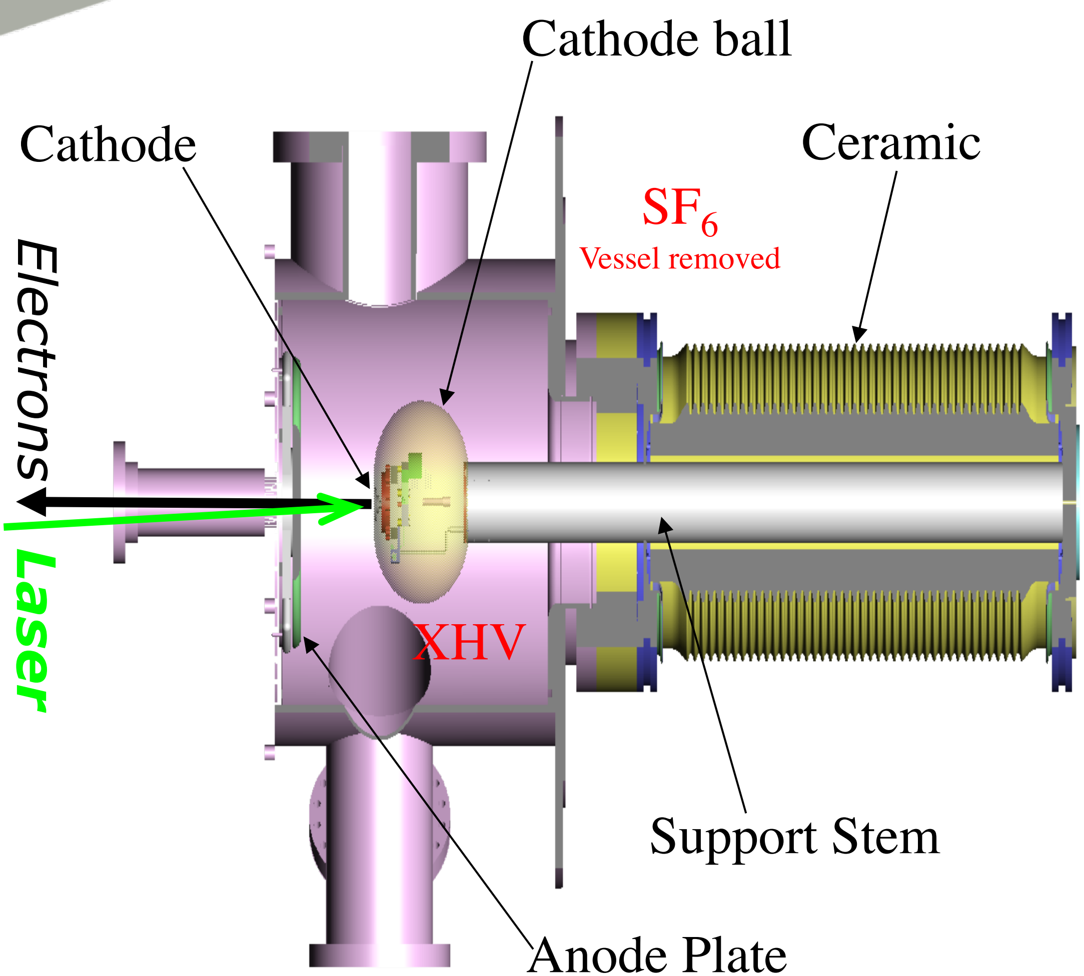


- Diode-pumped Nd:YVO_4
- Wavelength: 1064 nm, doubled to 532 nm
- Pulse repetition rate: 81.25 MHz
- Pulse duration: 7, 13, 28 ps FWHM
- Pulse energy: up to 45 nJ (at cathode)
- Macrobunch duration: 100 µs @ 20 Hz

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

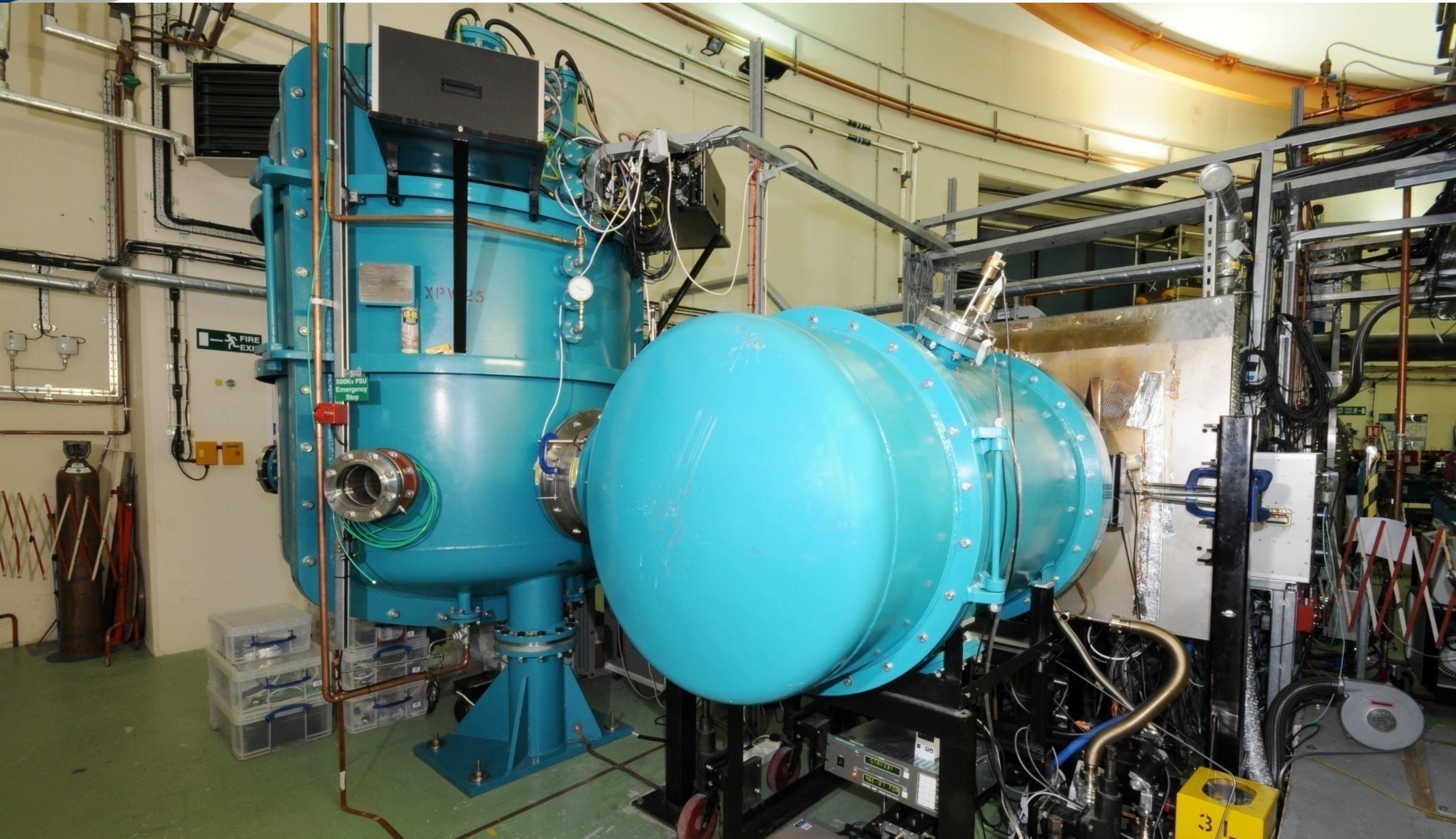
L.B. Jones, *Status of the ERLP photoinjector driver laser*, Proc. ERL '07, 110 – 112

Gun Assembly:

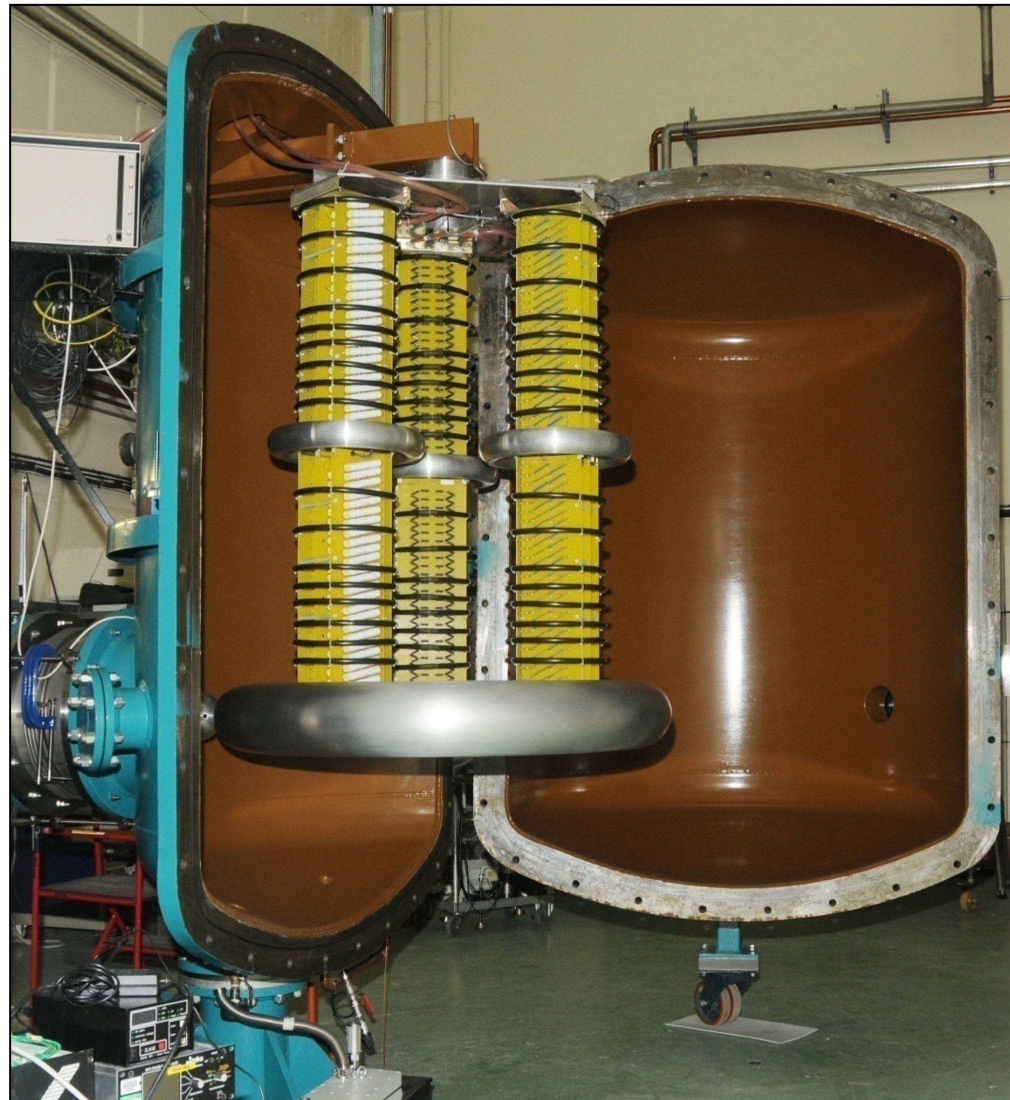


- JLab IR-FEL gun design
- 500 kV DC power supply
- Cs:GaAs photocathode
- Single bulk-doped ceramic
- Good electrical performance
- Poor mechanical performance

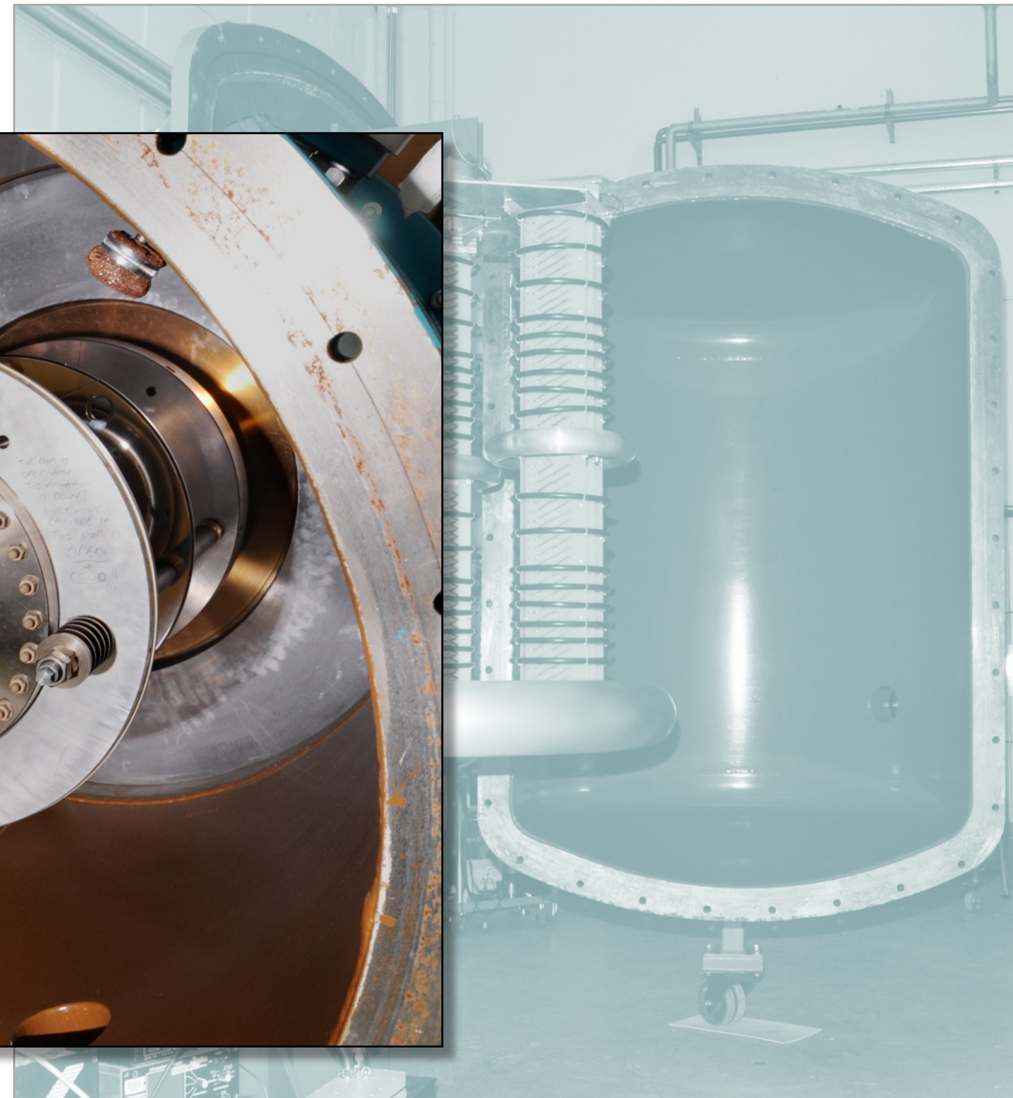
Photocathode Gun: 500 kV Power Supply

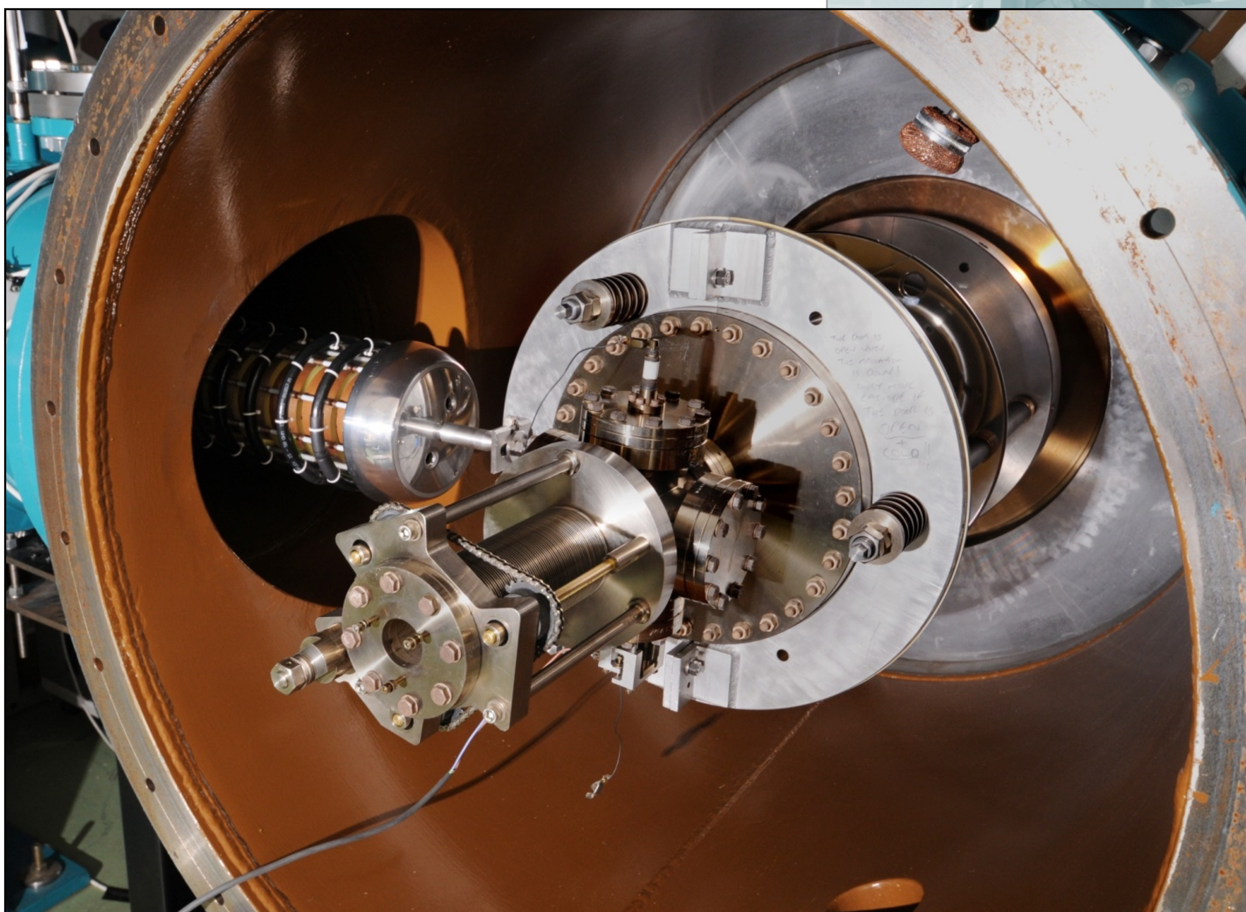


Photocathode Gun: 500 kV Power Supply



Photocathode Gun: 500 kV Power Supply





Photocathode Gun: Cathode and HV Electrode

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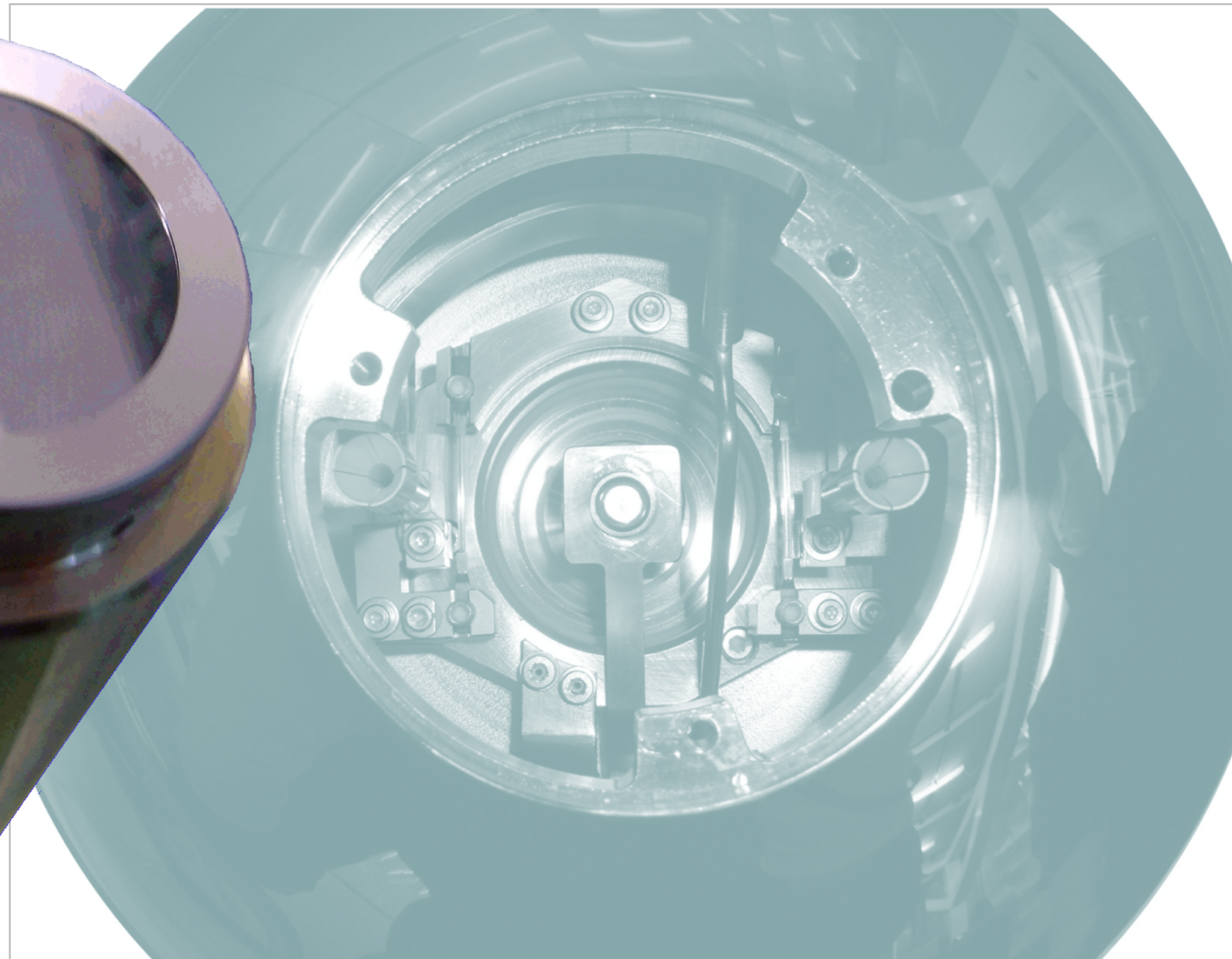
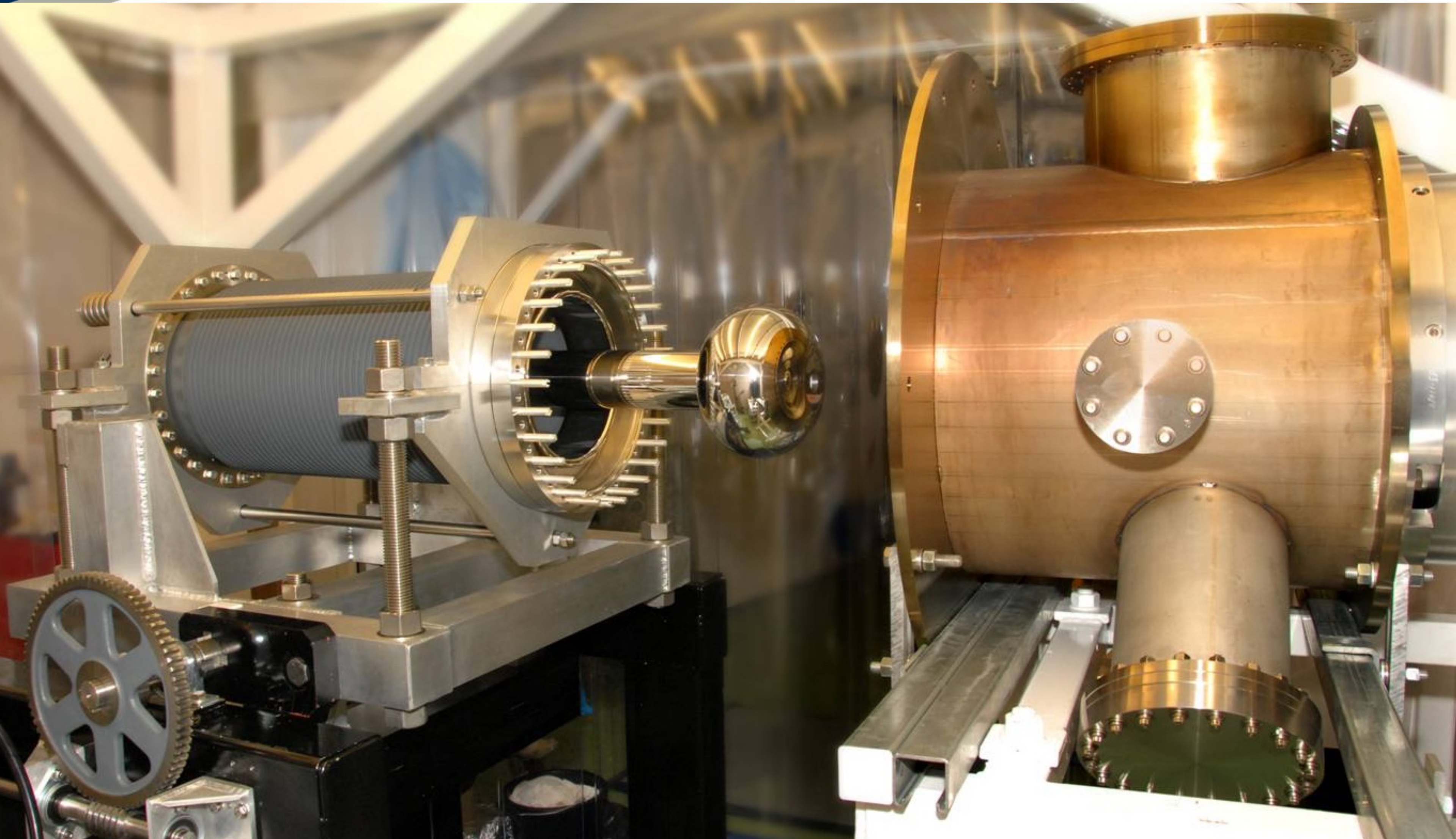


Cathode 'Ball', Insulating Ceramic & Vacuum Vessel



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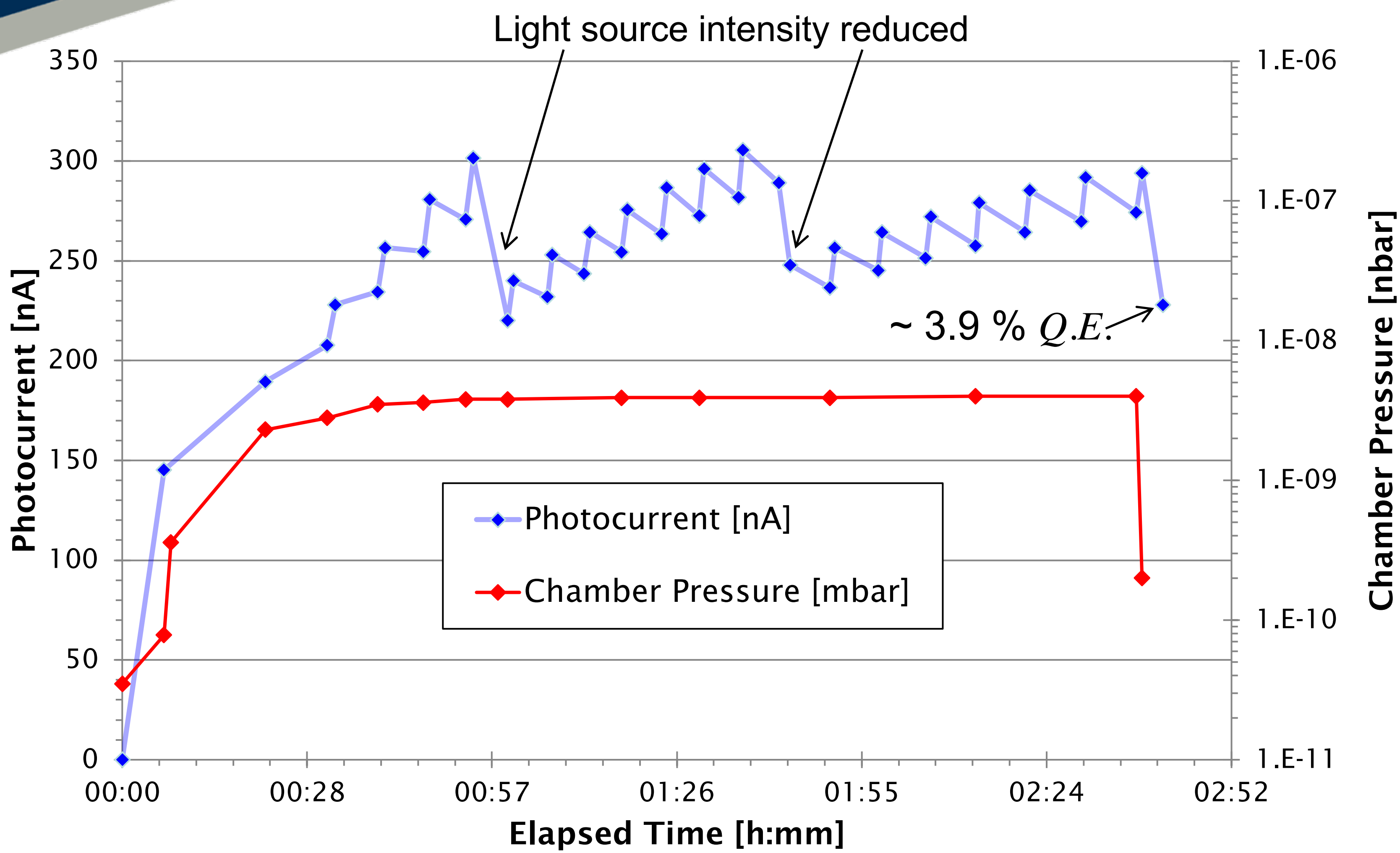
NF_3 Activation in the ALICE gun, February 12th 2009



The spreadsheet shows the *peak photocurrents* recorded on each Cs and NF_3 cycle. This is the 2nd activation of a VGF cathode wafer supplied by Mateck GmBH (Julich).

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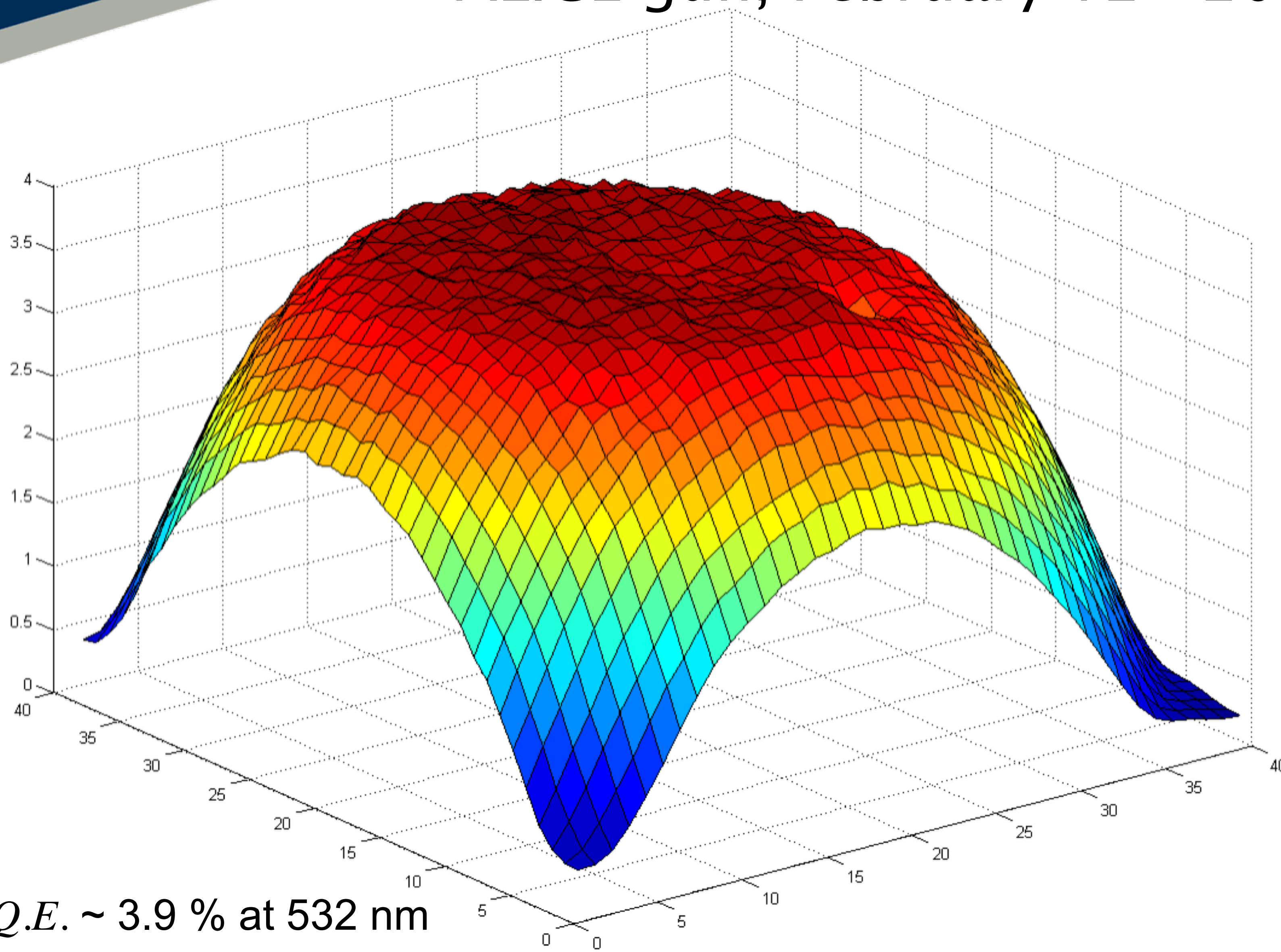
NF_3 Activation in the ALICE gun, February 12th 2009



Peak $Q.E.$ ~ 3.9 % at 532 nm

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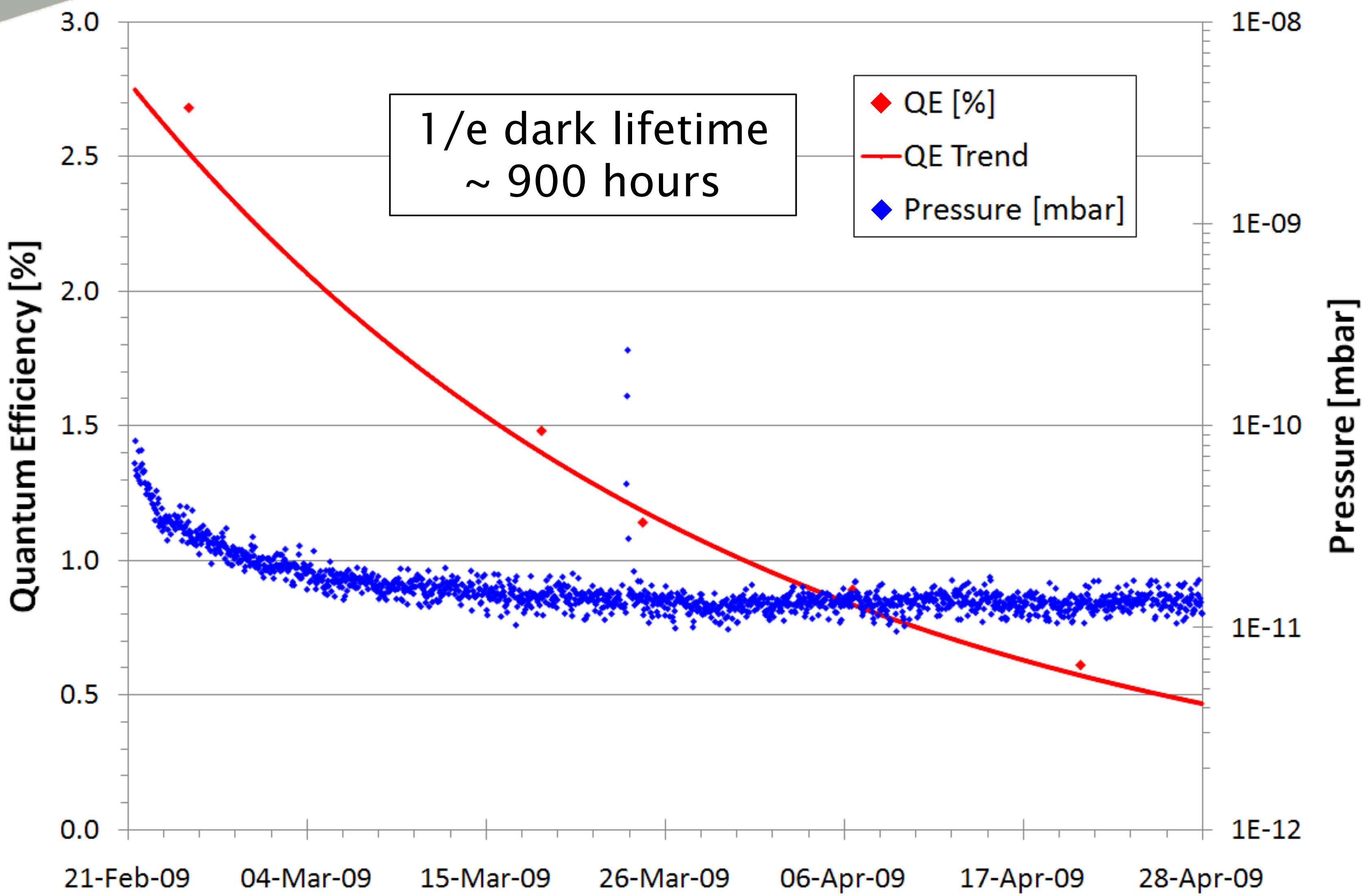
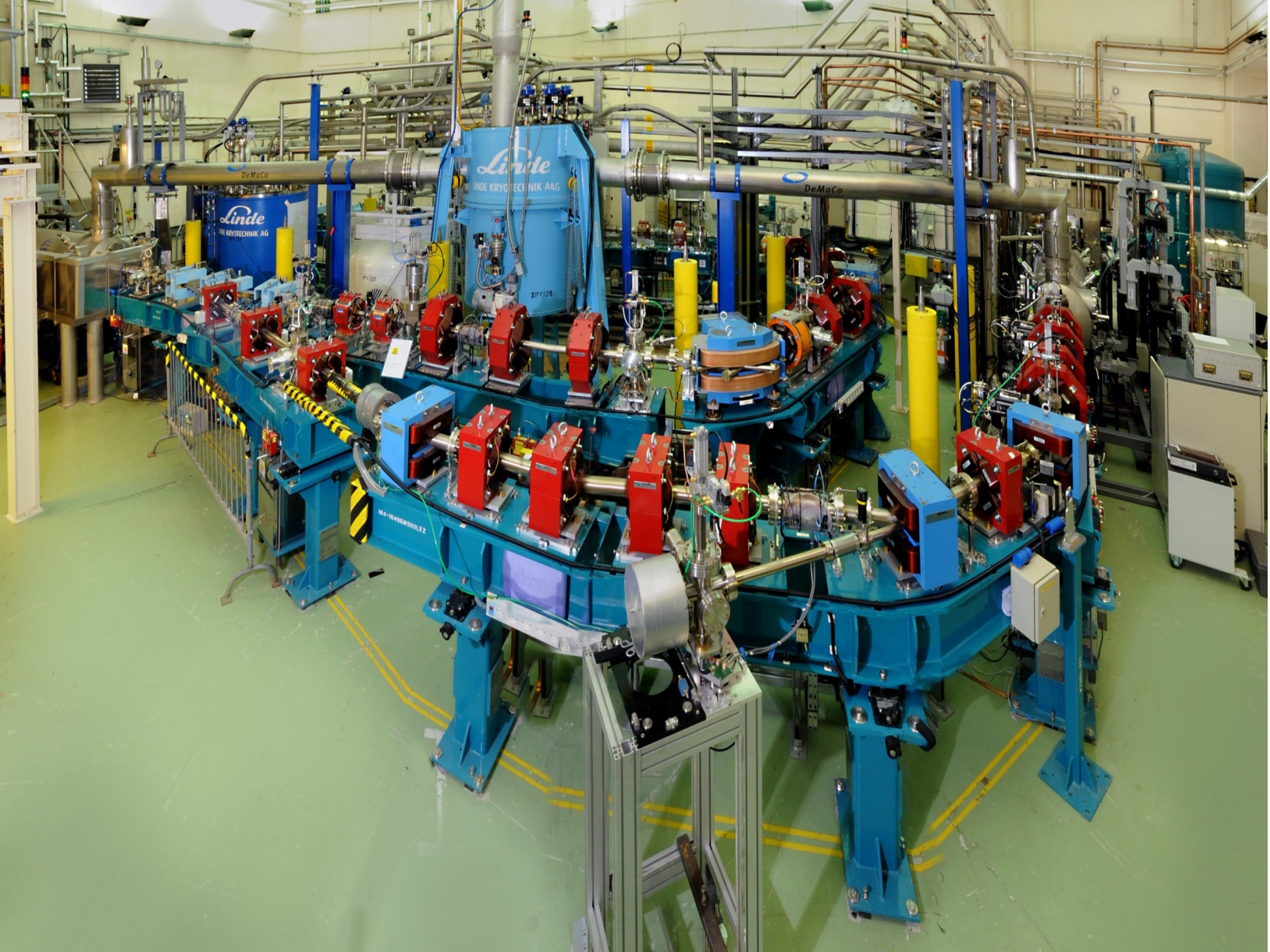
Photocathode Dark Lifetime:

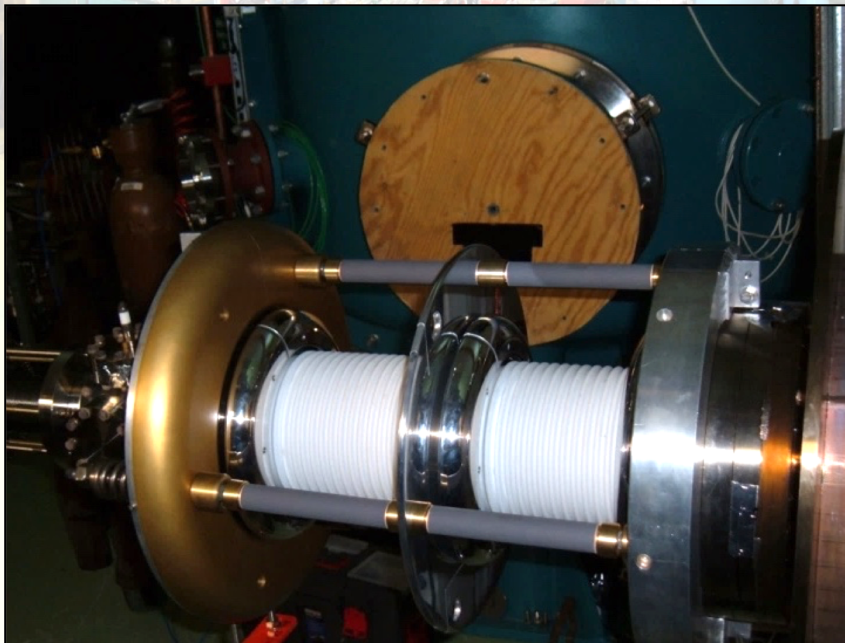



Linde
LINDE KRYOTECHNIK AG
DeMaCo

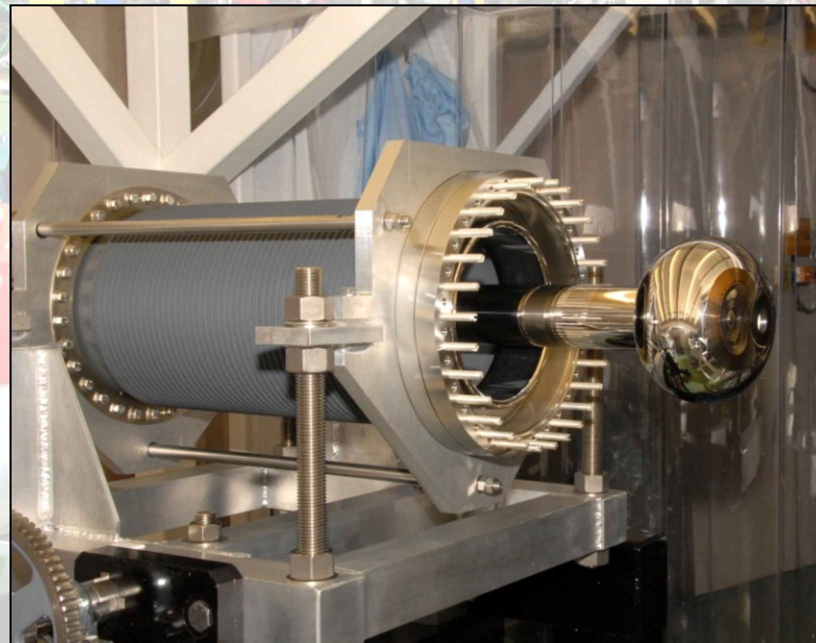
ALICE Photocathode Gun Timeline:

- Photocathode laser system operating since April 2006
- Electron gun installed and connected to a dedicated diagnostic beamline. Gun operated Jul–Aug '06, Jan–Apr '07 & Oct–Nov '07
- Problems experienced with cathode activation. *Q.E.* poor
- First beam from the gun recorded at 01:08 on Wednesday 16th August 2006, with the gun operating at 250 kV
- Operating at 350 kV soon afterwards
- Routinely conditioned gun to 450 kV
- Steady improvement in both *Q.E.* & photocathode lifetime
- Problems encountered with beam halo, field emission and high voltage breakdown
- Improved bakeout ➔ Better vacuum and photocathode lifetime
- Repeated failure of Wesgo ceramic forced use of Stanford spare

ALICE Photocathode Gun Timeline:



Smaller 12" diameter
double Stanford ceramic



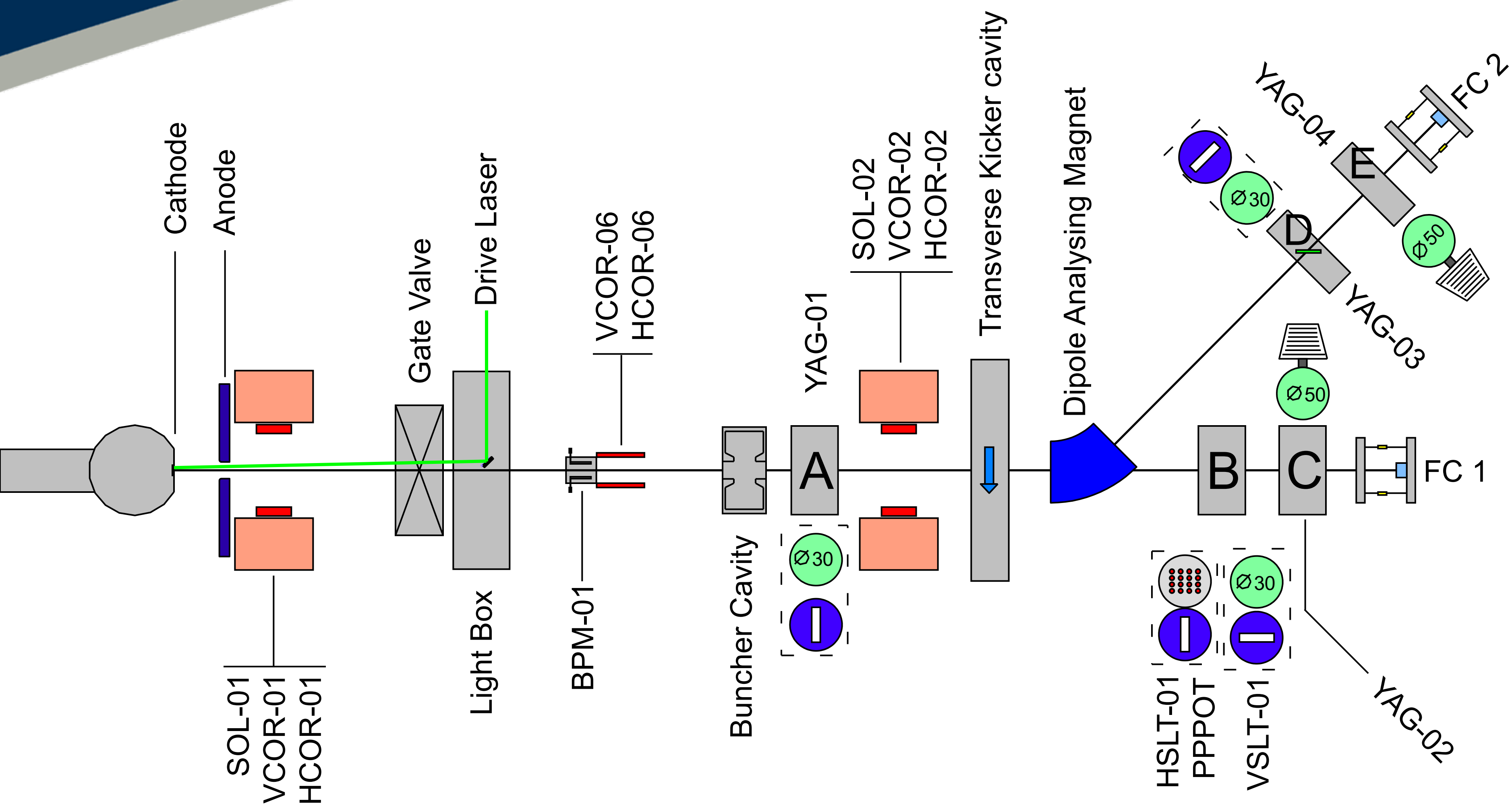
Larger 16" diameter
single Wesgo ceramic

ALICE Photocathode Gun Timeline:

Feb ‘07 – Oct ’08, we suffered 9 leaks and a major contamination:

- Feb ‘07 – Leak on Pirani gauge pins
- Jun ‘07 – Leak on Pirani gauge pins and also on a spacer flange
- Between June and July, the spacer flange was welded to the anode vessel. The first 2 attempts failed, the 3rd was successful
- Aug ‘07 – Leak on Wesgo ceramic braze at anode vessel end. Spare Wesgo ceramic installed
- Sep ‘07 – Leak on top instrument flange
- Feb ‘08 – Leak on **both** ends of the spare Wesgo ceramic
- Mar ‘08 – Smaller Stanford ceramic installed. Gun contaminated during bake. Complete stripdown and XHV clean required
- Jul ‘08 – Repaired Wesgo ceramic installed. Leak on braze
- Aug ‘08 – Leak on IMG feedthrough, and fine leak valve mechanism fails (used for photocathode activation)

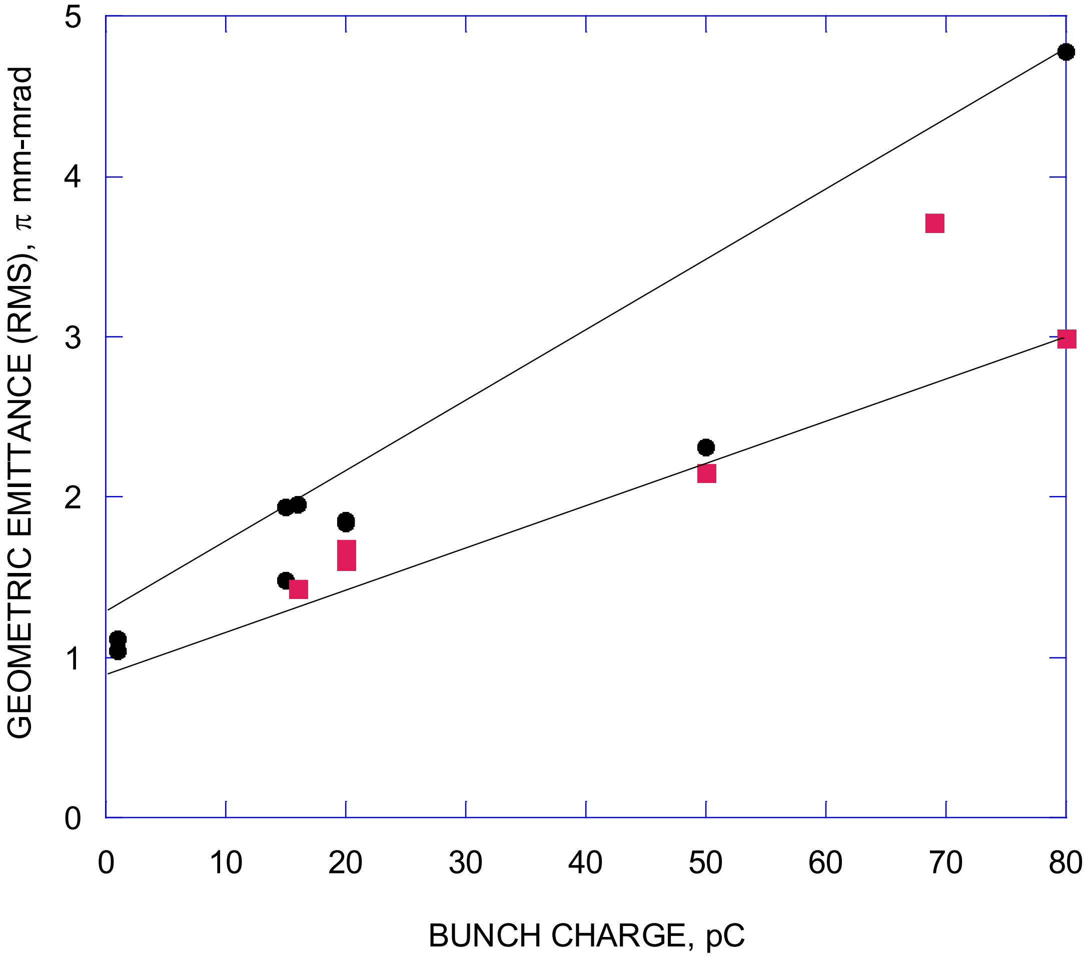
Diagnostic Beamline:



Laser spot size was 4.1 mm FWHM for all experiments

Courtesy Y.M. Saveliev, DL

RMS Geometric Emittance (function of bunch charge)



RMS geometric emittance as a function of bunch charge:

- Horizontal (●)
- Vertical (■)

ALICE ERLp ASTRA model predicted $1 \cdot \pi$ mm-mrad for $Q = 80$ pC.

Emittance compensation scheme is complex. Was not optimised for each bunch charge.

Some factors are missing from the ASTRA model [1,2]

[1] I.V. Bazarov *et al.*, Proc. PAC '07, 1221 – 1223.

[2] F. Zhou *et al.*, PR–STAB **5**, 094203, 2002.

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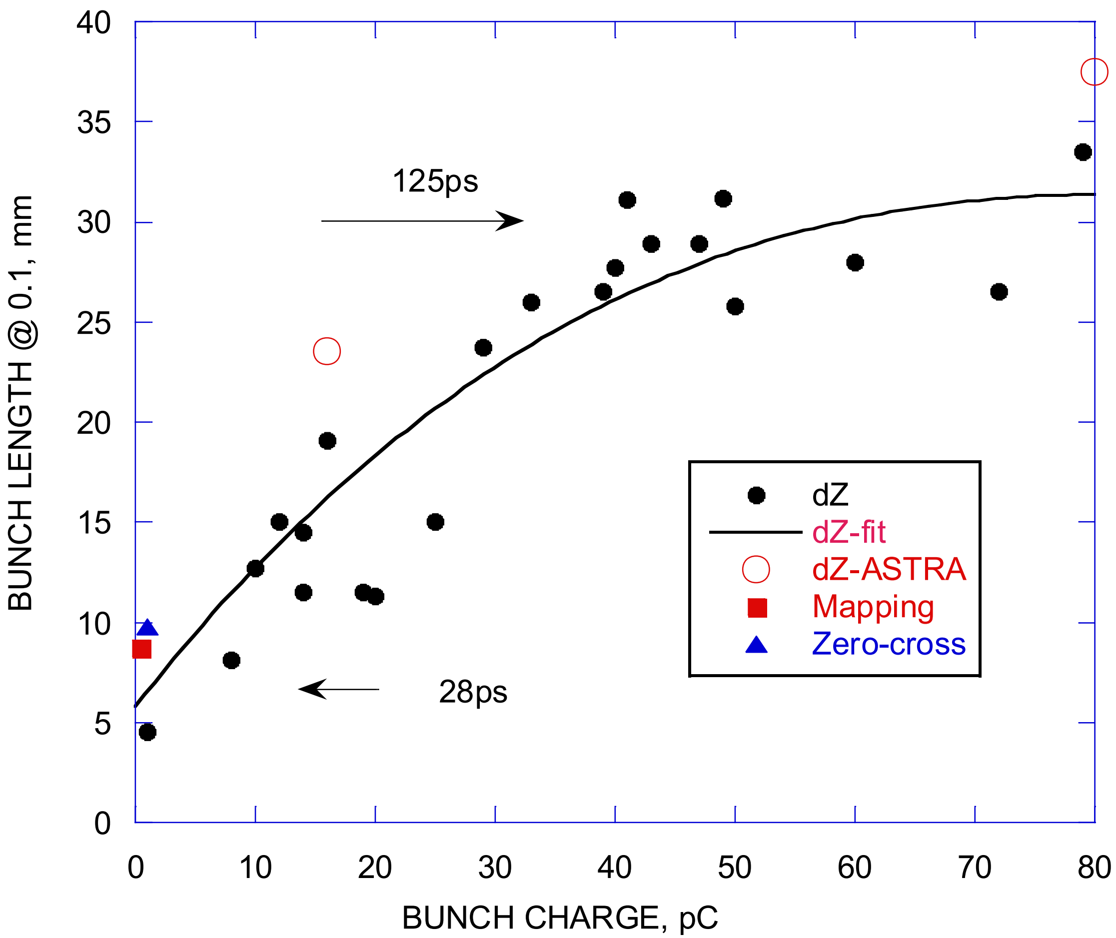
Bunch Length (function of bunch charge, at 10% level)



Bunch length at 10% of the peak value used due to non-uniformity of the longitudinal profile.

Data were obtained with the RF transverse kicker (●), and with the RF buncher cavity using the *zero-crossing* method[1] (▲), and the *energy mapping* method (■).

Open circles (○) are the results from the ASTRA model.

[1] D.X. Wang *et al.*, Phys. Rev. E, 57(2), 2283 – 2286, 1998

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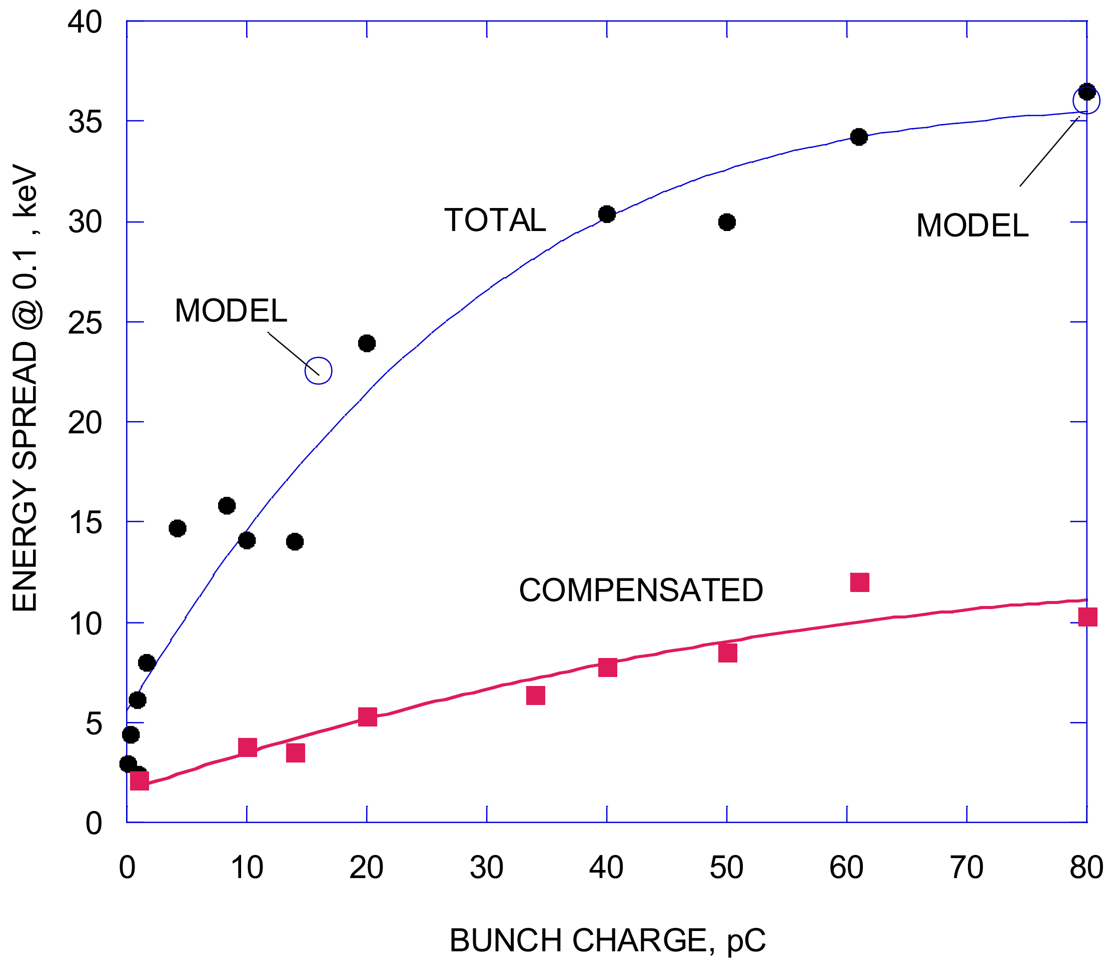
Total and Tilt-Compensated Energy Spread



Total energy spread (ΔE_{tot}) and compensated energy spread (ΔE_{comp}) measured as a function of Q_{bunch}.

Data were obtained using the magnetic spectrometer.

ΔE_{tot} is shown with black circles (●), and ΔE_{comp} with red squares (■).

Open circles (○) are the results from the ASTRA model.

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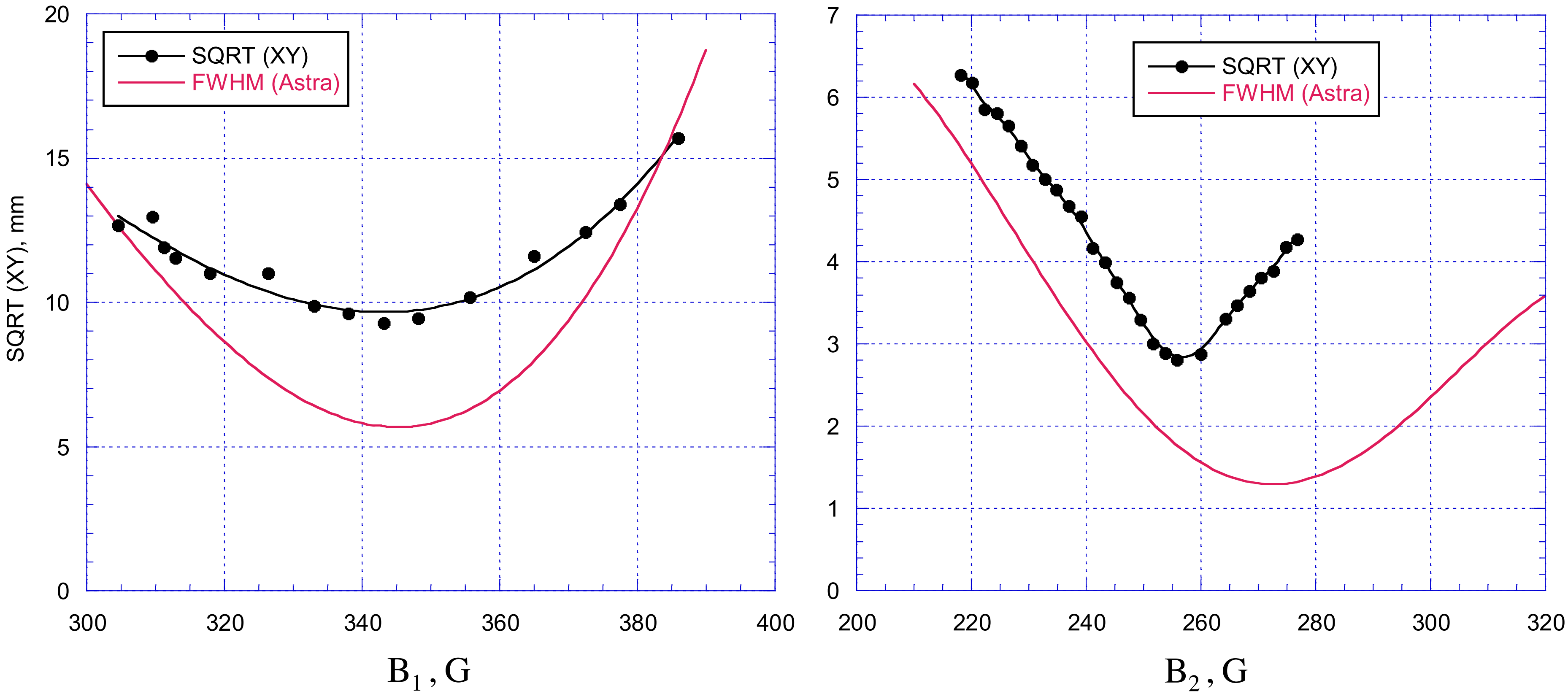
FWHM Beam Size for $Q_{bunch} = 54$ pC



First solenoid

Second solenoid

Comparison of the predicted and measured beam sizes [mm] as a function of solenoid field strength [G] for $Q_{bunch} = 54$ pC

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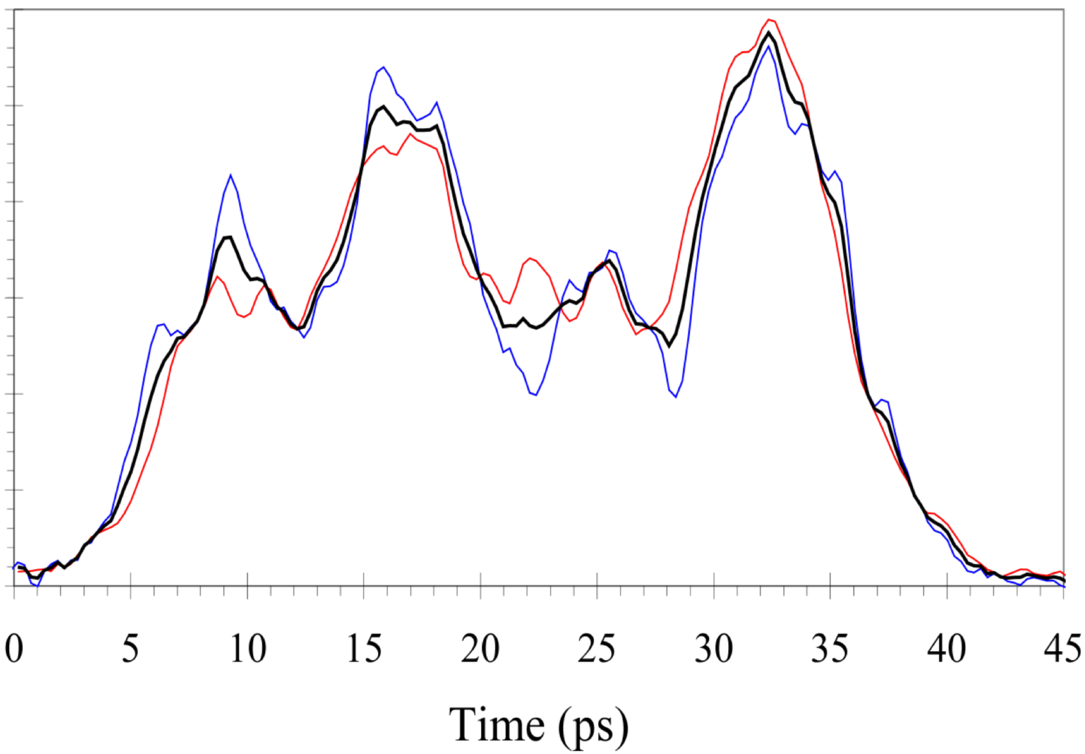
PI Gun Driven by Different Laser Pulse Durations

- Q_{bunch} = 16 pC
- Solenoid strengths constant



Longitudinal drive laser profile

	Experiment		ASTRA model		
	28 ps	7 ps	flat top	two pulse	single
e_x [µm]	1.95	1.91	0.56	0.80	0.49
e_y [µm]	1.43	1.47	0.56	0.80	0.49
Δz [mm]	19.1	18.6	23.8	23.5	25.5
ΔE_{tot} [keV]	24.4	29.7	22.5	23	28
ΔE_{comp} [keV]	5.1	2.8	6.0	7.2	1.3
$\Delta E_{tot}/\Delta z$ [keV/mm]	1.28	1.60	0.95	0.98	1.10

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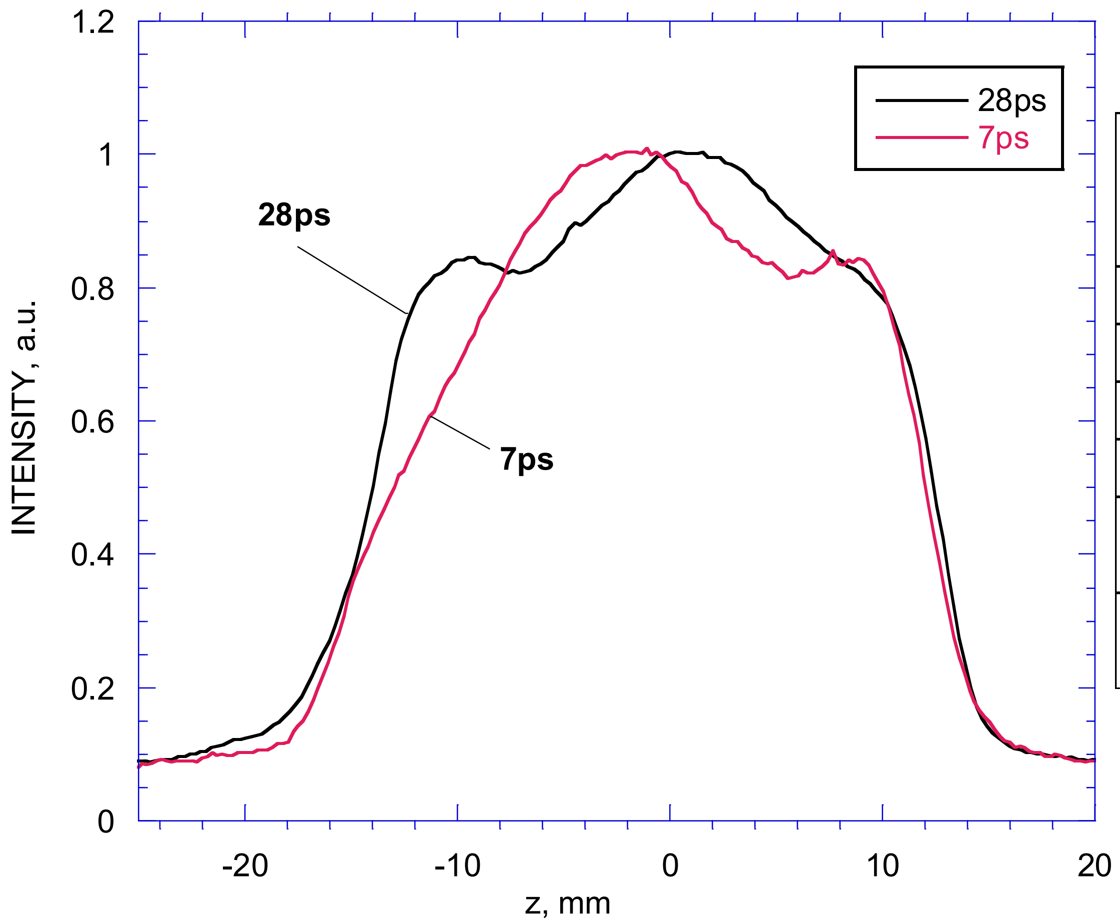

Longitudinal intensity profile measurements

	Experiment		ASTRA model		
	28 ps	7 ps	flat top	two pulse	single
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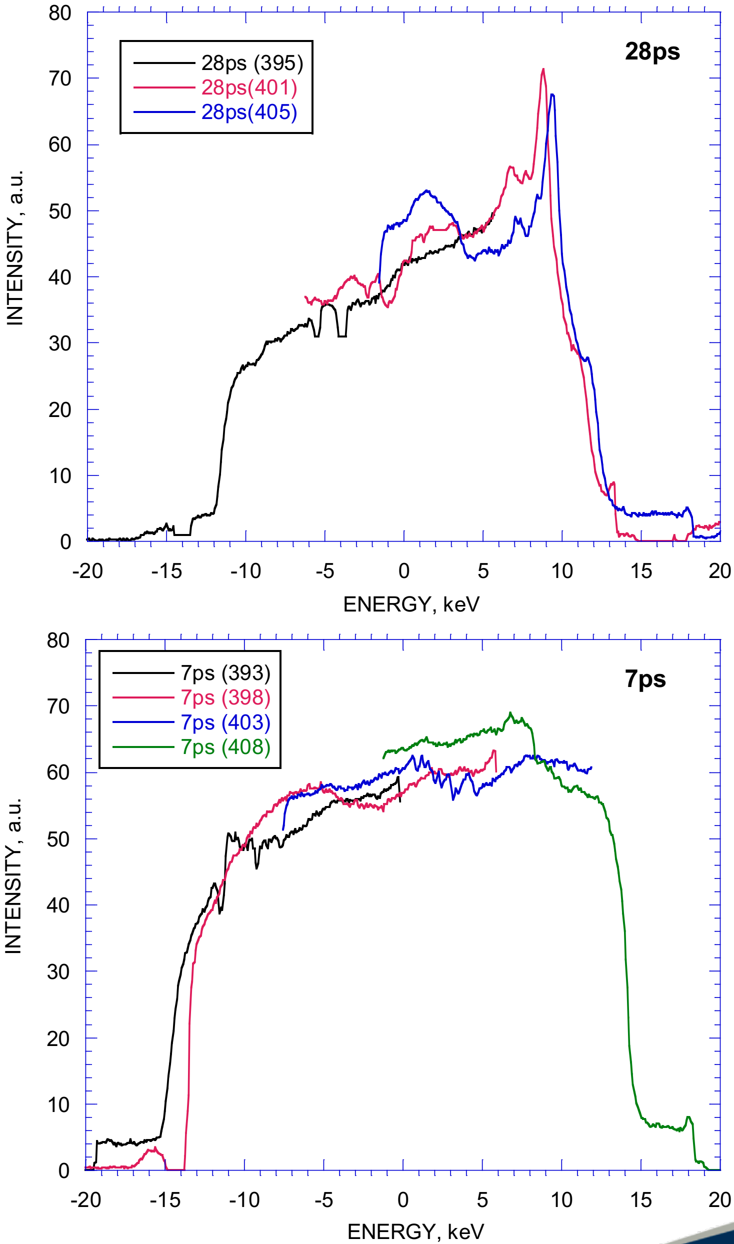

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Total energy spectra, ΔE_{tot}

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PI Gun Driven by Different Laser Pulse Durations

- Q_{bunch} = 16 pC
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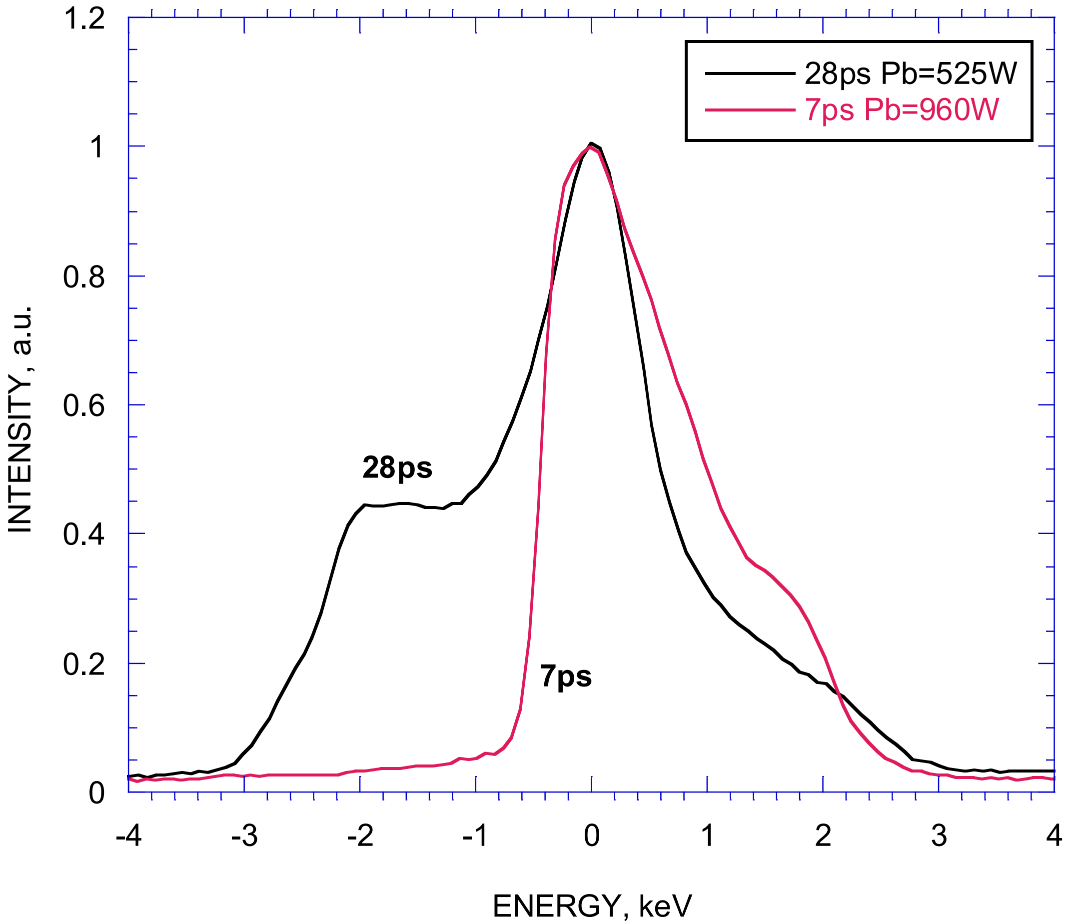

Tilt-compensated energy spectra, ΔE_{comp}

	Experiment		ASTRA model		
	28 ps	7 ps	flat top	two pulse	single
e_x [µm]	1.95	1.91	0.56	0.80	0.49
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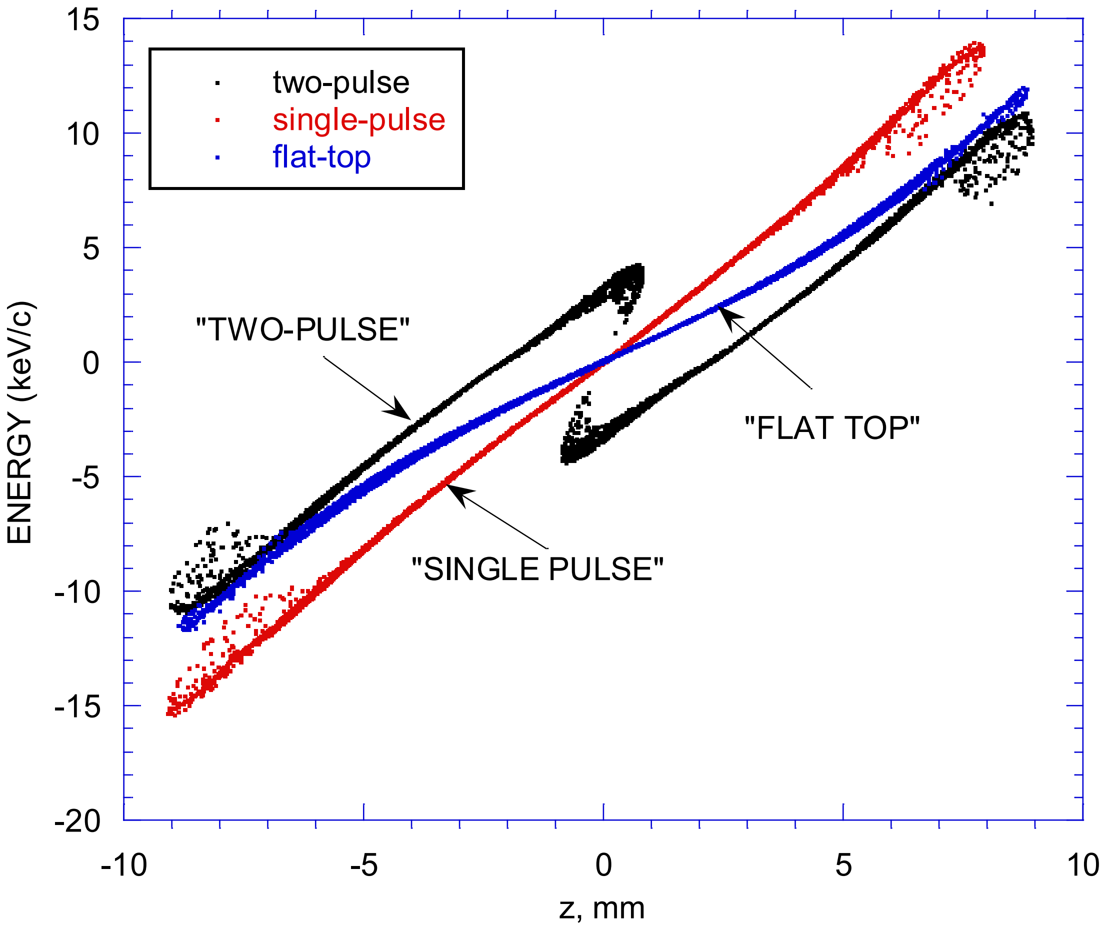
PI Gun Driven by Different Laser Pulse Durations

Conclusion: Longer laser pulses do not confer significant benefits below ~ 20 pC when compared to short pulses in terms of bunch length & energy spectra.



ASTRA Longitudinal phase space predictions

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Further reading:

L.B. Jones, Status of the ERLP photoinjector driver laser, Proc. ERL '07, 110 – 112

Y.M. Saveliev *et al.*, Results from ALICE (ERLP) DC photoinjector gun commissioning, Proc. EPAC '08, MOPC062, pages 208-210

Y.M. Saveliev *et al.*, Characterisation of electron bunches from ALICE (ERLP) DC photoinjector gun at two different laser pulse lengths, Proc. EPAC '08, MOPC063, pages 211-213

D.J. Holder on behalf of the ALICE team, First results from the ERL prototype (ALICE) at Daresbury, Proc. Linac '08, WE103, 694 – 696

P.H. Williams, 10 Years of ALICE: From concept to operational user facility, Proc. ERL '15

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Accelerators and Lasers
In Combined Experiments

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K.J. Middleman	B.L. Militsyn
Y.M. Saveliev	B.D. Muratori
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S.L. Smith	J.W. McKenzie

Thank you for listening ……

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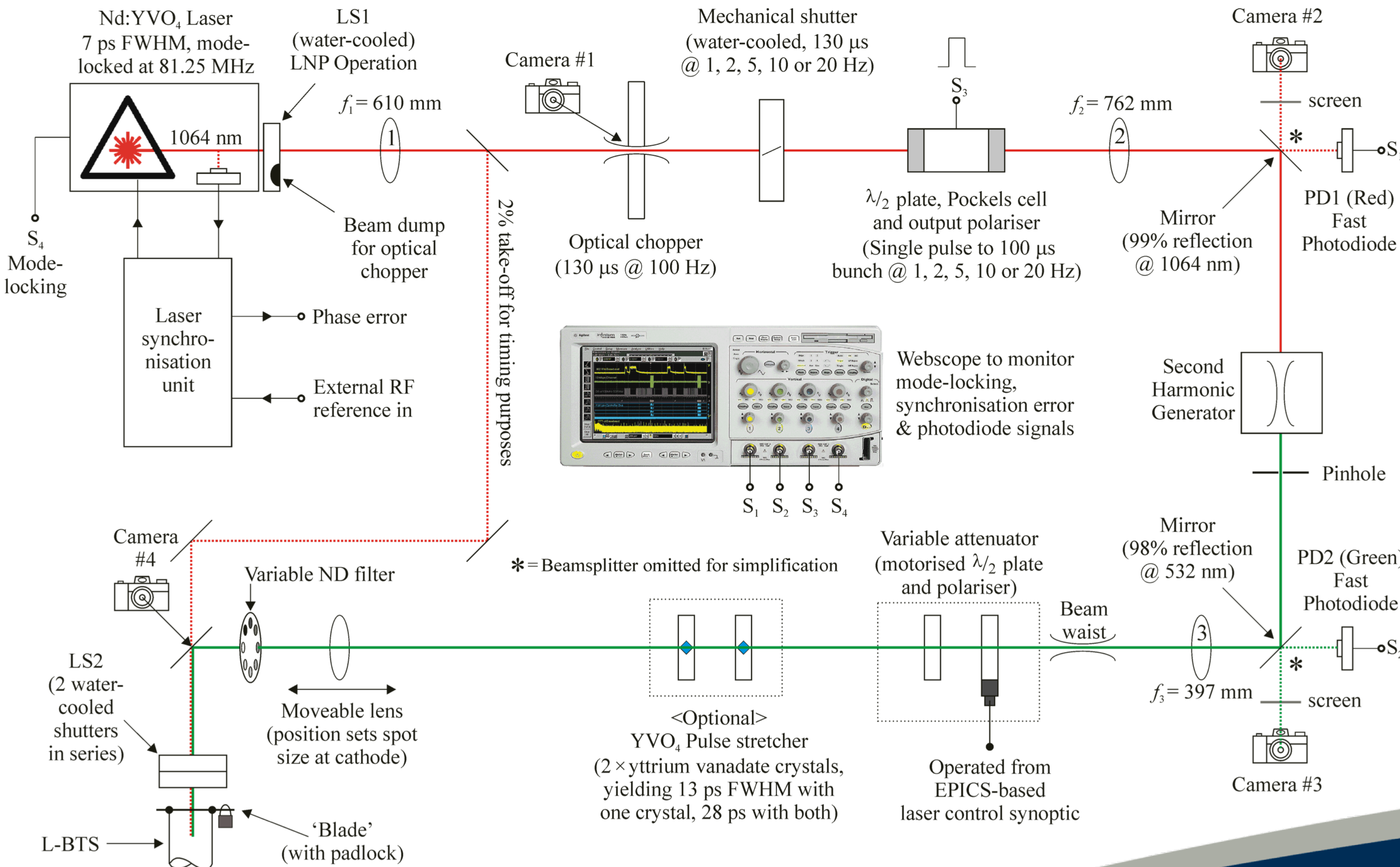
Additional Slides



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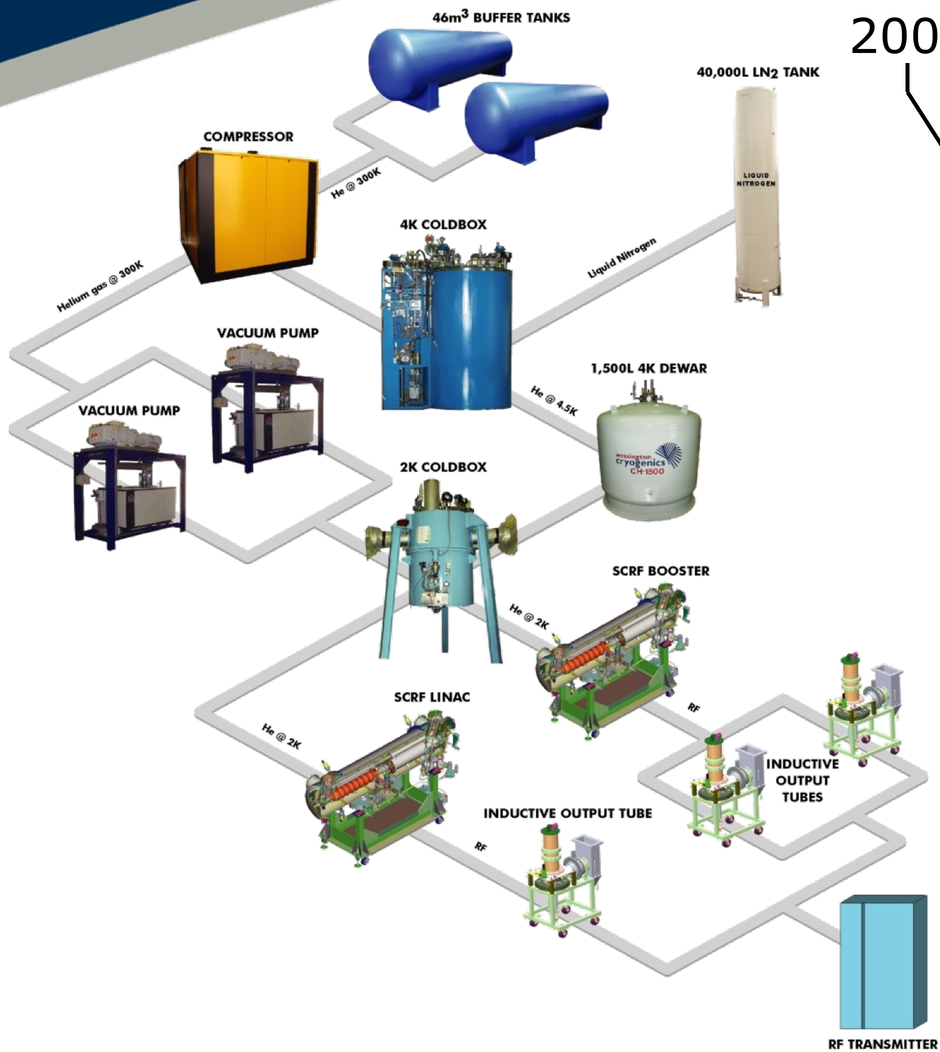
NF_3 Activation in the ALICE gun, February 12th 2009

- Our best photocathode performance (highest *Q.E.* and best dark lifetime) have been achieved using the Cs-NF_3 activation process
- However, activation success with NF_3 has been inconsistent (no first-peak photocurrent response seen in some activations, prompting a switch to O_2)
- NF_3 requires a higher partial pressure than O_2, typically a decade higher with O_2 in the mid E-10s, and NF_3 in the mid E-9s. This leads to a longer vacuum recovery
- The dark lifetime has not been specifically monitored since 2009, though chamber base pressure has improved significantly since. We now have good vacuum conditioning
- O_2 is used as the default oxidant due to health & safety considerations
- Re-caesiation typically every 10 to 12 days, having extracted ~ 0.3 C charge
- External connection to Cs channels for *fast re-caesiation* (no SF_6 extraction required)

Process	Date	Initial *Q.E.*	$^1/_e$ Lifetime	Life [hrs]	Final *Q.E.*
Activation	12/02/09	3.9	~ 200	156	0.3
Re-Cs # 1	21/02/09	3.4	~ 900	2,280	0.05
Re-Cs # 2	01/06/09	2.2	270	215	0.63
Re-Cs # 3	10/06/09	2.0	50	28	1.1

Cryosystem & accelerating modules



2006

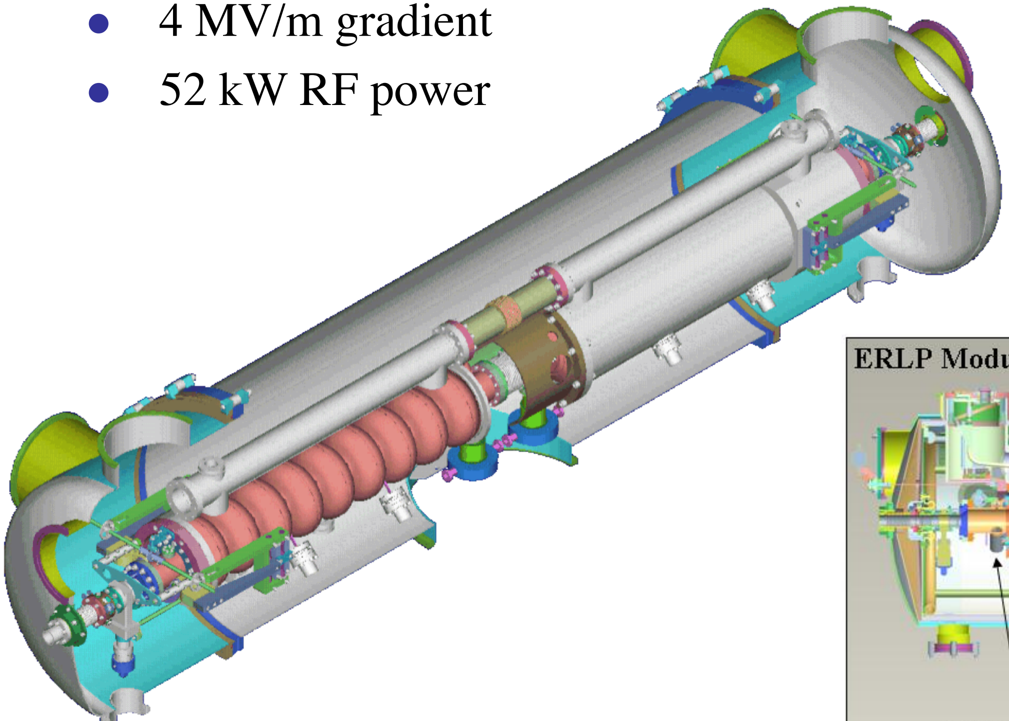
- Apr – 1st Accelerating module delivered
- May - 4 K cryo commissioning carried out
- Jul – 2nd Accelerating module delivered
- Oct - Linac cooled to 2 K
- Nov – Booster cooled to 2 K
- Dec - Modules cooled together

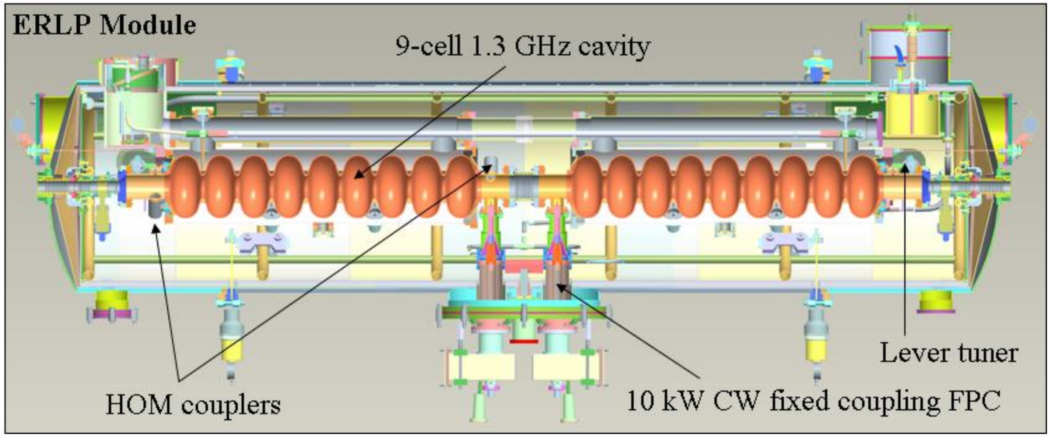
- Simulated a dynamic resistive heat load of ~ 112 W in both modules
- Achieved a pressure stability of ± 0.03 mbar at full (simulated) dynamic load in both of the modules at 2 K
- Achieved ± 0.10 mbar at 1.8 K

ScRF 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





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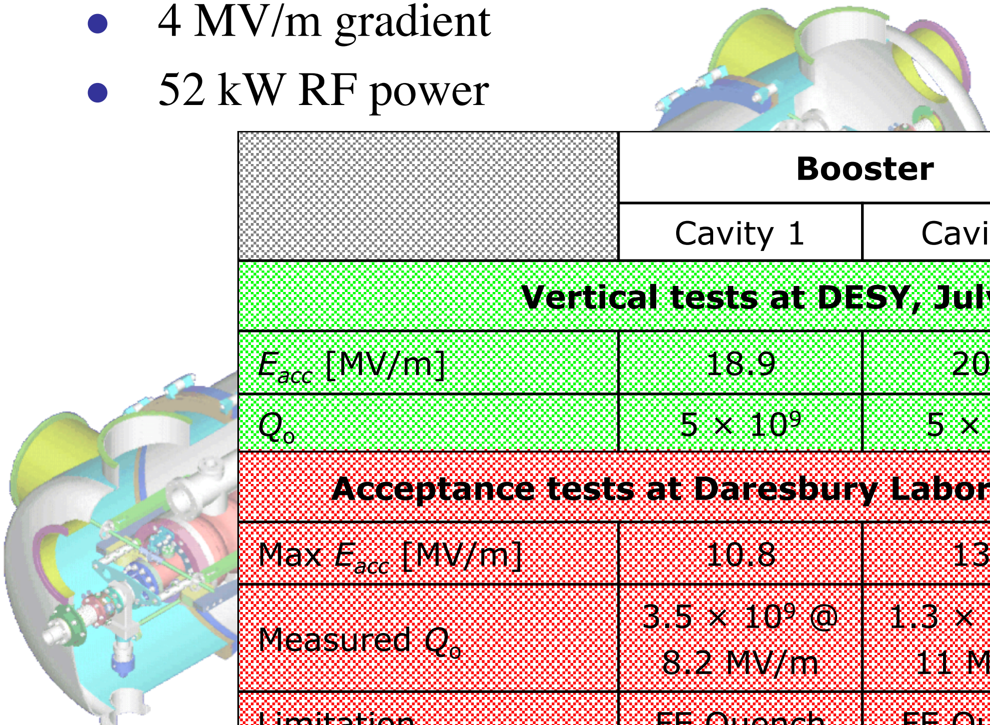
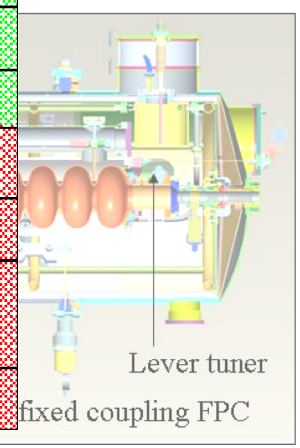
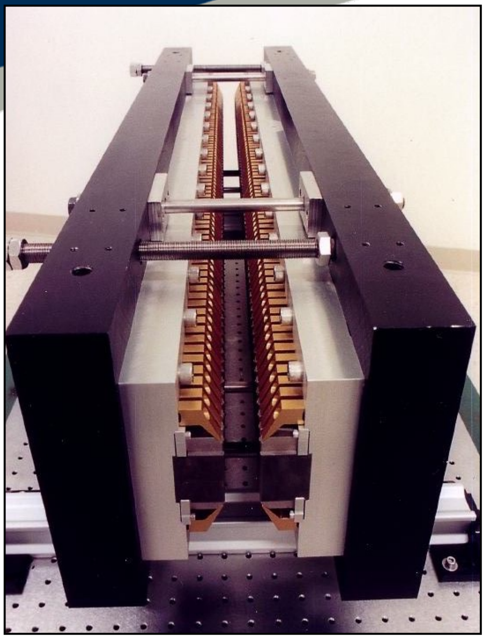


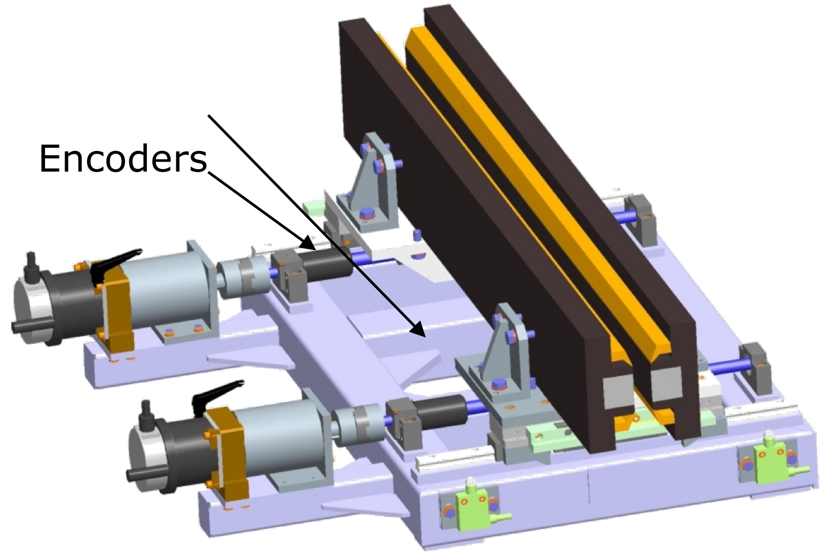
	Booster		Linac	
	Cavity 1	Cavity 2	Cavity 1	Cavity 2
Vertical tests at DESY, July - December 2005				
E_{acc} [MV/m]	18.9	20.8	17.1	20.4
Q_o	5×10^9	5×10^9	5×10^9	5×10^9
Acceptance tests at Daresbury Laboratory, May - September 2007				
Max E_{acc} [MV/m]	10.8	13.5	16.4	12.8
Measured Q_o	3.5×10^9 @ 8.2 MV/m	1.3×10^9 @ 11 MV/m	1.9×10^9 @ 14.8 MV/m	7.0×10^9 @ 9.8 MV/m
Limitation	FE Quench	FE Quench	RF Power	FE Quench

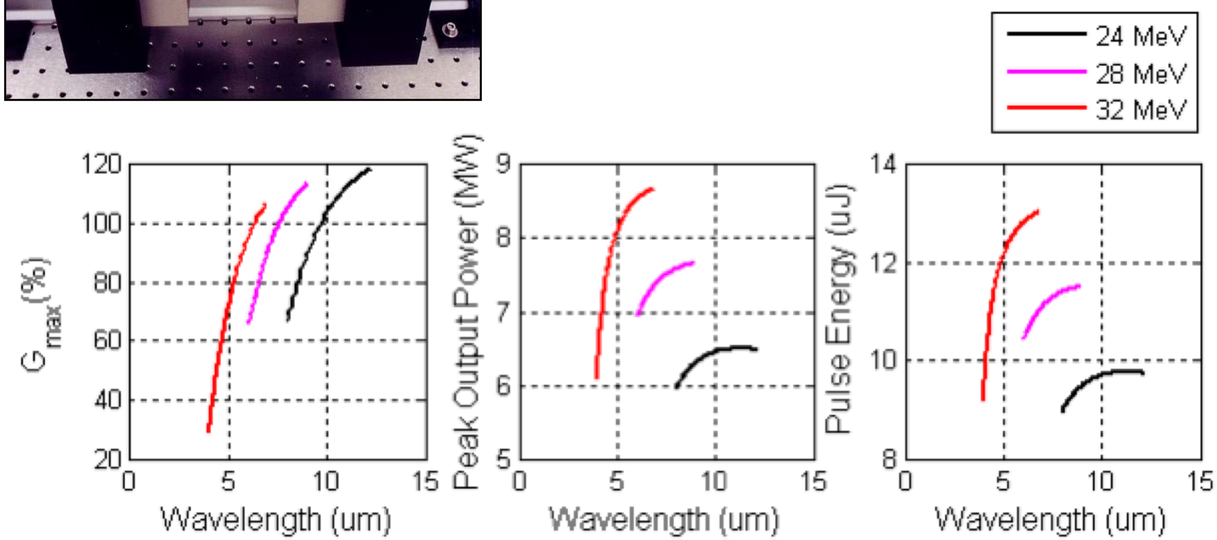


Tunable Free-Electron Laser



JLab Wiggler (on loan)





FEL Tunability by varying:

- electron energy (24-35 MeV range)
- undulator gap (12-20 mm range)

λ = 4 - 12 μm