ALICE History & Experience

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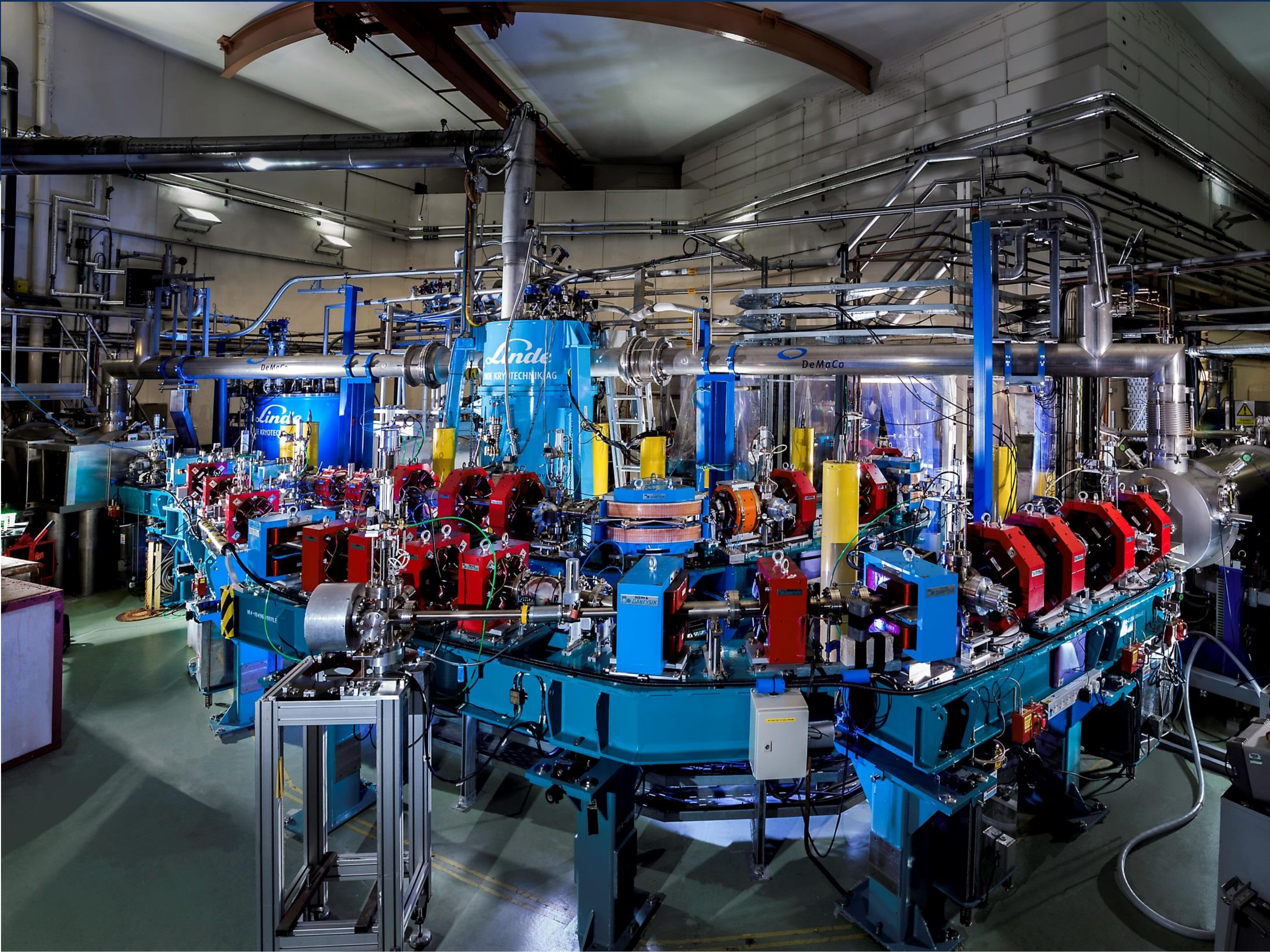
This talk draws on overviews I gave at ERL2015 and ERL 2017, with some updates and comments. More technical details in Frank's talk tomorrow

ERL2015

ERL17

The Cockcroft Institute
of Accelerator Science and Technology

Science & Technology Facilities Council
Daresbury Laboratory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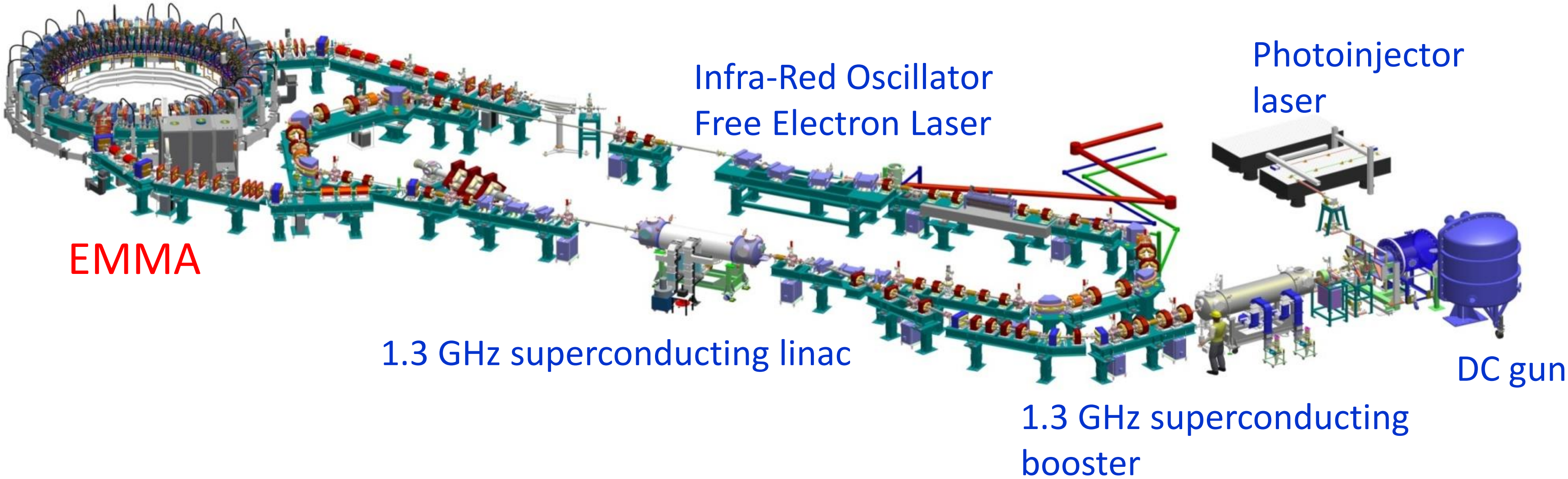
The ALICE Energy Recovery Linac @ Daresbury

Accelerators and Lasers In Combined Experiments

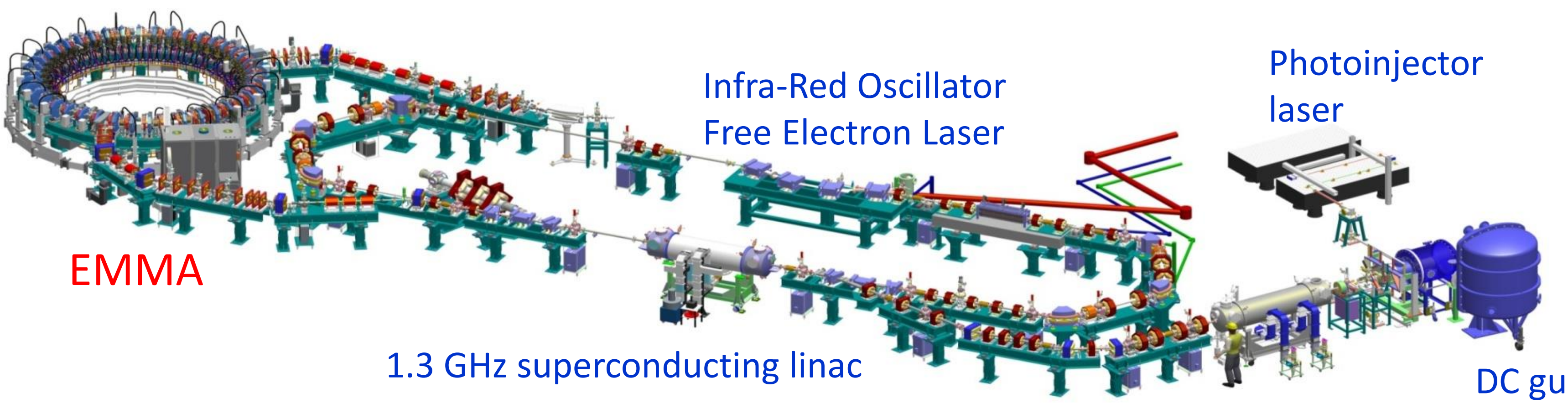
An accelerator R&D facility based on a superconducting energy recovery linac



The ALICE Energy Recovery Linac @ Daresbury

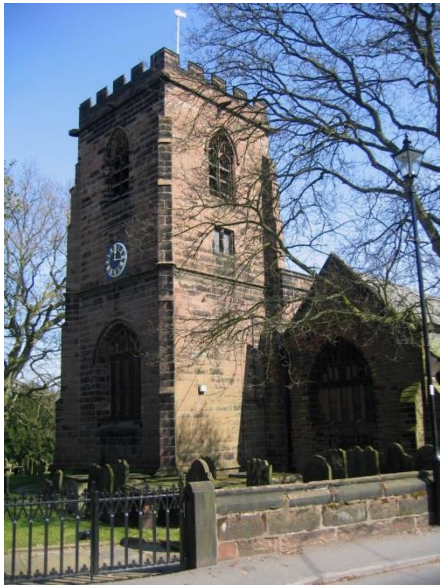
Accelerators and Lasers In Combined Experiments

A **USER** facility based on a superconducting energy recovery linac



Daresbury Laboratory

- ALICE was an ERL-FEL at STFC's Daresbury Laboratory in North-West England
- Daresbury Laboratory was established in 1964 to host NINA – a 6 GeV electron synchrotron for high-energy physics, then developed the first dedicated X-ray synchrotron light source (SRS 1980-2008) and designed UK's 3rd gen source, (Diamond 2007-…)
- ALICE sits in reused experimental areas of the Nuclear Structure Facility tower (20 MV tandem Van-de-Graaf 1981-1991)
- ALICE is **A**ccelerators and **L**asers **I**n **C**ombined **E**xperiments and was formerly known as ERLP – Energy Recovery Linac Prototype
- Lewis Carroll – author of "Alice in Wonderland" was born in 1832 in the Parsonage of Daresbury Church – adjacent to the laboratory



Ancient History: 1970's – 1990's

- Ambitions to host an FEL at Daresbury date back to 1978: Meeting on a balcony in Frascati - **Mike Poole**, John Madey, Todd Smith, Claudio Pellegrini, Vladimir Litvinenko…

- Many false starts:
  - FELIX at Daresbury (1980 – not funded)
  - UK-FEL in Glasgow (Built 1983-1986 – not operated)
  - Oxford FEL (1990 – not funded)
  - FELIX - Nieuwegein, Netherlands (Operational 1991 – present) re-used UK-FEL expertise and undulator

- 1986 Blundell Report then 1993 Woolfson Report for UK Government on SR provision:
  1. ESRF for hard X-ray
  2. Diamond for soft X-ray
  3. "Access to brilliant VUV radiation…a new low energy source, which would be unique, should be pursued…"

- This "three ring circus" concept was reiterated in through the 1990's, driven by ambitions of UK synchrotron user community

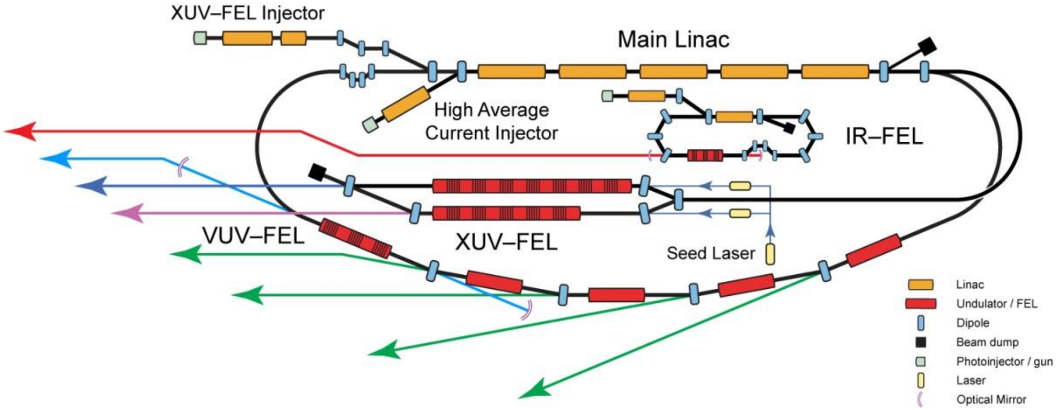
- At first storage rings – SINBAD and DAPS, were proposed, then the potential of FELs started to gain traction

FELIX
Free Electron Laser
for
Infrared eXperiments

First FEL worldwide which
- was really tunable
- worked "every day"

2000: A MHz Rep Rate XUV / VUV / IR FEL User Facility?

- **2000**: Daresbury responded to this challenge with a proposal for a new combined XUV, VUV and IR facility - 4GLS
- Key concept was a VUV-FEL driven by a **CW-Energy recovery linac** for high peak and average power simultaneously



- **2003**: We had a lot to learn, so as part of the proposal, funding was provided to **construct a prototype ERL machine** (ERLP → renamed ALICE in 2008).
  - Gain experience with assembling and operating TESLA cavities and cryomodules, and the associated cryogenics and controls technology
  - Develop and operate an energy-recovery system, including issues such as RF, synchronisation and optics.
  - Develop photoinjector technologies
  - Develop technologies for operating oscillator free-electron lasers (FELs)
  - Develop an understanding of bunch compression and associated beam transport issues in combination with simulations.
  - Develop diagnostics techniques and instruments for use on 4GLS.

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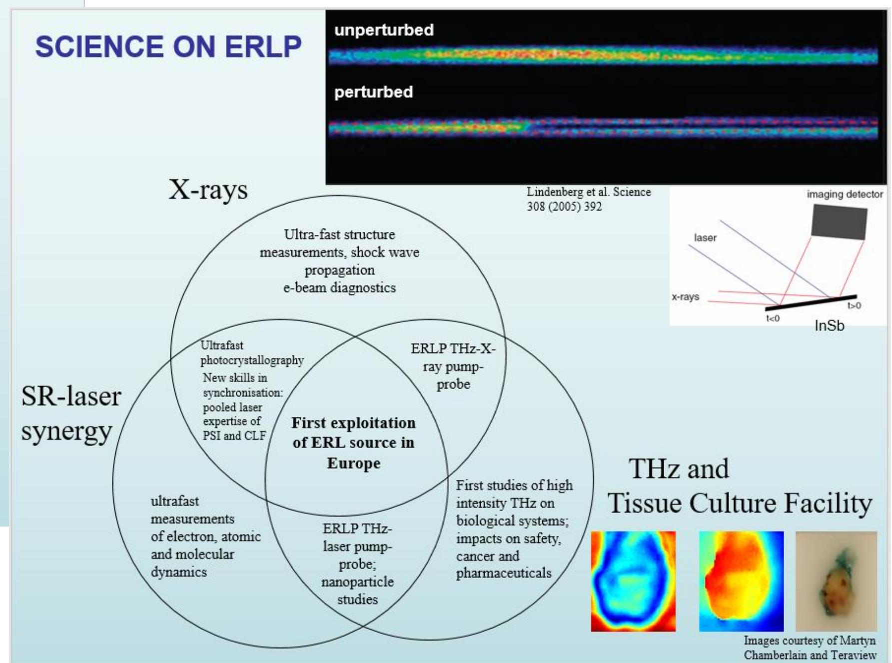
2003: ERLP – Prove we can build an ERL-FEL and USE IT for Science

ERLP Principal Aims

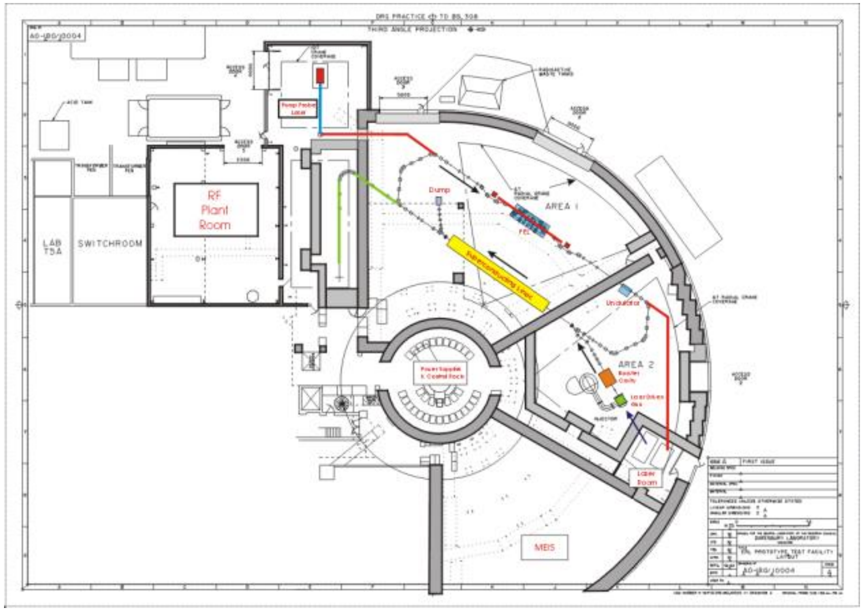
- To prove that the team has the skills to design and build 4GLS. Demonstrated by ERLP build and successful operation.
- To master energy recovery – first example in a SC linac machine in Europe
- Working photoinjector – first example in the UK
- Generation of sub ps pulses of light
- Synchronisation of laser and RF
- Accelerator physics simulations and studies

From Elaine Seddon: "4GLS User Consultation"



Remember at this time the ONLY SC-ERL in the world was the JLab IR-DEMO.
We had to prove we could build an ERL **without** the US Navy funding and CEBAF experience and make it useful!

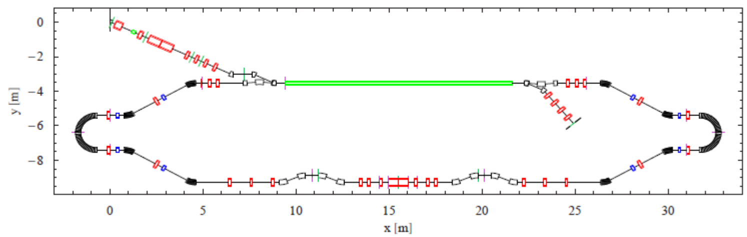
2003: Design an Energy Recovery Linac Prototype

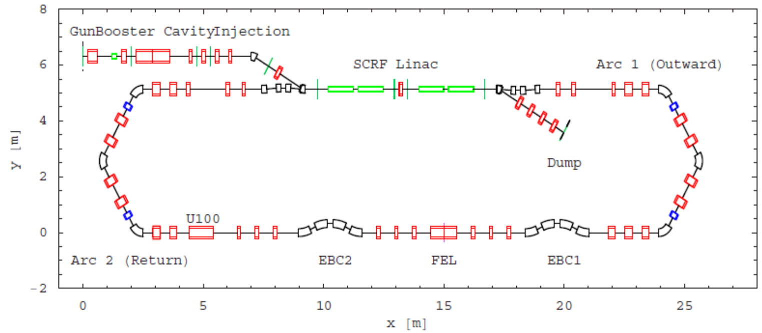


- Site in reused Nuclear Structure Facility experimental areas, underneath the 20 MV Van-De-Graff tower decommissioned 1991 -> many layout restrictions
- Extensive collaboration with JLab who had just had IR-upgrade funded
- 350 kV DC photocathode gun based on JLab design with GaAs cathodes with internal re-caesiation system
- 2K LHe Cryosystem with 120 W capacity
- 2 Stanford / Rossendorf cryomodules (Booster 8 MeV, 52 kW; Linac 27 MeV, 13 kW)
- Oscillator FEL using JLab IR-Demo wiggler re-engineered for variable gap
- 9 m optical cavity at 5th subharmonic of 81.25 MHz rep rate

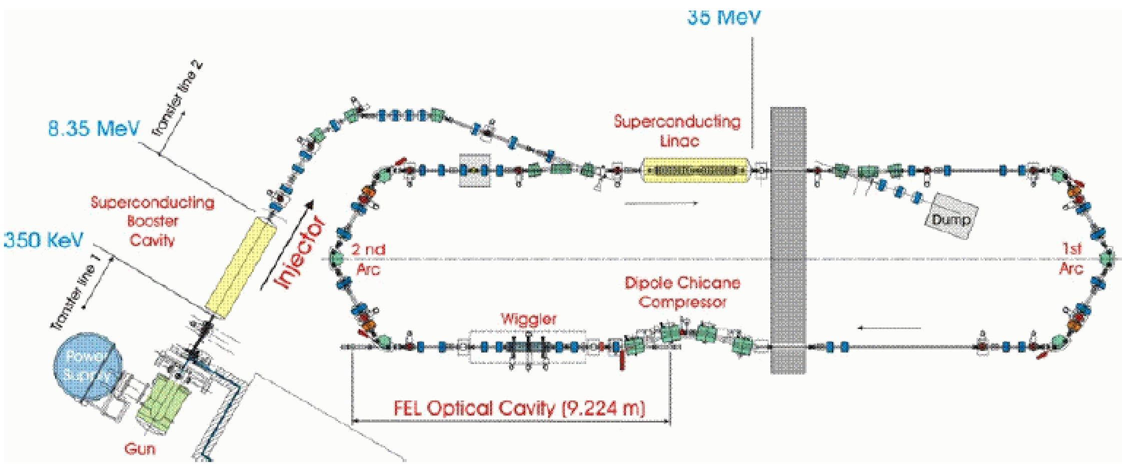
2003: Design an Energy Recovery Linac Prototype

- Lattice options considered included two chicanes (one compression, one decompression) with Bates or TBA arcs





- Settled on isochronous TBA, one compression chicane (R56 ~ 23 cm) with decompression in return TBA arc (R56 ~ -23 cm)
- Forced into a long, complex injection line by layout restrictions – BIG mistake!
- Exacerbated this mistake by removing some BPMs, screens in the injector



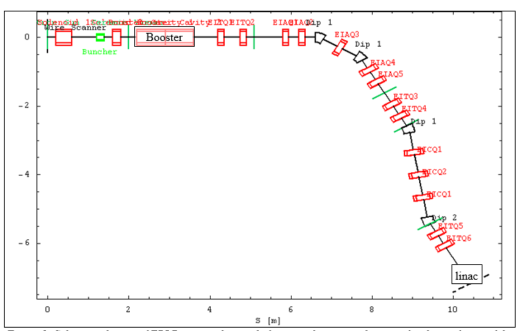
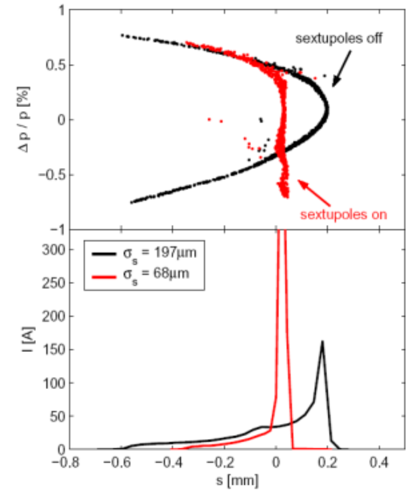


Figure 2: Schematic layout of ERLP injector line including gun, booster, achromat, dog-leg and part of the ERL ring

- The intention was to run ERLP for only ~18 months then reuse components in a 550 MeV 4GLS

2003: Design an Energy Recovery Linac Prototype

- One sextupole pair included into both outward and return TBAs to enable linearization of longitudinal phase space



- Longitudinal match to FEL was point-to-parallel: i.e.

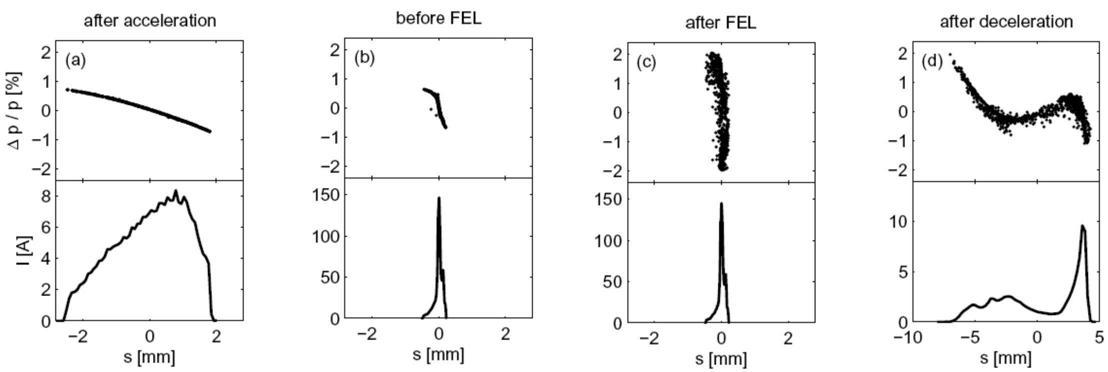
1. Inject at 7.5 MeV
2. Chirp and accelerator (nominal -8 degrees, rising side of crest) to 35 MeV
3. Compress and linearise: R56 = 0 (arc), +28 cm (chicane),

   T566 = -0.4m (chicane), -2.9 m (arc)

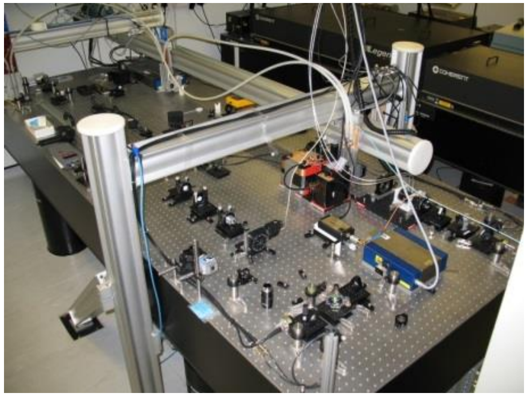
1. Lase (increase energy spread from 0.4% to FW 5% and decrease mean energy 2%
2. Decompress and linearise (R56 = -28 cm, T566 = +2.9 m)
3. Dechirp and decelerate (nominal 8 degrees on falling side of trough)
4. Dump below injection energy (as energy lost to FEL radiation) at ~ 6.9 MeV

- Return phase set with trombone

  1st arc movement up to 23 cm



2004: Procurement & Construction

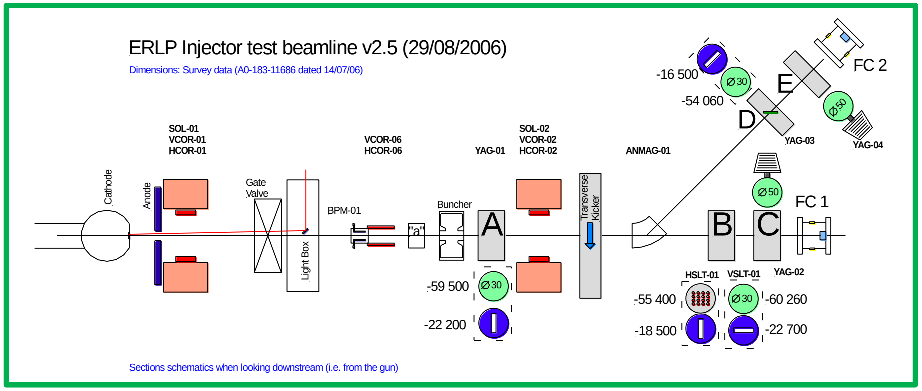


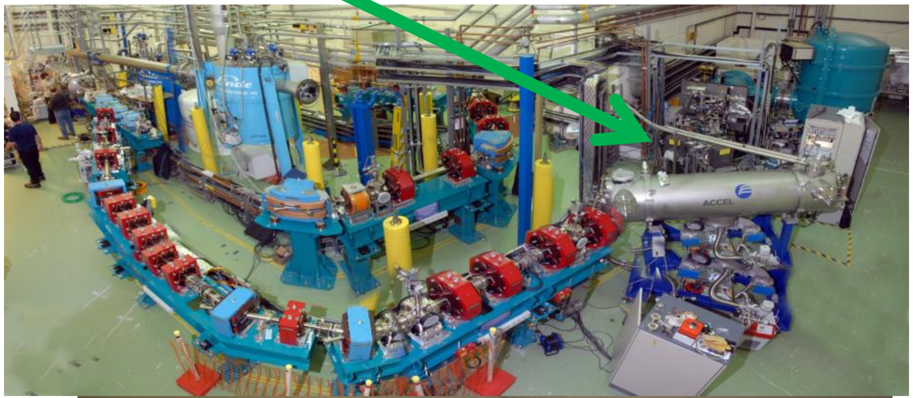
- **2004**
  - Photoinjector laser system commissioning
  - Layout and component specification completed
  - Magnets, IOTs, gun, SF6 vessels, DC HV delivered

- **2005**
  - Gun HV PS assembled
  - Problems with gun ceramic meant need to remanufacture
  - Problems with buncher
  - TW laser installed for a demo of Inverse Compton scattering X-ray generation (Gerd Priebe)

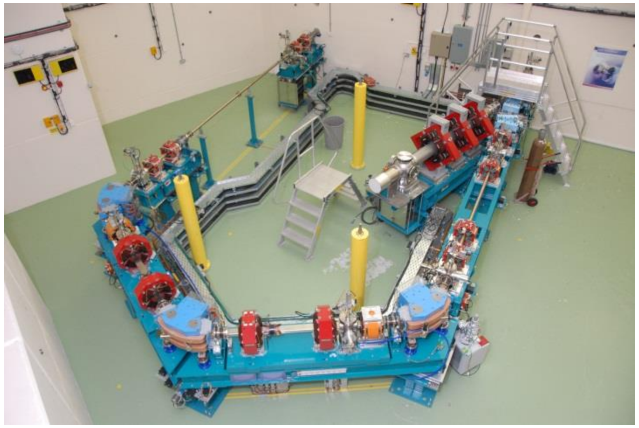
2005/6: Installation & Gun Commissioning

- Booster module is swung to the side to allow for gun diagnostic beamline



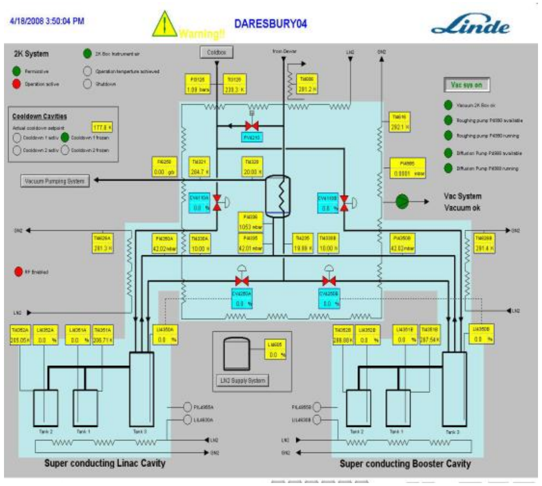


- The first beam – 16th August 2006

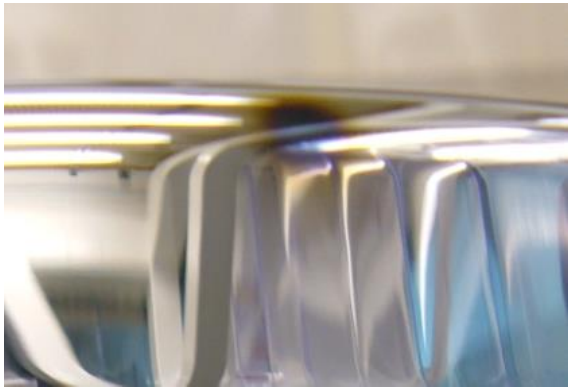


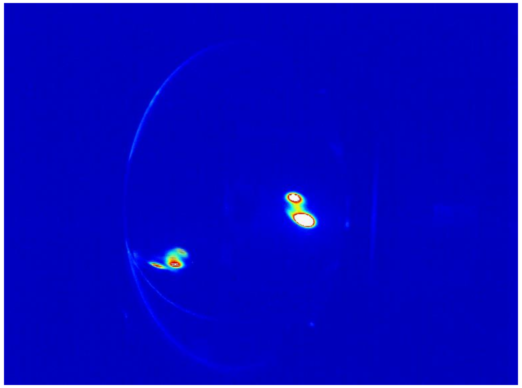
2007: The Year of Pain: Cryo & Gun Problems

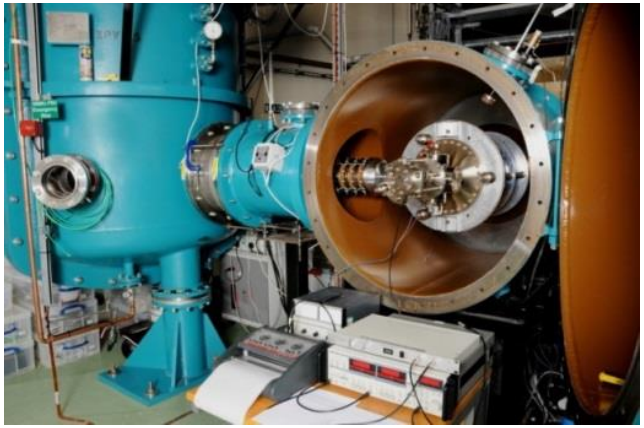
- Rebuild of transfer lines
- Cooldown rates inadequate
- 2K recuperator heater failures
- Contamination & Leaks…



- Strong field emission from the cathode and rapidly deteriorating QE, non-uniform QE map
- Mechanical failure inside the cathode ball (flap)
- Conditioning resistor failure
- Second cathode also suffered rapid QE deterioration
- Contamination after each cathode activation
- Gun disassembled then vacuum leak
- Nevertheless by end 2007 – 100 pC achieved (QE>3%) and full characterization at 350 keV

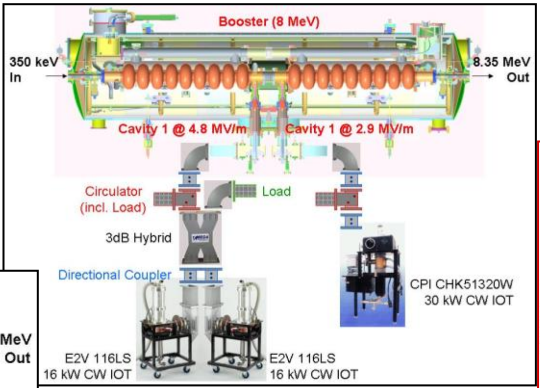


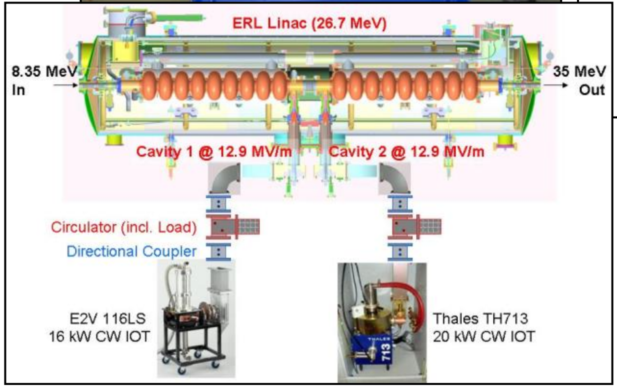


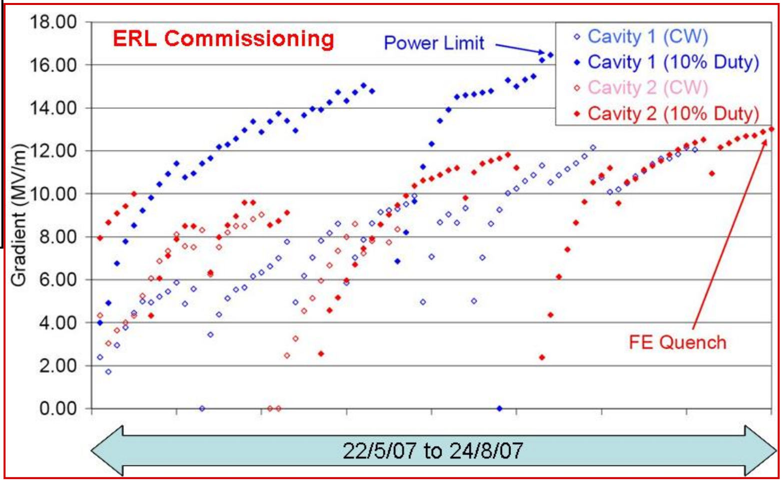


2007: The Year of Pain: RF Problems

- Significant field emission within linac limited gradient – these were some of the very first TESLA-type modules produced by ACCEL (now RI), and became badly contaminated during integration
- Installed additional shielding to protect control rack from radiation damage (but later the pumping platform rubber shock absorbers situated above ERL module hardened), ALICE operated at 27 MeV rather than 35 MeV throughout its life, situation improved somewhat after pulsed He processing in 2013
- Booster IOT co-axial couplers – too risky for the intended move from a macropulsed system to CW operation

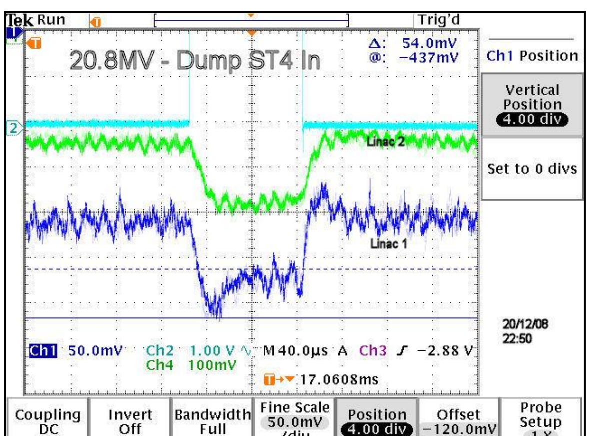


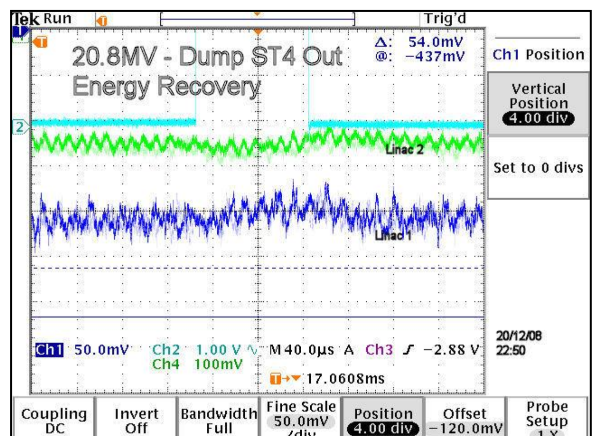




2008: Energy Recovery at Last

- Booster cryo-module sent for repair at ACCEL (January-March)
- Isolation window failure, IOT power supply failure
- 4GLS programme cancelled (political weakness of VUV community in UK vs hard X-ray) – ERLP renamed ALICE and exploitation becomes more important than test facility role
- Stanford U. (Todd Smith) ceramic with smaller diameter installed in the PI gun (June) → **230kV only** until 2012
- Then … FAST progress … First beam through the booster in October, first beam through the linac in December
- Just before Christmas full energy recovery at 20.8 MeV - just ~**10 pC** at first, but then **80 pC** achieved early 2009 – **ER efficiency > 100%** (i.e. possible to dump at less than injection energy





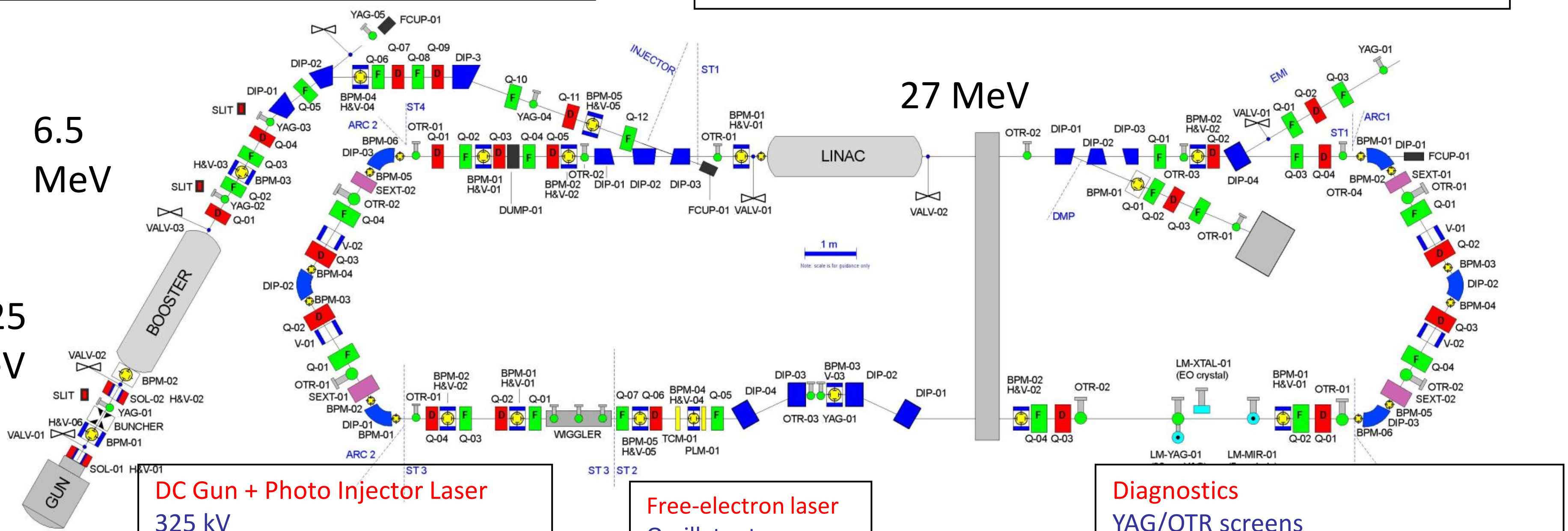
The gradient demand traces from the two linac cavities (original analogue LLRF system) as pop-in dump in return path is retracted

RF System
Superconducting booster + linac
9-cell cavities. 1.3 GHz, ~10 MV/m.
Pulsed up to 10 Hz, 100 μS bunch trains
Cryo capacity 180W @ 2K

Beam transport system.
Outward TBA arc tuned first-order isochronous, second order compensates T566 of chicane

4-dipole bunch compression chicane R_{56} = 28 cm

Return TBA arc decompresses and de-linearises – match to small energy spread at ER dump



DC Gun + Photo Injector Laser
325 kV
Green (532nm) laser
GaAs cathode; QE=2.5-3.0%
Up to 100 pC bunch charge
Up to 81.25 MHz rep rate

Free-electron laser
Oscillator type
Variable gap wiggler
11m optical cavity

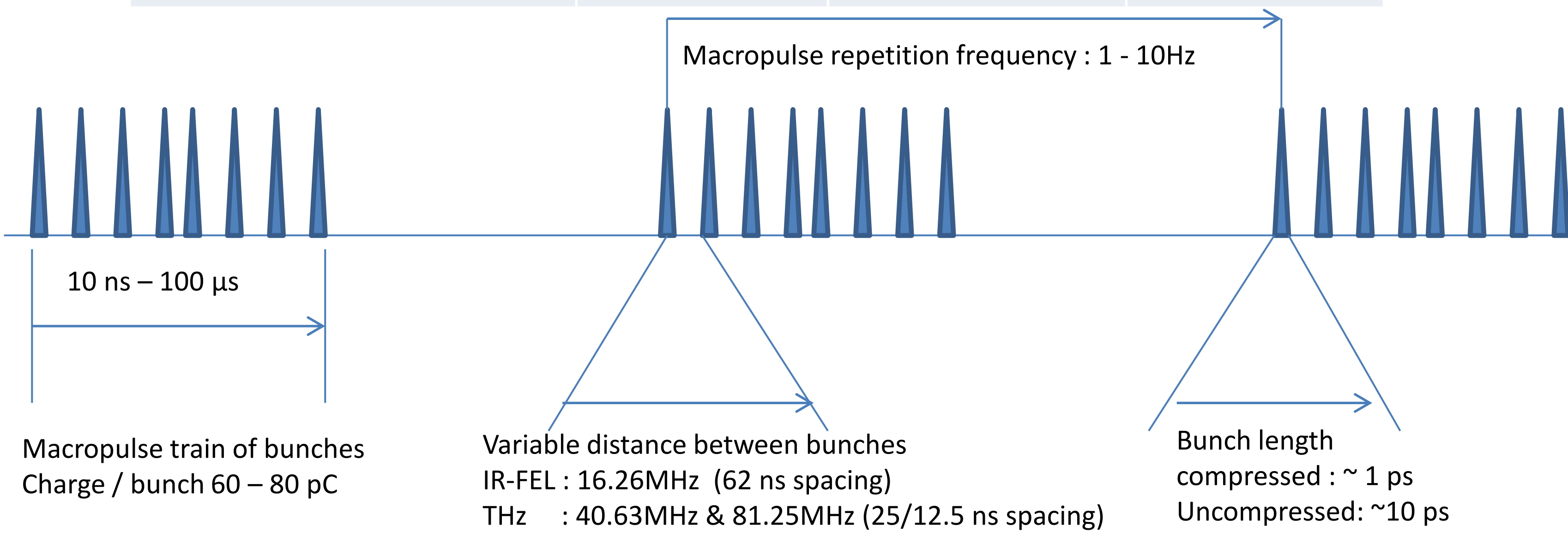
Diagnostics
YAG/OTR screens
BPMs (stripline / button)
Slits
Energy spectrometers
Electro-optic bunch profile monitor

The main goal of ALICE was to deliver the bunch as short as possible to IR oscillator FEL and for generation of broadband THz radiation from the bunch compression chicane

ALICE Parameters & Timing Structure

Parameter	Design	Operating	Units
Bunch charge	80	20 - 80	pC
Gun energy	350	230 → 325	kV
Booster energy	8.35	6.5	MeV
Linac energy	35	27	MeV
Repetition rate	81.25	16.25 - 81.25	MHz
Current within macropulse	Up to 6.5	> 6.5	mA

Due to Accel modules not meeting spec (refers to Linac energy)



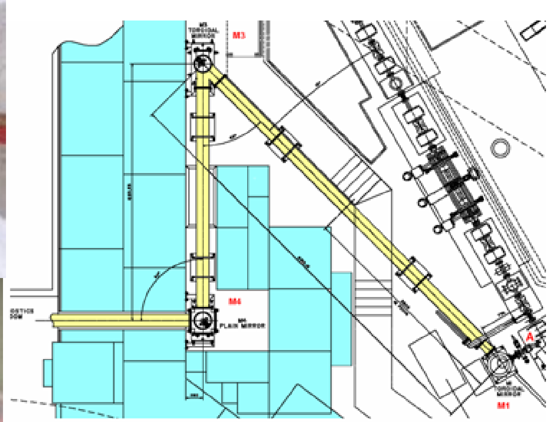
2009: Commissioning & First Exploitation: Broadband THz Source

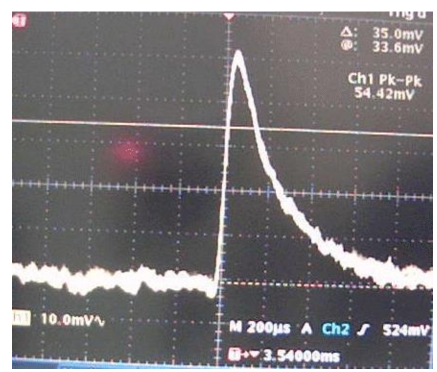
Commissioning progress:

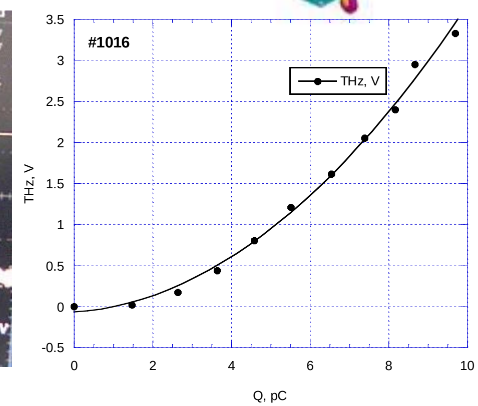
- Full cathode re-activation and elimination of vacuum leak → QE ~ 4% ; >80pC ; long lifetime of 4-5 days
- Kr based "plasma cleaning" of the gun → removed most field emission on cathode ball
- LLRF optimisation to alleviate beam loading in the booster → 40pC; 81MHz; 100us
- RF cavities conditioning and RF pulse reduction → operation at up to 30MeV possible if brave – but decided against to spare the controls rack and pumping platform from radiation damage

Coherent THz:

- Broadband (peak at 0.3 THz) radiation from 1 ps bunch at bunch compressor dipoles 3 (roughly 1/3 of the power) & 4 (roughly 2/3 of the power) – transport to the diagnostic room most tricky – 20% transmission. Typically 70 kW peak, 23 mW average power (70 nJ / pulse)







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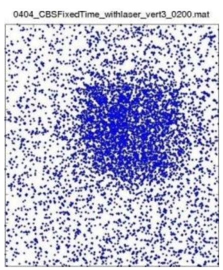
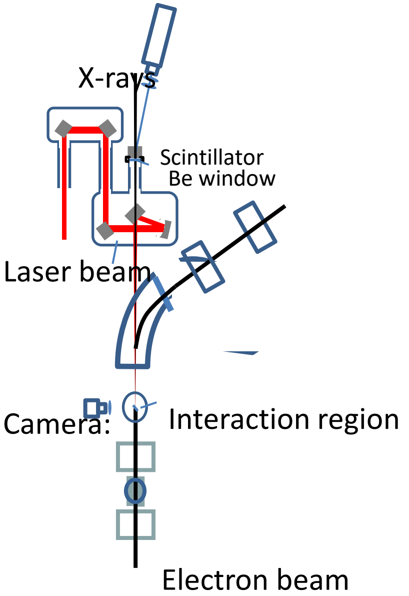
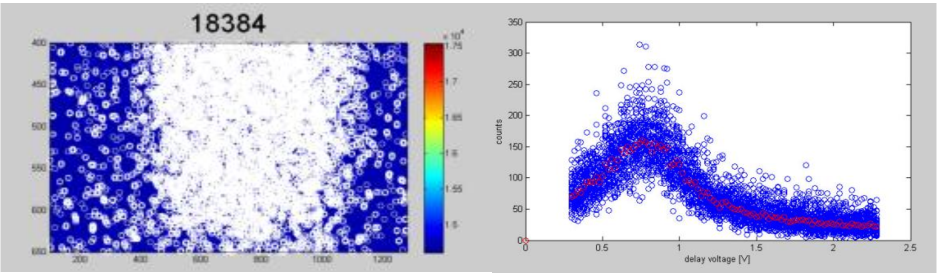
2009: Inverse Compton Scattering X-ray Demo

- 10 TW, 800 nm laser produced X-rays in head on configuration at ~30 keV
- Image shows X-rays detected on screen ~10^3 per macropulse





- Plot shows X-ray intensity as laser timing scanned, pulse ~100 fs duration



- This was just a demonstration – remember ALICE was not designed specifically with an optimised Compton interaction region and it was difficult to squeeze the beam. Also we could not go CW with beam, and no optical enhancement cavity

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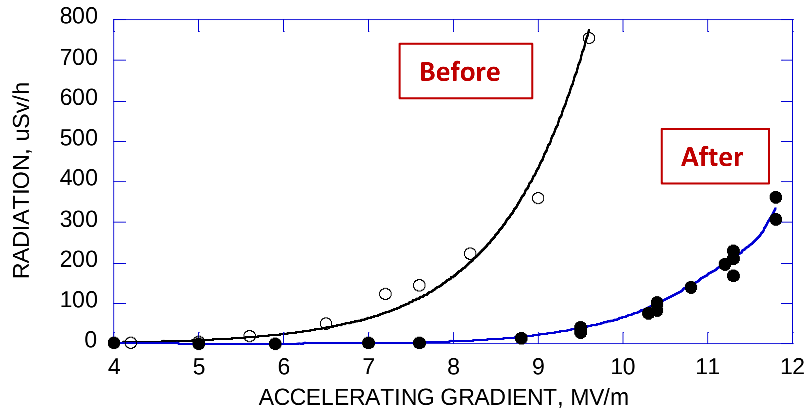
2010: The Lead-up to the IR-FEL Lasing

- Helium processing of linac cavities:
  Improvement in field emission onset in linac cavity after processing

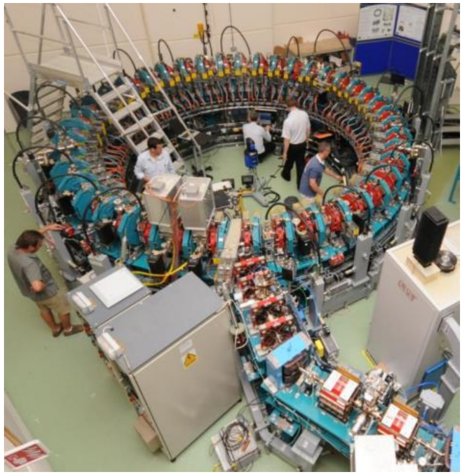


- PI laser burst generator installation:
  Second Pockels cell in series allows pulse picking and therefore < 81MHz operation, enables Q = 60pC standard and >100 pC possible as booster limited

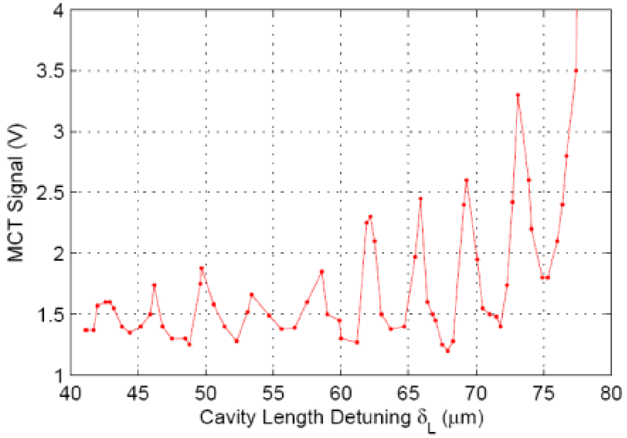
- THz cells exposure:
  Experimental programme to investigate effect of intense THz on living tissue in an incubator located in the accelerator hall

2010: The Lead-up to the IR-FEL Lasing

- EMMA ring:
  ALICE used as an injector for world's first Non-Scaling FFAG and completed many turns – not the subject of this talk!



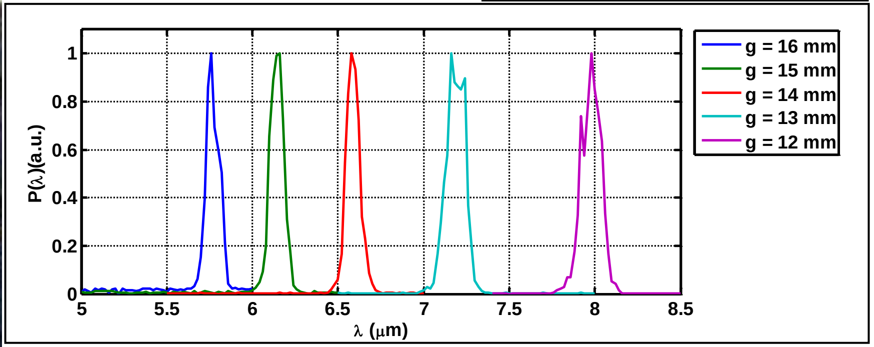
- FEL preparation: Cavity mirrors installed and aligned, first observation of spontaneous emission. Radiation was stored in the cavity immediately, indicating the transverse pre-alignment was reasonable. Spectrometer installed and tested. Strong coherent emission seen with dependence on cavity length…



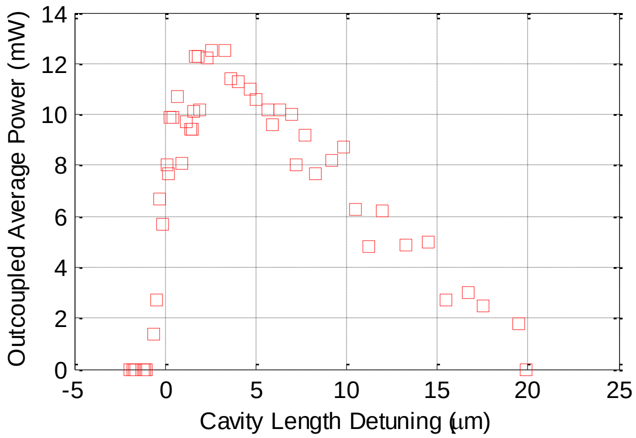
23rd October 2010 – First Lasing

Continuous tuning 5.7-8.0 µm, varying undulator gap

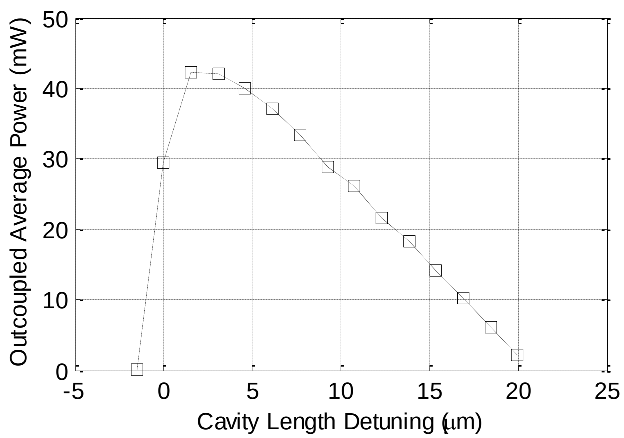
Lasing 100-40 pC @ 16.25 MHz

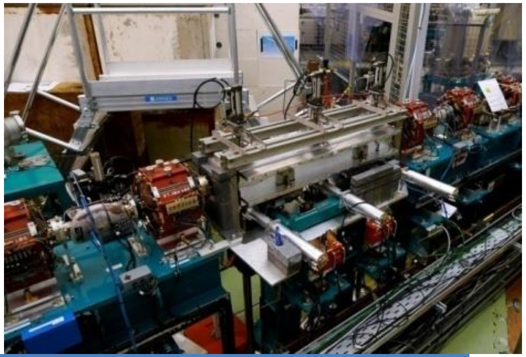


First Lasing Data: 23/10/10



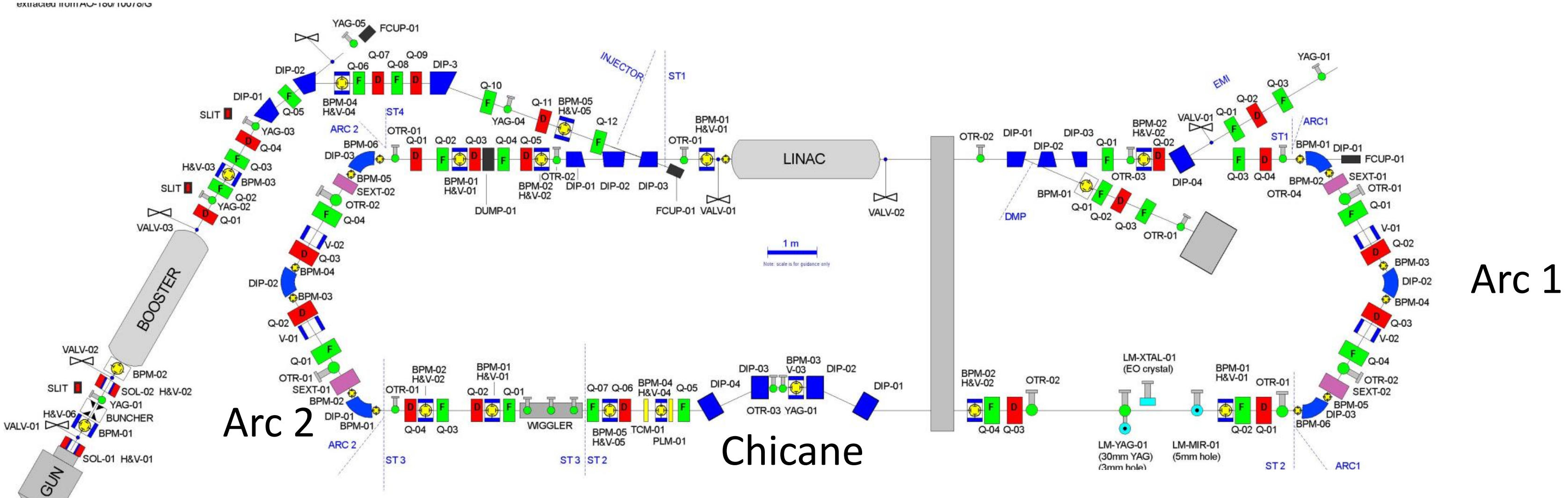
Simulation (FELO code)





The peak power ~3 MW
Single pass gain ~25 %

ALICE Energy Recovery Transport With FEL Lasing

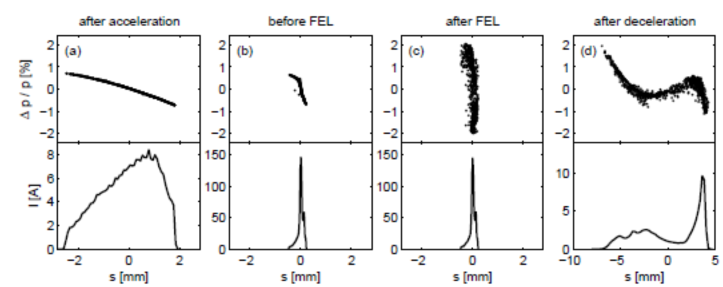


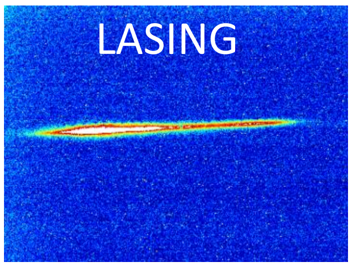
- Chicane R_{56} = 28 cm $\Rightarrow$ for a flat bunch on linac entrance at 6.5 MeV would need linac phase of +10°

- But need to compensate predominantly space-charge driven energy chirp in the bunch coming from injector from 0 to +5 °; hence overall off-crest phase +15 / +16 °

- Arc 1 nominally achromatic & isochronous at first order, sextupoles in AR1 ensure linearization of curvature (T_{566}~3m)

- Arc 2 R56 set to -28 cm and reintroduces curvature to ensure longitudinal match at linac re-entry





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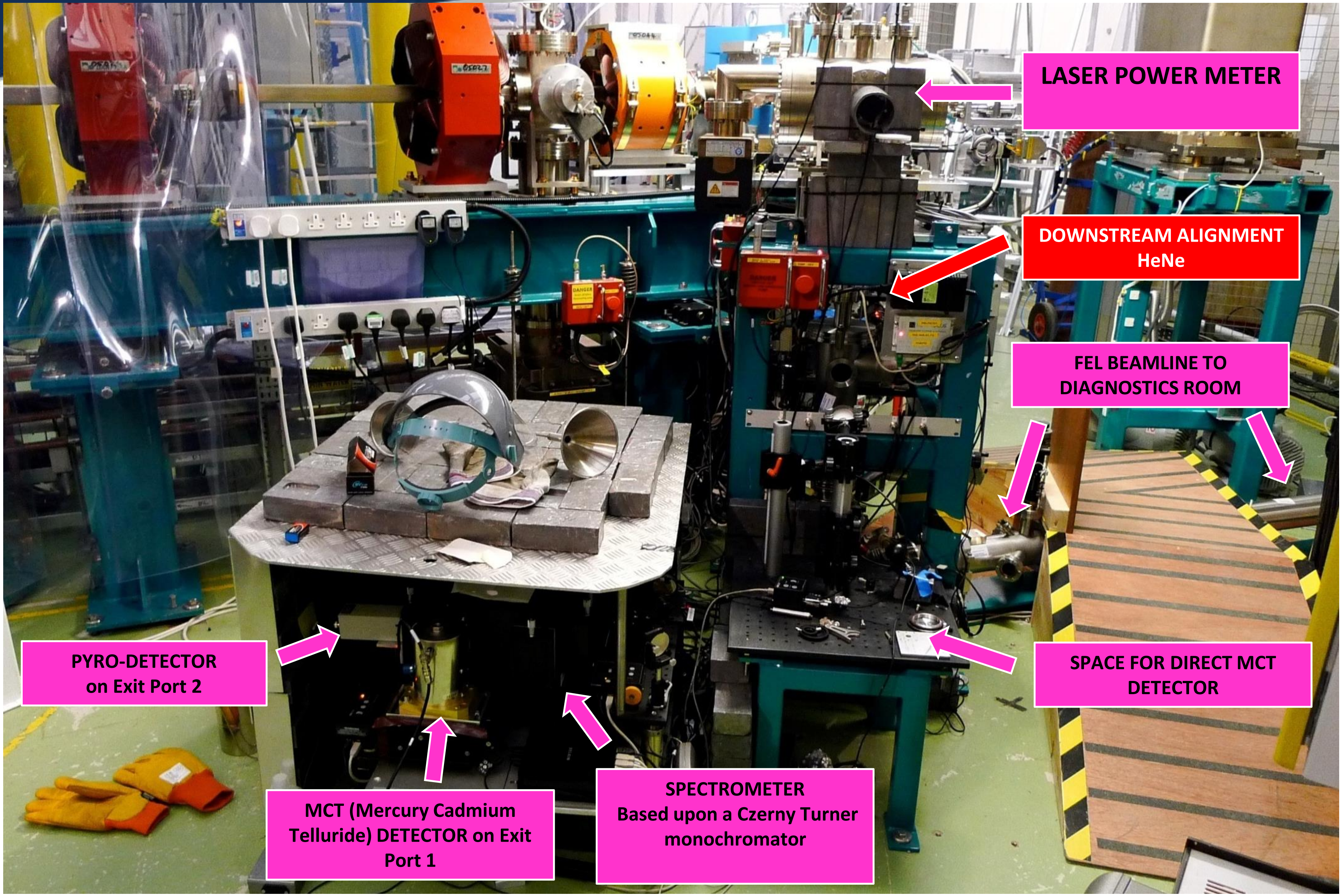
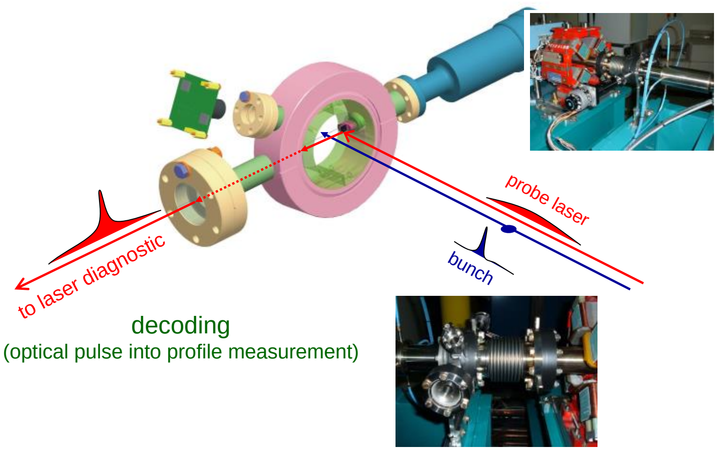


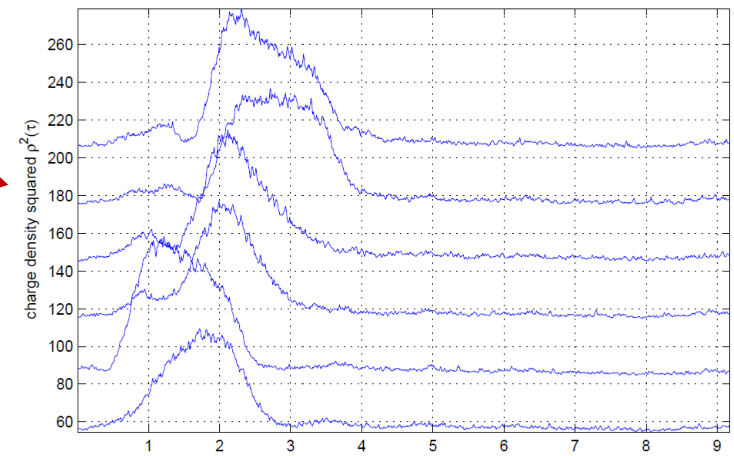
2010 – 2016: Typical Operational ERL with FEL Lasing Parameters

Full Energy (MeV)	24-27
Injector Energy (MeV)	6
Bunch Charge (pC)	60 – 80
Micropulse rep. rate (MHz)	16.25 / 32.5
Macropulse length (µs)	85 + 15 startup
Number of micropulses / macropulse	1400 / 2800
Macropulse rep. rate (Hz)	10
Wavelength range (µm)	5.5 – 11
Micropulse energy at sample (µJ)	2
Peak power at sample (MW)	2
Av. Power within macropulse (W)	20
Av. Power (mW)	40
Linear polarisation	>95%
Power stability	~0.2 – 1 %

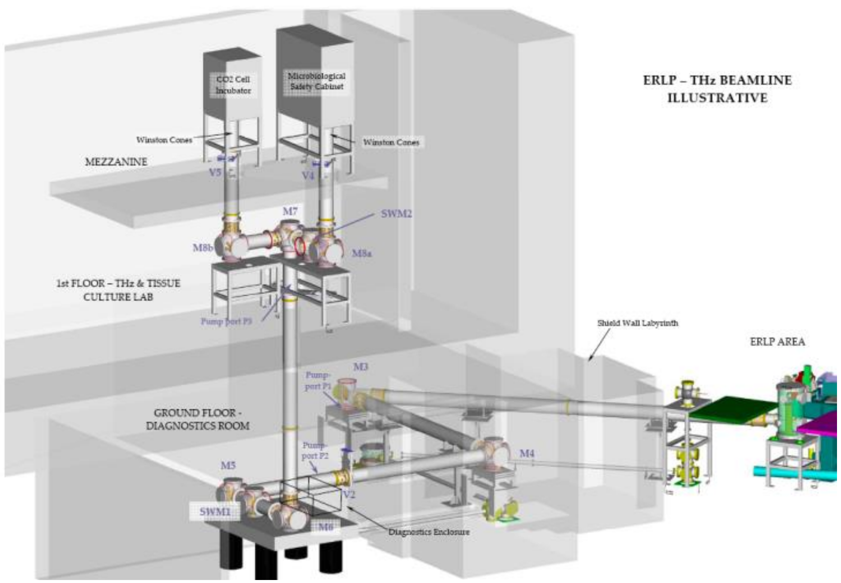
2011: THz and IR-FEL User Runs Commence

- Machine Development:
  Electro-Optic system confirms 1-2 ps bunch lengths after compression – individual pulse profiles





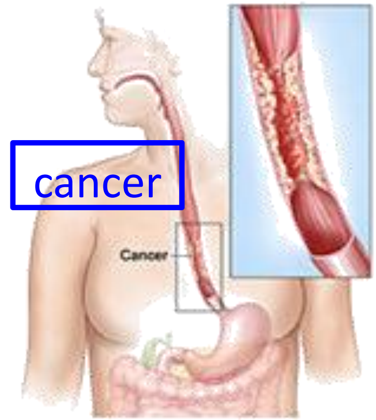
- Commissioning of THz and FEL user beamlines:
  THz beam transported to a Tissue Culture Lab
  Biological experiments to determine safe limits of exposure of human cells to THz and effect of THz on differentiation of stem cells



> 10 KW in single THz pulse with ~ 20% transport efficiency to tissue culture lab

2011: IR-FEL Illuminated Near-Field Microscopy for Oesophageal Cancer Diagnosis

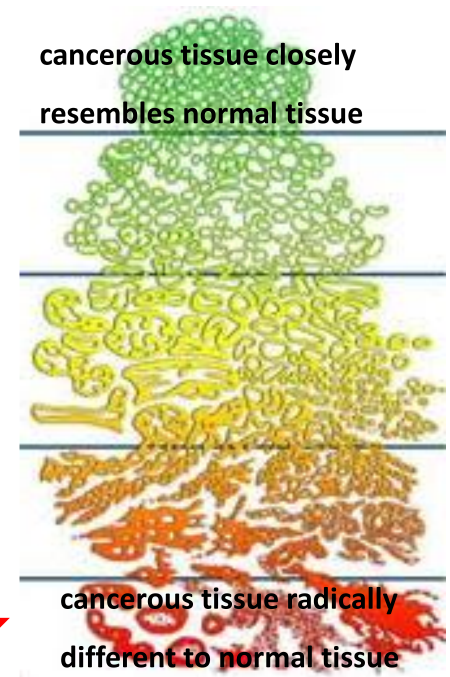
- FELIS:
  Scanning Near-Field Optical Microscope installed and integrated with IR-FEL beamline
- Motivation:
  - Oesophageal adenocarcinoma is the fastest rising incidence of cancer in the western world and survival rates are very poor
  - Oesophageal adenocarcinoma often progresses from **Barrett's oesophagus**: lining of the oesophagus is damaged by stomach acid and changed to a lining similar to that of the stomach.
  - **The challenge is to identify patients with Barrett's oesophagus who will develop oesophageal cancer.**
- Present method of diagnosis:
  - Subjective
  - Patterns difficult to interpret
  - Biopsy may not be representative



false positive -> patient has unnecessary surgery

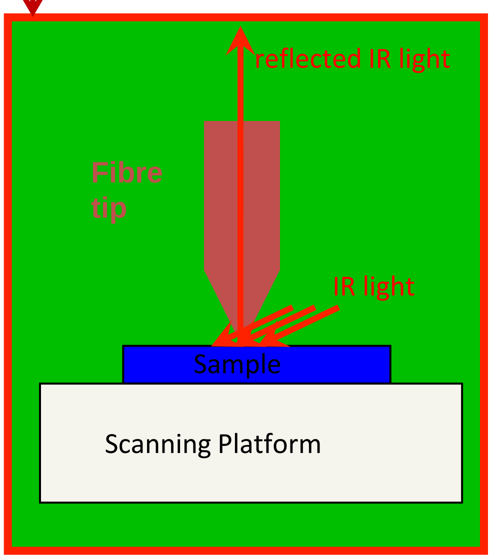
false negative -> patient dies

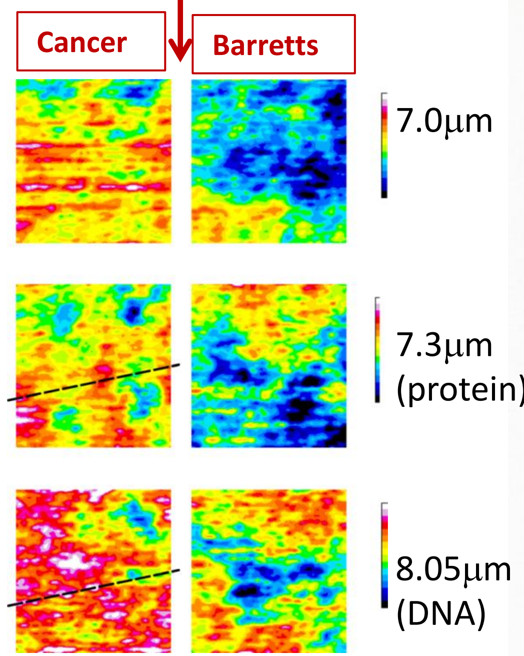
cancer increasing

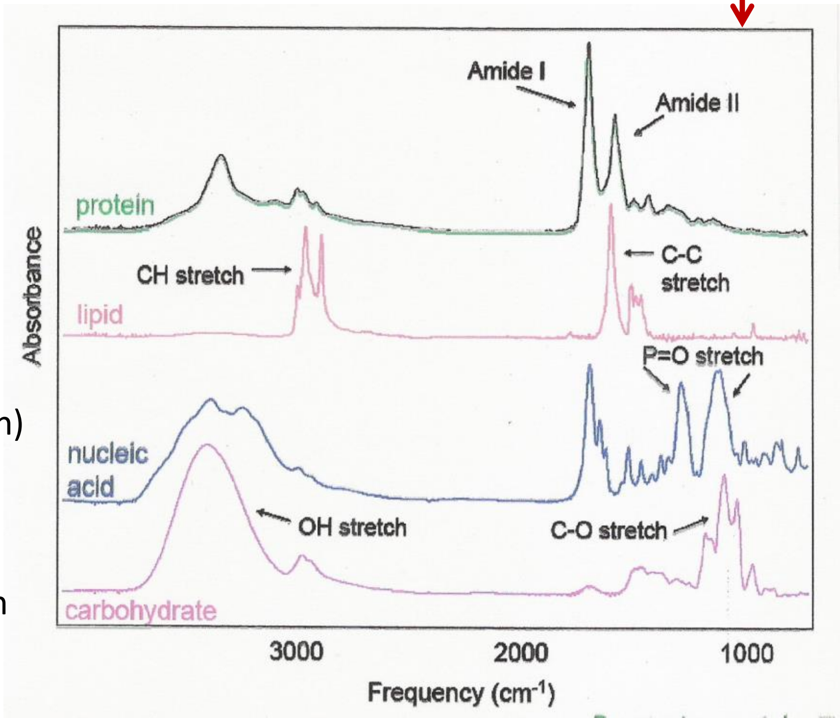


2011: IR-FEL Illuminated Near-Field Microscopy for Oesophageal Cancer Diagnosis

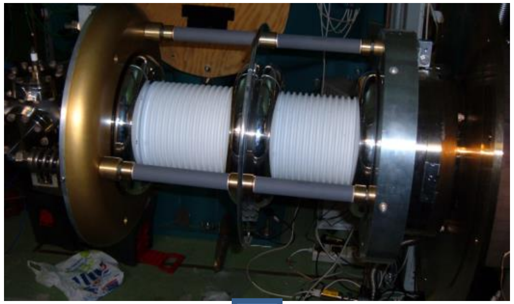
- Potential solution: Spectroscopy and microscopy in the IR
  - The different components of tissue have different IR spectra
  - Traditionally the weakness has been resolution ~ λ/2 ~ 3-4 μm – but the features are ~ 10 nm
  - The SNOM overcomes this by working in the near field
  - A tapered optical fibre probe is placed within a fraction of a wavelength in close proximity to a sample and scanned
  - The spatial resolution is now given by the tip diameter
  - However, there is strong reduction of the intensity due to the aperture of the fibre
  - So the technique needs a high-intensity tune-able IR source – ALICE FEL
  - Image cluster analysis at 3 wavelengths selected to differentiate the components and quantify the "spreaded-outness" of DNA -> diagnosis

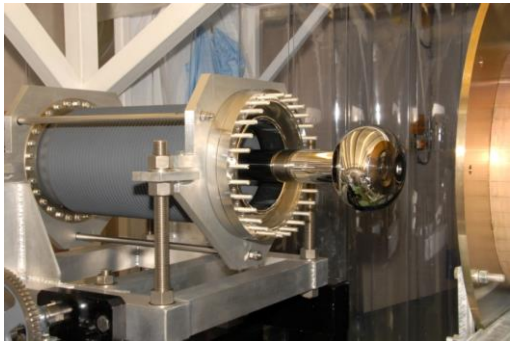






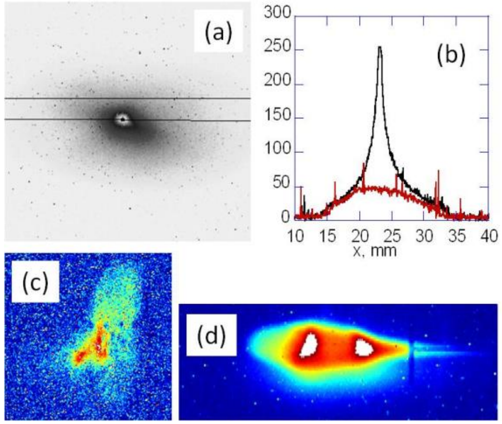
2012: DC PC Gun Upgrade



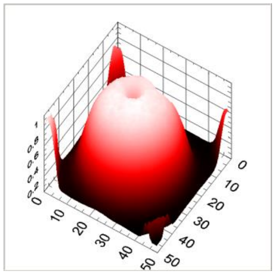


- HV DC photoelectron gun upgraded with installation of larger diameter ceramic as originally intended, followed by successful gun HV conditioning to > 400kV
  Operational voltage : 230kV → 325kV – close to the design value
- Field emitter on the cathode was evident (could not be conditioned) -> **Cathode changed in May 2012 :** much better "workable" cathode, running lifetime of 2-3 days, smooth QE map – Still there in 2015! ☺
- Beam quality much improved, two "beamlet" structure at 230 kV nearly disappears, normalised emittance reduces and more robust

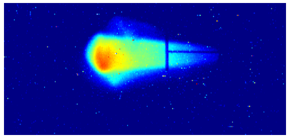
At 230kV DC gun voltage

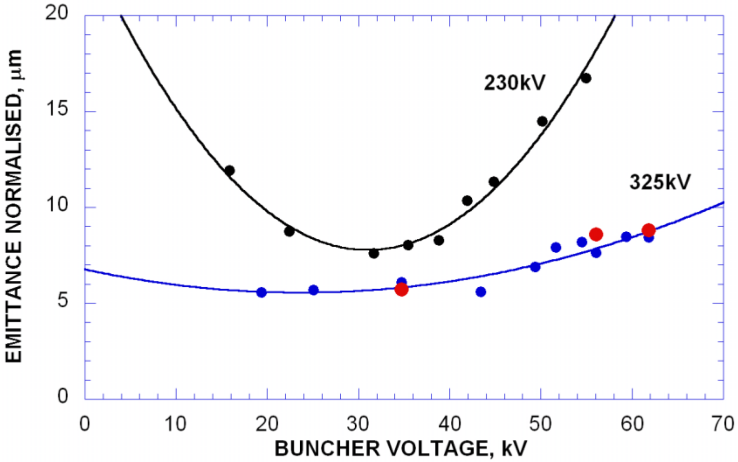


Improved QE map



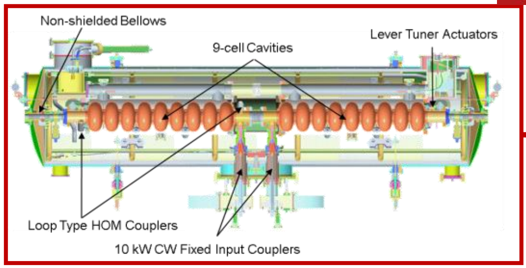
At 325kV DC gun voltage (injector spectrometer)

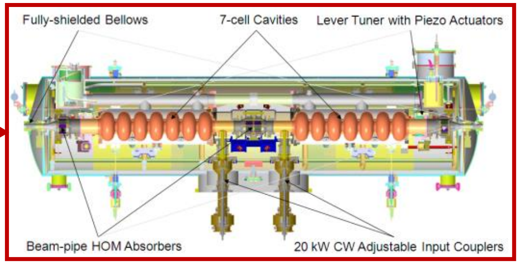




2013: DICC and Major Cryo Failure

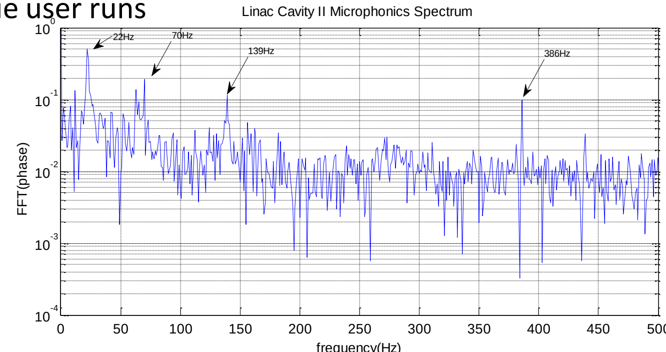
- As part of longstanding effort to validate DICC 7-cell ERL cryomodule much of 2013 dedicated to installation





- Series of setbacks encountered
  - Strong microphonics -> detuning of cavities -> not able to operate ALICE
  - Replacement of radiation damaged shock absorbers on pumping platform, implementation of variable pump speeds to reduce resonances
  - Blockage in helium liquefier -> complete refurbishment of cryosystem (6 months)
  - Swapped back in original linac to continue user runs
  - Offline alterations to module but

  no reinstallation possible -> Donated to NCBJ Polfel project in 2018



Linac cavity 2 detuning peaks at 22Hz, 70Hz,63Hz,139Hz,386Hz.

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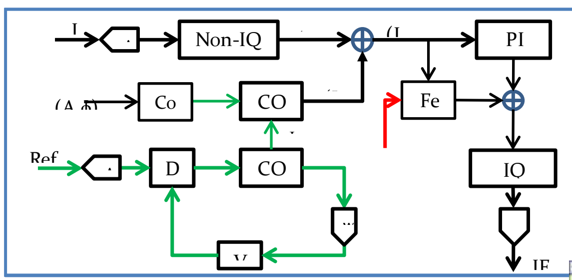
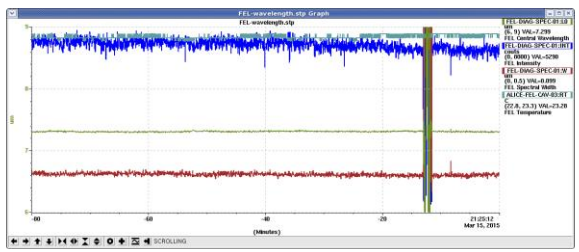
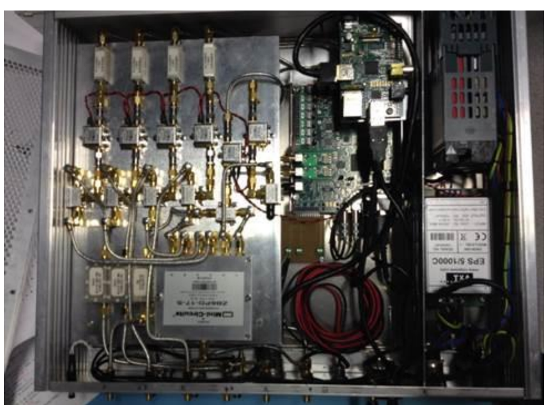
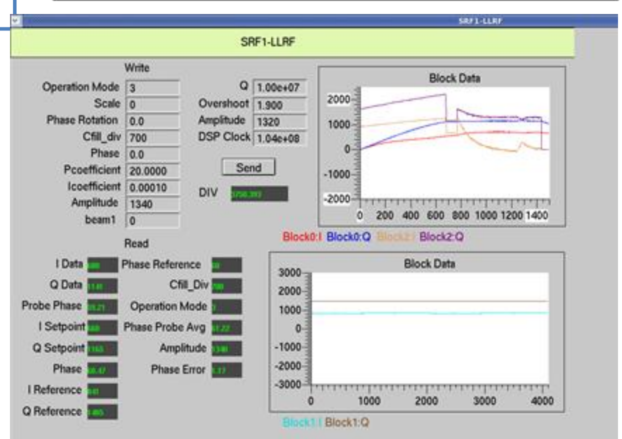
2014: Stability, Feedback and DLLRF

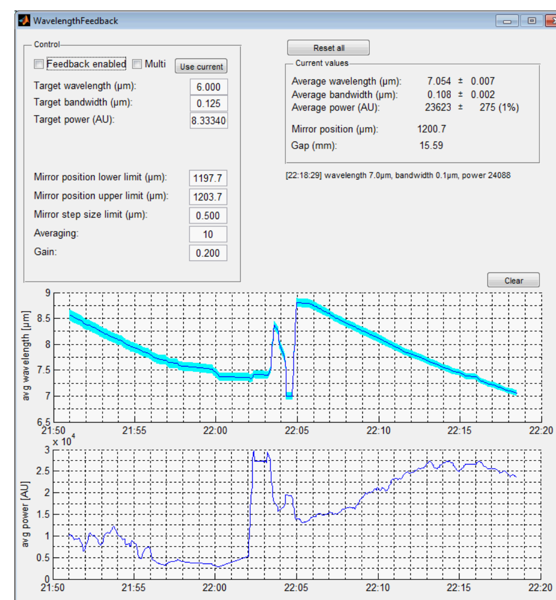
- Stability over 2-3 hours is important for microscope images -> DLLRF, other active feedback systems
- Master oscillator active phase correction system strongly suppresses jumps that were seen pre-2013
- Digital LLRF effort since 2009 - reasons for moving to digital systems are:
  - Ability to modify loop parameters during operations
  - Complex control algorithms such as adaptive feed forward to overcome beam loading effects, controlled cavity filling to limit the RF power reflection in the waveguide, Lorentz force induced detuning control, etc.
- DLLRF cards also used to diagnose and fix phase drifts and jumps found in the PI laser
- Development of AP / FEL / operational higher level software to automate processes, implement feedback e.g. on FEL wavelength











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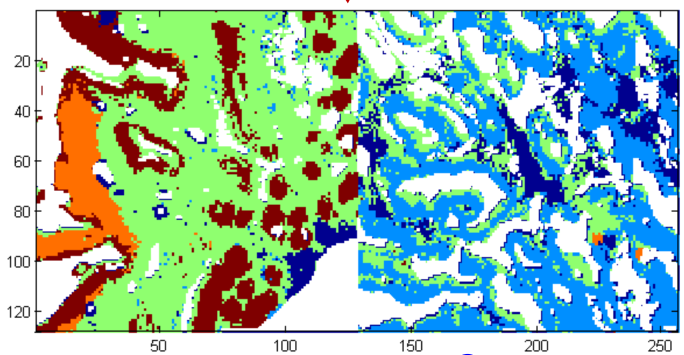
2014 - 2016: ALICE IR-FEL Defining Disease Diagnosis

- Example image from 2015 shows AFM topography, SNOM transmission image (world first), calibration image for 3 wavelengths
- Image cluster analysis will be used on the ratios of the images to identify tissue components

Example 5-cluster image analysis



Barrett's **Cancer**

each cluster corresponds to a (broad) tissue type

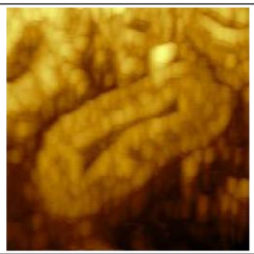
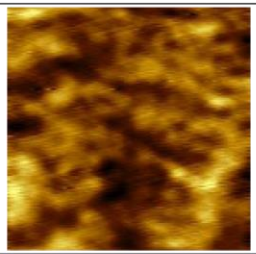
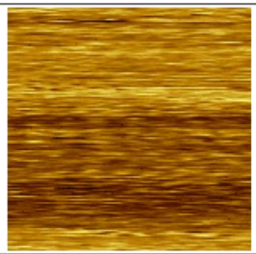
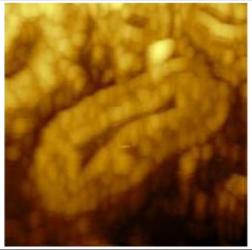
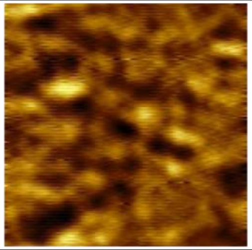
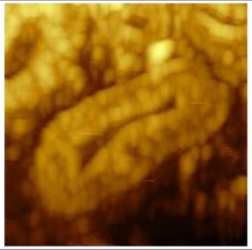
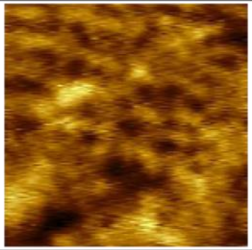
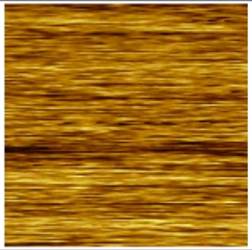
Blue: Stroma (cancerous sample)

Brown: Goblet Cells and Barrett's Oesophagus Tissue

Orange: Barrett's Oesophagus Nuclei

Green: Stroma (benign sample)

Cyan: Cancer

150411 Barrett's			
Filename/wavelength	FTOPO	FSNOM	FZERO
0314 – transmission o712 6.5 µm			
0315 – transmission o712 7.3 µm			
0316 – transmission o712 8.05 µm			

Operational Learning Experiences on the ALICE Energy Recovery Linac

- ALICE: What was HARD!!!
  - DC photocathode **gun** delayed the project more than 2 years
  - **Injector** beamline very tricky and time consuming to get right – initially took ~6 months, only two or three people ever were able to set it correctly. The buncher iris needed to be bigger (then we'd have got < 2 mm mrad emittance @ 60 pC). Too many stray fields in the low energy beam transport
  - Convincing management to spend enough on **diagnostics**
  - Bunch-bunch and macropulse-macropulse **stability**: down to things like immature cryosystem, no environmental control in accelerator hall, PI laser pointing stability / charge stability

- ALICE: What was EASY!!!
  - The energy recovery transport loop was commissioned **within a week** (so very different to the injector)! – when the beam was on crest
  - **BUT off-crest operation was much harder – few months!**
  - Getting the FEL required **emittance** of ~12 mm mrad at 60 pC, with work achieved ~ 5 mm mrad at 60 pC
  - Getting the FEL to **lase** only took a couple of weeks – good preparation and alignment key to this
  - The TBA **arcs** were a dream to work with, easy to vary R56 (sextupoles were misaligned though ☹)

- When we build another ERL we will …

  - Have a well thought out **diagnostics for the LATTICE, and separately the BEAM** – both transversely and longitudinally in the first design stages of the project – how will the diagnostics **work together** to give the information needed

  - In simulations, **model the step-by-step experimental procedures** to establish the beam conditions and prove have achieved the project goals

  - Never try to save money on **feedback systems**! Stability is key

2016: The End of ALICE

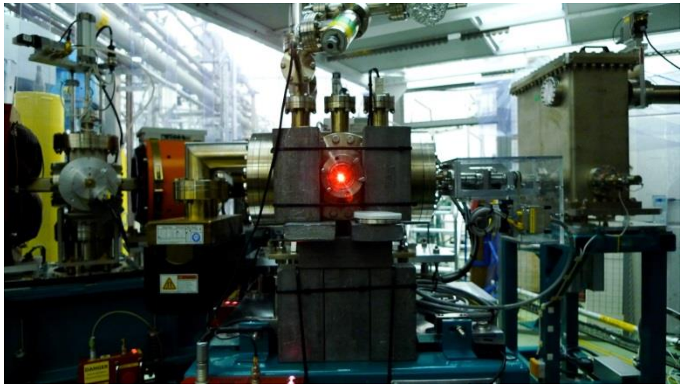
- By 2015 many components were showing their age and combined with the cost of running the cryo, and it requiring another major overhaul
- ALICE showed potential of ERLs, but ALICE itself had **gone as far as it could** in terms of accelerator physics
- Political factors also entered: FELIS user programme funders would not agree to fund accelerator operation only experiments – work now continuing at slower pace on FELIX in the Netherlands
- By the final run (2016) we ran 24 hours 5 days / week for users with little interruption for 3 months
- We also understood the machine in great detail – see Frank’s talk tomorrow
- ALICE was a success and ERLs are ready to go further as user facilities in both scientific and industrial contexts…

See my talk tomorrow ☺

ALICE Successes

- First SCRF linac operating in the UK
- First DC photoinjector gun in the UK
- First ERL in Europe
- First FEL driven by energy recovery accelerator in Europe
- First transmission IR-SNOM imaging

- ALICE was intended as a short lived test-bed and learning tool, but transcended it’s original purpose and became a scientific facility in its own right



Acknowledgements

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