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The ALICE Energy Recovery Linac Programme at Daresbury Laboratory

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Alice Accelerators and Lasers In Combined Experiments
Daresbury Laboratory, Science and Technology Facilities Council, UK

ASTeC

LHeC Seminar at CERN, 5 September 2012

Outline

- ERLs at ASTeC: historical perspective
- ALICE ERL overview
- Summary of ALICE modes of operation
- Science programme on ALICE
- Accelerator physics on ALICE
- SRF system : cryomodule upgrade

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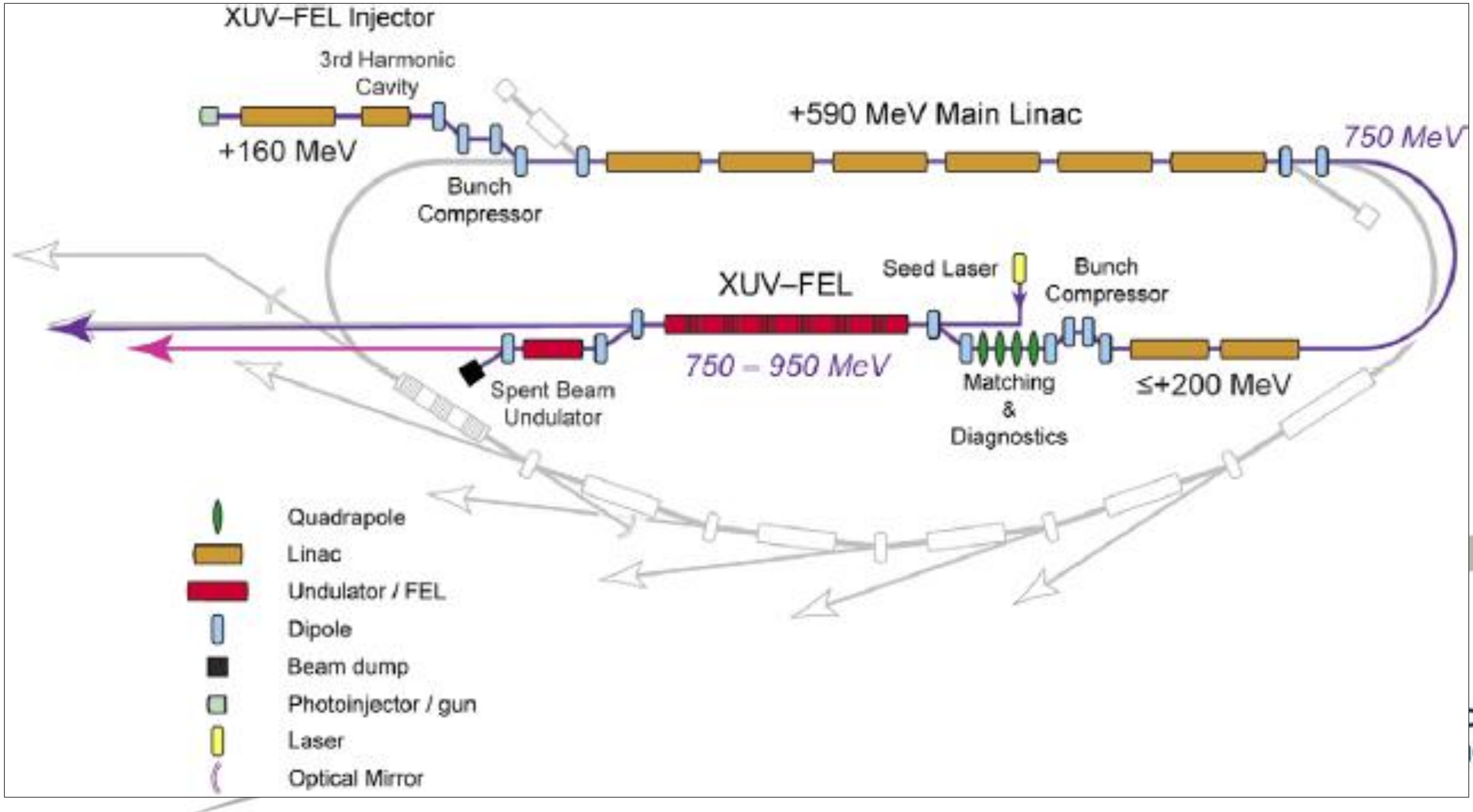
4GLS Project

- 4[th] Generation Light Source (sub-GeV; CW, 100mA ERL)
- A host of new (to the UK, at least) technologies :
  SC RF & cryogenics; photoelectron guns; FEL; ERL specific physics.
- Expertise build-up needed → ERLP → ALICE
- 4GLS has not been realised but ALICE remains .... so far



ERLs at DL : timeline

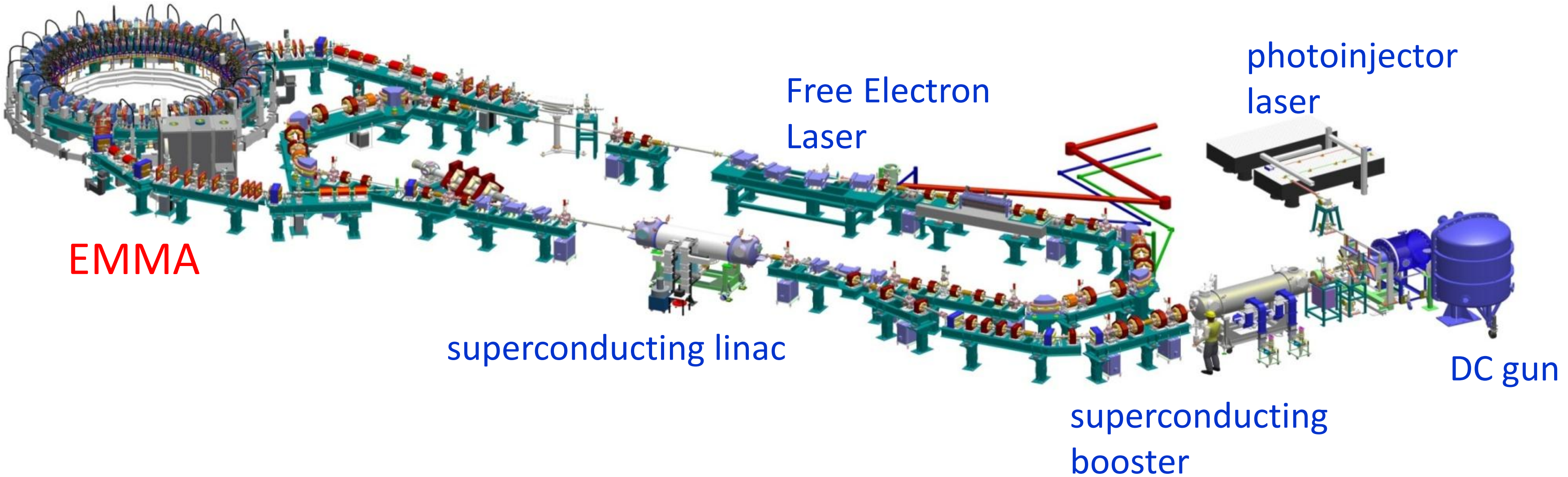
Date	4GLS	ERLP / ALICE
2001	Project started	
Dec 2001	The Science Case	
May 2003		First ERLP technical meeting
Apr 2006	Conceptual Design Report	
Aug 2006		First beam (at 250keV) from PI gun
Nov 2007		PI gun commissioning completed
Aug 2008	Project cancelled	
Dec 2008		Full Energy Recovery at 21MeV demonstrated
2009		Coherent THz generated; Compton Back Scattering X-ray generation demonstrated
2010		Biological cells exposures to THz radiation started; EMMA full ring commissioned. 1000s turns demonstrated; First lasing of the IR FEL
2011		Acceleration in EMMA from 12MeV to 21 MeV; SNOM commissioned
2012		Extensive science programme continues

ALICE ERL
Overview

The ALICE Facility @ Daresbury Laboratory

Accelerators and Lasers In Combined Experiments

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



Alice
Accelerators and Lasers
In Combined Experiments

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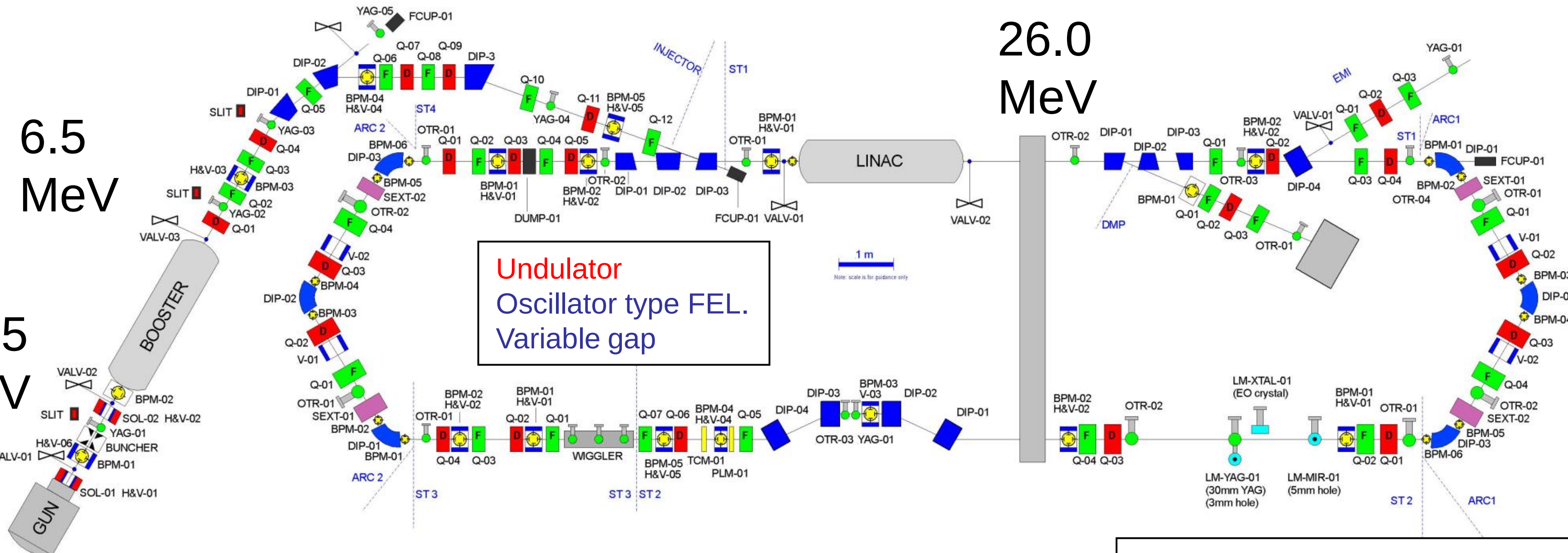
ALICE Machine Overview

RF System
Superconducting booster + linac
9-cell cavities. 1.3 GHz, ~10 MV/m.
Pulsed up to 10 Hz, 100 μS bunch trains

Beam transport system.
Triple bend achromatic arcs.
First arc isochronous
Bunch compression chicane R_{56} = 28 cm



6.5 MeV

325 keV

26.0 MeV

Undulator
Oscillator type FEL.
Variable gap

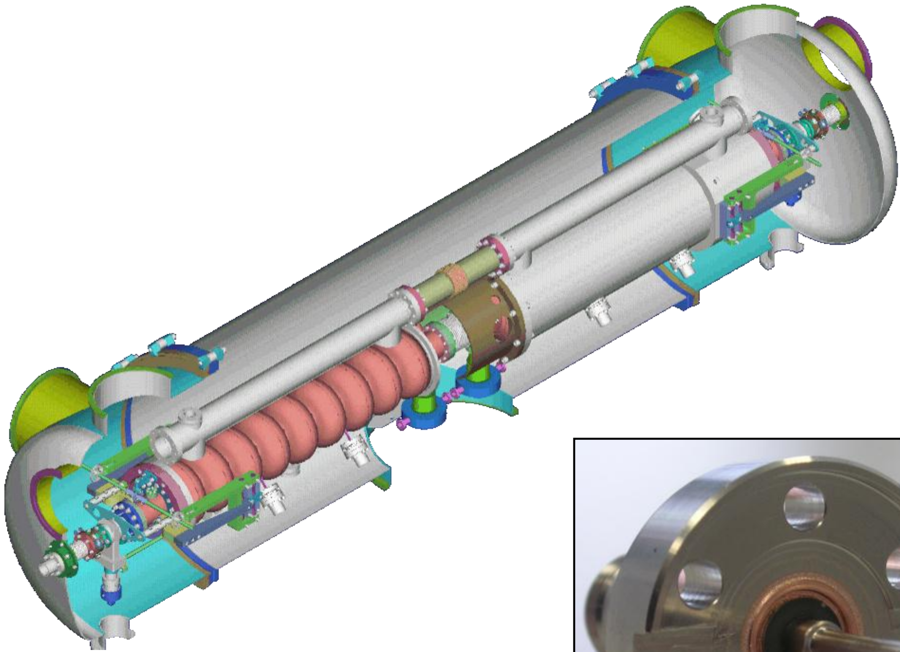
DC Gun + Photo Injector Laser
325 kV
GaAs cathode; QE=2.5-3.0%
Up to 100 pC bunch charge
Up to 81.25 MHz rep rate

TW laser
For Compton Backscattering and EO
~70 fS duration, 10 Hz
Ti Sapphire

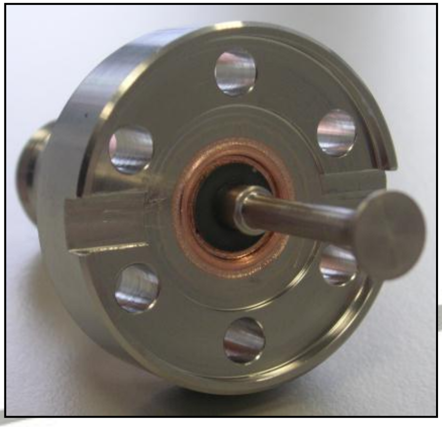
Diagnostics
YAG/OTR screens
BPMs (stripline / button)
Slits
Energy spectrometers
Electro-optic bunch profile monitor

SRF Modules

- 2 x Stanford/Rossendorf cryomodules
  - 1 Booster and 1 Main LINAC.
- Fabricated by ACCEL (now RI).



- JLab HOM coupler feedthrough design adopted for the LINAC module:
  - Sapphire loaded ceramic.
  - Higher power handling capability.



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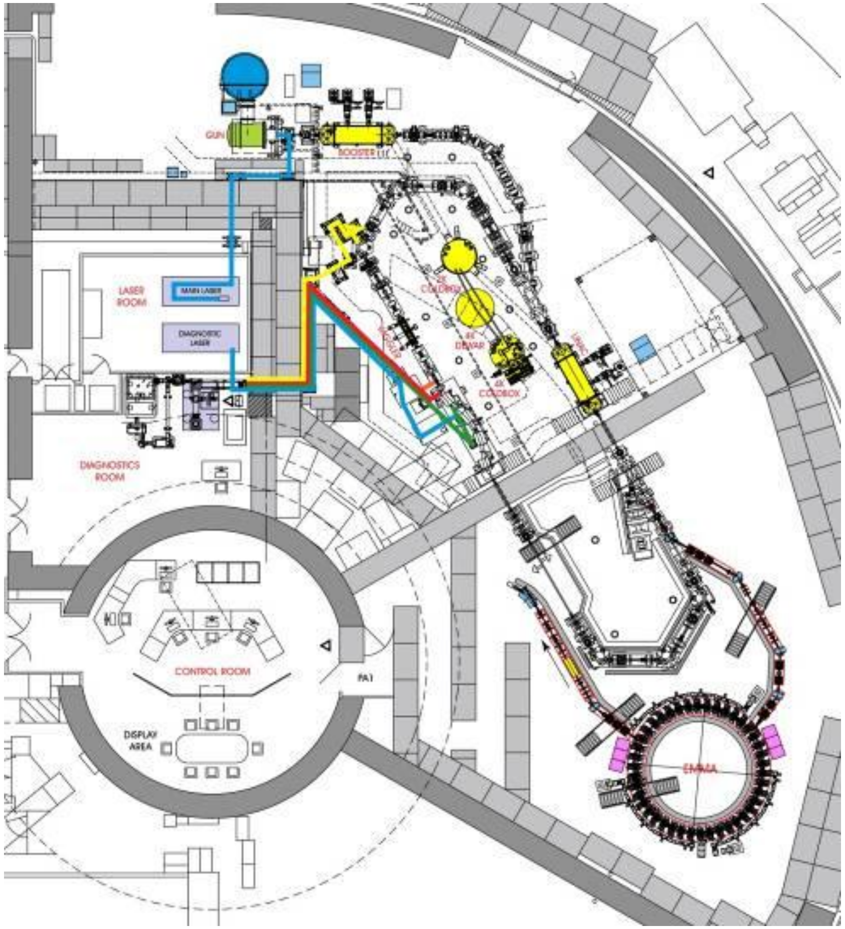
SRF System Specification

	Booster		ERL Linac	
	BC1	BC2	LC1	LC2
Eacc (MV/m)	4.8	2.9	12.9	12.9
Q_o	5×10^9	5×10^9	5×10^9	5×10^9
Q_e	7.4×10^5	4.5×10^5	7×10^6	7×10^6
Power (kW)	32	20	6.7	6.7
Power Source	2 x e2v	CPI	e2v	Thales

0.1ms bunch trains @ 10 Hz repetition rate

The ALICE (ERLP) Facility @ Daresbury Laboratory



Accelerators and
Lasers
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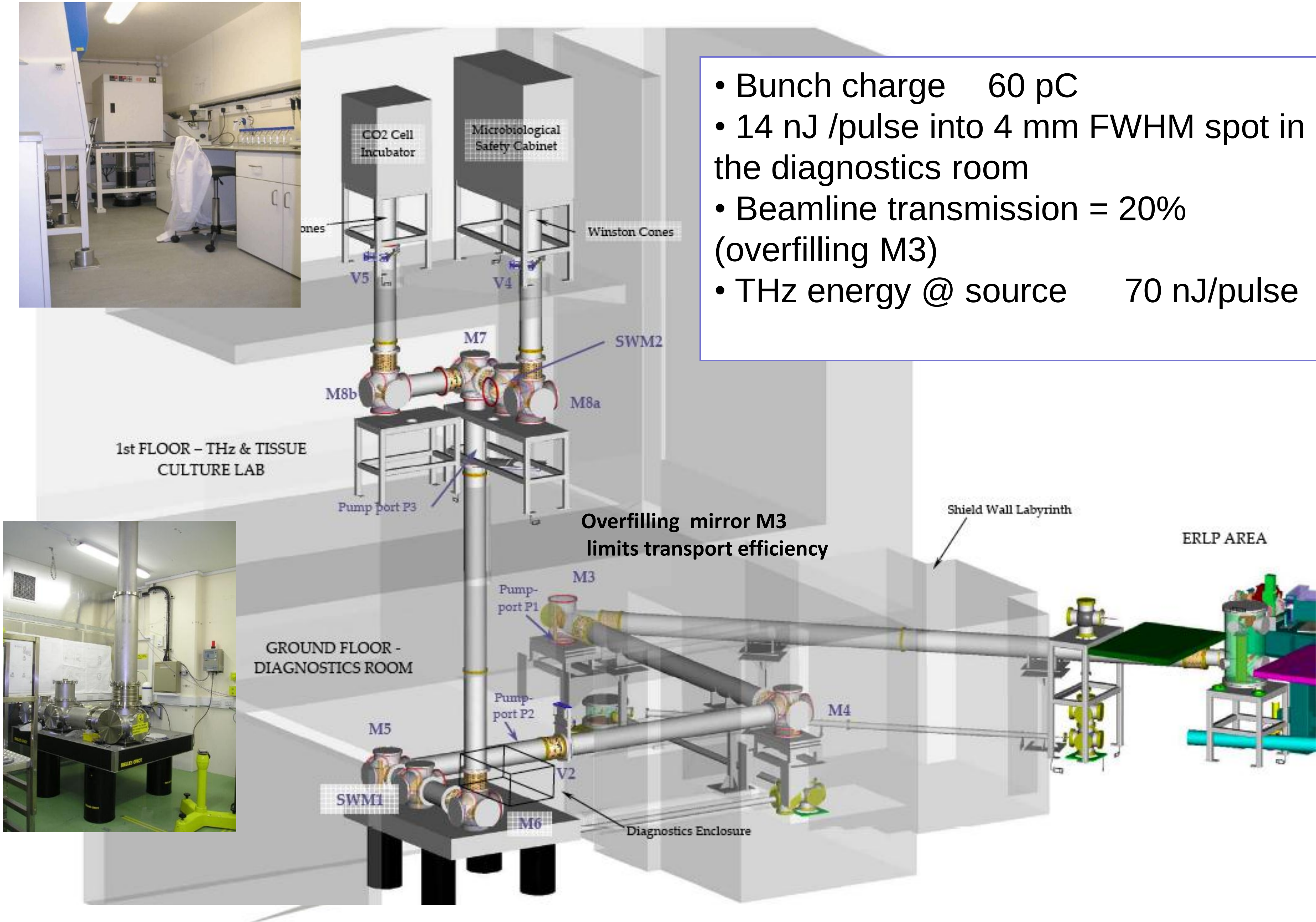
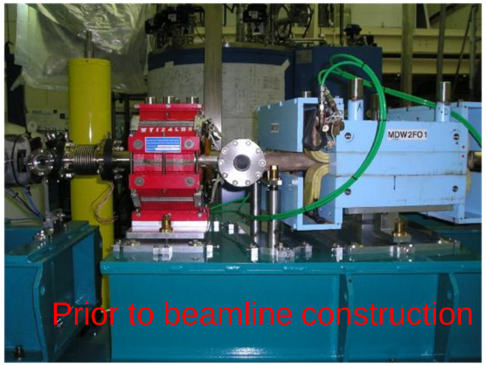
THz Radiation from ALICE

- Bunch charge 60 pC
- 14 nJ /pulse into 4 mm FWHM spot in the diagnostics room
- Beamline transmission = 20% (overfilling M3)
- THz energy @ source 70 nJ/pulse



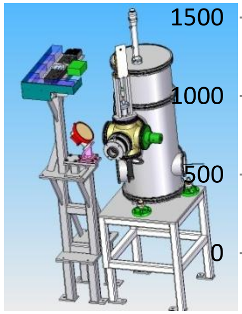
THz Diagnostics & Methods (1)

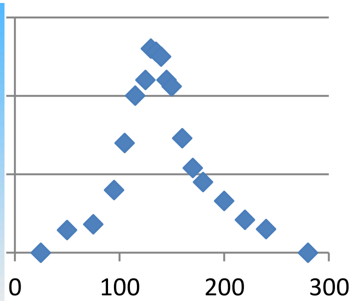
- Power meter
  - absolute power in 100 us train determined by its heating of absorbing film and induced pressure pulse in surrounding gas. Calibrate by electrical heating of film to give same signal on microphone. (Thomas Keating Power meter)
    - Alice 60 pC provides 70 nJ/pulse at port
    - Jlab 135 pC provides 1000 nJ/pulse
      - Expected Jlab output at 60 pC = 198 nJ (quaderatic scaling)
      - Alice output is factor 3 lower than Jlab - bunch compression



High aperture Thz extraction port
Internal mirror in chicane vessels sends THz out through wedgedCVD diamond window

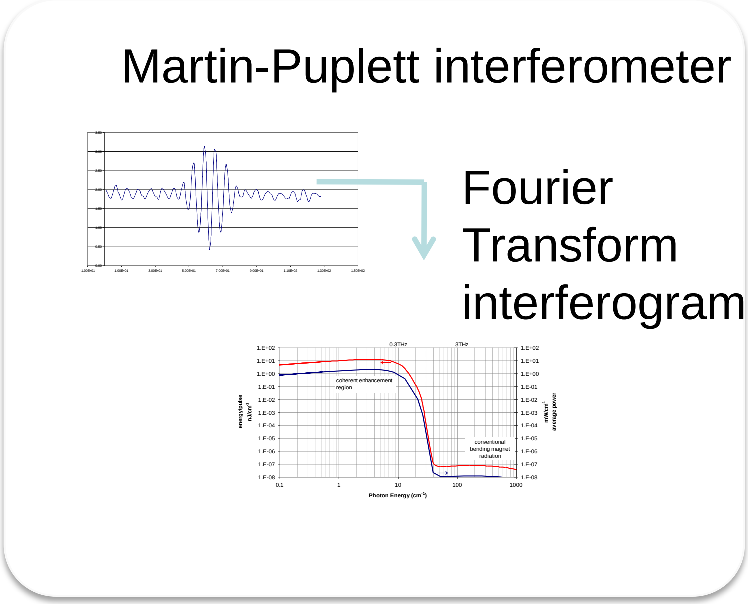
- Intensity and Beam Profiler
  - Small (2 mm) pyro element on scanning stage for beam profiling at known distances from extract port.
  - Relative intensity of THz signal is a quick check on re-establishing particular set ups e.g. For FEL do not obtain highest THz signals.

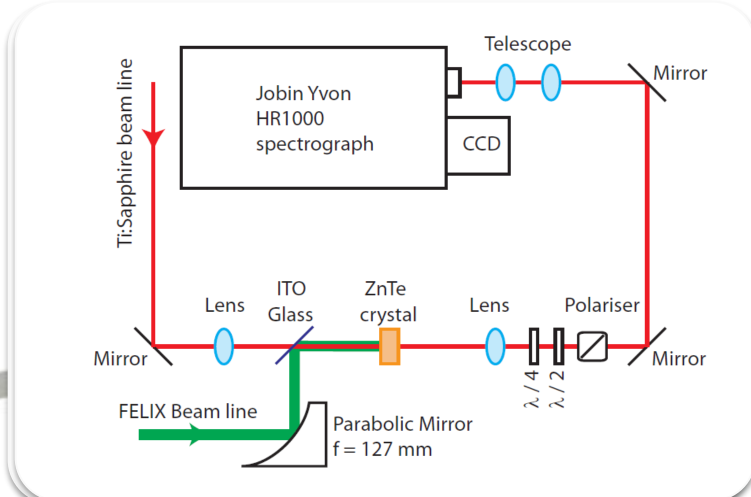




THz Diagnostics & Methods (2)

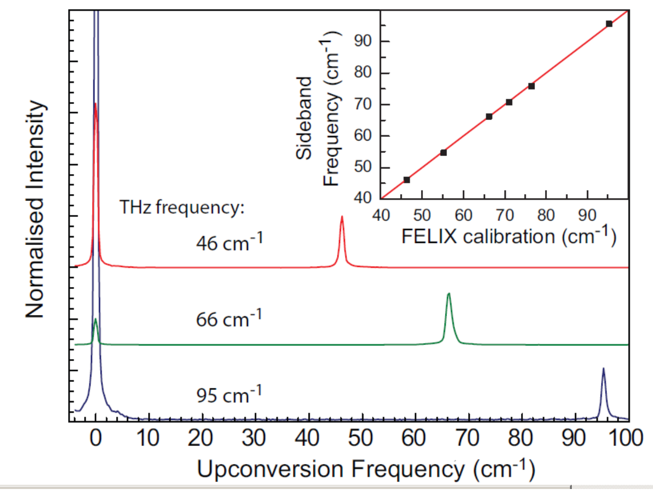
- Spectroscopy
  - Band Pass Filters (QMC Instruments) give estimate of CSR -THz spectrum:
    - it is below 0.5 THz / 16 cm^{-1}
  - Martin Puplett step scan interferometer requires high beam stability - obtain interfeogram by scanning mirror in one arm.
  - Train to train instability has moved the emphasis onto single shot spectrometry using THz up-conversion into the near IR e.g. See work from FELIX





THz Diagnostics & Methods (3)

- THz Upconversion
  - This has been done e.g at FELIX where a distinct THz FEL line is upconverted into Near IR. It will be more difficult for a broad band CTR source as upconverted spectrum will be in the wings of th



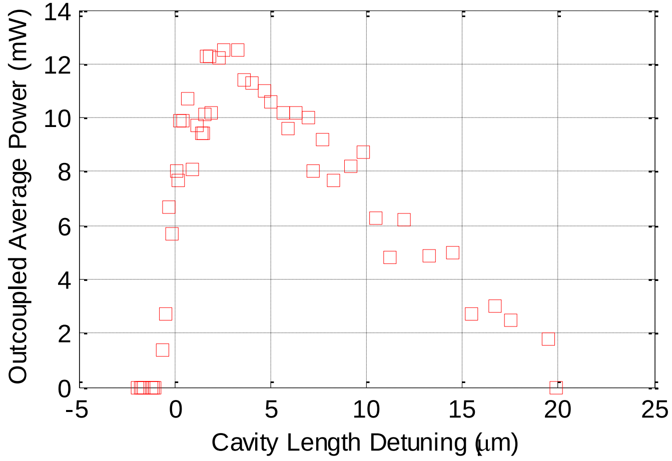
THz Instrumentation from STFC Space science

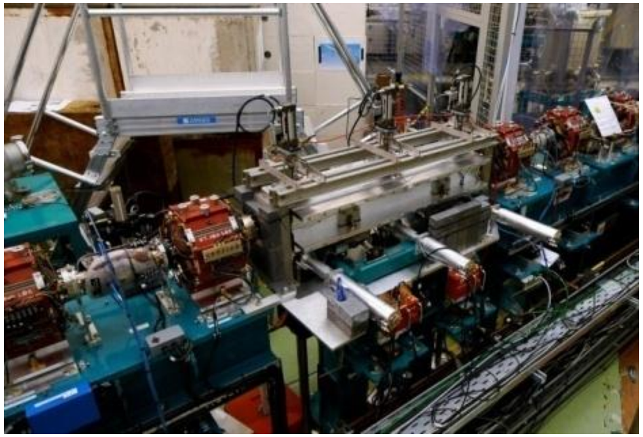
Fast detectors to resolve single bunches

THz optics – mirrors, polarisers

Interferometers

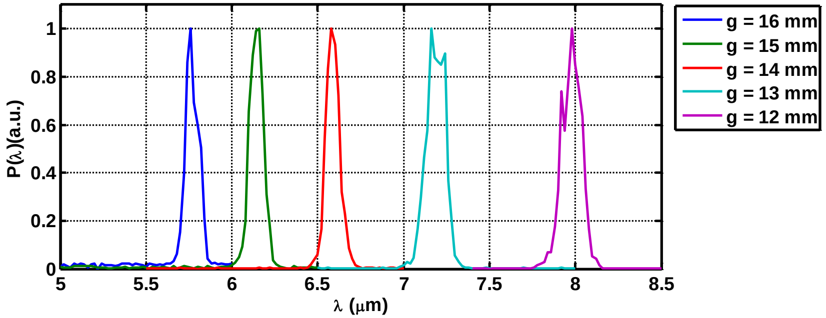
ALICE IR FEL





Undulator borrowed from Jefferson Lab

- period 27mm
- # periods 40
- min gap 12mm
- max K 1.0



•Continuous tuning demonstrated 5.5-9.0 µm, varying undulator gap.

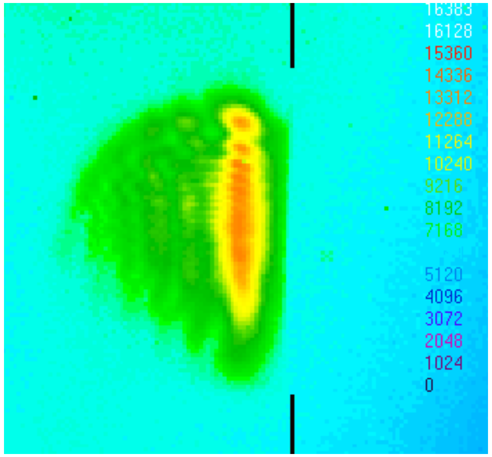
•The FEL pulse duration has been inferred from the spectral width to be ~1 ps The peak power is therefore ~3 MW

•Single pass gain measured at ~25 %.

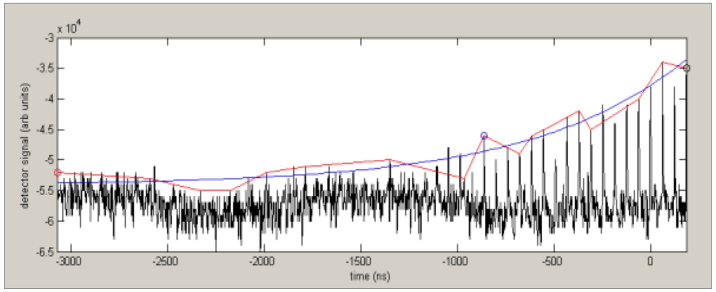
	Jlab IR-Demo	ALICE
Frequency	74.85MHz	16.25MHz
Bunch charge	~70pC	~60-80pC
Mode	CW	10Hz; 100us
Beam energy	48MeV	27.6MeV
Wavelength	3.1um	8um
IR power	1720W	32/0.7=45mW (~700W if scaled)

FEL Diagnostics & Methods (1)

- Power meter
  - Simple measurement of FEL average power (thermocouple)
  - Not sensitive enough to detect spontaneous undulator radiation but suitable when the FEL is lasing. Used for optimising the output power and stability + measuring some aspects of FEL behaviour e.g. power as a function of cavity length.
- Infra-Red camera
  - Measurements of transverse profile of FEL output.
- Mercury Cadmium Telluride (MCT) detector
  - Very sensitive liquid-nitrogen cooled IR detector.
  - Can be used to measure spontaneous undulator radiation, and for optimisation through to lasing. Can measure the envelope of the output profile along the train (does not resolve individual pulses), can be used for FEL gain + cavity loss measurements.
- Photoelectromagnetic (PEM) detector
  - Very fast-response detector which can resolve individual FEL pulses within a train when lasing (but not undulator radiation), can be used for gain measurements.



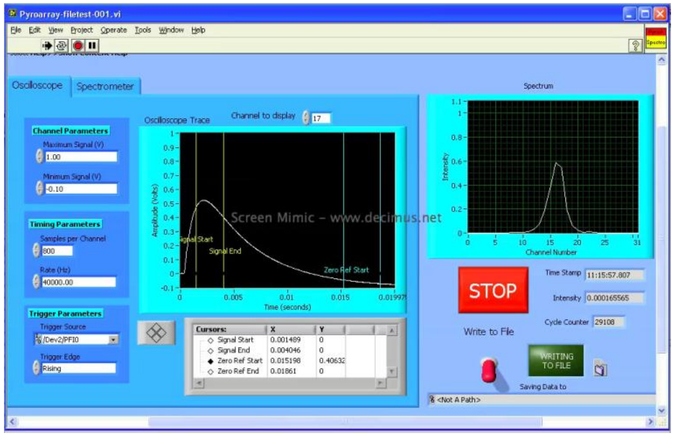
Unfocussed IR-FEL image in the diagnostics room.



Resolution of individual FEL pulse in the train using PEM detector – MATLAB program fits envelope to calculate gain.

FEL Diagnostics & Methods (2)

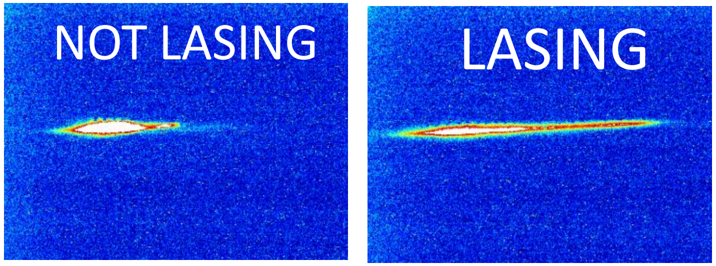
- Spectrometer
  - Czerny-Turner spectrometer with pyro-array detector.
  - Records real-time FEL spectra (per macropulse)
  - Used for measuring FEL wavelength, bandwidth, stability + can be used with MCT to measure spontaneous radiation, harmonics when lasing.



Screenshot of the LabView program used for real-time recording of the IR spectrum measured by the pyroarray.

- Polarisation measurements
  - Rotatable polariser in front of detector used for measurements of FEL polarisation.

- Post-FEL OTR screens
  - Records images of electron bunch transverse profile in a dispersive location immediately after the FEL.
  - Can be used to calculate FEL-induced energy loss + spread.



Electron bunch transverse profiles on OTR screen in dispersive location in second arc (AR2-1). The FEL induces energy spread and net energy loss.

- Electro-Optic/Cross-correlation
  - Electro-optic technique has been used for direct measurements of the electron bunch duration to confirm suitability for FEL operation. Preliminary work has been carried out towards making direct measurements of FEL pulse duration using cross-correlation technique (FEL pulse and external laser overlapped in non-linear crystal).

Summary of ALICE SRF modes of operation

BC1 gradient	~ 5.5MV (4.0MeV) FWDP = 11-12kW	Beam energy: Constant for all modes
BC1 off-crest phase	-10 to -20 deg	variable
BC2 gradient	2.8- 3.8 MV (2.5MeV) FWDP = 2-4kW	Beam energy: Constant for all modes
BC2 off-crest phase	+10 to +40 deg	+/- 90deg for some physics experiments
LC1 gradient	8-13 MV FWDP = 4-8kW	
LC1 off-crest phase	0 to +16 deg	
LC2 gradient	6.5-10 MV FWDP = 1.5-4kW	
LC2 off-crest phase	0 to +16deg	+180deg (deceleration) for EMMA injection
Beam energy (kinetic)	12.0 – 27.5MeV	[EMMA – FEL]

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ALICE Parameters

Parameter	Operating Value	Comments
Injector Energy	6.5 MeV	Limited only by the required ratio of full/injector beam energies
Total beam energy	12.0 – 26.0 (27.5) MeV	Various setups; upper value limited by FE in the main linac cavities.
RF frequency	1.3 GHZ	
Bunch repetition frequency	up to 81.25 MHz (variable)	Use of burst generator in PI laser system;
Train Length	0 - 100 μs	
Train repetition frequency	1 - 10 Hz	20Hz possible with some upgrade of cryogenic system
Compressed bunch length	<1 ps rms	Measured with EO technique
Bunch charge (standard)	40 pC @ 81.25MHz, 60pC @ 16MHz and 40MHz	Limited by beam loading; Q=60pC is a standard bunch charge for FEL and THz operation.
Bunch charge (potential)	~200pC	Allowed by achievable QE of 2.5-3.0%; requires digi LLRF with feedforward ability in buncher/booster systems
Energy Recovery Rate	>99%	Measured

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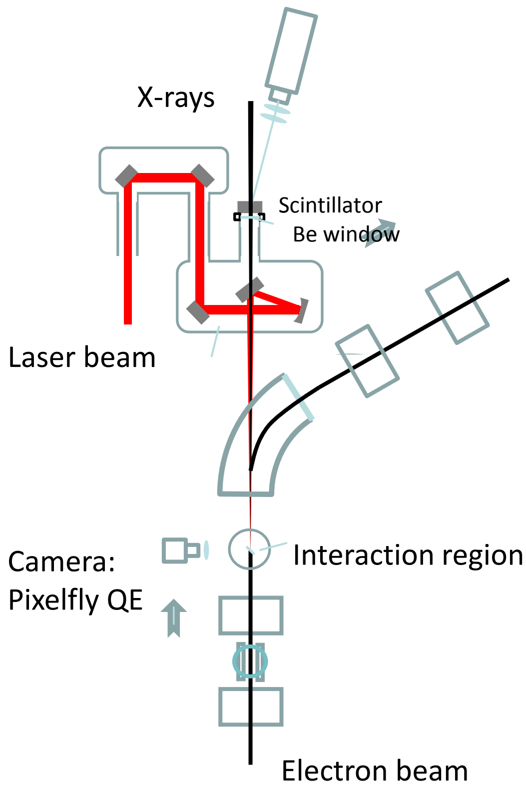
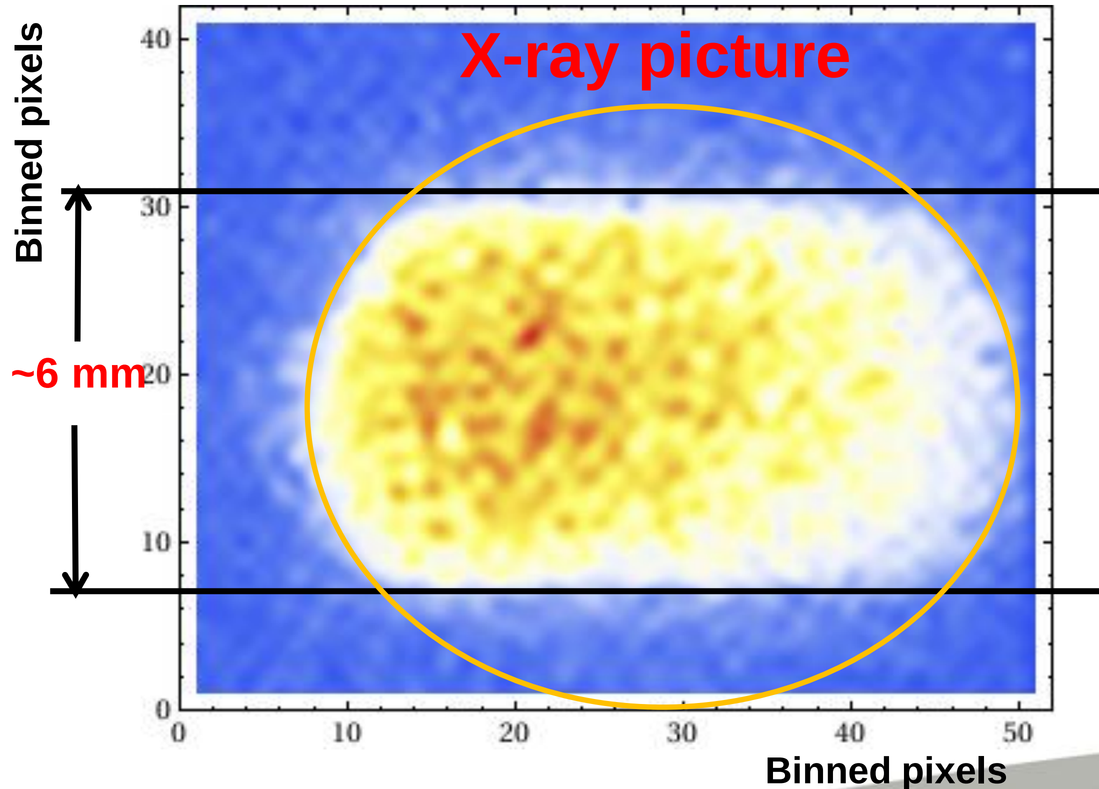
Science programme
on
ALICE

Compton Back Scattering experiment

Compton backscattering demonstrated on ALICE: November 2009

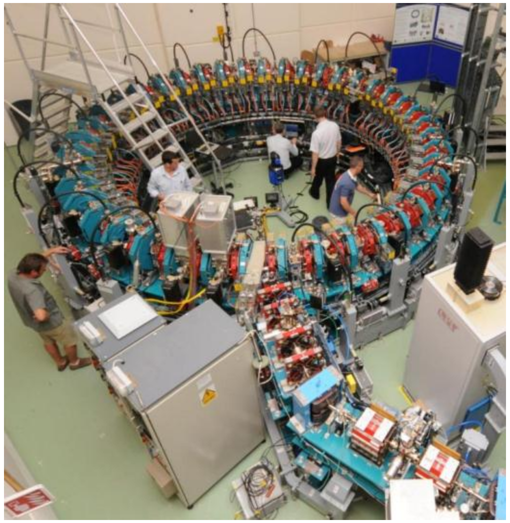
... just two days before the start of the shutdown !!!



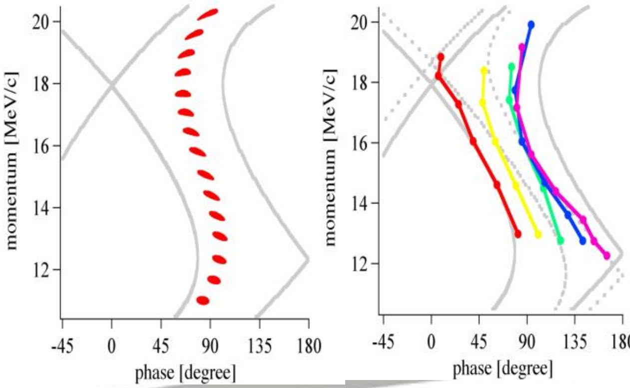


EMMA (Electron Model for Many Applications)

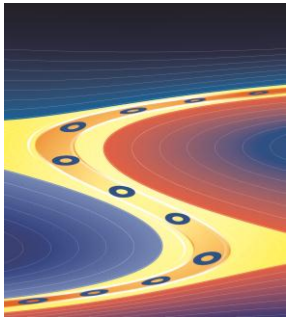
- **First proof-of-concept non-scaling FFAG designed, built and commissioned at Daresbury Lab.**
- **ALICE serves as injector for EMMA** and delivers 40pC single bunches with low ~10keV energy spread at 12.0MeV beam energy
- Multi-turn (1000s) operation without acceleration demonstrated
- Acceleration by 10MeV (design value) demonstrated
- Predicted acceleration in a serpentine channel demonstrated
- Crossing of resonances was shown to have little effect on the tune and TOF
- Paper in Nature Physics published (2012)



EMMA ring



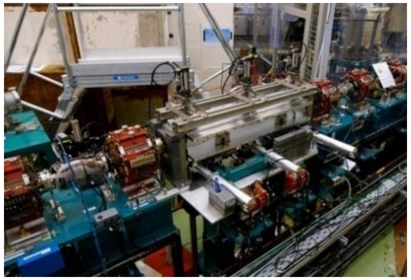
Predicted and measured serpentine channel longitudinal trajectories for different momenta.



Nature Physics March 2012

ALICE: multifunctional facility

ER modes of operation



- **IR FEL** (5.7-8um; 10-30W ; ~3MW peak power)
  26.0MeV; 60-100pC; 16.25MHz; 10Hz; 100us
- **THz source** (15-20nJ per pulse; >10kW peak power)
  26.0MeV ; 60pC; 40.63MHz; 10Hz; 100us

- **FELIS** : Free Electron Laser Integration with
  Scanning Near-field Optical Microscope

SNOM research programme is being transferred from Vanderbilt FEL;
Collaboration with Liverpool Uni., Cockcroft Institute and CNR
(Istituto di Struttura della Materia, Antonio Cricenti)
25.0-27.5MeV; 60pC; 16.25MHz; 10Hz; 100us

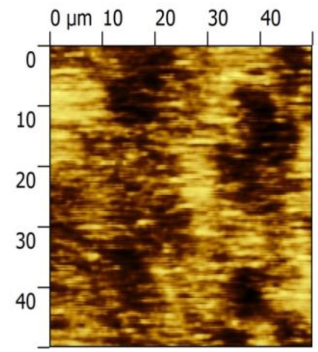
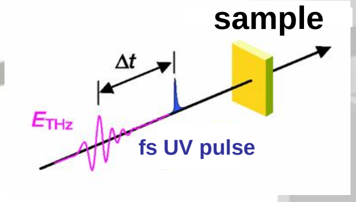
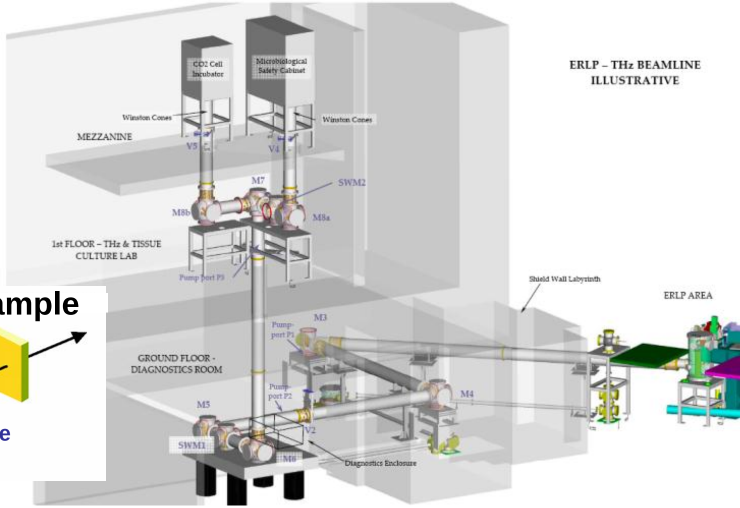


Image at 7.3 μm Glycoproteins distribution

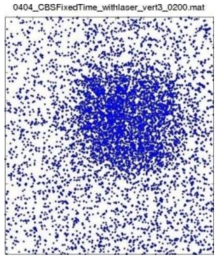
- **THz for biological exps**. in
  Tissue Culture Lab.
- **THz for quantum dots** studies
  for novel solar cells
- **Digital LLRF** development

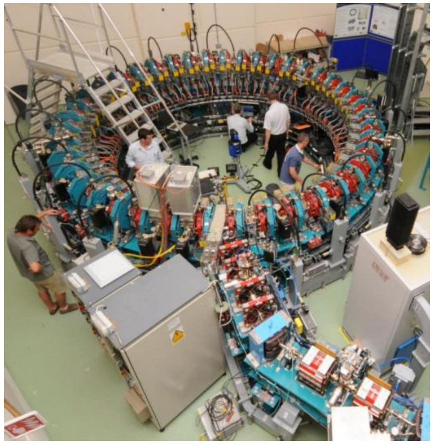




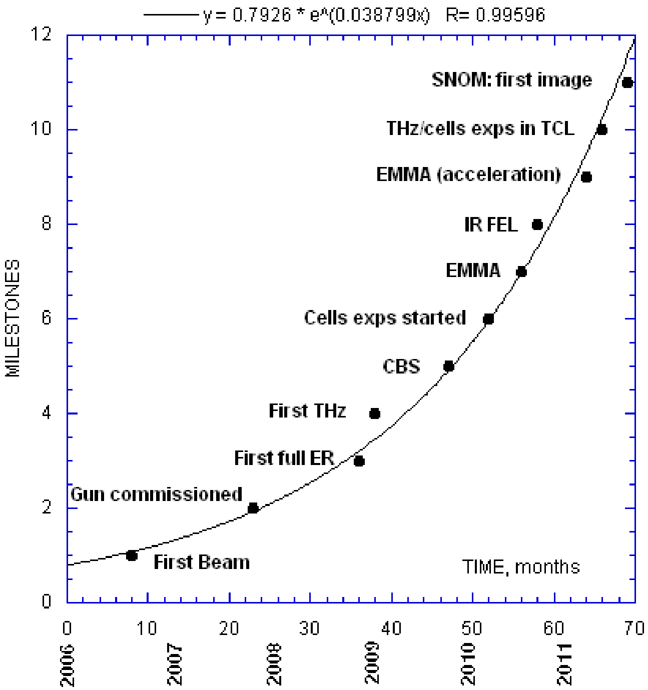
ALICE: multifunctional facility

Non-ER modes of operation (single bunch)





- **EMMA** : First NS FFAG demonstration
  12MeV; 40pC; single bunch
- **CBS** : Compton back Scattering Experiment
  30MeV; <100pC (completed in 2009)
- **Electron beam / EM radiation** interaction exps.
  22.5MeV; 20pC
- **Electron beam tomography**
- **Timing and synchronisation** exps.
  (fibre-ring-laser-based system)



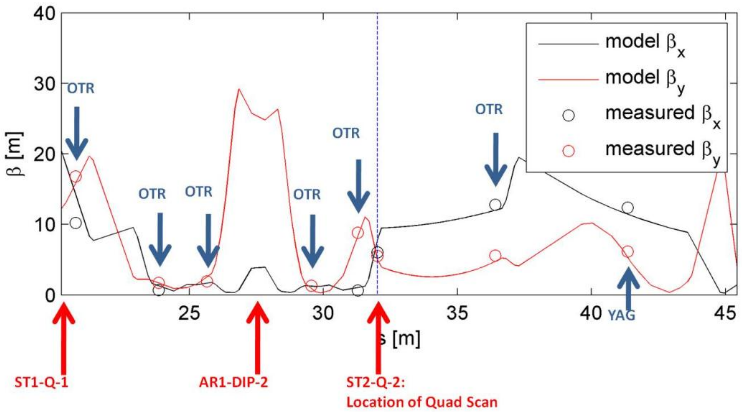
ALICE operates in a variety of modes differing in requirements for

- beam energies,
- bunch lengths,
- bunch charges,
- beam loading,
- energy spread etc.

Accelerator Physics on ALICE

Accelerator physics on ALICE

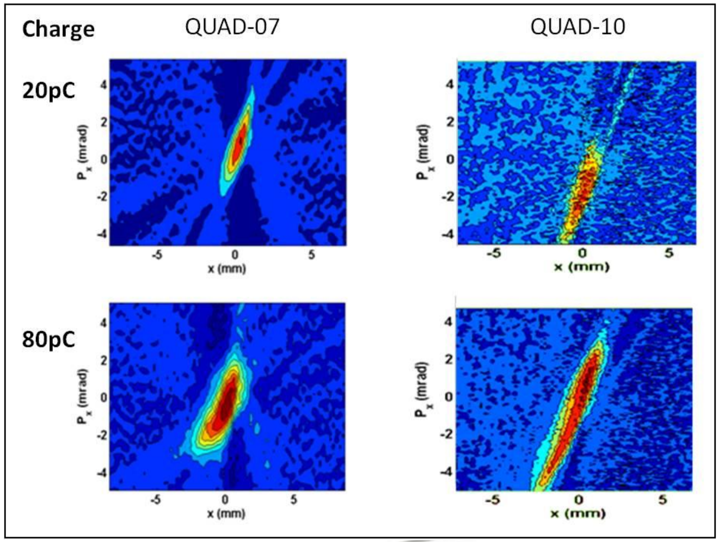
Beam optics post linac

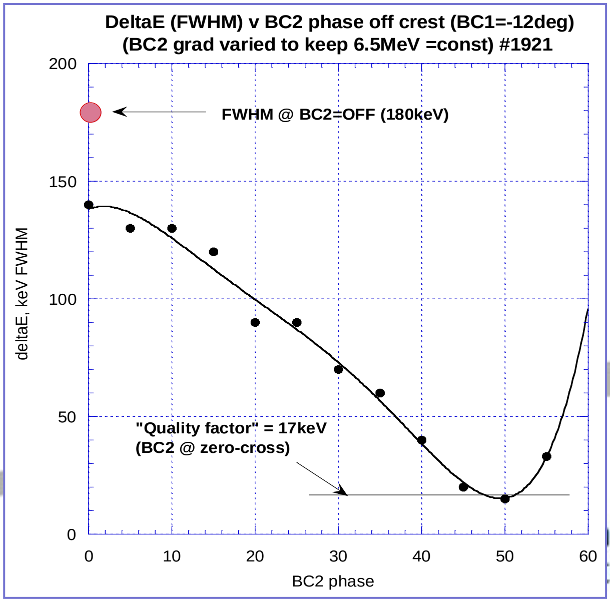


Longitudinal beam dynamics studies

- Zero-phasing method (bunch length; bunch "quality factor")
- Phase scan (bunch length)
- Gradient scan (bunch length, energy chirp, uncorrelated energy spread)
- Electro-optic diagnostic (bunch length/profile)
- TOA measurements (R56, T566)

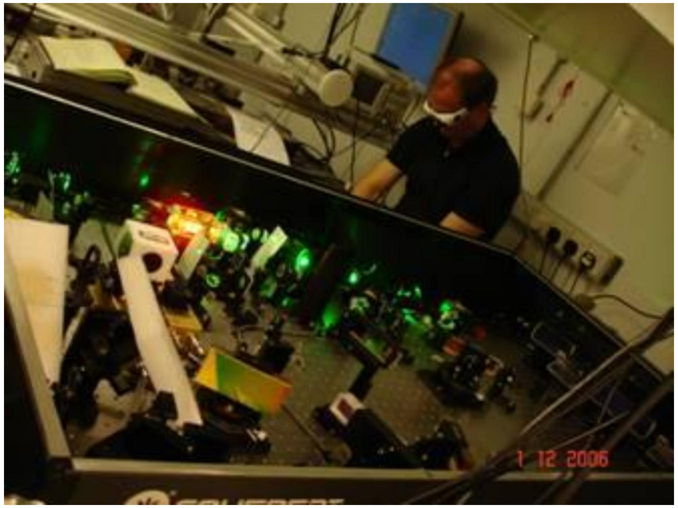
Beam tomography
(in EMMA injection line)

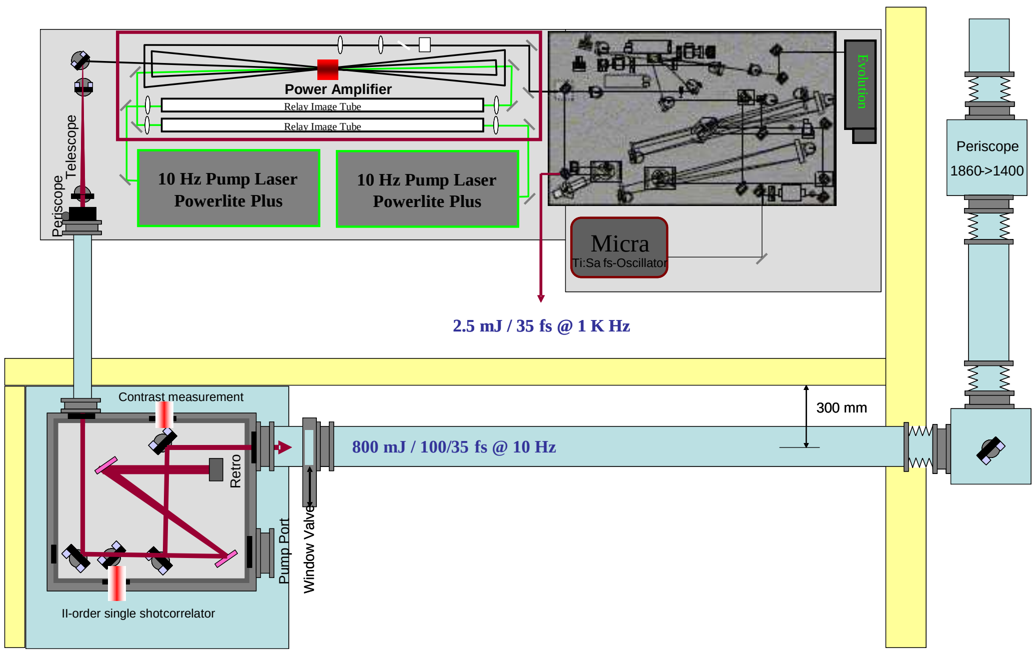




TW fs laser

Peak power	10 TW
Pulse length	100 / 35 fs
Wavelength	802nm
Bandwidth	13nm
PRF	10Hz





Pulse energy (after compressor)	0.8J
Average power	10W
Focal spot	~10μm
Peak power density	>10^{18} W/cm^2

- CBS experiment (2009)
- EO diagnostic
- Generation of short THz pulses

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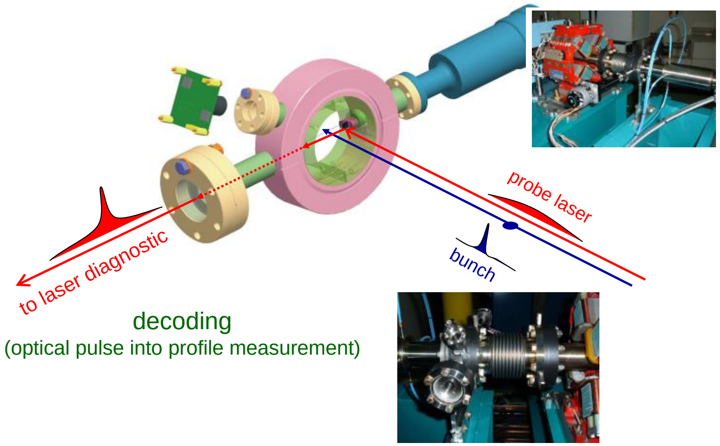
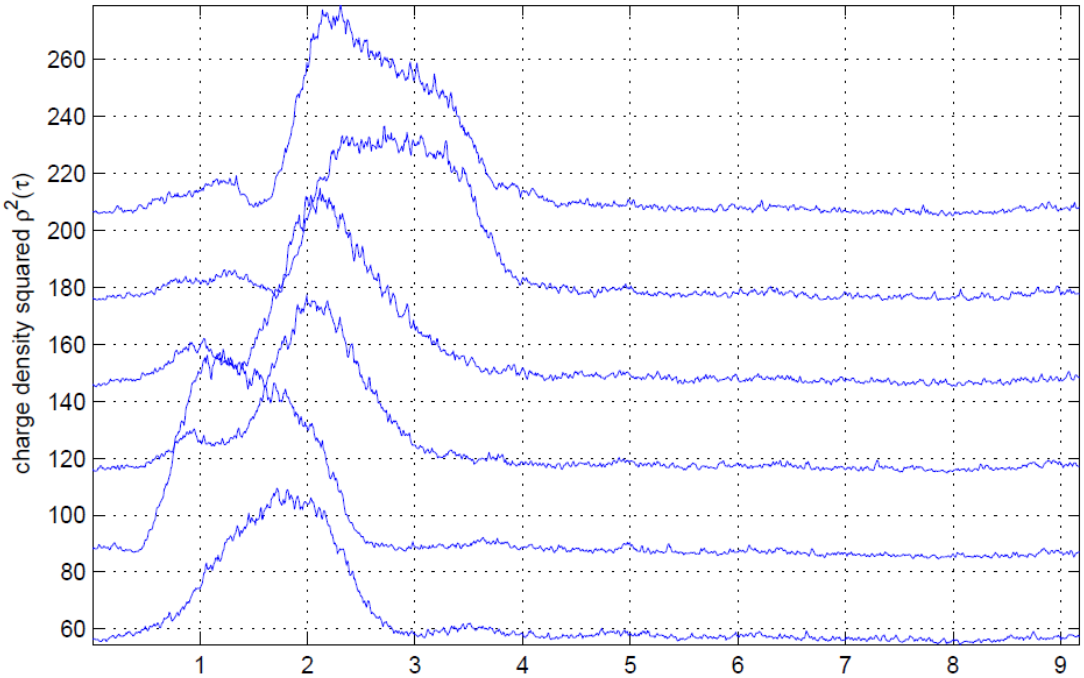
Electro-Optic Measurements

- Installed and commissioned during 2010
- Preliminary measurements appear to confirm expected bunch lengths (FWHM ~1 to 2 ps)
- ... limited usage so far due to time constraints and engagement of the fs laser system in other projects





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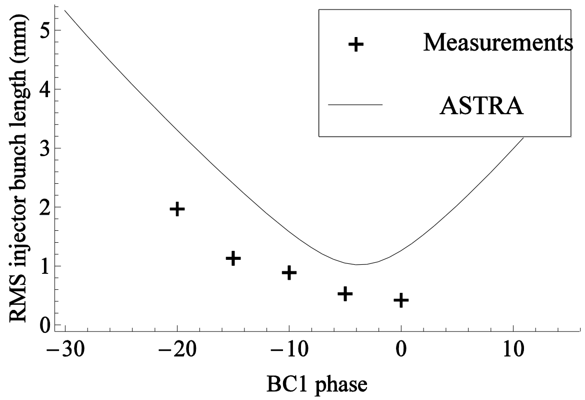
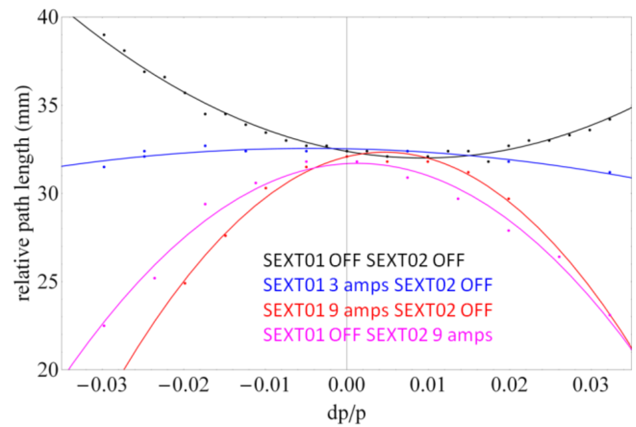
Longitudinal beam dynamics studies



Bunch length v BC1 phase (Injector)

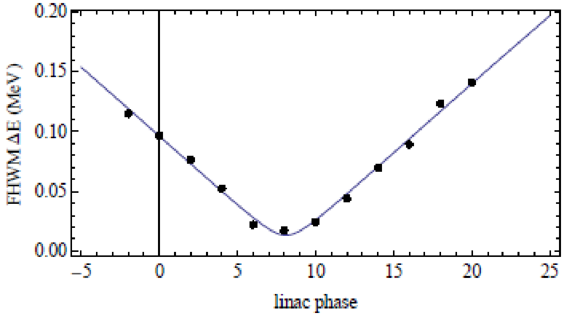


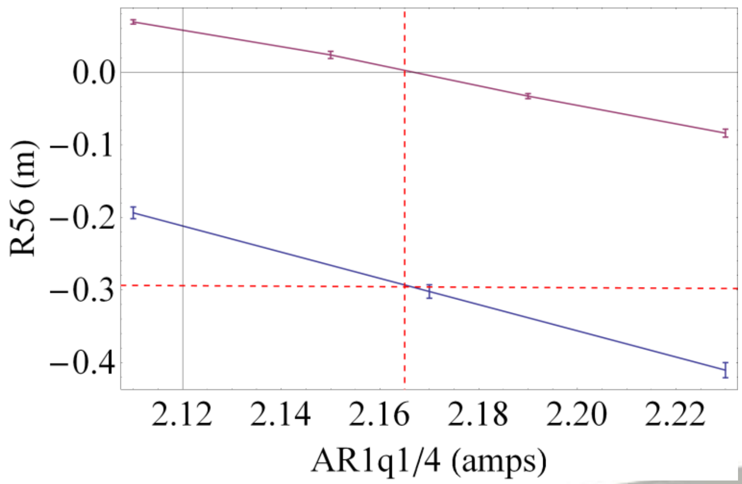
TOA v sextupoles strength in AR1

Phase scan method:

$$\Delta E = \sqrt{\Delta E_0^2 + h^2 \Delta z^2}$$

chirp $h = E_L \frac{2\pi}{\lambda} \sin(\phi - \phi_0)$





R56 v quadrupole strength in AR1

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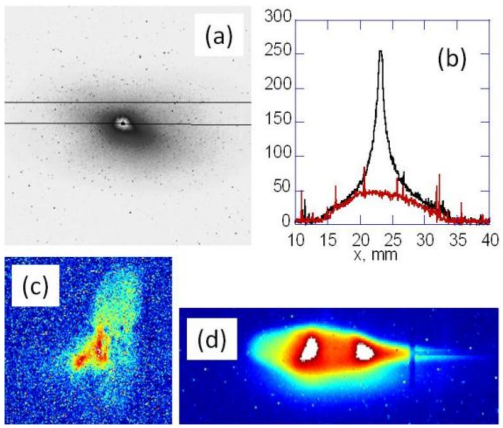
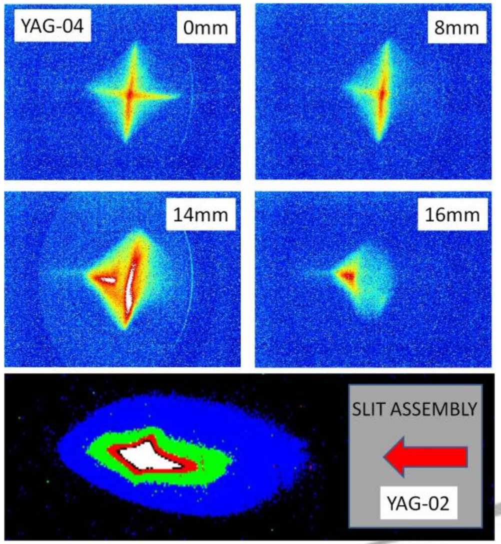
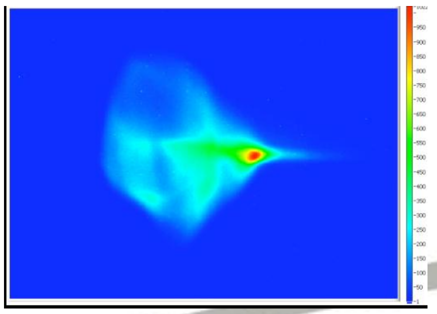
INJ studies : beam structure

Beam structure at
230kV DC gun voltage:
“normal” and “exaggerated”





- Clear “two beamlets” bunch structure observed at 230kV
- The structure is characterised by the existence of two well defined beams, at the head and the tail of the bunch.
- Two beams also have different transverse properties,
- Strong dependence on gun voltage: at 325kV, the bunch structure is much less pronounced (but still present !)
- “Two beams” substructure develops due to the low energy dynamics of the injector before the second booster cavity
- ... And we are not alone in that !



Jlab’s
“humming bird”
beam image

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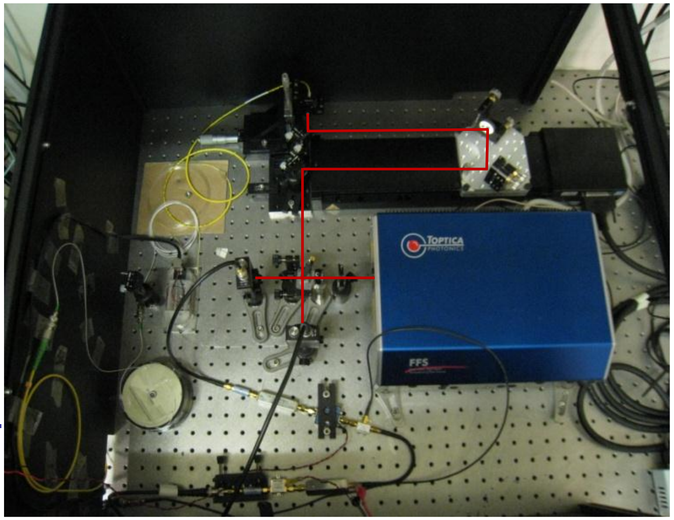
Optical Clock Distribution Scheme

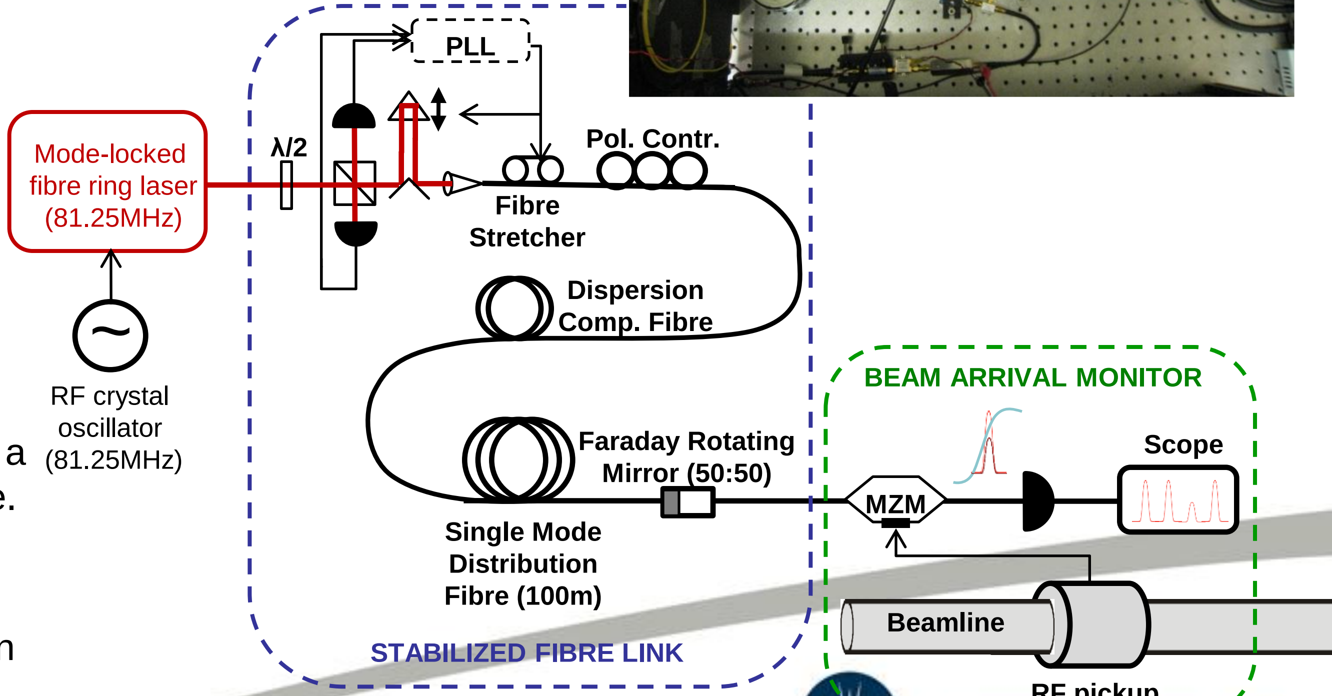
Highly stable clock distribution across large scale facilities is important for the synchronisation of beam generation, beam manipulation components and end station experiments.

An actively stabilised optical clock distribution system based on the propagation of ultra-short optical pulses has been installed on ALICE. Femtosecond pulses emerging at the far end are currently used to implement a beam arrival monitor.



Link Operation

- Pulses from the MLO are distributed to BAM sites around ALICE.
- Half the pulse power will be reflected back at the far end to enable detection of optical path length changes.
- Timing is actively stabilized with a with a fibre stretcher and delay line.
- The other half of the timing stabilized pulses will be used to measure the arrival time of electron bunches and other diagnostics.



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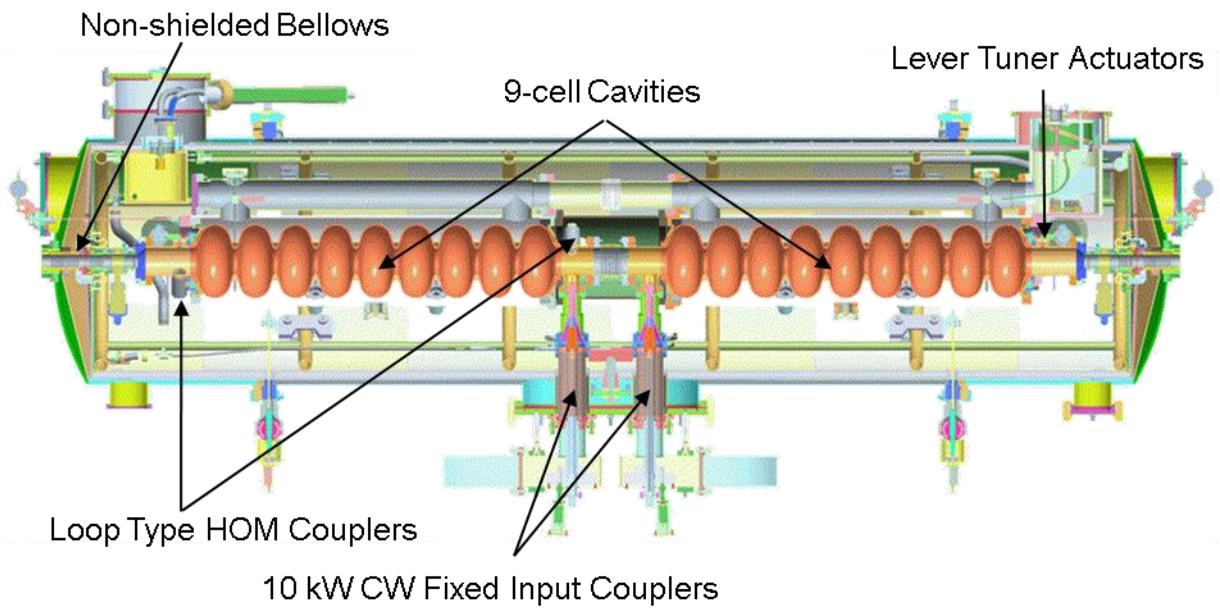
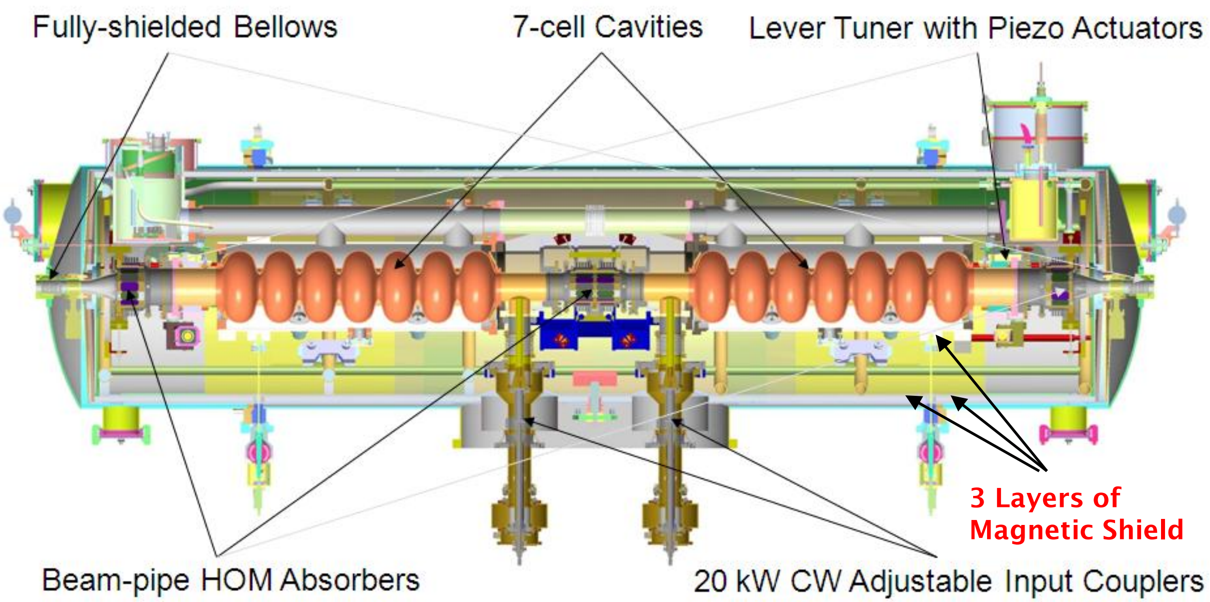
SRF system : cryomodule upgrade

Cryomodule Design Evolution



Existing ALICE CM

New CM



Collaboration Team

Target Cryomodule Specification

Parameter	ALICE	Target
Frequency (GHz)	1.3	1.3
Number of Cavities	2	2
Number of Cells/Cavity	**9**	**7**
Cavity Length (m)	1.038	0.807
Cryomodule Length (m)	3.6	3.6
R/Q (Ω)	1036	762
E_{acc} (MV/m)	**12 - 15**	**>20**
CM Energy Gain (MeV)	**27**	**>32**
Q_o	**$<5 \times 10^9$**	**$>10^{10}$**
Q_{ext}	**4×10^6**	**$4 \times 10^6 - 10^8$**
Max Cavity FWD Pwr (kW)	**10 SW**	**20 SW**

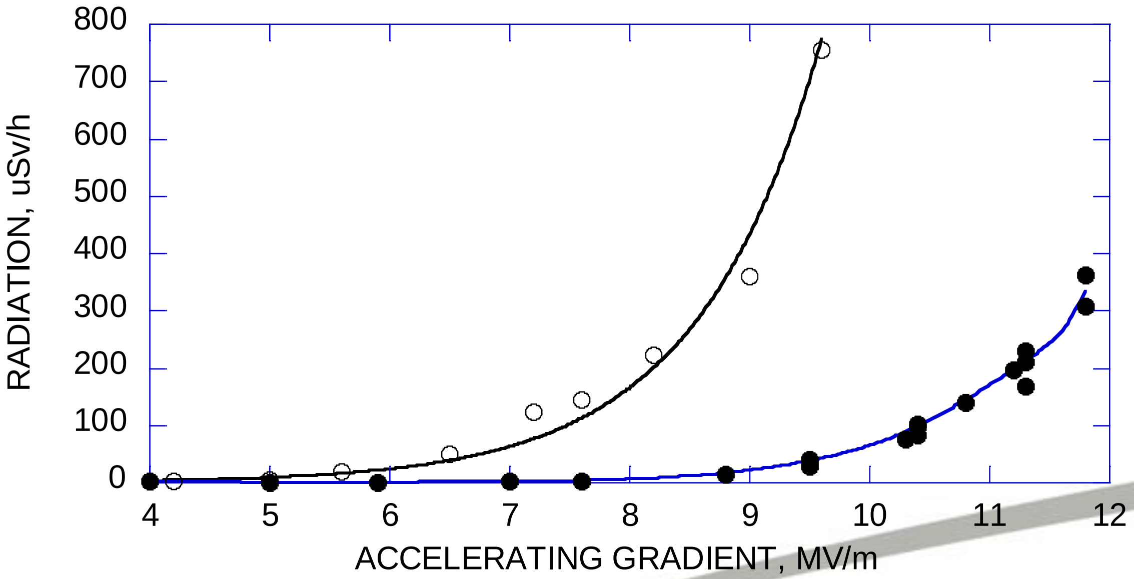
- International collaboration initiated in early 2006:
  - ASTeC (STFC)
  - Cornell University
  - DESY
  - FZD-Rossendorf
  - LBNL
  - Stanford University
  - TRIUMF (2009)
- Fabricate new cryomodule and validate with beam.
- Dimensioned to fit on ALICE:
  - Same CM footprint
  - Same cryo/RF interconnects
  - ‘Plug Compatible’

ALICE at 35MeV

With new cryomodule, ALICE can reach design beam energy of 35MeV (currently operation at 26.0 MeV)

The showstopper could be field emission → He processing was sufficiently successful in March 2010

New cryomodule to be installed at the end of 2012



He processing by ASTeC RF + cryogenic groups with assistance from T. Powers (Jlab)

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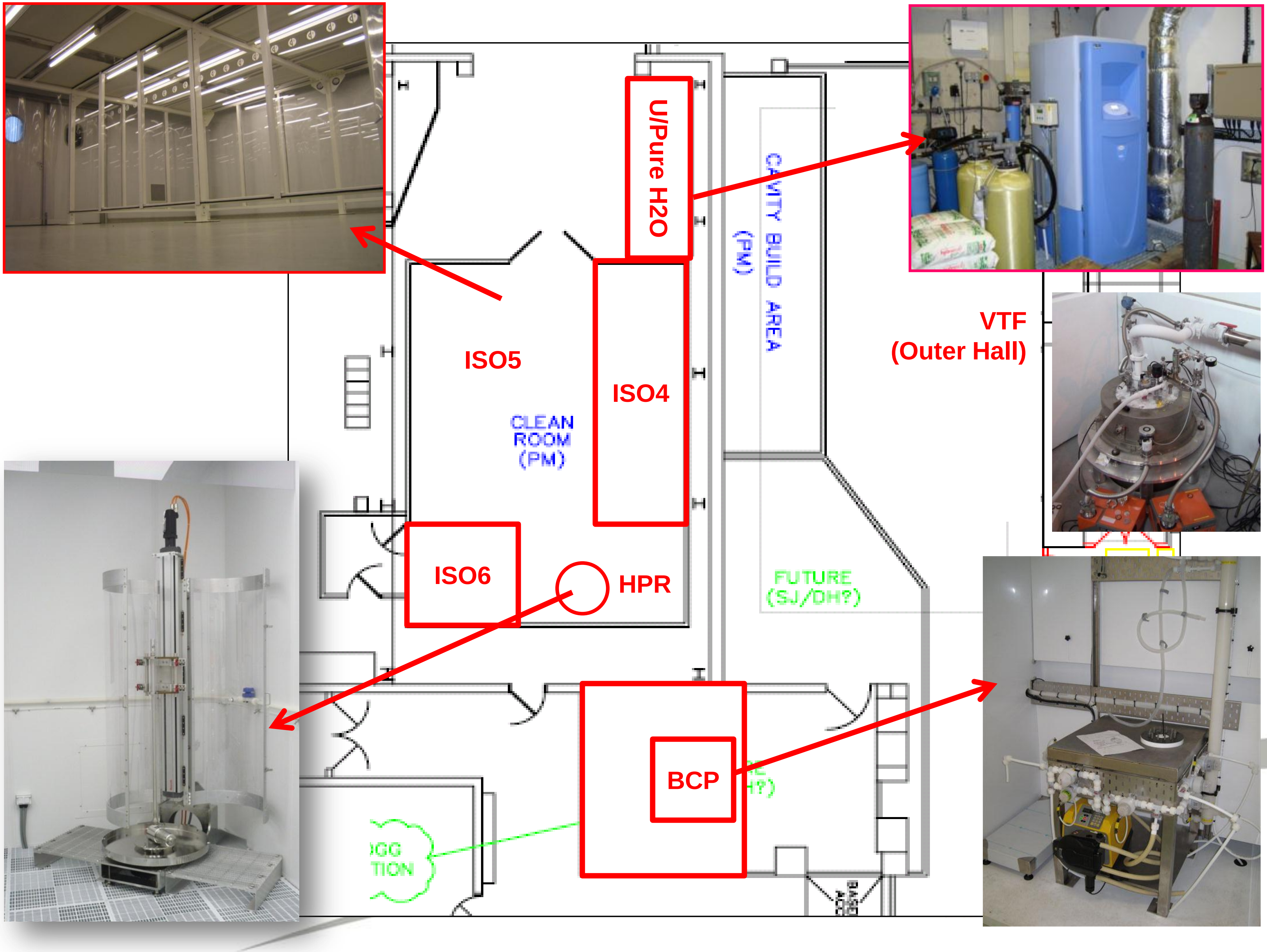
SRF Infrastructure

- Chemistry
  - New fully automated BCP facility being implemented that can accept TESLA sized cavity >1m long.
- HPR
  - >18 MΩ/cm, 100 Bar Ultra-pure water system, with automated HPR processing fixture (accepts 1.2m long cavity).
- Cleanroom
  - Area 4: ISO 4 (5.7 m x 2.8 m), ISO 5 (8.5 m x 3.5 m), ISO 6 (2.8 m x 2.8 m)
  - ETC: ISO 4 (6 m x 3.5 m), ISO 5 (10 m x 5 m)
- Testing
  - Single vertical test cryostat (0.85m diameter), with 2K cryogenics supply (dewar fed at present), upgrade underway to allow boil-off recovery.


U/Pure H2O
CAVITY BUILD AREA
(PM)
VTF
(Outer Hall)
ISO5
CLEAN
ROOM
(PM)
ISO4
ISO6
HPR
FUTURE
(SJ/DH?)
BCP

Summary

- ALICE is one of very few currently operational ERLs (and the only one in Europe !)

- ALICE has evolved from an ERL prototype to a multifunctional test facility hosting a range of science projects

- Good deal of ERL related design / experimental / operational expertise at ASTeC (inc. manipulation of e-bunches widely both transversely and longitudinally for various apps.)

- Expertise acquired in SRF, cryogenics, XHV, HV DC photoguns, and advanced instrumentation