ALICE : current status and developments

Yuri Saveliev,

on behalf of the ALICE team

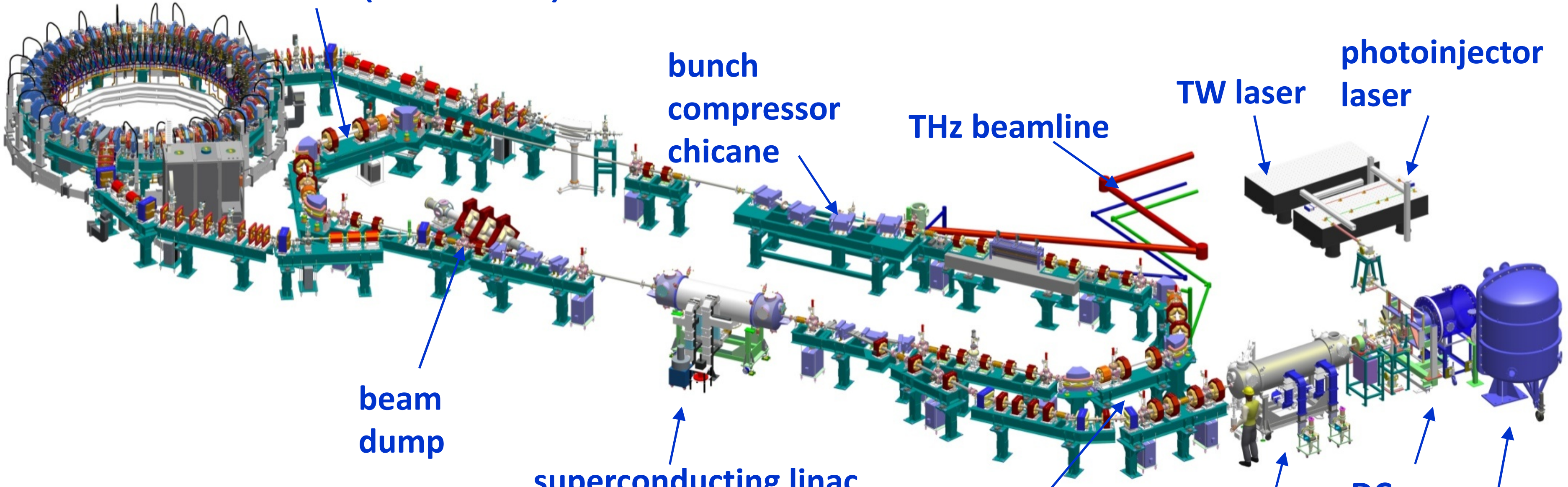
ASTeC, Daresbury Laboratory

ERL'2011 Workshop, Tsukuba, Japan, October 16-21, 2011

The ALICE Facility @ Daresbury Laboratory

Accelerators and Lasers In Combined Experiments

An accelerator facility based on a superconducting ERL-prototype
Operating in ER mode since 2008

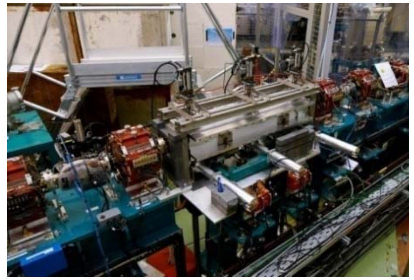


Alice

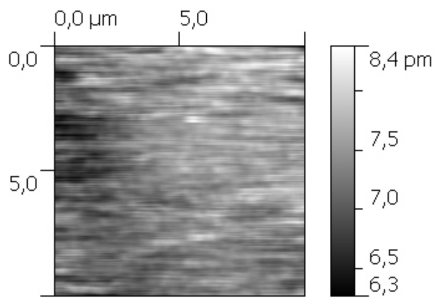
Science & Technology Facilities Council

ALICE: multifunctional facility

ER modes of operation



- **IR FEL** (5.7–8um; 10–30W ; ~3MW peak power)
  27.5MeV; 60–100pC; 16.25MHz; 10Hz; 100us
- **THz source** (15–20nJ per pulse; >10kW peak power)
  26.0MeV ; 60pC; 40.63MHz; 10Hz; 100us

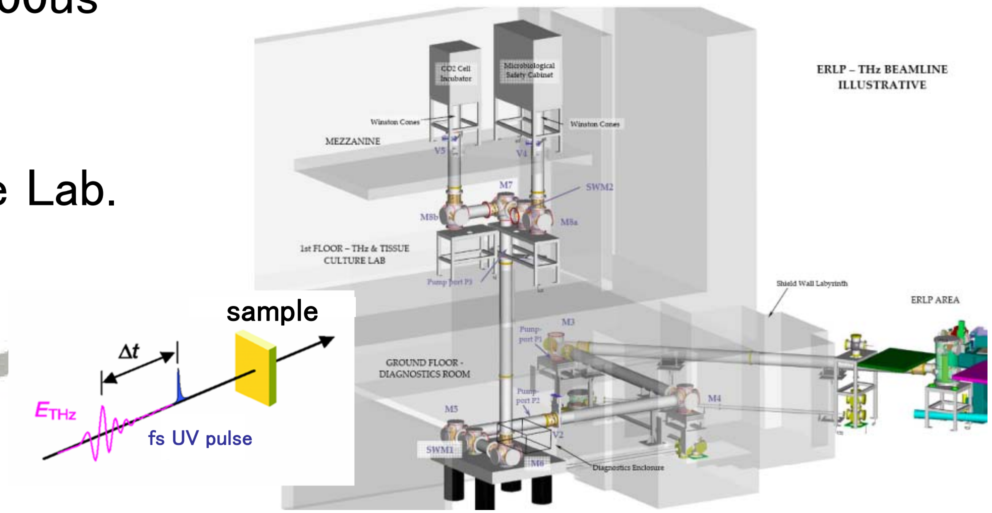


First SNOM image on ALICE

- **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

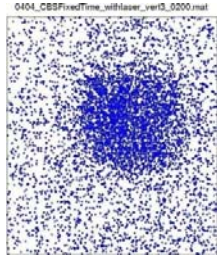
- **THz for biological exps**. in
  Tissue Culture Lab.
- **THz for quantum dots** studies
  for novel solar cells
- **Digital LLRF** development

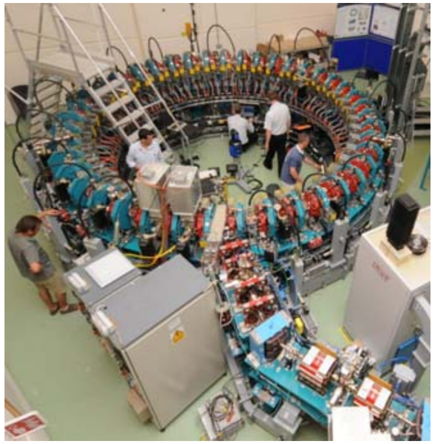


ALICE: multifunctional facility

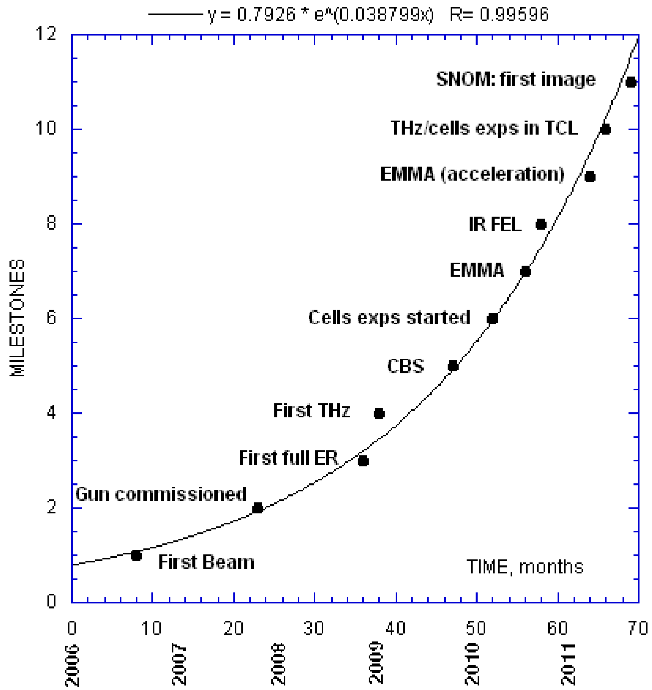
Non-ER modes of operation (single bunch)

- **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.

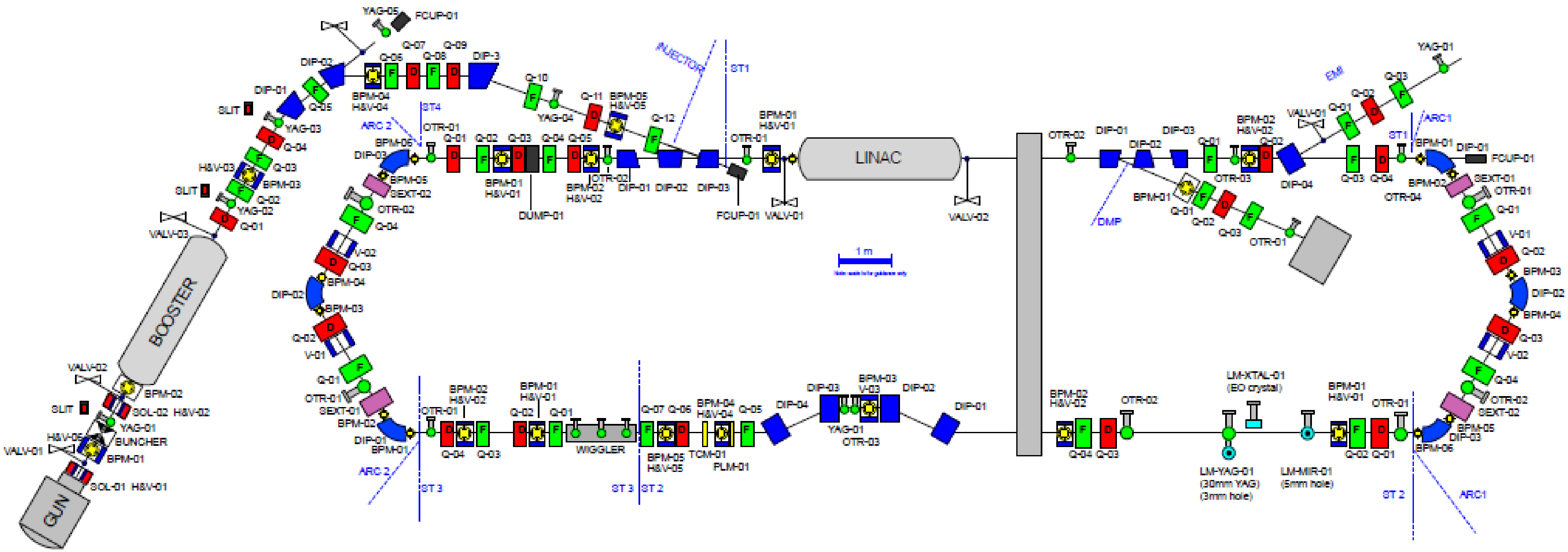


ALICE

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

IR FEL
Oscillator type FEL.
Variable gap

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



DC Gun + Photo Injector Laser
230 kV ; GaAs cathode
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

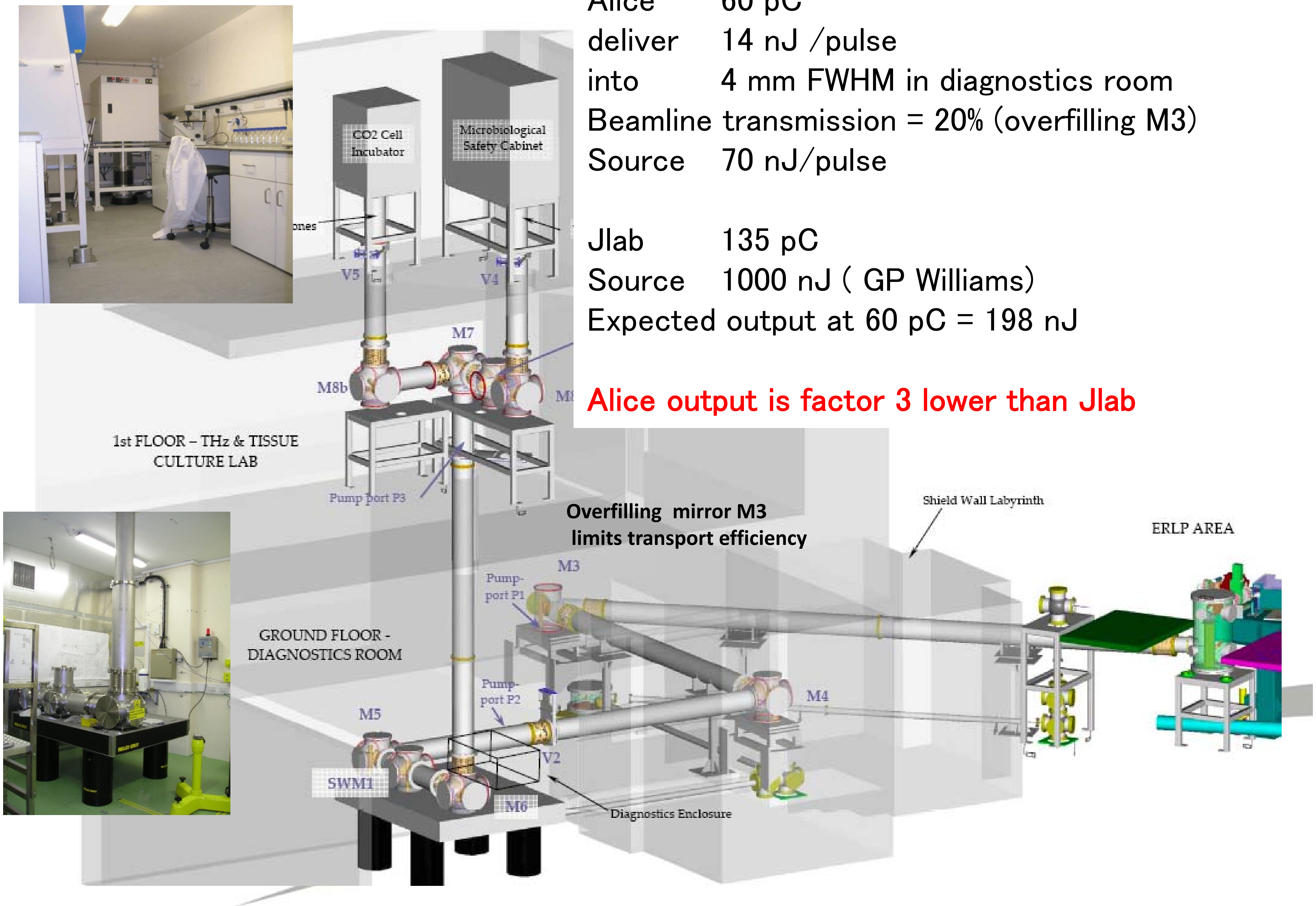
Diagnostics
YAG/OTR screens + stripline
BPMs
Electro-optic bunch profile
monitor

THz Radiation from ALICE

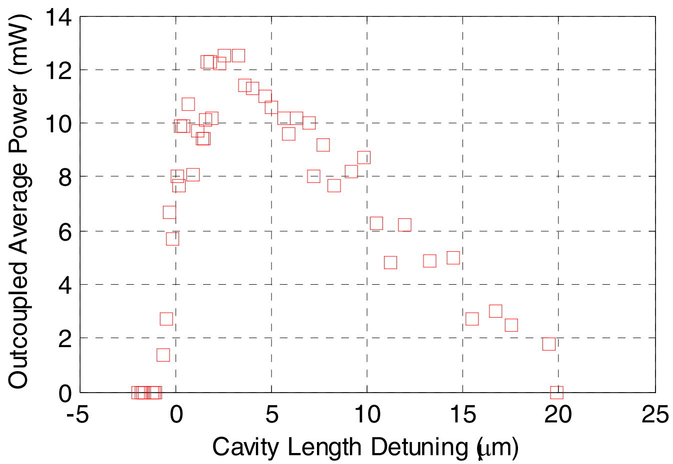
Alice	60 pC
deliver	14 nJ /pulse
into	4 mm FWHM in diagnostics room
Beamline transmission = 20% (overfilling M3)	
Source	70 nJ/pulse

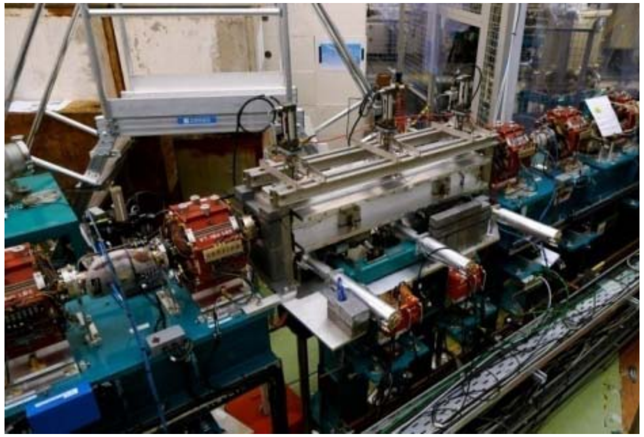
Jlab	135 pC
Source	1000 nJ (GP Williams)
Expected output at 60 pC = 198 nJ	

Alice output is factor 3 lower than Jlab



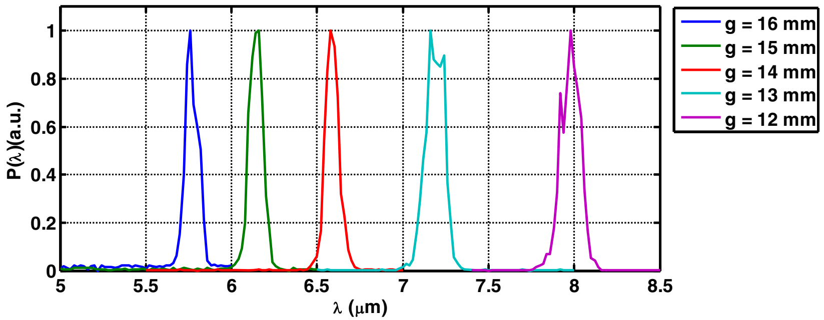
ALICE IR FEL





Undulator borrowed from Jefferson Lab

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



•Continuous tuning demonstrated 5.7-8.0 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 ~20 %.

	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)

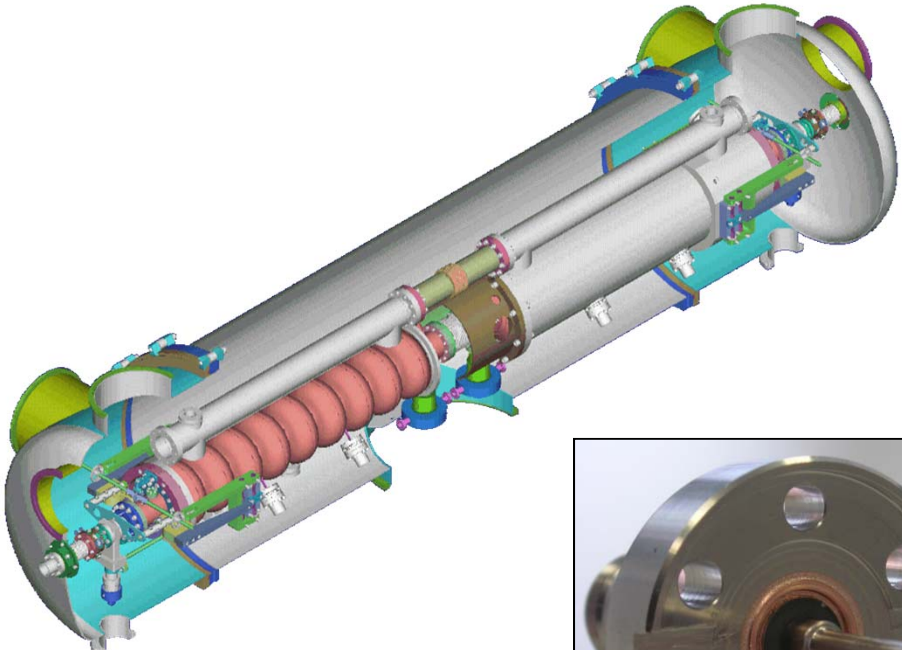
Summary of ALICE SCRF modes of operation

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]

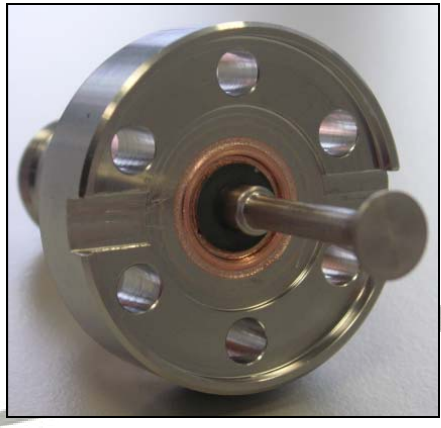
Science & Technology Facilities Council

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.



Science & Technology Facilities Council

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 @ 20 Hz repetition rate

Science & Technology Facilities Council

High Power Cavity Validation

Vertical Tests at DESY (Jul – Dec 2005)

	Booster		Linac	
	Cavity 1	Cavity 2	Cavity 1	Cavity 2
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

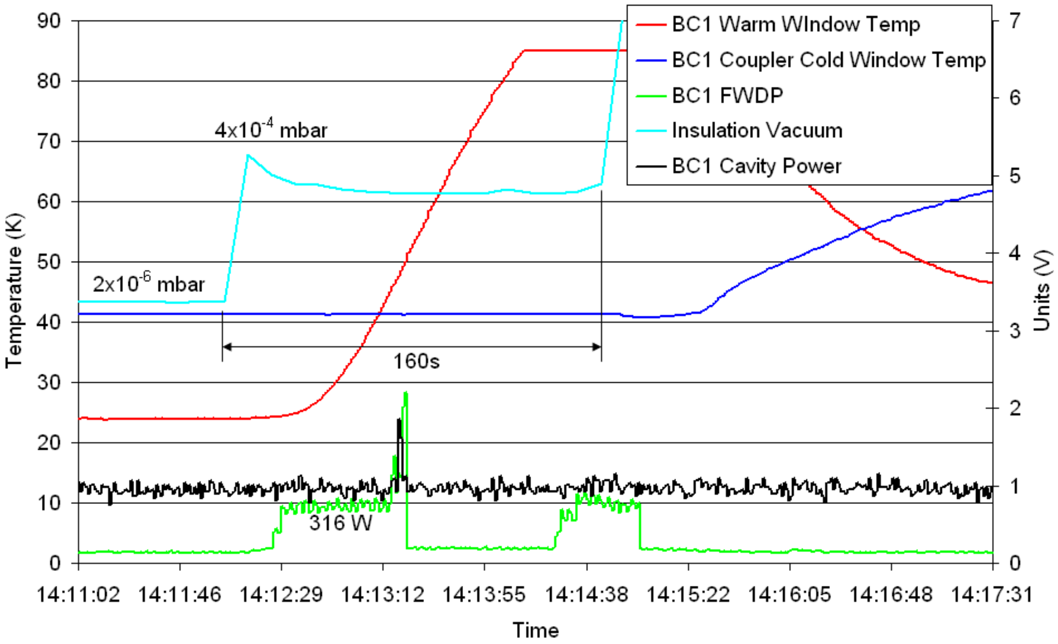
Module Acceptance Tests at Daresbury (May – Sept 2007)

Max E_{acc} (MV/m)	10.8	13.5	12.8	16.4
Q_o	3.5×10^9 @ 8.2 MV/m	1.3×10^9 @ 11 MV/m	7.0×10^9 @ 9.8 MV/m	1.9×10^9 @ 14.8 MV/m
Limitation	FE Quench	FE Quench	FE Quench	RF Power

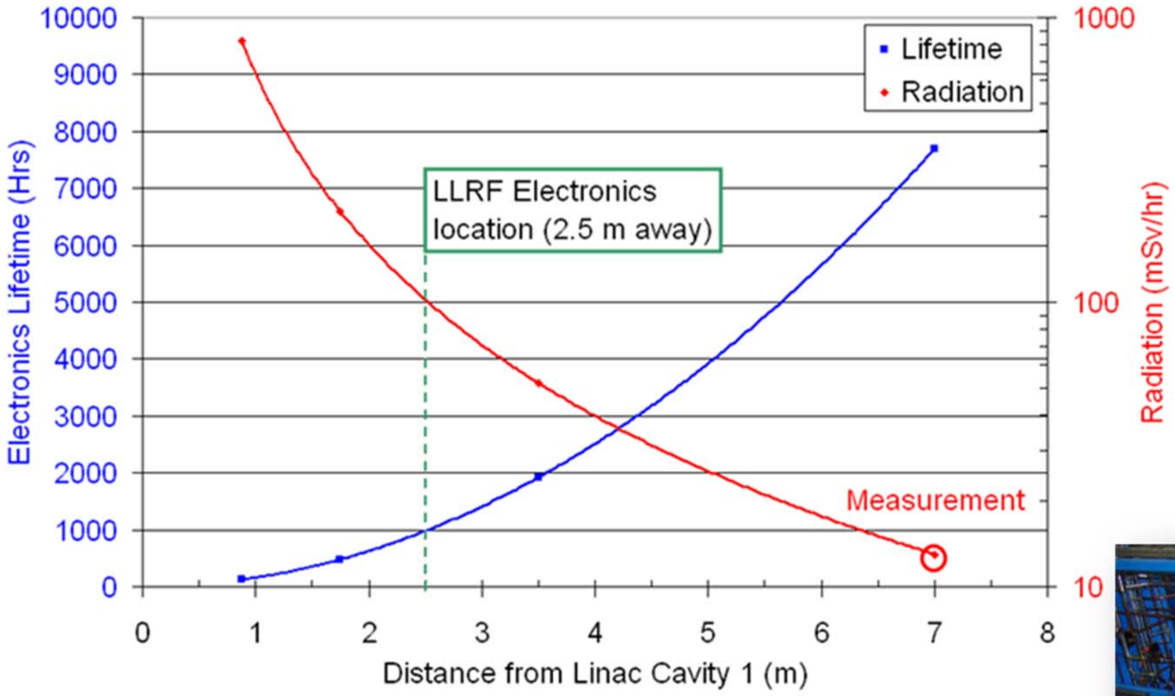
Science & Technology Facilities Council

Warm Window (BC2 – 10/2008)

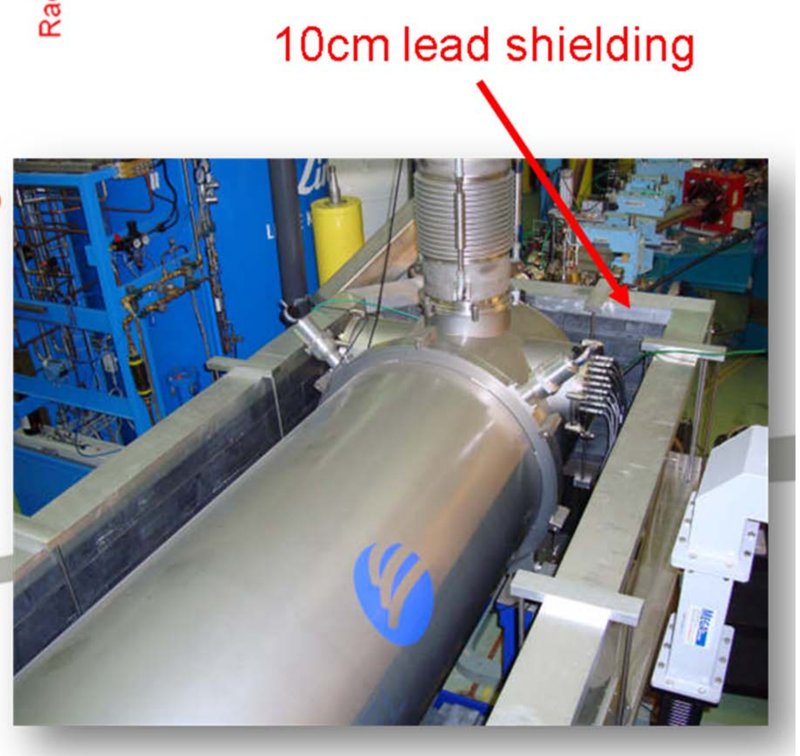
- Don't understand the mechanism for the window failure, as the fundamental RF power was so low (~300 W):
  - Contamination on window surface?
  - IOT instability?
- Isolation vacuum was not interlocked.
- Cavity interlocks were not active at all, due to an inadvertant control system mode change immediately before testing.
- Improved protection procedures now in place.



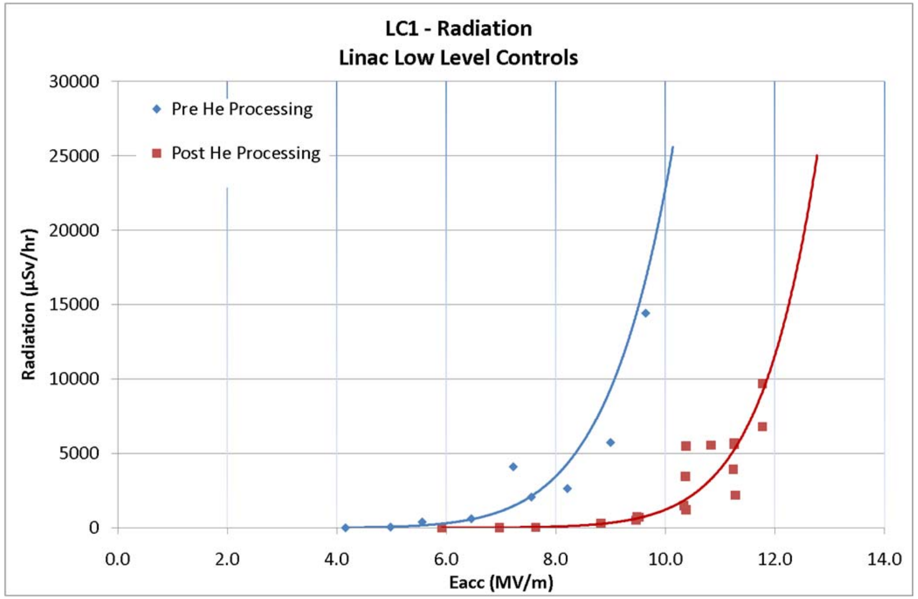
LINAC Field Emission: Short-term Mitigation

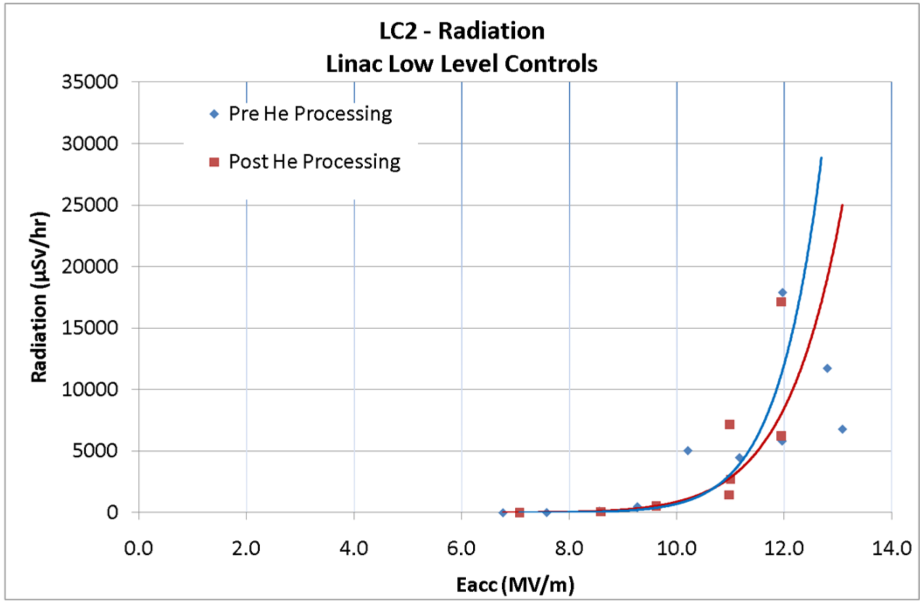


LINAC Cav1 @ 9 MV/m



Helium Processing



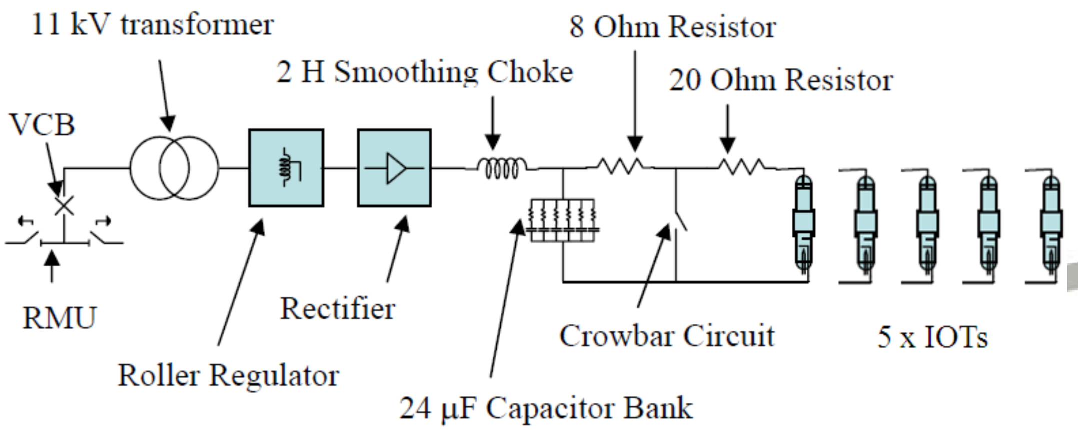


- LC1 improvement:
  - Originally had FE onset at ~6 MV/m with an operating limit of ~9 MV/m.
  - Now have FE onset at ~9 MV/m with an operating limit of ~12 MV/m.
- LC2 improvement:
  - Unable to achieve any measurable improvement, still limited to ~12 MV/m operationally.
- Both ⇒ 10 mSv/hr (~10,000 hrs lifetime).

Science & Technology Facilities Council

IOT HVPS Issues

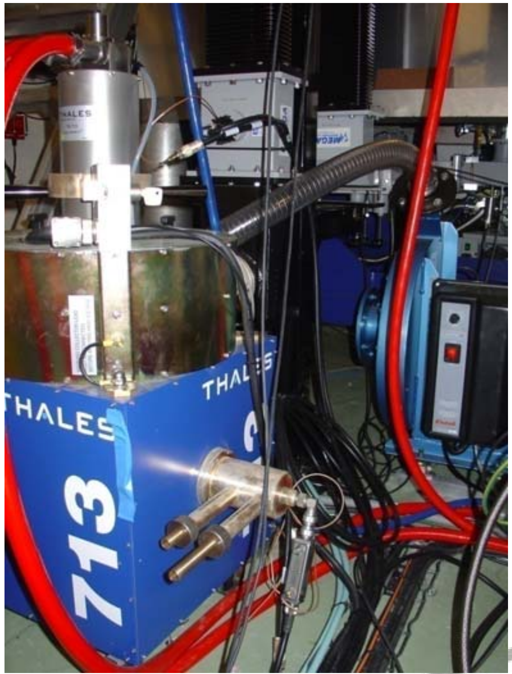
- Single HVPS:
  - Stored energy issues under fault conditions due to long HV cable runs (~60m)
  - Various types of IOTs have different requirements:
    - Filament settings
    - Ion pump reference (cathode and body)
    - Wiring not standardised
- Individual IOTs and complete system, earthing problems discovered.
- Reliable operation with:
  - Grid and heater supplies referenced at the HVPS
  - Spare HV cable along with ultra fast diodes used to control energy discharge
  - In-house grid supplies developed and installed:
    - Improved output isolation to protect against reverse voltages
  - Grid protection diodes added at the power supply and IOT
  - Spark gaps added between cathode and grid at the IOT

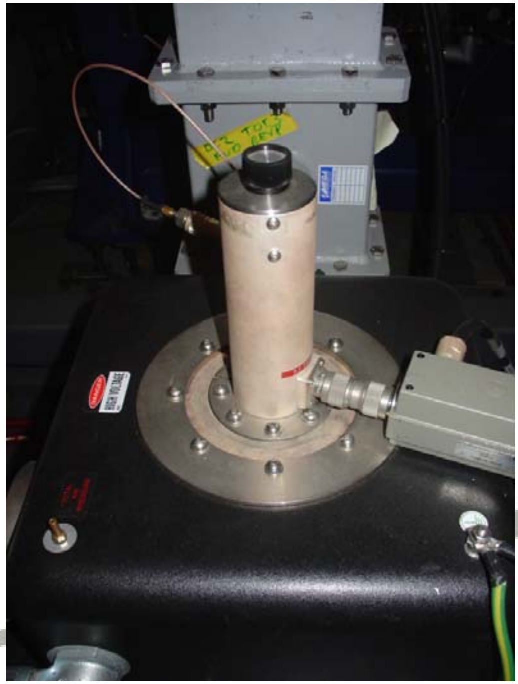


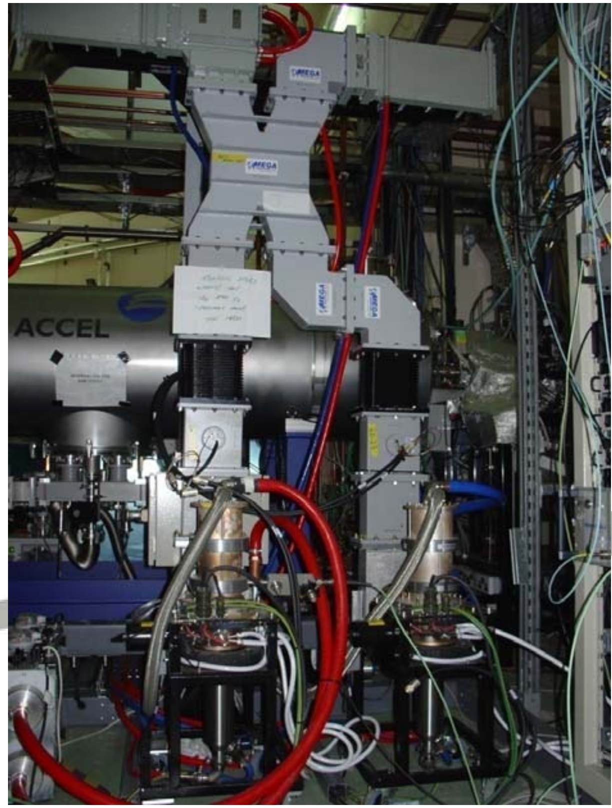
Science & Technology Facilities Council

IOTs issues

- e2v IOT116LS
  - failure after ~18 months (outgassing, unable to sustain HV)
- CPI K51320W
  - loss of output power, the input cavity had moved off frequency :
    an improved input cavity supplied by CPI
- Thales TH713
  - loss of output power; input stub very sensitive to movement
- CPI IOT
  - Gain Degradation (above ~ -14dBm)

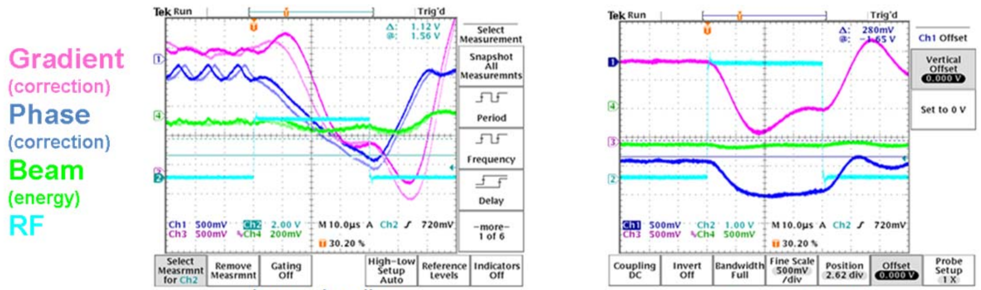




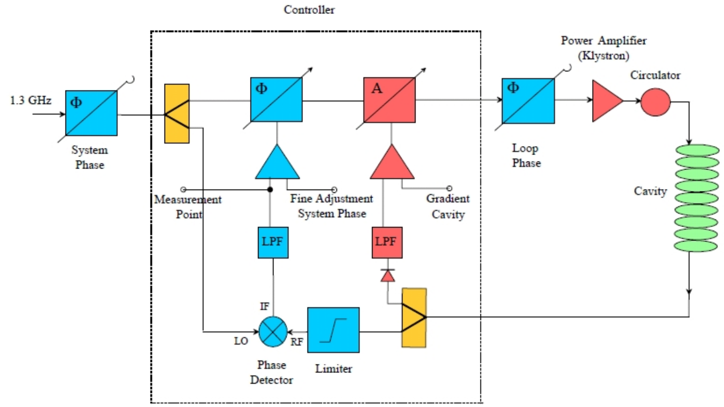


Beam loading with Analogue LLRF Control

- Analog LLRF card developed at ELBE FZR Rossendorf, proven technology but :
- Beamloading issues at 20pC; 81MHz (phase loop unable to cope)
- At 80pC; 81.25MHz would lead to a change in phase of 30 degrees and 16kW during 100us.



beam loading　　　no beam loading



Improvements made

•Speeding up the response of the cards by changing component values (= gain optimisation; limited by becoming unstable)

• HVPS droop compensation

• RF pulse reduction (from 20 ms ⇒ 4 ms) → cryo and RF systems more stable

40 pC achieved at 30 MeV with stable LLRF (no beamloading)

Further improvements

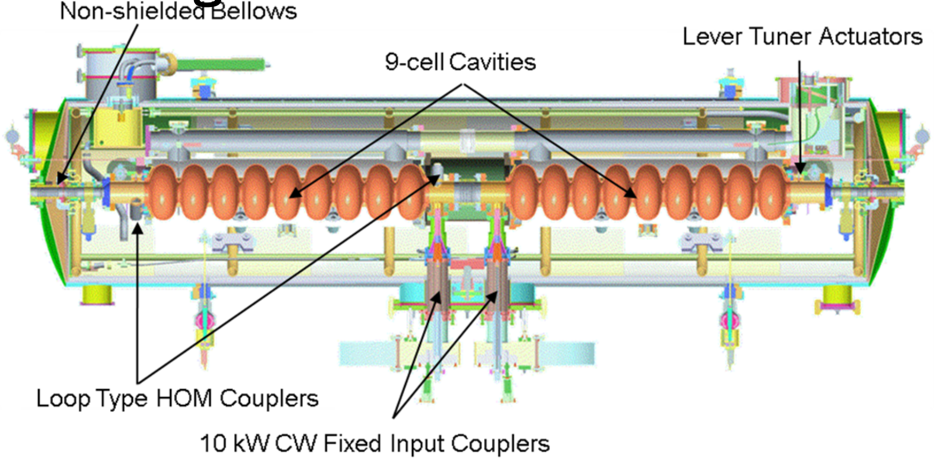
• Variable **burst selector in PI laser system** installed : can operate at 16.25 MHz, beamloading reduced → can now be compensated by LLRF → 60pC; 16MHz

• **Digital LLRF with feedforward compensation** under development.

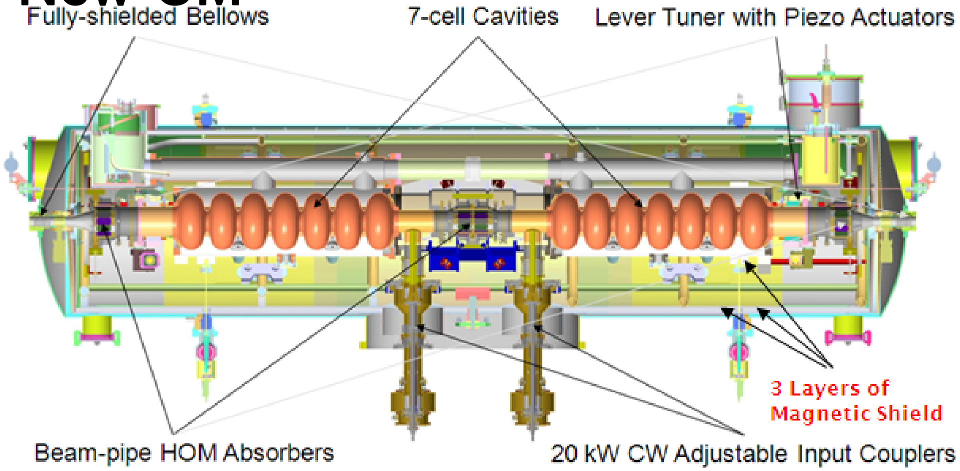
See “additional slides”

New Cryomodule Collaboration

Existing ALICE CM



New CM



- 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’

Science & Technology Facilities Council

Improved CM Capability

Fundamental ALICE benefits

Field emission free cavities:
- Local radiation problems removed.
- Electronics replacements minimised.

Better cavity performance:
- Higher gradients.
- Fewer cells ⇒ lower HOM contribution.

Higher power and adjustable input couplers:
- Larger beam currents and/or gradients.
- Reduced conditioning time and improved optimisation.
- Optimised tuning for FEL operation.

Piezo actuators for improved stability control:
- Requires digital LLRF system.

Improved thermal and magnetic shielding:
- Reduced static/dynamic cryogenic loads.
- Reduced operational costs.
- Reduced microphonics ⇒ improved stability.

Able to repair the removed FE limited CM:
- Providing ALICE with a spare!

Target Cryomodule Specification

Parameter	Target
Frequency (GHz)	1.3
Number of Cavities	2
Number of Cells per Cavity	7
Cavity Length (m)	0.807
Cryomodule Length (m)	3.6
R/Q (Ω)	762
E_{acc} (MV/m)	>20
E_{pk}/E_{acc}	2.23
H_{pk}/E_{acc}	46.9
CM Energy Gain (MeV)	>32
Q_o	$>10^{10}$
Q_{ext}	$4 \times 10^6 - 10^8$
Max Cavity FWD Power (kW)	20 SW

Science & Technology Facilities Council

ALICE SCRF: notes from the accelerator physicist

- RF and cryogenic systems reliability
  - complex systems hence one of the major factors in beam time losses; even minor problems normally require calling out RF specialists
- RF Phase stability (slow phase drifts)
  - makes machine optimisation and exps. very difficult (alleviated by developing the MO feedback system on ALICE)
  - phase drifts in a "non-global" sense are still an issue.
- RF trips (mostly on cold and warm windows interlocks)
  - sometime spurious; normally – RF switch back right away; cryo regains stability relatively quickly
- FE from linac: "kills" upstream / downstream screen cameras very quickly

Summary

- ALICE is a **very** multifunctional facility operating for a host of **very** different projects in both energy recovery and single bunch modes
- Major milestones achieved
  - Compton Back Scattering x-ray generation demonstrated
  - IR FEL lasing ; tuneable 5.7-8um; experiments with SNOM started;
  - coherent high power THz generation (biology and solid state physics experiments under way);
  - EMMA : first NS FFAG; injection & extraction, multiturn operation, and acceleration 12 → 21MeV demonstrated.
- SRF cavities do not perform as expected ⇒ heavy FE > 7 MV/m.
- Helium processing and module shielding introduced.
- IOT problems relating to input circuit match with 1 IOT failure in 3 years.
- More problems with IOT HVPS, used to power all 5 IOT's:

  HVPS and IOT system earthing critical.

  Inconsistent IOT and HV configurations.

  HVPS ~60m away ⇒ large HV cable stored energy.
- Injector cavity beamloading issues: improvements allow now to operate at ~60pC; 40MHz; or > 80pC; 16 MHz.
- Digital LLRF system development ongoing
- New CM development will improve ALICE performance considerably.

ALICE: current status and developments

Many thanks to Peter McIntosh and the whole ASTeC RF group for providing SCRF related slides

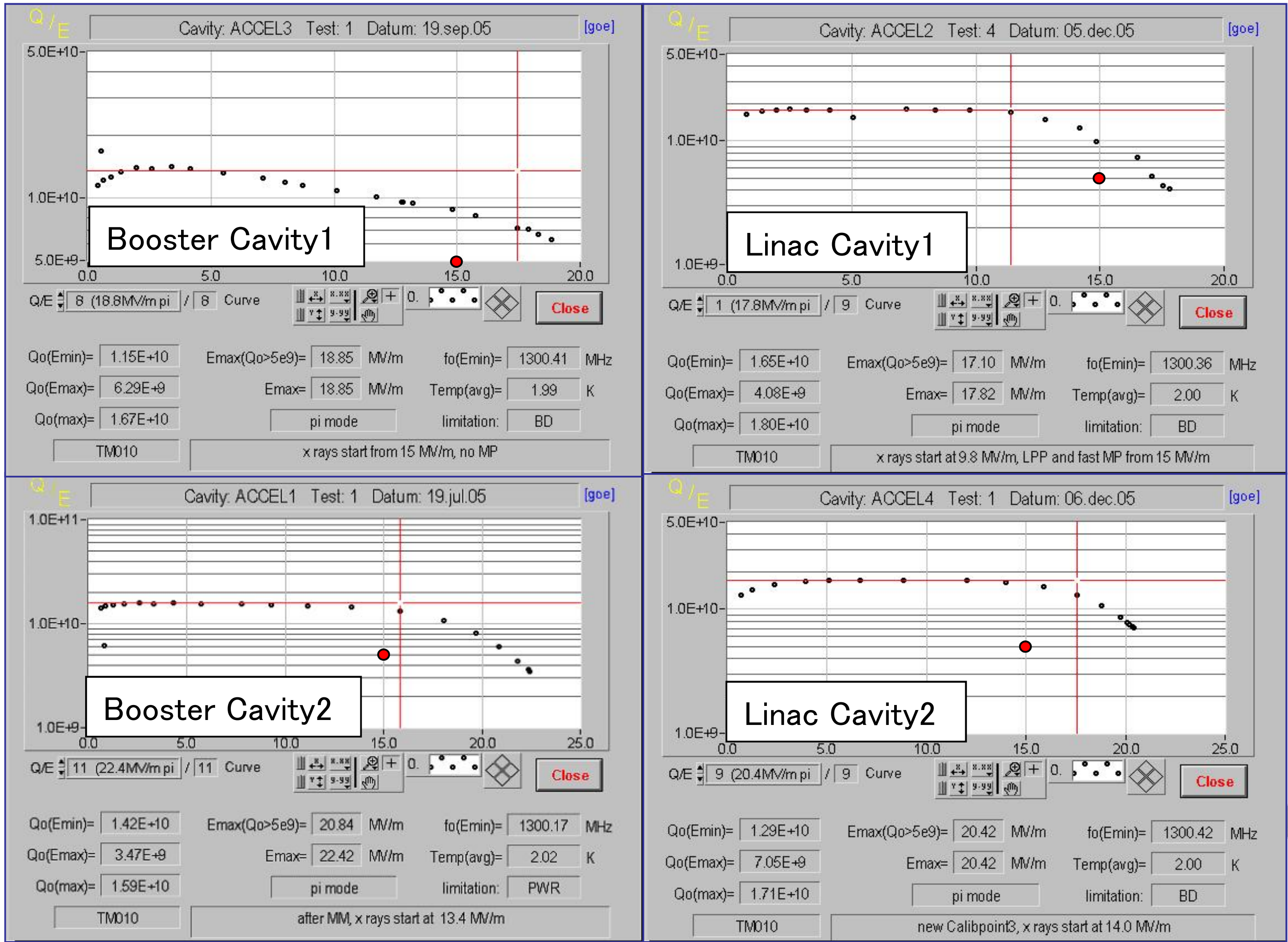
ADDITIONAL SLIDES

- Vertical tests
- Coupler heating
- Acceptance testing (2007)
- Helium processing (2010) – schematics
- ALICE IOTs and IOTs issues
- ALICE LLRF system
- Digital LLRF development

Science & Technology Facilities Council

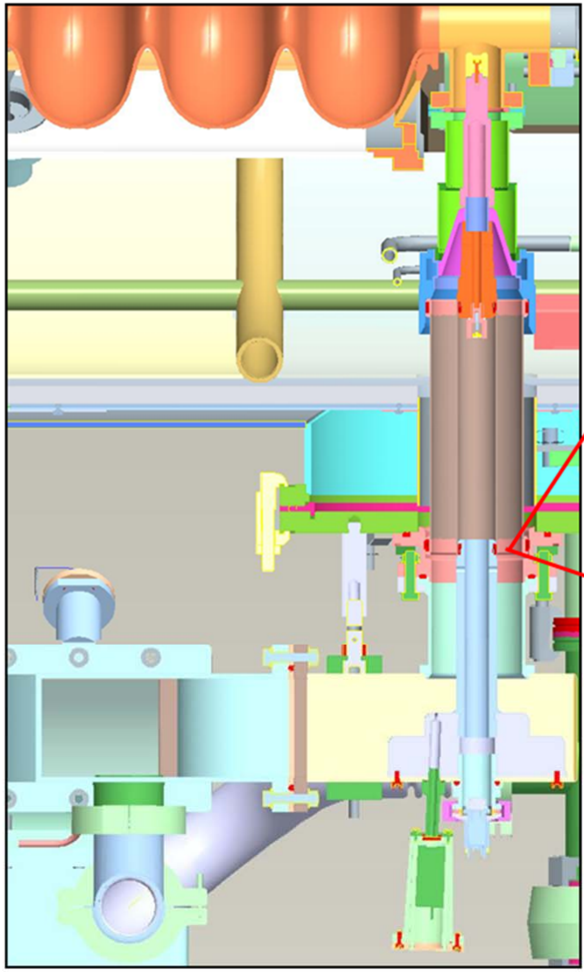
ADDITIONAL SLIDES

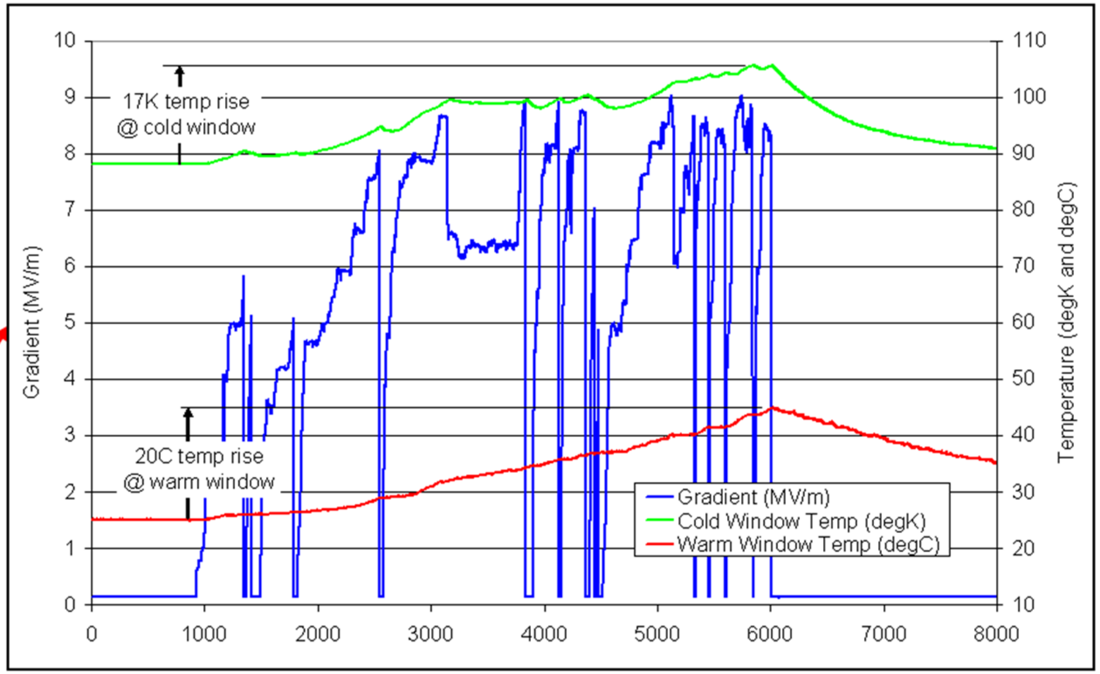
SRF Cavity Vertical Test Results @ DESY

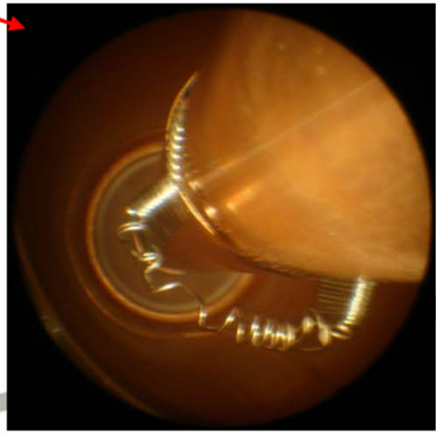


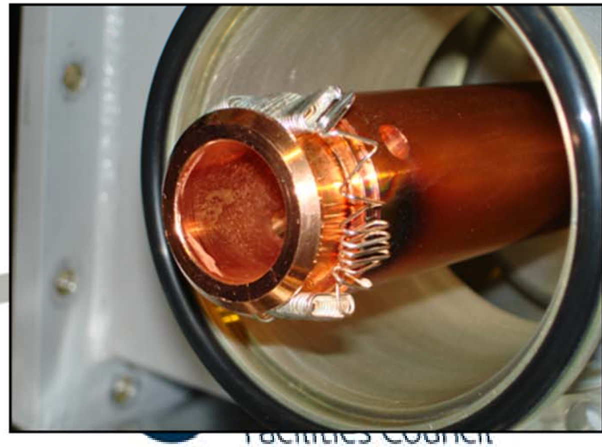
Jul – Dec 2005

Coupler Heating (LC2 – 6/2007)

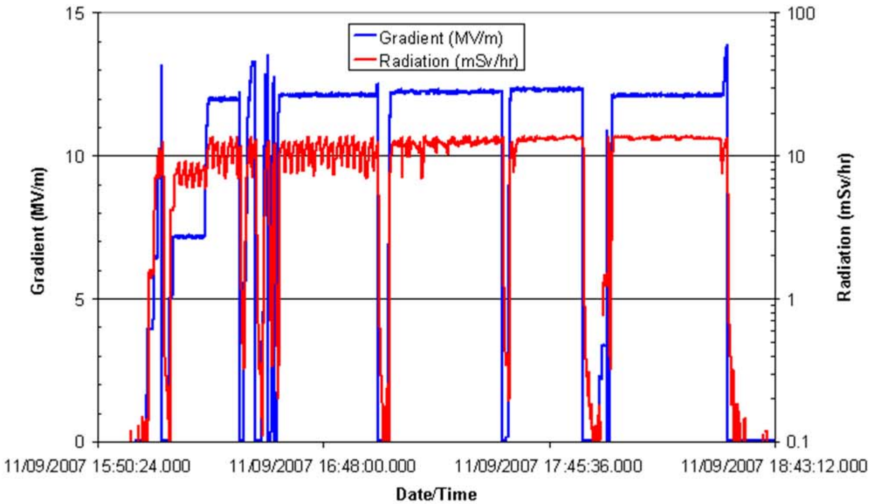


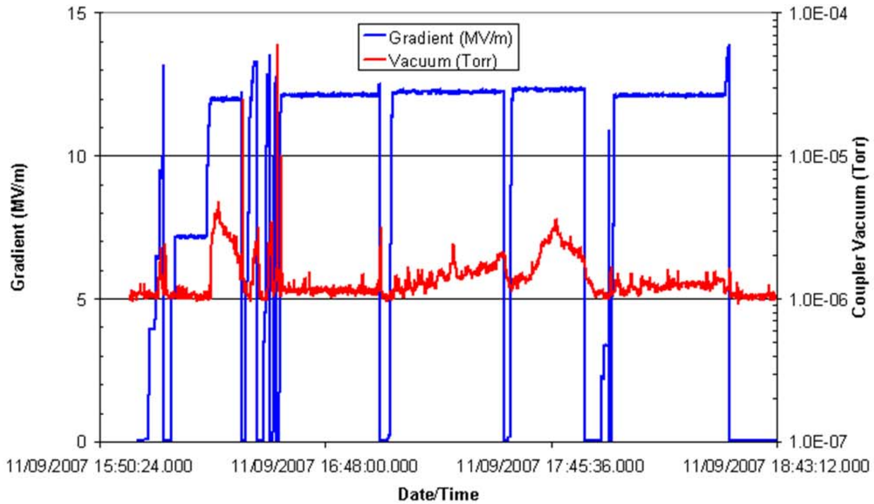


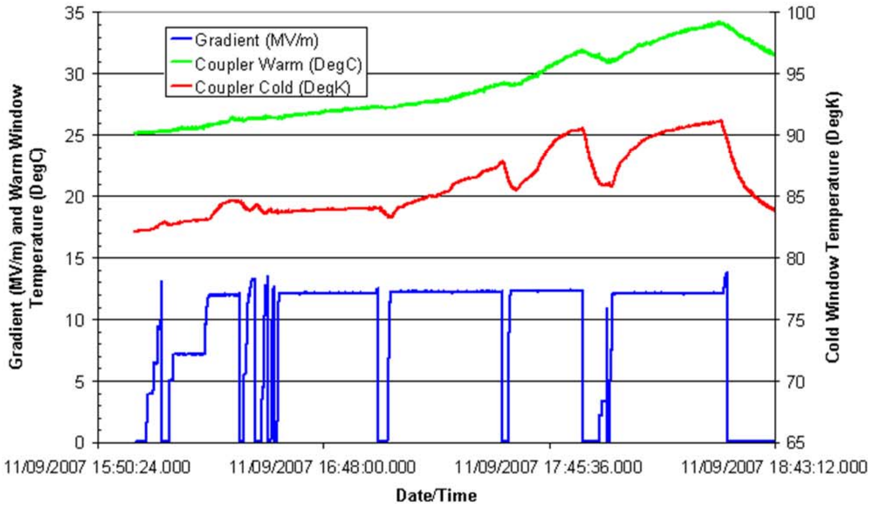




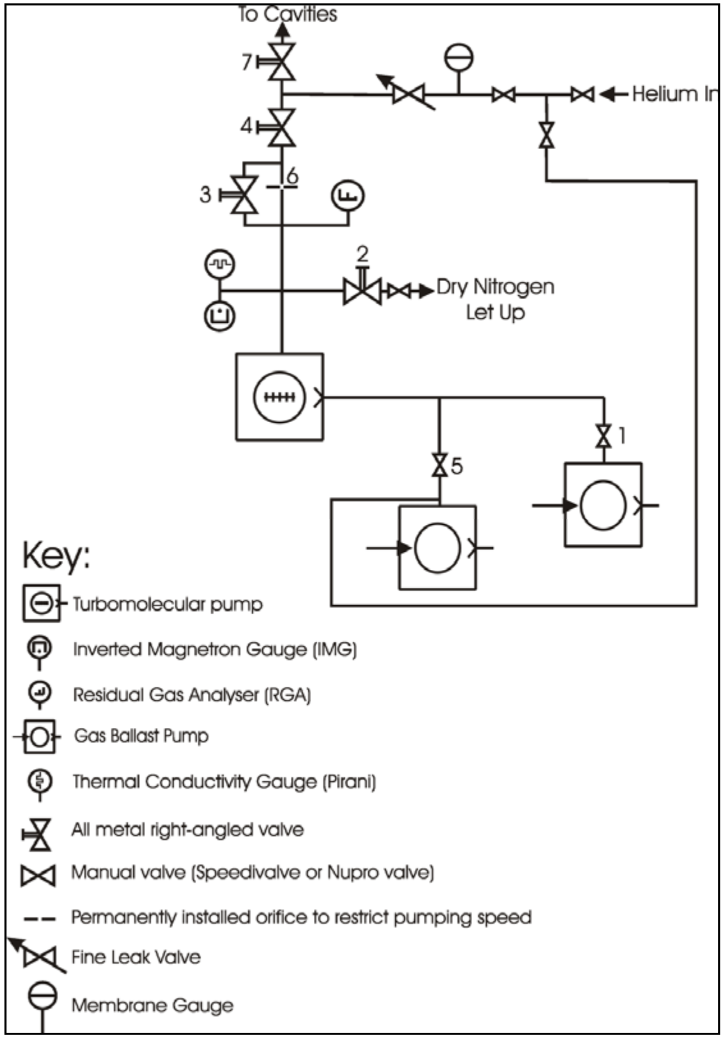
LC1 Acceptance Testing (9/2007)



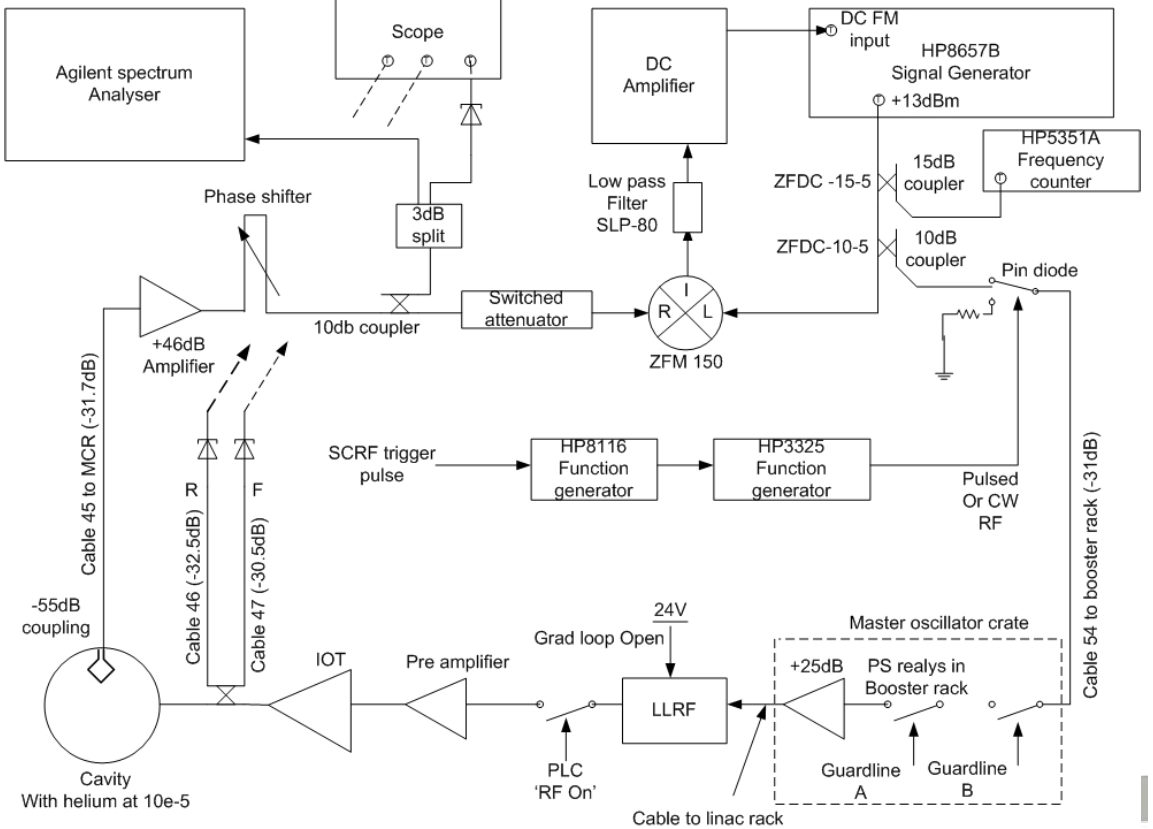




Helium Processing (Jun 2010)



RF Control Configuration



Vacuum and Helium Configuration

ALICE IOTs

CPI K51320W

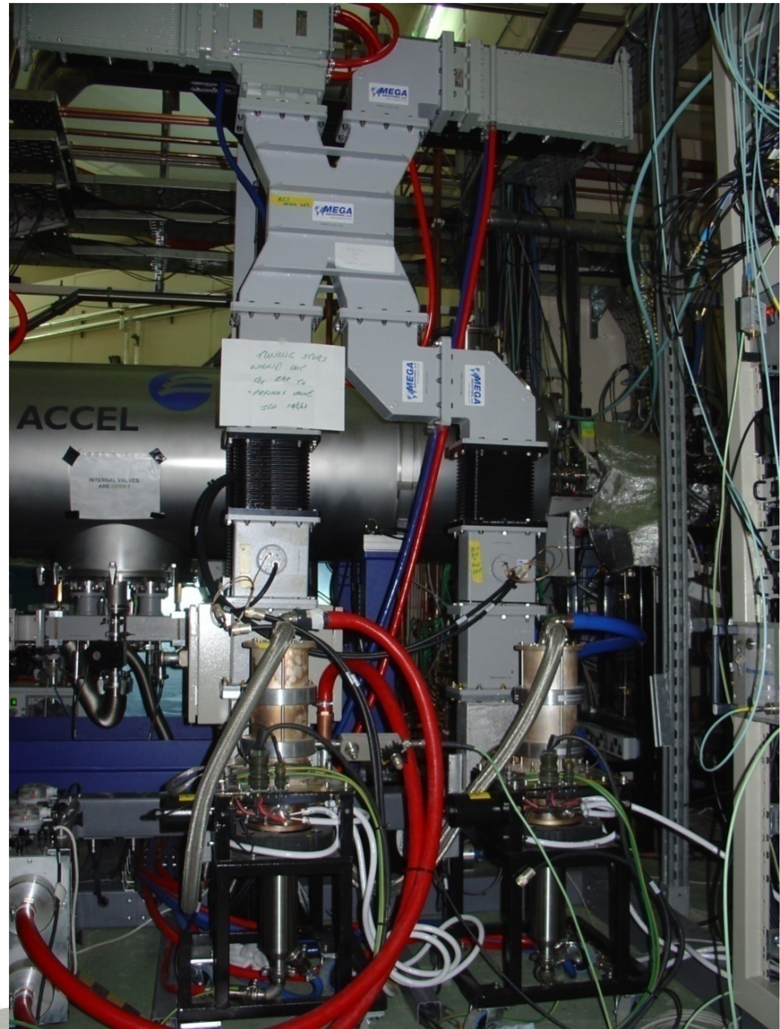
e2v IOT116LS

Thales TH713

Parameters	CPI K51320W	e2v IOT116LS	Thales TH713	Units
Frequency	1.3	1.3	1.3	GHz
Max CW Power	30	16	20	kW
Gain	21	>20	20.9	dB
Beam Voltage	34	25	25	kV
Bandwidth	4.5	>4	>5	MHz
Efficiency	63.8	>60	60.4	%

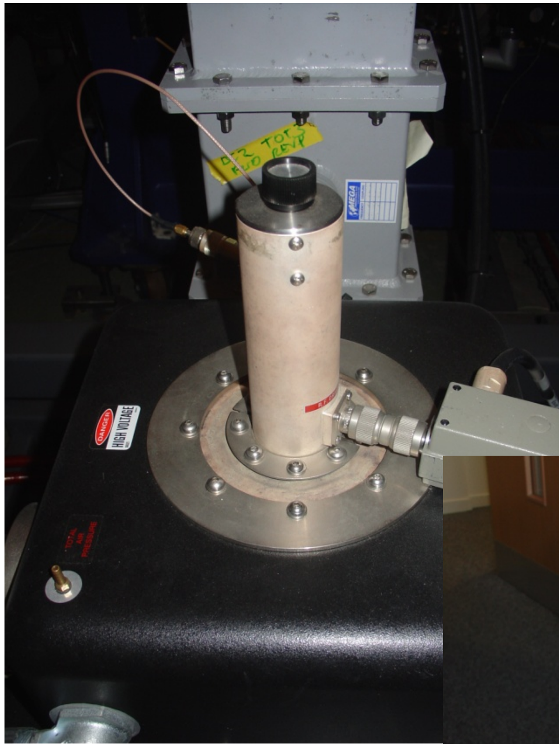
IOT Issues – e2v IOT116LS

- Tube failure Dec 08:
  - After ~18 months
- Tube gassed up on application of filaments:
  - Tube unable to sustain HV.
- Failure believe to be due to the tube being operated with too high a quiescent current:
  - ⇨ Leading to a melted collector or body.
  - ⇨ Poisoned cathode due Cu deposition.
- Additional protection added to HV PLC:
  - DC current trip level included HV PLC program.
  - Individual IOT current monitoring.



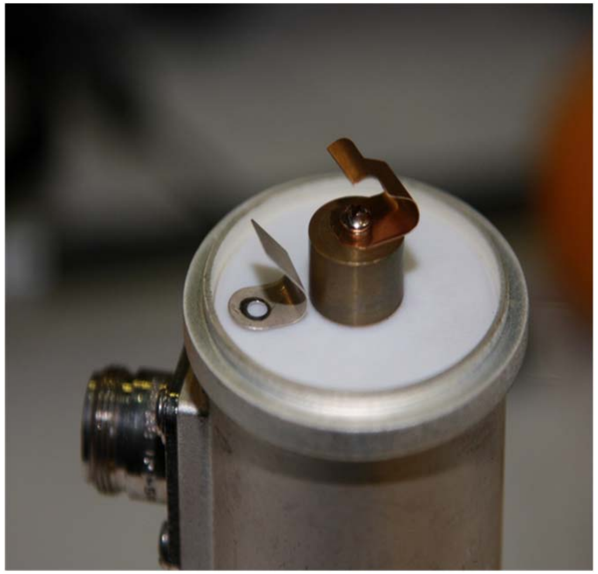
IOT Issues – CPI K51320W

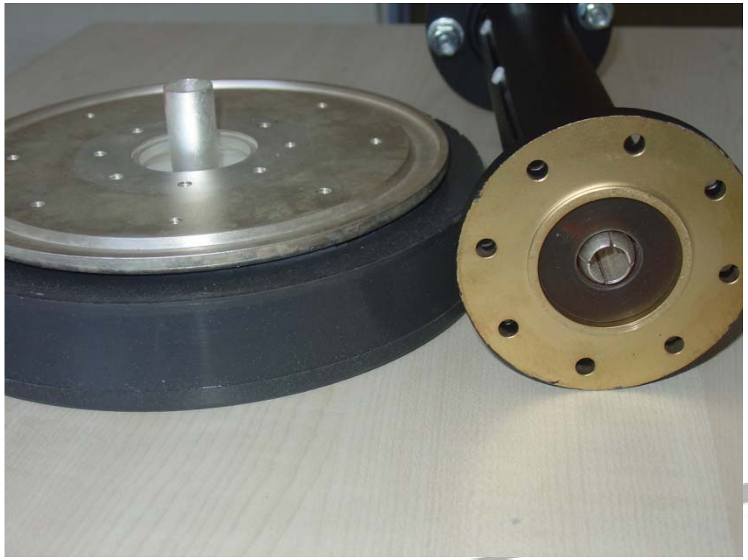
- Issues encountered with loss of output power.
- Discovered the input cavity had moved off frequency:
  - Difficult to tune and maintain a good input return loss.
- Similar issue encountered on spare IOT system.
- Resolved by tuning the input whilst tightening the screws on the input base plate.
- An improved input cavity supplied by CPI:
  - More robust coaxial connection.

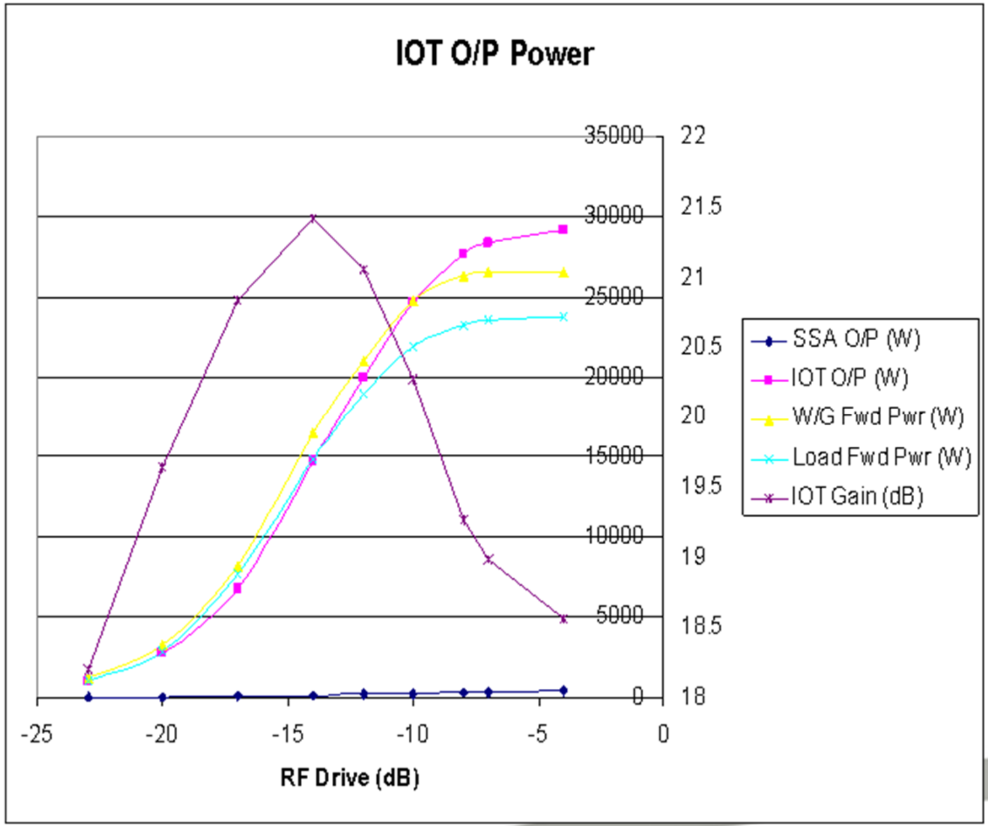


Science & Technology Facilities Council

CPI IOT Gain Degradation

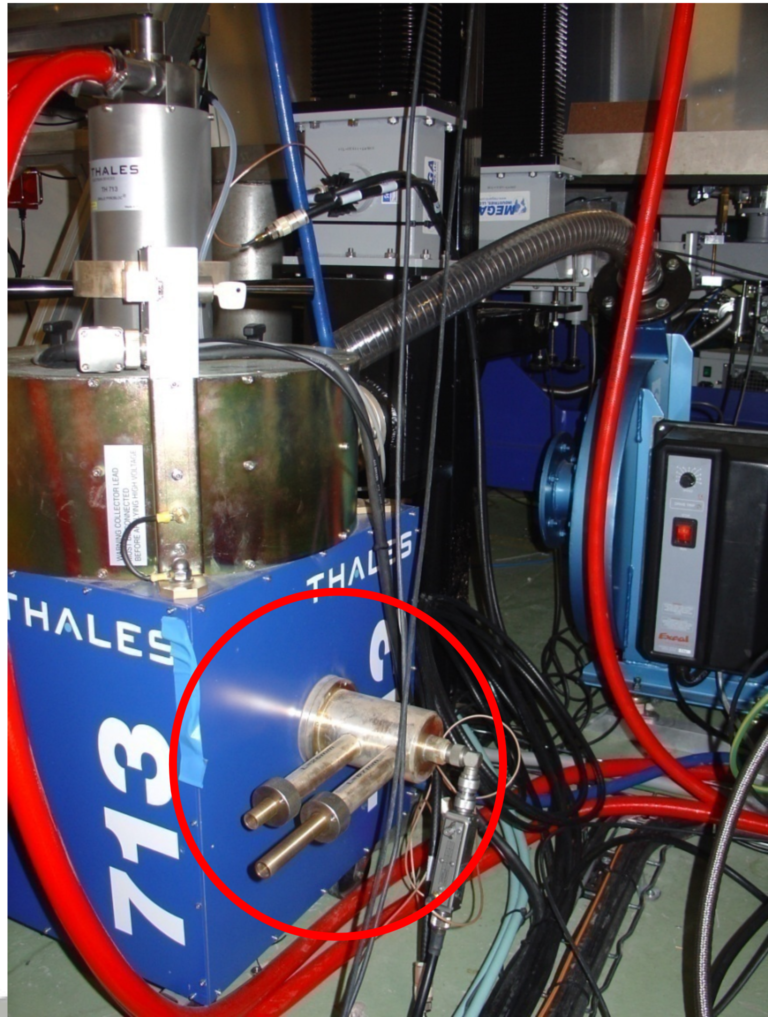






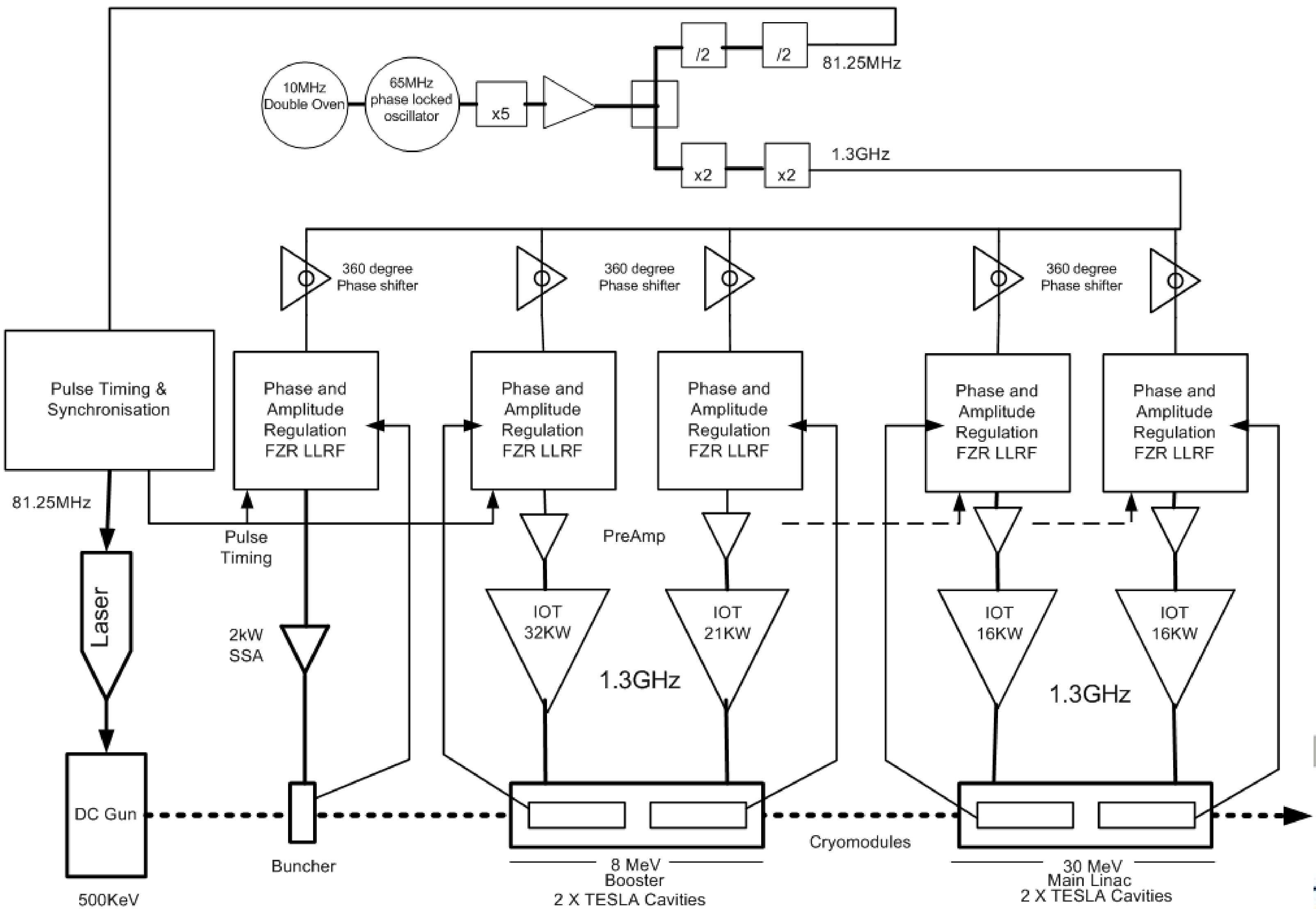
IOT Issues – Thales TH713

- Issues encountered with loss of output power.
- Input stub very sensitive to movement:
  - Poor input match.



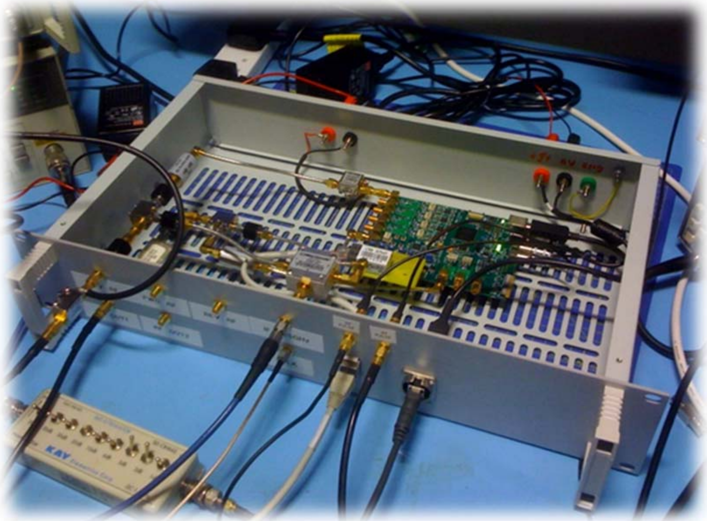
Science & Technology Facilities Council

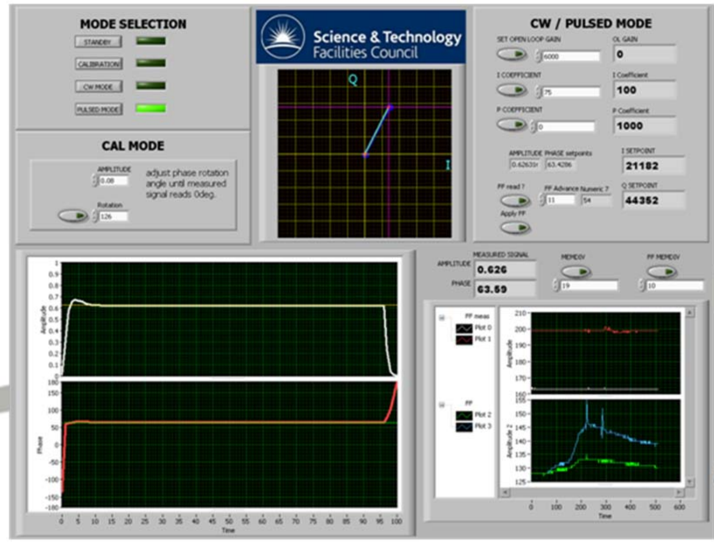
ALICE LLRF System



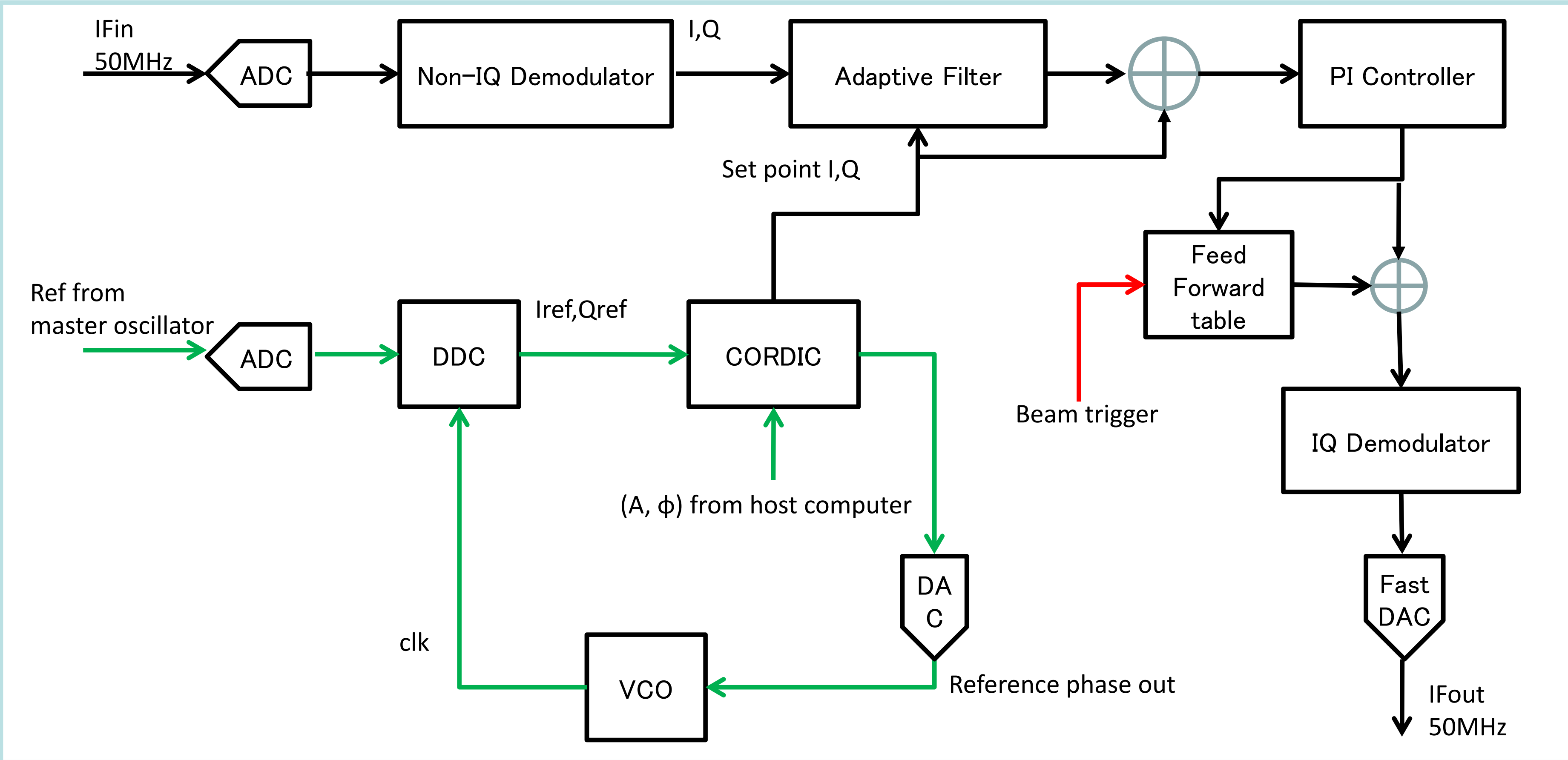
Digital LLRF Developments

- LLRF4 board (developed by Larry Doolittle at LBNL) used as the basis for the design.
- FPGA software written using VHDL, Matlab and Simulink.
- Supervision and control of the system performed by a Labview VI, which also implements adaptive feed forward for beam-loading compensation.
- Labview system interfaces with the ALICE EPICS control system.
- System developed and implemented in ~12 months.



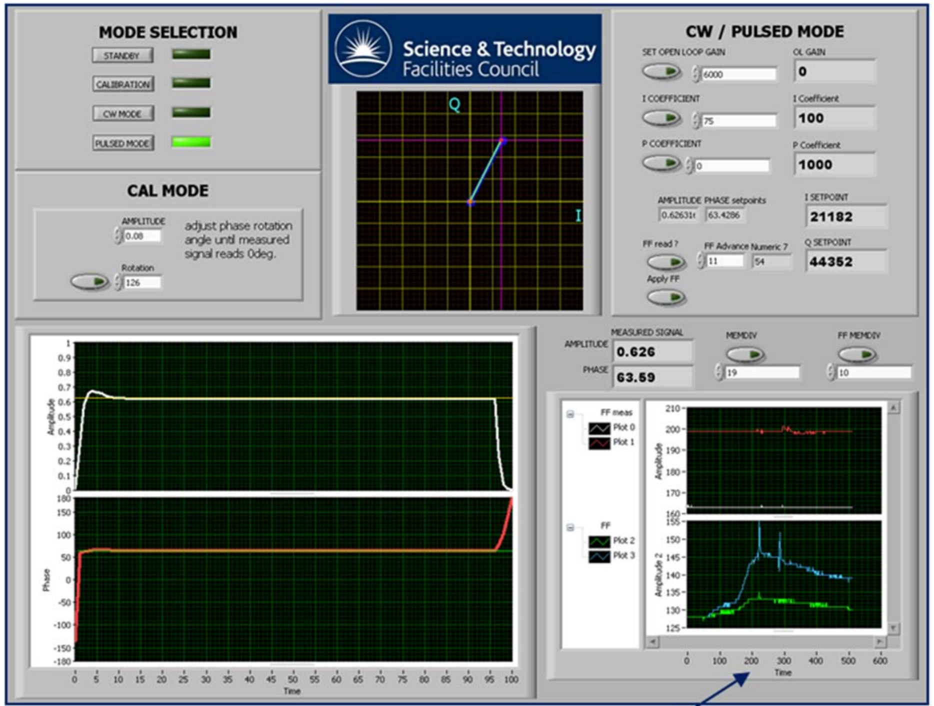


Digital Control Process



Operational Performance

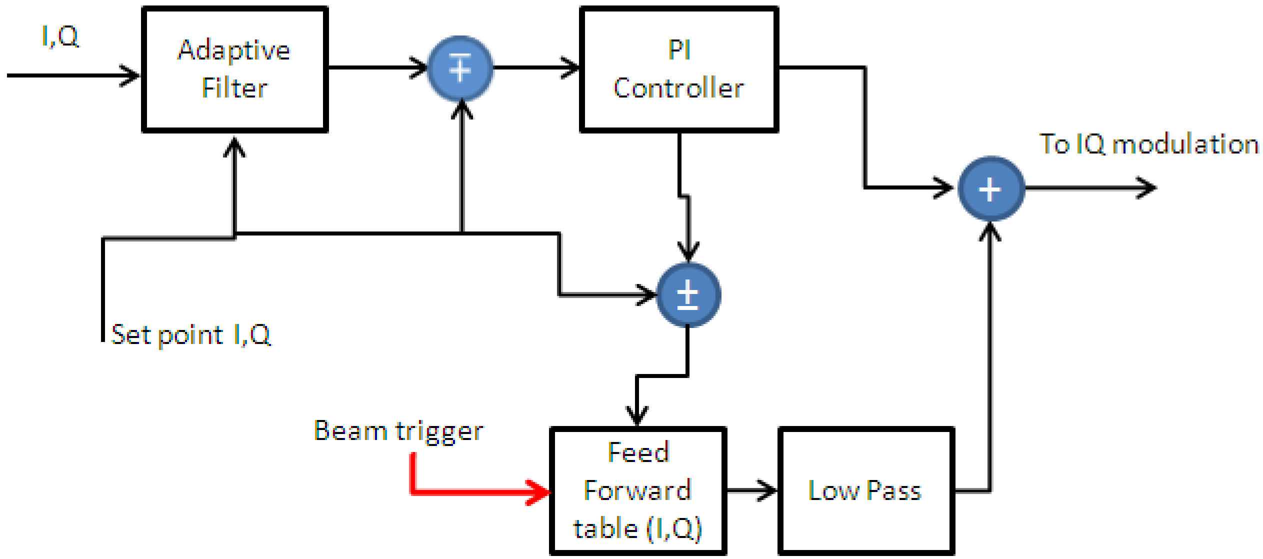
- The Digital LLRF system been operated on the ALICE NC buncher cavity.
- The system set up and locked within 10 min:
  - Short term stability better than the existing analogue system (0.02 degrees rms phase error).
  - Long term stability is limited by temperature drifts within the analogue front end.
  - Some non linear behaviour has been observed.
  - Non – Linearity within the analogue front end introduced phase changes of up to 10 degrees with increasing amplitude.
- Non-Linear effects:
  - The analogue front end's RF levels were optimised to maximise use of component linear regions.
  - A linearization look up table was introduced to linearise the rest of the system.
- The down/up conversion components have been moved into a temperature controlled enclosure:
  - controlled to +/- 0.1 deg C
  - Long term phase drifts are now limited to ~0.1 degree
- The Adaptive feedforward system is being investigated with beam.



Feed Forward Table

Science & Technology Facilities Council

Feed-Forward Process



- The feed forward is an adaptive table which records the error signal on beam trigger and adds up to the previous record.
- Table is updated on every beam pulse.
- Feed forward signal goes through a Low pass filter before being combined with the feed back and then sent to a digital IQ modulator.