Science & Technology Facilities Council
Daresbury Laboratory

Low Emittance Optimisation & Operation

Peter Williams

ASTeC, Daresbury Laboratory

22nd June 2017

ERL17

The 59th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs
18-23 June 2017, CERN

The Cockcroft Institute of Accelerator Science and Technology

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Low-ish Transverse Emittance and Longitudinal Phase Space* Optimisation & Operation

Peter Williams

ASTeC, Daresbury Laboratory

*I don't think the term "longitudinal emittance" is enlightening in the context of longitudinal phase space gymnastics required in driving an FEL

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Contents

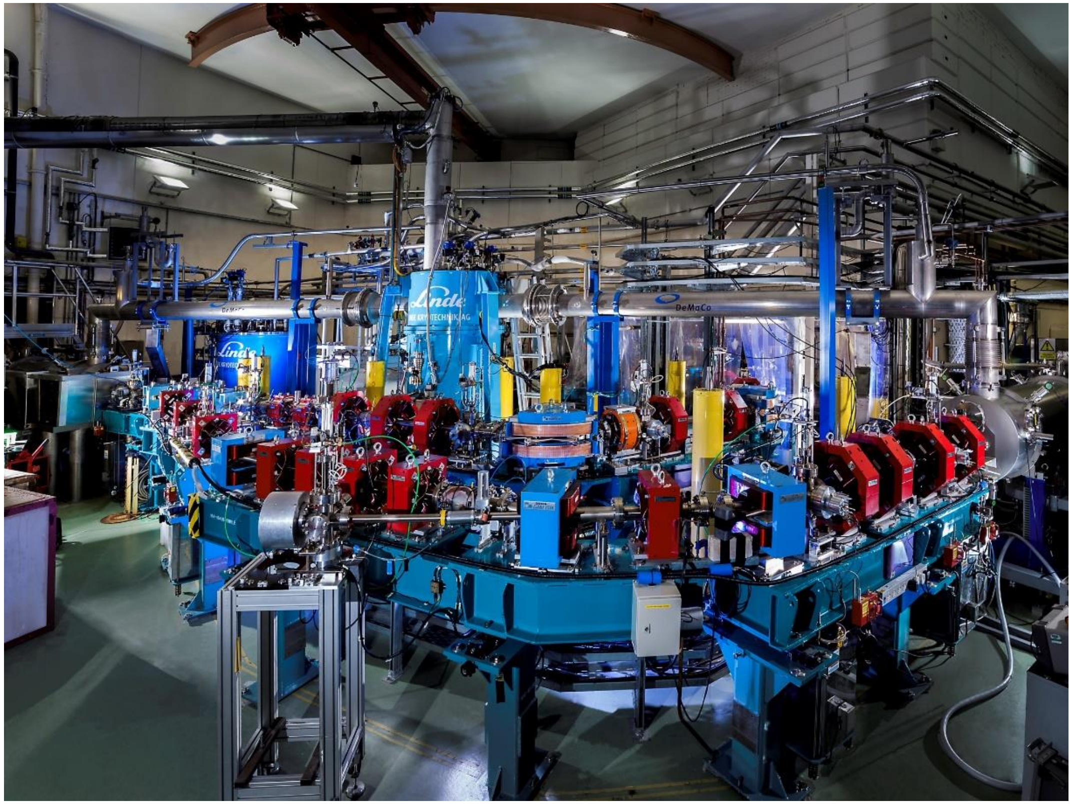
- This talk is a **personal** view of the operational experience on the ALICE Energy Recovery Linac at Daresbury Laboratory (currently decommissioning since May 2016) – I have selected some examples of **beam physics issues** that turned out to be most important in achieving good performance day-to-day. My aim is that this is useful in the context of future ERL projects

1. Introduction to ALICE

2. Optimisation, operation and measurements in the **Injector** in terms of transverse emittance and longitudinal properties

3. Optimisation, operation and measurements in the **Energy Recovery Transport** in terms of transverse emittance and longitudinal properties

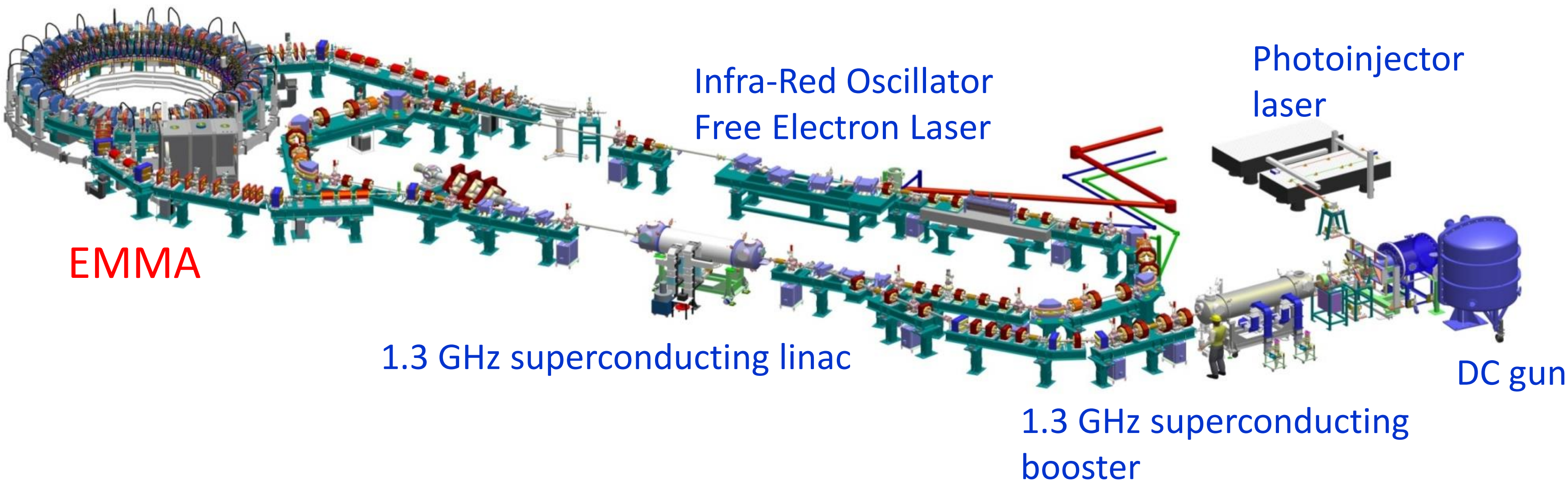
4. The importance of **Stability**



The ALICE Energy Recovery Linac @ Daresbury

Accelerators and Lasers In Combined Experiments

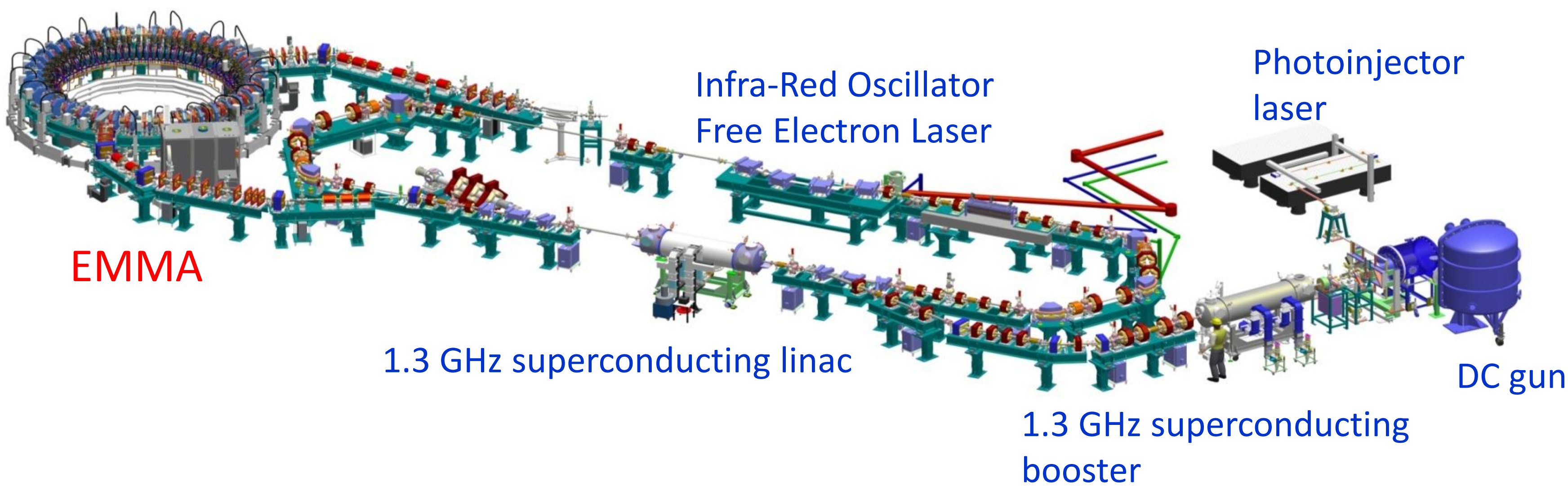
An accelerator R&D facility based on a superconducting energy recovery linac



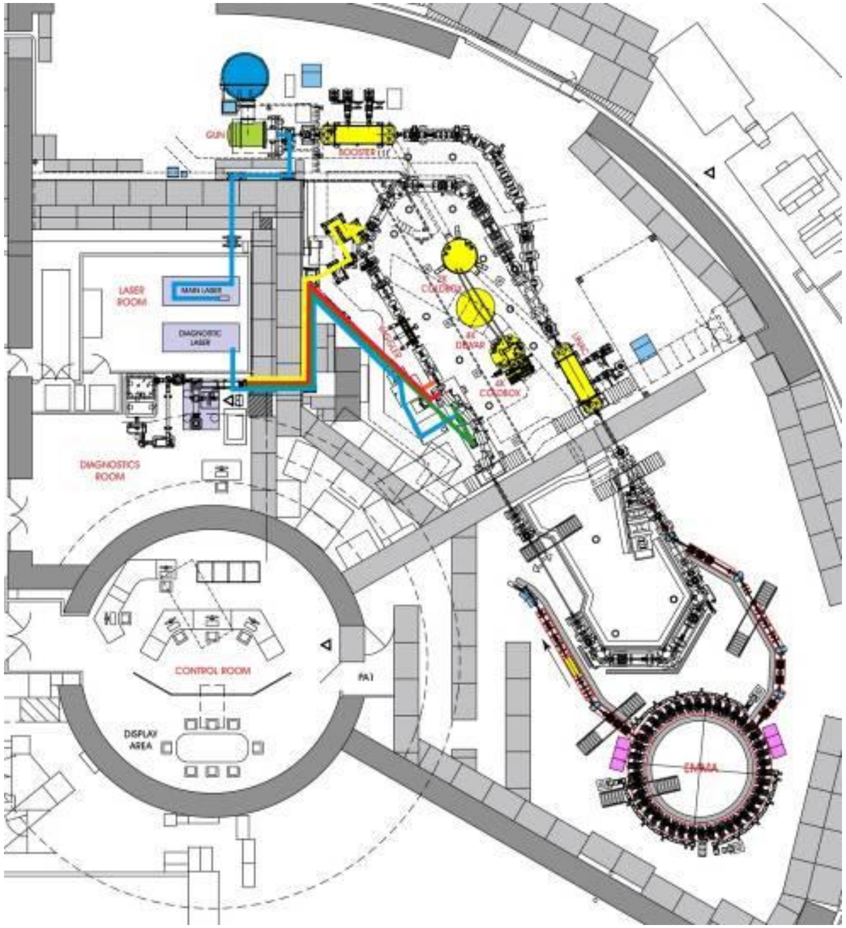
The ALICE Energy Recovery Linac @ Daresbury

Accelerators and Lasers In Combined Experiments

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



The ALICE Energy Recovery Linac @ Daresbury

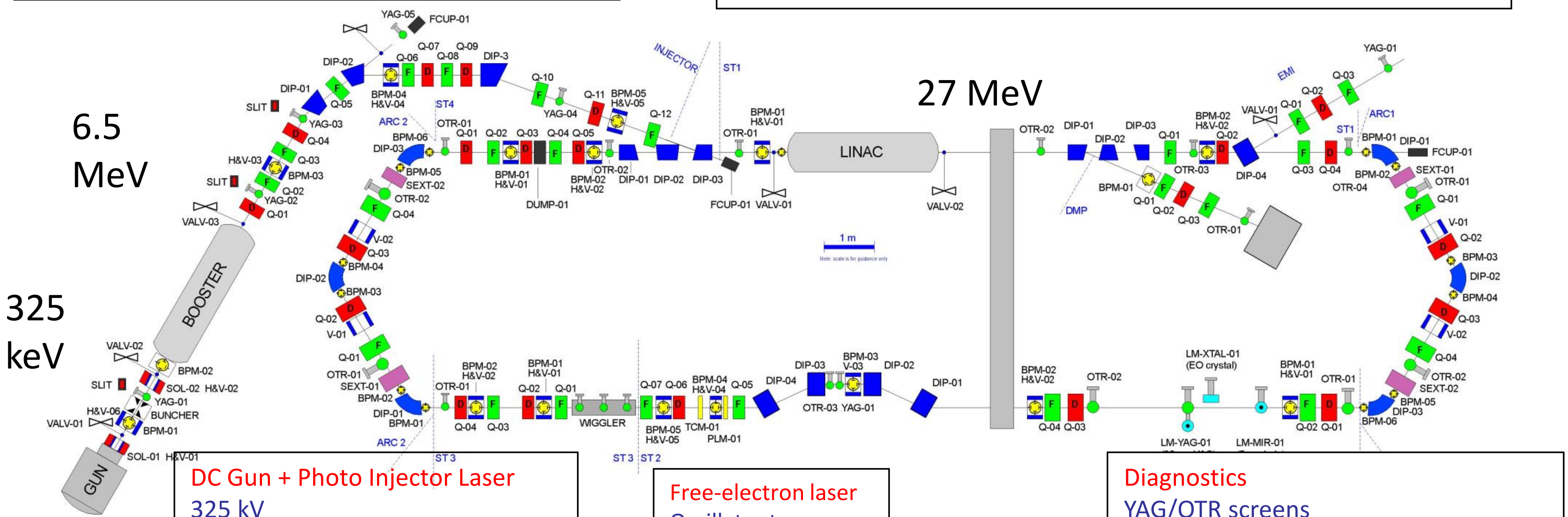


RF System
Superconducting booster + linac
9-cell cavities. 1.3 GHz, ~10 MV/m.
Pulsed up to 10 Hz, 100 μS bunch trains
Cryo capacity 180W @ 2K

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 Energy Recovery Linac: Timeline

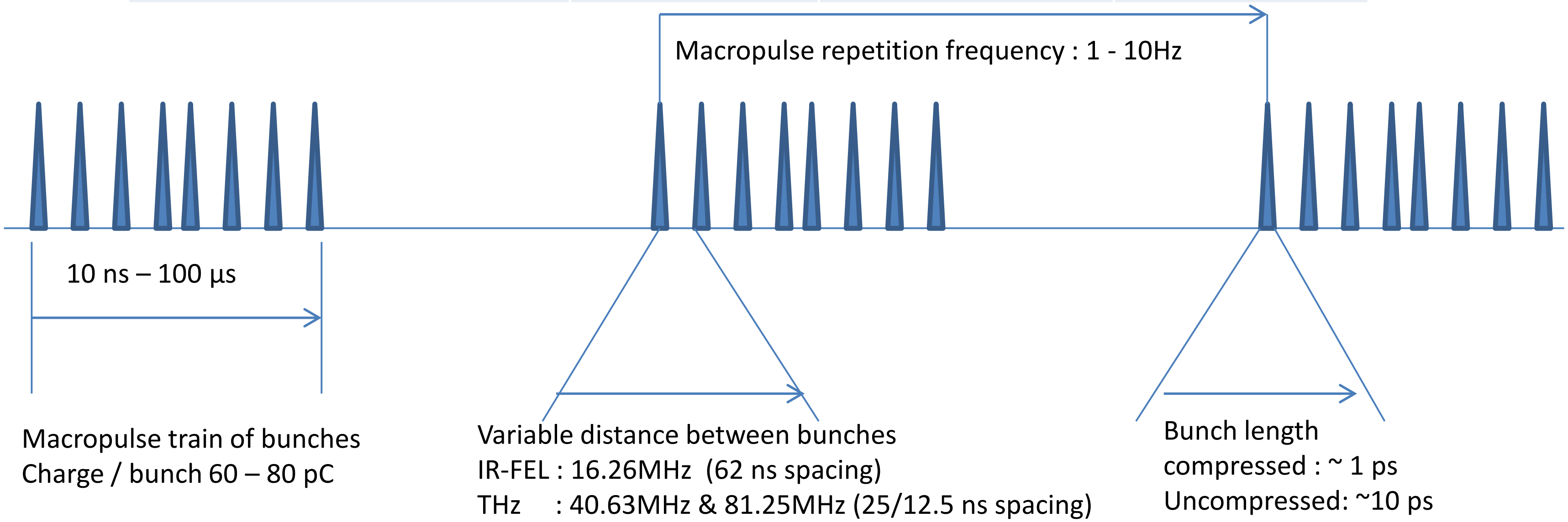
- **2000**: Proposed **4GLS** CW ERL driven VUV FEL as user facility (100mA, 600 MeV)
- **2003**: **E**nergy **R**ecovery **L**inac **P**rototype **funded** (pulsed 10 mA in 100us macropulse @ 10 Hz, 35 MeV)
- **2005/6**: Installation & commissioning of 350 keV DC photocathode **gun**, 120W **cryosystem**, 2 SC **Linacs**, recirculation **transport** & oscillator **IR-FEL**. **First beam August 2006**
- **2007**: Problems with gun, RF, cryo, see Wednesday's talk by Lee Jones *"Daresbury DC gun commissioning results"*
- **2008**: Fixing problems, then **full energy recovery** (initially at reduced gun voltage, linac gradient)
- **2009**: Gun Kr plasma cleaning & leak chasing, RF conditioning & LLRF optimisation
- **2010**: He processing of linac to mitigate FE, then **first lasing of IR-FEL** with full ER at 27 MeV
- **2011**: Diagnosing FEL radiation, Electro-optic bunch length measurements,
- **2012**: **Gun upgrade** -> 325 kV design voltage achieved -> **beam quality** much improved
- **2013**: Installation of DICC 7-cell cryomodule, module & cryo faults -> revert to original linac
- **2012 – 2015**: **Understanding** of machine through transverse & longitudinal beam dynamics studies, **stability of operation** through active feedback, DLLRF, high-level software
- **2016**: **Completion** of funded user runs – see Tuesday's talk by Mark Surman *"Photon Science Exploitation of ALICE in Biomedical Science"*
- **Currently: De-commissioning**

- *Further details: see my ERL'15 talk "10 years of ALICE: From Concept to Operational User Facility"*

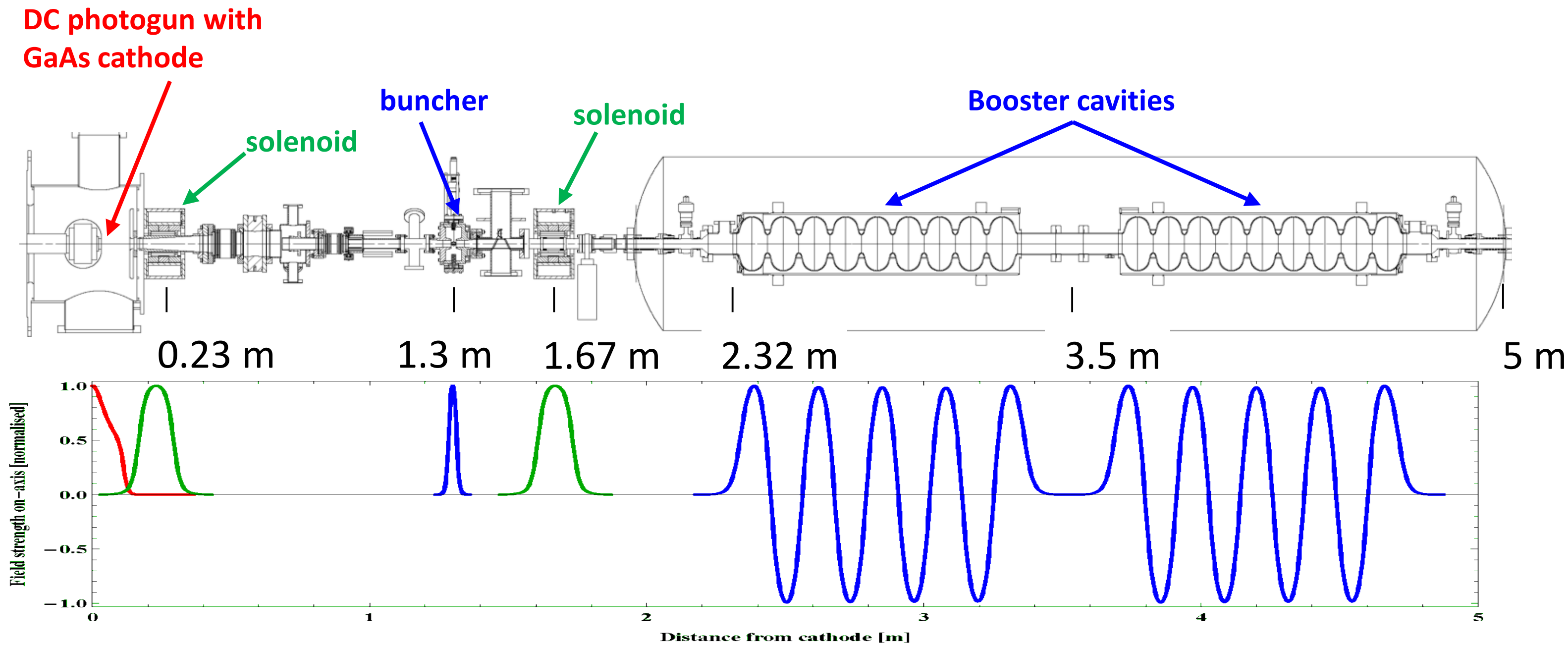
ALICE Parameters & Timing Structure

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

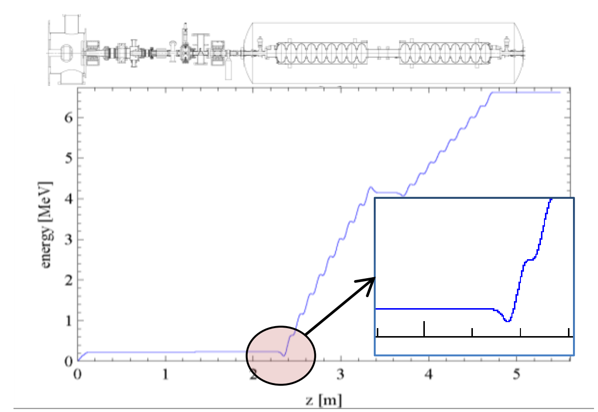


ALICE Injector Layout



- To achieve desired emittance requires careful careful compensation scheme in injector, with additional constraints of short bunch and minimal energy chirp = solenoid – buncher – solenoid sequence with correct 6-d "phase advance"

- Then capture this at booster entrance and freeze in – bearing in mind phase slippage of ~30° in first cell actually **decreases** the energy from gun voltage before acceleration in subsequent cells



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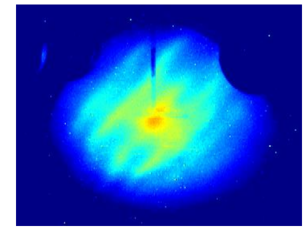
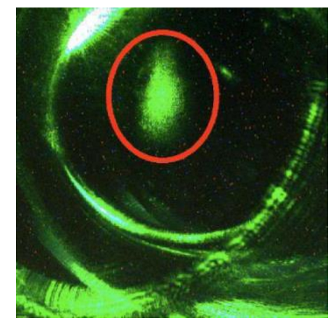
Achieving a low emittance: Ingredient 1- The Photoinjector Laser

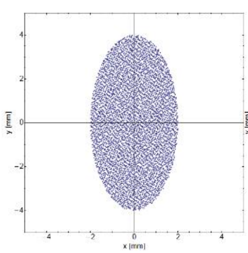
- Careful design and maintenance of laser and transport is essential



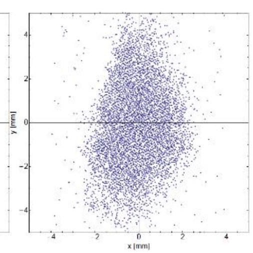
- **Example 1**: Contaminated laser transport led to **striations**, seen here on virtual cathode - you cannot make a beam from this! Fastidious cleaning of laser transport resolved this



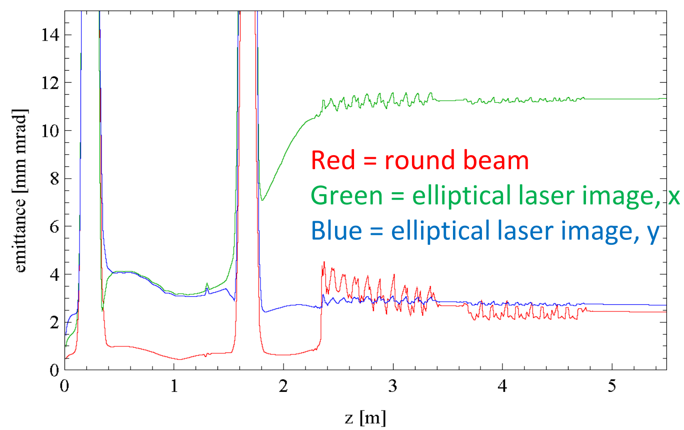
- **Example 2**: Poorly optimised laser transport led to **elliptical spot** (imaged here on real cathode), we needed to live with this for some years. Assessed the impact of this in GPT simulations

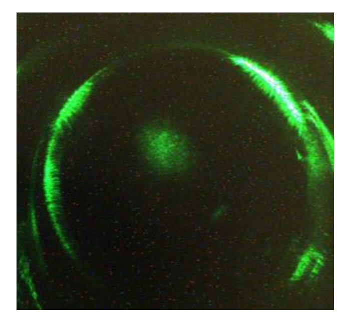


Ideal elliptical



"real spot" generated from image





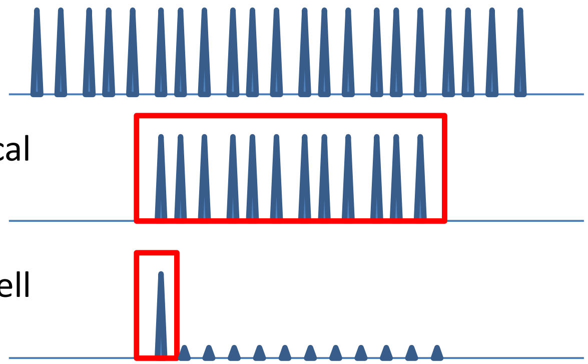
2014 realignment in laser transport led to round spot and subsequent emittance improvement

Achieving a low emittance: Ingredient 1- The Photoinjector Laser

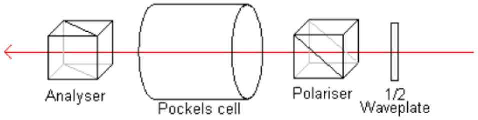
- **Example 3: Ghost pulses**

"Ghost" laser pulses are not visible on laser photodiode signal unless you specifically look for them

1. Laser pulses : CW @ 81.25MHz
2. Laser pulse train after mechanical choppers
3. Laser pulse train after Pockels cell (electro-optic shutter)

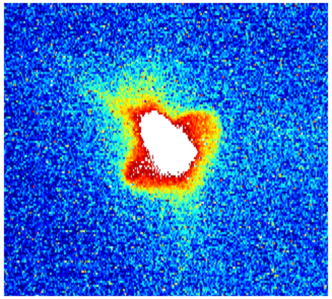


- Ghost laser pulses still generate electron bunches albeit with much lower bunch charge (< 1 pC compared to 60 pC) but there could be plenty of them (up to 8000)

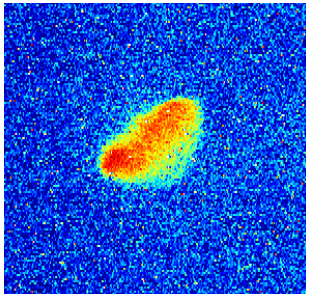


- Much lower bunch charge → completely different beam parameters at the exit from the gun → behave differently wrt the main bunches and ruins any measurements

With ghosts



No ghosts



- YAG screens are used in ALICE injector hence need a few or just one single bunch to see the beam) but ~8000 ghosts accompany the main bunch

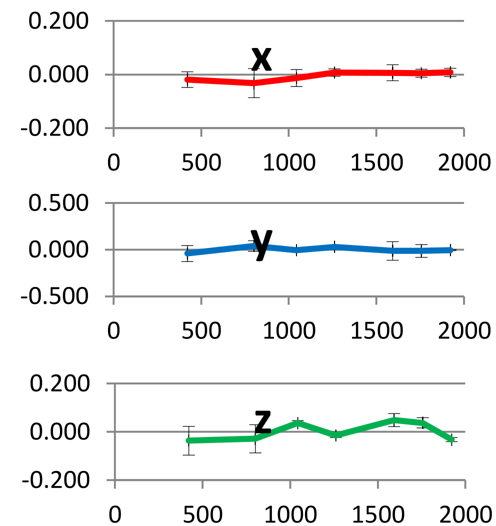
- Careful optimisation to properly extinguish ghosts necessary

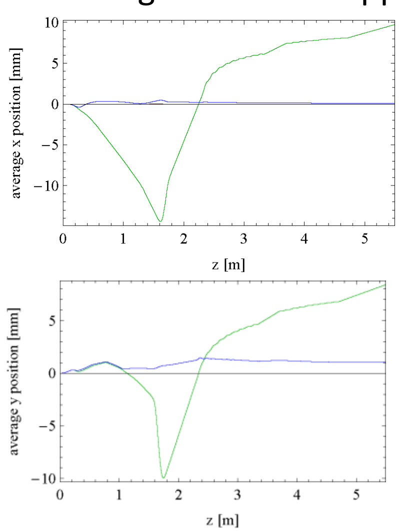
Achieving a low emittance: Ingredient 2 - For a DC Photogun, Stray Fields are Important

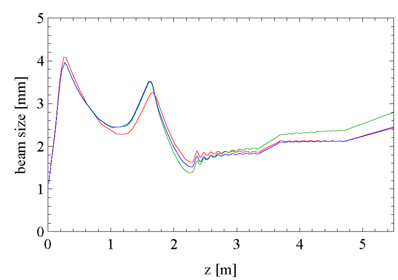
- Background fields measured at every accessible location pre-booster: above, below, and on either side of the vacuum vessel, ambient level also taken in the injector area. Shielding / relocation of equipment as necessary. Re-measure.

- Interpolation from these measurements to create a 3D fieldmap for input into GPT.

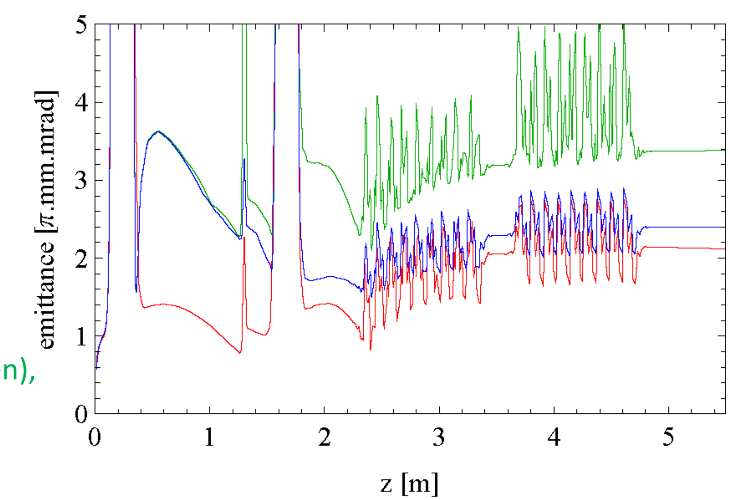
- Emittance increase assessed for raw application of stray field, then steering corrections applied – responsible for ~10% emittance increase





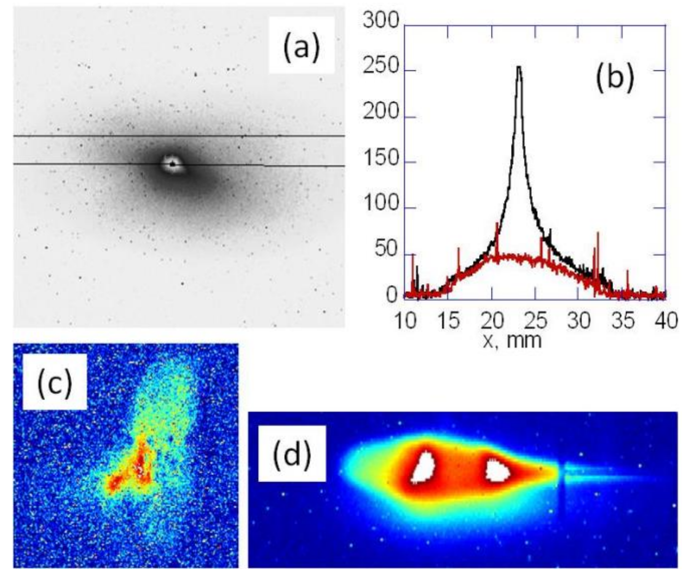


No stray fields (red), stray fields (green), stray fields with corrections (blue)

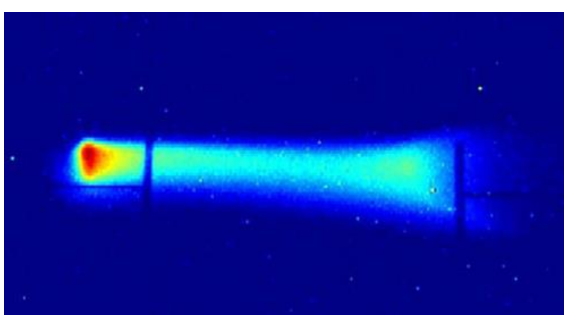


Achieving a low emittance: Ingredient 3 - What do you mean "emittance"? The Beam is NEVER Gaussian!

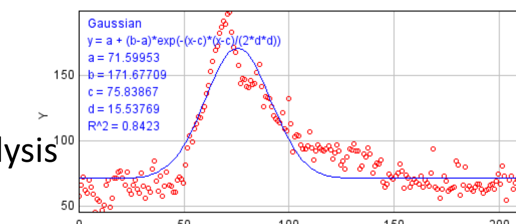
- (a) Image at exit of booster on YAG screen @ 6.5 MeV/c
- (b) Single-pixel horizontal profiles acquired along two horizontal lines shown in (a) with black through the centre and red offset vertically
- (c) Image at exit of linac on OTR screen @ 27 MeV/c
- (d) Image in injector spectrometer @ 6.5 MeV/c, during the period where the **gun voltage was limited to 230 kV**, we see a clear "two-beam" structure, separated in energy



- Below: Image in injector spectrometer @ 6.5 MeV/c **after we were able to raise gun voltage to 325 kV**, we see the longitudinal features are mitigated



Need to be flexible and imaginative in analysis



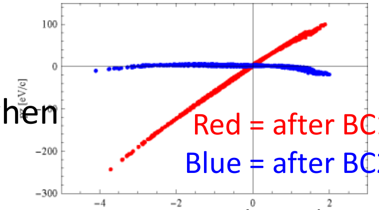
- Fit Gaussian even to clearly non-Gaussian beams and determine σ_x
- Work in terms of FWHM values rather than RMS
- Calculate beam widths @ 10% from peak value

Example Emittances Achieved in ALICE Injector @ 6.5 MeV

- Compensation scheme as designed was robust enough to withstand years of operation with FEL lasing at reduced gun voltage of 230 kV, however performance and stability much improved when we were able to reach nominal voltage of 325 kV

- Values below all at 60 pC with typical longitudinal parameters: **bunch length 2.5 mm (8 ps) FWHM** (measured using zero-crossing method in booster cavity 2), **uncorrelated energy spread = 5 keV (FWHM)** (measured by tipping the bunch)

- The required emittance for FEL lasing was ~12 µm, so no pressure to reduce, however when we were able to achieve 6 µm regularly, improvement was seen in stability

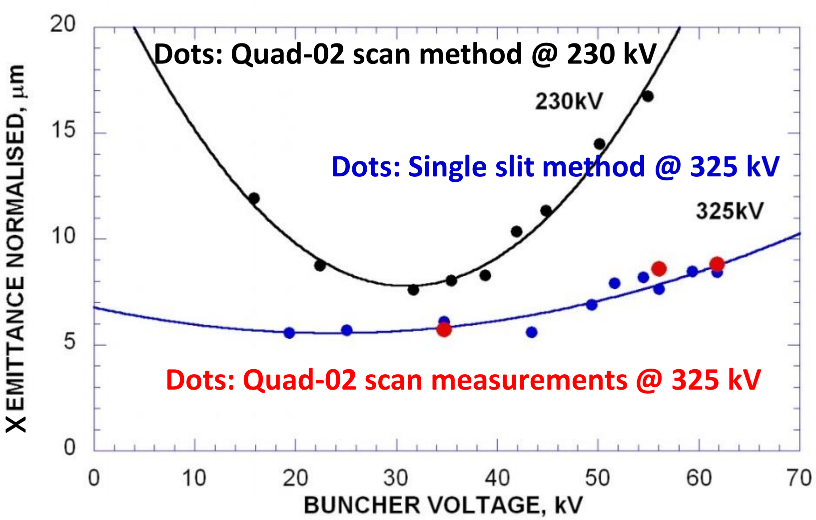


Y. Saveliev et. al. PR-AB ***19****, 094002 (2016)*

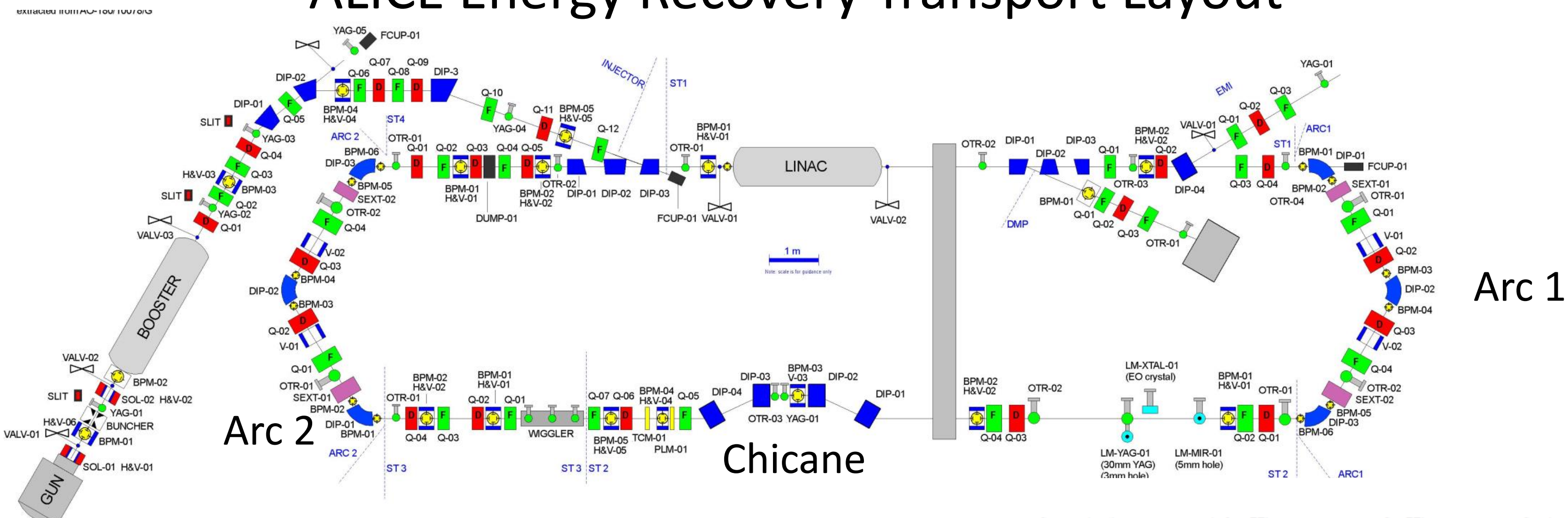
Comparison of various emittance measurement methods and GPT simulations at **reduced gun voltage of 230 kV**

Result	ϵ_x	ϵ_y
Single Slit	11.0	N/A
Slit Scan	9.1	N/A
Quad Scan	15.1	4.0
Measurement Average	11.7	4.0
GPT (Elliptical)	9.5	1.9
GPT (Real Spot)	17.7	3.8

"Characterisation of the ALICE accelerator as an injector for the EMMA NS-FFAG", J.M. Garland et. al. Proc. IPAC 10



ALICE Energy Recovery Transport Layout



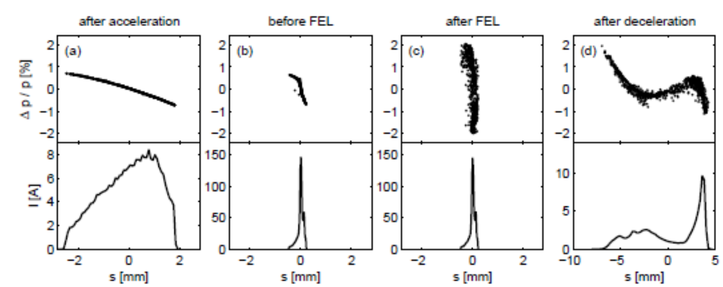
- Chicane R_{56} = 28 cm $\Rightarrow$ for a flat bunch on linac entrance at 6.5 MeV would need linac phase of +10°

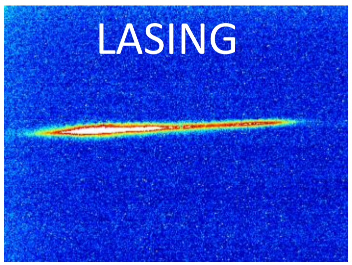
- But need to compensate energy chirp in the bunch coming from injector from 0 to +5 °; hence overall off-crest phase +15 / +16 °

- Arc 1 nominally achromatic & isochronous at first order

- Sextupoles in AR1 ensure linearization of curvature (T_{566})

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

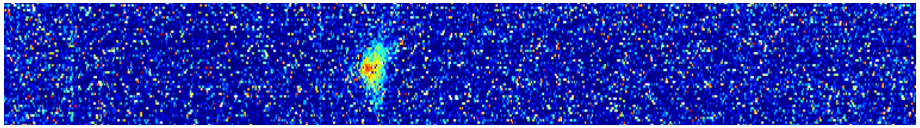




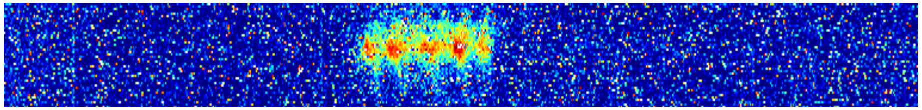
In the ER transport Beware of Destructive Measurements

- Always remember the **beam loading in RF cavities**
- When we are in energy recovery condition the LLRF easily controls the accelerating gradient and phase variation along the train
- When we do a destructive measurement e.g. insert an OTR screen, we lose the energy recovery condition and the LLRF cannot cope, leads to “phase pulling” (variation along the train)
- Cutting the train length doesn’t necessarily help, as the first few bunches of the train are not representative of the train

OTR in dispersive region
Beam energy increases to the left

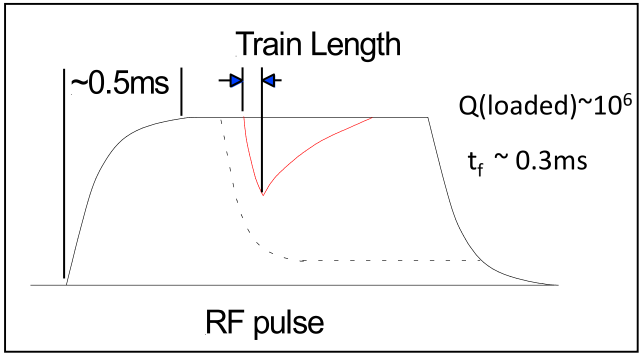


Train length = 10 μs



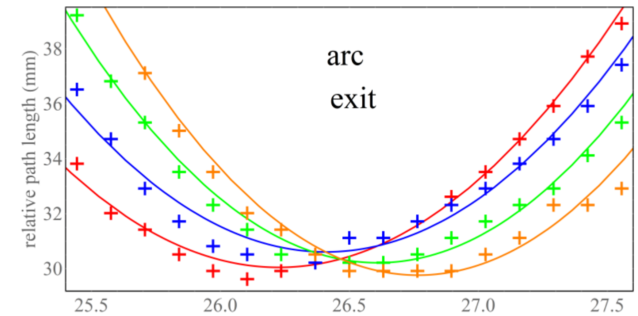
Train length = 50 μs

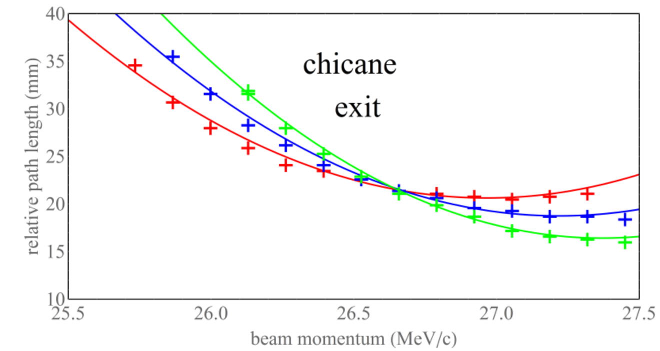
What happens if we spoil ER

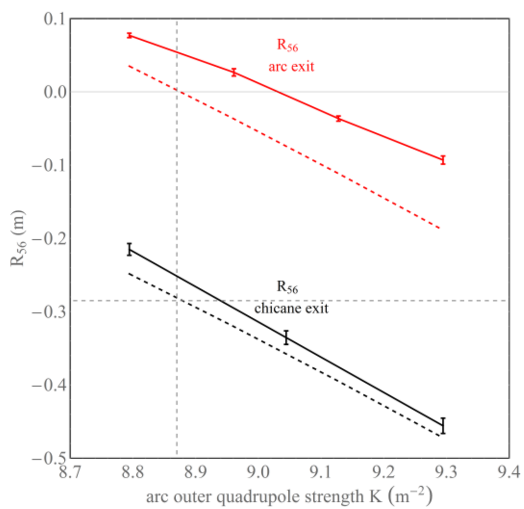


Energy “Difference Orbits” Should be Used to Set the Longitudinal Transport Properties of the Lattice

- Beam arrival monitors allow monitoring of **time-of-flight from point-to-point**
- Use to set isochronous condition of AR1 – outer quads iterated (red, blue, green orange) and beam energy scanned. Tangent should have zero gradient at nominal energy
- Then set R_{56} = 28 cm at chicane exit





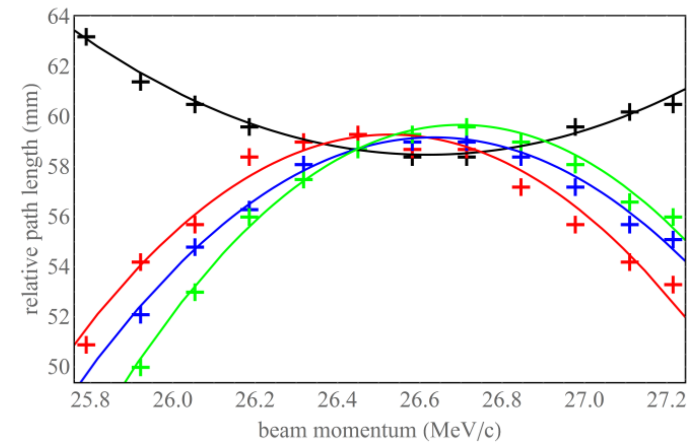


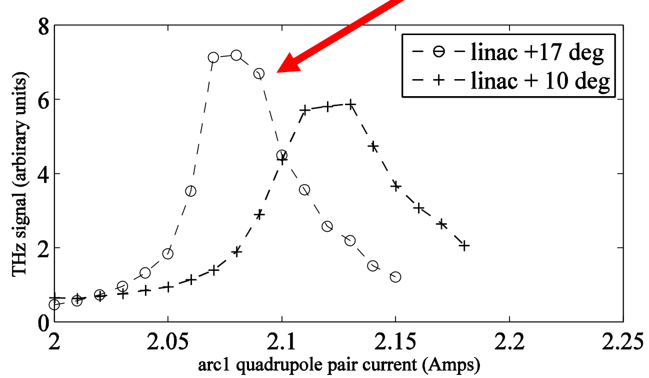
- Comparing with ELEGANT model shows reasonable agreement (remnant fields account for discrepancy

*F. Jackson et. al. PR-AB **19**, 120701 (2016)*

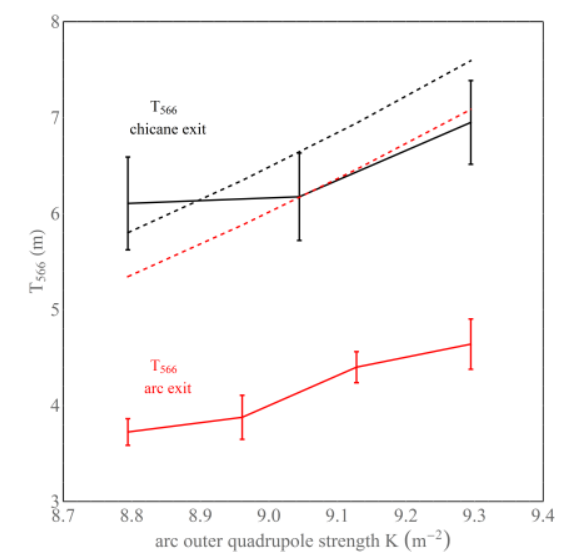
Energy "Difference Orbits" Should be Used to Set the Longitudinal Transport Properties of the Lattice

- Beam arrival monitors allow monitoring of **time-of-flight from point-to-point**
- Use to determine required T_{566} of AR1 – sextupole pair iterated (just blue, and black here) and beam energy scanned. Curvature changes sign
- Remembering the "the beam and the lattice are different" and correlating this against THz peak (maximum compression) lets us deduce the curvature of the bunch at linac entrance





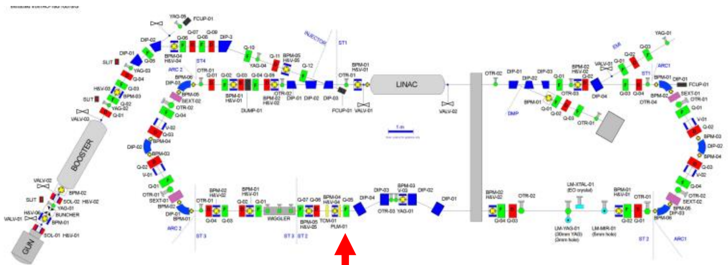
- Comparison with ELEGANT model for chicane is good, but large discrepancy seen for AR1 – it is thought this is due to a misaligned sextupole



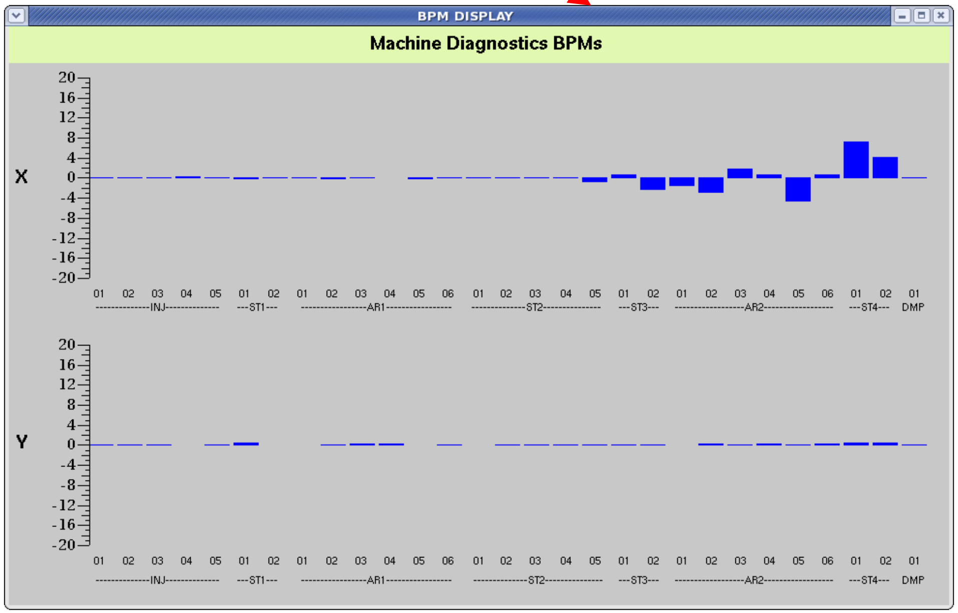
F. Jackson et. al. PR-AB ***19****, 120701 (2016)*

In the ER transport Ensure a Proper Transverse (and Longitudinal) Match of the Return Beam

- Raising current in ST2-Q05 (immediately post chicane) to 115% of nominal, we see that the beam is not centred in the quad and thus executes a **beta-wave**, although it still traverses the linac, decelerates and enters the dump line
 (beam seen on dump FCUP and linac DLLRF phase trace)

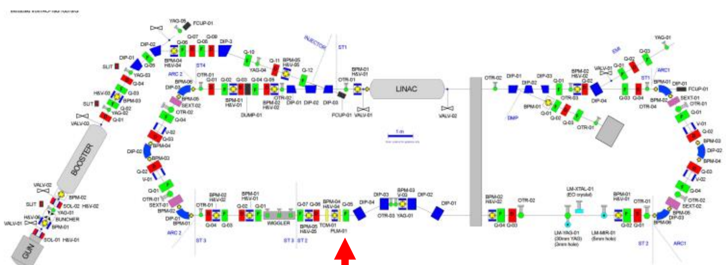


ST2-Q05

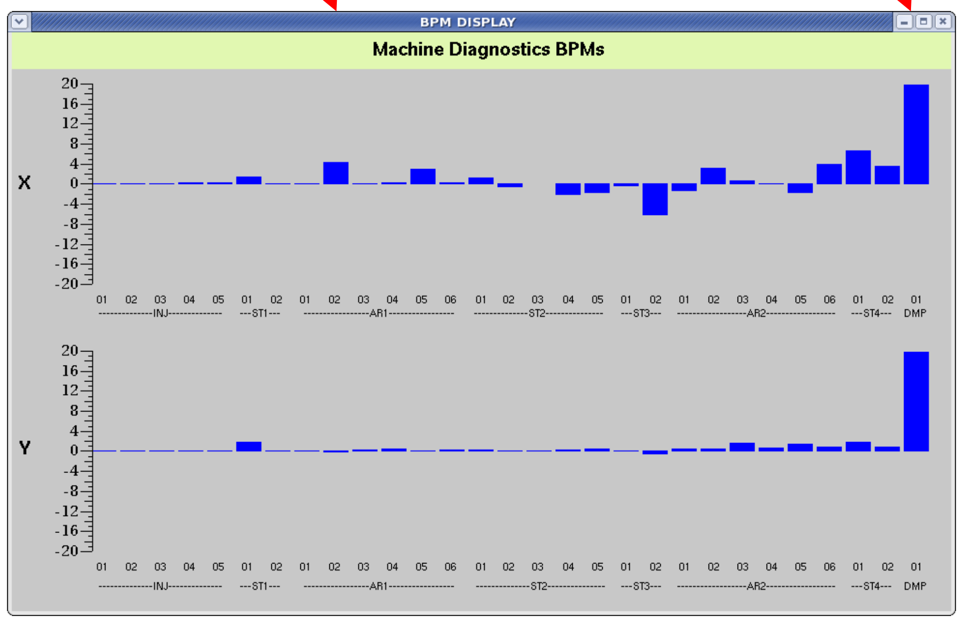


In the ER transport Ensure a Proper Transverse (and Longitudinal) Match of the Return Beam

- Continue raising current in ST2-Q05 (immediately post chicane) to 155% of nominal, the beam is now mis-steered by a large amount and although it still traverses the linac, it does so with a large horizontal offset. We see this **decelerating beam no longer sees the same field in the linac** and the ER condition is no longer perfect: result is accelerating beam loses energy (seen in AR-1) and decelerating beam gains energy (seen in ER dump



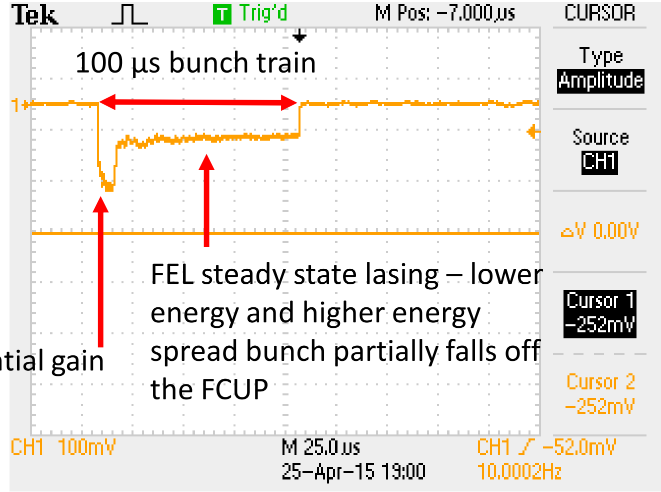
ST2-Q05



The ER condition can be used as a non-invasive diagnostic tool

- Using the energy recovery dump to diagnose the transport - here we see the FEL gain time through an energy drop on edge of ER dump FCUP (in a large dispersion position and change in BPM position as lasing initiates (point-to-parallel decompression in ARC-2 is detuned)

ER dump FCUP trace

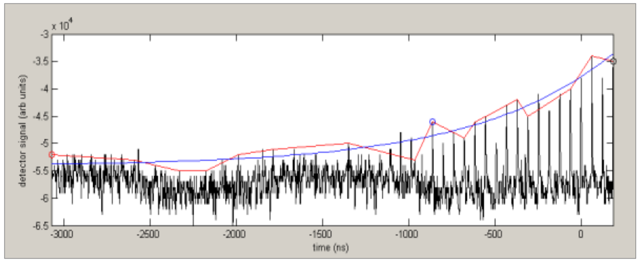


FEL exponential gain

ER dump BPM-x trace

FEL exponential gain

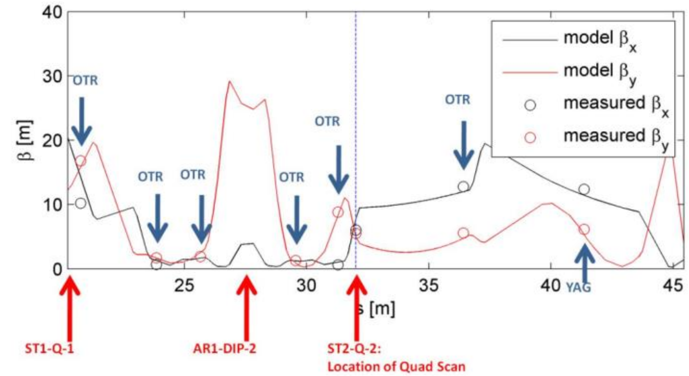
Confirmed with FEL photoelectromagnetic detector (Fast-response - can resolve individual FEL pulses within a train when lasing, image shows gain measurement by fitting to pulse intensities)



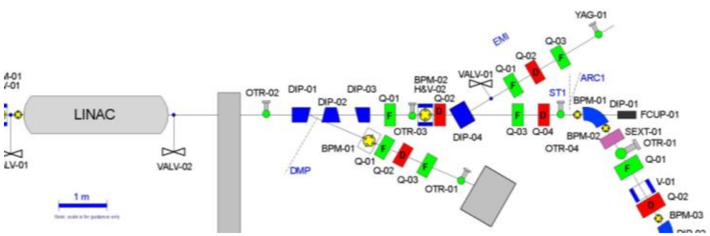
FEL steady state lasing – lower energy and higher energy spread bunch centroid shift

Example Emittance Measurements in the ER transport

- Best two examples at 20 pC and 60 pC
- **20 pC , E = 27 MeV** measurement (2011) made as part of optics retuning for laser-electron energy manipulation experiment
  - Combination of seven OTR screens used from linac exit to chicane, including around AR1
  1. Measure optics with quad scan in ST1 & ST2
  2. Propagate optics in model to chicane
  3. Fit emittance - goodness of fit determined from all intervening screens
  - **Result: ε_x = 3.7 μm , ε_y = 3.2 μm** (gun was still at 230 kV)



- **60 pC, E = 27 MeV** measurement (2014) measured in ST1 with using quads scans of Q-02/3/4 on OTR-04 and backtracking to Q-01

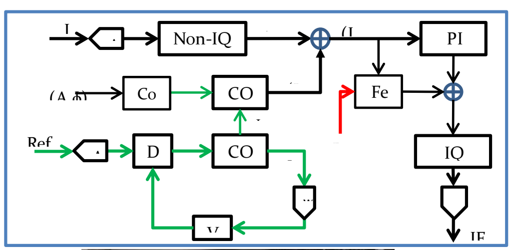


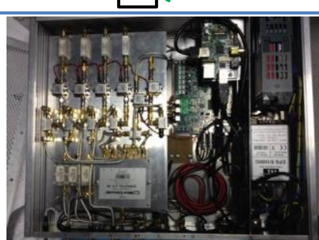
  - **Result: ε_x = 8.5 μm , ε_y =2.5 μm** (gun was at 325 kV)
  - Two suspected sources of growth in x
  1. horizontal mismatch on entrance to linac – very few diagnostics in final dogleg of long injection line, camera on screen on entrance to linac suffers from field emission and has a hole in it!
  2. Small residual dispersion from extraction chicane dipoles

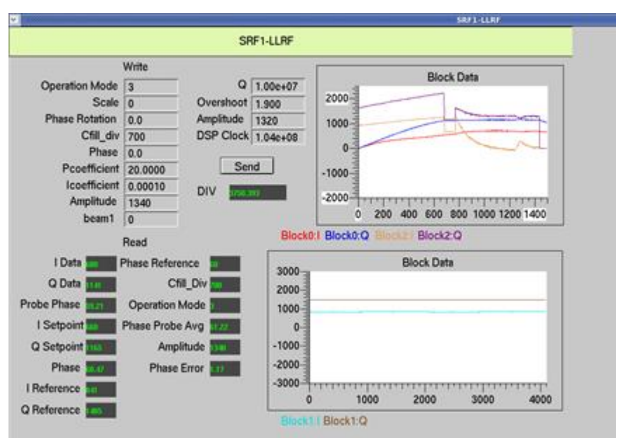
Remember these emittances were achieved with strongly chirped bunches: energy spread = 2% FW to enable compression to 1 ps ⇒ good control of chromatics and non-linear momentum compaction

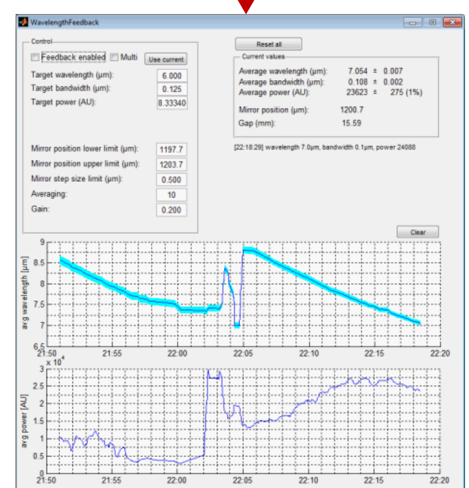
Implement Feedback Systems to Guarantee Long Term Stability

- Environmental control was absent in ALICE hall – very annoying operationally, could not perform consistent measurements, cryo-system stability was also a serious issue
- Stability over 2-3 hours is important for SNOM images -> DLLRF, other active feedback systems
- Master oscillator active phase correction system strongly suppresses jumps seen pre-2013 (e.g. during EMMA runs!)
- 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



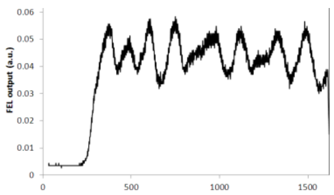


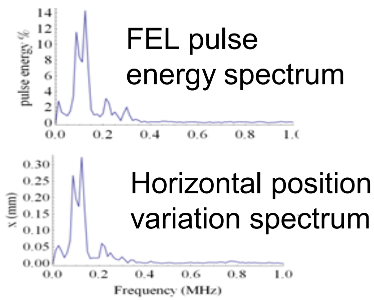




In an ERL, Damping Cannot Save You! : Fix Bunch-to-Bunch Instabilities at Source

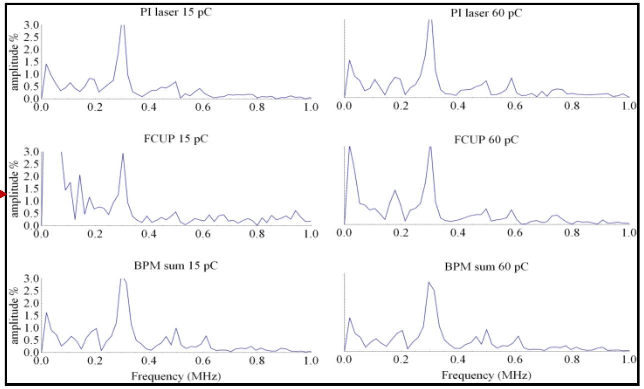
Example raw FEL Pulse Energy through train before correction



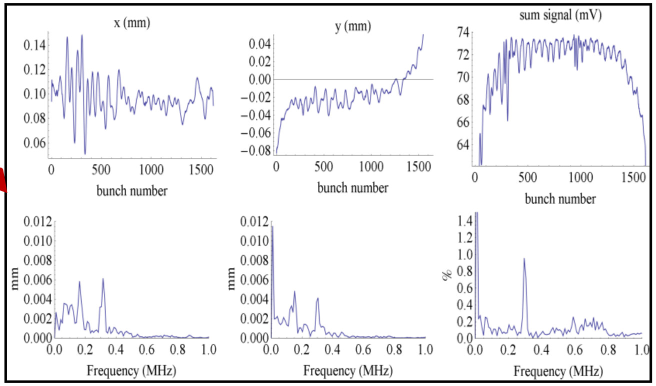


ALICE ERL Intra-train variation investigation using bunch-by-bunch BPMs, D. Angal-Kalinin et. al. Proc IPAC 13

"Application of EMMA BPMs to the ALICE Energy Recovery Linac", A. Kalinin et. al. Proc IBIC 12



- Implemented a bunch-by-bunch BPM system – here at 16.25 MHz, correlated this with FCUPs, laser photodiode and FEL PEM
- **Charge variation along 100 µs train** – DFFT of laser photodiode amplitude, injector Faraday cup, BPM intensity and FEL PEM all showed a **peak at 300 kHz** at the 2-3% level
- **Position variation along 100 µs train** – DFFT on quadrant position detector on PI virtual cathode, BPM x/y positions and FEL PEM. 300 kHz seen again and all **apart from PI laser also showed a peak at 100 kHz** at the 0.5% level
- **300 kHz jitter source identified** as photoinjector laser intensity and pointing stability using DFT of bunch-by-bunch BPM and correlation with laser photodiode and dump Faraday cup signal – **FIXED**
- **100 kHz jitter source not conclusively identified** – suggestion of DLLRF feedback as stability improved by tuning path length correction trombone such that some phase pull is seen



Summary: Operational Experience and Optimisation of ALICE Energy Recovery Linac

- ALICE: What we learned
  - Specific to emittance: FEL requirement ~12 μm, **met easily** at operational charge of 60 pC
  - Initially 10-15 μm. With experience / work achieved ~5 – injector first, then ER transport
  - Injector could have been better were it not for layout restrictions - e.g. buncher iris size, more careful stray field shielding. DID NOT CARE REALLY, because we'd met the spec
  - The ER transport with TBA arcs was robust and flexible
  - Operationally it was really the bunch-bunch and macropulse-macropulse stability that was trickiest: down to things like immature cryosystem, no environmental control in accelerator hall, PI laser pointing stability / charge stability

- By the final run (2016) we ran 24 hours 5 days/week for users with little interruption for 3 months

- ALICE was a success and ERLs are ready to go further as user facilities in both scientific and industrial contexts. It's up to us to make it happen: but please learn from the ALICE experience!

Summary: Operational Experience and Optimisation of ALICE Energy Recovery Linac

- Some advice for the developing ERL projects at this workshop
  - Do have 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 your diagnostics **work together** to give you the information you need
  - In your simulations, **model the step-by-step procedures** you will use to establish the beam conditions and prove you have achieved the goals of your project
  - Never try to save money on **feedback systems**! Stability is key

Science & Technology Facilities Council
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