CLIC-UK Programme Status

Philip Burrows

John Adams Institute

Oxford University

on behalf of CLIC-UK team

Thanks to: Graeme Burt, Stewart Boogert, Jim Clarke, Amos Dexter,

Allan Gillespie, Steve Jamison, Roger Jones, Pavel Karataev, Jack Roberts

+ CLIC colleagues

CLIC-UK2 programme

ASTeC:	**Permanent magnets +**
Dundee	**EO longitudinal profile monitor**
CI/Lancaster:	**crab cavities + RF efficiency**
JAI/Oxford:	**beam FB+FF, stripline BPMs**
JAI/RHUL:	**transverse beam size, cavity BPMs**
CI/Manchester:	**main beam RF**

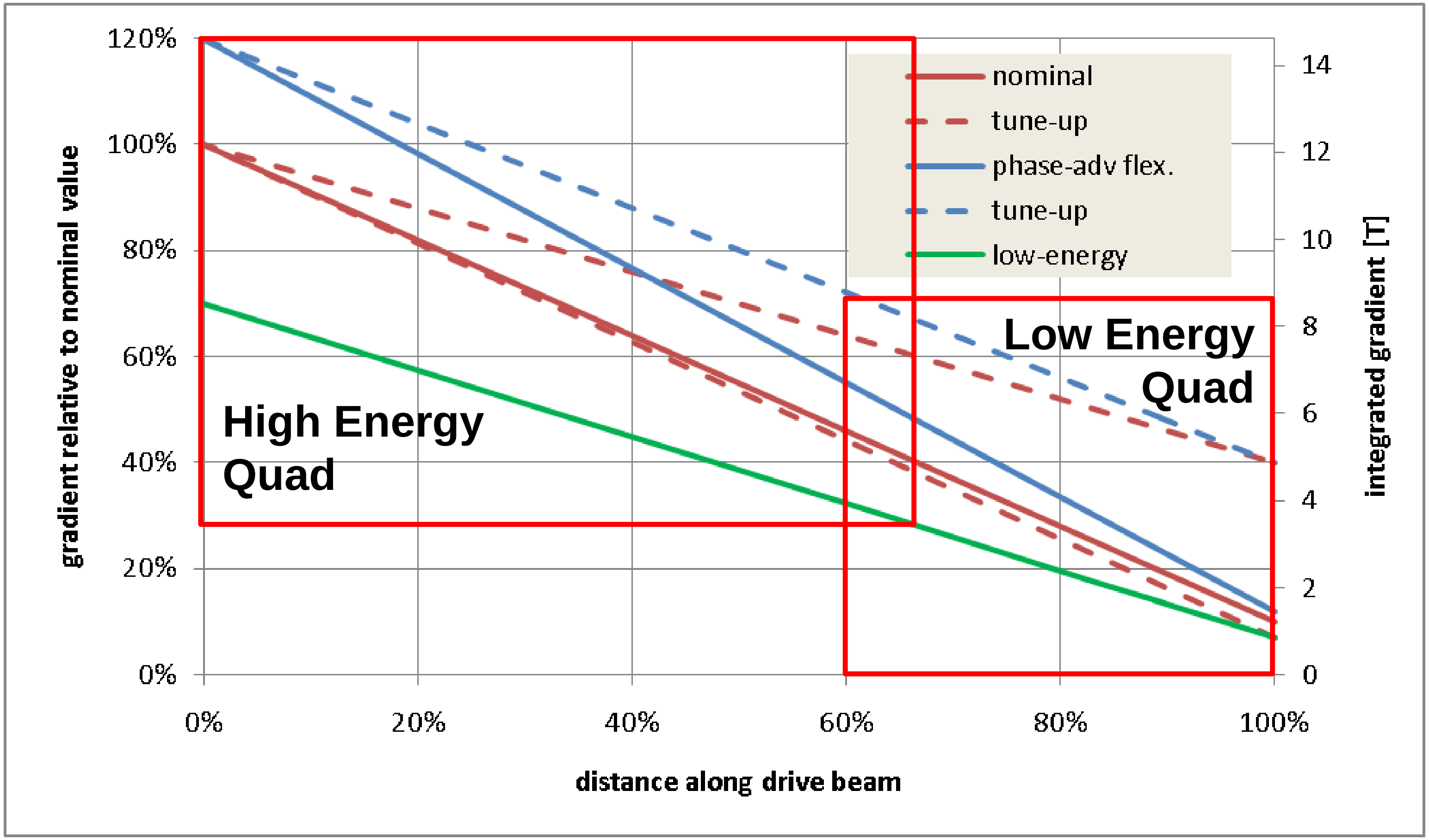
→ See also talks of Thibaut and Michele

Permanent Magnets (ASTeC)

STFC staff:

Jim Clarke
Ben Shepherd
Norbert Collomb
Graham Stokes

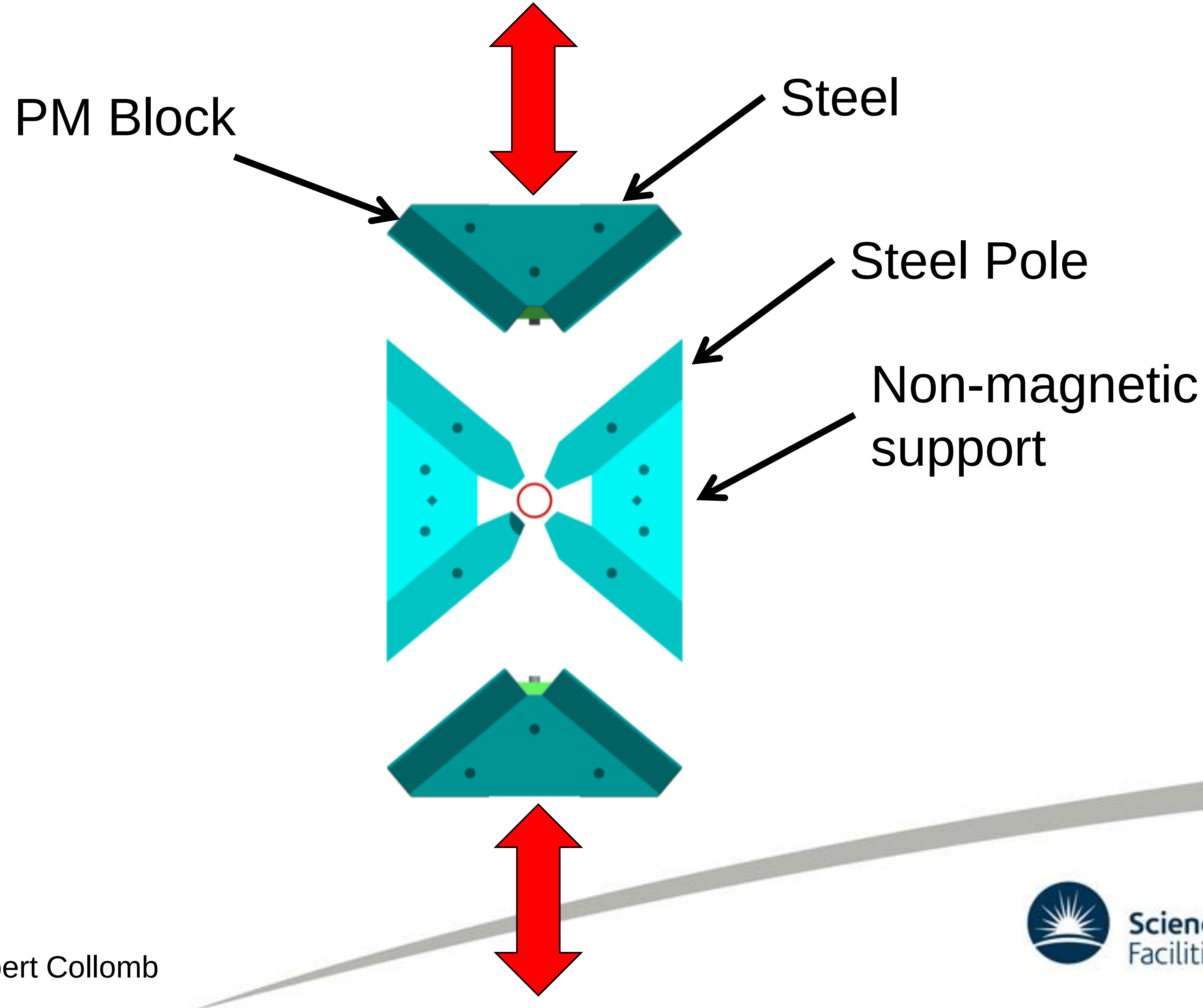
Drive Beam PM Quadrupoles



High energy quad – Gradient very high
Low energy quad – Very large dynamic range

Science & Technology Facilities Council

Basic Engineering Concept

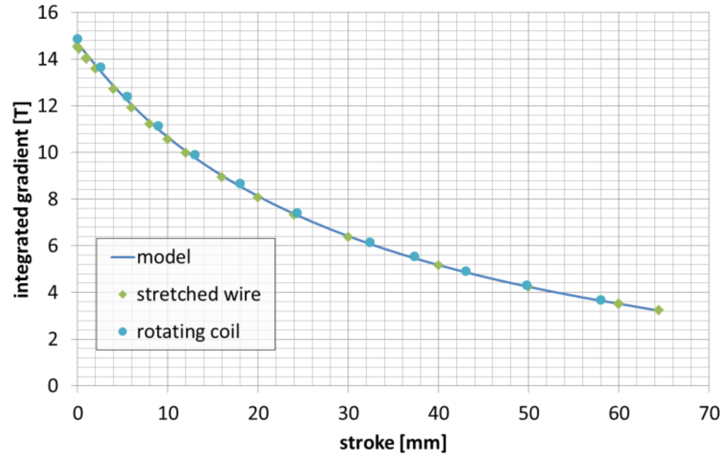


Norbert Collomb

Science & Technology
Facilities Council

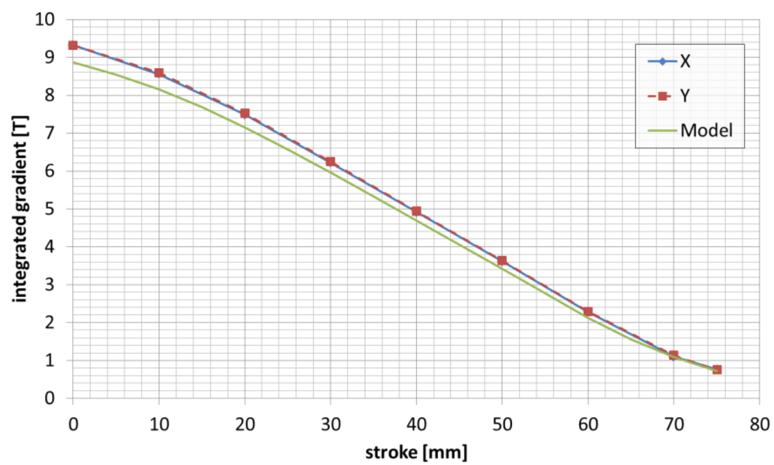
Drive Beam PM Quadrupoles

High Energy Quad



BJA Shepherd et al, Tunable high-gradient permanent magnet quadrupoles, 2014 JINST 9 T11006

Low Energy Quad



Patent granted to cover both designs

Team now focussed on PM Dipoles

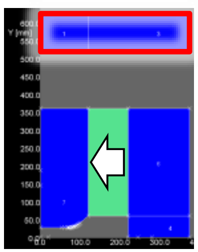
PM dipoles

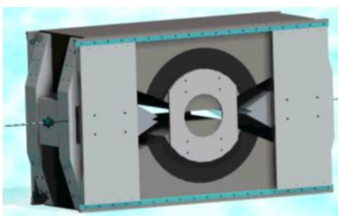
Investigate PM dipoles for:

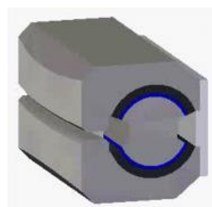
- **Drive Beam Turn Around Loop (DB TAL)**
- **Main Beam Ring to Main Linac (MB RTML)**

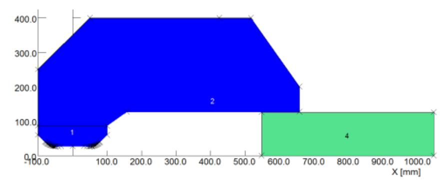
Total power consumed by both types: 15 MW

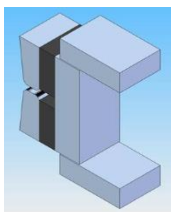
Several possible designs considered:

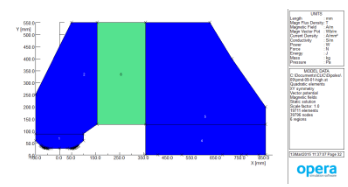










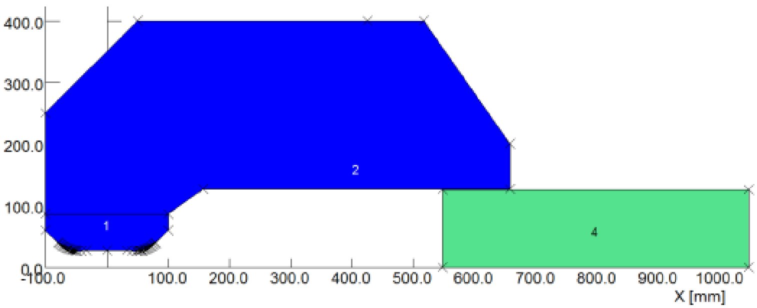


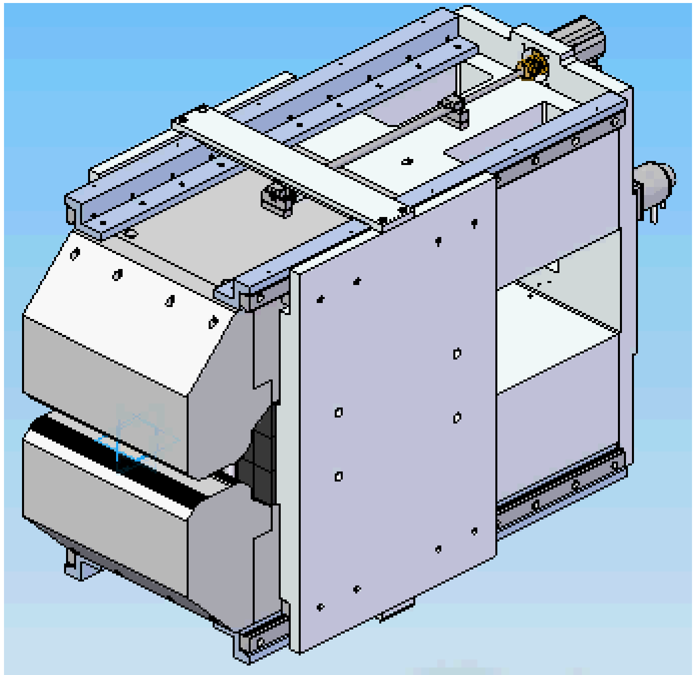
Type	Quantity	Length (m)	Strength (T)	Pole Gap (mm)	Good Field Region (mm)	Field Quality	Range (%)
MB RTML	666	2.0	0.5	30	20 x 20	1×10^{-4}	± 10
DB TAL	576	1.5	1.6	53	40 x 40	1×10^{-4}	50–100

Current Favourite: *“Python”*

Sliding PM in backleg

- Small forces
- Similar to low strength quad
- Rectangular PMs
- PM manufacturer on board
- C shaped (good for handling SR)
- Wide
- Large stroke





Field needs to be fine-tuned in 3D

Engineering to be detailed and cost estimate for prototype generated

Jim Clarke (STFC), Ben Shepherd (STFC), Norbert Collomb (STFC), Neil Marks (STFC), Michele Modena (CERN)

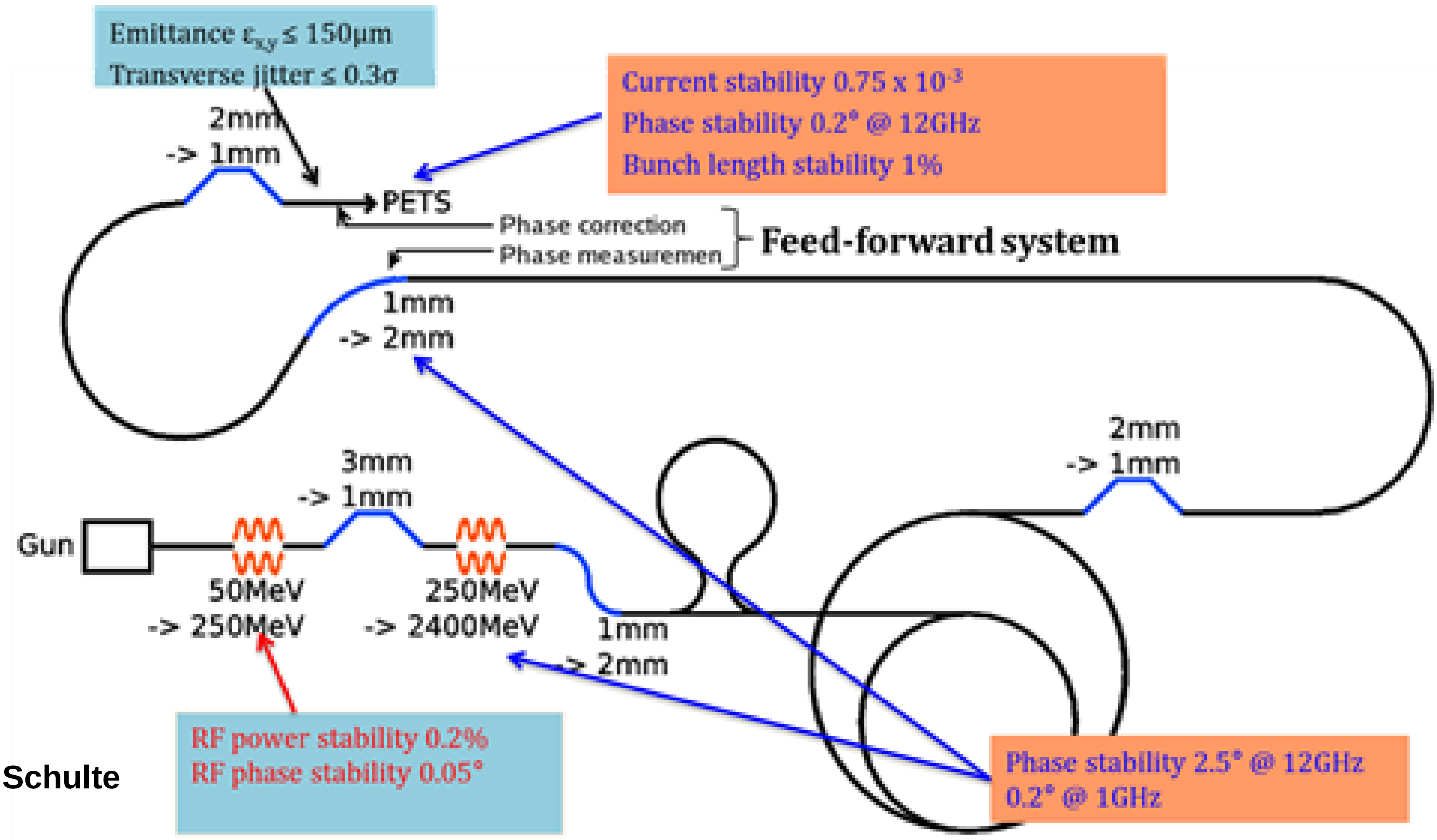
Phase feed-forward (Oxford)

Faculty: **Phil Burrows, Glenn Christian**

Staff: **Colin Perry**

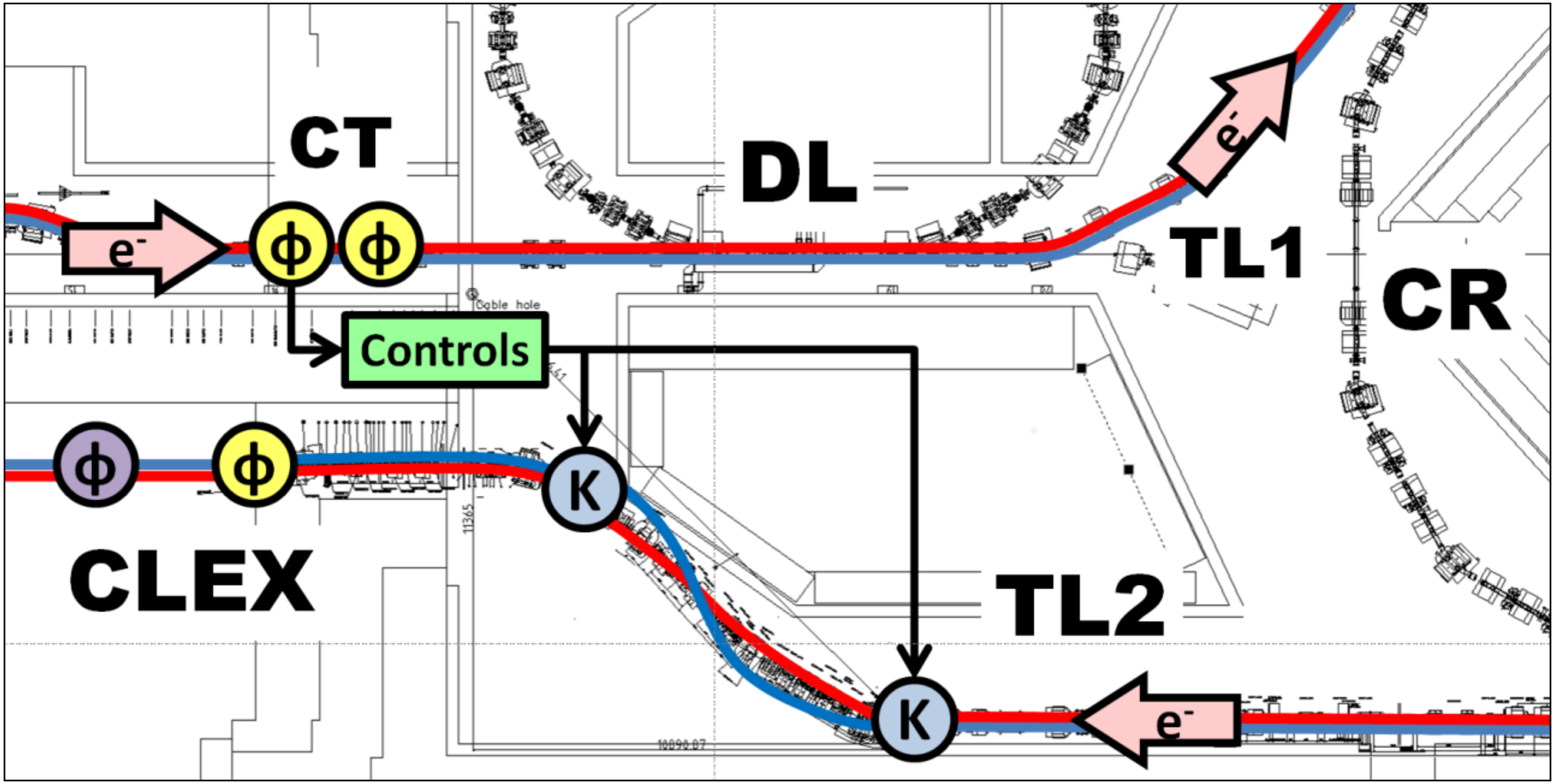
Students: **Jack Roberts, Davide Gamba**

Drive-beam phase feed-forward



Schulte

CTF3 phase FF prototype



CTF3 phase FF prototype

- Phase monitor (Frascati)
- Signal down-mixer (CERN)
- Feedback processor + firmware (JAI Oxford)
- Drive amplifier (JAI Oxford)
- Kickers (Frascati)

Piotr Skowroński, Stephane Rey, Alexandra Andersson (CERN)
Andrea Ghigo, Fabio Marcellini (INFN/LNF Frascati)
Philip Burrows, Glenn Christian, Colin Perry (JAI/Oxford U.)
Alexander Gerbershagen, Jack Roberts (JAI/Oxford U./CERN)
Emmanouil Ikarios (NTU Athens/CERN)

→ 1 mrad kick

→ 1.2 mm path length change

→ 17 degrees at 12 GHz

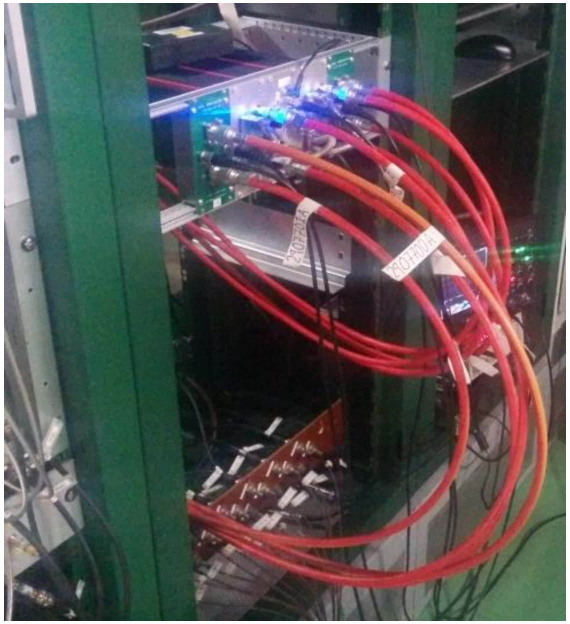
→ 0.2 degree resolution

Amplifier (JAI, Oxford)

Major challenge: >50 MHz bandwidth (slew rate limited) and 65kW peak power

Designed for operation over full 1.2 μs uncombined pulse, full performance over ~400 ns portion

First module available for feedforward tests 2014: 16kW, 345 V output.

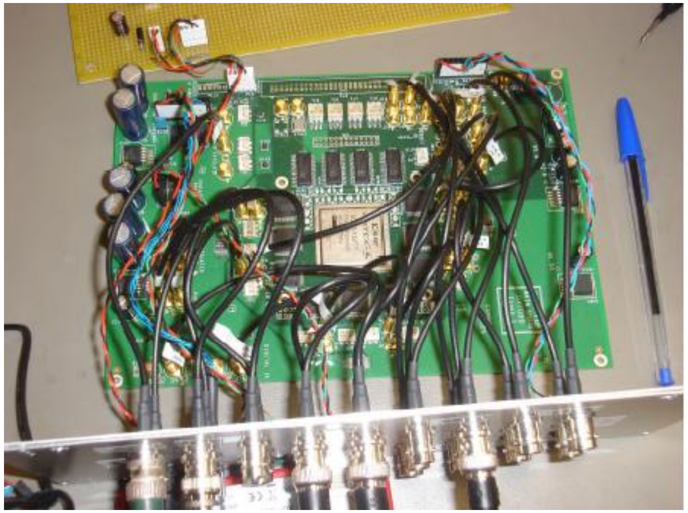


Double-up output FETs → 600 V: modules available for beam July 2015

Full 1.2 kV by combining modules: later 2015

FF controller (JAI Oxford)

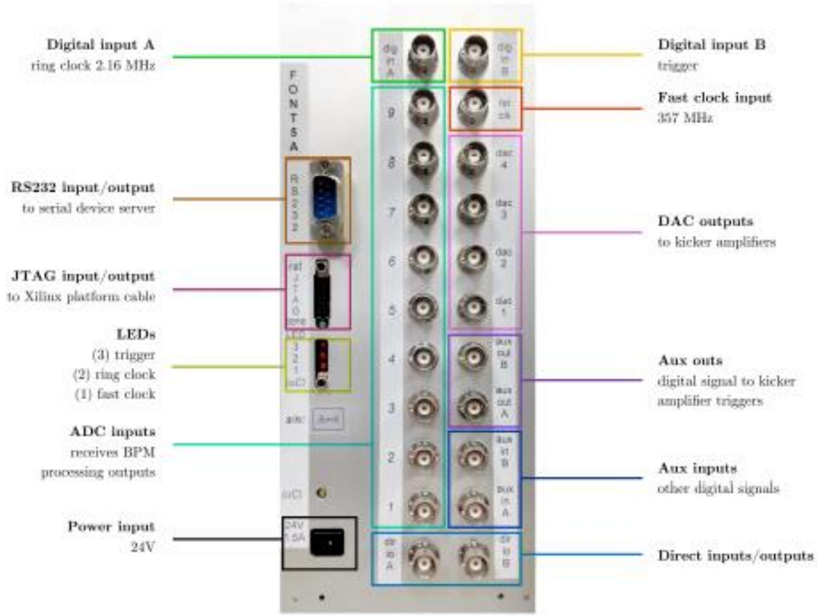
- Based around Xilinx Virtex-5 FPGA (XC5VLXT50)
  - Max speed 550 MHz
  - 2160 Kbit integrated block memory
- 9 ADC channels (3 groups of 3)
  - TI ADS5474
  - 14 bits (only upper 13 connected)
  - Max sampling speed 400 MHz
  - 3.5 clock cycles latency
  - One common clock per ADC group
- 4 DAC channels (2 brought out to front panel by default)
  - Analog Devices AD9744
  - 14 bit (upper 13 connected)
  - Max conversion speed: 210 MHz
  - ~0.5 cycle latency
- UART for serial data TX/RX over RS-232
  - Up to 460.8 kbps
- Fast comparator for external system clock and on-board 40 MHz oscillator fo[r] ancillary functions



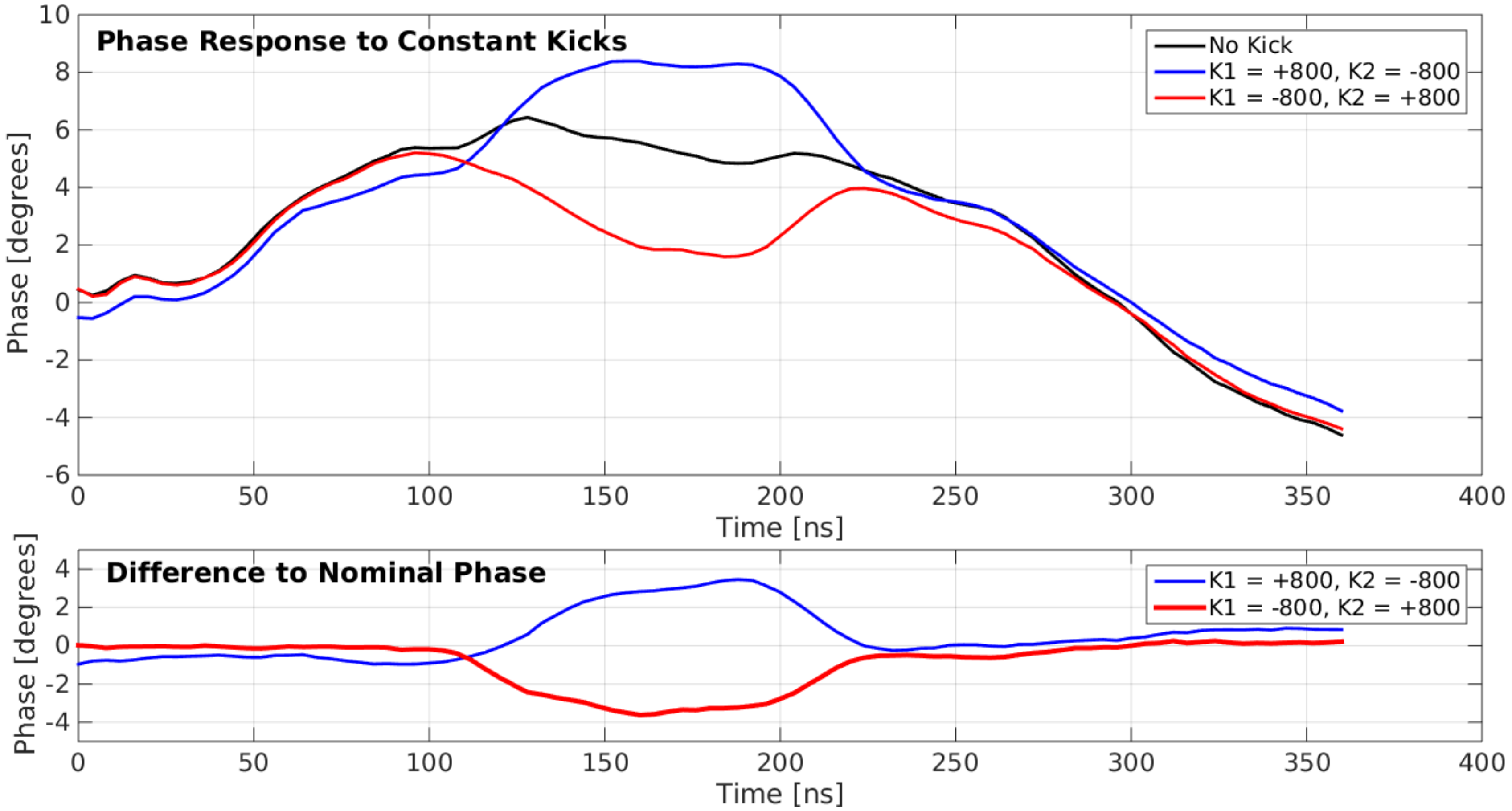
FONT5 board

5 new boards ('FONT5A')

→ 2 @ CTF3
→ 2 @ ATF2

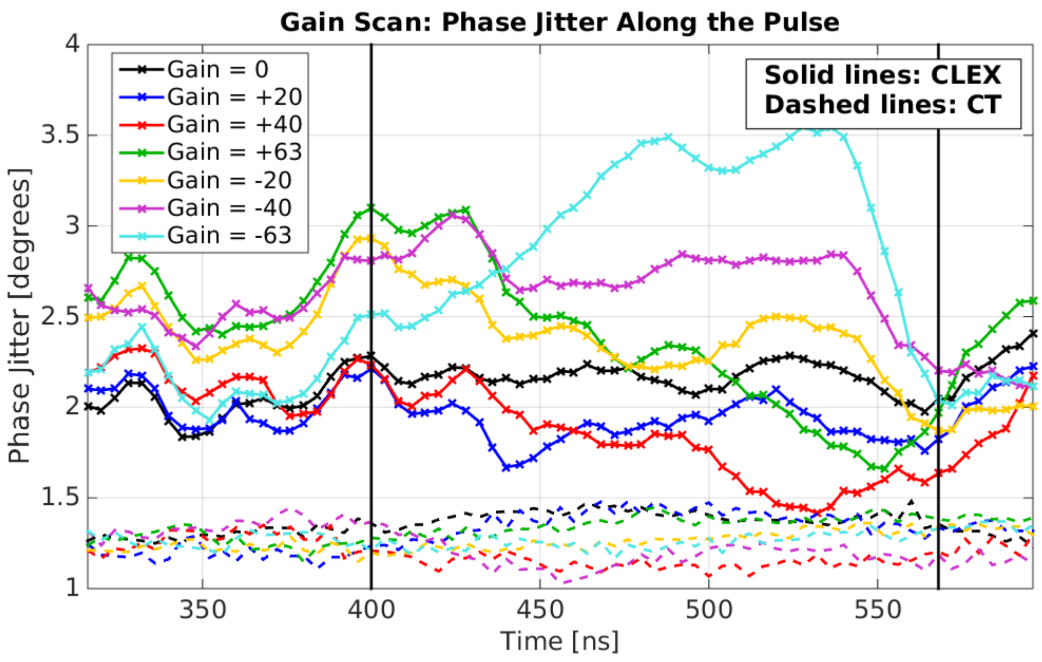


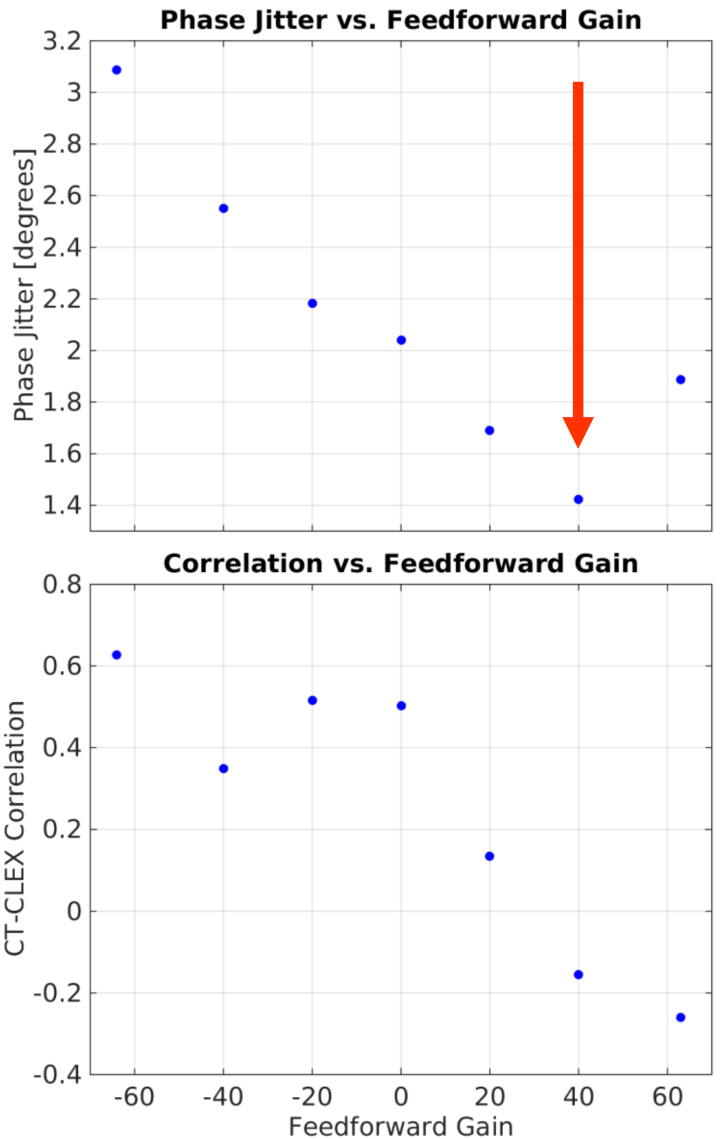
Initial tests: phase correction



Initial tests: close FF loop

Scan FF gain to minimise jitter





System works!

→ improve phase propagation

→ improve system performance

ATF2 / Feedback (Oxford)

Faculty: Phil Burrows, Glenn Christian

Staff: Colin Perry

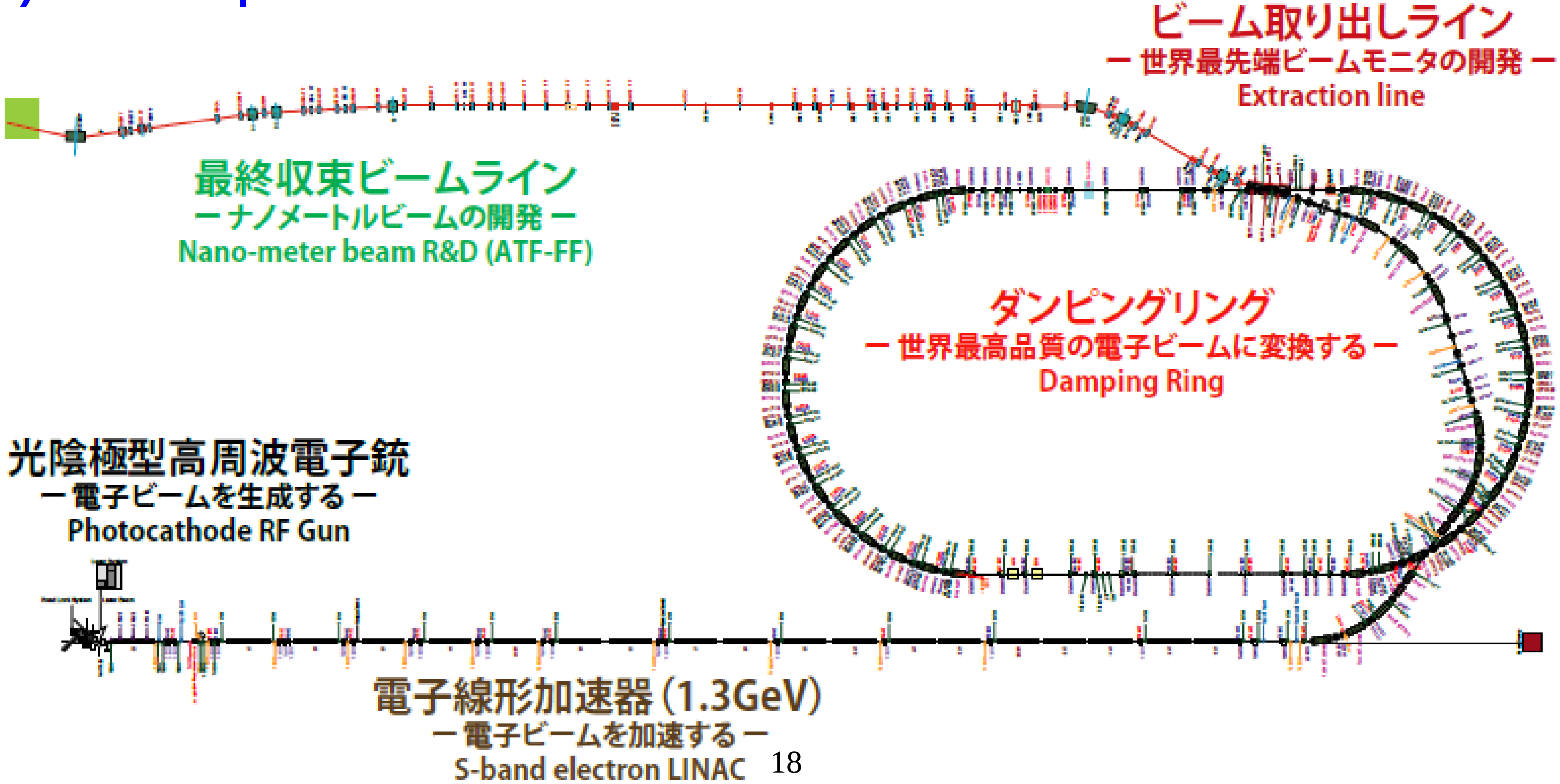
Postdoc: Ryan Bodenstein

Students: Neven Blaskovic Kraljevic,
Talitha Bromwich

ATF2/KEK: prototype final focus

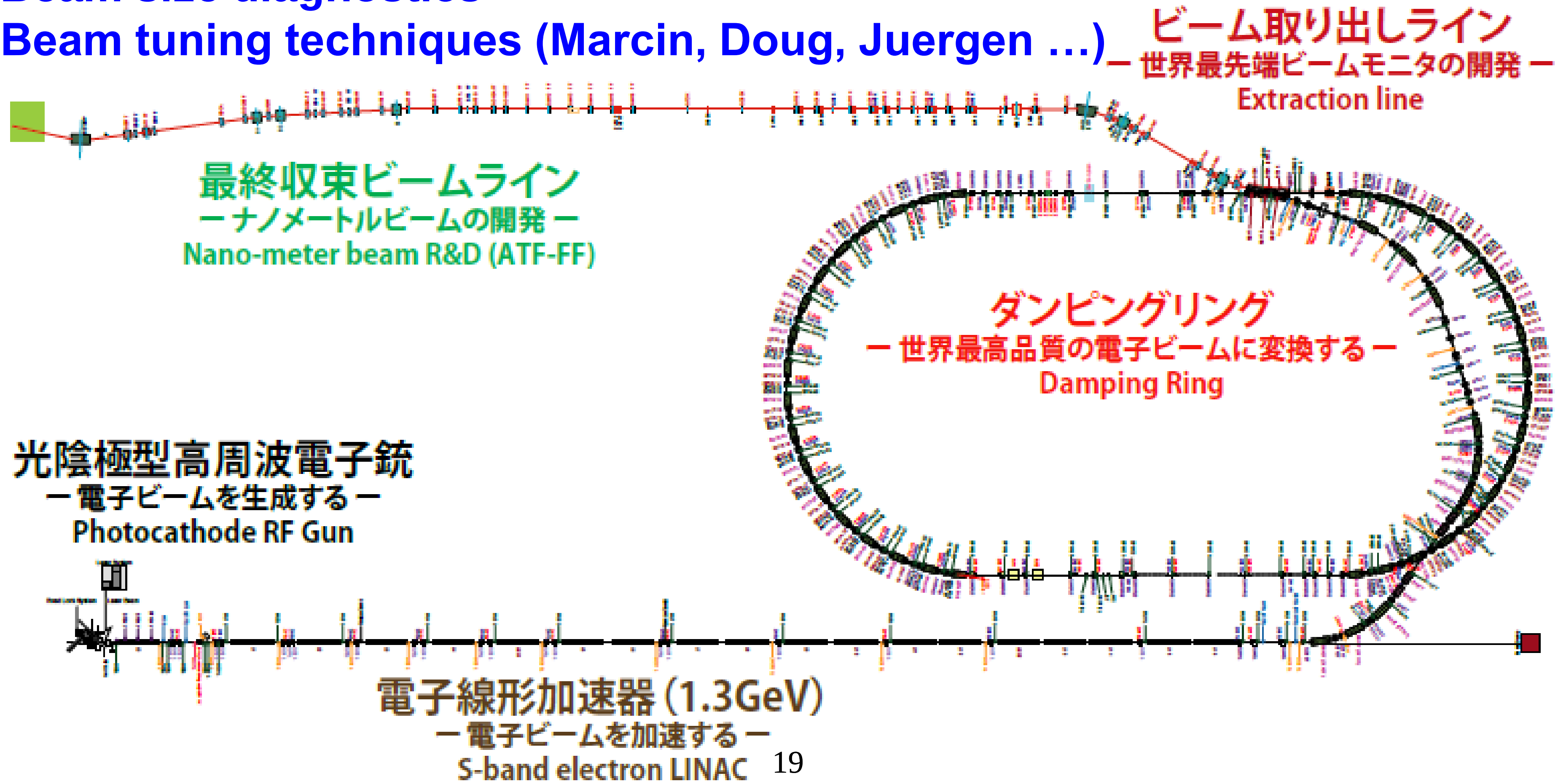
Goals:

1) 37 nm beam spot (44 nm achieved 2014 – reproducible!)
2) Beam spot stabilisation at few nm level

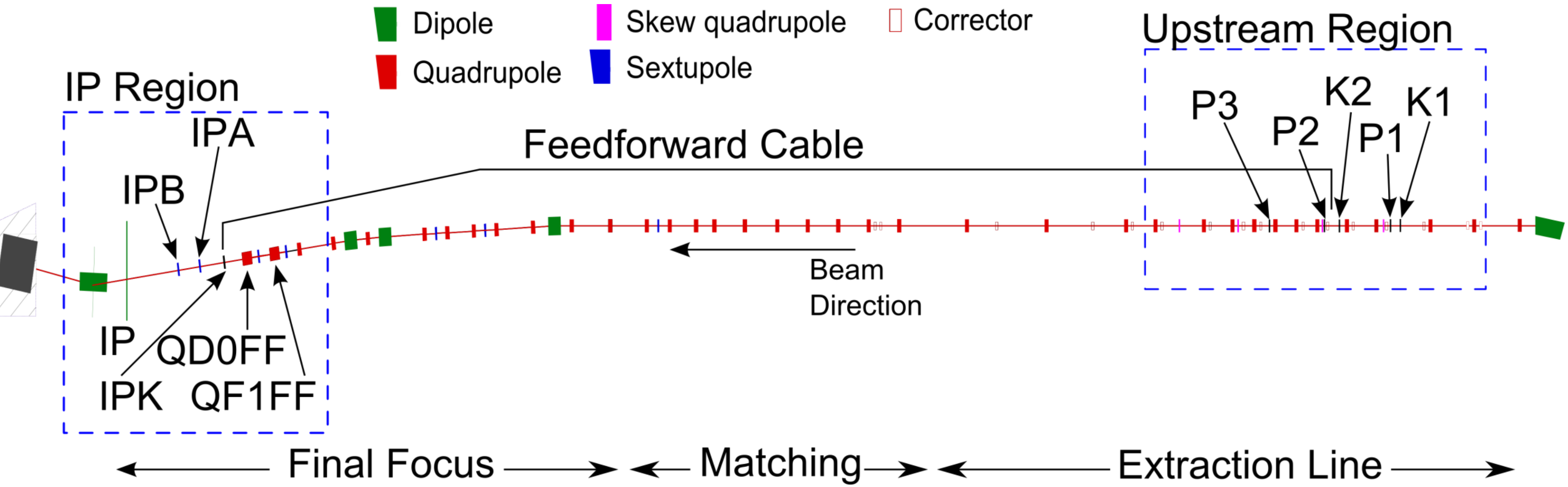


ATF2/KEK: prototype final focus

Beam feedback + feed-forward systems
Precision cavity + stripline BPMs
Beam size diagnostics
Beam tuning techniques (Marcin, Doug, Juergen …)



Beam feedback + feed-forward



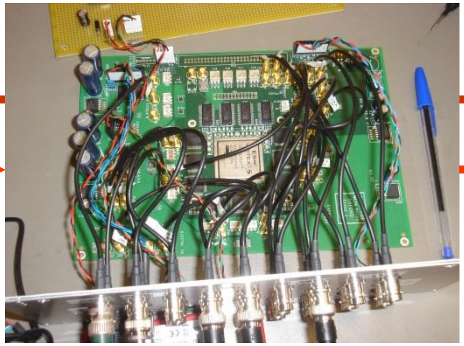
Aim to stabilise beam in IP region using 2-bunch spill:

1. **Upstream FB** — **monitor beam at IP**
2. **Feed-forward** — **from upstream BPMs → IP kicker**
3. **Local IP FB** — **using IPBPM signal and IP kicker**

Upstream FONT5 System

Analogue Front-end

BPM processor

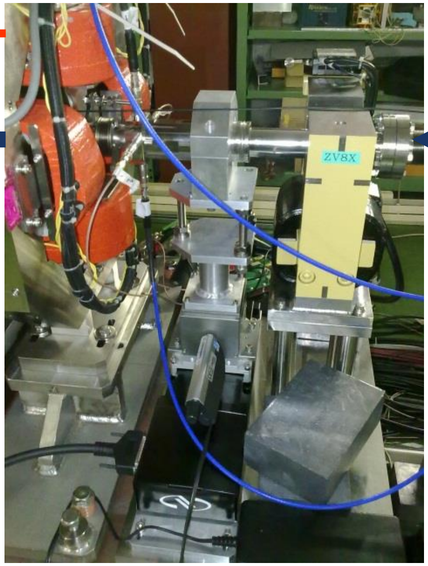


FPGA-based digital processor

Kicker drive amplifier

Strip-line kicker

Beam



Stripline BPM with mover system

BPM Resolution	< 300nm
Dynamic range of the BPM system	+/-500μm
System Latency	<150 ns
Amplifier Bandwidth	~30 MHz

Design and performance of a high resolution, low latency stripline beam position monitor system

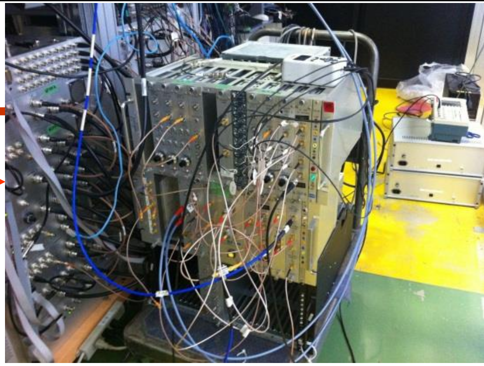
R. J. Apsimon,[*] D. R. Bett,[†] N. Blaskovic Kraljevic, P. N. Burrows, G. B. Christian,[‡]
C. I. Clarke,[§] B. D. Constance, H. Dabiri Khah, M. R. Davis, C. Perry,
J. Resta López,[‖] and C. J. Swinson[¶]

John Adams Institute for Accelerator Science at University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom

(Received 1 October 2014; published 19 March 2015)

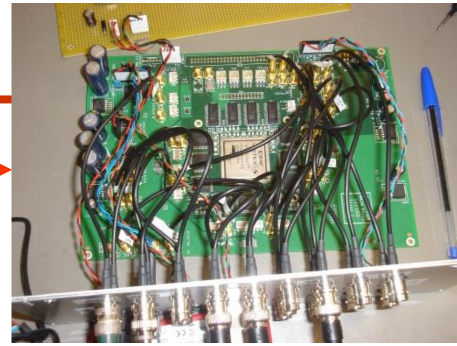
A high-resolution, low-latency beam position monitor (BPM) system has been developed for use in particle accelerators and beam lines that operate with trains of particle bunches with bunch separations as low as several tens of nanoseconds, such as future linear electron-positron colliders and free-electron lasers. The system was tested with electron beams in the extraction line of the Accelerator Test Facility at the High Energy Accelerator Research Organization (KEK) in Japan. It consists of three stripline BPMs instrumented with analogue signal-processing electronics and a custom digitizer for logging the data. The design of the analogue processor units is presented in detail, along with measurements of the system performance. The processor latency is 15.6 ± 0.1 ns. A single-pass beam position resolution of 291 ± 10 nm has been achieved, using a beam with a bunch charge of approximately 1 nC.

Interaction Point FONT System

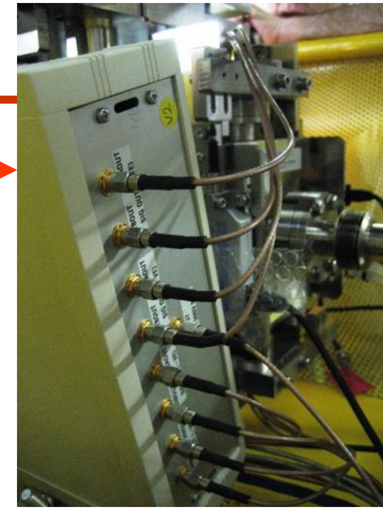


Analogue Front-end

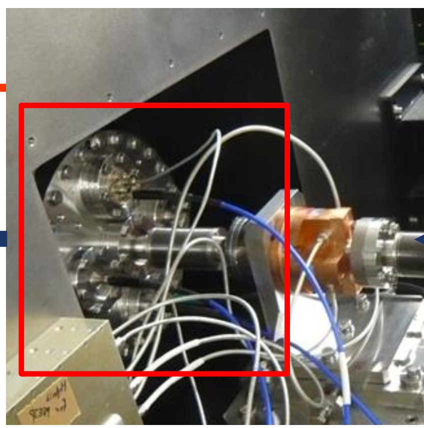
BPM processor



FPGA-based digital processor

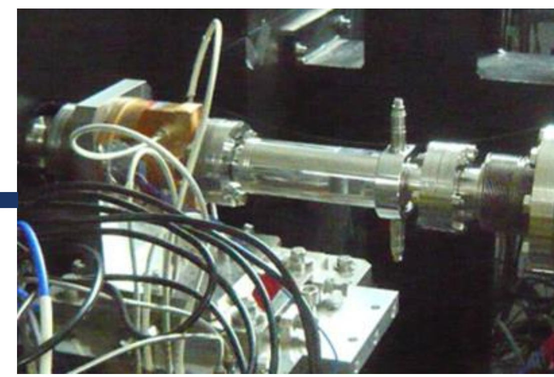


Kicker drive amplifier



Cavity BPM

Beam

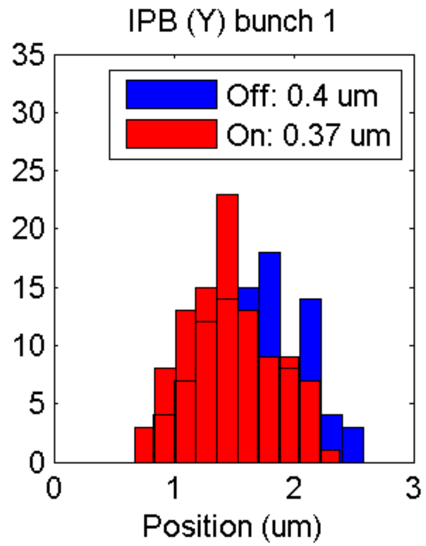


Strip-line kicker

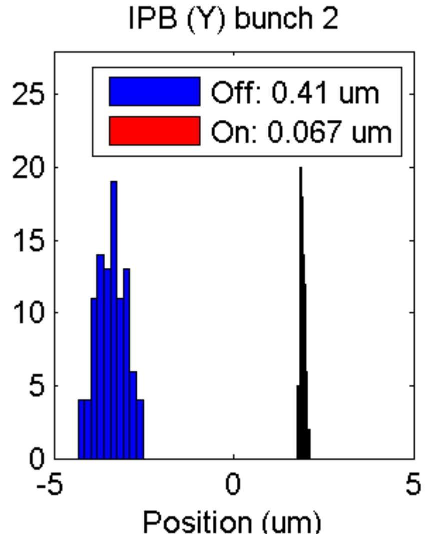
- Designed in house
- 12.5 cm stripline kicker
- Based on ATF stripline BPMs

Best IPFB results (2014)

Bunch 1:
not corrected,
jitter ~ 400nm



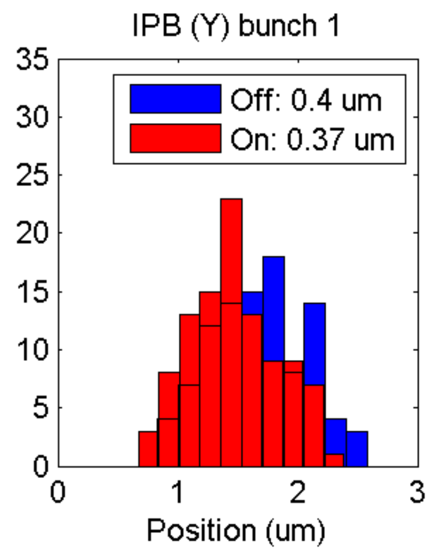
Bunch 2:
corrected,
jitter ~ 67nm

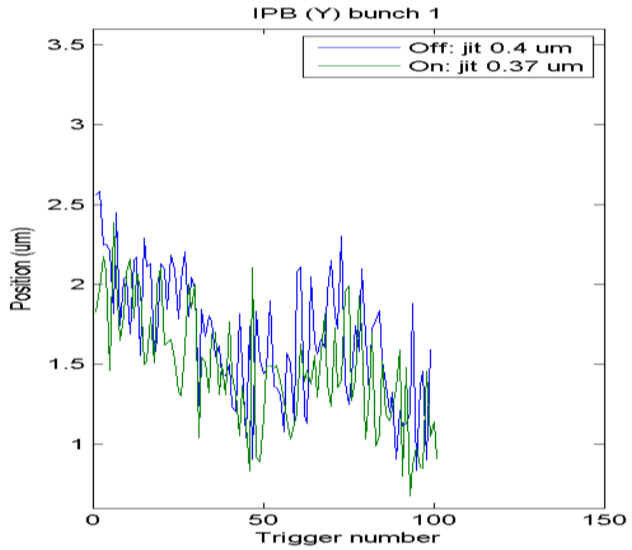


Corrected limited by BPM resolution of ~ 50nm

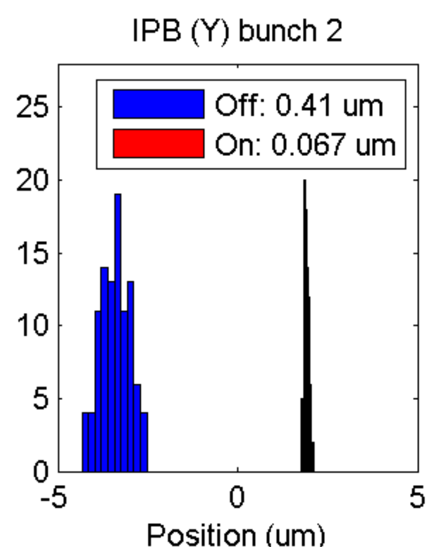
Best IPFB results (2014)

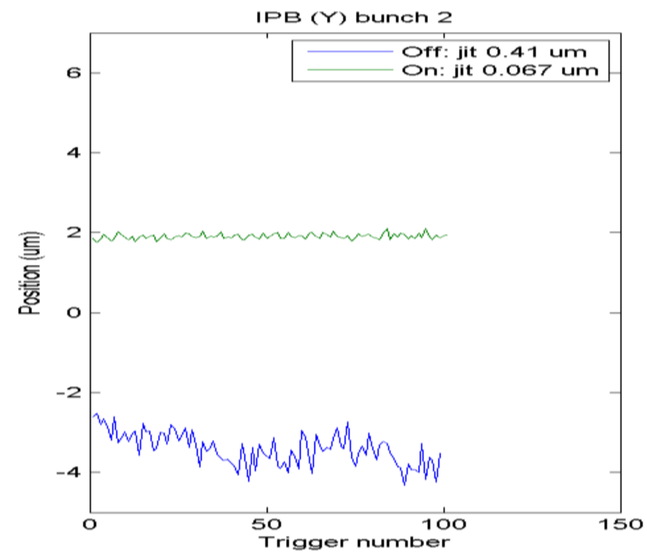
Bunch 1: not corrected, jitter ~ 400nm



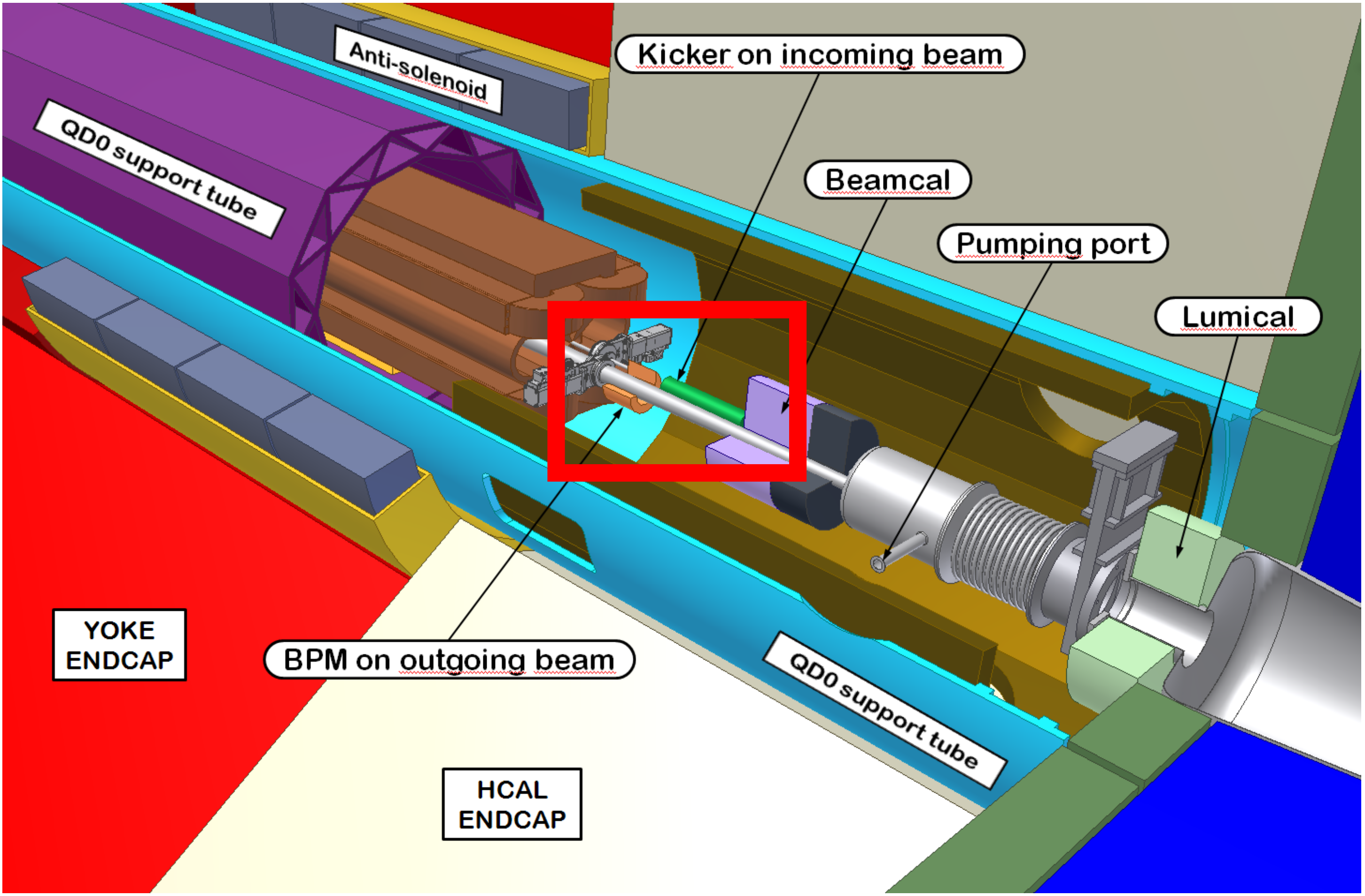


Bunch 2: corrected, jitter ~ 67nm





IP FB in CLIC IR



Working with CLIC MDI team (L. Gatignon et al) on extension of L* from 3.5m to 6m

Ideally IPFB hardware should stay close to IP

→ minimises latency
→ maximises lumi recovery

Will need some engineering thought once new L* design is solid

Instrumentation/beam dynamics (RHUL)

Faculty: Stewart Boogert, Pavel Karataev

Postdocs: Alexey Lyapin, Jochem Snuverink

Students: Lorraine Bobb, Michele Bergamaschi, Konstantin Kruchinin, Jack Towler

For ODR system + CLIC cavity BPMs → Thibaut

Cavity BPM system at ATF2 (1)

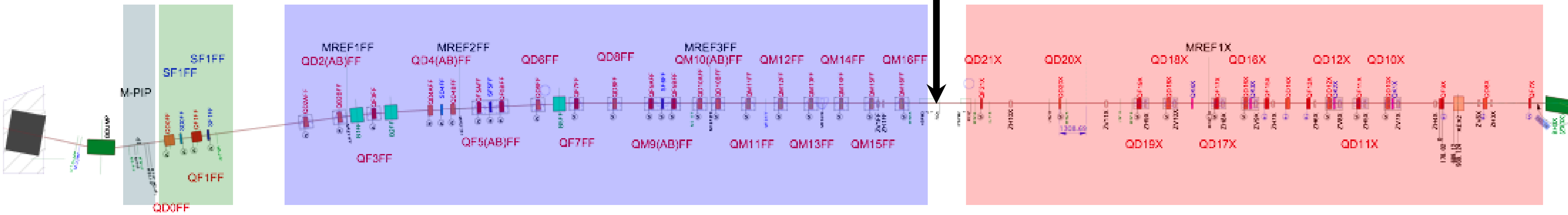
IP region (4 BPMs)

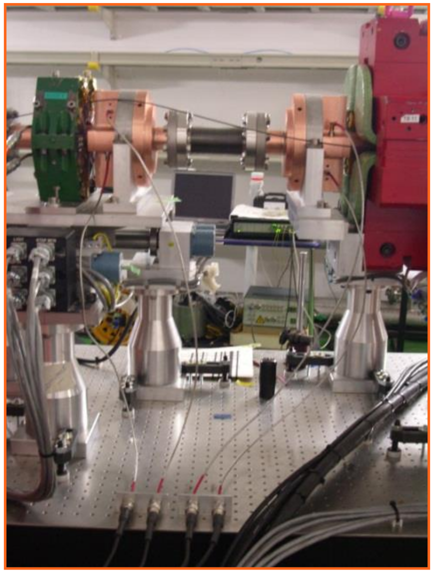
S-band BPMs (movers)

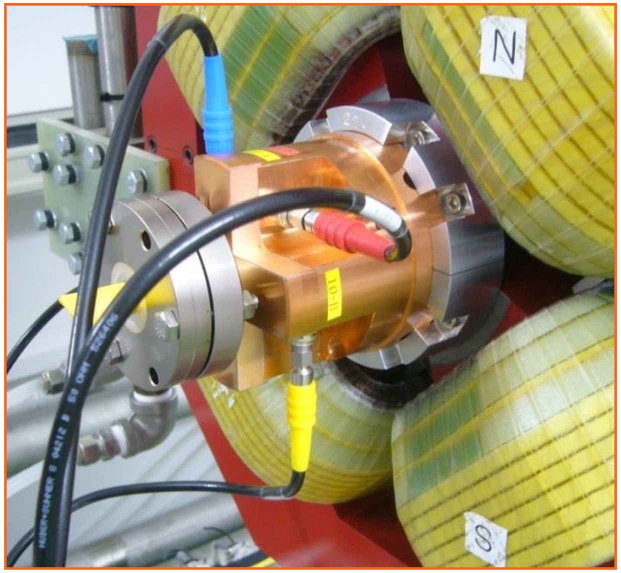
C-band BPMs (on movers)

BPM test area

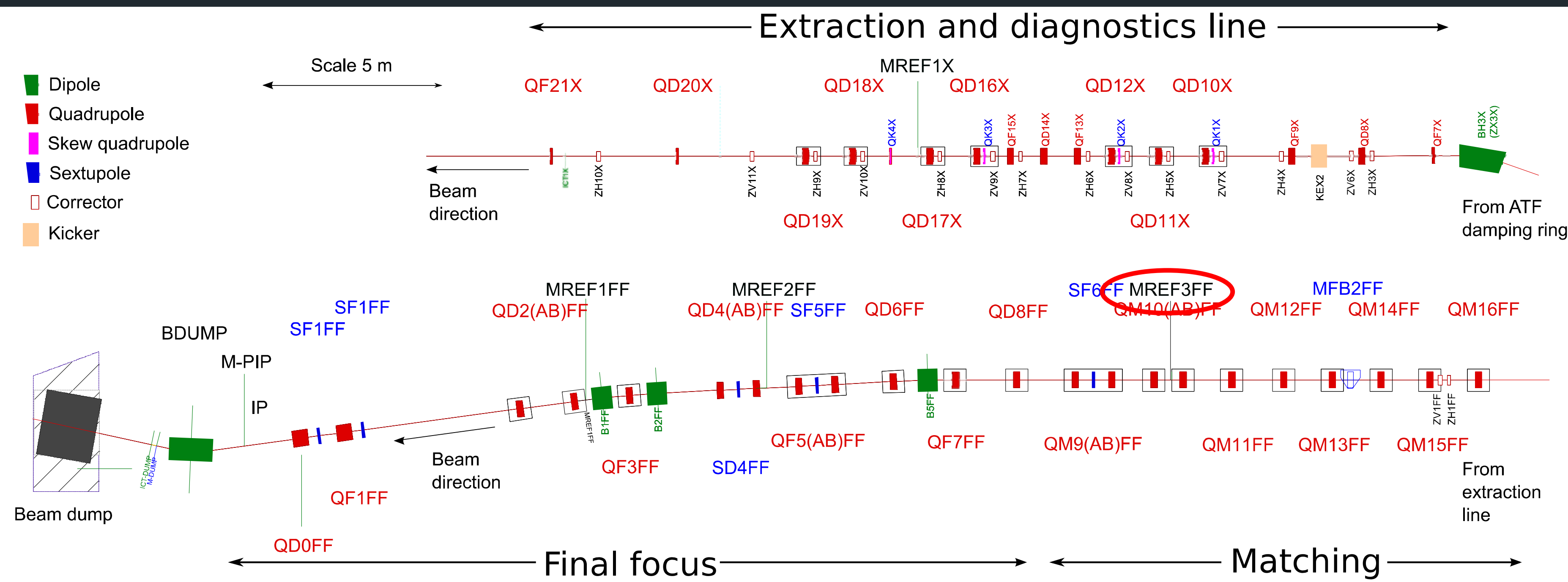
Strip line/Cavity BPMs (mounted rigidly)



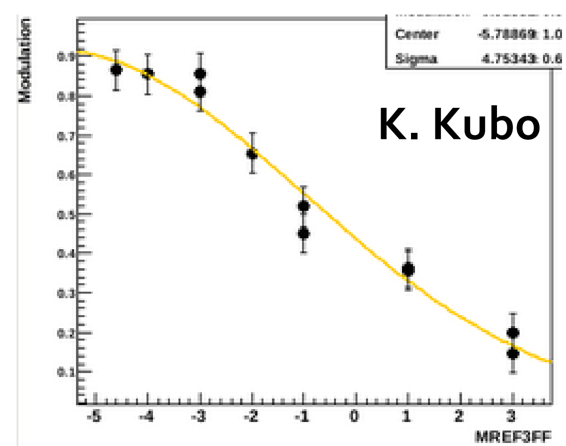




Wakefield source setup (1)

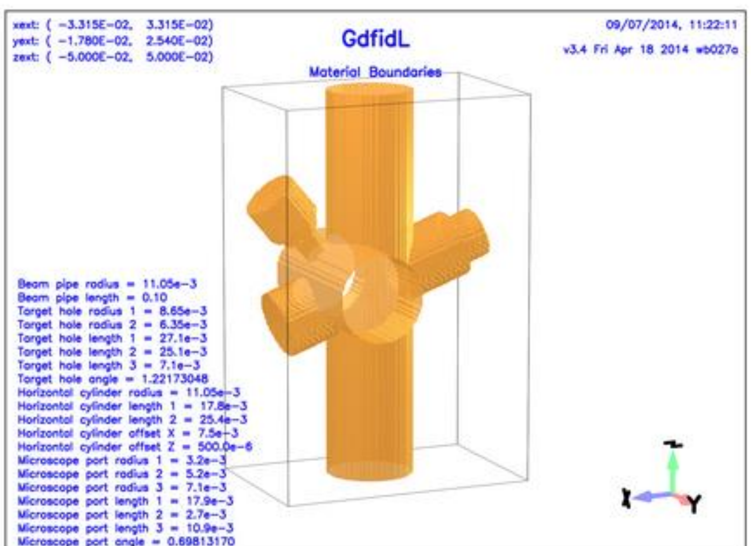


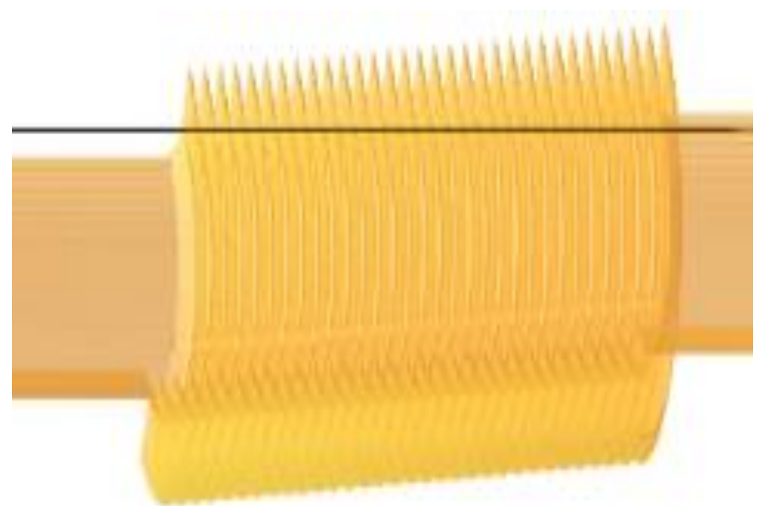
- 2 reference cavities on mover at high beta location ("MREF3FF"), later replaced by a collimator and unshielded bellows on independent movers
- Study and measure wakefield effects
- Partially compensate wakefields from other sources



Wakefield simulations

- Simulations done with a time domain FDTD solver (part of GdfidL software)
- gdfidl.de
- Geometries are meshed using a cubic mesh with diagonal fillings
- The beam is represented by a line charge travelling parallel to z-axis
- Most simulations are done for the nominal 7 mm bunch length (RMS)
- Typical mesh size 0.25 mm, 0.1 mm for more complex structures, such as bellows





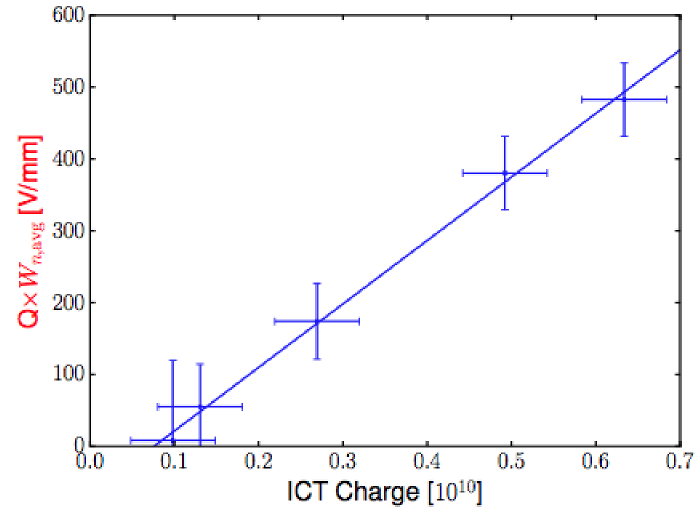
Wakefield simulations – component summary

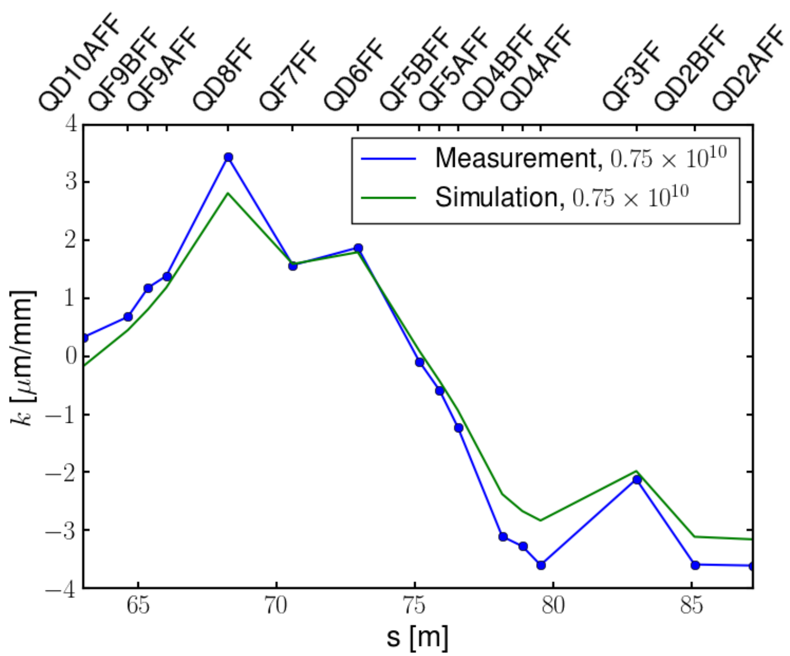
Element	Peak Wake (V/pC/mm)	Dipole kick factor (V/pC/mm)	Approximate quantity	Total
Bellows (unshielded)	0.10	0.06	100	6.00
Vacuum flange+step	0.06	0.04	100	4.00
C-band position	0.11	0.06	40	2.40
Vacuum flange	0.04	0.02	100	2.00
C-band reference	0.15	0.09	1	0.09
Vacuum ports(X)	0.07	0.05	6	0.30

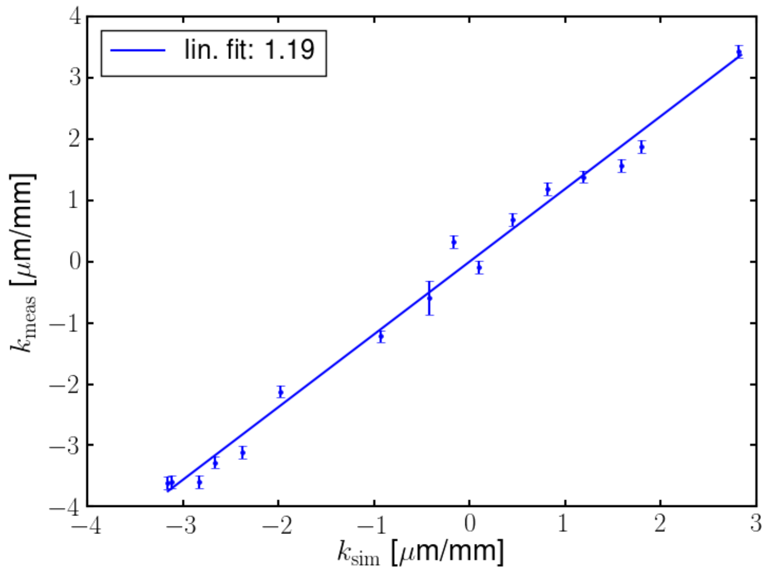
- Offsets and beta function are important (not taken into account here)
- Most bellows and adjacent flanges are now shielded
- Position cavities are likely to be much better aligned compared to other elements
- Not all components have been analysed, exact geometries are rarely known!

Measurements (3)

- Measured orbit shape agrees well, about a factor 1.2 between measurement and simulation
- Bunch length uncertainty: about half a mm in DR (not measured in EXT), effect on wakefield 5-10%
- Bunch charge uncertainty: ICT calibration error 5-10%
- PRSTAB paper about to be submitted







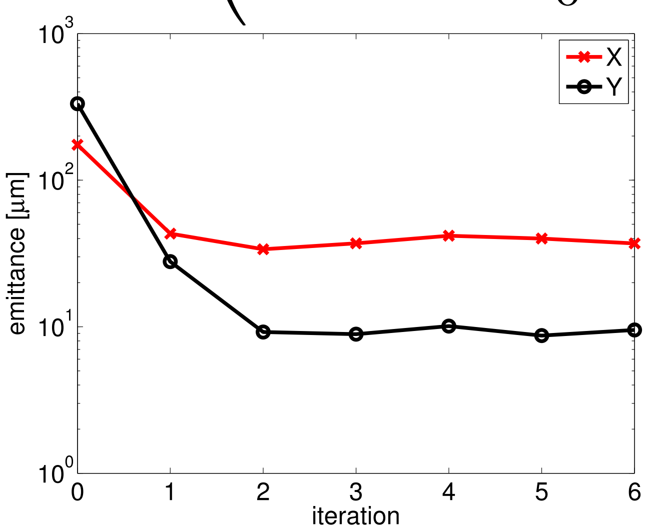
Recap on Dispersion-Free and Wakefield-Free Steering algorithms

- DFS: measure and correct the system response to a change in energy
  (changing klystron phase, voltage,)
- WFS: measure and correct the system response to a **change in the bunch charge**
  (use a fraction of the nominal bunch charge)

Recap of the equations

$$\begin{pmatrix} & & y - y_0 \\ \omega_{\mathrm{DFS}} & \cdot & (\eta - \eta_0) \\ \omega_{\mathrm{WFS}} & \cdot & y_{\mathrm{w}} \\ & & 0 \end{pmatrix} = \begin{pmatrix} & & \mathbf{R} \\ \omega_{\mathrm{DFS}} & \cdot & \mathbf{D} \\ \omega_{\mathrm{WFS}} & \cdot & \mathbf{W} \\ \beta & \cdot & \mathbf{I} \end{pmatrix} \begin{pmatrix} \theta_1 \\ \vdots \\ \theta_m \end{pmatrix}$$

$$\omega^2 = \frac{\sigma^2_{\text{bpm resolution}} + \sigma^2_{\text{bpm position}}}{2\sigma^2_{\text{bpm resolution}}}$$



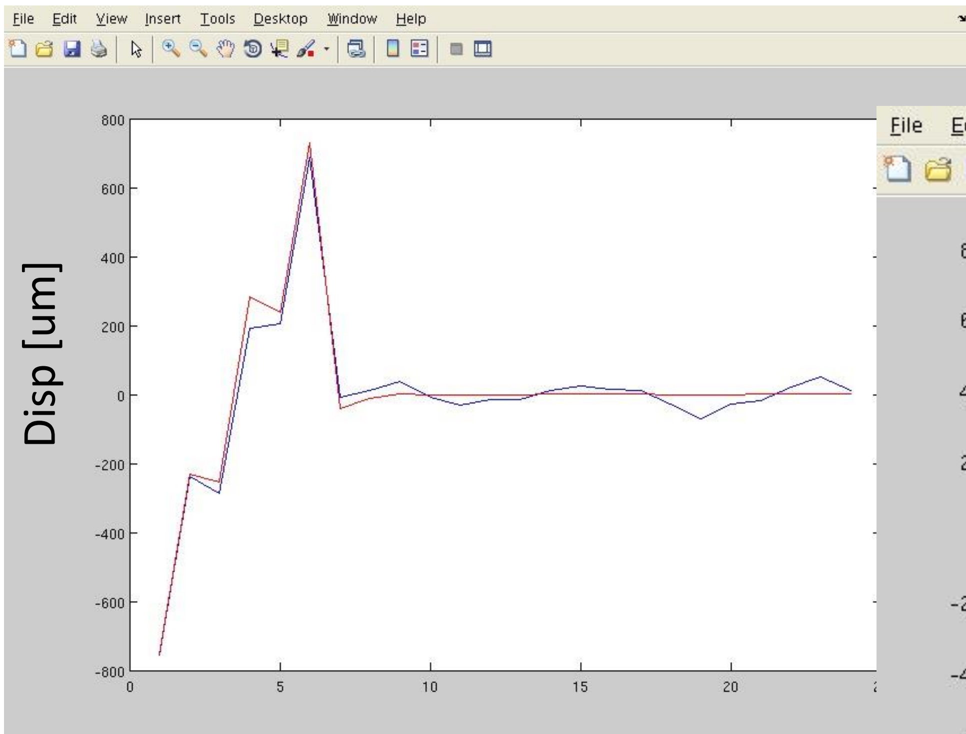
Application of BBA consists of two steps
- Response matrix(-ces) measurement
- Correction and parameters scan

← H and V emittance reduction thanks to DFS at SLAC

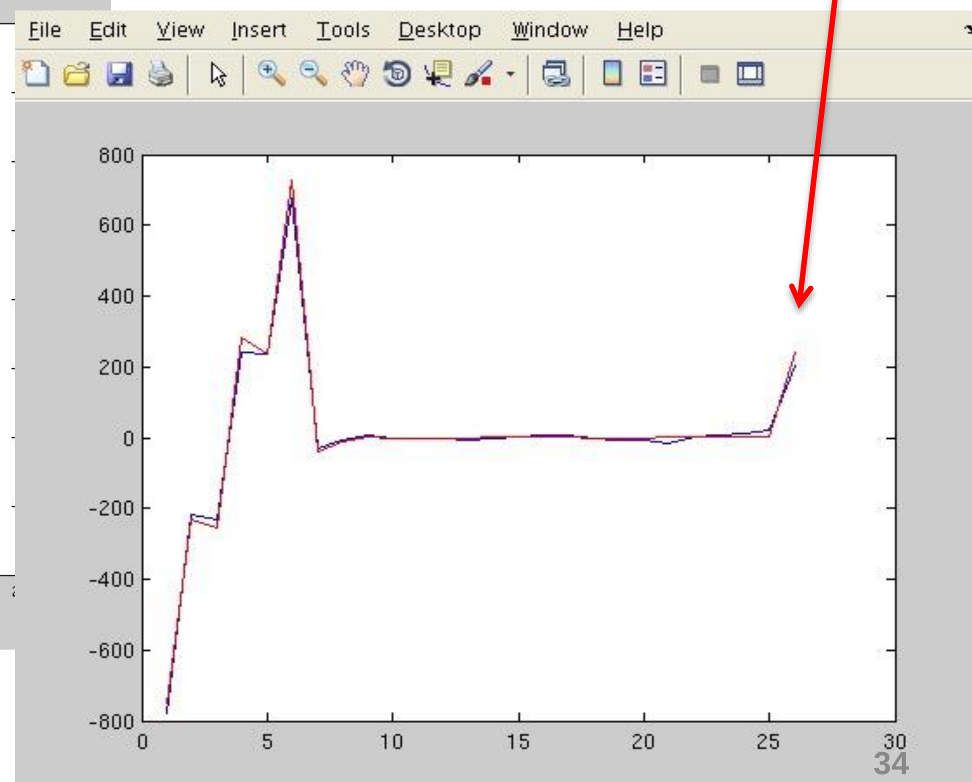
Step 2: DFS tests, h-axis

- Energy difference for DFS: +2 kHz in DR
  dE/E = -0.13%   (4 MeV)
- Matched-dispersion steering

Added 1 FF bpm
in dispersive region



Before the correction



After the correction

2 beam tuning

- So far only “1 beam tuning” for CLIC has been simulated
  - Optimise one BDS beamline from static errors
  - Collide beam with “itself” to measure luminosity
  - CPU-less intensive
- 2 beam tuning will be at least twice as long (except for BBA)
  - How much longer?
  - Luminosity measurement less precise for lower luminosity
  - Additional luminosity loss is expected as self-collision is often optimal

EO bunch length monitor (ASTeC/Dundee)

Faculty: Allan Gillespie

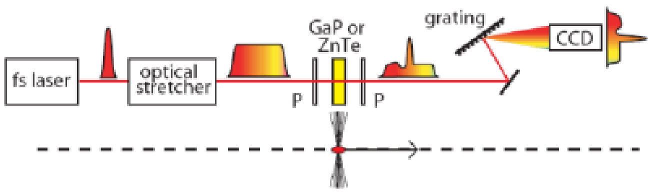
Staff: Steven Jamison, Edward Snedden

Postdoc: Mateusz Tyrk, David Walsh

Students: Rui Pan, Matt Cliffe

EO principle

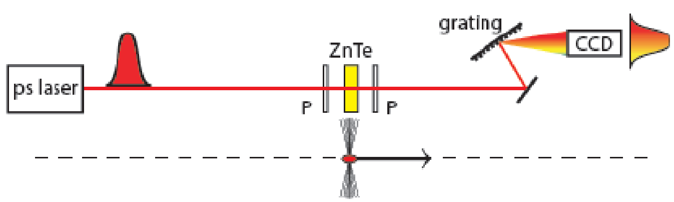
Spectral Decoding



- Chirped optical input
- Spectral readout
- Use time-wavelength relationship
- time resolution limited to > 1 ps

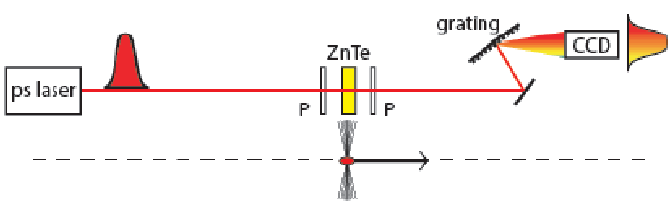
Installed on Califes

Spectral upconversion



- monochomatic optical input (long pulse)
- Spectral readout

EO Transposition



- monochomatic optical input (long pulse)
- self-referncced FROG temporal readout
- high time resoluation

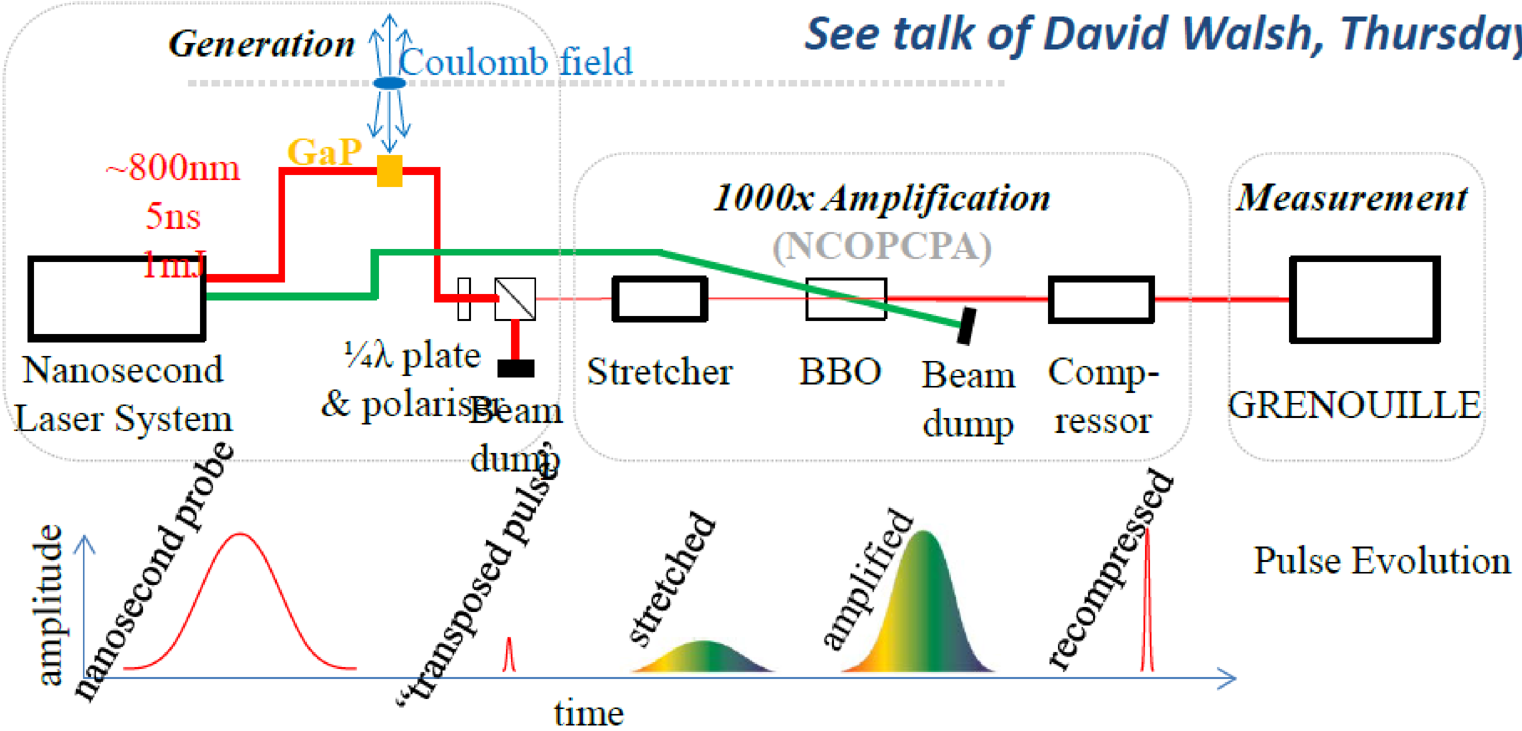
Developed for CLIC as robust, high time Resolution system

EO Transposition

Being developed for CLIC longitudinal profile diagnostics

Spectral upconversion, followed by self-referenced temporal measurement

See talk of David Walsh, Thursday, FEL session



'Industrial' 5-10 nanosecond laser for probe

- reliability & robustness; simplified ns synchronisation

Electro-optic diagnostics for 20fs resolution

Progress in last year

Laser system procurement completed

- Initial supplier failure on specification/competence
- complicated follow-up procurement to ensure spec delivery

'EOT' Frequency Resolved Optical Gating measurements of THz pulses

- Experimental proof of concept developed for CLIC
- Published in Applied Physics Letters (2015)

FROG measurements from metal surface

- Established measurement system for high-bandwidth non-linear materials

Nano-material testing

- STFC & STFC/Dundee experiments (STFC lasers, Dundee samples)
- FROG working for second harmonic, with enhanced efficiency
- THz induced FROG with intense THz sources – insufficient signal-noise

New understanding on taking FROG to femtosecond level

- Method for unambiguous femtosecond level electric field retrieval
- Surpasses established ultrafast laser measurement limitations
- Published Optics Express (2015)

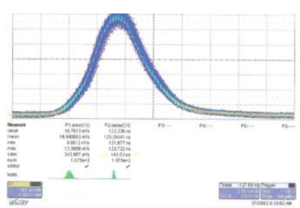
EOT System Build Status

- Primary laser systems finally delivered end of Nov 2014– Characterisation largely complete
- All other components being constructed, integrated, characterised, and made robust
- Dye laser not proposed for the final design – possibility of building a seeded OPO

Full system now being integrated

Sirah Cobra Dye laser

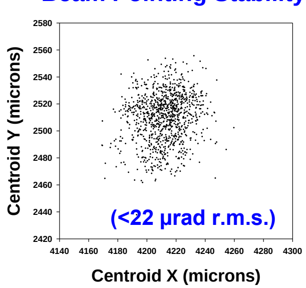
6 ns, 3 mJ, linewidth < 2 GHz



Continuum Surelite YAG

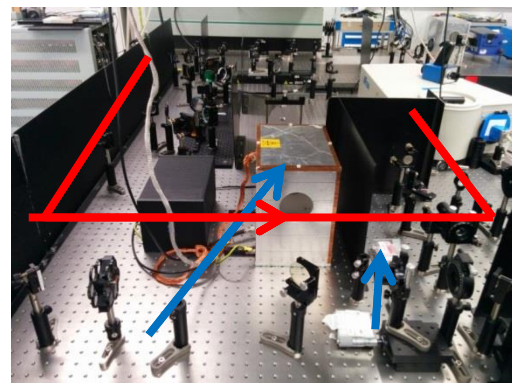
~ 4.5 ns, 150 mJ, seeded

Beam Pointing Stability

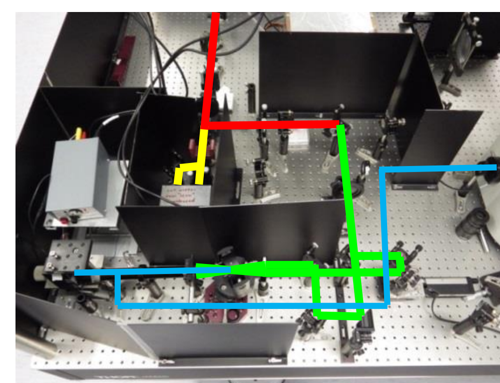


Jitter < 0.3 ns r.m.s.

THz Source & Optical Probe mixing

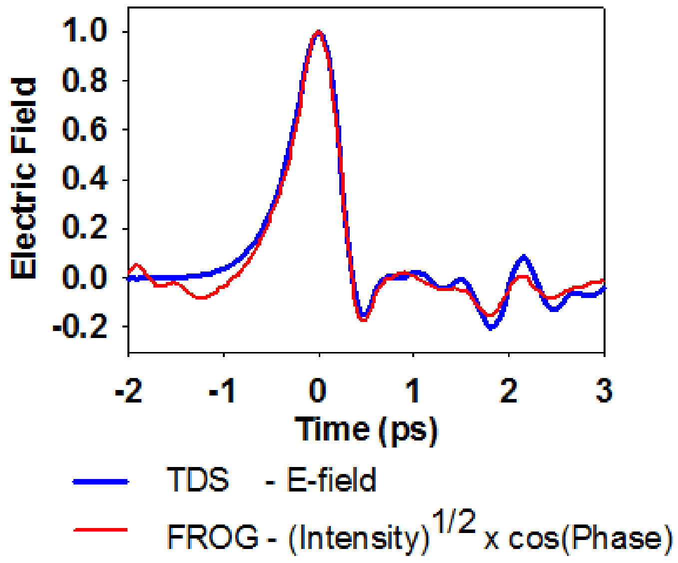


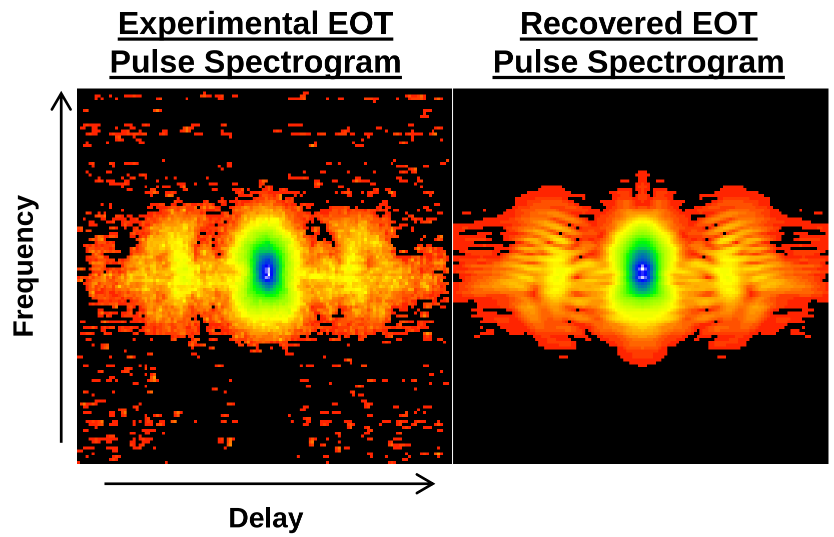
EOT pulse diagnostics – TDS & FROG set ups



Principle Behind EOT tested & confirmed

Mimic electric field profile, independently measured
Retrieved Field profile, using EOT





0.55 ps pulse successfully measured with a 10 ps, transform limited, probe!
The core principle of mapping a Coulomb field into an optical pulse envelope now proven

Published in Applied Physics Letters

"The time resolved measurement of ultrashort terahertz-band electric fields without an ultrashort probe"
Walsh, D. A. and Snedden, E. W. and Jamison, S. P., Applied Physics Letters, 106, 181109 (2015)

Electro-optic diagnostics for 20fs resolution

Plans for next year

Optical system integration

- All sub-systems have been tested, now to be integrated into full prototype
- Preparing for accelerator testing

Further development of FROG retrieval, including single-fs methods

- Algorithm development / benchmarking for robustness
- Manchester University collaboration assisting with ‘CEP stabilised’ lasers

Nano-material testing

- Using new high field THz sources being developed by STFC, further experimental testing for ‘TFISH’ (THz induced Second Harmonic) FROG with Dundee materials
- Decision point on nano-material vs multi-crystal detector for enhanced bandwidth

Accelerator testing

- Advanced stages of preparation for testing at an accelerator facility
- Testing to be during 2016; CLARA at Daresbury now likely location.
  [50MeV, <100fs, flexible access]

Crab cavity + RF (Lancaster)

Faculty: Graeme Burt, Amos Dexter,
Chris Lingwood

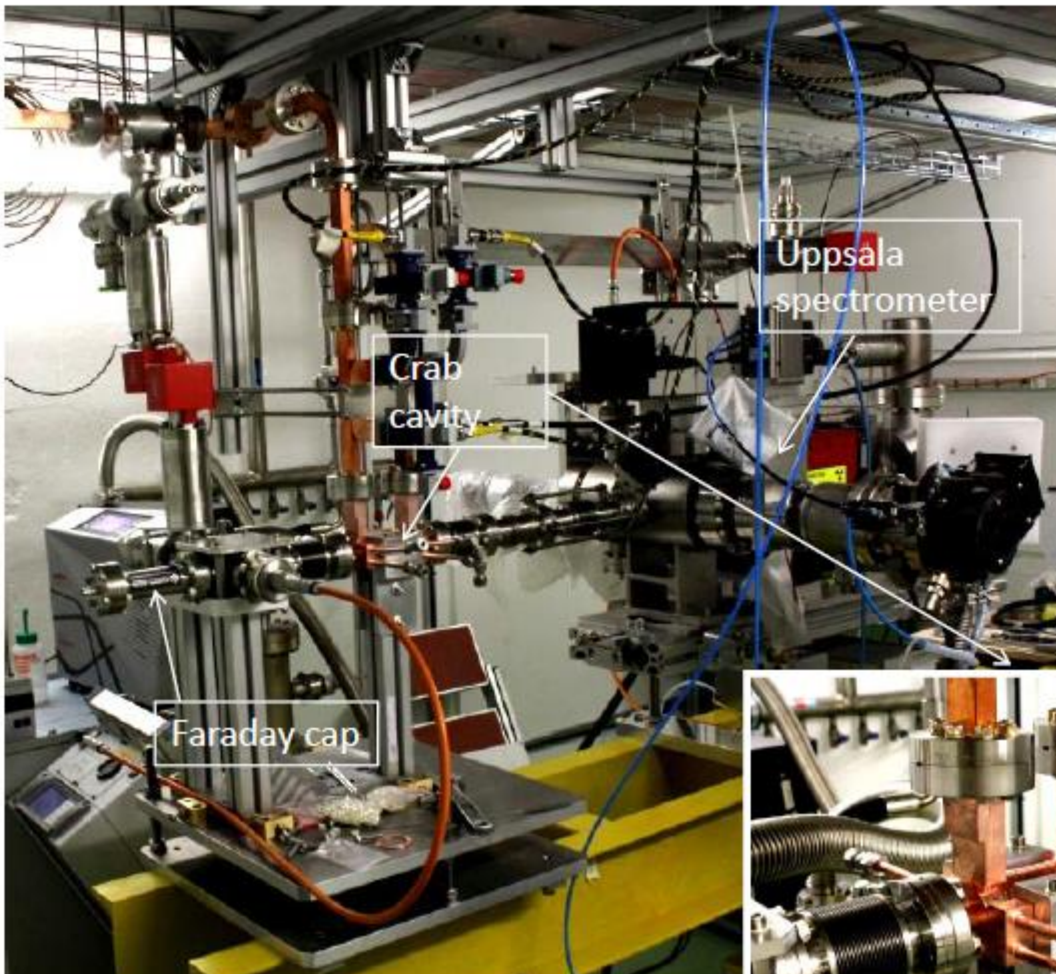
Postdocs: S. Karimian, D. Constable, M. Jenkins

Students: V. Hill, B. Woolley

Objectives:

- Design and fabricate a crab cavity appropriate for high gradient testing at CERN
- Feasibility studies and associated measurements for the Crab RF distribution system
- New approaches towards high-efficiency klystrons

CLIC crab Cavity



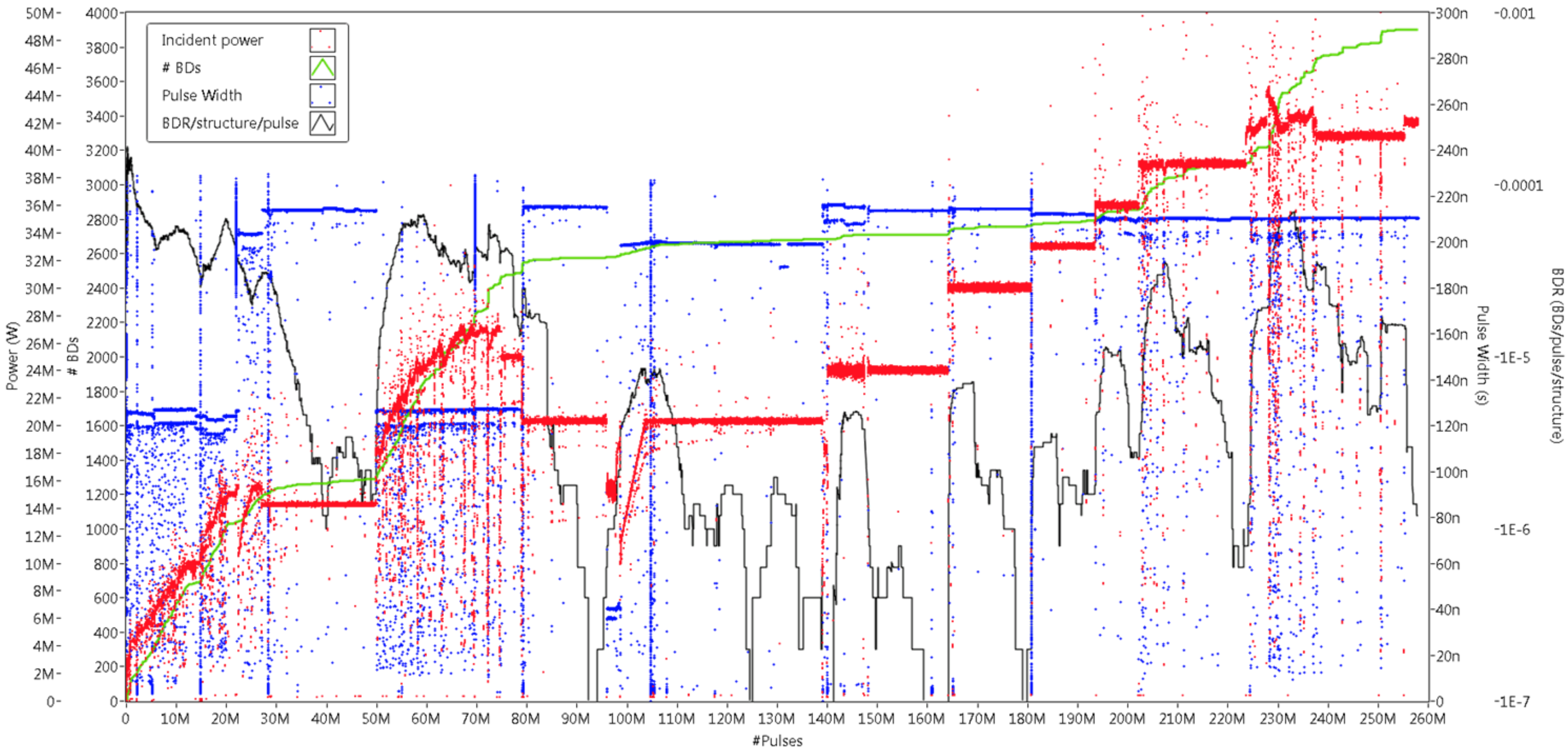
- Lancaster's X-band "crab" cavity currently running on XBOX2 to measure the maximum possible transverse gradient.

The Cockcroft Institute of Accelerator Science and Technology

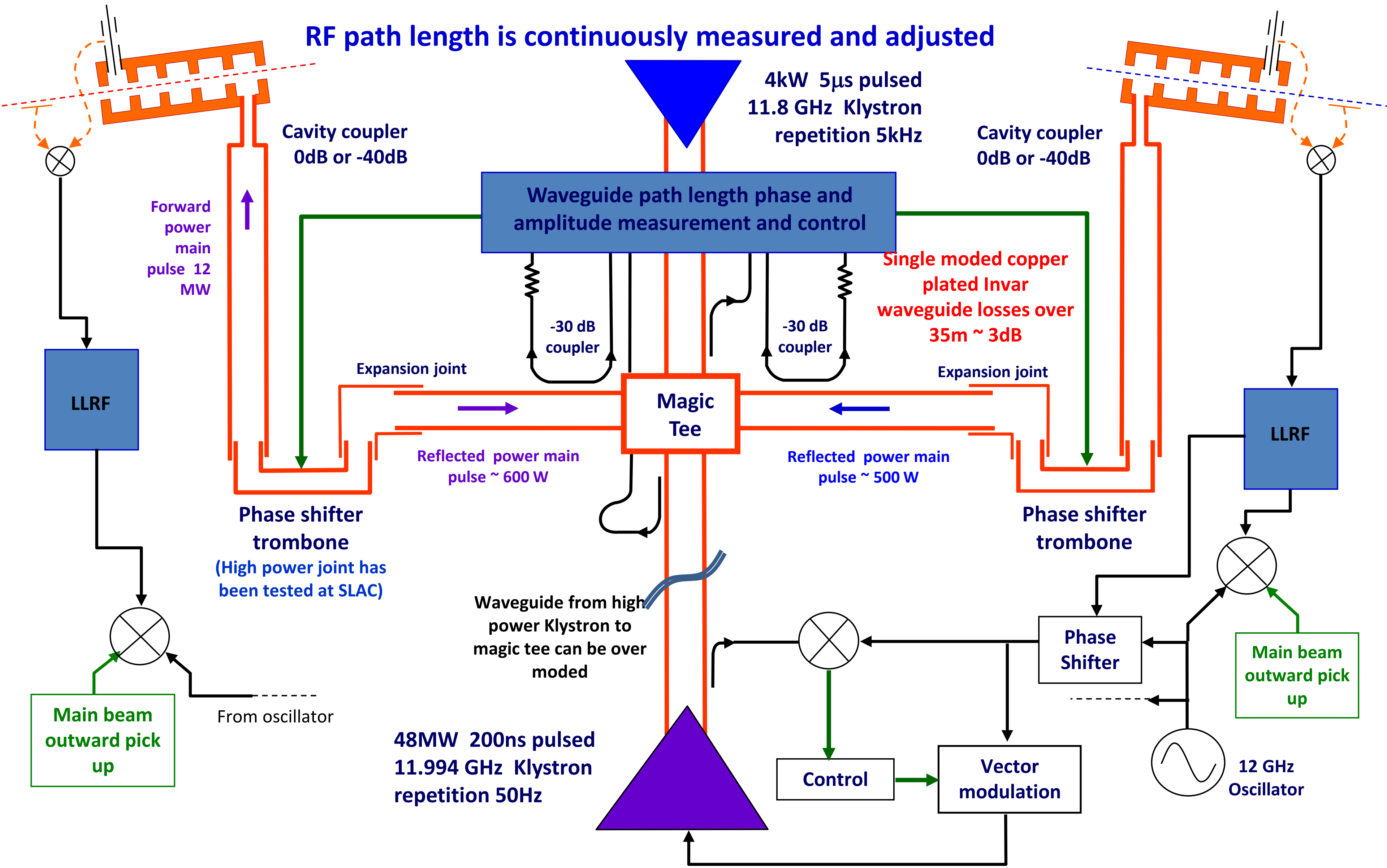
Lancaster University

High power test results

- Achieves up to 4.5 MV in a 100 mm structure with 40 MW, twice required CLIC and LCLS gradient. Group velocity could be reduced in a shorter structure.



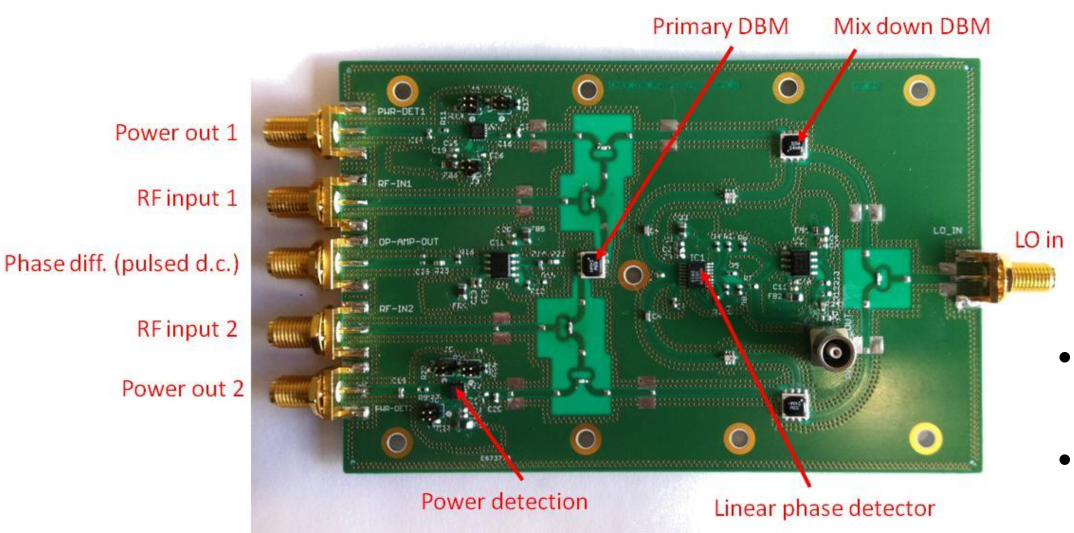
Revised Crab Synchronisation Scheme

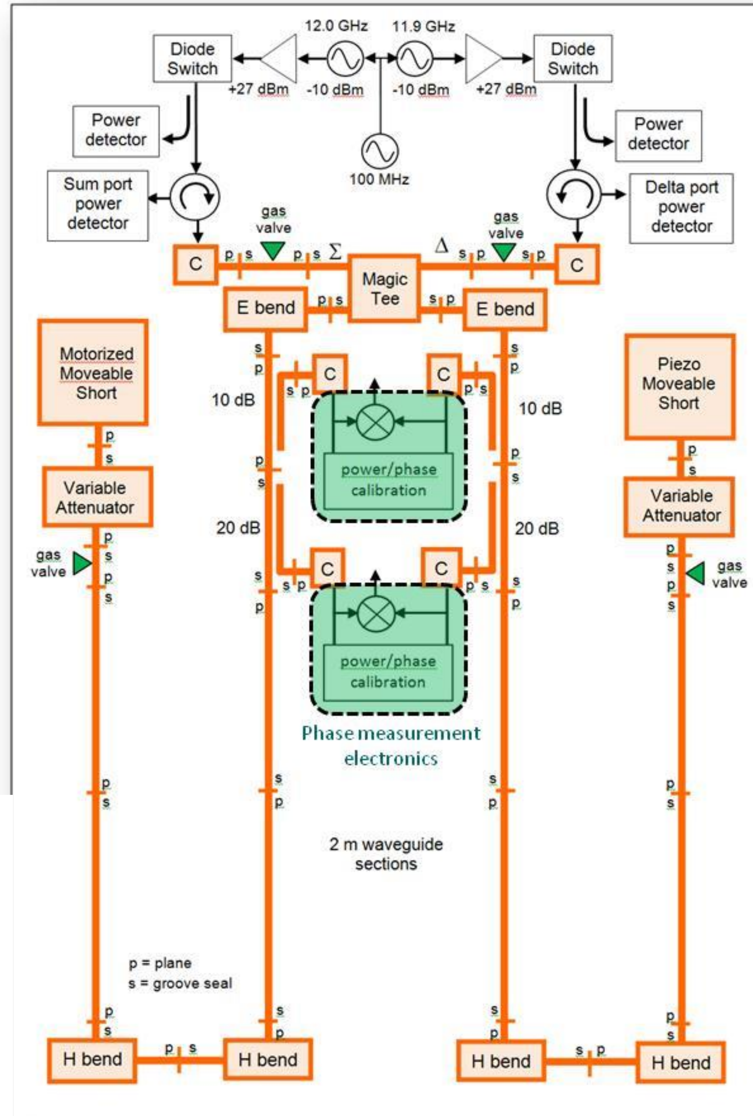


CLIC synchronisation scheme

Phase measurement board

- Calibration with this board mixes down to 1.3 GHz then uses a linear phase detector
- Pulsing signals allows offsets to be removed
- Future boards may mix to 400 MHz and calibrate by digital sampling of signal

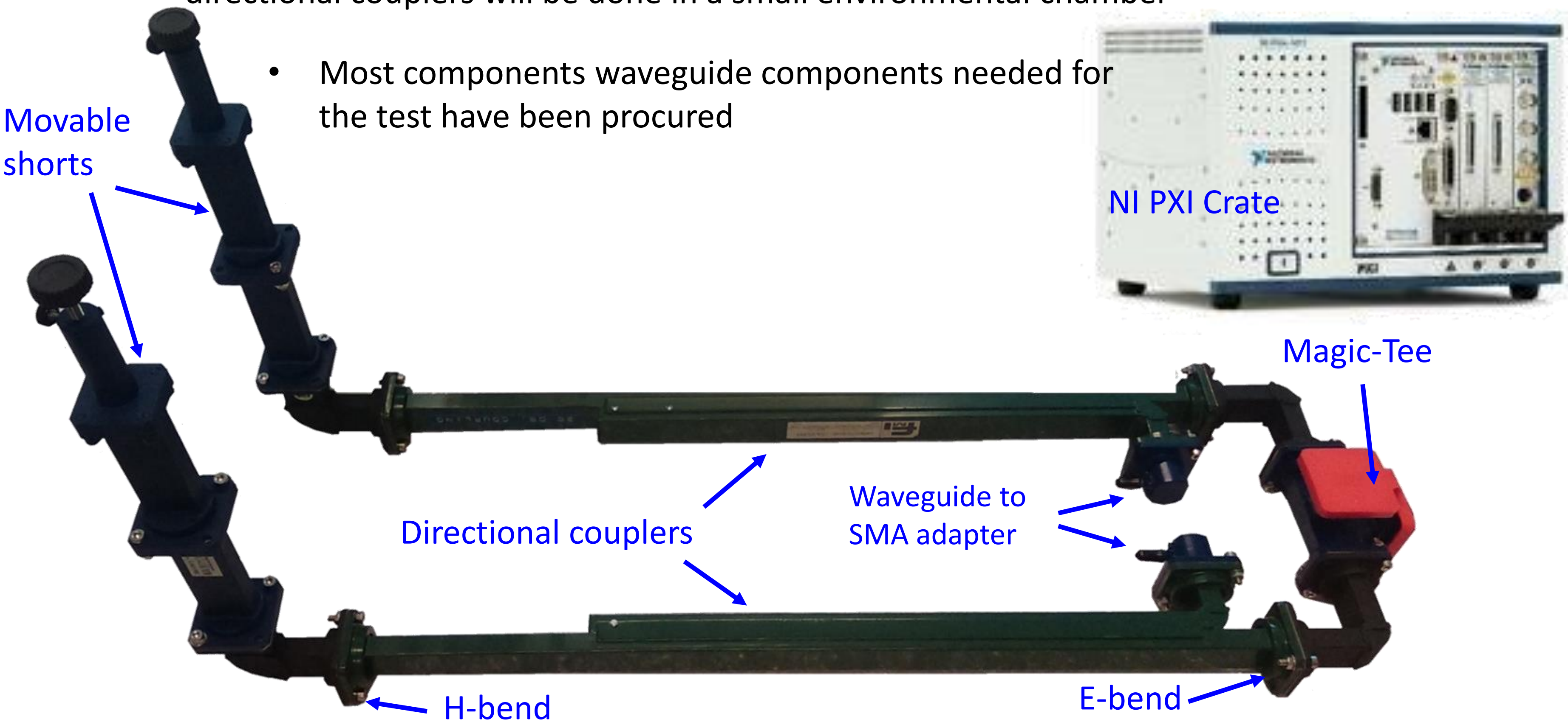




- Required delivery timing for RF power timing ~ 4.4 fs.
- Waveguide phase velocity: ~ 3.514×10^8 ms^{-1}

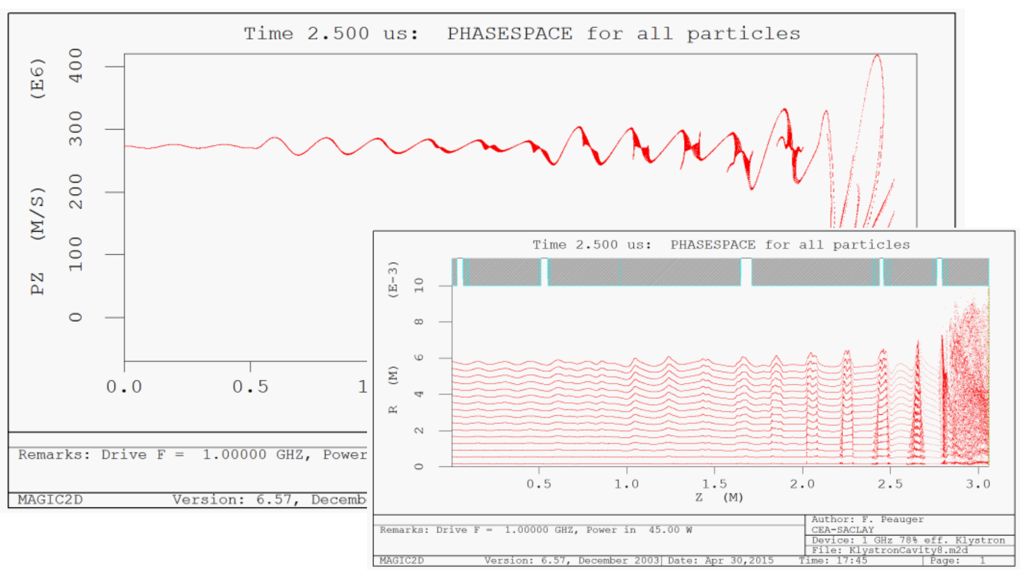
Initial Arrangement for Calibration

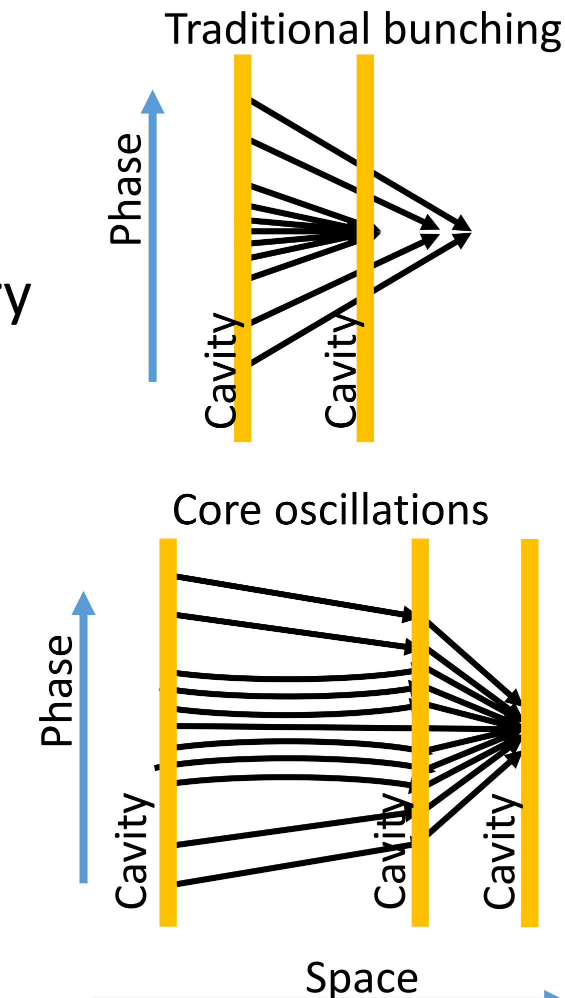
- Testing at 10 MW was regarded as unnecessary hence standard flanges can be used
- Initial calibrations of the phase measurement board, the Magic Tee and the directional couplers will be done in a small environmental chamber
    - Most components waveguide components needed for the test have been procured



High efficiency klystrons for accelerators

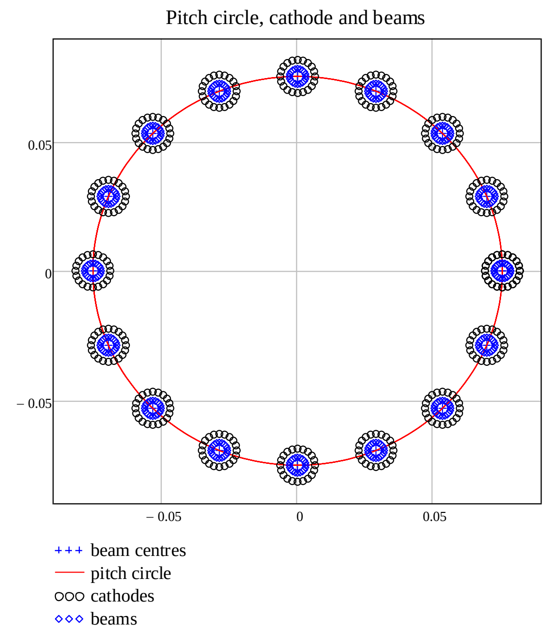
- Using core oscillation method 90 % efficient klystrons may be achievable
- PIC analysis of high efficiency bunching method, validation of approach
- Numerical noise currently an issue due to very long tubes (4m)

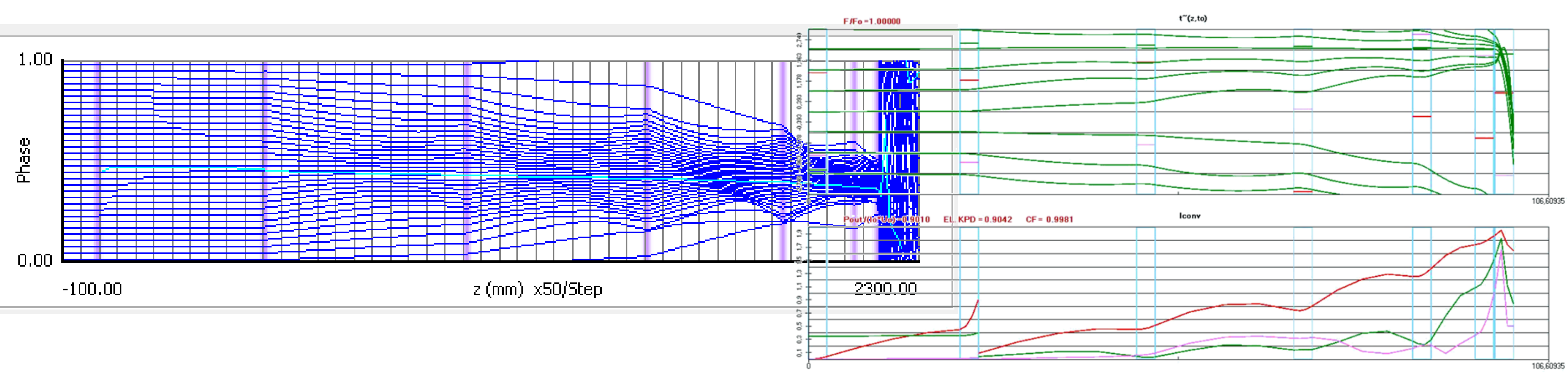




High efficiency klystrons for accelerators

- HEIKA international klystron collaboration
- Invited talk at FCC Week – with proposed 90 % efficient 1.5MW 40kV 16 beam MBK design
  - Uses same technique as CLIC klystron for further validation of approach





Main linac structure studies (Manchester)

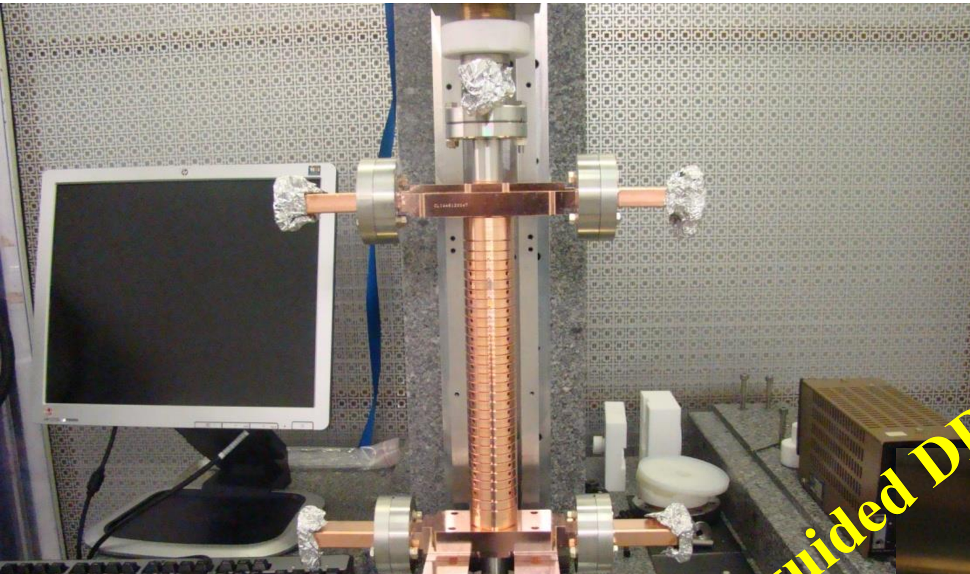
Alternative designs including wakefield suppression of HOMs

Faculty: Roger Jones

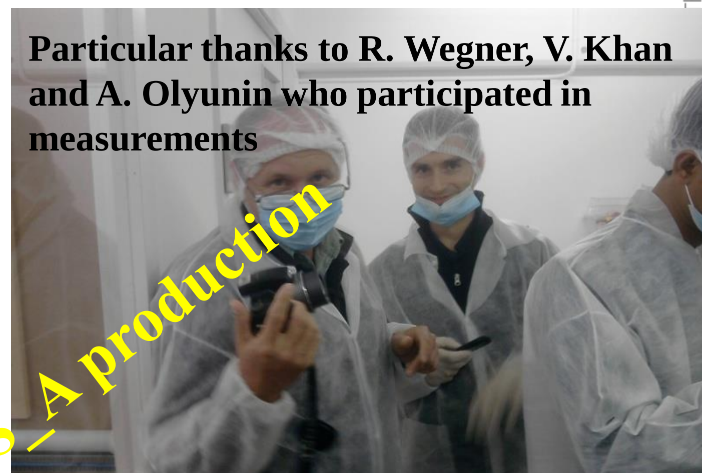
Postdocs: Alessandro D'Elia, Inna Nesmiyan

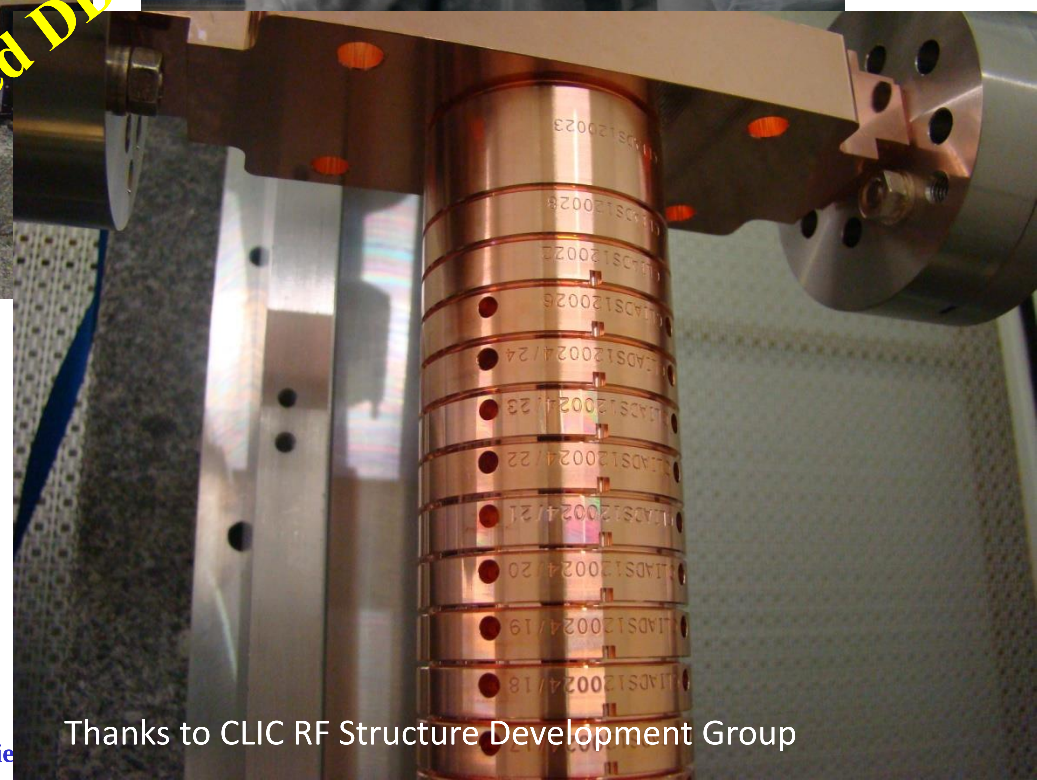
Students: Nick Shipman, Lee Carver

DDS_A Prototype –Measured at CERN



Particular thanks to R. Wegner, V. Khan and A. Olyunin who participated in measurements



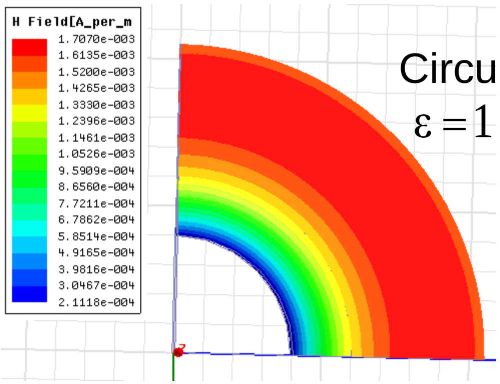


T. Higo (KEK) guided DDS_A production

Thanks to CLIC RF Structure Development Group

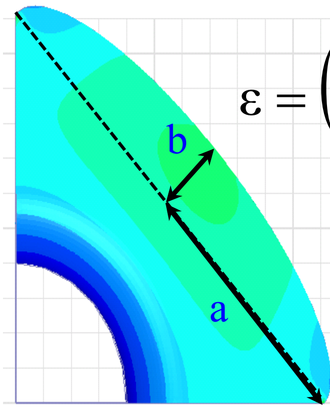
CLIC_DDS_E Elliptical Design –E Fields

Single undamped cell
Iris radius=4.0 mm



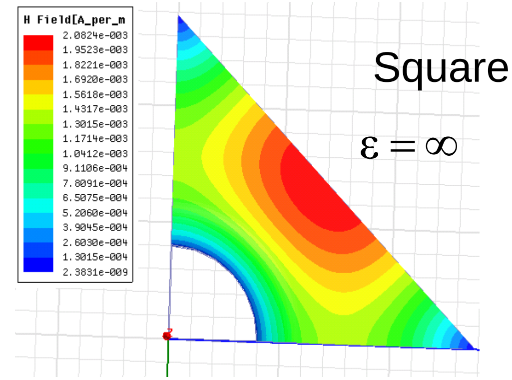
Circular

$\varepsilon = 1$



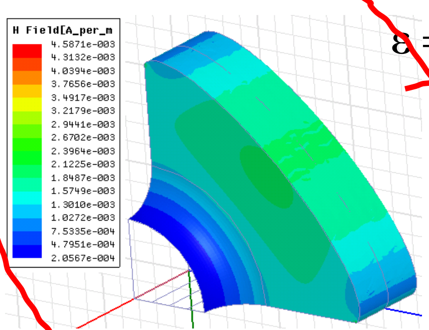
$$\varepsilon = \left(\sqrt{2} - 1\right)\frac{a}{b}$$

Convex ellipticity



Square

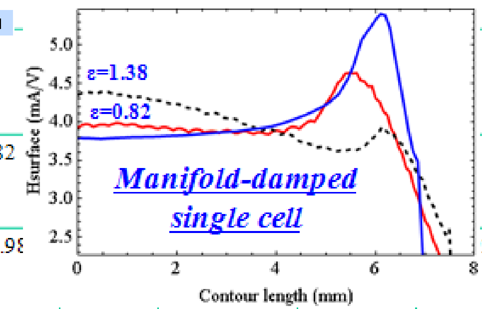
$\varepsilon = \infty$



$\varepsilon = 1.38$

	Circular	Rectangular	Elliptical (Convex)	0						
ε of cavity	1	∞	4.14	2.07	1.38	0.82				
f_{acc}(GHz)	12.24	12.09	11.98	12.0	11.99	11.98				35
Eacc(V/m)	0.43	0.43	0.42	0.43	0.43	0.42	0.42	0.43	0.43	0.42
H^{sur}_{max}/Eacc (mA/V)	3.64	4.86	4.71	4.54	4.29	3.75	3	4.94	4.99	5.11
E^{sur}_{max}/E_{acc}	2.27	2.27	2.33	2.28	2.28	2.33	2.33	2.27	2.27	2.33

0



Iris radius = 4. 0 mm
Iris thickness = 4.0 mm

0 Chosen design

Summary

- **CLIC-UK is delivering significant contributions**

- **Thanks to our CERN colleagues and CLIC partners for outstanding collaboration!**