# UK LC accelerator programme

**Philip Burrows**

***John Adams Institute***

***Oxford University***

# CLIC-UK (started March 2011)

**CI/Manchester:** main beam RF, crab cavities

**CI/Lancaster:** crab cavities

**ASTeC:** drive-beam quads + crab cavities

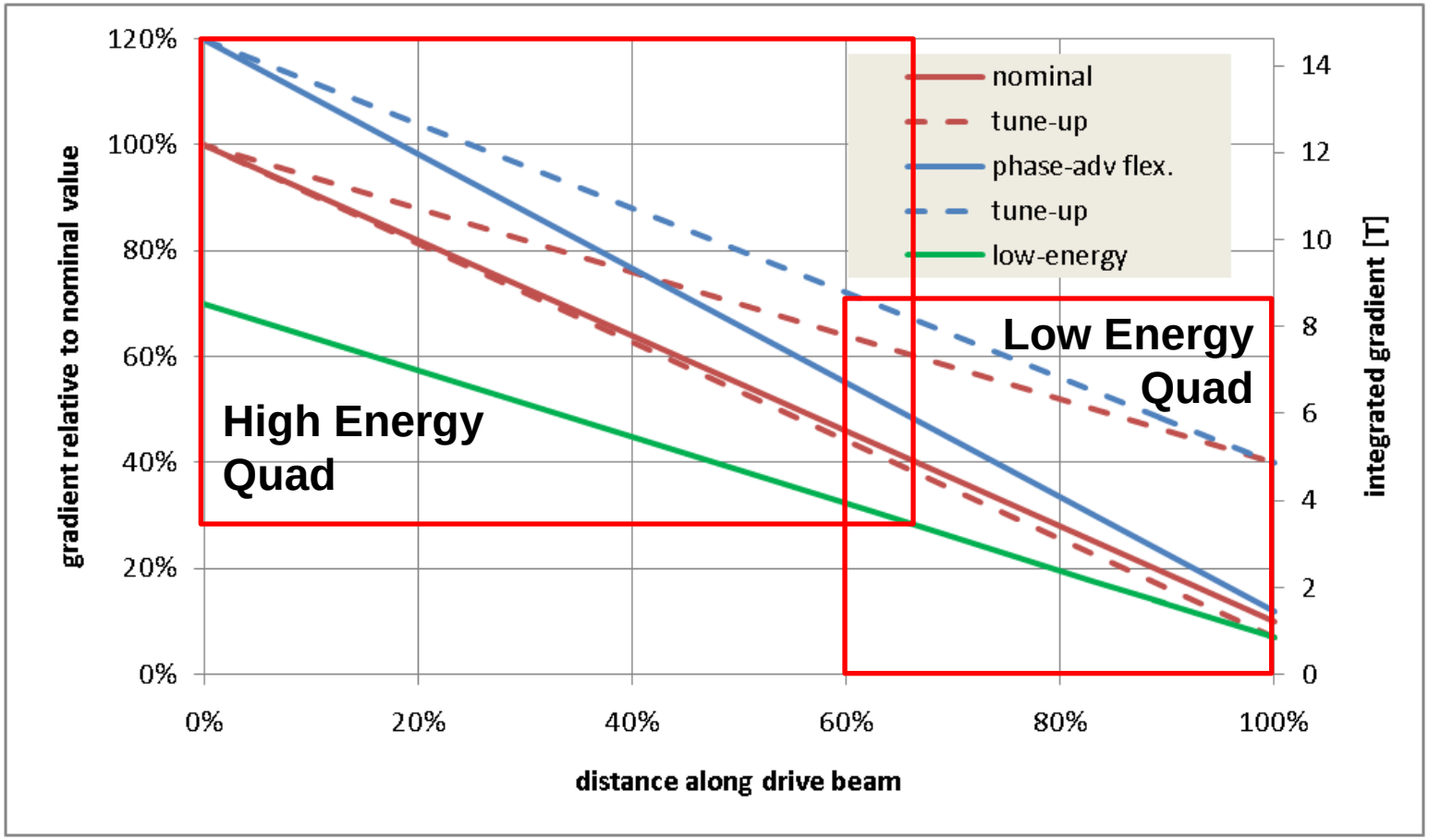
**JAI/Oxford:** beam FB+FF, laserwire, BPMs

**JAI/RHUL:** transverse beam size, cavity BPMs

**Dundee:** longitudinal beam profile monitor

# Drive beam

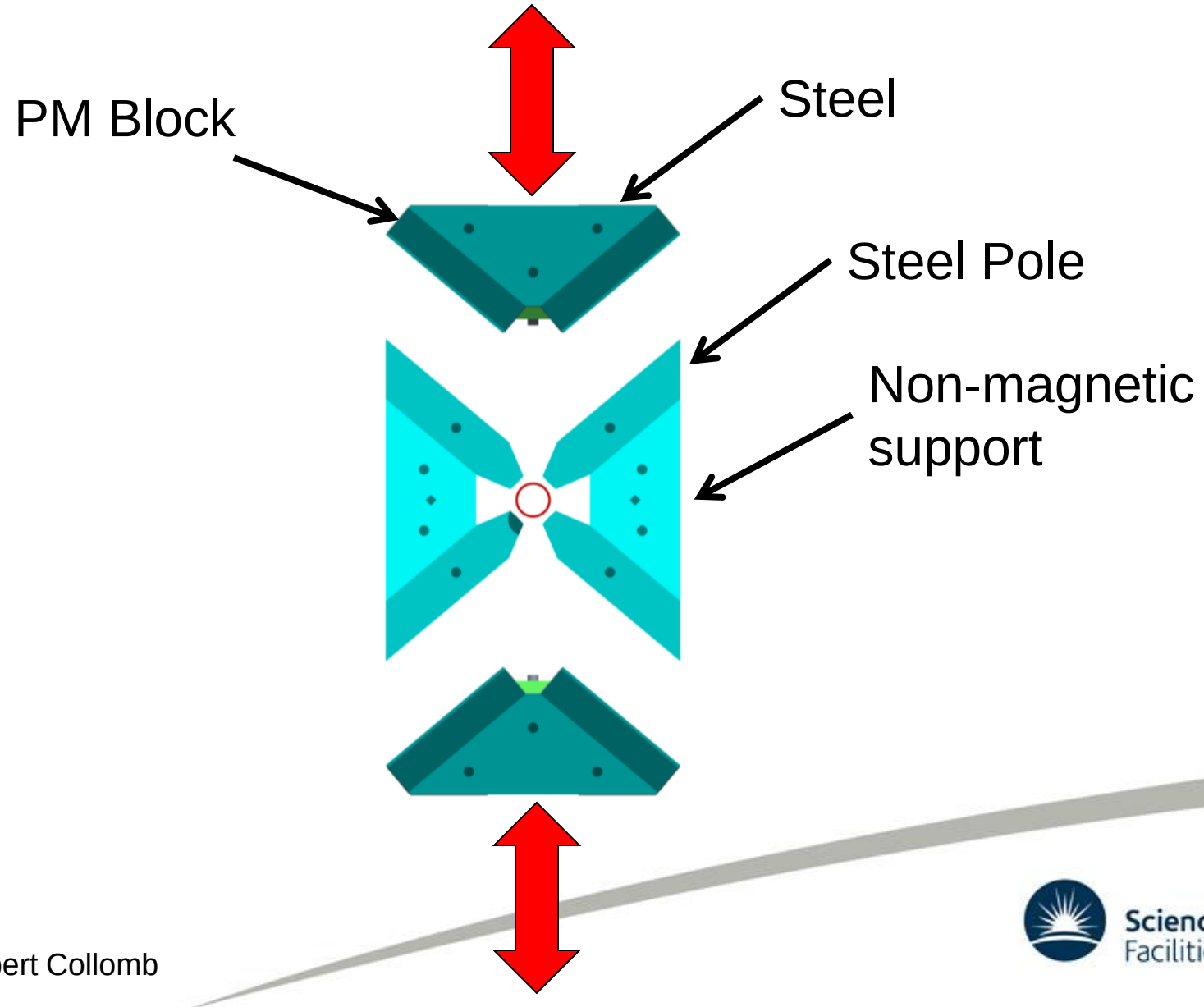
# Drive Beam Quadrupoles (ASTeC)

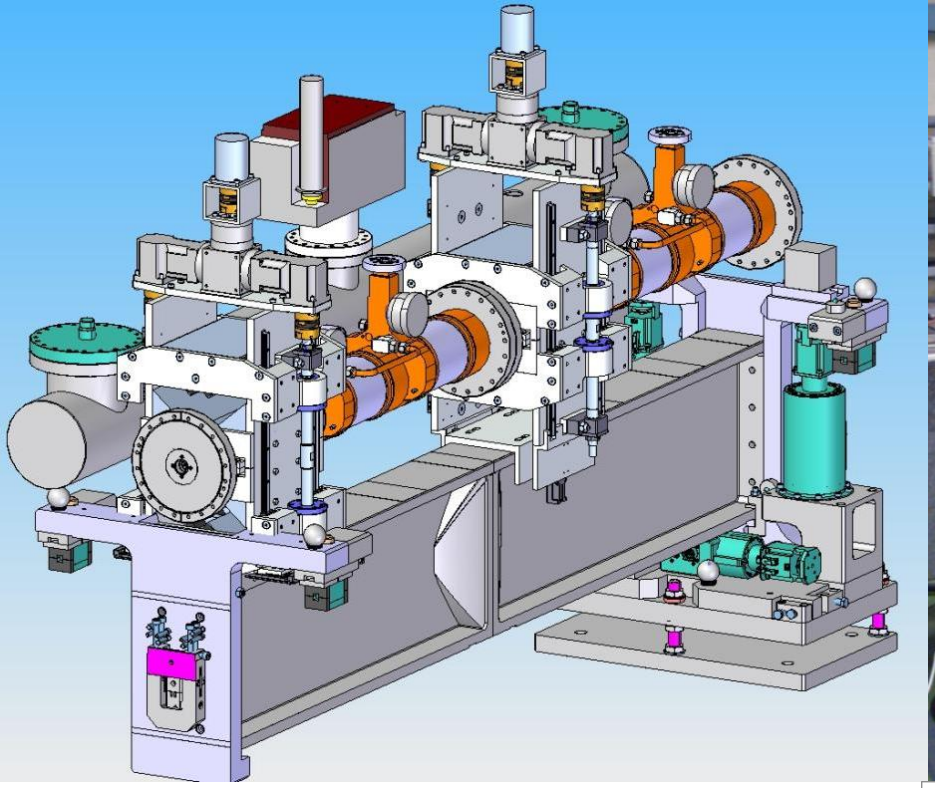


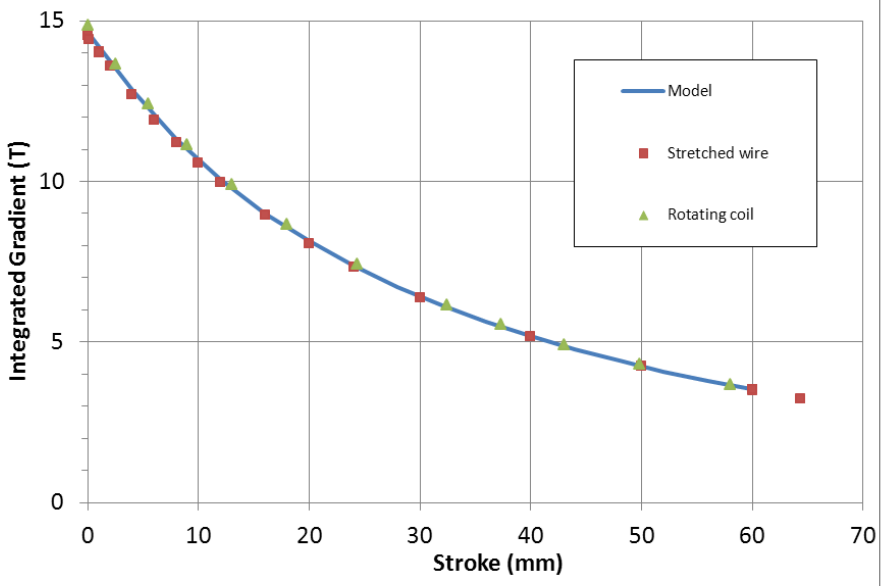

**High energy quad – Gradient very high**
**Low energy quad – Very large dynamic range**

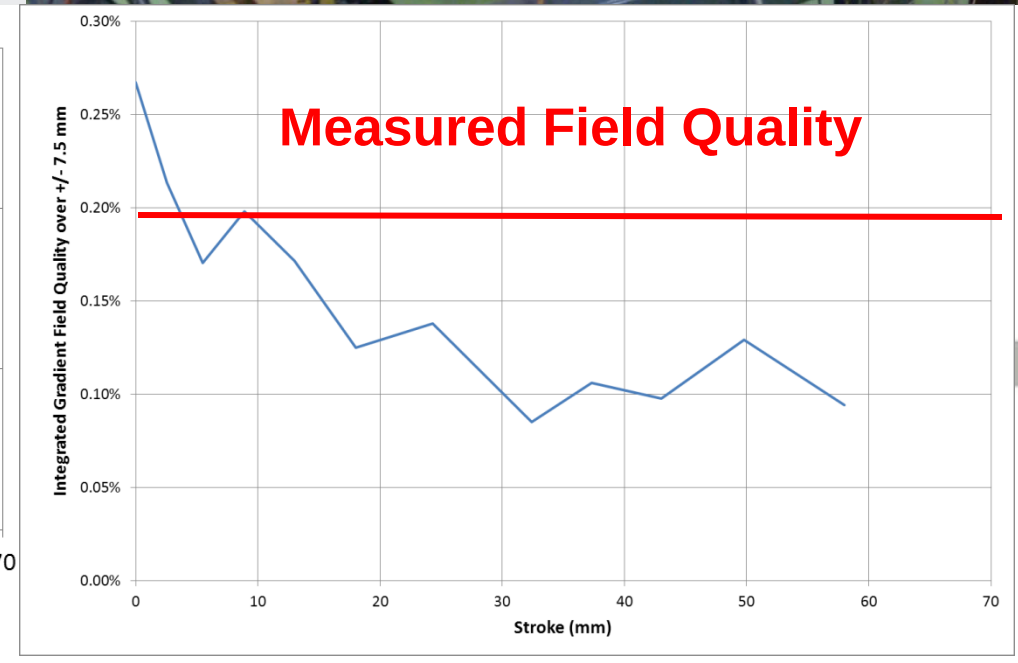
Science & Technology Facilities Council

# Basic Engineering Concept

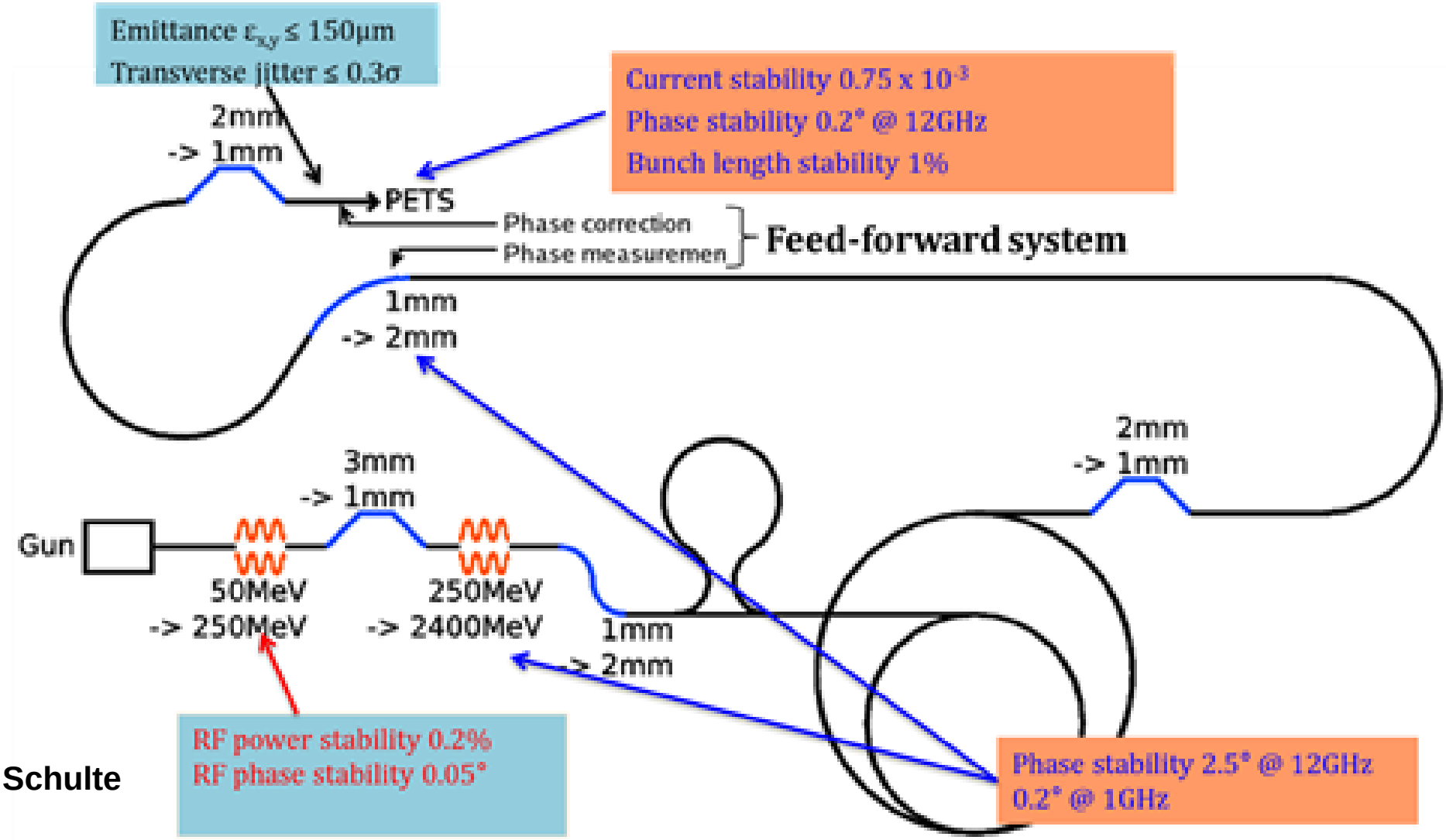





Integrated Gradient (T)
15
10
5
0
0
10
20
30
40
50
60
70
Stroke (mm)
Model
Stretched wire
Rotating coil

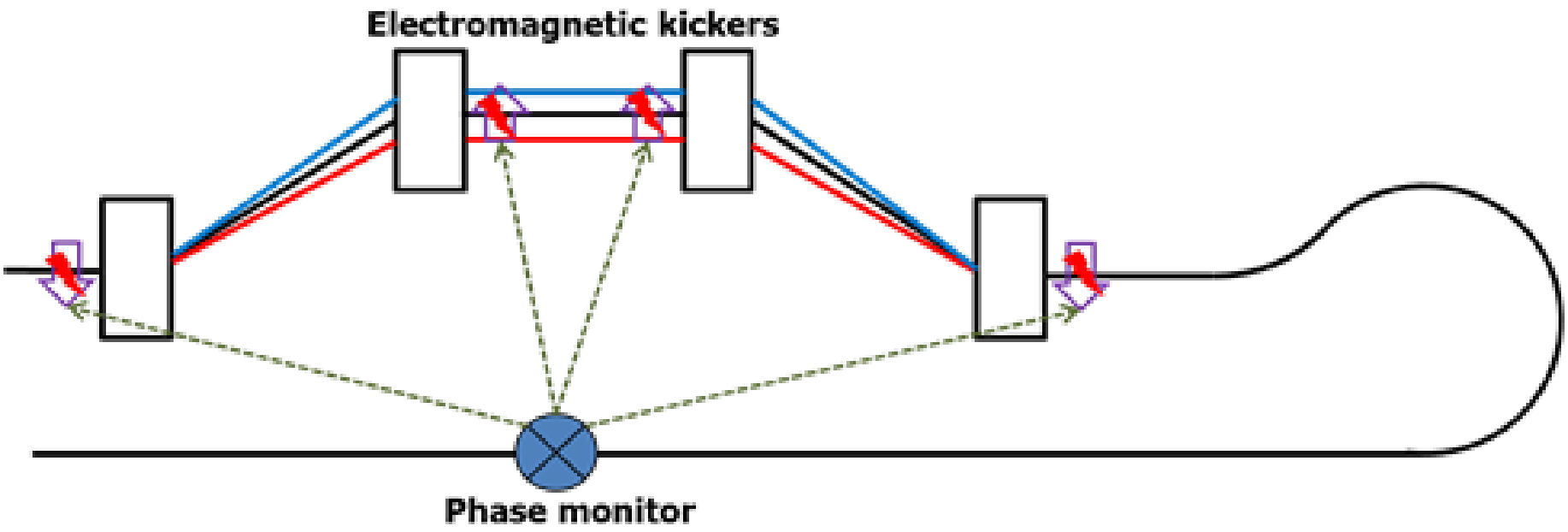

Measured Field Quality
Integrated Gradient Field Quality over +/- 7.5 mm
0.30%
0.25%
0.20%
0.15%
0.10%
0.05%
0.00%
0
10
20
30
40
50
60
70
Stroke (mm)

# Drive beam phase feed-forward (Oxford)



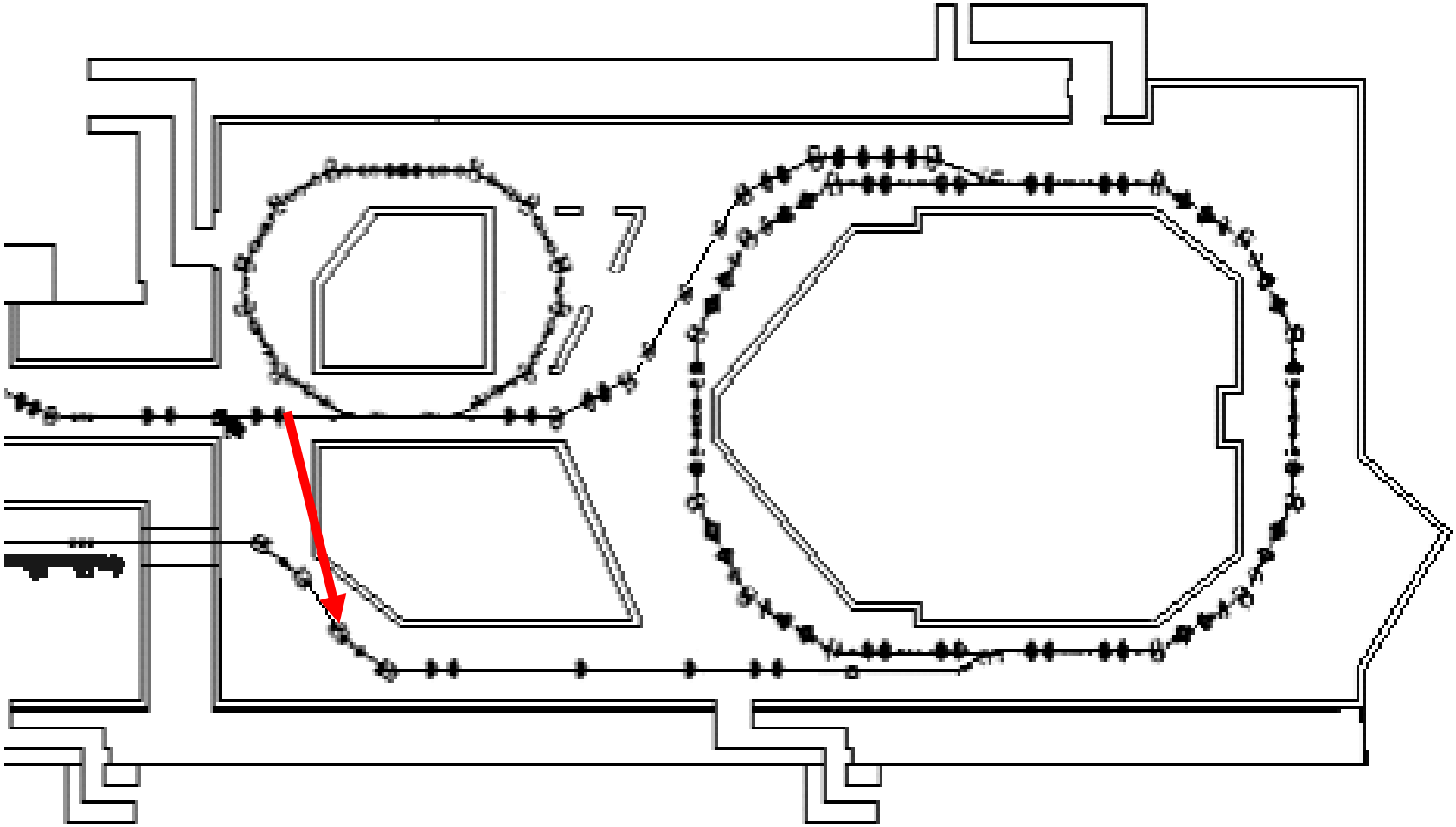

Schulte

# Drive beam phase feed-forward




**Skowronski**

# 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)**

**→ 1 mrad kick**

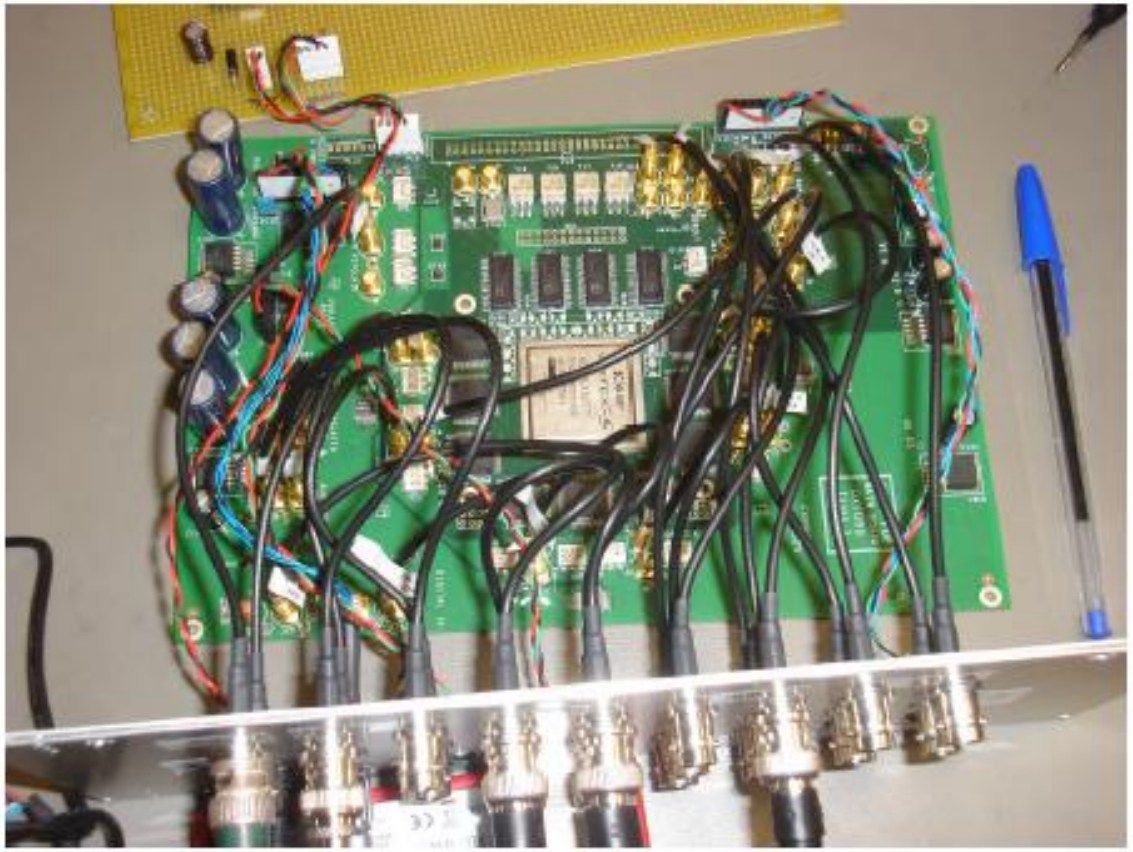
**→ 1.2 mm path length change**

**→ 17 degrees at 12 GHz**

**→ 0.2 degree resolution**

# FONT5 Digital Signal Processing board

- 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 for ancillary functions



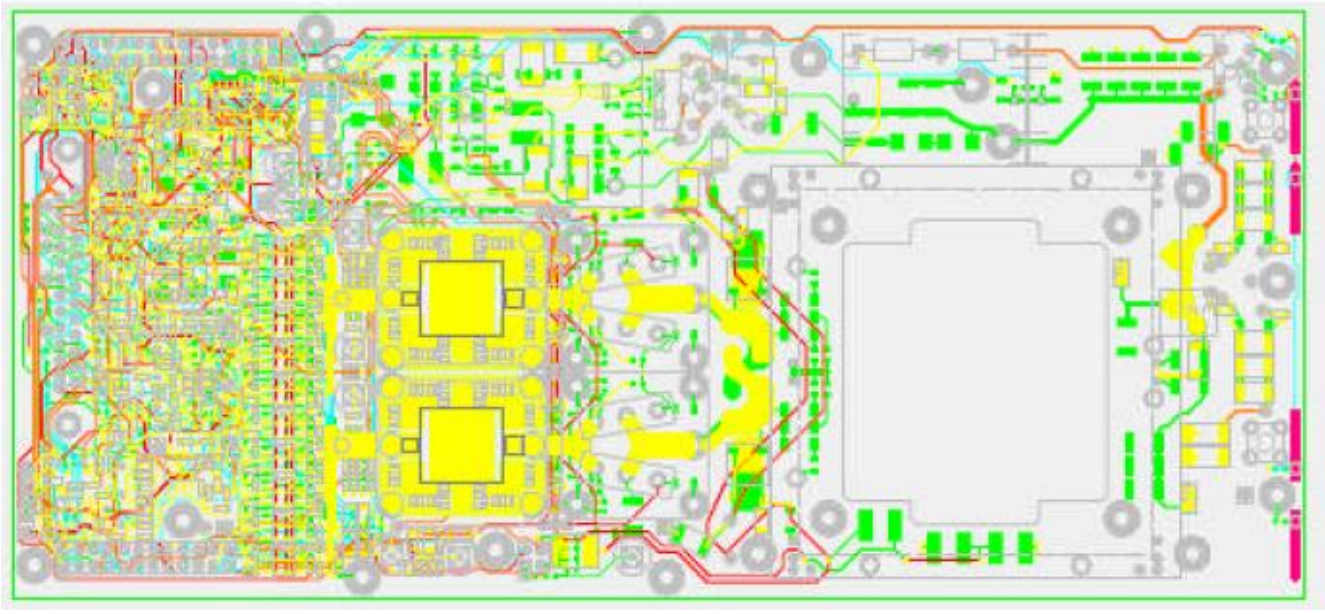
•Currently have two boards but ten new build (FONT5A) boards in production.

•Additional features: USB2 interface to support faster data rate; modified input transformers for CTF3 operation

•At least two boards will stay at CTF3 for Phase FF

# Drive amplifier

- 65kW peak power
- Bandwidth > 50 MHz
- 1.2 us (non-combined) beam pulse
- < 10% droop
- PCB-based design using SiC FETs

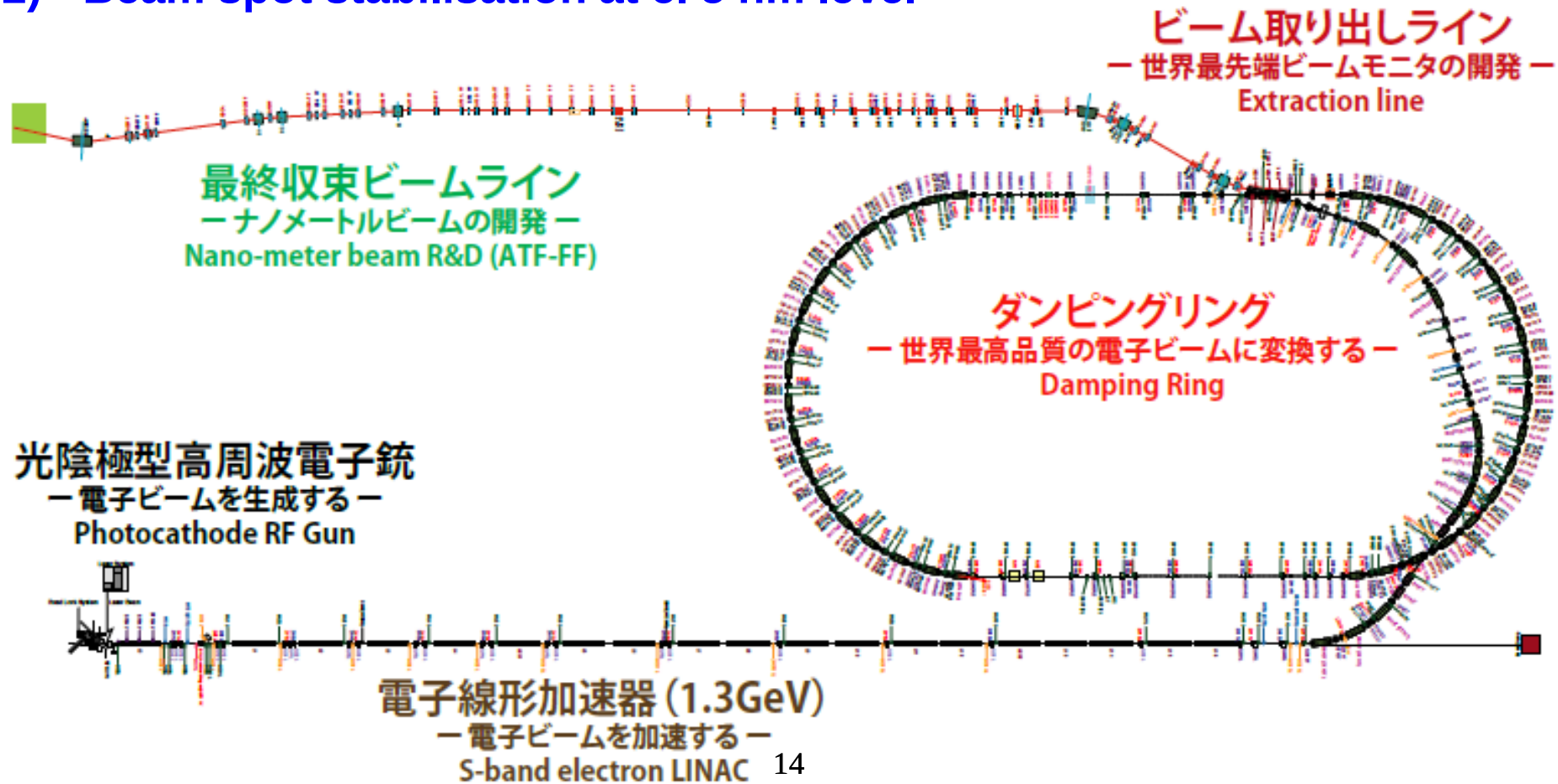


# Feedback and instrumentation

# ATF2/KEK: prototype final focus

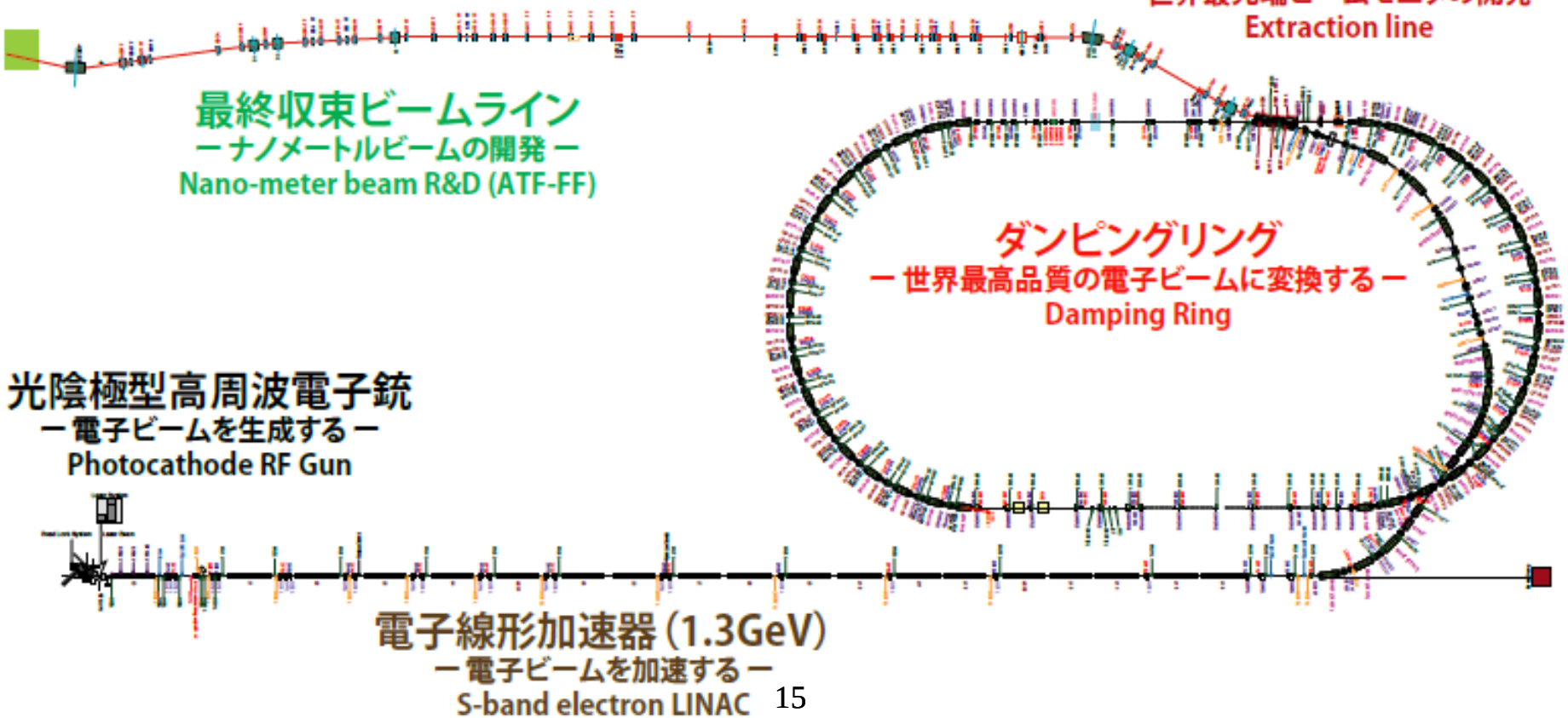
**Goals:**

1) **37 nm beam spot (65 nm achieved 2013)**
2) **Beam spot stabilisation at c. 5 nm level**

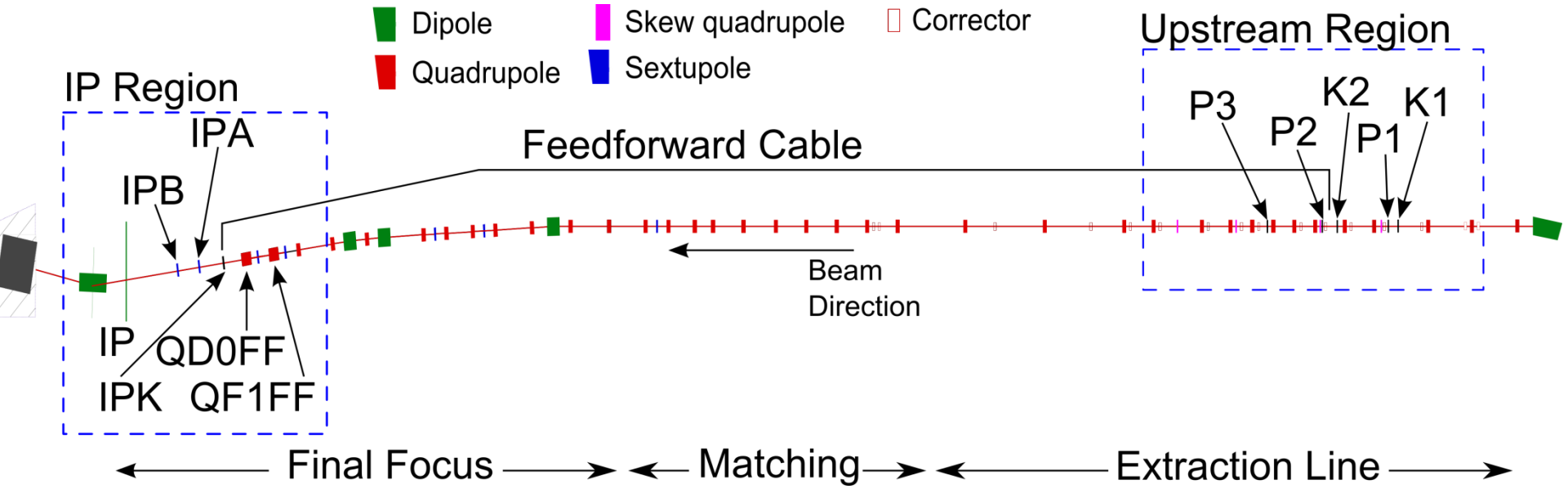


# ATF2/KEK: prototype final focus

**Beam feedback + feed-forward systems**
**Precision cavity + stripline BPMs**
**Beam size diagnostics**
**Beam tuning techniques**



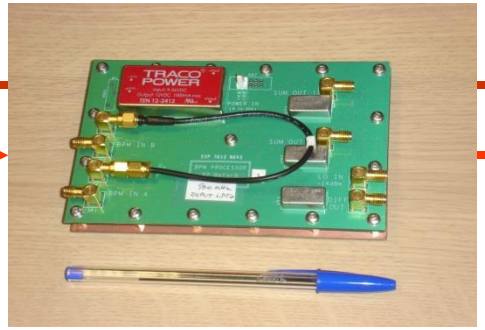
# Beam feedback + feed-forward (Oxford)




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

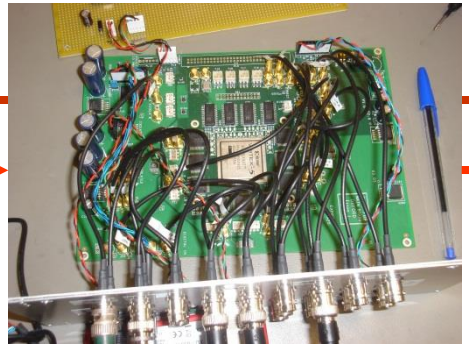
1. **Upstream FB** — **monitor beam at IP**
2. **Feed-forward** — **from upstream BPMs → IP kicker**
3. **Local IP FB** — **using IPBPM signal and IP kicker**

# Upstream FONT5 System




**Analogue Front-end**

**BPM processor**

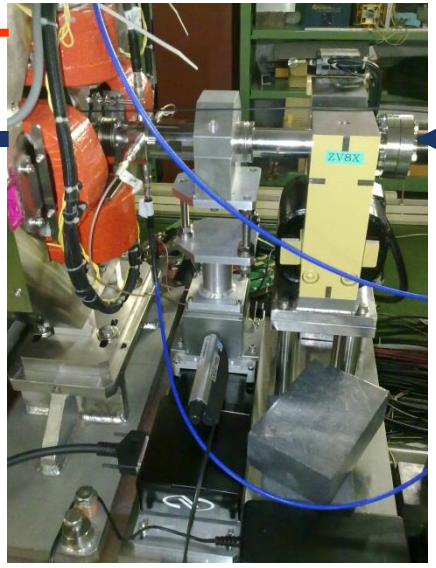


**FPGA-based digital processor**

**Kicker drive amplifier**

**Beam**

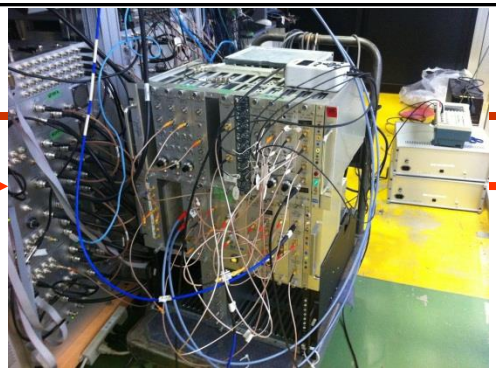
**Strip-line kicker**



**Stripline BPM with mover system**

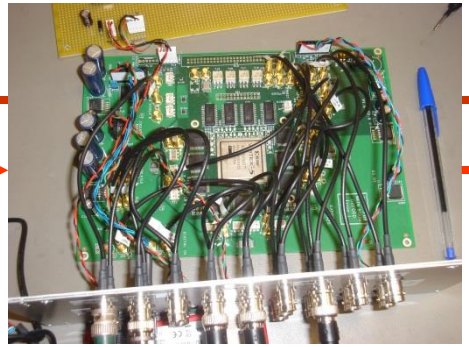
| | |
|---|---|
| BPM Resolution | < 350nm |
| Dynamic range of the BPM system | +/-500µm |
| System Latency | <150 ns |
| Amplifier Bandwidth | ~30 MHz |

# Interaction Point FONT System



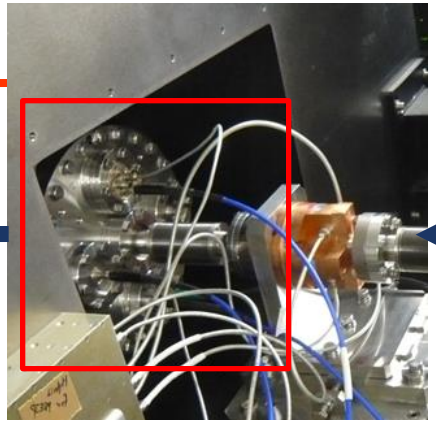
Analogue Front-end

BPM processor



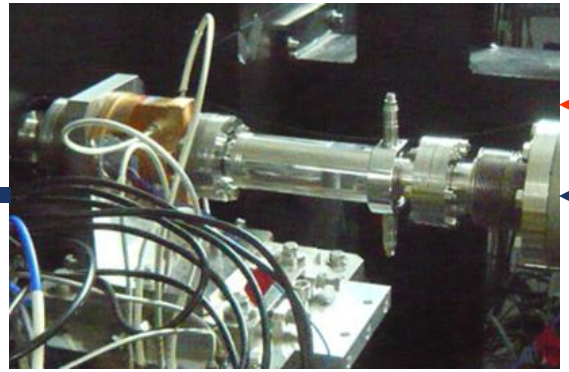
FPGA-based digital processor

Kicker drive amplifier



Cavity BPM

Beam



Strip-line kicker

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

# ATF2 beam stabilisation results

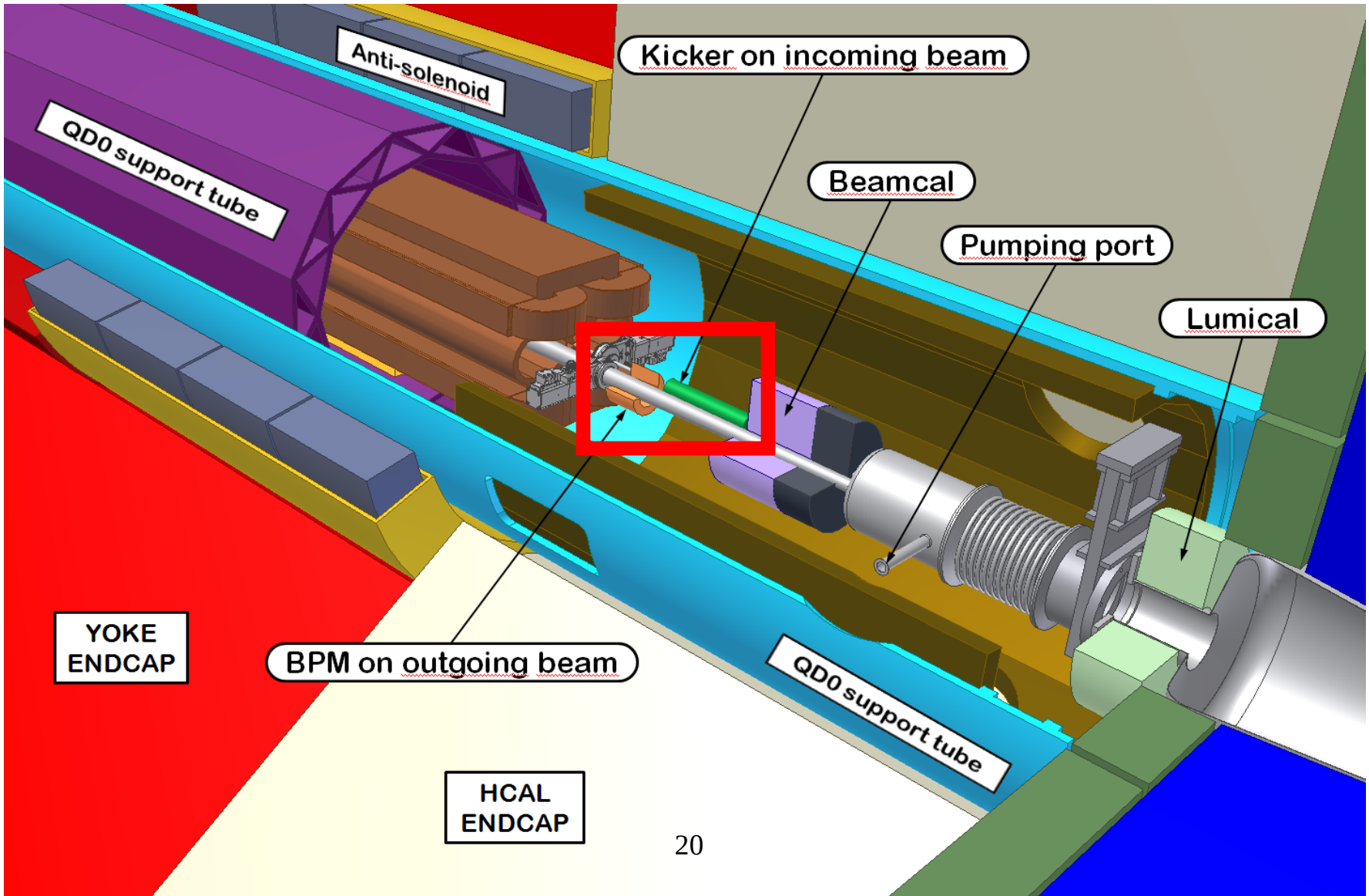
1. Upstream FB: beam stabilised at IP to ~ 300 nm

2. Feed-forward: beam stabilised at IP to ~ 106 nm

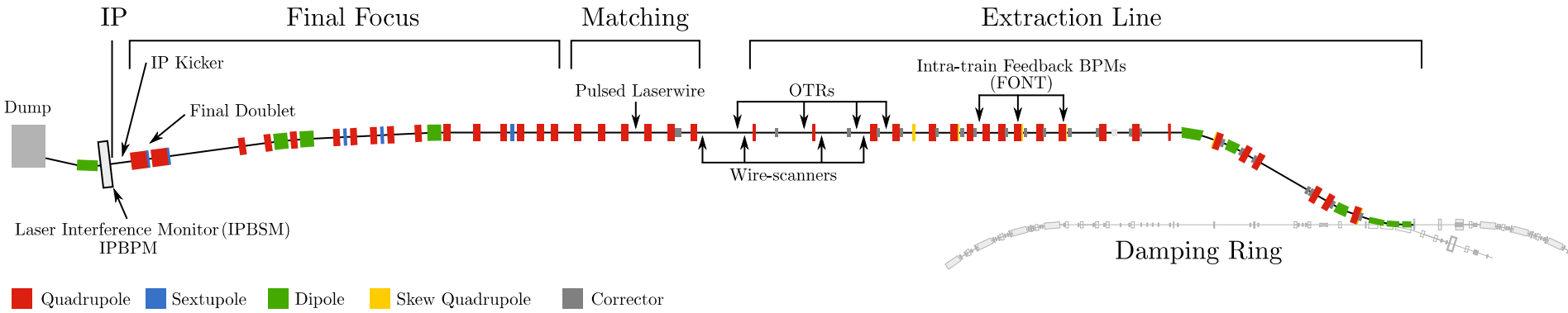
3. IP FB: beam stabilised at IP to ~ 93 nm

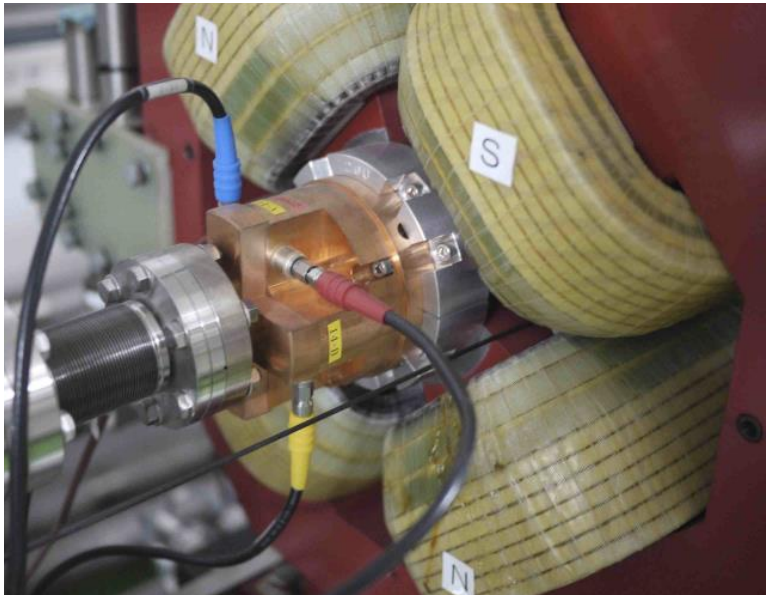
Getting interesting! (i.e. hard)

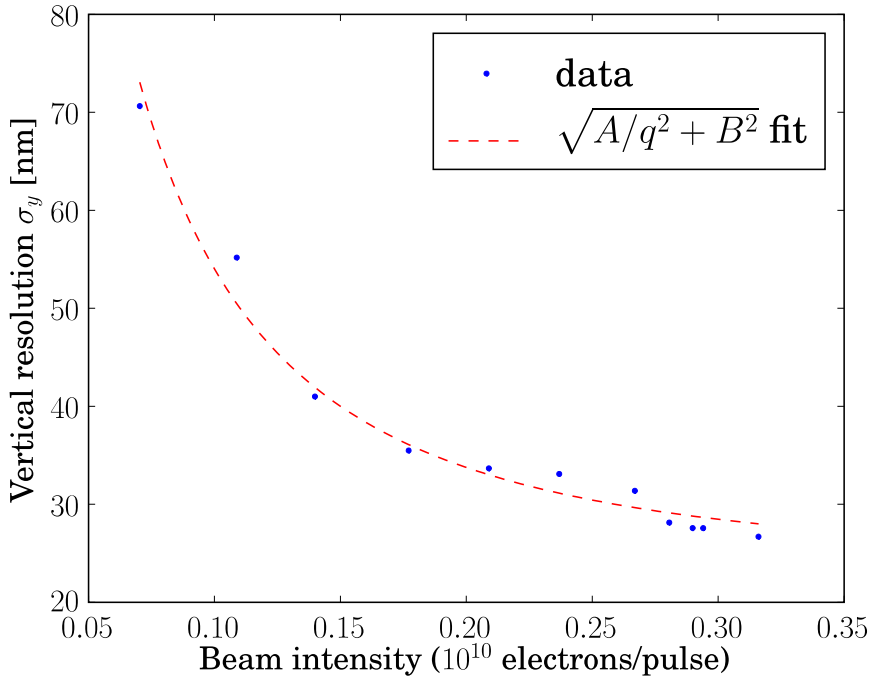
# IP Feedback in CLIC CDR



# ATF2 beam position monitors (RHUL)



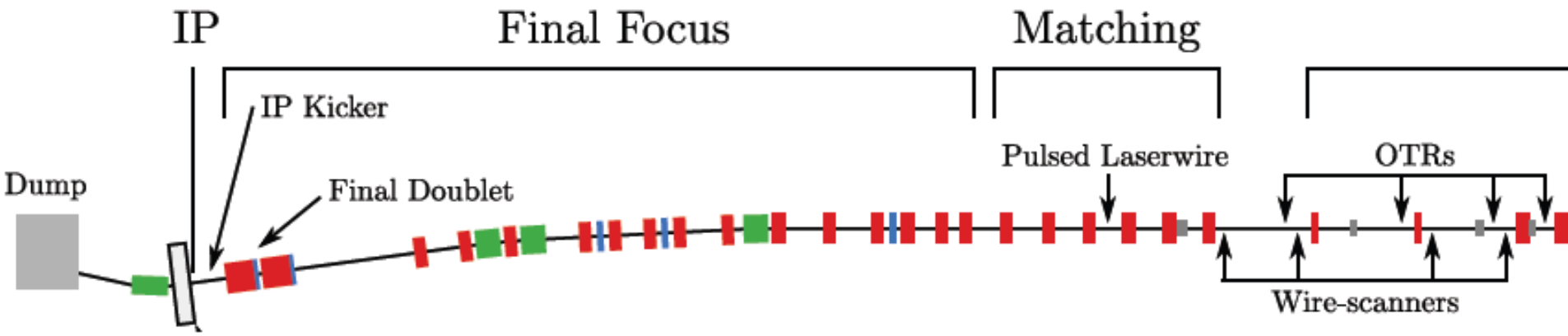



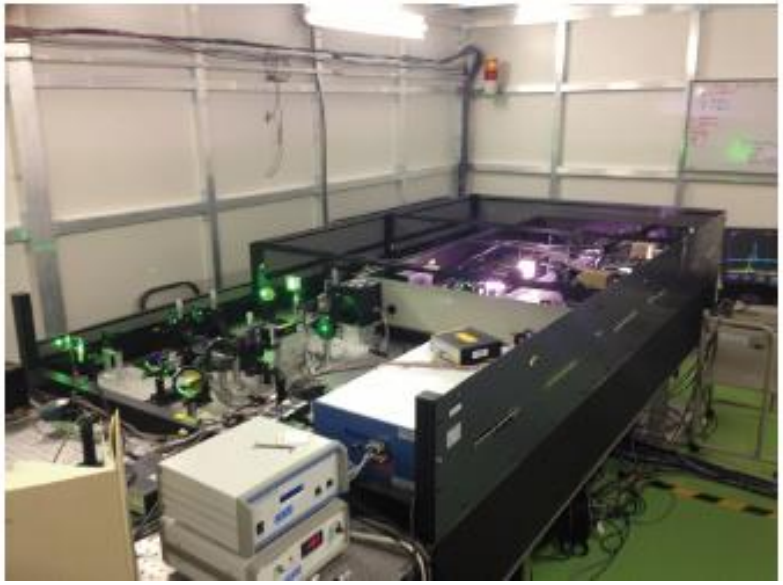



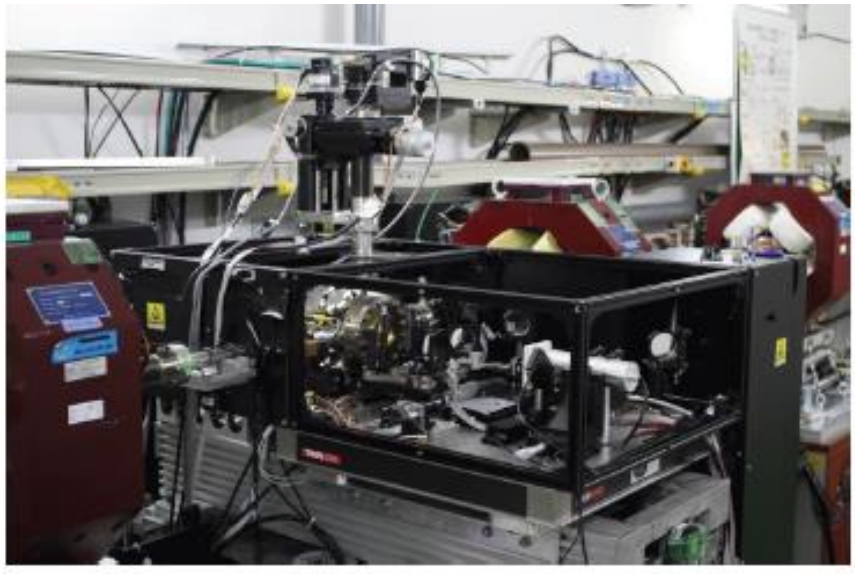
# CLIC Main beam BPM prototype

- Low-Q stainless steel cavity
- Simulation in
  - Gdfidl
  - Microwave studio
- Measurement
  - VNA @ RHUL (before) and CERN (after brazing)
  - Beam measurements @ CALIFES
- Dipole cavity
  - $f_{dipole}$=14.993 GHz
  - $Q_L$= 274
  - $Q_0$=450
- Reference cavity
  - $f_{dipole}$=14.960 GHz
  - $Q_L$= 150

# Transverse beam size (JAI)

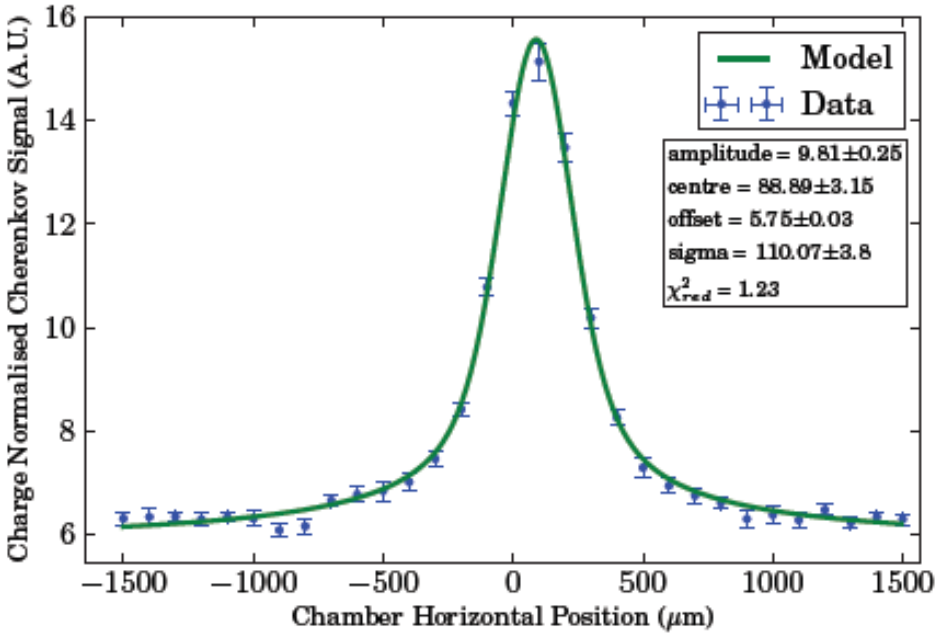


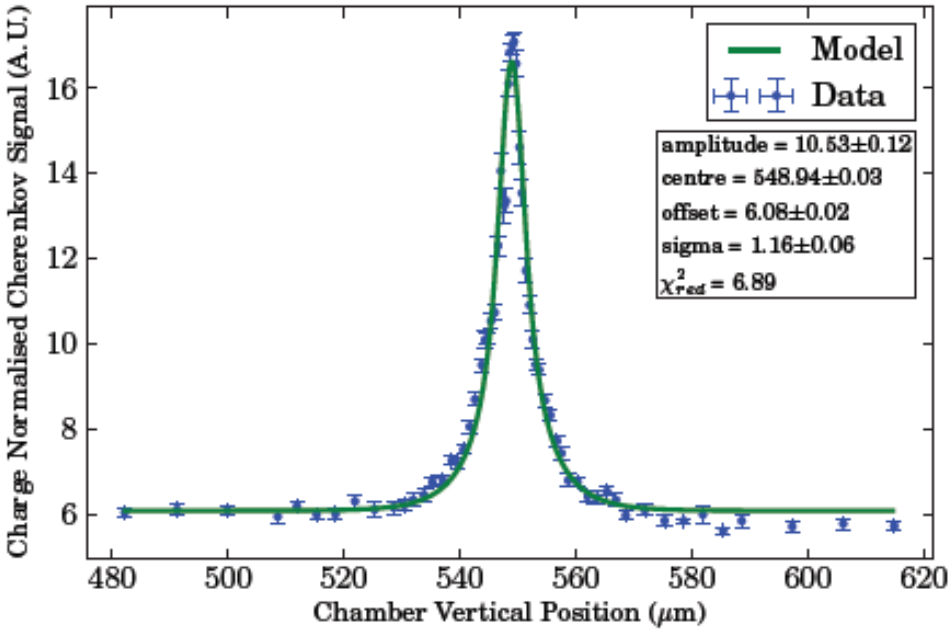





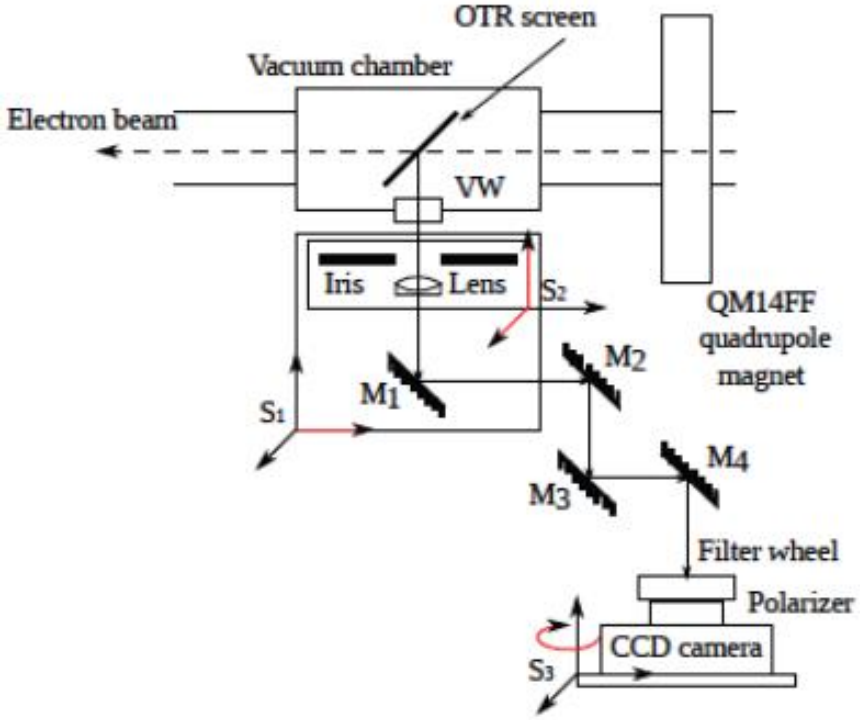
# Laser-Wire Micron-scale Beam size measurements

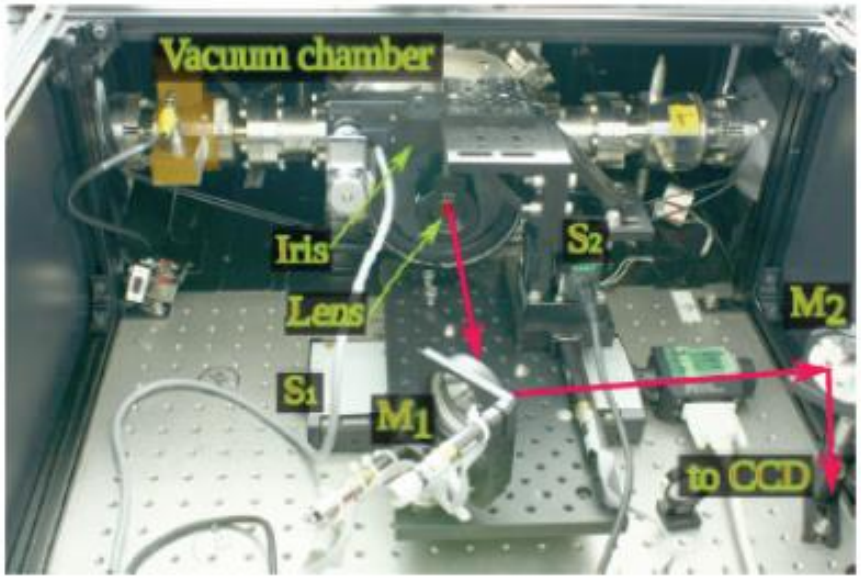
- First measure horizontal beam size
  - Shift focus position
  - Fit to overlap integral
- Vertical scan (at horizontal maximum)
  - Again fit using horizontal electron beam size
  - 5-10% uncertainty on 1 μm



# Sub-micrometer resolution OTR monitor



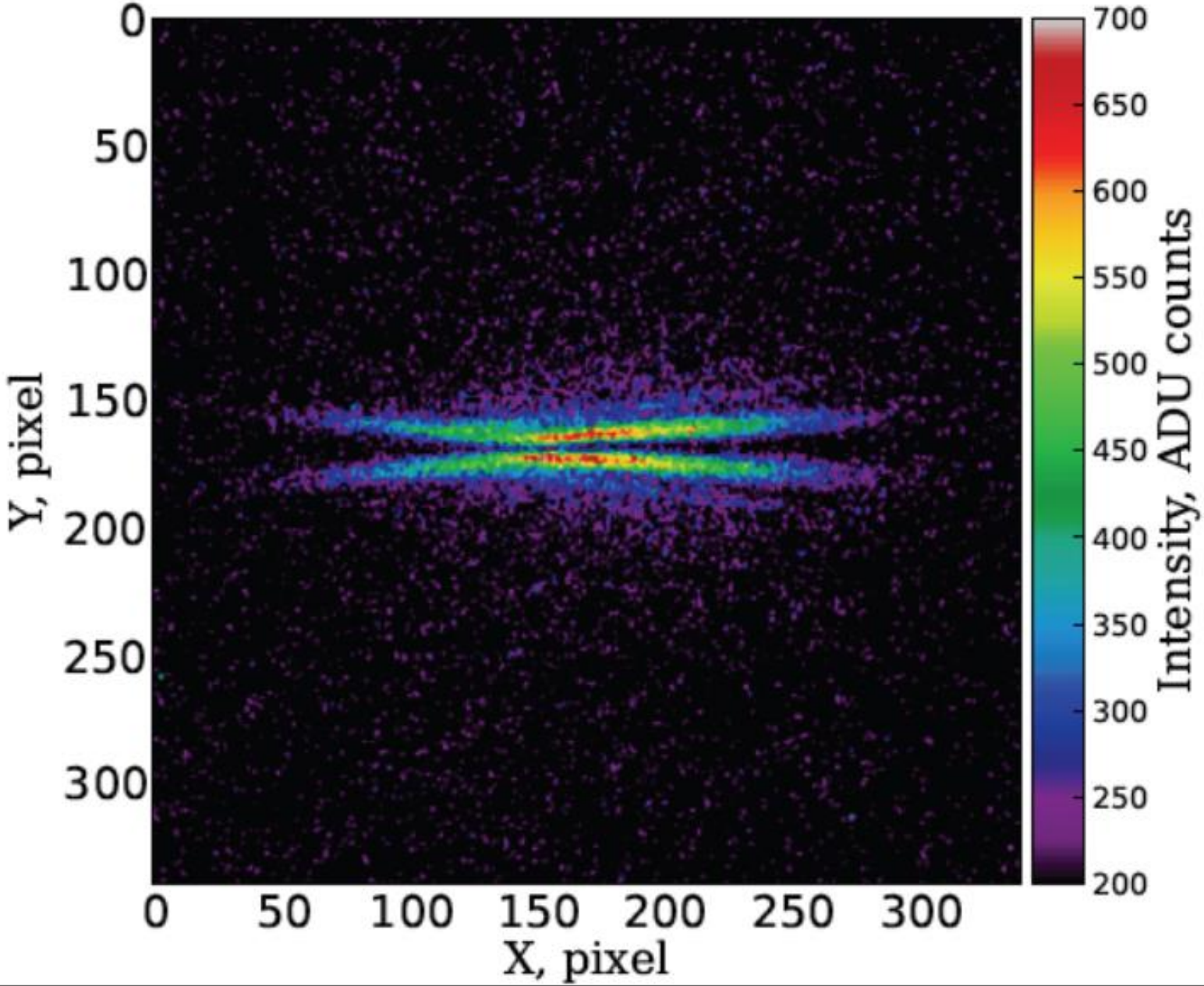




OTR screen

0.3×30×30 mm aluminized silicon

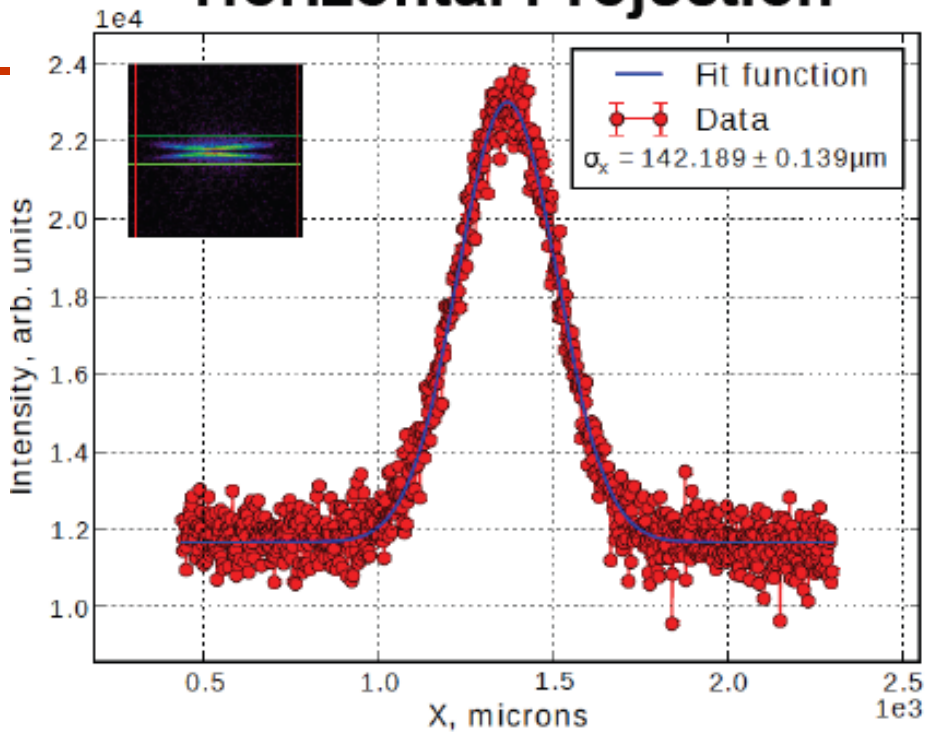
- Lens - "CVI Laser Optics" cemented achromat, $f$=120mm, ø=30mm
- CCD Camera - SBIG-ST8300M with 5.4 $\mu$m pixel size, 3352×2532 pixel array and ∼50% quantum efficiency

# Sub-micrometer resolution OTR monitor

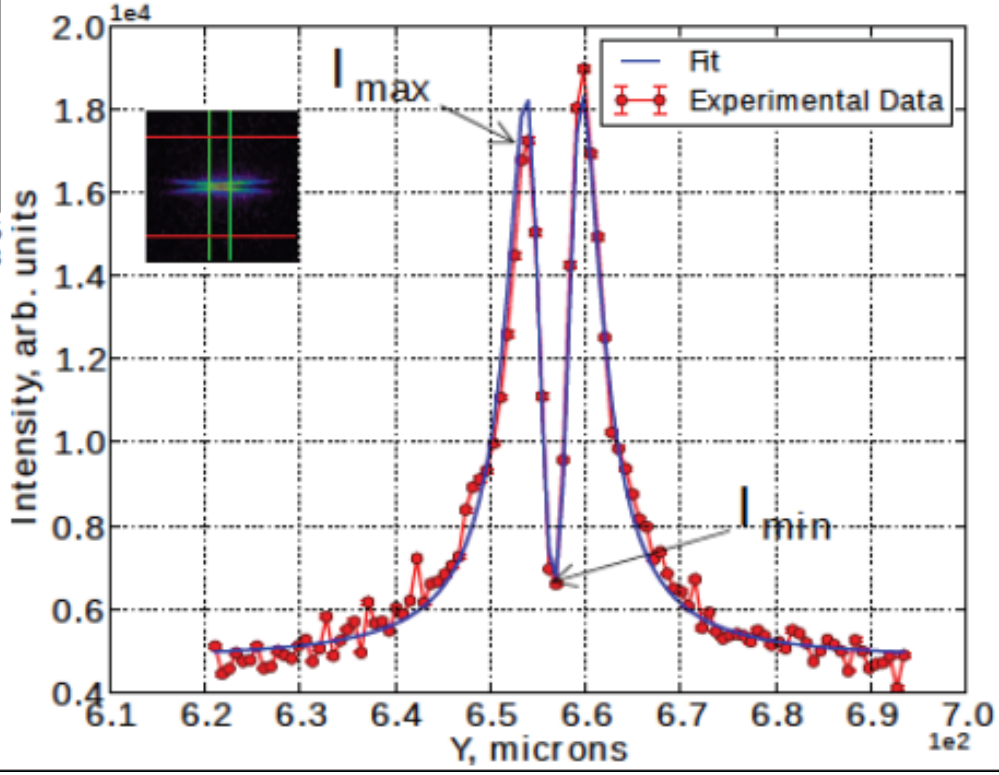


# Sub-micrometer resolution OTR monitor

## Horizontal Projection




## Vertical Projection

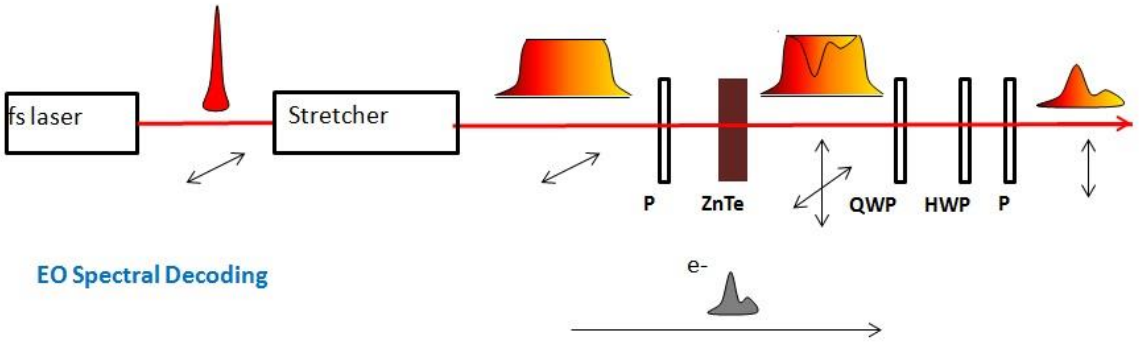



## Minimal Vertical Beam Size

$$\sigma_y = 0.754 \pm 0.034$$

# Electro-Optical Spectral Decoding (Dundee)

## Simulations of bunch-induced polarisation change and non-linear interaction



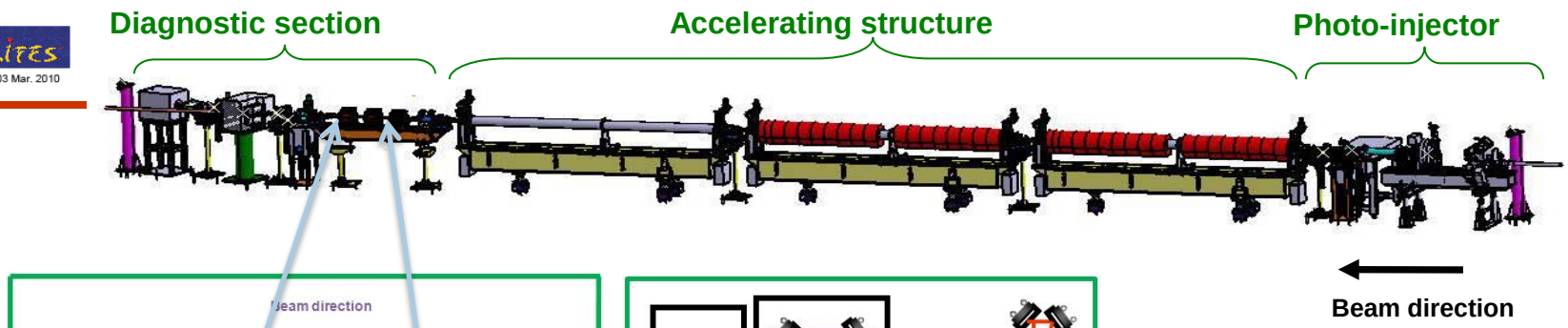

**Spectral Decoding (EOSD):** The Coulomb field temporal profile of the e-bunch is encoded on to a *time-wavelength correlated* optical probe pulse. The profile is read-out through the *spectrum* of the probe pulse.

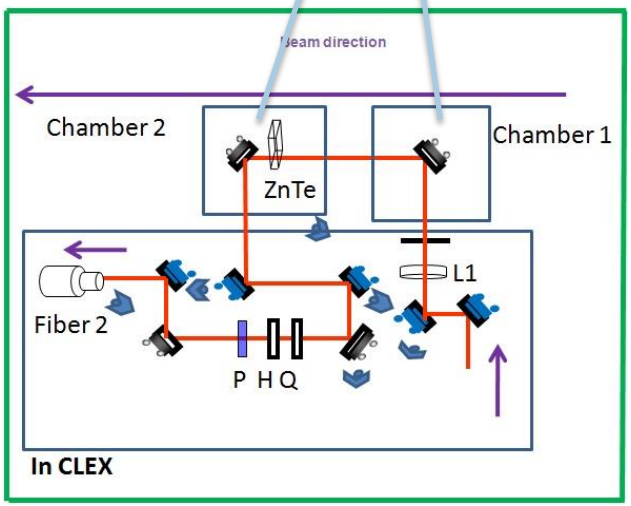
$$E_{\mathrm{Out}}(\omega) = \begin{bmatrix} 0 & 1 \end{bmatrix} R(\varphi)\, M_{\mathrm{H}} R(-\varphi)\, R(\alpha)\, M_{\mathrm{Q}} R(-\alpha)\, R(\theta)\, M_{\mathrm{EO}} R(-\theta) \begin{bmatrix} E_{\mathrm{Laser}}^{\mathrm{Chirp}}(\omega) \\ 0 \end{bmatrix}$$

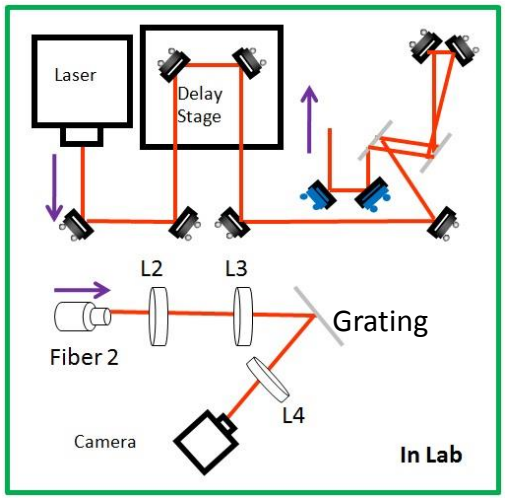
Where, $$M_{\mathrm{EO}} = \begin{bmatrix} \left(1 + \frac{i\omega}{2nc} \cdot \widetilde{E}_{\mathrm{Coul}*}^{Eff}\right) & 0 \\ 0 & \left(1 - \frac{i\omega}{2nc} \cdot \widetilde{E}_{\mathrm{Coul}*}^{Eff}\right) \end{bmatrix}$$

Where, $$\widetilde{E}_{\mathrm{Coul}}^{Eff}(0,\Omega) = \chi_{Eff}^{(2)} \left[\frac{e^{i\Delta k(\omega,\Omega)z} - 1}{i\Delta k(\omega,\Omega)}\right] \cdot \widetilde{E}_{\mathrm{Coul}}(0,\Omega)$$

# Implementation of the EO monitor at CALIFES




**P**: Polarizer **H**: Half wave plate
**Q**: Quarter wave plate
: Mirror with actuators
: Finger camera

**Laser:**
Wavelength: 780 nm Duration: 100 fs
Repetition: 37.4815 MHz Pulse energy: 2.7 nJ
**Crystal:** Thickness: 1mm Separation: 5-10 mm

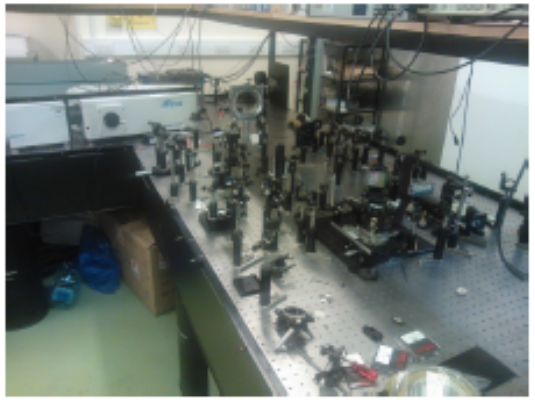
| In CLEX | | In Lab | |
|---|---|---|---|
| 10 Actuators | 7 Plane mirrors | 1 Laser | 10 Plane mirrors |
| 3 Rotation motors | 2 Polarizers | 1 ICCD Camera | 3 Gratings |
| 6 Finger cameras | 2 Wave plates | 1 Motor stage | 3 Lenses |
| | 1 Lens | | 1 Fibre head |
| | 1 Fibre head | | |

| Gated iCCD Camera | |
|---|---|
| Intensifier size | 25 mm |
| Number of Pixels | 1280 x 1024 |
| Pixel Size | 6.7 um x 6.7 um |
| Scan Area | 8.6mm x 6.9mm |
| Scaling Rates (magnification) | 1: 2.17 |
| CCD Temperature (by air) | -12 °C |
| Full Well Capacity (Image pixel well depth) | 25,000$e^-$ |
| Readout Noise | 7…8$e^-$ @12.5MHz |
| A/D convertor | 12 bit |
| A/D conversion factor (Sensitivity) | 5 $e^-$/count |
| Average Dark Charge (Equivalent Background Illuminance) | <0.1 $e^-$/pixel sec |
| Readout Time (Full frame) | 8 fps |
| Min gating time | 3 ns |

# Higher time resolution (<20fs) resolution with robust ns lasers

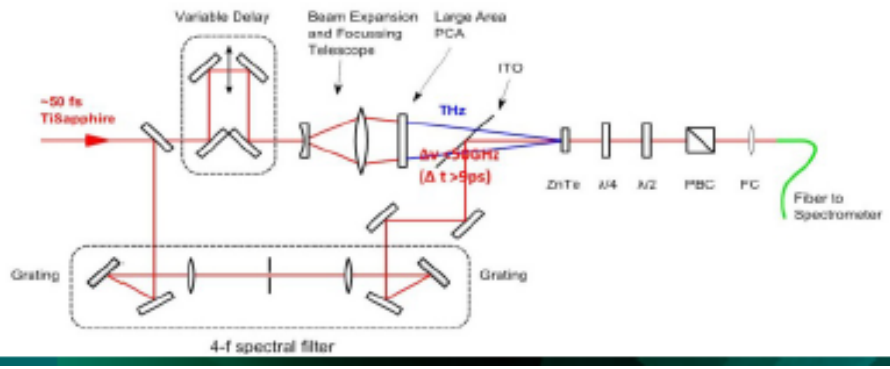
- Pulse carving of narrowband probe laser by Coulomb field
- Optical Parametric amplification of “carved” signal
- All optical, self referenced temporal characterisation (‘FROG’)

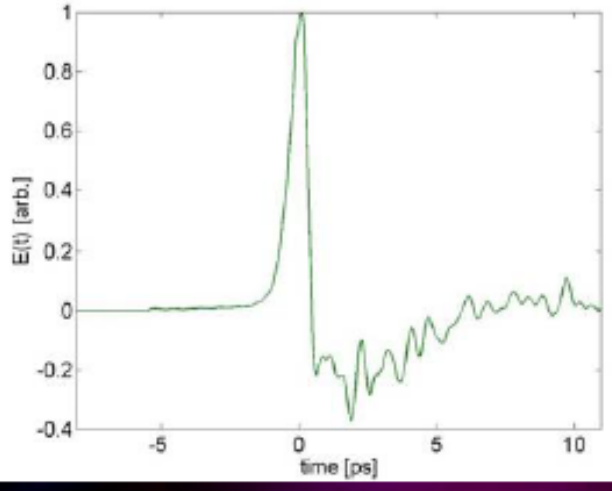
- Characterisation of process using ASTeC developed THz source as electron bunch mimic
  *(source development is independent project )*



- Synchronised, tuneable, narrow band (long pulse) probe of electron bunch mimic . Observation of optical sidebands as measure of process

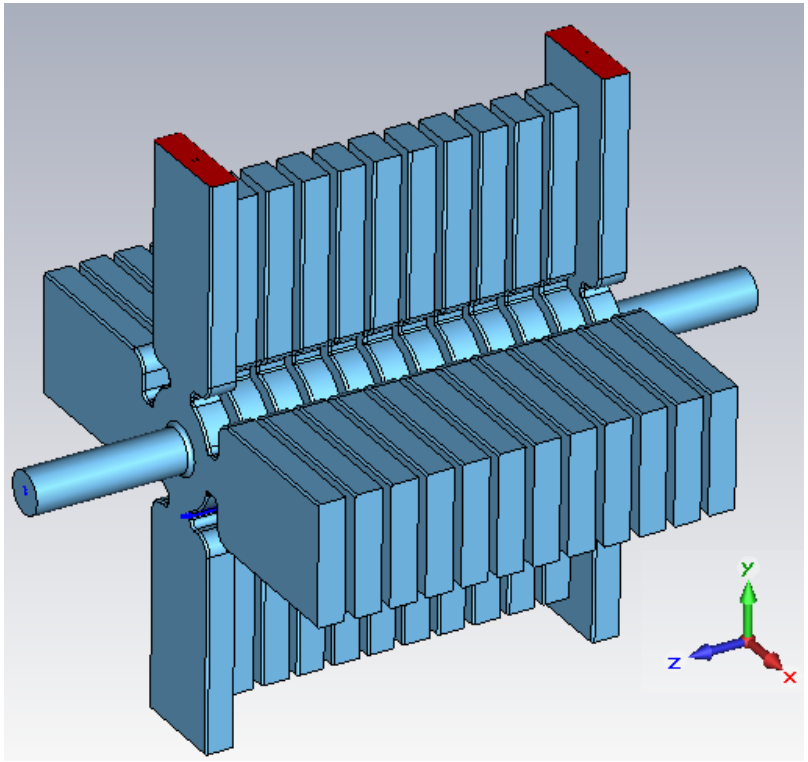
- Single-noise; directionality characterised; extrapolation to CLIC parameters

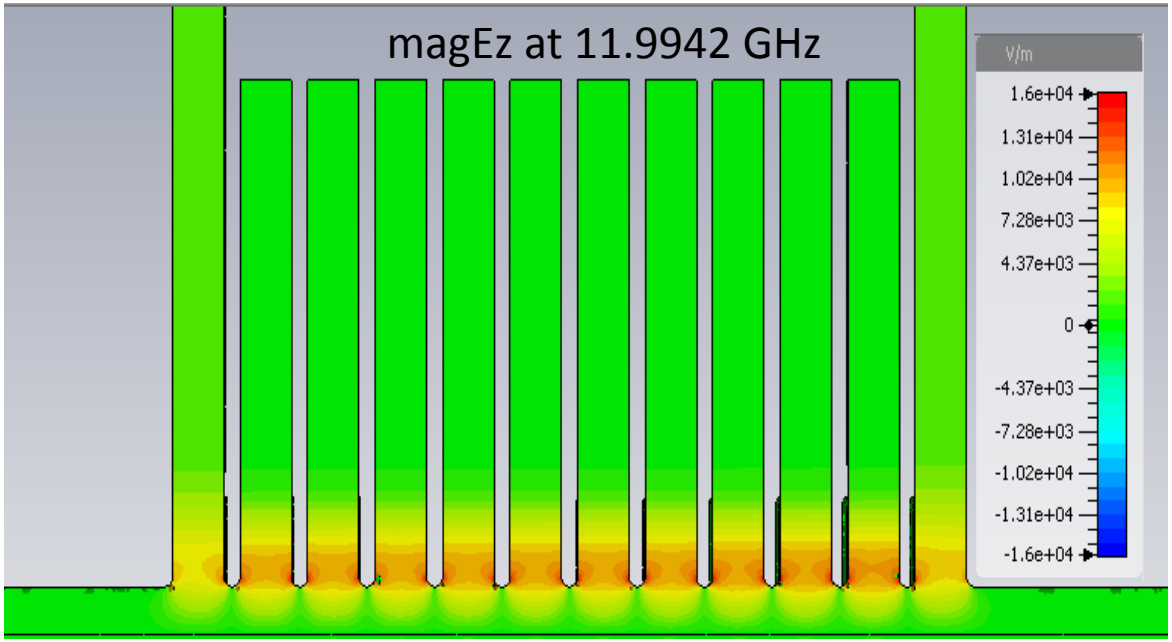


# Crab cavity (Lancaster, ASTeC)

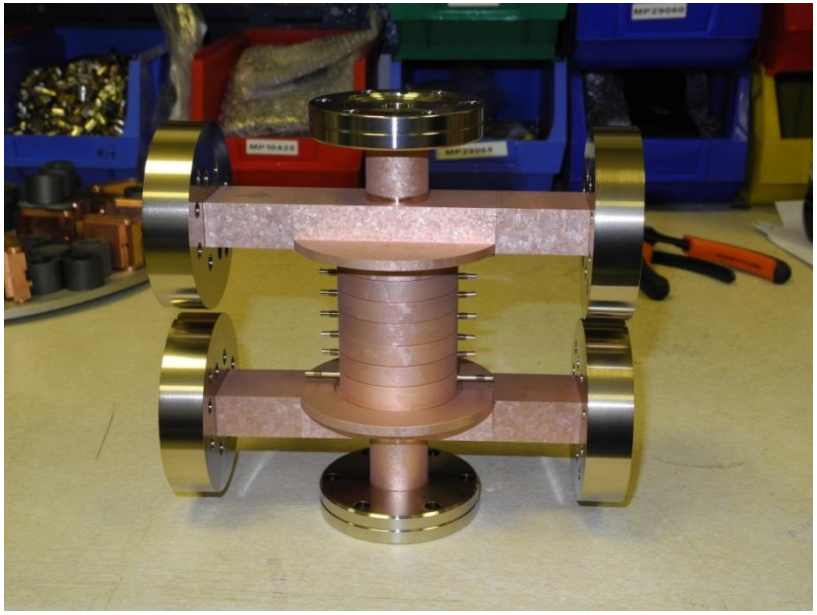
# Full structure (with coupling and damping)

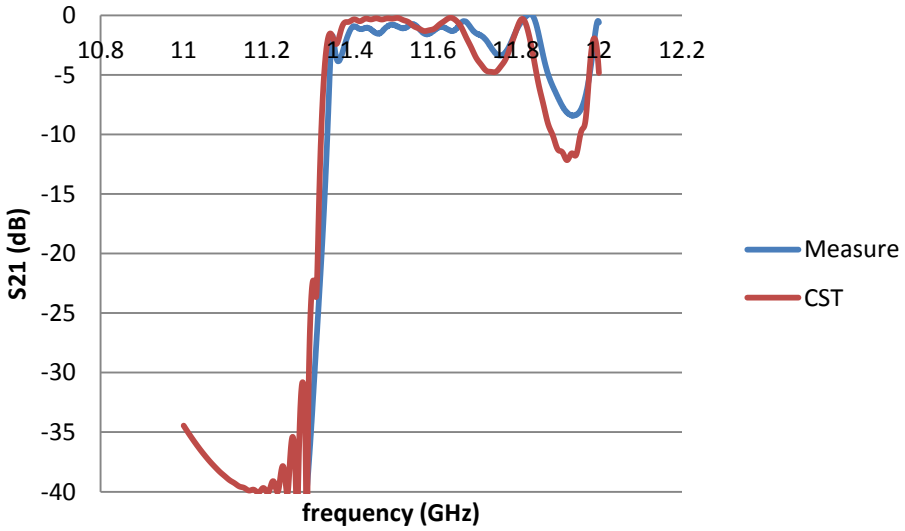


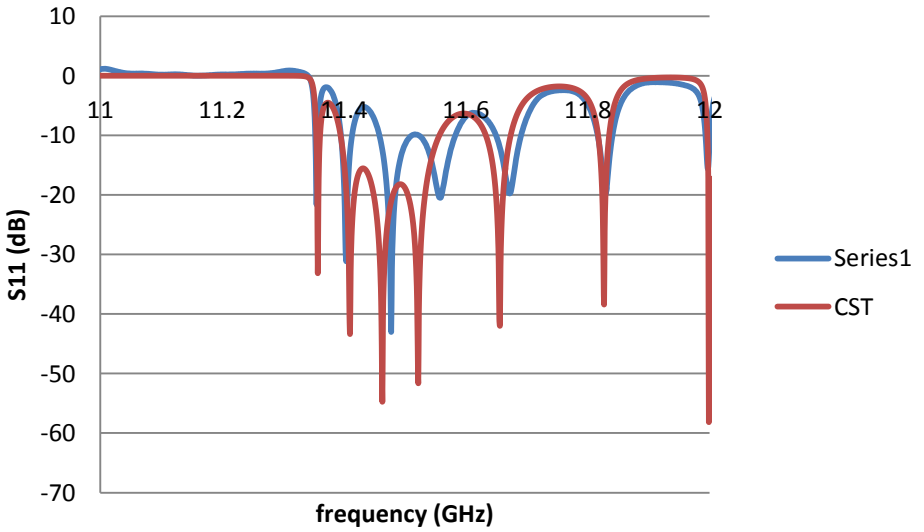



# CLIC Prototype 1 - UK manufactured

The 1st CLIC crab cavity prototype has been manufactured by Shakespeare Engineering in the UK. Tolerance and surface roughness on single parts have been measured and are acceptable.



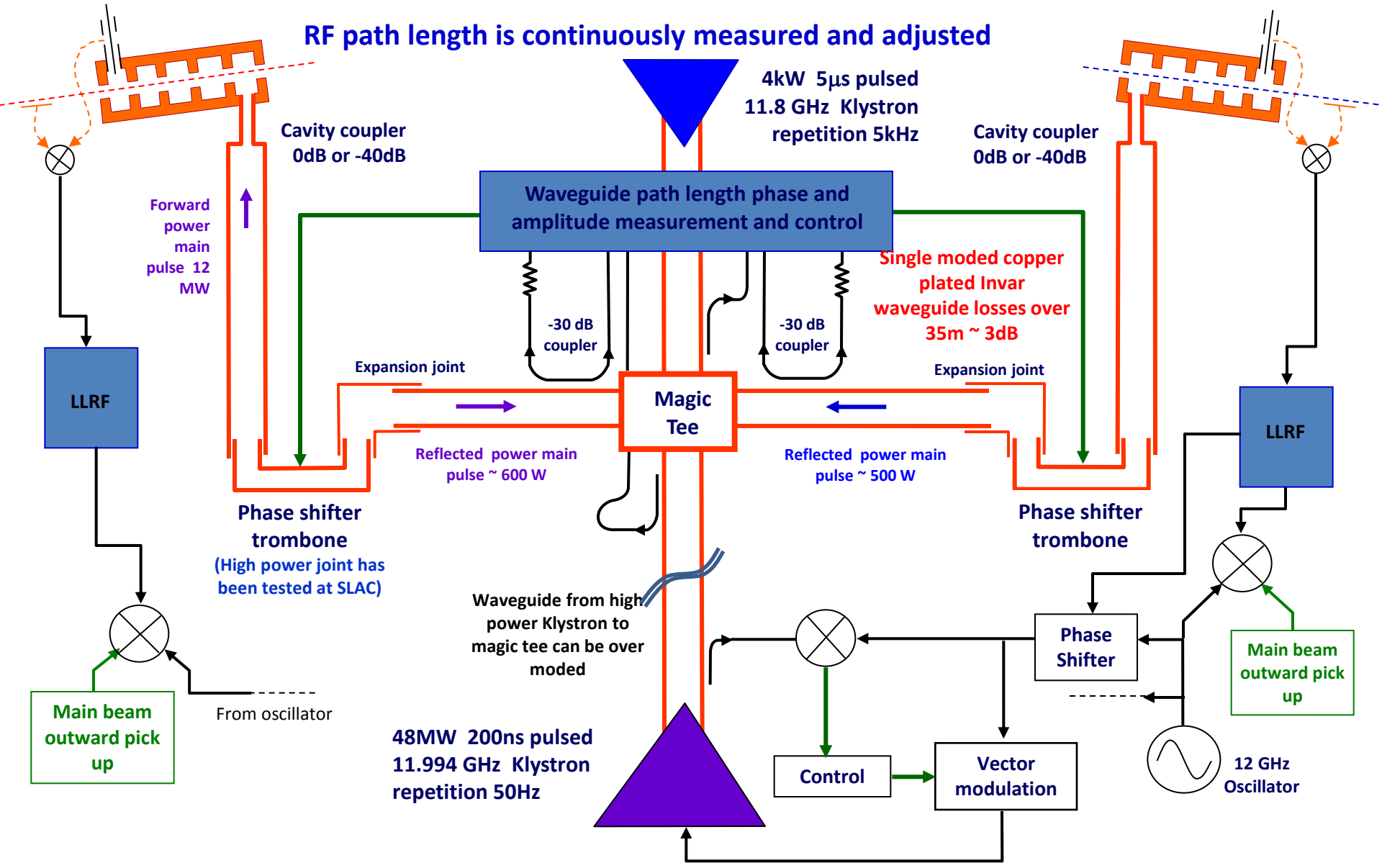



Structure is planned to be tested at SLAC in the near future.

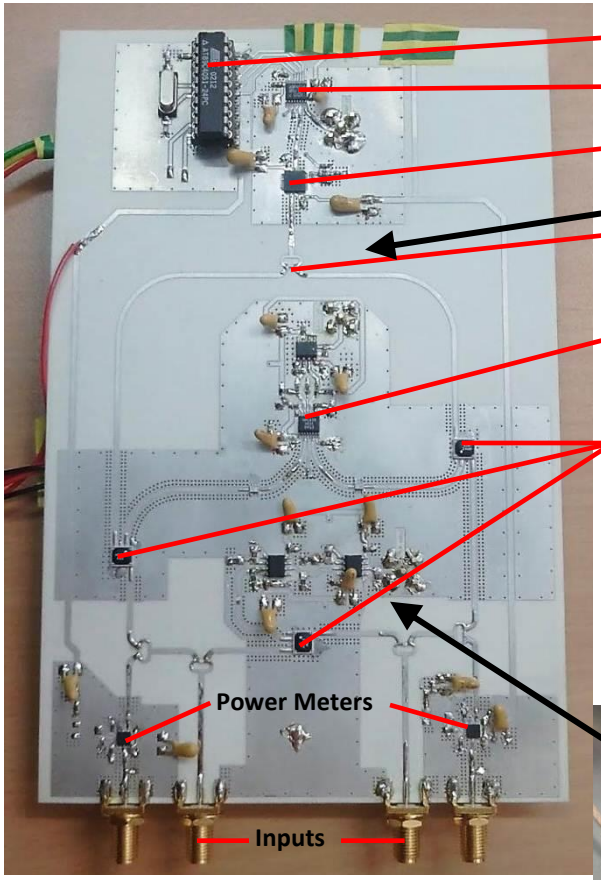
- Test by measuring S-parameters at each port then combining to get the dual port F-parameters.
- Cavities have not been tuned yet.

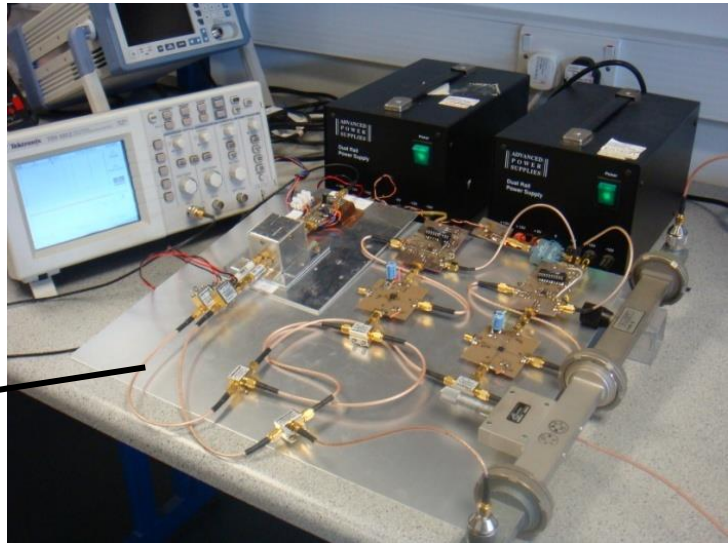
# Revised Crab Synchronisation Scheme



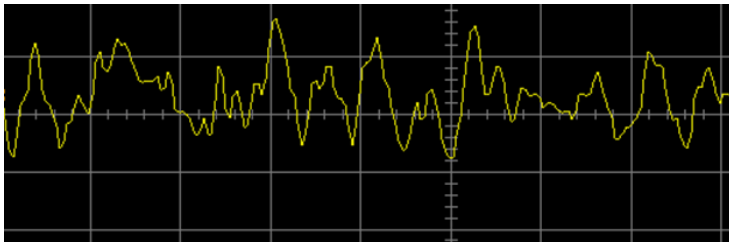
# Board Development and CW tests

Front end electronics to enable phase to be measure during the short pulses to an accuracy of 2 milli-degrees has been prototyped and dedicated boards are being developed.

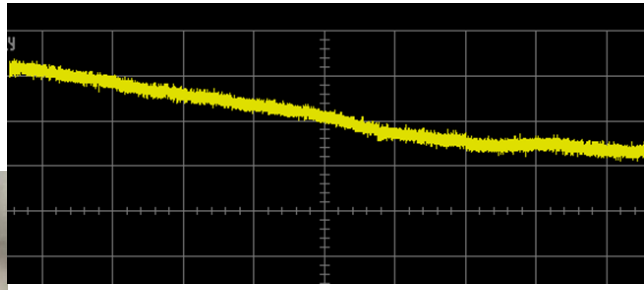


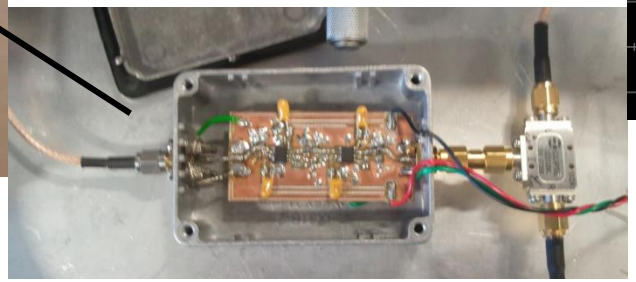



**400 ns span:**
RMS: 1.8 mdeg
Pk-Pk: 8.5 mdeg



**90 s span:**
Drift rate : 8.7 mdeg/10s
Total drift: 80 mdeg



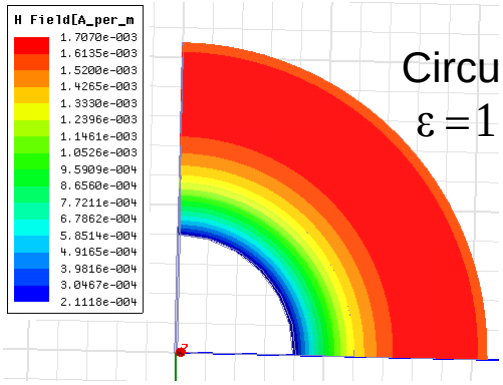


# Main linac structure studies (Manchester)

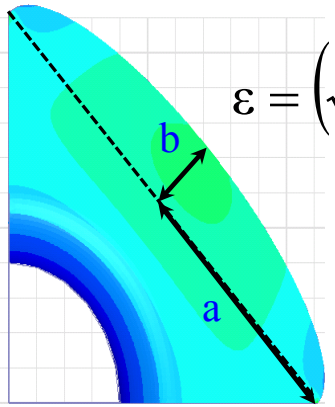
**Alternative designs including wakefield suppression of HOMs**

# CLIC_DDS_E Elliptical Design – E Fields

Single undamped cell
Iris radius=4.0 mm

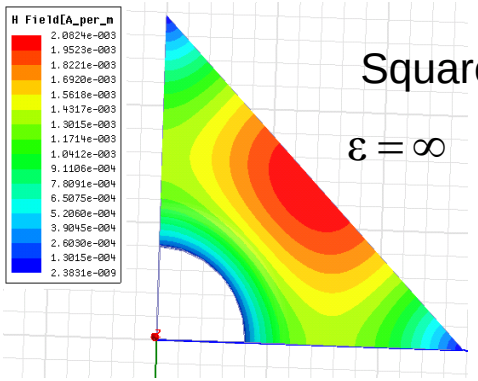



Circular
$\varepsilon = 1$

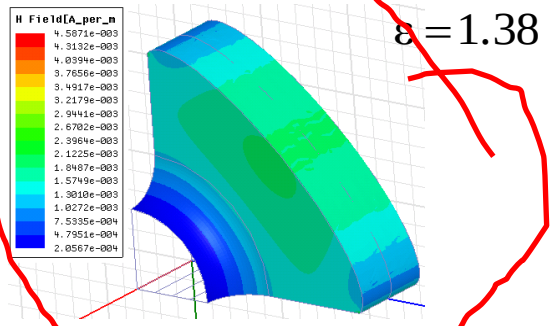



$$\varepsilon = \left(\sqrt{2} - 1\right)\frac{a}{b}$$

Convex ellipticity

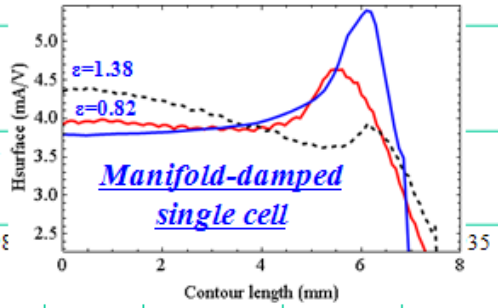



Square
$\varepsilon = \infty$




$\varepsilon = 1.38$

| | Circular | Rectangular | Elliptical (Convex) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 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 | | | | |
| 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 |




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

Chosen design

# UK LC machine expertise

- **Beam dynamics, beam transport, backgrounds …**

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- **Vacuum systems**
- **Magnet systems …**

# Applicable to

- **Beam delivery system**
- **Machine – detector interface**
- **Damping rings**
- **Positron source**

→ **Strong role in a European team to deliver key system(s) for ILC**