# Bunch compression, RF curvature correction and $R_{55}$, $T_{555}$ and $U_{5555}$ measurements at JLab FEL

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# Outline

- JLab FEL IR/UV Upgrade
- Compression "strategy"
  (and longitudinal phase space evolution)
- 180° Bates bend for nonlinear compression
  (RF curvature correction with multipole magnets; no harmonic RF)
- Longitudinal transfer function $R_{55}$, $T_{555}$, $U_{5555}$ etc.
  (connected to $R_{56}$ and $T_{566}$; measurements)
- Bunch length measurements
  (modified Martin-Puplett interferometer)
- Measurements results
  (Matrix elements and bunch length vs. quads and sextupoles; accuracy etc.)

# JLab IR/UV ERL Light Source

$E_{beam}$ 135 MeV

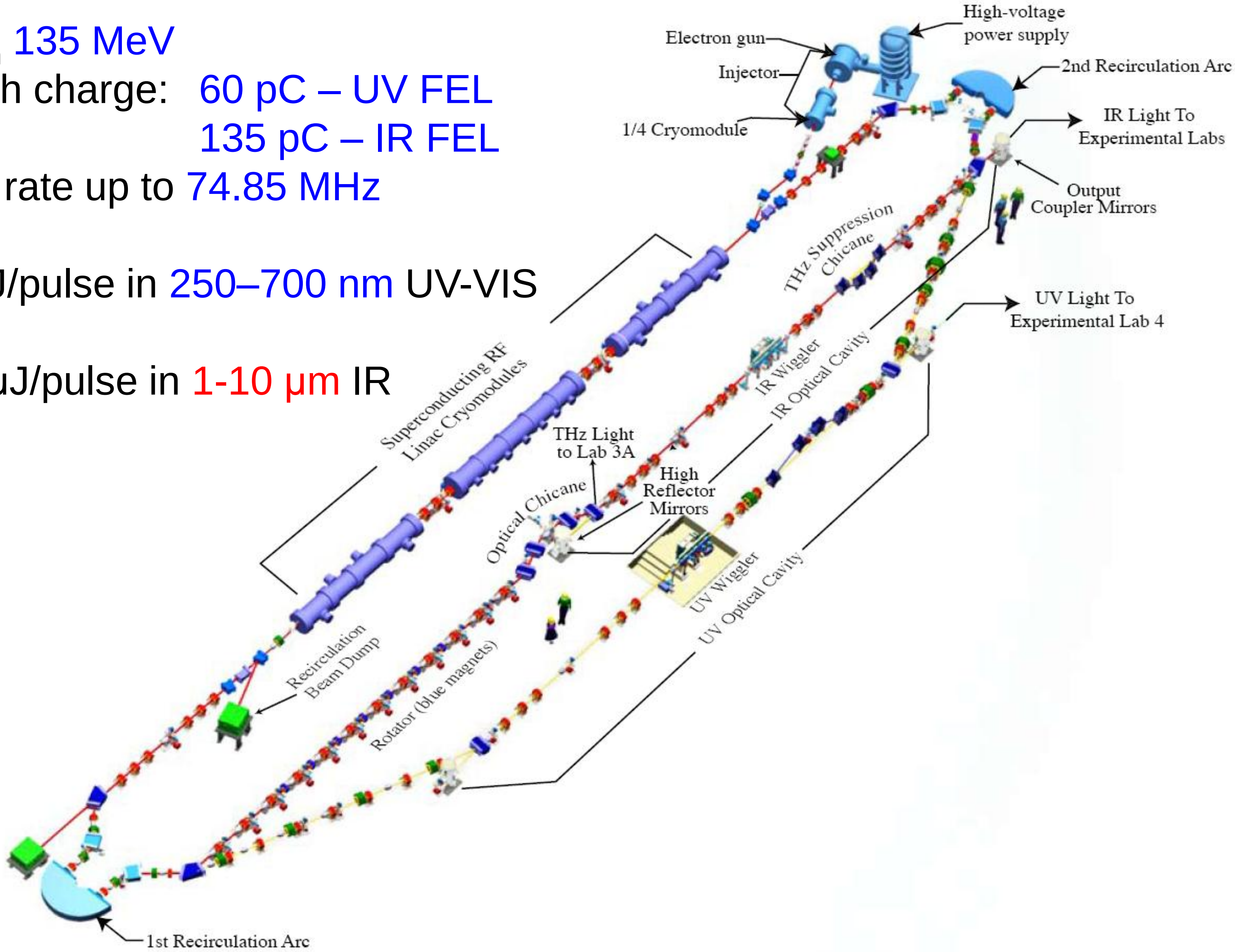
Bunch charge: 60 pC – UV FEL

135 pC – IR FEL

Rep. rate up to 74.85 MHz

25 µJ/pulse in 250–700 nm UV-VIS

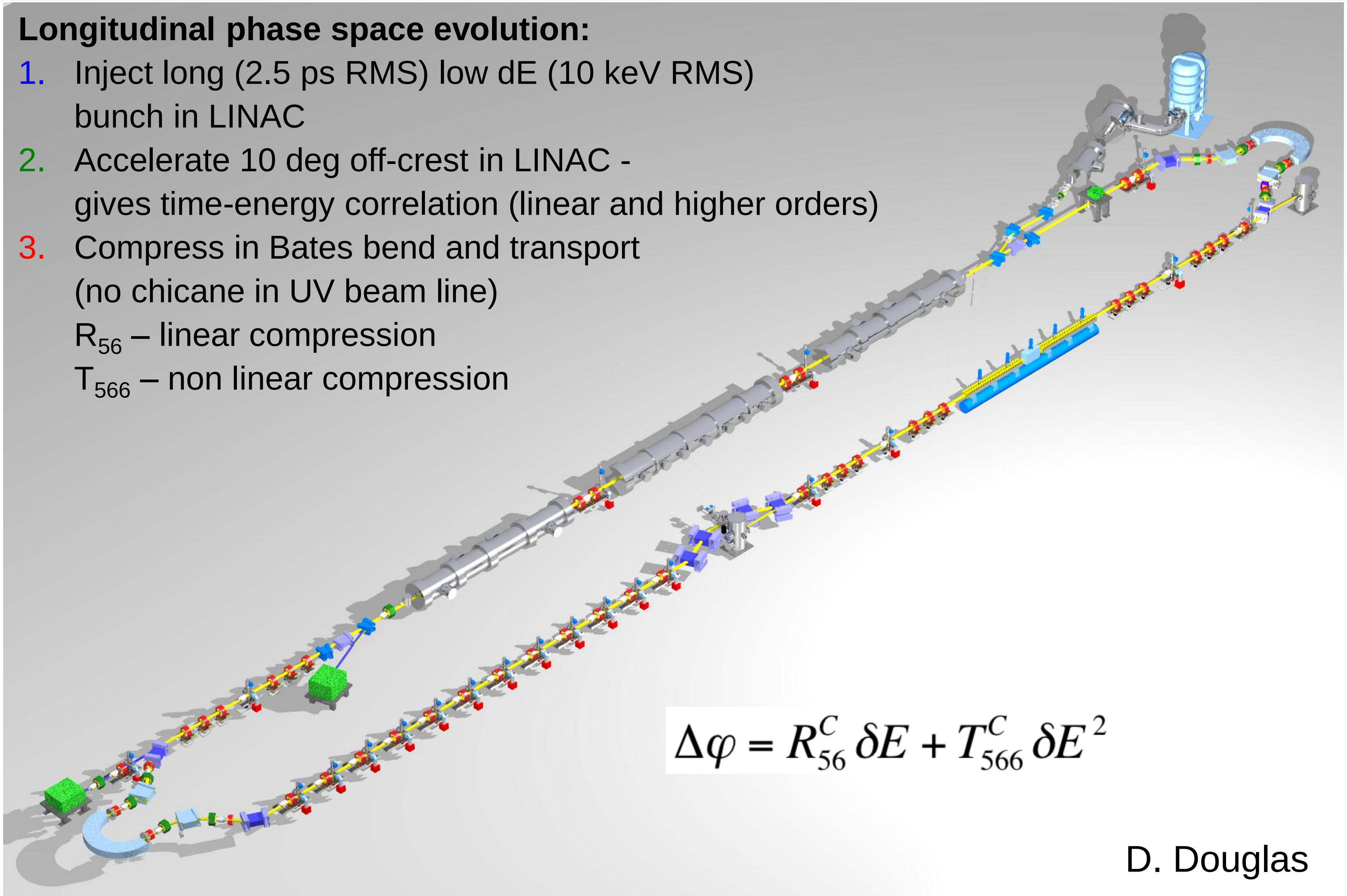
120 µJ/pulse in 1-10 µm IR



# Compression "strategy"

**Longitudinal phase space evolution:**

1. Inject long (2.5 ps RMS) low dE (10 keV RMS) bunch in LINAC
2. Accelerate 10 deg off-crest in LINAC - gives time-energy correlation (linear and higher orders)
3. Compress in Bates bend and transport (no chicane in UV beam line)
   $R_{56}$ – linear compression
   $T_{566}$ – non linear compression



$$\Delta\varphi = R^C_{56}\,\delta E + T^C_{566}\,\delta E^2$$

D. Douglas

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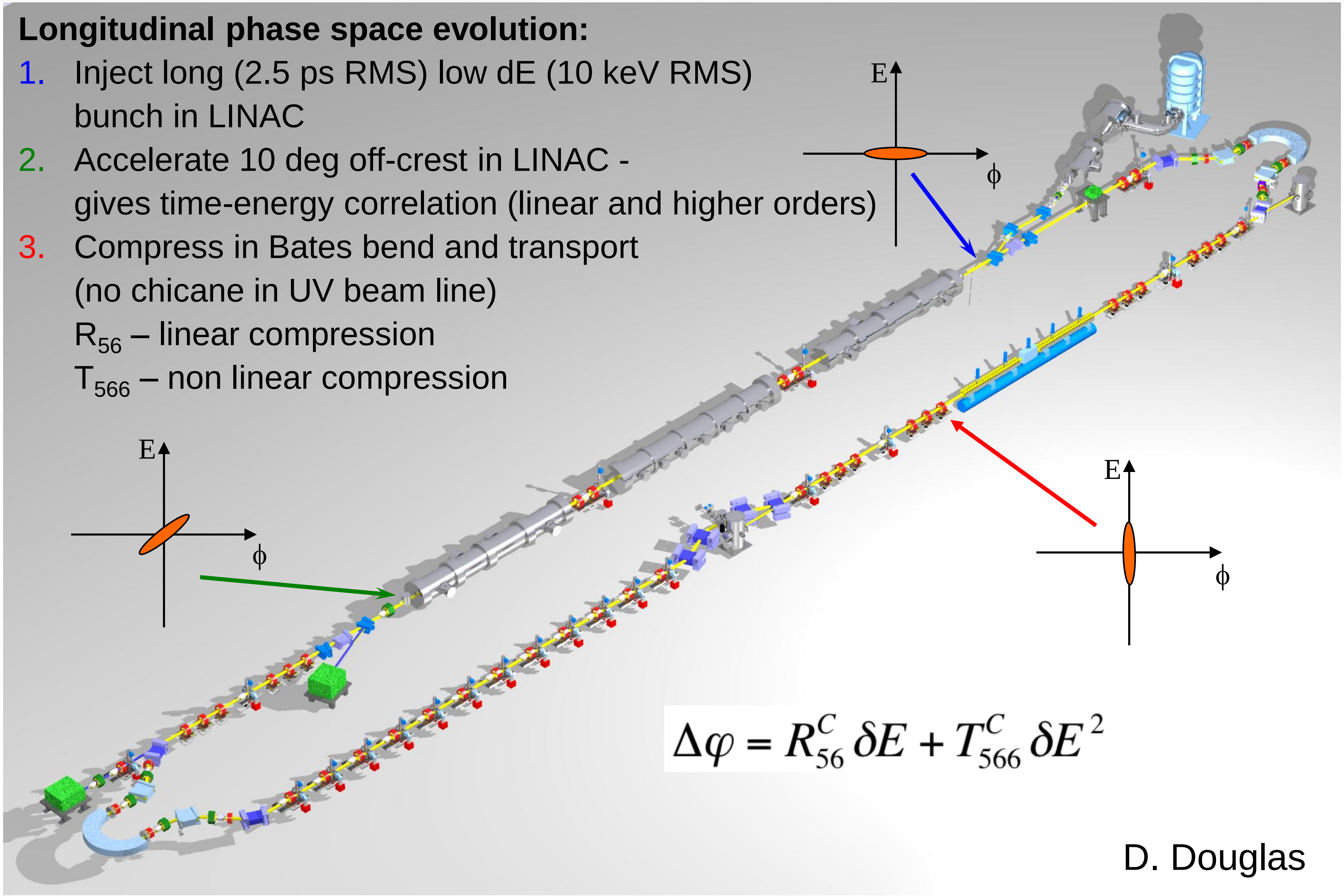


$$\Delta\varphi = R^{C}_{56}\,\delta E + T^{C}_{566}\,\delta E^{2}$$

D. Douglas

# Bunch length evolution

- ✧ Beam is generated in a HV DC gun (325 kV now) – GaAs photocathode, Drive Laser with almost Gaussian distribution and ~ 13.5 ps RMS pulse length

- ✧ compressed down to ~ 5 ps by 1497 MHz buncher cavity before injection in to the booster where it is accelerated to 9 MeV

- ✧ During acceleration in the booster (5-cell SRF x2) gets compressed down to ~ 2.5 ps - not measured directly but inferred from δE downstream of the LINAC – in good agreement with PARMELA model

- ✧ Compressed in the first 180 deg band and transport line between the band and FEL wiggler; final bunch length 100 – 110 fs (UV); 130-150 fs (IR)

- ✧ LINAC RF curvature imprinted on the longitudinal phase space compensated for by sextupoles in the Bates bend (no harmonic RF) by introducing second order dependence of the path length on energy

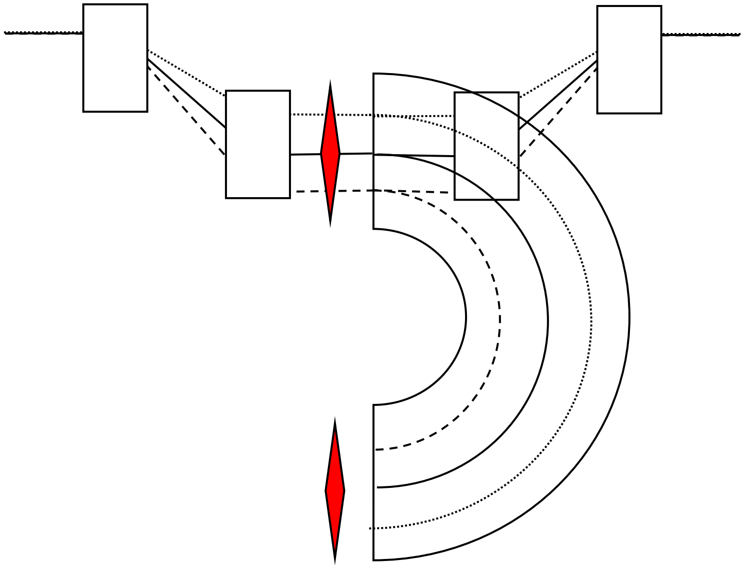
- ✧ Compression ration from the cathode to the wiggler ~ 125 – 135

# 180° Bates bend

Bates band - design by Sargent/Flanz from MIT (combined function magnets)

J. B. Flanz and C. P. Sargent, “Operation of an Isochronous Beam Recirculation System,” *Nucl. Instrum. and Methods* **A241** (1985) 325–333

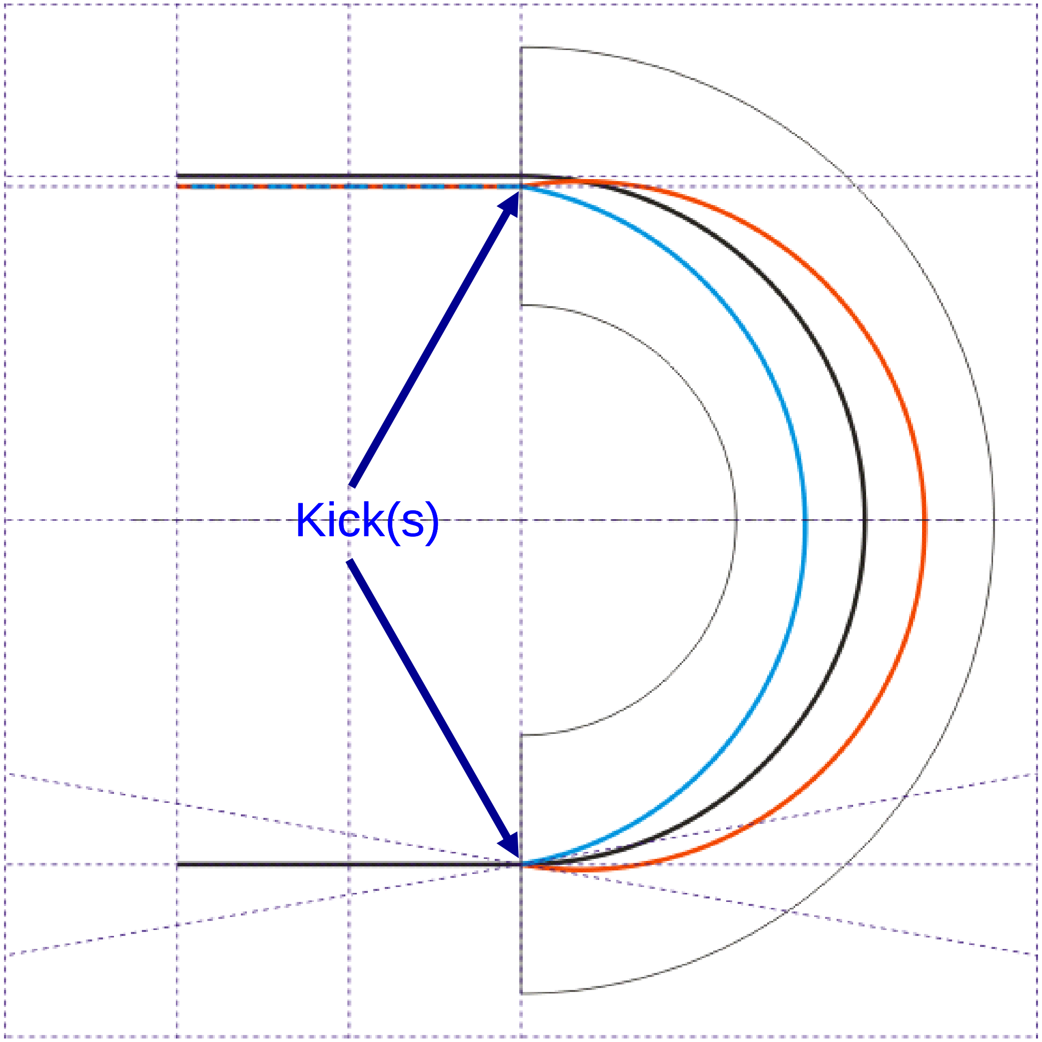
D. Douglas
separated sextupoles
and added quads



Courtesy of D. Douglas

- Really robust
- Really easy to operate (if it is instrumented)
- Really simple (if you think about it the right way)
- Good acceptance (>10% energy, 30-40 deg phase)
- Symmetry – aberrations corrections
- Match in/out with chromatically balanced telescopes

# 180° Bates bend (1)

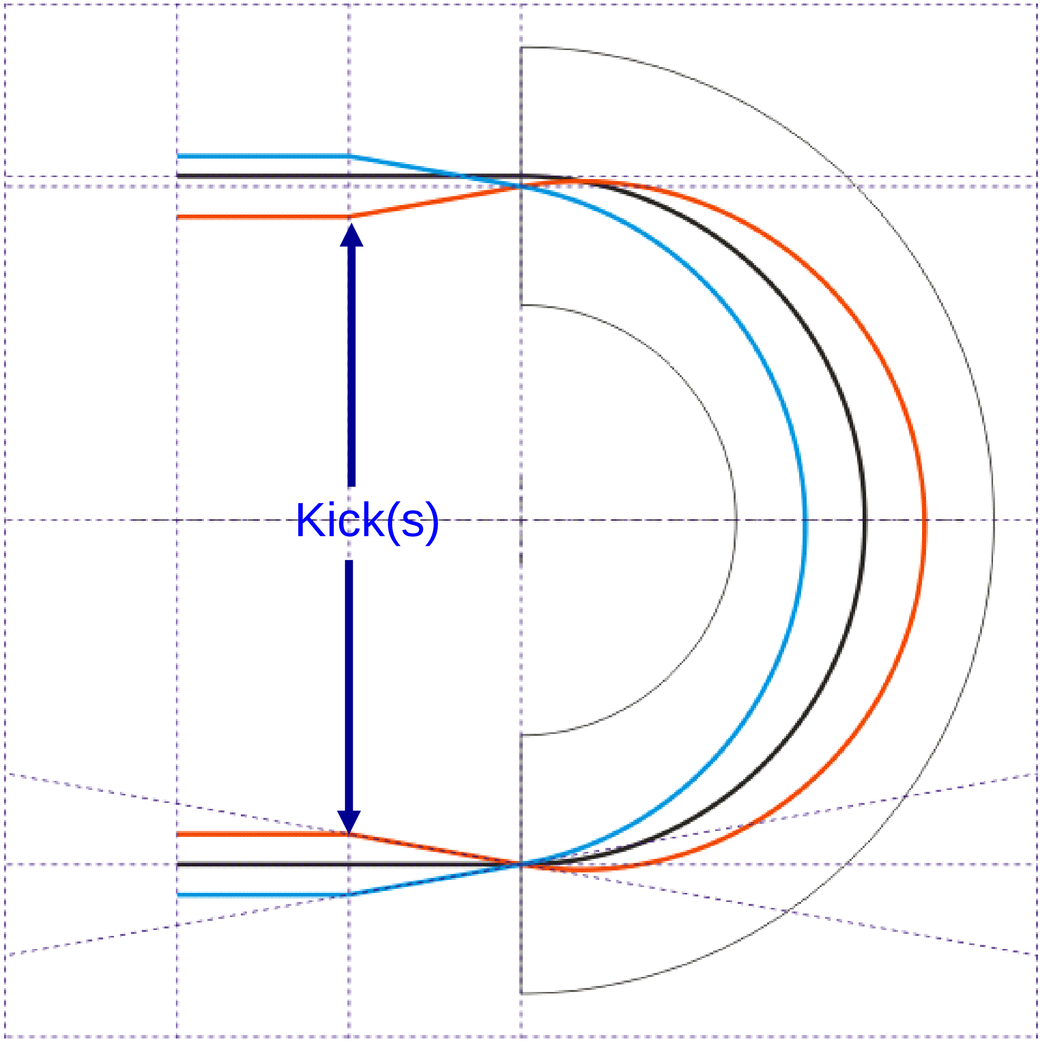


Path length change with kick;

$$\delta L = 2\rho\,\delta x'$$

Used to adjust the path length i.e. phase of the energy recovered beam

# 180° Bates bend (2)



Path length change with kick;

$$\delta L = 2\rho\,\delta x'$$

Kick by quadrupole;

$$\delta x'(x) = A \cdot x$$

Kick by sextupole;

$$\delta x'(x) = B \cdot x^2$$

Due to dispersion created by first two dipoles;

$$E \propto x$$

# Connecting $R_{56}$ & $T_{566}$ to $M_{55}$

$$\varphi_W = \left(1 + R_{56}^C \cdot R_{65}^L\right)\varphi_0 + \left[R_{56}^C \cdot T_{655}^L + \left(R_{65}^L\right)^2 \cdot T_{566}^C\right]\varphi_0^2$$

taking second order transport matrix elements

directly measured

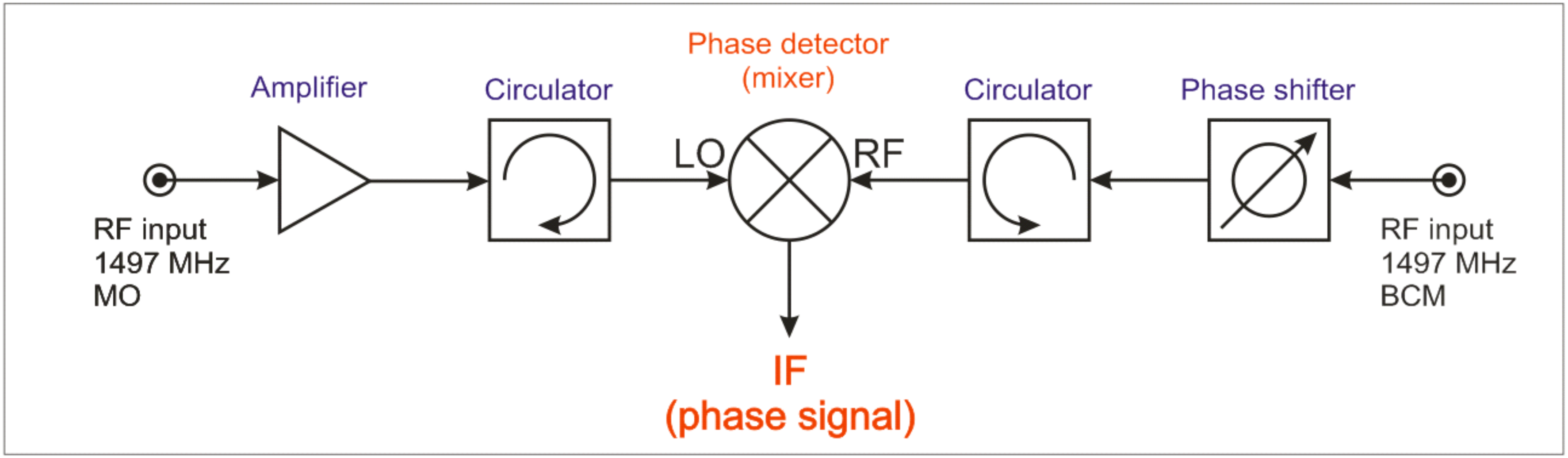
$$R_{55}^{inj \to w} = 1 + R_{56}^C \cdot R_{65}^L$$

$$T_{555}^{inj \to w} = R_{56}^C \cdot T_{655}^L + \left(R_{65}^L\right)^2 \cdot T_{566}^C$$

are adjusted in compressor

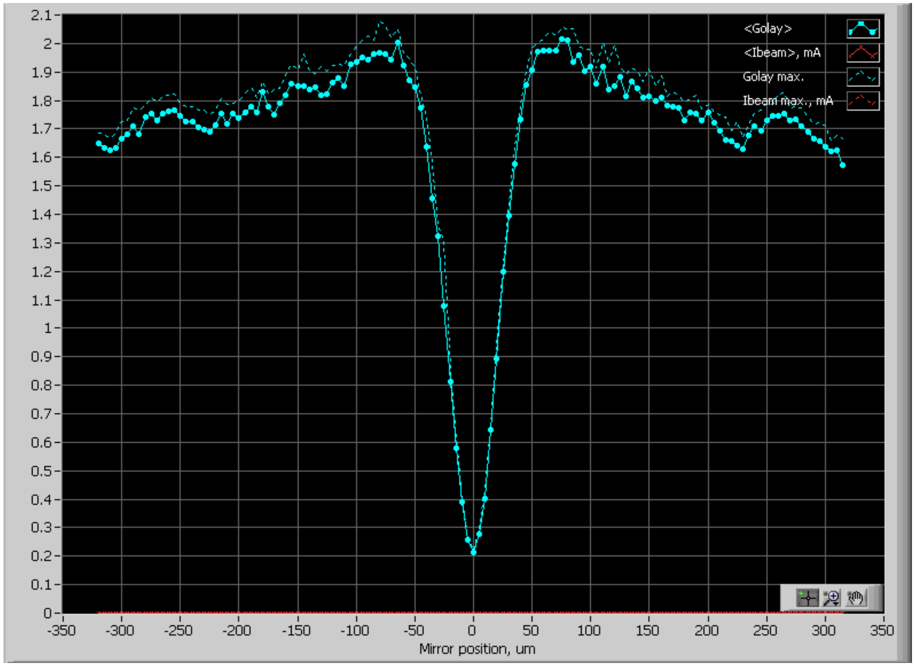
- $R_{56}$ and $T_{566}$ are validated via longitudinal transfer function measurements.
- Arrival phase is measured with a pillbox cavity + heterodyne receiver.
- Phase of the injector is modulated relative to the LINAC phase
- Essential ~ 15 % energy acceptance and ~ 30 % phase acceptance

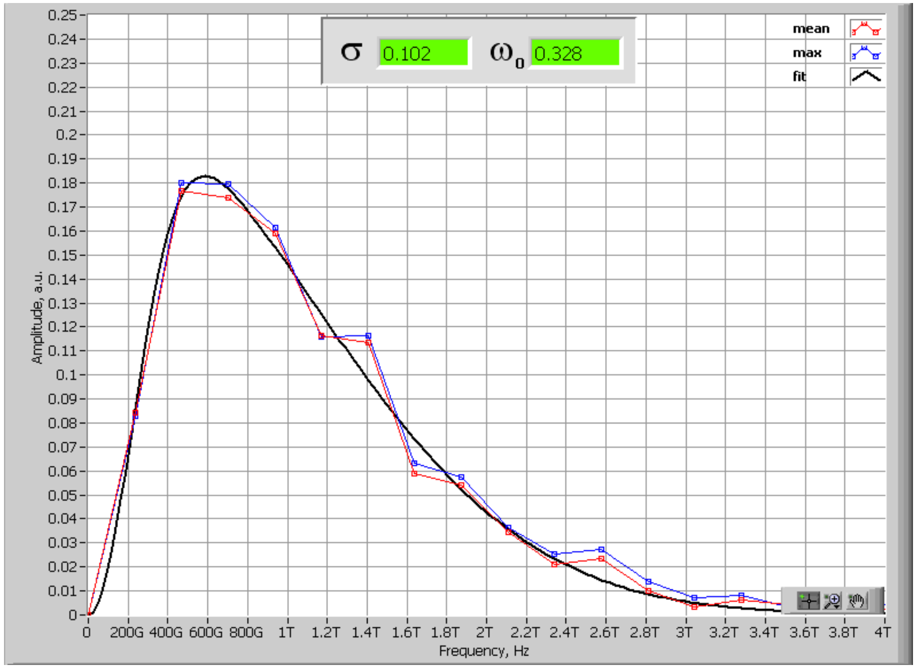
# $M_{55}$ Measurements hardware (receiver side)



- Receiver - simplest phase detector (mixer, but goes down to DC)
- Pick up – simplest pillbox cavity ($f_0$=1497 MHz, Q~1000, BW ~ 1.5 MHz)
- 2.5 MHz – 14 bit ADC is essential to compensate for receiver “imperfections”
- the “$M_{55}$“ receiver chassis is placed very close to MO – minimizes cable phase drift
- the phase shifter is calibrated first with the help of Network analyzer
- For the calibration phases of the MO and beam are kept constant, while the phase sifter is scanned in the range ~ 380 deg (takes 30 sec)
- the calibration gives the sensitivity i.e. $V_{out} – \Delta\phi$ and $\phi_1^* \phi_2^*$ zero crossing angles
- around zero crossing the $V_{out} = V_{out} (\Delta\phi)$ is almost linear and least amplitude dependent

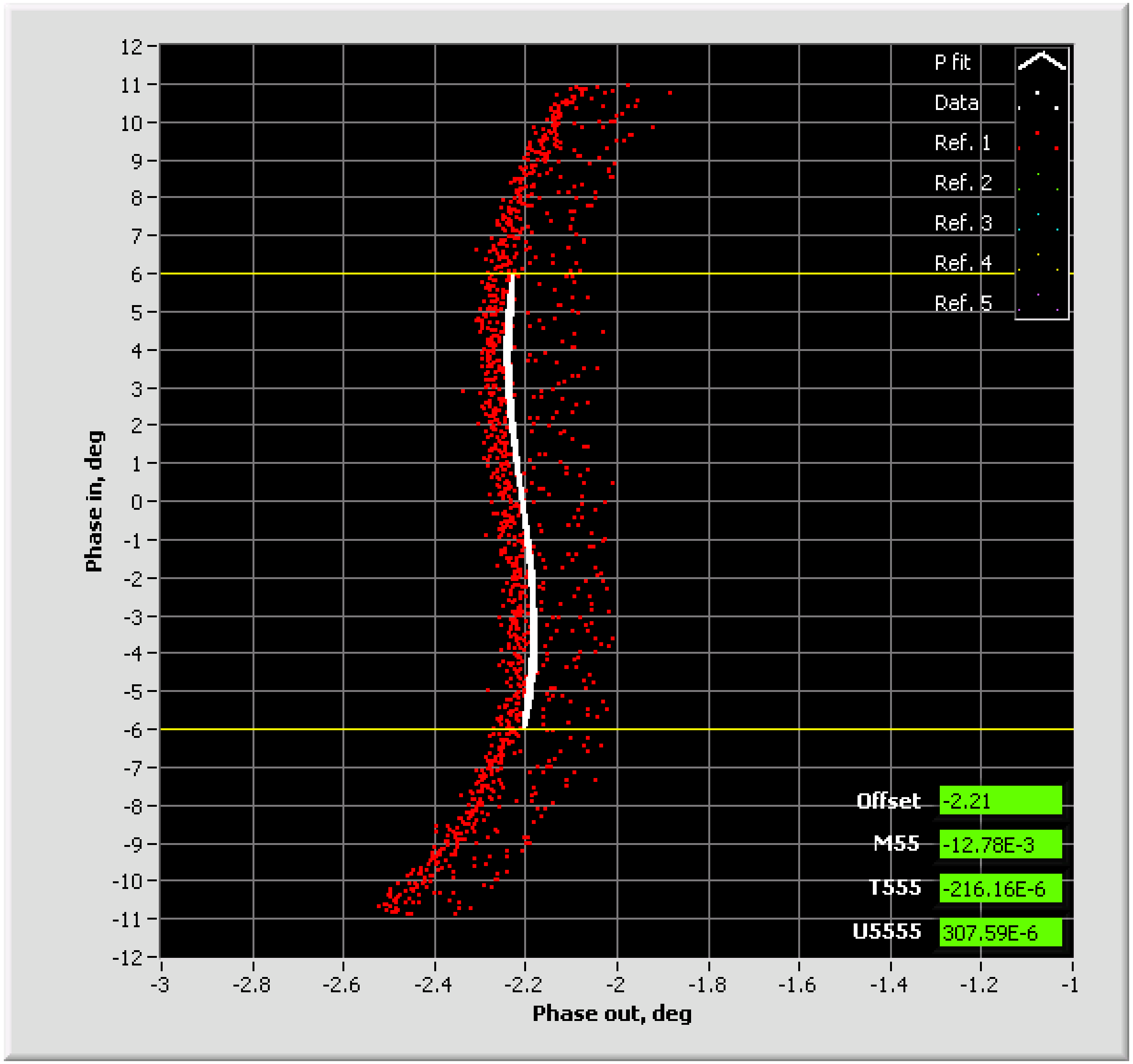
# Bunch length at full compression





- modified Martin-Puplett interferometer with single detector (Golay cell)
- measures autocorrelation function of CTR or CSR (phase information lost)
- data evaluation in frequency domain assuming Gaussian distribution
- Gaussian power spectrum × HPF fitted to measured spectrum
- blackbody spectral measurements used to estimate limit of the setup (~ 50 fs)

# $M_{55}$ measurements vs. quads



Offset -2.21

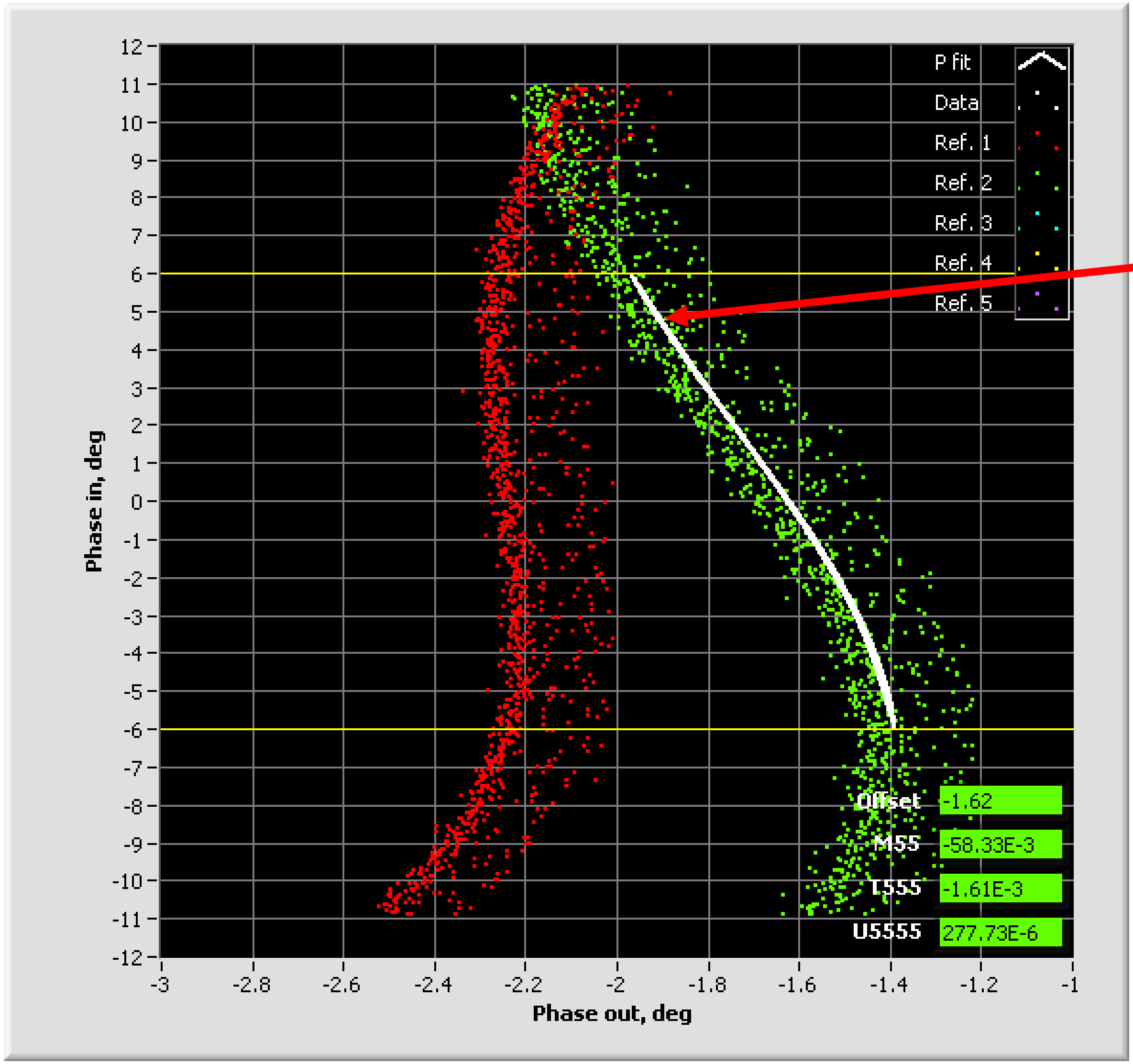
M55 -12.78E-3

T555 -216.16E-6

U5555 307.59E-6

Trim quads – nominal set point of 700 G

# $M_{55}$ measurements vs. quads

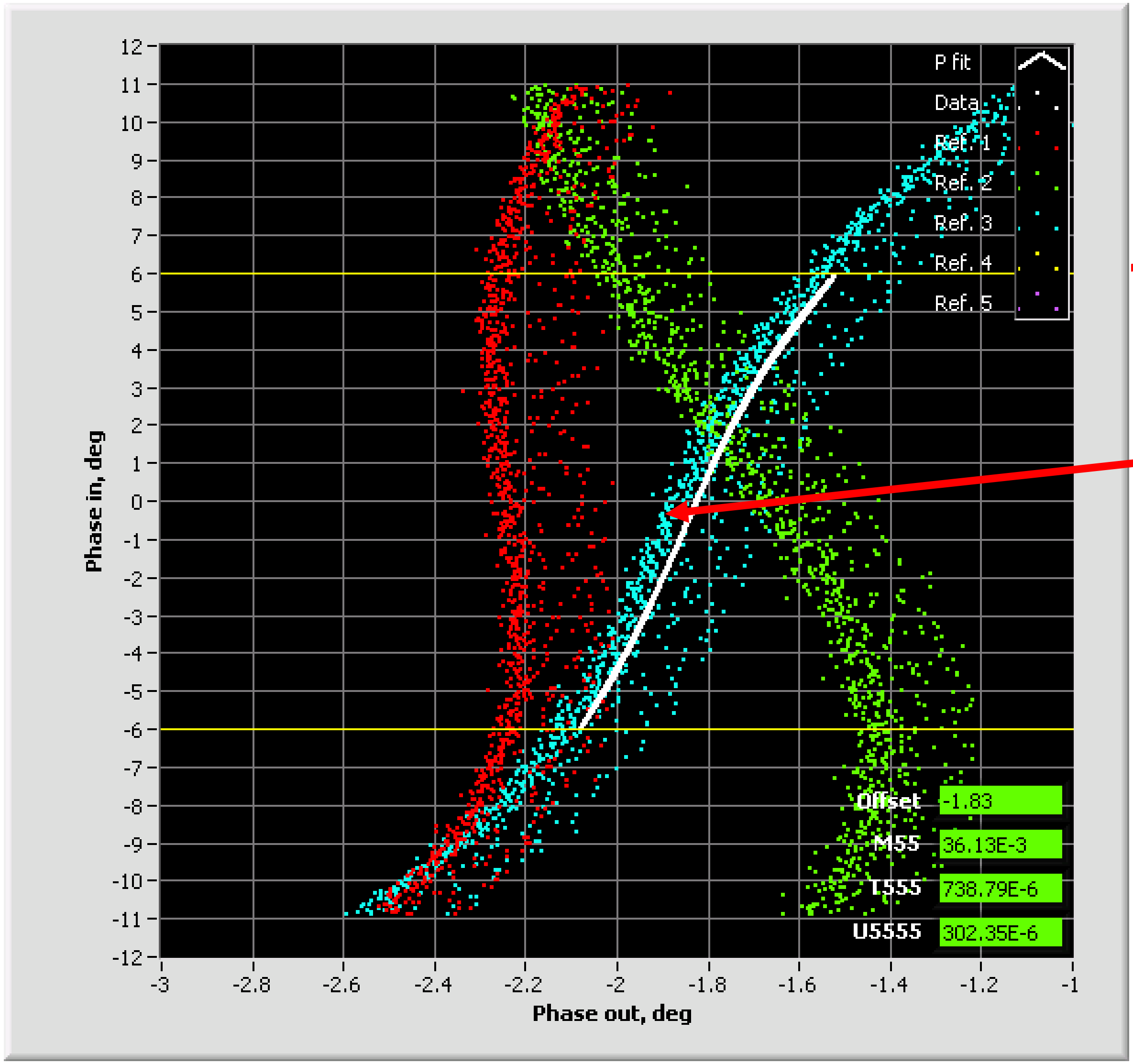


Offset -1.62
M55 -58.33E-3
T555 -1.61E-3
U5555 277.73E-6

Trim quads – nominal set point of 700 G

Trim quads set point – nominal + 40 G (~ 5.7%)

# M$_{55}$ measurements vs. quads



Offset -1.83

M55 36.13E-3

T555 738.79E-6

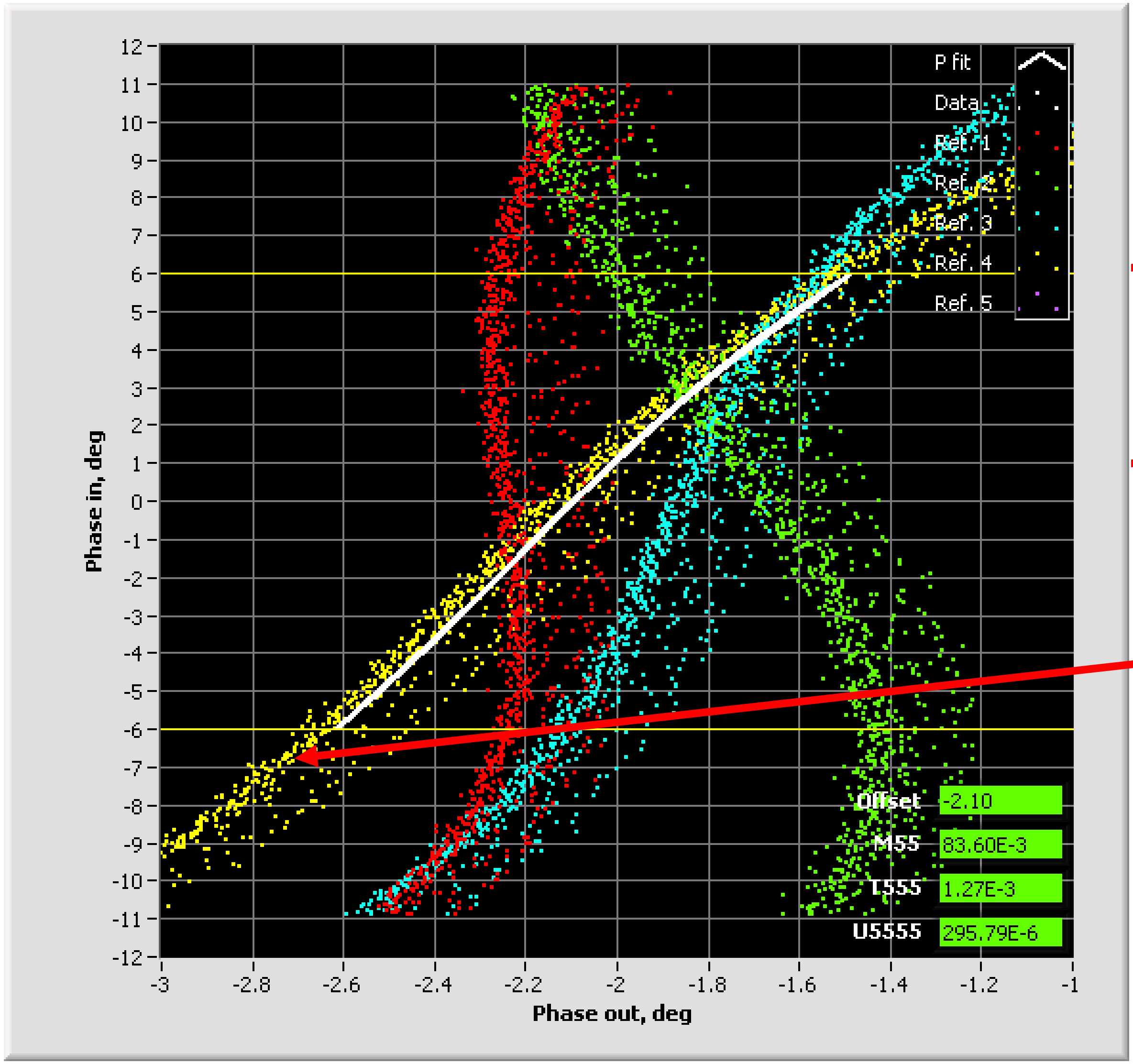
U5555 302.35E-6

Trim quads – nominal set point of 700 G

Trim quads set point – nominal + 40 G (~ 5.7%)

Trim quads set point – nominal - 40 G (~ 5.7%)

# $M_{55}$ measurements vs. quads



| | |
|---|---|
| Offset | -2.10 |
| M55 | 83.60E-3 |
| T555 | 1.27E-3 |
| U5555 | 295.79E-6 |

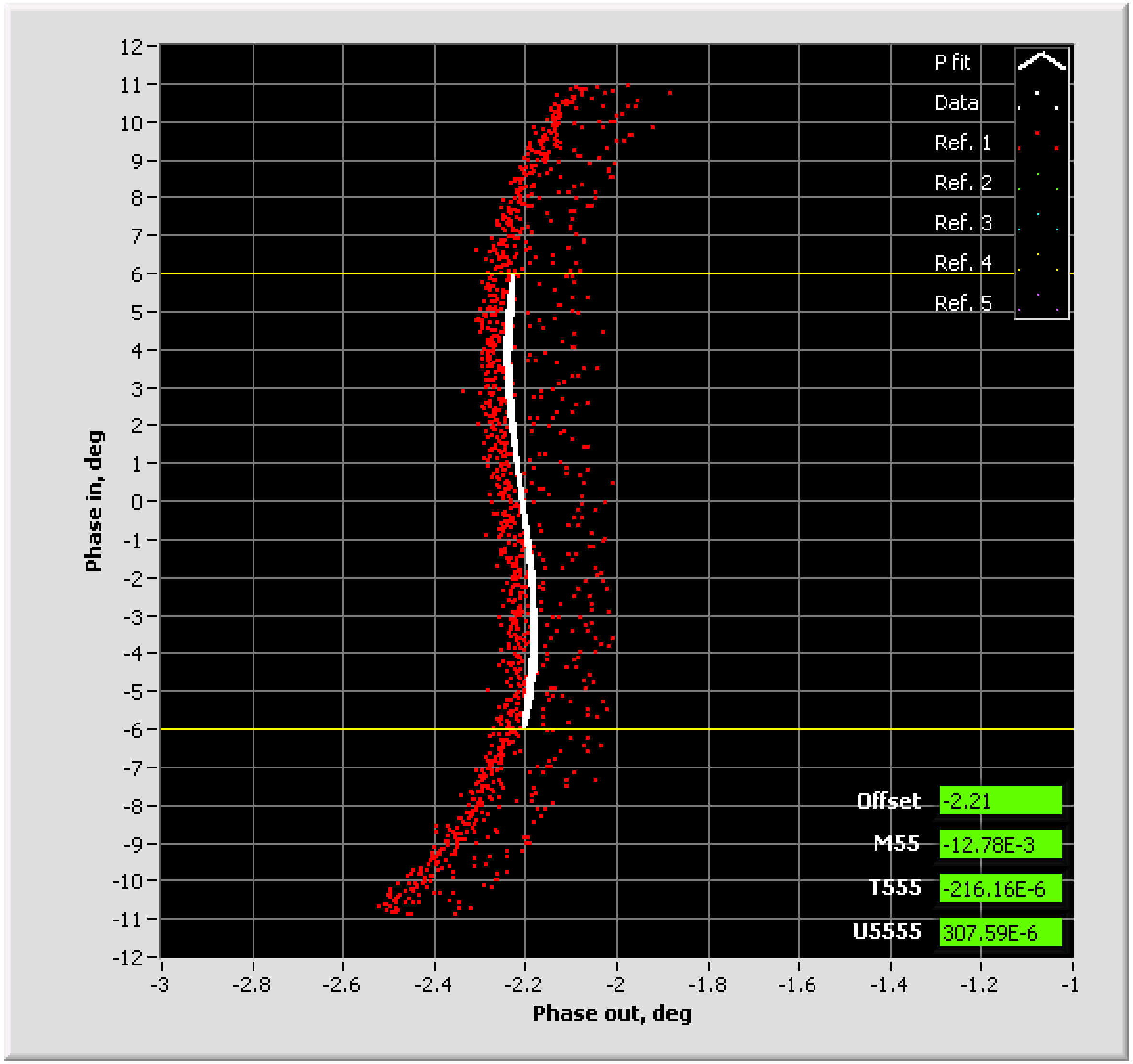
Trim quads – nominal set point of 700 G

Trim quads set point – nominal + 40 G (~ 5.7%)

Trim quads set point – nominal - 40 G (~ 5.7%)

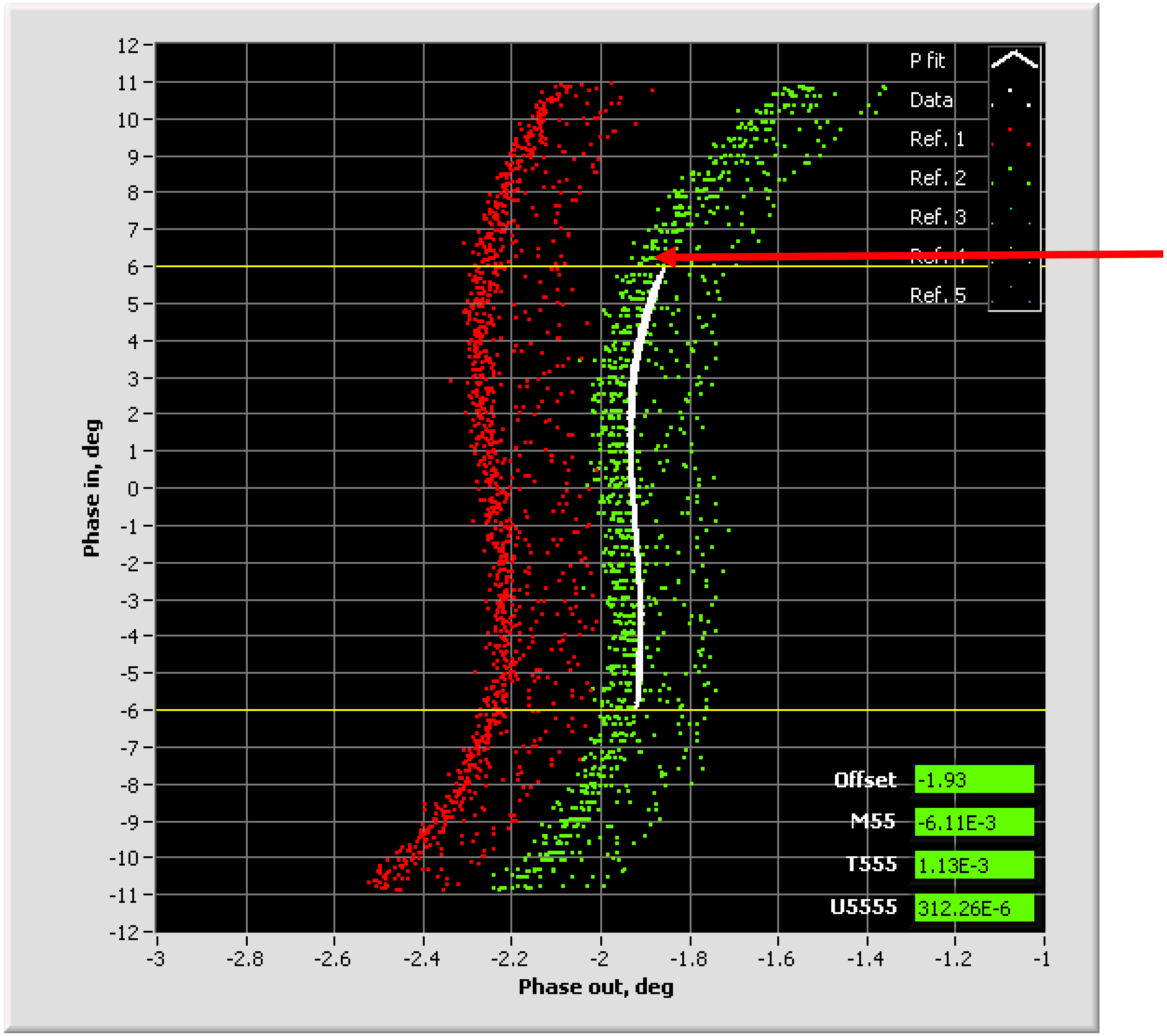
Trim quads set point – nominal - 80 G (~ 11.4%)

# $M_{55}$ measurements vs. sextupoles



ARC1 sextupoles nominal set point 10730 G

# $M_{55}$ measurements vs. sextupoles

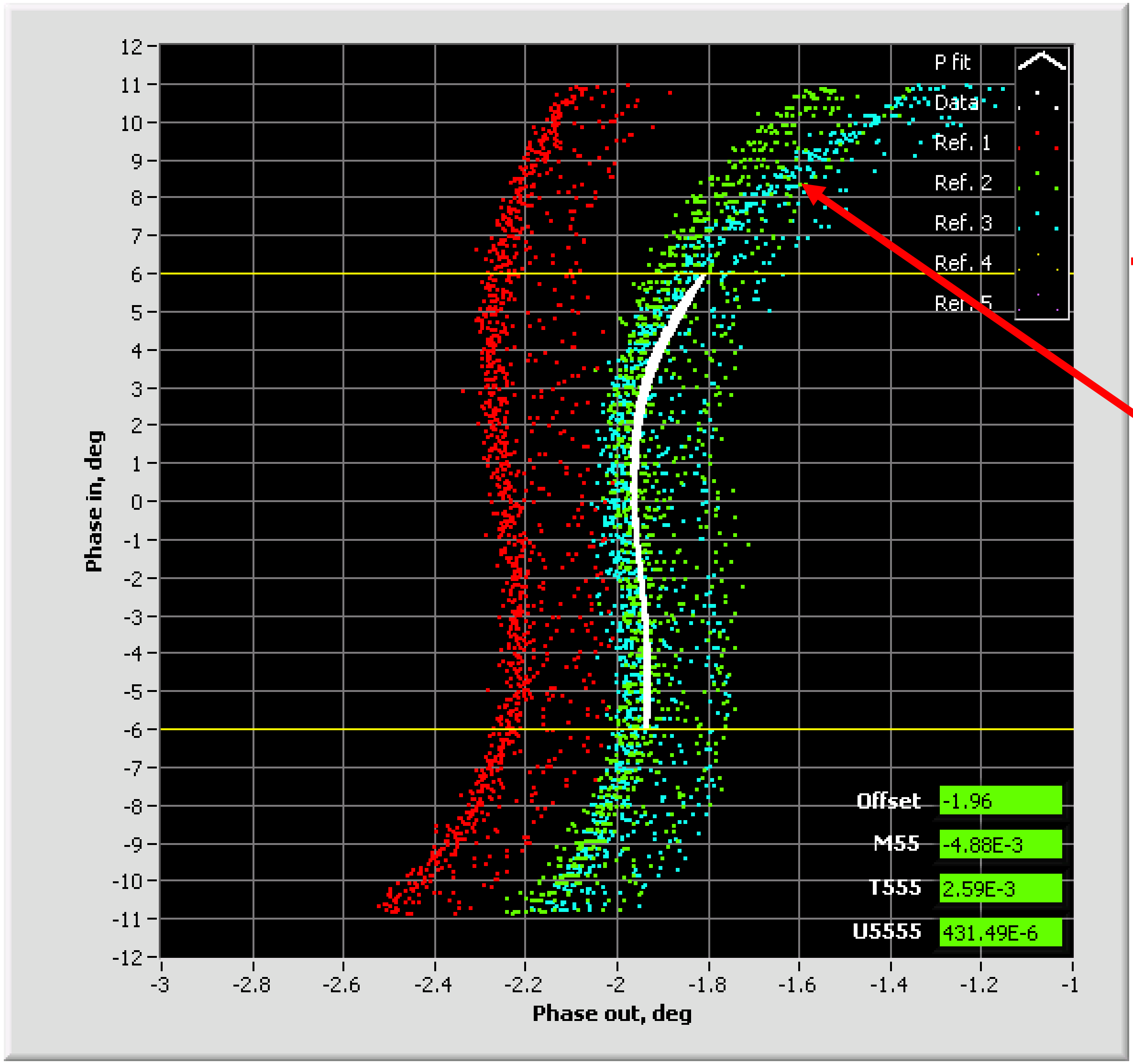


Offset -1.93
M55 -6.11E-3
T555 1.13E-3
U5555 312.26E-6

ARC1 sextupoles nominal set point 10730 G

ARC1 sextupoles nominal set point +500 G (~ 4.7 %)

# $M_{55}$ measurements vs. sextupoles



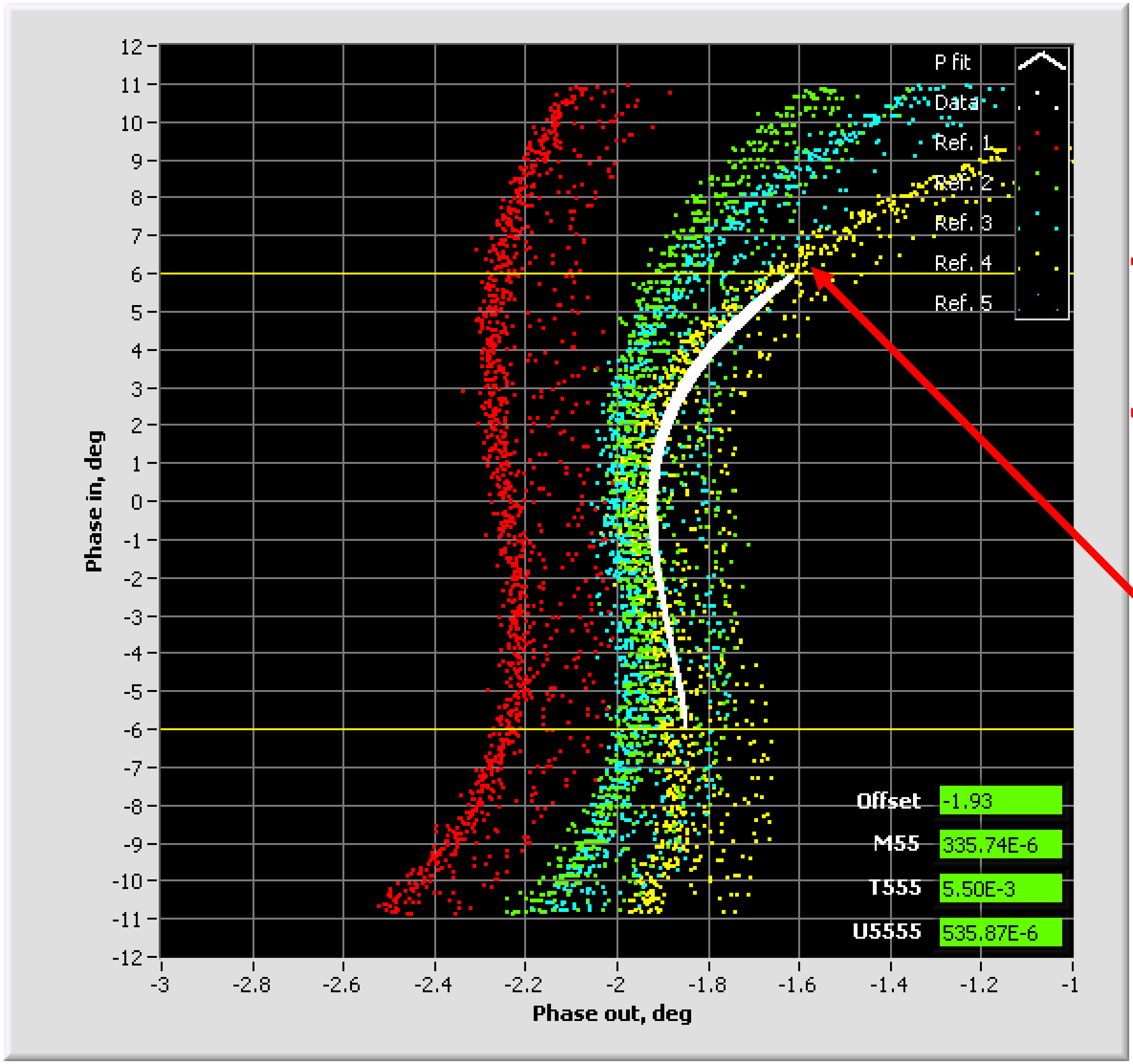
| | |
|---|---|
| Offset | -1.96 |
| M55 | -4.88E-3 |
| T555 | 2.59E-3 |
| U5555 | 431.49E-6 |

ARC1 sextupoles nominal set point 10730 G

ARC1 sextupoles nominal set point +500 G (~ 4.7 %)

ARC1 sextupoles nominal set point +1000 G

# $M_{55}$ measurements vs. sextupoles



Offset -1.93

M55 335.74E-6

T555 5.50E-3

U5555 535.87E-6

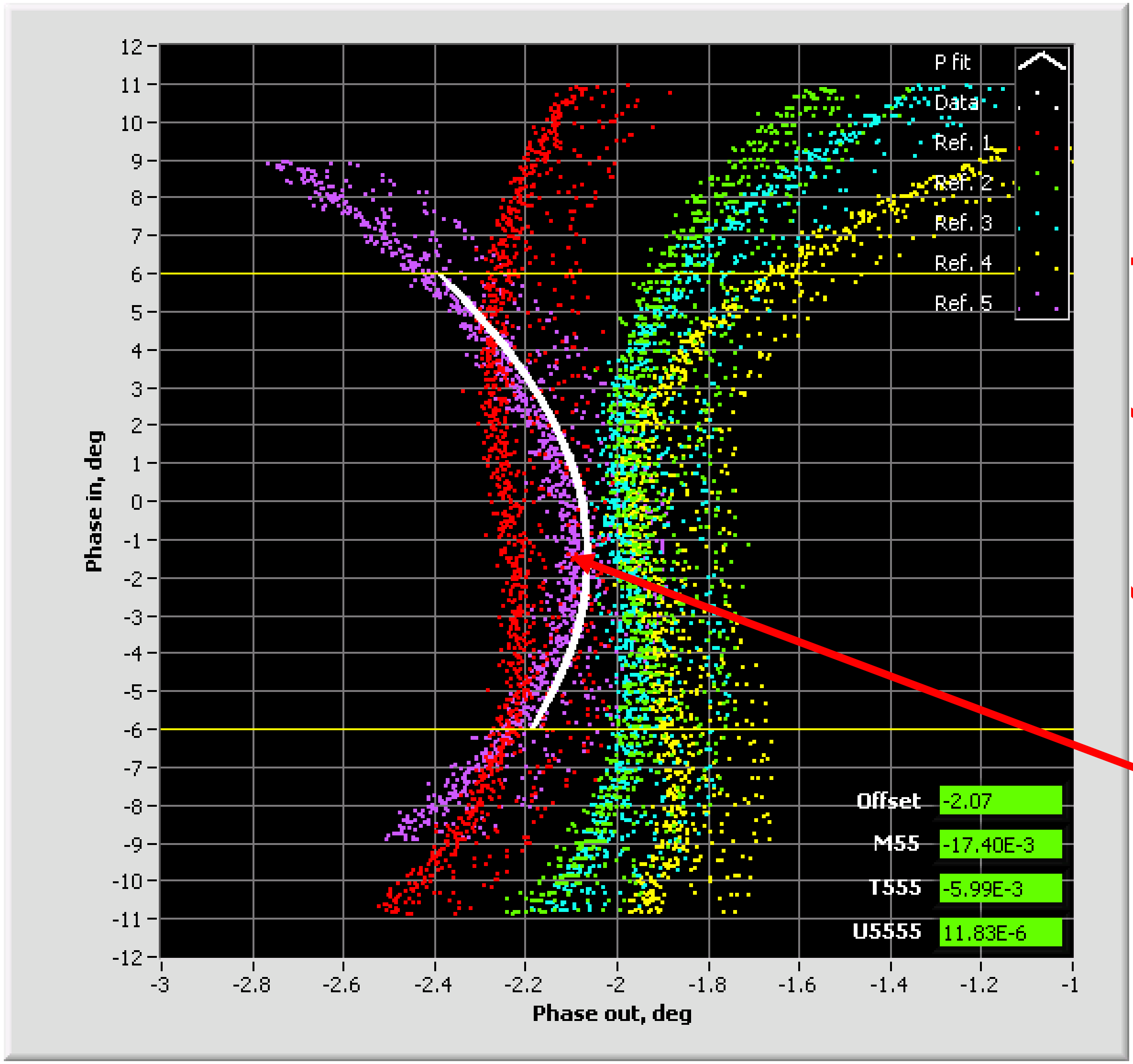
ARC1 sextupoles nominal set point 10730 G

ARC1 sextupoles nominal set point +500 G (~ 4.7 %)

ARC1 sextupoles nominal set point +1000 G

ARC1 sextupoles nominal set point +2000 G

# $M_{55}$ measurements vs. sextupoles



Offset -2.07
M55 -17.40E-3
T555 -5.99E-3
U5555 11.83E-6

ARC1 sextupoles nominal set point 10730 G

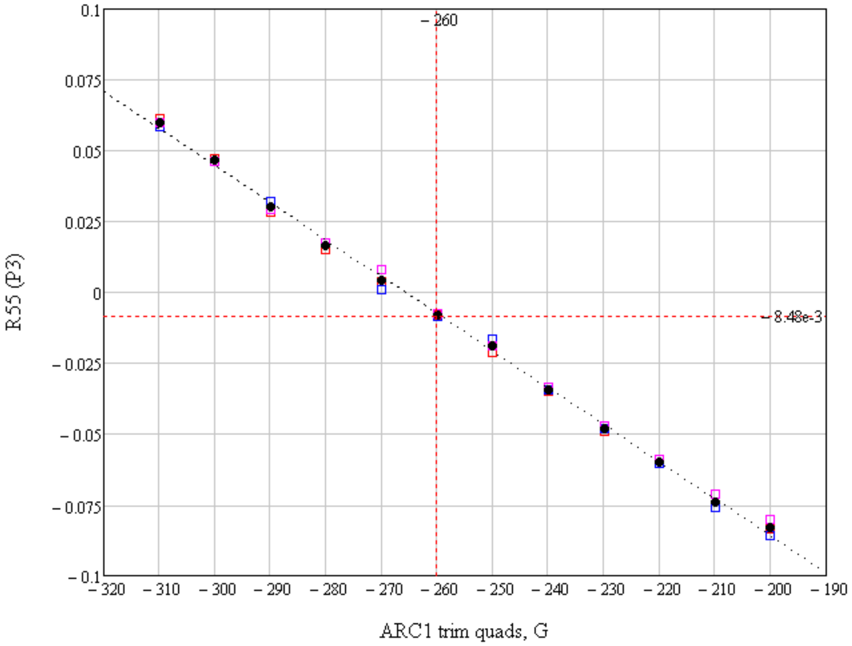
ARC1 sextupoles nominal set point +500 G (~ 4.7 %)

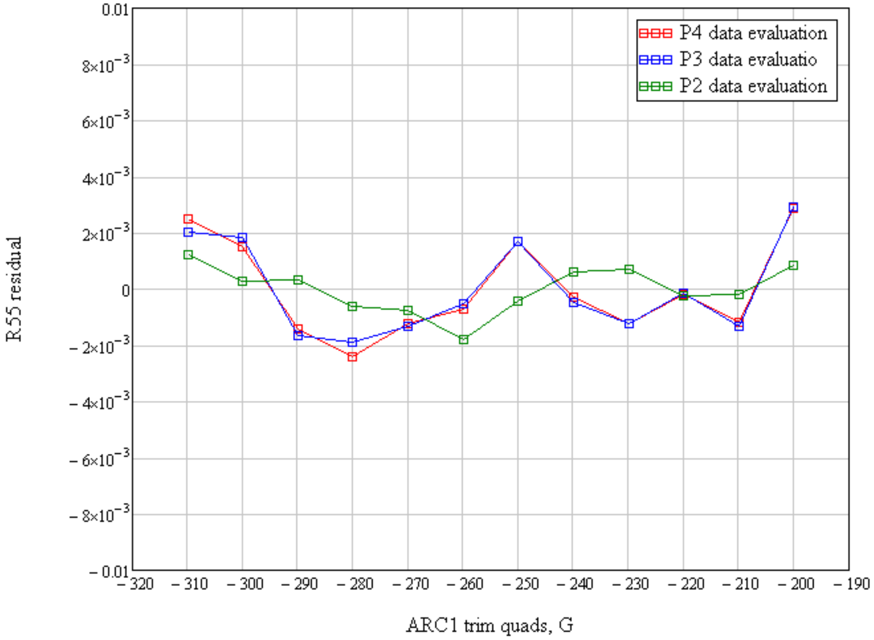
ARC1 sextupoles nominal set point +1000 G

ARC1 sextupoles nominal set point +2000 G

ARC1 sextupoles nominal set point -2000 G

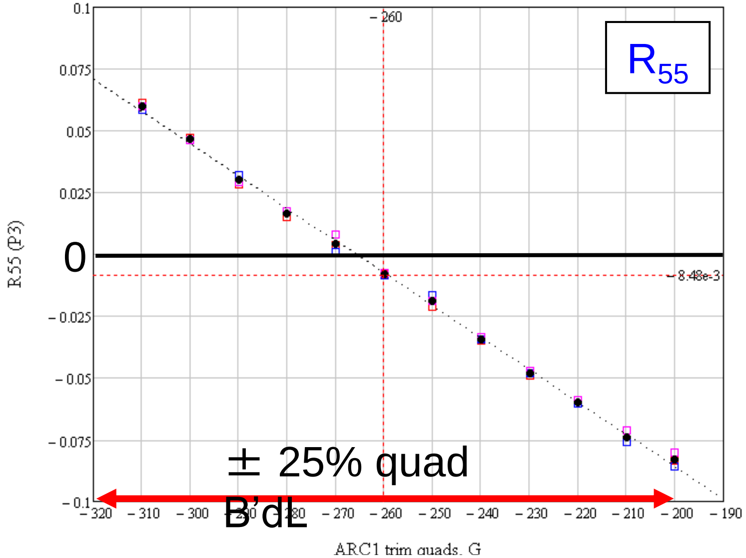
# $M_{55}$ measurements accuracy



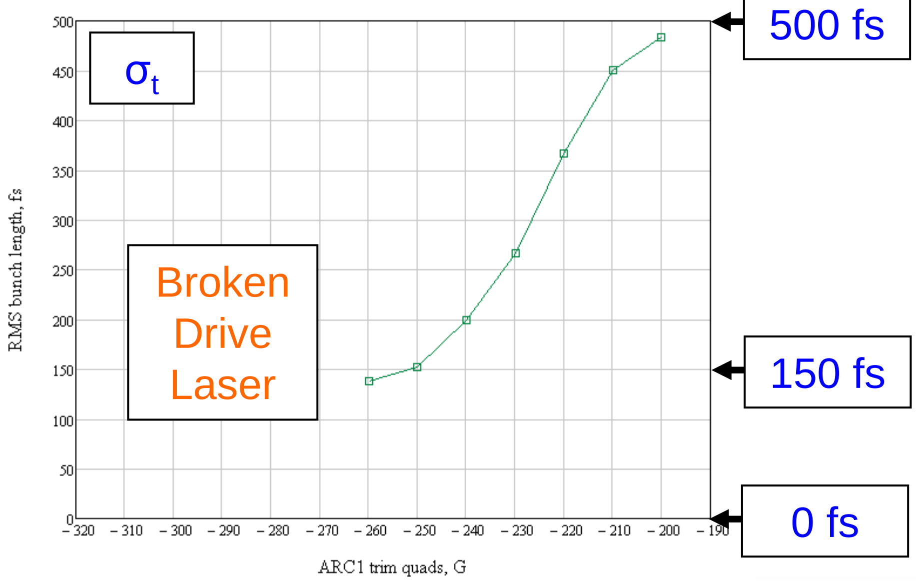


- $M_{55}$ (long. transfer function) measured as a function of the ARC1 quads
- Linear dependence is expected per optics model
- Fit line to the model to the data; calculate residual
- RMS of the residual is a upper limit of the absolute accuracy
- Relative accuracy (%) is irrelevant; we are trying to make measurable zero
- Polynomial order can make a difference – coefficients “talk” to each other
- The absolute error: $1.6 \times 10^{-3}$; $R_{55}$’$\approx 1.3 \times 10^{-3}$ 1/G; ➔ $\Delta_Q \approx 1.2$ G (0.5% - quad B’dL; IR-FEL)

# Bunch length - $M_{55}$ – trim quads



± 25% quad B'dL



Broken Drive Laser

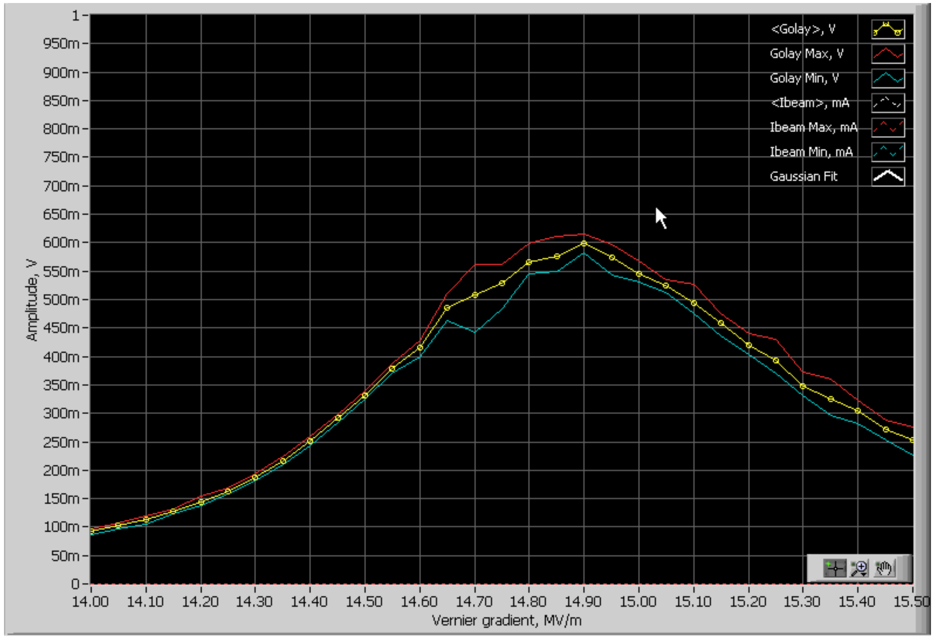
500 fs

150 fs

0 fs

Both $R_{55}$ and $T_{555}$ depend on energy i.e. LINAC gradient and phase.

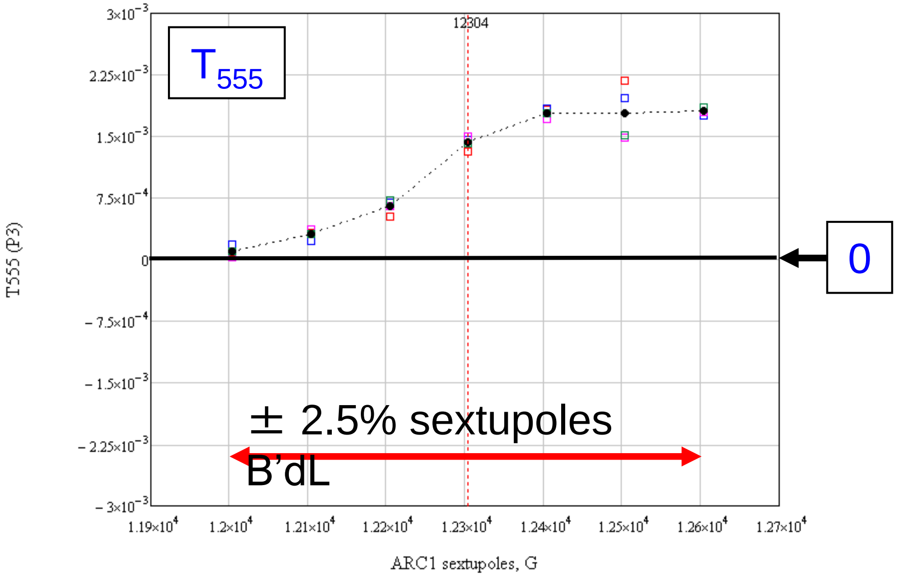
1. LINAC gradient and rel. phase to beam must stay constant
2. Adjusting beam energy at the level ~ $2.5 \times 10^{-4}$ is used to optimized compression



# Conclusion & Outlook

- JLab IR/UV Upgrade FEL operates with bunch compression ration of 90-135 (cathode to wiggler); 17-25 (LINAC entrance to wiggler).
- To achieve the compression ratio nonlinear compression is used – compensating for LINAC RF curvature (2nd order).
- The RF curvature compensation is made with multipoles installed in dispersive locations of 180° Bates bend (no harmonic RF)
- Operationally longitudinal match relies on:
  - a. Bunch length measurements at full compression (MPI)
  - b. Longitudinal transfer function measurements $R_{55}$, $T_{555}$, $U_{5555}$
  - c. Energy spread measurements in injector and exit of the LINAC
- Accuracy of the matrix elements measurements is at the level corresponding to the accuracy of the multipoles (few $10^{-3}$) or better
- <u>Octupoles in ARC2 allows proper energy compression of large ΔE (FEL exhaust) beam in process of energy recovery.</u>

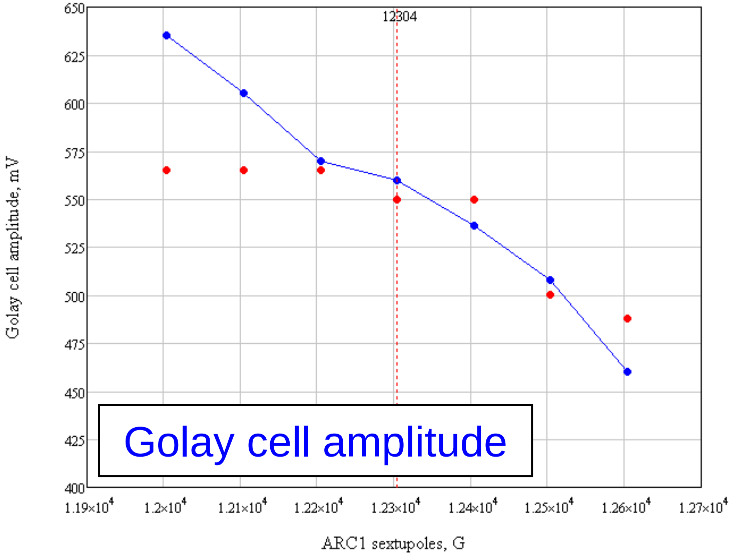
# Bunch length - $T_{555}$ – sextupoles



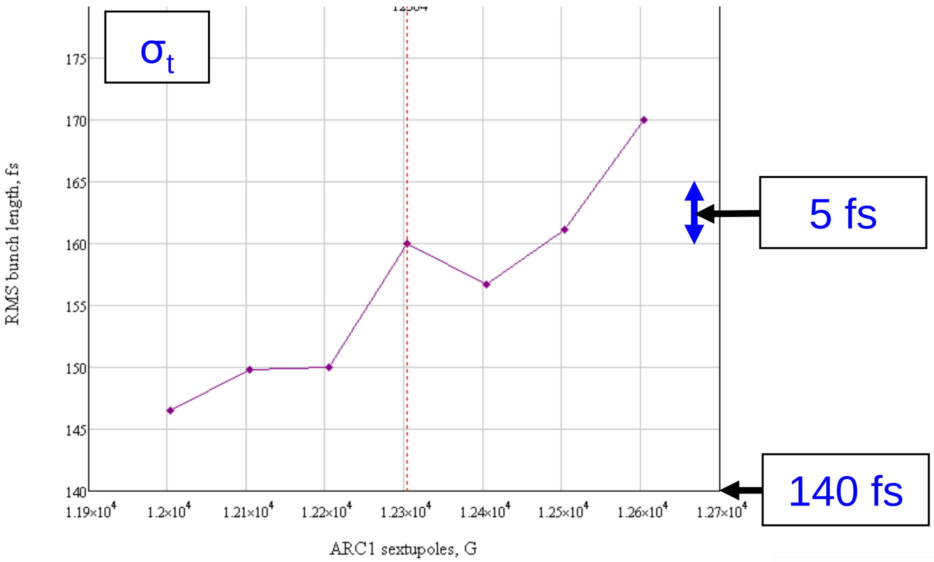
$T_{555}$

0

± 2.5% sextupoles B'dL



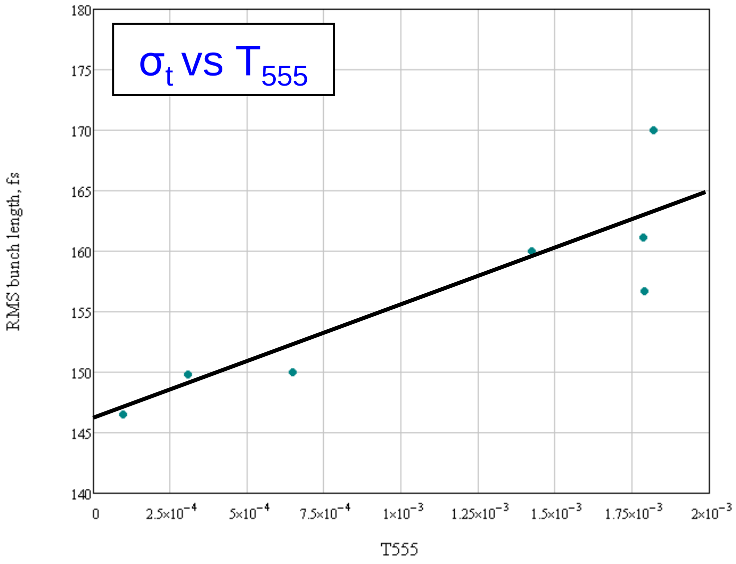
Golay cell amplitude



$\sigma_t$

5 fs

140 fs



$\sigma_t$ vs $T_{555}$