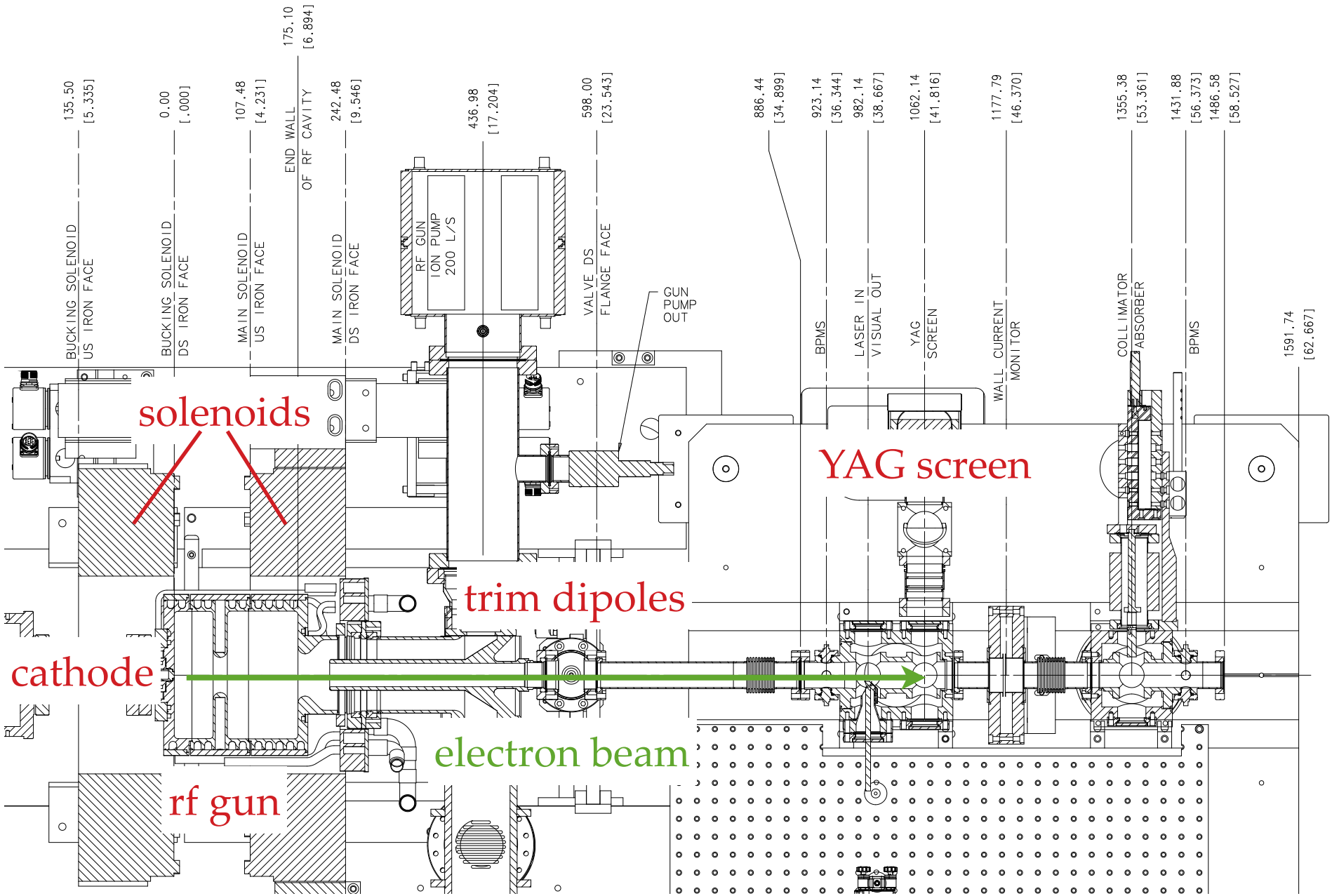
Electron beam measurements in the ASTA rf gun

G. Stancari, J.-P. Carneiro, D. Crawford, D. Edstrom, J. Ruan, A. Vivoli
Fermilab

- Experimental procedures
- Models
- Results
  - beam-based rf gradient calibration
  - beam energy calibration
  - emittance measurement
  - centroid motion

ASTA Users Meeting
Fermilab, June 9, 2014

Apparatus


135.50 [5.335]
BUCKING SOLENOID US IRON FACE
0.00 [.000]
BUCKING SOLENOID DS IRON FACE
107.48 [4.231]
MAIN SOLENOID US IRON FACE
175.10 [6.894]
END WALL OF RF CAVITY
242.48 [9.546]
MAIN SOLENOID DS IRON FACE
436.98 [17.204]
RF GUN ION PUMP 200 L/S
598.00 [23.543]
VALVE DS FLANGE FACE
GUN PUMP OUT
886.44 [34.899]
923.14 [36.344]
BPMS
982.14 [38.667]
LASER IN VISUAL OUT
1062.14 [41.816]
YAG SCREEN
1177.79 [46.370]
WALL CURRENT MONITOR
1355.38 [53.361]
COLLIMATOR ABSORBER
1431.88 [56.373]
BPMS
1486.58 [58.527]
1591.74 [62.667]
solenoids
YAG screen
trim dipoles
cathode
electron beam
rf gun

Solenoid scans: Method

1. Measure **beam spot** at YAG screen **vs. solenoid settings**
   at low charge (< 2 pC)
   with short pulses (4.5 ps)
   for different gradients and phases

2. **Model linear transport** in rf gun from cathode to screen

beam size at YAG beam size at cathode

$$\sigma^2 = M_{11}^2 \cdot \sigma_0^2 + M_{12}^2 \cdot \frac{\epsilon^2}{\sigma_0^2}$$

emittance

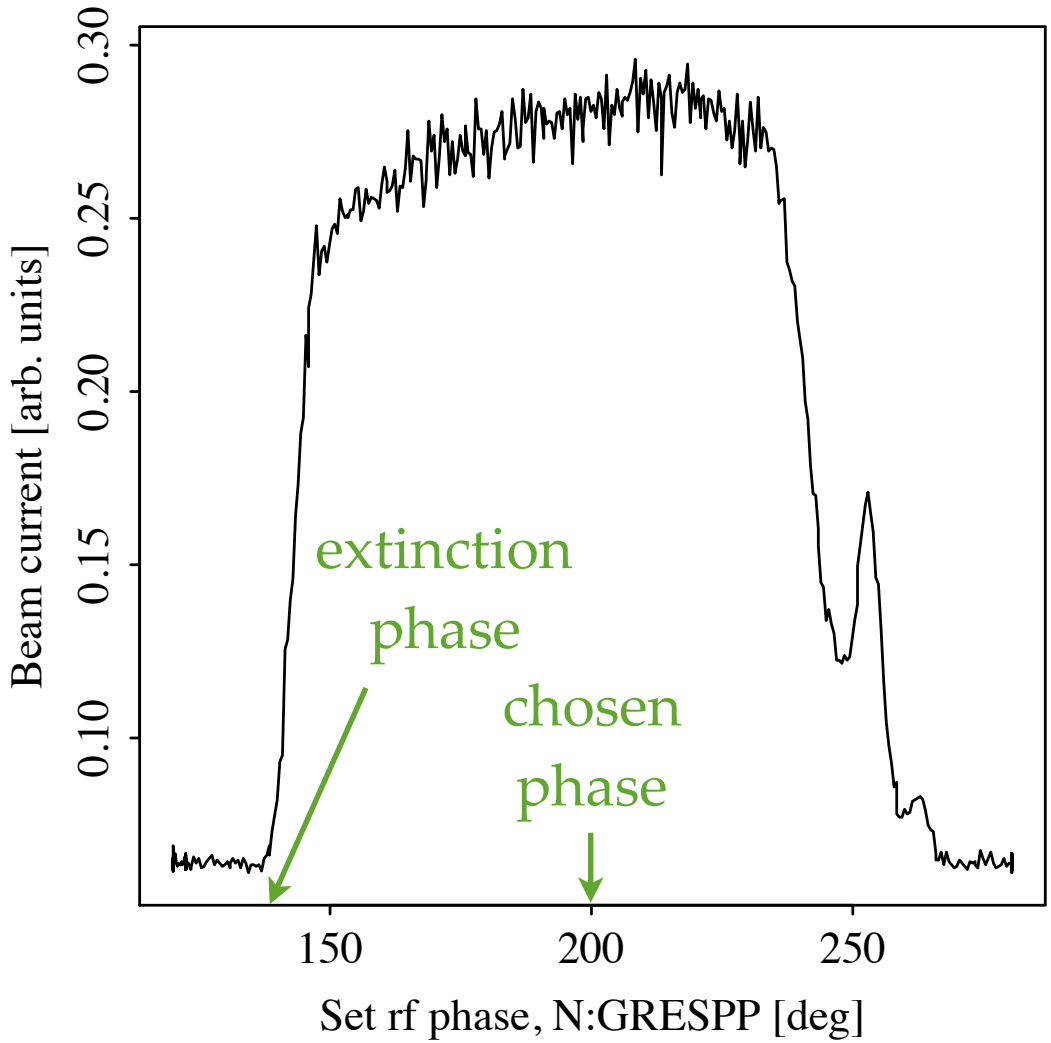
Matrix elements from
- integration of trajectories in time (Astra) or
- longitudinal slices (Gulliford/Bazarov, gs tramalargu code)

3. Find **best fit of model to measurements** to estimate:
   peak gradient, rf phase => final beam energy
   initial emittance

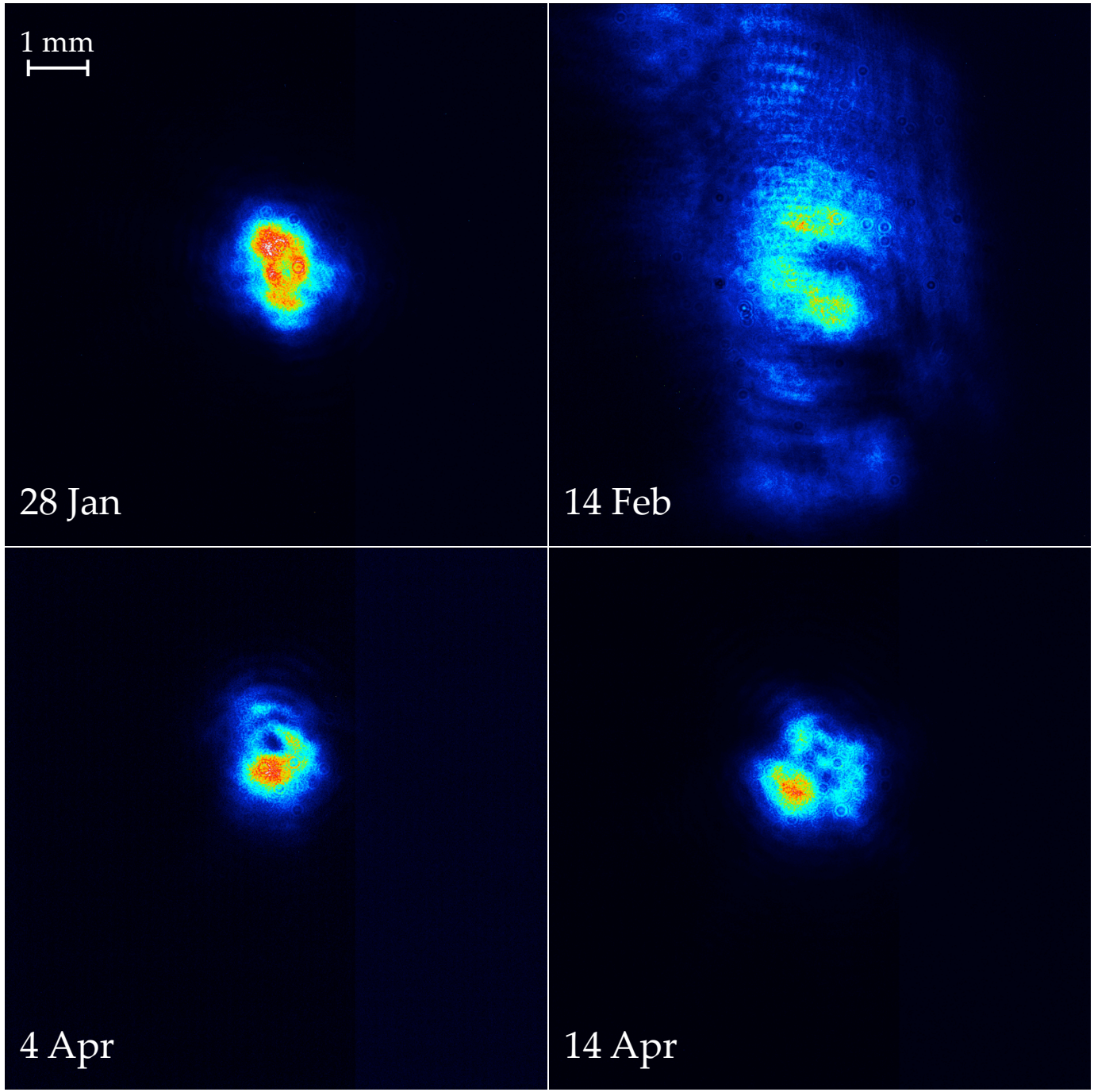
Solenoid scans: Data sets

Date	Cathode	Set gradient N:GRESPA [MV/m]	Set rf phase N:GRESPP (phys.) [deg]	Gun power N:GCVFP [MW]	Laser spot h, v [mm]	Number of bunches	Charge/bunch [pC]	Numer of data points
28 Jan 2014	Mo	25	-20 (+59?)	2.840	0.43, 0.58	100	0.10	16
29 Jan 2014	Mo	20	-20 (+59?)	2.217	0.43, 0.58	100	0.12	18
14 Feb 2014	Mo	25	192 (+65.5)	2.787	0.98, 2.2	100	0.19	10
14 Feb 2014	Mo	20	192 (+65.5)	2.173	0.98, 2.2	100	0.17	10
3 Apr 2014	Cs_2Te	26.6	187 (+60.5)	2.870	0.41, 0.76	100	0.81	32
4 Apr 2014	Cs_2Te	23	187 (+60.5)	2.472	0.42, 0.69	20	0.47	26
14 Apr 2014	Cs_2Te	45	200 (+61.5)	3.463	0.53, 0.67	250	2.3	23
14 Apr 2014	Cs_2Te	37	200 (+61.5)	2.299	0.57, 0.61	250	2.3	25

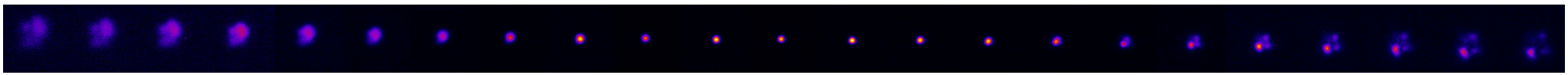
Example of phase scan (14 Apr 2014 at 45 MV/m)

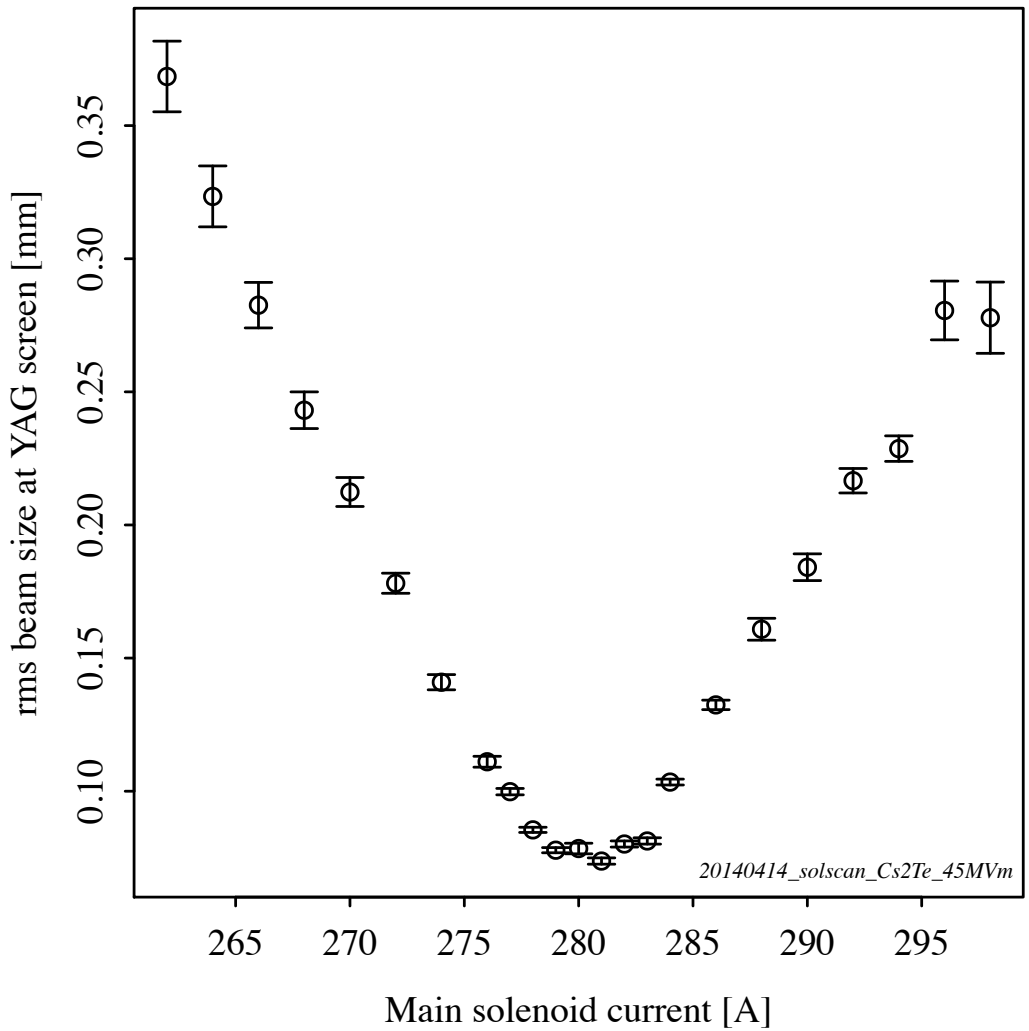


Laser spots at virtual cathode

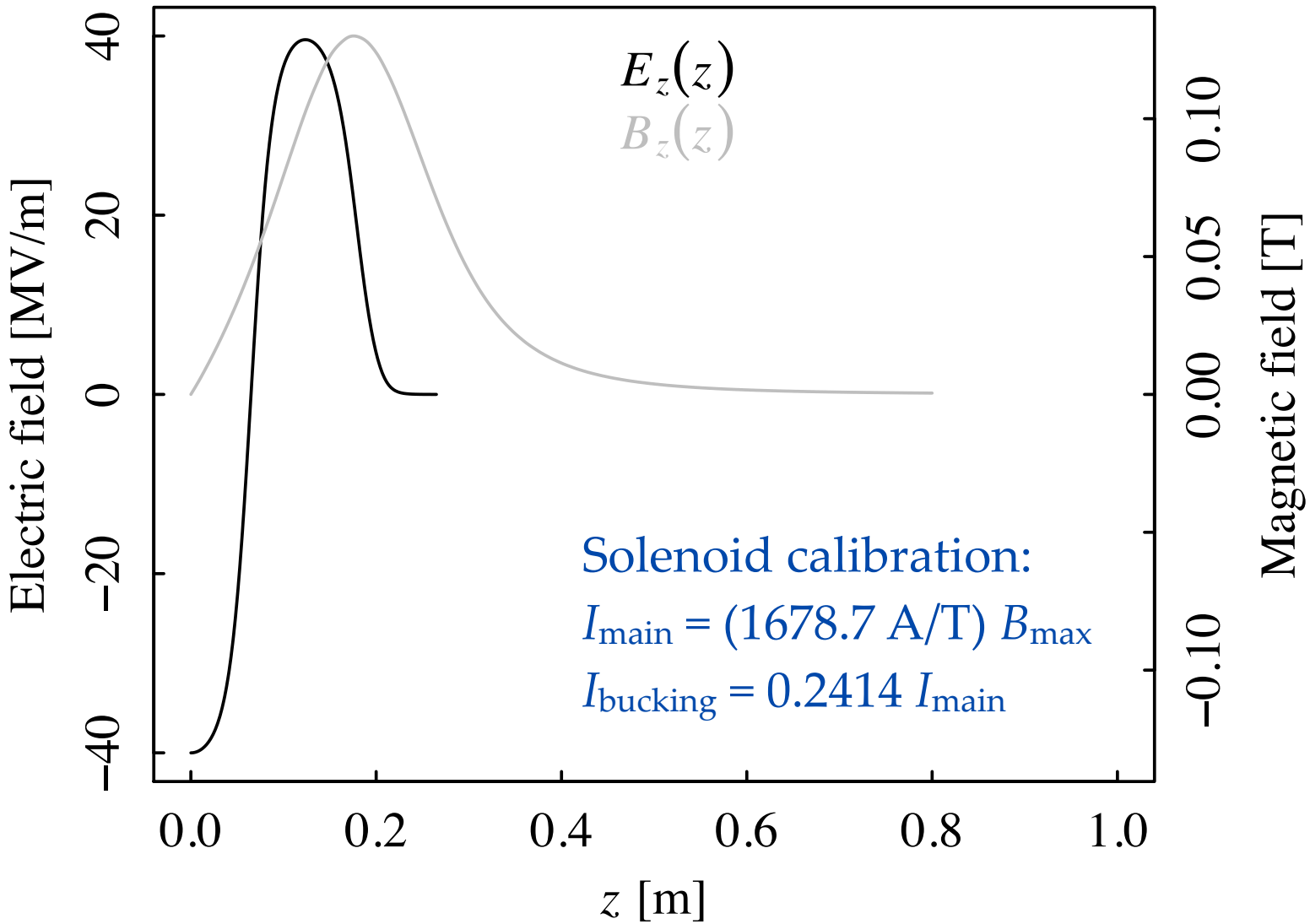


Example of electron beam on YAG screen vs. solenoid current





Rf gun model: field maps



Two models for particle transport in rf gun (no space charge)

1. Obtain transfer matrix M by **tracking** principal trajectories using the Astra code (*"time integration"* approach)

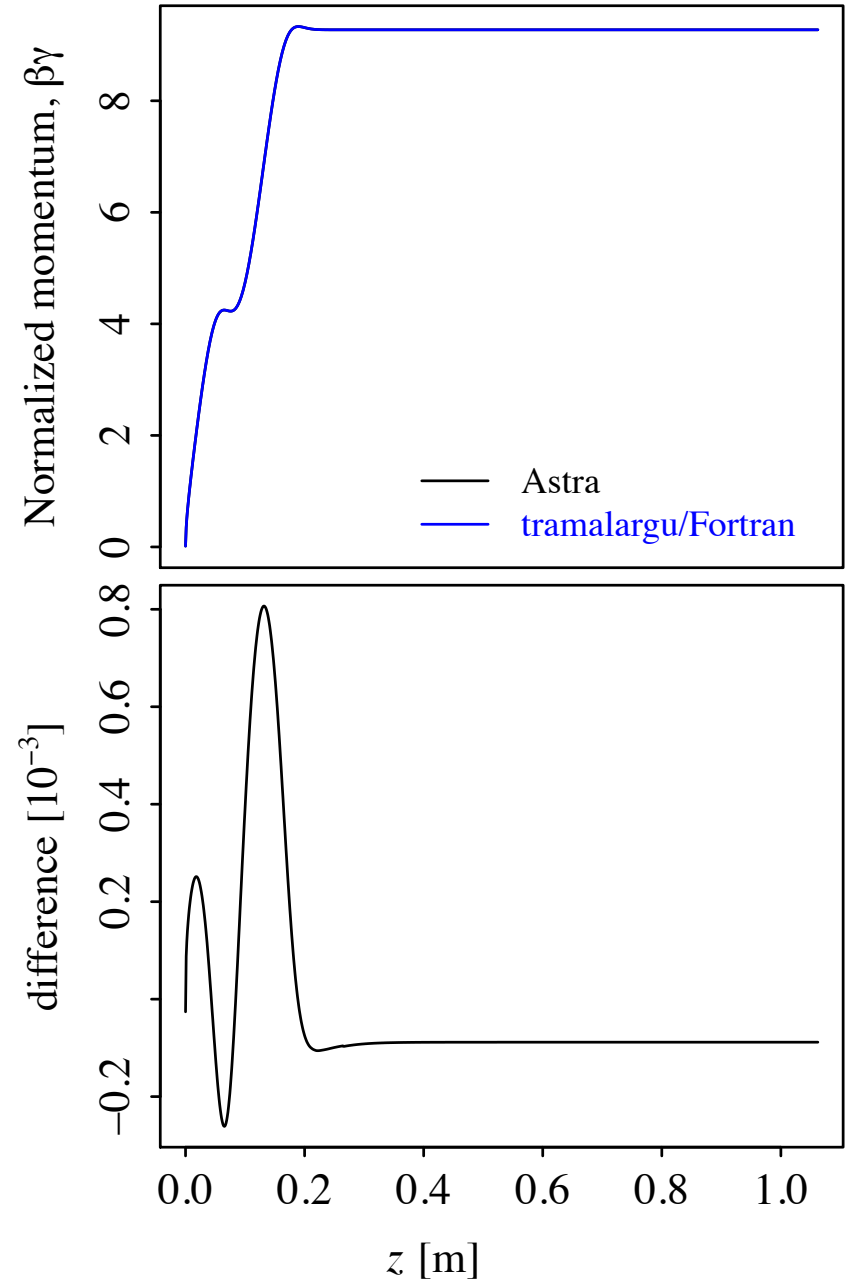
2. Calculate and multiply transfer matrices of small **slices in z** [according to Gulliford and Bazarov, PRSTAB **15**, 024002 (2012)] using new Fortran code (`tramalargu`) (*"space integration"* approach)

Why 2 models?
- to evaluate systematic uncertainties
- to set up Astra for later analyses with space charge

Comparison between models: longitudinal dynamics

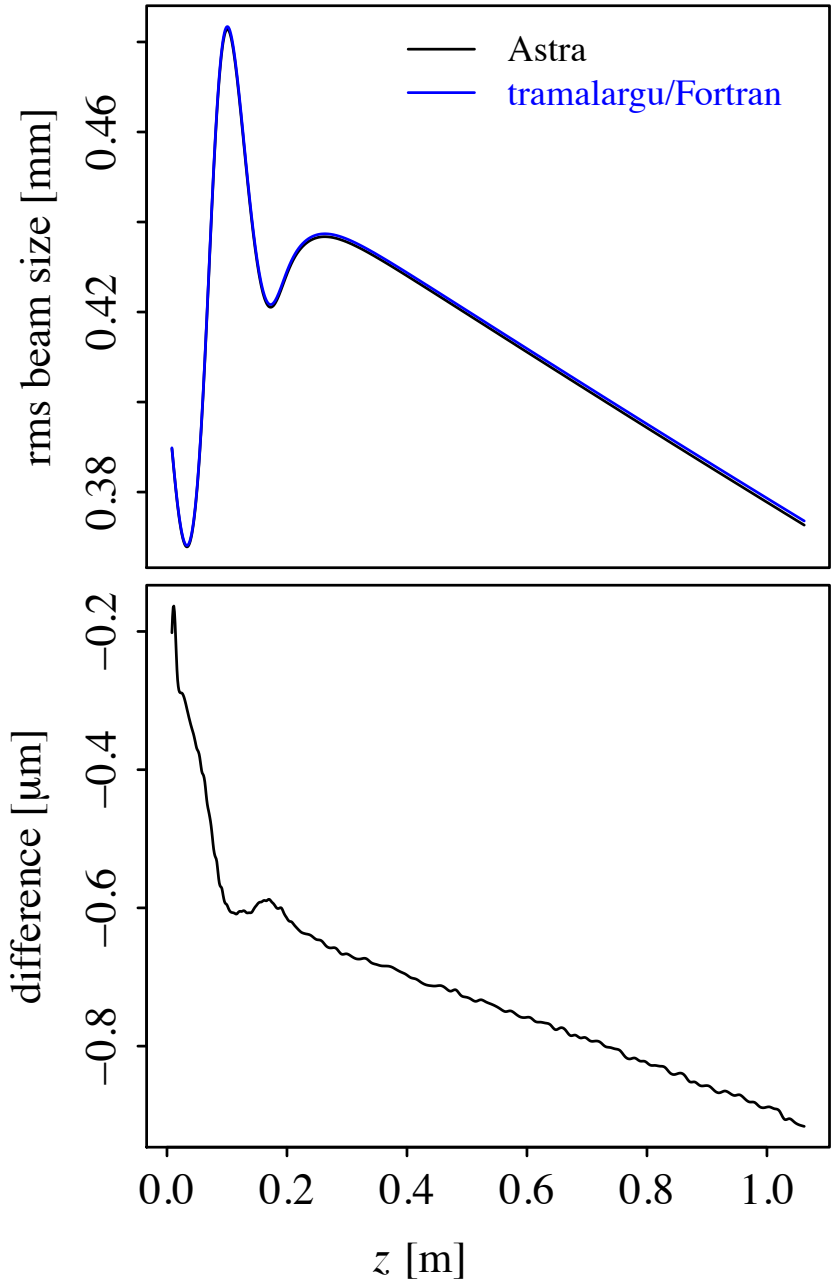
Test case
40 MV/m, 1.3 GHz, 38.5 deg
0.13 T max. in solenoids
0.4 mm initial rms size
0.23 eV initial kinetic energy
0.19 um initial normalized rms emittance
From cathode (z = 0 m) to YAG screen (z = 1.06 m)

Accuracy:
1 ps max. time step (Astra)
10^{-6} phase tolerance (tramalargu)



Difference in $\beta\gamma$ is less than 10^{-3}

Comparison between models: transverse dynamics



Difference in beam envelope is less than 1 micron

Fitting model to data

- Use **2 data sets** with different gradients, same phase, same laser spot size

- Inputs: **initial spot size** (measured) and **initial kinetic energy** (almost irrelevant)

- Free parameters:
  1. **Gradient in first data set**, E_1
  2. **Gradient in second data set**, E_2
  3. **Rf phase of laser pulse**, ϕ
  4. **Emittance (normalized rms)**, ε_0

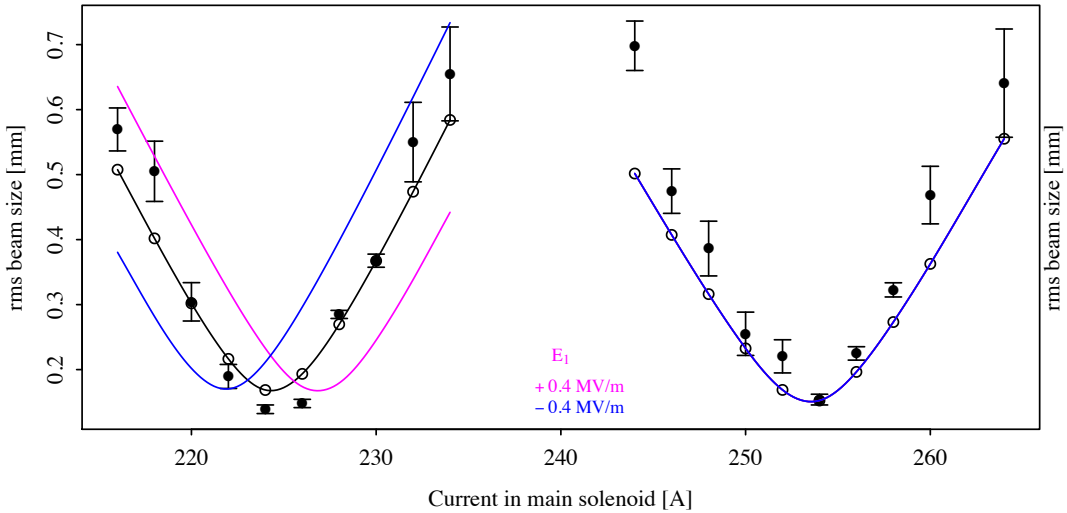
- **Final kinetic energies** T_1 and T_2 **as derived quantities** from longitudinal calculation

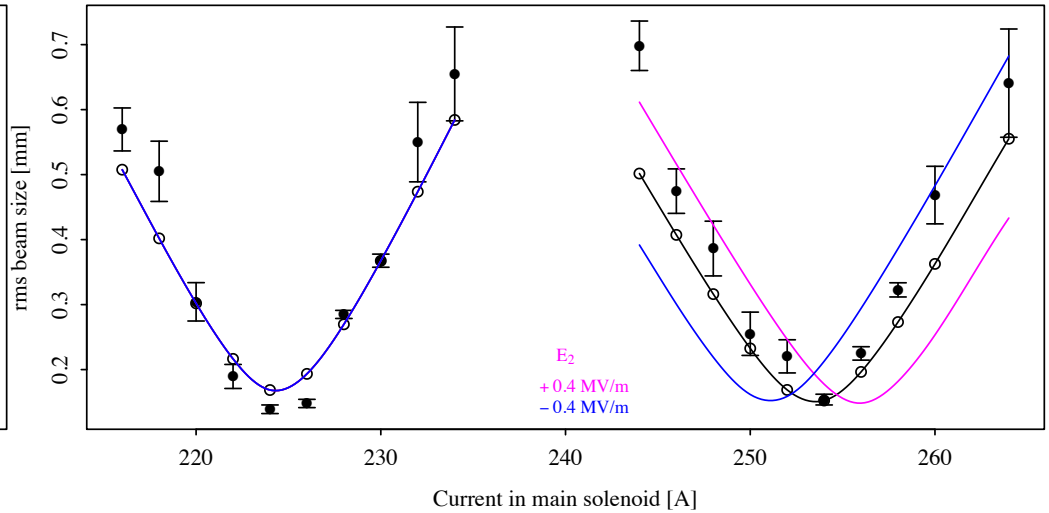
- Statistical **uncertainties** from bootstrap; systematic from different models

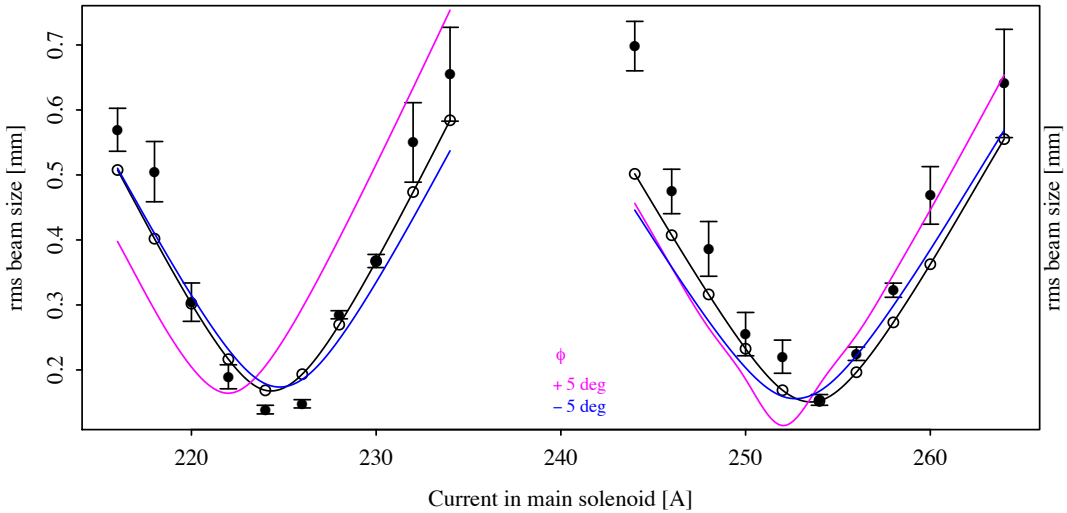
Parameter independence and model sensitivity

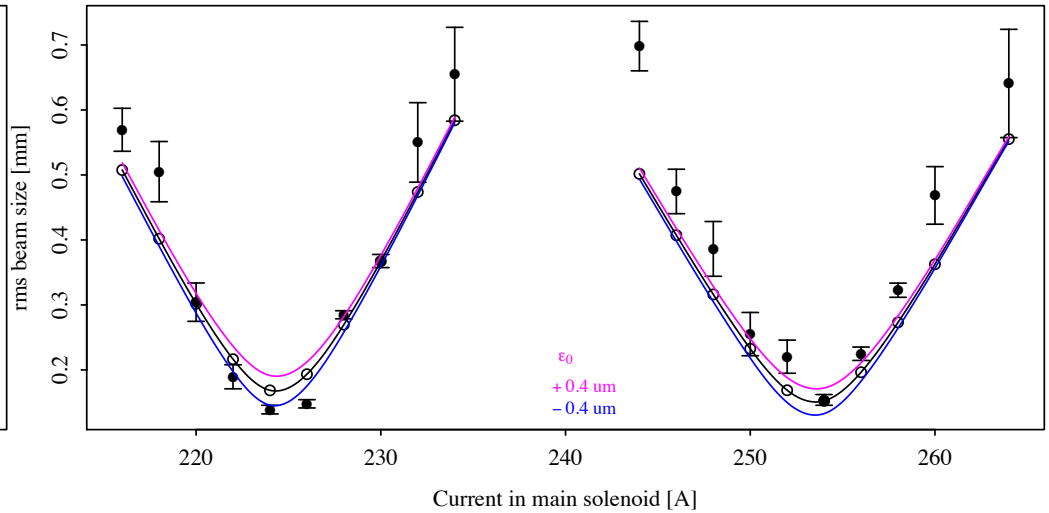
The first gradient is determined by the position of the first data set

The second gradient is determined by the position of the second data set





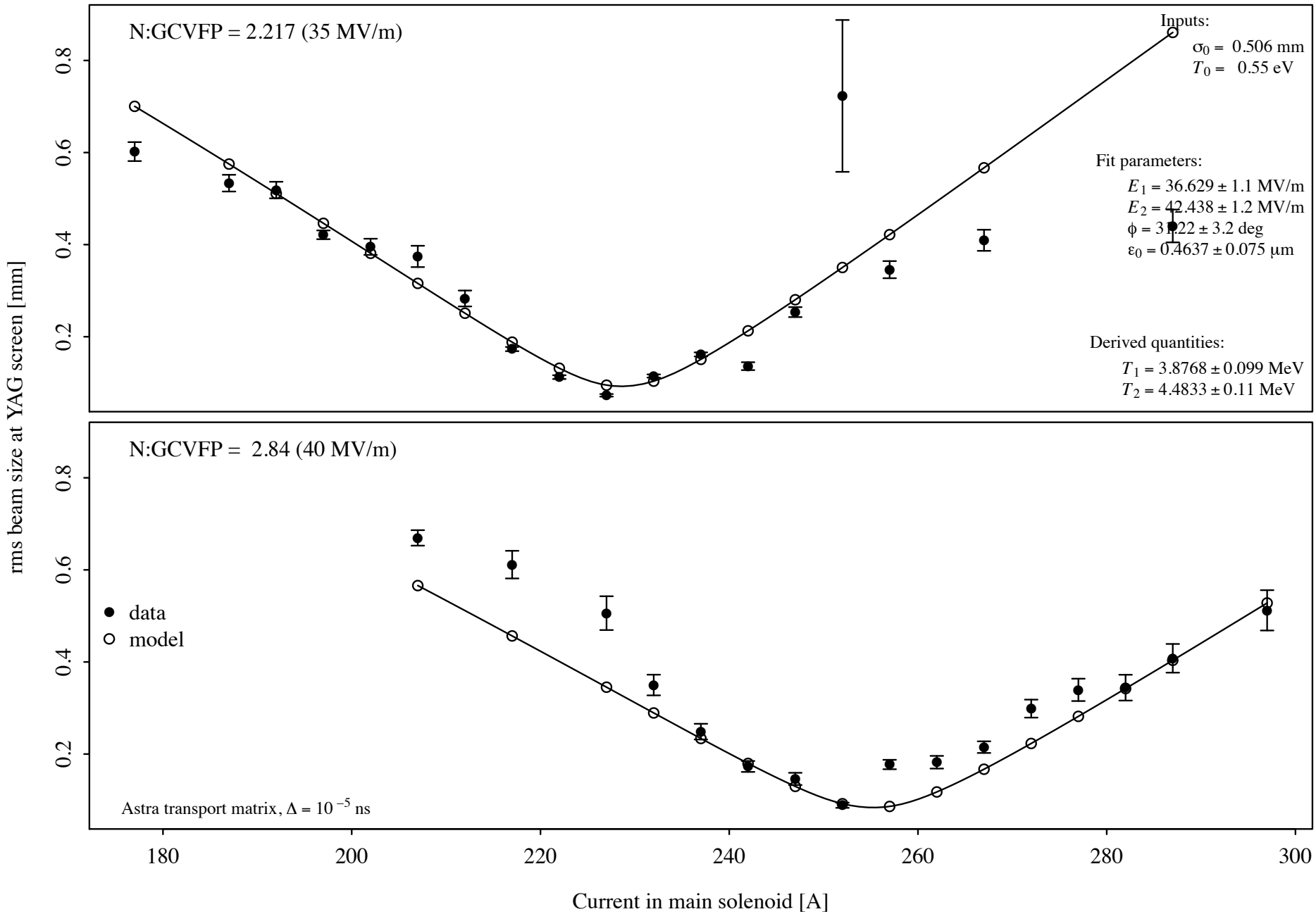




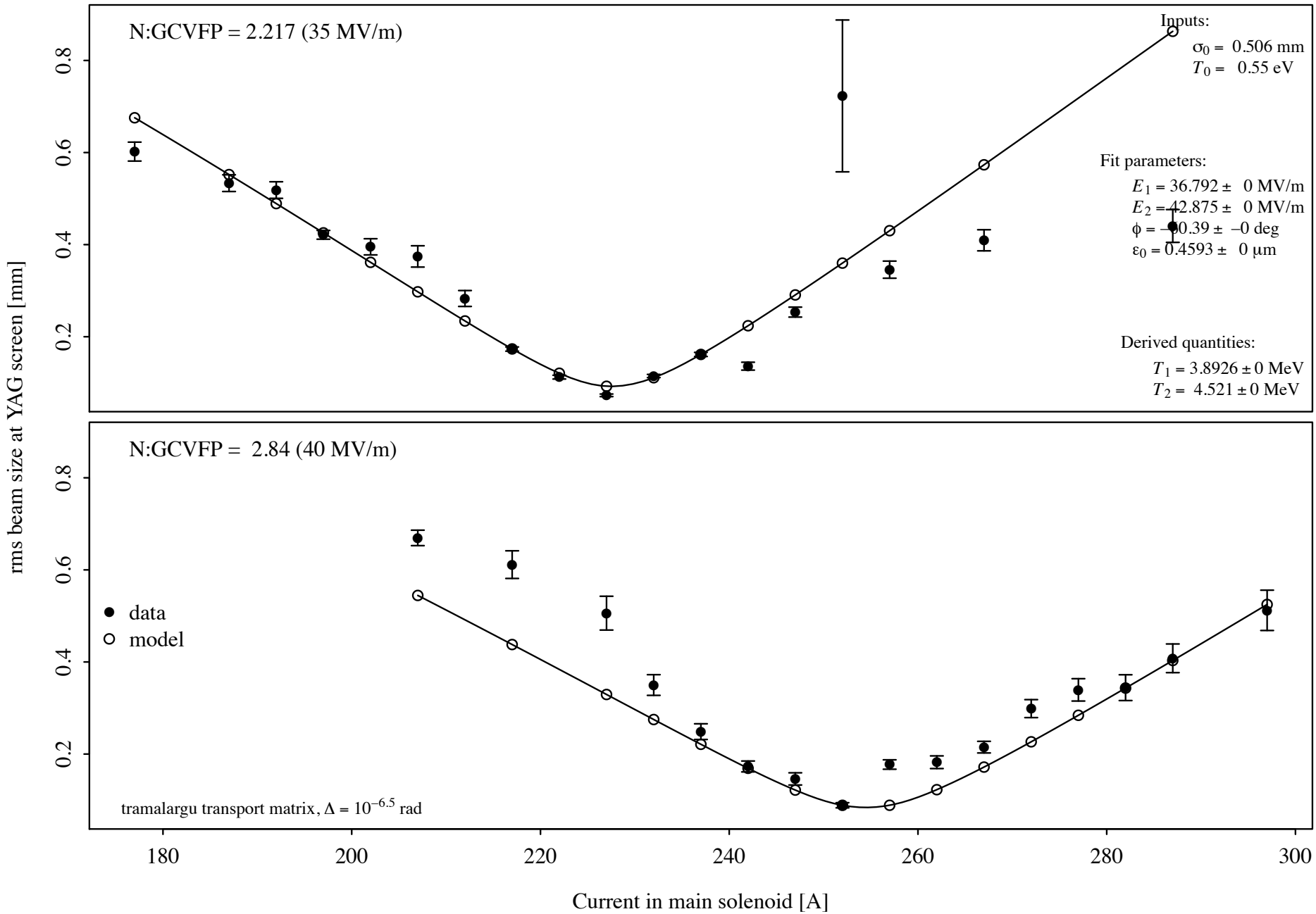
Changing the phase affects both data sets, but by different amounts

The emittance is determined by the depth of the dip

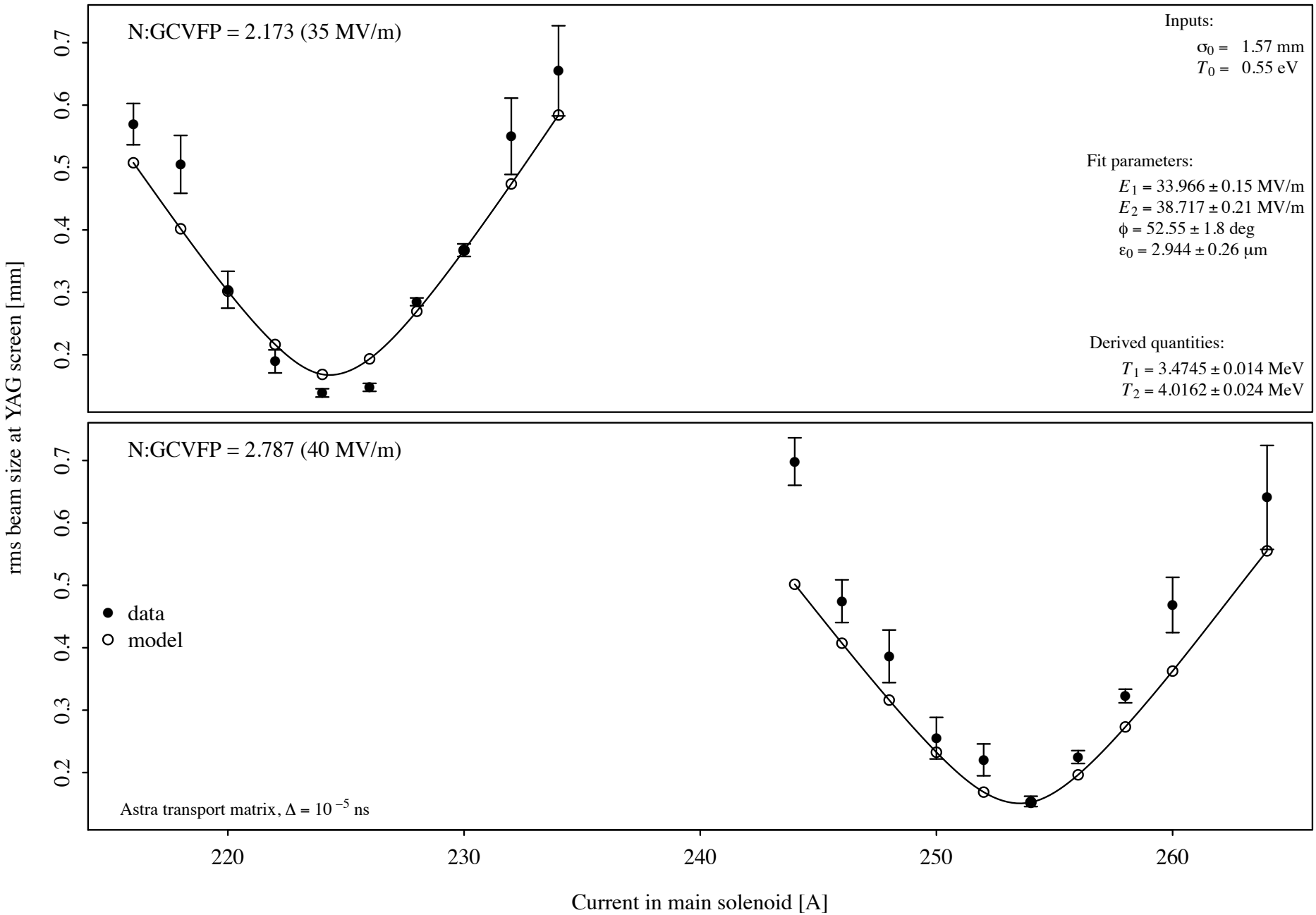
Data and model: solenoid scans of 28-29 Jan 2014



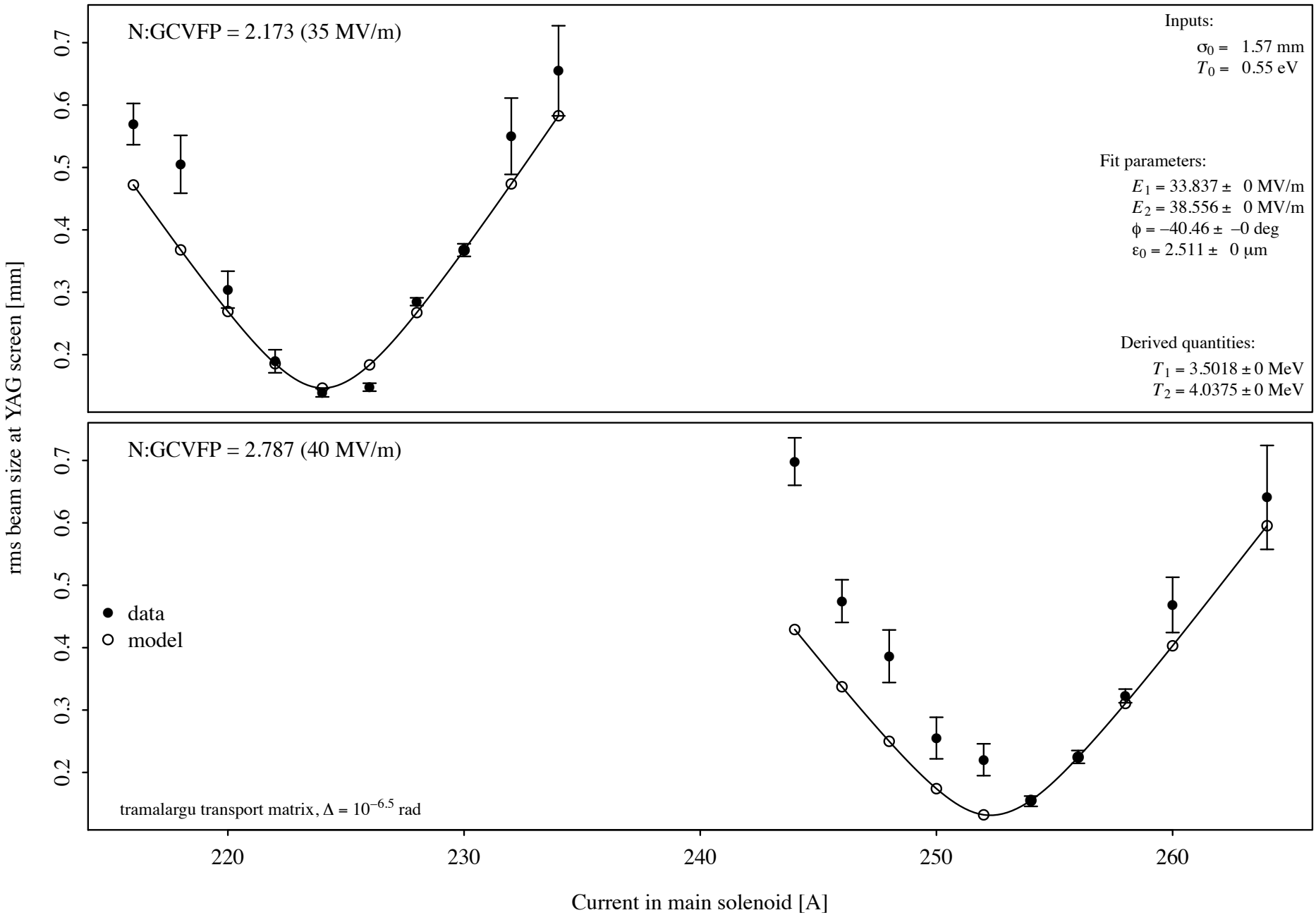
Data and model: solenoid scans of 28-29 Jan 2014



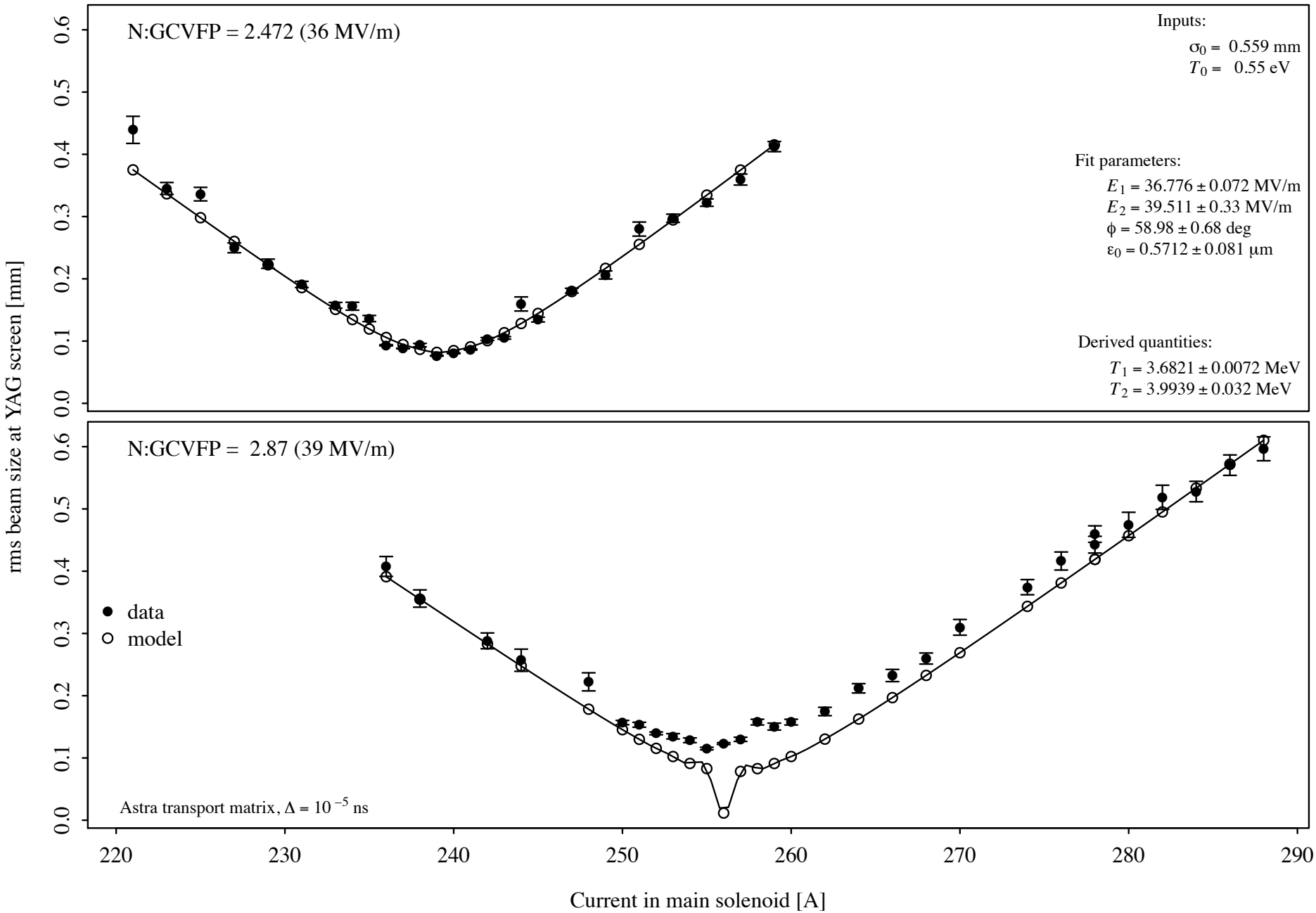
Data and model: solenoid scans of 14 Feb 2014



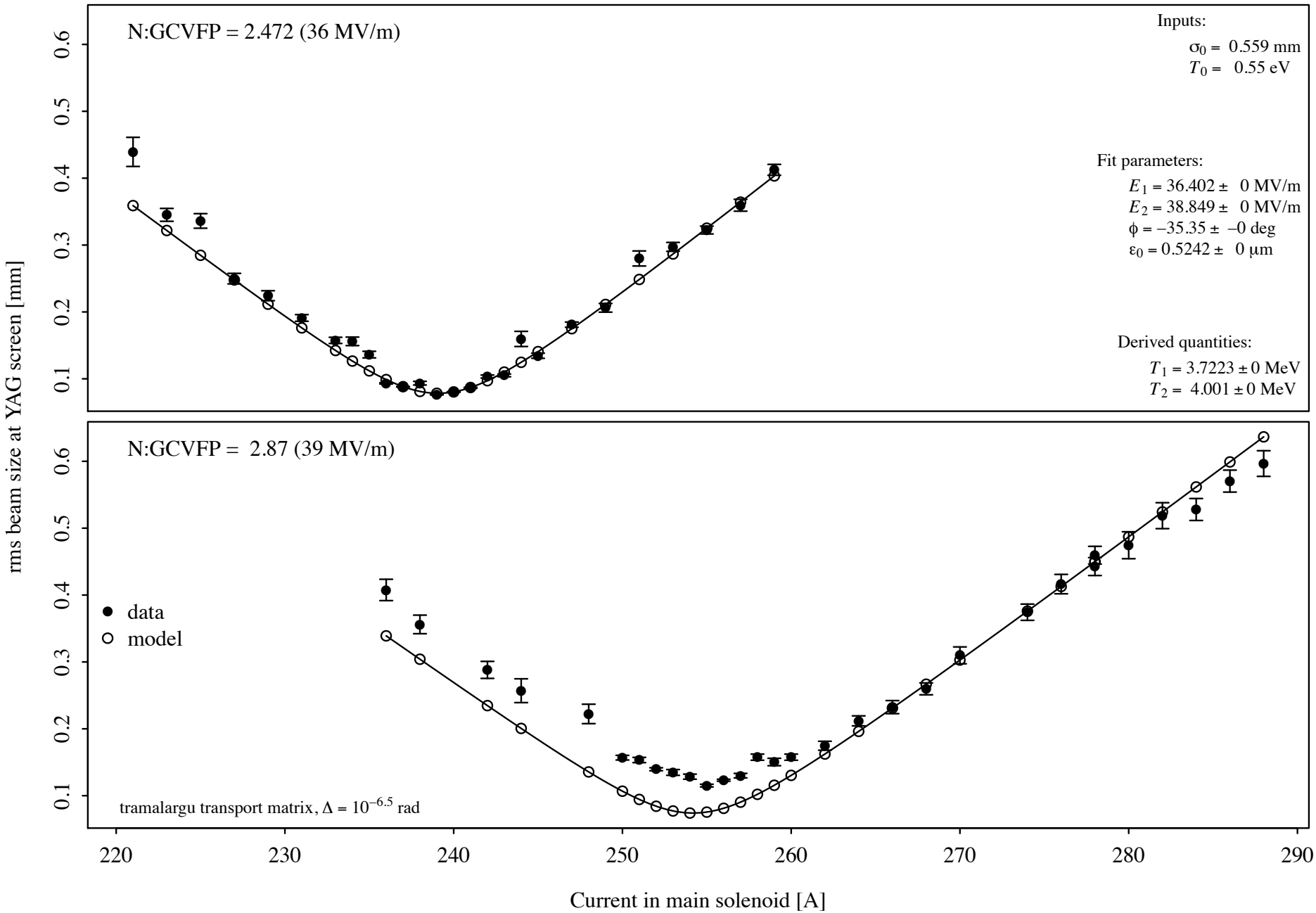
Data and model: solenoid scans of 14 Feb 2014



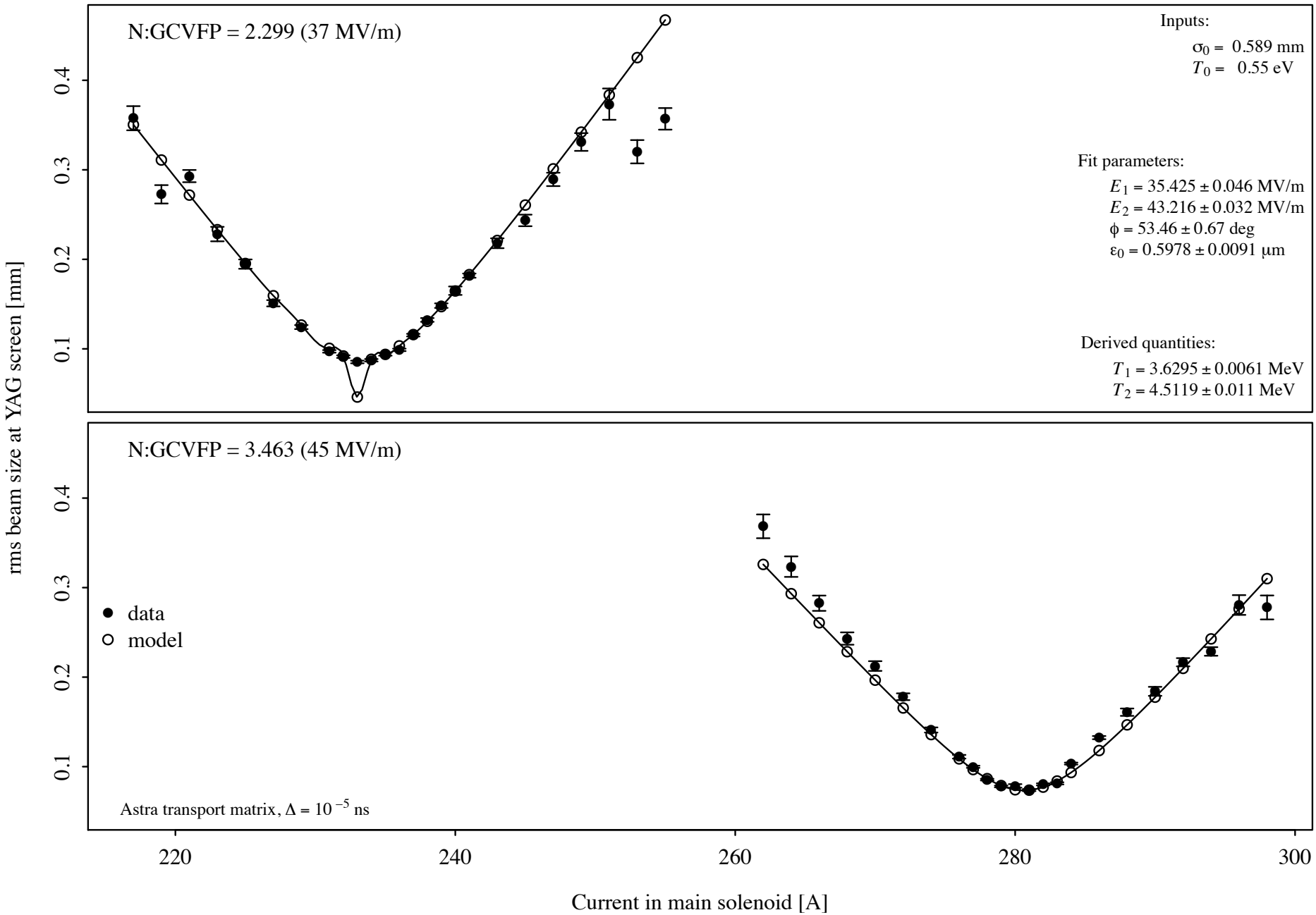
Data and model: solenoid scans of 3-4 Apr 2014



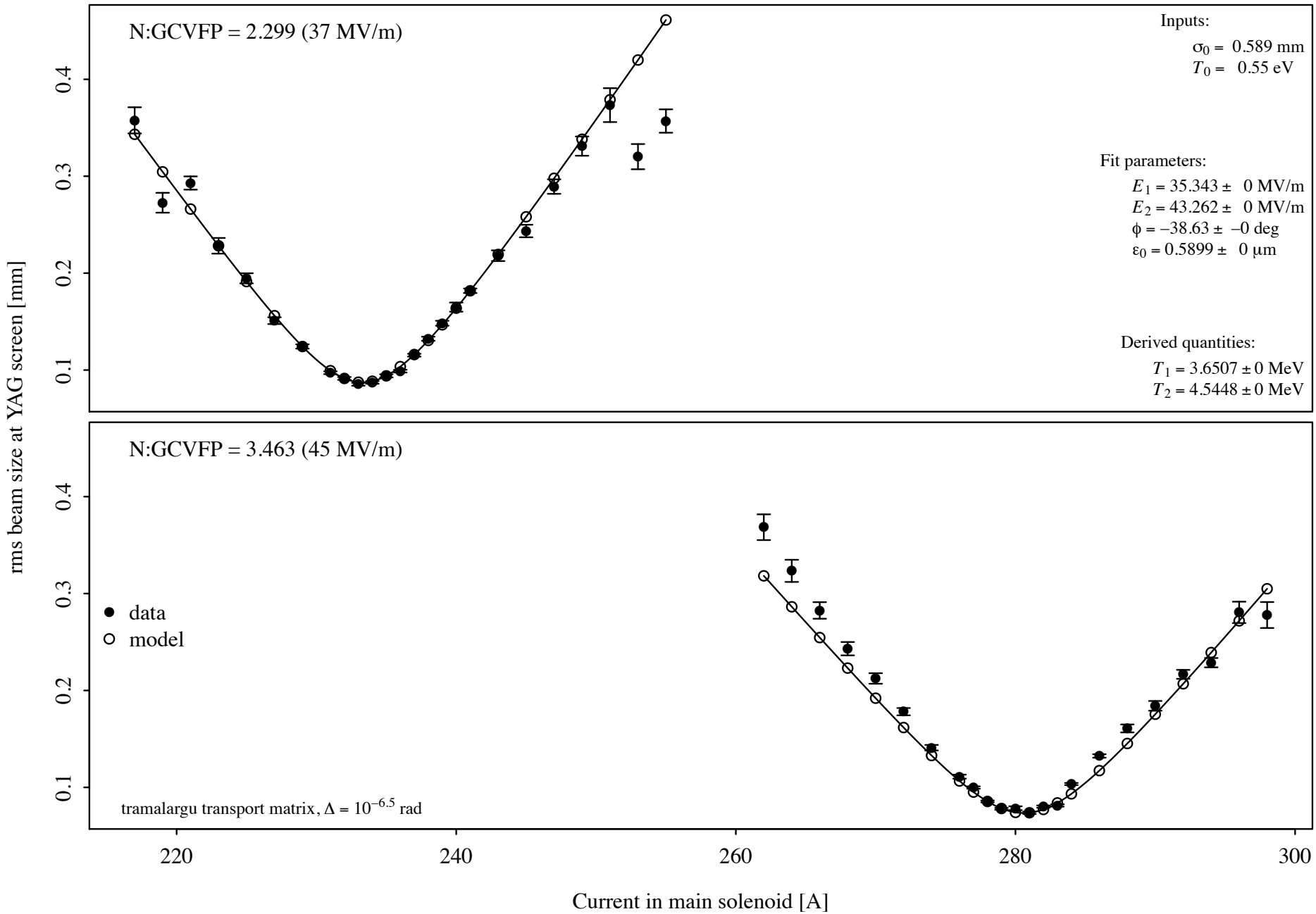
Data and model: solenoid scans of 3-4 Apr 2014



Data and model: solenoid scans of 14 Apr 2014



Data and model: solenoid scans of 14 Apr 2014



Summary of results

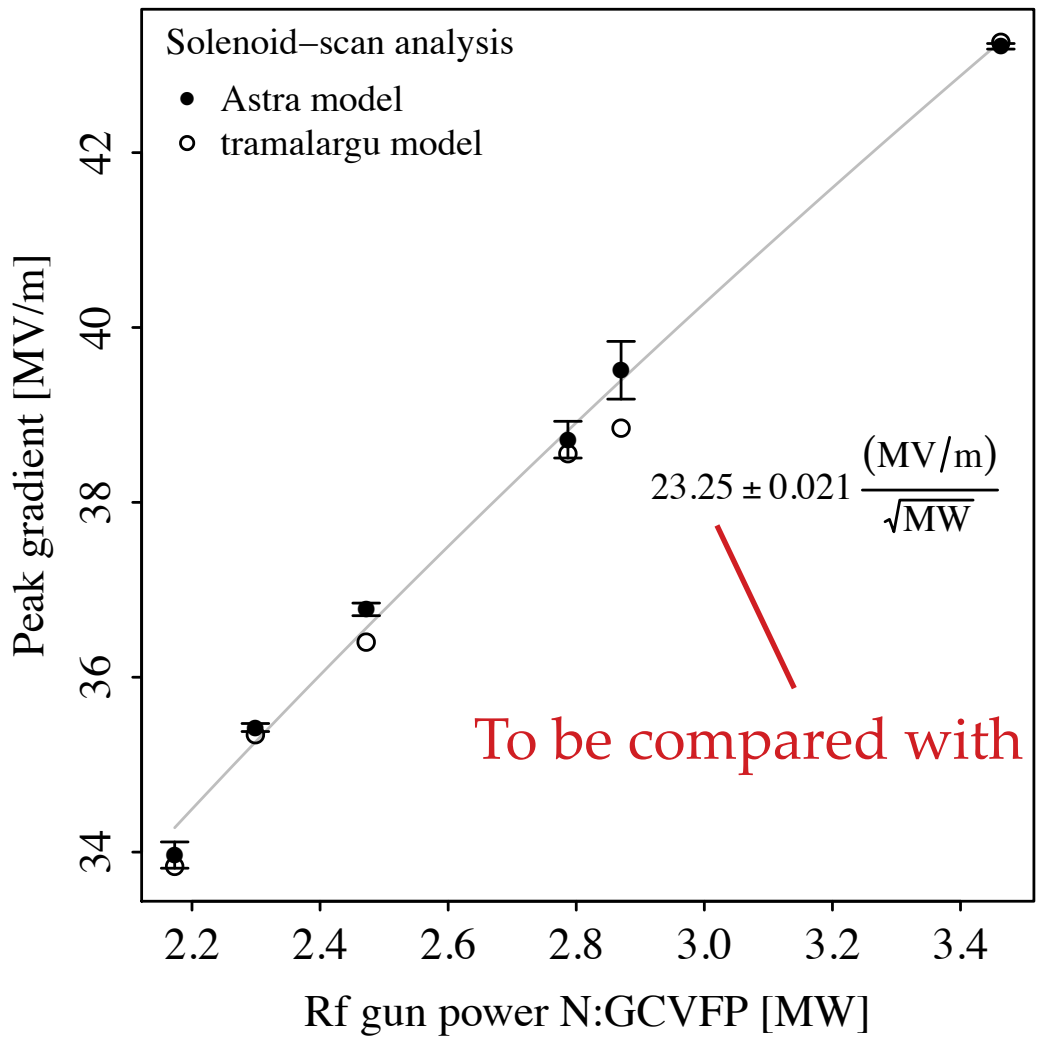
Data-set pair	Gun power 1 [MW]	Gun power 2 [MW]	Model	Gradient 1 [MV/m]	Gradient 2 [MV/m]	Phase [deg]	Emittance [um]	Energy 1 [MeV]	Energy 2 [MeV]
28-29 Jan	2.217	2.840	*Astra*	36.6 ± 1.1	42.4 ± 1.2	31.2 ± 3.2	0.464 ± 0.075	3.877 ± 0.099	4.48 ± 0.11
			tramalargu	36.79	42.87	29.6	0.459	3.89	4.52
14 Feb	2.173	2.787	*Astra*	33.97 ± 0.15	38.72 ± 0.21	52.6 ± 1.8	2.94 ± 0.26	3.474 ± 0.014	4.016 ± 0.024
			tramalargu	33.84	38.56	49.5	2.51	3.502	4.037
3-4 Apr	2.472	2.870	*Astra*	36.776 ± 0.072	39.51 ± 0.33	58.98 ± 0.68	0.571 ± 0.081	3.6821 ± 0.0072	3.994 ± 0.032
			tramalargu	36.402	38.85	54.7	0.524	3.7223	4.001
14 Apr	2.299	3.463	*Astra*	35.425 ± 0.046	43.216 ± 0.032	53.46 ± 0.67	0.5978 ± 0.0091	3.6295 ± 0.0061	4.512 ± 0.011
			tramalargu	35.343	43.262	51.37	0.5899	3.6507	4.545

First beam-based measurements of gradient, phase, and emittance at ASTA

Uncertainties are statistical

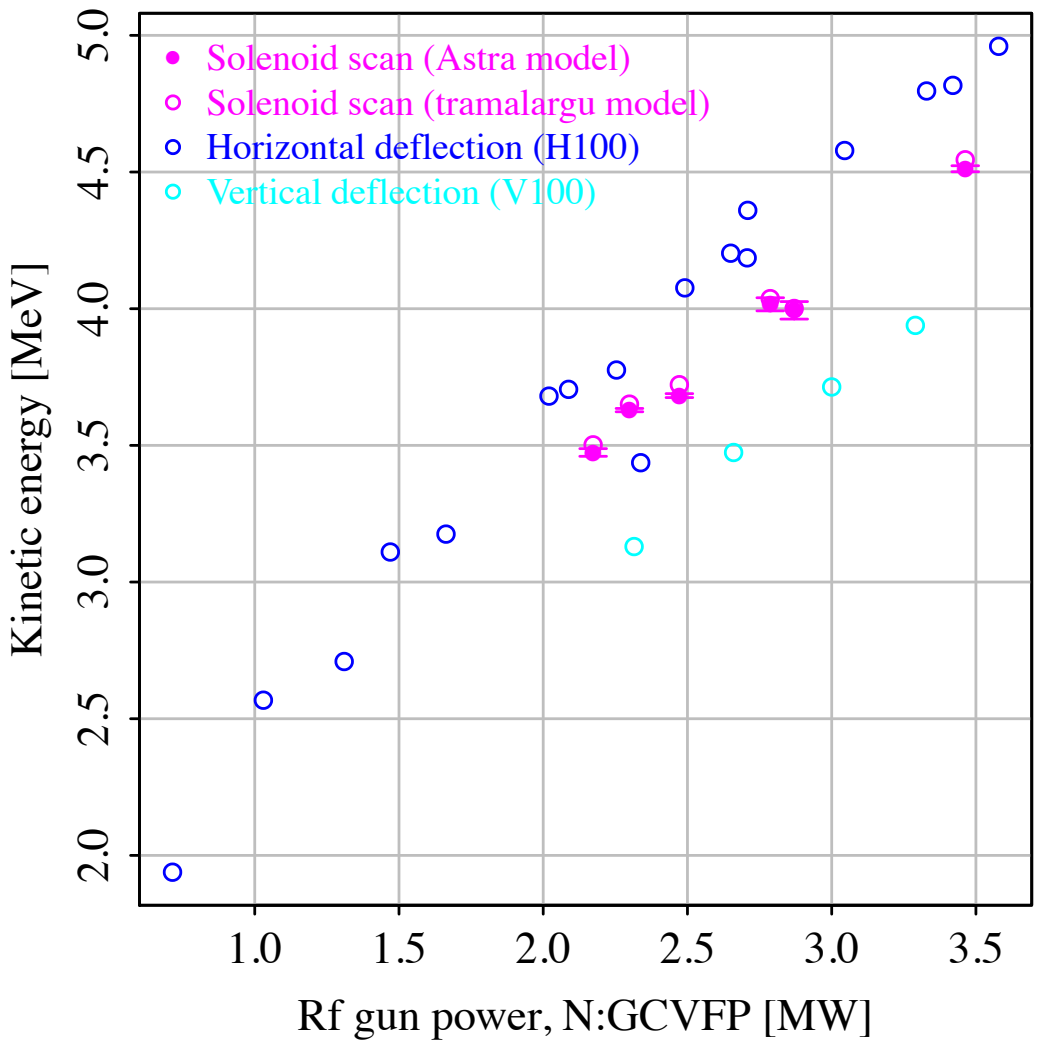
Estimate of systematic errors from difference between models

Results: calibration of rf gun gradient



To be compared with "nominal" 23.6

Results: final electron beam energy



Deflection with trim dipoles

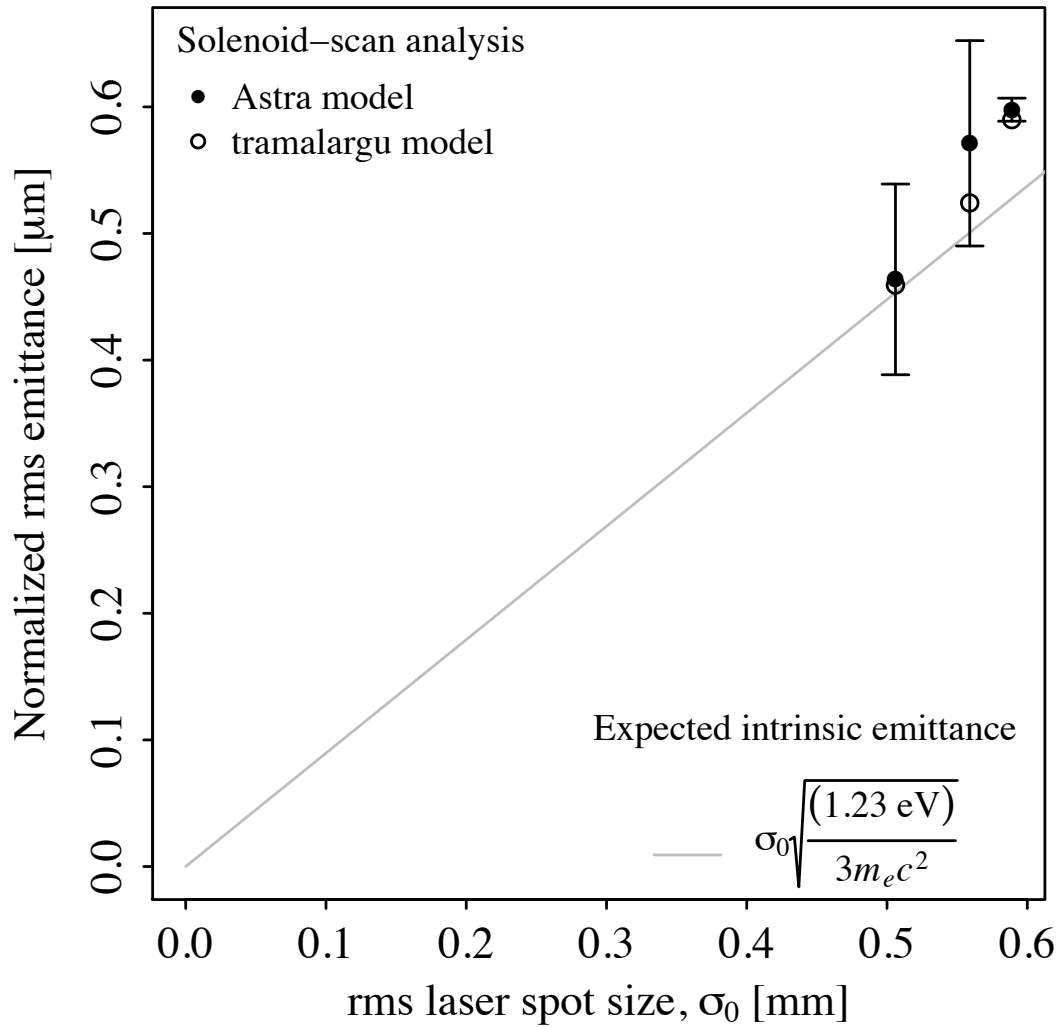
- direct measurement
- depends on final beam energy and fields in trim dipoles

[see D. Crawford's note]

Solenoid scan depends on dynamics in rf gun

- Independent measurements
- Systematic difference due in part to rf phase

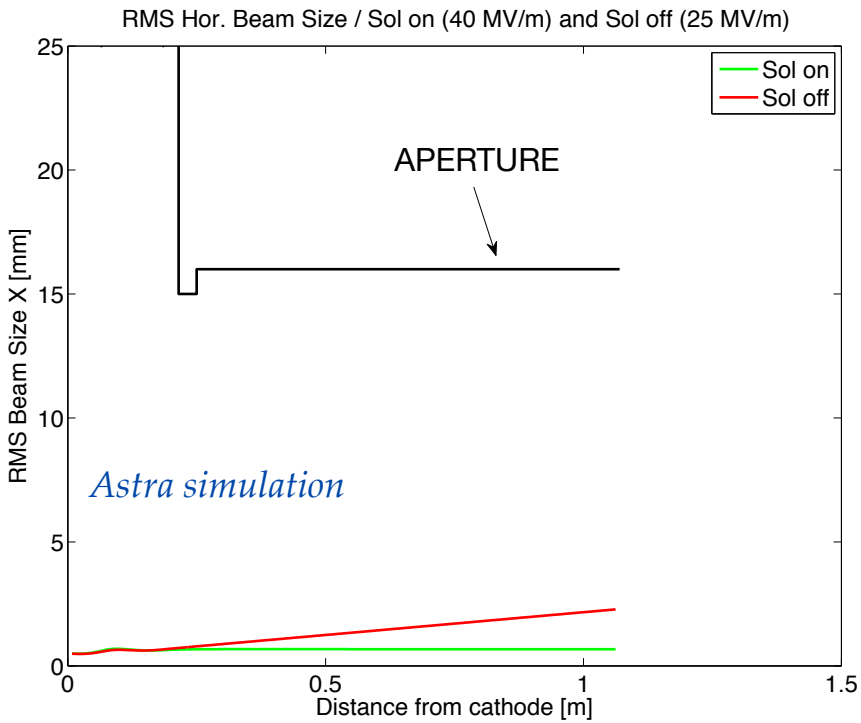
Results: Emittance vs. laser spot size



- Measurements close to expected
- Wider range of spot sizes will be explored

Beam-based alignment of laser, gun, and solenoids

A. Observe **centroid motion vs. rf phase** (solenoids off, low gradient):
Relative alignment of cathode yield (laser, quantum efficiency) with gun fields



- Transmission to YAG with solenoids off should be good
- Need to boost ratio of signal (number of bunches) to dark current (low gradient) for experiments

B. Observe **centroid motion vs. solenoid current**
Relative alignment of solenoid fields with gun axis

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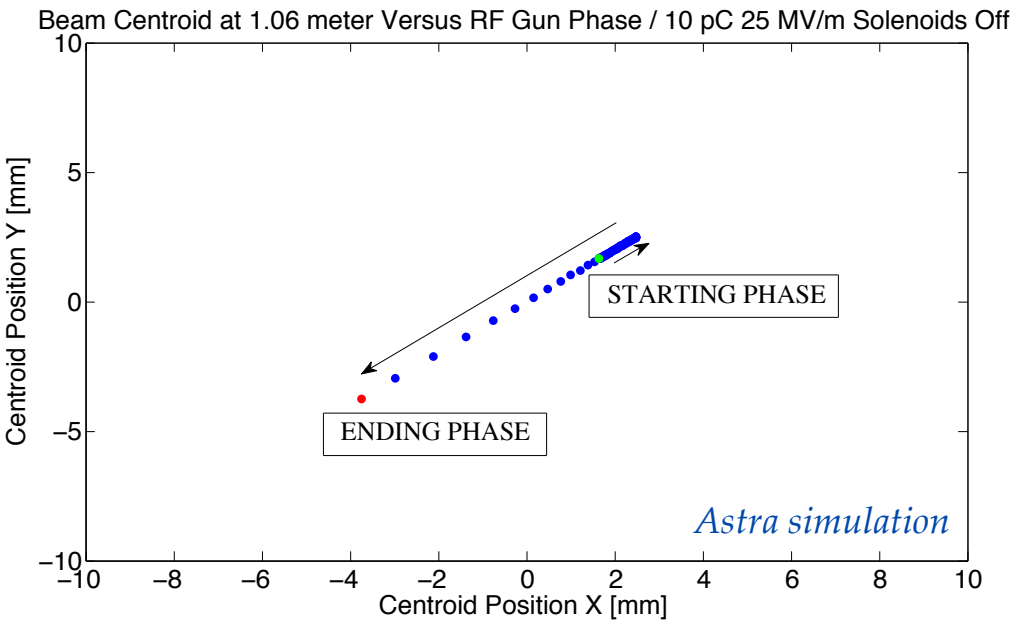
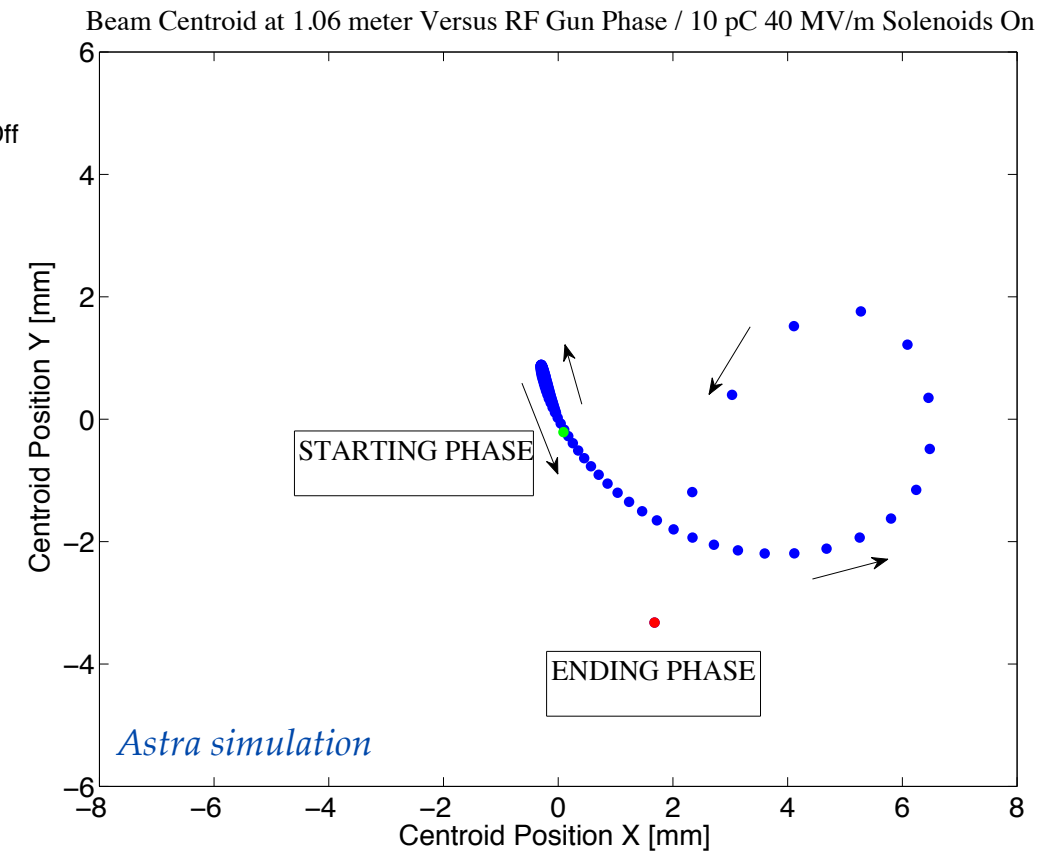
Expected effect of phase scan on centroid with 0.5-mm x/y initial offset

Solenoids off



Solenoids on



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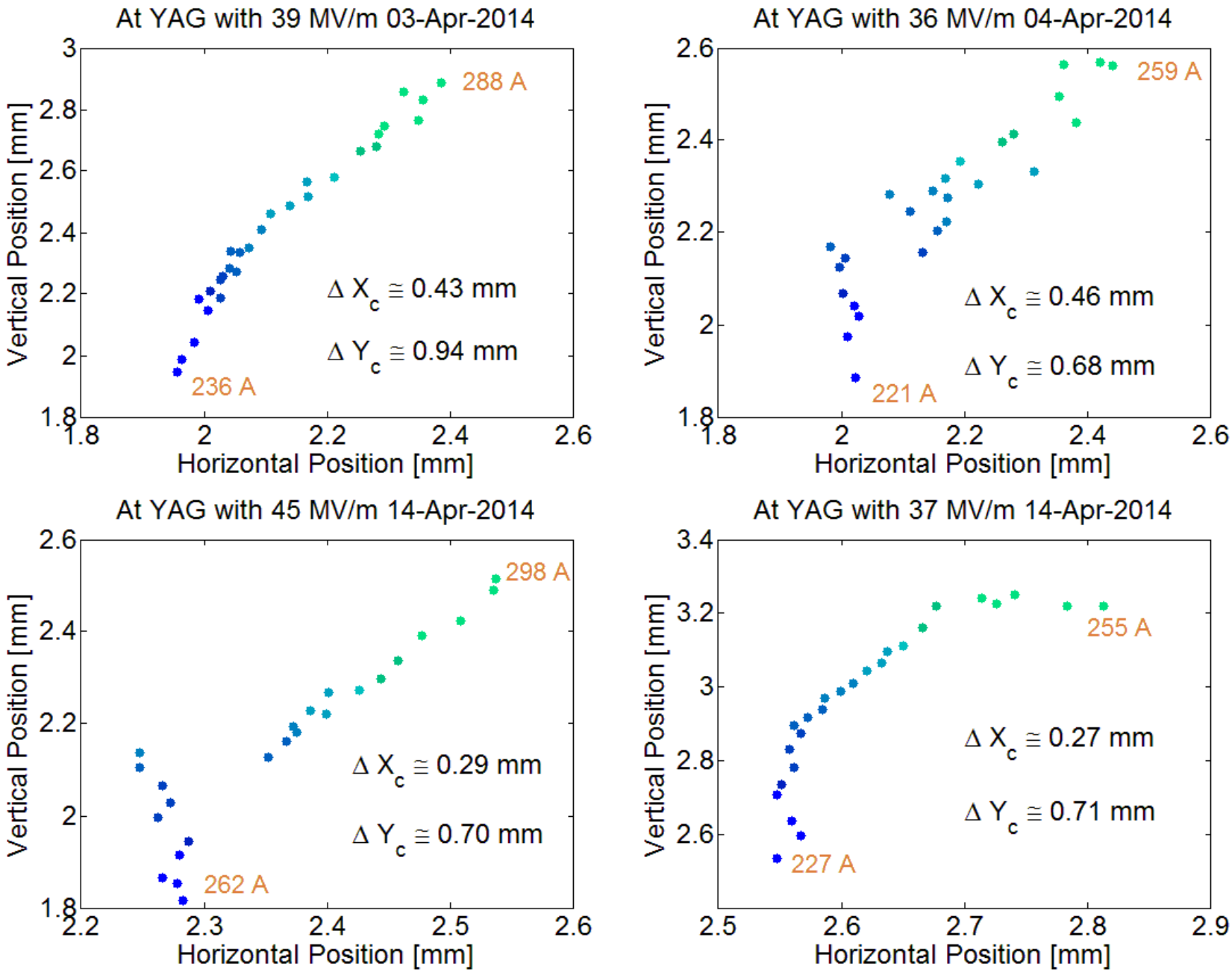
Measured beam centroid motion vs. solenoid current



- Not bad (e.g., 0.2 mm at PITZ), but can be improved

J.-P. Carneiro

Conclusions

- Solenoid scans at low charge and short pulse length provide **tests of single-particle dynamics in rf gun**
- Main purpose of this work was to get first estimates, set up procedure, and get input for machine commissioning
- Obtained **first beam-based measurements** of
  - **rf gun gradient**
  - **rf phase** of laser pulse
  - **electron beam emittance**
- **Final electron beam energy** from independent measurements:
  - **deflections with trim dipoles**
  - **solenoid scans**
- **Started beam-based alignment** of electron emission, rf fields, and solenoids (measurements and simulations)

Thank you for your attention!