Analysis of the ASTA rf gun solenoid scans

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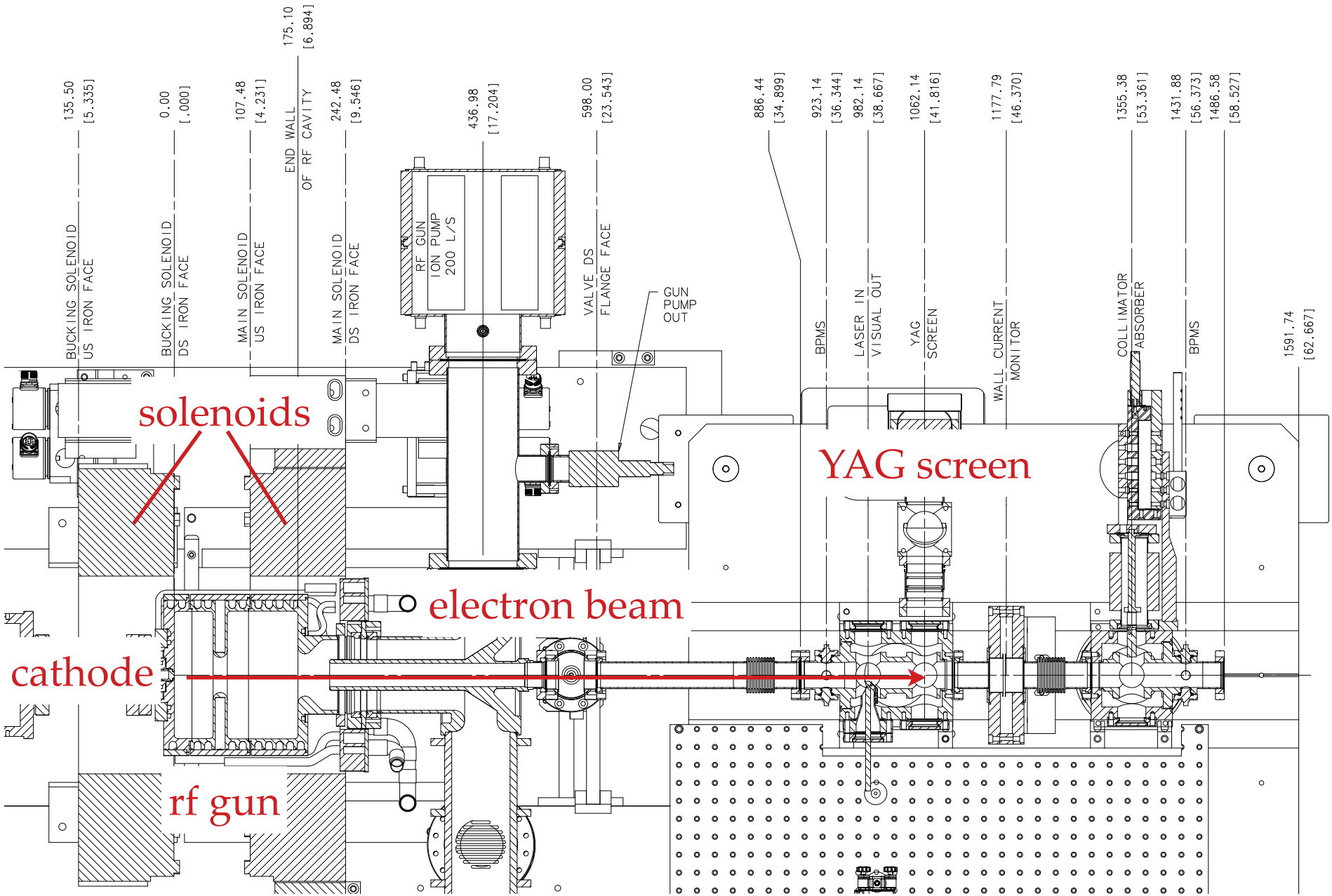
- Experimental procedure
- Model
- Results
  - gradient and energy calibration
  - emittance

AD SRF-el Department Meeting
Fermilab, April 11, 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
electron beam
cathode
rf gun

Method

1. Measure beam spot at YAG screen vs. solenoid settings, at low charge, for different gradients and phases
2. Model 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

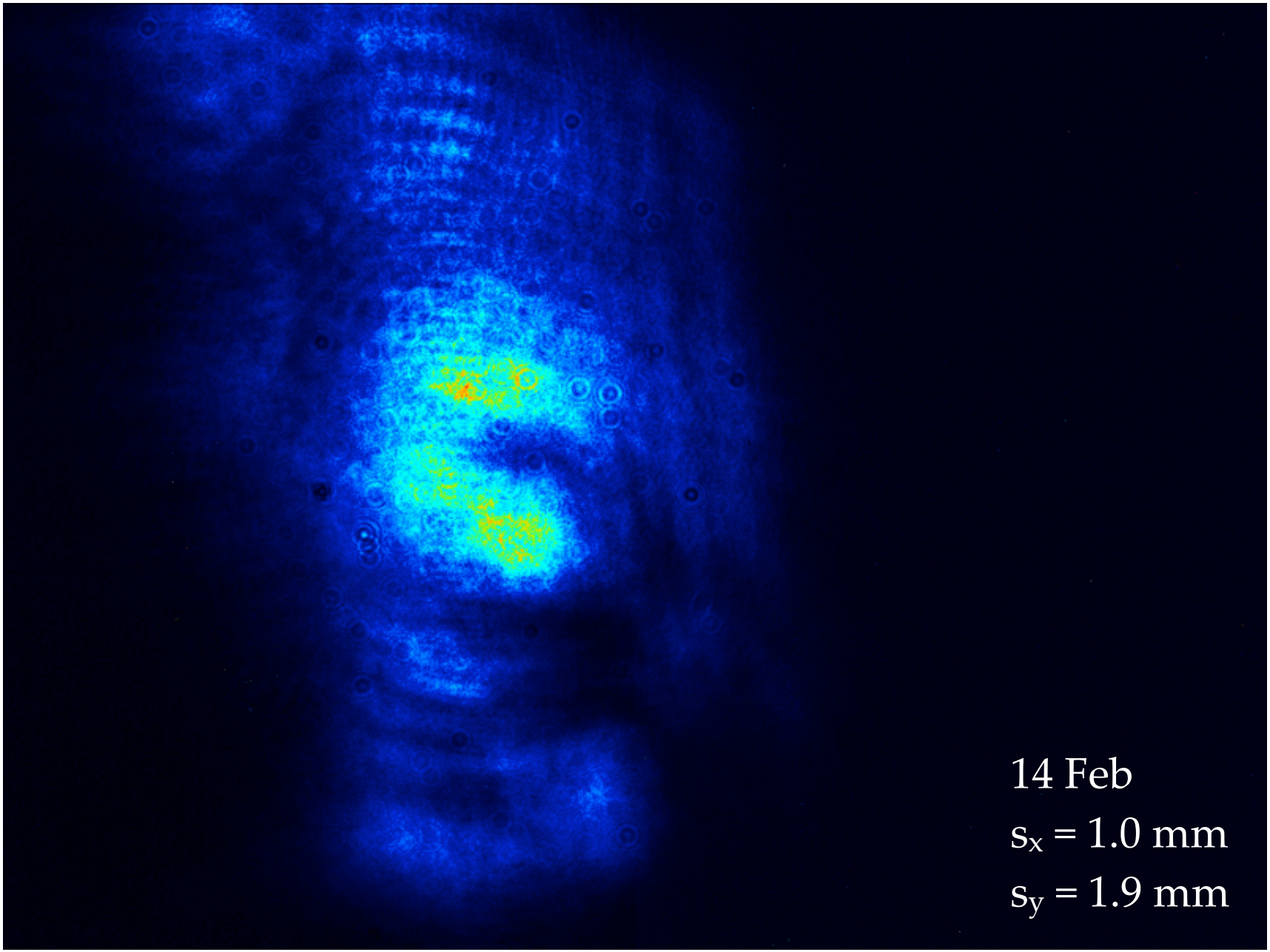
- integration of trajectories in time (Astra) or
- longitudinal slices (Gulliford/Bazarov, gs tramalargu code)

3. Find best fit of model to measurements to estimate:
   peak gradient, rf phase => final beam energy;
   spot size at cathode, initial kinetic energy => initial emittance

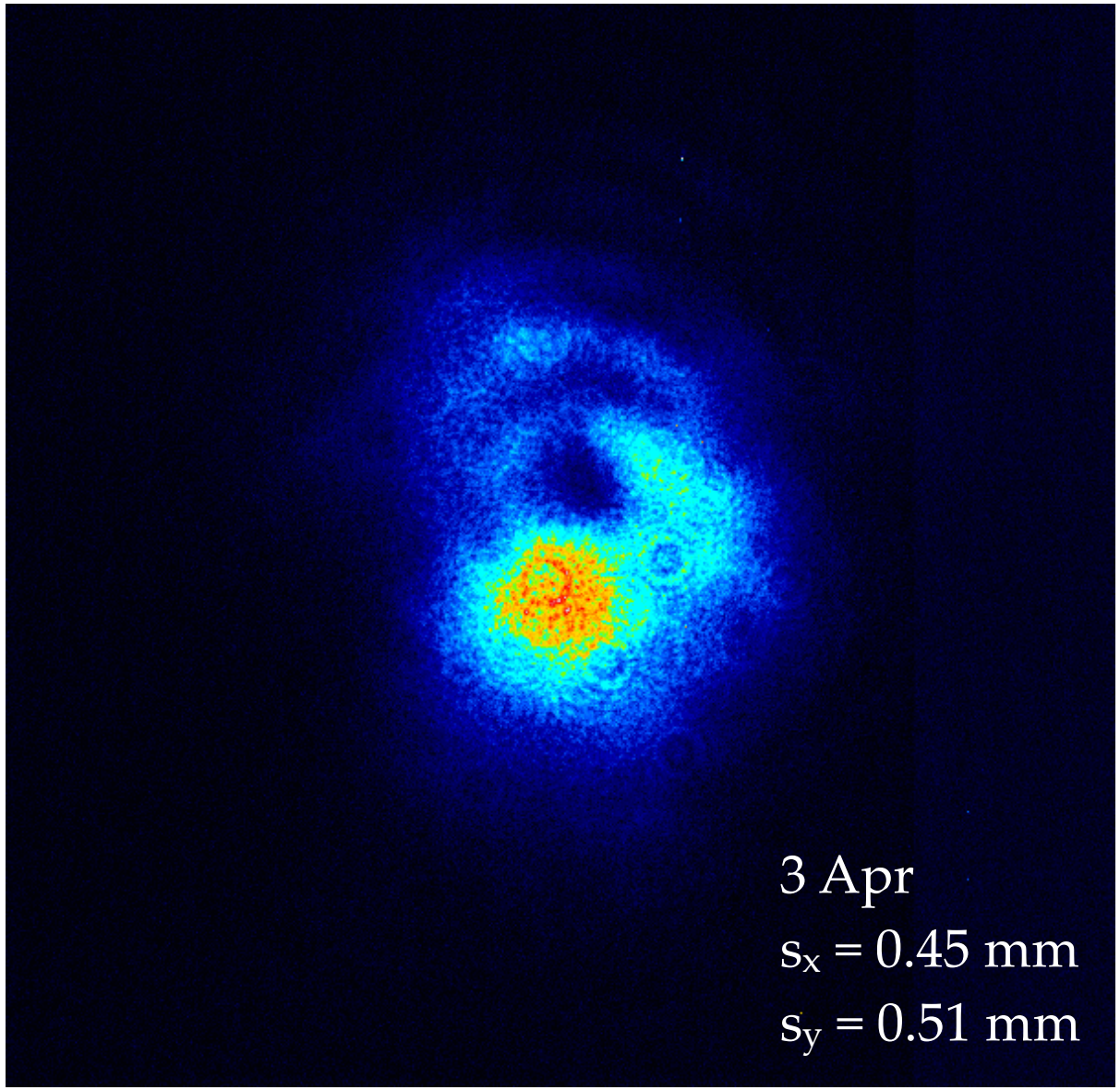
Data sets

Date	Cathode	Set gradient N:GRESPA [MV/m]	Rf phase N:GRESPP [deg]	Gun power N:GCVFP [MW]	Laser spot [mm]	Number of bunches	Charge/ bunch [pC]	Numer of data points
28-29 Jan	Mo	(Not used in this analysis)						
14 Feb	Mo	25	192	2.787	1.0, 1.9	100	0.19	10
14 Feb	Mo	20	192	2.173	1.0, 1.9	100	0.17	10
3 Apr	Cs_2Te	26.6	187	2.870	0.45, 0.51	100	0.81	32
4 Apr	Cs_2Te	23	187	2.472	0.45, 0.52	20	0.47	26

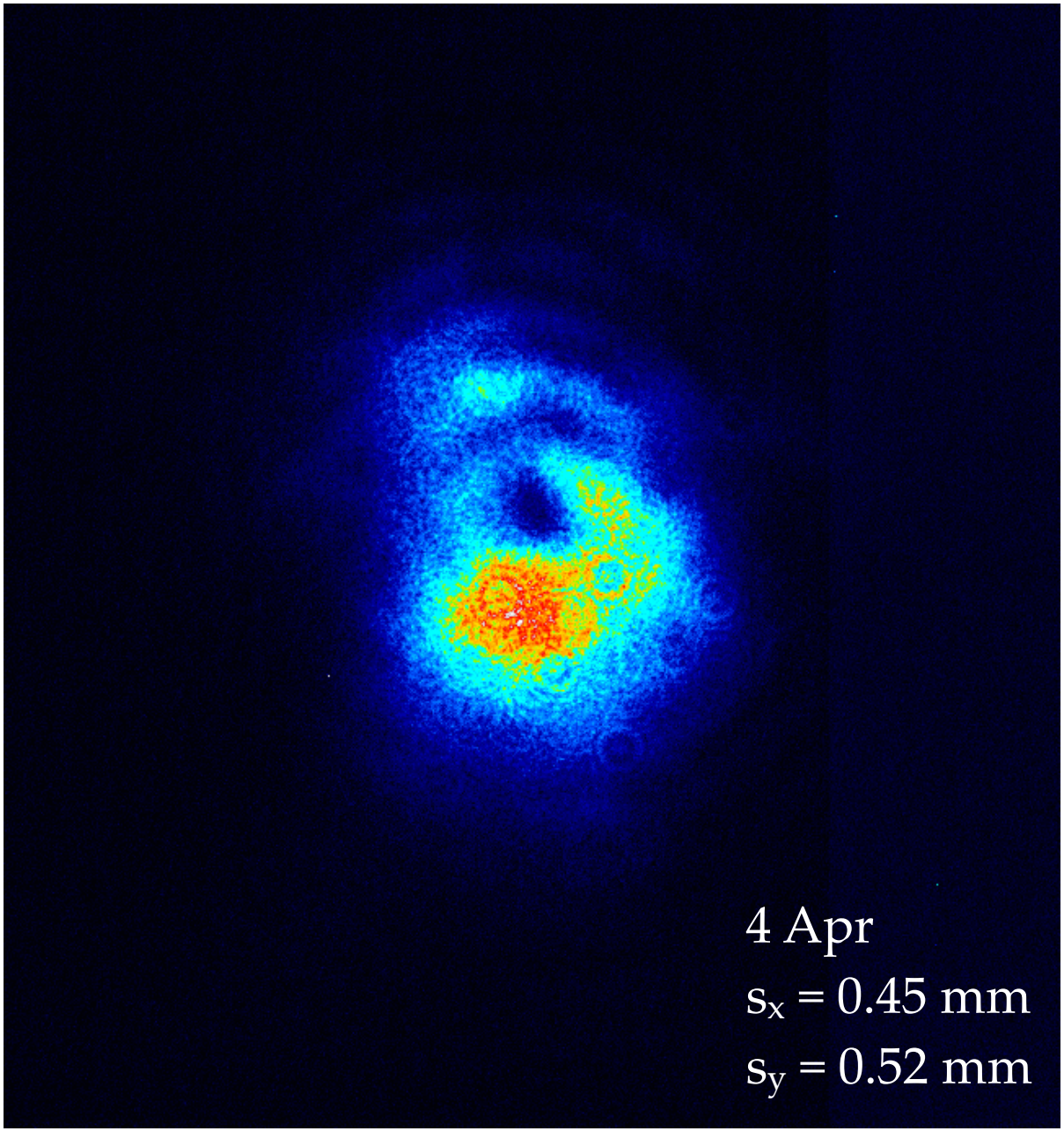
Laser spot at virtual cathode



Laser spot at virtual cathode

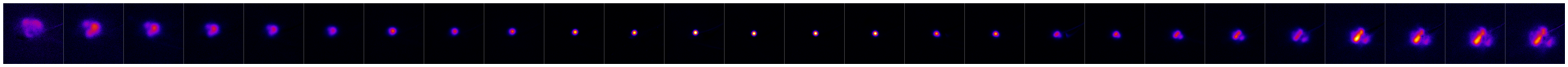


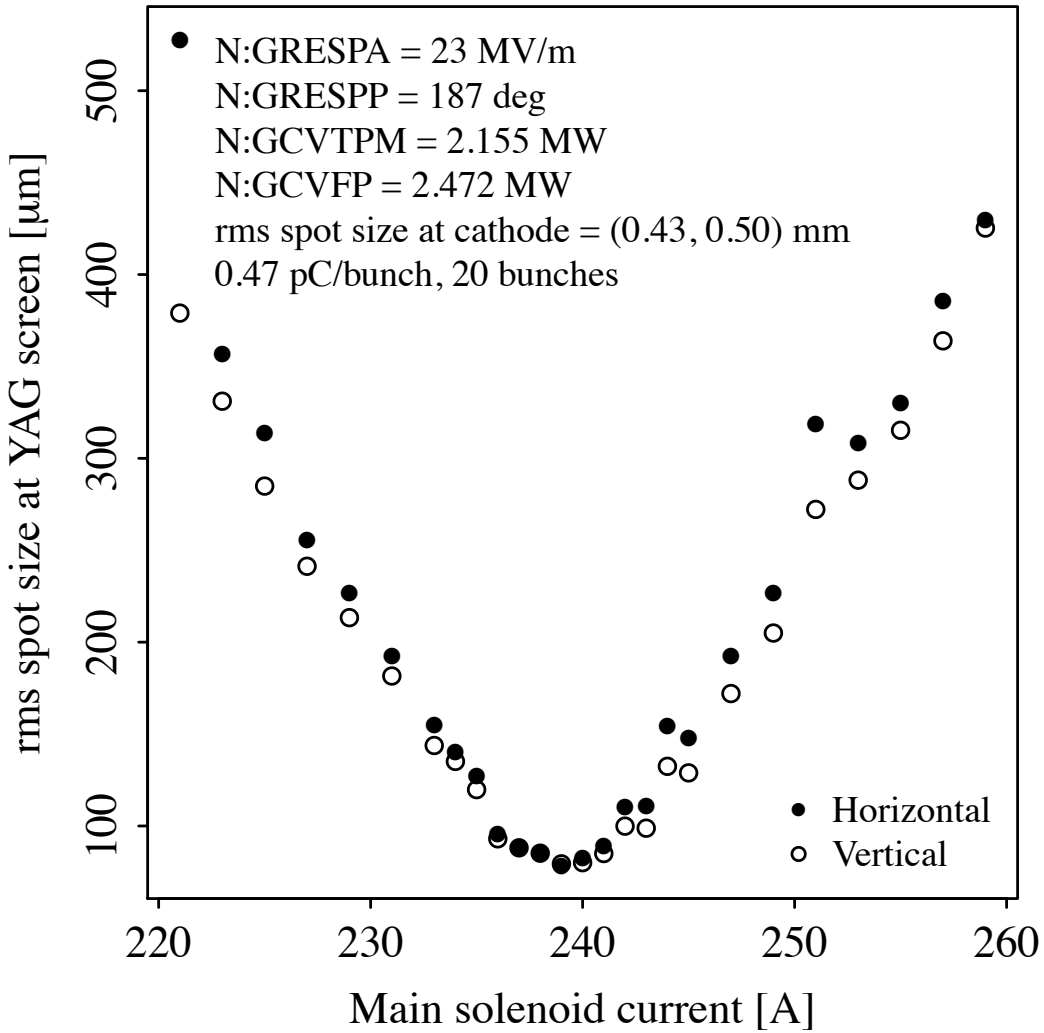
Laser spot at virtual cathode



Measured spot can be used as input to calculation, or as an independent cross check

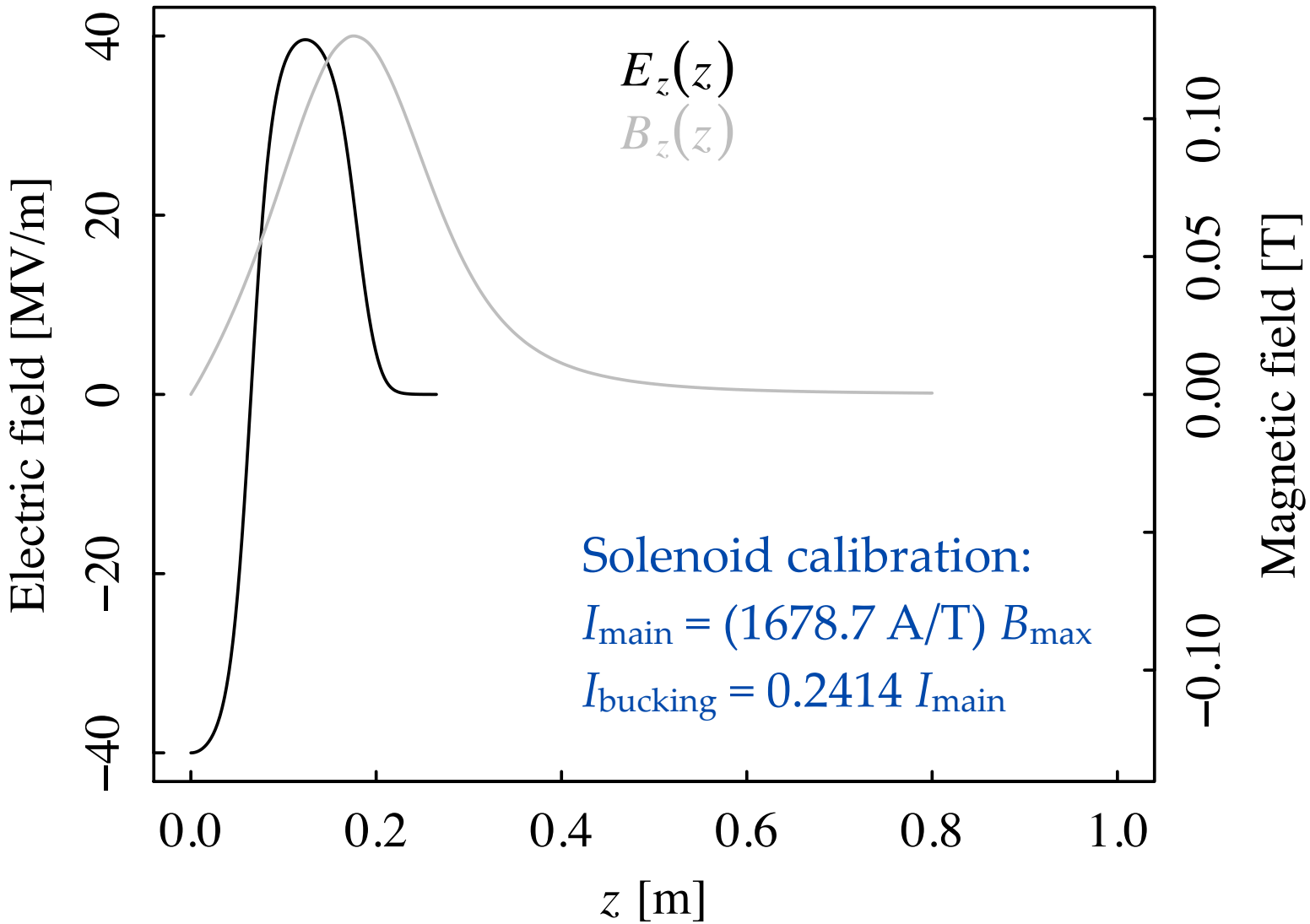
Example of electron beam on YAG screen vs. solenoid current





Min. spot size
~0.1 mm

Rf gun model: field maps



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

1. Obtain transfer matrix M by **tracking** 2 principal trajectories using the Astra code ("time integration" approach)

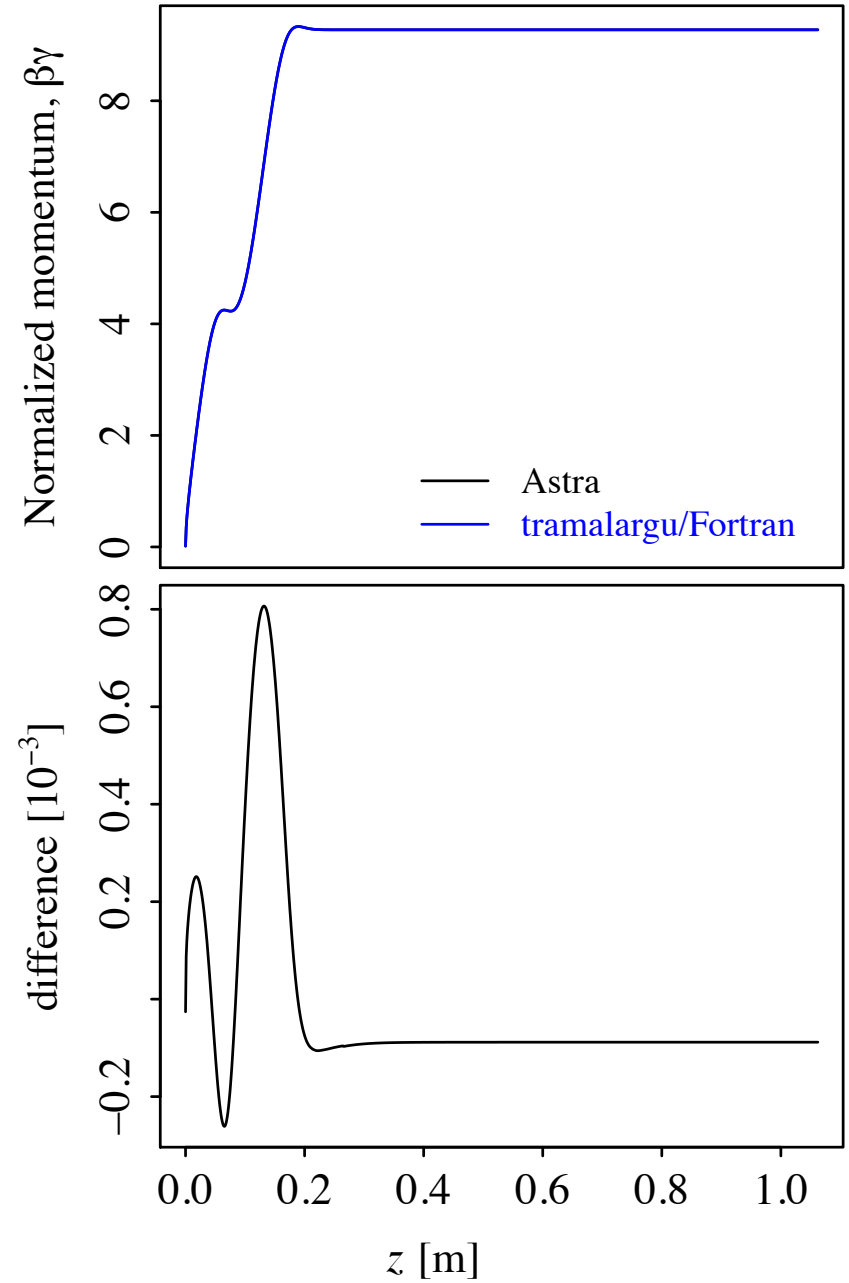
2. Calculate and multiply transfer matrices of small **slices in z** according to Gulliford and Bazarov, PRSTAB 15, 024002 (2012) using new Fortran code (tramalargu) ("space integration" approach)

Why 2 models?
- to evaluate systematic uncertainties
- to speed up calculations, if possible (not as much as expected)
- to set up Astra for later analyses with space charge

Comparison between models: longitudinal dynamics

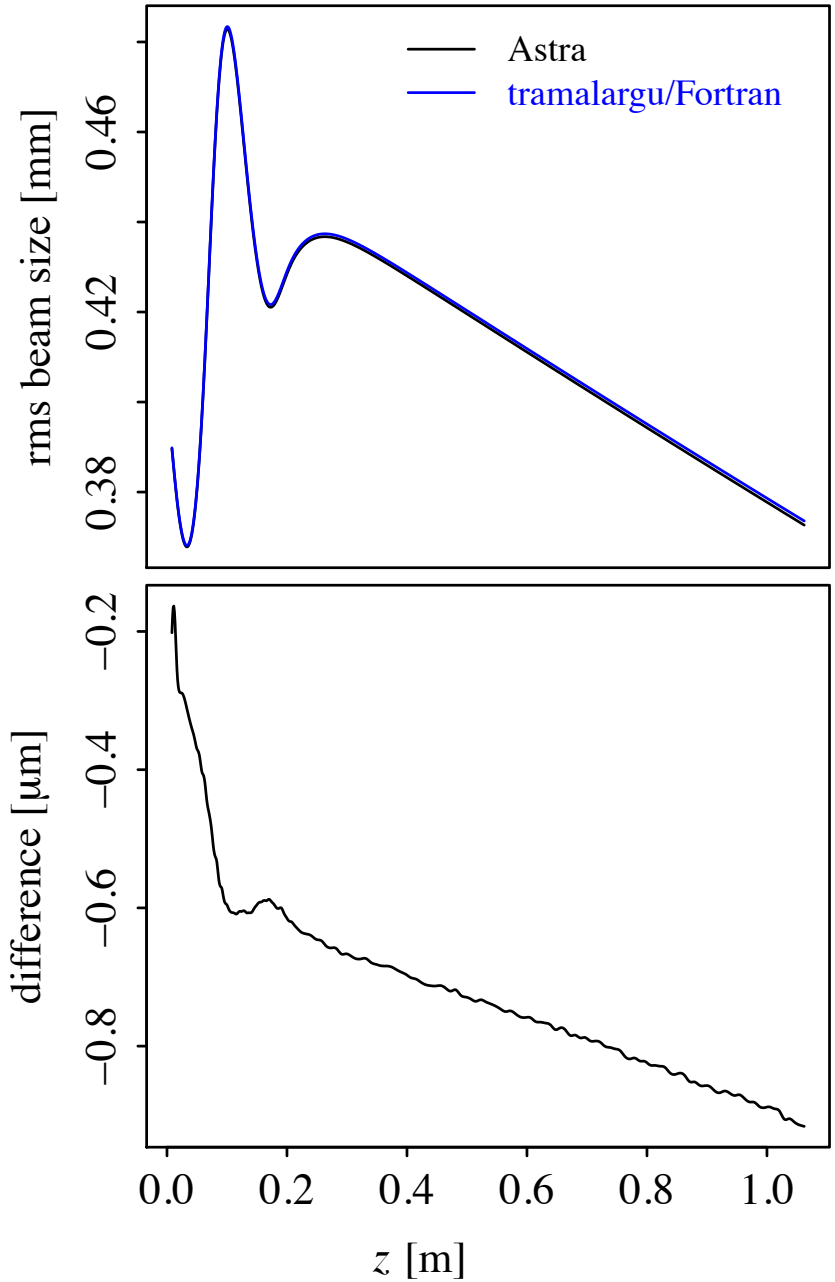
Test case
40 MV/m, 1.3 GHz, 38.5 deg
0.13 T max. in solenoids
0.4 mm initial rms size
0.23 eV initial kinetic energy
0.19 um initial normalized rms emittance
From cathode (z = 0 m) to YAG screen (z = 1.06 m)

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: parameterization

- Identify a set of independent parameters

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

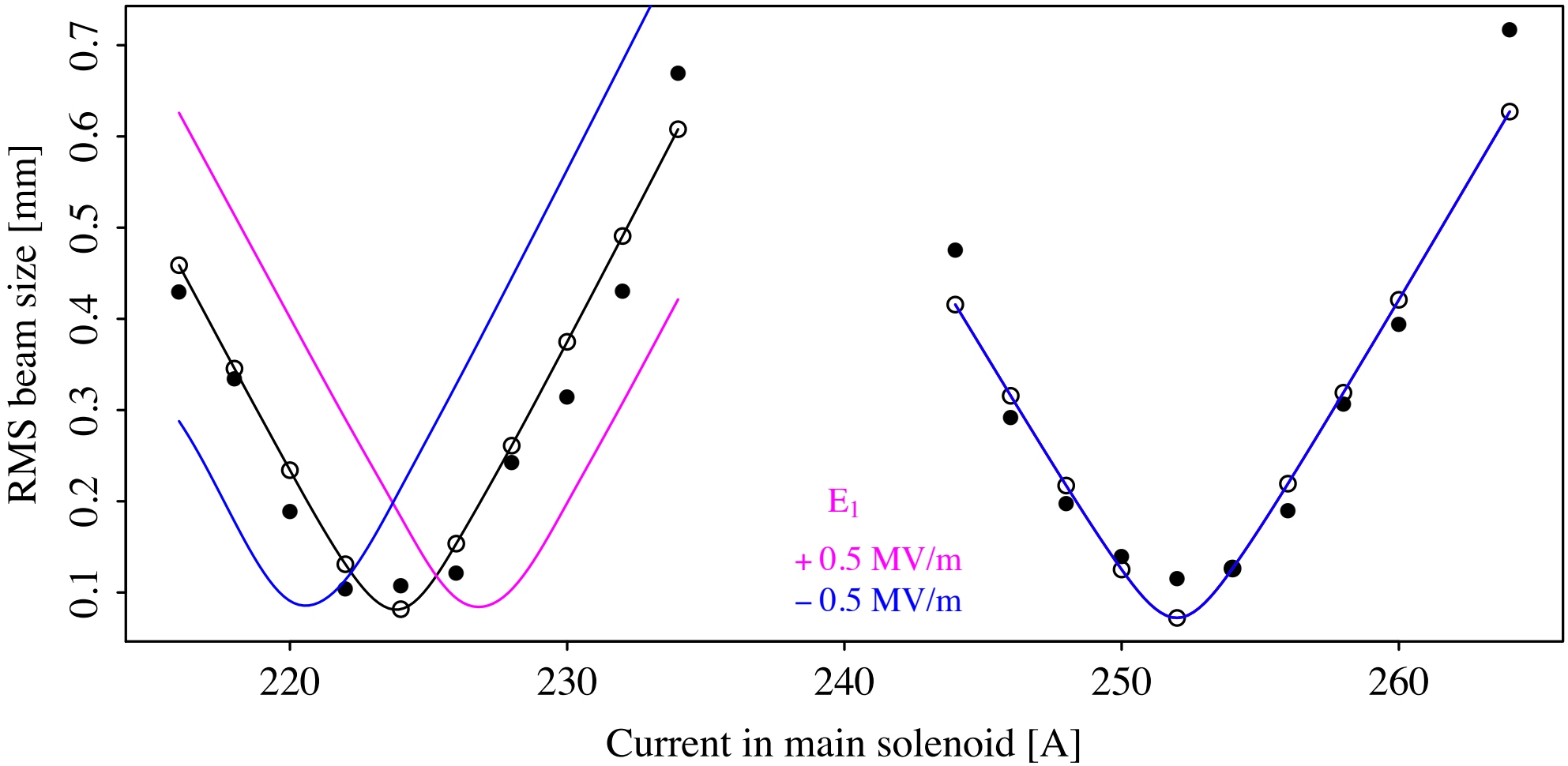
- A possible choice of parameters:
  1. Gradient in first data set, E_1
  2. Gradient in second data set, E_2
  3. Rf phase of laser pulse, ϕ
  4. Initial kinetic energy, T_0
  5. Initial rms beam size, σ_0

Emittance as derived quantity: $\epsilon = \sigma_0 \sqrt{\frac{2\,T_0}{3\,m_e c^2}}$

Final kinetic energies T_1 and T_2 from longitudinal calculation

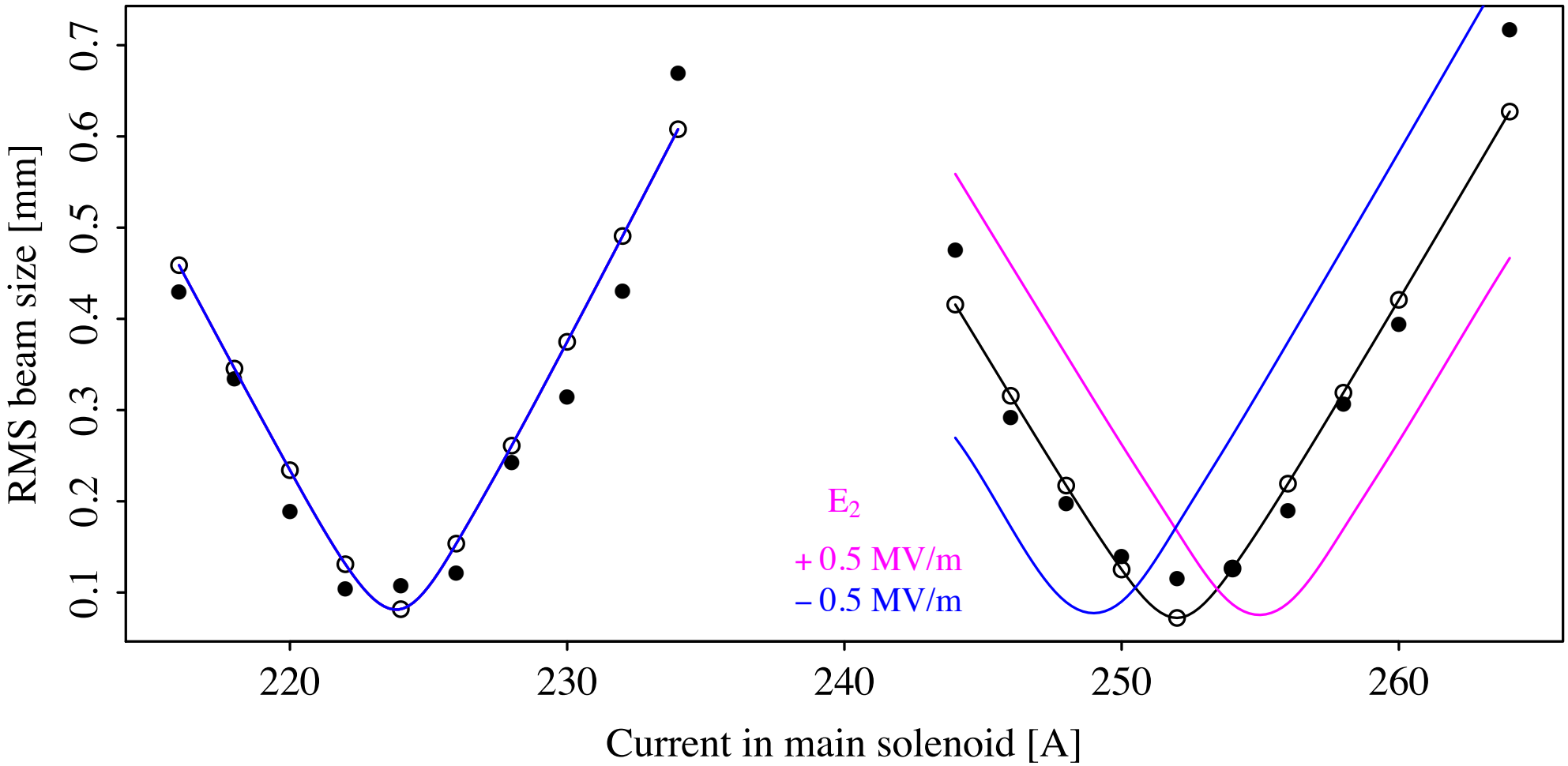
Parameter sensitivity: peak gradient in data set 1

The first parameter is determined by the position of the dip in the first data set



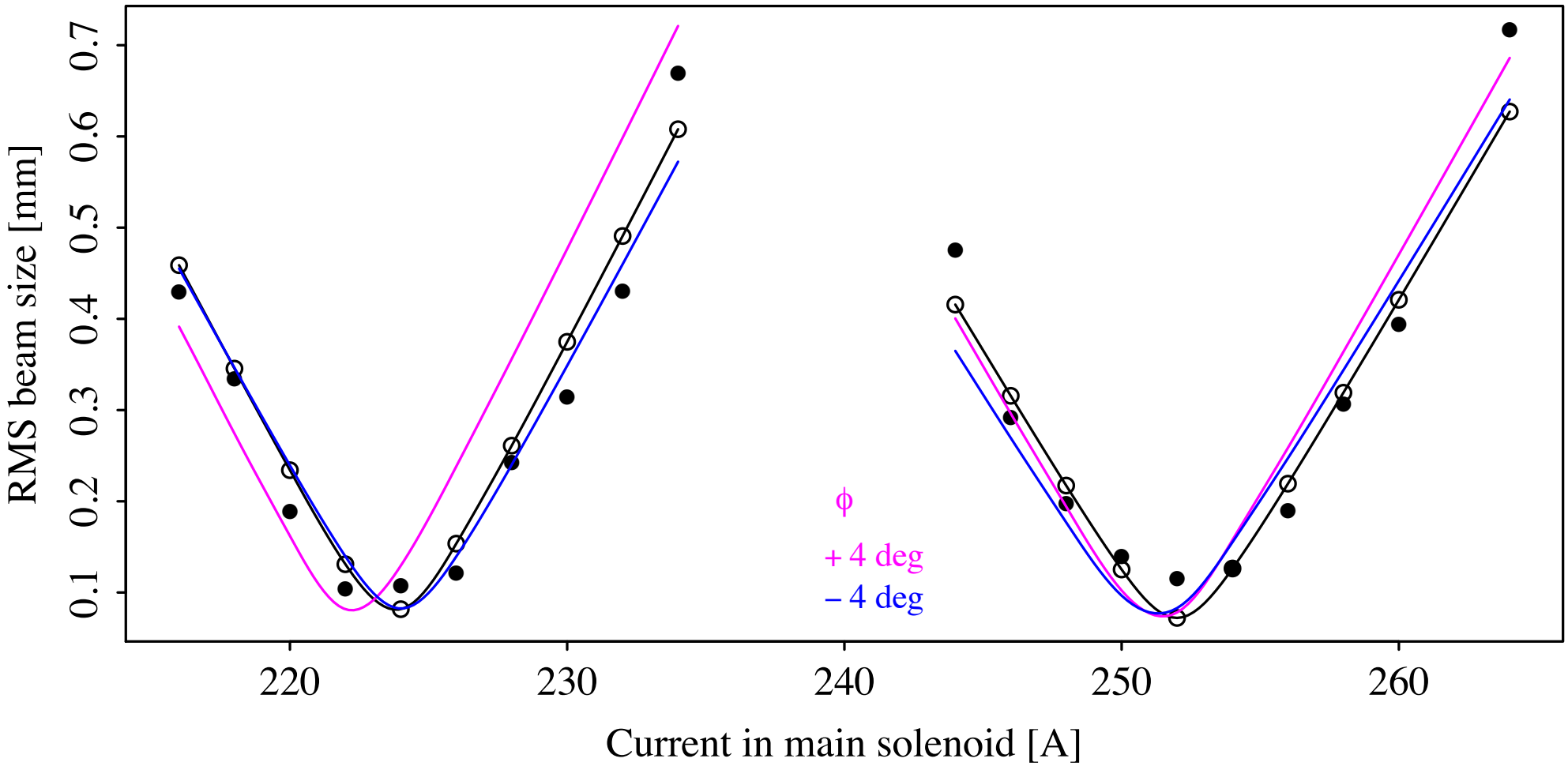
Parameter sensitivity: peak gradient in data set 2

The second parameter is determined by the position of the dip in the second data set



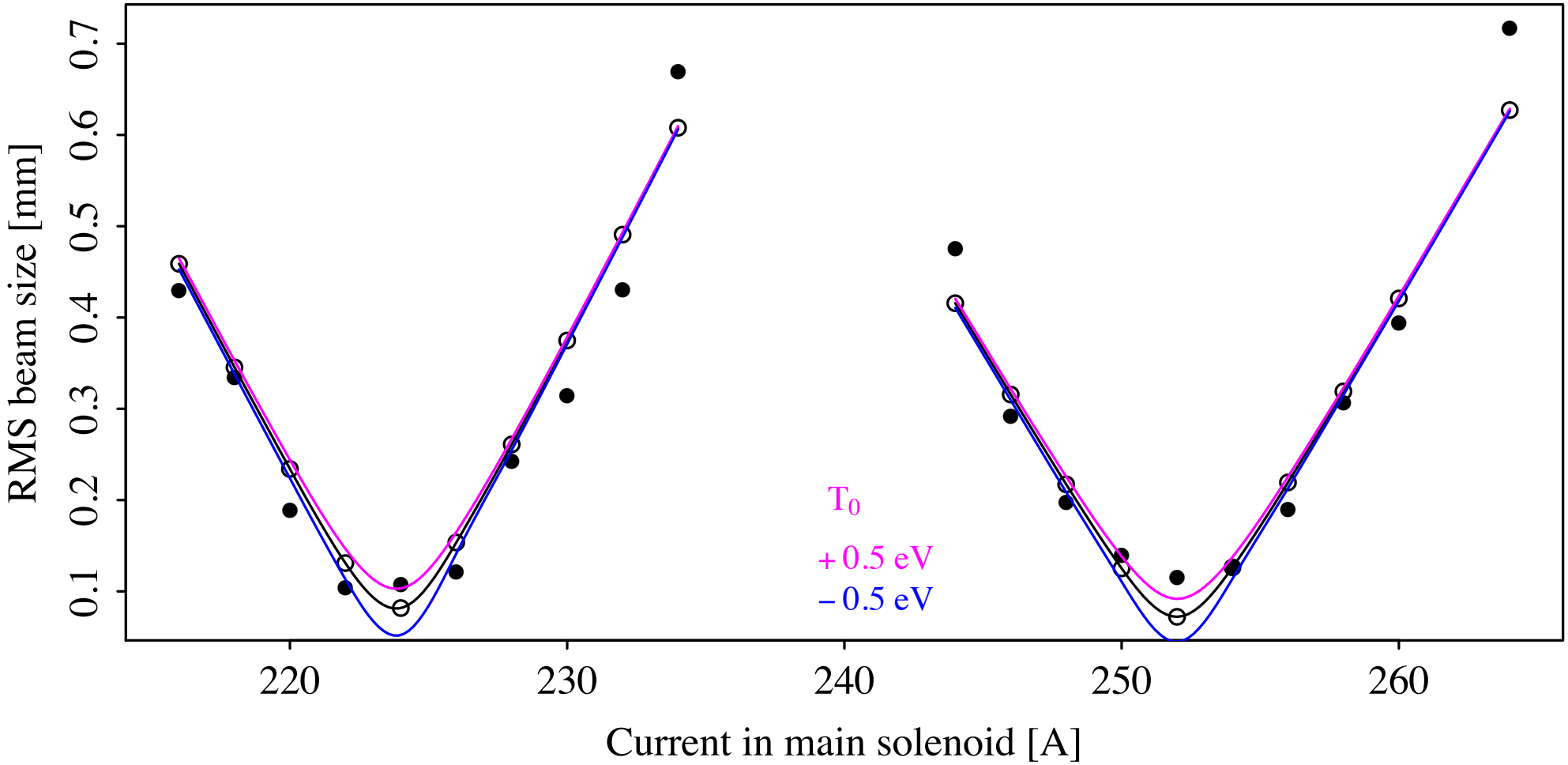
Parameter sensitivity: rf phase

Changing the phase affects predictions for both data sets



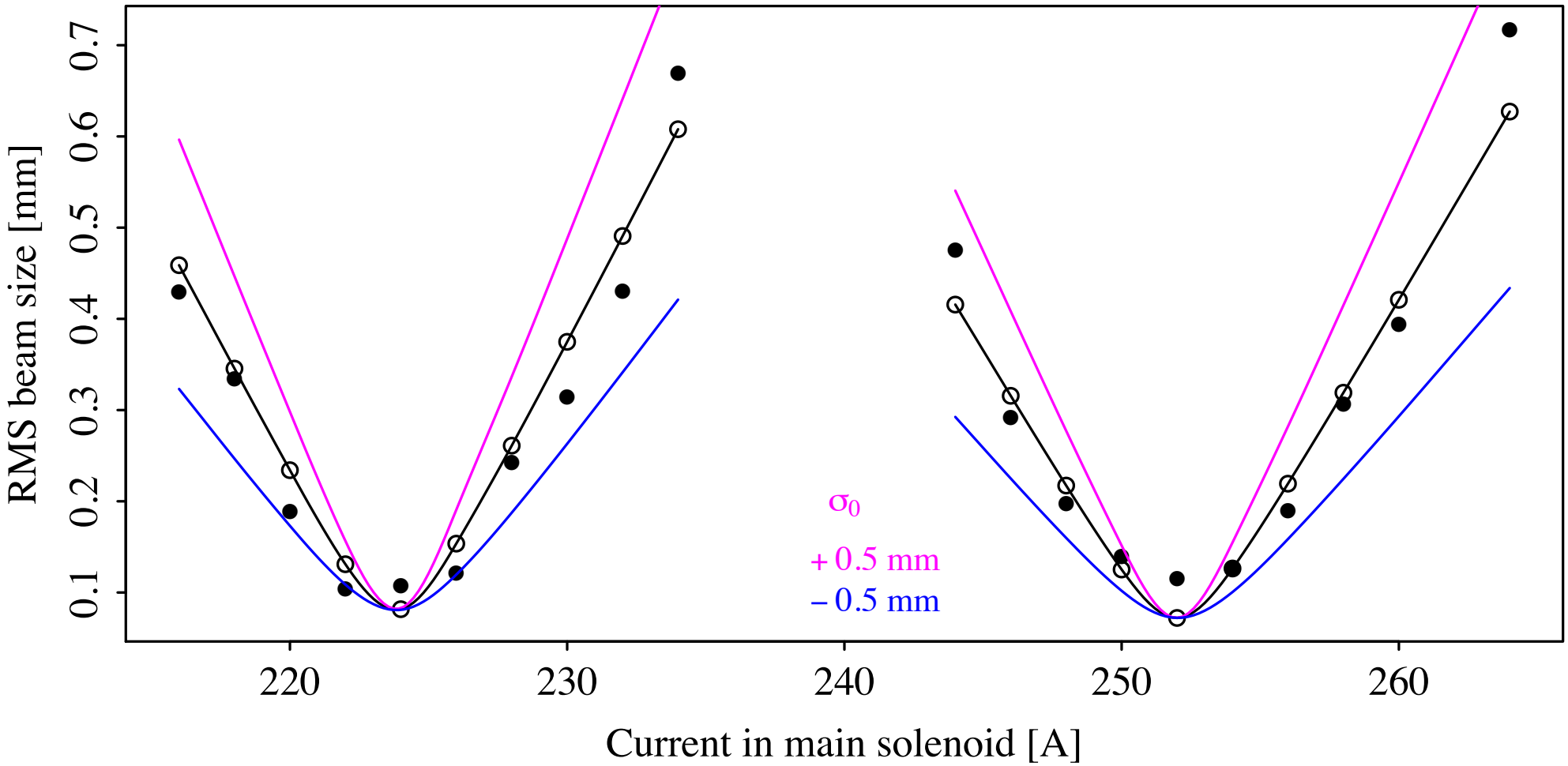
Parameter sensitivity: initial kinetic energy at cathode

The initial kinetic energy enters through the emittance (main effect) and through the matrix elements (negligible)

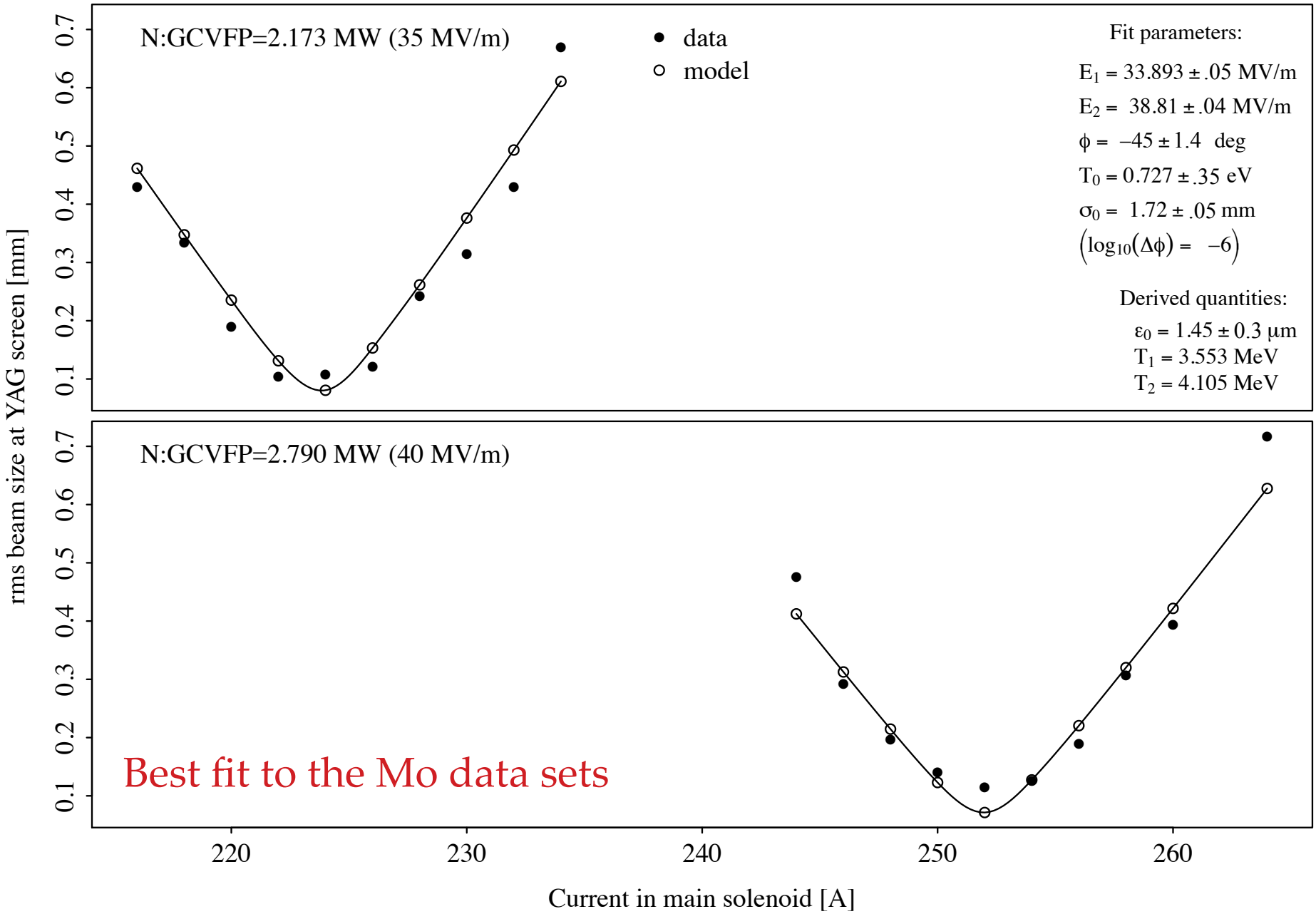


Parameter sensitivity: initial beam size at cathode

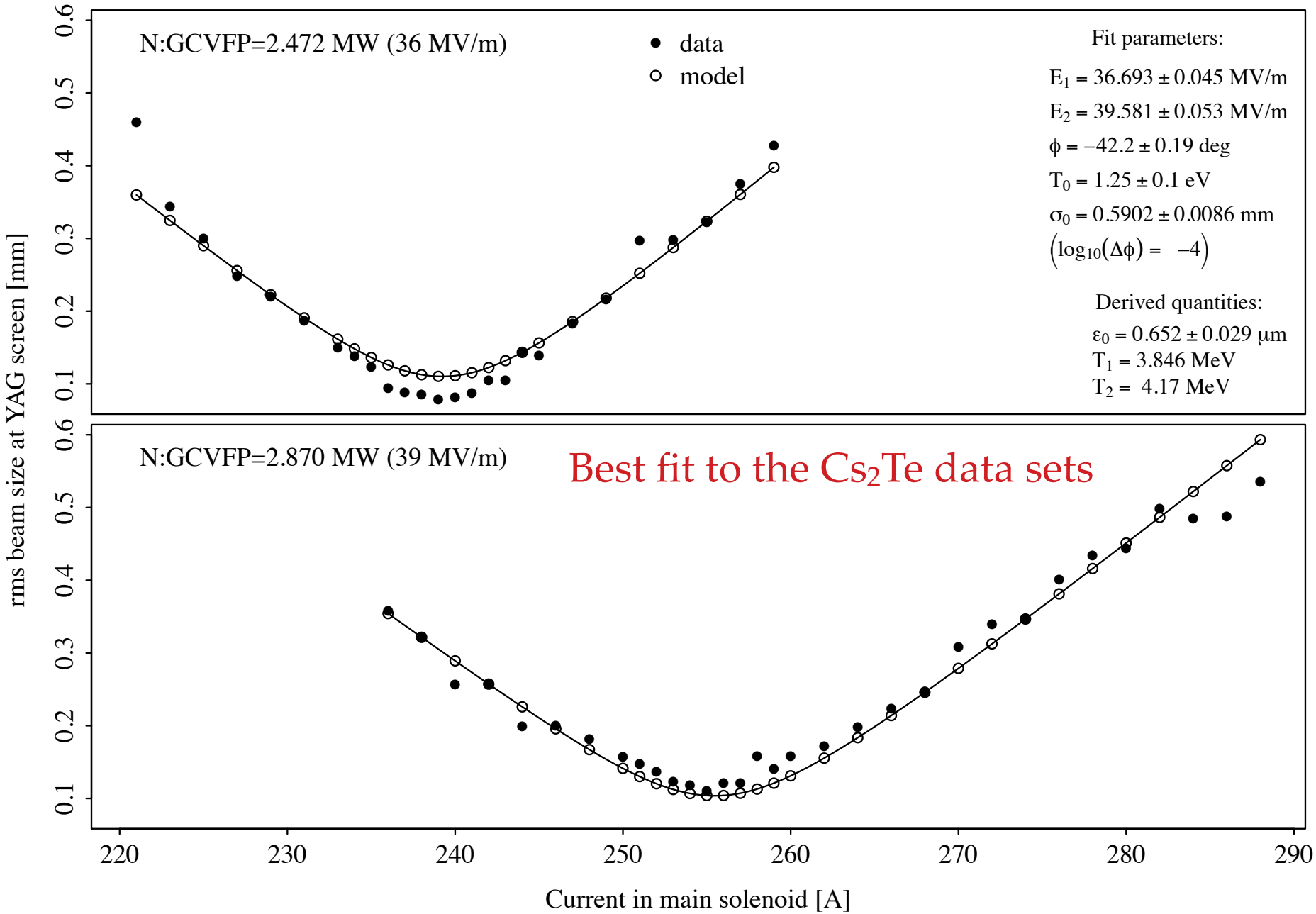
A larger initial beam size makes the dip steeper



Results


N:GCVFP=2.173 MW (35 MV/m)
data
model
Fit parameters:
E_1 = 33.893 ± .05 MV/m
E_2 = 38.81 ± .04 MV/m
ϕ = −45 ± 1.4 deg
T_0 = 0.727 ± .35 eV
σ_0 = 1.72 ± .05 mm
$(\log_{10}(\Delta\phi) = -6)$
Derived quantities:
ε_0 = 1.45 ± 0.3 μm
T_1 = 3.553 MeV
T_2 = 4.105 MeV
N:GCVFP=2.790 MW (40 MV/m)
Best fit to the Mo data sets
rms beam size at YAG screen [mm]
0.1
0.2
0.3
0.4
0.5
0.6
0.7
220
230
240
250
260
Current in main solenoid [A]

Results


N:GCVFP=2.472 MW (36 MV/m)
data
model
Fit parameters:
$E_1 = 36.693 \pm 0.045$ MV/m
$E_2 = 39.581 \pm 0.053$ MV/m
$\phi = -42.2 \pm 0.19$ deg
$T_0 = 1.25 \pm 0.1$ eV
$\sigma_0 = 0.5902 \pm 0.0086$ mm
$(\log_{10}(\Delta\phi) = -4)$
Derived quantities:
$\varepsilon_0 = 0.652 \pm 0.029$ μm
$T_1 = 3.846$ MeV
$T_2 = 4.17$ MeV
N:GCVFP=2.870 MW (39 MV/m)
Best fit to the Cs_2Te data sets
rms beam size at YAG screen [mm]
Current in main solenoid [A]
0.1
0.2
0.3
0.4
0.5
0.6
220
230
240
250
260
270
280
290

Summary of results

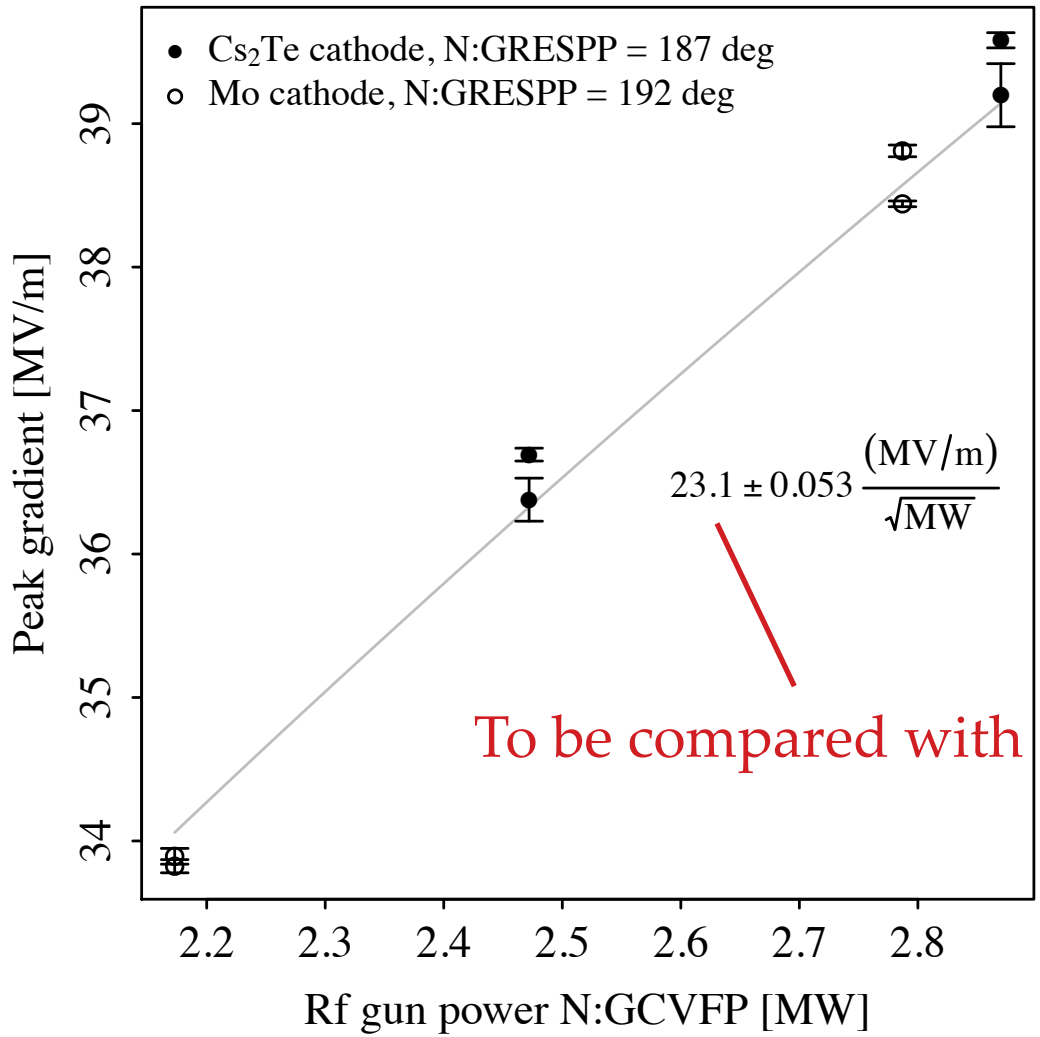
Quantity	Model	Data set (cathode / rf power [MW])			
		Mo / 2.173	Mo / 2.787	Cs_2Te / 2.472	Cs_2Te / 2.870
Gradient [MV/m]	*tramalargu*	33.893(55)	38.810(41)	36.693(45)	39.581(53)
	Astra	33.824(46)	38.441(20)	36.38(15)	39.20(22)
phase [deg]	*tramalargu*	-45(2)		-42.2(2)	
	Astra	-39(2)		-44(3)	
laser spot [mm]	*tramalargu*	1.720(46)		0.5902(86)	
	Astra	1.52(15)		0.586(19)	
emittance [um]	*tramalargu*	1.45(31)		0.652(29)	
	Astra	1.36(18)		0.723(22)	
kinetic energy [MeV]	*tramalargu*	3.553	4.105	3.846	4.170
	Astra	3.476	4.002	3.823	4.139

First measurements of gradient and emittance at ASTA

Statistical errors in parentheses

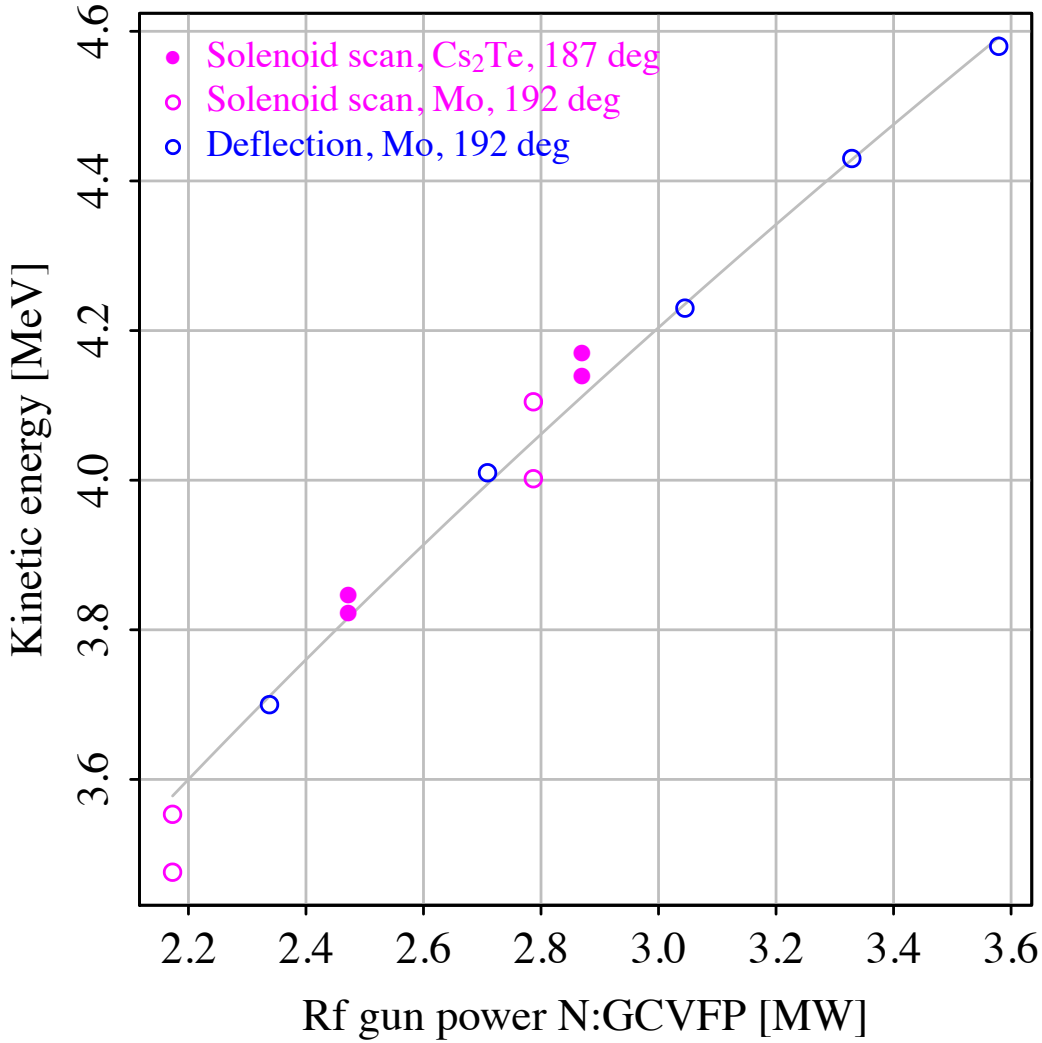
Estimate of systematic uncertainties from difference between models

Results: calibration of rf gun gradient



To be compared with "nominal" 23.6

Results: calibration of electron beam energy



Deflection technique
depends on final beam energy and fields in dipole corrector

Solenoid scan depends on dynamics in rf gun

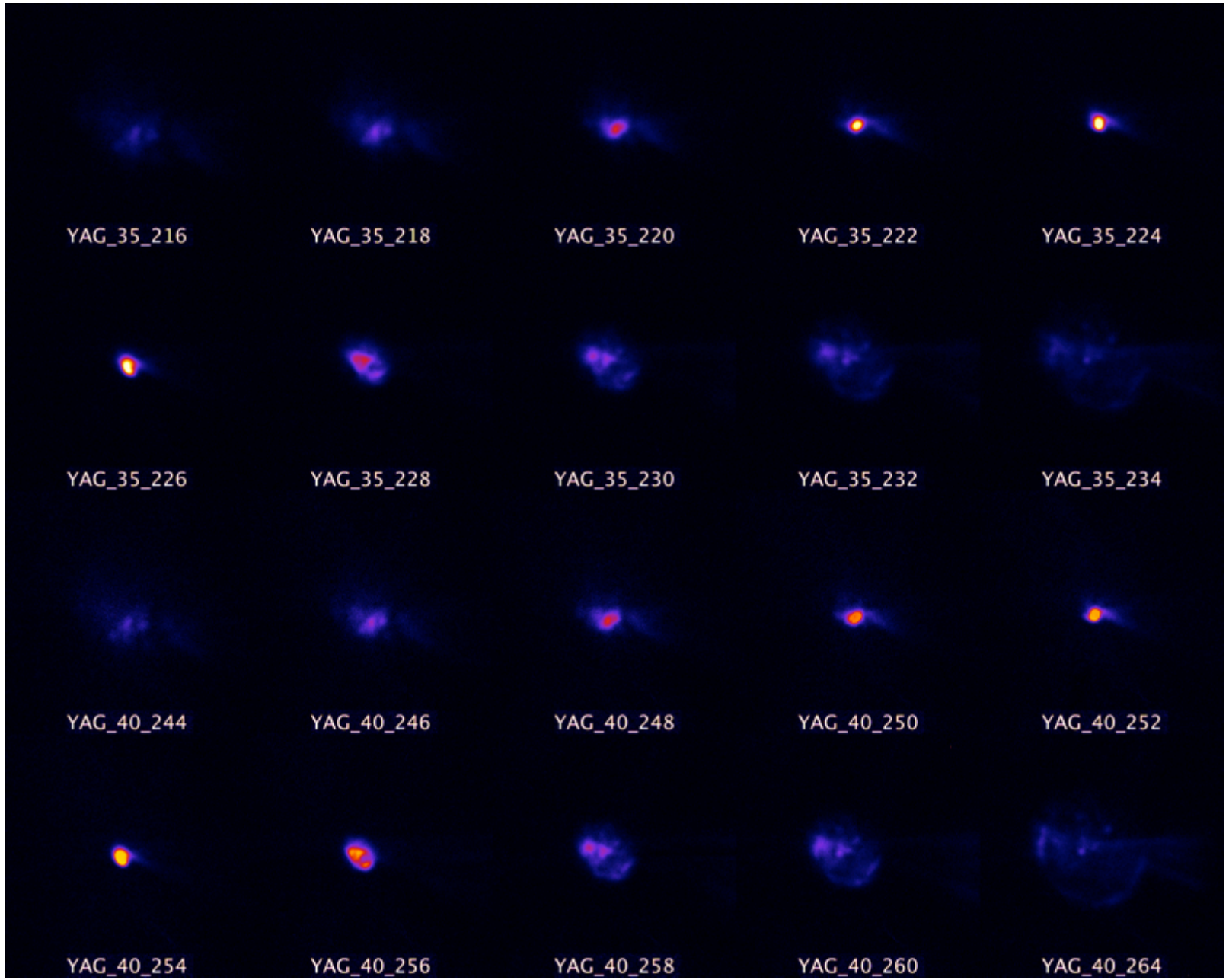
Independent measurements, results within 1%!

Conclusions

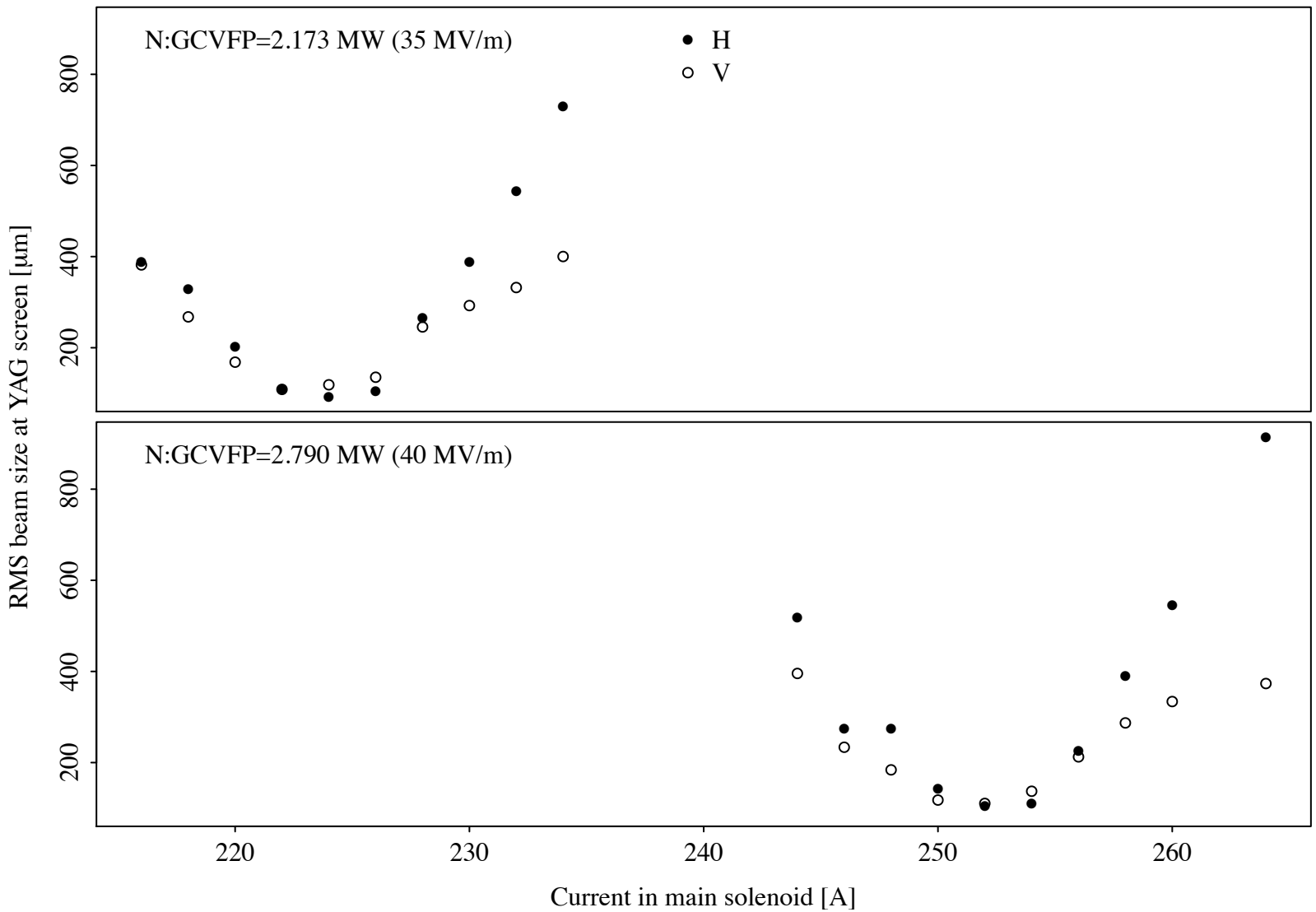
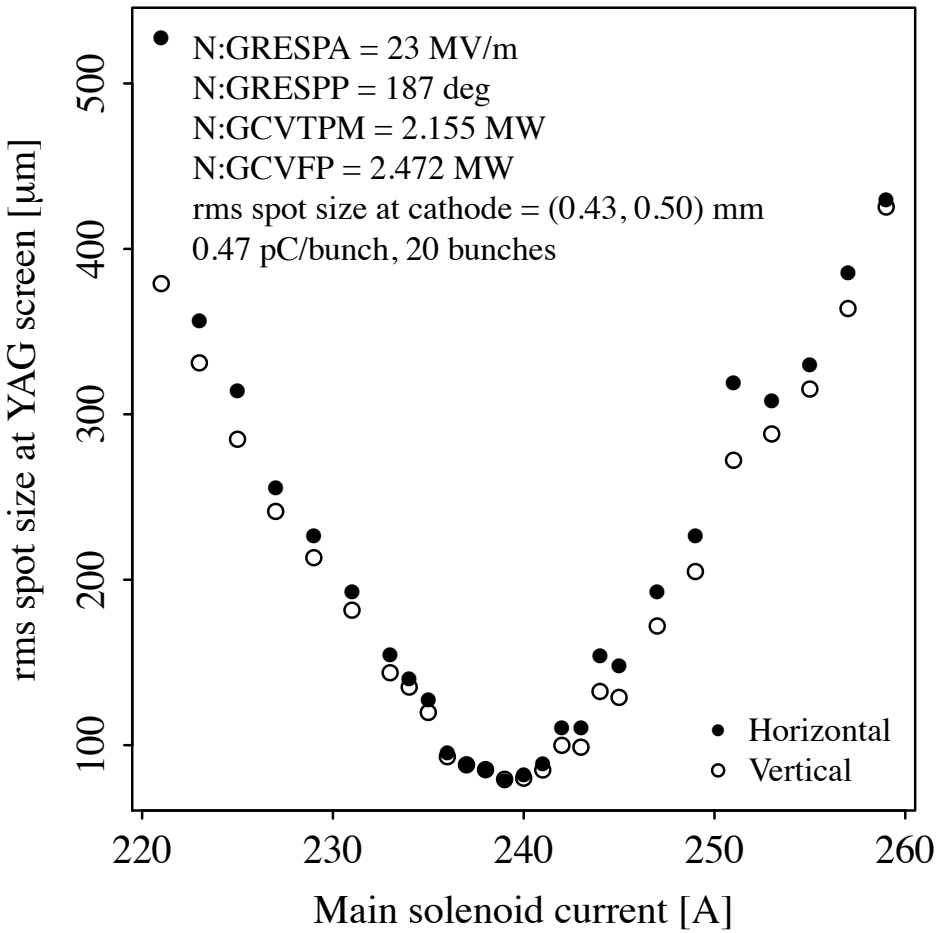
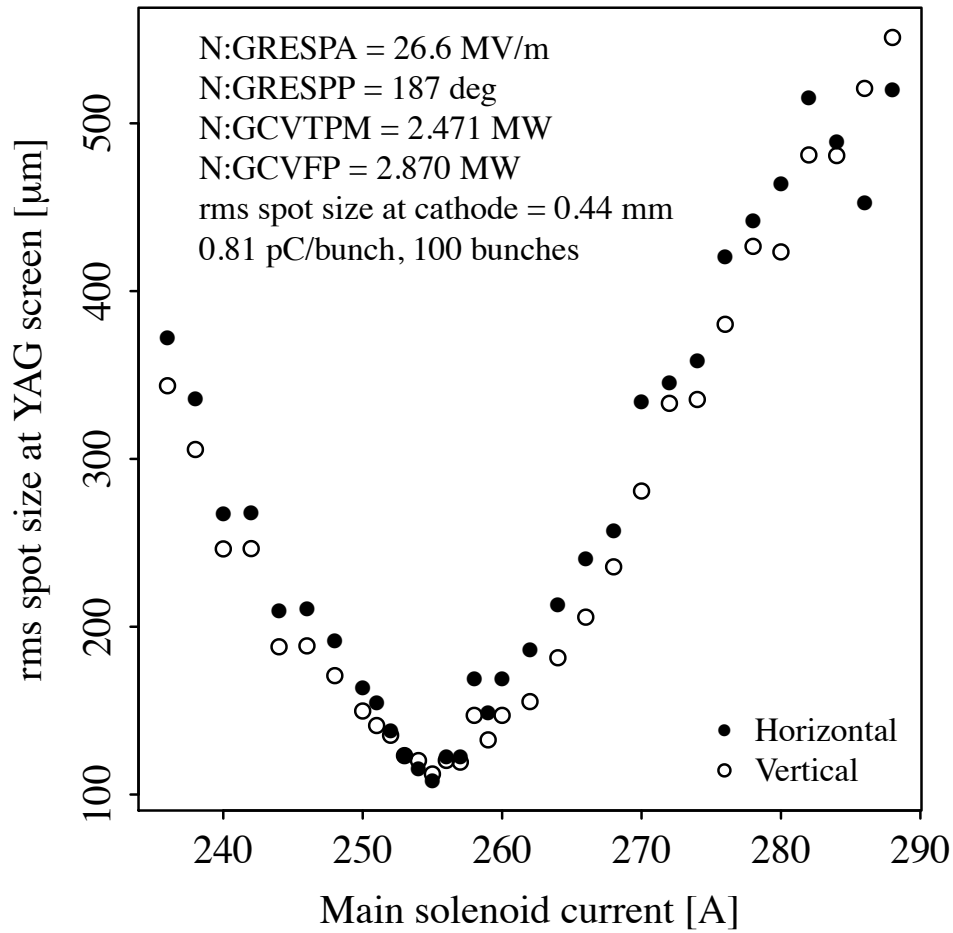
- Solenoid scans provide tests of single-particle dynamics in rf gun
- Results are preliminary. Main purpose of this work was to get first estimates, set up procedure, and get feedback
- Dynamics is well understood at this stage, no “fudge factors” in field maps
- Beam-based calibration of rf gun gradient agrees with nominal to ~2%
- Very good agreement (~1%) between independent beam energy calibration techinques: dipole deflectors and solenoid scans
- First estimates of beam emittance at low charge
- Next steps:
  - review models and uncertainties, write report
  - same data set: any information on solenoid alignment from displacements of spot size centroid?

Backup

Electron beam spot at YAG screen vs. gradient and solenoid current



Spot-size data (14 Feb 2014)



Spot-size data (3-4 Apr 2014)