Workshop on Linac Operation with Long Bunch Trains

DESY, Hamburg

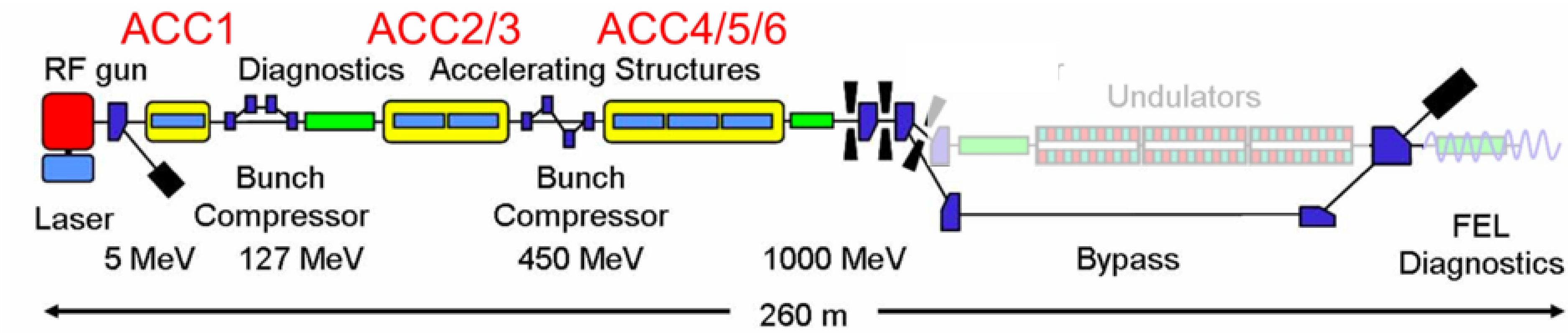
22-24.02.2010

Why Long Bunch Trains?

- Efficient production of high beam-power
- For ILC → Luminosity!
  - Also push bunch charge to 3nC (9mA)
  - Brute-force – relatively weak dependence on other single bunch parameters (emittance)
- FLASH / XFEL → Intensity but also high rep-rate and *Flexibility*!
  - Single-bunch parameters critical (lasing!)
  - Lower bunch charges (~1nC)
  - *FLEXIBILITY* to use long train to simultaneously serve more than one experiment.

Long bunch-trains are fundamental to the concept (advantage) of the TESLA SCRF Technology

TTF/FLASH 9mA Experiment



		XFEL X-Ray Free-Electron Laser	ilc	FLASH design	FLASH experiment
Bunch charge	nC	1	3.2	1	3
# bunches		3250*	2625	7200*	2400
Pulse length	μs	650	970	800	800
Current	mA	5	9	9	9

Major achievements
(Sept 2009 studies)

Metric	Goal	Achieved
Bunches per pulse	800 x 3nC (1MHz)	800 x 3nC
	2400 x 3nC (3MHz)	1800 x 3nC 2100 x 2.5nC ~2400 x 2nC
Charge per pulse	7200nC @ 3MHz	5400nC @ 3MHz
Beam power	36kW (7200nC, 5Hz, 1GeV)	22kW (5400nC, 5Hz, 800MeV)
Gradients close to quench	Up to 32Mv/m	Several cavities above 30Mv/m at end of long pulse

- 15 contiguous hours running with 3mA and 800us bunch trains
- Running at ~9mA with bunch trains of 500-600us for several hours
- Full pulse length (800us, ~2400 bunches) at ~6mA for shorter periods

- Energy deviations within long bunch trains: <0.5% p-p (7mA beam)
- Energy jittter pulse-pulse with long bunch trains: ~0.13% rms (7mA)

Working Groups

- Working Group #1:
  FLASH setup, tuning, and operation
  - Leaders: B. Faatz, J. Carwardine

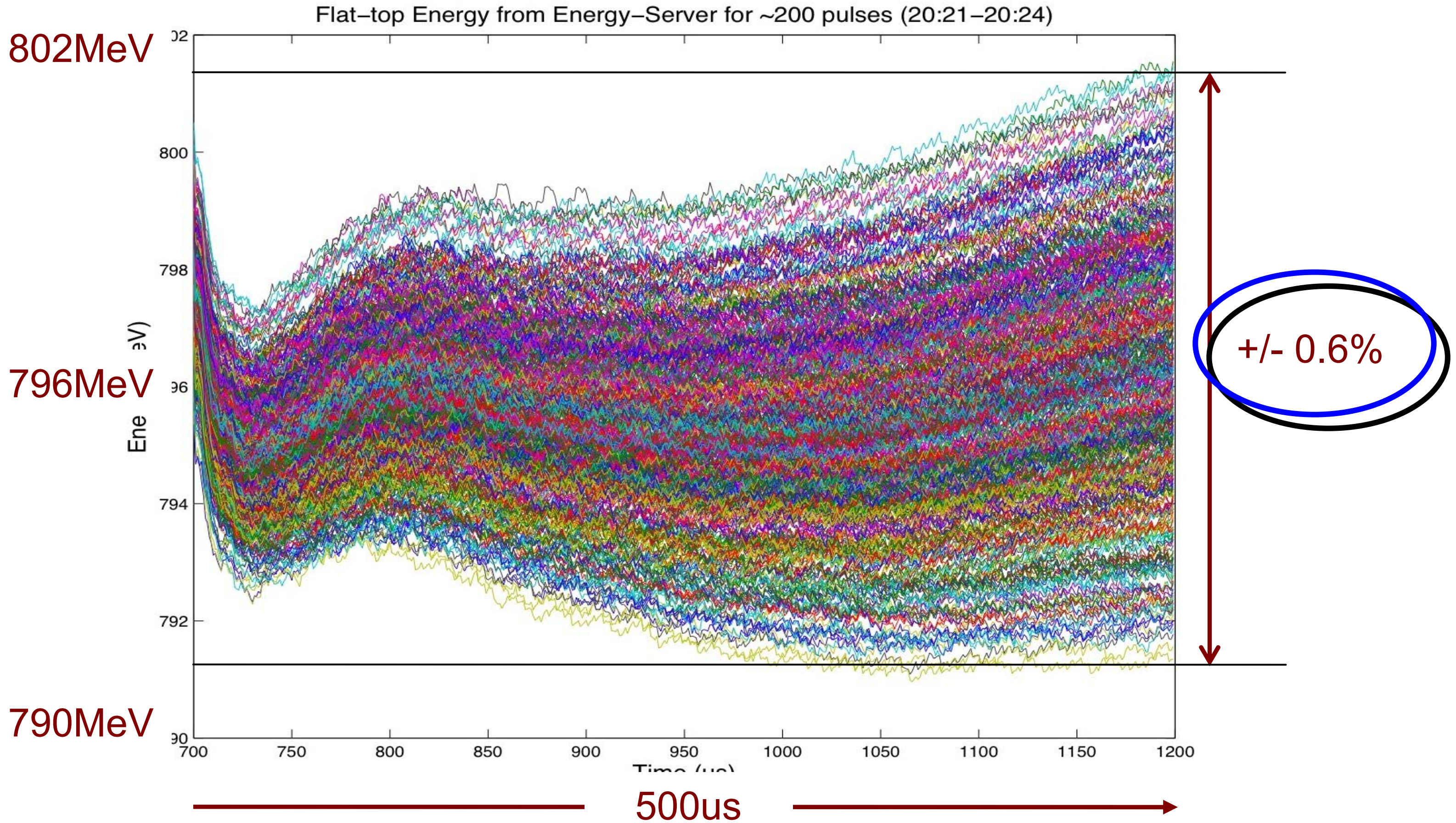
- Working Group #2:
  FLASH feedback and control
  - Leaders: H. Schlarb, V. Ayvazyan

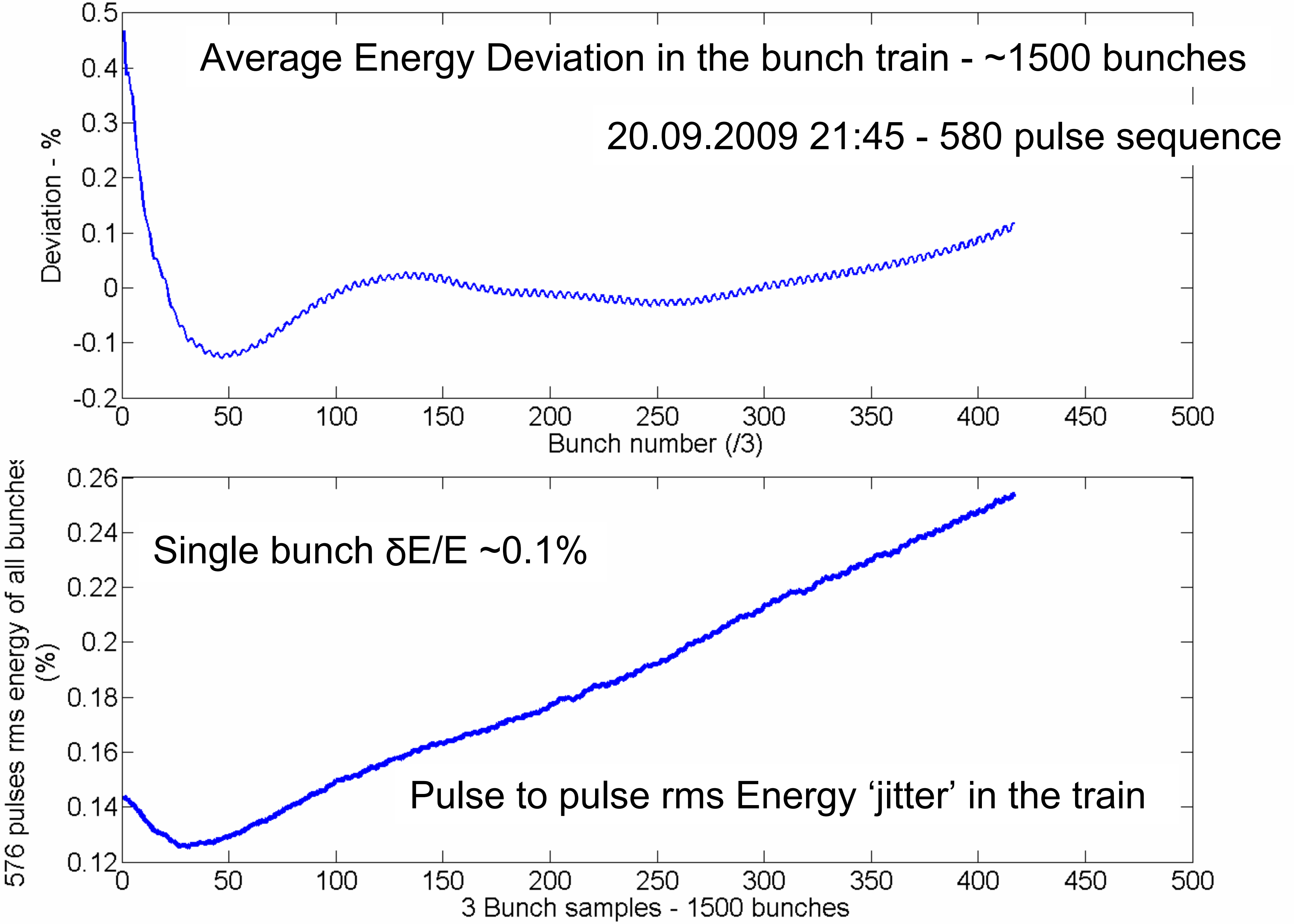
- Working Group #3:
  ILC studies at FLASH
  - Leaders: N. Solyak, S. Michizono

- Working Group #4:
  DAQ and data analysis
  - Leaders: T. Wilksen, N. Arnold)

Pulse train properties

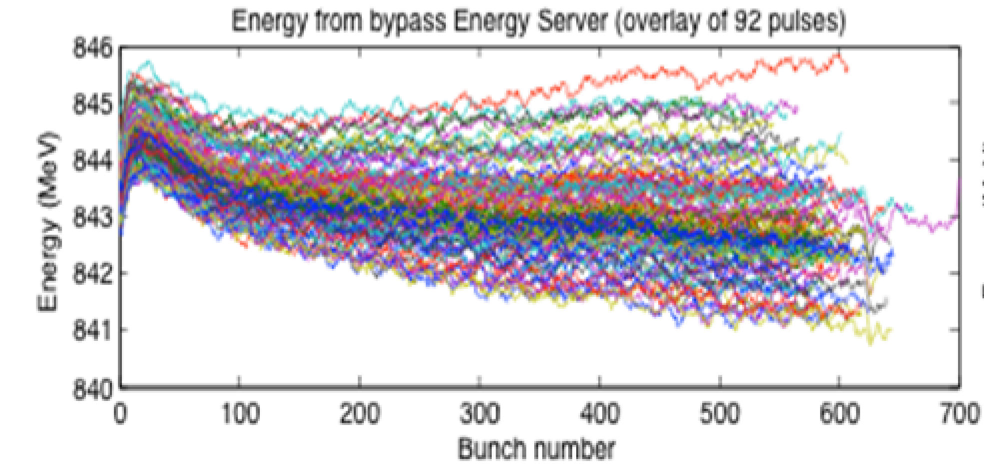
Example of pulse-to-pulse energy jitter (500us, ~3mA, 200 pulses overlaid)

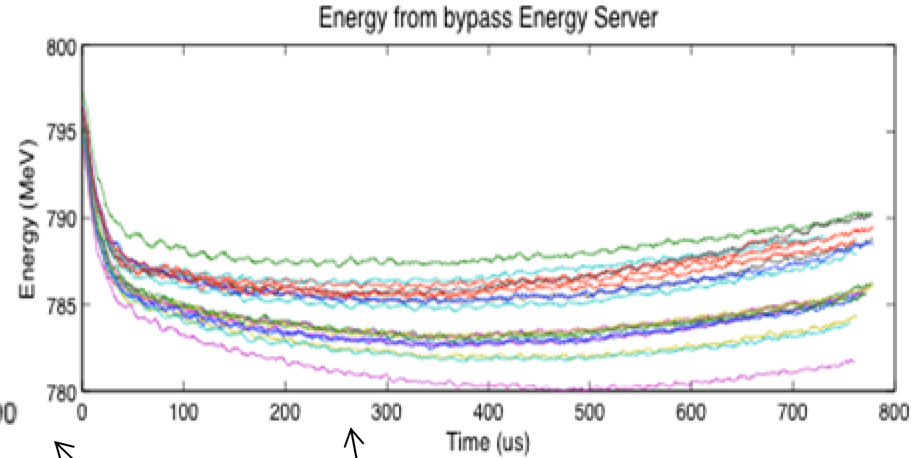


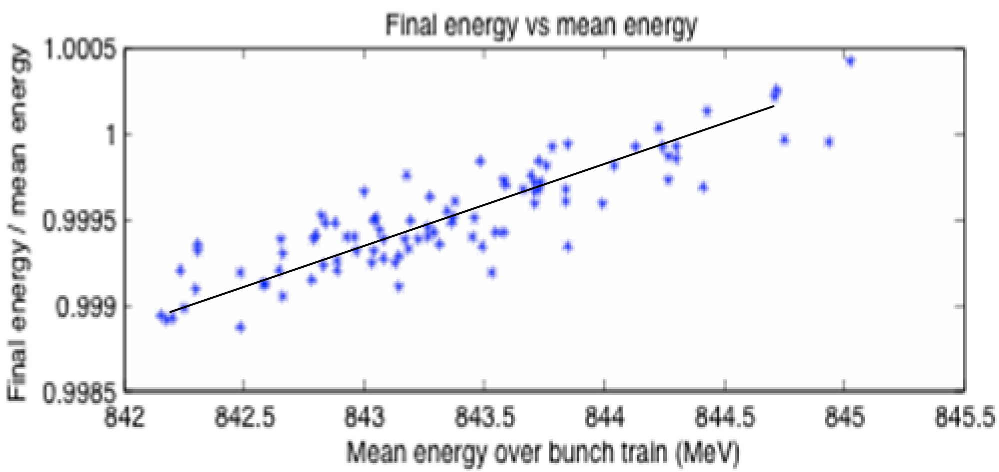


Average Energy Deviation in the bunch train - ~1500 bunches
20.09.2009 21:45 - 580 pulse sequence
Deviation - %
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
0
50
100
150
200
250
300
350
400
450
500
Bunch number (/3)
Single bunch δE/E ~0.1%
Pulse to pulse rms Energy 'jitter' in the train
576 pulses rms energy of all bunches (%)
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
3 Bunch samples - 1500 bunches

Energy profile pulse-to-pulse jitter



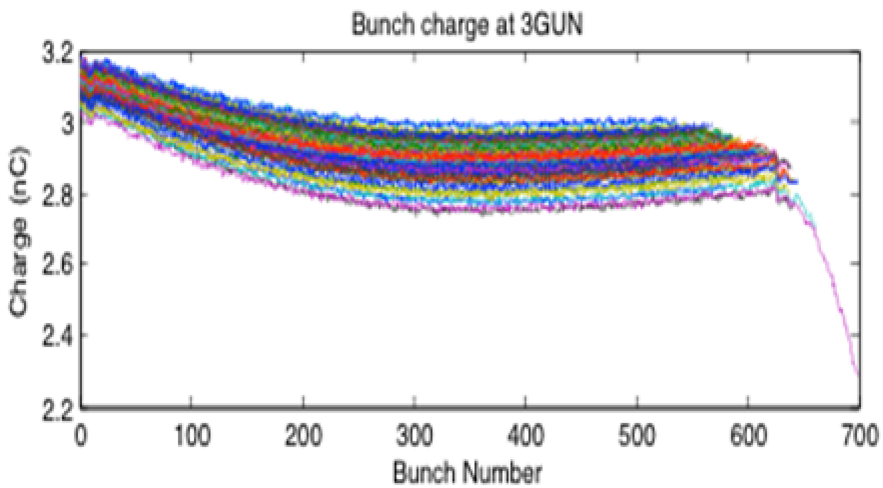




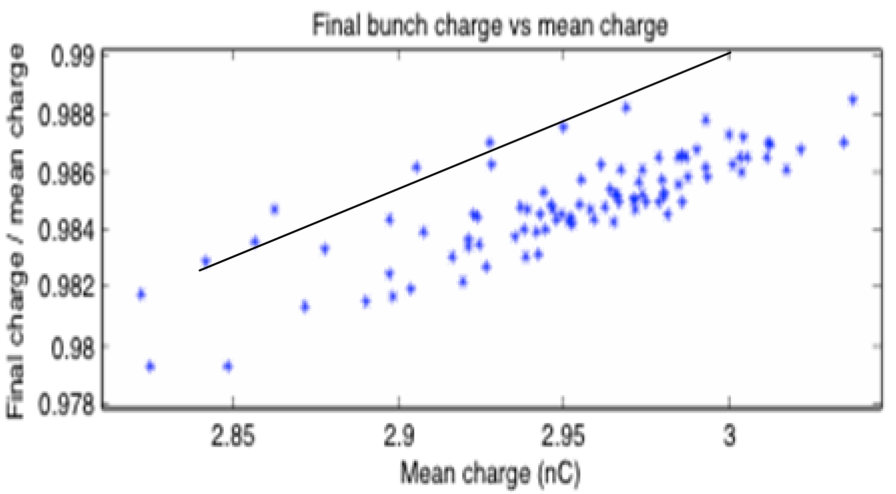
Ratio of final energy to mean energy as function of mean energy

Two example where the energy profiles of consecutive pulses appear to diverge

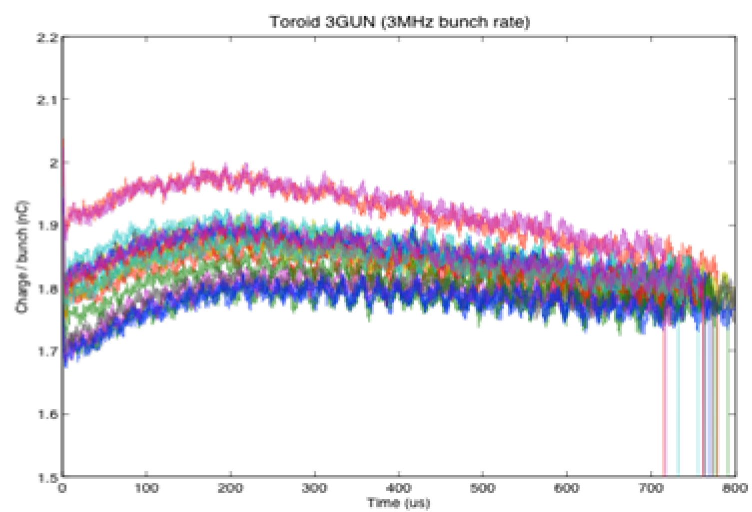
Charge profile pulse-to-pulse jitter



Ex.1: charge profiles appear to diverge (1MHz ~600 bunches)

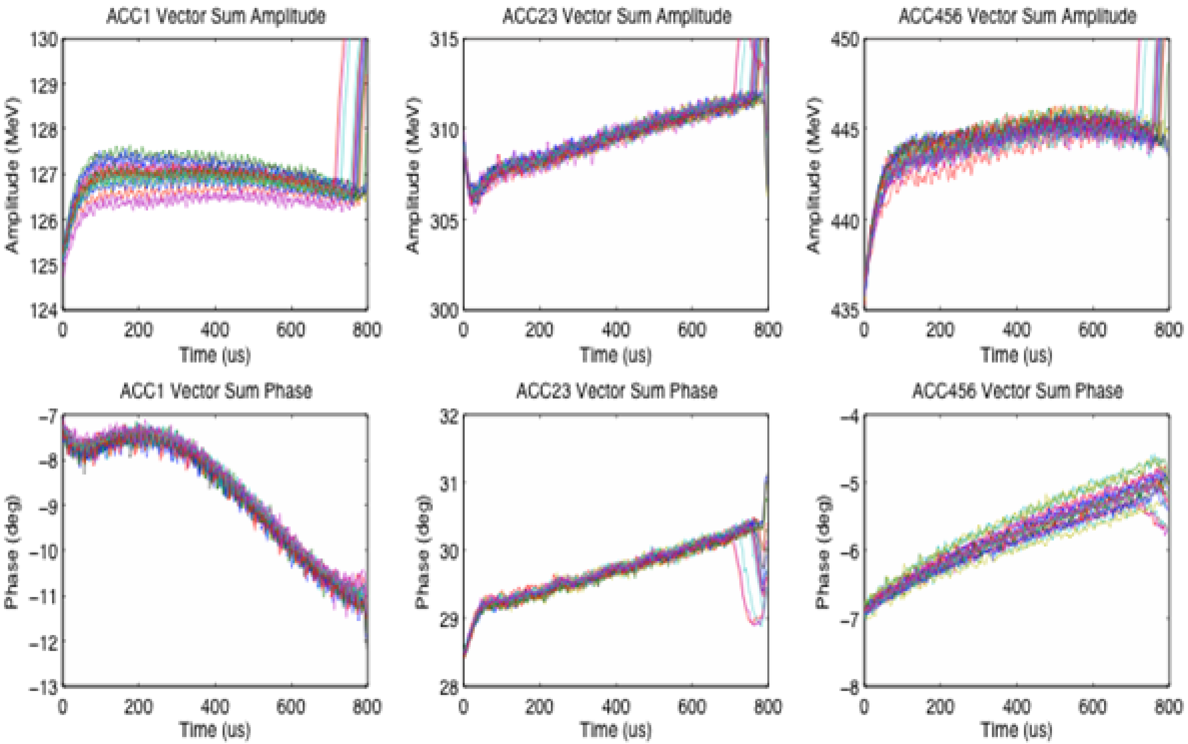


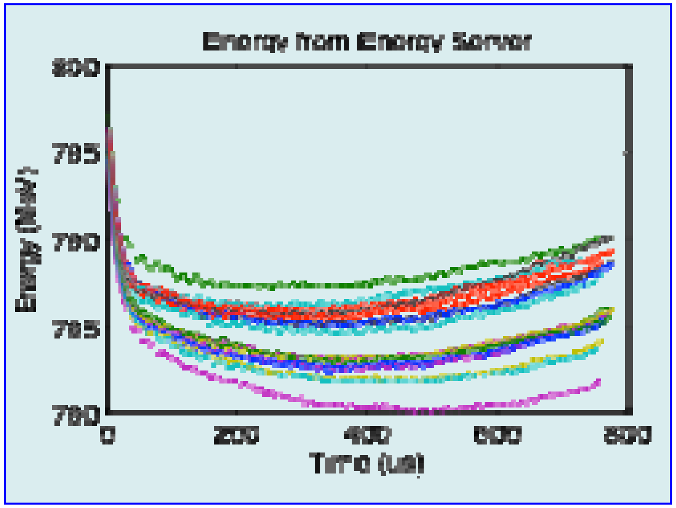
Ex.2: charge profiles appear to converge (3MHz, ~2200 bunches)



How do we match the final energy with the RF vector sums?

ACC1 + ACC23 + ACC456 = …?



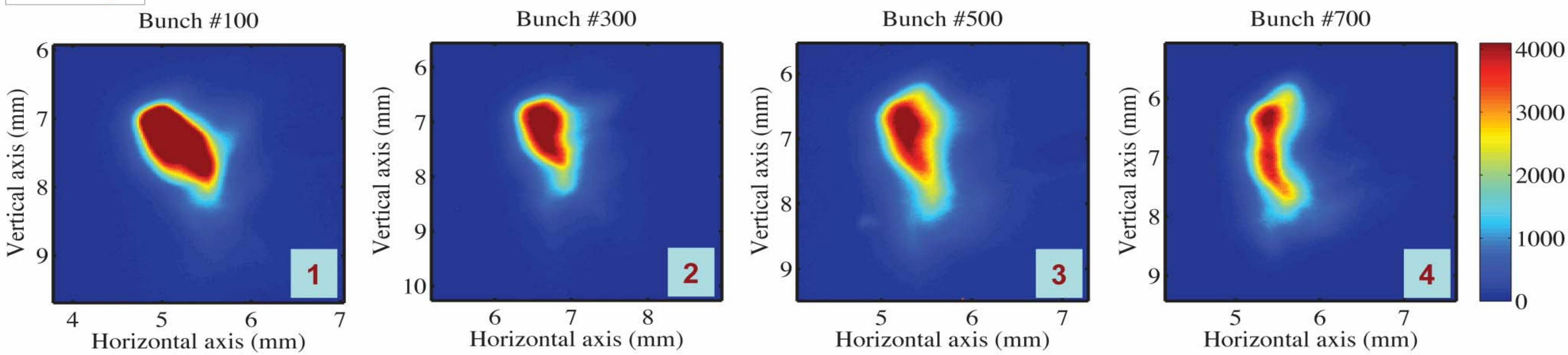


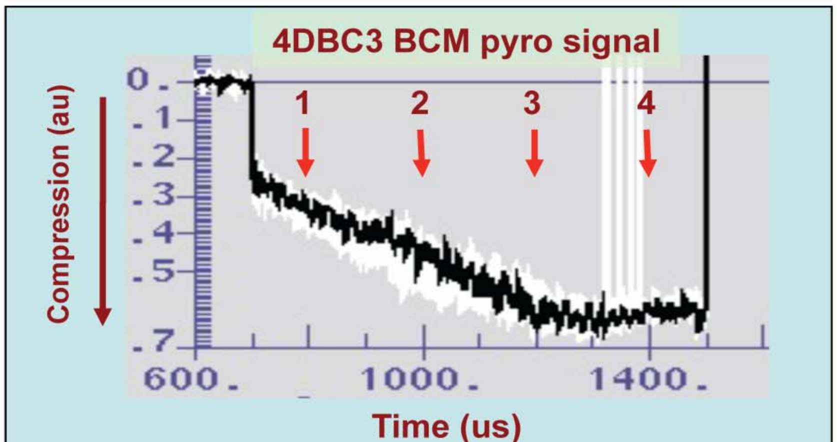
Three measurements of energy:

1. D1 bypass dipole
2. RF vector sums
3. Energy server

The measurements were consistently not in agreement

Transverse bunch distributions along bunch-train (800 bunches @ 1MHz, ~3nC/bunch)

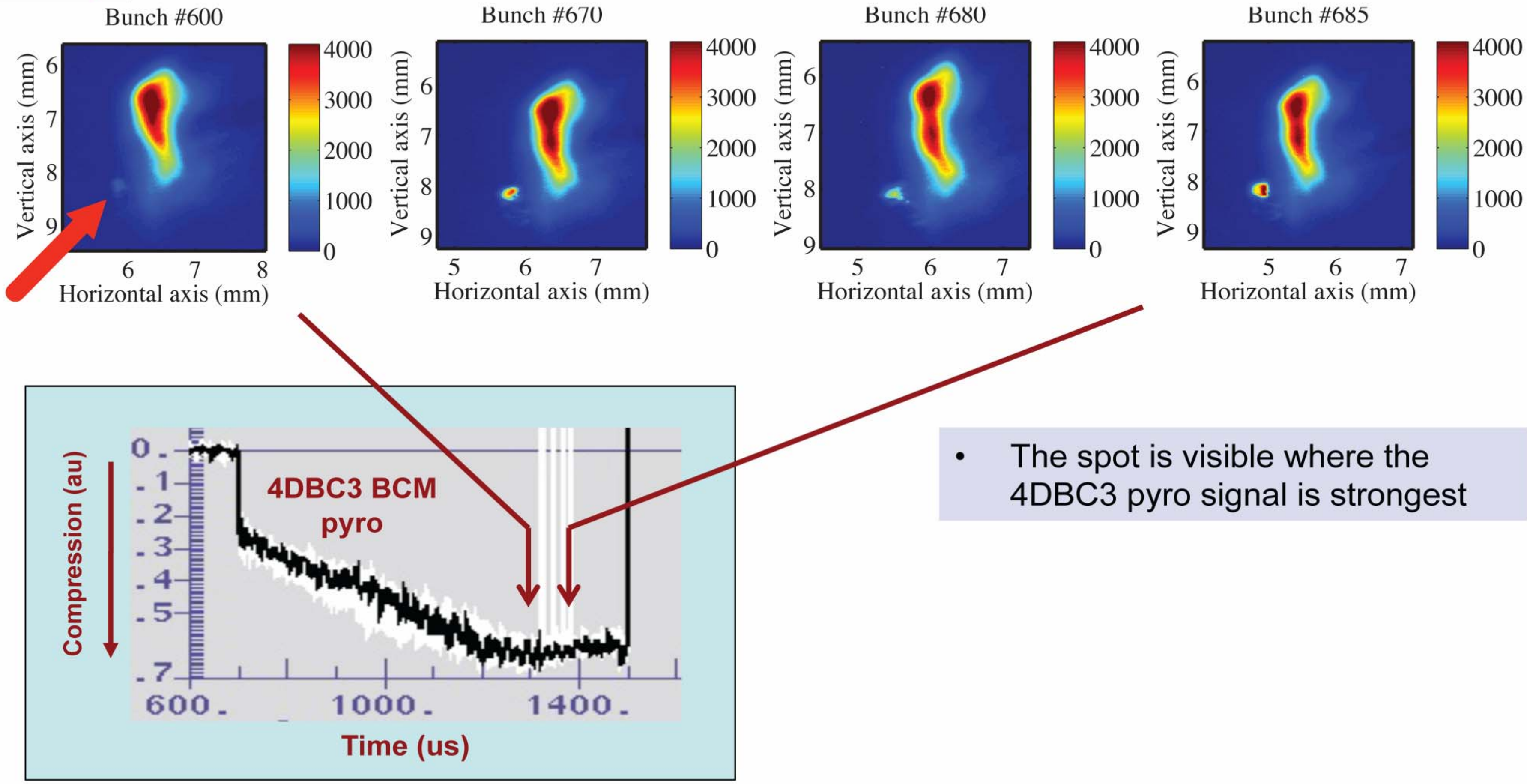




First bunch at 700us, last bunch at 1500us

- Transverse bunch distributions clearly show changes in bunch size and shape over the long bunch train
- ACC1 phase and BCM signals appear correlated with the changes in bunch distributions
- **LOLA was only available diagnostic for single-bunch measurements with long bunch trains at full-energy**

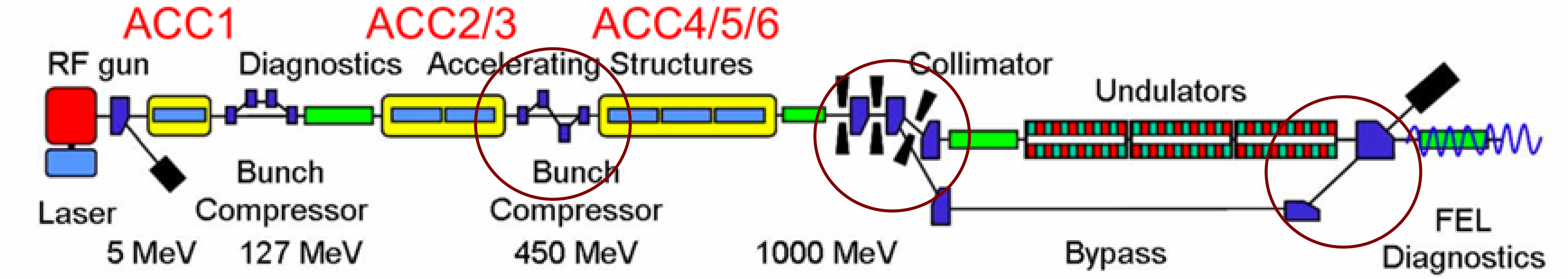
What is this?
(800 bunches @ 1MHz, ~3nC/bunch)

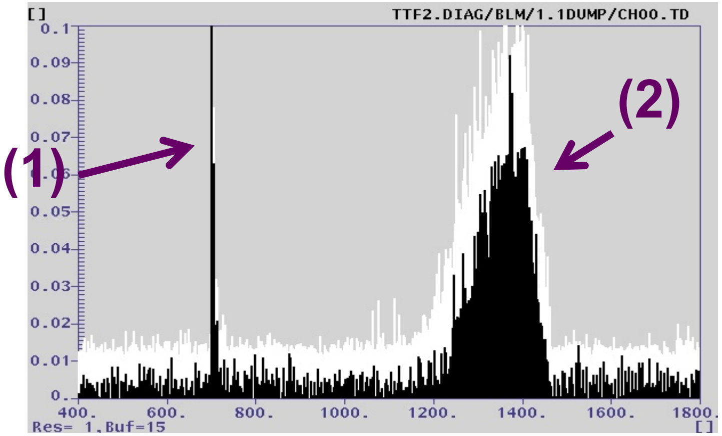


- The spot is visible where the 4DBC3 pyro signal is strongest

Beam loss

- Spent a lot of time fighting beam loss alarms, mainly in three locations
  - Bunch compressor BC3; first dipole of bypass line; dump line
- Largely about trying to find good operating points…





BLMs pick up gun dark current from gun

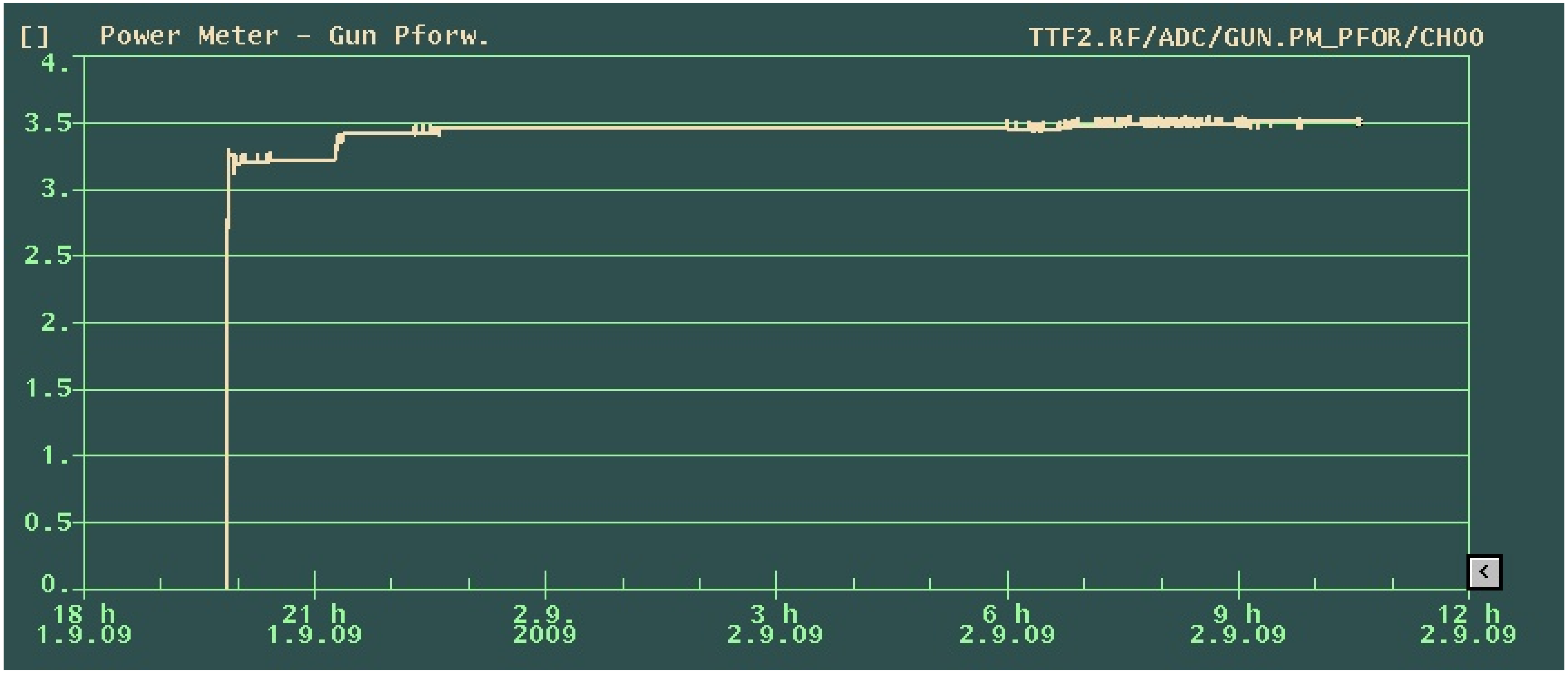
(1) Beam loss signal from bunch

(2) Gun dark current loss signature at the end of the RF flat-top

Injector Setup

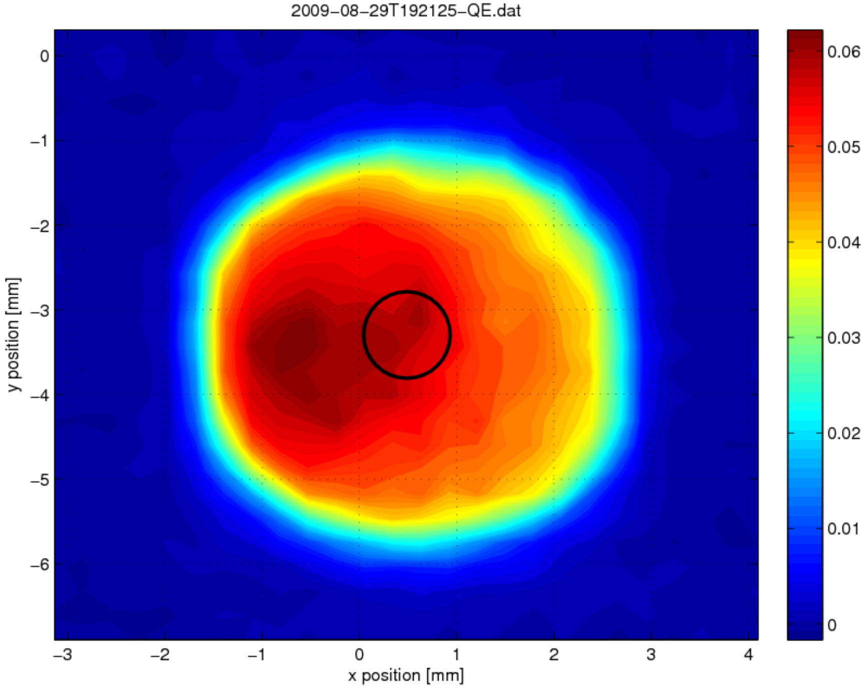
RF gun preconditioned

- RF gun was running with Pfwd=3.5 MW and a pulse length of 850 μs well ahead of full beamloading experiment



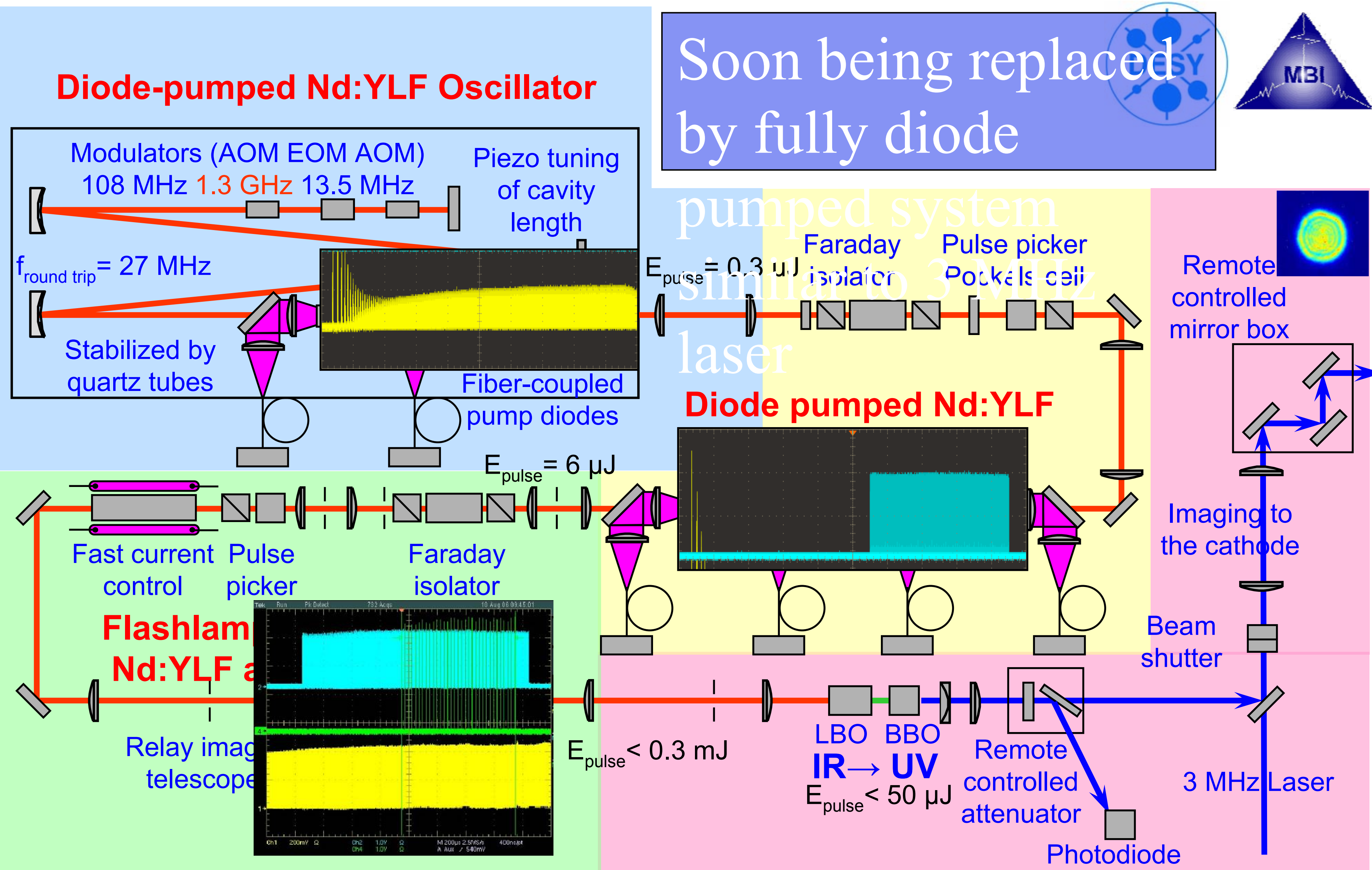
Alignment of laser on cathode

- Initial alignment of laser beam onto the cathode using a scintillator mounted into the plug
- Fine adjustment with
  - Beam based alignment
    → time consuming (2 shifts) and difficult,
    but yields center in respect to rf
  - Scan laser over cathode (QE map):
  → scan with small laser spot (200 μm) over the cathode (step size 300 μm)
  → assumes that cathode film is centered in respect to the rf
  → time consuming (2 shifts)
- Laser beam size 0.8 mm rms (3 mm diameter iris)
  - simulation optimum 1 mm rms



Laser 1: 1 MHz, flashlamp pumped

Soon being replaced by fully diode pumped system similar to 3 MHz laser



Space charge effects

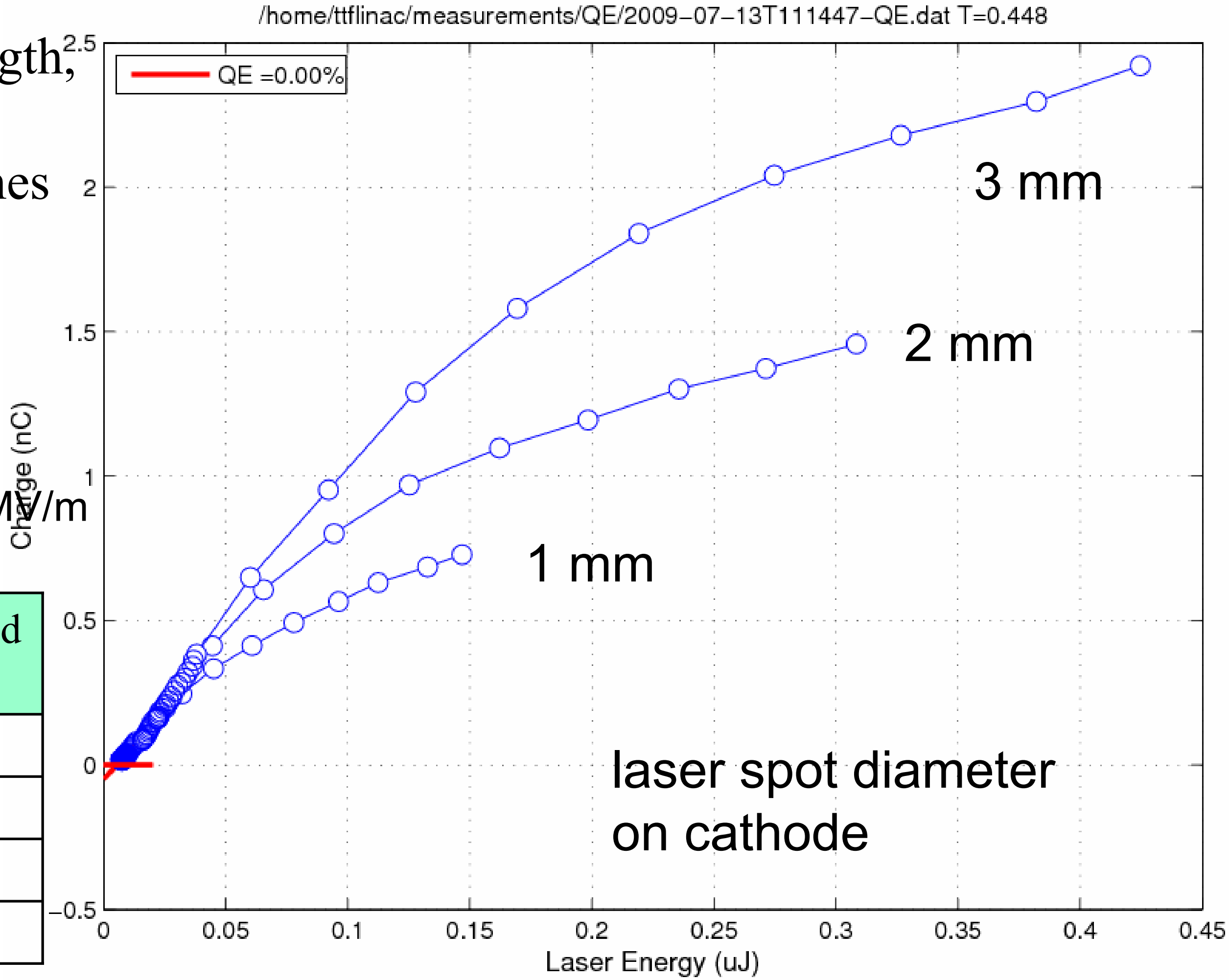
- Charge at rf gun exit as a function of laser pulse energy for different charge densities
- Extractable charge is limited by space charge effects

- For a given laser pulse length, the spot size and the accelerating field determines the extractable charge

Example:
simple model: $E = \sigma/\varepsilon_0$
spot size = 3 mm

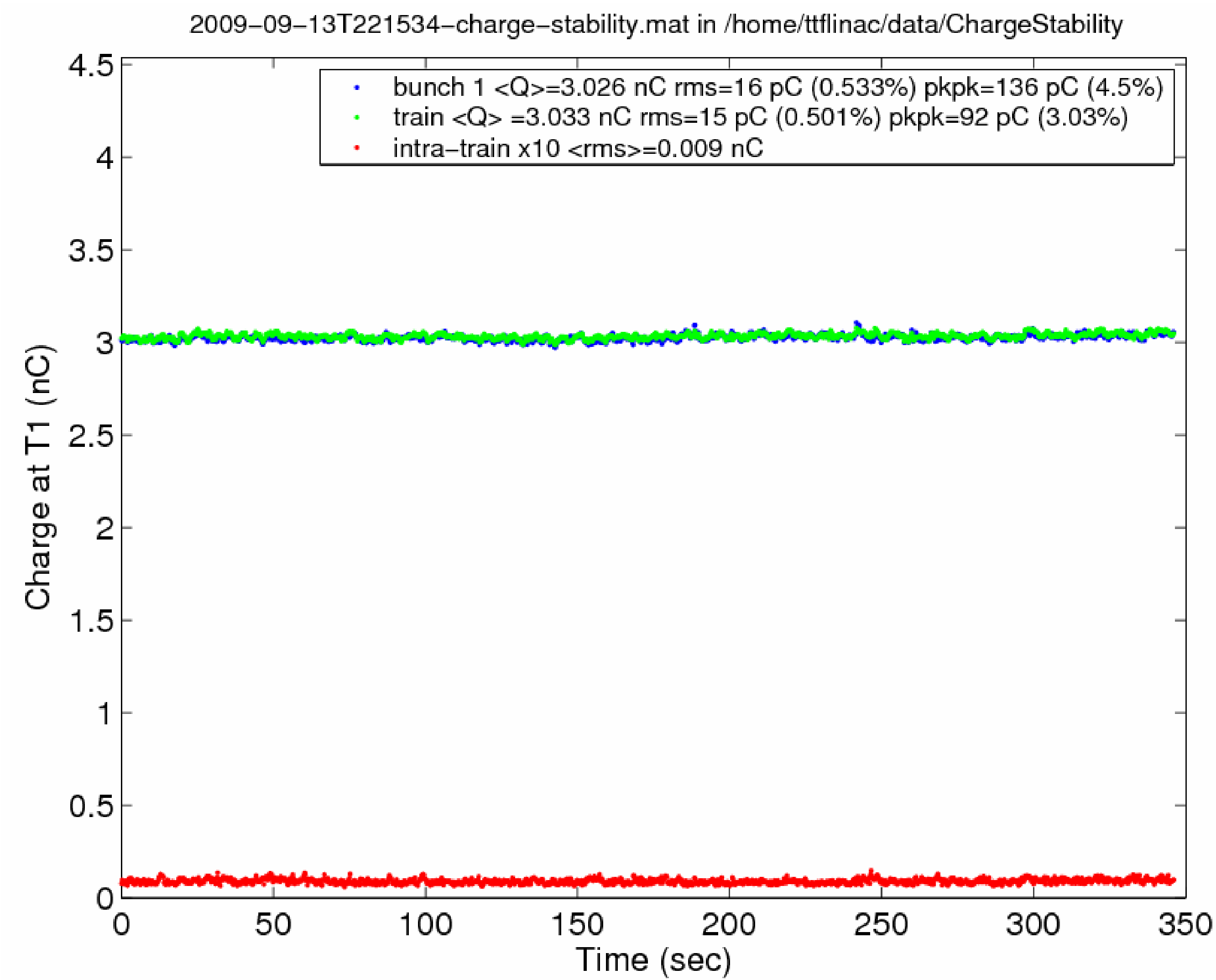
note: maximum field on crest 46 MV/m

Charge nC	space charge field MV/m
1	16
2	32
3	48
4	64



Laser pulse energy stability

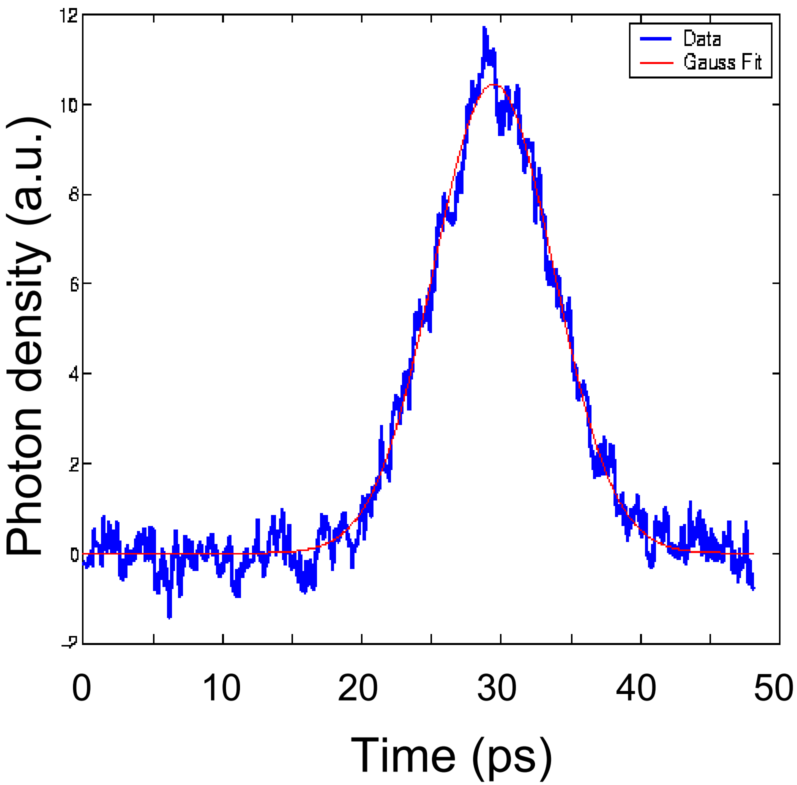
- Charge stability measured at T1 (gun toroid) @ 3 nC
- bunch 1: 0.5 % rms - whole train: 0.5 % rms – intra train: 0.3 %

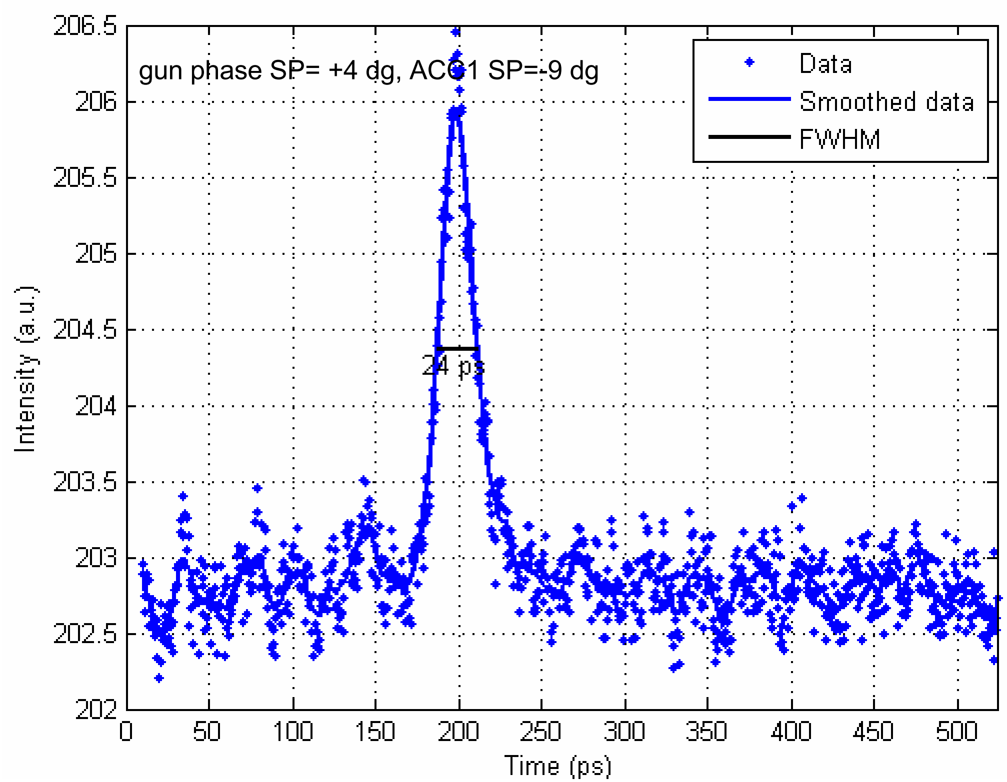


Laser pulse length and bunch length at BC2

- Measured with a FESCA-200 streak camera

□ $\sigma_L = 4.4 \pm 0.1$ ps (at 262 nm) --- bunch length at BC2: 8 ps rms (3 nC)





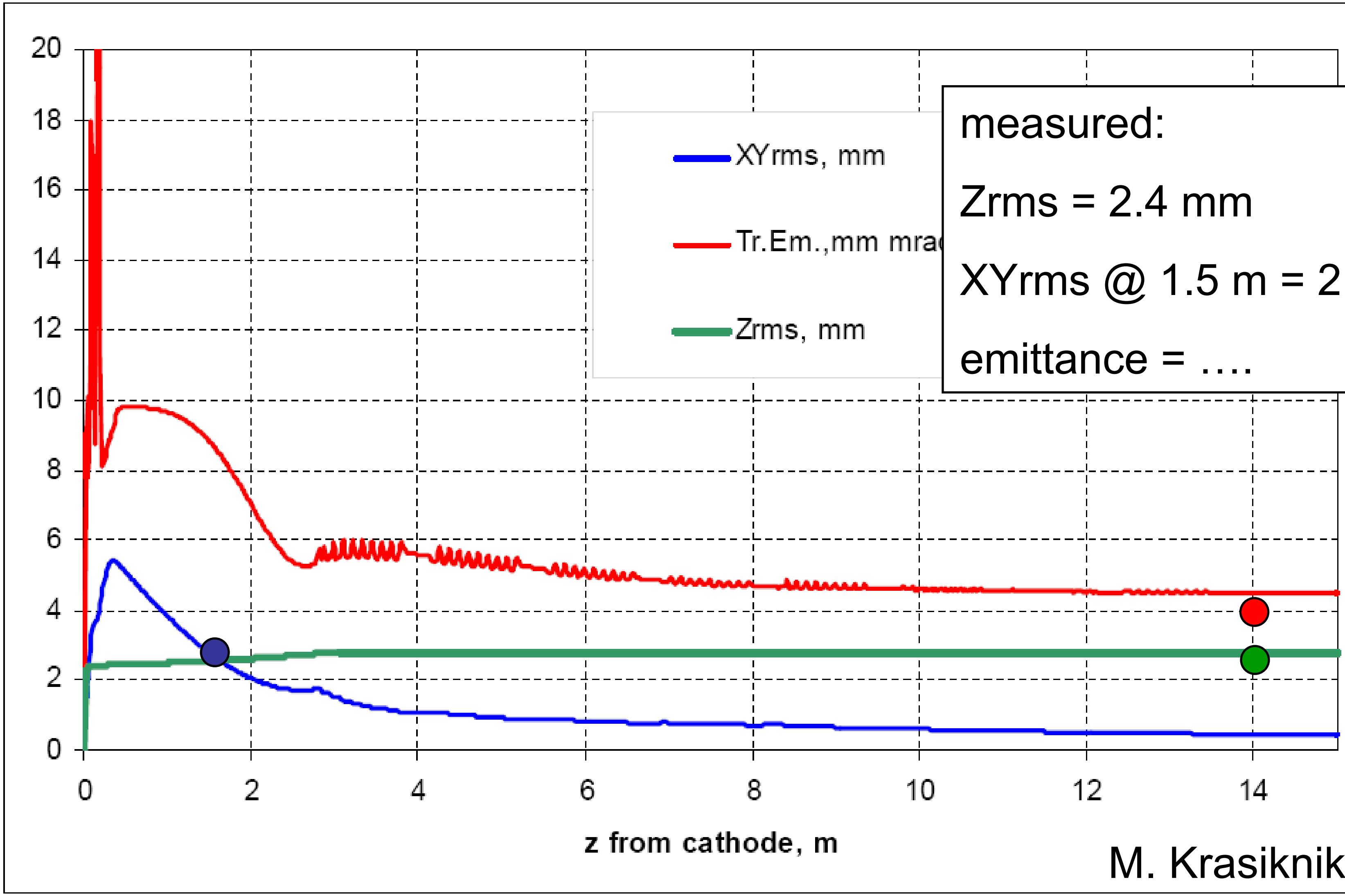
on crest: gun -2 dg, ACC1 -4 dg

gun phase SP= +4 dg, ACC1 SP=-9 dg -> sigma = 10 ps

gun phase SP= +2 dg, ACC1 SP=-7 dg -> sigma = 7.7 ps

gun phase SP= +4 dg, ACC1 SP=-9 dg -> sigma = 8 ps = 2.4 mm = 3.7 dg

Expected emittance and beam sizes



measured:

Zrms = 2.4 mm

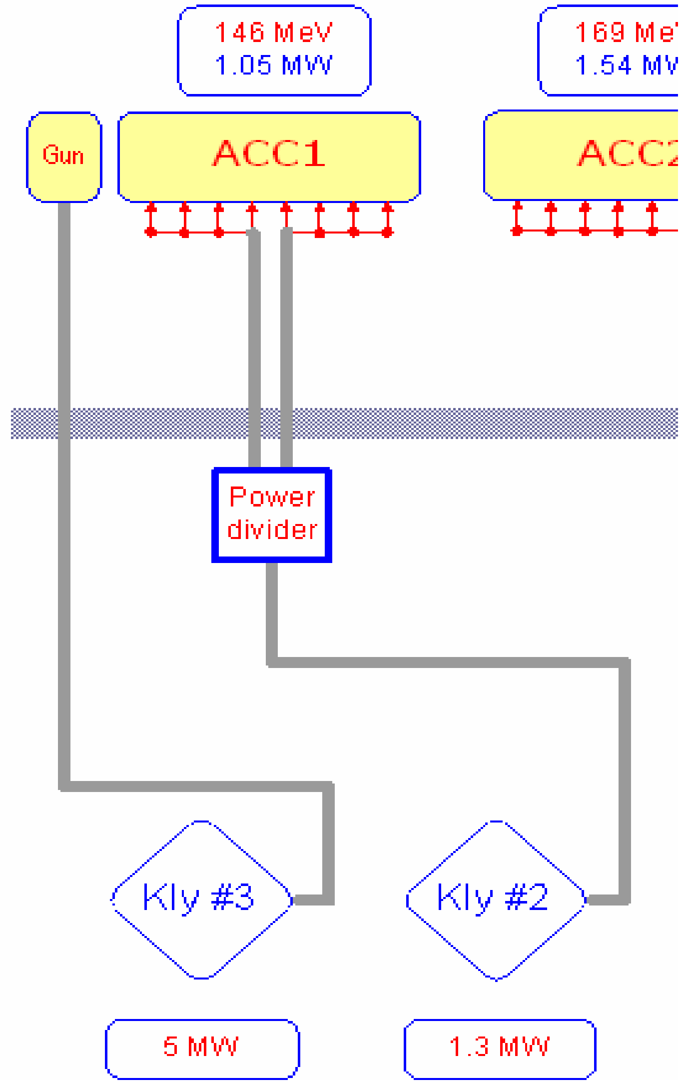
XYrms @ 1.5 m = 2.3 mm

emittance = ….

M. Krasiknikov

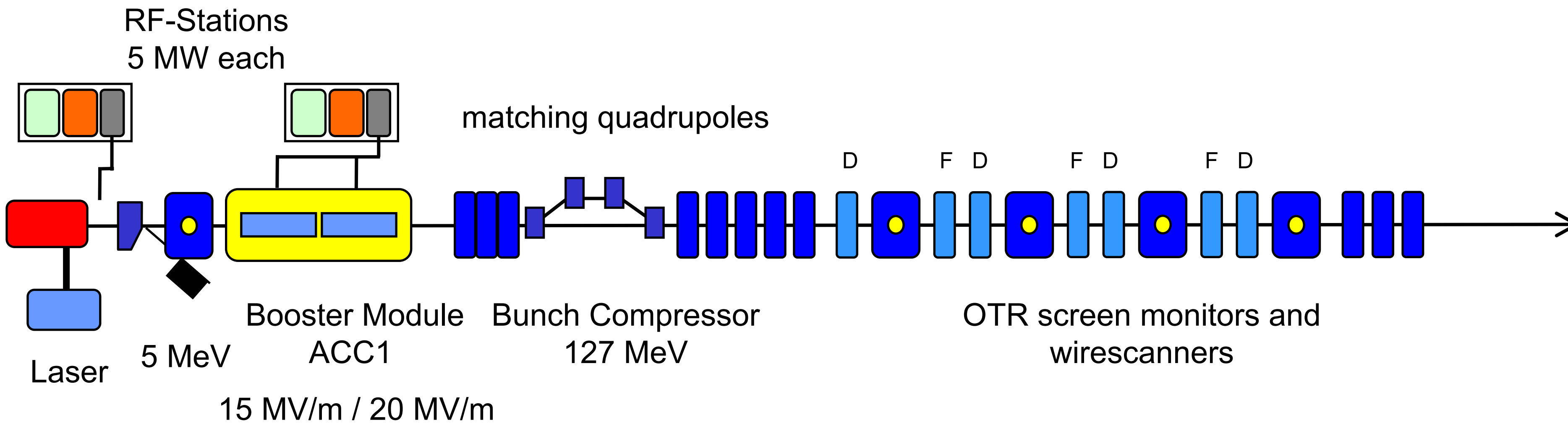
RF-Stations

- RF-Gun: 5 MW klystron
- ACC1: 5 MW klystron
- ACC1 waveguides have two arms: power can be divided between the cavities 1-4 and cavities 5-8

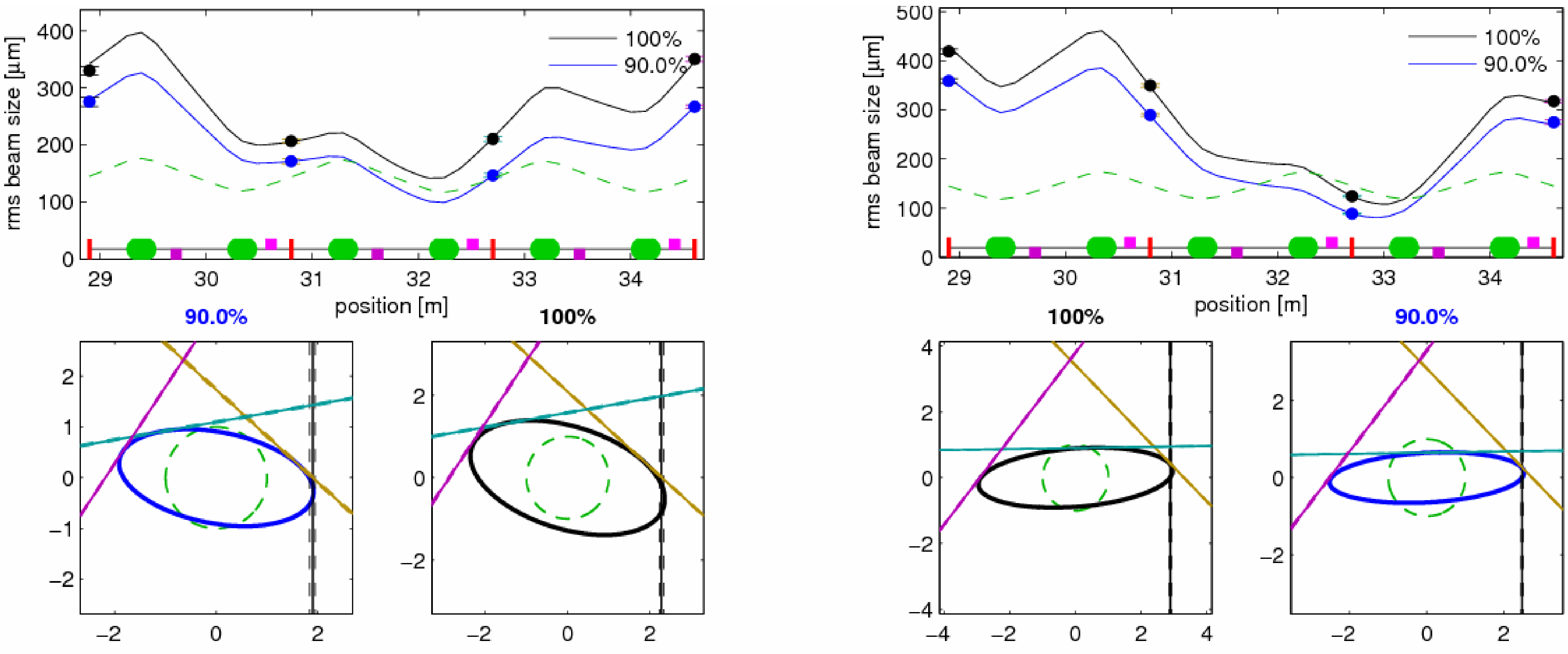


Matching and emittance

- Matching is based on the 1 nC, 2 mm mrad case
- to match 3 nC, where space charge effects play a more dominant role is more difficult – the beamline is optimized for 1 nC, 2 mm mrad

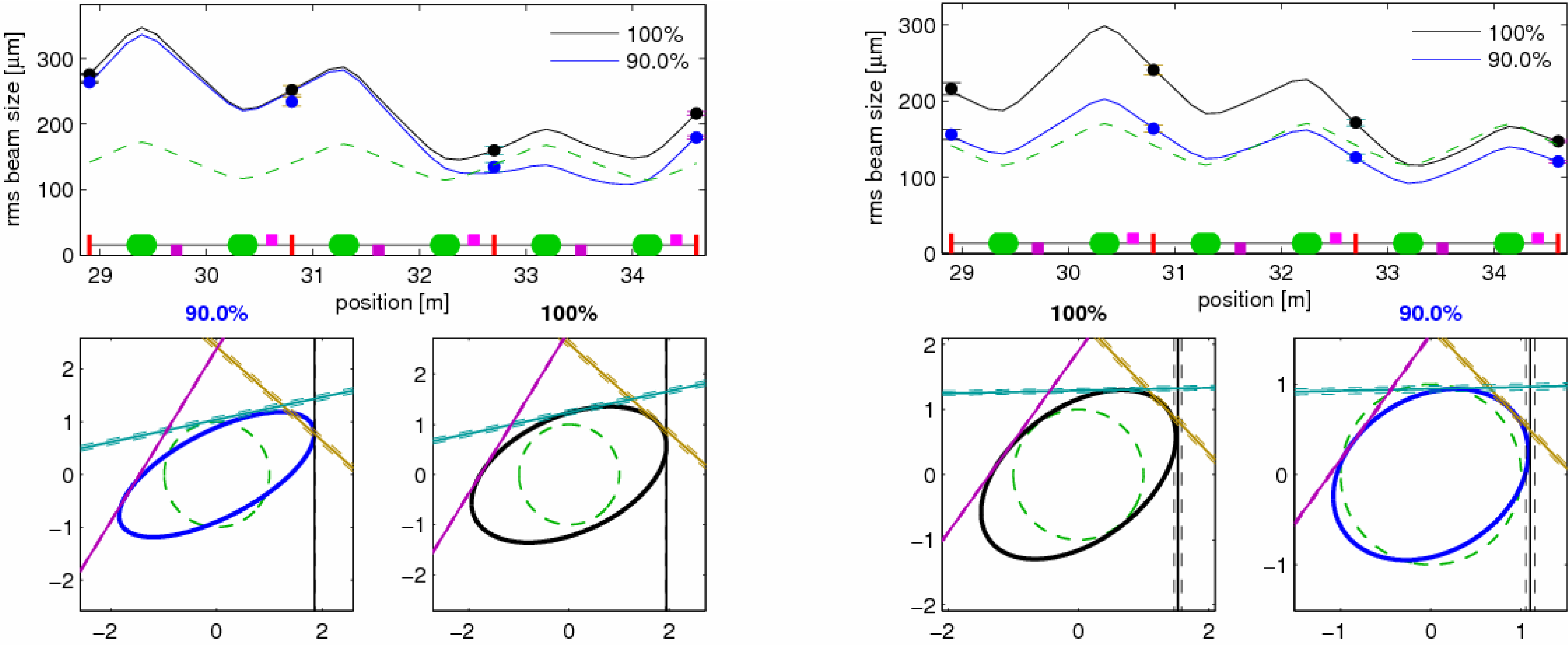


Matching in BC2



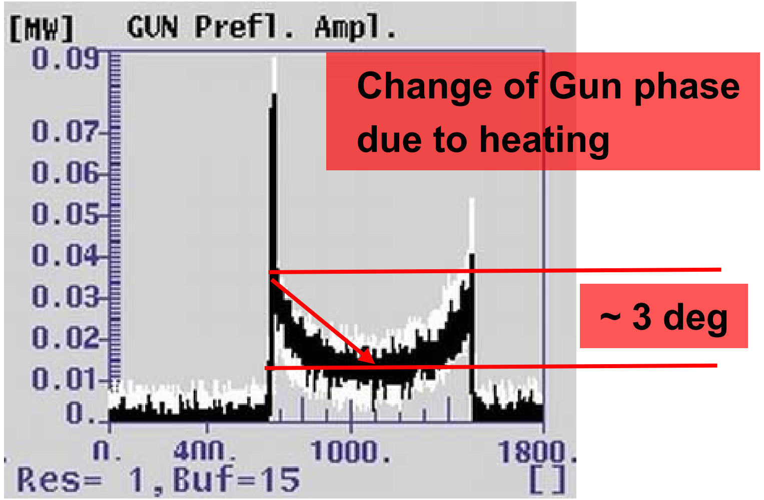
x-plane					y-plane	
90.0%	**100%**		**2009–09–02T184659**		**100%**	**90.0%**
3.49±0.13	6.06±0.15	(2.00)	γε [mm mrad] (1−σ emittance)	(2.00)	5.26±0.08	3.24±0.06
−2.27±0.10	−1.84±0.07	(−1.23)	$\alpha_{\text{Screen 4DBC2}}$	(1.21)	3.79±0.06	4.56±0.08
5.33±0.23	4.65±0.17	(2.54)	$\beta_{\text{Screen 4DBC2}}$ [m]	(2.53)	8.42±0.14	9.94±0.16
1.310	1.235	(1.000)	B_{mag}	(1.000)	1.821	2.095
			energy = 123.07 MeV			
			charge = 1.06 ± 0.01 nC			
			bunch # 1			
275.4± 8.3	330.3± 7.5		σ(Screen 4DBC2)		419.0± 5.4	359.0± 4.4
171.5± 4.2	206.6± 3.5		σ(Screen 6DBC2)		349.7± 3.4	289.4± 2.8
146.7± 3.7	210.4± 4.2		σ(Screen 8DBC2)		124.3± 1.6	89.1± 1.2
266.7± 2.7	350.3± 4.5		σ(Screen 10DBC2)		317.5± 3.7	275.0± 4.4

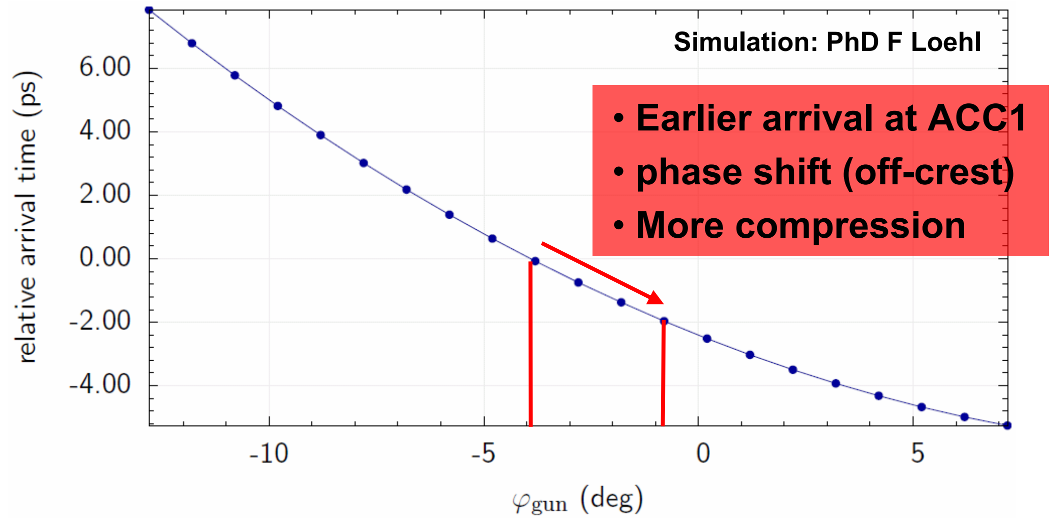
Matching in BC2



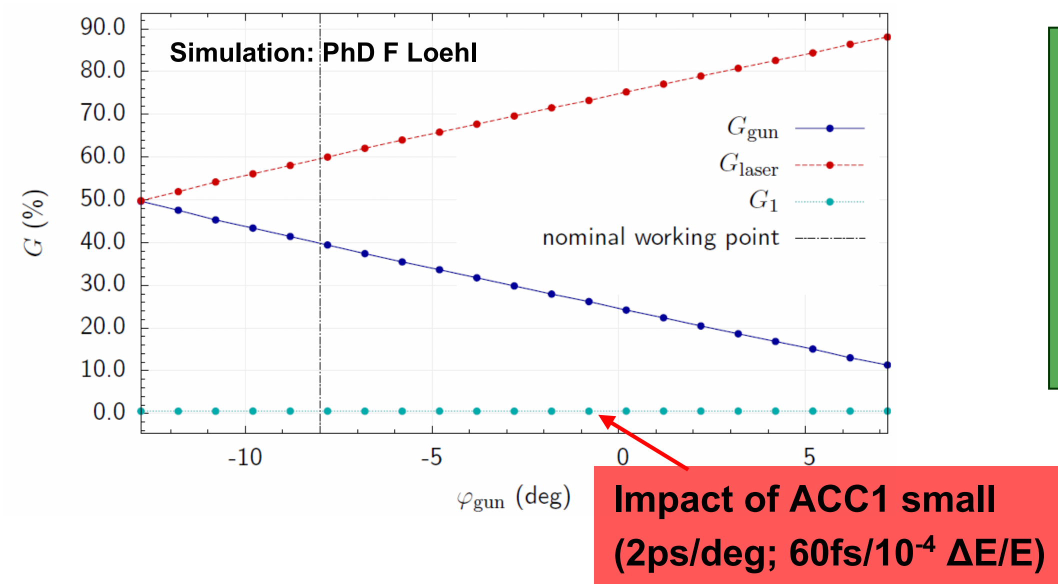
x-plane 90.0%	x-plane 100%		2009–09–03T211404		y-plane 100%	y-plane 90.0%
3.32±0.18	4.79±0.17	(2.00)	γε [mm mrad] (1−σ emittance)	(2.00)	3.48±0.08	1.98±0.06
−3.40±0.19	−2.40±0.09	(−1.23)	$\alpha_{Screen\ 4DBC2}$	(1.21)	1.06±0.05	1.16±0.07
5.24±0.30	4.01±0.15	(2.54)	$\beta_{Screen\ 4DBC2}$ [m]	(2.53)	3.27±0.16	2.99±0.17
1.456	1.173	(1.000)	B_{mag}	(1.000)	1.129	1.043
			energy = 128.80 MeV			
			charge = 2.92 ± 0.02 nC			
			bunch # 1			
263.6± 1.4	275.9± 1.3		σ(Screen 4DBC2)		216.3± 7.9	156.2± 6.9
234.1± 7.0	251.9± 7.2		σ(Screen 6DBC2)		241.1± 6.4	163.6± 4.4
134.6± 6.8	159.9± 6.7		σ(Screen 8DBC2)		171.7± 4.4	126.2± 4.5
179.3± 2.4	216.2± 2.7		σ(Screen 10DBC2)		147.3± 1.7	120.9± 1.9

Detour: Timing jitter at BC2





Influence of Laser, Gun and ACC1 on arrival time



Summary:

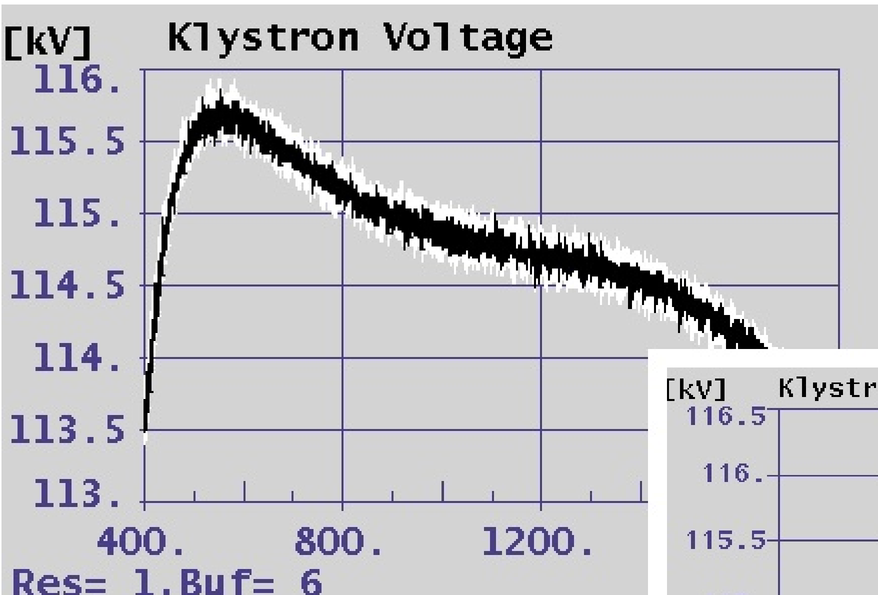
A correction of the arrival time at BC2 due to a phase shift at ACC1 by using the ACC1 amplitude induces energy spread!

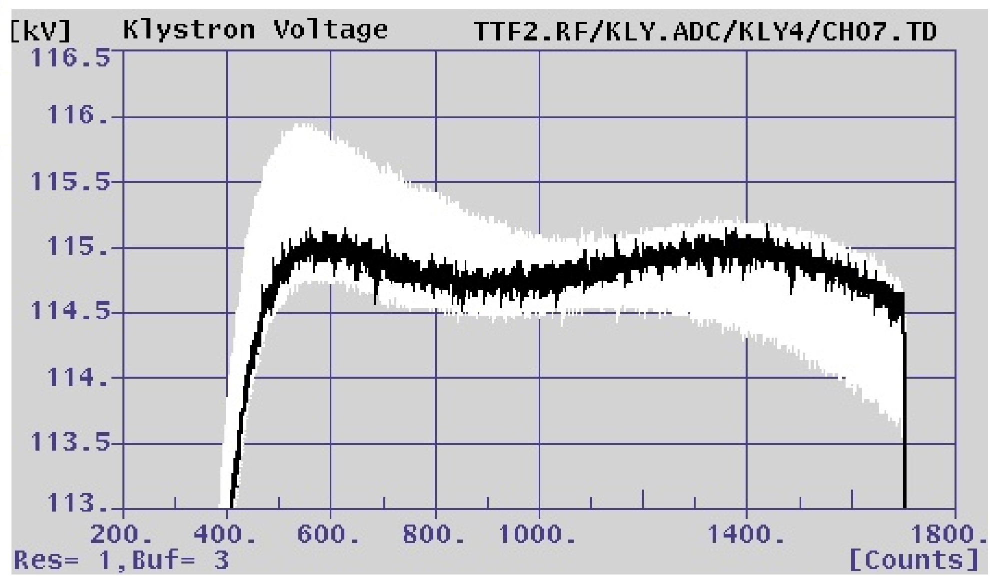
=> Correct the source of phase shift!

LLRF Talks

Klystron HV Pulse

Klystron voltage change by 1 kV during the flat-top causes phase change of about 14 deg.
The cavity tuning procedure should take this effect into account

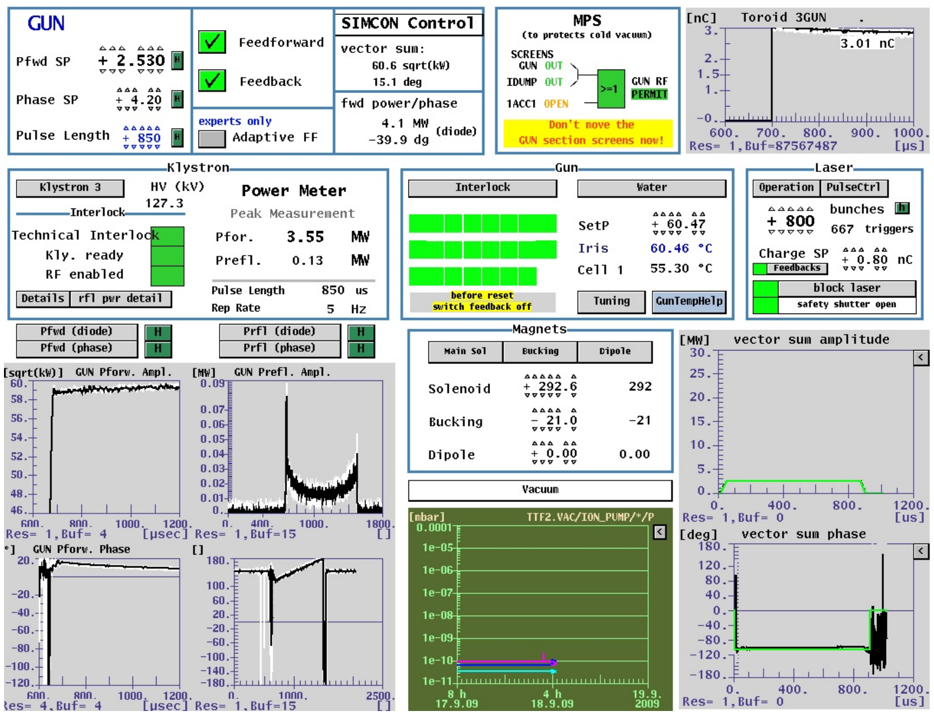


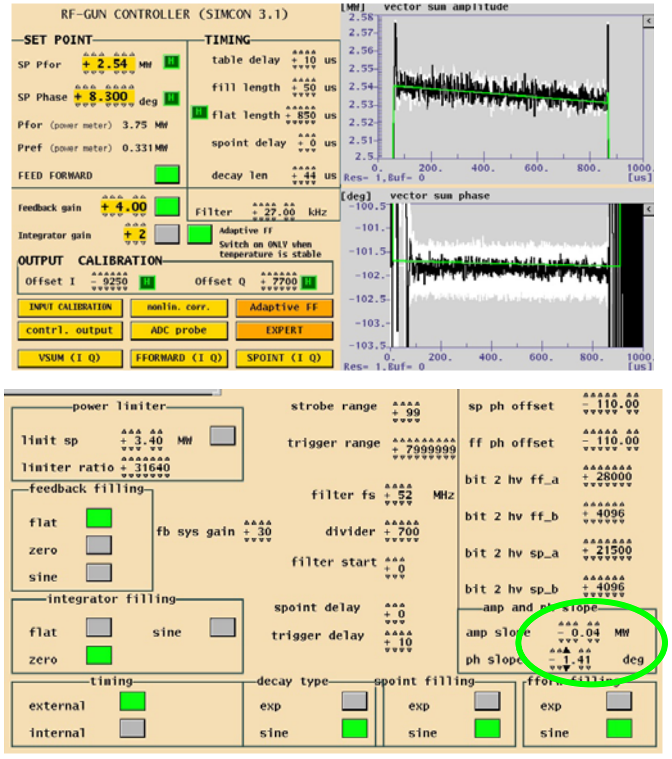


- HV rise time of klystrons:
- 100 us for 5MW
- 200 us for 10MW

Set-up RF Gun

- Adjust Gun iris temperature and forward power level below from saturation regime, minimize reflected power level, correct loop phase, apply feedback, increase gain, check amplitude and phase slopes (maintain flat vector-sum in amplitude and phase without any slopes)
- Sometimes amplitude phase slope **required** for flat charge trains

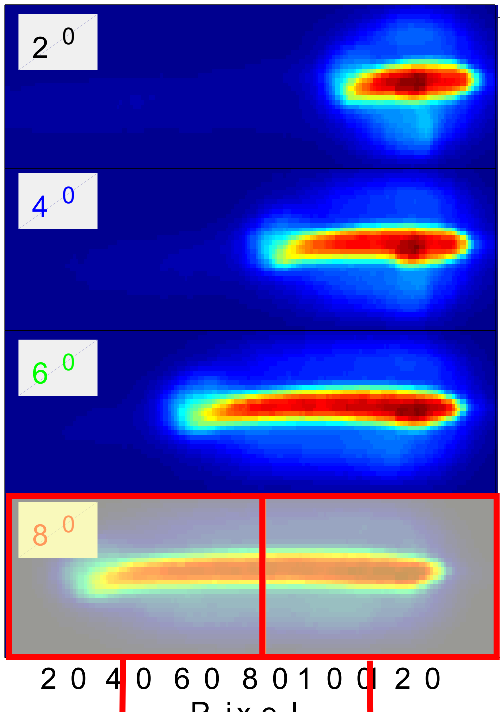


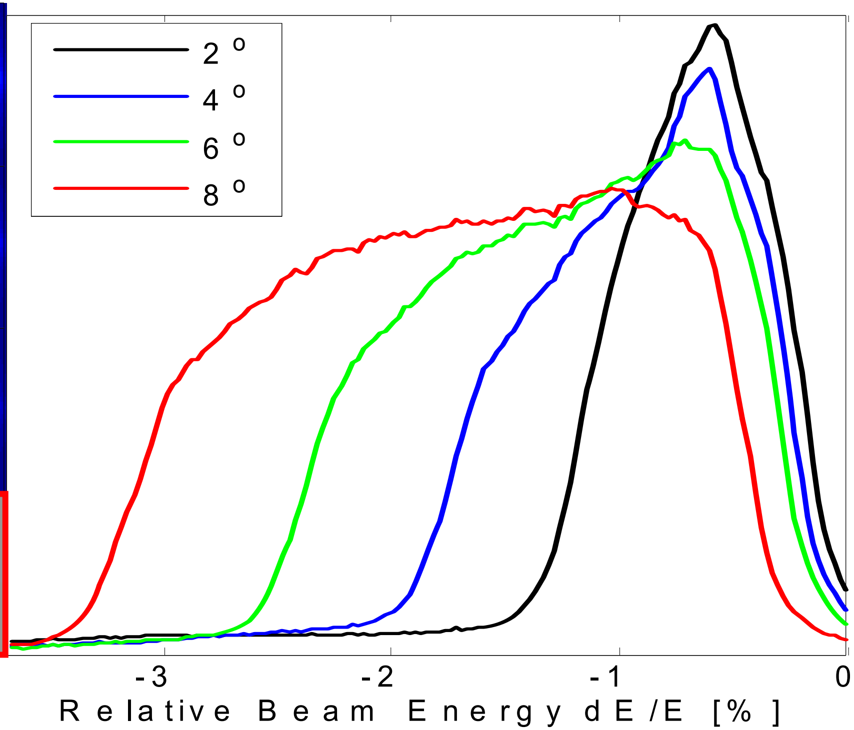


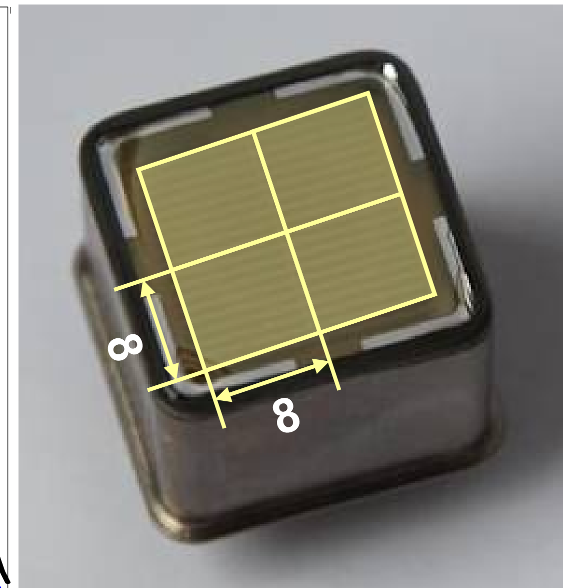
Diagnostics

Intensified CCD Camera

- x-y projection of bunch at entrance of D3BC2 imaged onto ICCD camera
- at off-crest operation, x axis related to beam energy $\Delta x = R_{16} * \Delta E/E$
- ns-gate of image intensifier allows to recorded 1 bunch out of bunch train







I_2 I_1

$$s = \frac{I_1 - I_2}{I_1 + I_2},$$ Centre-of-gravity beam position