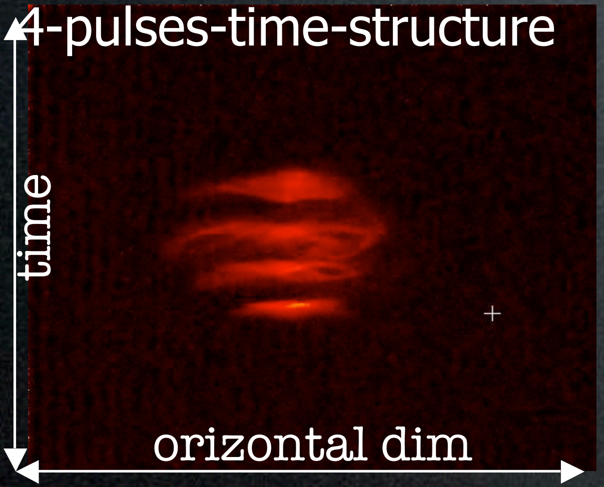
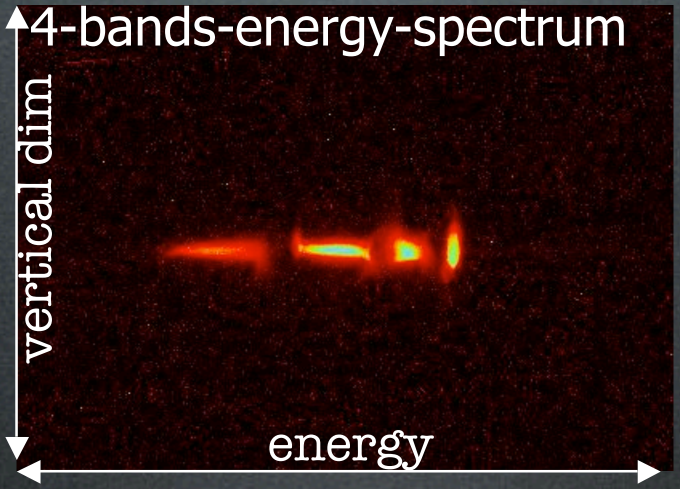
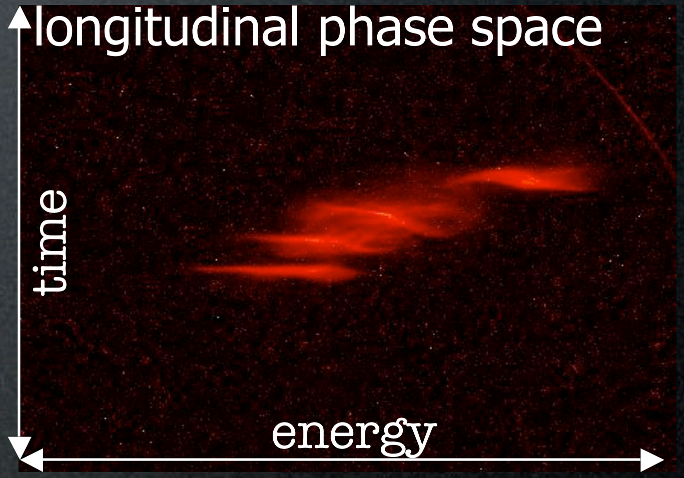
Recent results at SPARC

Massimo Ferrario
on behalf of the SPARC team

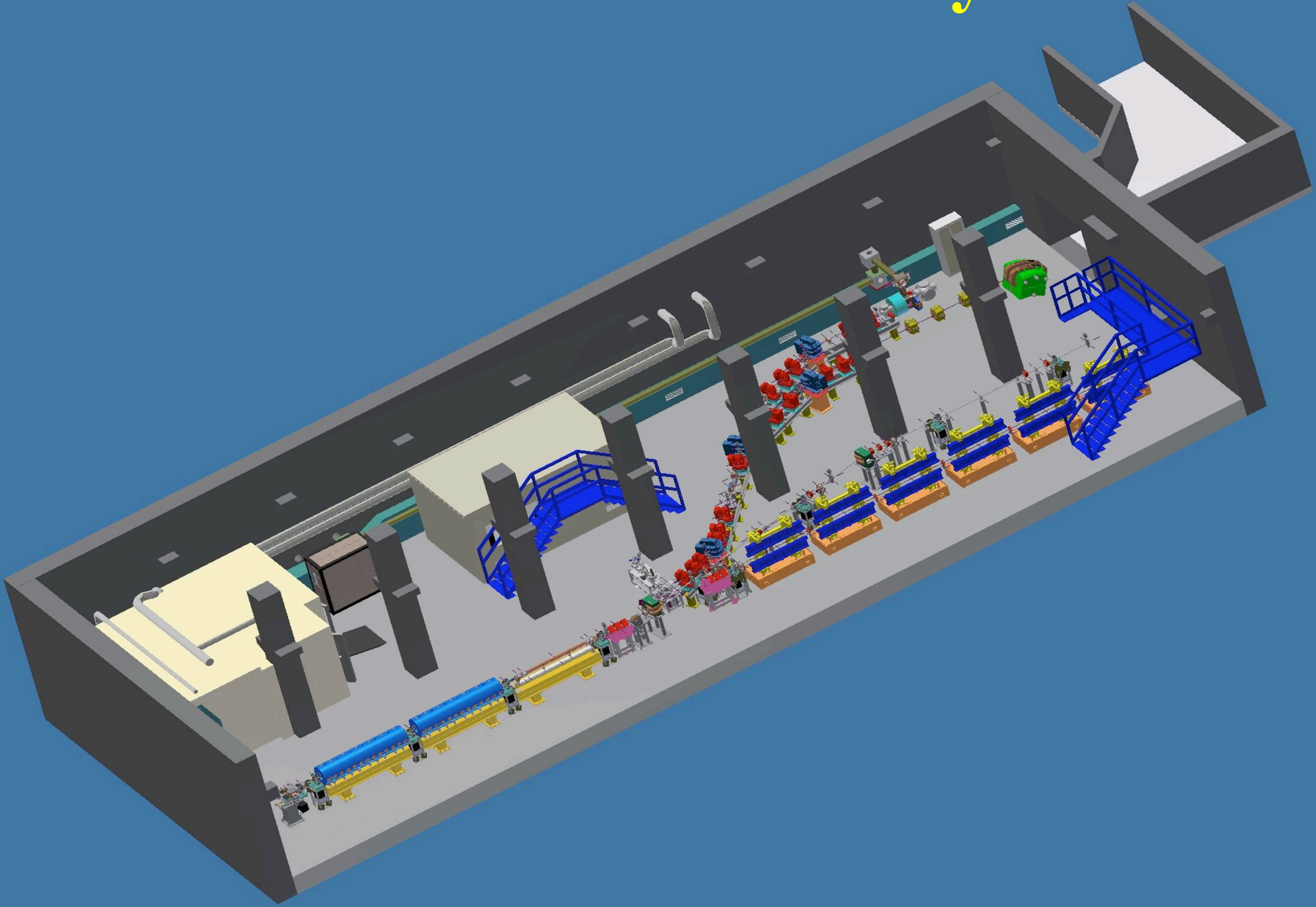

4-pulses-time-structure


4-bands-energy-spectrum

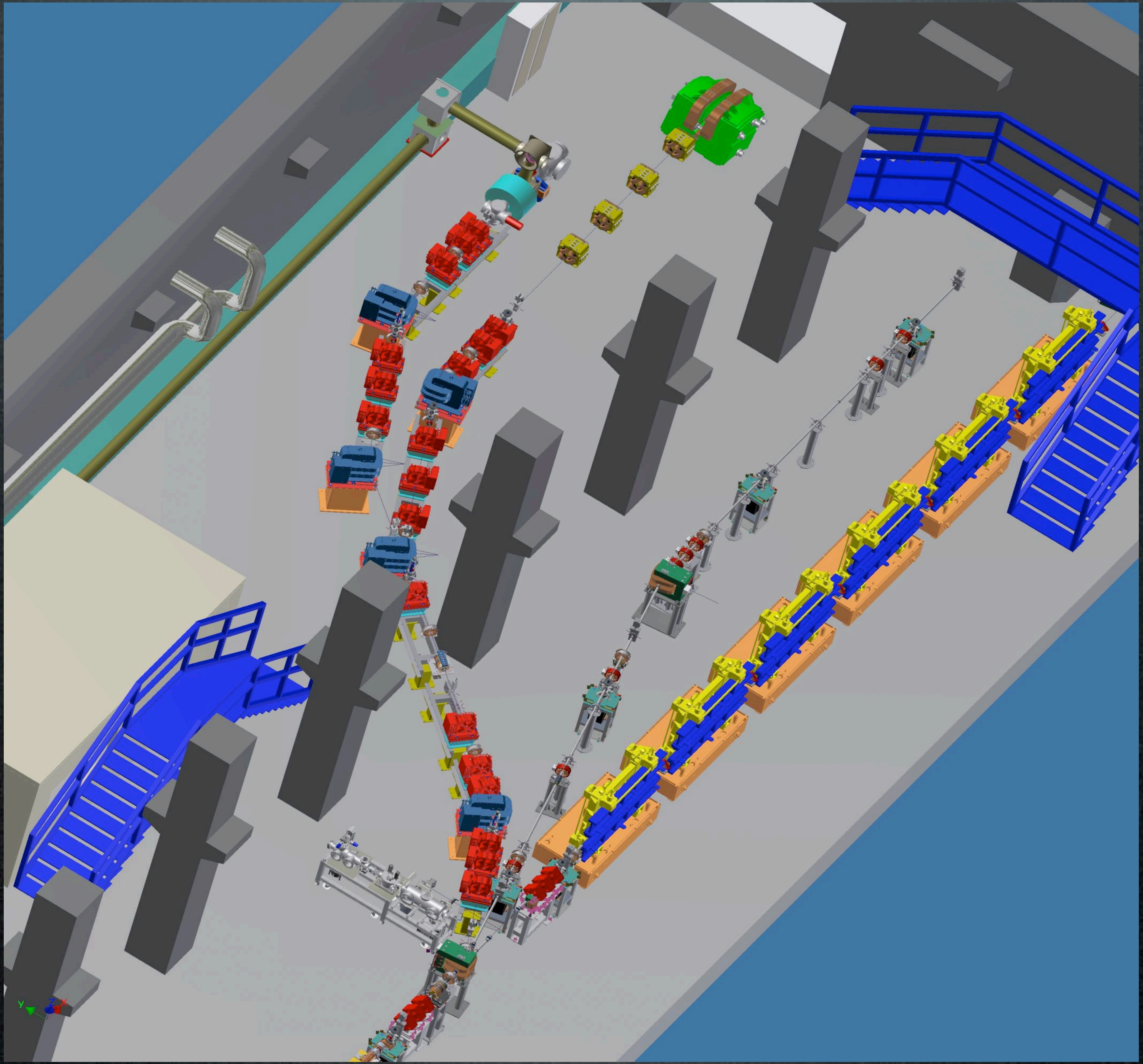

longitudinal phase space

42nd LNF Scientific Committee Meeting - June 6, 2011

Near future SPARC layout

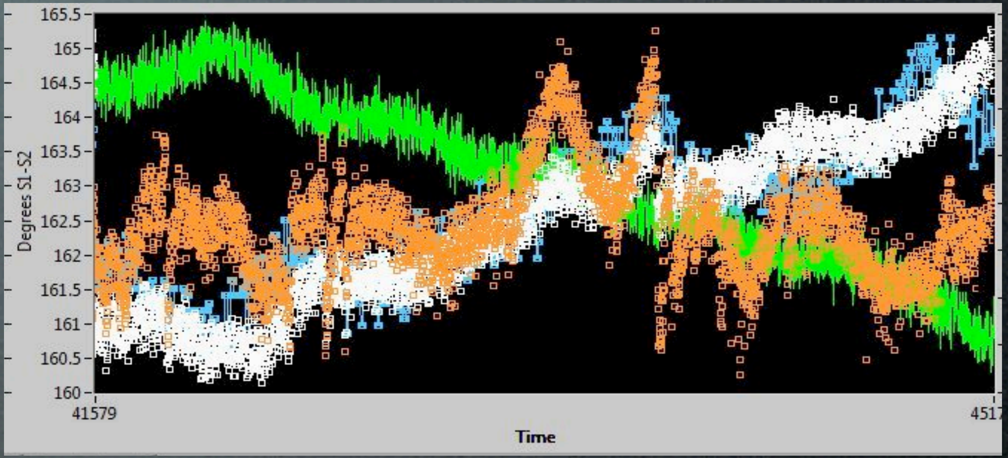


Summer installations



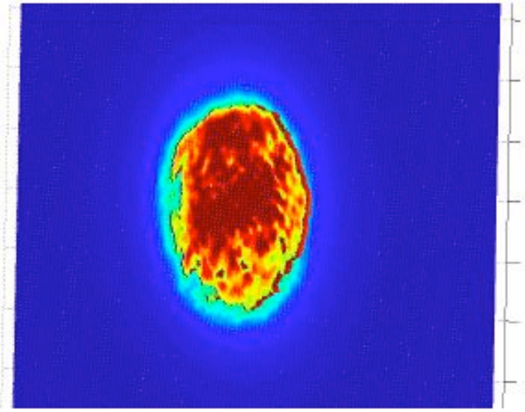
Progress towards high brightness beams

Water pipes re-welding and VB temperature stabilization

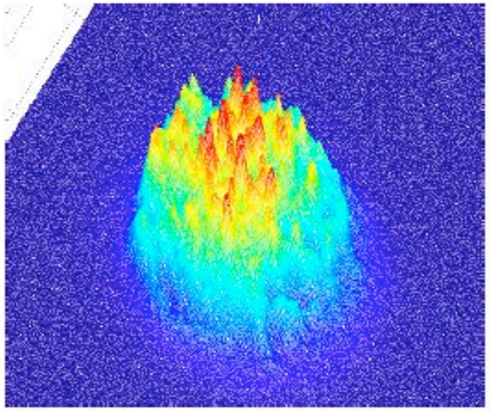


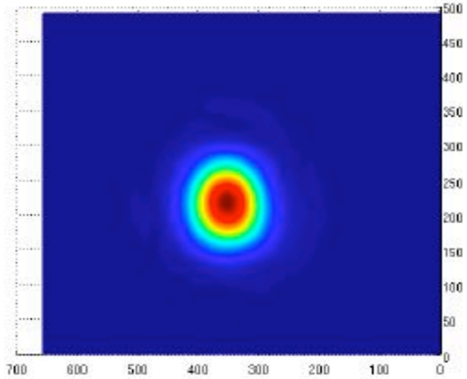
Now temperature stability is 0.2 deg

LASER SPATIAL PROFILE OPTIMIZATION

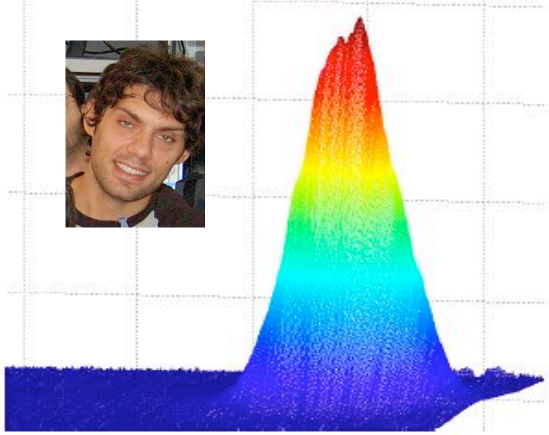


BEFORE





AFTER



Changes in harmonic generations could give further improvement on stability

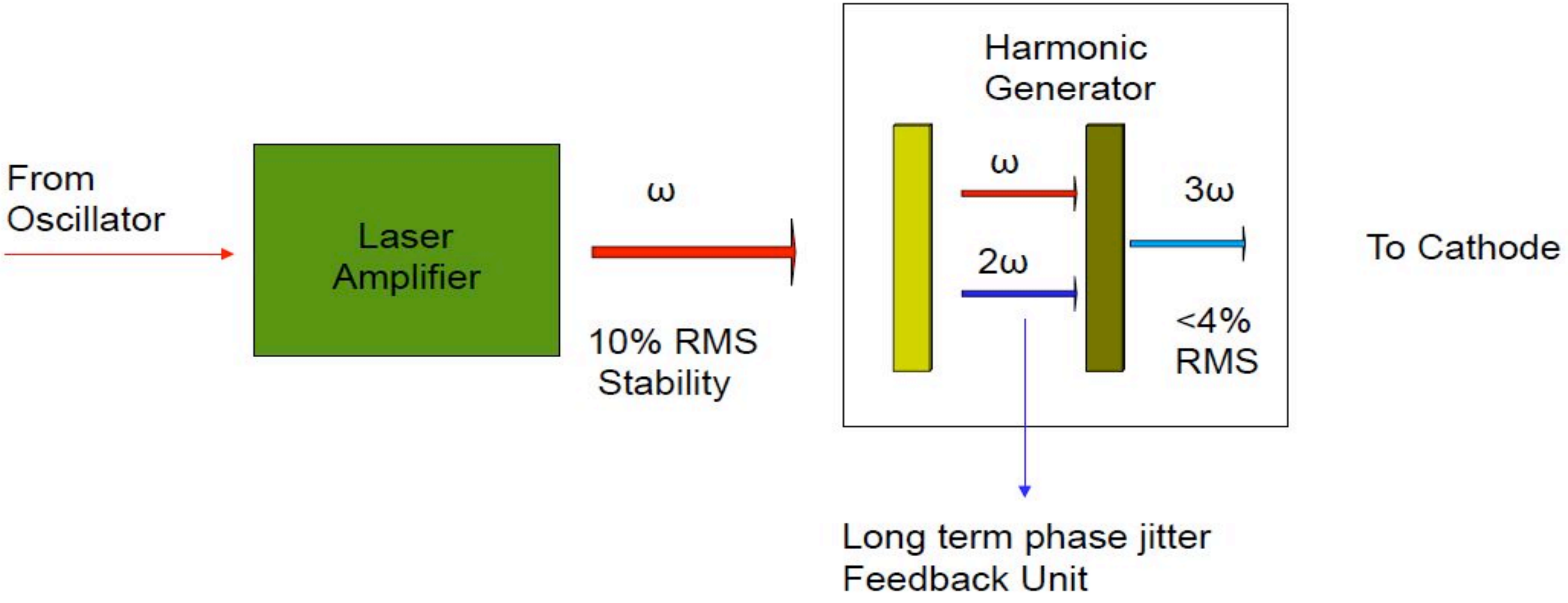
Profile Improvement from quasi-gaussian to quasi-flat to lower emittances

-Full saturation of harmonic crystals crucial for charge distribution and stability

-Good input profile very important for this task (saturation on whole beam) in connection with time duration (nonlinear interaction depends on the instantaneous power)

-Phase jitter correction measurement more reliable (optimal conversion optical/electrical)

-Important to keep under control damage and dust on the optics
(hotspots add coherently in a transfer line and soon fullfill the beam)



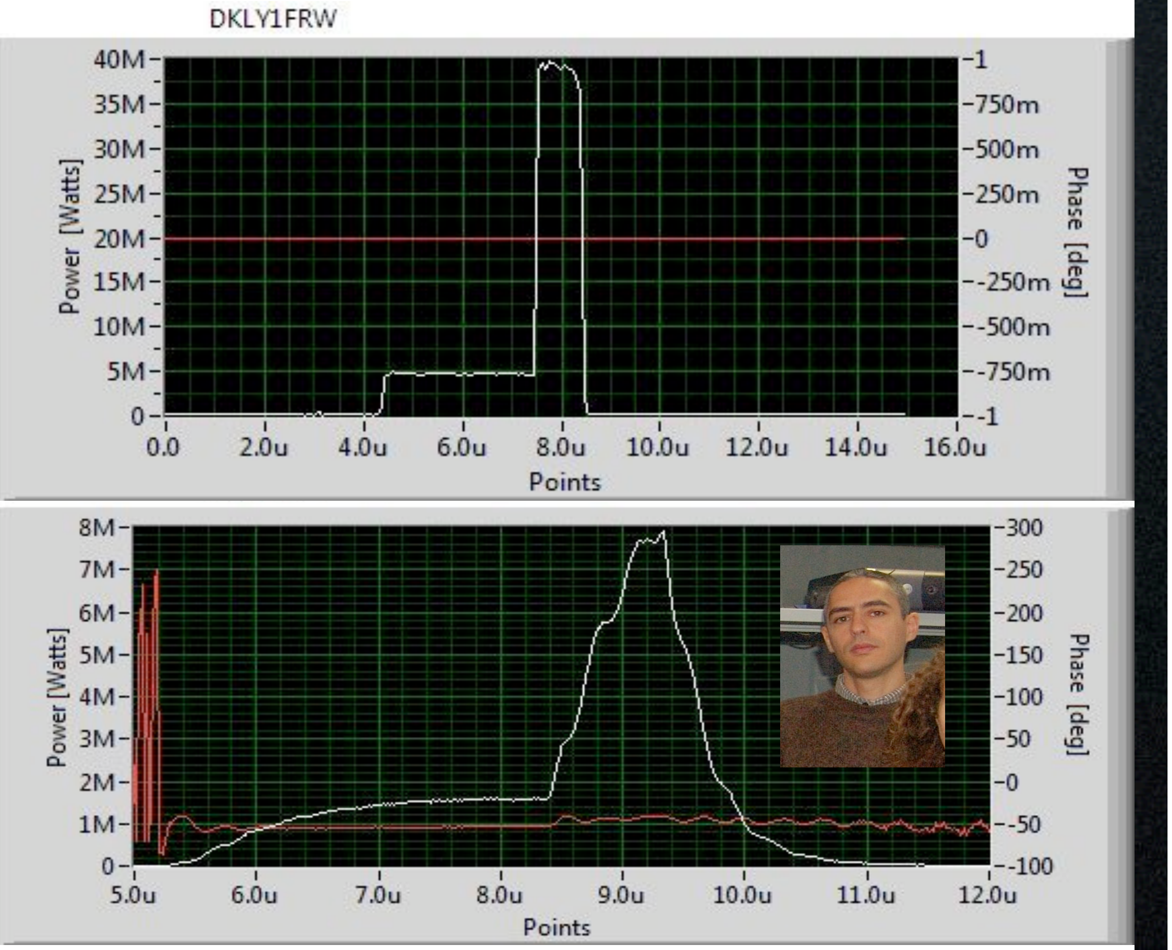
New RF pulse shaping system for RF-gun feeding

Goals:

- Increase the gun accelerating gradient
- Maintain the residual phase noise respect to the main oscillator below 100fs
- Have a breakdown rate as low as possible

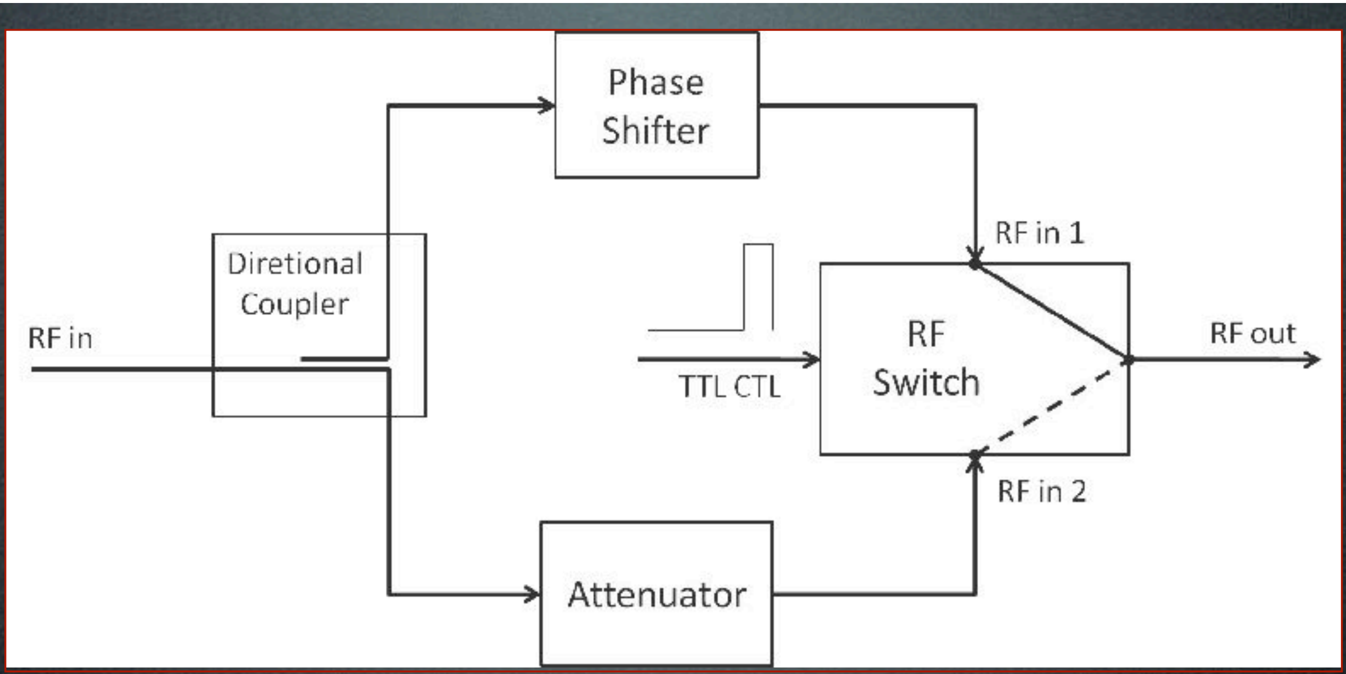
Issues and solutions:

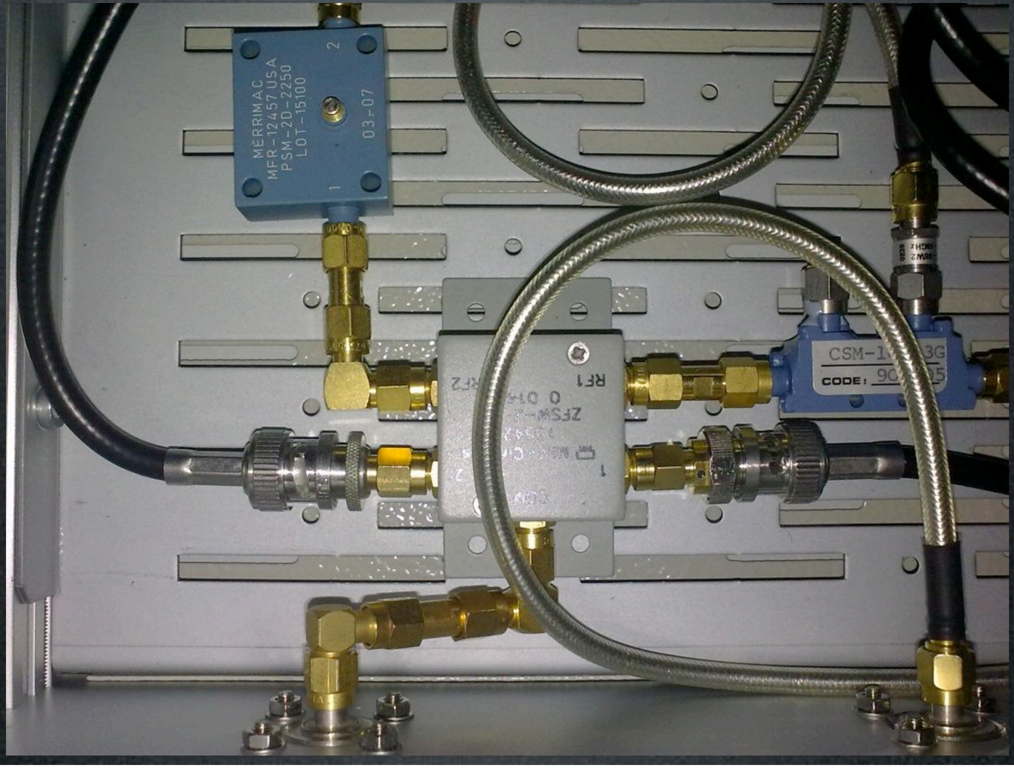
- The RF power pulse has to be shortened from 1.5us to 0.8us
- The PLL to compress the phase noise introduced by klystron needs 1us to set up correctly
- The pulse forming network of the LLRF system has been modified to fit this request
- The RF pulse has been modulated as described in the figure:
  - in the first 3us the RF level is kept as low as possible to make the PLL working
  - The RF is brought to the maximum level in the last us



11 MW - 125 MV/m - 5.8 MeV

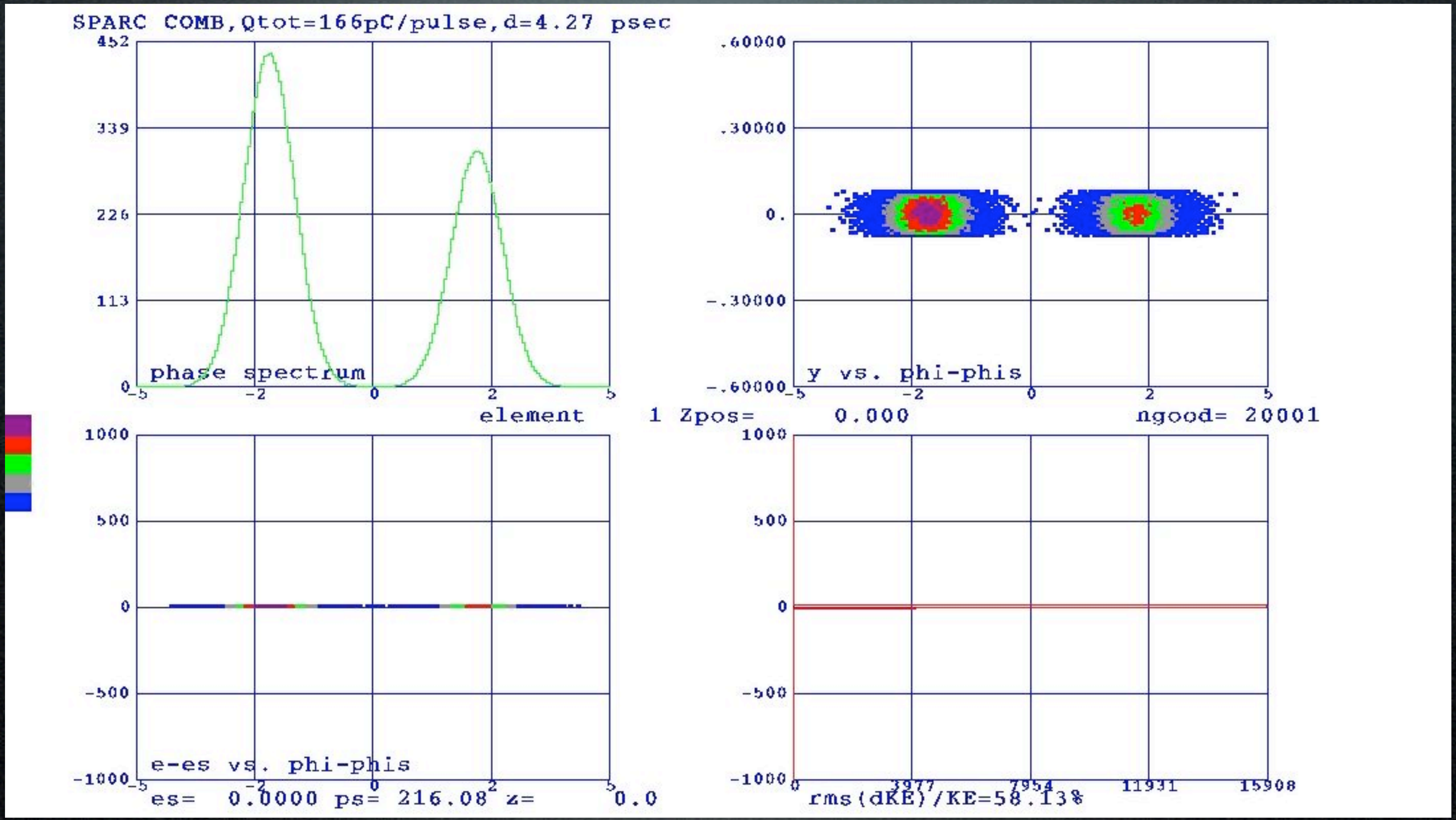
m. bellaveglia & a. gallo


Phase Shifter
RF in 1
Diretional Coupler
RF in
TTL CTL
RF Switch
RF out
RF in 2
Attenuator


MERRIMAC
MFR-12457 USA
PSM-2D-2250
LOT-15100
03-07
1
2
RF1
RF2
CODE:

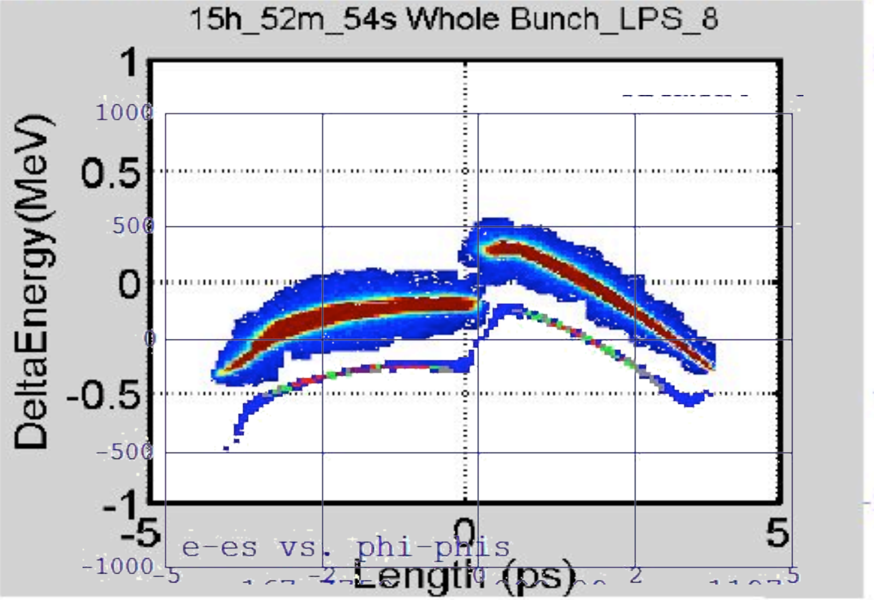
- Time jitter relative to the main RF clock (PLLs ON)
  - Linac RF devices phase noise (standard phase detection): 40÷100 $\mathrm{fs_{RMS}}$
  - Photo-cathode LAM measured time jitter (resonant Laser Arrival Monitor): <250$\mathrm{fs_{RMS}}$
  - e-bunch time jitter
    - BAM (resonant Bunch Arrival Monitor): <250$\mathrm{fs_{RMS}}$
    - RF deflector centroid jitter (image analysis): <150$\mathrm{fs_{RMS}}$
- Laser amplitude stability (from new timing)
  - Laser amplification timing locked to machine trigger
  - Amplitude jitter always <5%

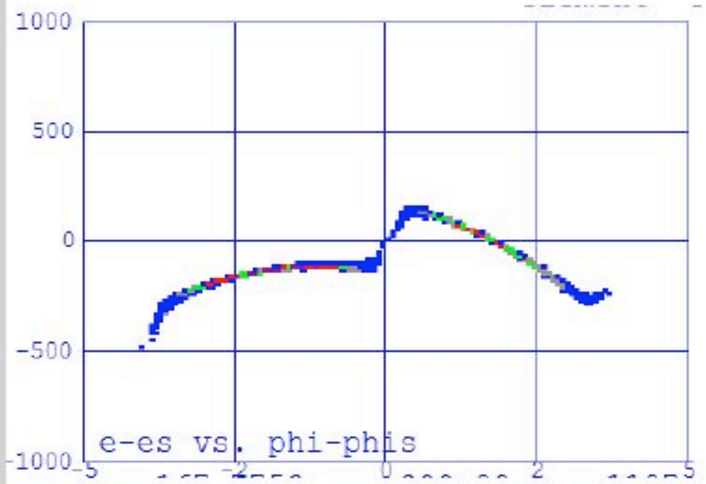
On Crest



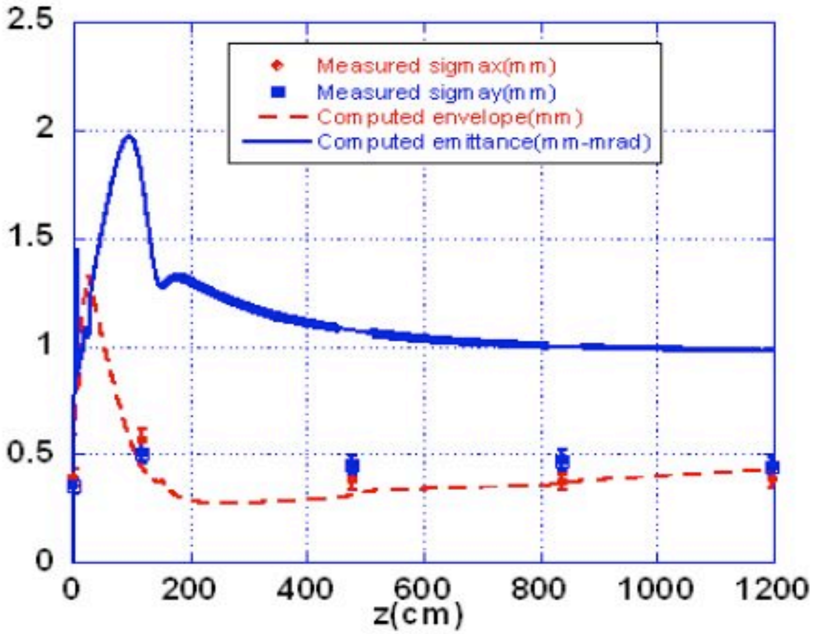
c. ronsivalle & a. mostacci

13 MAY: ON CREST BEAM. MEASUREMENTS-SIMULATIONS COMPARISON





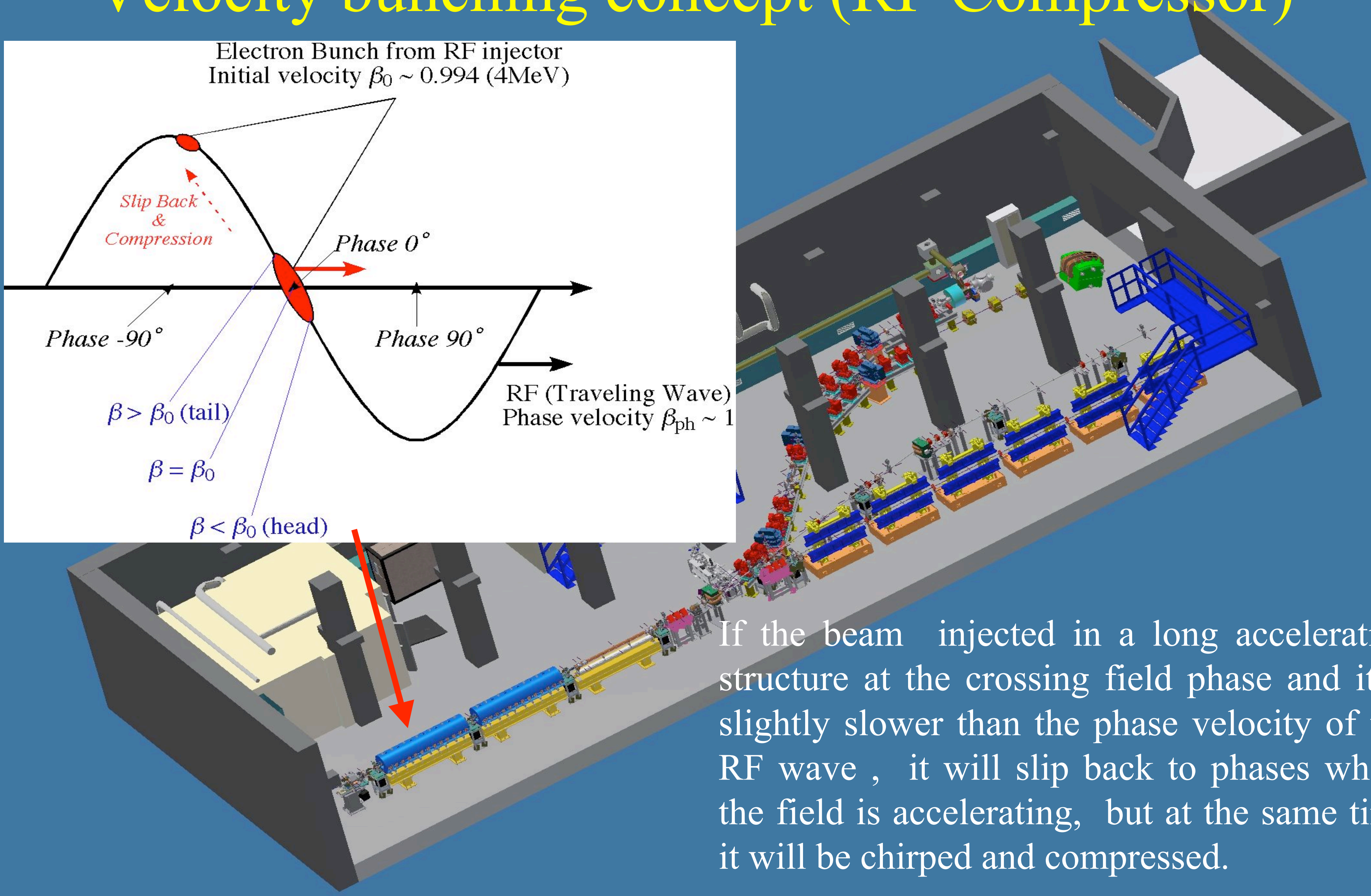
Q=166 pC



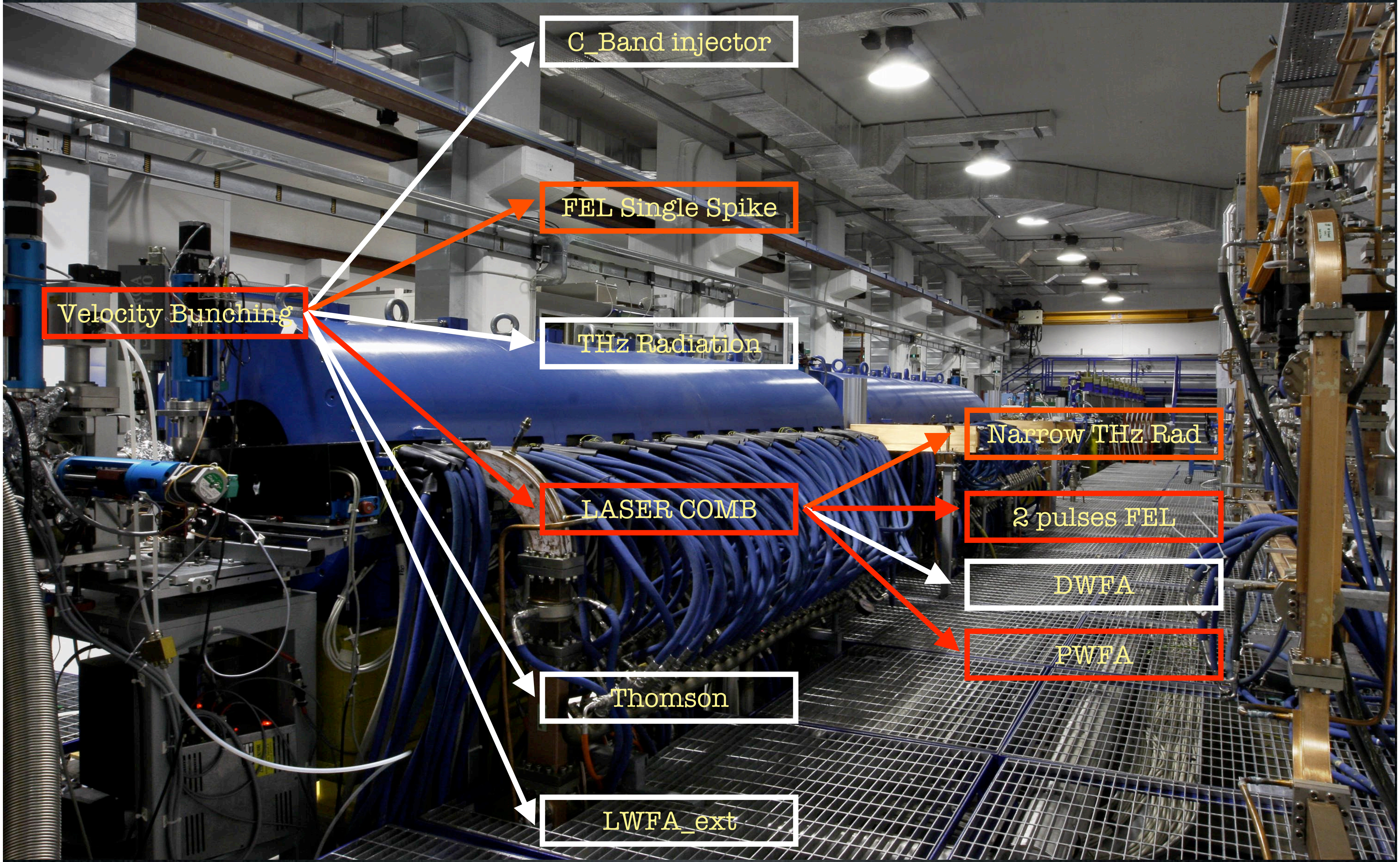
	MEASUREMENTS	SIMULATIONS
Total length (ps)	2.06	1.96
Time Separation (ps)	3.7	3.63
Energy Separation(MeV)	0.11	0.12
Emittance(100%)	√(εxεy)=0.97	0.98 (total) 0.99 (bunch 1) 0.665 (bunch 2)
Emittance(90%)	√(εxεy)=0.52	

Experiments with Velocity Bunching

Velocity bunching concept (RF Compressor)



If the beam injected in a long accelerating structure at the crossing field phase and it is slightly slower than the phase velocity of the RF wave , it will slip back to phases where the field is accelerating, but at the same time it will be chirped and compressed.



Velocity Bunching

C_Band injector

FEL Single Spike

THz Radiation

LASER COMB

Thomson

LWFA_ext

Narrow THz Rad

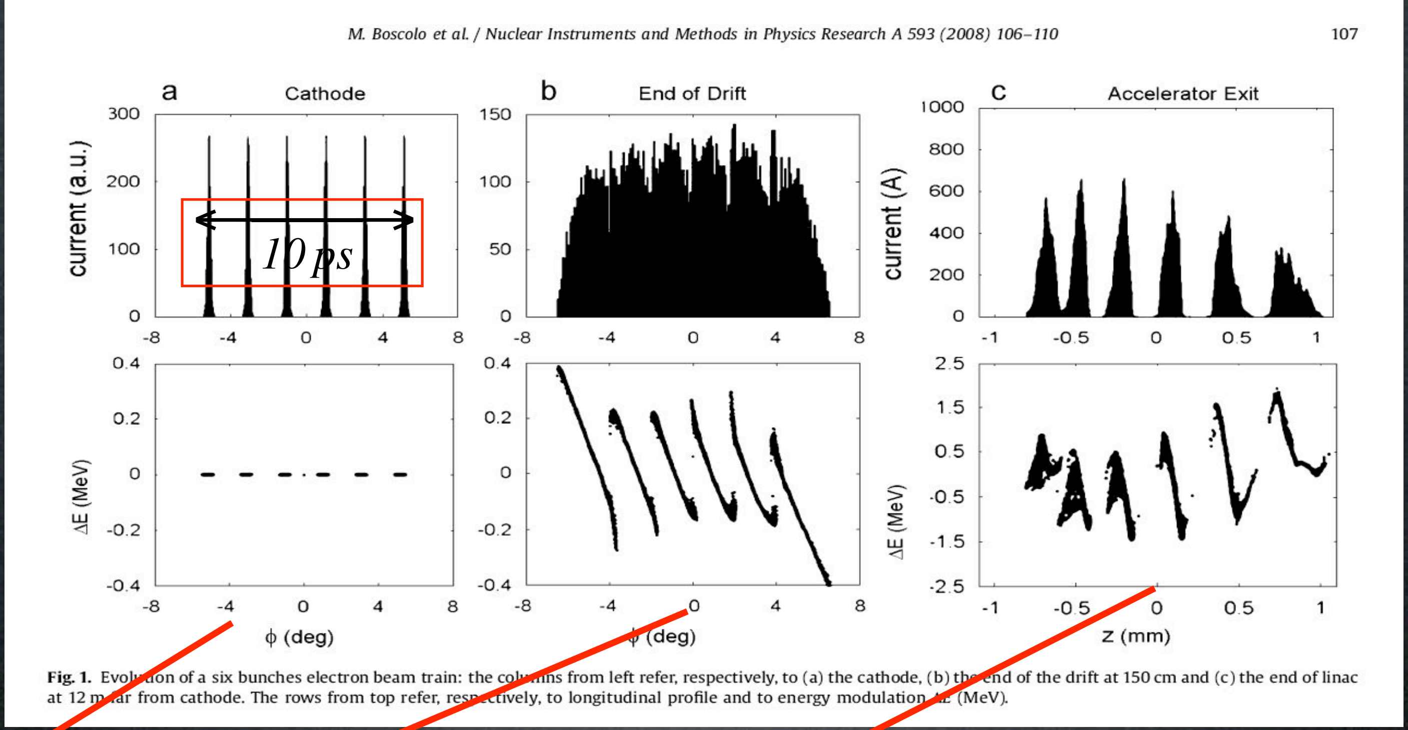
2 pulses FEL

DWFA

PWFA

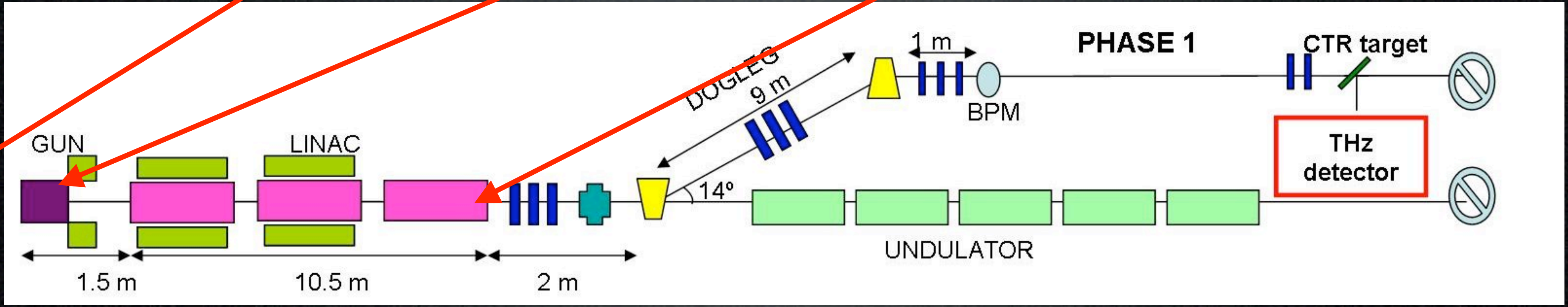
Laser Comb technique

Laser Comb: beam echo generation of a train bunches



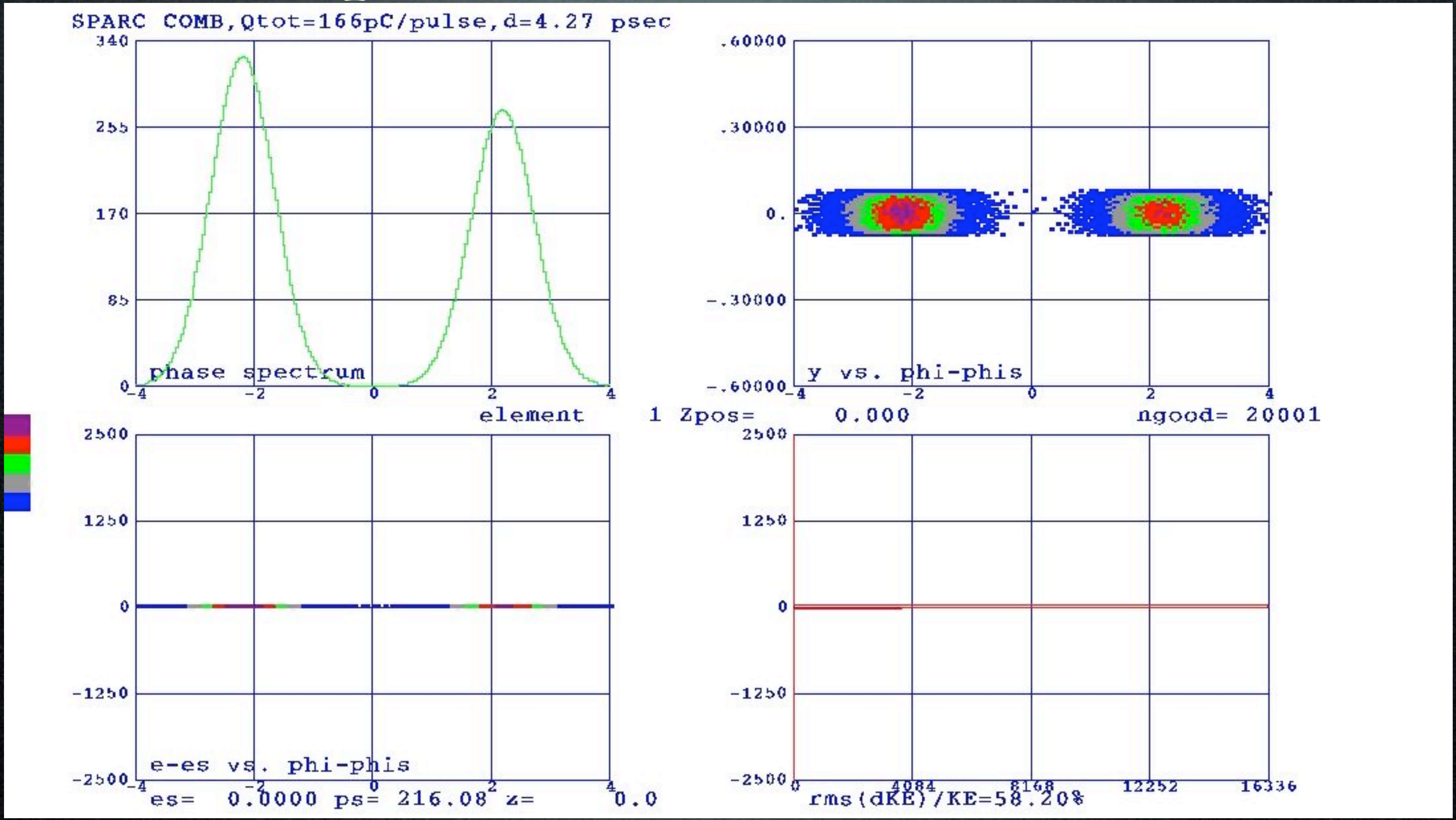
M. Boscolo et al. / Nuclear Instruments and Methods in Physics Research A 593 (2008) 106–110 107

Fig. 1. Evolution of a six bunches electron beam train: the columns from left refer, respectively, to (a) the cathode, (b) the end of the drift at 150 cm and (c) the end of linac at 12 m far from cathode. The rows from top refer, respectively, to longitudinal profile and to energy modulation ΔE (MeV).

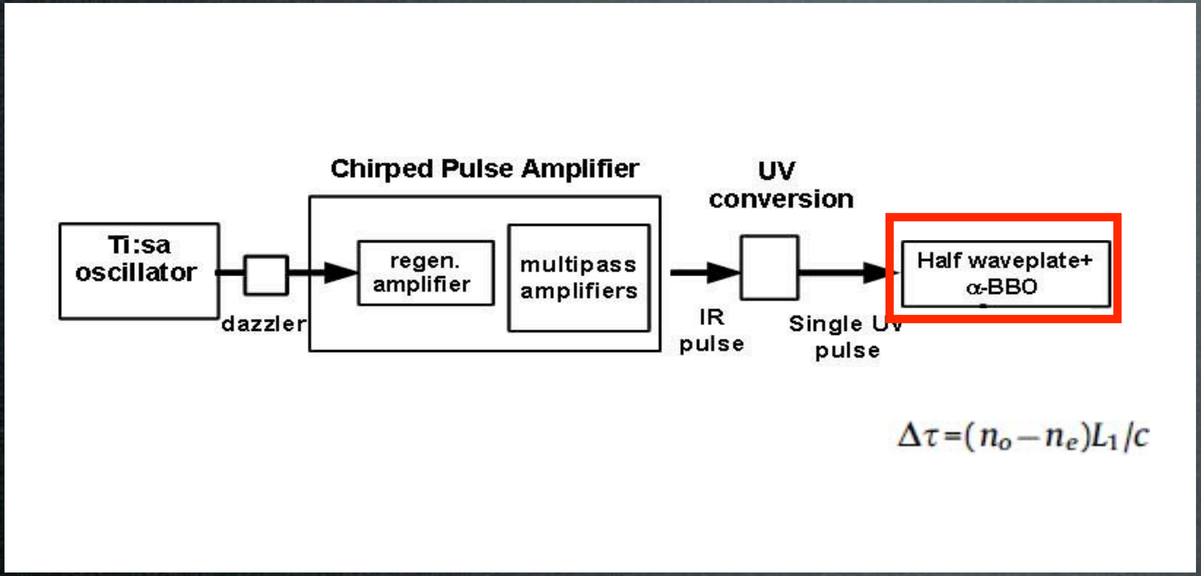


- P.O.Shea et al., Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704.
- M. Ferrario. M. Boscolo et al., Int. J. of Mod. Phys. B, 2006 (Taipei 05 Workshop)

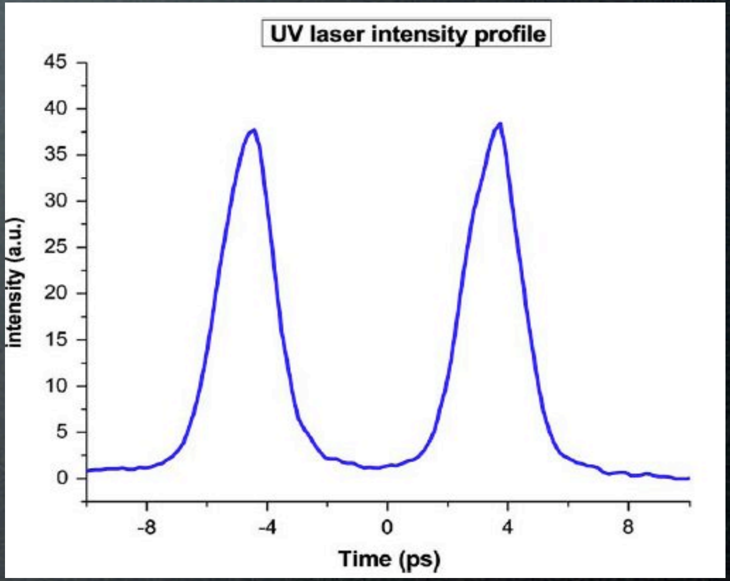
Overcompression



2 laser pulses at the cathode by birefringent cristal



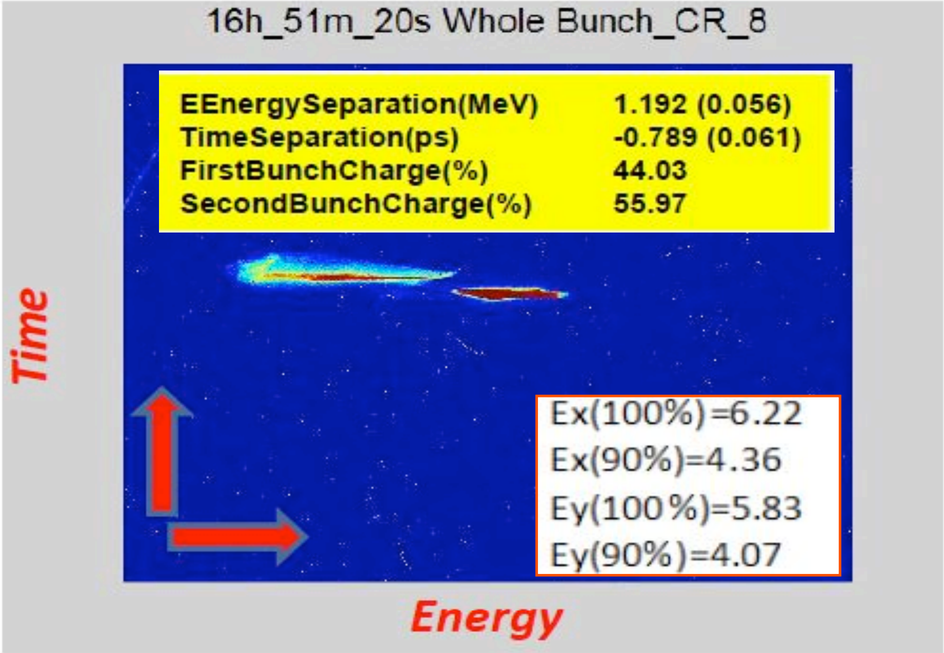
$$\Delta\tau = (n_o - n_e) L_1 / c$$



The technique used for this purpose relies on a birefringent crystal, where the input pulse is decomposed in two orthogonally polarized pulses with a time separation proportional to the crystal length.

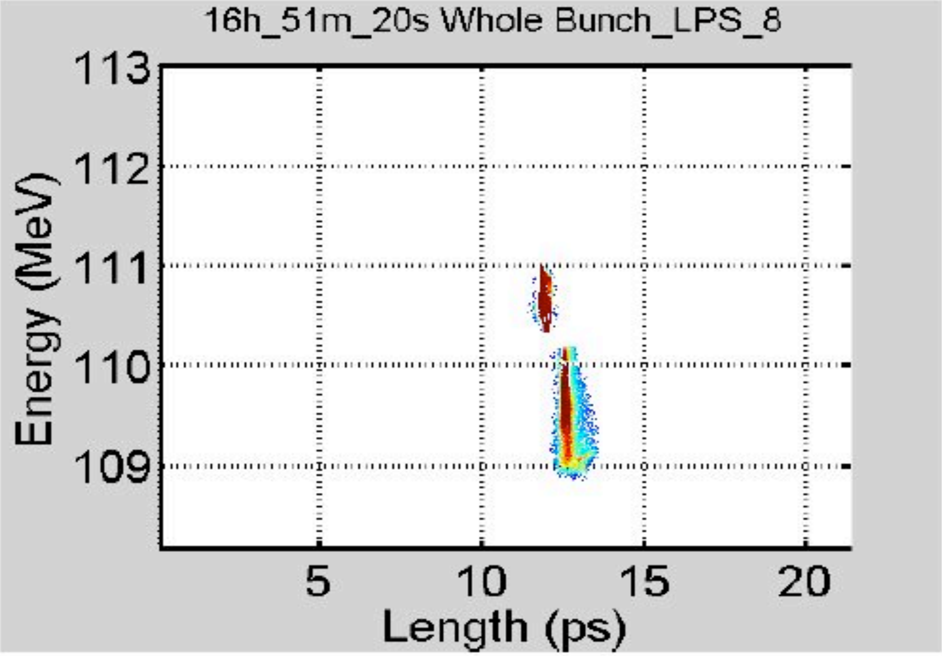
The crystal thickness is 10.353 mm

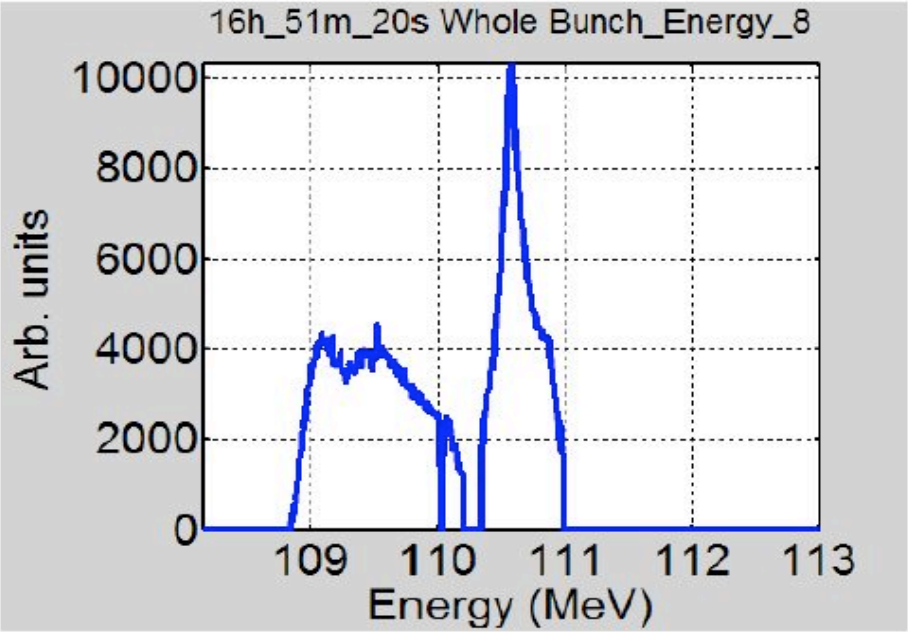
18 MAY: OVERCOMPRESSION-Q=180pC

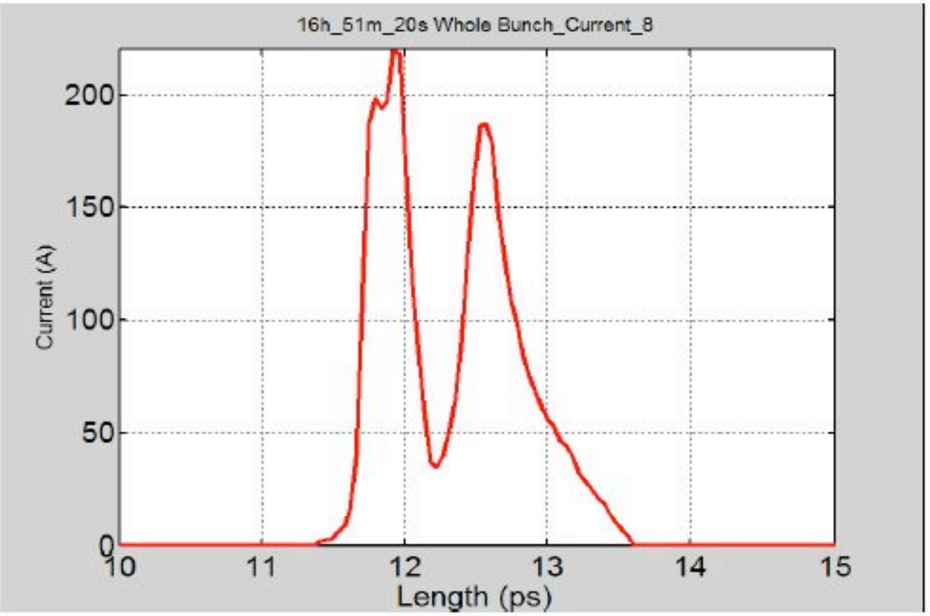

16h_51m_20s Whole Bunch_CR_8

EEnergySeparation(MeV)	1.192 (0.056)
TimeSeparation(ps)	-0.789 (0.061)
FirstBunchCharge(%)	44.03
SecondBunchCharge(%)	55.97

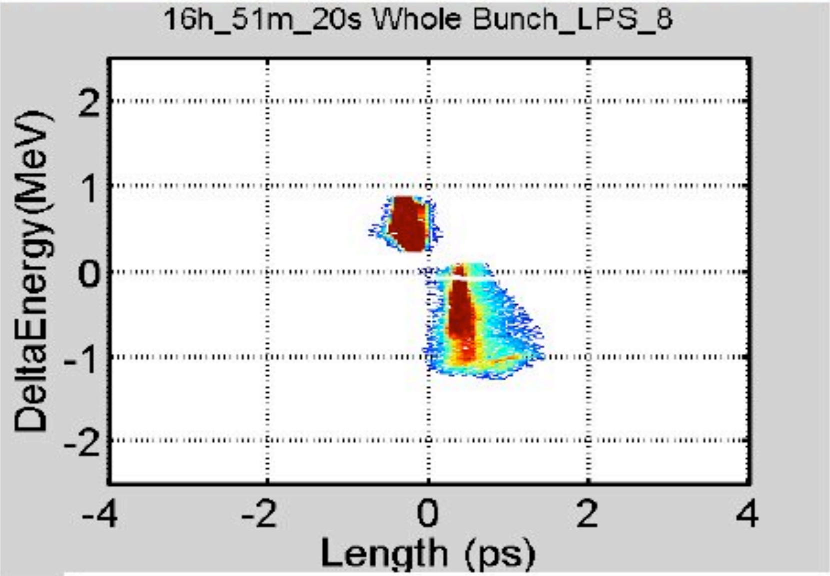
Ex(100%)=6.22
Ex(90%)=4.36
Ey(100%)=5.83
Ey(90%)=4.07

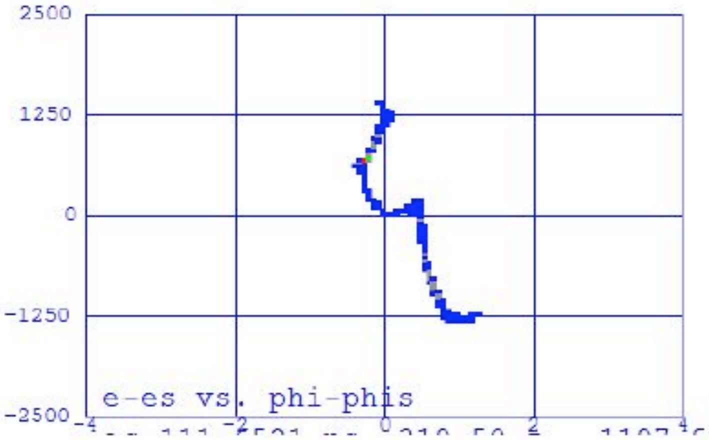

16h_51m_20s Whole Bunch_LPS_8


16h_51m_20s Whole Bunch_Energy_8


16h_51m_20s Whole Bunch_Current_8

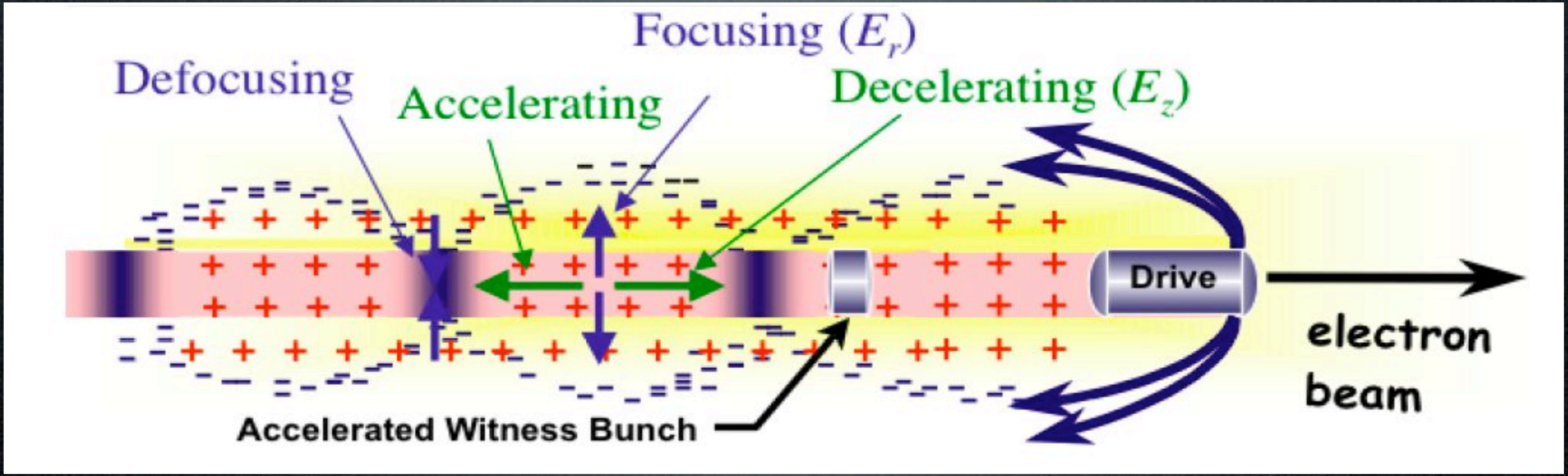
18 MAY: OVERCOMPRESSION-Q=180pC.MEASUREMENTS-SIMULATIONS COMPARISON





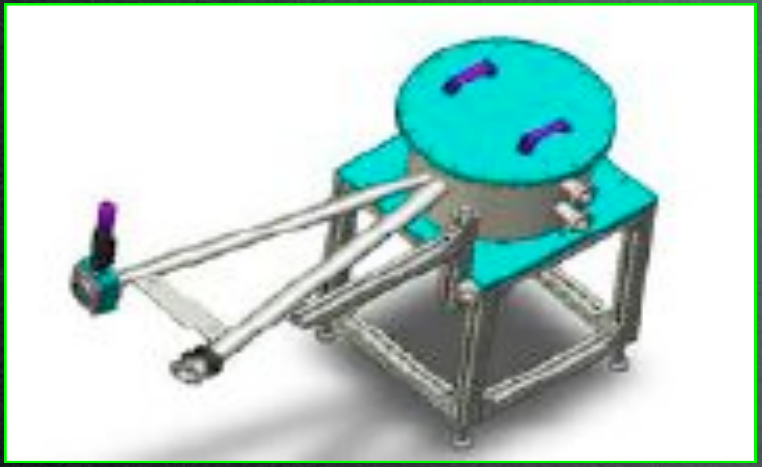
	MEASUREMENTS	SIMULATIONS
Total length (ps)	0.3998 (σ/√10=0.0098)	0.3995
Time Separation (ps)	0.789 (σ/√10=0.061)	0.7743
Energy Separation(MeV)	1.192 (σ/√10=0.056)	1.4
Bunch 1 length (ps)	<0.21 (res.)	0.0963
Bunch2 length (ps)	0.172 (σ/√10=0.022)	0.1108

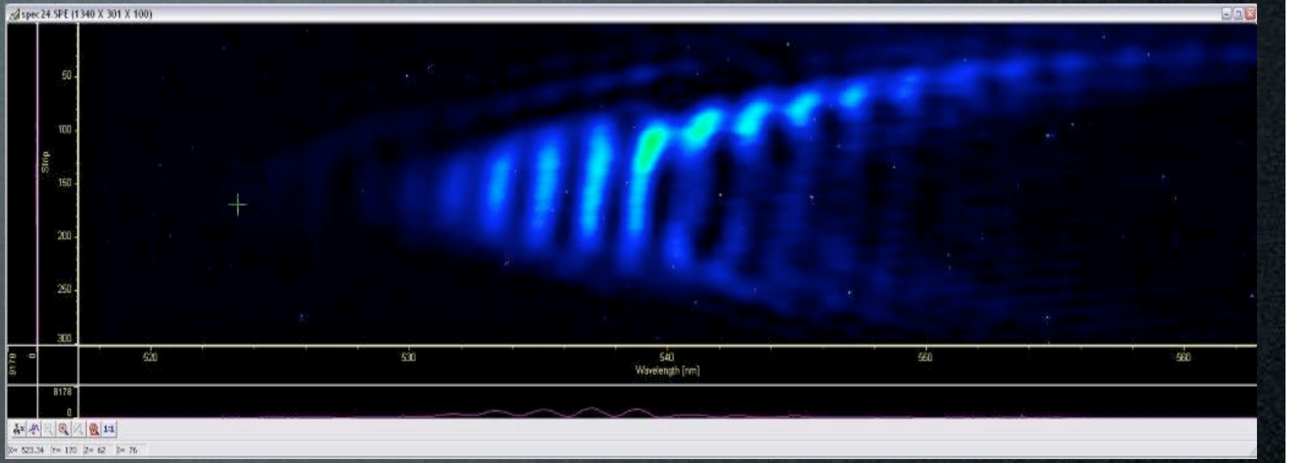
Using a high charge driving bunch to accelerate a low charge witness bunch

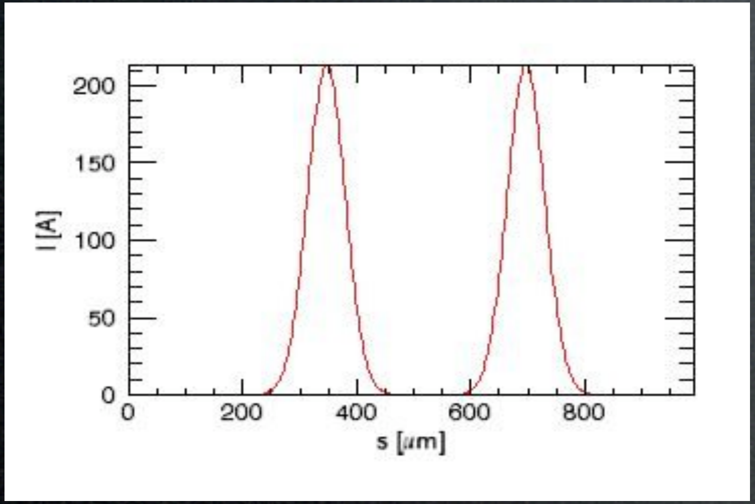


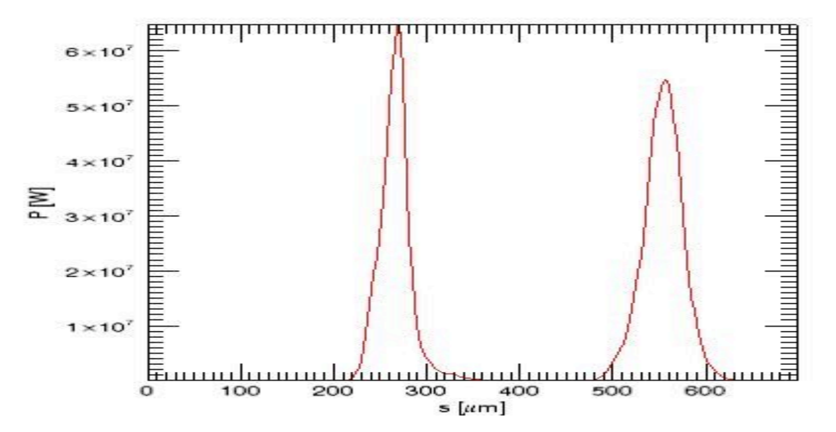
Double FEL pulse

Two Beams Spectrum



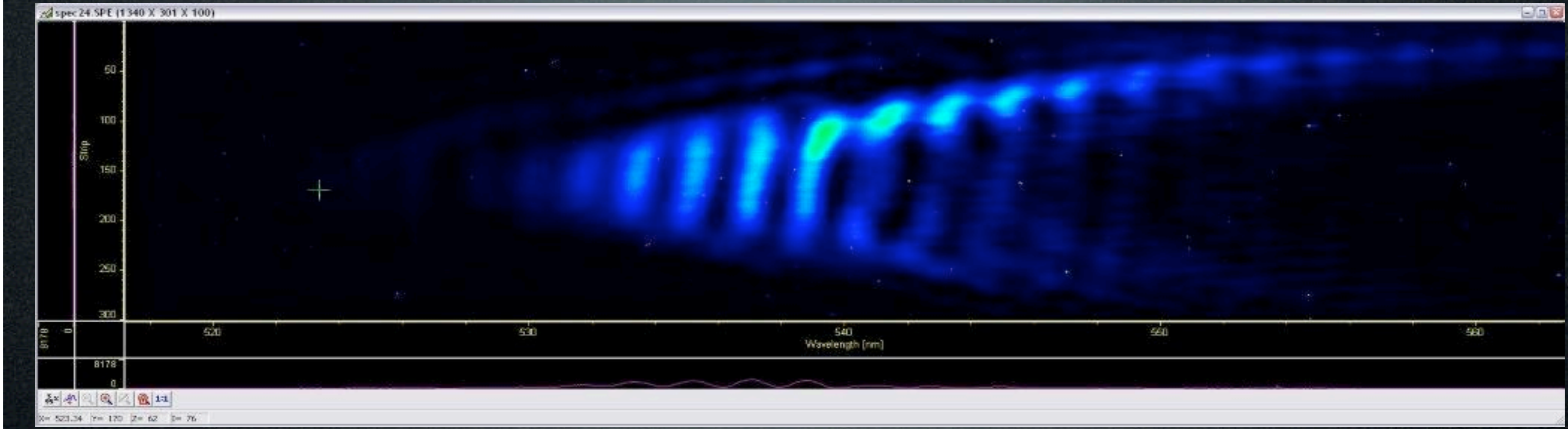




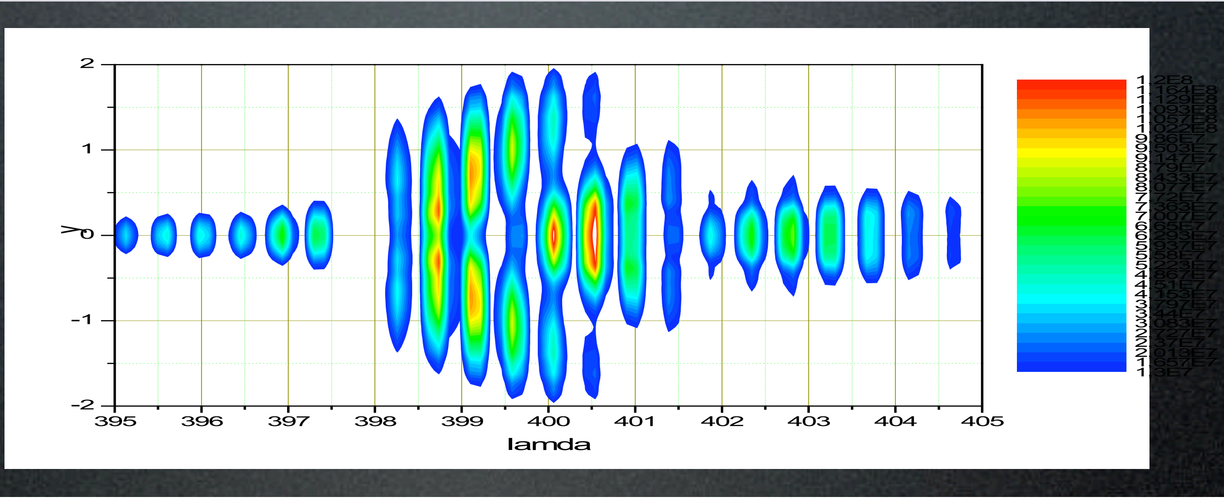


$$I = I_1 e^{-\frac{(x-x_1)^2}{\sqrt{2\sigma_{1,I}^2}}} + I_2 e^{-\frac{(x-x_2)^2}{\sqrt{2\sigma_{2,I}^2}}}$$

$$P = P_1 e^{-\frac{(x-x_1)^2}{\sqrt{2\sigma_1^2}}+ik_1 x} + P_2 e^{-\frac{(x-x_2)^2}{\sqrt{2\sigma_2^2}}+ik_2 x}$$



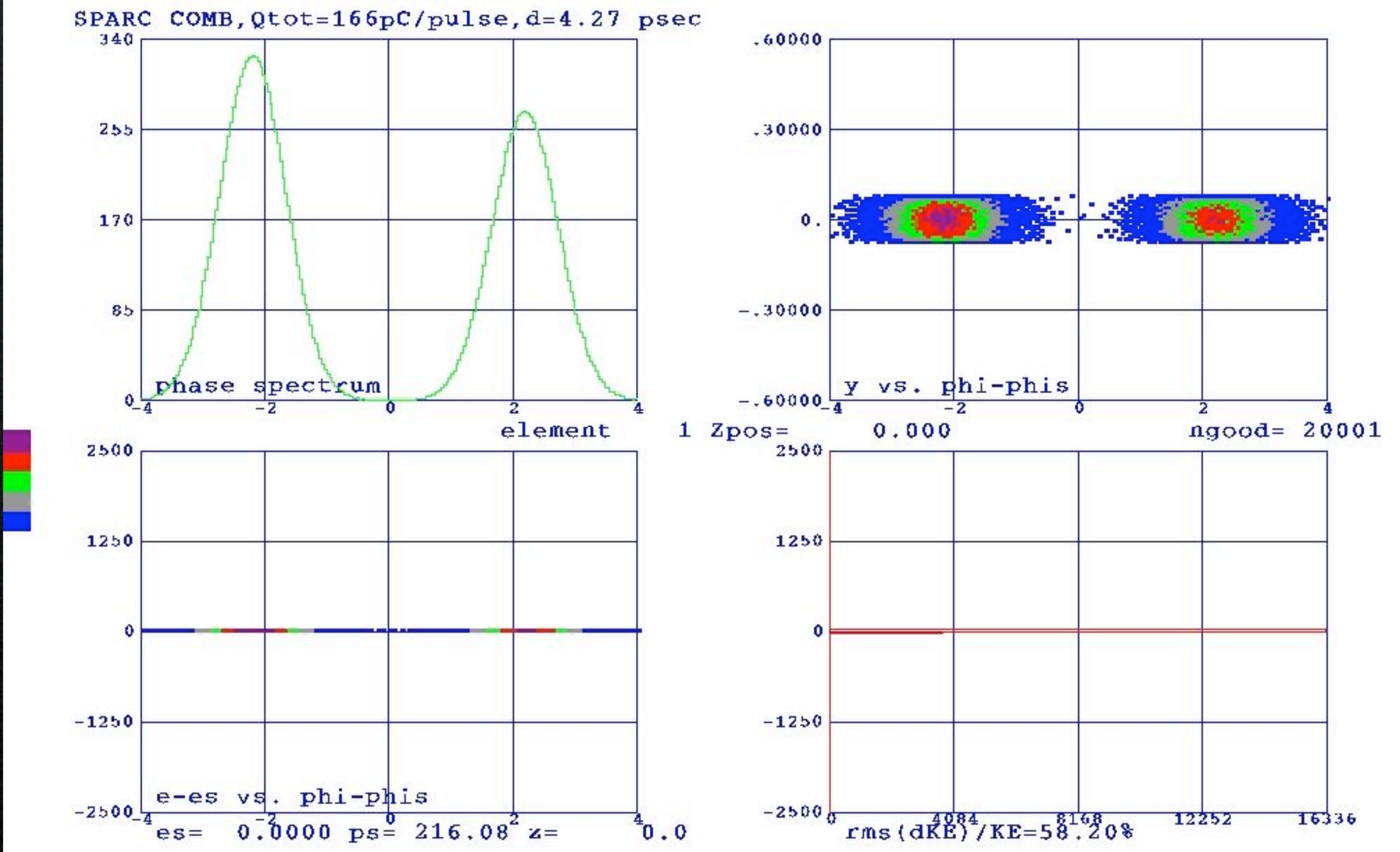
$$\Delta x = \frac{\lambda^2}{\Delta\lambda}$$



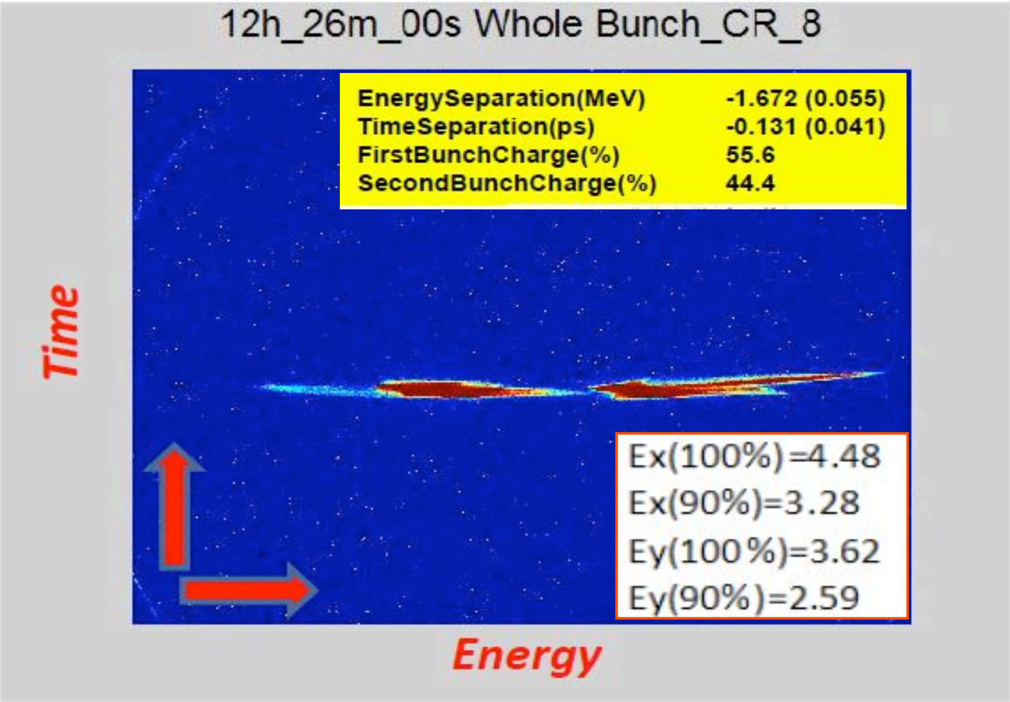
$$|T|^2 = |T_1|^2 e^{-(k-k_1)^2 \frac{\sigma_1^2}{\sqrt{2}}} + |T_2|^2 e^{-(k-k_2)^2 \frac{\sigma_2^2}{\sqrt{2}}}$$

$$+ 2T_1T_2 e^{-(k-k_1)^2 \frac{(\sigma_1^2+\sigma_2^2)}{2\sqrt{2}}} \cos(k(x_1 - x_2) - k_1x_1 + k_2x_2)$$

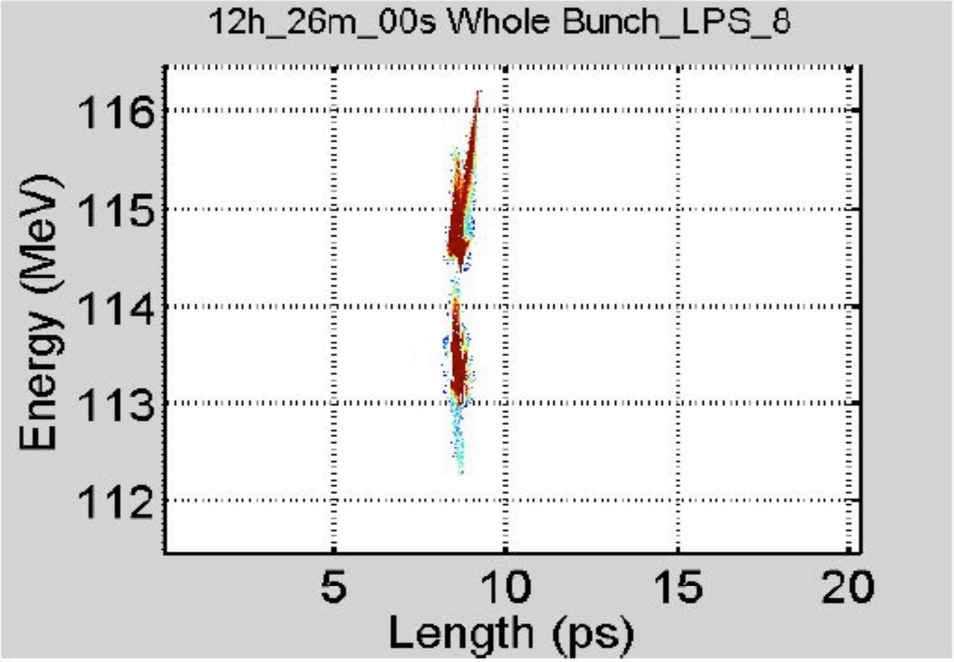
Time overlap



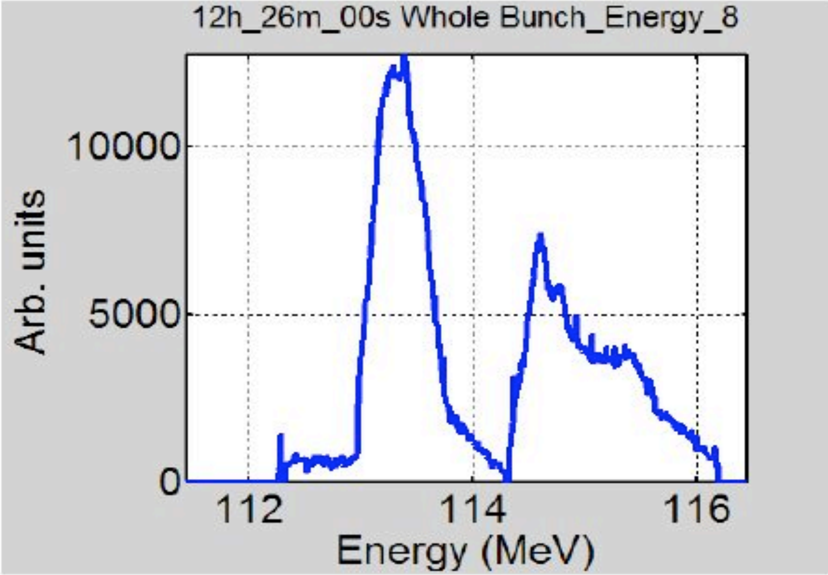
18 MAY: MAX. COMPRESSION-Q=180pC



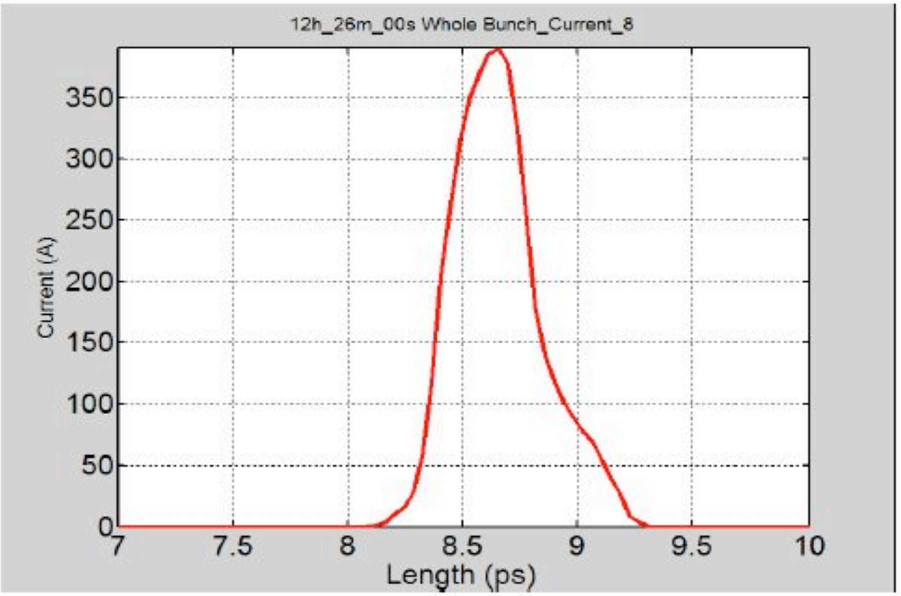
12h_26m_00s Whole Bunch_CR_8



12h_26m_00s Whole Bunch_LPS_8

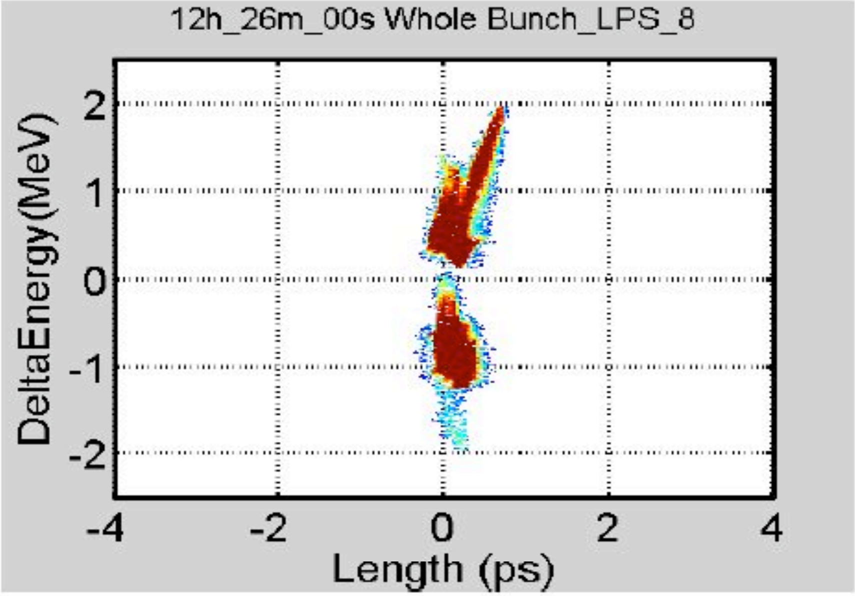


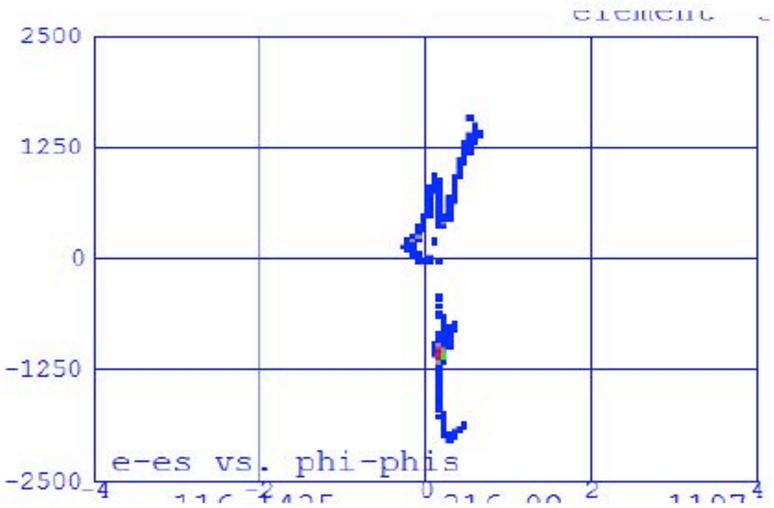
12h_26m_00s Whole Bunch_Energy_8



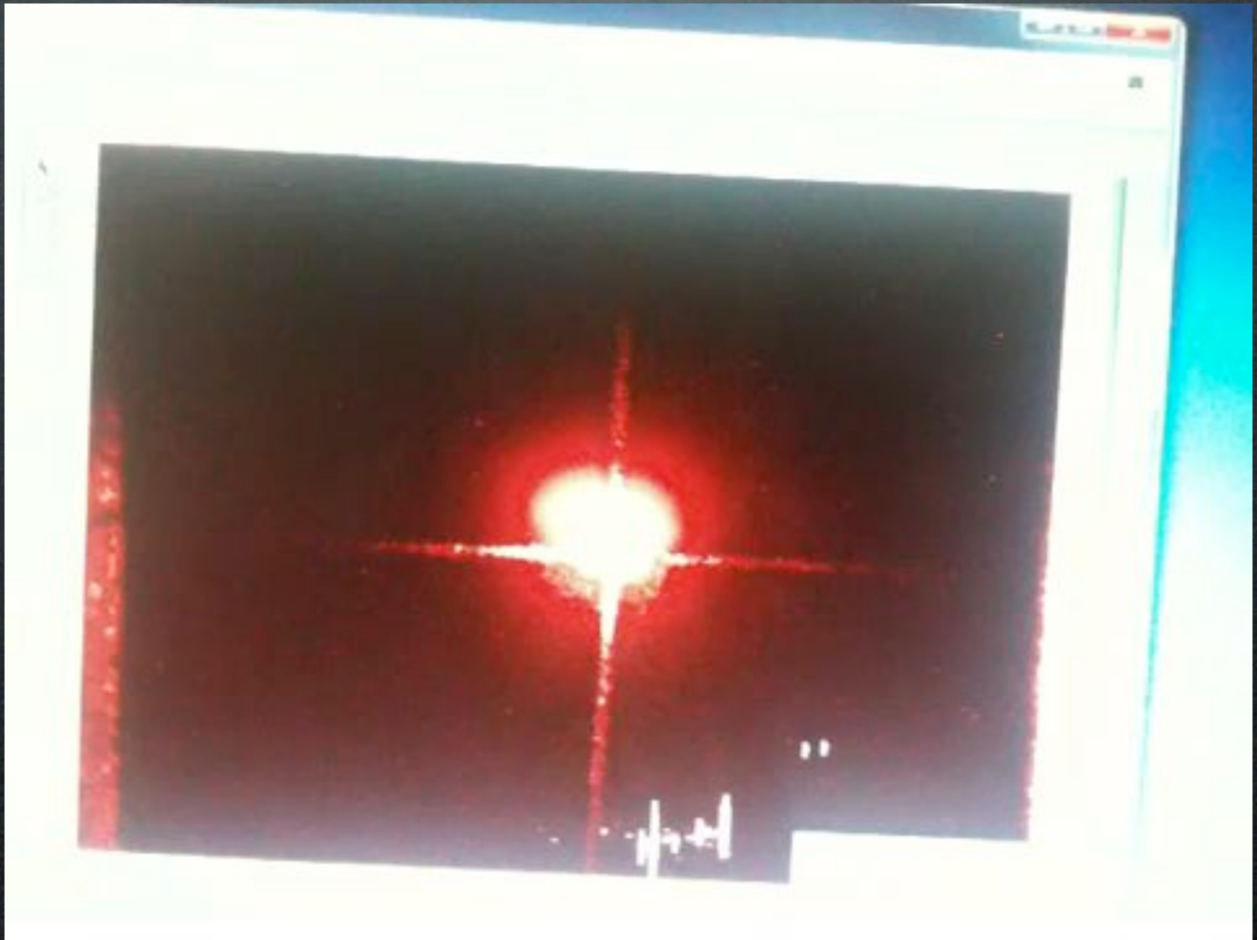
12h_26m_00s Whole Bunch_Current_8

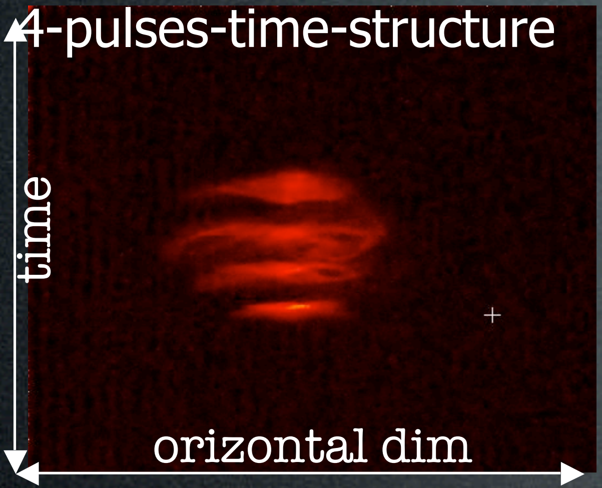
18 MAY:S1phase=-90.3° MAX. COMPRESSION. MEASUREMENTS-SIMULATIONS COMPARISON

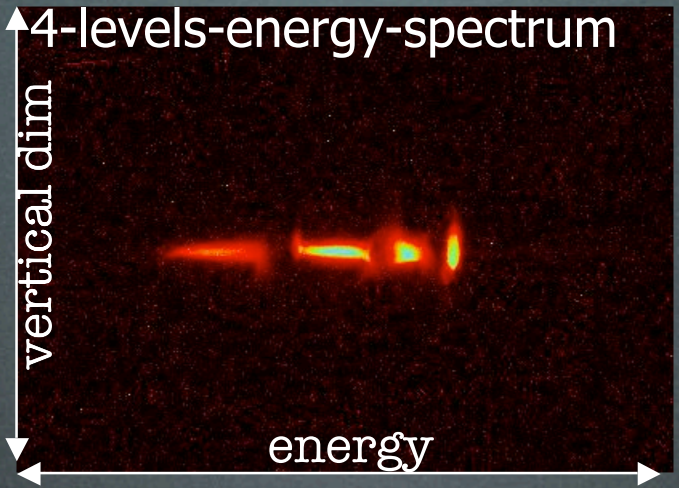


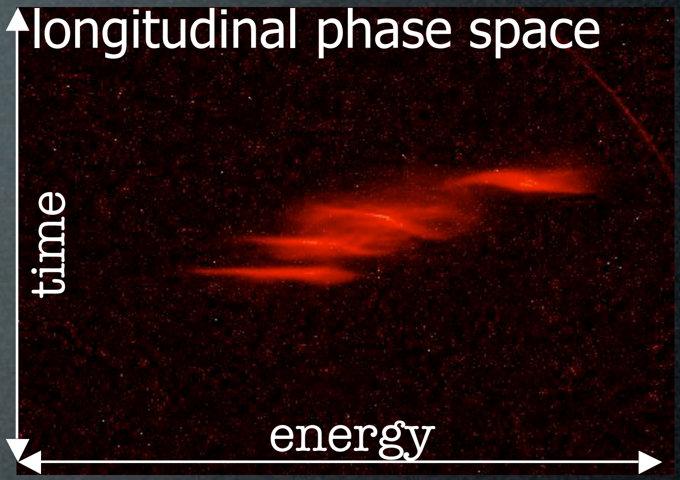


	MEASUREMENTS	SIMULATIONS
Total length (ps)	0.138 (σ/√10=0.013)	0.143
Time Separation (ps)	0.131 (σ/√10=0.041)	0.05
Energy Separation(MeV)	1.672 (σ/√10=0.055)	1.67
Bunch 1 length (ps)	<0.148 (res.)	0.045
Bunch2 length (ps)	0.182 (σ/√10=0.0091)	0.206



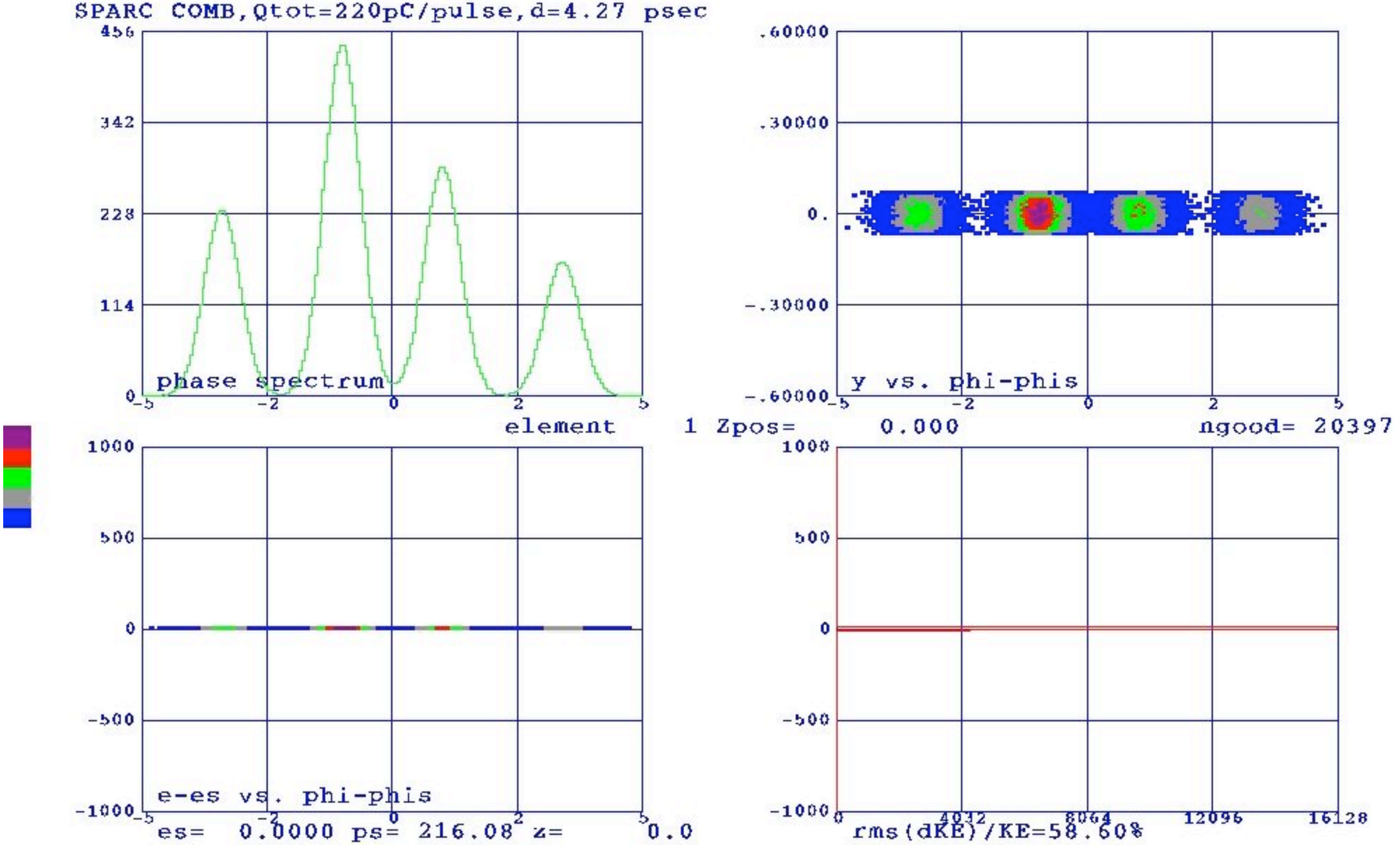

4-pulses-time-structure

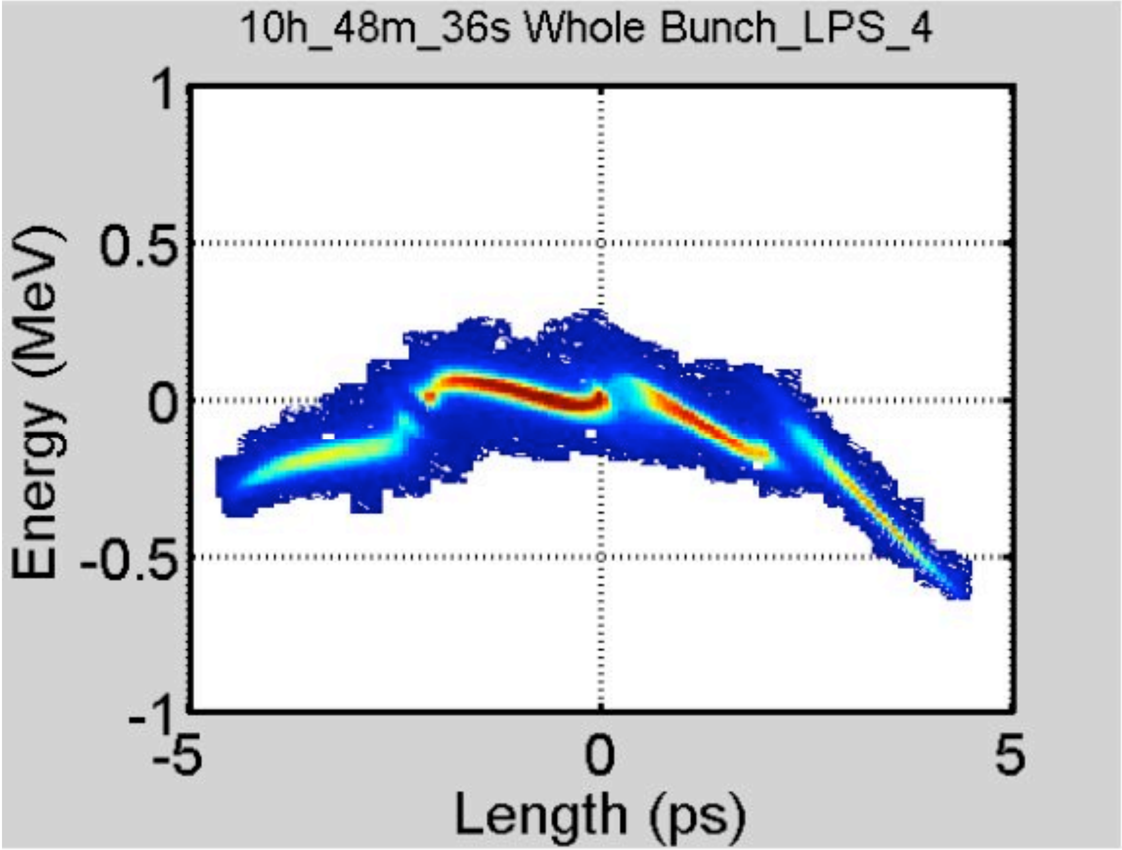

4-levels-energy-spectrum

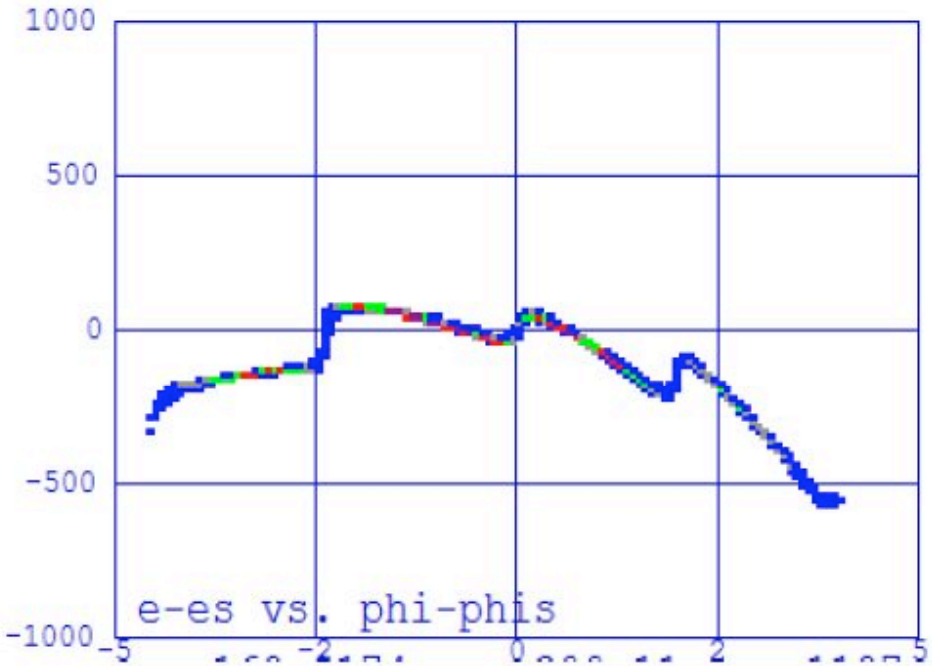

longitudinal phase space

4 pulses

On Crest


SPARC COMB,Qtot=220pC/pulse,d=4.27 psec
456
342
228
114
0
phase spectrum
-5
-2
0
2
5
.60000
.30000
0.
-.30000
-.60000
y vs. phi-phis
element 1 Zpos= 0.000 ngood= 20397
1000
500
0
-500
-1000
e-es vs. phi-phis
es= 0.0000 ps= 216.08 z= 0.0
4032
8064
12096
16128
rms(dKE)/KE=58.60%


10h_48m_36s Whole Bunch_LPS_4
Energy (MeV)
1
0.5
0
-0.5
-1
-5
0
5
Length (ps)

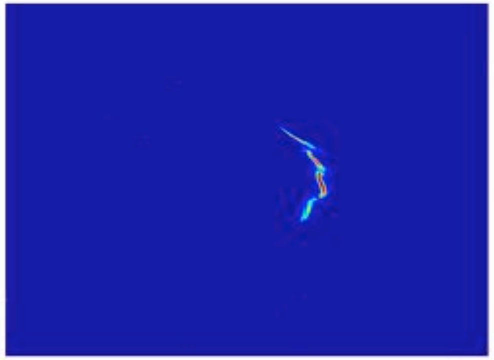

1000
500
0
-500
-1000
e-es vs. phi-phis
-5
-2
0
2
5

2011/06/03 - 200 pC - on Cest

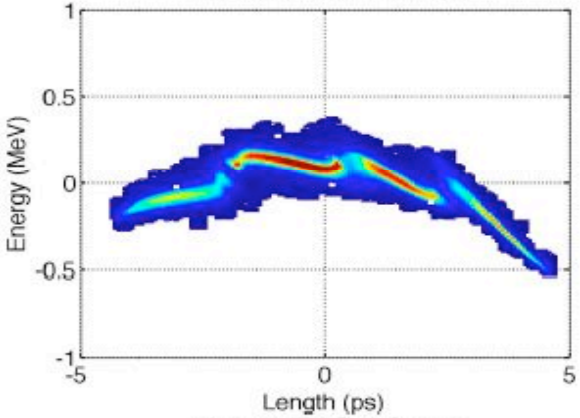
Total projected emittance: 2.05 μm (1.08 μm)

	Energy (MeV)	En. Spread(%)	Length (ps)	Charge(%)
I	168.099(0.045)	0.048(0.001)	0.602(0.004)	21.03(0.15)
II	168.277(0.042)	0.040(0.001)	0.722(0.007)	39.84(0.64)
III	168.192(0.040)	0.049(0.001)	0.564(0.008)	25.93(0.47)
IV	167.966(0.042)	0.084(0.002)	0.550(0.007)	15.18(0.28)
Whole	168.172(0.041)	0.085(0.003)	2.141(0.005)	100.00(1.08)

10h_48m_36s Whole Bunch_CR_4

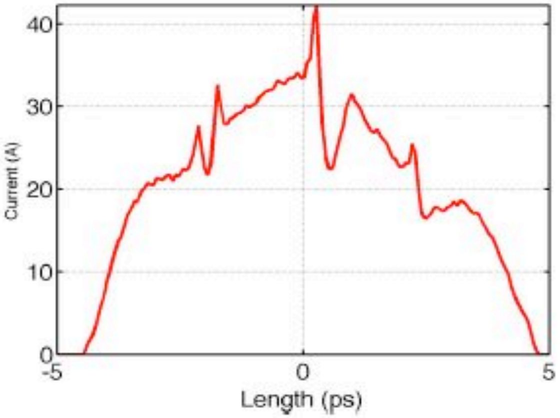


10h_48m_36s Whole Bunch_LPS_4



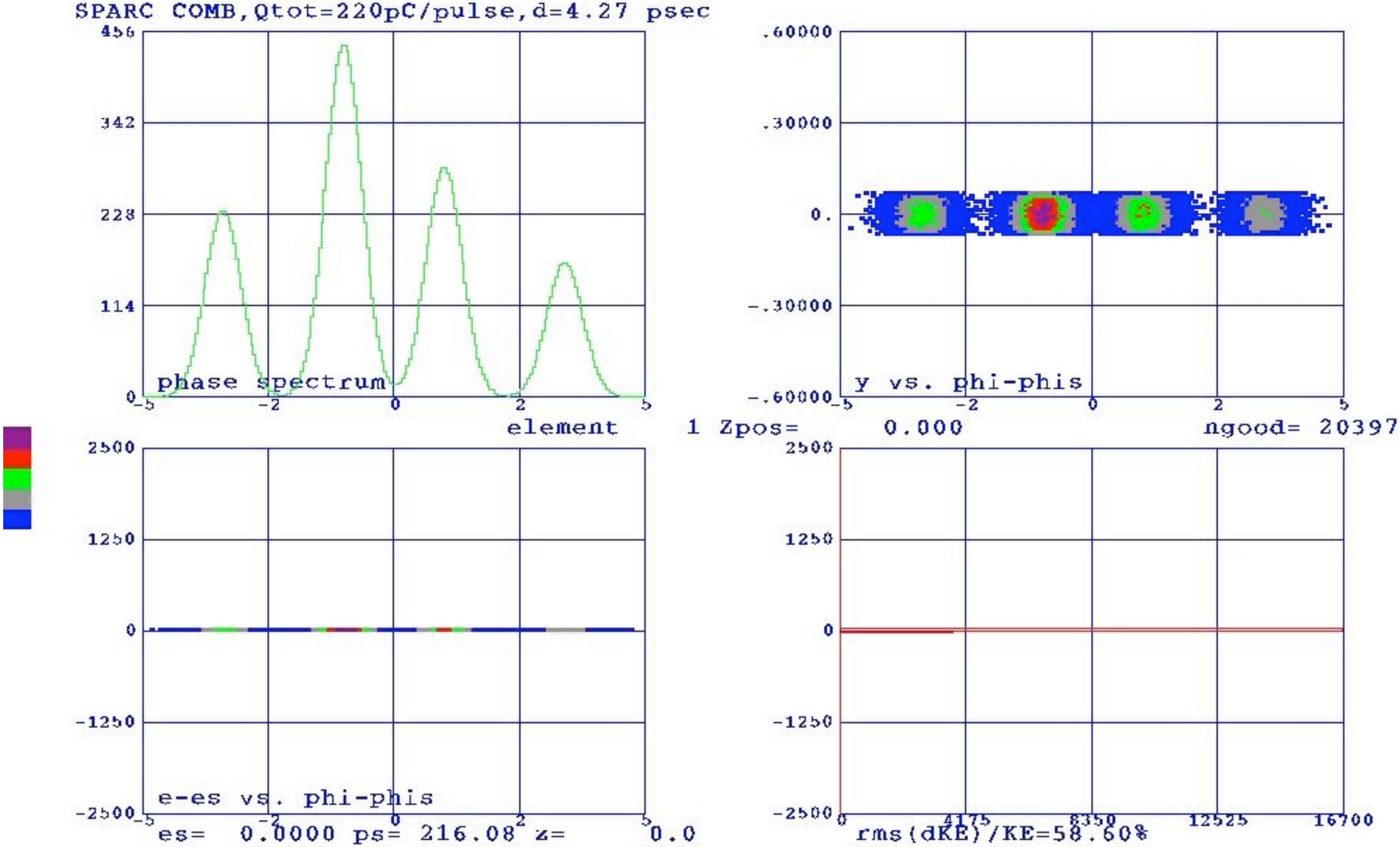
EnergySeparation I-II(MeV)	-0.1782 (0.06)
TimeSeparation I-II(ps)	-2.2188 (0.13)
EnergySeparation II-III(MeV)	0.0842 (0.06)
TimeSeparation II-III(ps)	-2.1478 (0.13)
EnergySeparation III-IV(MeV)	0.2261 (0.06)
TimeSeparation III-IV(ps)	-1.9031 (0.12)
FirstBunchCharge(%)	21.03
SecondBunchCharge(%)	39.84
ThirdBunchCharge(%)	25.93
FourthBunchCharge(%)	15.18
ConsistencyCheck(%)	101.97

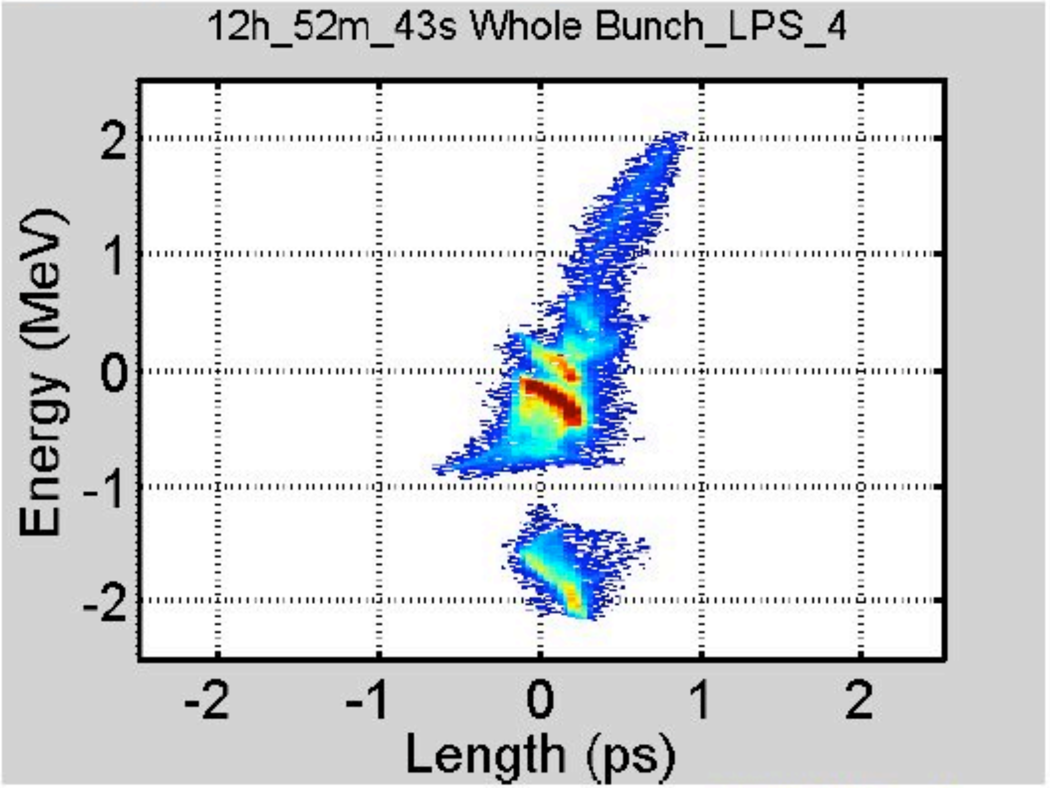
10h_48m_36s Whole Bunch_Current_4

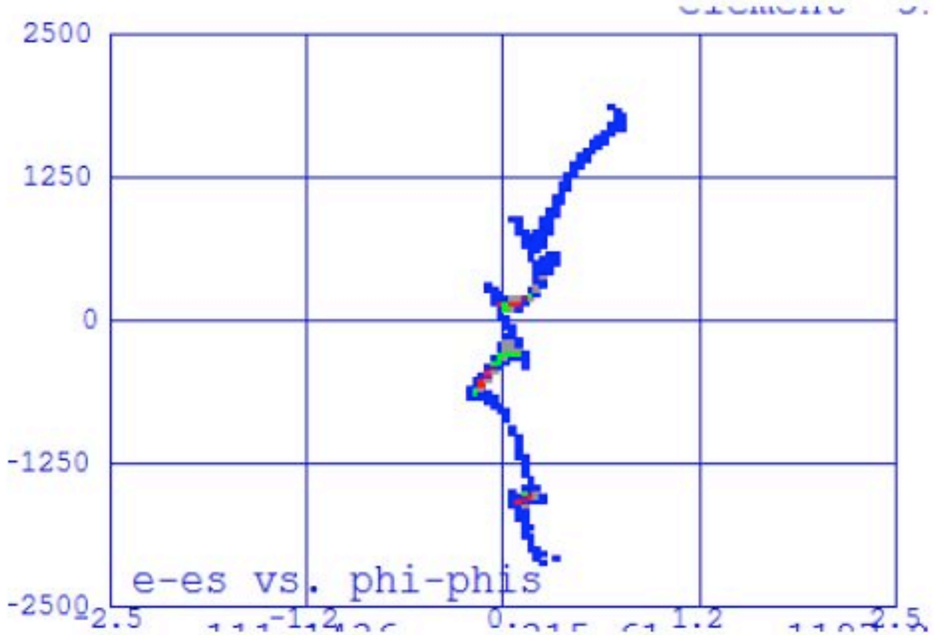


	Length (ps)
First Beam	0.5490 (0.0058)
Second Beam	0.6787 (0.0078)
Third Beam	0.5072 (0.0093)
Fourth Beam	0.4916 (0.0059)
Whole Beam	2.1263 (0.0087)

Time Overlap




12h_52m_43s Whole Bunch_LPS_4
Energy (MeV)
2
1
0
-1
-2
-2
-1
0
1
2
Length (ps)

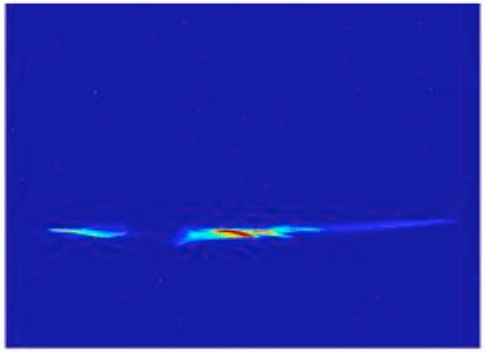

2500
1250
0
-1250
-2500
-2.5
-1.2
0
1.2
2.5
e-es vs. phi-phis

2011/06/03 - 200 pC -Time Overlap

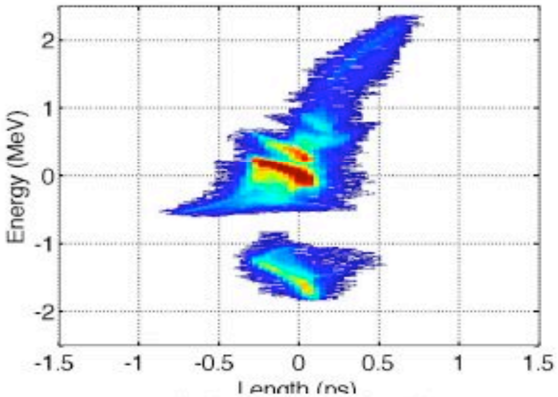
Total projected emittance: 5.72 μm (4.00 μm)

	Energy (MeV)	En. Spread(%)	Length (ps)	Charge(%)
I	108.877(0.057)	0.192(0.003)	0.155(0.001)	19.53(0.15)
II	110.164(0.055)	0.210(0.009)	0.200(0.001)	48.67(2.05)
III	110.776(0.078)	0.097(0.005)	0.168(0.004)	15.60(1.92)
IV	111.654(0.073)	0.398(0.010)	0.189(0.002)	16.25(0.55)
Whole	110.246(0.054)	0.812(0.006)	0.233(0.003)	100.00(0.57)

12h_52m_43s Whole Bunch_CR_4

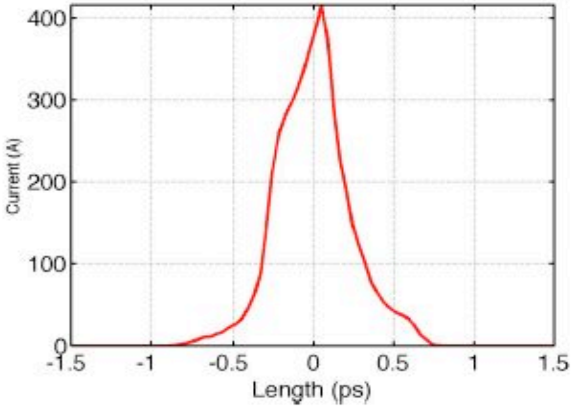


12h_52m_43s Whole Bunch_LPS_4



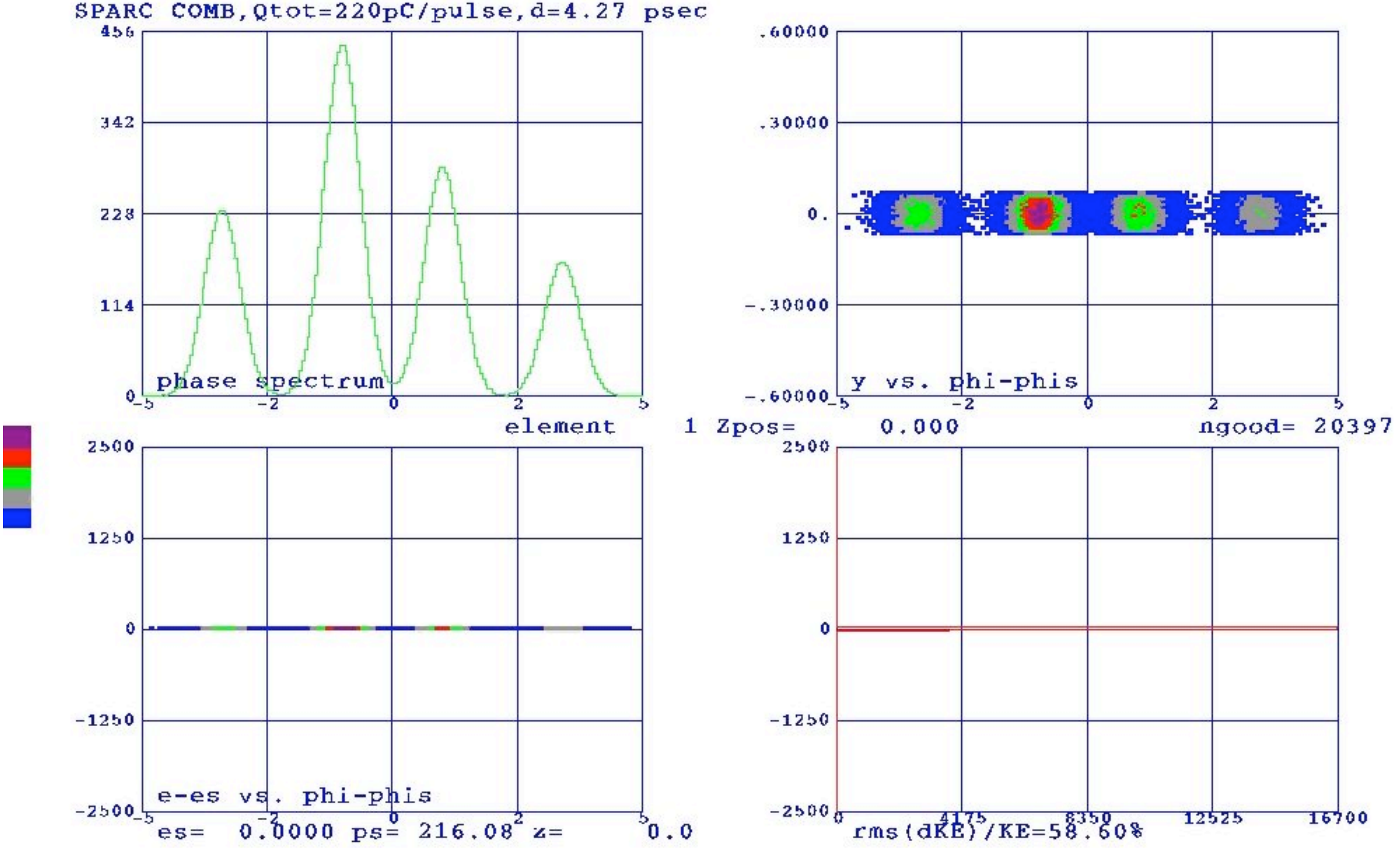
EnergySeparation I-II(MeV)	-1.2877 (0.08)
TimeSeparation I-II(ps)	0.0854 (0.04)
EnergySeparation II-III(MeV)	-0.6114 (0.09)
TimeSeparation II-III(ps)	-0.1520 (0.03)
EnergySeparation III-IV(MeV)	-0.8784 (0.11)
TimeSeparation III-IV(ps)	-0.2530 (0.03)
FirstBunchCharge(%)	19.53
SecondBunchCharge(%)	48.67
ThirdBunchCharge(%)	15.60
FourthBunchCharge(%)	16.25
ConsistencyCheck(%)	100.05

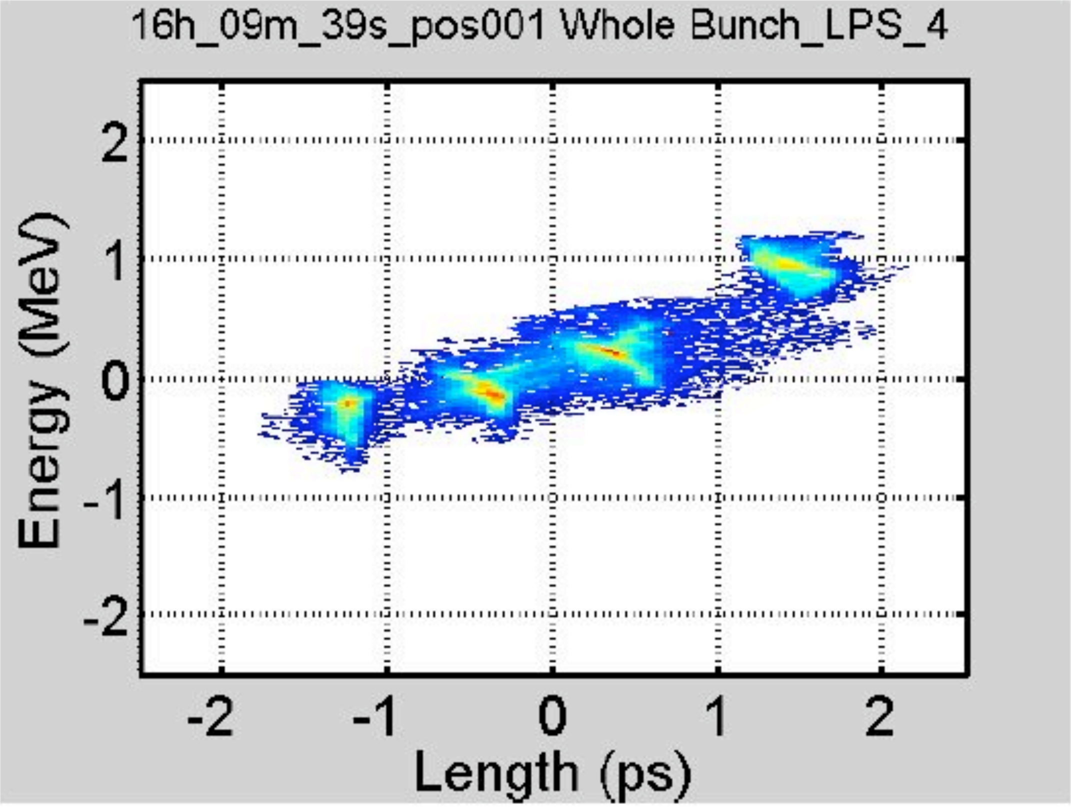
12h_52m_43s Whole Bunch_Current_4

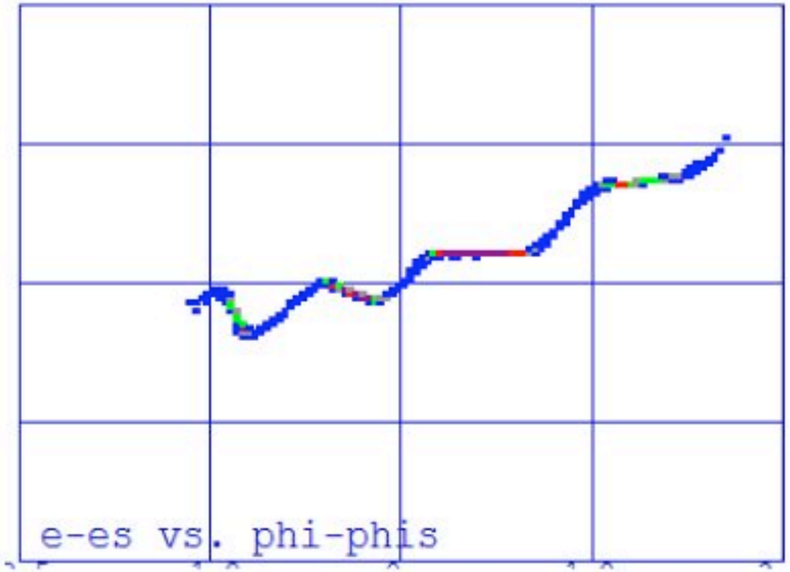


	Length (ps)
First Beam	??
Second Beam	0.1180 (0.011)
Third Beam	0.0431 (0.033)
Fourth Beam	0.0979 (0.0140)
Whole Beam	0.1682 (0.0091)

Overcompression




16h_09m_39s_pos001 Whole Bunch_LPS_4
Energy (MeV)
2
1
0
-1
-2
-2
-1
0
1
2
Length (ps)

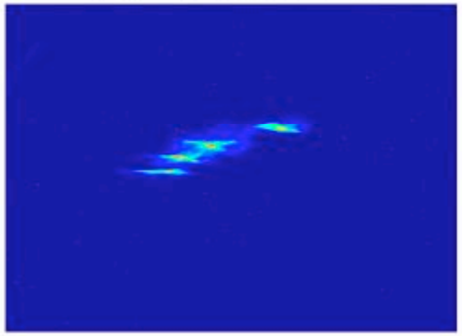

e-es vs. phi-phis

2011/06/03 - 200 pC - Overcompression

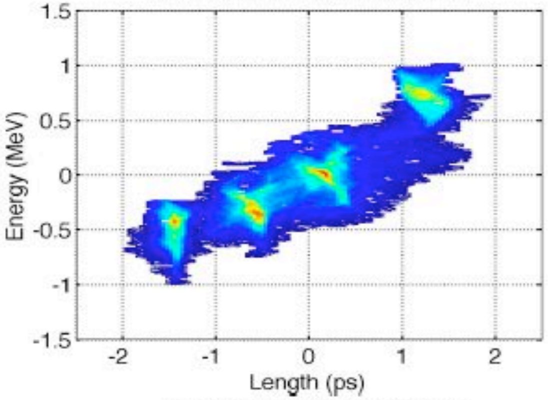
Total projected emittance: 5.68 μm (4.09 μm)

	Energy (MeV)	En. Spread(%)	Length (ps)	Charge(%)
I	108.555(0.045)	0.158(0.002)	0.141(0.002)	14.48(0.19)
II	108.756(0.050)	0.177(0.002)	0.202(0.004)	25.45(0.42)
III	108.998(0.051)	0.191(0.002)	0.278(0.005)	35.80(0.37)
IV	109.609(0.051)	0.235(0.003)	0.230(0.005)	25.95(0.41)
Whole	109.033(0.048)	0.393(0.003)	0.937(0.002)	100.00(0.93)

16h_09m_39s_pos001 Whole Bunch_CR_4

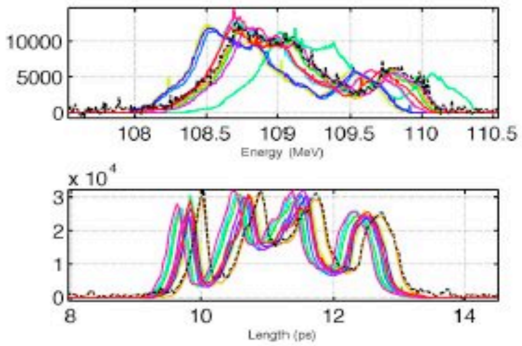


16h_09m_39s_pos001 Whole Bunch_LPS_4

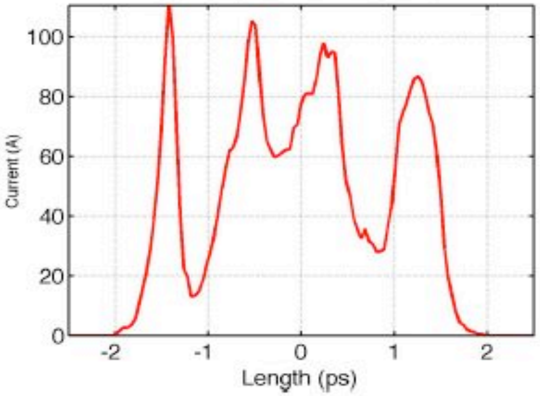


EnergySeparation I-II(MeV)	-0.2007 (0.07)
TimeSeparation I-II(ps)	-0.8326 (0.05)
EnergySeparation II-III(MeV)	-0.2425 (0.07)
TimeSeparation II-III(ps)	-0.8231 (0.05)
EnergySeparation III-IV(MeV)	-0.6104 (0.07)
TimeSeparation III-IV(ps)	-1.0587 (0.05)
FirstBunchCharge(%)	14.48
SecondBunchCharge(%)	25.45
ThirdBunchCharge(%)	35.80
FourthBunchCharge(%)	25.95
ConsistencyCheck(%)	101.68

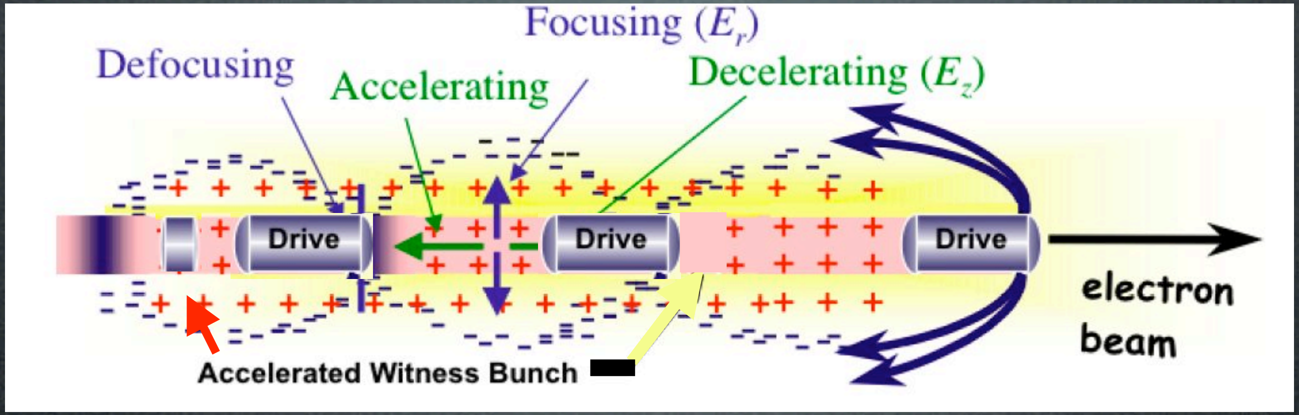
16h_09m_39s_pos001_New_AllProfiles_pos1



16h_09m_39s_pos001 Whole Bunch_Current_4



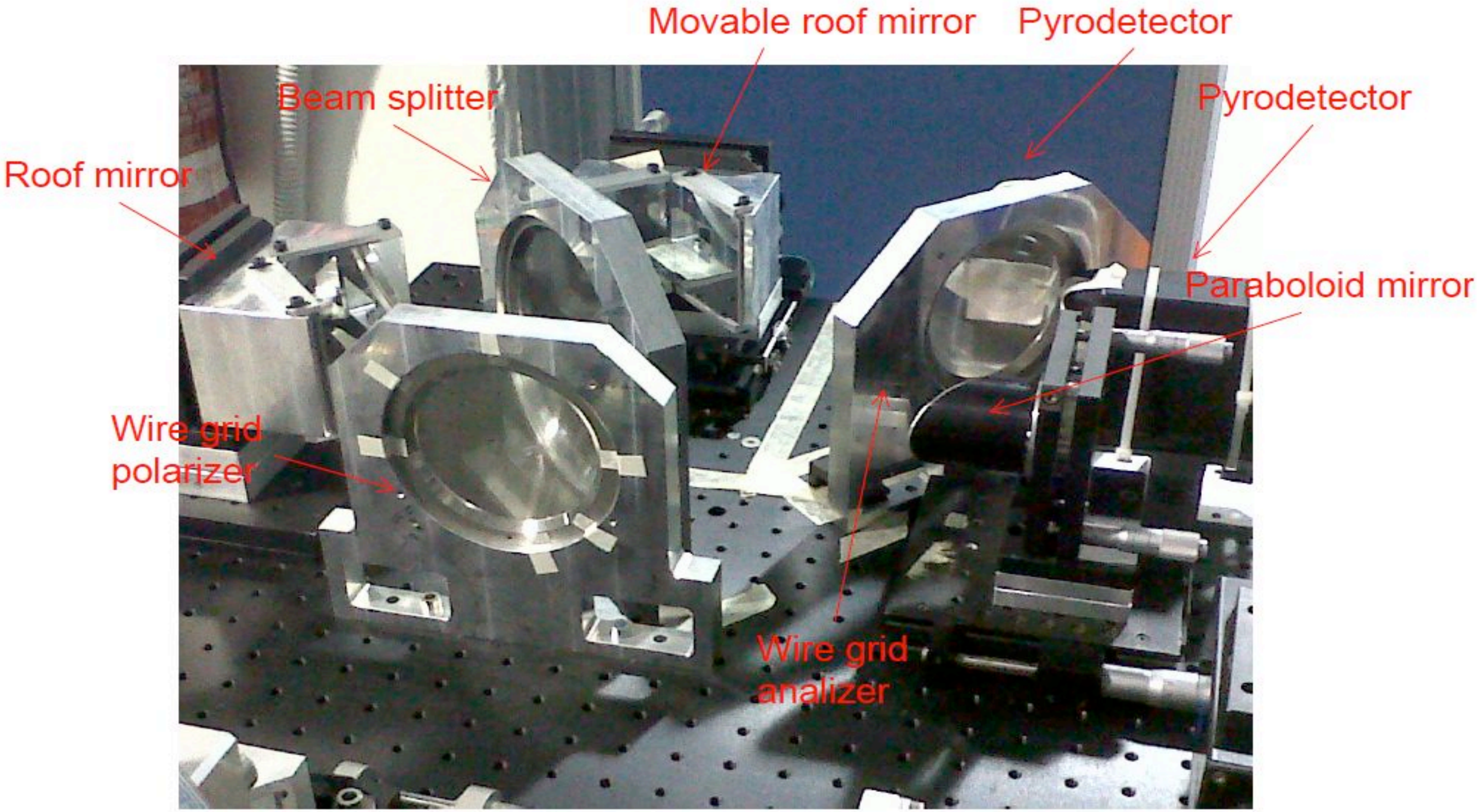
Resonant plasma Oscillations by Multiple electron Bunches

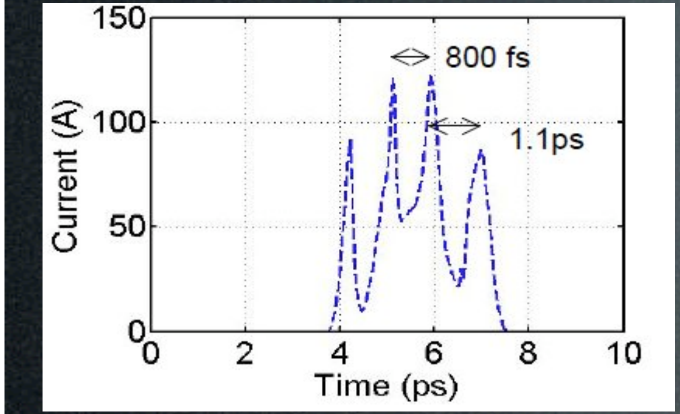


- **Weak blowout regime** with resonant amplification of plasma wave by a train of high Brightness electron bunches produced by **Laser Comb** technique ==> **5 GV/m** with a train of 3 bunches, 100 pC/bunch, 50 μm long, 20 μm spot size, in a plasma of density 10^{22} e^-/m^3 at λ_p=300 μm ?
- **Ramped bunch train configuration** to enhance tranformer ratio?
- **High quality bunch** preservation during acceleration and transport?
- **Strong blowout regime** with pC/fs bunches ==> **TV/m** regime ?

Narrow band THz radiation

Martin-Puplett Interferometer

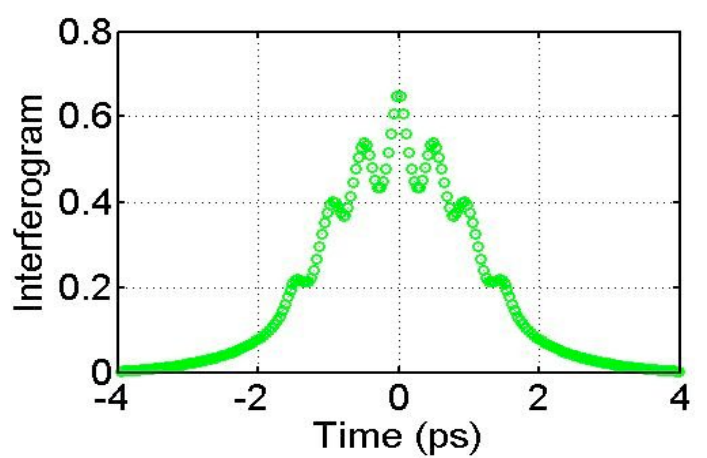


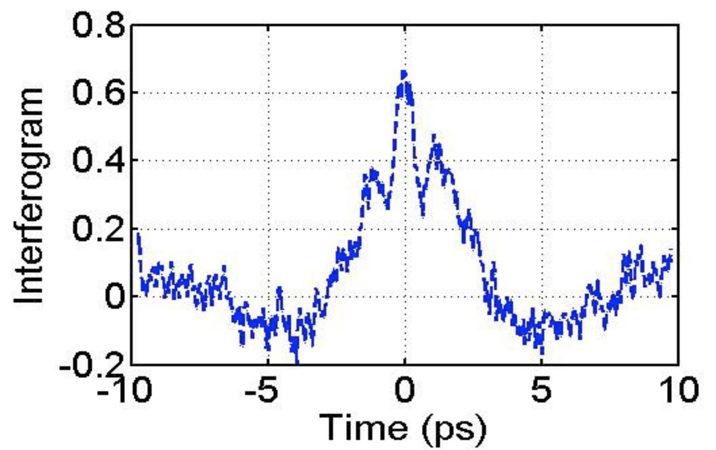


Expected

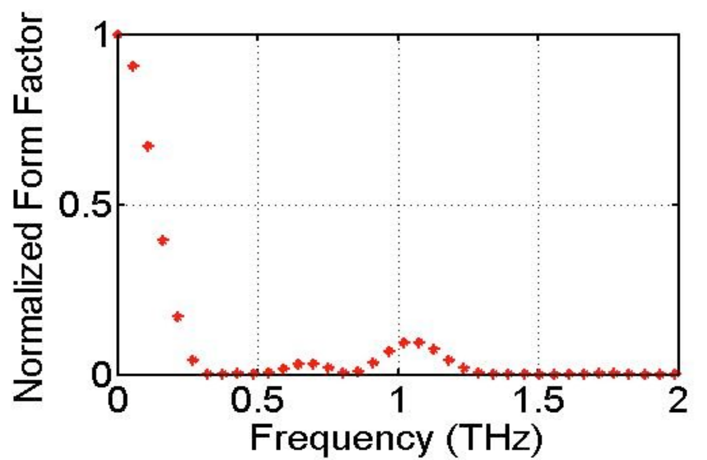
Measured

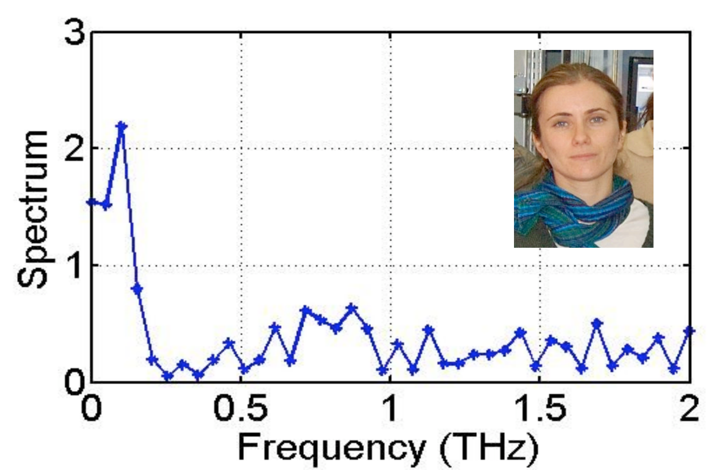
Interferogram

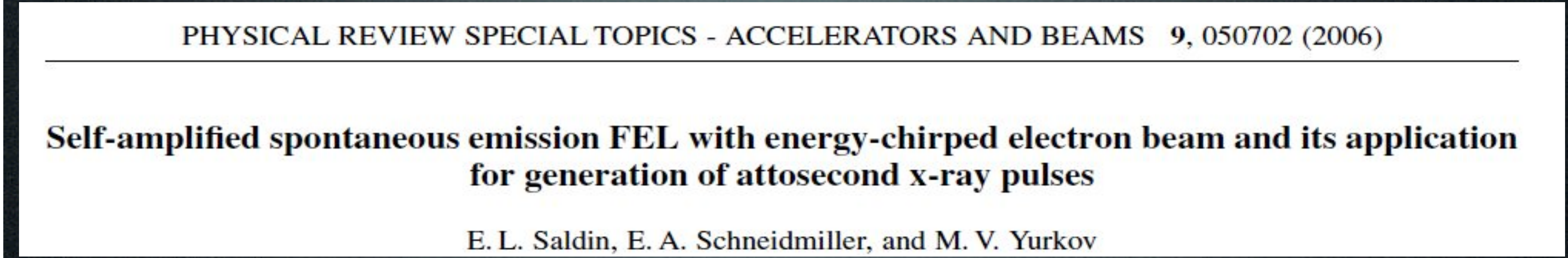




Spectrum







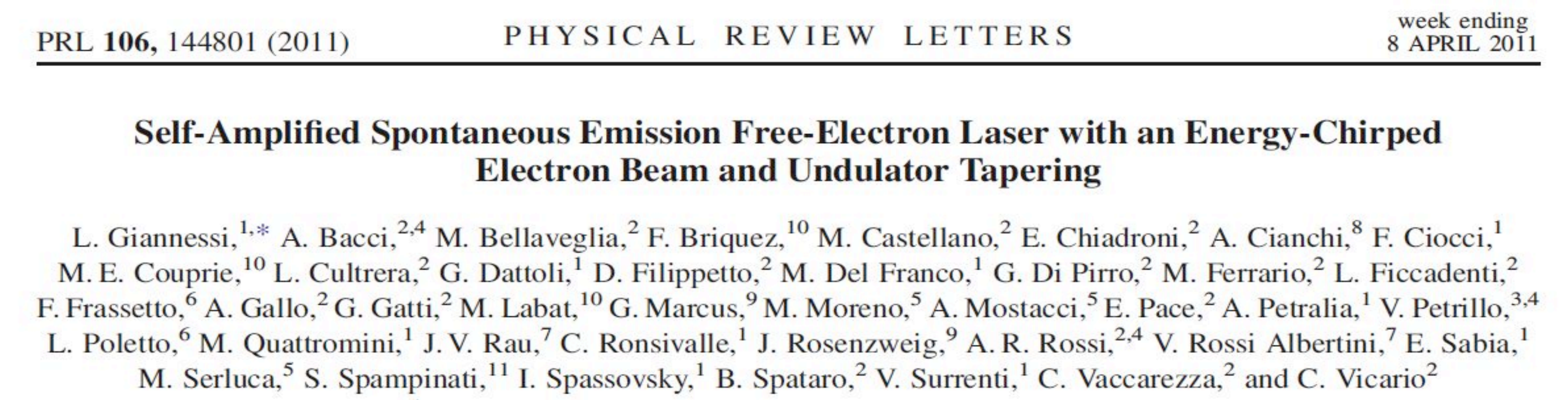
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **9**, 050702 (2006)

Self-amplified spontaneous emission FEL with energy-chirped electron beam and its application for generation of attosecond x-ray pulses

E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov

FEL Single Spike

With Chirped Beam and Undulator Tapering

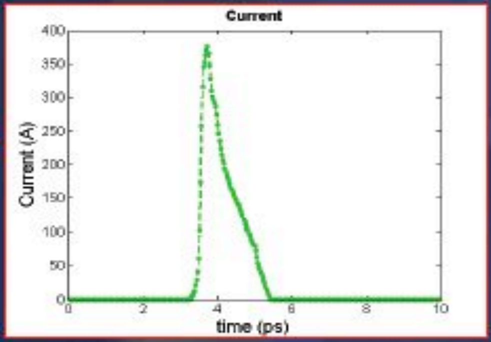


PRL **106,** 144801 (2011) PHYSICAL REVIEW LETTERS week ending 8 APRIL 2011

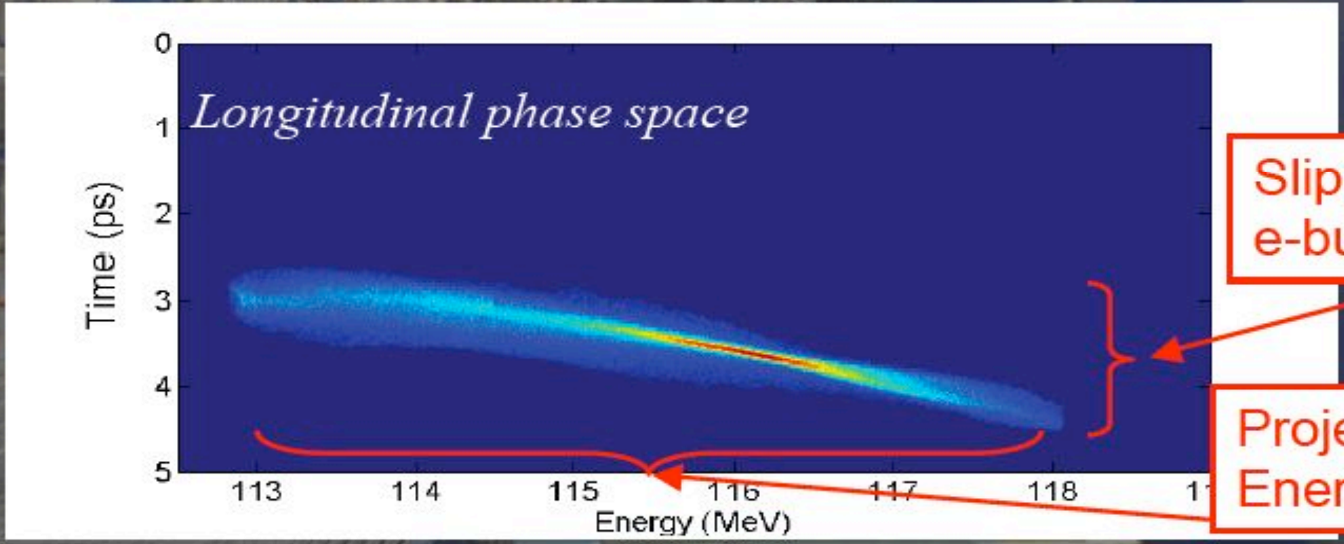
Self-Amplified Spontaneous Emission Free-Electron Laser with an Energy-Chirped Electron Beam and Undulator Tapering

L. Giannessi,[1,*] A. Bacci,[2,4] M. Bellaveglia,[2] F. Briquez,[10] M. Castellano,[2] E. Chiadroni,[2] A. Cianchi,[8] F. Ciocci,[1] M. E. Couprie,[10] L. Cultrera,[2] G. Dattoli,[1] D. Filippetto,[2] M. Del Franco,[1] G. Di Pirro,[2] M. Ferrario,[2] L. Ficcadenti,[2] F. Frassetto,[6] A. Gallo,[2] G. Gatti,[2] M. Labat,[10] G. Marcus,[9] M. Moreno,[5] A. Mostacci,[5] E. Pace,[2] A. Petralia,[1] V. Petrillo,[3,4] L. Poletto,[6] M. Quattromini,[1] J. V. Rau,[7] C. Ronsivalle,[1] J. Rosenzweig,[9] A. R. Rossi,[2,4] V. Rossi Albertini,[7] E. Sabia,[1] M. Serluca,[5] S. Spampinati,[11] I. Spassovsky,[1] B. Spataro,[2] V. Surrenti,[1] C. Vaccarezza,[2] and C. Vicario[2]

- Compression with “Velocity Bunching”
  - High peak current (up to 380A)



Strong chirp / energy spread in the longitudinal phase space



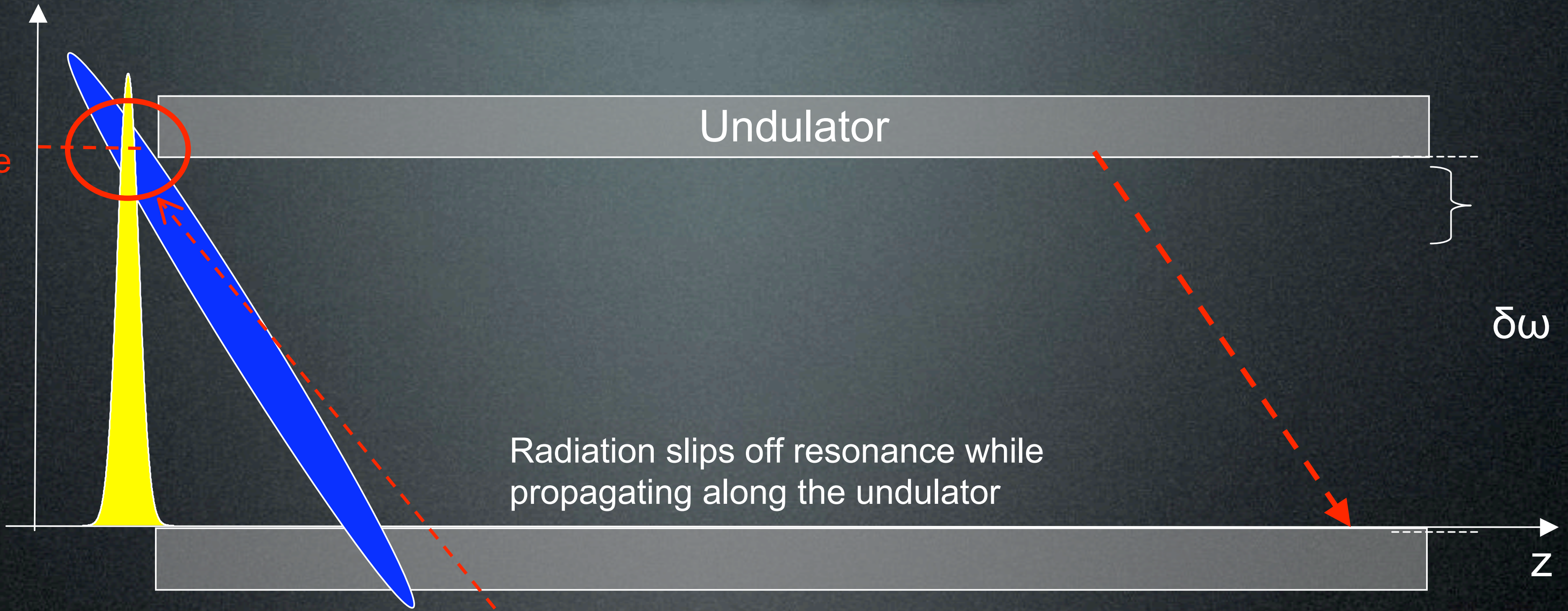
Slippage length ~ e-bunch length

Projected r.m.s. Energy spread ~ 1%

Average beam energy	115 MeV
Energy spread	1.33 % (0.7 MeV) [-8.7 keV/μm]

rms bunch length	0.42 ps
Peak current	380 A
Transv. emittance	2.7/3 μm

Chirped Beam Spectrum



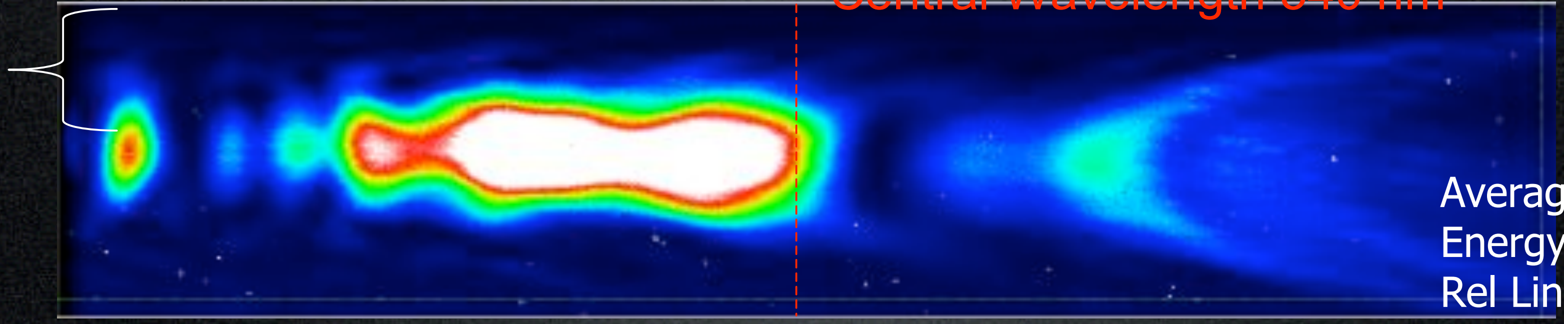
Initial resonance condition

Radiation slips off resonance while propagating along the undulator

Spectrum

Resonance condition is a function of
Beam energy (chirp) / Undulator K (untapered)

Central Wavelength 540 nm



Spectrometer slit (vertical positition)

Average over 100 spectra
Energy 8 uJ (max 38 uJ)
Rel Linewidth 1.6% rms

Wavelength range 40 nm

Compensation with Undulator taper

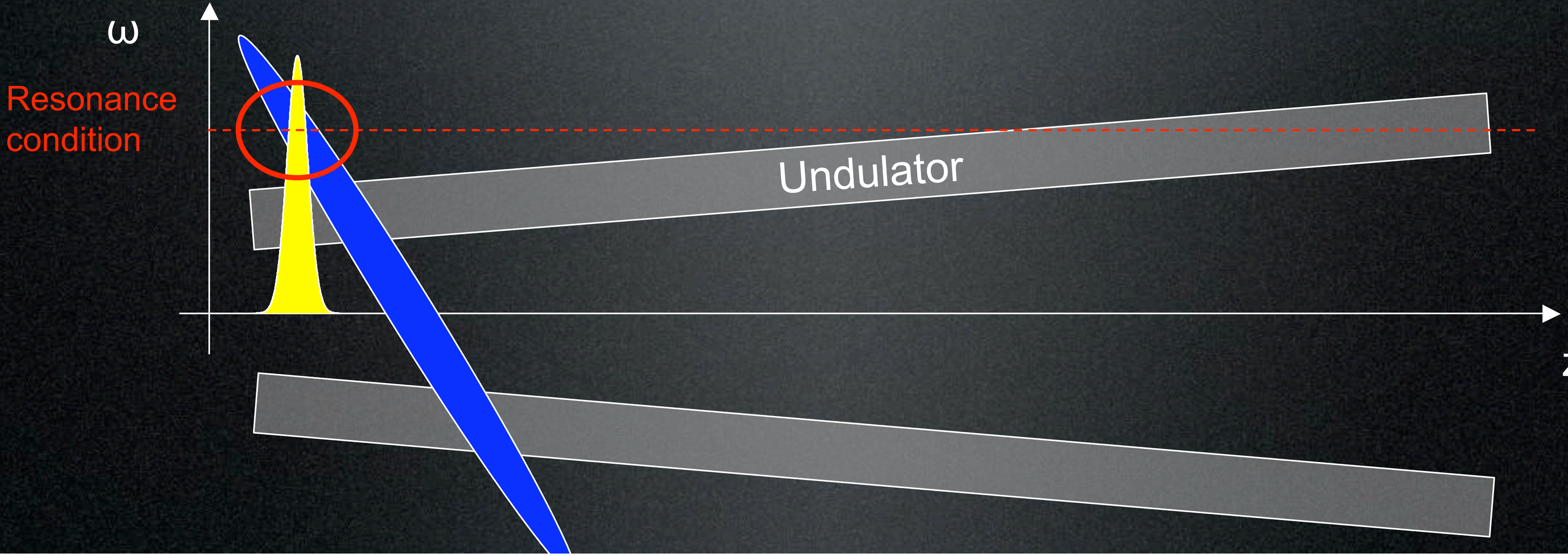
$$\omega_r = \frac{2\gamma^2}{1+\frac{K^2}{2}}\omega_u$$

$$\omega_u = \frac{2\pi c}{\lambda_u}$$

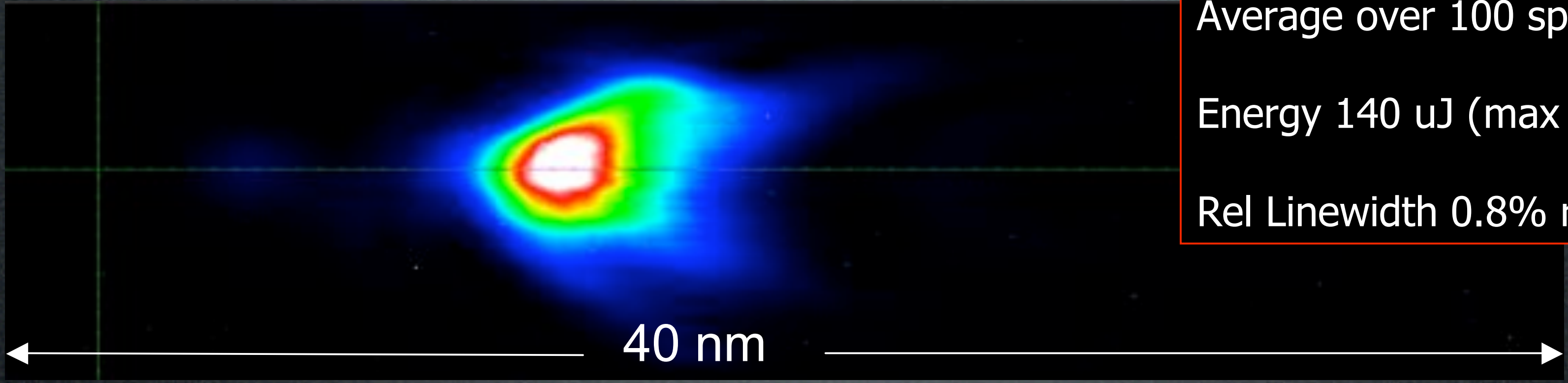
Chirp $\bar{\gamma} = \bar{\gamma}(s) = \gamma_0 + \alpha(s - s_0)$

Taper $K = K(z) = K_0 + \alpha_k(z - z_0)$

Resonance is maintained by tuning the undulator taper



Single Spike observed in many spectra

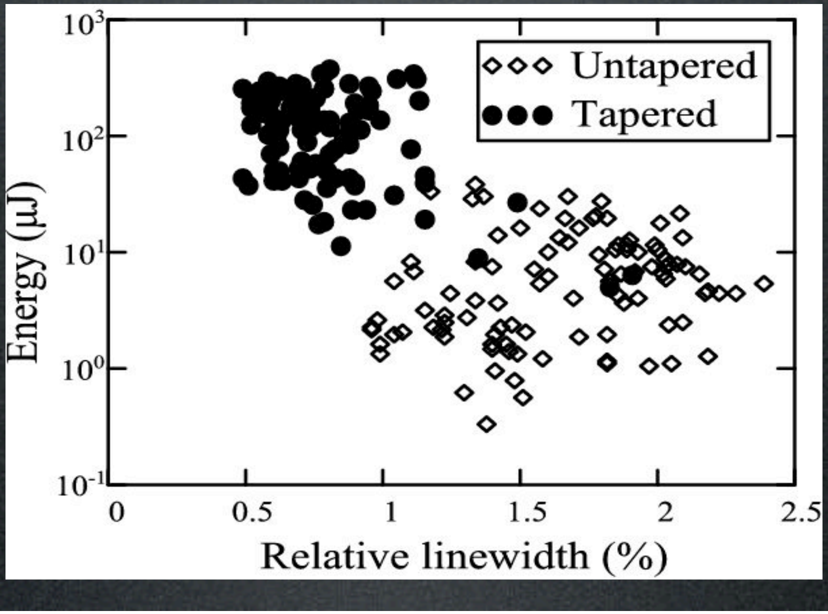


Average over 100 spectra:

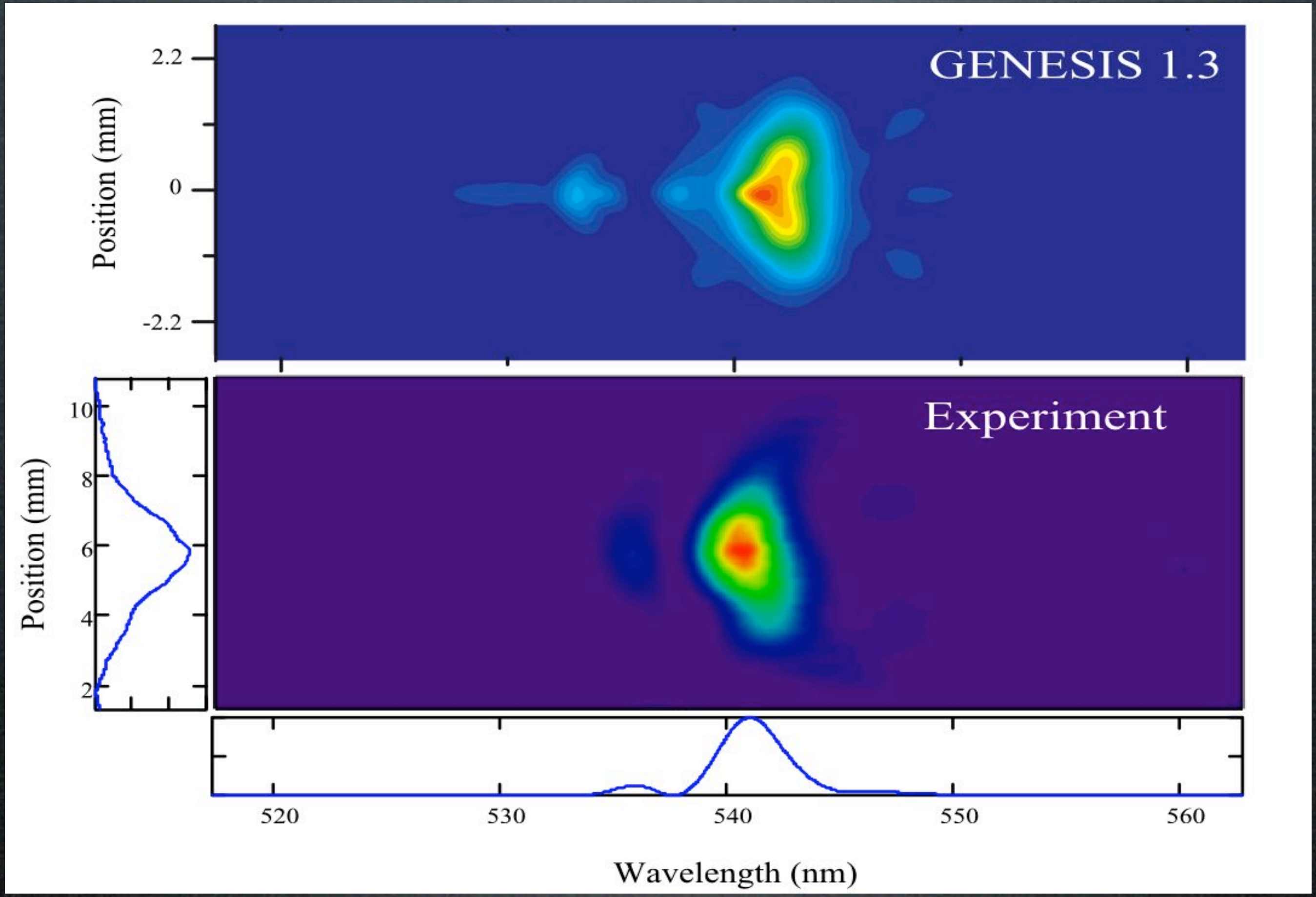
Energy 140 uJ (max 380 uJ)

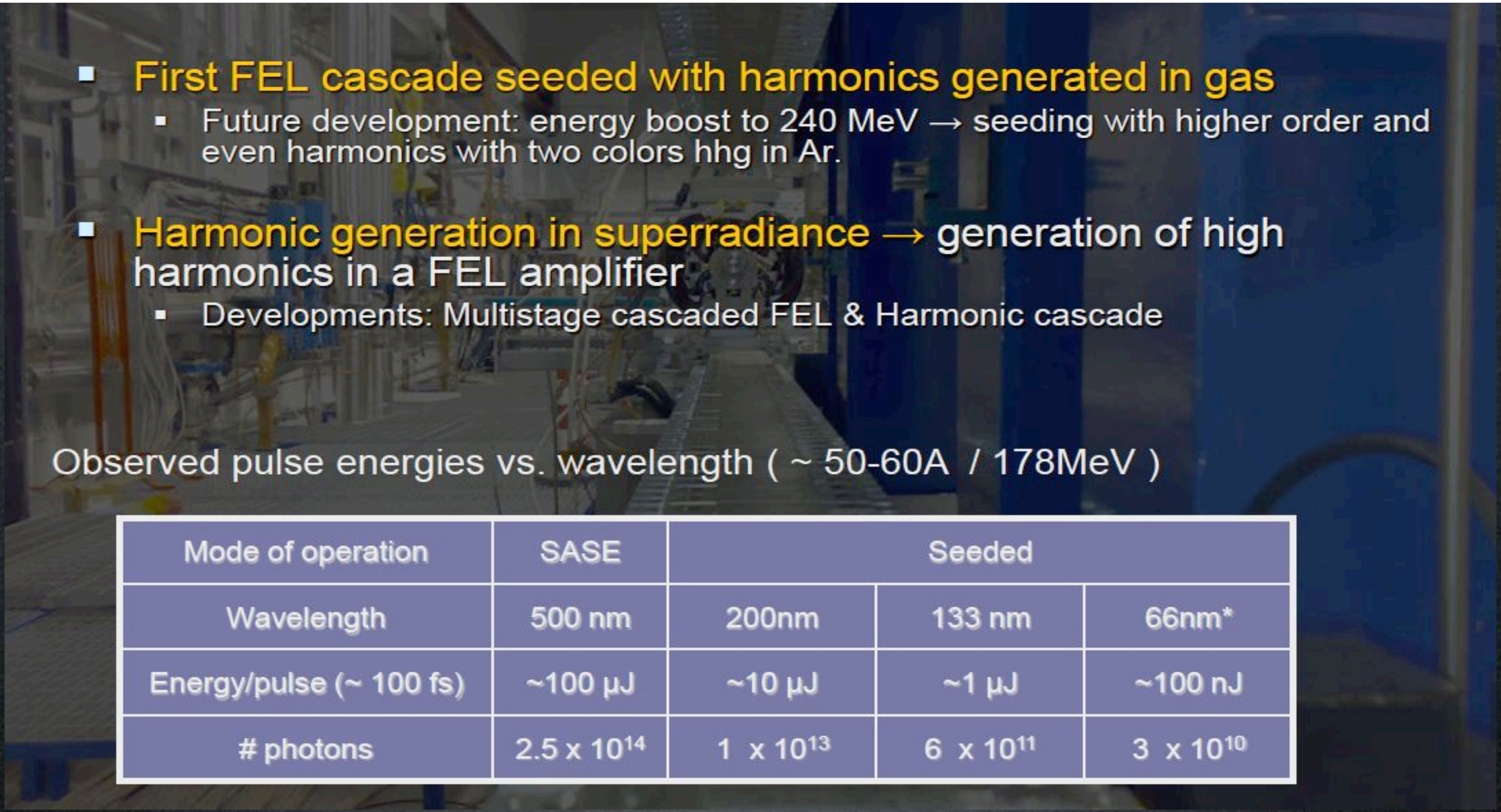
Rel Linewidth 0.8% rms

Average energy per pulse 18 times higher in a narrower bandwidth



Comparison with GENESIS 1.3 simulations





- First FEL cascade seeded with harmonics generated in gas
  - Future development: energy boost to 240 MeV → seeding with higher order and even harmonics with two colors hhg in Ar.
- Harmonic generation in superradiance → generation of high harmonics in a FEL amplifier
  - Developments: Multistage cascaded FEL & Harmonic cascade

Observed pulse energies vs. wavelength (~ 50-60A / 178MeV)

Mode of operation	SASE	Seeded		
Wavelength	500 nm	200nm	133 nm	66nm*
Energy/pulse (~ 100 fs)	~100 μJ	~10 μJ	~1 μJ	~100 nJ
# photons	2.5 x 10^{14}	1 x 10^{13}	6 x 10^{11}	3 x 10^{10}

•Harmonic FEL cascade 400nm-200nm-100nm

• Amplification of harmonic generated in gas – generation & amplification of odd & even harmonics (Collaboration with M.E. Couprie, M. Labat, F. Briquetz, Soleil – B. Carrè M. Bougeard CEA, G. Lambert, ENSTA)

• Continue study of saturation in seeded and SASE FEL amplifiers

• FROG diagnostic of FEL radiation in seeded and SASE mode (Collaboration with G. Marcus, J. Rosenzweig – UCLA)

• Diagnostic of transverse coherence (specle, wavefront monitor)

Thank you

Comparison SPARC (2pulses) LCLS (1pulse)

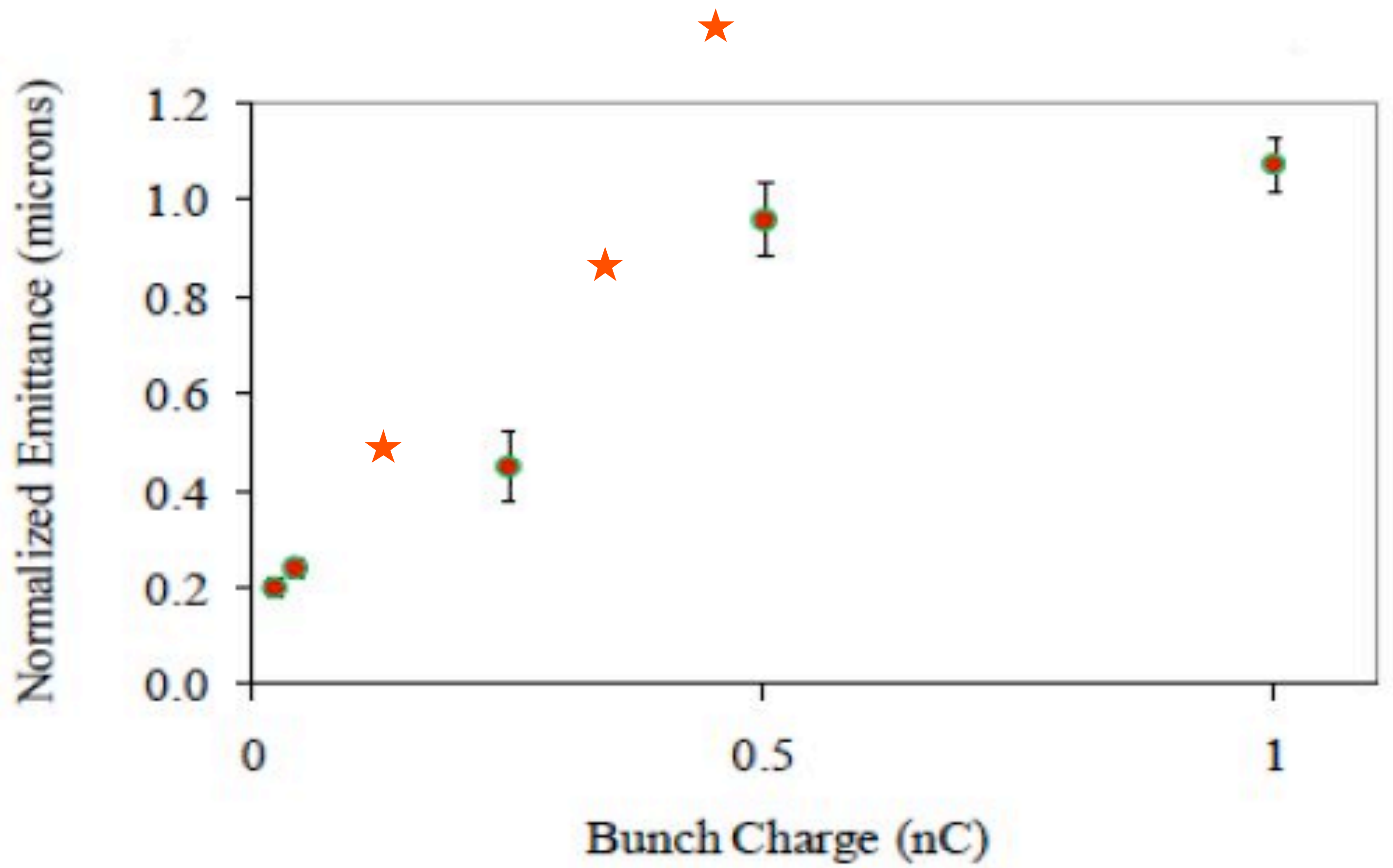


Figure 4: Emittance measured at the LCLS injector exit (135 MeV) versus bunch charge