Advanced Beam Manipulation Techniques at SPARC

A. Mostacci,
on behalf of the SPARC team

SPARC in Frascati is a high brightness photo-injector used to drive Free Electron Laser experiments and explore advanced beam manipulation techniques. The R&D effort made for the optimization of the beam parameters will be presented here, together with the major experimental results achieved. In particular, we will focus on the generation of sub-picosecond, high brightness electron bunch trains via velocity bunching technique (the so called comb beam). Such bunch trains can be used to drive tunable and narrow band THz sources, FELs and plasma wake field accelerators.

OUTLINE

Advanced Beam Manipulation Techniques at SPARC

Recent and forthcoming technological upgrades have made SPARC a unique test bench for R&D on high brightness electron beam and their applications, other than SASE FEL activity already assessed.

Main technological aspects of SPARC present layout.

Longitudinal bunch compression @ 5-6 MeV: the velocity bunching.

Advanced beam manipulation technique: generation of sub-ps, high brightness electron bunch trains (COMB beam).

Application of COMB beams (THz source, FEL, PWFA).

On going technological upgrades and perspectives (e.g. Thomson source).

ACKNOWLEDGMENTS

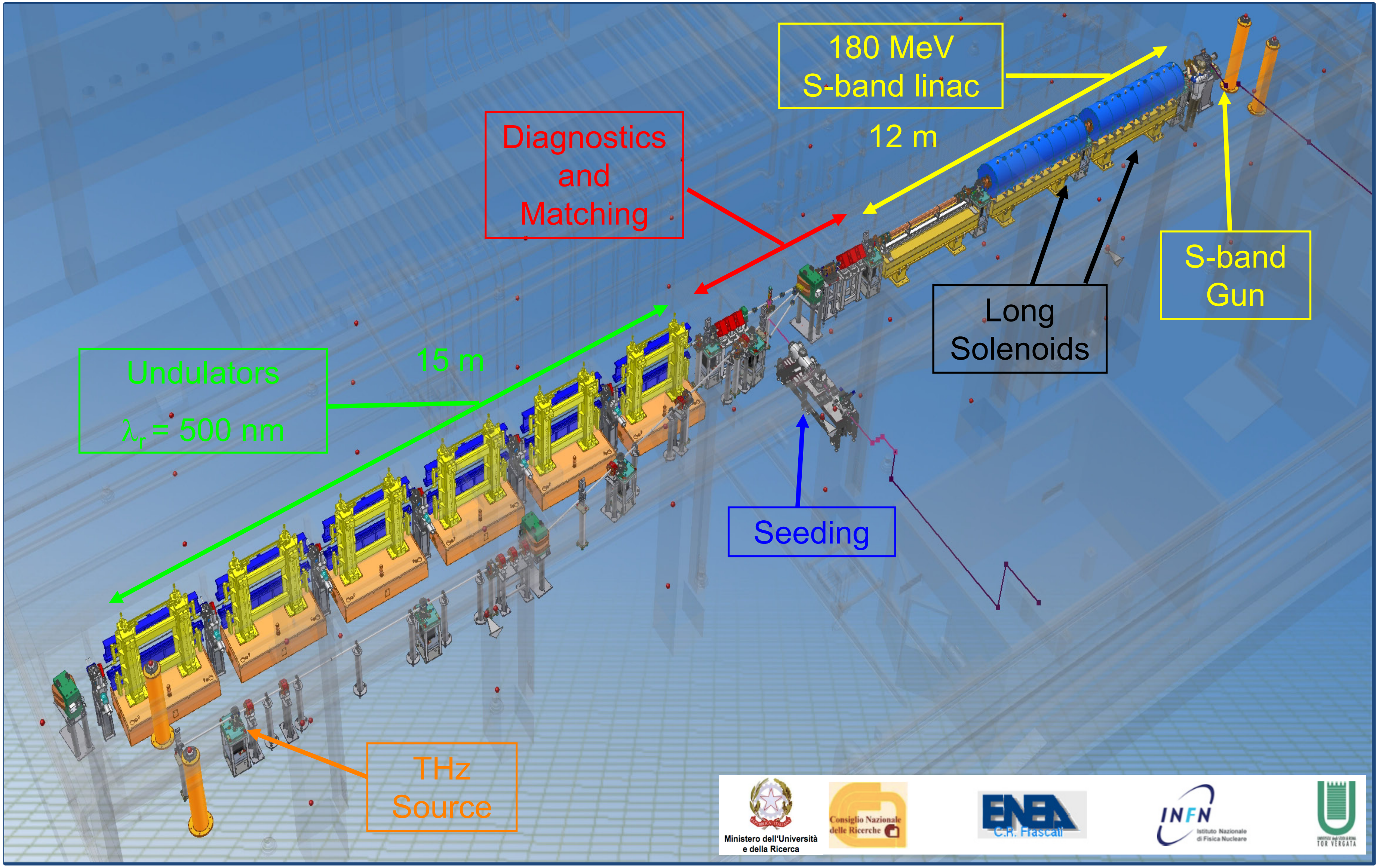
Beam dynamics, RF technology, Machine operation, THz radiation, FEL theory and experiments
(INFN, Sapienza University, Tor Vergata University, Enea, CNR)

M. Ferrario, D. Alesini, P. Antici, A. Bacci, M. Bellaveglia, R. Boni, P. Calvani, M. Castellano, L. Catani, E. Chiadroni, A. Cianchi, F. Ciocci, G. Dattoli, M. Del Franco, G. Di Pirro, A. Drago, F. Frassetto, A. Gallo, G. Gatti, A. Ghigo, L. Giannessi, O. Limaj, S. Lupi, B. Marchetti, M. Migliorati, A. Nucara, E. Pace, L. Palumbo, A. Petralia, V. Petrillo, L. P. Poletto, M. Quattromini, J.V. Rau, C. Ronsivalle, A. R. Rossi, V. Rossi Albertini, E. Sabia, L. Serafini, M. Serluca, B. Spataro, I.P. Spassovsky, V. Surrenti, C. Vaccarezza.

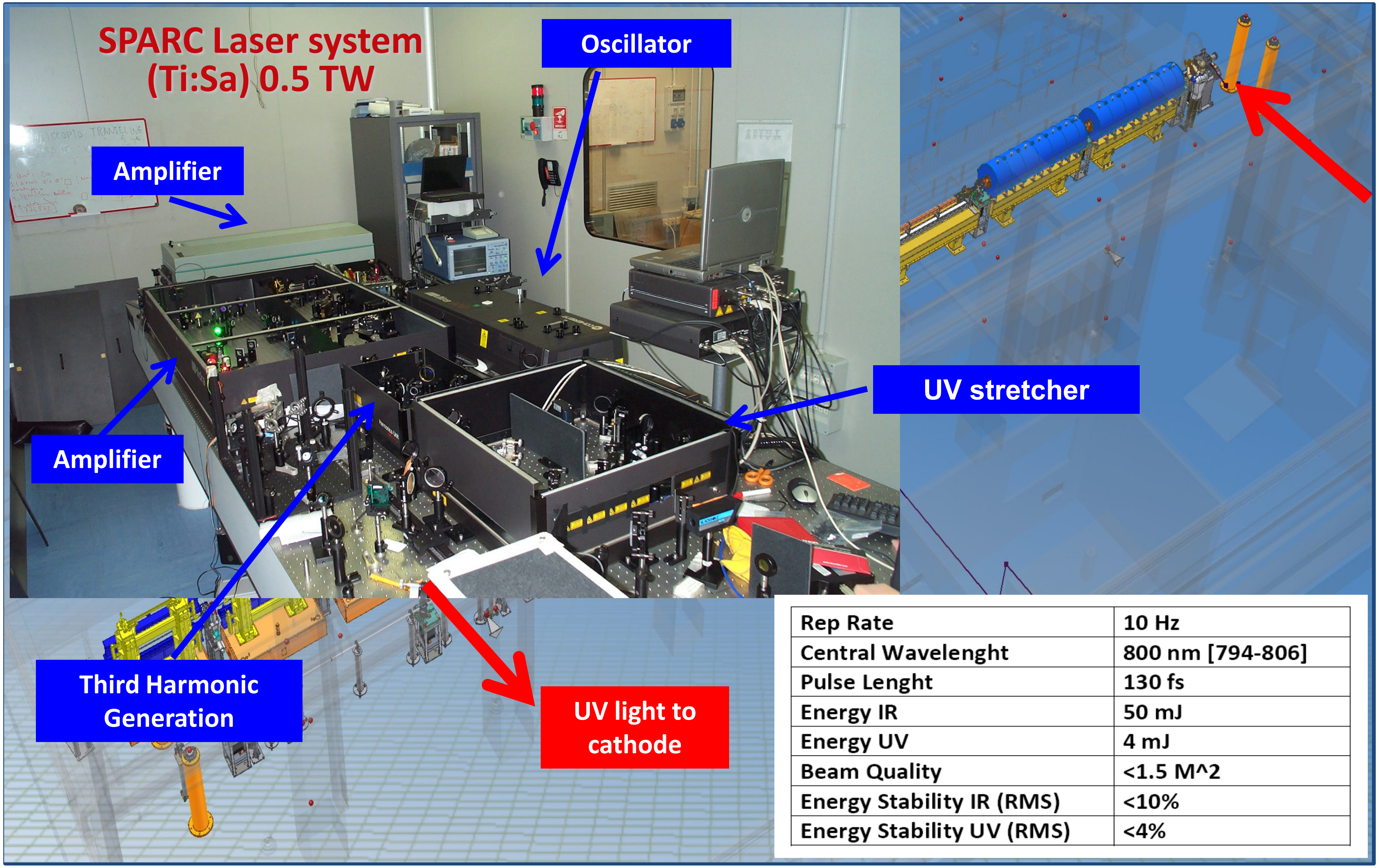
National and International collaboration and networks

C. Pellegrini, J.B. Rosenzweig, P. Musumeci PBPL @ UCLA (beam dynamics, FEL physics, RF technology, advanced diagnostics), M. Couprie group @ SOLEIL (FEL seeding), Fermi @ ELETTRA (commissioning, FEL, LLRF, advanced diagnostics), PSI SwissFEL (C band RF systems), KEK (C band RF sections), P. Muggli @ MAX PLANK(PWFA future experiment), Tiara, EuroNac, L. Cultrera (Cornell), L. Ficcadenti (CERN), D. Filippetto (LBNL), C. Vicario (PSI).

SPARC LAYOUT

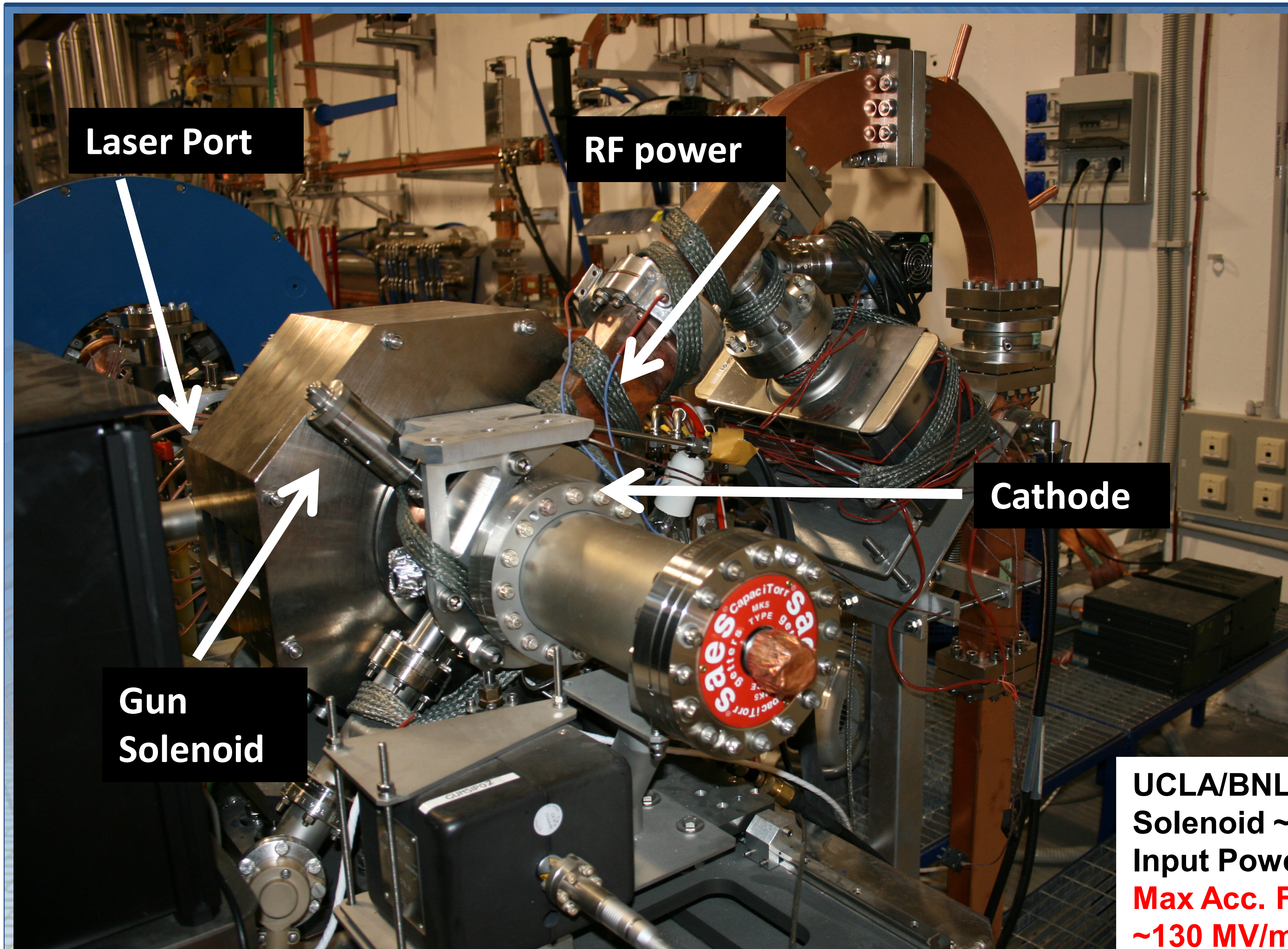


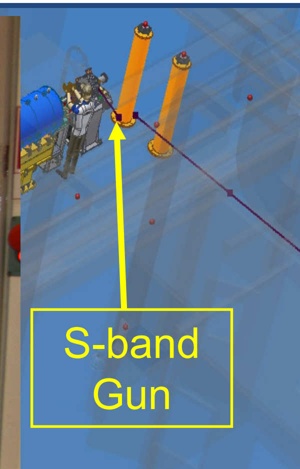
SPARC LAYOUT: LASER SYSTEM



Rep Rate	10 Hz
Central Wavelenght	800 nm [794-806]
Pulse Lenght	130 fs
Energy IR	50 mJ
Energy UV	4 mJ
Beam Quality	<1.5 M^2
Energy Stability IR (RMS)	<10%
Energy Stability UV (RMS)	<4%

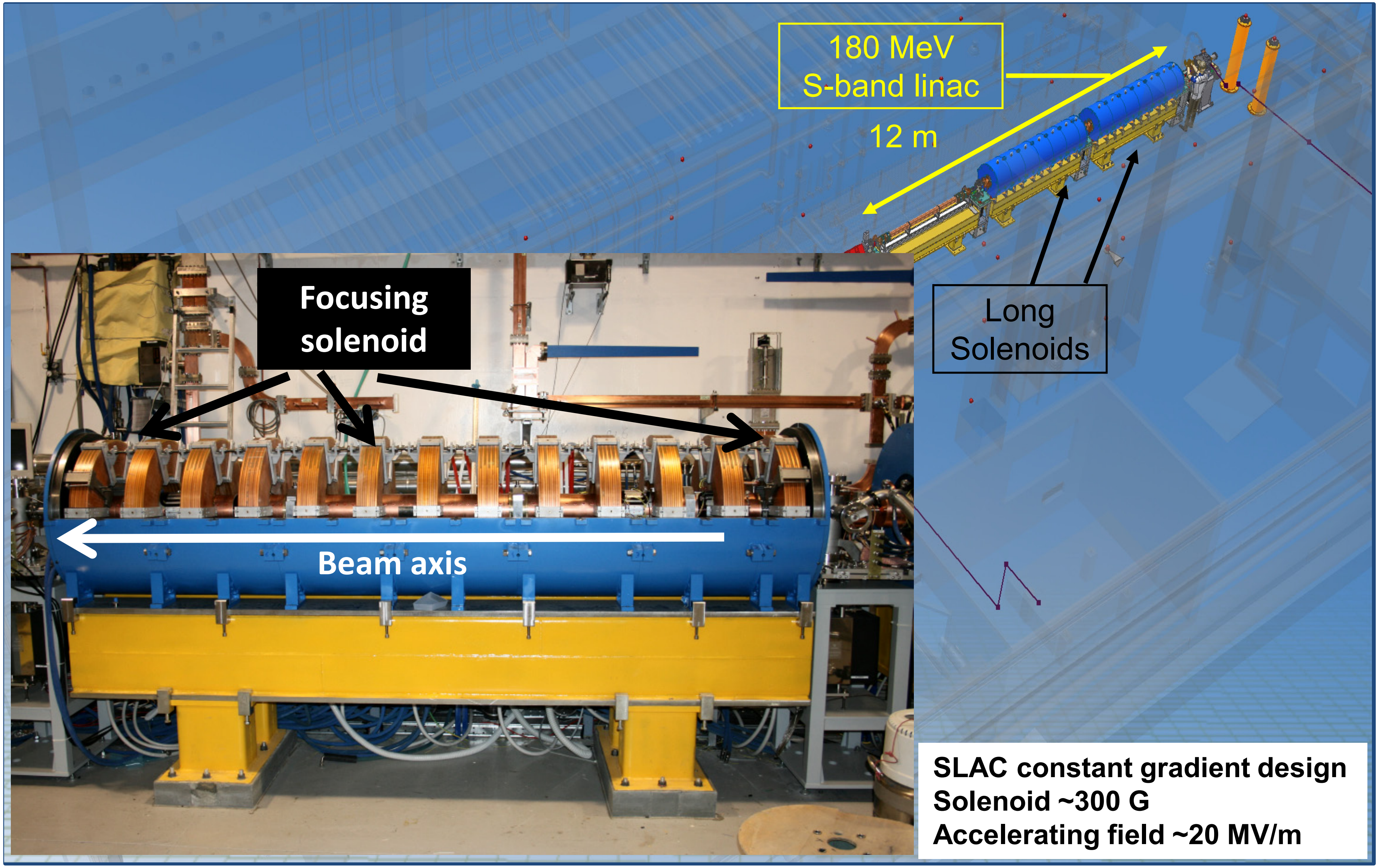
SPARC LAYOUT: S-BAND GUN





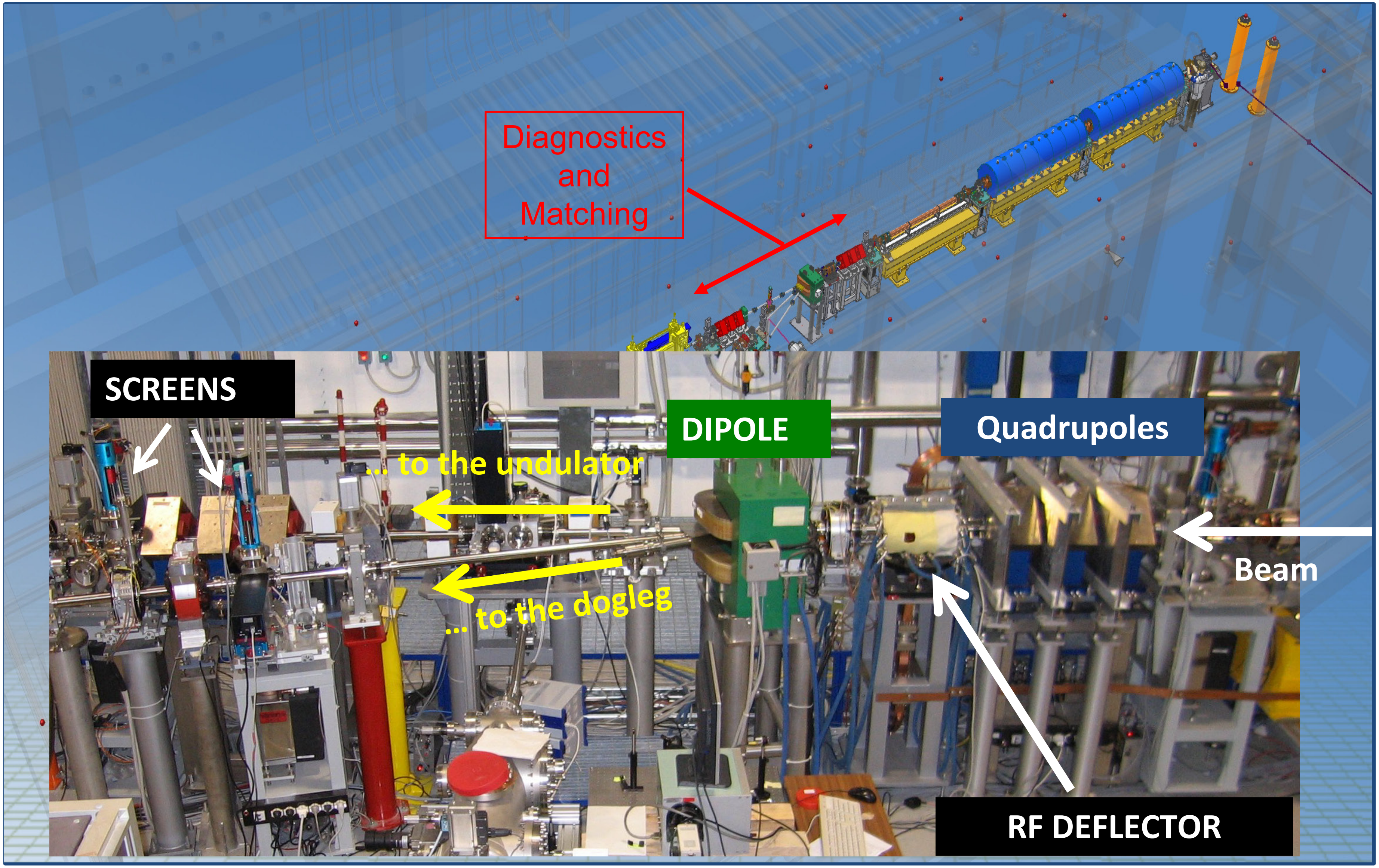
UCLA/BNL design
Solenoid ~3 kG
Input Power 14 MW
Max Acc. Field @ cathode ~130 MV/m

SPARC LAYOUT: S-BAND LINAC



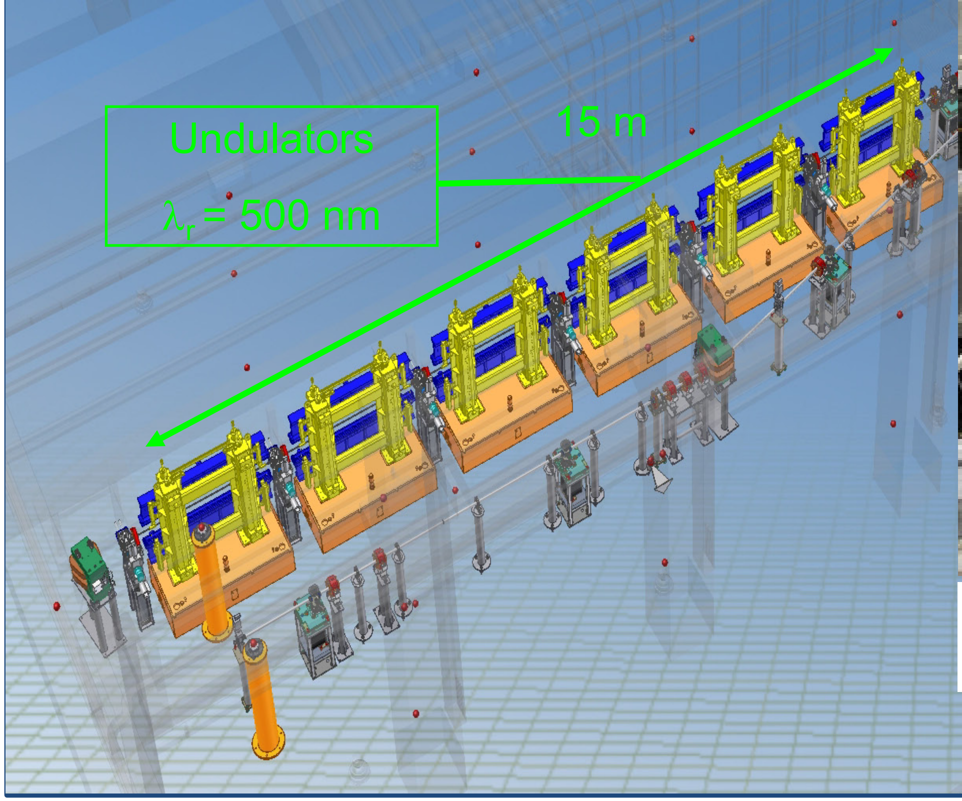
SLAC constant gradient design
Solenoid ~300 G
Accelerating field ~20 MV/m

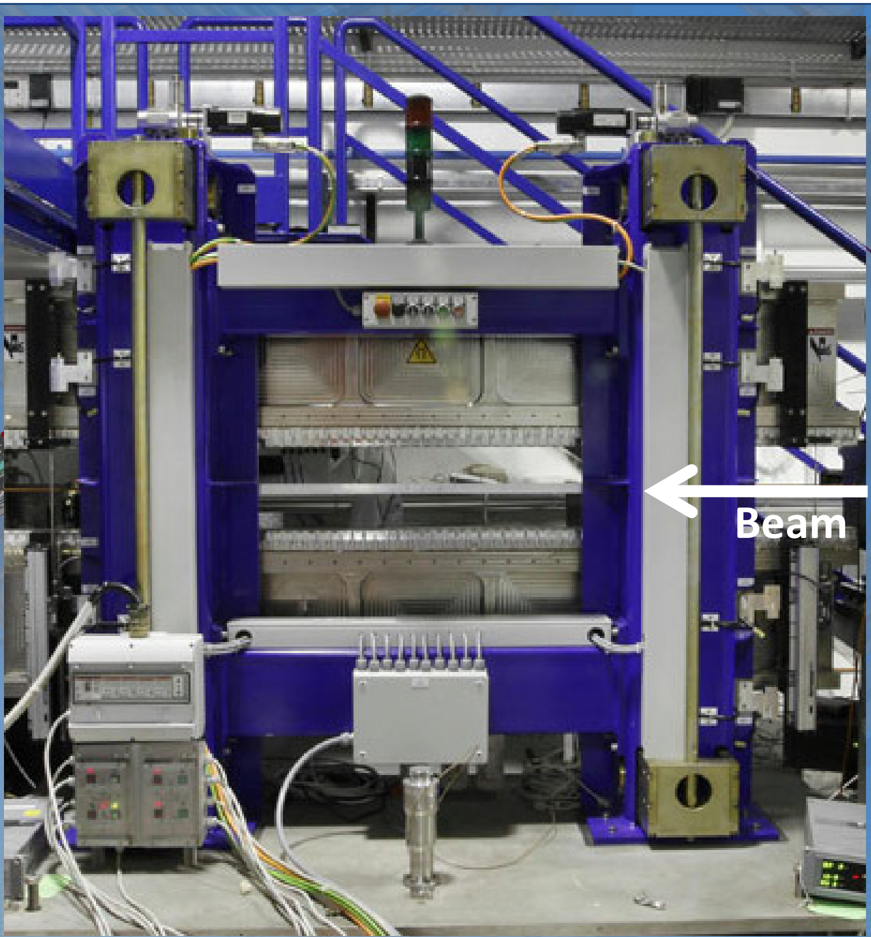
SPARC LAYOUT: DIAGNOSTICS AND MATCHING



SPARC LAYOUT: UNDULATORS

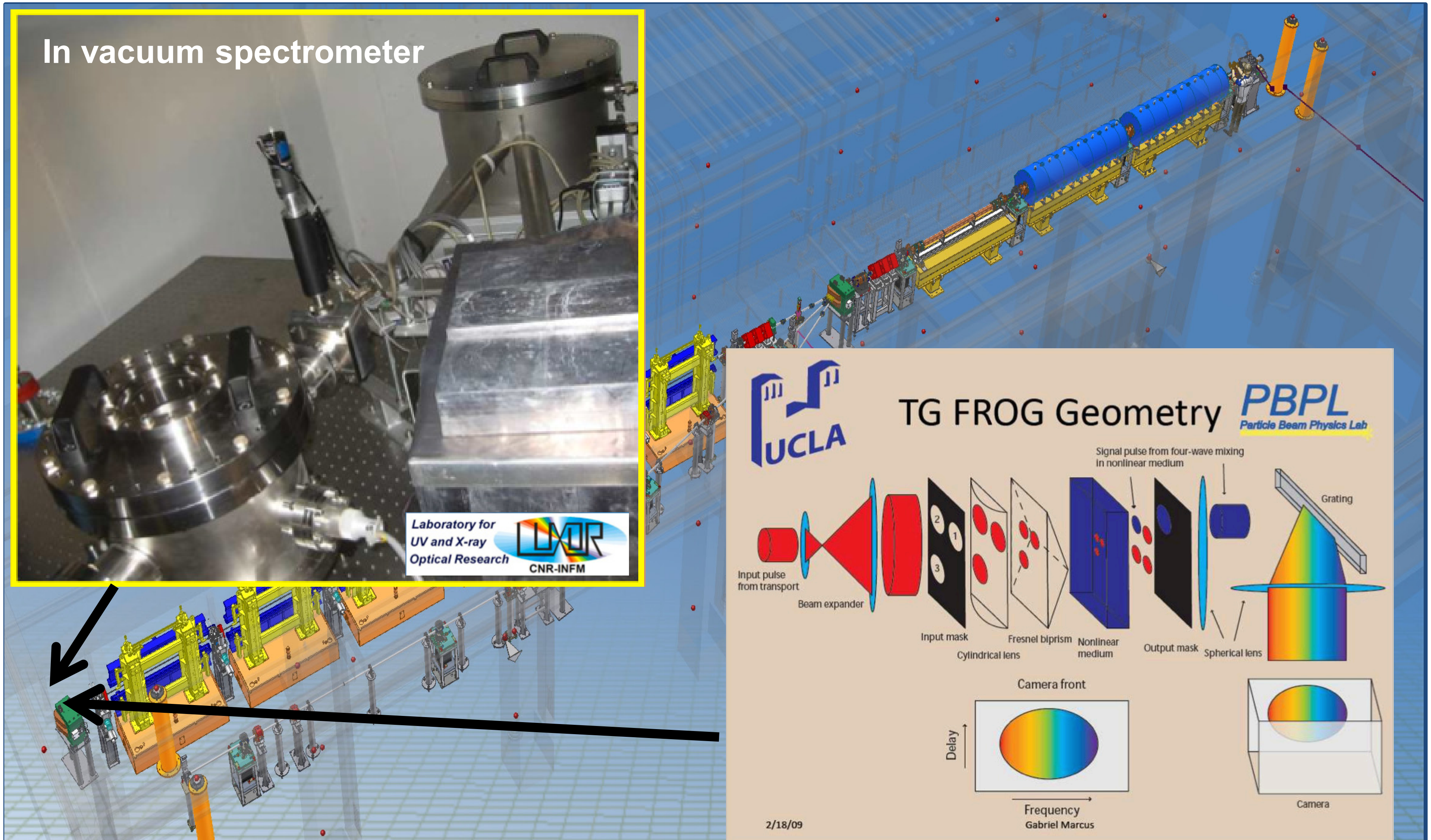
Period	2.8 cm
Undulator length	2.156.m
No of Periods	77
Gap (nom./min/max)	0.958 / 0.6 / 2.5 cm
K (nom./max/min)	2.145 / 3.2 / 0.38
Remanent field	1.31 T
Blocks per period	4
Block size (h x l x w)	2 x 0.7 x 5 cm





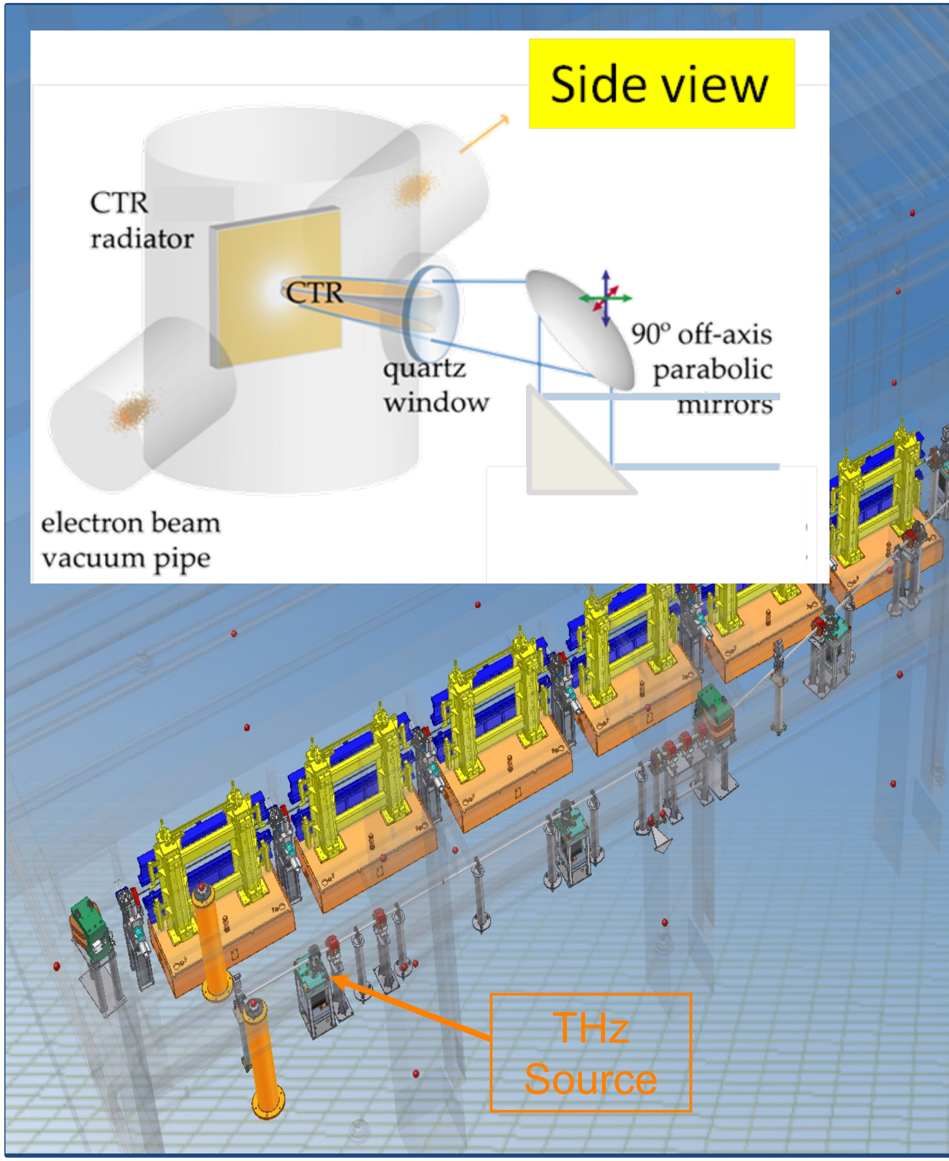
Variable gap undulator
Halbach type

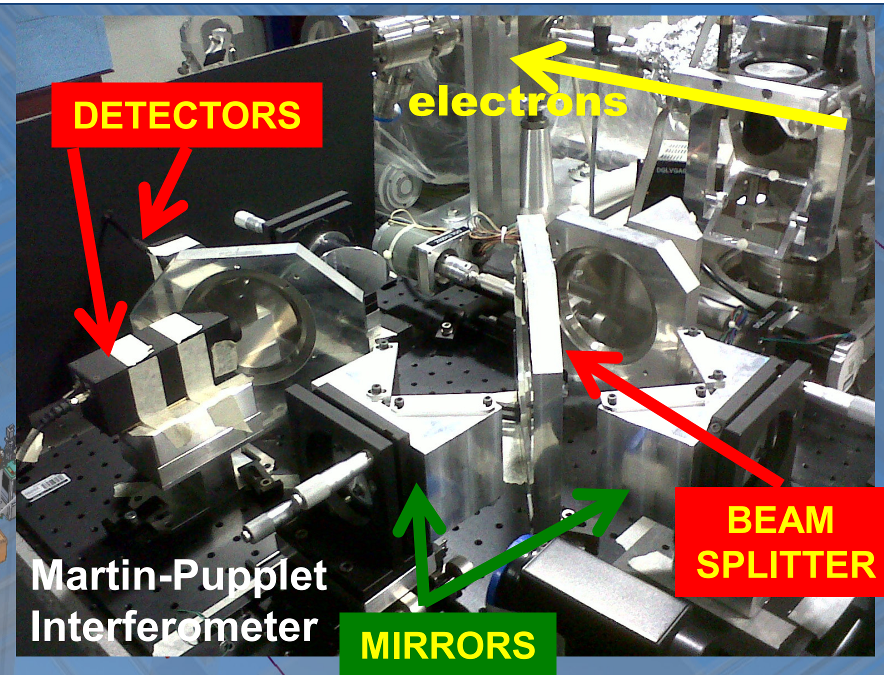
SPARC LAYOUT: PHOTON DIAGNOSTICS

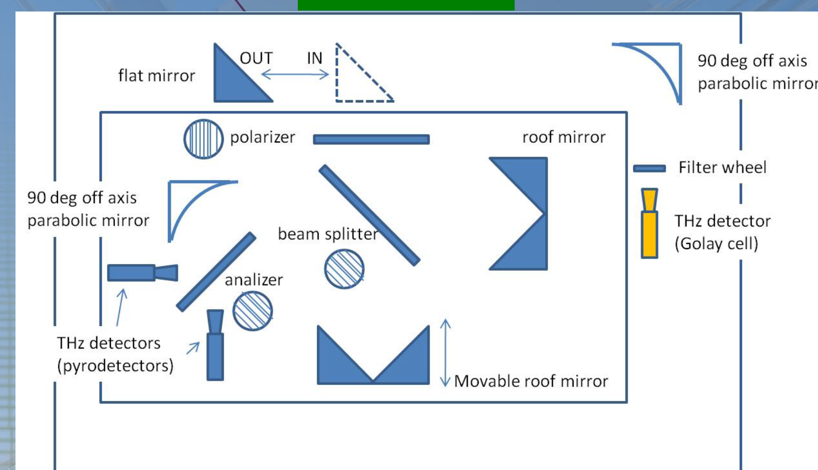


See G. Marcus, THPC100

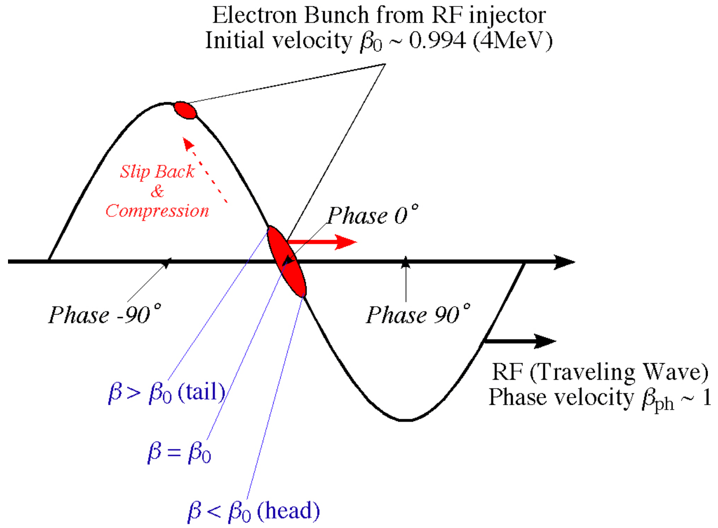
SPARC LAYOUT: THZ SOURCE

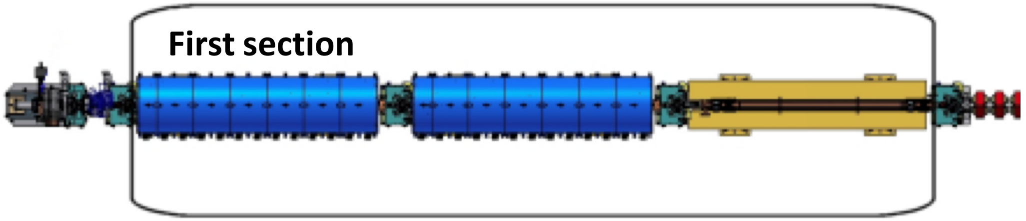




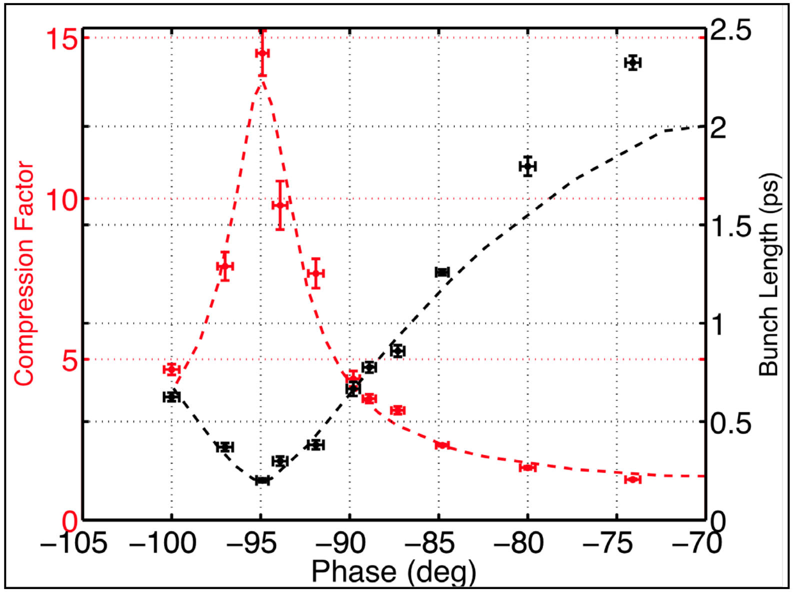


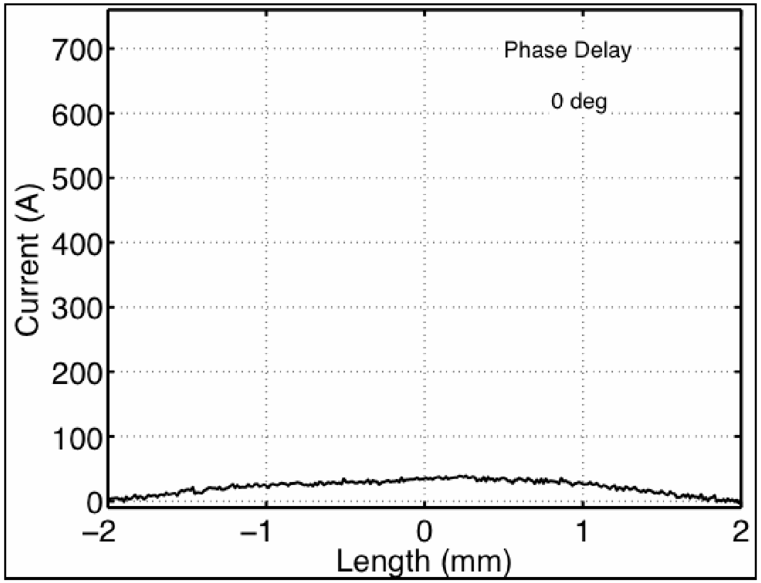
THE VELOCITY BUNCHING



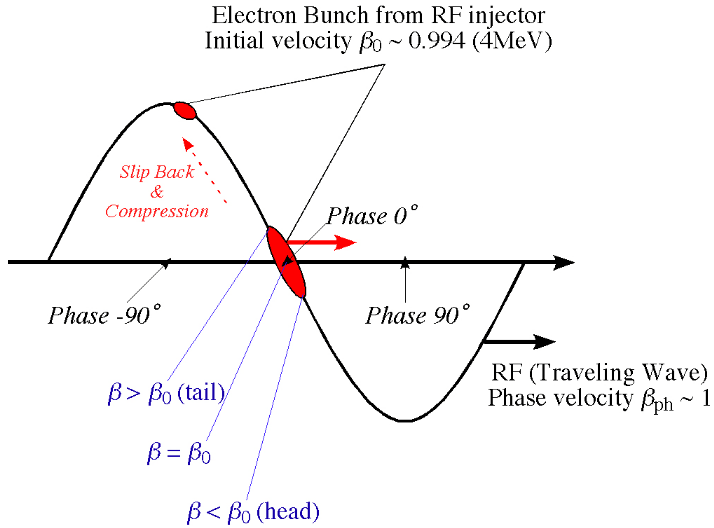


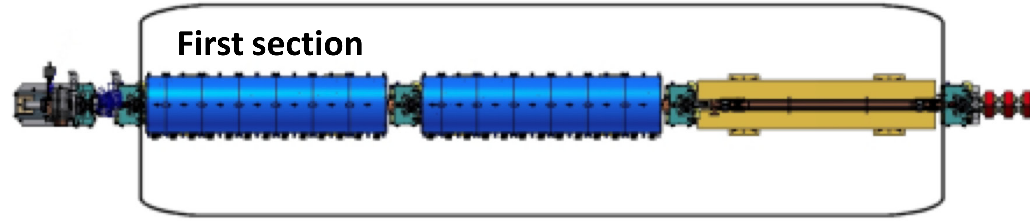
By shifting phase of the first accelerating section, one can modify the bunch length and current profile.





THE VELOCITY BUNCHING





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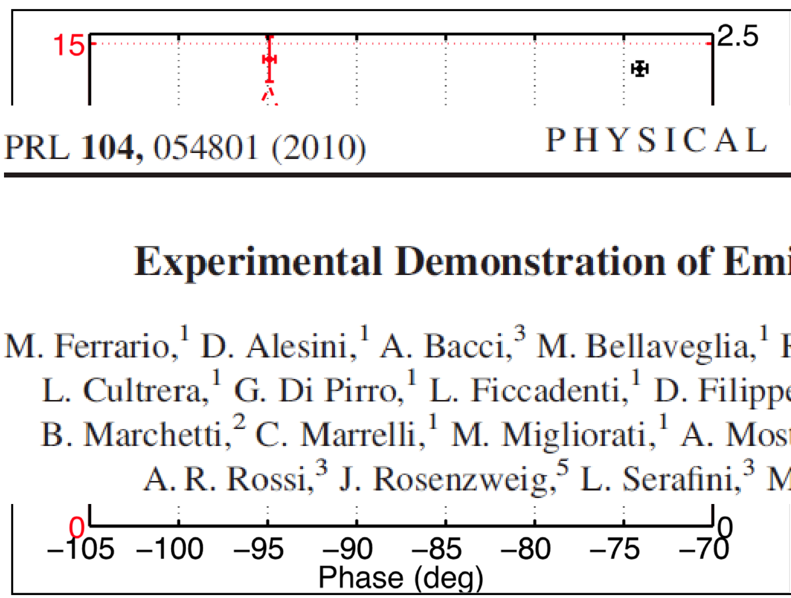
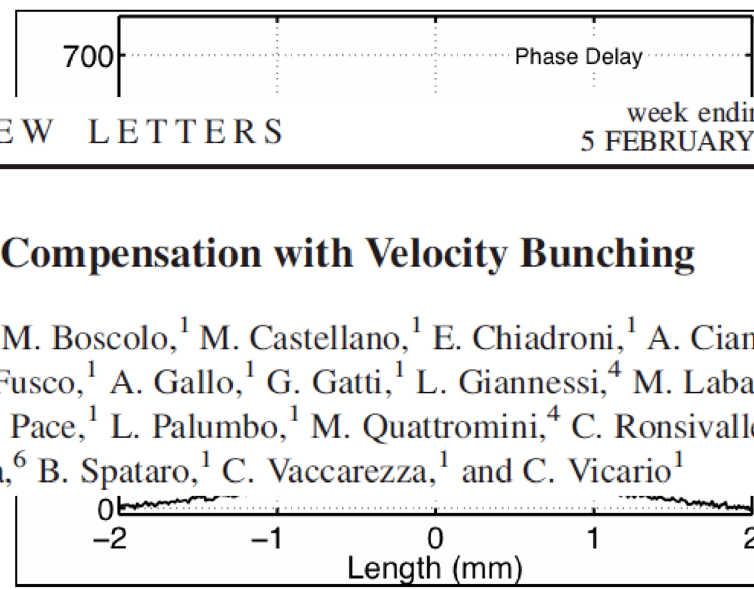




PRL 104, 054801 (2010) PHYSICAL REVIEW LETTERS week ending 5 FEBRUARY 2010

Experimental Demonstration of Emittance Compensation with Velocity Bunching

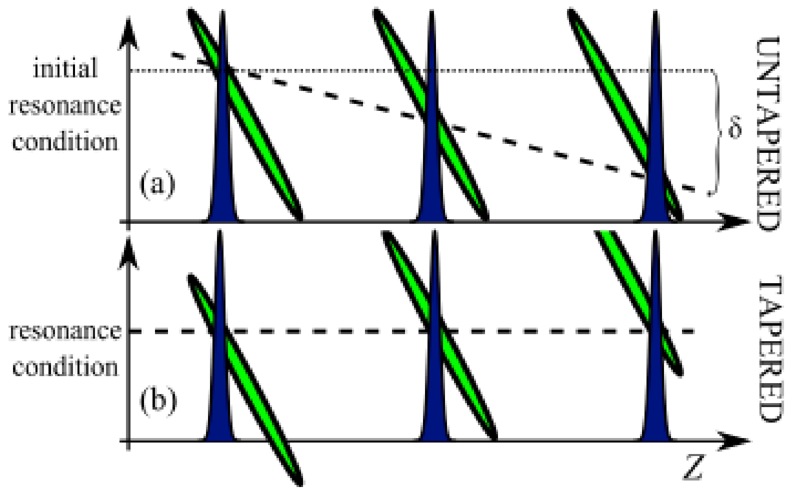
M. Ferrario,[1] D. Alesini,[1] A. Bacci,[3] M. Bellaveglia,[1] R. Boni,[1] M. Boscolo,[1] M. Castellano,[1] E. Chiadroni,[1] A. Cianchi,[2] L. Cultrera,[1] G. Di Pirro,[1] L. Ficcadenti,[1] D. Filippetto,[1] V. Fusco,[1] A. Gallo,[1] G. Gatti,[1] L. Giannessi,[4] M. Labat,[4] B. Marchetti,[2] C. Marrelli,[1] M. Migliorati,[1] A. Mostacci,[1] E. Pace,[1] L. Palumbo,[1] M. Quattromini,[4] C. Ronsivalle,[4] A. R. Rossi,[3] J. Rosenzweig,[5] L. Serafini,[3] M. Serluca,[6] B. Spataro,[1] C. Vaccarezza,[1] and C. Vicario[1]

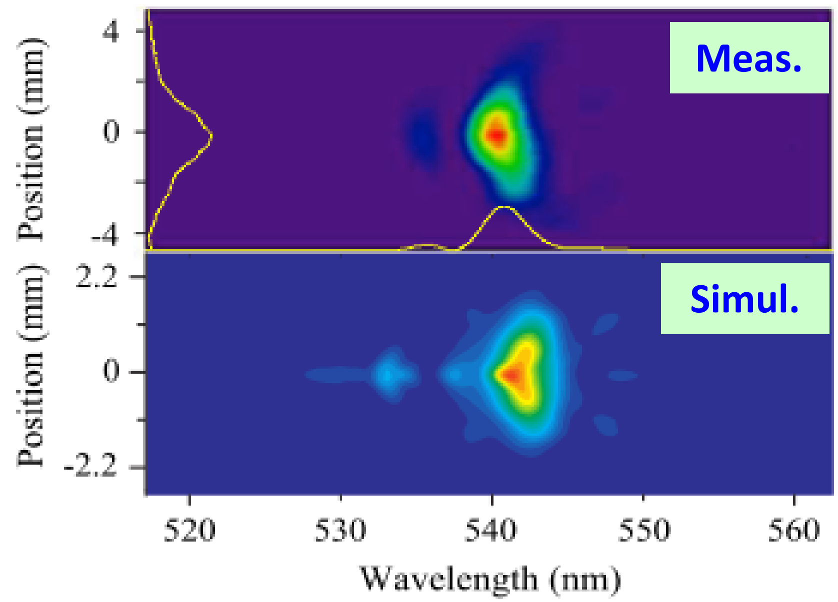
VB CHIRPED BEAM INTO AN UNDULATOR

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]

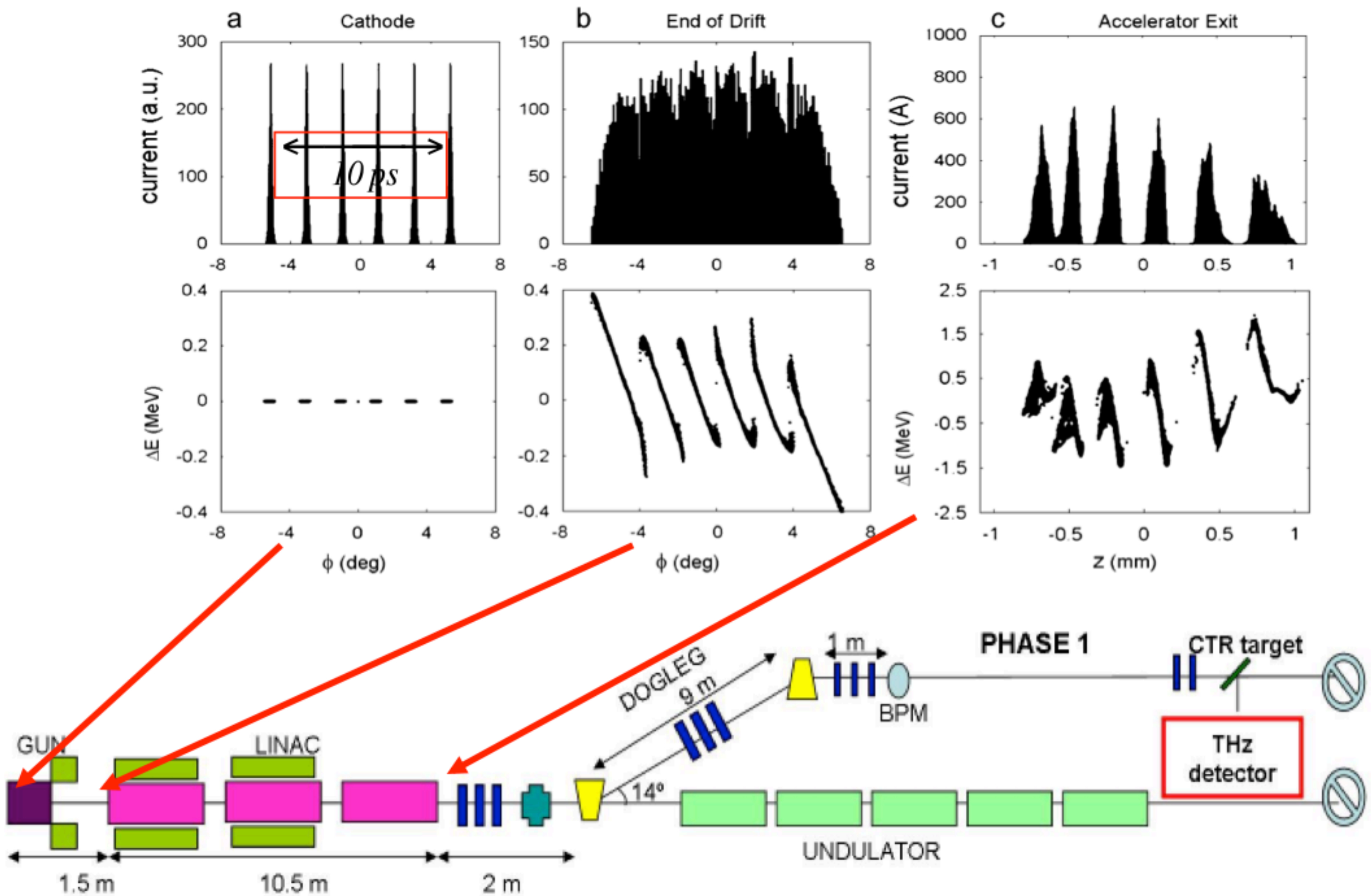




D. Filippetto et al. @ FEL11

GENERATION OF A TRAIN OF BUNCHES: LASER COMB

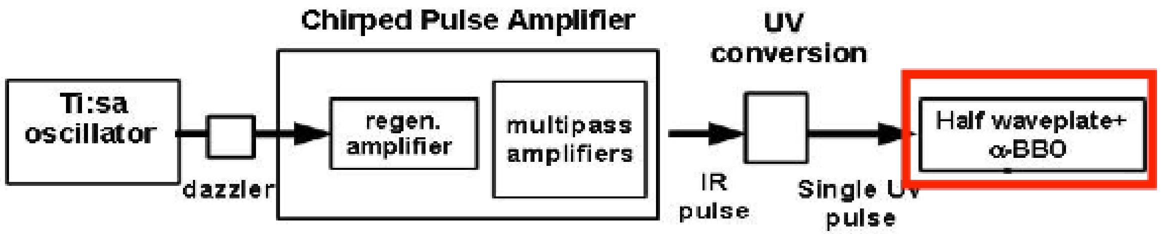
COMB BEAM GENERATION AND MANIPULATION



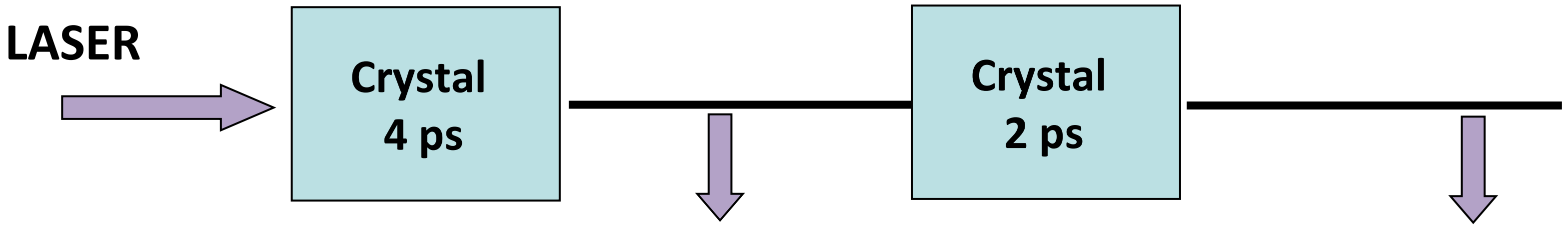
P. O'Shea et al., Proc. of PAC05, p.704 (2005).

M. Boscolo, M. Ferrario et al., NIM A 577, 409-416 (2007)

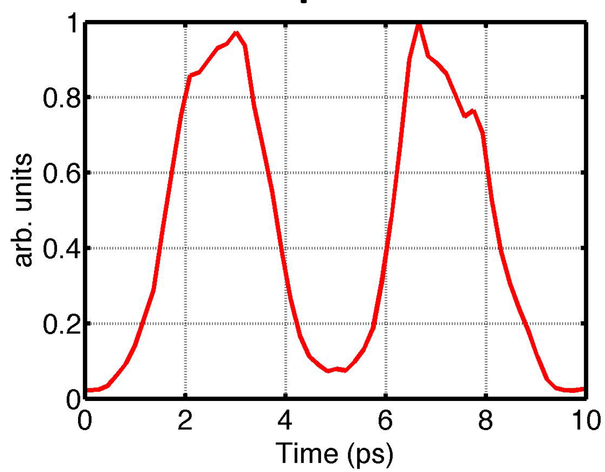
LASER PULSE TRAIN GENERATION



$$\Delta\tau = \left| \frac{1}{v_{ge}} - \frac{1}{v_{go}} \right| L_{crystal}$$

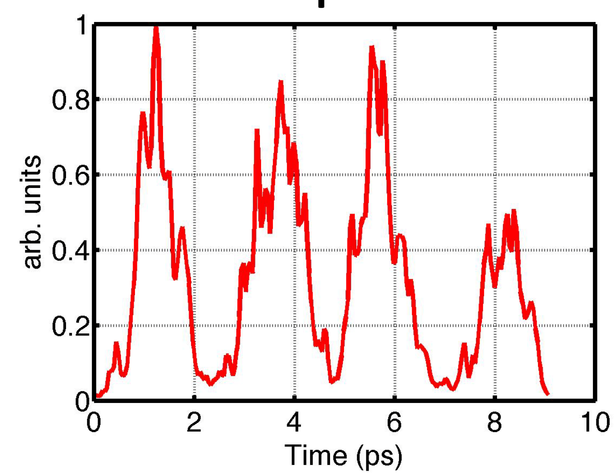


UV pulses



Streak camera

UV pulses

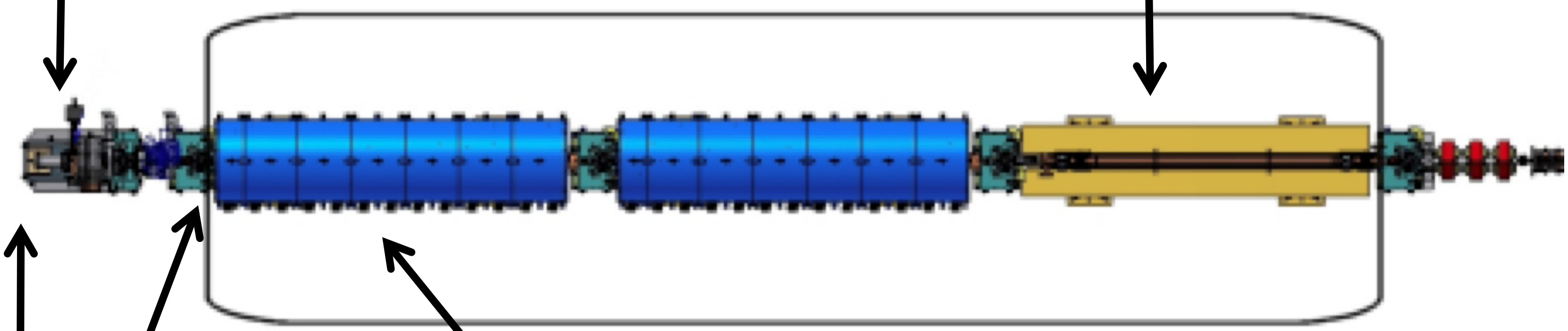


Streak camera

COMB BEAM MANIPULATION

Gun focusing field (~3kG)
Emittance
Bunches current, length

Accelerating field
Energy separation



Inj. phase
Bunch spacing
Train length

TW focusing field (~300G)
Emittance
Bunches current, length and their max compression phase

Gun inj. phase and space charge
Bunches distance at the linac entrance

Gun exit energy
Beam brightness

Compression phase stability
Bunch separation stability

PERFORMANCE IMPROVEMENTS

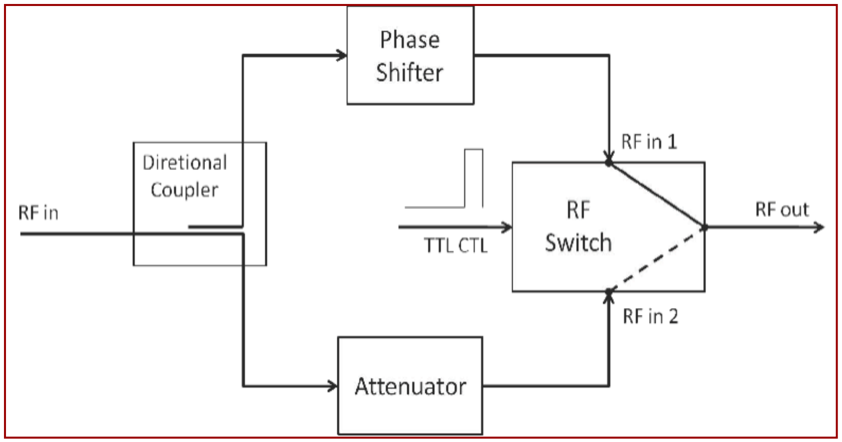
Beam energy at the gun exit

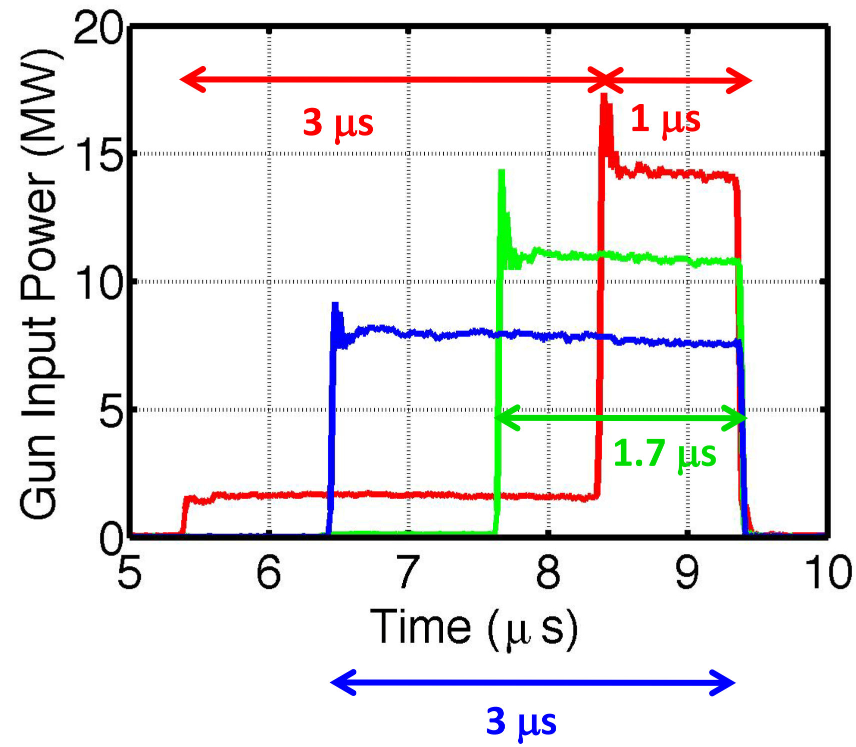
14 MW - 130 MV/m – 6.2 MeV

11 MW - 115 MV/m – 5.1 MeV

7.5 MW - 95 MV/m – 4.4 MeV

M. Bellaveglia, M. Ferrario, A. Gallo, SPARC Note in preparation.



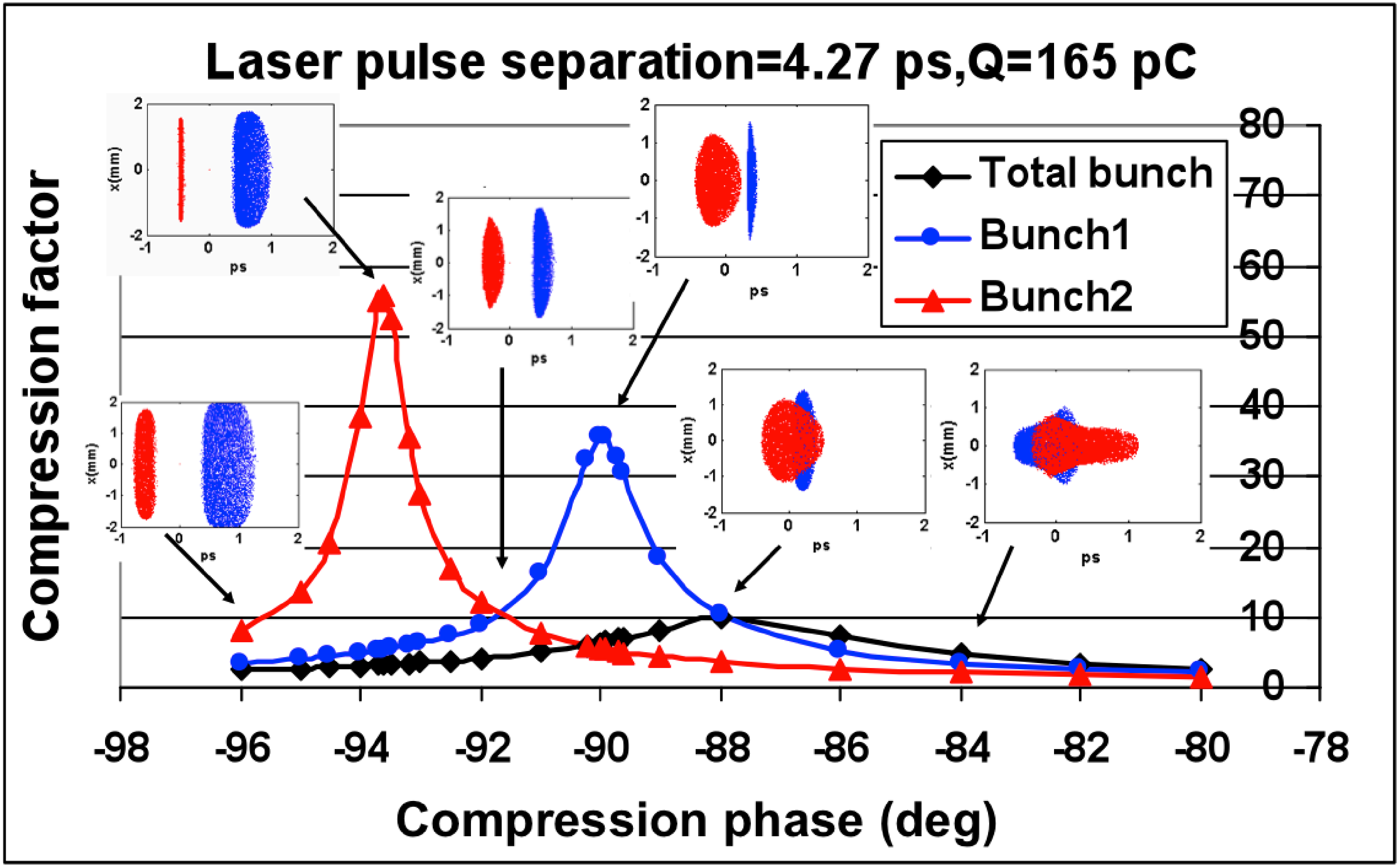


Peak brightness improved of a factor 2.6.

Machine stability

Locking the RF synchronization to the laser master clock, we achieved a machine jitter stability < 150fs$_{RMS}$

LONG. DYNAMICS: THE COMPRESSION CURVE



TSTEP simulation by C. Ronsivalle

TWO SUB-BUNCHES BEAM: LONG. PHASE SPACE

Measurements with 200pC, 300pC, 400pC bunch train.

Gun energy 5.6MeV

Charge 150pC/150pC

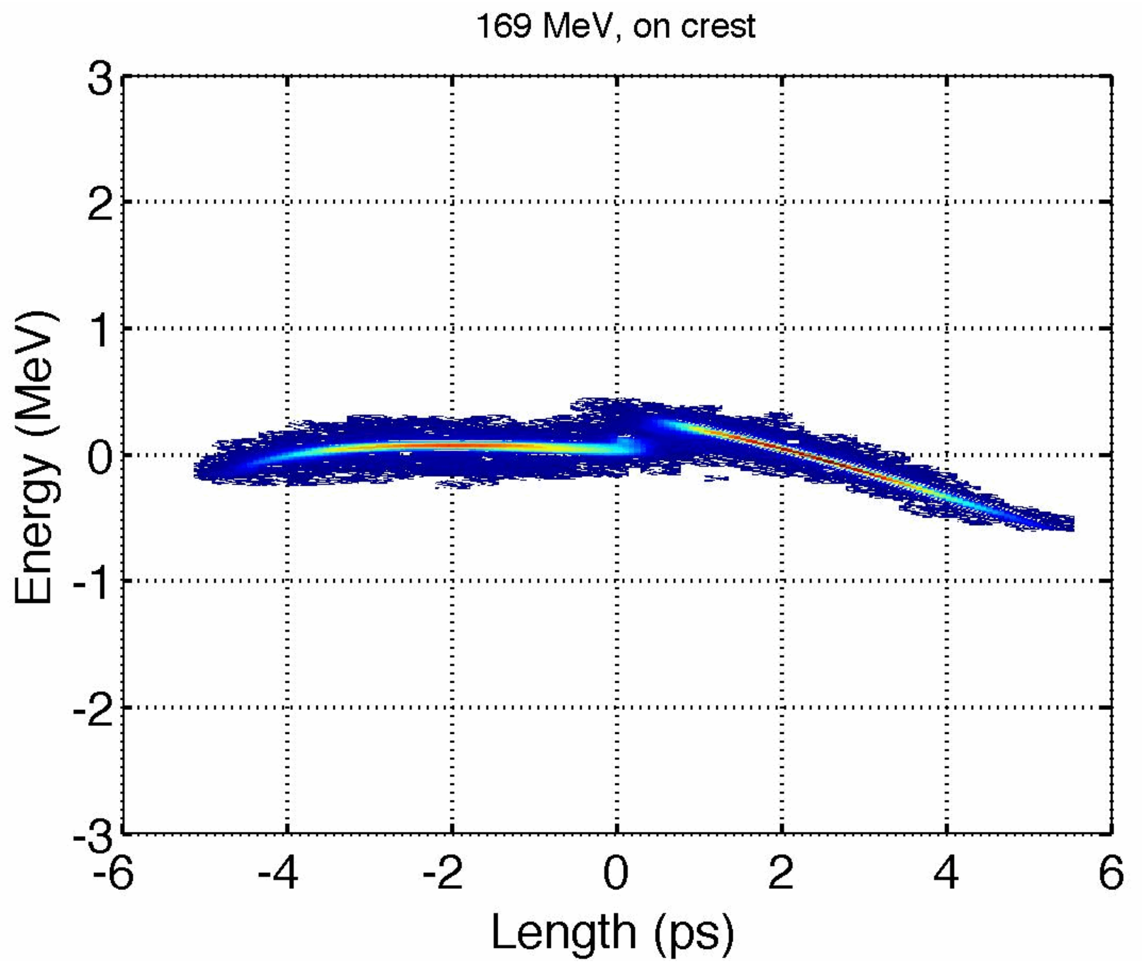
Energy 169-109 MeV

Energy Spread <0.7%

Bunch length on crest
2.505 (0.010) ps

Min. bunch length
244 (11) fs

Gun ext. phase
35 deg



TWO SUB-BUNCHES BEAM: SEPARATION

Measurements with 160pC compared to TSTEP simulation

Gun energy 4.5MeV

Charge 100pC/60pC

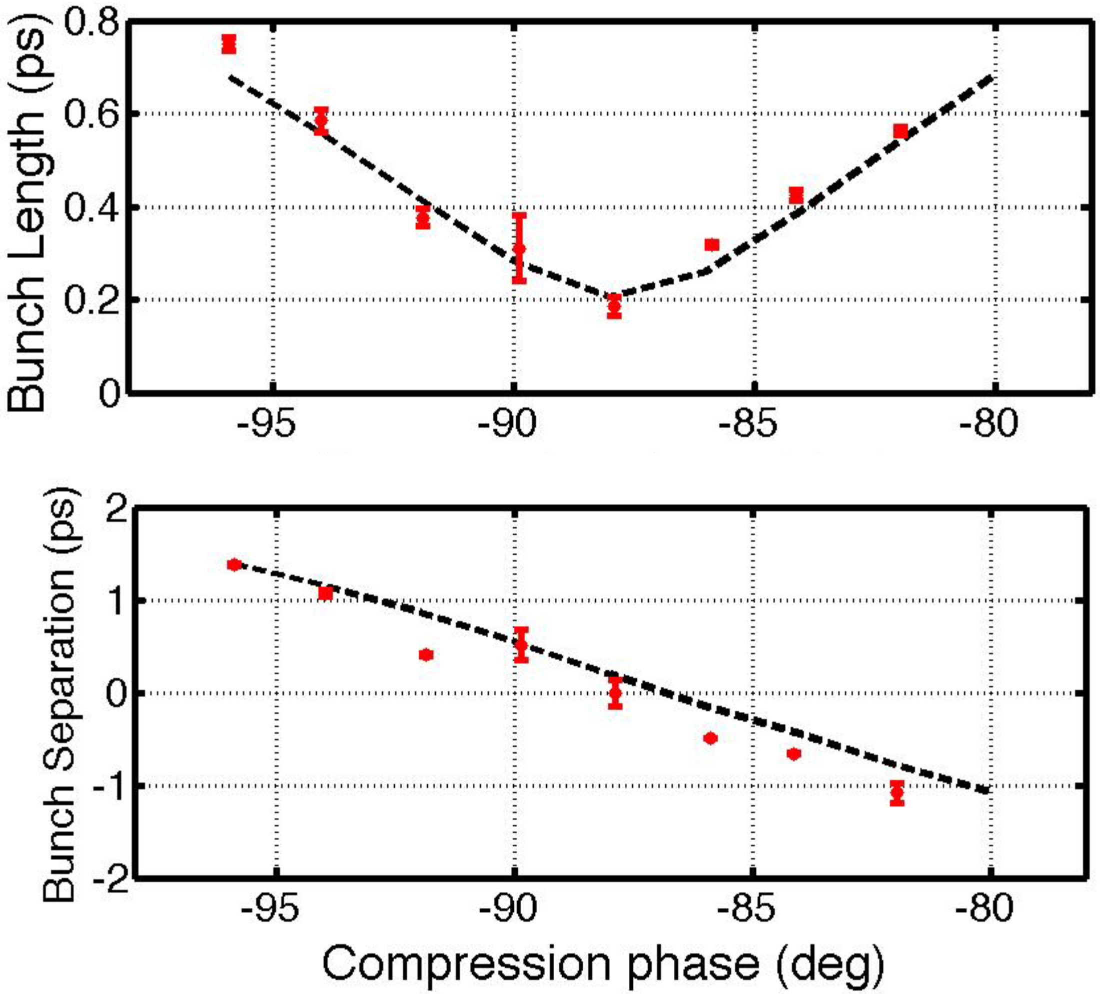
Energy 177-110 MeV

Energy Spread <0.7%

Bunch length on crest
1.880 (0.041) ps

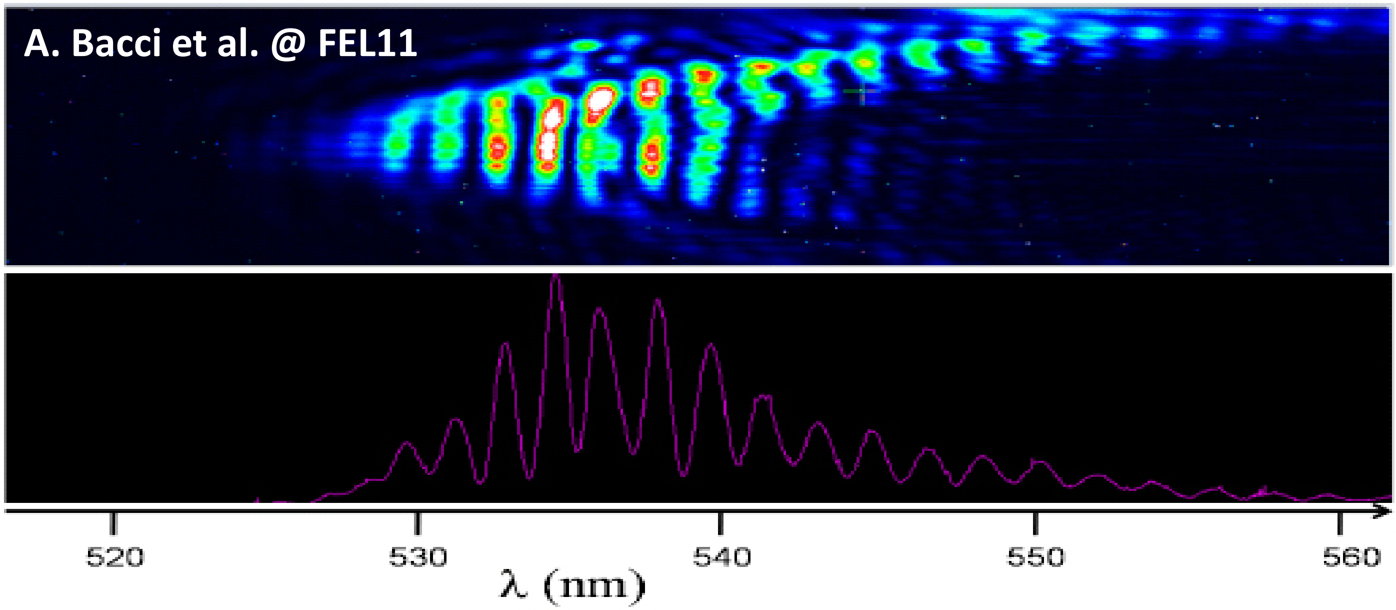
Min. bunch length
186 (21) fs

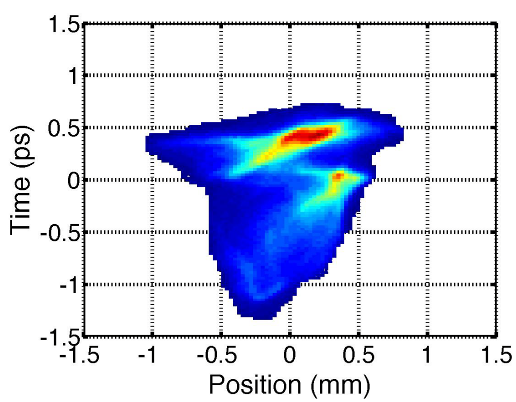
Gun ext. phase
23 deg

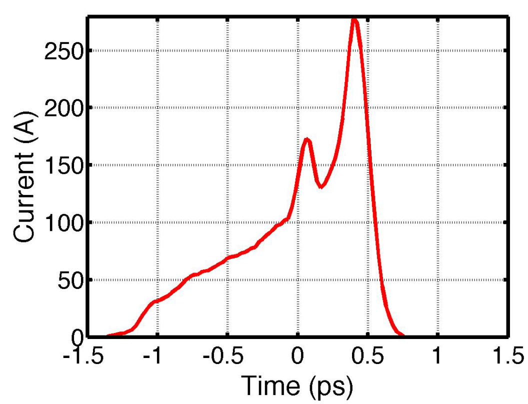


TSTEP simulation by C. Ronsivalle

FEL LIGHT FROM A TWO BUNCHES COMB BEAM







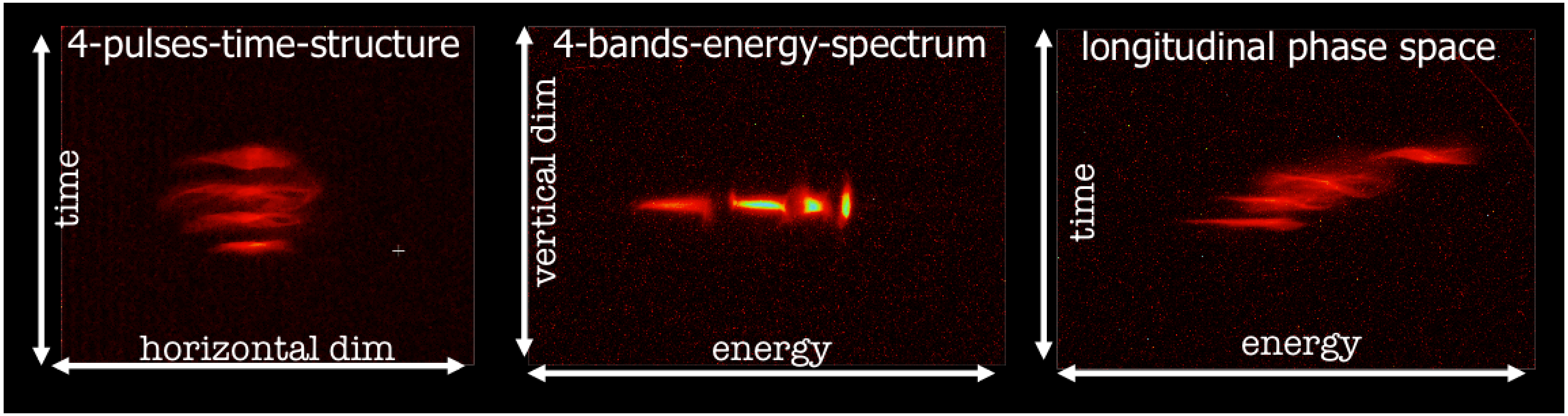
Bunch Separation (from RFD)
0.8091 (0.053)ps

$$\Delta\tau = \frac{\lambda^2}{\Delta\lambda} =$$ **0.62 (0.16)ps**

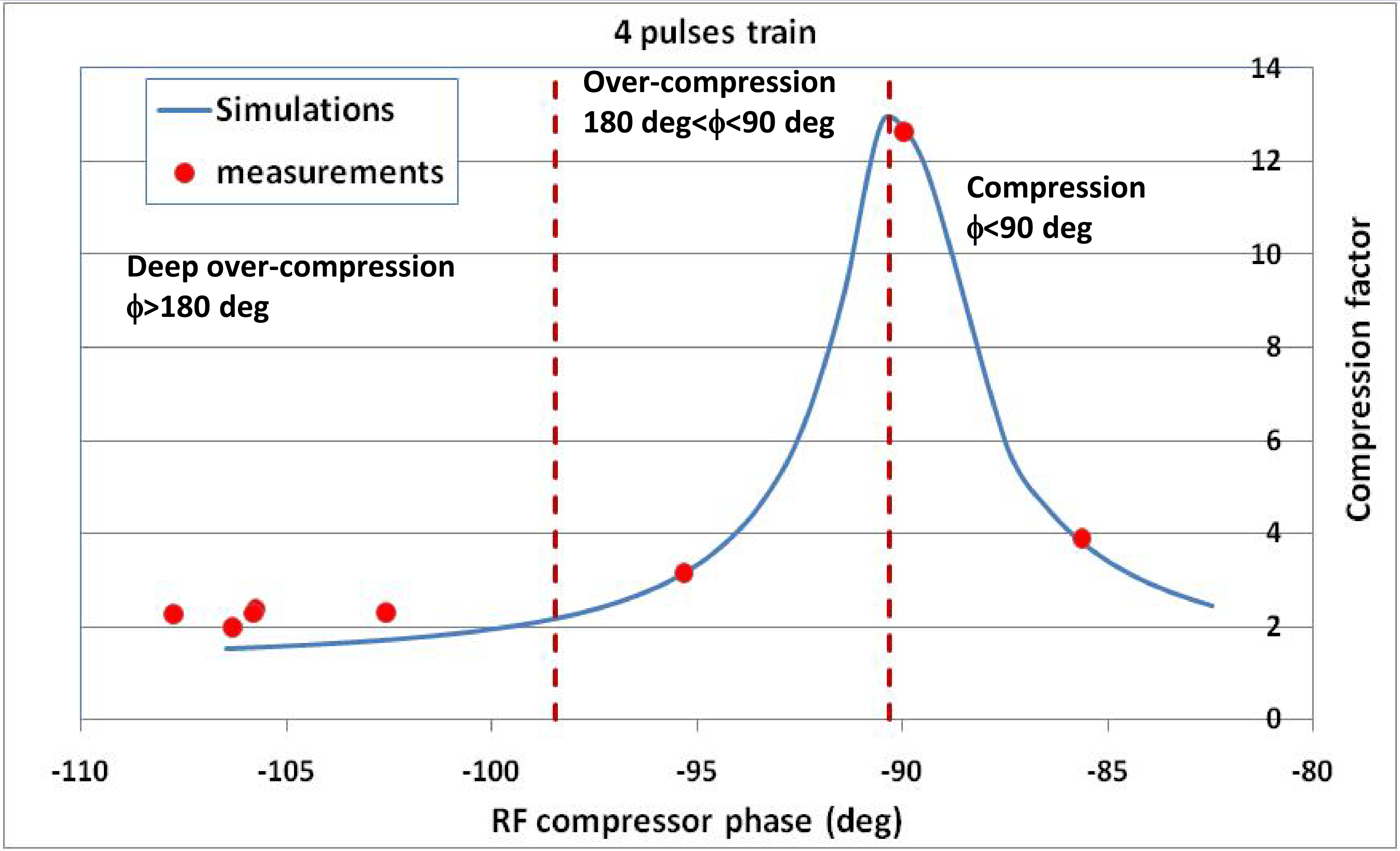
Preliminary results.

Charge **90pC/90pC**

FOUR PULSES COMB BEAM

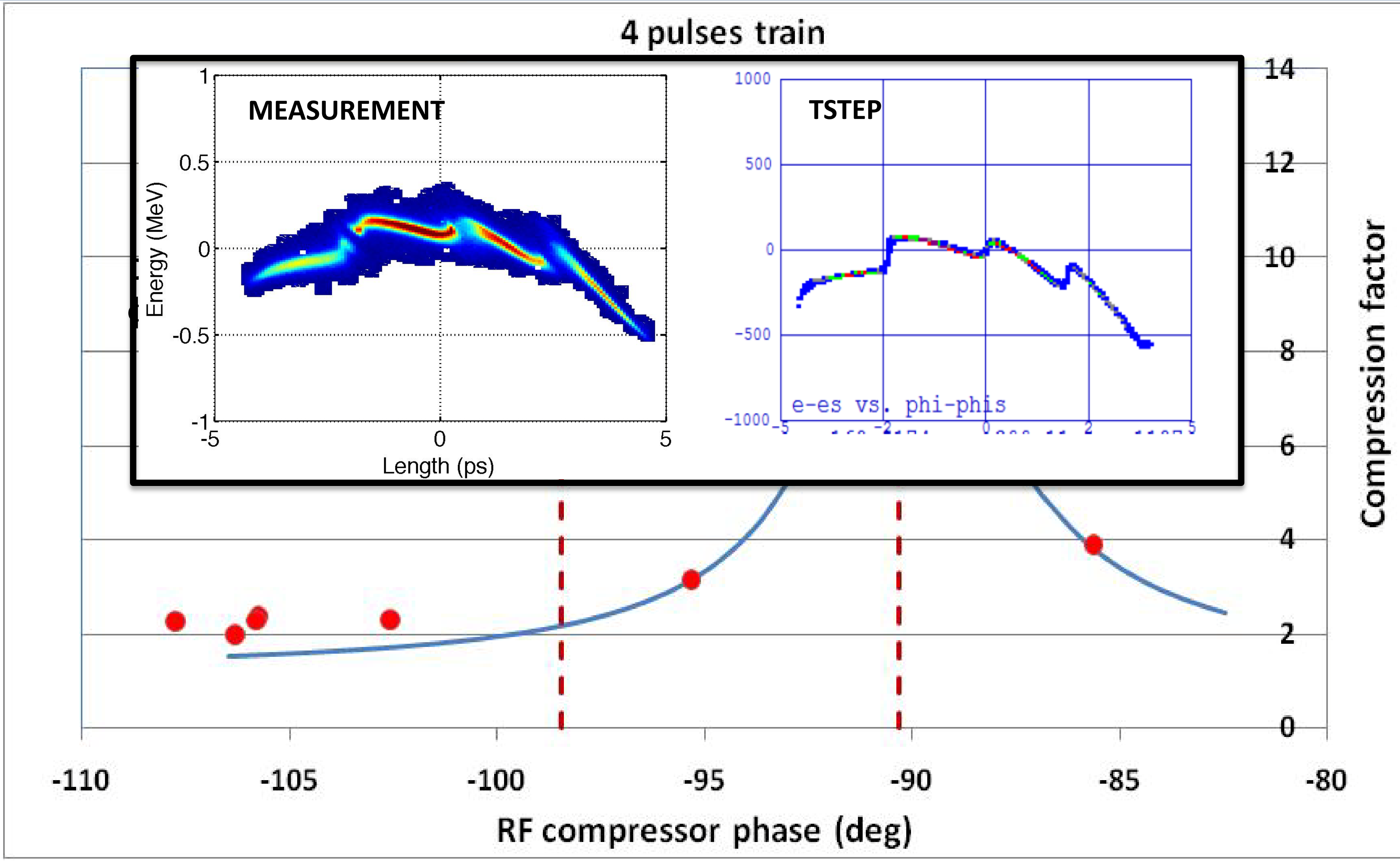


FOUR BUNCHES COMB BEAM: COMP. CURVE



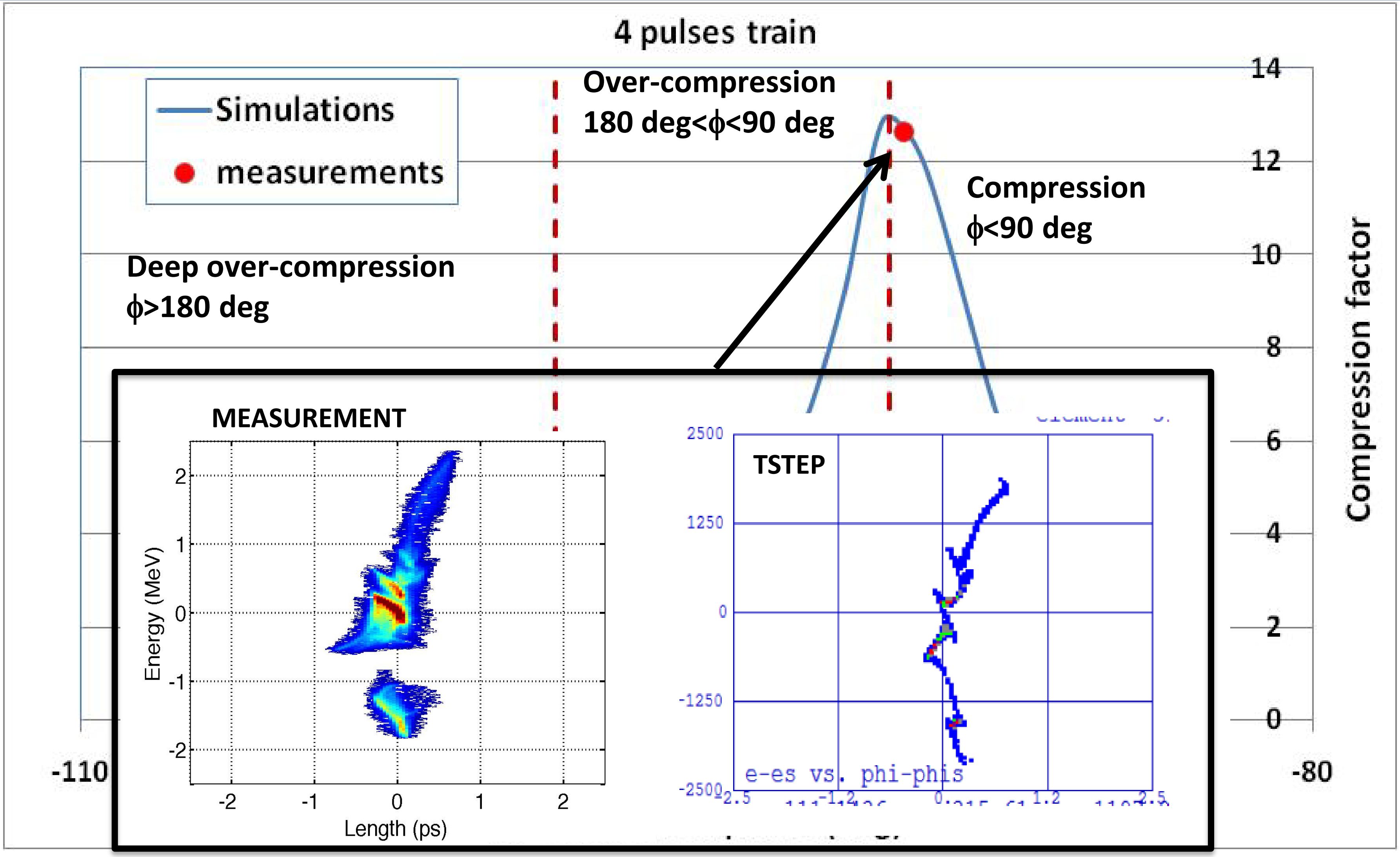
TSTEP simulation by C.Ronsivalle

FOUR BUNCHES COMB BEAM: COMP. CURVE



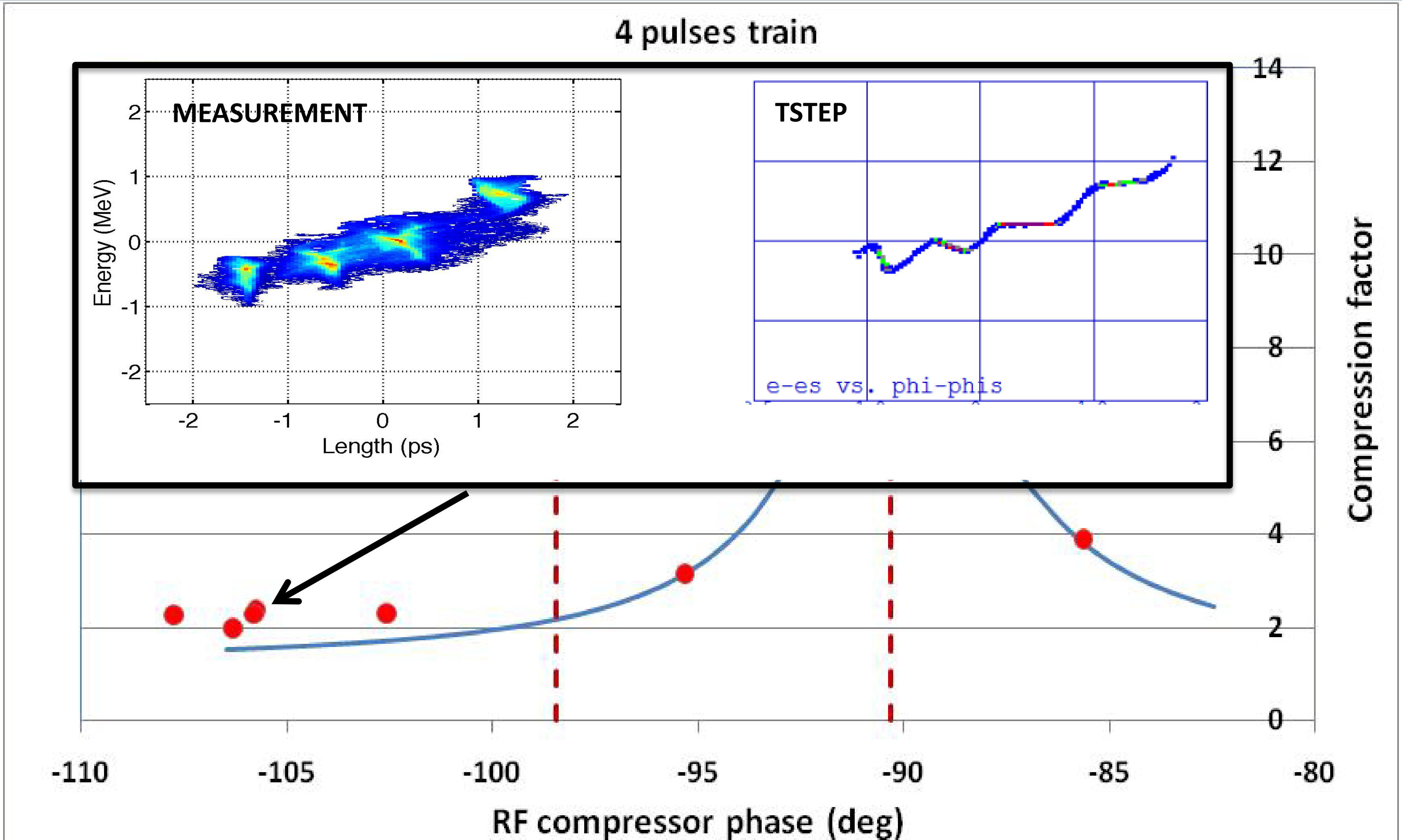
TSTEP simulation by C. Ronsivalle

FOUR BUNCHES COMB BEAM: COMP. CURVE



TSTEP simulation by C. Ronsivalle

FOUR BUNCHES COMB BEAM: COMP. CURVE



TSTEP simulation by C. Ronsivalle

LONGITUDINAL PHASE SPACE ROTATION

Measurements with 200pC

Gun energy 5.7MeV

Charge
40pC/80pC/50pC/30pC

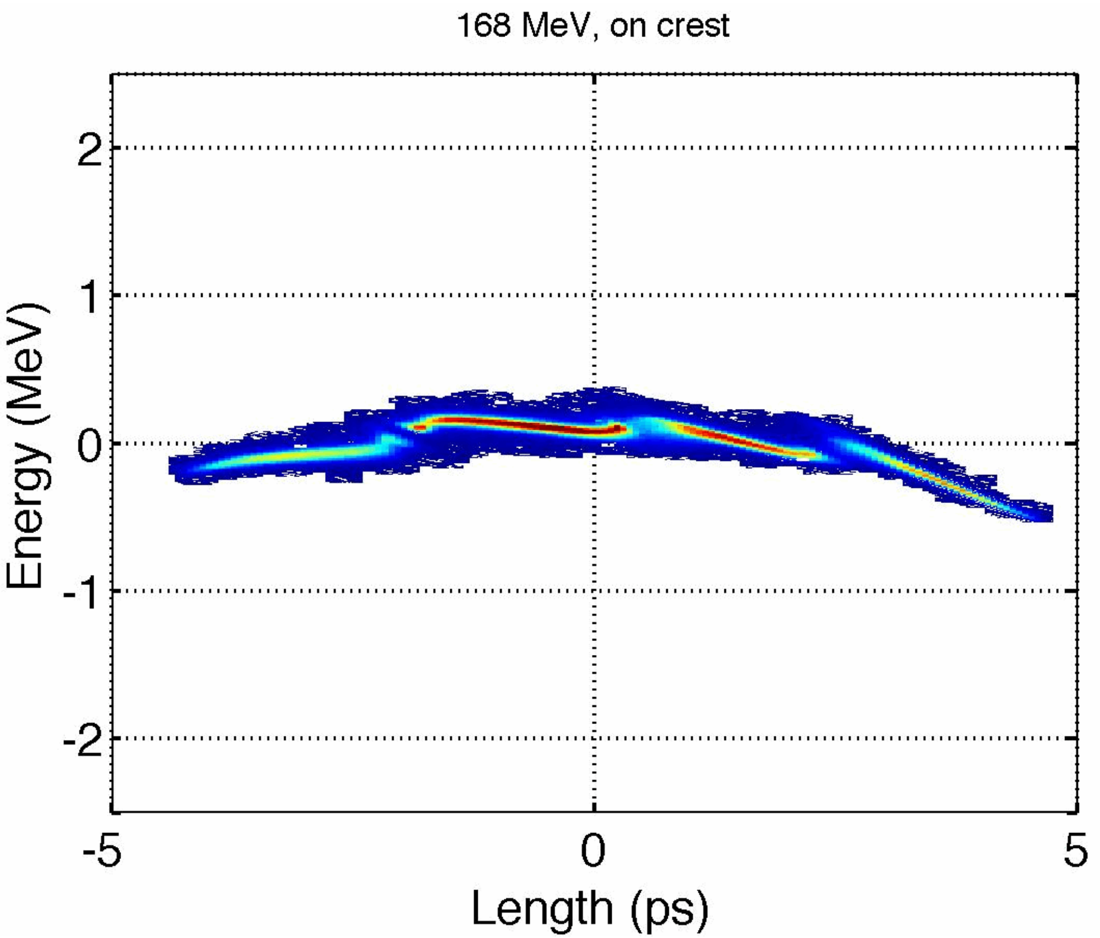
Energy 168-109 MeV

Energy Spread <0.8%

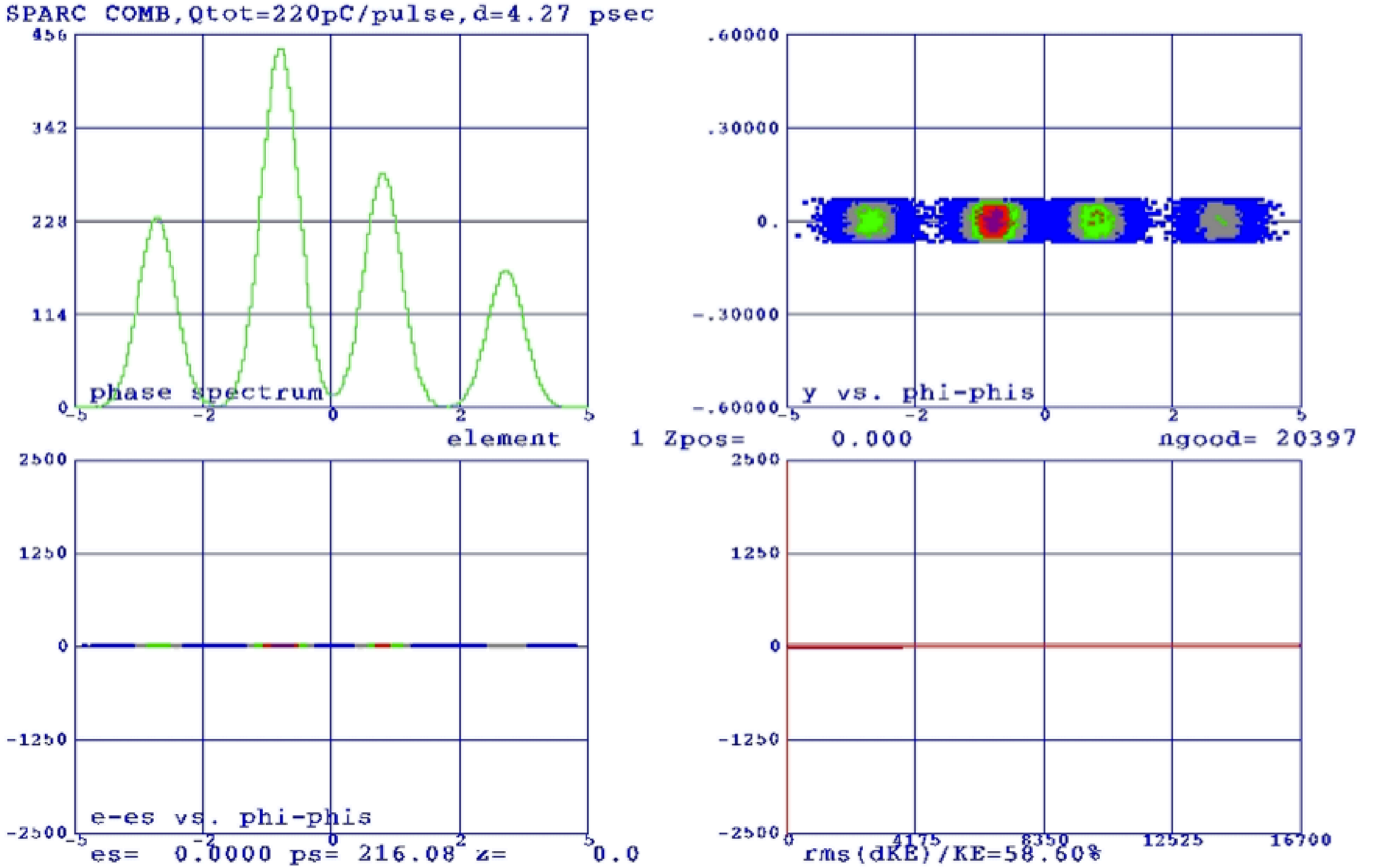
Bunch length on crest
2126.3 (8.7) fs

Min. bunch length
168.2 (8.7) fs

Gun ext. phase
35 deg

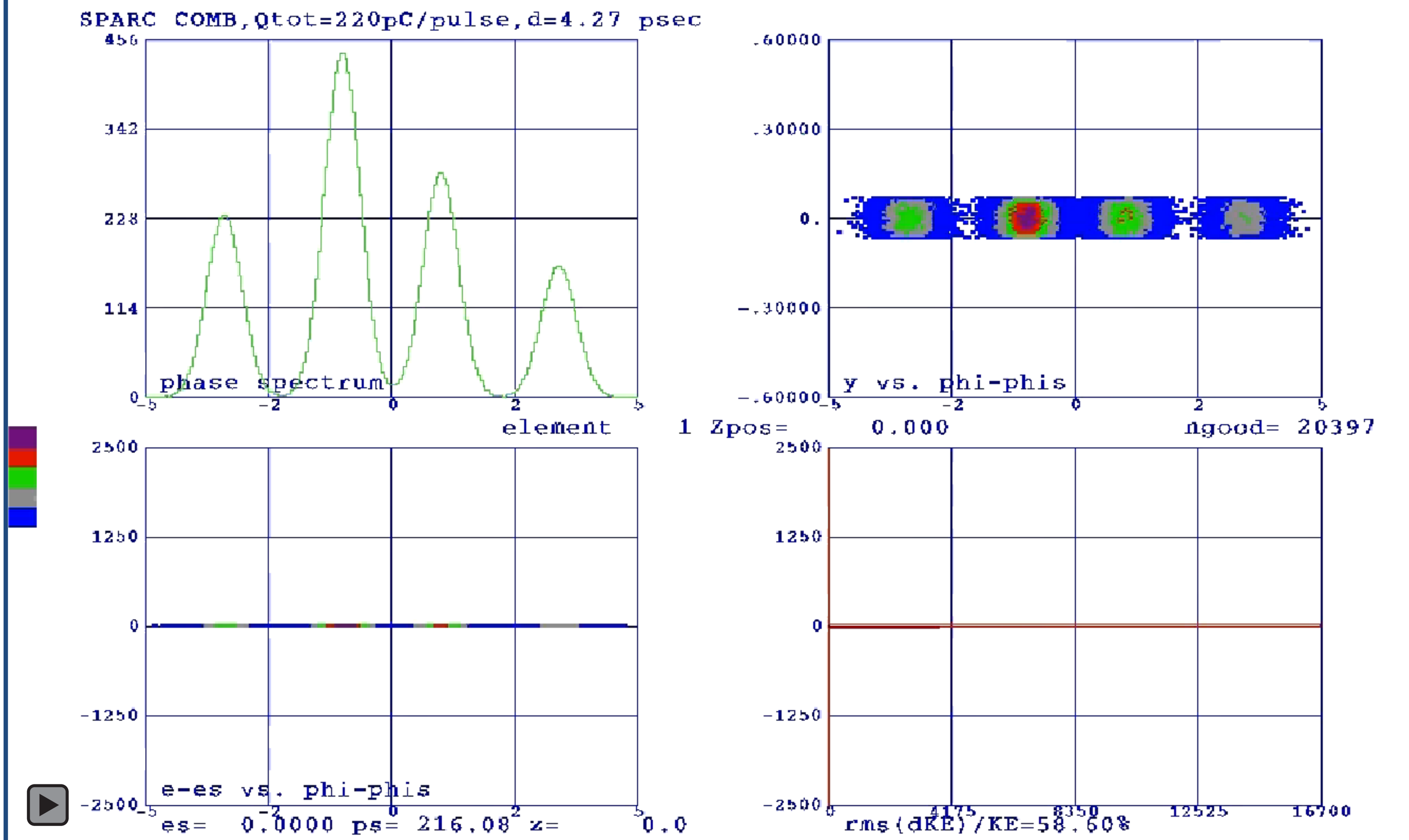


DEEP OVER-COMPRESSION



C. Ronsivalle, TSTEP simulations.

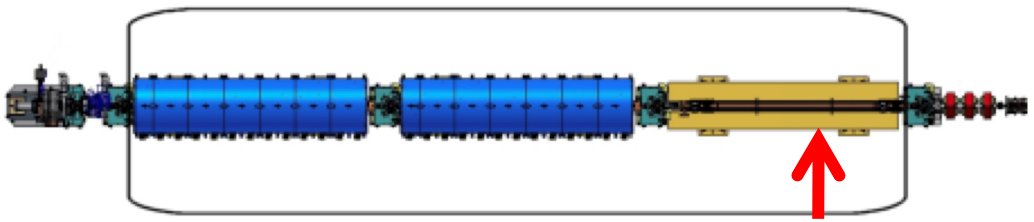
DEEP OVER-COMPRESSION

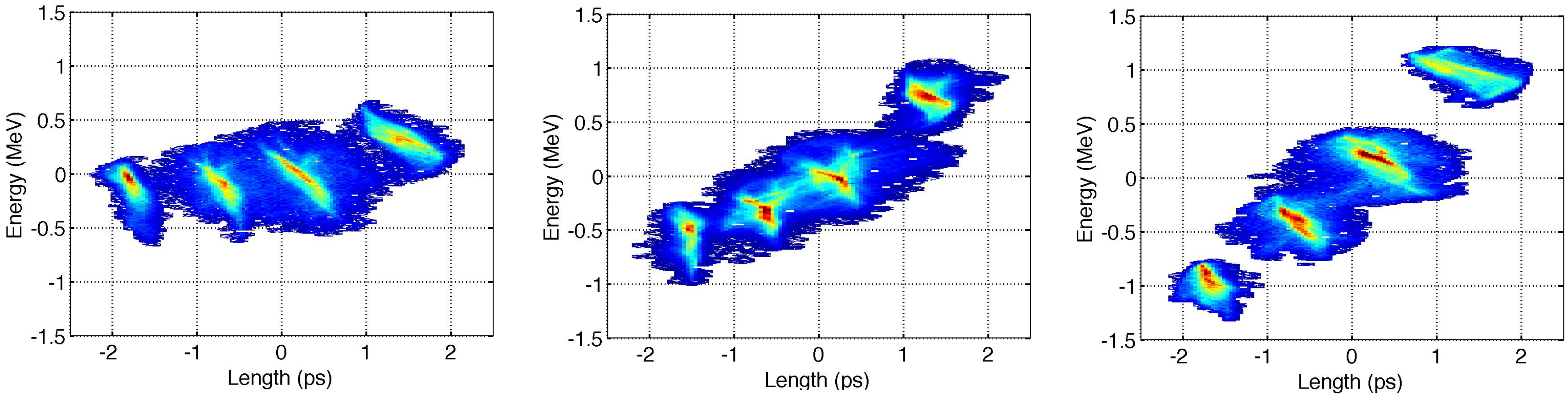


C. Ronsivalle, TSTEP simulations.

ENERGY SEPARATION TUNABILITY

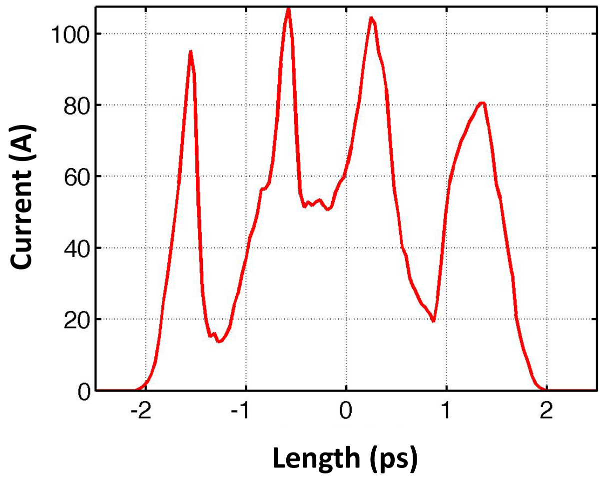
Measurements with 200pC

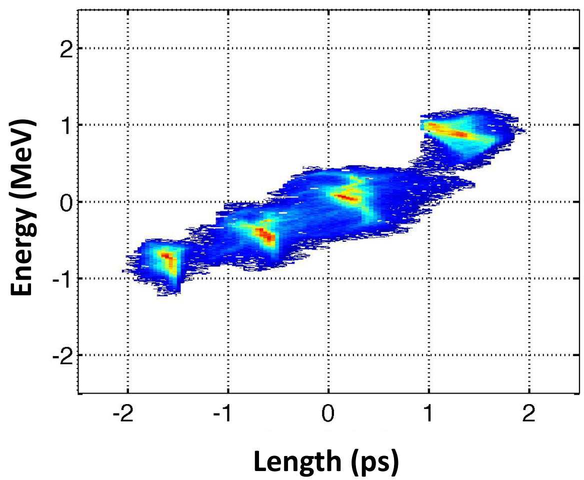




Parameter	Case 1	Case 2	Case 3
Comp. Phase	106.3deg	105.8deg	106.3deg
Bunch length	1.06ps	0.93ps	0.97ps
Time sep. av.	1.03ps	0.96ps	1.00ps
Energy	91.4MeV	111.4MeV	112.5MeV
En. Spread	0.3%	0.4%	0.6%
Energy sep. av.	0.13MeV	0.45MeV	0.65MeV

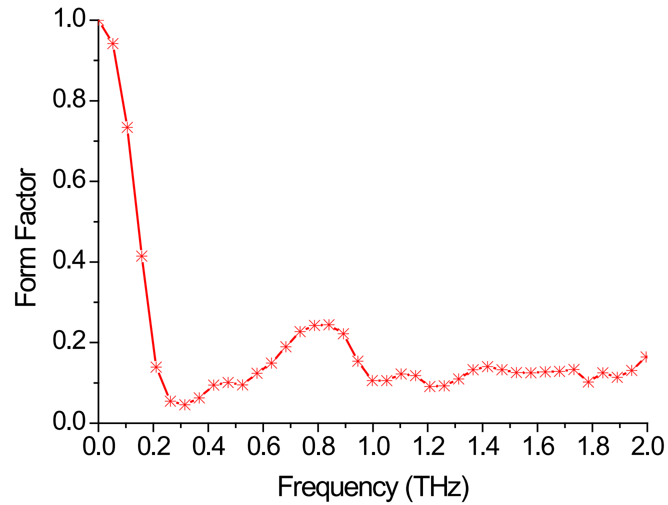
FOUR BUNCHES COMB BEAM: THZ RADIATION

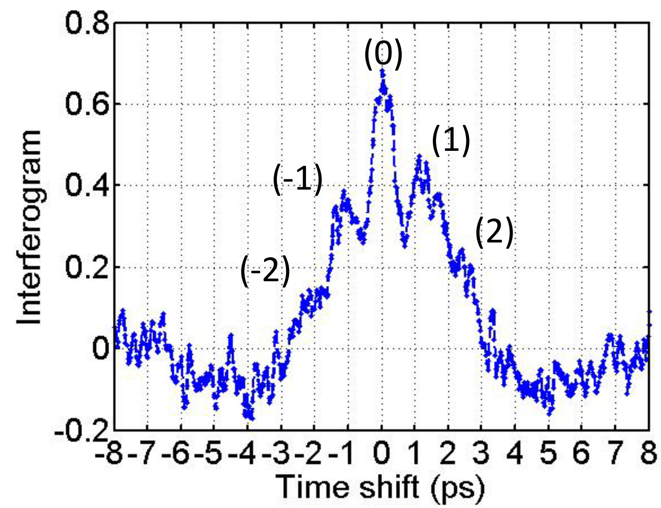




Measurements with 200pC

CTR screen



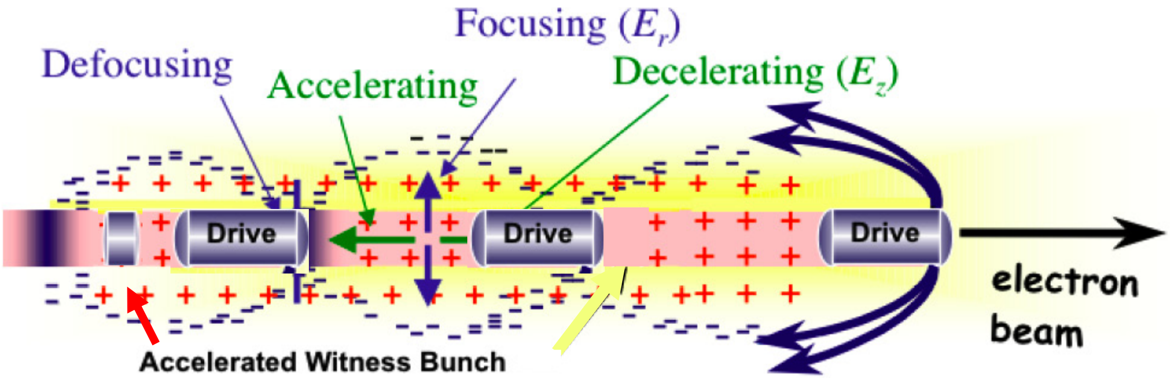


E. Chiadroni et al., THPS101

B. Marchetti et al., THPS104

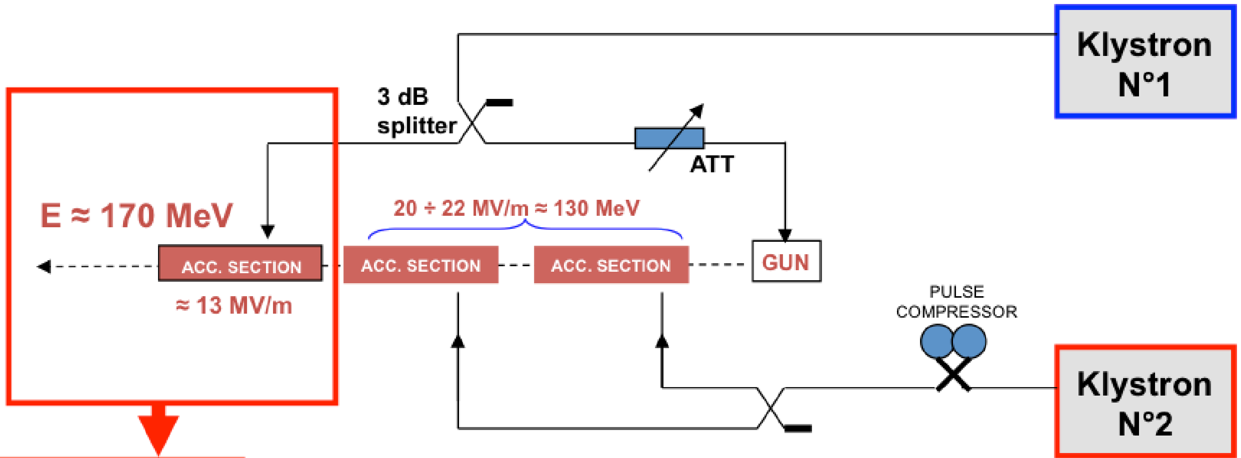
FUTURE APPLICATIONS OF COMB BEAMS

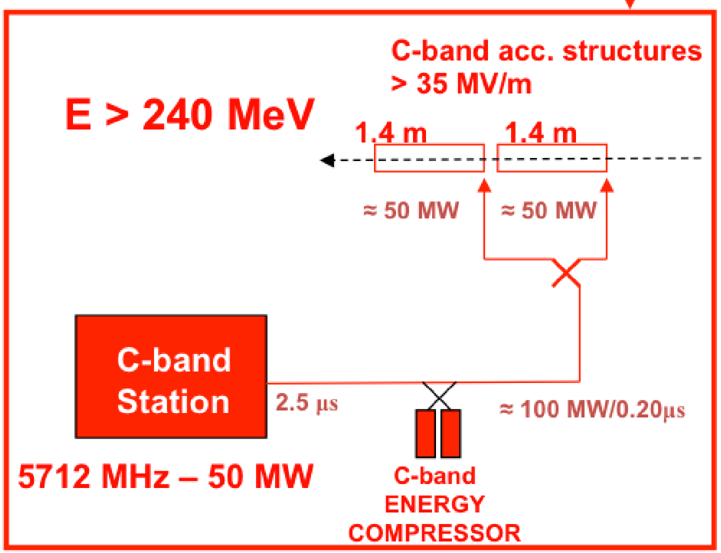
Resonant plasma Oscillations by Multiple electron Bunches



- **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 transformer ratio
- **High quality bunch** preservation during acceleration and transport

SPARC ENERGY UPGRADE





The new C-band system consists mainly of:

⇒ **2 accelerating sections** (1.4 m long)

⇒ 1 C-band **klystron** (50 MW), by Toshiba Ltd (JP)

⇒ 1 **Pulsed HV modulator** supplied by ScandiNova (S)

⇒ WR187 waveguide system

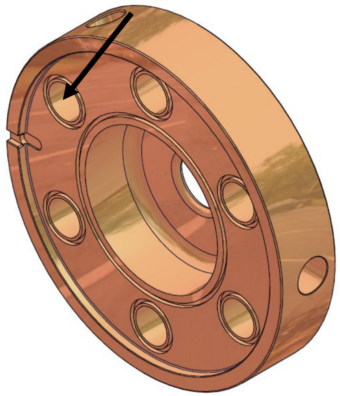
⇒ **400 W solid state driver** supplied by MitecTelecom (CDN)

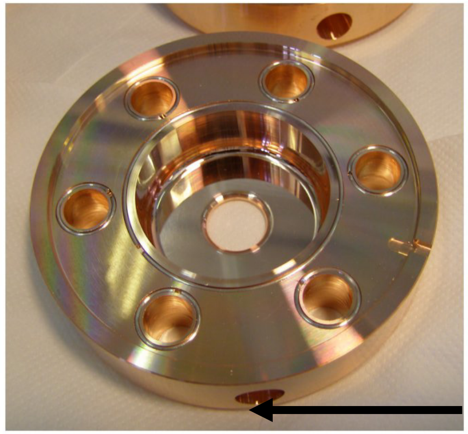
⇒ **SLED**

D. Alesini et al. SPARC-RF-11/002 (2011)

SPARC ENERGY UPGRADE: C-BAND SECTIONS

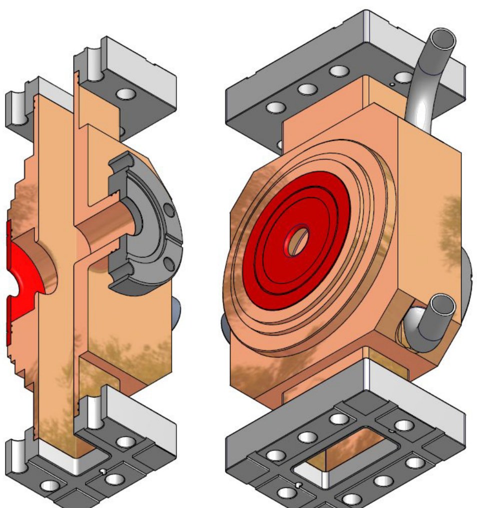
Cooling pipes

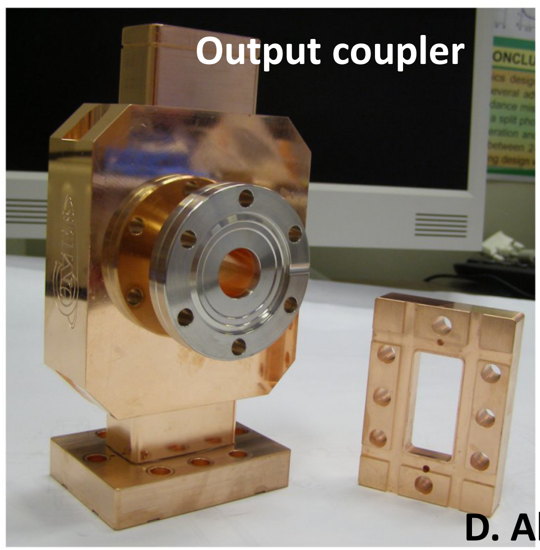




Tuning by deformation

Cell Ra<0.05μm tolerances ±2μm



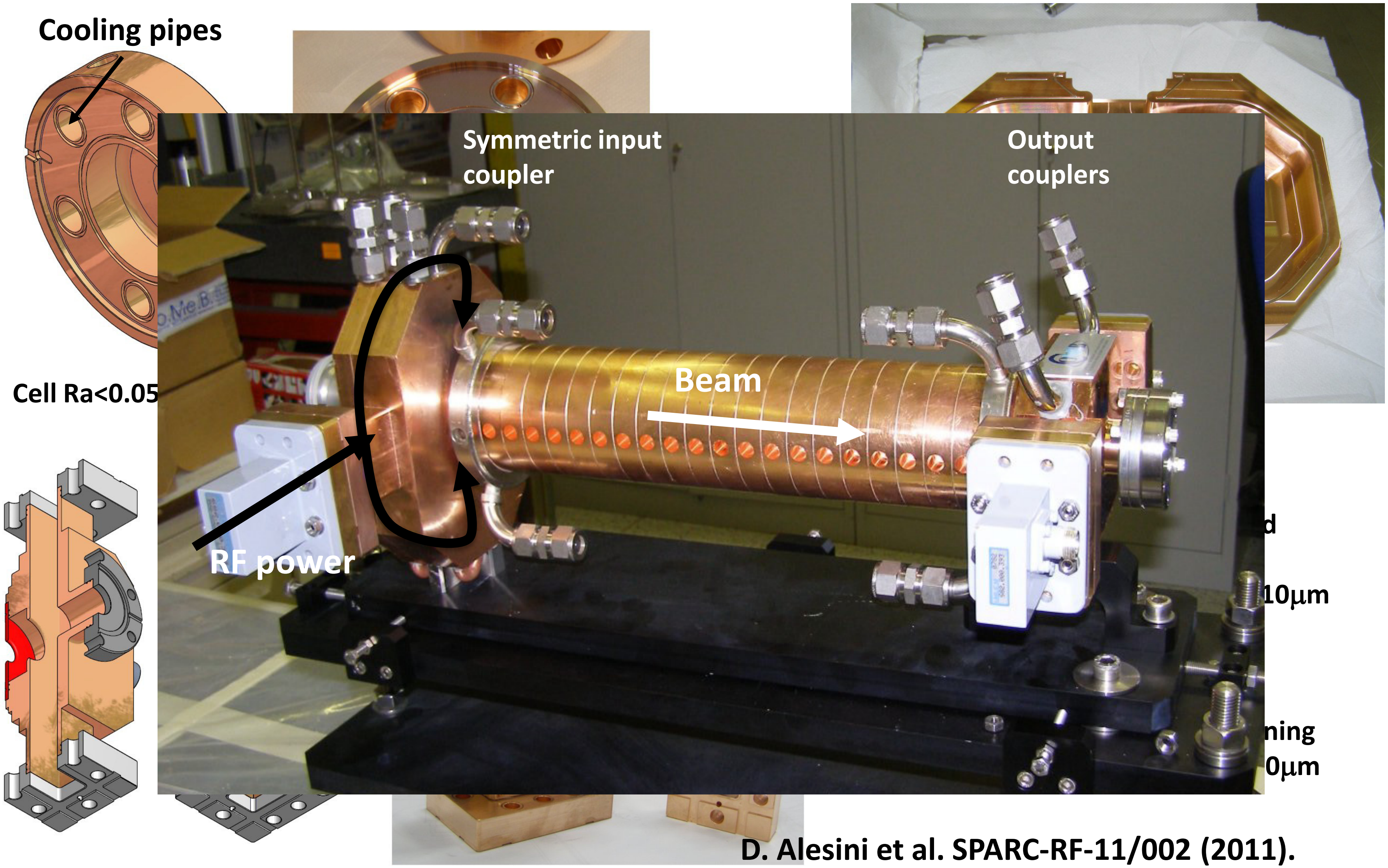


Input coupler
cumputer controlled
milling machine
Ra<0.2μm tolerances ±10μm

Output coupler:
Electro discharge machining
Ra<1.2μm tolerances ±20μm

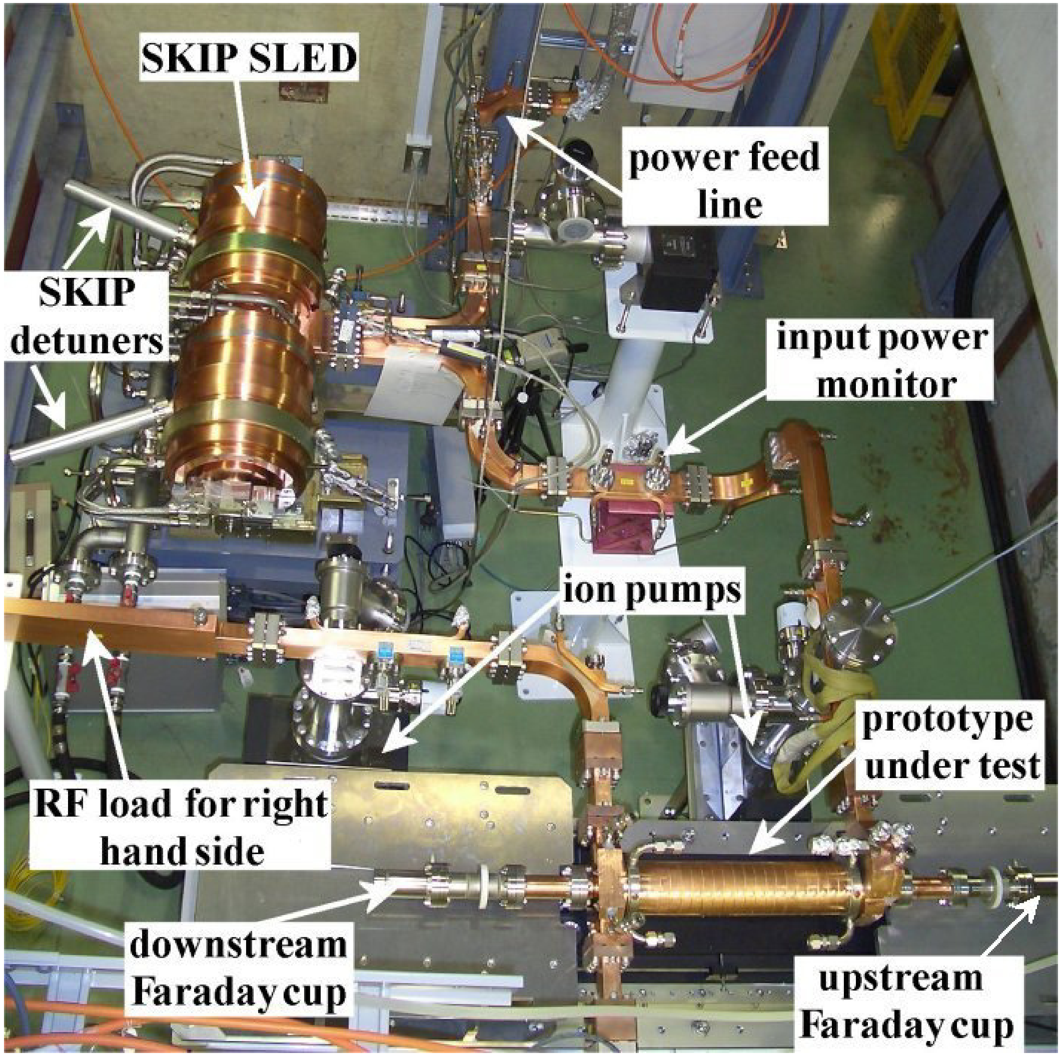
D. Alesini et al. SPARC-RF-11/002 (2011).

SPARC ENERGY UPGRADE: C-BAND SECTIONS



D. Alesini et al. SPARC-RF-11/002 (2011).

HIGH POWER TEST OF C-BAND PROTOTYPE

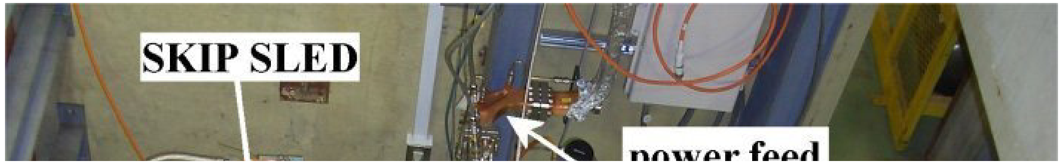


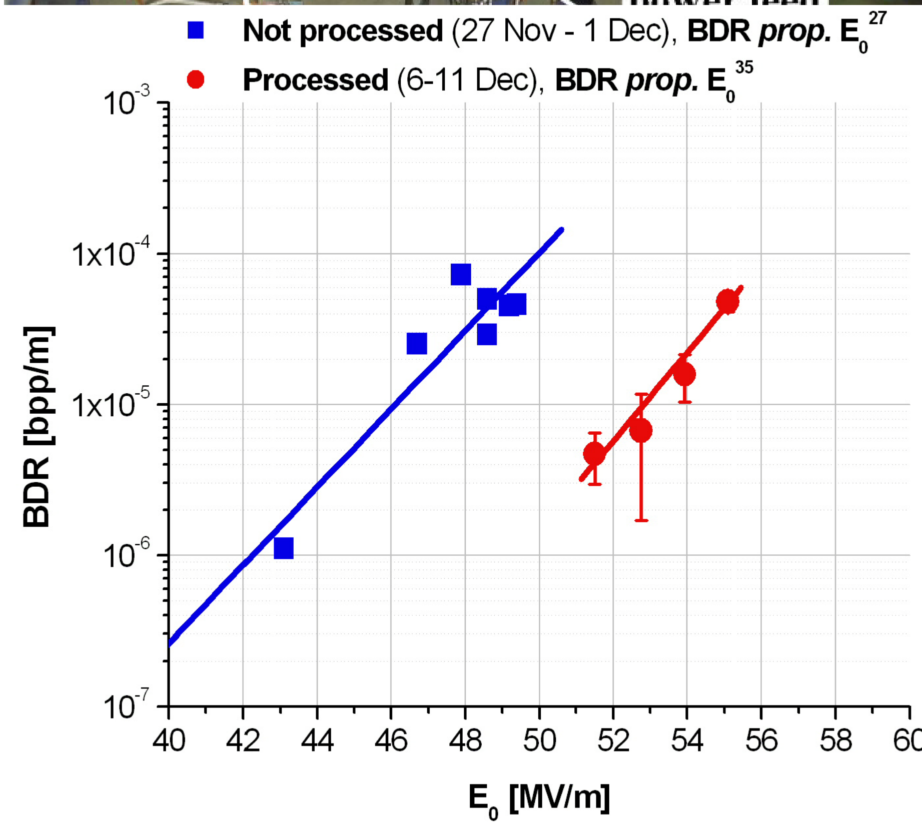
1.5 month long tests @ KEK

D. Alesini et al., SPARC-RF-11/005 (2011)

D. Alesini et al., MOPC013.

HIGH POWER TEST OF C-BAND PROTOTYPE



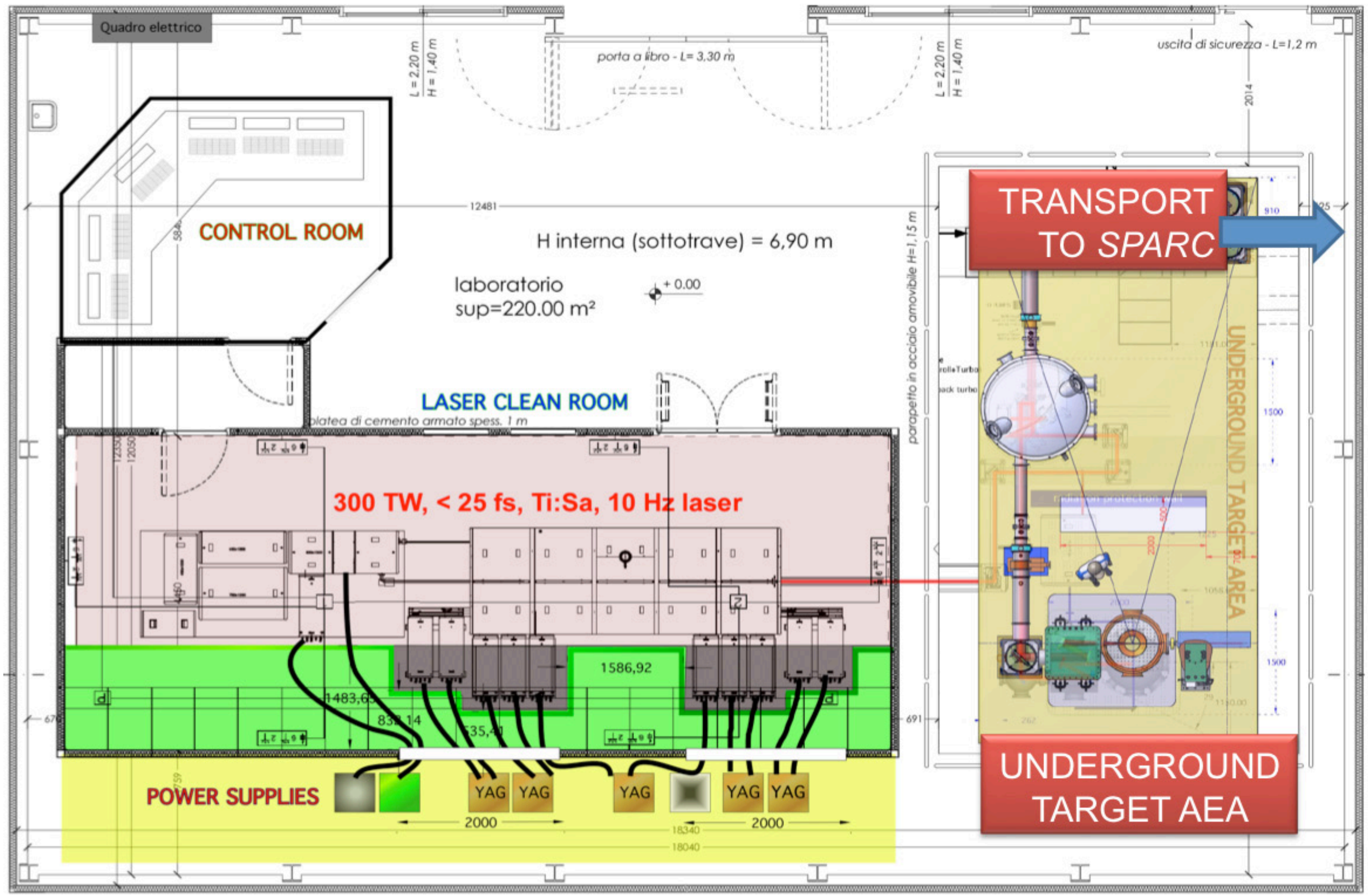


1.5 month long tests @ KEK

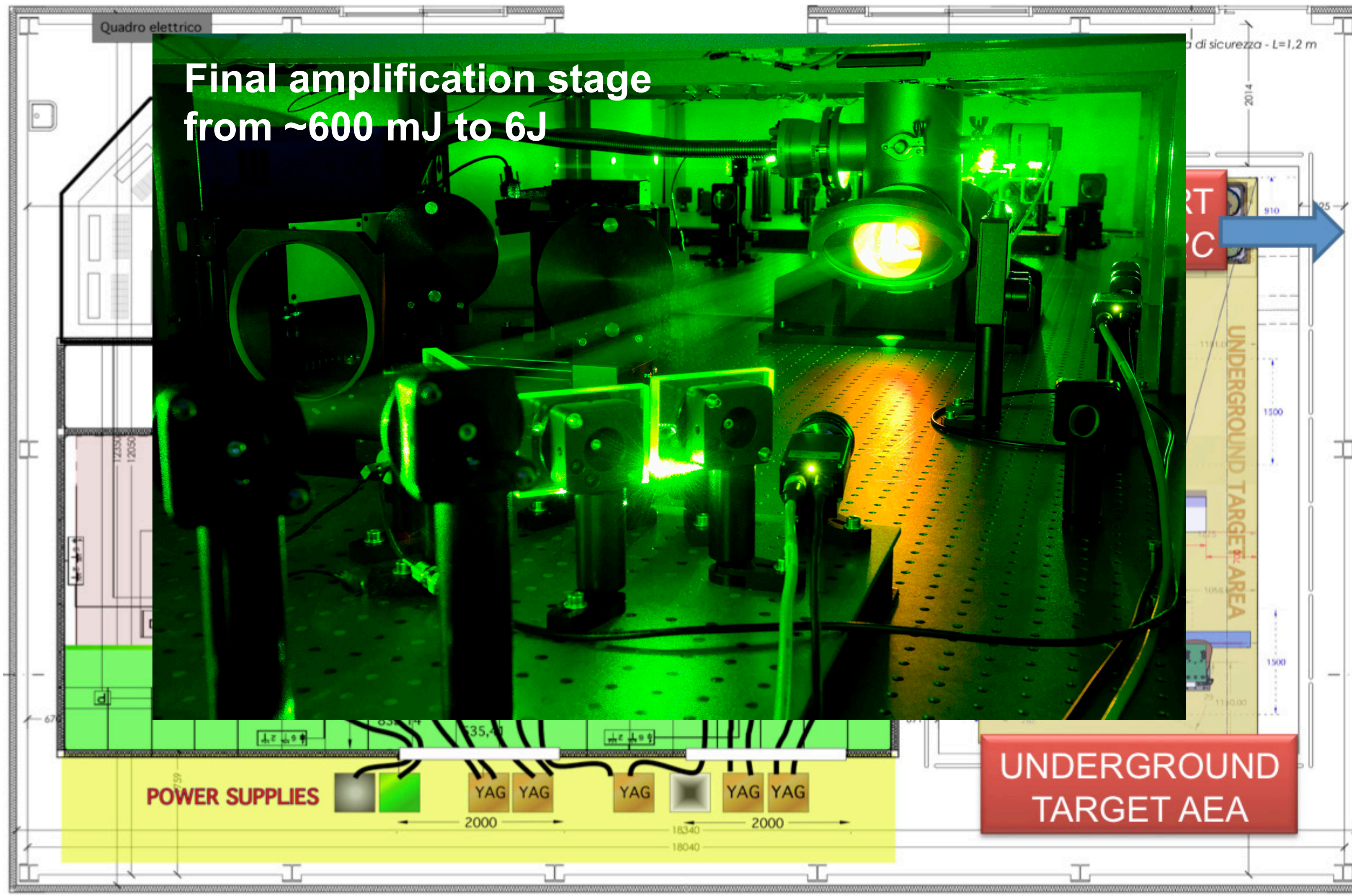
D. Alesini et al., SPARC-RF-11/005 (2011)

D. Alesini et al., MOPC013.

FLAME: A 300 TW TI:SA LASER

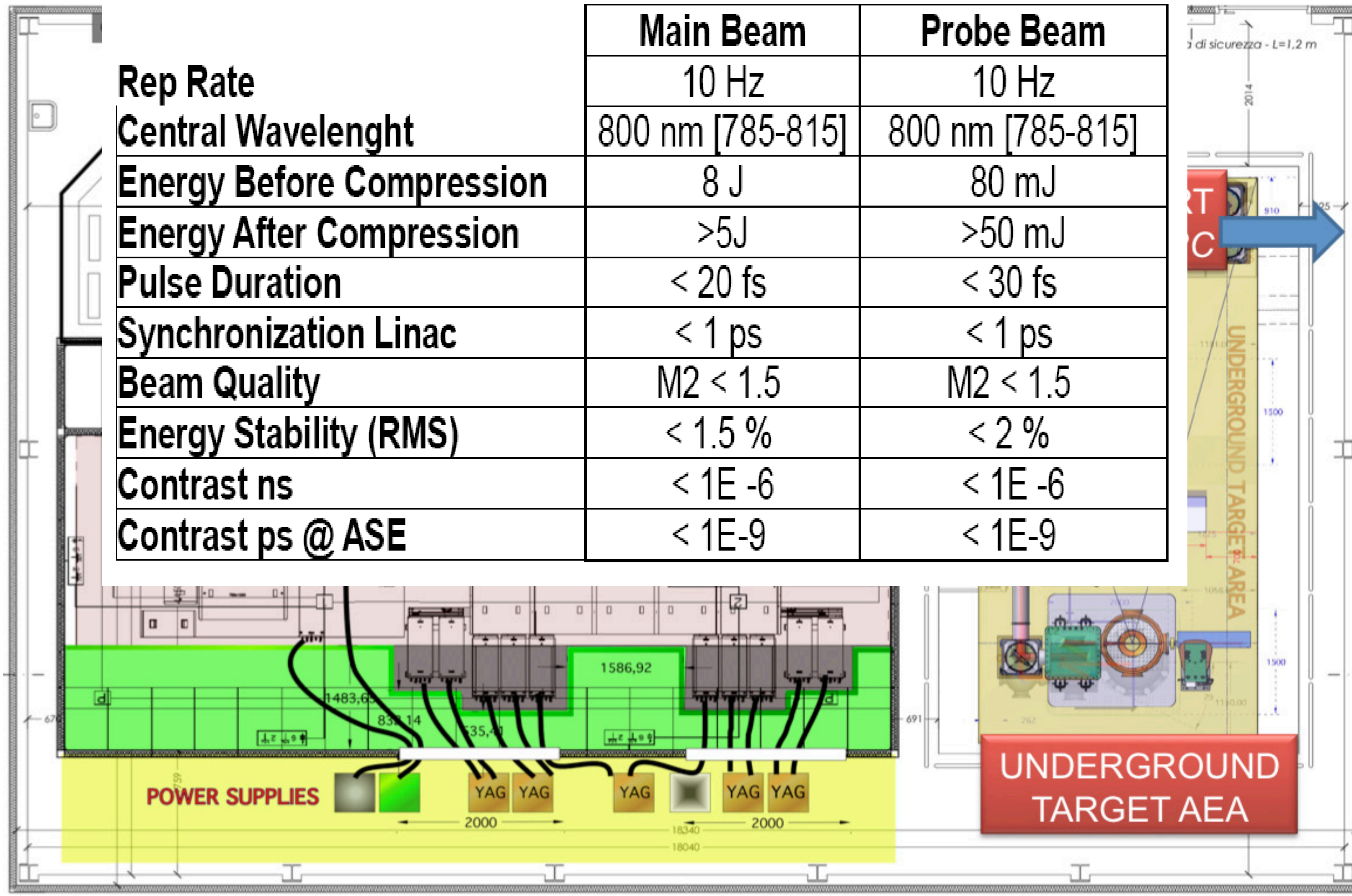


FLAME: A 300 TW TI:SA LASER

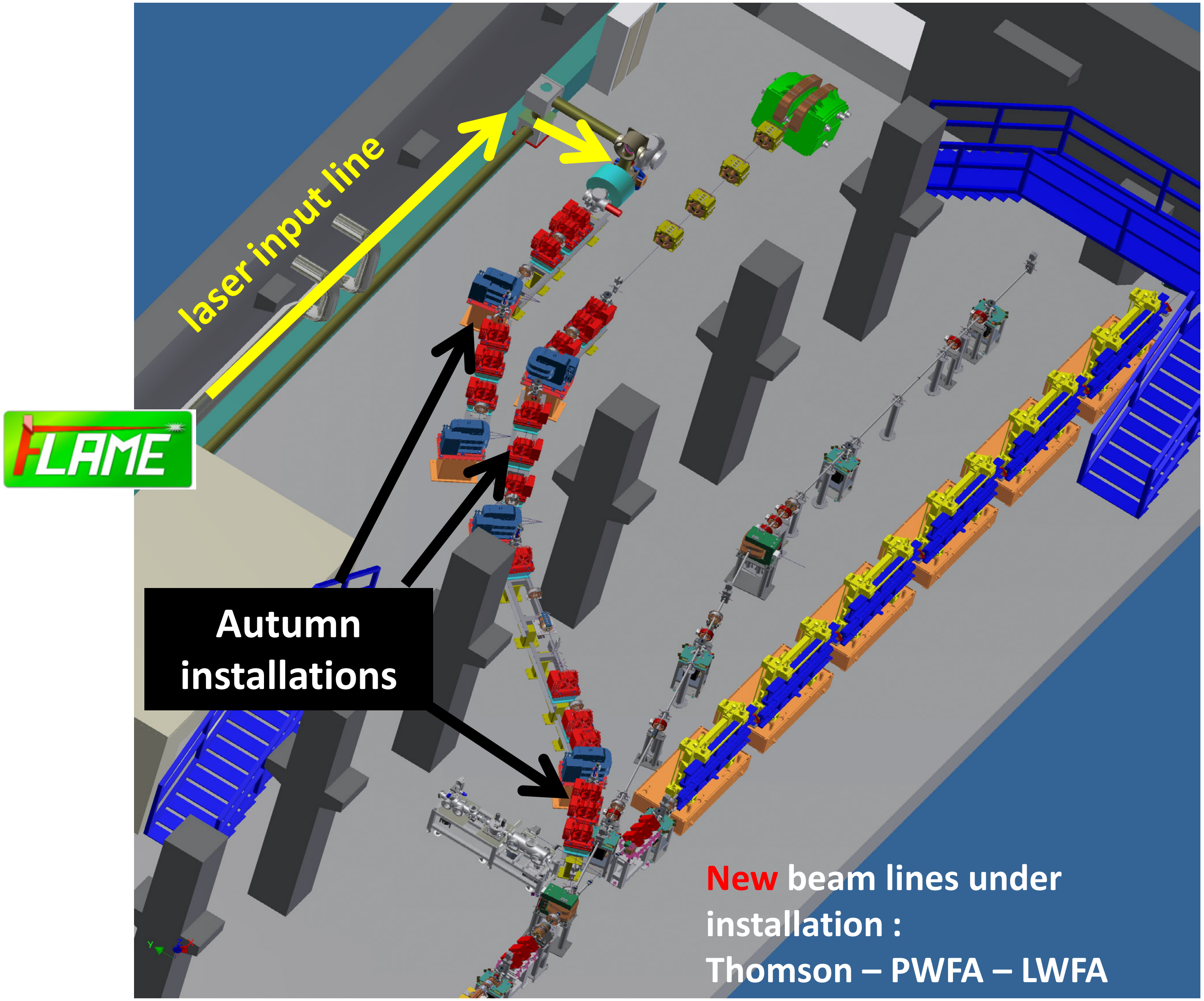


FLAME: A 300 TW TI:SA LASER

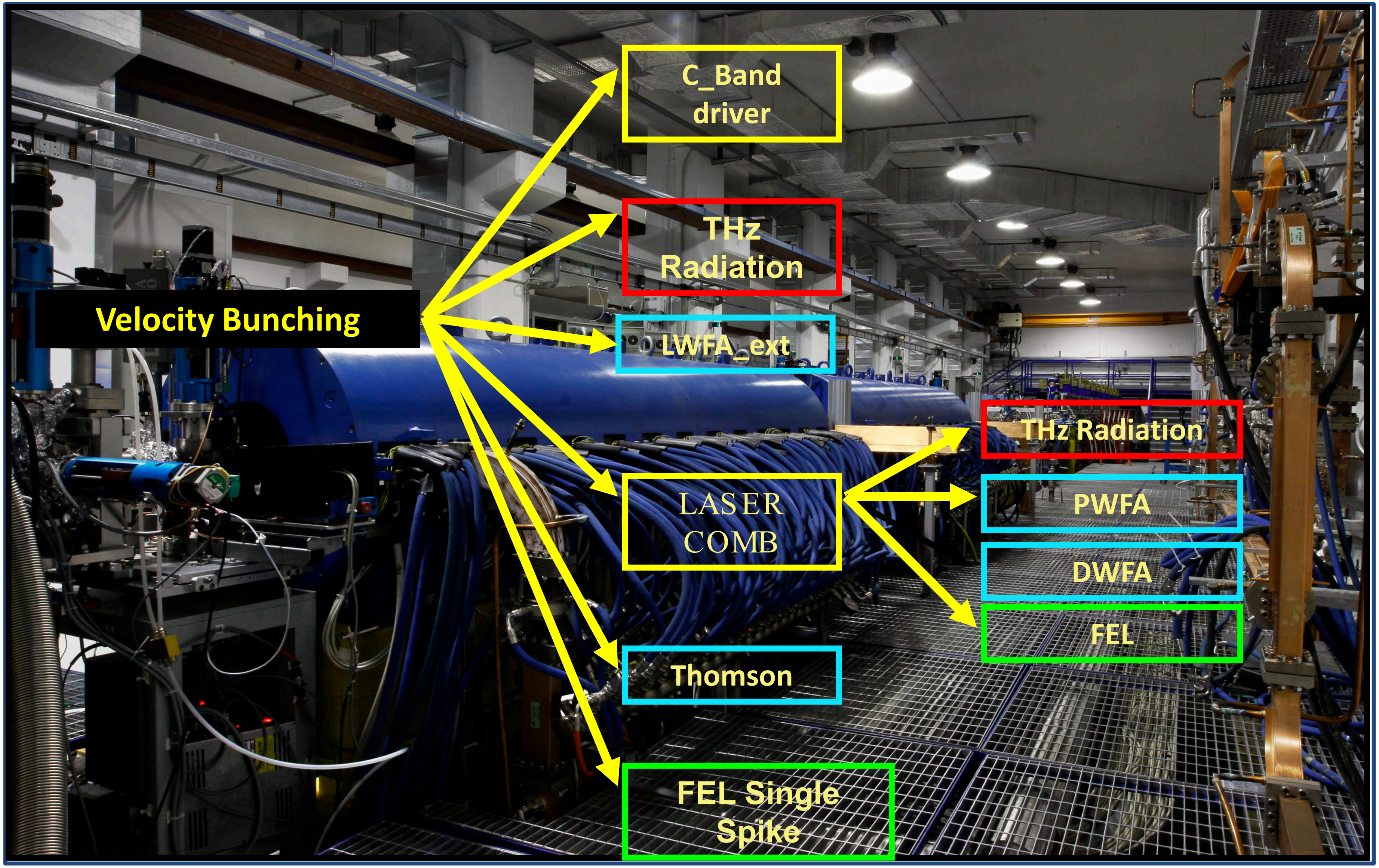
	Main Beam	Probe Beam
Rep Rate	10 Hz	10 Hz
Central Wavelenght	800 nm [785-815]	800 nm [785-815]
Energy Before Compression	8 J	80 mJ
Energy After Compression	>5J	>50 mJ
Pulse Duration	< 20 fs	< 30 fs
Synchronization Linac	< 1 ps	< 1 ps
Beam Quality	M2 < 1.5	M2 < 1.5
Energy Stability (RMS)	< 1.5 %	< 2 %
Contrast ns	< 1E -6	< 1E -6
Contrast ps @ ASE	< 1E-9	< 1E-9



NEAR FUTURE SPARC UPGRADE



ADVANCED BEAM MANIPULATION AT SPARC



EL PEINE DE LOS VIENTOS - COMB OF THE WIND

PUNTA TORREPEA, SAN SEBASTIAN