SIMULATIONS OF THE EMITTANCE COMPENSATION IN PHOTOINJECTORS AND COMPARISON WITH SPARC MEASUREMENTS

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On behalf of SPARC collaboration

EPAC08, Genoa, Italy,
23-27 June 2008

Outline

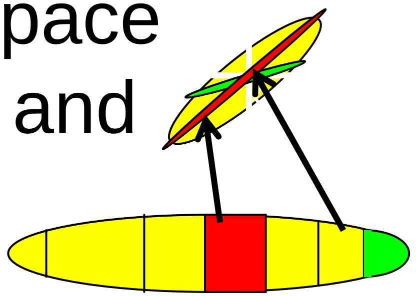
- Short review of emittance compensation in photoinjectors and space charge numerical models
- Emittance compensation studies in SPARC and comparison between measurements and simulations:

  first commissioning stage

  second commissioning stage
- Conclusions

Emittance compensation in photoinjectors (Carlsten scheme+SR theory)

- Slice phase spaces realignment
- Emittance oscillations are driven by space charge differential defocusing in core and tails of the beam

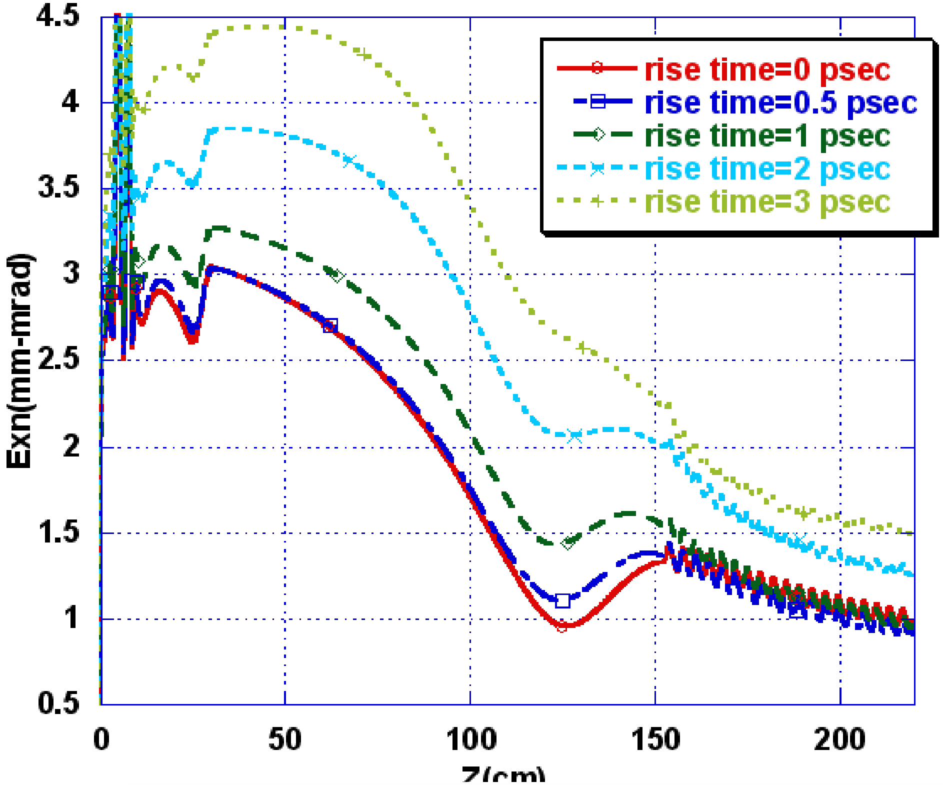


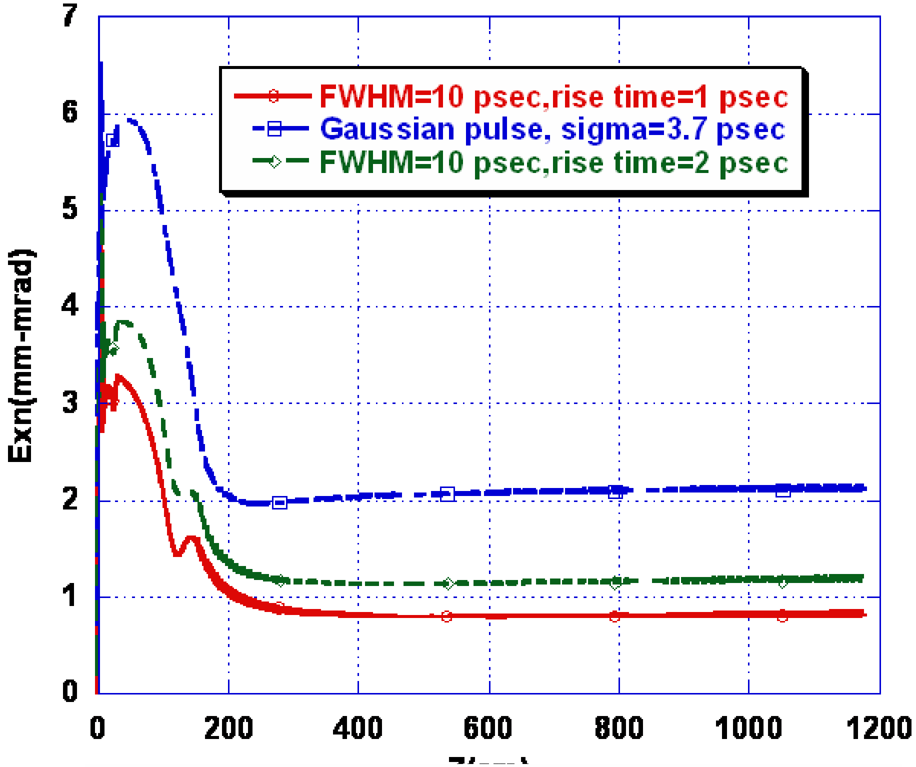
- Invariant envelope matching with the booster for damping of emittance oscillations

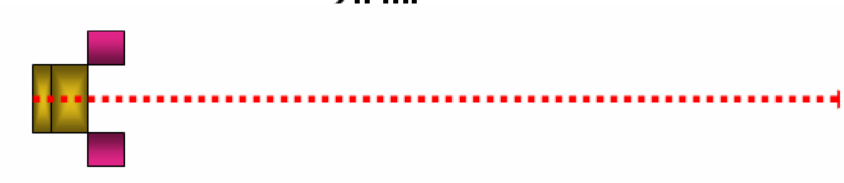
$$\sigma' = 0$$

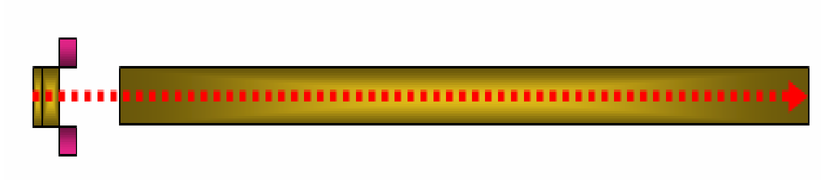
$$\gamma' = \frac{2}{\sigma_w}\sqrt{\frac{\hat{I}}{I_0\gamma}}$$

Emittance compensation in photoinjectors







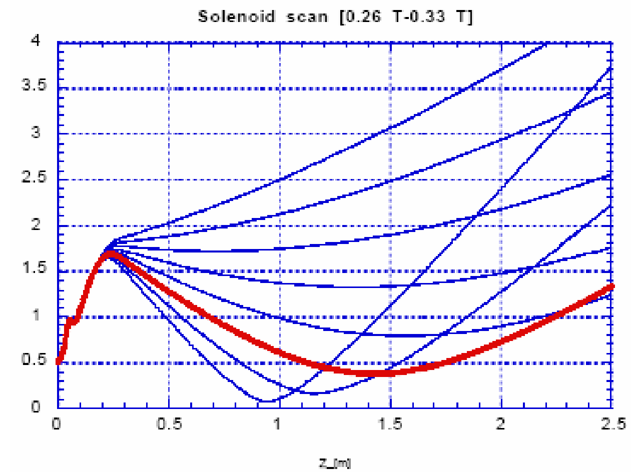


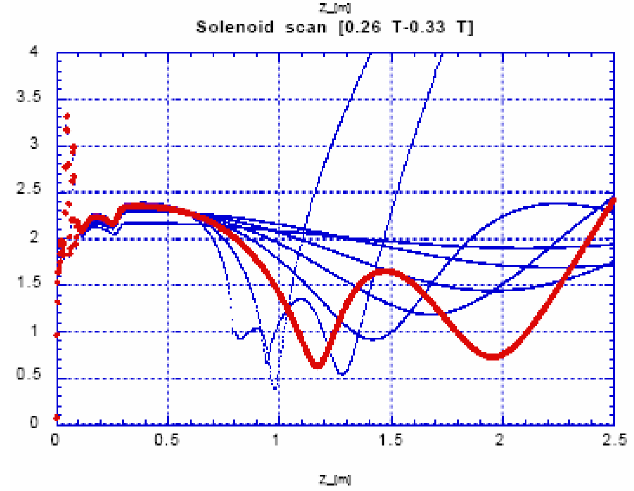
SPACE CHARGE NUMERICAL MODELS:LEVEL 1

HOMDYN CODE

- semi-analytical (envelope-equations)
- Fast
- Assumptions: uniform transverse and longitudinal distribution, non-linearities associated to electromagnetic fields neglected
- Useful for first fast scan of parameters

LCLS working point optimization

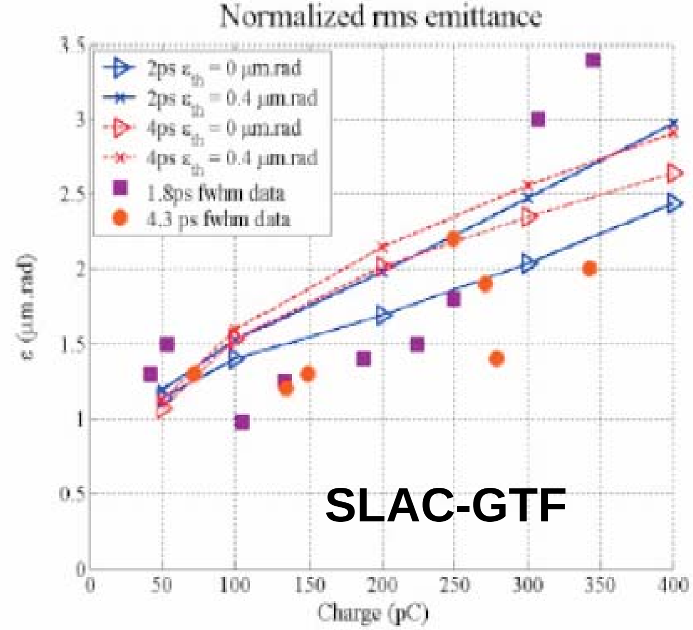


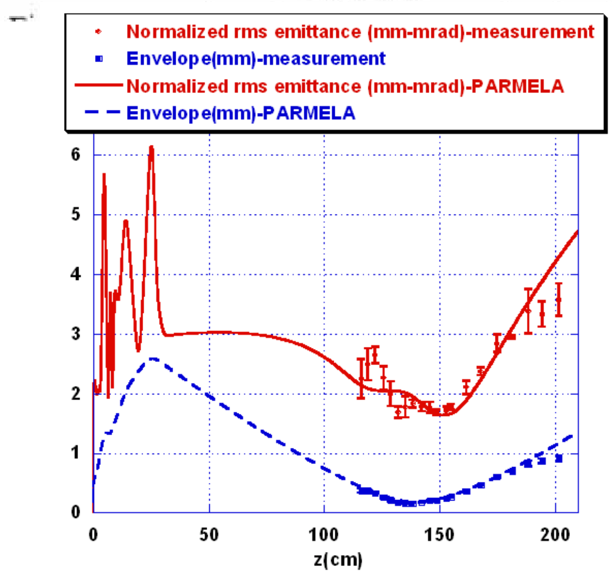


SPACE CHARGE NUMERICAL MODELS:LEVEL 2

2D macro-particles codes (PARMELA-SCHEFF (LCLS,SPARC…),ASTRA (PITZ,FLASH…)…..) for fine tuning + sensitivity study

- "static approximation"
- azimuthal symmetry (SCHEFF includes a correction factor for slightly elliptical beams: ok for $x_{max}/y_{max}<1.2$)
- Accurate even with small number of particles due to 2D and sufficiently fast
- PARMELA is extensively compared with measurements during SPARC commissioning and is routinely used to benchmark other codes





SPACE CHARGE NUMERICAL MODELS:LEVEL 3

3D macro-particles codes (PARMELA-SPCH3D,IMPACT-T…)

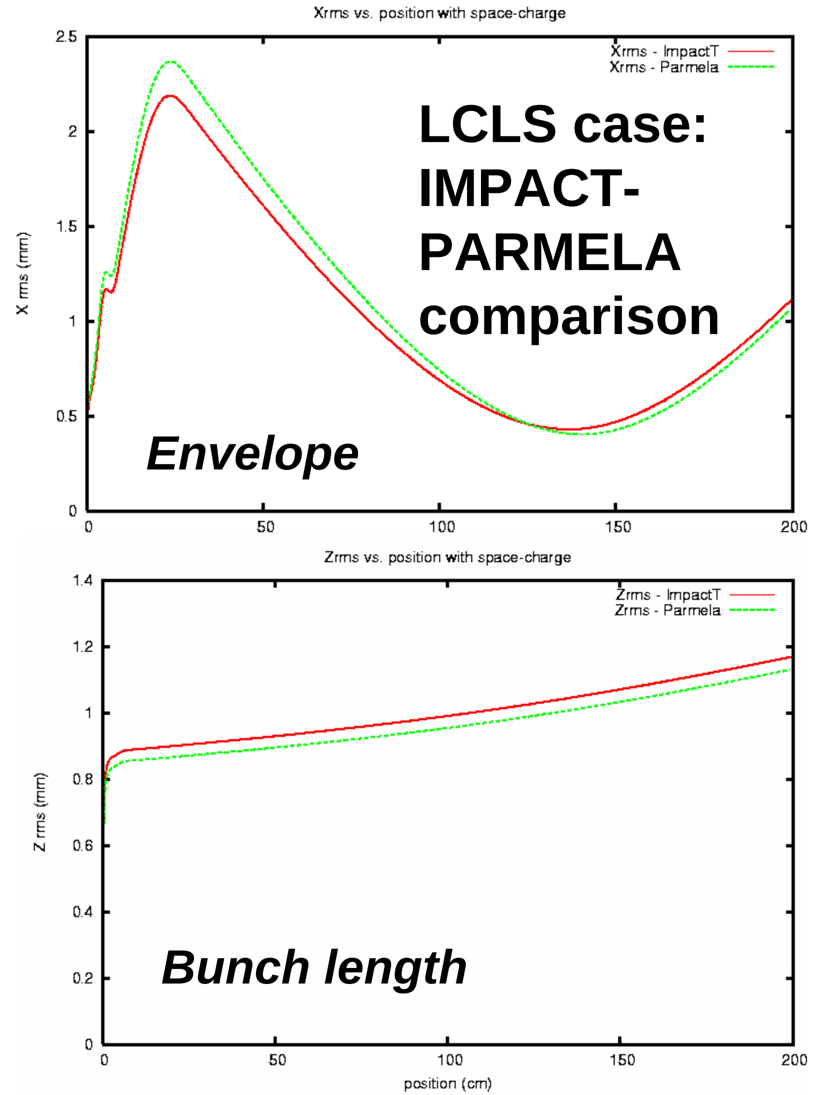
- “static approximation”
- IMPACT peculiarities:

-*Parallel processing* (*IMPACT-T parallel simulation using 1M particles is more than 2x faster than PARMELA using 100K particles)*

-*Energy binning for large ΔE*

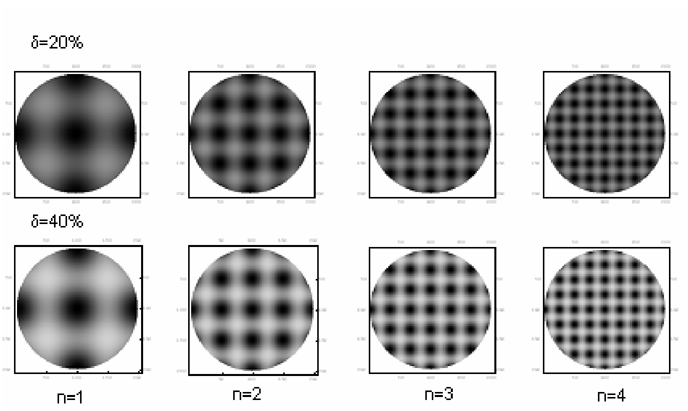
-*Integrated Green function* (large aspect ratios) (recently included by L. Young also in an upgraded version of SPCH3D)

-*Images from cathode*

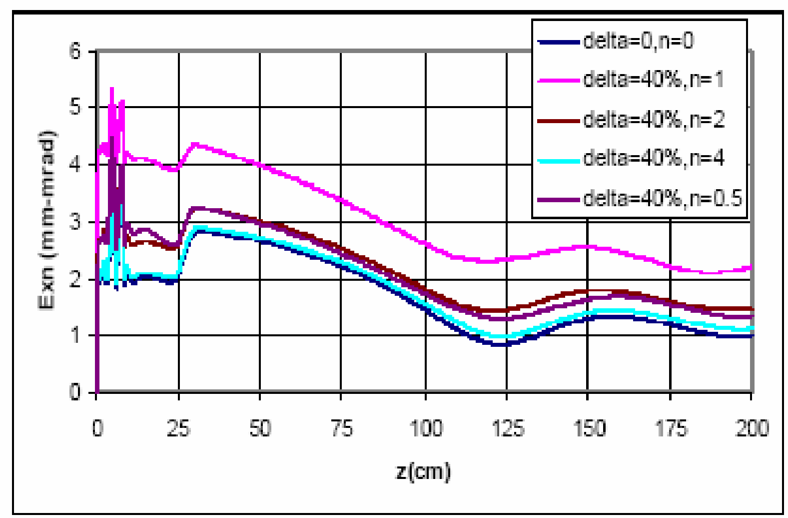


SPACE CHARGE NUMERICAL MODELS:LEVEL 3

- Necessary for studying the effect of beam offsets or of non-uniformities in the beam spot (bad spatial autocorrelation index*)



$$\rho(i,j) = \rho_0(1+\delta\cos k_n i)(1+\delta\cos k_n j)$$

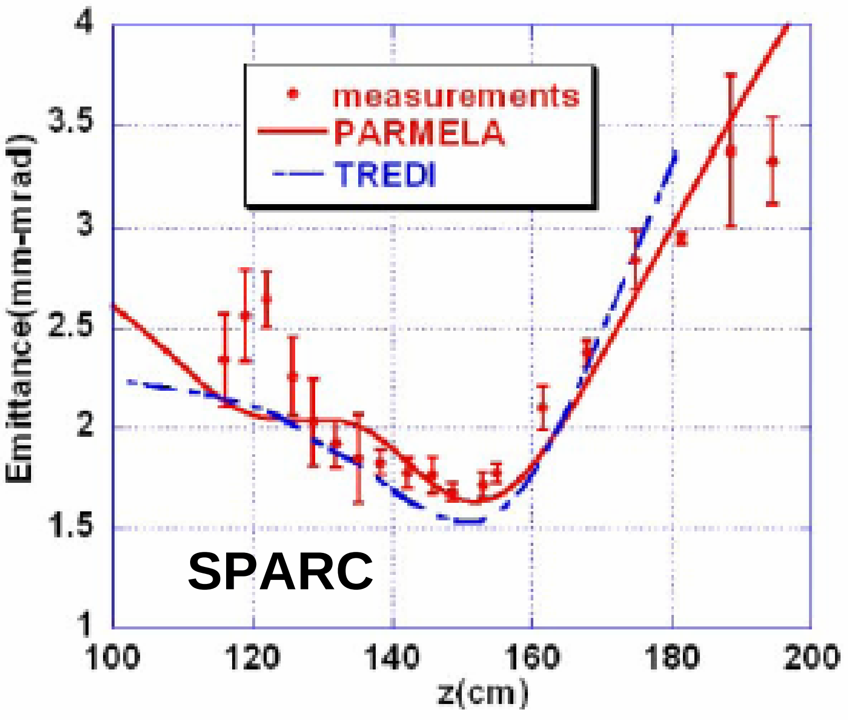


"Spatial autocorrelation for transverse beam quality characterization" POSTER: TUPC027-V. Fusco

SPACE CHARGE NUMERICAL MODELS:LEVEL 4

3D macroparticles "retarded mode" codes (TREDI,RETAR…)

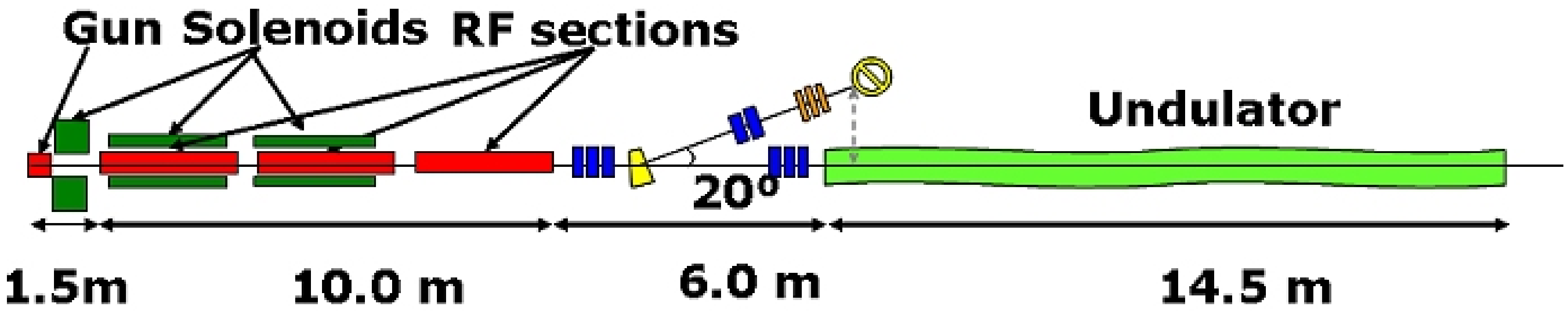
- no "static approximation"
- finite velocity of signals propagation is taken into account (the effect can be neglected in photoinjectors simulation)
- parallel processing
- particularly suitable for treatment of CSR effects in bendings



PARMELA-TREDI comparison

EMITTANCE COMPENSATION STUDIES IN SPARC AND COMPARISON BETWEEN MEASUREMENTS AND SIMULATIONS

SPARC LAYOUT



Frequency 2856 MHz

Gun Peak Field 120 MV/m

Beam Energy 150 MeV

Charge 1 nC

Energy Spread 10^{-3}

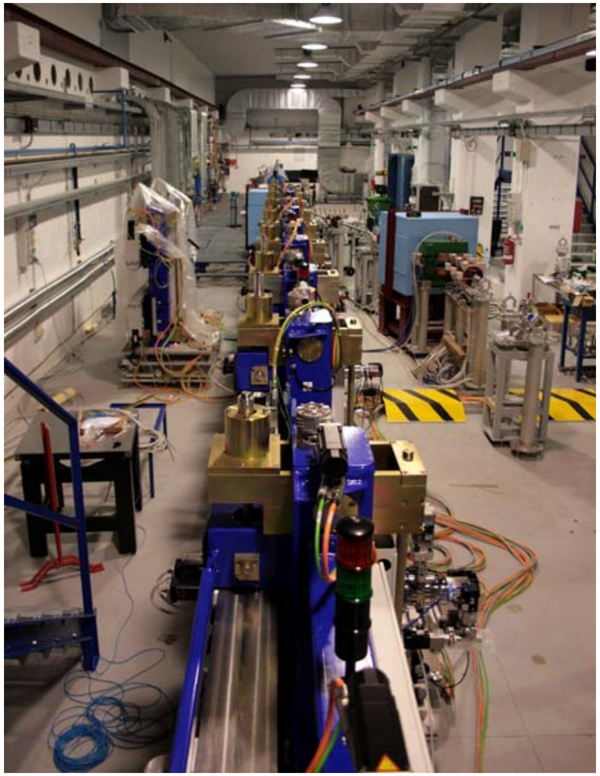
Emittance < 2 mm-mrad

Peak Current 100 A

Laser 10 ps (Flat Top with <2 ps rise time)

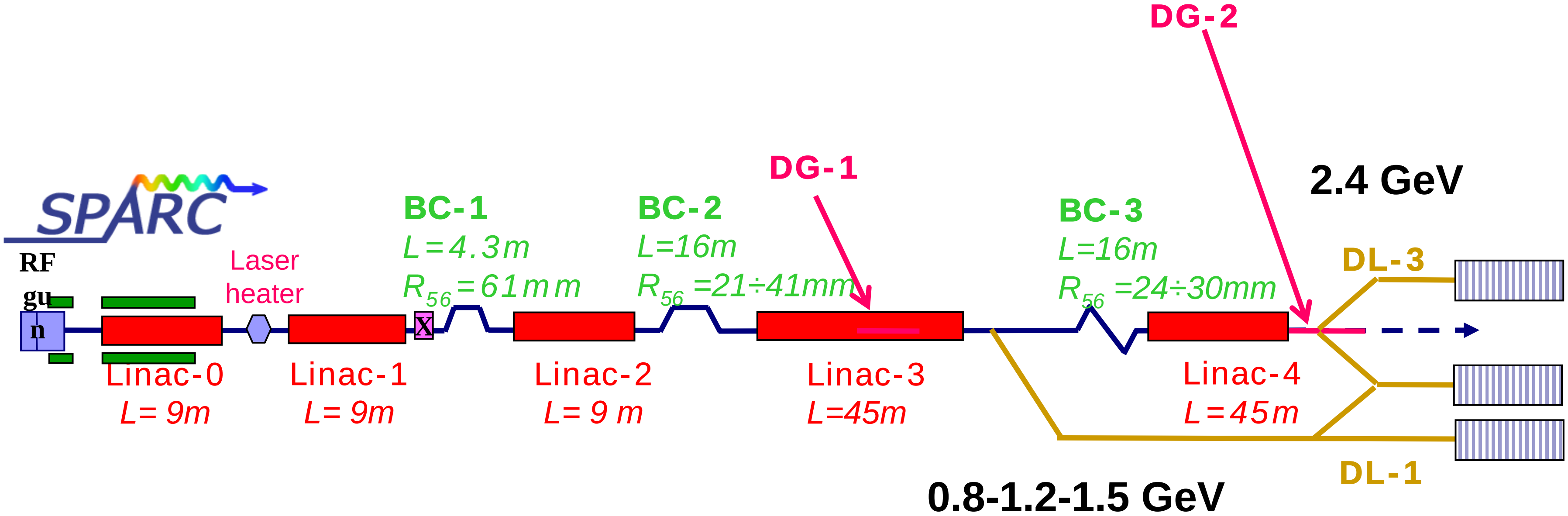
SASE experiment @530 nm

SASE&Seeding HHG test @266,160,114 nm



***POSTER:** WEPC075-M. Ferrario*

SPARC AS TEST PROTOTYPE FOR SPARX PHOTOINJECTOR

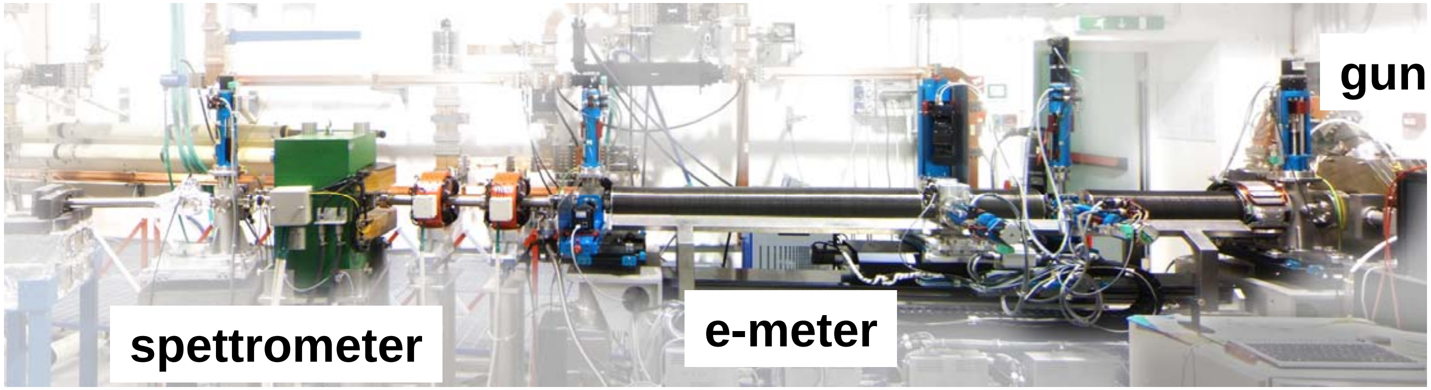


	0.8-1.2 GeV	1.2-1.5 GeV	2.4 GeV	2.4 GeV
Wavelengths	40-10 nm	15-3 nm	4-1.2 nm	1.2-0.6 nm

POSTER: MOPC026-L. Palumbo

SPARC first commissioning stage

- Low energy beam characterization through the use of the **movable emittance-meter** accomplished by experimental studies of beam dynamics during the emittance compensation process under different operating conditions
- Firstly the envelope vs z is measured and then the emittance vs z is measured moving the slit over ± 3σ (13 positions, step= σ/2) across the beam size



SPARC first commissioning stage: measurements-simulation comparison

- **Used code:** PARMELA
- **Beam model:**

  Longitudinal distribution: time profile reconstructed by a cross-correlator based measurement

  Transverse distribution: virtual cathode image (640x480 pixels image. Resolution=9.9 μm/pixel)

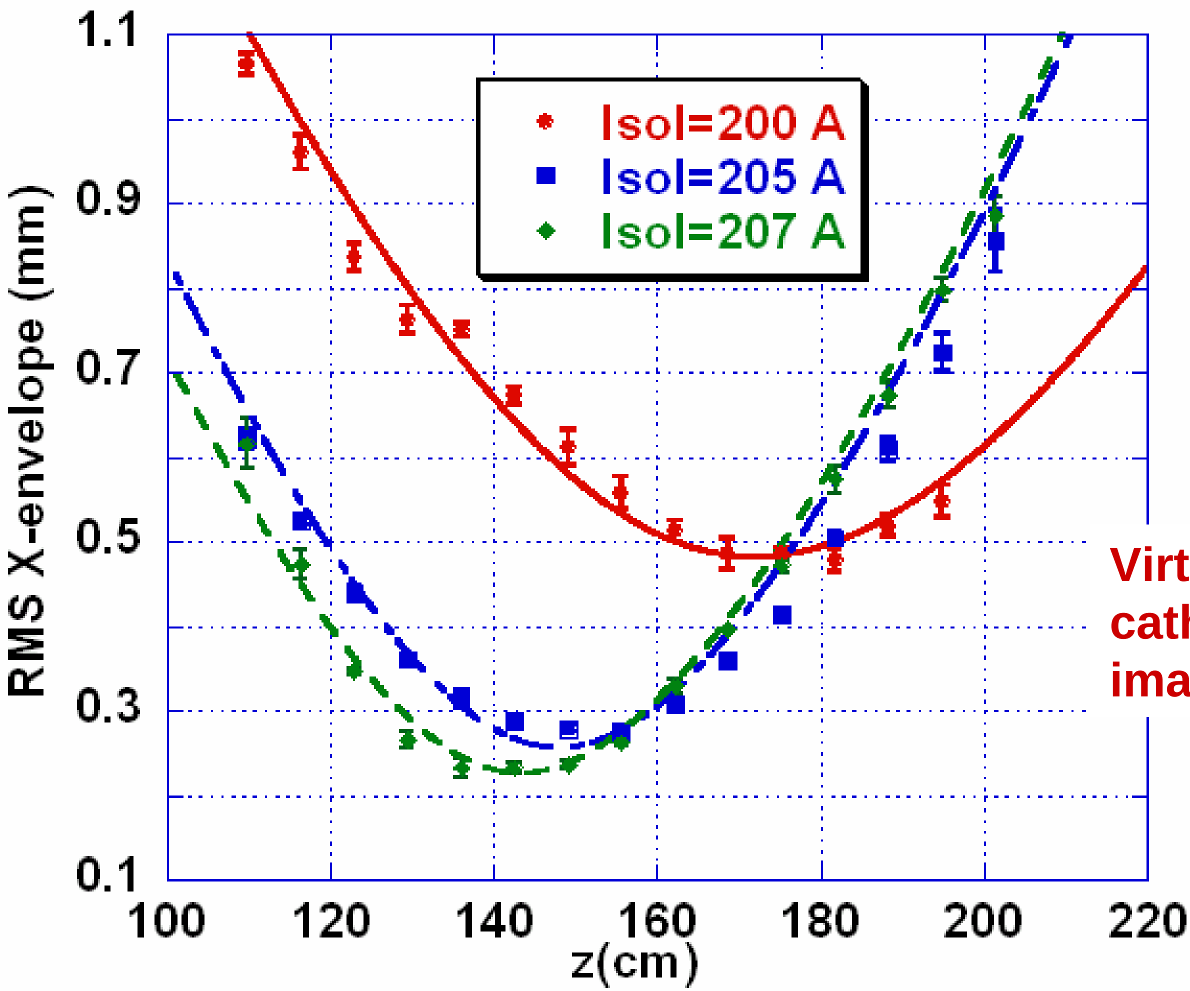
  Thermal emittance: 0.6 mm-mrad/mm
- **Beamline model:** computed fields in the gun and in the emittance compensating solenoid in the actually used configuration (null rotation) in SPARC. The POISSON magnetic field distribution was corrected by a factor taking into account the difference between the computed and the measured field.

SIMULATIONS-MEASUREMENTS COMPARISON STRATEGY: two steps procedure

- **STEP 1**: Check of consistency of the main beam parameters with the measured envelope by using an **equivalent uniform beam** (with a transverse rms size retrieved from the virtual cathode image and a longitudinal profile equal to the measured pulse shape) - **2D computations** (Np=20K). The parameters are moved within the following ranges

Charge Q, measured value ±5%
Phase φ, measured value $\pm$ 0.5°
Energy E, measured value ±1%

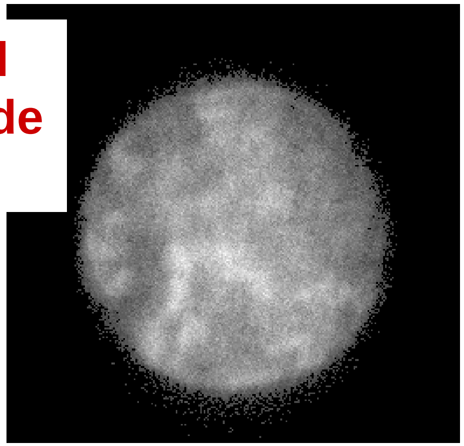
Beam envelopes for different solenoid currents



Input beam:
Q=1nC
Energy=5.47 MeV
Gaussian pulse:
FWHM=9 psec
φ-φ_{max}= -5°

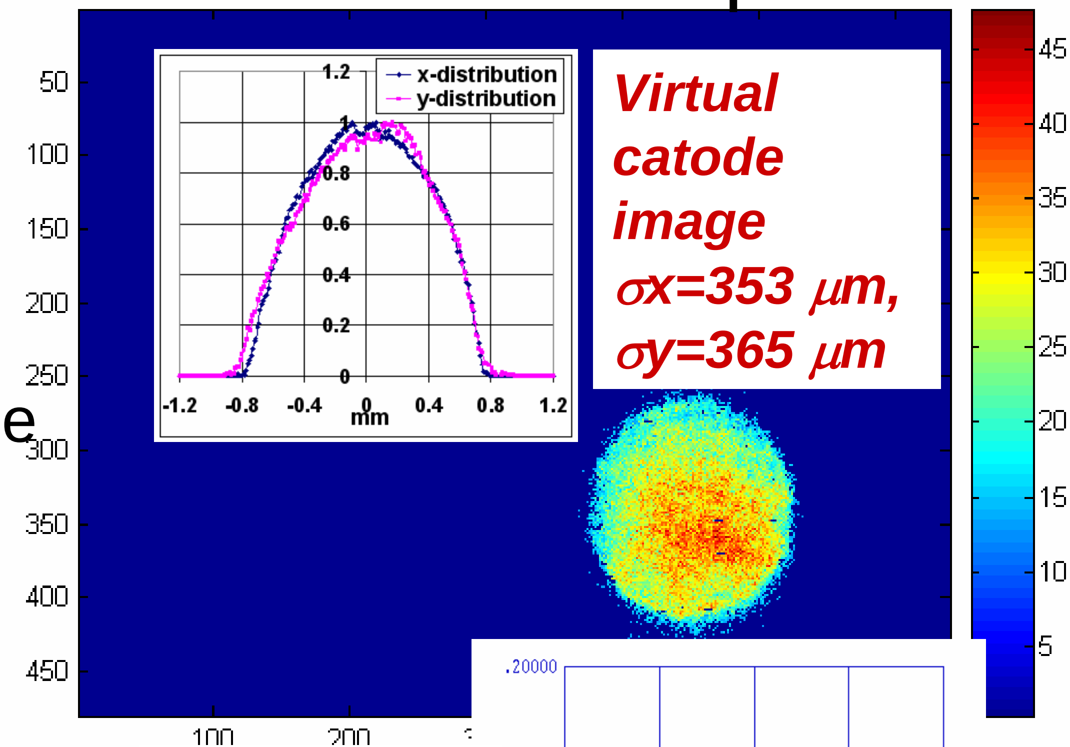
Transverse size of the equivalent uniform beam:
σ_x=σ_y=400 μm

Virtual cathode image



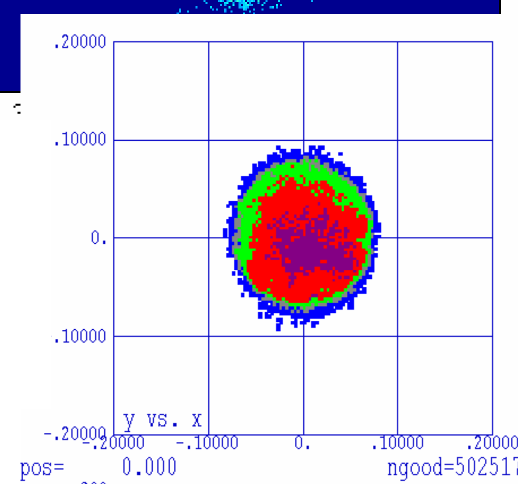
SIMULATIONS-MEASUREMENTS COMPARISON STRATEGY: two steps procedure

- **STEP 2**: Use of the “real” transverse distribution from the virtual cathode image taking into account local disuniformities– **3D computations** (Np=500K. Mesh: Nx=32, Ny=32, Nz=64) for the comparison with the measured emittance



Simulation:

PARMELA input beam (Np=500 K)



Main results in:

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **11**, 032801 (2008)

High brightness electron beam emittance evolution measurements in an rf photoinjector

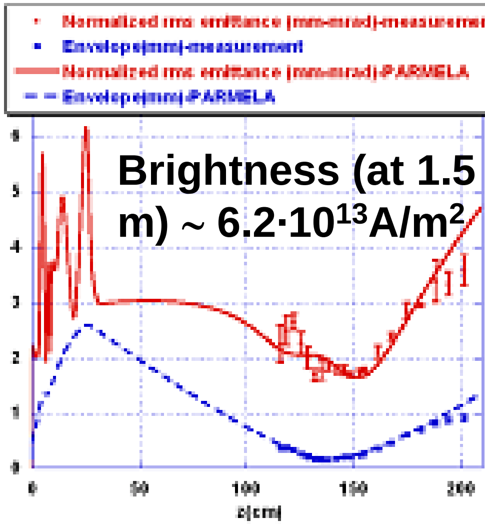
A. Cianchi,[1,*] D. Alesini,[2] A. Bacci,[3] M. Bellaveglia,[2] R. Boni,[2] M. Boscolo,[2] M. Castellano,[2] L. Catani,[1] E. Chiadroni,[2] S. Cialdi,[3] A. Clozza,[2] L. Cultrera,[2] G. Di Pirro,[2] A. Drago,[2] A. Esposito,[2] M. Ferrario,[2] L. Ficcadenti,[4] D. Filippetto,[2] V. Fusco,[2] A. Gallo,[2] G. Gatti,[2] A. Ghigo,[2] L. Giannessi,[5] C. Ligi,[2] M. Mattioli,[6] M. Migliorati,[2,4] A. Mostacci,[2,4] P. Musumeci,[7] E. Pace,[2] L. Palumbo,[2,4] L. Pellegrino,[2] M. Petrarca,[8] M. Preger,[2] M. Quattromini,[5] R. Ricci,[2] C. Ronsivalle,[5] J. Rosenzweig,[7] A. R. Rossi,[3] C. Sanelli,[2] L. Serafini,[3] M. Serio,[2] F. Sgamma,[2] B. Spataro,[2] F. Tazzioli,[2] S. Tomassini,[2] C. Vaccarezza,[2] M. Vescovi,[2] and C. Vicario[2]

PRL **99,** 234801 (2007) PHYSICAL REVIEW LETTERS week ending 7 DECEMBER 2007

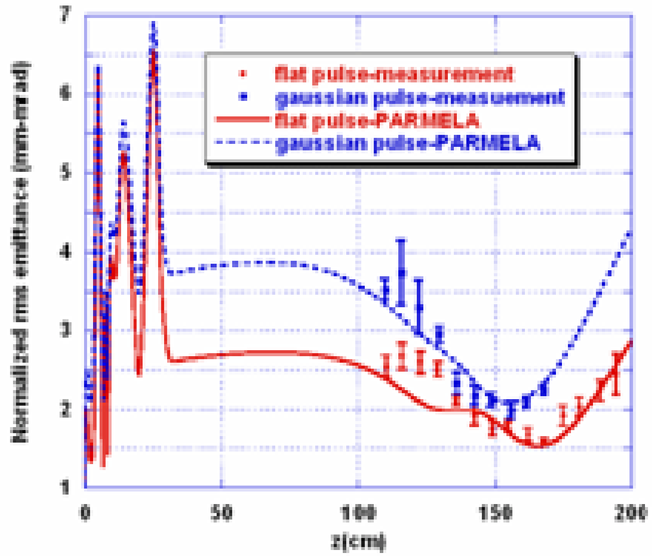
Direct Measurement of the Double Emittance Minimum in the Beam Dynamics of the Sparc High-Brightness Photoinjector

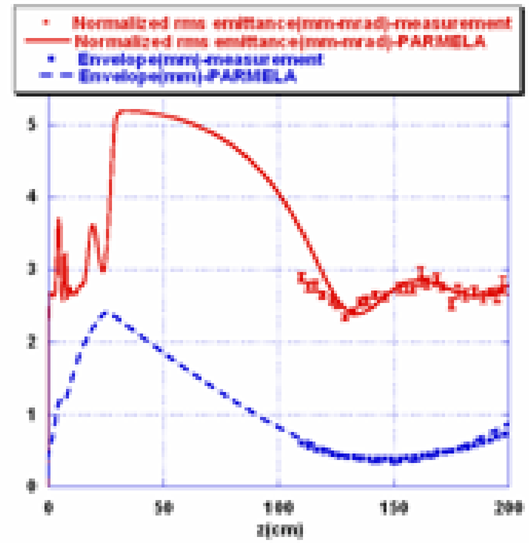
M. Ferrario,[1] D. Alesini,[1] A. Bacci,[3] M. Bellaveglia,[1] R. Boni,[1] M. Boscolo,[1] M. Castellano,[1] L. Catani,[2] E. Chiadroni,[1] S. Cialdi,[3] A. Cianchi,[2] A. Clozza,[1] L. Cultrera,[1] G. Di Pirro,[1] A. Drago,[1] A. Esposito,[1] L. Ficcadenti,[5] D. Filippetto,[1] V. Fusco,[1] A. Gallo,[1] G. Gatti,[1] A. Ghigo,[1] L. Giannessi,[4] C. Ligi,[1] M. Mattioli,[7] M. Migliorati,[5] A. Mostacci,[5] P. Musumeci,[6] E. Pace,[1] L. Palumbo,[5] L. Pellegrino,[1] M. Petrarca,[7] M. Quattromini,[4] R. Ricci,[1] C. Ronsivalle,[4] J. Rosenzweig,[6] A. R. Rossi,[3] C. Sanelli,[1] L. Serafini,[3] M. Serio,[1] F. Sgamma,[1] B. Spataro,[1] F. Tazzioli,[1] S. Tomassini,[1] C. Vaccarezza,[1] M. Vescovi,[1] and C. Vicario[1]

SPARC

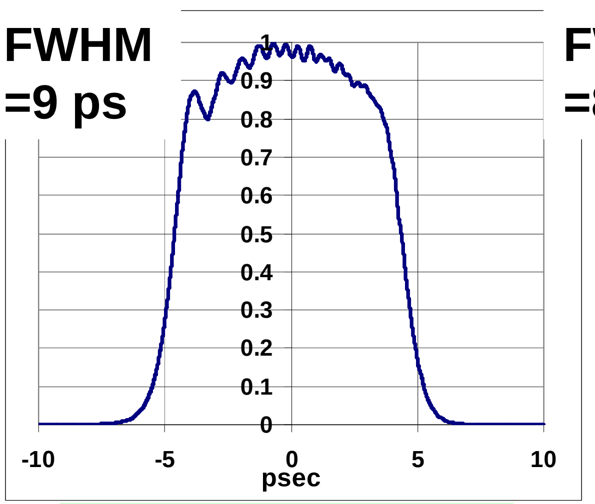


Brightness (at 1.5 m) ~ $6.2 \cdot 10^{13} A/m^2$

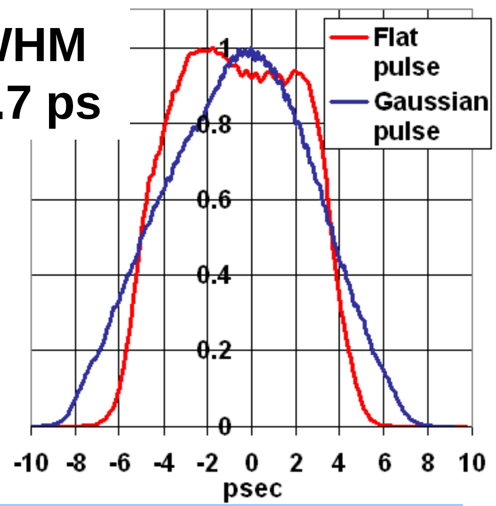




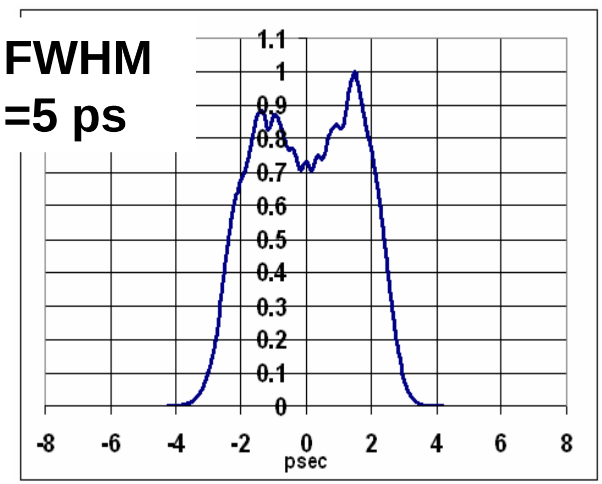
FWHM =9 ps



FWHM =8.7 ps



FWHM =5 ps

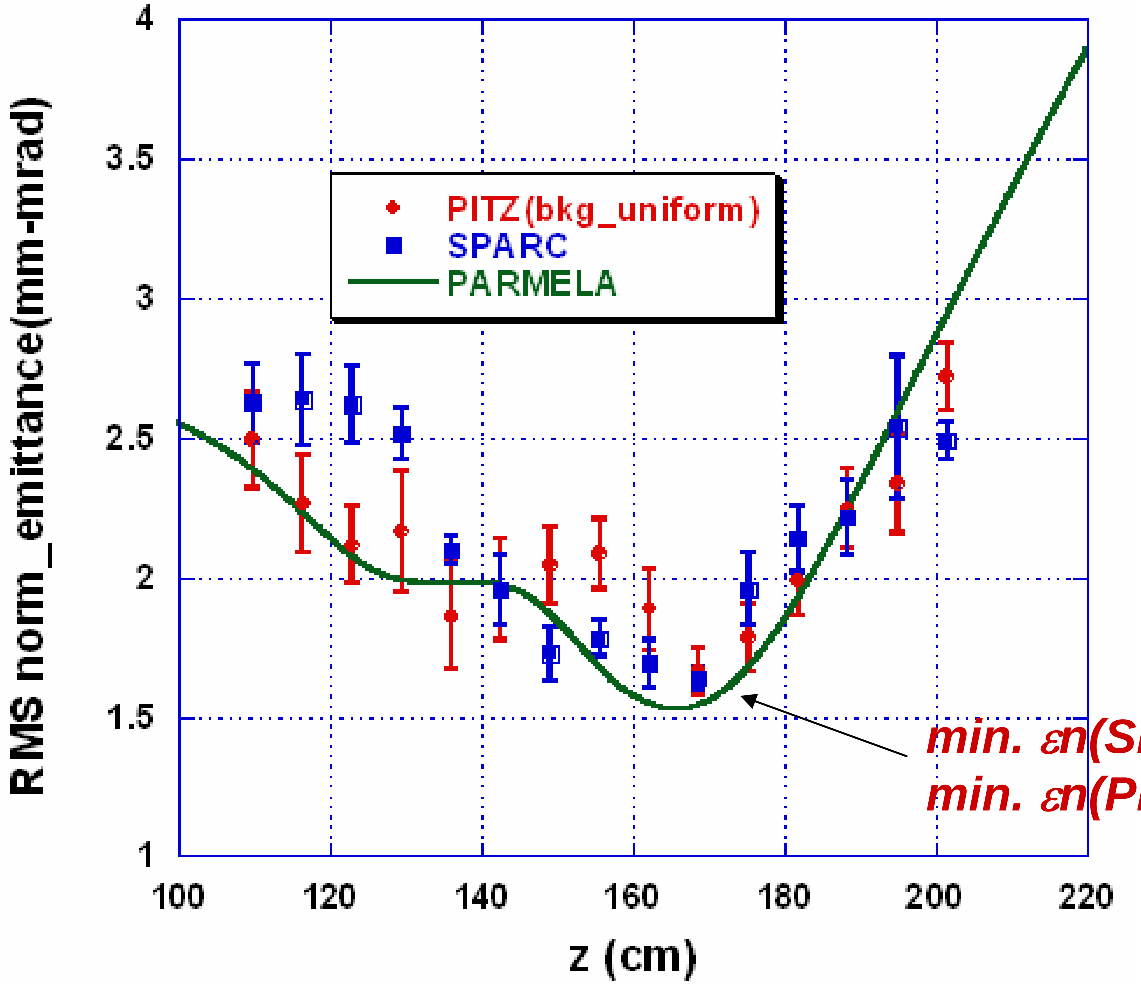


Q=825 pC
Energy=5.65 MeV
φ-φm= -8°

Q= 740 pC
Energy= 5.4 MeV
φ-φm= -8°

Q= 540 pC
Energy= 5.5 MeV
φ-φm= +12°

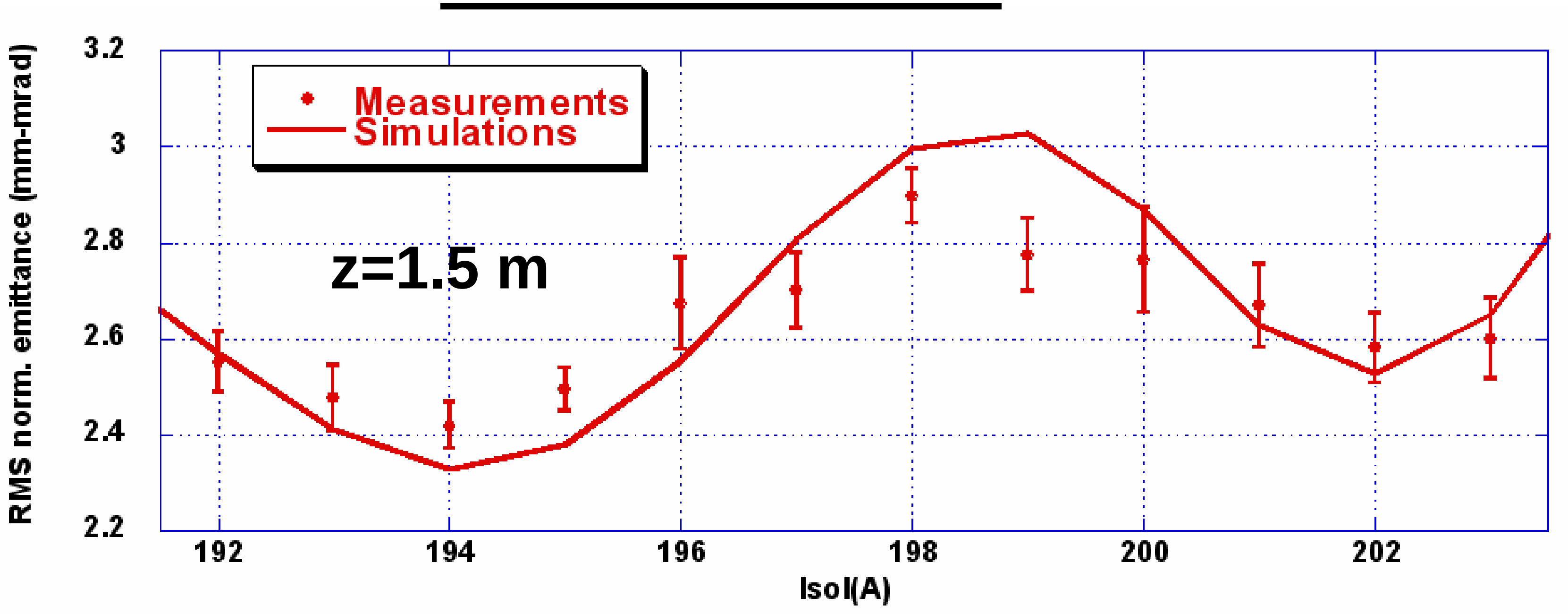
Mini workshop at Zeuthen CHHB08 (May 2008): benchmark on SPARC data

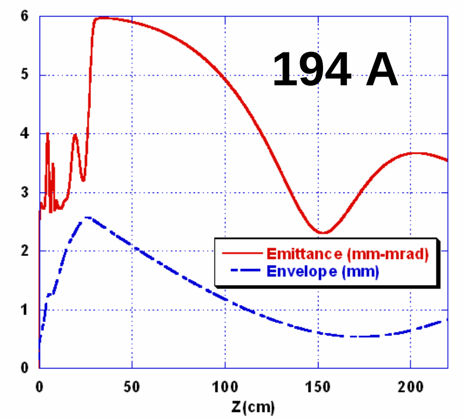


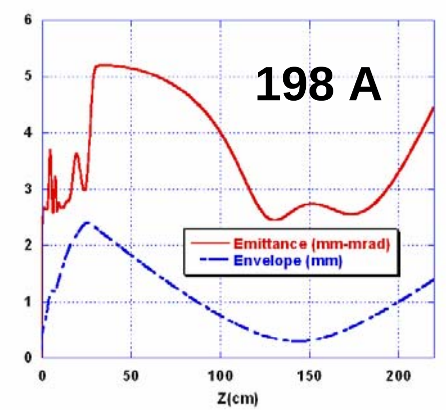
min. εn(SPARC tool)=1.64 μm
min. εn(PITZ tool)=1.66 μm

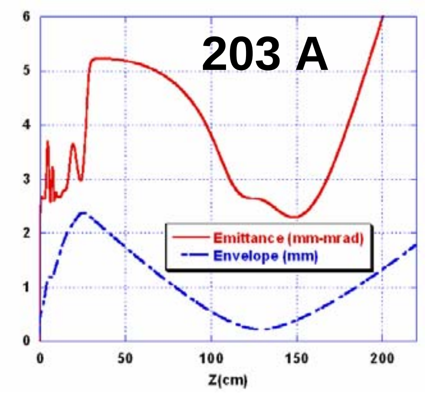
“double minimum” emittance oscillation

- **First measurement:** B-scan



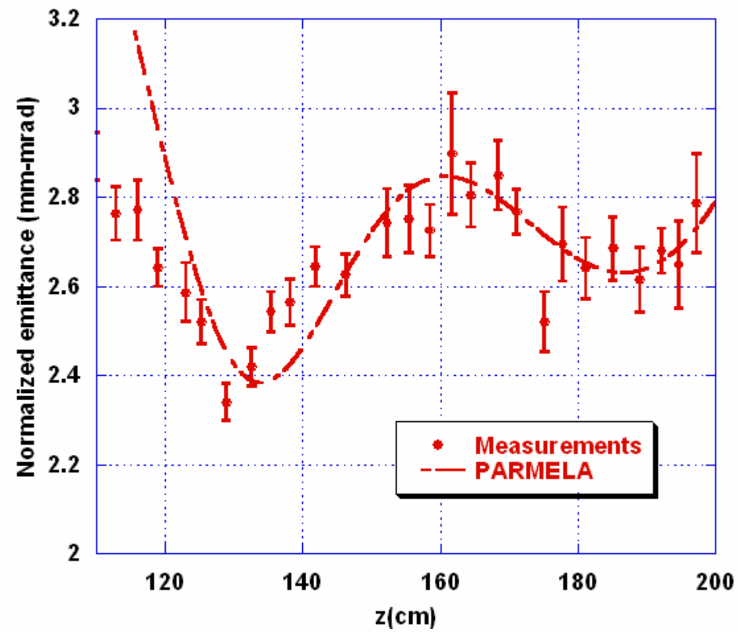






“double minimum” emittance oscillation

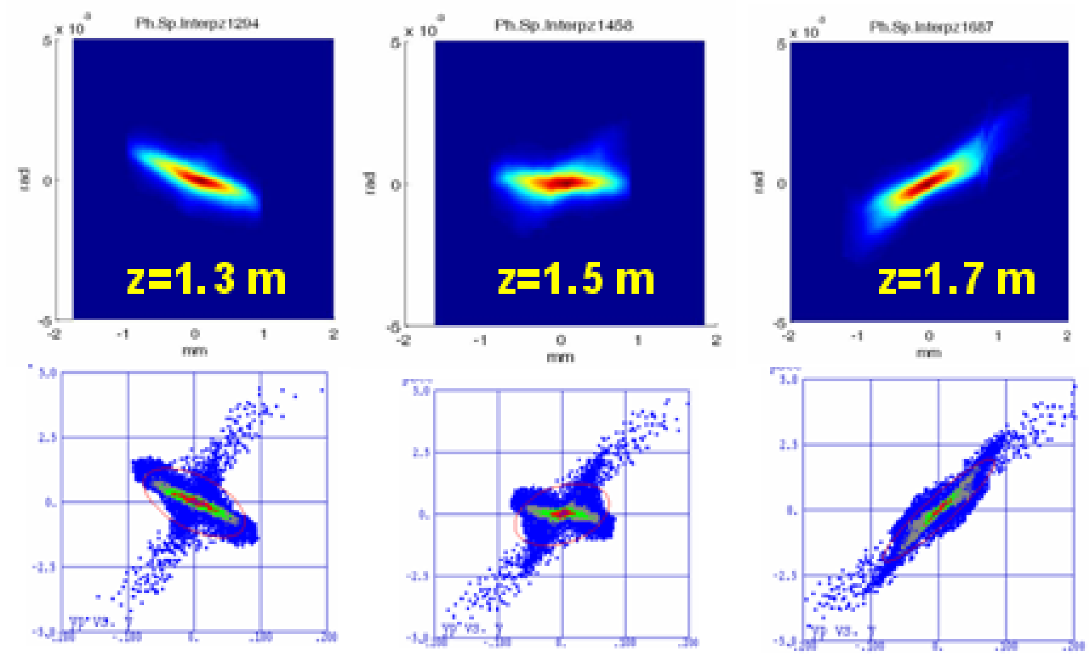
- **<u>Second measurement:</u> z-scan**



- **<u>Phase spaces comparison:</u>**

Measured

Computed



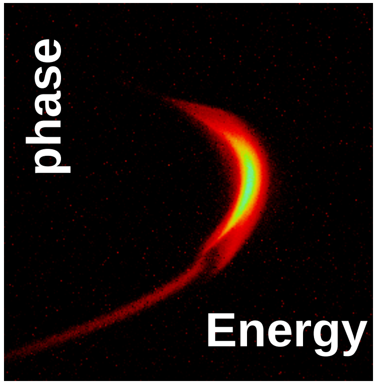
SPARC second commissioning stage

Main goals:

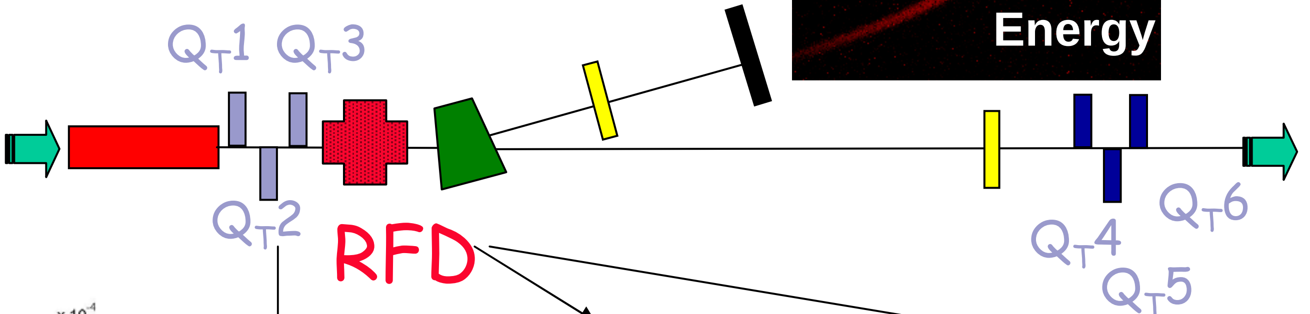
- **detailed analysis of the beam matching with the linac in order to confirm the theoretically prediction of emittance compensation based on the “invariant envelope”**
- **demonstration of the “velocity bunching” technique in the linac**

SPARC second commissioning stage

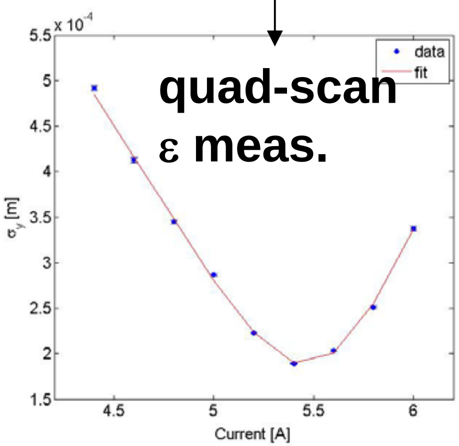
Preliminary tests of beam transport to the linac exit, for diagnostics check and first comparisons with simulations

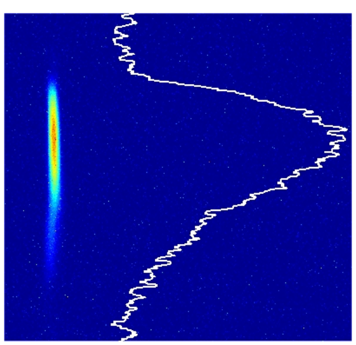


POSTERS:
MOPC068-A. Cianchi
TUPC105-C. Vaccarezza

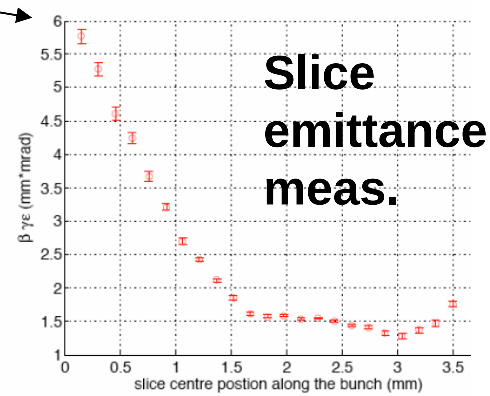


to undulator

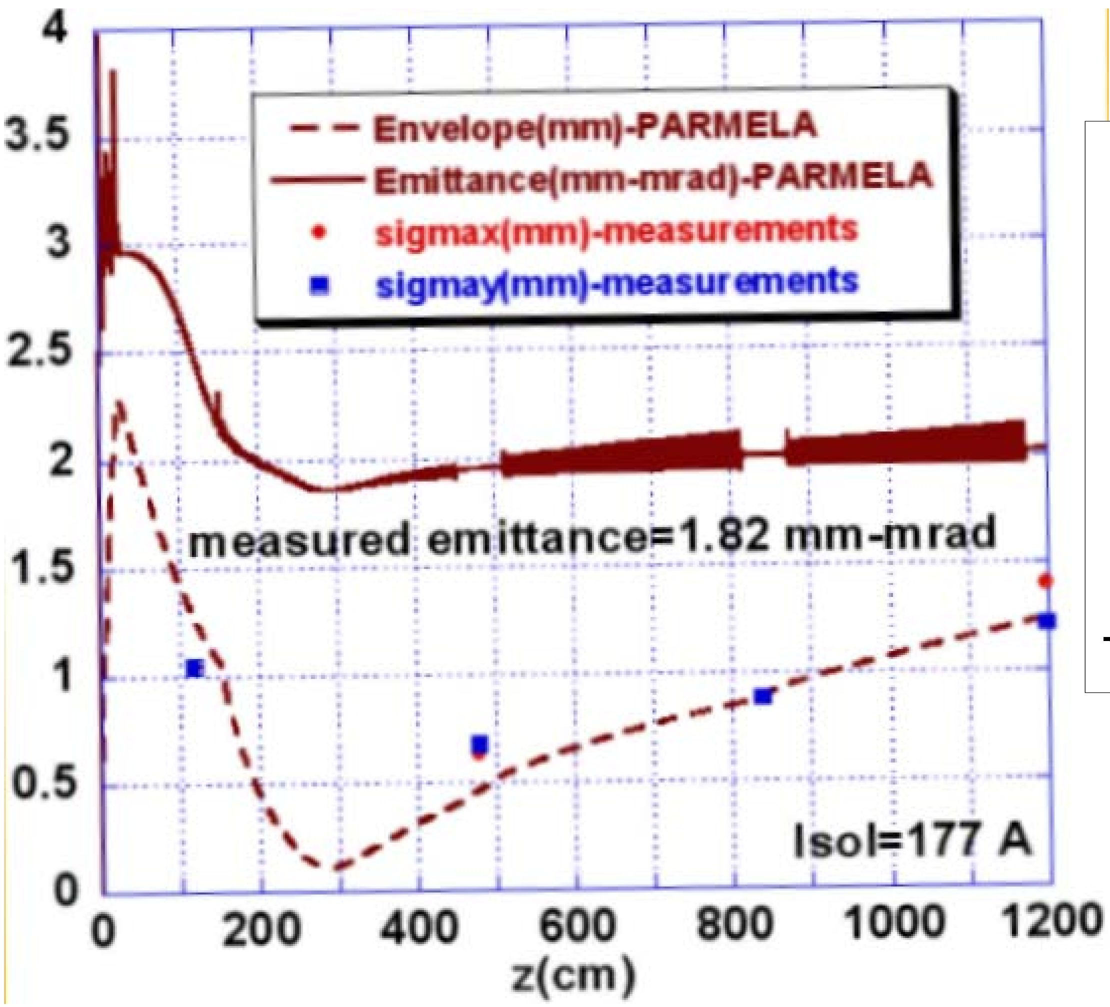




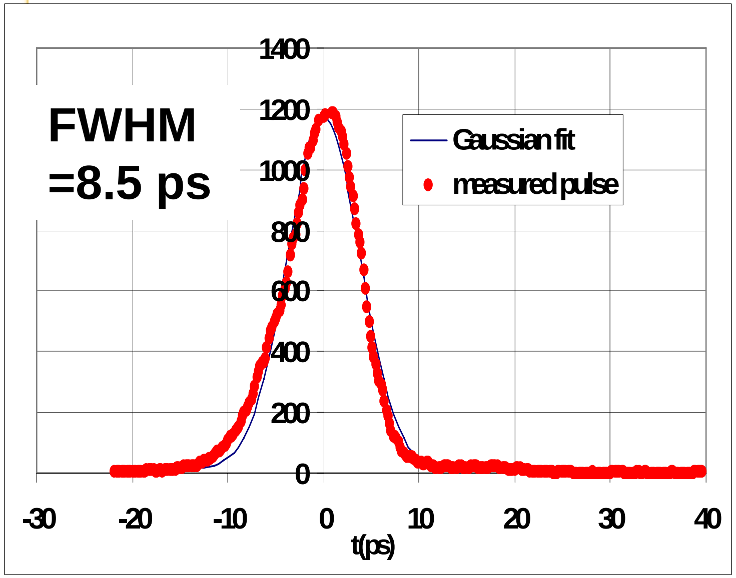
bunch length meas.



SPARC second commissioning stage: beam matching with the linac

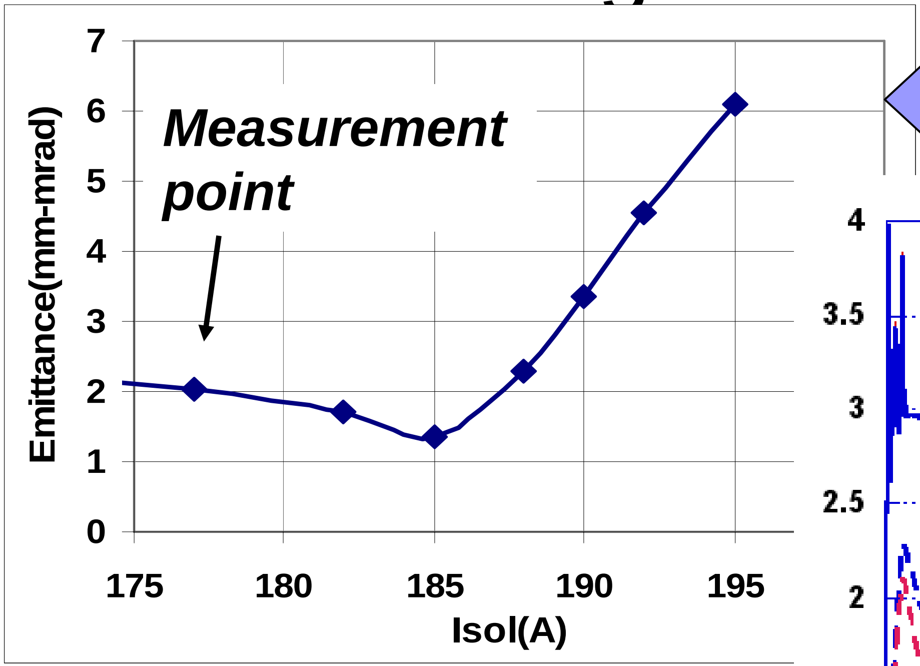


Q=500 pC
Energy=147 MeV

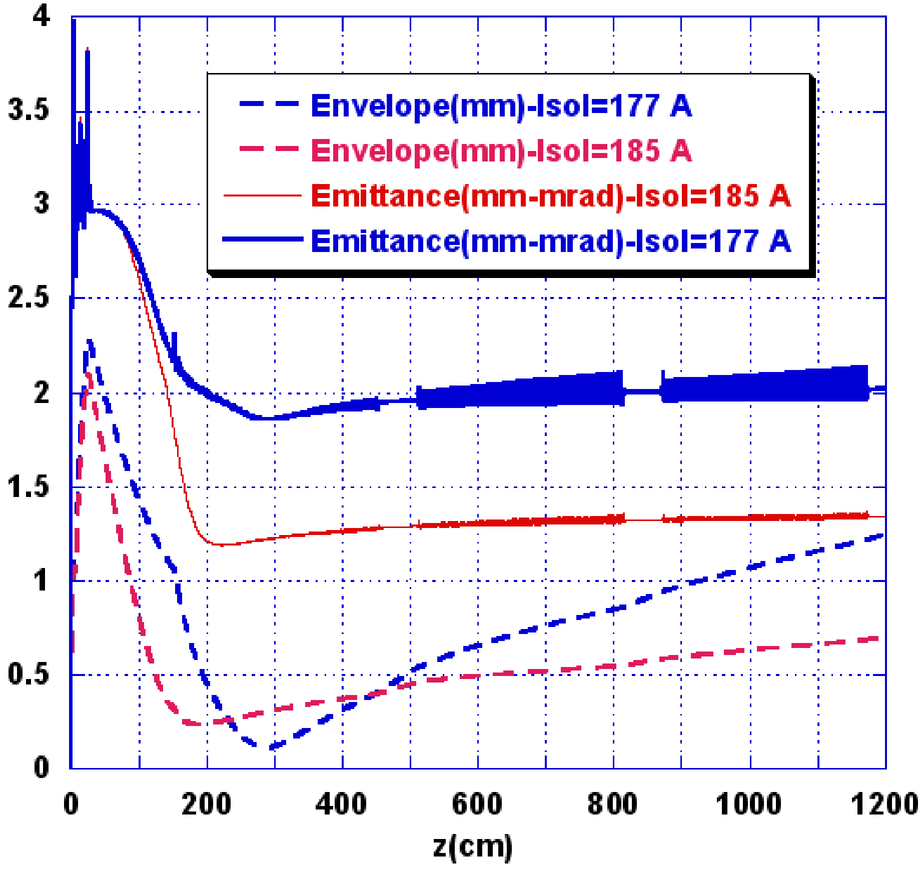


Good agreement with simulations,
Non-optimized matching

SPARC second commissioning stage: beam matching with the linac

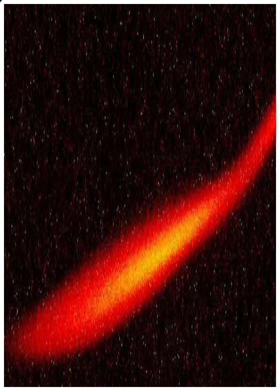


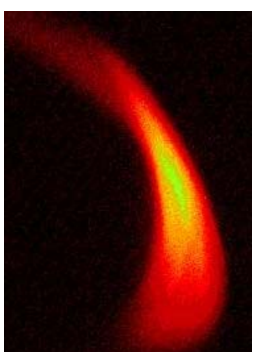
Simulated B-scan

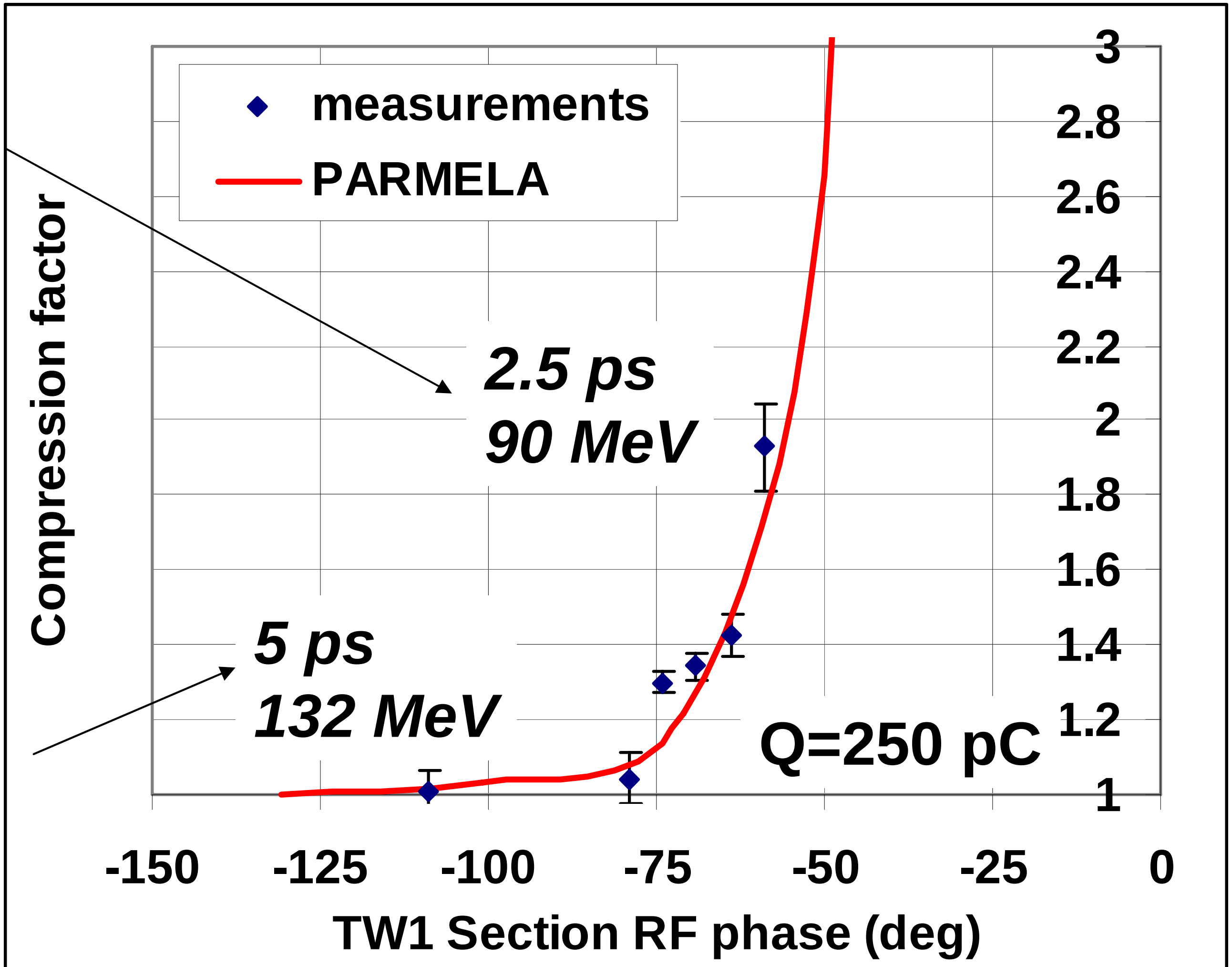


Simulations indicate that in this case an emittance of 1.34 mm-mrad could be achieved in optimized matching conditions

SPARC second commissioning stage: longitudinal dynamics in “velocity bunching” regime







CONCLUSIONS

- The emittance compensation in a photoinjector can be numerically modelled at different levels of accuracy by different codes developed to simulate the beam transport in space-charge dominated conditions
- The comparison with measurements can allow to understand the limits of the applicability of the different models and how to take advantage of the different features of the codes (indications about reliability of analysis tools, support to commissioning...)
- The comparisons between measurements and simulations based on PARMELA code during the SPARC commissioning confirm the theoretical predictions. Codes benchmark and validation continue…..