Start-to-End Simulations for IR/THz Undulator Radiation at PITZ

(Radiation Wavelength of 100 μm)

Outline

- Introduction
- Simulations Setup
- Simulation Results
- Summary & Outlook

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Thanks:
Martin Khojoyan
Georgios Kourkafas
Barbara Marchetti

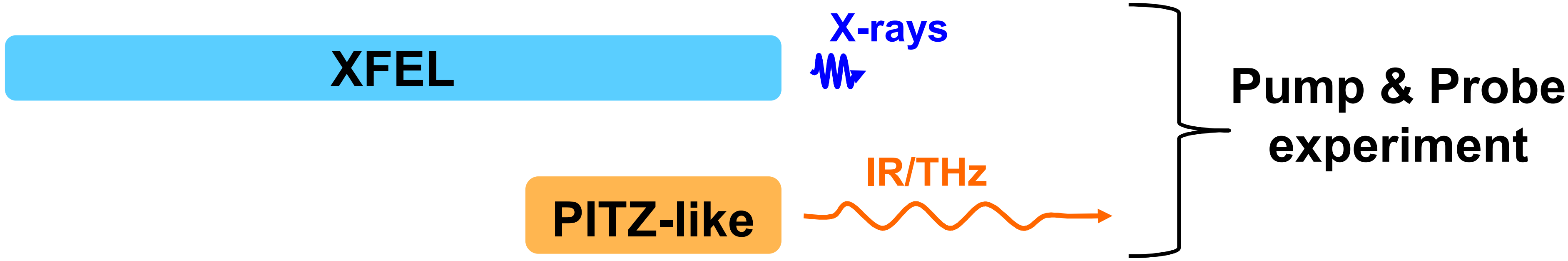
PITZ Physics Seminar
26.06.2014

HELMHOLTZ
ASSOCIATION

PITZ Photo Injector Test Facility Zeuthen

DESY

Introduction: IR/THz source Project at PITZ



E.A.Schneidmiller, et al., WEPD55, FEL2012 Proceeding.

Motivation

Development of IR/THz source for Pump-probe experiment at European XFEL with following requirements:

- generate IR/THz radiation by electron bunches from a separate electron accelerator.
- Tunable in a wide range (um to mm).
- synchronization with X-ray pulse.
- Test Facility for study of generation of IR/THz radiation is needed.

"PITZ is the proper test facility"

- Our infrastructure is as same as the injector of European XFEL.
- Ready for expansion.
- Many options of cathode laser pulse shapes.

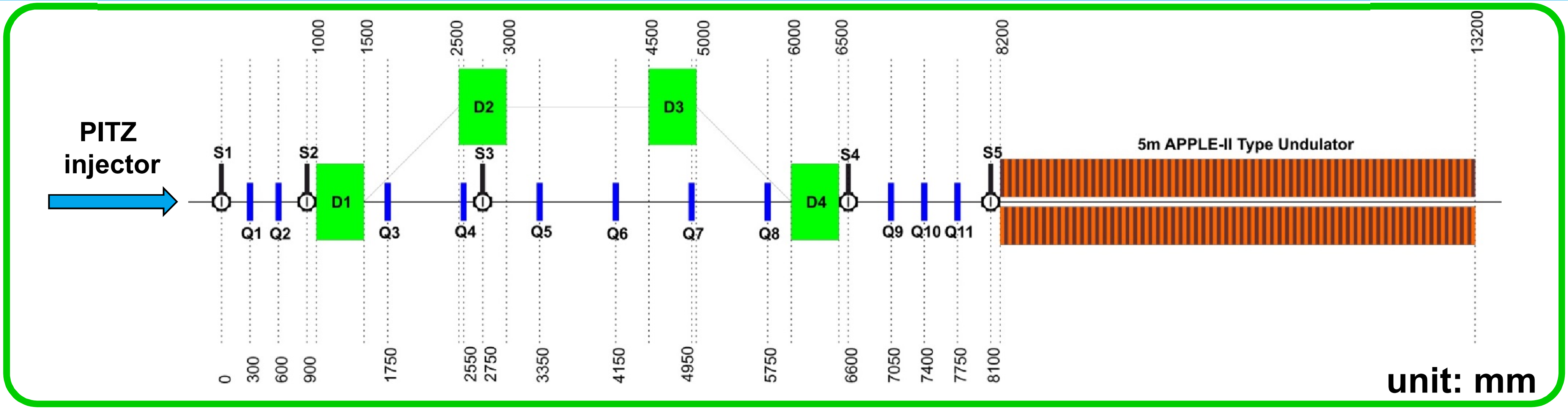
Types of Radiation

- High gain FEL
- Coherent Transition Radiation (CTR)
- Dipole Magnet Radiation
- etc.

My PhD Works for This Project

- Start-to-end (S2E) simulations of SASE FEL using high bunch charge and uncompressed beam.
- S2E simulations of CTR using compressed beam from a chicane bunch compressor.
- Simulations and experimental setup of CTR for current PITZ facility (in collaboration with HZDR).

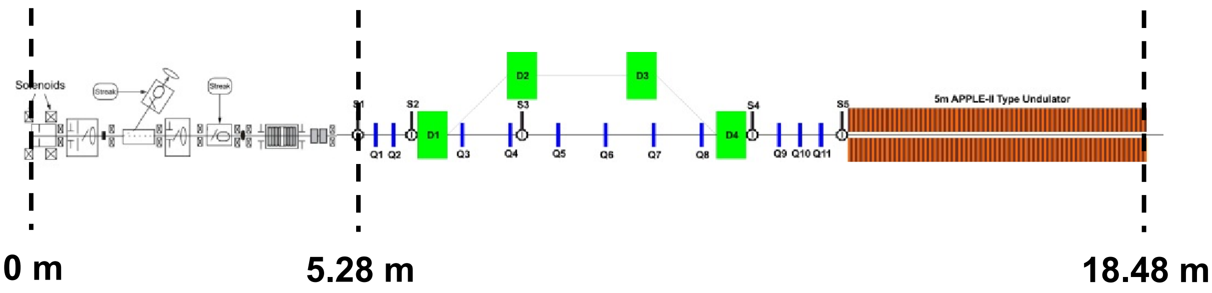
Introduction: Layout of IR/THz Beamline



- S = **S**creen station, Q = **Q**uadrupole magnet, D = 45° **D**ipole magnet
- Length of screen stations are 200 mm, Length(mechanical) of a quadrpole magnet are 63 mm.
- D1-D4 work as a C-shape chicane bunch compressor
- Purposes of the screen stations:
  - S1 ➔ Optimize beam from PITZ injector, this screen is assumed as the High1.Scr1 in actual PITZ beamline.
  - S2 ➔ Monitor the beam transverse profiles at the entrance of the bunch compressor.
  - S3 ➔ Screen for the emittance measurement by slit scan technique
  - S4 ➔ Monitor the beam transverse profiles at the exit of the bunch compressor.
  - S5 ➔ Monitor the beam transverse profiles at the entrance of the undulator.
- Emittance measurement stations by using single slit scan technique:
  - S1 and S3 (ΔL = 1.850 m)
  - S4 and S5 (ΔL = 1.500 m)

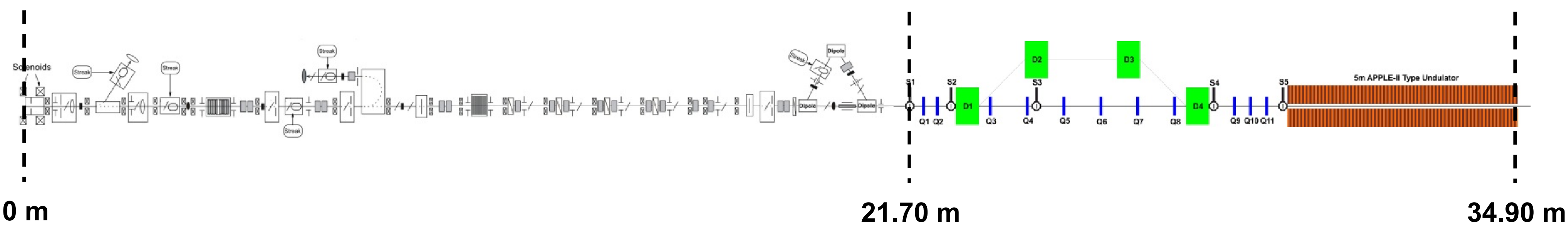
Introduction: Layout for S2E simulations

Layout 1: PITZ until H1.Scr1 + IR/THz beamline



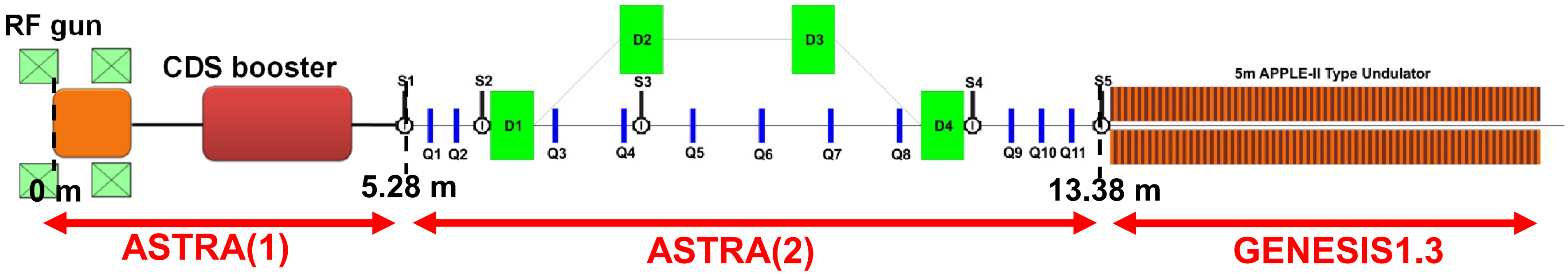
Used for works in this presentation and further studies.

Layout 2: PITZ until beam dump + IR/THz beamline



Study later, after the studies with Layout 1 are done.

Simulation Setup: ASTRA(1)



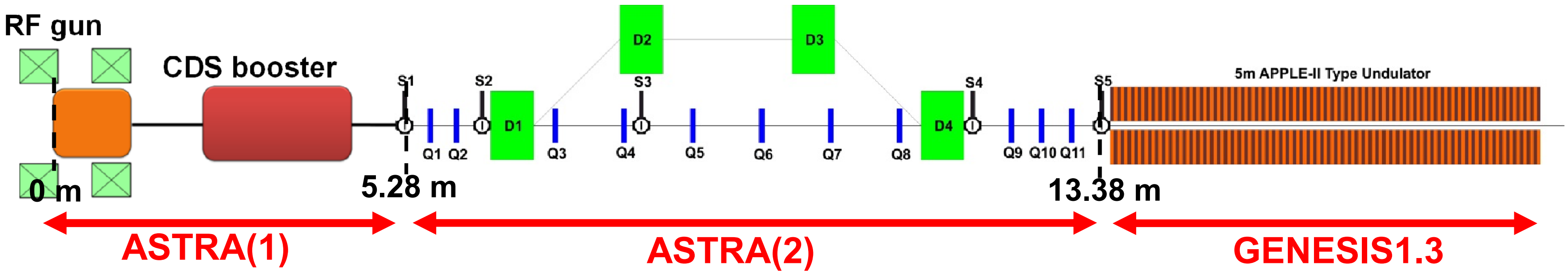
ASTRA (1)

- 200k particles, 4 nC bunch charge
- 2D algorithm for space charge calculation
- Optimization strategy:
  - Tuned parameters: main solenoid current
  - Optimize the beam at z = **5.28 m for 2 cases:**

    1.) minimum transverse size
    2.) minimum transverse emittance

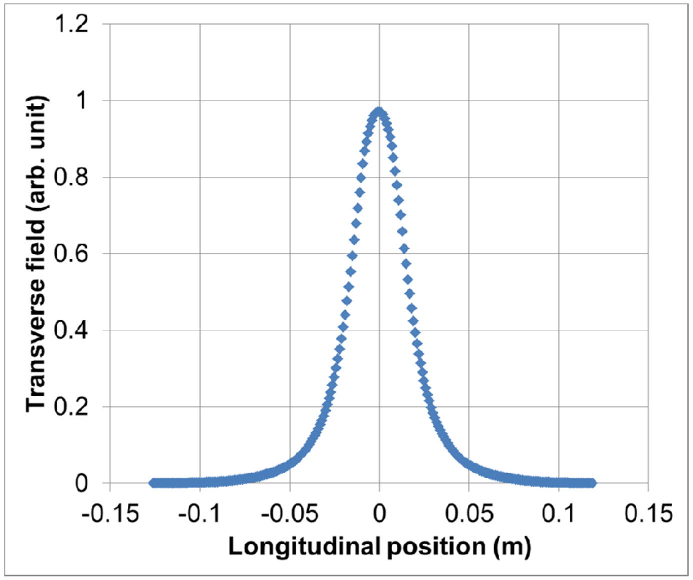
Input Parameters for ASTRA	
laser pulse shape	Flattop
laser temporal time	2/21.5\2 ps
main solenoid current	vary
Z_{start} to Z_{end}	0 to 5.28 m
rms laser spot size	1 mm
gun peak field	60 MV/m
booster peak field	10 MV/m (for e-beam with 15 MeV/c)
gun phase	0
booster phase	0

Simulation Setup: ASTRA(2)



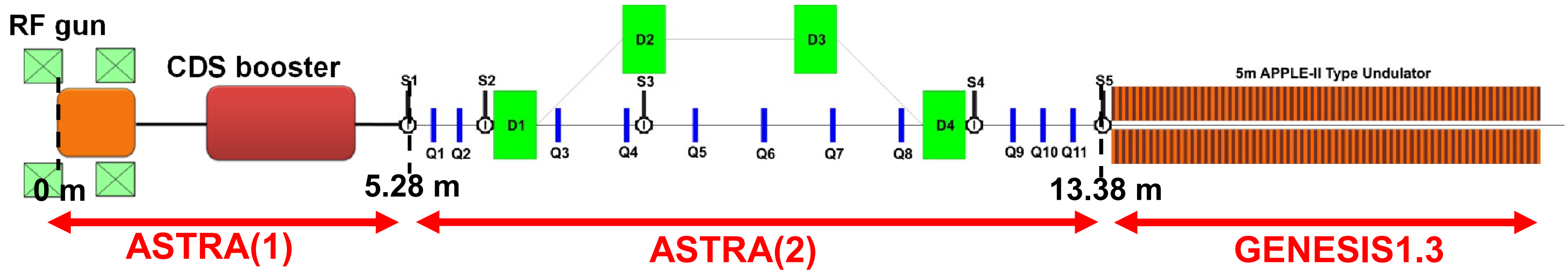
ASTRA (2)

- Simulation from S1 to S5 (ΔL = 8.100 m)
- Use 3D algorithm for space charge calculation
- All quadrupole magnets have identical properties
- Use real quadrupole field profile (right hand side picture)
- Use MADX to define the field gradients for beam matching without space charge effect
- Goal for matching at the undulator entrance:
  - symmetric beam
  - beam transverse size as small as possible
  - parallel beam, small convergence or divergence



Effective length = 43 mm

Simulation Setup: GENESIS



GENESIS 1.3

- 8192 particles per slice
- Space calculation is included
- Radiation by SASE mode (no seed power)
- Resonant formula for related parameter calculations

$$\lambda_{rad} = \frac{\lambda_u}{2\gamma^2}(1 + a_w^2)$$

where λ_{rad} is radiation wavelength

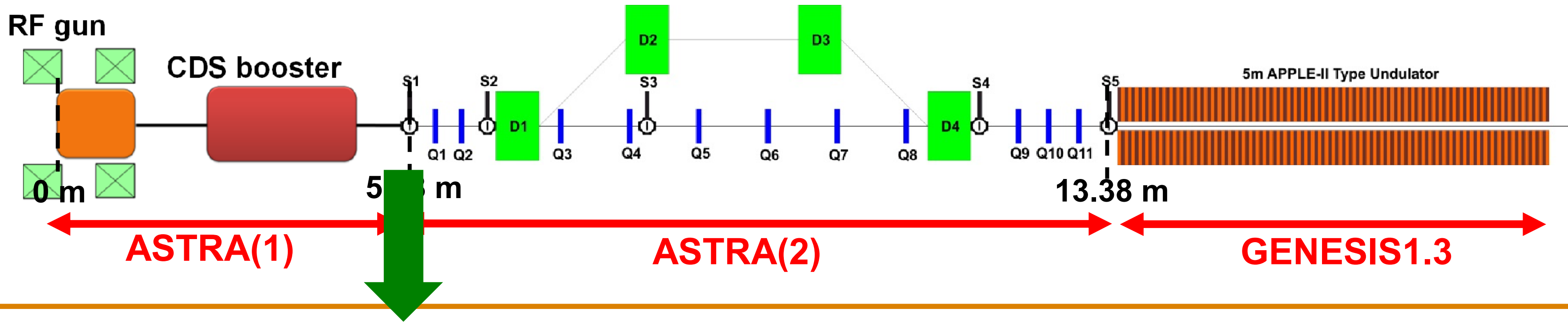
λ_u is undulator period length

a_w is undulator parameter

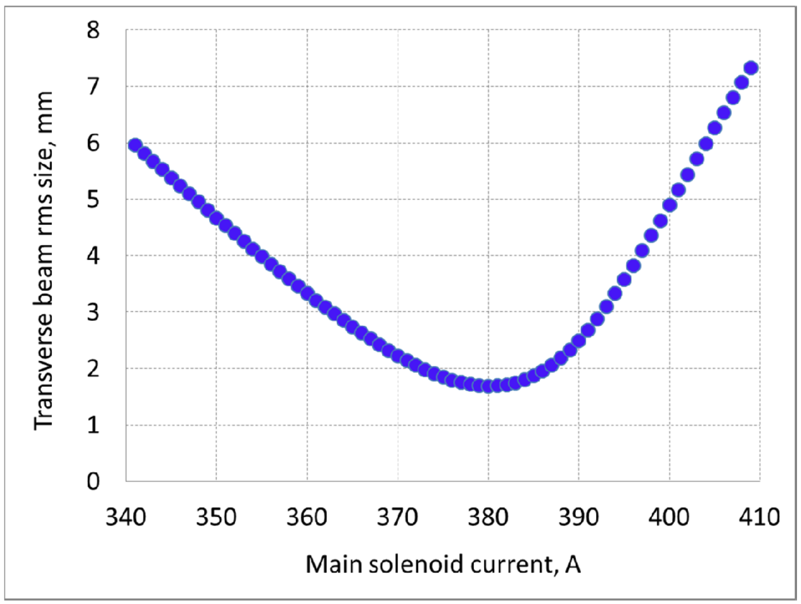
γ is Lorentz factor

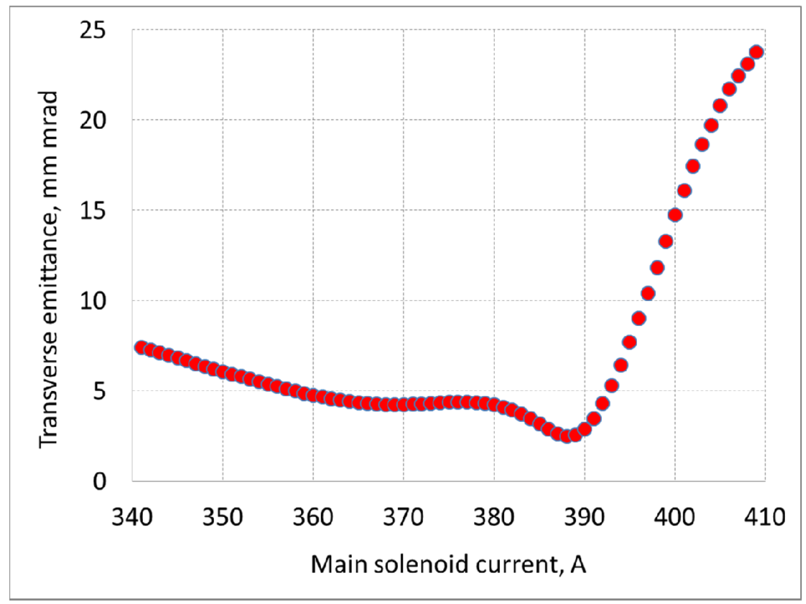
Input Parameters for GENESIS	
undulator type	Helical
λ_u	40 mm
number of period	125
λ_{rad}	100 µm (3 THz)
a_w	2.0372 (for γ = 32.094)

ASTRA(1): Simulation Results



Transverse size and emittance at S1 from various main solenoid currents

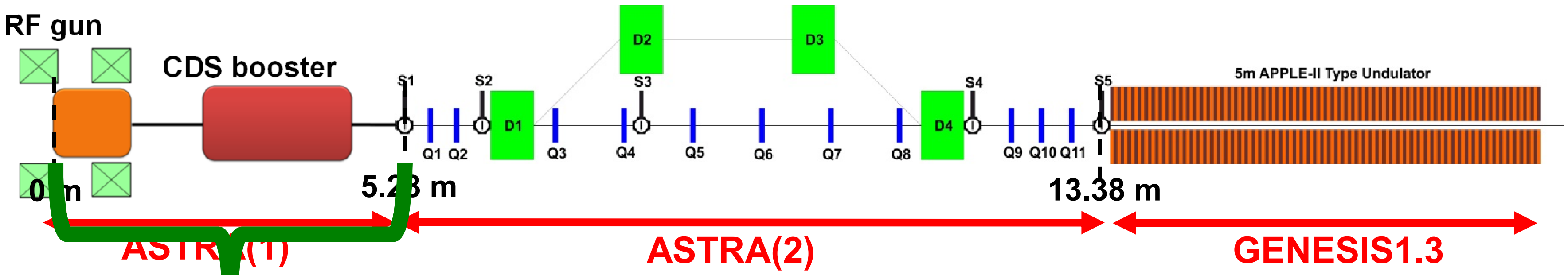




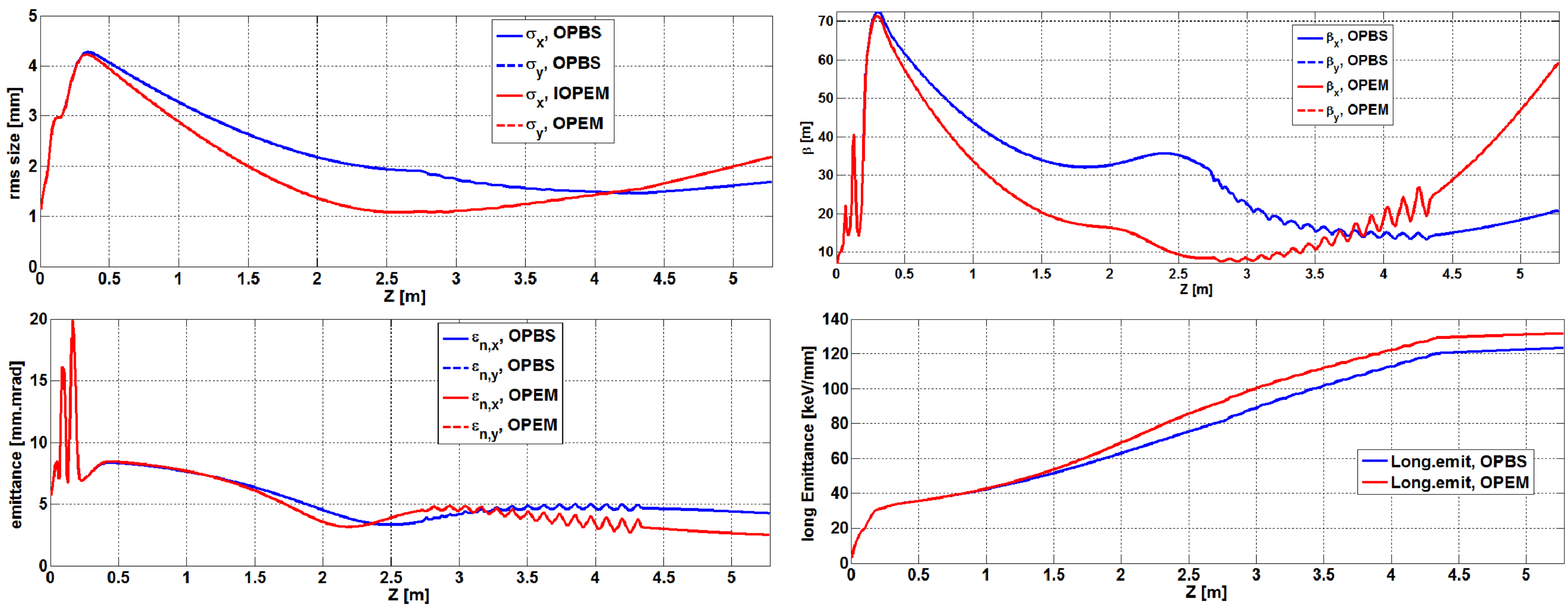
Imain = 380 for OPtimum Beam Size (OPBS)

Imain = 388 for OPtimum EMittance (OPEM)

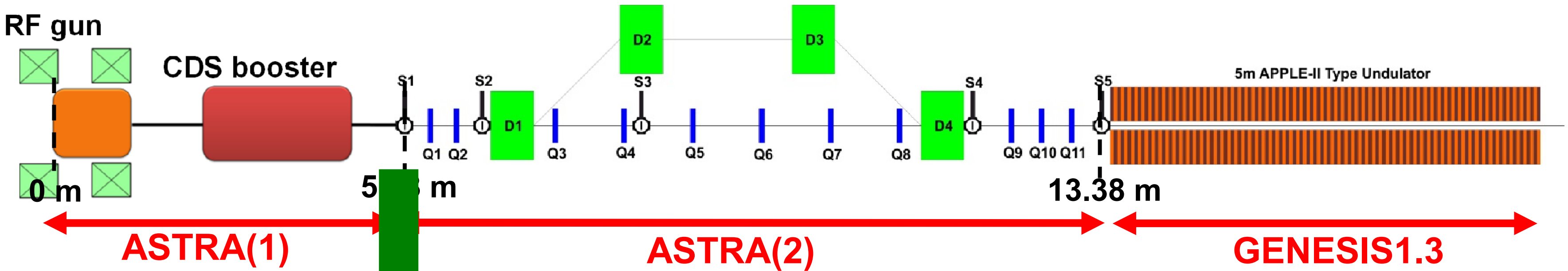
ASTRA(1): Simulation Results



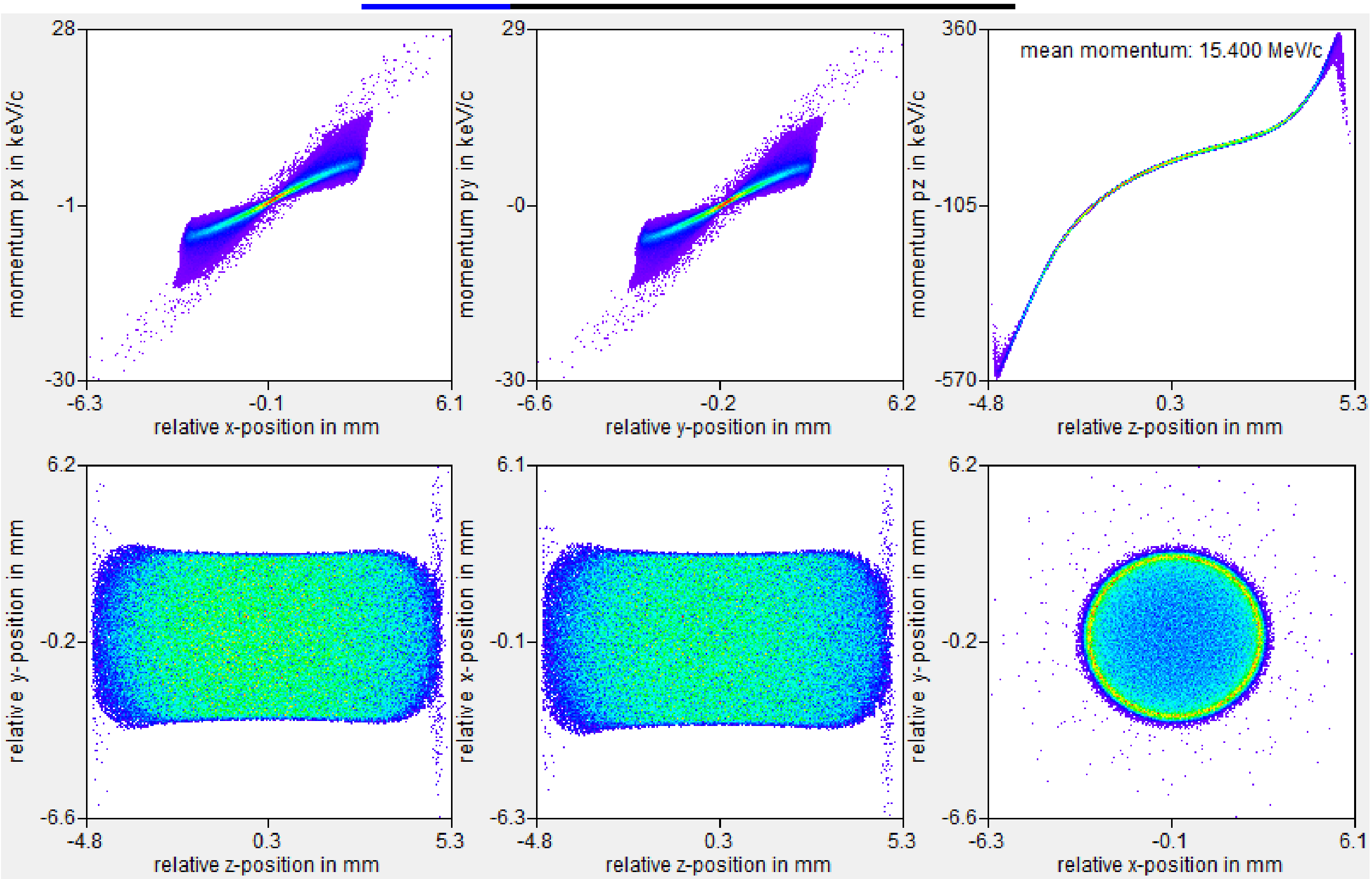
Evolution of the optimum beam parameters from cathode to S1



ASTRA(1): Simulation Results

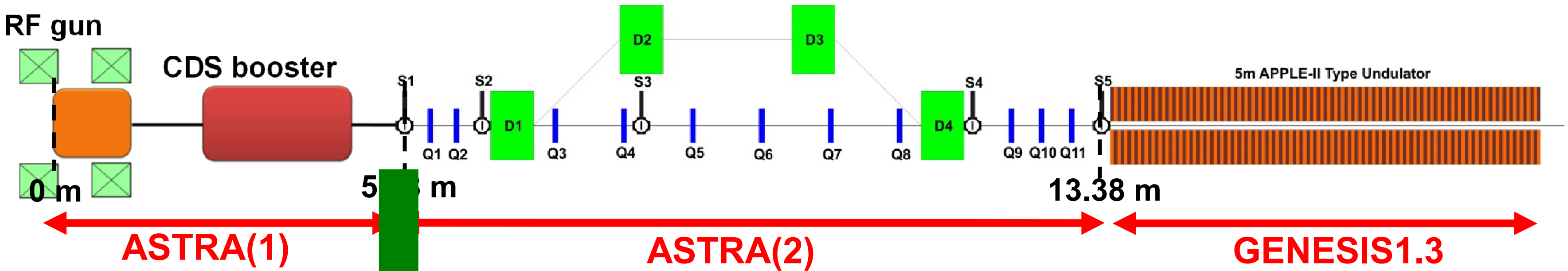


OPBS Beam Profiles at S1

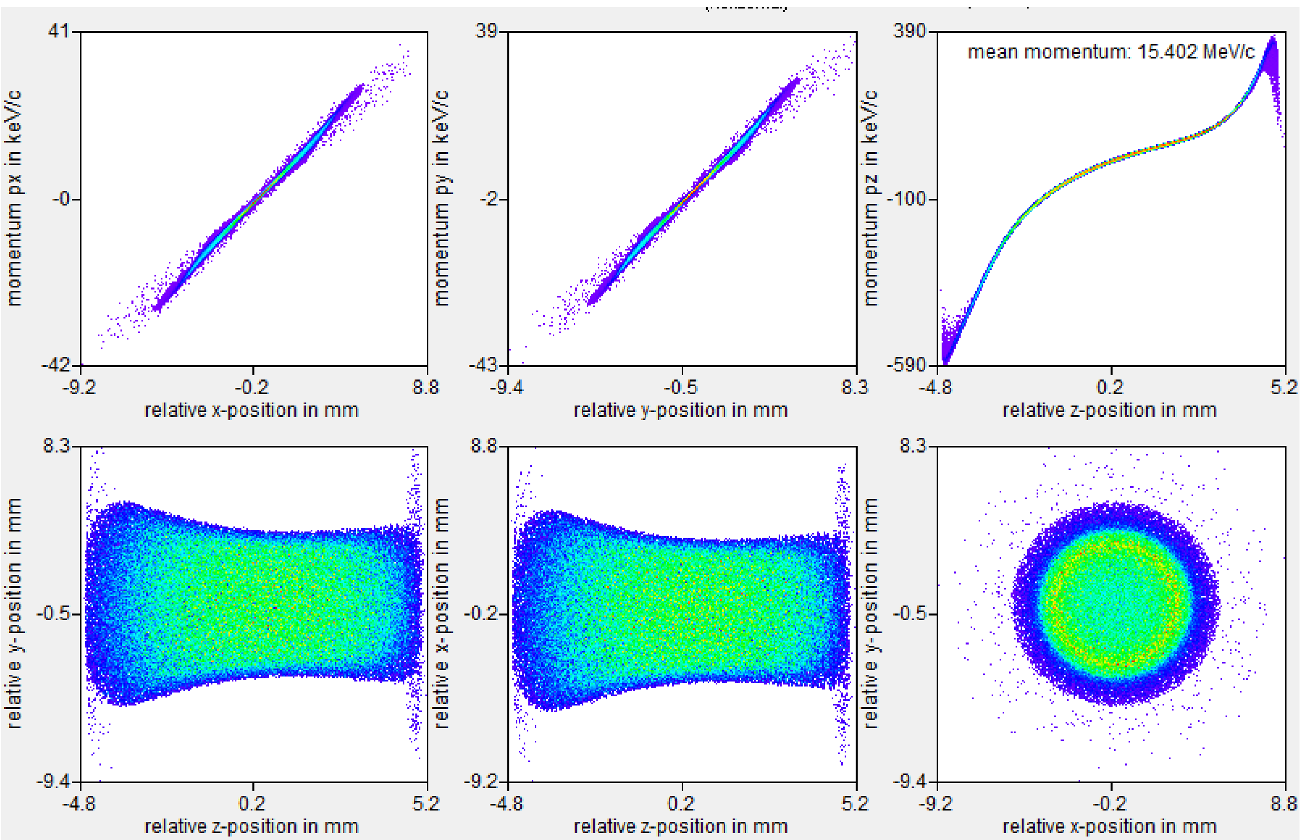


Parameters	Value
σ_x	1.70 mm
σ_y	1.70 mm
ε_n,x	4.23 um
ε_n,y	4.23 um
β_x	19.77
β_y	19.76
α_x	-3.40
α_y	-3.40
P_z	15.4 MeV/c
P_z,rms	152 keV/c

ASTRA(1): Simulation Results

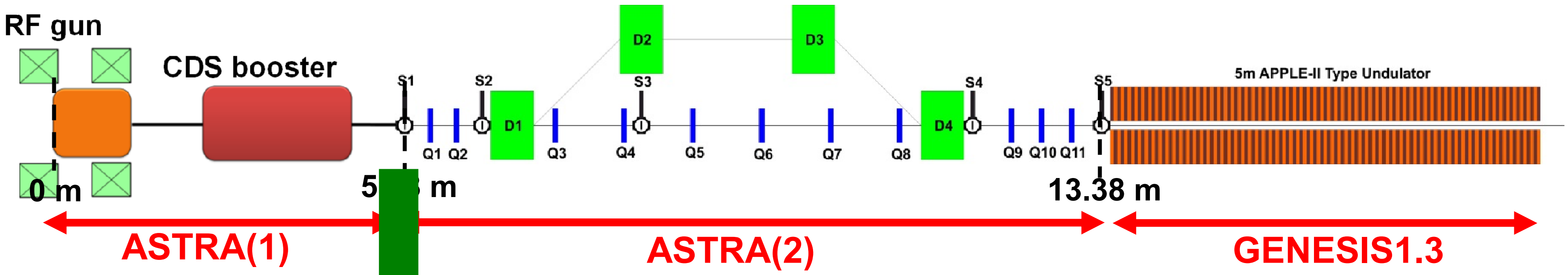


OPEM Beam Profiles at S1

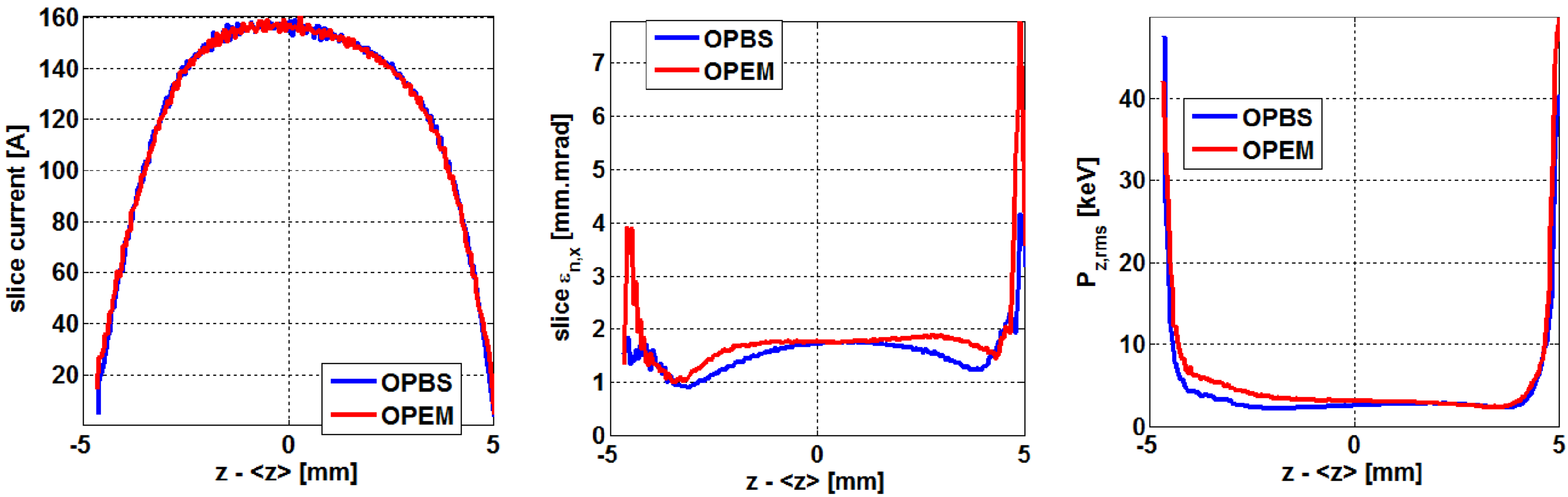


Parameters	Value
σ_x	2.20 mm
σ_y	2.20 mm
ε_n,x	2.50 um
ε_n,y	2.50 um
β_x	52.8099
β_y	52.8099
α_x	-17.1674
α_y	-17.1674
P_z	15.4 MeV/c
P_z,rms	162 keV/c

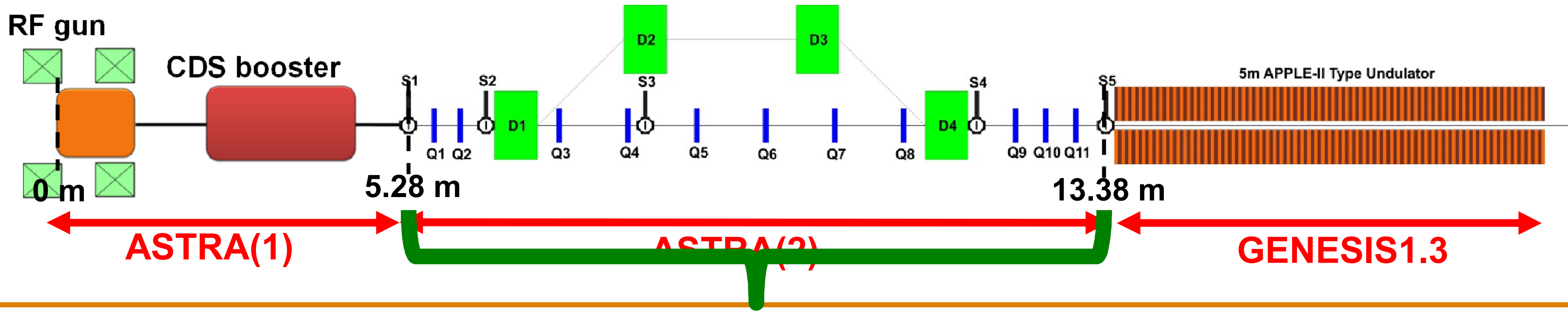
ASTRA(1): Simulation Results



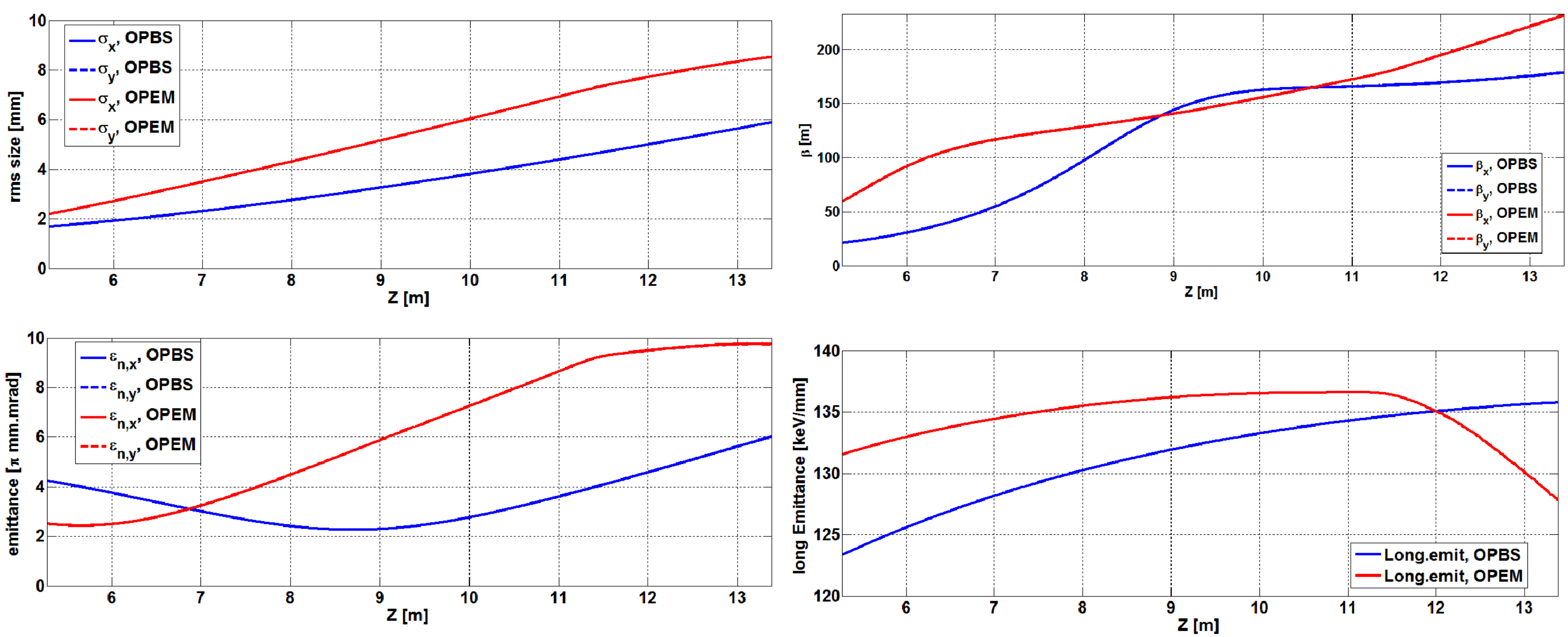
Local Profiles of OPBS and OPEM at S1



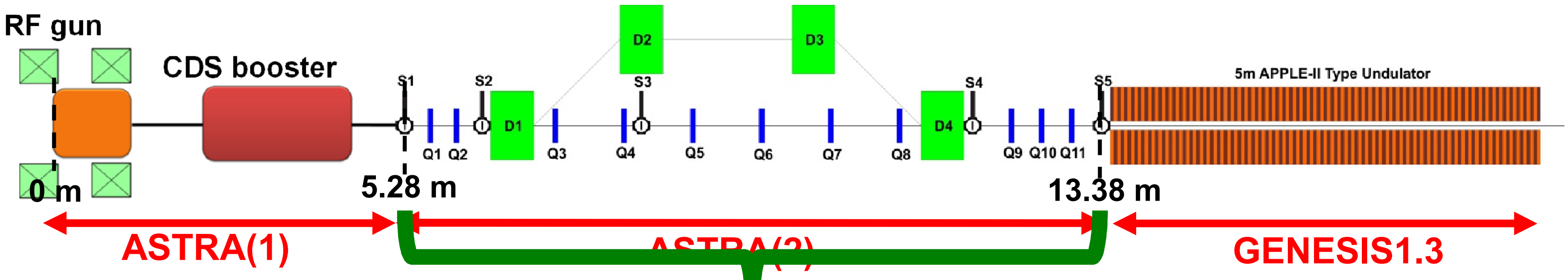
ASTRA(2): Simulation Results



Evolution of the beam parameters from S1 to S5 without QM fields

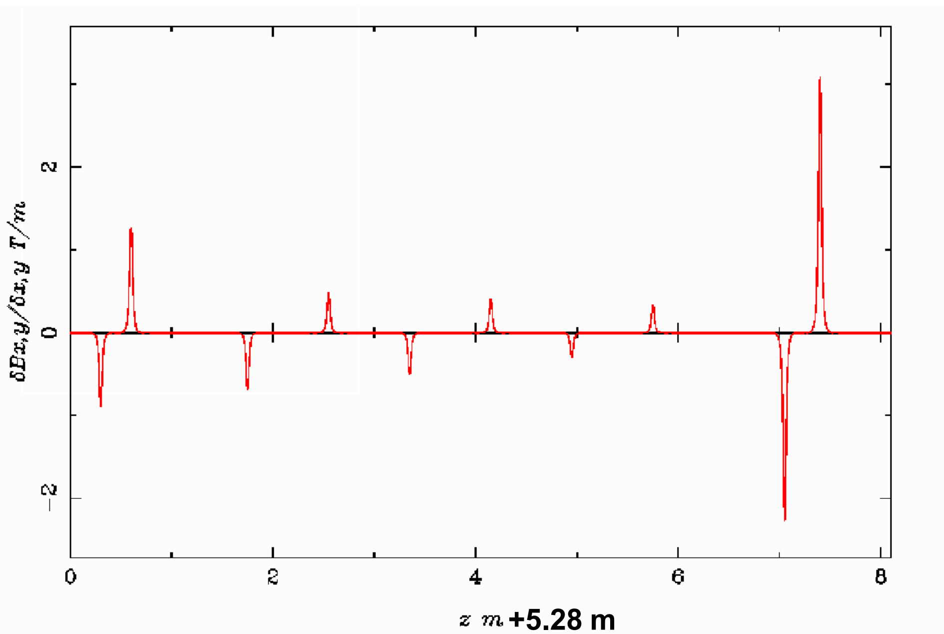


ASTRA(2): Simulation Results

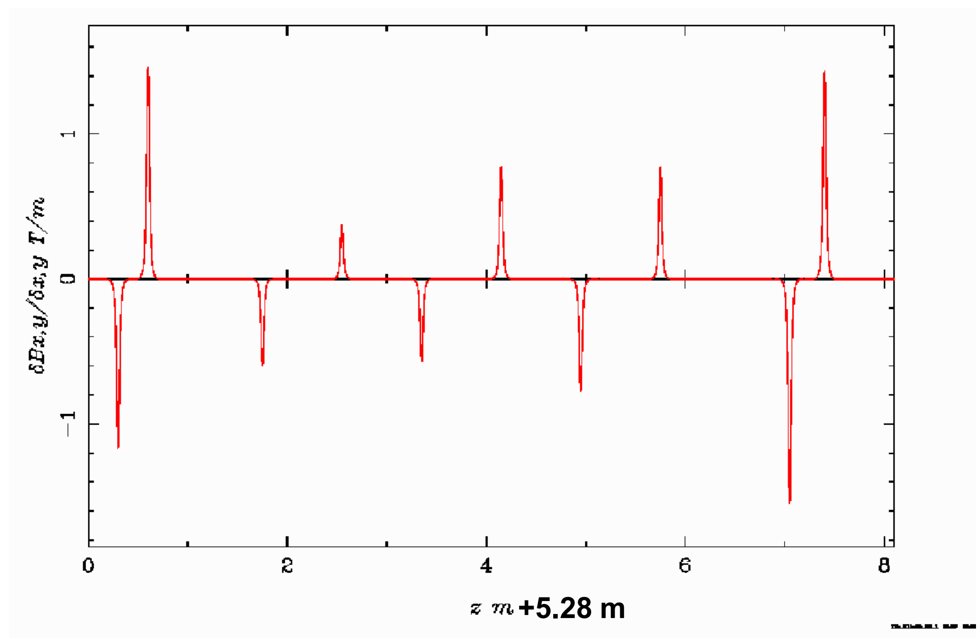


Optimized QM gradients for matching the beams from S1 to S5

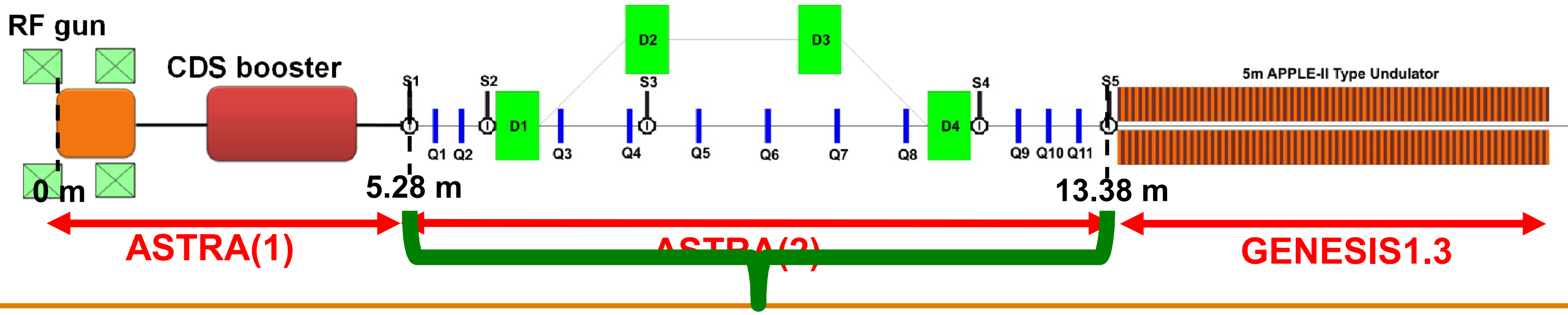
OPBS



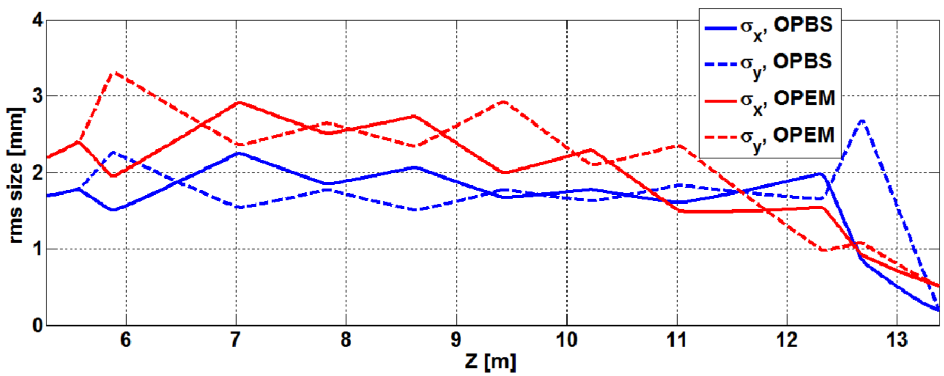
OPEM

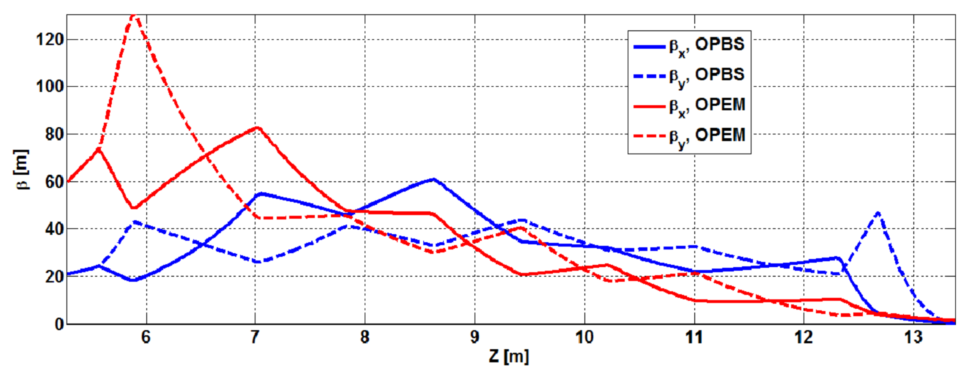


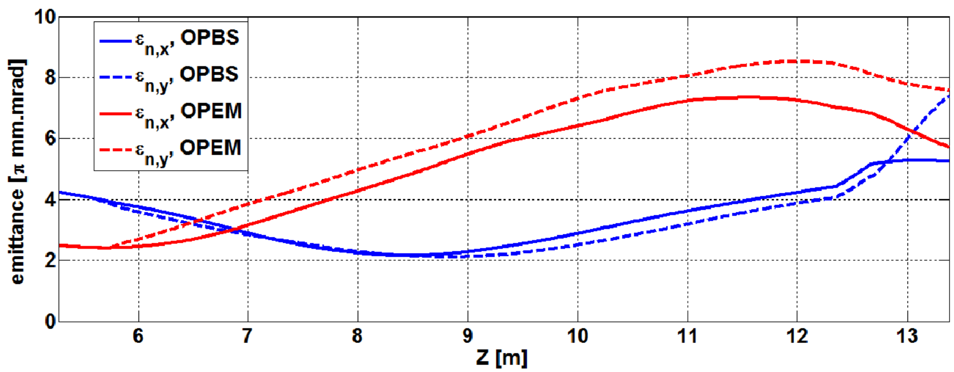
ASTRA(2): Simulation Results

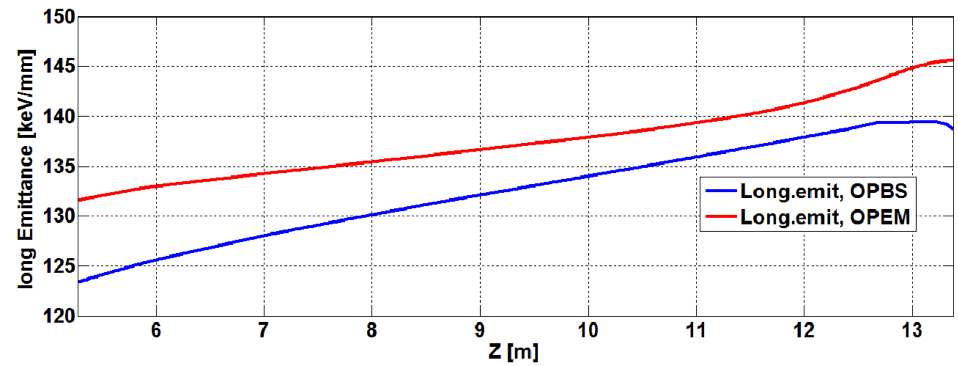


Evolution of the beam parameters from S1 to S5 with QM fields

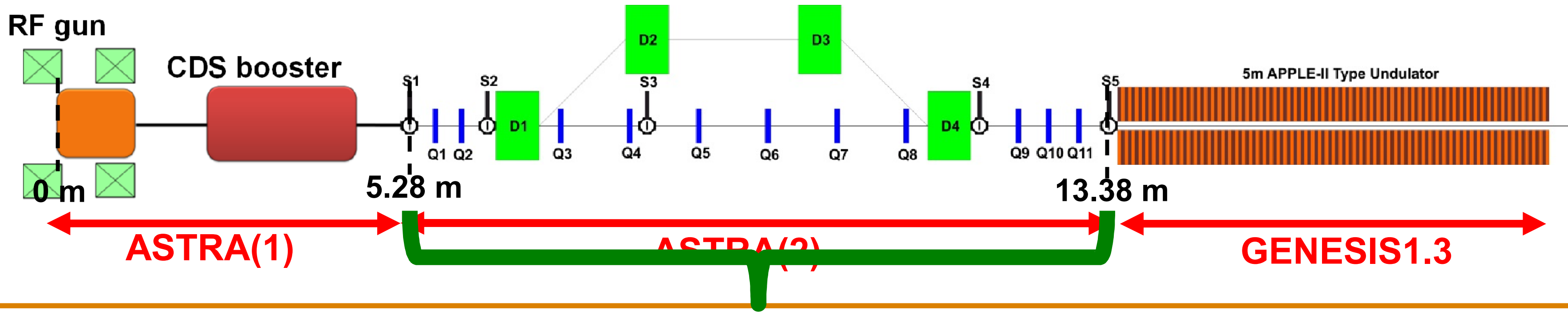






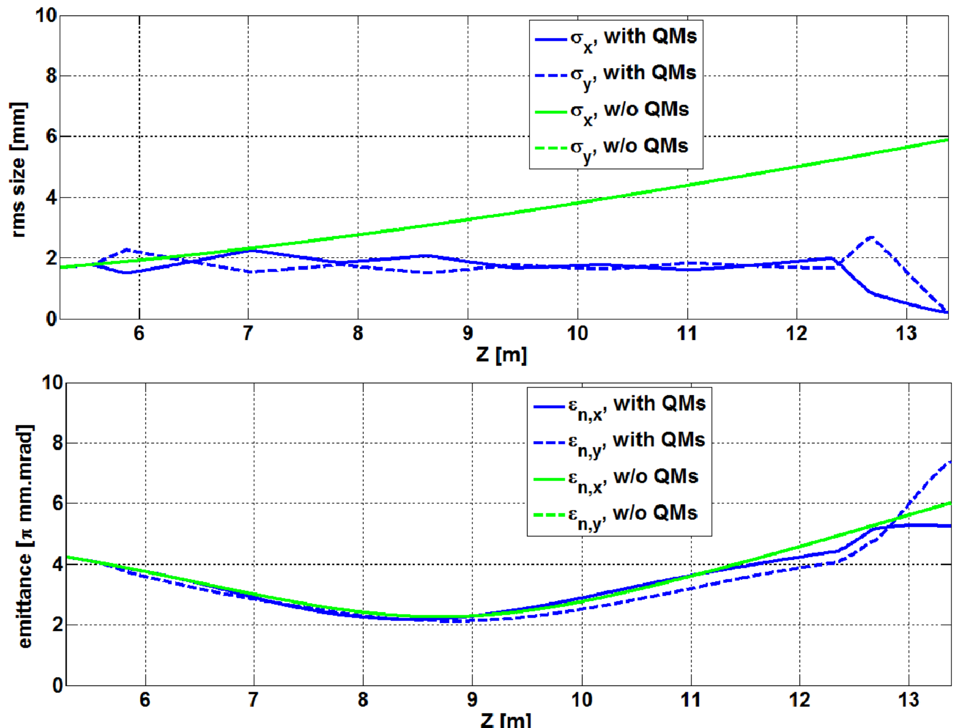


ASTRA(2): Simulation Results

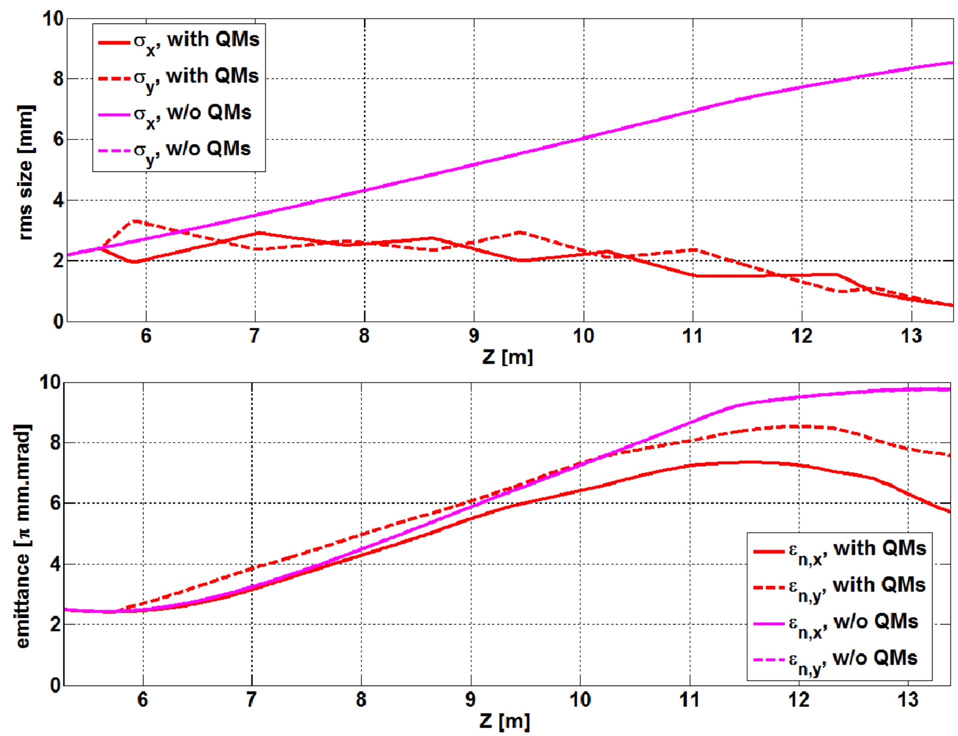


Comparison for w and w/o QM fields cases

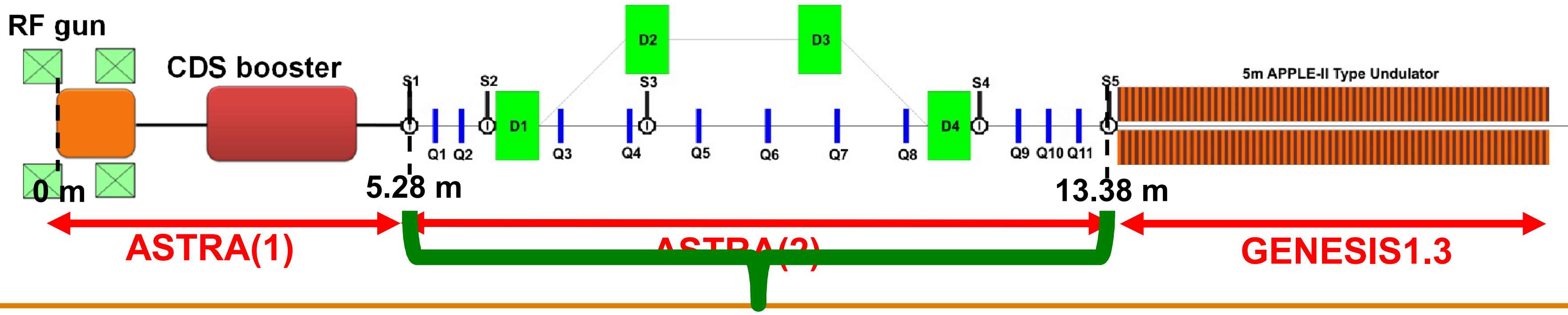
OPBS



OPEM

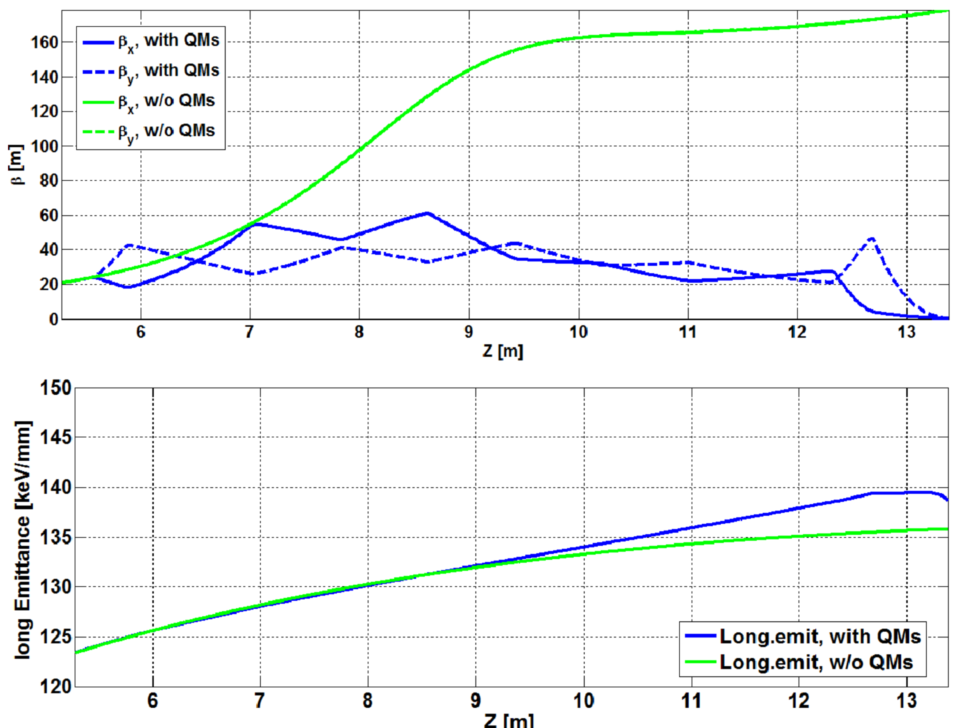


ASTRA(2): Simulation Results

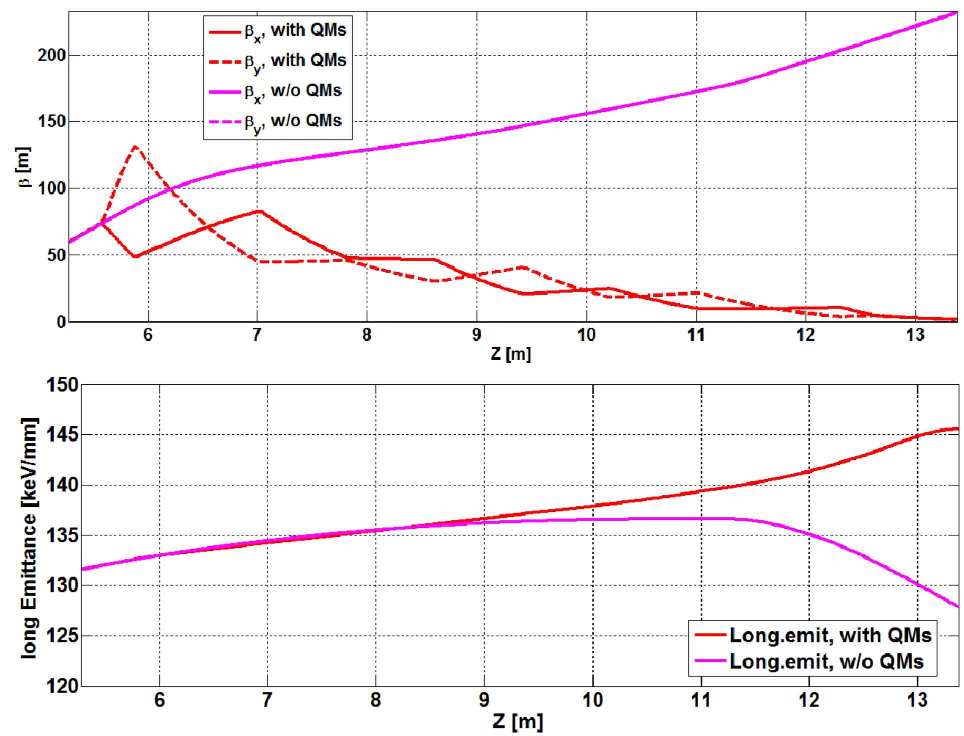


Comparison for w and w/o QM fields cases

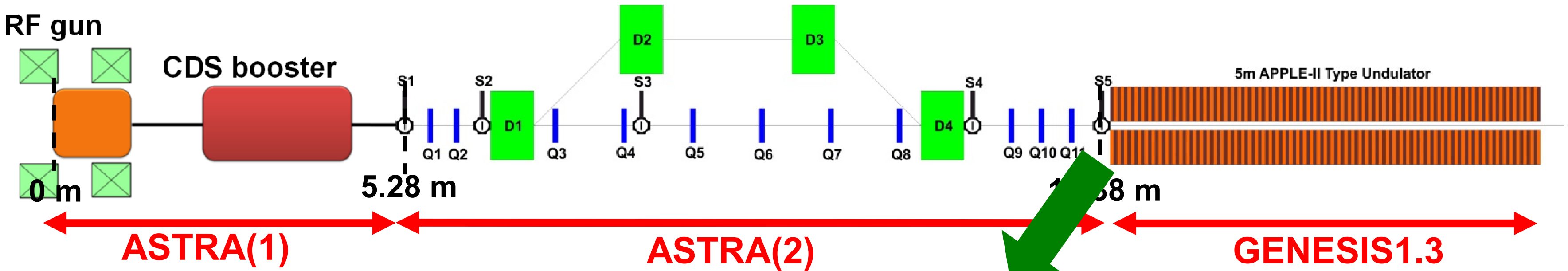
OPBS



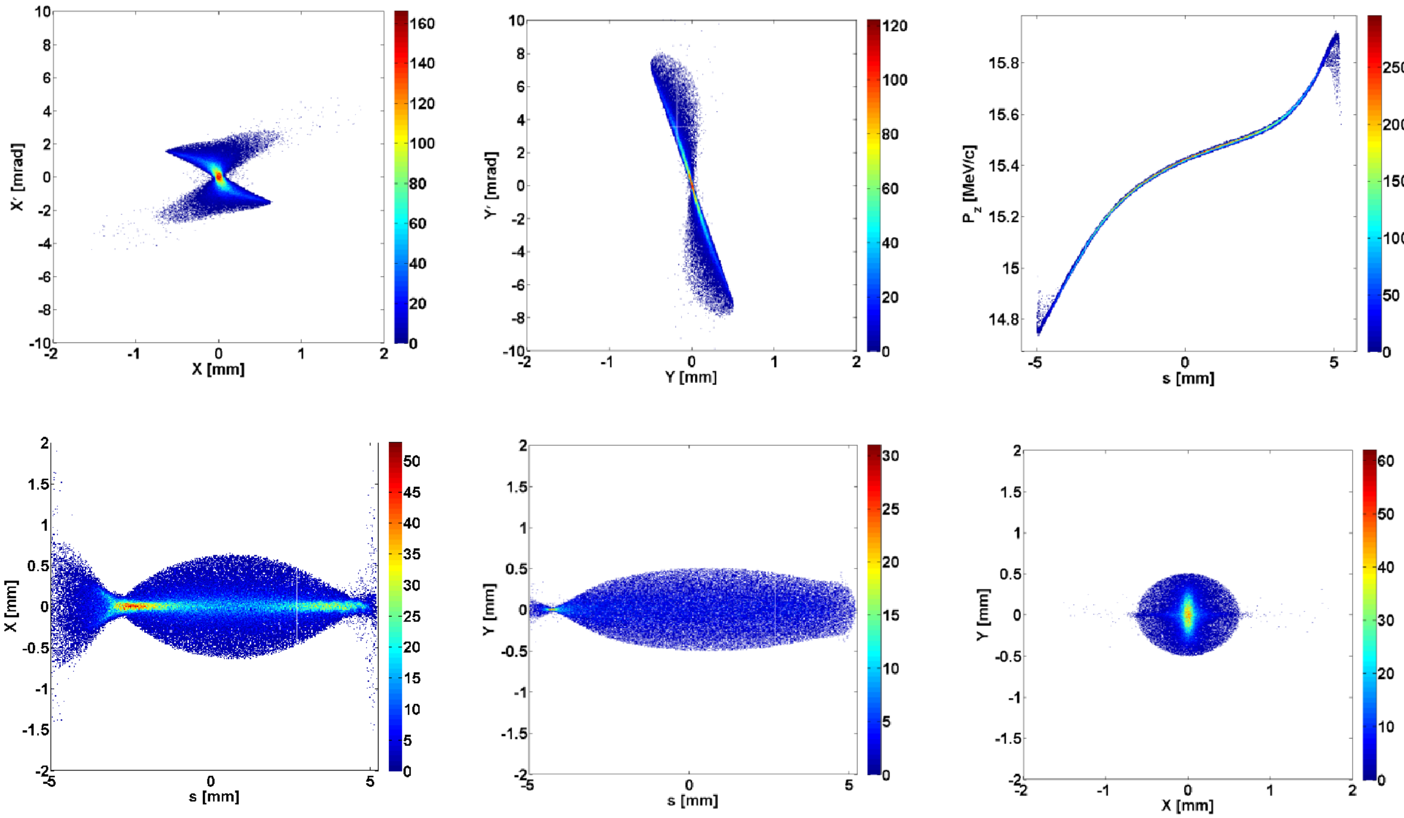
OPEM



ASTRA(2): Simulation Results

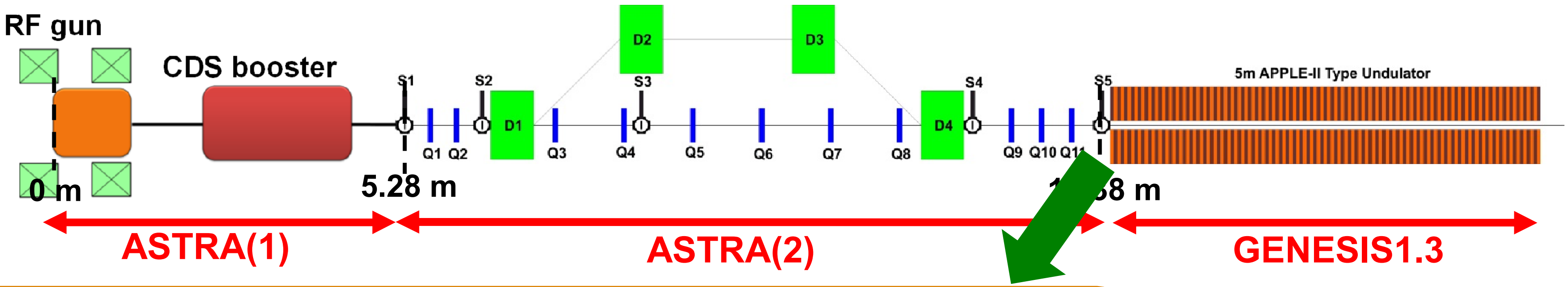


OPBS Beam Profiles at S5

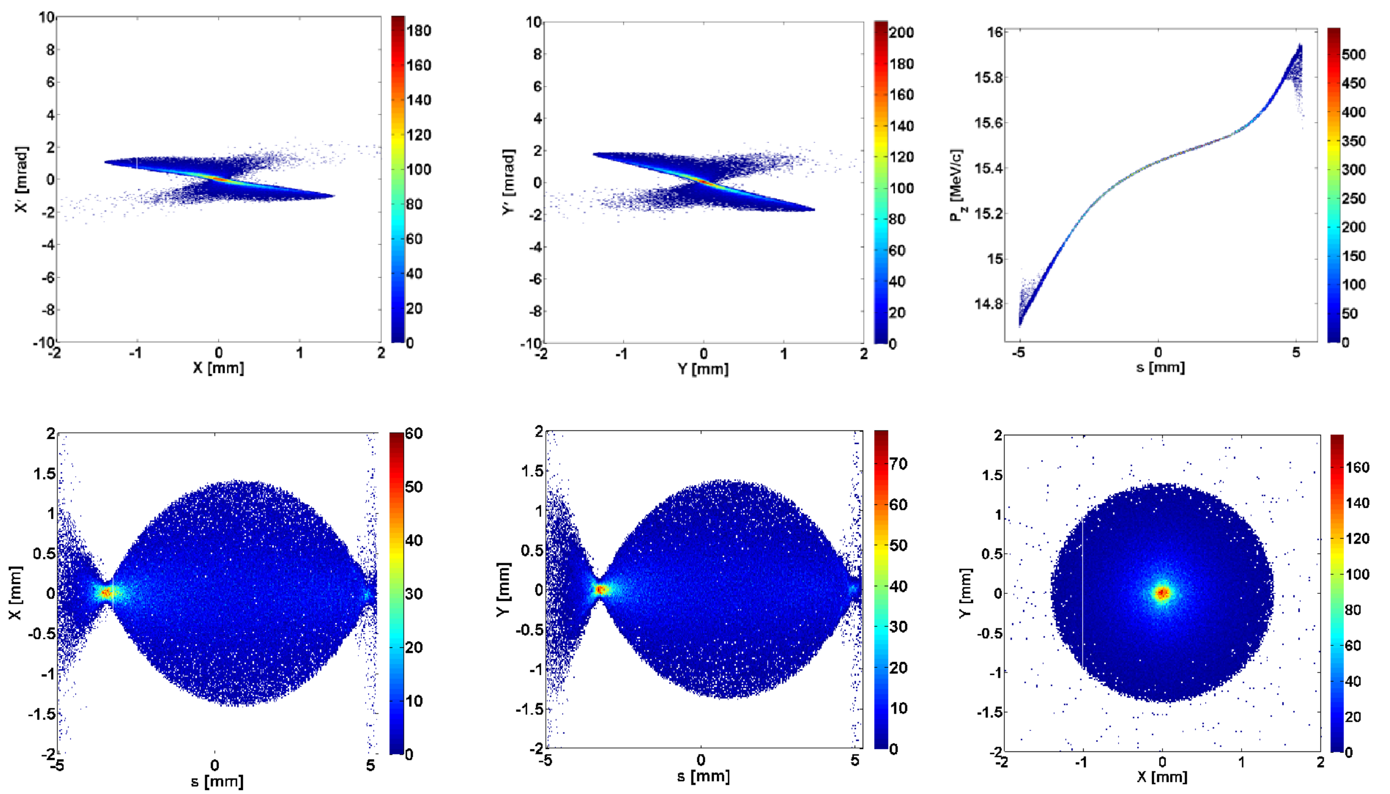


Parameters	Value
σ_x	0.196 mm
σ_y	0.197 mm
ε_n,x	5.20 um
ε_n,y	6.75 um
β_x	0.2216
β_y	0.1674
α_x	0.4542
α_y	2.8457
P_z	15.4 MeV/c
P_z,rms	203 keV/c

ASTRA(2): Simulation Results

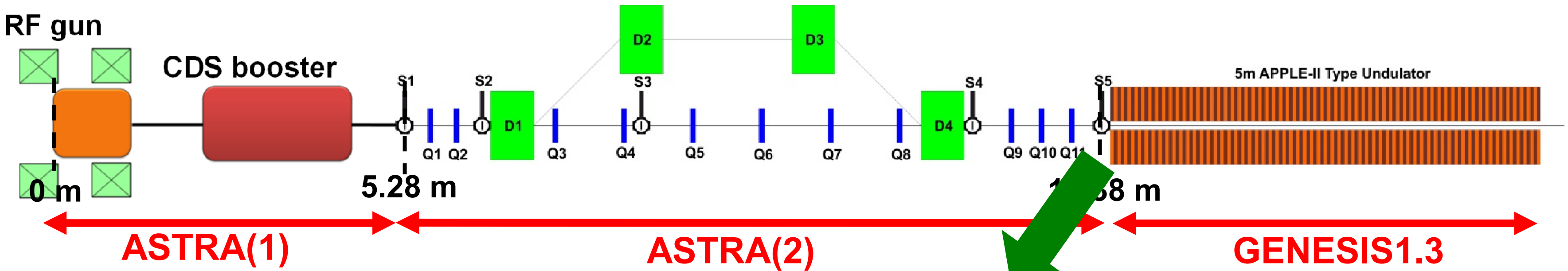


OPEM Beam Profiles at S5

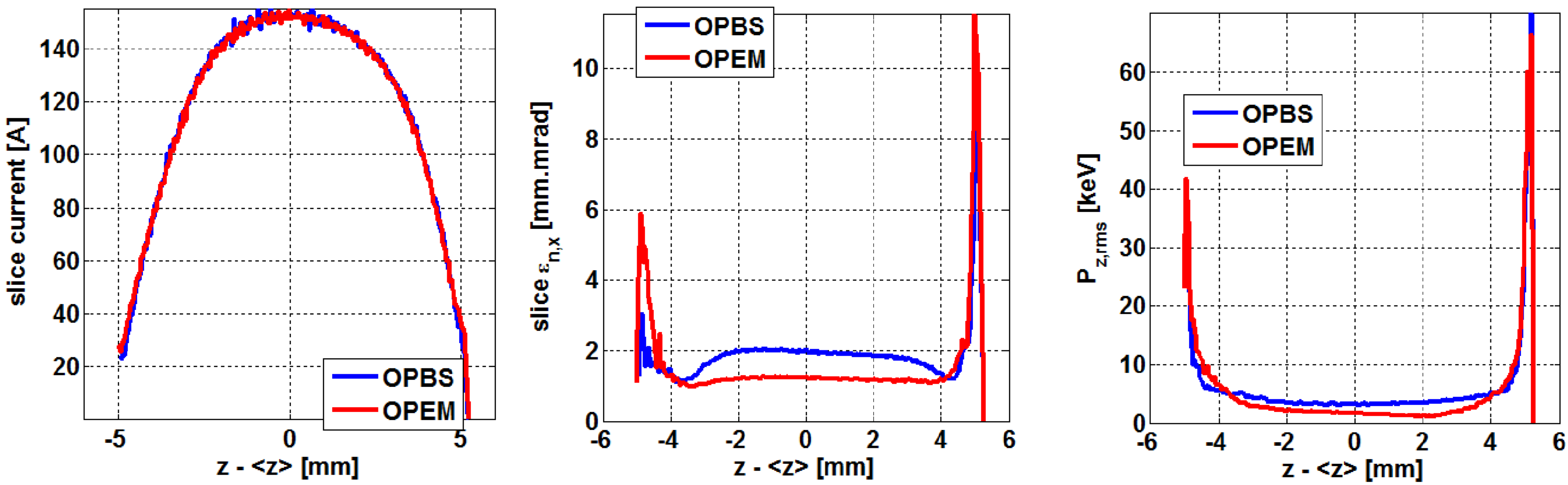


Parameters	Value
σ_x	0.52 mm
σ_y	0.51 mm
ε_n,x	5.72 um
ε_n,y	7.56 um
β_x	1.39
β_y	1.02
α_x	1.16
α_y	1.33
P_z	15.4 MeV/c
P_z,rms	211 keV/c

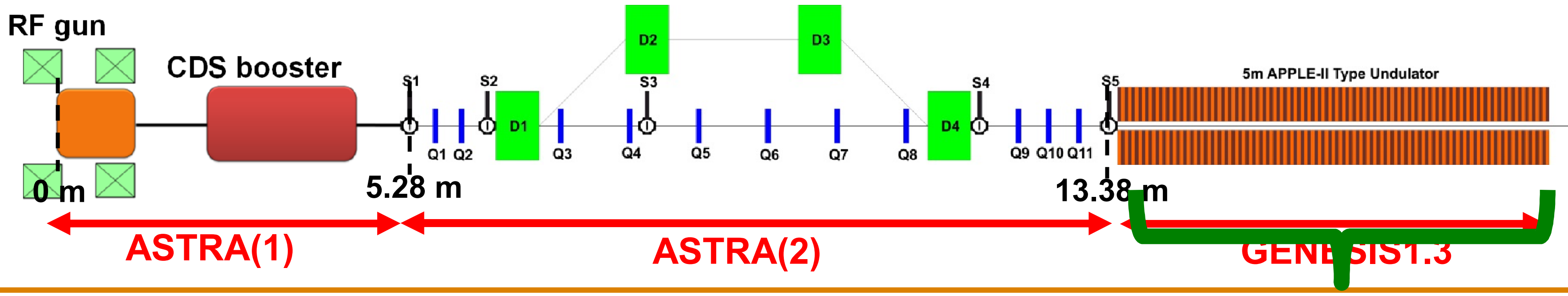
ASTRA(2): Simulation Results



Local Profiles of OPBS and OPEM at S5

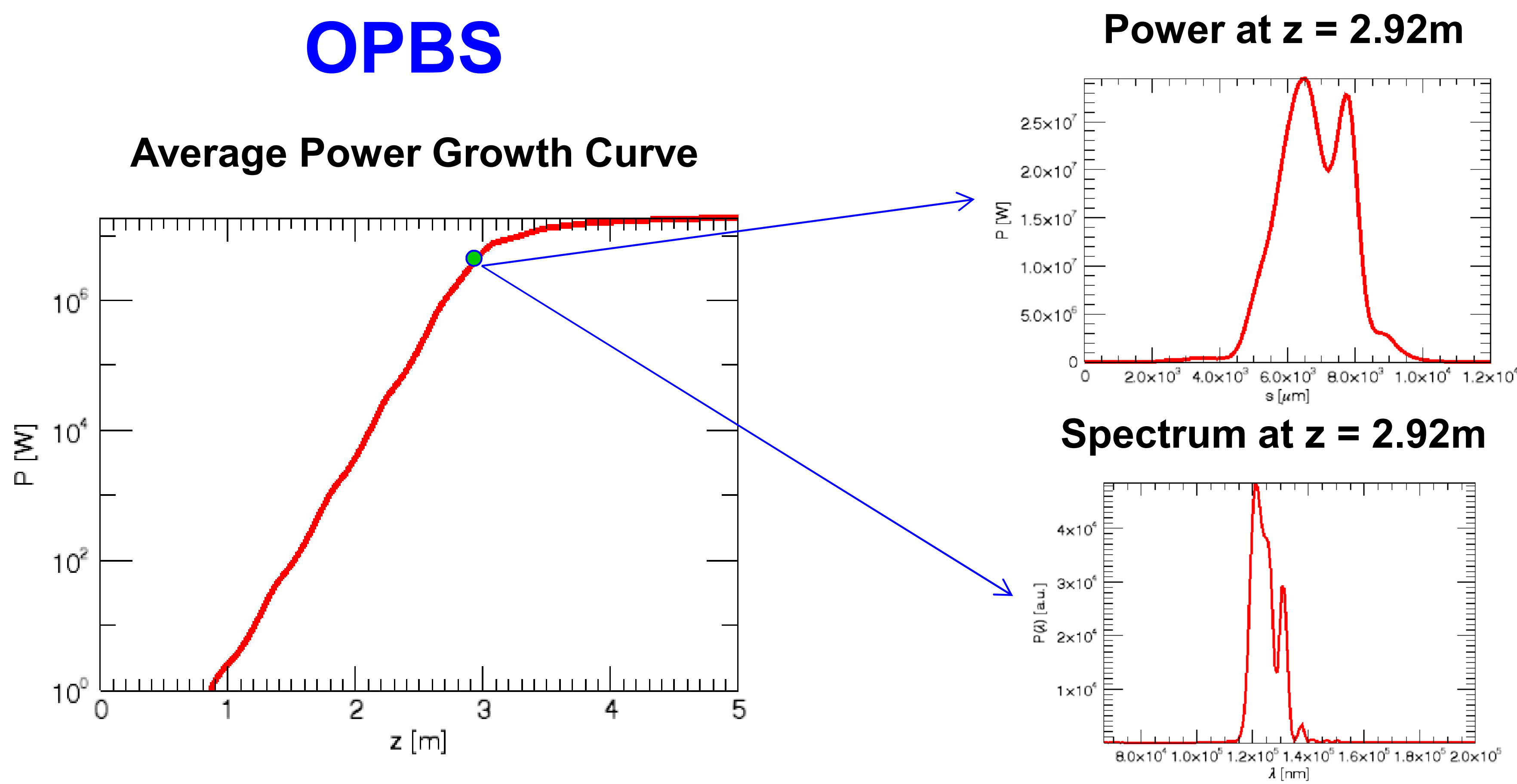


GENESIS1.3: Simulation Results

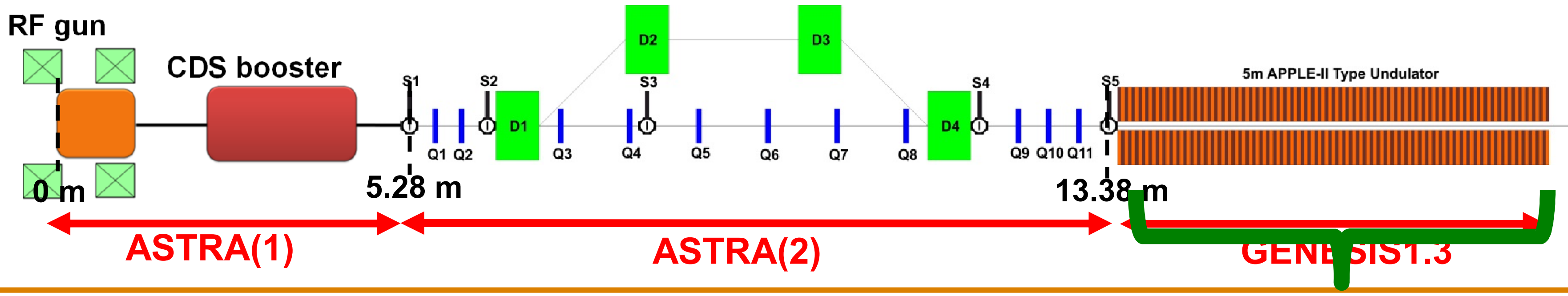


OPBS

Average Power Growth Curve

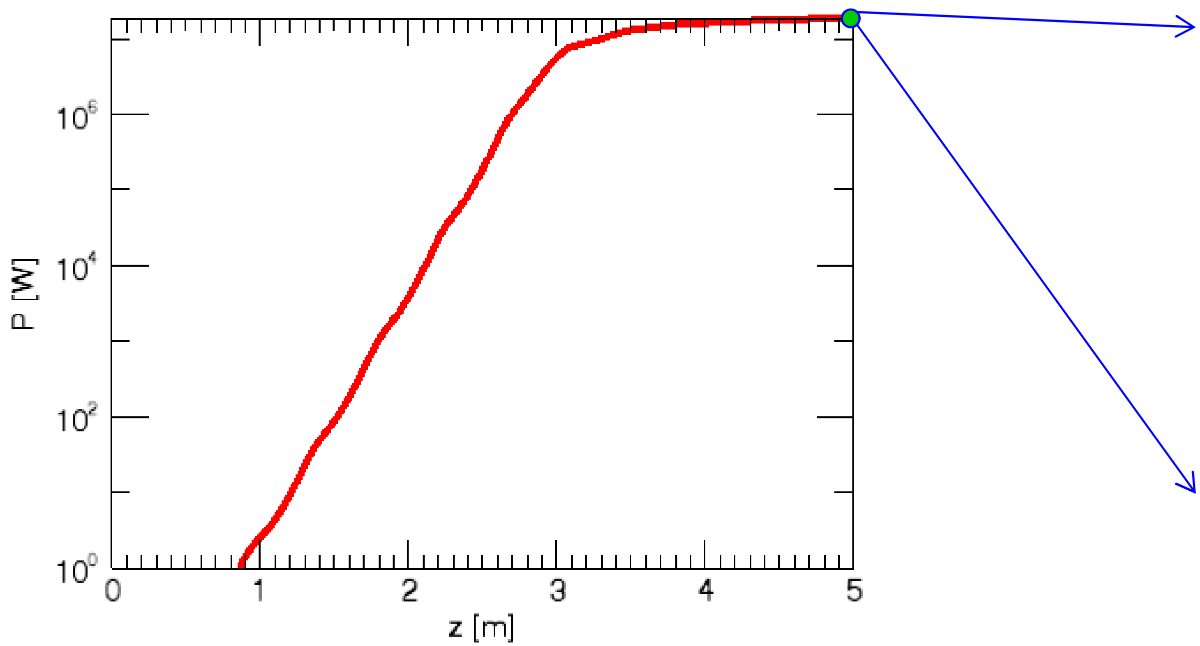


GENESIS1.3: Simulation Results

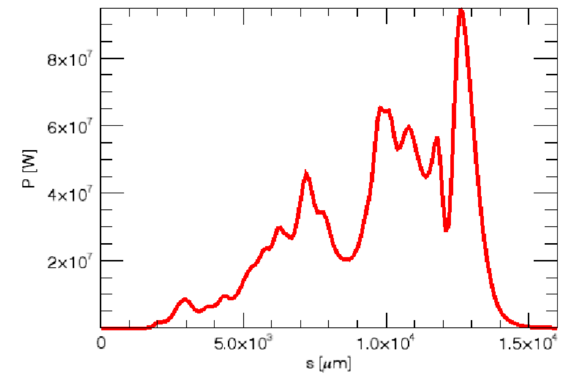


OPBS

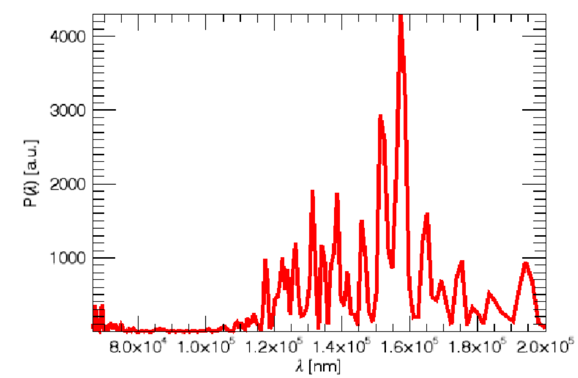
Average Power Growth Curve



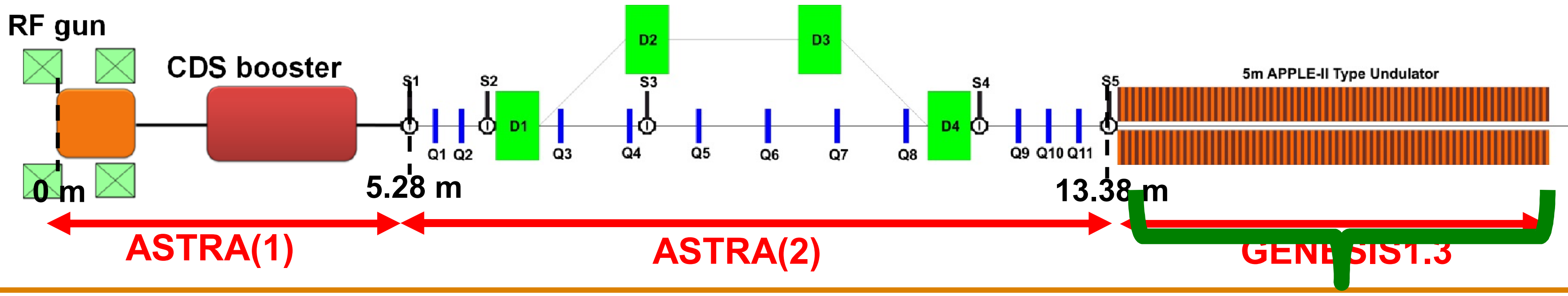
Power at z = 5.00m



Spectrum at z = 5.00m

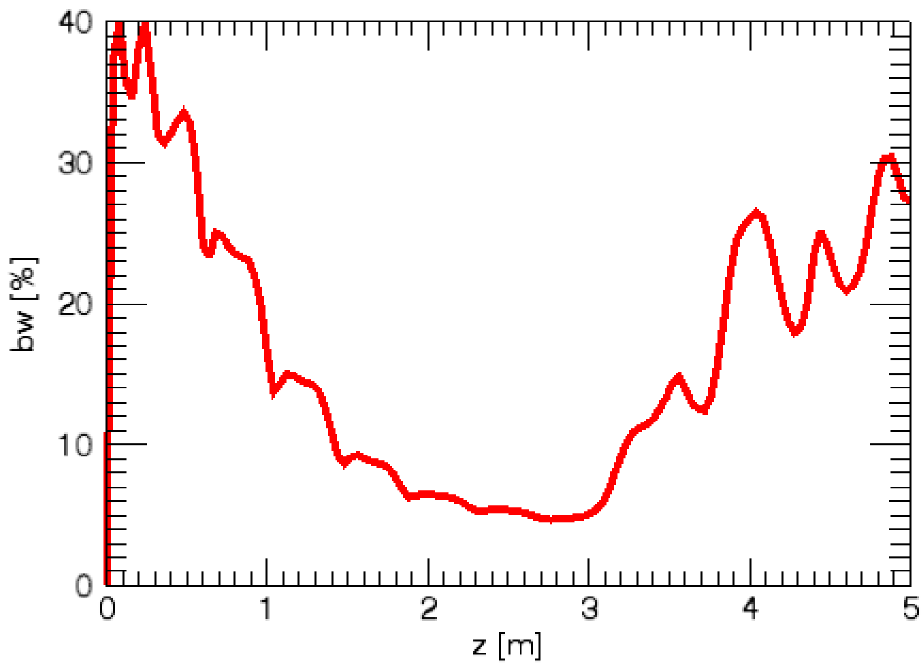


GENESIS1.3: Simulation Results

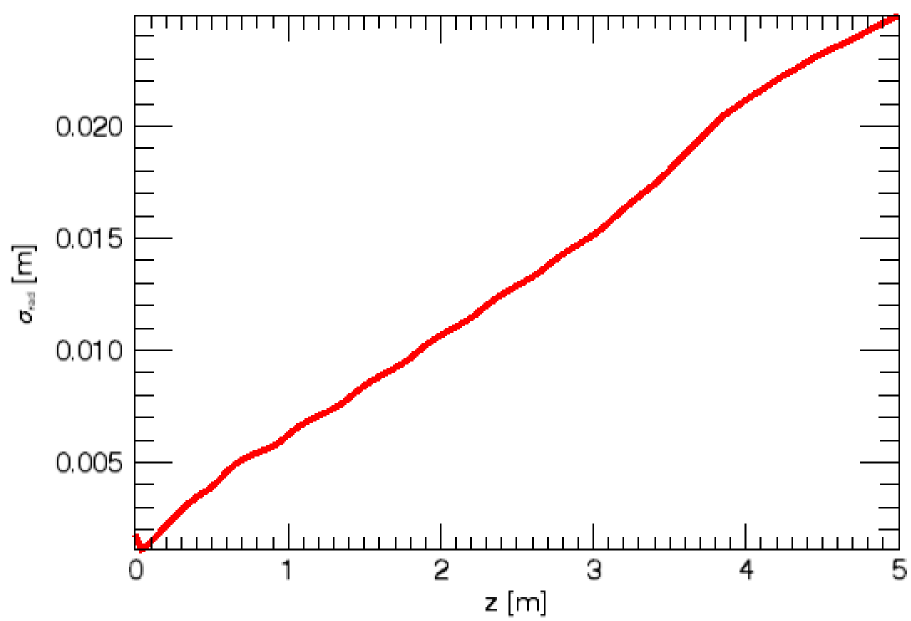


OPBS

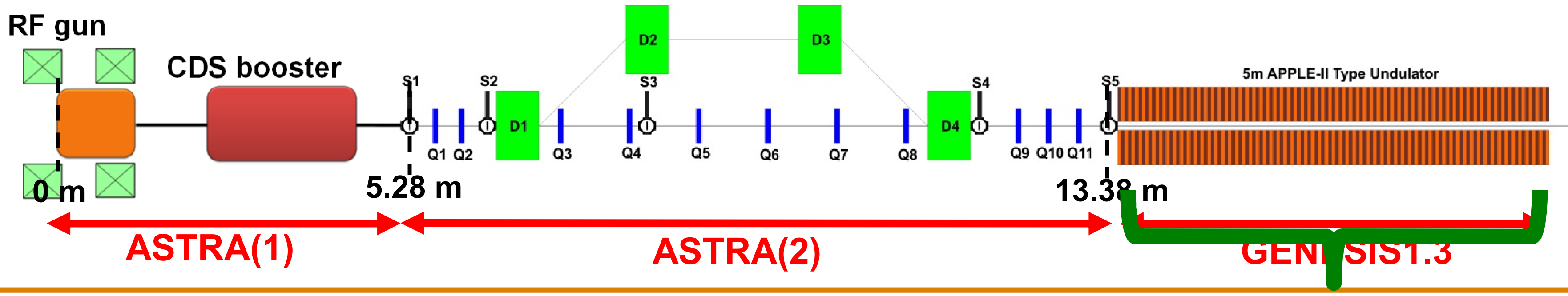
Bandwidth Evolution



Average Radiation Size

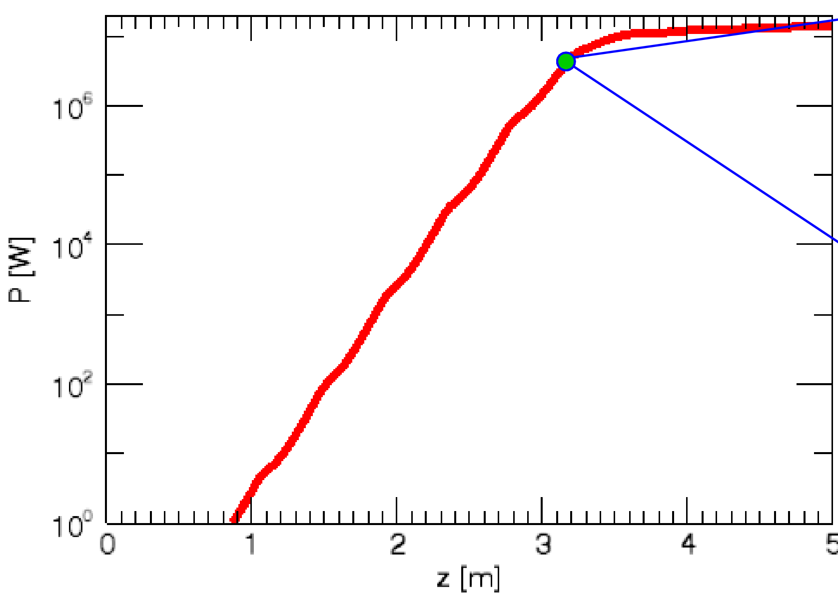


GENESIS1.3: Simulation Results

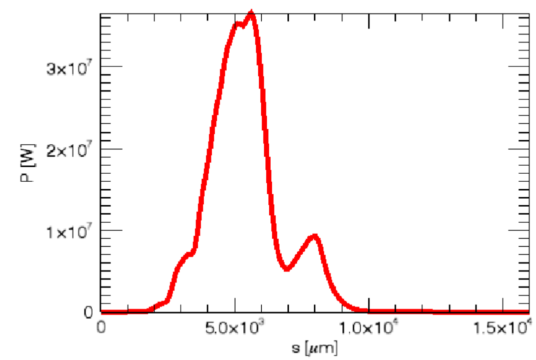


OPEM

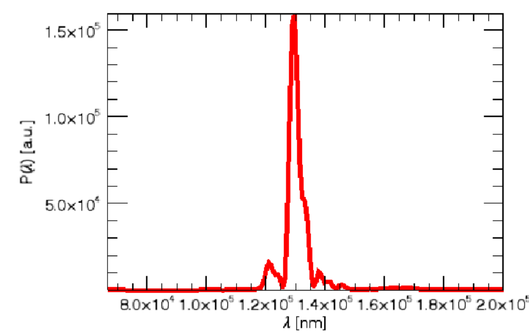
Average Power Growth Curve



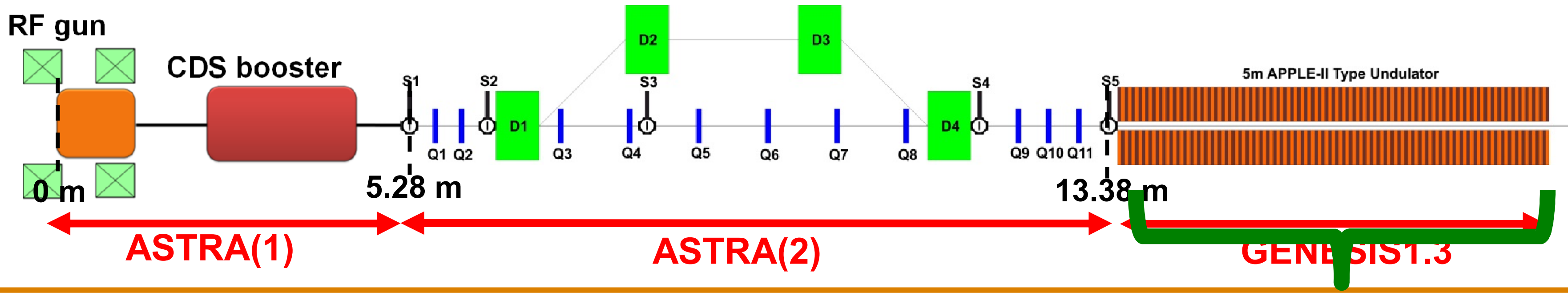
Power at z = 3.20m



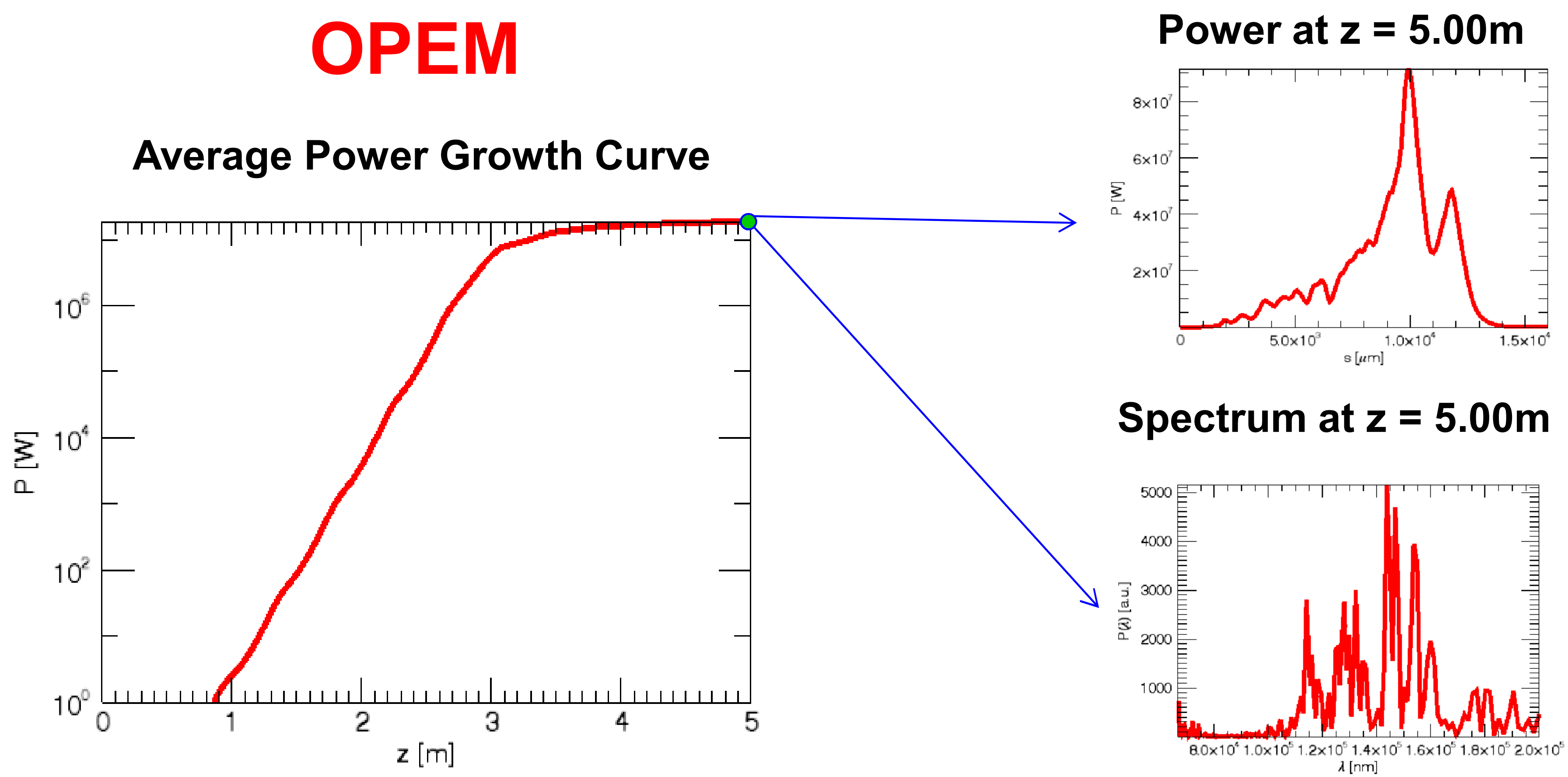
Spectrum at z = 3.20m



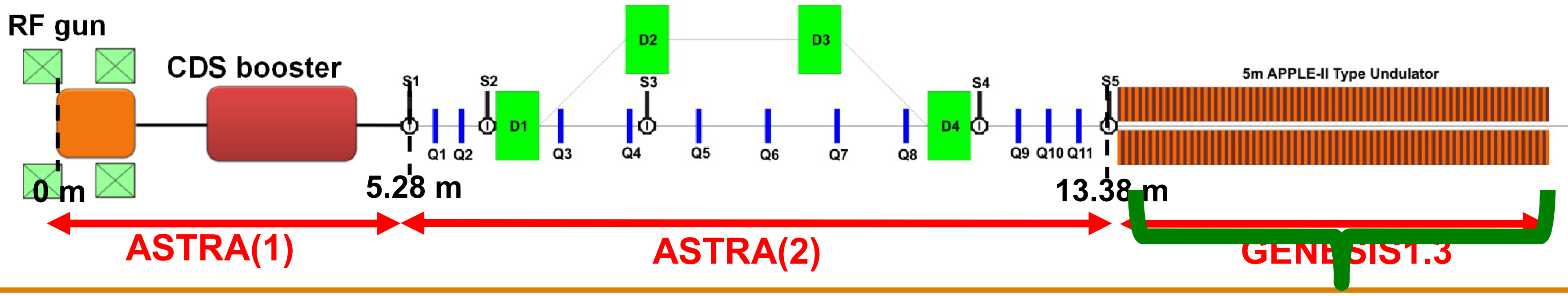
GENESIS1.3: Simulation Results



OPEM

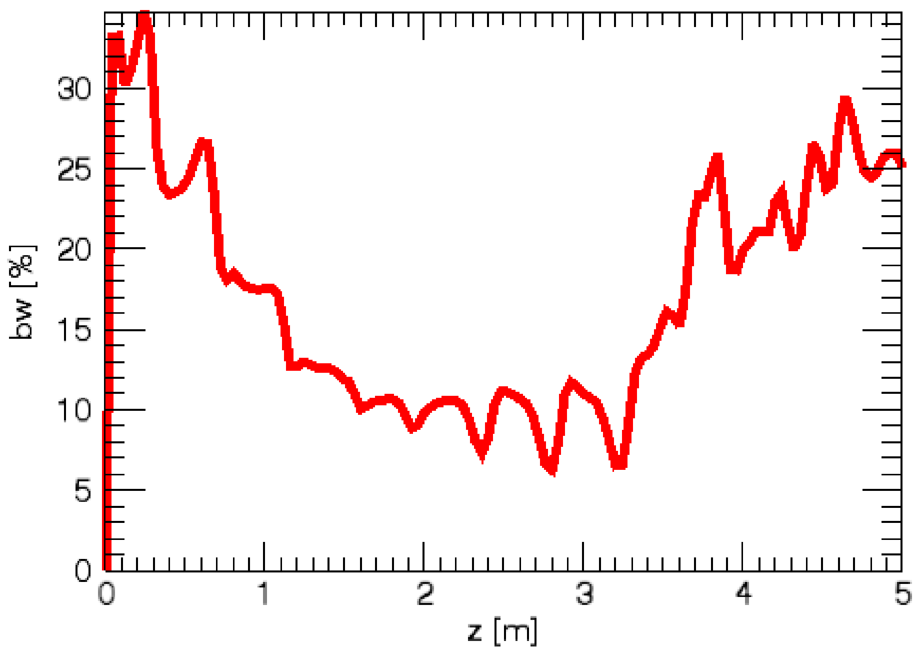


GENESIS1.3: Simulation Results

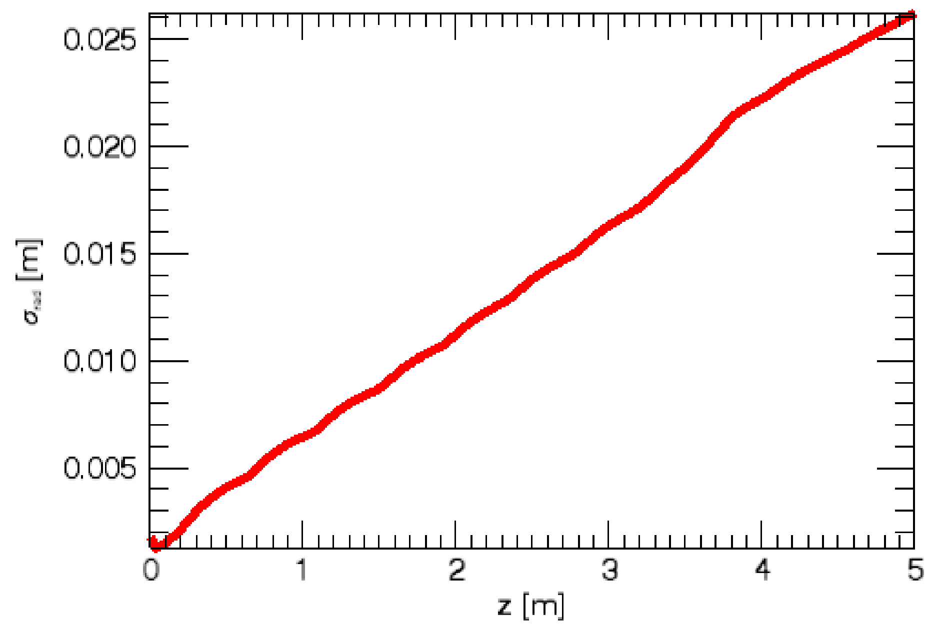


OPEM

Bandwidth Evolution



Average Radiation Size



Summary

- S2E Simulations of the undulator radiation for radiation wavelength of 100 µm were done.

- At Z = 5.28 m, for electron beam with 4nC bunch charge (using 1 mm rms laser spot size, flat-top temporal profile), when scanning the main solenoid current:
  - the optimized transverse rms size is 1.70 mm using I_{main} = 480 A.
  - the optimized transverse normalized emittance is 2.50 mm.mrad using I_{main} = 488 A.

- Beam matching studies were done. Providing beam with $\beta_x, \beta_y \leq 1\ \mathrm{m}$ and $-5 < \alpha_x, \alpha_y < 5$ at the undulator entrance is possible.

- FEL simulations were performed. The results show that we can derived peak power in order of 10^7 W at the saturation range of ~3 m. However, the spectrum shift and growth of radiation size need to be investigated.

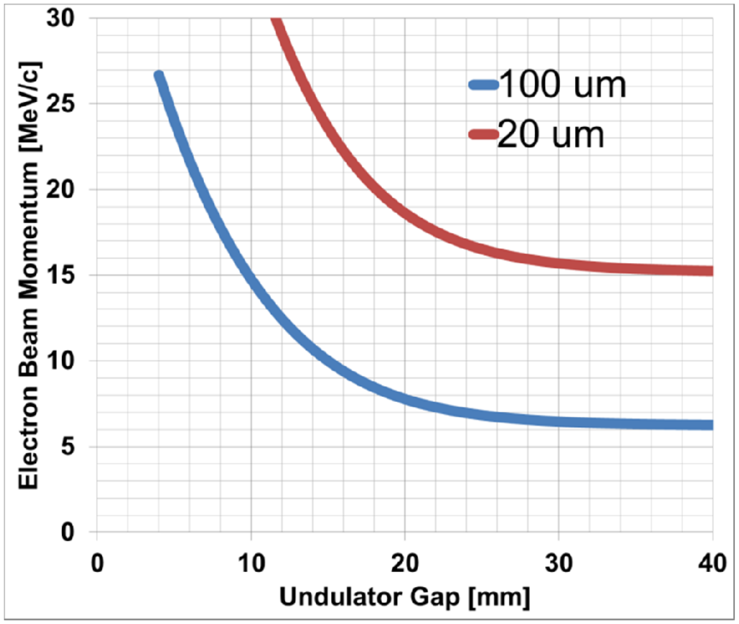
Outlook

Before FEL2014 conference:

- Study with the optimized laser spot size (see next slide)
- Repeat all study for radiation wavelength of 20 µm with 22 MeV electron beam
- Including calculation of waveguide effect?

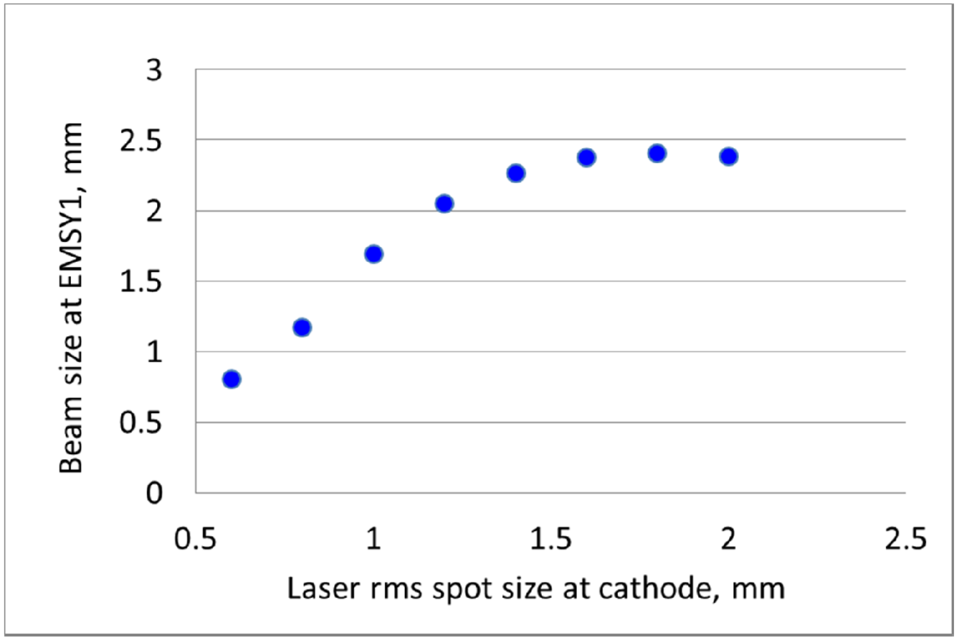
After FEL2014 conference:

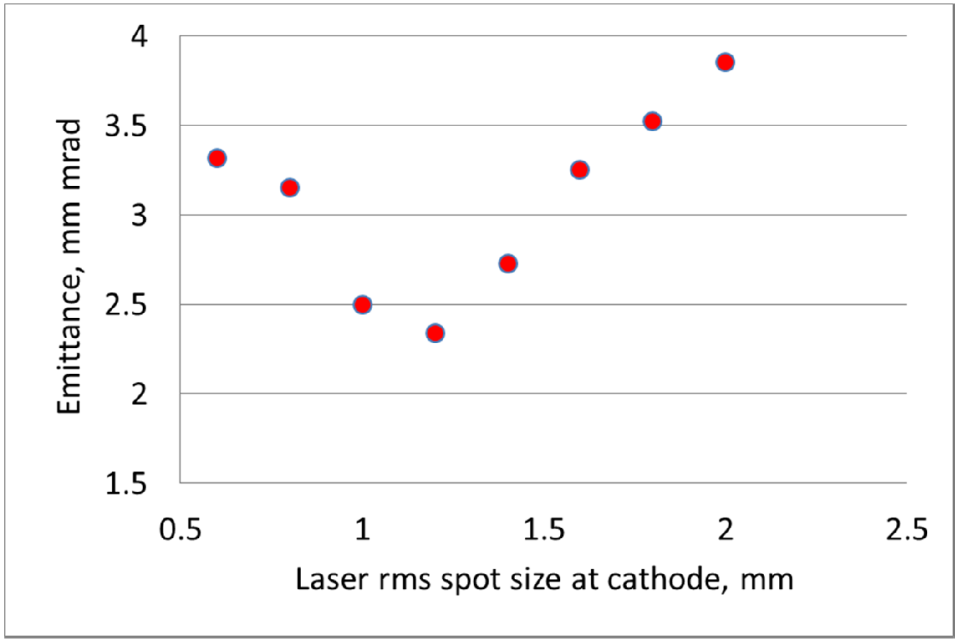
- Study with bunch charge of 2nC and 1nC
- Study with other laser temporal profiles



APPLE-II with $\lambda_u = 40$ mm

Appendix: Optimization of Laser Spot Size





Input Parameters for ASTRA	
laser pulse shape	Flattop
laser temporal time	2/21.5\2 ps
main solenoid current	vary
Z_{start} to Z_{end}	0 to 5.28 m
rms laser spot size	vary
gun peak field	60 MV/m
booster peak field	10 MV/m (for e-beam with ~15 MeV/c)
gun phase	-2
booster phase	0

Appendix: Name of the Project ?

PITZ **A**pplication for IR/THz **S**ynchrotron Radiation **S**ources

↓

PASS

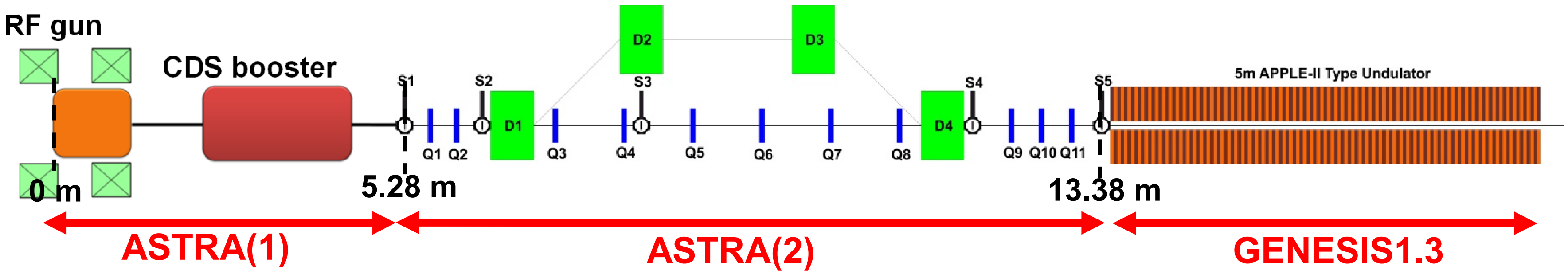
PITZ Application for **I**R/**T**Hz **S**ynchrotron R**A**diation Sources

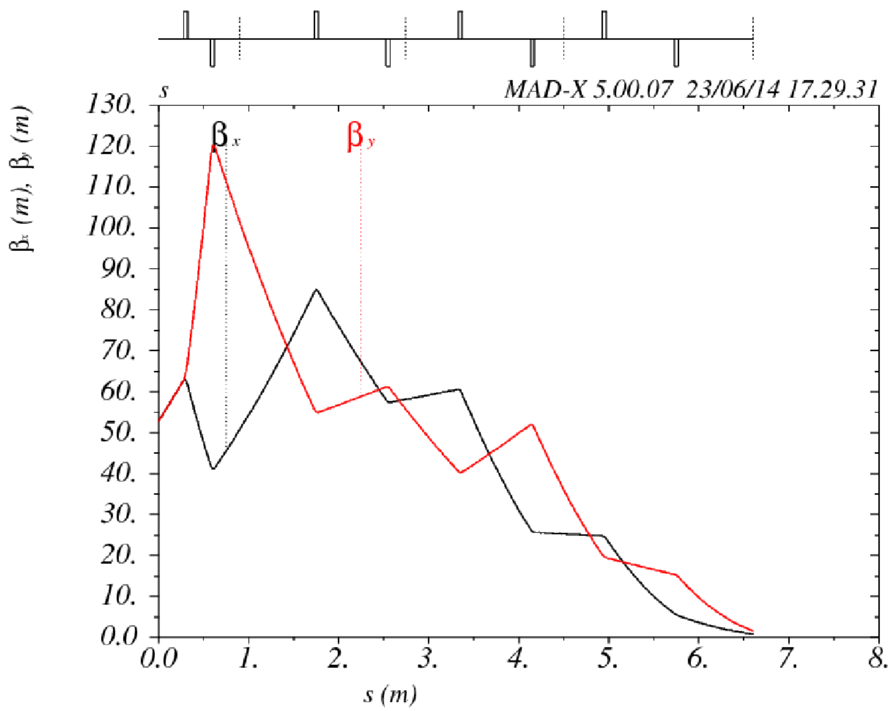
↓

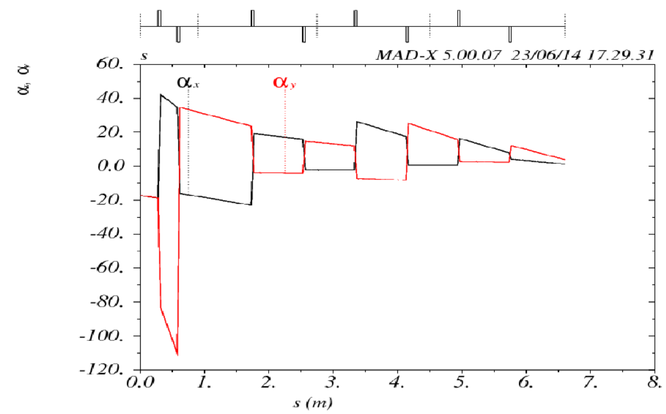
PITSA

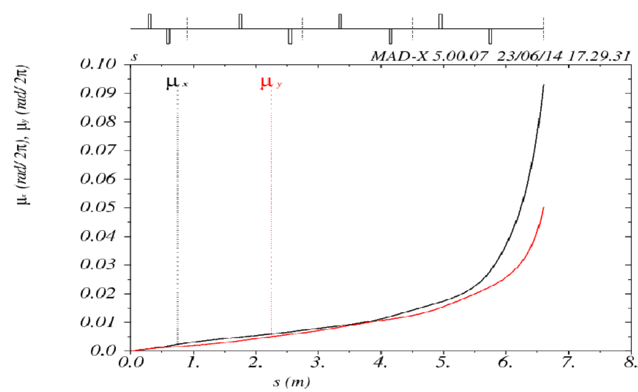
Backup Slide

Matching, OPEM, S1 to S4: MADX Plots










```
kq1  =          22.646 ;
gq1  =     1.163299445 ;
value,KQ2,GQ2;

kq2  =         -28.373 ;
gq2  =    -1.457488967 ;
value,KQ3,GQ3;

kq3  =          11.567 ;
gq3  =    0.5941837269 ;
value,KQ4,GQ4;

kq4  =          -7.204 ;
gq4  =   -0.3700613442 ;
value,KQ5,GQ5;

kq5  =              11 ;
gq5  =    0.5650575773 ;
value,KQ6,GQ6;

kq6  =             -15 ;
gq6  =   -0.7705330599 ;
value,KQ7,GQ7;

kq7  =              15 ;
gq7  =    0.7705330599 ;
value,KQ8,GQ8;

kq8  =             -15 ;
gq8  =   -0.7705330599 ;
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!value,KQ10,GQ10;
```
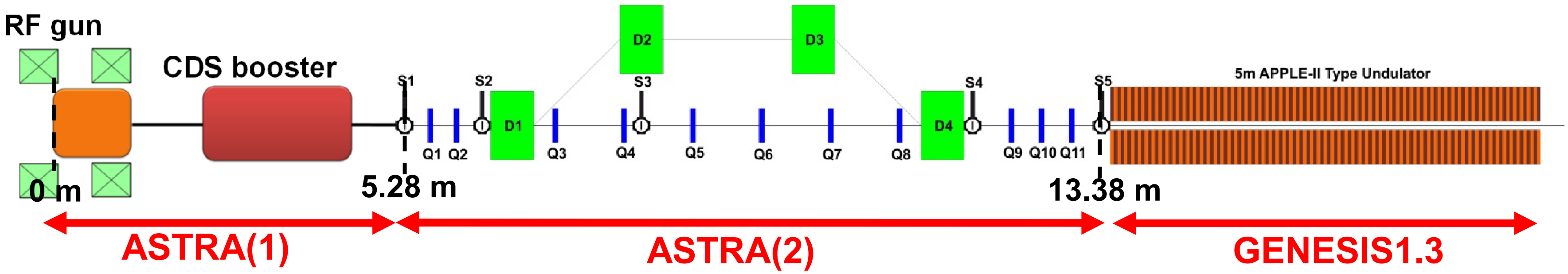
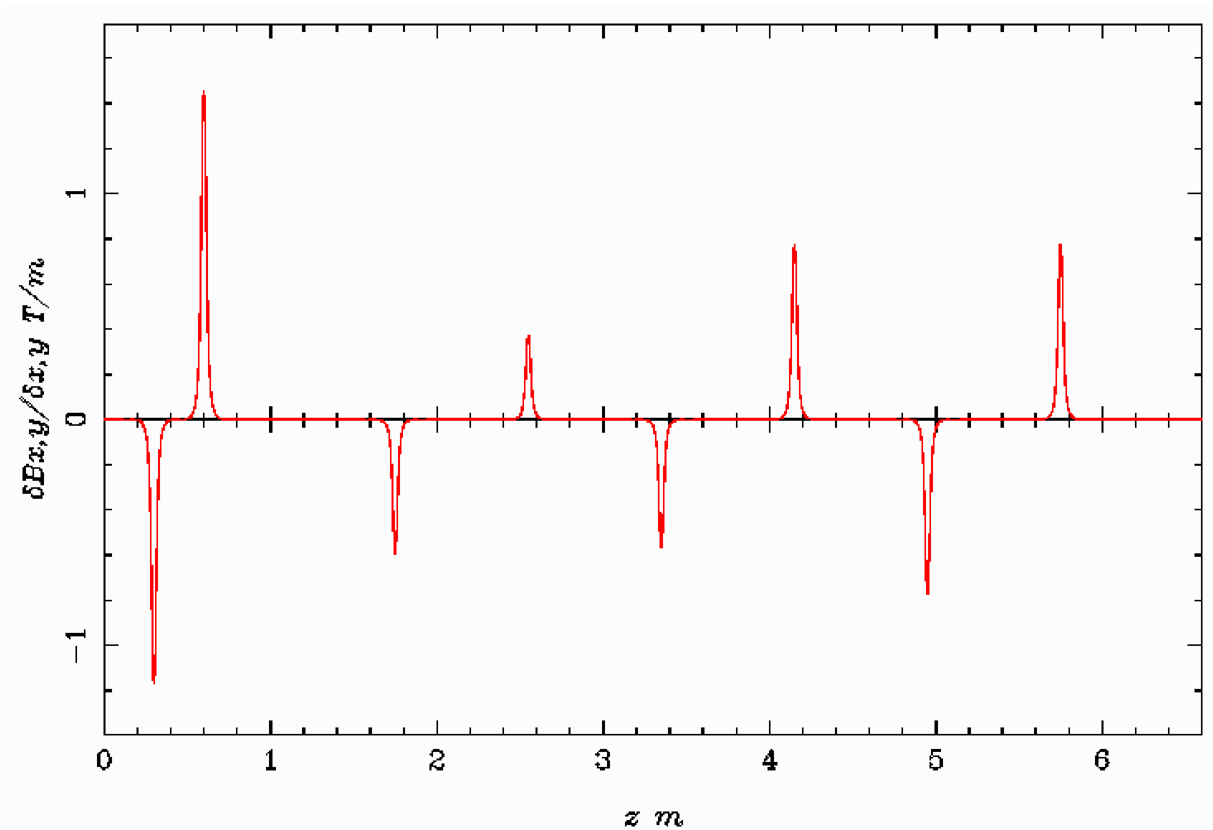
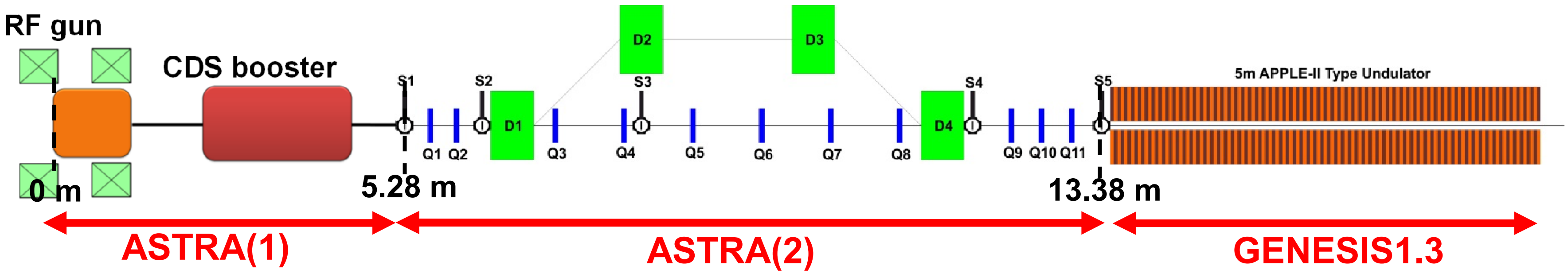

Matching, OPEM, S1 to S4: QMs Gradients



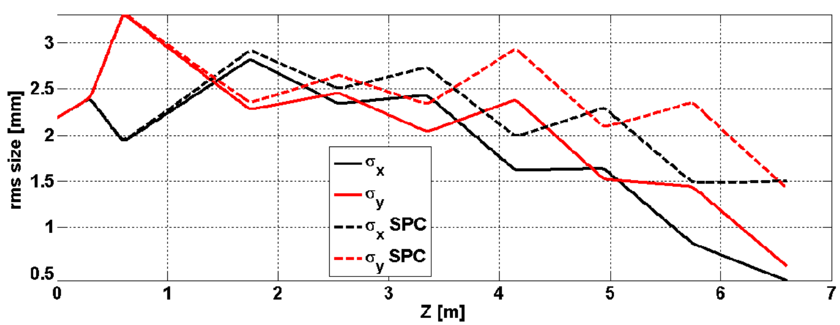


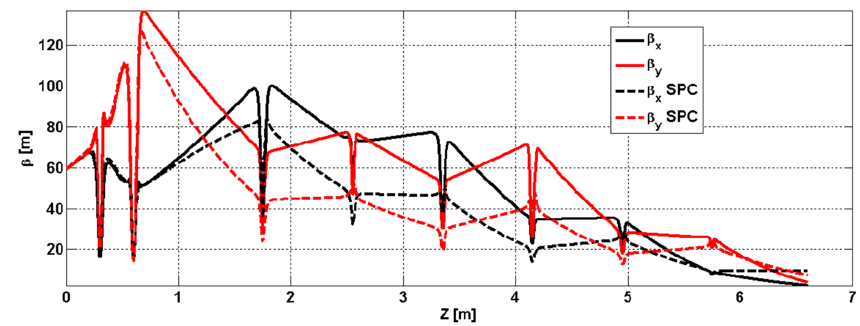

```
kq1 =              22.646 ;
gq1 =         1.163299445 ;
value,KQ2,GQ2;

kq2 =             -28.373 ;
gq2 =        -1.457488967 ;
value,KQ3,GQ3;

kq3 =              11.567 ;
gq3 =        0.5941837269 ;
value,KQ4,GQ4;

kq4 =              -7.204 ;
gq4 =       -0.3700613442 ;
value,KQ5,GQ5;

kq5 =                  11 ;
gq5 =        0.5650575773 ;
value,KQ6,GQ6;

kq6 =                 -15 ;
gq6 =       -0.7705330599 ;
value,KQ7,GQ7;

kq7 =                  15 ;
gq7 =        0.7705330599 ;
value,KQ8,GQ8;

kq8 =                 -15 ;
gq8 =       -0.7705330599 ;
!value,KQ9,GQ9;

!value,KQ10,GQ10;
```

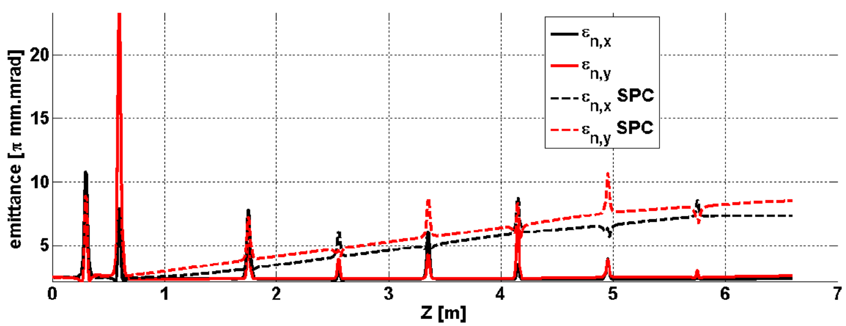
Matching, OPEM, S1 to S4: Evolutions

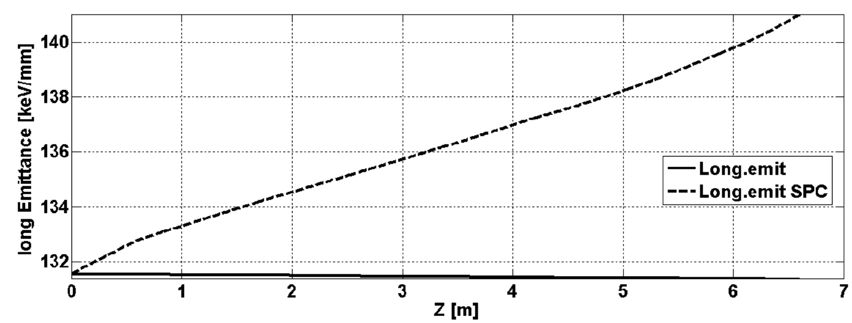


Evolution of Beam Parameters from S1 to S4

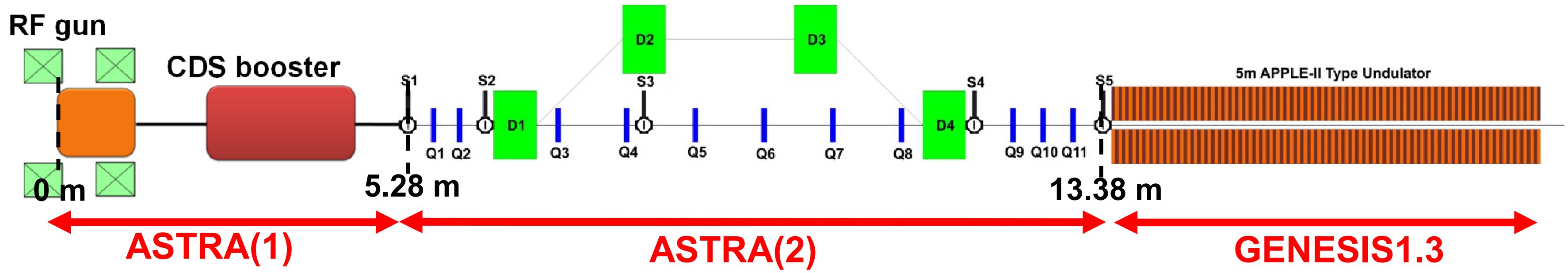


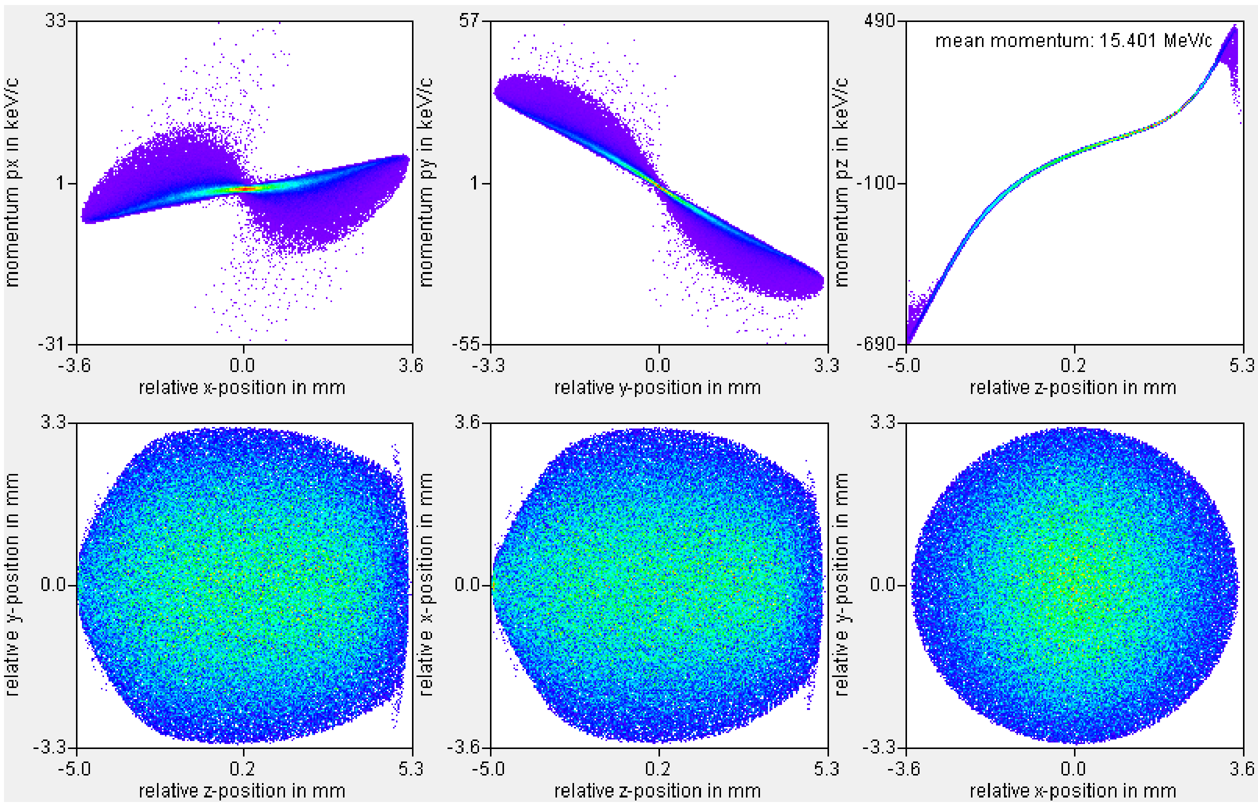






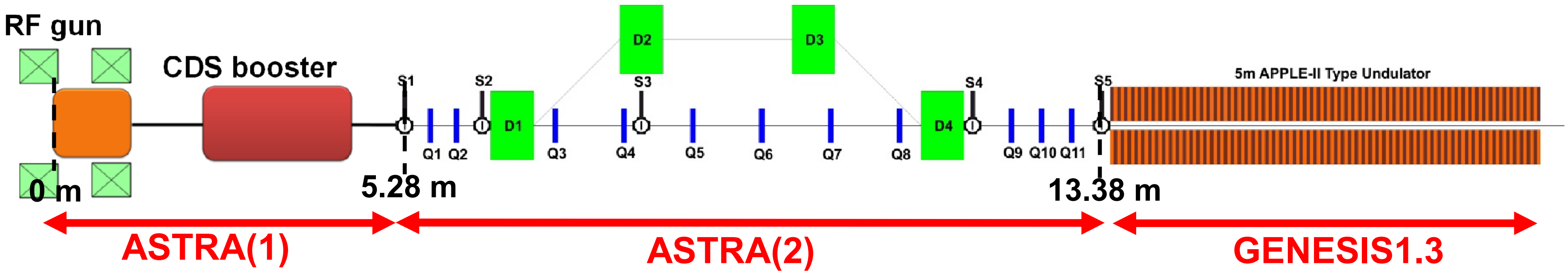
Matching, OPEM, S1 to S4: Matched Beam Profile at S4

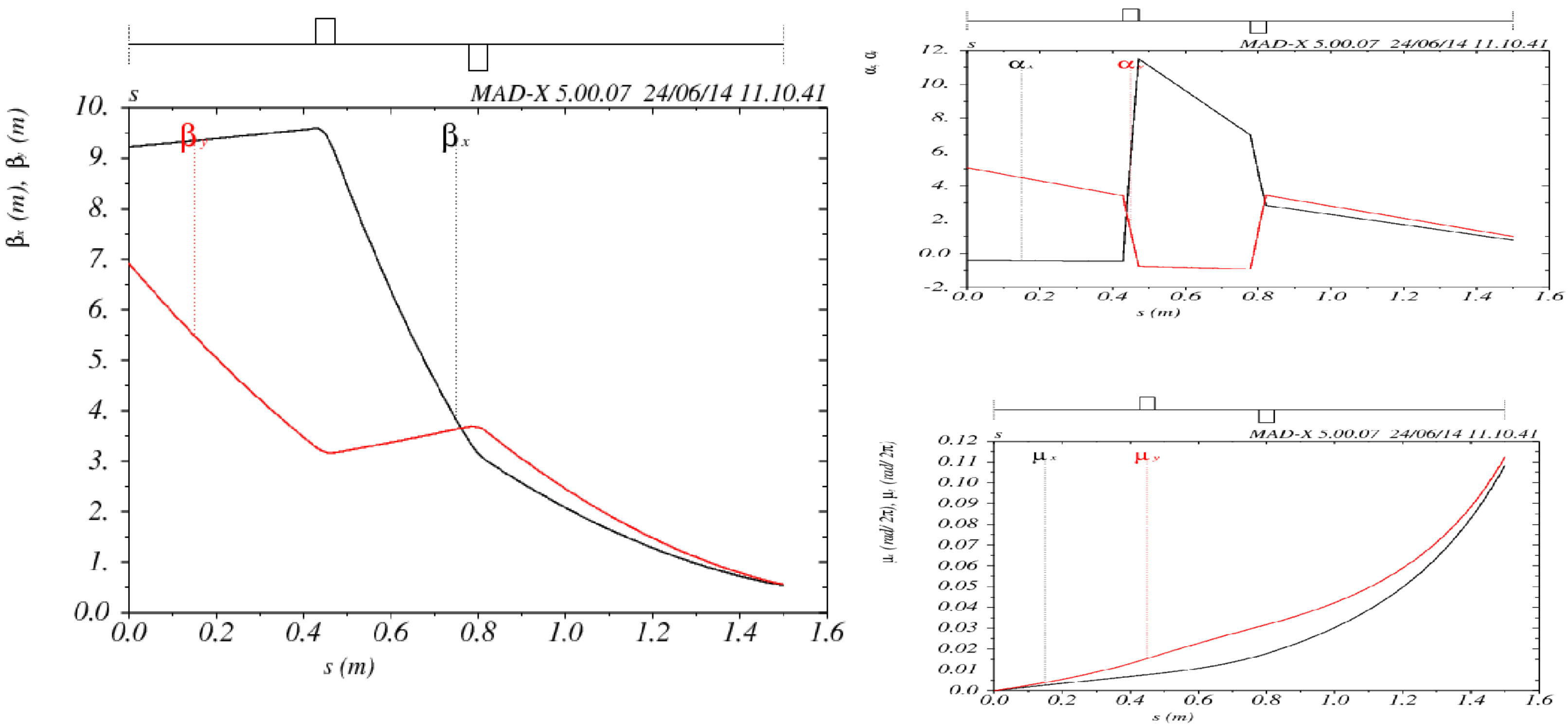




Parameters	Value
σ_x	1.50 mm
σ_y	1.40 mm
ε_n,x	7.30 um
ε_n,y	8.47 um
β_x	9.2250
β_y	6.9170
α_x	-0.3953
α_y	5.0685
P_z	15.4 MeV/c
P_z,rms	200 keV/c

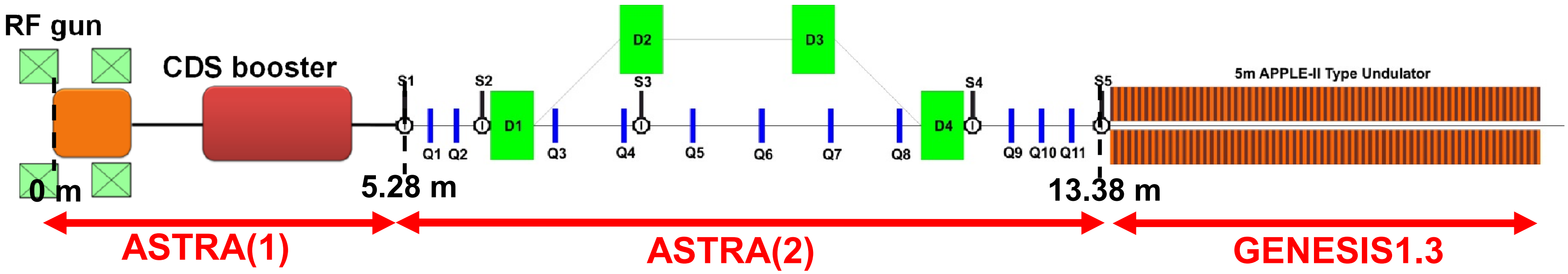
Matching, OPEM, S4 to S5: Matching Calculation with MADX

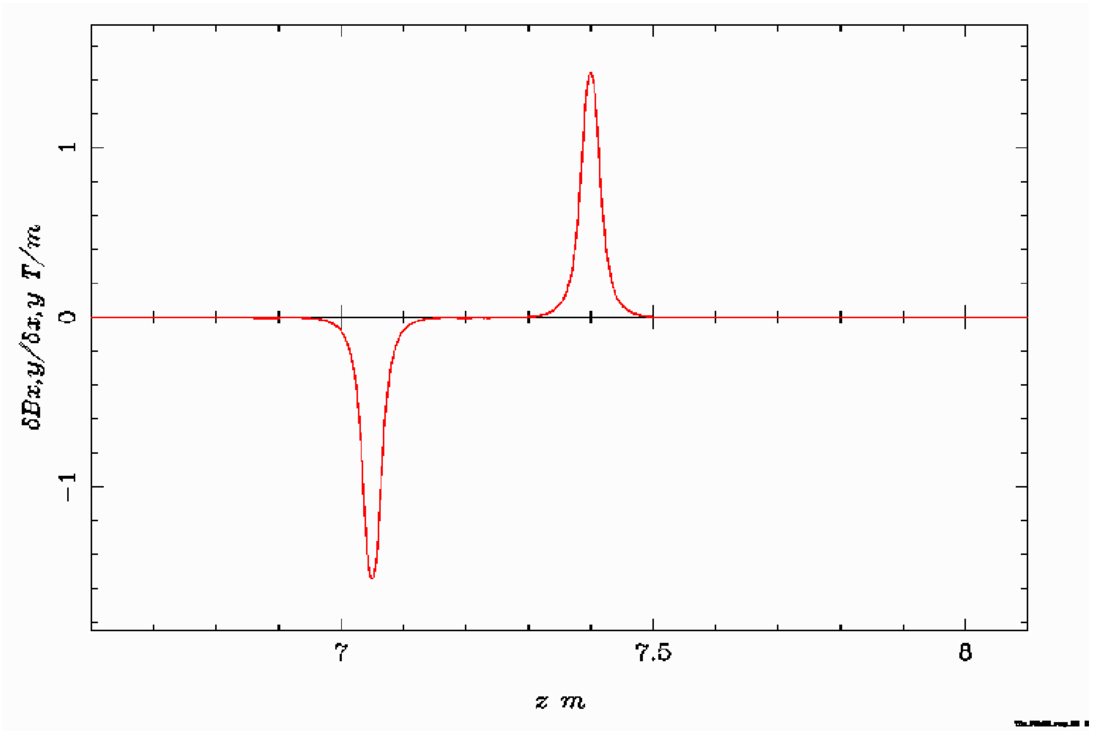


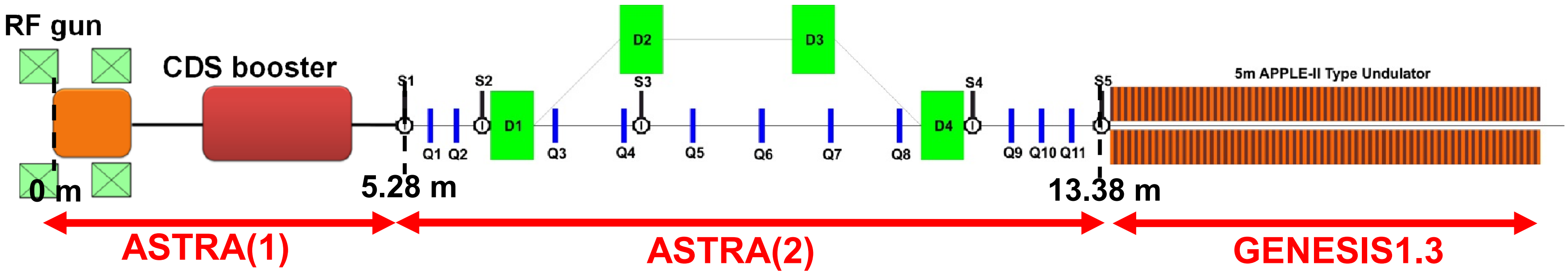



```
!value, momentum;
!value,KQ1,GQ1;
!value,KQ2,GQ2;
!value,KQ3,GQ3;
!value,KQ4,GQ4;
!value,KQ5,GQ5;
!value,KQ6,GQ6;
!value,KQ7,GQ7;
!value,KQ8,GQ8;
value,KQ9,GQ9;

kq9 =                   30 ;
gq9 =           1.54106612 ;
value,KQ10,GQ10;

kq10 =                 -28 ;
gq10 =        -1.438328378 ;
value,KQ11,GQ11;

kq11 =                   1 ;
gq11 =       0.05136887066 ;
```

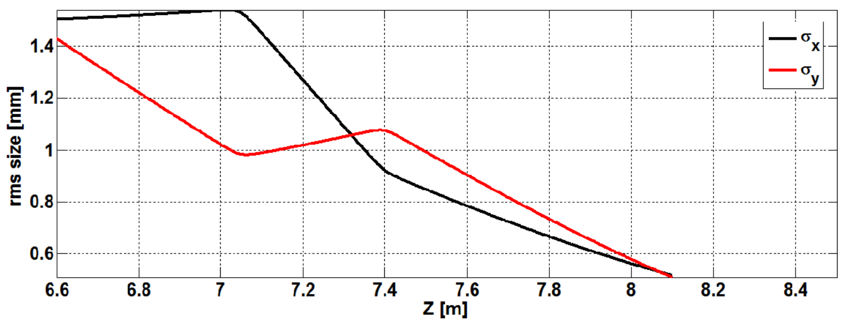
Matching, OPEM, S4 to S5: Gradients Plot

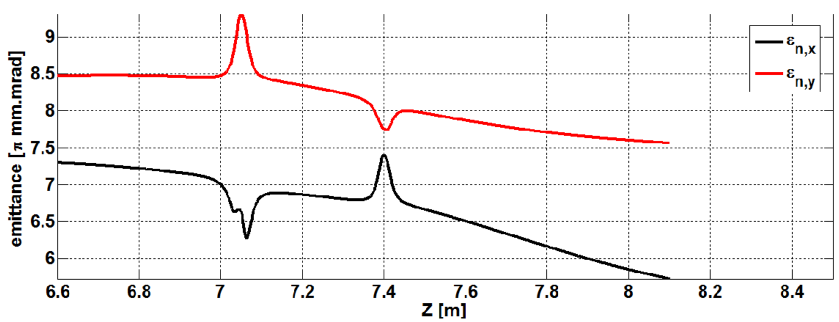


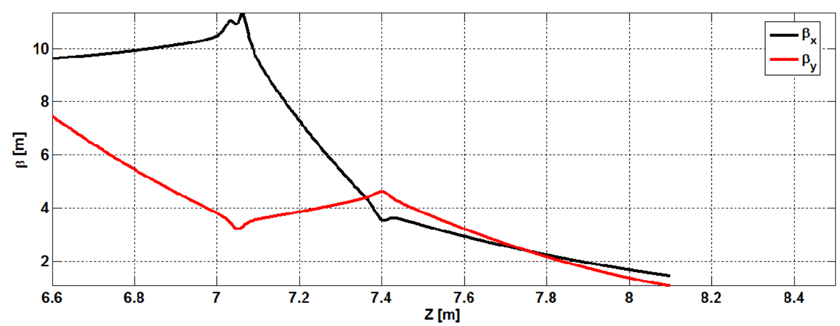




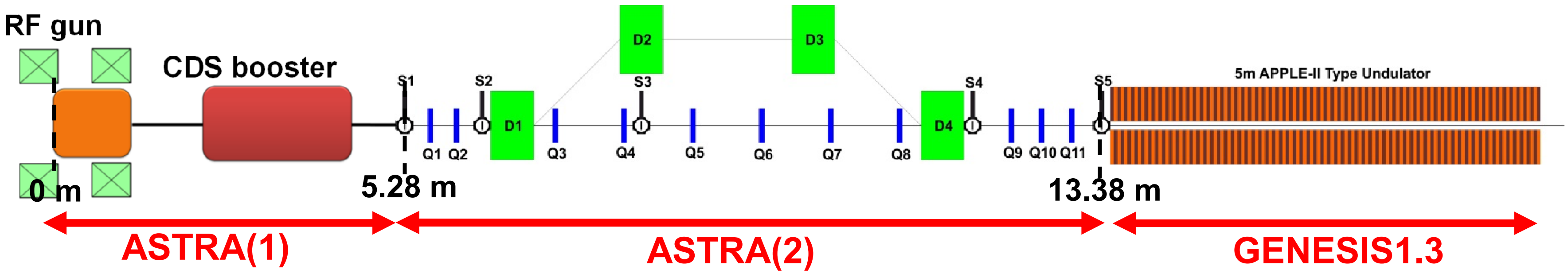
Evolution of Beam Parameters from S4 to S5

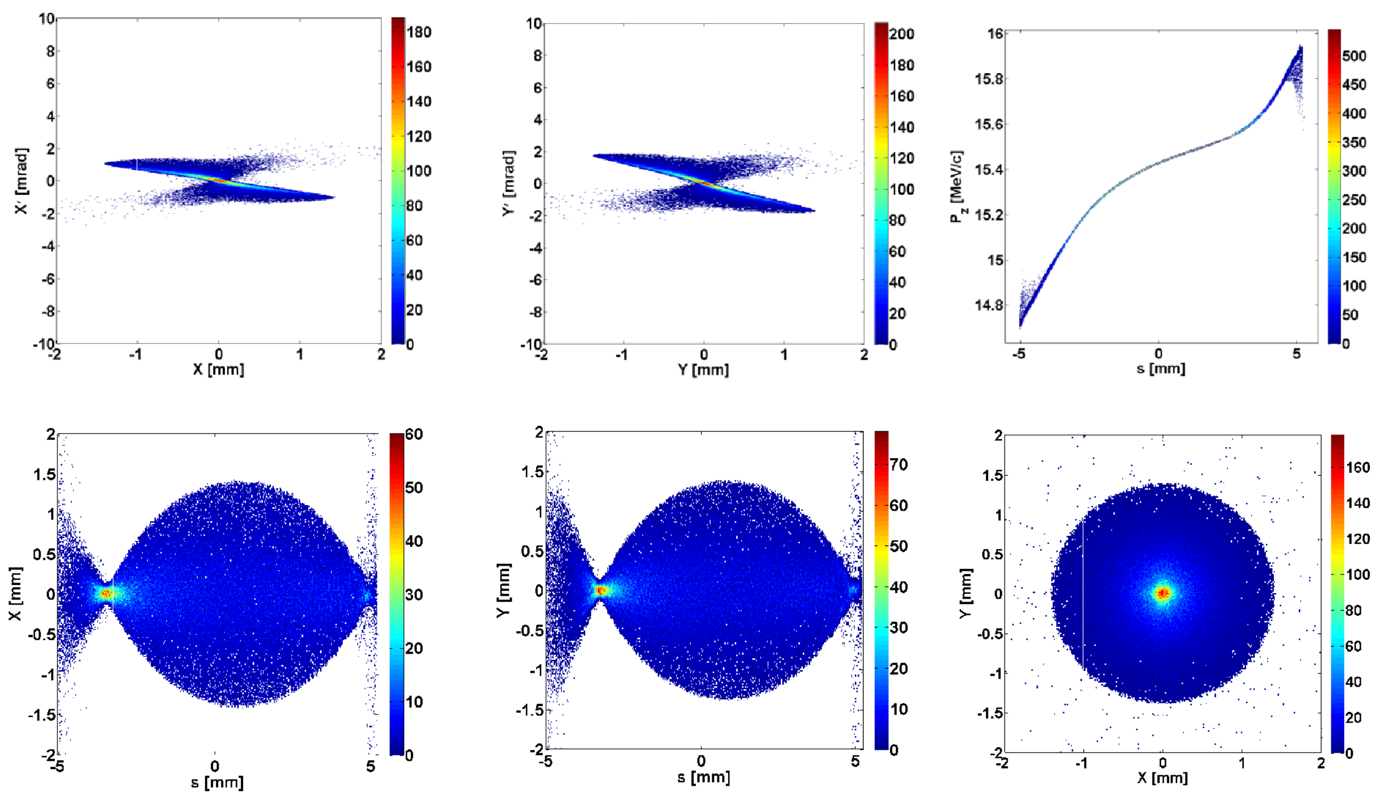






Matching, OPEM, S4 to S5: Matched Beam Profile at S5





Parameters	Value
σ_x	5.17 mm
σ_y	5.11 mm
ε_n,x	5.72 um
ε_n,y	7.56 um
β_x	1.3902
β_y	1.0265
α_x	1.1611
α_y	1.3286
P_z	15.4 MeV/c
P_z,rms	211 keV/c