Introduction to GENESIS1.3, v4 by the example of an Echo-Enabled Harmonic Generation based FEL

PITZ Physics Seminar

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Contents

Motivation

- FLASH: first free-electron laser in the X-ray range
- based on a linear accelerator
- 2 FEL lines and 8 experimental stations
  - SASE principle
- ongoing R&D seeding experiment *Xseed*

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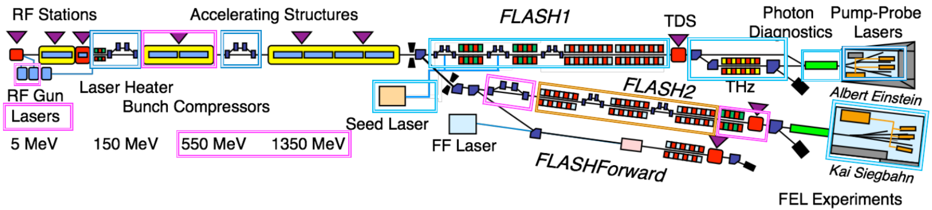
  - implementation at FLASH finished by 2025

FLASH2020+



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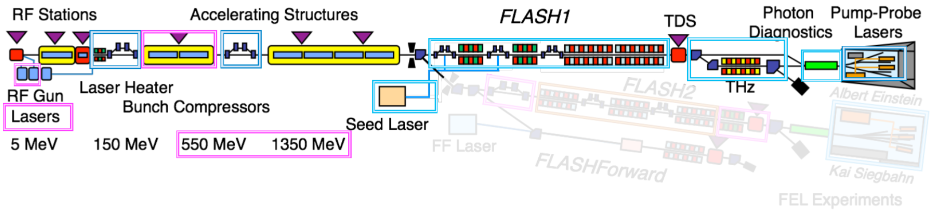

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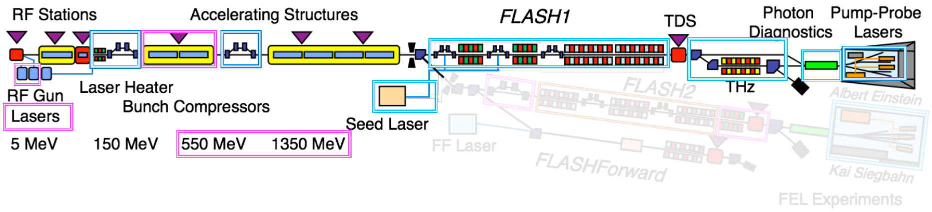
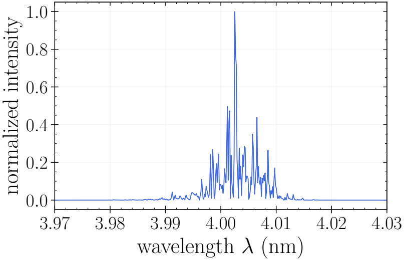


- FLASH2020+ upgrade of FLASH
  - implementation at FLASH finished by 2025
- first high repetition rate (MHz) externally seeded XUV FEL
- fourier limited pulses from 60nm to 4nm
  - High Gain Harmonic Generation (HGHG)
  - Echo-Enabled Harmonic Generation (EEHG)

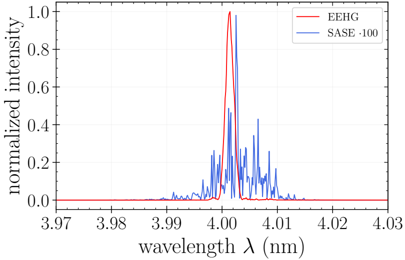
EEHG: Echo-Enabled Harmonic Generation

- SASE: originates from incoherent, spontaneous synchrotron radiation
  - statistical fluctuations of the spontaneous emission
  - limited longitudinal coherence
  - limited shot-to-shot reproducibility, spectral and temporal

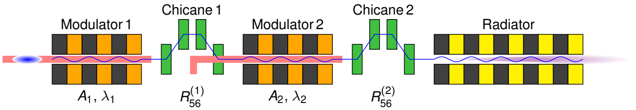


EEHG: Echo-Enabled Harmonic Generation

- SASE: originates from incoherent, spontaneous synchrotron radiation
  - statistical fluctuations of the spontaneous emission
  - limited longitudinal coherence
  - limited shot-to-shot reproducibility, spectral and temporal
- EEHG: deterministic process, seeded
  - electron beam gets pre-bunched before entering the undulator (radiator)
  - less sensitive to initial electron-beam imperfections
  - better control of initial seed / shot-to-shot reproducibility



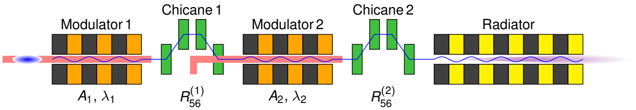
EEHG Principle



EEHG Principle

energy modulation amplitudes:

$$A_1 = \frac{\Delta E_1}{\sigma_E} \qquad A_2 = \frac{\Delta E_2}{\sigma_E}$$



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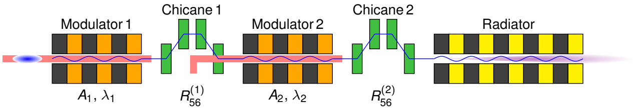
$R_{56}^{(1)}$ $R_{56}^{(2)}$



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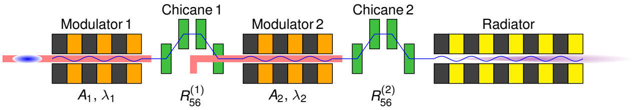
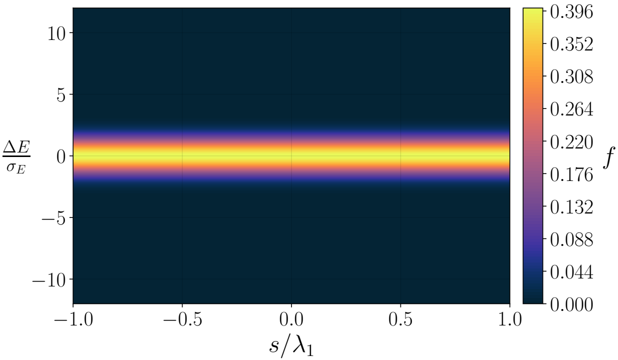
longitudinal coordinate s





EEHG Principle - Bunching Factor

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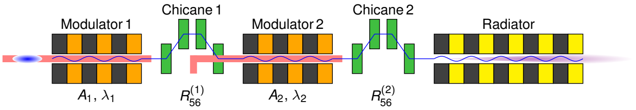

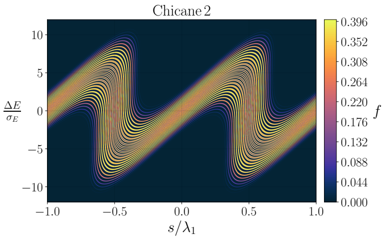

- bunching factor $|b|$
  - describes degree of bunching
  - in EEHG: maximum $|b| \approx 0.39 \cdot m^{-1/3}$ for $m > 4$
  - m: harmonic number

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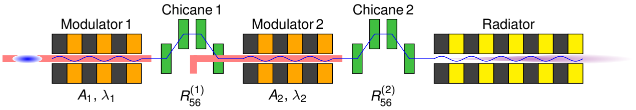

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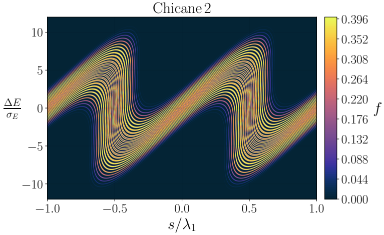
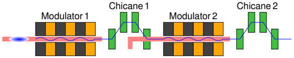
  - describes degree of bunching
  - in EEHG: maximum $|b| \approx 0.39 \cdot m^{-1/3}$ for $m > 4$
  - m: harmonic number
- should be larger than a few percent
  - efficient FEL amplification in radiator

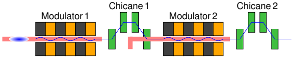


Parameters - 4 nm EEHG



- Gaussian electron beam distribution
- energy spread 150 keV rather pessimistic assumption
- electron beam without energy chirp

Case Study	4 nm EEHG
Harmonic	75
Electron Beam	
E (GeV)	1.35
σ_E (keV)	150
I_p (A)	500
σ_z (µm)	100
σ_t (fs)	333
ε_n (mm mrad)	0.6



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- set both seed lasers to 300 nm for simplicity
- Gaussian seed laser distribution

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λ (nm)	300 | 300
A	3 | 5
σ_z (µm)	64 | 6.4
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λ_u (mm)	82.6
Periods	30
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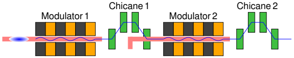

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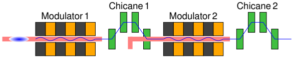

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Periods	30
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Chicanes	
length (m)	6.1 | 2.8
L_{dipole} (m)	0.4 | 0.3
L_{drift} (m)	2.0 | 0.6
R_{56} (mm | µm)	7.05 | 81.25

GENESIS: FEL code

- GENESIS1.3, v4
- time-dependent, 3D
- entire bunch and field is kept in memory
- based on the Slowly Varying Envelope Approximation (SVEA)
  - equations of motion are Undulator-Period Averaged (UPA)
- coordinate system is based on slices
  - electron bunch consists of slices
- photon field
  - calculated with the same longitudinal granularity
  - transversely: rectangular grid
    - each gridpoint contains the complex field amplitude

GENESIS: Matching

- periodic lattice: `zmatch` allows auto-matching within GENESIS
- here: same lattice in ELEGANT to get proper matching
- final twiss parameters and quadrupole settings are then transfered to GENESIS

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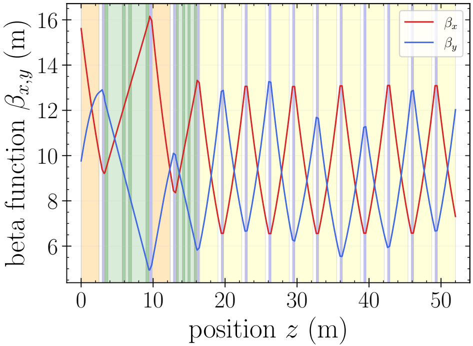
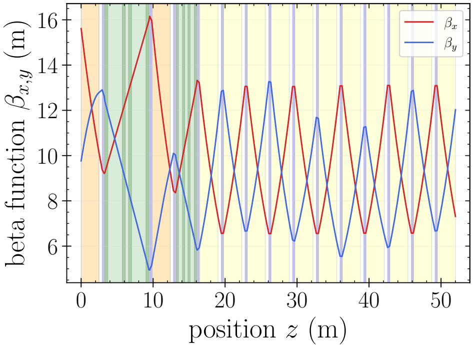


GENESIS: Lattice File

- `.lat` file describes the beamline and its components
- syntax: `label:element_type={parameter=value [,...]};`
- undulator, quadrupole, drift, corrector, chicane, phaseshifter, line, marker



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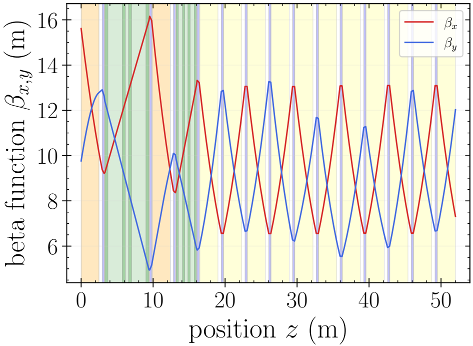
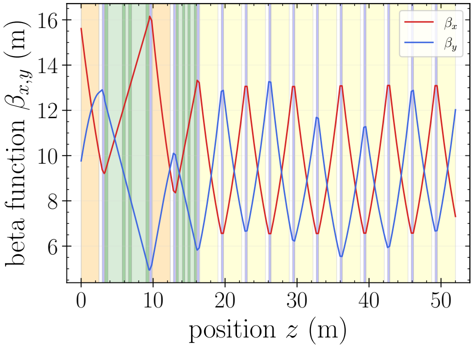



```
# DUMP MARKERS
#=========================================================
BEAMDUMP:    MARK = {dumpbeam=1};
FIELDDUMP:   MARK = {dumpfield=1};
```

GENESIS: Lattice File - EEHG Section 1

- several beamlines can be defined in same lattice file



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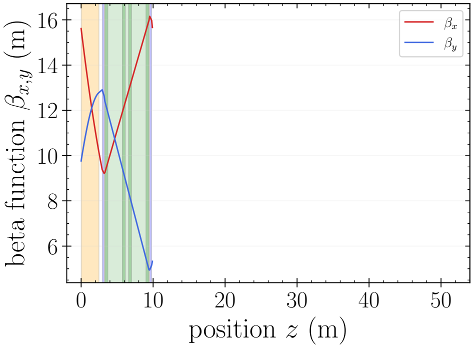


```
# FIRST EEHG SECTION
#======================================================
# Cell length modulator 1: 3.3 m
#======================================================
FL1MOD1U:   UNDU = {lambdau=0.0826, nwig=30, aw=7.049746};
FL1MOD1D2:  DRIF = {l = 0.446};
FL1MOD1Q2:  QUAD = {l = 0.276, k1 = -0.377931};
FL1MOD1D3:  DRIF = {l = 0.1};
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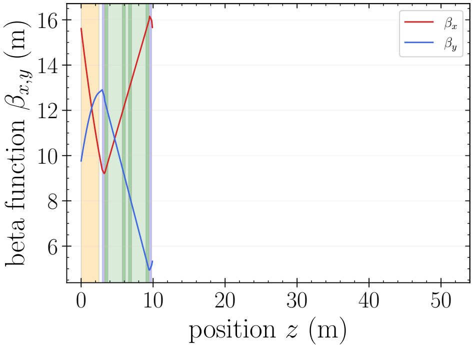


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# Cell length chicane 1: 6.6 m
#==================================================
FL1MOD1C3:  CHIC = {l=6.124, lb=0.420, ld=2, delay=3.521233e-03};
FL1MOD1D9:  DRIF = {l = 0.1};
FL1MOD1Q9:  QUAD = {l = 0.276, k1 = 0.560897};
FL1MOD1D91: DRIF = {l = 0.1};
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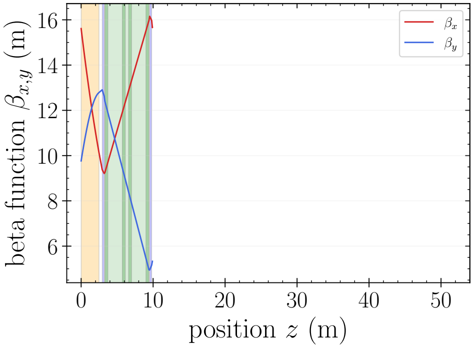


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# Complete EEHG Section 1
#===================================================
FL1MOD1: LINE = {FL1MOD1U,FIELDDUMP,FL1MOD1D2,FL1MOD1Q2,FL1MOD1D3,
                 FL1MOD1C3,FL1MOD1D9,FL1MOD1Q9,FL1MOD1D91};
```
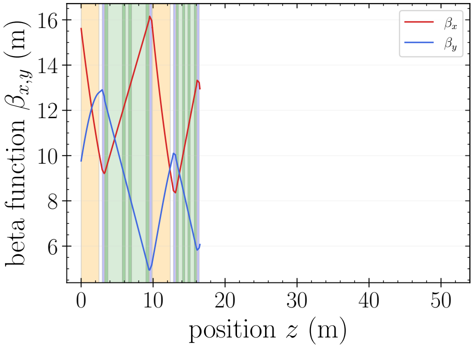

GENESIS: Lattice File - EEHG Section 2

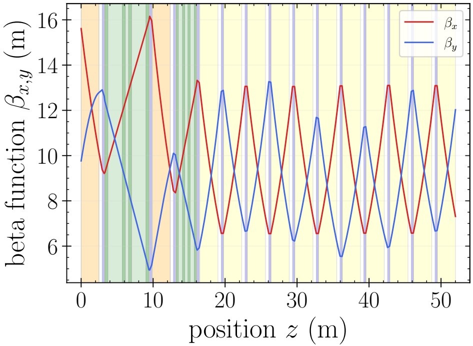
- several beamlines can be defined in same lattice file
- Modulator 2, Chicane 2 and Quads:




```
# SECOND EEHG SECTION
#=====================================================
# Cell length modulator 2: 3.3 m
#=====================================================
FL1MOD2U:   UNDU = {lambdau=0.0826, nwig=30, aw=7.049746};
FL1MOD2D2:  DRIF = {l = 0.446};
FL1MOD2Q2:  QUAD = {l = 0.276, k1 = -0.631953};
FL1MOD2D3:  DRIF = {l = 0.1};

# Cell length chicane 2: 3.3 m
#=====================================================
FL1MOD2C3:  CHIC = {l=2.824, lb=0.31, ld=0.57, delay=40.6237e-06};
FL1MOD2D6:  DRIF = {l = 0.1};
FL1MOD2Q6:  QUAD = {l = 0.276, k1 = 0.678084};
FL1MOD2D61: DRIF = {l = 0.1};

# Complete EEHG Section 2
#=====================================================
FL1MOD2: LINE = {FL1MOD2U,FL1MOD2D2,FL1MOD2Q2,FL1MOD2D3,FL1MOD2C3,
                 FL1MOD2D6,FL1MOD2Q6,FL1MOD2D61,BEAMDUMP};
```

GENESIS: Lattice File - Radiator Section

- several beamlines can be defined in same lattice file
- Radiator and Quads:




```
# RADIATOR SECTION
#=========================================================
FL1RAD1U:  UNDU = {lambdau=0.033, nwig=76, helical=1, aw=0.831873,
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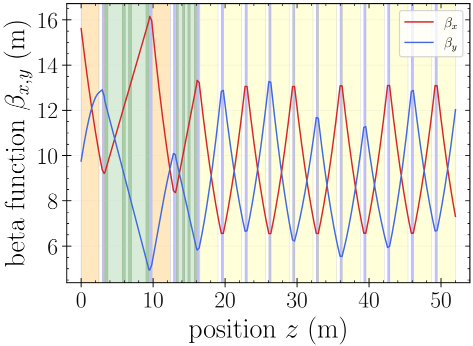


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# Half-cell 1 (Focusing): Cell length: 3.3 m
#====================================================
FL1RAD1P:  DRIF = { l = 0.15};
FL1RAD1D2: DRIF = { l = 0.316};
FL1RAD1Q2: QUAD = { l = 0.276, k1 = -0.800377};
FL1RAD1D3: DRIF = { l = 0.05};
FL1RAD1: LINE = {FL1RAD1U,FL1RAD1P,FL1RAD1D2,FL1RAD1Q2,FL1RAD1D3};
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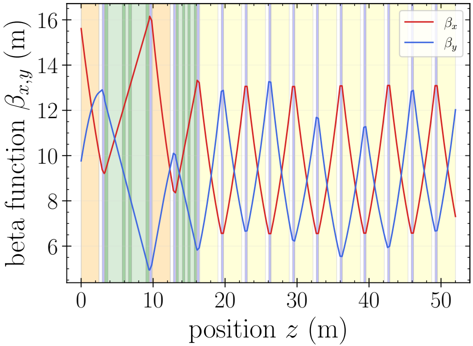


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# Half-cell 2 (Defocusing): Cell length: 3.3 m
#====================================================
FL1RAD2Q2: QUAD = { l = 0.276, k1 = 0.778685};
FL1RAD2: LINE = {FL1RAD1U,FL1RAD1P,FL1RAD1D2,FL1RAD2Q2,FL1RAD1D3};
```

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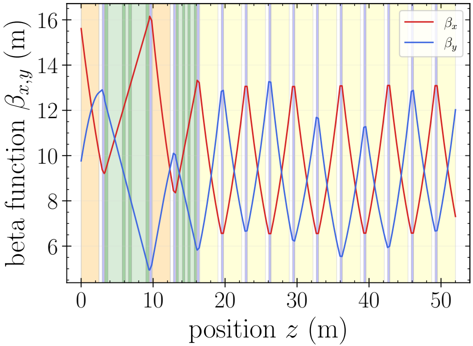


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#==================================================
FL1RADCELL: LINE = {FL1RAD1,FL1RAD2};
FL1RAD:     LINE = {5*FL1RADCELL,FL1RAD1U};
```

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  - definitions of basic simulation parameters

```
&setup
rootname=example
lattice=example.lat
beamline=FL1MOD1
```

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- .in contains the commands for the simulation
  - namelists start with & and finish with &end
- mandatory at top: &setup
  - definitions of basic simulation parameters
  - delz: preferred integration stepsize
  - lambda0: reference wavelength / sample distance
  - gamma0: reference energy in units of electron rest mass

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&setup
rootname=example
lattice=example.lat
beamline=FL1MOD1
delz=0.0826
lambda0=3e—07
gamma0=2641.884
```

GENESIS: Input File - Basic Definitions

- .in contains the commands for the simulation
  - namelists start with & and finish with &end
- mandatory at top: &setup
  - definitions of basic simulation parameters
  - delz: preferred integration stepsize
  - lambda0: reference wavelength / sample distance
  - gamma0: reference energy in units of electron rest mass
  - shotnoise: enable shot-noise calculation
  - seed: for random number generator → shot-noise

```
&setup
rootname=example
lattice=example.lat
beamline=FL1MOD1
delz=0.0826
lambda0=3e-07
gamma0=2641.884
shotnoise=1
seed=43617235
```

GENESIS: Input File - Basic Definitions

- `.in` contains the commands for the simulation
  - namelists start with & and finish with &end
- mandatory at top: `&setup`
  - definitions of basic simulation parameters
  - `delz`: preferred integration stepsize
  - `lambda0`: reference wavelength / sample distance
  - `gamma0`: reference energy in units of electron rest mass
  - `shotnoise`: enable shot-noise calculation
  - `seed`: for random number generator → shot-noise
  - `npart`: macro particles per slice
  - `nbins`: macro particles grouped into beamlets for shot-noise generation
  - `one4one`: resolve each electron in the simulation; makes npart and nbins obsolete

```
&setup
rootname=example
lattice=example.lat
beamline=FL1MOD1
delz=0.0826
lambda0=3e-07
gamma0=2641.884
shotnoise=1
seed=43617235
npart=8192
nbins=4
one4one=true
```

GENESIS: Input File - Basic Definitions

- `.in` contains the commands for the simulation
  - namelists start with & and finish with &end
- mandatory at top: `&setup`
  - definitions of basic simulation parameters
  - `delz`: preferred integration stepsize
  - `lambda0`: reference wavelength / sample distance
  - `gamma0`: reference energy in units of electron rest mass
  - `shotnoise`: enable shot-noise calculation
  - `seed`: for random number generator $\rightarrow$ shot-noise
  - `npart`: macro particles per slice
  - `nbins`: macro particles grouped into beamlets for shot-noise generation
  - `one4one`: resolve each electron in the simulation; makes npart and nbins obsolete
  - `beam_global_stat`: output file contains quantities describing the whole bunch
  - `field_global_stat`: output file contains quantities describing the whole field
  - `exclude_current_output`: output current profile for each integration step

```
&setup
rootname=example
lattice=example.lat
beamline=FL1MOD1
delz=0.0826
lambda0=3e-07
gamma0=2641.884
shotnoise=1
seed=43617235
npart=8192
nbins=4
one4one=true
beam_global_stat=true
field_global_stat=true
exclude_current_output=false
&end
```

GENESIS: Input File - Time Dependence

- `.in` contains the commands for the simulation
  - namelists start with & and finish with &end
- time-dependence: `&time`
  - enables time-dependent simulations

GENESIS: Input File - Time Dependence

- `.in` contains the commands for the simulation
  - namelists start with & and finish with &end
- time-dependence: `&time`
  - enables time-dependent simulations
  - `s0`: starting point of the time-window
  - `slen`: length of the time-window
  - `sample`: sample rate in units of `lambda0`
  - `time`: disable the slippage in the tracking
  - to restrict the simulation to steady-state the whole time namelist has to be omitted

```
&time
s0=0
slen=0.00012
sample=1
time=true
&end
```

GENESIS: Input File - Electron Beam

- `.in` contains the commands for the simulation
  - namelists start with & and finish with &end
- Gaussian distribution: `&profile_gauss`
  - dependence on the position in the time frame
- Electron Beam: `&beam`
  - initiates generation of the particle distribution

GENESIS: Input File - Electron Beam

- `.in` contains the commands for the simulation
  - namelists start with & and finish with &end
- Gaussian distribution: `&profile_gauss`
  - dependence on the position in the time frame
  - `label`: name of the profile
  - `c0`: Gaussian peak value
  - `s0`: Gaussian center point with respect to time-window
  - `sig`: standard deviation of the Gaussian
- Electron Beam: `&beam`
  - initiates generation of the particle distribution

```
#===========================
&profile_gauss
label=cur
c0=500
s0=60e-6
sig=40e-6
&end
```

GENESIS: Input File - Electron Beam

- `.in` contains the commands for the simulation
  - namelists start with & and finish with &end
- Gaussian distribution: `&profile_gauss`
  - dependence on the position in the time frame
  - `label`: name of the profile
  - `c0`: Gaussian peak value
  - `s0`: Gaussian center point with respect to time-window
  - `sig`: standard deviation of the Gaussian
- Electron Beam: `&beam`
  - initiates generation of the particle distribution
  - `delgam`: rms energy spread in units of electron rest mass
  - `current`: beam current

```
#===========================
&profile_gauss
label=cur
c0=500
s0=60e-6
sig=40e-6
&end

&beam
delgam=0.2935
current=@cur
```

GENESIS: Input File - Electron Beam

- `.in` contains the commands for the simulation
  - namelists start with & and finish with &end
- Gaussian distribution: `&profile_gauss`
  - dependence on the position in the time frame
  - `label`: name of the profile
  - `c0`: Gaussian peak value
  - `s0`: Gaussian center point with respect to time-window
  - `sig`: standard deviation of the Gaussian
- Electron Beam: `&beam`
  - initiates generation of the particle distribution
  - `delgam`: rms energy spread in units of electron rest mass
  - `current`: beam current
  - `ex/ey`: normalized emittance
  - `alphax/alphay/betax/betay`: initial alpha- and beta-functions

```
#===========================
&profile_gauss
label=cur
c0=500
s0=60e-6
sig=40e-6
&end

&beam
delgam=0.2935
current=@cur
ex=6e-07
ey=6e-07
alphax=1.323598
alphay=-0.994951
betax=15.612829
betay=9.765122
&end
#===========================
```

GENESIS: Input File - Field, Tracking and Sorting

- `.in` contains the commands for the simulation
  - namelists start with & and finish with &end
- Field: `&field`
  - initiates generation of the field distribution

GENESIS: Input File - Field, Tracking and Sorting

- `.in` contains the commands for the simulation
  - namelists start with & and finish with &end
- Field: `&field`
  - initiates generation of the field distribution
  - `power`: radiation power
  - `waist_pos`: focus location relative to undulator entrance
  - `waist_size`: waist size
    - radius at which intensity has fallen to $1/e^2$ of its peak value

```
#===========================
&profile_gauss
label=seed1prof
c0=19700000.0
s0=60e-6
sig=1.9097e-05
&end

&field
power=@seed1prof
waist_pos=1.239
waist_size=750.0e-6
```

GENESIS: Input File - Field, Tracking and Sorting

- `.in` contains the commands for the simulation
  - namelists start with & and finish with &end
- Field: `&field`
  - initiates generation of the field distribution
  - `power`: radiation power
  - `waist_pos`: focus location relative to undulator entrance
  - `waist_size`: waist size
    - radius at which intensity has fallen to $1/e^2$ of its peak value
  - `dgrid`: grid extension from center to edge
  - `ngrid`: number of grid points in one dimension

```
#==========================
&profile_gauss
label=seed1prof
c0=19700000.0
s0=60e-6
sig=1.9097e-05
&end

&field
power=@seed1prof
waist_pos=1.239
waist_size=750.0e-6
dgrid=2.0e-3
ngrid=301
&end
#==========================
```

GENESIS: Input File - Field, Tracking and Sorting

- `.in` contains the commands for the simulation
  - namelists start with & and finish with &end
- Field: `&field`
  - initiates generation of the field distribution
  - `power`: radiation power
  - `waist_pos`: focus location relative to undulator entrance
  - `waist_size`: waist size
    - radius at which intensity has fallen to $1/e^2$ of its peak value
  - `dgrid`: grid extension from center to edge
  - `ngrid`: number of grid points in one dimension
- Tracking: `&track`
  - initiates tracking through the beamline

```
#==========================
&profile_gauss
label=seed1prof
c0=19700000.0
s0=60e-6
sig=1.9097e-05
&end

&field
power=@seed1prof
waist_pos=1.239
waist_size=750.0e-6
dgrid=2.0e-3
ngrid=301
&end
#==========================
&track
&end
```

GENESIS: Input File - Field, Tracking and Sorting

- `.in` contains the commands for the simulation
  - namelists start with & and finish with &end
- Field: `&field`
  - initiates generation of the field distribution
  - `power`: radiation power
  - `waist_pos`: focus location relative to undulator entrance
  - `waist_size`: waist size
    - radius at which intensity has fallen to $1/e^2$ of its peak value
  - `dgrid`: grid extension from center to edge
  - `ngrid`: number of grid points in one dimension
- Tracking: `&track`
  - initiates tracking through the beamline
- Sorting: `&sort`
  - initiates sorting and redistribution of particles only if one4one=true

```
#==========================
&profile_gauss
label=seed1prof
c0=19700000.0
s0=60e-6
sig=1.9097e-05
&end

&field
power=@seed1prof
waist_pos=1.239
waist_size=750.0e-6
dgrid=2.0e-3
ngrid=301
&end
#==========================
&track
&end

&sort
&end
#==========================
```

GENESIS: Input File - Second Run

- so far: run of Modulator 1 and Chicane 1 beamline
- multiple runs are possible in same input file

GENESIS: Input File - Second Run

- so far: run of Modulator 1 and Chicane 1 beamline
- multiple runs are possible in same input file
- now: run Modulator 2 and Chicane 2 beamline
- `&alter_setup`: change basic parameters
  - `beamline`: switch beamline

```
#===========================
&alter_setup
beamline=FL1MOD2
&end
#===========================
```

GENESIS: Input File - Second Run

- so far: run of Modulator 1 and Chicane 1 beamline
- multiple runs are possible in same input file
- now: run Modulator 2 and Chicane 2 beamline
- `&alter_setup`: change basic parameters
  - `beamline`: switch beamline
- define new field for seed 2

```
#===========================
&alter_setup
beamline=FL1MOD2
&end
#===========================
&profile_gauss
label=seed2prof
c0=57400000.0
s0=60e-6
sig=6.366e-06
&end

&field
power=@seed2prof
dgrid=2.000000e-3
ngrid=301
waist_size=750.0e-6
waist_pos=1.239
&end
#===========================
```

GENESIS: Input File - Second Run

- so far: run of Modulator 1 and Chicane 1 beamline
- multiple runs are possible in same input file
- now: run Modulator 2 and Chicane 2 beamline
- `&alter_setup`: change basic parameters
  - `beamline`: switch beamline
- define new field for seed 2
- `bunchharm`: bunching of harmonics in output

```
#==========================
&alter_setup
beamline=FL1MOD2
&end
#==========================
&profile_gauss
label=seed2prof
c0=57400000.0
s0=60e-6
sig=6.366e-06
&end

&field
power=@seed2prof
dgrid=2.000000e-3
ngrid=301
waist_size=750.0e-6
waist_pos=1.239
&end
#==========================
&track
bunchharm=75
&end

&sort
&end
#==========================
```

GENESIS: Input File - Third Run

- run Radiator section

GENESIS: Input File - Third Run

- run Radiator section
- `&alter_setup`: change basic parameters
  - `beamline`: switch beamline
  - `delz`: switch preferred integration step size

```
#==========================
&alter_setup
beamline=FL1RAD
delz=0.033
```

GENESIS: Input File - Third Run

- run Radiator section
- `&alter_setup`: change basic parameters
  - `beamline`: switch beamline
  - `delz`: switch preferred integration step size
  - `harmonic`: harmonic conversion
    - reference wavelength is divided by harmonic number
  - `resample`: re-sample to the new wavelength
    - only if `one4one=true`
    - slices are split, total number of slices increases

```
#=========================
&alter_setup
beamline=FL1RAD
delz=0.033
harmonic=75
resample=true
&end
#=========================
```

GENESIS: Input File - Third Run

- run Radiator section
- `&alter_setup`: change basic parameters
  - `beamline`: switch beamline
  - `delz`: switch preferred integration step size
  - `harmonic`: harmonic conversion
    - reference wavelength is divided by harmonic number
  - `resample`: re-sample to the new wavelength
    - only if `one4one=true`
    - slices are split, total number of slices increases
- `&field`: define field for FEL radiation

```
#==========================
&alter_setup
beamline=FL1RAD
delz=0.033
harmonic=75
resample=true
&end
#===========================
&field
power=0
dgrid=0.002
ngrid=301
&end
#==========================
```

GENESIS: Input File - Third Run

- run Radiator section
- `&alter_setup`: change basic parameters
  - `beamline`: switch beamline
  - `delz`: switch preferred integration step size
  - `harmonic`: harmonic conversion
    - reference wavelength is divided by harmonic number
  - `resample`: re-sample to the new wavelength
    - only if `one4one=true`
    - slices are split, total number of slices increases
- `&field`: define field for FEL radiation
- `&track`: initiate tracking
  - `zstop`: stops simulation at this beamline position

```
#==========================
&alter_setup
beamline=FL1RAD
delz=0.033
harmonic=75
resample=true
&end
#===========================
&field
power=0
dgrid=0.002
ngrid=301
&end
#==========================
&track
#zstop=0.1
&end
```

GENESIS: Output Files

- ready to simulate all 3 beamlines
- output consists of
  - `.out`: simulation runtime information
  - `.err`: information if simulation fails
  - `.out.h5` / `.Runx.out.h5`: general output file for each run
  - `.xx.fld.h5`: field dump file (optional)
  - `.xx.par.h5`: beam dump file (optional)

GENESIS: Output Files

- ready to simulate all 3 beamlines
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  - `.out`: simulation runtime information
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  - `.out.h5` / `.Runx.out.h5`: general output file for each run
  - `.xx.fld.h5`: field dump file (optional)
  - `.xx.par.h5`: beam dump file (optional)
- general output `.out.h5` file:

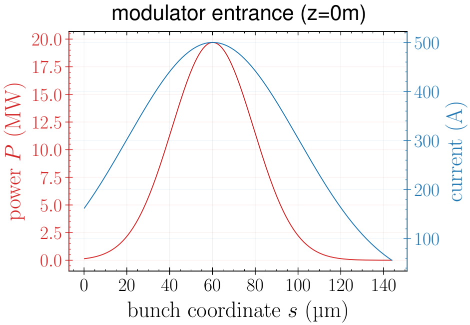
```
Beam:
 ['Global', 'alphax', 'alphay', 'betax', 'betay', 'bunching', 'bunchingphase', 'current', 'efield', 'emitx', 'emity',
  'energy', 'energyspread', 'pxposition', 'pyposition', 'xposition', 'xsize', 'yposition', 'ysize']
Field:
 ['Global', 'dgrid', 'intensity-farfield', 'intensity-nearfield', 'ngrid', 'phase-farfield', 'phase-nearfield', 'power',
 'xdivergence', 'xpointing', 'xposition', 'xsize', 'ydivergence', 'ypointing', 'yposition', 'ysize']
Global:
 ['frequency', 'gamma0', 'lambdaref', 'one4one', 's', 'sample', 'scan', 'slen', 'time']
Lattice:
 ['aw', 'ax', 'ay', 'chic_angle', 'chic_lb', 'chic_ld', 'chic_lt', 'cx', 'cy', 'dz', 'gradx', 'grady', 'ku', 'kx', 'ky',
  'phaseshift', 'qf', 'qx', 'qy', 'slippage', 'z', 'zplot']
Meta:
 ['InputFile', 'LatticeFile', 'TimeStamp', 'User', 'Version', 'mpisize']
```

GENESIS: General Output File

- most field and beam quantities are 2D datasets: beamline position, slice

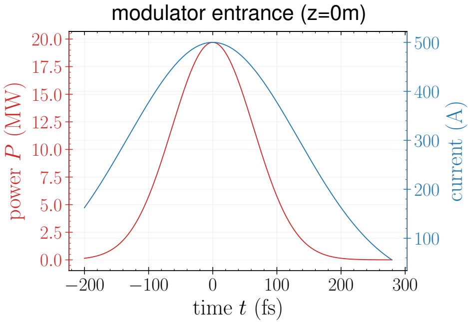
GENESIS: General Output File

- most field and beam quantities are 2D datasets: beamline position, slice
  - for example power or current profile



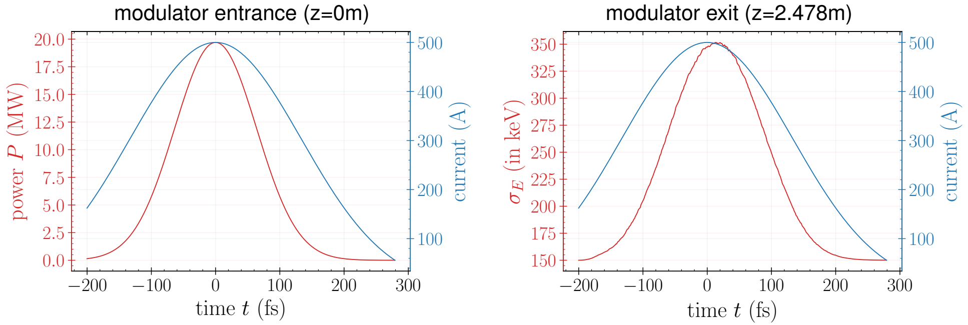
GENESIS: General Output File

- most field and beam quantities are 2D datasets: beamline position, slice
  - for example power or current profile



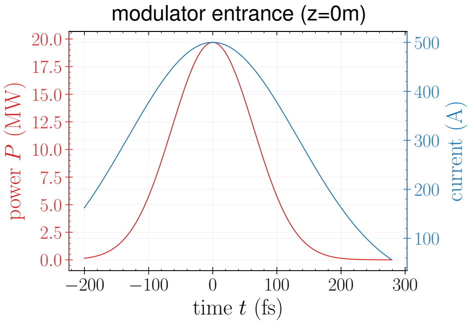
GENESIS: General Output File

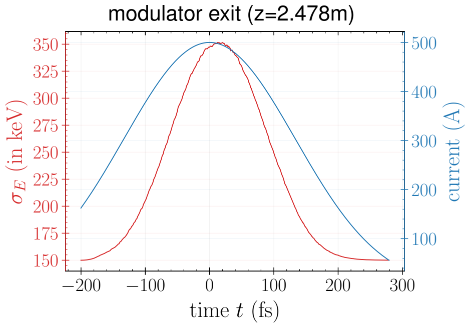
- most field and beam quantities are 2D datasets: beamline position, slice
  - for example power or current profile, energy spread
  - here: laser-electron interaction increases energy spread in modulator



GENESIS: General Output File

- most field and beam quantities are 2D datasets: beamline position, slice
  - for example power or current profile, energy spread
  - here: laser-electron interaction increases energy spread in modulator
    - can be used to calculate energy modulation amplitudes $A_{1,2}$

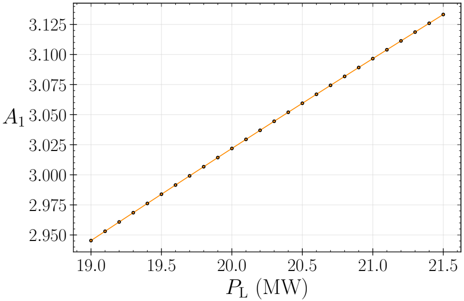




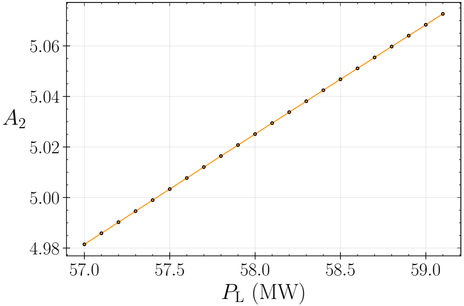
GENESIS: Energy Modulation Scan

- scan laser power in GENESIS around analytical values
- calculate energy modulation from energy spread

Modulator 1



Modulator 2



GENESIS: General Output File

- plotting along the beamline:
  - electron beam quantities should be weighted with current profile
  - radiation field quantities should be weighted with power profile
  - `global` quantities are already weighted

GENESIS: General Output File

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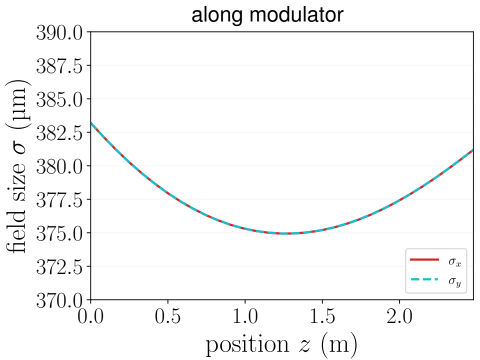
  - electron beam quantities should be weighted with current profile
  - radiation field quantities should be weighted with power profile
  - `global` quantities are already weighted



GENESIS: Field Dump File - Field Grid

- detailed information in field dump file:
    - `gridpoints`: number of grid points in one dimension
    - `gridsize`: length of one grid point
    - `refposition`: starting point of the time-window
    - `slicecount`: total number of slices
    - `slicespacing`: spacing of slices (start to start)
    - `wavelength`: reference wavelength / sample distance

GENESIS: Field Dump File - Field Grid

- detailed information in field dump file:
  - `gridpoints`: number of grid points in one dimension
  - `gridsize`: length of one grid point
  - `refposition`: starting point of the time-window
  - `slicecount`: total number of slices
  - `slicespacing`: spacing of slices (start to start)
  - `wavelength`: reference wavelength / sample distance

  - `int_xy, int_xz, int_yz`: (unscaled?) projected intensity distribution on plane
  - `slicexxxxxx/field-imag`: imaginary part of the wavefront at each grid point
  - `slicexxxxxx/field-real`: real part of the wavefront at each grid point

GENESIS: Field Dump File - Field Grid

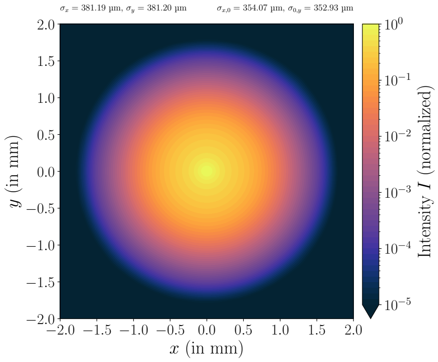
- detailed information in field dump file:
  - `gridpoints`: number of grid points in one dimension
  - `gridsize`: length of one grid point
  - `refposition`: starting point of the time-window
  - `slicecount`: total number of slices
  - `slicespacing`: spacing of slices (start to start)
  - `wavelength`: reference wavelength / sample distance

  - `int_xy, int_xz, int_yz`: (unscaled?) projected intensity distribution on plane
  - `slicexxxxxx/field-imag`: imaginary part of the wavefront at each grid point
  - `slicexxxxxx/field-real`: real part of the wavefront at each grid point

  - can be used to calculate power or intensity:
    - $\texttt{power} = \texttt{field\_real}^2 + \texttt{field\_imag}^2$
    - $\texttt{intensity} = (\texttt{field\_real}^2 + \texttt{field\_imag}^2)/(\texttt{gridsize}^2)$

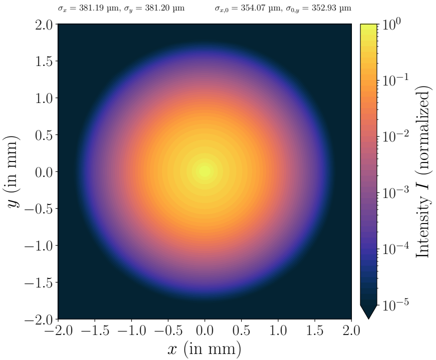
GENESIS: Field Dump File - Field Grid

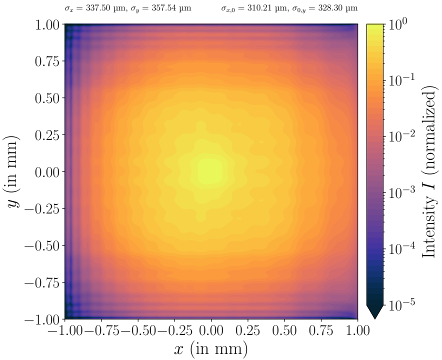
- field grid has to be large enough (`dgrid`, `ngrid`)
- projected intensity at exit of modulator 1:



GENESIS: Field Dump File - Field Grid

- field grid has to be large enough (`dgrid`, `ngrid`)
- projected intensity at exit of modulator 1:
  - field gets reflected at grid boundaries





GENESIS: Beam Dump File

- detailed information in beam dump file:
  - `slicelength`: reference length
  - `slicespacing`: sample length per slice
  - `slicecount`: total number of slices
  - `refposition`: starting position of time-window
  - `one4one`: resolving all electrons?
  - `beamletsize`: distribution generated with beamlets?

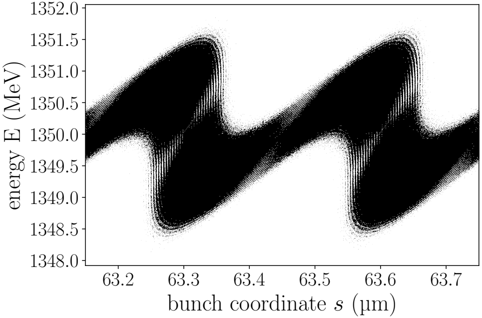
GENESIS: Beam Dump File

- detailed information in beam dump file:
  - `slicelength`: reference length
  - `slicespacing`: sample length per slice
  - `slicecount`: total number of slices
  - `refposition`: starting position of time-window
  - `one4one`: resolving all electrons?
  - `beamletsize`: distribution generated with beamlets?

  - `slicexxxxx/`: 6D particle distribution for each slice
    - `x, y`: x-, y-position
    - `px, py`: x-, y-momentum
    - `gamma`: energy
    - `theta`: ponderomotive phase
    - `current`: local current value

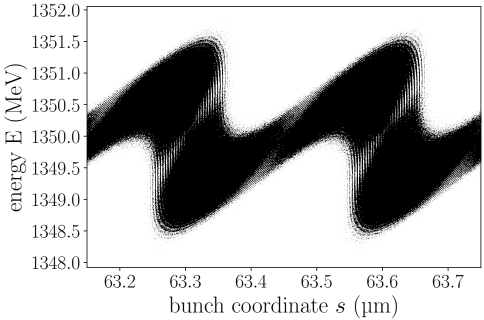
GENESIS: Beam Dump File

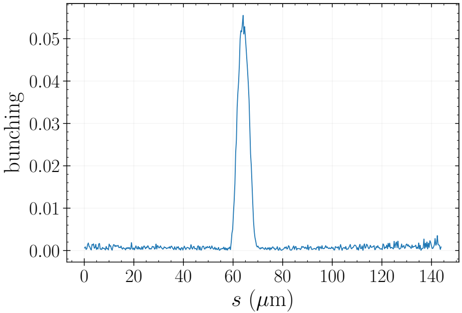
- after Chicane 2 (run2): longitudinal phase space



GENESIS: Beam Dump File

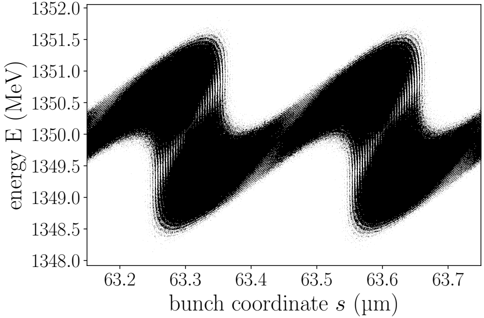
- after Chicane 2 (run2): longitudinal phase space and bunching

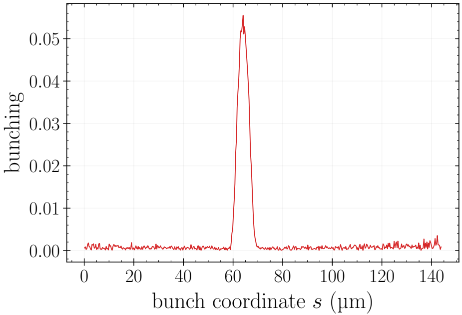




GENESIS: Beam Dump File

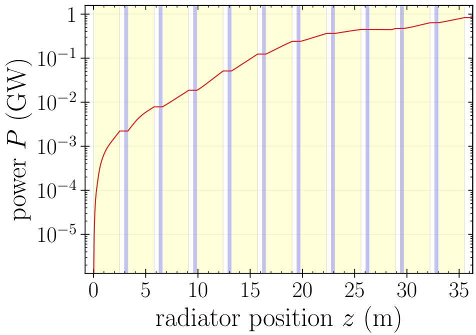
- after Chicane 2 (run2): longitudinal phase space and bunching
- bunching also from general output file
  - after resampling better to calculate from beam dump





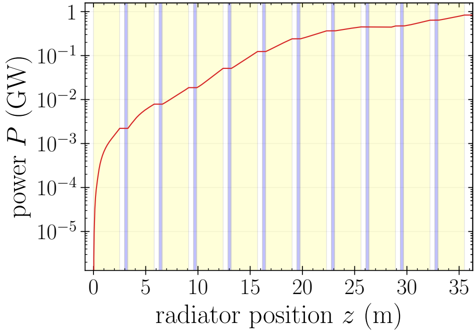
GENESIS: General Output File - Radiator Section

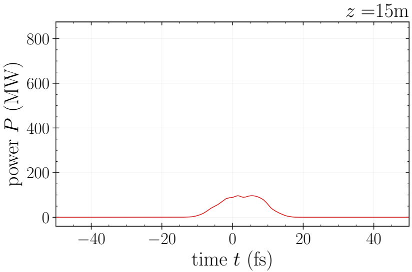
- power gain curve



GENESIS: General Output File - Radiator Section

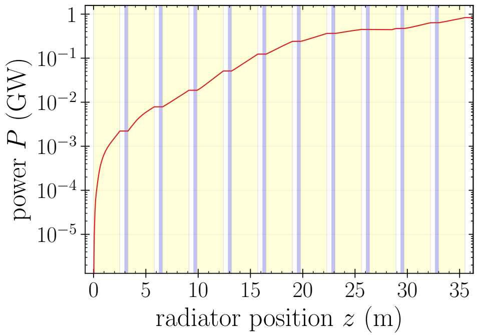
- power gain curve
- power profile

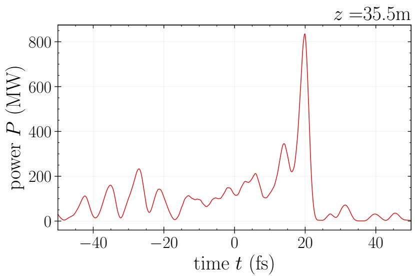


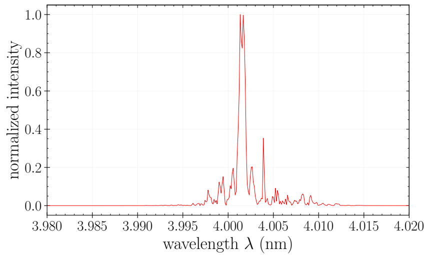


GENESIS: General Output File - Radiator Section

- power gain curve
- power profile
- spectrum
  - calculated from phase and intensity







Undulator Tapering

- compensation of the electron beam energy loss
- undulator tapering to preserve resonance condition

$$\lambda_\mathrm{r} = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \quad , \quad \text{with} \quad \frac{K^2}{2} = a_\mathrm{w}^2$$

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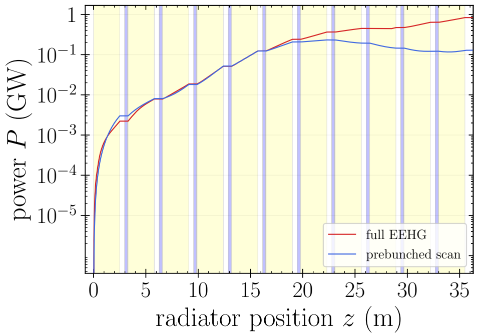
- undulator strength K should be decreased along the undulator length

- optimize K-values of individual radiator segments for maximum power output
- use time-independent simulations for optimization
  - fast parameter scans
- for optimum set of K-values: time-dependent simulation

Undulator Tapering: Optimization

- find proper steady-state simulation section
  - input file without `&time` only for radiator section
  - make use of `bunch` parameter: pre-bunched electron beam



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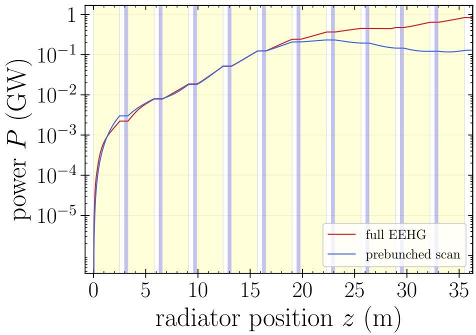
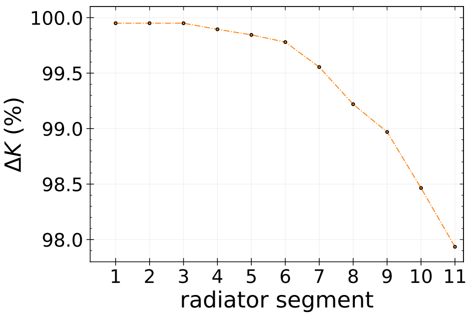
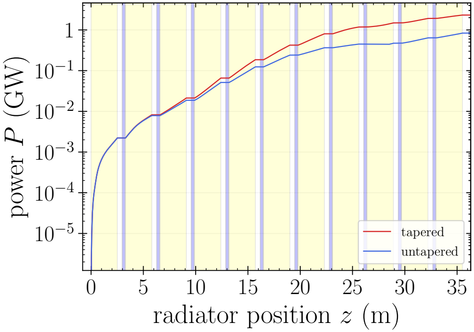




Undulator Tapering: Comparison

- power gain curve



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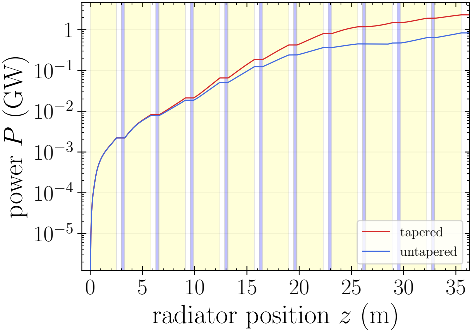

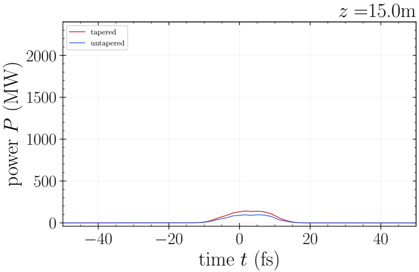

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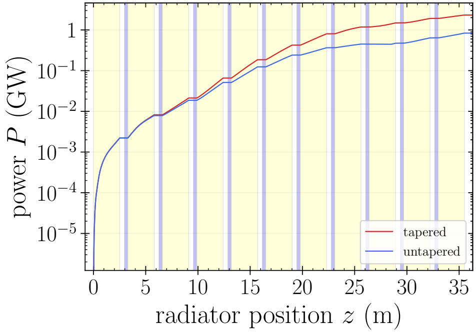

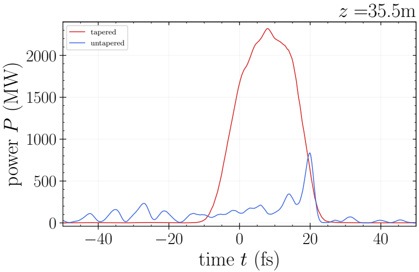

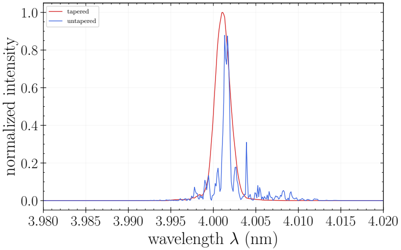

Summary

- set up `.lat` and `.in` file for GENESIS EEHG at 4 nm
- insight into field, beam dump and general output file
- utilized steady-state scan simulations to optimize undulator strength
- detailed information: ▸ https://github.com/svenreiche/Genesis-1.3-Version4

Backup Slides

- Trivia
- Analytical Approach in Detail
- Energy Modulation Estimation

Trivia

- sorting can also be used as a marker in the lattice file
  - can be used right after the chicane to get output based on sorted distribution
- `npart`: must be a multiple of `nbins`; should be increased with the harmonic
- `nbins`: in order to upload the correct shot noise for the electrons, it should be higher than 4 and greater then 2+2n for the n-th harmonic
- bunch coordinate from ponderomotive phase:
  - $s = \frac{\texttt{theta}}{2\pi} \cdot \texttt{slicelength} + \texttt{slicespacing} \cdot (N_{\text{slice}} - 1)$
- power and nearfield-intensity are scaled to SI-units, farfield-intensity is in arbitrary units
- nearfield-intensity is the intensity on the central grid point
- there is a scaling factor difference when comparing the `int_xy` distribution with the manually calculated one: $510999.06^2/376.73/(2 \cdot \pi/\texttt{wavelength})^2$

Bunching Formula

$$|b_{n,m}| = \left| J_m\left[-(n+Km)A_2B_2\right] \cdot J_n\left[-A_1\xi\right] \cdot e^{-\frac{1}{2}\xi^2} \right|$$

- $J_{n,m}$: first kind Bessel function of order n, m
- final wavelength: $\lambda_e = \frac{1}{\frac{n}{\lambda_1}+\frac{m}{\lambda_2}} \overset{\lambda_1=\lambda_2}{=} \frac{\lambda_1}{n+m}$
- $K = \frac{k_2}{k_1} = \frac{\lambda_1}{\lambda_2}, \quad \xi = nB_1 + (n+Km)B_2, \quad A_{1,2} = \frac{\Delta E_{1,2}}{\sigma_E}, \quad B_{1,2} = R_{56}^{(1,2)} \frac{\sigma_E}{E_0} k_1$

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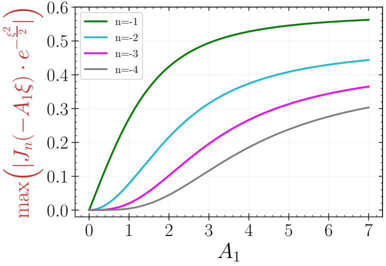

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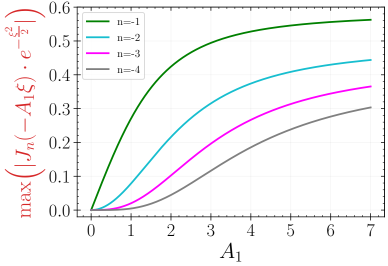


- $n = -1$ for high bunching
- $h = m + n$
- $A_1 \lesssim 2$: linear decrease
- $A_1 > 3$: converges asymptotically

Bunching Formula: Fix A_1 and A_2

Modulator 1: A_1

- $A_1 = 3$
  - $A_1 \lesssim 2$: bunching factor decreases linearly with A_1
  - $A_1 > 3$: bunching factor converges asymptotically to a constant value

Modulator 2: A_2

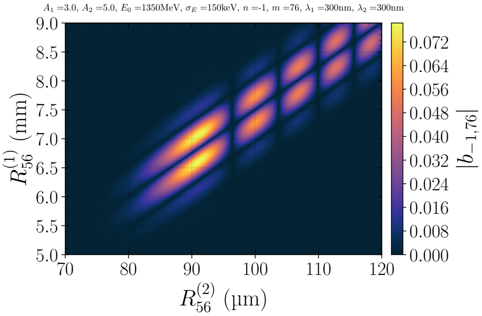
- $A_2 = 3 \ldots 5$
  - no significant effect on absolute value of the bunching
  - large A_2 decreases required dispersion strength of first chicane
  - should not be too large

    $\rightarrow$ (slice) energy spread in radiator gets too large
    $\rightarrow$ decreases FEL performance

Bunching Formula: Find $R_{56}^{(1)}$ and $R_{56}^{(1)}$

$$|b_{n,m}| = \left| J_m\left[-(n+Km)A_2B_2\right] \cdot J_n\left[-A_1\xi\right] \cdot e^{-\frac{1}{2}\xi^2} \right|$$

- A_1, A_2, n, m and K already fixed!
- just scan $B_{1,2}$-values and find maximum bunching



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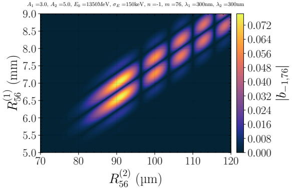
- or solve the bunching equation for optimum $B_{1,2}$-values
  - maximize $\left| J_m\left[-(n+Km)A_2B_2\right] \right|$
    - for $m > 4$ calculate B_2 by

$$B_2 = \frac{m + 0.8087m^{1/3}}{A_2(Km+n)}$$



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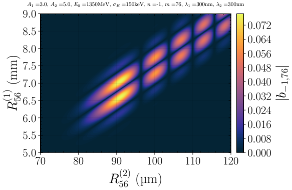

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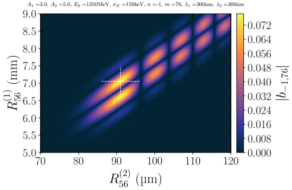
  - maximize $\left| J_n\left[-A_1\xi\right] \cdot e^{-\frac{1}{2}\xi^2} \right|$
    - scan ξ to find maximum
    - two possible solutions $\pm\xi$
    - $\xi = nB_1 + (n+Km)B_2$

$$\rightarrow B_1 = \frac{\pm\xi_{max} - B_2(Km+n)}{n}$$

Bunching Formula: Choice of the Bunching Isle

$$|b_{n,m}| = \left| J_m\left[-(n+Km)A_2B_2\right] \cdot J_n\left[-A_1\xi\right] \cdot e^{-\frac{1}{2}\xi^2} \right|$$



- choose negative ξ, that is larger $R_{56}^{(1)}$
  - has advantages if there are longitudinal variations in the average electron energy
    - G. Penn, 2014: "*Stable, coherent free-electron laser pulses using echo-enabled harmonic generation*"
    - G. Penn, 2013: "*EEHG Performance and Scaling Laws*"

GENESIS Optimization: $R_{56}^{(1,2)}$ Scan

- effects not taken into account in bunching formula:
  - dispersion of modulators
    - path length difference of electrons depends on energy modulation
    - energy modulation builds up linearly along modulator $\rightarrow$ consider half of the dispersion
    - $R_{56}^{(m)} = \left(2 \cdot N_u \cdot \lambda_1\right)/2$
    - in the order of 10 µm   (30 · 300 nm = 9 µm)

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  - velocity bunching
    - $R_{56}^{(v)} = \frac{L}{\beta^2 \gamma^2}$
    - in the order of 1 µm (5.4 m drift: 1.35 GeV $\rightarrow$ 0.8 µm, 0.95 GeV $\rightarrow$ 1.5 µm)

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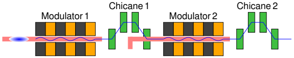
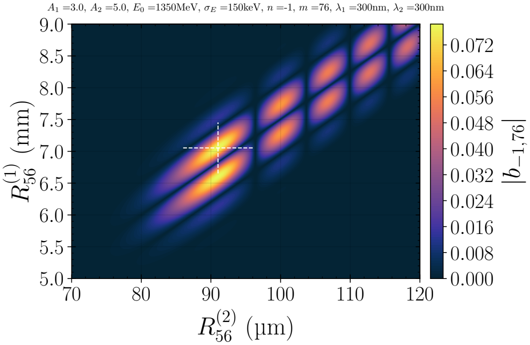
- $R_{56}^{(1)}$ in the order of mm $\rightarrow$ additional dispersion can be neglected
- $R_{56}^{(2)}$ in the order of 100 µm $\rightarrow R_{56}^{(2)} = R_{56,\text{analytical}}^{(2)} - R_{56}^{(m)} - R_{56}^{(v)}$

Parameters - 4 nm EEHG: Bunching Map





Case Study	4 nm EEHG
Harmonic	75
Electron Beam	
E (GeV)	1.35
σ_E (keV)	150
I_p (A)	500
σ_z (µm)	100
σ_t (fs)	333
ε_n (mm mrad)	0.6
Seed Laser	
λ (nm)	300 | 300
A	3 | 5
σ_z (µm)	64 | 6.4
σ_t (fs)	212 | 21.2
Modulators	
λ_u (mm)	82.6
Periods	30
K	9.97
Chicanes	
length (m)	6.1 | 2.8
L_{dipole} (m)	0.4 | 0.3
L_{drift} (m)	2.0 | 0.6
R_{56} (mm | µm)	

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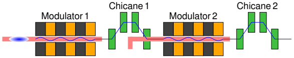

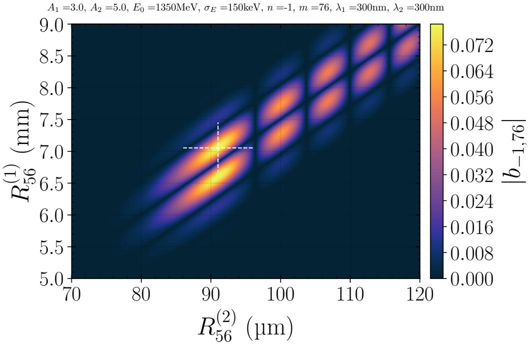

- longitudinal dispersion of modulators not considered in analytical approach ($\sim$ 10 µm)

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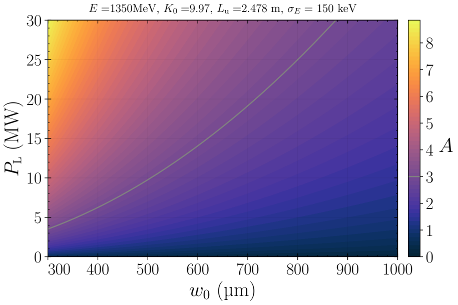
R_{56} (mm | µm)	7.05 | 81.25

Energy Modulation Estimation

- estimate required laser power for desired $A_{1,2}$ from analytical formula

$$\Delta\gamma(s) = \sqrt{\frac{P_L}{P_0}\frac{2L_u\widehat{K}}{\gamma w_0}}\cos(k_L s)$$

Modulator 1



Modulator 2