FLAME Documentation

Release 1.5.1

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CONTENTS:

FLAME - Fast Linear Accelerator Model Engine

FLAME is high-speed envelope tracking code developed in FRIB.

Remarkable Features

- Envelope tracking with multiple charge states
- Support general lattice elements and asymmetric rf cavity by Thin-Lens-Model
- Transfer matrix caching for iterative running
- Python interface (include ipython-notebook)

CHAPTER ONE

INSTALLATION

1.1 Build from source code

Git clone from FLAME repository.

```
$ git clone *repository-address*
```

Pre-requisites (may need to apt-get with sudo)

```
$apt-get install libboost-dev libboost-system-dev \
    libboost-thread-dev libboost-filesystem-dev \
    libboost-regex-dev libboost-program-options-dev \
    libboost-test-dev \
    build-essential cmake bison flex cppcheck git libhdf5-dev \
    python-numpy python-nose python3-numpy python3-nose
```

FLAME supports python 2.7 and 3.4, EPICS interface is optional.

Make `build` directory and compile with CMake.

```
$ cd flame
$ mkdir build
$ cd build
$ cmake ..
$ make
```

Test FLAME (include the beam dynamics test).

```
$ make test
```

Install with proper permissions.

```
$ make install # may need to install with sudo
```

CHAPTER

TWO

TUTORIAL

2.1 1. Basic usage

In Python interface (include IPython-notebook), user can import flame *Machine* class.

```
>>> from flame import Machine
```

Create *Machine* object with input file.

```
>>> with open('lattice_file.lat', 'rb') as f :
>>>     M = Machine(f)
```

Allocate the beam state. - *Machine.allocState()*, *State*

```
>>> S = M.allocState({})
```

Run envelope tracking simulation. - *Machine.propagate()*

```
>>> M.propagate(S)
```

The beam state has the finite state beam information. - *State()*

```
>>> S            # centroid vector
State: moment0 mean=[7](3.18839,0.00871355,-12.0779,-0.00254204,-35.2039,0.000489827,
↪1)
>>> S.ref_IonEk  # reference energy
11969.995341581
```

The attribute list of the beam state can be found here.

User can observe the beam state history by using `observe` keyword in *propagate()*.

```
>>> result = M.propagate(S, observe=range(len(M))) # observe the beam state in all␣
↪elements
```

It returns enumerated list of the beam state.

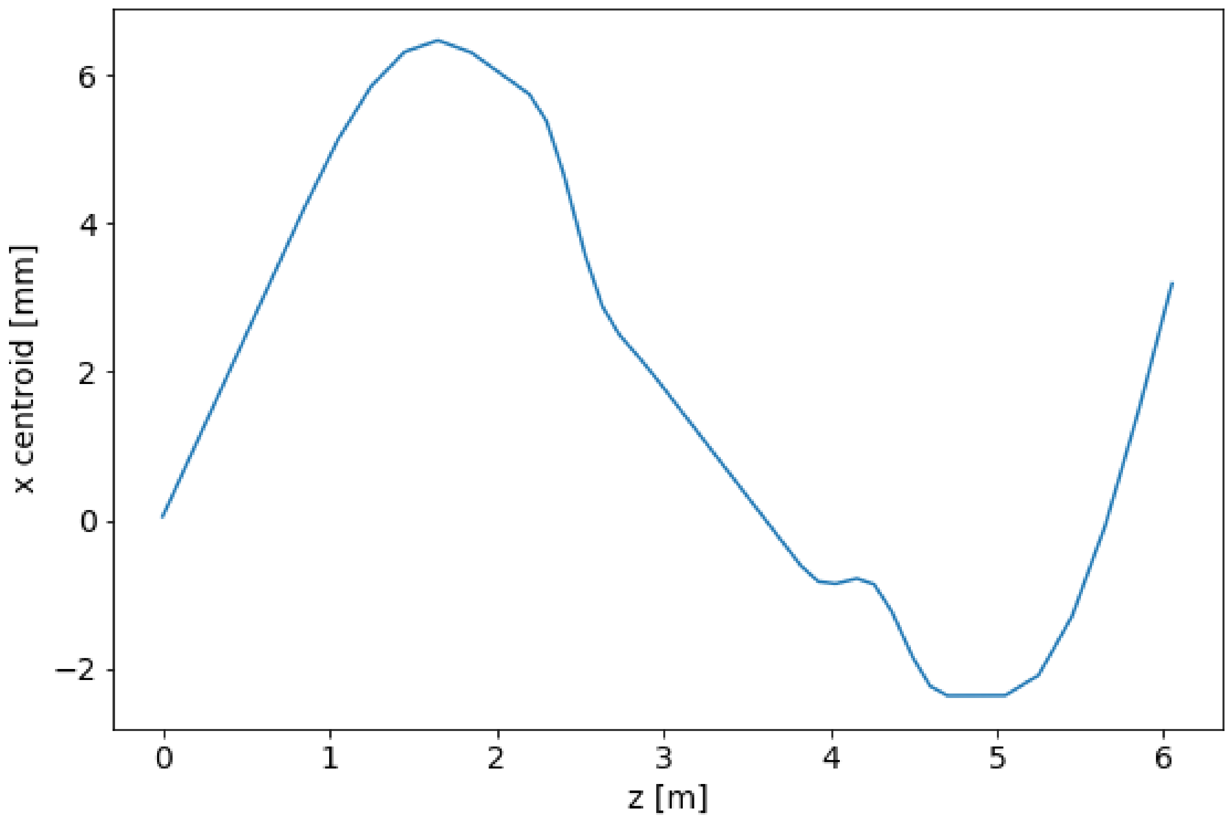
```
>>> result[3]
(3, State: moment0 mean=[7](2.2532,0.00489827,2.2532,0.00489827,-2.7162,0.000489827,
↪1))
```

User can generate the history data from the list of beam states,

```
>>> z = [s[1].pos for s in result] # reference beam position history
>>> x = [s[1].moment0_env[0] for s in result] # x centroid history
```

and plot.

```
>>> import matplotlib.pylab as plt
>>> plt.plot(z, x)
>>> plt.ylabel('x centroid [mm]')
>>> plt.xlabel('z [m]')
>>> plt.show()
```



2.2 2. Lattice parameter control

`conf()` returns initial machine parameter.

```
>>> M.conf()
OrderedDict([('AMU', 931494320.0),
             ('BaryCenter0',
              array([ 0.1   ,  0.01  ,  0.1   ,  0.01  ,  0.001,  0.001,  1.   ])),
             ('BaryCenter1', array([ 0.,  0.,  0.,  0.,  0.,  0.,  1.])),
             ('IonChargeStates', array([ 0.13865546,  0.14285714])),
             ('IonEk', 11969.995341581),
             ('IonEs', 931494320.0),
             ('IonW', 931506289.9953415),
             ('IonZ', 0.13865546218487396),
             ('NCharge', array([ 10111.,  10531.])),
```

```
            ('S0',
             array([  3.68800000e+02,   2.50000000e-02,   0.00000000e+00,
                      0.00000000e+00,   0.00000000e+00,   0.00000000e+00,
                      0.00000000e+00,   2.50000000e-02,   2.88097000e-05,
                      0.00000000e+00,   0.00000000e+00,   0.00000000e+00,
...
```

User can `find` the element index by *element type* or *element name*.

```
>>> M.find(type='solenoid')
[15, 16, 18, 19, 21, 22, 27, 28, 30, 31, 33, 34]
>>> M.find(name='q1h_1')
[15]
```

`conf(index)` returns all parameters of the element.

```
>>> M.conf(15).keys() # parameter keywords
['AMU', 'B2', 'BaryCenter0', 'BaryCenter1', 'IonChargeStates', 'IonEk', 'IonEs', 'IonW
↪', 'IonZ', 'L', 'NCharge', 'S0', 'S1', 'aper', 'name', 'sim_type', 'type']
>>> M.conf(15)['B2'] # quadrupole strength
0.942438547187938
```

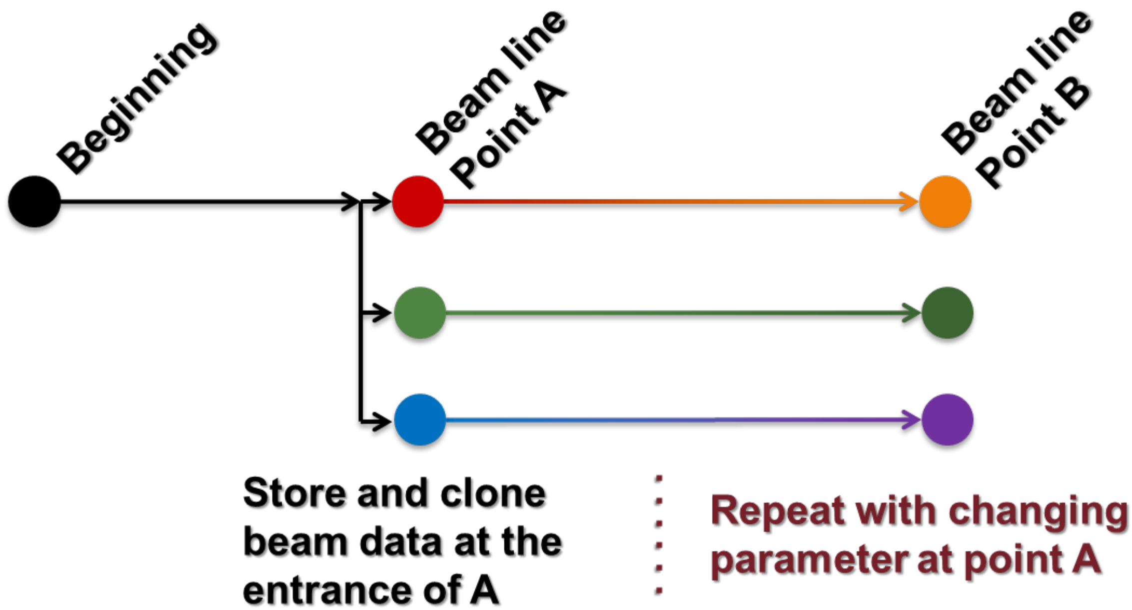
Change the parameter by using `reconfigure()`.

```
>>> M.reconfigure(15, {'B2': 0.8})
```

Check new parameter of the solenoid.

```
>>> M.conf(15)['B2']
0.8
```

2.3 3. Run for the selected section



User can input *start-point index* and *end-point index* to `propagate`.

```
>>> M.propagate(S, 0, 10) # simulate from 0th to the entrance of 10th element
>>> S1 = S.clone() # clone the beam state
>>> M.propagate(S1, 10, -1) # simulate from 10th to the last element
```

In this case, “S” has the beam state after the 9th element, and “S1” has the finite beam state.

2.4 4. Example: Quadrupole scan

Run simulation up to the target element.

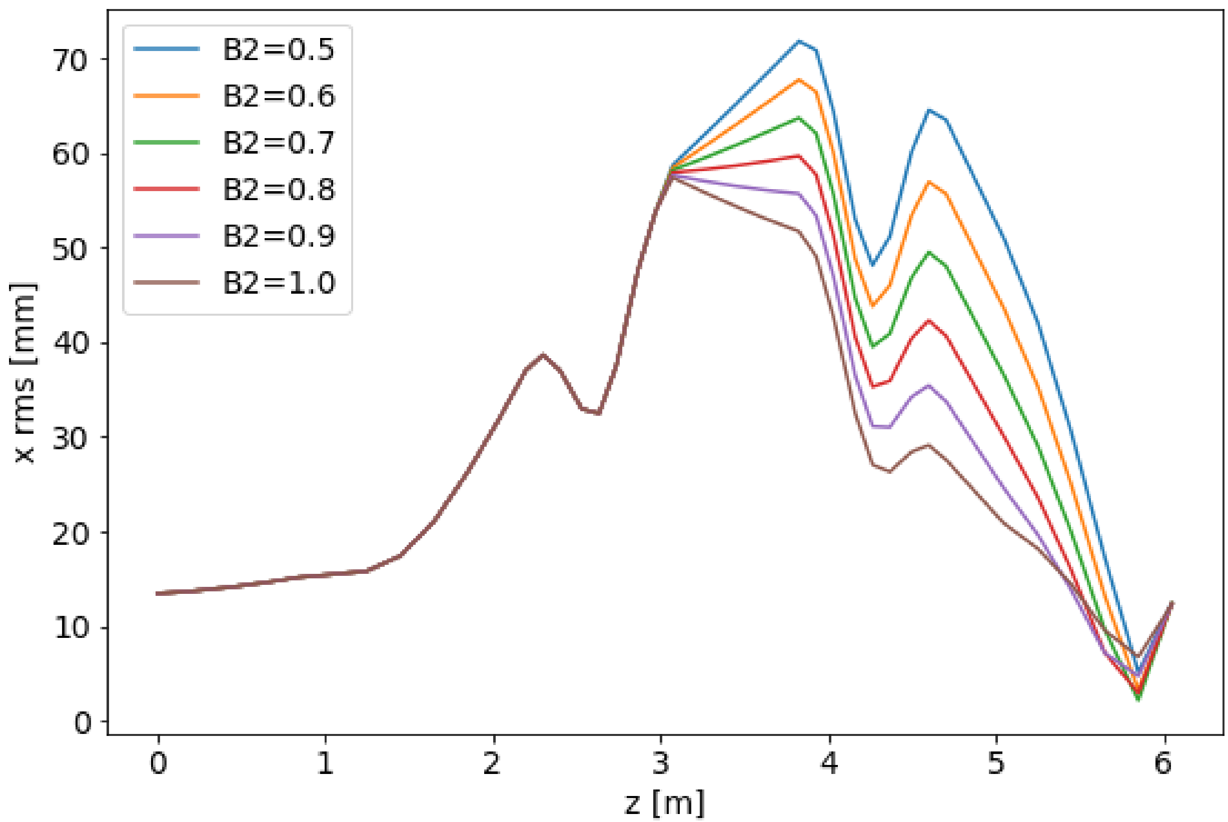
```
>>> M.find(name='q3h_6') # get index of the target element
[22]
>>> ini = M.conf(22)['B2'] # store the initial quadrupole strength
>>> ini
0.853489750615018
>>> SA = M.allocState({})
>>> rA = M.propagate(SA, 0, 22, observe=range(len(M))) # propagate 22 elements from 0
```

Scan parameters by using simple loop.

```
>>> b2lst = [0.5, 0.6, 0.7, 0.8, 0.9, 1.0]
>>> rlst = []
>>> for b2 in b2lst:
>>>     SB = SA.clone()
>>>     M.reconfigure(22, {'B2':b2})
>>>     rt = M.propagate(SB,22,-1,observe=range(len(M)))
>>>     rlst.append(rt)
```

Plot the scan result.

```
>>> zA = [s[1].pos for s in rA]
>>> xA = [s[1].moment0_rms[0] for s in rA] # get the x rms size
>>>
>>> for b2,rt in zip(b2lst,rlst):
>>>     zt = zA + [s[1].pos for s in rt] # join the history result
>>>     xt = xA + [s[1].moment0_rms[0] for s in rt]
>>>     plt.plot(zt, xt, label='B2='+str(b2))
>>>
>>> plt.ylabel('x rms [mm]')
>>> plt.xlabel('z [m]')
>>> plt.legend(loc='best')
>>> plt.show()
```



CHAPTER

THREE

LATTICE FILE

3.1 General parameter

Basic format of the general parameters are,

```
keyword1 = "value1";
keyword2 = "value2";
...
```

keyword	value	description
sim_type	“MomentMatrix”	Simulation mode. FRIB simulation uses the particular mode “MomentMatrix”.
MpoleLevel	“0”, “1”, or “2”	Multipole term controller for the rf cavities. “0” - only include focusing and defocusing effect “1” - include dipole terms “2” - include dipole and quadrupole terms
EmitGrowth	“0” or “1”	Flag for cross-cavity emittance growth effect. “0” - False (no emittance growth) “1” - True (calculate emittance growth)
HdipoleFitMode	“0” or “1”	Flag for auto-adjustment of bending element “0” - use “bg” or “beta” for the bending strength “1” - auto-adjust the bending strength

3.2 Beam parameter

Basic format of the beam parameters are,

```
keyword1 = value1;
keyword2 = [value2, value3]; # list input
...
```

keyword	value	description
IonEs	float	Nucleaon mass of the reference beam. [eV/u]
IonEk	float	Initial kinetic energy of the reference beam. [eV/u]
IonChargeStates	list of float	List of charge to mass ratios of the all charge states. [1] The first element is used as the reference beam.
NCharge	list of float	List of macro weights of the all charge states. [1]
${vector_variable}${n}	vector[7]	Initial centroid vector of the **n**-th charge state. *${vector_variable}* is defined in `source`. $[x, x', y, y', \phi, E_k, 1]$ with [mm, rad, mm, rad, rad, MeV/u, 1]
${matrix_variable}${n}	vector[49]	Flattened initial envelope matrix of the **n**-th charge state. *${matrix_variable}* is defined in `source`. Cartisan product of $[x, x', y, y', \phi, E_k, 1]^2$ with [mm, rad, mm, rad, rad, MeV/u, 1] ^{2}
Eng_Data_Dir	string	Directory path of the rf cavity data. `dir(path)` supports relative path.

3.3 Lattice elements

Basic format of the one lattice element is,

```
name_of_element1: element_type, parameter1 = value1, parameter2 = value2, ... ;
```

After writing down the all lattice elements, user need to specify the lattice cell and the cell to USE.

```
# define the cell
name_of_cell: LINE = ( name_of_element1, name_of_element2, name_of_element3, ... );

# set the cell to USE
USE: name_of_cell;
```

element_type	description
`source`	Starting point of the simulation.
`marker`	Marker element.
`stripper`	Chage stripper element.
`tmatrix`	User input transfer matrix.
`orbtrim`	Orbit trim element.
`drift`	Drift space element.
`solenoid`	Solenoid magnet element.
`quadrupole`	Magnetic quadrupole element.
`equad`	Electrostatic quadrupole element.
`sbend`	Magnetic bend element.
`edipole`	Electrostatic dipole element.
`rfcavity`	RF cavity element.

3.3.1 Special element

type source

Starting point of the simulation. Initial beam state parameters are set at this element.

Parameters **vector_variable**: string

Name key of the initial centroid vector.

matrix_variable: string

Name key of the initial envelope matrix.

type marker

Marker element. Nothing to do.

type stripper

Stripper element.

Parameters **IonChargeStates**: list of float

List of charge to mass ratios after the charge stripper. [1]

charge_model: string

Macro weight model for stripper.
- **"baron" (default)**: Use Baron formula for the macro weights.
- **"off"**: Use `NCharge` parameter for the macro weights.

NCharge: list of float

List of macro weights after the charge stripper. [1]
This list length must be same as the `IonChargeStates`

This parameter is used only in the case of `charge_model = "baron"`.

Stripper_IonZ: float (optional, default is **78.0/238.0**)

Charge to mass ratio of the reference beam. [1]

Stripper_IonMass: float (optional, default is **238.0**)

Ion mass of the reference beam. [amu]

Stripper_IonProton: float (optional, default is **92.0**)

Proton number of the reference beam. [1]

Stripper_E1Para: float (optional, default is **2.8874e-3**)

Constant part of the energy struggling parameter of the charge stripper. [MeV/u]

Stripper_lambda: float (optional, default is **5.5740**)

Momentum spread factor λ of the charge stripper. [1]

Stripper_upara: float (optional, default is **2.6903**)

Momentum spread factor U of the charge stripper. [1]
The momentum spread is defined as $\sqrt{(U/\lambda^2)}$ [mrad].

Stripper_E0Para: vector[3] (optional, default is **[16.348e6, 1.00547, -0.10681]**)

Energy loss parameters due to the ionization.
[Constant_part, Energy_dependence, Thickness_depenedence] with [eV/u, 1, 1]

Stripper_Para: vector[3] (optional, default is **[3.0, 20.0, 16.623e6]**)

Stripper foil parameters.
[Thickness, Thickness_variation, reference_energy] with [um, %, eV/u]

`type tmatrix`

User input transfer matrix element.

Parameter matrix: vector[49]

Flattened 7×7 transfer matrix.

3.3.2 Optical element

`type orbtrim`

Orbit trim element. This can be use as steering magnet.

Parameters realpara: int

Realistic input parameter flag for the beam kick angle.
0 - use `theta_x` and `theta_y` for the beam kick.
1 - use `tm_xkick` and `tm_ykick` for the beam kick.

theta_x: float

Horizontal beam kick angle. [rad]

theta_y: float

Vertical beam kick angle. [rad]

tm_xkick: float

Magnetic field strength for the horizontal beam kick. [T*m]

tm_ykick: float

Magnetic field strength for the vertical beam kick. [T*m]

xyrotate: float

Transverse rotation angle of the beam. [deg]

Note: In the case of user puts both “beam kick information” and “transverse rotation angle” to the ONE orbtrim element, the process order is, beam kick -> transverse rotation. In other words, the beam kick is effected BEFORE the transverse rotation.

`type drift`

Drift space element.

Parameters **L**: float

Length of the lattice element. [m]

`type solenoid`

Solenoid magnet element.

Parameters **L**: float

Length of the lattice element. [m]

B: float

Solenoid strength (B_z). [T]

dx: float (default: 0.0)

Misalignment of horizontal shift. [m]

dy: float (default: 0.0)

Misalignment of vertical shift. [m]

pitch: float (default: 0.0)

Misaglignment of pitch angle. [rad]

yaw: float (default: 0.0)

Misaglignment of yaw angle. [rad]

roll: float (default: 0.0)

Misaglignment of roll angle. [rad]

`type quadrupole`

Magnetic quadrupole element.

Parameters **L**: float

Length of the lattice element. [m]

B2: float

Quadrupole field gradient. [T/m]
Positive value means horizontal focusing.

dx, **dy**, **pitch**, **yaw**, **roll**: float

Misalignment parameters. See `solenoid` case.

type equad

Electrostatic quadrupole element.

Parameters **L**: float

Length of the lattice element. [m]

V: float

Electrostatic quadrupole pole tip voltage. [V]
Positive value means horizontal focusing.

radius: float

Electrostatic quadrupole pole tip radius. [m]

dx, **dy**, **pitch**, **yaw**, **roll**: float

Misalignment parameters. See `solenoid` case.

type sbend

Magnetic bend element.

Parameters **L**: float

Length of the lattice element. [m]

phi: float

Bend angle. [deg]

phi1: float

Front pole face angle. [deg]

phi2: float

Back pole face angle. [deg]

bg: float (optional: Used in the case of *"HdipoleFitMode"* is **0**.)

Lorentz $\beta\gamma$ for the reference beam. [1]
This parameter is correspond to the bend field strength.

dx, **dy**, **pitch**, **yaw**, **roll**: float

Misalignment parameters. See `solenoid` case.

type edipole

Electrostatic dipole (bend) element.

Parameters **L**: float

Length of the lattice element. [m]

phi: float

Bend angle. [deg]

beta: float (optional: Used in the case of *"HdipoleFitMode"* is **0**.)

Lorentz β for the reference beam. [1]

This parameter is correspond to the bend field strength.

fringe_x: float

Horizontal fringe term. [rad/mm]

fringe_y: float

Vertical fringe term. [rad/mm]

asymfac: float

Characteristic parameter of the kinetic energy change due to the middle point potential deviation from ground. [1]

spher: int

Flag for the electrostatic dipole shape.
0 - cylindrical electrostatic dipole
1 - spherical electrostatic dipole

ver: int

Flag for the bending direction.
0 - horizontal bend
1 - vertical bend

dx, **dy**, **pitch**, **yaw**, **roll**: float

Misalignment parameters. See `solenoid` case.

`type rfcavity`

RF cavity element.

Parameters **L**: float

Length of the lattice element. [m]

cavtype: string

Cavity type. Supports “Generic”, “0.041QWR”, “0.085QWR”, “0.29HWR”, and “0.53HWR”. *The file format is described here.*

f: float

RF frequency of the cavity. [Hz]

phi: float

Input phase of the cavity. [deg]

syncflag: int

Flag for synchronous phase input (for above parameter **phi**).
- **0** for driven phase input.
- **1** for synchronous phase input with complex fit model. (default)
- **2** for synchronous phase input with sinusoidal fit model.

scl_fac: float

Scaling factor of the field. [1]

datafile: string (optional: Used in the case of `cavtype` = “Generic”)

File path of the rf cavity data.

Rm: float (optional: Used in the case of `cavtype` = “Generic”)

Characteristic radial length of the multipole expansion. [mm]

dx, **dy**, **pitch**, **yaw**, **roll**: float

Misalignment parameters. See `solenoid` case.

3.4 Rf cavity data format

FLAME using Thin-Lens-Model for rf cavity calculation. Rf cavity data is composed of "Longitudinal axis data", "Multipole lattice data", "Multipole field data", and "TTF fitting data".

3.4.1 Hard-coded FRIB cavity models

For typical rf cavity in FRIB, the "TTF fitting data" is hard-coded in FLAME. Following files are required for each rf cavity type.

cavtype	Longitudinal axis data	Multipole lattice data	Multipole field data
"0.041QWR"	"axisData_41.txt"	"Multipole41/thinlenlon_41.txt"	"Multipole41/CaviMlp_41.txt"
"0.085QWR"	"axisData_85.txt"	"Multipole85/thinlenlon_85.txt"	"Multipole85/CaviMlp_85.txt"
"0.29HWR"	"axisData_29.txt"	"Multipole29/thinlenlon_29.txt"	"Multipole29/CaviMlp_29.txt"
"0.53HWR"	"axisData_53.txt"	"Multipole53/thinlenlon_53.txt"	"Multipole53/CaviMlp_53.txt"

3.4.2 Generic rf cavity model

FLAME supports *lattice format* input for the generic rf cavity model.

The basic format of the rf cavity data is similar to the main lattice file,

```
Rm = value1;

Ez = [
z1, Ez1,
z2, Ez2,
z3, Ez3,
...
];

name_of_element1: element_type, parameter1 = value1, parameter2 = value2, ... ;
...

cell: LINE =(name_of_element1, ...);
USE: cell;
```

keyword	value	description
Rm	float	Characteristic radial length of the multipole expansion. [mm]
Ez	vector[2*n]	On axis E_z data. The odd index (1,3,5,...) is z position. [mm] The even index (2,4,6,...) is Electric field strength. [V/m]
RefNorm	float	Reference normalization factor for complex synchronous phase definition. This value is defined by qA/m where A is the scaling factor of the 3D EM field. If **RefNorm** or **SyncFit** are not defined, sinusoidal model is used for the synchronous phase definition.
SyncFit	vector[5*n]	Fitting parameters for complex synchronous phase definition. The fitting model is shown *here*.
EnergyLimit	vector[2]	Lower and higher limit for incident energy. [MeV] This value is used for warning signs only.
NormLimit	vector[2]	Lower and higher limit for normalization factor. This value is used for warning signs only.

Lattice element for the rf cavity data

Drift space is the same format as the main lattice but unit of `L` is [mm] - `drift`

`type EDipole`

Dipole term generated by the electric field.

Parameters **L**: float

Length of the lattice element. [mm]
This parameter should be 0.0 in Thin-Lens-Model.

V0: float

Amplitude of the multipole term. [MV]

attr: vector[20]

TTF fitting parameter. *(see here)*
1 to 10 - fitting parameter for T
11 to 20 - fitting parameter for S

type EFocus
Constant focusing term generated by the electric field.

Parameters are the same as *EDipole*.

type EQuad
Quadrupole term generated by the electric field.

Parameters are the same as *EDipole*.

type HMono
Dipole term generated by the magnetic field.

Parameters **L**: float

Length of the lattice element. [mm]
This parameter should be 0.0 in Thin-Lens-Model.

V0: float

Amplitude of the multipole term. [MA]

attr: vector[20]

TTF fitting parameter. *(see here)*
1 to 10 - fitting parameter for T
11 to 20 - fitting parameter for S

type HFocus
Constant focusing term generated by the magnetic field.

Parameters are the same as *HMono*.

type HQuad
Quadrupole term generated by the magnetic field.

Parameters are the same as *HMono*.

type AccGap
Acceleration gap term by the longitudinal electric field.

Parameters **L**: float

Length of the lattice element. [mm]
This parameter should be 0.0 in Thin-Lens-Model.

V0: float

Amplitude of the multipole term. [MV]

attr: vector[23]

TTF fitting parameter. *(see here)*
1 to 10 - fitting parameter for T
11 to 20 - fitting parameter for S
21 to 23 - fitting parameter for the synchronous phase

Note: FLAME is using TTF-calculation acceleration technique to boost cavity modeling speed. TTF factor T and S are pre-calculated and fitted using 9th order polynomial function according to different particle phase speed k. n-th fitting parameter p_n is listed as,

$$T(k), S(k) = \sum_{n=0}^{9} p_n k^{(9-n)}.$$

The driven-phase calculation is also boosted by using fitting model for the energy gain curve.

For the sinusoidal fitting model, the phase transferring factor φ_c is fitted by using

$$\varphi_c = p_0 E^{p_1} + p_2.$$

Here, E is the kinetic energy and $p_{i=0,1,2}$ are the fitting parameters.

For other complex models (e.g. peak-base model), the phase transferring factor depends on the normalization factor $g = qA/m$ where A is the scaling factor of the 3D EM field. The fitting model for φ_c is,

$$\varphi_c = \sum_{i=0}^{n} (p_{5i} E^{p_{5i+1}} + p_{5i+2} \ln(E) + p_{5i+3} e^E + p_{5i+4}) \times g^i.$$

Here, user can determine n value corresponds to the size of **SyncFit**.

The driven phase φ_d is calculated by using φ_c,

$$\varphi_d = \varphi_s - \varphi_c - m\varphi_{\text{abs}}$$

where, φ_s is the synchronous phase in input, φ_{abs} is absolute phase in front of the rf cavity, and m is the harmonic number.

CHAPTER

FOUR

CLASS LIBRARY

4.1 Machine class

class Machine(*config*)

FLAME Machine class for Python API.

Parameter config: dict, list of tuples, or byte buffer

Input lattice data.

conf(*index=None*)

Check configuration of the Machine object.

Parameter index: int (optional)

Index of the lattice element.

Returns

dict

Configuration of the lattice element

Note: In the case of `index` is *None*, `conf()` returns *initial* configuration of the lattice.

allocState(*config=None*)

Allocate the beam state object.

Parameter config : dict

Input lattice data. Empty dict is required as dummy data.

Returns

`State` object

Beam state object (see here)

`propagate`(*state*, *start=0*, *max=-1*, *observe=None*)

Run envelope tracking simulation.

Parameters **state**: `State` object

Allocated beam state object

start: int (optional)

Index of the starting lattice element.

max: int (optional)

Index of the max (ending) lattice element. It propagates to the entrance of the max-th element.

observe: list of int (optional)

List of indexes for observing the beam state.

Returns

list

List of the beam states at `observe` points. Each tuple has (*index*, *State*).

`reconfigure`(*index*, *config*)

Reconfigure the lattice element configuration.

Parameters **index**: int

Index of the lattice element.

config: dict

New configuration of the lattice element parameter.

`find`(*name=None*, *type=None*)

Find the indexes of the lattice elements by *name* or *type*.

Parameter **name**: str or unicode

Name of the lattice element to find.

type: str or unicode

Type of the lattice element to find.

Returns

list

List of matched element indexes.

4.2 State Class

class State(*object*)

FLAME beam state class for Python API.

clone()

Clone the beam state object.

Returns *State* object

- **Attributes - reference beam**

pos	z position [m]
ref_beta	Lorentz β [1]
ref_bg	Lorentz $\beta\gamma$ [1]
ref_gamma	Lorentz γ [1]
ref_IonEk	Kinetic energy [eV/u]
ref_IonEs	Nucleon mass [eV/u]
ref_IonQ	Macro weight [1]
ref_IonW	Total energy [eV/u]
ref_IonZ	Charge to mass ratio [1]
ref_phis	Absolute phase [rad]
ref_SampleIonK	Phase speed [rad]
last_caviphi0	Driven phase of the last rf cavity [deg]

- **Attributes - actual beam**

beta	Lorentz β [1]
bg	Lorentz $\beta\gamma$ [1]
gamma	Lorentz γ [1]
IonEk	Kinetic energy [eV/u]
IonEs	Nucleon mass [eV/u]
IonQ	Macro weight [1]
IonW	Total energy [eV/u]
IonZ	Charge to mass ratio [1]
phis	Absolute phase [rad]
SampleIonK	Phase speed [rad]
moment0	Centroids of the all charge states.
moment0_env	Weighted average of centroids for the all charge states.
moment0_rms	Weighted average of rms size for the all charge states.
moment1	Envelope matrixes of the all charge states.
moment1_env	Weighted average of envelope matrixes for the all charge states.

pos

float: z position of the reference beam. [m]

ref_beta

float: Lorentz β of the reference beam. [1]

ref_bg

float: Lorentz $\beta\gamma$ of the reference beam. [1]

ref_gamma

float: Lorentz γ of the reference beam. [1]

ref_IonEk
float: Kinetic energy of the reference beam. [eV/u]

ref_IonEs
float: Nucleon mass of the reference beam. [eV/u]

ref_IonQ
float: Macro weight of the reference beam. [1]

ref_IonW
float: Total energy of the reference beam. [eV/u]

ref_IonZ
float: Charge to mass ratio of the reference beam. [1]

ref_phis
float: Absolute synchrotron phase of the reference beam. [rad]

ref_SampleIonK
float: Phase speed of the reference beam. [rad]

last_caviphi0
float: Driven phase of the last rf cavity. [deg]

beta
list of float: Lorentz β of the all charge states. [1]

bg
list of float: Lorentz $\beta\gamma$ of the all charge states. [1]

gamma
list of float: Lorentz γ of the all charge states. [1]

IonEk
list of float: Kinetic energy of the all charge states. [eV/u]

IonEs
list of float: Nucleon mass of the all charge states. [eV/u]

IonQ
list of float: Macro weight of the all charge states. [1]

IonW
list of float: Total energy of the all charge states. [eV/u]

IonZ
list of float: Charge to mass ratio of the all charge states. [1]

phis
list of float: Absolute synchrotron phase of the all charge states. [rad]

SampleIonK
list of float: Phase speed of the all charge states. [rad]

moment0
Centroids of the all charge states.

list of vector[7]: $[x, x', y, y', \phi, E_k, 1]$ with [mm, rad, mm, rad, rad, MeV/u, 1].

moment0_env
Weighted average of centroids for all charge states.

vector[7]: $[x, x', y, y', \phi, E_k, 1]$ with [mm, rad, mm, rad, rad, MeV/u, 1].

`moment0_rms`

Weighted average of rms beam envelopes (2nd order moments) for the all charge states.

vector[7]: rms of $[x, x', y, y', \phi, E_k, 1]$ with [mm, rad, mm, rad, rad, MeV/u, 1].

`moment1`

Envelope matrixes of the all charge states.

list of matrix[7,7]:

Cartisan product of $[x, x', y, y', \phi, E_k, 1]^2$ with [mm, rad, mm, rad, rad, MeV/u, 1] ^{2}.

`moment1_env`

Weighted average of envelope matrixes for the all charge states.

matrix[7,7]:

Cartisan product of $[x, x', y, y', \phi, E_k, 1]^2$ with [mm, rad, mm, rad, rad, MeV/u, 1] ^{2}.

CHAPTER FIVE

INDICES

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