Magnetic Field Optimization for Isochronous Cyclotron

using OPAL-cycl

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OPAL off kai

Objective

- Design isochronous field with a iron-less coil system.

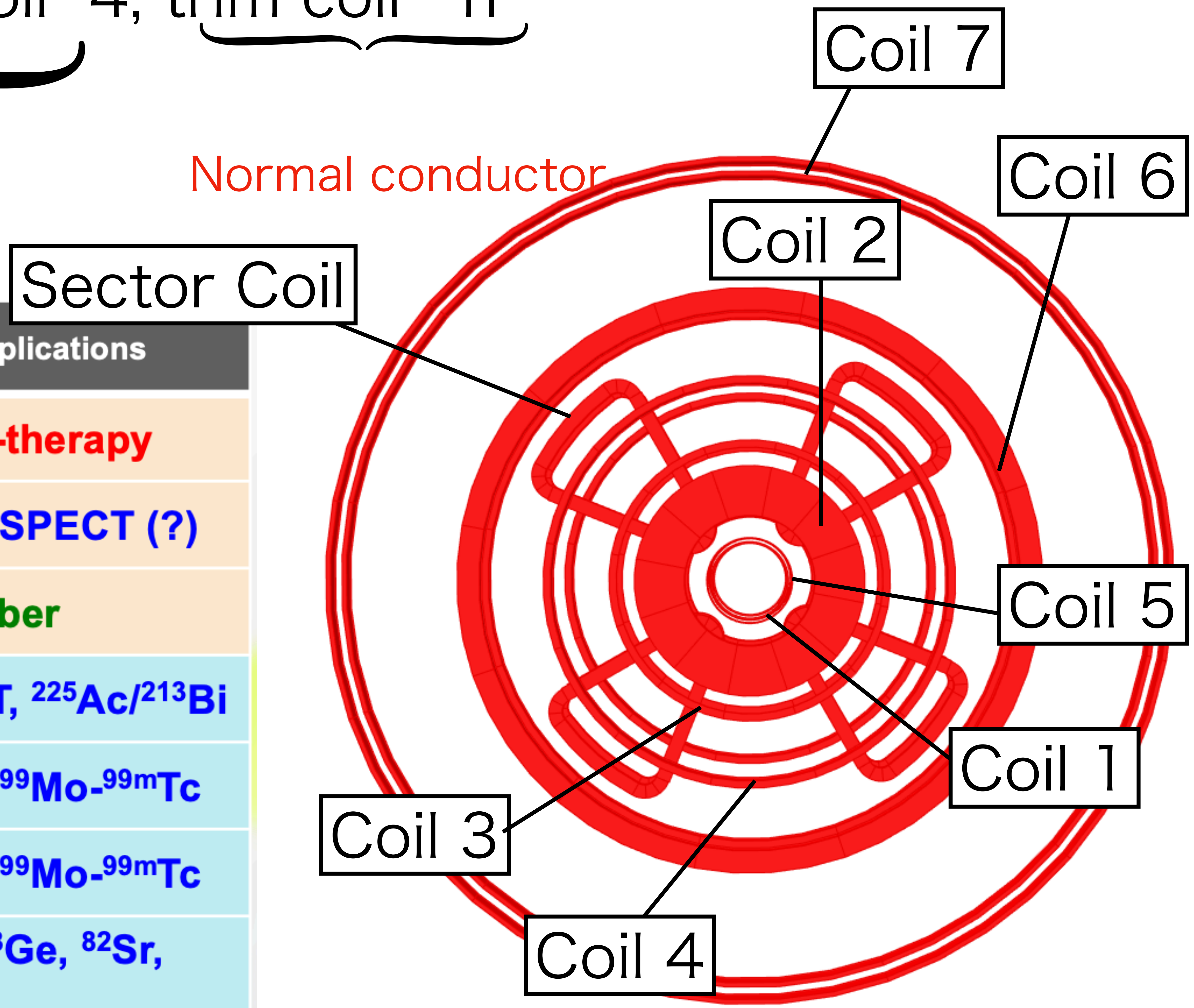
→decide current on Main coil *7, Sector coil *4, trim coil * n

Super conductor

Normal conductor

Beam we want to accelerate

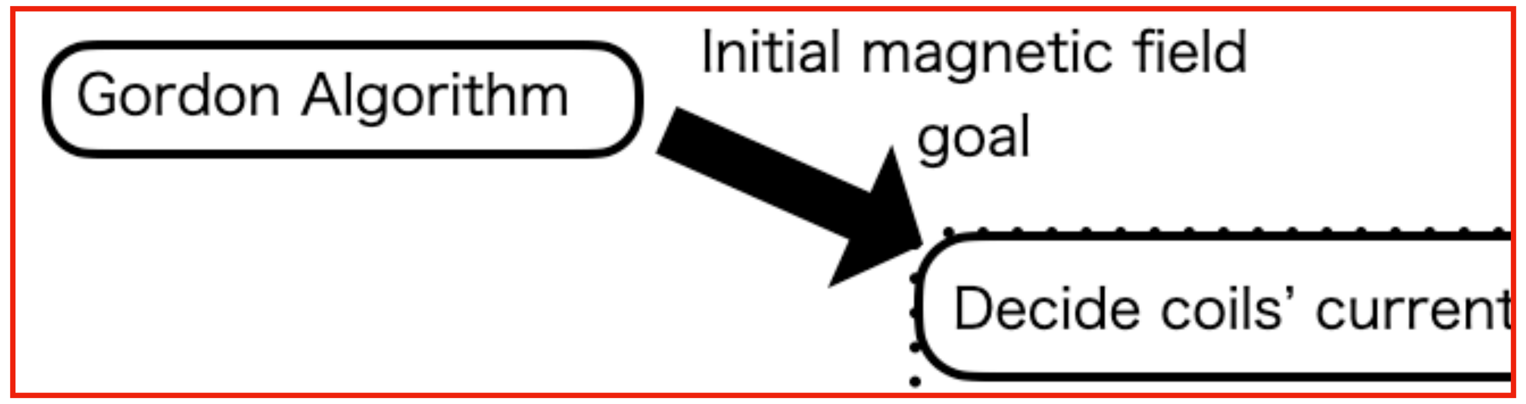
Ion	Energy (MeV)	B_{av} (T) @50cm	B_0 (T) @center	f_{RF} (MHz)	h	Applications
$^4He^{2+}$	36	1.732	1.715	26.344	2	^{211}At α-therapy
$^4He^{2+}$	40	1.826	1.806	27.747	2	^{210}At γ-SPECT (?)
$^4He^{2+}$	80	2.589	2.534	38.931	2	K-number
H^-/H^+	18	1.232	1.209	36.856	2	PET-CT, ^{225}Ac/^{213}Bi
H^+	30	1.596	1.546	47.140	2	BNCT, ^{99}Mo-^{99m}Tc
H^+	50	2.071	1.966	59.937	2	BNCT, ^{99}Mo-^{99m}Tc
H^+	70	2.461	2.290	69.872	2	^{22}Na, ^{68}Ge, ^{82}Sr, etc.
D^+／H_2^+	40	2.589	2.534	38.798	2	^{99}Mo-^{99m}Tc, BNCT



(trun coil omited)

Method

Gordon Algorithm
Initial magnetic field goal
Decide coils' current with least square method
OPERA-3D
magnetic field
OPAL- orbit finder
E_0, r_0 for closed orbit
"Auto analyze" using OPAL-cycl
SEO calculation for every 1 MeV
Obtain : $\nu_r, \nu_z, r_{avg}, B_{avg}, B_{error}$
Modify current according to B_{error}
Loop
Optimized field, with $B_{error} < 0.1\,\%$



Gordon Algorithm

CALCULATION OF ISOCHRONOUS FIELDS FOR SECTOR-FOCUSED CYCLOTRONS†

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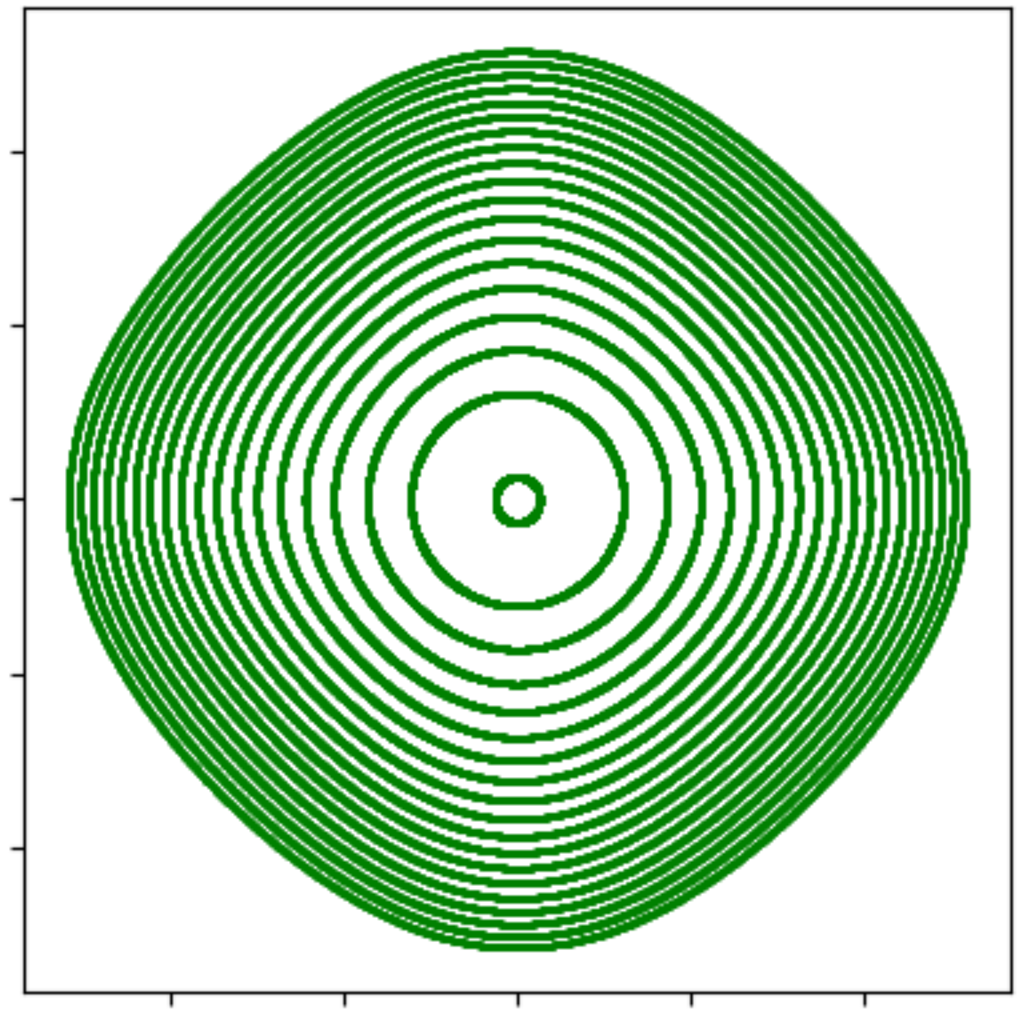
(*Received October 14, 1982*)

- **Beam orbit is not circle** in isochronous cyclotron.

  →simply modifying magnetic field with γ factor doesn't give a isochronous field.

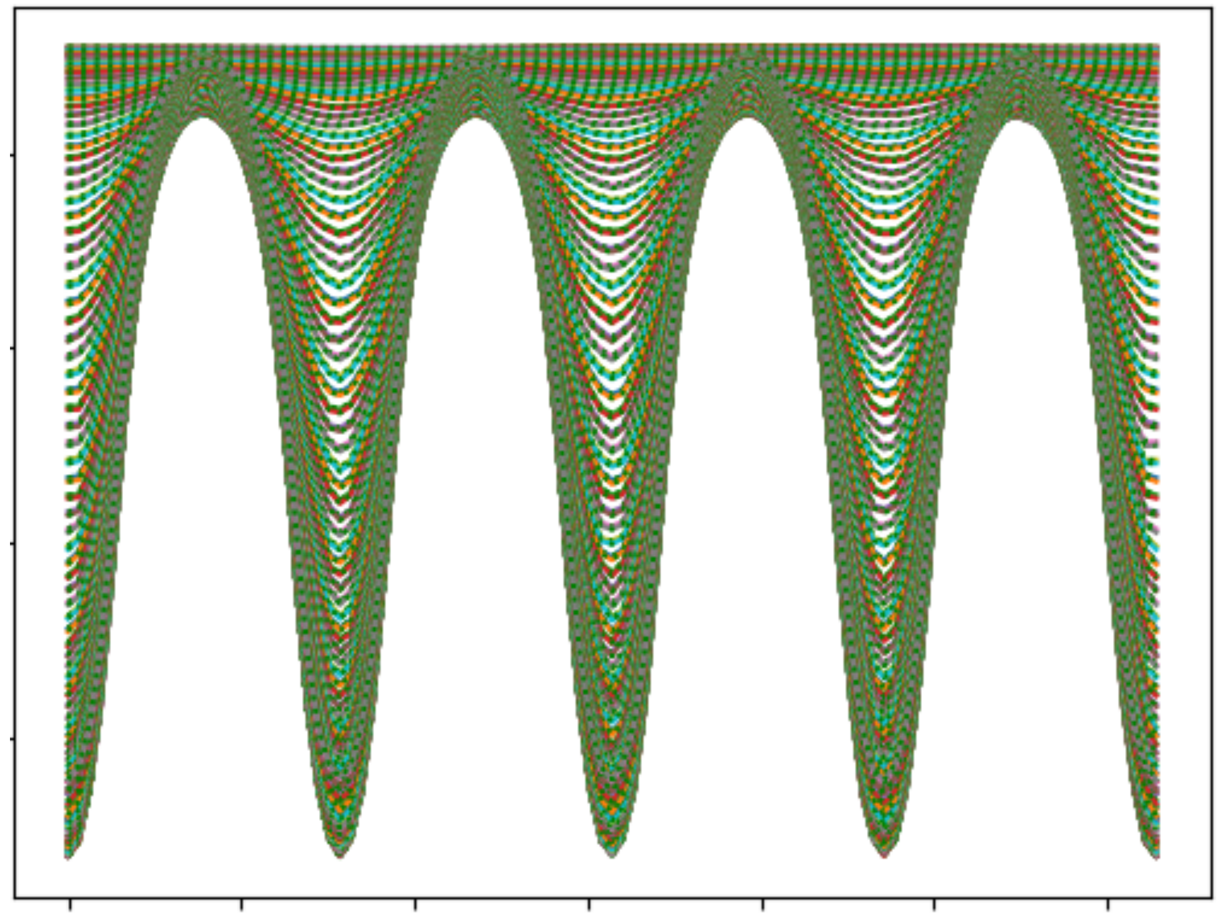


Gordon Algorithm,

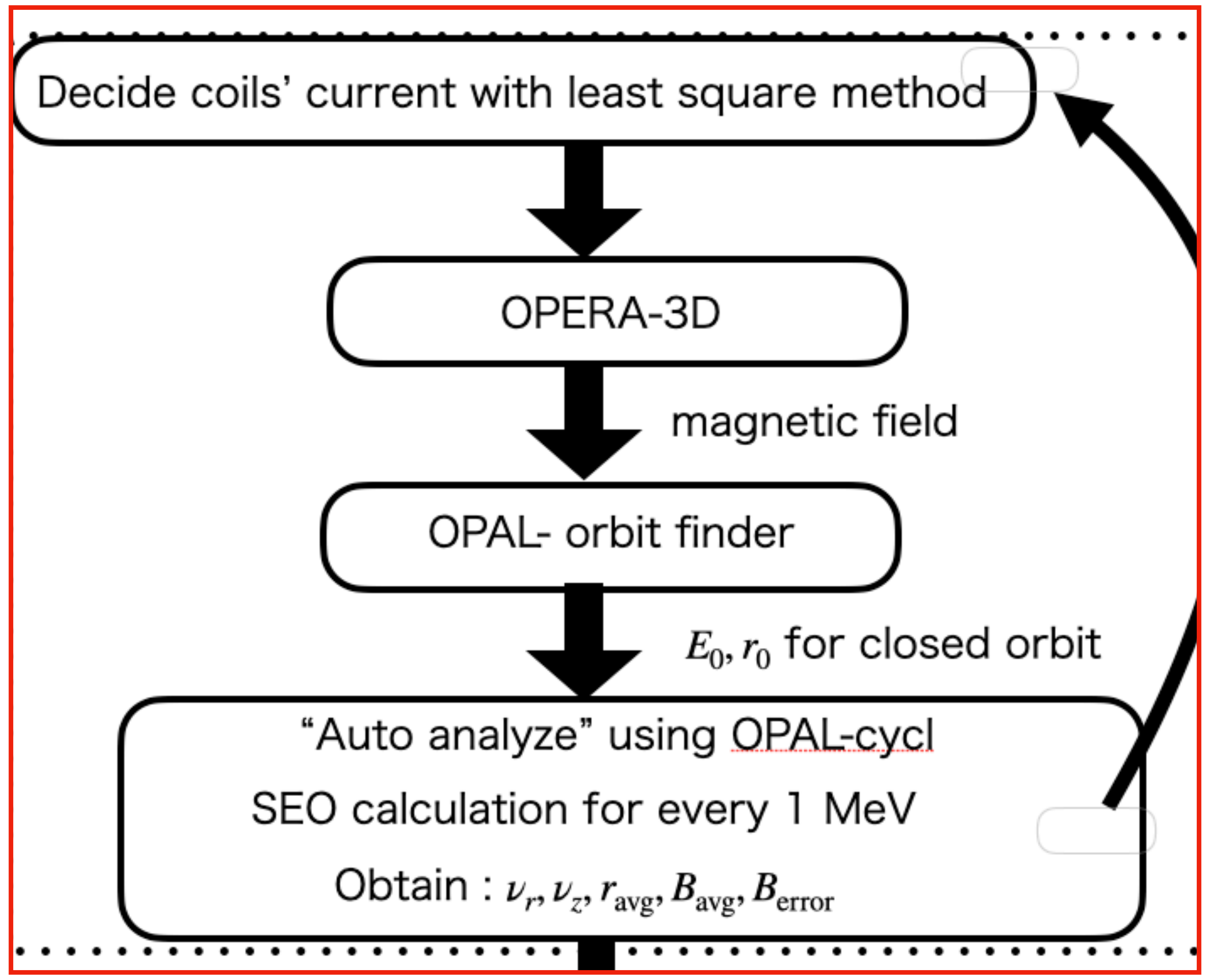
Needed : Fourier coefficient of sector field in each r.

Get: $B(r)$ profile that **produce isochronous field on beam orbit**.

Fourier transformation of sector field.

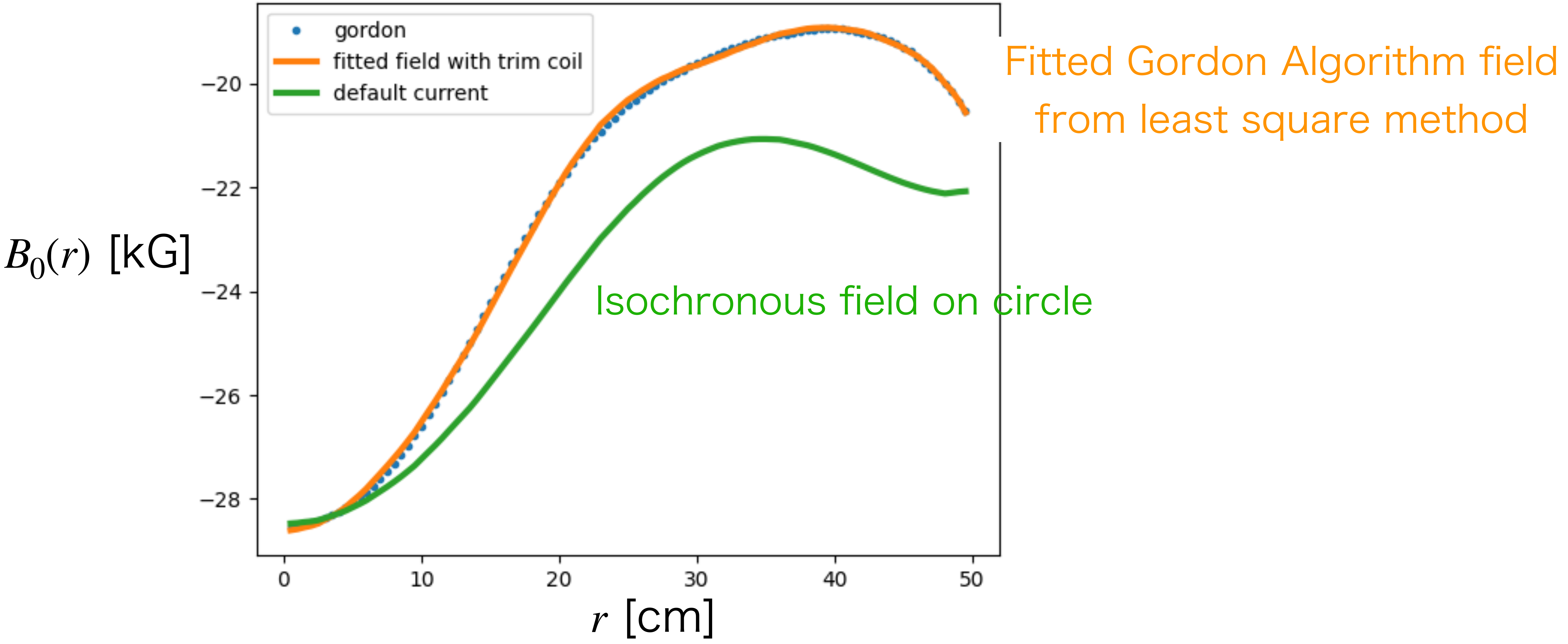


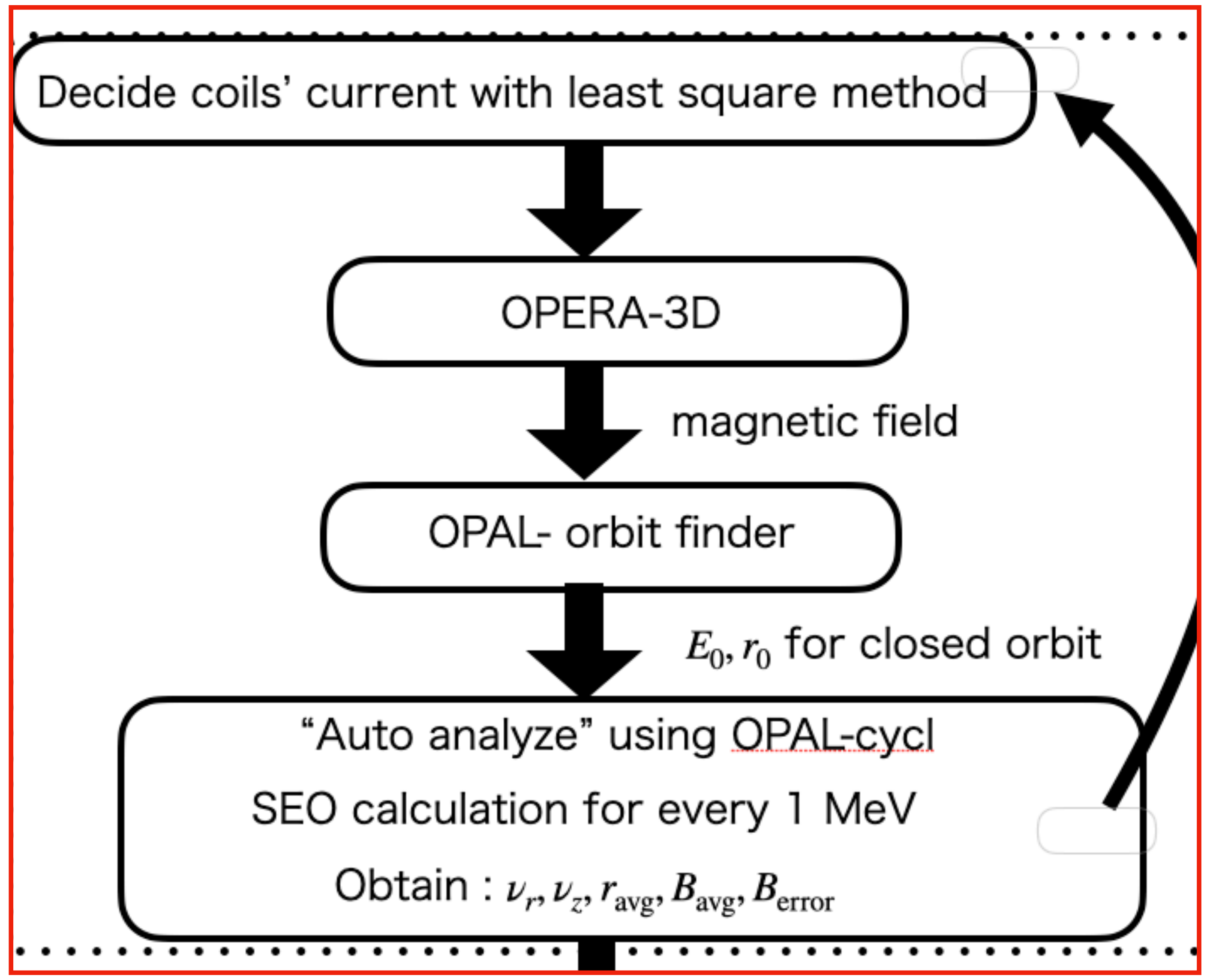
Deciding coils' current



- Realizing $B(r)$ from Gordon Algorithm with **least square fitting method.**

$B(r)$ profile, (sector field not include)





Orbit finder

- Calculating magnet field $B(r, \theta)$ with OPERA 3D.

Orbit finder

Needed : Magnetic field $B(r, \theta)$

Get: E_0, r_0 that make closed orbit.

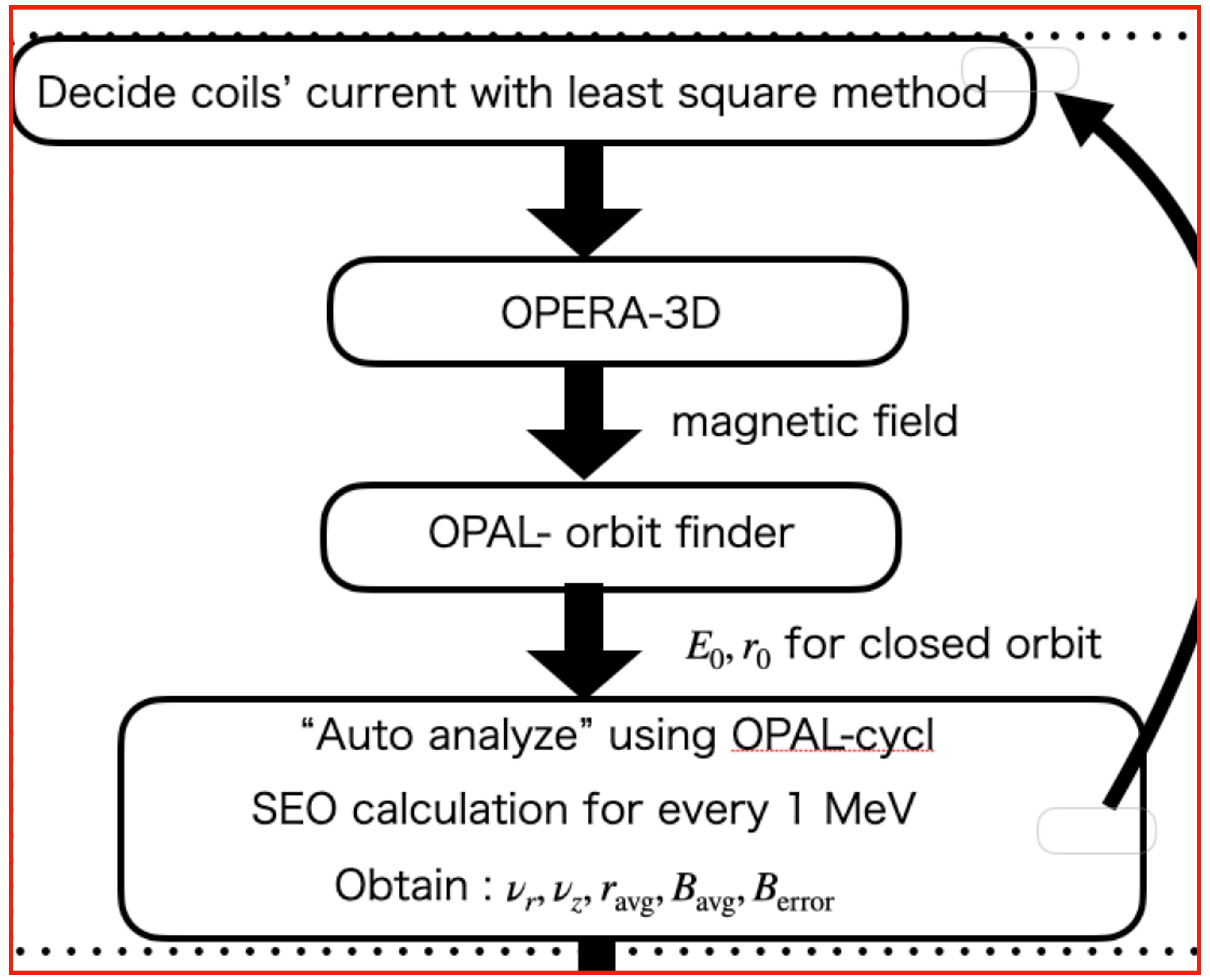
ν_z, ν_r of each orbit.

Input file

```
OPTION, VERSION=20000;

OPTION, ECHO=FALSE;
OPTION, PSDUMPFREQ=24500000;
OPTION, SPTDUMPFREQ=50;
OPTION, PSDUMPEACHTURN=FALSE;
OPTION, PSDUMPFRAME=GLOBAL;

// For Tune Calculation
OPTION, CLOTUNEONLY=TRUE;

TITLE, STRING= "PSI Ring";

REAL Edes = 50.0e-6;    // GeV
```

Output file

# energy[MeV]	radius_ini[m]	momentum_ini[Beta Gamma]	radius_avg[m]	nu_r	nu_z
0.05	0.0260199	1.50918e-07	0.0260196	0.998346	0.0574983
1.05	0.122661	-7.78423e-07	0.12216	0.992002	0.154508
2.05	0.172817	-1.52704e-07	0.170809	1.01508	0.132365
3.05	0.211656	-7.79641e-06	0.207773	1.02	0.237214
4.05	0.244705	-2.8074e-06	0.238936	1.02311	0.302996
5.05	0.274152	4.48786e-06	0.266575	1.0311	0.330884
6.05	0.300499	-2.40562e-05	0.291254	1.03672	0.354115



Orbit finder

Output file

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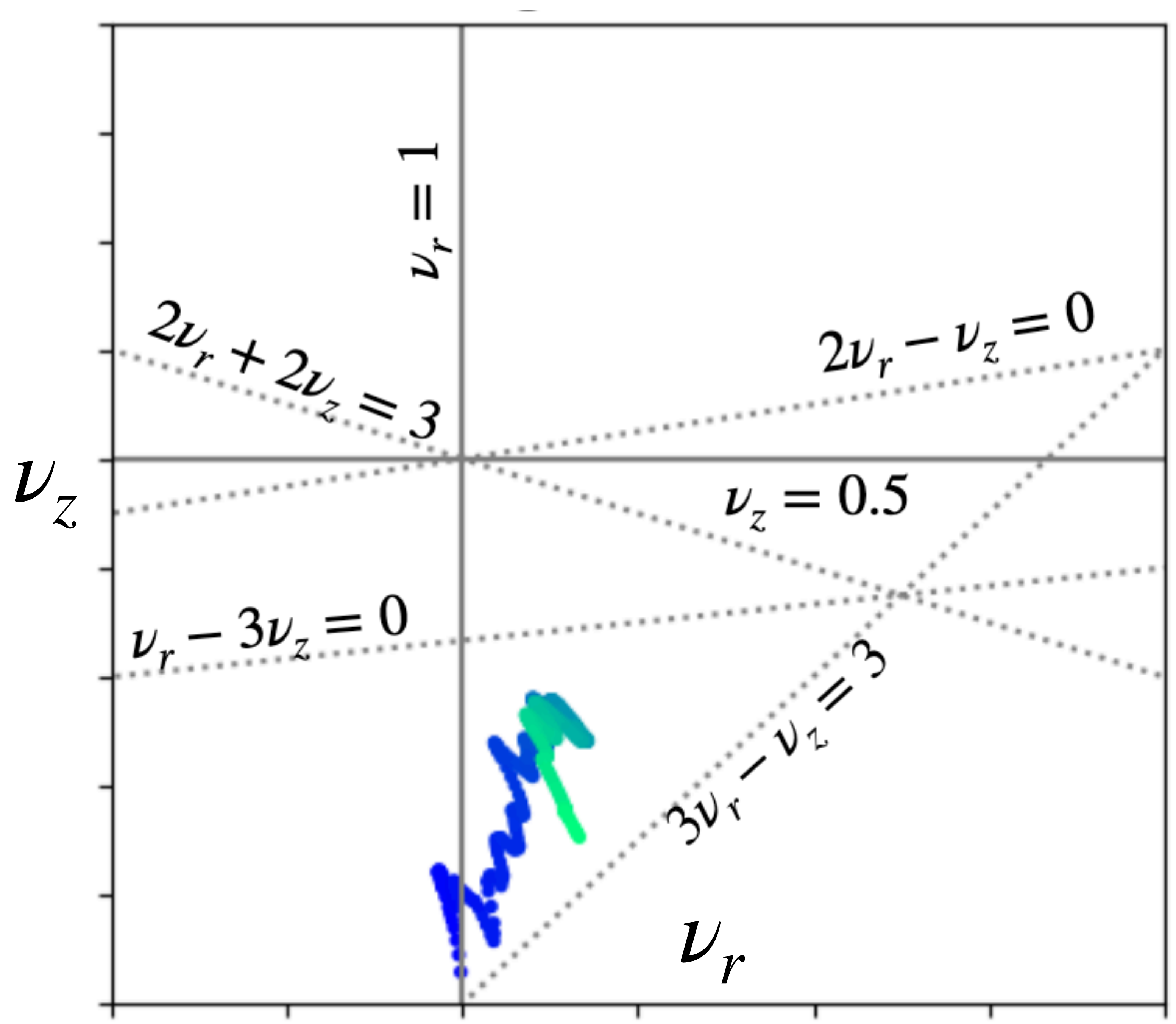
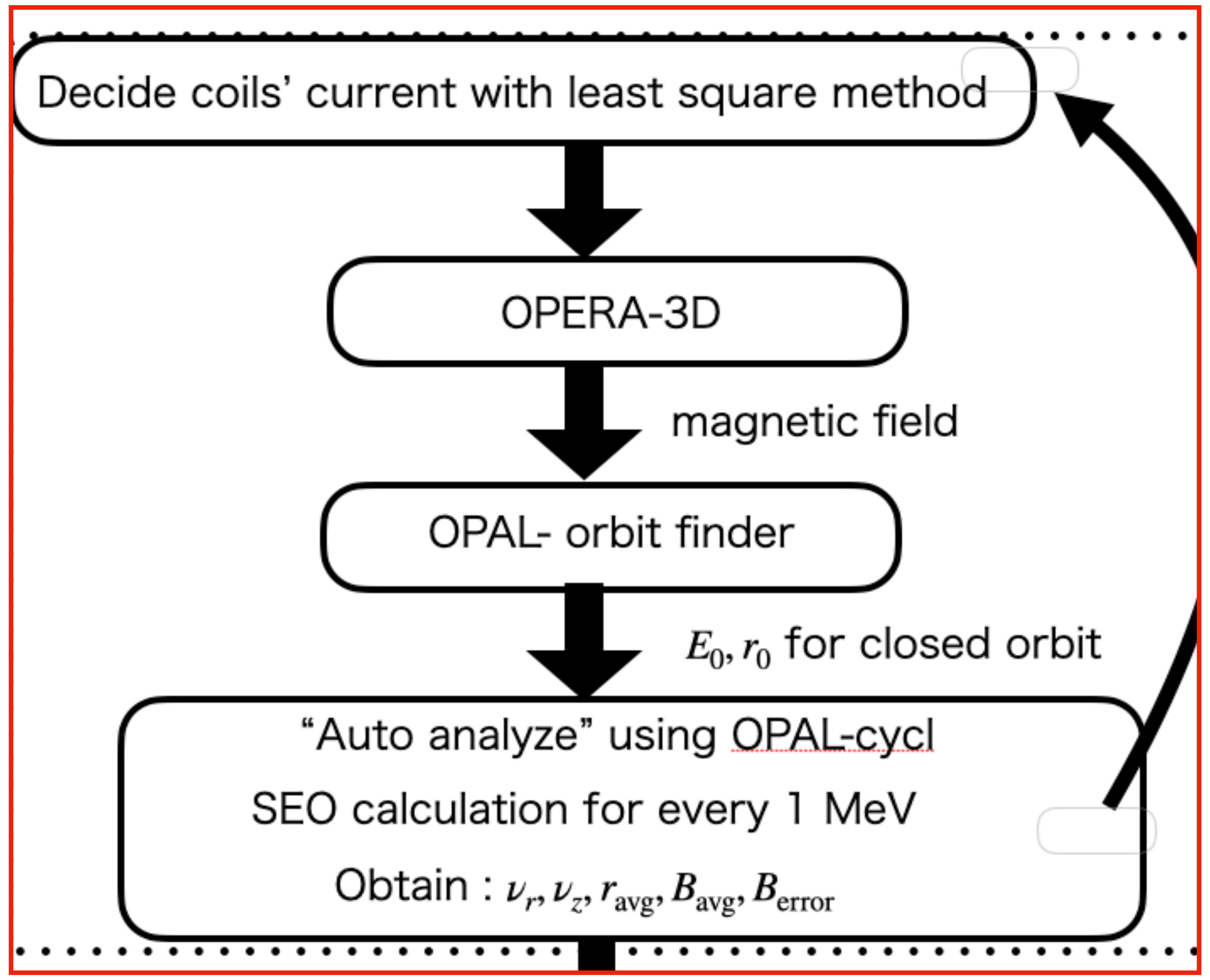
- From the output file, tune diagram can be plotted.
- Decide if sector field (flutter) is enough from ν_z





"Auto analyze"

- with $B(r,\theta), r_0, E_0$ in hands, the quality of closed orbits and magnetic field can be analyzed with OPAL-cycl.

  →Different r_0, E_0 for each calculation.

  →**one orbit per calculation**. Not so efficient.

Auto Analyze (all done in python)

① create r_0, E_0 input file "data.txt"

② start opal calculation with **subprocess module**, with CALL,FILE in input file

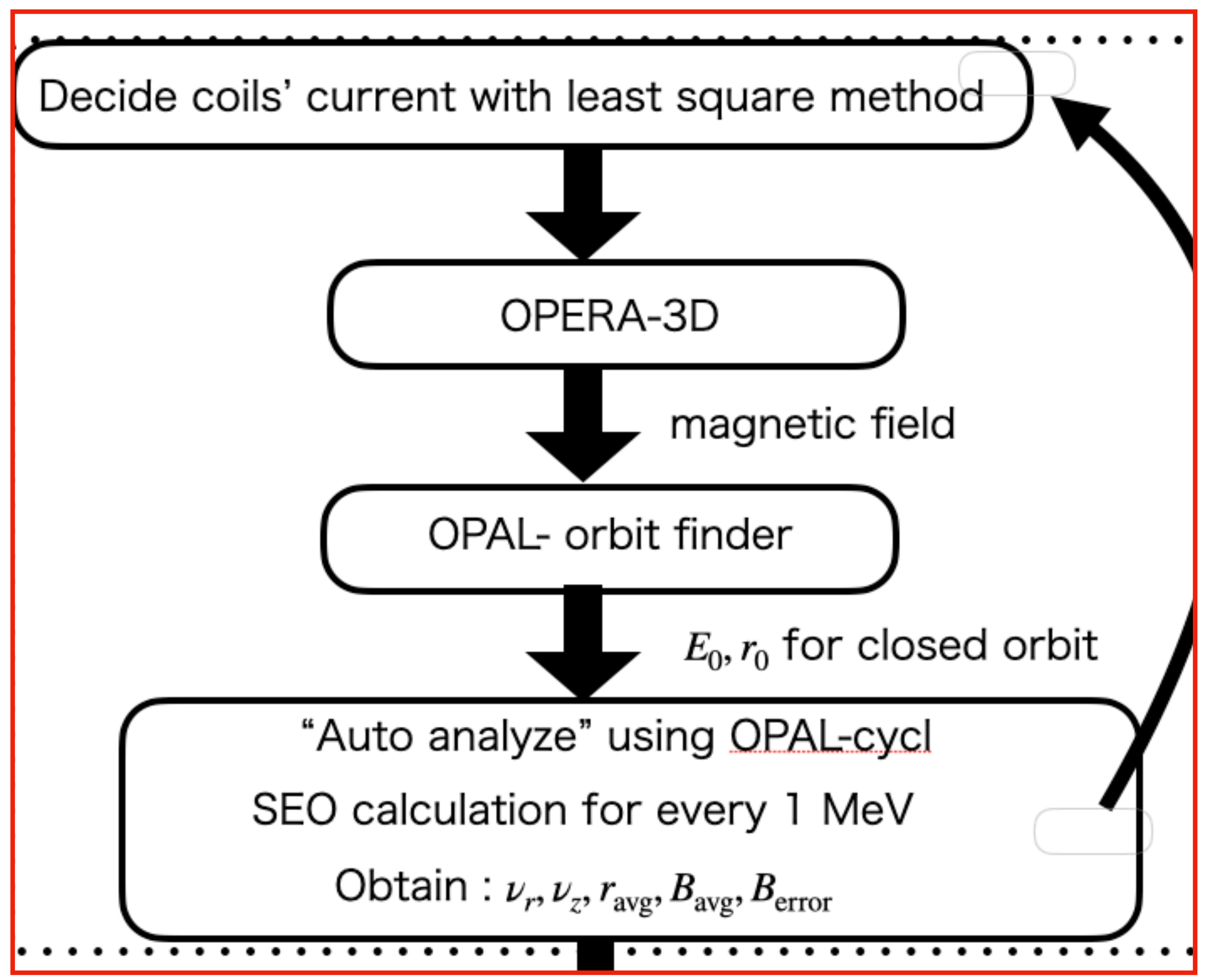
③ accumulate $B_{\mathrm{particle}}, E, x(t), y(t)\cdots$ from .stat to output file.

Repeat ①②③ for all closed orbit E_0, r_0

data.txt

```
REAL EBEAM = 0.040049999999999995;
REAL r0 = 515.402;
```

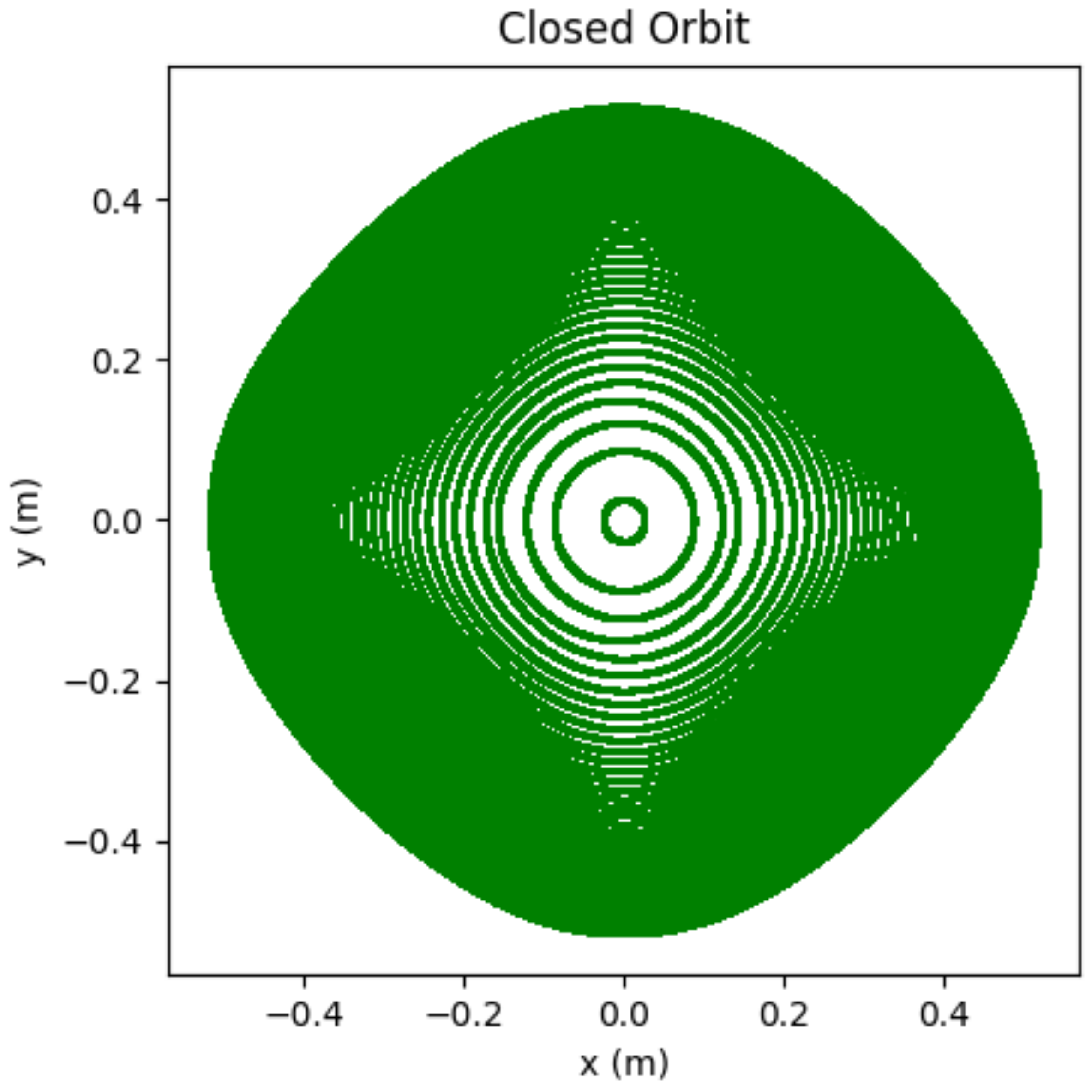
```
CALL,FILE= "data.txt";
//-----------------------------------------
//                                     Phys
//-----------------------------------------
//REAL Ebeam                  =.0008685;
//REAL Ebeam                  =0.14e-3;
REAL gamma                   =(Ebeam+DMASS)/
```

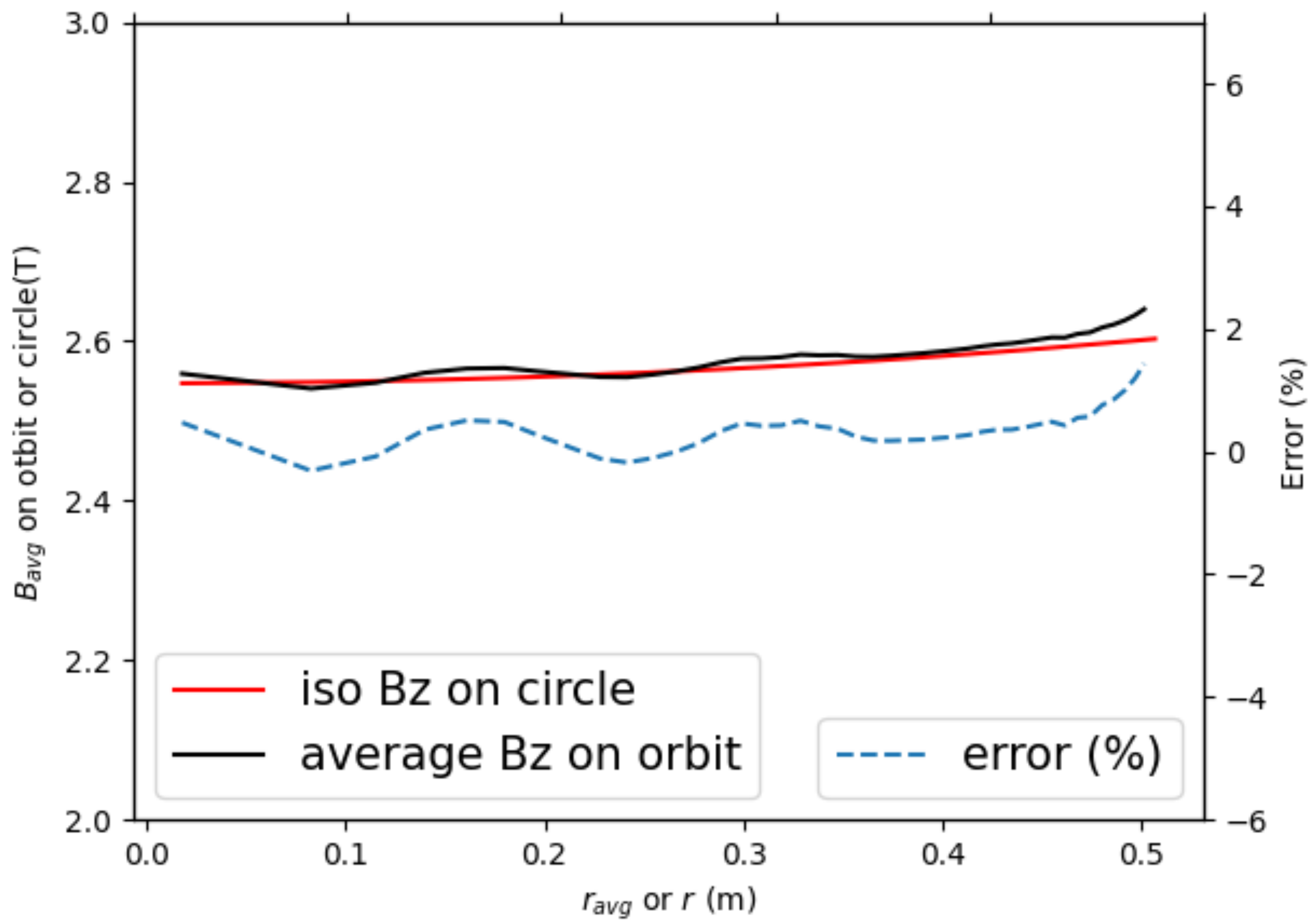


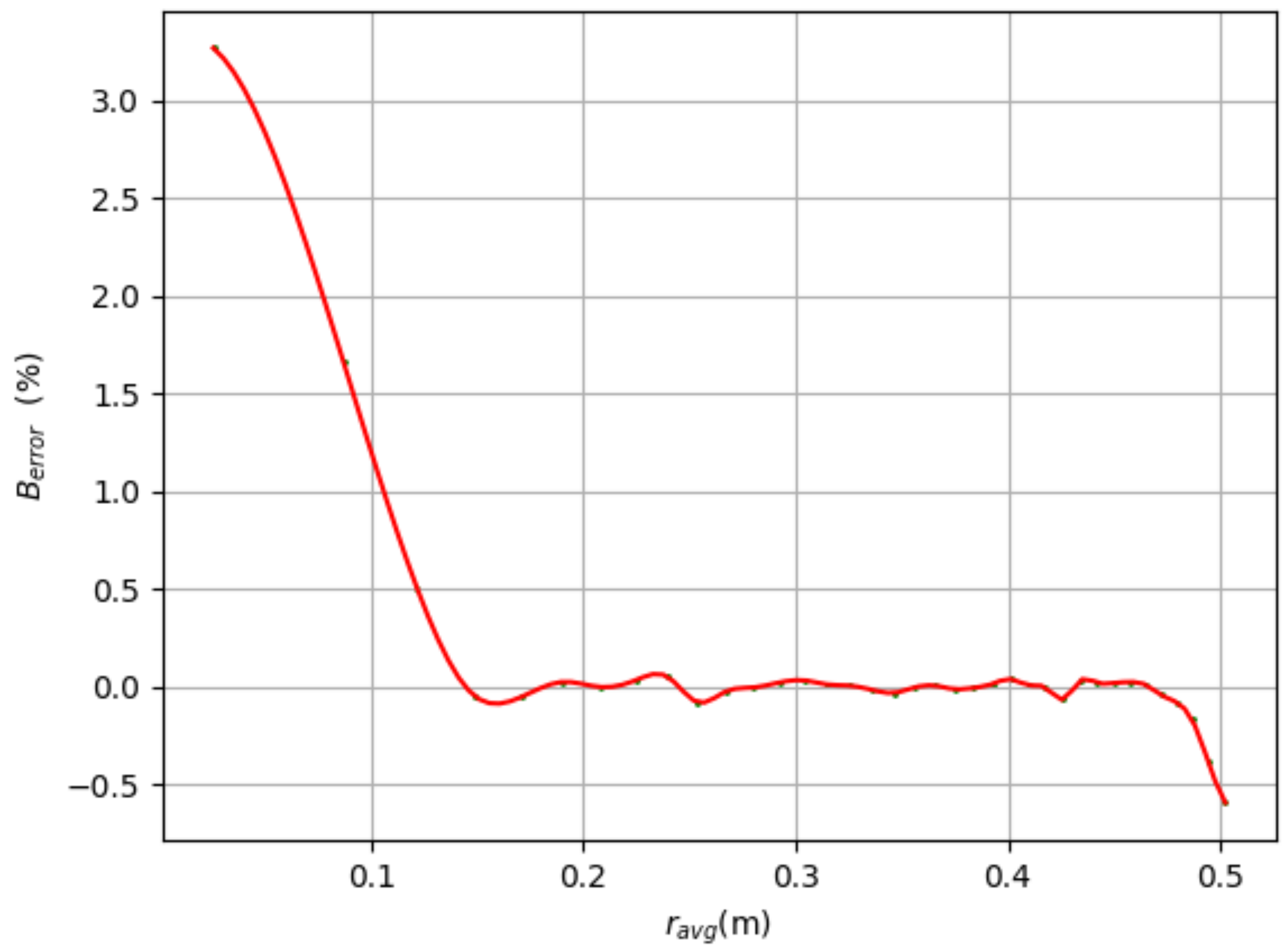
"Auto analyze"

- With $B_{\text{particle}}, E, x(t), y(t)\cdots$ of each closed orbit in hands,

  Useful data like $B_{\text{avg}}, r_{\text{avg}}, F^2, B_{\text{error}}$ can be obtained.

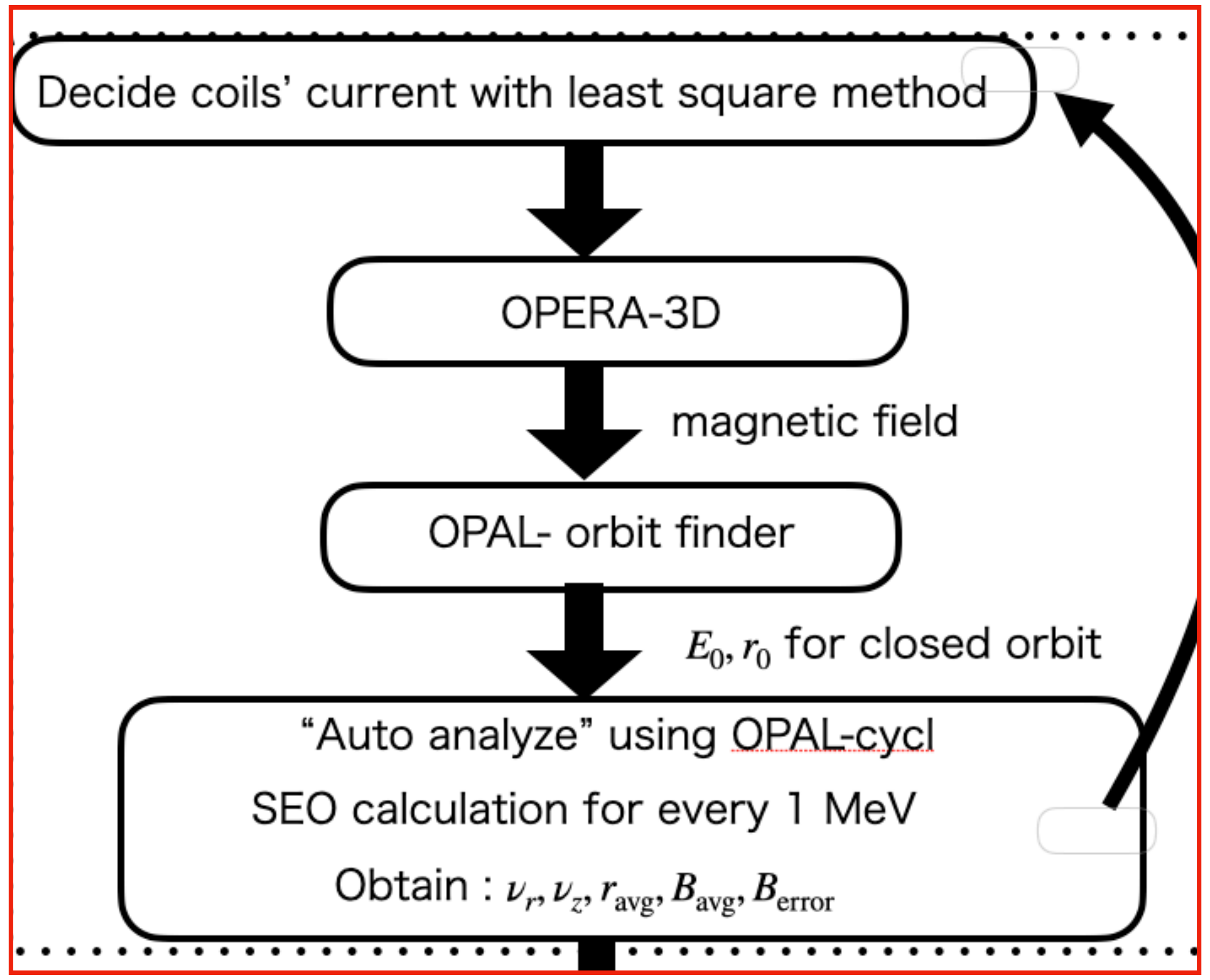




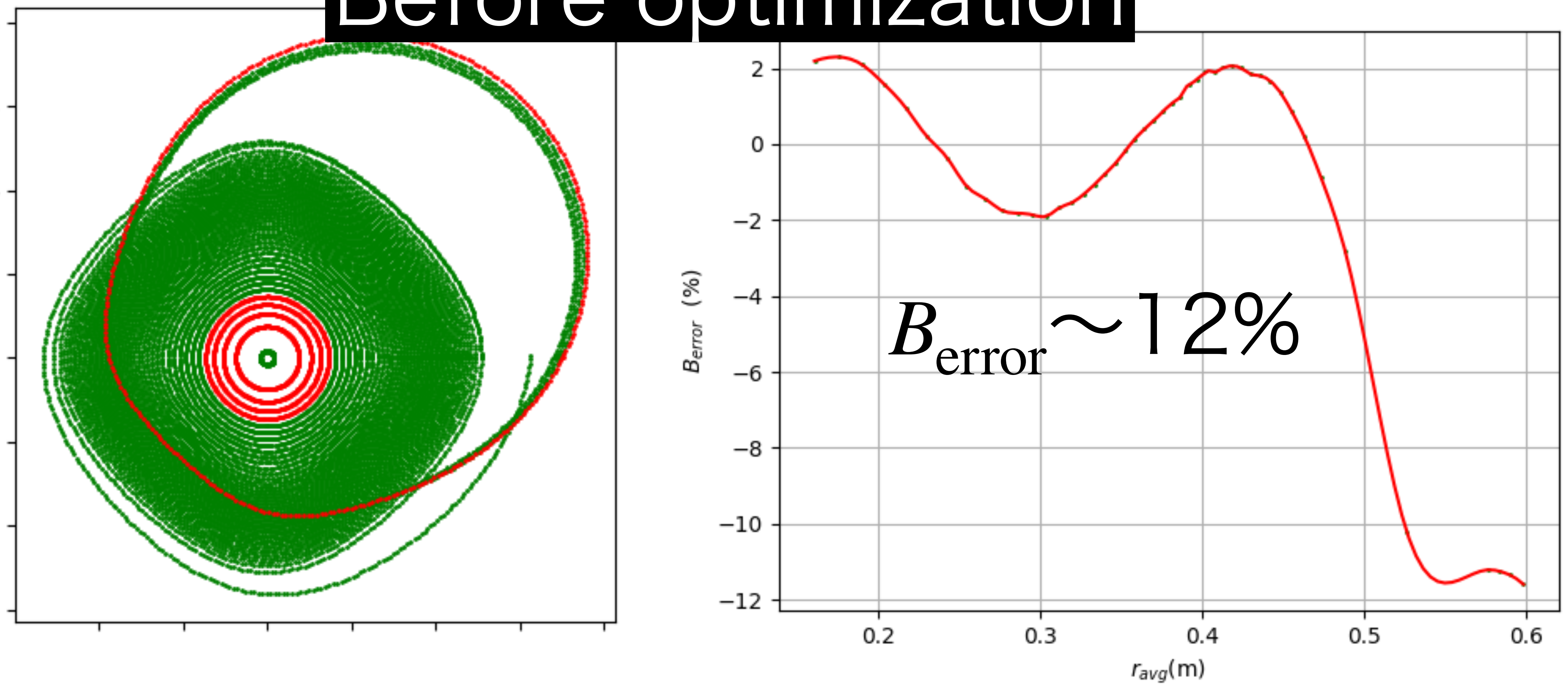


→With B_{error}, modify the "goal" of least square fitting.

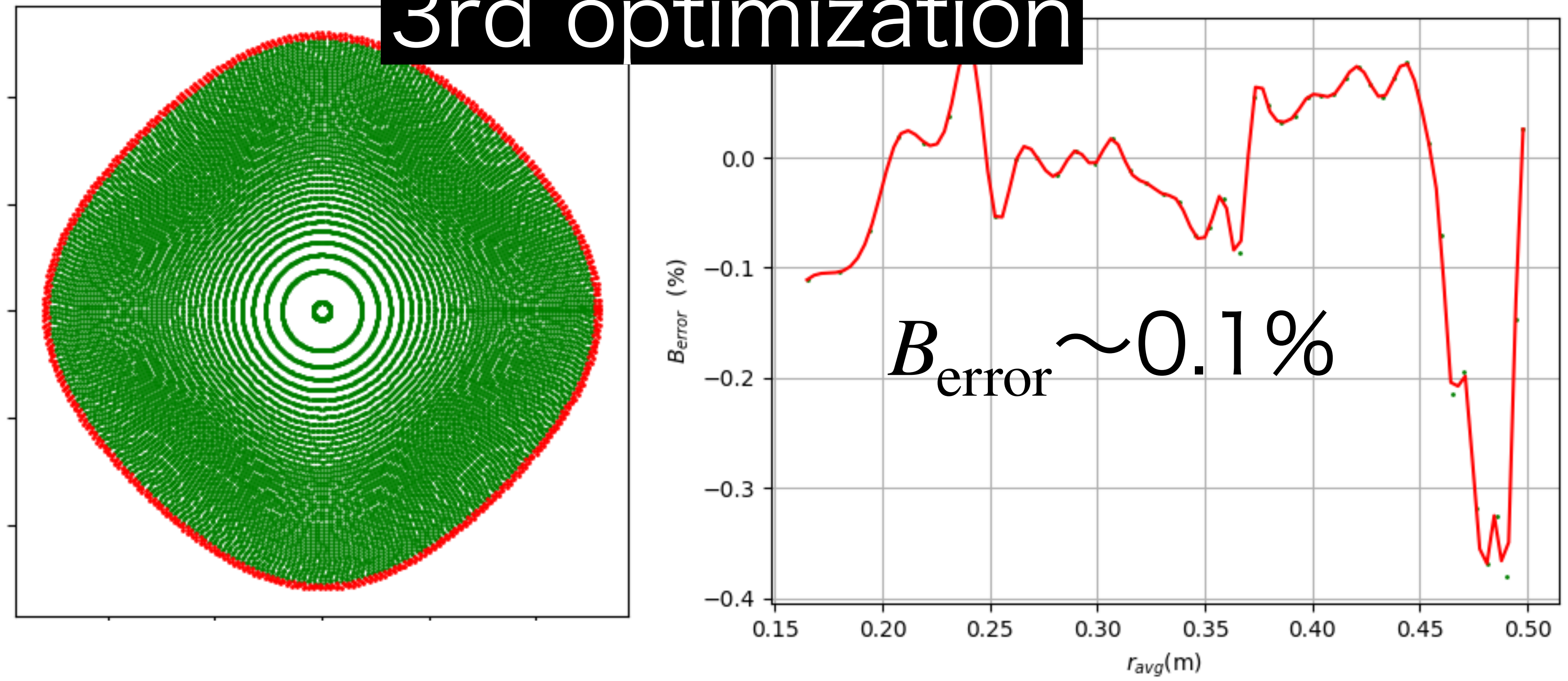
Example of optimization



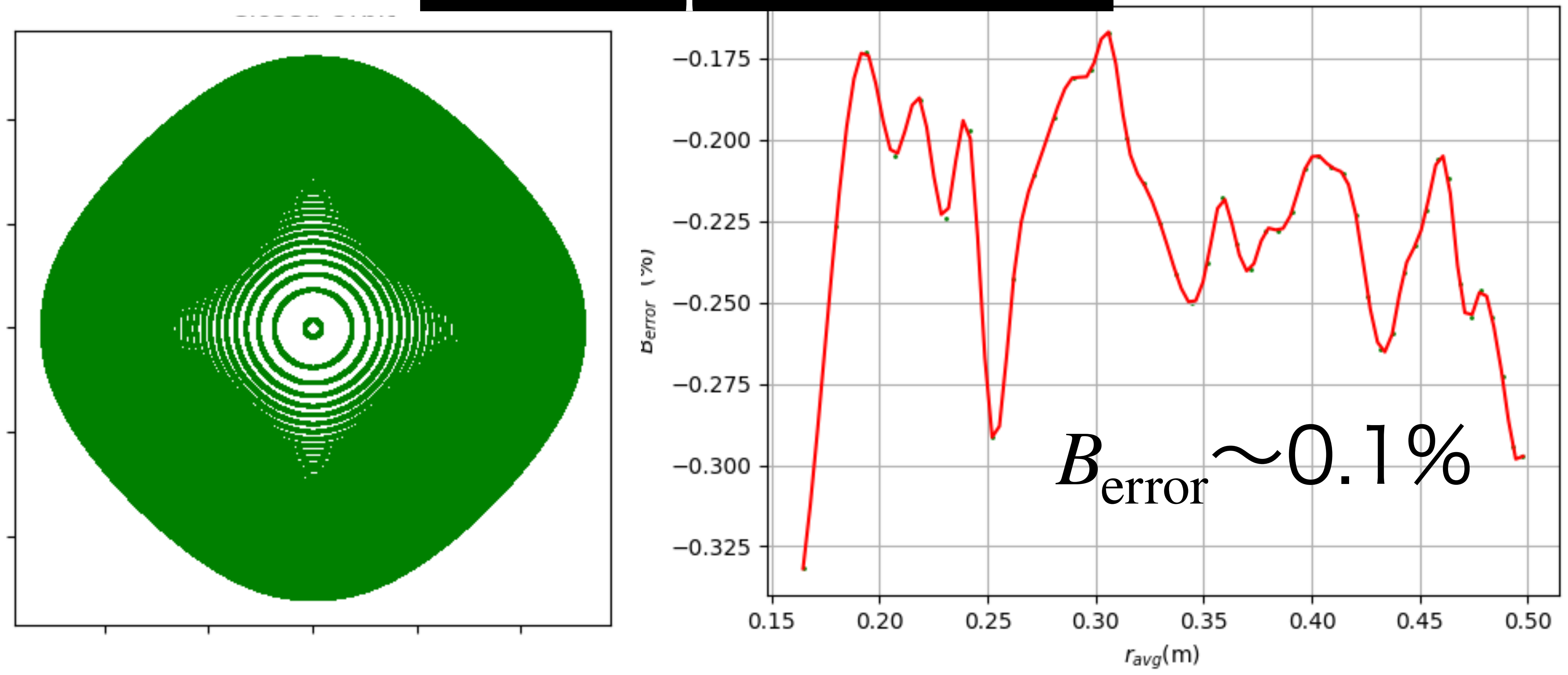
Before optimization



3rd optimization



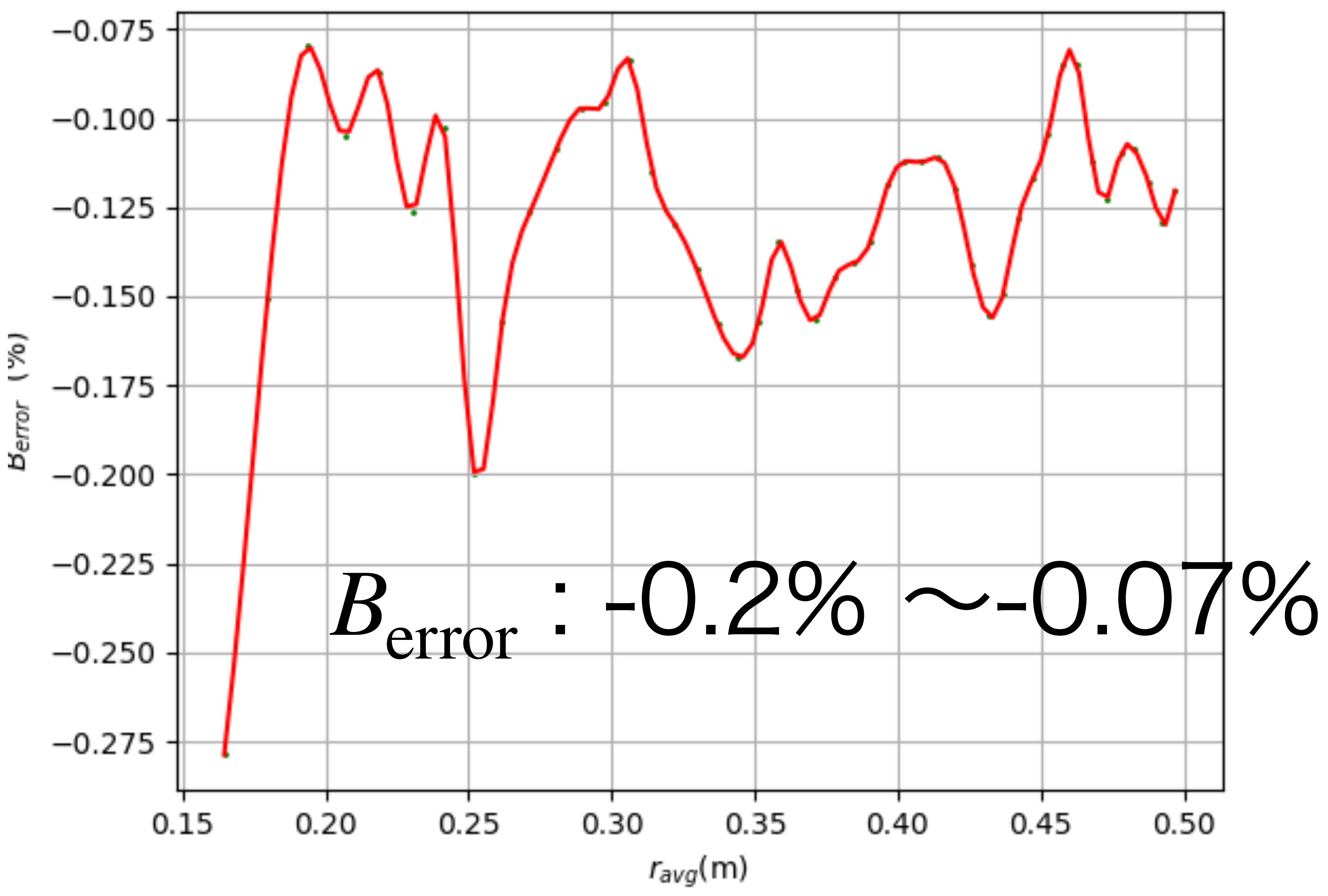
12st optimization

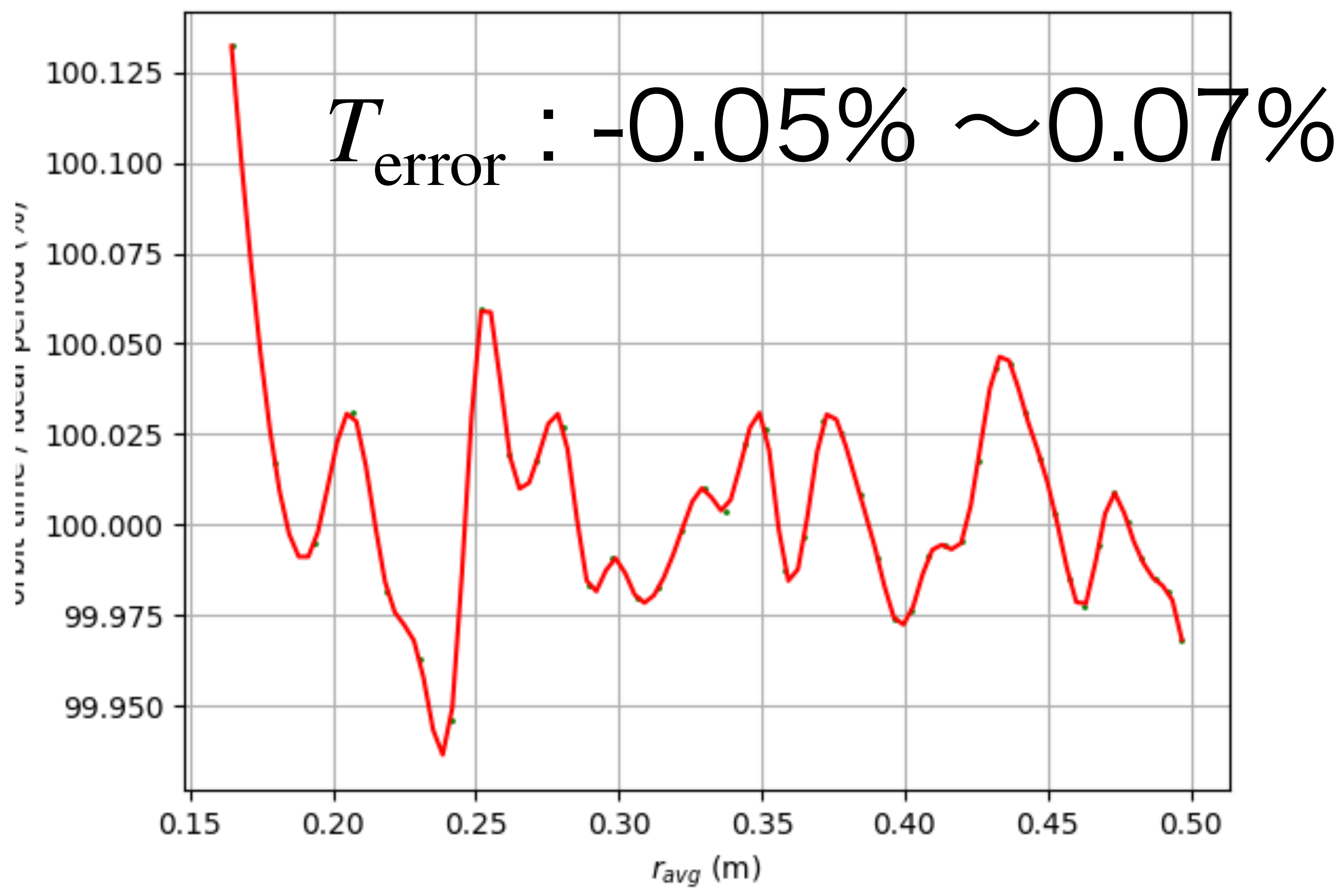


- Calculation time, accuracy depends on **nstep** in OPAL file.

Some problems

- Using a same magnet field, analyze result T_{error} and B_{error} is different.





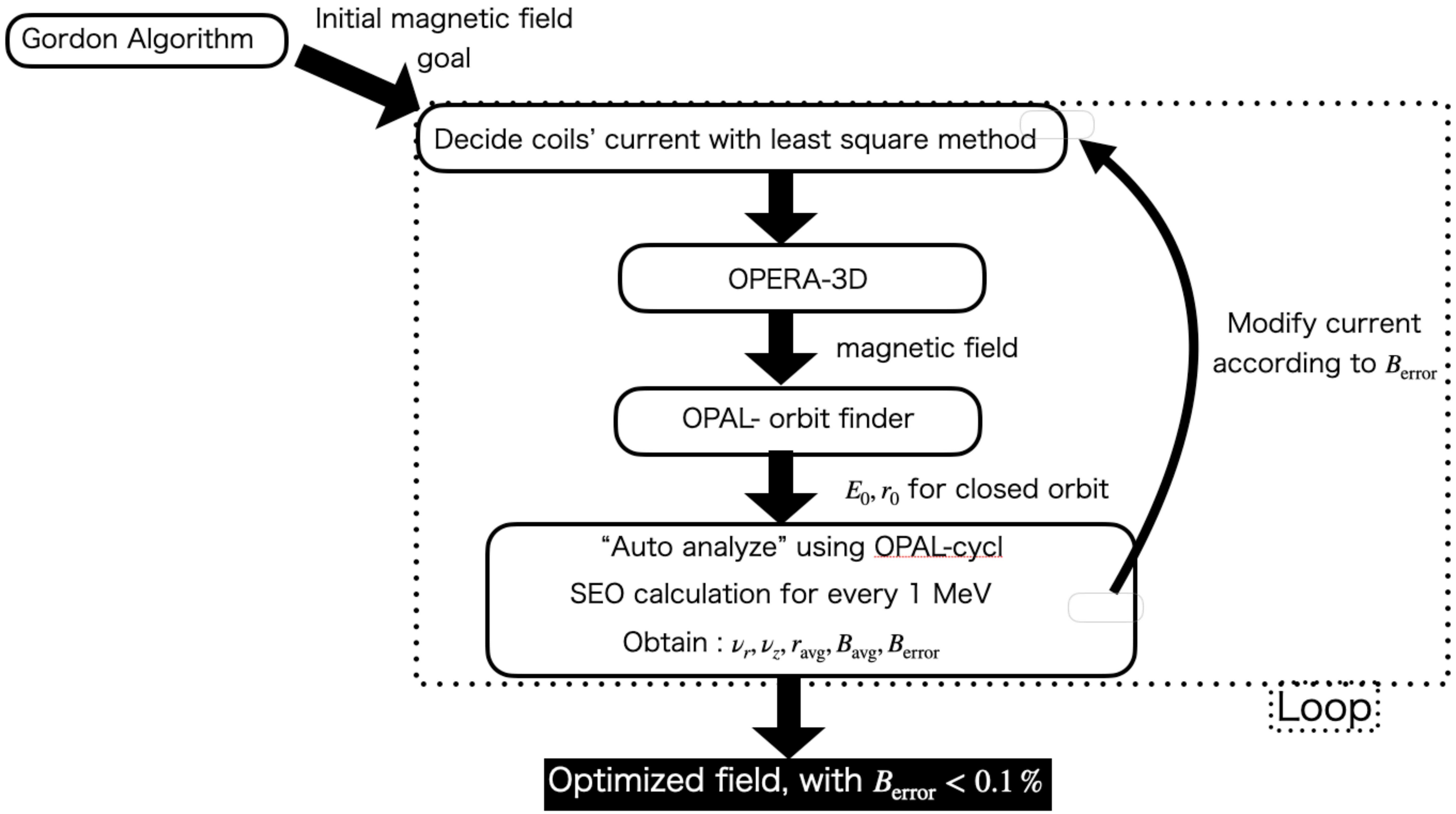
- One need to choose between minimizing B_{error} or T_{error}

- Minimizing T_{error} seems better, according to AEO calculation result.

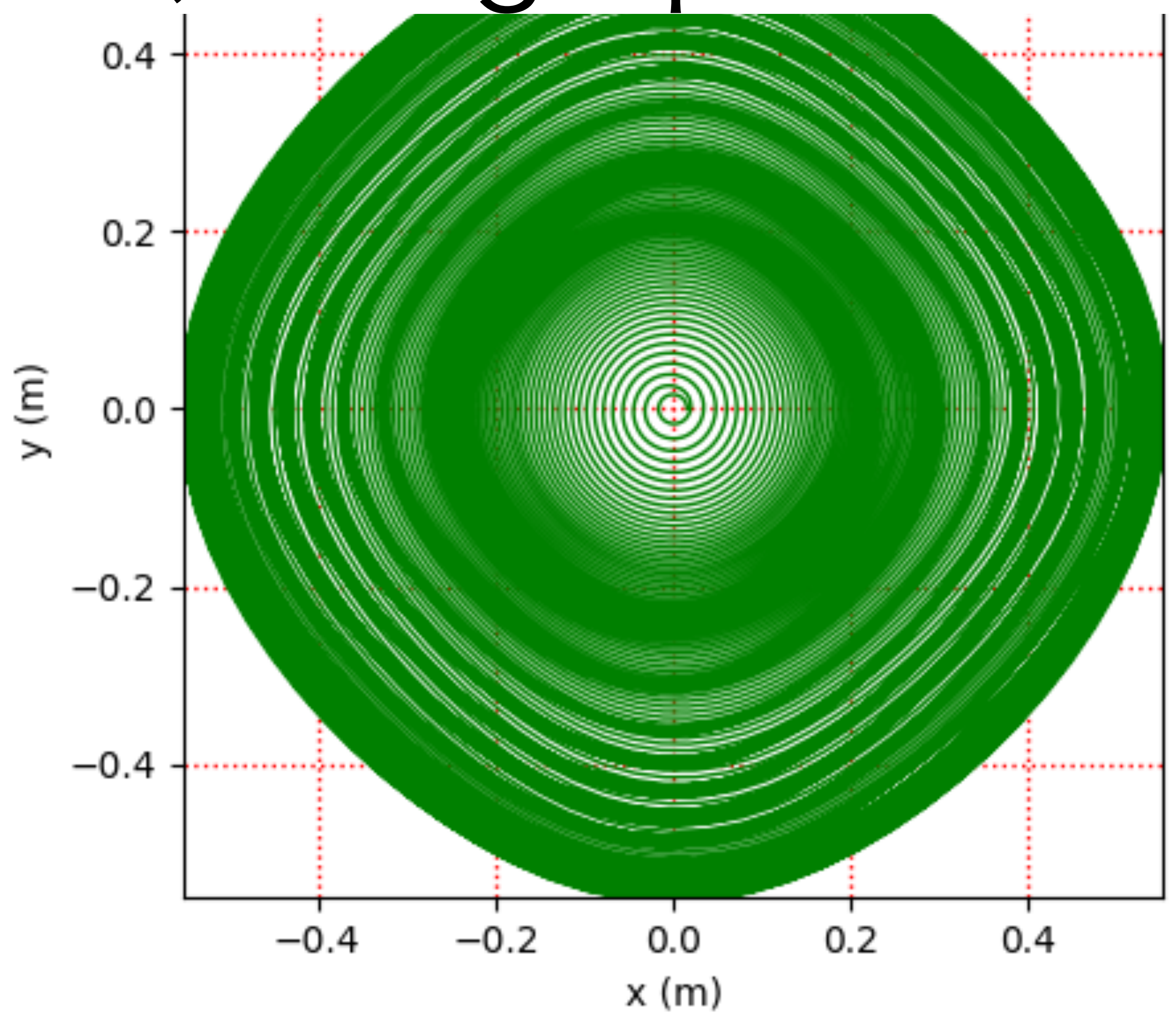
Summary

・Combing python and OPAL, magnetic field can be optimized.

・AEO calculation has proven the optimized field is highly isochronous.



AEO, using optimized field



Energy gain