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ION OPTICS: LECTURE 2

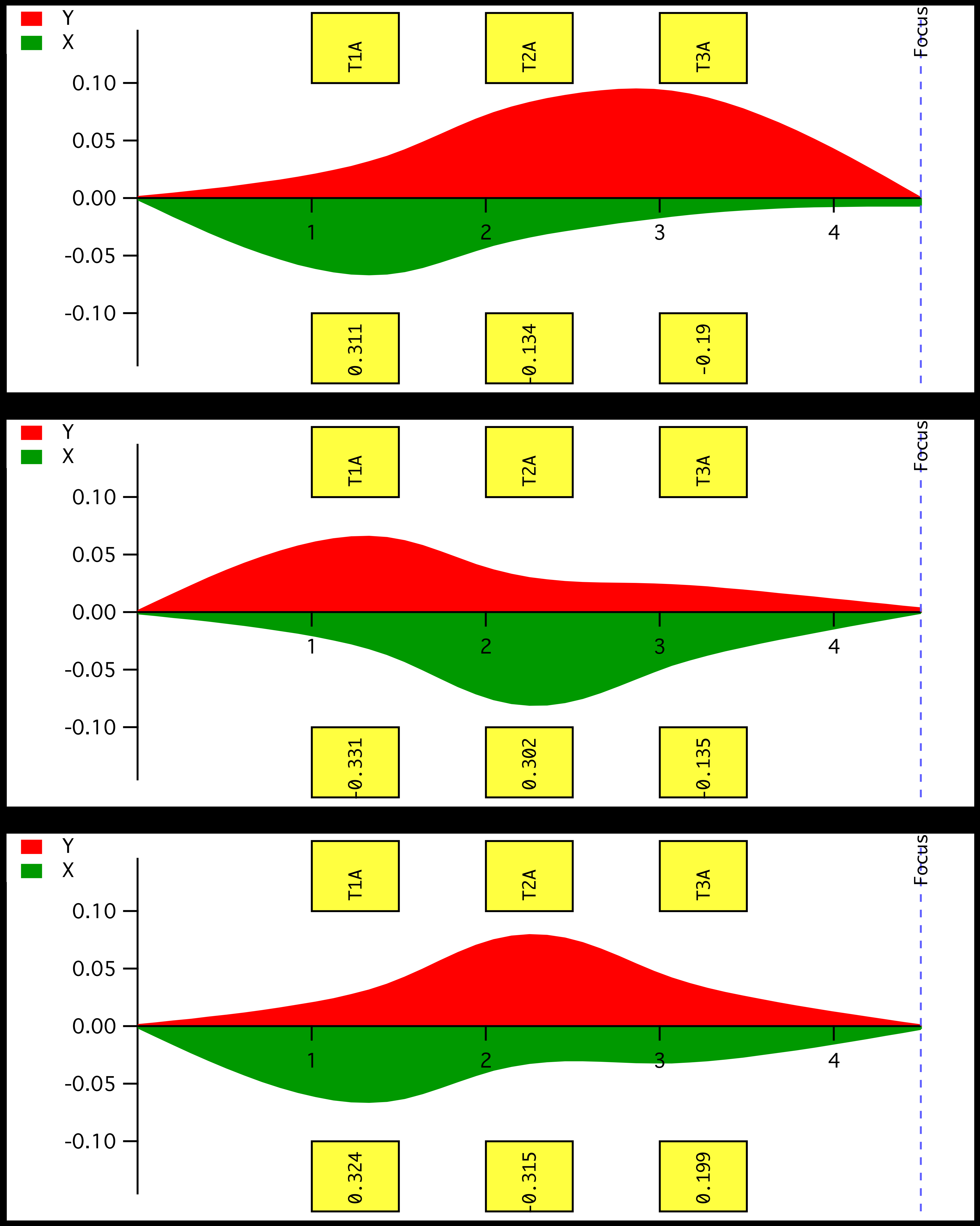
TOOLS

- Complex optics systems are difficult/impossible to model analytically
- Computer programs have been developed to find solutions numerically
- The finding process involves minimization of an objective function based on the definition of constraints
- The number of parameters that can be adjusted define the number of degrees of freedom of the system
- Consider N constraints and M degrees of freedom
  - if N>M: the system has no solution (too many constraints)
  - if N=M: the system has one solution (just enough constraints)
  - if N<M: the system has several solutions (not enough constraints)

EXAMPLE: QUADRUPOLE TRIPLET

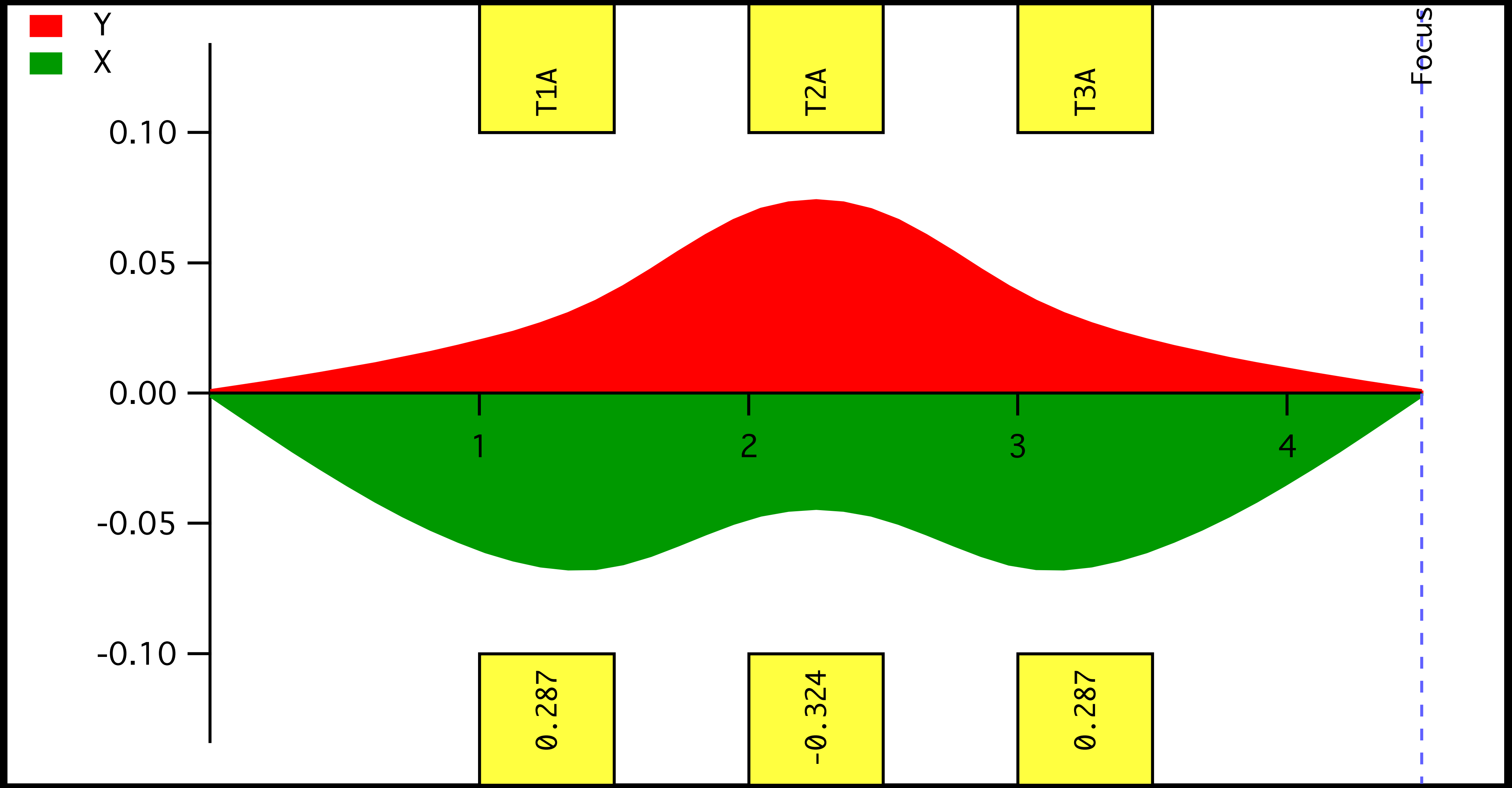
- Transfer matrix $T_{triplet} = \begin{bmatrix} T_{11} & T_{12} & 0 & 0 \\ T_{21} & T_{22} & 0 & 0 \\ 0 & 0 & T_{33} & T_{34} \\ 0 & 0 & T_{43} & T_{44} \end{bmatrix}$

  - Suppose strength of 3 quadrupoles can be adjusted (3 parameters)
  - Suppose constraints are double focussing $T_{12} = 0$ and $T_{34} = 0$ (2 constraints)
  - Several solutions are possible
  - Each has different magnifications and acceptances



EXAMPLE: QUADRUPOLE TRIPLET

- Now add constraint $T_{11} = -1$
- There should be only one solution
- All magnifications are equal to -1 (can you tell why?)
- When not enough constraints
  - Objective function has several minima
  - Which minimum the program ends up into greatly depends on starting point



Transfer | Sigma | Inverse | Emittances

	x(m)	a(rad)	y(m)	b(rad)	l(m)	d(1)
xf	-1	6.08e-05	0	0	0	0
af	0.824	-1	0	0	0	0
yf	0	0	-1	-0.000101	0	0
bf	0	0	-1.24	-1	0	0
lf	0	0	0	0	1	0
df	0	0	0	0	0	1

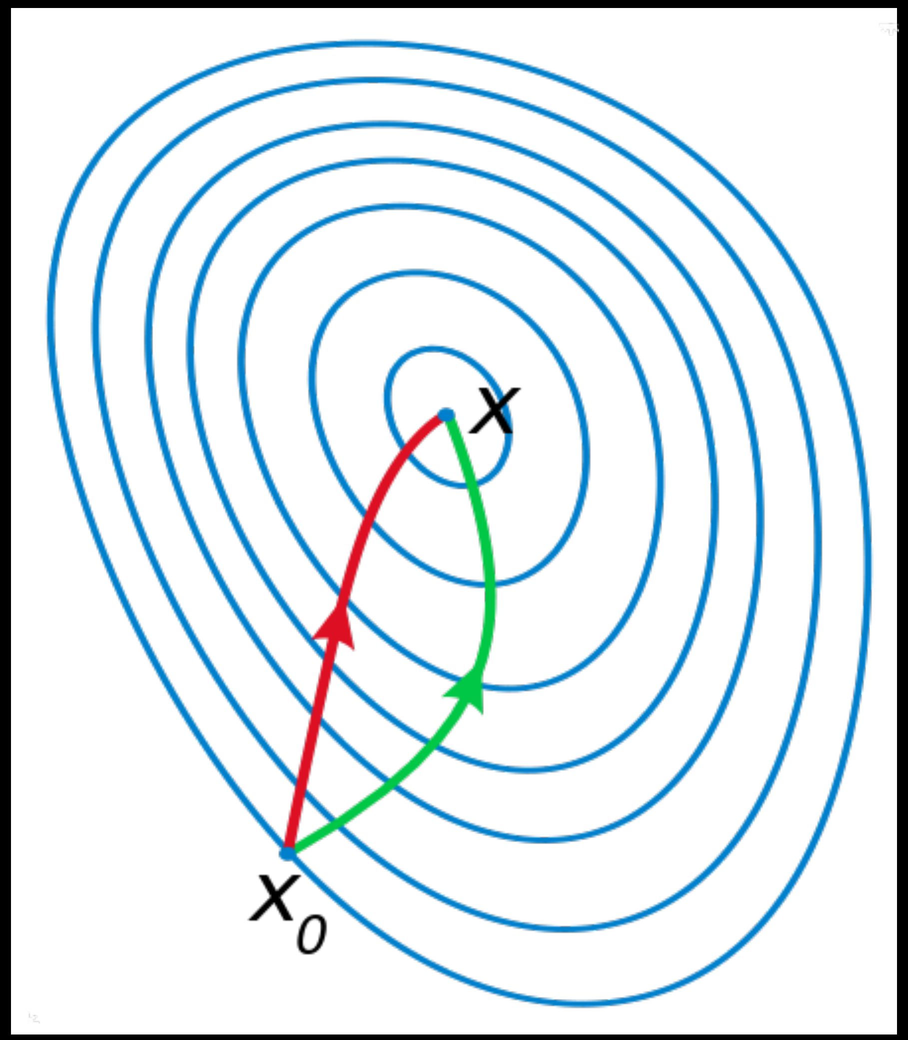
Dismiss

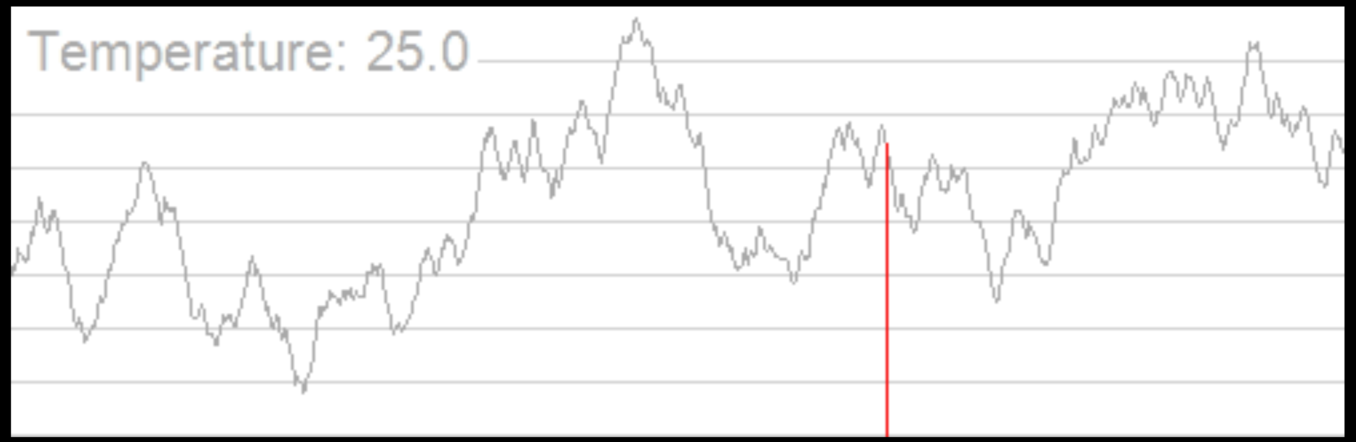
PARAMETERS AND CONSTRAINTS

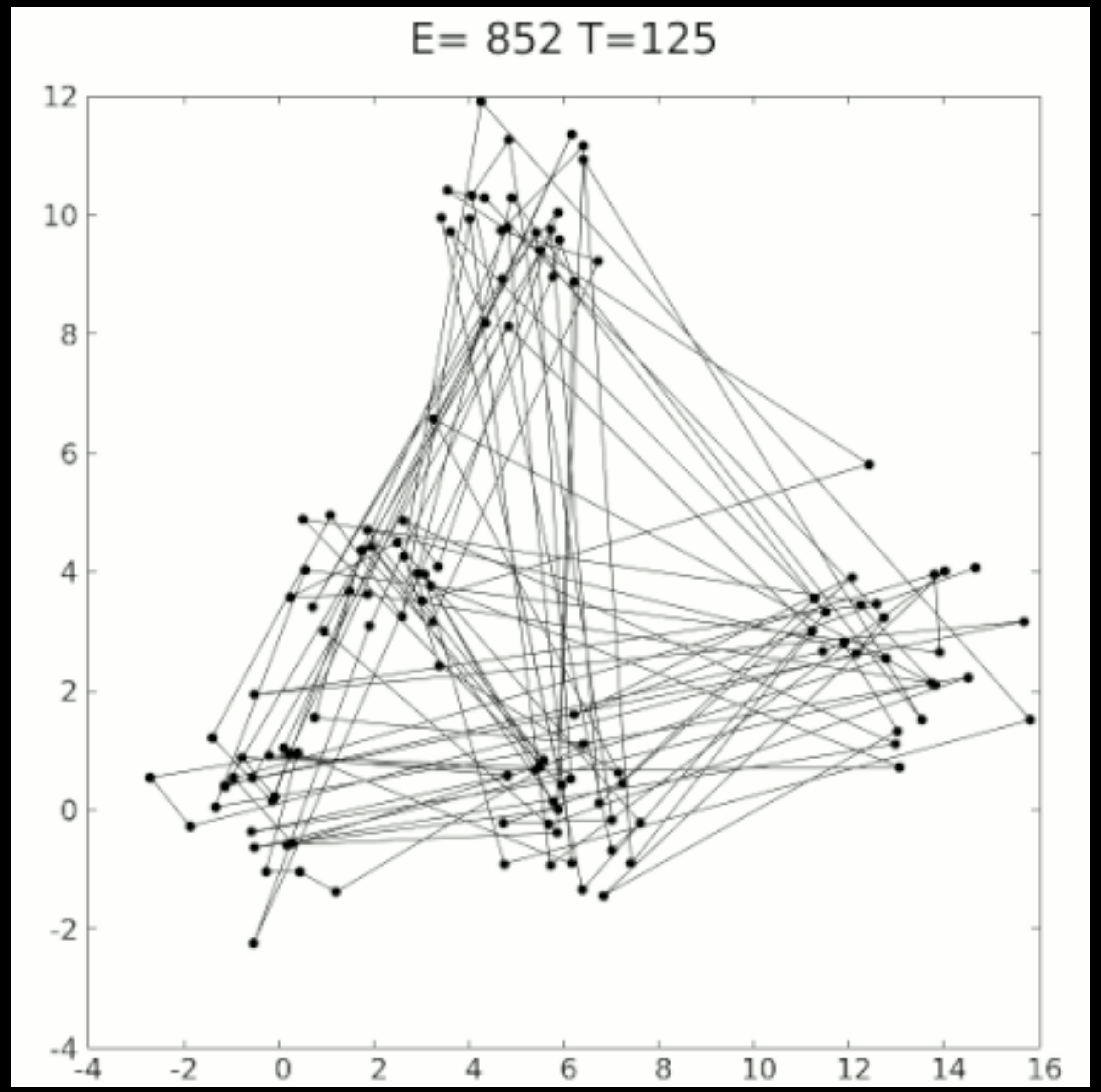
- Choice of parameters depends on the task at hand
  - Designing optical systems: parameters can be any characteristics of the magnets, such as length, radius, gap, bending angle, edge angle, etc…, and strength
  - Tuning optical systems or looking for different optical solution of an existing system: only strength can be parameters usually
- Choice of constraints depends on the purposes of the optical system
  - For instance: spectrometers want finite dispersion, separators zero dispersion
  - Beam size can also be a constraint to find solutions with largest acceptances

MINIMIZATION ALGORITHMS

- Methods based on derivatives
  - Gradient descent and Newton's method: use derivatives of objective function to find the shortest path to minimum
  - Well adapted to well-behaved function with smooth second derivatives
  - Can end up in local minima: need good starting point! ☹
  - Fast convergence 😊
- Methods based on Monte-Carlo
  - Simulated annealing or Metropolis: random search within the phase space of parameters
  - Well adapted to problems with several local minima and/or functions with discontinuities 😊
  - Slow because of random search ☹







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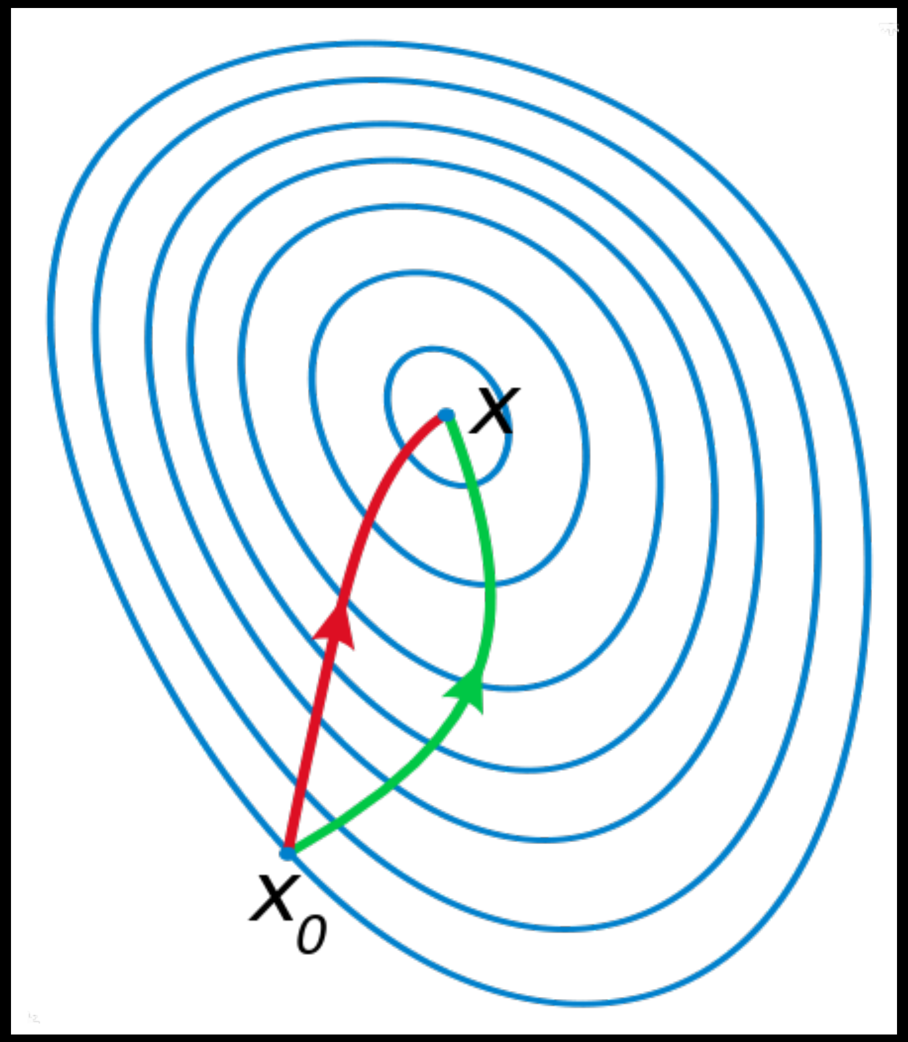

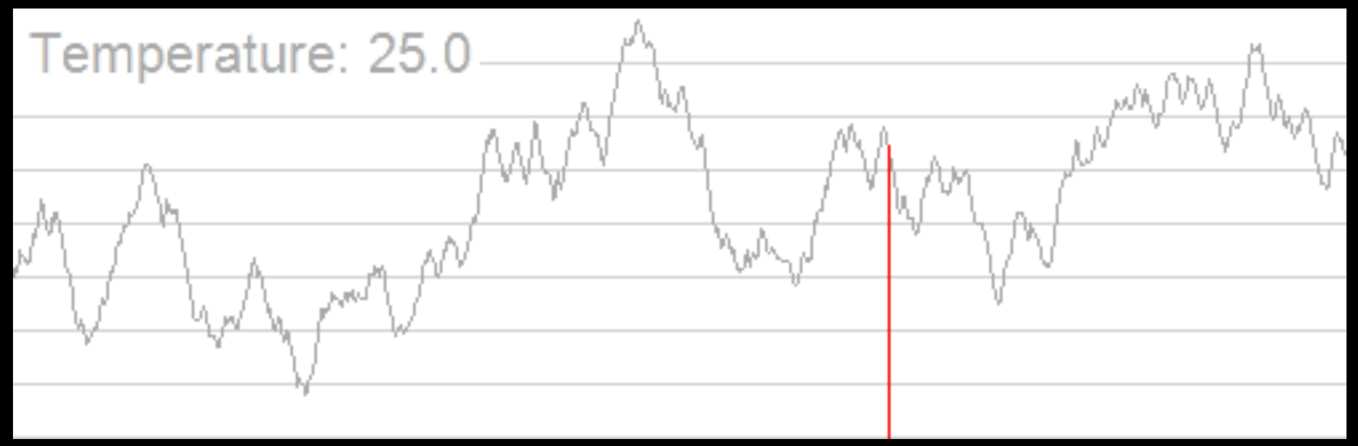

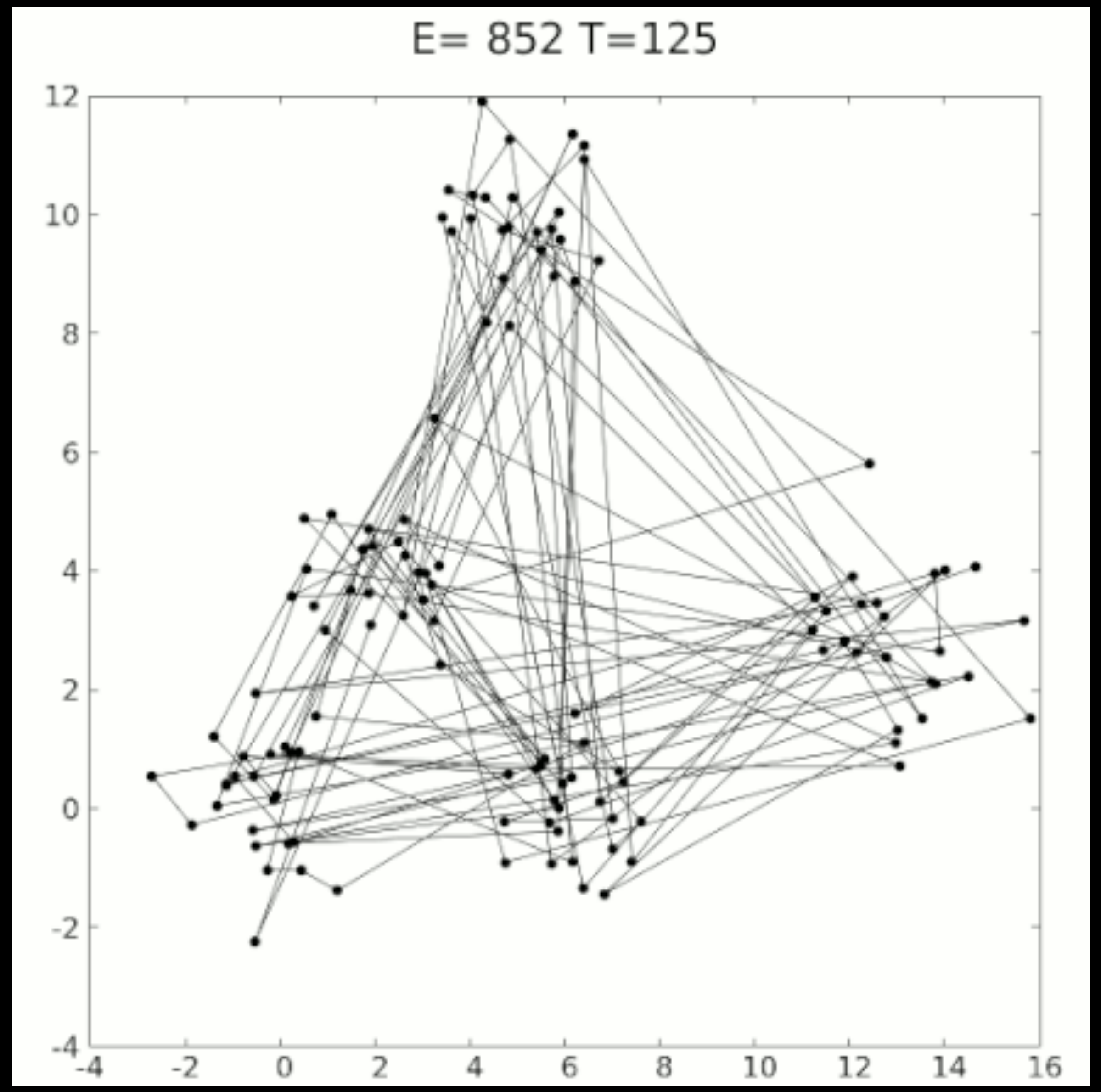

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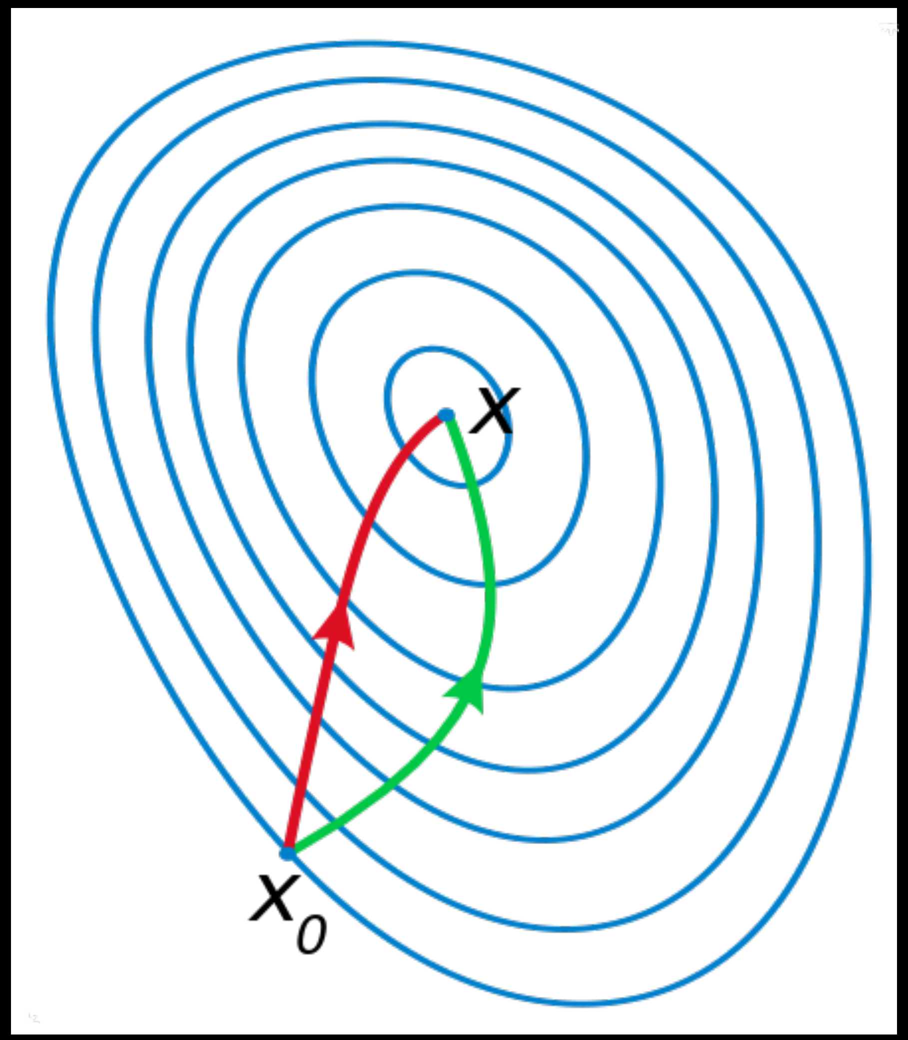
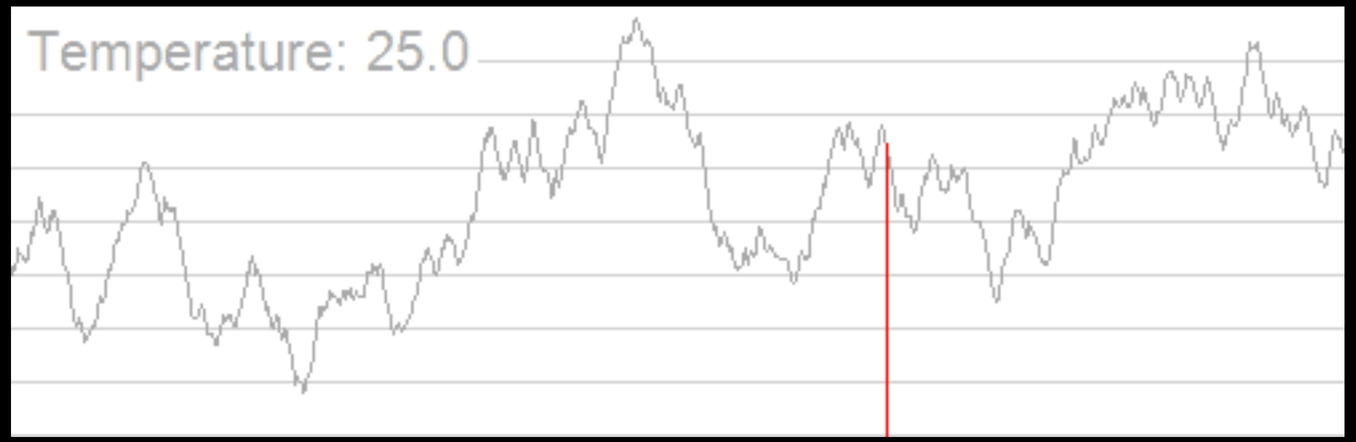
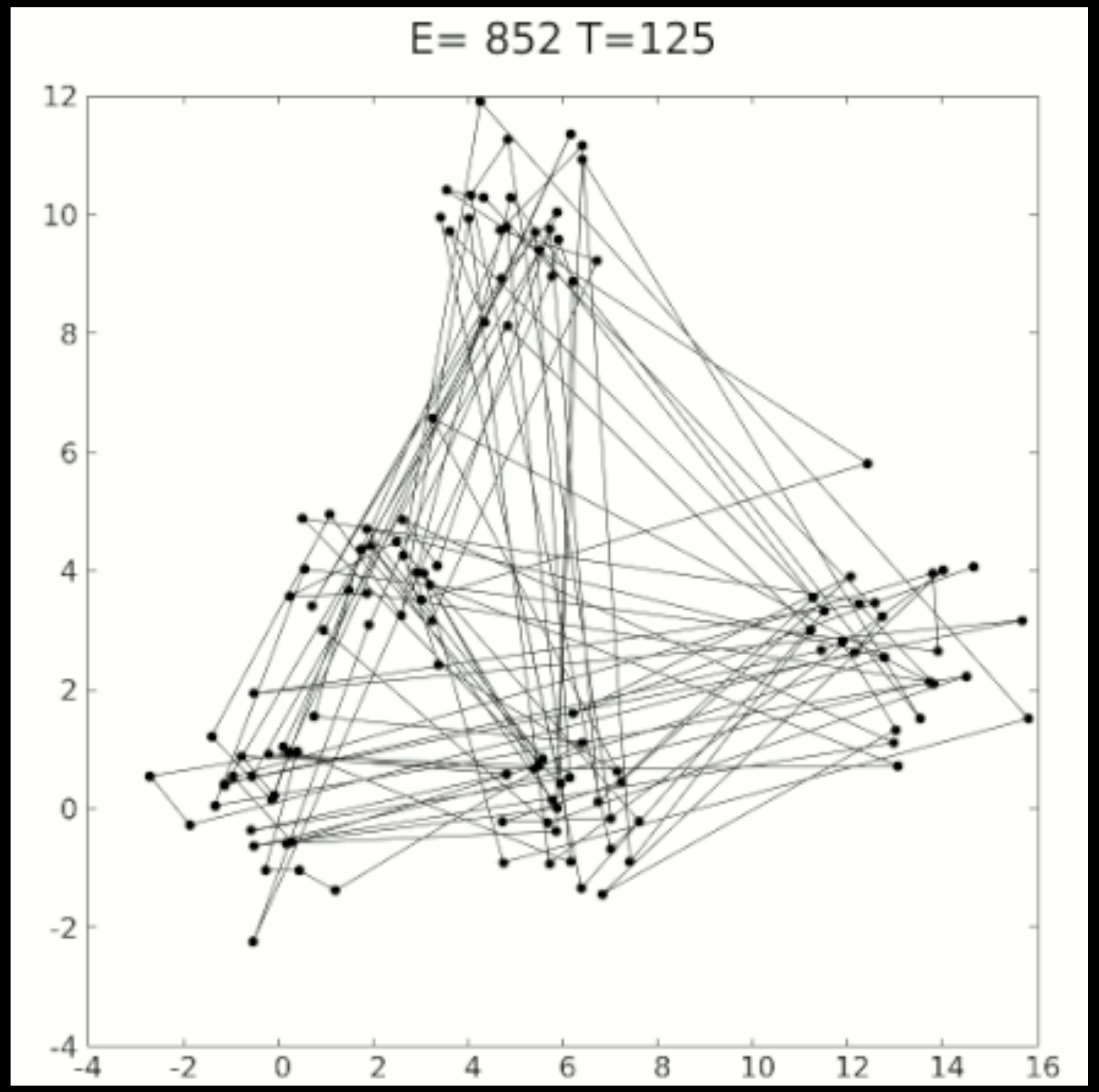






DESIGN TOOLS (NON EXHAUSTIVE LIST)

- TRANSPORT
  - Developed in SLAC in 1960's
  - Used primarily to design systems
  - First order with some 2nd and 3rd added
- MAD
  - Developed in CERN
  - Used primarily for accelerator design
- GIOS, GICOSY & COSY INFINITY
  - Developed in Mainz and MSU
  - Use of Differential Algebra (DA) techniques
  - Calculates to any order
- TUNER
  - Developed at MSU
  - Dynamic visualization of ion optics
  - Limited to first order

SIMULATION TOOLS (NON EXHAUSTIVE LIST)

- RAYTRACE
  - Developed in the 1980's
  - Use of magnet field maps to integrate trajectories
- MOCADI
  - Monte-Carlo simulation of optics system using output from GICOSY
  - Used to simulate acceptances and filtering properties of separators
- ZGOUBI
  - Calculates trajectories through magnet field maps
  - Use truncated Taylor series
- LISE++
  - Simulates production of secondary beams including reaction processes
  - Can use either first order analytical or COSY matrices for optics

PROGRAMS DEMOS

- TUNER
  - Designed to allow manipulations of the optics with direct feedback
  - Manual search for specific optics configuration before setting up constraints and fitting
  - Find close-by initial tune that will converge towards desired optics
  - Educational tool to understand effects of optical parameters on properties of optics systems
  - Based on Igor Pro software (www.wavemetrics.com)
  - Download: https://people.nscl.msu.edu/~bazin/Tuner/Home.html

PROGRAMS DEMOS

- LISE++
  - Designed to simulate the production of secondary beams
  - As realistic as possible simulation using various models for reactions, stragglings, energy loss, charge states, etc…
  - Fast calculations of distribution convolutions based on Transport Integral
  - More realistic calculations based on Monte-Carlo methods
  - Web site and download: http://lise.nscl.msu.edu/lise.html

TUNER DEMO

- Introduce main control panel features
  - List of elements with their parameters and related controls
  - Types of elements and their various parameters
- Types of plots: envelope, rays, schematic, acceptances
  - Envelope plot: dynamic controls of parameters, informations at viewer locations
  - Manual search for optical solutions
  - Fitting based on enabled constraints and fitting range
- Savesets and input/output
  - Save sets to quickly store progress towards desired solution
  - Save and recall beam lines, compatibility with TRANSPORT file format

LISE++ DEMO

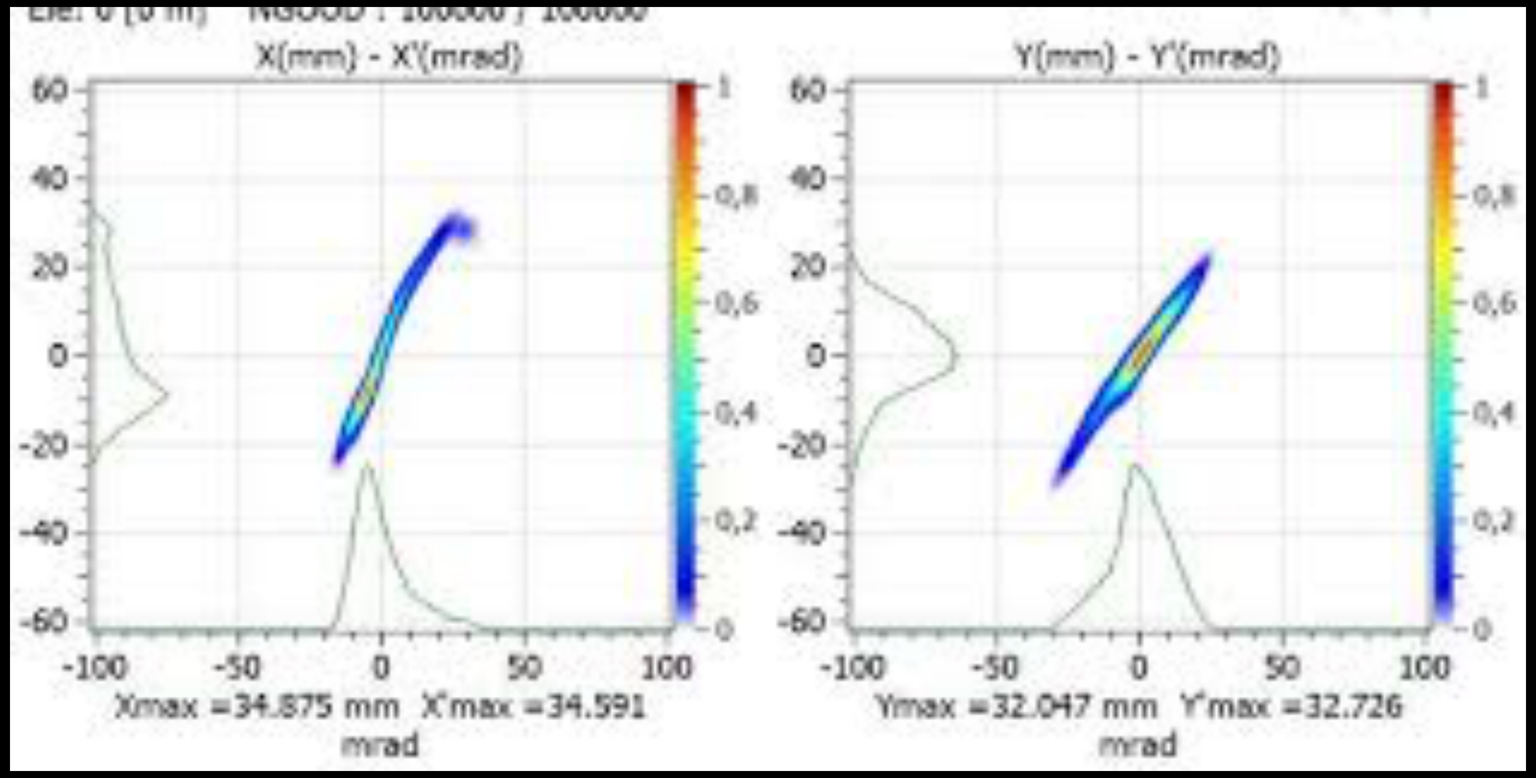
- Introduce optics main panel and 2 different optics configurations
  - Standard: optical elements grouped together in sections for fast calculations
  - Extended: separate optical elements for more accurate calculations
- Input/output
  - Transport-like input uses formulas for 1st and 2nd order matrix elements
  - Fitting is possible using defined constraints along beam line
  - COSY infinity maps can be linked to elements for calculations with higher order
- Simulations
  - Monte-Carlo engine pushes rays with distributions based on reaction model
  - Realistic transmissions, resolutions and optical properties can be obtained

REAL LIFE ION OPTICS

- Possible differences between calculated model and reality
  - Magnet misalignments (off beam axis) or misplacements (not located as in model)
  - Magnet effective lengths vary with field strength (optics valid at only one setting)
  - Fringe field shape also vary with field strength: change of aberrations
- Methods to compensate for these differences
  - Diagnostics! Be able to measure beam properties quickly (~1s response time)
  - Process gradually and systematically using guidance from calculations
  - Decouple tuning of various characteristics: alignment, focussing, transmission,…

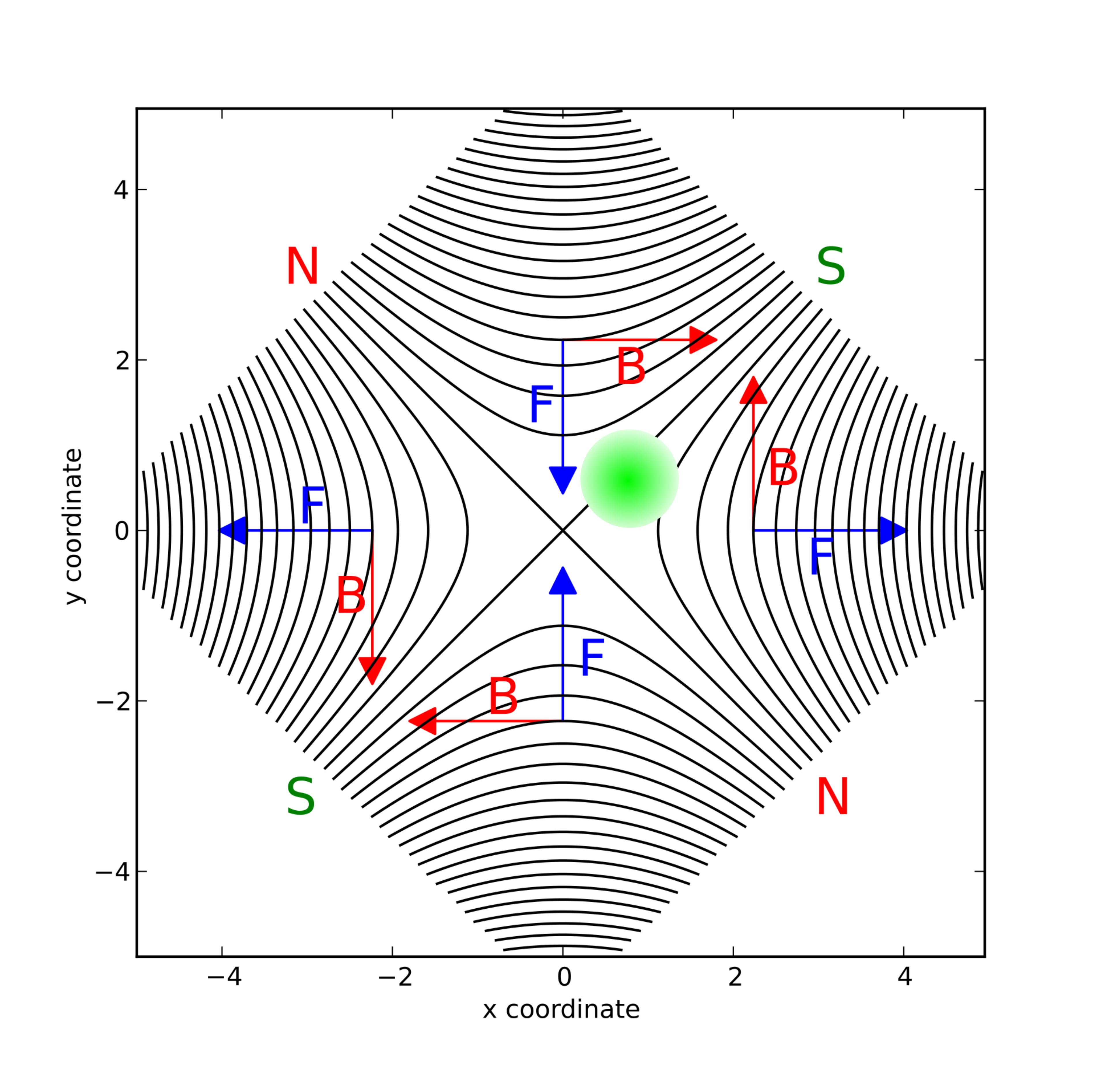
TYPES OF DIAGNOSTICS

- Viewer and camera
  - Easy to implement, fast feedback 😊
  - Intercept beam, only one location ☹️
- Non-intercepting detector
  - Wire detector, Parallel plates detector
  - Harder to implement, slow feedback ☹️
  - Measure beam properties at several locations 😊
  - Can be used to quantify emittance properties 😊



QUADRUPOLE OR BEAM MISALIGNMENT

- Effect of misaligned quadrupole
  - Net force on beam will deviate beam from center of magnet
  - The center of gravity of the beam spot will move left-right and/or up-down when changing the strength
  - This is called "steering effect"
- Possible corrections
  - If same effect in close-by quadrupoles: steer beam on axis
  - If different effects: realign quadrupoles



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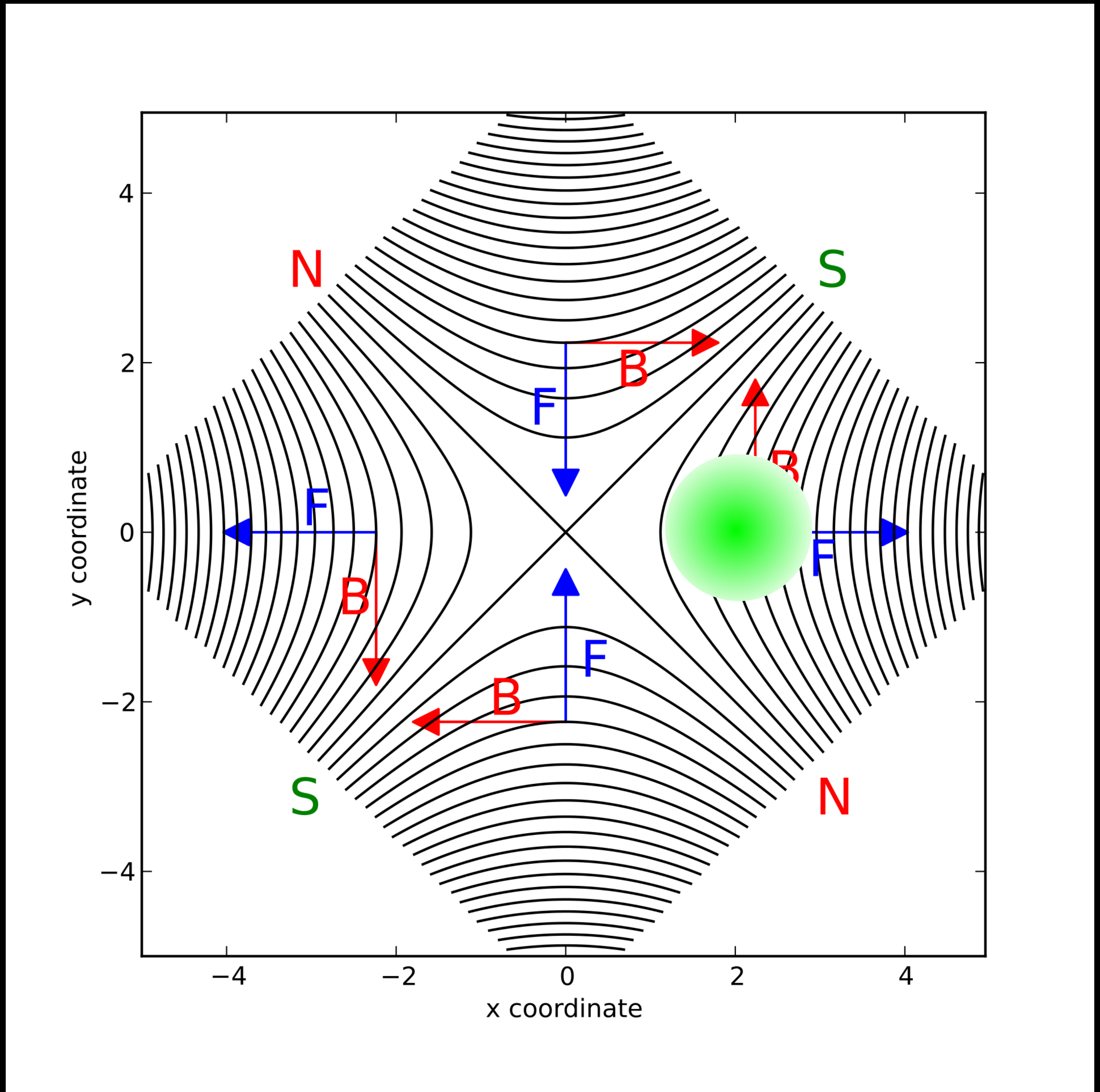
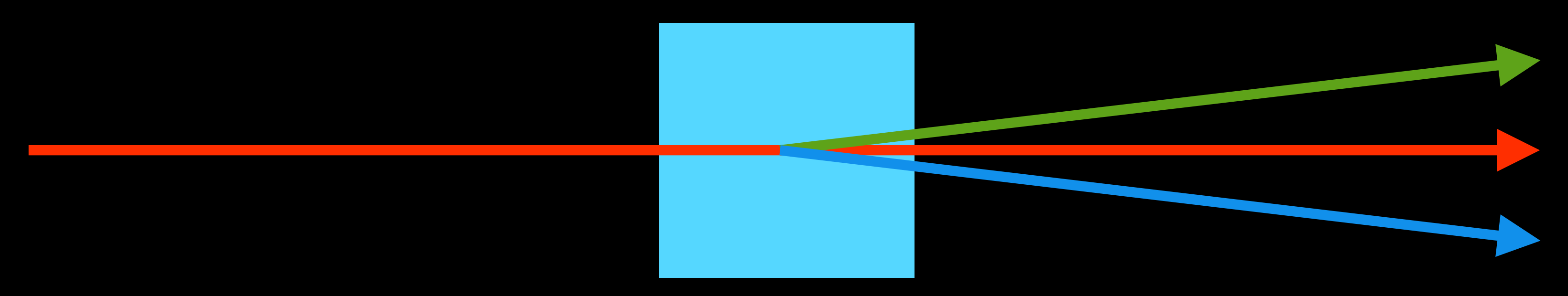
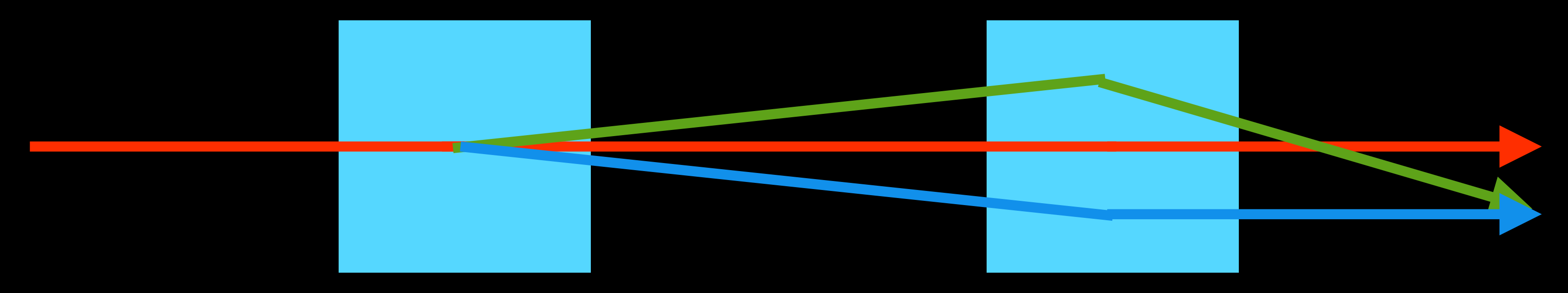


TUNING POSITIONS AND ANGLES

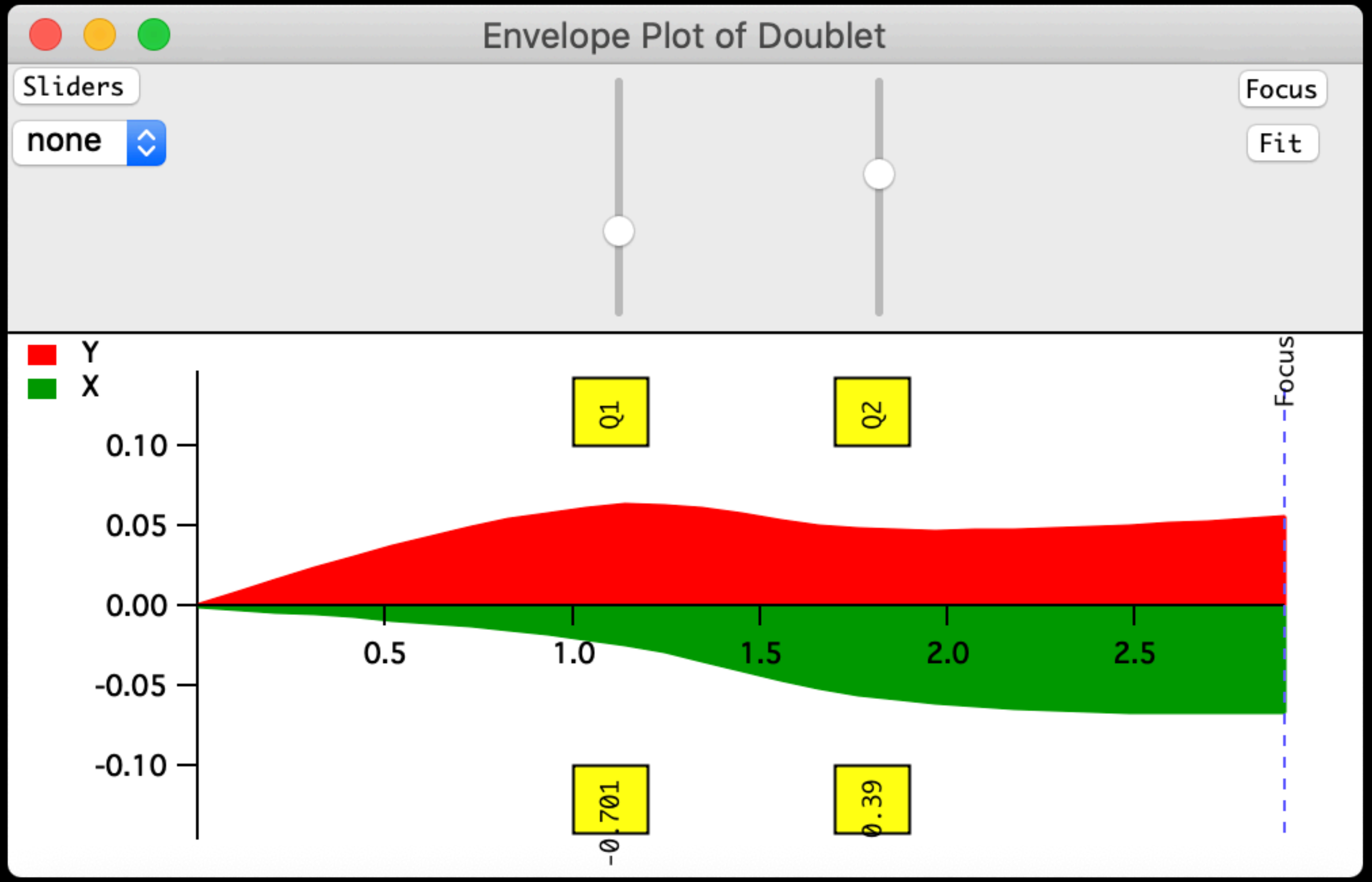
- Small dipoles are used to tune position and angle
- Also called "steerers"
- One steerer: position and angle are correlated
- Two steerers: position and angle can be tuned independently



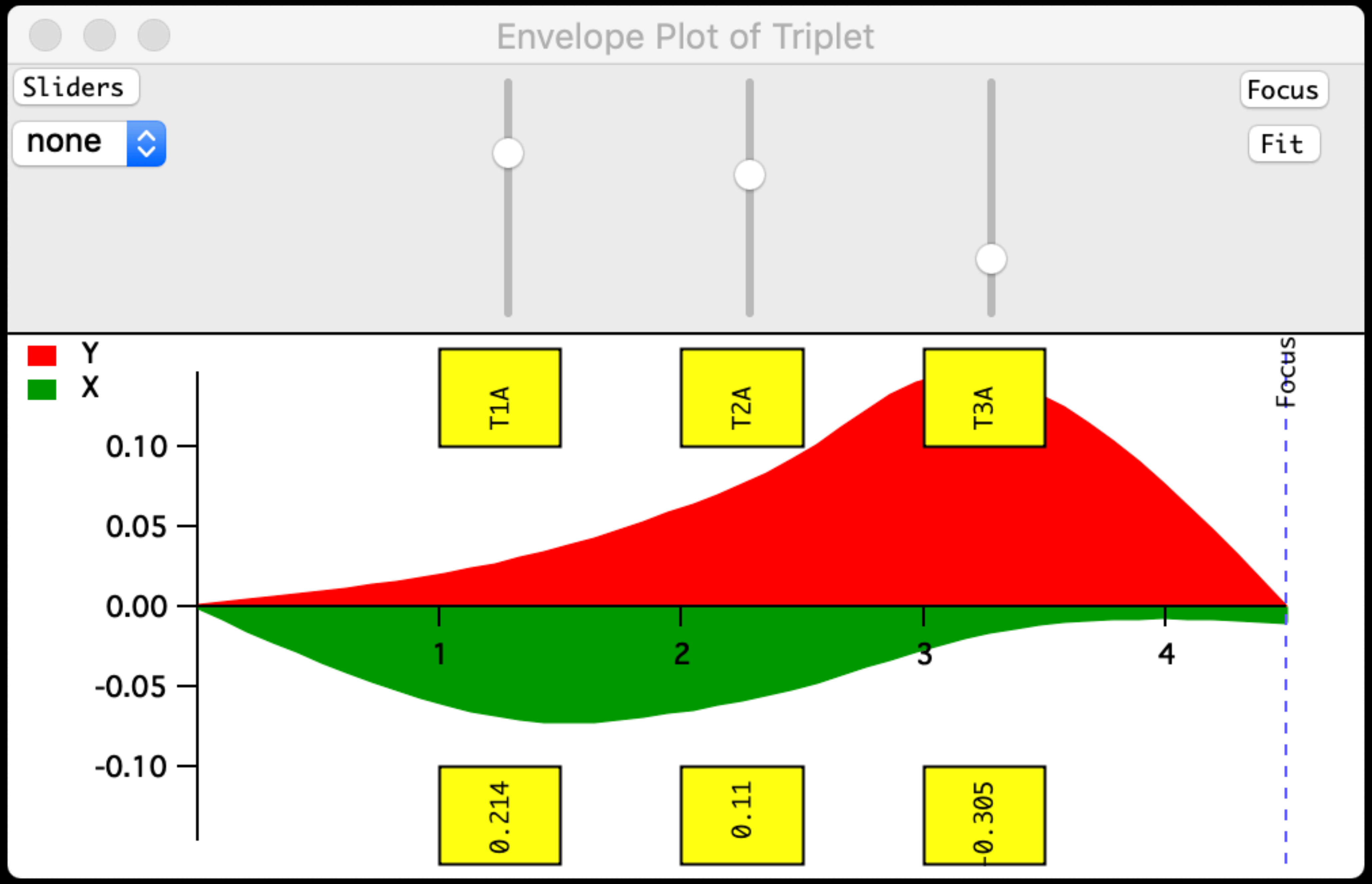


TUNING FOCUSSING

- Quadrupole doublets
  - Relatively easy
  - Only one configuration to obtain double focussing (+-)
  - Tuner demo…

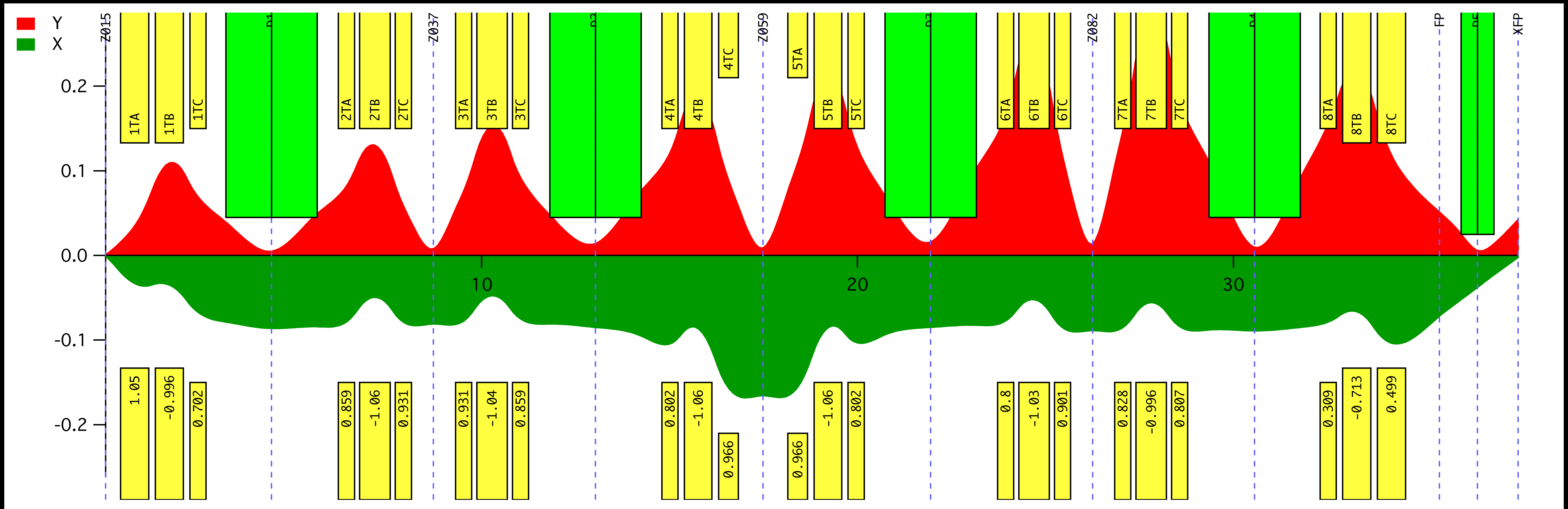


- Quadrupole triplets
  - Much more difficult
  - Several possible configurations
  - Tuner demo…



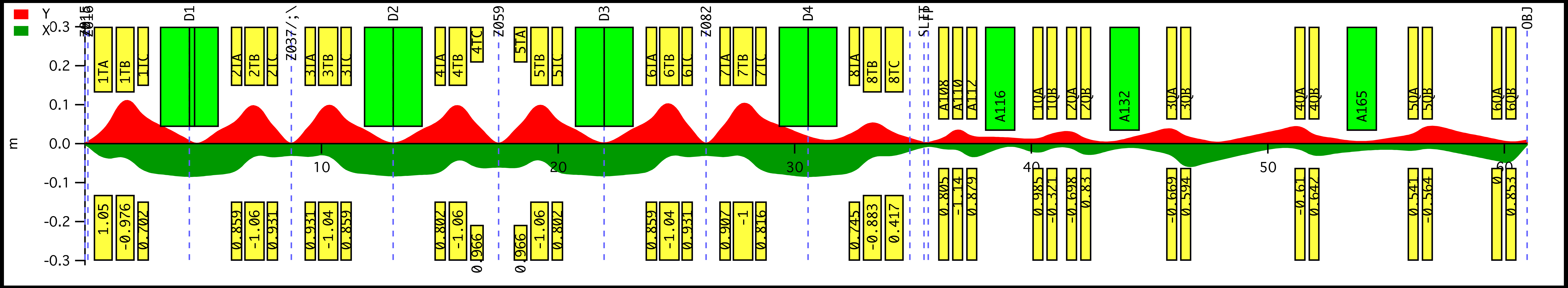
PROGRESSIVE TUNING

- Influence of upstream elements always greater than downstream elements
  - "Cascade" effect: small error is amplified by following sections
  - Diagnostics along system are necessary to tune step by step (focus by focus)
  - Example on the A1900: Tuner demo…



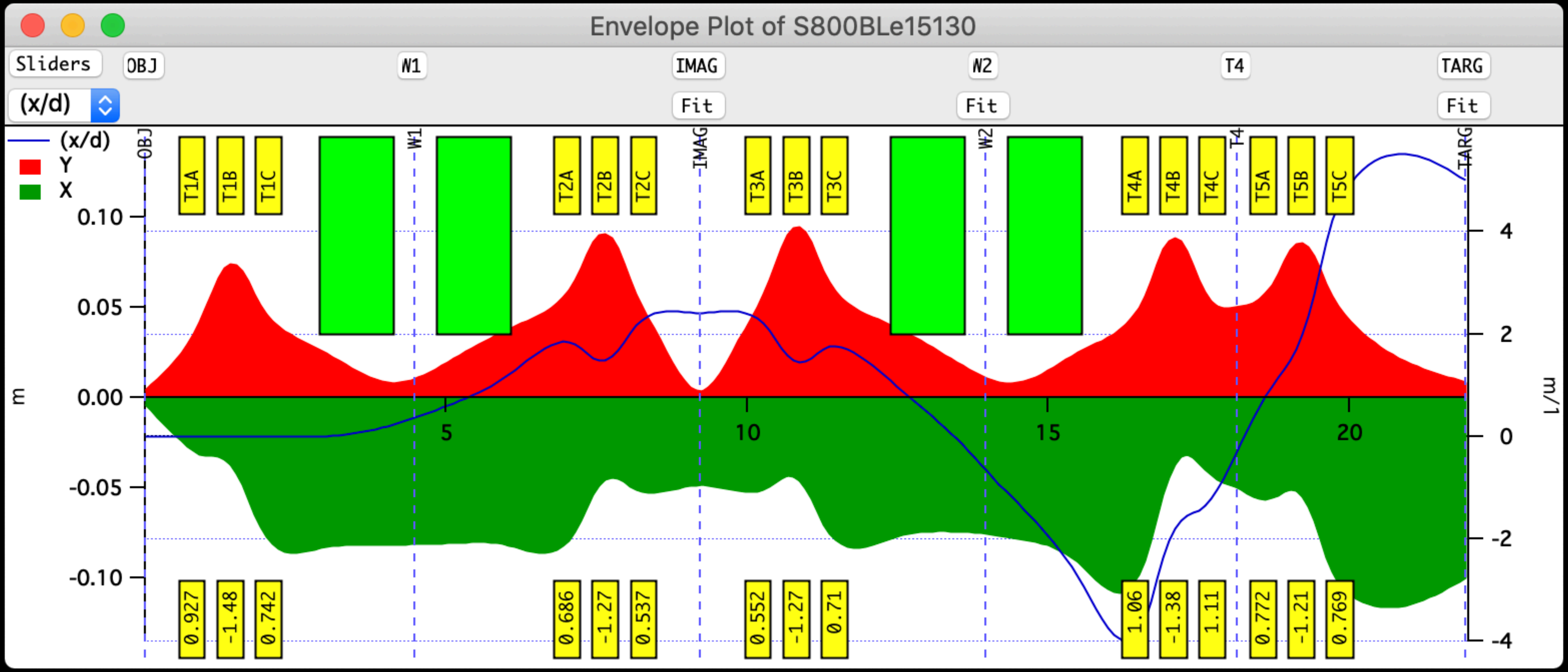
TUNING TRANSMISSION

- Identify "bottle necks" where space is restrained
  - Typical location: gap of dipoles
  - Constraints should include waists located at the middle of bending sections
- Take into account emittance properties of the beam to transmit
  - Larger angular acceptances can be achieved by increasing position magnifications
  - This can be important when transmitting secondary beams produced from nuclear reactions



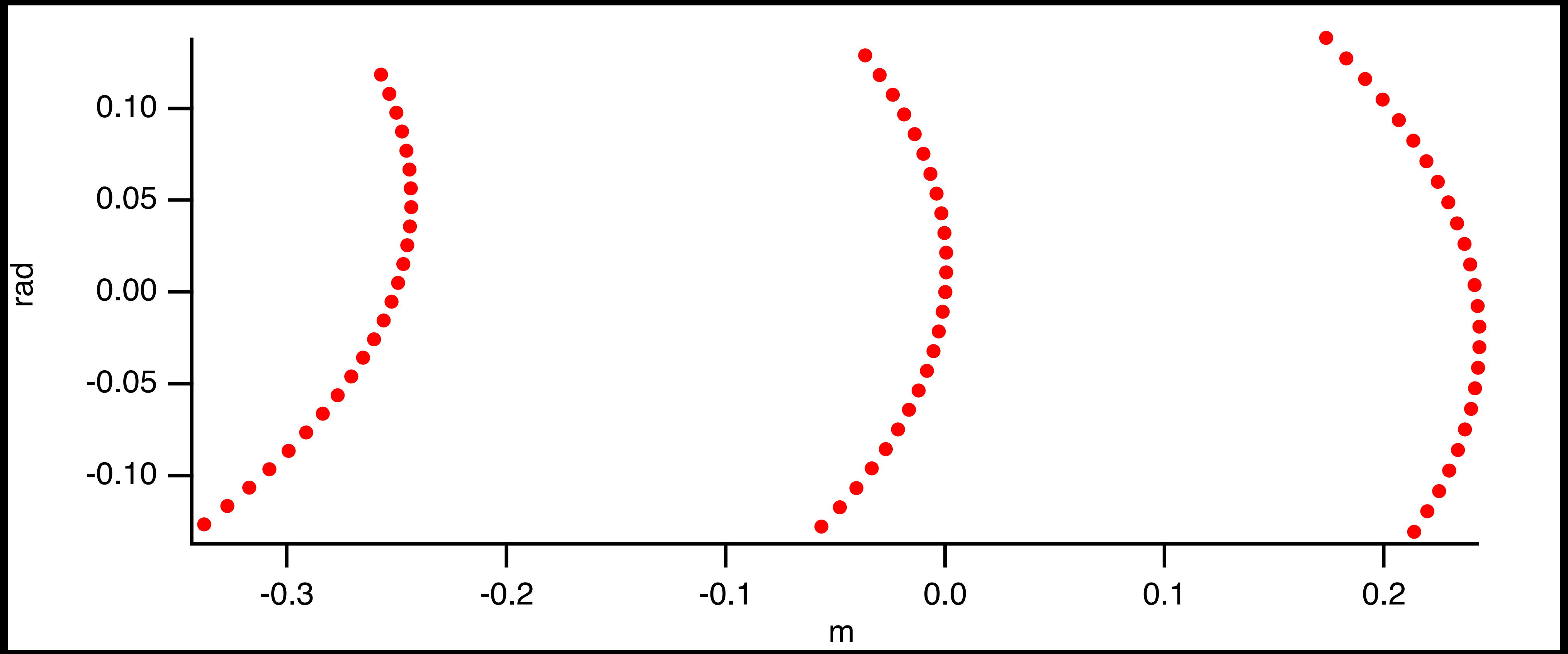
SELECTIVE TUNING

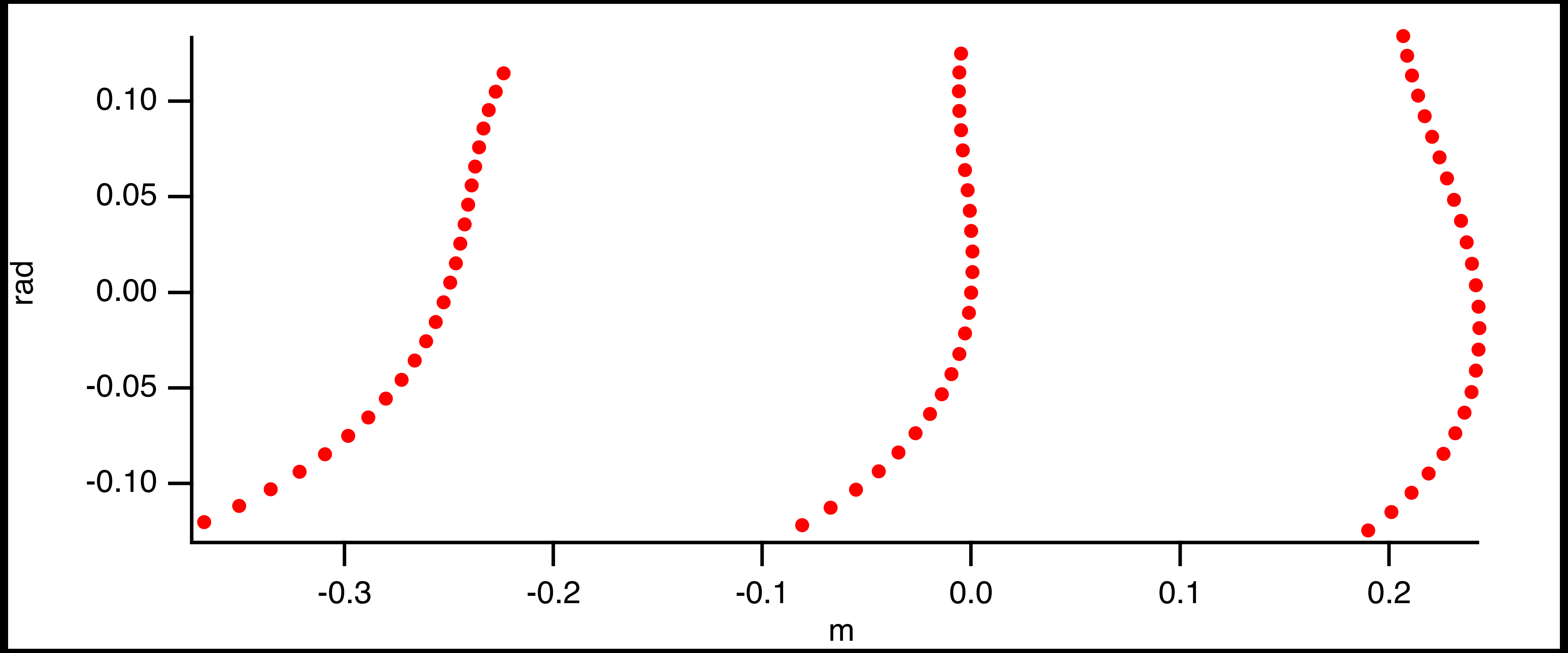
- Depending on their location, some focussing elements act differently on certain matrix elements
- Typical application: tuning dispersion matching condition while preserving focussing conditions
- Tuner demo…

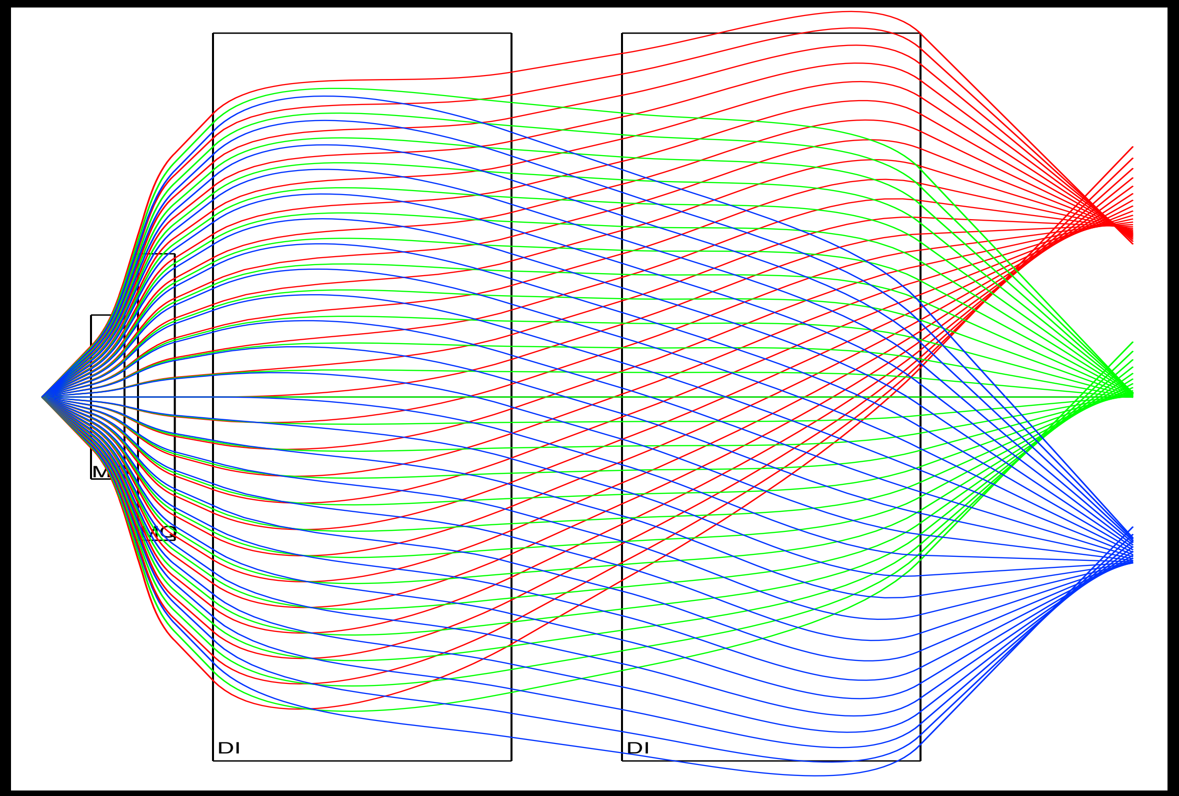


ABERRATIONS TUNING

- Identification of aberration order
  - "Moon-shaped" profiles: 2nd order
  - "S-shaped" profiles: 3rd order
  - Variation with $B\rho$: chromatic
- Charge states: a very useful tool
  - Transmit different charge states of the same beam simultaneously
  - Each charge state has a different rigidity: identify chromatic aberrations







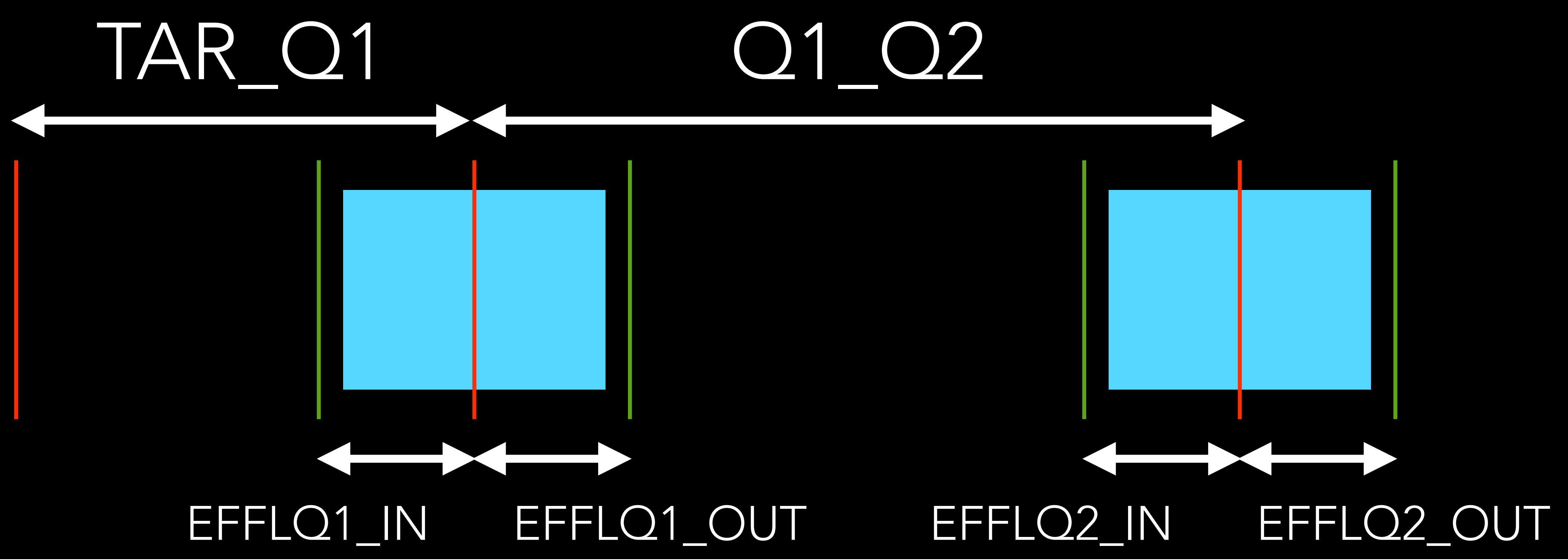
VARYING EFFECTIVE LENGTHS

- How to take into account effective length variations?
  - Modeling of the effective length variations with field
  - Option 1: calculate optics at different rigidities and interpolate
  - Option 2: use programs that allow variables for drift and quadrupole lengths
  - One such program is COSY infinity that uses a pseudo-language to define optics elements

```
PROCEDURE S800Q1 Q1 ;
  DL 0.0 ;                                                    {Target}
  DL TAR_Q1-EFFLQ1_IN ;
  MQ EFFLQ1_IN+EFFLQ1_OUT Q1*APERQ1 APERQ1 ;                  {Q1}
ENDPROCEDURE ;

PROCEDURE S800Q2 Q2 ;
  DL Q1_Q2-EFFLQ1_OUT-EFFLQ2_IN ;
  MQ EFFLQ2_IN+EFFLQ2_OUT Q2*APERQ2 APERQ2 ;                  {Q2}
ENDPROCEDURE ;

PROCEDURE S800D1D2 ;
  DL Q2_D1-EFFLQ2_OUT-EFFLD1_IN ;
  DI RHOD1 ANGLED1 APERD1 0 0 EDGED1 0 ;                      {D1}
  DL D1_D2-EFFLD1_OUT-EFFLD2_IN ;
  DI RHOD2 ANGLED2 APERD2 EDGED2 0 0 0 ;                      {D2}
  DL D2_FOC-EFFLD2_OUT ;
  DL 0.0 ;                                                    {Focus}
ENDPROCEDURE ;
```



CONCLUSIONS

- Ion optics should be an exact science: only Maxwell equations!
- Reality is much more complex than simple equations
- Designing ion optical systems requires well defined physics goals
- Tuning ion optical systems requires detailed understanding of the behavior as a function of tuning parameters
- Software tools are an essential part of the designing and tuning processes
- Several tools are usually necessary
- Ion optics is an art: practice and experience are paramount!