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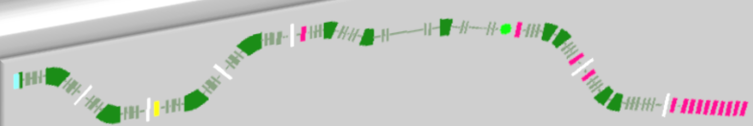
Production of Fast Rare Ion Beams

Euroschool on Exotic Beams 2013, Dubna
26-31 / 08 / 2013
Euroschool on Exotic Beams 2013, Dubna

LISE++

1. Introduction to production of Fast Rare Ion Beams
2. Production Area
3. Separation
4. Identification
5. Production of new isotopes
6. LISE++ : Utilities
7. Radioactive beam physicist task

LISE++

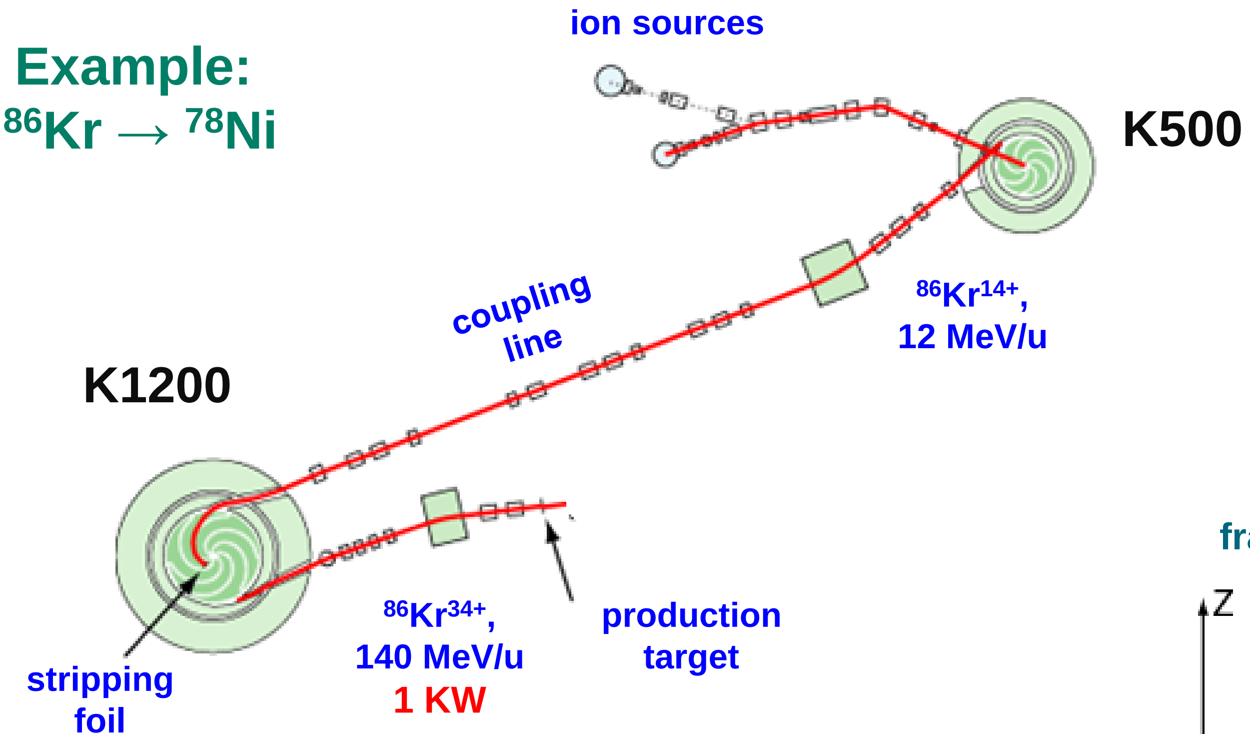


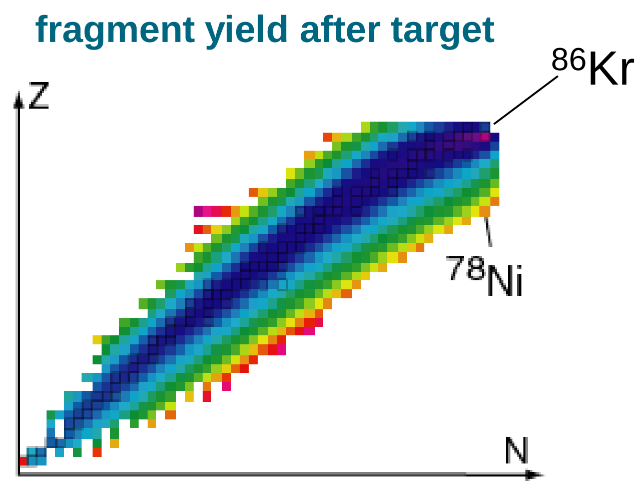
3. Separation

1. **Beam optics**
   - ✓ Coordinate system
   - ✓ Transport matrix
   - ✓ Definitions
   - ✓ Focusing conditions
   - ✓ Separation and beam optics
   - ✓ Achromatic fragment separator
   - ✓ High order optics
2. **Separator features**
   - ✓ Ion transport codes
   - ✓ Fragment separator design
   - ✓ LISE++ block classification
   - ✓ Block properties
   - ✓ LISE++ configuration types
   - ✓ Angular acceptances
3. **Types of transmission calculations**
4. **Selections with EM devices**
   - ✓ Magnetic rigidity (Bρ) – selection
     - *Gas-filled separator*
   - ✓ Electrostatic rigidity (Eρ) – selection
     - *E & B bends combination : m & q dispersions*
   - ✓ Velocity selection
     - *Wien & B-bend combination : A/q dispersion*
   - ✓ Time selection
   - ✓ Selection with bunching
   - ✓ Selection with focusing
5. **"Wedge" selection**
   - ✓ Types of wedge
   - ✓ Fragment production in material
   - ✓ Two stage separation
6. **Transmission**
7. **Optimization utilities**
8. **New generation of fragment separators**
9. **Example of secondary beam production**

In-Flight Production

Example:
$^{86}Kr \rightarrow ^{78}Ni$

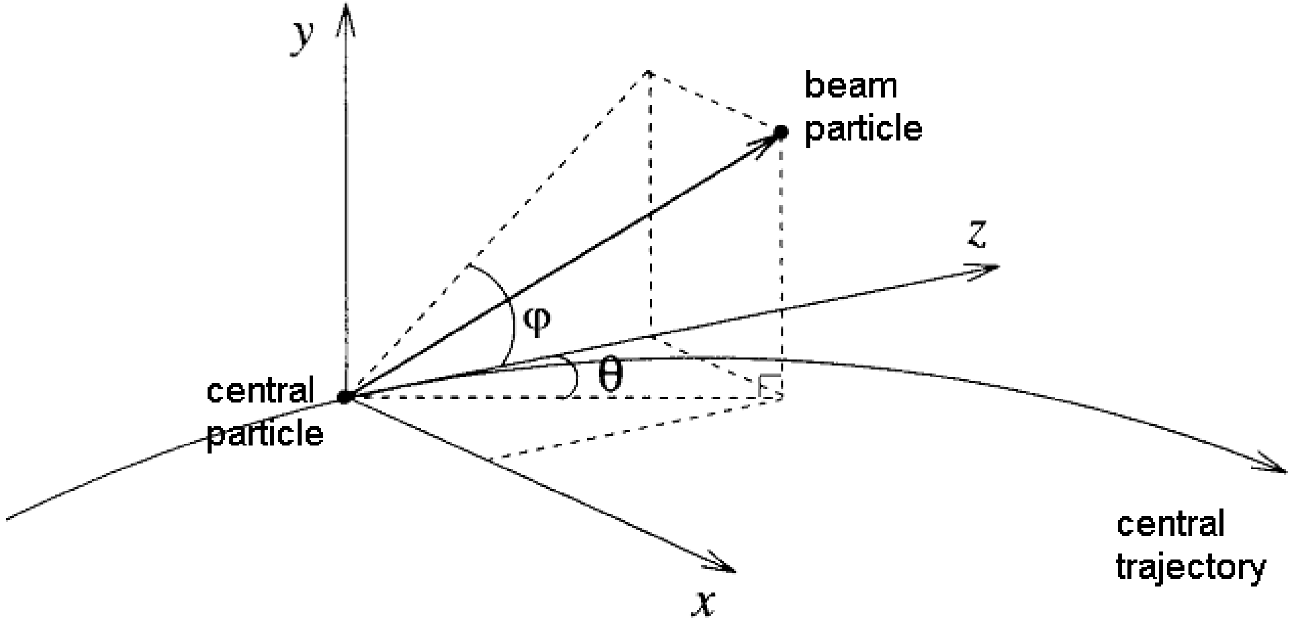




How we are doing this selection?

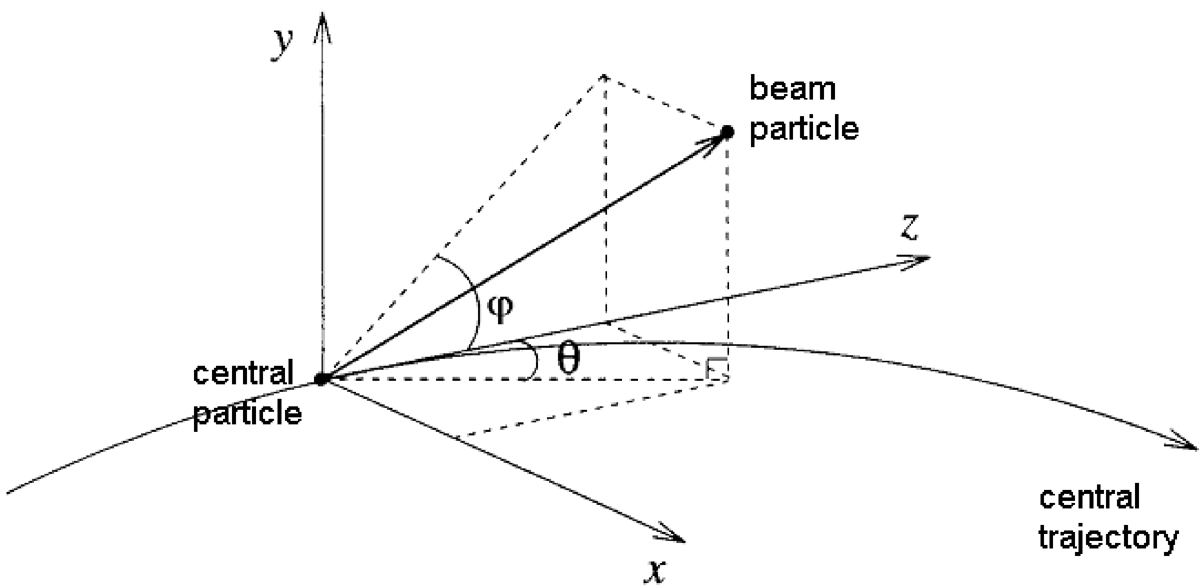
Introduction to an Ion Optics

- Electromagnetic devices (dipoles, quadrupoles etc) are used for transportation and selection of ion beams
- Transport (optical) matrices are used to describe ion trajectories through these devices
- It serves for estimation of first order deviations for each particle trajectory from the central axis



The beam particle motion can be described by 6 dimensional vector
("Transport" code formalism)

- x – distance from the central axis in the horizontal plane
- θ (or x' or a) – angle between projection on the horizontal plane and the central axis
- y – distance from the central axis in the horizontal plane
- φ (or y' or b) – angle between projection on the vertical plane and the central axis
- l – length difference between the central and projectile trajectories
- δ - relative difference of projectile and central particles $\delta = (p-p_C) / p_C$



Projectile motion (Transport) matrix

- **Let's consider a charge particle passing through magnet elements between Z_i and Z_f, then final coordinates are defined as:**

$$\begin{cases} x_f = f_x(x_i, \theta_i, y_i, \varphi_i, l_i, \delta_i) \\ \theta_f = f_\theta(x_i, \theta_i, y_i, \varphi_i, l_i, \delta_i) \\ y_f = f_y(x_i, \theta_i, y_i, \varphi_i, l_i, \delta_i) \\ \varphi_f = f_\varphi(x_i, \theta_i, y_i, \varphi_i, l_i, \delta_i) \\ l_f = f_l(x_i, \theta_i, y_i, \varphi_i, l_i, \delta_i) \\ \delta_f = f_\delta(x_i, \theta_i, y_i, \varphi_i, l_i, \delta_i) \end{cases}$$

- **where the functions f_x f_θ f_y f_φ f_l f_δ are motion equations of charge particle in electromagnetic field**

- **Assuming small deviations the Taylor expansion can be used:**

$$x_f = \left(\frac{\partial f_x}{\partial x}\right)_{z_f} x_i + \left(\frac{\partial f_x}{\partial \theta}\right)_{z_f} \theta_i + \left(\frac{\partial f_x}{\partial y}\right)_{z_f} y_i + \left(\frac{\partial f_x}{\partial \varphi}\right)_{z_f} \varphi_i + \left(\frac{\partial f_x}{\partial l}\right)_{z_f} l_i + \left(\frac{\partial f_x}{\partial \delta}\right)_{z_f} \delta_i$$

- **Obtained first order values can be compiled as 6x6 matrix, which describes action on the charged particle from electromagnetic devices located between on Z_i and Z_f**

$$\begin{pmatrix} x_f \\ \theta_f \\ y_f \\ \varphi_f \\ l_f \\ \delta_f \end{pmatrix} = \begin{pmatrix} \frac{\partial f_x}{\partial x} & \frac{\partial f_x}{\partial \theta} & \frac{\partial f_x}{\partial y} & \frac{\partial f_x}{\partial \varphi} & \frac{\partial f_x}{\partial l} & \frac{\partial f_x}{\partial \delta} \\ \frac{\partial f_\theta}{\partial x} & \frac{\partial f_\theta}{\partial \theta} & \frac{\partial f_\theta}{\partial y} & \frac{\partial f_\theta}{\partial \varphi} & \frac{\partial f_\theta}{\partial l} & \frac{\partial f_\theta}{\partial \delta} \\ \frac{\partial f_y}{\partial x} & \frac{\partial f_y}{\partial \theta} & \frac{\partial f_y}{\partial y} & \frac{\partial f_y}{\partial \varphi} & \frac{\partial f_y}{\partial l} & \frac{\partial f_y}{\partial \delta} \\ \frac{\partial f_\varphi}{\partial x} & \frac{\partial f_\varphi}{\partial \theta} & \frac{\partial f_\varphi}{\partial y} & \frac{\partial f_\varphi}{\partial \varphi} & \frac{\partial f_\varphi}{\partial l} & \frac{\partial f_\varphi}{\partial \delta} \\ \frac{\partial f_l}{\partial x} & \frac{\partial f_l}{\partial \theta} & \frac{\partial f_l}{\partial y} & \frac{\partial f_l}{\partial \varphi} & \frac{\partial f_l}{\partial l} & \frac{\partial f_l}{\partial \delta} \\ \frac{\partial f_\delta}{\partial x} & \frac{\partial f_\delta}{\partial \theta} & \frac{\partial f_\delta}{\partial y} & \frac{\partial f_\delta}{\partial \varphi} & \frac{\partial f_\delta}{\partial l} & \frac{\partial f_\delta}{\partial \delta} \end{pmatrix} \begin{pmatrix} x_i \\ \theta_i \\ y_i \\ \varphi_i \\ l_i \\ \delta_i \end{pmatrix}$$

Transport matrix : symmetries

- The matrix also reflects upon many of the symmetries of the motion.

  The most notable of them is referred to as horizontal midplane symmetry and it is a result of having only electromagnetic fields that are symmetric about the y=0 plane.

  As a consequence, all cross terms between the horizontal and vertical plane will vanish

$$\mathbf{A} = \begin{bmatrix} (x,x) & (x,a) & 0 & 0 & (x,l) & (x,\delta) \\ (a,x) & (a,a) & 0 & 0 & (a,l) & (a,\delta) \\ 0 & 0 & (y,y) & (y,b) & 0 & 0 \\ 0 & 0 & (b,y) & (b,b) & 0 & 0 \\ (l,x) & (l,a) & 0 & 0 & (l,l) & (l,\delta) \\ (\delta,x) & (\delta,a) & 0 & 0 & (\delta,l) & (\delta,\delta) \end{bmatrix}.$$

- If midplane symmetry about y=0 is imposed, along with explicit time-independence and energy constancy, then the resulting form of the transfer matrix is

$$\mathbf{A} = \begin{bmatrix} (x,x) & (x,a) & 0 & 0 & 0 & (x,\delta) \\ (a,x) & (a,a) & 0 & 0 & 0 & (a,\delta) \\ 0 & 0 & (y,y) & (y,b) & 0 & 0 \\ 0 & 0 & (b,y) & (b,b) & 0 & 0 \\ (l,x) & (l,a) & 0 & 0 & (l,l) & (l,\delta) \\ 0 & 0 & 0 & 0 & 0 & (\delta,\delta) \end{bmatrix}$$

M.Portillo's thesis

- **The transport matrix R of system from n blocks is the result of production of n transport matrices:**

$$R = R_n \times R_{n-1} \times \cdots \times R_1$$

- **In practice the next designation are used:**

$$\frac{\partial f_x}{\partial x} = \left(\frac{x}{x}\right)$$

$$\frac{\partial f_\theta}{\partial x} = \left(\frac{\theta}{x}\right)$$

$$\vdots$$

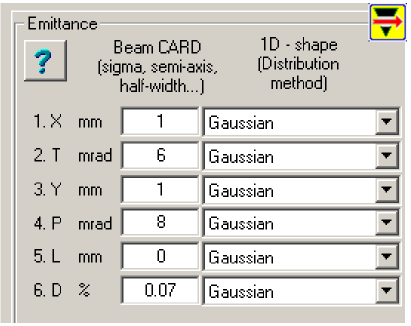
- **The σ- matrix describes phase space widths**

$$\sigma = \begin{pmatrix} \sigma_{xx} & \sigma_{x\theta} & \sigma_{xy} & \sigma_{x\varphi} & \sigma_{x\delta} \\ \sigma_{\theta x} & \sigma_{\theta\theta} & \sigma_{\theta y} & \sigma_{\theta\varphi} & \sigma_{\theta\delta} \\ \sigma_{yx} & \sigma_{y\theta} & \sigma_{yy} & \sigma_{y\varphi} & \sigma_{y\delta} \\ \sigma_{\varphi x} & \sigma_{\varphi\theta} & \sigma_{\varphi y} & \sigma_{\varphi\varphi} & \sigma_{\varphi\delta} \\ \sigma_{\delta x} & \sigma_{\delta\theta} & \sigma_{\delta y} & \sigma_{\delta\varphi} & \sigma_{\delta\delta} \end{pmatrix}$$

- **Transmission will be done by cuts in distribution, defined by the σ-matrix and transport matrices**

$$\sigma' = R \cdot \sigma \cdot R^T$$

- **σ- vector**



Definitions

- **Meanings of some coefficients:**
  - (x/x) – horizontal spatial magnification
  - (θ/θ) – horizontal angular magnification
  - (y/y) – vertical spatial magnification
  - (φ/φ) – vertical angular magnification
  - (x/θ) – horizontal **focus (if equal to 0)**
  - (y/φ) – vertical **focus (if equal to 0)**
  - (x/δ) – horizontal spatial dispersion
  - (θ /δ) – horizontal angular dispersion
  - (y/δ) – vertical spatial dispersion
  - (φ /δ) – vertical angular dispersion

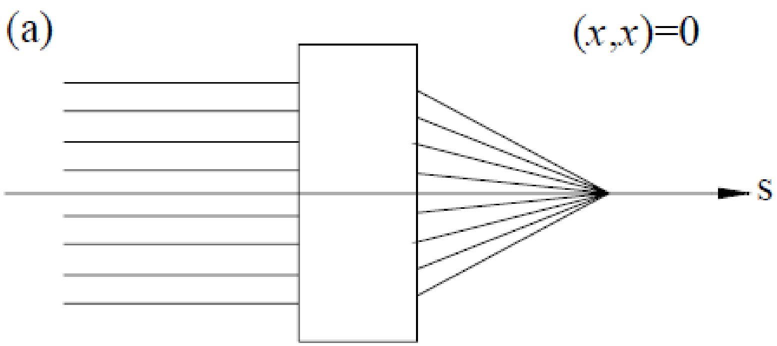
Emittance

$$\varepsilon_h = \pi \Delta x \, \Delta\theta$$

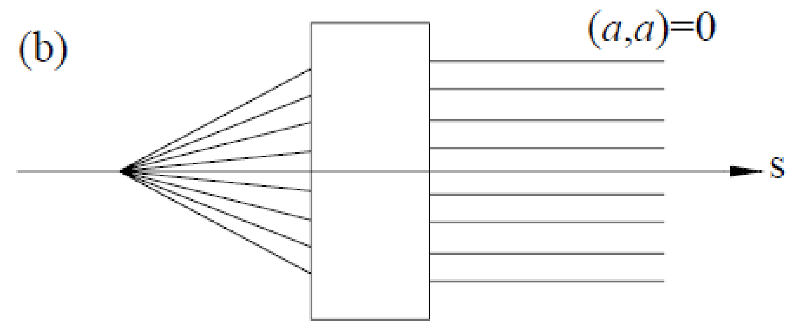
Δx – initial beam size in the object point,
Δθ - angular spread

- the system is **achromatic** in the horizontal space $\left(\frac{x}{\delta}\right) = \left(\frac{\theta}{\delta}\right) = 0$
- betatron isochronism $\left(\frac{l}{x}\right) = \left(\frac{l}{\theta}\right) = \left(\frac{l}{y}\right) = \left(\frac{l}{\varphi}\right) = 0$
- isochronous chromatism $\left(\frac{l}{\delta}\right) = 0$

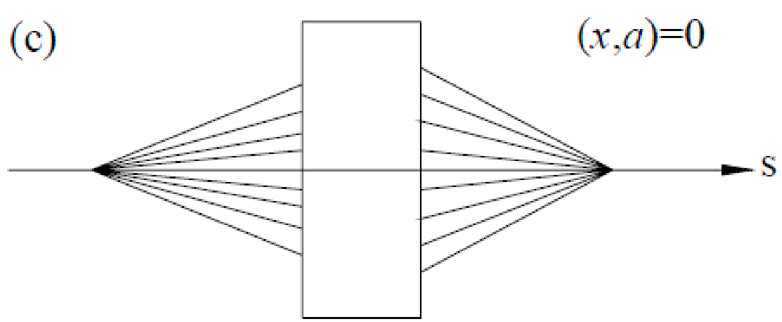
Focusing conditions



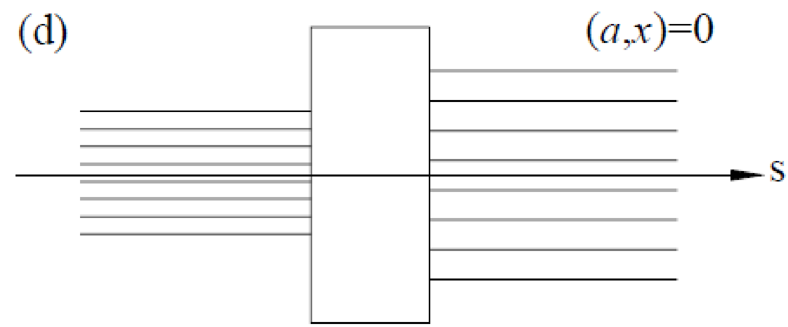
parallel-to-point



point-to-parallel



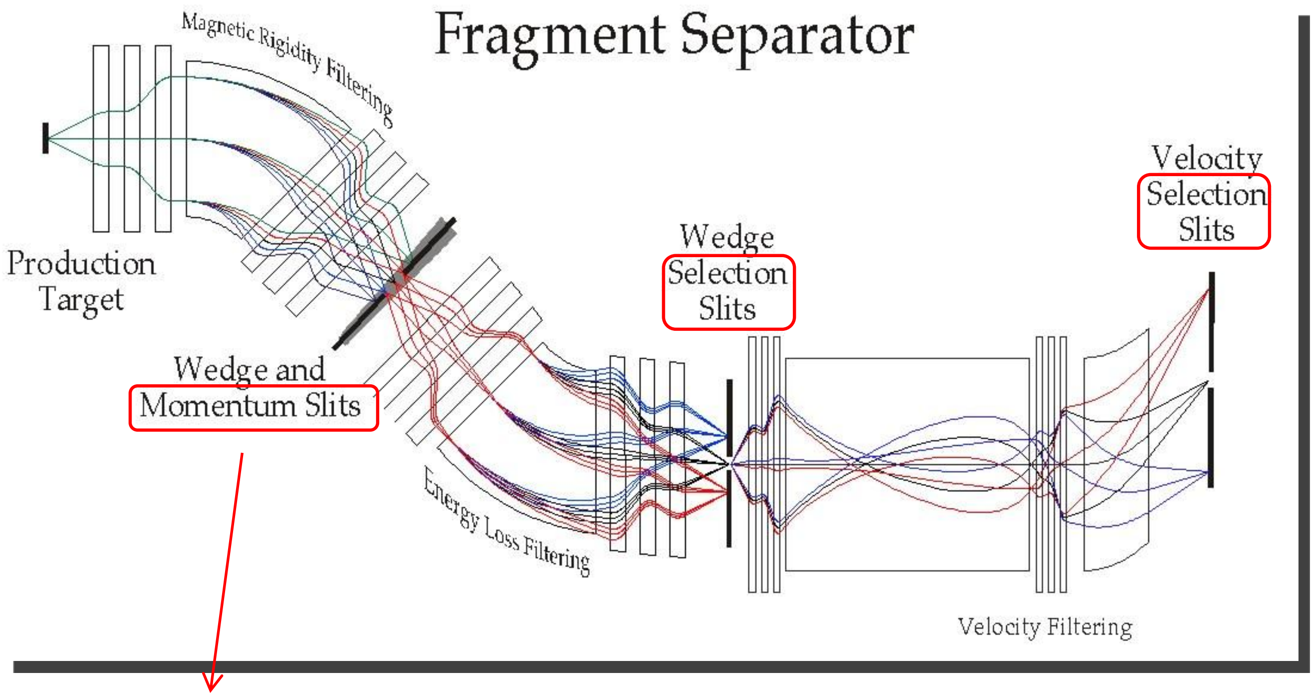
point-to-point



parallel-to-parallel

M.Portillo's thesis

What is "Separation", where and when it takes place?



Magnetic rigidity selection

Global matrix

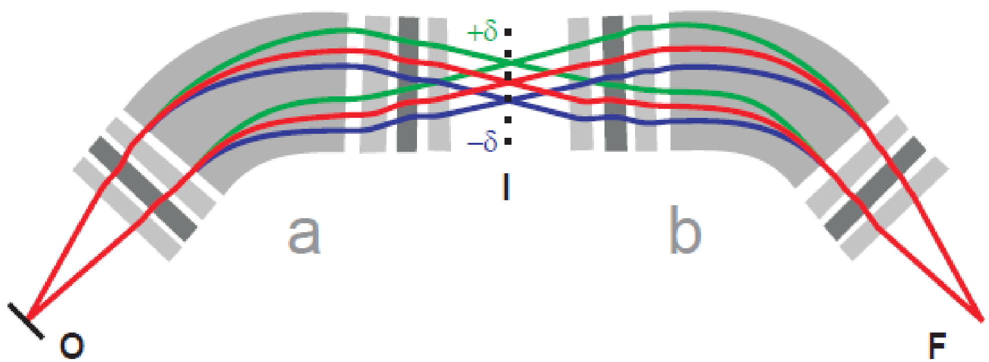
1. X	2.19739	0.04483	0	0	0	-59.12102	[mm]
2. T	-1.05083	0.43363	0	0	0	0	[mrad]
3. Y	0	0	0.83626	-0.00008	0	0	[mm]
4. F	0	0	6.30069	1.19541	0	0	[mrad]
5. L	6.21266	-2.56373	0	0	1	12.20843	[mm]
6. D	0	0	0	0	0	1	[%]
	/[mm]	/[mrad]	/[mm]	/[mrad]	/[mm]	/[%]	

1. Selection is cuts by slits
2. There is some kind of dispersion
3. In Focal planes

Achromatic fragment separator

achromatic in the horizontal space $\left(\frac{x}{\delta}\right)=\left(\frac{\theta}{\delta}\right)=0$

No wedge

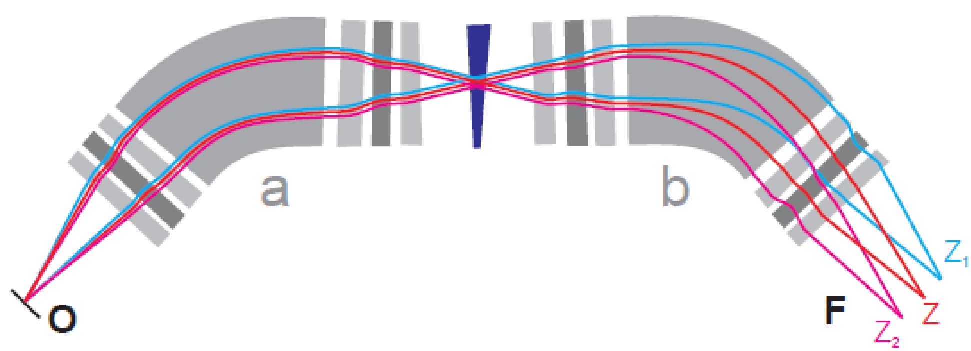


Figures by courtesy of Th.Baumann (MSU)

A1900 matrix

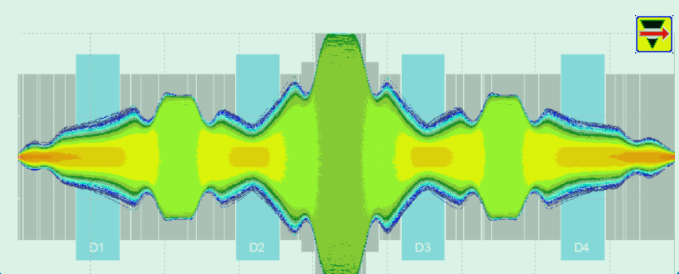
1. X	2.52039	-0.00767	0	0	0	-0.06177	[mm]
2. T	-1.05985	0.39998	0	0	0	0.00317	[mrad]
3. Y	0	0	2.39004	0.01879	0	0.00003	[mm]
4. F	0	0	6.43696	0.46906	0	0.00005	[mrad]
5. L	0.00578	-0.00251	0	0	1	30.1454	[mm]
6. D	0	0	0	0	0	1	[%]
	/[mm]	/[mrad]	/[mm]	/[mrad]	/[mm]	/[%]	

With achromatic wedge

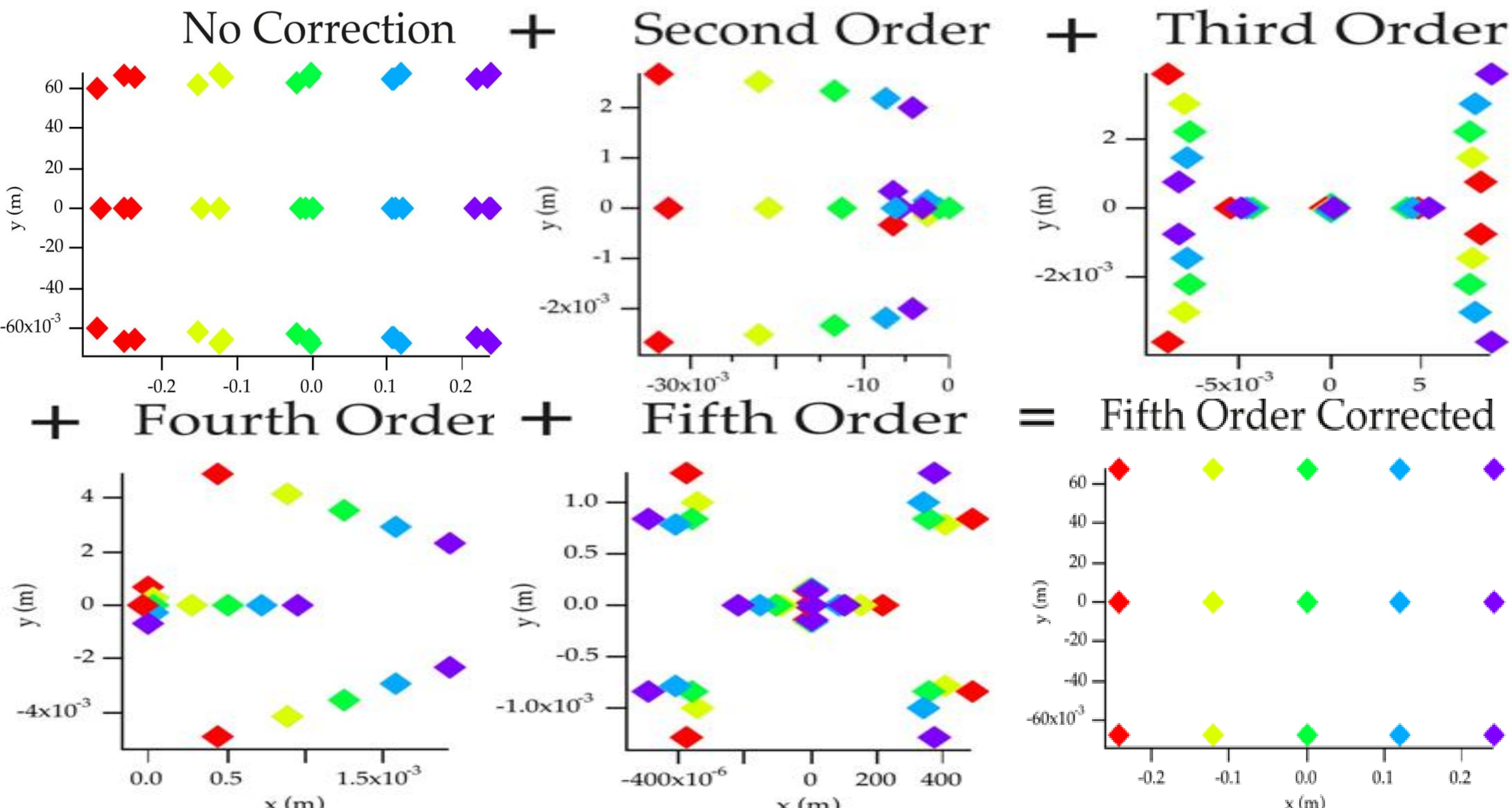


Be a researcher!

Play with LISE++ in Monte Carlo mode changing optical matrices parameters



- **In order to create the Transport matrix we used the first order coefficients of the Taylor expansion assuming small deviation**
- **In reality the life is more complicated…..**
  Nowadays we are using devices with large angular and momentum acceptances



S800 spectrograph simulation by D.Bazin (MSU)

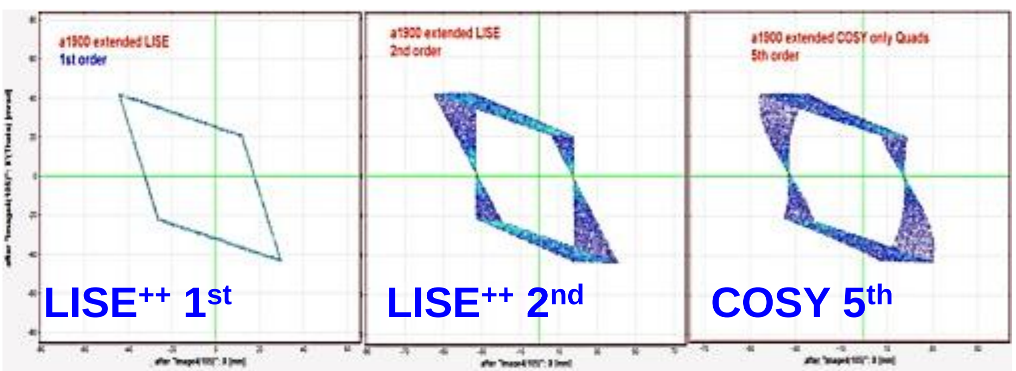
High Order Optics in LISE++

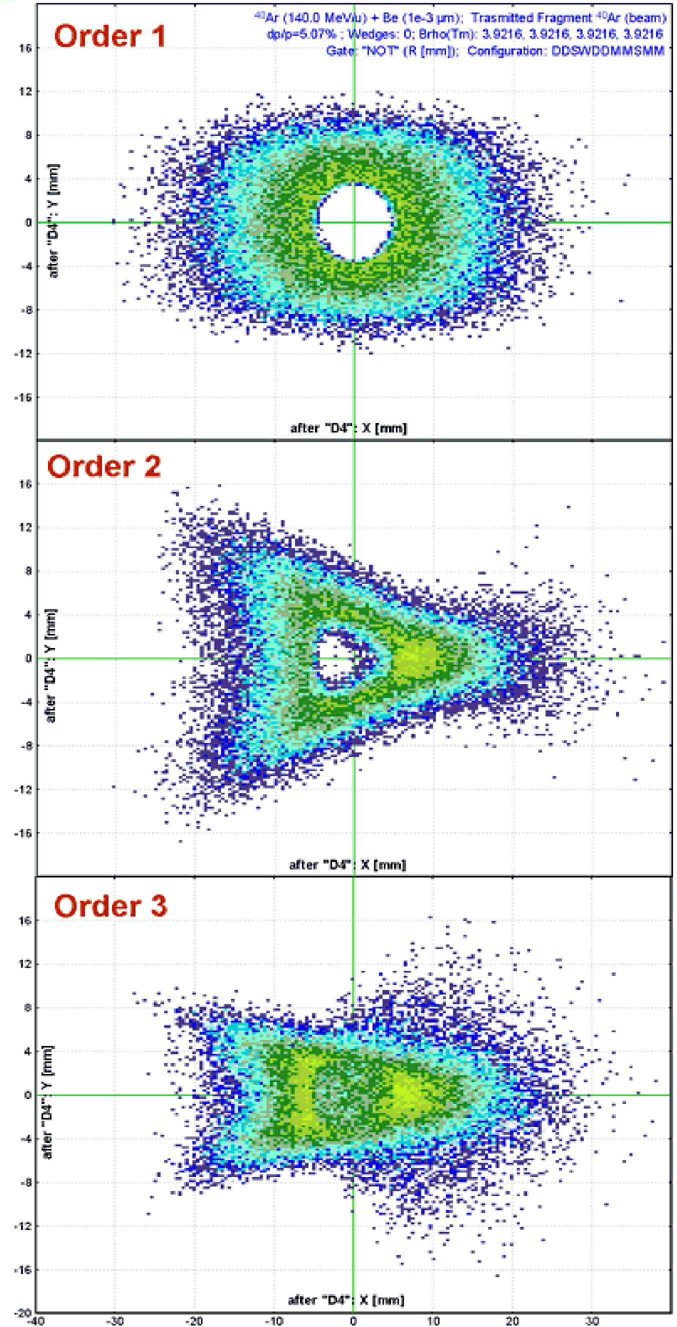
- LISE++ is able to operate with 5th order matrices
- High order optics can be used only in Monte Carlo mode

  http://lise.nscl.msu.edu/8_3/HighOrder_v8_3_158.pdf

- LISE++ can calculate 1st and 2nd order matrices based on the Transport formalism
- Higher matrices can be loaded (or linked) from files prepared by the COSY code

  http://lise.nscl.msu.edu/9_2/9_2_33/9_2_33.pdf





Beam transport codes

❑ Linear Algebra (Matrix calculations)

- first and second order ion-optics calculations (e.g. TRANSPORT, LISE^{++})
- use up to 5th order (e.g. LISE^{++}, MOCADI)

❑ Higher order ion-optics code to solve equation of motion

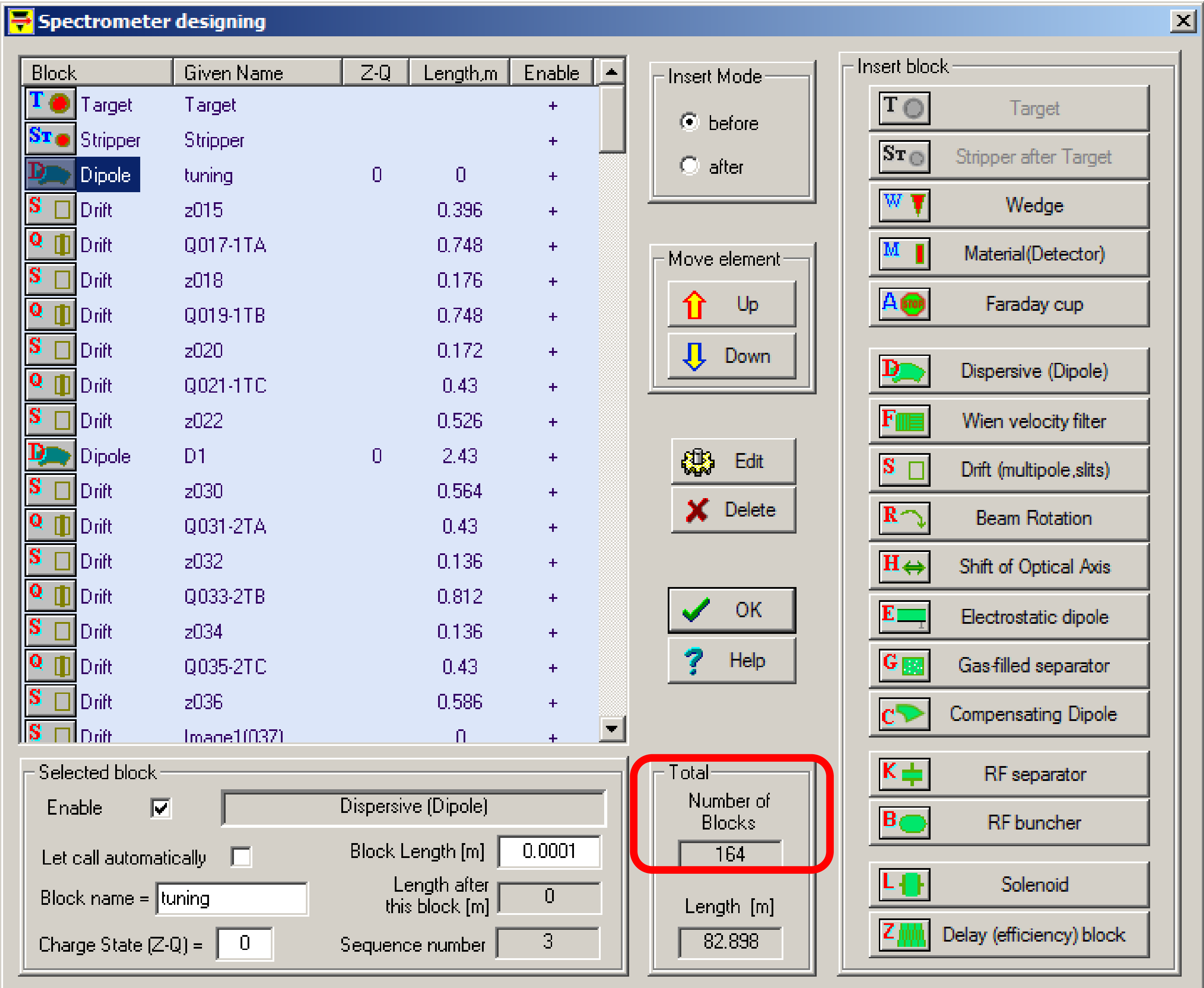
- Code COSY Infinity uses Differential Algebraic techniques to arbitrary orders using matrix representation for fast calculations.
- Code RAYTRACE slices the system in small sections along the z-axis and integrates numerically the particle ray through the system
- MOTER – RAYTRACE version with optimizer.
  The new update has not been finished.. Anybody?

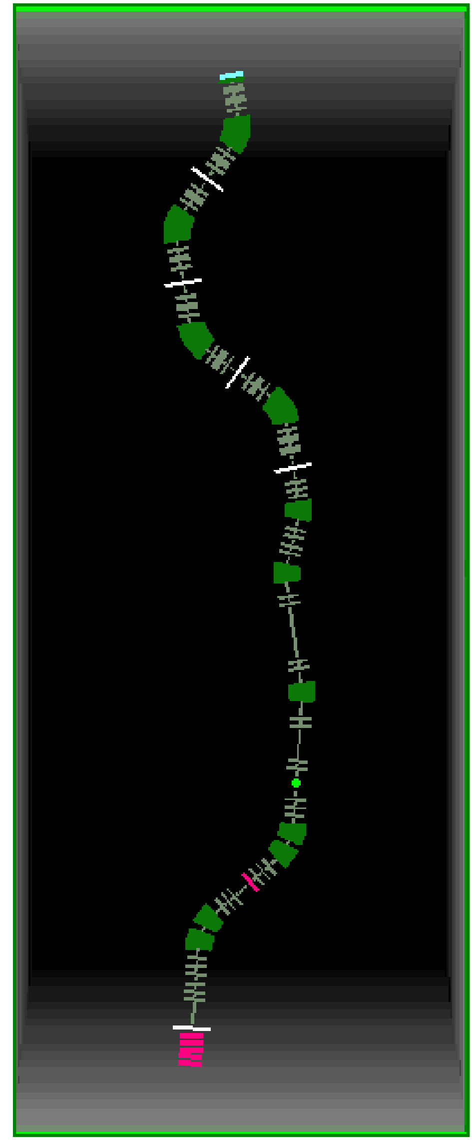
❑ Electro-magnetic field program (solution of Maxwell's Equations)

- (e.g. finite element (FE) codes, 2d & 3d: POISSON, MagNet et al.)

TRANSPORT	K. L. Brown, The ion optical program TRANSPORT. Technical Report 91, SLAC, 1979; Graphic Transport Framework by Urs Rohrer http://aea.web.psi.ch/Urs_Rohrer/MyWeb/trans.htm
LISE^{++}	http://lise.nscl.msu.edu/
MOCADI	http://web-docs.gsi.de/~weick/mocadi/
COSY 10.0	http://www.bt.pa.msu.edu/index_cosy.htm
GIOS	H. Wollnik, J. Brezina and M. Berz, NIM, A258, (1987) 408
GICOSY	http://web-docs.gsi.de/~weick/gicosy/ (based on COSY 5.0)
RAYTRACE	
MOTER	http://lise.nscl.msu.edu/moter.html

Configuration: A1900_S800BL_extended_LISE 2012 2nd order

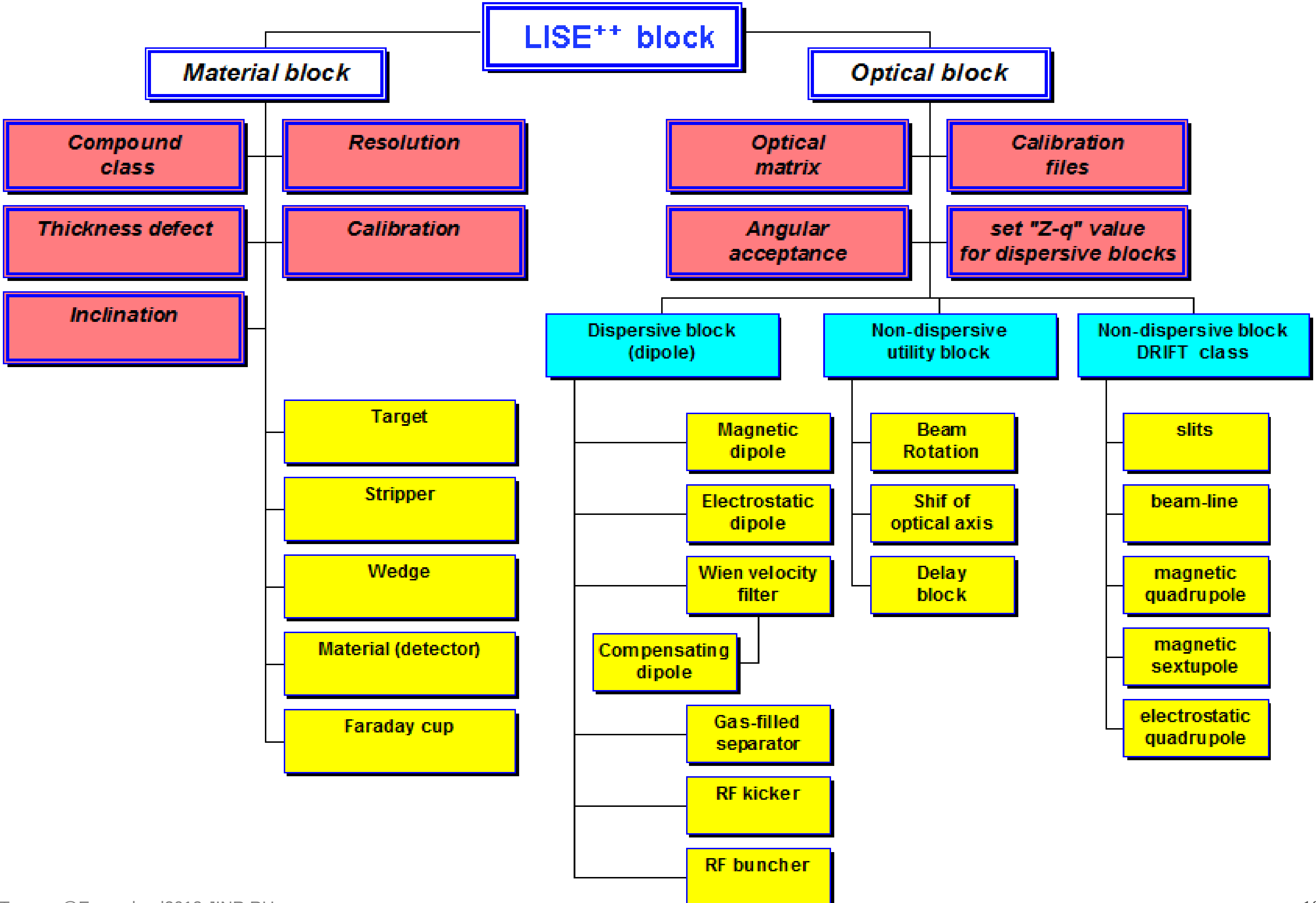




Fragment separator design @ LISE^{++}

- **Setup of fragment separator**
  - "Blocks" are individual elements with their own characteristics
  - Optics blocks describe beam line components with optical matrix, acceptances, length and slits
  - Material blocks describe things in the way of the beam such as targets, wedges, detectors
- **Up to 300 blocks**

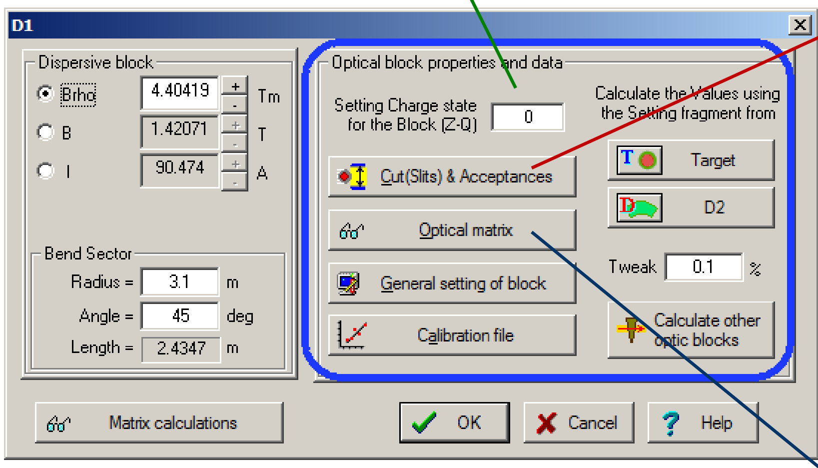
LISE++ block classification

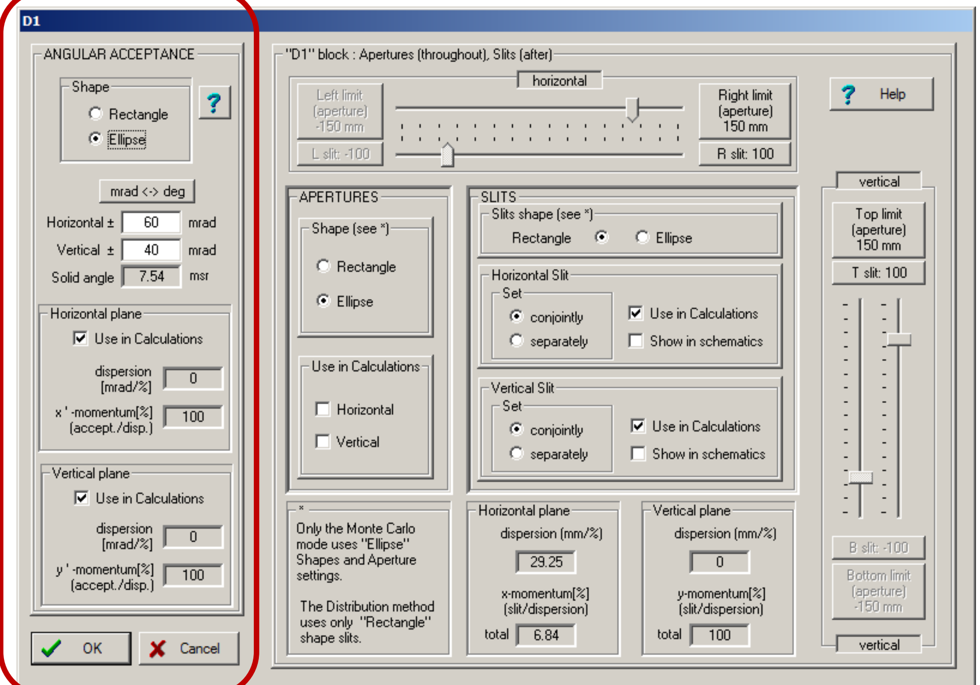


"Optical" block property

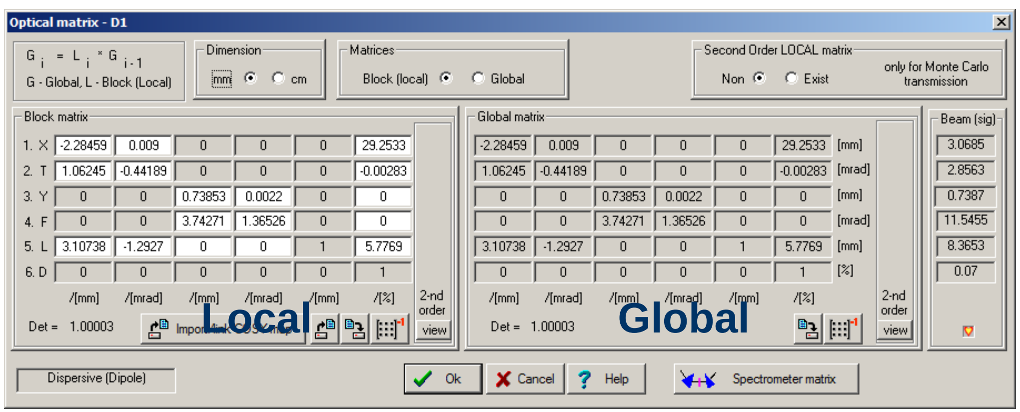
Charge State (Z-Q): property of dispersive optical block -- you can edit the charge state value for the setting fragment.

Angular acceptance





Optical matrices



Block matrix:

1. X	-2.28459	0.009	0	0	0	29.2533
2. T	1.06245	-0.44189	0	0	0	-0.00283
3. Y	0	0	0.73853	0.0022	0	0
4. F	0	0	3.74271	1.36526	0	0
5. L	3.10738	-1.2927	0	0	1	5.7769
6. D	0	0	0	0	0	1
	/[mm]	/[mrad]	/[mm]	/[mrad]	/[mm]	/[%]

Global matrix:

							Beam (sig)
-2.28459	0.009	0	0	0	29.2533	[mm]	3.0685
1.06245	-0.44189	0	0	0	-0.00283	[mrad]	2.8563
0	0	0.73853	0.0022	0	0	[mm]	0.7387
0	0	3.74271	1.36526	0	0	[mrad]	11.5455
3.10738	-1.2927	0	0	1	5.7769	[mm]	8.3653
0	0	0	0	0	1	[%]	0.07
/[mm]	/[mrad]	/[mm]	/[mrad]	/[mm]	/[%]		

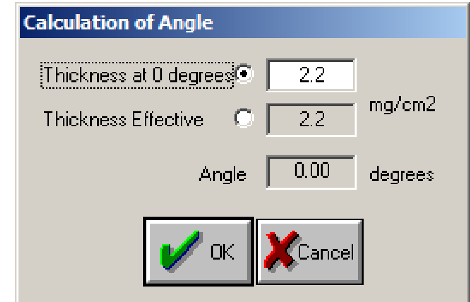
$$G_i = L_i \times G_{i-1}$$

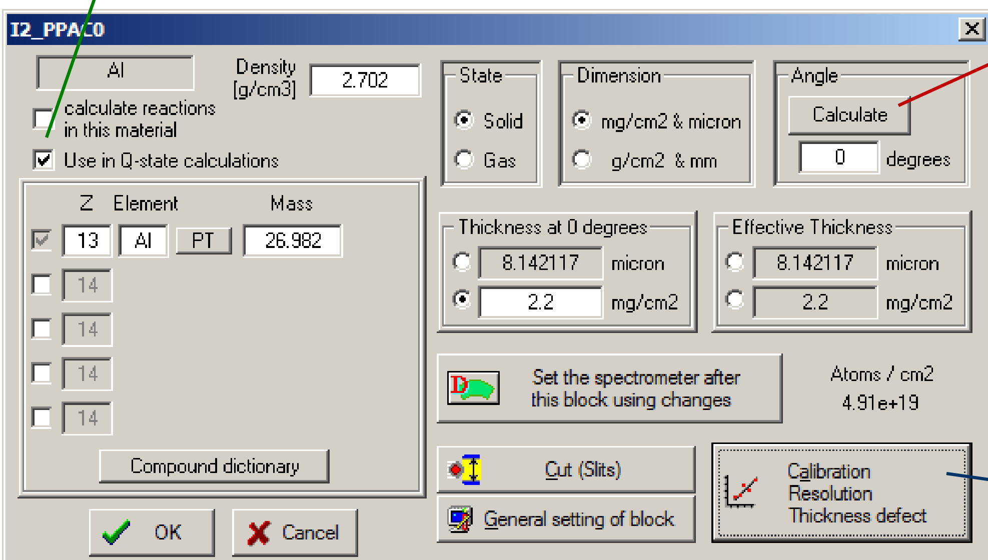
where G is the global matrix, and L is the local matrix

“Material” block property

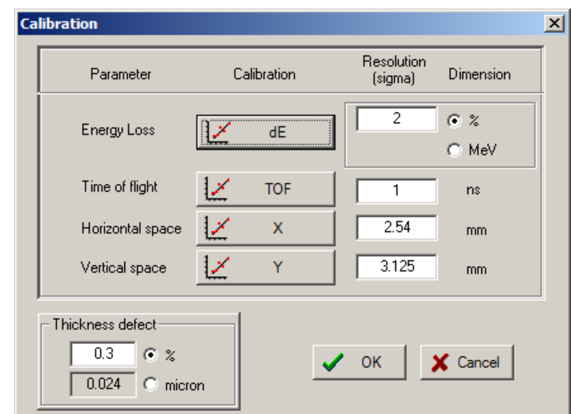
Depending from material thickness or necessity you can set this material being used for charge state calculations

inclination





Resolution, Calibration, Thickness defect

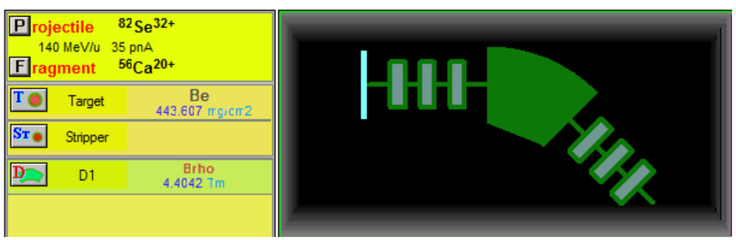


LISE++ configuration types

- **Classical** (segmented) **configuration:**
  dispersive block contains quads, drifts, dipole and so on
- **Extended** (elemental) **configuration:**
  like in TRANSPORT all elements are separated, and their matrices can be calculated inside LISE++

So, let's take the first dispersive block of A1900

segmented *1 block after stripper*

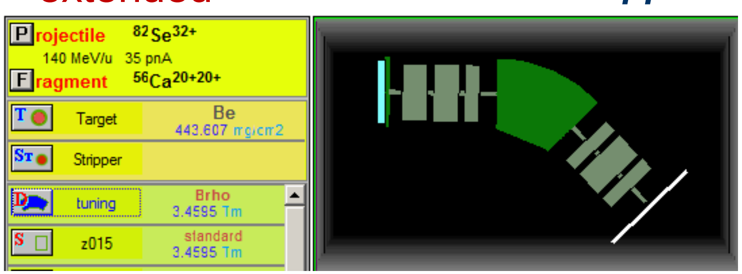


Taken from TRANSPORT

Block matrix

1. X	-2.28459	0.009	0	0	0	29.2533
2. T	1.06245	-0.44189	0	0	0	-0.00283
3. Y	0	0	0.73853	0.0022	0	0
4. F	0	0	3.74271	1.36526	0	0
5. L	3.10738	-1.2927	0	0	1	5.7769
6. D	0	0	0	0	0	1

extended *17 blocks after stripper*



Calculated by LISE++ including 2nd order

Global matrix

-2.30361	0.00906	0	0	0	28.88518	[mm]
1.07573	-0.43836	0	0	0	-0.00018	[mrad]
0	0	0.73839	0.00259	0	0	[mm]
0	0	3.731	1.36722	0	0	[mrad]
3.10724	-1.26623	0	0	1	-2.42226	[mm]
0	0	0	0	0	1	[%]
/[mm]	/[mrad]	/[mm]	/[mrad]	/[mm]	/[%]	

Tuning of Optical Blocks

Calculations

- Optics ▸
  - Tune spectrometer for setting fragment on beam axis
  - Tune spectrometer for setting fragment at middle of slit
  - Update matrices linked with COSY files
  - Envelope plot
  - First order matrix elements : PLOT
  - First order matrix elements : View & Print
  - Quad & Dipole settings : EDIT
  - Quad & Dipole settings : View & Print
  - Brho(Erho) Analyzer
  - The First- and Second-Order Matrix Elements for an Ideal Magnet
- Goodies
- Calibrations
- Transmission and rate ▸
- Optimum Target
- Optimum Target-Wedge and Wedge-Wedge configurations
- Brho scanning
- Optimum charge state combination
- Monte Carlo calculation of transmission ▸
- Calculators ▸

segmented

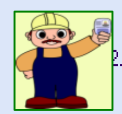
Block	Given Name	Start(m)	Length(m)	B0(kG)	Br(Tm)corr/*real	DriftM/*Angle	Rapp(cm)/*R(m)	L_eff(m)/*L_dip(m)	2 nd order	CalcMatr/*Z-Q	AngAcc,Apps,Slits
Dipole	D1	0.000	8.7190	+14.2116	* 4.4056	* 45.0	* 3.1000	* 2.4347	no	* 0	HV -- HV

Brho

Slits, acceptance

extended

Block	Given Name	Start(m)	Length(m)	B0(kG)	Br(Tm)corr/*real	DriftM/*Angle	Rapp(cm)/*R(m)	L_eff(m)/*L_dip(m)	2 nd order	CalcMatr/*Z-Q	AngAcc,Apps,Slits
Dipole	tuning	0.000	0.0001	+14.6853	* 4.4056	* 0.0	* 3.0000	* 0.0000	no	* 0	-- -- --
Drift	z015	0.000	0.3960			standard					-- HV --
Drift	Q017-1TA	0.396	0.7480	+15.4196	4.4056	quadrupole	13.3000	0.7480	yes	1	-- HV --
Drift	z018	1.144	0.1756			standard					-- HV --
Drift	Q019-1TB	1.320	0.7480	-14.3295	4.4056	quadrupole	13.3000	0.7480	yes	1	-- HV --
Drift	z020	2.068	0.1720			standard					-- HV --
Drift	Q021-1TC	2.240	0.4300	+10.3091	4.4056	quadrupole	15.0000	0.4300	yes	1	-- HV --
Drift	z022	2.670	0.5260			standard					-- HV --
Dipole	D1	3.196	2.4300	+14.2396	* 4.4056	* 45.0	* 3.0939	.4299	yes	* 0	-- HV --
Drift	z030	5.626	0.5640			standard					-- HV --
Drift	Q031-2TA	6.190	0.4300	+12.6140	4.4056	quadrupole	15.0000	0.4300	yes	1	-- HV --
Drift	z032	6.620	0.1358			standard					-- HV --
Drift	Q033-2TB	6.755	0.8120	-15.5591	4.4056	quadrupole	15.0000	0.8120	yes	1	-- HV --
Drift	z034	7.567	0.1358			standard					-- HV --
Drift	Q035-2TC	7.703	0.4300	+13.6724	4.4056	quadrupole	[illegible]	[illegible]	[illegible]	1	-- HV --
Drift	z036	8.133	0.5860			standard					-- HV --
Drift	Image1(037)	8.719	0.0000			SLITS					-- -- HV

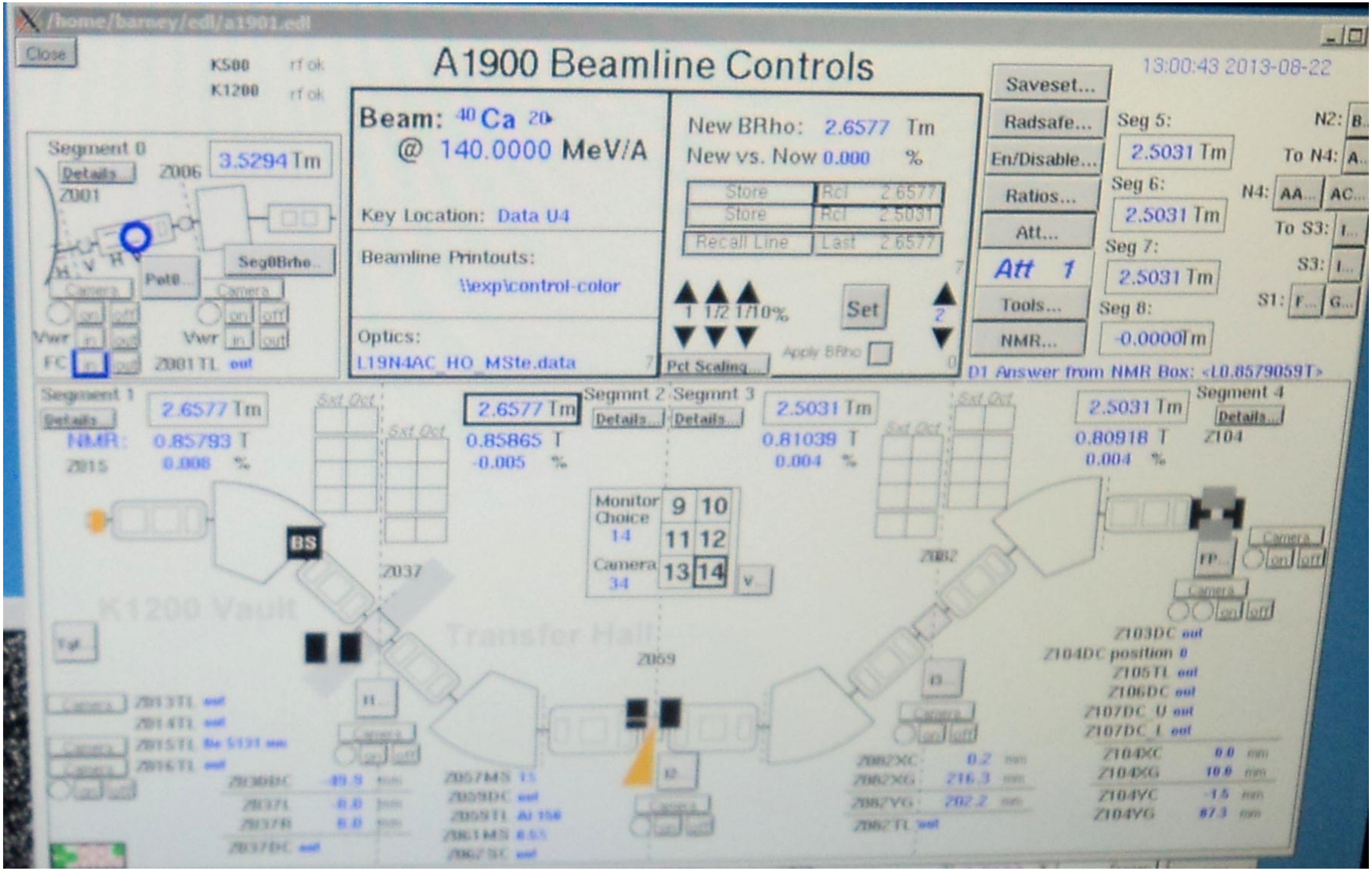


Beam dump location

A1900 Beamline controls

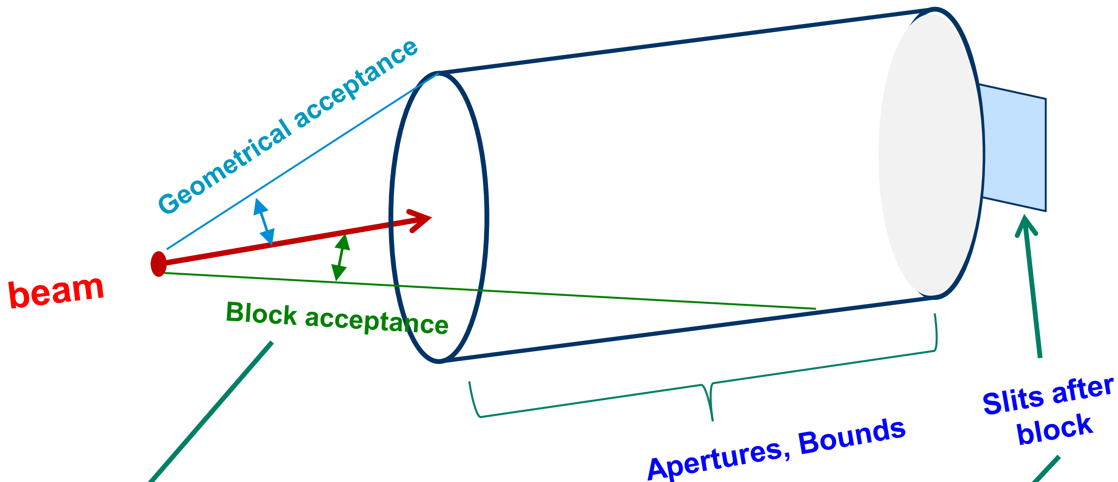
A1900 beam dump

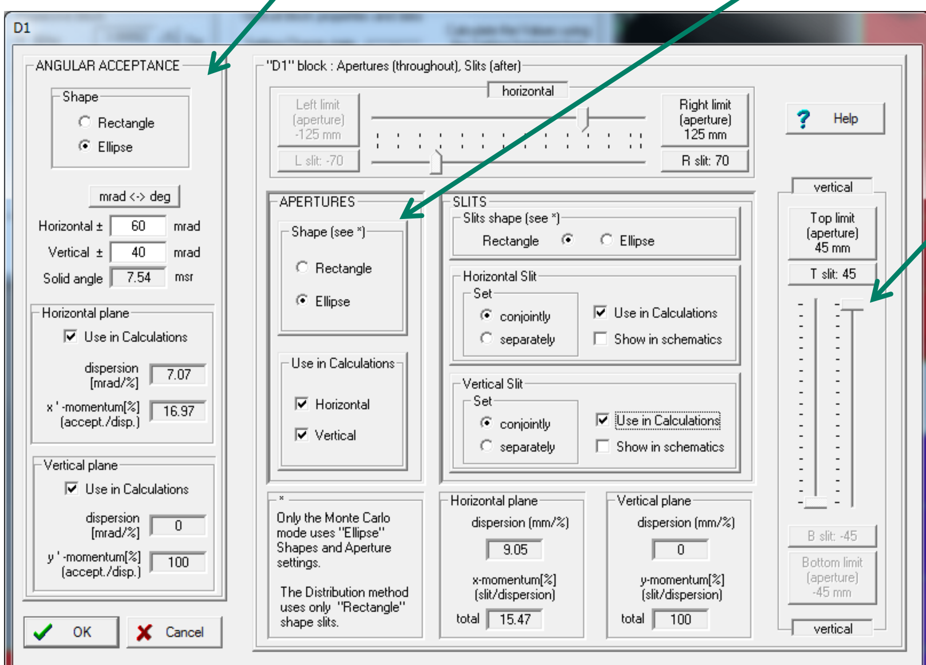
A1900 Beamline controls



Slits, Acceptances in LISE++

Block angular acceptance < Geometrical acceptance

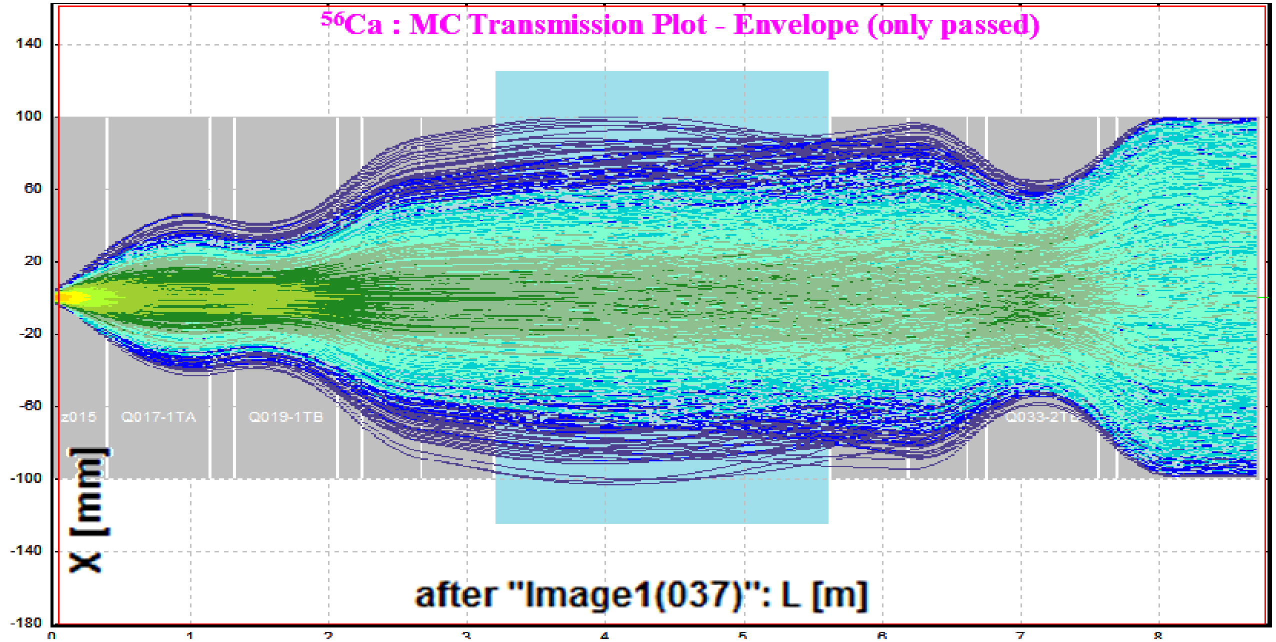




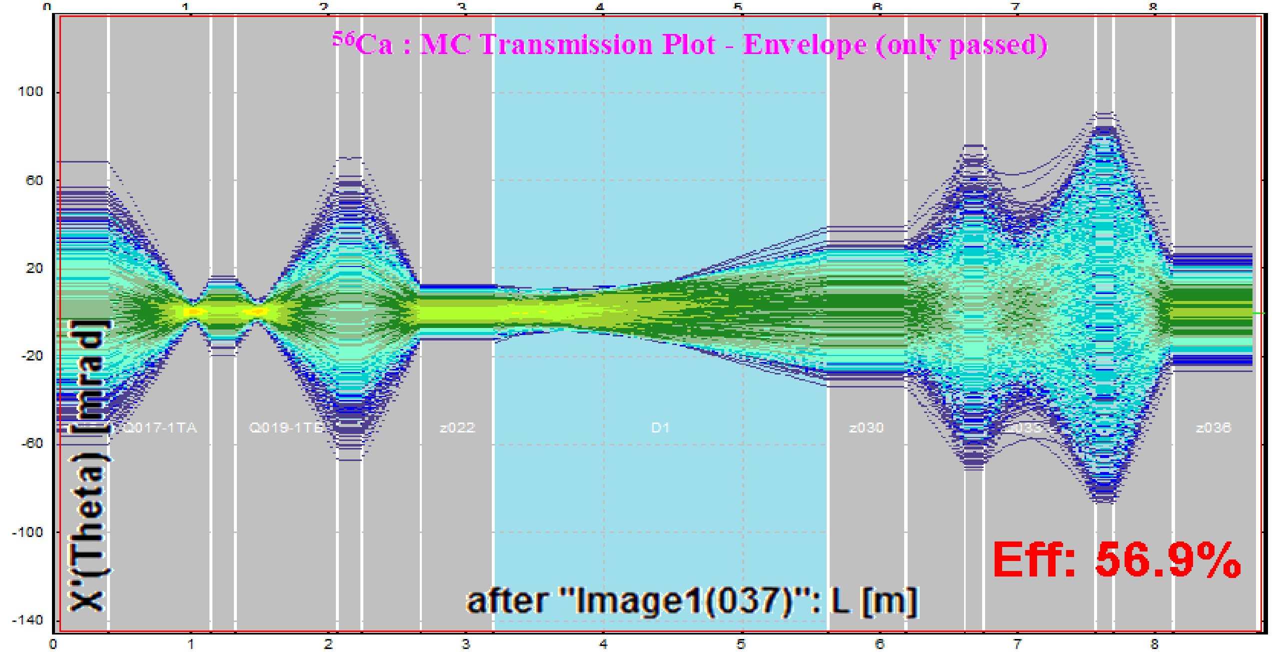
Configuration	Angular Acceptance	Apperture	Slits after block
Classical ("segment")	Yes	No	Yes
Extended ("element")	No	Yes*	please use only for "slits" element

** - Apertures are used only in Monte Carlo calculations*

Envelopes with extended configurations

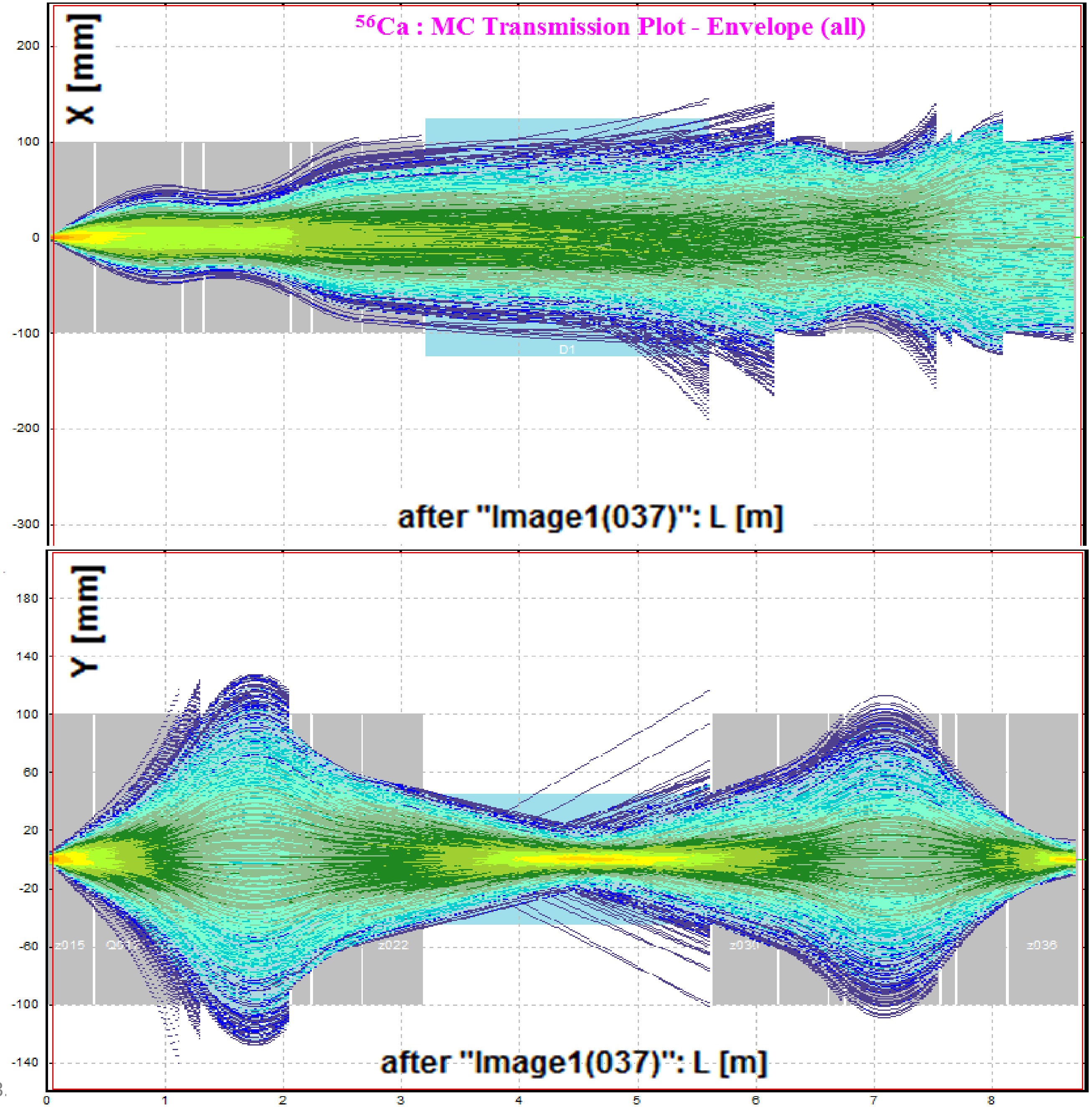


SUM
2.838e+03
CPU speed
0 pps
Eff: 56.8%



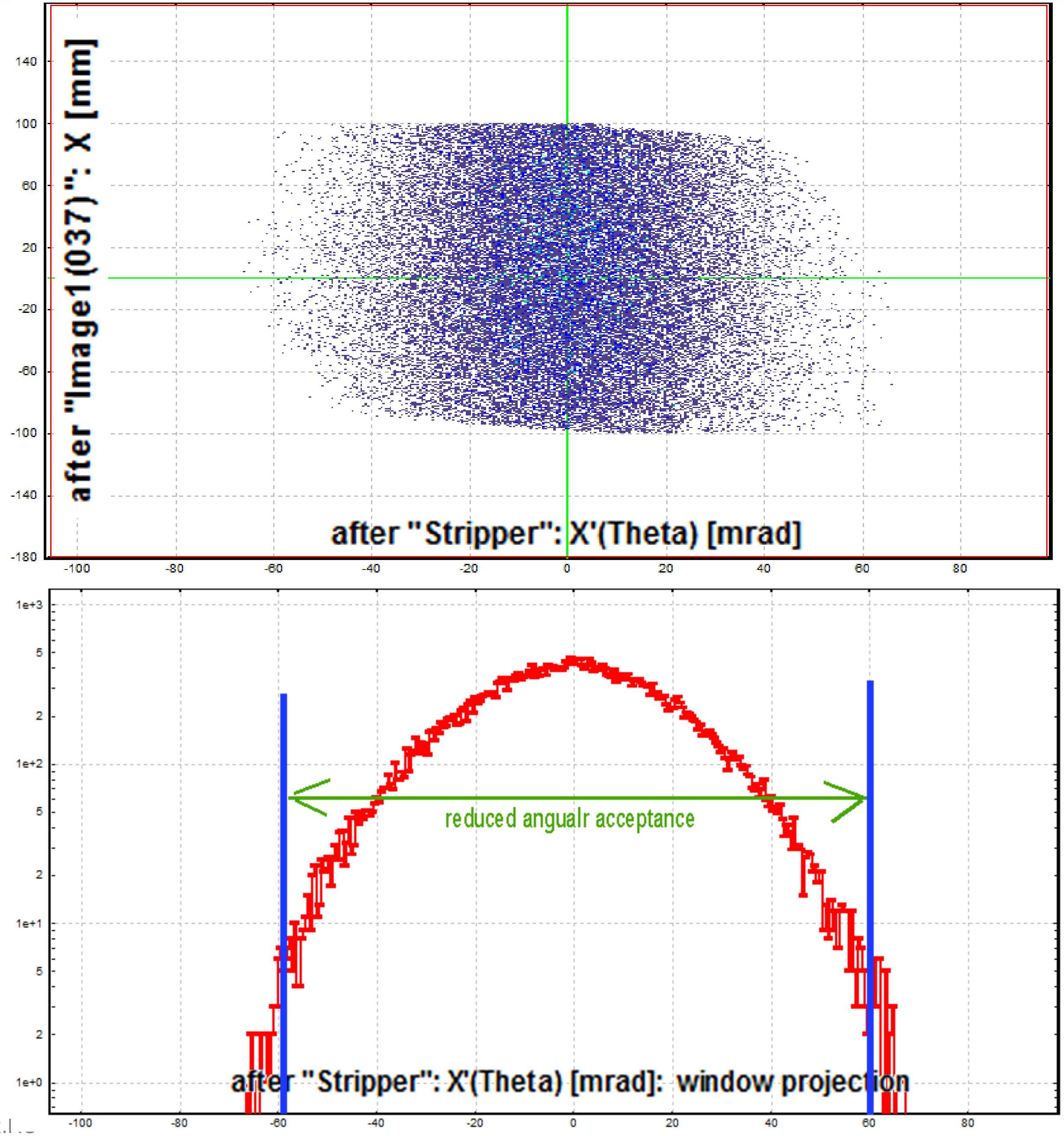
Where fragments have been lost?

extended configurations



Angular acceptances from extended configurations

These Fragments passed through the system



Classical (segmented) configuration:

- Fast transmission calculations
- Simple structure
- Effective with analytical calculations for experiment planning

Extended (elemental) configuration:

- Detailed analysis of transmission
- Optical matrices can be calculated in the code, and used in segmented configurations
- Tools to obtain angular acceptances, which can be used in segmented configurations
- Good tools for understanding (learning) ion-beam optics issues
- Effective with Monte Carlo calculations for fragment separator design

Types of transmission calculations

➢ "Distribution" (analytical) method

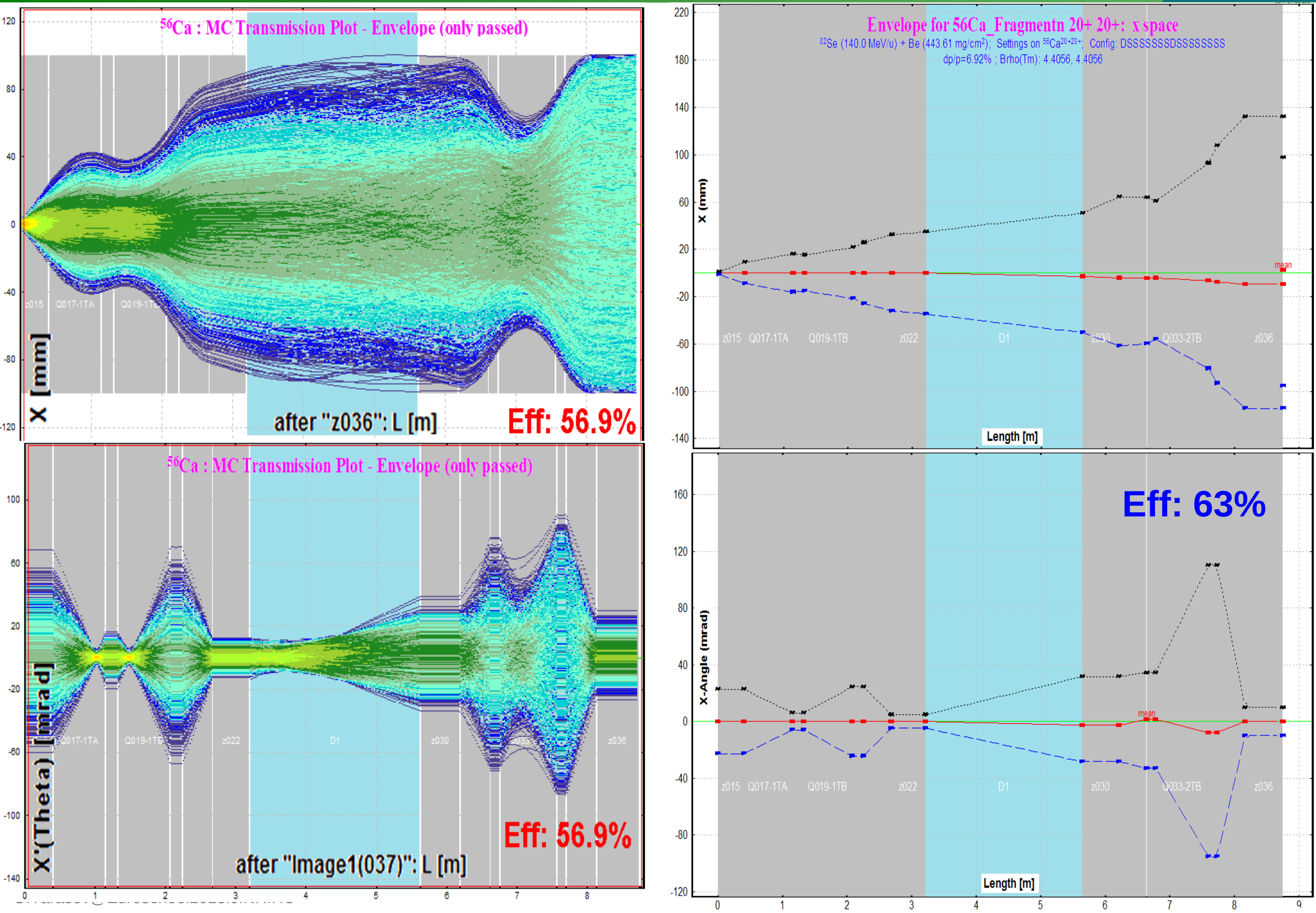
- **Fast calculations**
- **All Optimization procedures in the code based on this method**
- **Effective with segmented configurations for experiment planning**
- **Calculation of low transmission (important for primary beams)**

LISE class	"Distribution"	:	D. Bazin, B. Sherrill, Phys. Rev. E 50 (1994) 4017
LISE class	"Distribution2"	:	2000
LISE++ class	"Distribution4"	:	2003

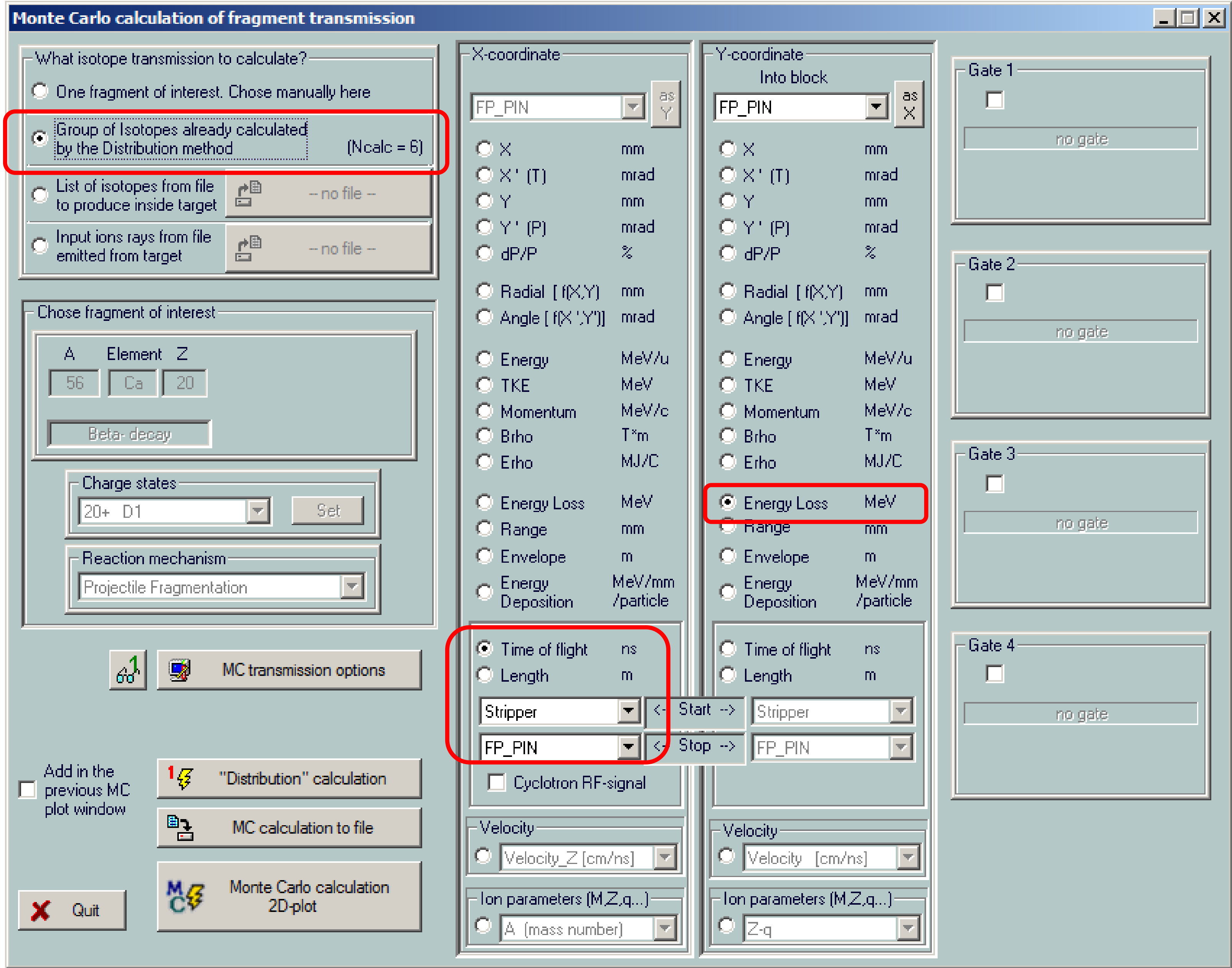
➢ Monte Carlo method: (from 2007)

- **Benchmark for the "Distribution" method**
- **Detailed analysis of transmission with extended configurations**
- **Possibility to use High Order Optics**
- **Observation of correlations between different parameters of different blocks**
- **Possible gates on different parameters**
- **Good tools for understanding (learning) ion-beam optics issues**
- **Effective for fragment separator design**
- **Some optical blocks (Solenoid, RF buncher) are effective only in MC mode**

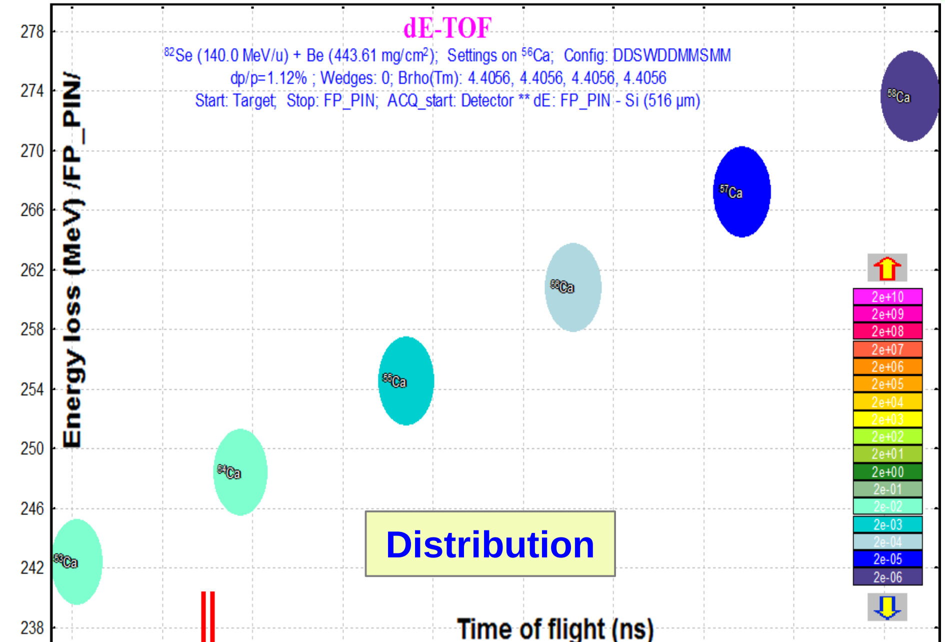
Envelope calculations by different methods

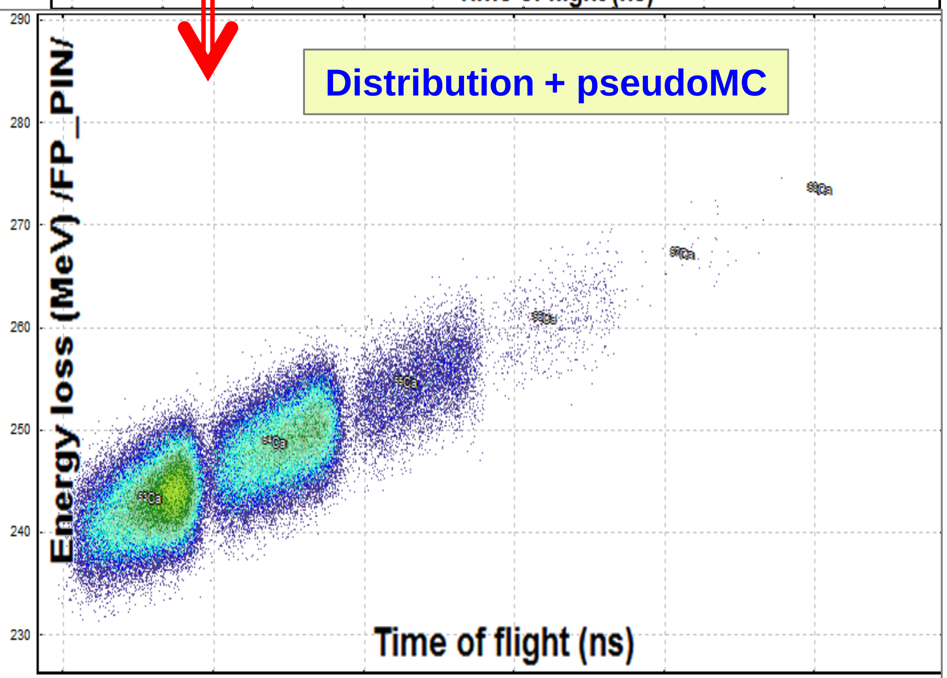


Monte Carlo calculation of fragment transmission



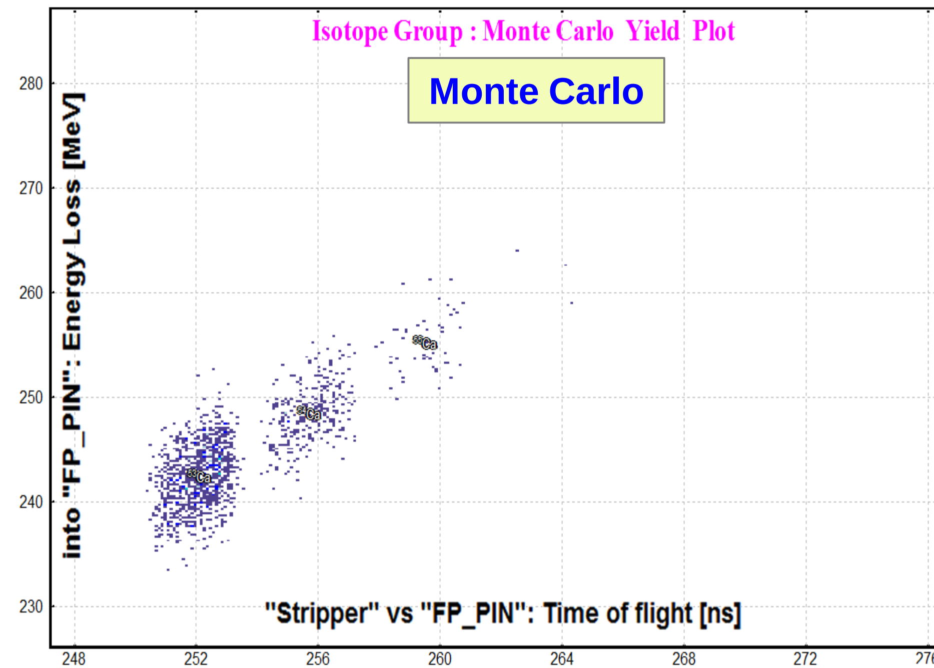
Distribution & Monte Carlo methods





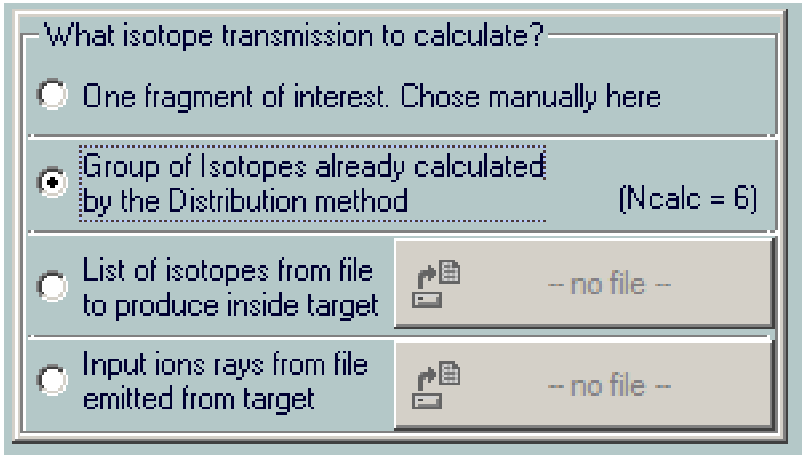
pseudoMC method for plots :

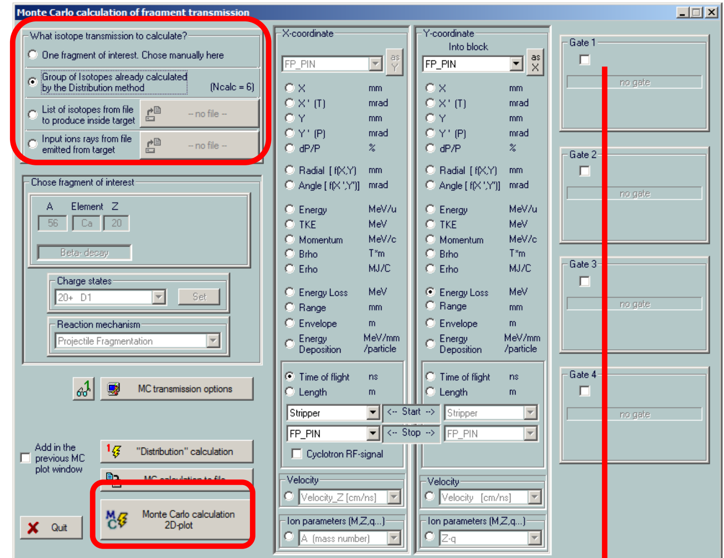
Monte Carlo method is applied to analytically calculated Final Distributions



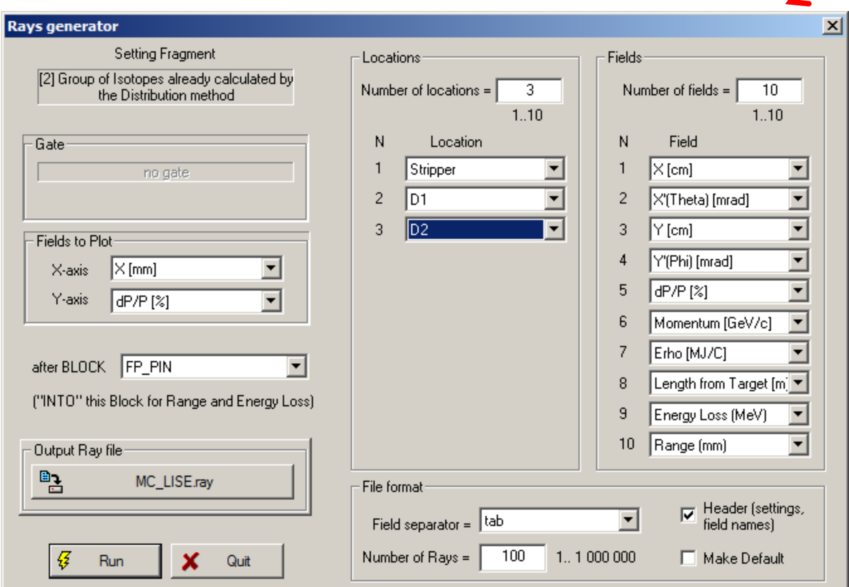
Important features of the Monte Carlo dialog

Different input sources

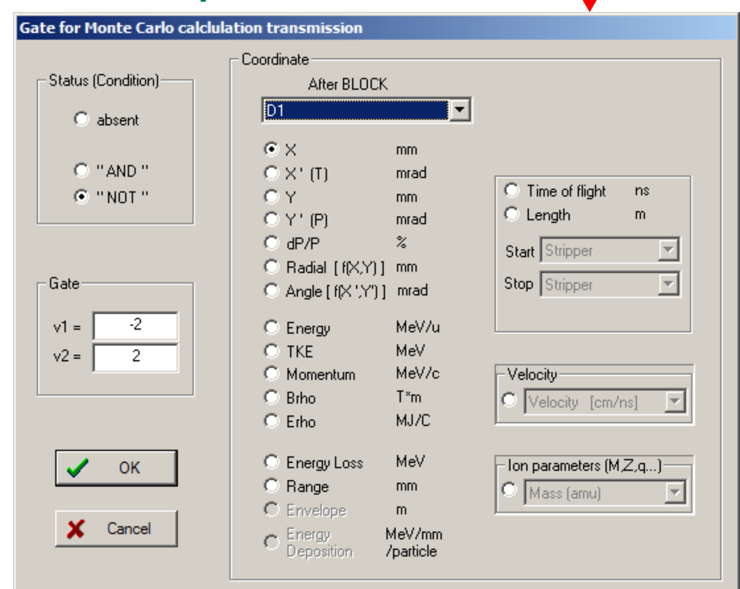




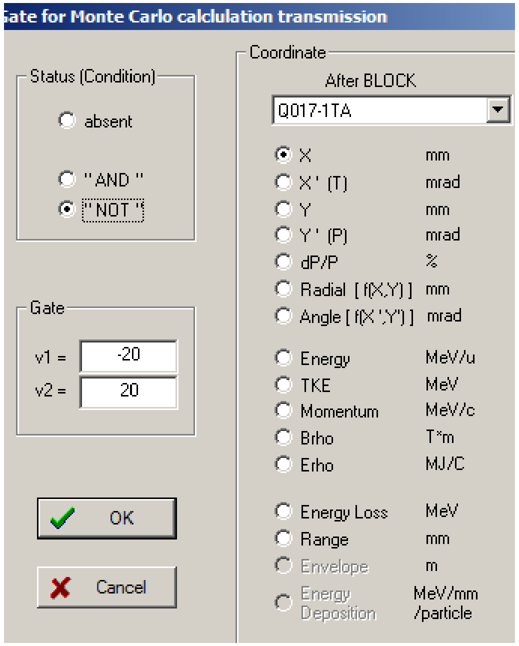
Output in file : Rays generator



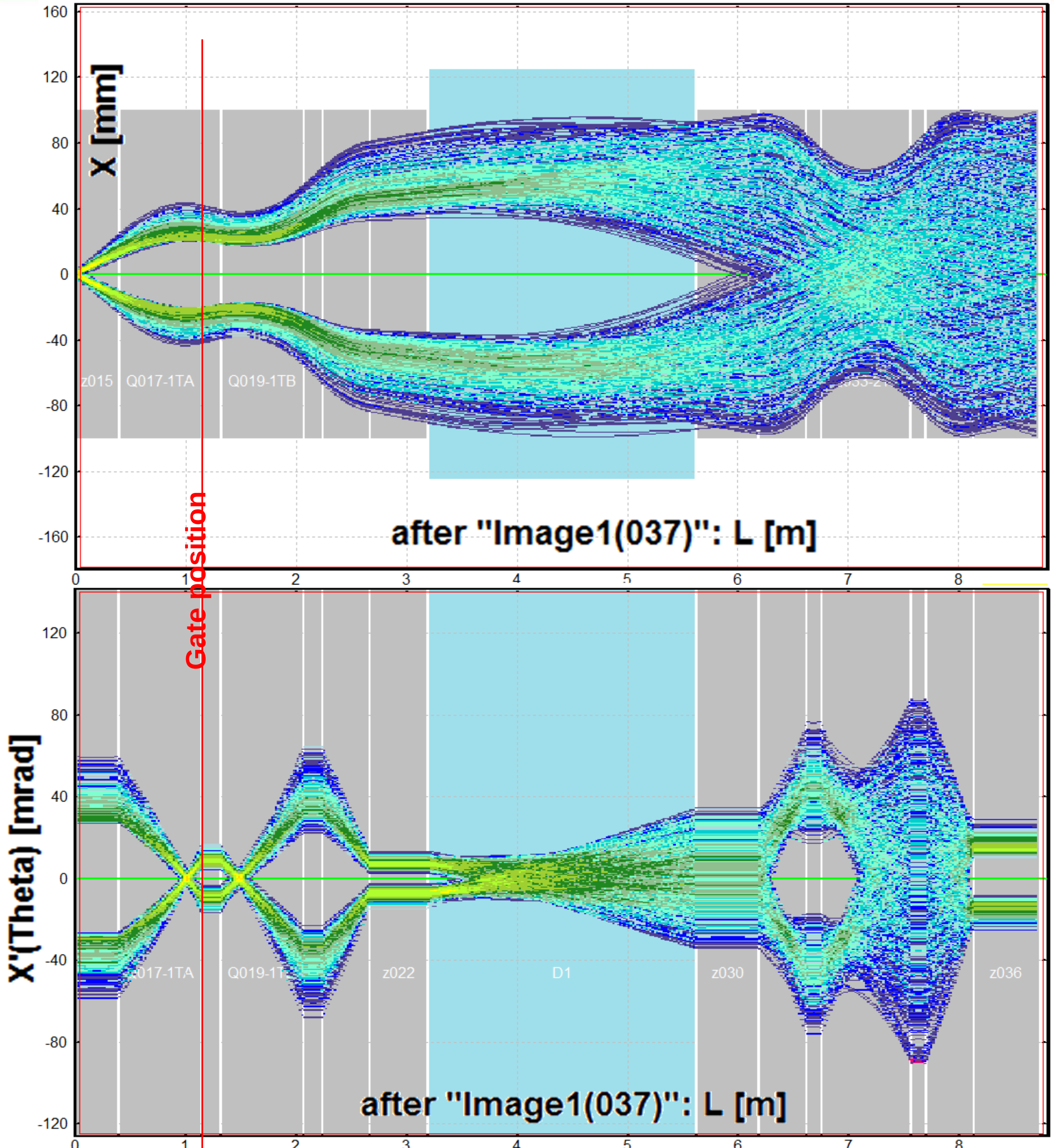
Up to 4 Gates



MC Gate example



Exclude x=[-20,20] after the first quadrupole



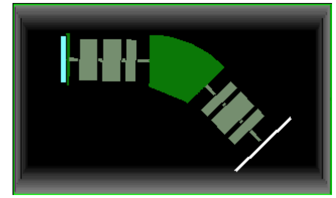
4. Selection with electromagnetic devices

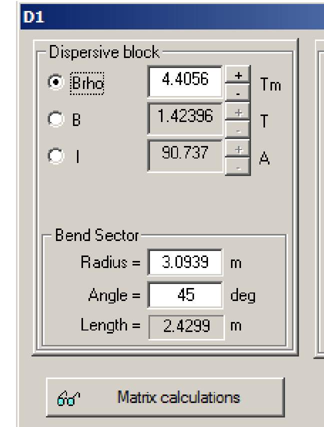
Electromagnetic separation devices in LISE++

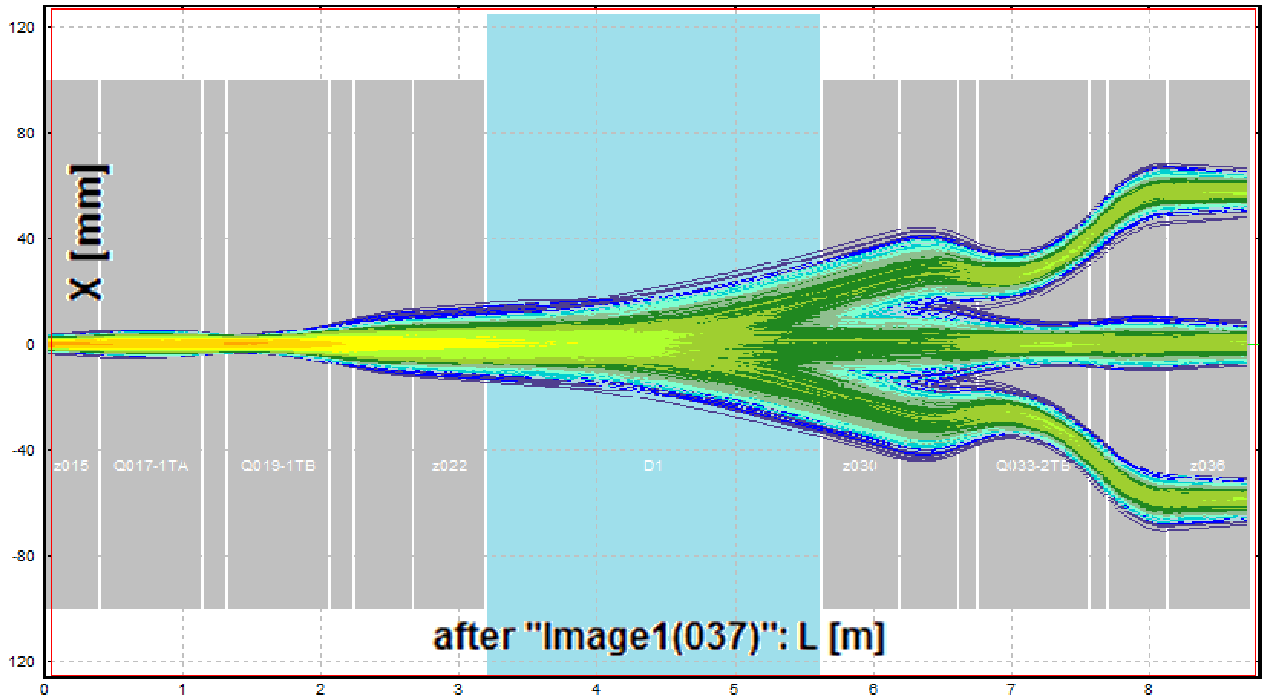
Separation device	Changeable field	Strength	Selection by
Magnetic dipole	Magnetic (B[T])	$\vec{F}_B = q\vec{v} \times \vec{B}$	Magnetic rigidity $B\rho = \frac{mv}{q}$ [T·m]
Gas-filled separator	Magnetic (B[T])	$\vec{F}_B$	Magnetic rigidity
Solenoid	Magnetic (B[T])	$\vec{F}_B$	Focusing (combination A,q,v)
Electrostatic dipole	Electric (E [kV/m])	$\vec{F}_E = q\vec{E}$	Electric rigidity $E\rho = \frac{mv^2}{q}$ [J/C]
RF kicker	Electric (E [kV/m])	$\vec{F}_E$	Time
RF buncher	Electric (E [kV/m])	$\vec{F}_E$	Bunching
Wien-filter *E-cross-B filter*	Magnetic (B[T]) Electric (E [kV/m])	$\vec{F} = \vec{F}_B + \vec{F}_E$	Velocity

Magnetic Dipole

Separation device	Changeable field	Strength	Selection by
Magnetic dipole	Magnetic (B[T])	$\vec{F}_B = q\vec{v} \times \vec{B}$	Magnetic rigidity $B\rho = \frac{mv}{q}$ [T·m]







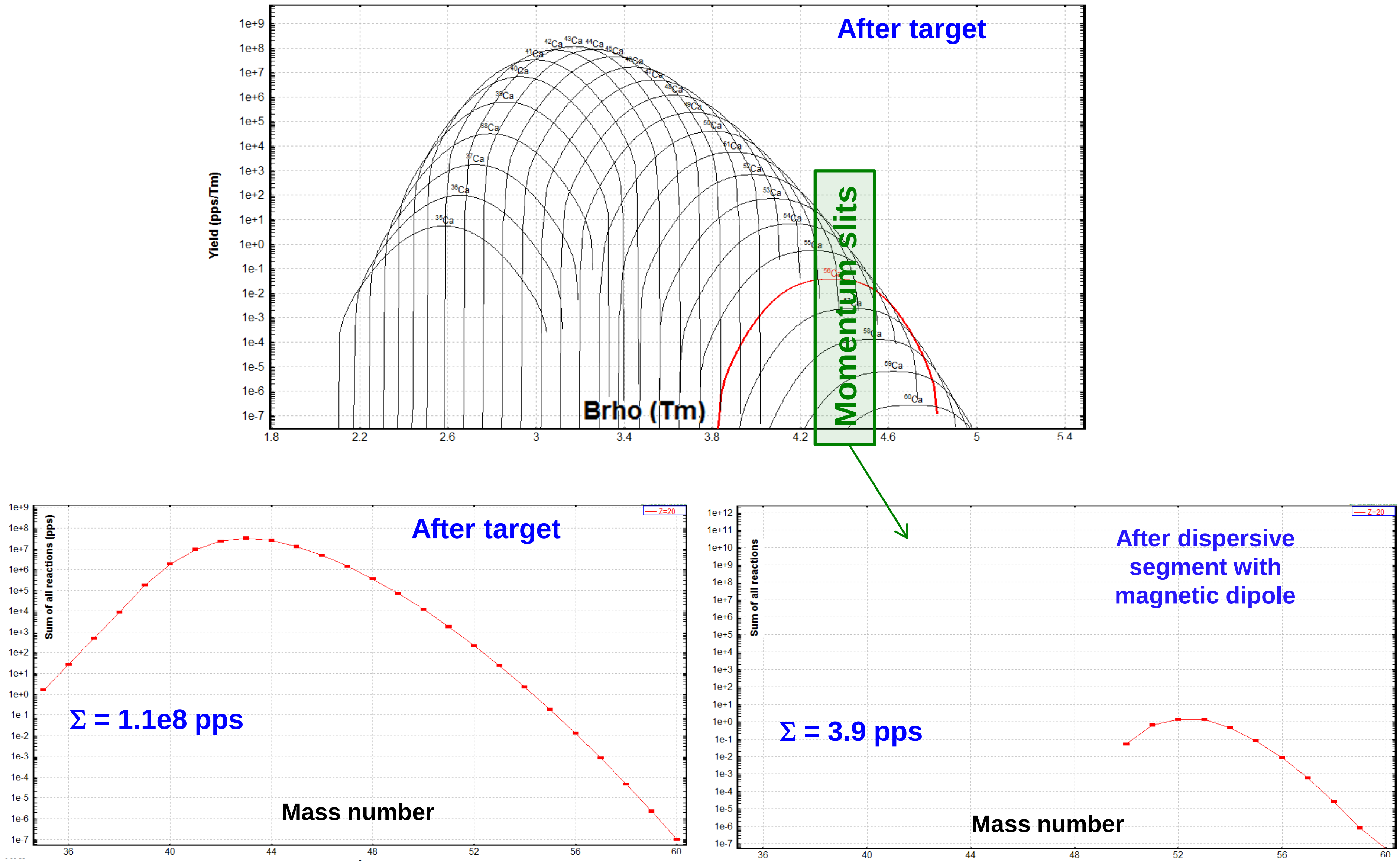
$\Delta p/p$= +2%

$\Delta p/p$= 0%

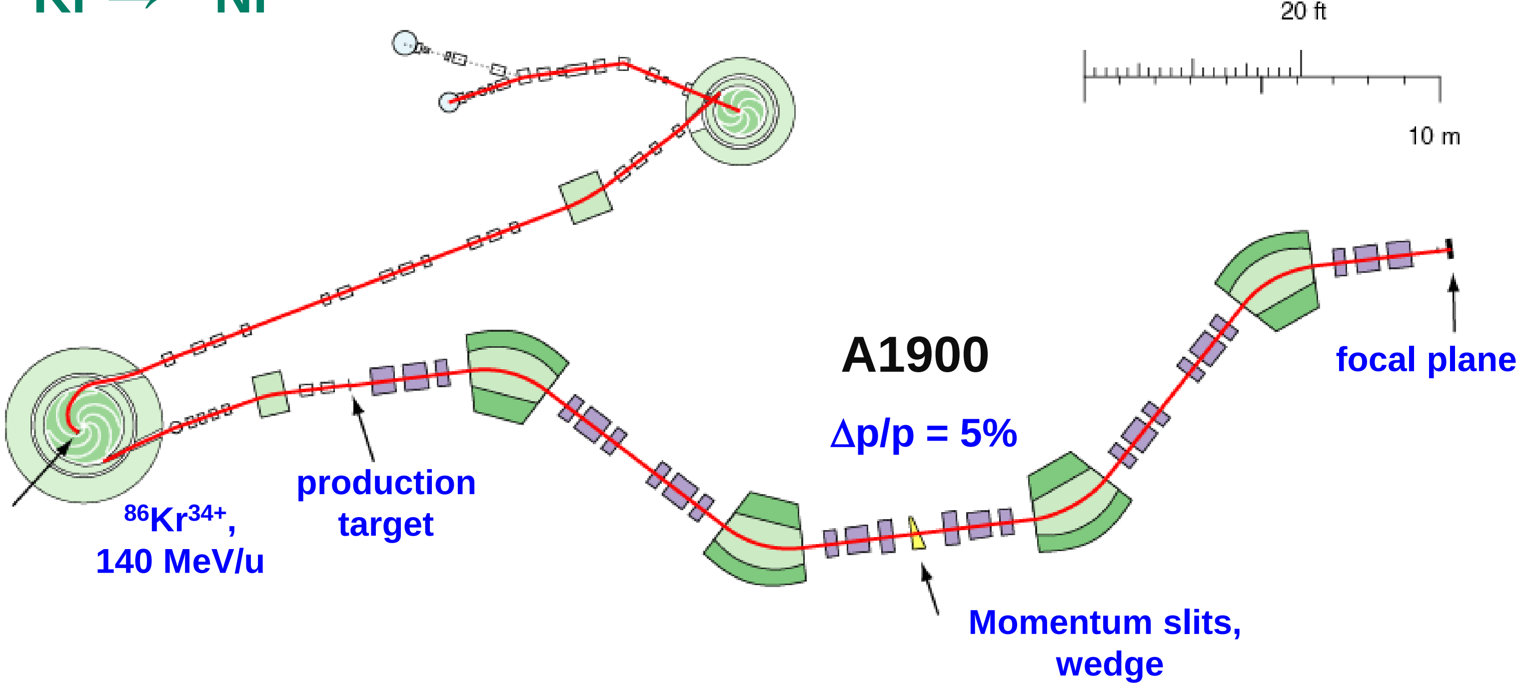
$\Delta p/p$= -2%

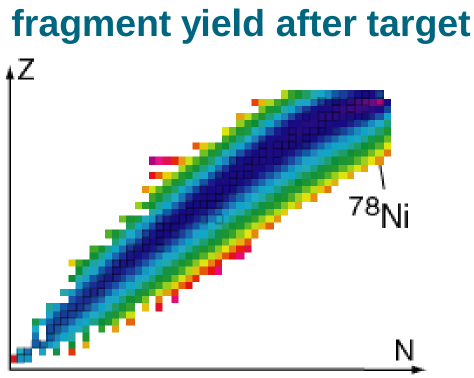
Selection with Magnetic Dipole

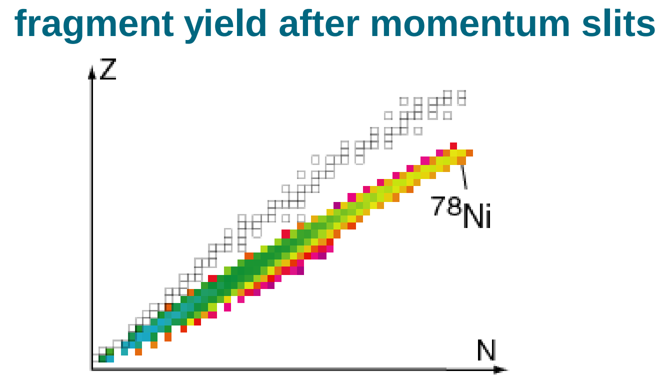
^{82}Se (140 MeV/u) + Be (443mg/cm^2) $\Rightarrow$ **Ca



Example: $^{86}Kr \rightarrow ^{78}Ni$

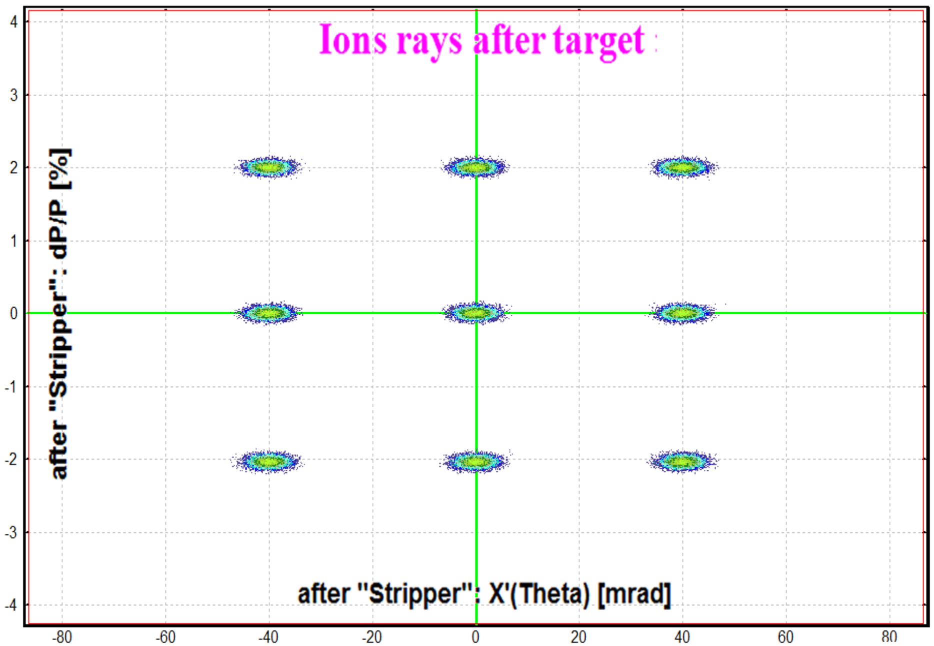


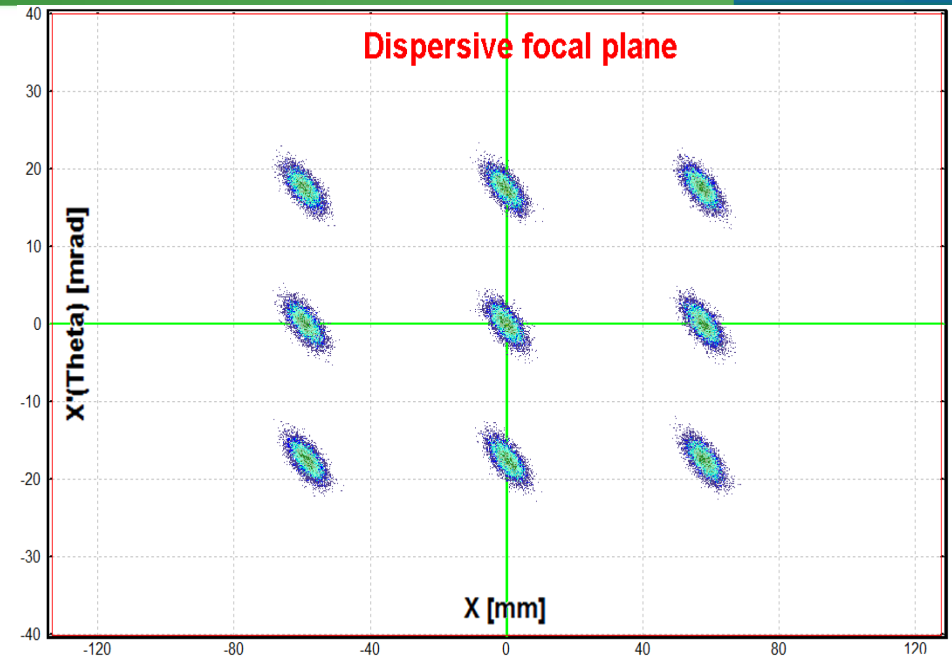


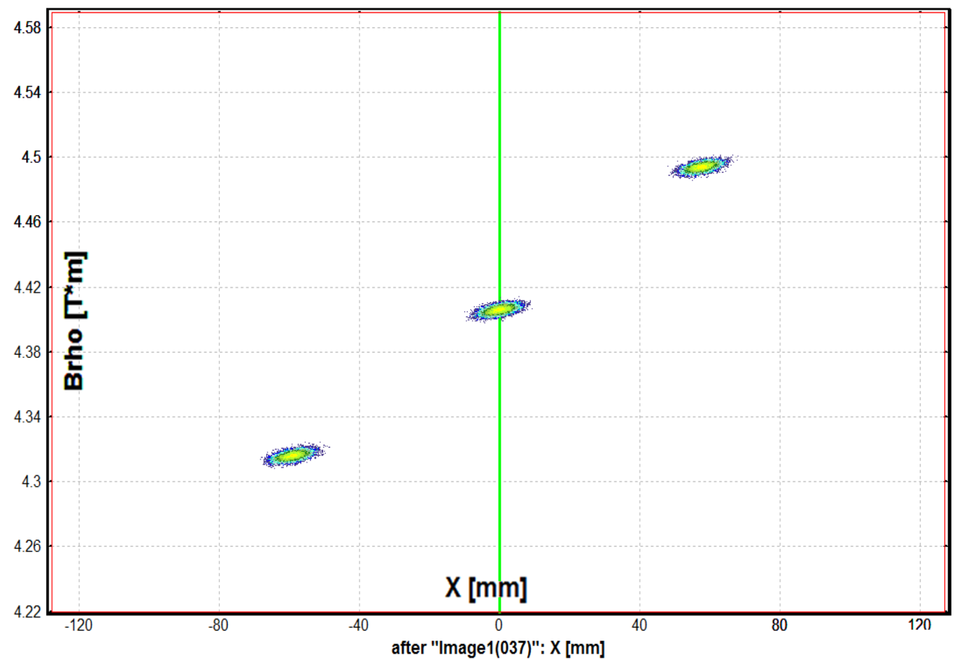


Selection quality

Initial conditions





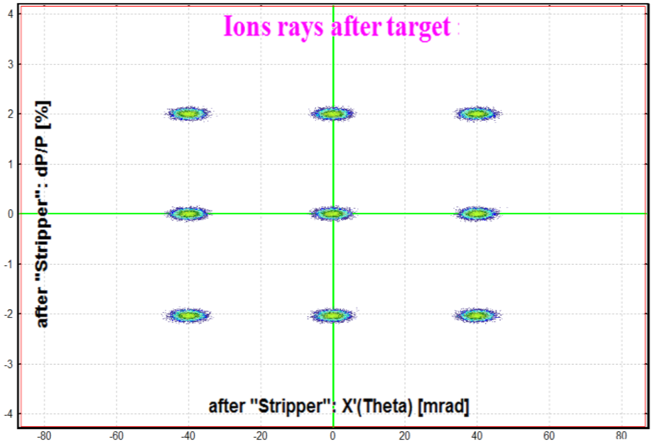


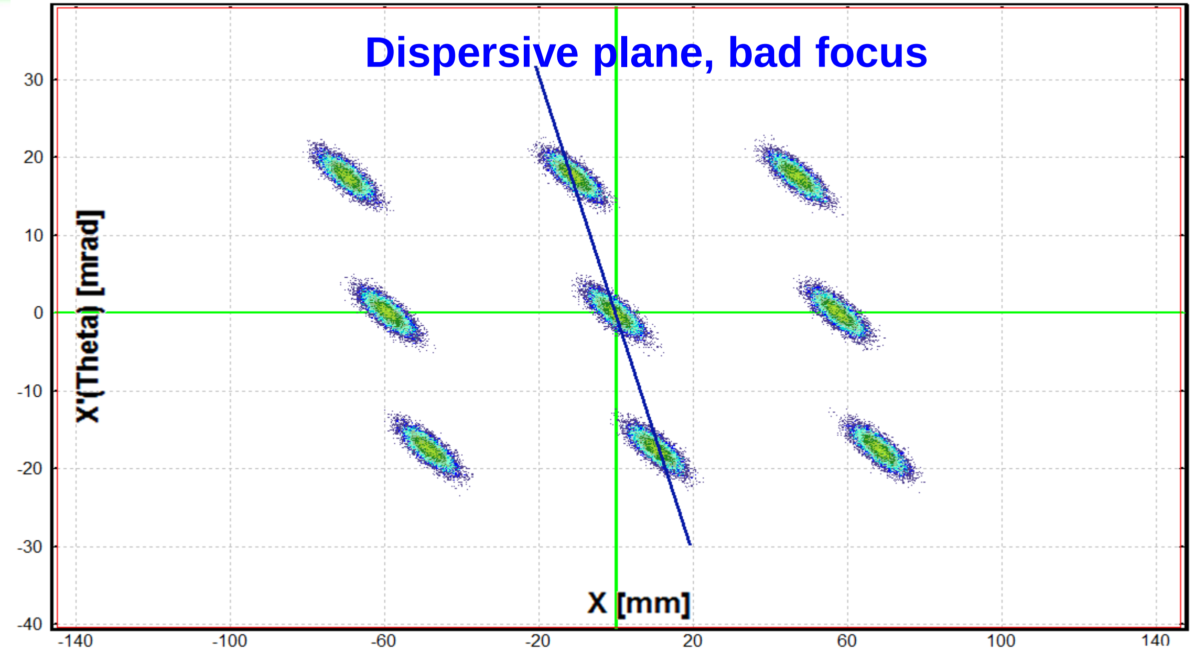
- Small object size
- Good focus in the dispersive plane

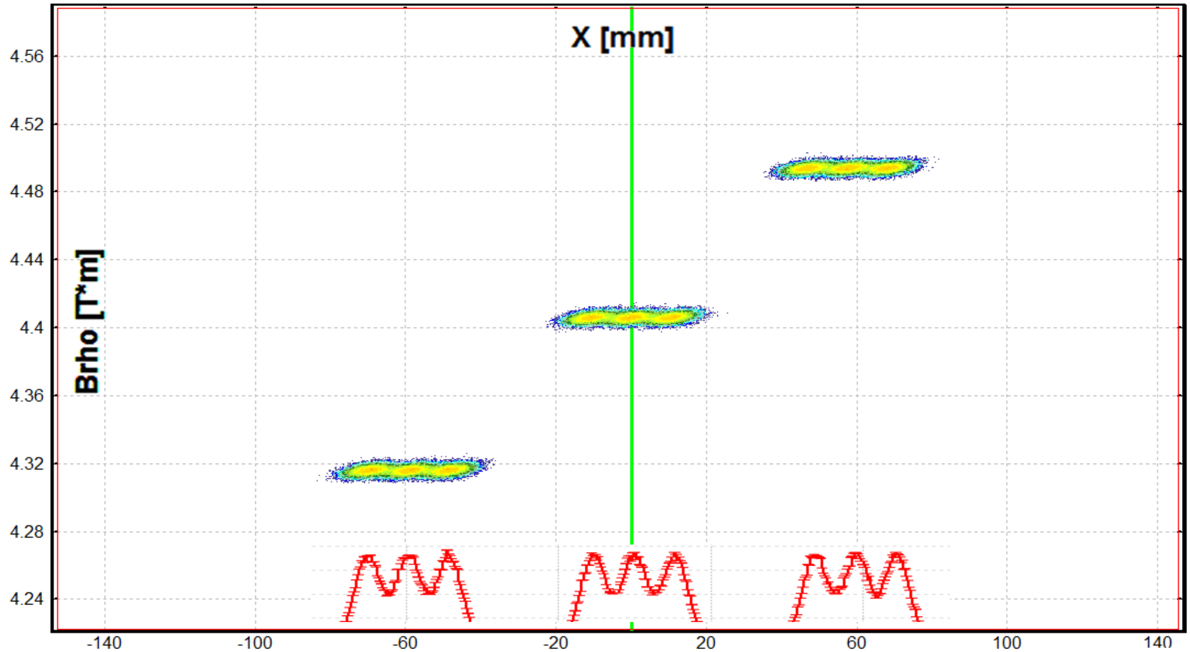
Good resolution !

Selection quality

Initial conditions





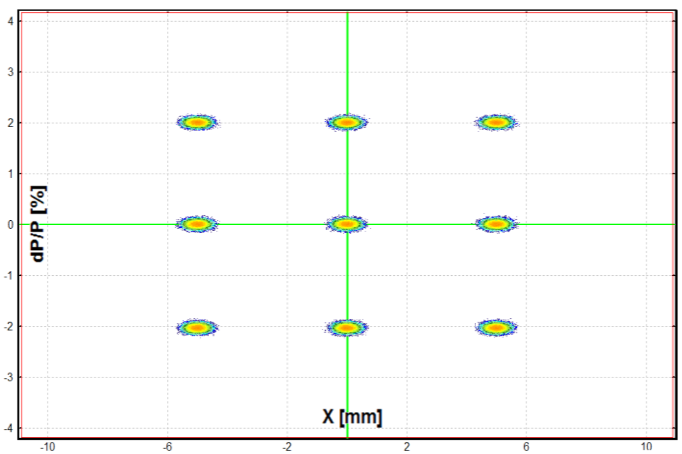


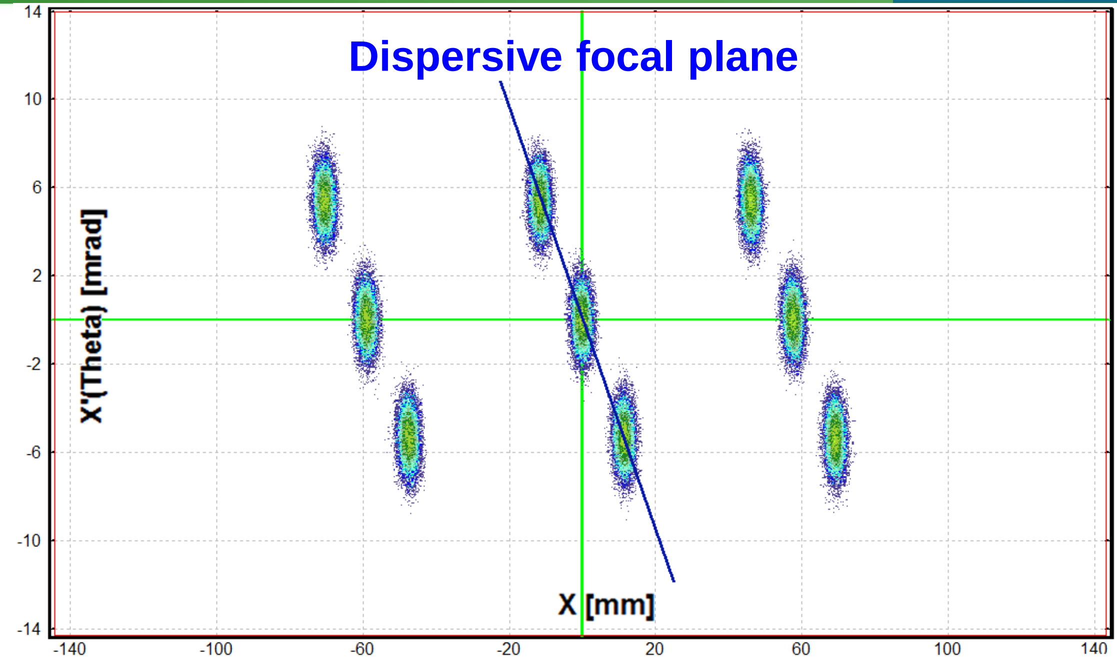
- Small object size
- Bad focus in the dispersive plane

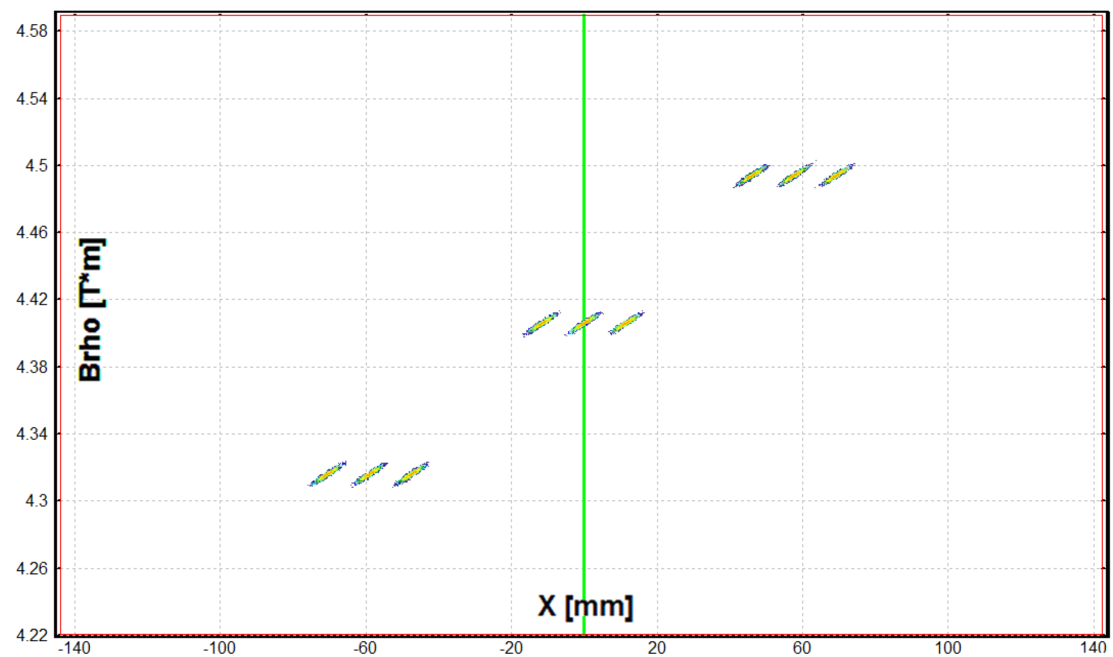
BAD resolution !

Selection quality

Initial conditions





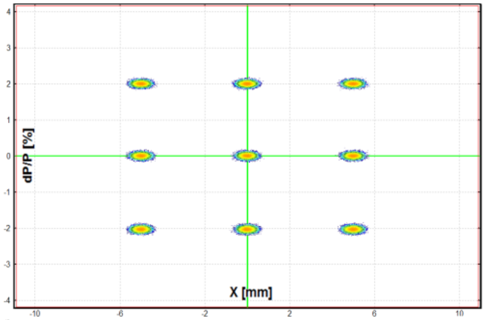


- Large object size
- Good focus in the dispersive plane

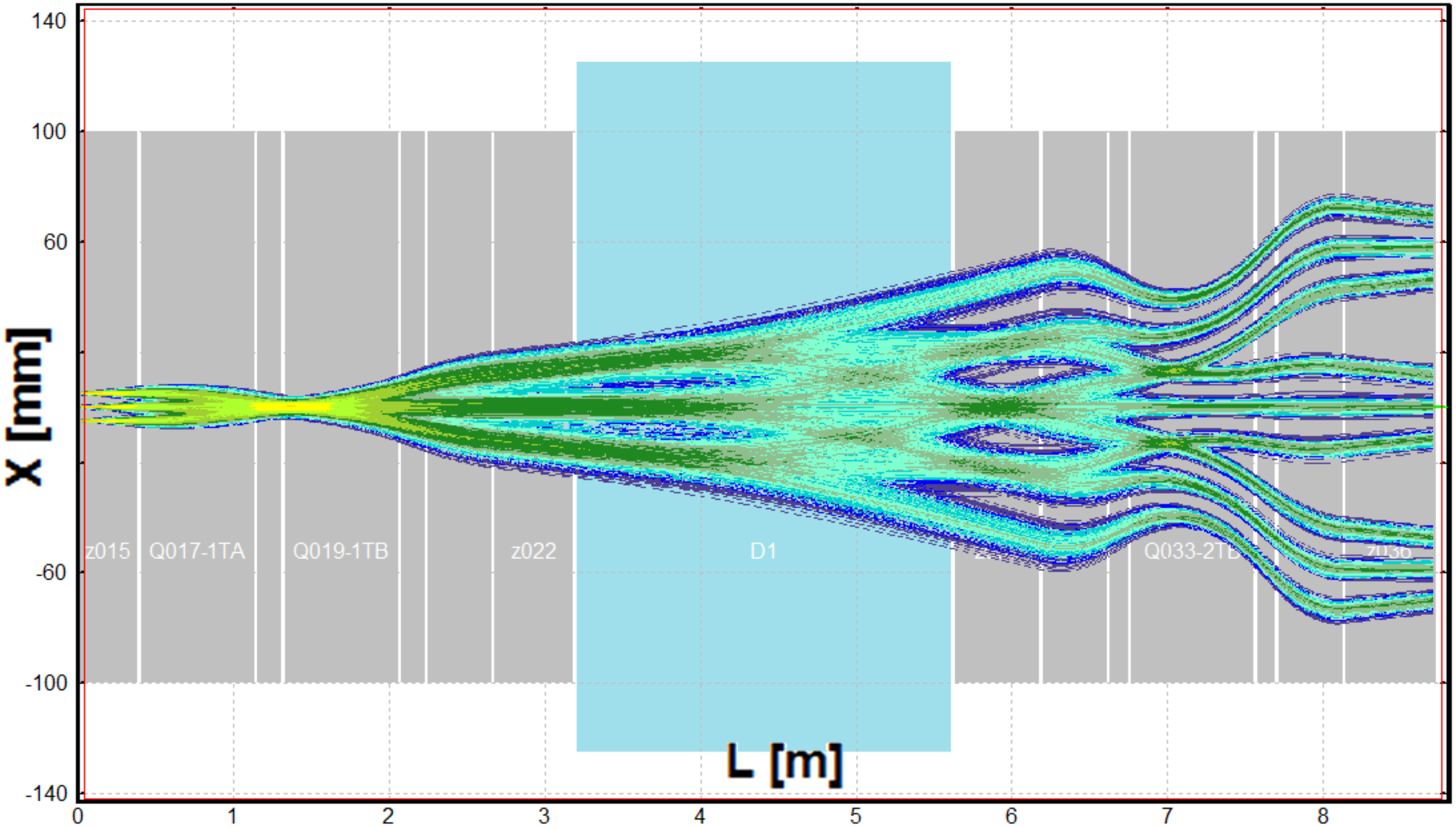
BAD resolution !

Selection quality : previous example

Initial conditions

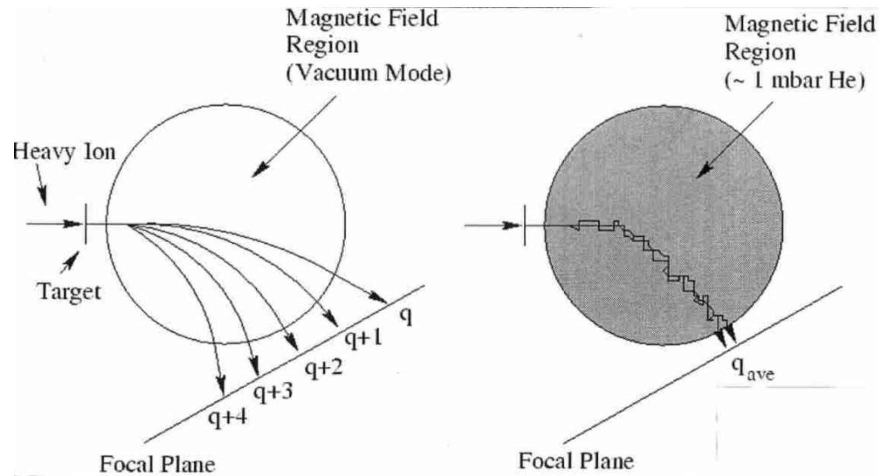


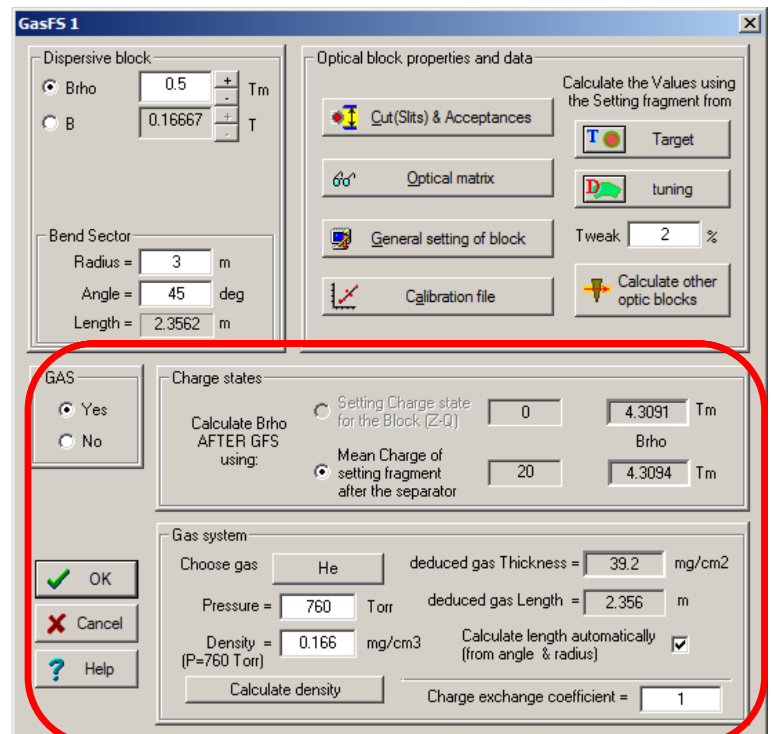
Large object



Gas-filled separator

- It is used at low energy for heavy recoils
- Gas is used to increase transmission efficiency cause of broad ionic charge distribution after target
- Gas-filled separators make use of magnetic field elements only
- Electric fields of needed strength cannot be maintained in gas atmosphere when the pressure is in the order of 1 mbar
- This block should be optimized in LISE++ Implementation of RayTracing solution?



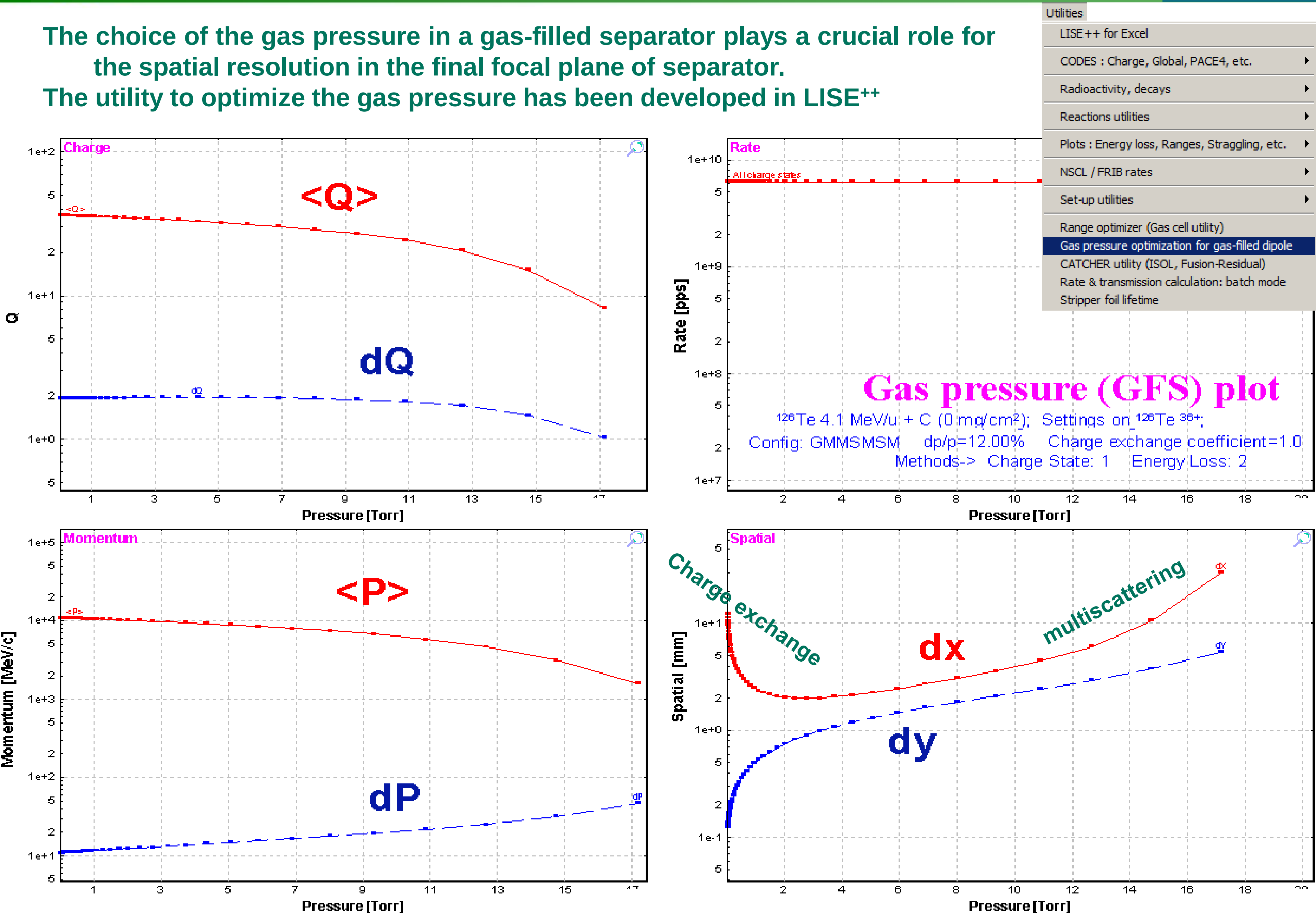


See for details
M. Paul et al. NIM A 277 (1989) 418

Gas pressure optimization plot

The choice of the gas pressure in a gas-filled separator plays a crucial role for the spatial resolution in the final focal plane of separator.

The utility to optimize the gas pressure has been developed in LISE^{++}

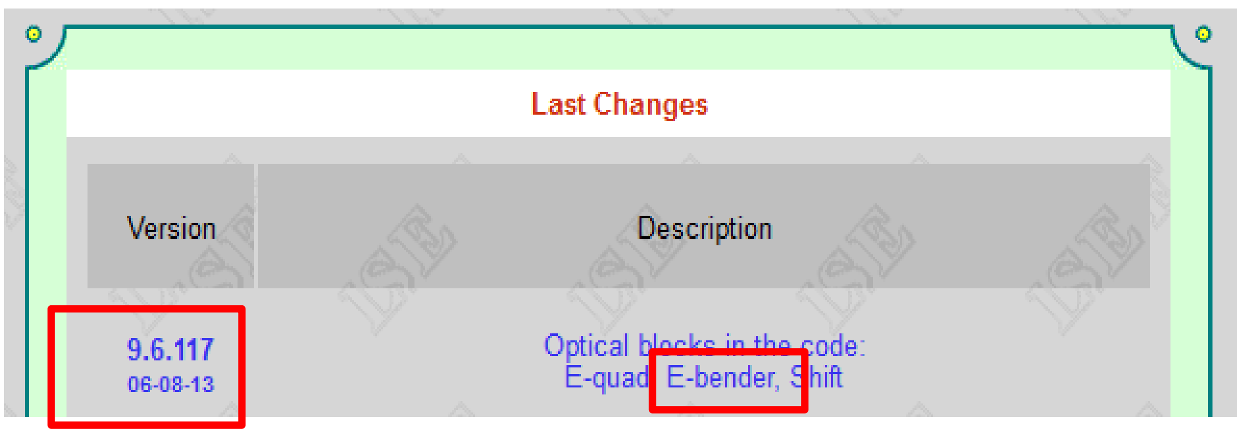


Electrostatic rigidity (Eρ) – selection

Separation device	Changeable field	Strength	Selection by
Electrostatic dipole	Electric (E [kV/m])	$\vec{F}_E = q\vec{E}$	Electric rigidity $E\rho = \frac{mv^2}{q}$ [J/C]

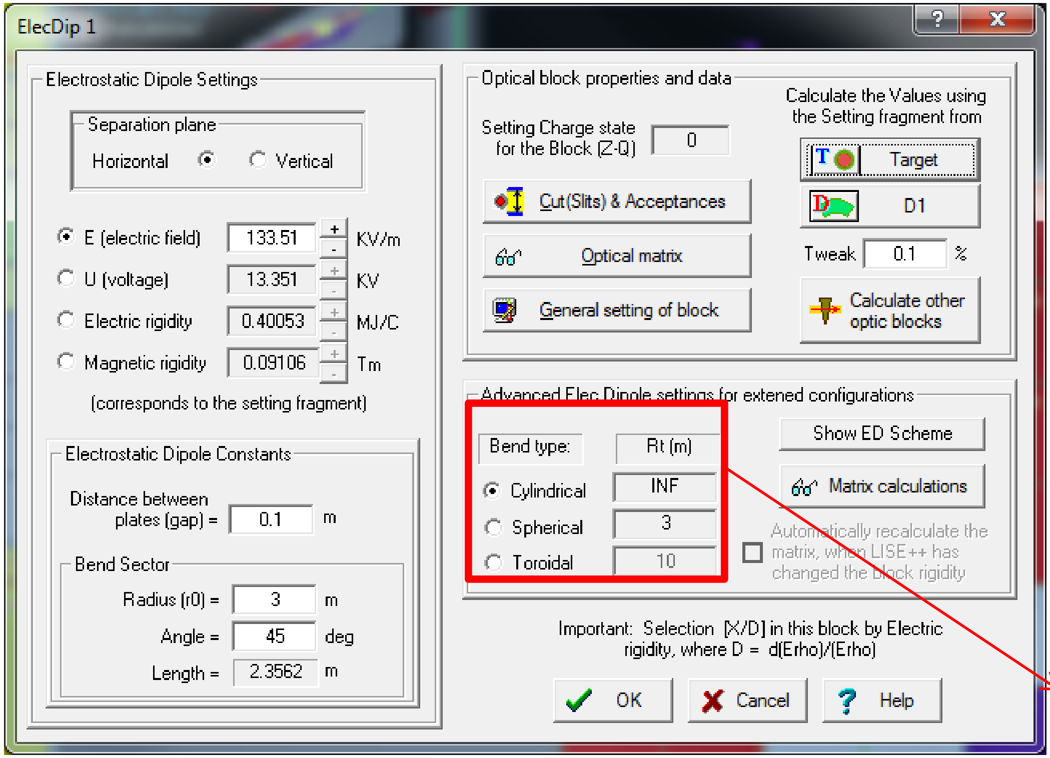
* This block is used at low energy

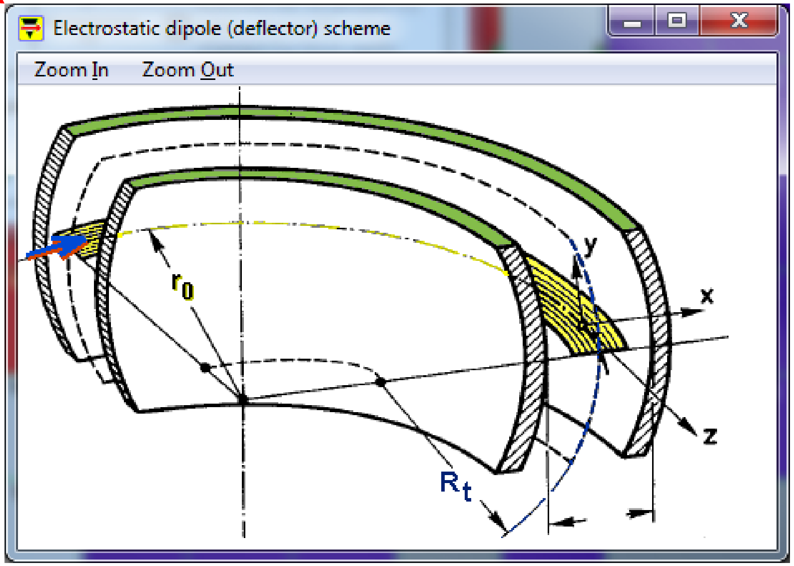
- Electric rigidity corresponds to TKE selection
- Therefore instead J/C (MJ/C) we can use eV (MeV)



http://lise.nscl.msu.edu/9_6/Edipole/9_6_117.pdf

Electrostatic rigidity (Eρ) – selection





Optical matrices for E-dipole

Matrix calculations

Utility: Electrostatic deflector

```
Electrostatic dipole
mode = Cylindrical

direct = X
radius = 1 m
 angle = 45 deg
length = 0.7854 m
     n = 0
  beta = 0.02674
  e_xi = 1.414
 n_eta = 0
    Nk = 0.99982
    Nm = 0.00017876
   k2x = 2 m^(-2)
   k2y = 0 m^(-2)
```

transport format [cm-mrad]

* TRANSFORM 1 *

[D] -- Momentum transfer matrix (Important!)

it is used for calculation of the Global matrix

1 [X]:	+4.4419e-01	+6.3363e-02	0	0	0	+5.5581e-01
2 [T]:	-1.2668e+01	+4.4419e-01	0	0	0	+1.2668e+01
3 [Y]:	0	0	1	+7.8540e-02	0	0
4 [F]:	0	0	0	1	0	0
5 [L]:	-1.2668e+00	-5.5581e-02	0	0	1	-3.0342e-01
6 [D]:	0	0	0	0	0	1

transport format [cm-mrad]

* TRANSFORM 1 *

[D] -- Electrostatic rigidity selection (Important!)

it is used for transmission calculations, which are based on ERHO selection for E-static benders

1 [X]:	+4.4419e-01	+6.3363e-02	0	0	0	+2.7800e-01
2 [T]:	-1.2668e+01	+4.4419e-01	0	0	0	+6.3363e+00
3 [Y]:	0	0	1	+7.8540e-02	0	0
4 [F]:	0	0	0	1	0	0
5 [L]:	-6.3363e-01	-2.7800e-02	0	0	1	-7.5910e-02
6 [D]:	0	0	0	0	0	1

E & B bends example

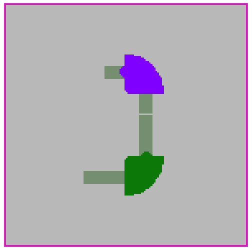
http://lise.nscl.msu.edu/9_6/Edipole/EB_case.lpp

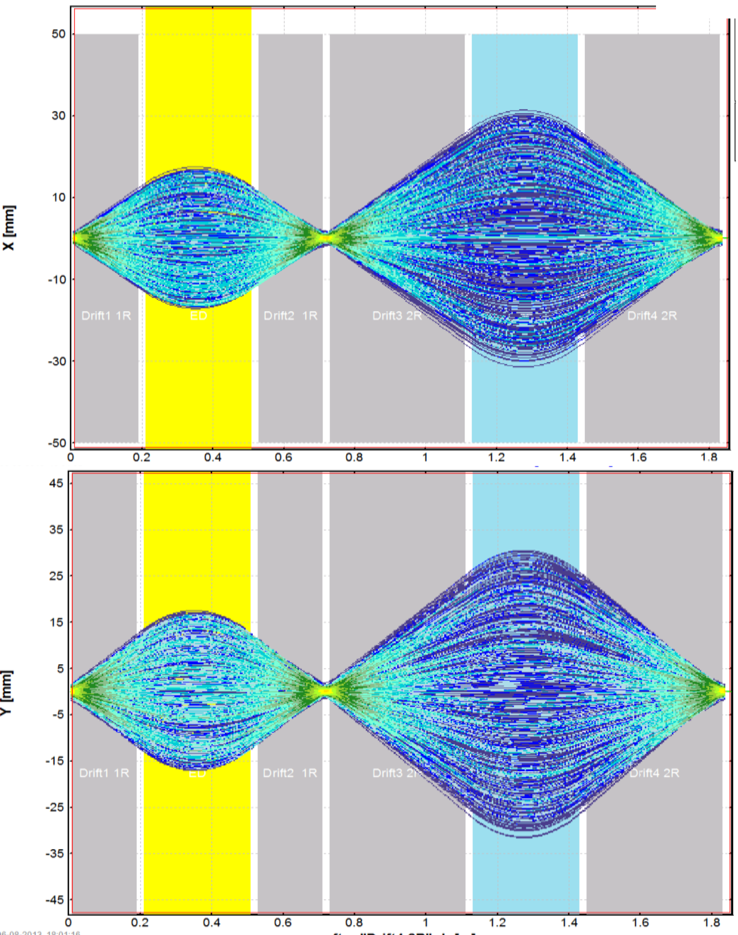
Purpose

[MM.Portillo's example,](#) and COSY calculations

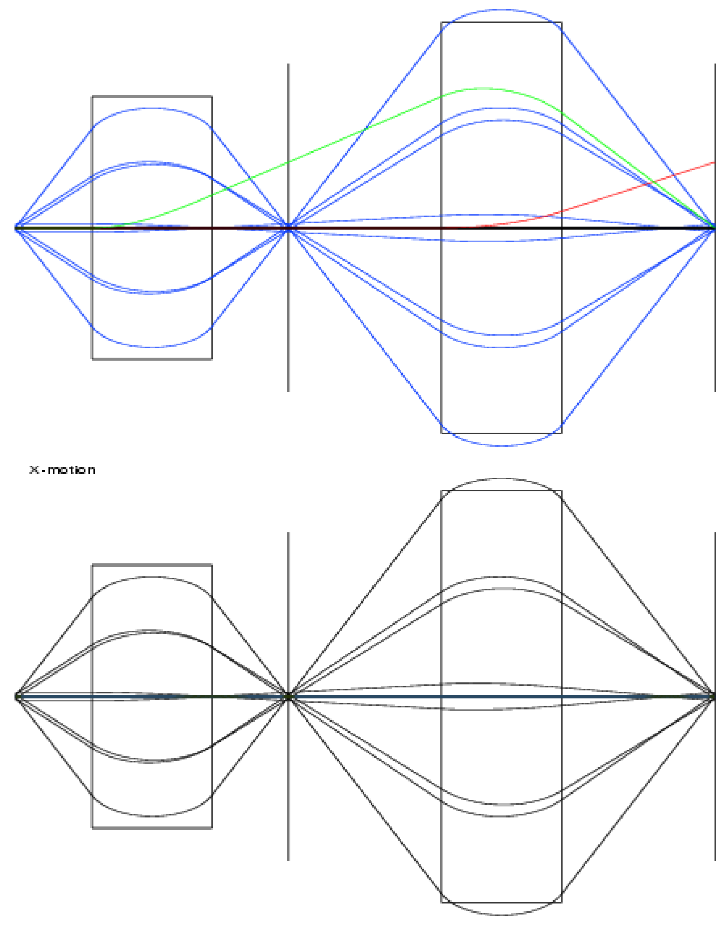
- Create an energy achromat system
  - Using double focusing
  - E-dipole
    - » Bend of 90deg at R=0.2 m
      spherical electrodes for equal x- and y-focus strength
    - » Drift before and after bend = R
  - B-dipole
    - » Bend of 90deg at R=0.2 m
    - » 26.56deg entranc & exit edge angles for equal x- and y-focus strength
    - » Drift before and after bend = 2R

LISE++



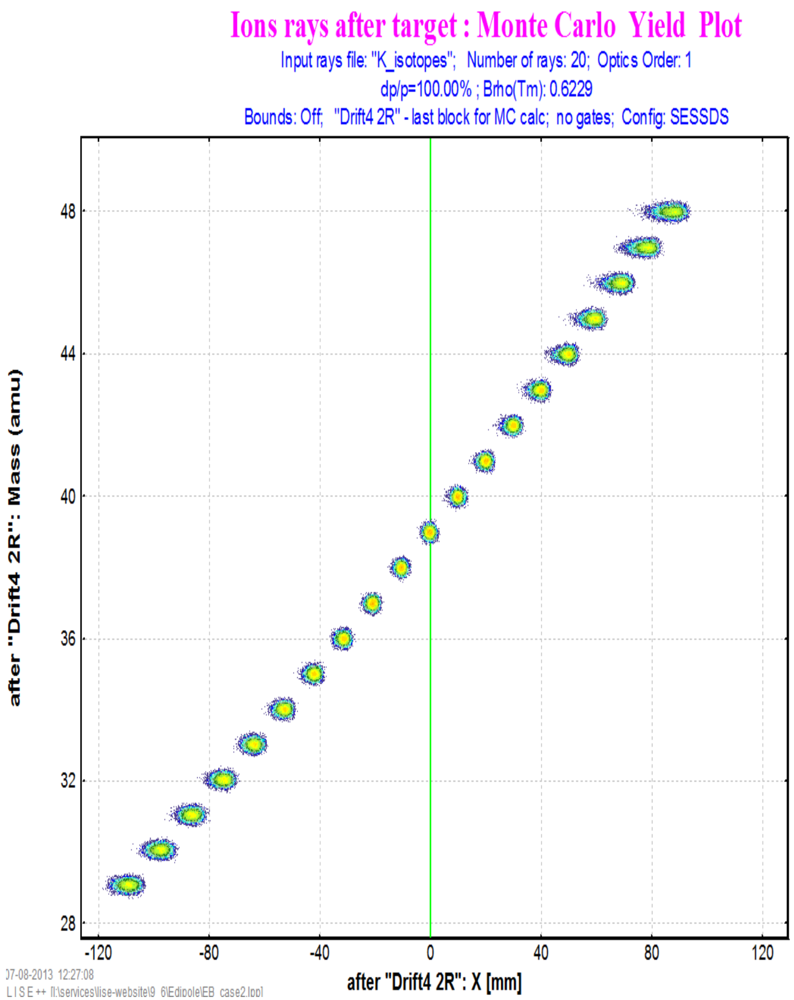


COSY

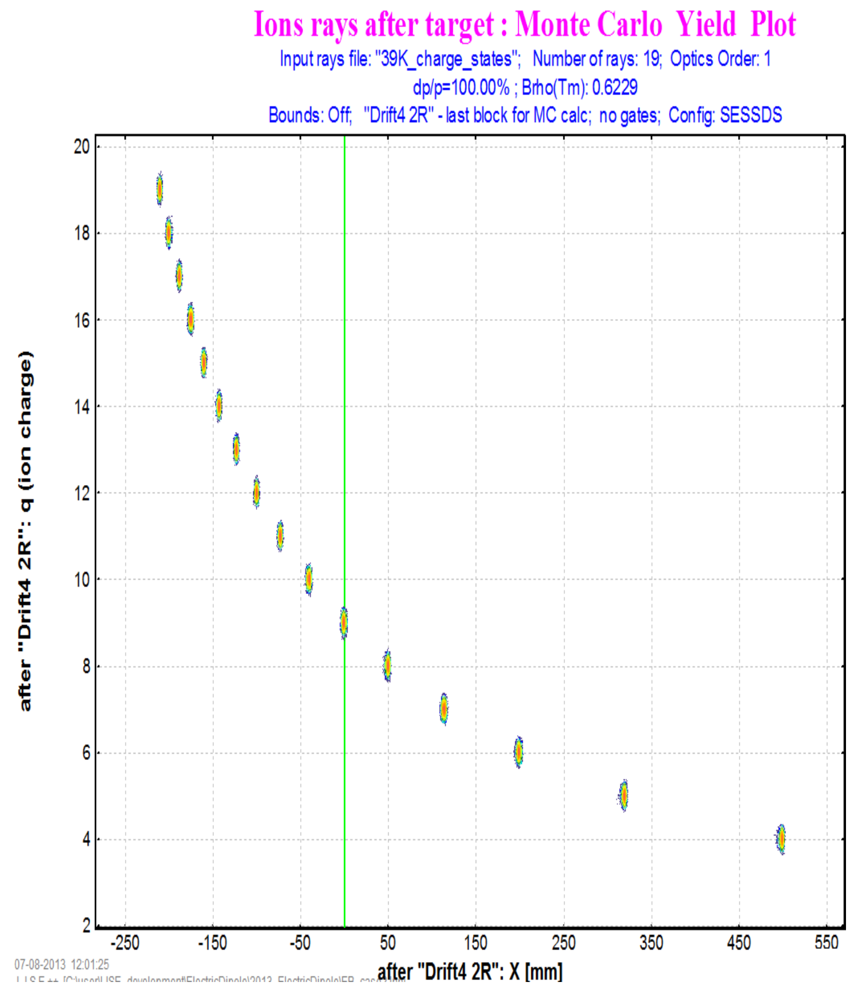


E & B bends example : M- & q- dispersions

http://lise.nscl.msu.edu/9_6/Edipole/EB_case2.lpp



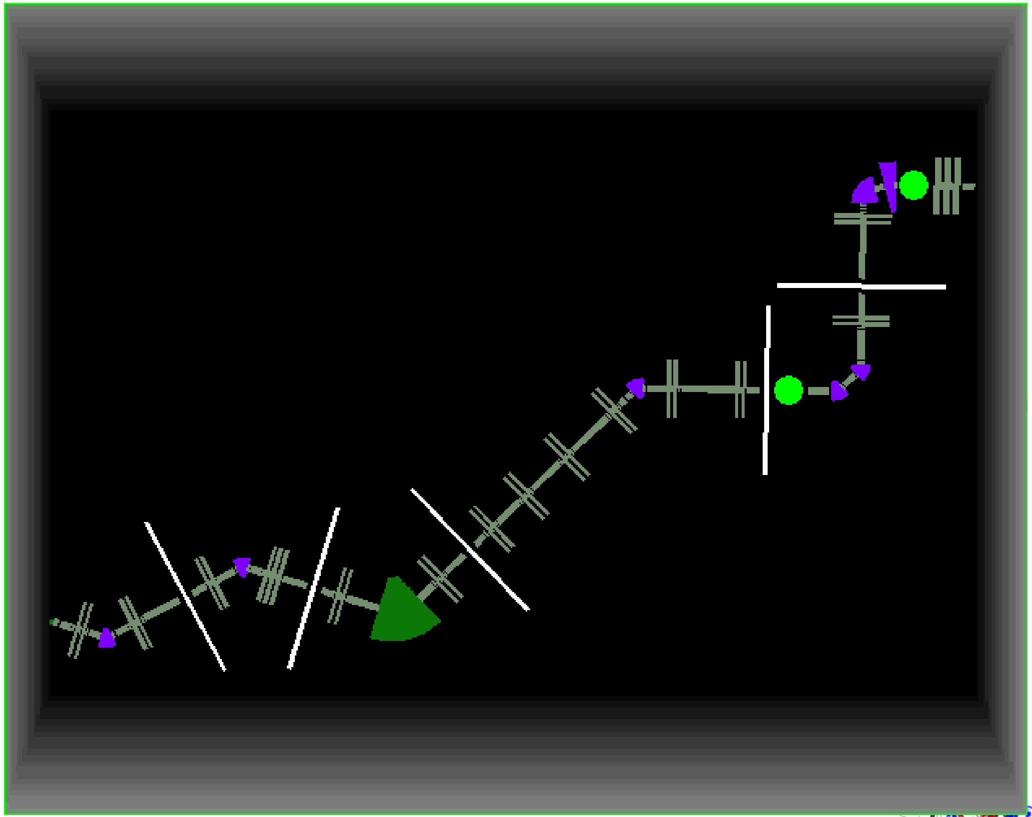
The same *q*, *TKE*
Different *M*asses



The same *M*asses, *E*
Different *q*

D-line : extended configuration

LISE++ file: http://lise.nscl.msu.edu/9_6/Edipole/D-line_BTS01-12%20with%20rotation.lpp

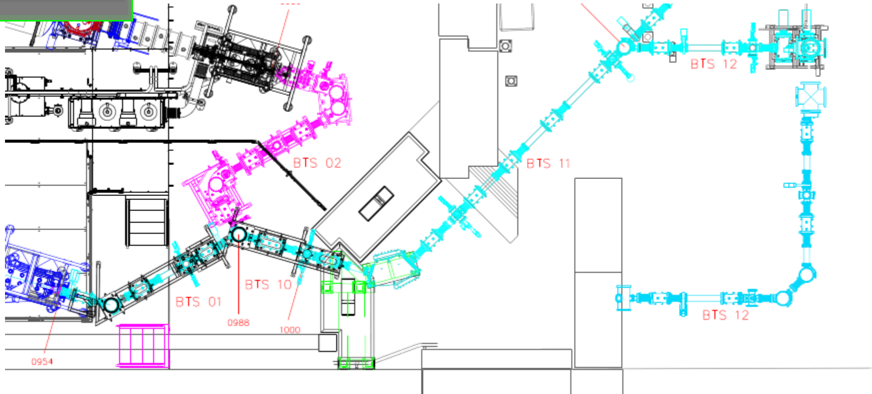


Almost 137 blocks, where

M-dipole : 1

E-dipole : 7

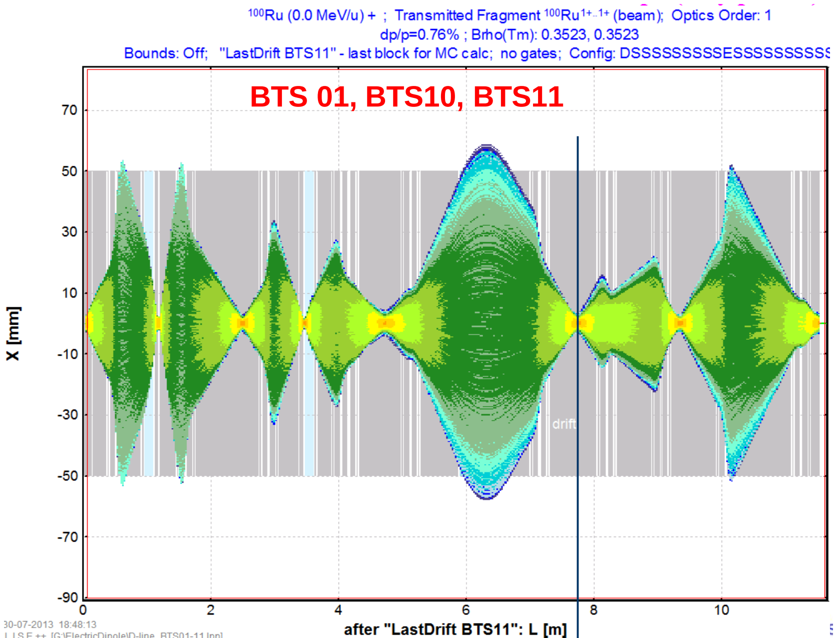
E-quad : 32



D-line : extended configuration BTS01-BTS12

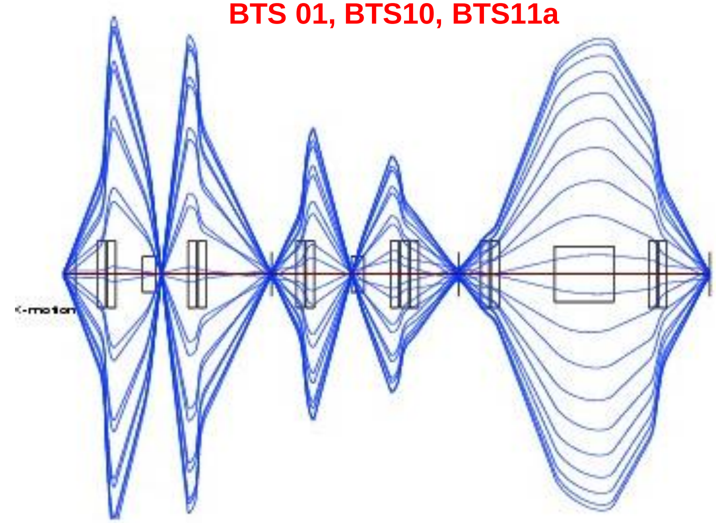
LISE++ file: http://lise.nscl.msu.edu/9_6/Edipole/D-line_BTS01-12%20with%20rotation.lpp

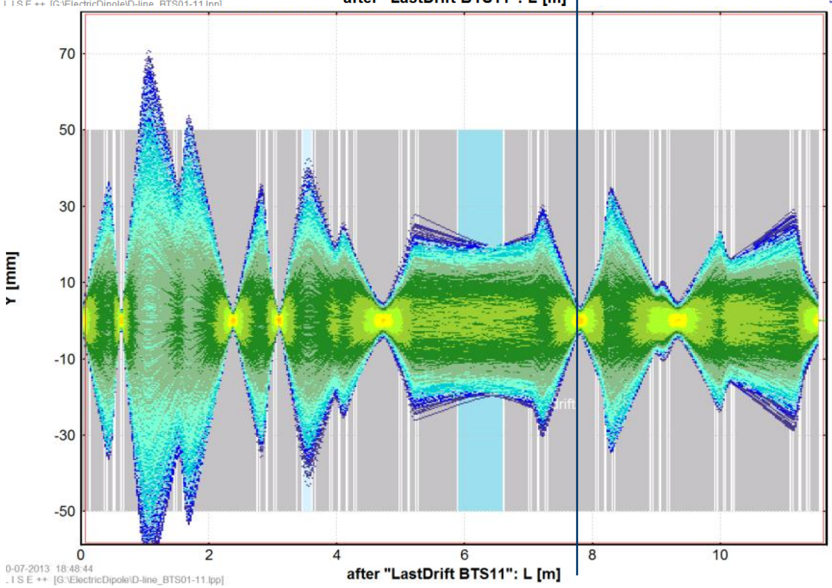
From "Report on recalculation of Low-E beam lines" by M.Portillo



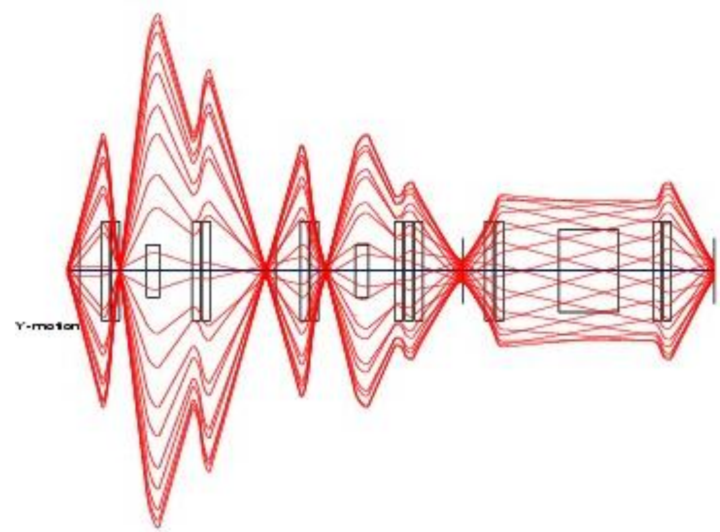
X

BTS 01, BTS10, BTS11a





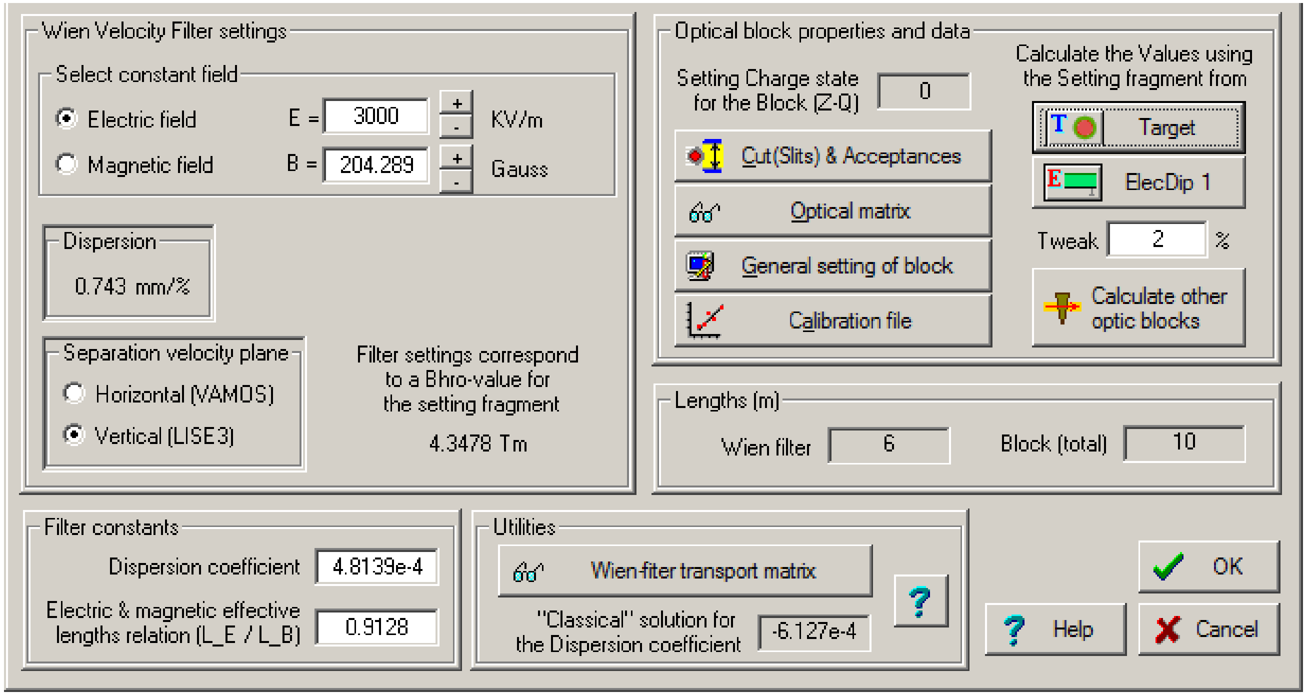
Y



Velocity selection

Velocity selection

Separation device	Changeable field	Strength	Selection by
Wien-filter *E-cross-B filter*	Magnetic (B[T]) Electric (E [kV/m])	$\vec{F} = \vec{F}_B + \vec{F}_E$	Velocity



* **This block is used for energies below 40-50 MeV/u**

* **It is an unique block with floating dispersion in an optical matrix. It is recalculated for each ion**

http://lise.nscl.msu.edu/8_5/8_5_040_Wien.pdf

See more for Wien-filter

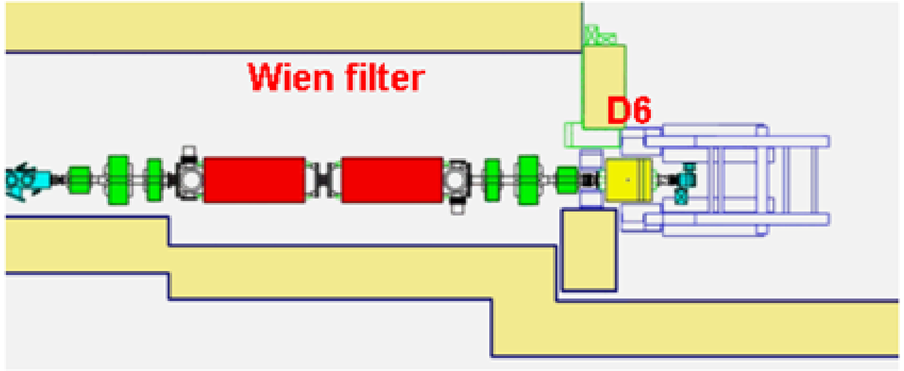
LISE 3: a magnetic spectrometer—Wien filter combination for secondary radioactive beam production by Remy Anne, Alex C. Mueller

Nuclear Instruments and Methods in Physics Research Section B
Volume 70, Issues 1-4, 1 August 1992, Pages 276-285
http://dx.doi.org/10.1016/0168-583X(92)95943-L

Wien velocity filter

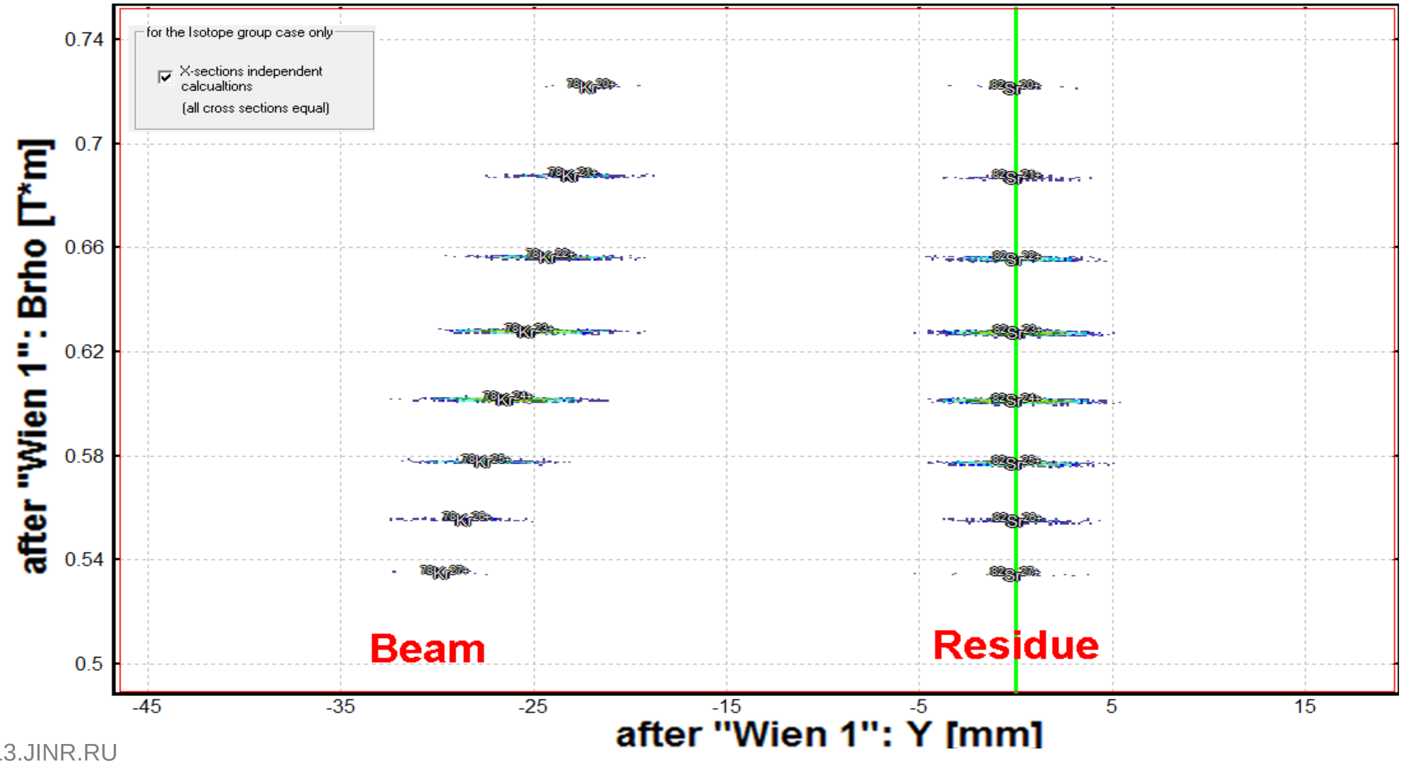
$$E = \beta \cdot v_c \cdot B \; / \; R_{L_E/L_B}$$

E	*electric field [in KV/m]*
β	*setting fragment velocity*
v_c	*speed of light*
B	*magnetic filed [in Gauss]*
R_{L_E/L_B}	*effective electric & magnetic lengths ratio*



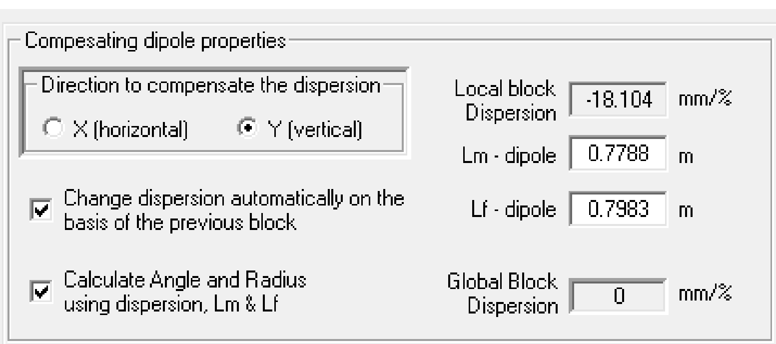
Isotope Group : Monte Carlo Transmission Plot

^{78}Kr (1.7 MeV/u) + He (5e-2 mg/cm^2); Transmitted Fragment $^{82}Sr^{24+}$ (FusRes)



Compensating dipole after Wien-filter

- Wien filter provides velocity selection : υ
- Magnetic Dipole provides $B\rho$ selection (momentum) $B\rho = m\upsilon / q$
- If Dipole Dispersion (% / mm) = - Wien Dispersion (% / mm) then A/q selection
- Realized with VAMOS & LISE3 (GANIL), MARS (TAMU)



http://lise.nscl.msu.edu/3_4/lise_3_4.html#Dipole%20D6

Image shift

The image shift of nuclei in the final focus plane can be roughly determined

$$shift_{FD} = shift_{filter} + shift_{D6} ,$$

where

$$shift_{filter} = D_{filter} \cdot \frac{v - v_0}{v_0} ,$$

$$shift_{D6} = D_{D6} \cdot \frac{\Delta B\rho}{B\rho} ,$$

D_{filter} is the filter dispersion [mm/%] and D_{D6} is the dipole dispersion [mm/%].

Using equation

$$B\rho = c \, \frac{A}{Q} \, \frac{\beta}{\sqrt{1-\beta^2}} ,$$

we find that

$$\frac{\Delta B\rho(A/Q,\beta)}{B\rho} = \frac{\frac{\partial B\rho}{\partial(A/Q)} \cdot \Delta(A/Q)}{B\rho} + \frac{\frac{\partial B\rho}{\partial\beta} \cdot \Delta\beta}{B\rho}$$

and then

$$\frac{\Delta B\rho(A/Q,\beta)}{B\rho} = \frac{\Delta(A/Q)}{A/Q} + \frac{\Delta\beta}{\beta \cdot (1-\beta^2)} .$$

Taking into account that the sum

$$\frac{\Delta\beta_{D6}}{\beta_{D6} \cdot (1-\beta_{D6}^2)} \cdot D_{D6} + \frac{\Delta\beta_{filter}}{\beta_{filter}} \cdot D_{filter}$$

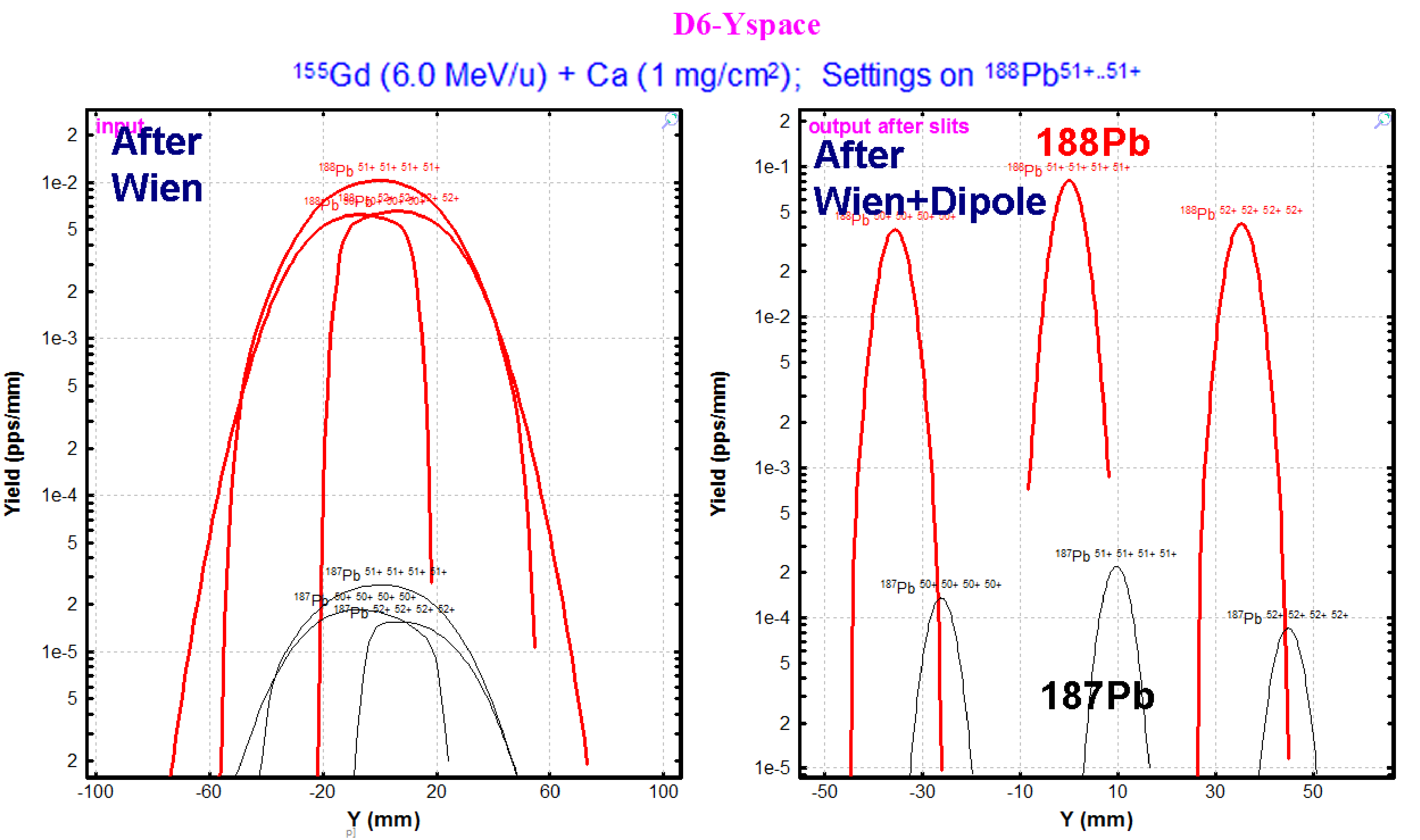
is close to 0 (in the case of combined work must be $\beta_{D6} = \beta_{filter}$),

$$shift_{FD} \cong \frac{\Delta(A/Q)}{A/Q} \cdot D_{D6}$$

or, in other words, only the A/Q selection takes place.

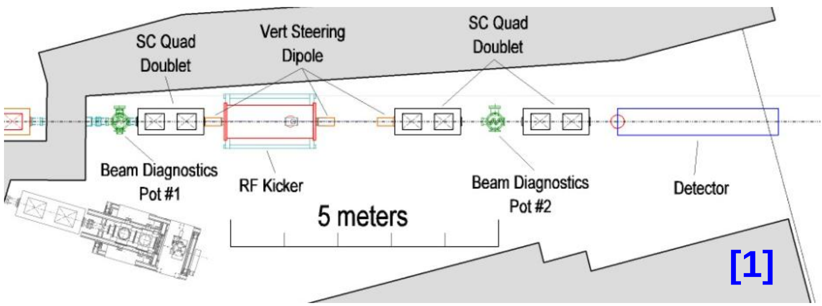
Some possible combinations are considered in the program :

Compensating dipole after Wien-filter



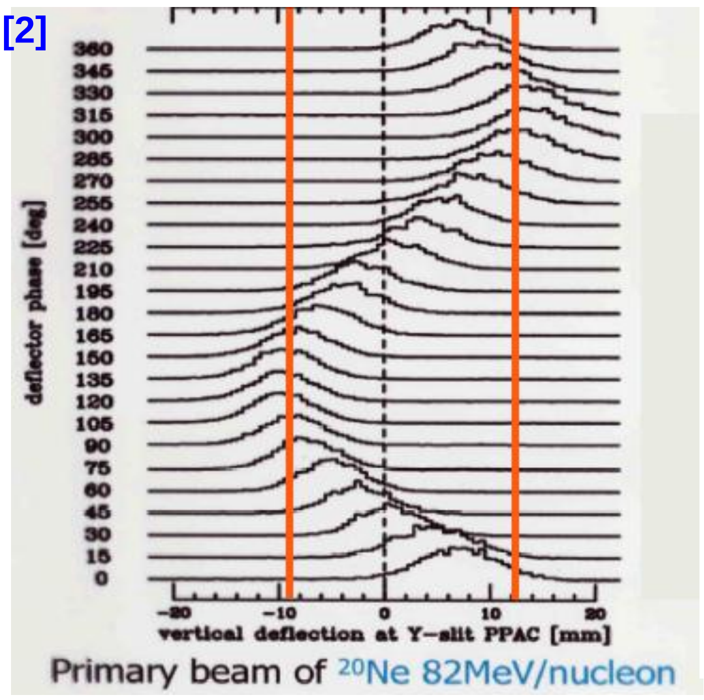
RF
kicker

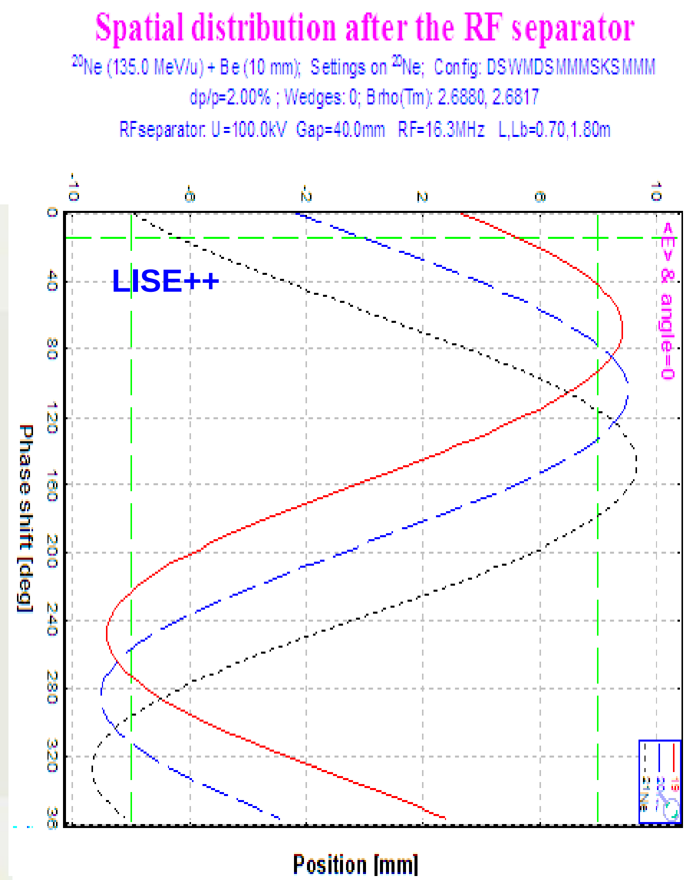
RF kicker (RFFS)



RF Kicker provides vertical (RIKEN,NSCL[3]) beam separations for different secondary beam species due to their different time of flight values

RF Separation System (RFSS)



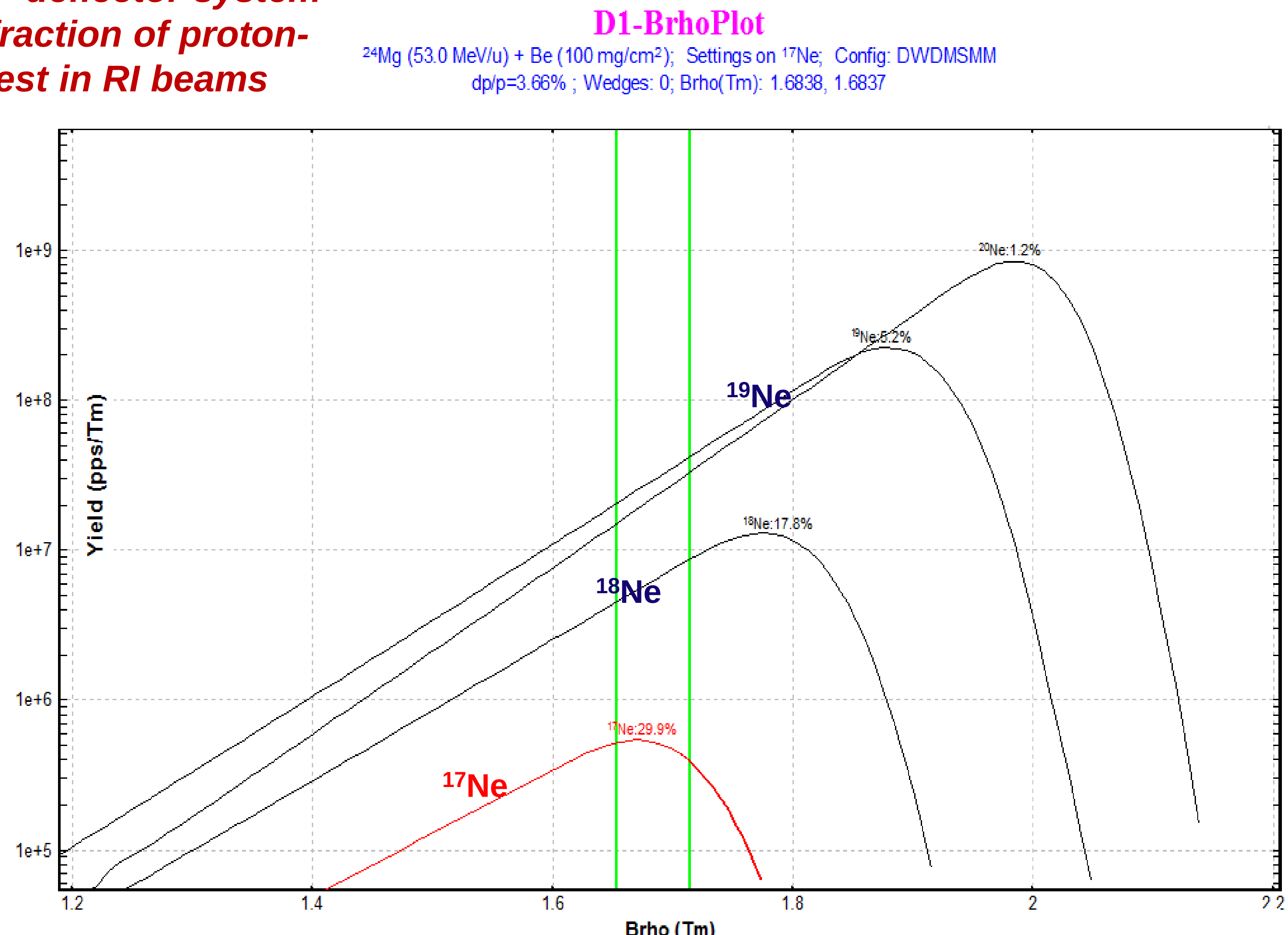


1) RF kicker proposal, V. Andreev, D.Bazin, M. Doleans, D.Gorelov, F. Marti, X. Wu; RF-KICKER SYSTEM FOR SECONDARY BEAMS AT THE NSCL", D. Gorelov, V. Andreev, D. Bazin, M. Doleans, T. Grimm, F. Marti, J. Vincent, X. Wu, Proceedings of 2005 Particle Accelerator Conference, Knoxville,
2) K.Yamada et al., Nuclear Physics A746 (2004) 156c-160c.
3) J. Stoker et al., "Commissioning Report on the NSCL RF Fragment Separator," future presentation at the 234th ACS National Meeting, Boston, MA, 19th –23rd, August 2007

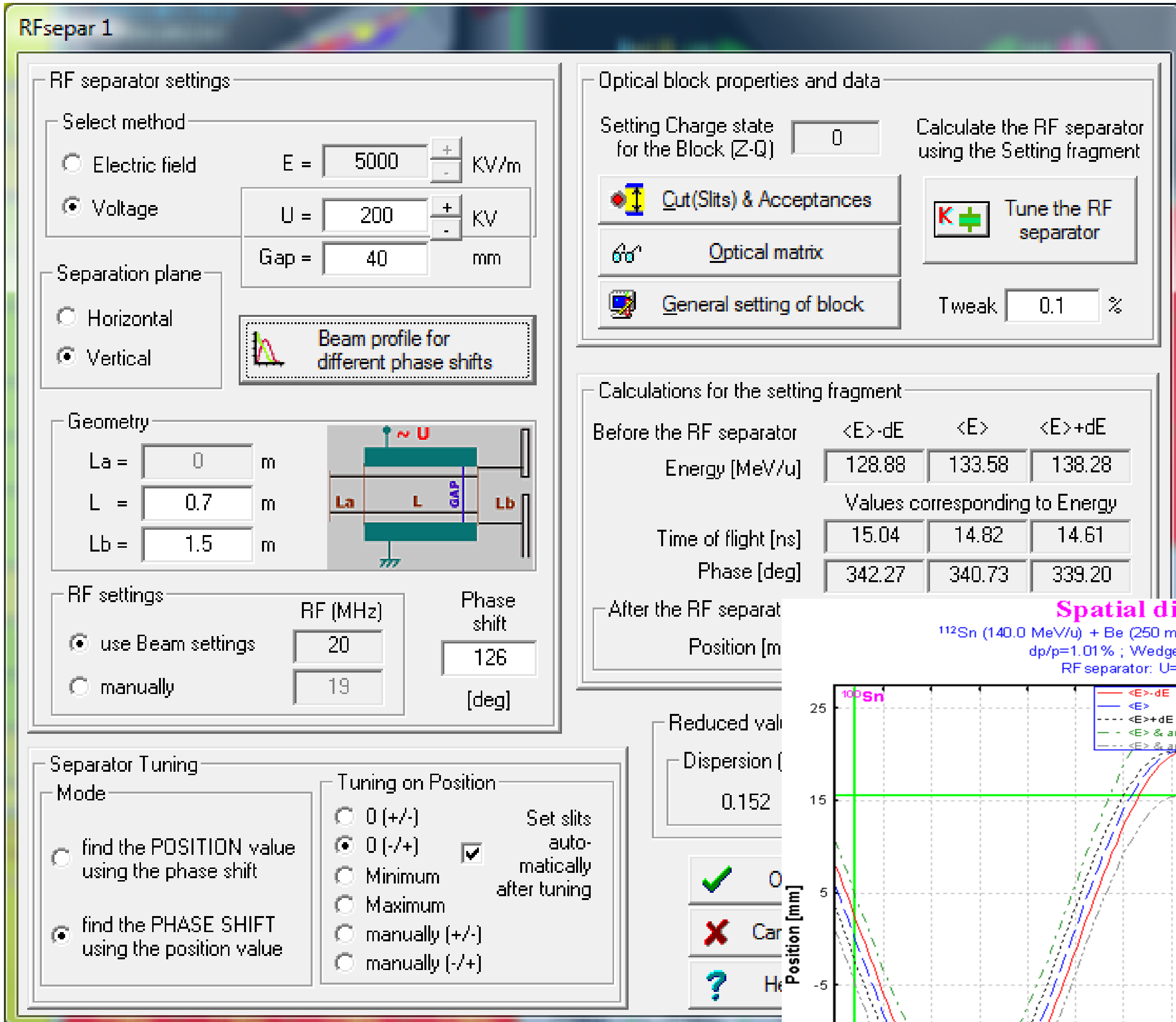
RF kicker: proton rich side

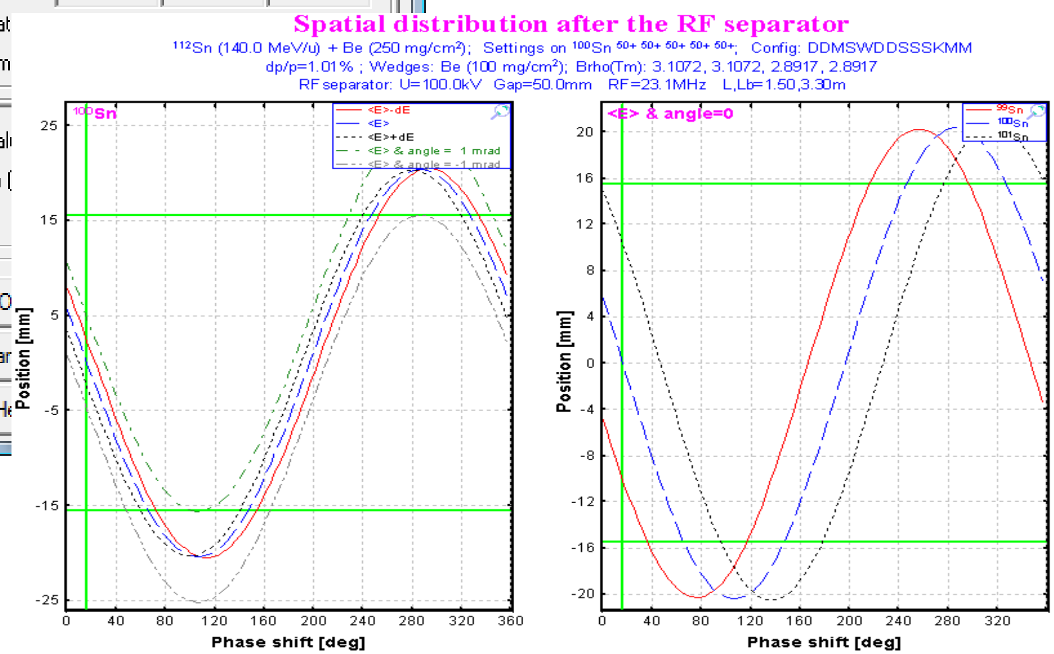
- Low energy exponential tails create difficulties to separate proton-rich nuclei
- Wien filter is not effective for energies above 50 MeV/u

The main aim of RF deflector system is to increase the fraction of proton-rich nuclei of interest in RI beams

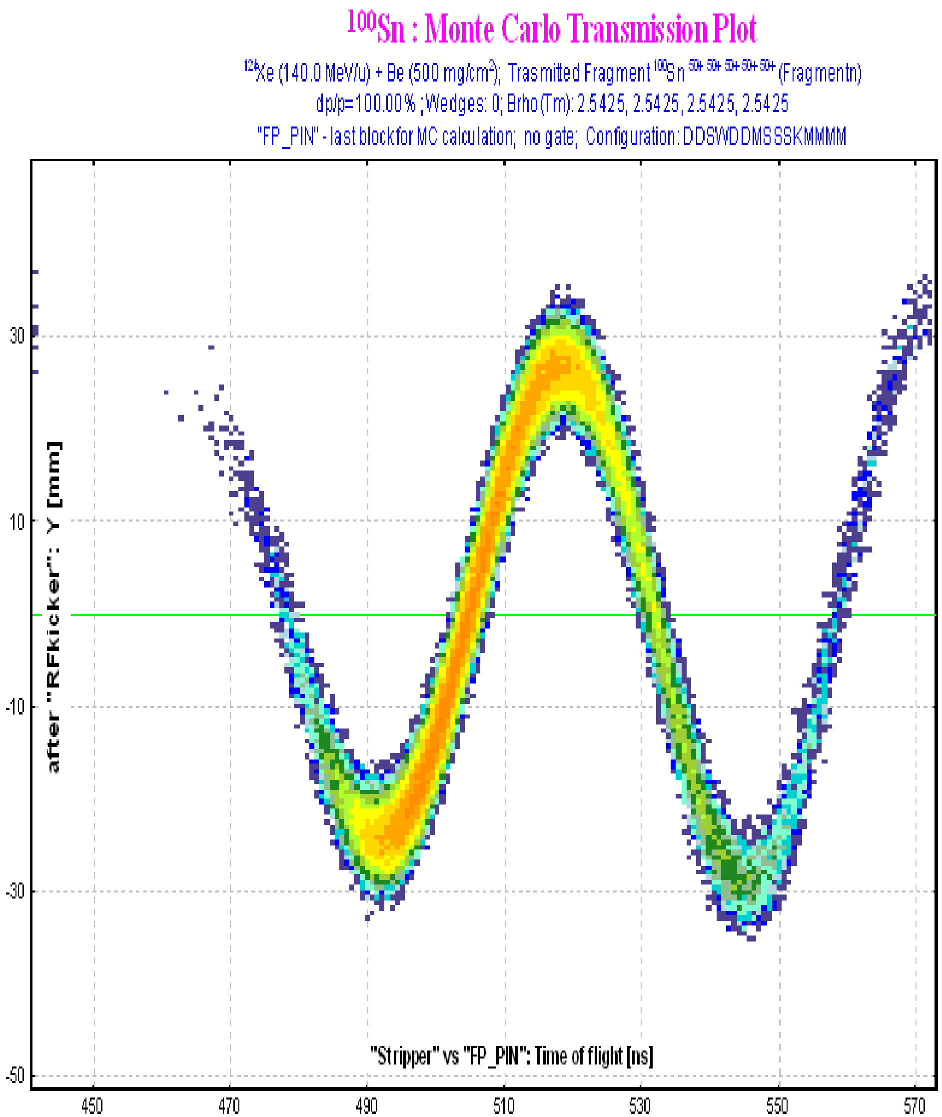


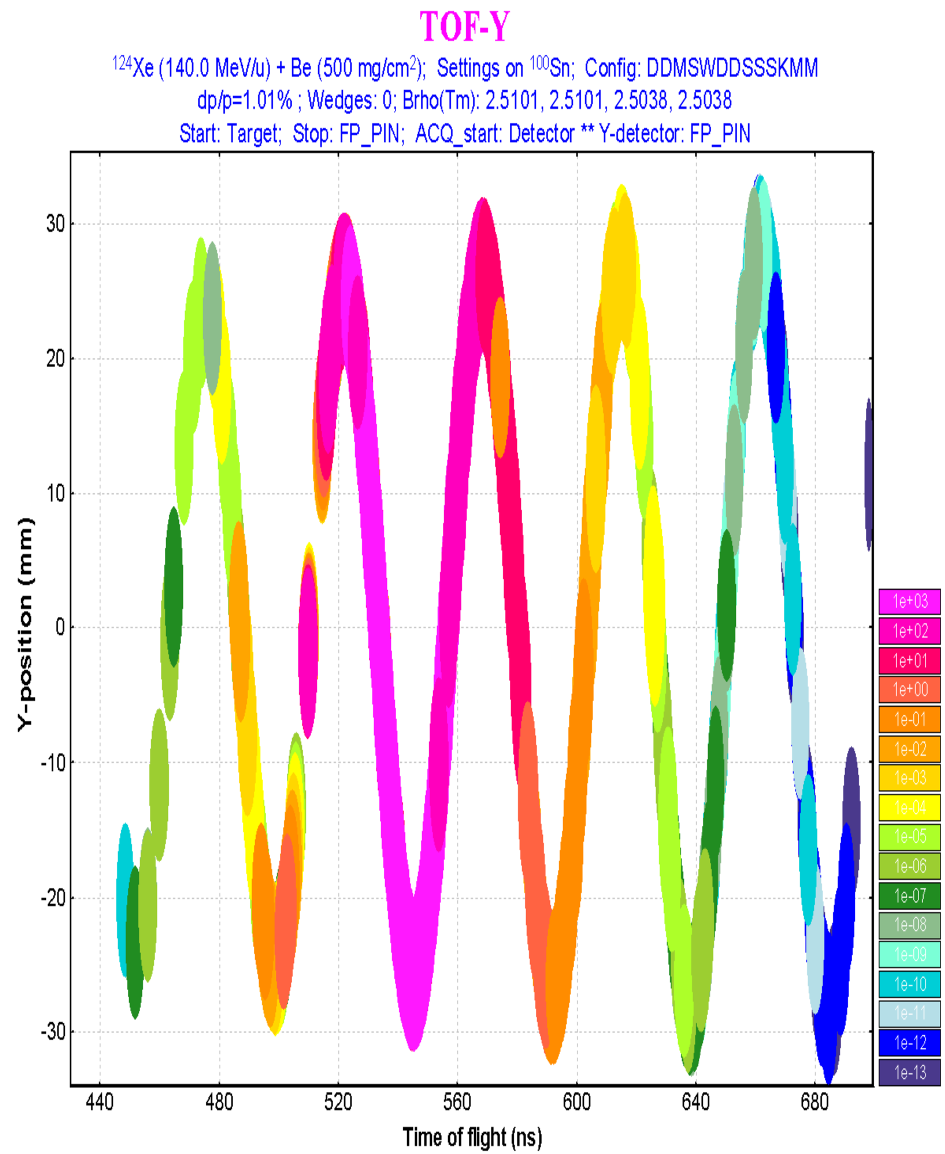
RF kicker in LISE++





RF-kicker example



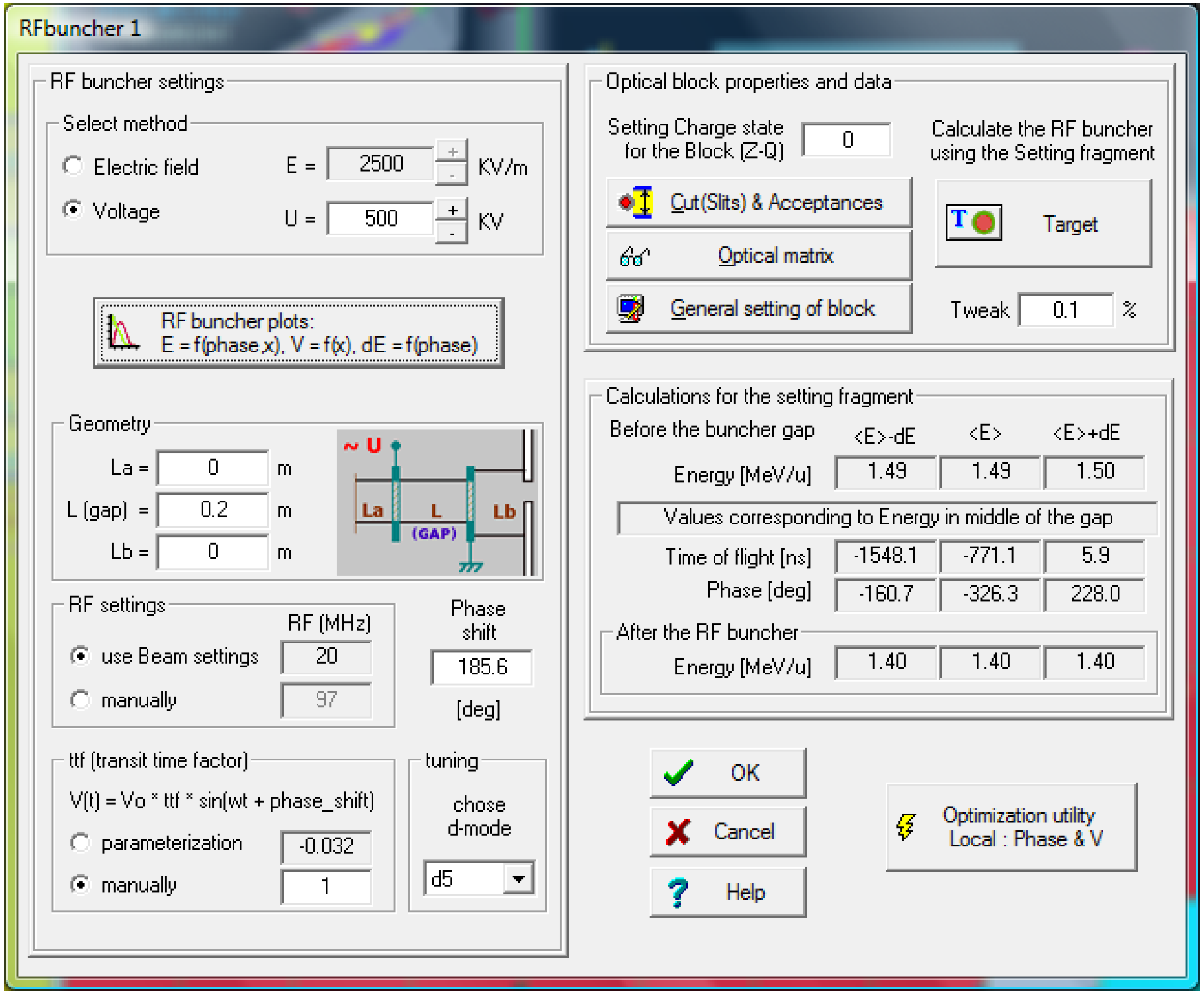


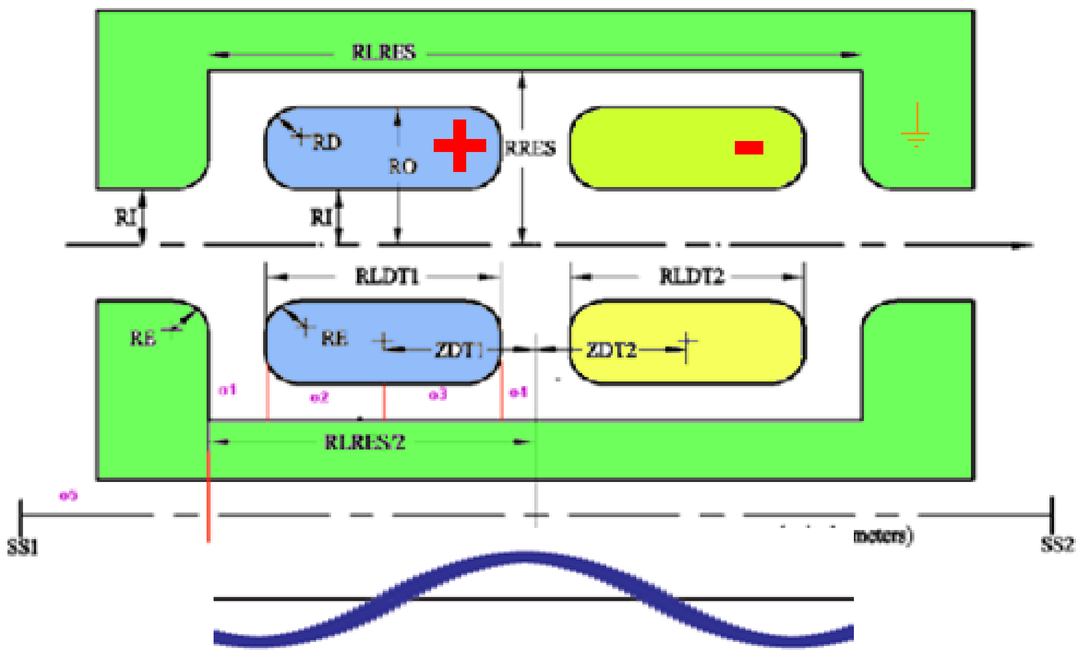
RF buncher

Note: RF-buncher block is more effective in MC mode

RESOLUT (FSU) configuration

http://lise.nscl.msu.edu/9_4/buncher/9_4_87_buncher.pdf





Gap	Gap Size	Bias
1	D	+V
2	2D	-2V
3	D	+V

Multi-gaps bunchers are constructed for specified speed

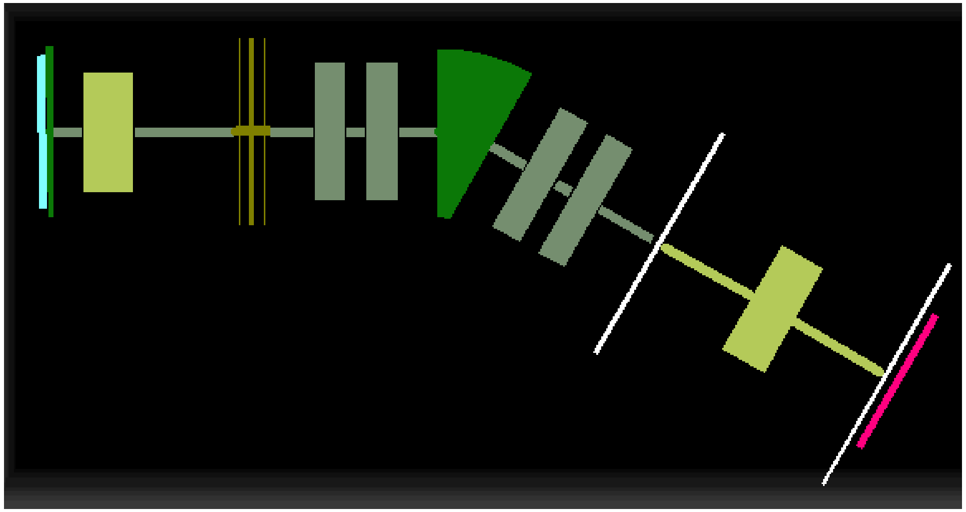
Initial RESOLUT scheme

Tuning dipole to define magnetic rigidity of the separator, Unitary matrix, no slits, zero length

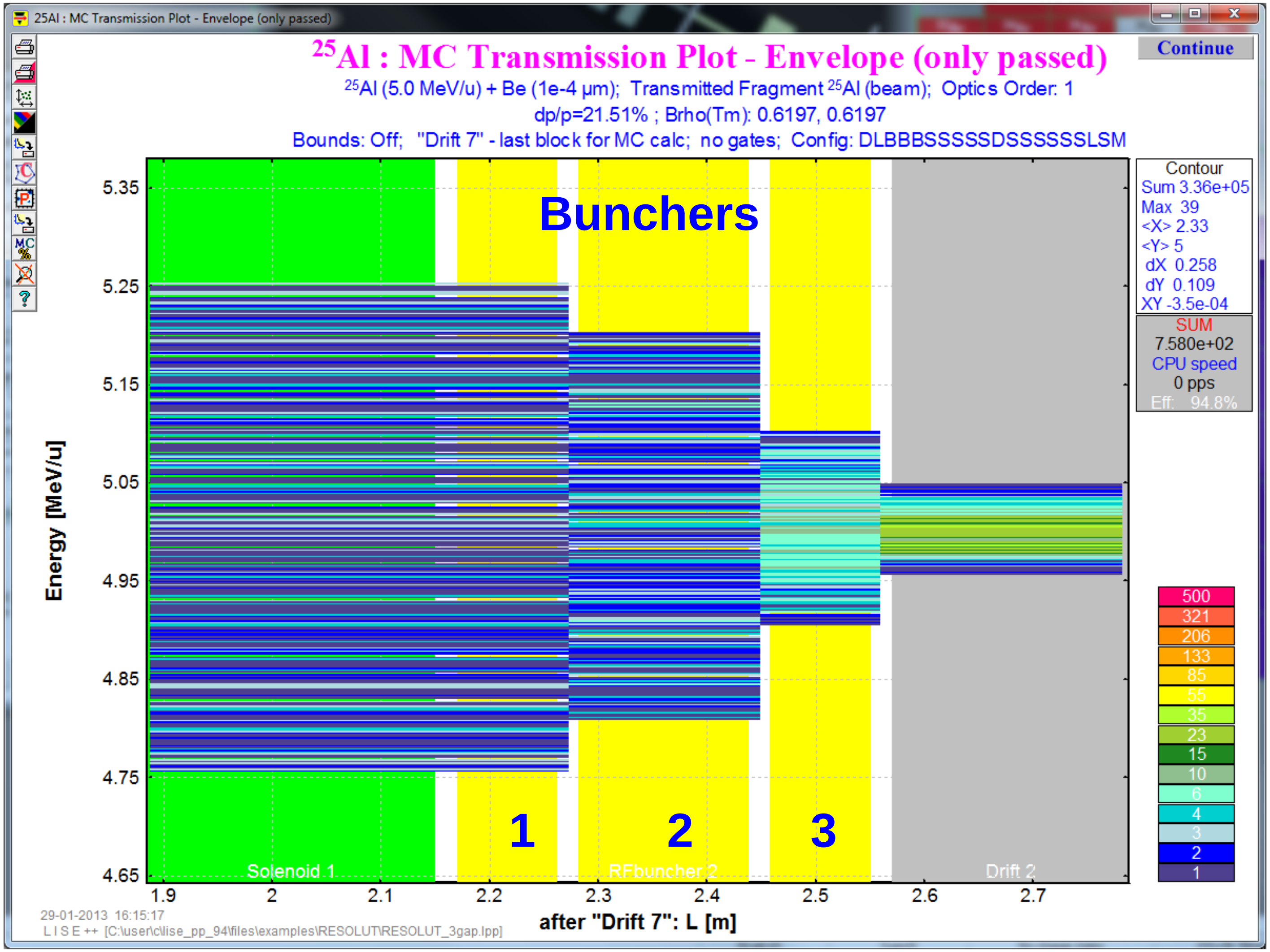
Initial drift+solenoid+drift configuration to define angular acceptance

3 gap Rf-buncher was realized as 3 RF bunchers

QQDQQ spectrometer

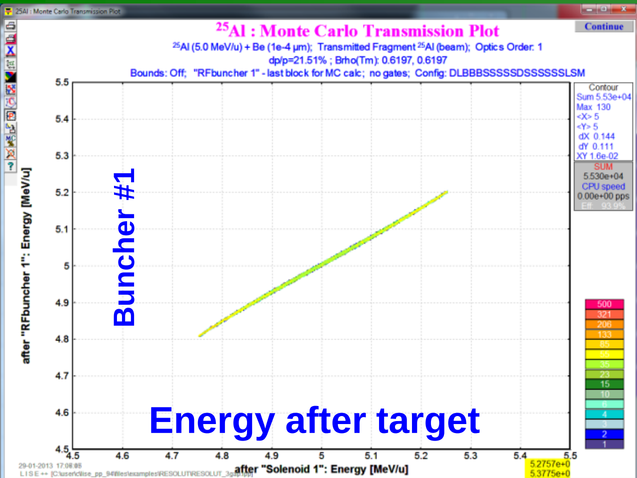


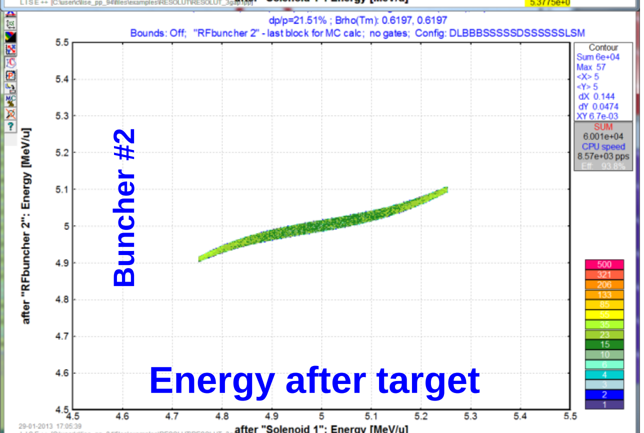
Three RF-bunchers in LISE++

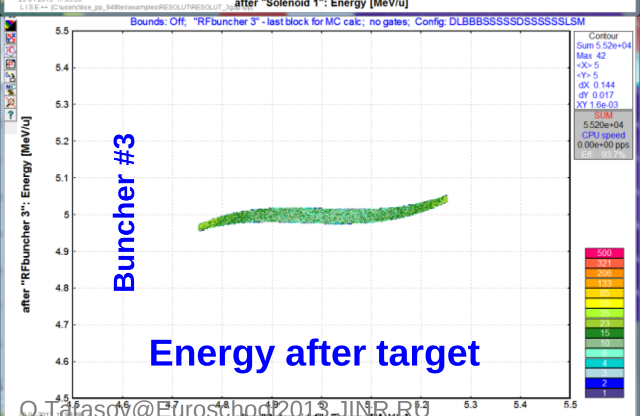


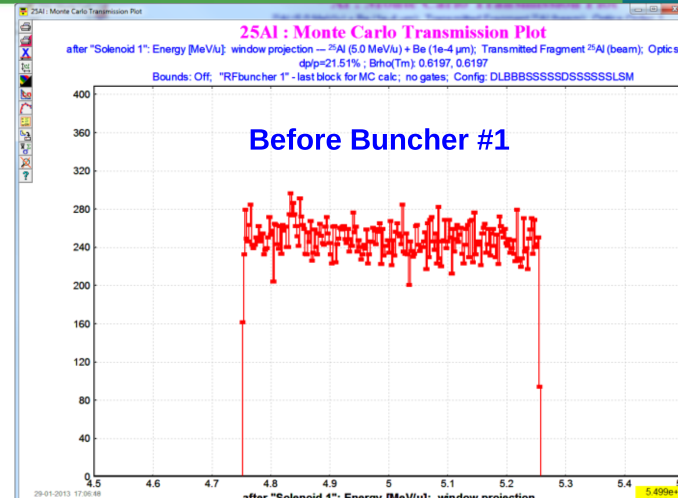
File: RESOLUT_3gap.lpp

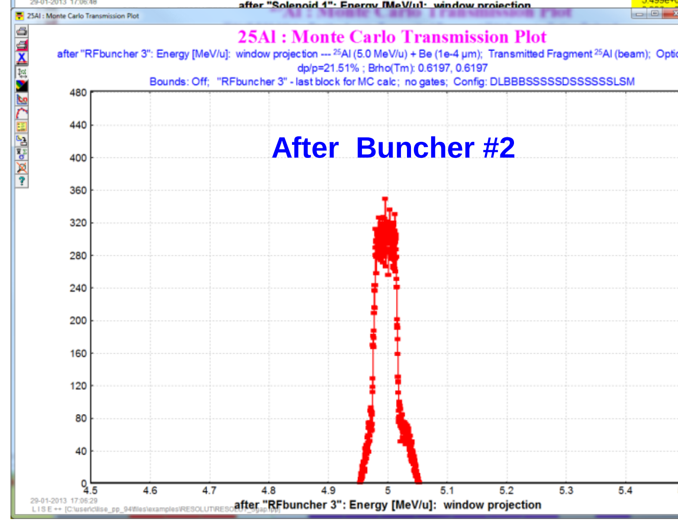
Three RF-bunchers in LISE++





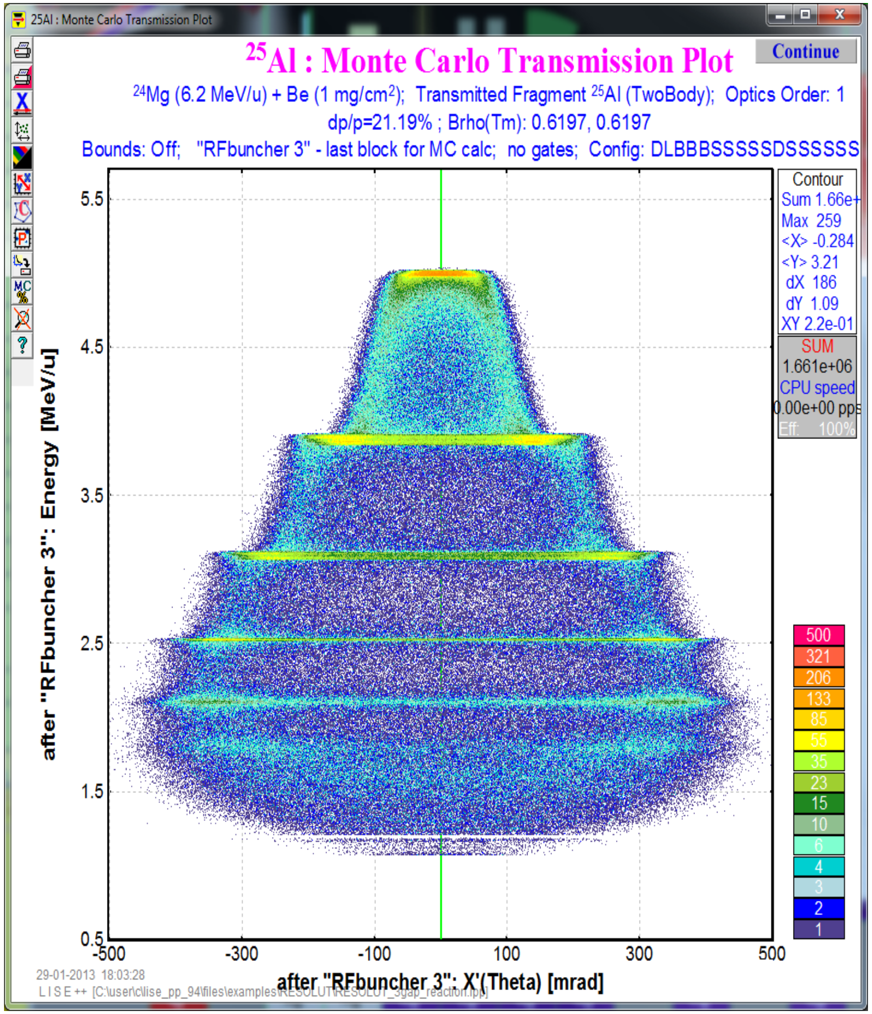




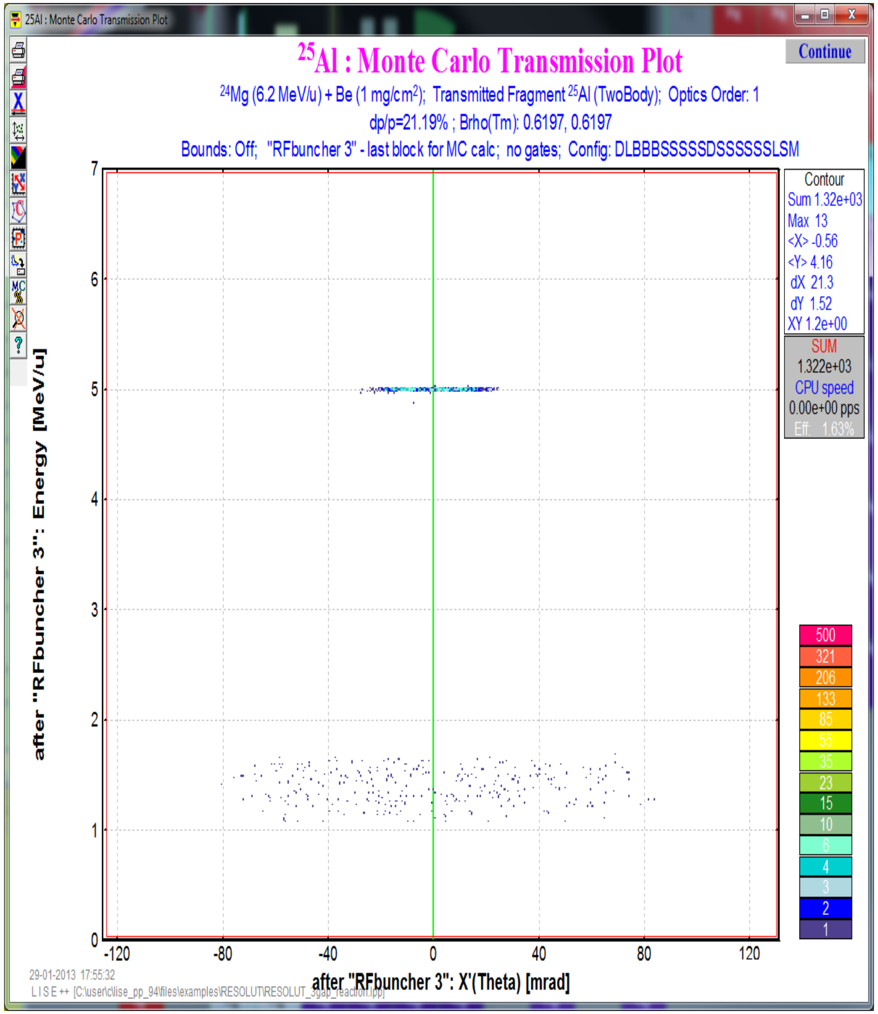


	StDev
Before Buncher#1	0.144
After Buncher #1	0.111
After Buncher #2	0.0474
After Buncher #3	0.017

After the 3 gap buncher without angular acceptance

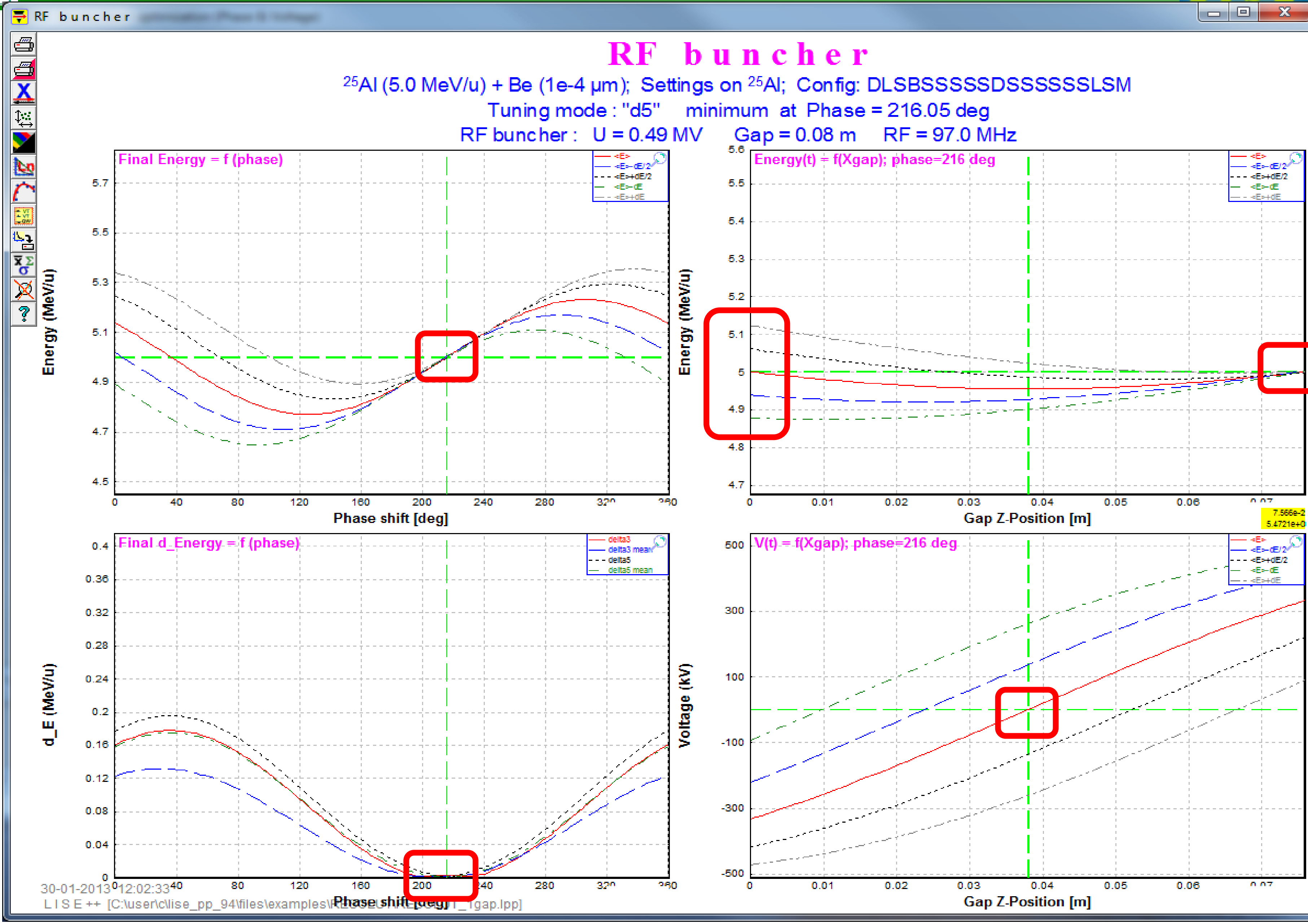


After the 3 gap buncher with angular acceptance



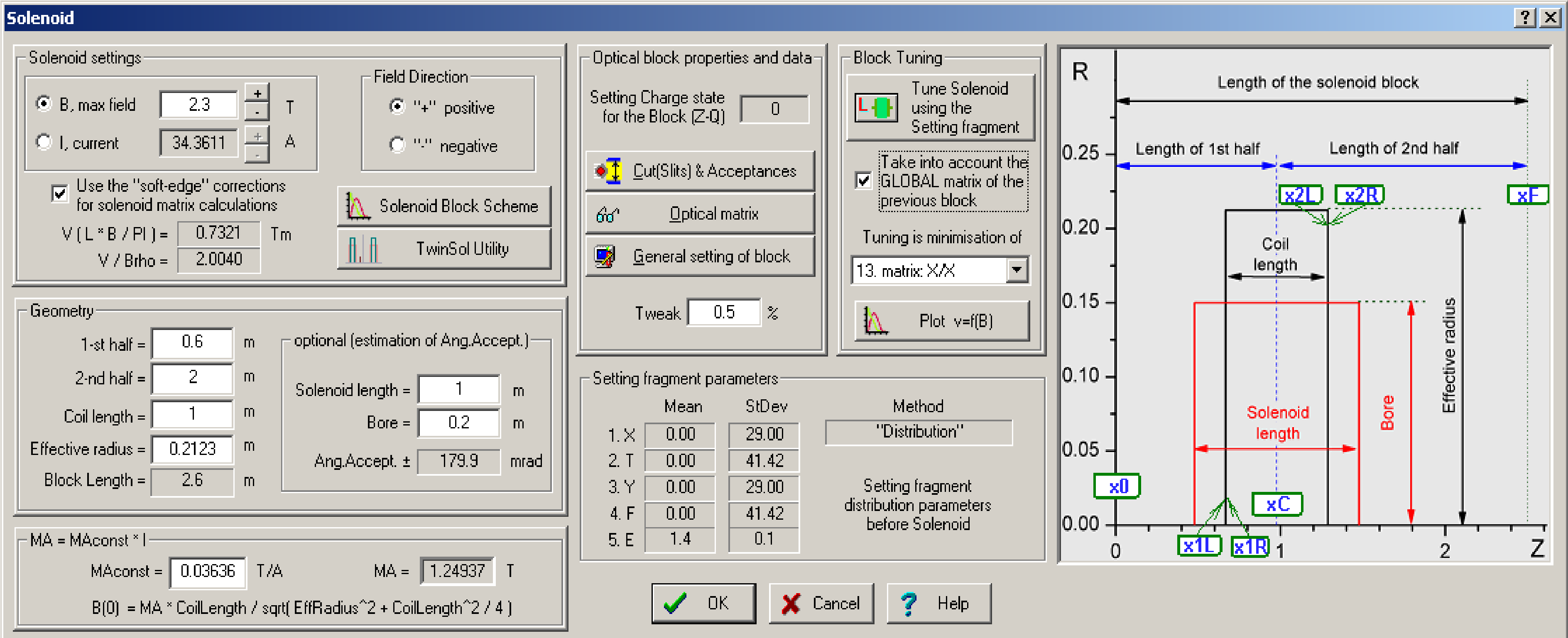
+/- 47 mrad acceptance, Transmission 1.6%

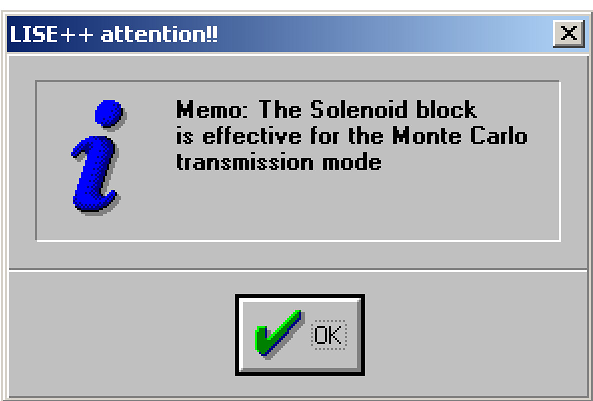
RESOLUT : RF buncher plots



Solenoid

The Solenoid block dialog



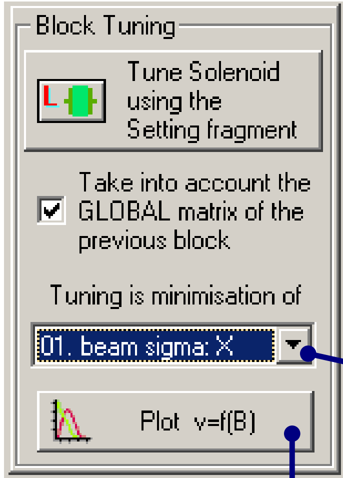


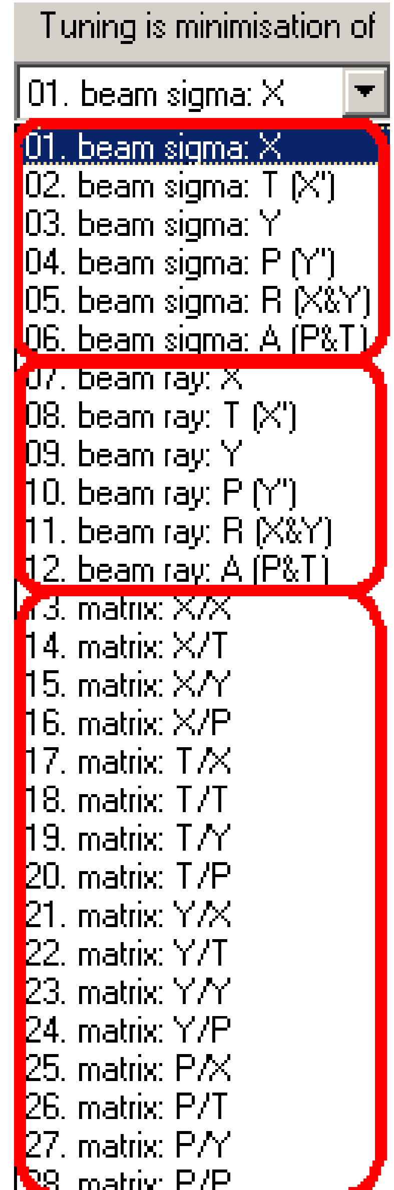
Calculation of setting fragment parameters in front of the solenoid and solenoid tuning are done by the "Distribution" method.

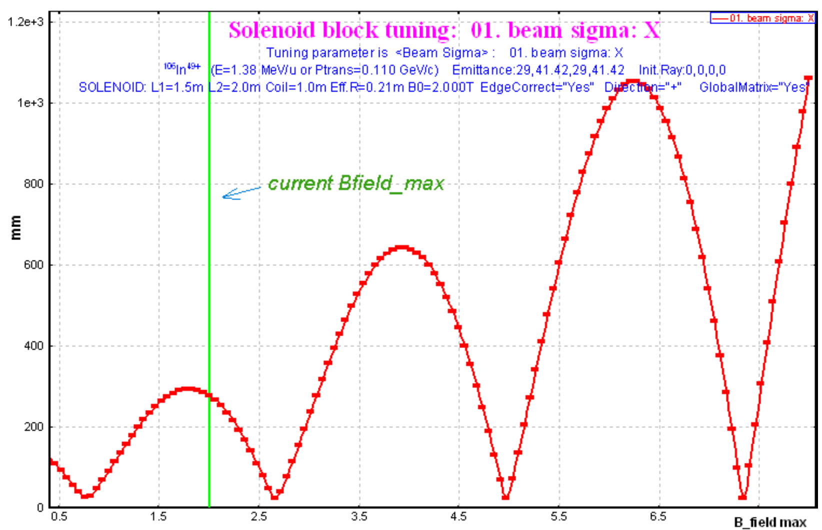
Phase space distributions and transmission with the Solenoid block are recommended with the Monte Carlo transmission method.

http://lise.nscl.msu.edu/8_3/SolenoidBlock_v8_3_58.pdf

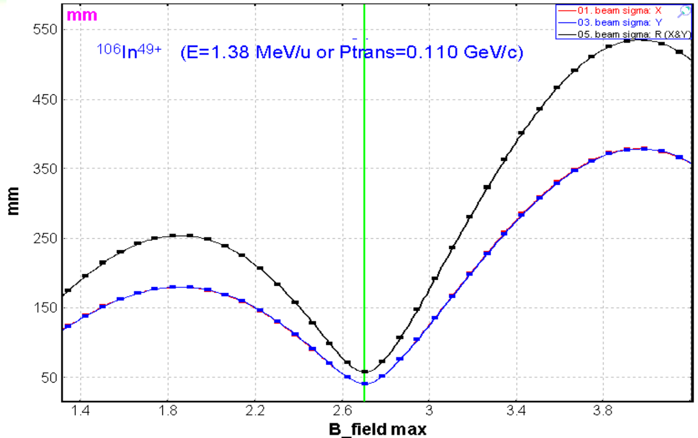
Solenoid Tuning





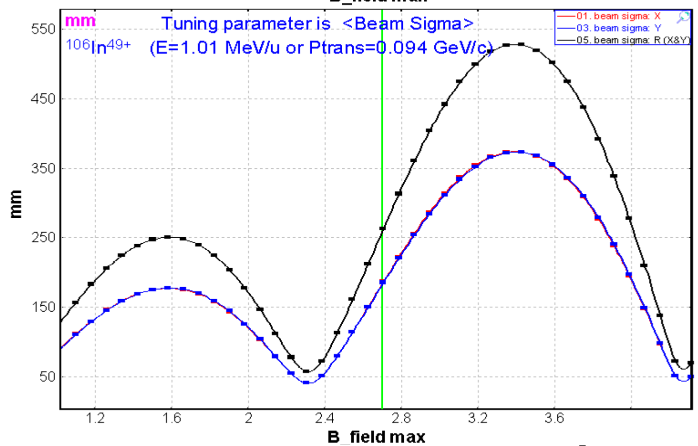


Matrices as function of Energy and A,Z



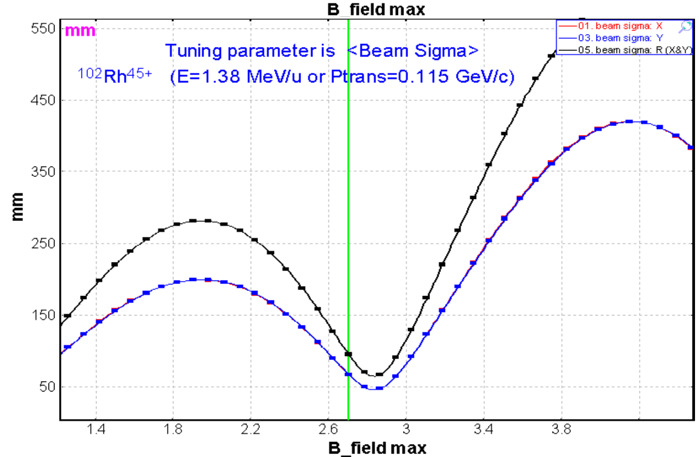
^{106}In at 1.4 MeV/u

	Block matrix						Global matrix							Beam
1. X	-0.9105	1.1786	-0.5655	0.7319	0	0	-0.9105	0.5413	-0.5655	0.3361	0	0	[mm]	12.654
2. T	-1.1175	0.6539	-0.694	0.4061	0	0	-1.1175	-0.1283	-0.694	-0.0797	0	0	[mrad]	3.292
3. Y	0.5655	-0.7319	-0.9105	1.1786	0	0	0.5655	-0.3361	-0.9105	0.5413	0	0	[mm]	12.927
4. F	0.694	-0.4061	-1.1175	0.6539	0	0	0.694	0.0797	-1.1175	-0.1283	0	0	[mrad]	3.306
5. L	0	0	0	0	1	0	0	0	0	0	1	0	[mm]	0
6. D	0	0	0	0	0	1	0	0	0	0	0	1	[%]	0.07
	/[mm]	/[mrad]	/[mm]	/[mrad]	/[mm]	/[%]	/[mm]	/[mrad]	/[mm]	/[mrad]	/[mm]	/[%]		



^{106}In at 1.0 MeV/u

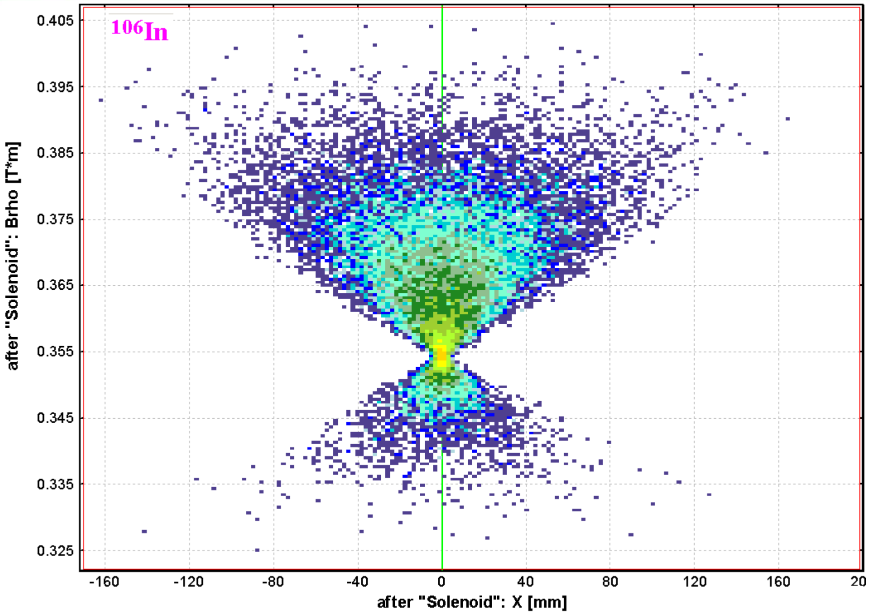
	Block matrix						Global matrix							Beam
1. X	-1.8574	0.1773	-4.4777	0.4273	0	0	-1.8574	-1.1229	-4.4777	-2.7071	0	0	[mm]	59.83
2. T	-1.3632	0.0511	-3.2863	0.1231	0	0	-1.3632	-0.9031	-3.2863	-2.1773	0	0	[mrad]	48.098
3. Y	4.4777	-0.4273	-1.8574	0.1773	0	0	4.4777	2.7071	-1.8574	-1.1229	0	0	[mm]	57.823
4. F	3.2863	-0.1231	-1.3632	0.0511	0	0	3.2863	2.1773	-1.3632	-0.9031	0	0	[mrad]	46.476
5. L	0	0	0	0	1	0	0	0	0	0	1	0	[mm]	0
6. D	0	0	0	0	0	1	0	0	0	0	0	1	[%]	0.07
	/[mm]	/[mrad]	/[mm]	/[mrad]	/[mm]	/[%]	/[mm]	/[mrad]	/[mm]	/[mrad]	/[mm]	/[%]		

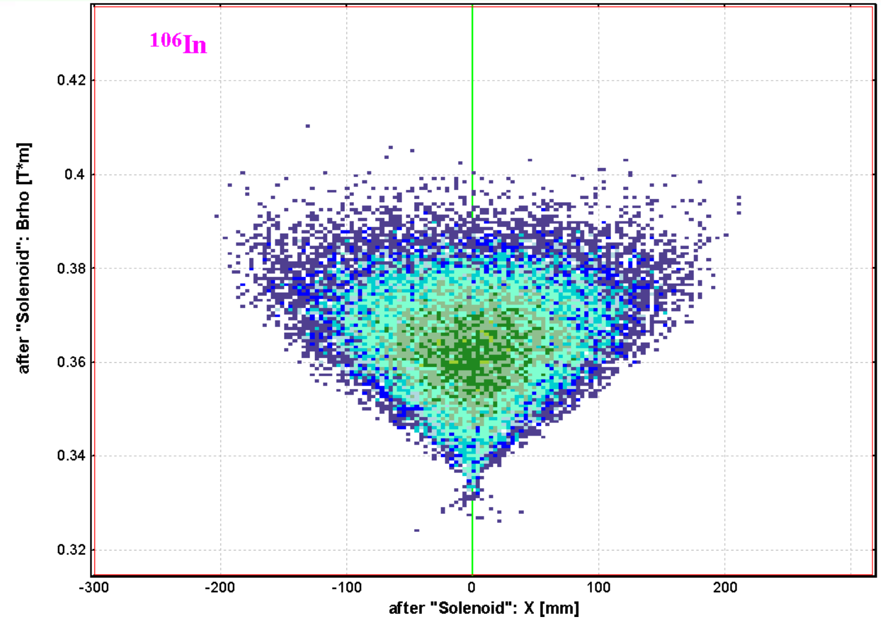


^{102}Rh at 1.4 MeV/u

	Block matrix						Global matrix							Beam
1. X	-0.0842	1.4274	-0.0341	0.5788	0	0	-0.0842	1.3685	-0.0341	0.5549	0	0	[mm]	29.009
2. T	-0.6504	0.8264	-0.2637	0.3351	0	0	-0.6504	0.3711	-0.2637	0.1505	0	0	[mrad]	7.903
3. Y	0.0341	-0.5788	-0.0842	1.4274	0	0	0.0341	-0.5549	-0.0842	1.3685	0	0	[mm]	30.068
4. F	0.2637	-0.3351	-0.6504	0.8264	0	0	0.2637	-0.1505	-0.6504	0.3711	0	0	[mrad]	8.181
5. L	0	0	0	0	1	0	0	0	0	0	1	0	[mm]	0
6. D	0	0	0	0	0	1	0	0	0	0	0	1	[%]	0.07
	/[mm]	/[mrad]	/[mm]	/[mrad]	/[mm]	/[%]	/[mm]	/[mrad]	/[mm]	/[mrad]	/[mm]	/[%]		

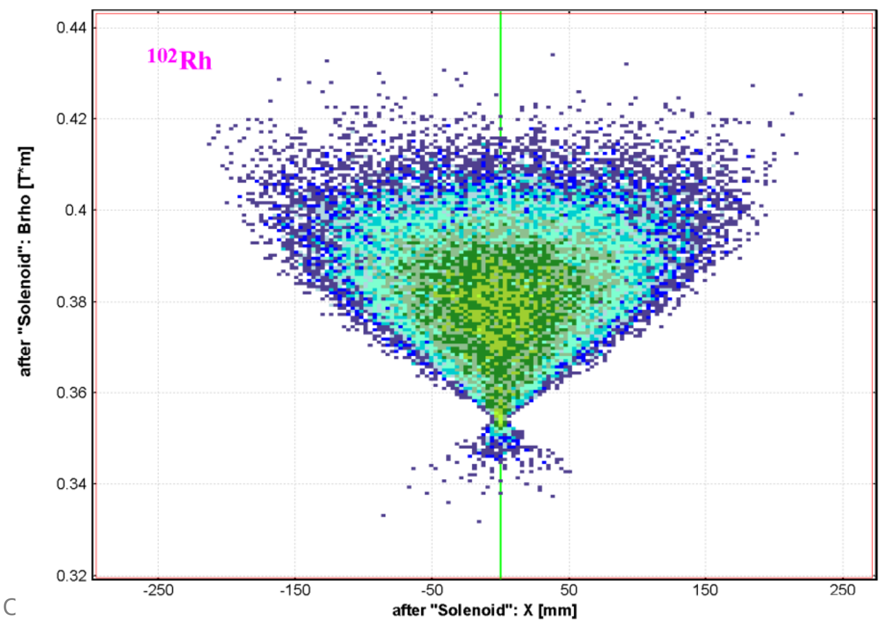
Function of Field

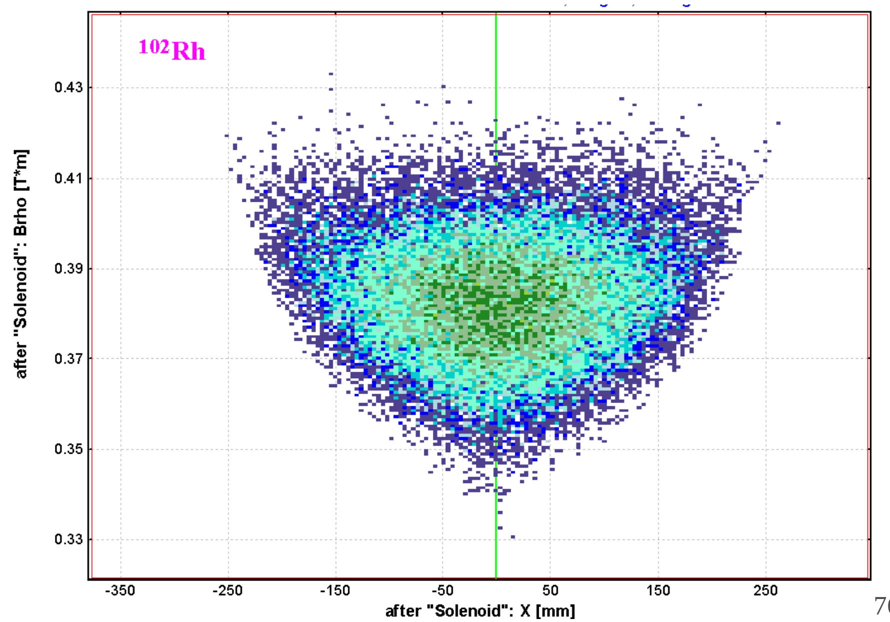




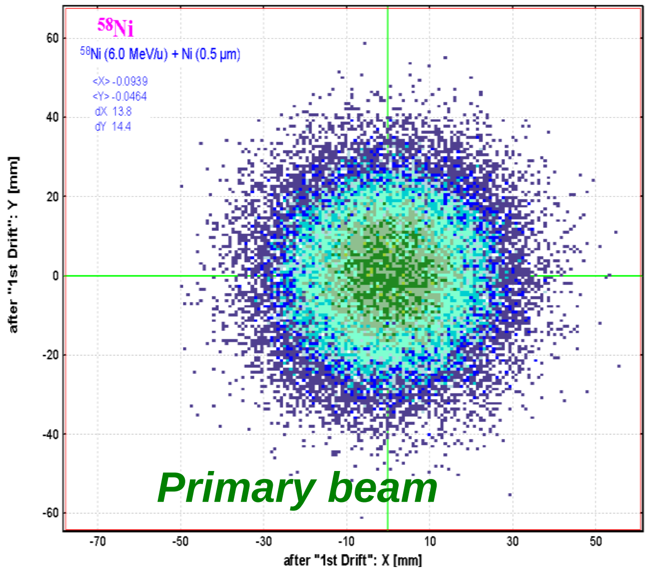
$B_{solenoid}$ = 2.7 T

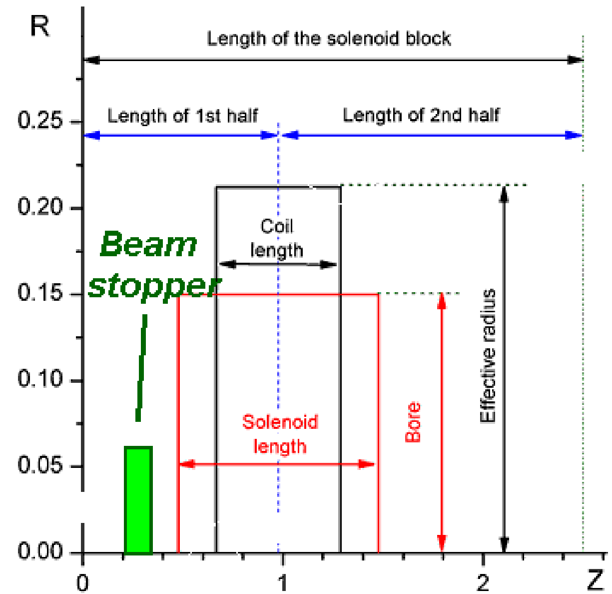
$B_{solenoid}$ = 2.55 T

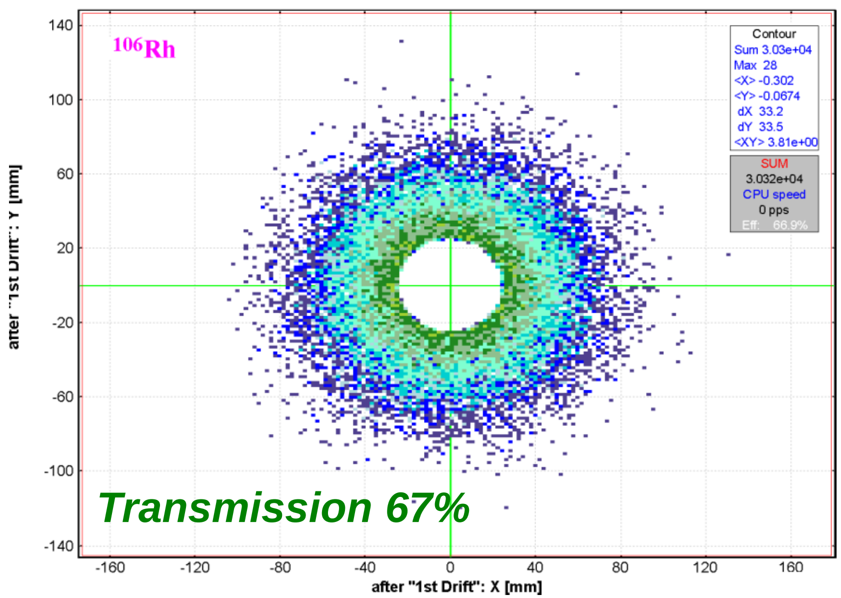


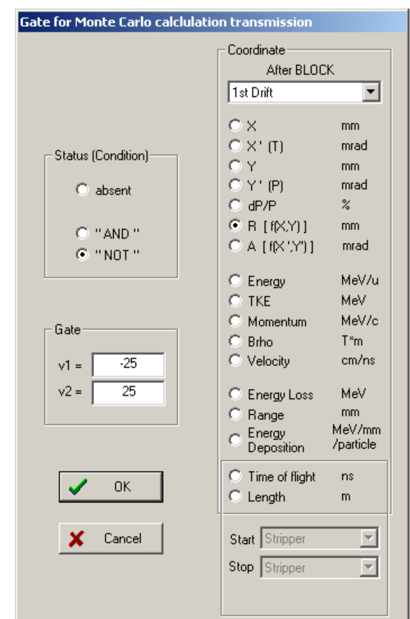


Working with Solenoid: Beam Stopper



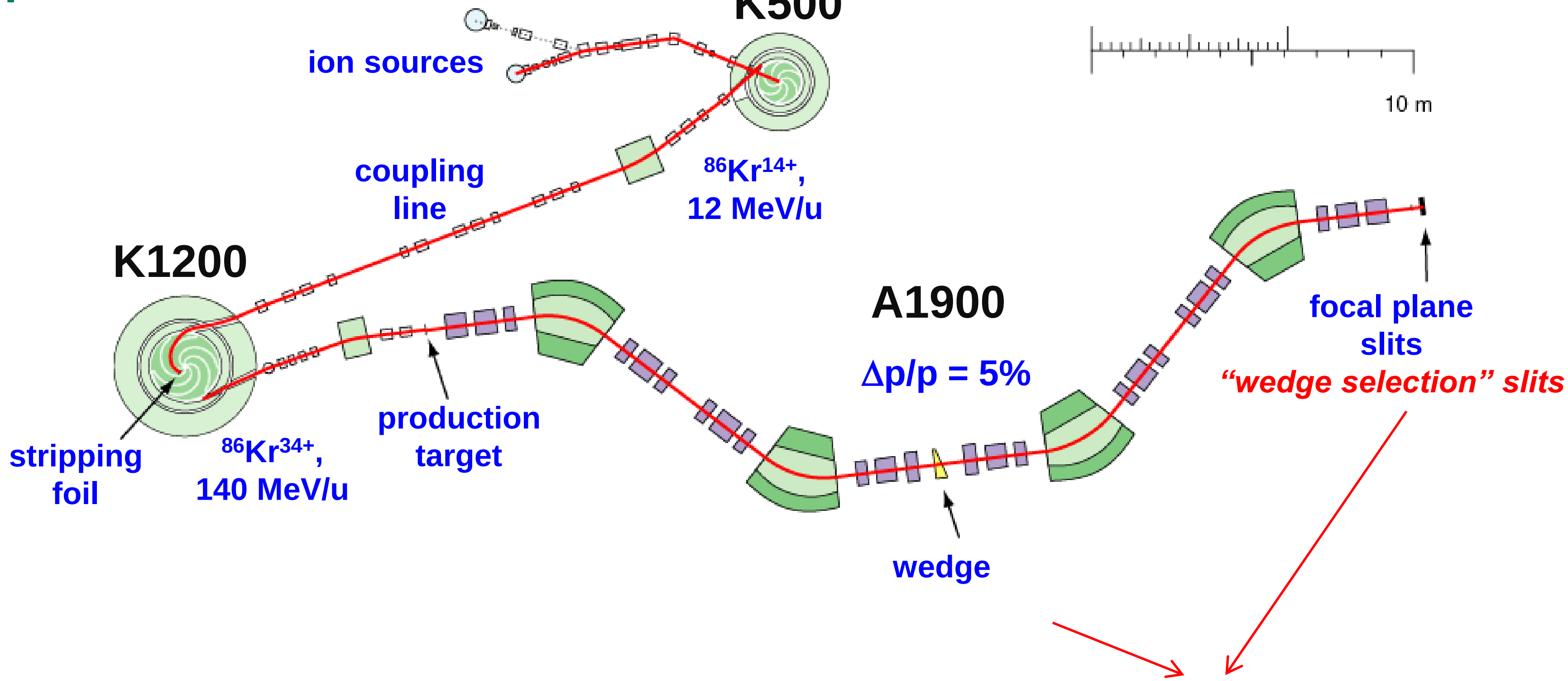


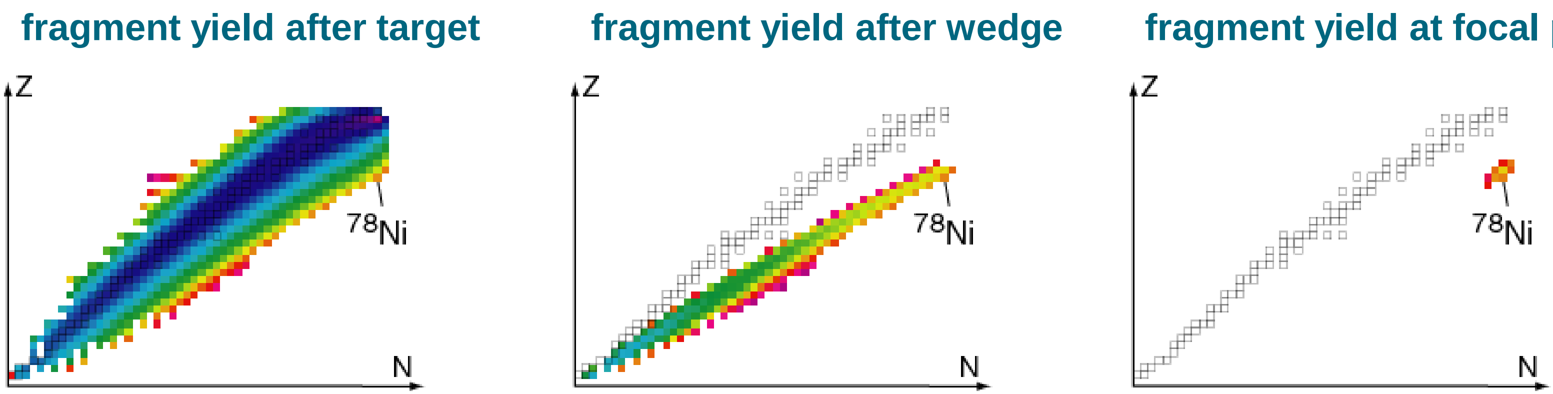




5. Selection with WEDGE

Example: $^{86}Kr \rightarrow {}^{78}Ni$



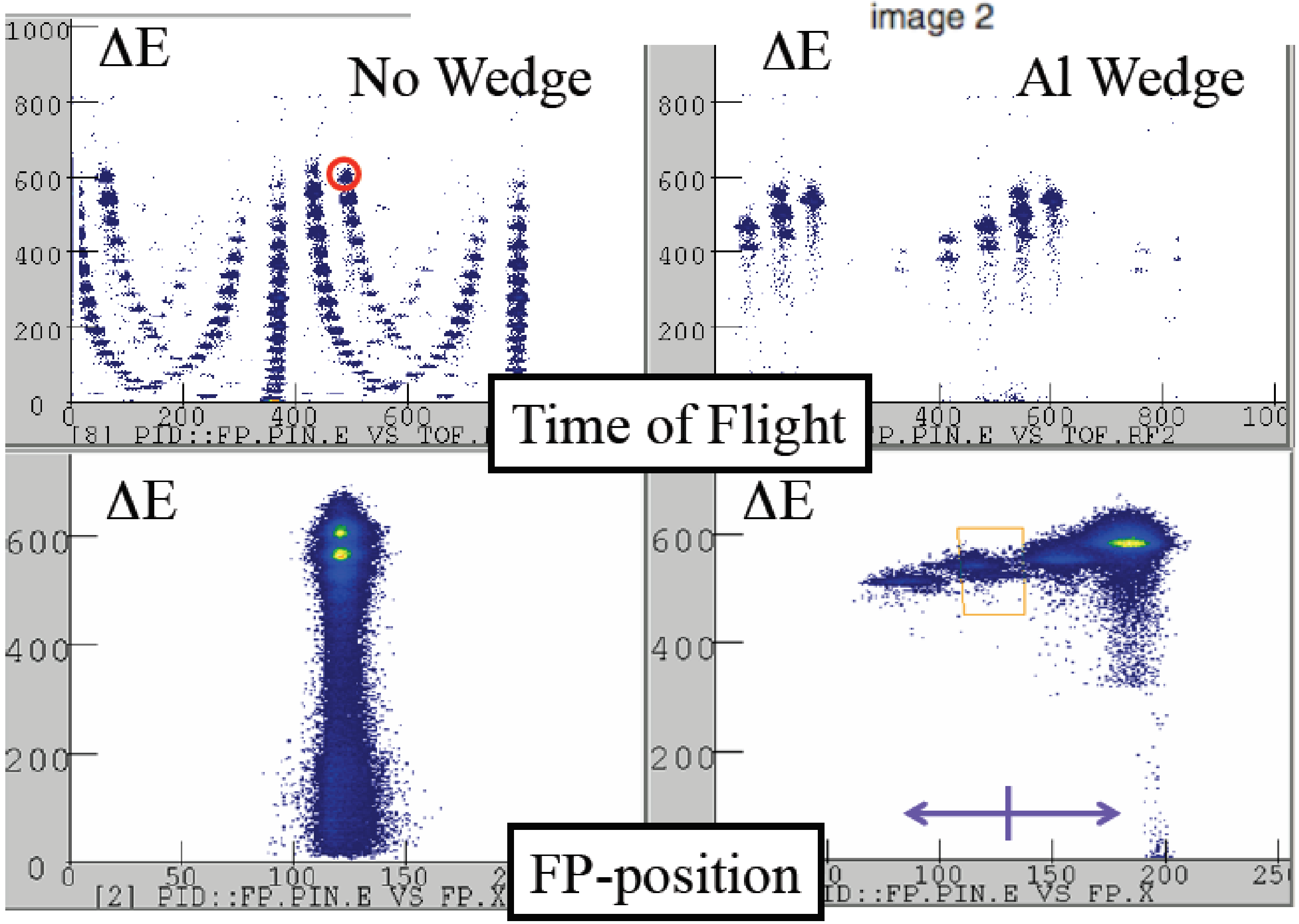


Wedge selection

Example:

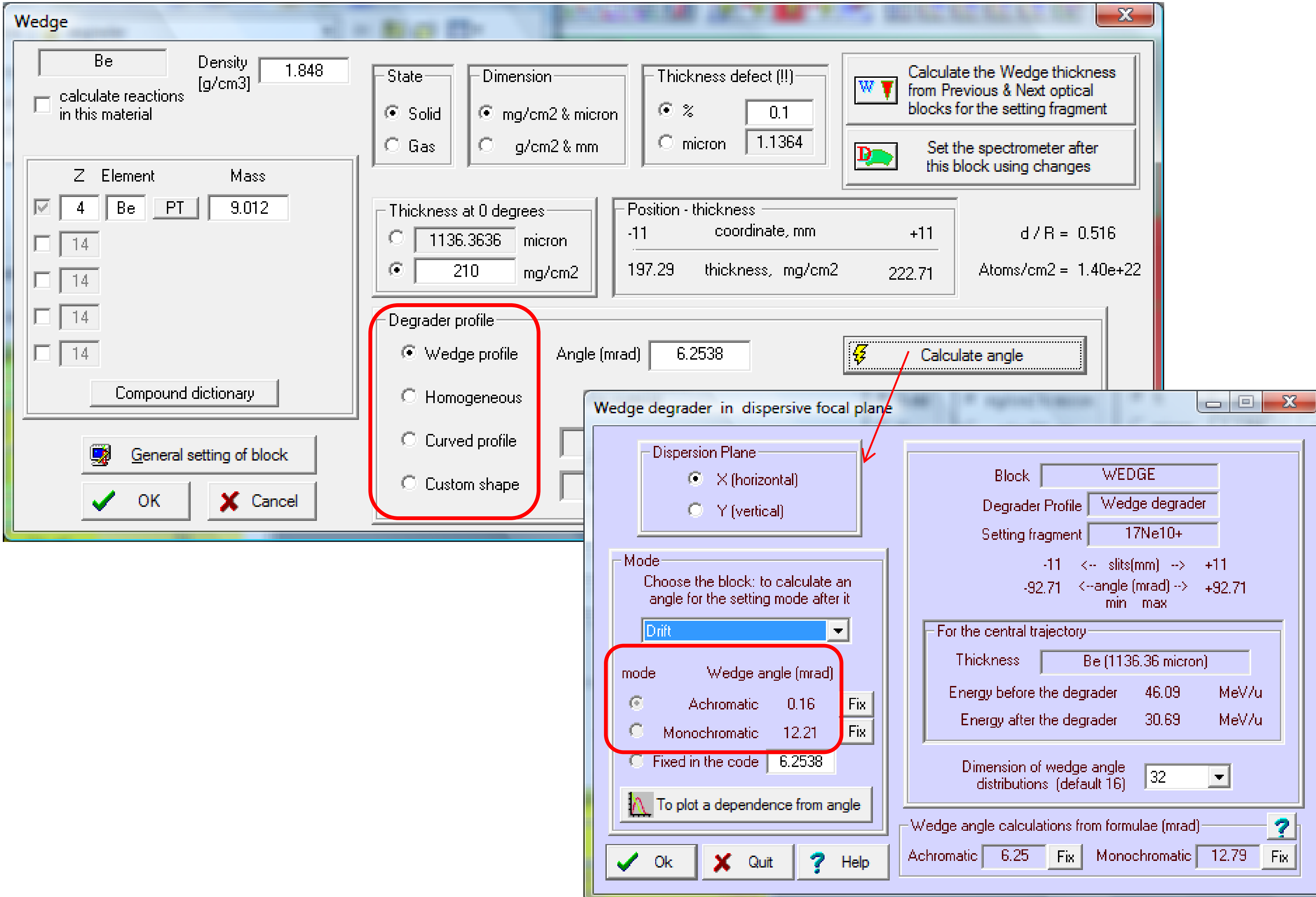
$^{40}Ca \rightarrow {}^{38}_{20}Ca_{18}$

$B\rho_{1,2}$
$= B\rho_{3,4}$



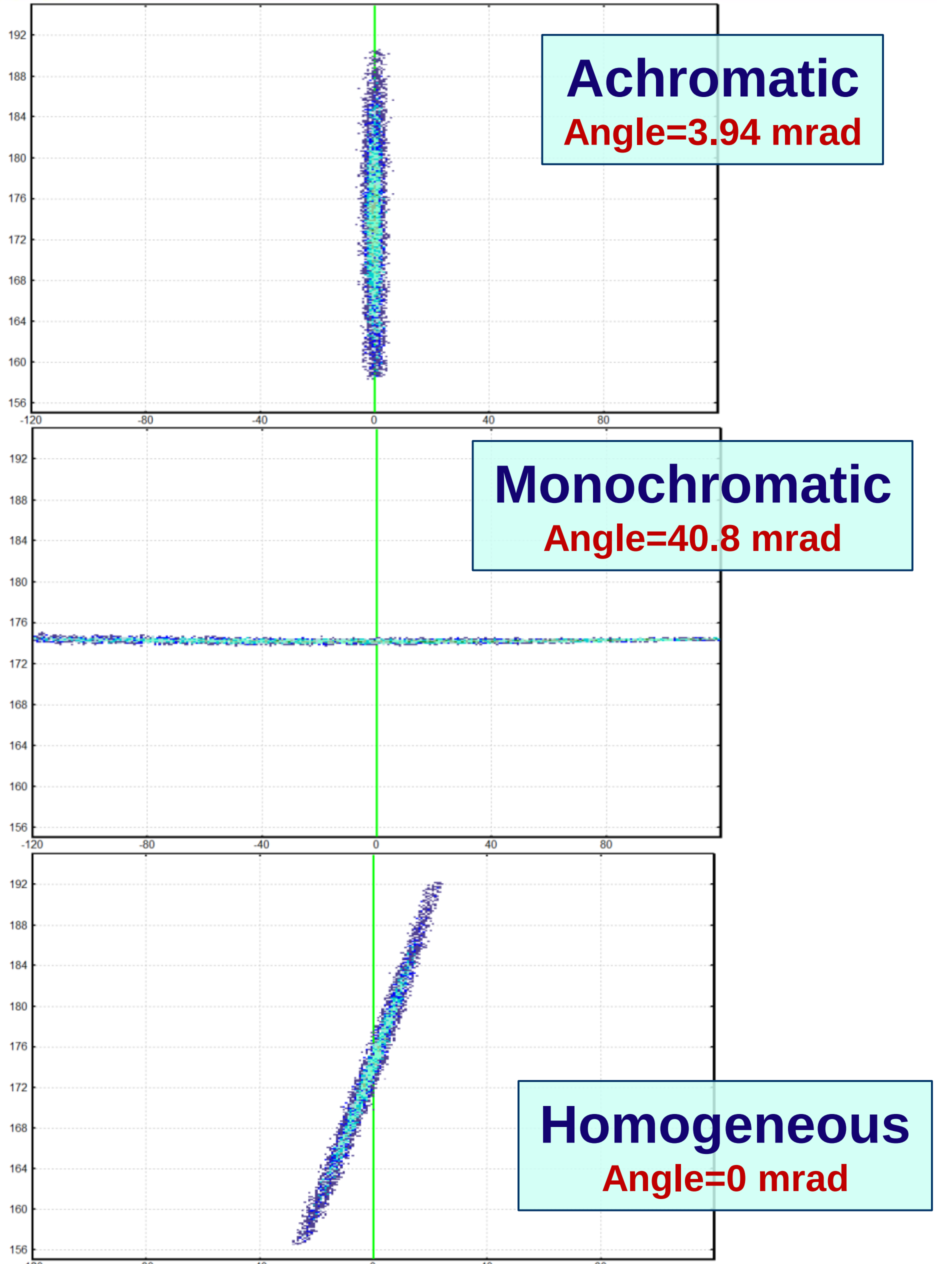
$B\rho_{1,2}$
$> B\rho_{3,4}$

Wedge: Profiles, Modes



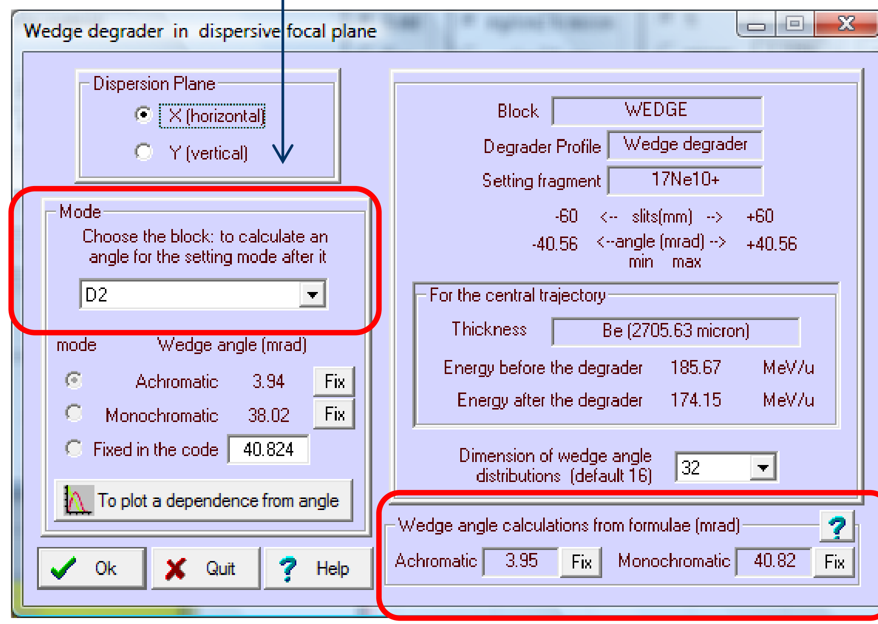
Wedge: Modes

Universal:
Any number of blocks including material



Energy in focal plane, MeV/u

X-position in focal plane, mm

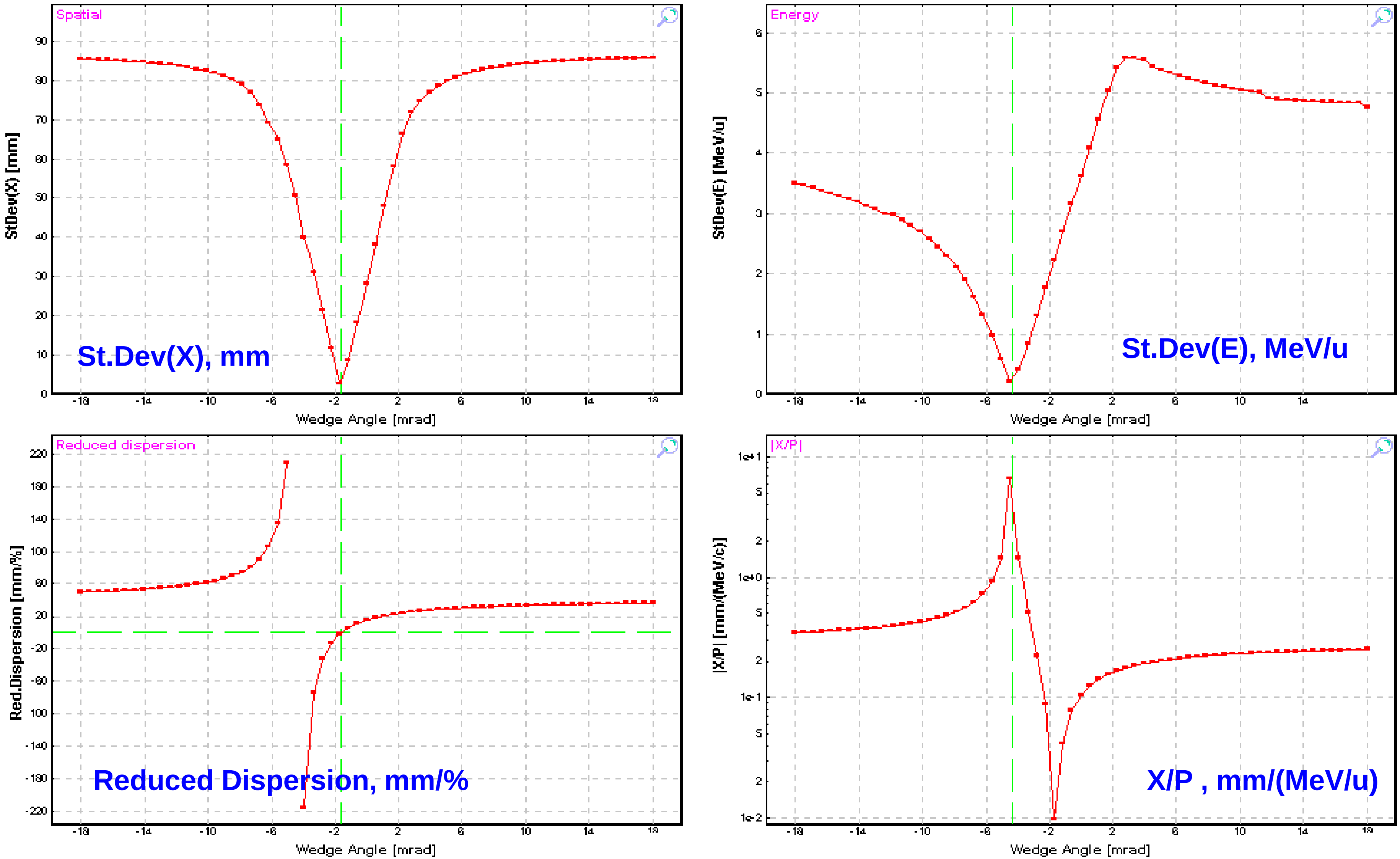


Assuming wedge &
1 dipole combination

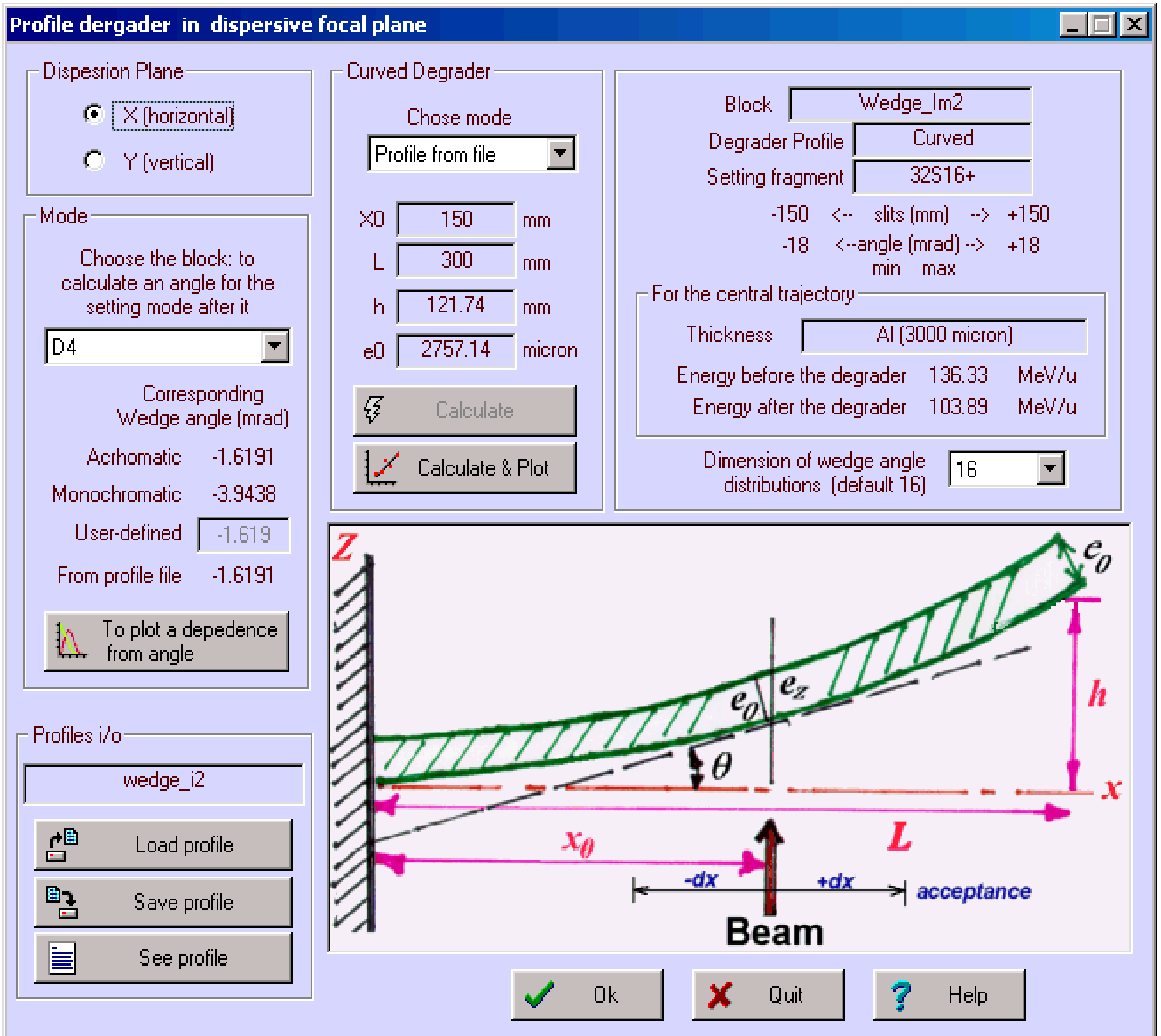
Calculated Angles

Wedge_Im2 calculations for D4

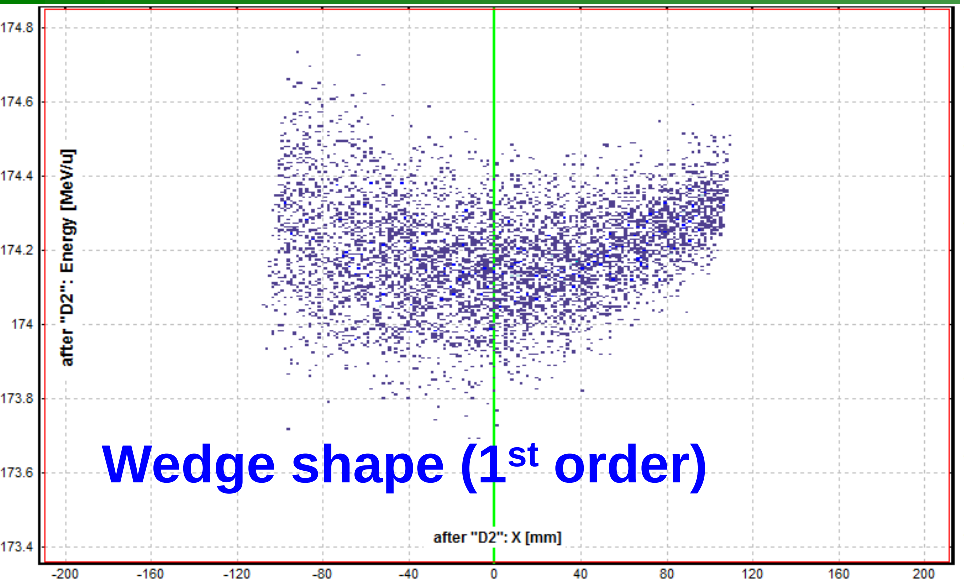
^{40}Ar 140.0 MeV/u + Be (500 μm); Settings on ^{32}S; Config: DDMSWMDSDMMMMMMMMMM
dp/p=5.07% ; Wedges: Al (3000 μm); Brho(Tm): 3.4821, 3.4821, 3.0101, 3.0101
Horizontal direction

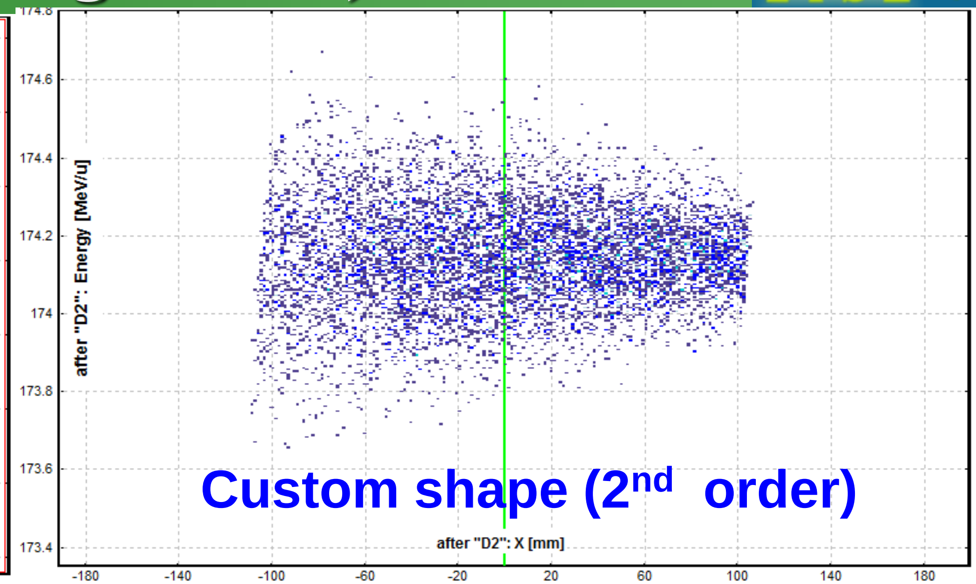


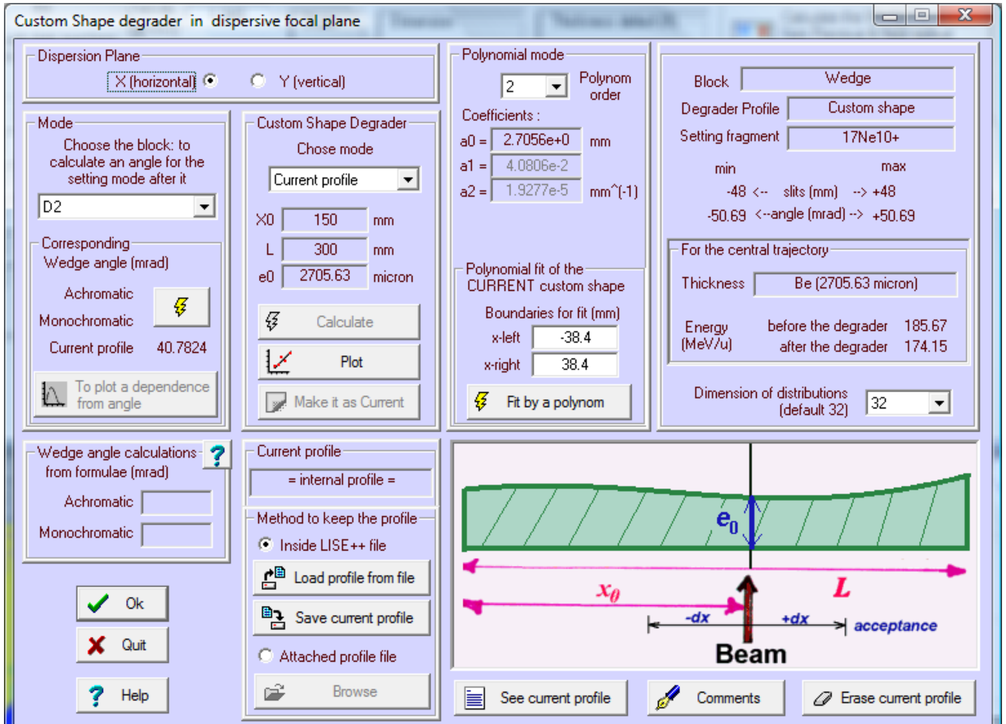
Curved profile



Custom profile (High order)

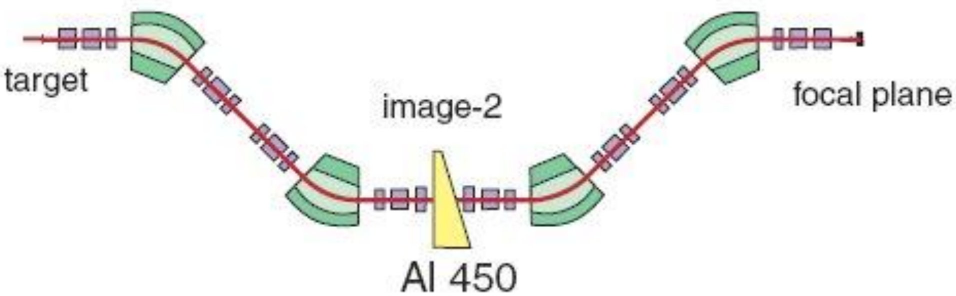






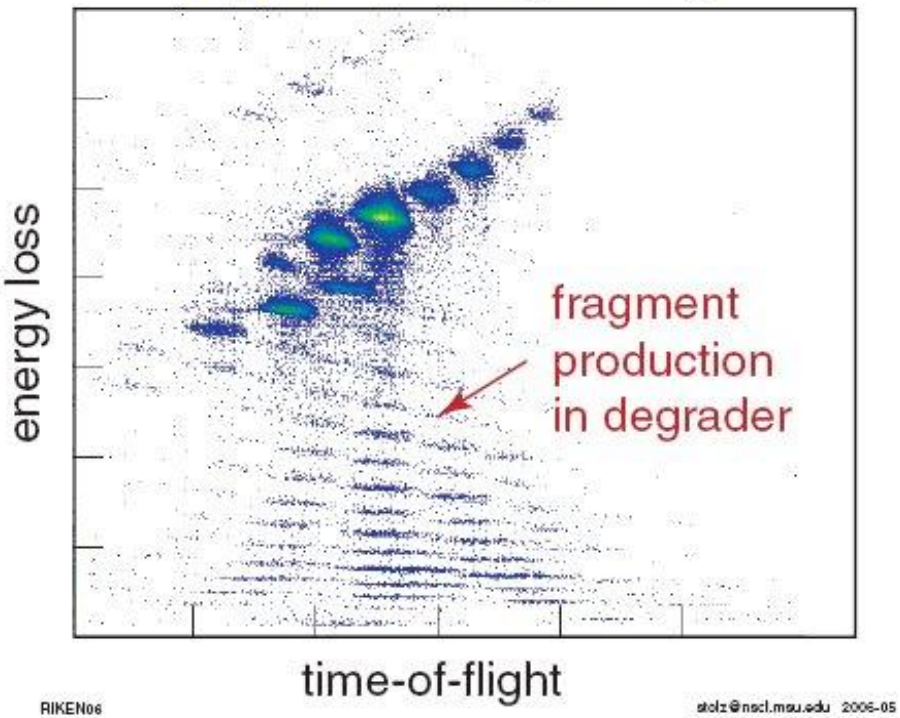
Fragment production in material

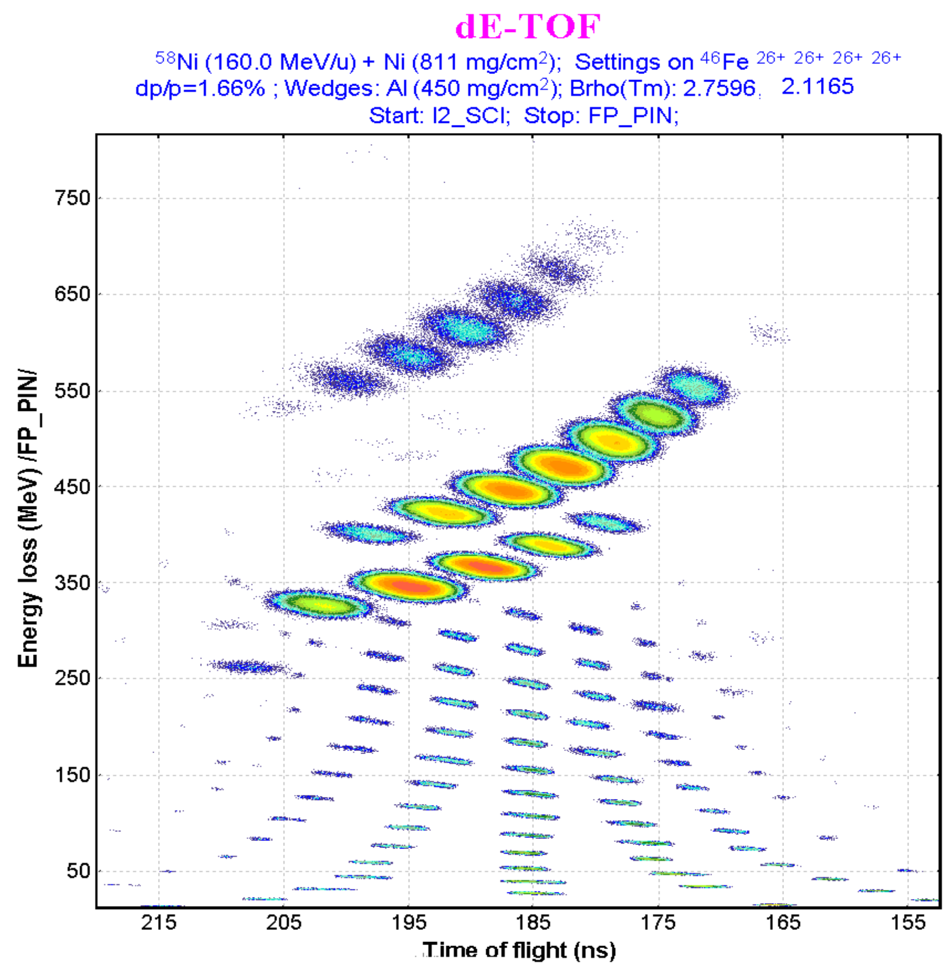
^{58}Ni, 160 MeV/u + ^{nat}Ni, 811 mg/cm^2 → ^{46}Fe



Comparasion with experimental data

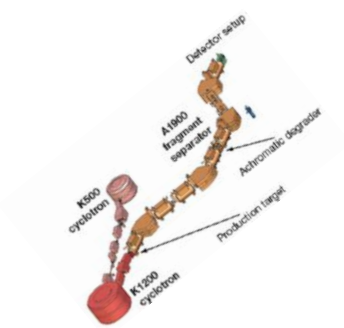
degrader @ image-2 only

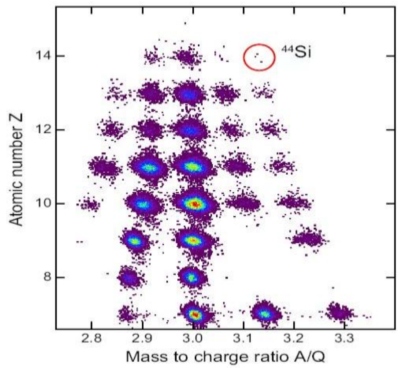




O.T. et al., *Phys.Rev. C 75, 064613 (2007)*

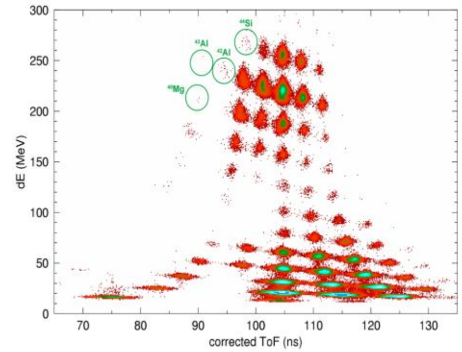
^{44}Si

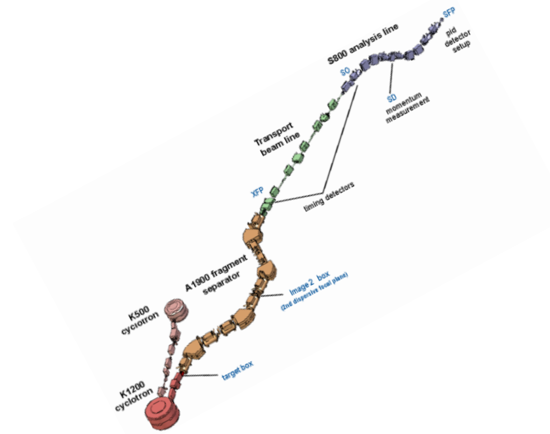


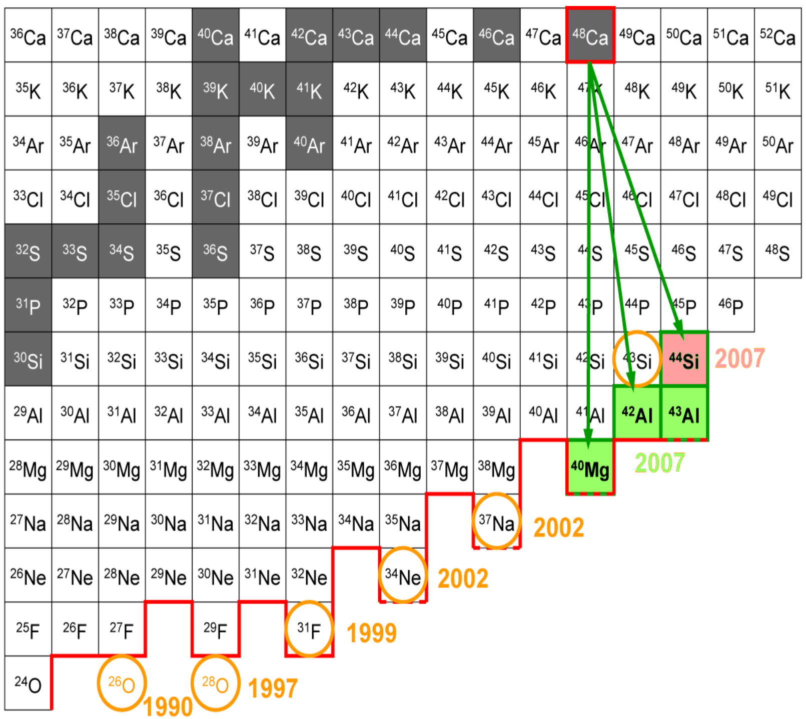


^{40}Mg, ^{42}Al, ^{43}Al

T.Baumann et al.,Nature (London) 449, 1022 (2007)





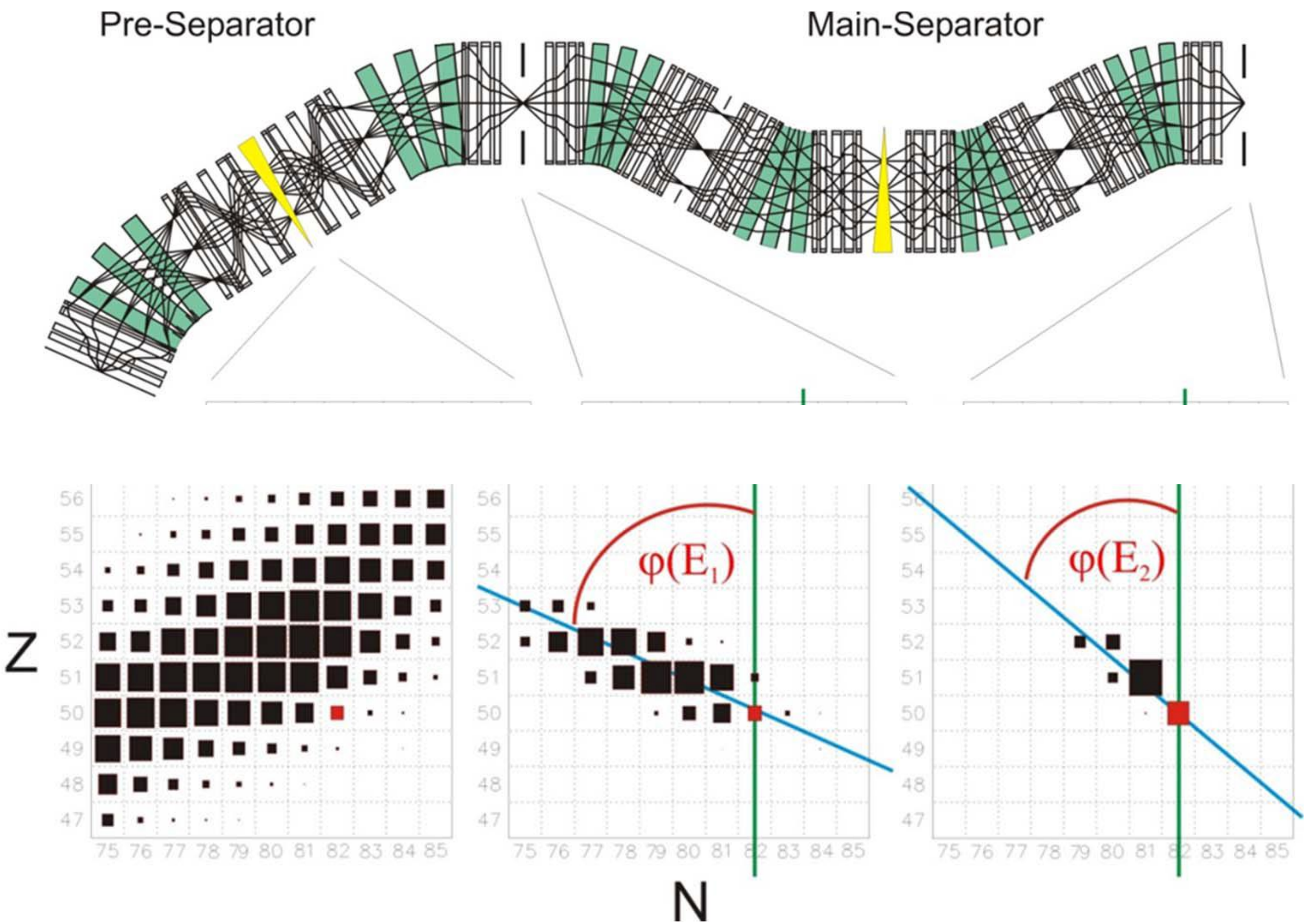


Two-stage separation

- No detectors in beam line down to wedge selection slits (A1900 FP).
- Position (Bρ) measurement in the dispersive focal plane in the second stage (S800BL)
- The first stage (A1900) of the system serves as a <u>selector</u> whereas the second stage (transfer hall line + S800BL) contains detectors and functions as <u>analyzer</u>
- All new fragment separators BigRIPS, SuperFRS, A2400 are multi-stage separators.

Two wedge stages required at the Super-FRS

1.1 A GeV ^{238}U on 4 g/cm^2 C target, two Al degraders d/R=0.3, d/R=0.7



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6. Transmission

In-flight RIB yields

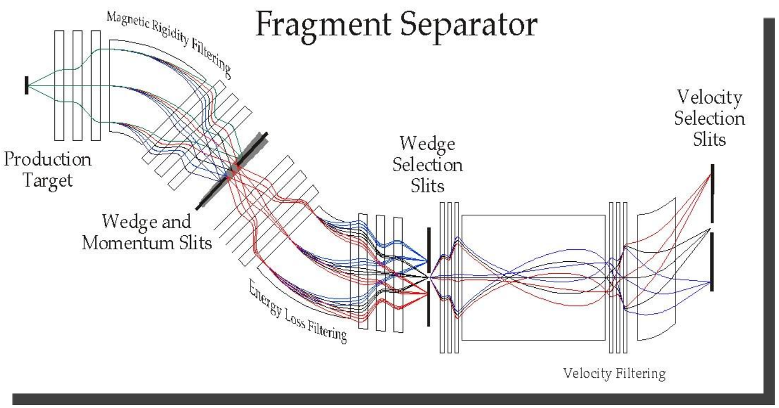
$$Y = I \; t \; N_t \; \sigma \; \varepsilon_t \; \varepsilon_s \; \varepsilon_i$$

Y	number of registered events
σ	production cross section
N_t	number of target atoms
I	beam intensity
t	duration of measurement
ε_t	efficiency transmission at target
ε_s	efficiency transmission through separator
ε_i	identification efficiency

Depends on:

- Fragment separator characteristics
- Optics mode
- Production mechanism of fragments
  - Fragment velocity
  - Momentum width
- Energy loss straggling in materials

1. Production Area



3. Identification

2. Separation

ε_t efficiency transmission at target
- lost of primary beam and fragments of interest due to reaction in target and stripper
- charge state factor after target (stripper)
- Gain due to secondary reactions

ε_s efficiency transmission through separator
- lost of fragments of interest due to reaction in materials located in the separator
- charge state factor after materials
- Angular acceptance
- Momentum selection
- Wedge selection
- Other selections

ε_i identification efficiency
- lost of fragments of interest due to reaction in detectors
- Live time (as well pile-ups)

Transmission through separator

statistics: 188Pb

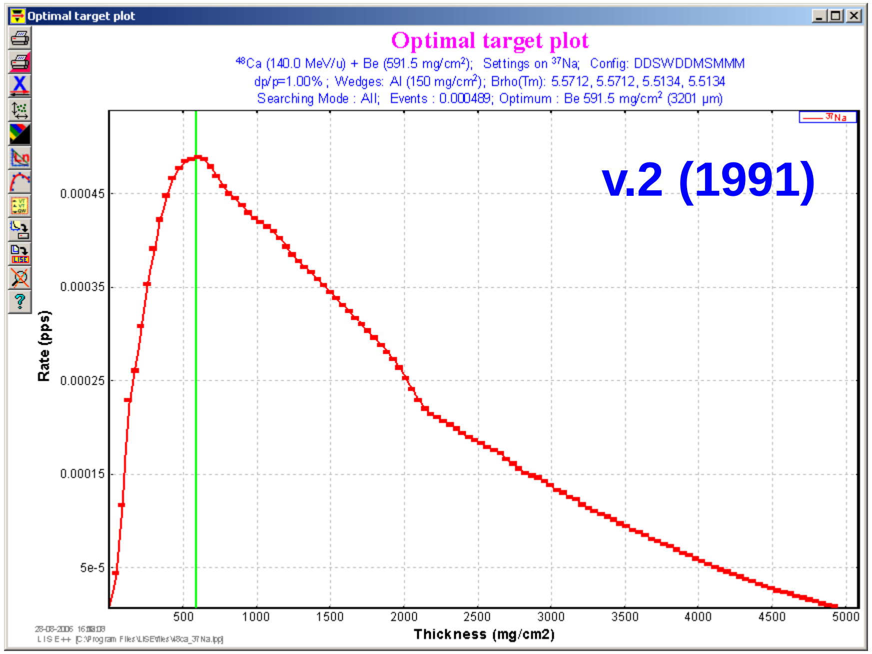
188Pb	Alpha and Beta+ decay (Z=82, N=106)	
Q1(Dipole 1)		51
Q2(Dipole 2)		51
Q3(Wien)		51
Q4(D6)		51
Production Rate	(pps)	4.44e-1
Sum of charge states	(pps)	4.44e-1
Reaction		FusRes
Sum of all reactions	(pps)	4.44e-1
CS in the target	(mb)	1.67e-1
Total transmission	(%)	2.834
Target	(%)	25.14
Unreacted in mater.	(%)	100
Q (Charge) ratio	(%)	25.14
Unstopped in mater.	(%)	100
Dipole 1	(%)	68.01
X space transmission	(%)	97.64
Y space transmission	(%)	100
X angular transmisn.	(%)	83.46
Y angular transmisn.	(%)	83.46
PPAC	(%)	25.11
Unreacted in mater.	(%)	100
Q (Charge) ratio	(%)	25.11
Unstopped in mater.	(%)	100
Dipole 2	(%)	70.35
X space transmission	(%)	85.24
Y space transmission	(%)	100
X angular transmisn.	(%)	90.8
Y angular transmisn.	(%)	90.89
Wien	(%)	100
D6	(%)	100
Final_Slits	(%)	93.84
X space transmission	(%)	100
Y space transmission	(%)	93.84
Material 2	(%)	0
Unreacted in mater.	(%)	100
Unstopped in mater.	(%)	0

7. Optimization utilities

Optimization procedures

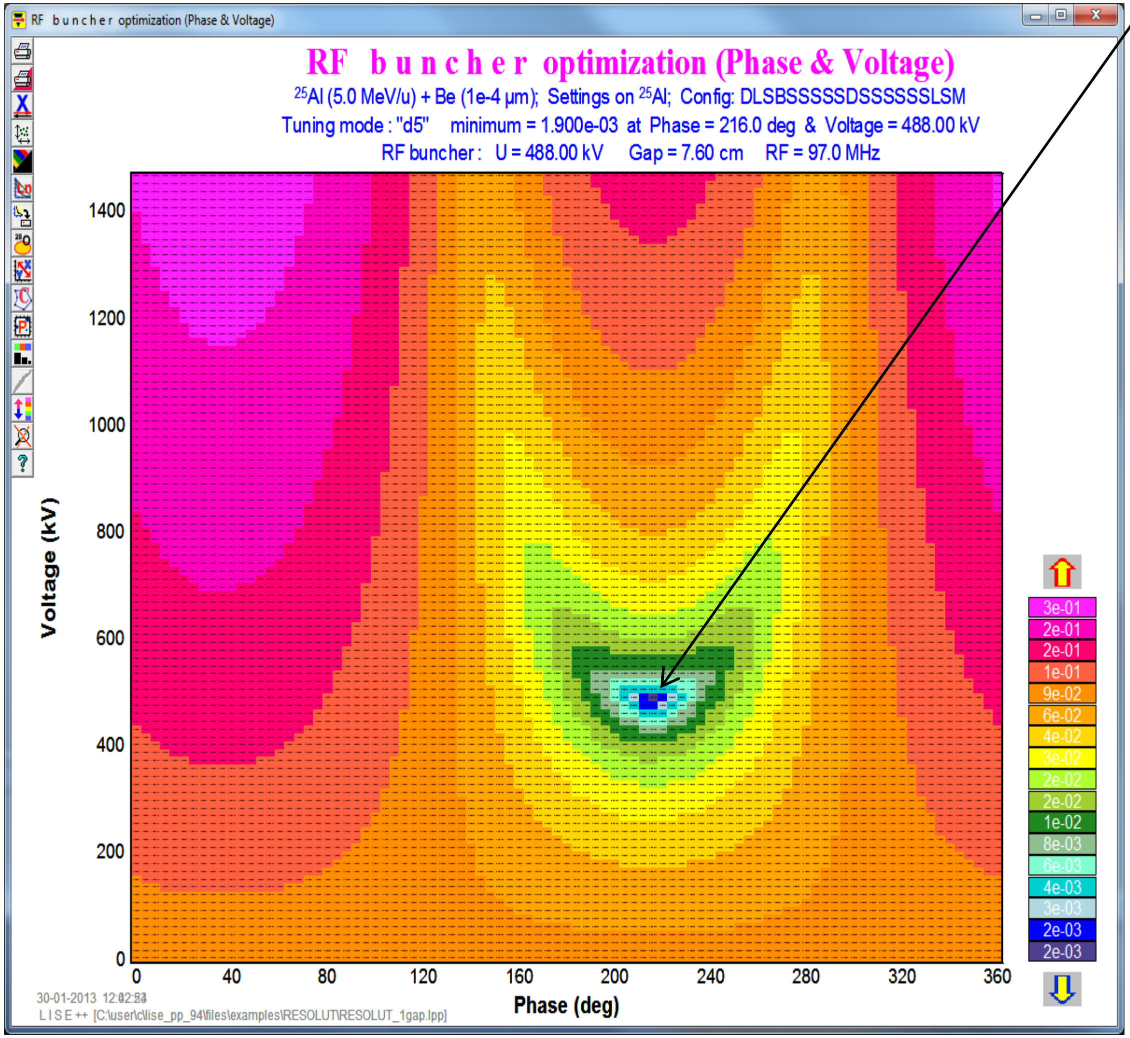
- **Target thickness (v.2.0)**
- **Range optimizer (v.6.1)**
  Gas cell utility
- **Gas pressure optimization (v.6.2)**
  Gas-filled separator utility
- **Charge states combination (v.7.5)**
- **Target thickness (v.7.5)**
  charge states optimization + secondary reactions
- **Brho scanning (v.7.5)**
  background rate calculation

to produce an intense and pure secondary beam using different reaction mechanisms



- **Target – Wedge (v7.5)**
  yield vs purity
- **RF kicker (v.7.6)**
  position, slits size, phase: yield vs purity
- **Wedge – Wedge (v.7.8)**
  yield vs purity
- **RF buncher optimization (v.9.5)**
  voltage, phase: energy compression

488 kV
216 degrees

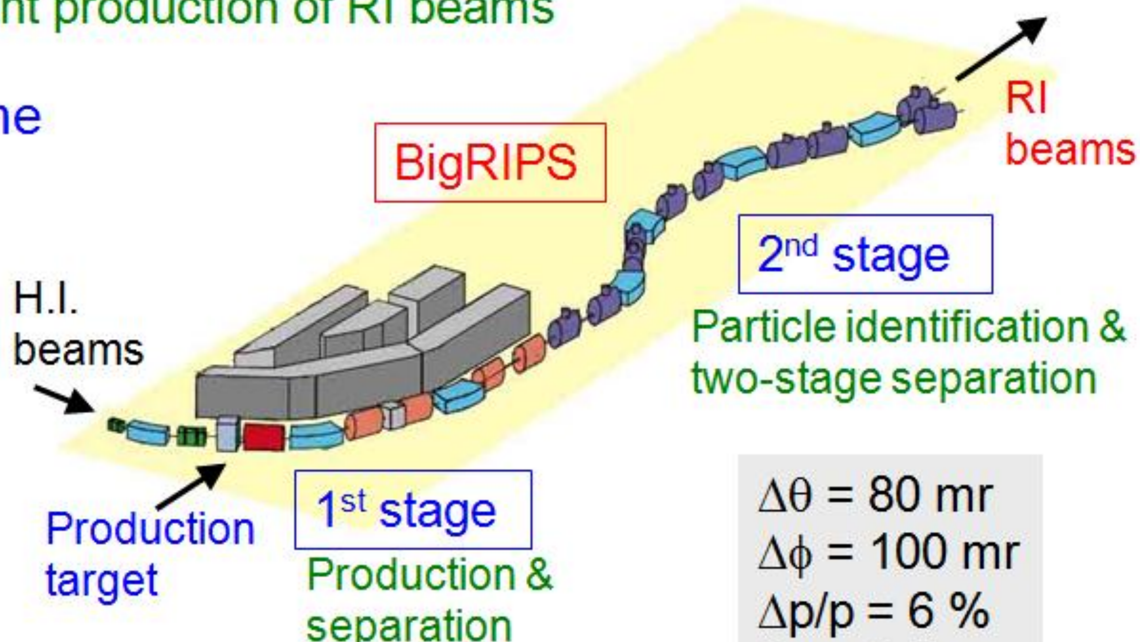


8. New generation of fragment separators

BigRIPS (March 2007)

- Large acceptances
  - Comparable with spreads of in-flight fission of U beam at RIBF energies, allowing efficient production of RI beams
- Two-stage separator scheme

BigRIPS 2nd stage



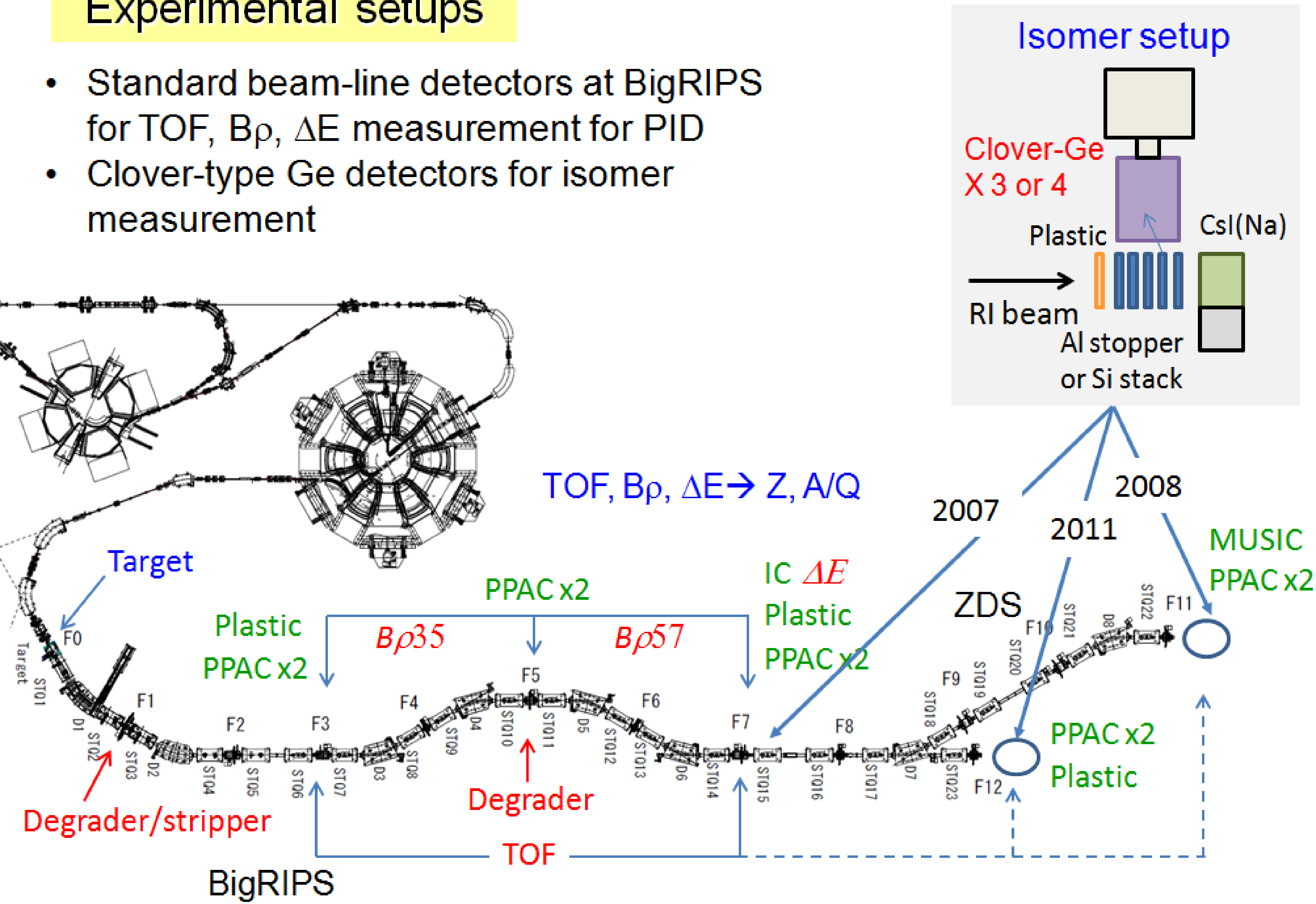
$\Delta\theta$ = 80 mr
$\Delta\phi$ = 100 mr
$\Delta p/p$ = 6 %
$B\rho$ = 9 Tm
L = 78.2 m

- 2nd stage with high resolution
  - Allows excellent particle identification (PID) including charge states of RI beams
  - Charge states are a crucial issue at our energies

Courtesy of T.Kubo (RIKEN)

Experimental setups

- Standard beam-line detectors at BigRIPS for TOF, Bρ, ΔE measurement for PID
- Clover-type Ge detectors for isomer measurement



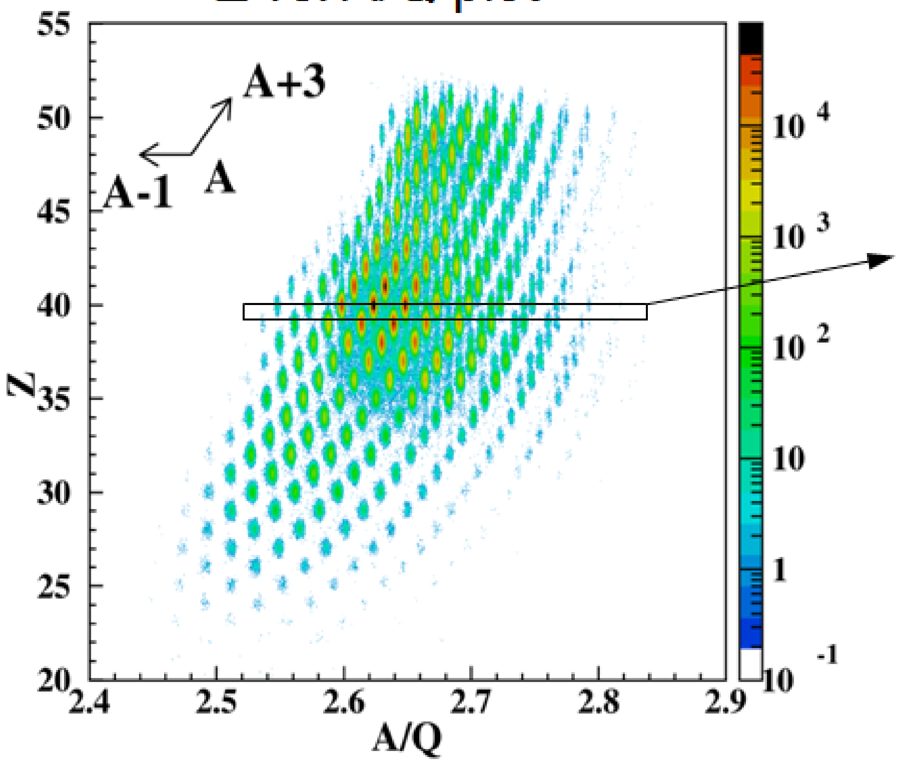
Isotope separation: F1 degrader/stripper + F5 degrader

Excellent particle identification (PID) power for fission fragments

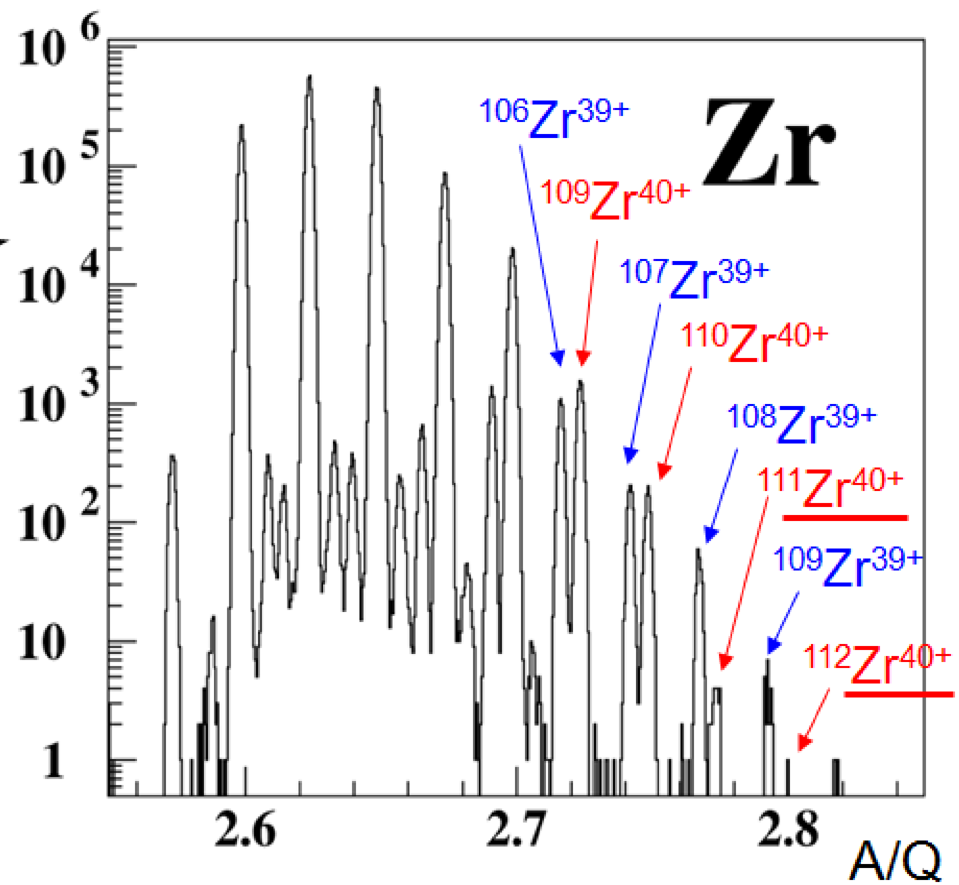
TOF-Bρ-ΔE method with track reconstruction

High enough to well identify charge states of fragments

Z vs. A/Q plot



A/Q spectrum for Zr isotopes (Z=40)

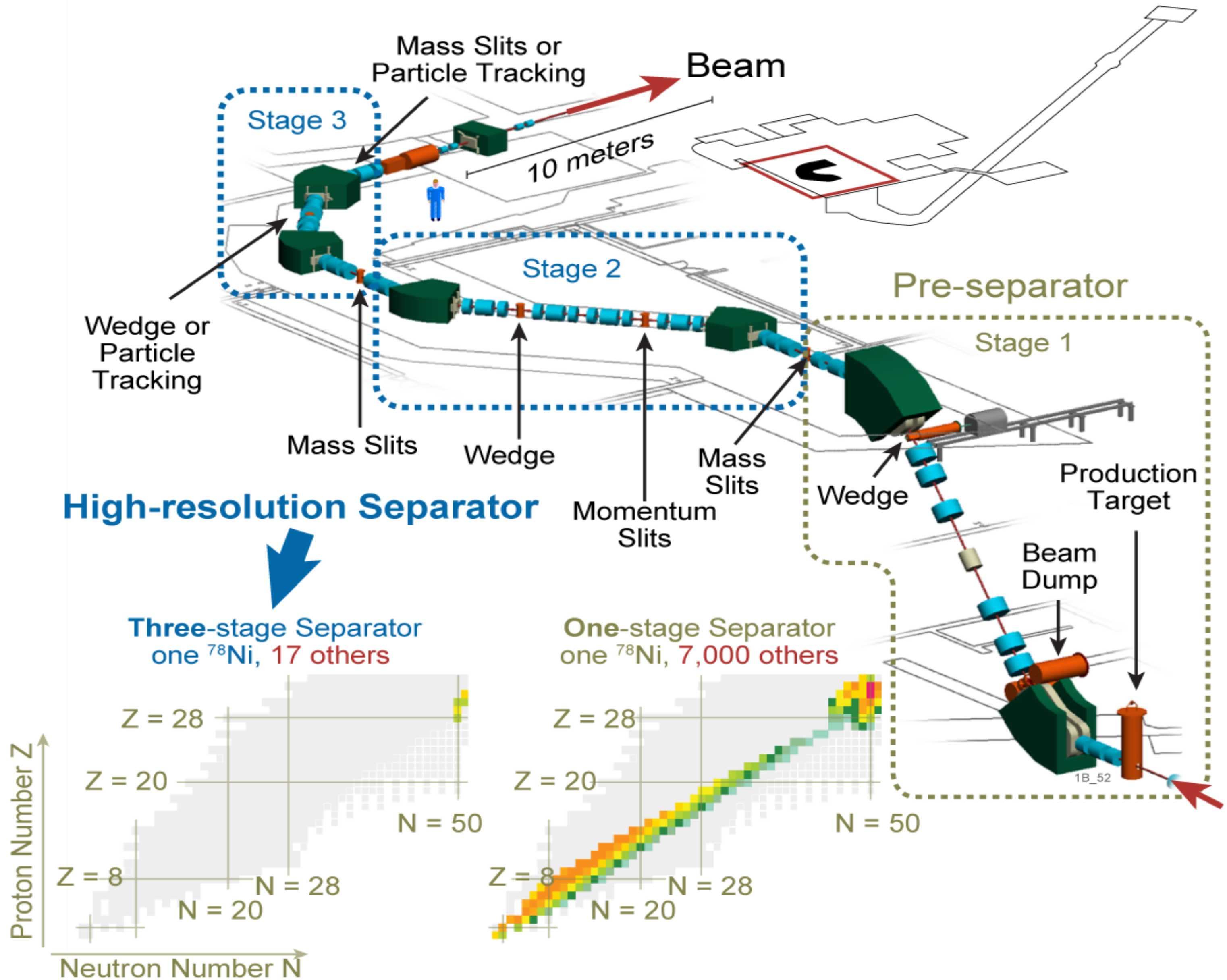


U+Be 2.9 mm Bρ 01 = 7.990 Tm
F1 deg Al 2.18mm ΔP/P =+-3%
G3 setting in J. Phys. Soc. Jpn. 79 (2010) 073201.

Courtesy of T.Kubo (RIKEN)

r.m.s. A/Q resolution: 0.035 %

FRIB Fragment Separator



Layout of the Super-FRS

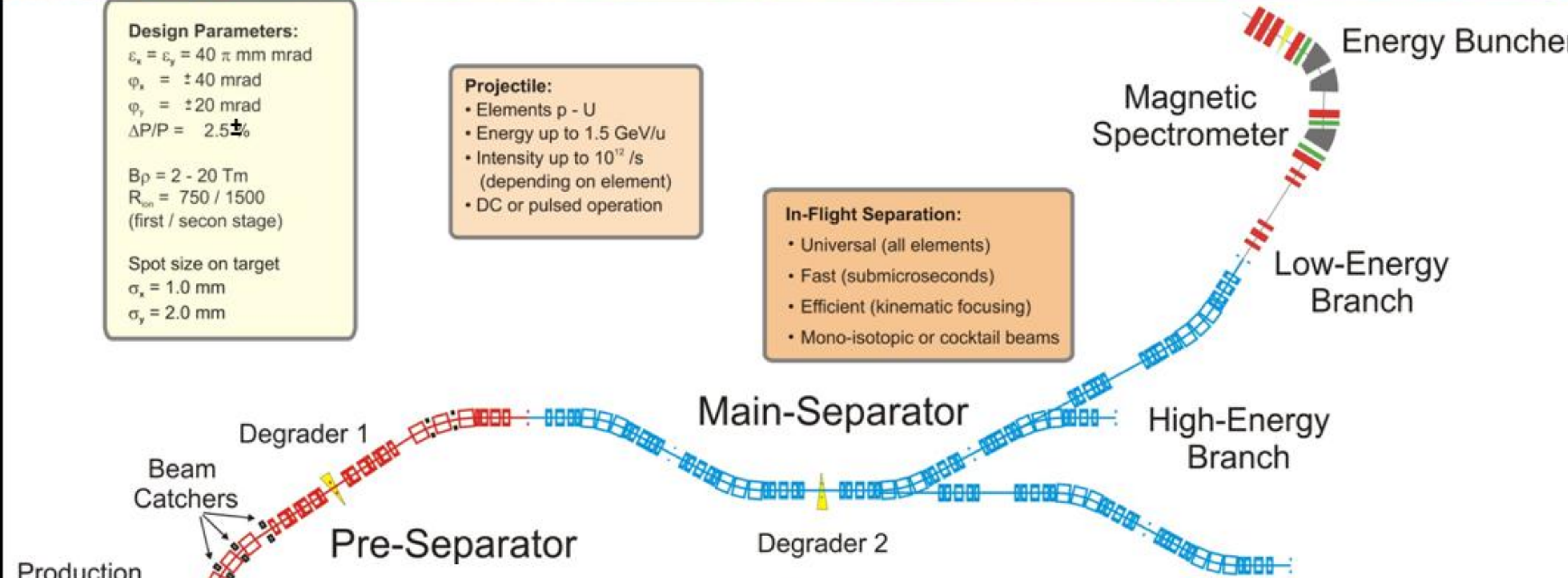
Design Parameters:
$\varepsilon_x = \varepsilon_y = 40\ \pi$ mm mrad
$\varphi_x = \pm 40$ mrad
$\varphi_y = \pm 20$ mrad
$\Delta P/P = 2.5 \pm \%$

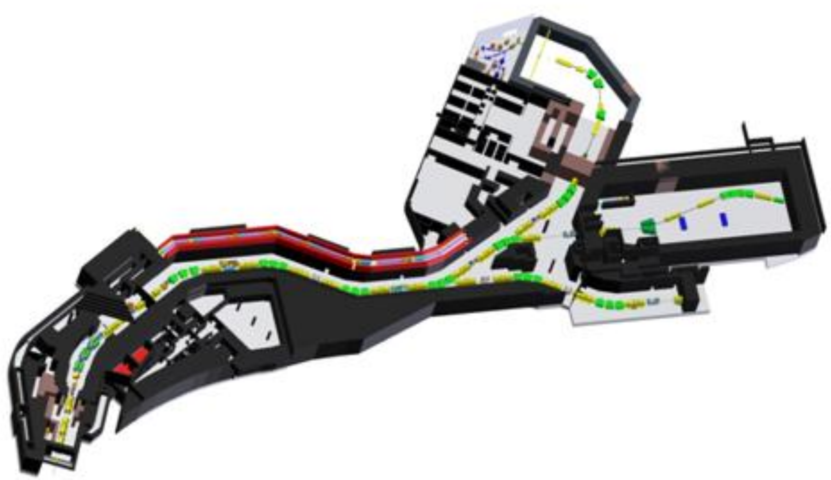
$B\rho = 2 - 20$ Tm
$R_{ion} = 750 / 1500$
(first / secon stage)

Spot size on target
$\sigma_x = 1.0$ mm
$\sigma_y = 2.0$ mm

Projectile:
- Elements p - U
- Energy up to 1.5 GeV/u
- Intensity up to 10^{12} /s (depending on element)
- DC or pulsed operation

In-Flight Separation:
- Universal (all elements)
- Fast (submicroseconds)
- Efficient (kinematic focusing)
- Mono-isotopic or cocktail beams





The Super FRS is a new two stage in flight separator to be built on the site of GSI, Darmstadt, Germany as part of FAIR (Facility for Anti-proton and Ion Research)

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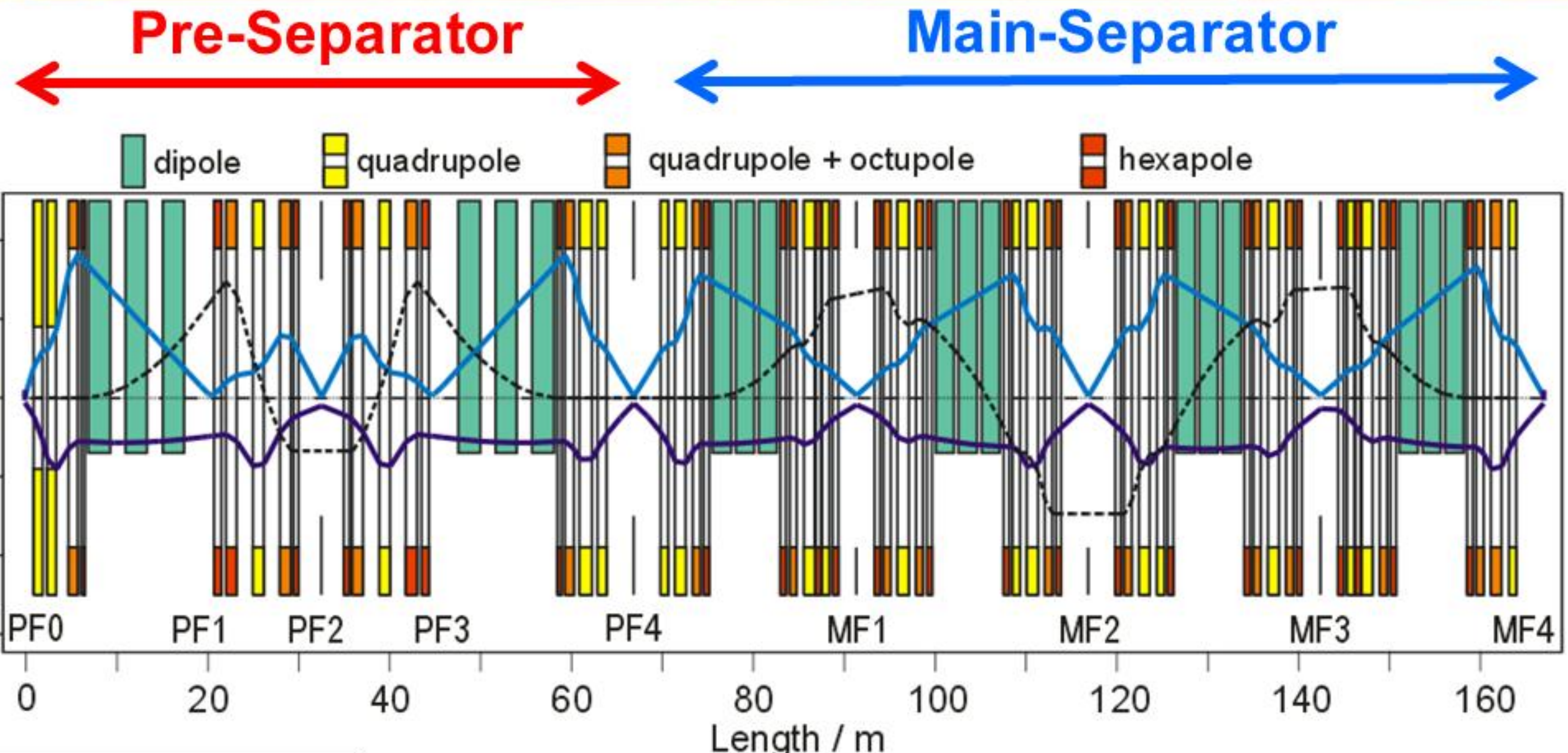
Ion-optical design of the Super-FRS

High-Energy Branch (HEB)



ε_x = 40 π mm mrad
φ_x = ±40 mrad

ε_y = 40 π mm mrad
φ_y = ±20 mrad

$\Delta p/p$ = ±2.5 %

Main magnet requirements:

Dipole (unit): ρ = 12.5 m, ϕ = 9,75°, G = ±85 mm, B = 1.6 T

Quadrupole: L = 0.8/1.2m, G = ±190 mm, g_{Max} = 10 T/m

+ Sextupole Magnets and Octupole correction coil

Martin Winkler & Helmut Weick

9. Example of secondary beam production

Attempt to compare ISOL & In-Flight yields with LISE++

Let's start from ISOL using HRIBF

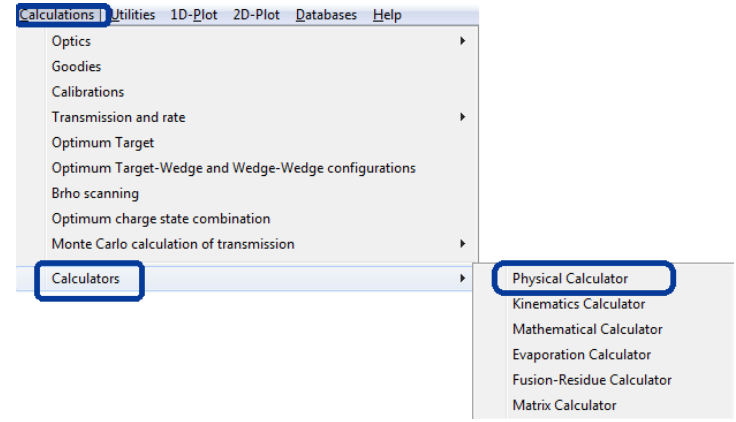
p(40MeV, 5uA) + ^{238}U

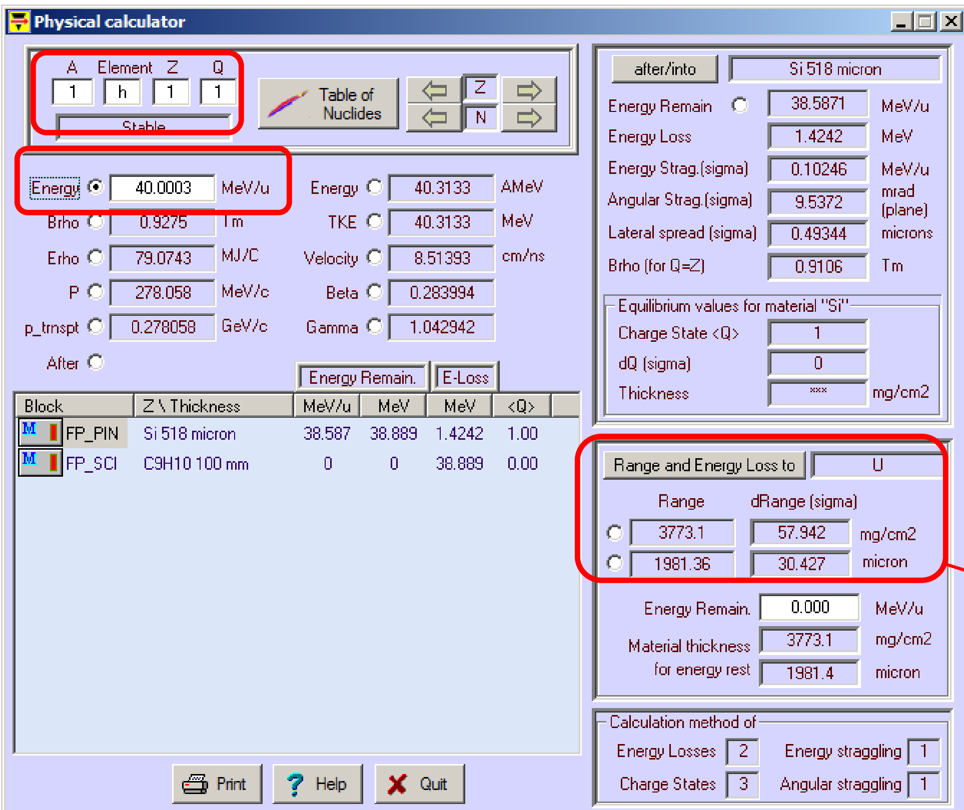
1. **Calculate a range of protons, define number of atoms**
2. **Appling inverse kinematics, set p- target thickness (using the same number of atoms)**
3. **Appling inverse kinematics, set Beam characteristics. No charge states**
4. **Set Abrasion-Fission as production mechanism**
5. **Load settings for ^{238}U+p abrasion-Fission**
6. **Insert "Delay" and "Faraday cup" blocks after the stripper**
7. **Set values in the "Delay" block** *
8. **Calculate calcium isotopes production**
9. **Plot calcium isotopes yields, Save yields in file**
10. **Set "Delay" block disable**
11. **Repeat 8 and 9**
12. **Include additional production mechanism?**

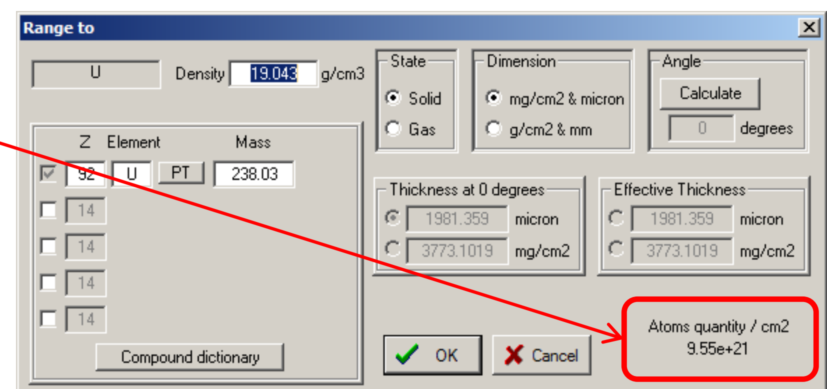
* *do not forget to save sometimes all your changes in a LISE++ file*

Calculate a range of protons, define the number of atoms

for all icons in the toolbar there are corresponding commands in the menu

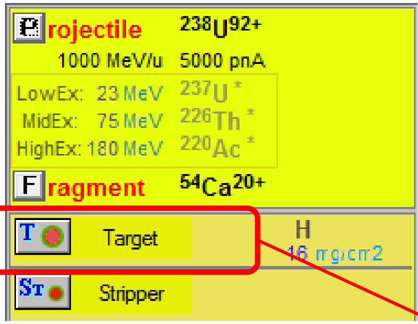






Range p(40 MeV) in ^{238}U ~ 2 mm, 9.55e21 atoms/cm^2, that corresponds to number of atoms in 16 mg/cm^2 of H-target

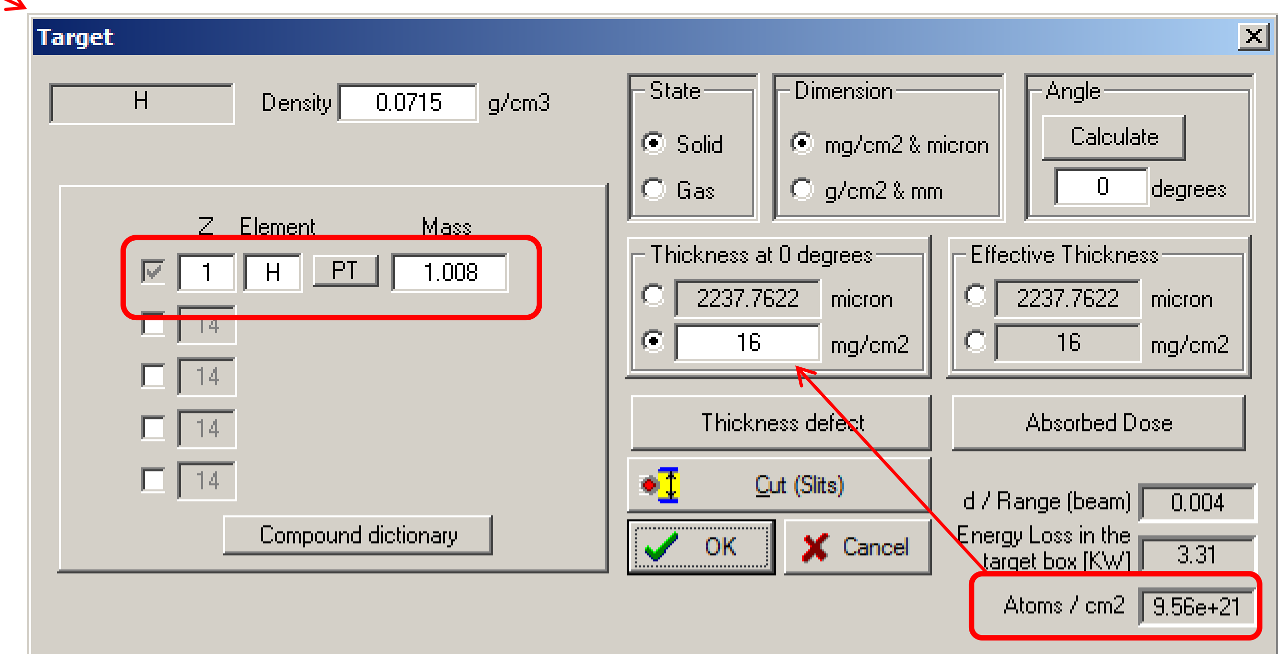
Appling inverse kinematics, set p- target thickness (using the same number of atoms)



p(40MeV, 5uA) + ^{238}U

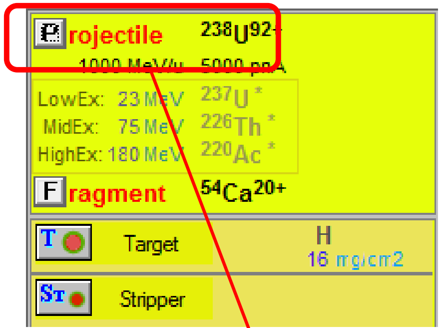
inverse

^{238}U (high energy, 5uA) + p (16 mg/cm^2)



Range p(40 MeV) in ^{238}U ~ 2 mm, 9.55e21 atoms/cm^2, that corresponds to number of atoms in 16 mg/cm^2 of H-target

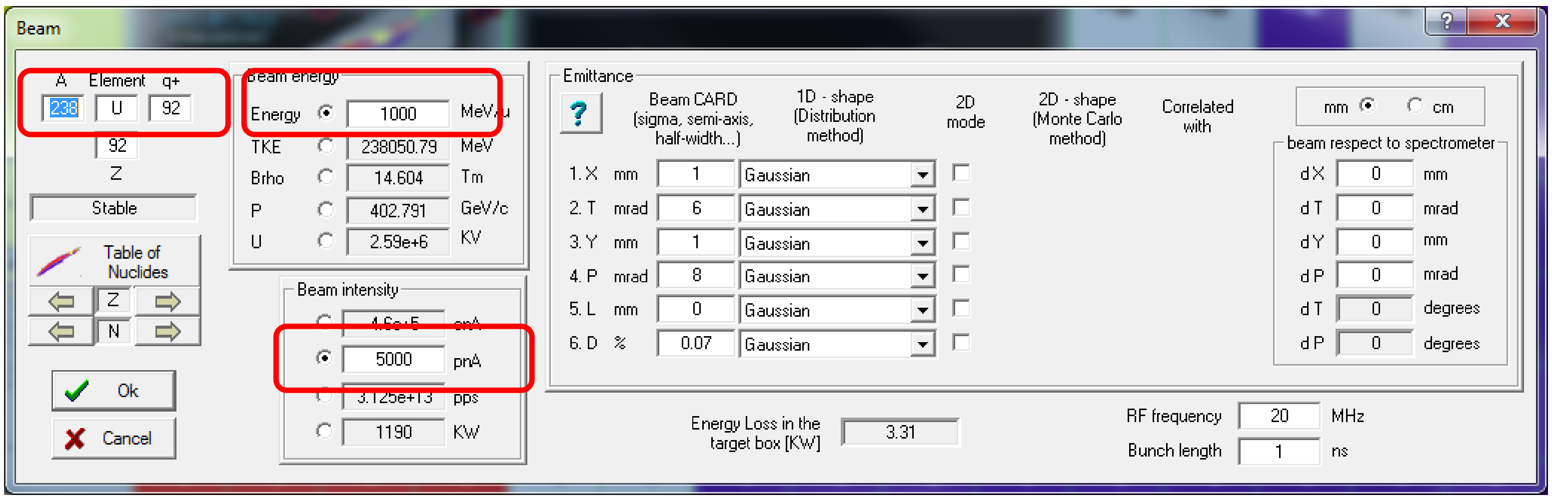
Appling inverse kinematics, set Beam characteristics



p(40MeV, 5uA) + ^{238}U

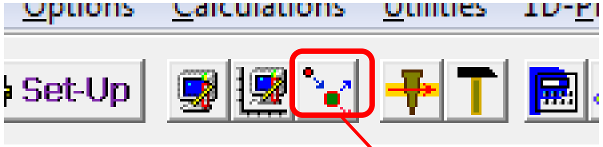
inverse

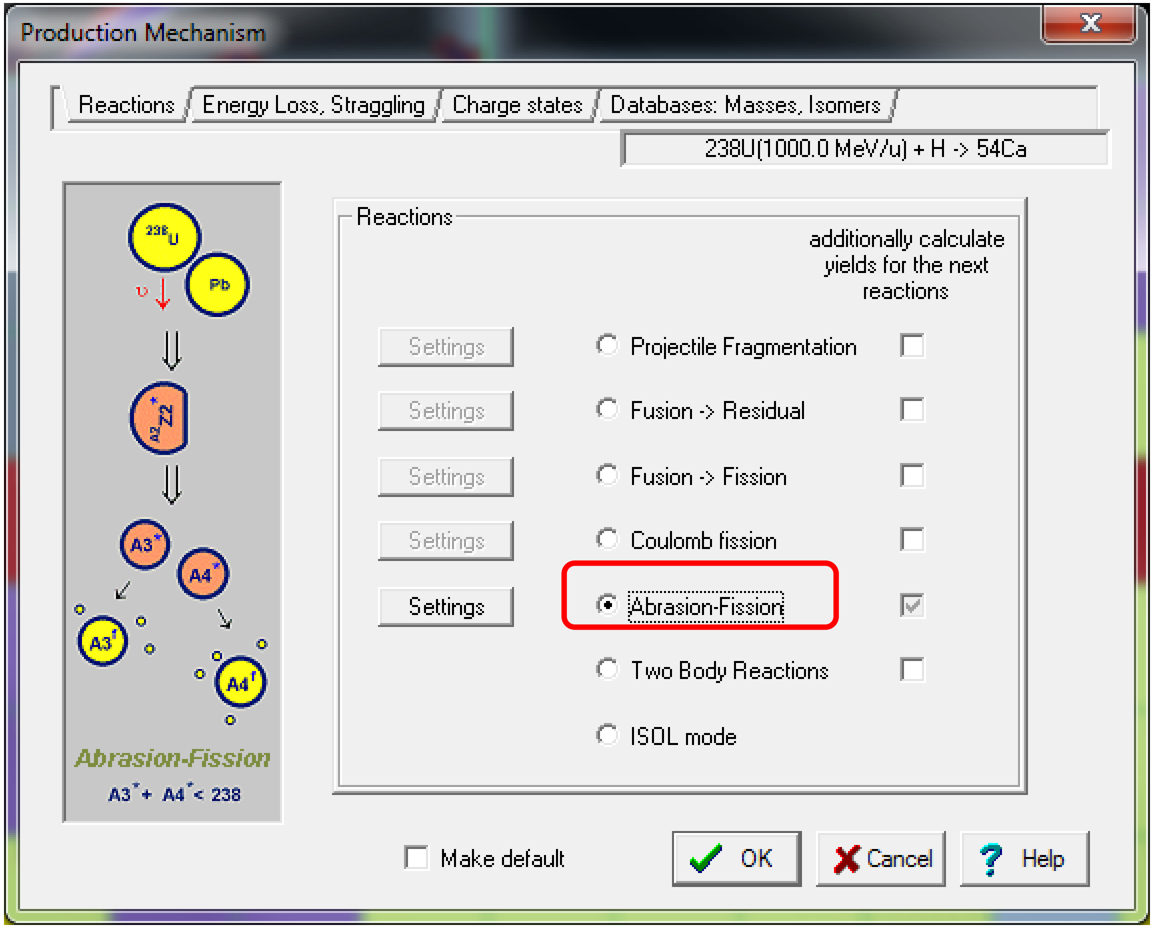
^{238}U (high energy, 5uA) + p (16 mg/cm^2)



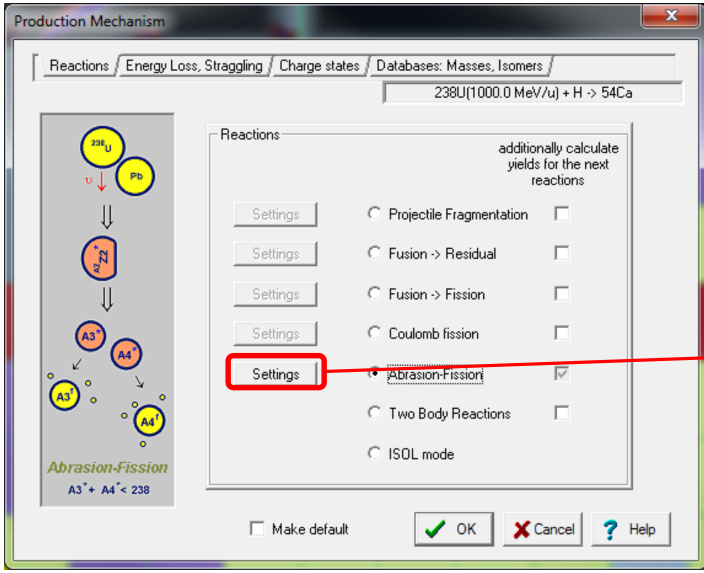
Range p(40 MeV) in ^{238}U ~ 2 mm, 9.55e21 atoms/cm^2,
that corresponds to number of atoms in 16 mg/cm^2 of H-target

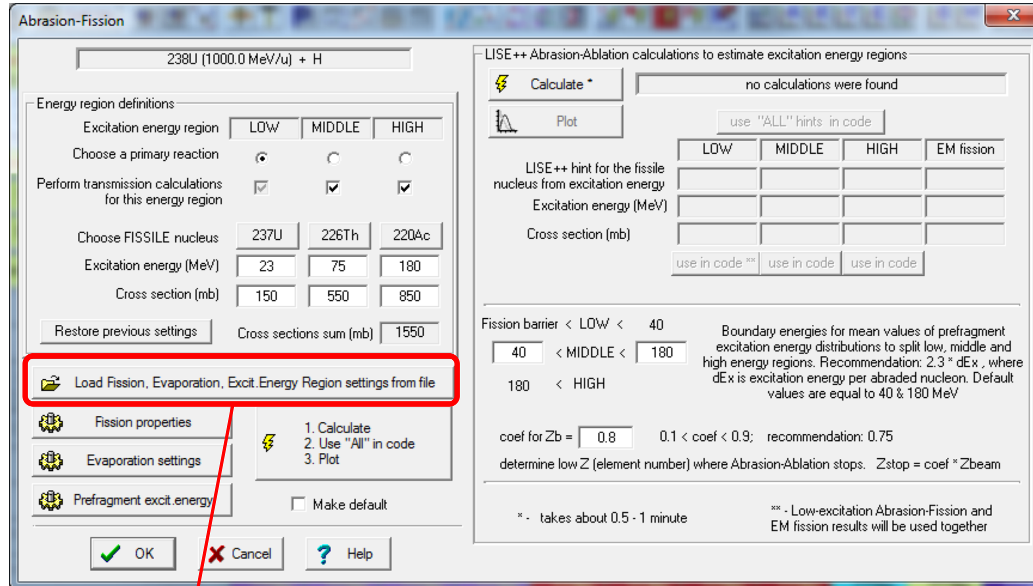
Set Abrasion-Fission as production mechanism



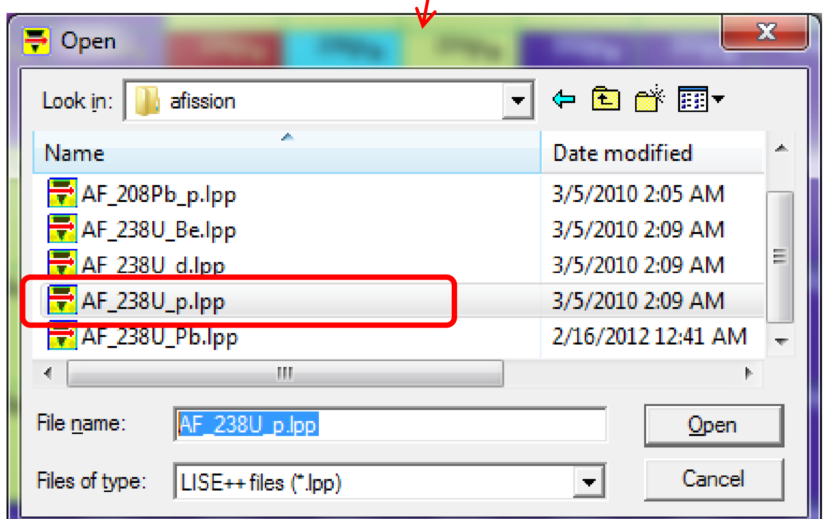


Load settings for ^{238}U+p abrasion-Fission

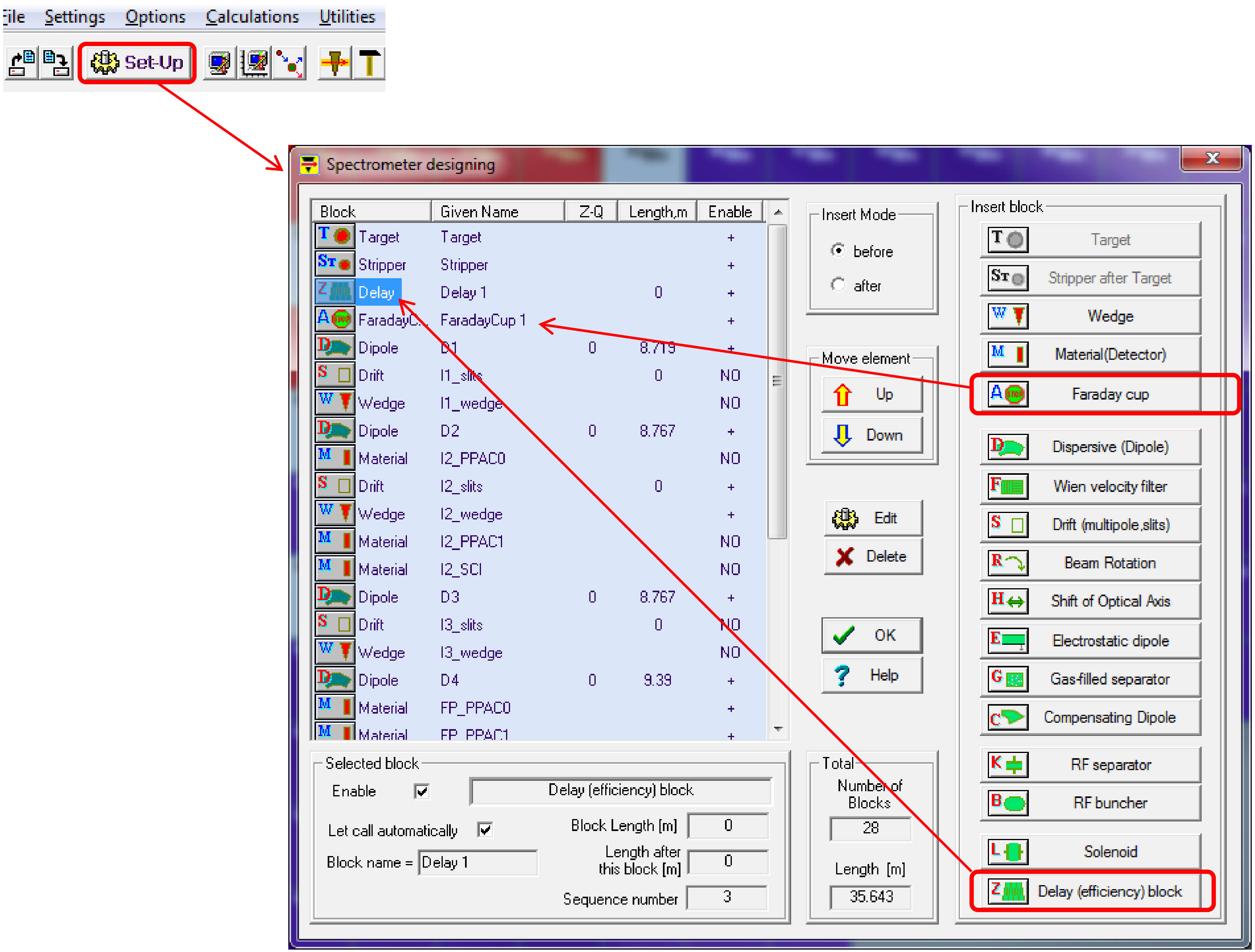




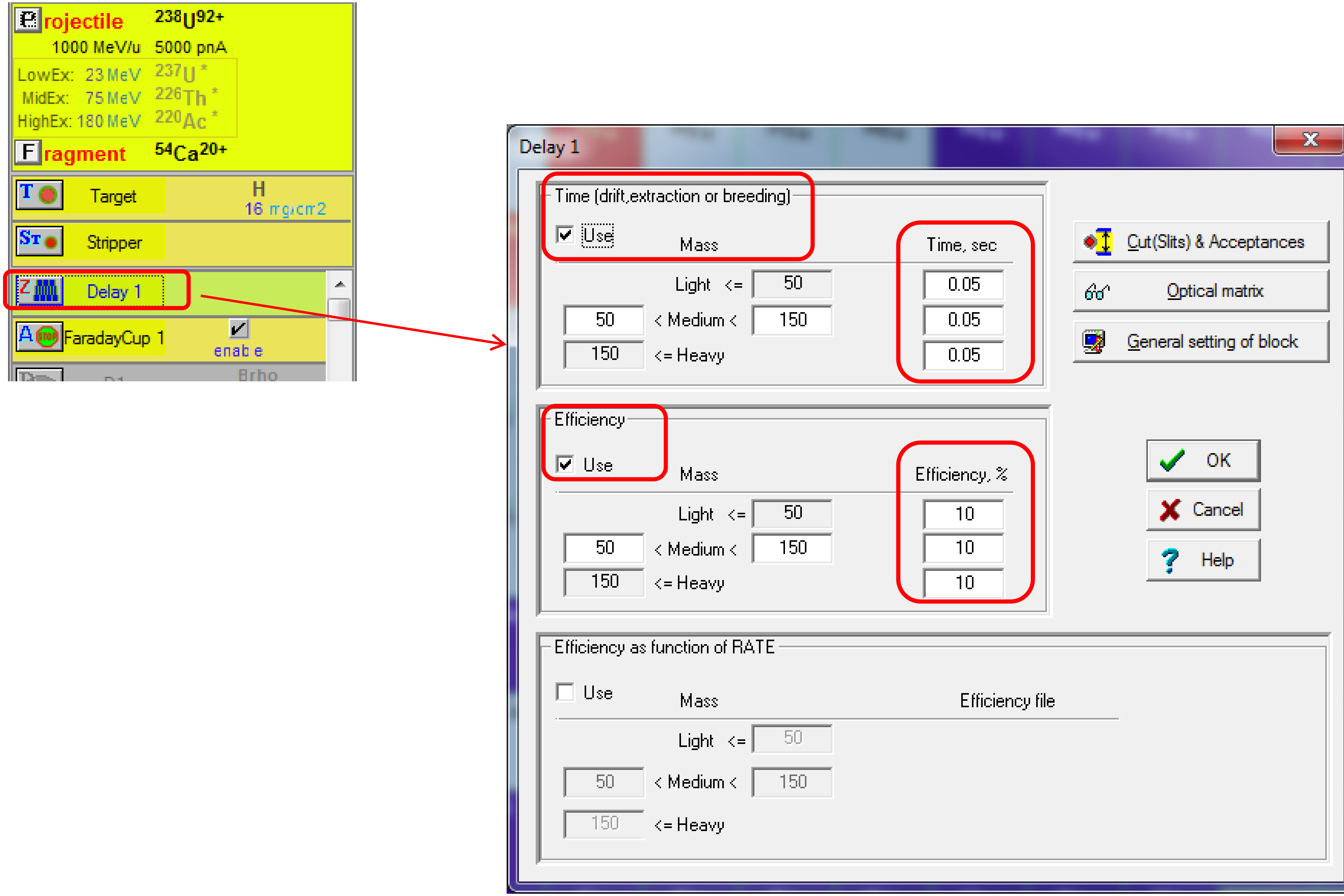
Documents\LISE\files\examples\afission\AF_238U_p.lpp



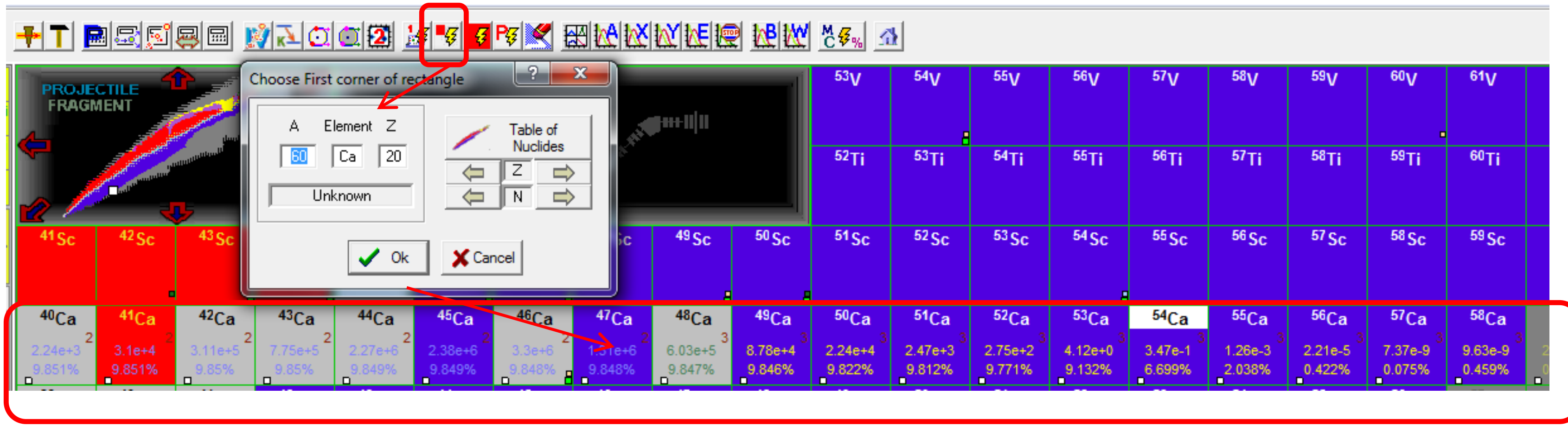
Insert "Delay" and "Faraday cup" blocks after the stripper



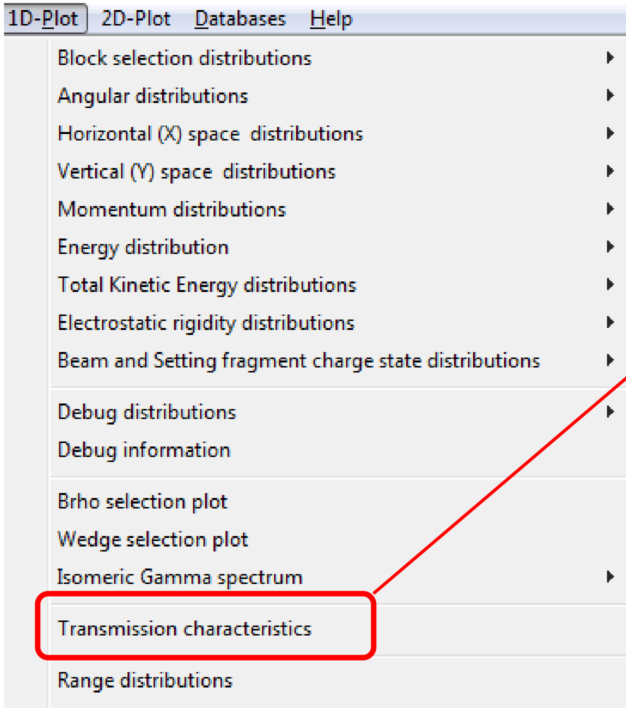
Set values in the "Delay" block

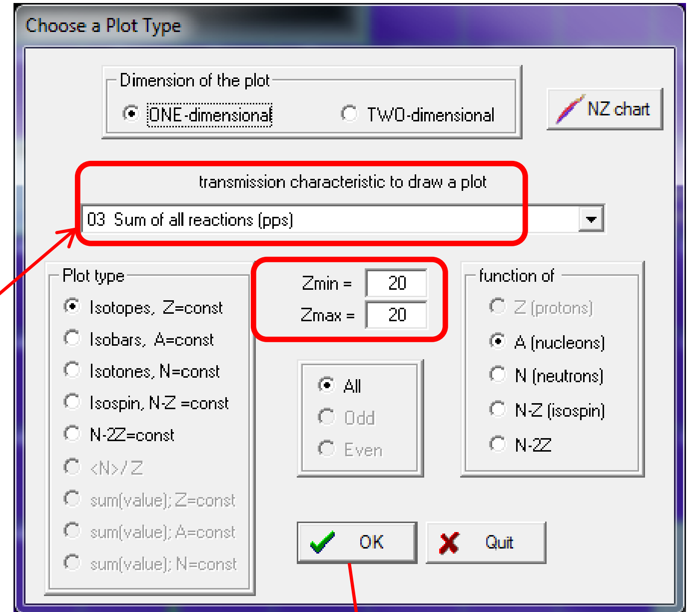


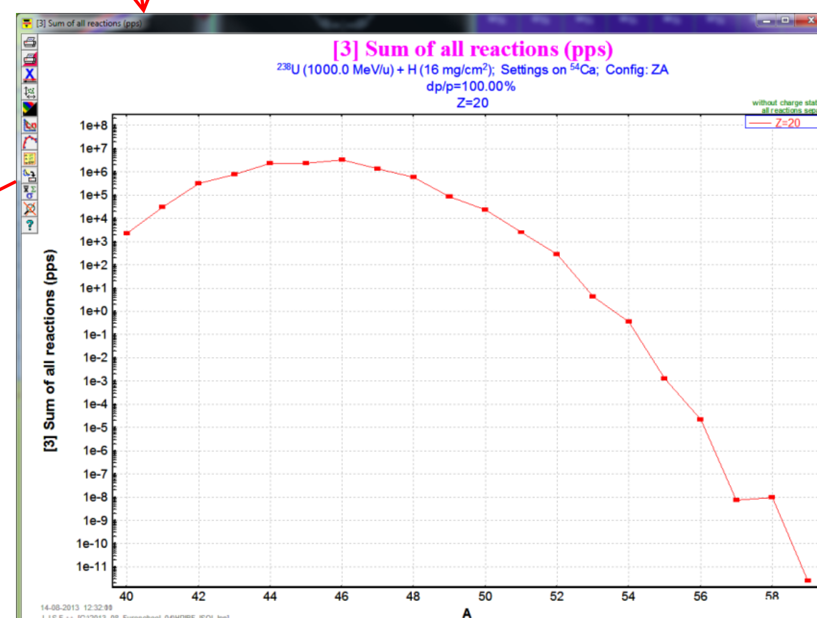
Calculate calcium isotopes production

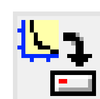


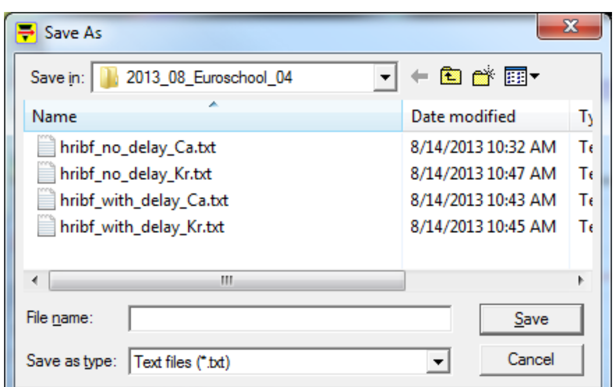
Plot calcium isotopes yields, Save yields in file

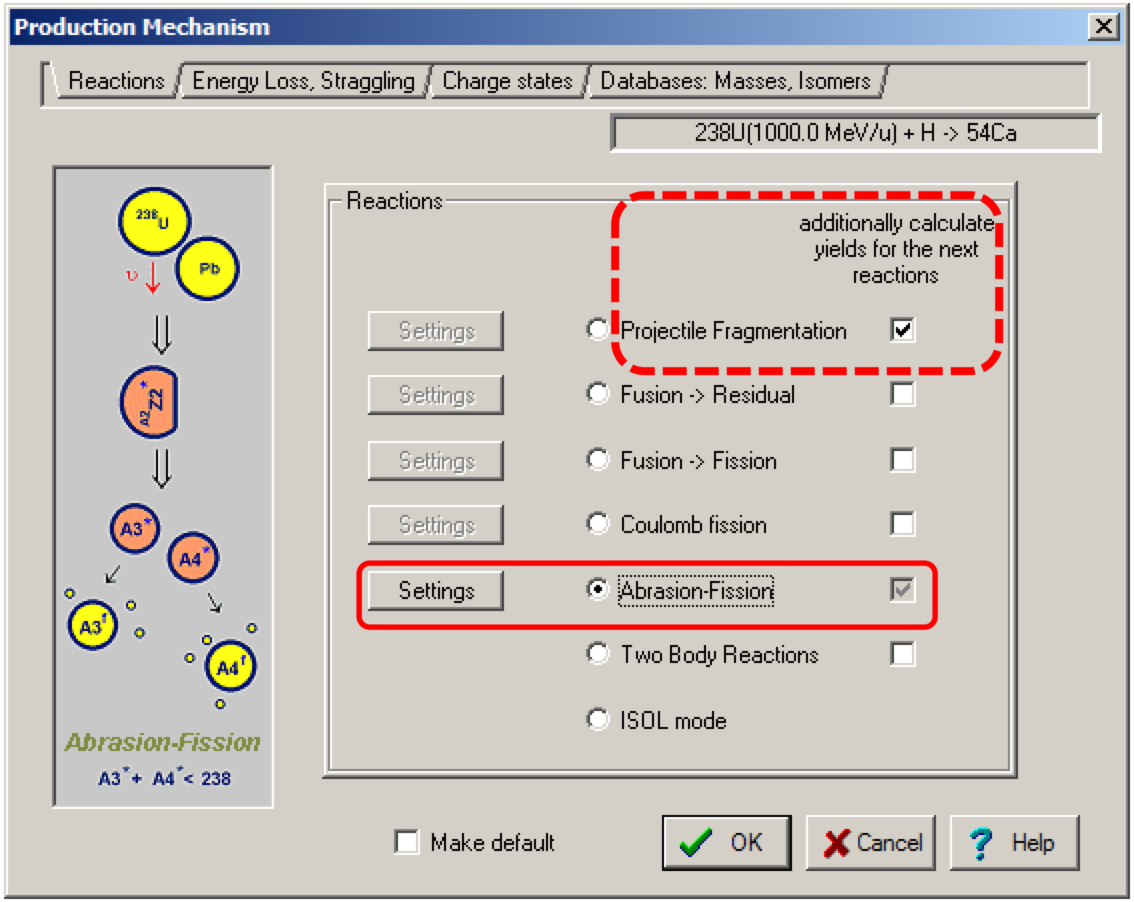











Production Mechanism
Reactions
Energy Loss, Straggling
Charge states
Databases: Masses, Isomers
238U(1000.0 MeV/u) + H -> 54Ca
Reactions
additionally calculate yields for the next reactions
Settings
Projectile Fragmentation
Settings
Fusion -> Residual
Settings
Fusion -> Fission
Settings
Coulomb fission
Settings
Abrasion-Fission
Two Body Reactions
ISOL mode
Abrasion-Fission
Make default
OK
Cancel
Help

Attempt to compare ISOL & In-Flight yields with LISE++

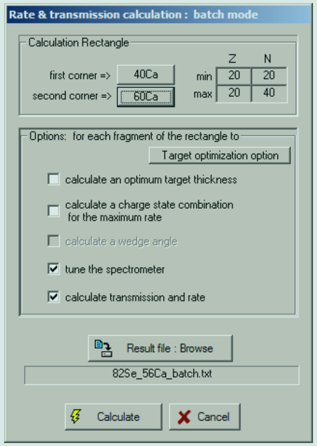
In-Flight : NSCL

For neutron-rich Ca-isotopes

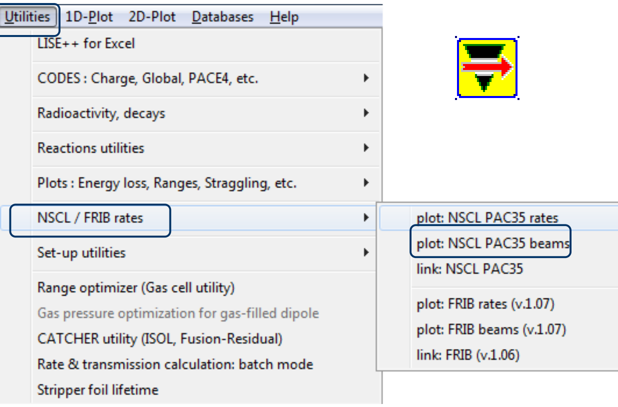
^{82}Se (140 MeV/u) + Be

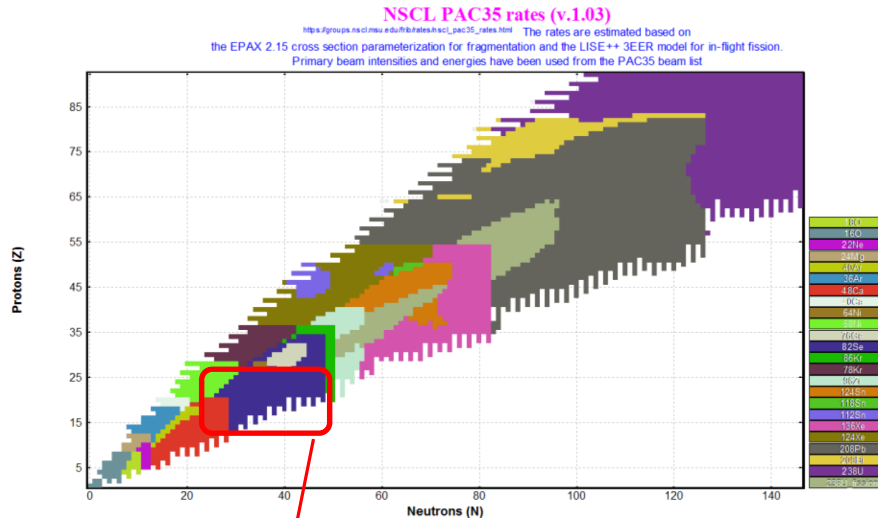
1. **Why ^{82}Se for neutron rich calcium isotopes?**
2. **Load the A1900 configuration**
3. **Set beam characteristics using the NSCL primary beam list**
4. **Set target - Be**
5. **Set Projectile fragmentation as production mechanism**
6. **Set fragment of interest (assume ^{56}Ca).**
7. **Set No charge states option**
8. **Set maximum momentum acceptance**
9. **Calculate the Optimum thickness target**
10. **Estimate wedge thickness**
11. **Set the fragment separator for ^{56}Ca**
12. **Calculate ^{56}Ca ion transmission***
13. **Insert “Delay” and “Faraday cup” blocks after the stripper**
14. **Set values* in the “Delay” block**
15. **Calculate calcium isotopes production**
16. **Plot calcium isotopes yields, Save yields in file**

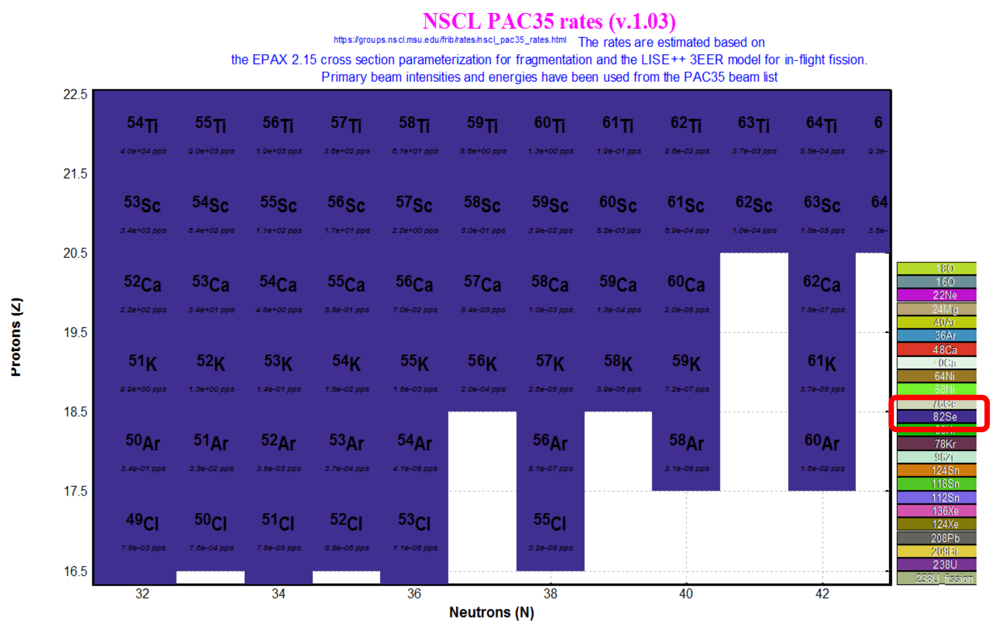
Instead 11-15 it is possible to use “Rate& transmission calculation: batch mode” in the “Utilities” menu



Why ^{82}Se for neutron rich calcium isotopes?

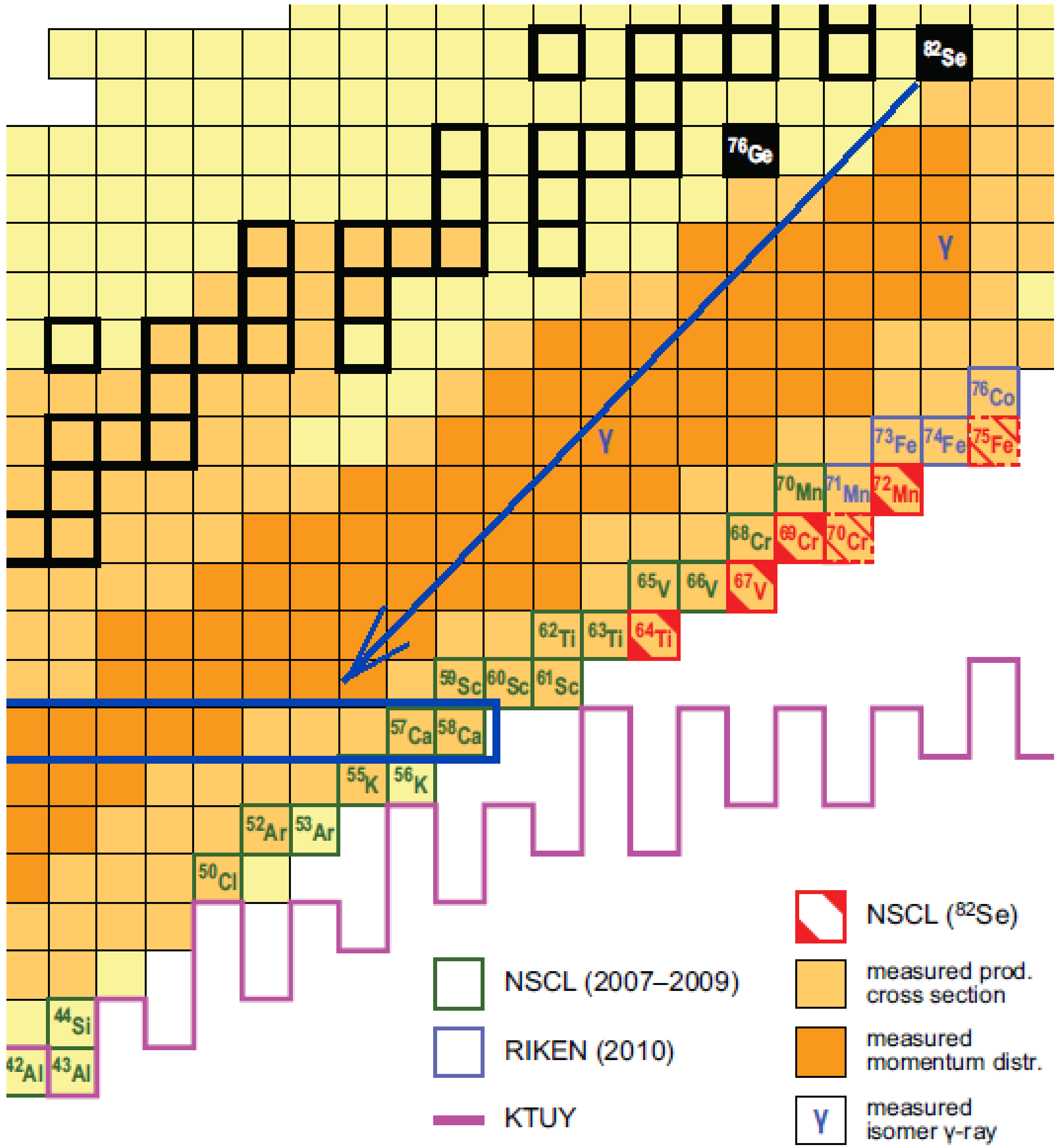




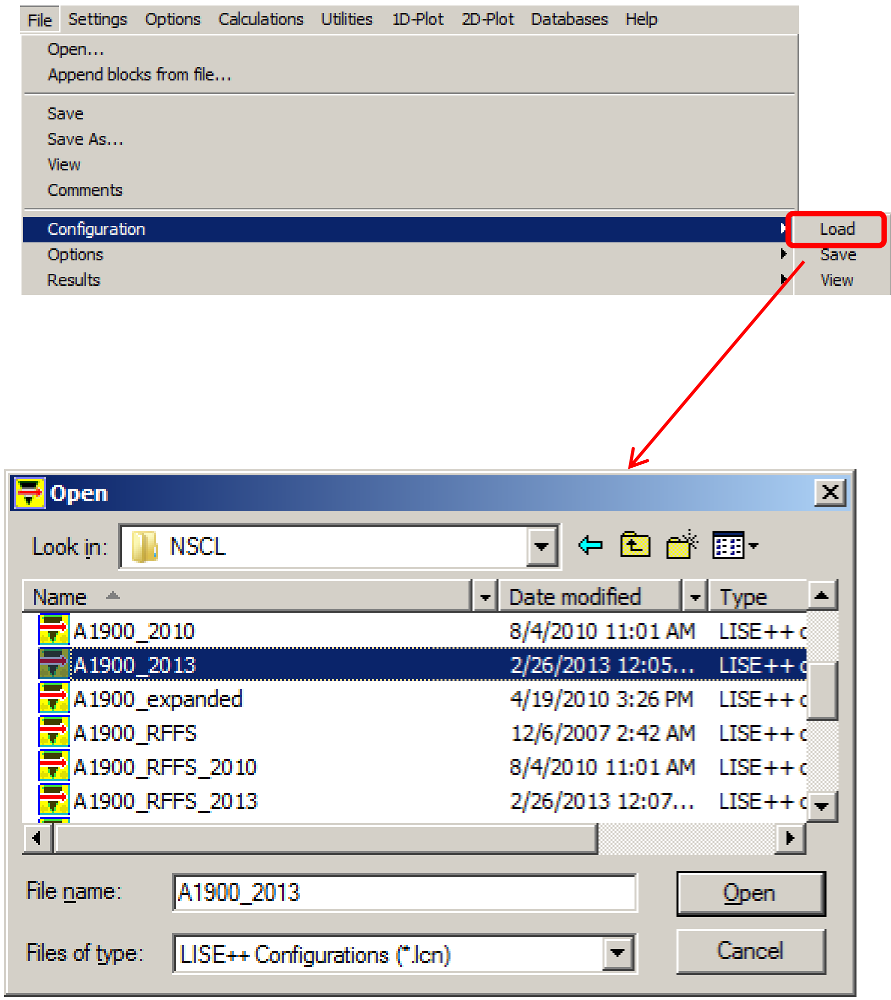


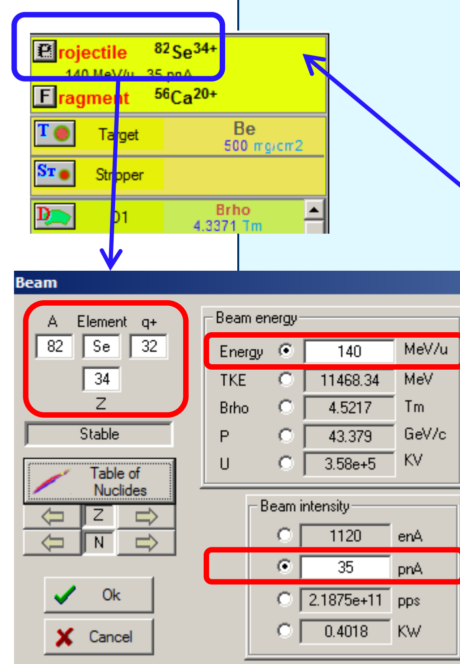
Why ^{82}Se for neutron rich calcium isotopes?

O.T. et al, PRC 87, 054612 (2013)



Load the A1900 configuration,
Set beam characteristics using the NSCL primary beam list





http://www.nscl.msu.edu/exp/propexp/beamlist

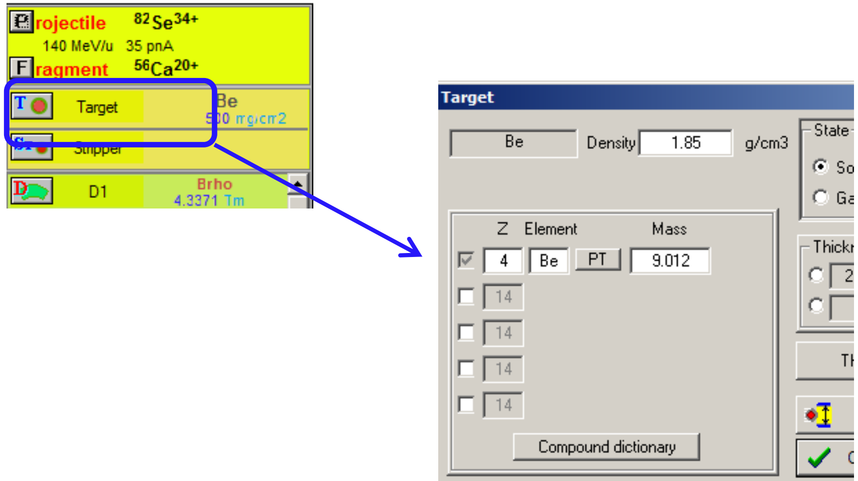
Home › NSCL Primary Beam List

Developed Primary Beams

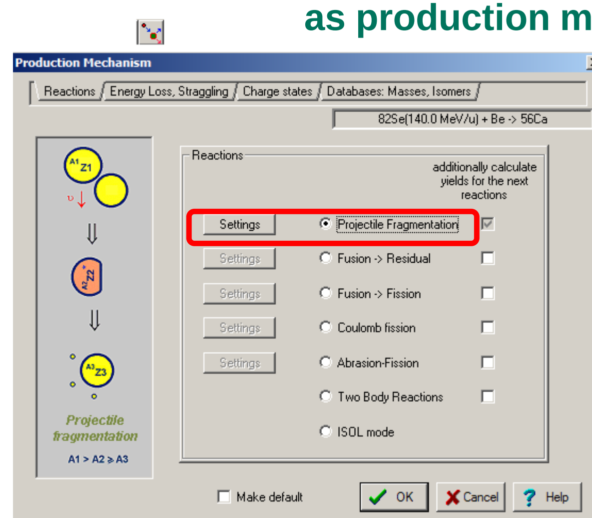
Particle	Energy (MeV/nucleon)	Intensity (pnA)
^{16}O	150	175
^{18}O	120	150
^{20}Ne	170	80
^{22}Ne	120	80
^{22}Ne	150	100
^{24}Mg	170	60
^{36}Ar	150	75
^{40}Ar	140	75
^{40}Ca	140	50
^{48}Ca	90	15
^{48}Ca	140	80
^{58}Ni	160	20
^{64}Ni	140	7
^{76}Ge	130	25
^{82}Se	140	35
^{78}Kr	150	25
^{86}Kr	100	15
^{86}Kr	140	25
^{96}Zr	120	1.5
^{112}Sn	120	4
^{118}Sn	120	1.5
^{124}Sn	120	1.5
^{124}Xe	140	10
^{136}Xe	120	2
^{208}Pb	85	1.5
^{209}Bi	80	1
^{238}U	45	0.1
^{238}U	80	0.2

Settings : Target, Production mechanism, Fragment of interest, Charge states

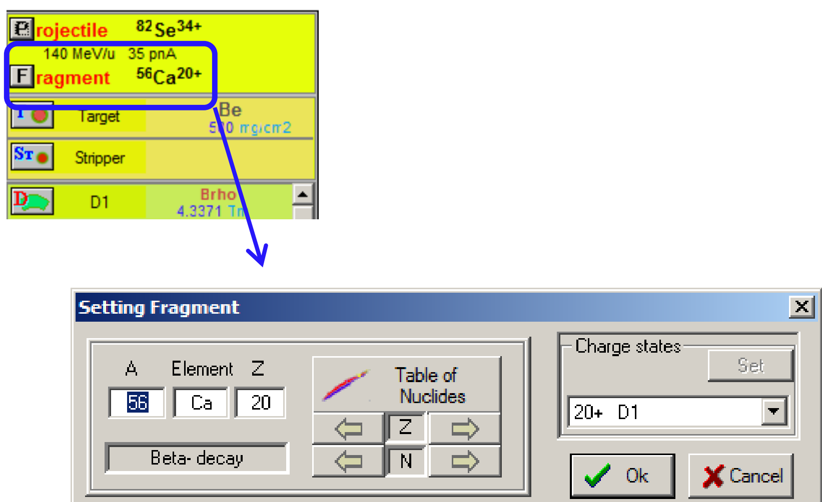
Set target - Be



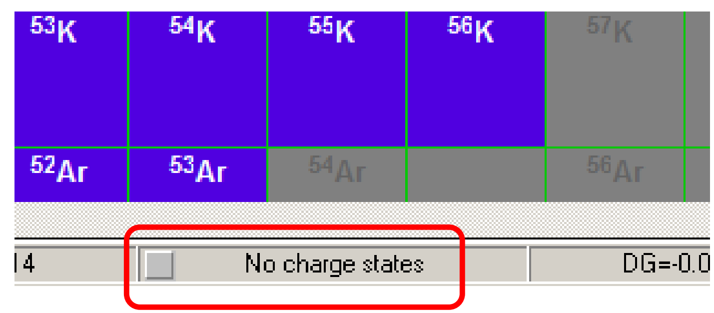
Set Projectile fragmentation as production mechanism



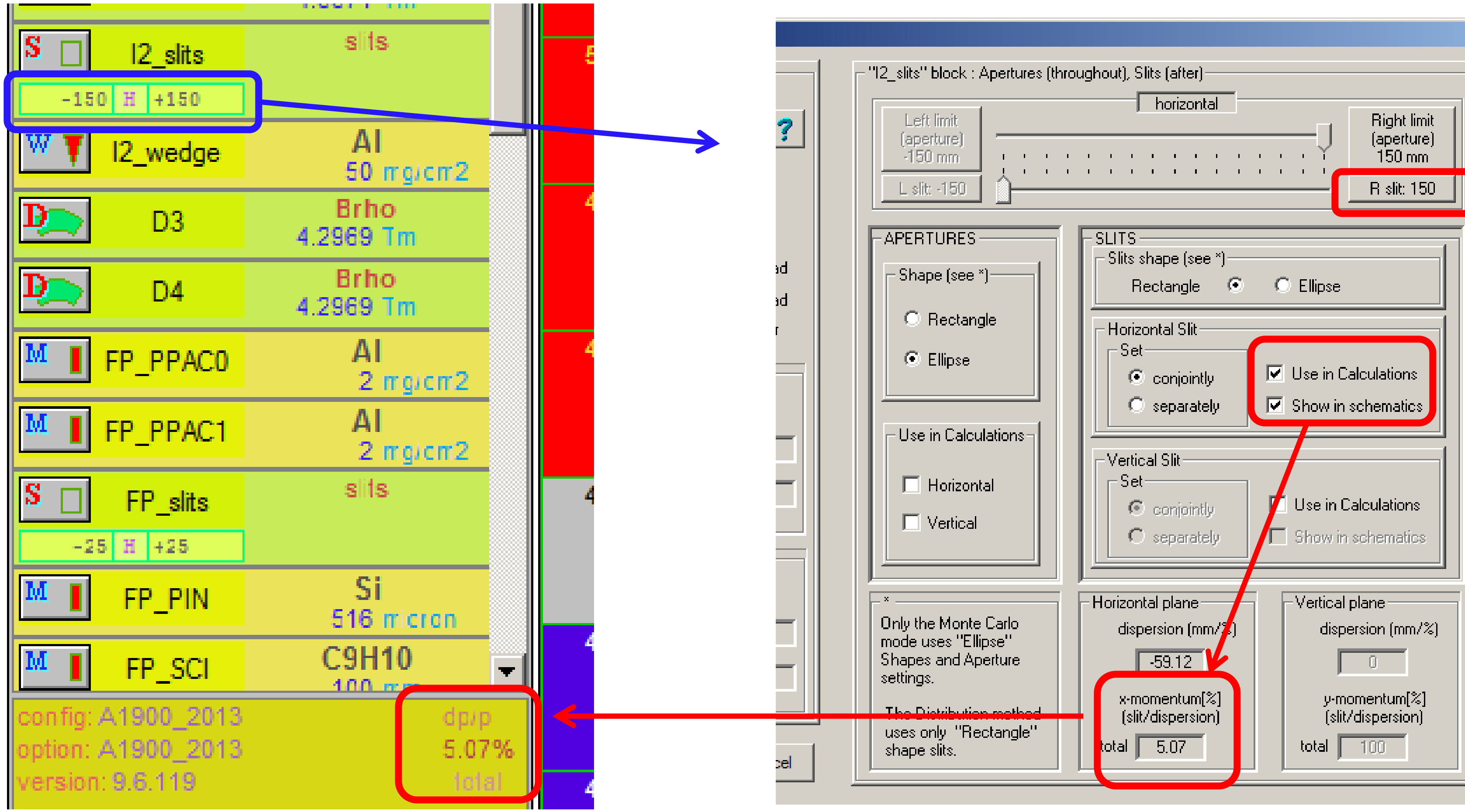
Set fragment of interest (assume ^{56}Ca)



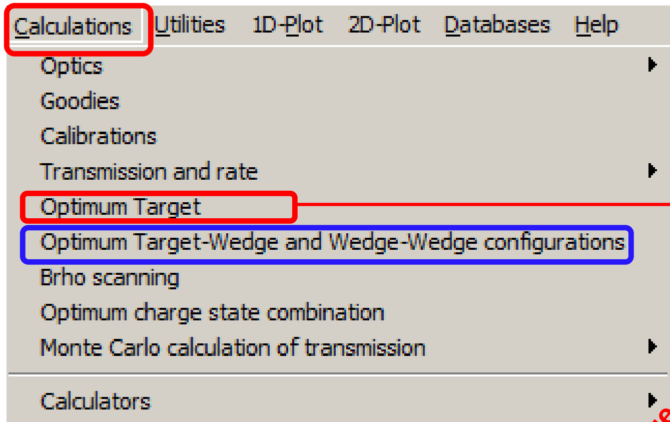
Set "No charge states" option

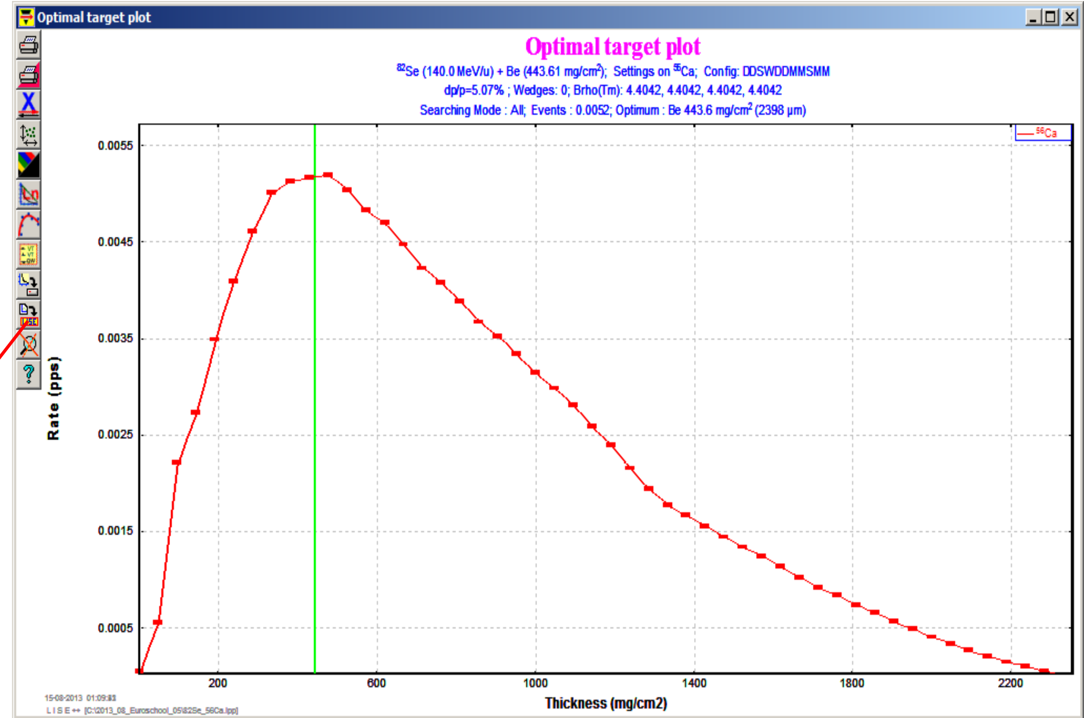


Set maximum momentum acceptance

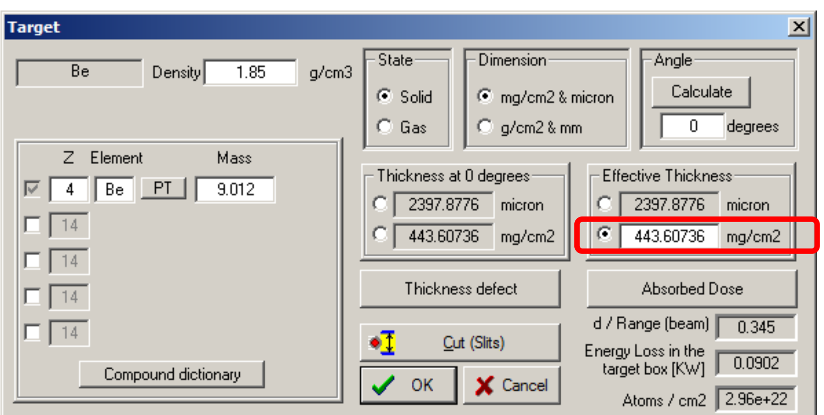


Calculate the Optimum thickness target





Assign the calculated value to the target thickness

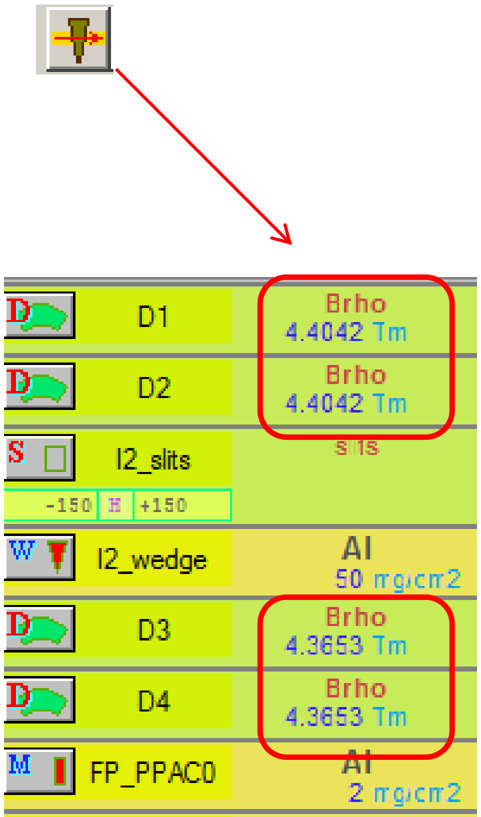


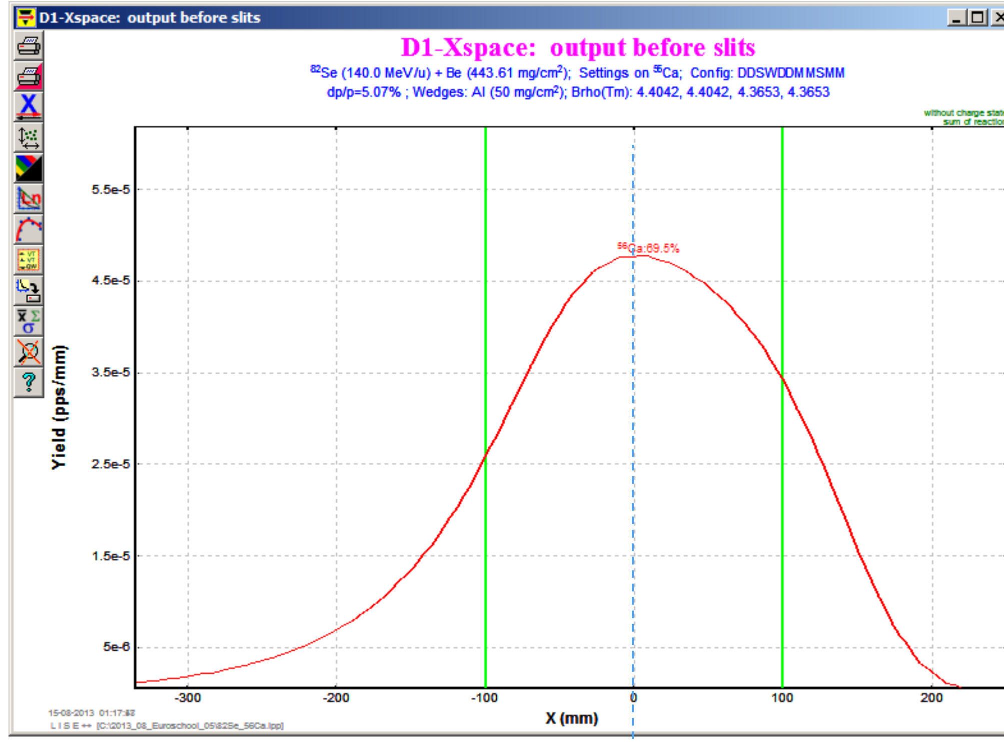
!!! Remember you should also enter a wedge thickness

Several iterations, or use the Optimum target-wedge optimization

Estimate wedge thickness

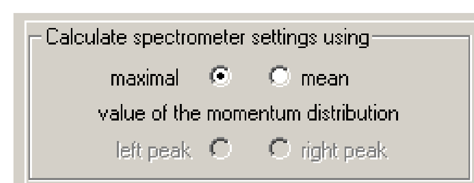
Tune the fragment separator for the setting fragment (^{56}Ca)





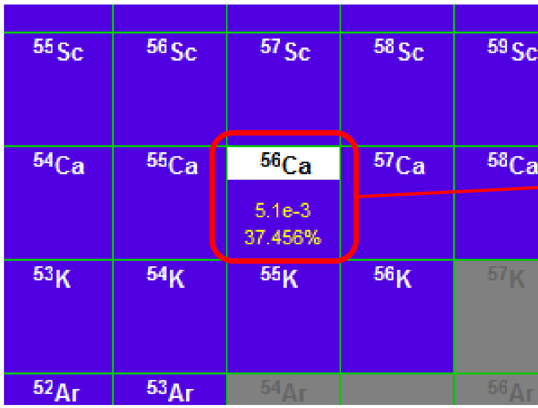
LISE++ tunes the fragment separator to be maximum* of spatial distributions (in dispersive direction) at the central optical axis

*** - tuning options can be modified at the Preference dialog**



Calculate ^{56}Ca ion transmission

Click by a right button of mouse on the ^{56}Ca cell



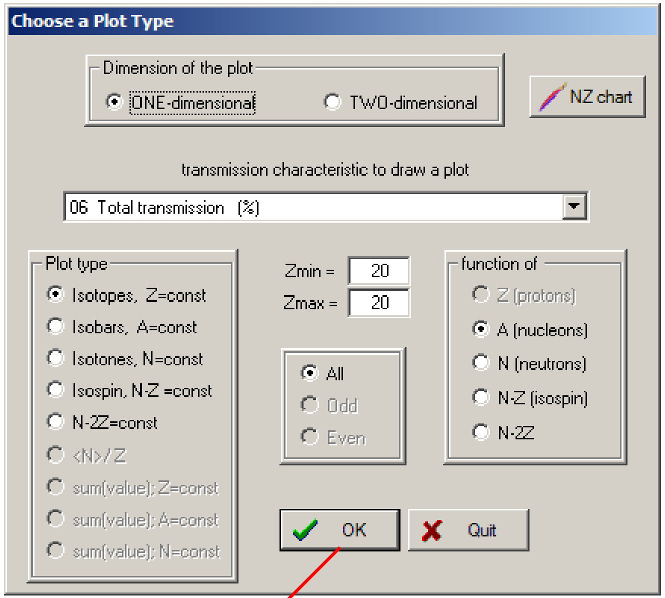
statistics: 56Ca

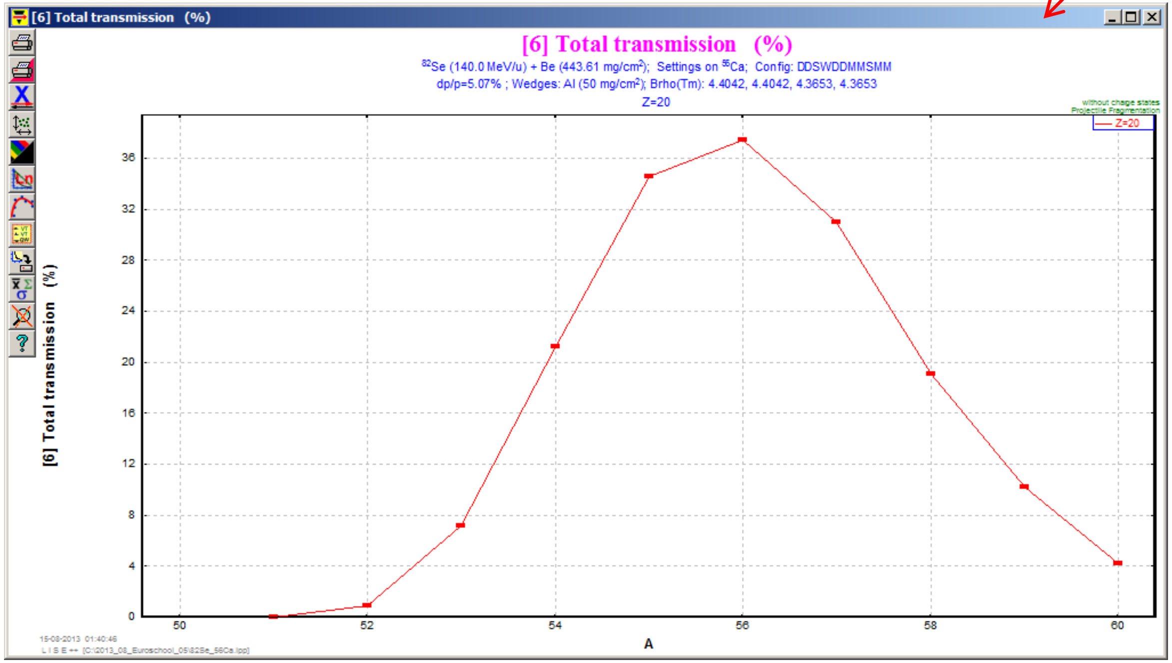
56Ca Beta- decay (Z=20, N=36) Calcium

Q1 (D1)		20
Q2 (D2)		20
Q3 (D3)		20
Q4 (D4)		20
Production Rate	(pps)	5.1e-3
Reaction		Fragmentn
Sum of all reactions	(pps)	5.1e-3
CS in the target	(mb)	2.1e-9
Total transmission	(%)	37.456
Target	(%)	94.59
X space transmission	(%)	100
Y space transmission	(%)	100
Unreacted in mater.	(%)	94.59
Unstopped in mater.	(%)	100
D1	(%)	64.61
X space transmission	(%)	69.51
Y space transmission	(%)	100
X angular transmisn.	(%)	99.66
Y angular transmisn.	(%)	93.25
D2	(%)	72.86
X space transmission	(%)	72.92
Y space transmission	(%)	100
X angular transmisn.	(%)	100
Y angular transmisn.	(%)	100
I2_slits	(%)	91.15

Assume, that this value is nearby the same for other neutron rich calcium isotopes at their tunings

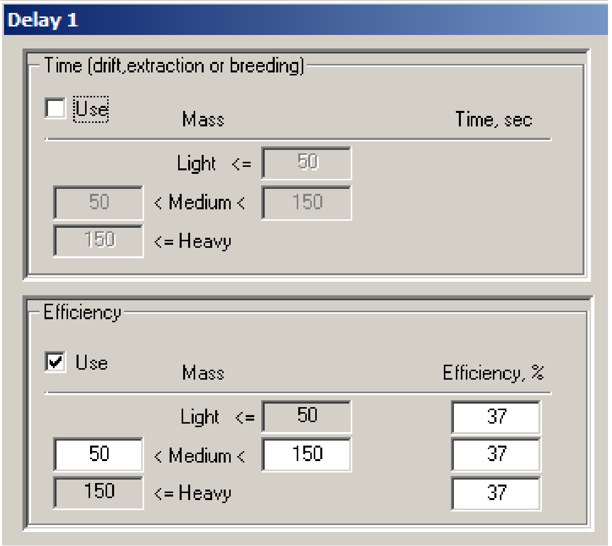
1. **Calculate calcium isotopes production**
2. **Plot Calcium isotopes transmission**

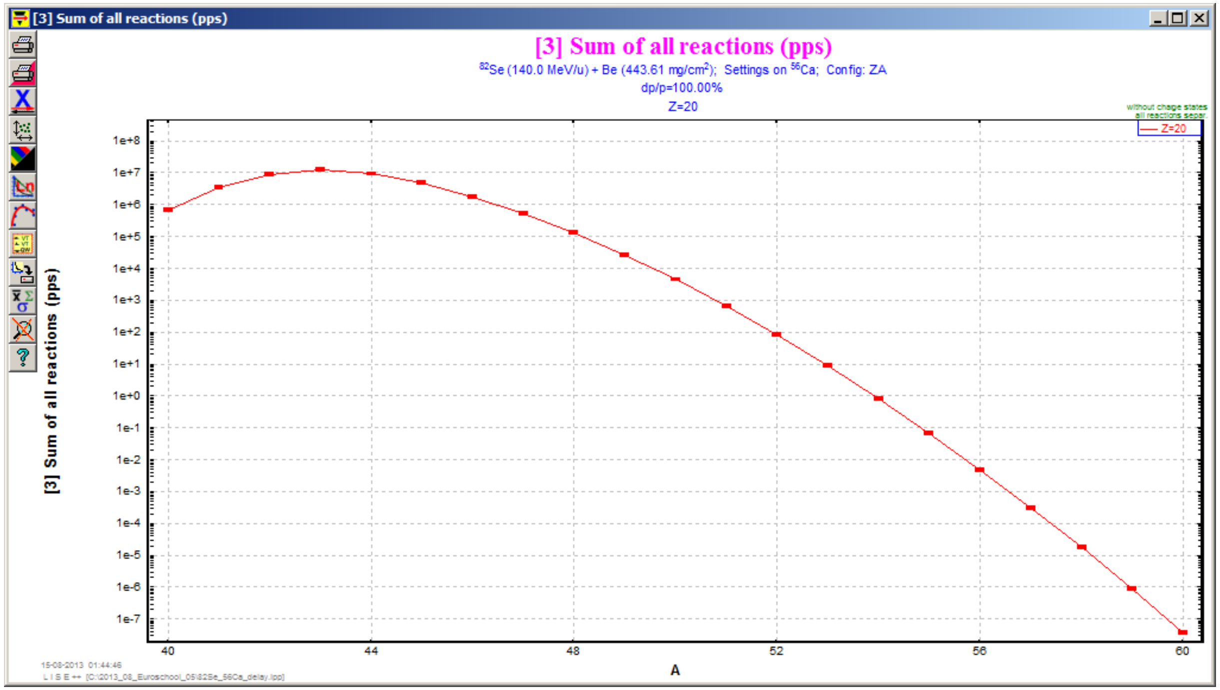




Why ^{82}Se for neutron rich calcium isotopes?

1. Insert "Delay" and "Faraday cup" blocks after the stripper
2. Set values* in the "Delay" block
3. Calculate calcium isotopes production
4. Plot calcium isotopes yields, Save yields in file





ISOL : the same steps as for Calcium isotopes

In-flight:

1. Projectile fragmentation of ^{136}Xe
2. Abrasion-fission of ^{238}U (turn on the "charge state" option !!)

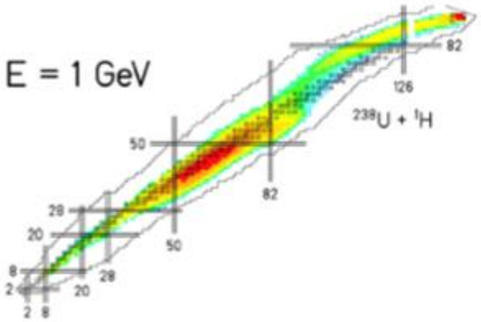
NSCL PAC35 rates (v.1.03)

https://groups.nscl.msu.edu/frib/rates/nscl_pac35_rates.html The rates are estimated based on the EPAX 2.15 cross section parameterization for fragmentation and the LISE++ 3EER model for in-flight fission. Primary beam intensities and energies have been used from the PAC35 beam list

Attempt to estimate ISOL & In-Flight yields with LISE^{++}

HRIBF : p(40MeV, 5uA) + ^{238}U

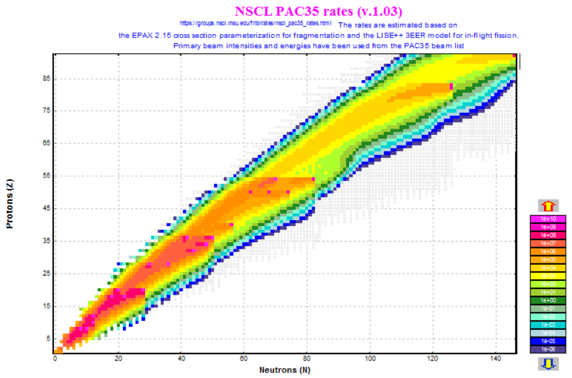
Assumptions for ISOL method:
Total efficiency: 10%
Extraction time: 50 ms



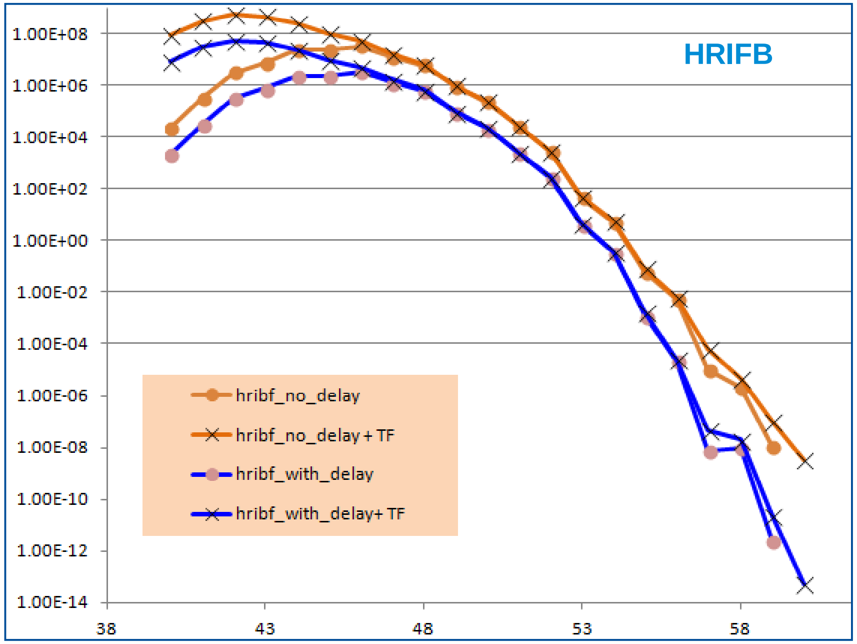
NSCL : from the beam list

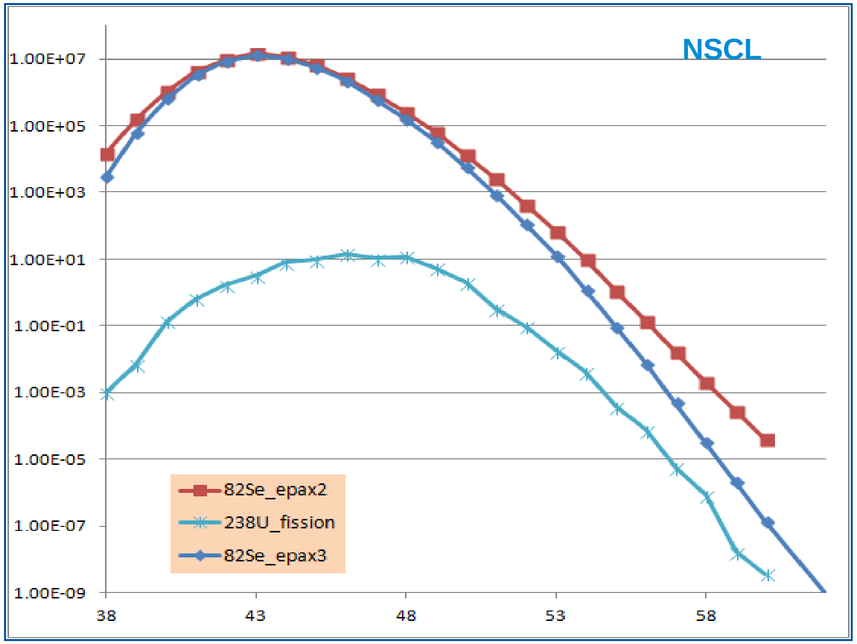
for Ca isotopes ^{82}Se(140MeV/u, 35 pna)
^{238}U(80MeV/u, 0.2 pna)

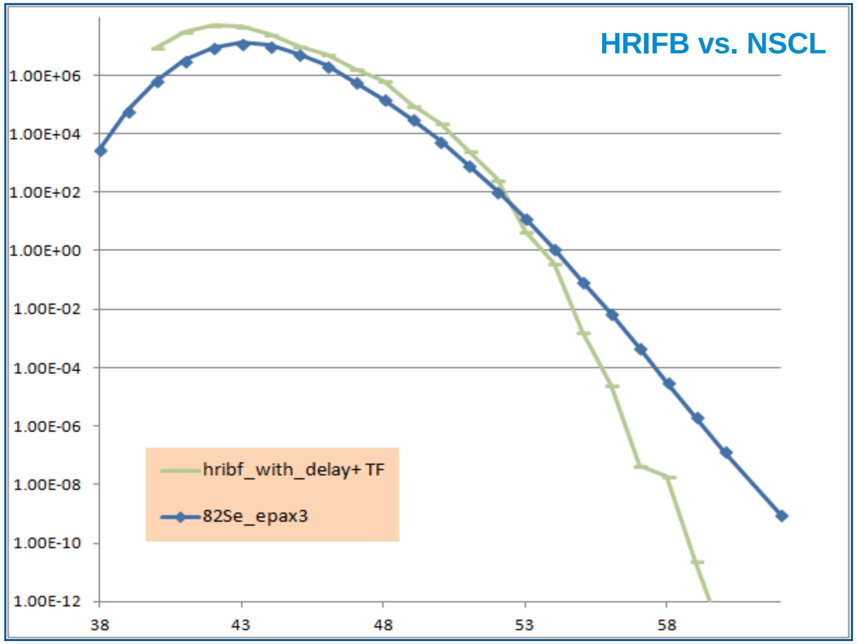
for Kr isotopes ^{136}Xe(120MeV/u, 2 pna)
^{238}U(80MeV/u, 0.2 pna)



ISOL & In-Flight : Ca isotopes







"Delay" block

Total efficiency: 10%

Extraction time: 50 ms

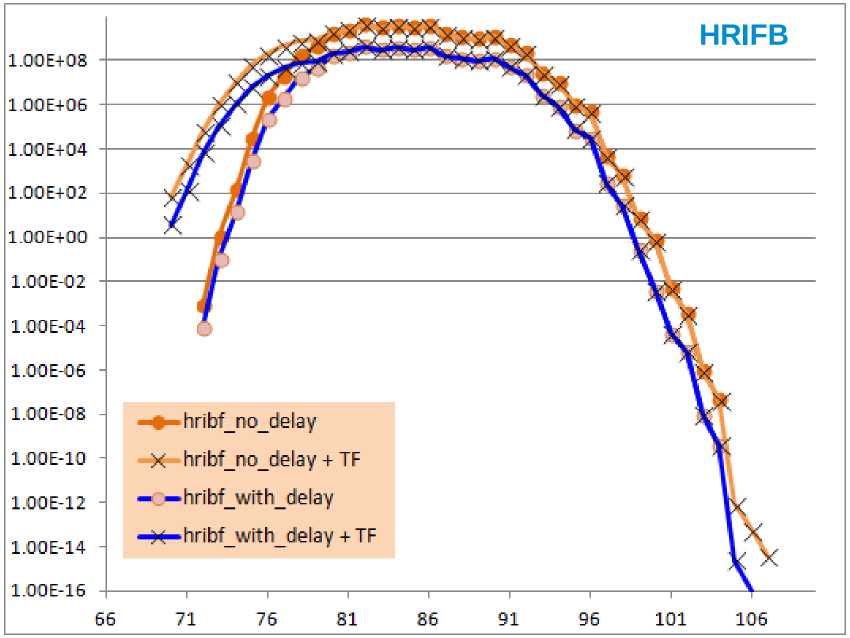
X-axis : Mass number

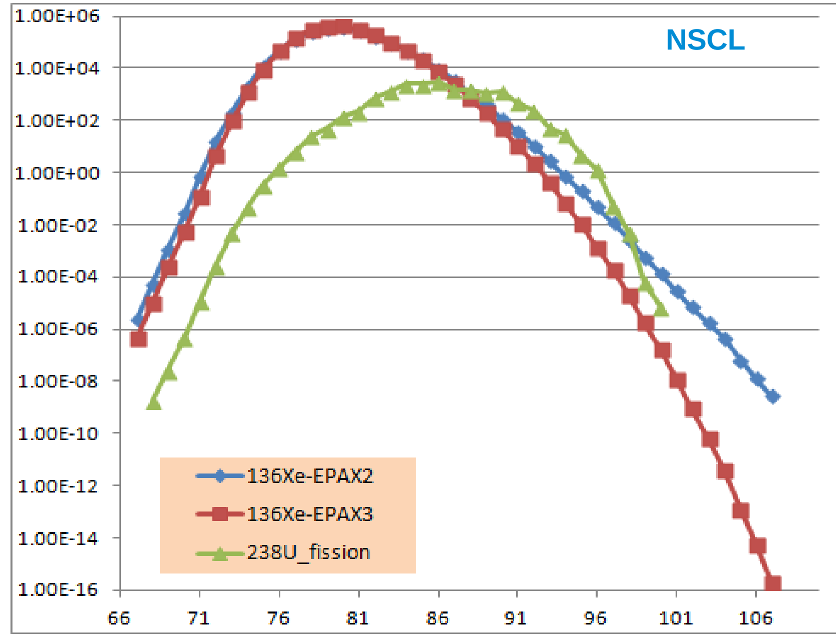
Y-axis : rate (pps)

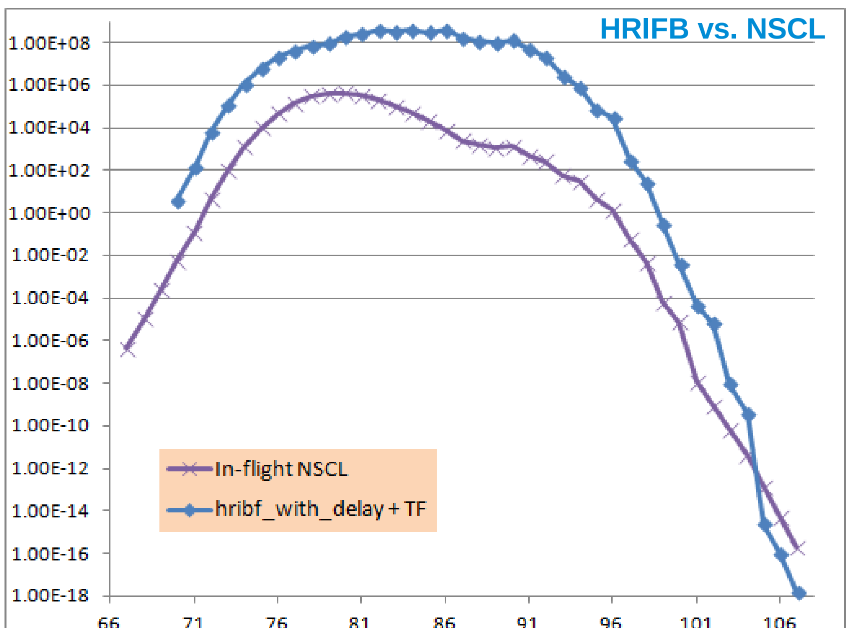
TF – target fragmentation calculated with EPAX3

Last neutron-rich Calcium isotopes ^{57,58}Ca have been observed @ NSCL in projectile fragmentation of ^{76}Ge and ^{82}Se

ISOL & In-Flight : Kr isotopes







Last neutron-rich Krypton isotopes $^{98-101}$Kr have been observed @ GSI & RIKEN in in-flight fission of ^{238}U

"Delay" block

Total efficiency: 10%

Extraction time: 50 ms

X-axis : Mass number

Y-axis : rate (pps)

TF – target fragmentation calculated with EPAX3

Future for Two-step process?

1. **ISOL fission**
2. **In-flight PF**

End of Lecture 3

Questions ?

Haben Sie Fragen?

Вопросы ?

有問題嗎？

¿Preguntas?

Demandoj?

質問？

Pytania?

Domande?

Sorular?