
重离子核物理
Heavy Ion Nuclear Physics

放射性束物理介绍

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提纲

1

原子核物理简介

2

核的稳定性

3

放射性束及实验装置

4

放射性束物理

下载、安装

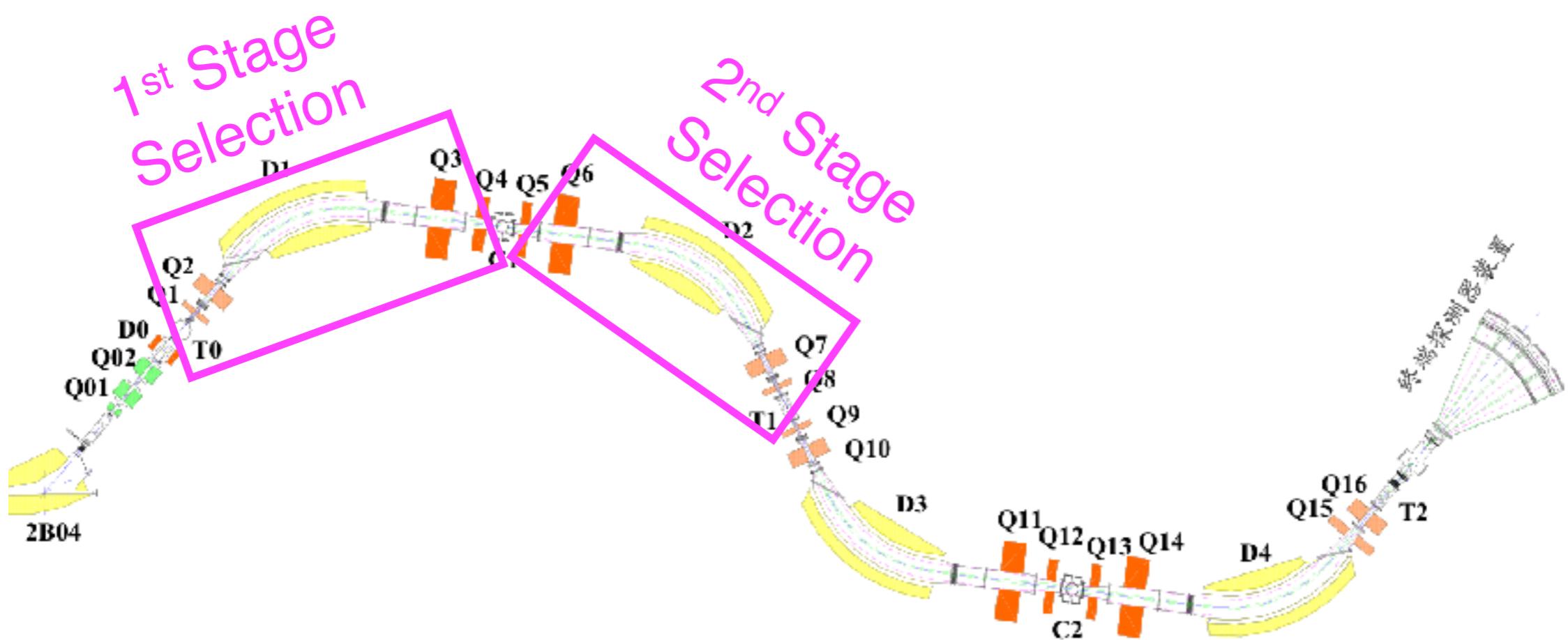
1. LISE++

<https://lise.frib.msu.edu/lise.html>

2. SRIM

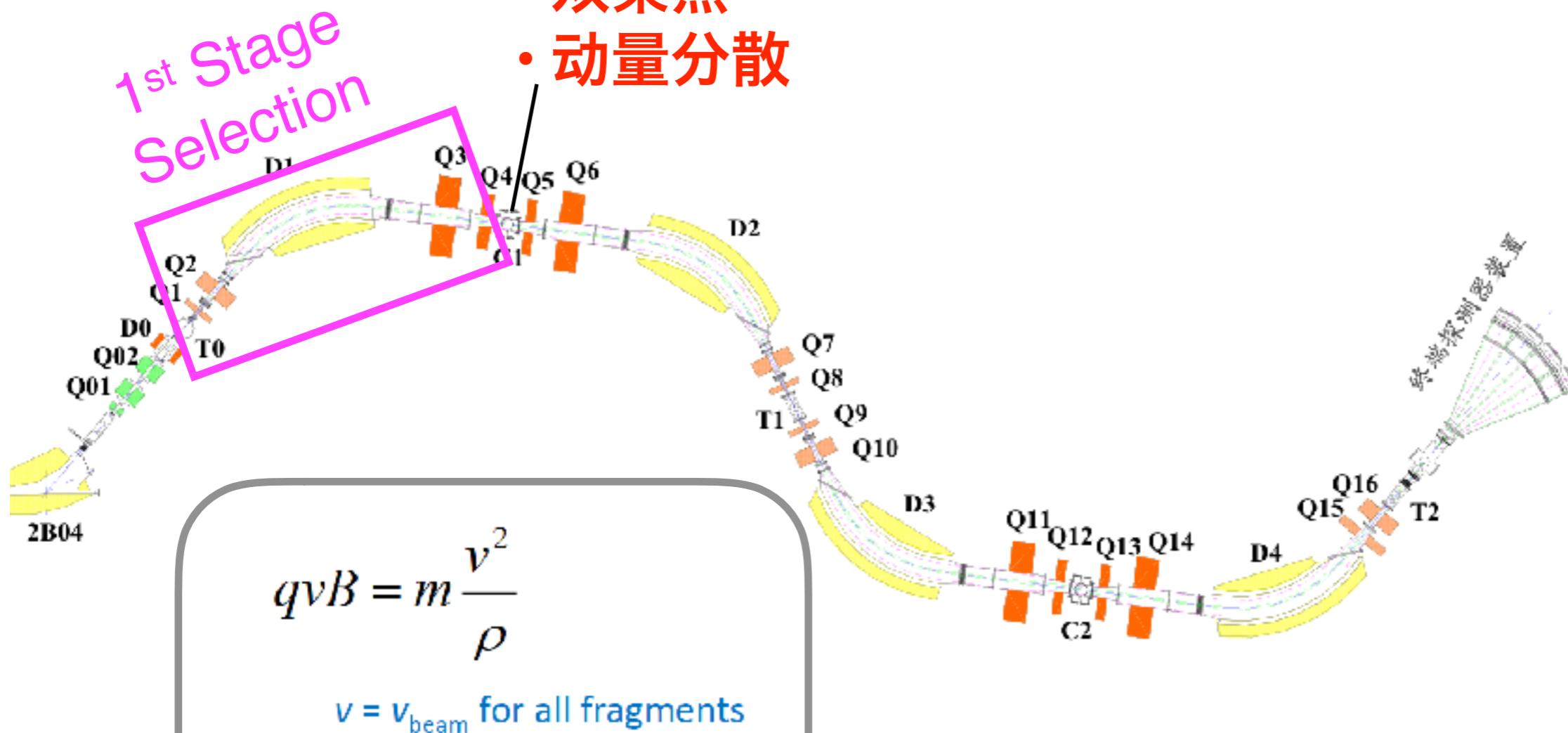
<http://www.srim.org/SRIM/SRIMLEGGL.htm>

放射性束调制



放射性束调制

- 双聚焦
- 动量分散



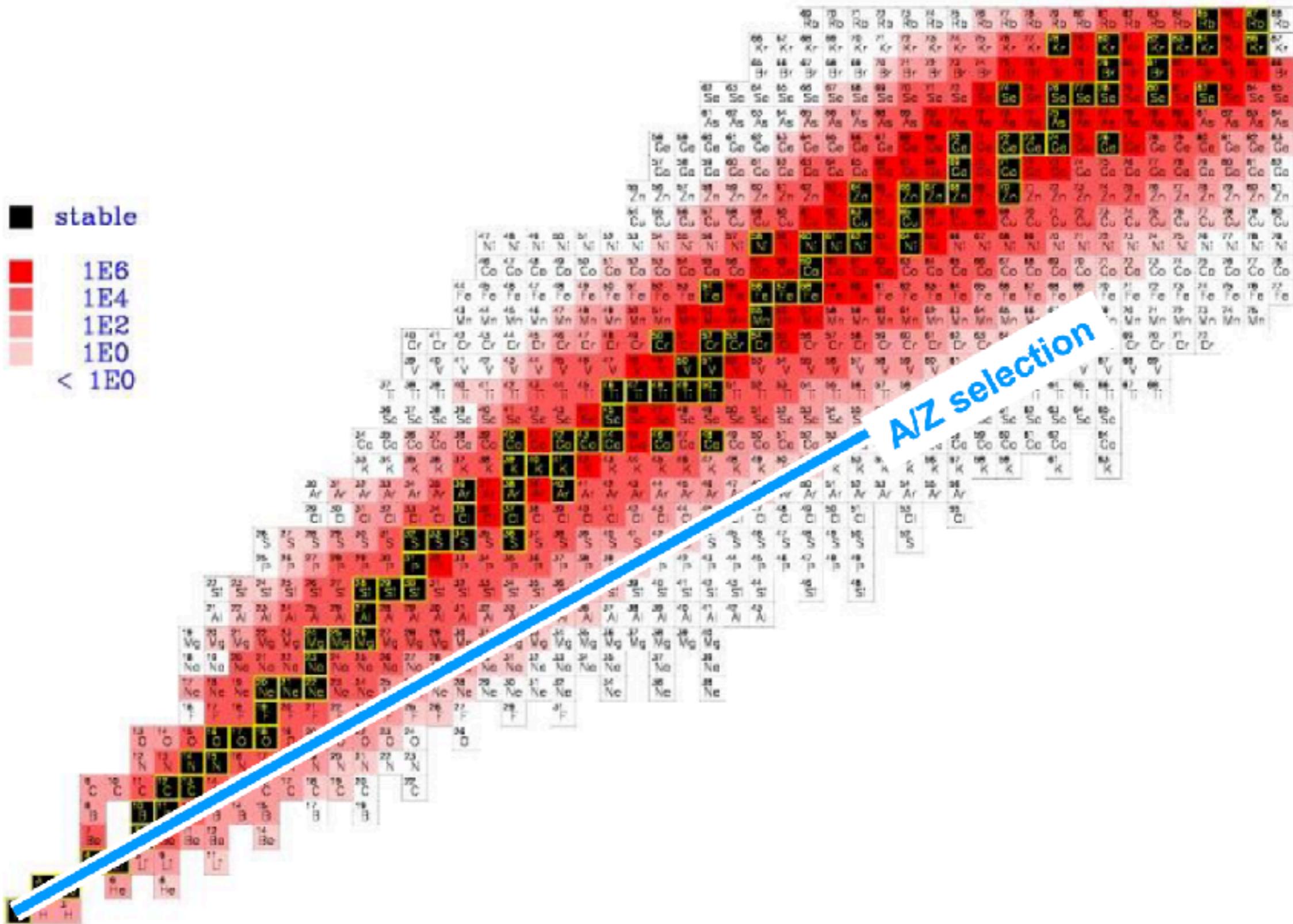
$$qvB = m \frac{v^2}{\rho}$$

$v = v_{beam}$ for all fragments

$$ZevB = Am_{nucl} \frac{v^2}{\rho}$$

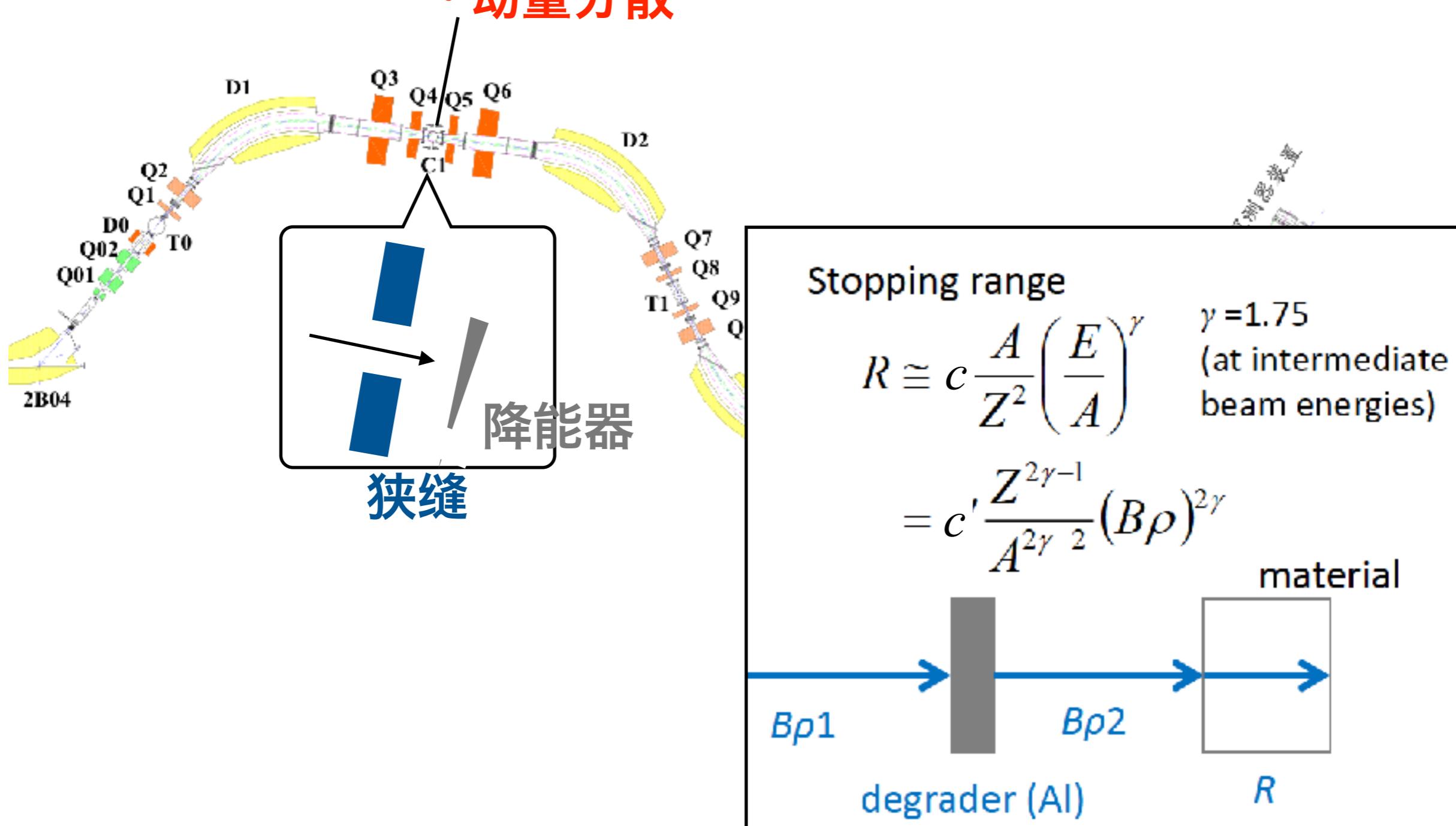
$$B\rho = \frac{A}{Z} \frac{p_{nucl}}{e}$$

第一阶段筛选

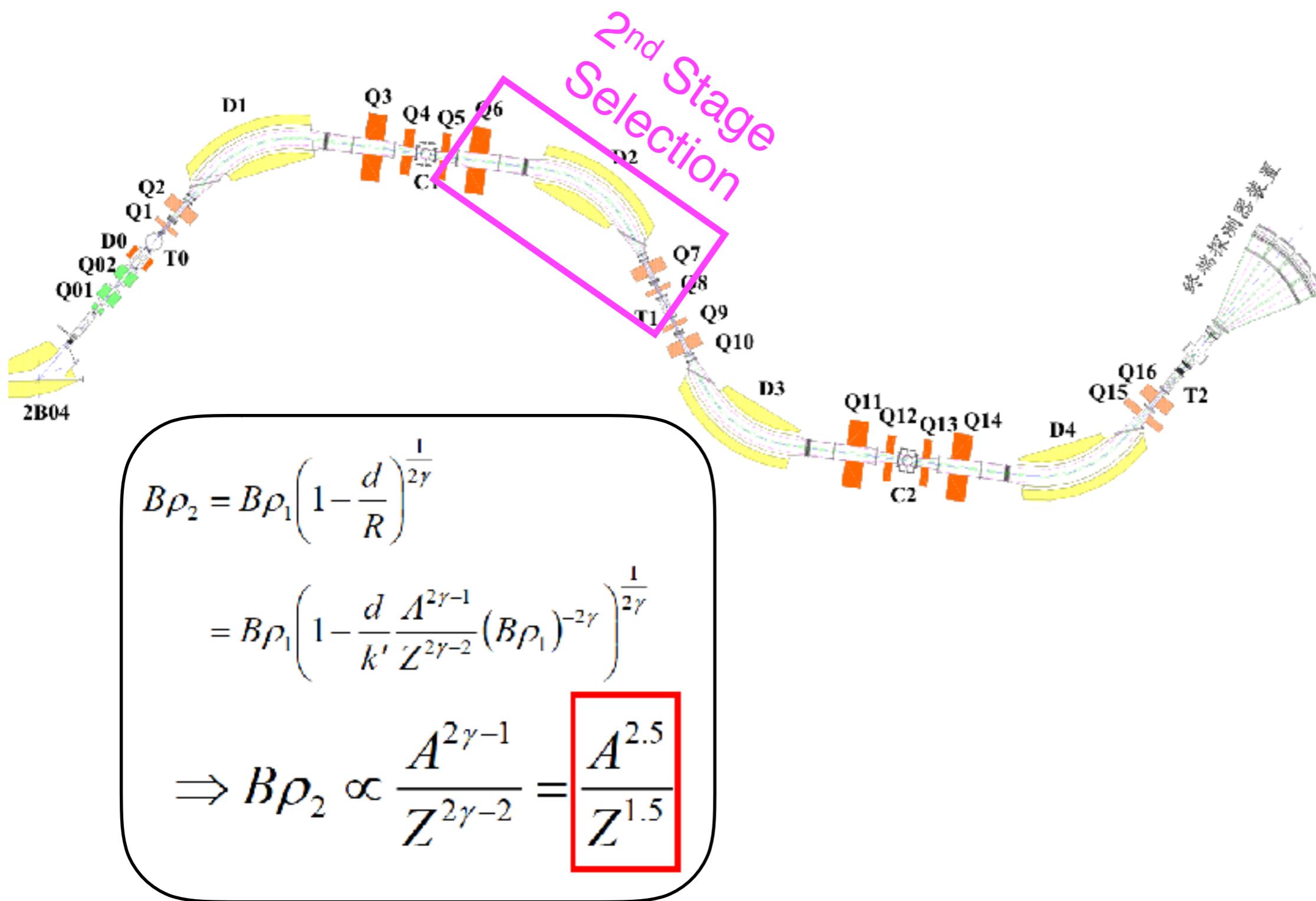


放射性束调制

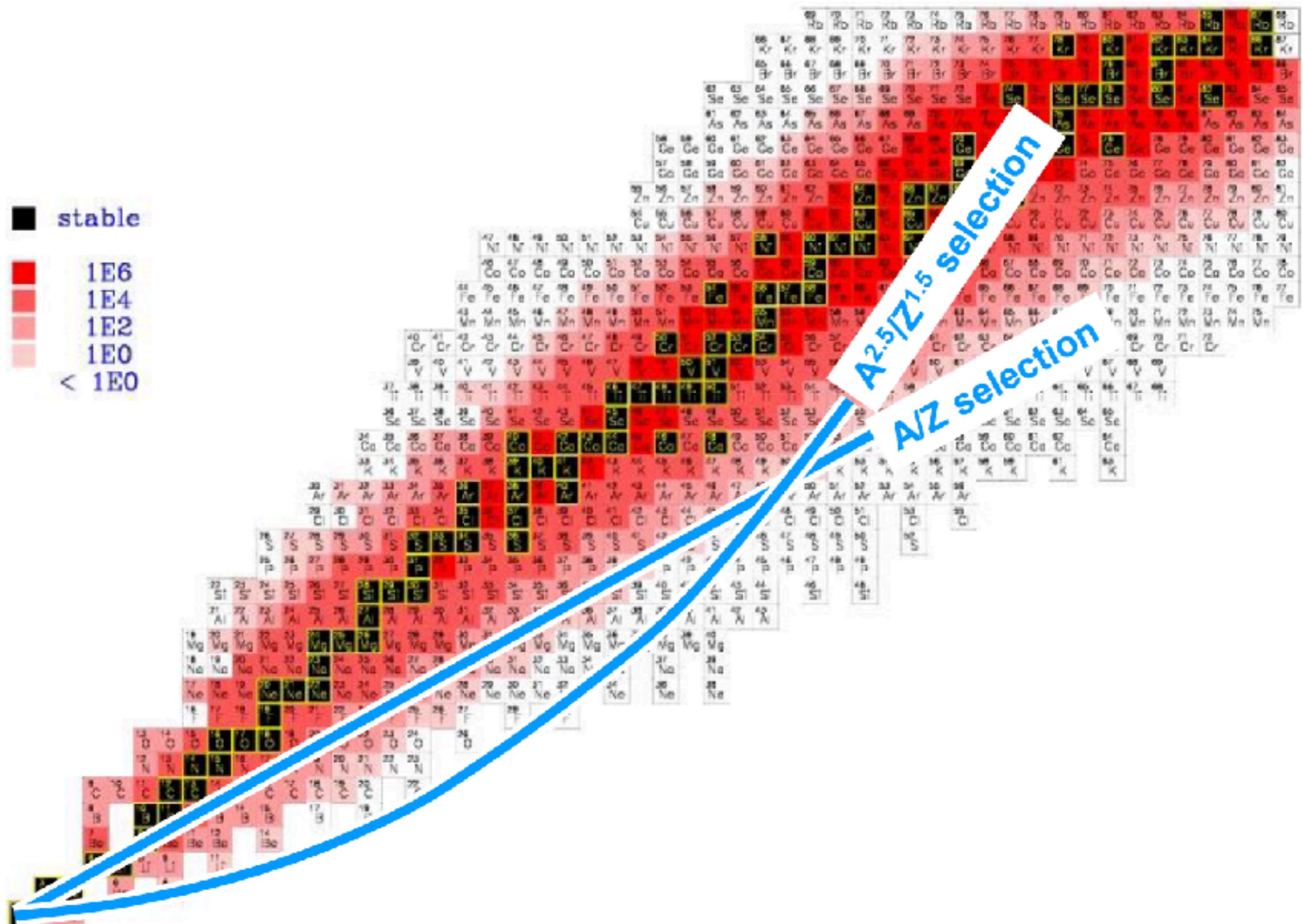
- 双聚焦
- 动量分散



放射性束调制



第二阶段筛选



带电粒子与物质的相互作用

主要是入射带电粒子与靶原子的核外电子和原子核的库仑场中的作用。

- 带电粒子与靶原子的核外电子的弹性、非弹性散射
- 带电粒子与靶原子的原子核的弹性、非弹性散射

◆ 能损公式 (Bethe-Bloch)

$$-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} \right] \quad [\text{MeV/g} \cdot \text{cm}^{-2}]$$

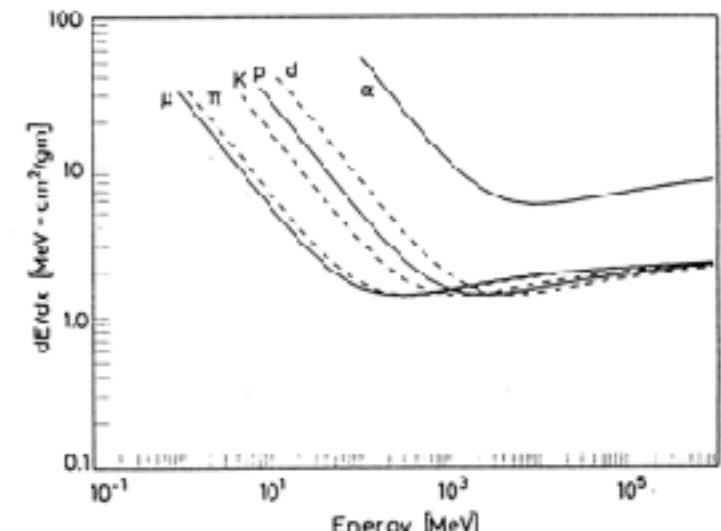
$$T_{\max} = \frac{2m_e \beta^2 \gamma^2}{1 + 2\gamma m_e / M + (m_e / M)^2} \quad \text{电子的最大动能}$$

$$K = 4\pi N_A r_e m_e = 0.307 \quad [\text{MeV g}^{-1} \text{ cm}^2]$$

◆ 射程

$$R = c \frac{A_{\text{proj}}}{z^2} \left(\frac{E_k}{A_{\text{proj}}} \right)^\gamma$$

E_k : 动能; c, γ : 参数



z, A_{proj} : 带电粒子的质子、质量数

Z, A : 物质的 Z, A

m_e : 电子静止质量 [0.511 MeV]

I : 平均激发能 [eV]

δ : 密度修正参数

X_0 : 物质的辐射长度 [g/cm^2]

p : 带电粒子动量 [MeV/c]

习题：射程公式

我们在开展原子核物理实验时经常需要考虑带电粒子在物质中的能损。我们可以利用能损公式或射程公式计算能损，但很多时候后者比前者方便。利用SRIM程序计算 $E_k=300-800$ MeV的 ^{12}Be 在铝的射程 R 。通过拟合得到 c, γ 参数以及 ^{12}Be 在铝的射程公式。

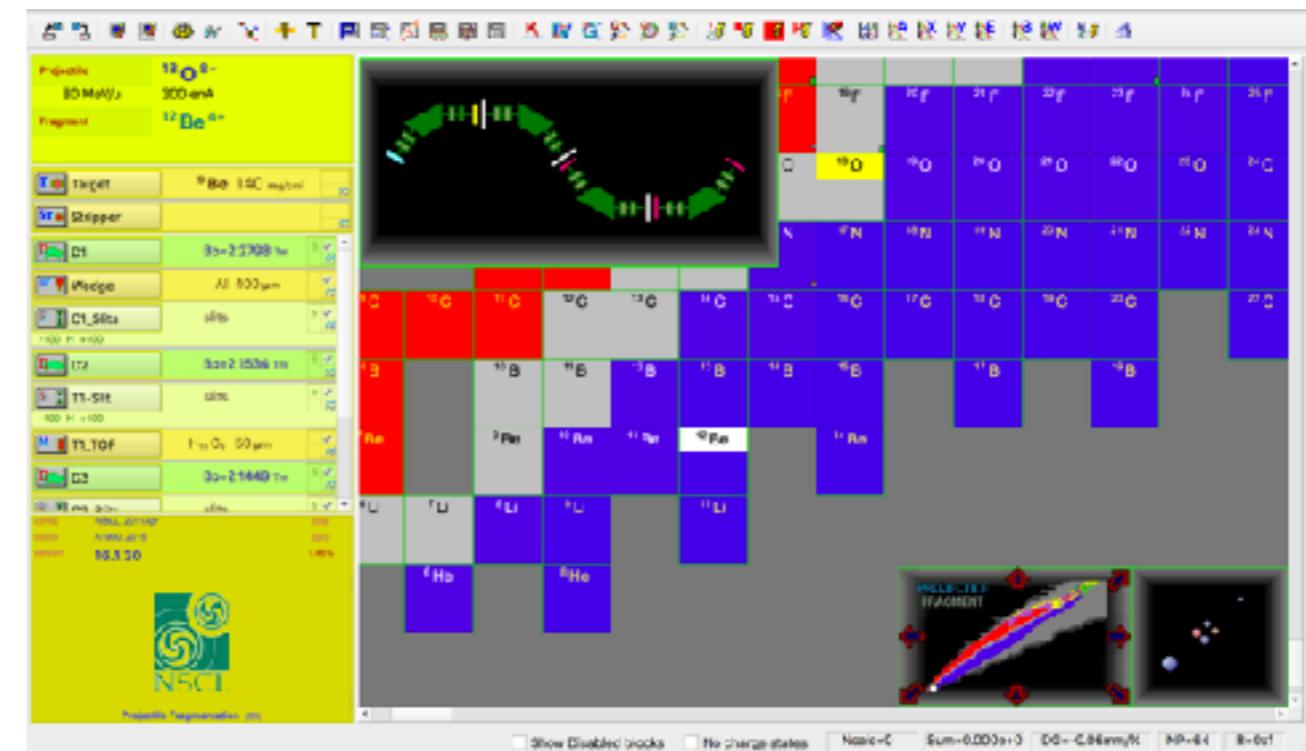
$$R = c \frac{A_{\text{proj}}}{z^2} \left(\frac{E_k}{A_{\text{proj}}} \right)^\gamma$$

LISE++简介

放射性束物理实验设计的四维口袋



- 开发于法国Ganil研究所，美国MSU/NSCL进行维护、更新
- 用于计算碎片分离器中生产、分离和收集的碎片的传输及产额



LISE++的目标和特点

- Predict fragment separator settings to obtain a specific RNB
针对目标放射性核束，模拟碎片分离器各装置的预设值
- Predict the intensity and purity of the chosen RNB
目标放射性核束的产额和纯度预言
- Simulate identification plots to be compared online
通过模拟得到粒子鉴别图，为在线粒子鉴别提供支撑
- Provide a highly user-friendly environment
提供方便使用的程序
- Possibility to configure the program for different fragment separators
可扩充性；用于各种碎片分离器的设计和程序编译

LISE++网站

<https://lise.nscl.msu.edu/lise.html>

The screenshot shows the LISE++ website homepage. The top navigation bar includes links for Home, Introduction, Documentation, Last Changes, Utilities, Perspectives, Download, Spectrometers, Related topics, Personal pages, Registration, and Email. A sidebar on the left indicates 'version 16.5.1'. The main content area features a heading 'EXOTIC BEAM PRODUCTION WITH FRAGMENT SEPARATORS' and a section titled 'Range of application'. The text describes the program's purpose of calculating transmission and yields of fragments produced and collected in a spectrometer, starting from reaction mechanism parameters and ending with fragment selection by a spectrometer. It highlights optimization, maximum output estimation, and identification features like Wedge and Wien filter selections. The LISE++ package is described as freeware running on Windows, macOS, and Linux environments.

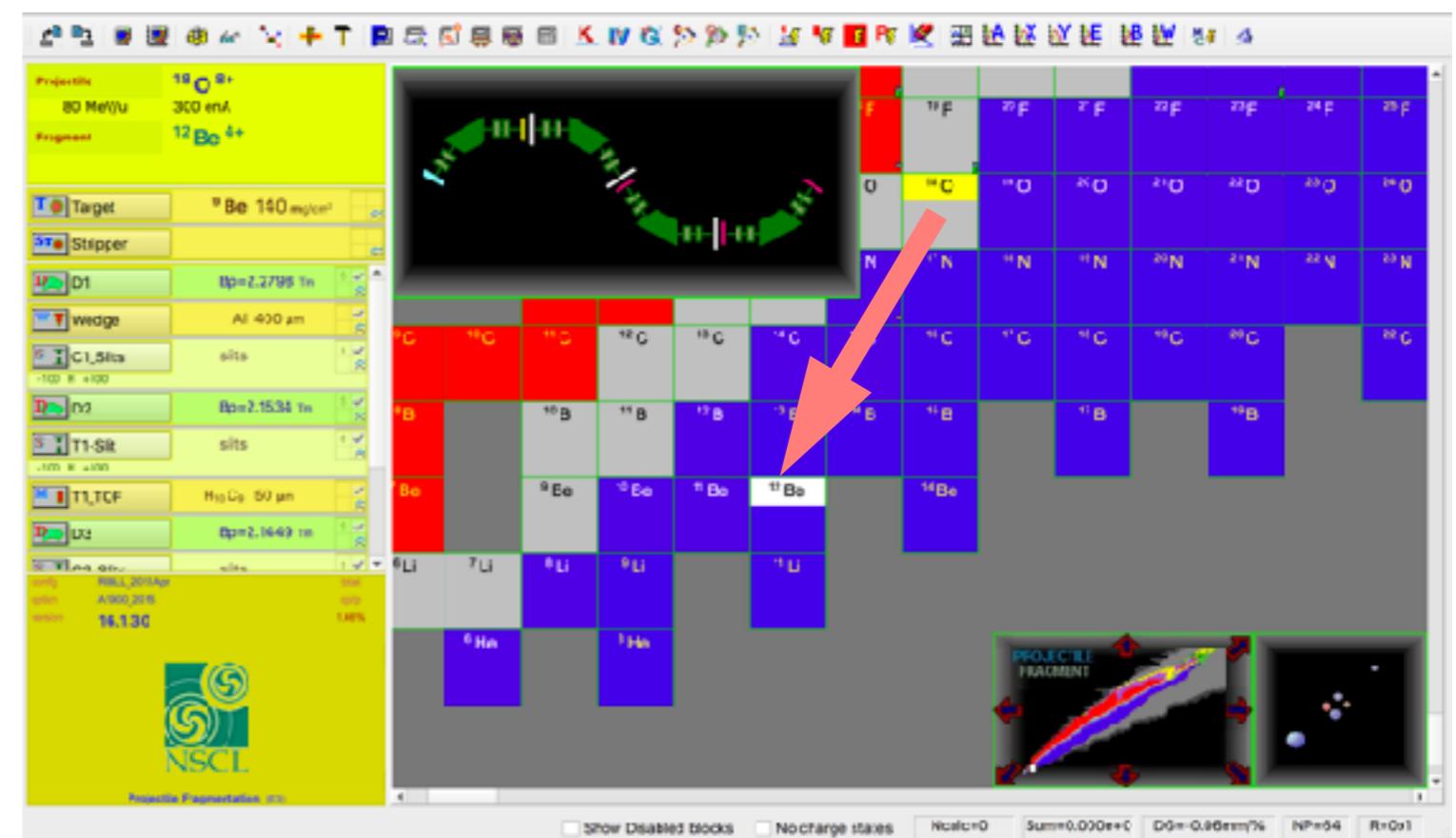
- LISE++简介、使用说明、文章等
- 可免费下载LISE++程序
- 支持的操作系统：



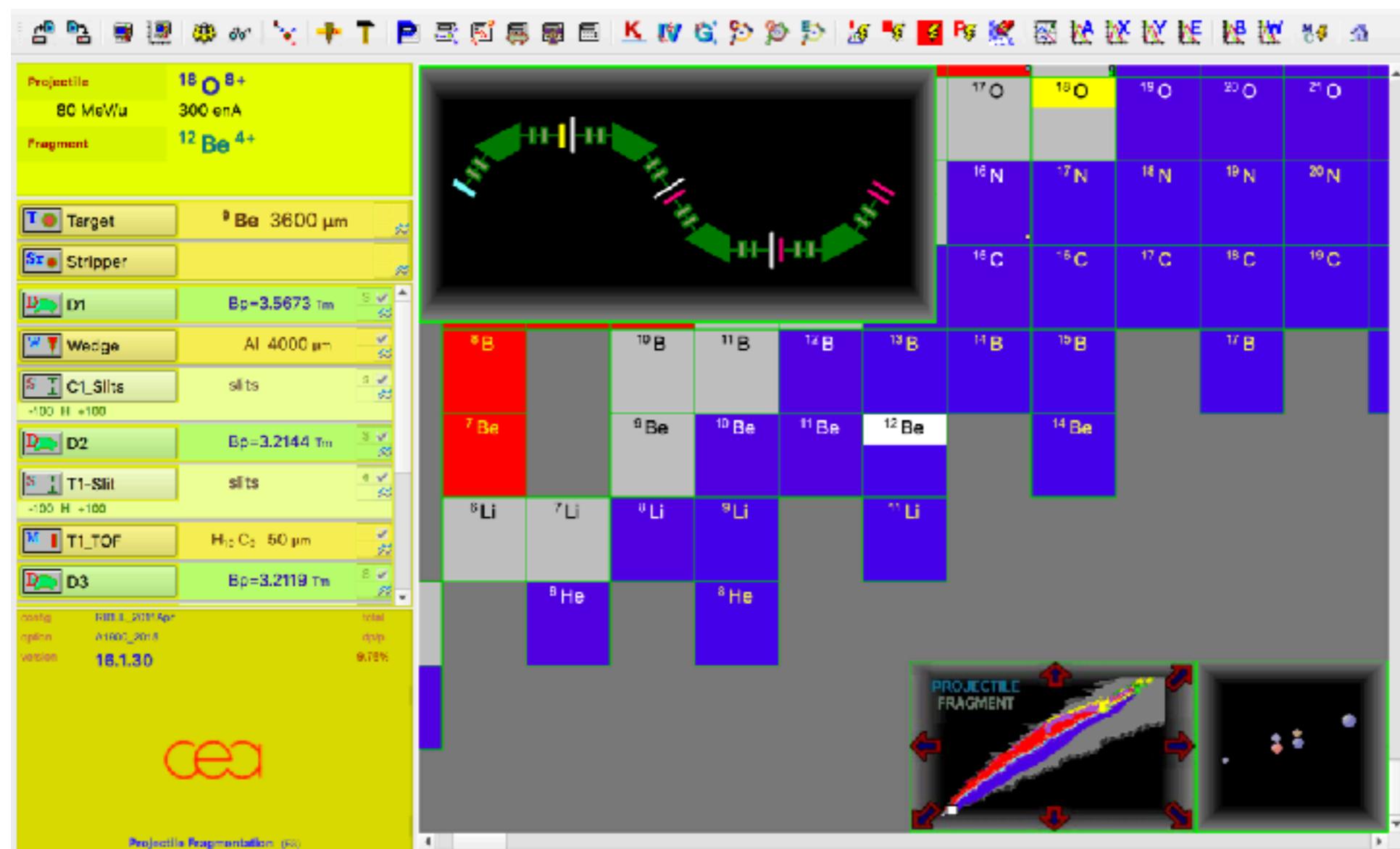
利用LISE++计算次级束

利用能量 $80A$ MeV, 流强 300 enA 的 ^{18}O 初级束产生 ^{12}Be 束流
► ^{12}Be 产额优先

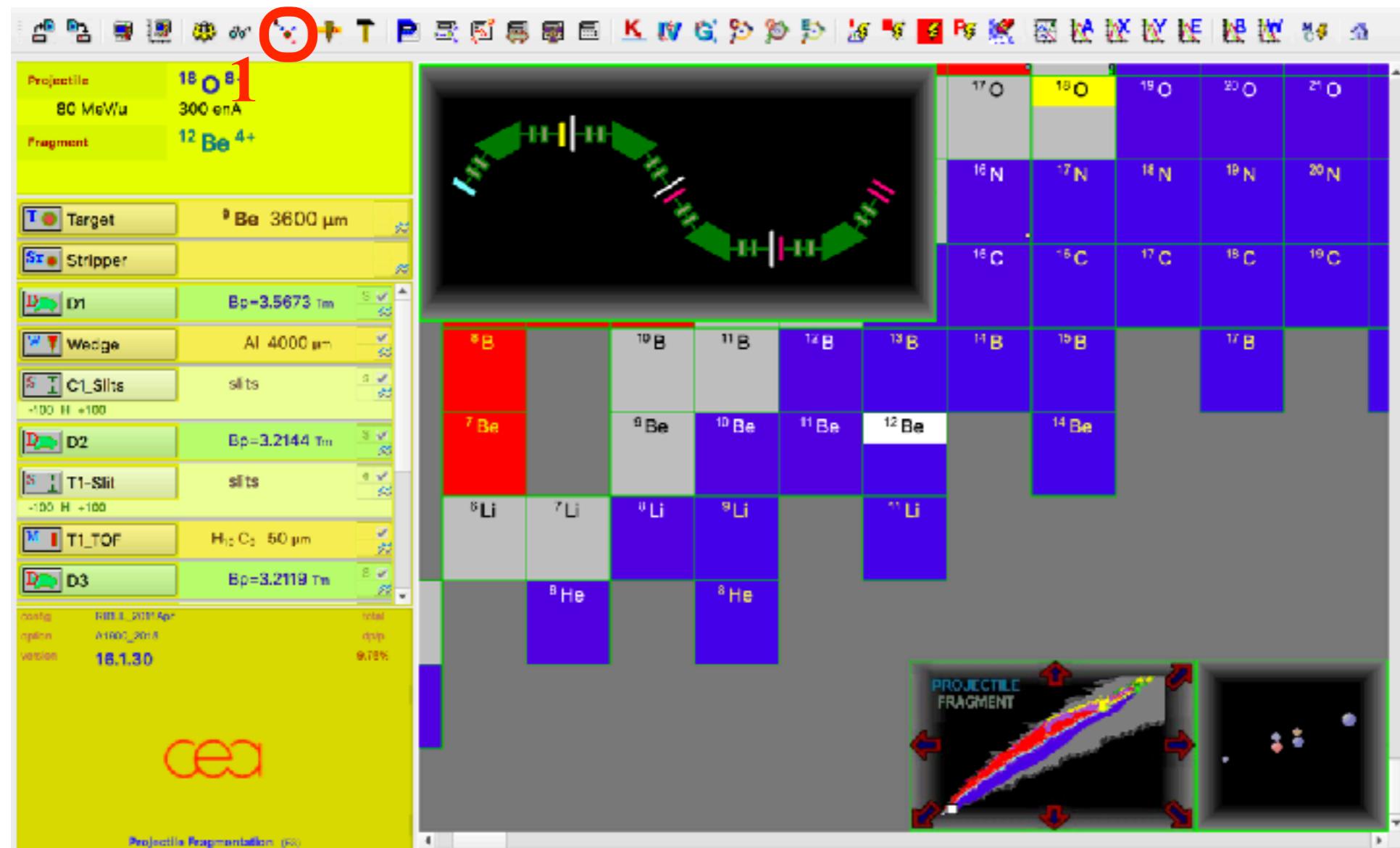
1. 计算产额与纯度
2. 得到粒子鉴别
3. 进一步优化碎片分离



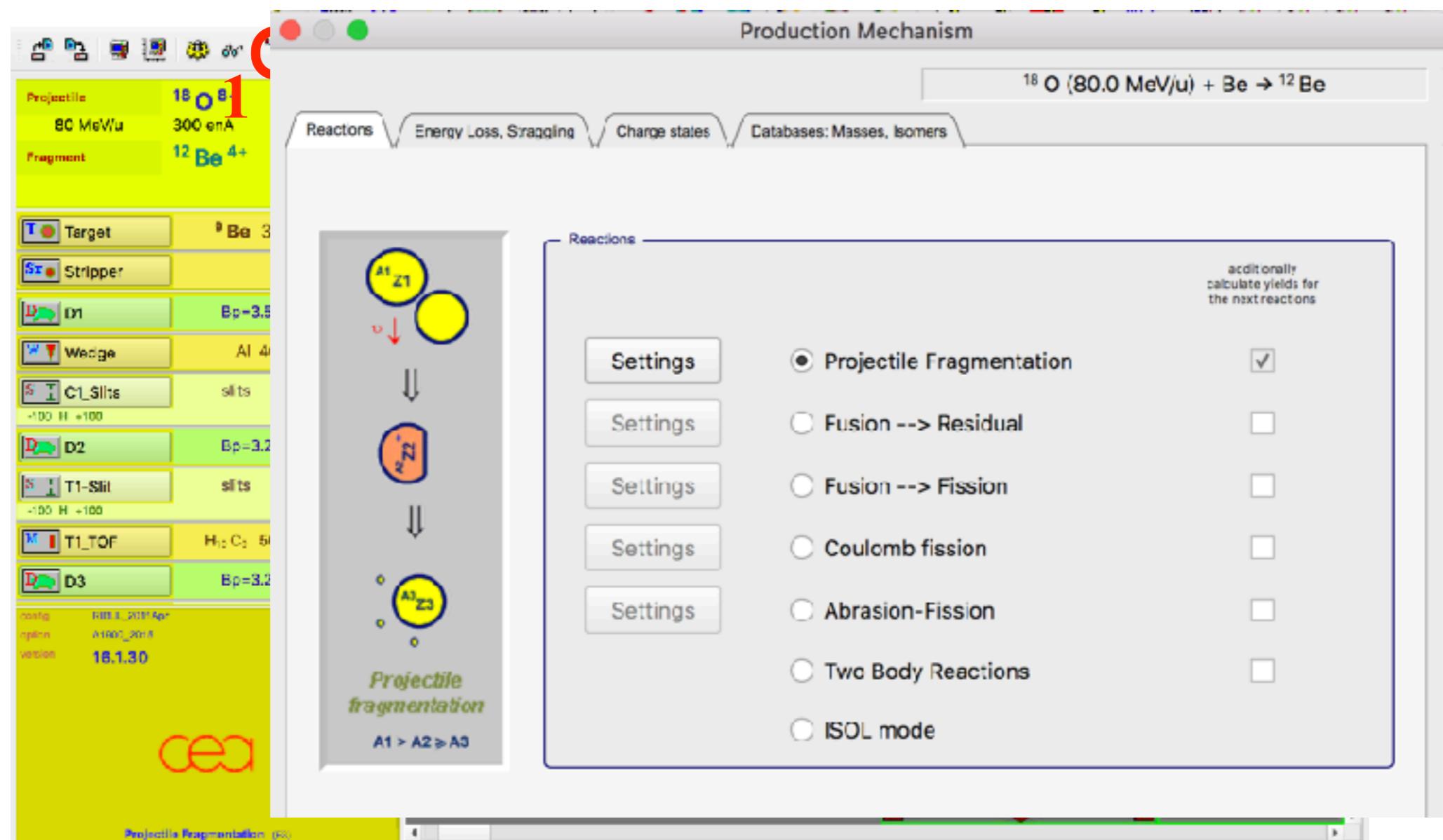
放射性束的产生



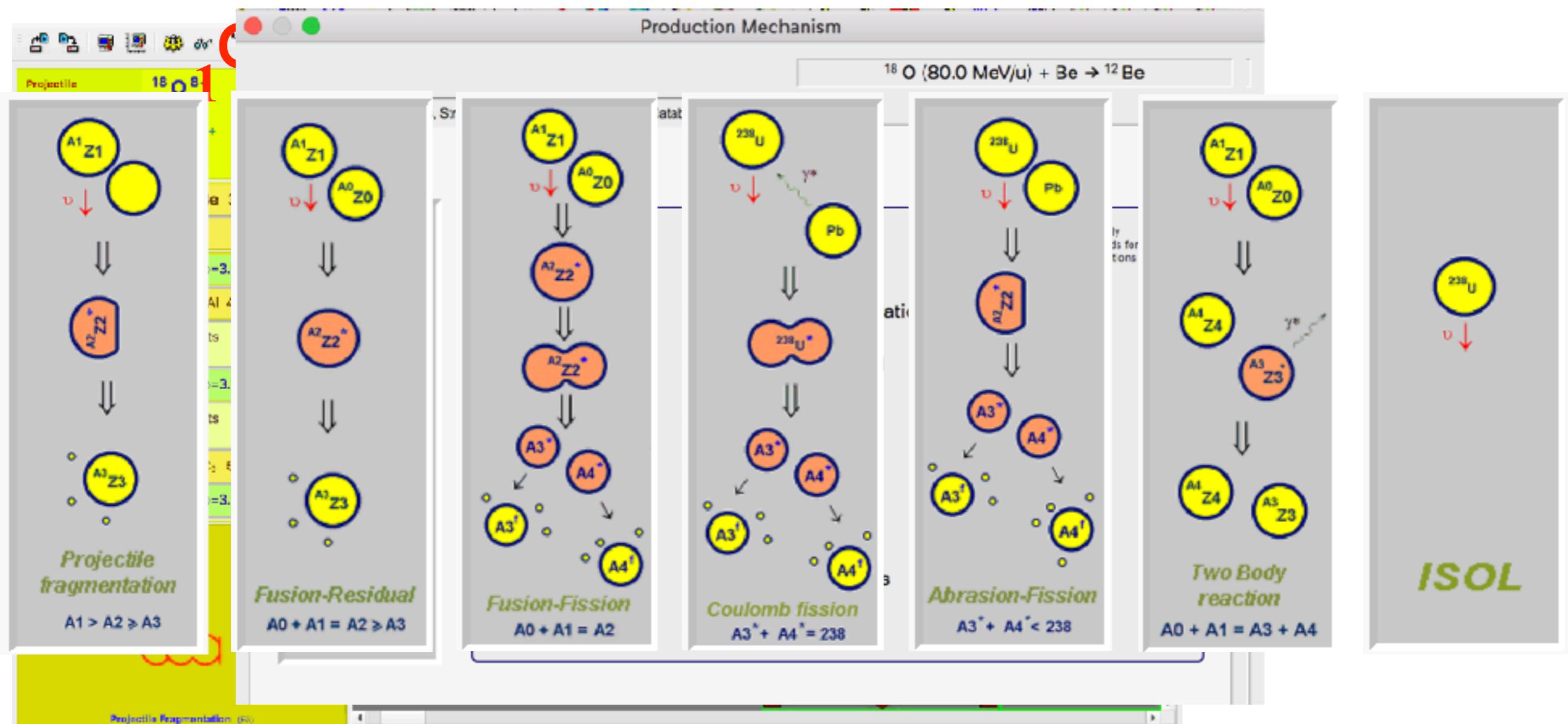
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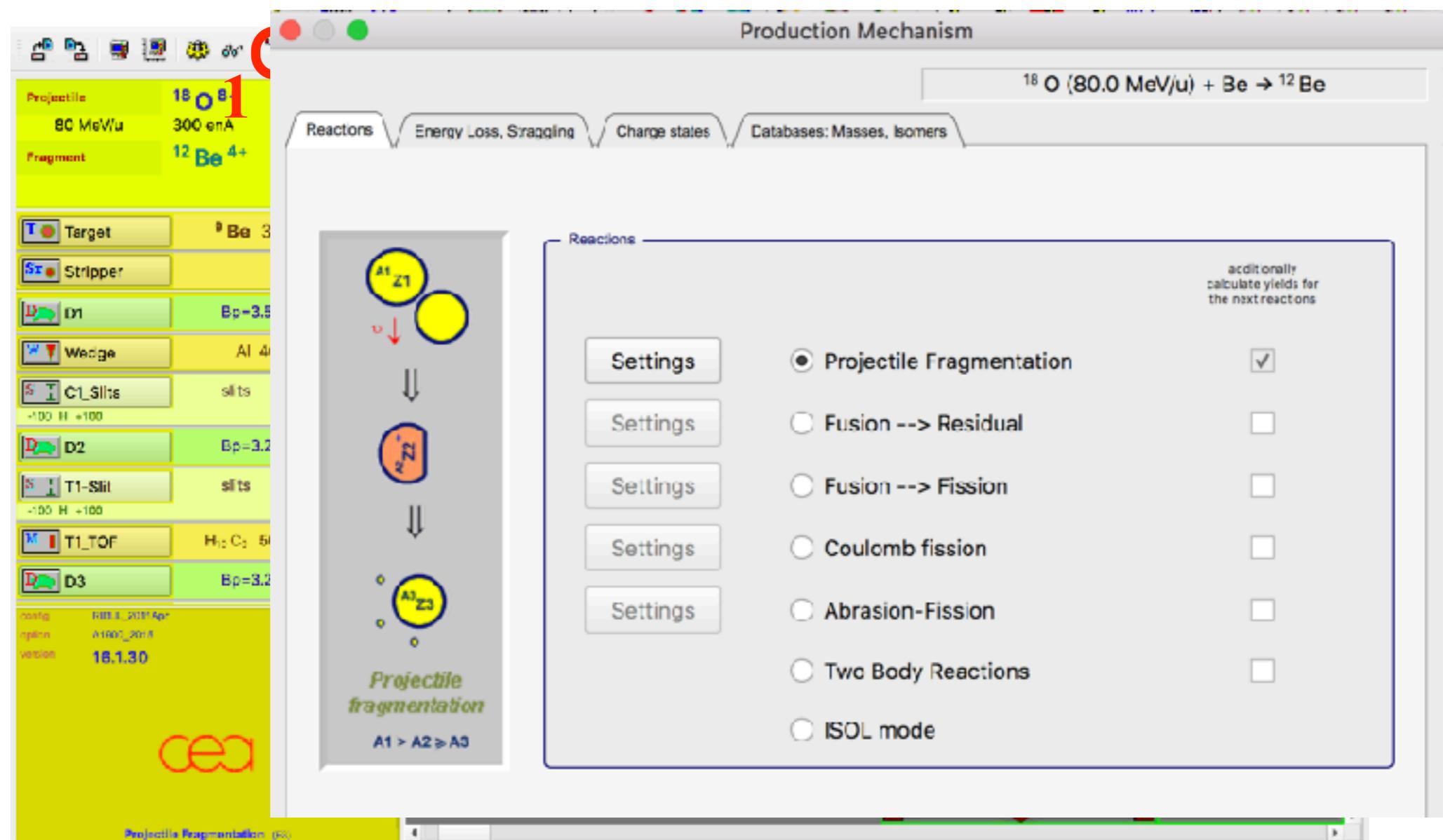
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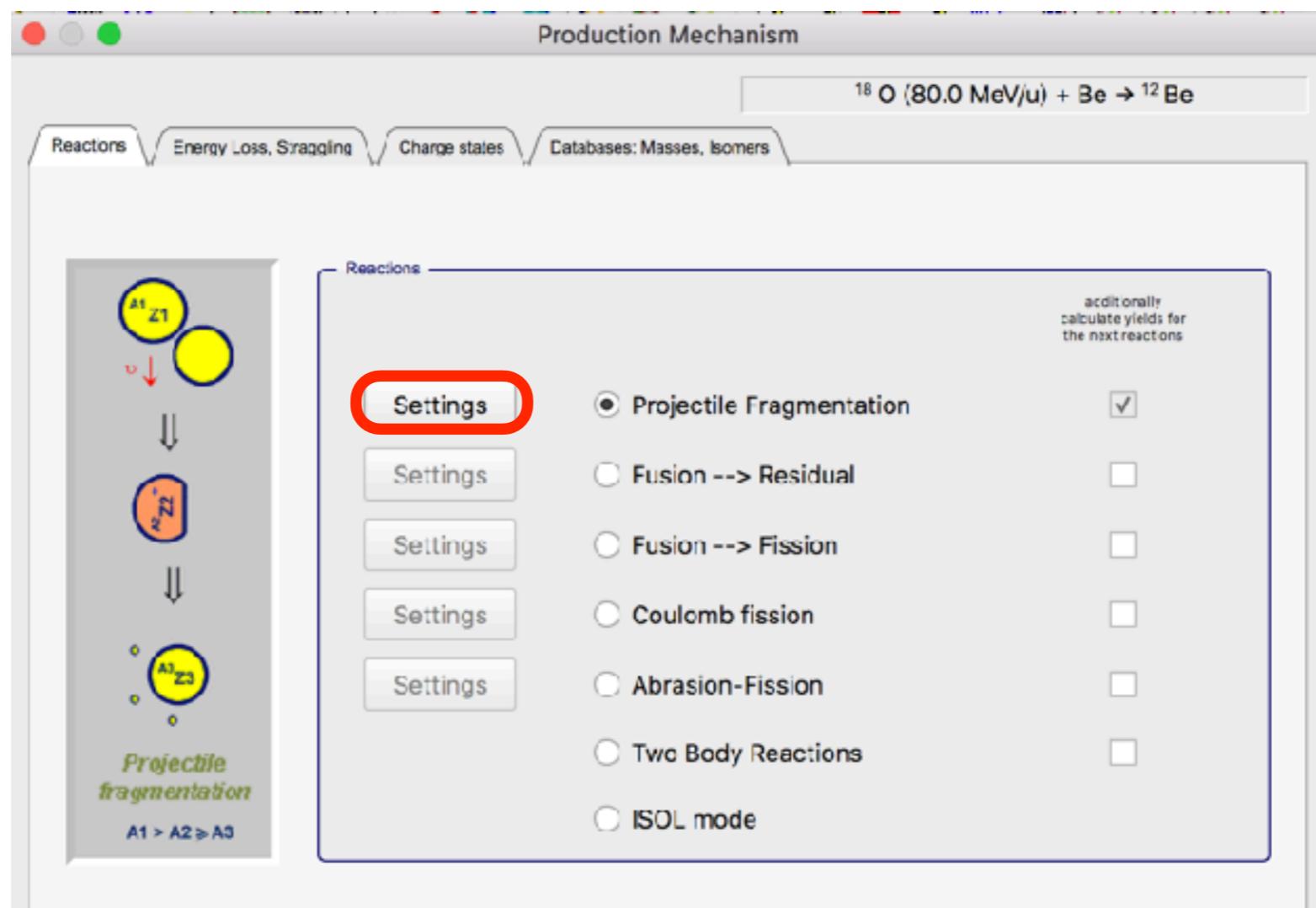
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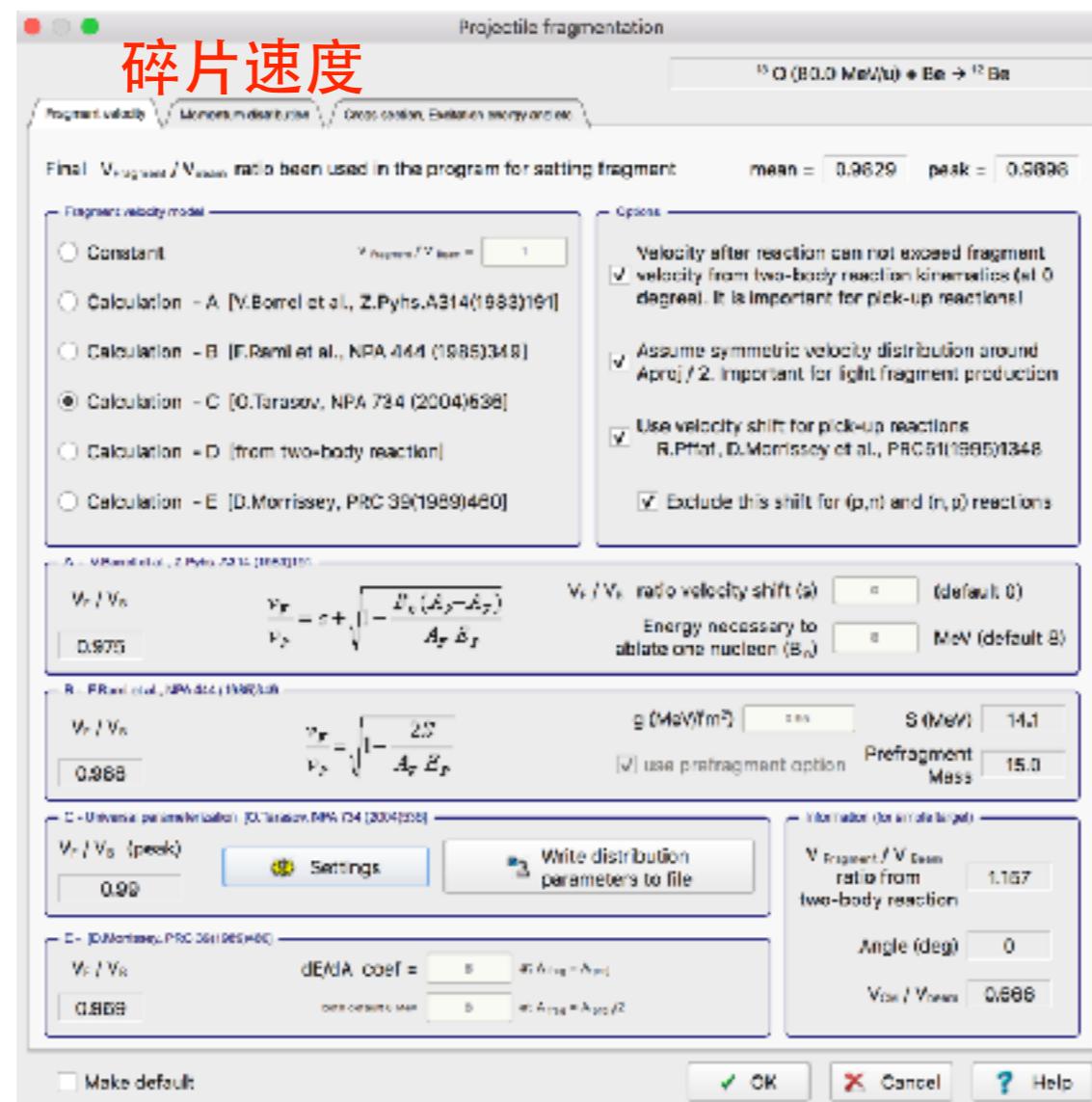
放射性束的产生



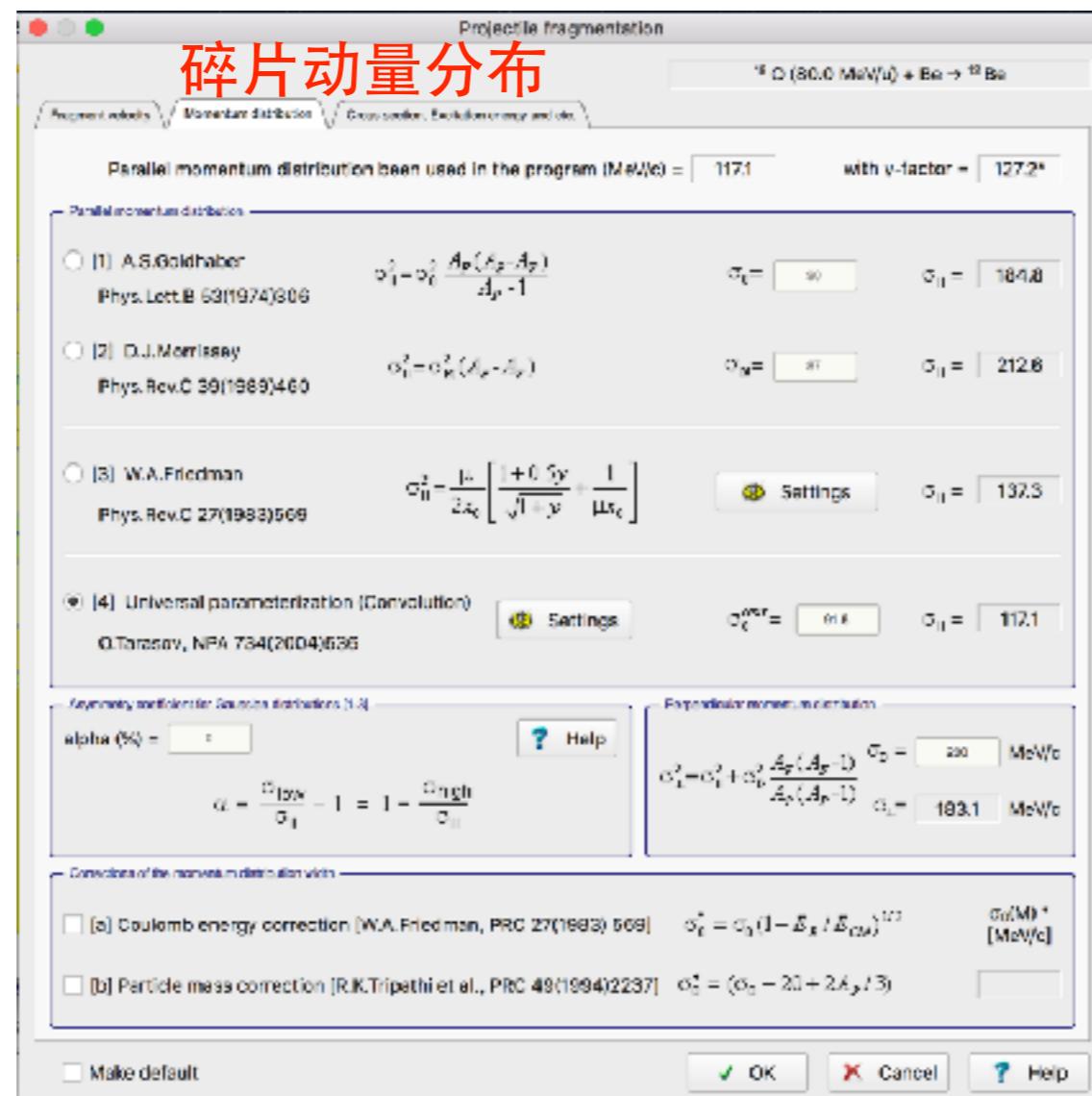
放射性束的产生



放射性束的产生



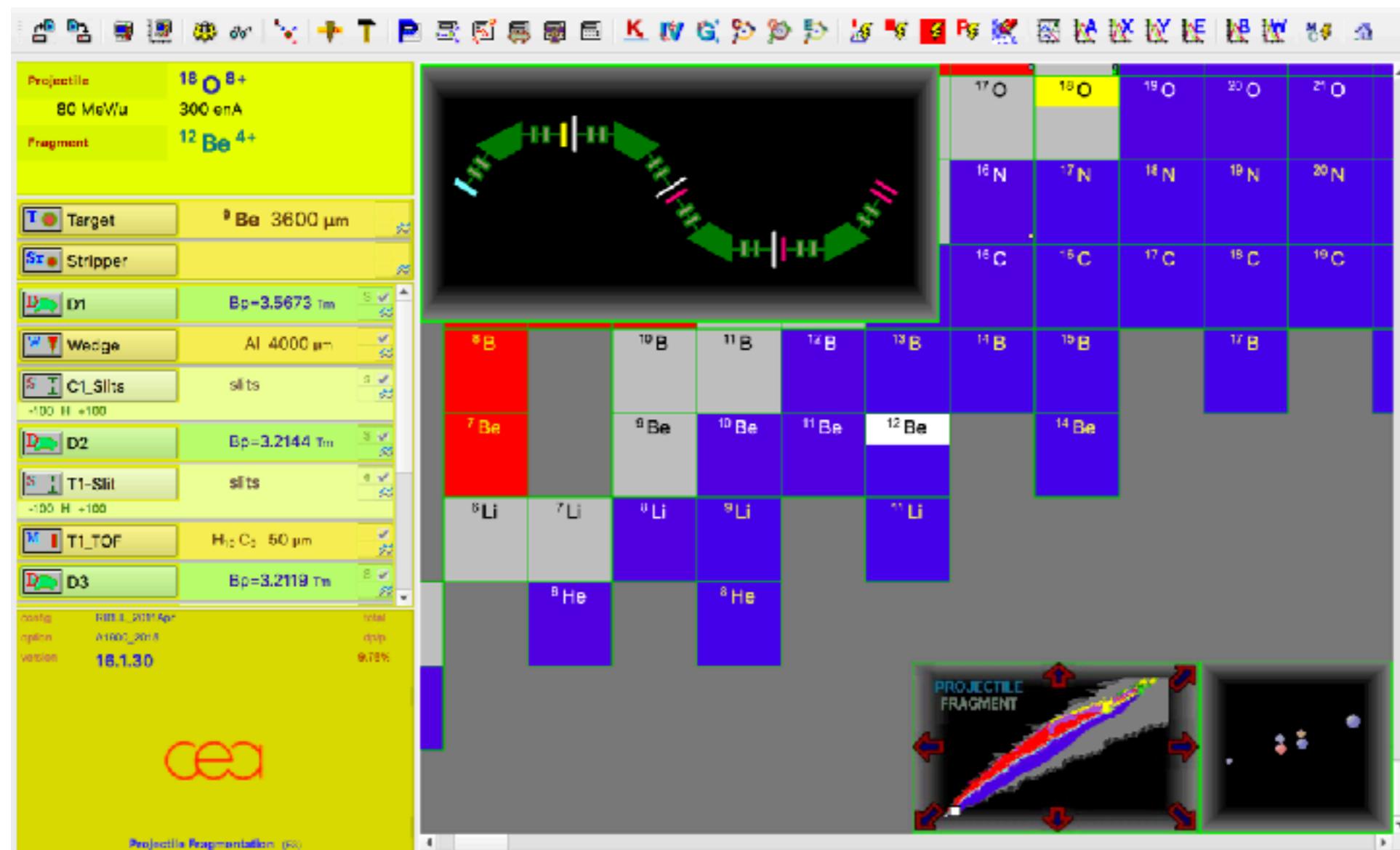
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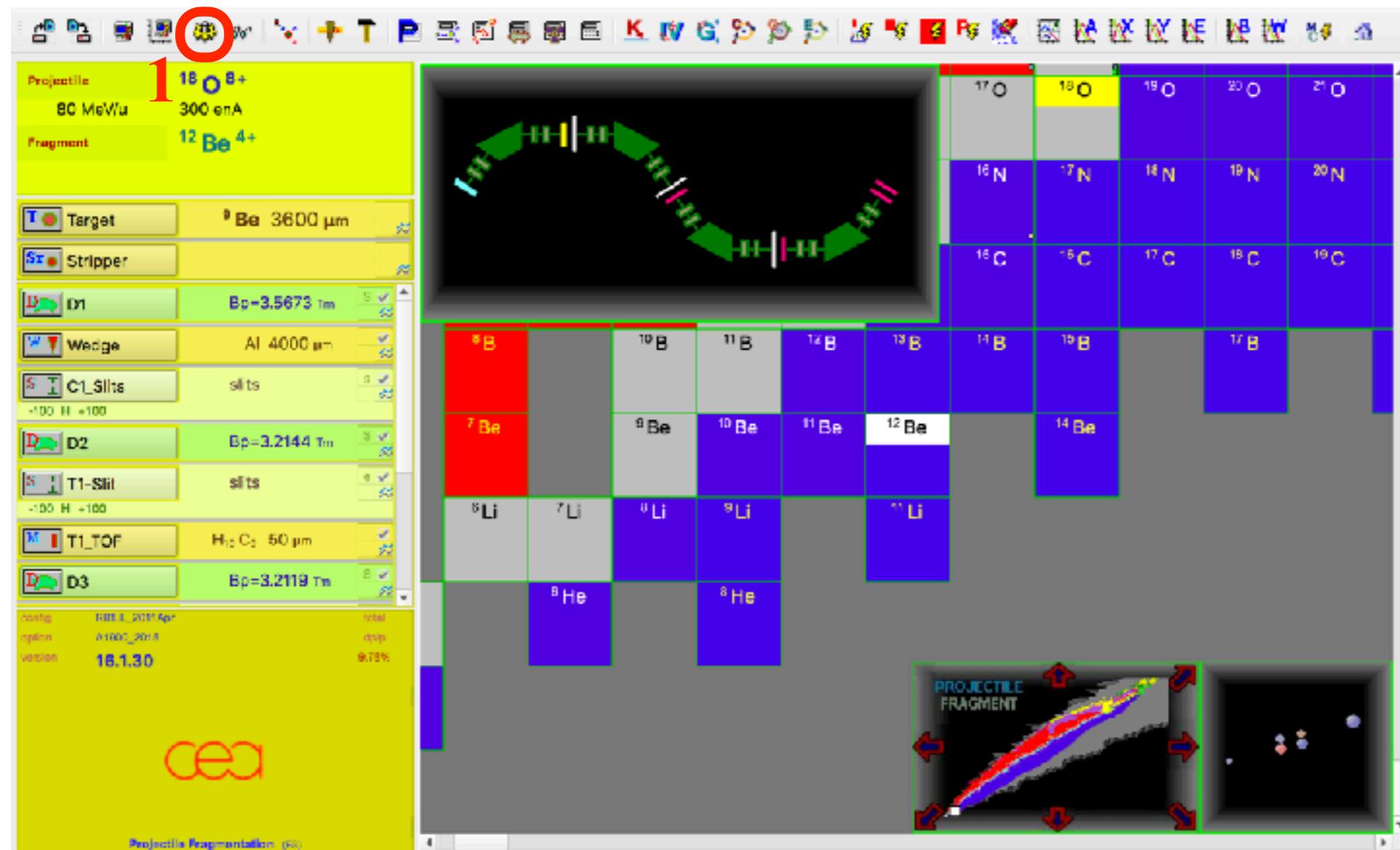
放射性束的产生



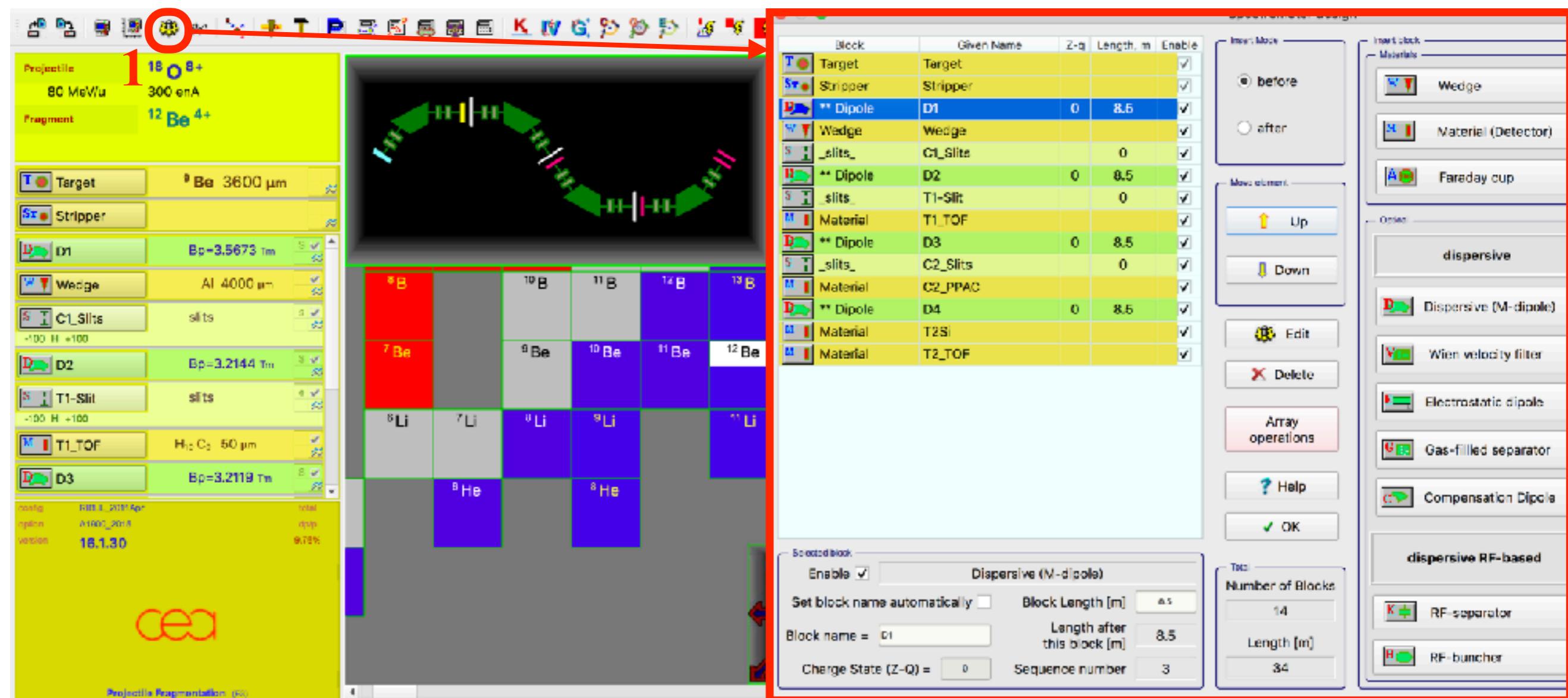
碎片分离器：HIRFL-RIBLL1



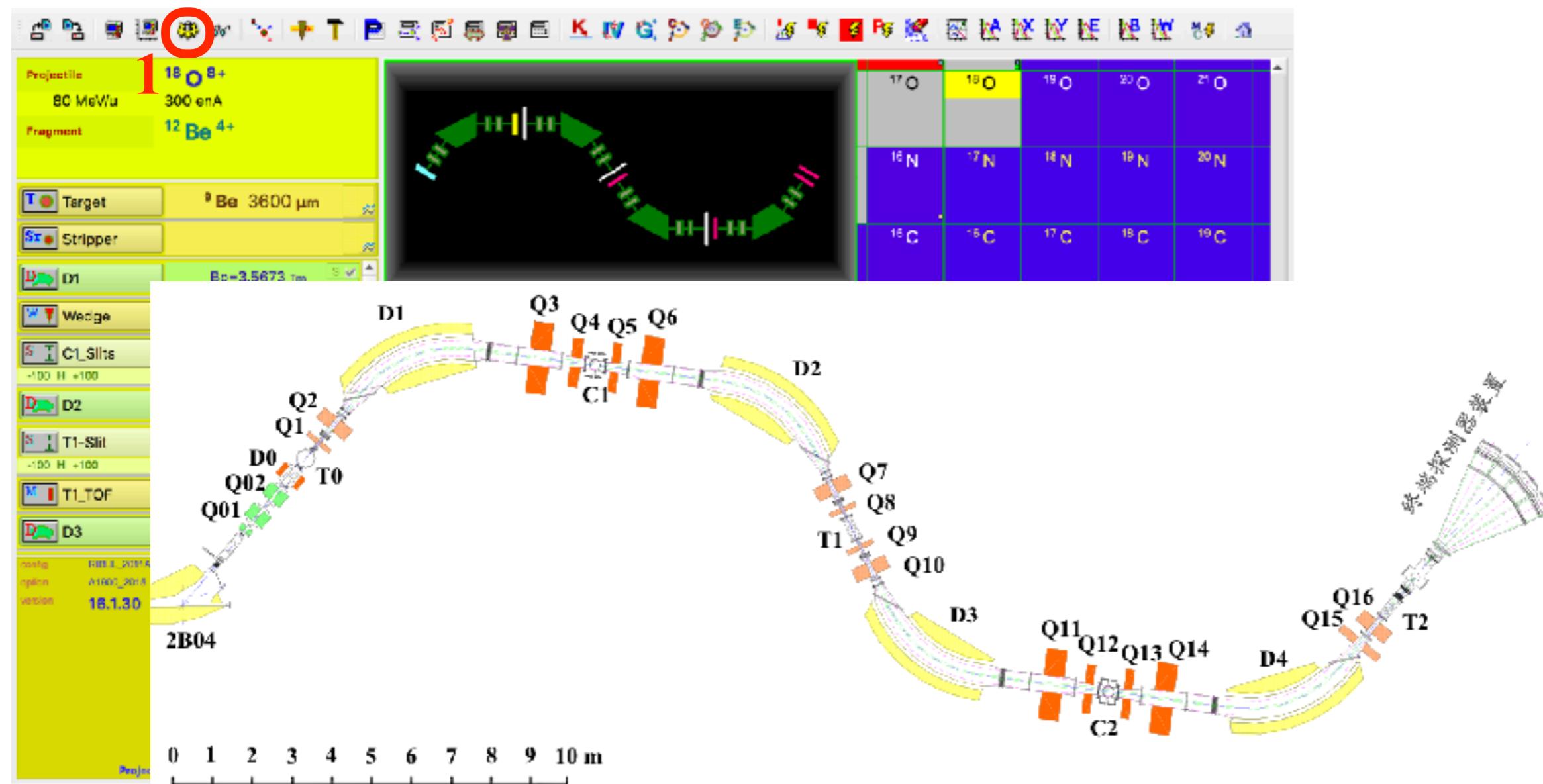
碎片分离器：HIRFL-RIBLL1



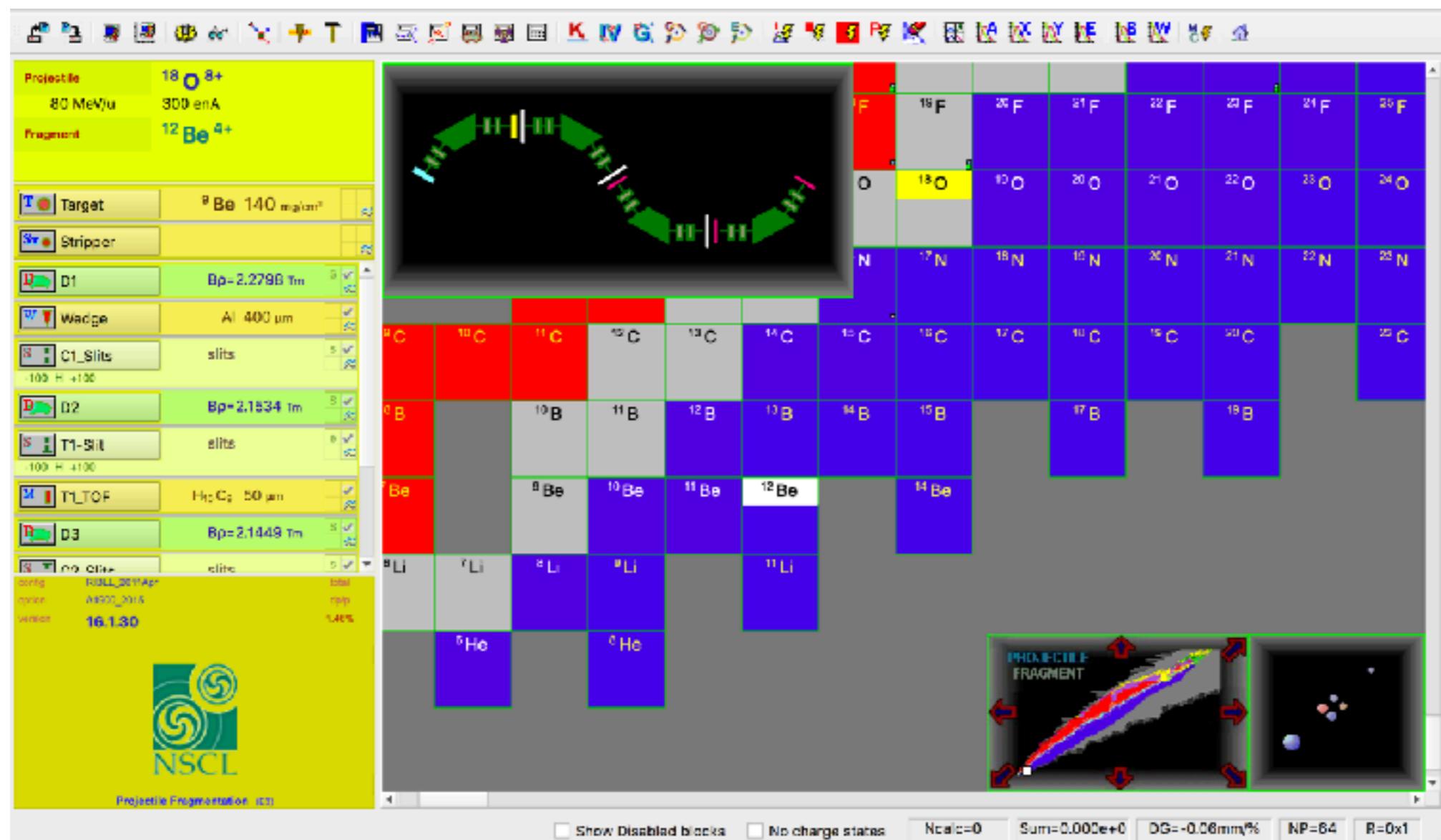
碎片分离器：HIRFL-RIBLL1



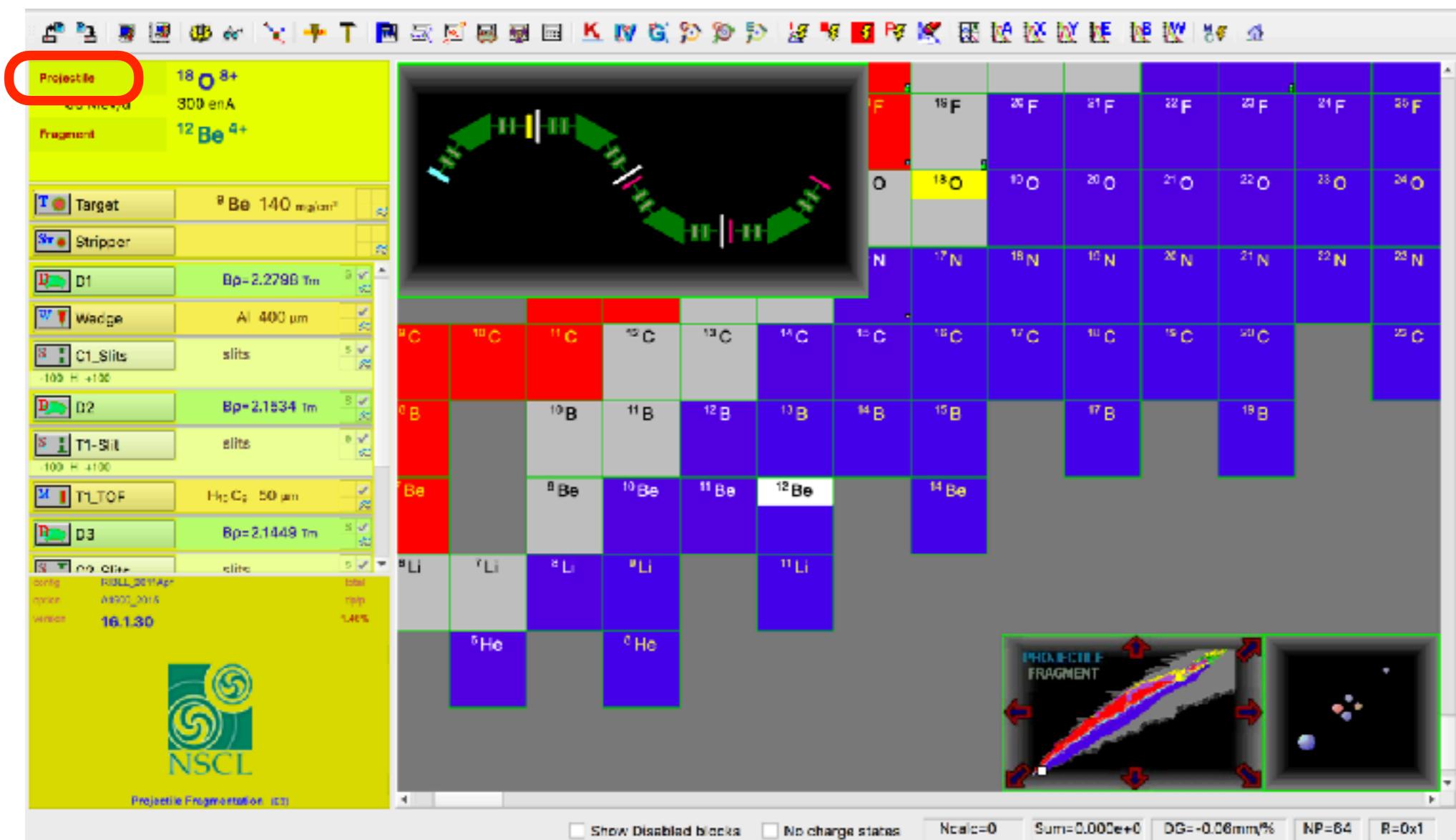
碎片分离器：HIRFL-RIBLL1



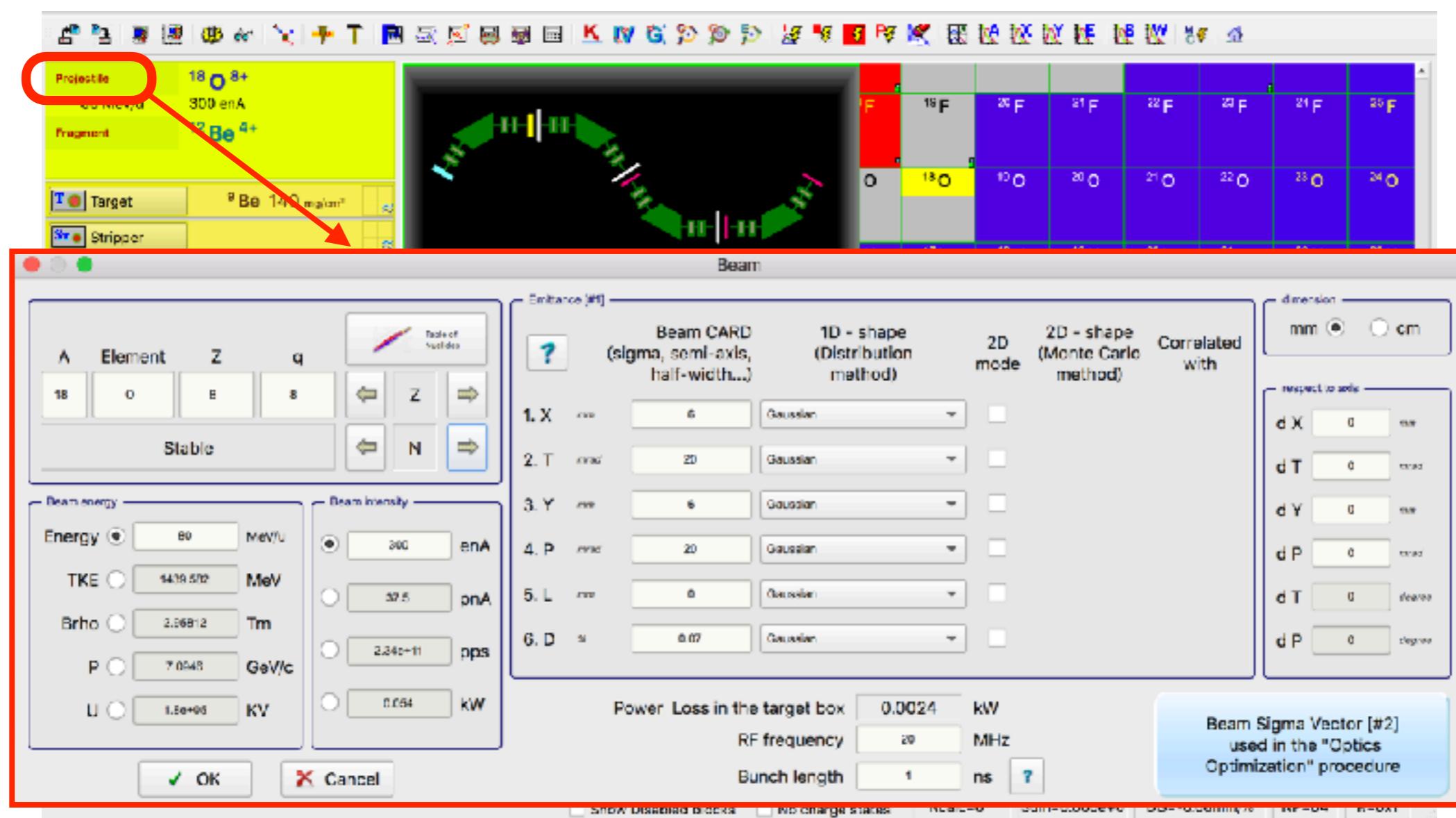
初级束设置



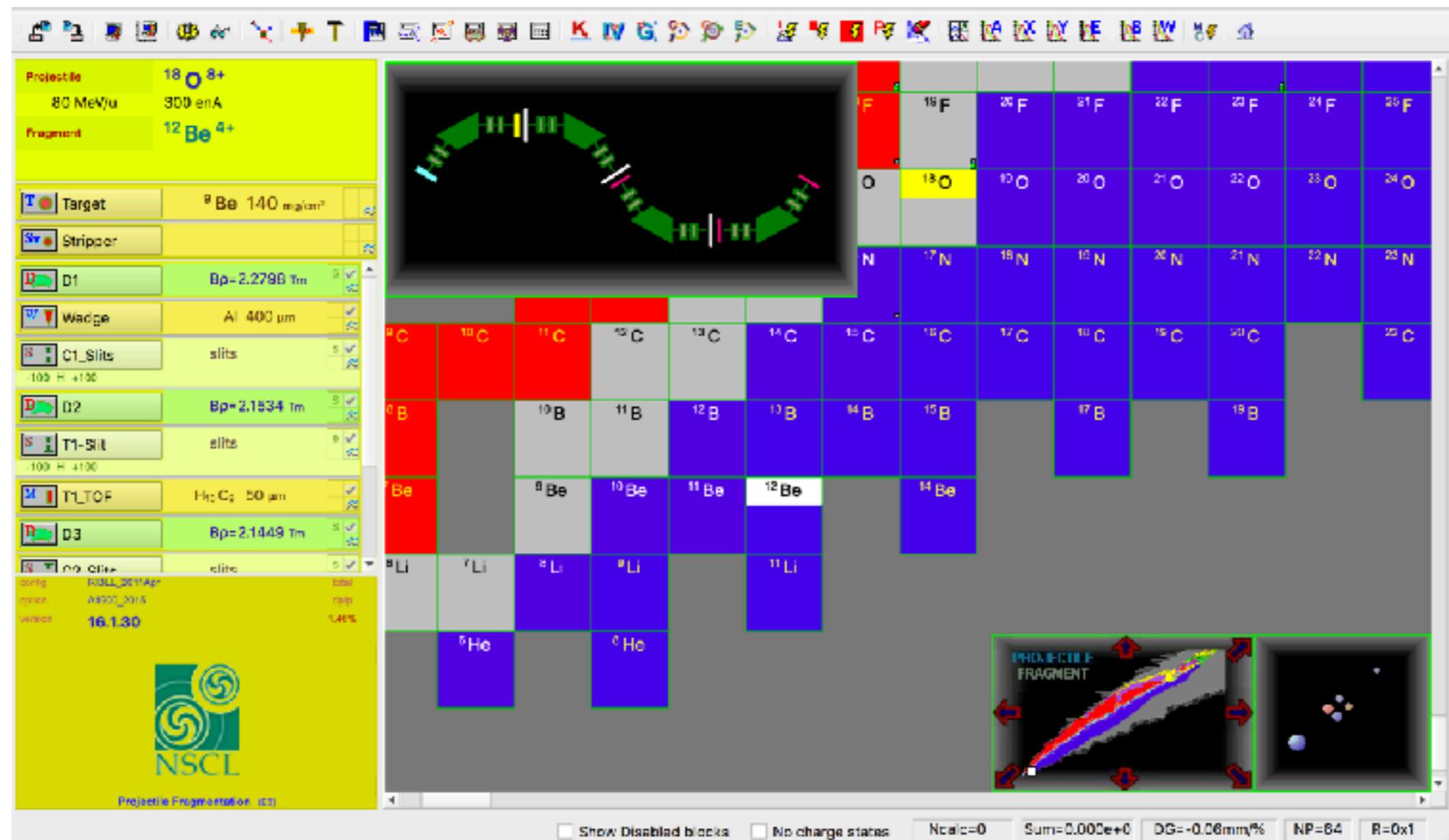
初级束设置



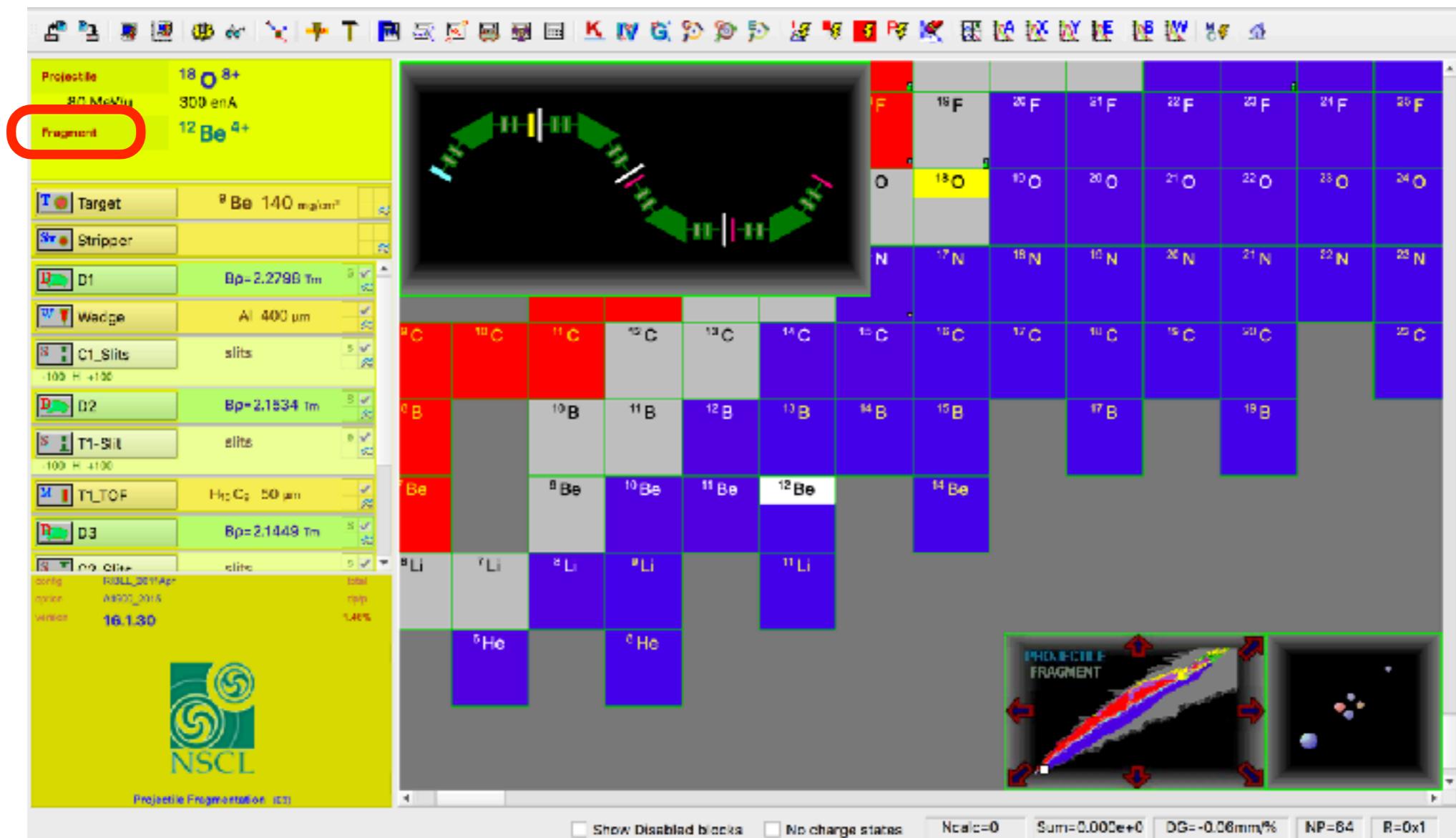
初级束设置



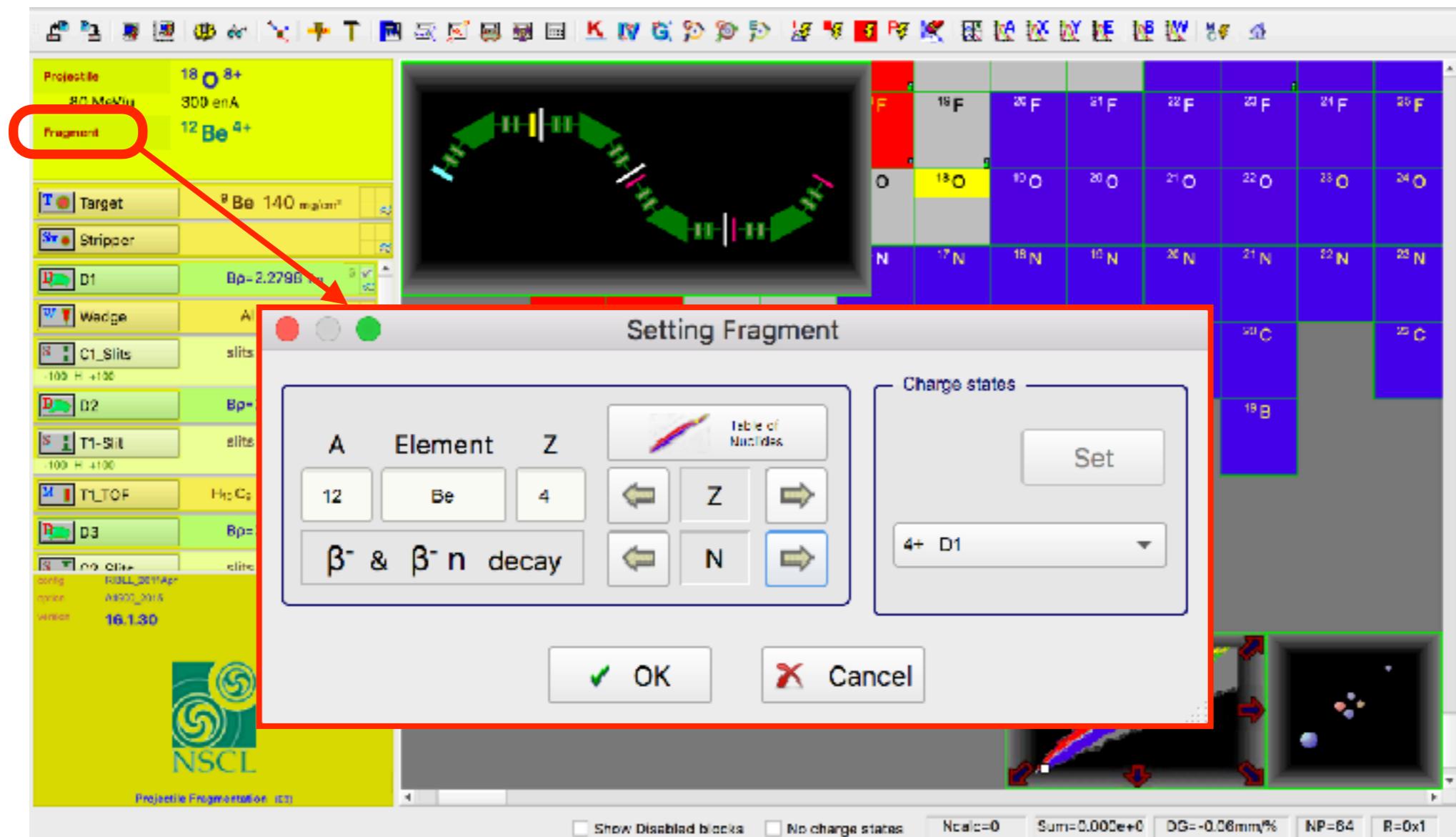
次级束设置



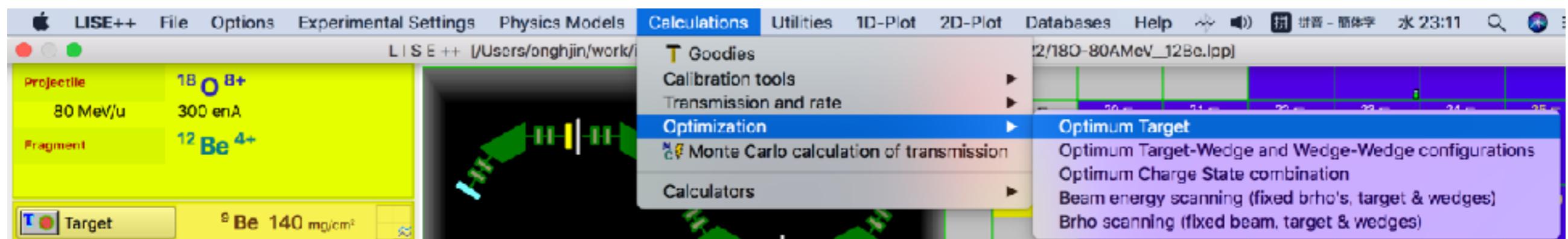
次级束设置



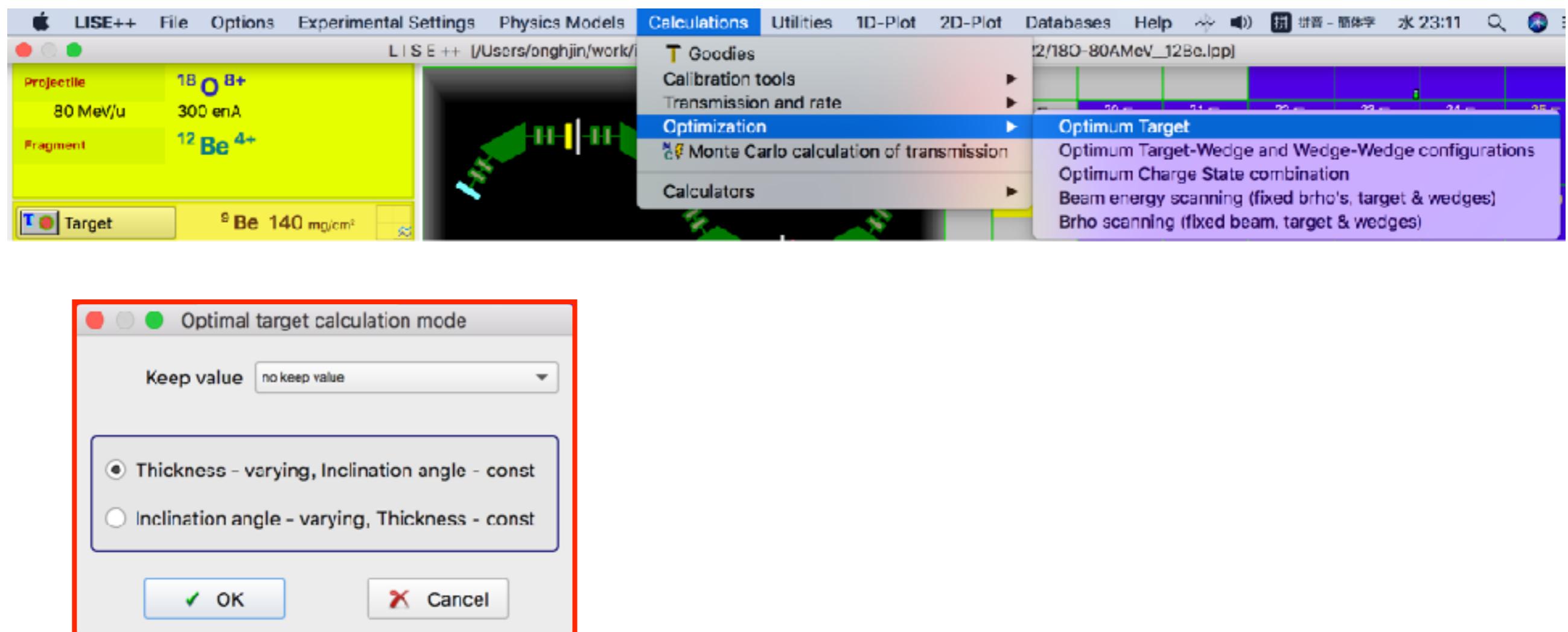
次级束设置



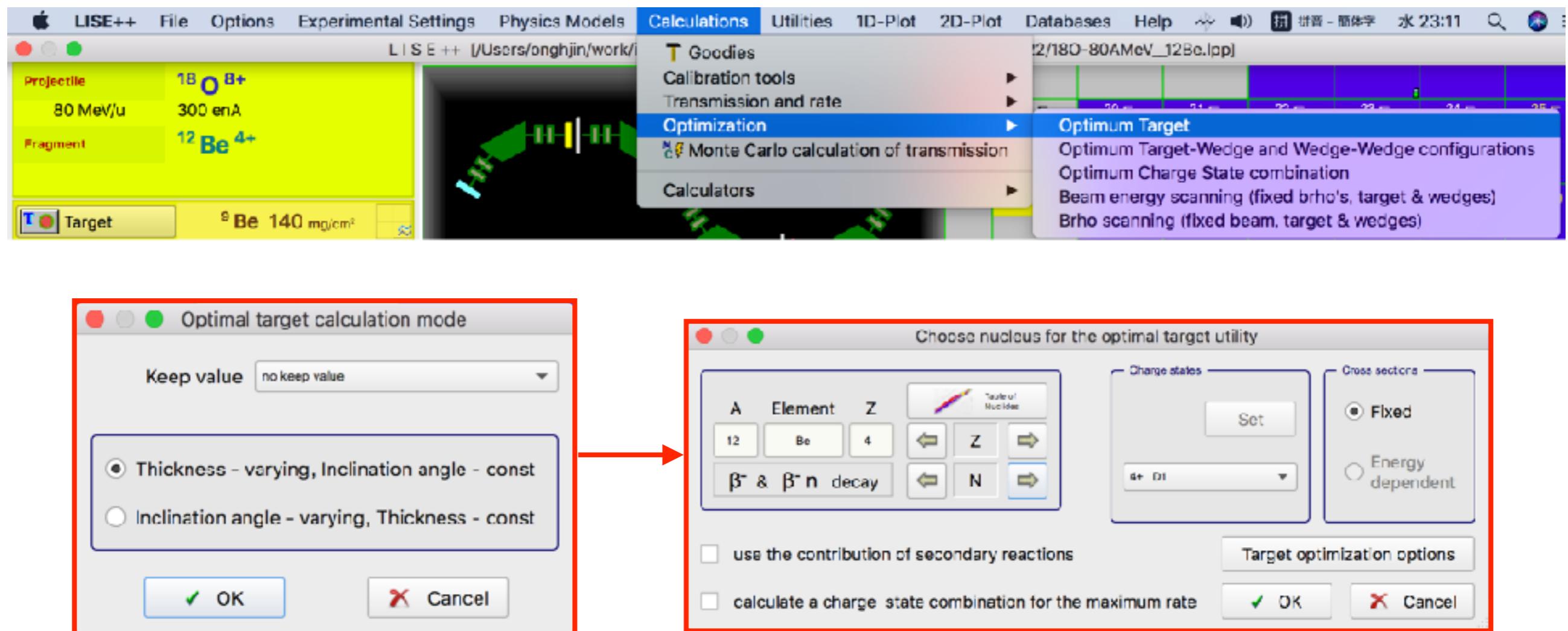
优化初级靶厚



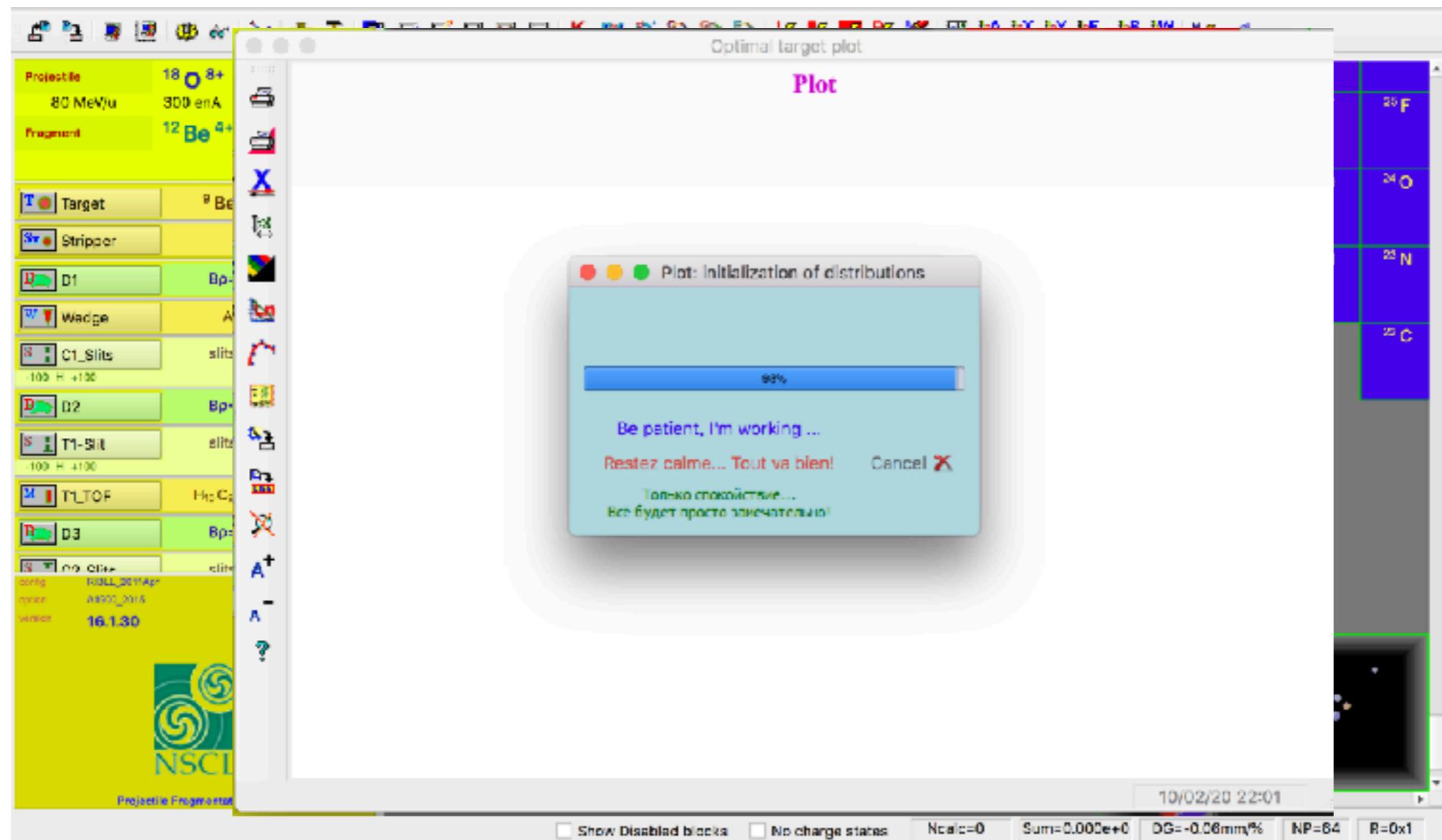
优化初级靶厚



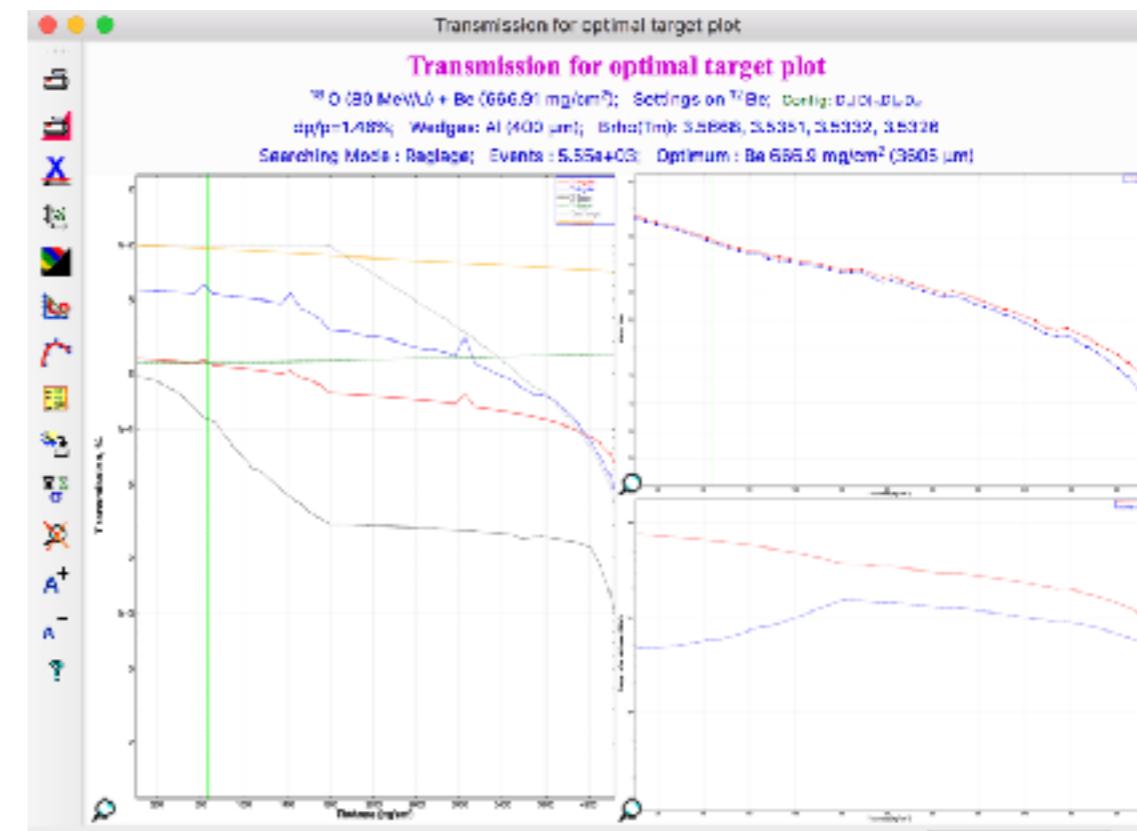
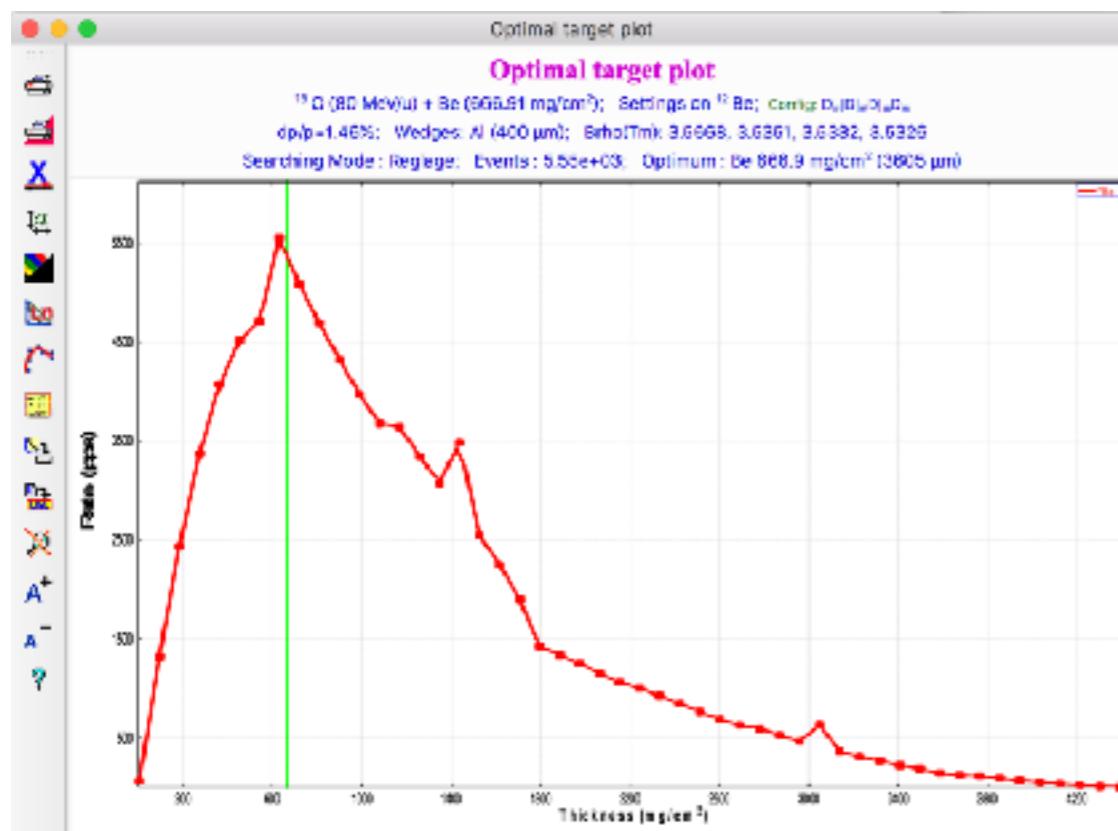
优化初级靶厚



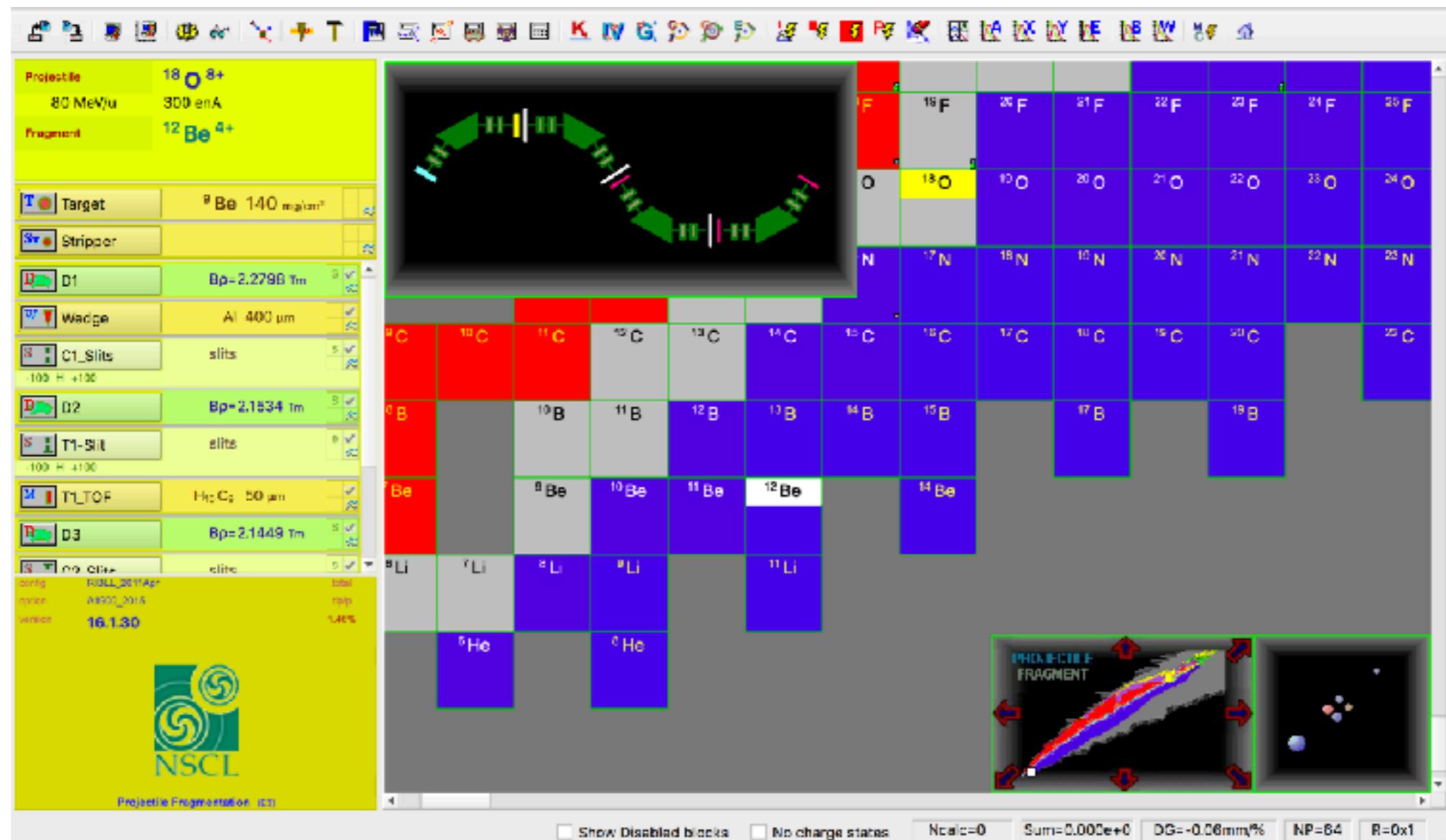
优化初级靶厚



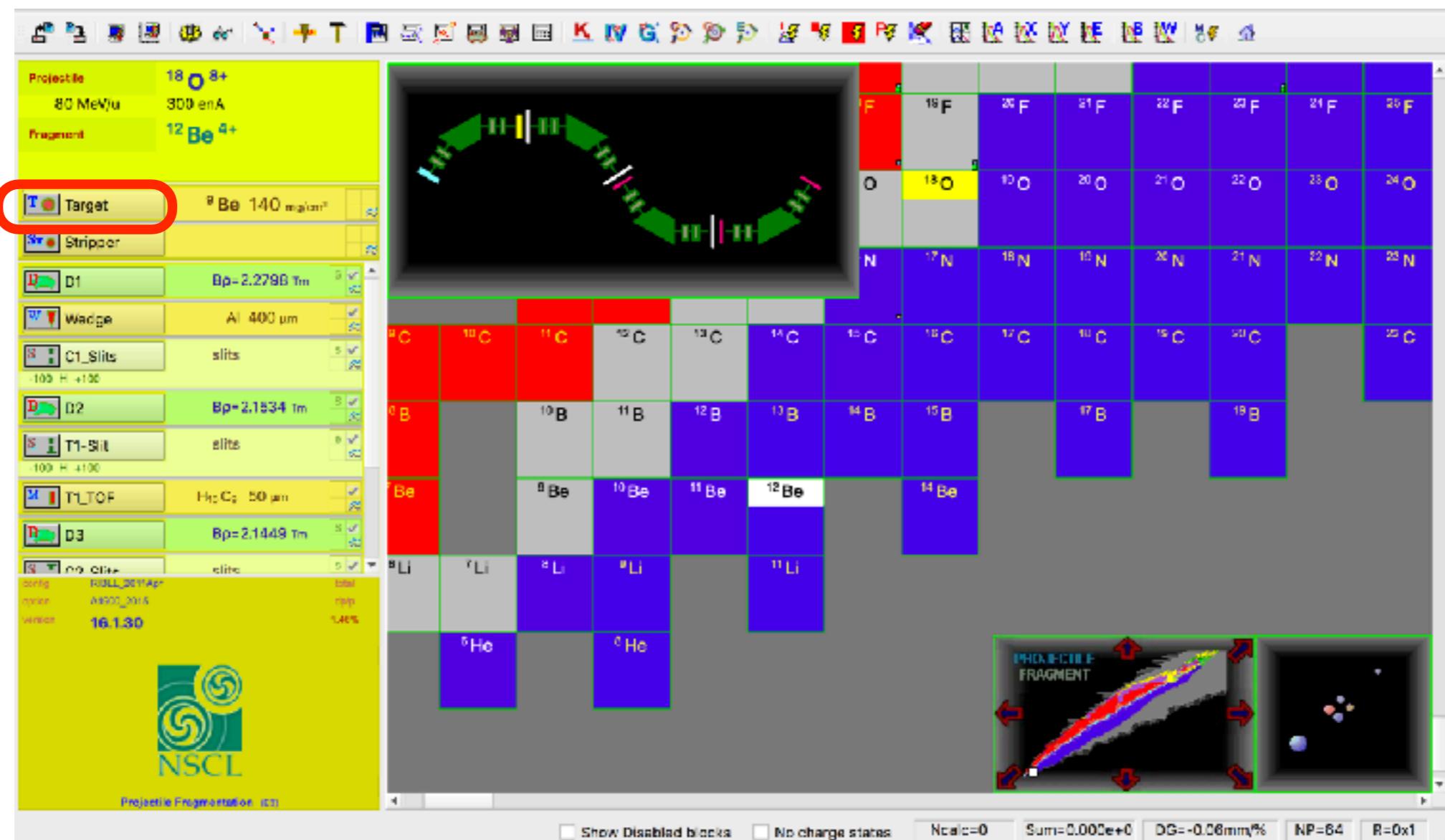
优化初级靶厚



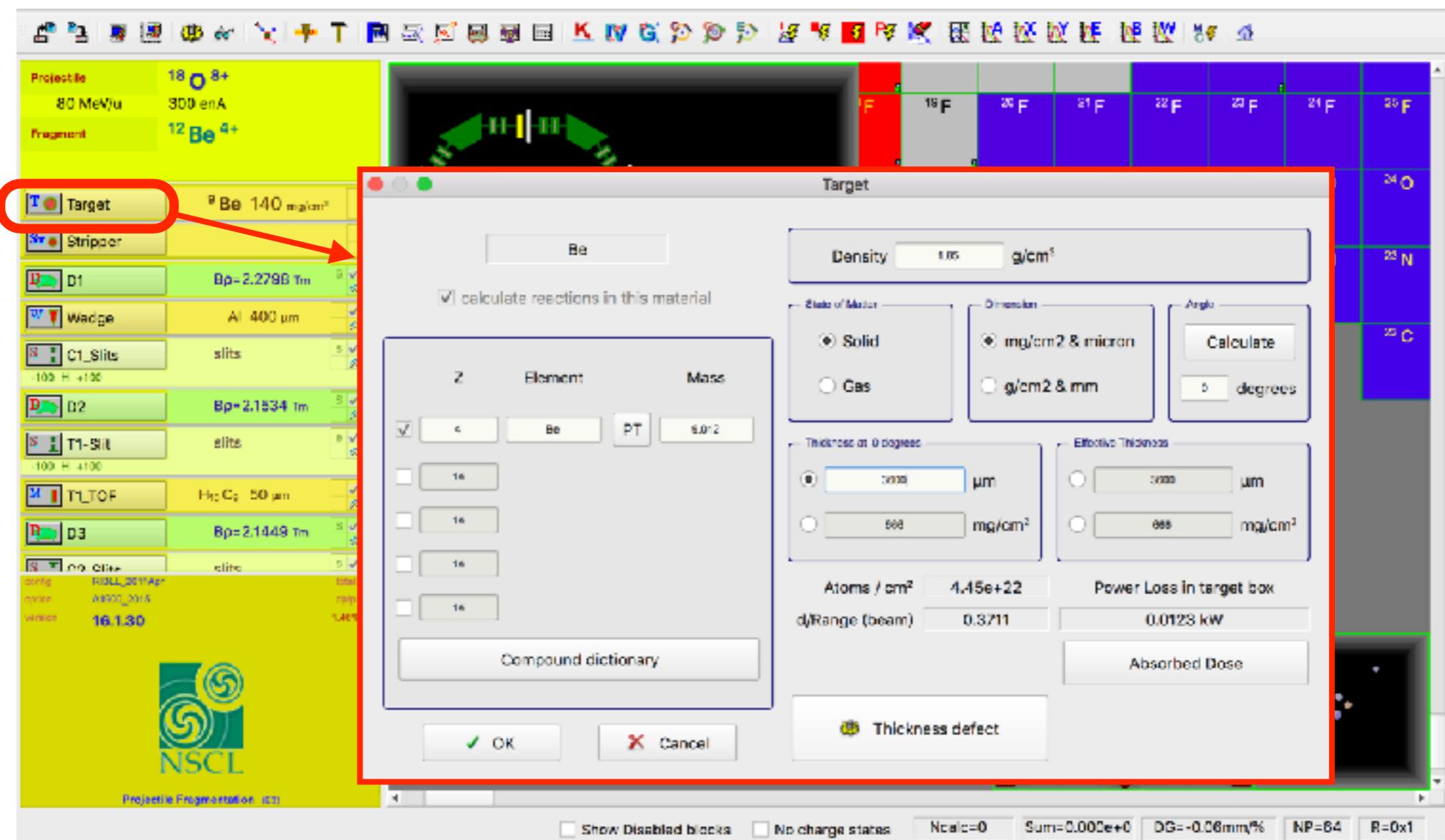
初级靶设置



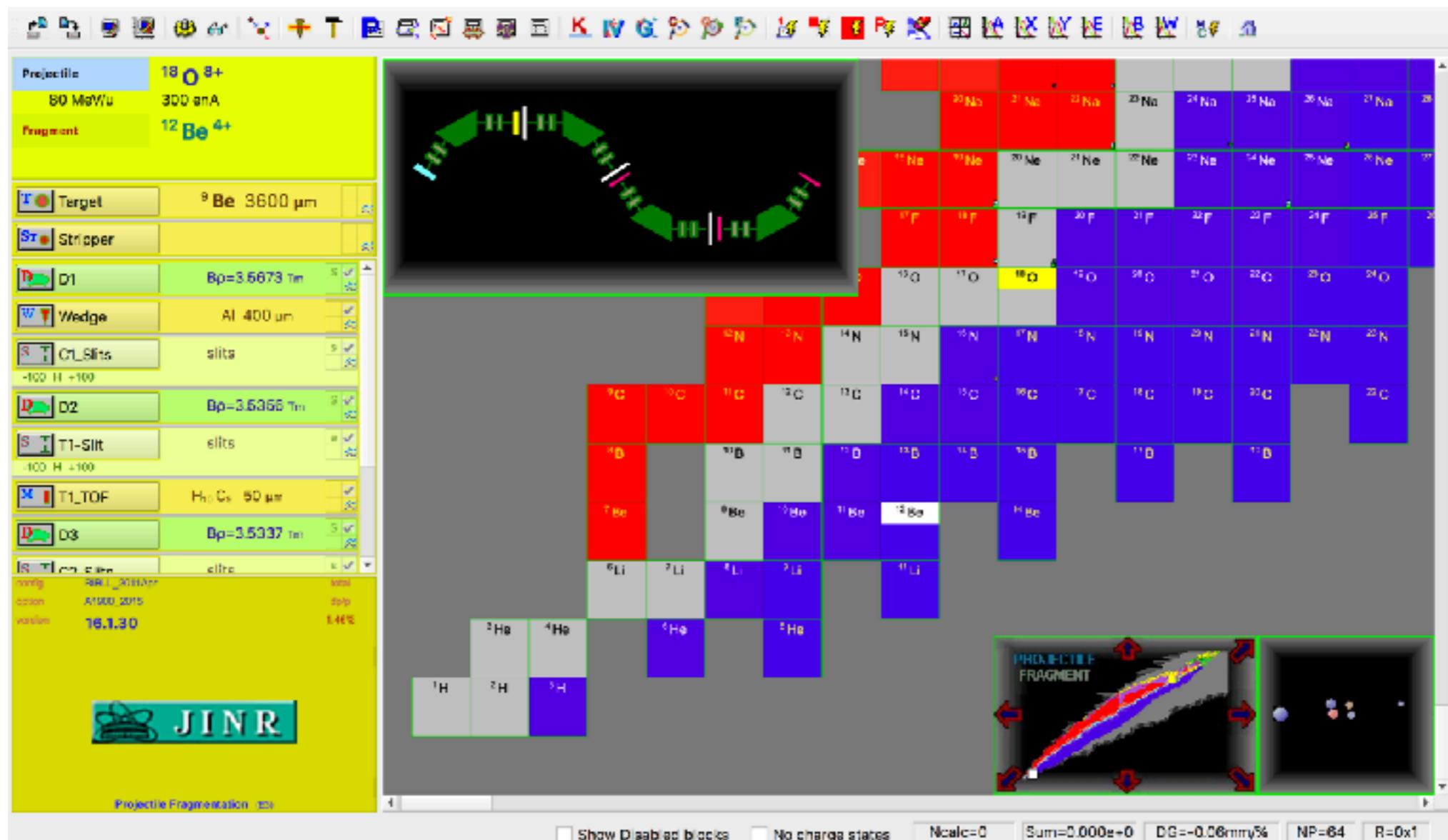
初级靶设置



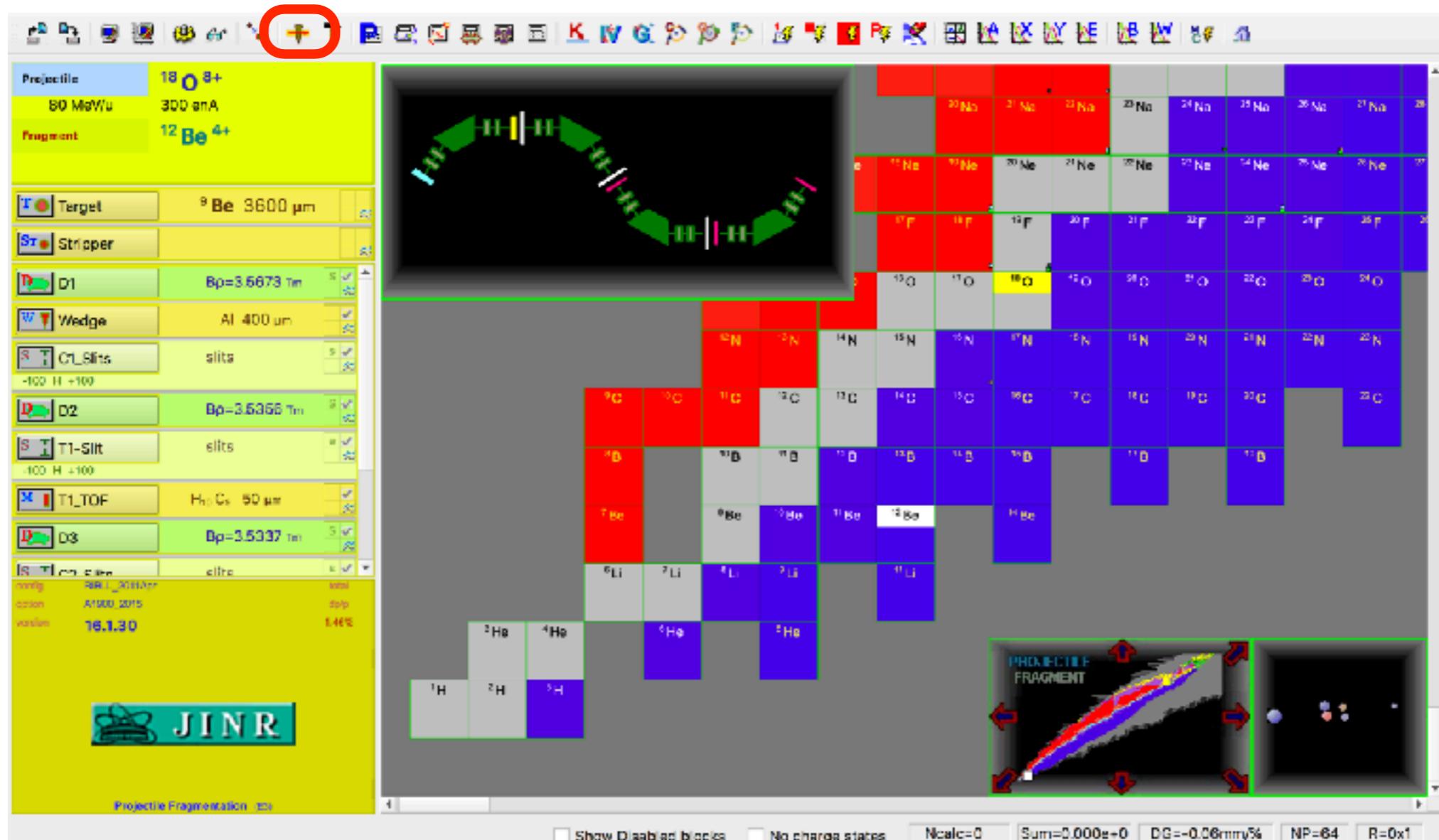
初级靶设置



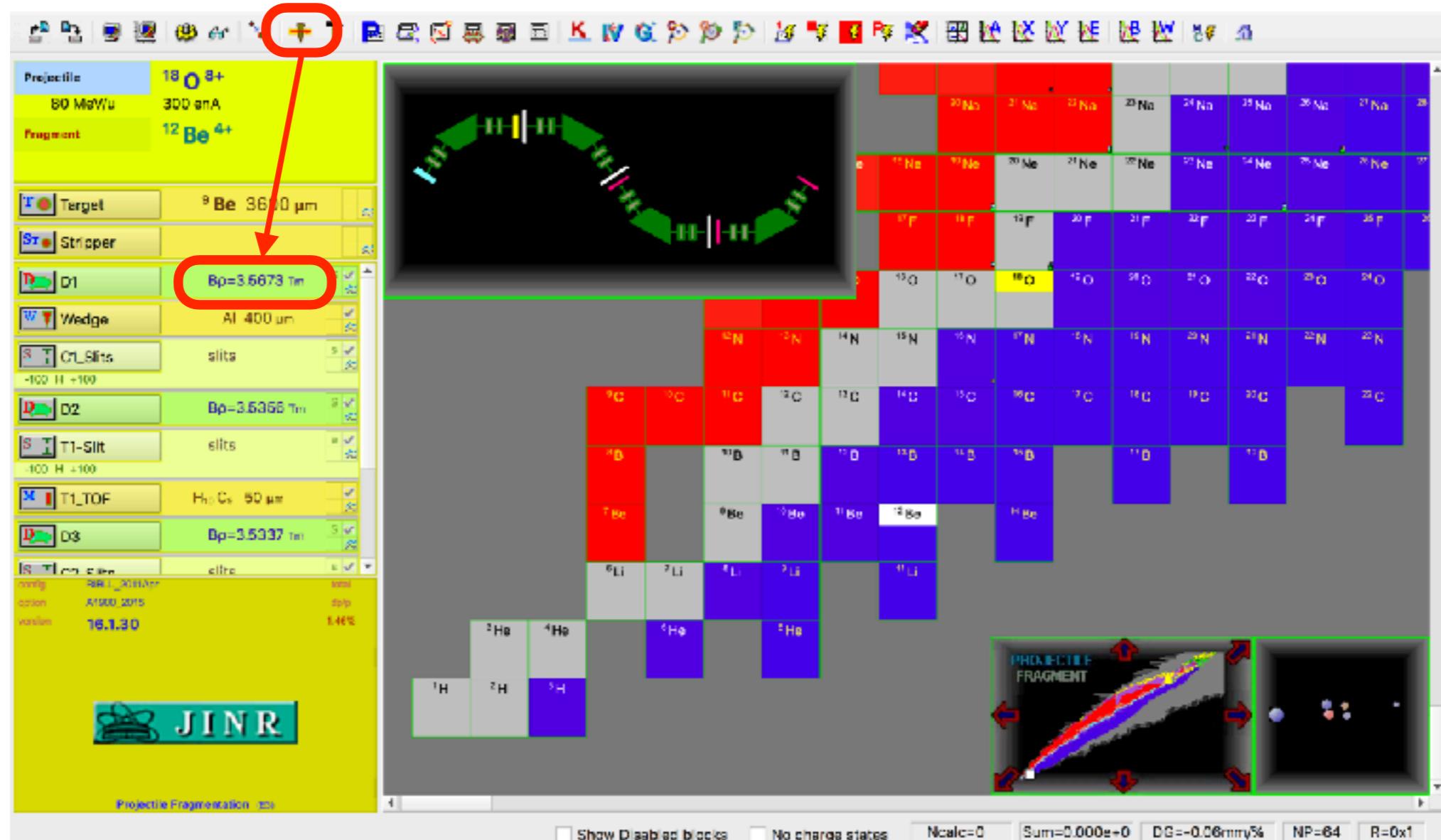
D1设置



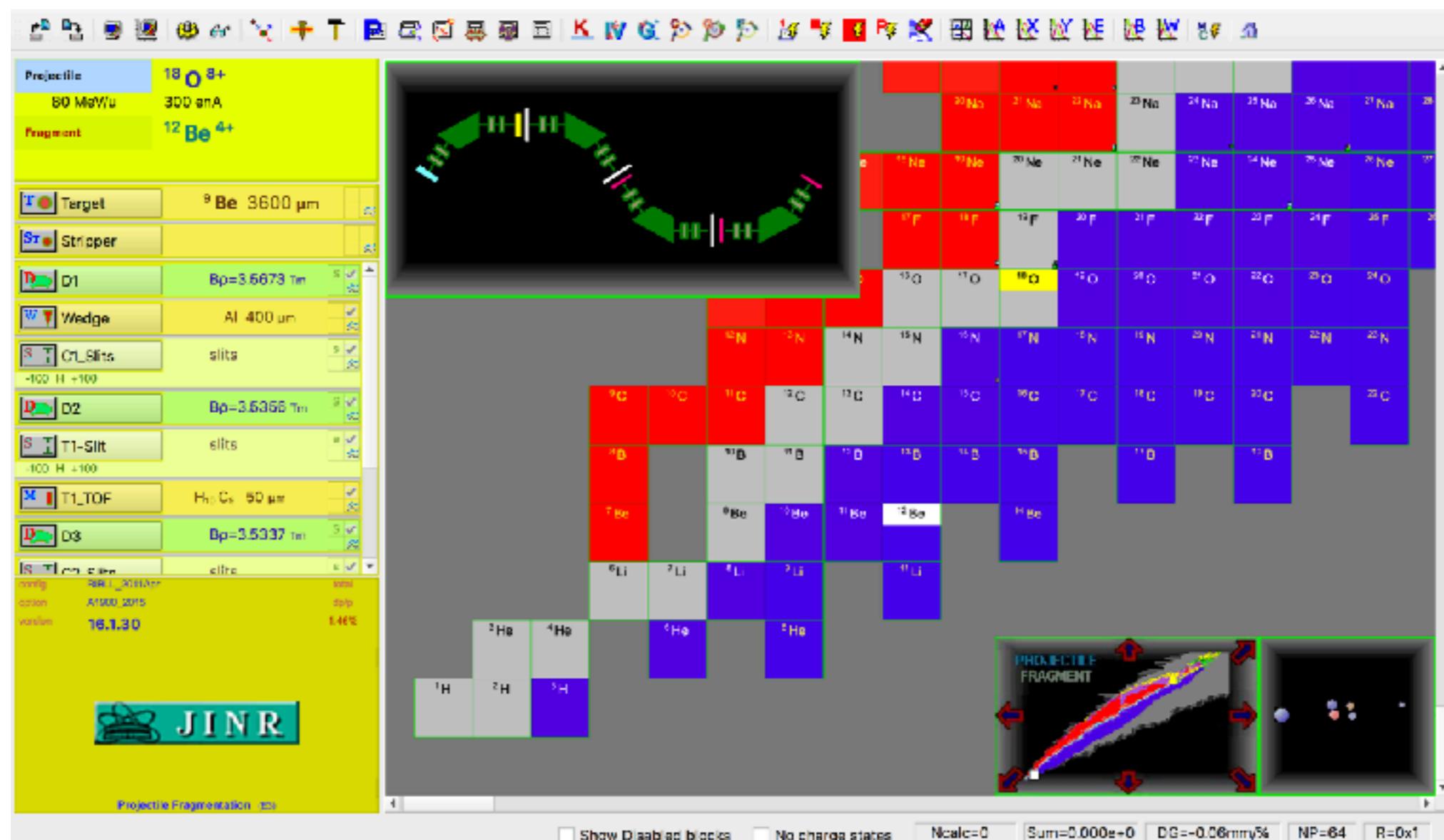
D1设置



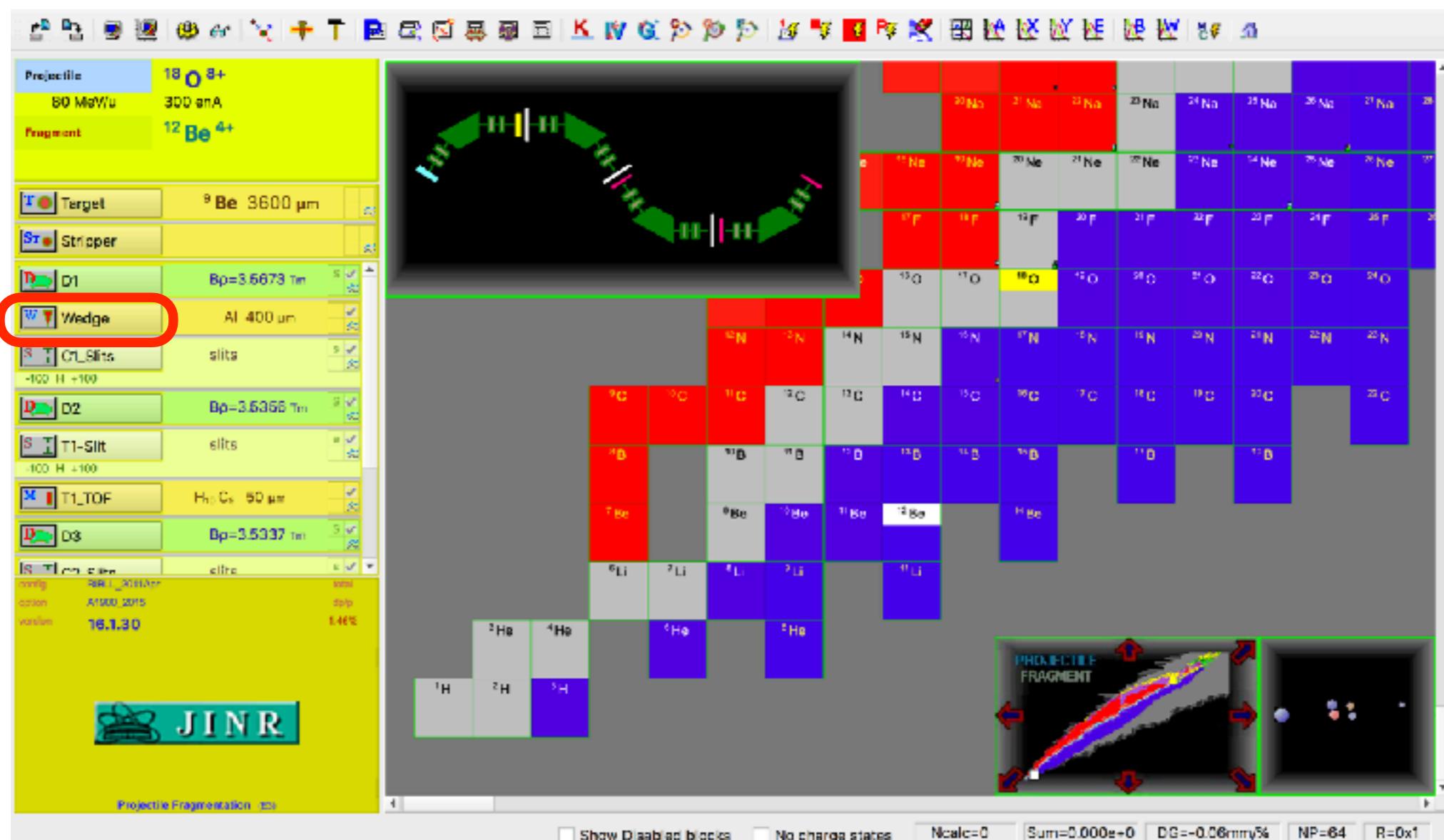
D1设置



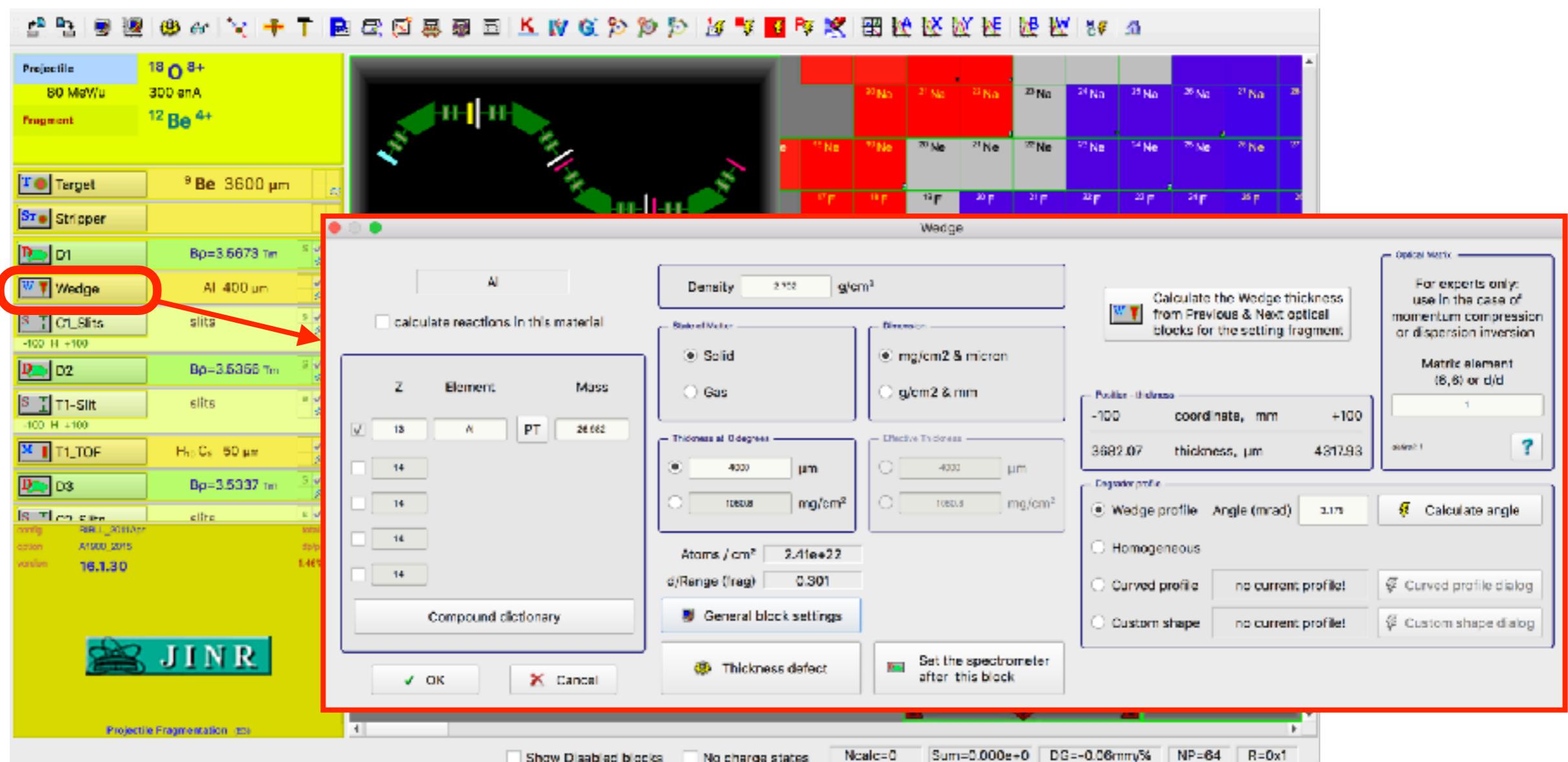
降能器设置



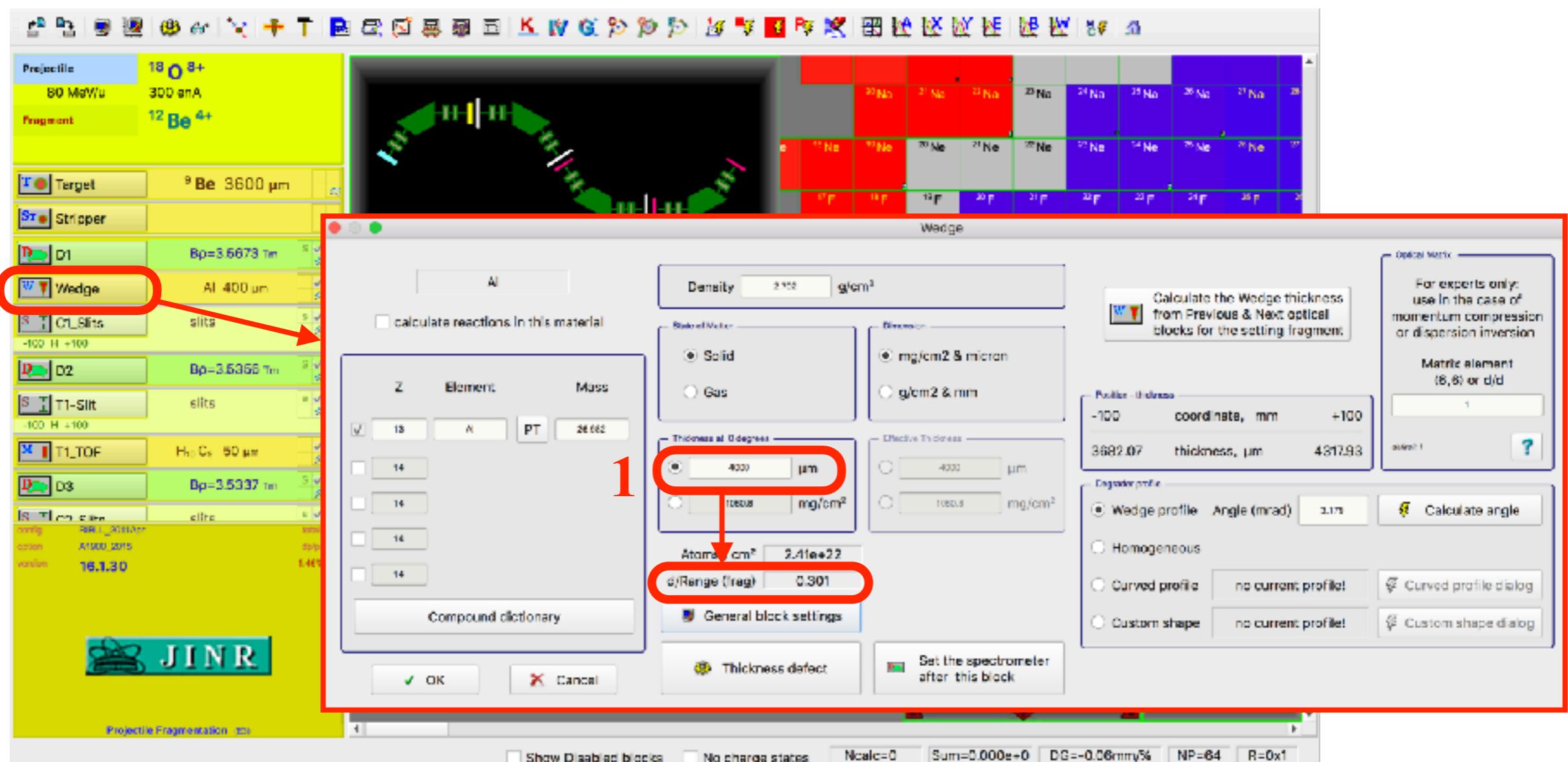
降能器设置



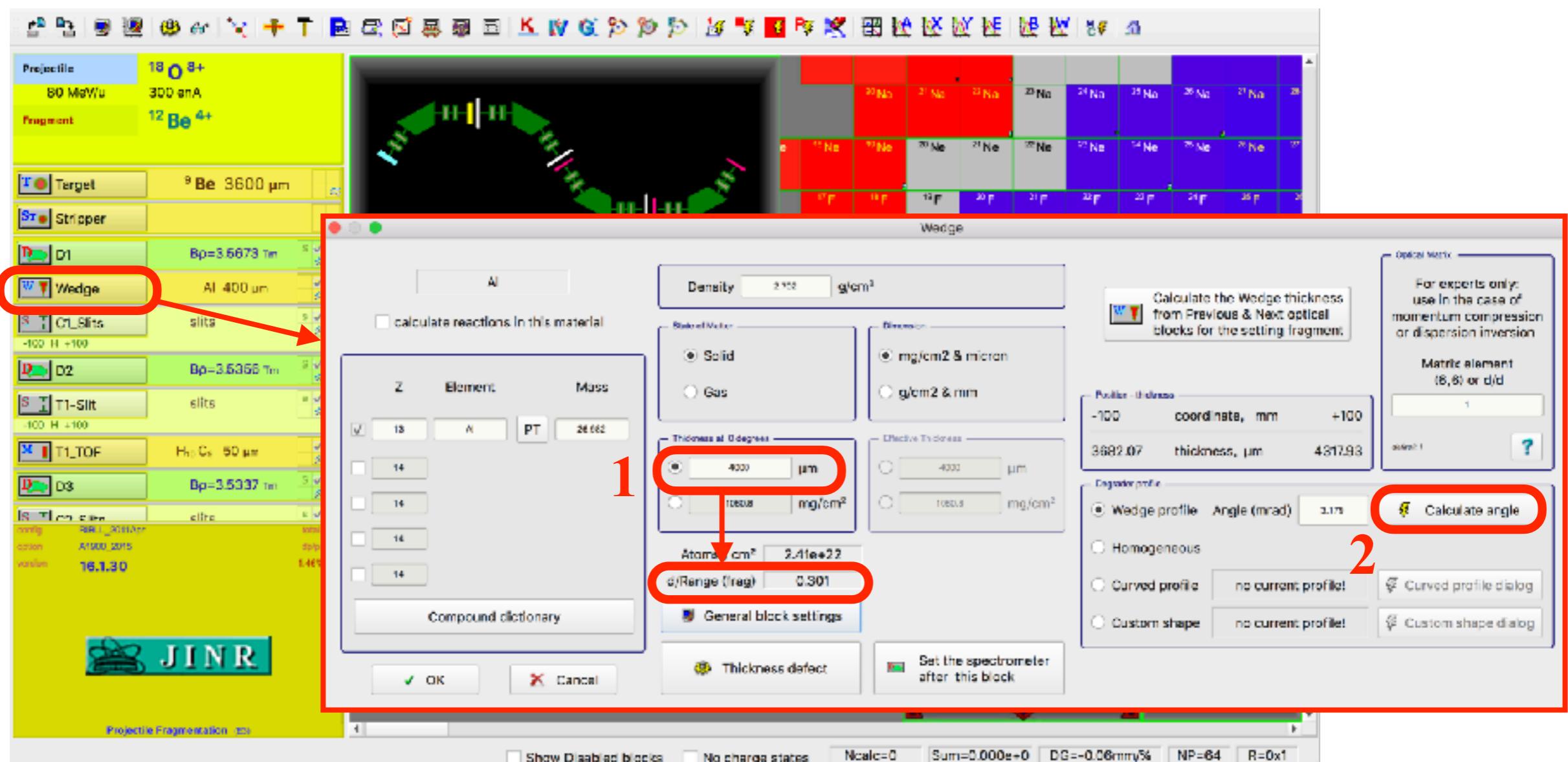
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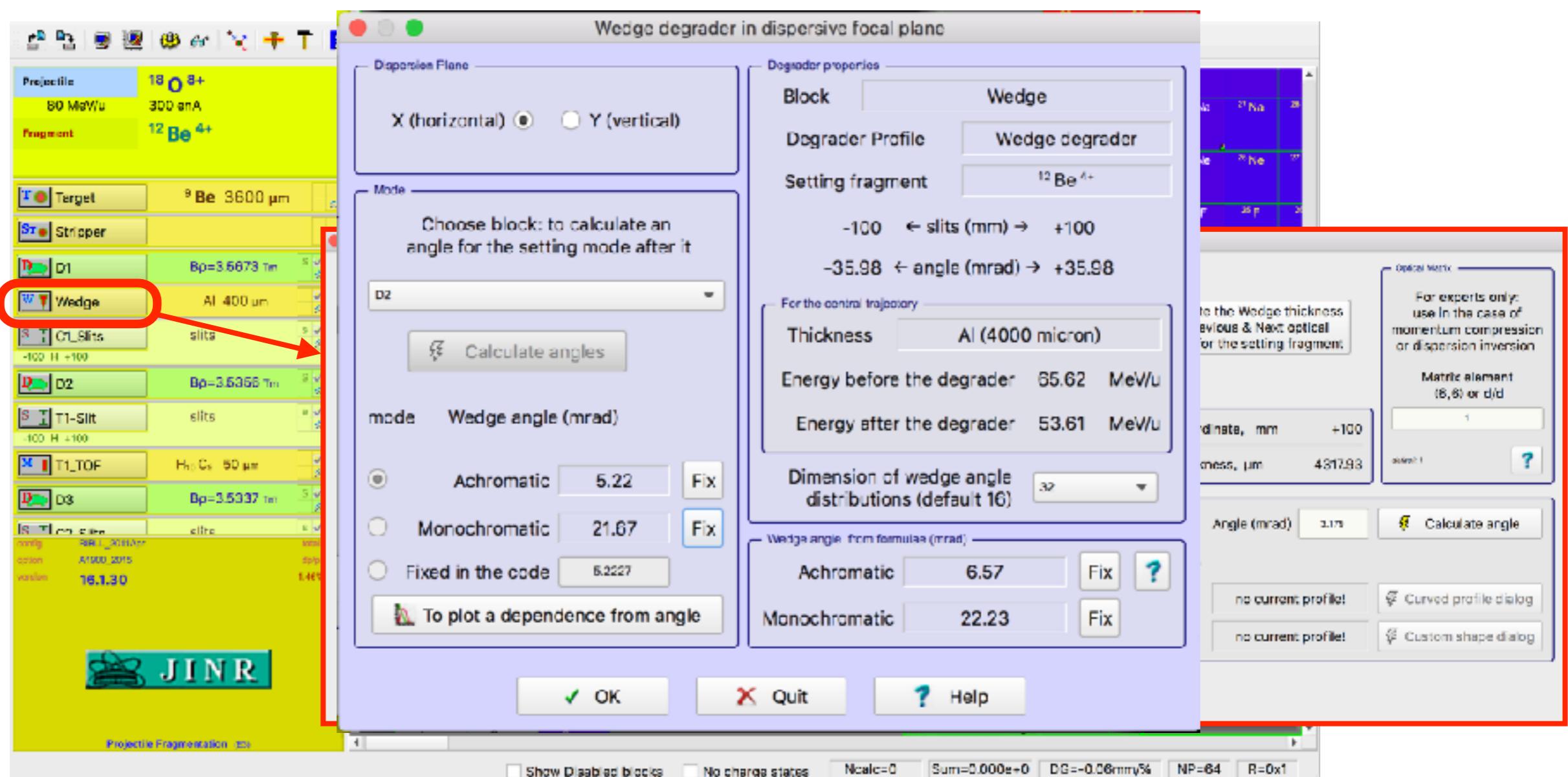
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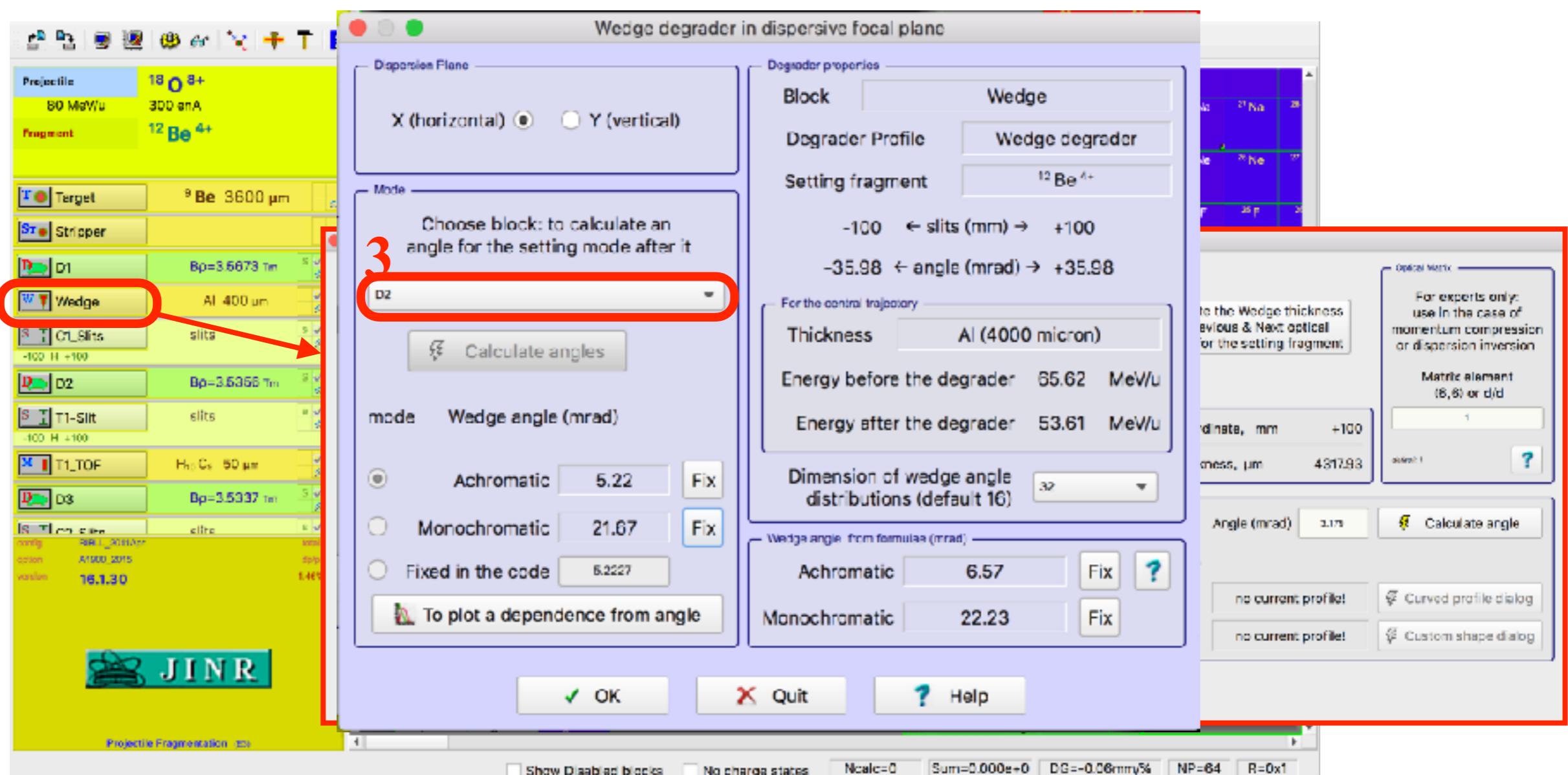
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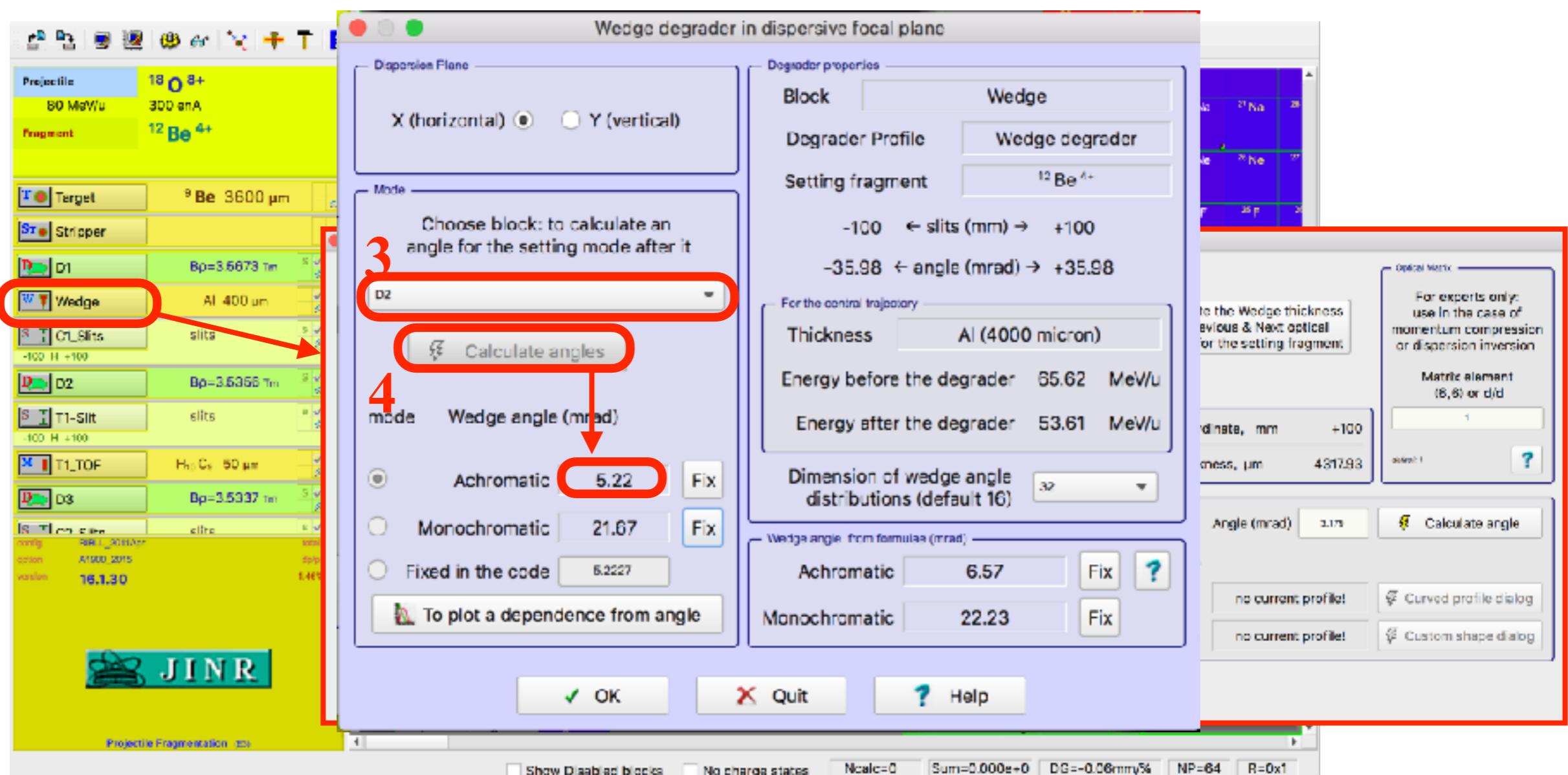
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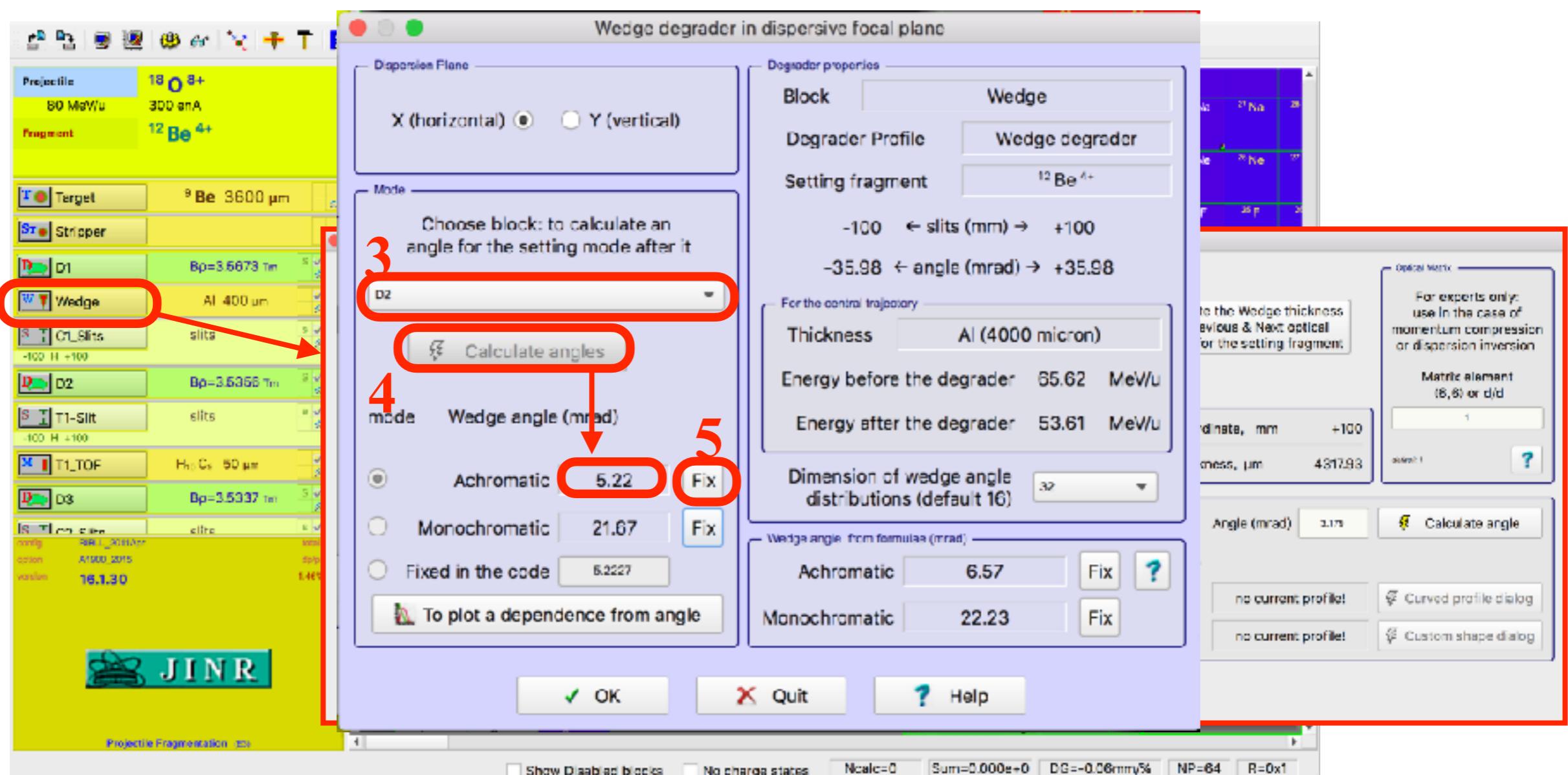
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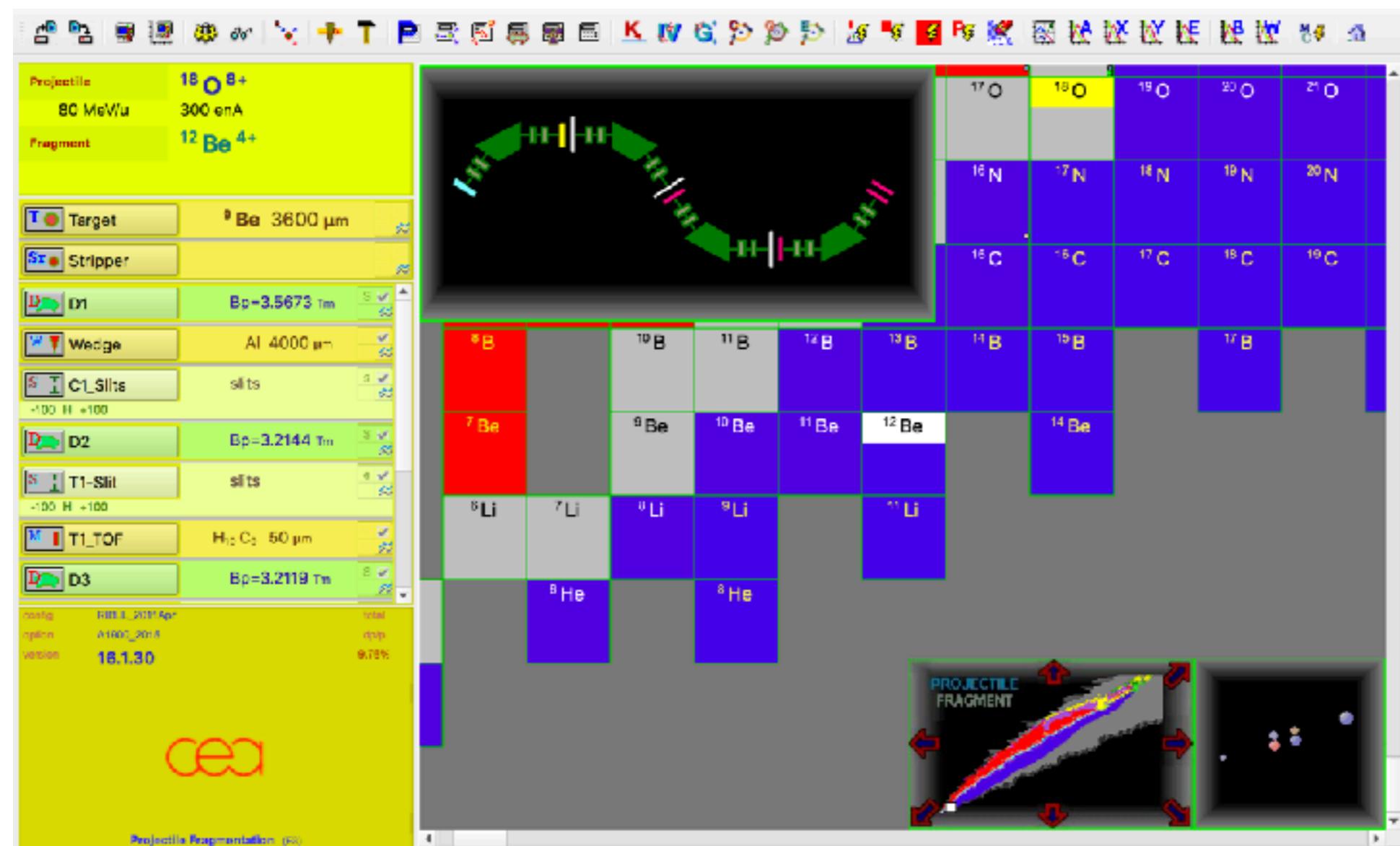
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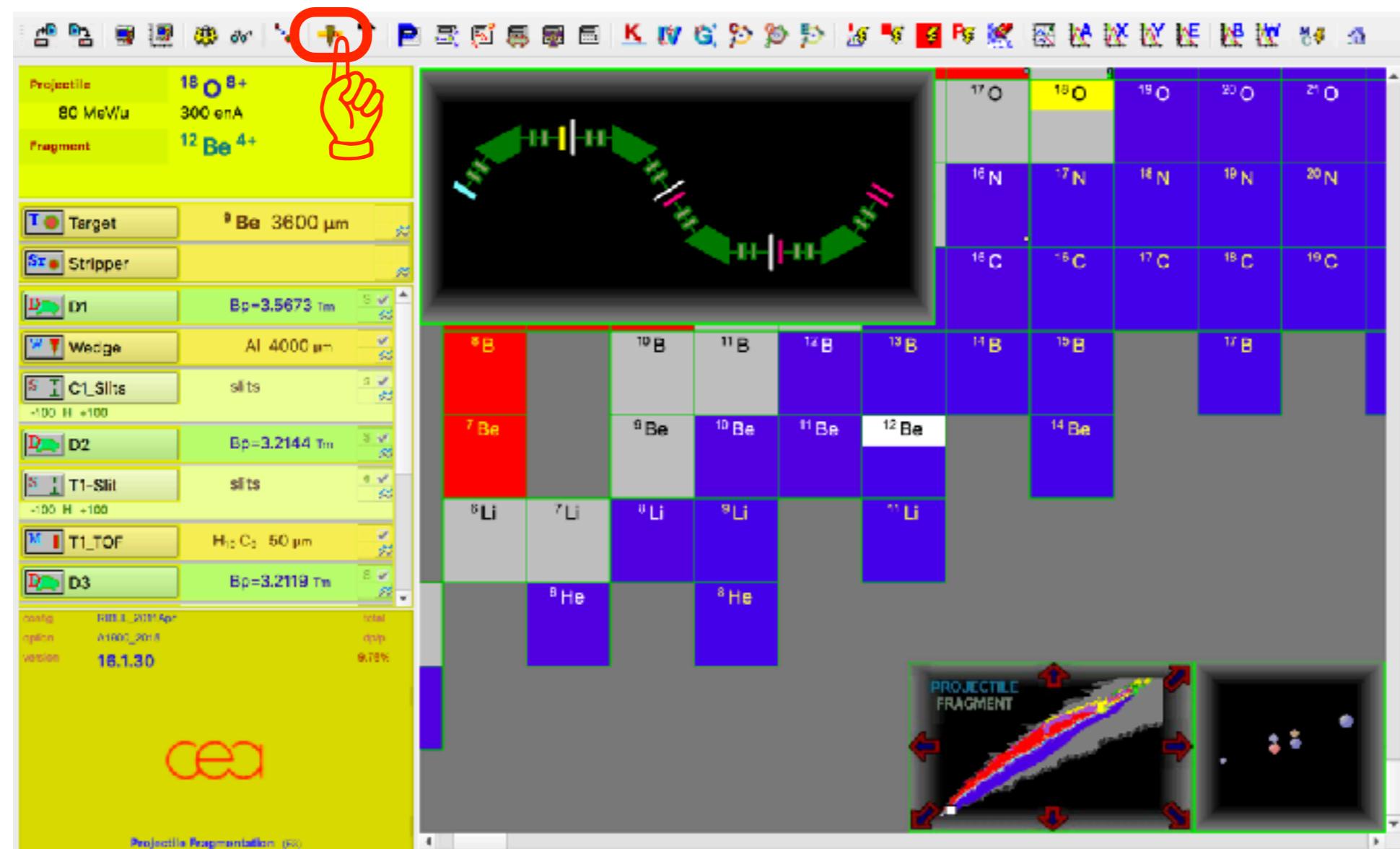
降能器设置



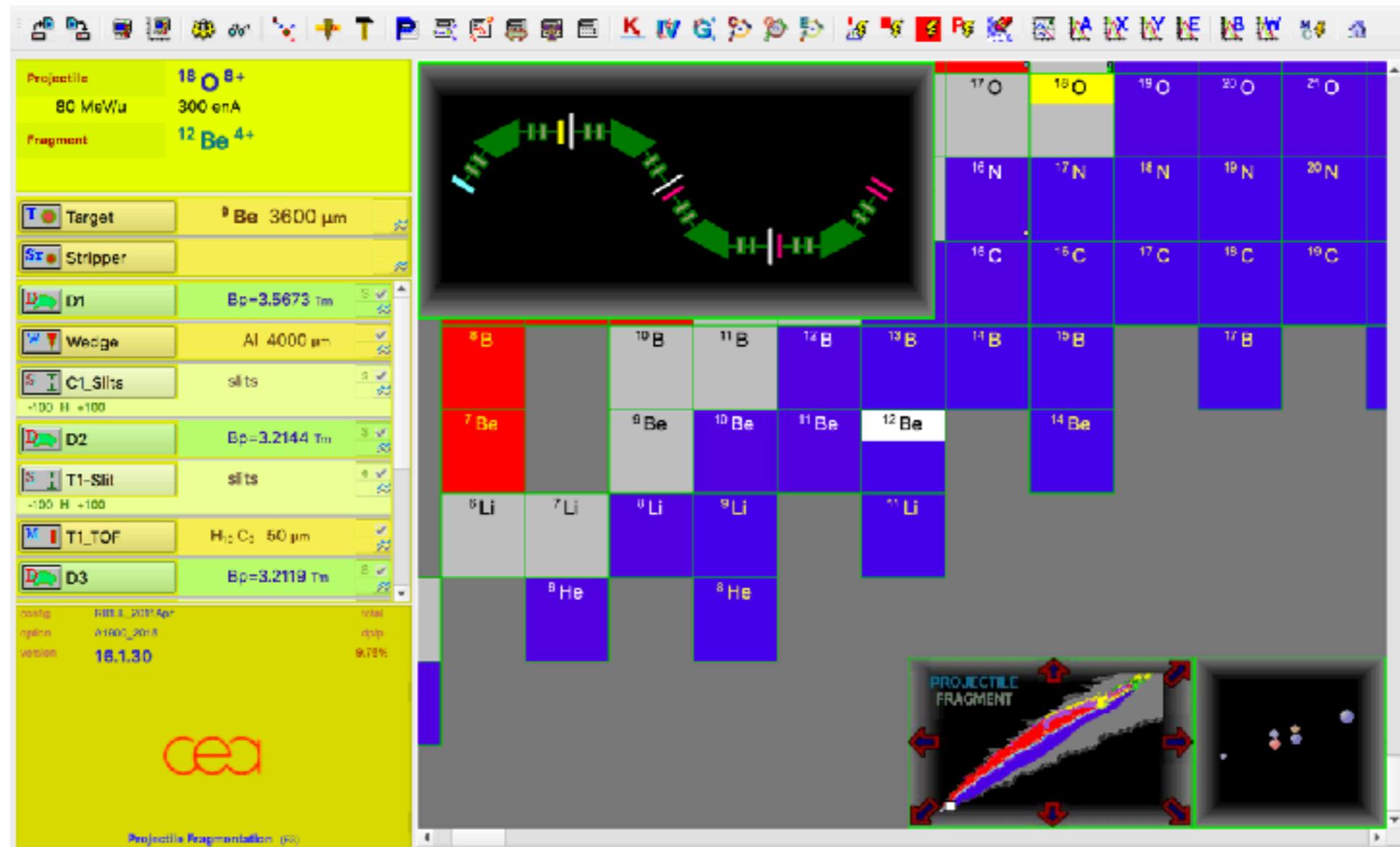
D2~D4设置



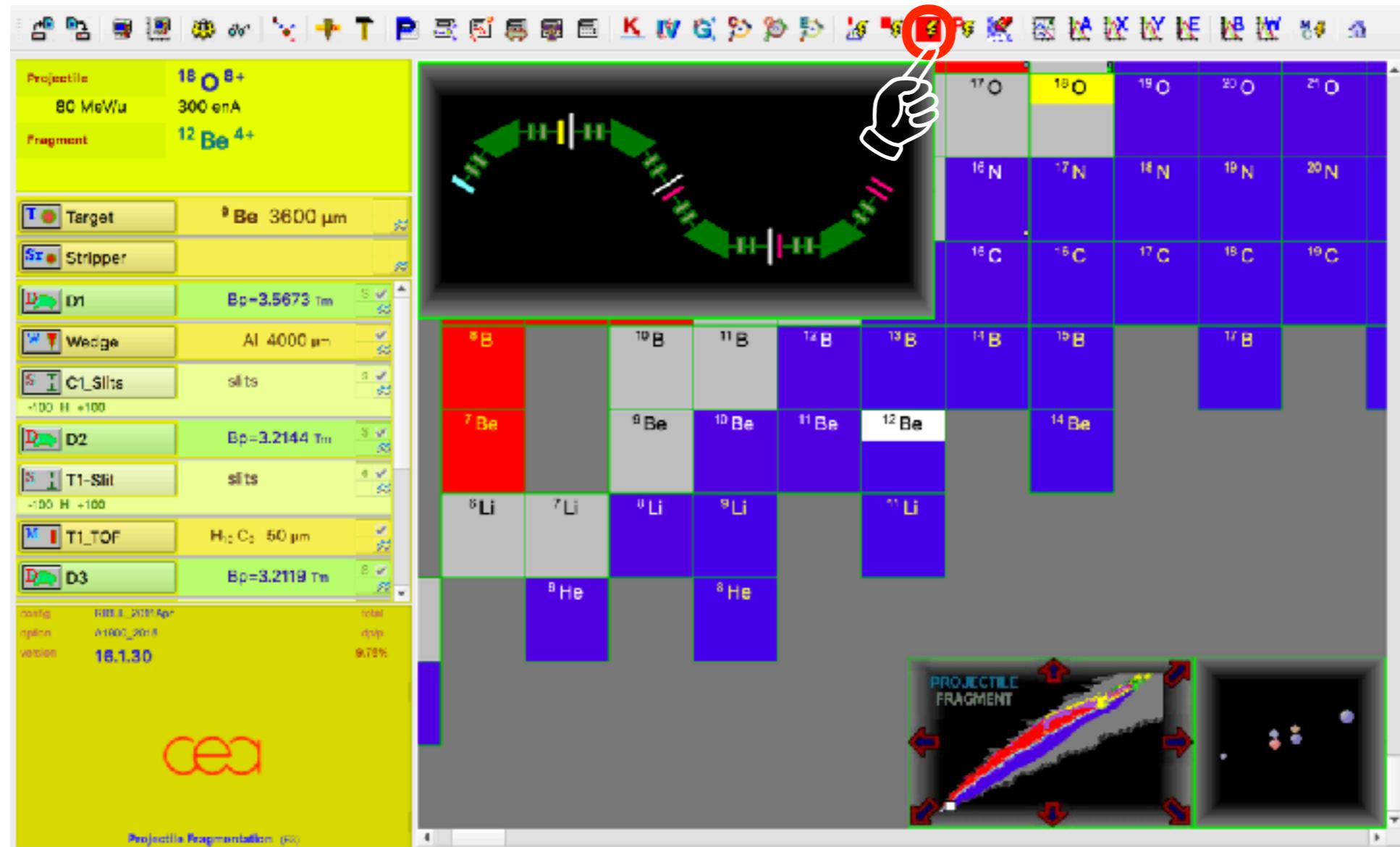
D2~D4设置



计算 ^{12}Be 次级束产额与纯度



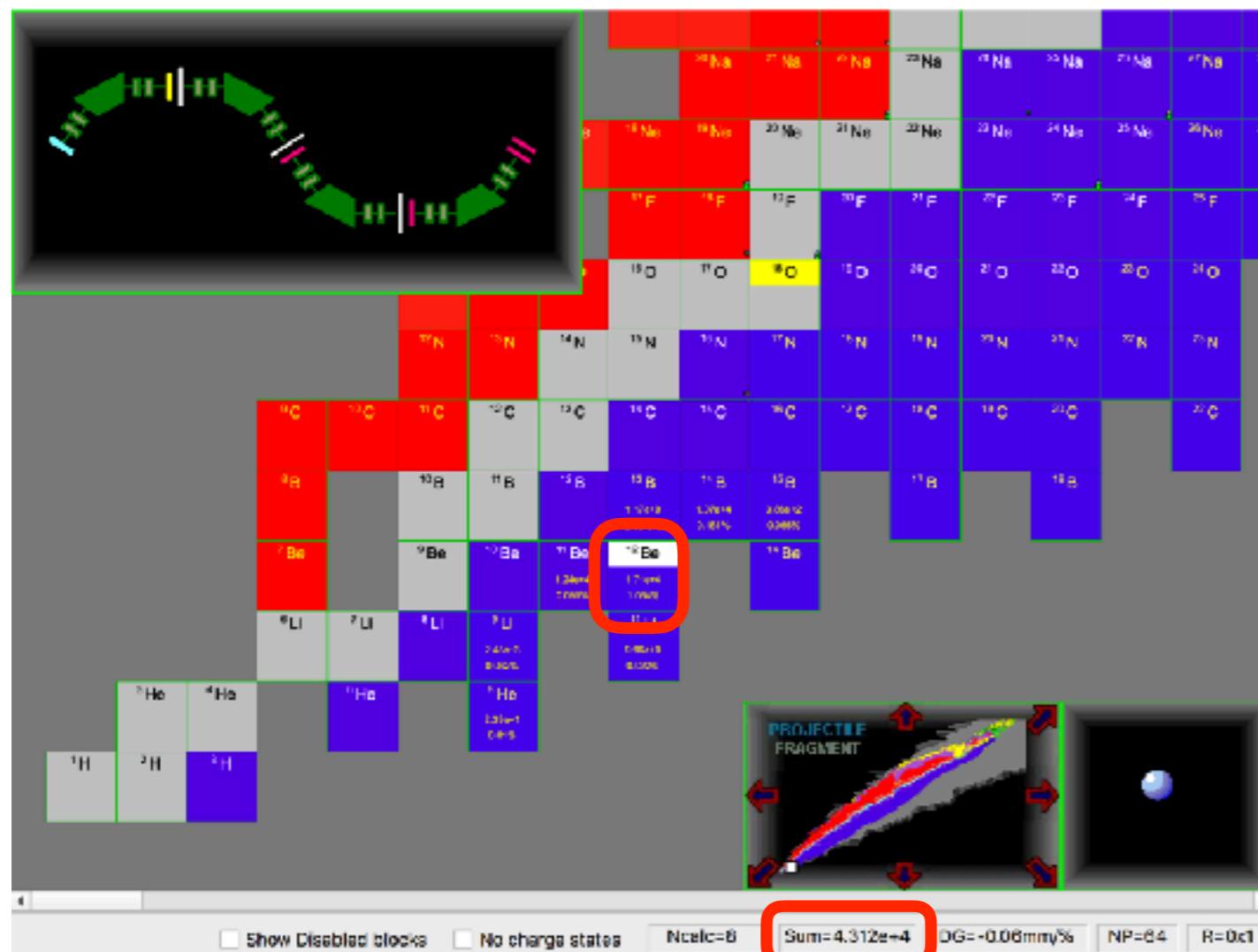
计算 ^{12}Be 次级束产额与纯度



计算 ^{12}Be 次级束产额与纯度

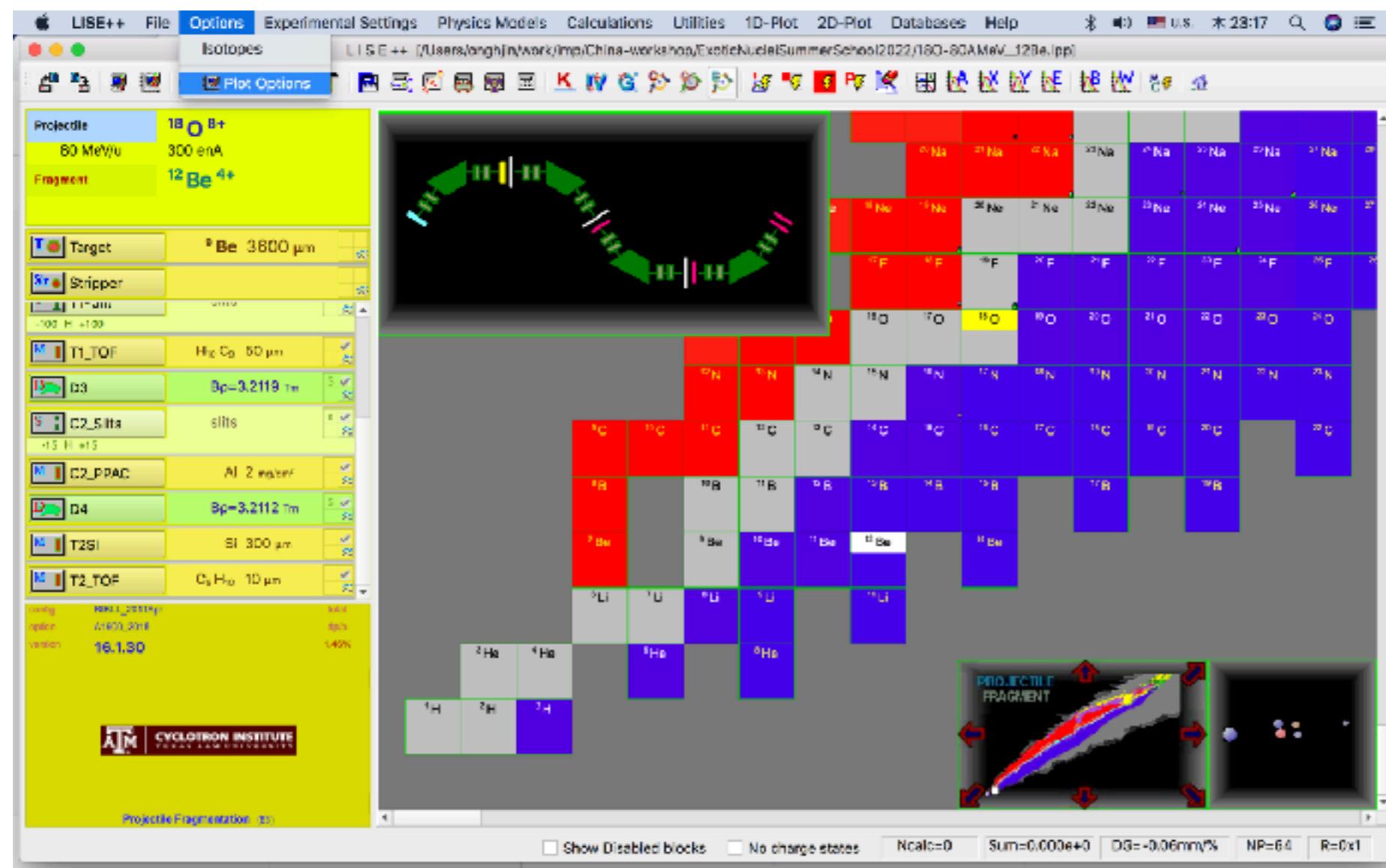


计算 ^{12}Be 次级束产额与纯度

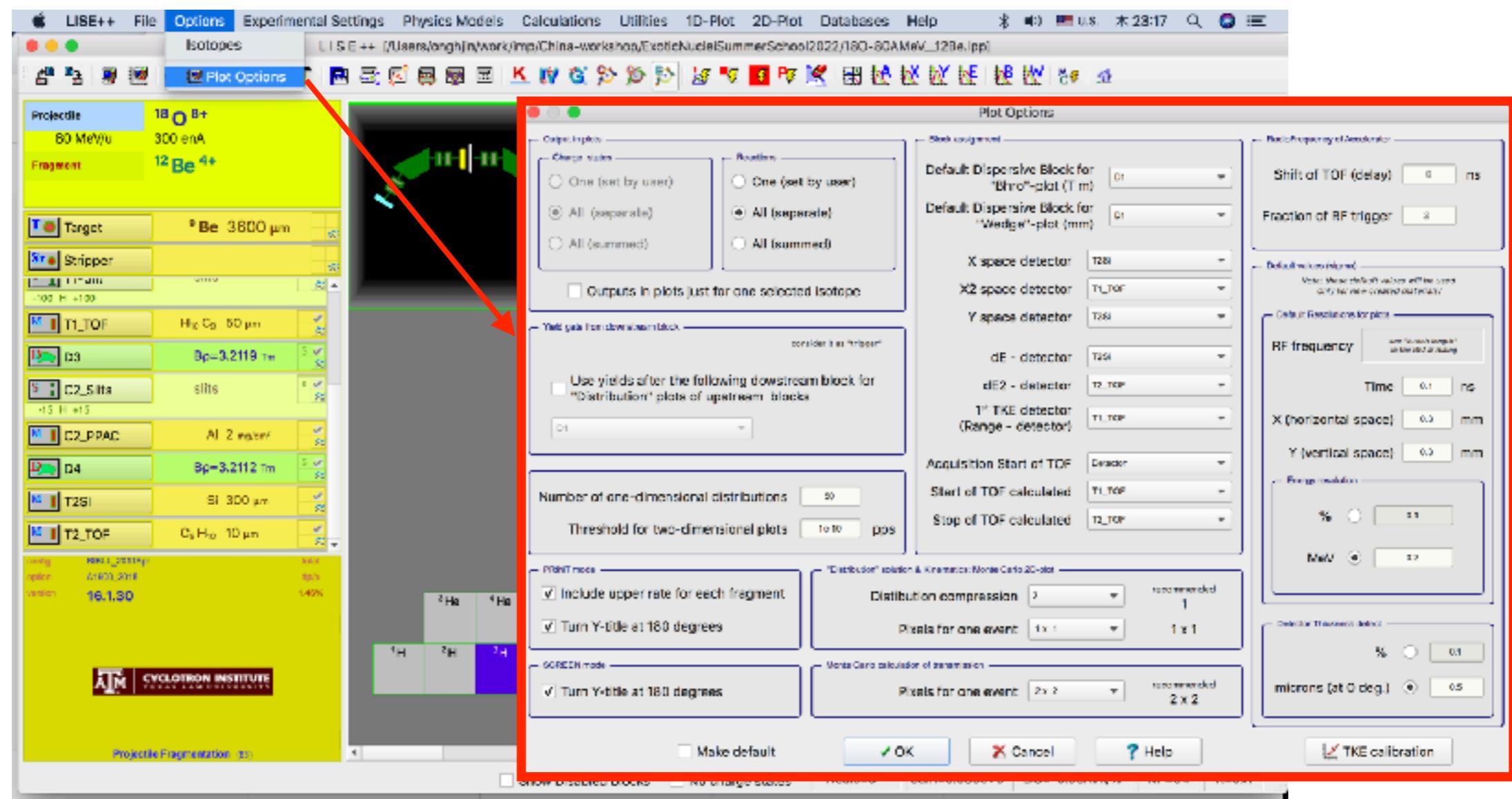


- ^{12}Be 产额 $\sim 1.7 \times 10^4$ pps
 - ^{12}Be 纯度 =
 $1.71 / 4.31 \times 100\%$
 $\sim 40\%$

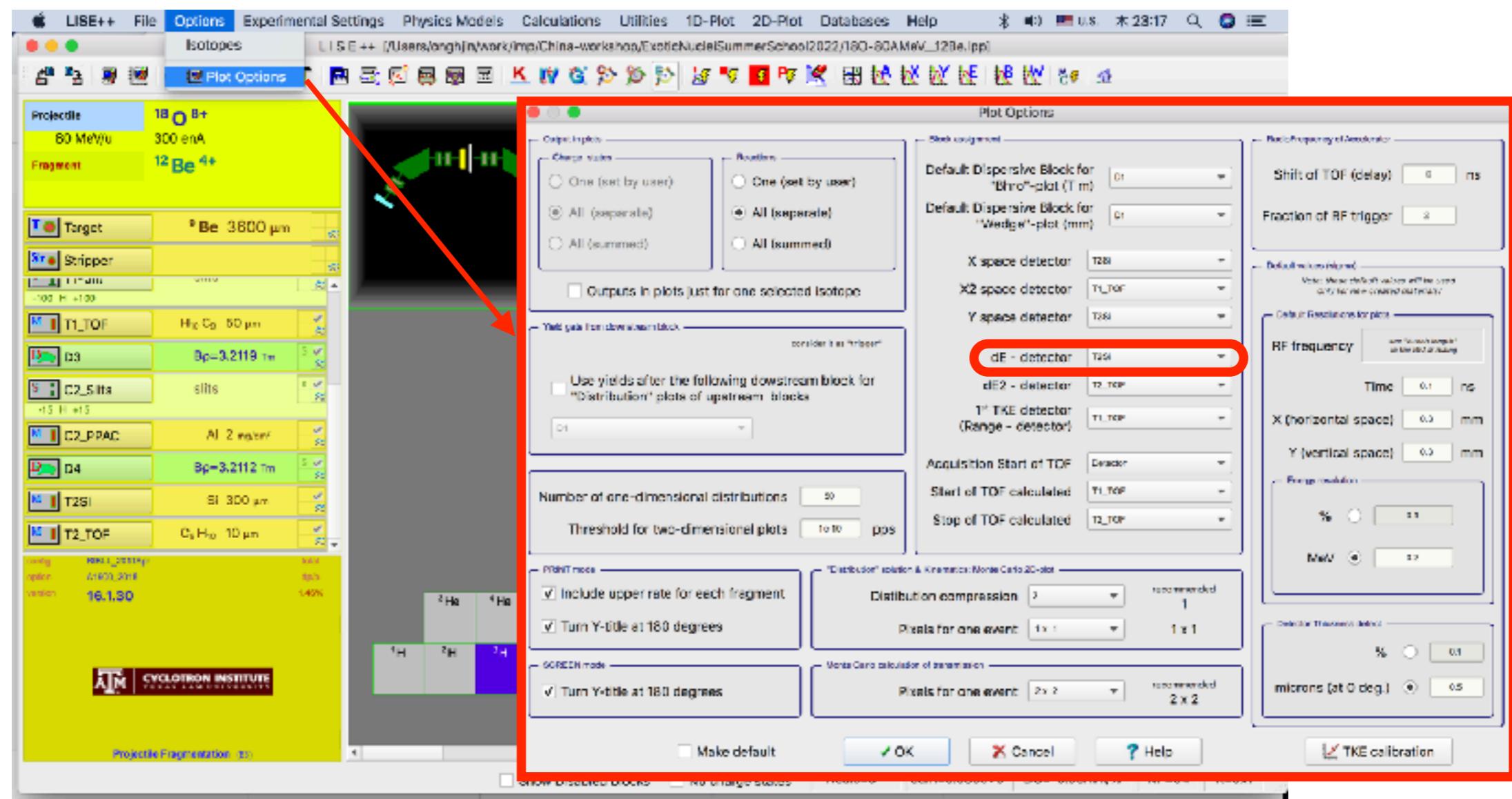
粒子鉴别：探测器设置



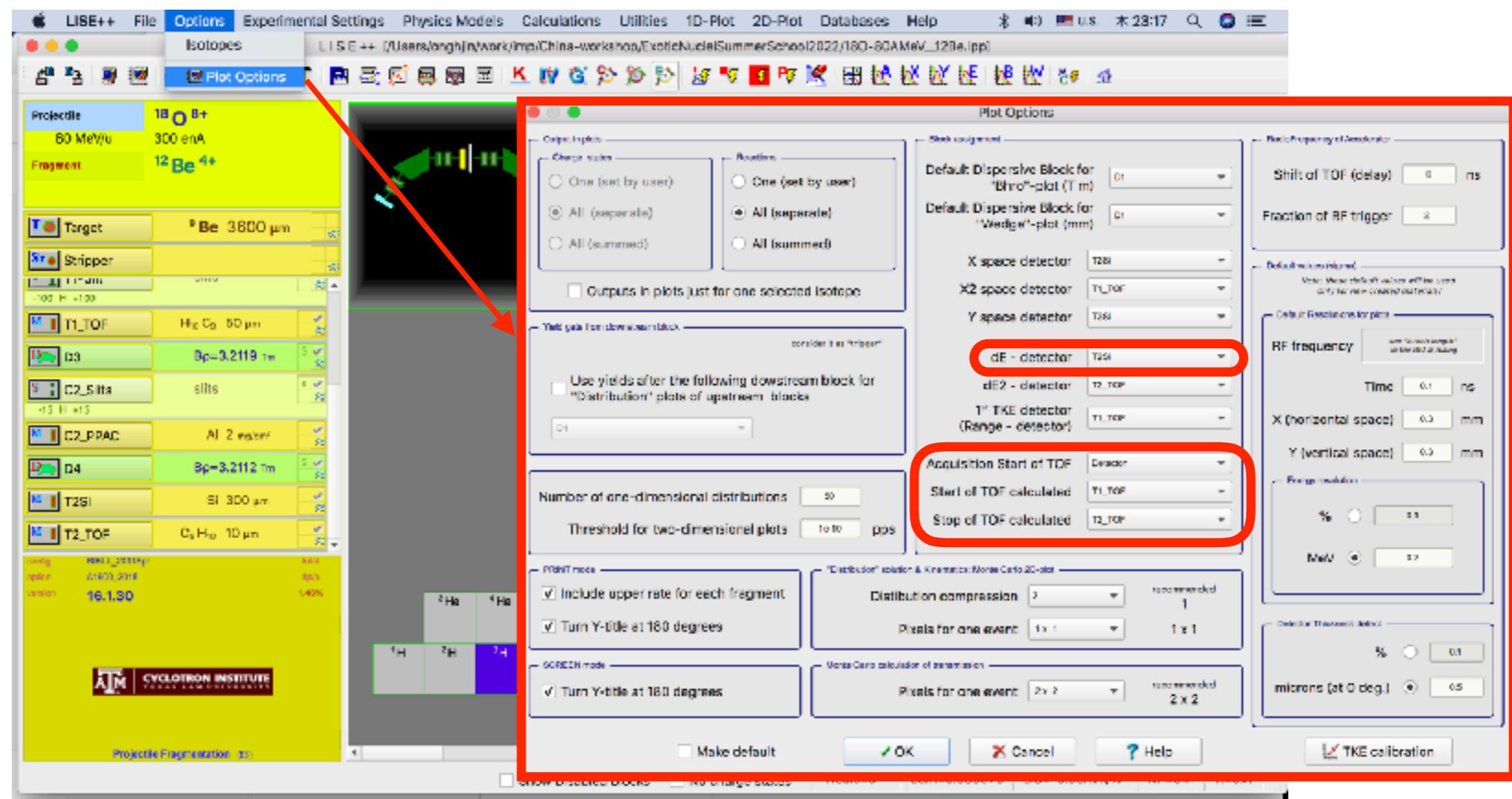
粒子鉴别：探测器设置



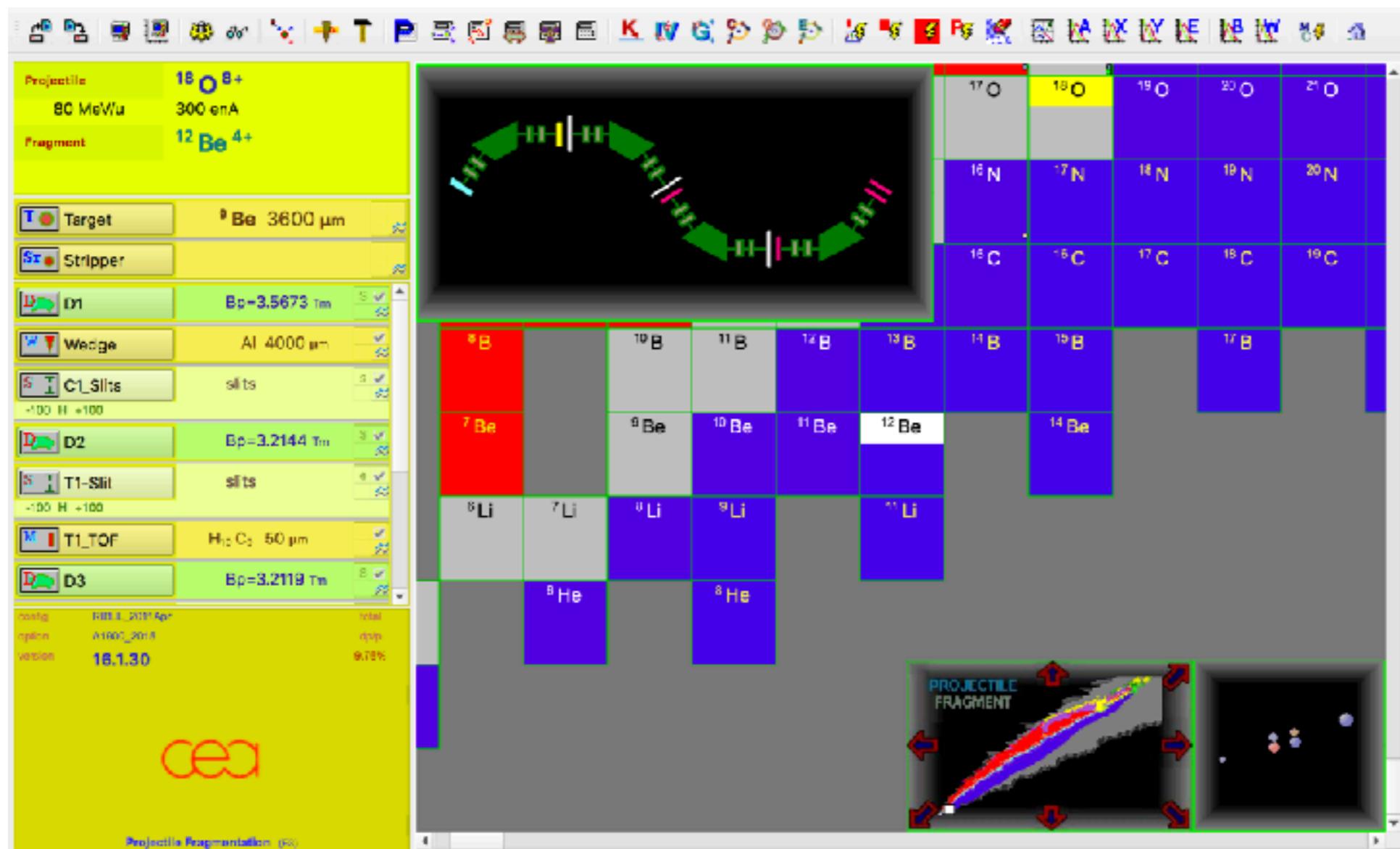
粒子鉴别：探测器设置



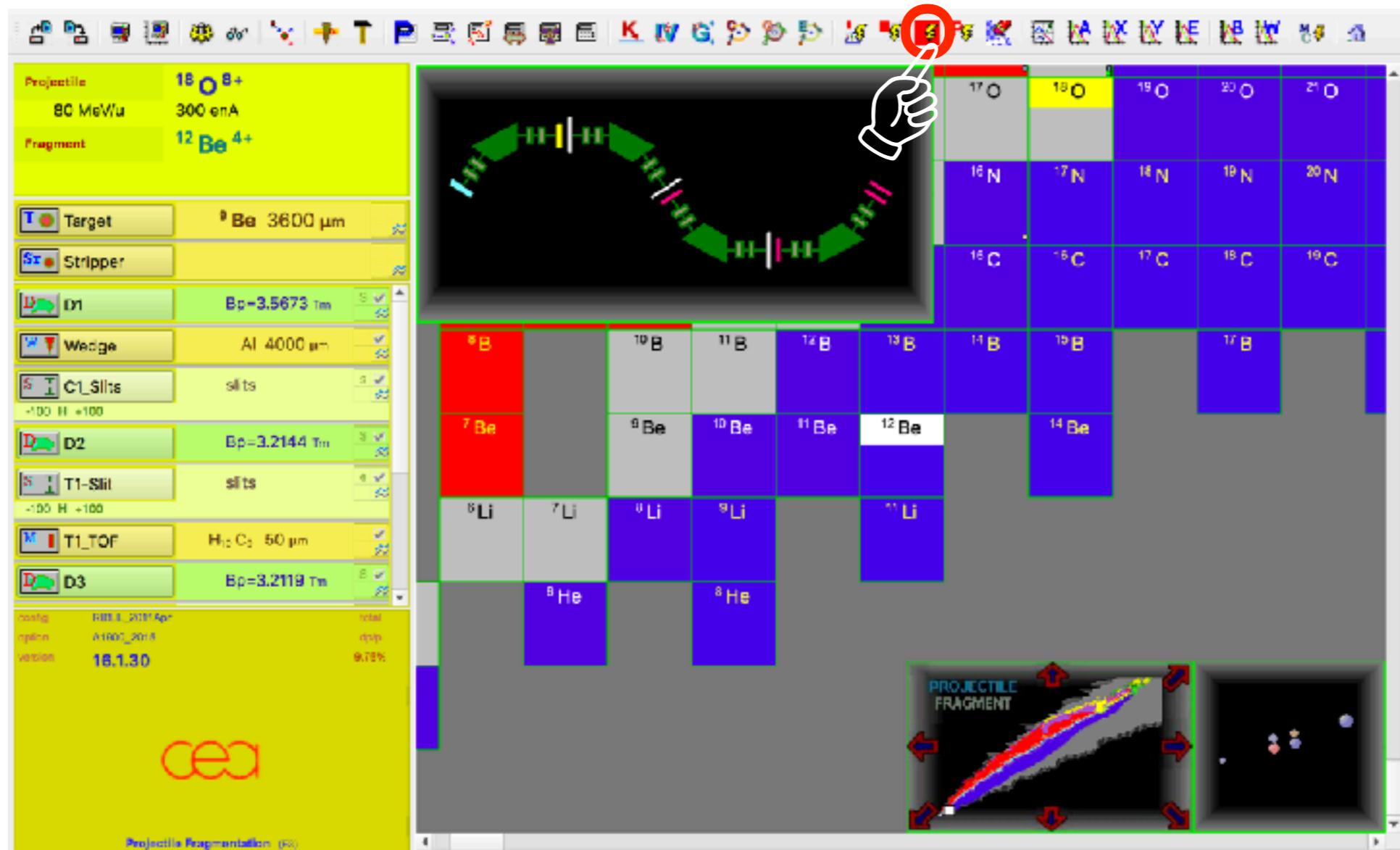
粒子鉴别：探测器设置



粒子鉴别：重新计算次级束



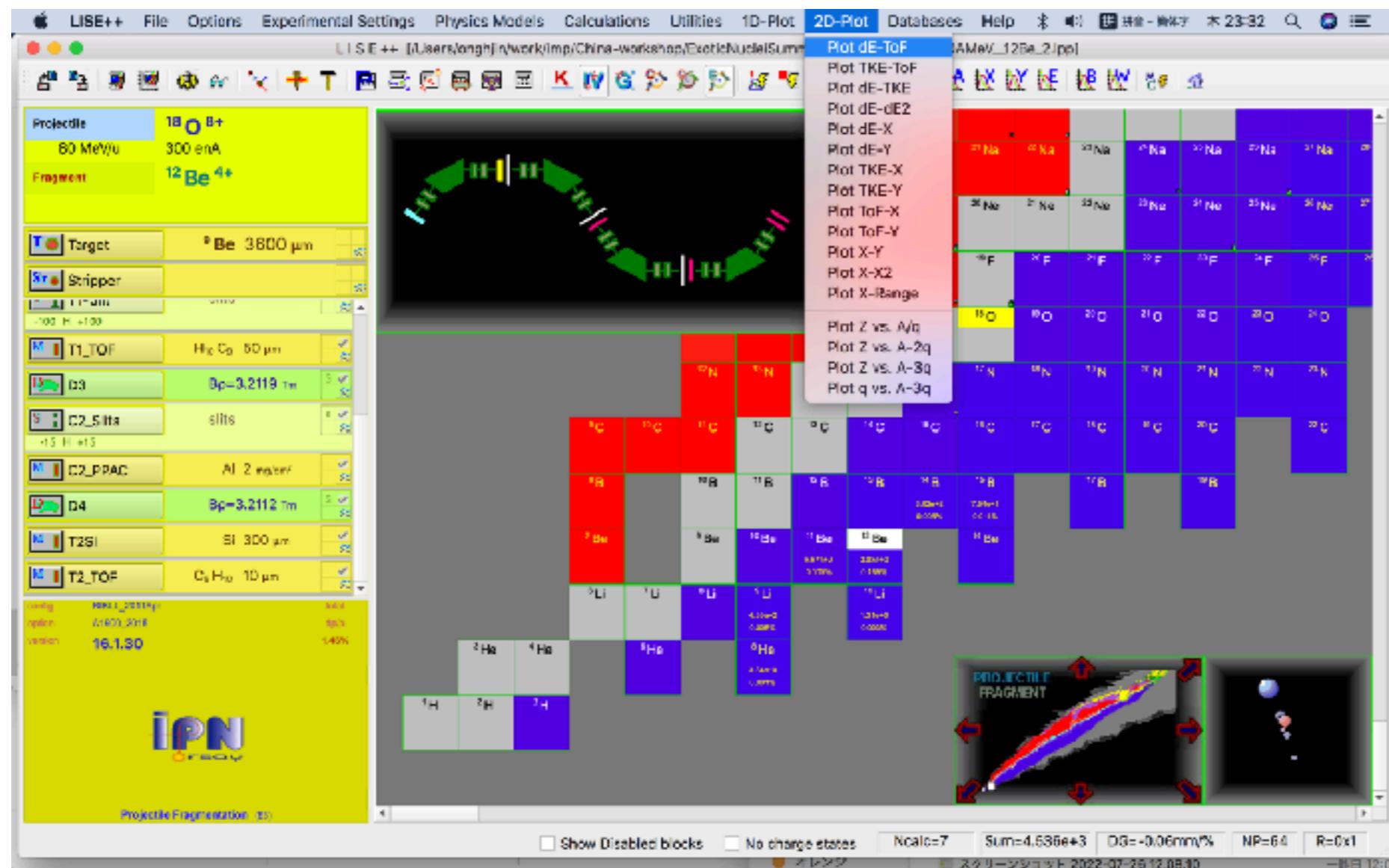
粒子鉴别：重新计算次级束



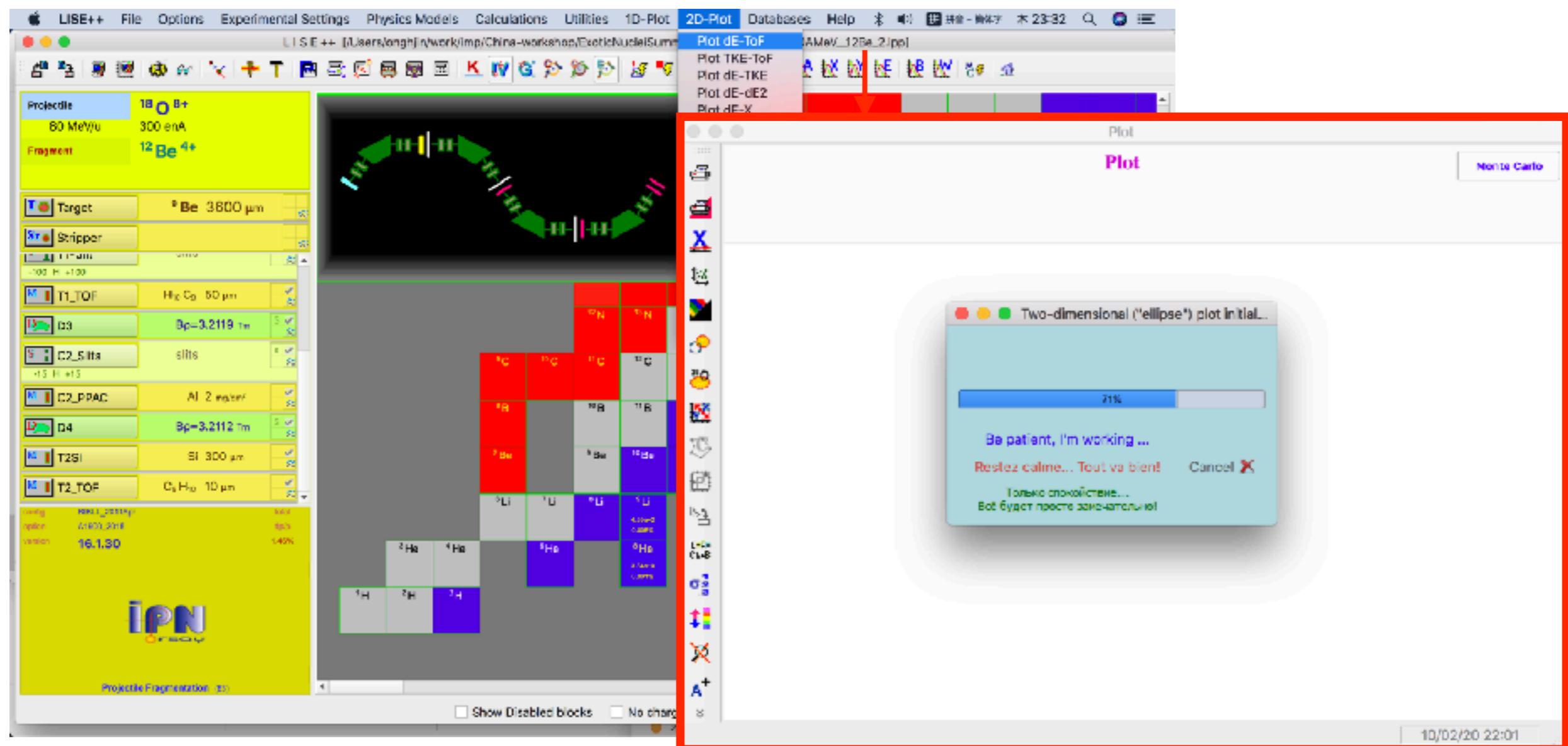
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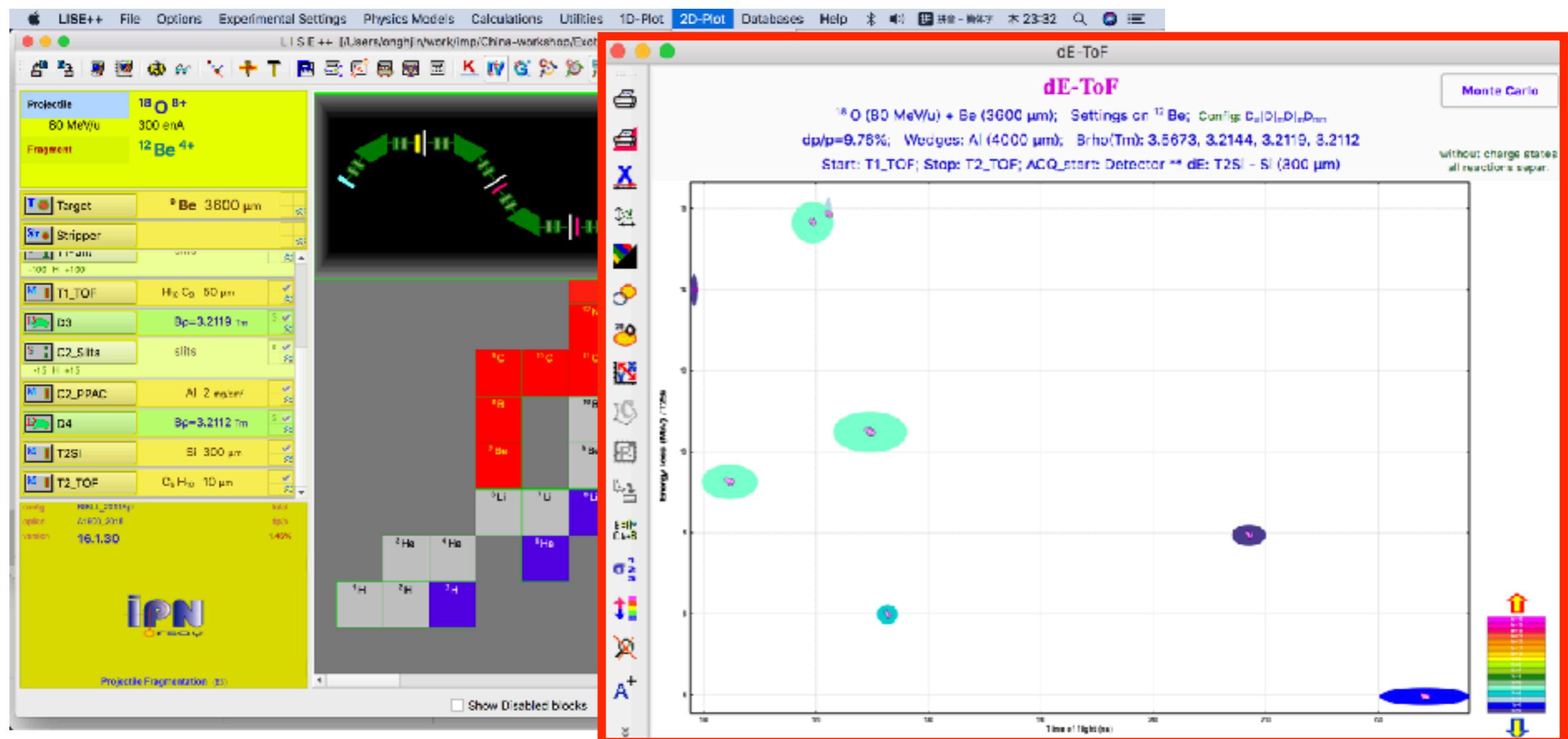
粒子鉴别



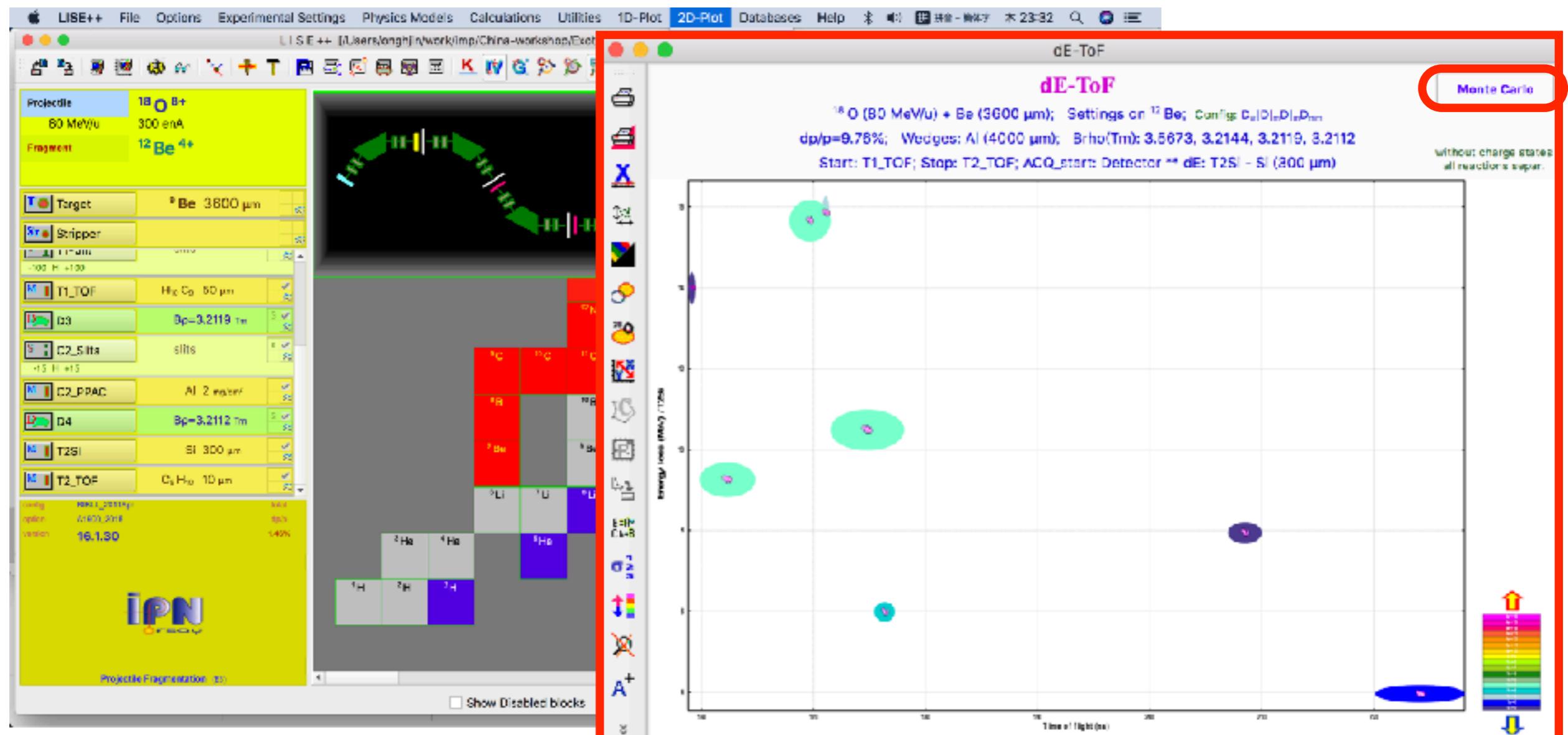
粒子鉴别



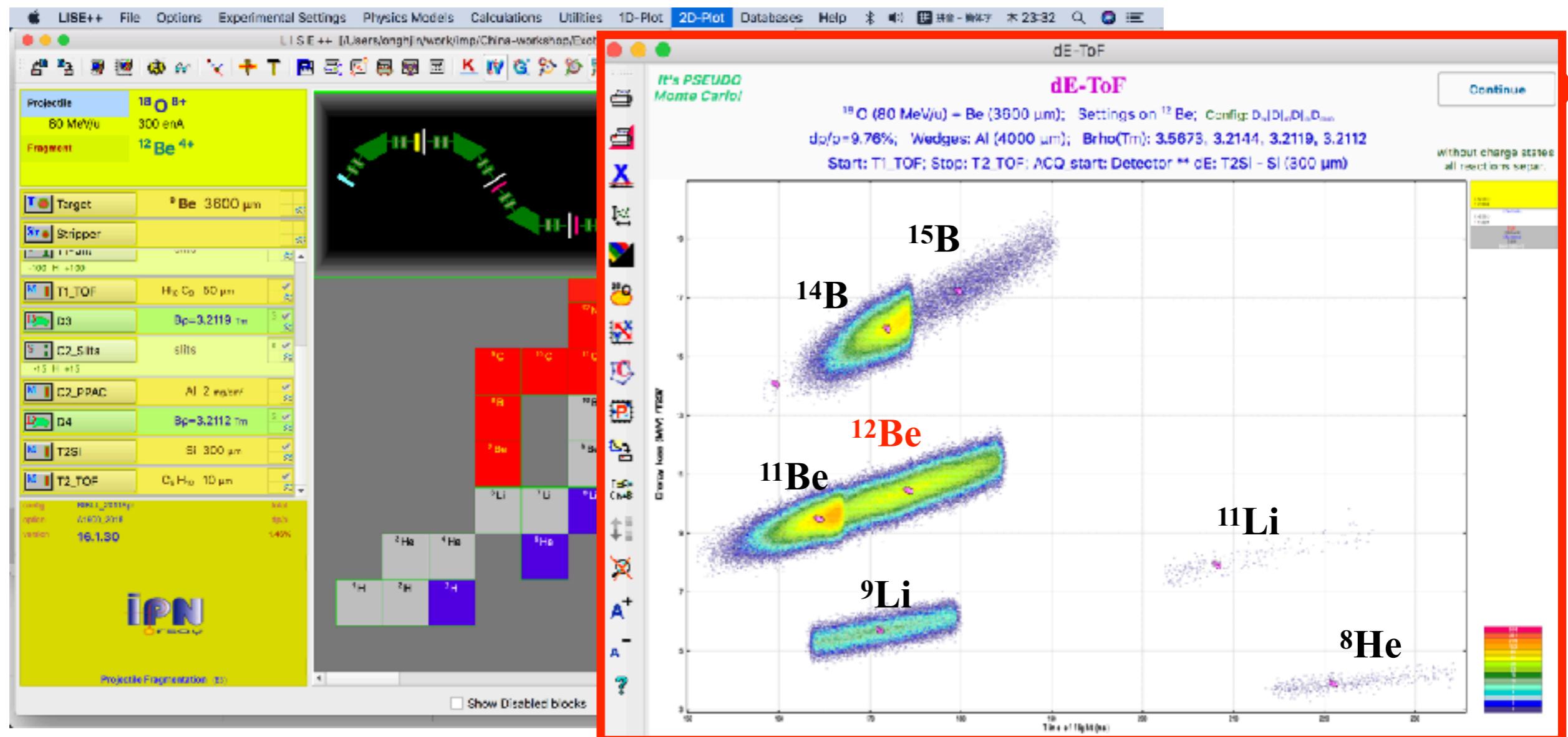
粒子鉴别



粒子鉴别



粒子鉴别

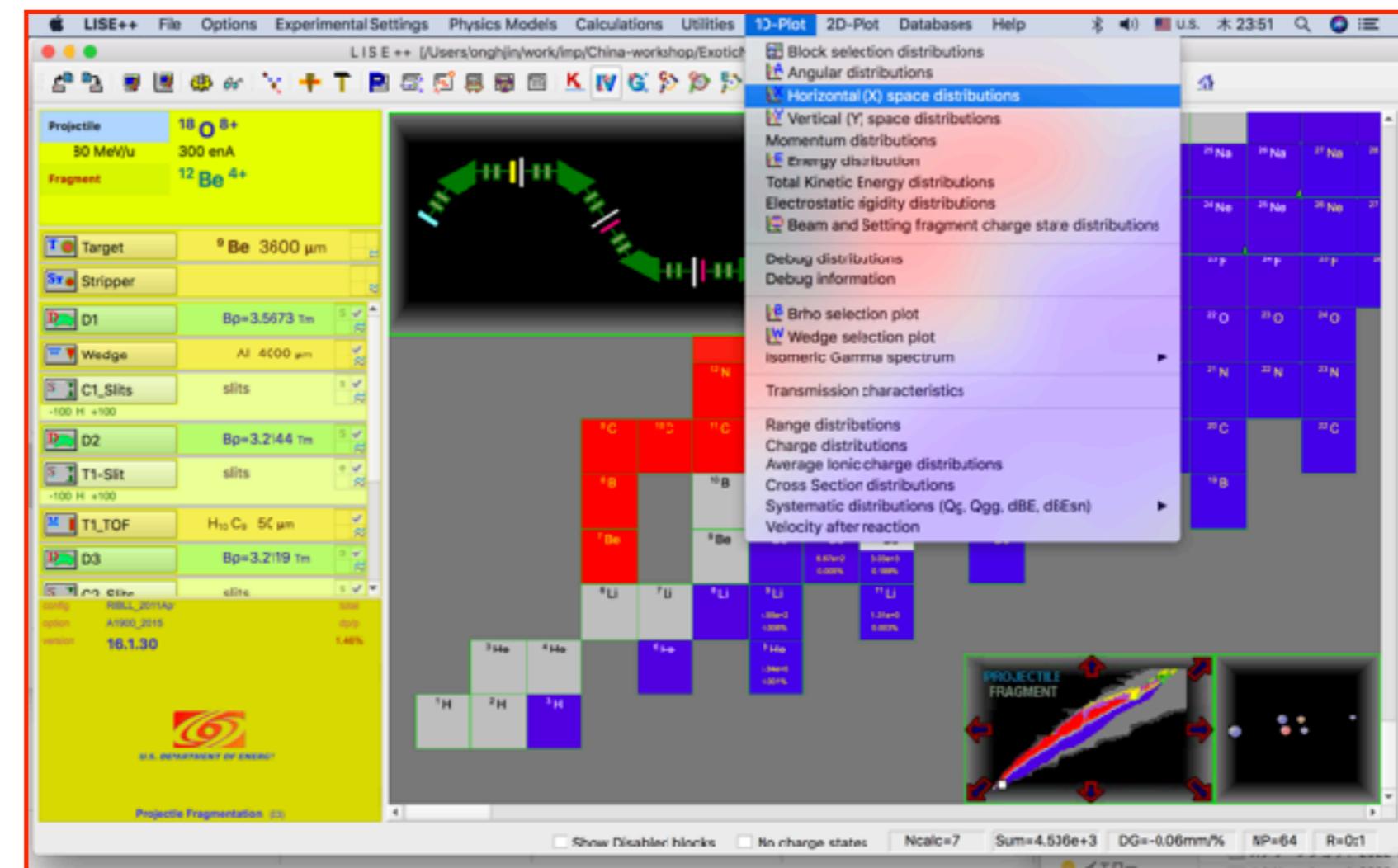


进一步优化碎片分离

1. 提高纯度
2. 设定能量展宽

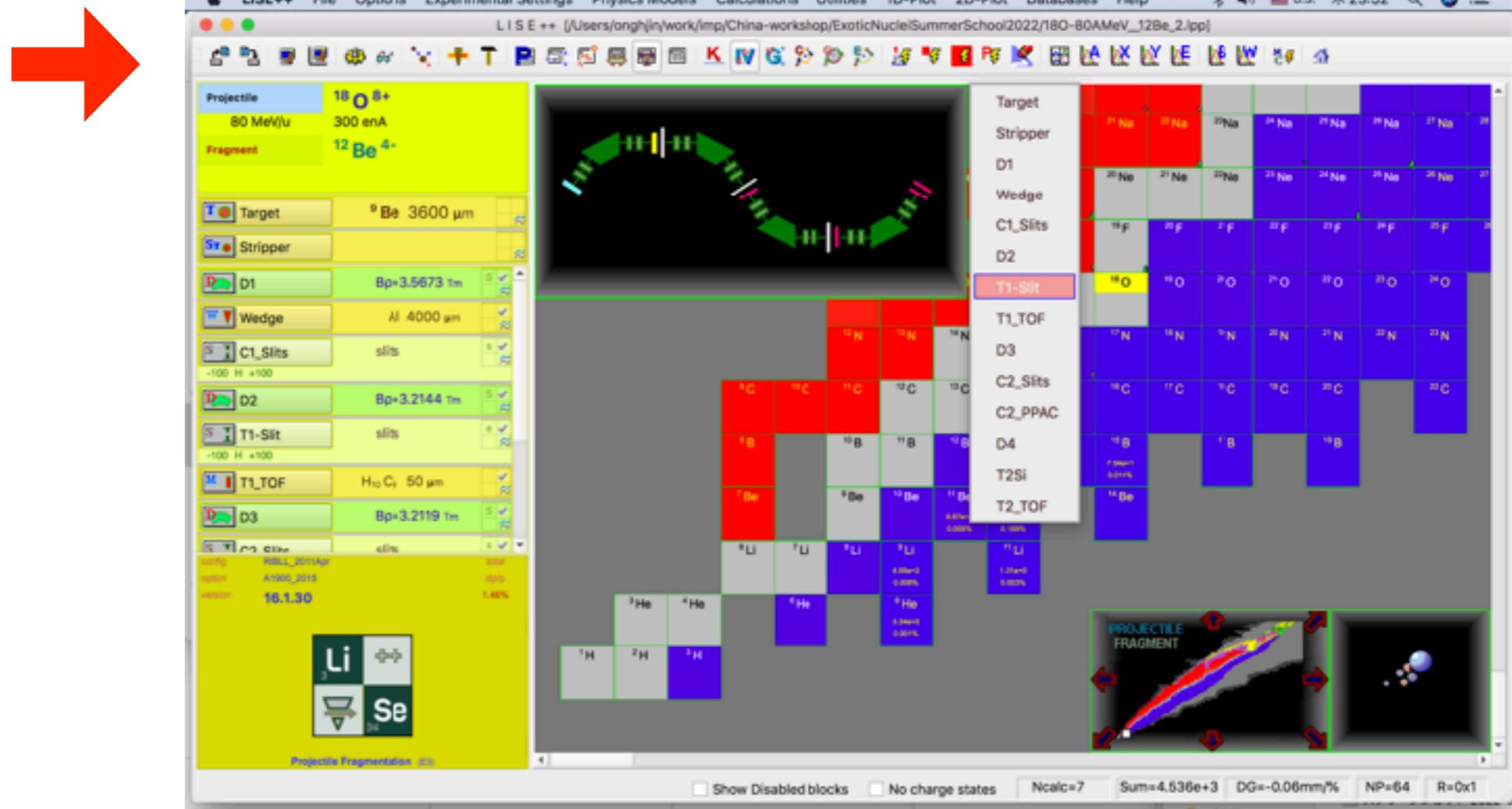
进一步优化碎片分离

1. 提高纯度
2. 设定能量展宽



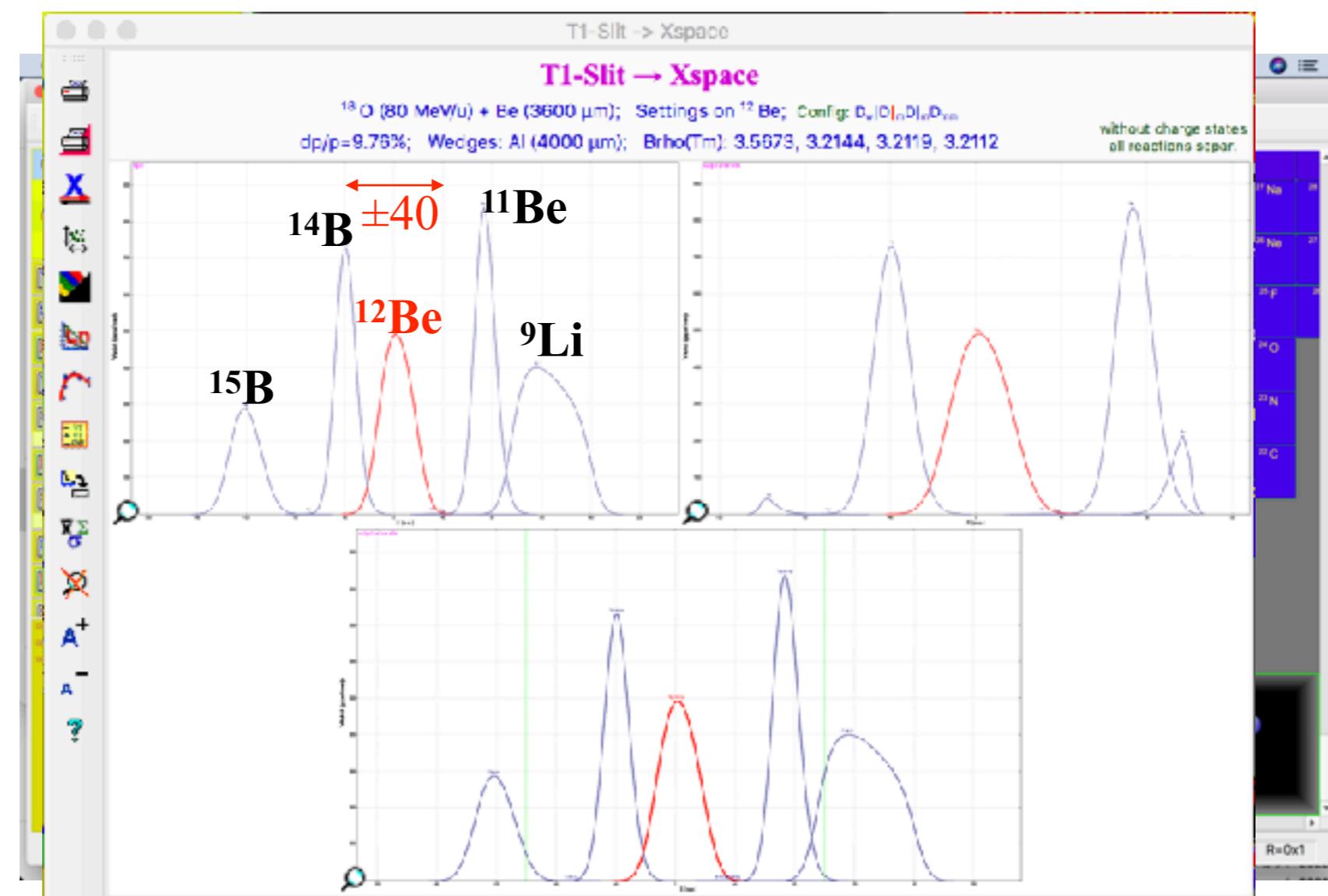
进一步优化碎片分离

1. 提高纯度
2. 设定能量展宽



进一步优化碎片分离

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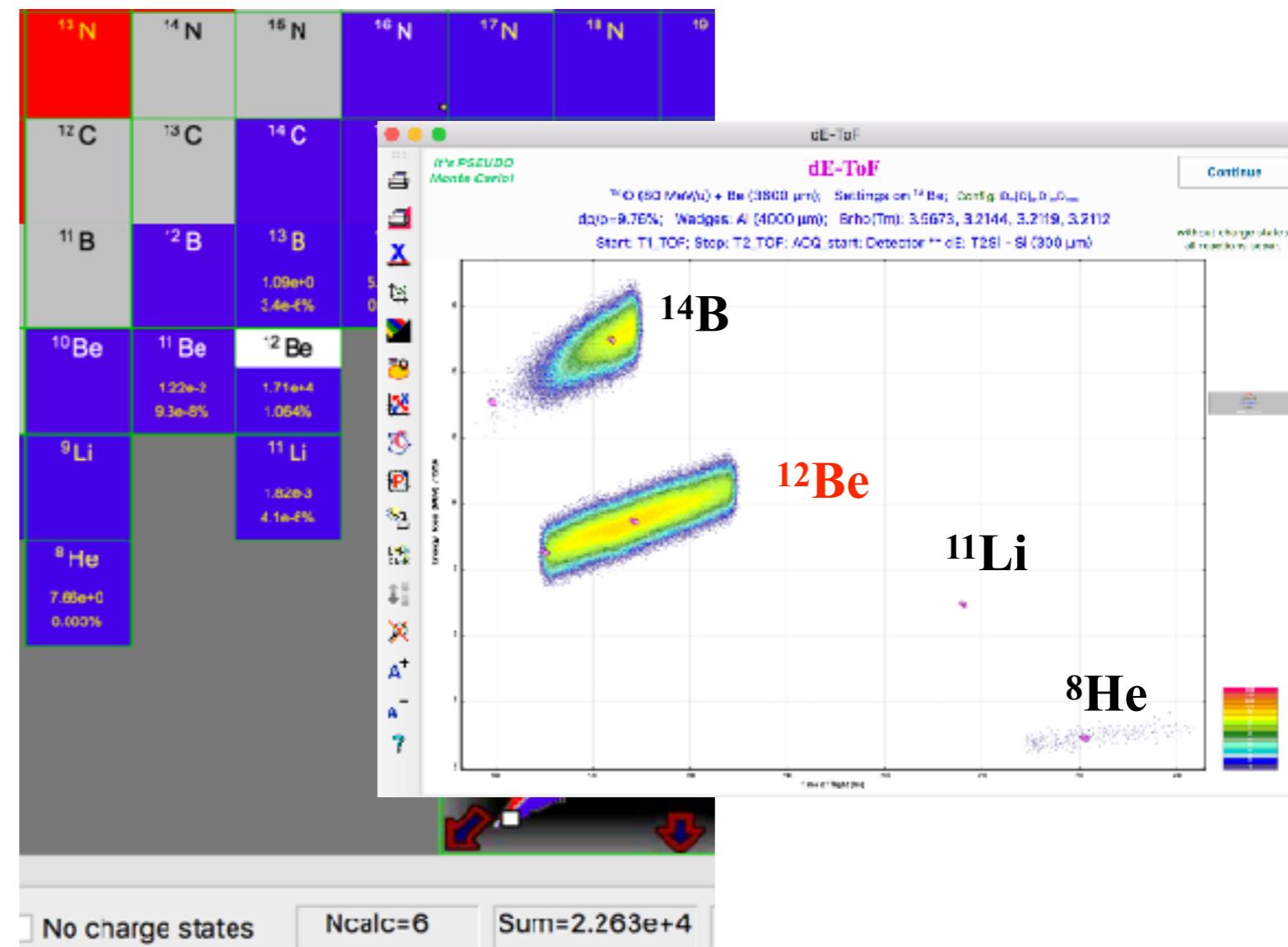
进一步优化碎片分离

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进一步优化碎片分离

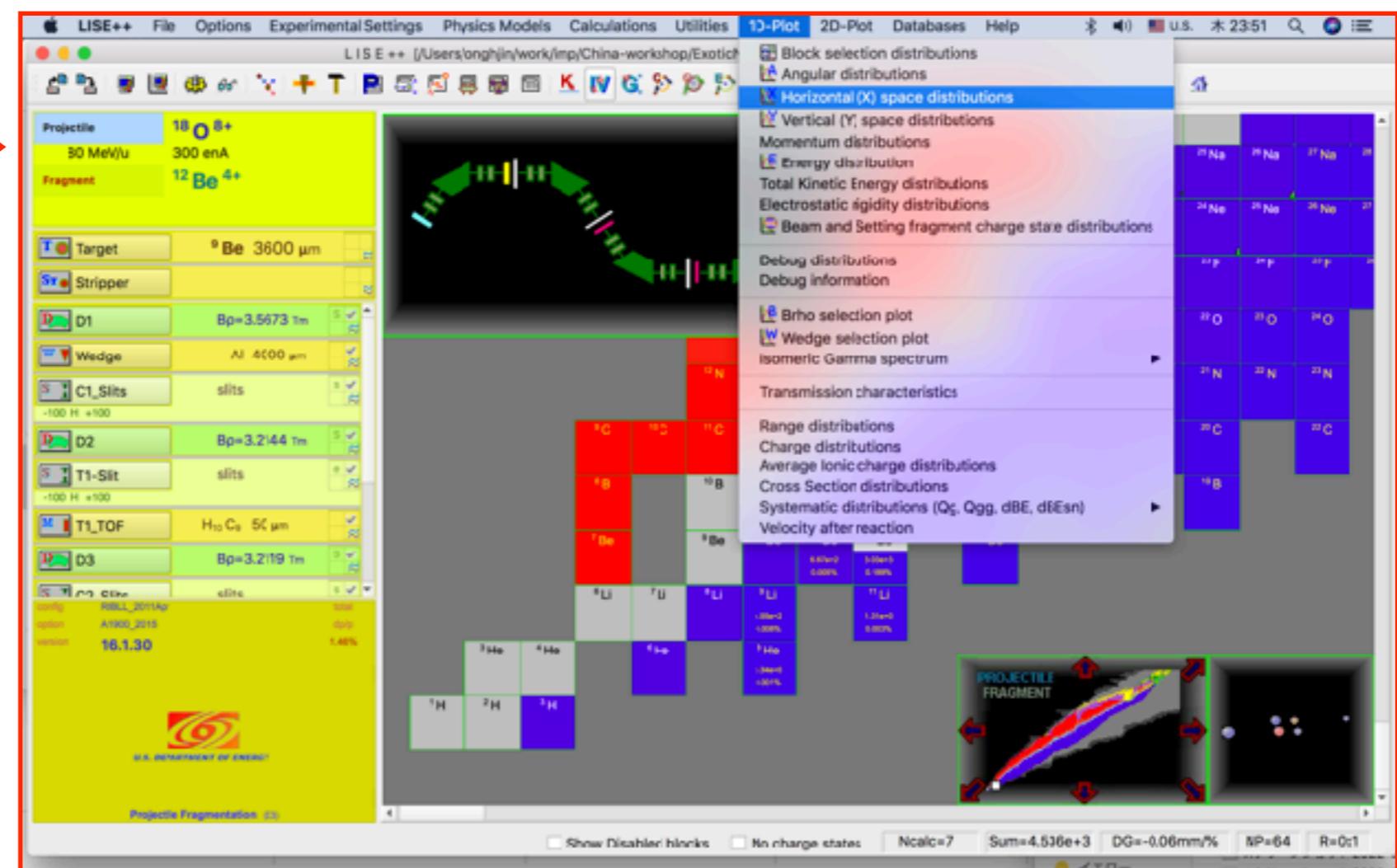
1. 提高纯度
2. 设定能量展宽



- ^{12}Be 产额 $\sim 1.7 \times 10^4$ pps
- ^{12}Be 纯度 =
 $1.71 / 2.26 \times 100\%$
 $\sim 52\%$

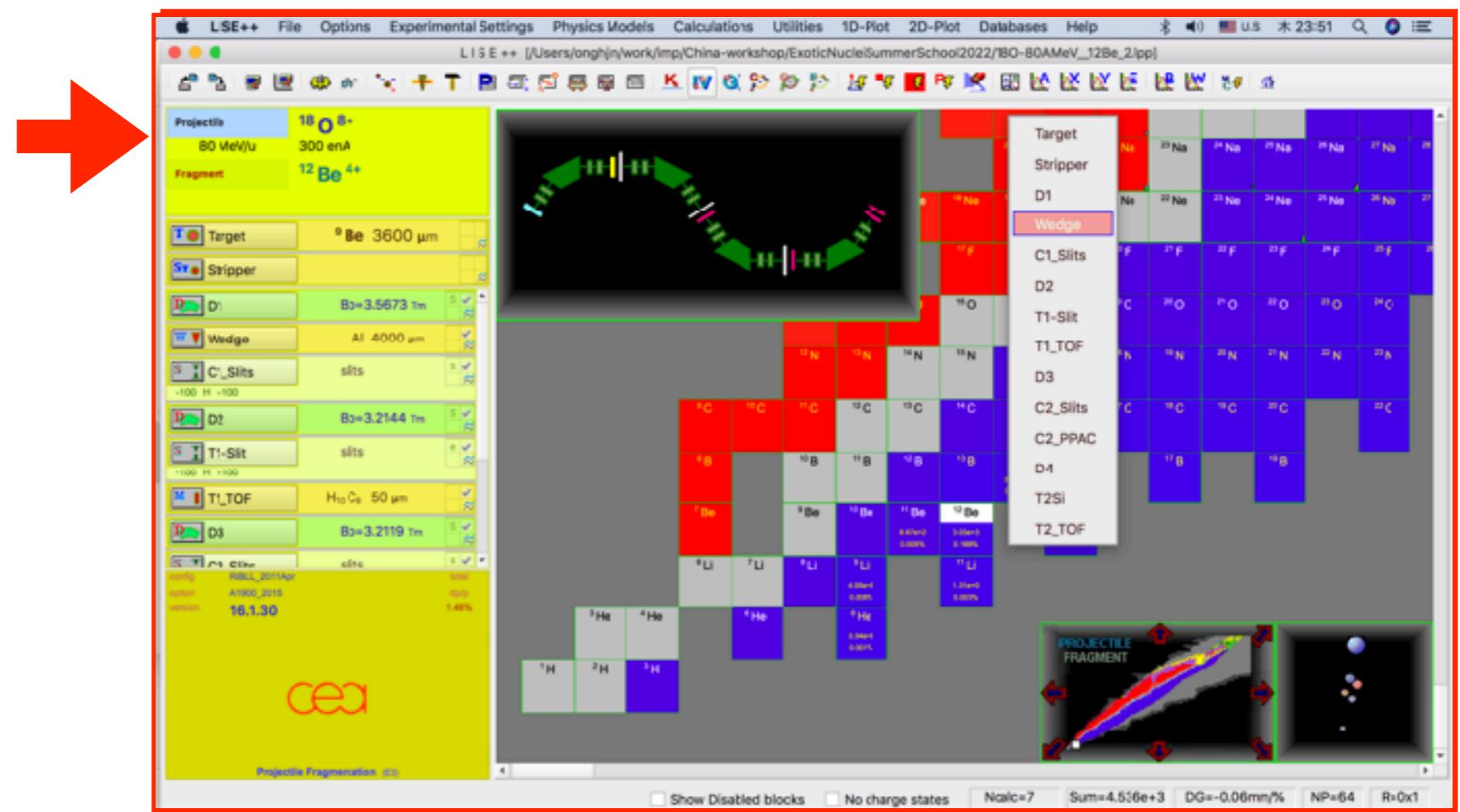
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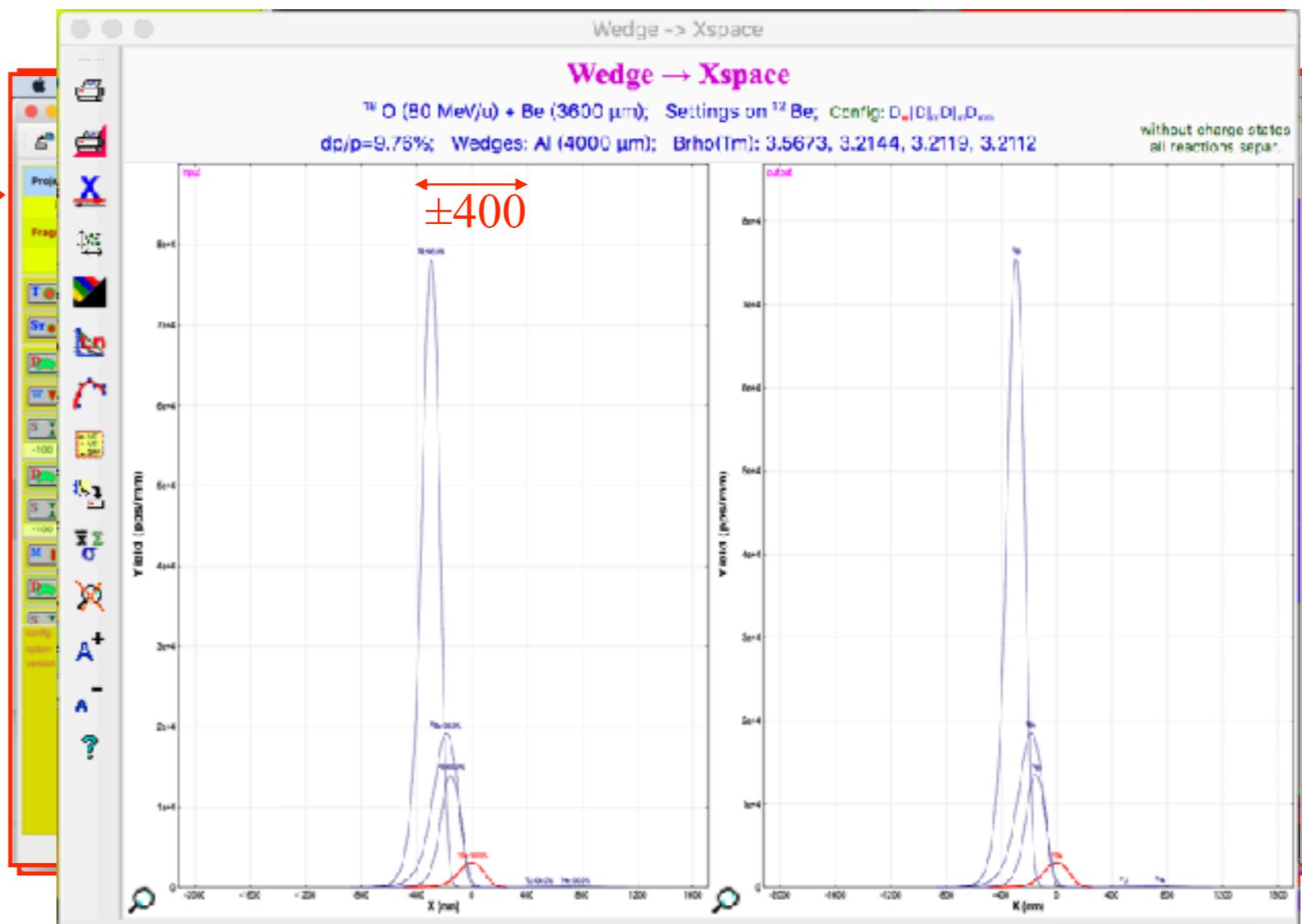
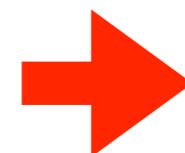
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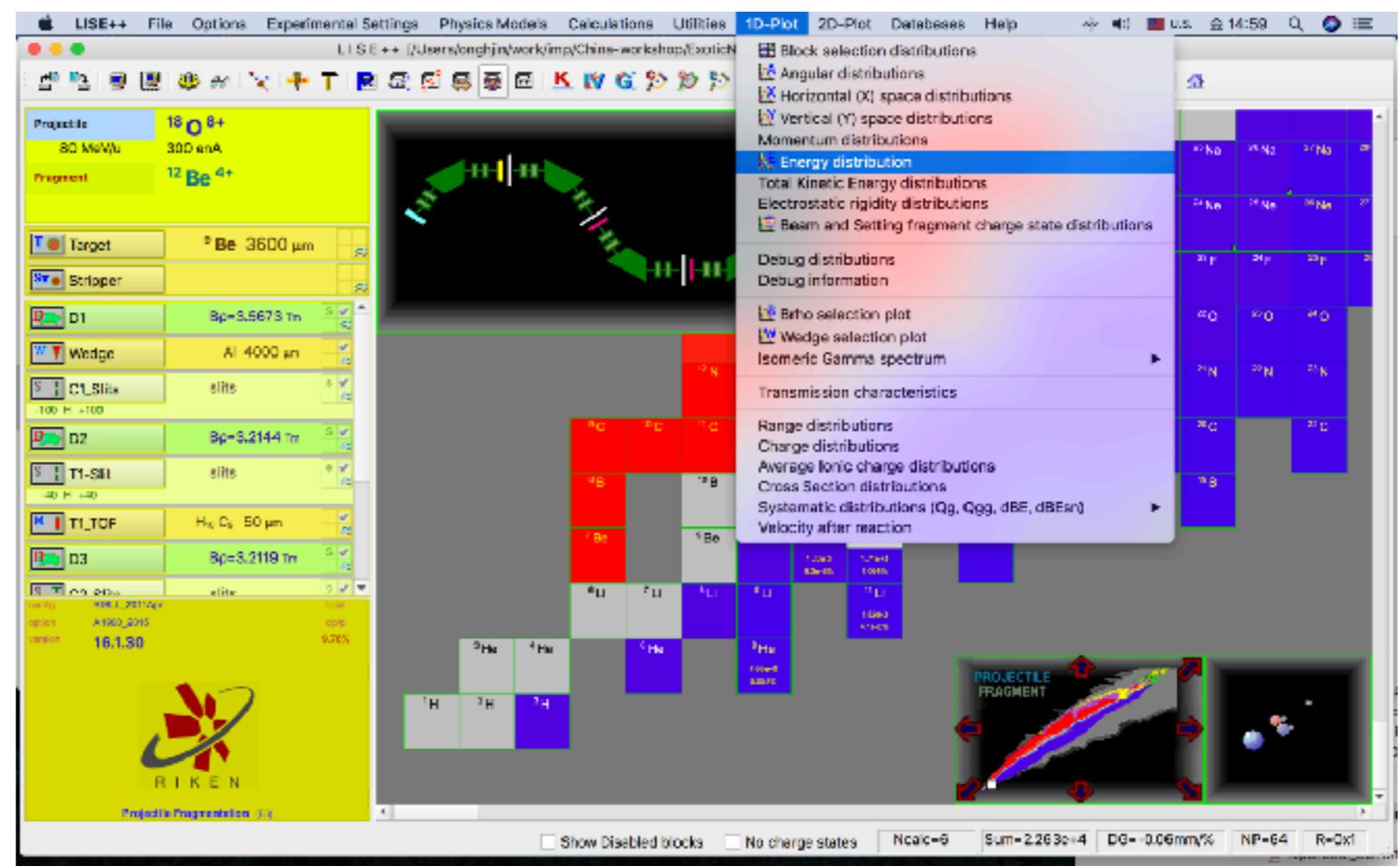
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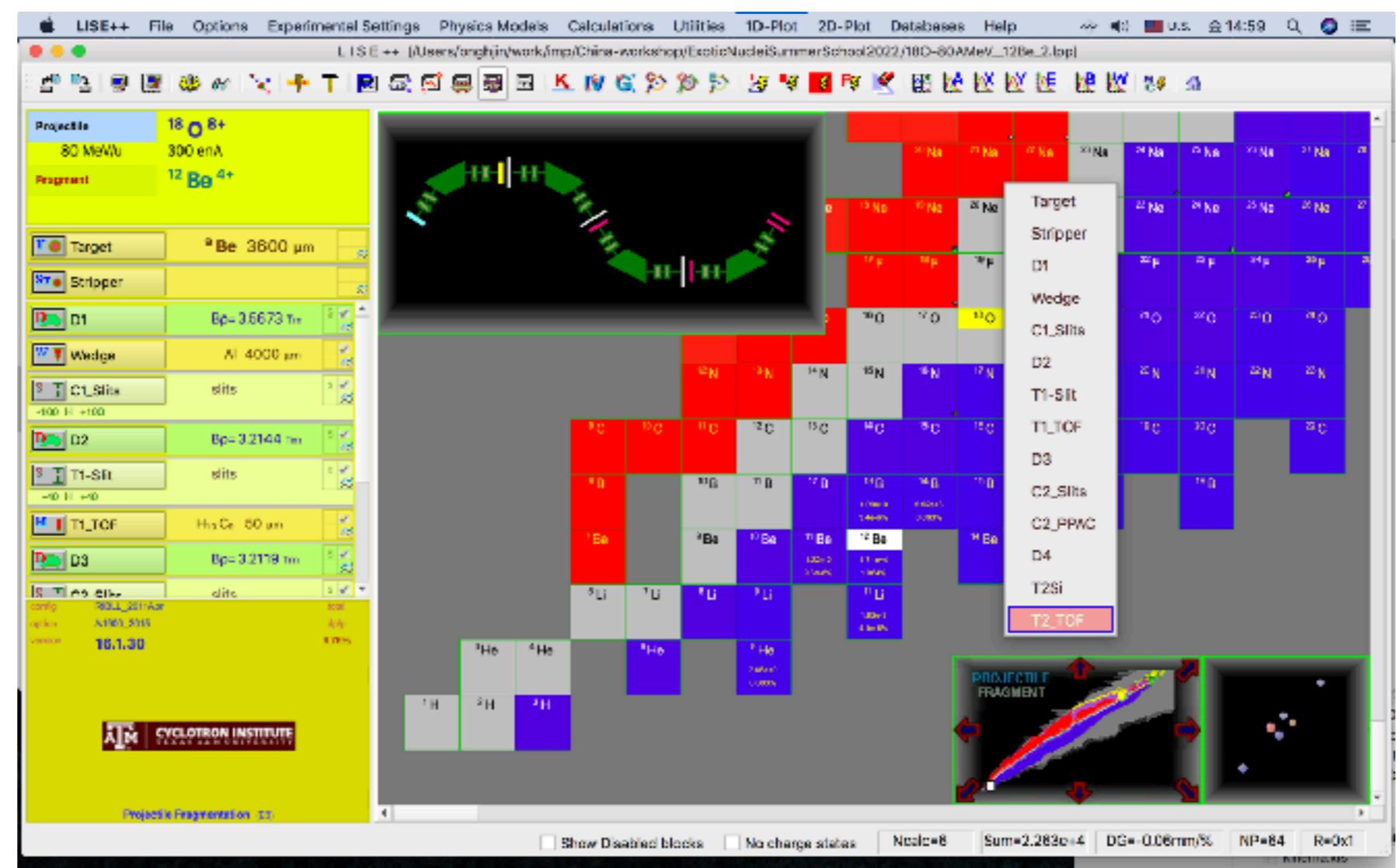
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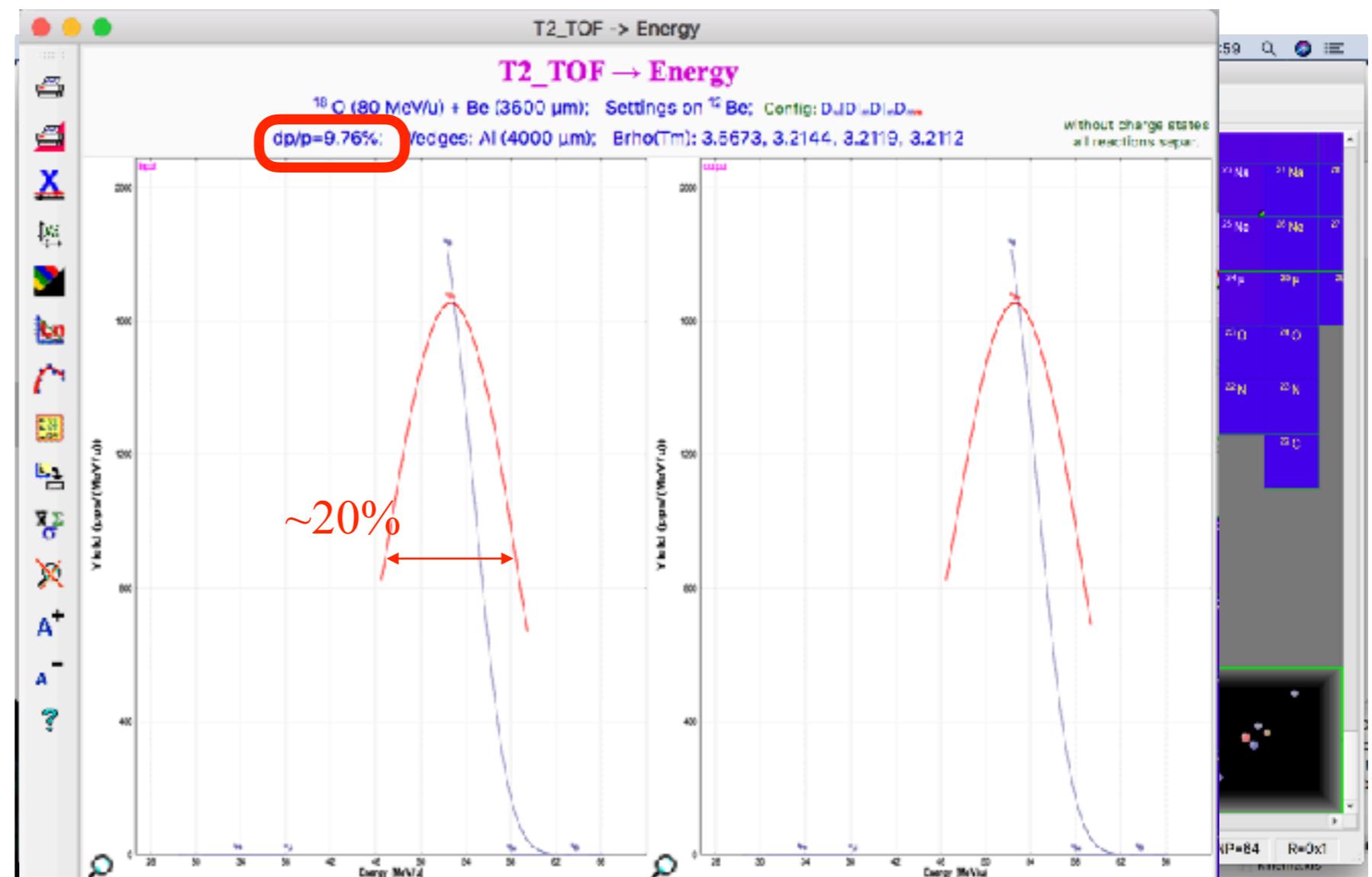
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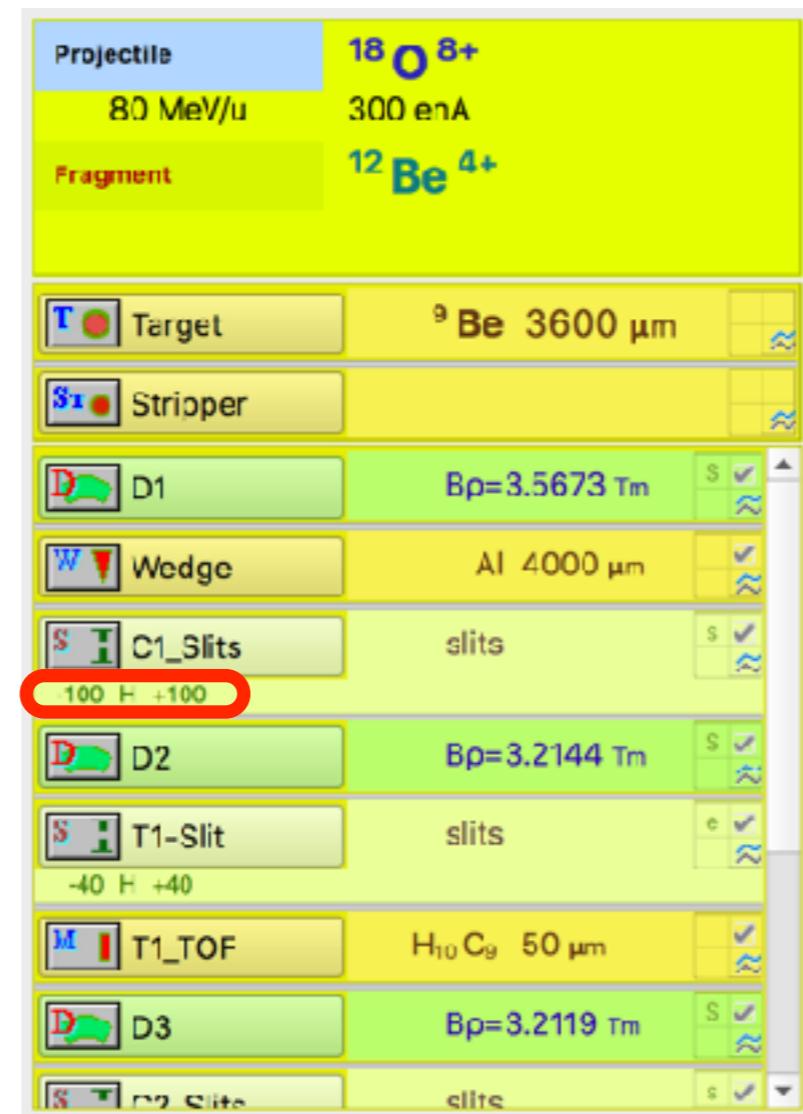
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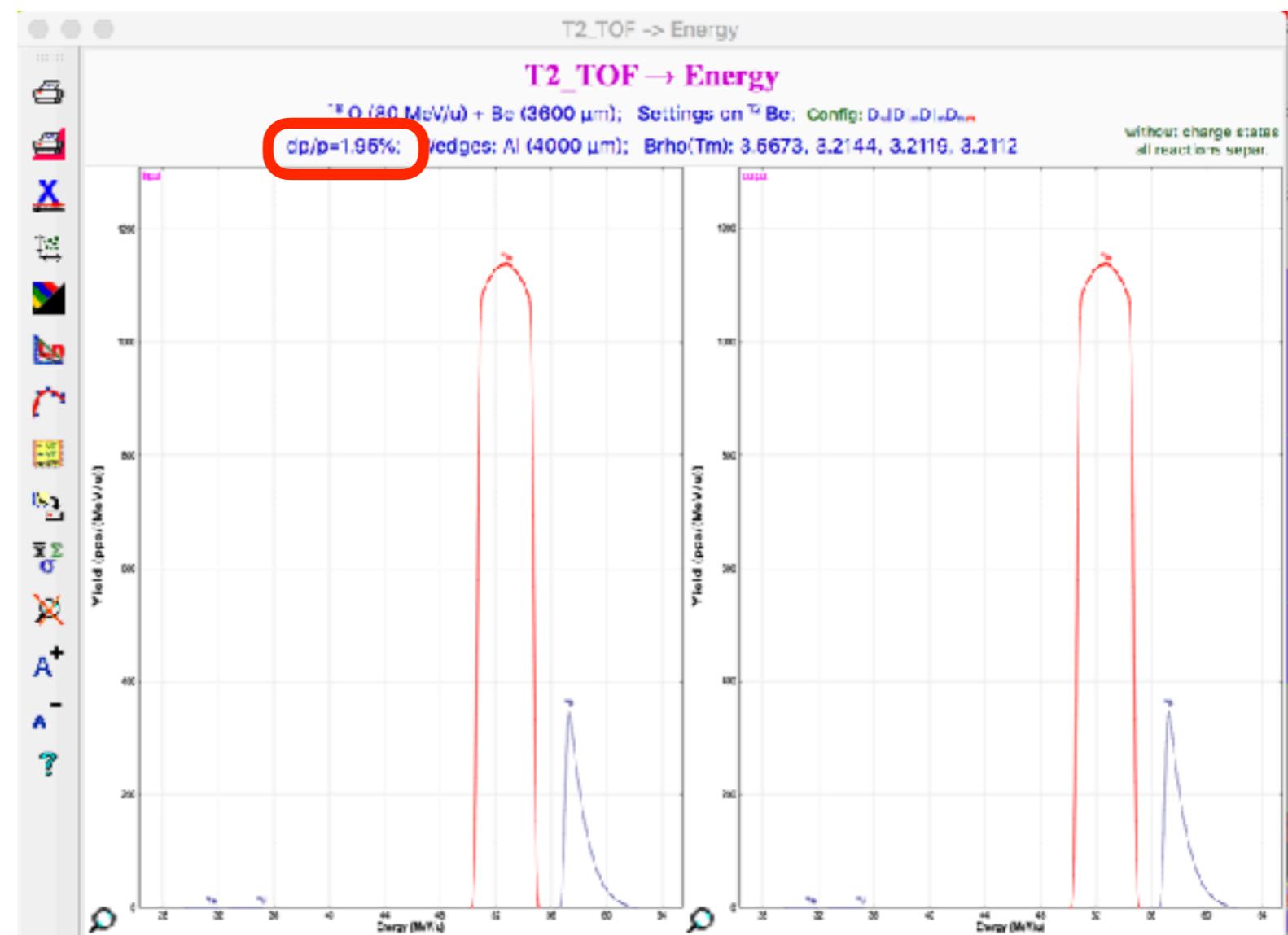
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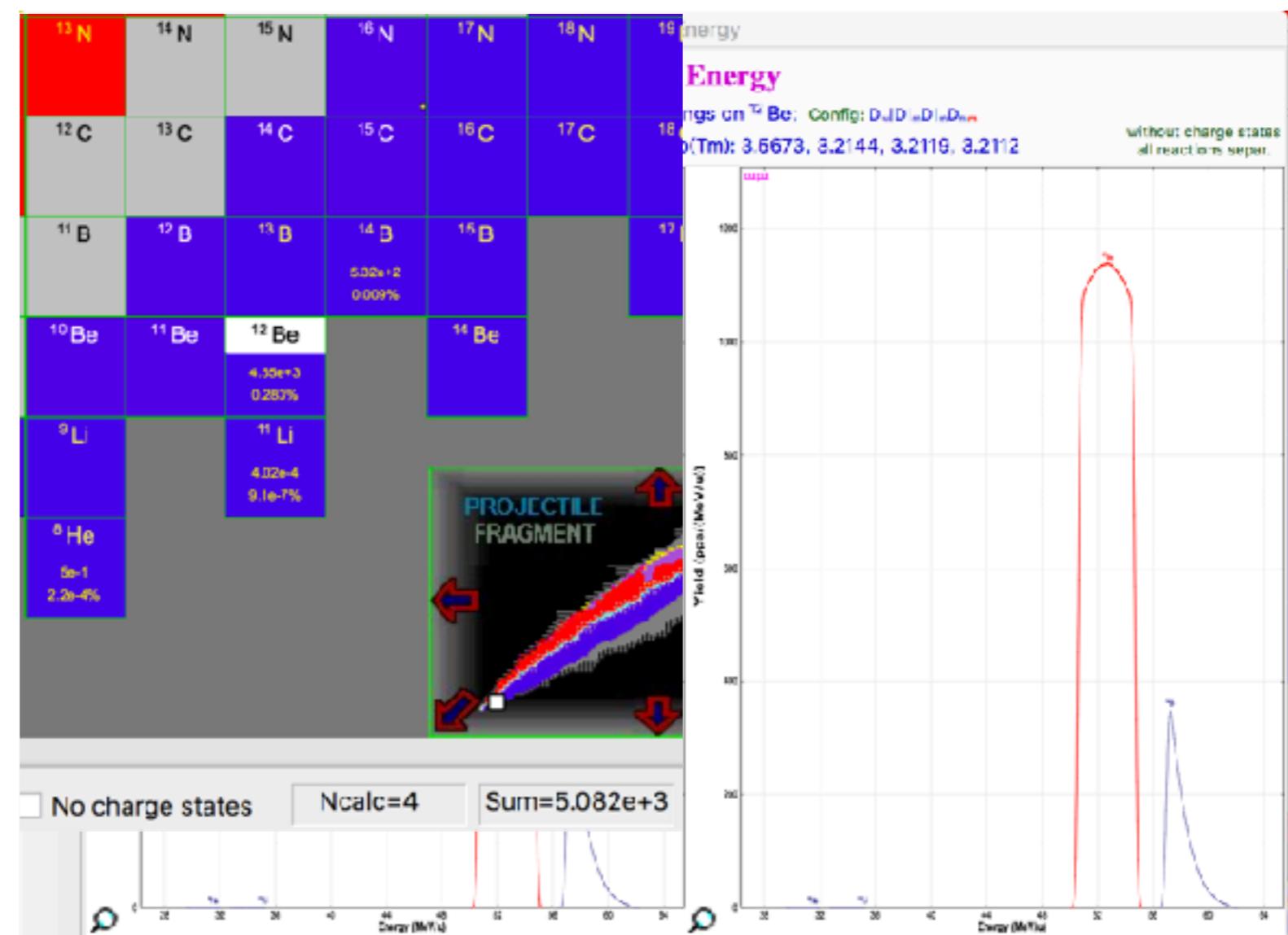
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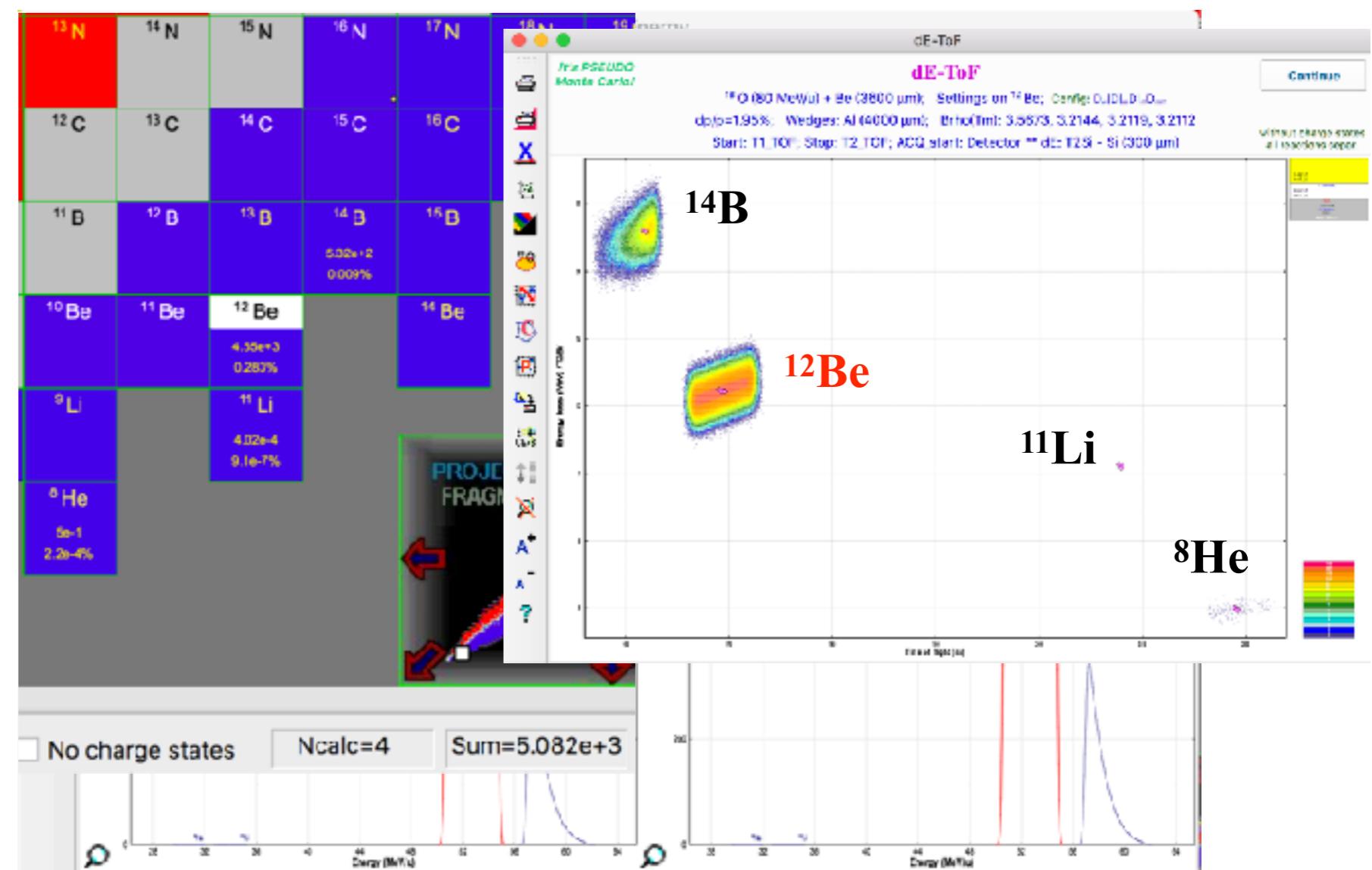
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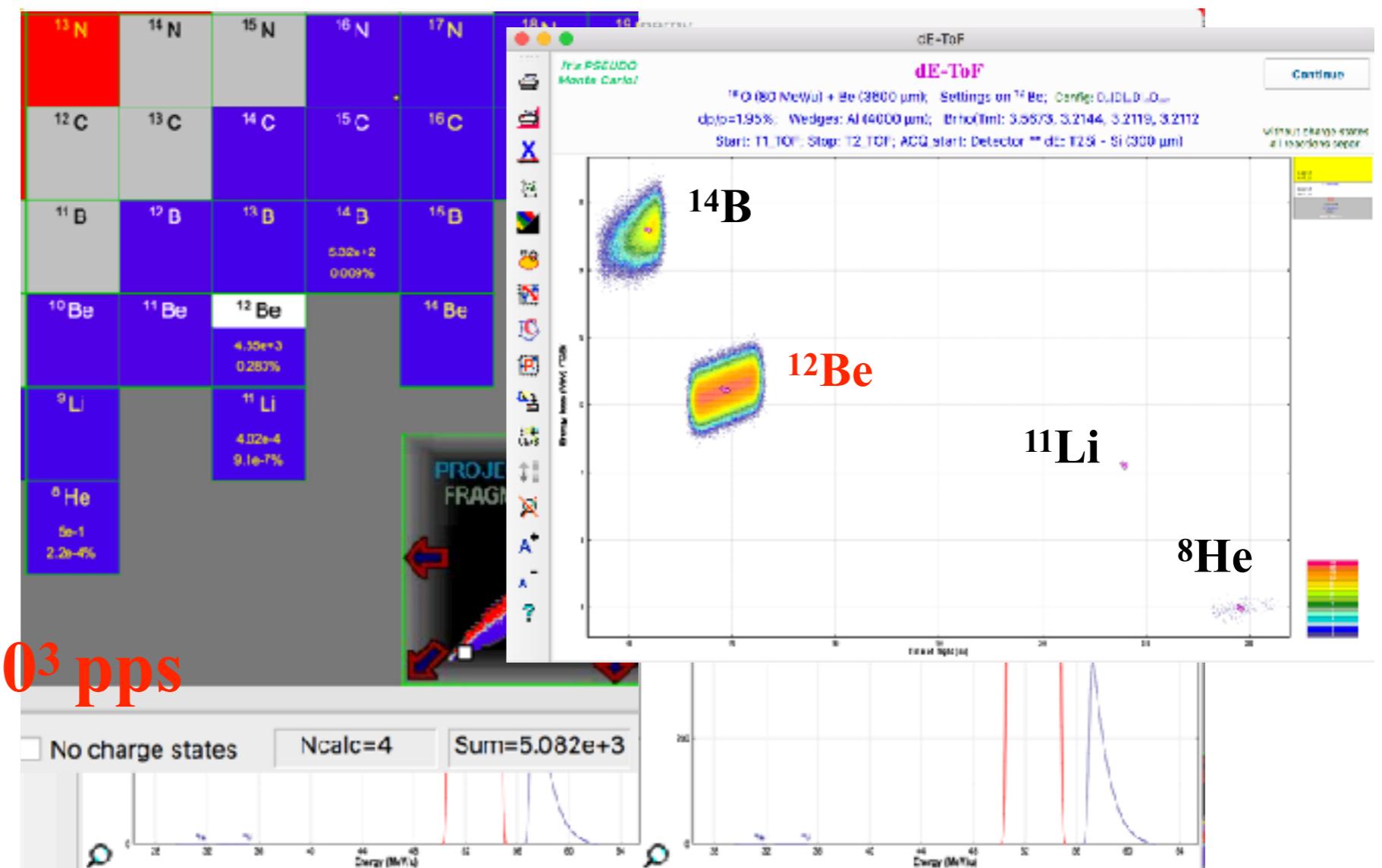
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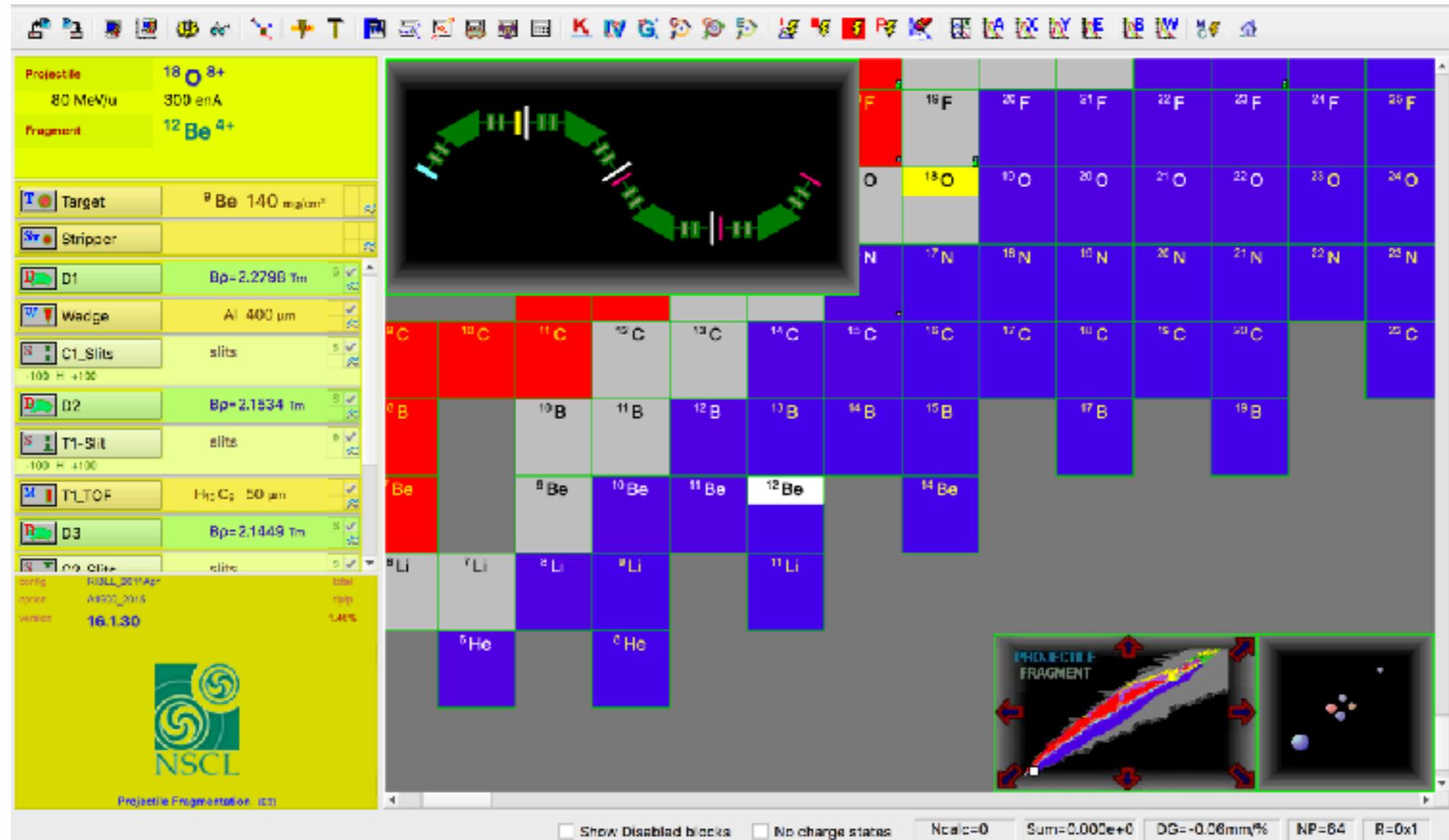
进一步优化碎片分离

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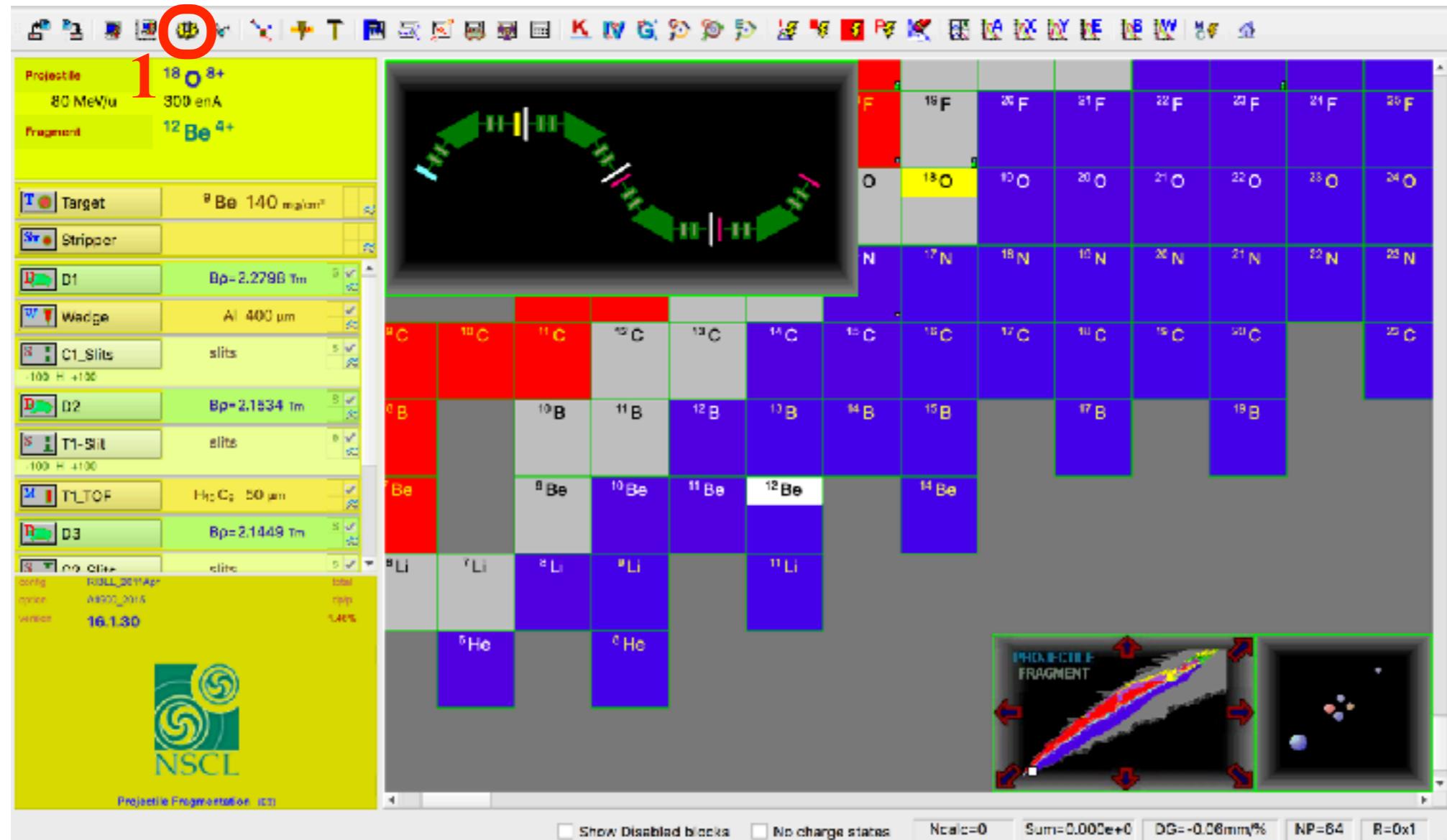


- ¹²Be产额 $\sim 4.6 \times 10^3$ pps
- ¹²Be纯度 =
 $4.55/5.08 \times 100\%$
 $\sim 90\%$

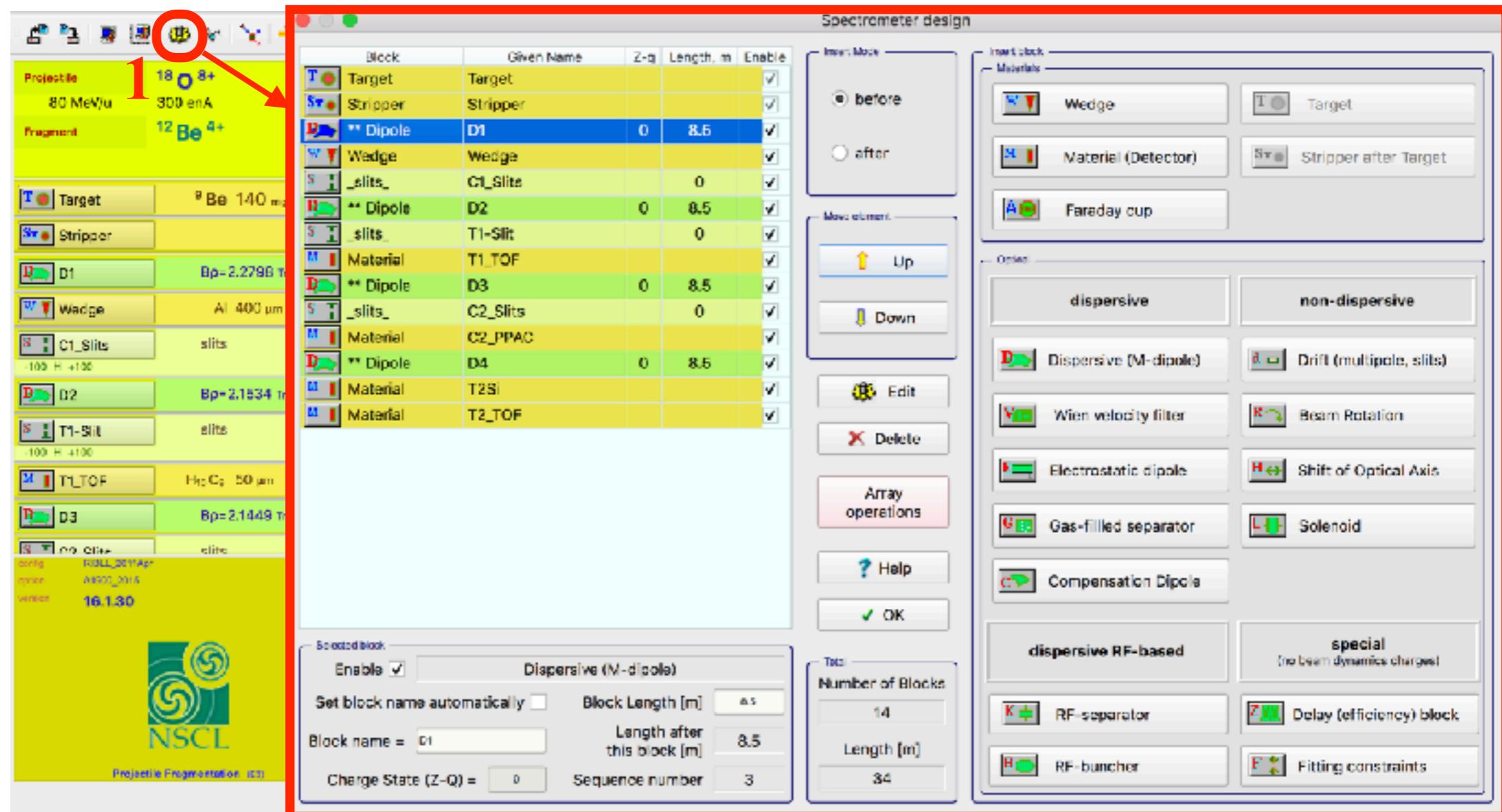
碎片分离器设计：传输矩阵



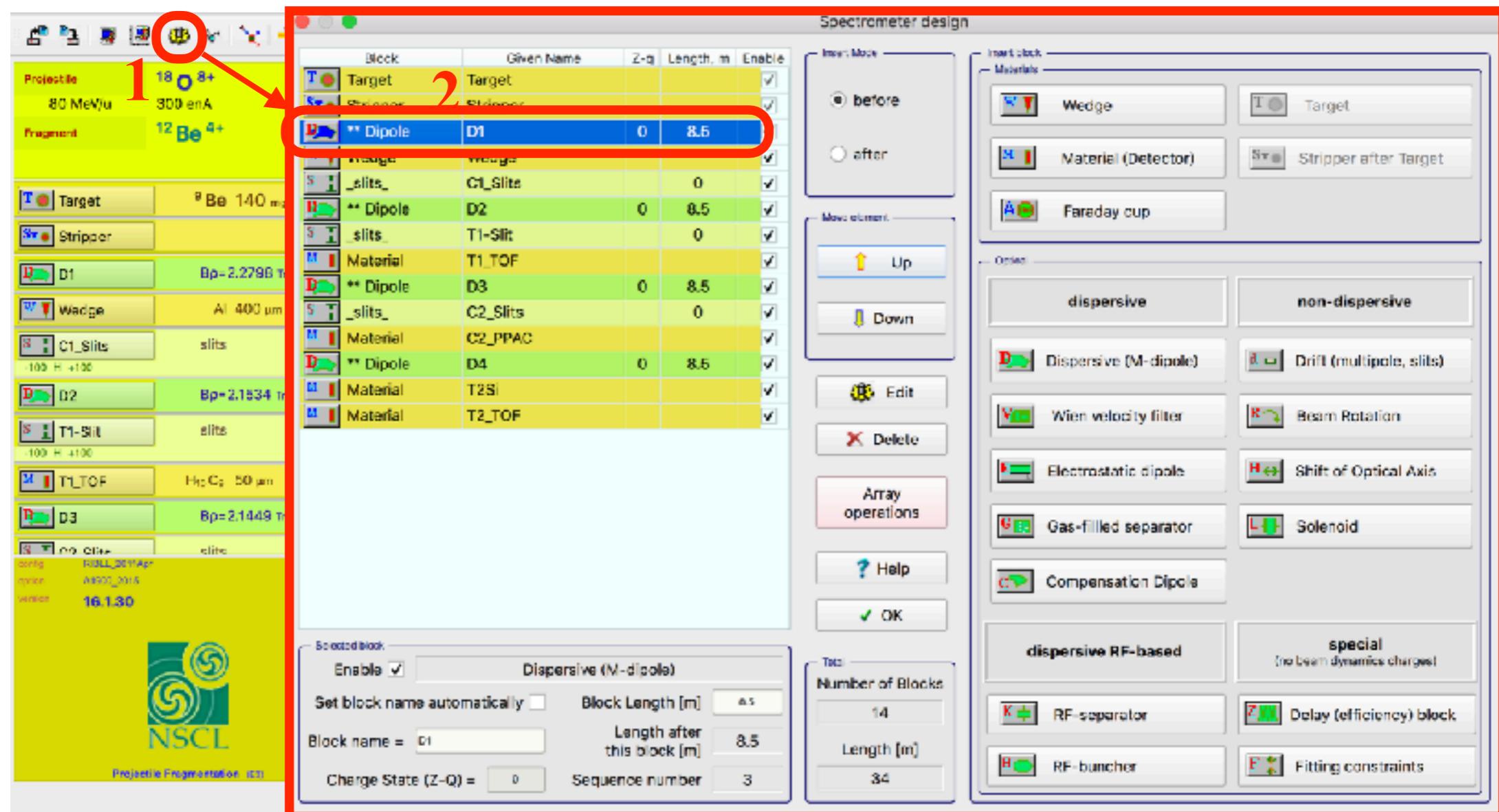
碎片分离器设计：传输矩阵



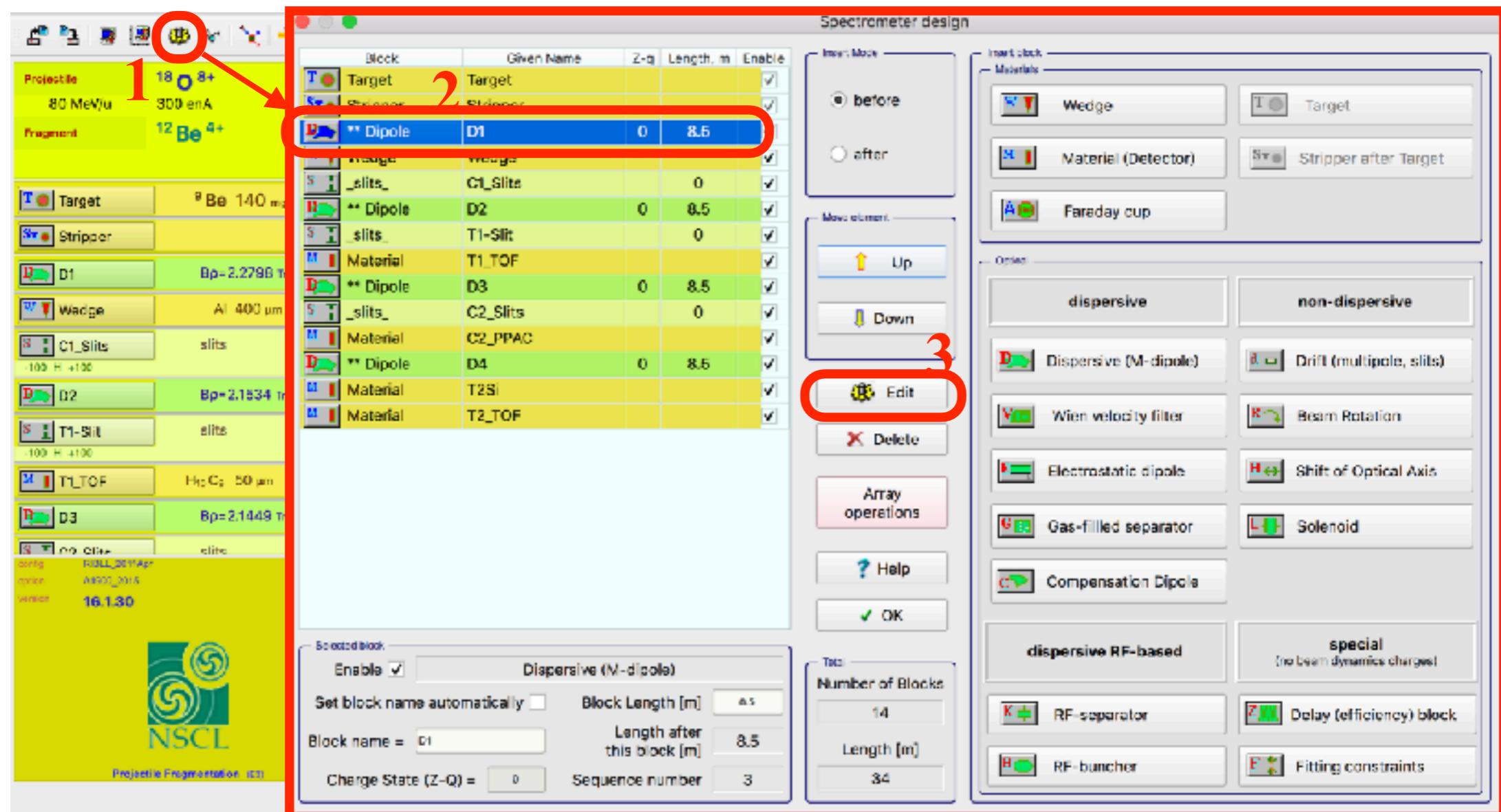
碎片分离器设计：传输矩阵



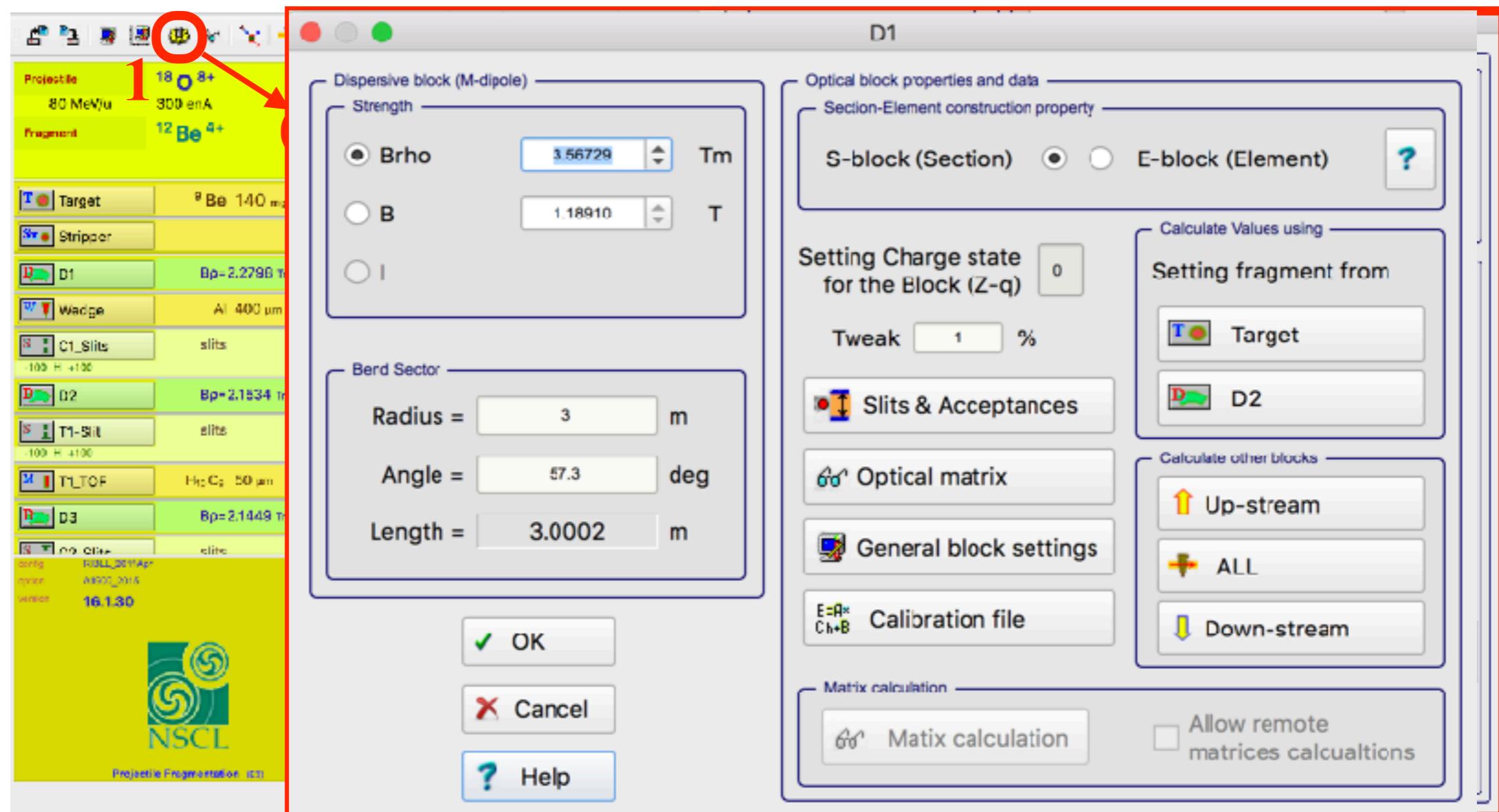
碎片分离器设计：传输矩阵



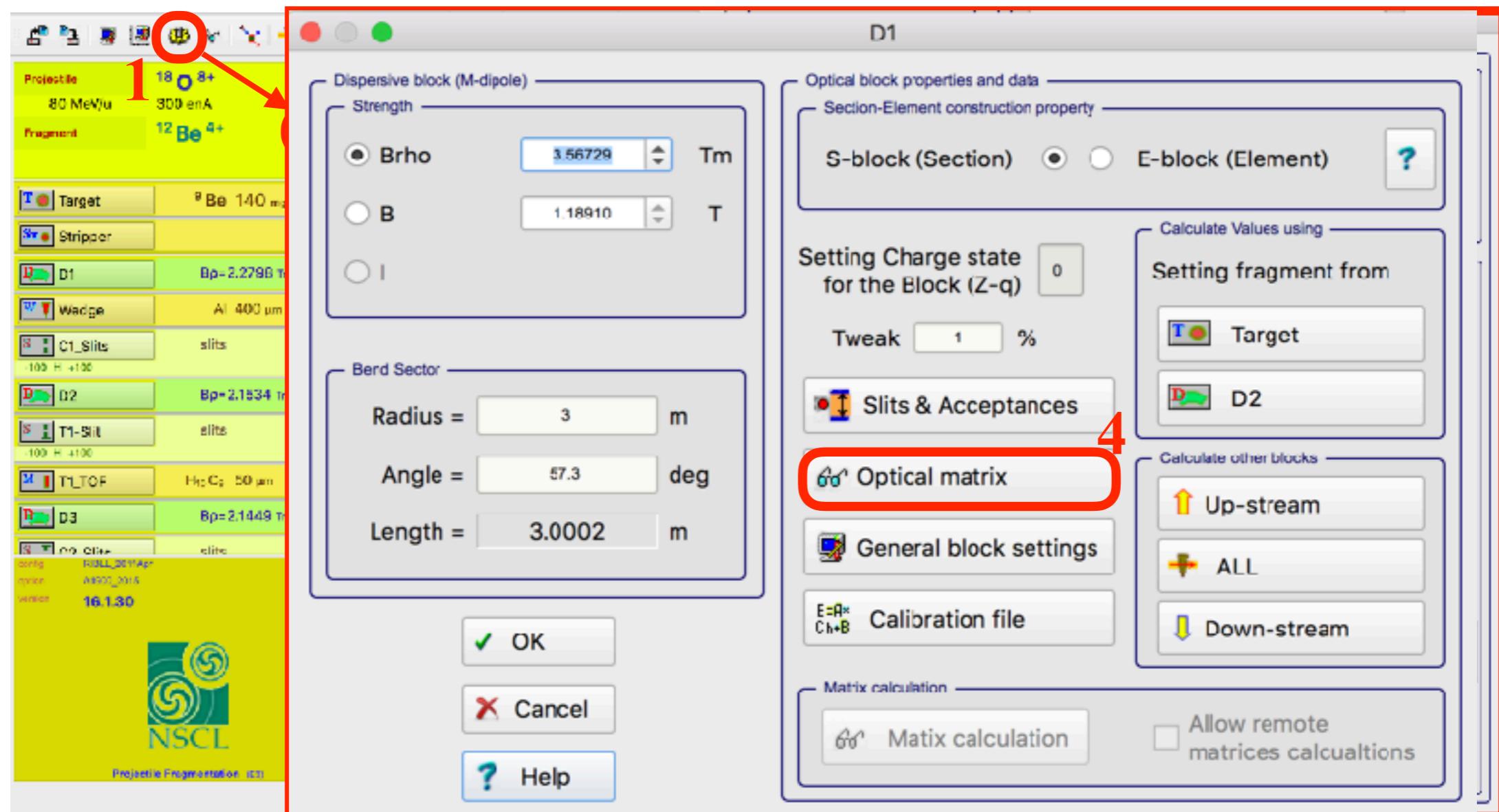
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碎片分离器设计：传输矩阵



碎片分离器设计：传输矩阵



碎片分离器设计：传输矩阵

Optical matrix - D1

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

G - Global, L - Block (Local)

Dimensional: mm cm

Matrices: Block (local) Global

Second (& Higher) Order LOCAL matrix: Non Exist only for Monte Carlo transmission

T0 → C1

1. X	-0.5428	0.0824	0	0	0	20.482	[mm]
2. T	-0.0249	-1.3385	0	0	0	-0.0333	[mrad]
3. Y	0	0	-10.142	1.3268	0	0	[mm]
4. P	0	0	-0.0169	-0.0964	0	0	[mrad]
5. L	-0.5289	-3.7652	0	0	1	7.0278	[mm]
6. D	0	0	0	0	0	1	[%]
	/[mm]	/[mrad]	/[mm]	/[mrad]	/[mm]	/[%]	

Det= 1.00000

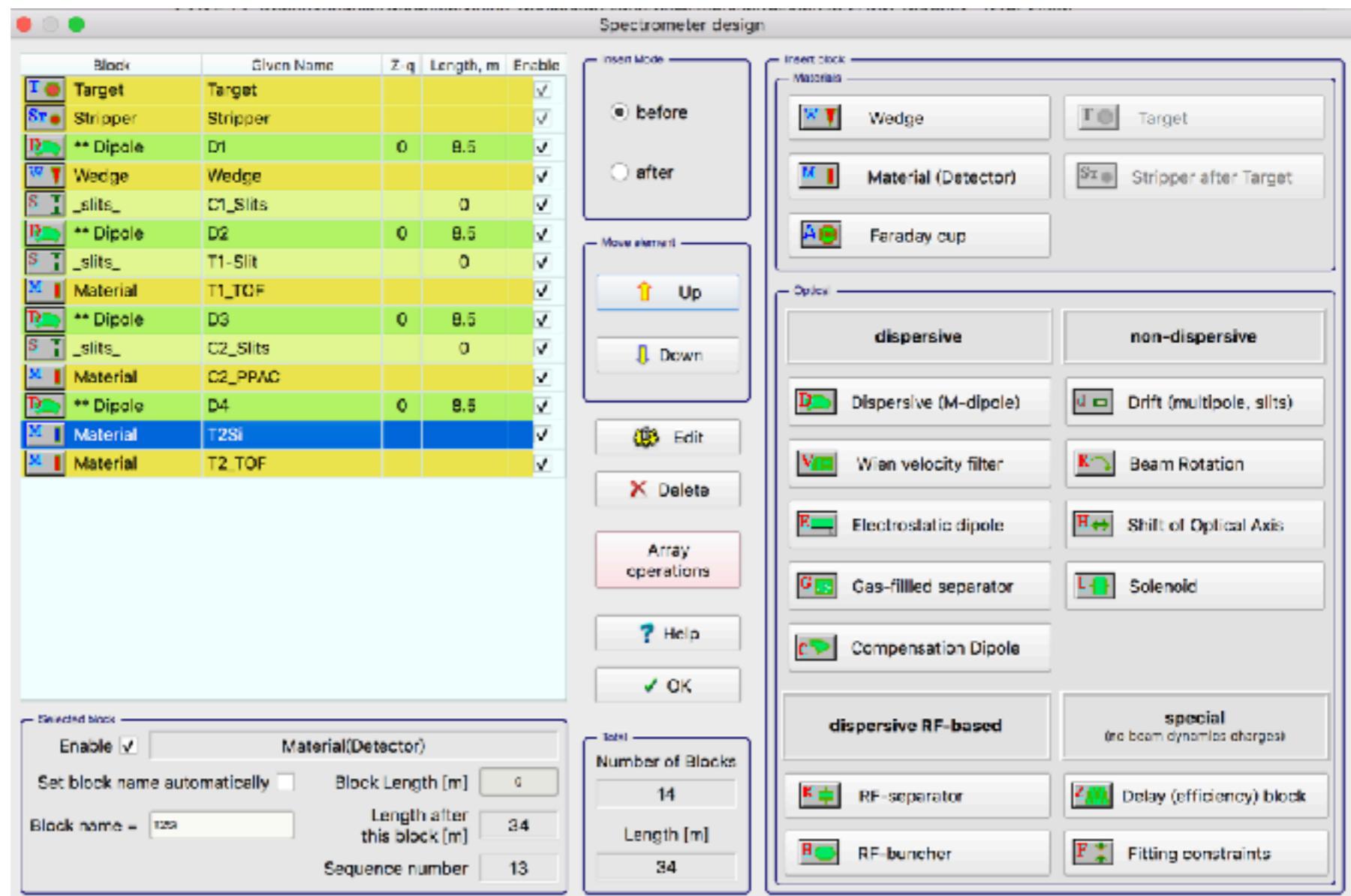
1. X	-0.5428	0.0824	0	0	0	20.482	[mm]
2. T	-0.0249	-1.3385	0	0	0	-0.0333	[mrad]
3. Y	0	0	-10.142	1.3268	0	0	[mm]
4. P	0	0	-0.0169	-0.0964	0	0	[mrad]
5. L	-0.5289	-3.7652	0	0	1	7.0278	[mm]
6. D	0	0	0	0	0	1	[%]
	/[mm]	/[mrad]	/[mm]	/[mrad]	/[mm]	/[%]	

Det= 1.0001

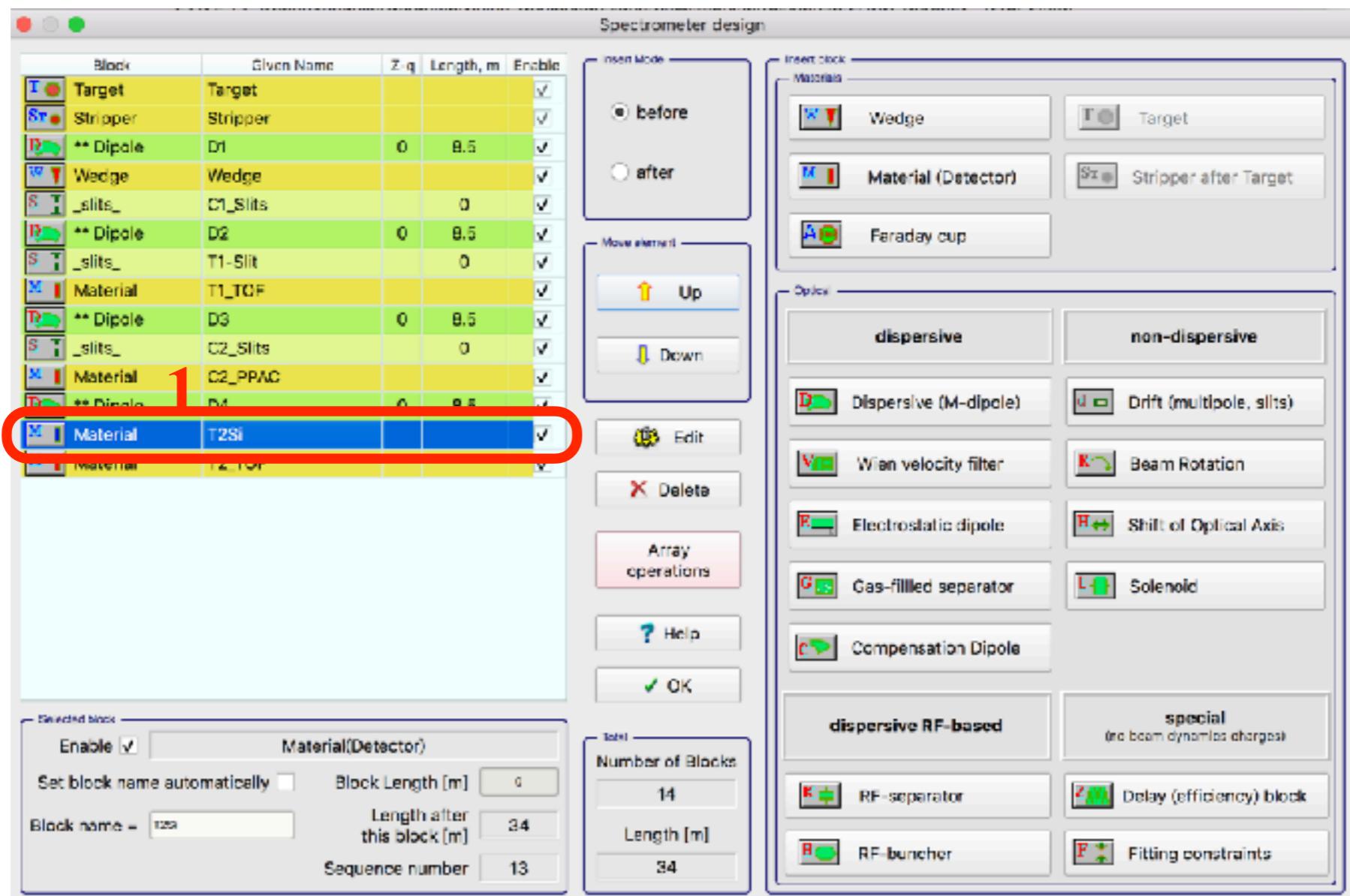
Dispersive (M-dipole)

OK Cancel Help Spectrometer matrix

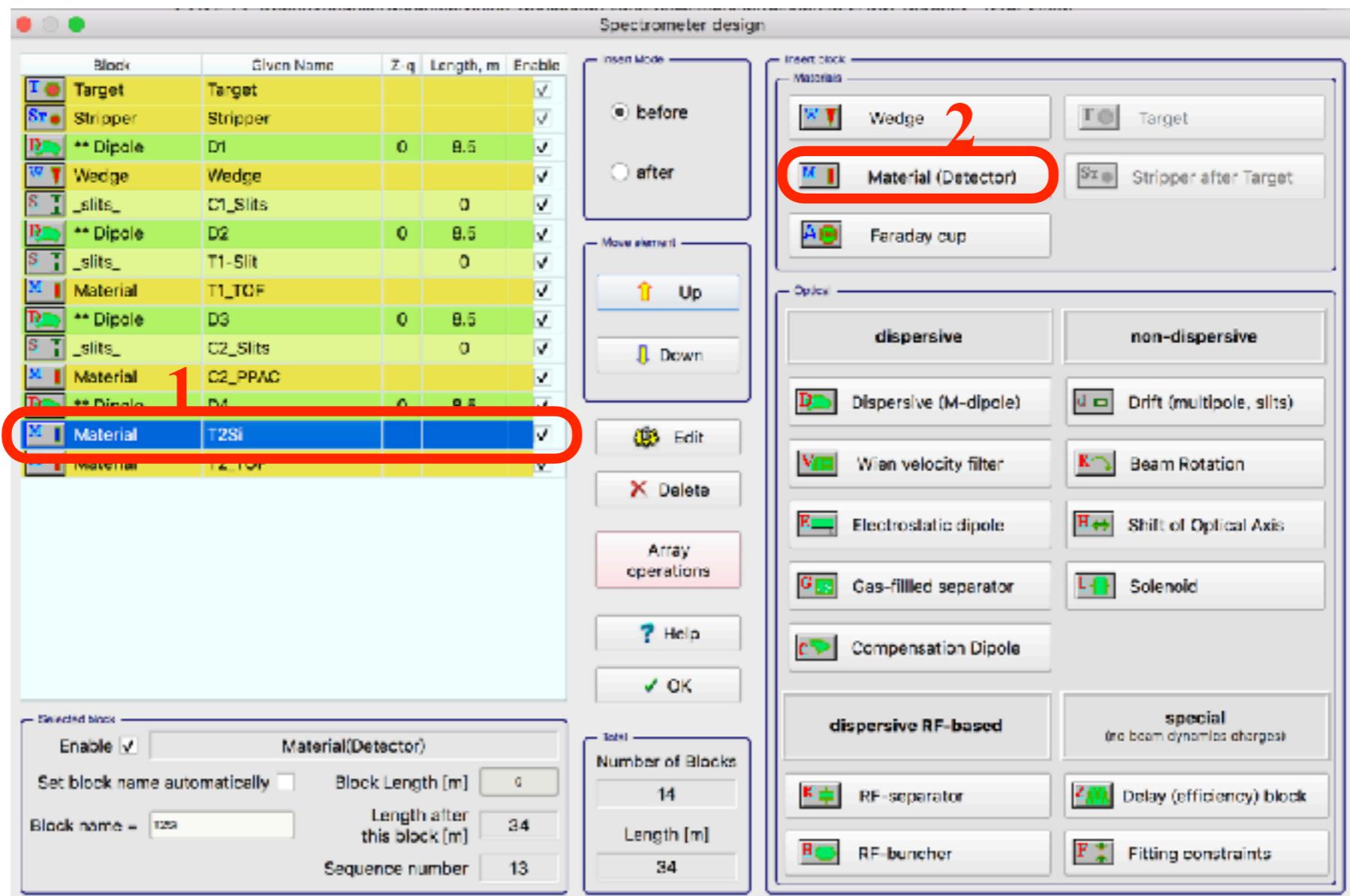
碎片分离器设计：探测器增设



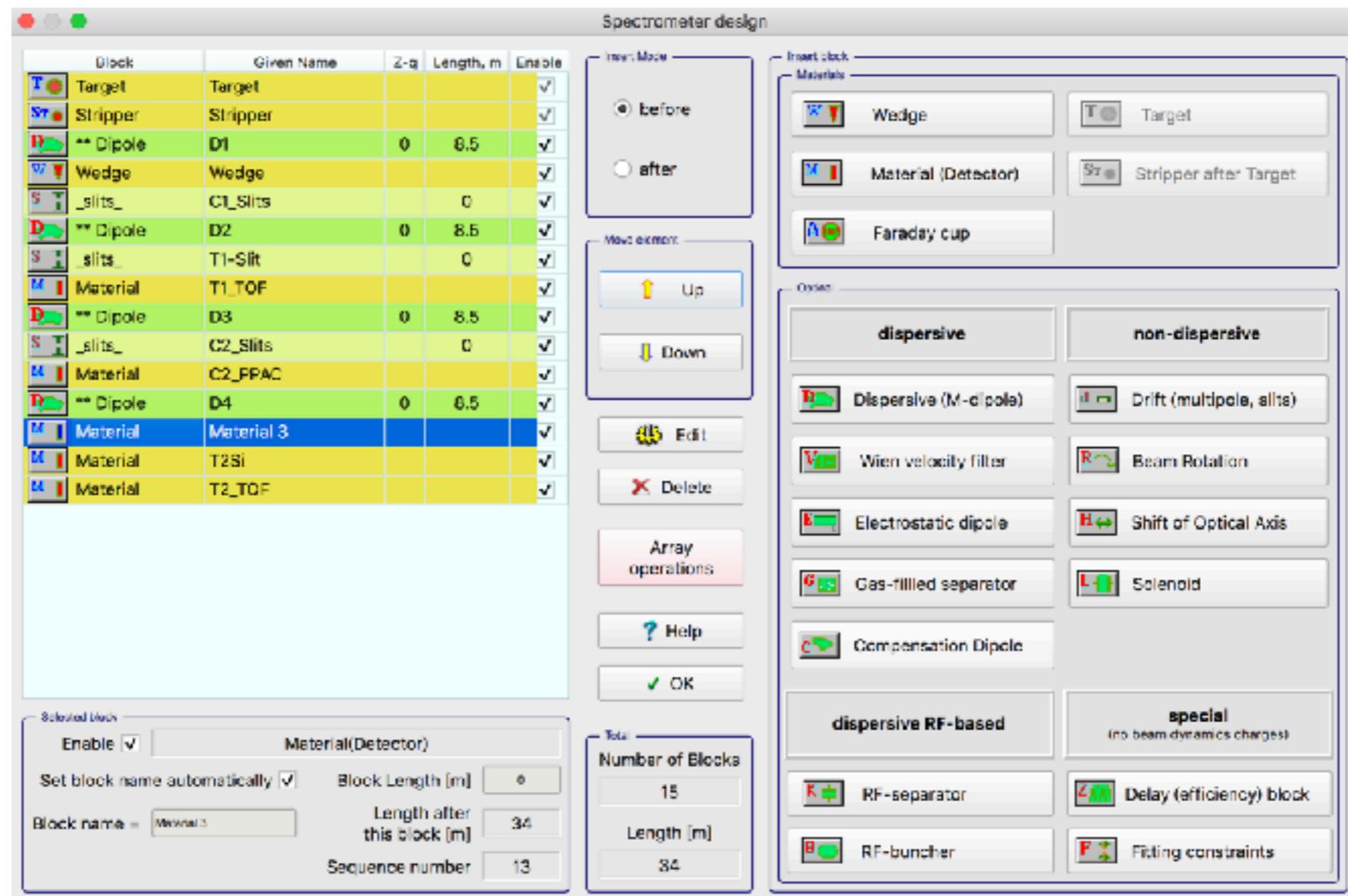
碎片分离器设计：探测器增设



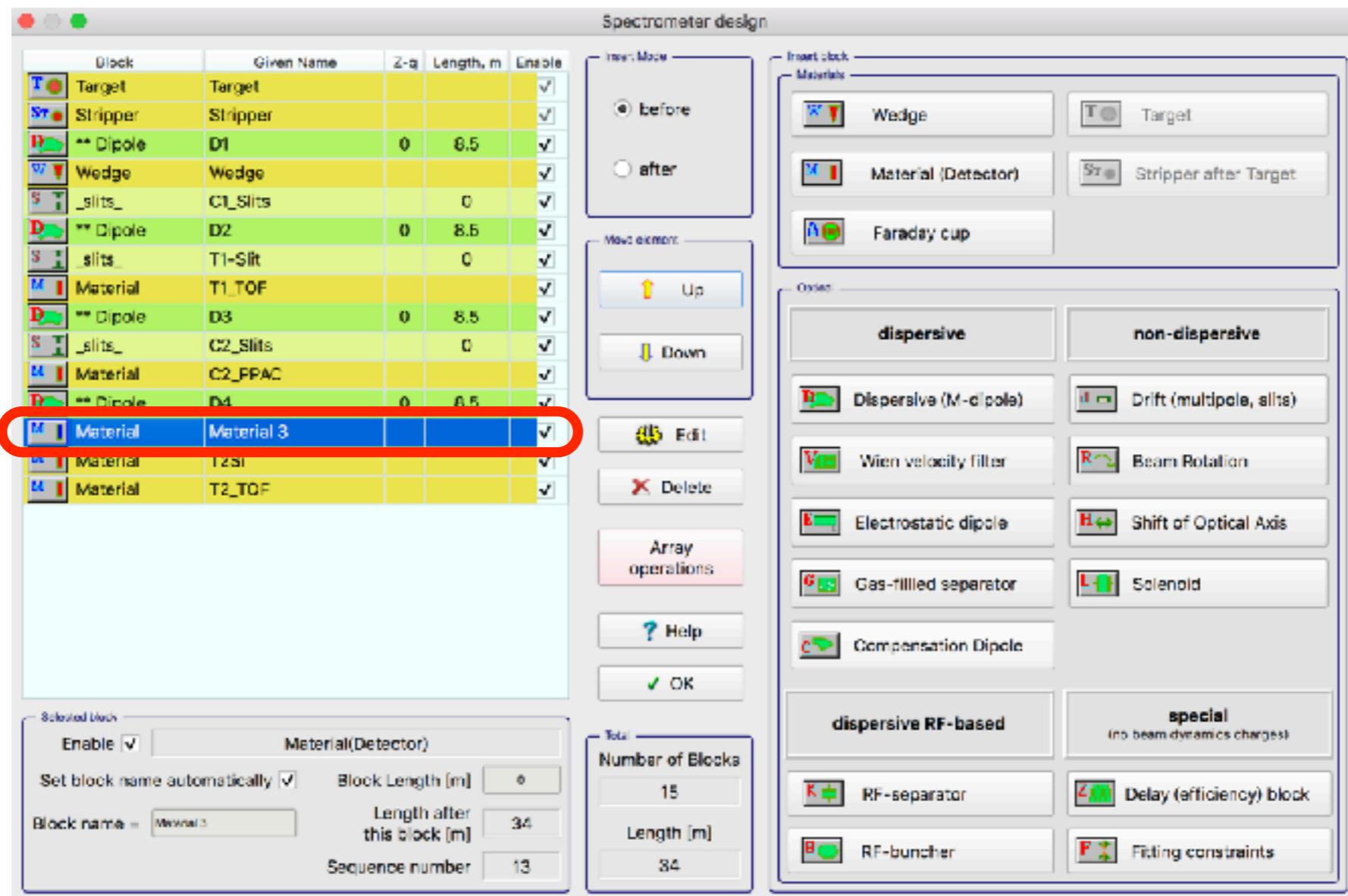
碎片分离器设计：探测器增设



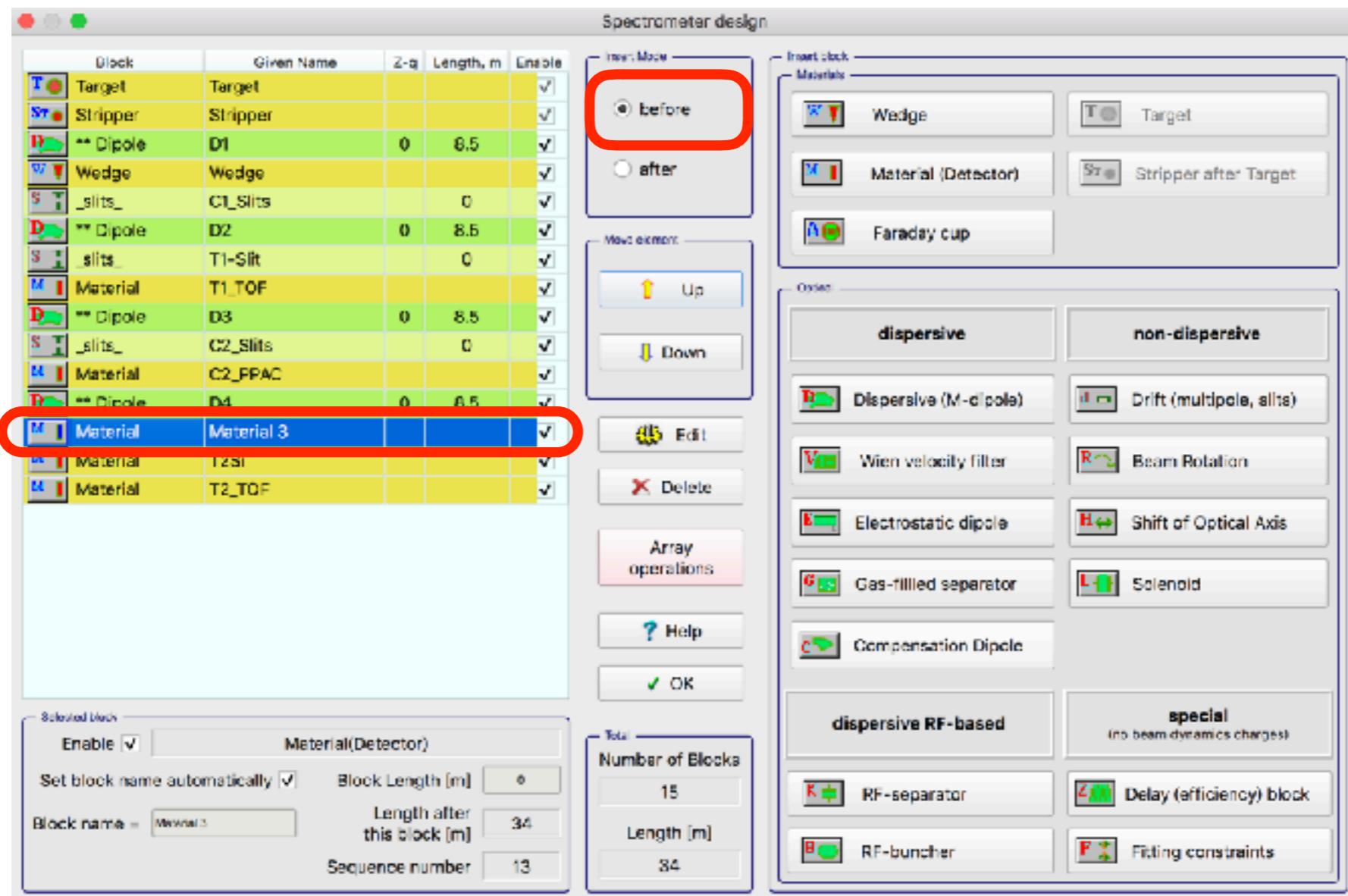
碎片分离器设计：探测器增设



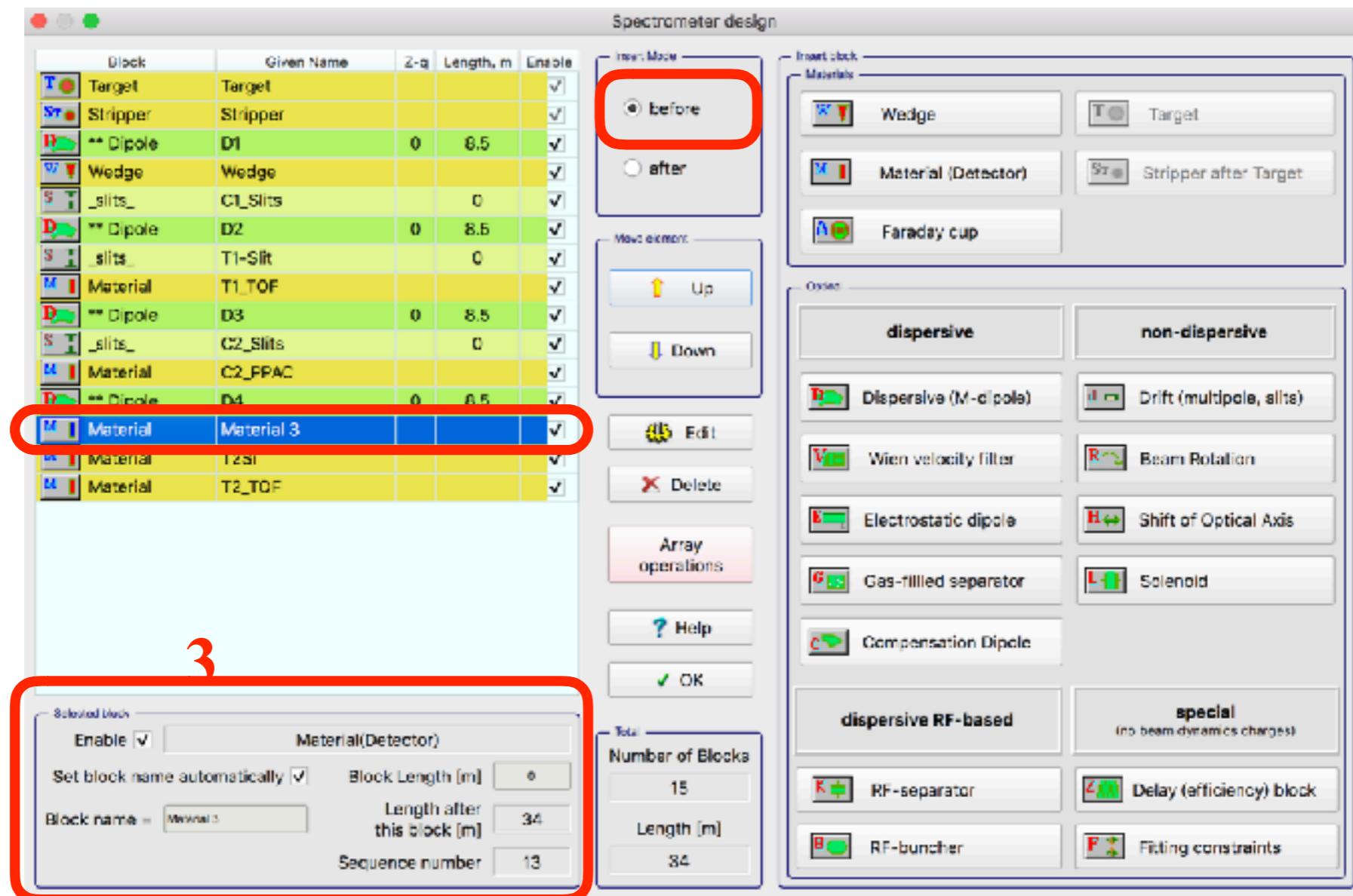
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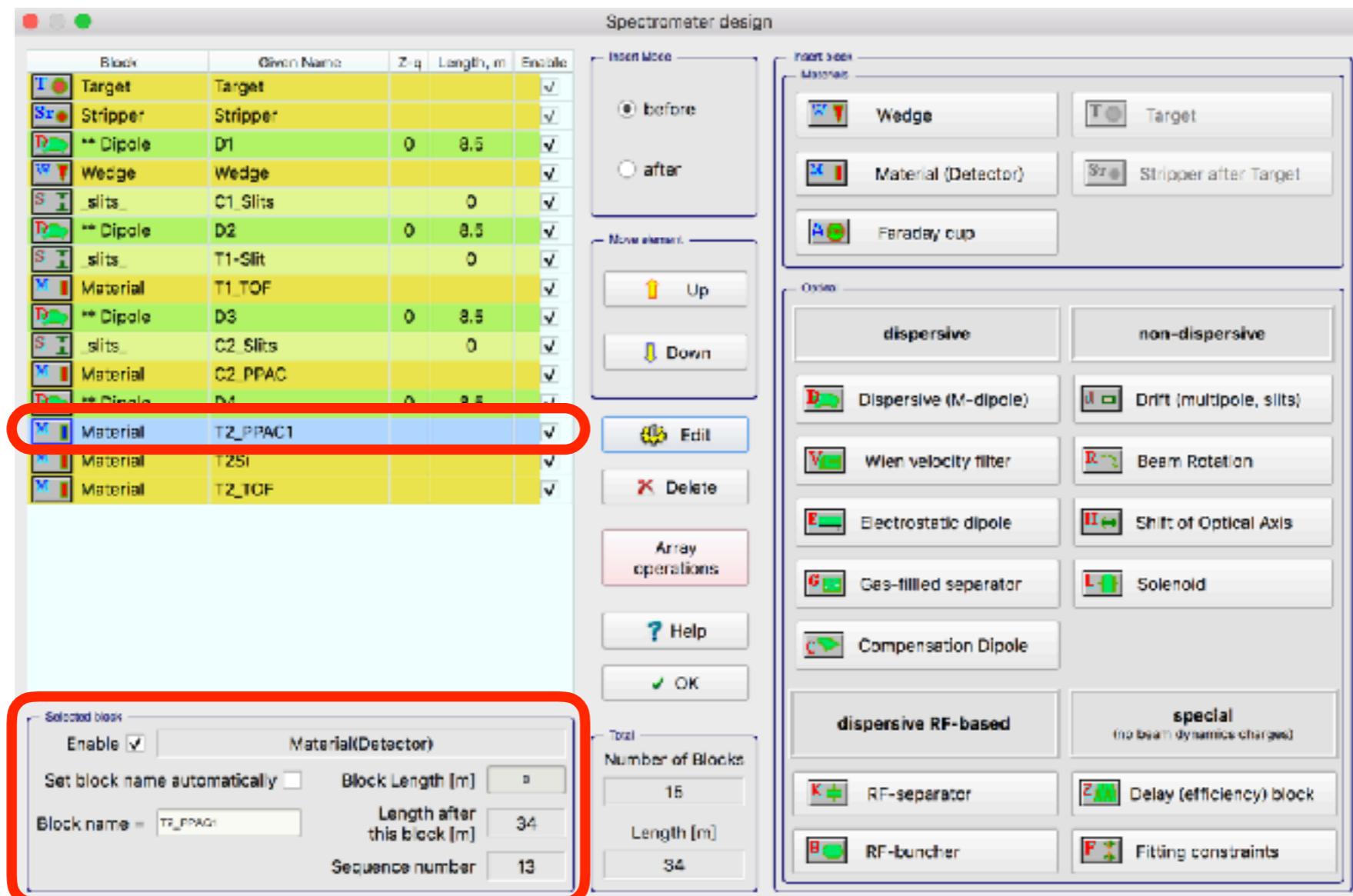
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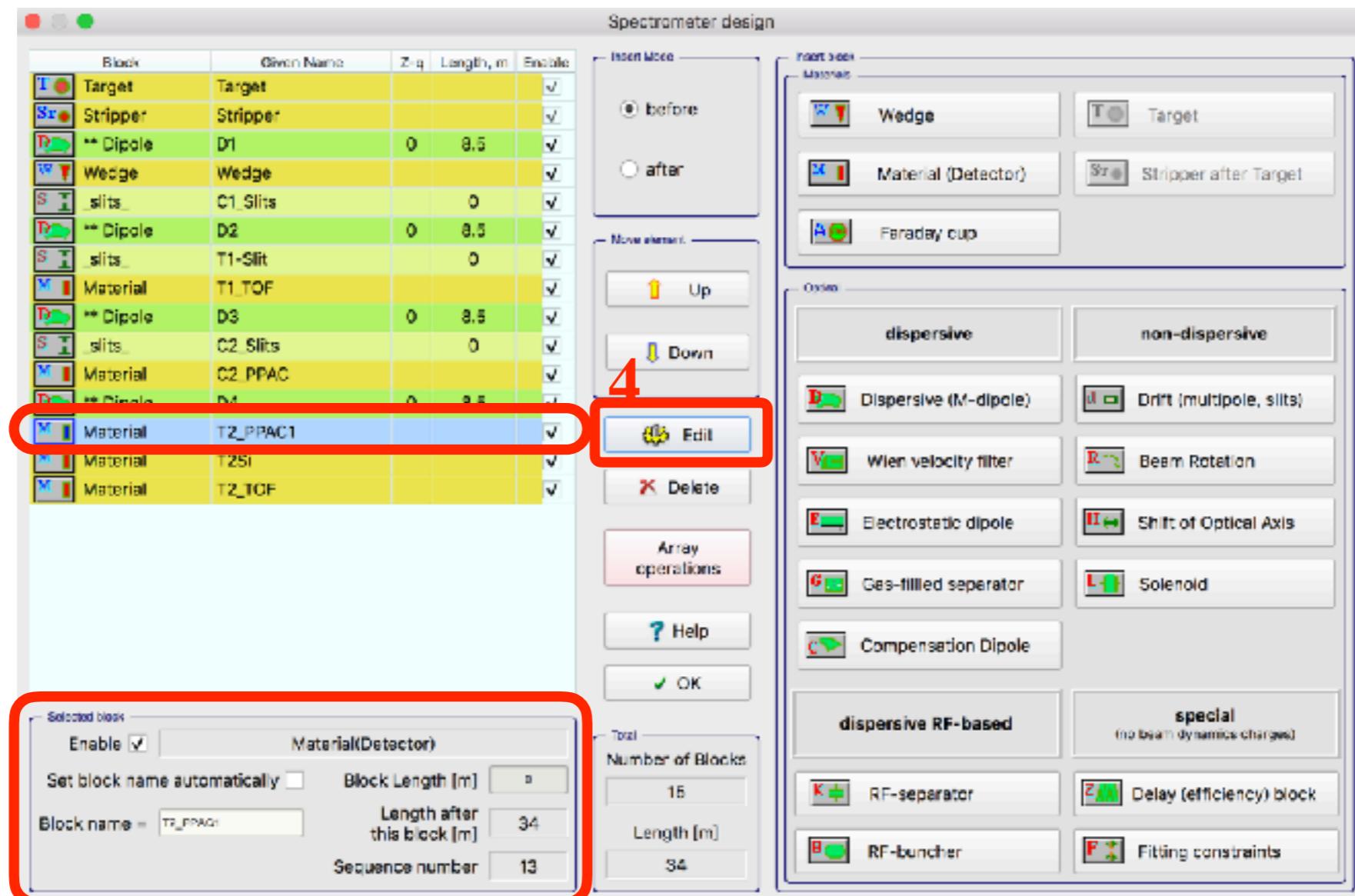
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碎片分离器设计：探测器增设

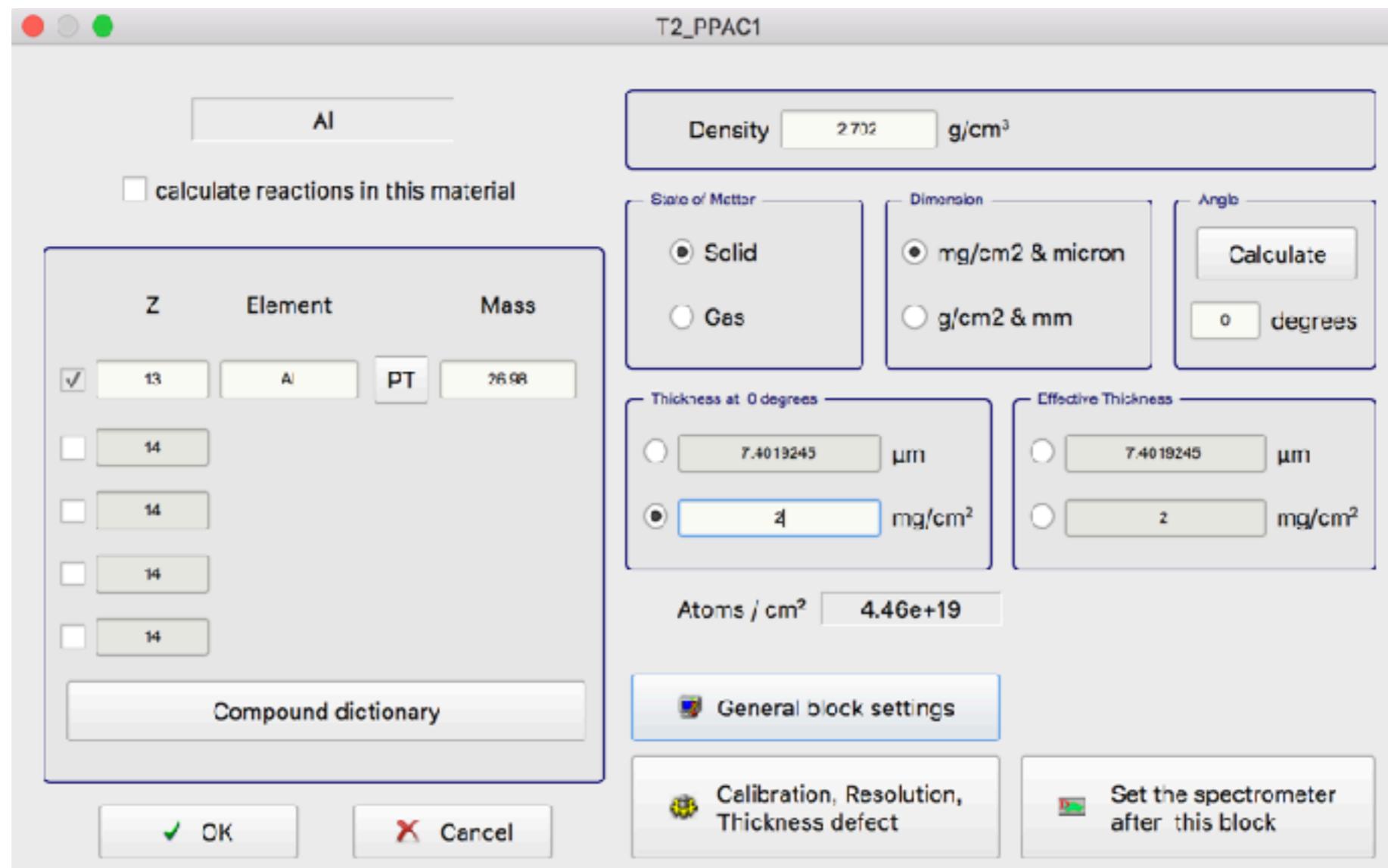


碎片分离器设计：探测器增设

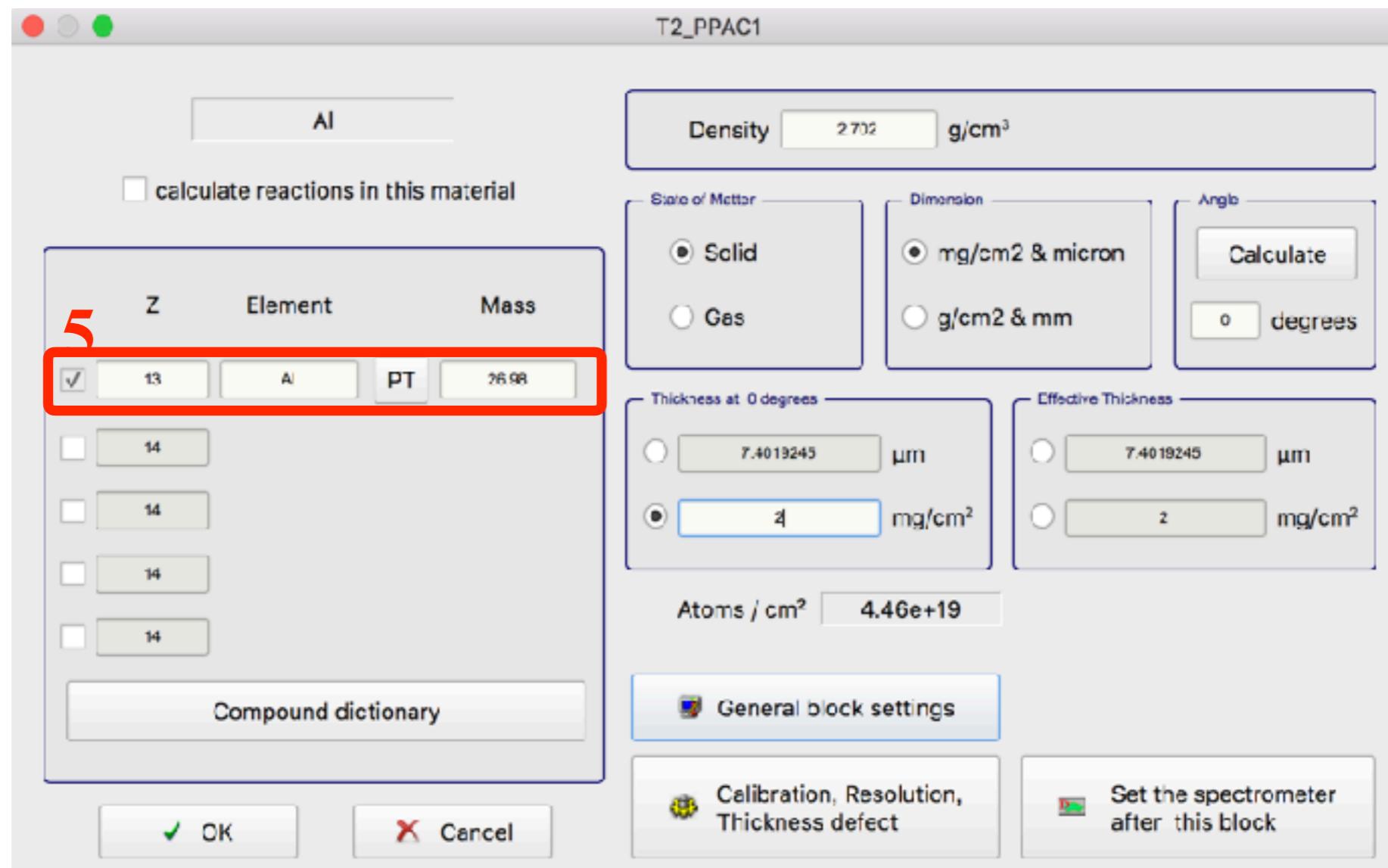


碎片分离器设计：探测器增设

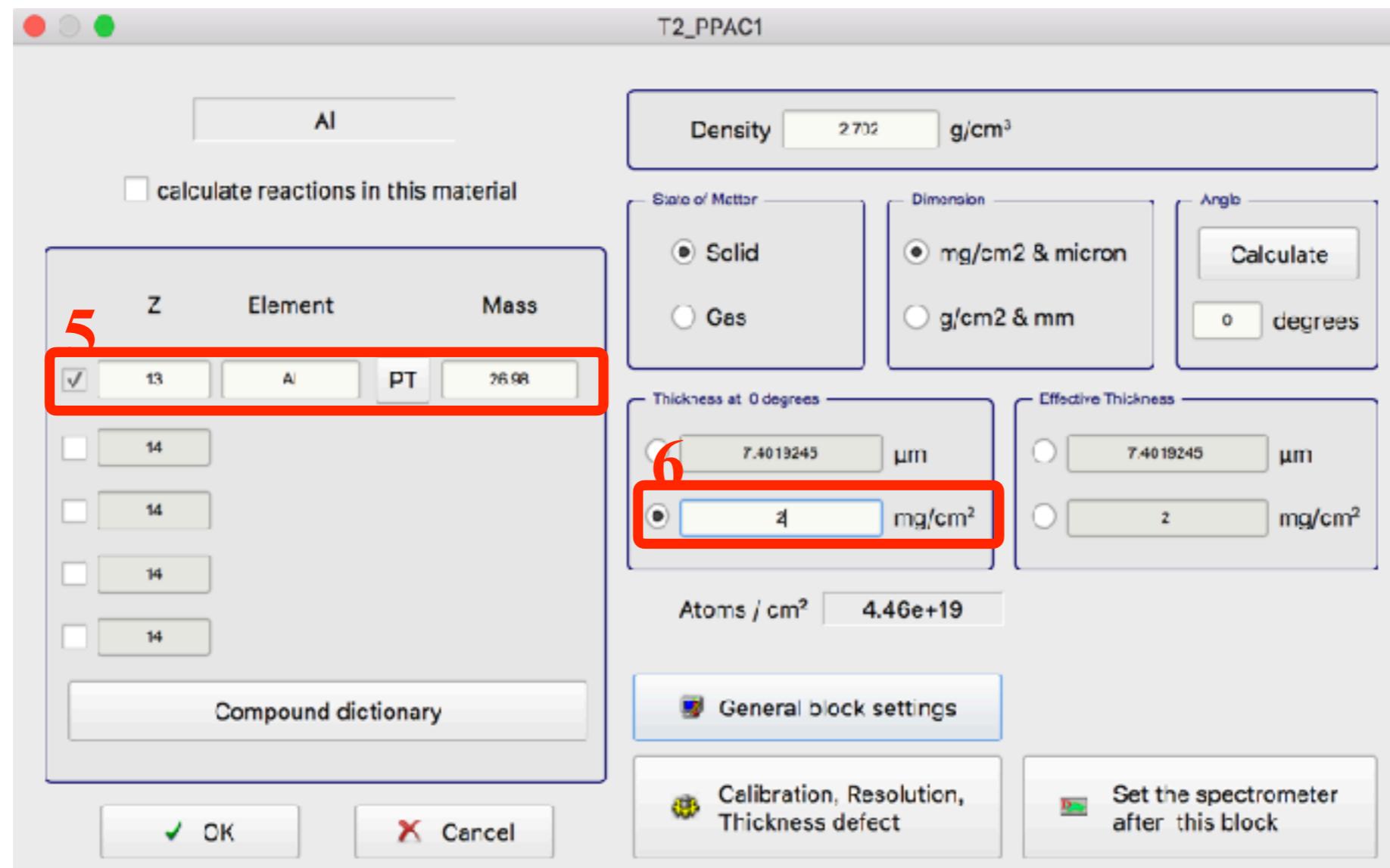
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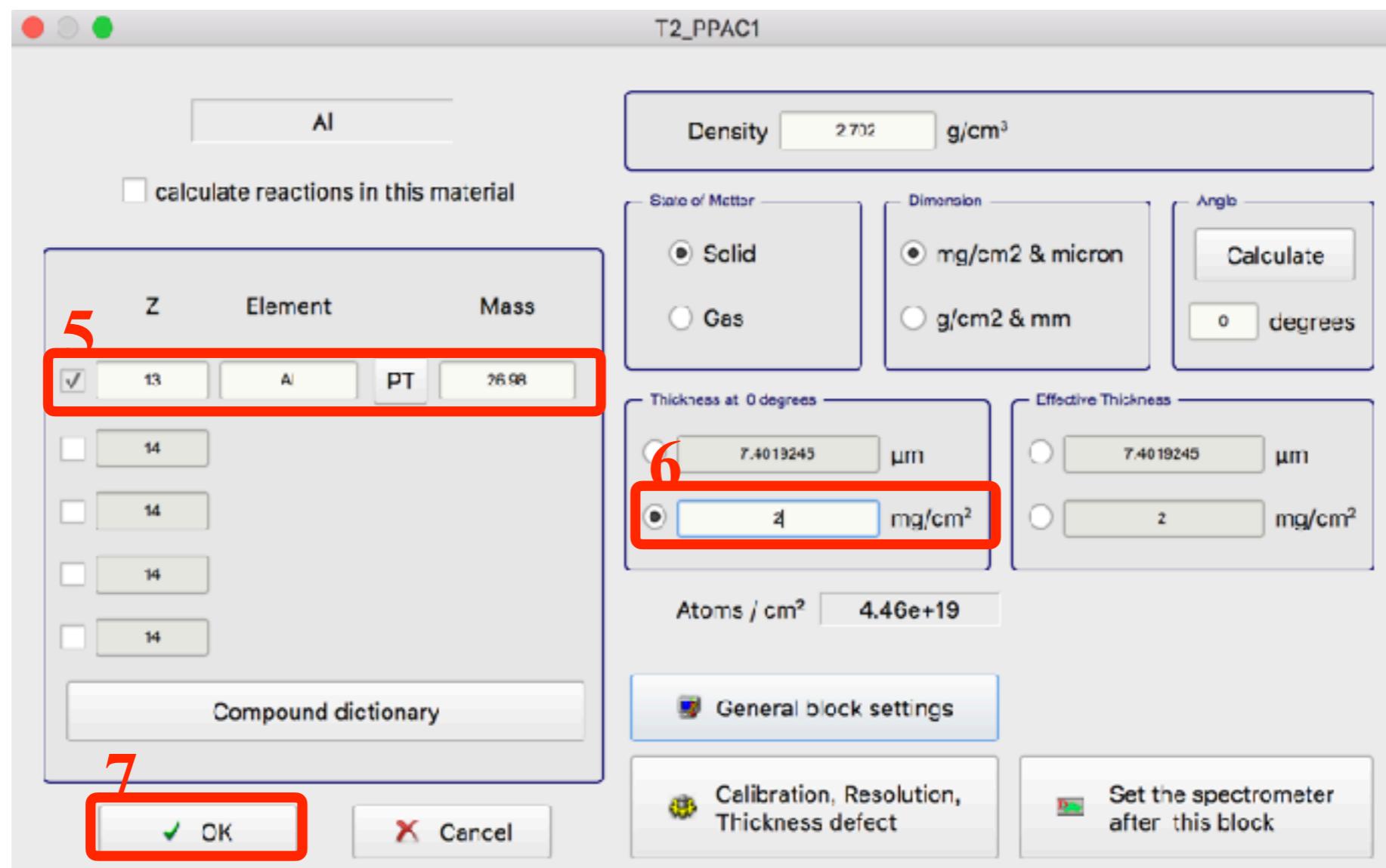
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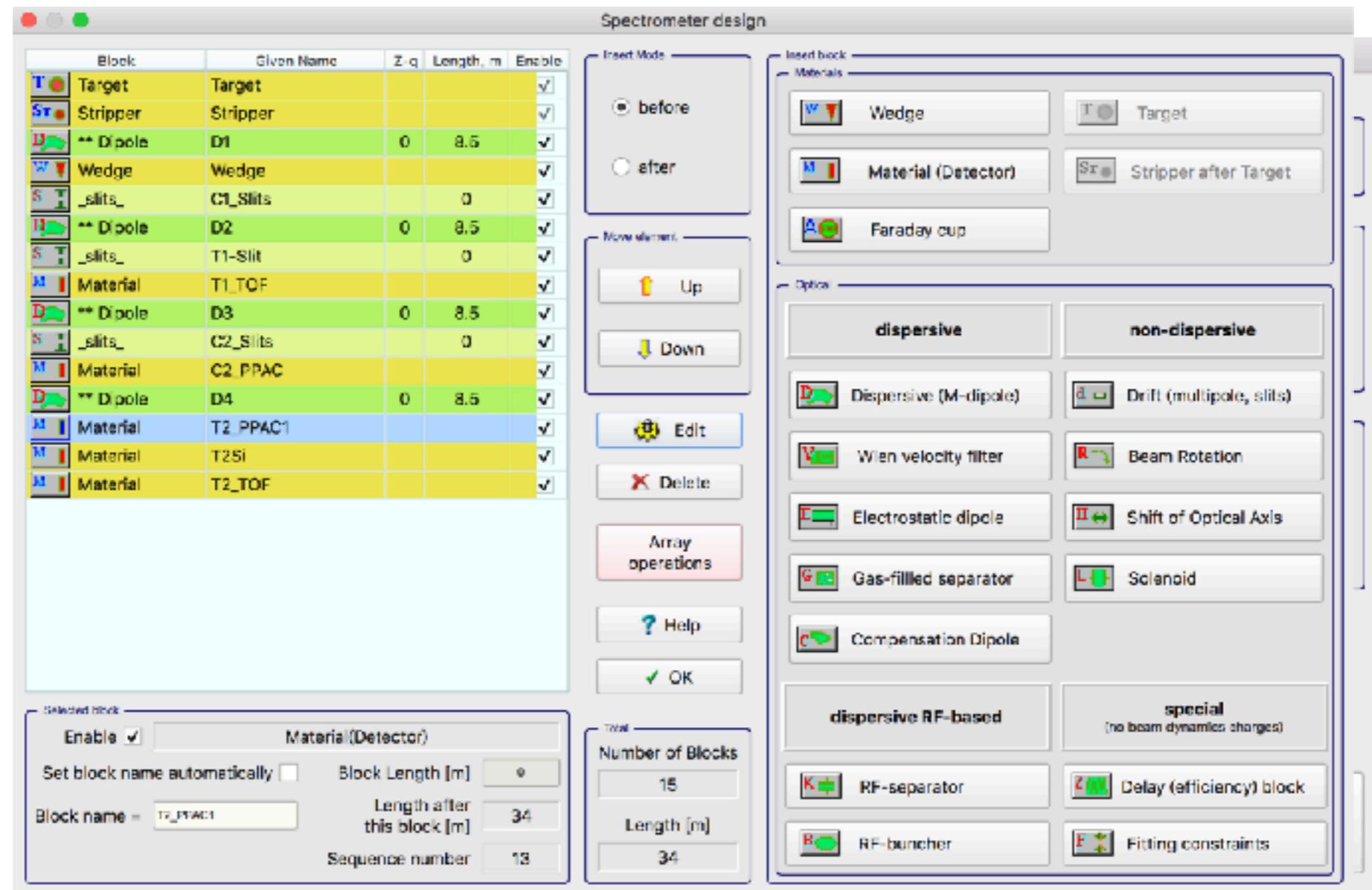
碎片分离器设计：探测器增设



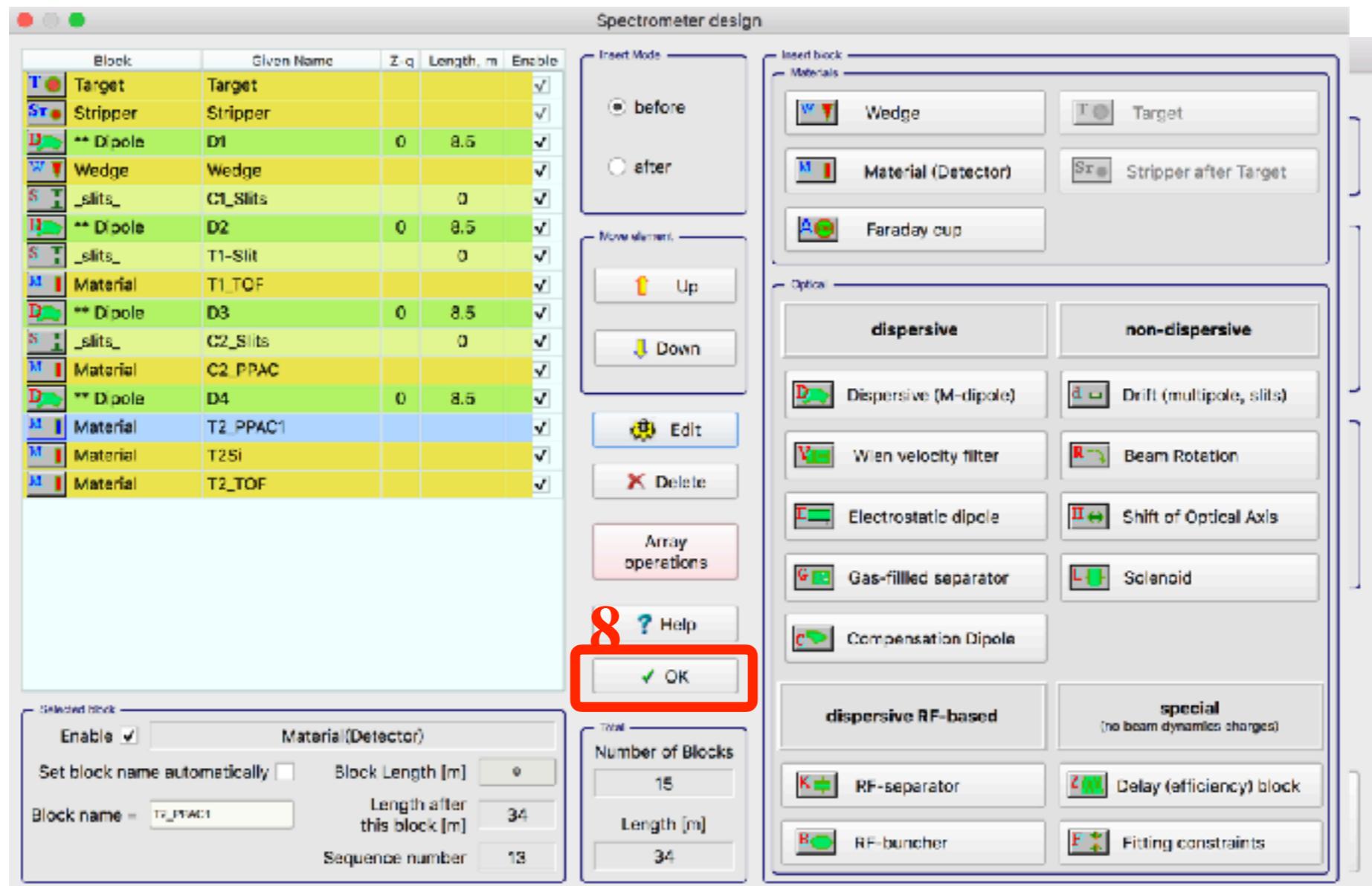
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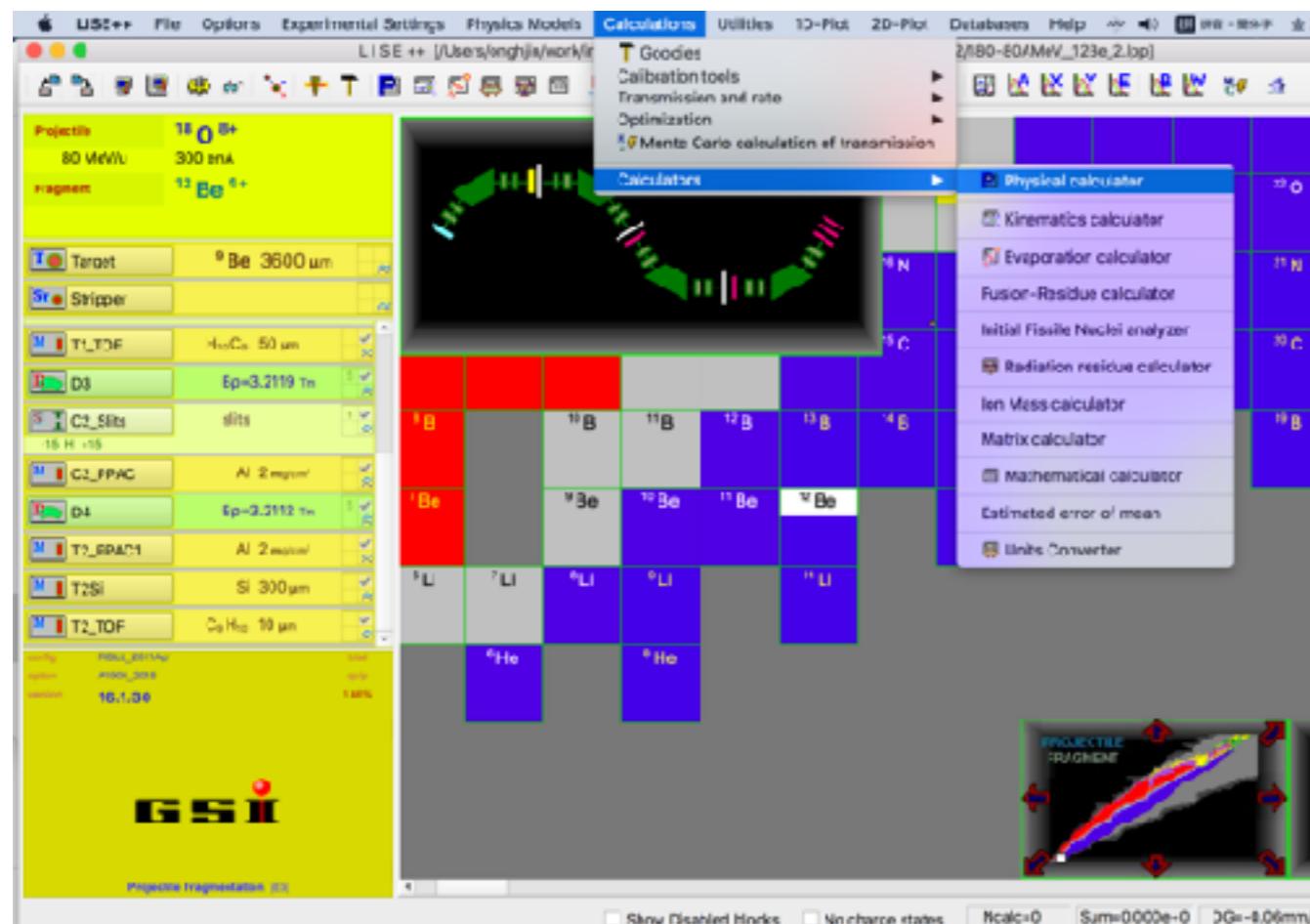
利用LISE++计算固定能量次级束

- 反应截面考量，例如核子转移反应： $10A \sim 30A$ MeV
- β 衰变测量、融合反应；需要把束流阻停在探测器
- 反应机制考量，例如弹性散射测量：束流能量~库仑位垒

利用LISE++计算固定能量次级束

利用能量80A MeV, 流强300 enA 的¹⁸O初级束产生¹²Be束流

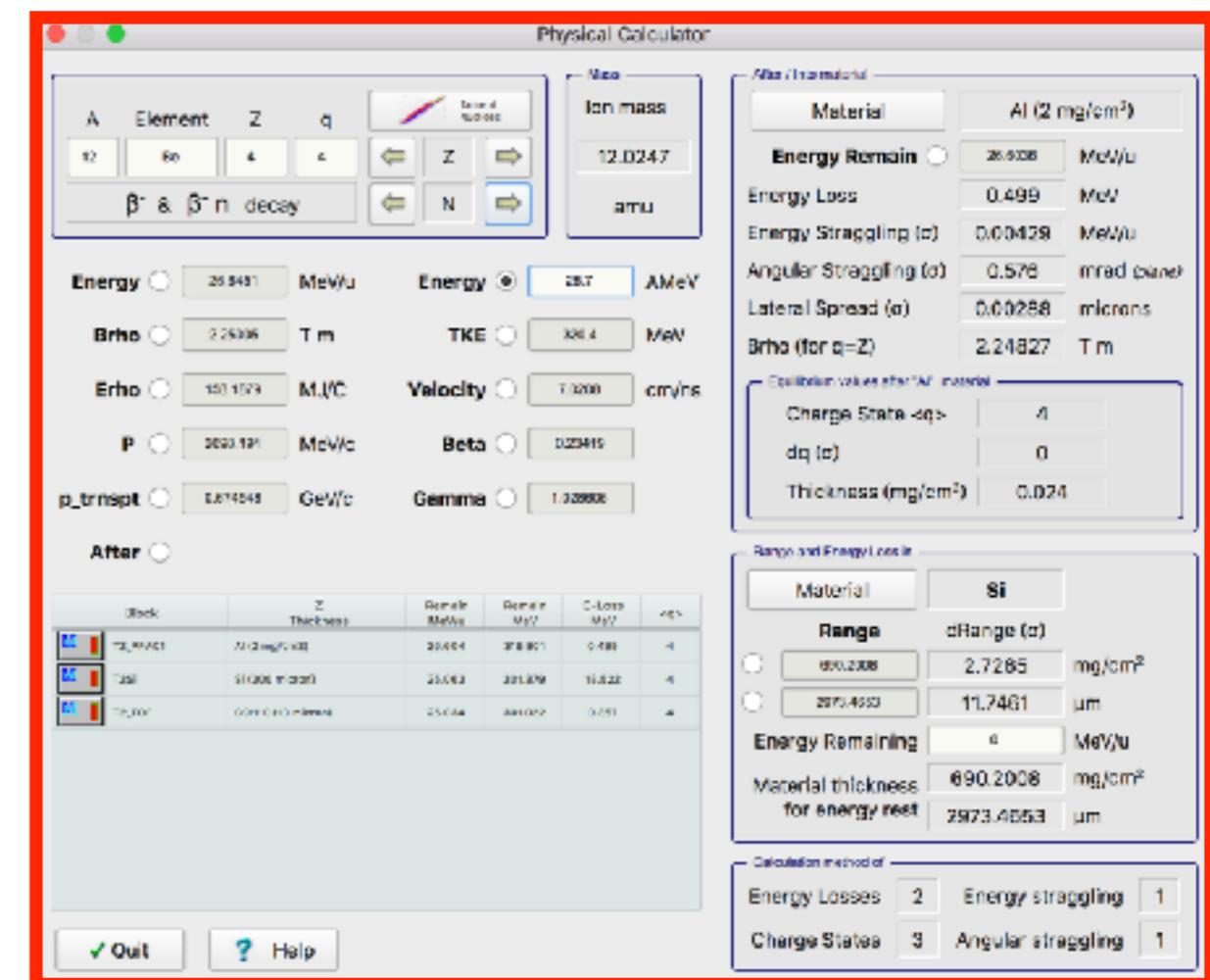
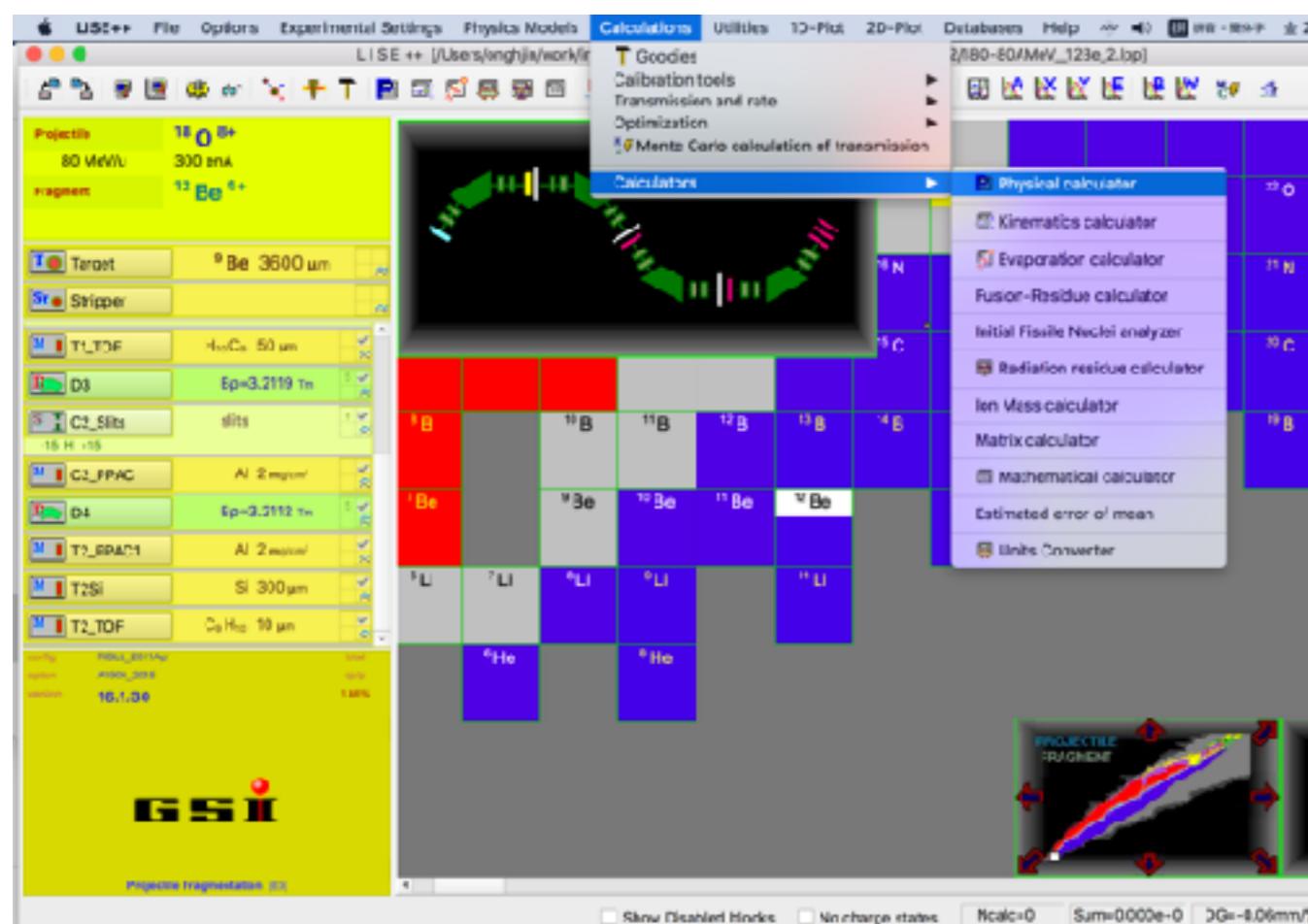
- ▶ 反应靶前¹²Be能量 25A MeV



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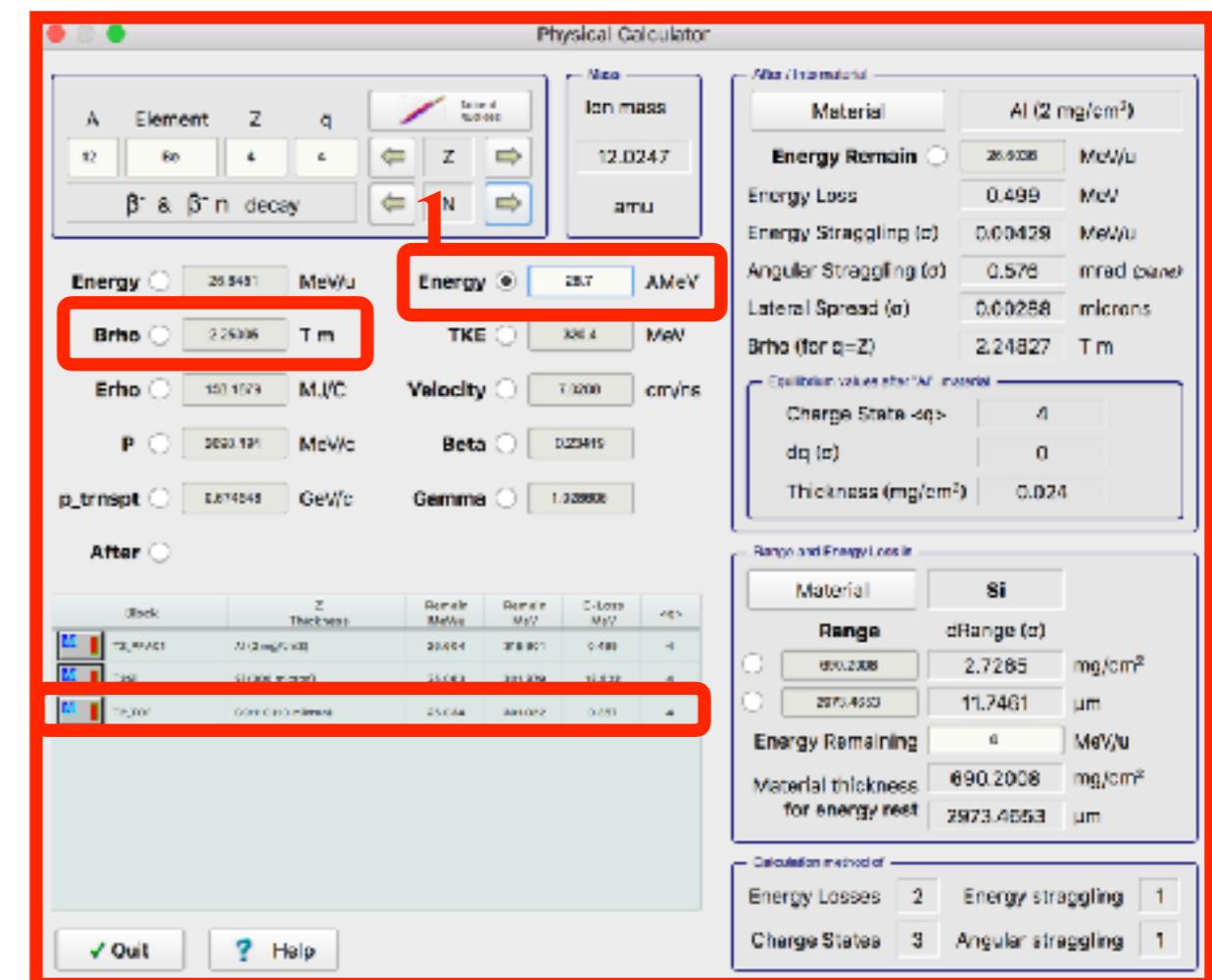
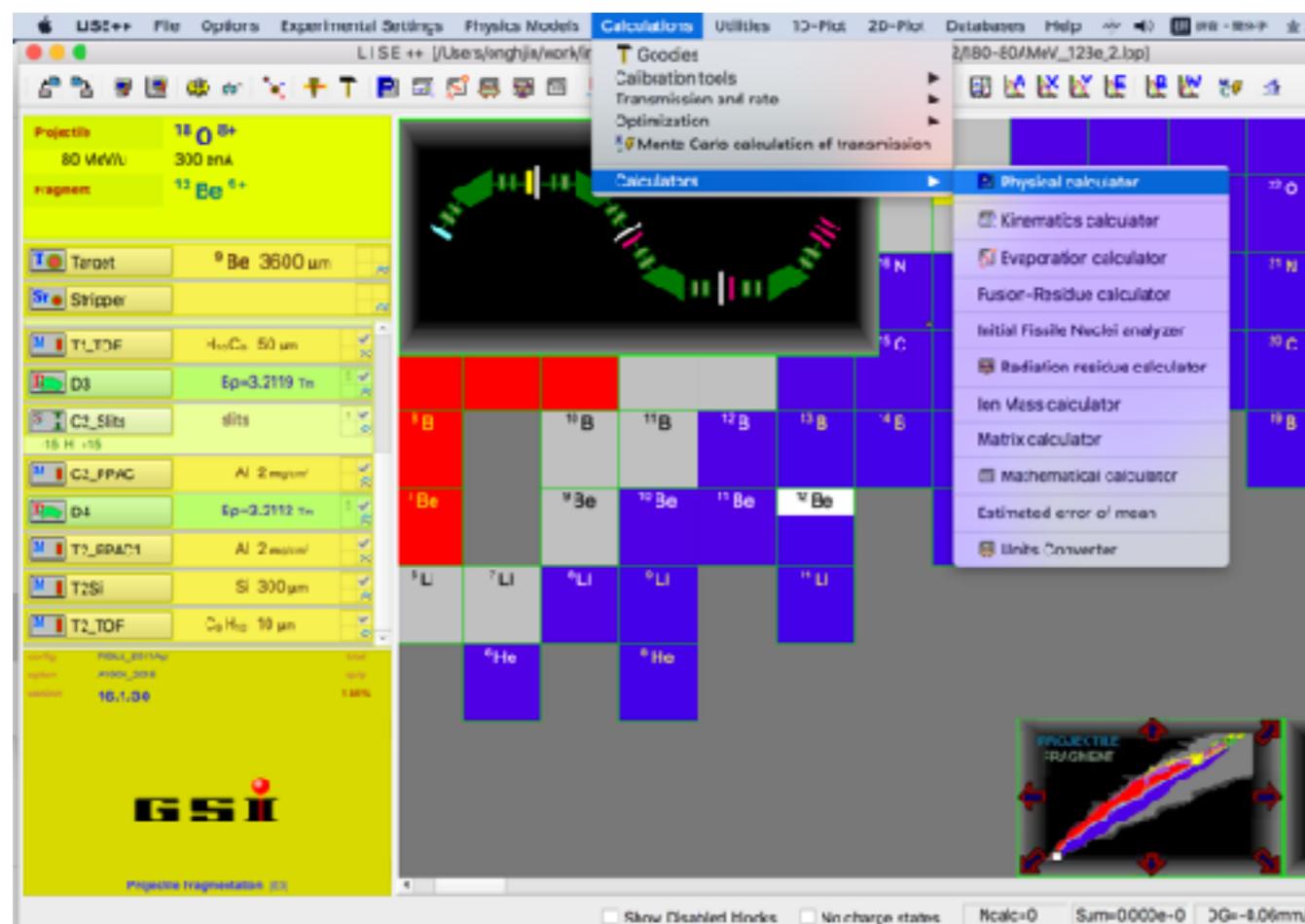
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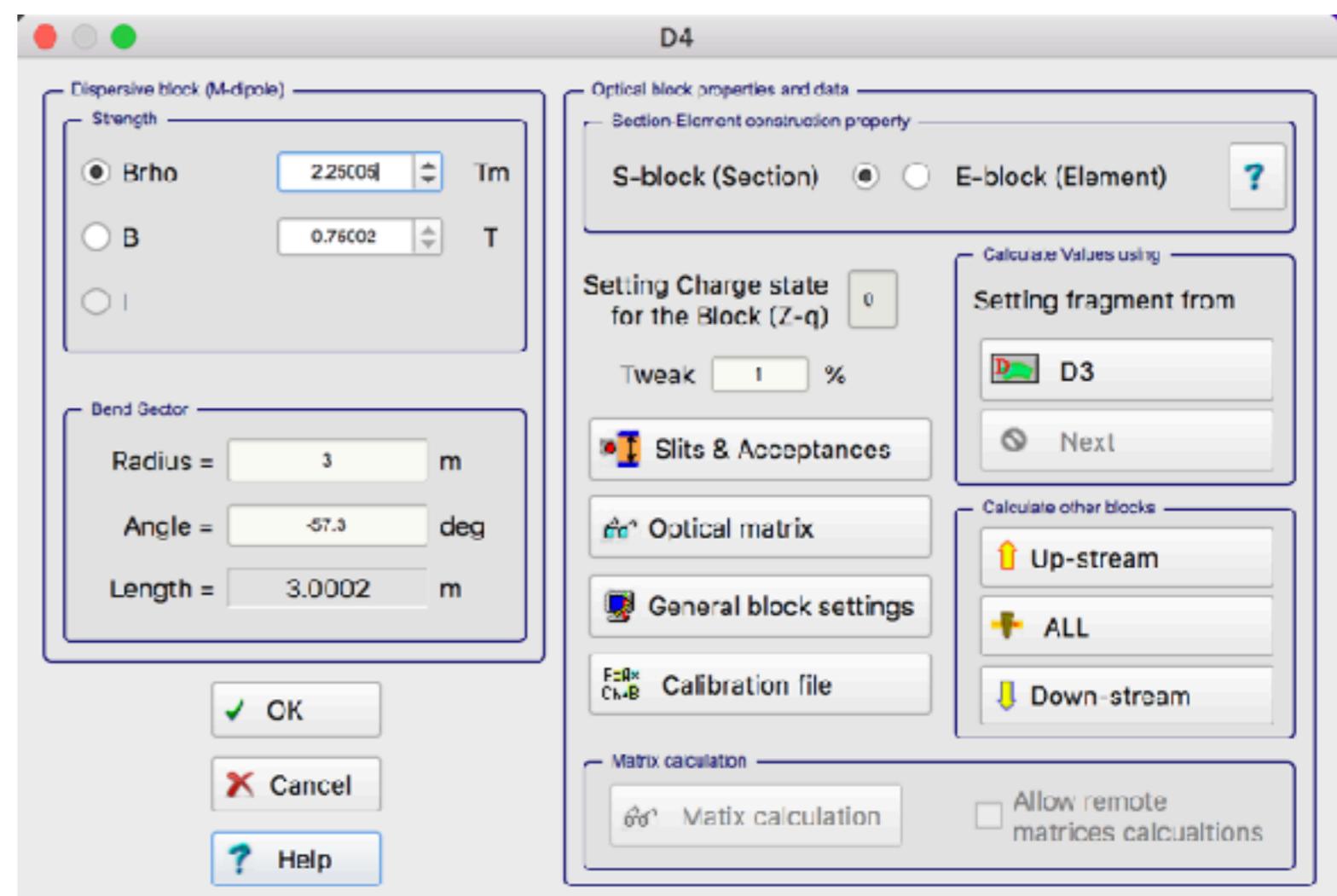
固定D4磁钢度

Projectile	$^{18}\text{O}^{8+}$
80 Mev/u	300 enA
Fragment	$^{12}\text{Be}^{4+}$
T Target	^9Be 3600 μm
St Stripper	
M T1_TOF	H ₁₀ C ₉ 50 μm
D D3	B ρ =3.2119 T _m
S C2_Slits	slits -15 H +15
M C2_PPAC	Al 2 mg/cm ²
D D4	B ρ =3.2112 T _m
M T2_PPAC1	Al 2 mg/cm ²
M T2Si	Si 300 μm
M T2_TOF	C ₉ H ₁₀ 10 μm

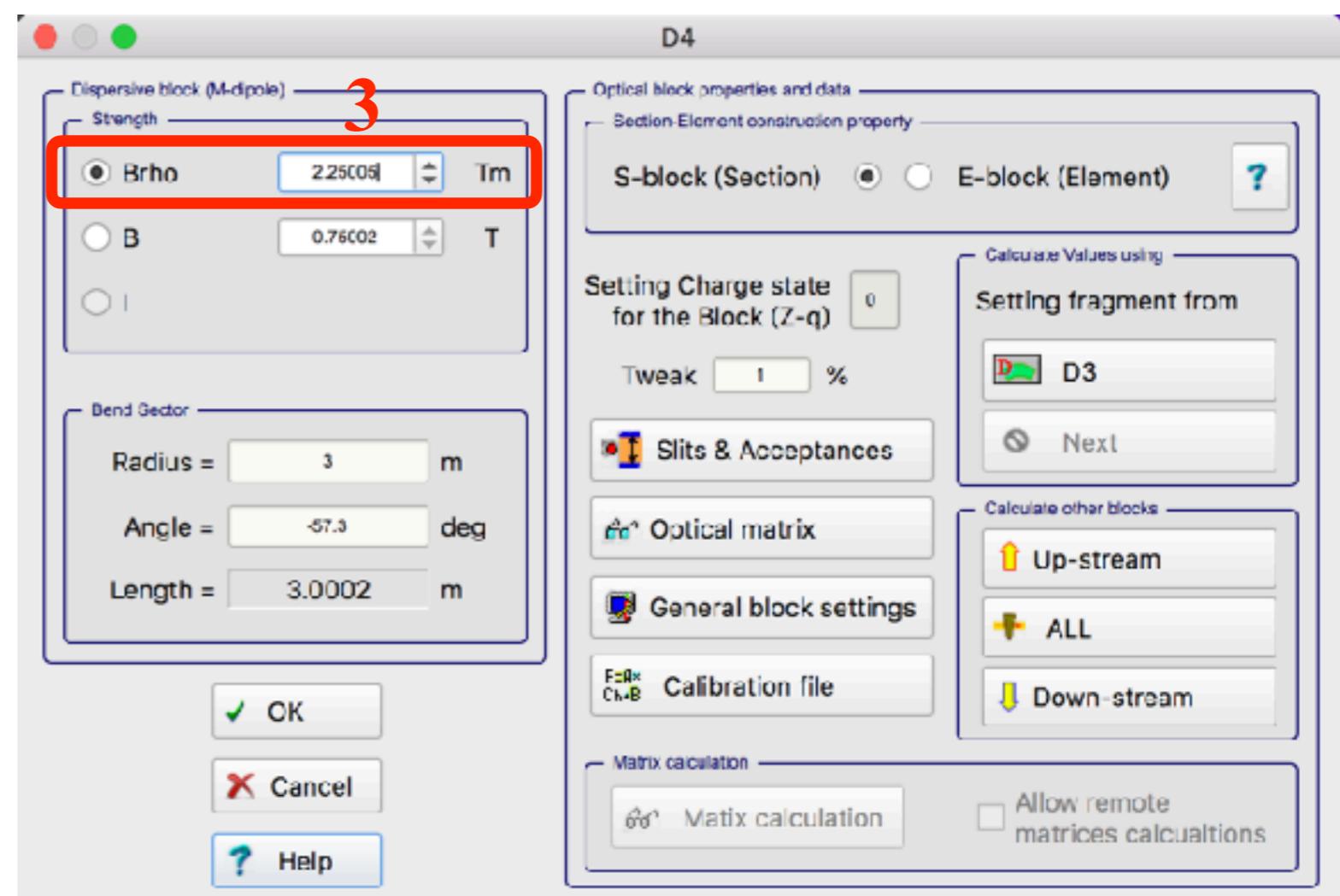
固定D4磁钢度



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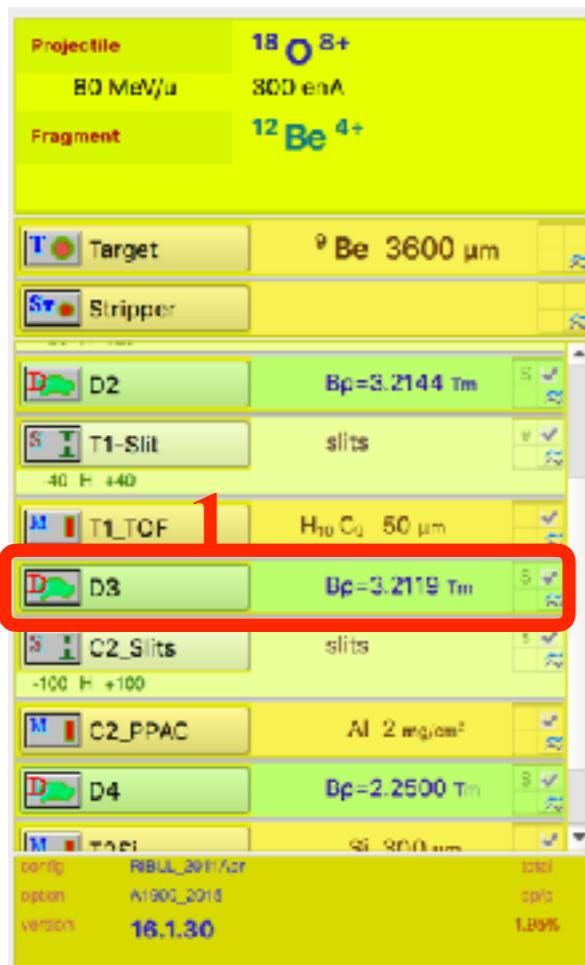
如何得到25A MeV次级束？

通过增加降能器厚度降低能量？



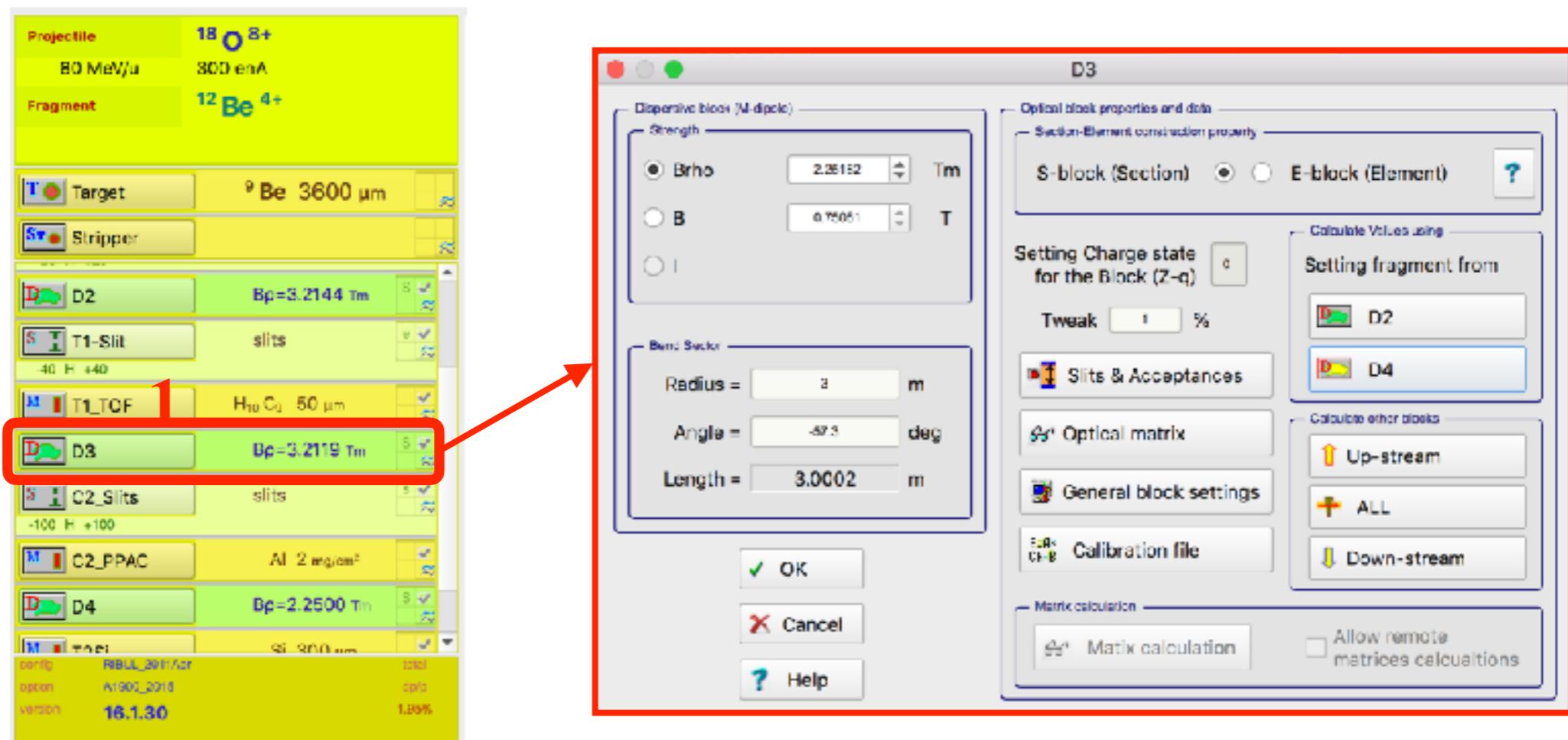
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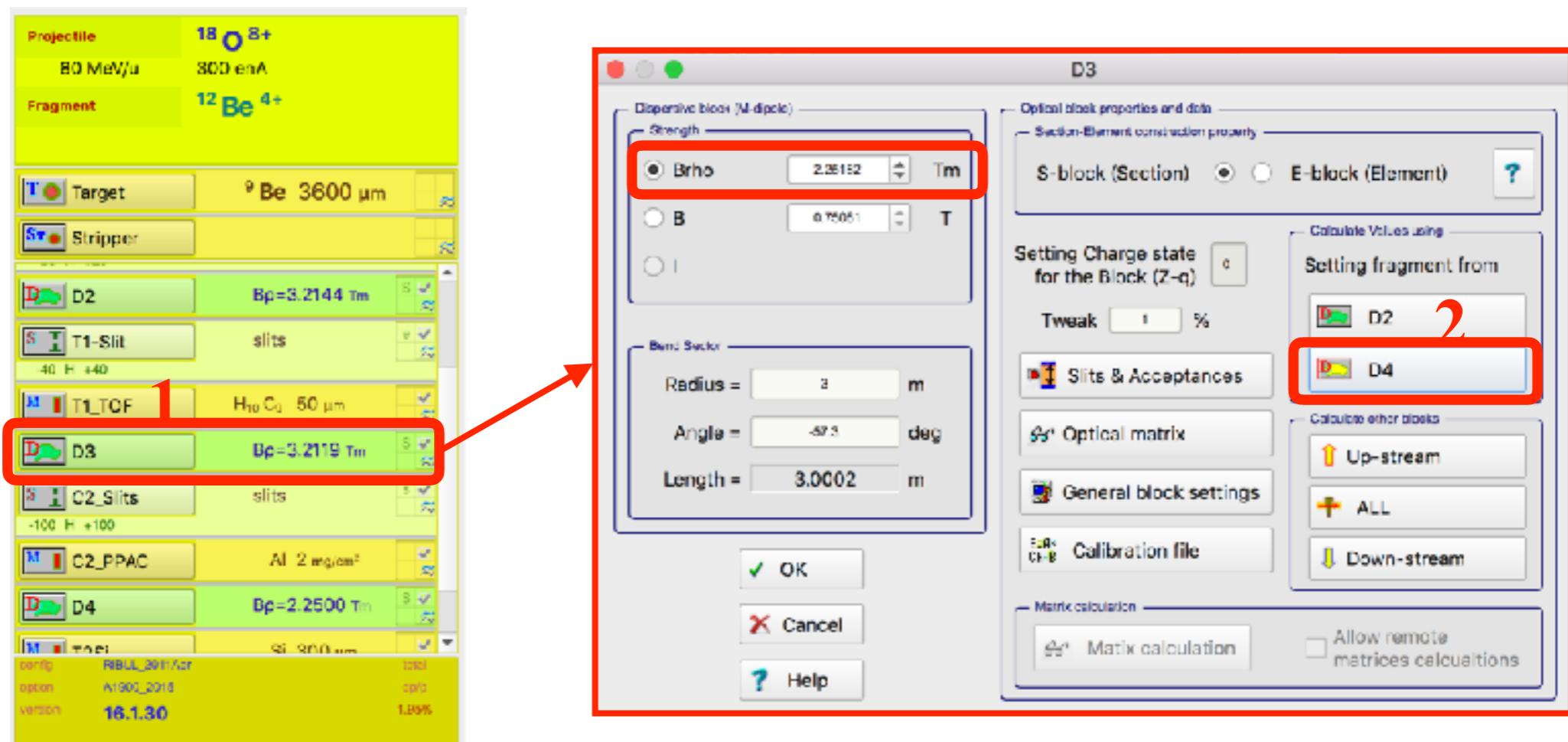
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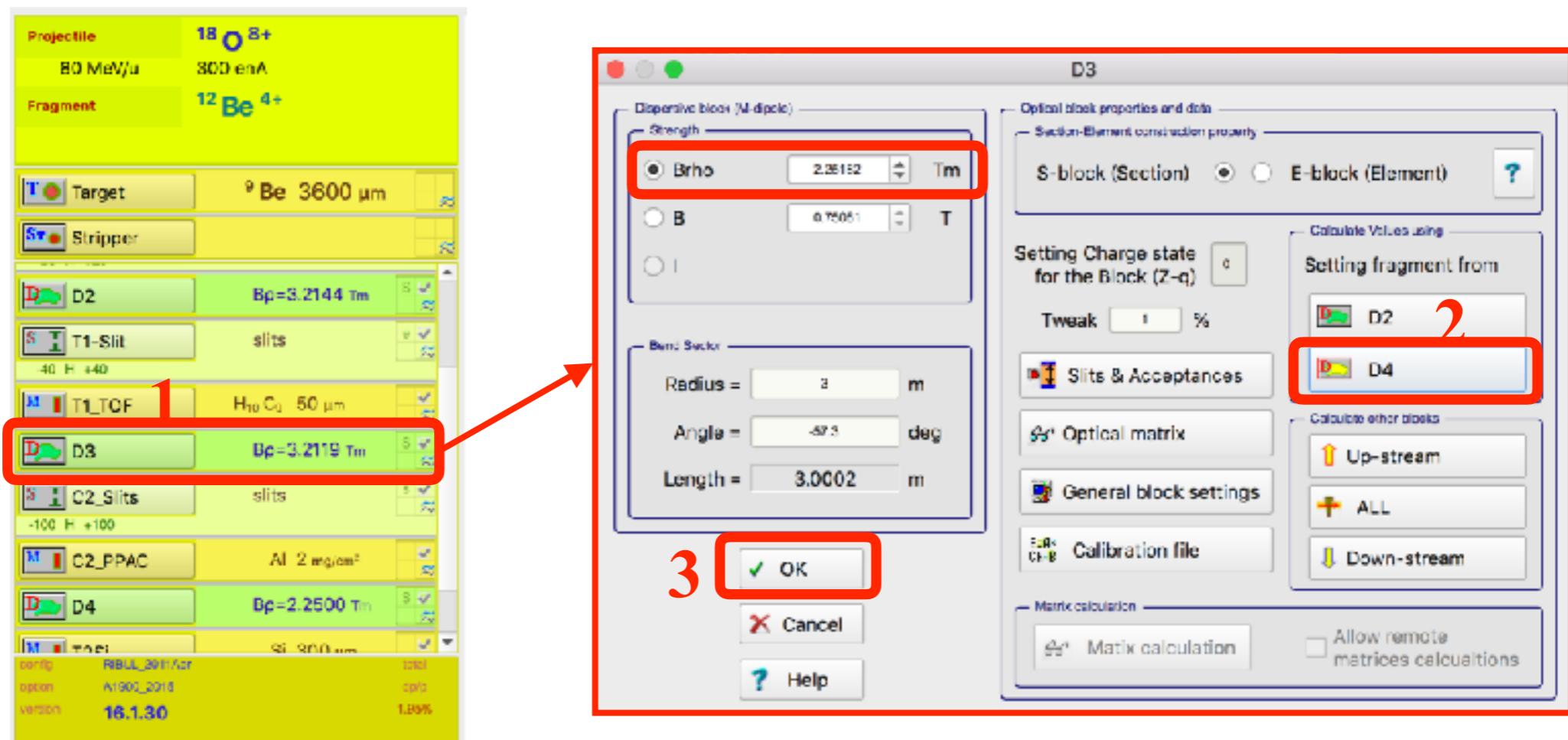
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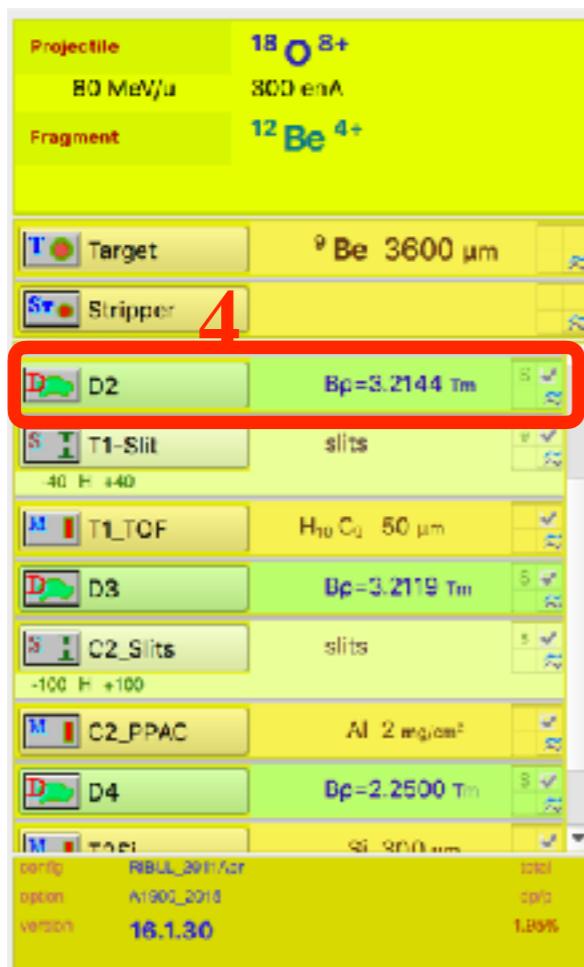
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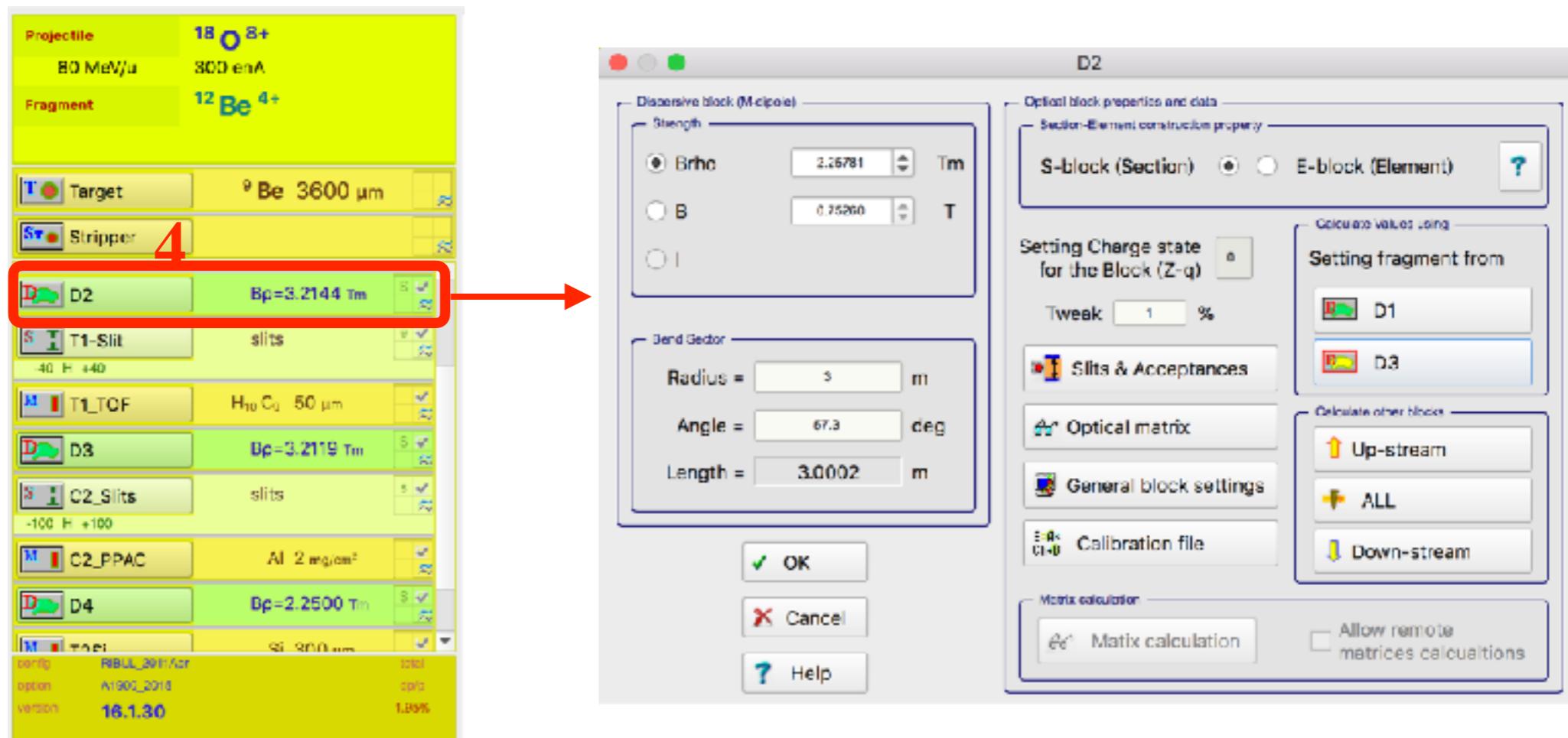
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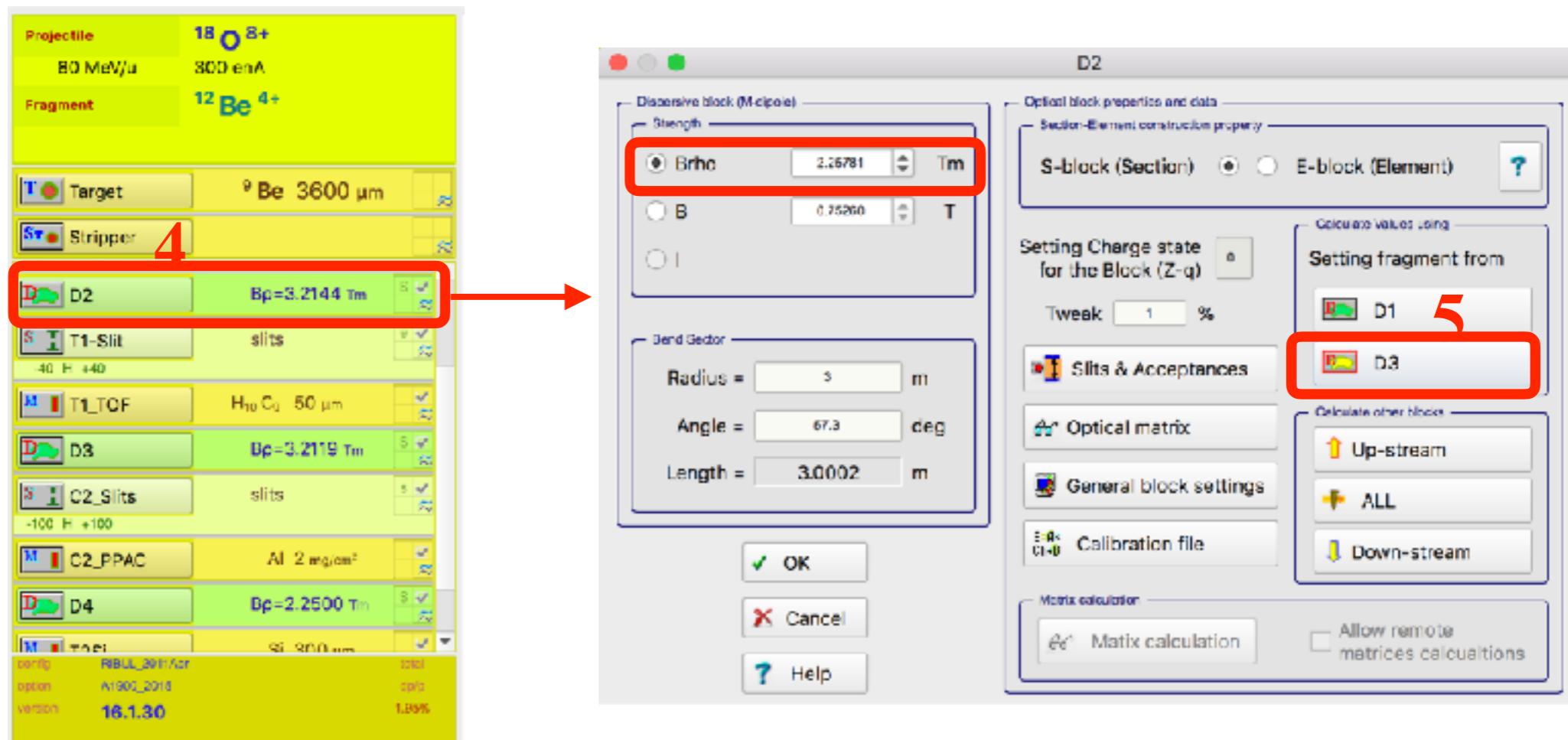
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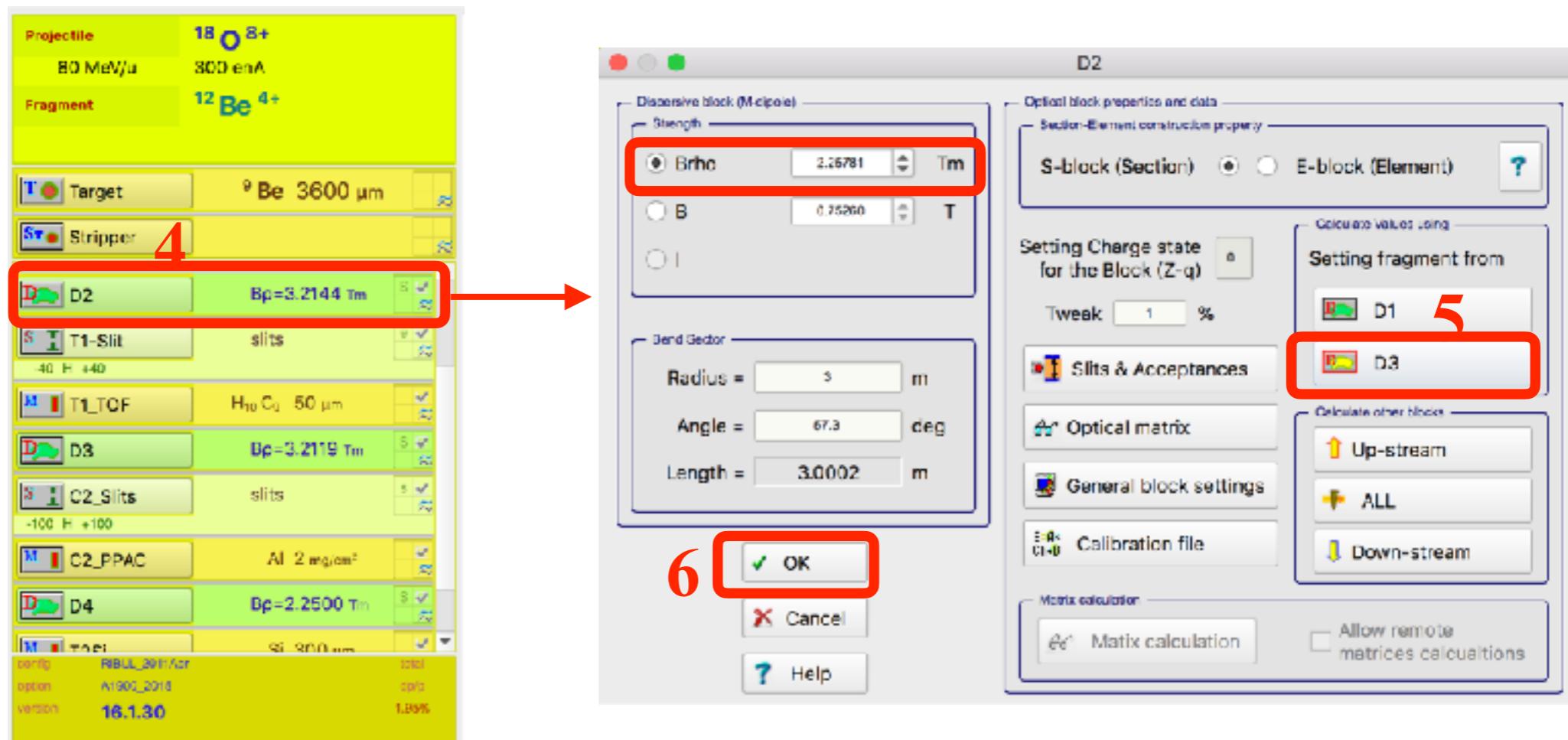
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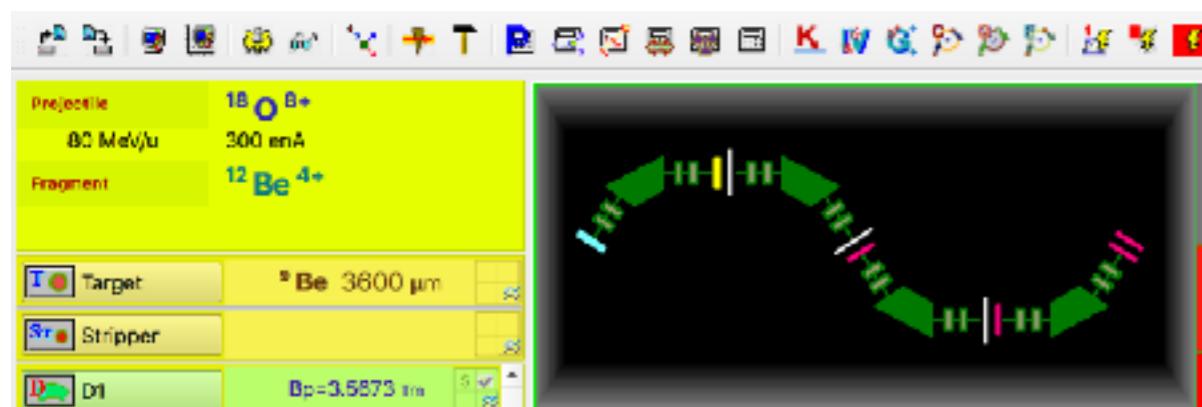
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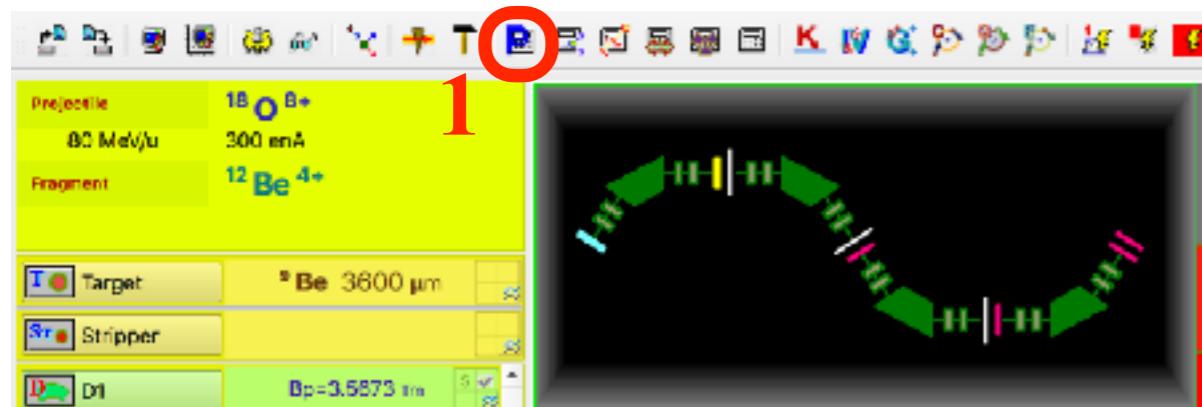
$$B\rho(D1) \nabla B\rho(D2)$$



如何得到25A MeV次级束？

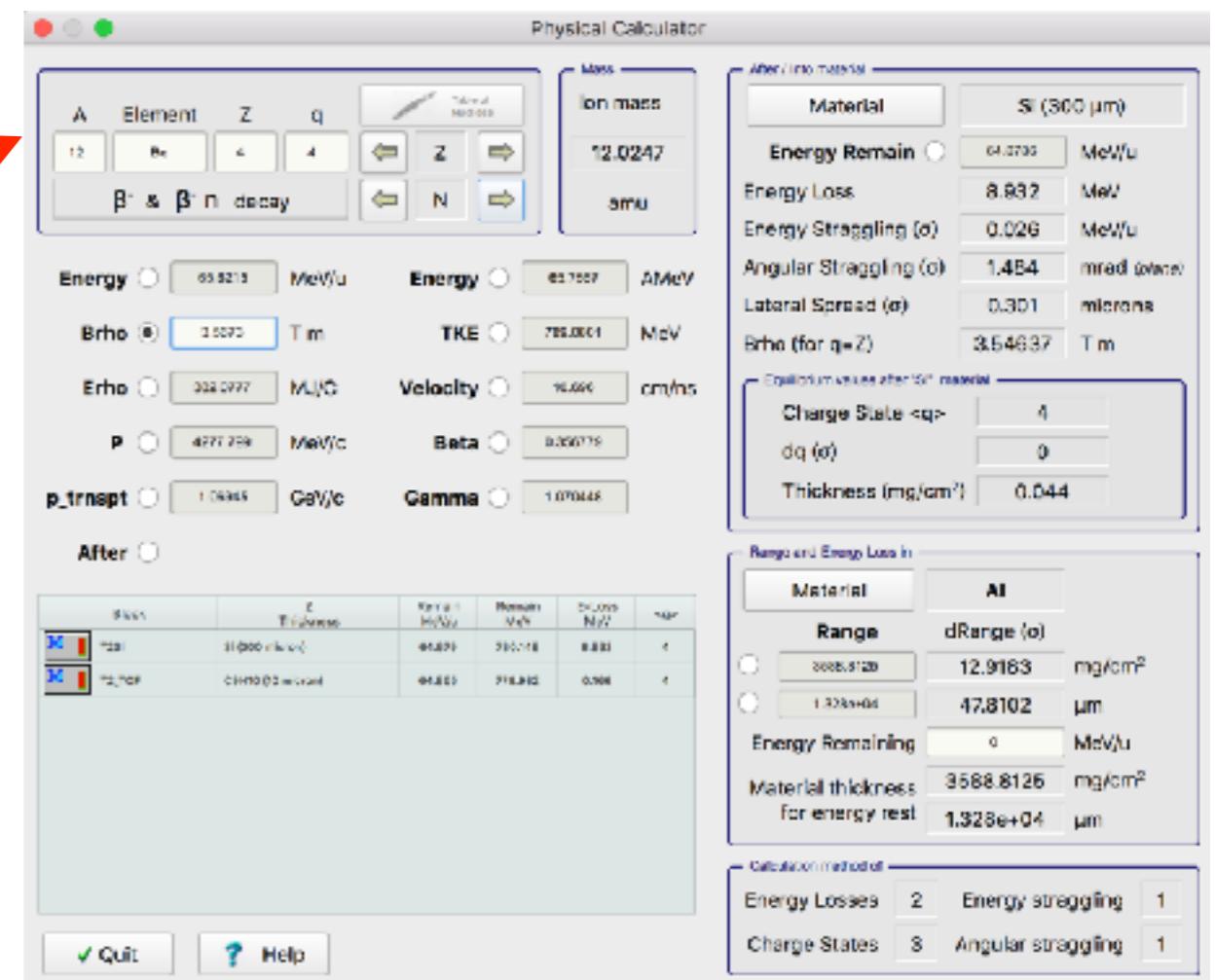
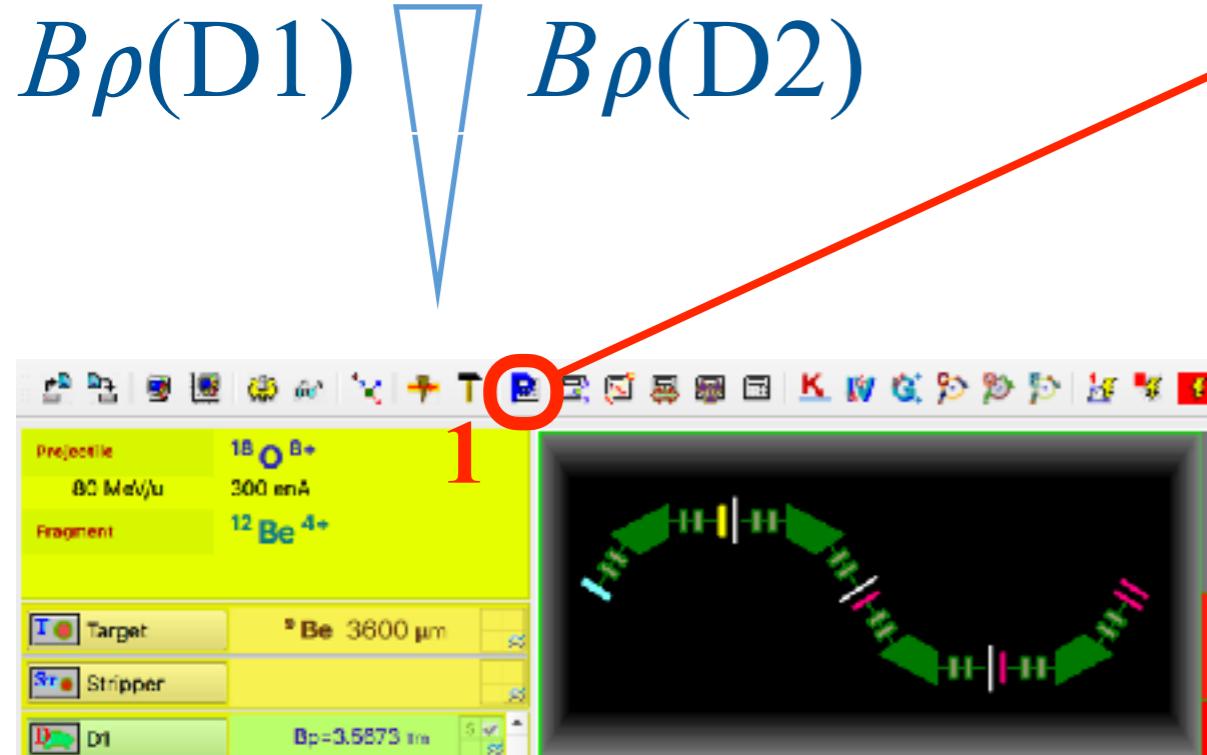
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$$B\rho(D1) \nabla B\rho(D2)$$



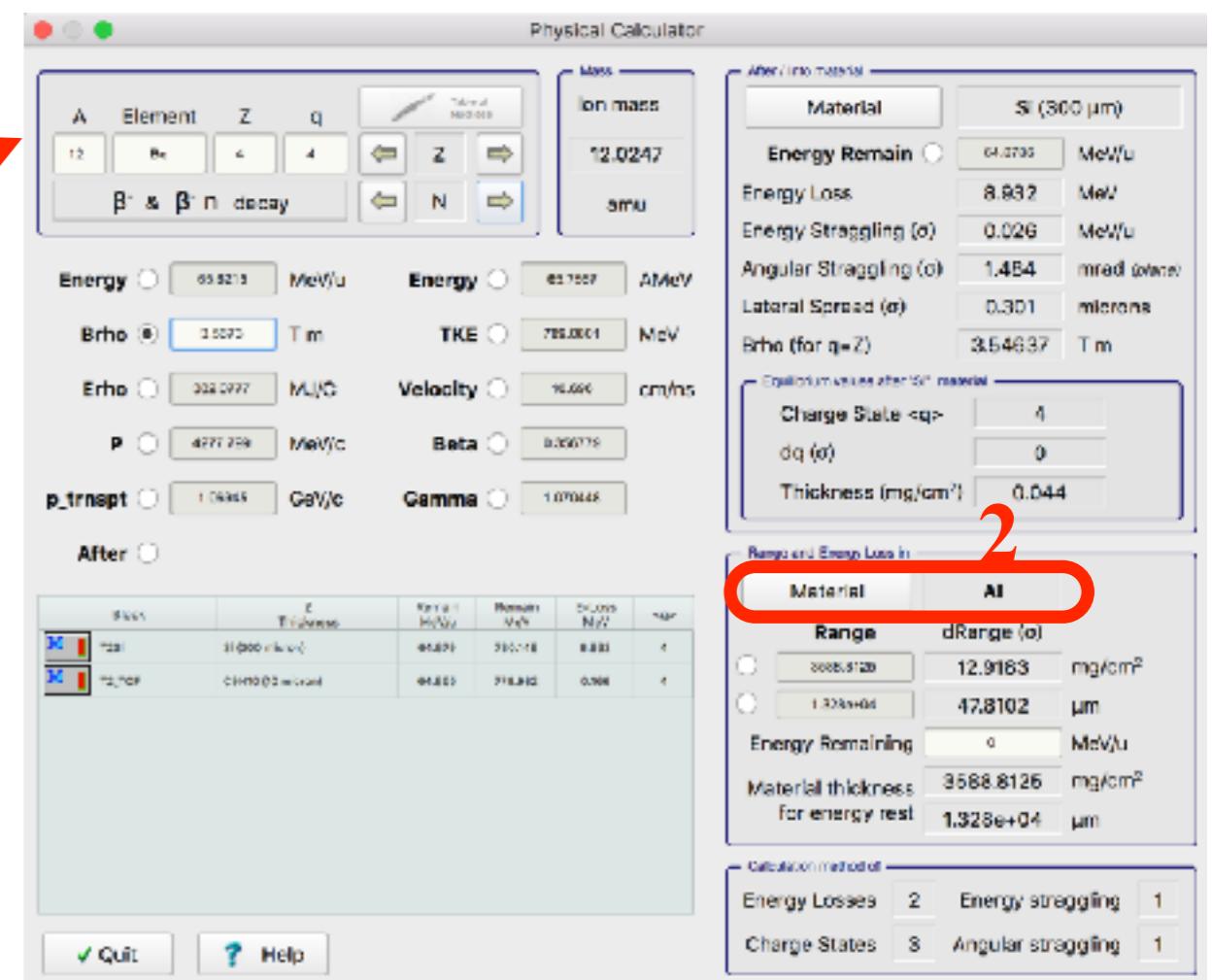
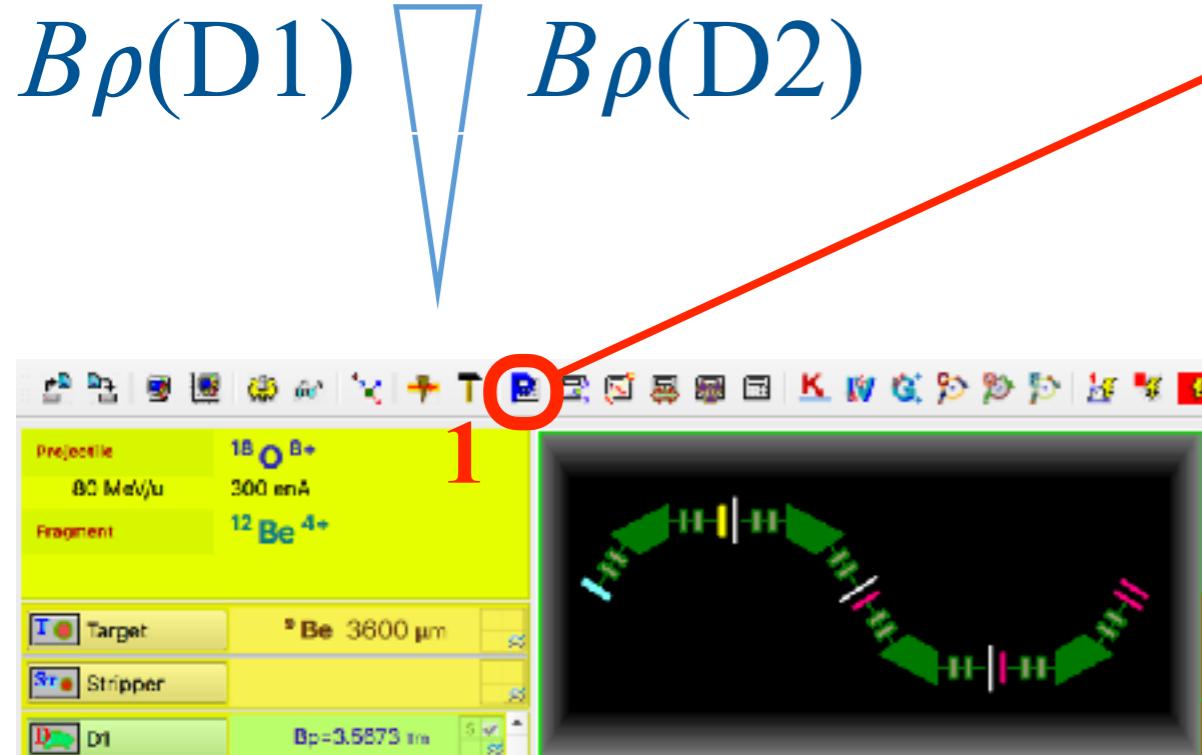
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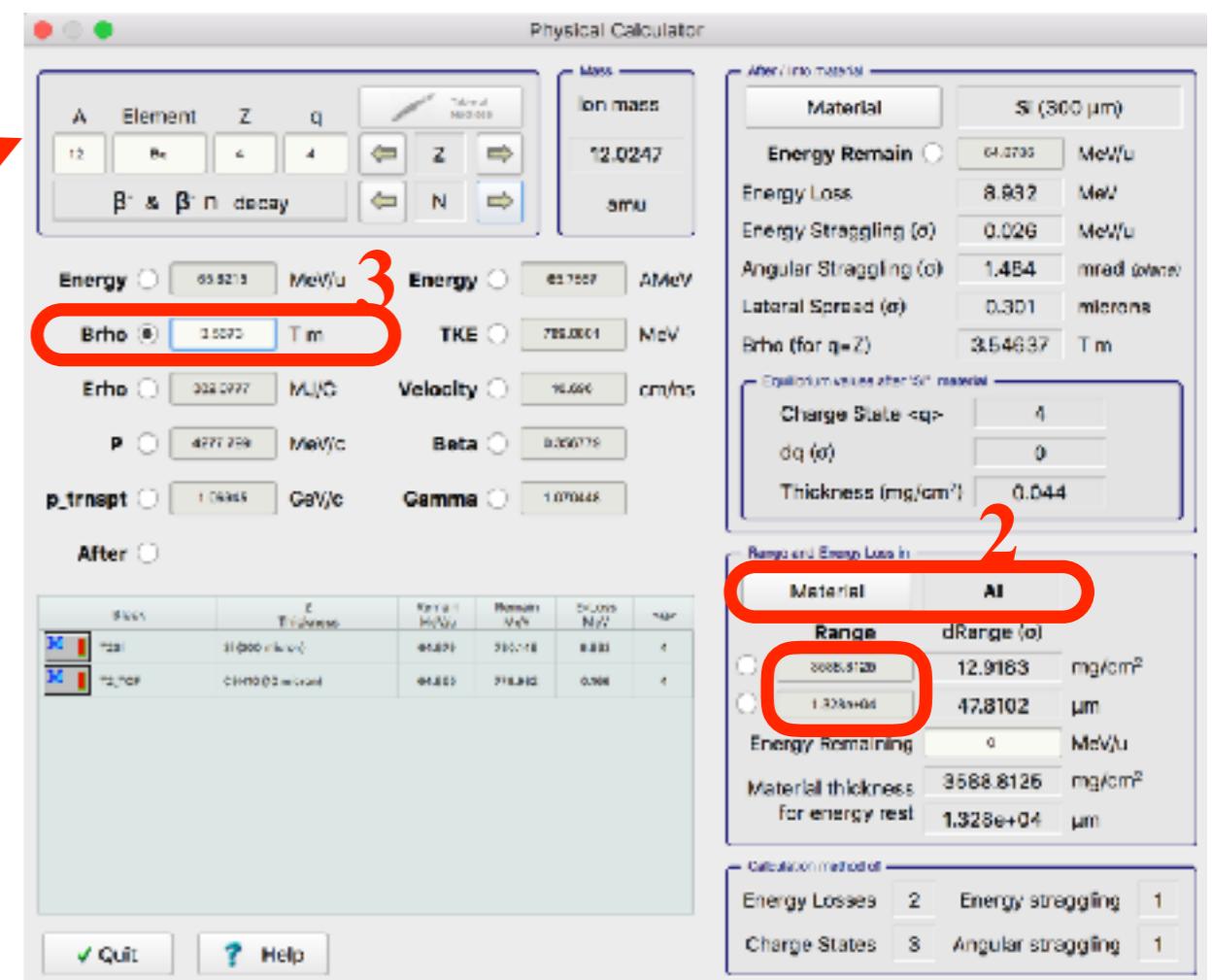
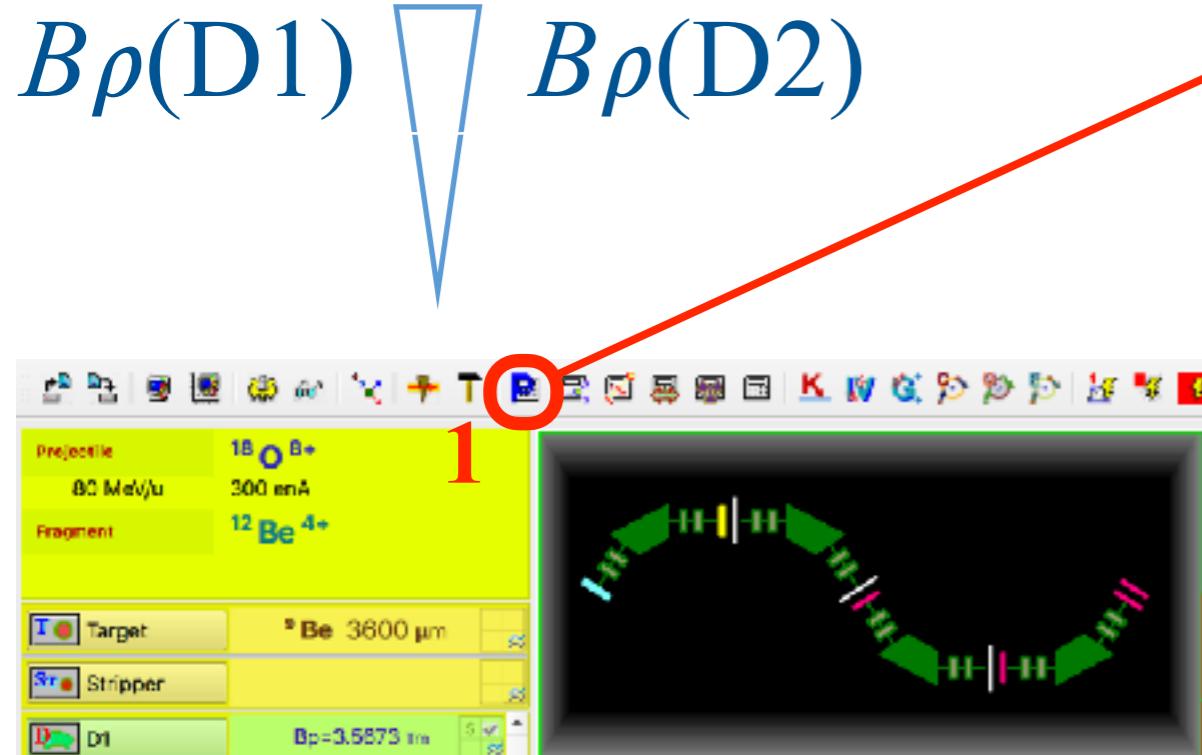
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如何得到25A MeV次级束？

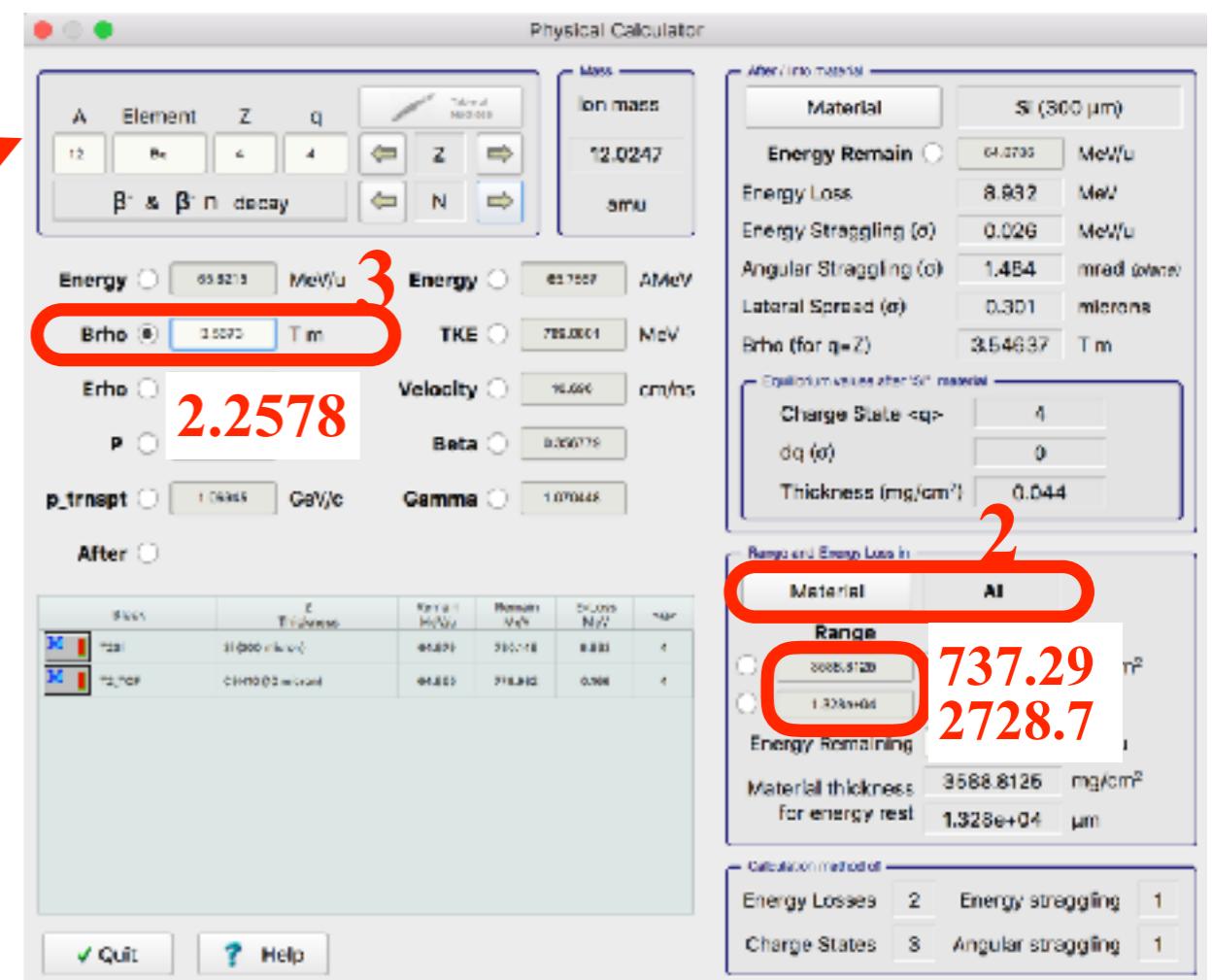
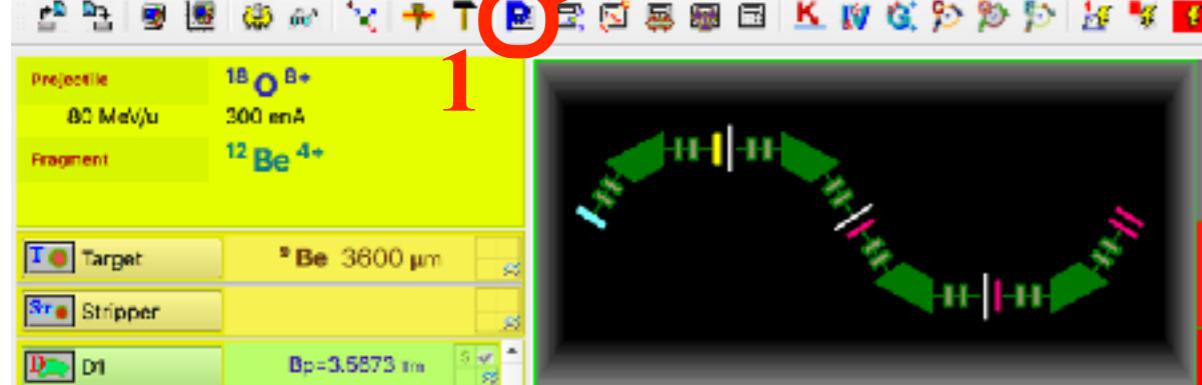
通过增加降能器厚度降低能量？



如何得到25A MeV次级束？

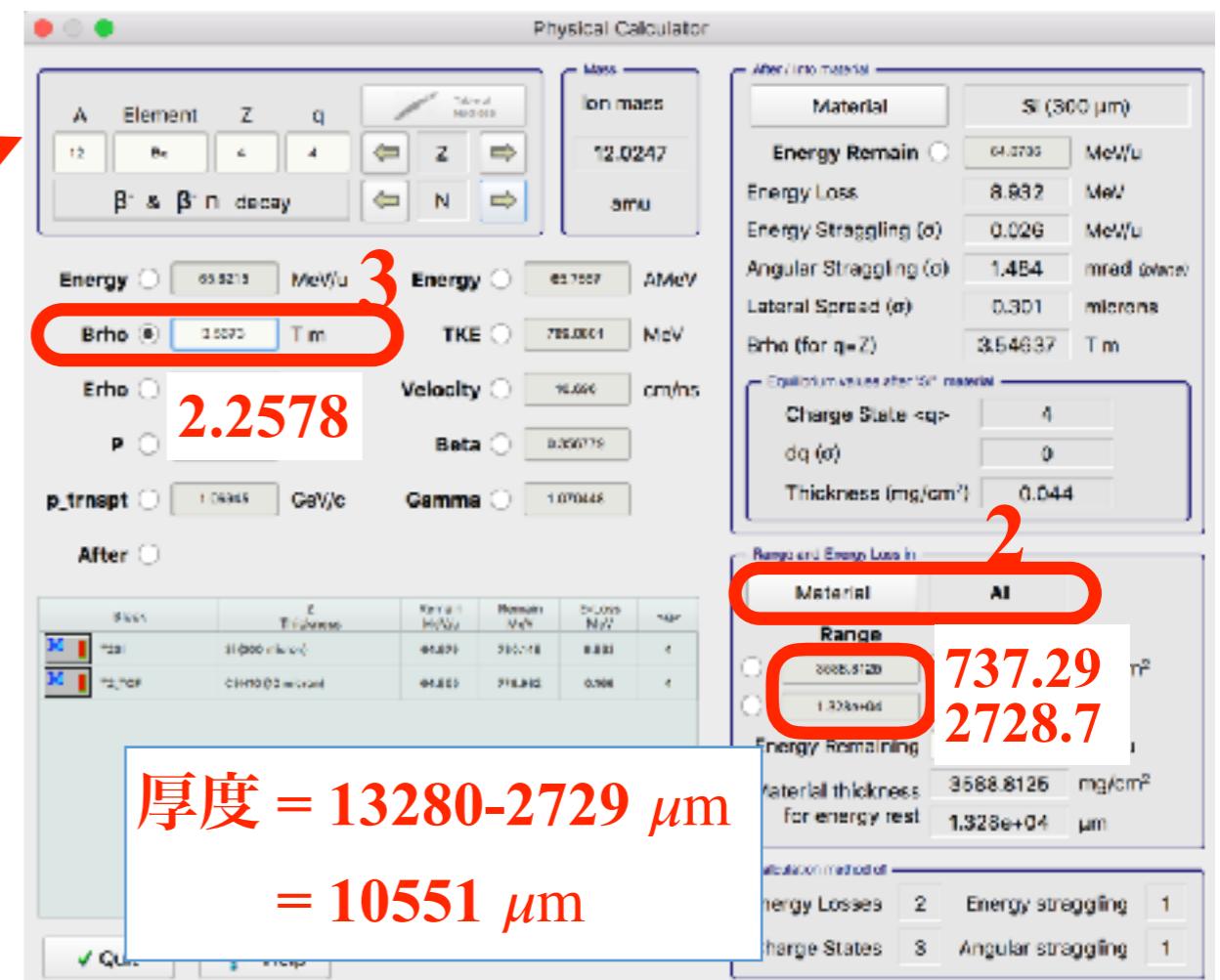
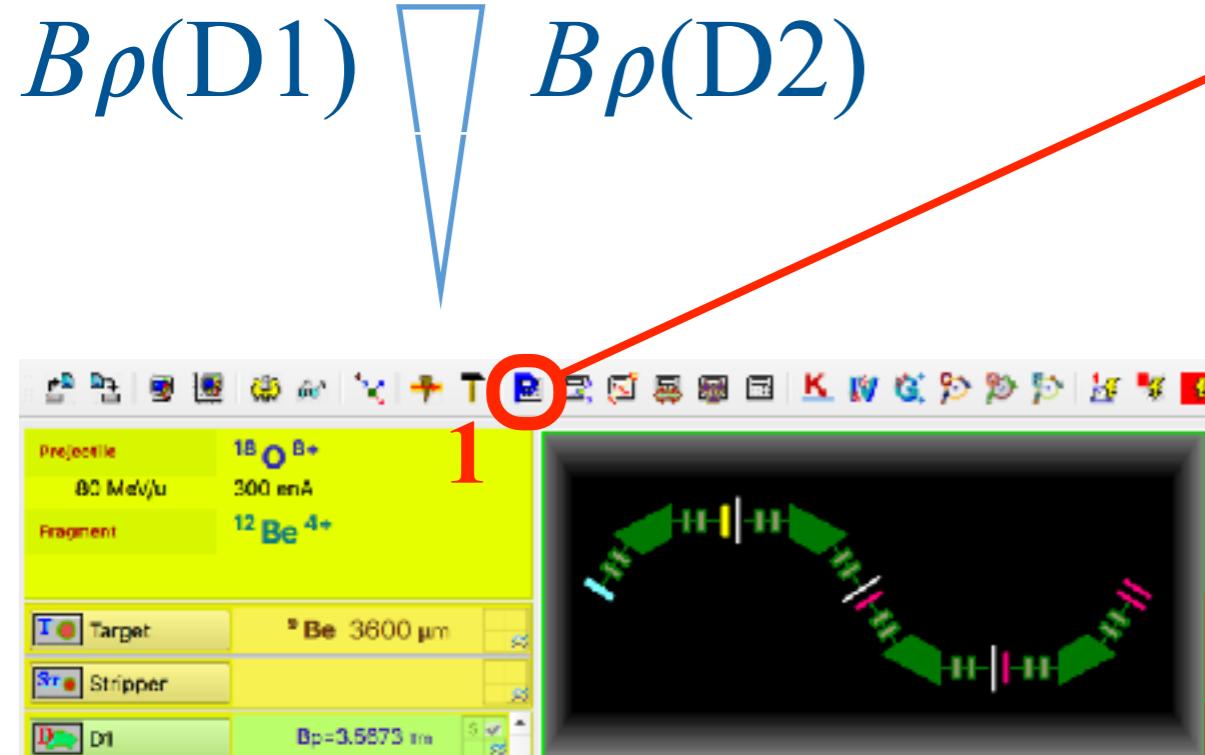
通过增加降能器厚度降低能量？

$$B\rho(D1) \quad B\rho(D2)$$



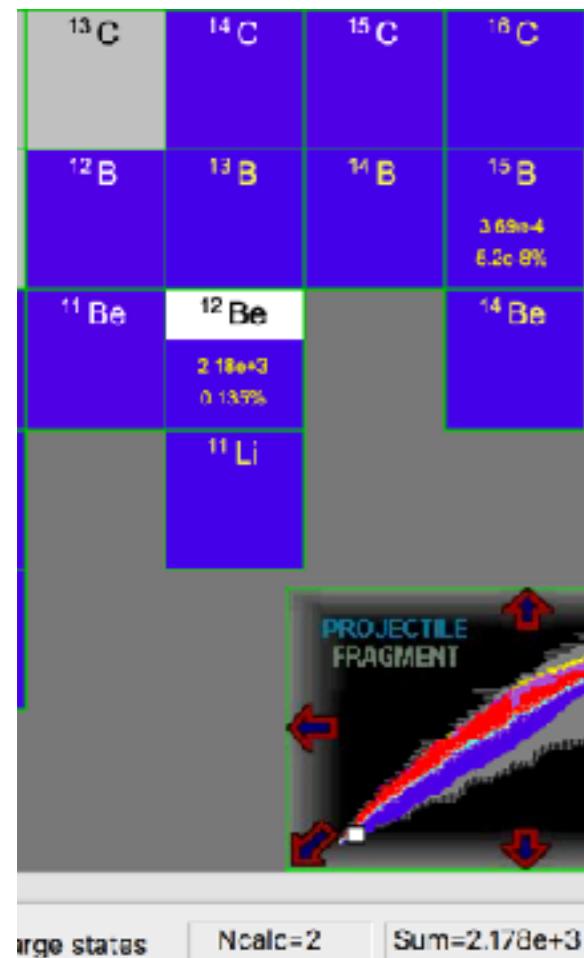
如何得到25A MeV次级束？

通过增加降能器厚度降低能量？



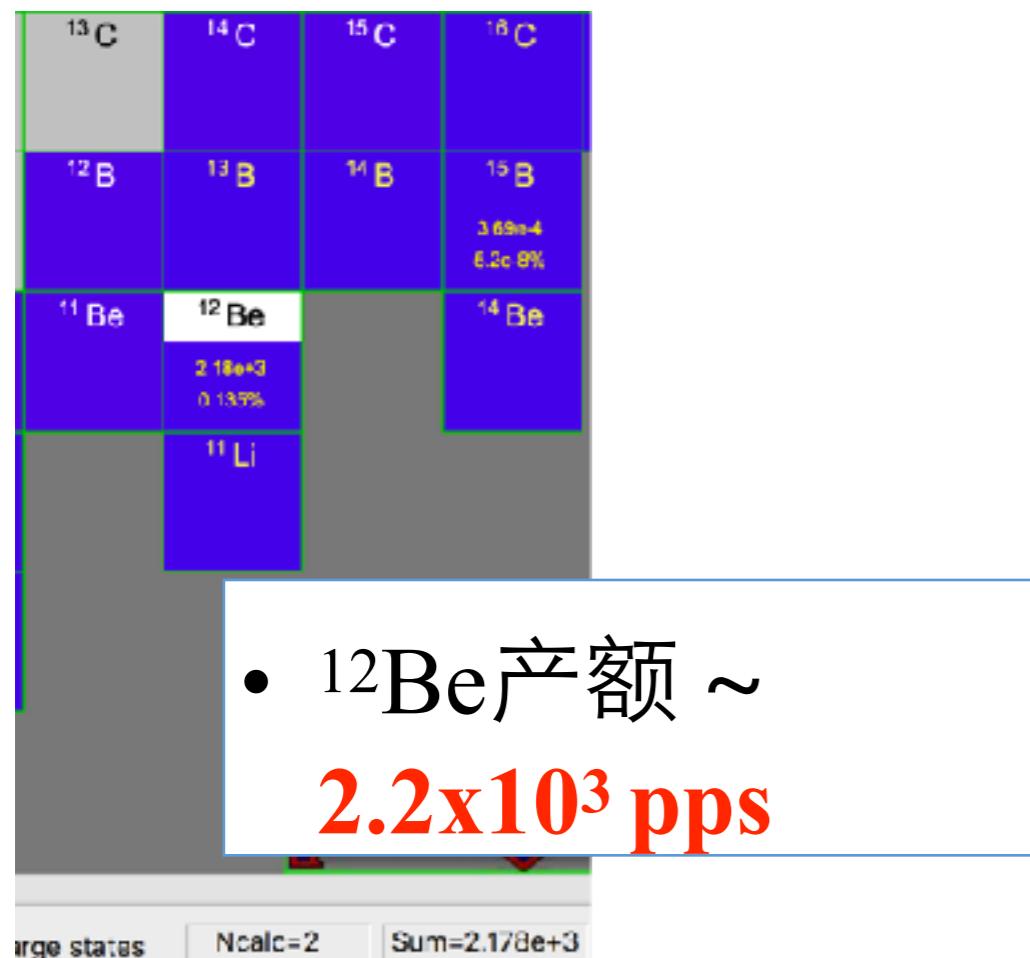
如何得到25A MeV次级束？

通过增加降能器厚度降低能量？



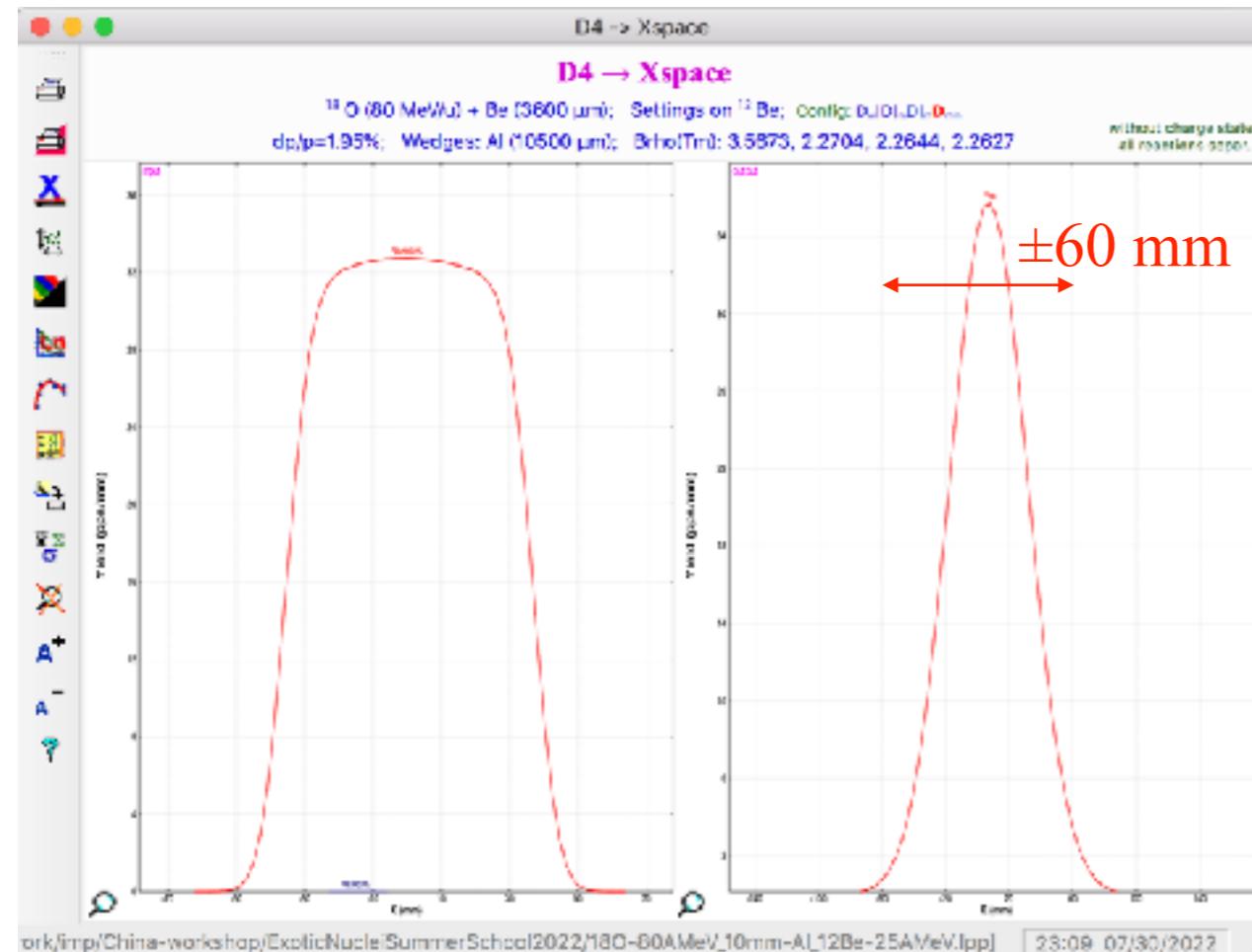
如何得到25A MeV次级束？

通过增加降能器厚度降低能量？



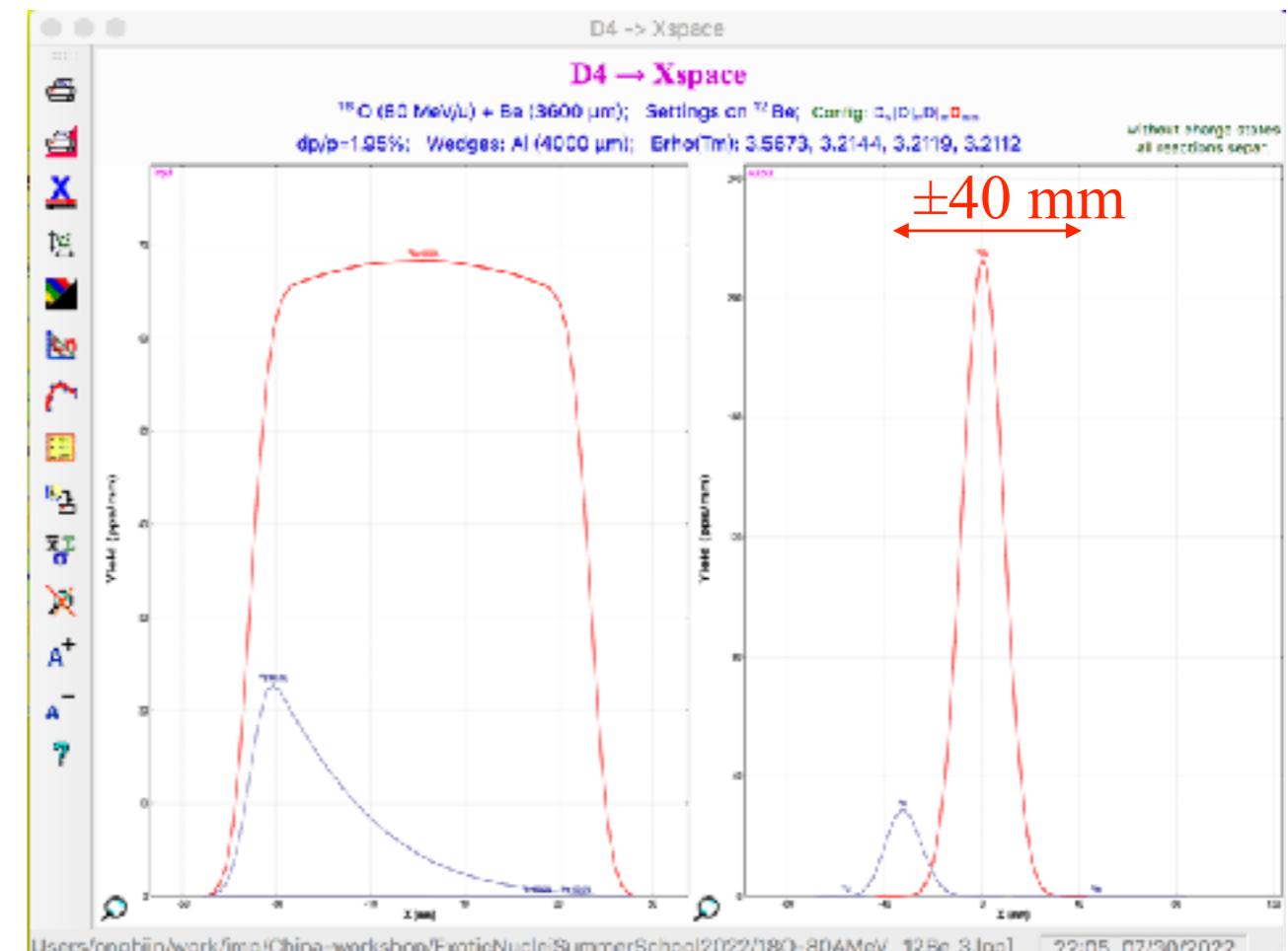
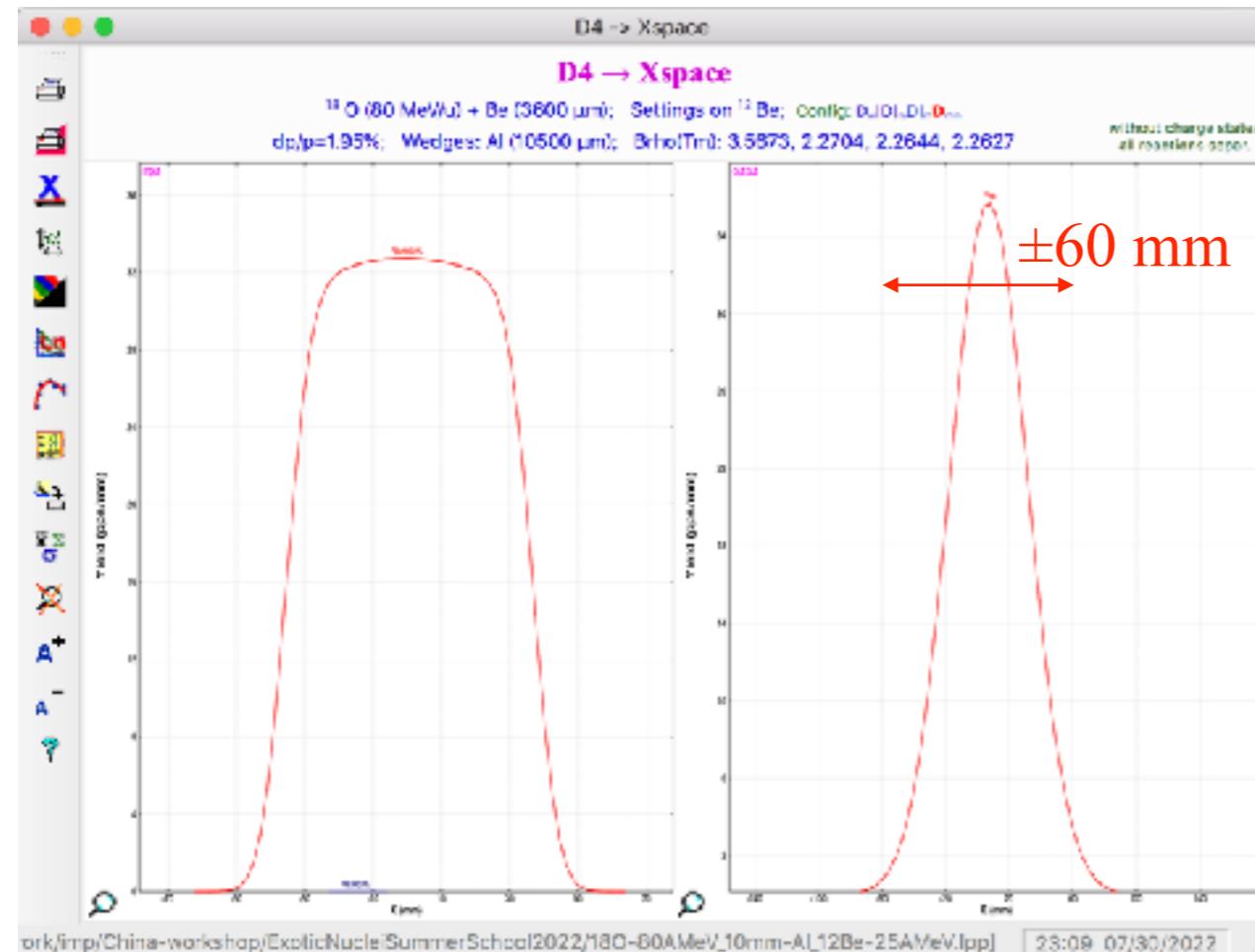
如何得到25A MeV次级束？

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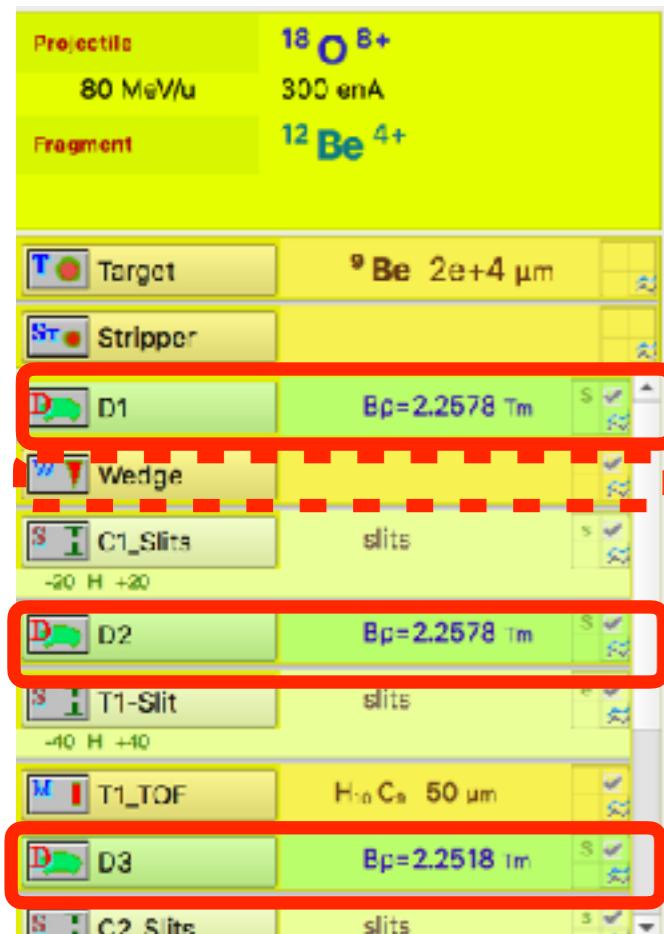


如何得到25A MeV次级束？

使用厚Be靶，不用降能器？

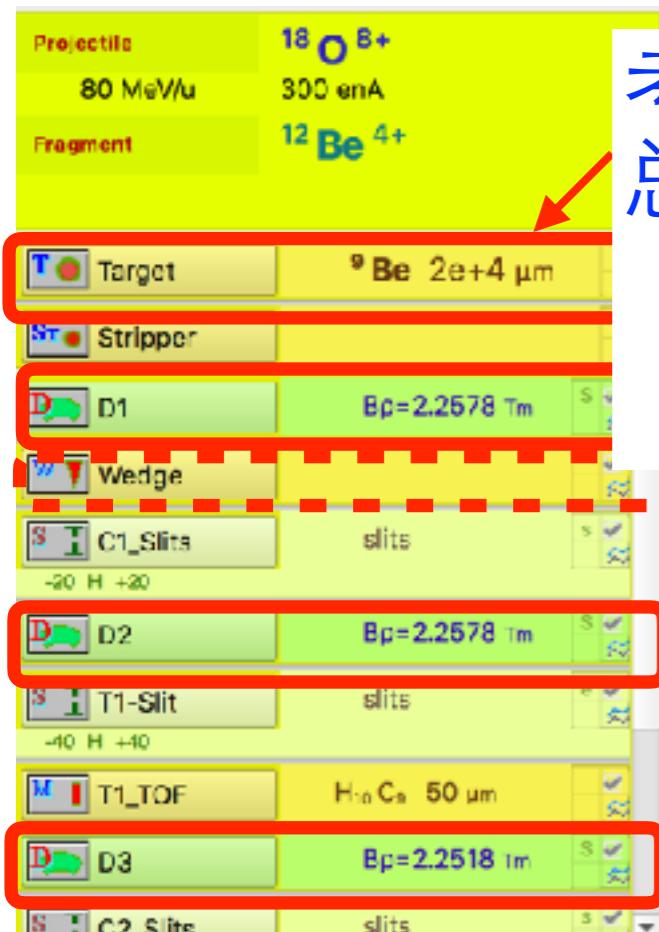
如何得到25A MeV次级束？

使用厚Be靶，不用降能器？



如何得到25A MeV次级束？

使用厚Be靶，不用降能器？



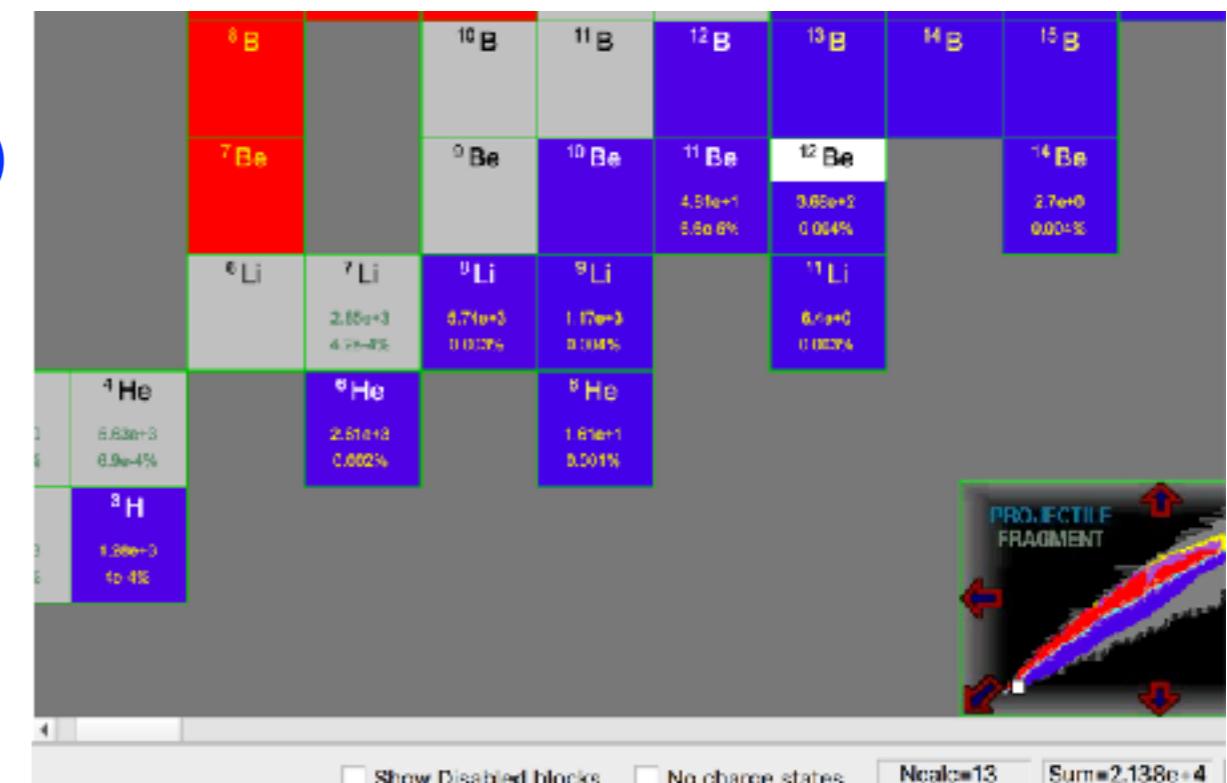
考慮Be+厚降能器
总厚度 ($\sim 3.5 \text{ g/cm}^2$)

如何得到25A MeV次级束？

使用厚Be靶，不用降能器？

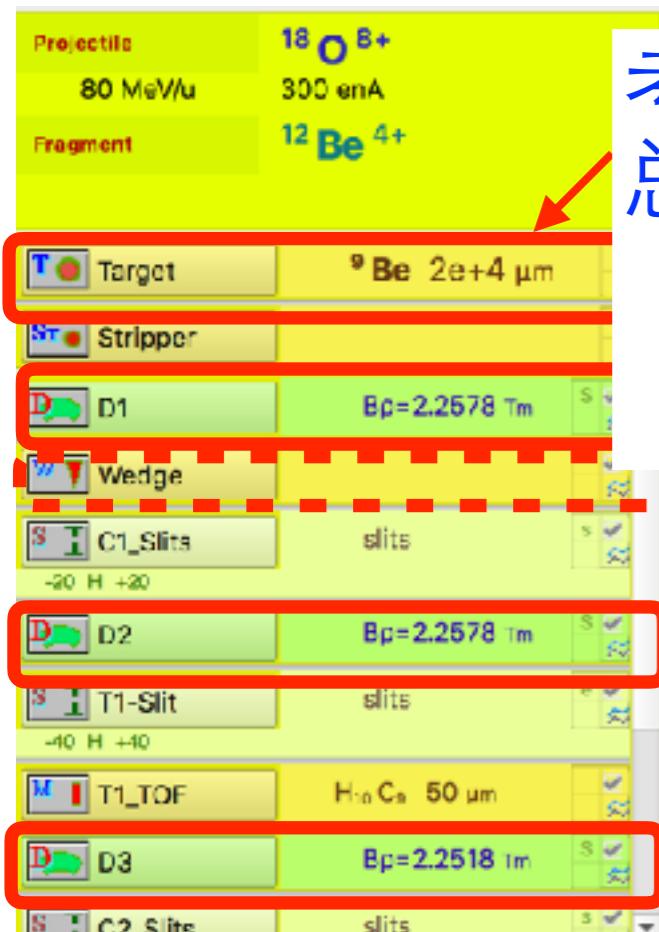


考慮Be+厚降能器
总厚度 ($\sim 3.5 \text{ g/cm}^2$)

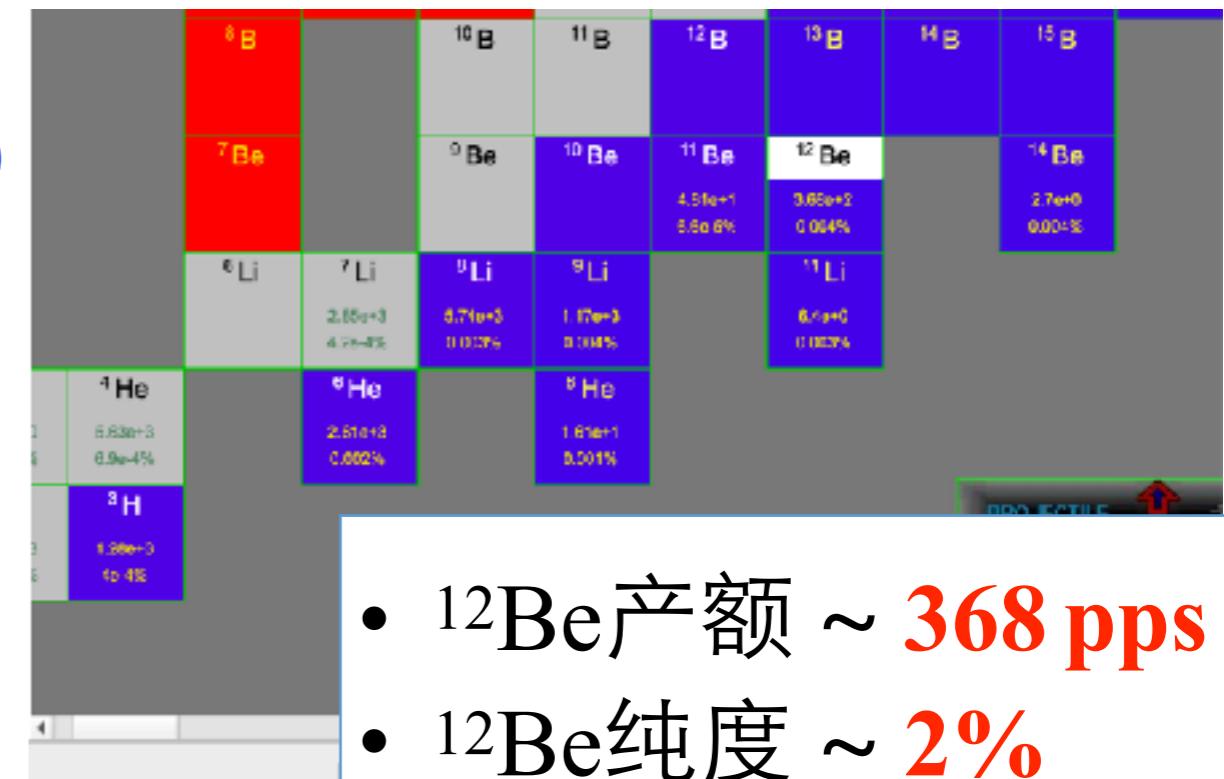


如何得到25A MeV次级束？

使用厚Be靶，不用降能器？



考慮Be+厚降能器
總厚度 ($\sim 3.5 \text{ g/cm}^2$)



- 12Be产额 ~ **368 pps**
- 12Be纯度 ~ **2%**

如何得到25A MeV次级束？

- 使用更低能初级束，例如 50A MeV的 ^{18}O
- “优化”初级靶、降能器厚度

検出器和实验装置

物理量和目的

1. 时间信息

- 测量开始和停止时间
 - ⇒ 触发 (trigger)
 - ⇒ 衰变寿命
- 粒子从一个点到另一个点的飞行时间(Time Of Flight, TOF)
 - ⇒ 粒子鉴别
 - ⇒ 动能／动量 ⇒ 反应／跃迁相关信息

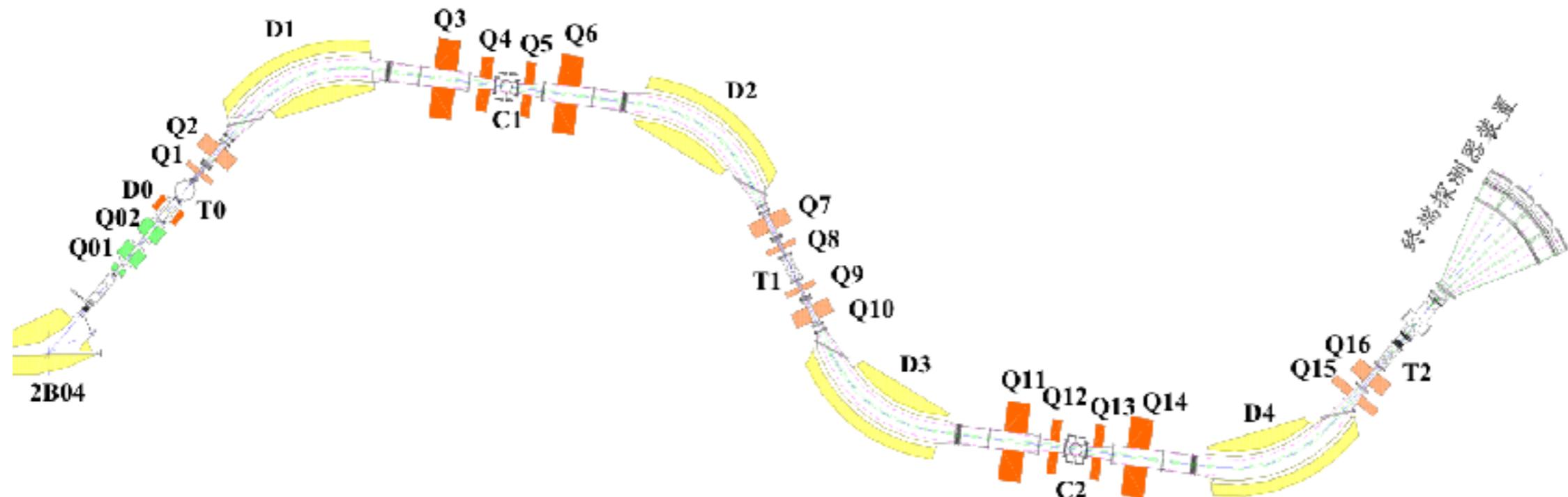
2. 位置信息

- 粒子在探测器上的位置 ⇒ 动量 (动量分散焦点面上的位置)
- 粒子的入射/出射角度 ⇒ 束流发射度、散射角度

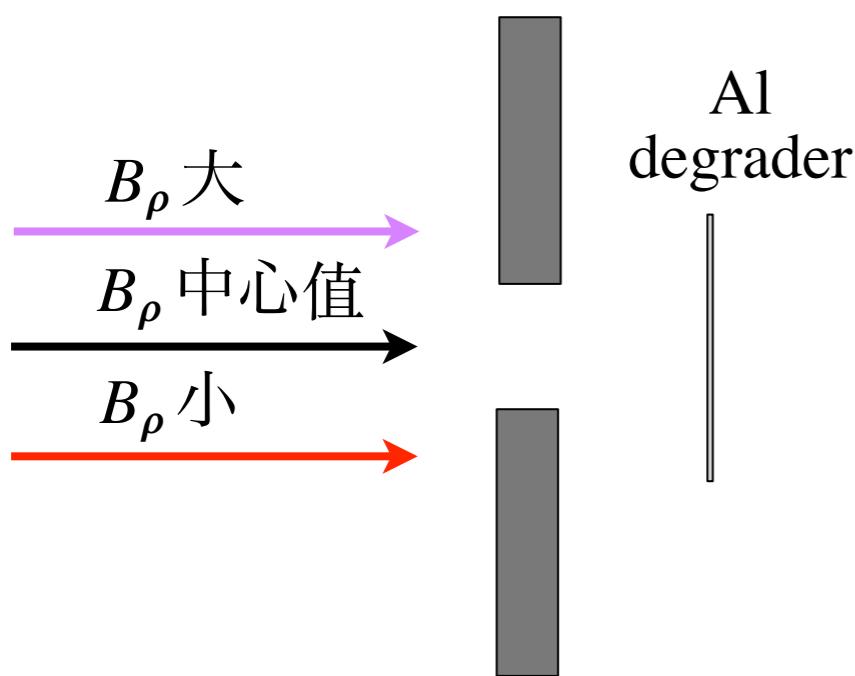
3. 能量损失

- ⇒ 动能／动量 ⇒ 反应／跃迁相关信息
- ⇒ 粒子鉴别

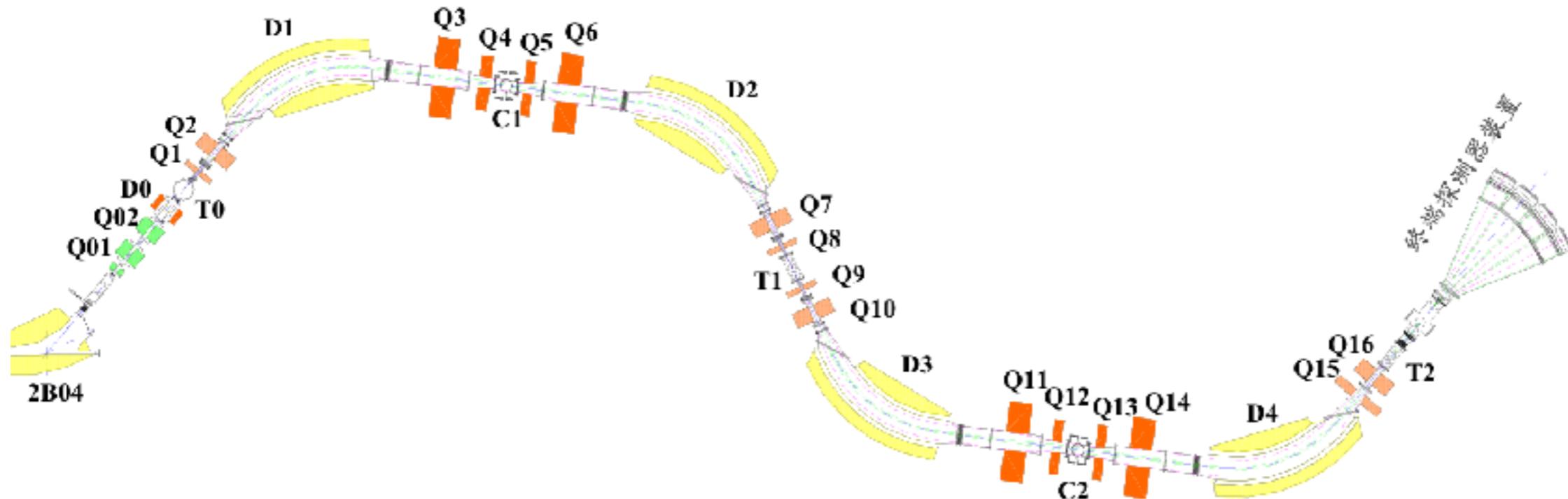
放射性束的粒子鉴别



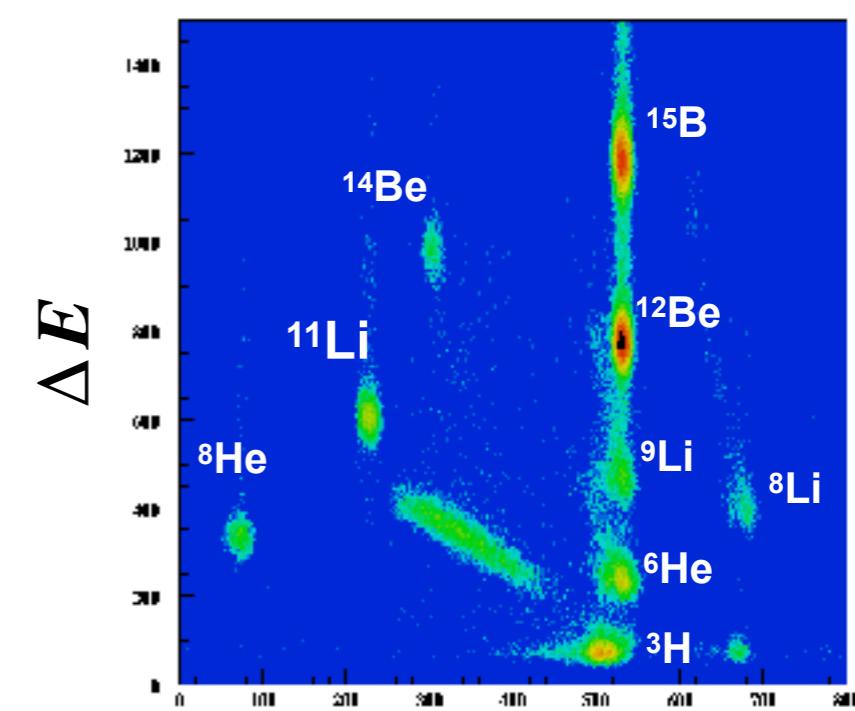
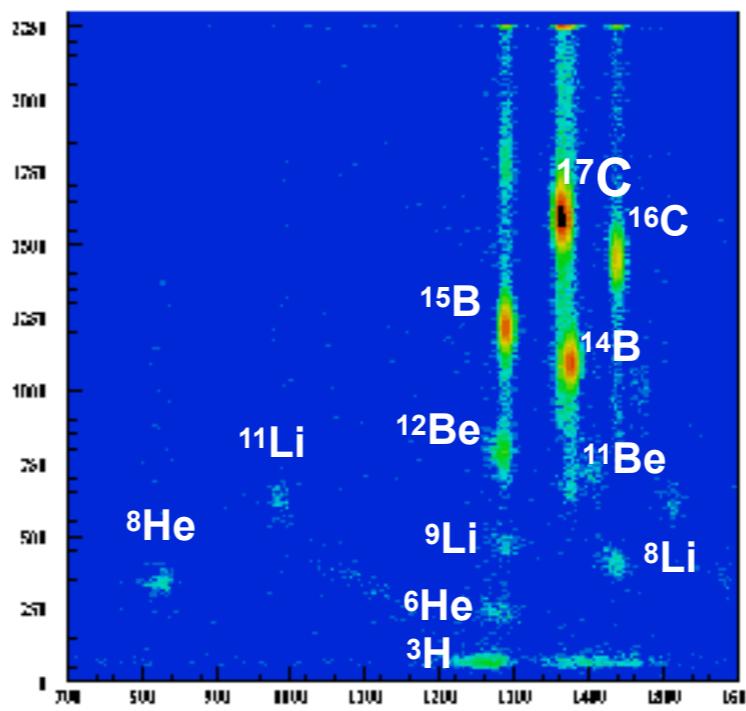
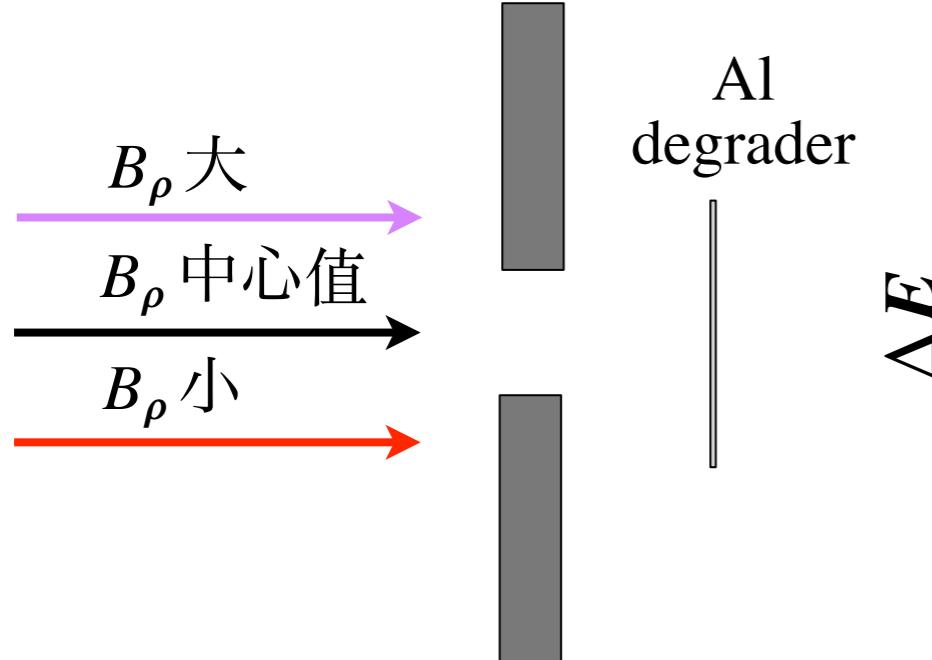
Collimator



放射性束的粒子鉴别



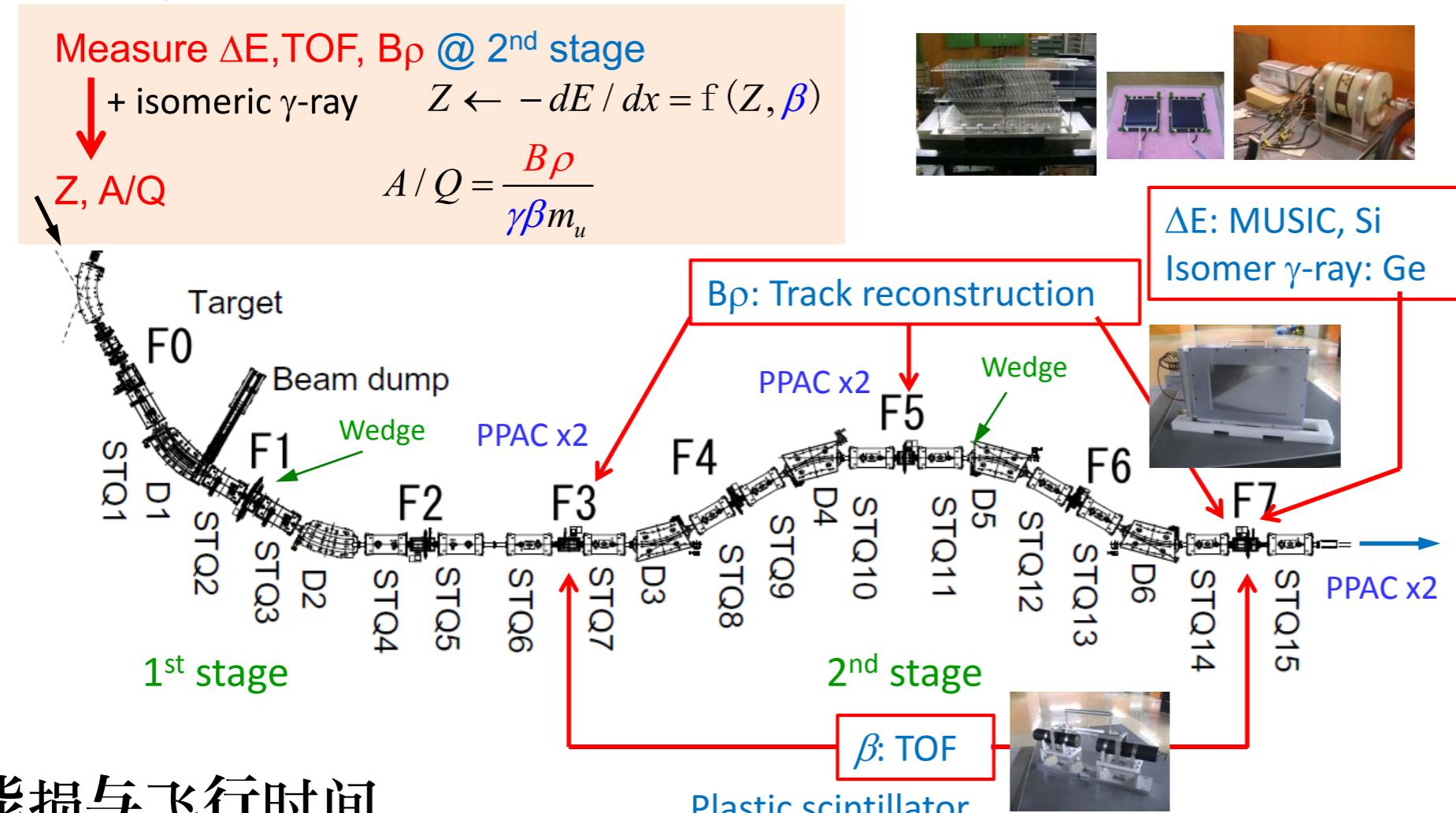
Collimator



放射性束的粒子鉴别

ΔE -TOF- $B\beta$ method with track reconstruction

→ Improve $B\beta$ and TOF resolution



能损与飞行时间

$$dE \propto z^2/v^2 \propto z^2(\text{TOF})^2$$

磁刚度与飞行时间

$$qvB \propto Av^2/R$$

$$B_\rho = BR \propto Av/q \propto A/q/(\text{TOF})$$

放射性束的粒子鉴别

ΔE -TOF- B_ρ method with track reconstruction

→ Improve B_ρ and TOF resolution

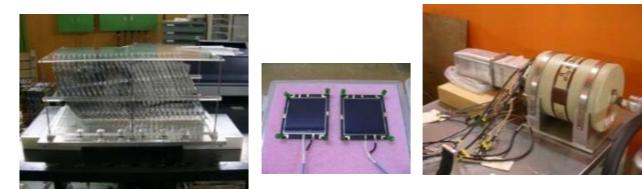
Measure ΔE , TOF, B_ρ @ 2nd stage

+ isomeric γ -ray

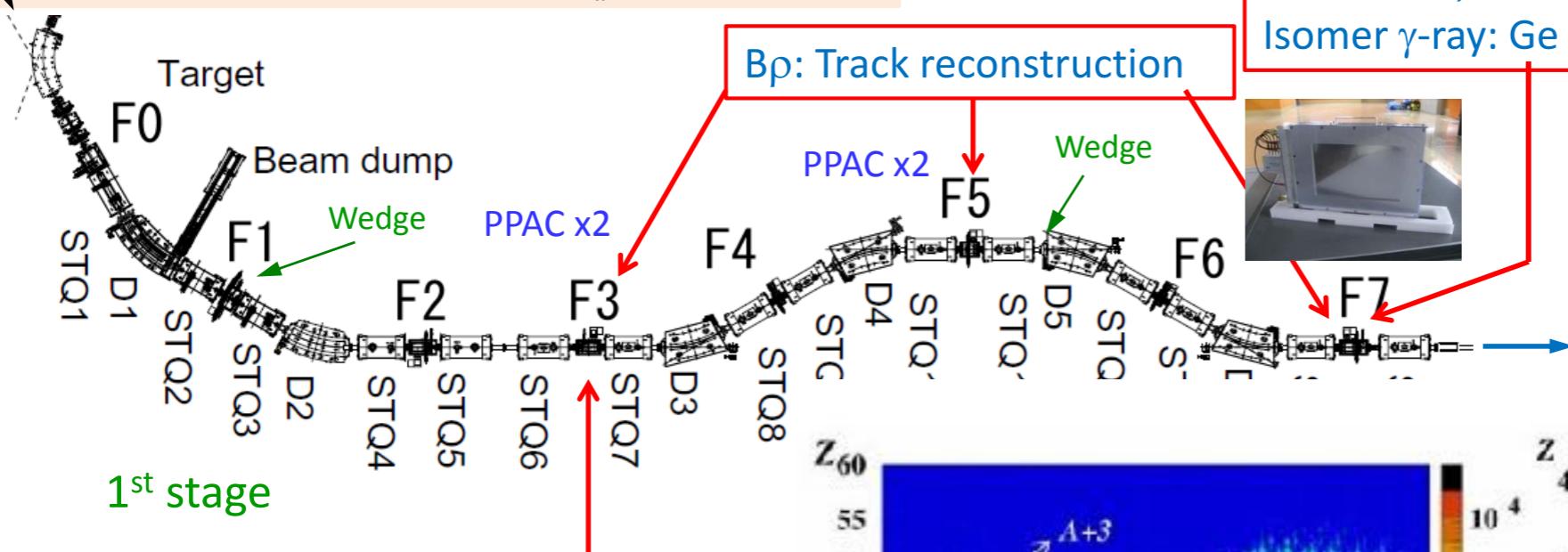
$$Z \leftarrow -dE / dx = f(Z, \beta)$$

$$Z, A/Q$$

$$A/Q = \frac{B_\rho}{\gamma \beta m_u}$$



ΔE : MUSIC, Si
Isomer γ -ray: Ge



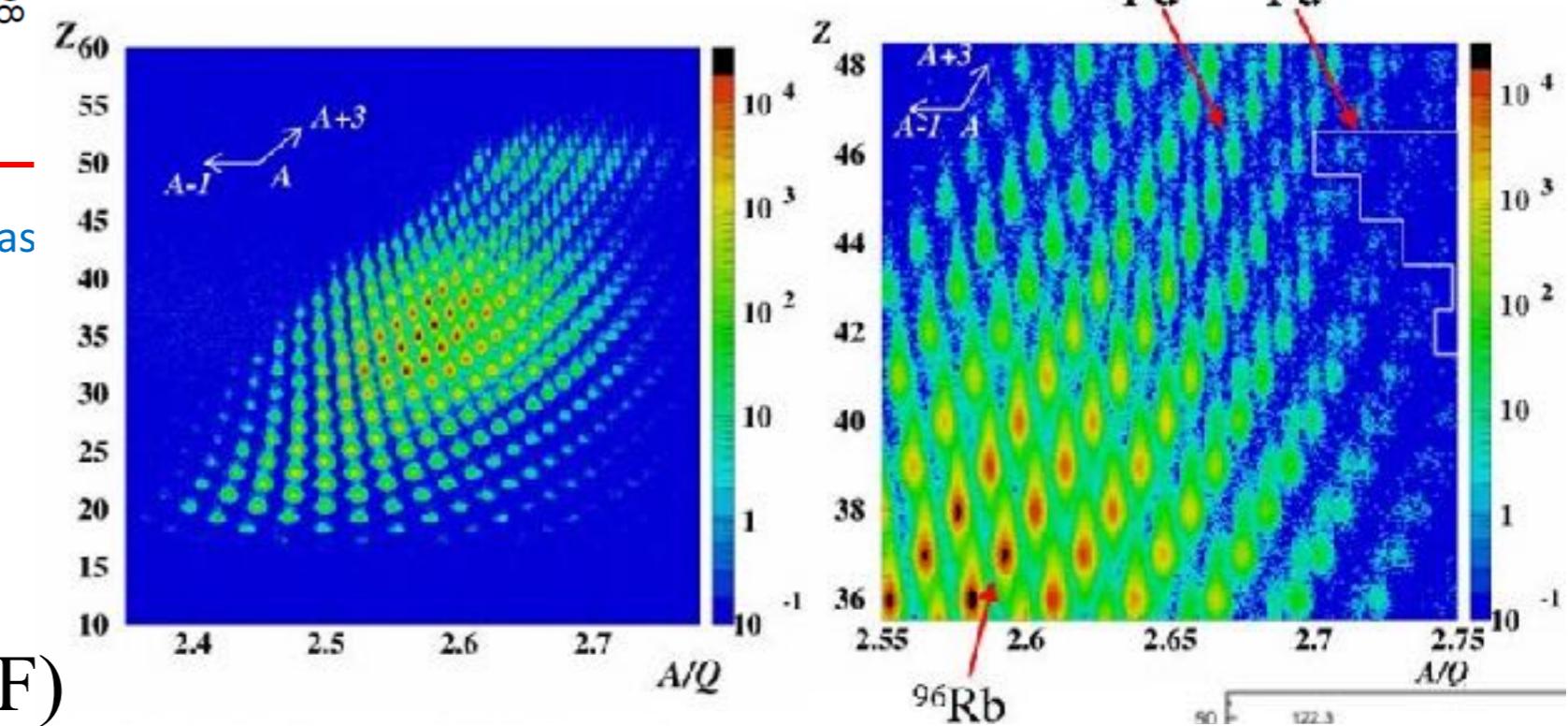
能损与飞行时间

$$dE \propto z^2/v^2 \propto z^2(\text{TOF})^2$$

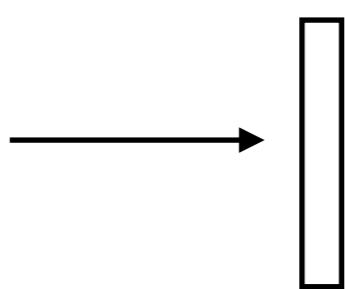
磁刚度与飞行时间

$$qvB \propto Av^2/R$$

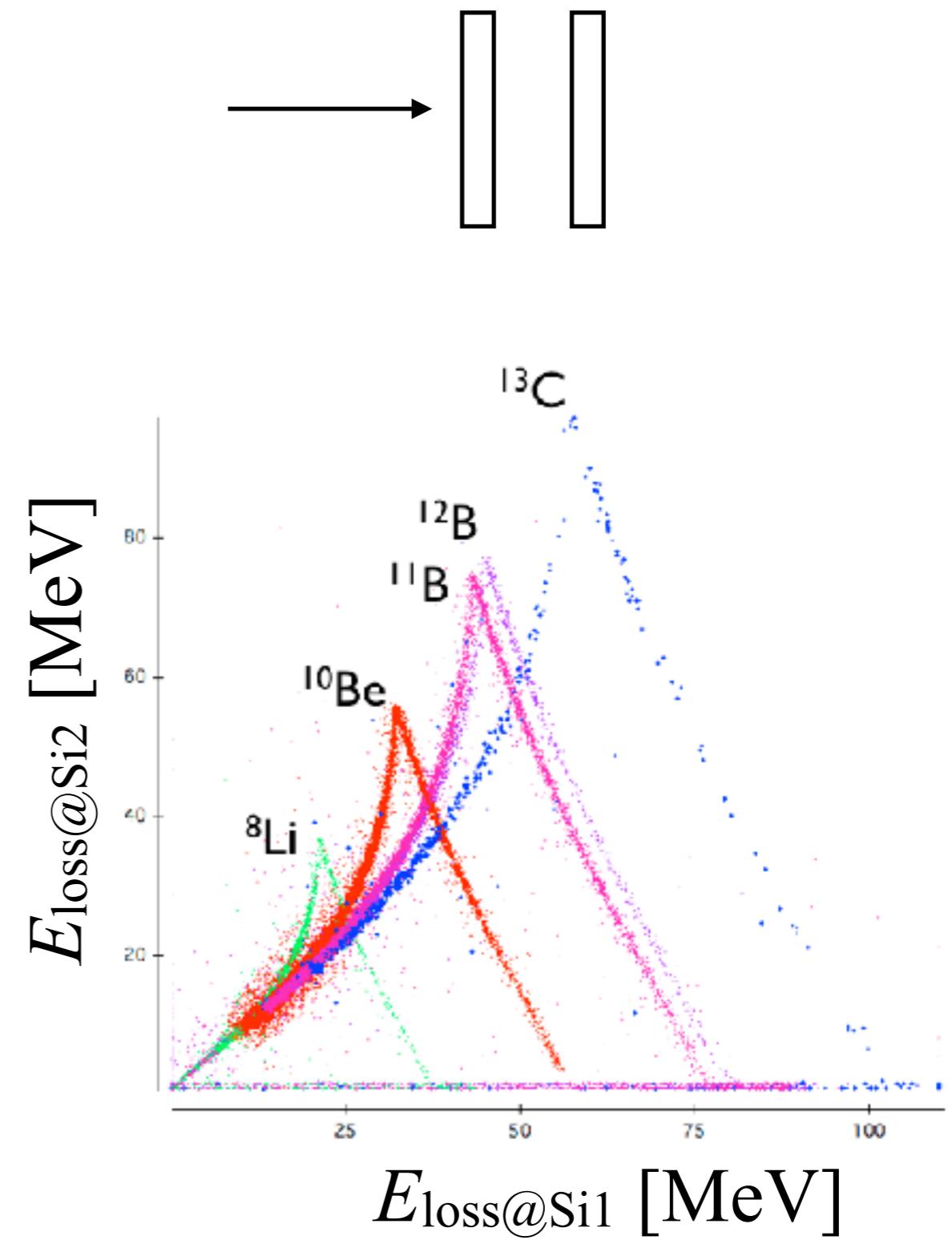
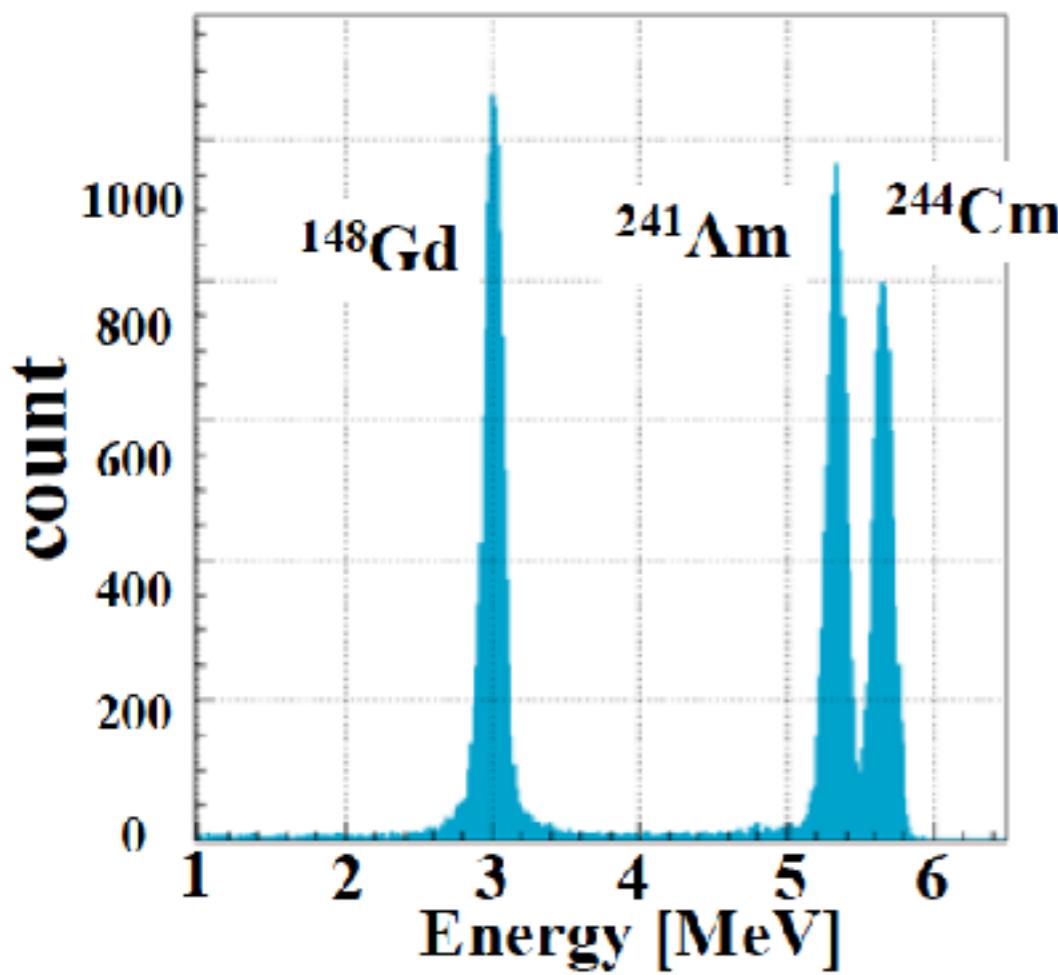
$$B_\rho = BR \propto Av/q \propto A/q/(\text{TOF})$$



利用硅探测器测量能损、动能

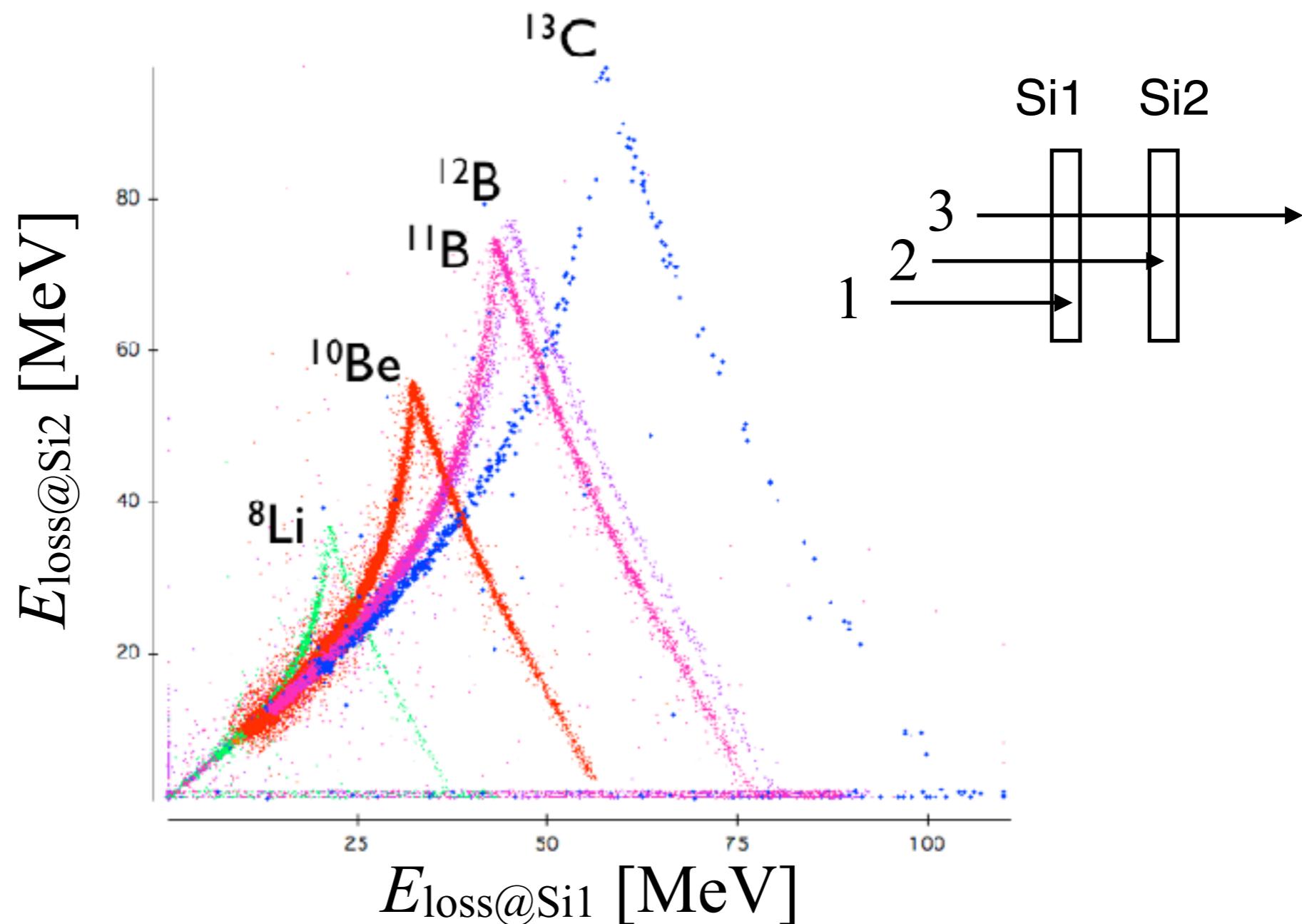


3组份alpha源



硅探测器的能谱

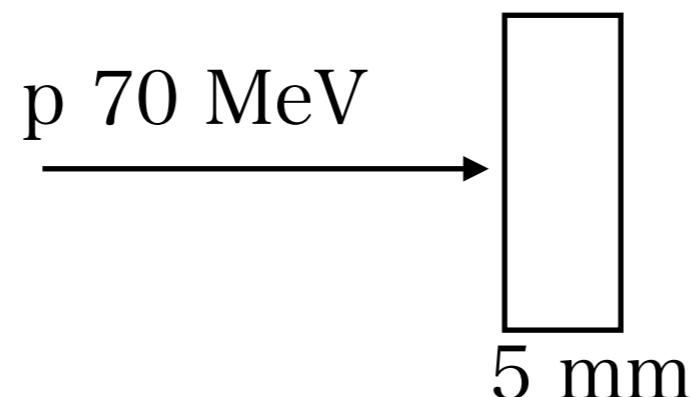
以下的散布图显示各种重离子次级束在 2 个硅探测器中的能损。右图的1、2、3物理过程对应图中的哪些部分？



习题：质子束在物质中的动能

在原子核物理实验等情况下，有时需要计算具有一定动能的带电粒子入射物质后，在物质中某一深度处的动能。此时，相比Bethe-Bloch公式，下述射程（range）公式更为便利。现在假设将70 MeV的质子束垂直入射到厚度为5 mm的塑料闪烁体上。试计算70 MeV质子束在塑料闪烁体中的射程。假设质子束直线前进，求其到达2.5 mm深度时的质子束能量。（设 $c=0.02$, $\gamma = 1.75$, 长度单位为mm。）

$$R = c \frac{A}{Z^2} \left(\frac{E_k}{A} \right)^\gamma$$

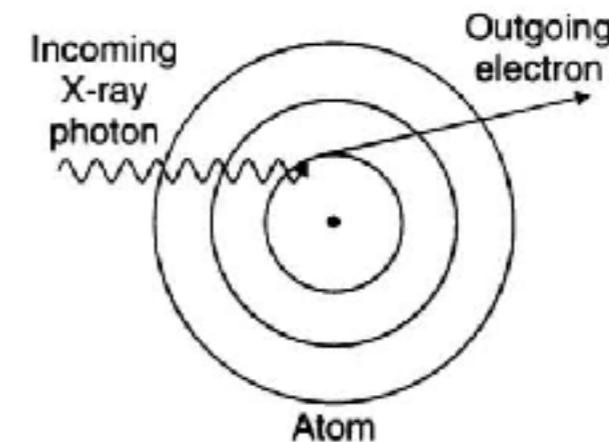


电磁波与物质的相互作用

◆ 光电效应 (photoelectric effect)

$$E_e = h\nu - E_B$$

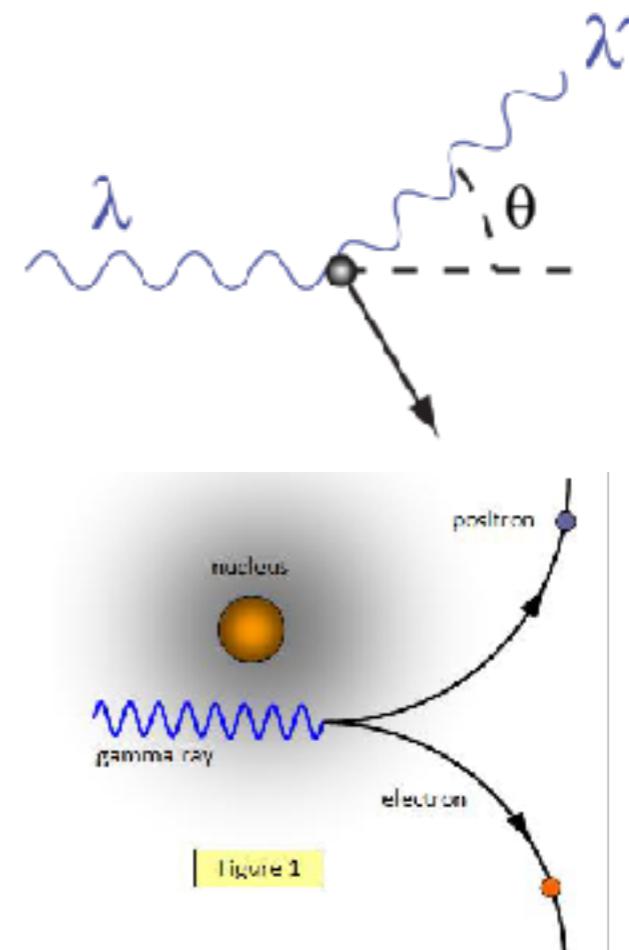
电子的束缚能 / 功函数 (小)



◆ 康普顿散射 (Compton scattering)

$$E_{\gamma'} = \frac{E_\gamma}{1 + \left(\frac{E_\gamma}{m_e c^2} \right) (1 - \cos \theta)}$$

$$E_e = E_\gamma - E_{\gamma'} - E_B$$

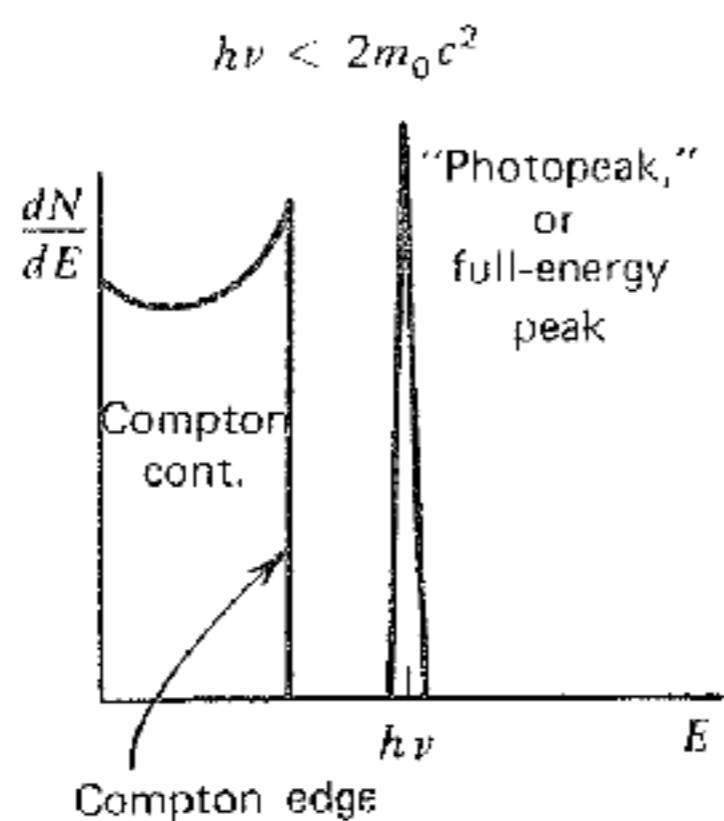


◆ 电子对产生 (pair creation)

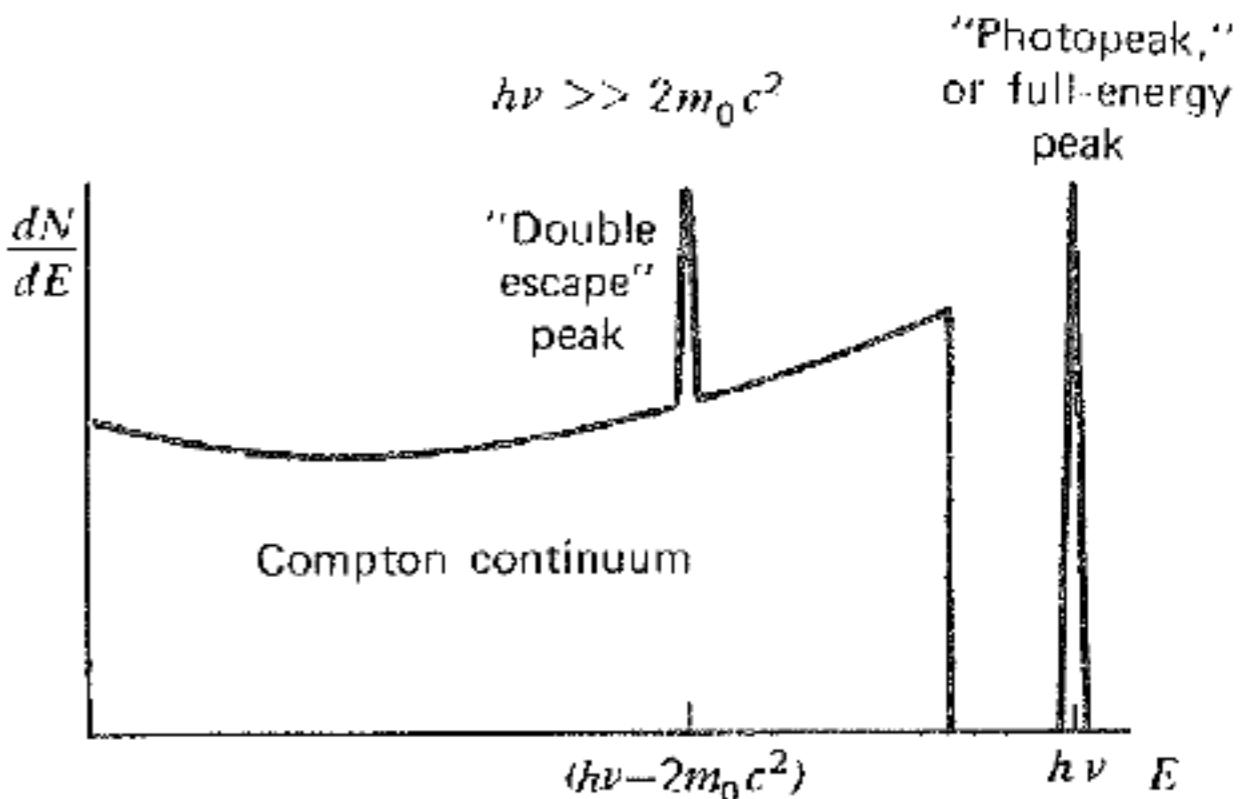
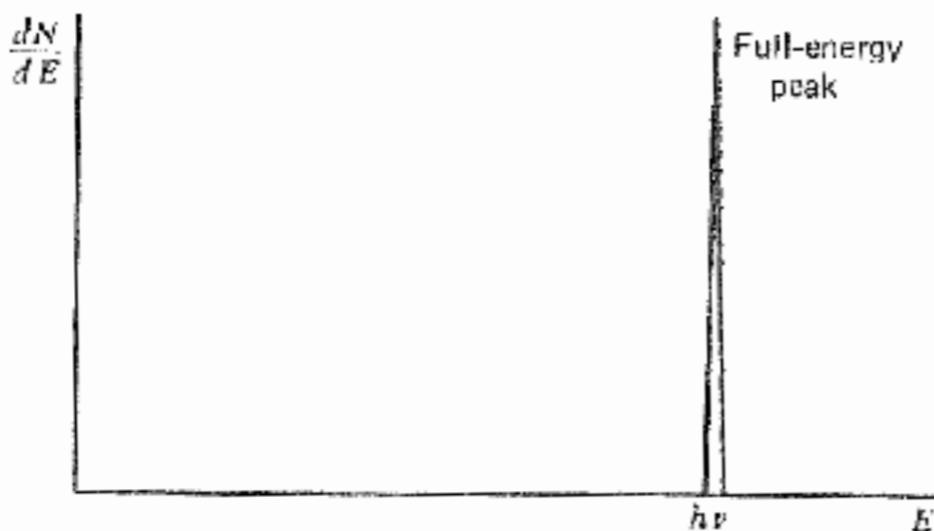
$$E_e = E_\gamma - 2m_e c^2 - E_B$$

电磁波与物质的相互作用

小探测器



大探测器



习题：康普顿散射公式

推导康普顿散射公式。计算能量为662 keV的 γ 射线在物质中发生180度康普顿散射时，电子所获得的能量。（可忽略电子的束缚能。）

$$E_{\gamma'} = \frac{E_\gamma}{1 + \left(\frac{E_\gamma}{m_e c^2} \right) (1 - \cos \theta)}$$

闪烁体探测器

工作原理

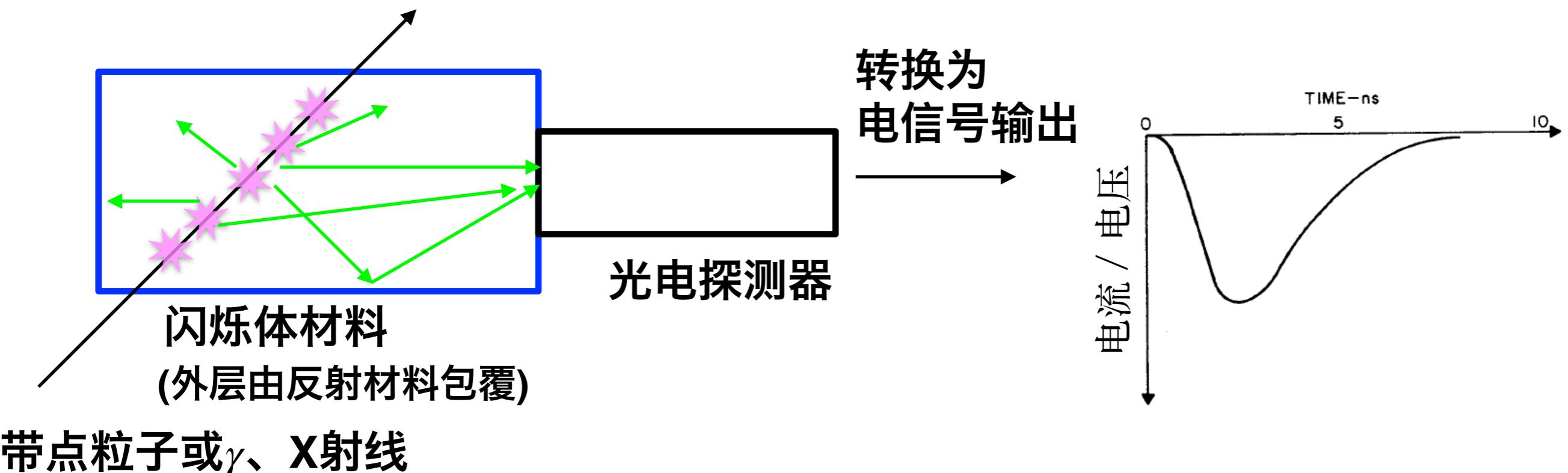
- 当带电粒子、 γ 射线或X射线穿过闪烁体探测器时，会与物质相互作用导致能量损失。这些损失的能量被转换为可见光（光子）。
- 释放出的可见光（光子）由光传感器进行检测。



特点：

- 对带电粒子、 γ 射线或X射线能量具有灵敏度
=> 可实现能损 / 能量测量
- 响应时间快
=> 适合用于测量时间
- 对不同带电粒子具有不同响应特性
=> 可利用脉冲形状甄别技术进行粒子鉴别

闪烁体探测器原理和结构



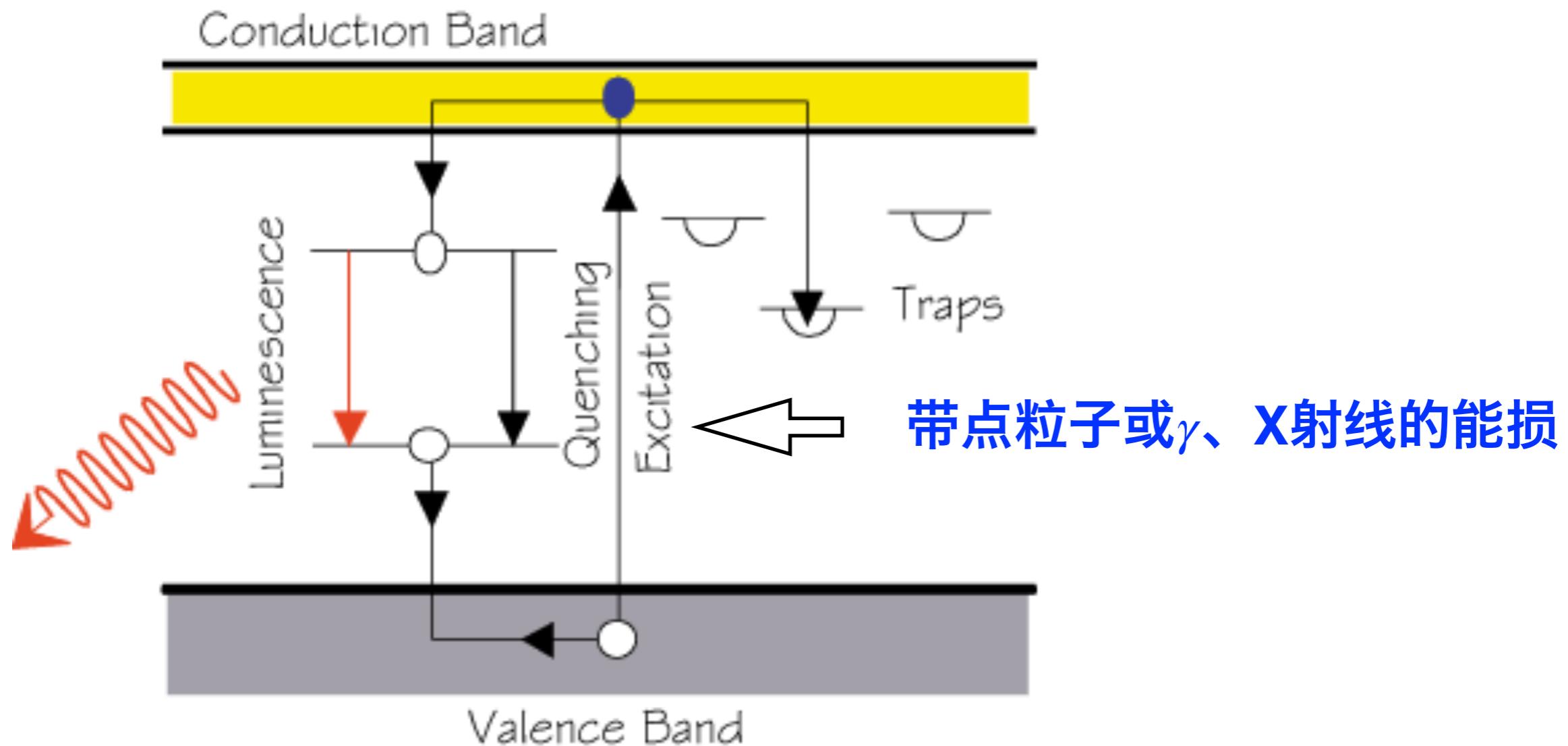
闪烁体材料分类：

1. 有机闪烁体 (固体、液体)
2. 无机闪烁体
3. 气体闪烁体

光电探测器：

1. 光电倍增管 (PMT)
2. 微通道板 (MCP)
3. 光电二极管
4. 硅光电倍增管 (SiPM)

闪烁体探测器原理



有机闪烁体

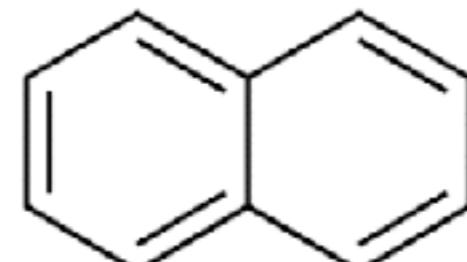
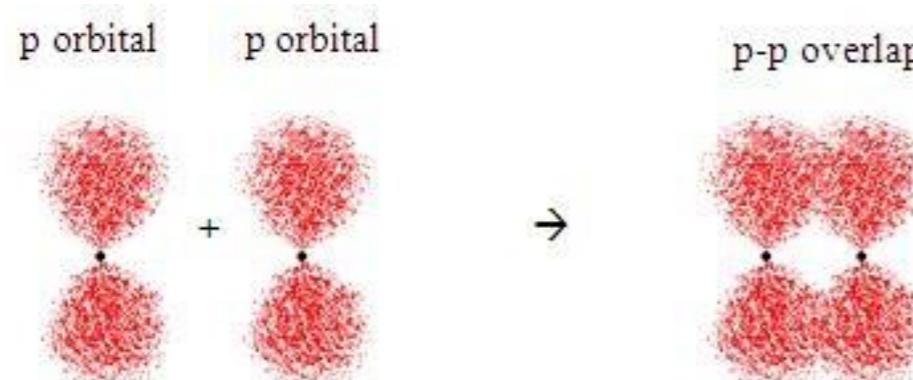
芳香族碳氢化合物

举例：

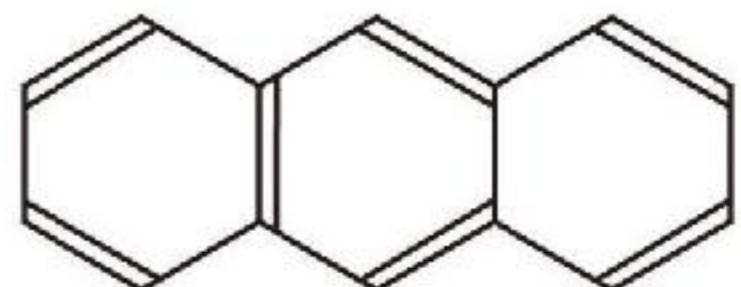
- 萍 (C₁₀H₈)
- 蒽 (C₁₄H₁₀)
- 苯 (C₁₄H₁₂)

当π轨道中的自由电子在能级间跃迁时，会释放荧光。

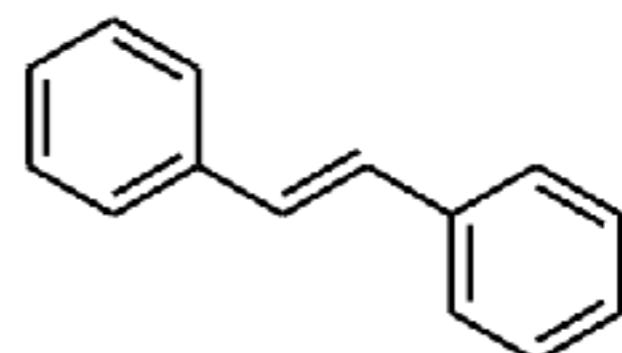
具有超快衰减时间（响应）！ (~ns)



naphthalene
ナフタレン C₁₀H₈

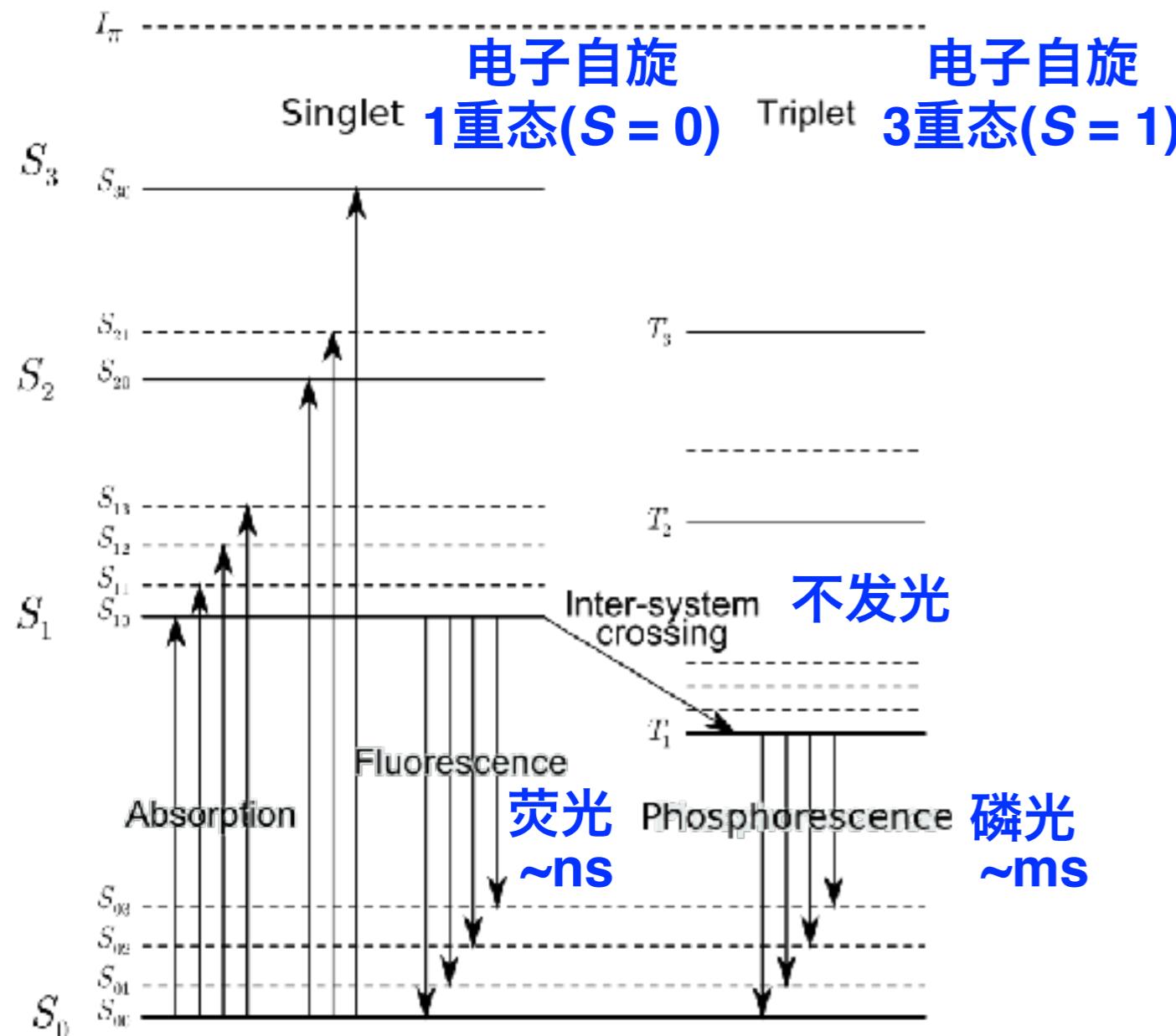


anthracene
アントラセン C₁₄H₁₀



stilbene
スチルベン

有机闪烁体

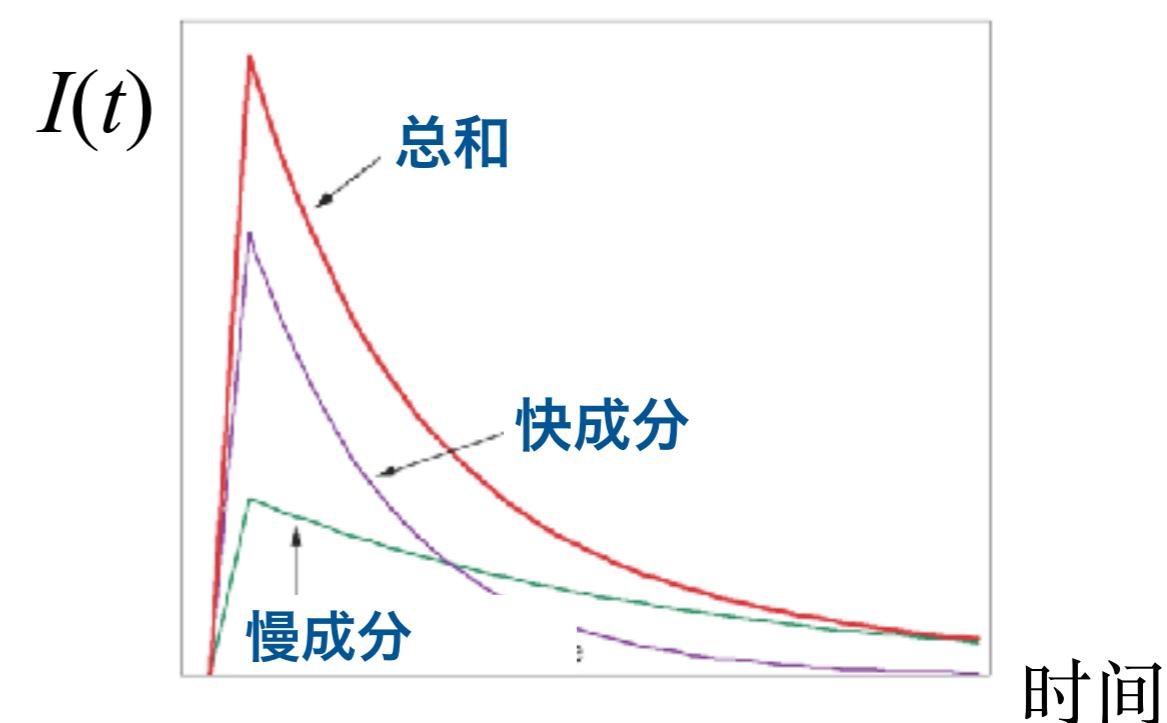


发光强度的时间变化由 $S_1 \rightarrow S_0$ 的衰减时间 (decay time) τ 决定。

$$I(t) = I_0 e^{-t/\tau}$$

不过，当混有经由 T_1 态的发光成分时，光强的时间变化会相对减缓。此时必须考虑慢成分的影响。

$$I(t) = A e^{-t/\tau_f} + B e^{-t/\tau_s}$$



有机闪烁体商品

ELJEN Technology Organic scintillators physical constants and cross-reference:

www.apace-science.com/eljen/

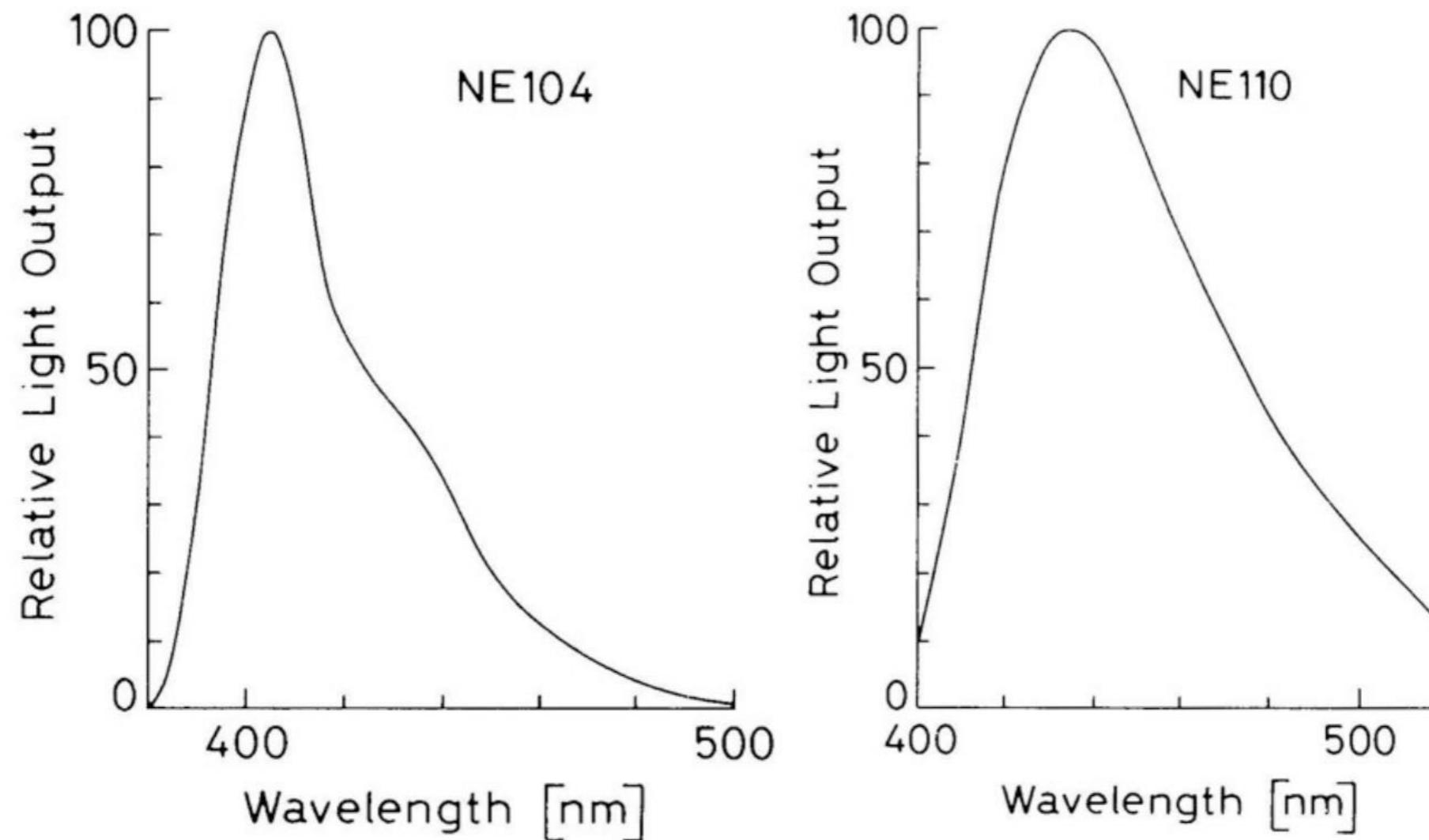
	scintillator material	type	Light output % anthracene [%]	wavelength of max emission [nm]	decay constant of main component [nSec]	Loading element	Attenuation Length (typ.) [cm]	H:C ratio	refractive Index	softening or flash point [°C]	density	Principal applications and Features	commercial equivalents		
													Saint Gobain	NE	
Plastics	plastic	EJ-200	64	425	2.1	380	1.104	1.58	75	1.02	Best overall general properties TOF counters, Large detectors	BC-408	Pilot F	
	plastic	EJ-204	68	408	1.8	160	1.107	1.58	75	1.02	High speed and good attenuation rise = 0.7nsec / decay = 1.8nsec	BC-404	NE-104	
	plastic	EJ-208	60	435	3.3	400	1.104	1.58	75	1.02	Long optical attenuation, longer than 3m rise = 1.0ns / fall = 3.3ns / pulse w=4.2ns	BC-412	NE-110	
	plastic	EJ-208B	38	434	4.0	400	1.103	1.58	75	1.02	Lower cost variant of EJ-208.	BC-416	
	plastic	EJ-212	65	423	2.4	250	1.103	1.58	75	1.02	Most common type, Thin film for alpha.	BC-400	NE-102A	
	plastic	EJ-228	67	391	1.4	n/a	1.103	1.58	75	1.02	Very fast timing with smaller dimension rise = 0.5nsec	BC-418	Pilot U	
	plastic	EJ-230	64	391	1.5	120	1.104	1.58	75	1.02	Very fast timing for longer (>10cm) use rise = 0.5nsec	BC-420	Pilot U2	
	plastic	EJ-232	55	370	1.4	n/a	1.102	1.58	75	1.02	Ultra fast timing, high pulse pair resolution rise = 0.35nsec.	BC-422	NE-111A	
	plastic	EJ-240	41	435	~285	380	1.109	1.58	75	1.02	Very long decay time constant for phoswich combination use with liquid for PSD	BC-444	NE-115	
	plastic	EJ-244	51	435	3.3	400	1.104	1.58	99	1.02	Elevated temperature use. analog to EJ-208.	BC-440	
	plastic	EJ-248	54	425	2.1	380	1.104	1.59	100	1.049	Elevated temperature environment analog to EJ-200, general purpose.	BC-448	
	plastic	EJ-252	46	423	2.4	n/a	1.098	1.58	75	1.037	Dosimetry (general) air equivalent	BC-470	NE-105	
	plastic	EJ-256	32	425	2.1	5% Pb	n/a	1.134	1.58	75	1.08	Lead loaded, 5.0 w% Pb for standard. X-ray dosimetry use.	BC-452	NE-142	
	plastic	EJ-299-07	n/a	435	~2.0	n/a	1.11	~1.5	75	1.02	for very thin foil shape, beam pick-up, etc. 0.005mm (5μm) as the thinnest	9000 blue photons per 1 MeV electron	
	plastic	EJ-299-13	41	435	~285	n/a	1.11	1.58	75	1.035	Long principal decay component. To use with Liquid, equivalent EJ-240	
	plastic	EJ-299-15		425	1.9	n/a	1.60	1.49	~80	1.21	Cherenkov counter (not scintillator) wave-shifting quantum efficiency = 84%	
Liquid	Liquid	EJ-301	78	425	2.1	1.217	1.505	26	0.874	Fast neutron, neutron/Gamma PSD. primary decay = 3.16, 32.3 & 270nSec.	BC-501A	NE-213	
	Liquid	EJ-305	80	424	2.5	1.331	1.505	47	0.877	High Light output	BC-505	NE-224	
	Liquid	EJ-309	60	425	3.5	>3.5m	1.607	1.48	138	0.90	Low attackability to plastics, similar to EJ-301 neutron/gamma pulse shape discrimination	renamed type of former EJ-399-06	
	Liquid	EJ-313	20	424	3.1	F	0.0035	1.377	10	1.61	Fast neutron and gamma ray Hydrogen free.	BC-509	NE-228	
	Liquid	EJ-315	38	425	3.5	D	>3m	D:H ratio 141.5	1.498	-11	0.954	Deuterated Deuterated standard for neutron study.	BC-537	NE-230	
	Liquid	EJ-315HD	38	425	3.5	D	>3m	D:H ratio 222	1.498	-11	0.954	High deuterated ratio D:H ratio = 222	
	Liquid	EJ-315UHD	38	425	3.5	D	>3m	D:H ratio 1651	1.498	-11	0.954	Ultra high deuterated ratio D:H ratio = 1,651	
	Liquid	EJ-321L	39	425	2.0	>5m	2.01	1.47	102	0.86	Mineral oil base, Large vessel detector use.	BC-517L	NE-235L	
	Liquid	EJ-321H	52	424	2.0	>5m	1.89	1.48	81	0.86	High Light output type mineral oil base. also EJ-321P and EJ-321S available.	BC-517H	NE-235H	
	Liquid	EJ-325	60	424	4.0	1.73	1.49	74	0.875	Mineral oil base, for large vessel detector use. fast neutron — gamma discrim.	BC-519	NE-235C	
	Liquid	EJ-399-08	42	428	3.5	>1m	1.899	1.50	>150	0.86	Very low attackability to plastics. use with plastic scintillators.	
Loaded Liq.	Liq.	scintillator material	type	Light output % anthracene [%]	wavelength of max emission [nm]	decay constant of main component [nSec]	Loading element	Attenuation Length (typ.) [meters]	H:C ratio	refractive Index	softening or flash point [°C]	density	Principal applications and Features	commercial equivalents	
	Gd Loaded	EJ-331	68	424	3.6	Gd to 1%	>4m	1.32	1.50	44	0.90	Highest light output Gd Loaded	BC-621	NE-323	
	Gd Loaded	EJ-335	55	424	3.8	Gd to 0.5%	>4.5m	1.57	1.49	64	0.88	Mineral Oil base for Large tanks Neutron spectrometry, neutrinos	BC-625	
	B-10 Loaded	EJ-339	65	424	3.7	B-10 5%	1.67	1.411	8	0.98	Pulse shape discrimination, neutron spectrometry, thermal neutron	BC-623A	NE-321A	
	Dioxane based	EJ-361	65	425	3.8	1.65	1.44	12	1.036	Dioxane based cocktail for aqueous samples for Tritiated water assay.	BC-220	NE-220	



denotes: Plastics – 1MeV of energy deposited in EJ-200 from an energetic electron produces approximately 10,000 blue photons.
Liquids – 1MeV of energy deposited in EJ-301 from an energetic electron produces approximately 12,000 blue photons.

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有机闪烁体的光学特性

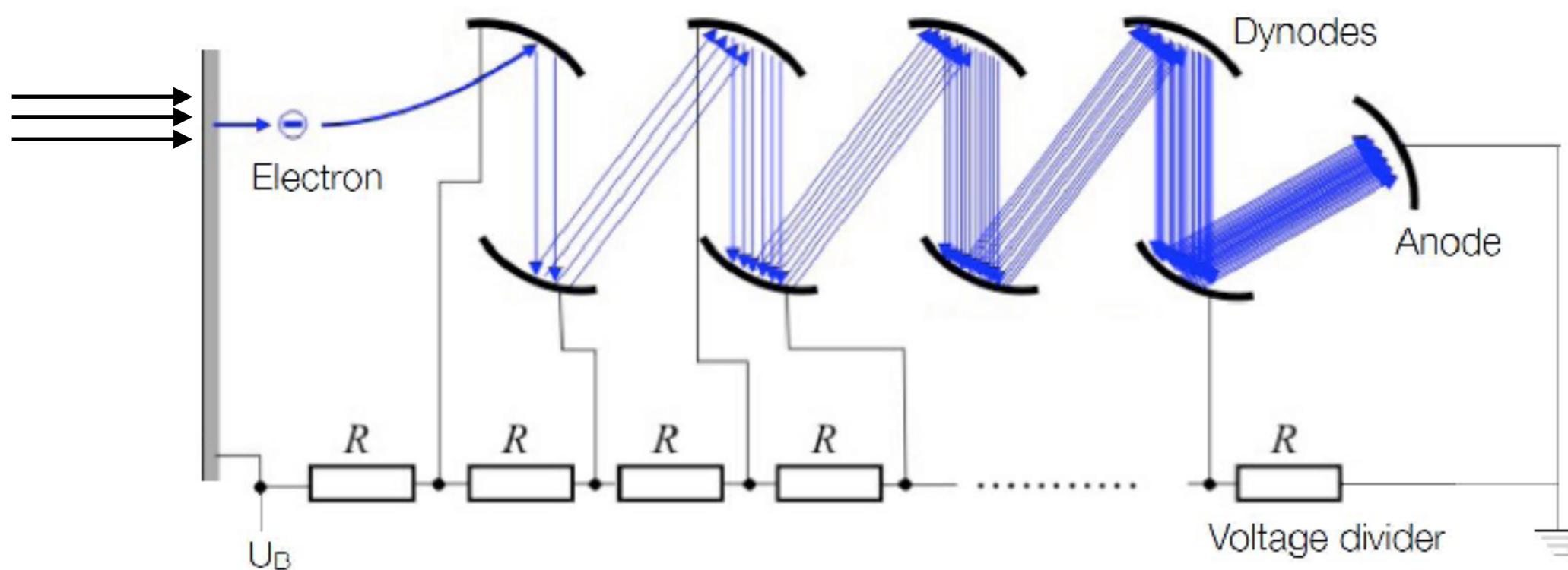
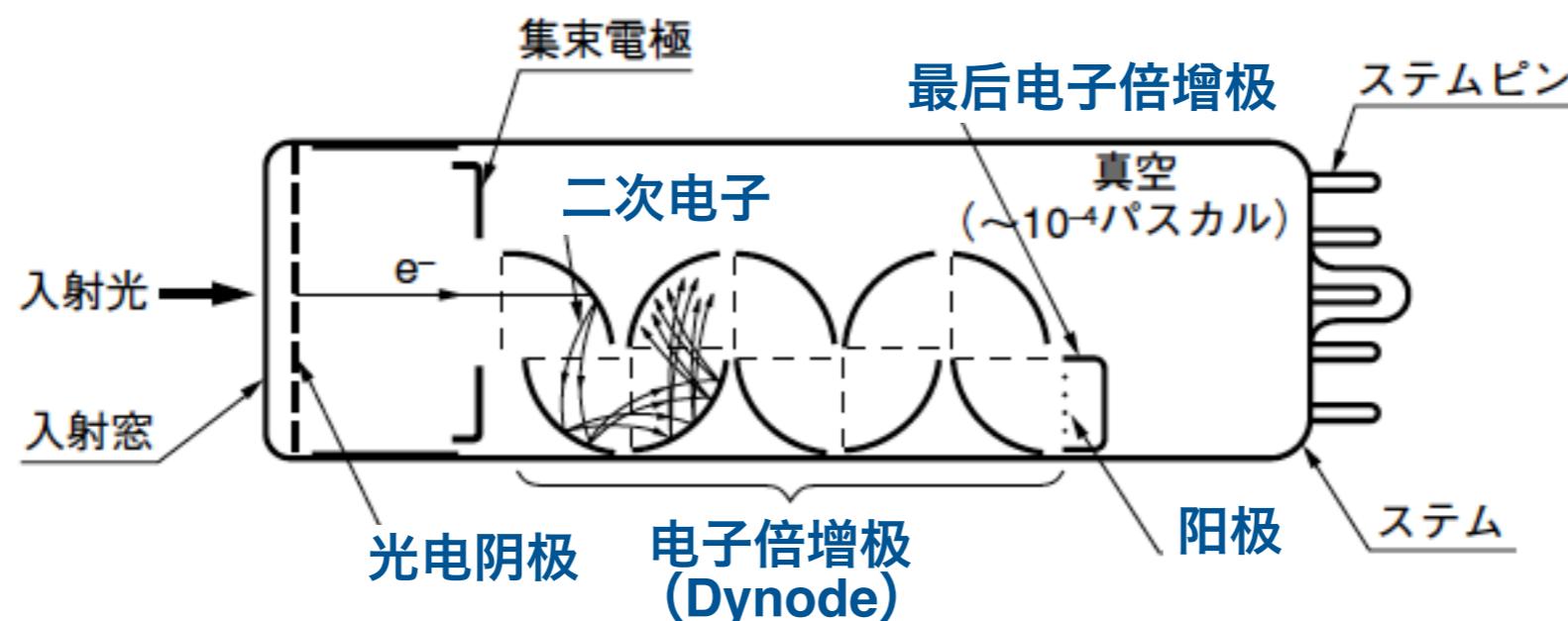


光电倍增管

光电转换与信号放大装置



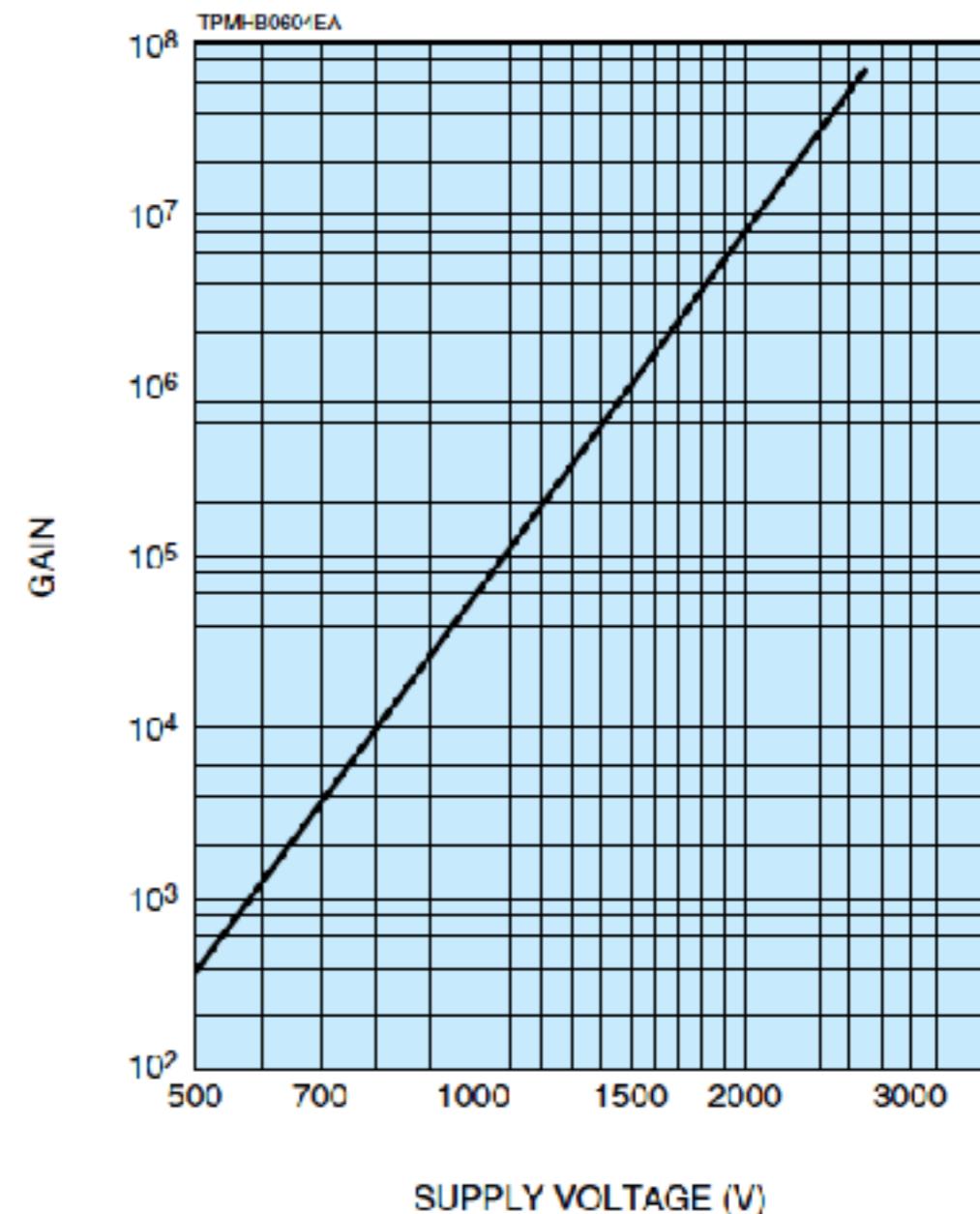
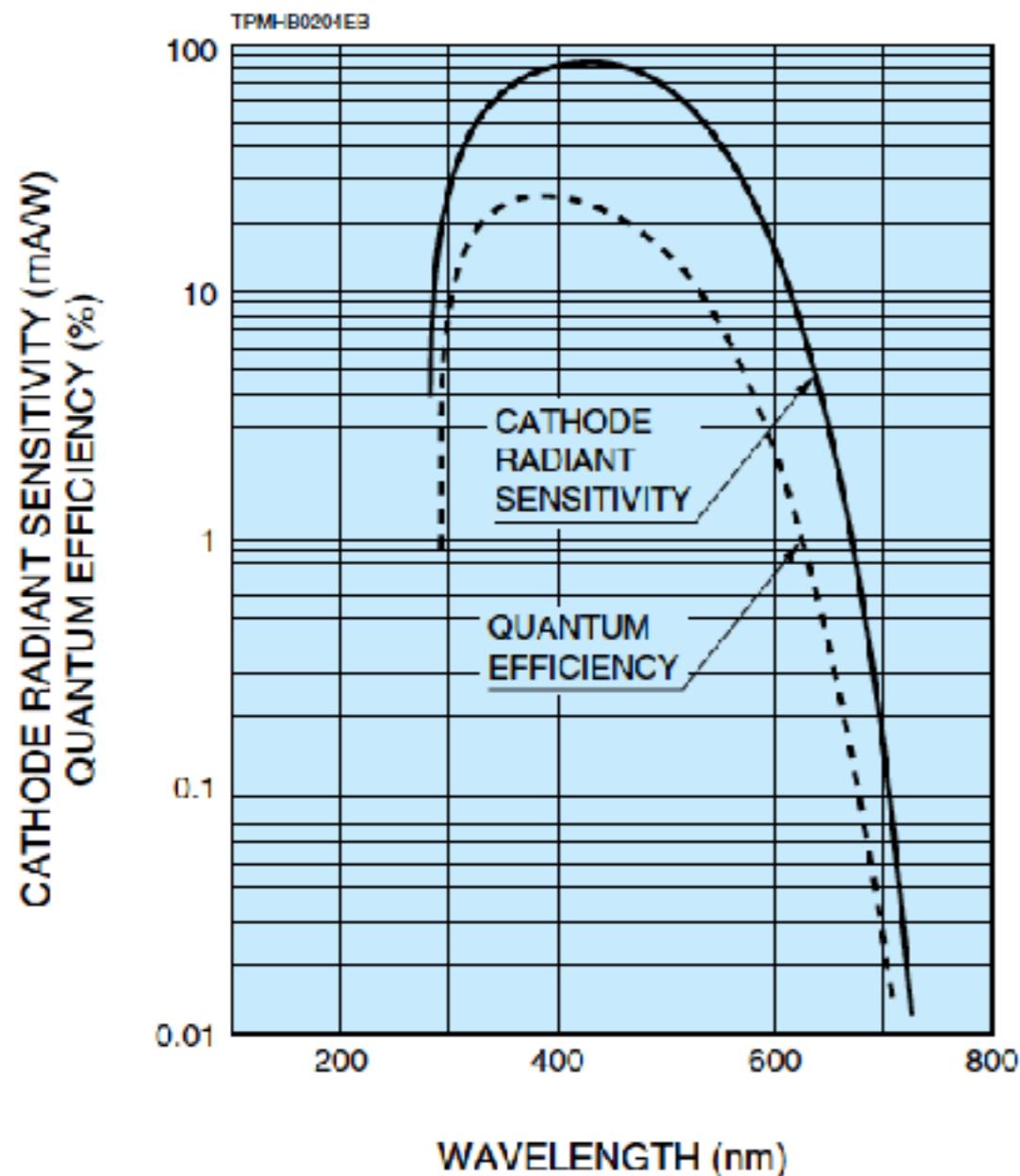
光电倍增管的工作原理



$$\text{二次电子发射比} = \delta, \text{ 倍增极级数} = n \Rightarrow \text{增益} = \delta^n$$

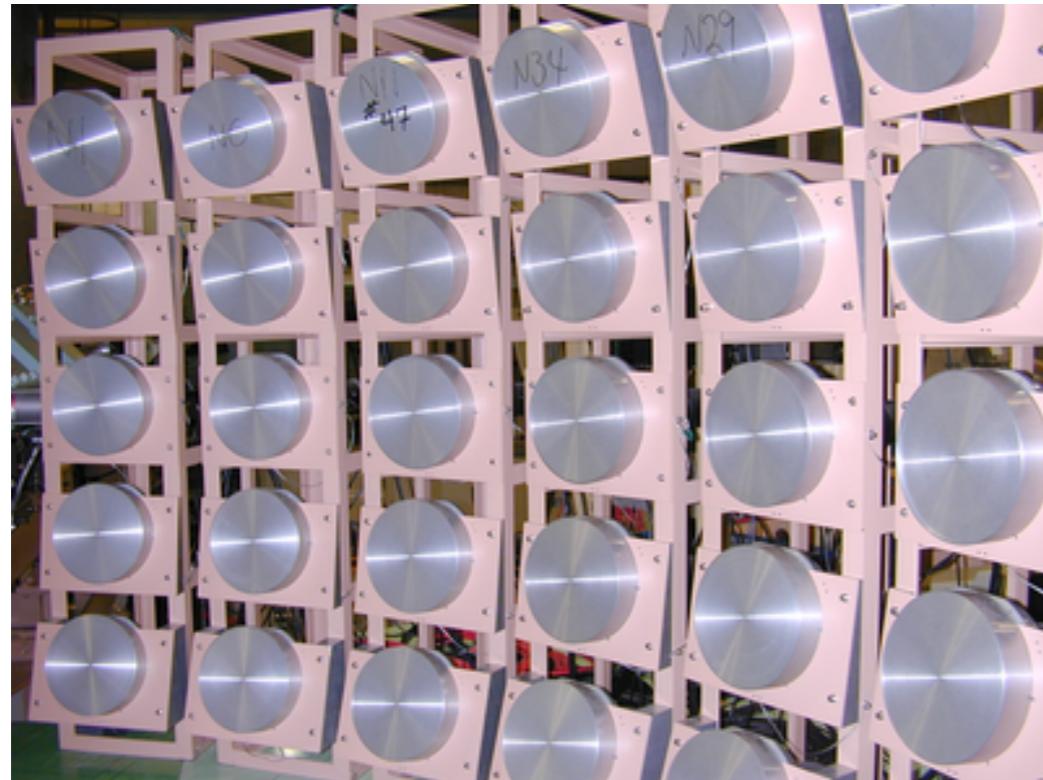
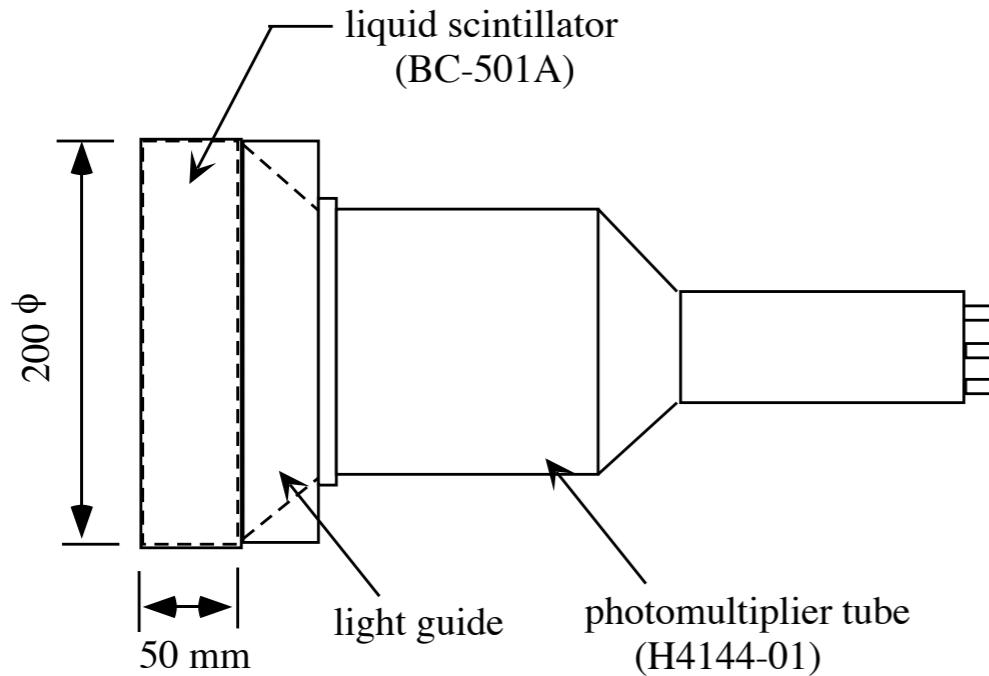
光电倍增管的特性

日本滨松公司
型号：R329-02



倍增极级数=？

液态有机闪烁体探测器

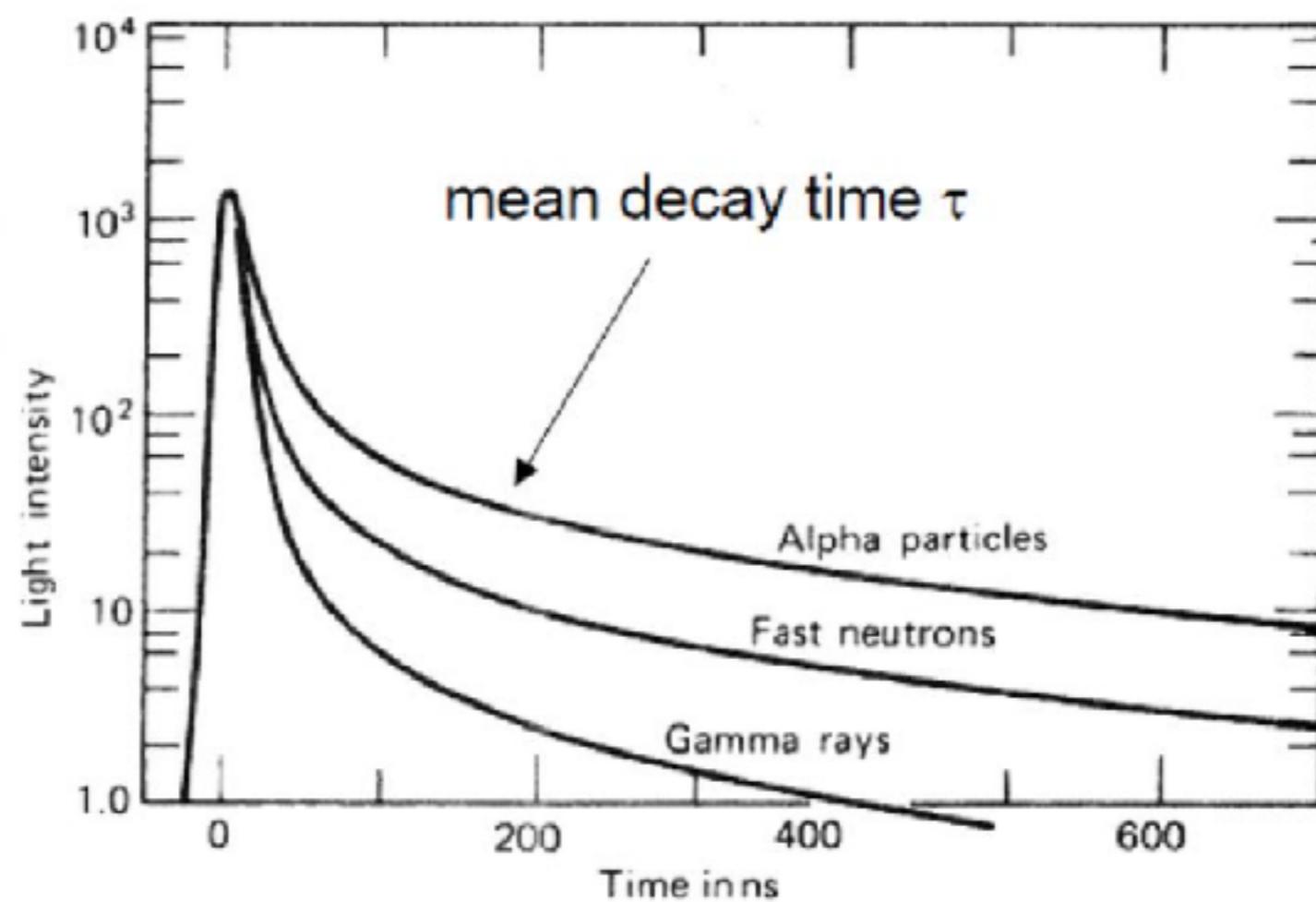


Neutron Polarimeter
(NPOL-2) @ RCNP



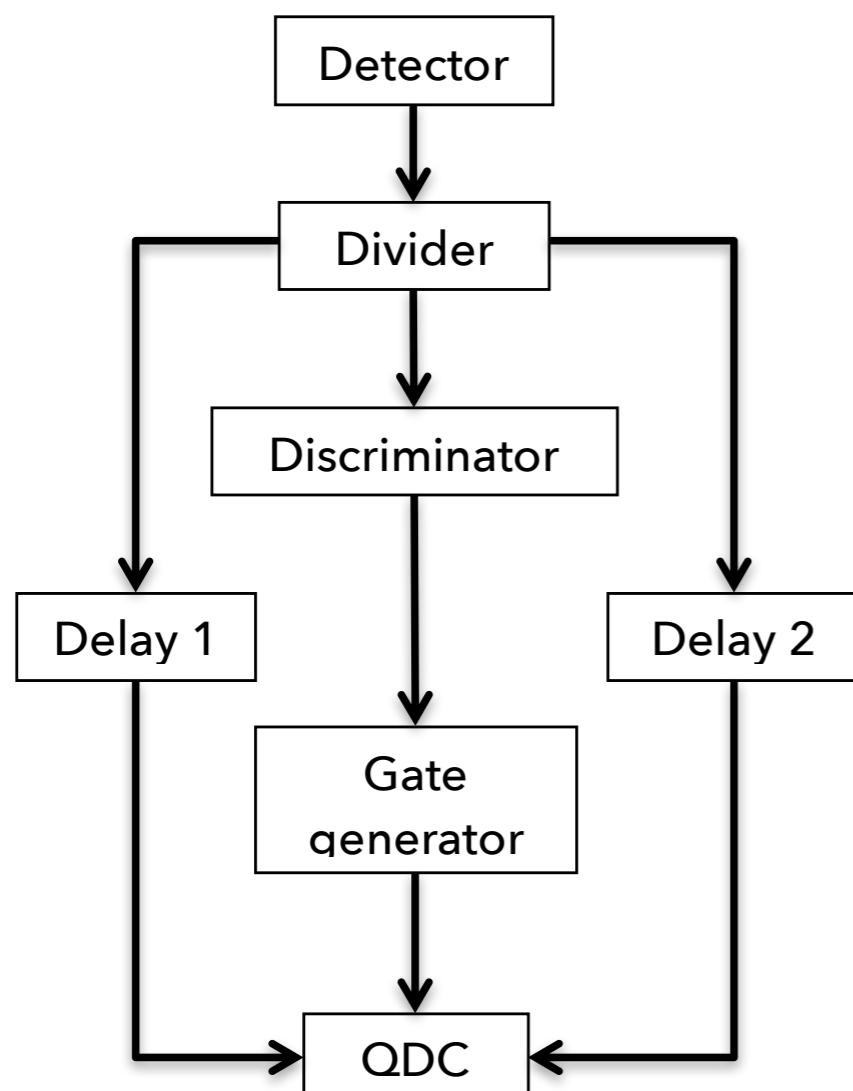
脉冲形状甄别

- 带电粒子差异响应特性
⇒ 可利用脉冲形状甄别技术 (Pulse-Shape Discrimination, PSD)
实现粒子鉴别



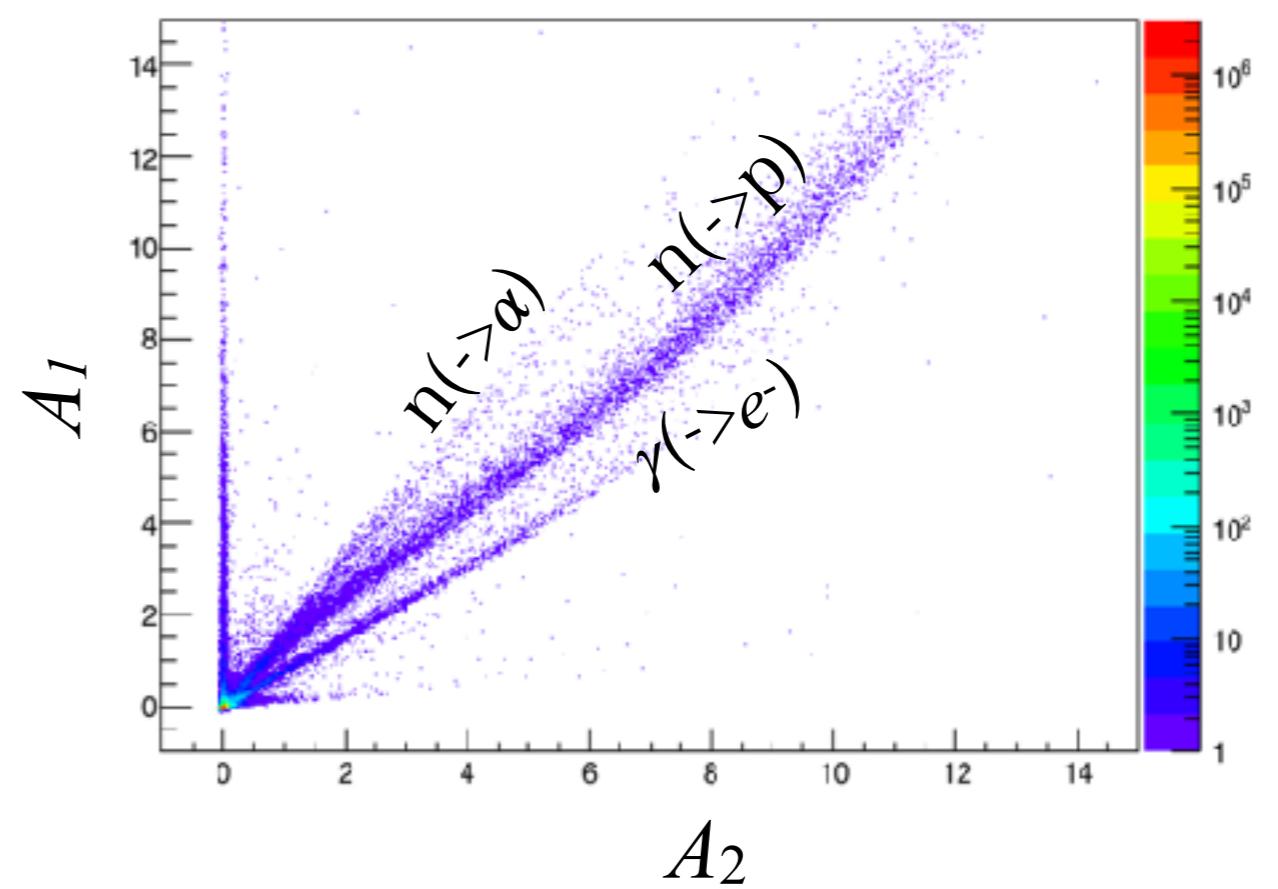
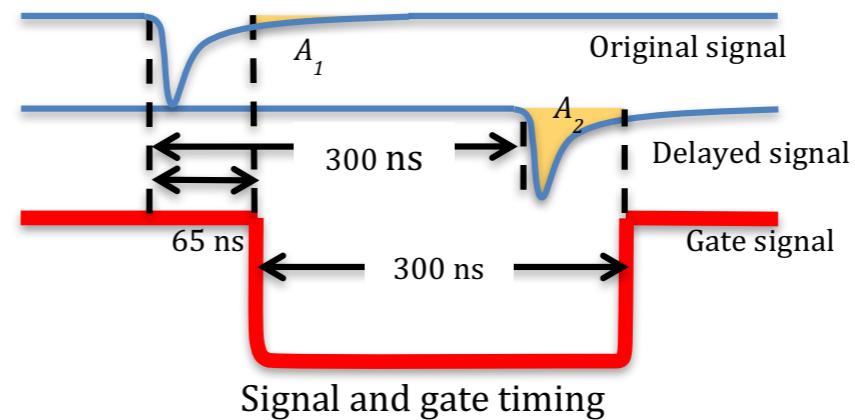
脉冲形状甄别

PSD信号处理电路



Circuit diagram for liquid scintillators

信号时序关系



无机闪烁体

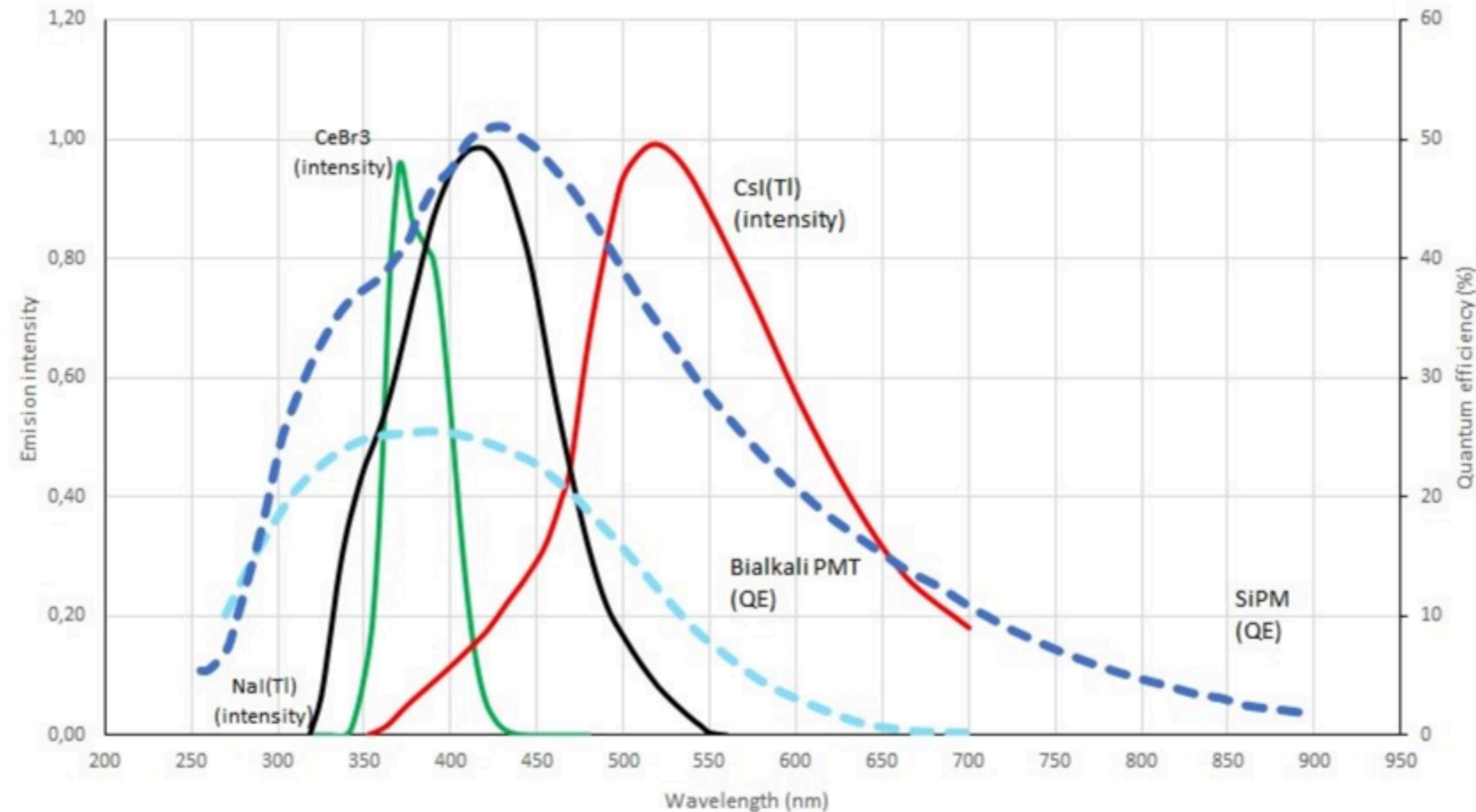
- 碱金属卤化物（Alkali Halide）晶体掺杂活化杂质材料
- 由于原子序数较大，因此具有高密度和强阻止能力的特性
- 相较于有机闪烁体，具有更高的光输出产额

Composition	Fastest Decay Component (ns)	Light Yield (Photons/MeV)	Emission Wavelength
BaF ₂	0.6	9400 ± 600	220 nm
CsF	2.8	500	380 nm
PbI ₂	<1	40,000	520 nm
BaLu ₂ F ₈	1.0	200	298 nm
BaMgF ₄	0.57	1300	205 nm
LiBaF ₃	0.8	1200	300 nm
Cs ₂ LiYCl ₆	6600	6535	240–460 nm
Cs ₂ ZnCl ₄	1.8	630	255 nm
Cs ₂ CaCl ₃	2.3	410	300 nm
NaI:Tl ⁺	239	18,800 ± 940	430 nm
CsI:Tl ⁺	1050	40,000–60,000	550 nm
LuI ₃ :Ce ³⁺	6–10	98,000 ± 10,000	470 nm
LaCl ₃ :Ce ³⁺	25	46,000 ± 3000	352 nm
SrI ₂ :Eu ²⁺	1200	90,000	435 nm
CaI ₂ :Eu ²⁺	790	-	470 nm
BaI ₂ :Eu ²⁺	<1000	>30,000	420 nm
GAGG (Gd ₃ Al ₂ Ga ₃ O ₁₂)	90-150	46,000	520-530 nm



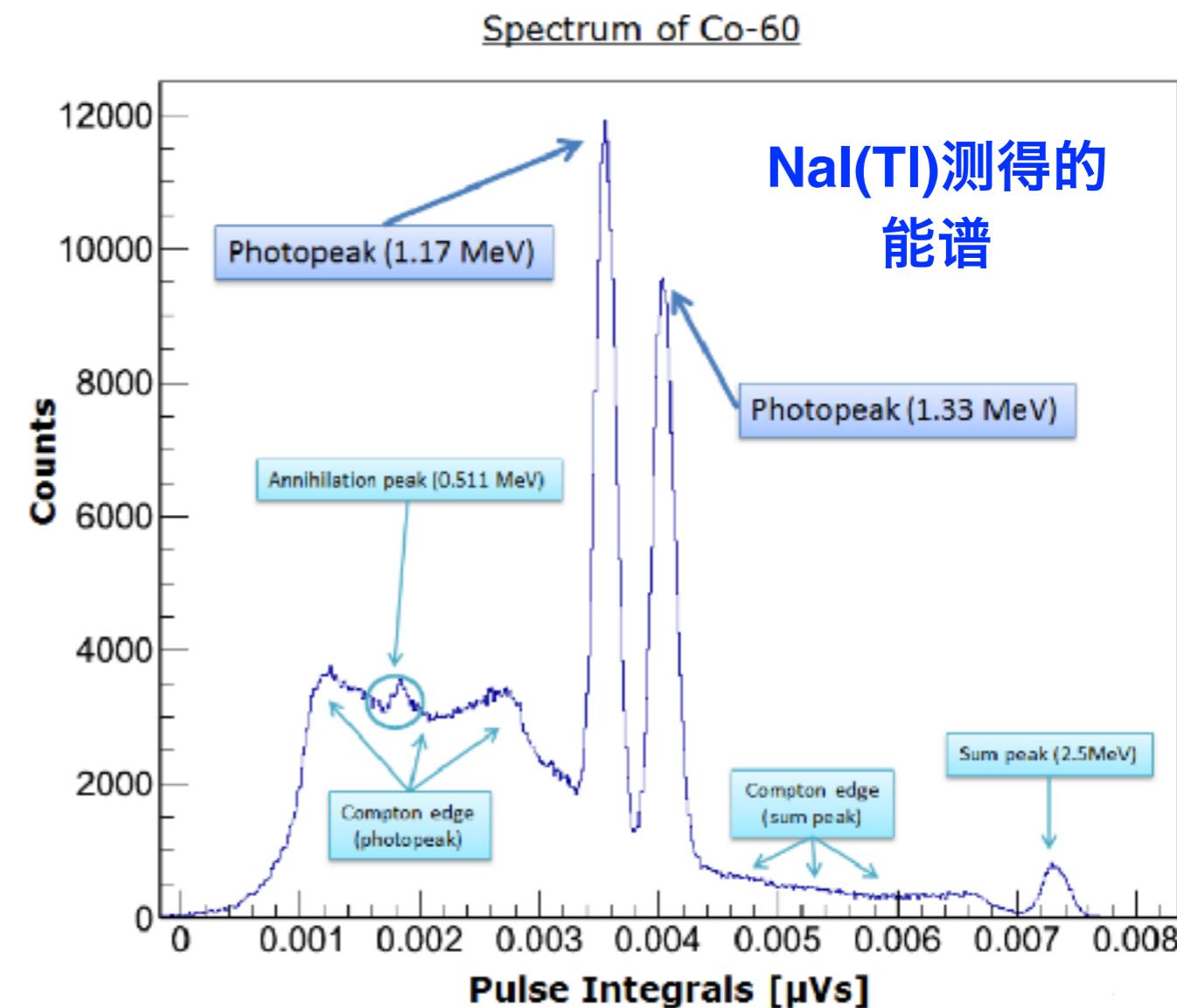
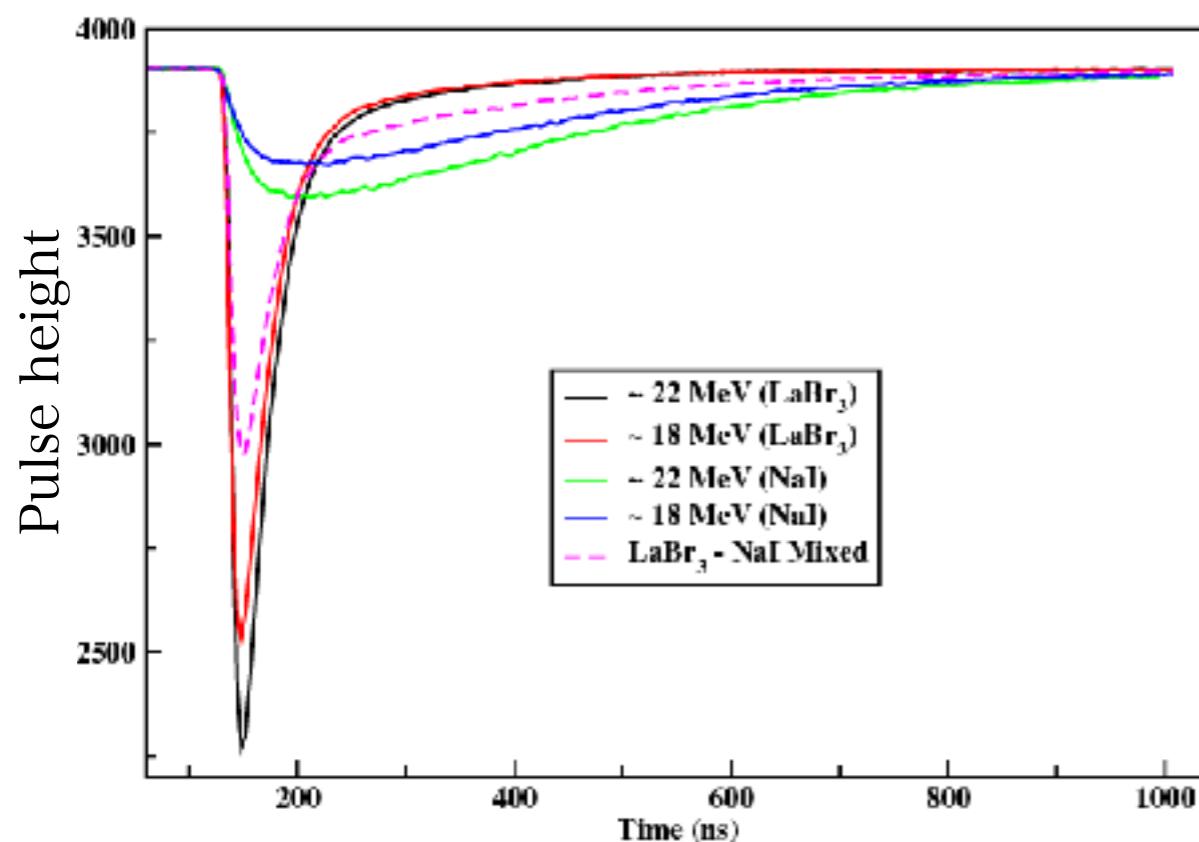
无机闪烁体的光学特性

Emission intensity and quantum effeciency compared to wavelength.



无机闪烁体的信号和能谱

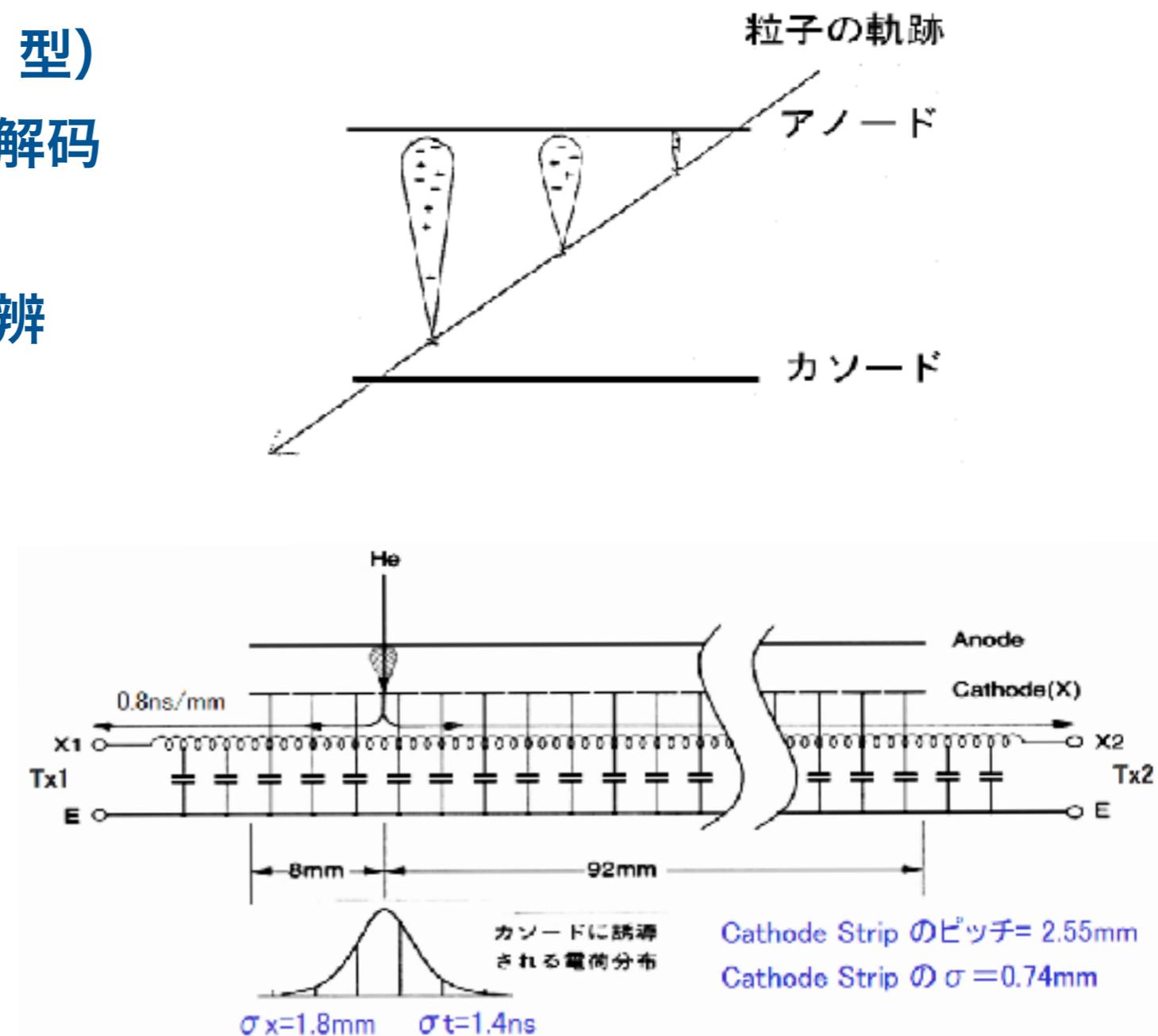
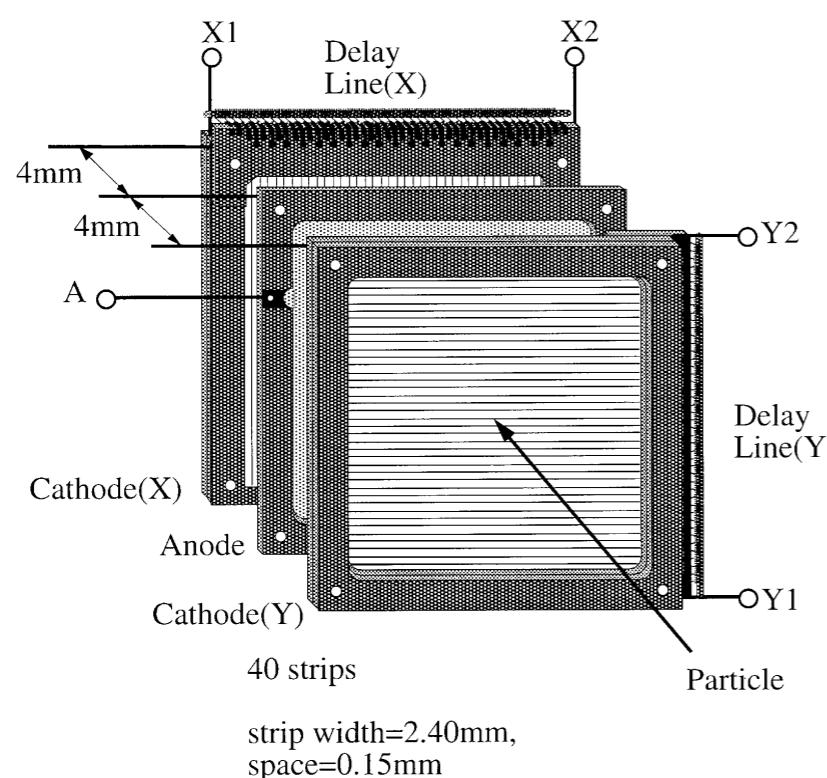
无机闪烁体信号



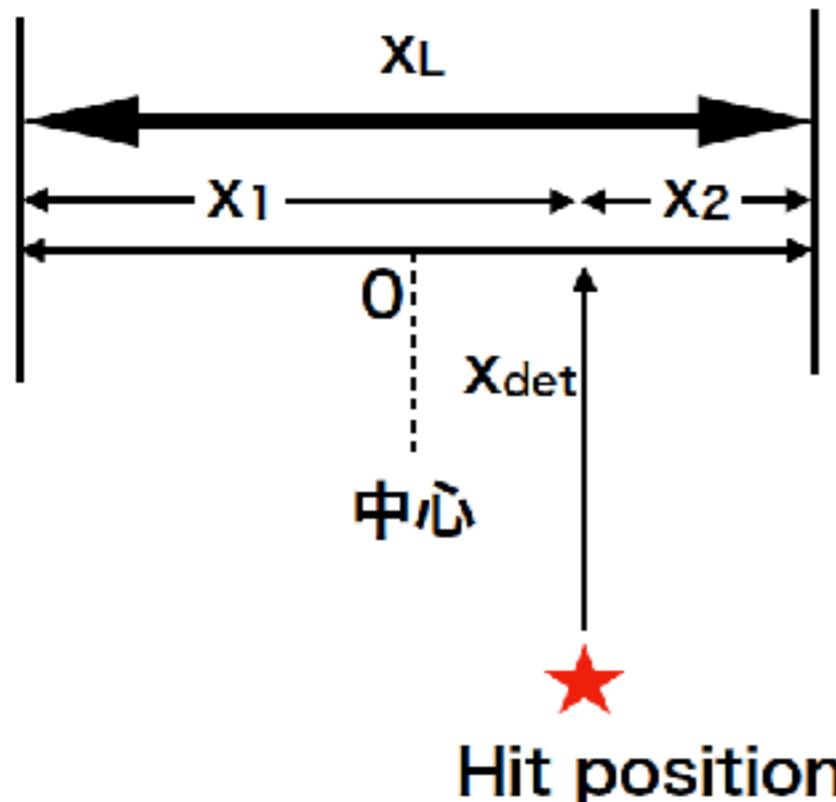
位置灵敏探测器:PPAC

平行板雪崩计数器 (Parallel-Plate Avalanche Counter)

- 电荷分配型 (Charge-division 型)
 - 利用电荷分配原理进行位置解码
- 延迟线型 (Delay-line 型)
 - 基于信号时间差实现位置分辨



位置灵敏探测器:PPAC



$$X_1 + X_2 = X_L$$

$$(TX_1 - TX_2) = (x_1 - x_2) / \text{ns2posiX} - \text{offset_TX}$$

$$(x_1 - x_2) = [(TX_1 - TX_2) + \text{offset_TX}] * \text{ns2posiX}$$

$$dTX \equiv TX_1 - TX_2$$

$$(x_1 - x_2) = [dTX + \text{offset_TX}] * \text{ns2posiX}$$

$$x_1 = X_L / 2 + X_{\text{det}}$$

$$x_2 = X_L / 2 - X_{\text{det}}$$

$$2 * X_{\text{det}} = [dTX + \text{offset_TX}] * \text{ns2posiX}$$

$$X_{\text{det}} = 0.5 * [(dTX + \text{offset_TX}) * \text{ns2posiX}]$$

ns2posiX : PPAC延迟线上的信号传输速度

offset_TX : 信号线、电子学等引起的 TX_1 、 TX_2 之间的信号传输时间差

位置灵敏探测器: 双PPAC

