BRIF and BISOL progress

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China Institute of Atomic Energy
中国原子能科学研究院

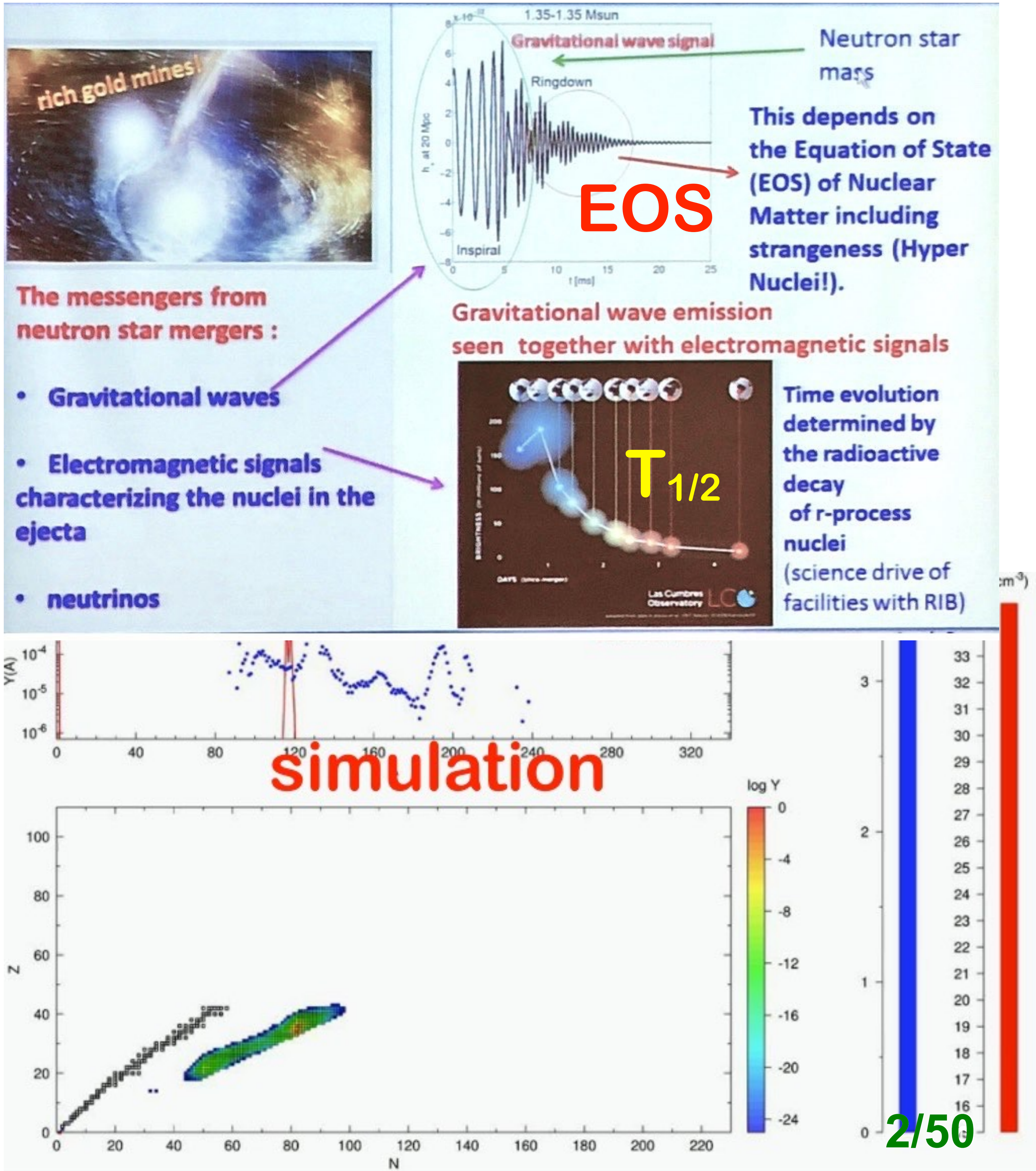
HIAT2018，Oct. 23, 2018, Lanzhou, China

What in my talk

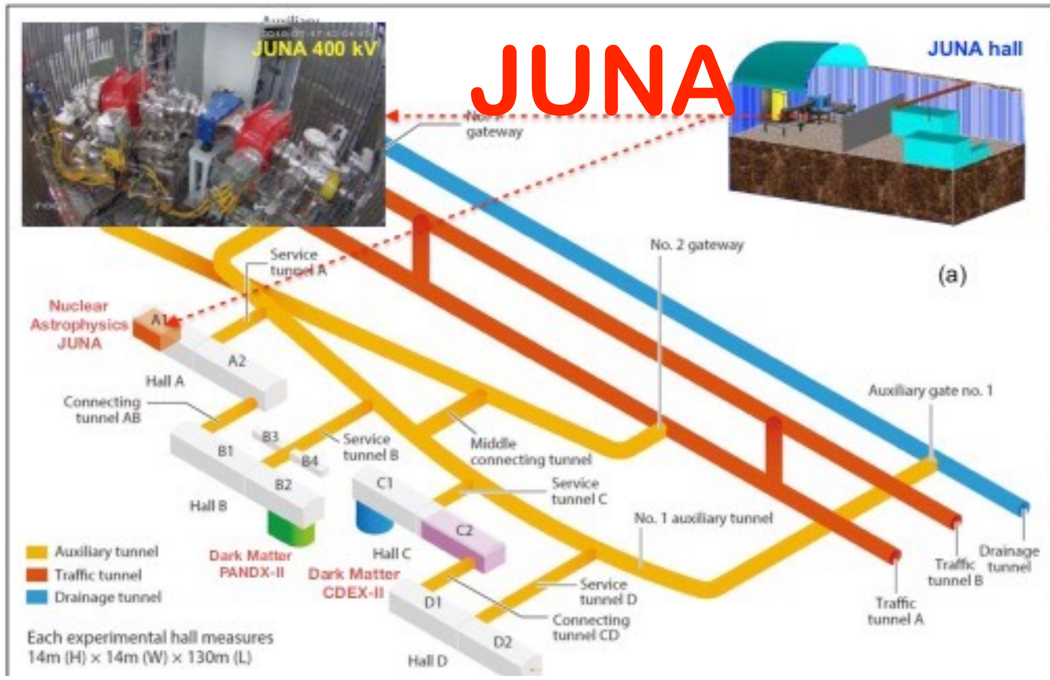
- Physics frontier
- World facilities
- BRIF progress
- BISOL design
- Conclusion

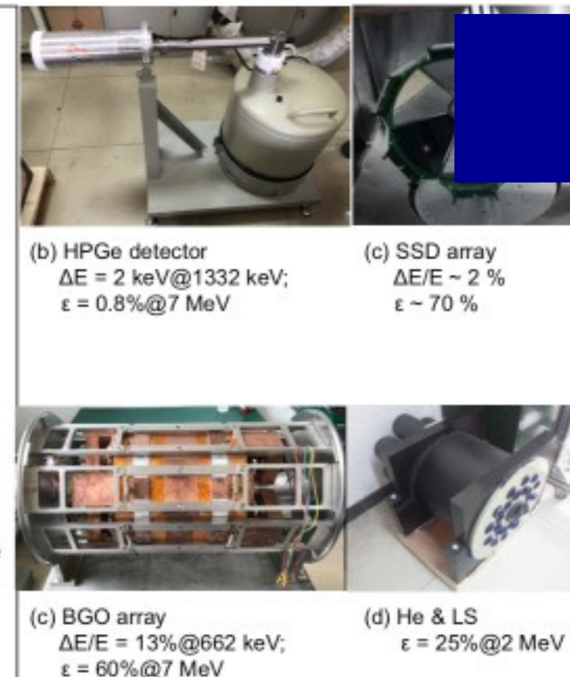
Let's start from MSN

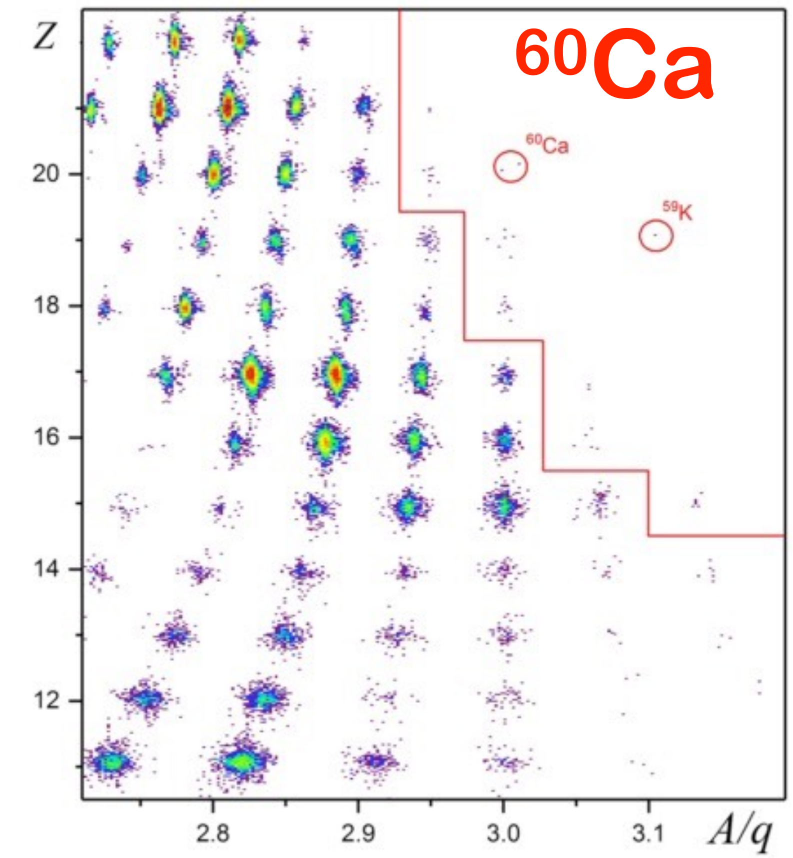
- NSM
- LIGO find
- Other messengers
- r process elements
- NP play role
- Far from enough
- n-rich physics
- Facility enough?



High I and T_z





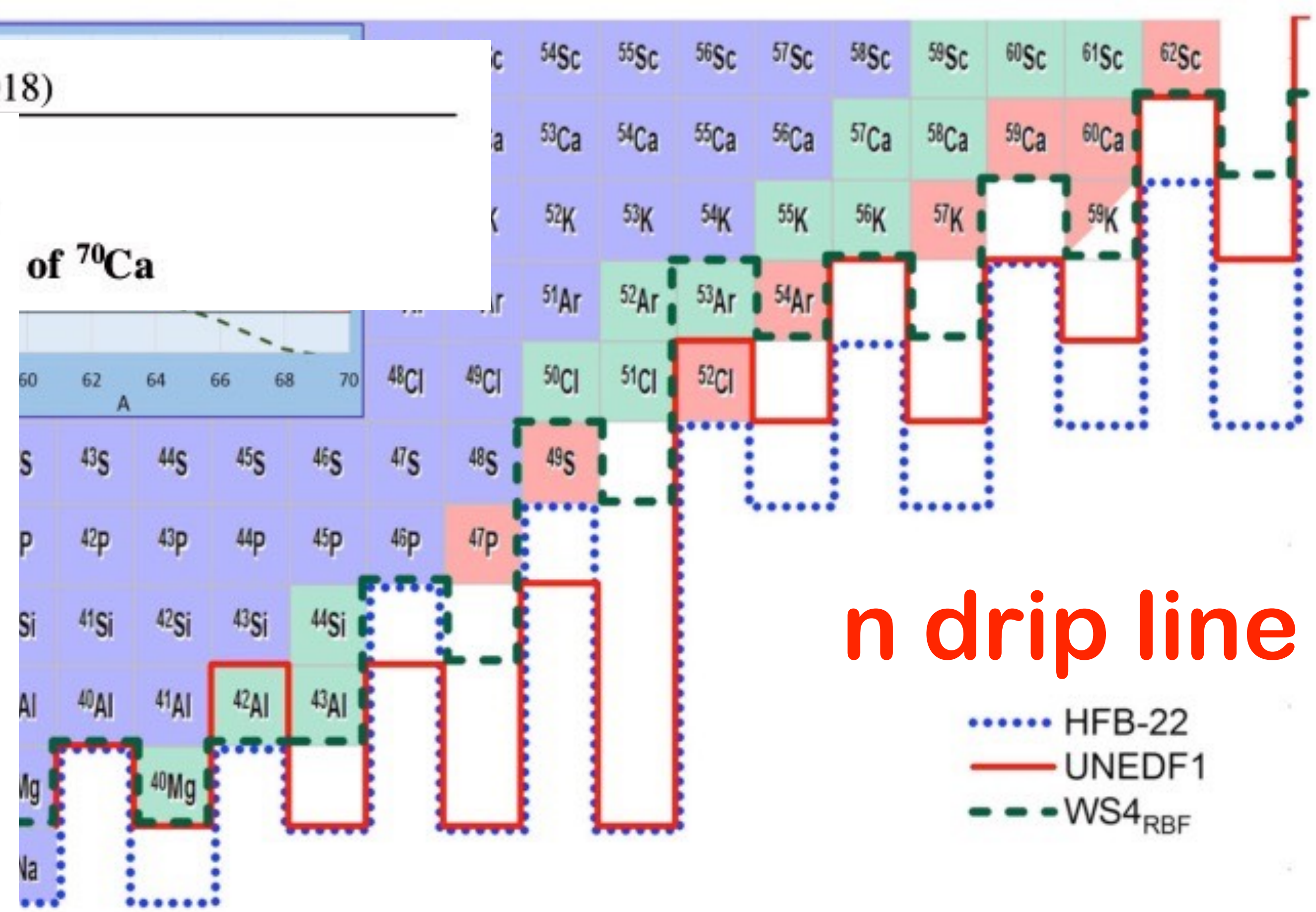


reaction	ion beam	int. (emA)	$E_{c.m.}$ (keV)	σ or $\omega\gamma$ (mb or eV)	target (/cm^2)	eff. (%)	CNT (/day)	BKD (/day)
^{12}C$(\alpha,\gamma)^{16}$O	^{4}He^{2+}	2	600	1×10^{-10}	10^{18} atoms	60	32	1.0
^{13}C$(\alpha,n)^{16}$O	^{4}He^{1+}	10	200	4×10^{-11}	thick target	20	7	1.0
^{25}Mg$(p,\gamma)^{26}$Al	^{1}H^{1+}	10	58	$\omega\gamma$ 2.1×10^{-13}	0.6 μg	38	1.4	1.0
^{19}F$(p,\alpha_\gamma)^{16}$O	^{1}H^{1+}	0.1	100	$7.2\times$[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

PHYSICAL REVIEW LETTERS **121**, 022501 (2018)

of ^{70}Ca

RIBF



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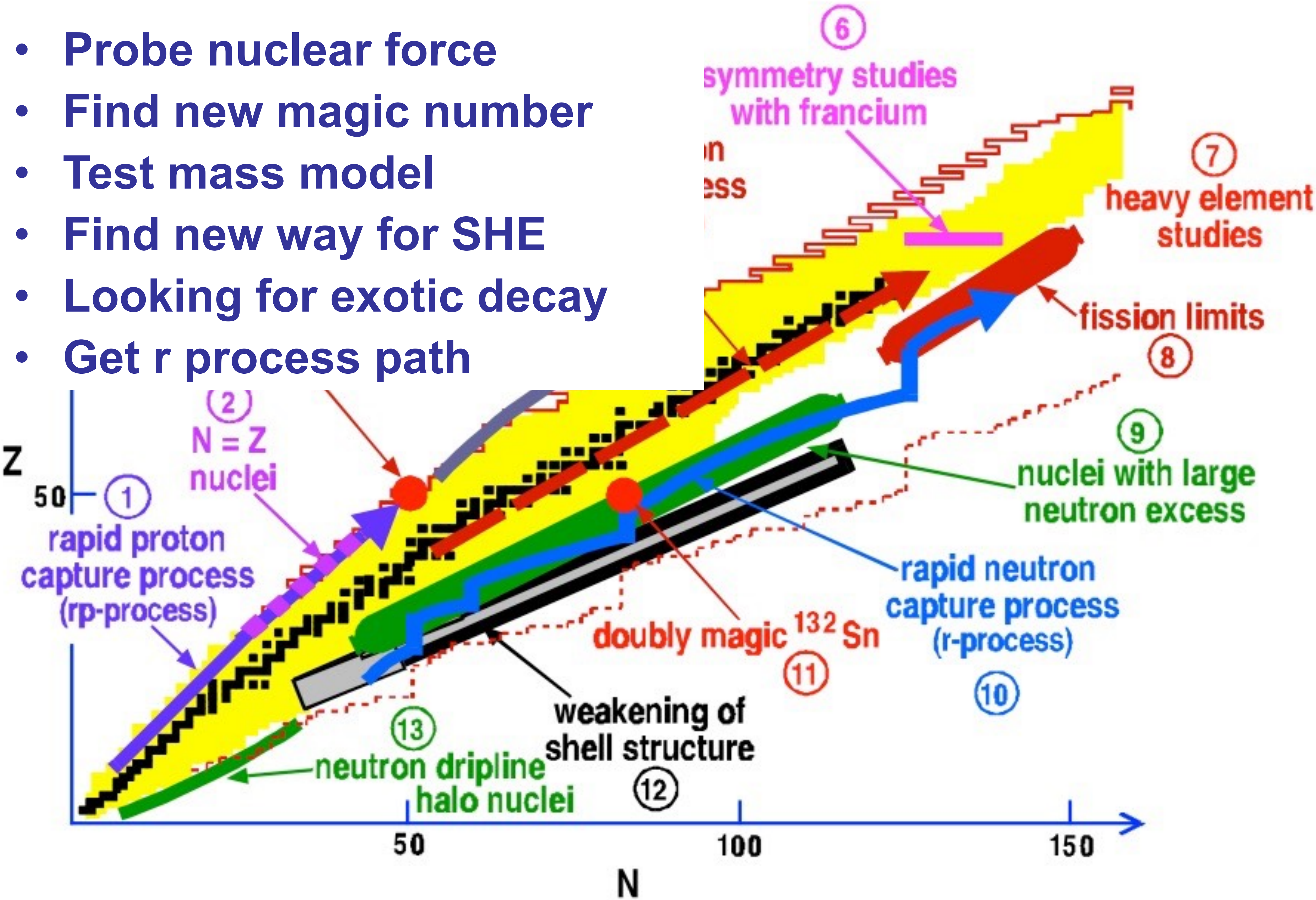
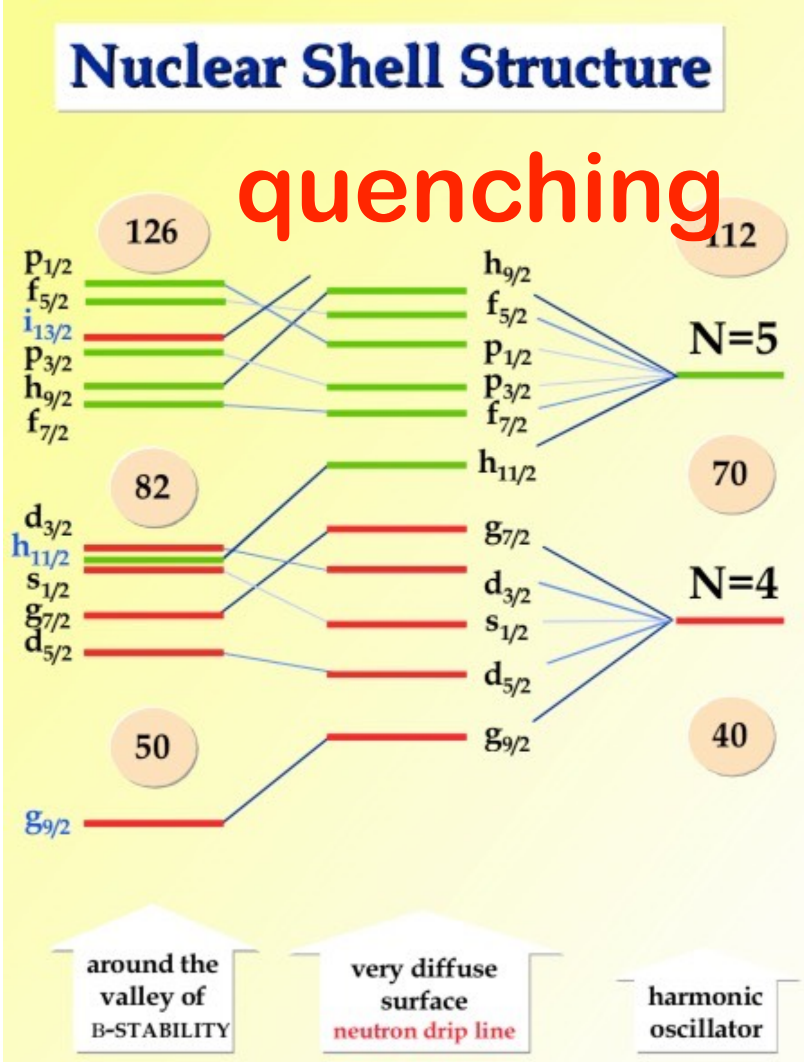
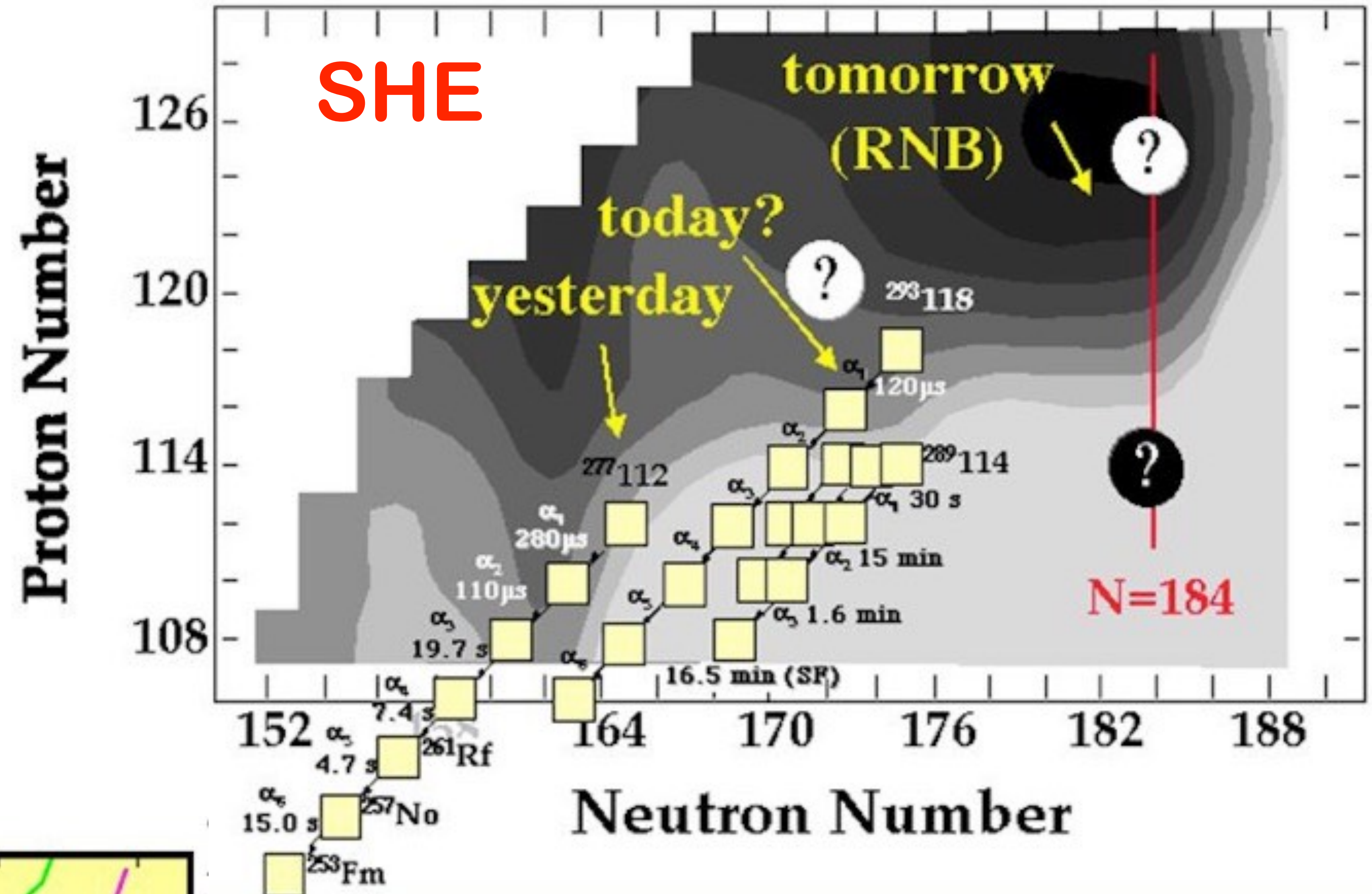
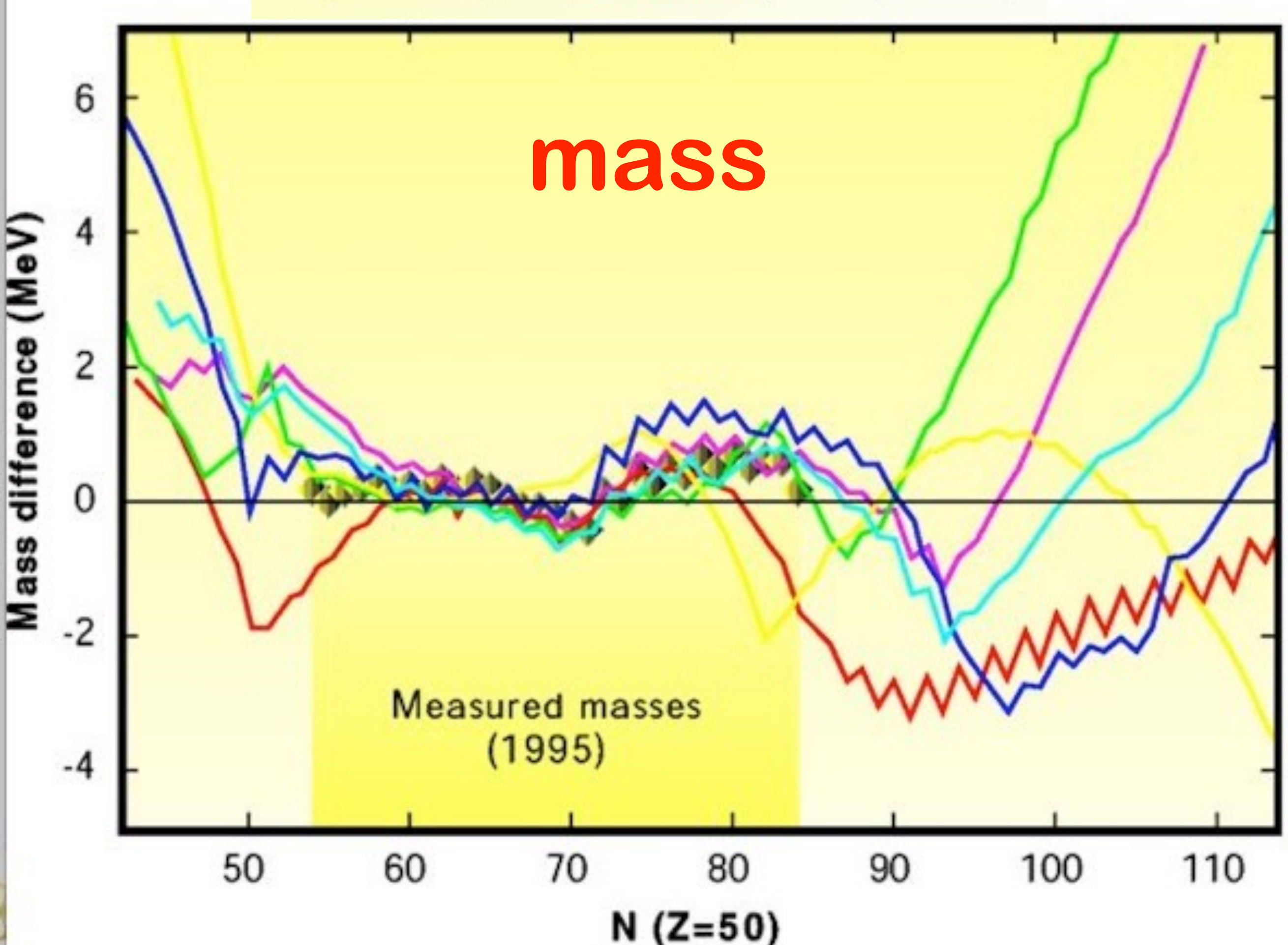
Why search for n-rich

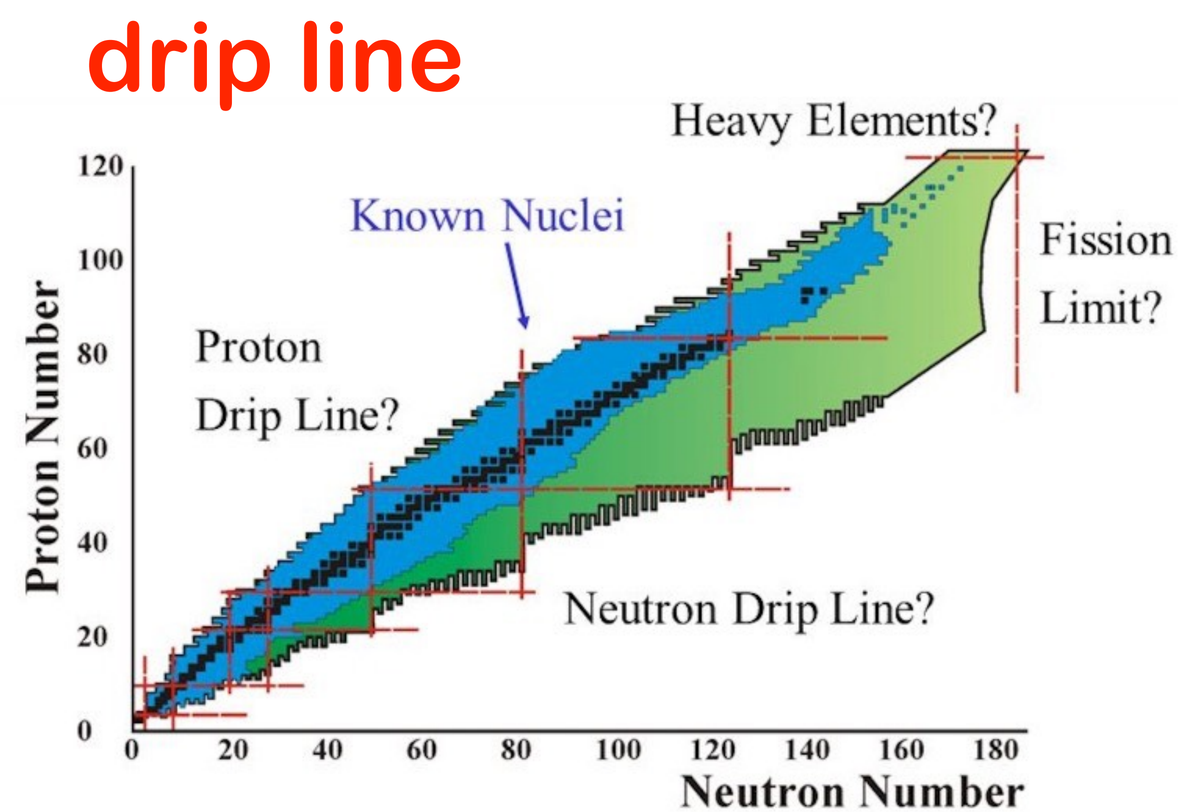
- Probe nuclear force
- Find new magic number
- Test mass model
- Find new way for SHE
- Looking for exotic decay
- Get r process path




Nuclear Shell Structure
quenching
126
82
50
112
70
40
N=5
N=4
around the valley of B-STABILITY
very diffuse surface
neutron drip line
harmonic oscillator


SHE
tomorrow (RNB)
today?
yesterday
N=184
Proton Number
Neutron Number
^{293}118
^{289}114
^{277}112
^{261}Rf
^{257}No
^{253}Fm
16.5 min (SF)


mass
Measured masses
(1995)
Mass difference (MeV)
N (Z=50)


drip line
Heavy Elements?
Known Nuclei
Fission
Limit?
Proton
Drip Line?
Neutron Drip Line?
Proton Number
Neutron Number

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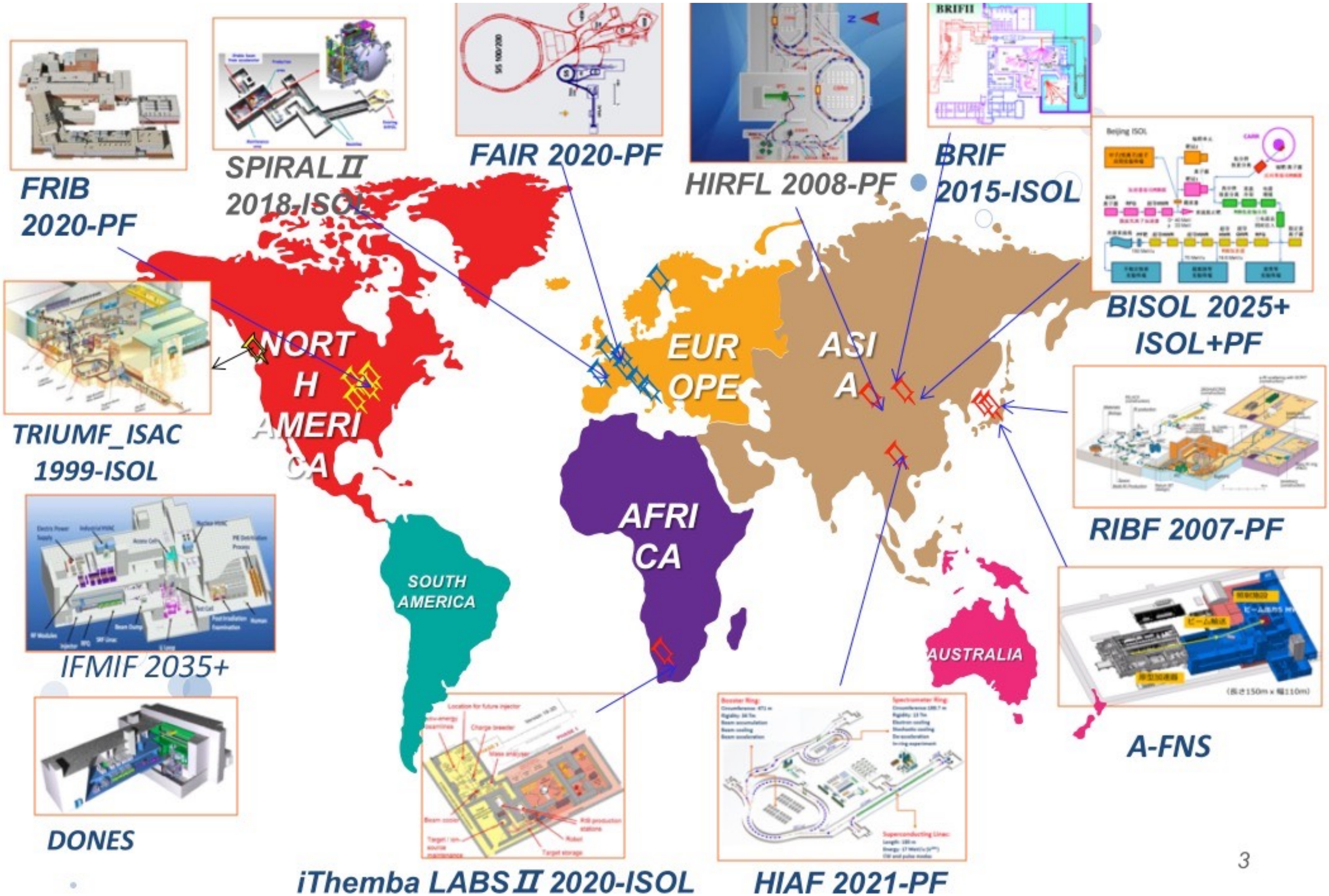
World wide efforts



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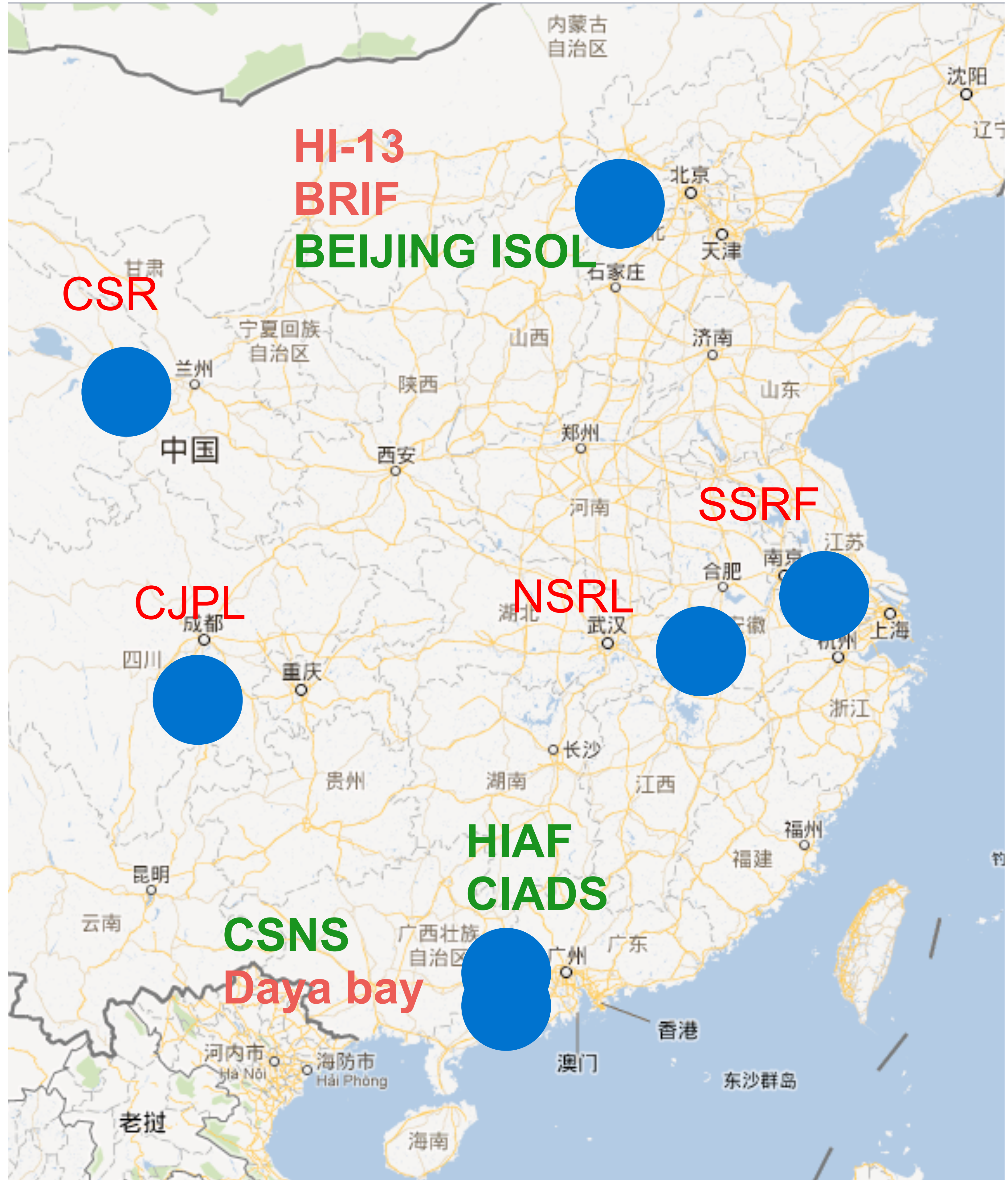
Part of NP facilities in China



Summary of PF facilities

实验室(国家)	运行时间	驱动加速器参数	次级束流线名称
GANIL(法国)	1985年	95 A MeV 重离子回旋	LISE，SISSI
GSI(德国)	1989年	1 A GeV 重离子直线+同步	FRS，ESR
Dubna(俄罗斯)	1996年	重离子回旋	ACCULINNA， COMBAS
KVI(荷兰)	2007年	K600 重离子回旋	TRIMP
NSCL(美国)	1981年，2001年	K500—1200重离子回旋	A1200，A1900
RIBF(日本)	1992年，2005年	135—400 A MeV 重离子回旋	RIPS，BIGRIPS
IMP(中国)	1988年，2009年	80 A MeV重离子回旋，1 A GeV CSRm同步	RIBLL，RIBLL-II，CSRe

- For physics of extreme isospin
- Using in-flight separation PF method

Some data adapted from EURISOL report

Summary of ISOL facilities

装置(国家)	运行时间	驱动加速器参数	后加速器参数
LISOL(比利时)	1989年	30 MeV 质子 200 μA 回旋	K110 回旋
SPIRAL(法国)	2001 年	95 A MeV 重离子 6 kW 回旋	K265 回旋
SPIRALII(法国)	2010年	40 MeV 重离子超导直线	K265 回旋
REX ISOLDE(瑞士)	2001 年	1.4 GeV 质子 2 μA 同步	3 A MeV 直线
EXCYT(意大利)	2006年	重离子 回旋	15 MV 串列
ALTO(法国)	2010年	50 MeV 10 μA 电子直线	15 MV 串列
HRIBF(美国)	1997年	50—100 MeV 质子、氘和α粒子 20 μA 回旋	25 MV 串列
ISAC-1(加拿大)	2000年	500 MeV 质子 100 μA 回旋	1.5 A MeV 直线
ISAC-2(加拿大)	2010年	500 MeV 质子 100 μA 回旋	6.5 A MeV 直线
BRIF(中国)	2014年	100 MeV 质子 200 μA 回旋	15 MV 串列

- For precise physics with high quality beams
- Advanced target and ion source technology needed

Some data adapted from EURISOL report

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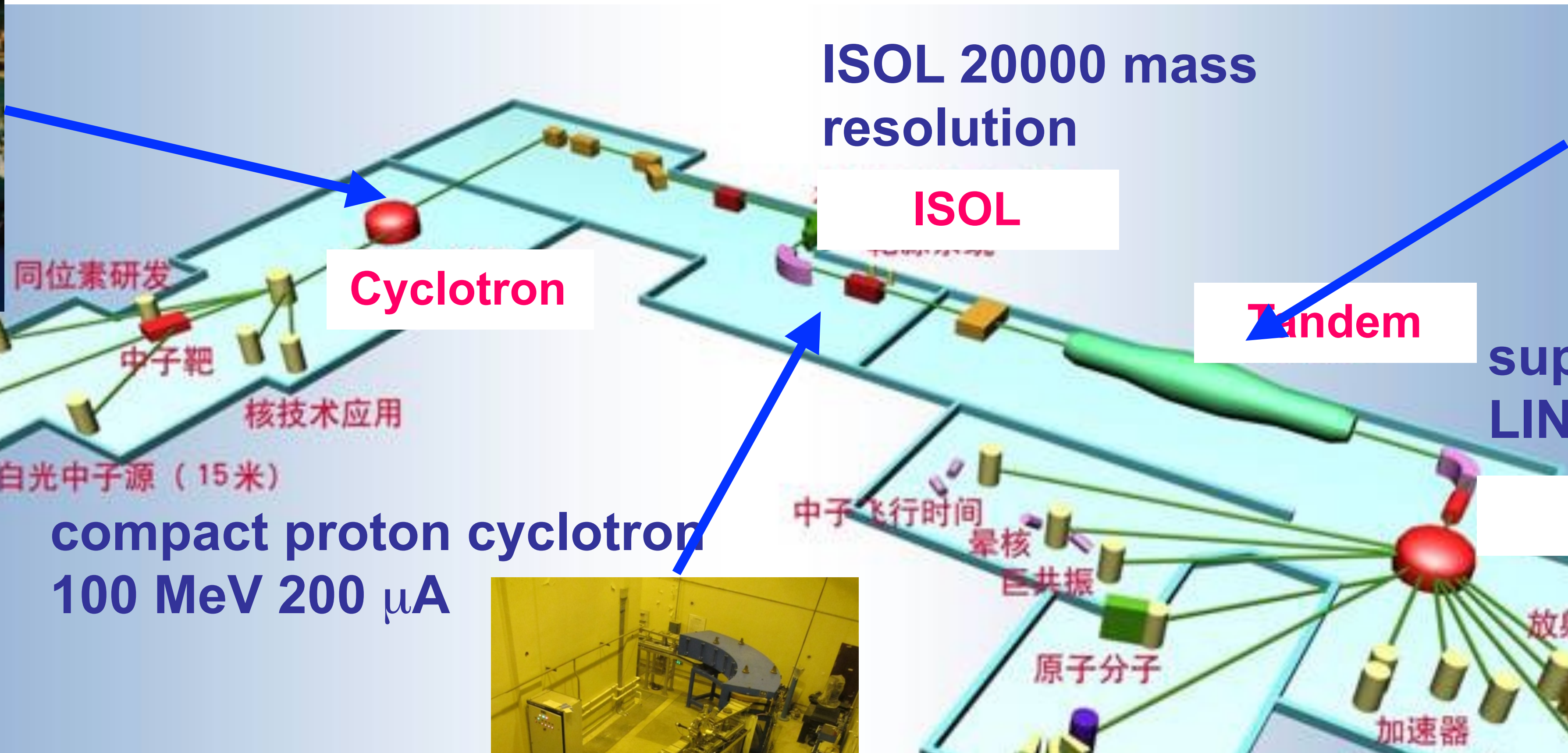
BRIF (Beijing Rare Ion beam Facility)

cyclotron

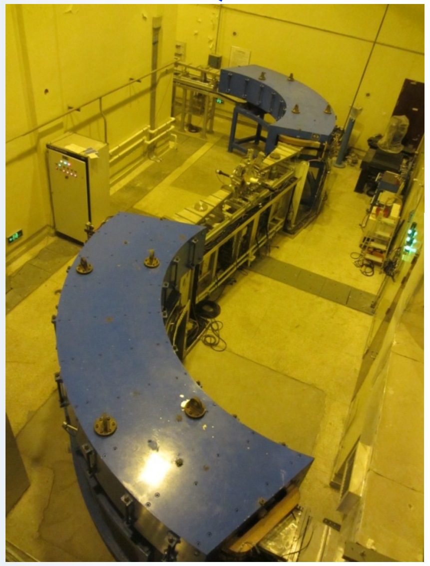
Tandem



ISOL 20000 mass resolution

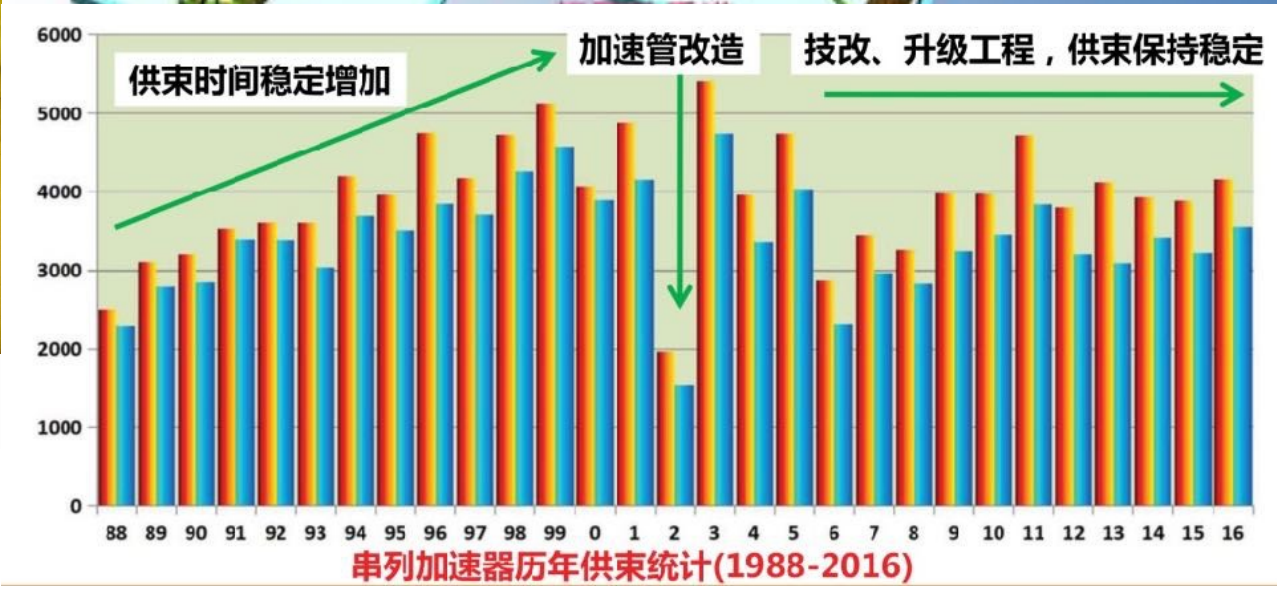
super-conducting LINAC 2 MeV/q

compact proton cyclotron 100 MeV 200 μA



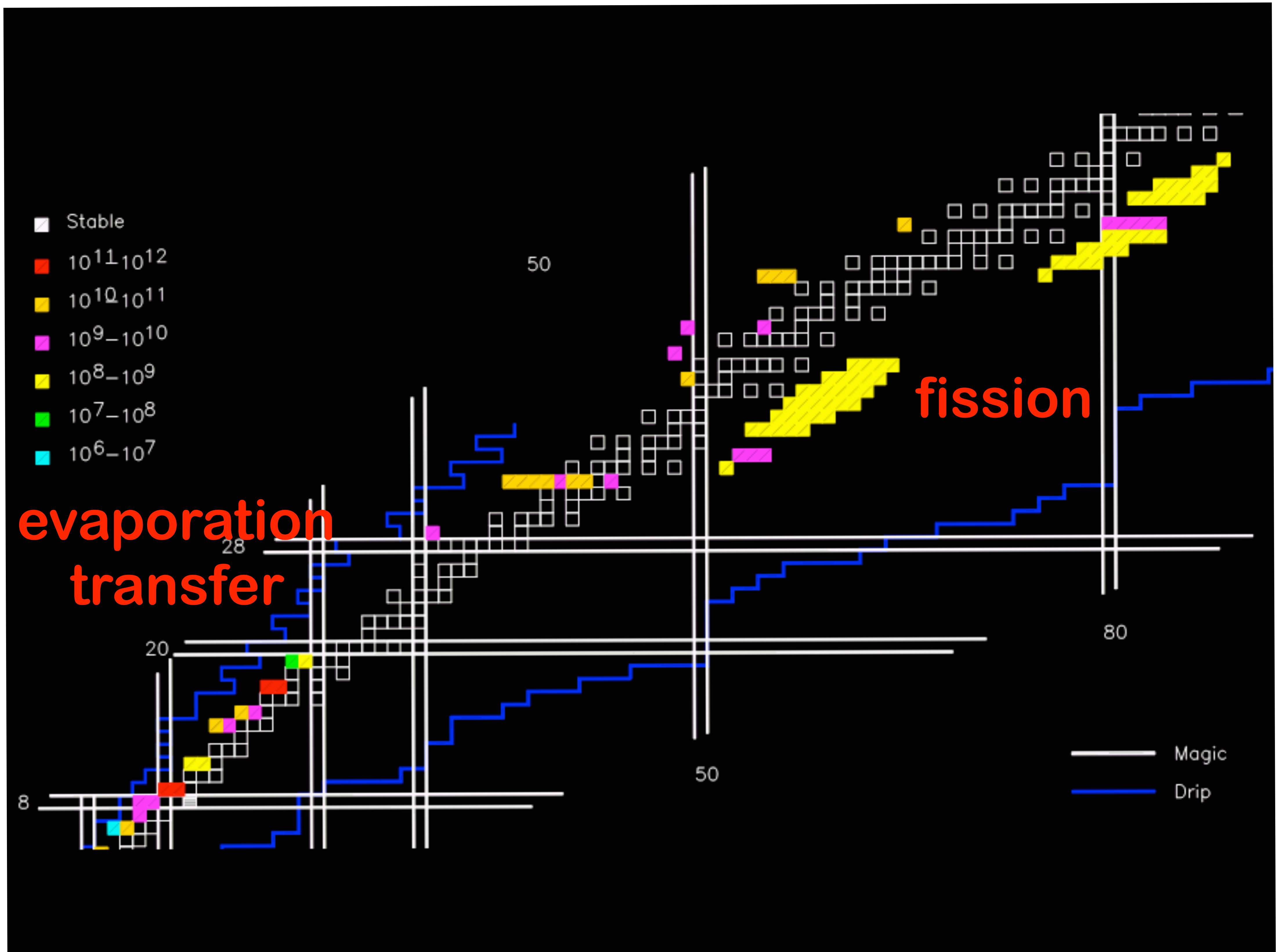
ISOL

Approved 2004
Final budget 2009
Civil engineering 2011
Cyclotron move in 2012
Commission 2016
Day 1 exp. 2018



beam time

BRIF beams



Stable
10^{11}–10^{12}
10^{10}–10^{11}
10^{9}–10^{10}
10^{8}–10^{9}
10^{7}–10^{8}
10^{6}–10^{7}
50
evaporation
28
transfer
20
8
fission
80
50
Magic
Drip

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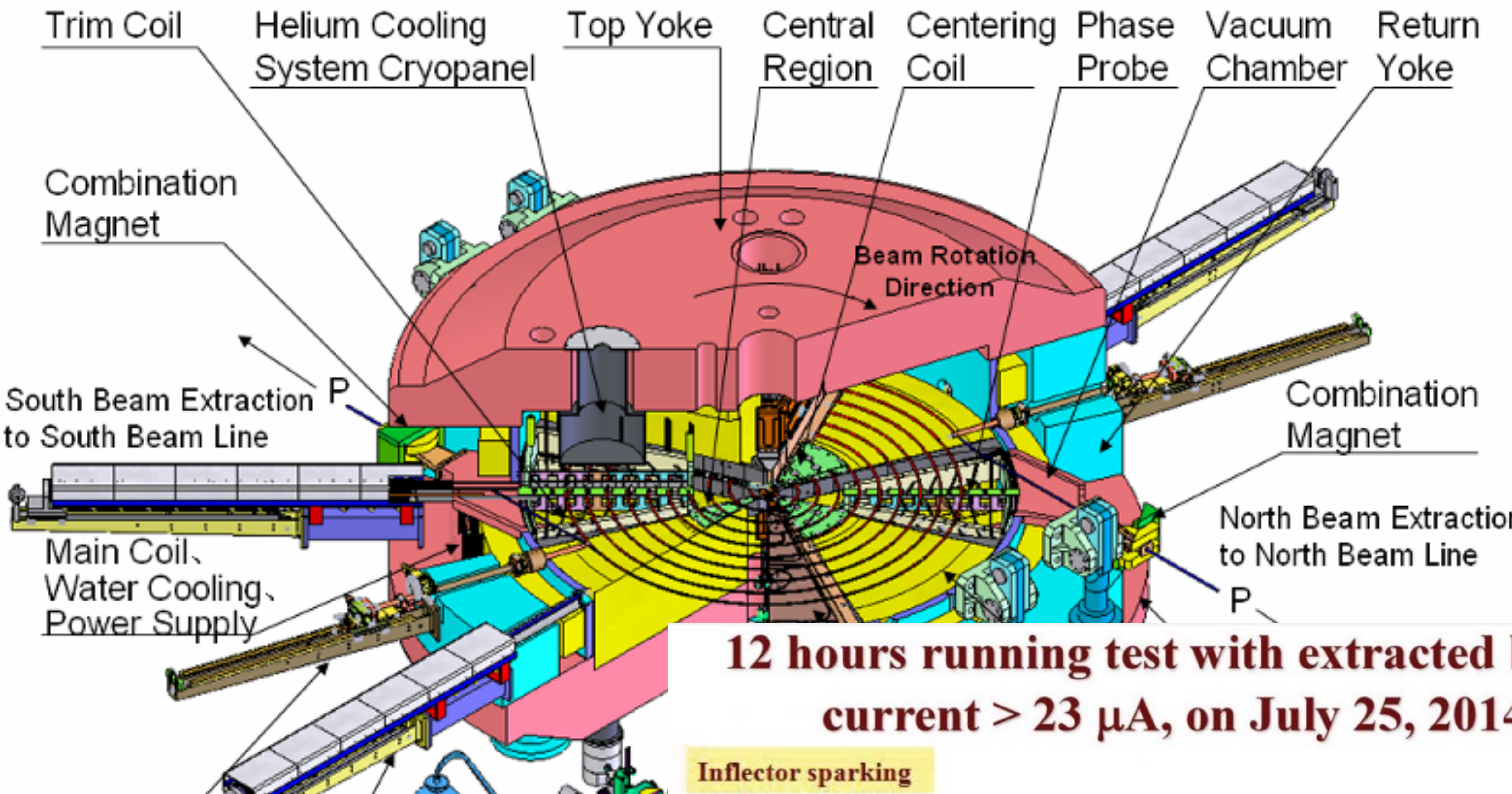
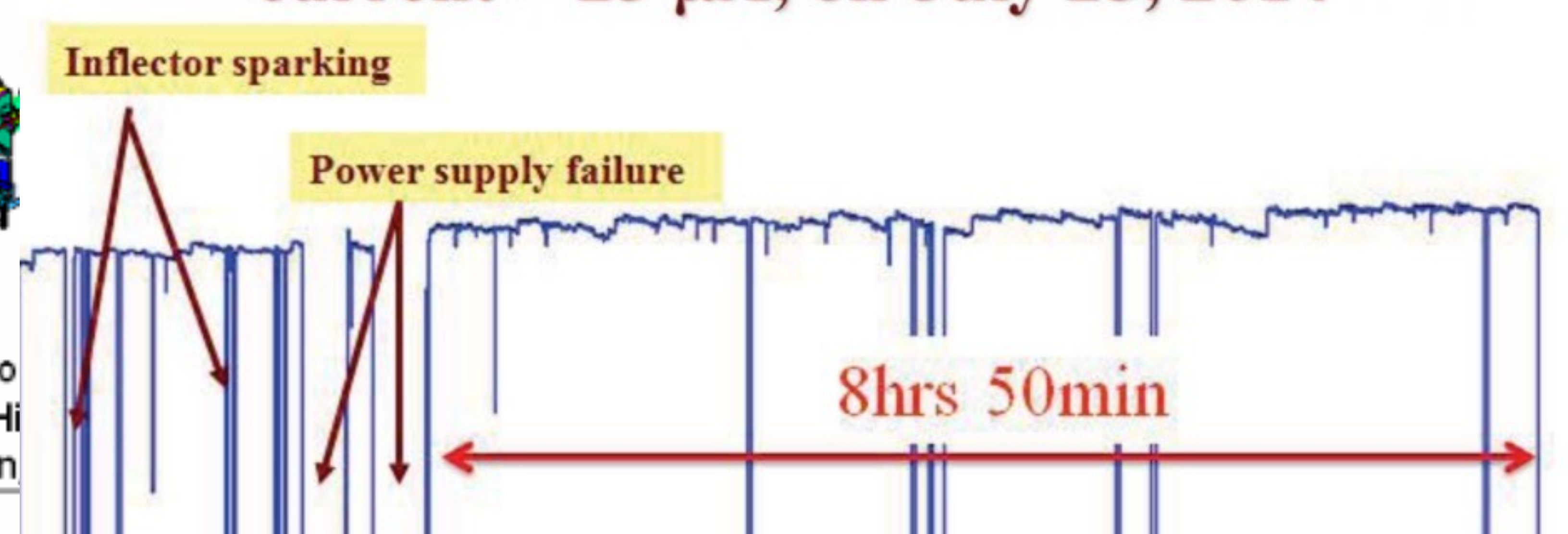
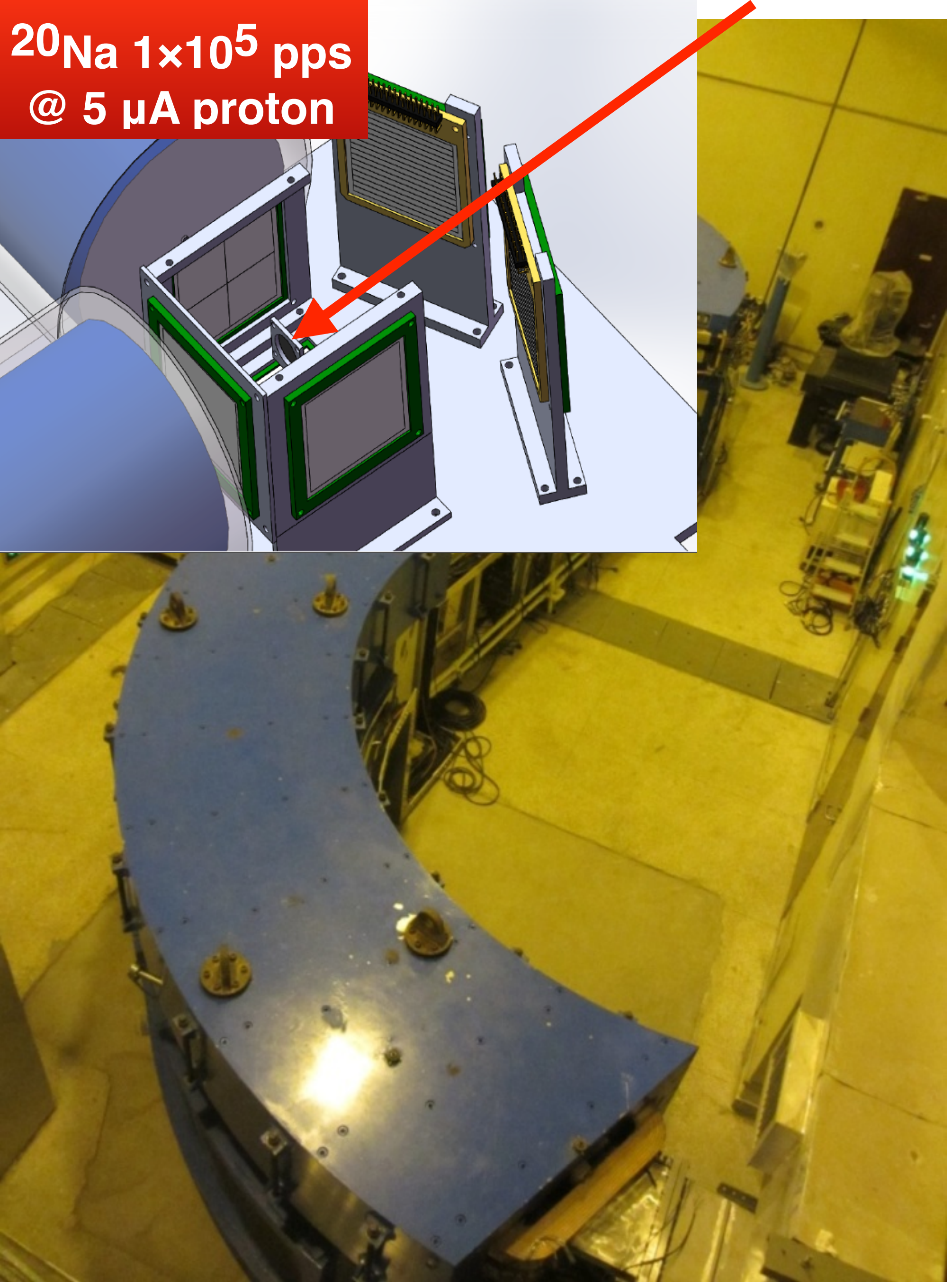
H- compact cyclotron for BRIF



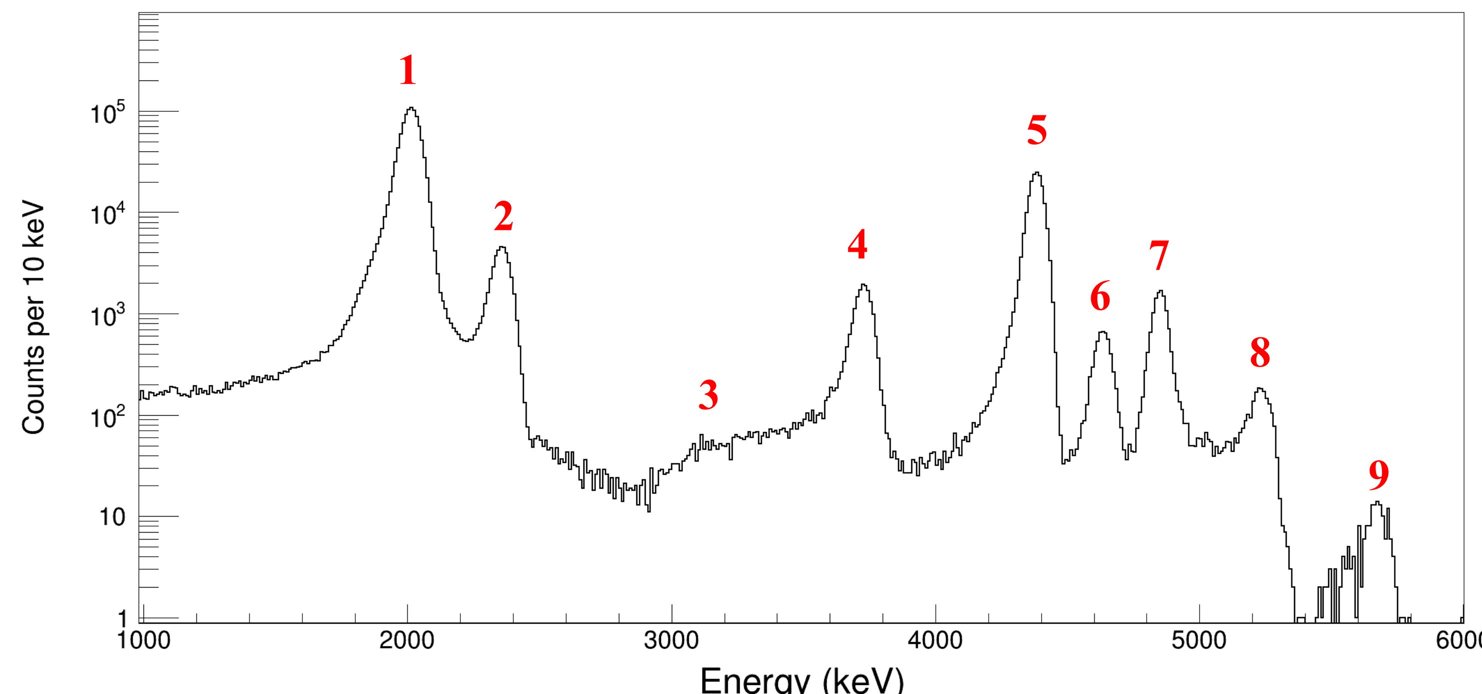
12 hours running test with extracted beam current > 23 μA, on July 25, 2014



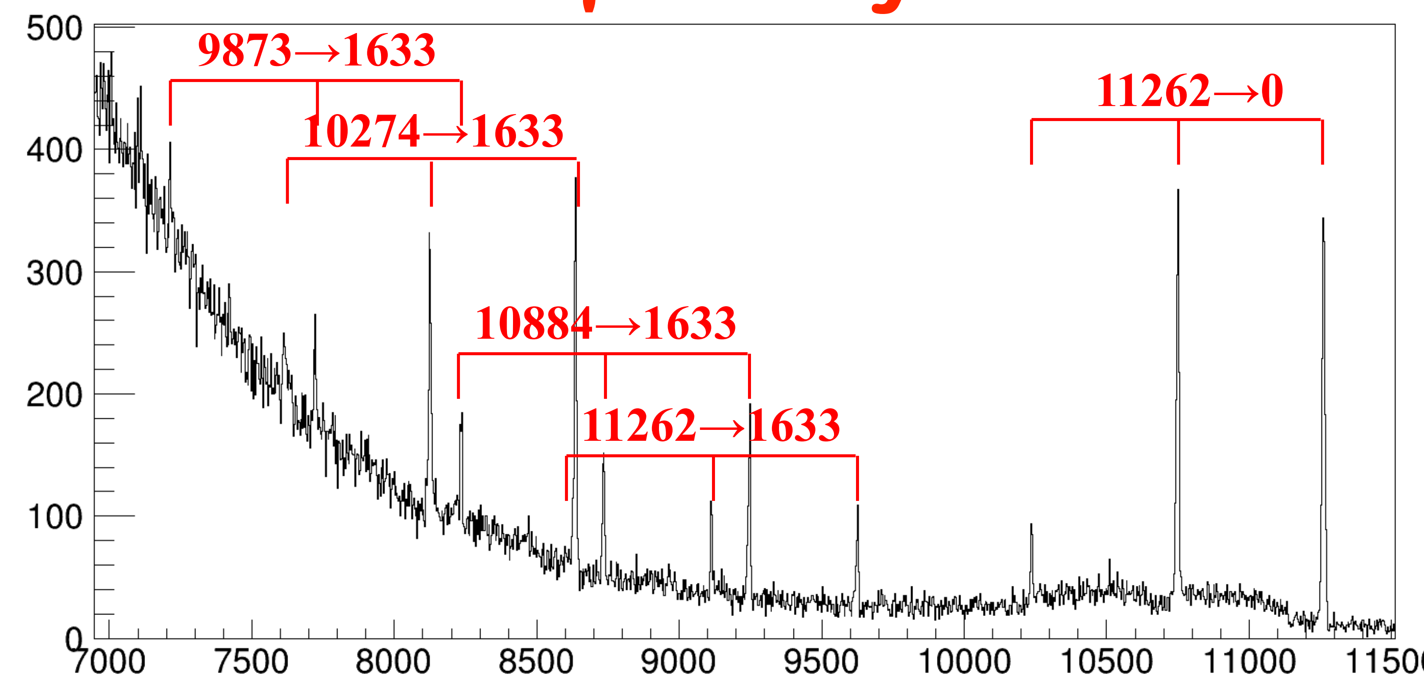
ISOL day-one exp.



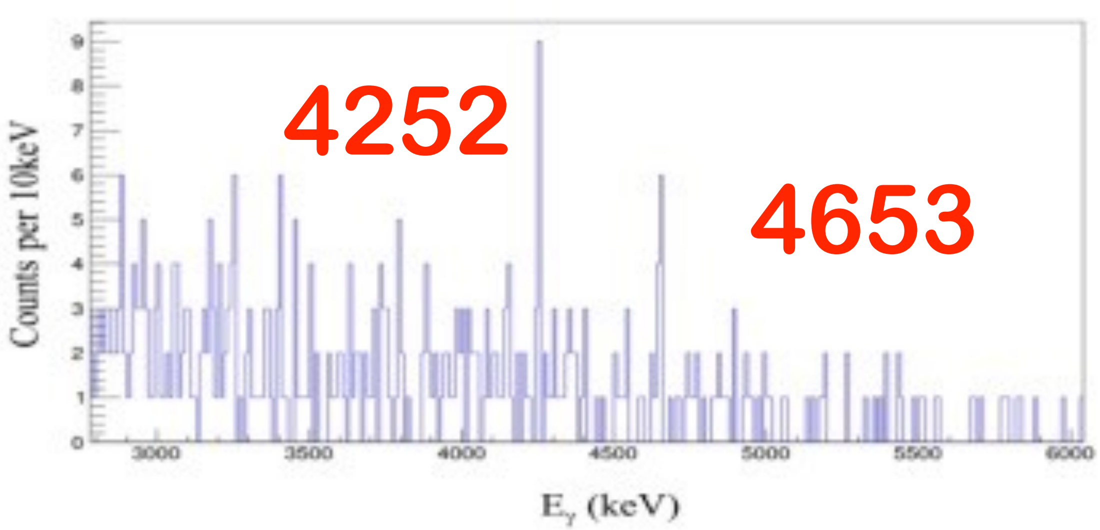
β-α decay



γ decay



β-α-γ decay



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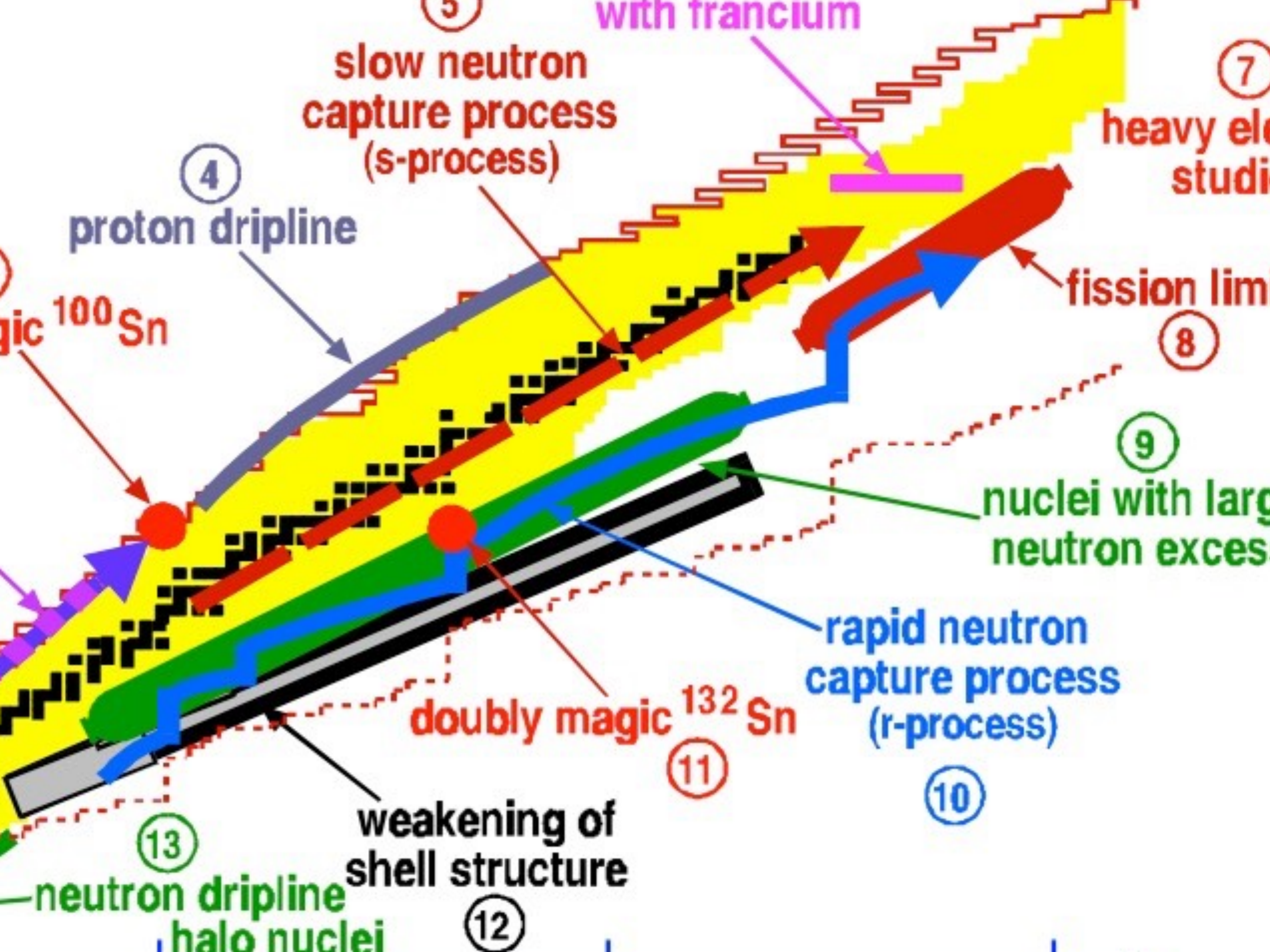

with francium
slow neutron
capture process
(s-process)
7
heavy ele
studi
4
proton dripline
fission lim
8
gic ^{100}Sn
9
nuclei with larg
neutron exces
rapid neutron
capture process
(r-process)
doubly magic ^{132}Sn
11
10
weakening of
shell structure
13
neutron dripline
halo nuclei
12

RIB facilities under construction and in design stage

地点(装置)	驱动加速器	后加速器	装置类型
美国(FRIB)	重离子直线200 A MeV		PF
德国(FAIR)	重离子同步1.5 A GeV		PF
欧洲(EURISOL)	质子，1 GeV，1—5MW	超导直线 100 A MeV	ISOL+PF
韩国(RAON)	70 MeV 质子 70 kW	重离子直线 200 A MeV	ISOL+PF
中国(HIAF)	重离子同步4.4 A GeV		PF
美国(FRIB)	重离子直线，148 A MeV，400 kW	计划中15 A MeV	PF
加拿大(ARIEL)	电子直线10 mA 50 MeV		ISOL
中国(Beijing ISOL)	60 MW反应堆/直线10 mA 20 MeV A d	超导直线 150 A MeV	ISOL+PF

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Intensity and physics

Experiment

$$N = I\,\sigma\,\varepsilon$$

event
事件率
越高研究越精细

cross section
反应截面
学术价值越高
截面越低

不稳定束流强度
越高越好

RI intensity

$$I = \Phi\,\sigma\,\varepsilon$$

intensity
稳定束流强度
受到技术限制

靠近滴线核
碎裂截面极低

10^{-5} pps，可以发现 discovery

10^{-2} pps，可以测量半衰期和质量，目前的最好状态 half life

10^{2} pps，可以测量核反应 reaction

10^{4} pps，可以对反应和低激发态测量 structure

RI intensity by fission driver

$$I = \Phi_n\,\sigma_{fis}\,\sigma_{fra}\,\varepsilon$$

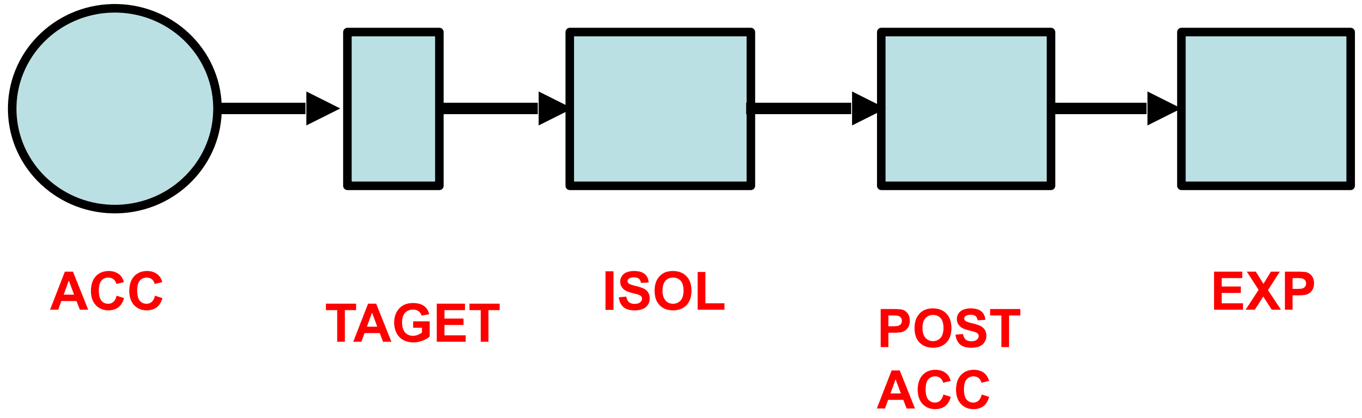
中子束流强度
高

裂变截面很高

靠近滴线核
丰中子核碎裂
截面提升

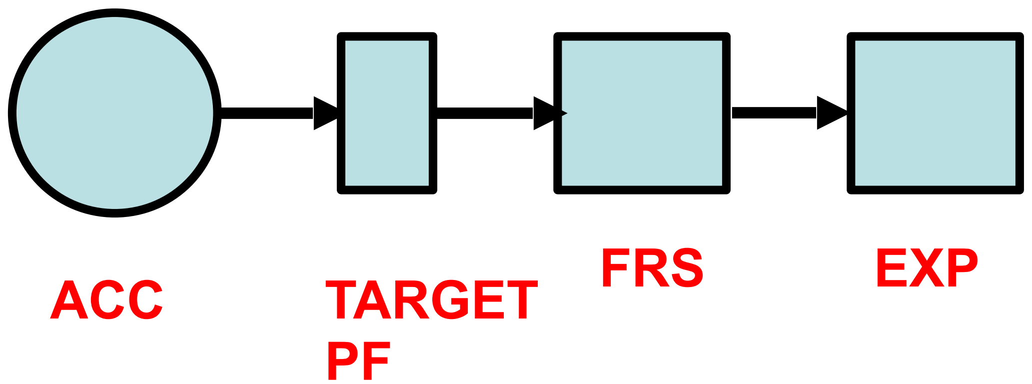
Way of RI production

ISOL



BRIF, HRIBF, ISOLDE, ISAC, LEUVEN

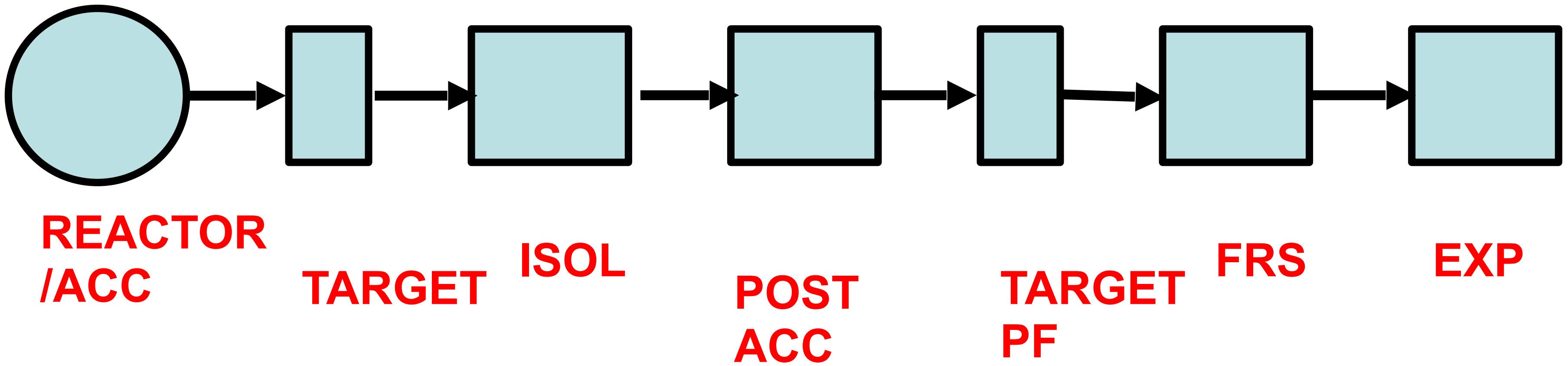
PF



GANIL, FAIR, NSCL RIBF, CSR

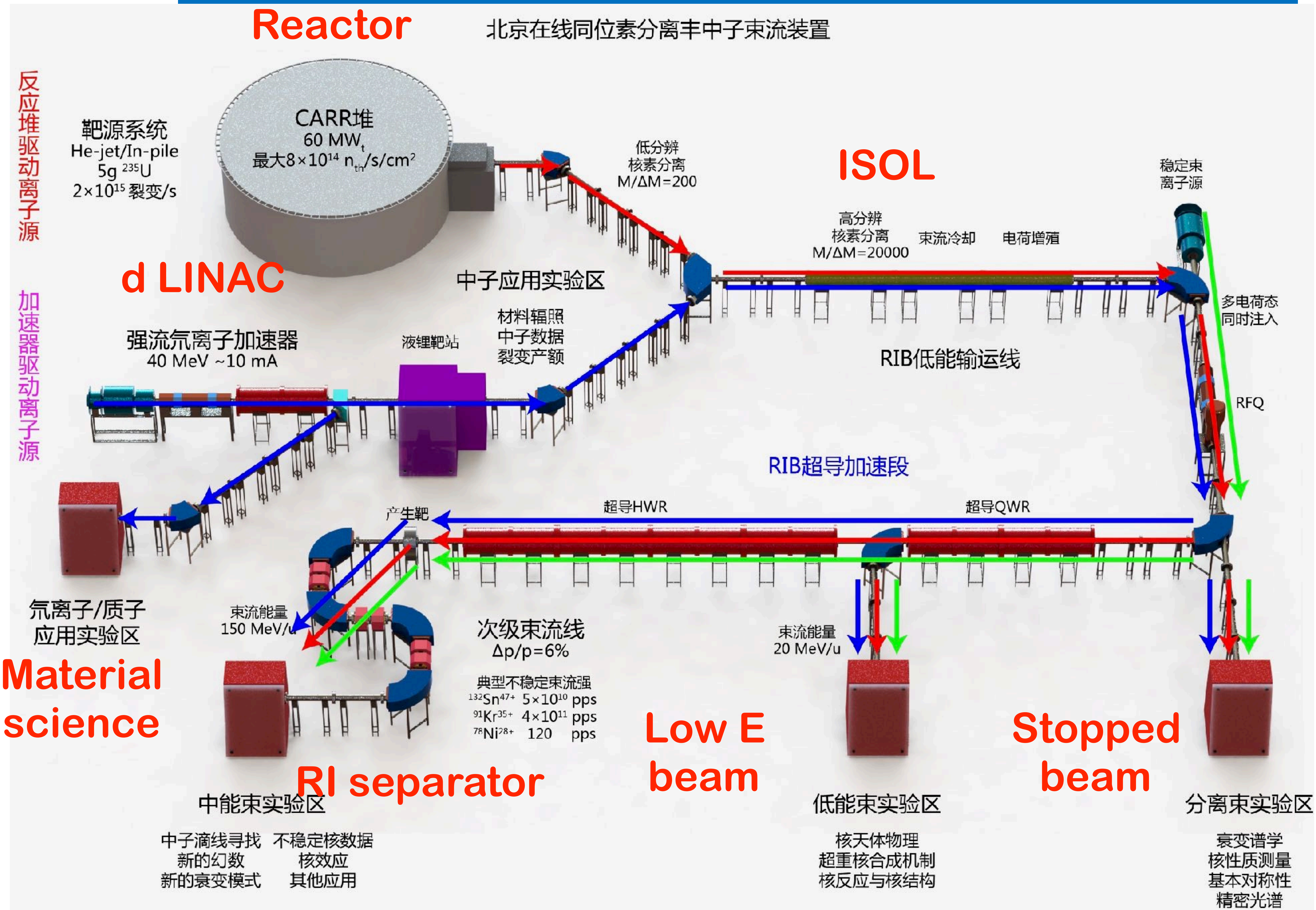
Beijing ISOL, EURISOL

ISOL+PF

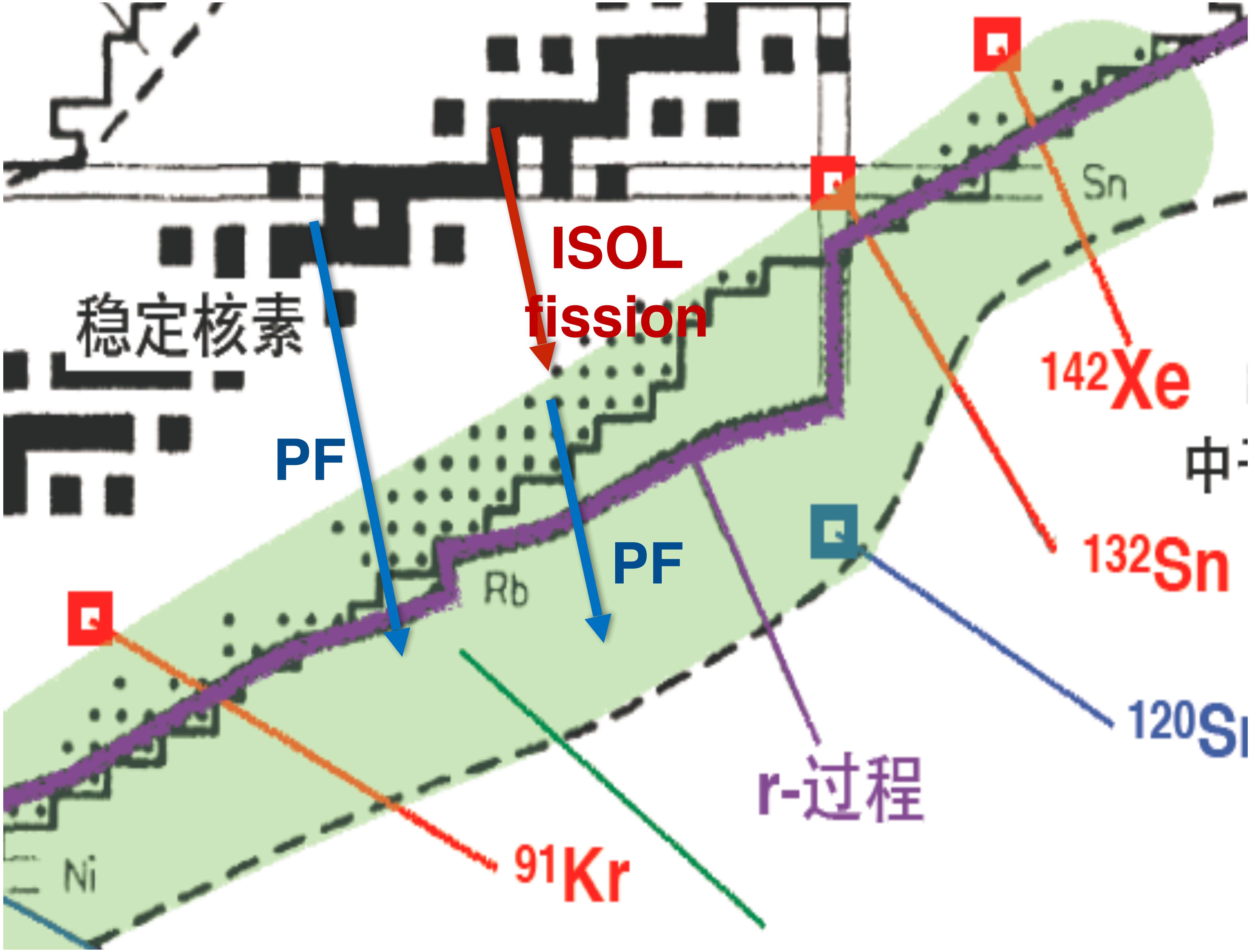


New!

BISOL layout



ISOL+PF approach

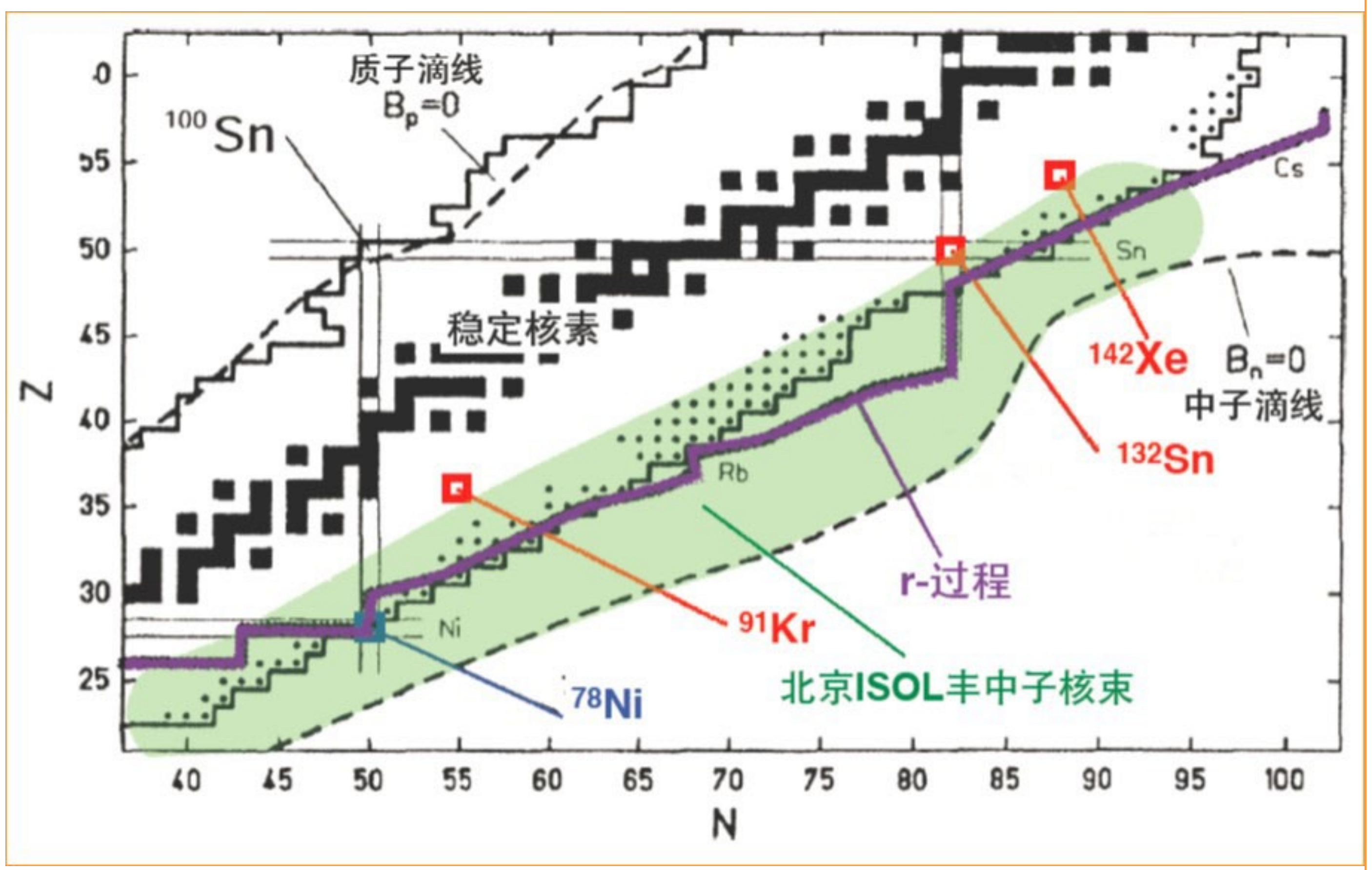


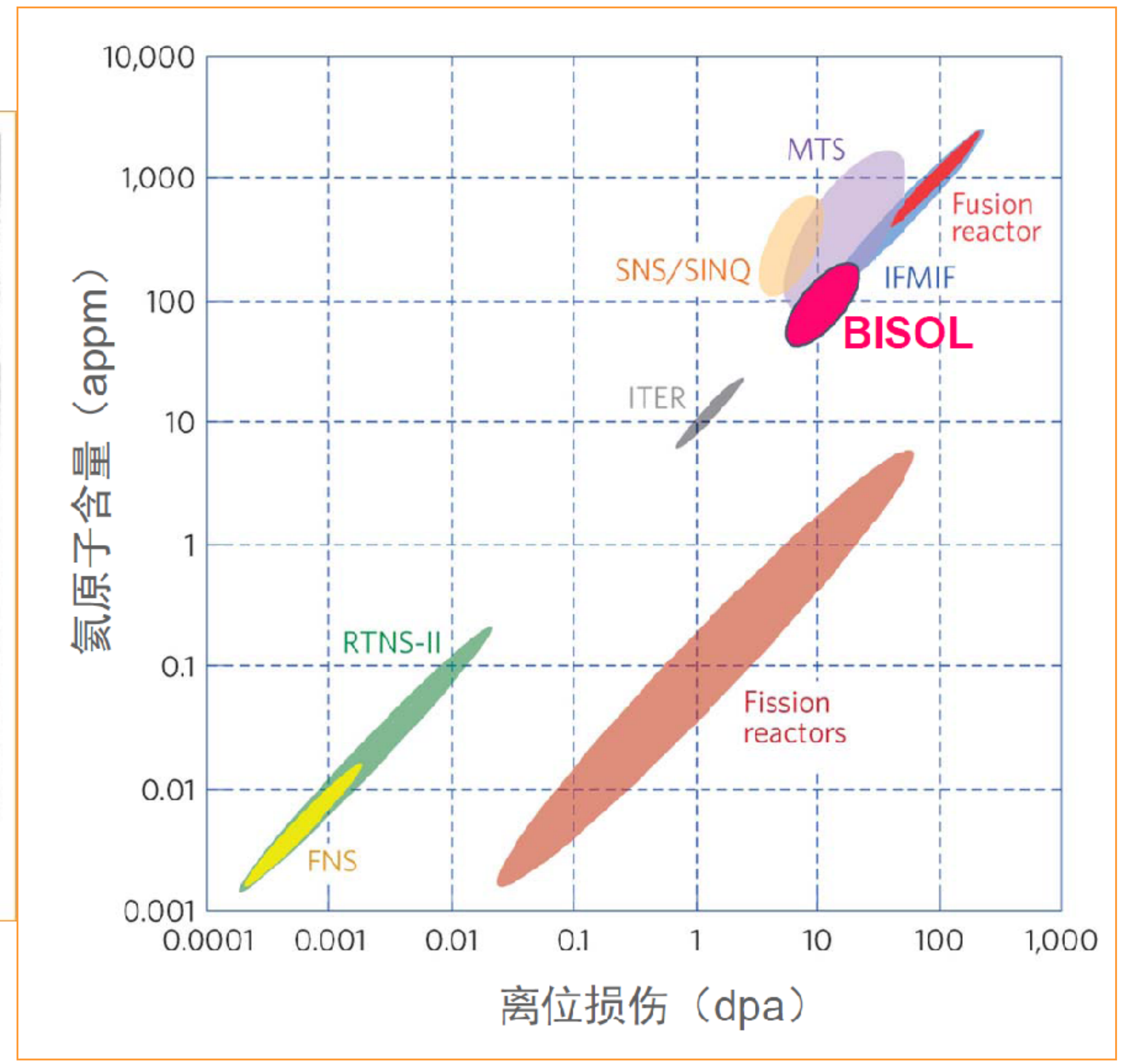
Basic research and application on BISOL

- **Basic research**
- **Middle mass n-rich beam physics**
- **astrophysical r-process**
- **new way to SHE**

Applied research

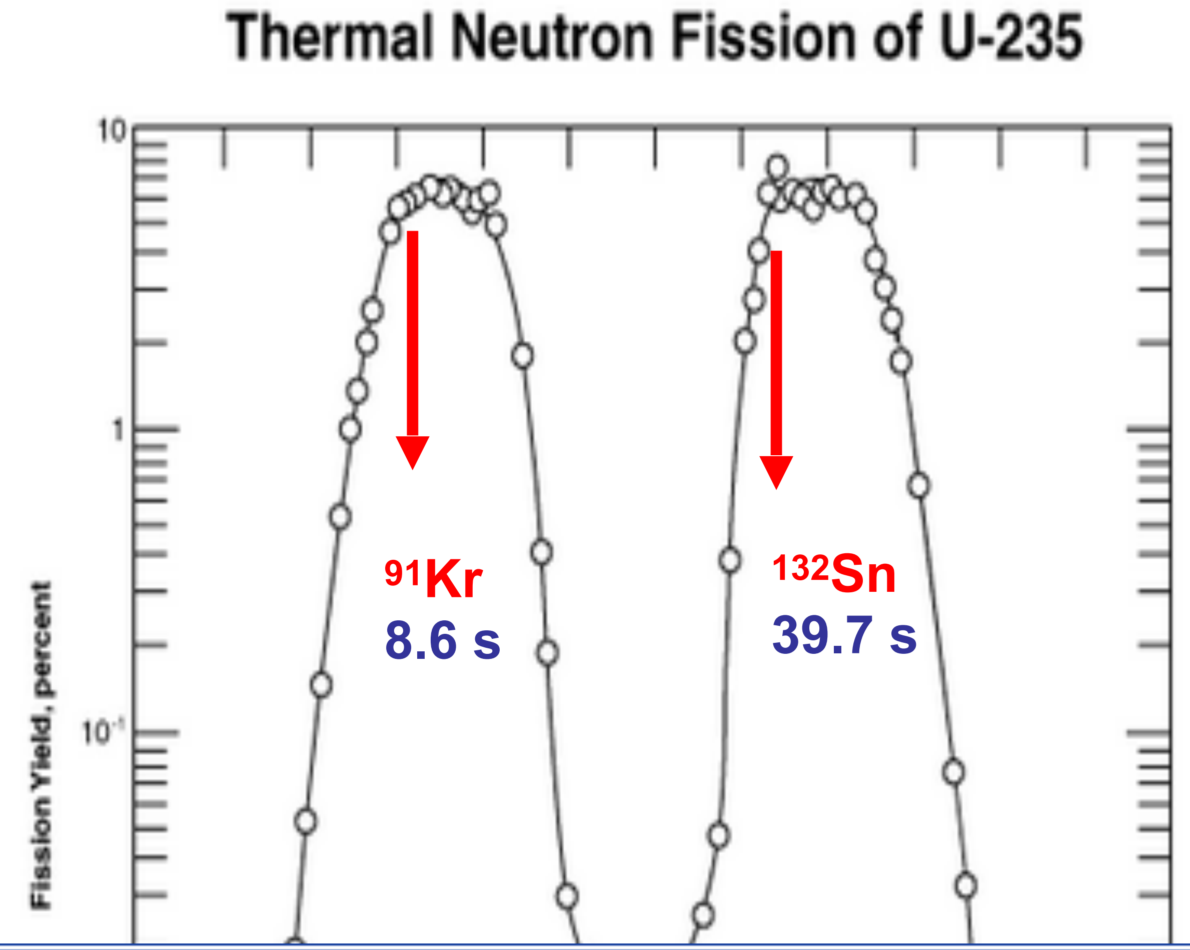
- **n irradiation of fusion reactor material**
- **neutron physics**
- **production of isotopes**

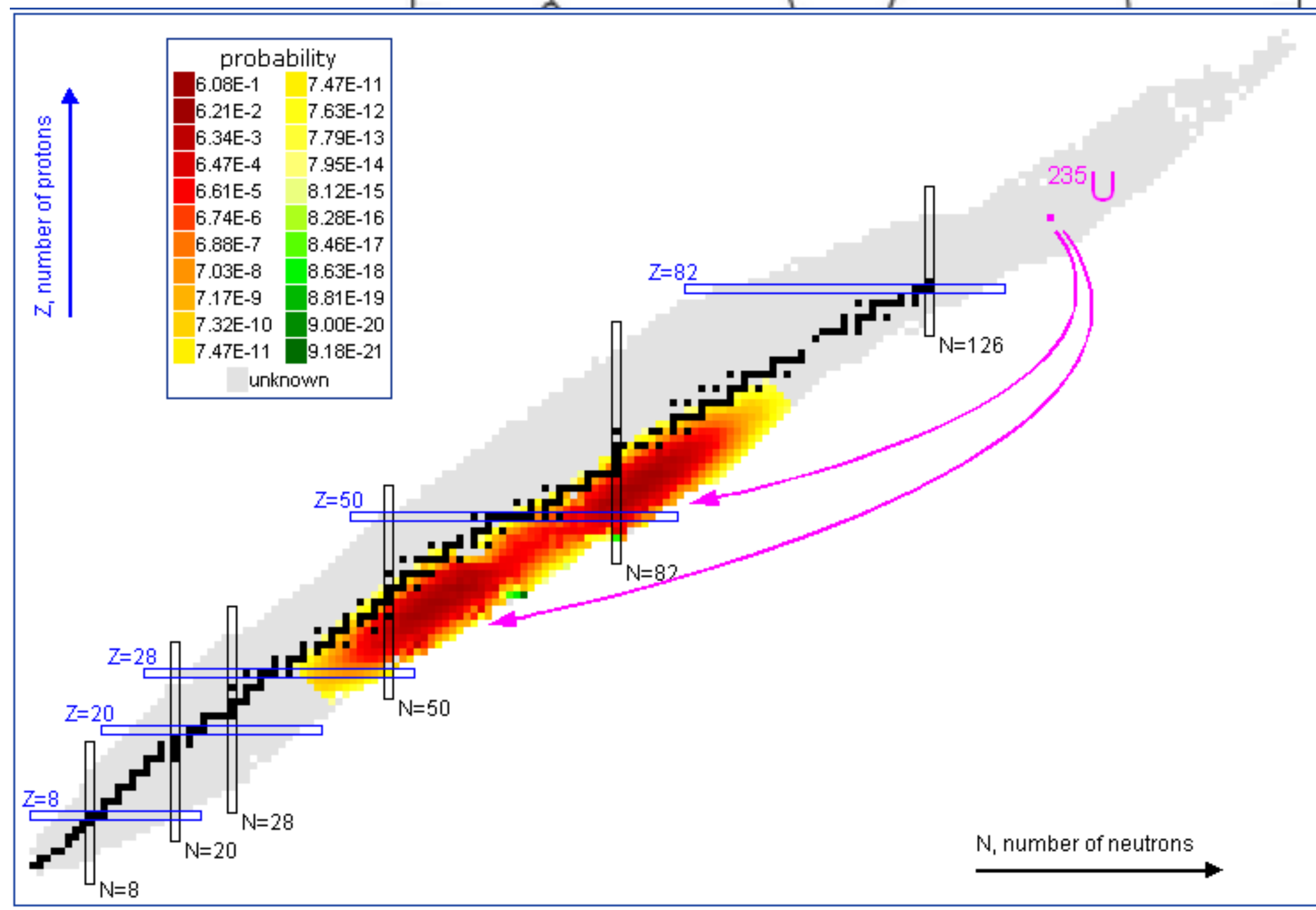




Advantage of using reactor

- **High intensity of thermal neutron: 10^{14} n/s/cm^2**
- **Large fission cross section: 585 b**
- **Simultaneous use: only using one terminal: a super spectrometer**
- **Reactor delivers stable n flux once it operated: a stable and parallel beam**
- **Large yield, long half life, easy to separate**





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Basic parameters for Beijing ISOL

- **Reactor and target:** $3X10^{14}$ n/cm^2/s, 5 g of ^{235}U
- **Fission beam:** $2X10^{15}$ fission/s
- **D-LINAC:** 20-33 MeV/u 10 mA
- **High power target station:** thermal power 400 kW.]
- **Isotope separator:** mass resolution 1000–20000
- **Post accelerator:** HI-LINAC, 150 MeV/u
- **RIB intensity for ^{78}Ni:** $10^{2\text{-}3}$ pps

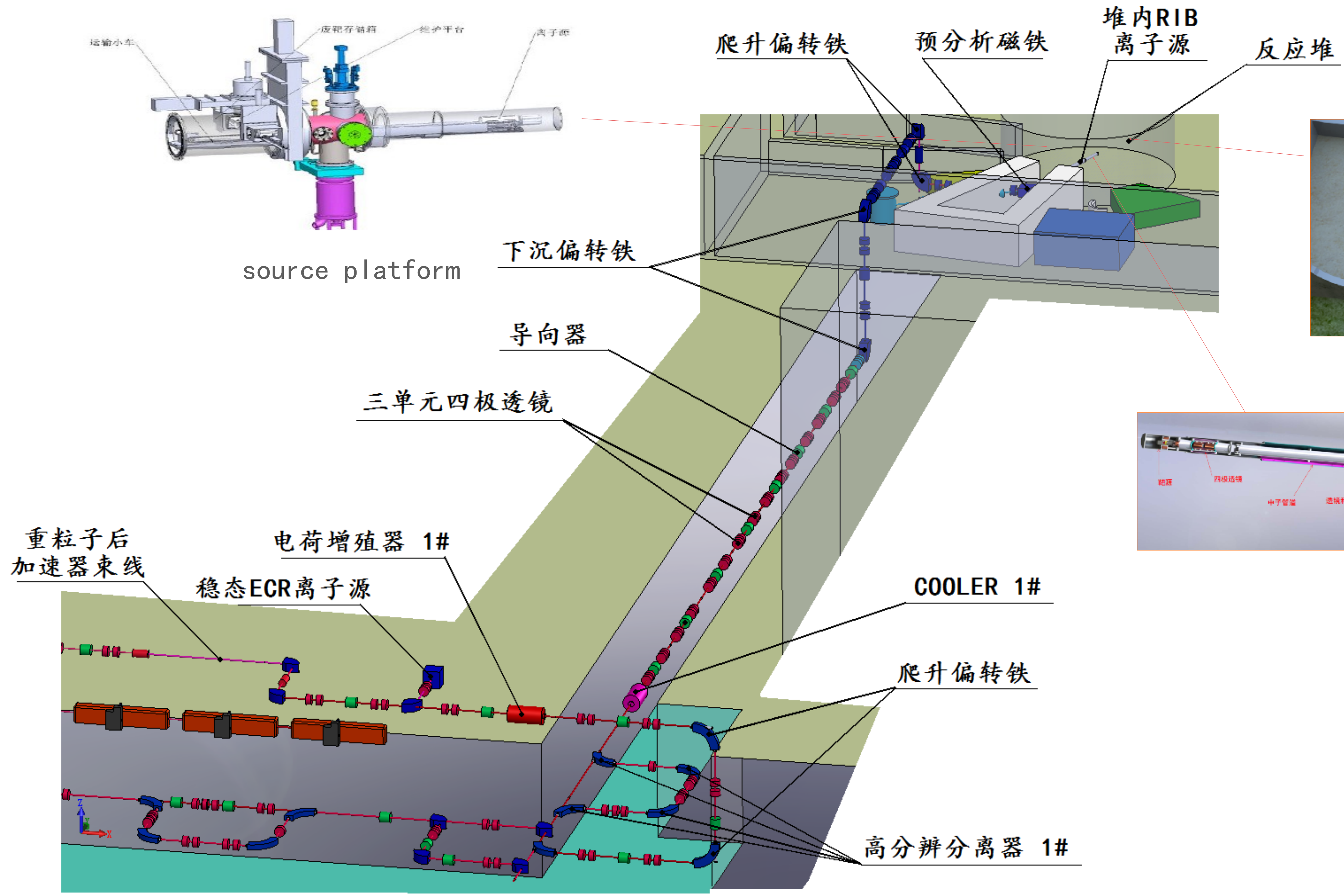
- Easy ISOL beam: long half life, high yield, normal ISOL
- 10 pnA order beam acceleration: no limitation of space charge and difficulty of beam diagnostics
- Techniques of PS are well established
- Light duty PF target: lower intensity primary beams

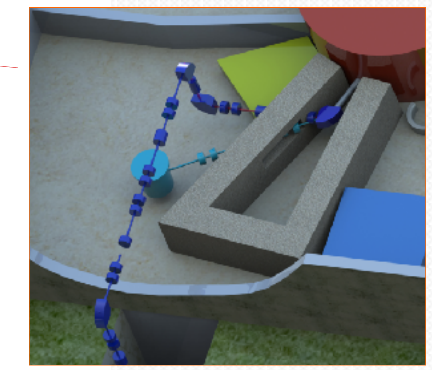
Design goal of Beijing ISOL

- **Competitiveness**: first class research platform → reactor-accelerator coupling
- **Multiple purposes**: user ranging from basic science to applications → multi-beam, multi-energy and multi-terminal
- **Feasibility**: mature and advanced technologies → double driver to high duty factor, high cost performance ratio
- **Complement to world facilities**: middle mass very n-rich beam in middle energy → PF of ISOL n-rich fission beam

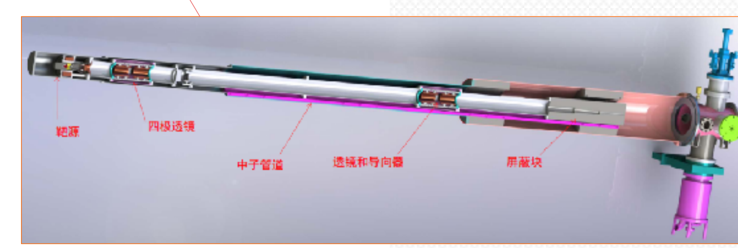
- BISOL experiment
- Look for the active and productive cases up to year of 2030
- Not determine very soon, and keep more space for future
- Open to domestic and international community
- Select the basic detector idea and spokes person world wide

Reactor ion source





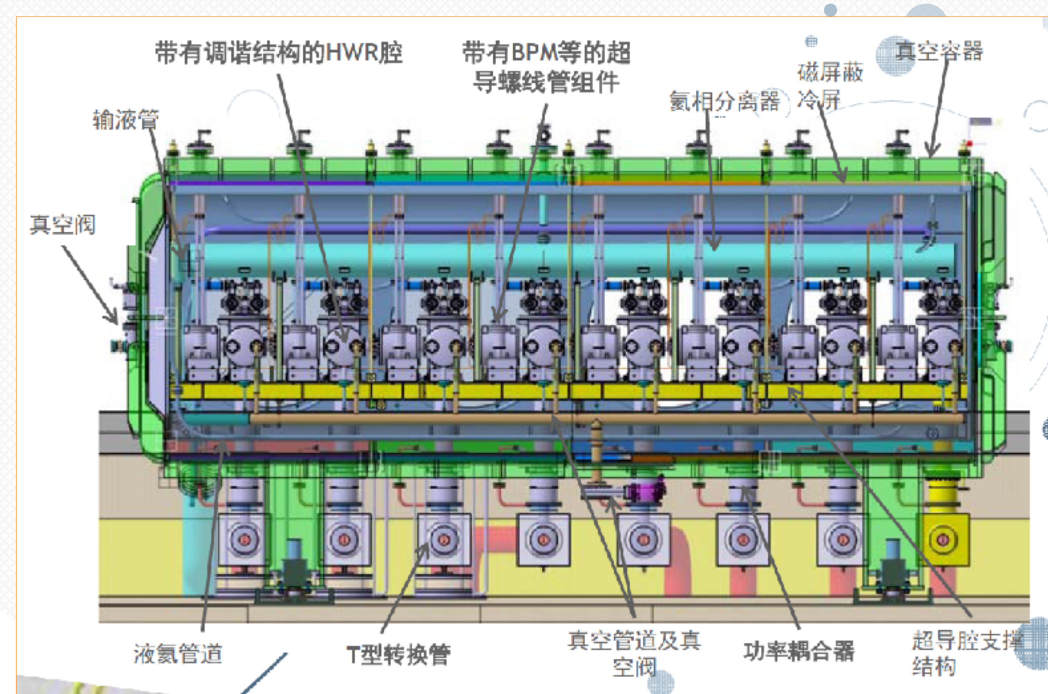
ion source in reactor hall



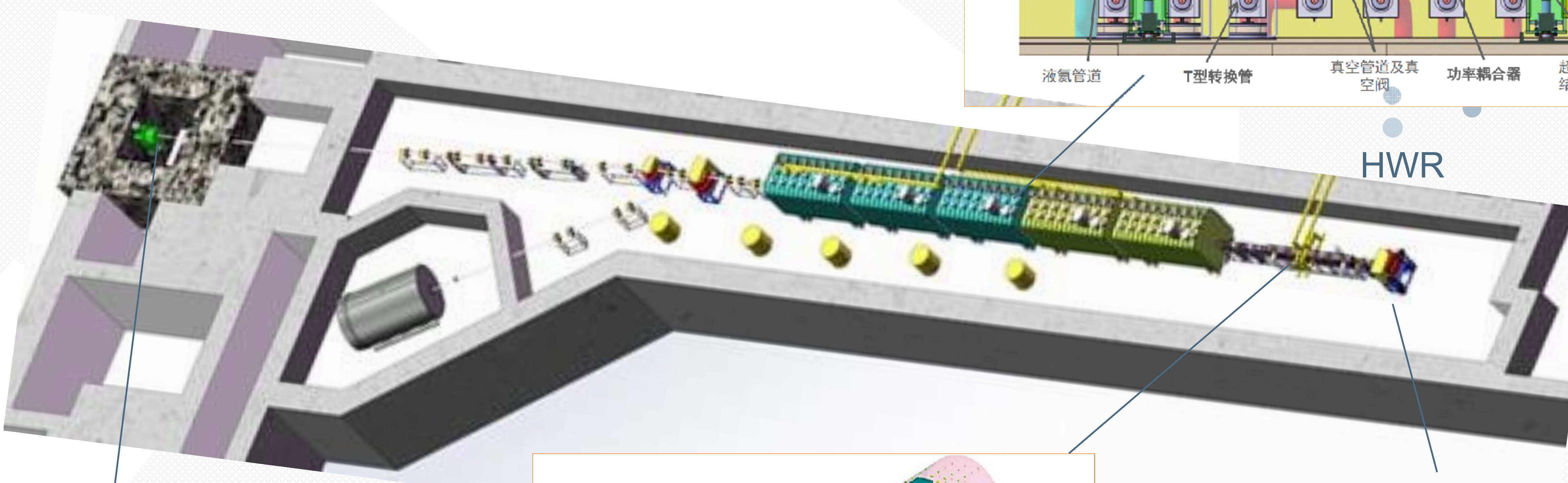
ion source in horizontal tube

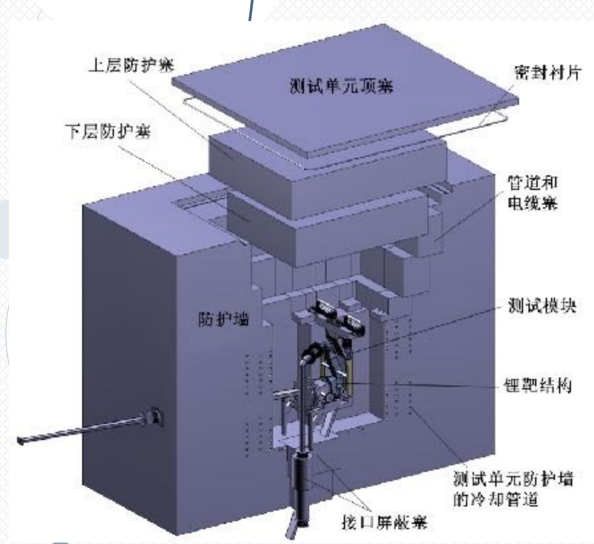
d LINAC

Ion source,RFQ, HWR, beam line, 40 MeV, 10 mA, d beam, LLi target n converter

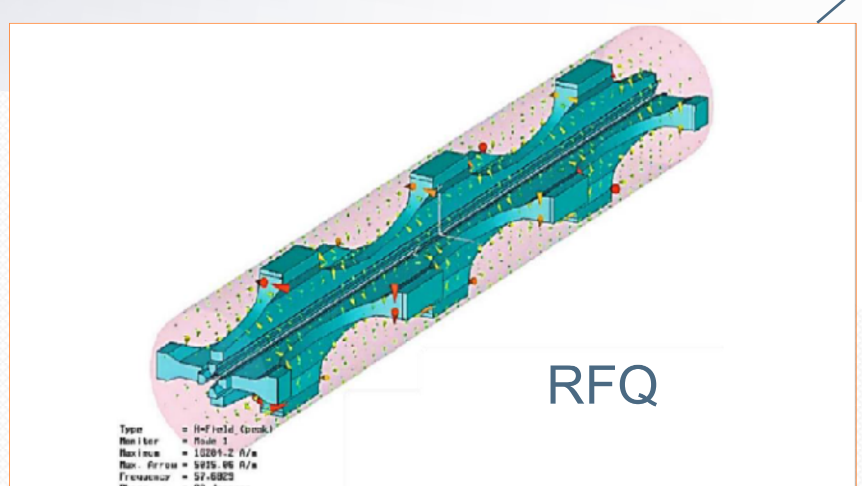


HWR

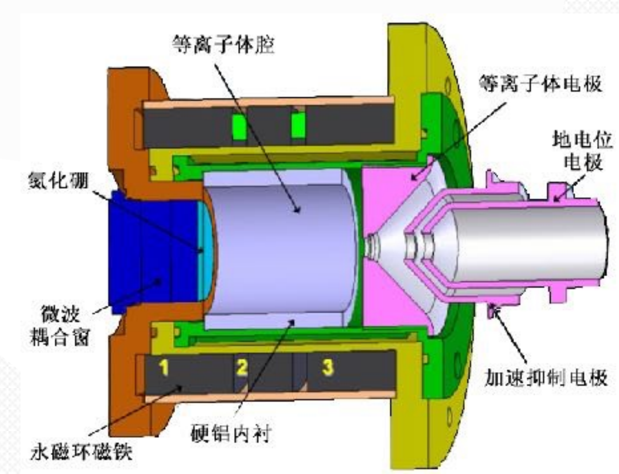




LLi n converter



RFQ



ion source

High power target

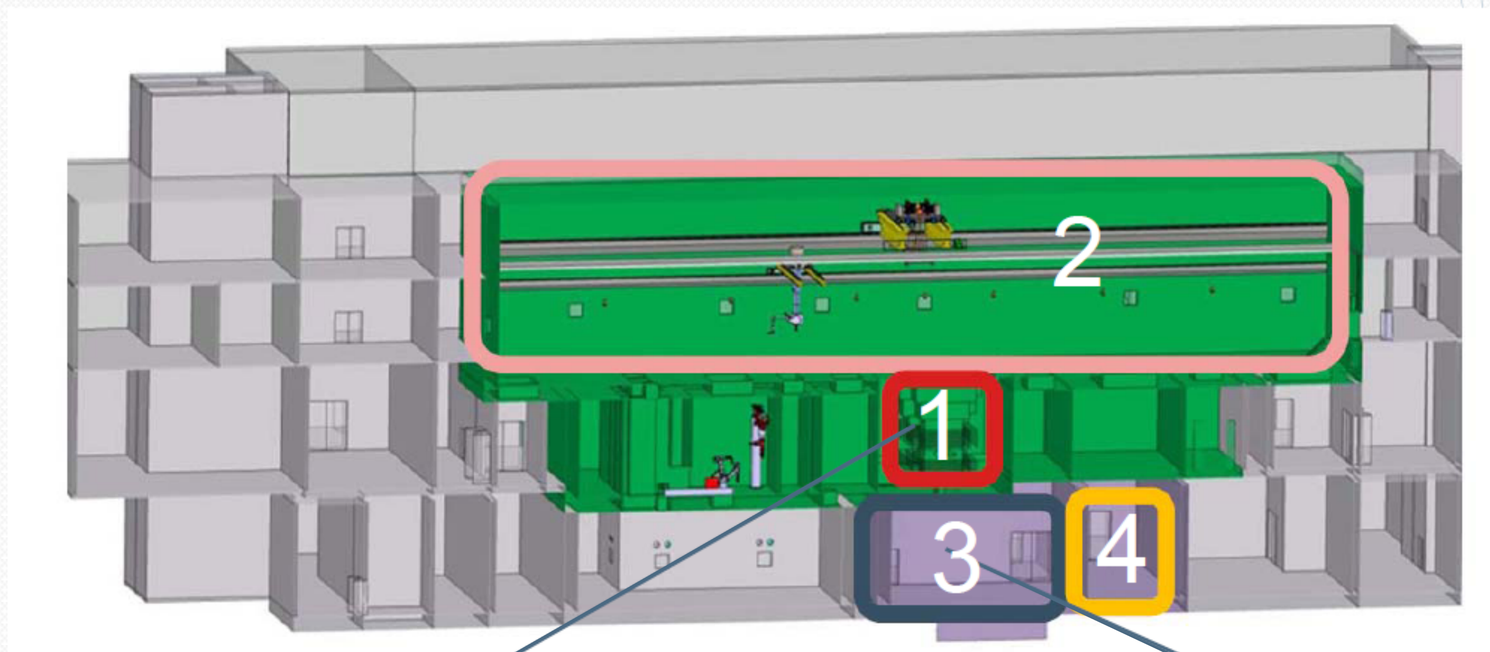
高功率靶站利用强流氘束轰击液锂靶，产生通量达 $5 \times 10^{14}\ s^{-1}cm^{-2}$中子，用于材料辐照或在重靶中产生裂变碎片。主要包括4个部分：

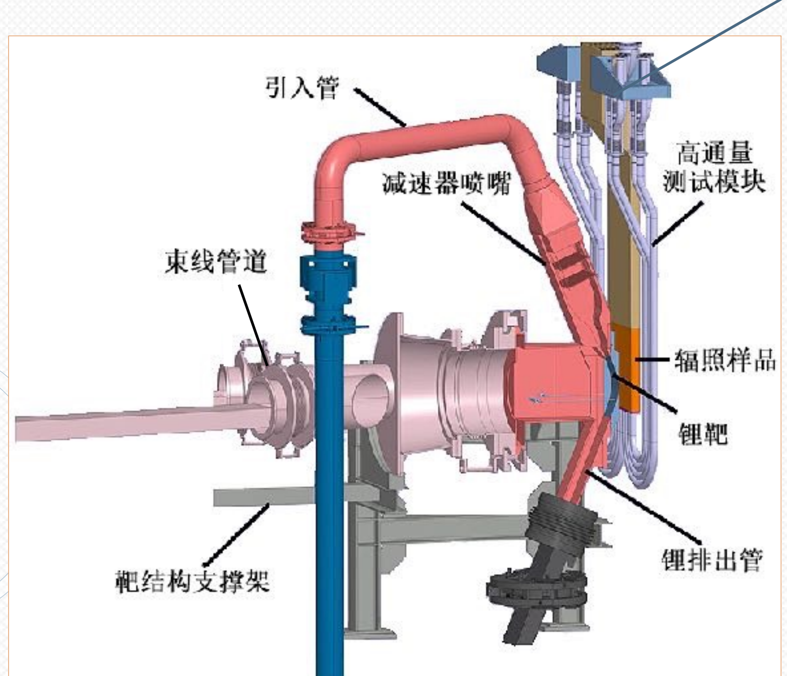
1、Li靶及辐照单元（红色框）：容纳液Li靶、测试模块、放射性离子源

2、靶维护及样品更换区(AC)（粉色框）：出入通道（天车通道）、热室及远程操控

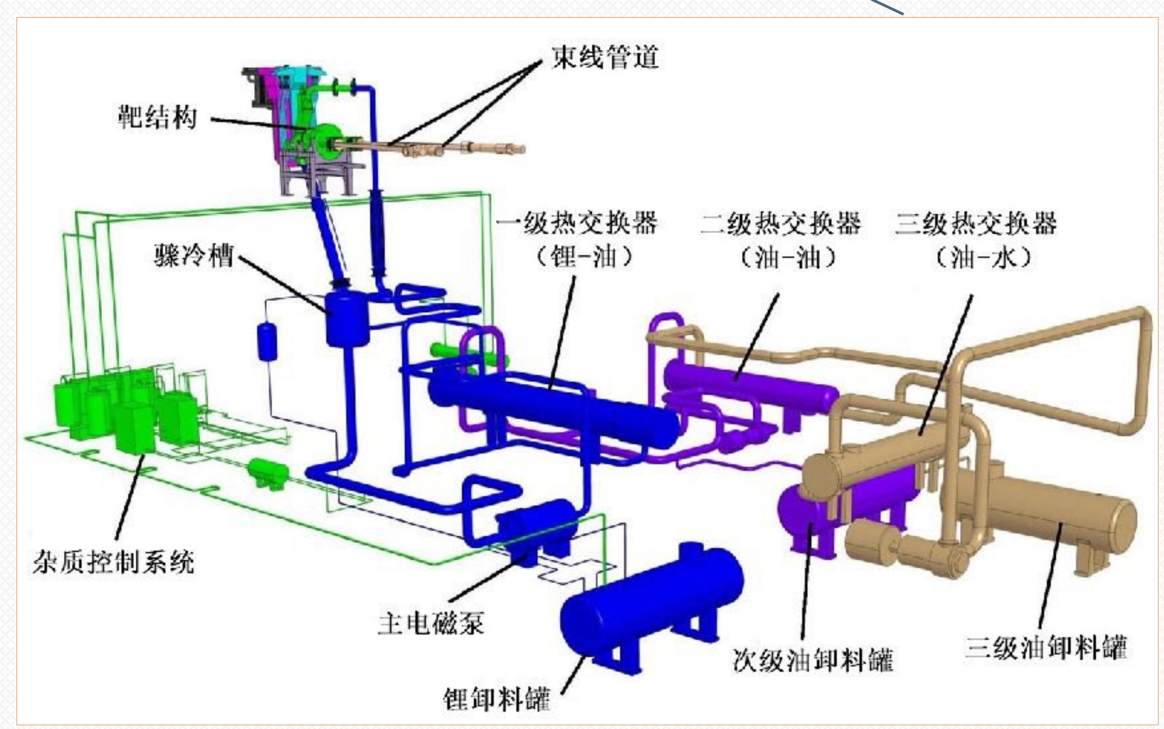
3、液Li回路（蓝色框）：主回路、纯化回路、冷却回路

4、放射性废物处理及存储区（黄色框）：液态及固态放射性废物





radiation module

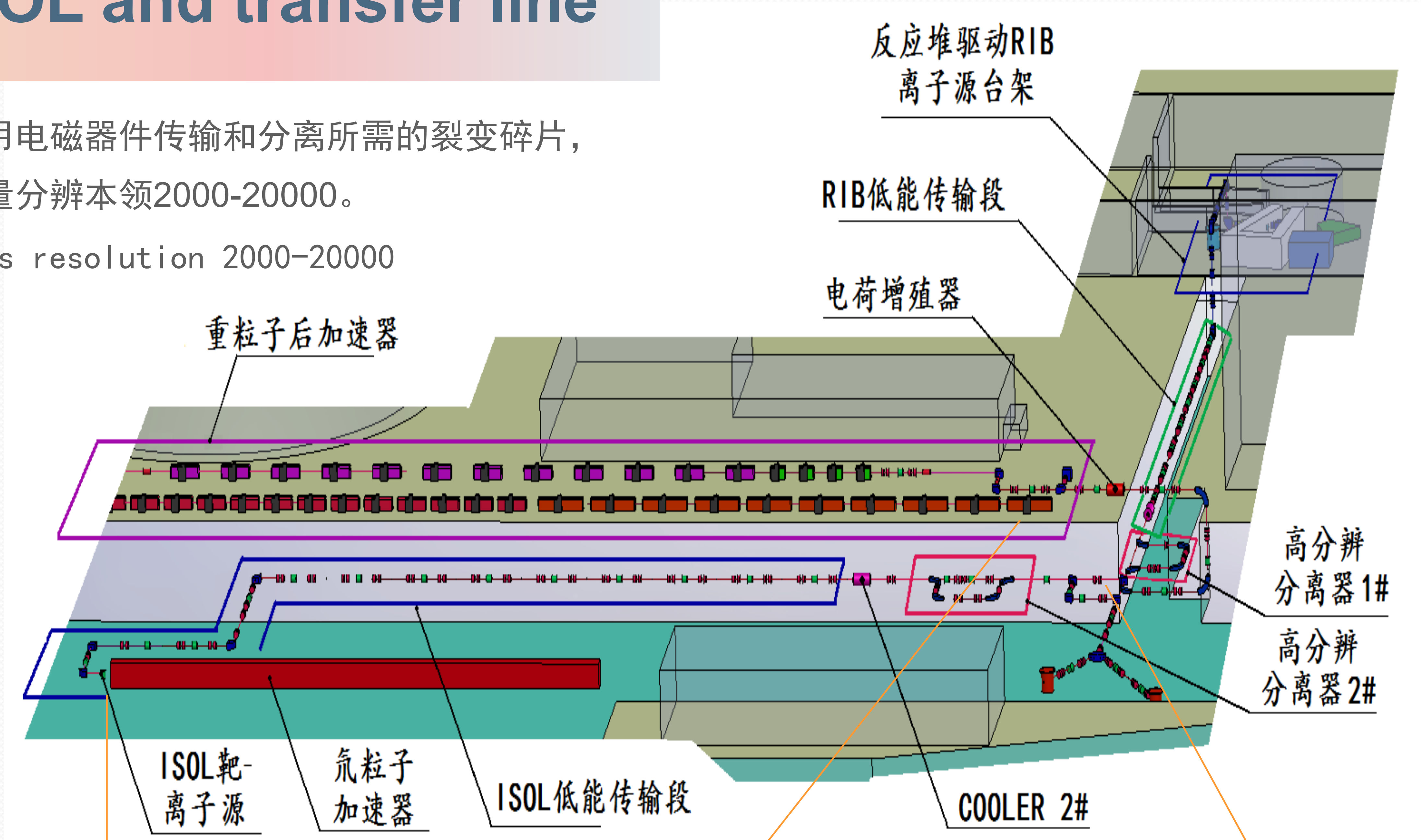


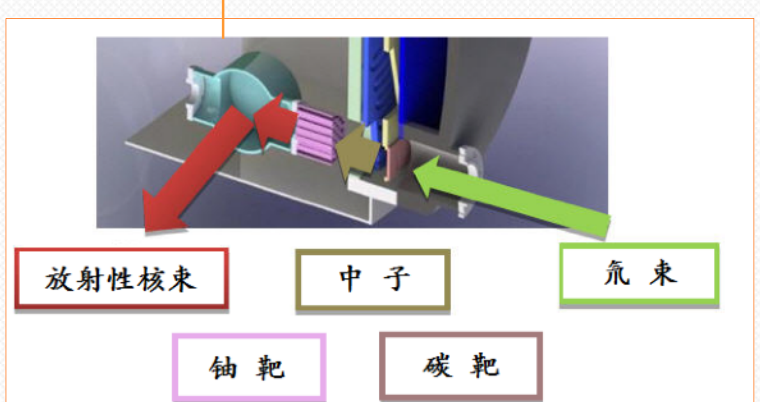
ISOL and transfer line

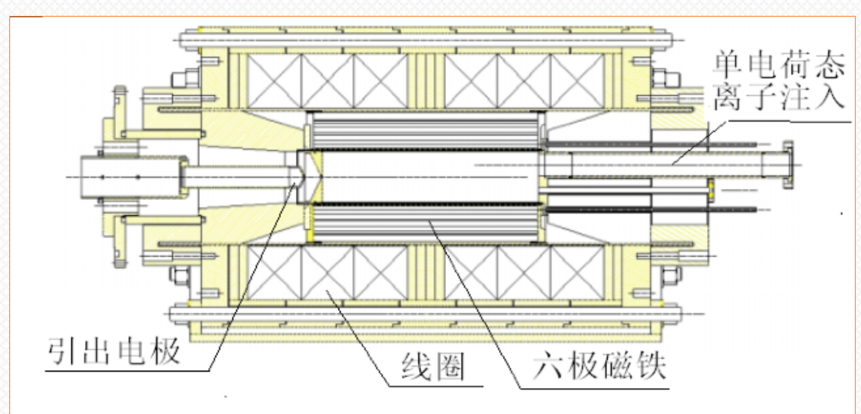
利用电磁器件传输和分离所需的裂变碎片，

质量分辨本领2000-20000。

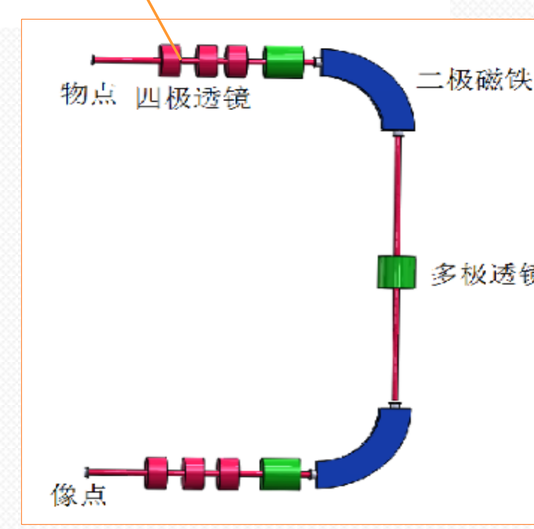
mass resolution 2000-20000







ECR charge breeder



mass analysis

HI LINAC

多重电荷态束流注入RFQ加速，

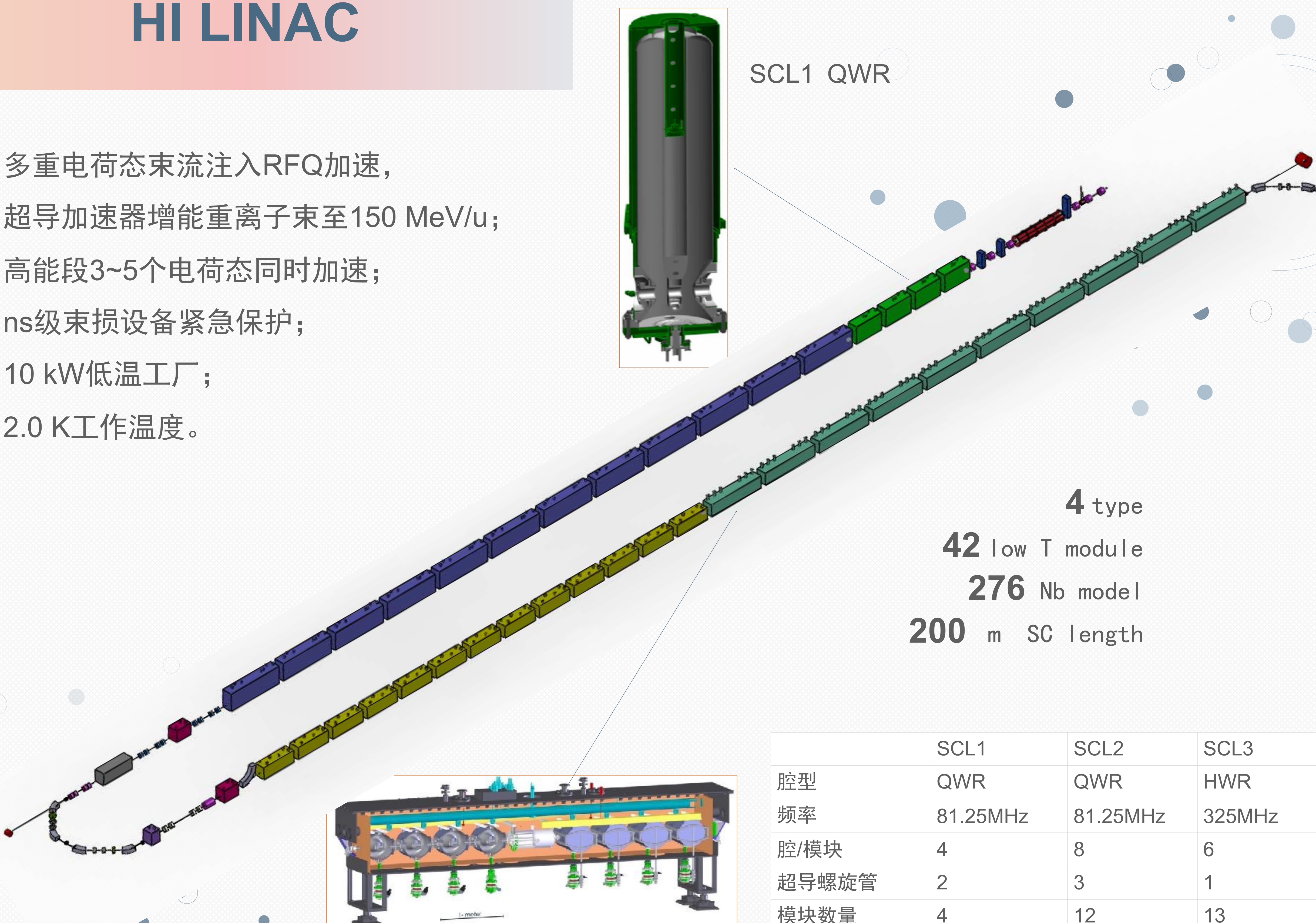
超导加速器增能重离子束至150 MeV/u；

高能段3~5个电荷态同时加速；

ns级束损设备紧急保护；

10 kW低温工厂；

2.0 K工作温度。



SCL1 QWR

4 type

42 low T module

276 Nb model

200 m SC length

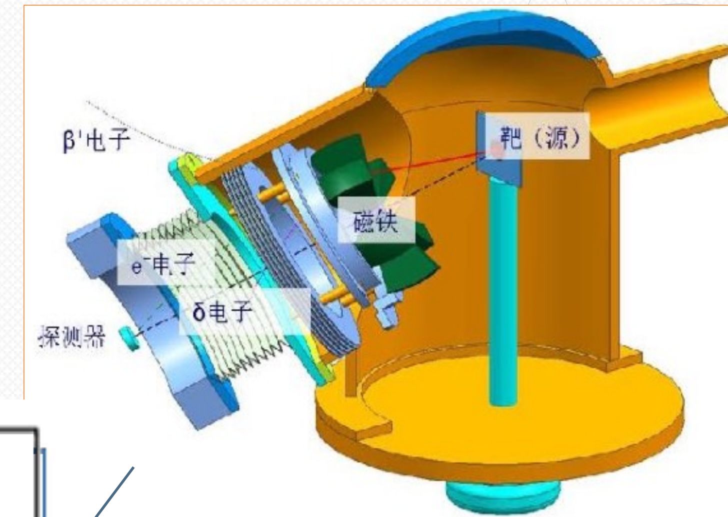
HWR2 low T cabin

	SCL1	SCL2	SCL3	SCL4
腔型	QWR	QWR	HWR	HWR
频率	81.25MHz	81.25MHz	325MHz	325MHz
腔/模块	4	8	6	8
超导螺旋管	2	3	1	1
模块数量	4	12	13	10
总超导腔	16	96	78	80

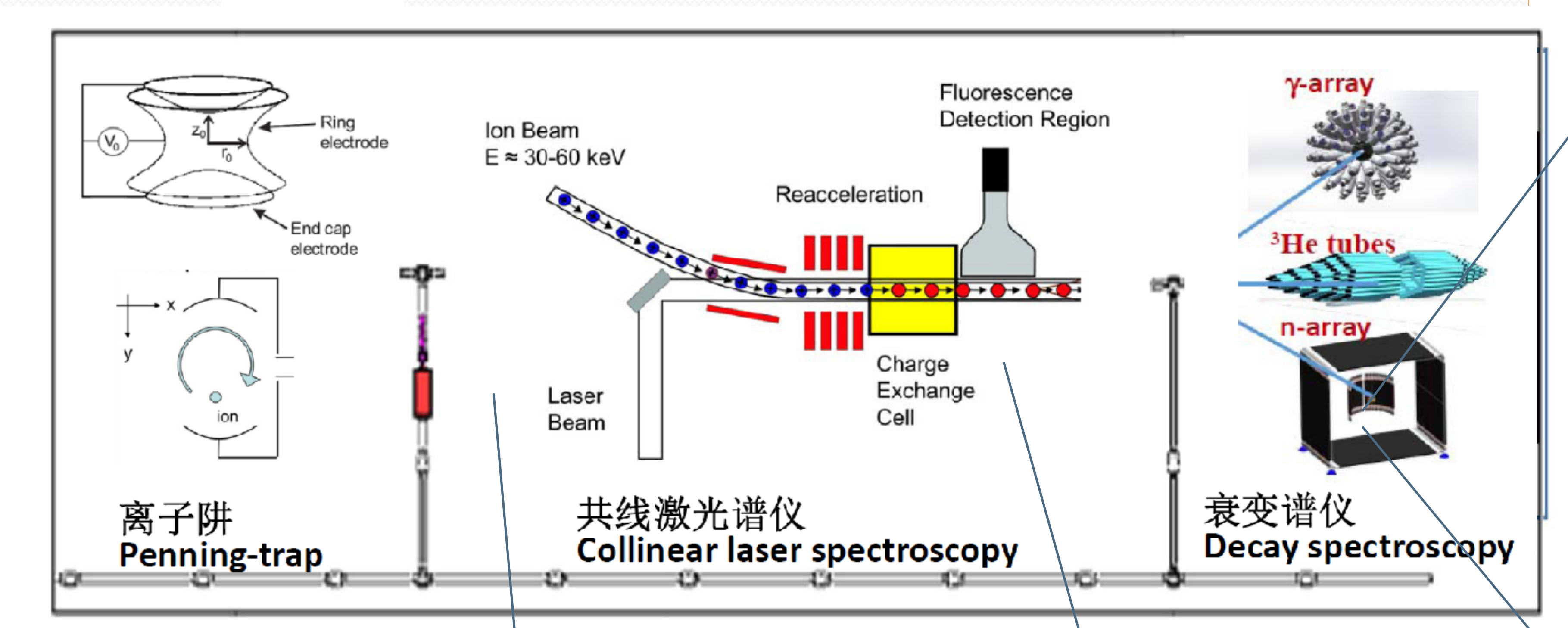
Stopped beam facility

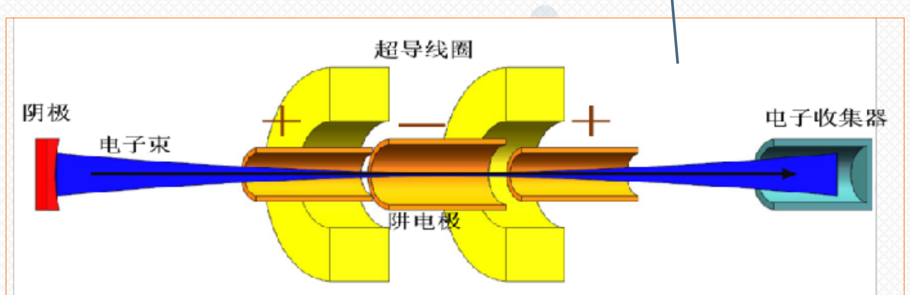
分离能区实验（SEE）seperation energy experiment

采用ISOL分离出来的不稳定核束（~20 keV/q），
或者从中能束减速引出的极端丰中子核束，
开展核性质或核衰变测量。

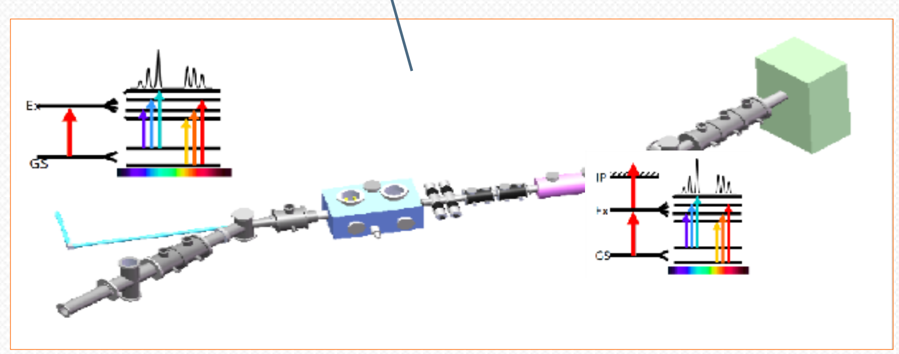


内转换电子谱仪
Internal conversion spectrometer

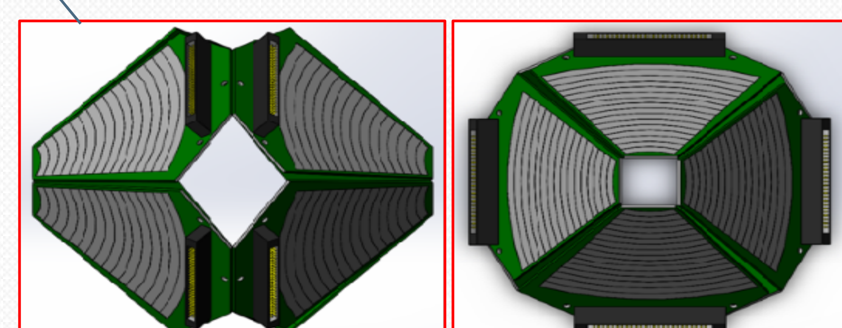




电荷增殖电子束离子阱
Penning trap



共线共振电离谱仪
collider laser

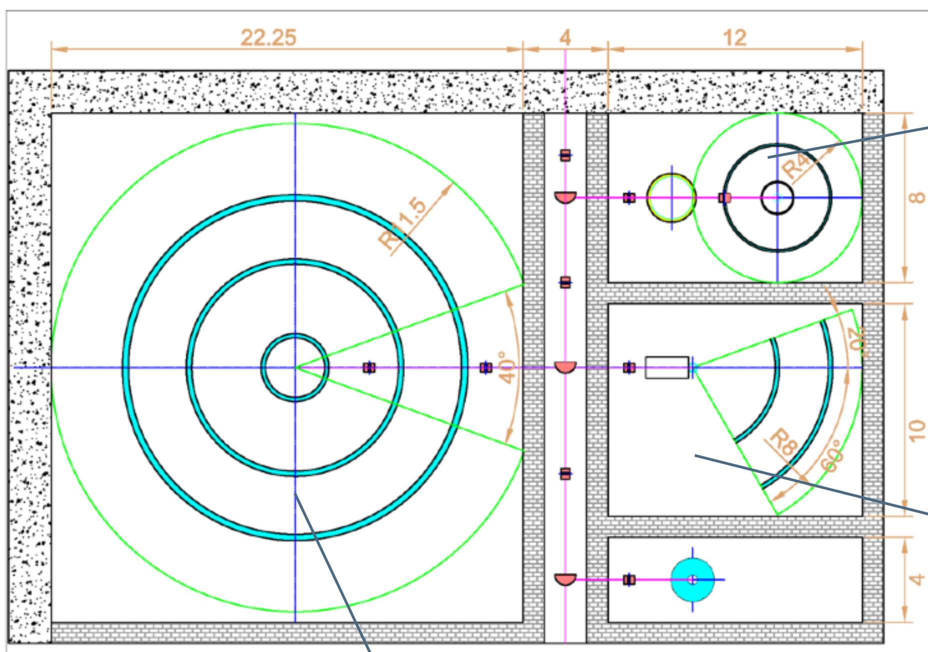


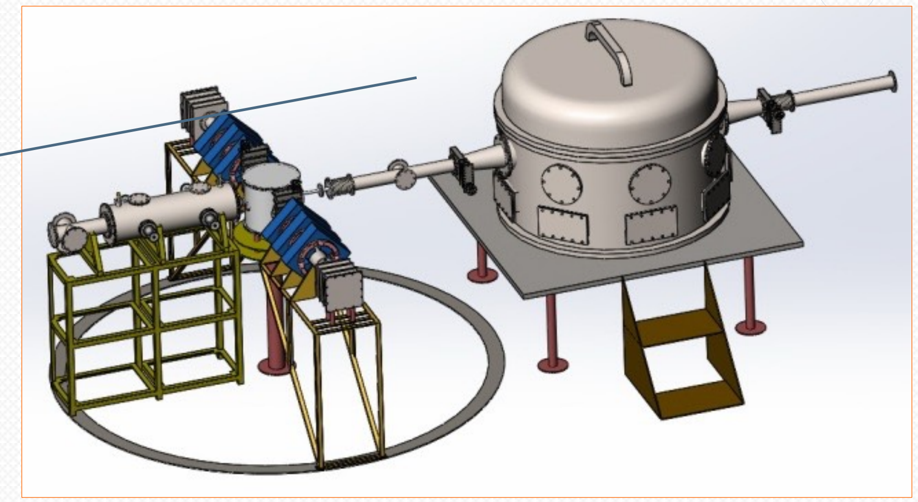
4π带电粒子探测器阵列
charged array

Low energy beam facility

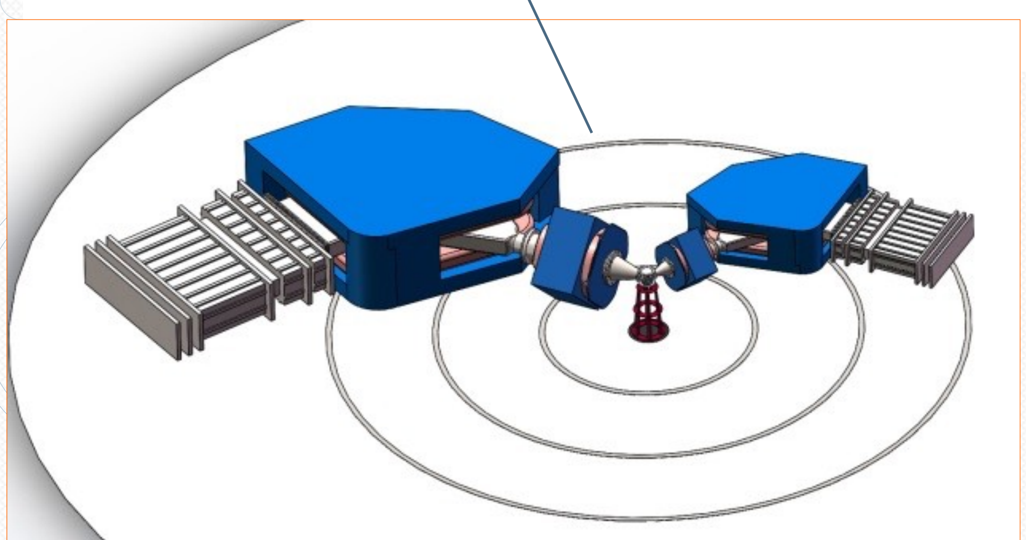
低能区实验 low energy experiment（LEE）

采用后加速中段产生的低能不稳定核束（~20 MeV/u），开展核反应和结构测量。

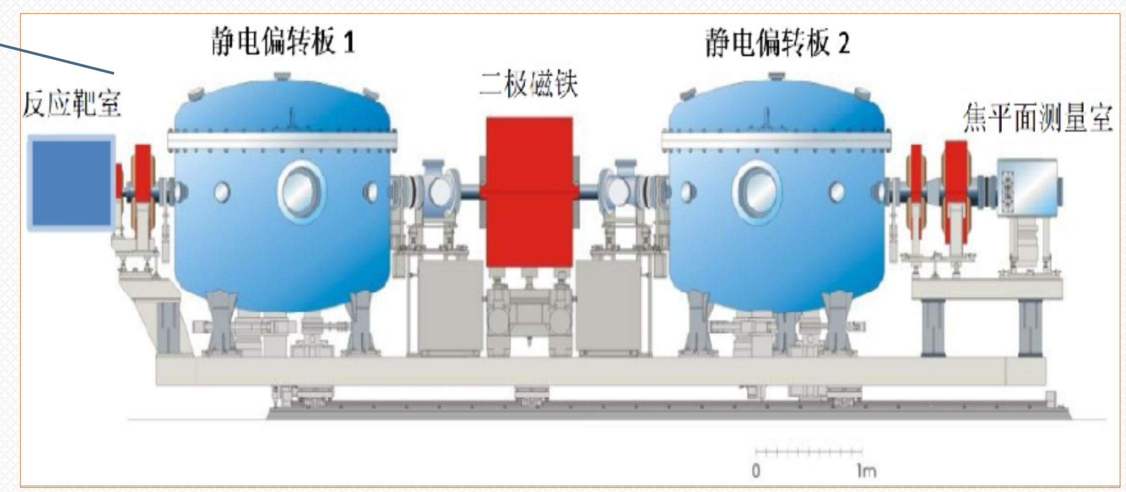




直径2米大靶室+旋转靶室+飞行时间谱仪+静电偏转板 target chamber



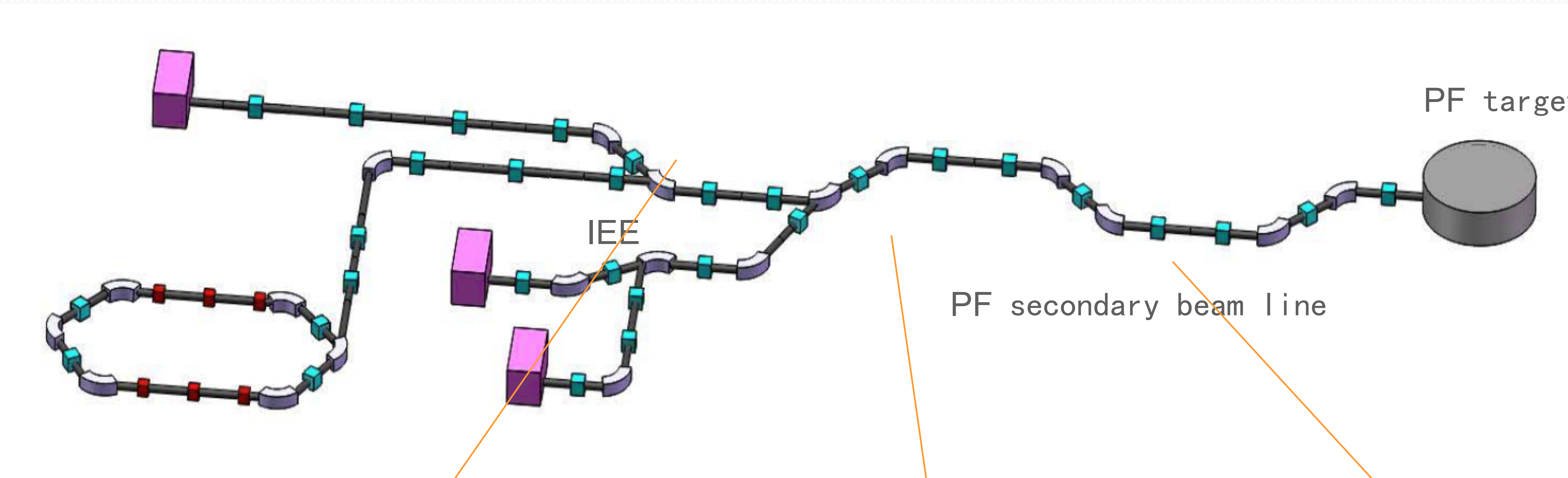
双臂大接受度磁谱仪 Large acceptance spectrometer

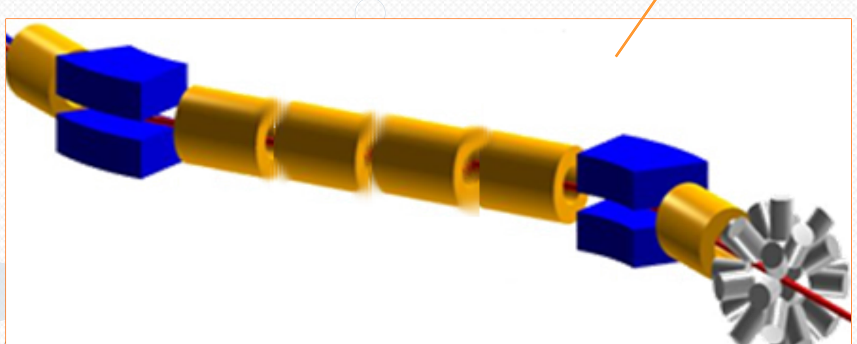


RMS

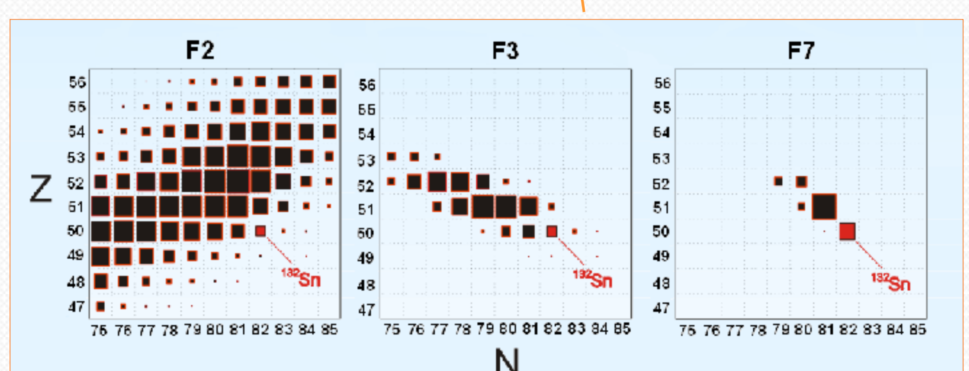
PF facility

利用弹核破裂（PF）方法，将150 MeV/u的裂片束流打靶产生极端丰中子同位素，经次级束流分离器选择后送到中能实验区。

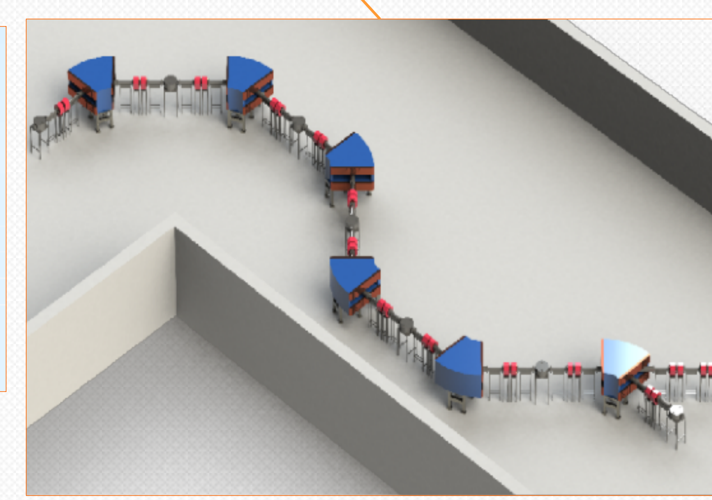




零度谱仪
zero angle
spectrometer

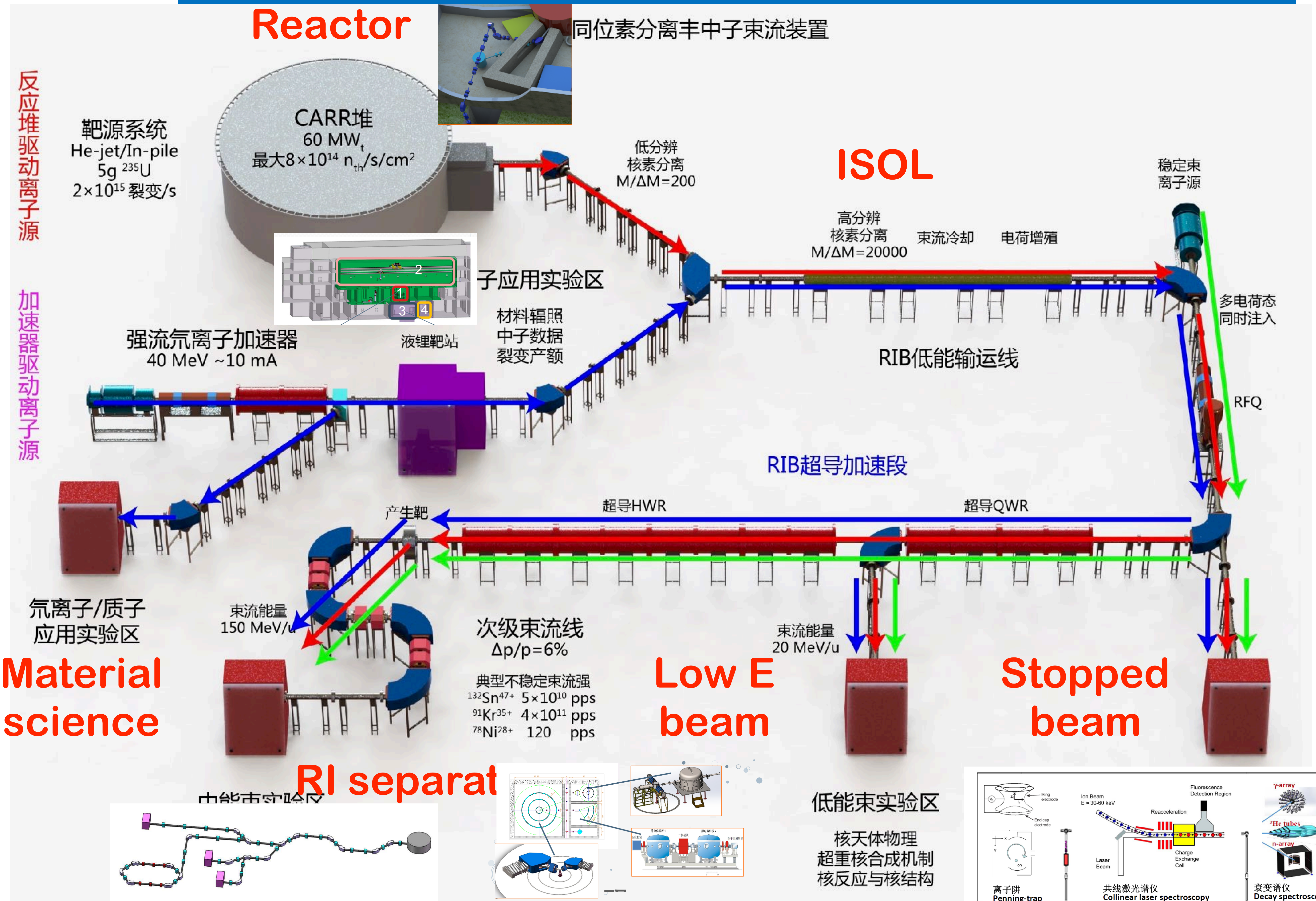


双消色差系统粒子分离能力
double acrobatic

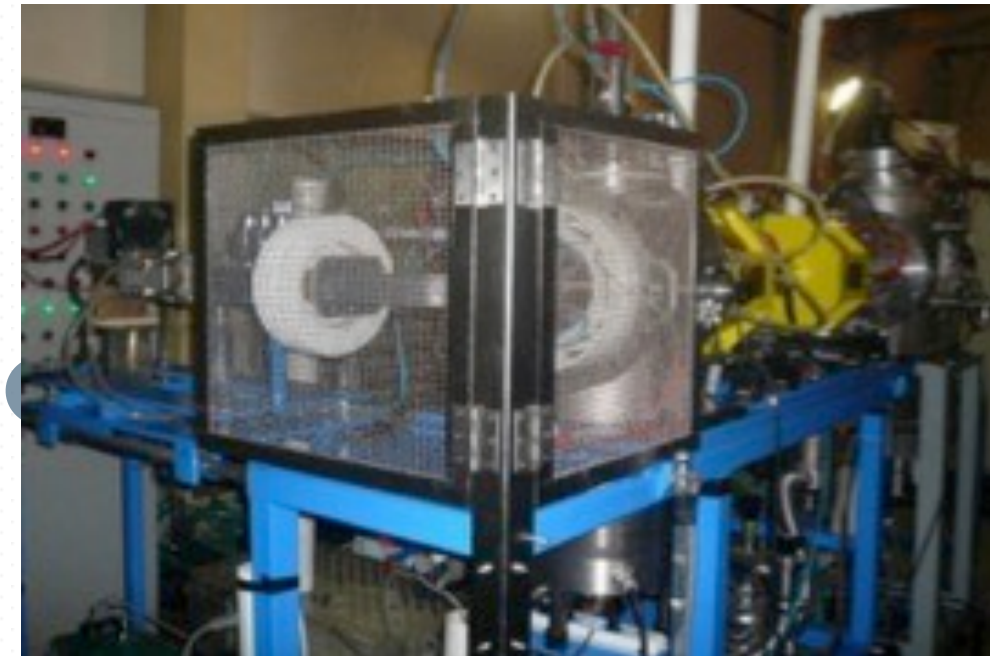


次级束流分离器
secondary beam lien

BISOL layout



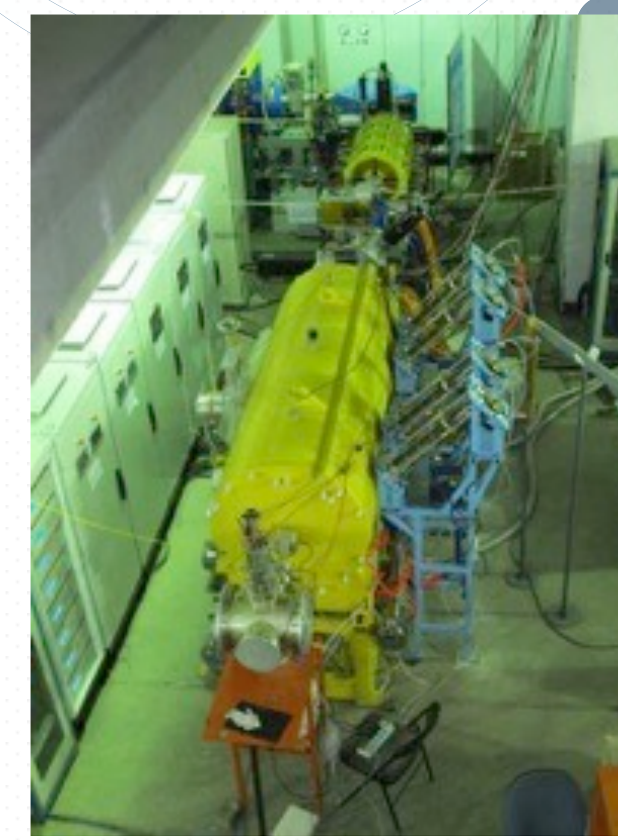
R&D in PKU



PKUNIFTY ECR d ion source

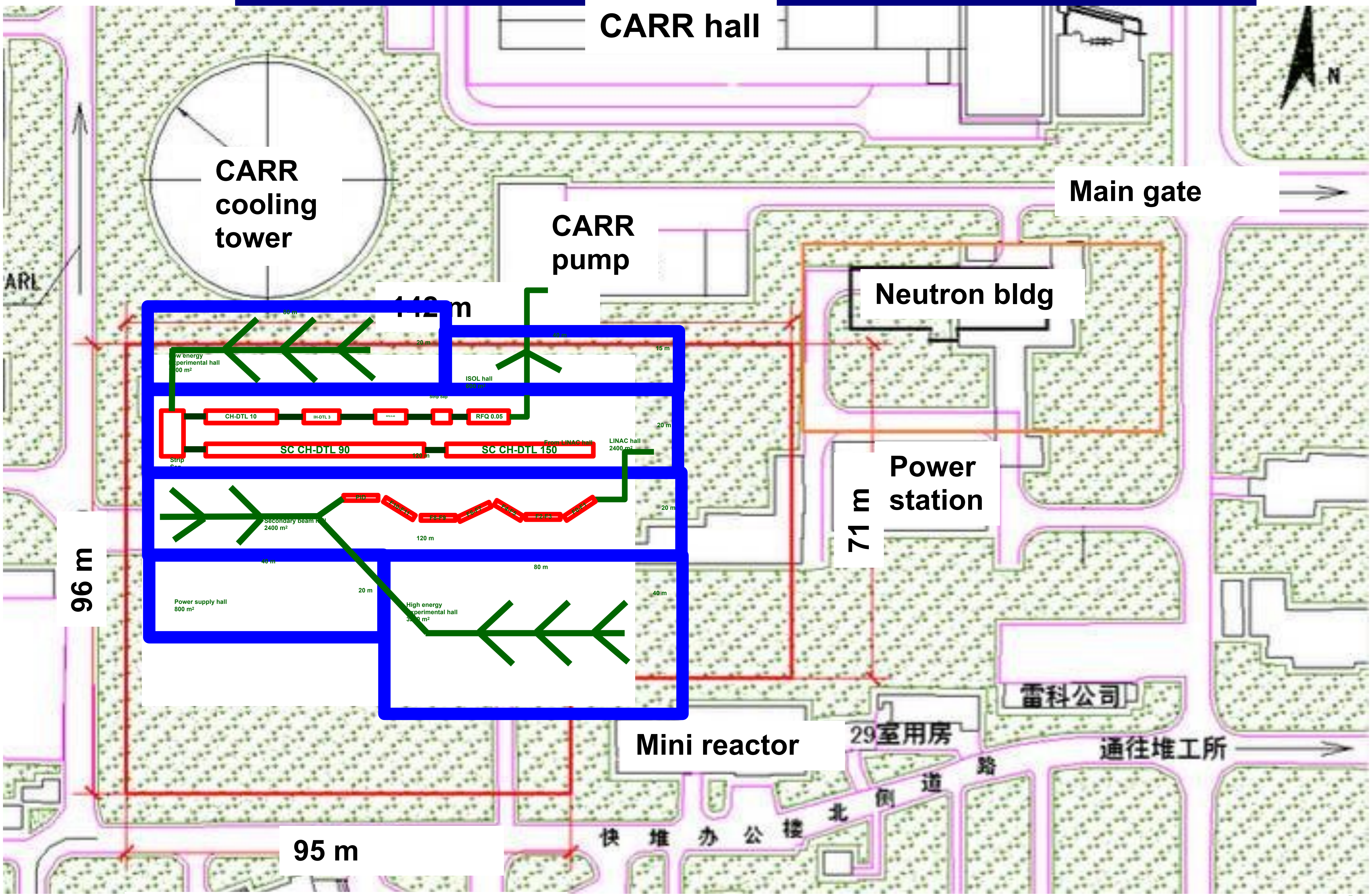
n photography based
on d LINAC

2X9cell LINAC



RFQ LINAC

The space allowed for Beijing ISOL



Total space: 12455 m²

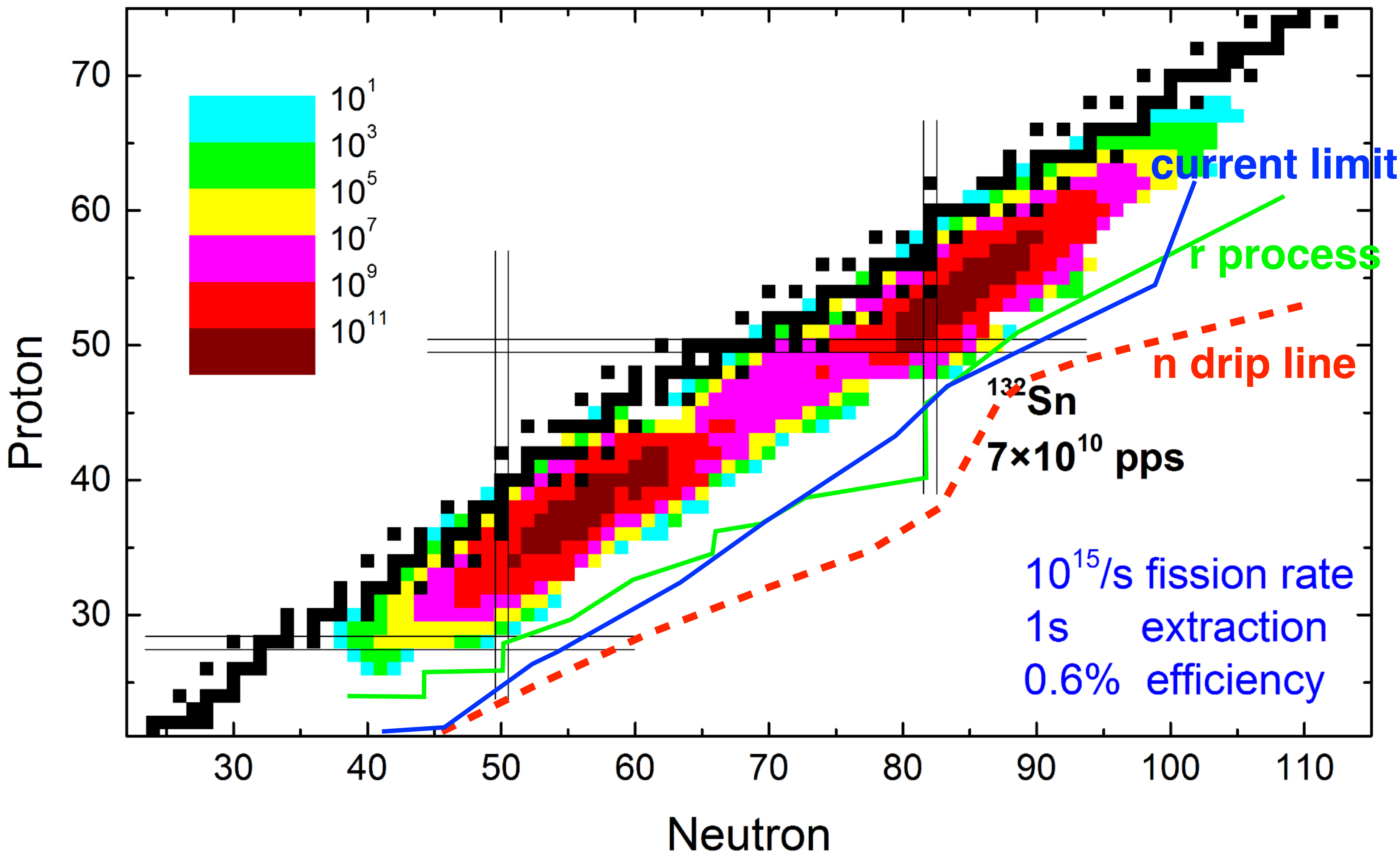
ISOL beam intensity

^{235}U/g	σ/b	n-flux, /cm²/s	f /s
5	585	3×10^{14}	2×10^{15}

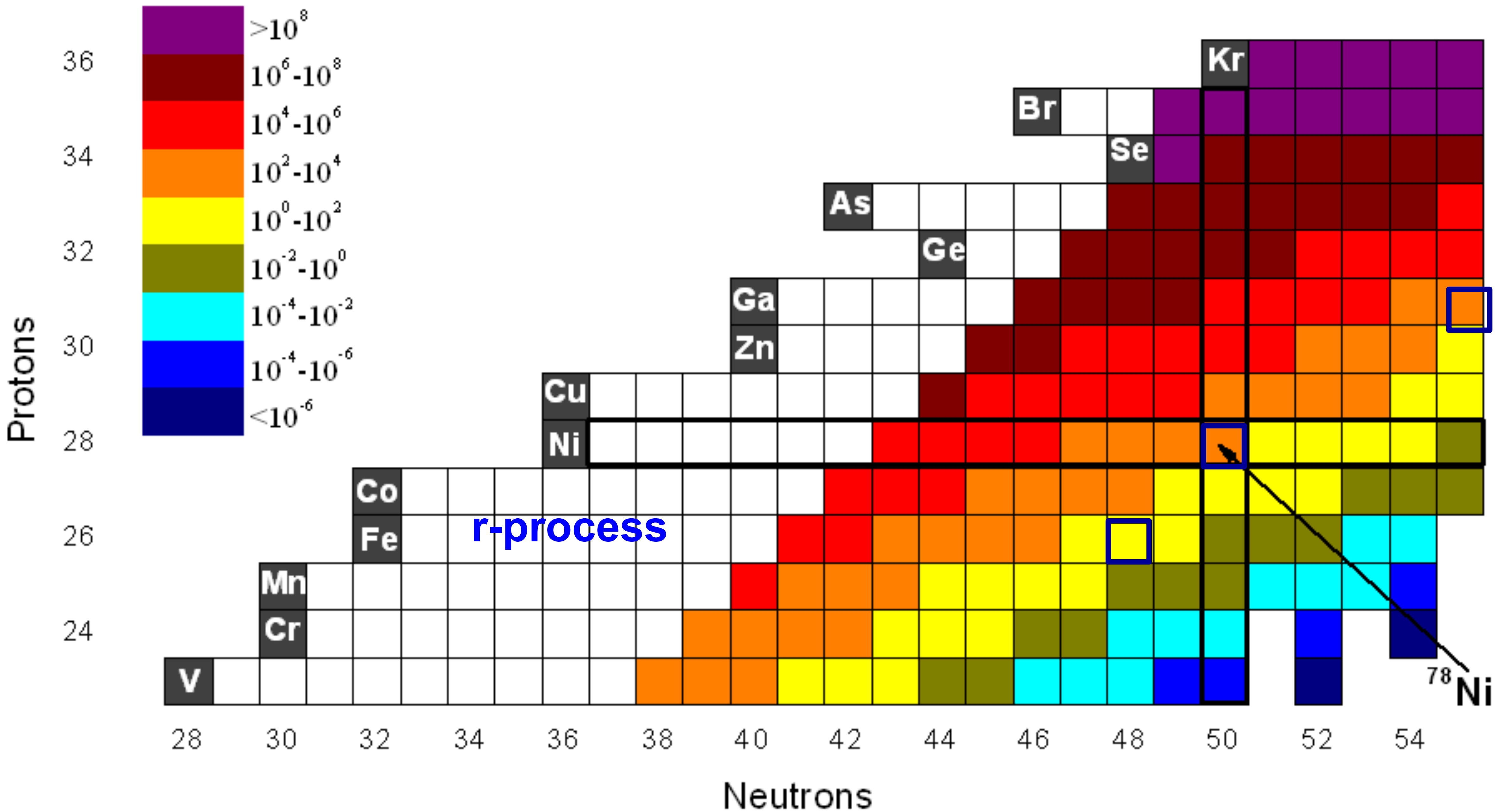
nuclei	Fis. yield	rate	Target +isol eff. (ref. PIAFE)	CB eff	Linac eff.	intensity
^{91}Kr	3.2×10^{-2}	6.4×10^{13}	13.0%	10%	50%	4×10^{11}
^{142}Xe	4.3×10^{-3}	8.8×10^{12}	2.0%	10%	50%	9×10^{9}
^{132}Sn	5.7×10^{-3}	1.2×10^{13}	8.0%	10%	80%	7×10^{10}
^{81}Ga	7.6×10^{-5}	2×10^{11}	8.0%	10%	95%	1×10^{9}

Latest calculation by J. Su

RIB produced by CARR

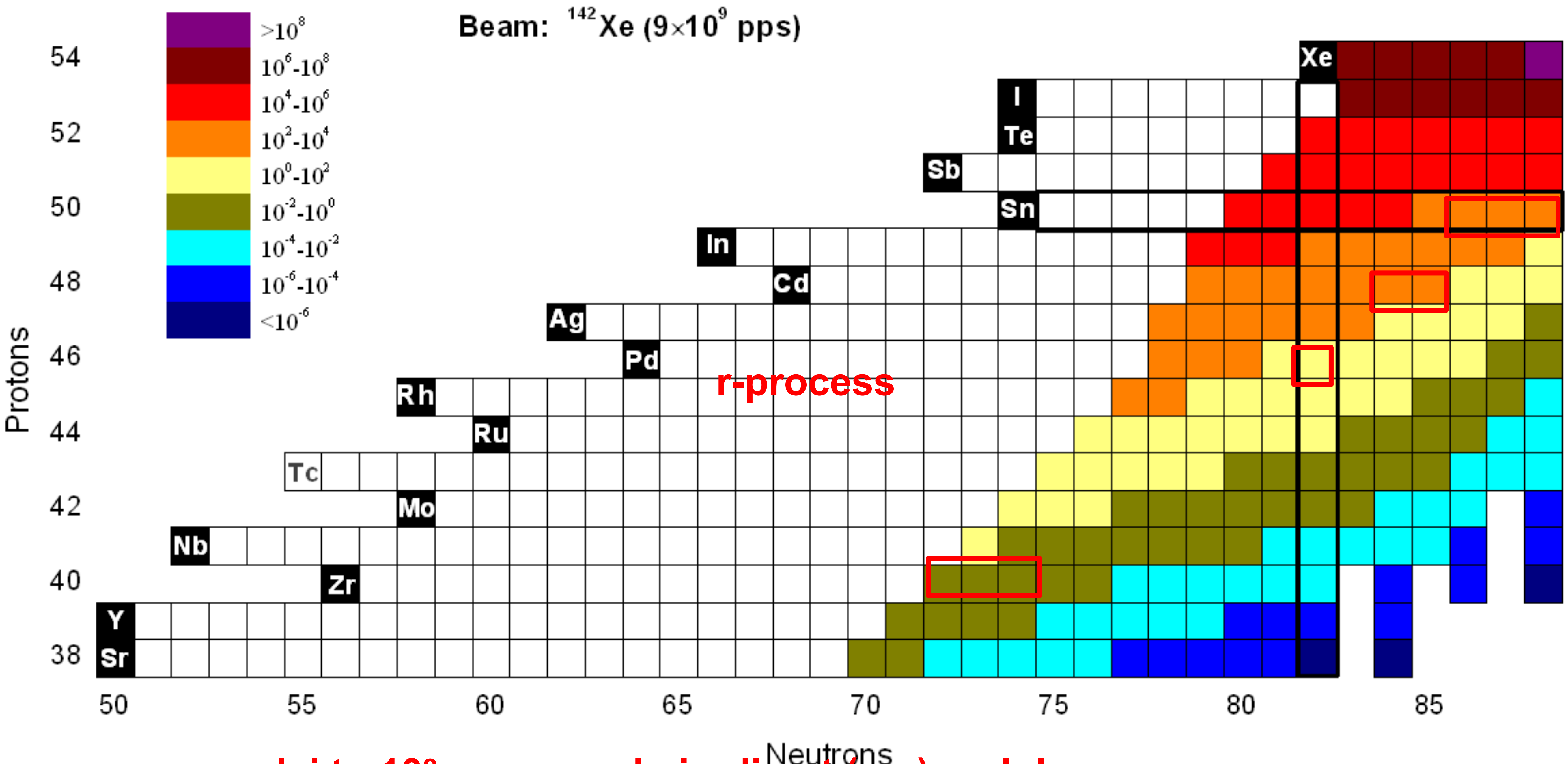


RIB with ^{81}Ga beams



^{78}Ni 400-700 pps, the possibility to do transfer reactions for structure and r-process

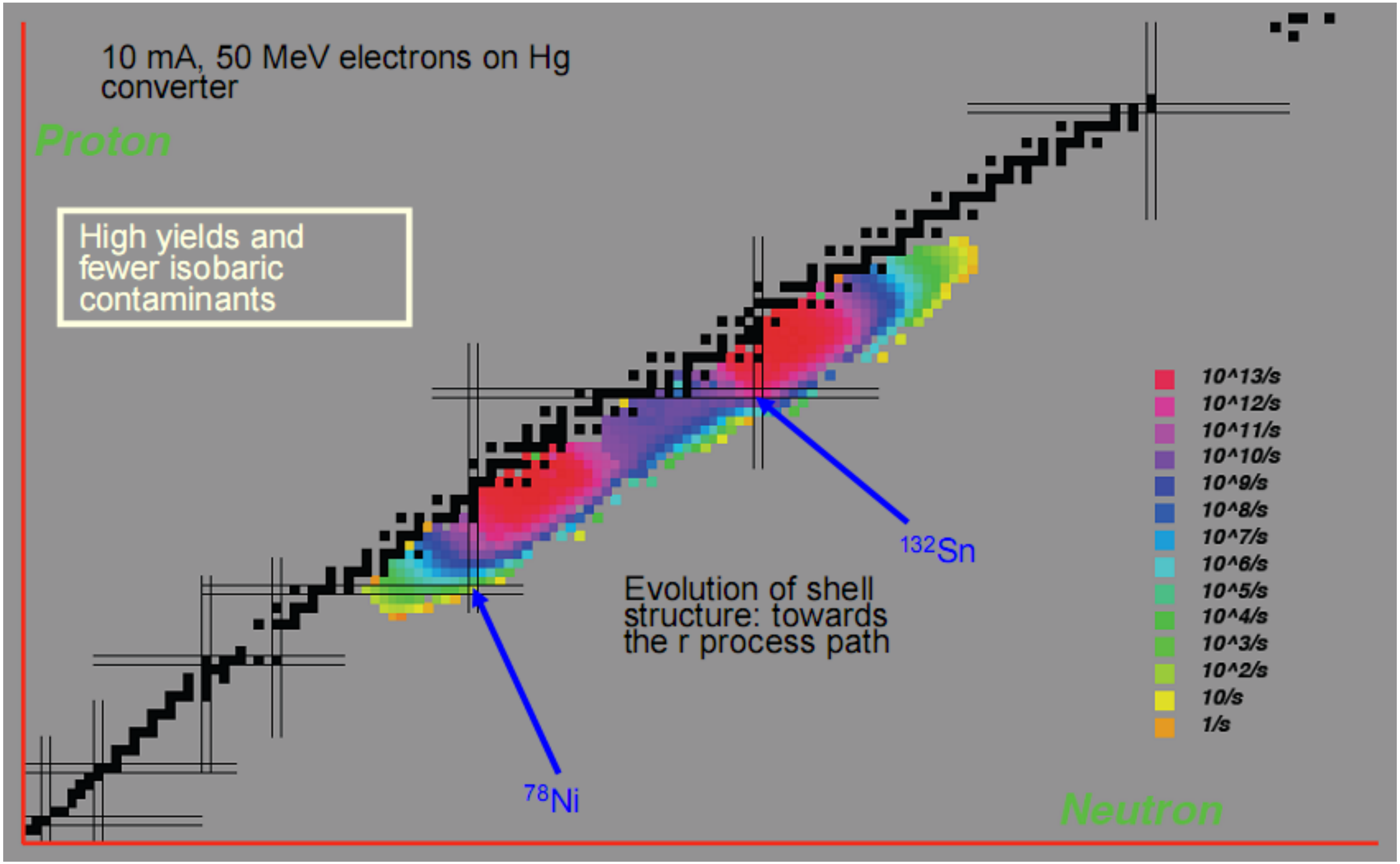
RIB with ^{142}Xe beams



r-process nuclei to 10^{2} pps, can do in-direct (n,g) and decay

The possibility to explore neutron drip line

RIB produced by D driver



Can also reach r-process and detect drip line !

BISOL as RI factory

- ^{132}Sn, for SHE
- ^{78}Ni, for structure, using double driver merge, 400 pps (CARR)，300 pps （d LINAC）：RI factory!
- ^{66}Ca, for drip line search, now to ^{60}Ca

PHYSICAL REVIEW LETTERS **121**, 022501 (2018)

Editors' Suggestion

Discovery of ^{60}Ca and Implications For the Stability of ^{70}Ca

stable | SHE now | SHE in BISOL?

^{40}Ca	^{41}Ca	^{42}Ca	^{43}Ca	^{44}Ca	^{45}Ca	^{46}Ca	^{47}Ca	^{48}Ca	^{49}Ca	^{50}Ca	^{51}Ca	^{52}Ca	^{53}Ca	^{54}Ca
^{55}Ca	^{56}Ca	^{57}Ca	^{58}Ca	^{59}Ca	^{60}Ca	^{61}Ca	^{62}Ca	^{63}Ca	^{64}Ca	^{65}Ca	^{66}Ca	^{67}Ca	^{68}Ca	^{69}Ca

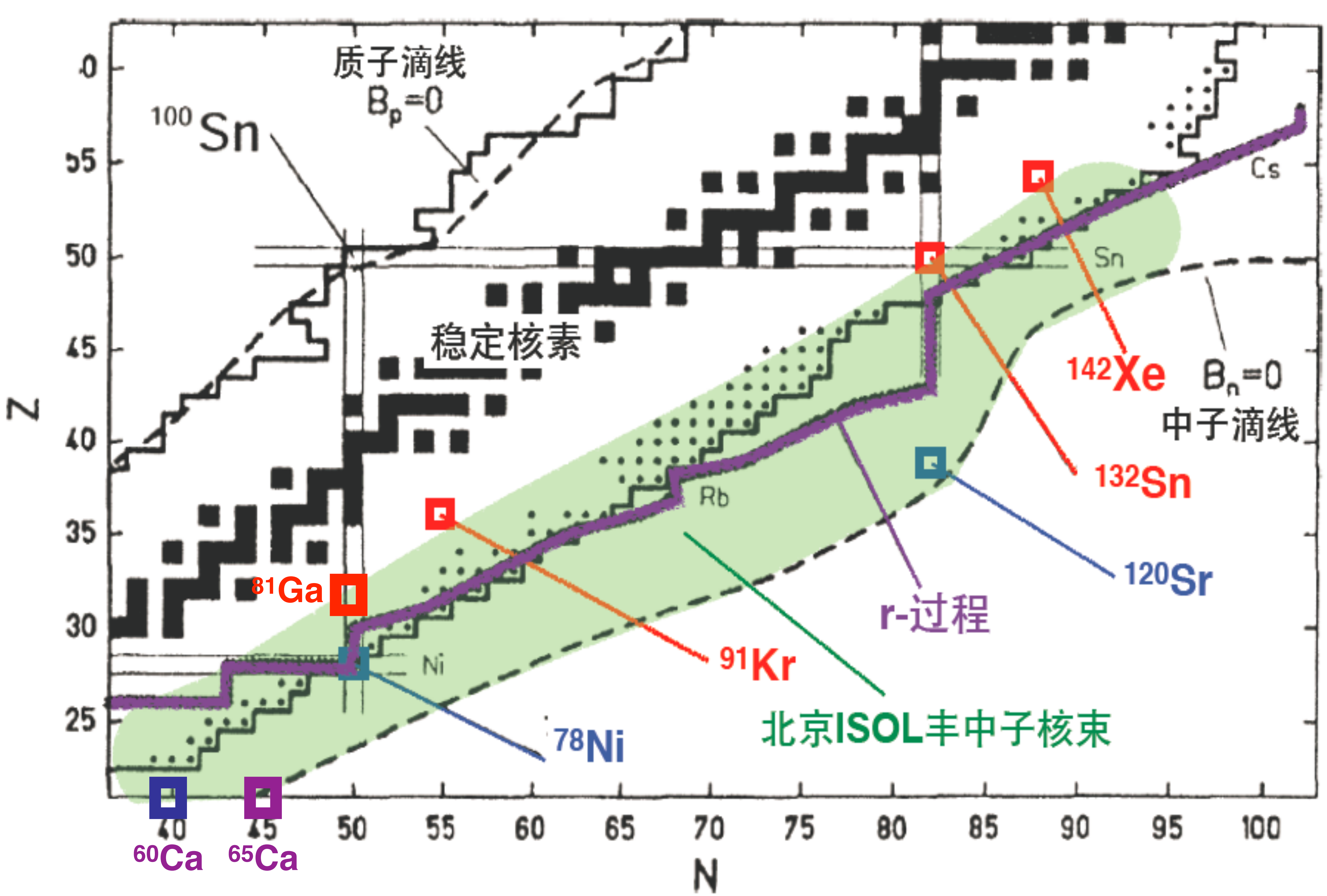
RIBF 2/week | BISOL 1/week

	BIGRIPS $^{70}Zn+Be \rightarrow ^{60}Ca$	BISOL $^{80}Zn+Be \rightarrow ^{66}Ca$
beam intensity (pps)	1.25×10^{12}	5.5×10^{7}
beam energy (MeV/u)	345	150
Be target (atom/cm2)	1.85×10^{23}	5.70×10^{22}
cross section (mb)	2.0×10^{-13}	1.0×10^{-8}
transport efficiency(%)	12	12
Count rate (pps)	5.5×10^{-6}	3.7×10^{-6}
time (hour)	99	100
Total counts	2	1.3

^{80}Zn ISOL ion source eff. 10%

$^{80}Zn+Be$—>^{66}Ca is assumed same with $^{70}Zn+Be$—>^{56}Ca

Reach new region



Comparison of highest fission rates of various facilities

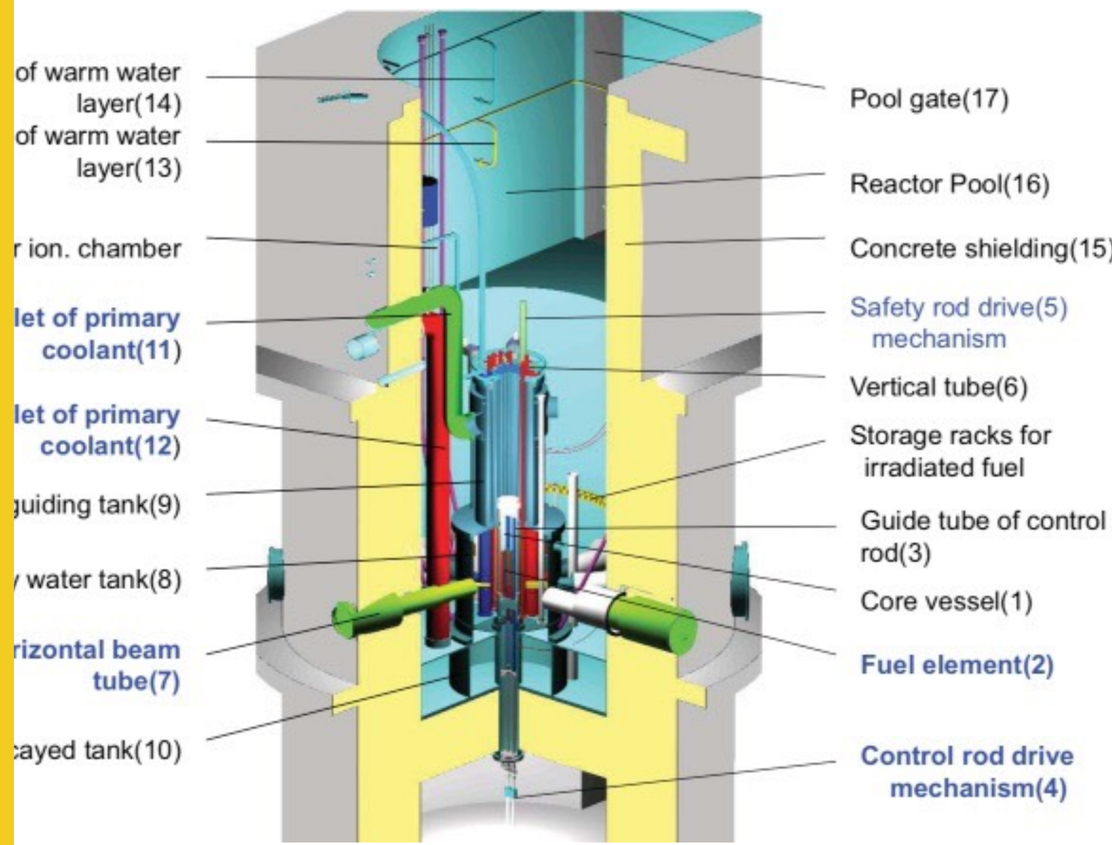
	BISOL Chain	CARIBU US	SPIRAL2 France	TRIUMF Canada	SCRIT Japan
status	plan	operation	construction	constrution	operation
fis/s	$2X10^{15}$	10^{9}	$1X10^{14}$	$5X10^{13}$	$2X10^{11}$
target	reactor, ^{235}U 5g	^{252}Cf fission	spallation ^{238}U 280g	photo fission	photo fission

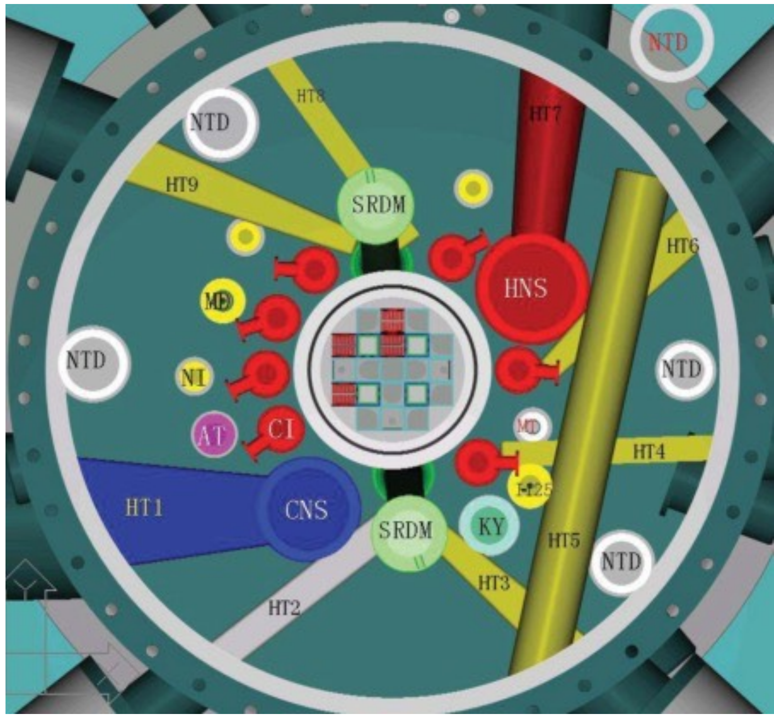
Comparison of relevant facilities in the world

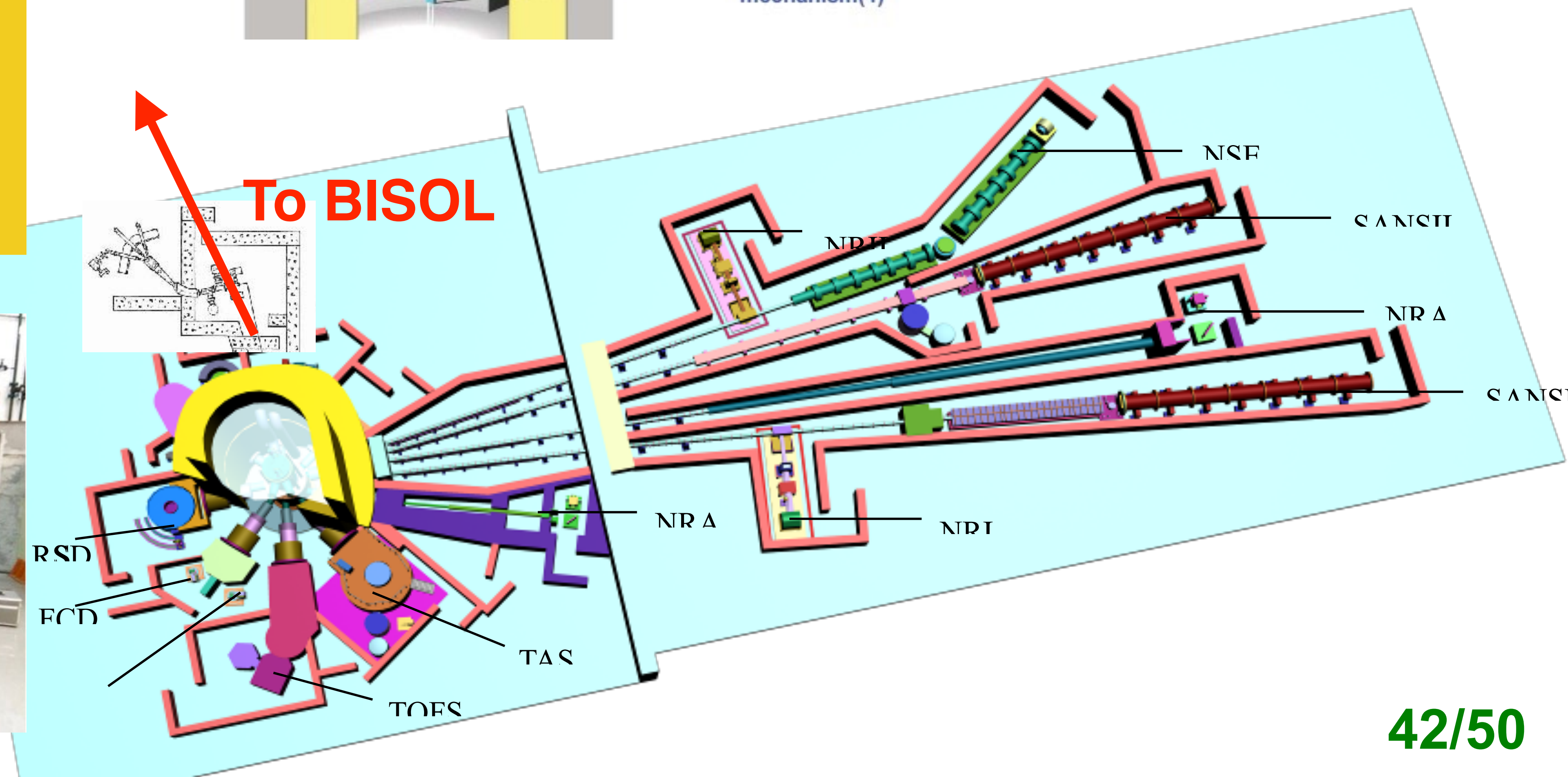
Facility Country	Beijing ISOL China	FRIB USA	RIBF Japan	FAIR Germany	EURISOL EU
Commission	2020+	2016	2009	2016	2025+
Budget(100M USD)	5	7	6	14	
^{91}Kr (pps)	4×10^{11}				3×10^{10}
^{132}Sn (pps)	7×10^{10}			1×10^{8}	9×10^{11}
^{78}Ni (pps)	400	150	10	10	20

China Advanced Research Reactor CARR

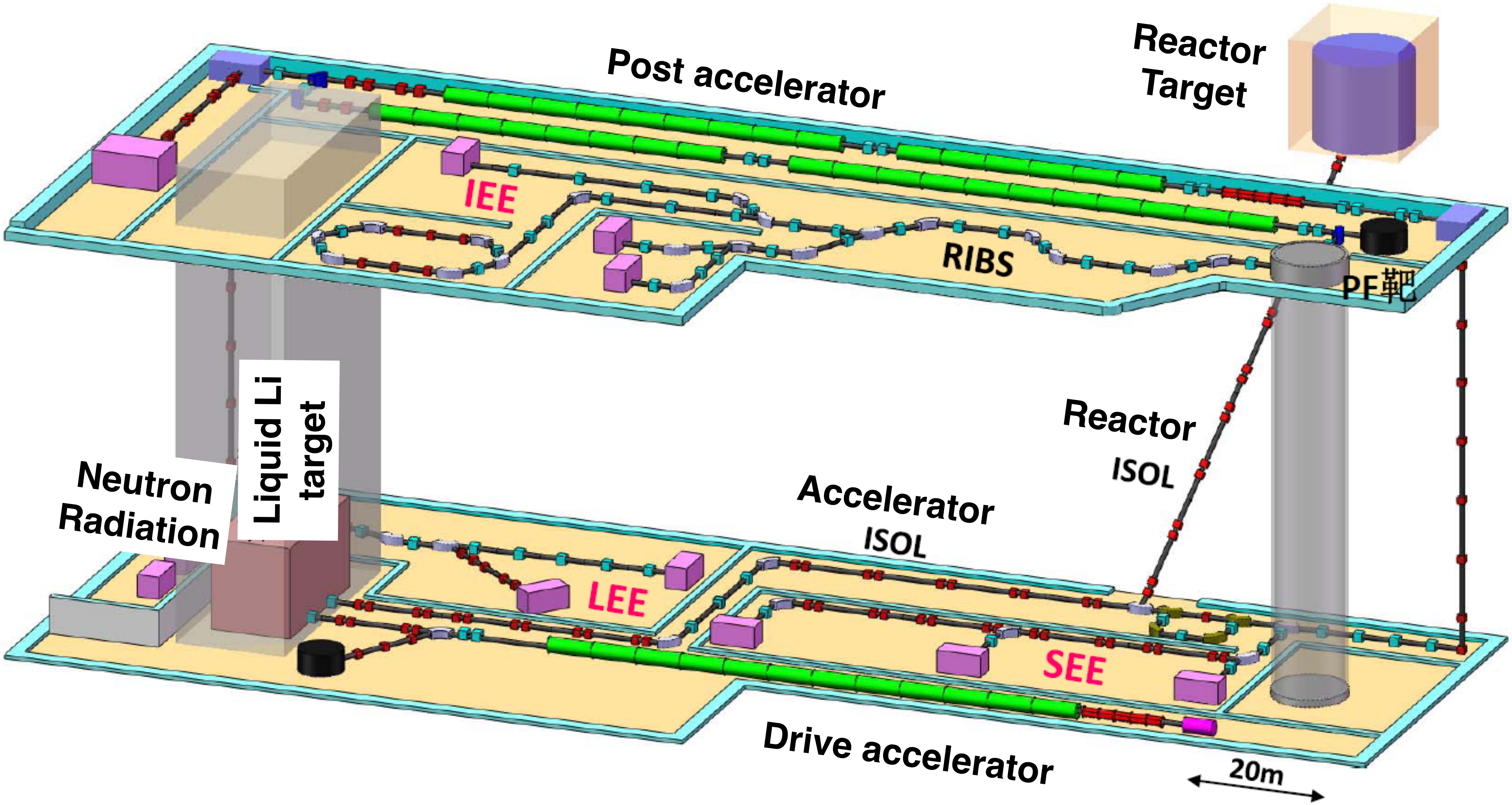
- Light water cooling, heavy water reflecting,
- 60MW, neutron flux to be 8×10^{14} n/cm$^2\cdot$s, one of the world level
- Engineering started in 2002
- Civil engineering finished in 2005
- Reactor core finished in 2007
- First critical in 2010
- Full power in 2012
- ^{138}Cs fission ISOL extracted 2013
- Cold neutron source 2017
- 30 days continuous operation in 30 MW in 2018



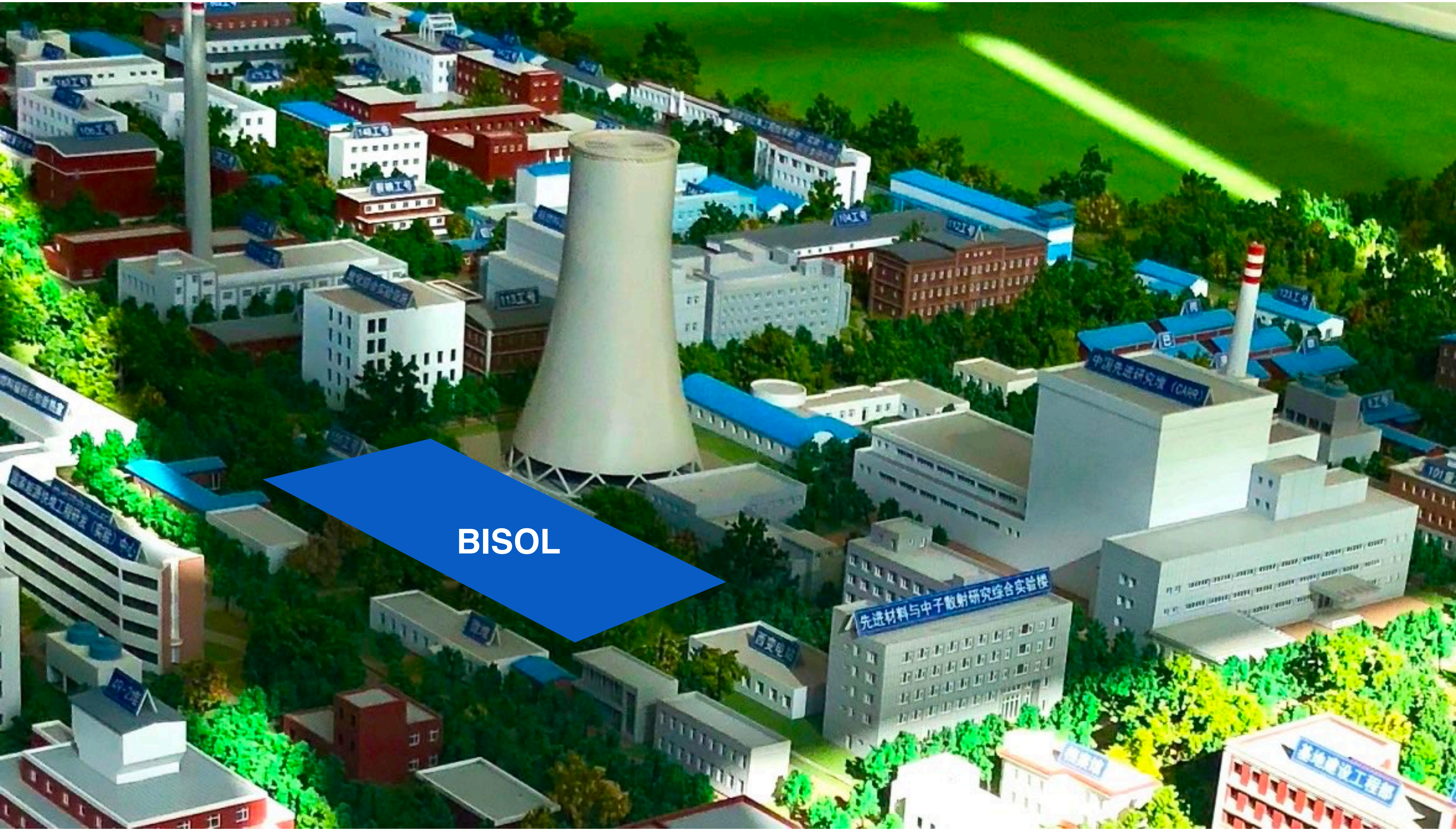




Components layout in details



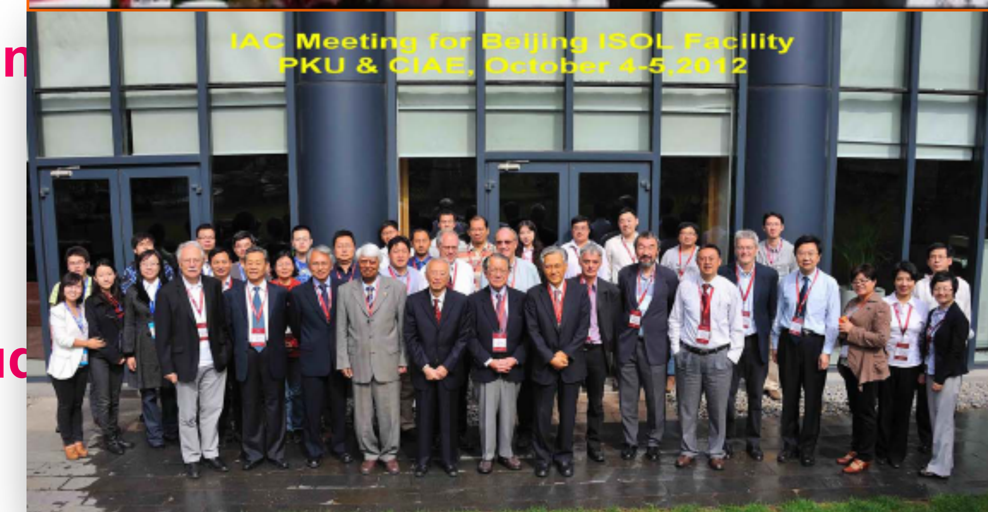
From Y. L. Ye



中国先进研究堆（CARR）
BISOL
先进材料与中子散射研究综合实验楼

BisoL Milestones

- 2011, CIAE-PKU MOU
- 2012, IAC Review Beijing
  - as excellent and highly competitive on the world level. It promises a unique science reach in several respects
  - in particular with regard to the most neutron rich exotic nuclei and the study of the astrophysical r-process
- 2016, national large-scale science facilities selected BISOL as candidate facilities
- 2017, IAC meeting for high-power target; 1st BISOL user meeting, with ～150 participants and very active discussions;BISOL-CD-1 ready



特 急

国家发展和改革委员会
教育部
科学技术部
财政部
中国科学院
中国工程院
国家自然科学基金委员会
国家国防科技工业局
中央军委装备发展部
文件

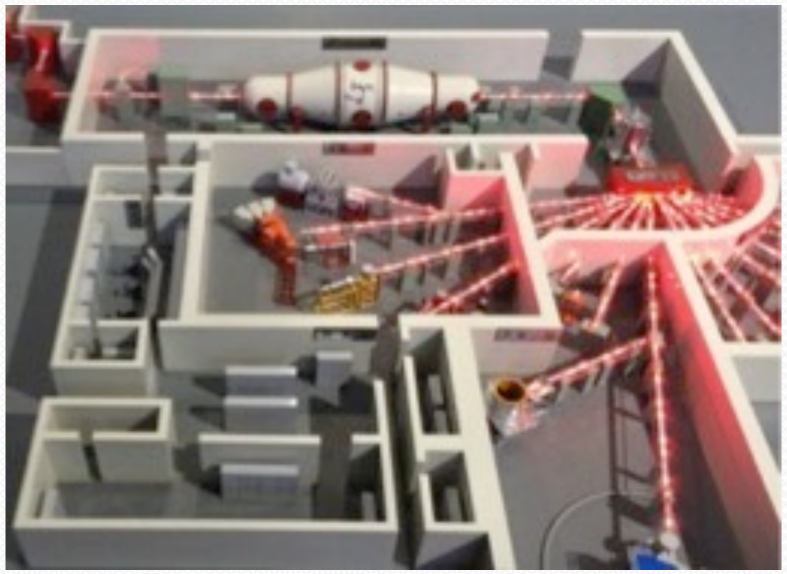
发改高技〔2016〕2736 号

关于印发国家重大科技基础设施建设
“十三五”规划的通知

（二）深化后备项目的筹备论证。对科学意义重大、国家需求强烈、抢占科技创新制高点、预先研究较为充分并纳入综合评审的设施，加强对其设施属性、建设紧迫性、科学目标、工程目标、技术风险等的深化论证，开展国内外同类设施的对比分析，逐步形成成熟的设施建设方案。按照设施建设紧迫性、方案成熟度和财力保障状况，适时启动若干筹备论证充分的设施建设工作。“十三五”期间，设施筹备论证的后备项目包括：北京在线同位素分离丰中子束流装置，中国陆地生态系统观测实验网络，生物医学大数据基础设施，作物表型组学研究设施，大气环境模拟系统等纳入专家综合评

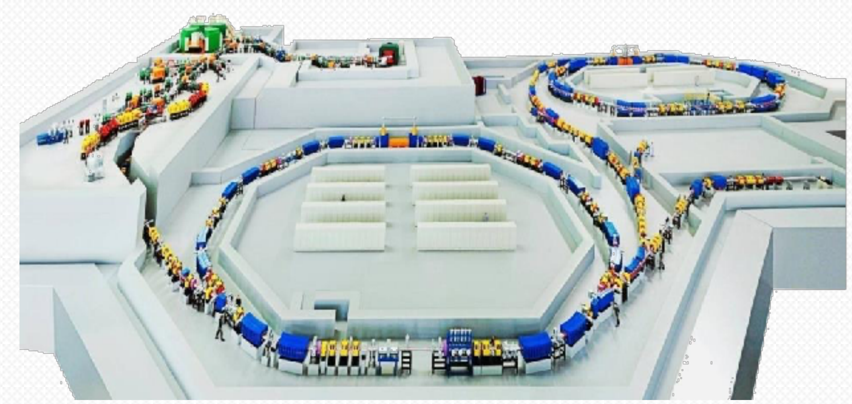
Part of Nuclear physics road map in China

1986
Beijing Tandem **HI-13**

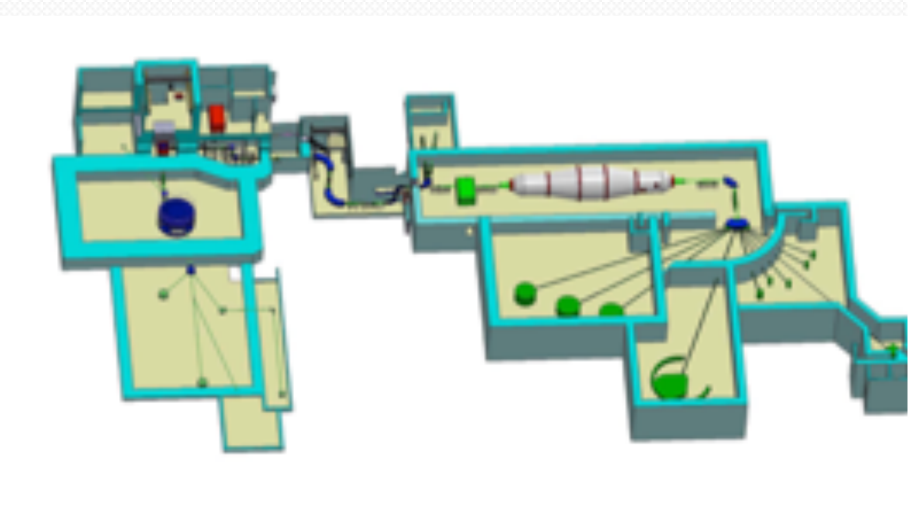


1988
Lanzhou cyclotron **SSC**

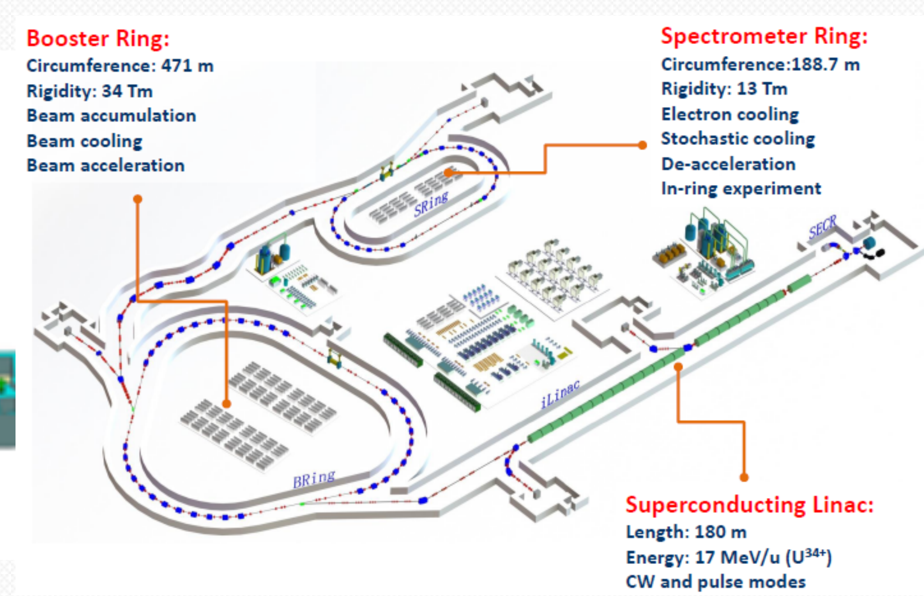
2008
Lanzhou storage ring **CSR**



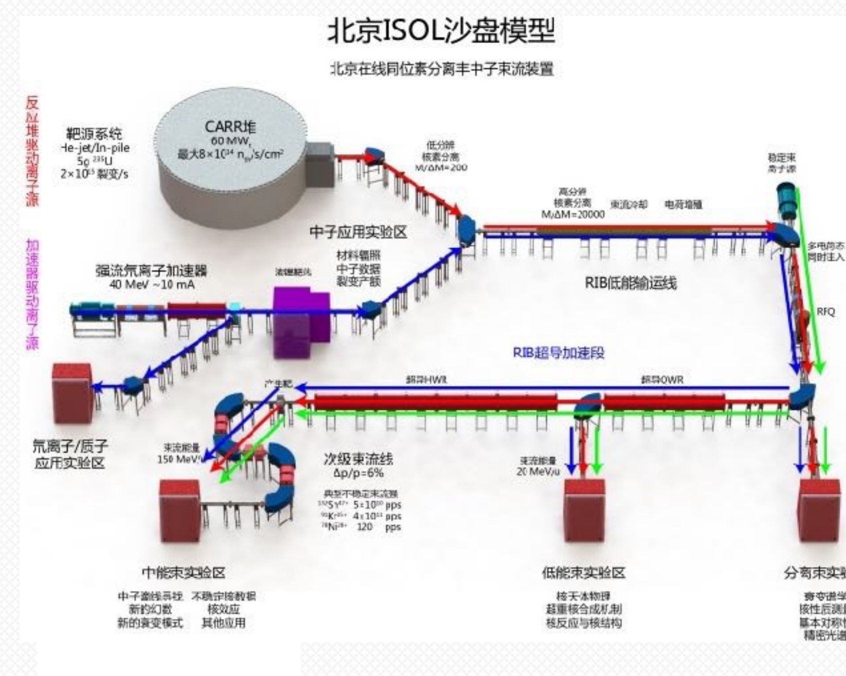
2014
Beijing **BRIF**



～2022+
Huizhou **HIAF**



～2026+
Beijing ISOL



BISOL in the world

Accelerators for Nuclear Physics in the World					
	Beams	Asia	Europe	America	Comments
Hot QCD	A+A	--	LHC(ALICE) FAIR(SIS300) NICA	RHIC	Missing Asian? J-PARC-HI for dense matter?
Cold QCD	hadron	J-PARC+Hdex HIRFL+HIAF	FAIR(SIS100)	--	Missing American?
	e-	Spring8 (LEPS) ELPH	MAMI	JLAB-12GeV	1+many
	collider	BES-III Belle-II	NICA	eRHIC eIC	1 in the world?
Many body Problem (RI Beam)	PF	RIBF+upgrade HIRFL+HIAF	GSI/FAIR	FRIB	Good competitions!!
	Both	RISP			
	ISOL	BRIF RIB-ANURIB HIAF+CiADS?	SPIRAL2 SPES HIE-ISOLDE	ARIEL-II	
	Super ISOL	Beijing- ISOL	EURISOL	--	FRIB upgrade for US?
(High Resolution)	Pol proton	RCNP RC	KVI	Texas A&M	iThemba (South Africa)

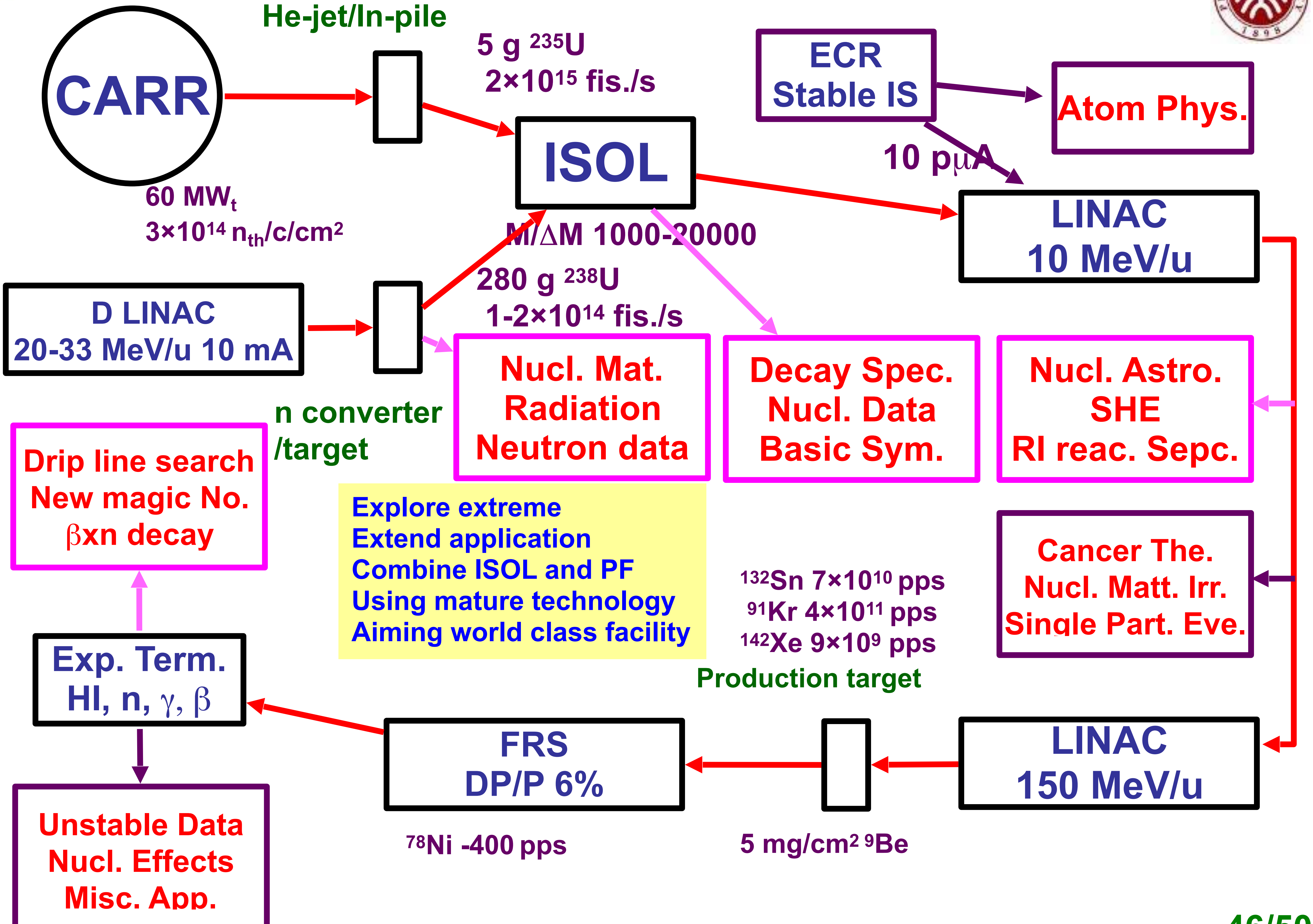
From Kazuhiro Tanaka

ANPhA chair , Japanese Nuclear Physics Executive Committee and KEK

What in my talk

- Physics frontier
- World facilities
- BRIF progress
- BISOL design
- Conclusion

Beijing ISOL output



Summary

- n-rich region is a rich play ground for nuclear frontier
- Current facilities still far from the limit
- BISOL uses double driver and two step ISOL+PF, and would result the extremely neutron-rich beam, with intensity by 1-2 order higher than current and coming facilities
- Wish to have your great suggestions and comments; your support is most important!