缪子束加速和对撞技术及其应用论坛

中科院理论物理所/北京

16/04/2022

基于惠州核中心的缪子研究

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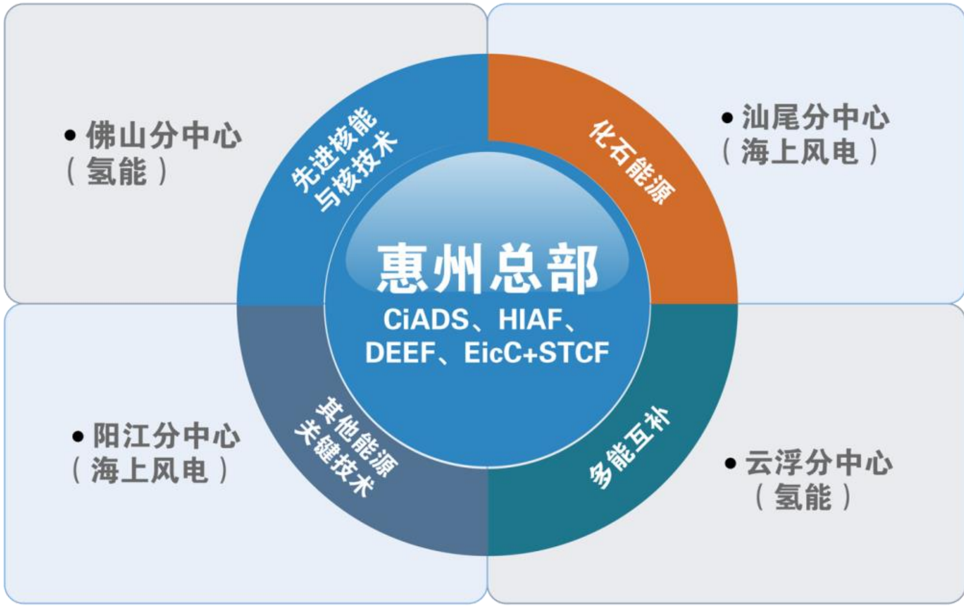
报告提纲

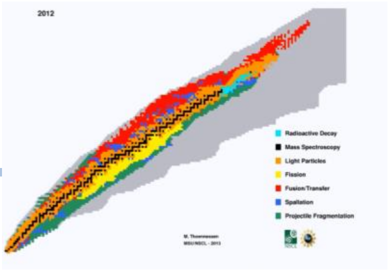
- 惠州核中心大科学装置
  - 惠州核中心简介
  - HIAF进展
  - CIADS进展

核研究中心简介

- 国家十二五重大科技基础设施：
  - 强流重离子加速器装置(HIAF)
  - 加速器驱动嬗变实验装置(CiADS)
- 广东省先进能源(东江)实验室
  - 2019年底挂牌启动
  - 引进12个相关团队
- 主要依托单位：
  - 中科院近代物理研究所
- 主要合作单位(已参与)：
  - 中科院：>10研究院所
  - 大学：＞6家
  - 企业：中核、中广核…
  - 其它



HIAF项目批复概要



➢ 科学目标：

- **研究原子核内有效相互作用：** 研究原子核壳层结构在非稳定核区的系统演变、奇特原子核结构和反应机制，探索核内有效相互作用的新形式，发展和完善核理论模型
- **探索宇宙中从铁到铀重元素的来源：** 精确测量丰中子核素的质量、寿命及反应率，探索快中子俘获核合成的路径、时间标度和物理环境

➢ 工程建设目标

- 一台国际领先水平的重离子加速器综合研究装置，具备产生极端远离稳定线核素的能力；
- 能提供高流强的中低能长脉冲重离子束流、产生高功率的短脉冲高能重离子束团；
- 为鉴别新核素扩展核素版图、研究弱束核结构和反应机制、特别是精确测量远离稳定线短寿命原子核质量提供国际领先的研究条件

强流重离子加速器装置 (HIAF)

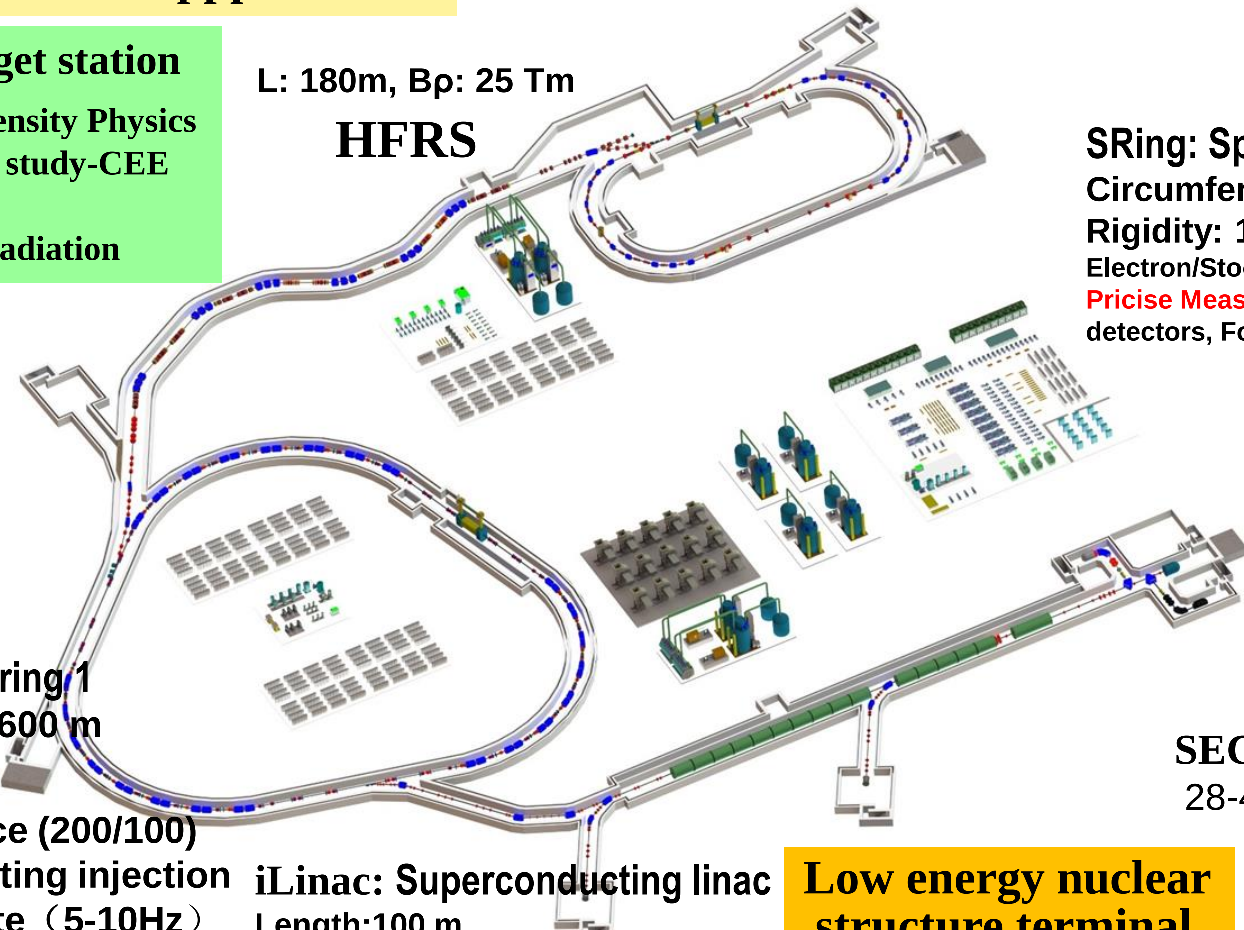
0.8 AGeV, 3×10^{10}ppp $^{238}U^{35+}$
1.75AGeV, 7.5×10^{10}ppp $^{78}Kr^{19+}$
3.0AGeV, 1.0×10^{11}ppp $^{16}O^{6+}$

HIAF-I: 2018-2025

Budget: 1.62(国家)+1.175(广东) B CNY

External target station

- High Energy Density Physics
- Nuclear Matter study-CEE
- Hypernuclear
- High energy irradiation



L: 180m, Bρ: 25 Tm

HFRS

SRing: Spectrometer ring
Circumference: 273m
Rigidity: 15 Tm
Electron/Stochastic cooling
Pricise Measurement by Two TOF detectors, Four operation modes

BRing1: Booster ring 1
Circumference: 600 m
Rigidity: 34 Tm

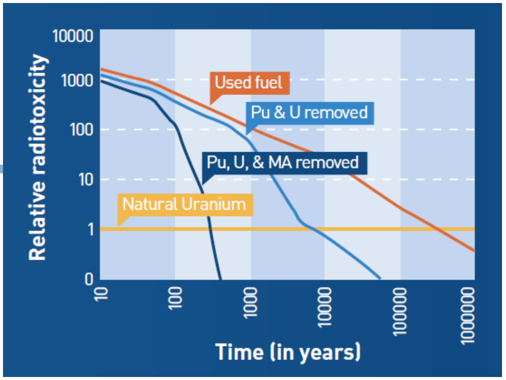
Large acceptance (200/100)
Two planes painting injection
Fast ramping rate（5-10Hz）

iLinac: Superconducting linac
Length:100 m
Energy: 17/22 MeV/u($U^{35+/45+}$)

Low energy nuclear structure terminal

SECRAL and FECR
28-45GHz,1.0emA(U^{35+})

CIADS项目批复概要



- **科学目标：**
  - 深入探索核废料嬗变过程中的科学问题
  - 突破系列核心关键技术：研究加速器-散裂靶-反应堆耦合特性及加速器驱动嬗变嬗变研究性能，检验系统稳定性核可靠性
  - 次锕系元素嬗变原理性实验等、具有自主知识产权的加速器驱动嬗变系统软件研究，为建设加速器驱动嬗变工业示范奠定基础
- **工程建设目标**
  - 强流质子直线加速器系统(250/500MeV&10/5mA)
  - 高功率散裂靶靶及其与反应堆耦合系统(2.5MW)
  - 次临界快中子反应堆系统(10MW含束流功率)，并进行联调联试
  - 相关建安工程及配套设施

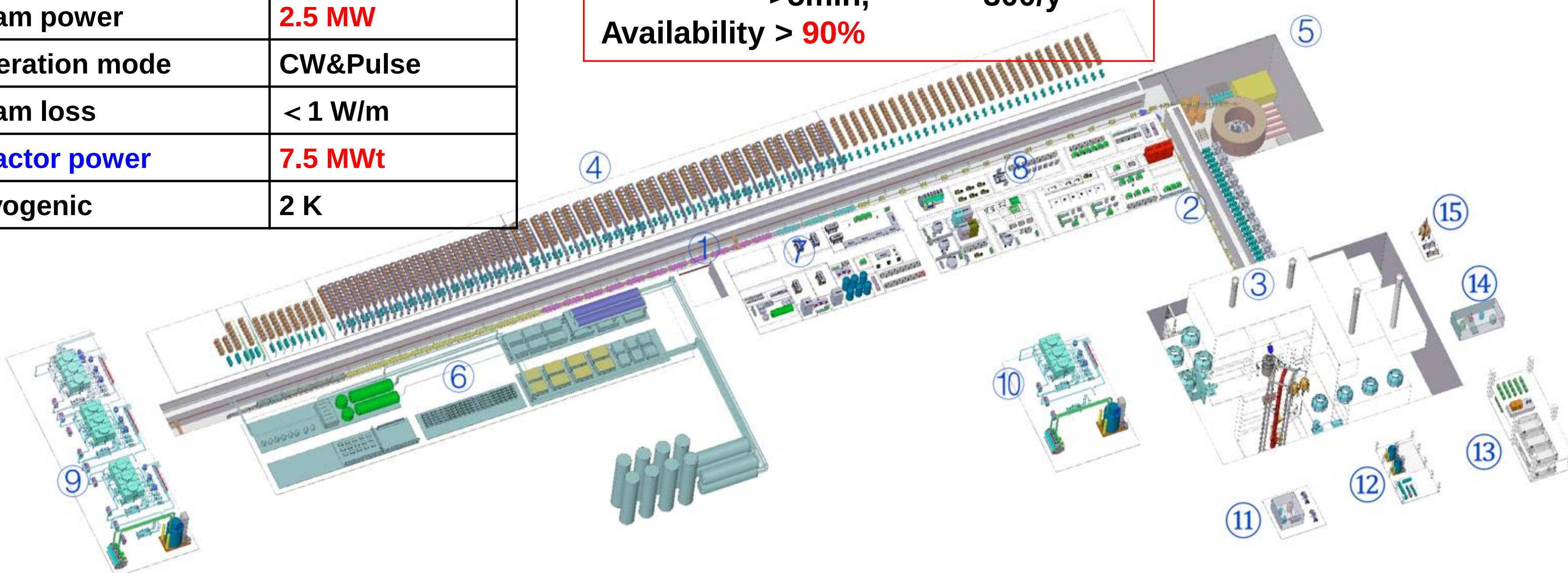
Chinese initial ADS (CiADS 2021-2027)

Design Particle	proton
Energy	500 (250) MeV
Beam current	5 (10) mA
Beam power	2.5 MW
Operation mode	CW&Pulse
Beam loss	＜1 W/m
Reactor power	7.5 MWt
Cryogenic	2 K

Beam trips goal:

<10s,	-
10s～5min,	2500/y
>5min,	300/y

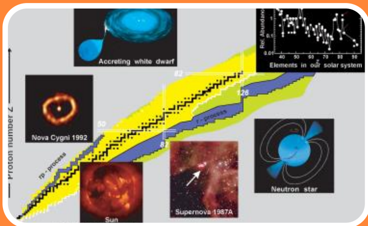
Availability > 90%



① SC linac
② Coupling transport
③ Target and reactor hall
④ Accelerator equ. hall
⑤ Beam dump and granular target exp.
⑥ Cryogenic plant
⑦ SRF hall

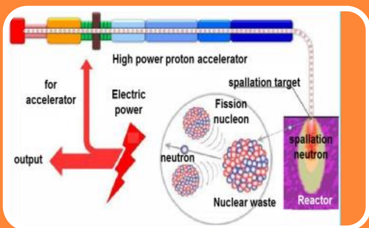
Funding: 1.8(国拨) + 1.175(广东) + 1.0(中核) CNY

核中心主要研究领域（基于强流加速器）



核科学

- 核物理：*<u>核结构</u>*，*<u>核天体</u>*；核物质，*<u>强子物理</u>*
- 基础物理：超高电场QED，*<u>高能量密度（HEDP）</u>* → *<u>重离子惯性聚变</u>*
- *高亮度前沿：μ、k、反质子、中微子（β束）、EIcC，超标准模型…*



能源及相关材料

- *CIADS →ADANES燃烧器：燃烧=嬗变+增值(殖)+产能，燃料循环*
- *核燃料研究：裂变嬗变元件、再生乏燃料、贵重同位素，<u>聚变燃料自持</u>*
- *关键核材料：高通量裂变、聚变堆芯材料、包壳材料、冷却材料*

放射生物医疗

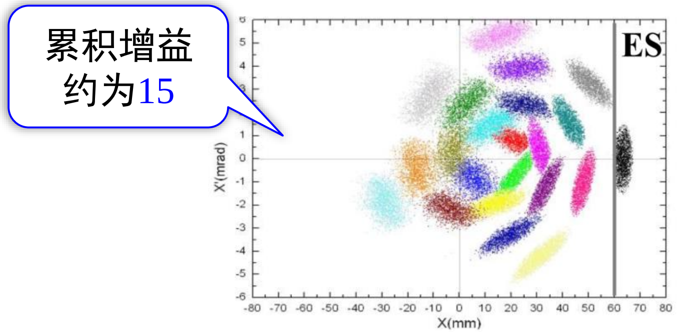
- <u>离子束治癌</u>：定型肿瘤(重离子外辐照)治疗，*<u>β^+束敏感器官外辐照</u>*
- *<u>靶向放药</u>：无定型及轻度扩散肿瘤（α、β带电粒子内辐照）治疗*
- 辐照变异新药研制，辐照诱变育种

核技术应用 → *<u>μ 成像</u>*

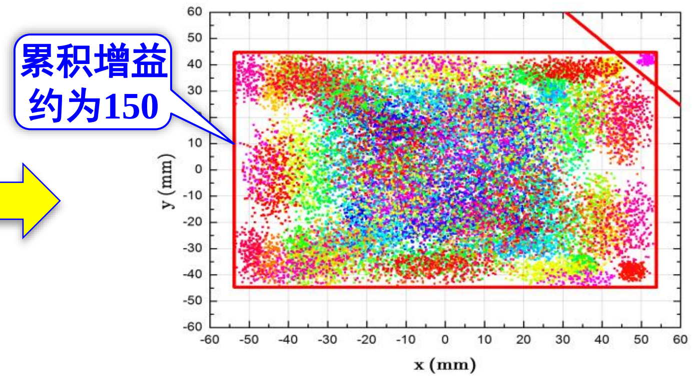
- 加速器：强流加速器制作（核能、量产同位素）；
- 辐射技术：器件加固、核孔膜制作，辐射消毒、保鲜，等
- 探测技术：高灵敏探测器制作

HIAF主要进展：先进性-1

原创基于 Corner Septum 4 维相空间束流涂抹累积方案，充分利用垂直相空间，将重离子累积增益提高10倍，达国际最高脉冲流强



多圈注入方案-2 维相空

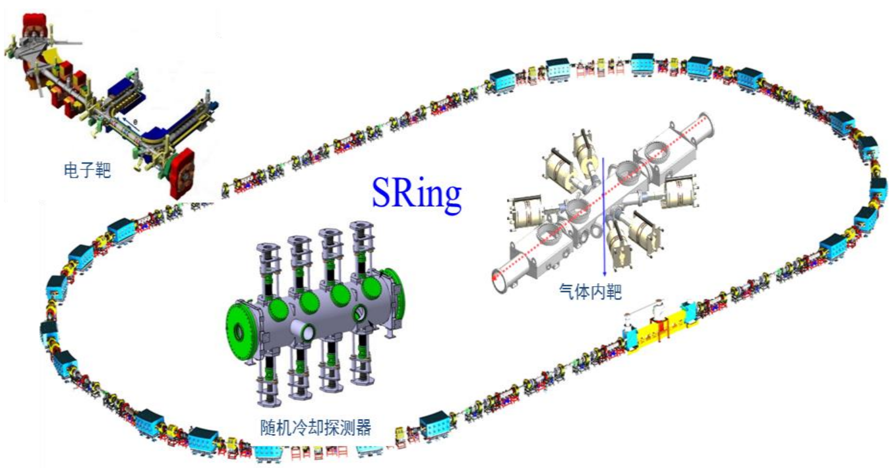


4 维相空间Painting方案

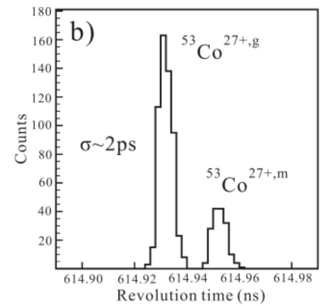
实验室	装置	设计流强	达到流强	离子	重复频率
BNL	AGS Booster		5×10^{9}	Au^{32+}	
JINR	NICA Booster	4×10^{9}		Au^{32+}	
GSI	SIS18	1.0×10^{11}	3×10^{10}	U^{28+}	2.7Hz
FAIR	SIS100	4.0×10^{11}		U^{28+}	
IMP	HIAF-Sring	$5/20\times10^{11}$		$U/Bi^{(35-45)+}$	≥ 5Hz, 10-20Hz
IMP	HIAF-BRing -SRing	$1/5\times10^{12}$ $2/12\times10^{12}$		$U/Bi^{(35-45)+}$	

HIAF主要进展：先进性-2

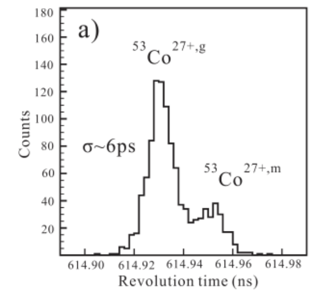
国际精度最高多功能短寿命原子核质量测量谱仪→10^{-8}



在HIRFL-CSRe实现世界首个双TOF等时性核质量谱仪测量精度达10^{-7}，为世界同类装置最高

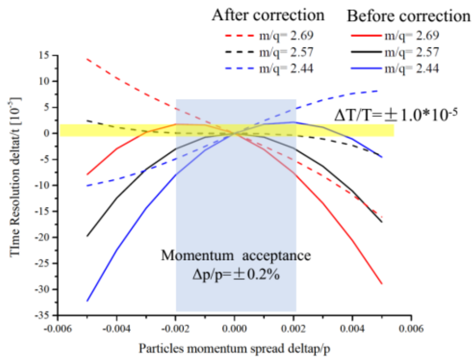


兰州CSRe



德国ESR

- **HIAF-SRing**
  - 打靶流强提高4-5个量级，产额大幅提高，提高统计精度
  - 增大TOF距离，减小测量误差
  - 采用对称光学，降低系统误差
  - 大动量接收度ΔP~2.5%



$\Delta M/M \sim 10^{-8}$

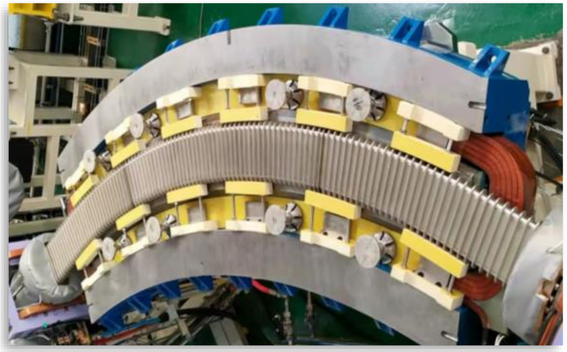
国际短寿命核质量精度最高

HIAF主要进展：创新技术应用验证

➢ 空间环境地面模拟装置：H(300MeV)-Bi(7MeV/A)同步环

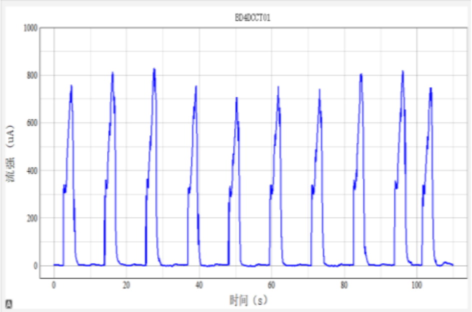
➢ 低能重离子要求：

- 真空~10^{-12}mbar→薄壁真空室
- 快积累快注入→磁合金高频腔
- 动力学导向的束流精准控制软件
- 数字孪生设计、安装与调试

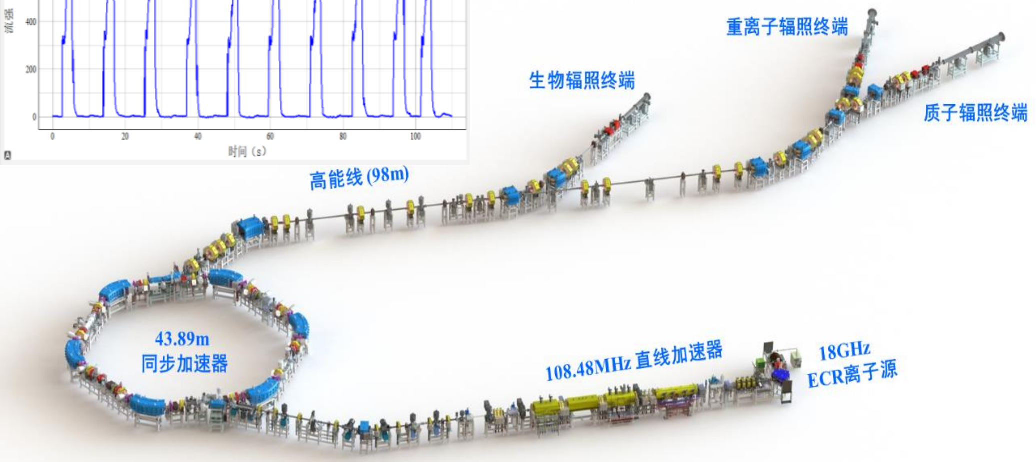


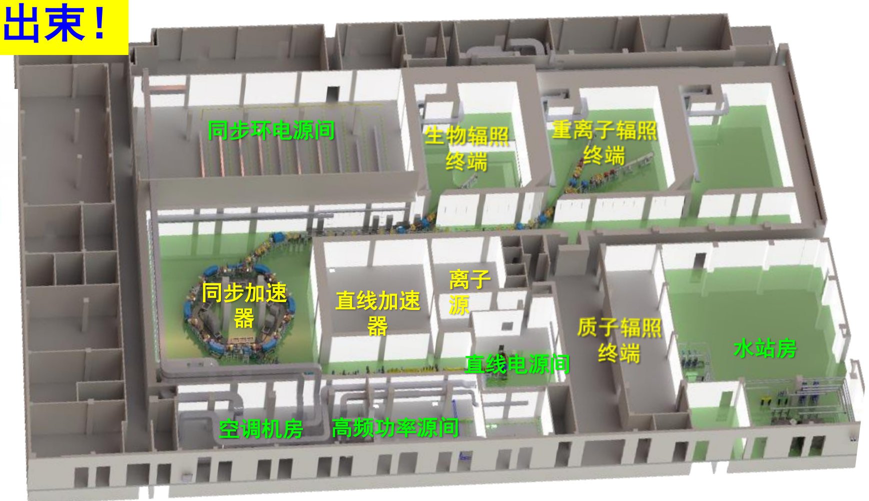
二极铁薄壁弧形真空室

高梯度磁合金环



4个月安装调试，束调一天出束！





BIM建筑设备数字装配→准数字孪生

CiADS的进展

- CiADS于2021.7开工，建设周期6年
- 按环保局批复工程建设分3阶段
  ① 2025.12 超导直线：>25kW
  ② 2026.10 高功率散裂靶：>1.0 n/p
  ③ 2027.12束流及靶功率：>250kW，堆芯~30kW，稳定运行>1小时

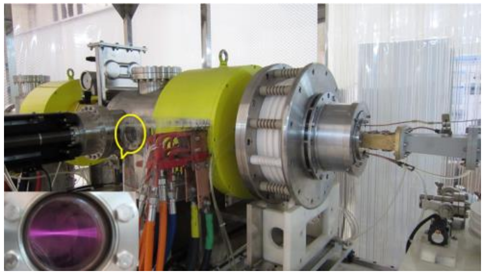
- 低温系统进展

运行模式	热负载（2 K工作模式）		
	2K heat load [W]	4.5-75 K heat load [W]	50-75K heat load [W]
名义值	**4400**	**4300**	**13500**

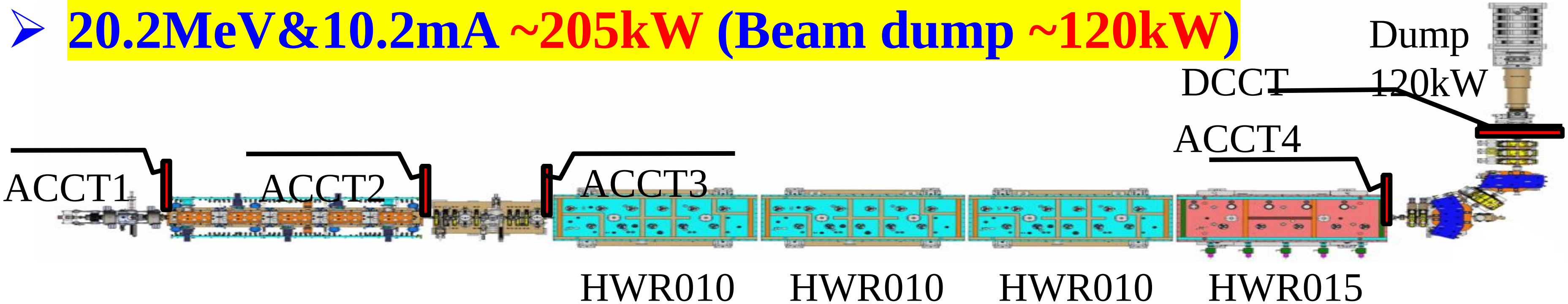
运行模式	热负载（2 K待机模式）		
	2K heat load [W]	4.5-75 K heat load [W]	50-75K heat load [W]
名义值	1800	1400	7000

运行模式	热负载（4.5 K待机模式）		
	2K heat load [W]	4.5-75 K heat load [W]	50-75K heat load [W]
名义值	1800	1400	7000

强流超导直线加速器样机

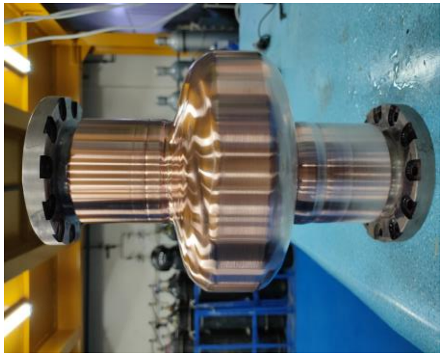


- **17.3MeV&7.3mA ~126kW, Availability ~ 93.6% (108hr) 3/2021**
- **17.3MeV&10.1mA ~174kW, Availability ~ 96.2% (12hr) 3/2021**
- **20.2MeV&10.2mA ~205kW (Beam dump ~120kW)**



面向RAMI的技术研发

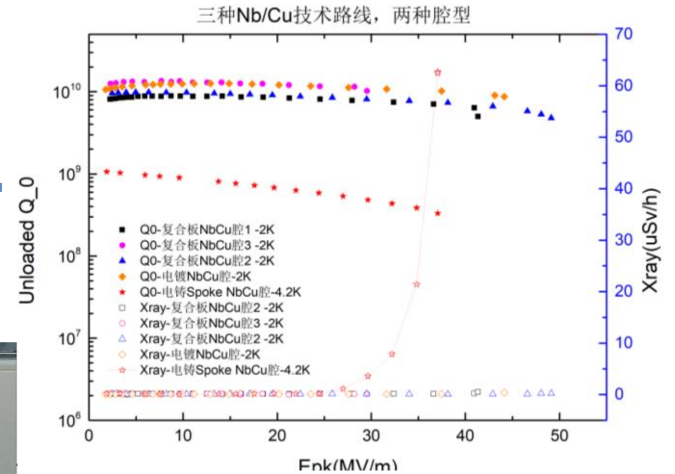
Nb/Cu 复合腔 （中低β）

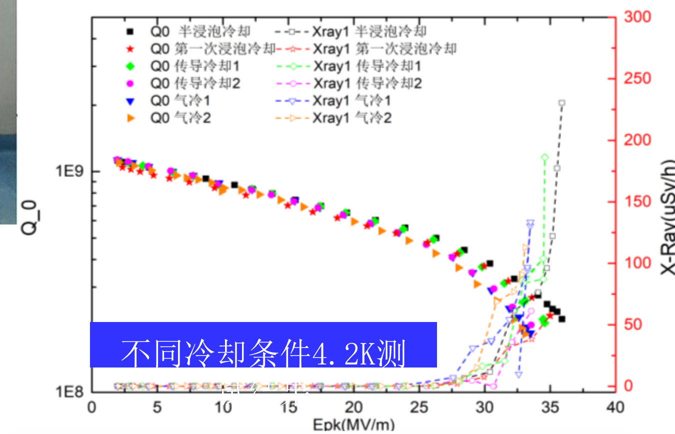


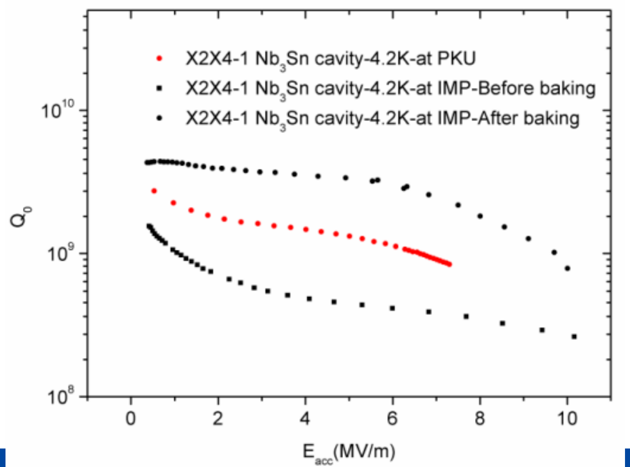

$Nb_3Sn/Nb/Cu$ 复合腔 （高β）

Nb_3Sn镀层进展：

- Q=$5e^9$@10MV/m
  4.2K冷却
- 2W，达到可应用性能







数字孪生设计、安装与调试平台

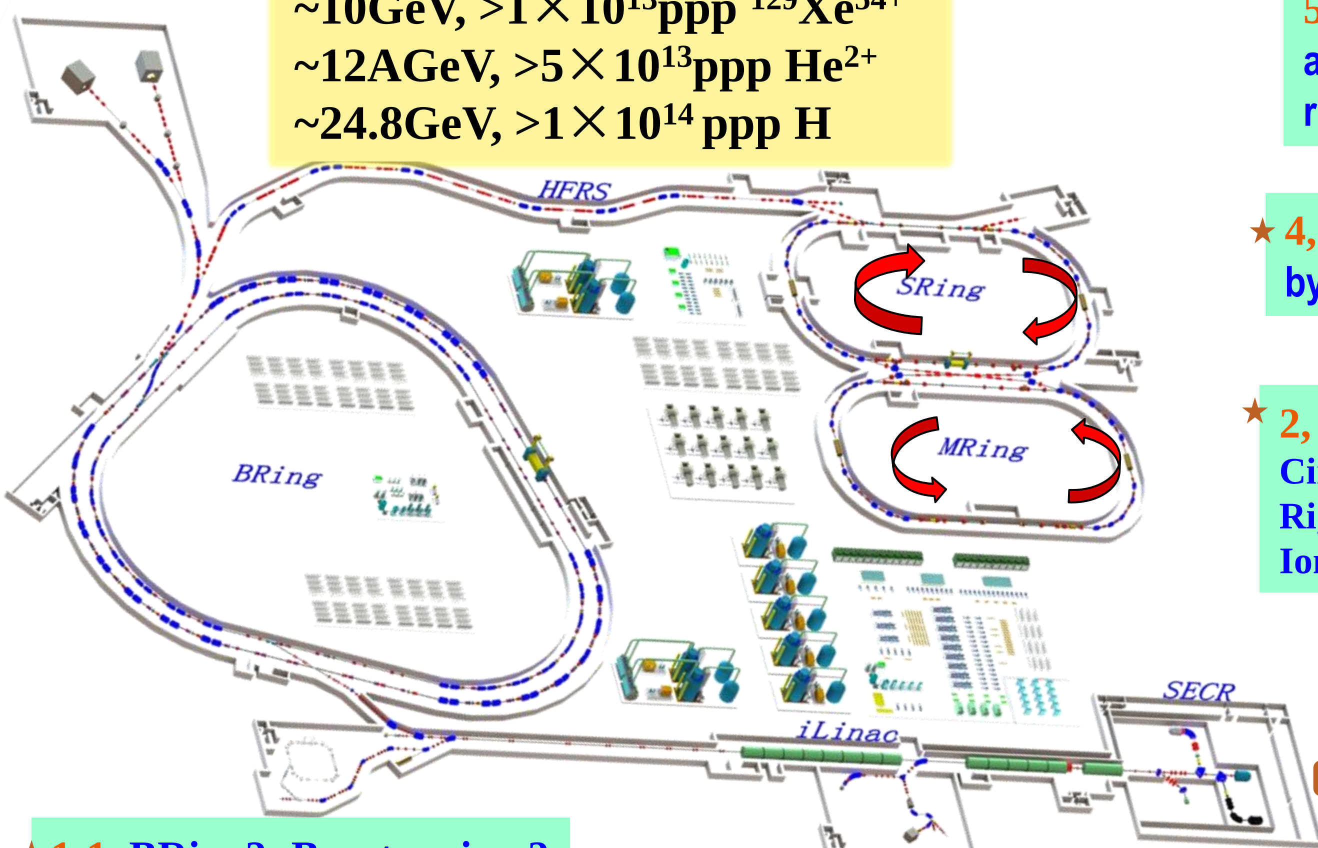
报告提纲

- 两大科学装置缪子束研究及优化
  - HIAF上缪子束研究及优化
  - CiADS上缪子束研究及优化

HIAF-CIADS Update

E_{B2}: >9AGeV, 1×10^{12}ppp U^{92+}
~10GeV, >1×10^{13}ppp $^{129}Xe^{54+}$
~12AGeV, >5×10^{13}ppp He^{2+}
~24.8GeV, >1×10^{14} ppp H

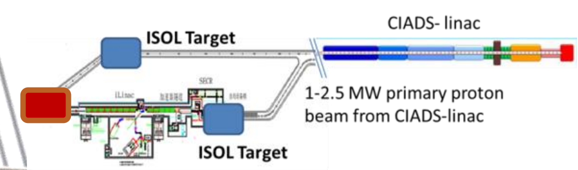
HIAF-U



5, + Polarized e, h beam and inject to Figure "8" ring → EIcC-1

★ 4, Pion, Muon…2nd beam by Intense ion beams

★ 2, MRing: Double rings
Circumference: 273m
Rigidity: 15/>30 Tm
Ion-ion merging

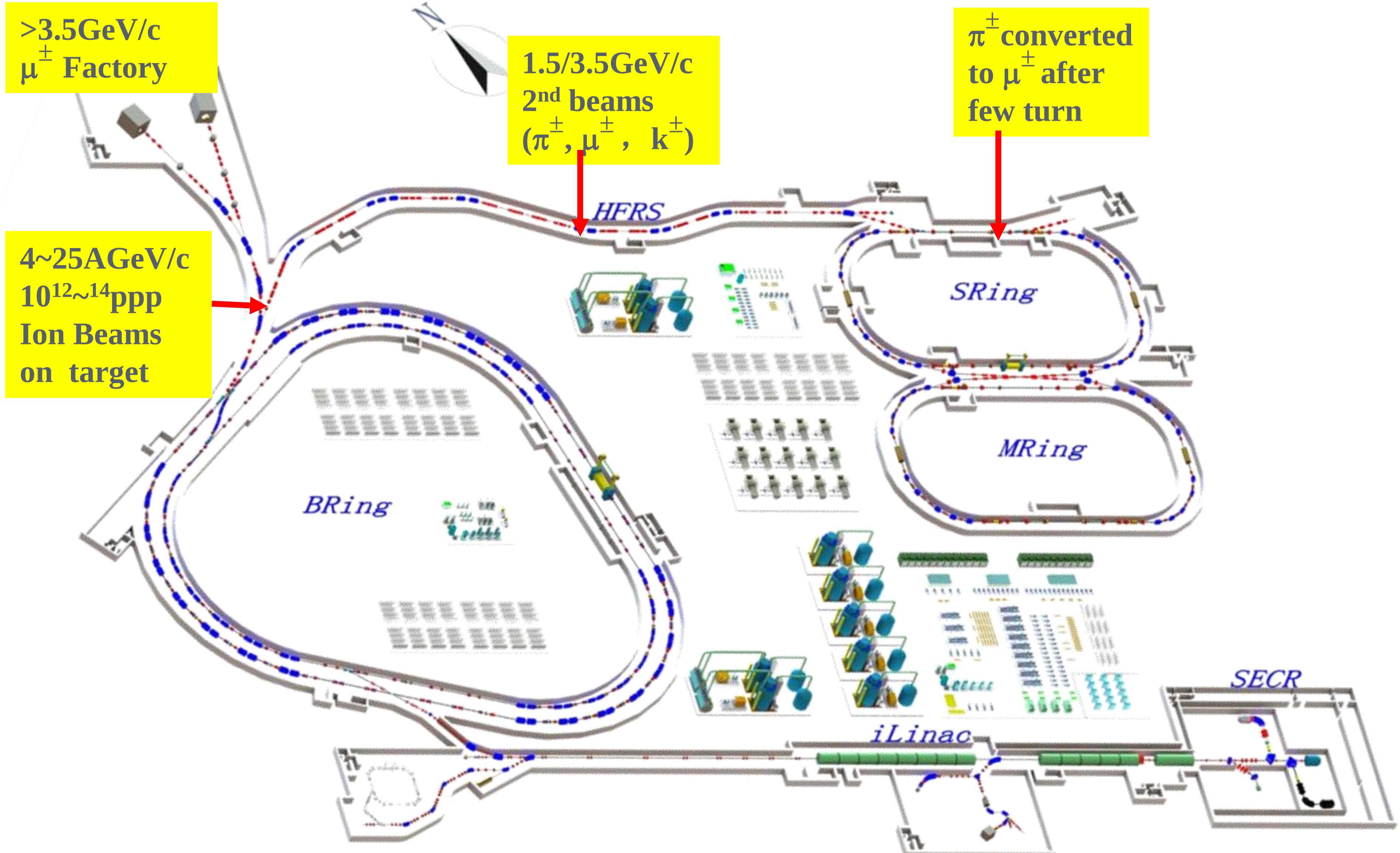


★ 1-1, BRing2: Booster ring 2
Circumference: 600 m
Rigidity: 86 Tm（T_{max}<3.6T）
Beam stacking
Superconducting

★ 1-0, iLinac: Superconducting linac
Energy: 100~150 MeV/u($U^{46+\sim54+}$)

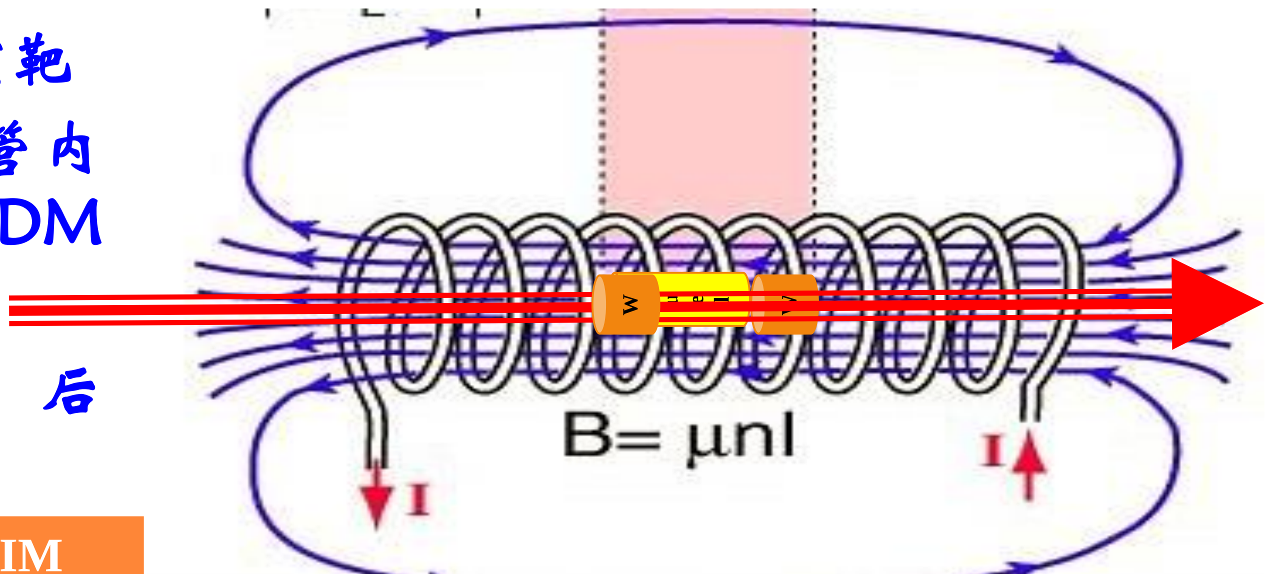
★3, ISOL RIB/β/μ beam
HIAF+CIADS linac

HIAF: In-Flight Muon Beam → Muon Factory

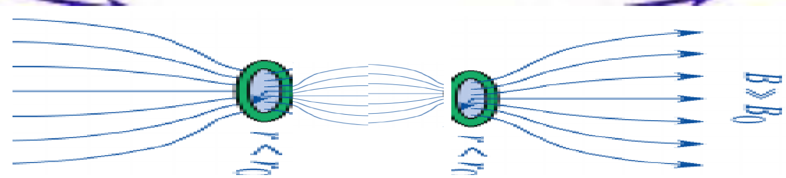


重离子驱动超强磁场μ束产生(HIM)

- In Flight 次级束束线接收度=ΔxΔx'
  - 缩小Δx可增大Δx'→即增大动量接收能力
- μ产生靶前后超强磁场 (→100T)
  - μ靶前后装W/Pb重靶
  - HI轰击超导螺线管内两端重靶产生HEDM→超强磁场
  - 前HI束产生磁场，后HI束产生μ

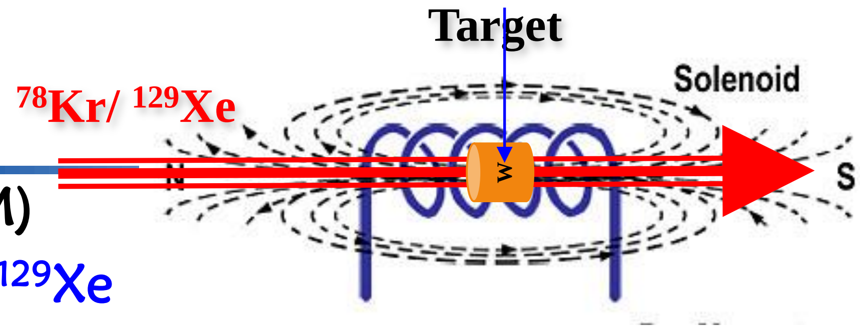


	Horn	HIM
约束模式	Z箍缩 (ϕ3mm)	Θ箍缩
典型峰值	~70kA(<10T)	→100T
使用寿命	不长	长

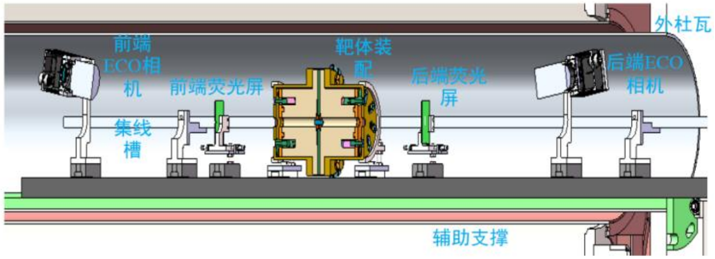


Magnetic Field Distribution

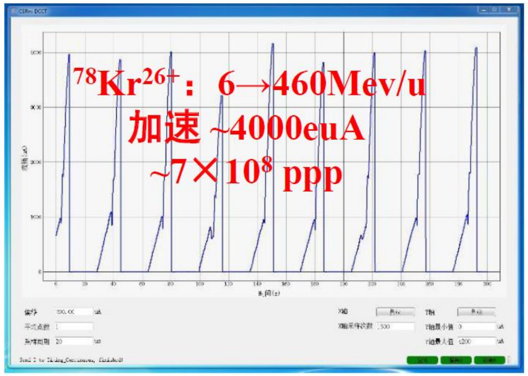
HIB驱动HEDM研究

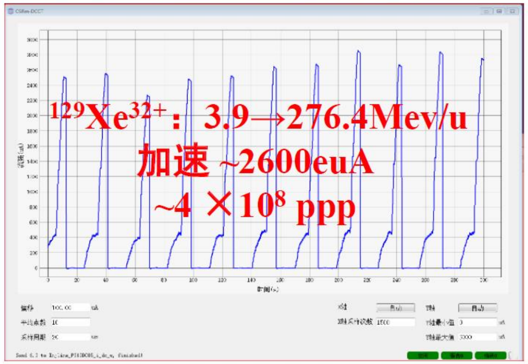


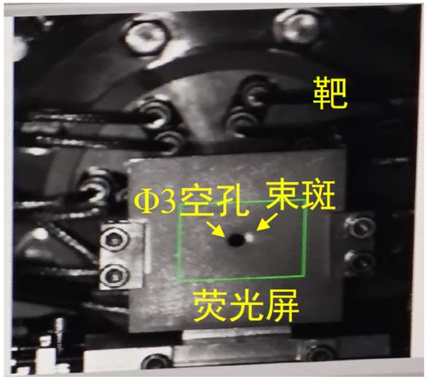
- 重离子束(HIB)驱动高能量密度物质(HEDM)
  - 实验：重离子束：4/2.28J (300ns) $^{78}Kr/^{129}Xe$
    → E_{hedm}<100J/300ns.cm³ $|_{Al}$, B≤6T
  - 结果：1,HEDM为特殊逆磁物质；2,磁导率μ_{HEDM}随E_{hedm}提高而减小；3,磁化HEDM吸取外磁场能量；4,韧致辐射随E_{hedm}提高而减小

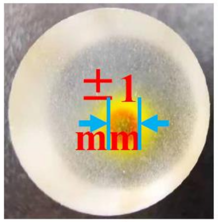


靶区设备布局

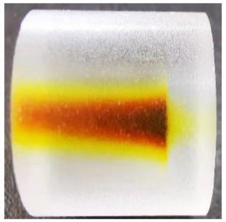




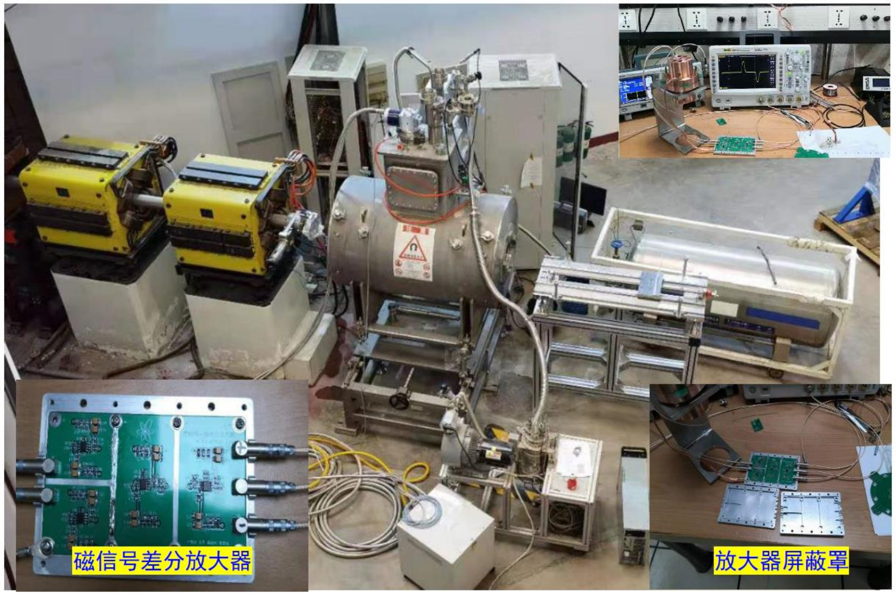




束斑尺寸



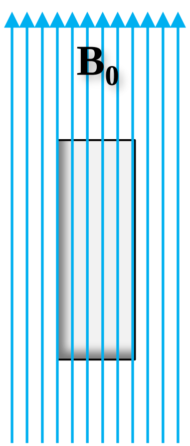
LiF中布拉格峰



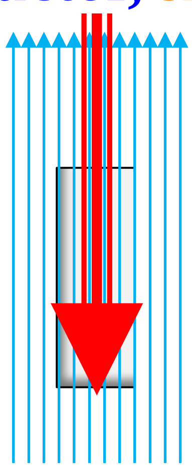
实验终端

HEDM magnetic Property

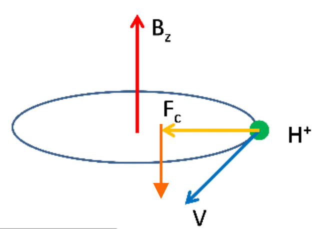
- **HEDM is Special Diamagnetism Matter**
  - **dense plasma (HEDM) driven by pulse HIB under magnetic field B_0**
  - **Magnetized HEDM is Magnetism Matter**
  - **Charged particle magnetic moment is opposite to $\vec{B}$ → Diamagnetism**
- **Magnetized HEDM take in energy from B_0 → $B_{tip} > B_{mp} > B_0$**
  - **Magnetic permeability μ_c is decreasing with E_{mp} increasing**
  - **Best conductor, similar as SC, but need B to maintain → take in flux ϕ**



Normal

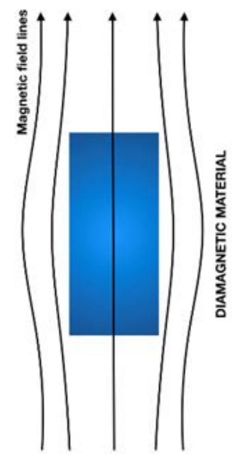


HI driven

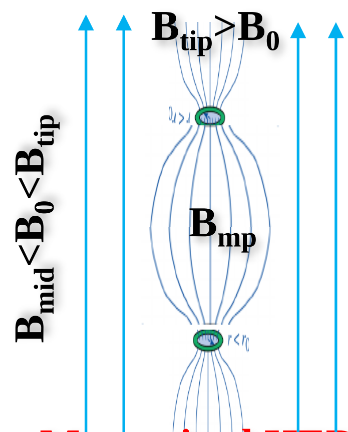


$$\frac{mv^2}{r} = qvB \Rightarrow \omega = \frac{v}{r} = \frac{qB}{m}$$

$\mu = - E_r/B$

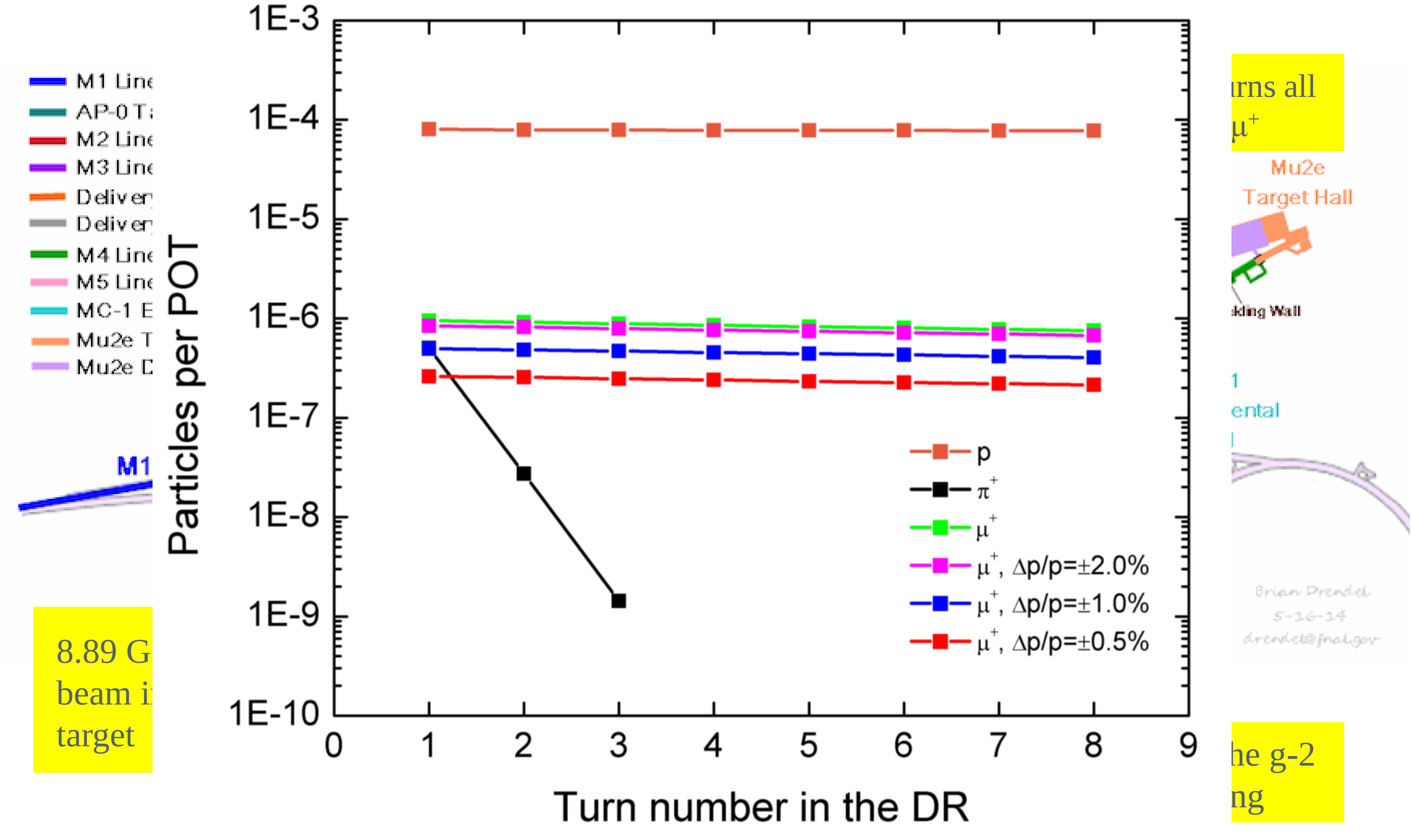


Diamanetism

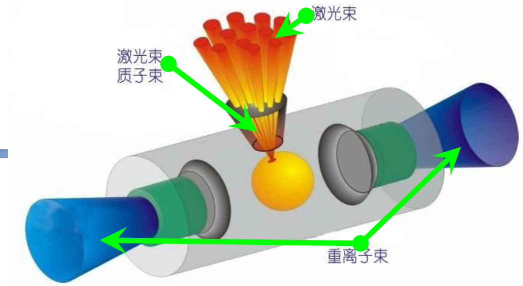


Magnetized HEDM Special Diamagnetism

Muon Campus Overview



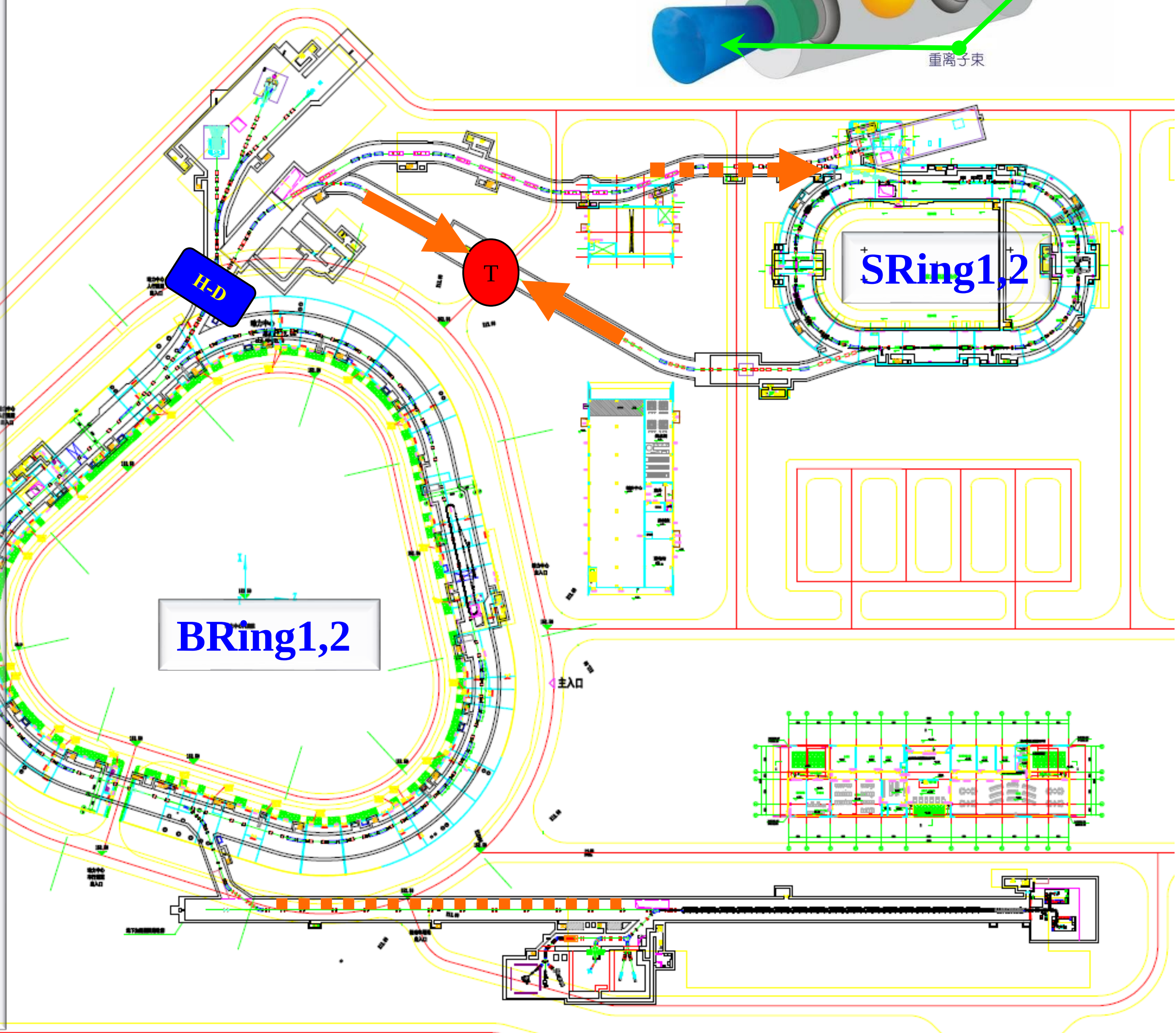
Optimizing of HIAF (~2027)



- Beams from BRing and SRing head on collision for **HEDM :**

E_{HIB} = 1kJ/ppp→2x50kJ/ppp

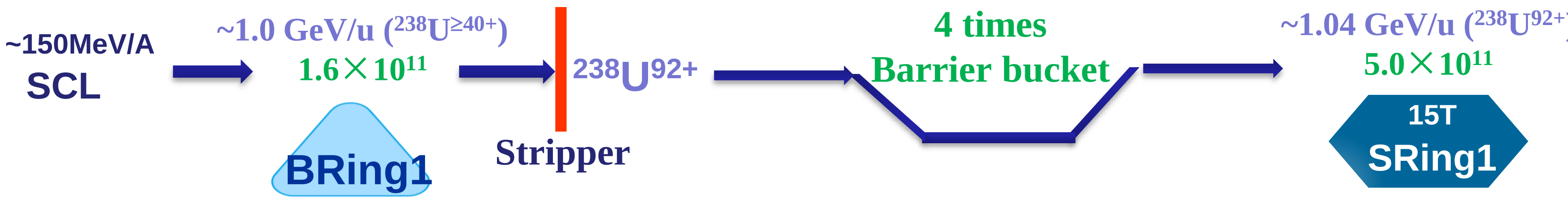
- Beam + Target in front of **H magnetic ion** and Produce **2nd Beams** :
  1. RIB on HFRS
  2. Neutron in 0°
  3. Meson at both side in downstream
- **Single beam → Multi-Beam → Multi-Exp.**



Optimizing for CW to Pulse Transform Efficient

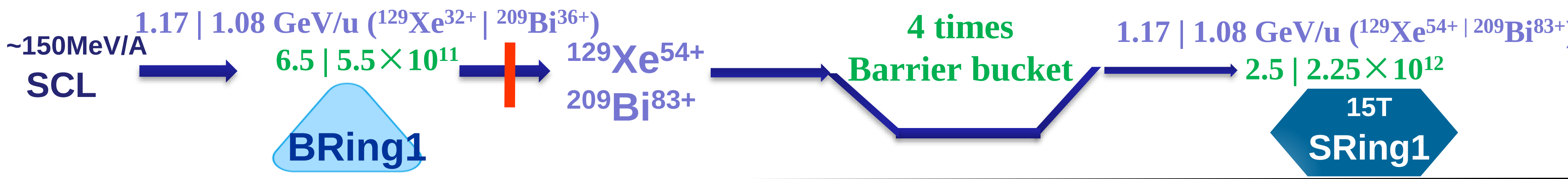
Intense CW Beam → Transformer (HF_RCS + Storage) → Power Pulse Beam

Compression: BRing→SRing Accum.$_{long}$ 5×10^{11} 1.04GeV/A $^{238}U^{92+}$ →19.8kJ/ppp



or: BRing→SRing Accum.$_{long}$ 2.5×10^{12} 1.168GeV/A $^{129}Xe^{54+}$ → ~60kJ/ppp

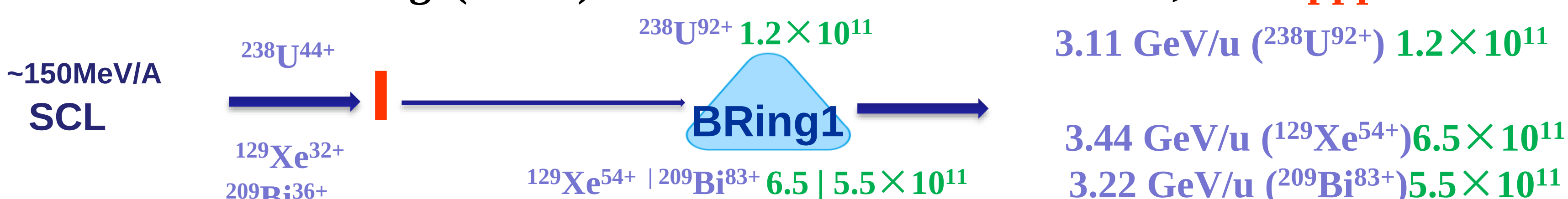
or: BRing→SRing Accum.$_{long}$ 2.25×10^{12} 1.08GeV/A $^{209}Bi^{54+}$ → ~ 80kJ/ppp



Heating: SCL → BRing1(34Tm) → 1.2×10^{11} 3.11GeV/A $^{238}U^{92+}$, ~14kJ/ppp

or: SCL → BRing1(34Tm) → 6.5×10^{11} 3.44GeV/A $^{129}Xe^{54+}$, 46kJ/ppp

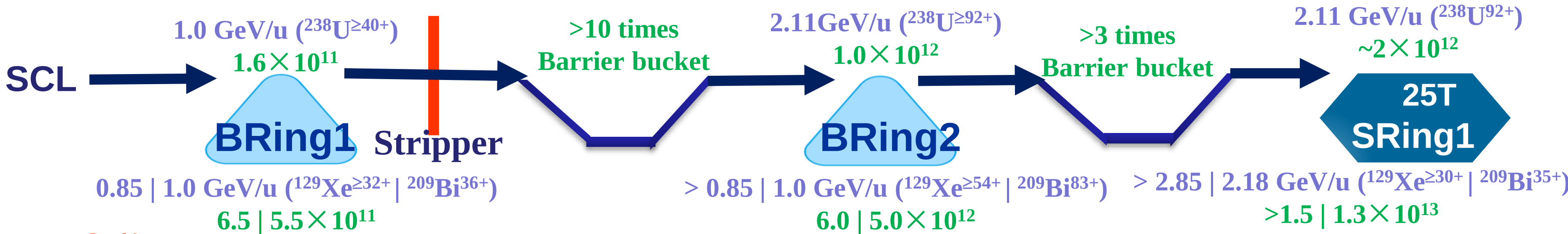
or: SCL → BRing1(34Tm) → 5.5×10^{11} 3.22GeV/A $^{209}Bi^{83+}$, 59kJ/ppp



Upgrade1-2 for CW to Pulse Transform Efficient

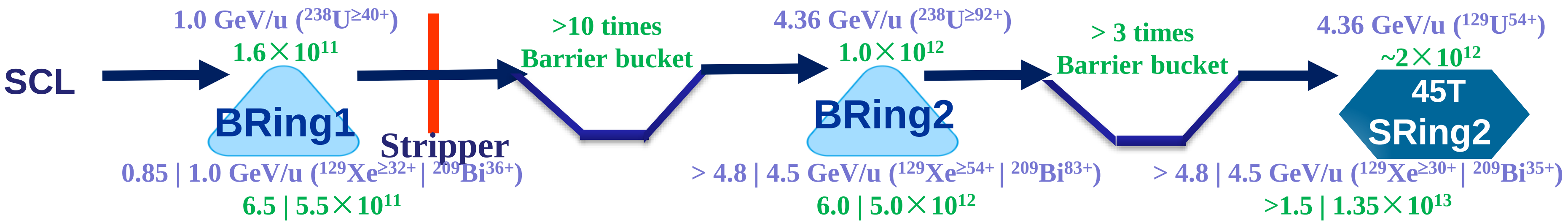
Intense CW Beam → Transformer (HF_RCS + Storage) → Power Pulse Beam

Compression(SRing1): 2.11GeV/u $^{238}U^{92+}$ ~160kJ/ppp



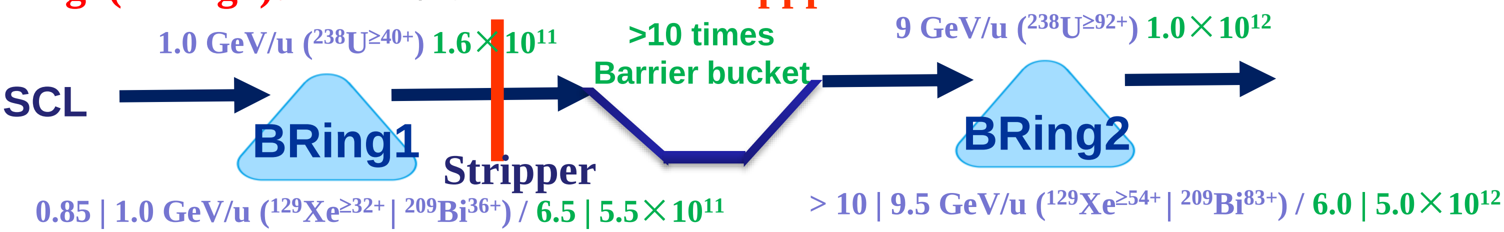
or: >2.34GeV/u $^{129}Xe^{54+}$ >724kJ/ppp; or: ~2.18GeV/u $^{209}Bi^{83+}$ >950kJ/ppp

Heating1(SRing2): 4.36GeV/u $^{238}U^{92+}$ ~332kJ/ppp



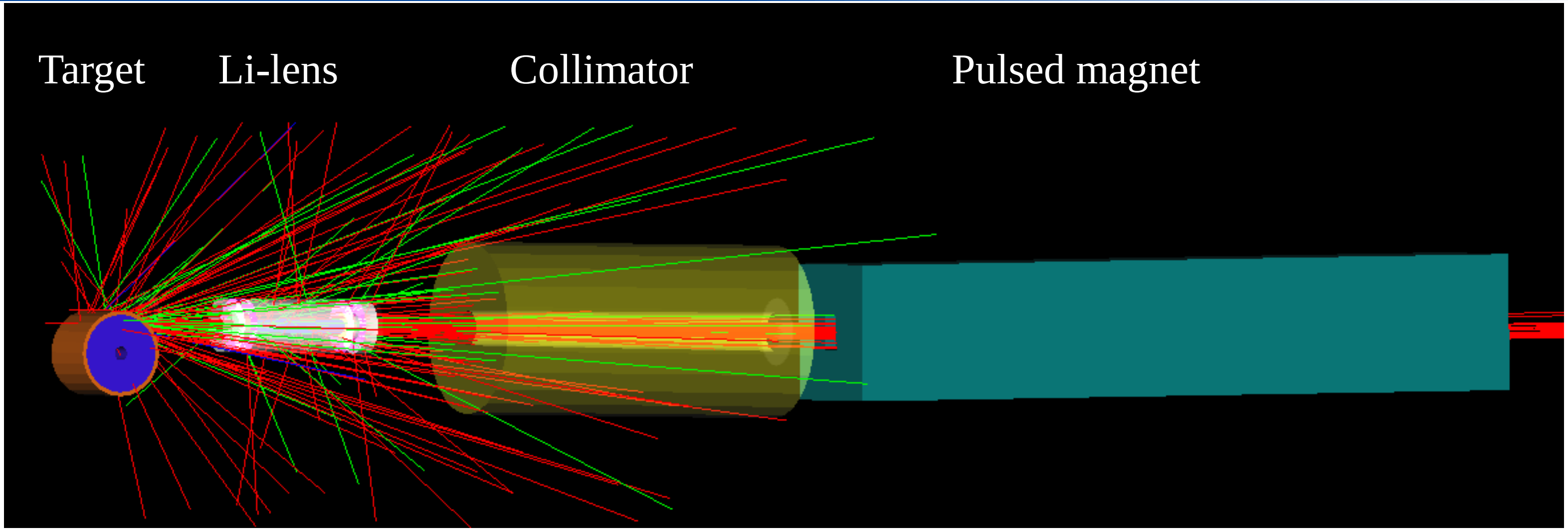
or: 4.8GeV/u$^{129}Xe^{54+}$ > 1.4MJ/ppp; Or: >4.5GeV/u $^{209}Bi^{83+}$ >2MJ/ppp

Heating2(BRing2): 9GeV/u $^{238}U^{92+}$ ~342kJ/ppp



or: 10GeV/u $^{129}Xe^{54+}$ > 1.2MJ/ppp; Or: > 9.5GeV/u $^{209}Bi^{83}$+ >1.5MJ/ppp

μ: HIAF-U vs Campus at F-lab (10^1~10^2)



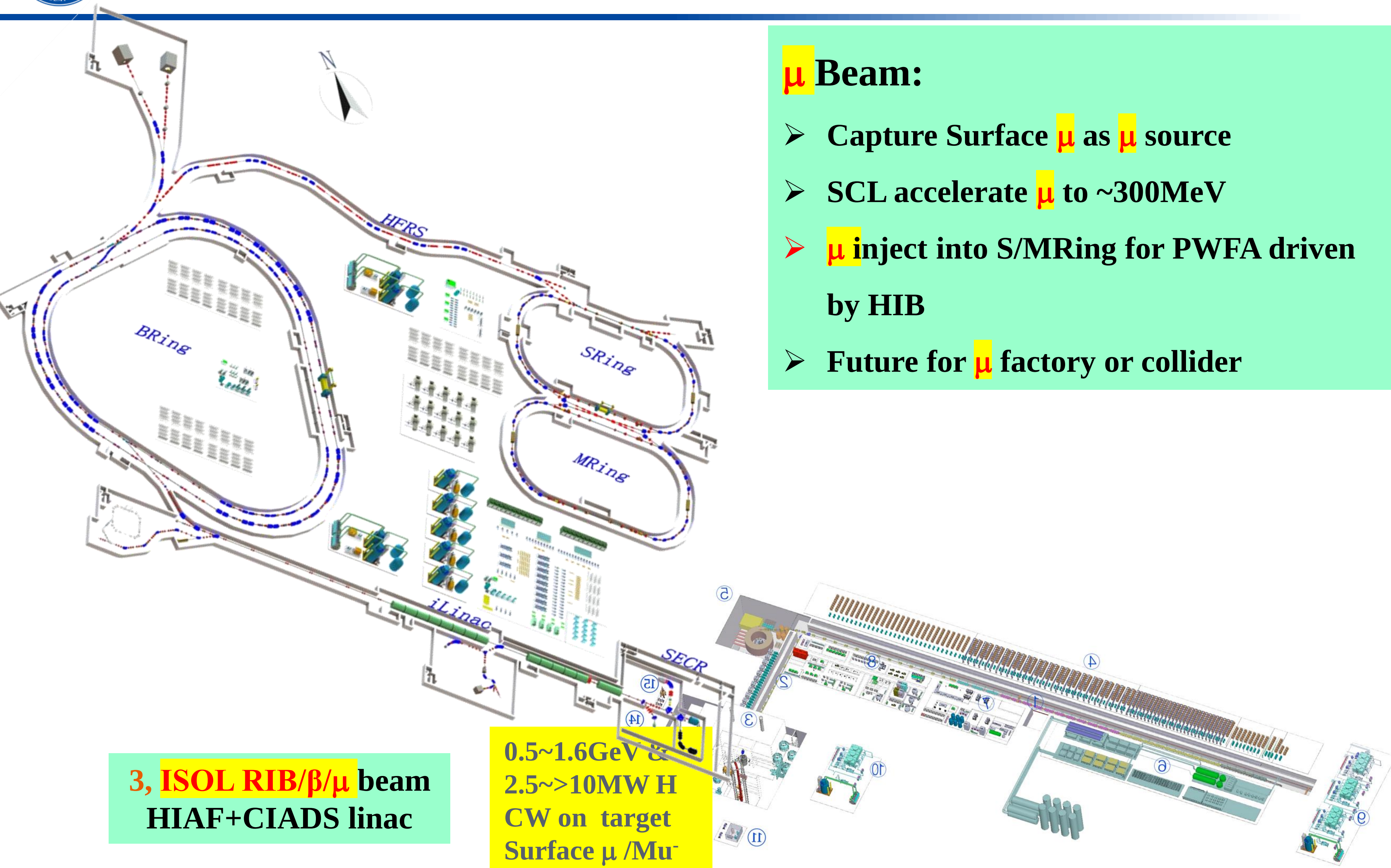
HIAF-μ-Beam in Huizhou

Parameter	1-0 (^{36}Ar)	1-0(^{1}H)	1-1 (^{209}Bi)
Nucleon on target per pulse	$36^{2/3}*4e^{12}$	$1e^{14}$	$209e^{13}$
Pulse width (ns)	200~300	200-300	200~300
Number of pulses	≥1	≥1	≥1
Frequency (Hz)	>5 Hz	>5Hz	~3 Hz
Beam momentum (GeV/c)	5.097	10.19	10.23
μ momentum (GeV/c)	>1.5	~3.5	>3.5

μ Campus at Fermilab

Parameter	Value （^{1}H）
Protons on target (POT) per pulse	10^{12}
Pulse width	120 ns
Number of pulses	16
Cycle length	1.4 s
Frequency	12 Hz
Incoming beam momentum	8.89 GeV/c
Selection momentum	3.1 GeV/c

CiADS: ISOL Type μ Beams (+HIAF)



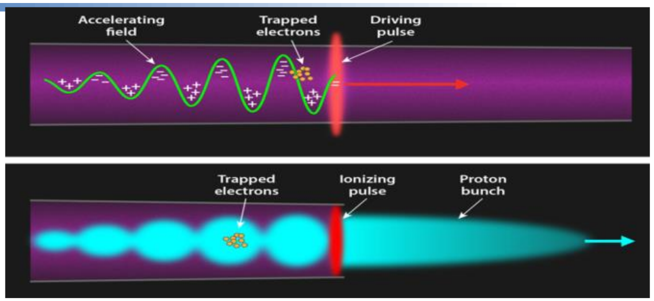
μ Beam:

- Capture Surface μ as μ source
- SCL accelerate μ to ~300MeV
- μ inject into S/MRing for PWFA driven by HIB
- Future for μ factory or collider

3, ISOL RIB/β/μ beam
HIAF+CIADS linac

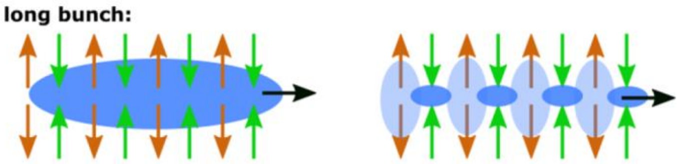
0.5~1.6GeV &
2.5~>10MW H
CW on target
Surface μ /Mu$^-$

Feature of Ion Driven PWFA



- **Energy of Driven Beam**
  - **Laser: ~ 50J/pulse (high rate)**
  - **Electron : ~ 50J/bunch**
  - **Proton: SPS 19 kJ/bunch (SPS), LHC 300kJ/bunch**
  - **HIB: HIAF-U>1MJ/bunch, high energy deposit density→ excite plasma**
- **Ion driver: large energy per bunch allow single stage acceleration in ultra-high(5~10GeV/m) gradient**
- **Seeded Self-Modulation of plasma driven by Ion Beam (beam bunch 10cm~10m vs plasma wavelength ~1mm)**
- **Storage ring :**
  - **~ MHz rate**
  - **RF acceleration**

} **quasi CW**



AWAKE at CERN

SPS Proton beam

Parameter	Protons
Momentum [MeV/c]	400 000
Momentum spread [%]	±0.035
Particles per bunch	$3 \cdot 10^{11}$
Charge per bunch [nC]	48
Bunch length [mm]	120 (0.4 ns)
Norm. emittance [mm·mrad]	3.5
Repetition rate [Hz]	0.033
1σ spot size at focal point [μm]	200 ±20
β-function at focal point [m]	5
Dispersion at focal point [m]	0

Plasma linear theory: $k_{pe}\ \sigma_r \le 1$

With $\boldsymbol{\sigma_r}$ **= 200 μm**

$k_{pe} = \omega_{pe}/c = 5\ mm^{-1}$

➔ $\mathbf{n_{pe} = 7x10^{14}\ cm^{-3}}$

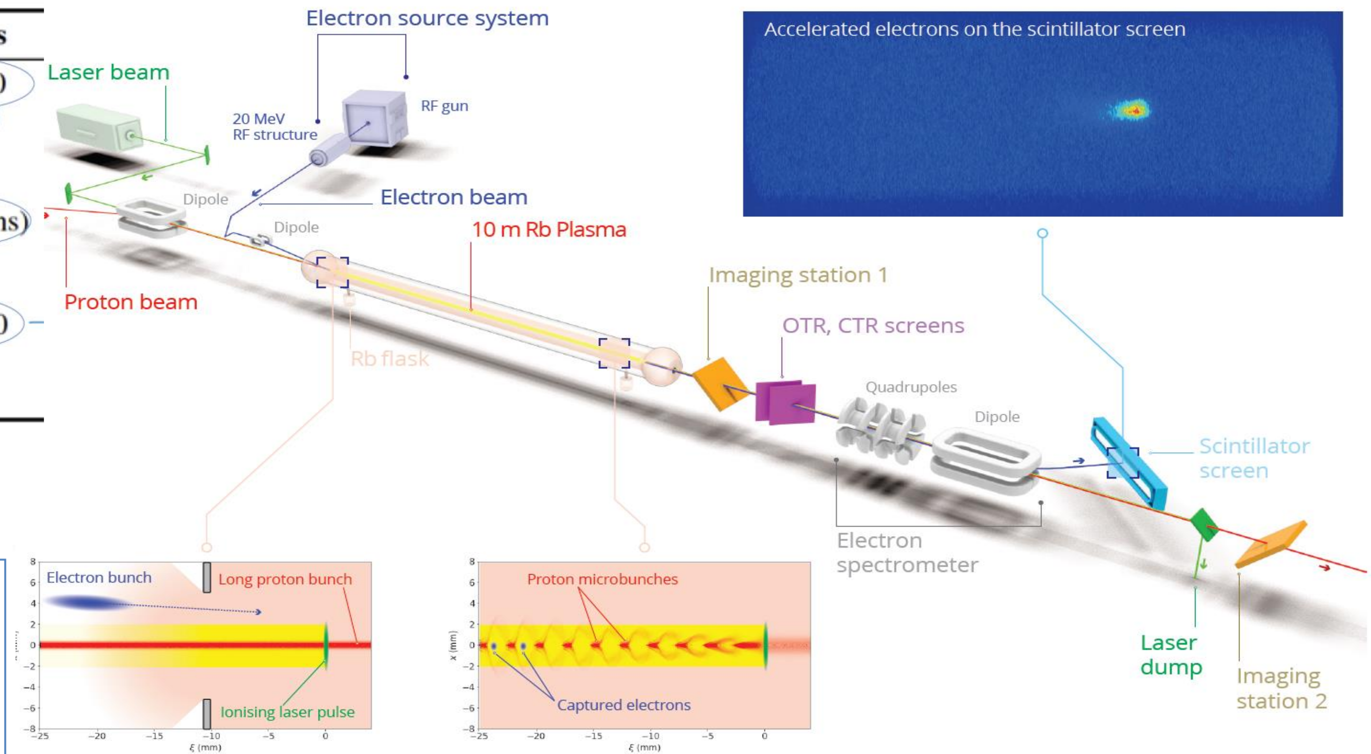
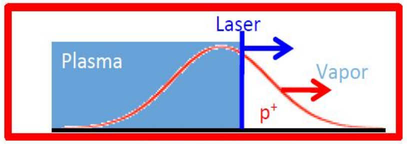
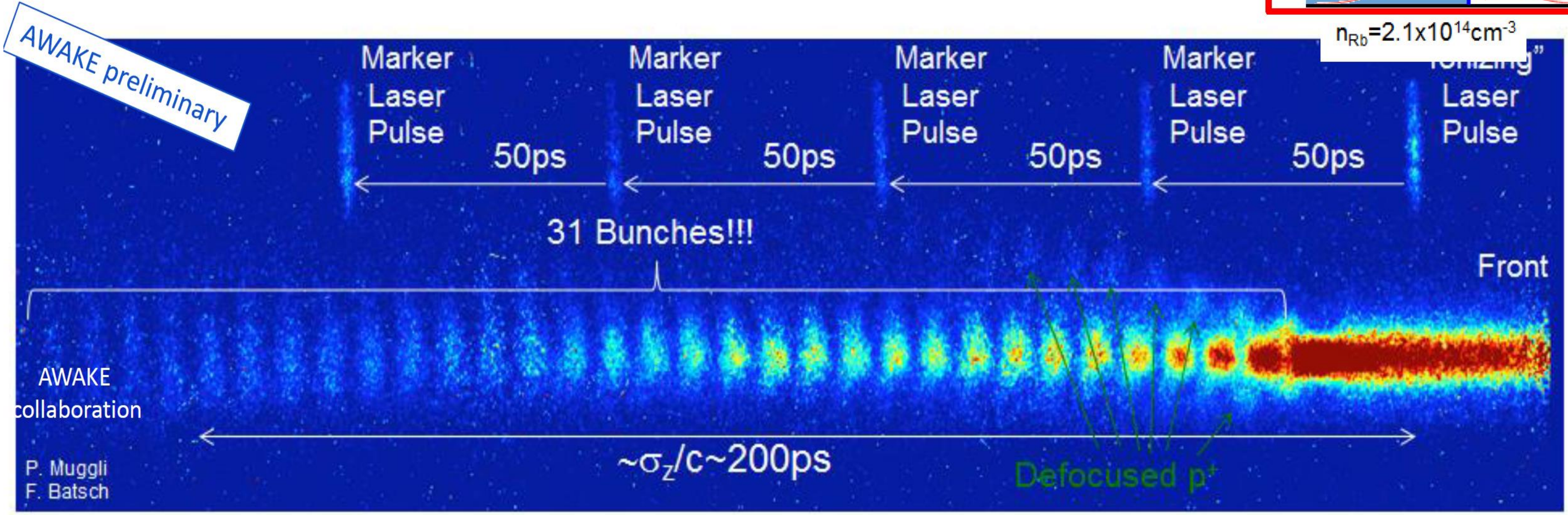


Figure 1. Schematic layout and description of the AWAKE experimental facility, beams and diagnostics. The insert panel on the bottom left shows a schematic of the spatial and temporal alignment of the proton, laser and electron bunch entering the vapor source; the bottom middle panel shows a schematic of the transverse and longitudinal proton microbunch density structure in plasma (after the self-modulation process saturated); the panel on the top right shows an experimental image obtained by the spectrometer camera, for when electrons were accelerated.

1^{st} AWAKE Experiment → Milestone

Results: Direct Seeded Self-Modulation Measurement



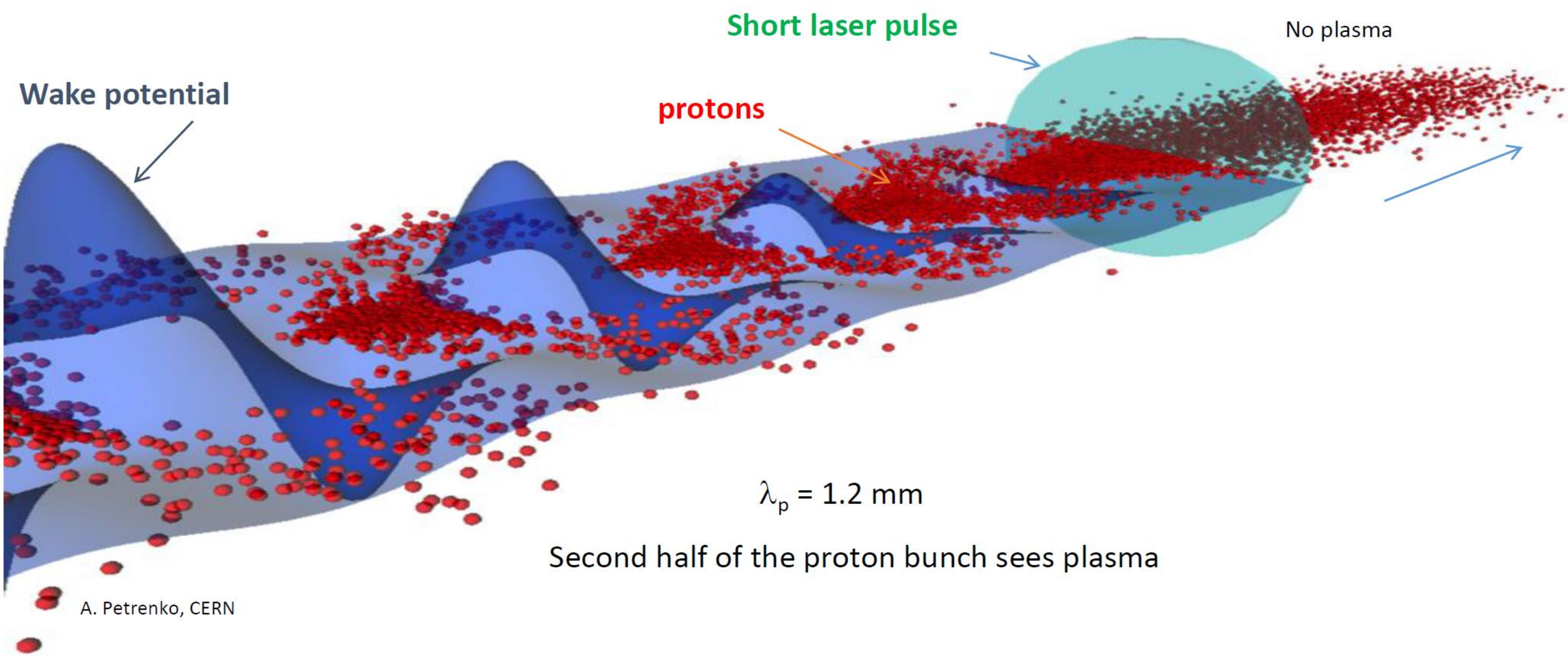


- Effect starts at laser timing → **SM seeding**
- **Density modulation** at the ps-scale visible
- Micro-bunches **present over long time scale** from seed point
- **Reproducibility** of the μ-bunch process against bunch parameters variation
- **Phase stability** essential for e^- external injection.

→ 1^{st} AWAKE Milestone reached

AWAKE Collaboration, 'Experimental observation of proton bunch modulation in a plasma, at varying plasma densities'. **Phys. Rev. Lett. 122, 054802 (2019).**

Seeded Self-Modulation Results



SSM align the laser pulse to long proton bunch (>>λ_{pe}) in plasma (time & space)

AWAKE Run 2

Goal:

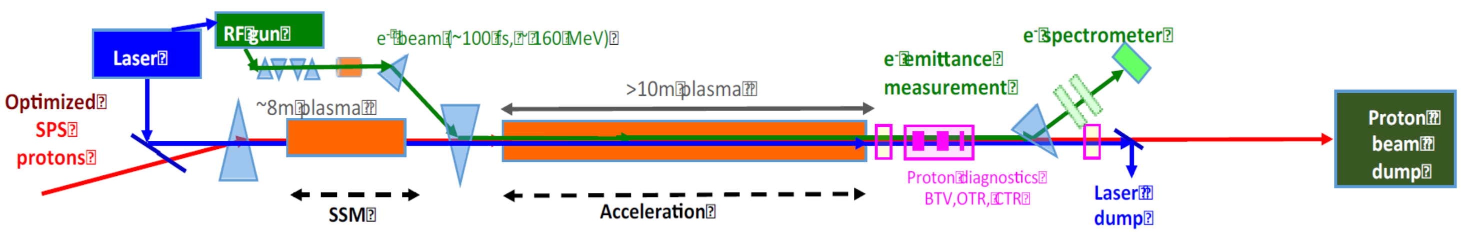
Accelerate an electron beam to high energy (gradient of 0.5-1GV/m)

Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)

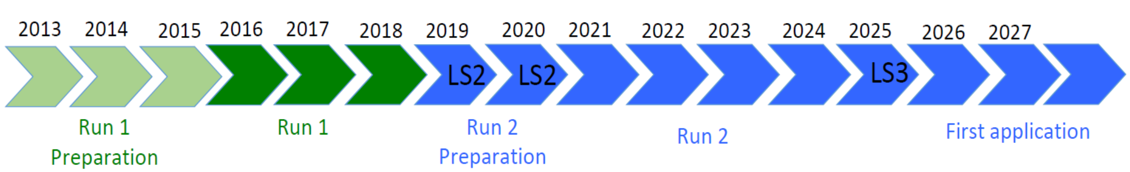
Demonstrate scalable plasma source technology (e.g. helicon prototype)

- ➔ Freeze the modulation with **density step** in first plasma cell
- ➔ For emittance control: need to work in **blow-out regime** and do **beam-loading**
- ➔ R&D on different **plasma source technologies**

e(μ) 0.1~1GeV/m



E. Adli (AWAKE Collaboration), IPAC 2016 proceedings, p.2557 (WEPMY008)

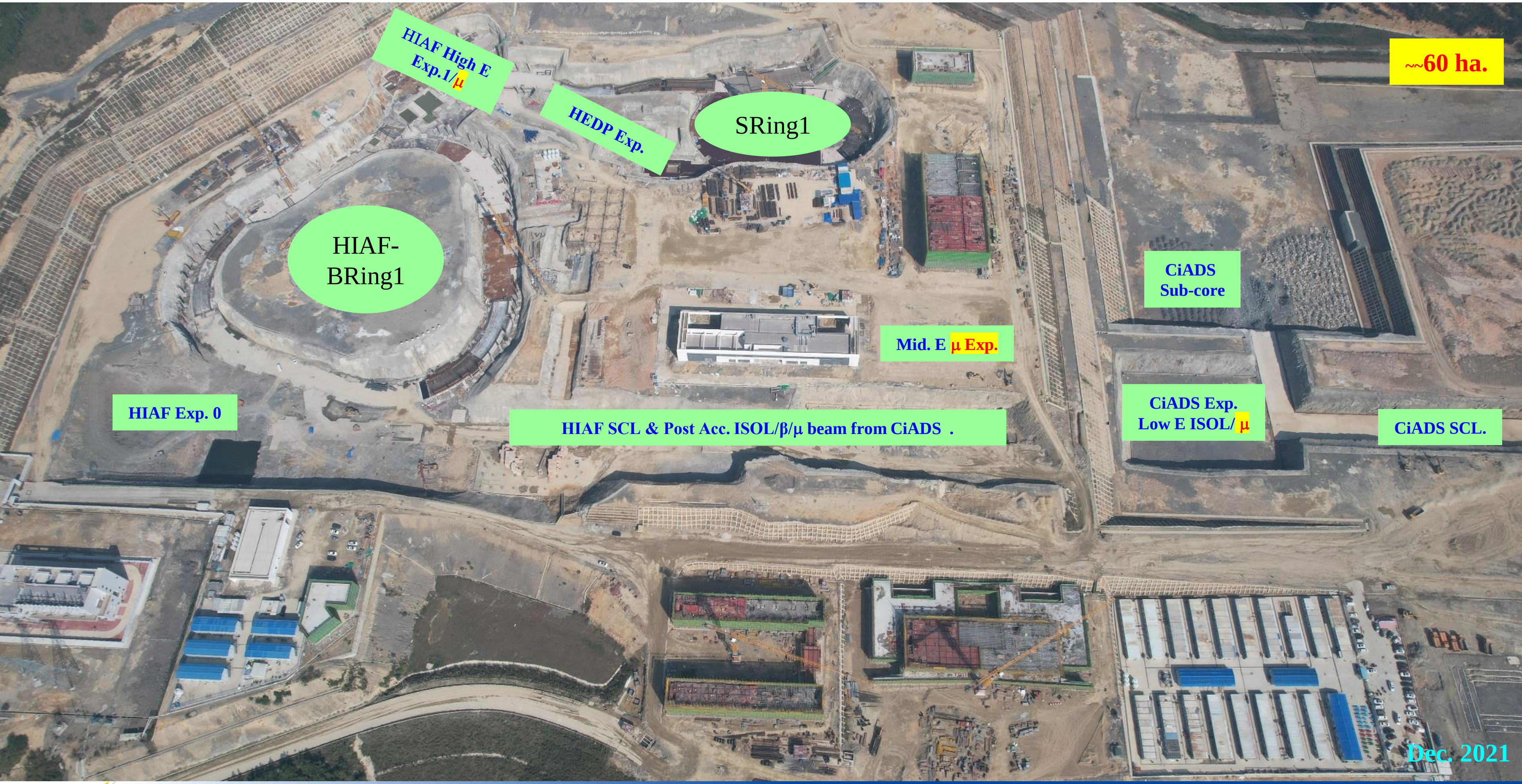


Design of HI Driven PWFA Test at CSRe

- HI: 250~450MeV/A ^{78}Ke, ^{129}Xe
- Accelerate : electron

HIAF + CiADS Civil Construction

- **HIAF's civil construction finished in 2022**
- **HIAF's hardware assemble starting 2023, 1st beam ~ end of 2025**



报告提纲

- 小结

小结

- **HIAF: (按研制进度)**
  - ✓ ~2027 (优化):>10^{11}μ/s (外靶实验及大部件缪子成像) >10 x μ campus
  - ✓ ~2032 (升级): >10^{12}μ/s (外靶实验) >100 x μ campus
- **CiADS: (按研制进度)**
  - ✓ ~2028: 2.5MW 质子束
  - ✓ ~2032: >15MW 质子束

  } 最强缪子源
- **HIAF+CiADS: → PWFA** (兼顾π→μ ?)
  - ➢ 高亮度→PWFA→高能量
  - ➢ 准连续缪子束


THANKS FOR ATTENTION
Welcome to
Collaboration !