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High-intensity High-Power Ion Accelerators and Technical Challenge

Hongwei ZHAO

Institute of Modern Physics (IMP), Chinese Academy of Sciences
Lanzhou, China

Outline

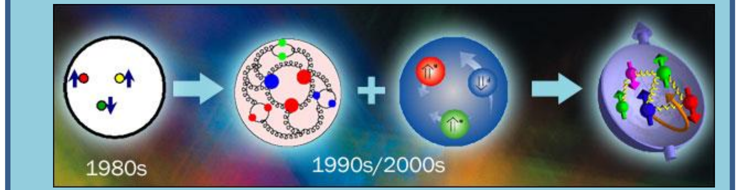
High-Intensity High-Power Ion Accelerator (HIHPIA)

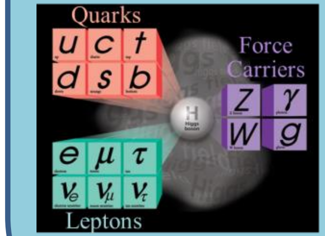
1. **Brief introduction of HIHPIA**
2. **Key technologies and challenges**
3. **World-wide HIHPIA and HIAF&CiADS at IMP**
4. **Conclusion remarks**

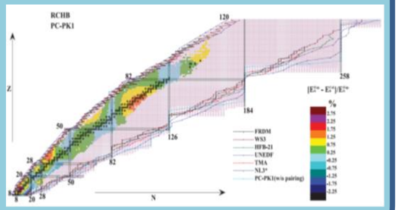
Applications of high-intensity high-power ion beams

Particle physics
Nuclear physics
HED physics
(Intens.& lumin. frontier)

- Neutrino factory
- Muon source
- Collider
- Rare isotope facility
- Secondary beam
- .....

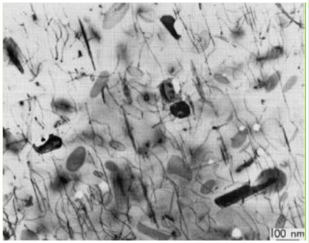


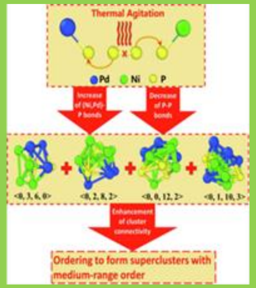


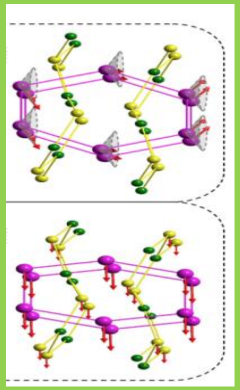


Material science
Bioscience and medicine
Condensed matter physics

- Neutron beam、neutron source
- Muon beam and muon source
- Detection and irradiation
- Medical isotope production
- Particle and radiation imaging
- .....

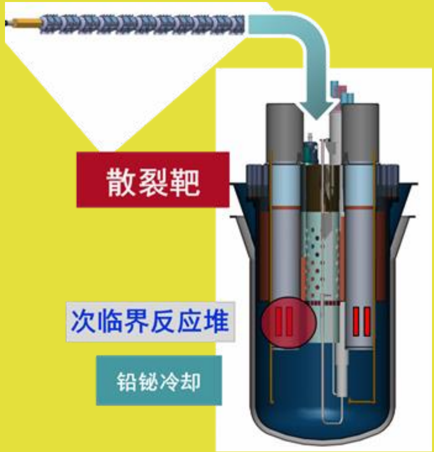






Advanced nuclear power

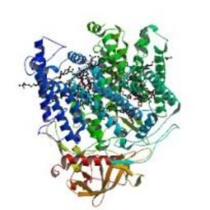
- ADS
- Advanced nuclear-fission power
- Heavy ion driven fusion
- Neutral beam for MCF
- Fusion material irradiation
- .....

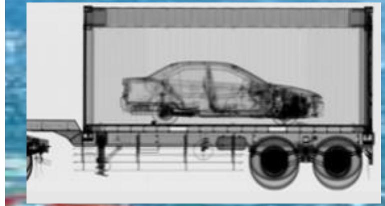


How can our users utilize the accelerator beams

Main parameters of ion beam

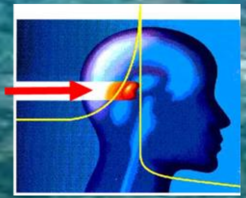
Ion species, beam intensity, kinetic energy, time structure, repetition rate, bunch length, emittance, beam loss...

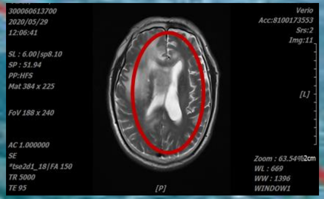




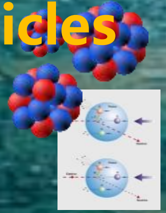
LHC

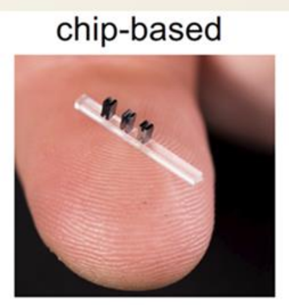
- Reaction products: secondary beams
  Photos,neutrons...





- Rare isotopes, elementary particles
  Quark,μ,τ,π...





- Beam intensity determines reaction productivity or event numbers.
- Beam energy is related to matter structure and hierarchy studied such as levels of the atom, nucleon, nucleus, elementary particle
- Charge state of heavy ion beam is related to accelerator scale and performance-cost –effective.

How to achieve high-intensity and high-power ion beam with radiation security

- Raise beam intensity from ion source
- Raise beam energy
- Reduce beam loss as low as possible during transmission and acceleration
- Raise intensity through beam accumulation and cooling for synchrotron and storage ring
- Raise repetition rate, pulse peak intensity, pulse length for pulsed ion beam

Beam average power:

$$P = E_{kinetic}\, I_{average}$$

Beam average intensity:

$$I = f_n N_p\, e$$

f_n *Repetition rate*
N_p *Number of particles per pulse*

Significance of exposure to radiation

- Occupational limit of radiation dose: maximum 50 mSv/year in US and China (<20 mSv/year for 5 year)
- Lab management guideline of radiation dose: 12.5 mSv in US DOE, 5 mSv in China

(Chest CT examination: 5-7 mSv; Whole body PET-CT scan: 15-25 mSv)

Production of high-intensity ion beams --Ion source

- **What is an ion source?**

Ion source is a plasma device for producing ion beam. Ions can be produced by electron-impact ionization and the electrons are generated from plasma

- **What are the most important parameters for an ion-source user ?**

Beam intensity and beam emittance(beam brightness): related to ion source itself (plasma parameters), beam extraction system and LEBT.

- **2.45 GHz microwave-driven ion source for single-charged ion beam production**

Chalk River

Taylor &Wills

Beginning of '90s

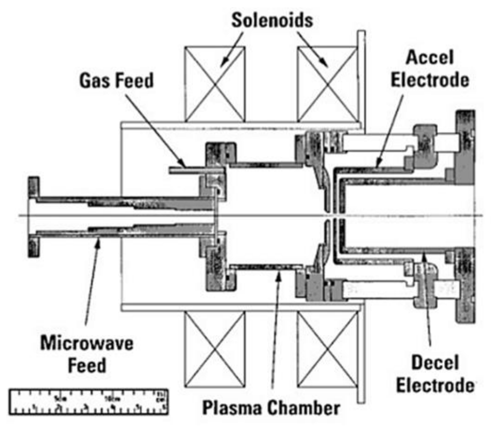
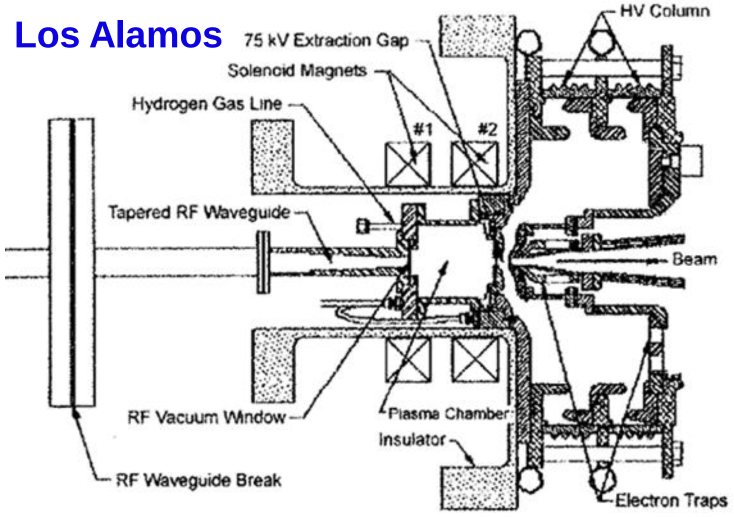


FIG. 1. Microwave-driven Chalk River proton source.

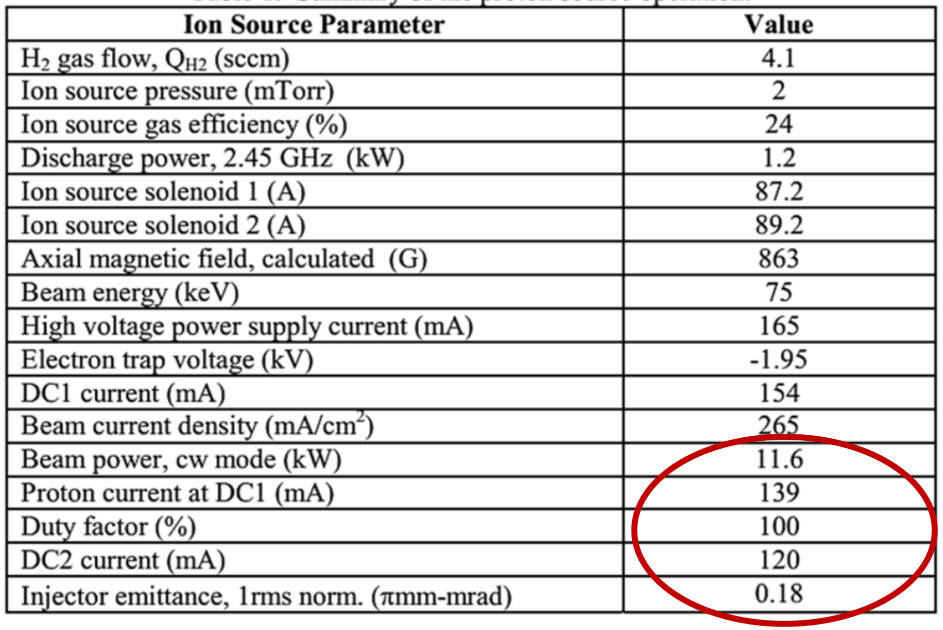
T. Taylor and J. Wills, Proc. Linac'92, Ottawa

Los Alamos



J. Sherman, et al., RSI, 69, 1003 (1998)

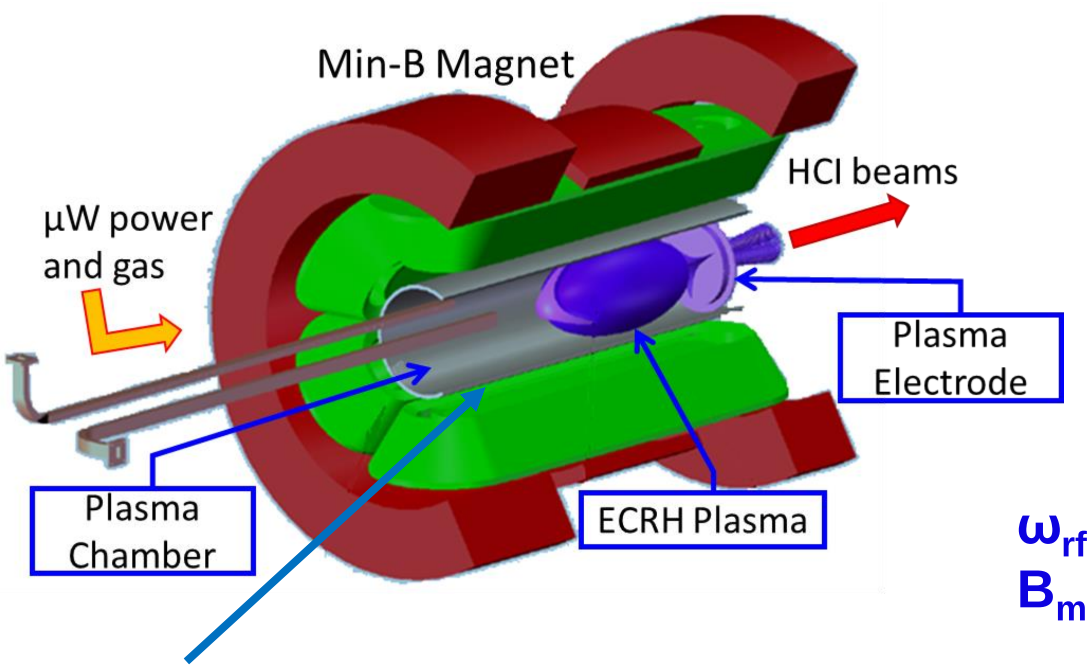
Table 1. Summary of the proton source operation.



Ion Source Parameter	Value
H_2 gas flow, Q_{H2} (sccm)	4.1
Ion source pressure (mTorr)	2
Ion source gas efficiency (%)	24
Discharge power, 2.45 GHz (kW)	1.2
Ion source solenoid 1 (A)	87.2
Ion source solenoid 2 (A)	89.2
Axial magnetic field, calculated (G)	863
Beam energy (keV)	75
High voltage power supply current (mA)	165
Electron trap voltage (kV)	-1.95
DC1 current (mA)	154
Beam current density (mA/cm^2)	265
Beam power, cw mode (kW)	11.6
Proton current at DC1 (mA)	139
Duty factor (%)	100
DC2 current (mA)	120
Injector emittance, 1rms norm. (πmm-mrad)	0.18

ECR ion sources for highly-charged ion beam production

ECR: Electron Cyclotron Resonance



Min-B Magnet

HCI beams

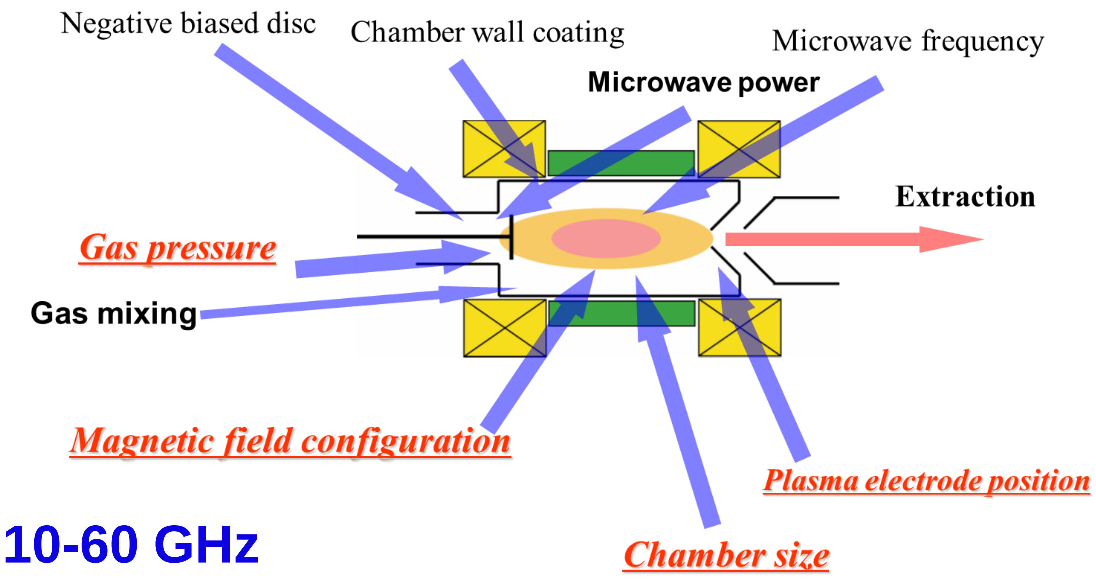
µW power and gas

Plasma Electrode

Plasma Chamber

ECRH Plasma

Multi-Mode Cavity ?



Negative biased disc

Chamber wall coating

Microwave frequency

Microwave power

Extraction

Gas pressure

Gas mixing

Magnetic field configuration

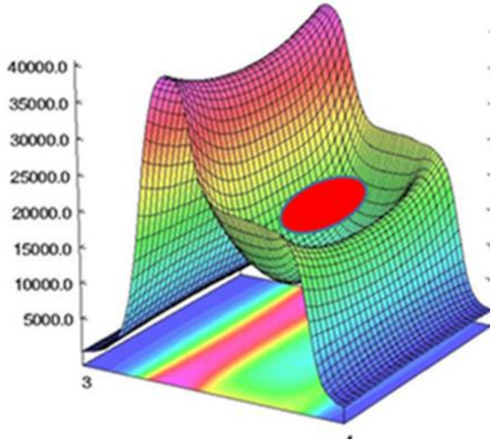
Plasma electrode position

Chamber size

ω_{rf} = 10-60 GHz

B_{max} =1-16 T

$$\omega_{rf}, P_{rf}, B, n_0 \Leftrightarrow n_e\, T_e\ \ \tau_e,\ n_i\, T_i\ \ \tau_i$$



- **Confinement of high density highly-charged plasma**

  --- long-time confinement for electrons and ions ---Minimum B structure

- **Electron stepwise collisional ionization producing highly-charged ions**

  --- high density and hot elelctons with required energy distribution --- high power microwave ECR heating

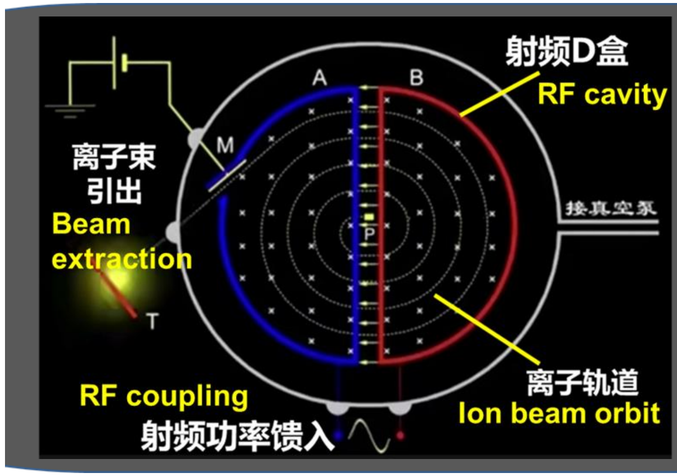
Record beam intensities produced by IMP SECRAL-II ECR ion source

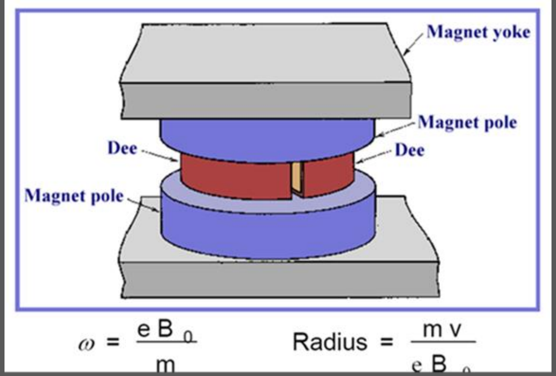
Ion species	Charge state	SECRAL& SECRAL-II 24~28 +18 GHz 6-10 kW [eμA]
^{40}Ar	12+	1420
	16+	620
	18+	15
^{78}Kr	18+	1030
	28+	145
^{129}Xe	26+	1100
	30+	365
	42+	16
^{209}Bi	31+	680
	41+	100
^{238}U	34+	620
	35+	545
	46+	61
	55+	13

24-28GHz SECRAL-II ECR ion source

More than 5000 hours operation each year in the past 10 years demonstrating high performance and long-term stability

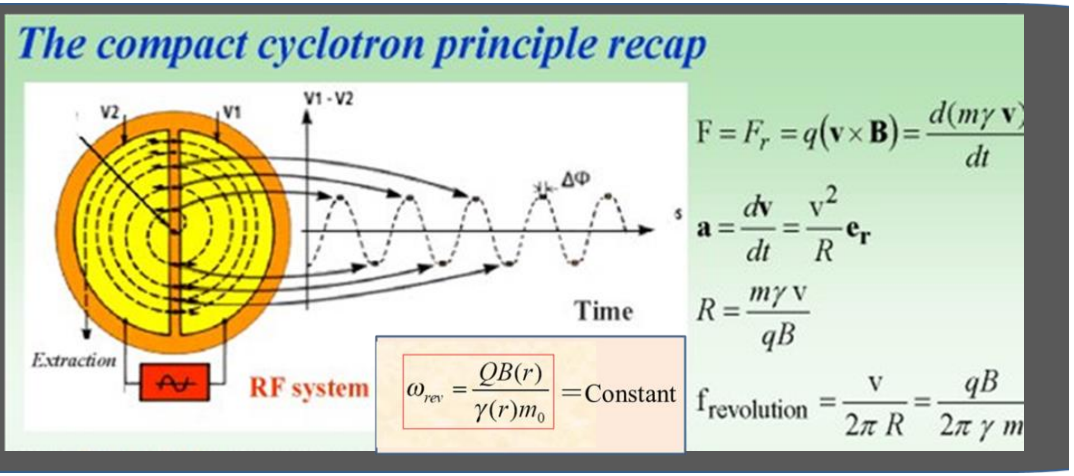
Typical accelerators for high intensity ion beam acceleration(1)





$$\omega = \frac{e B_0}{m} \qquad \text{Radius} = \frac{m v}{e B_0}$$

Cyclotron, compact, CW



The compact cyclotron principle recap

$$\omega_{rev} = \frac{QB(r)}{\gamma(r) m_0} = \text{Constant}$$

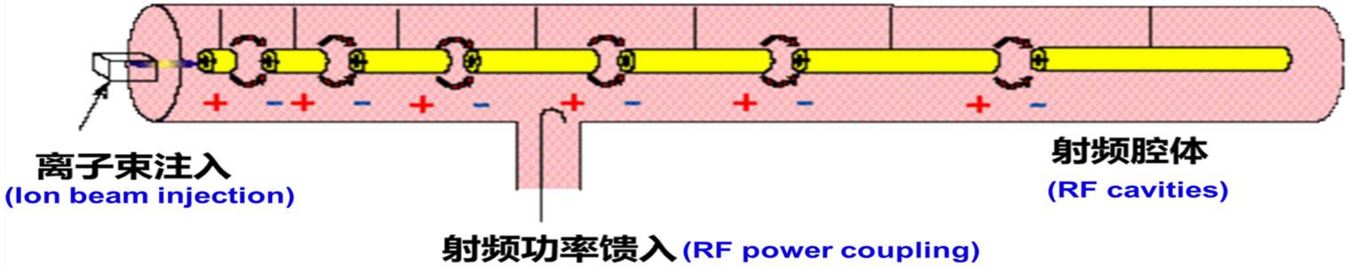
$$F = F_r = q(\mathbf{v} \times \mathbf{B}) = \frac{d(m\gamma \mathbf{v})}{dt}$$

$$\mathbf{a} = \frac{d\mathbf{v}}{dt} = \frac{v^2}{R}\mathbf{e_r}$$

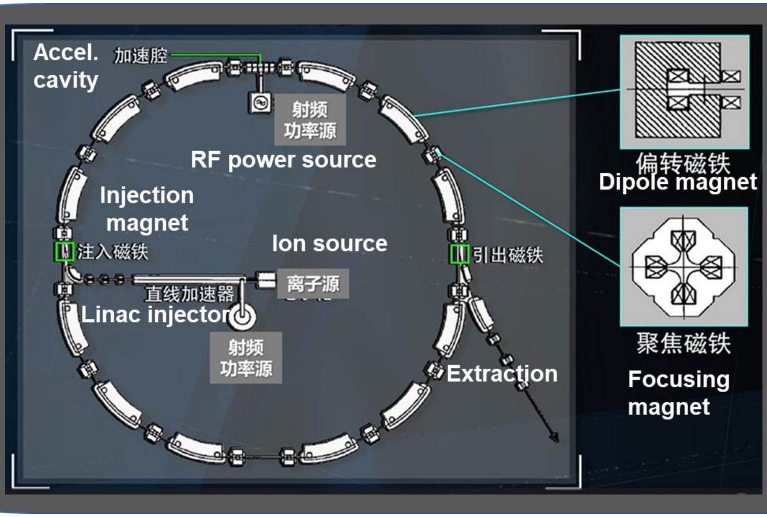
$$R = \frac{m\gamma v}{qB}$$

$$f_{revolution} = \frac{v}{2\pi R} = \frac{qB}{2\pi \gamma m}$$

Linac



CW or pulsed beam
Easy to adjust beam energy



$$B\rho = P/q$$

$$B(t) = C\{W(t)[W(t) + 2\,\varepsilon_0]\}^{1/2}$$

$$T_c = kT_{rf} = (W + \varepsilon_0)[W(W + 2\,\varepsilon_0)]^{-1/2}\, L/c$$

Synchrotron

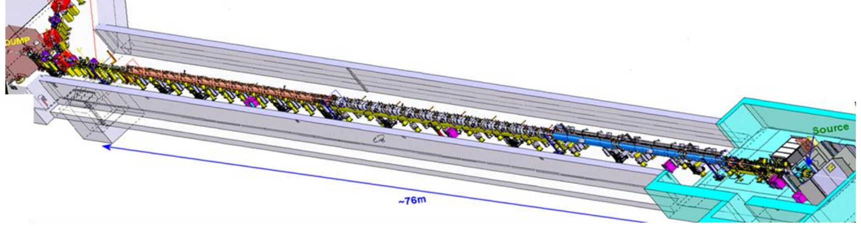
$$R = \frac{m\gamma v}{qB} = \text{Constant}$$

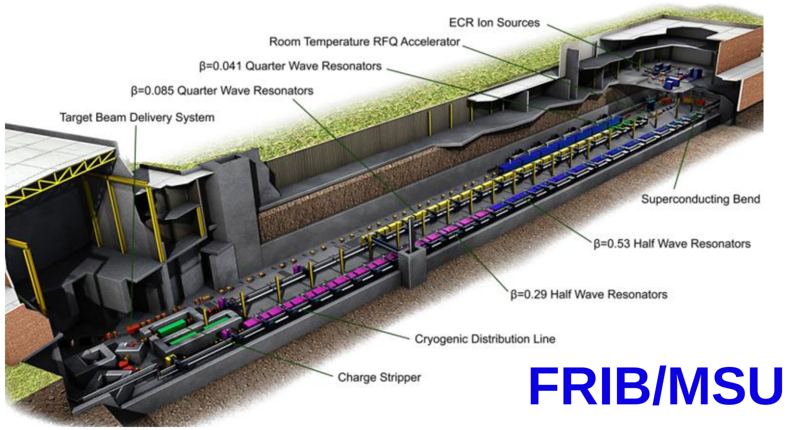
Only pulsed beam
Easy vary beam energy

Typical accelerators for high intensity ion beam acceleration(2)

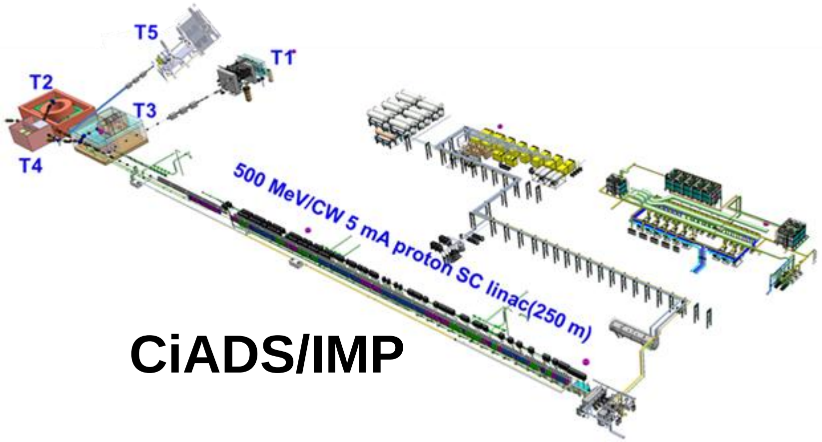

RIKEN-SRC

Linac4/CERN



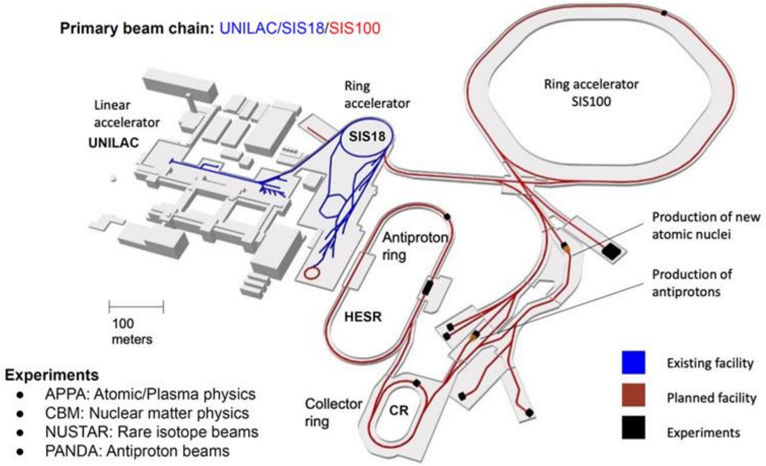


FRIB/MSU

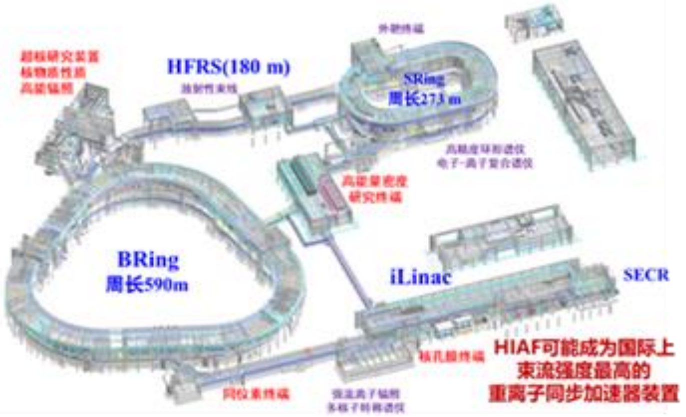


CiADS/IMP

FAIR/GSI



Experiments
- APPA: Atomic/Plasma physics
- CBM: Nuclear matter physics
- NUSTAR: Rare isotope beams
- PANDA: Antiproton beams



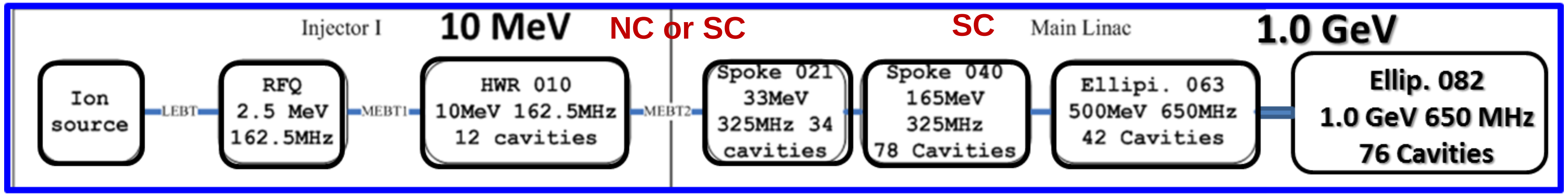
HIAF可能成为国际上
束流强度最高的
重离子同步加速器装置

HIAF/IMP

Technical approaches of high-intensity and high-power ion accelerators (1)

1. High-intensity and high-power (Frontier of intensity and luminosity)

-- SC ion linac (1-10 MW,< 3 GeV, 5-10 mA)

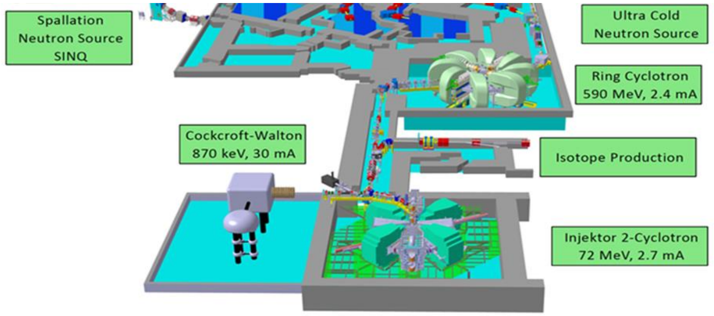

Injector I
10 MeV
NC or SC
SC
Main Linac
1.0 GeV

Ion source
LEBT
RFQ 2.5 MeV 162.5MHz
MEBT1
HWR 010 10MeV 162.5MHz 12 cavities
MEBT2
Spoke 021 33MeV 325MHz 34 cavities
Spoke 040 165MeV 325MHz 78 Cavities
Ellipi. 063 500MeV 650MHz 42 Cavities
Ellip. 082 1.0 GeV 650 MHz 76 Cavities

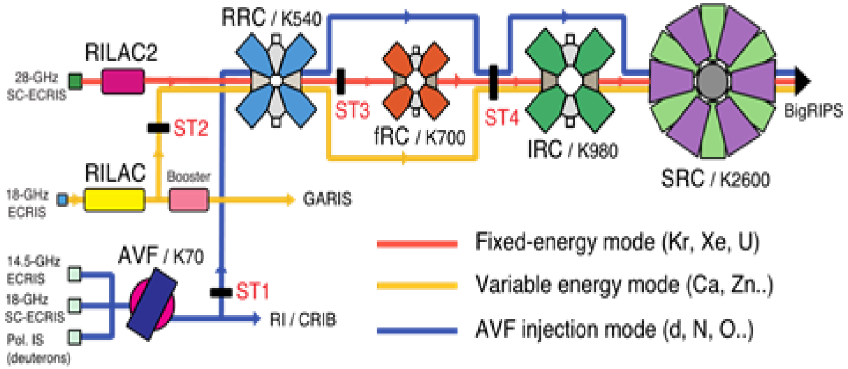
SNS injector, ESS, CiADS, FRIB, SPIRAL2,IFMIF…

2. High-intensity and high-power cyclotrons (1-3 MW, < 1 GeV/A, <5 mA)

GANIL, PSI, RIKEN, IMP, TRIUMF…



PSI proton cyclotrons



RIKEN-RIBF—Heavy ion cyclotrons

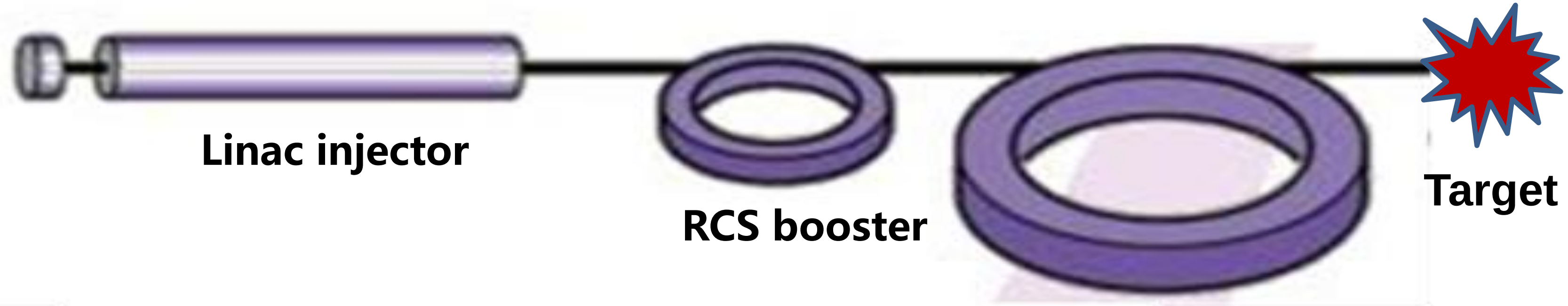
GANIL –Heavy ion cyclotrons

Technical approaches of high-intensity and high-power hadron accelerators (2)

3. High-energy and high-power (Frontier of high energy)

-- Linac+ synchrotrons (1-5 MW, >3 GeV/A)

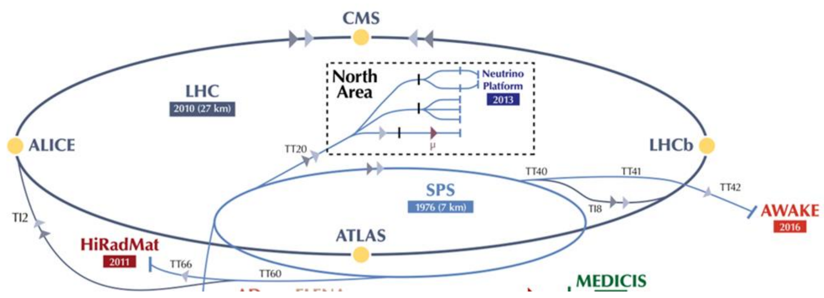
SNS, JPARC, CSNS, HIAF, FAIR,FNAL proton complex, ….



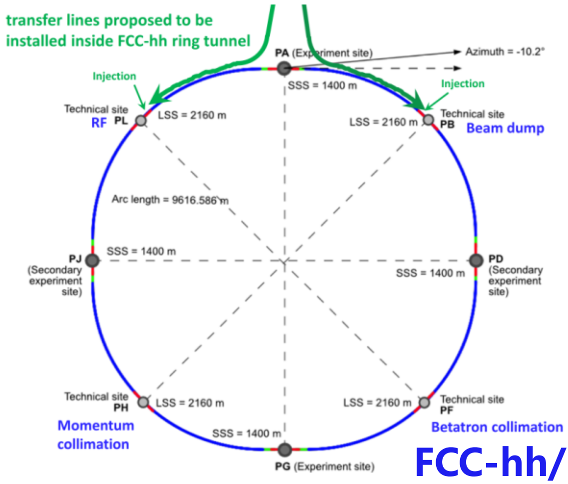
Several synchrotrons and storage rings for acceleration and accumulation, compression, and finally to the target

-- Linac+ RCS synchrotrons + colliders (1-3 MW, hundred GeV/A – TeV)

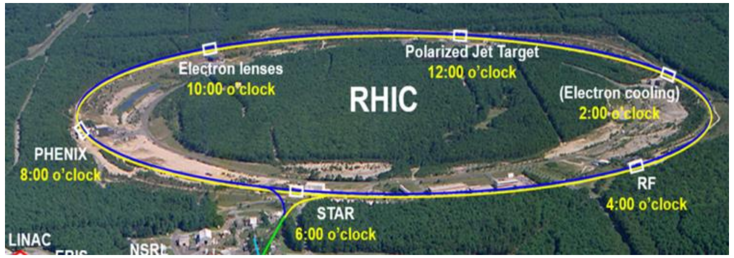
Ion beam-beam collision



CERN LHC



FCC-hh/SPPC



BNL RHIC

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1. Brief introduction of HIHPIA
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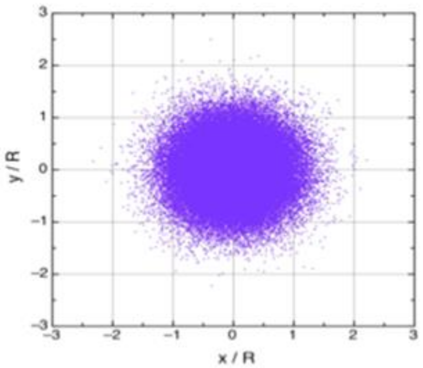
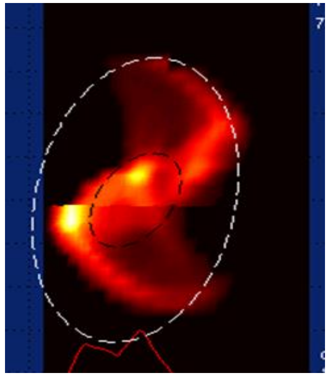
Key issues & challenges for HIHPIA

Key issues and challenges of beam dynamics

- Interactions between charged-particles;
- Interactions between ion beam and electric-magnetic elements
- Space-charge effect, instabilities, collective effect, wakefields …
- Extremely low beam-losses for HIHPIA ion beam, <1 W/m



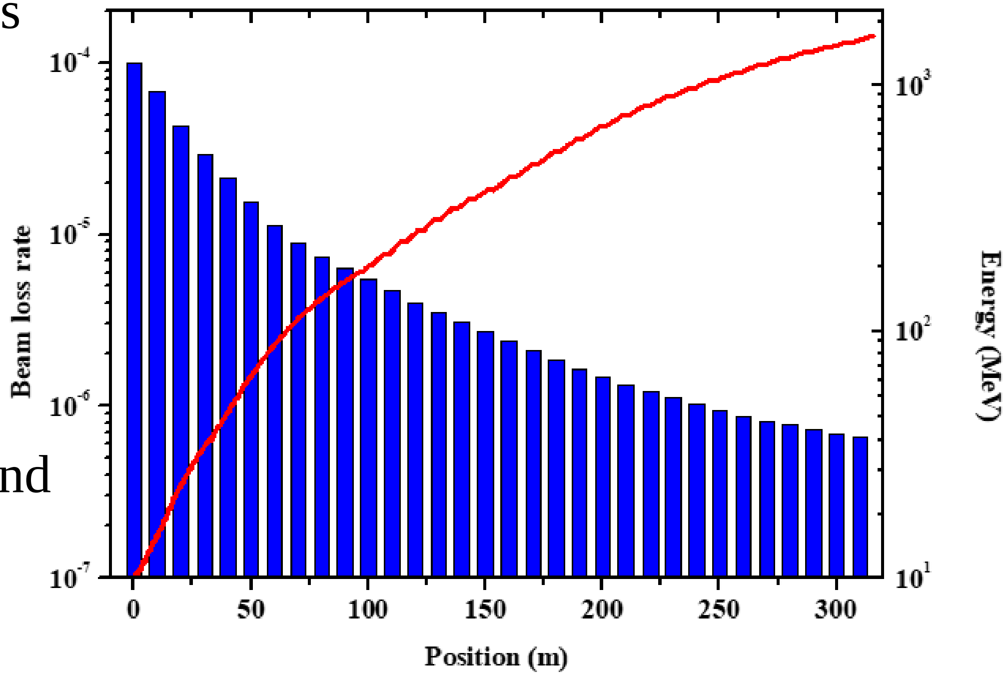
Beam halo



Beam distortion

Technical challenges

- A few accelerators coupled and connected together, or hundreds SRF cavities, stripping foil for H^- and heavy ions
- **Beam loss rate** 10^{-4}-10^{-6},
  CW: 10^{15}-10^{16} pps, pulsed: 10^{12}-10^{15} ppp
- Stabilization of RF frequency、phase and voltage amplitude (hundreds SRF cavities)
- Beam dynamics--LLRF control--beam loss detection--machine protection-- automatic recovery of beam trips – fast feedback and diagnostics （tens μs）, **for long-term operation**
- **Long-term stability and availability** with MW beam
- **AI&ML** …..



Acceleration of high-intensity low-energy ion beam by RFQ

RFQ is a typical low-energy accelerator for high intensity ion beam acceleration

Transversal match

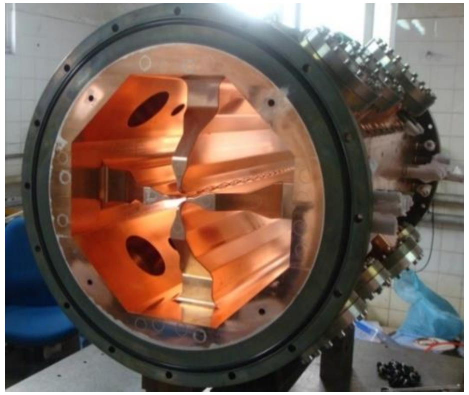
Beam Focusing and shaping

Longitudinal bunching

Acceleration

Beam match、focusing、bunching and acceleration in the RFQ cavity

Four rods RFQ

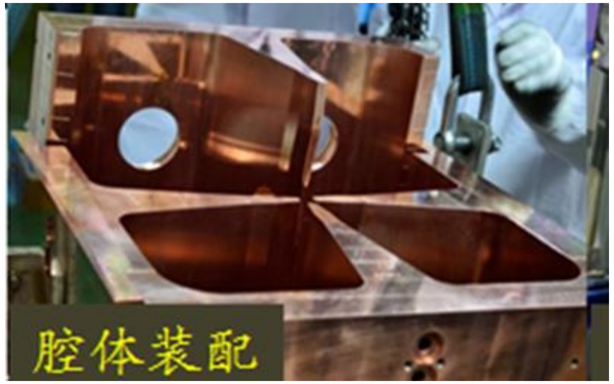


Four vane RFQ

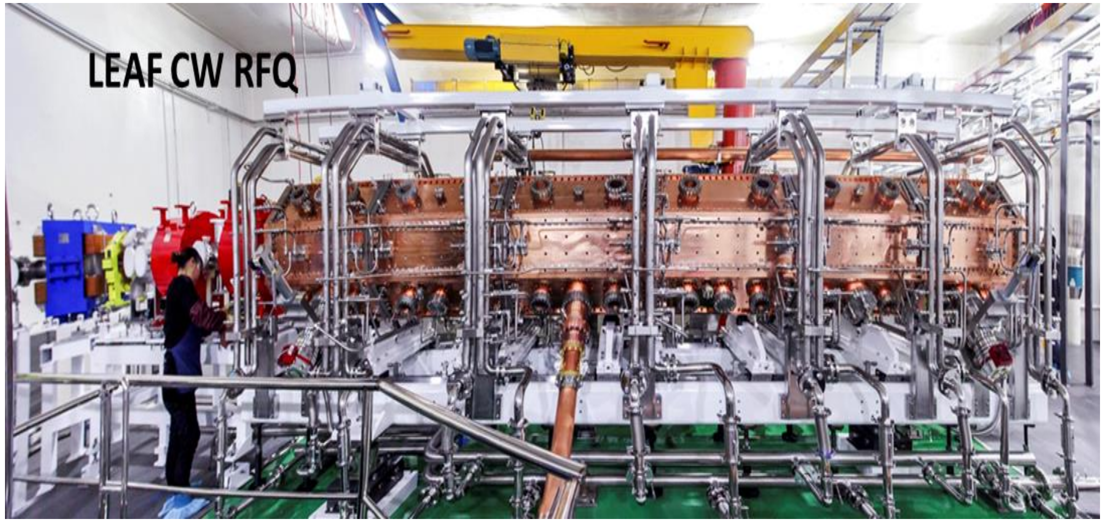
Key issues

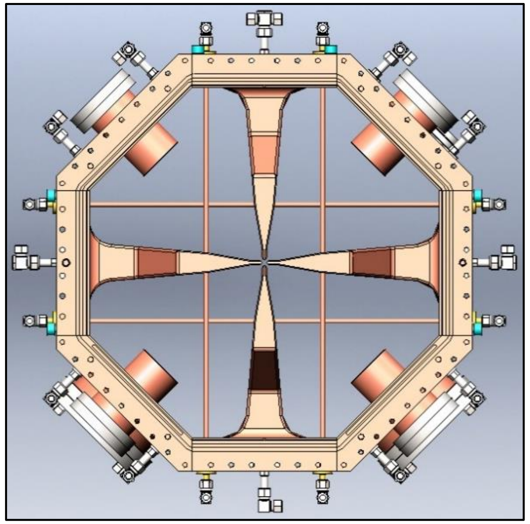
- Stable and high-power electric-magnetic fields for beam focusing, bunching and acceleration
- Interaction between the electric-magnetic fields and the high intensity ion beam in RFQ
- Long-term operation (weeks) at CW 10 mA proton and 1 emA heavy ion beams not yet demonstrated

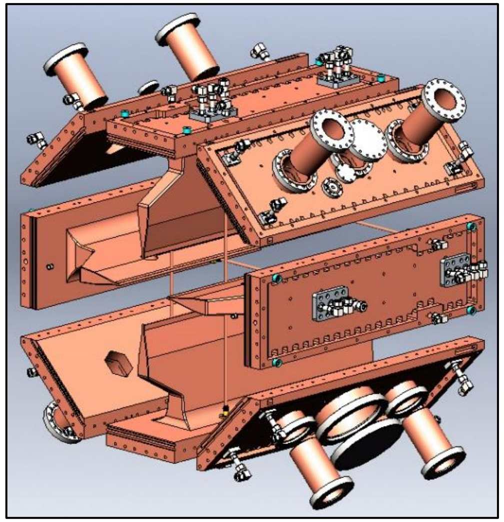
Proton and heavy ion RFQ accelerators developed by IMP



2.1 MeV/H$^+$ 10 mA, 2011-2014, 3 such RFQs were built and being operated at IMP (collaborated with LBNL)







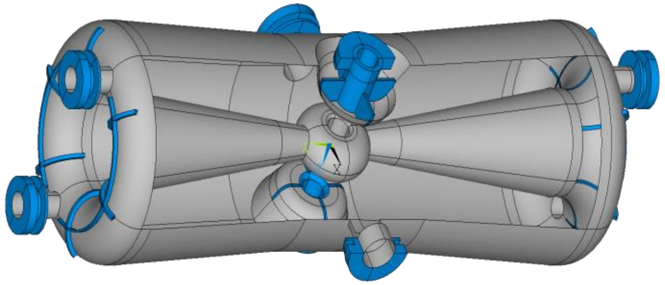
0.5 MeV/A, A/Q=2-7, 2015-2024, 1 mA O^{6+}, 0.2 mA Bi^{35+}, 2 such heavy ion RFQs were built for LEAF and HIAF

CW 10 mA proton and 1 mA O^{6+} beams were demonstrated in hours

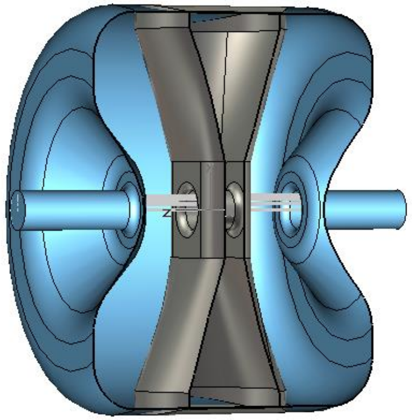
SRF cavities for high intensity beam acceleration achieving higher E

Key issues

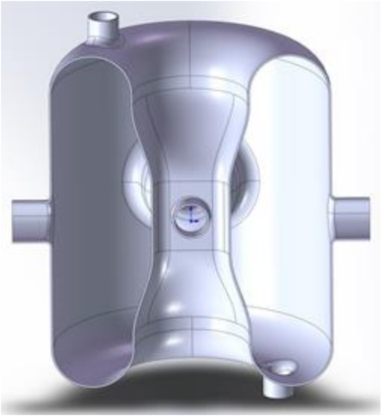
- Generate high electric-field gradient （E_{acc}） with high Q 、low RF power loss、low electric and magnetic peak field (E_{peak}、 B_{peak}) and stable RF frequency、phase and voltage amplitude by optimization of cavity structure and cavity surface processing.
- Realize acceleration and transmission of high intensity ion beam almost no any beam loss.



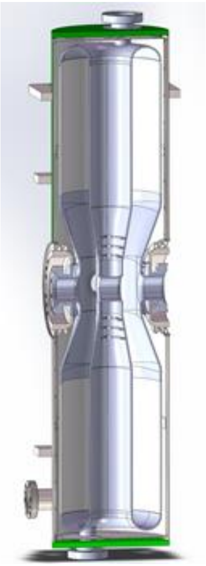
THWR



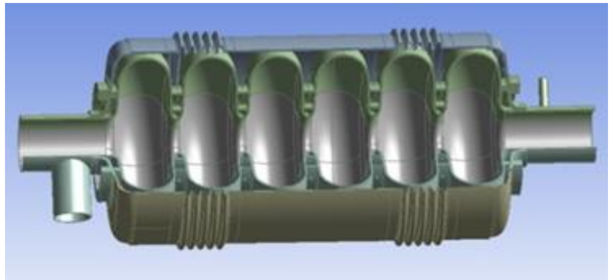
Spoke



HWR



QWR

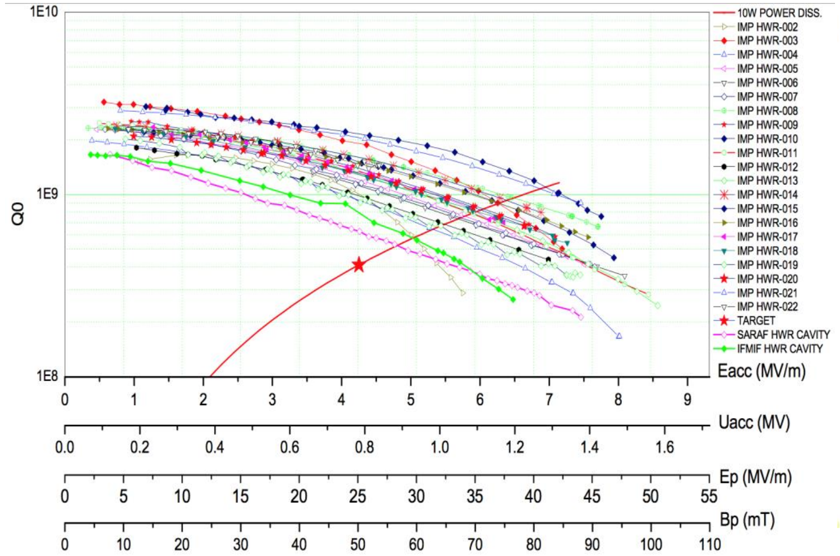


Elliptical multi-cell

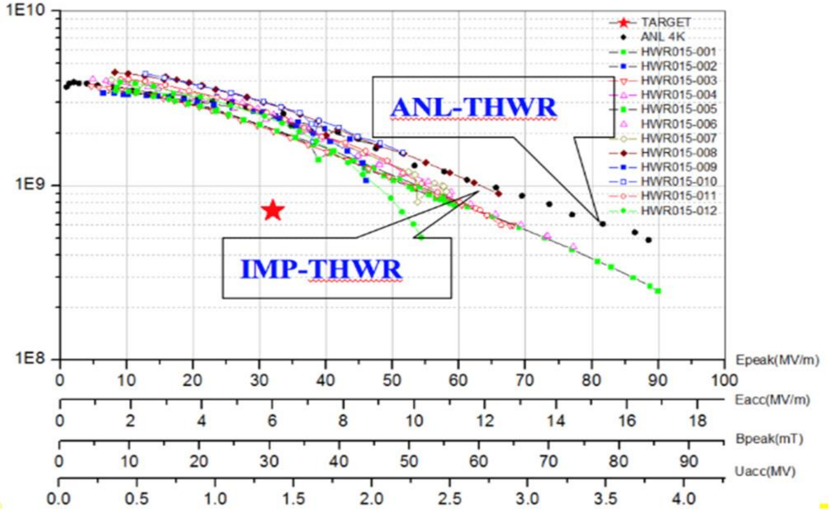
Typical SRF cavities for ion acceleration with low and high β

Low and medium β SRF cavity for proton and heavy ions

- β= 0.82. 5-cell prototype built by IMP Q_0 1 x 10^{10}, ~30 MV/m in VT. 650 MHz



HWR010 by IMP

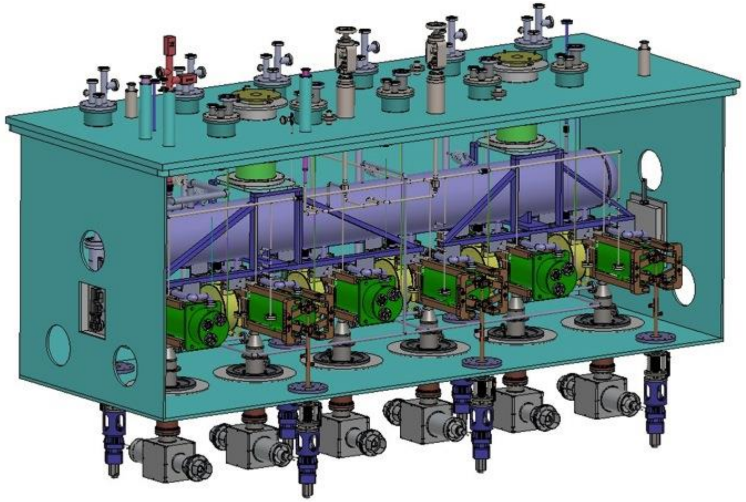


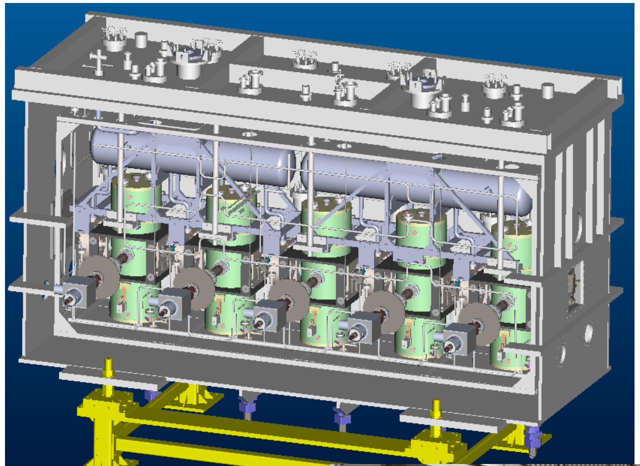
HWR015 by IMP

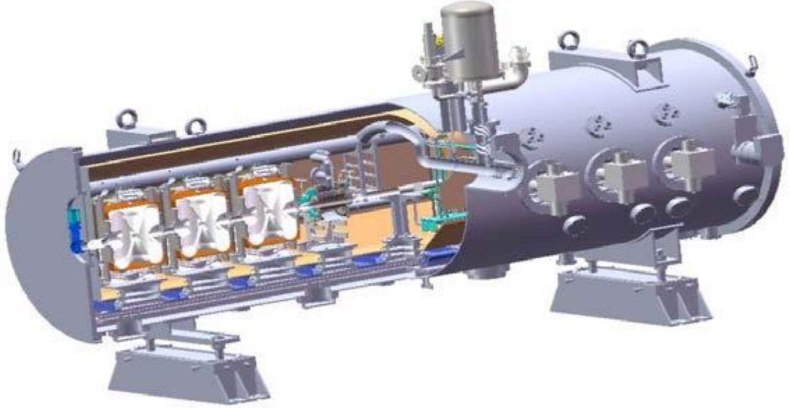
- **Gradient E_{acc} and Q_0 need to be improved for both bulk-Nb and thin film**
- **New structure and new material need to be developed.**
- **Recent surface processing and thin film advances (surface coating Nb & Nb_3Sn, electro-polishing, N-doping/infusion …) potentially enable much higher performance.**

SRF Cryomodule

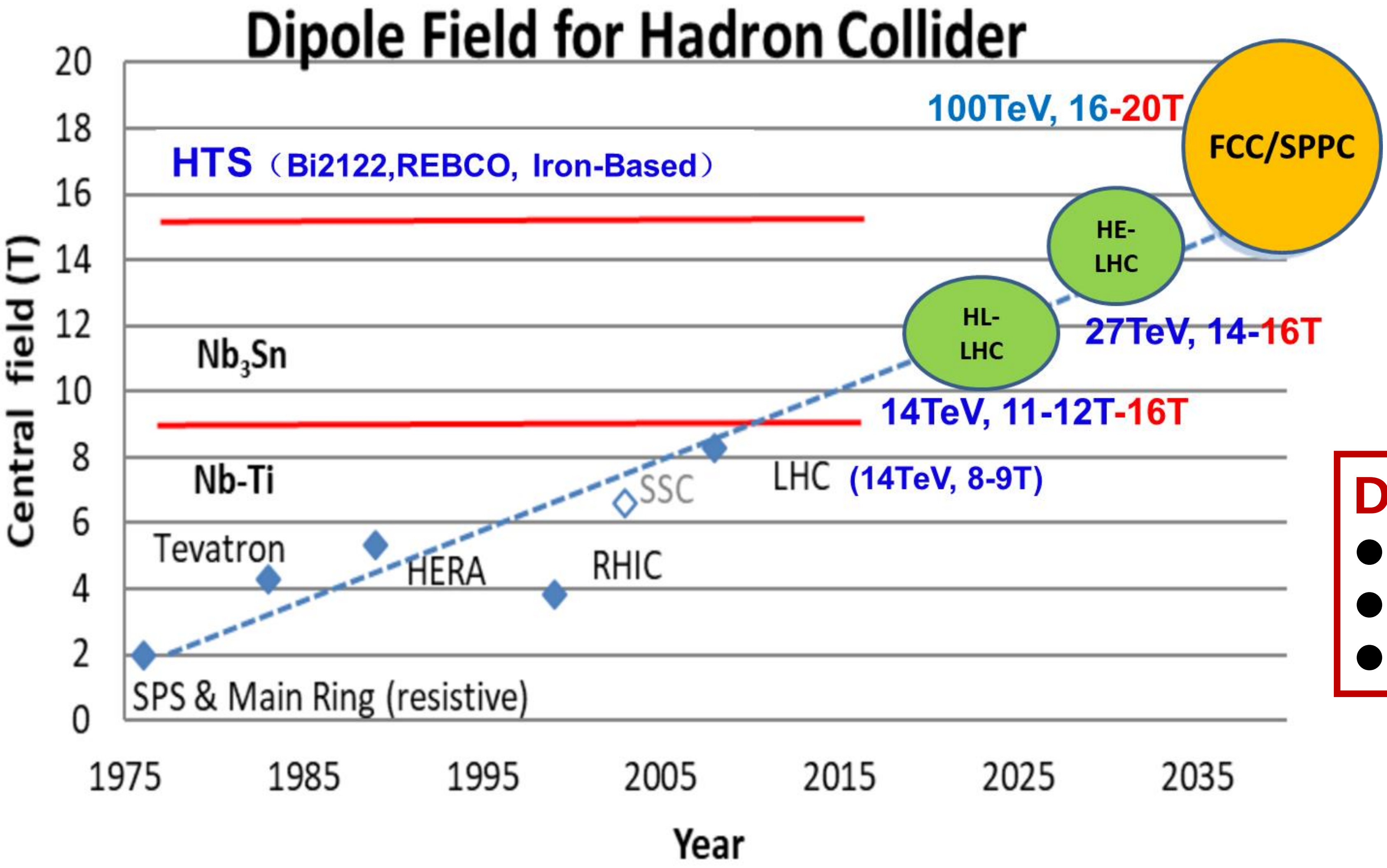
Integration of SRF cavities, SC solenoids, BPM, powers couplers, frequency tuners, LHe vessel, cavity support, magnetic shielding, multi-layer thermal shielding, …..







Accelerator high-B SC magnet：Development and State-of-the-Art



Two approaches

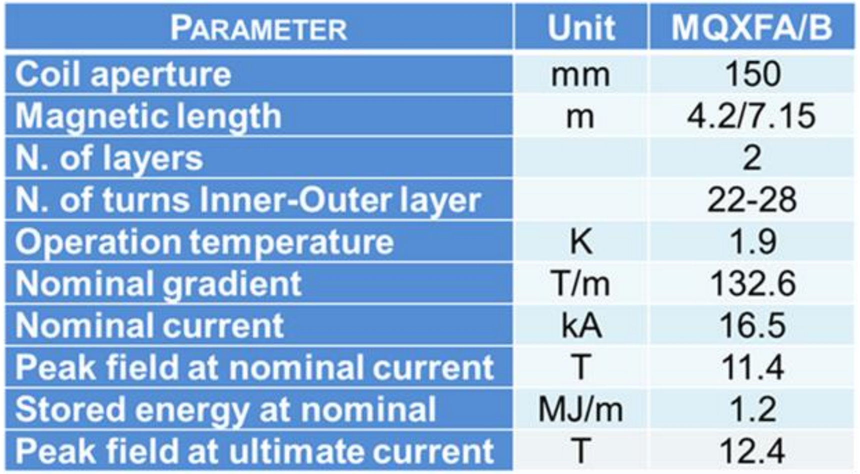
- LTS (Nb3Sn)
- HTS (REBCO) conductors

Demand and challenge

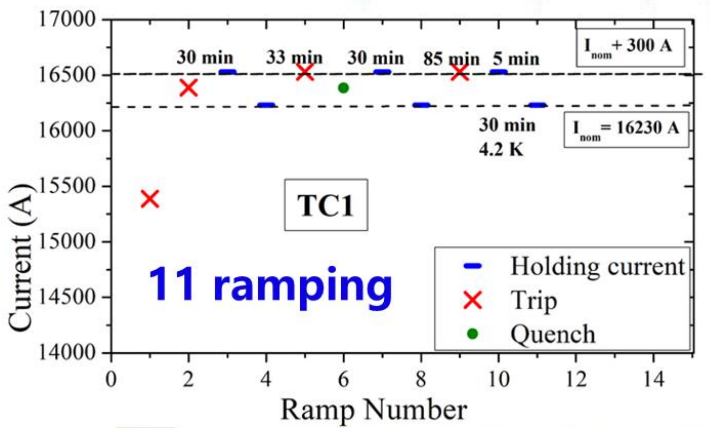
- 16-20 T dipole magnets
- ϕ1-1.5 m, 30 T solenoids
- 100-kT/s fast ramping dipole

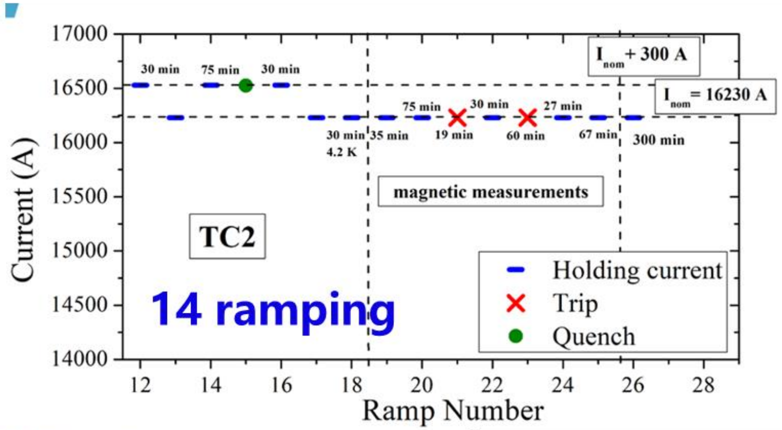
- Nb$_3$Sn Q-magnet：11-12T，in series production；12-16T dipole in prototyping
- HTS Bi2212、REBCO，solenoids >20T，16-20T dipole in prototyping

Nb_3Sn HL-LHC Quadrupole magnet



PARAMETER	Unit	MQXFA/B
Coil aperture	mm	150
Magnetic length	m	4.2/7.15
N. of layers		2
N. of turns Inner-Outer layer		22-28
Operation temperature	K	1.9
Nominal gradient	T/m	132.6
Nominal current	kA	16.5
Peak field at nominal current	T	11.4
Stored energy at nominal	MJ/m	1.2
Peak field at ultimate current	T	12.4



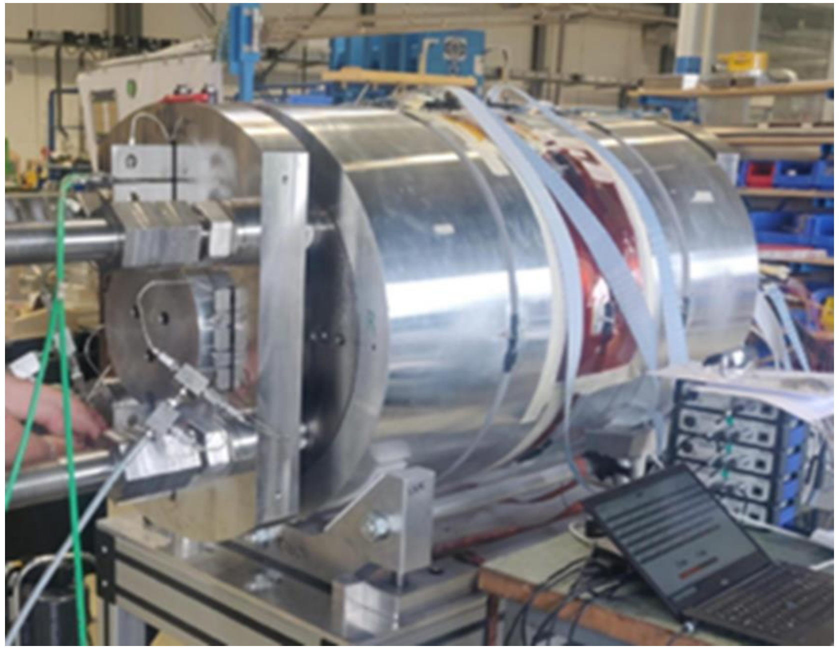


©M.Baldini, FNAL, IPAC24,

LTS Nb_3Sn dipole magnet

- **Nb_3Sn dipole demonstrator: 17 T achieved**

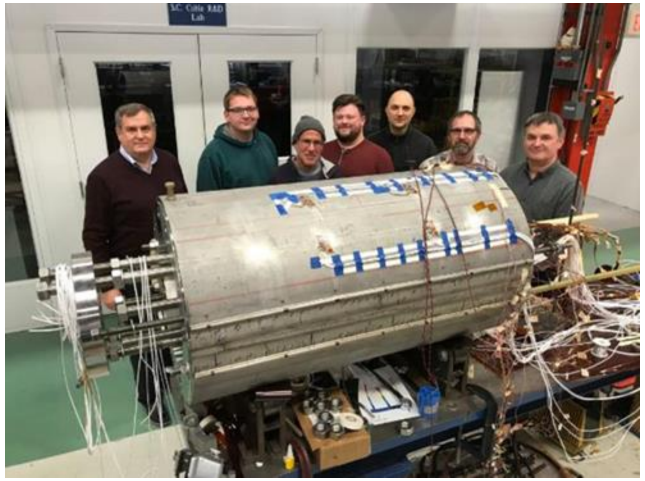
  Demonstrators: magnets not having all features of a short model, but proving a part of the technology (aperture 50 mm)



©D. Tommasini et al, CERN

- **LTS Nb_3Sn R&D directions:**

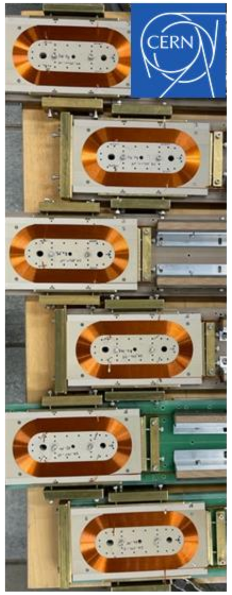
  - Improve performance / cost
  - Nb_3Sn / NbTi hybrid magnets at 1.9 K
  - Reduce cryogenic system complexity and cost for 4.5 K operation
  - Need intensive R&D: verify reproducibility and margins, reliable quench protection at high field



14.5T Dipole by Fermilab

Future high field SC magnets: HTS magnet

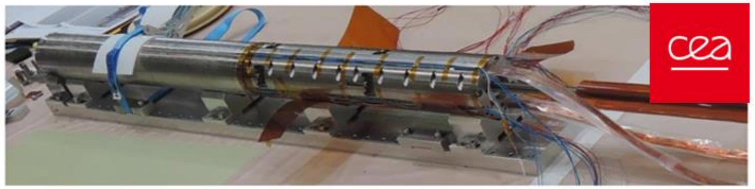
- Possible to realize J >1000 A/mm2 , B > 20T, T > 20K
- HTS conductors: ReBCO, BSCCO(Bi-2223,2221), IBS
- Key issues: degradation, quench losses and quench protection, cost
- Accelerator demands: field quality, reproducibility, long-term stability, uniformity
- HTS/LTS hybrid technology: Possible cost saving but still need 1.9 or 4.5K for LTS, strong interaction between the LTS coils and HTS coils.


CERN insulated
tape-stack cable racetracks

So many labs involved

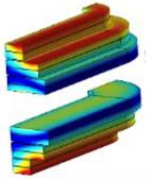
EUCARD2 Feather M2 (CERN)

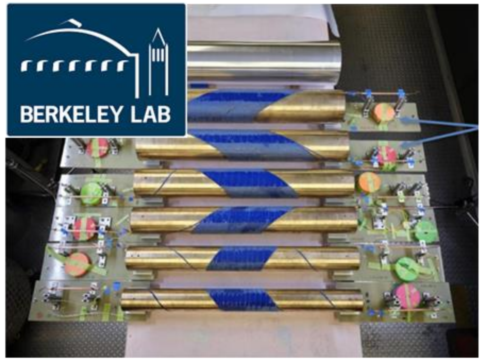
EUCARD2 Cos Theta (CEA)




CEA MI
Racetrack


6 T insert coils by IHEP




REBCO CCT with CORC ® Cable

Beam Temperature and Beam Cooling

The beam particles are generated in a “hot” source

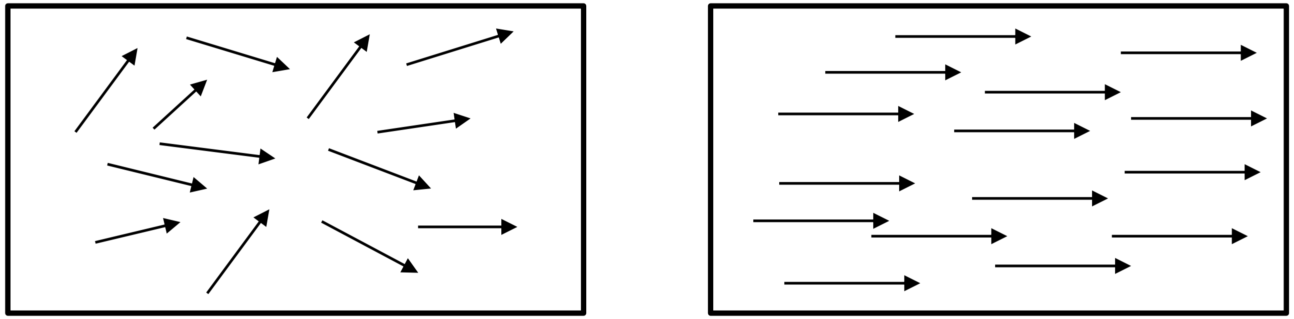
- Longitudinal beam temperature

$$\frac{1}{2}k_B T_\parallel = \frac{1}{2}m\langle v_\parallel^2\rangle = \frac{1}{2}mc^2\beta^2\left(\frac{\delta p_\parallel}{p}\right)^2$$

- Transverse beam temperature

$$\frac{1}{2}k_B T_\perp = \frac{1}{2}m\langle v_\perp^2\rangle = \frac{1}{2}mc^2\beta^2\gamma^2\theta_\perp{}^2$$

$$\theta_\perp(s) = \frac{v_\perp(s)}{\beta c} = \sqrt{\frac{\varepsilon_\perp}{\beta_\perp(s)}}$$


hot beam

cold beam

Beam temperature depends on “momentum spread” and “emittance”, the **phase space volume**

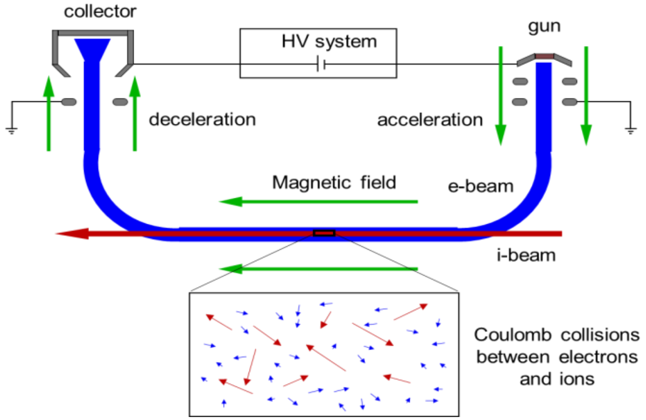
- **Liouville’s theorem** (in Hamiltonian dynamics) states that **the volume of phase space is invariant** under time evolution (conserved).
- **Need beam cooling** to reduce momentum spread and emittance.

Typical beam cooling methods and technologies

Beam cooling methods are non-Liouvillean processes which are used for a reduction of beam temperature and improvement of beam quality

Electron cooling

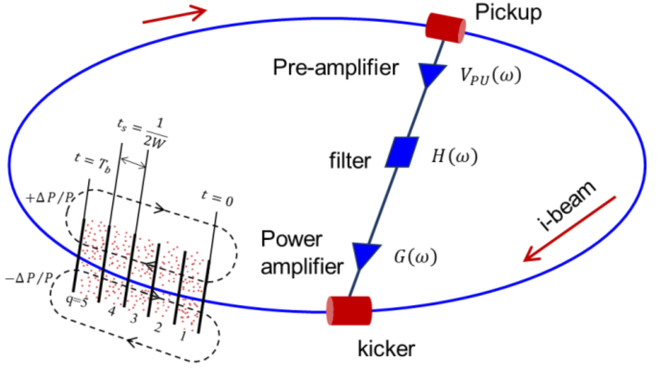
Principle: momentum transfer by coulomb collisions between electron and ion



- for low or medium energy beams
- strong cooling effects
- very slow for high energy beam and high beam power.
- Cooling time ~ γ^3

Stochastic cooling

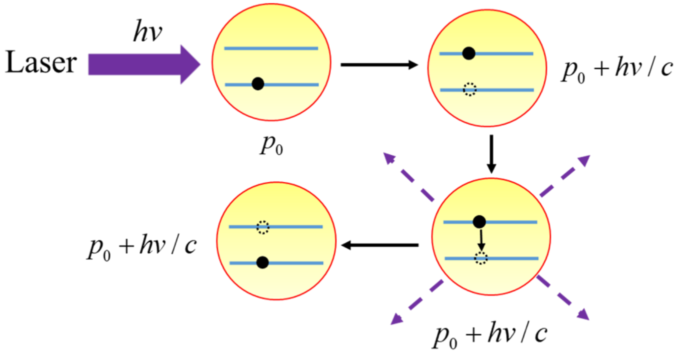
Principle: measurement of deviation from ideal orbit is used for correction kick (feedback)



- for low intensity and hot beams
- pre-cooling for secondary ions
- limited by bandwidth and beam density, slow for high energy and high intensity beam

Laser cooling

Principle: directed excitation and random emission result in a transfer of momentum



- ultra fast cooling process
- very strong cooling effect
- quite particular method, limited by laser frequency

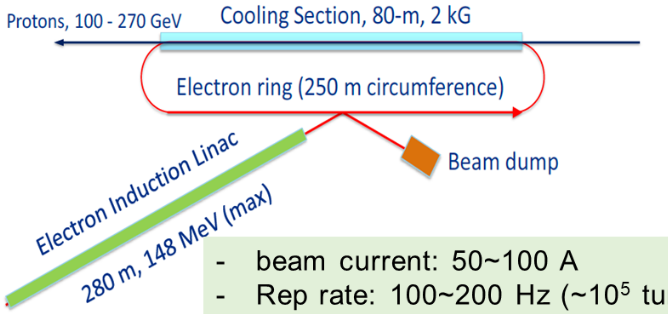
Coherent electron cooling : use electron beam as cooling media and to cool ions stochastically with bandwidth at f 1-100 THz

Beam cooling challenge

Key challenge and demand:

- Fast beam cooling dedicated to particle beams with high energy, high intensity and high momentum spread, such as for proton, heavy ion or secondary ion beam, muon beam, not yet demonstrated successfully.
- New ideas， new technology, breakthrough needed urgently. Coherent electron cooling, ionization cooling…, not yet demonstrated.

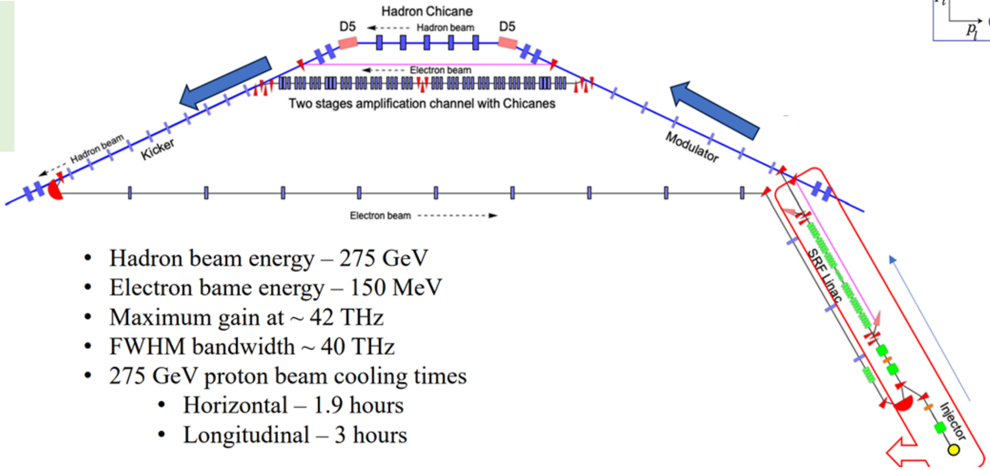
Fermilab: induction linac+ring for EIC project, weakly-magnetized cooling



- beam current: 50~100 A
- Rep rate: 100~200 Hz (~10^5 turns storage time)
- Beam power to dump: <400 kW

Cooling for EIC high energy proton beam

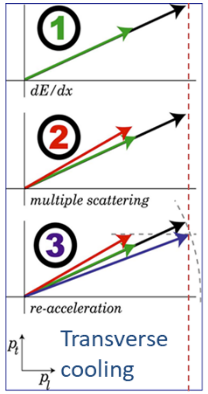
CeC cooler for EIC at BNL

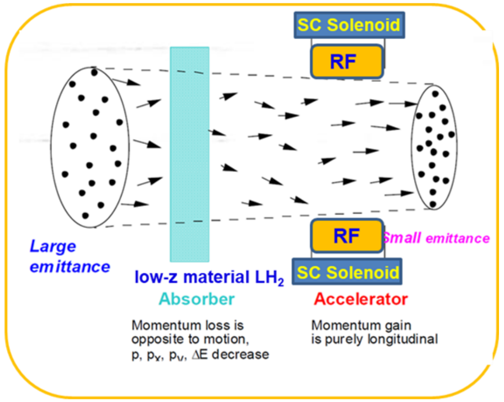


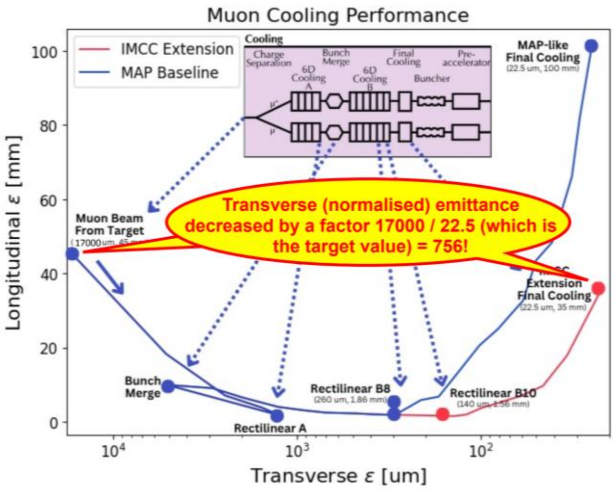
- Hadron beam energy – 275 GeV
- Electron bame energy – 150 MeV
- Maximum gain at ~ 42 THz
- FWHM bandwidth ~ 40 THz
- 275 GeV proton beam cooling times
  - Horizontal – 1.9 hours
  - Longitudinal – 3 hours

©Vladimir N Litvinenko, SBU, HB2025.

Muon ionization cooling for muon collider







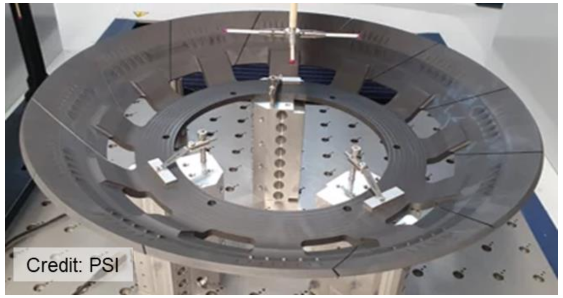
Transverse (normalised) emittance decreased by a factor 17000 / 22.5 (which is the target value) = 756!

©E. Métral, CERN, HB2025

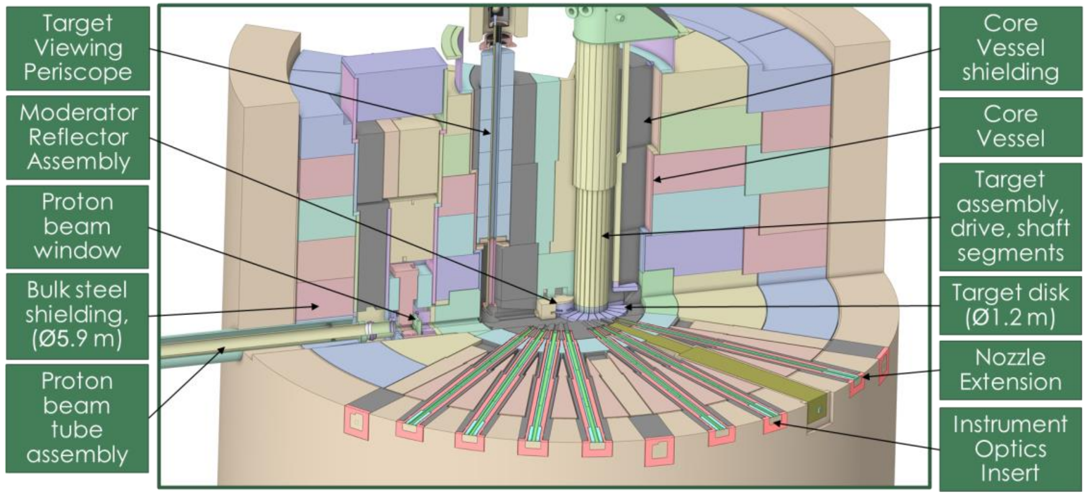
Target for high power beam

- Utilize high power beam on target to produce secondary particles
- Target for spallation neutrons, ADS, μ and neutrino beam, ~ MW power
- Target for radiactive isotope. tens kw-hundreds kW
- Graphite, solid metal, flowing liquid metal, fluidised powders…
- Fixed, rotating, Conveyors,…
- **Key issues:**
  - Rapid temperature cycling, active cooling e.g. forced flow Helium.
  - Extreme high-radiation damage, swelling, structural degradationTarget
  - Lifetime and beam window lifetime (Ti/Al, Be)
  -

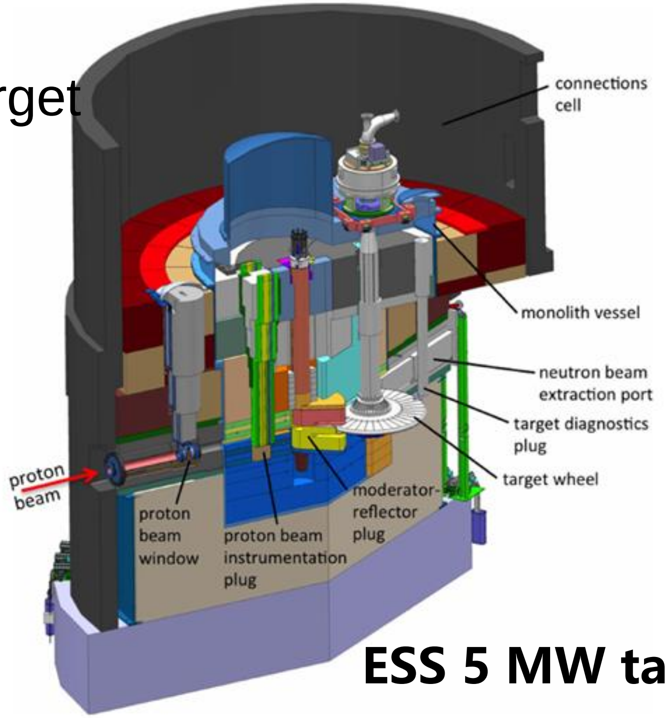
CSNS target(150-180 kW



PSI target for surface μ



SNS 2 MW target design



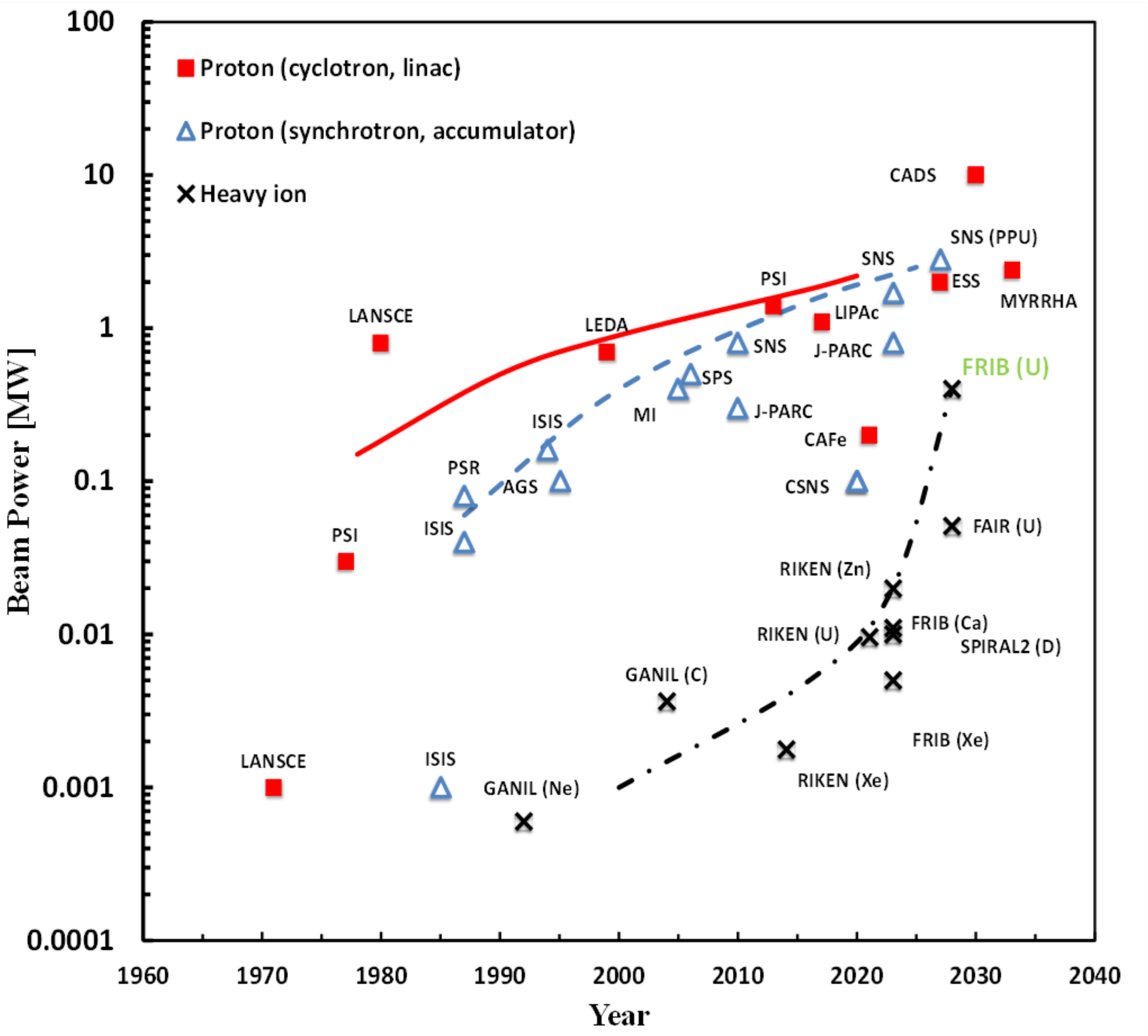
ESS 5 MW target

Outline

High-Intensity High-Power Ion Accelerator （HIHPIA)

1. Brief introduction of HIHPIA
2. Key technologies and challenges
3. **World-wide HIHPIA and HIAF&CiADS at IMP**
4. Conclusion remarks

Evolution of proton and heavy ion beam power

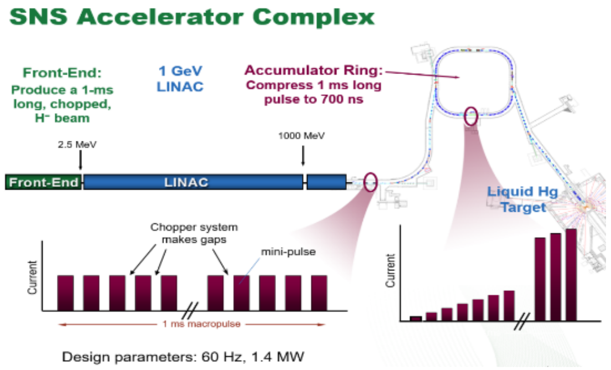


Proton: 1-10 mA, 0.1-5 MW

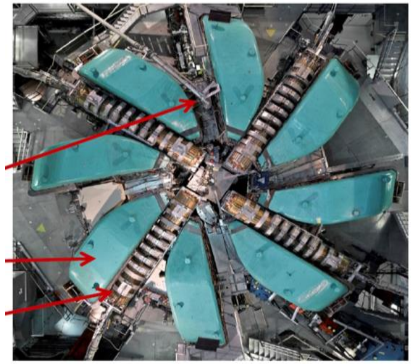
Heavy ion: tens pμA, 10-400 kW

©J. Wei, FRIB/MSU, HB2023

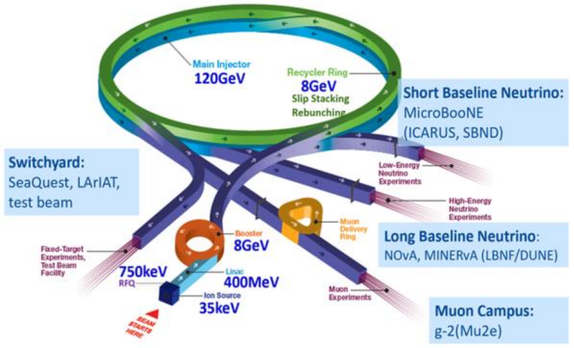
World-wide high-intensity and high-power ion accelerators （kW-MW)



ORNL SNS

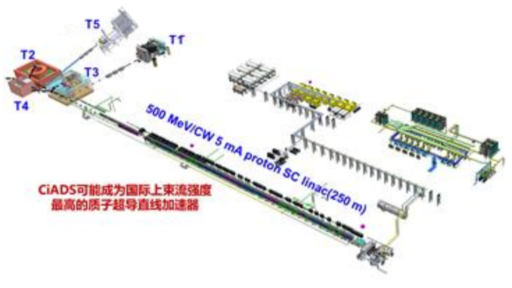


PSI cyclotrons

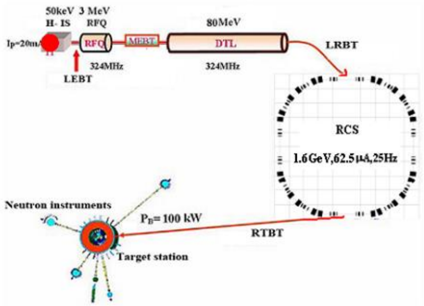


FNAL proton accelerator complex

JPARC

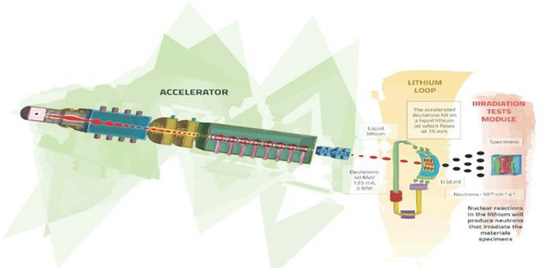


IMP CIADS （construction)

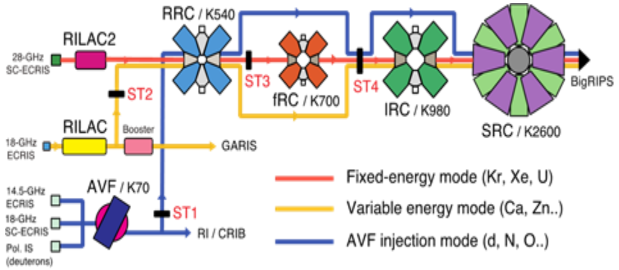


IHEP CSNS

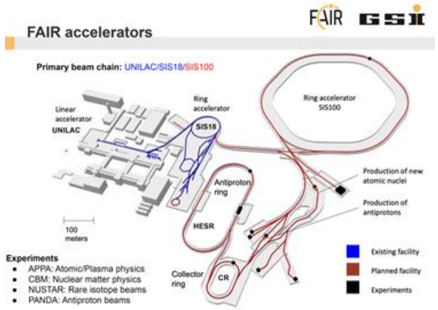
ESS （construction and commiss.)



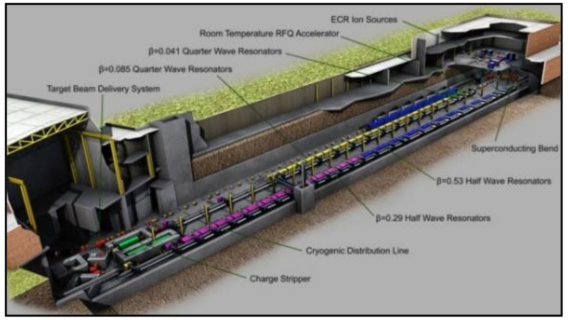
IFMIF （Plan)



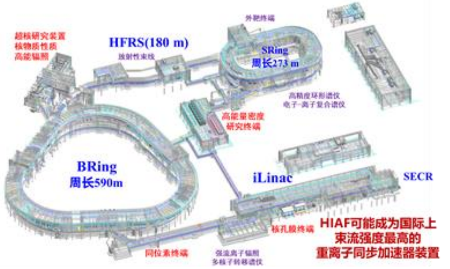
RIKEN-RIBF



GSI FAIR （construction)

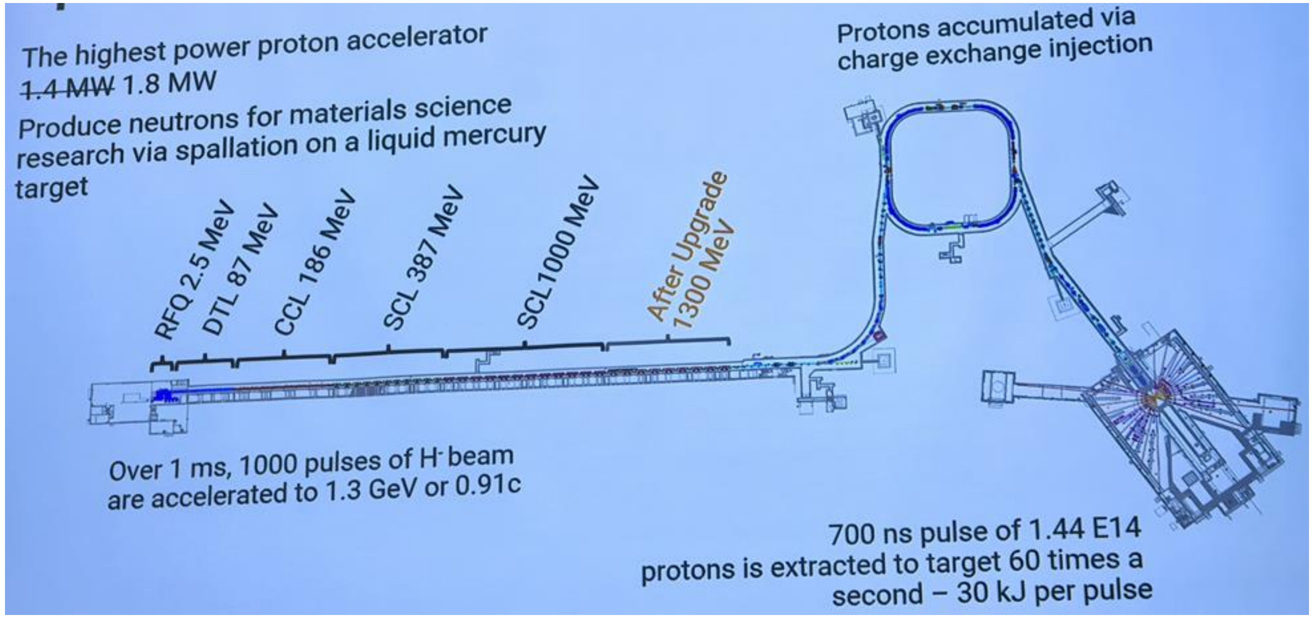


MSU FRIB



IMP HIAF （started operation)

ORNL-SNS average beam power 2 MW

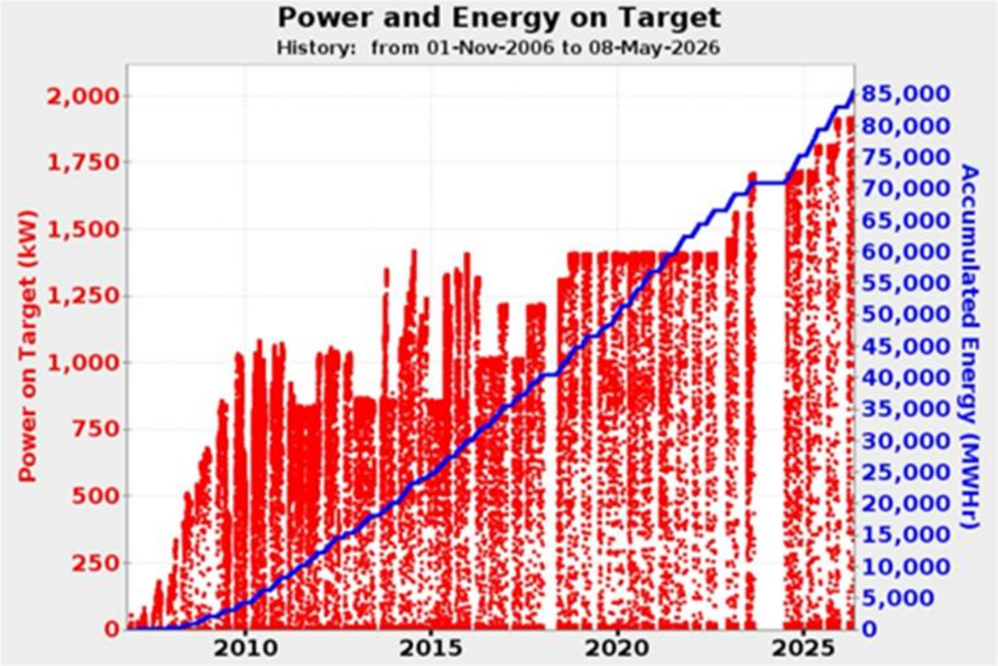


The highest power proton accelerator
~~1.4 MW~~ 1.8 MW
Produce neutrons for materials science research via spallation on a liquid mercury target

Protons accumulated via charge exchange injection

Over 1 ms, 1000 pulses of H^- beam are accelerated to 1.3 GeV or 0.91c

700 ns pulse of 1.44 E14 protons is extracted to target 60 times a second – 30 kJ per pulse

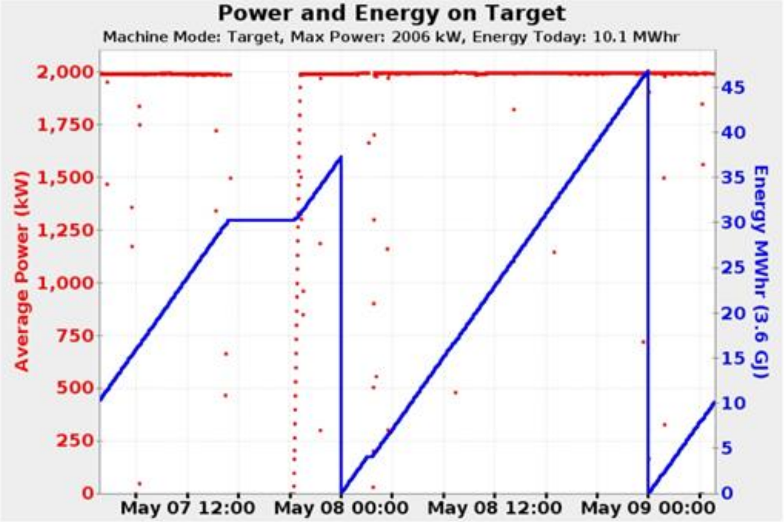


Power and Energy on Target

History: from 01-Nov-2006 to 08-May-2026

To be upgraded to 2.8 MW

The world most powerful proton accelerator facility

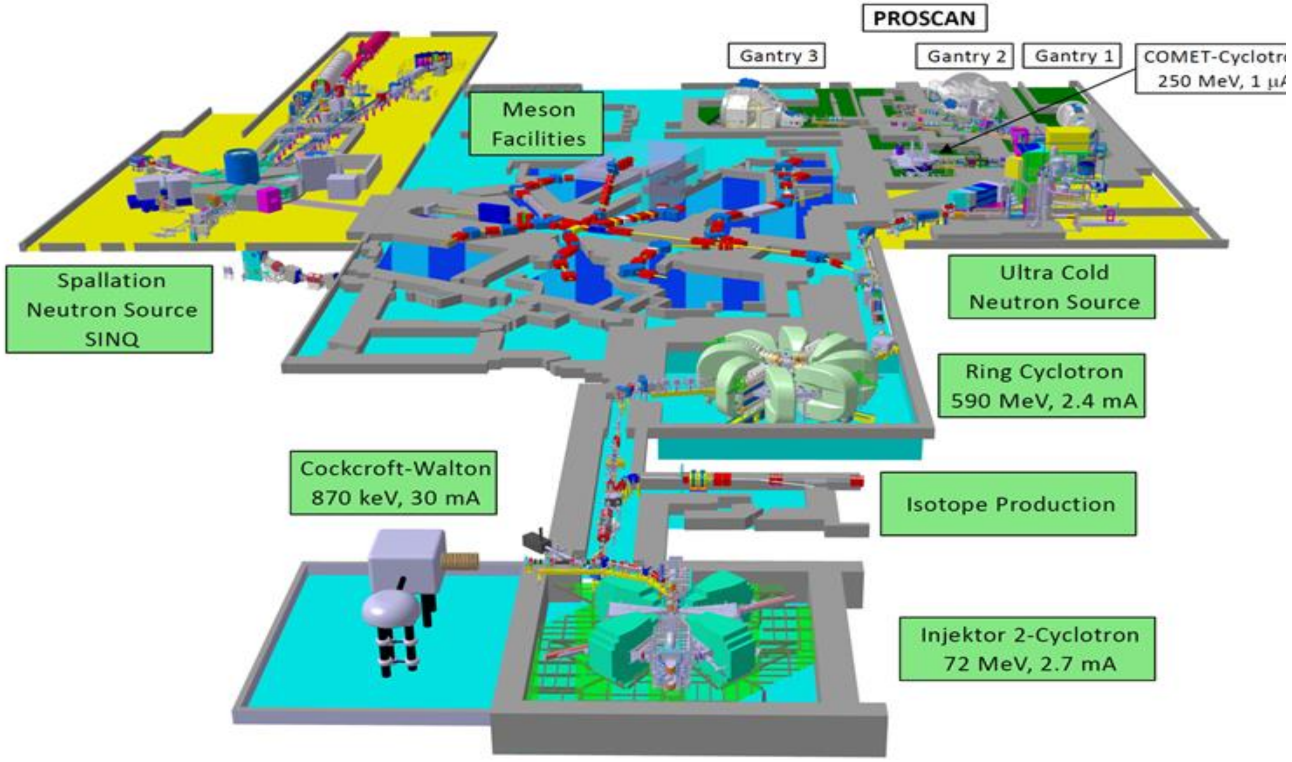


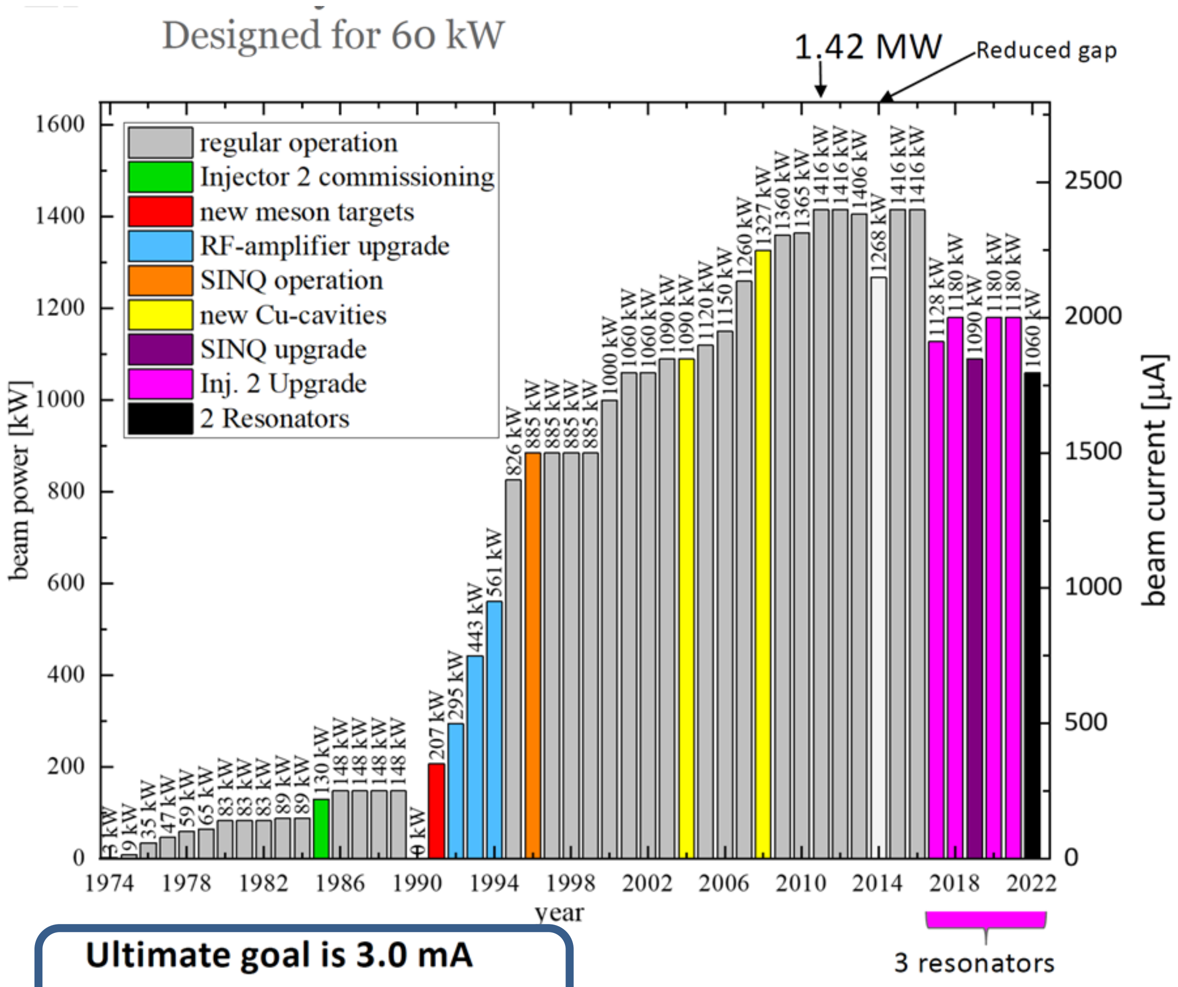
Power and Energy on Target

Machine Mode: Target, Max Power: 2006 kW, Energy Today: 10.1 MWhr

https://status.sns.ornl.gov/beam.jsp

PSI proton cyclotron complex 1.4 MW



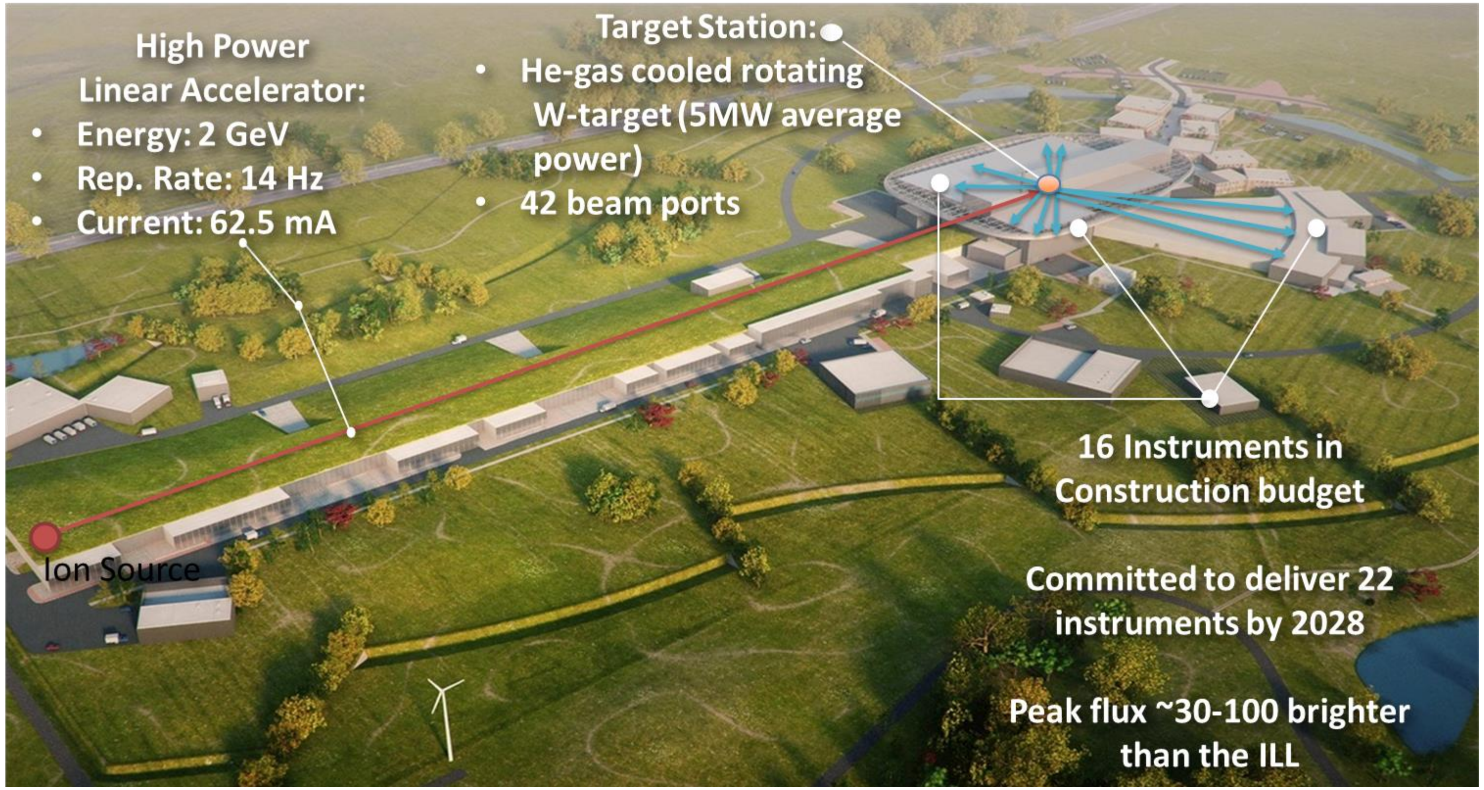


©Joachim Grillenberger, PSI, talk at HB2023

Ultimate goal is 3.0 mA
Corresponds to 1.8 MW

Being upgraded to 1.8 MW

ESS 5MW average beam power Commissioning



High Power Linear Accelerator:
- Energy: 2 GeV
- Rep. Rate: 14 Hz
- Current: 62.5 mA

Target Station:
- He-gas cooled rotating W-target (5MW average power)
- 42 beam ports

16 Instruments in Construction budget

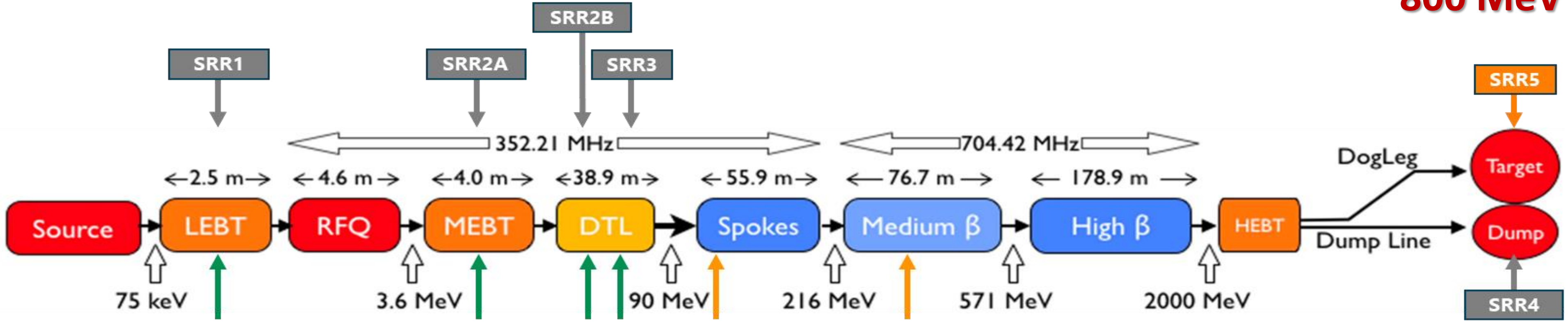
Committed to deliver 22 instruments by 2028

Peak flux ~30-100 brighter than the ILL

SC linac 2 GeV/5 MW

- 2014 start construction, 3 phases.
- **Beam on target milestone requires capability for 1.4 MW at 571 MeV with nominal pulse structure**
- Start Of User Operation requires capability for 2 MW at 870 MeV with nominal pulse structure
- Full scope is 5 MW at 2 GeV with 2.86 ms long pulses at 14 Hz

Commissioning
800 MeV beam on target in 2026



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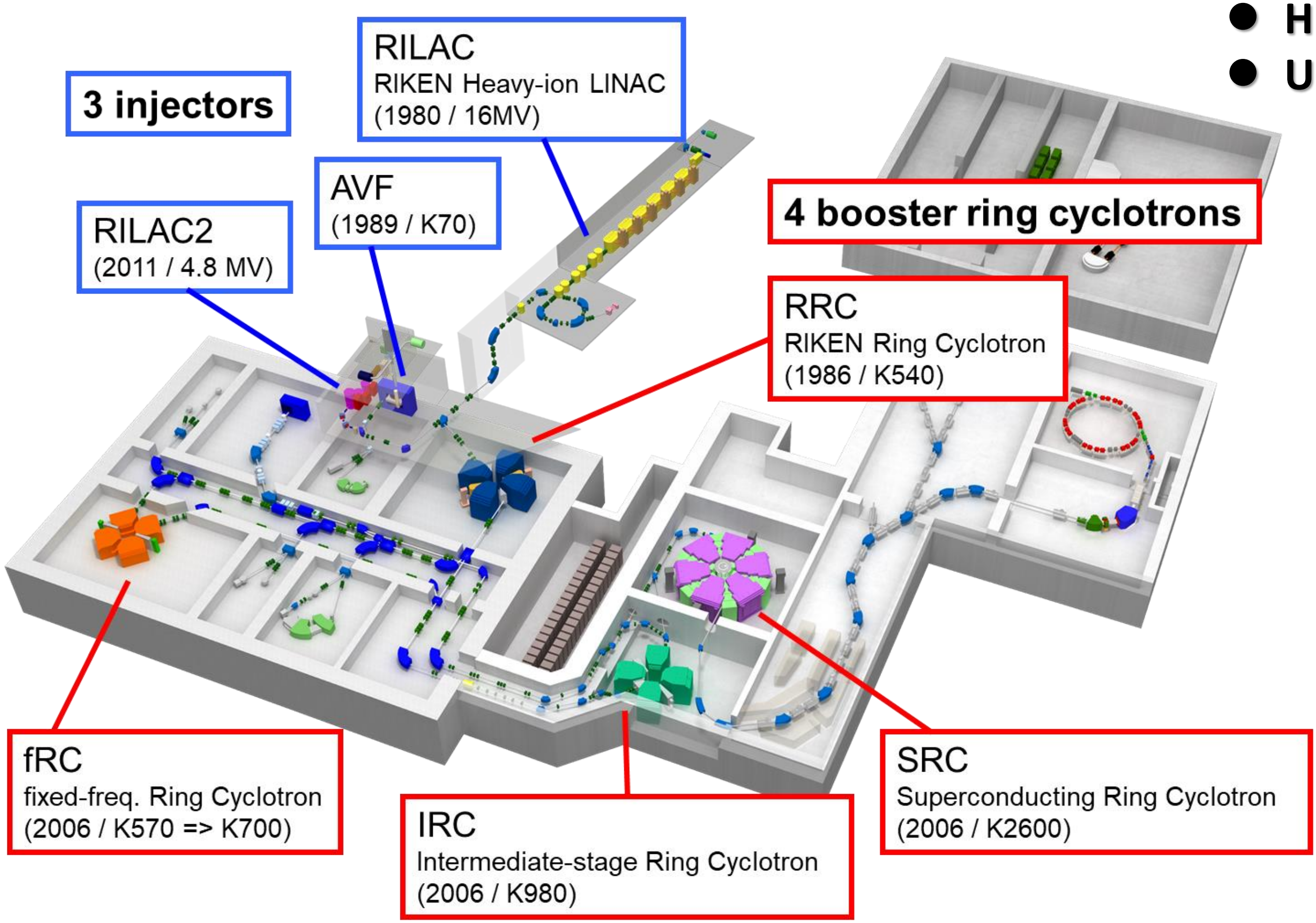
RIKEN RIBF heavy ion cyclotron complex



3 injectors

RILAC
RIKEN Heavy-ion LINAC
(1980 / 16MV)

AVF
(1989 / K70)

RILAC2
(2011 / 4.8 MV)

4 booster ring cyclotrons

RRC
RIKEN Ring Cyclotron
(1986 / K540)

fRC
fixed-freq. Ring Cyclotron
(2006 / K570 => K700)

IRC
Intermediate-stage Ring Cyclotron
(2006 / K980)

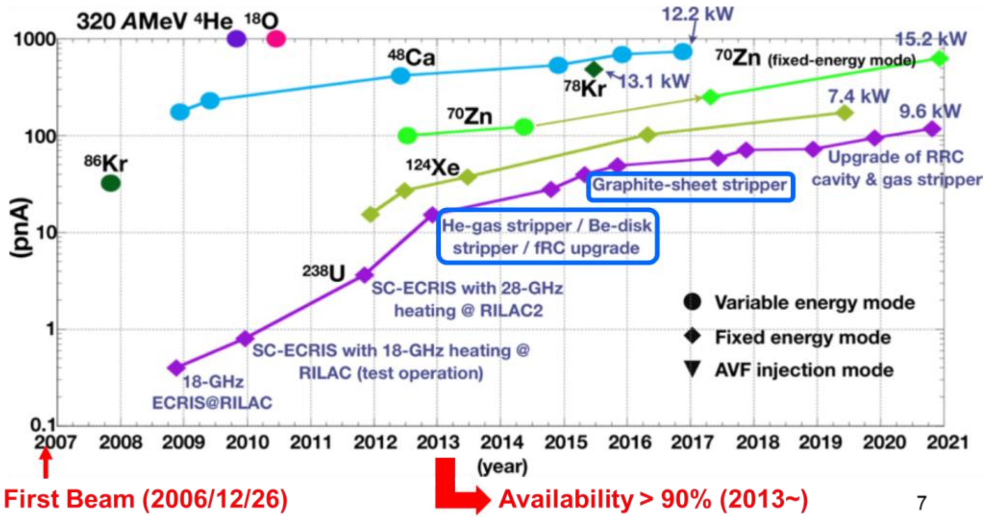
SRC
Superconducting Ring Cyclotron
(2006 / K2600)

- **Highest energy of CW heavy ion accelerator complex**
- **Used to be a highest power heavy ion accelerator**

History of accelerator performance

Our goal: 1pμA (6 x 10^{12} #/s) for all elements

^{48}Ca 736 nA → 12.2 kW	^{70}Zn 629 nA → 15.2 kW	^{124}Xe 173 nA → 7.4 kW	^{238}U 117 nA → 9.6 kW



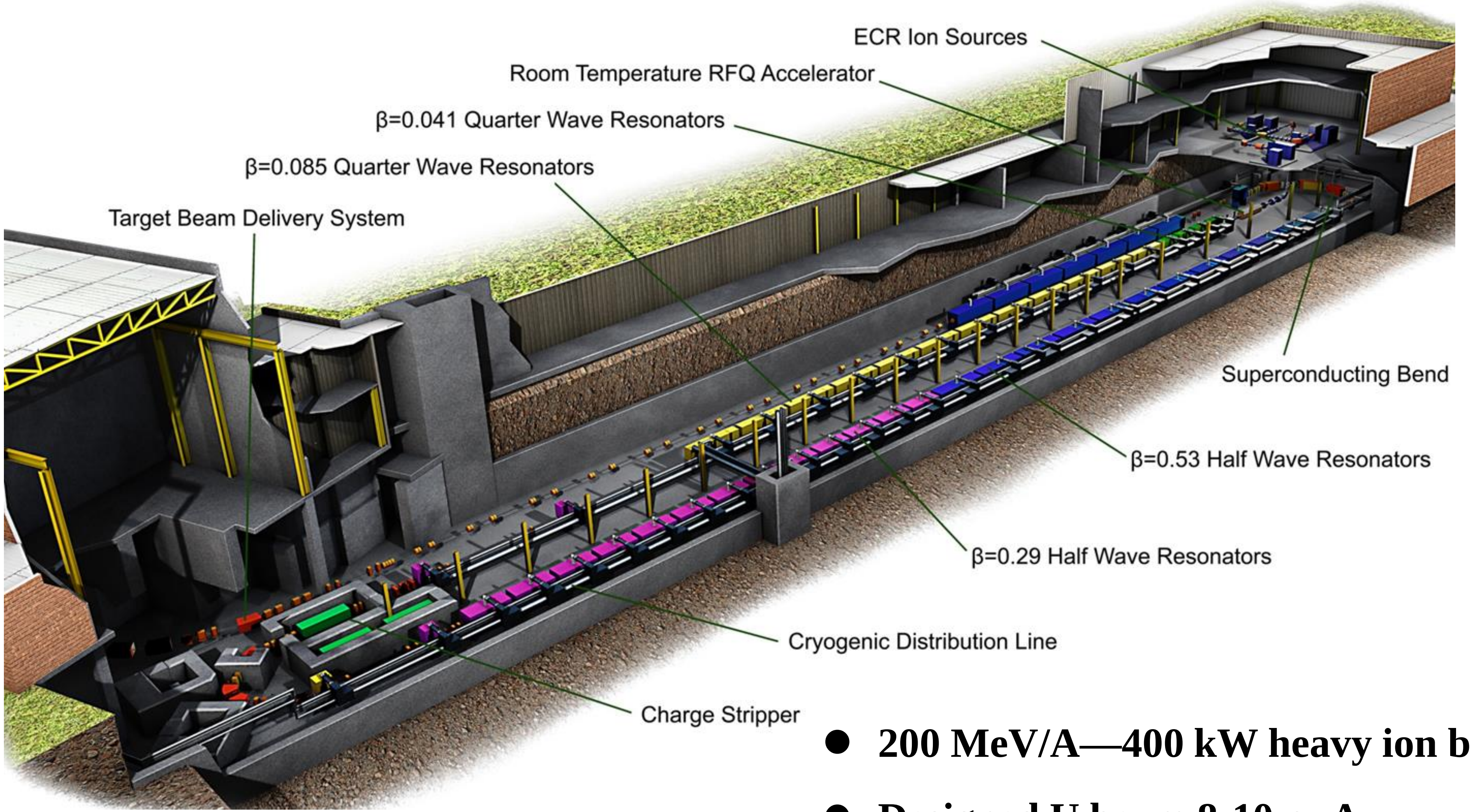
First Beam (2006/12/26)

Availability > 90% (2013~)

1) AVF-injection mode (< 440 MeV/u) : d, He, O, …
2) Variable-energy mode (< 400 MeV/u) : Ar, Ca, Zn, Kr, …
3) Fixed-energy mode (345 MeV/u) : Xe, U …

© H. Okuno, RIKEN, talk at HPTW2023

MSU-FRIB Heavy ion SC linac

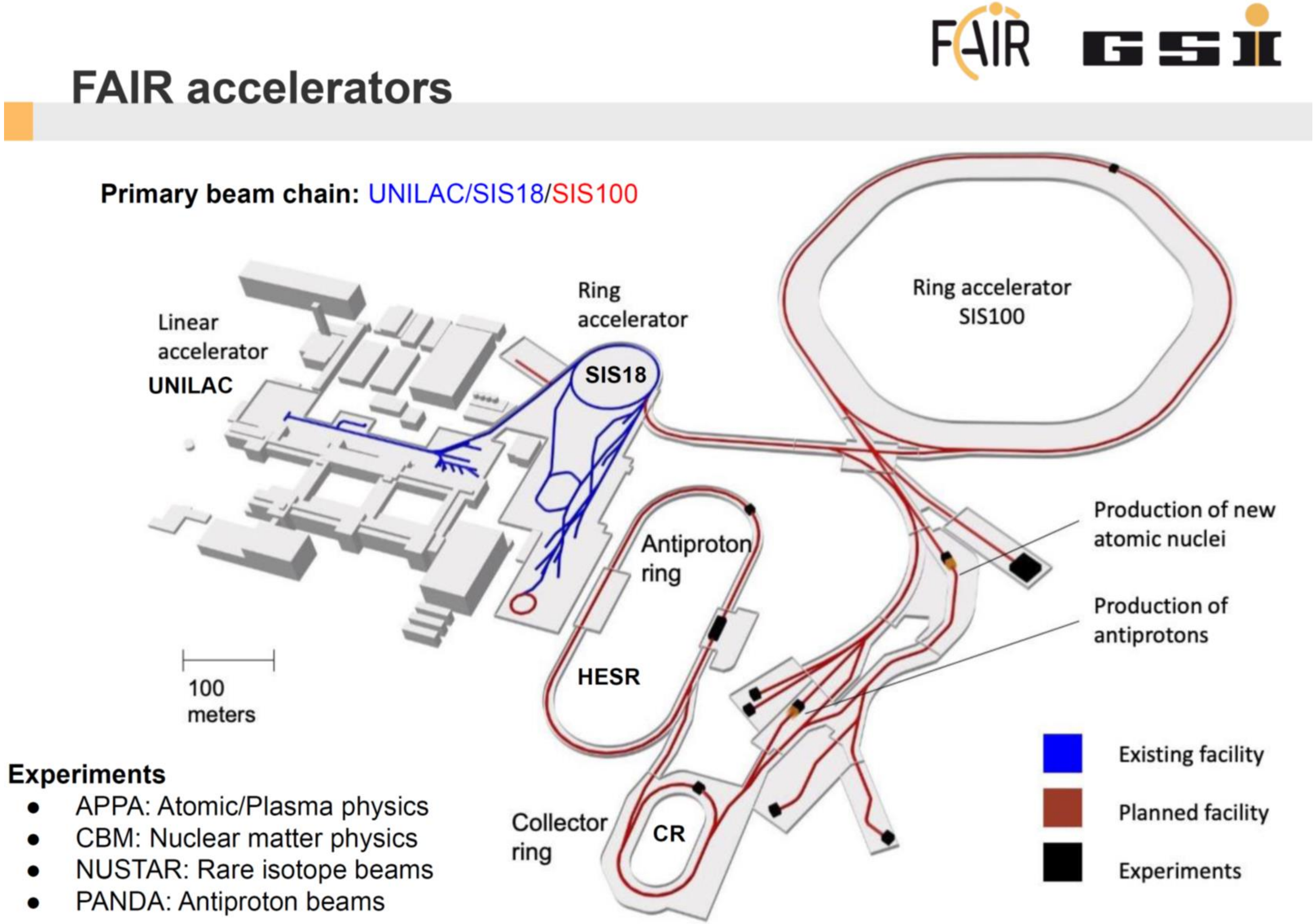


- 200 MeV/A—400 kW heavy ion beam， now 30 kW
- Designed U beam 8-10 pμA
- Started routine operation in 2022

The world most powerful heavy ion accelerator!

GSI-FAIR accelerator complex

Construction



FAIR accelerators

Primary beam chain: UNILAC/SIS18/SIS100

Experiments

- APPA: Atomic/Plasma physics
- CBM: Nuclear matter physics
- NUSTAR: Rare isotope beams
- PANDA: Antiproton beams

Operation in 2030

- **$^{238}U^{28+}$ 1.5 GeV/A, 5×10^{11} ppp**

HIAF&CiADS at IMP --- Brief introduction

- **HIAF: High Intensity heavy ion Accelerator Facility**
- **CiADS: China Initiative Accelerator Driven System**
- **Being built by IMP in Huizhou of Guangdong Prov.**

- **Two of 16 large-scale scientific infrastructure facilities approved by China Government during the 12th 5-year-plan 2016-2020**

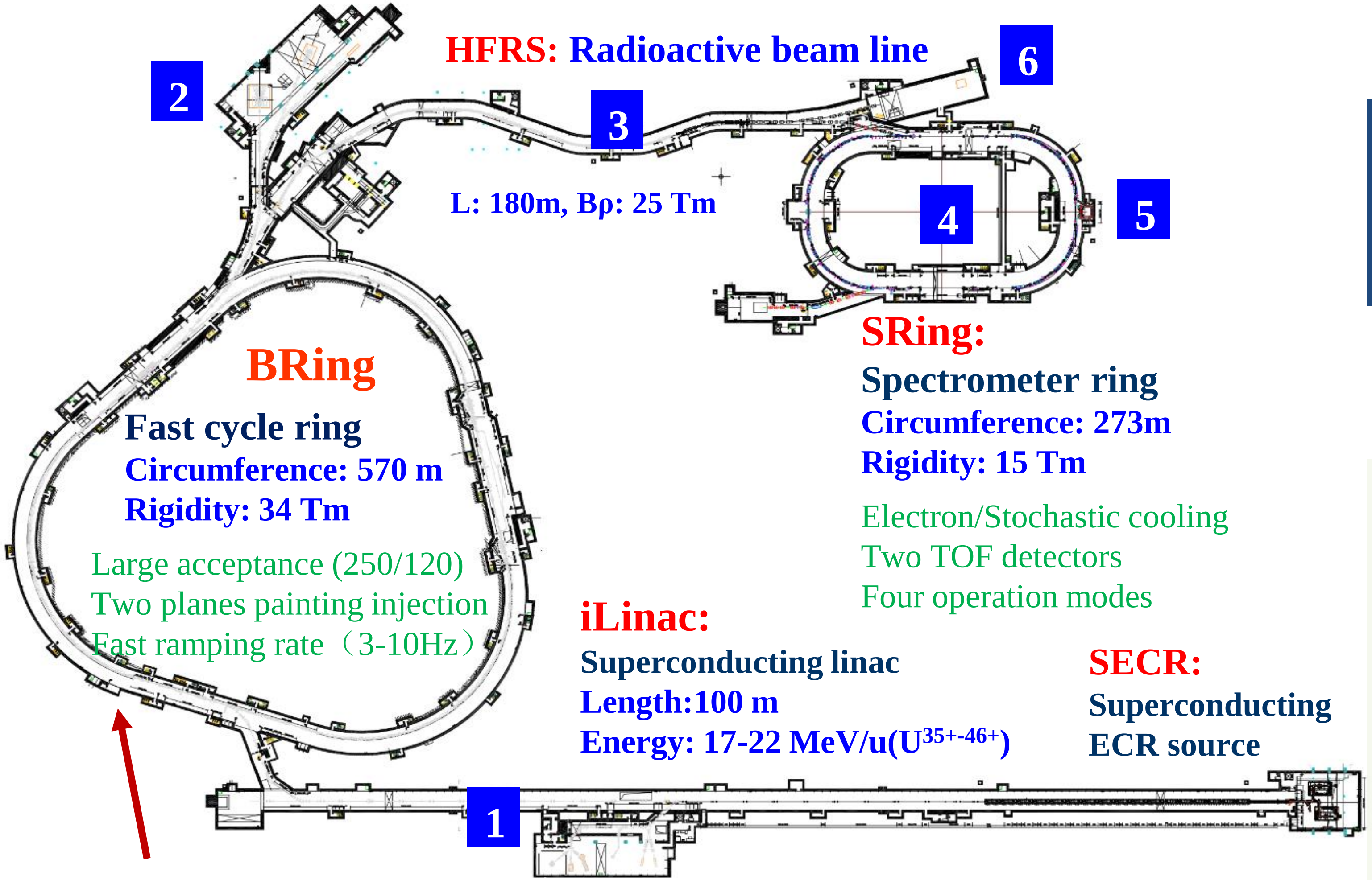
- **HIAF:** Nuclear physics research
- **Total budget:** 2.8 B CNY ¥ (424 M USD $)
- **Schedule:** 2018-2025
- Construction started officially Dec. 2018

- **CiADS:** Nuclear waste transmutation
- **Total budget:** 4.0 B CNY ¥ (606 M USD $)
- **Schedule:** 2021-2027
- Construction started officially July. 2021

HIAF&CiADS Construction Site

HIAF general layout and overview

☐ **HIAF is aimed to provide the highest intensity heavy ion beams in the world**



HFRS: Radioactive beam line

L: 180m, Bρ: 25 Tm

BRing

Fast cycle ring

Circumference: 570 m

Rigidity: 34 Tm

Large acceptance (250/120)

Two planes painting injection

Fast ramping rate（3-10Hz）

SRing:

Spectrometer ring

Circumference: 273m

Rigidity: 15 Tm

Electron/Stochastic cooling

Two TOF detectors

Four operation modes

iLinac:

Superconducting linac

Length:100 m

Energy: 17-22 MeV/u(U$^{35+-46+}$)

SECR:

Superconducting ECR source

^{238}U^{35+}	0. 8 GeV/u	0. 5-2. 0×10^{11} ppp
^{238}U^{76+}	2. 45 GeV/u	0. 25-0. 5×10^{11} ppp
p	9.3 GeV/u	5×10^{13}ppp

Accelerator main components

- 4th ECR ion source (**SECR**)
- Superconducting Linac (**iLinac**)
- Fast ramping synchrotron (**BRing**)

Experimental terminals in Phase-I

① Low energy nuclear structure terminal
② High energy experimental terminal
③ High energy fragment separator HFRS
④ High precision spectrometer ring SRing
⑤ Electron ion recombination terminal
⑥ Radioactive ion beam physics terminal

Major Challenges

HIAF Could be the world most intense pulsed heavy-ion facility

Institute	Machine	Planned	Achieved	Ion
BNL	AGS Booster		5×10^{9}	Au^{32+}
CERN	LEIR		9×10^{8}	Pb^{54+}
JINR	NICA Booster	4×10^{9}	/	Au^{32+}
GSI	SIS18	1.0×10^{11}	$\sim 4\times10^{10}$	U^{28+}
FAIR	SIS100	4.0×10^{11}	/	U^{28+}
IMP	**HIAF-BRing**	**$>1.0\times10^{11}$**	**/**	**U^{35+}**
IMP	**HIAF-SRing**	**$>5.0\times10^{12}$**	**/**	**U^{92+}**
IMP	**HIRFL-CSR**	**1.0×10^{9}**	**1.0×10^{8}**	**U^{74+}**

Challenge-1:
Beam dynamics

leads to

- **Nonlinear effects**
- **Space charge effects**
- **Collective effects**
- **Dynamic vacuum**

limits

Beam intensity
Beam quality

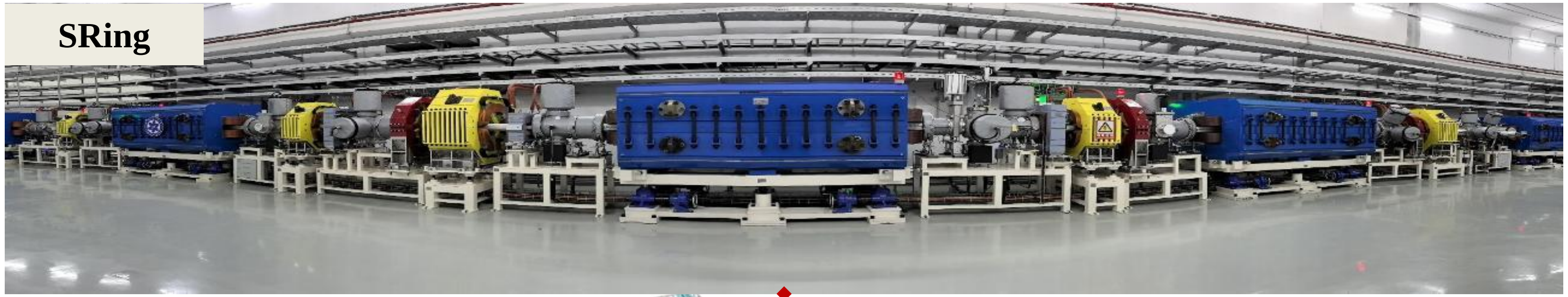
Challenge-2
Technology aspect

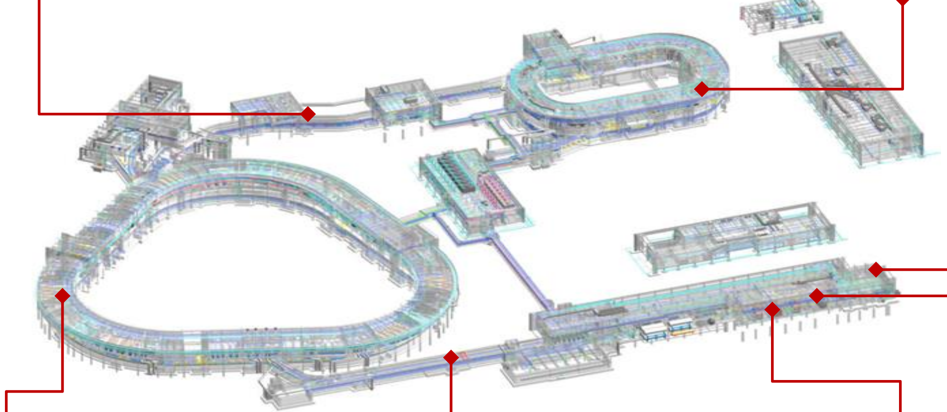
- **Beam production**
- **Low energy manipulation**
- **Fast ramping acceleration**

HIAF project construction (1)

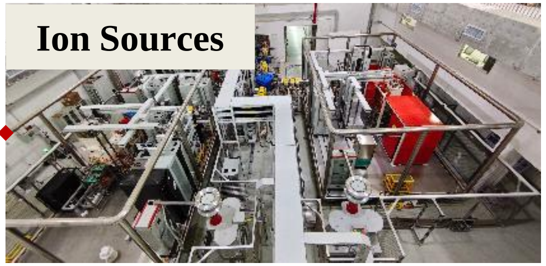
HiRIBL (HFRS)

SRing





Ion Sources

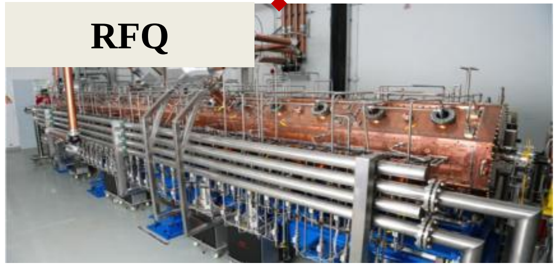


BRing

BRing Injection Line

iLinac

RFQ



HIAF project construction (2)


Radiation resistant dipoles


Warm iron SC-dipoles


Electron Cooler


Full energy storage PS


Extraction Kicker PS

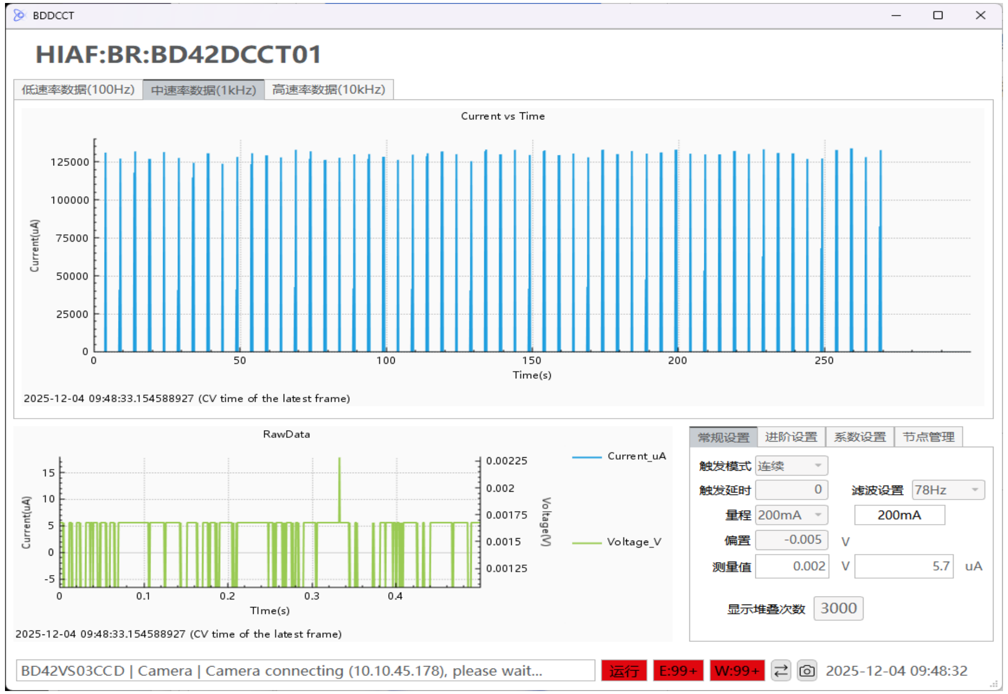

RF Power Station


Injection Kicker

HIAF Beam Commissioning (1)

Typical nonmetallic ions ^{18}O

New High Energy ^{18}O Beam Intensity Record



HIAF:BR:BD42DCCT01

2025-12-04 09:48:33.154588927 (CV time of the latest frame)

2025-12-04 09:48:33.154588927 (CV time of the latest frame)

触发模式 连续

触发延时 0

滤波设置 78Hz

量程 200mA 200mA

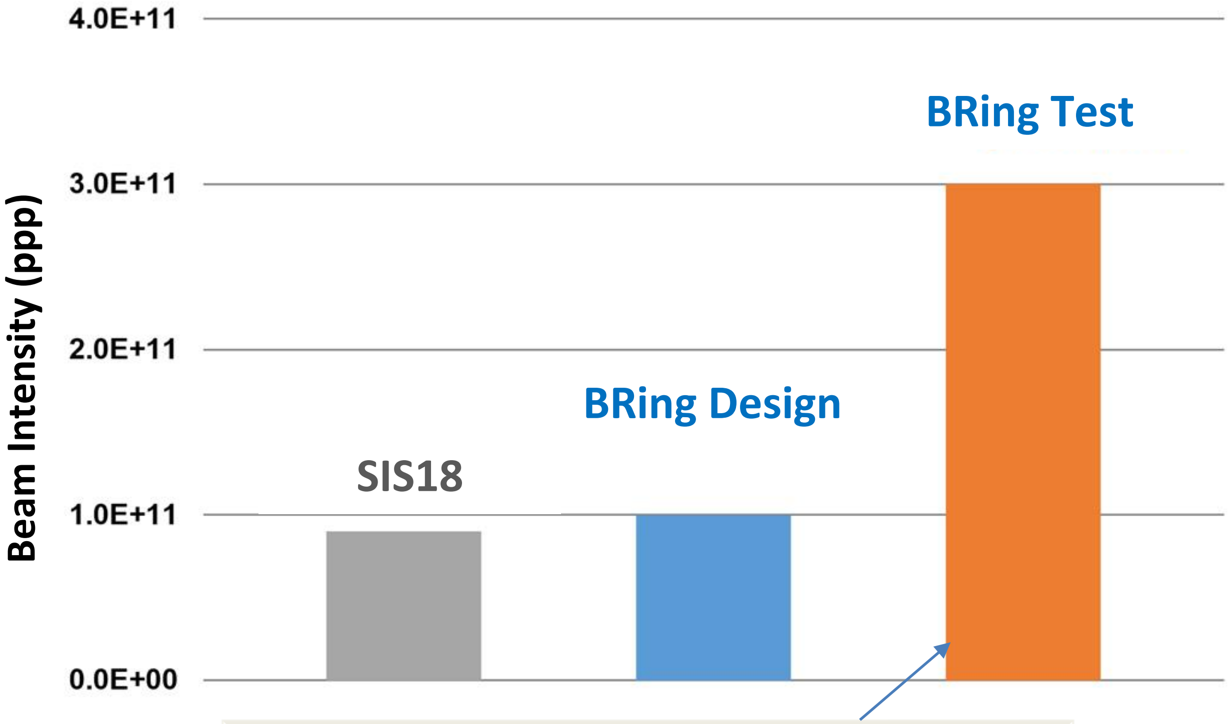
偏置 -0.005 V

测量值 0.002 V 5.7 uA

显示堆叠次数 3000

BD42VS03CCD | Camera | Camera connecting (10.10.45.178), please wait...

2025-12-04 09:48:32

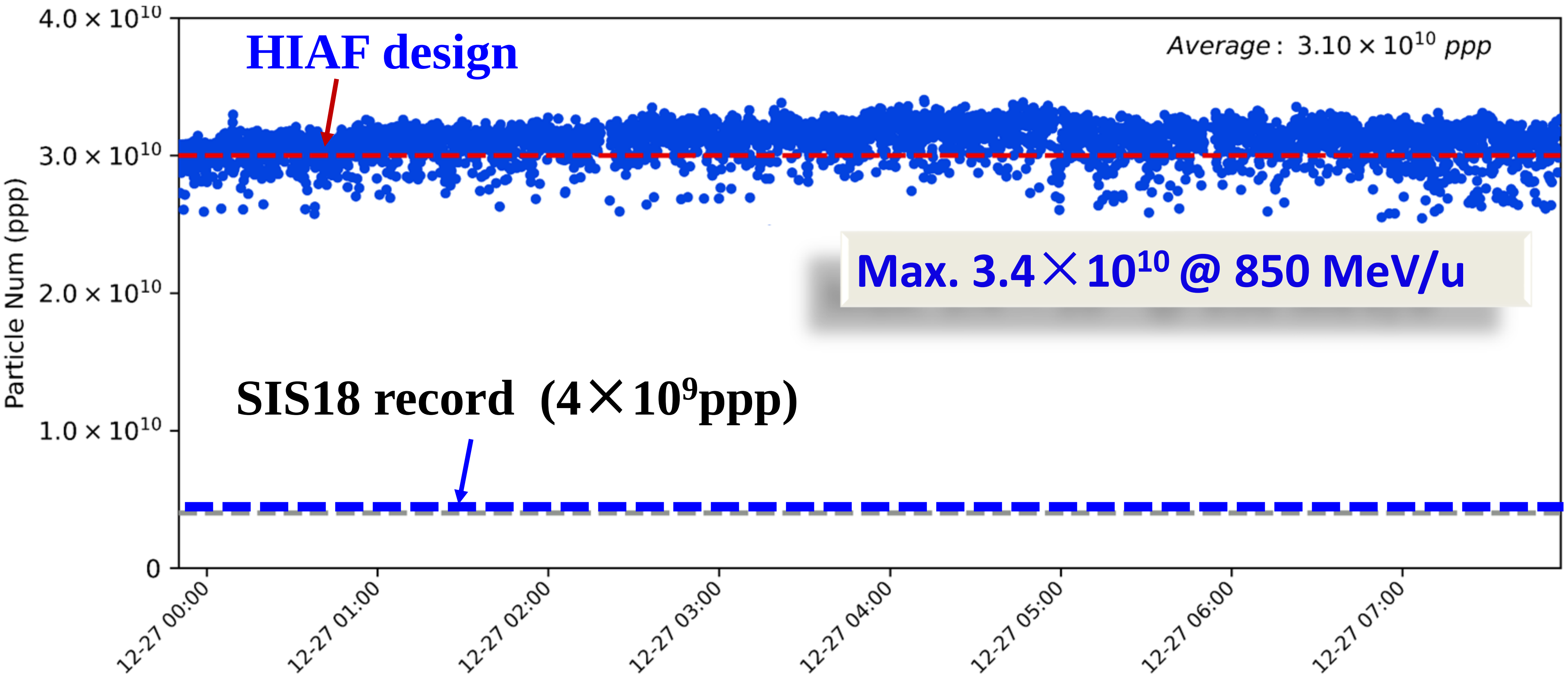


Max. 3.0×10^{11}@2.6 GeV/u

HIAF Beam Commissioning (2)

Typical metallic ions ^{209}Bi

New High Energy ^{209}Bi Beam Intensity Record



HIAF design

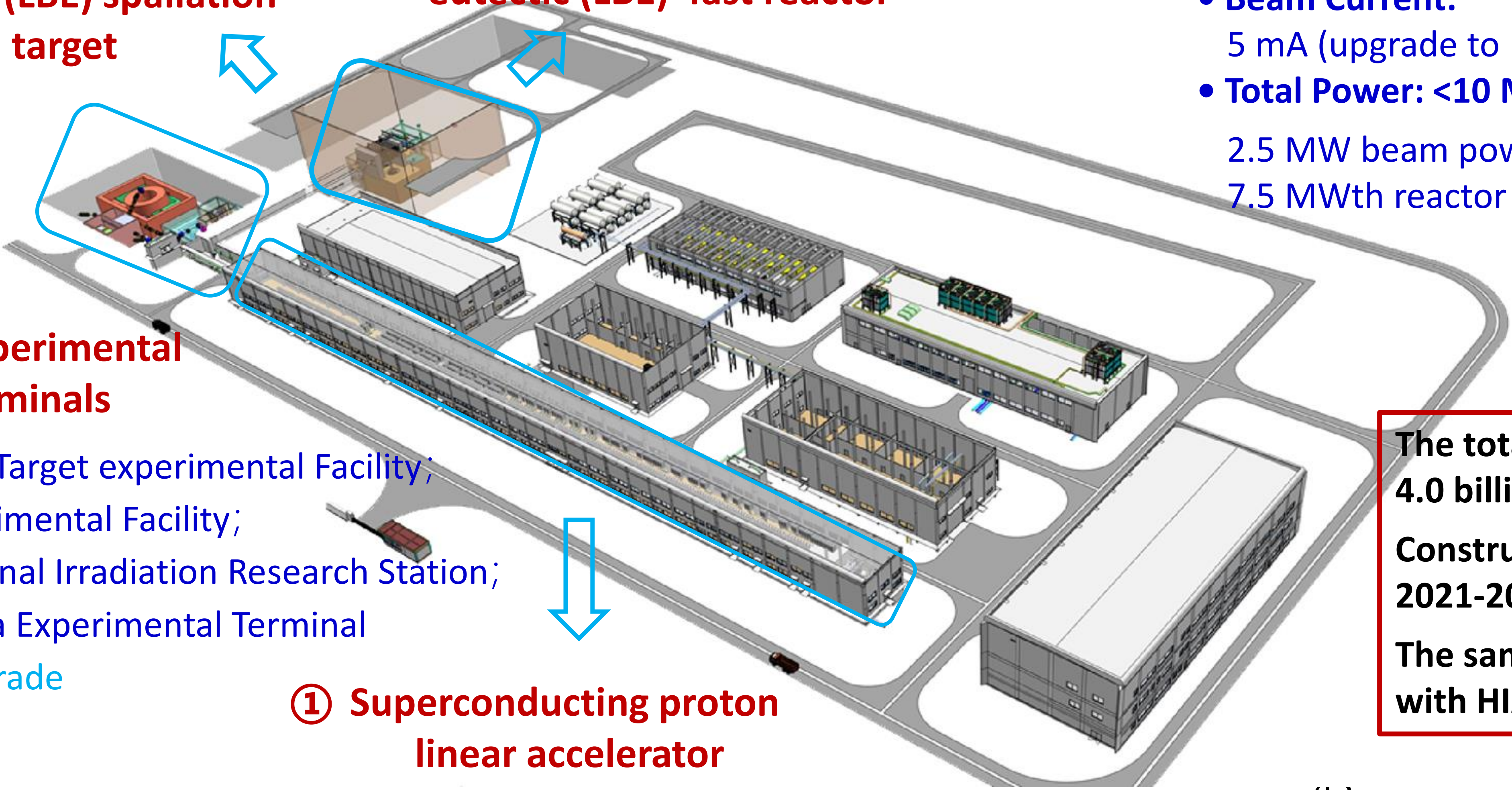
Average: 3.10×10^{10} *ppp*

Max. 3.4×10^{10} @ 850 MeV/u

SIS18 record (4×10^{9}ppp)

CiADS-China Initiative Accelerator Driven System

Accelerator-driven subcritical systems (ADS) is considered to be the most effective and promising method to solve the nuclear waste. CiADS will be the world's first prototype of ADS facility



② High power lead-bismuth eutectic (LBE) spallation target

③ Sub-critical lead-bismuth eutectic (LBE) fast reactor

- **Beam Energy:**
  500 MeV (upgrade to 1.5 GeV)
- **Beam Current:**
  5 mA (upgrade to 10 mA)
- **Total Power: <10 MW**
  2.5 MW beam power,
  7.5 MWth reactor power

④ The experimental terminals

- High power Target experimental Facility;
- Muon experimental Facility;
- Multifunctional Irradiation Research Station;
- Nuclear Data Experimental Terminal
- ISOL for upgrade

① Superconducting proton linear accelerator

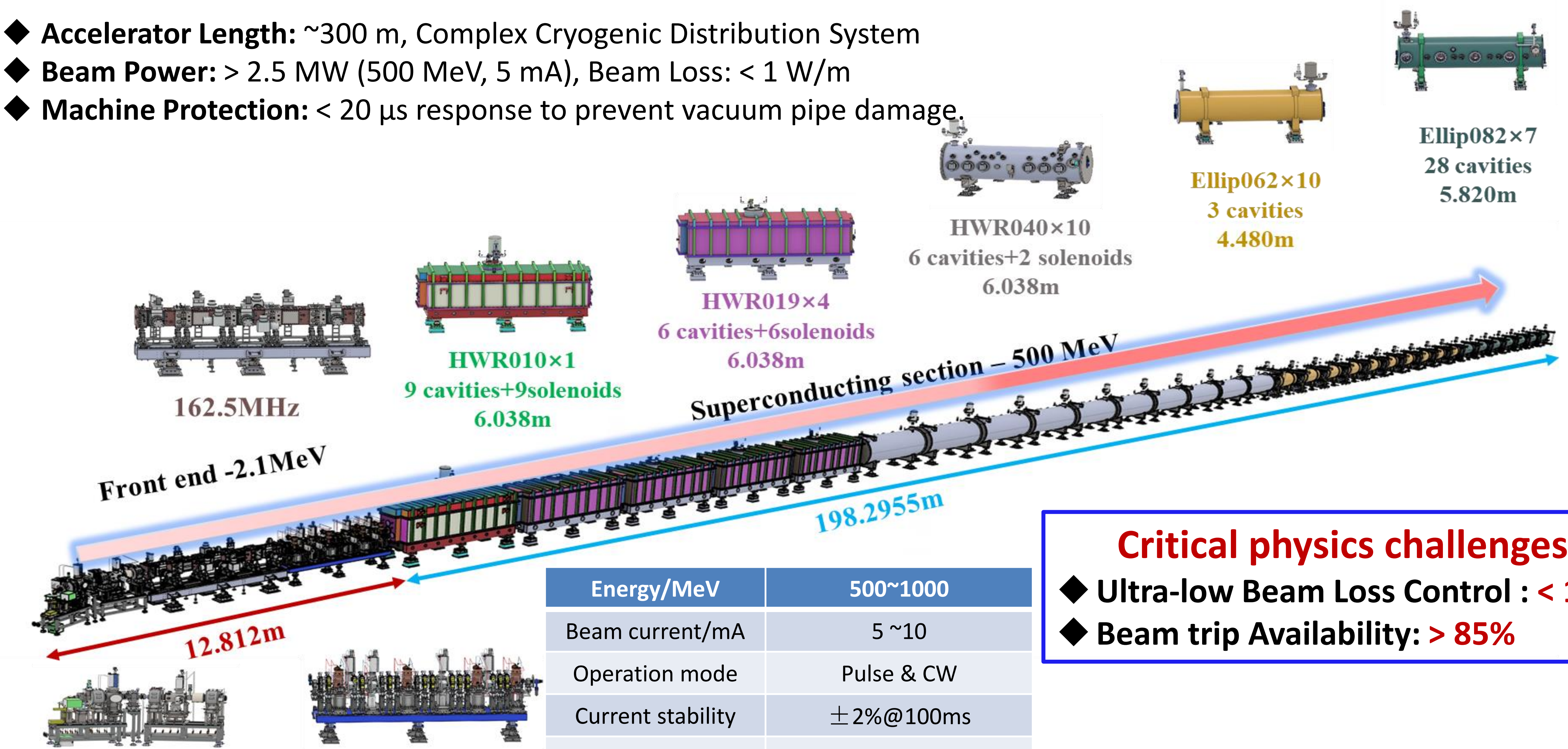
The total budget is 4.0 billion CNY

Construction period: 2021-2027, 6 years

The same campus with HIAF

CiADS SC-linac and its challenge

- **Accelerator Length:** ~300 m, Complex Cryogenic Distribution System
- **Beam Power:** > 2.5 MW (500 MeV, 5 mA), Beam Loss: < 1 W/m
- **Machine Protection:** < 20 µs response to prevent vacuum pipe damage.



Energy/MeV	500~1000
Beam current/mA	5 ~10
Operation mode	Pulse & CW
Current stability	±2%@100ms
Cavity number	151
CM number	32

Critical physics challenges

- **Ultra-low Beam Loss Control : $< 10^{-6}$**
- **Beam trip Availability: > 85%**

CiADS SC-linac installation

Ion source + LEBT + RFQ+ MEBT+11 cryomodules, Installed at the tunnel.

Total CM numbers:32

18 kW at 4 k cryogenic domestic-made refrigerator system installation and commissioning completed.

Conclusion remarks

- HIHPIA, large-scale scientific facility, support for scientific research, the related technologies have a lot applications in our society. Facing many technical challenges, long-term reliable operation with high availability significant. Encouraging the young generation to get involved in HIHPIA.

- Need very big team working together, efficient and strong collaboration with the team members

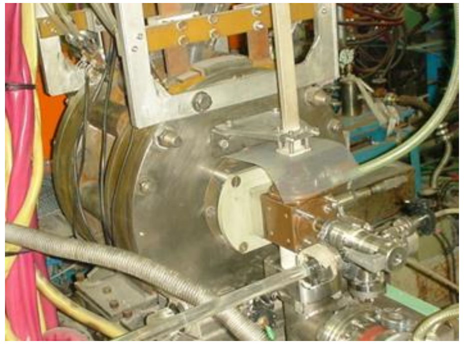
- International communication and collaboration very important. “Standing on the shoulders of giants”.

- Keep the major mission and objective in mind for years long-term and innovative R&D to achieve key technology breakthrough （3 examples）.

Development of IMP highly-charged ECRIS

IMP ECRIS

1986-1995
(10GHz)



LECR1

LECR0

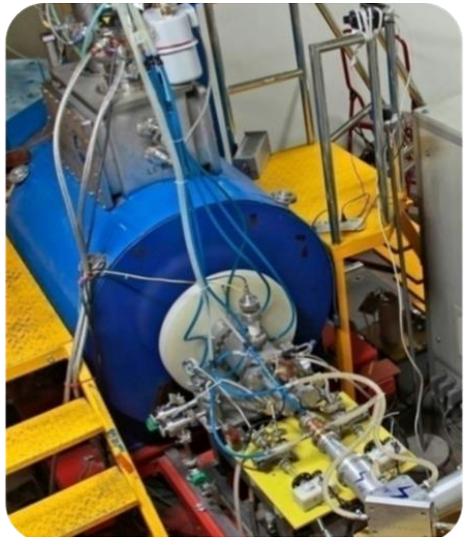
1996-2002- present
(14-18 GHz)

LECR3

LECR2

2002-2016-2023
(24-28 GHz)

SECRAL II



SECRAL

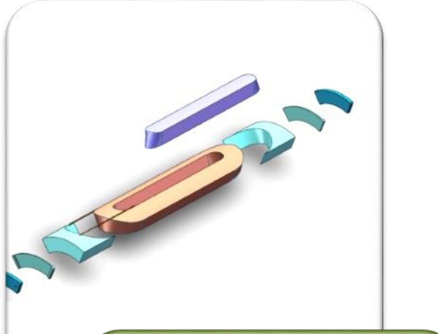
2015-2024-present
(45 GHz--)

FECR

The world leading
>10 years

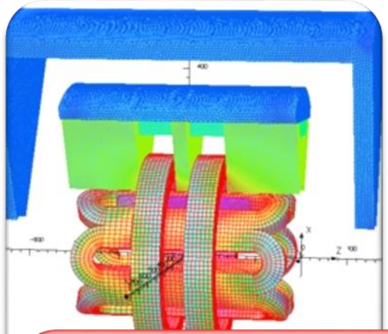
FECR Nb_3Sn magnet development

From prototyping to operational machine (2015-2024)



Key technologies

- Coils fabrication
- Keys & Bladder
- Quench protection
- Know-how of Nb_3Sn coil

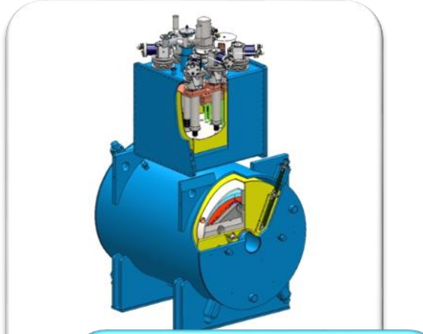


½ Prototype Coldmass

- Quality control and analysis
- SG assisted mechanical assembly
- Quench protection
- Reliability

Full Sized coldmass

- Quality control of mass production
- Quench protection
- Reliability
- System integration



FECR Magnet

- System integration
- Coldmass alignment
- Reliable operation

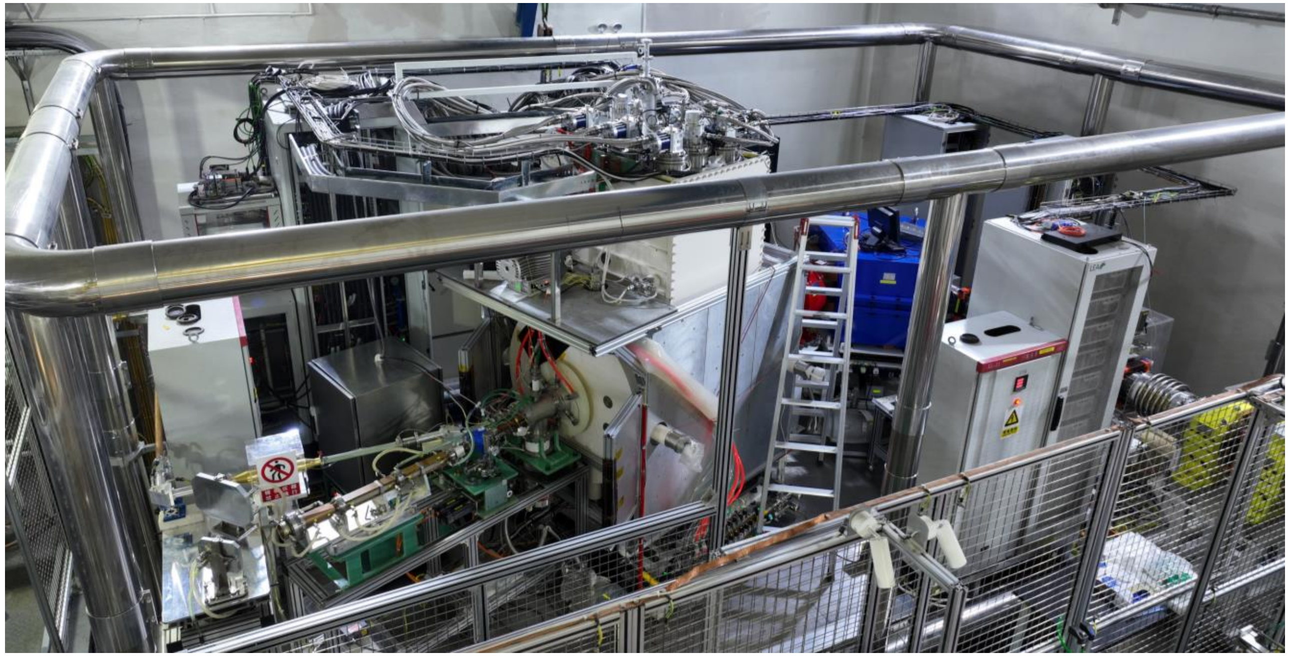
To demonstrate 80~85% of FECR coldmass performance

Operational FECR Nb_3Sn magnet

9 years R&D for FECR Nb_3Sn magnet

LEAF/HIAF - 45 GHz FECR

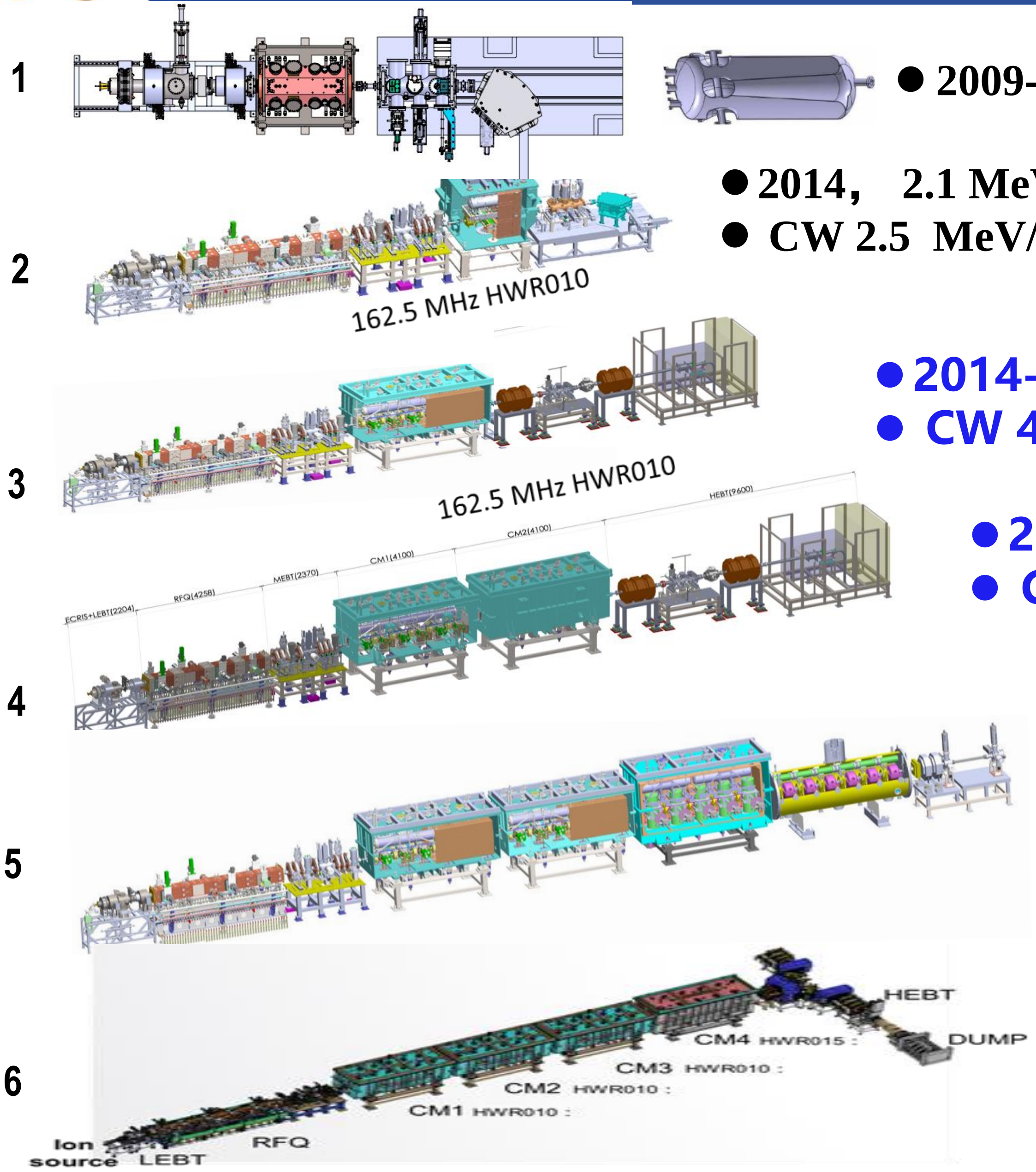
FECR-I with hybrid magnet
Nb_3Sn solenoids + NbTi sextupole



FECR-I already in routine operation since 05/2024

FECR-II Nb_3Sn magnet with
Nb_3Sn solenoids + Nb_3Sn sextupole
being tested at 4 k in 05/2026

10 years milestones of CW proton SC linac as R&D for CiADS



- **2009-2012, SRF and RFQ design, prototyping**

- **2014， 2.1 MeV RFQ+single HWR cavity**
- **CW 2.5 MeV/10 mA (RFQ collaboration with LBNL)**

- **2014-2015，RFQ+6 HWR cavity**
- **CW 4-5 MeV/4 mA**

- **2016，RFQ+12 HWR cavity**
- **CW 10 MeV/2 mA**

- **2017-2019，RFQ+23 HWR cavity**
- **CW 15-25 MeV/2 mA**

- **2019-2021，RFQ+23 HWR cavity**
- **CW 20 MeV/10 mA**
- **7.3 mA@126 kW，108 hours**

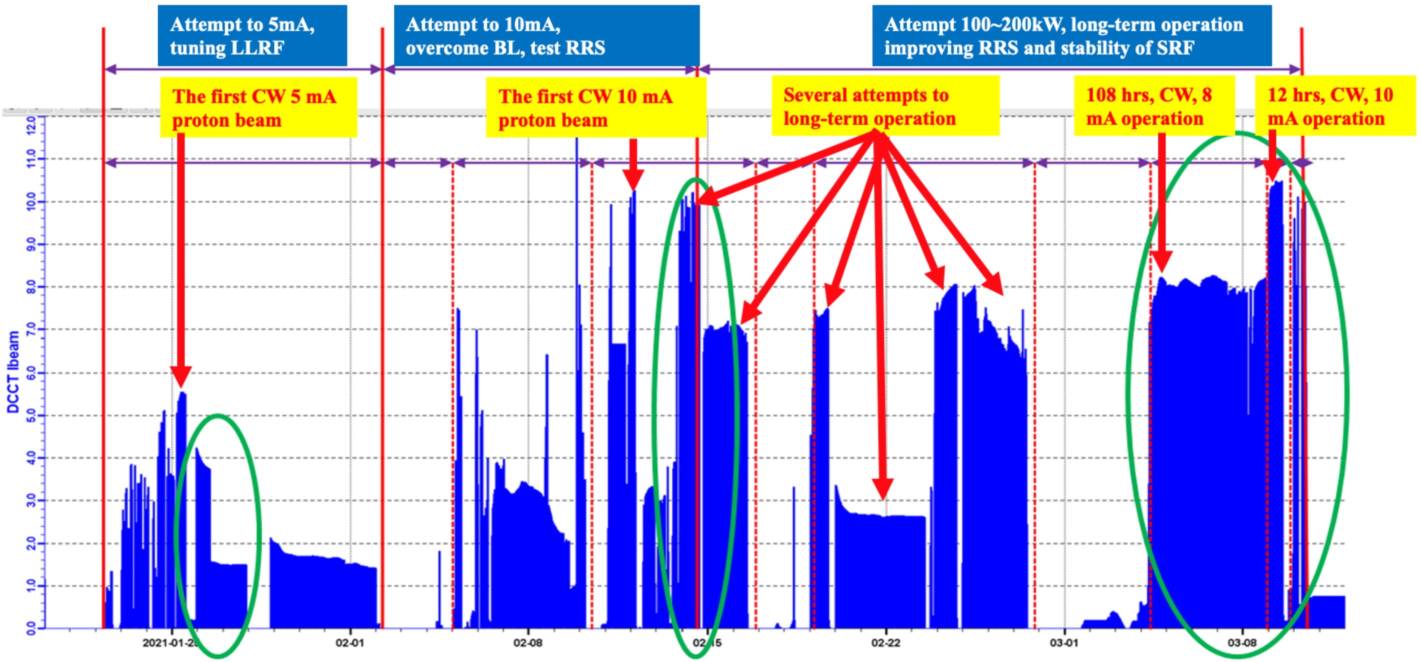
Collaborated with many labs over the world

The world first demonstration for high intensity CW proton linac

High power CW SC proton linac reliability demonstration

- **Operation from Jan. 20 to Mar. 10, 2021**

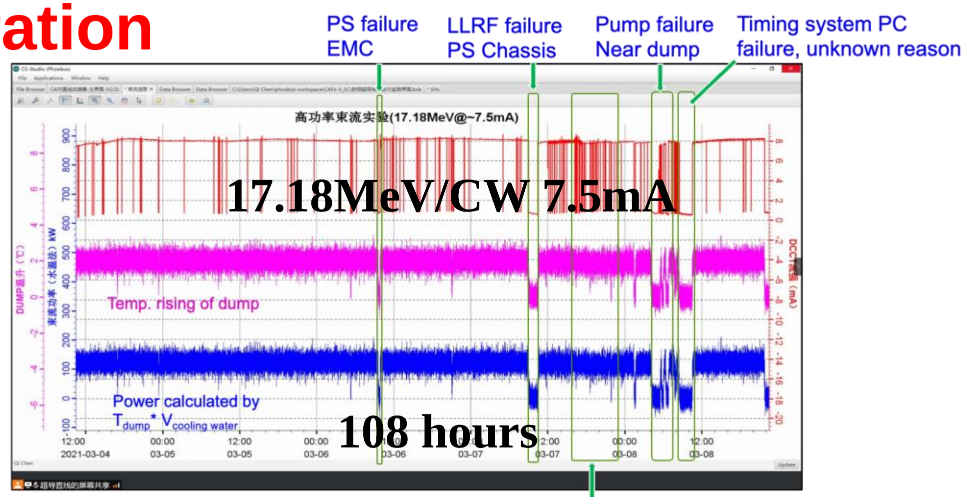
The world first demonstration



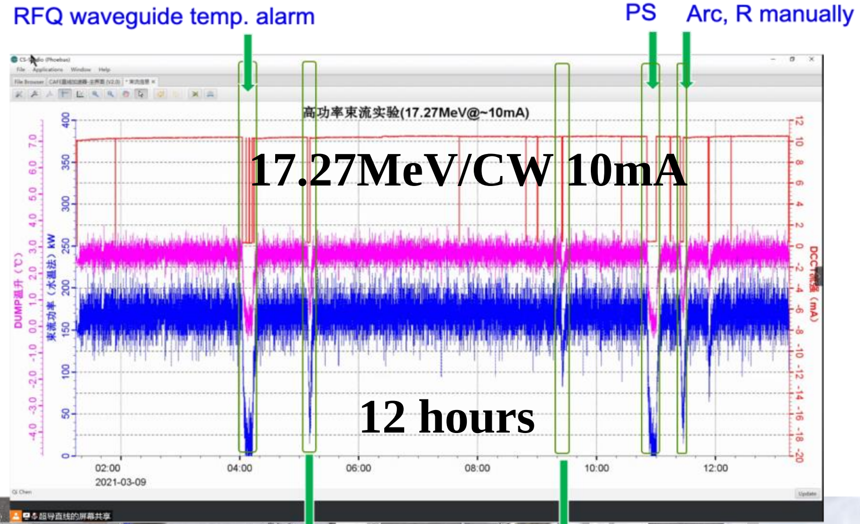
Availability: 126.1 kW, op. time **108 hs, availability 93.6%**

Beam current: 174.4 kW、**10.08 mA**, op. time 12 hs

High power: 20.18 MeV、10.18 mA、**beam power 205.5 kW**



IS arcs, maybe mistake of MPS and RRS Logic



10 years R&D of large-size magnetic alloy core loaded RF for HIAF (1)

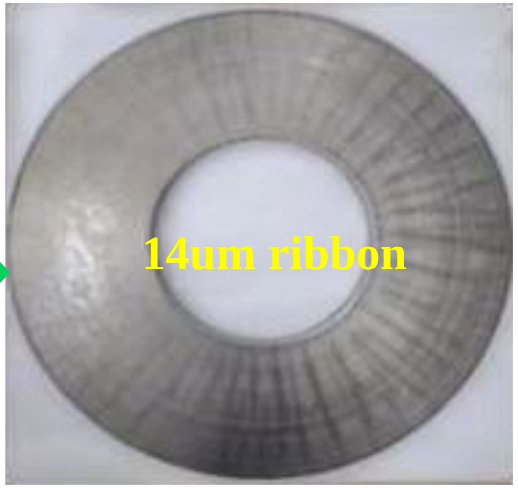
- **The BRing RF system can only be achieved by large-size magnetic alloy loaded cavity RF technology, the large-size MA core material is not available in China and forbidden sale to China.**

☐ **Over 10 years R&D from small(Φ90mm), medium (Φ 460mm), to large (Φ 780mm**

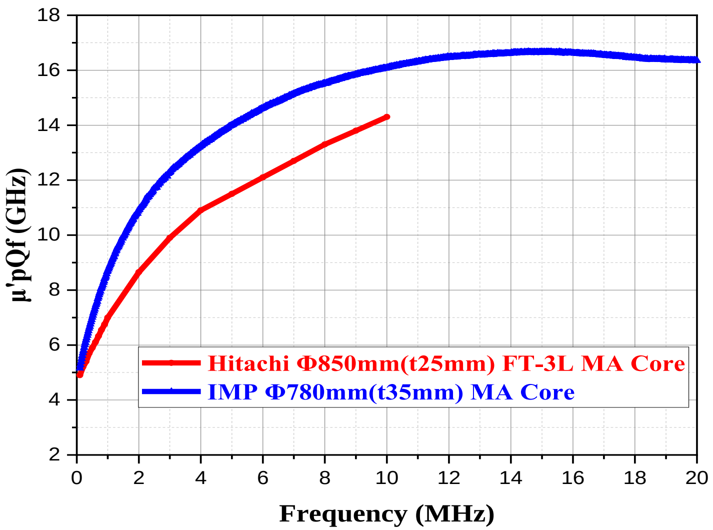
☐ **Ultrathin ribbons from 18 to 14 µm are getting thinner and have better performance**

95×65×25mm

460×230×25mm



780×360×35mm



Parameters of MA core

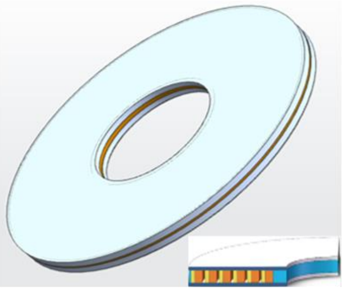
➢ **The key performance µQf value of the domestic large-sized magnetic alloy ring exceeds the internationally best FT3-L magnetic alloy by more than 30% (FT3-L Hitachi product).**

10 years R&D of large-size magnetic alloy core loaded RF for HIAF (2)

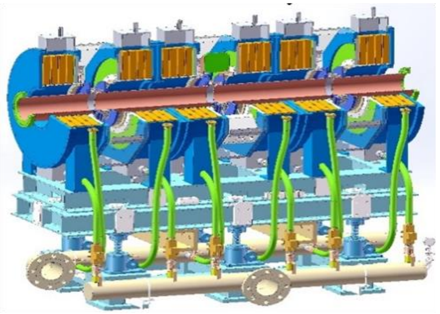
Successfully achieved requirements through collaboration with a domestic company

MA loaded RF system

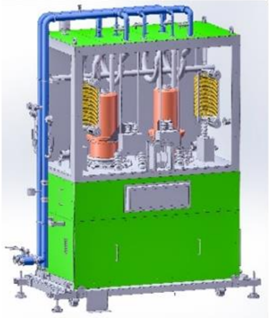
Large size oil cooled MA core



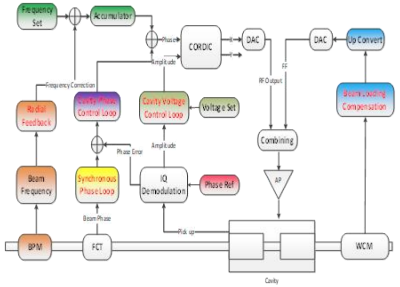
High gradient direct cooling MA- loaded cavity



Broad band push-pul tetrode amplifier



Multi harmonic digital LLRF



MA loaded RF system in the HIAF tunnel

Facilities	Voltage (kV)	Length (m)	Gradient(kV/m)
JPARC-RCS	41	1.78	23
JPARC-MR	46.7	1.78	26.2
SIS18	50	2	25
HIAF-BRing	70	2	35

Total RF voltage: 350kV

Thank you for your attention !