# Physics of High Intensity Muon and Neutrino Beams at CIADS-HIAF Accelerator Complex

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# Contents

- Introduction

# Contents

- Introduction
- High Power Hadronic Accelerators

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- ISOLDE, EURISOL and $\beta$ Beam

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  - Nucleons are heavier like Bulls,
  - Collision is creating new states;

- According to TD Lee's idea the late famous Chinese painter Ke-Ran Li created a paint;


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COLLISIONS
SYMPOSIUM / WORKSHOP
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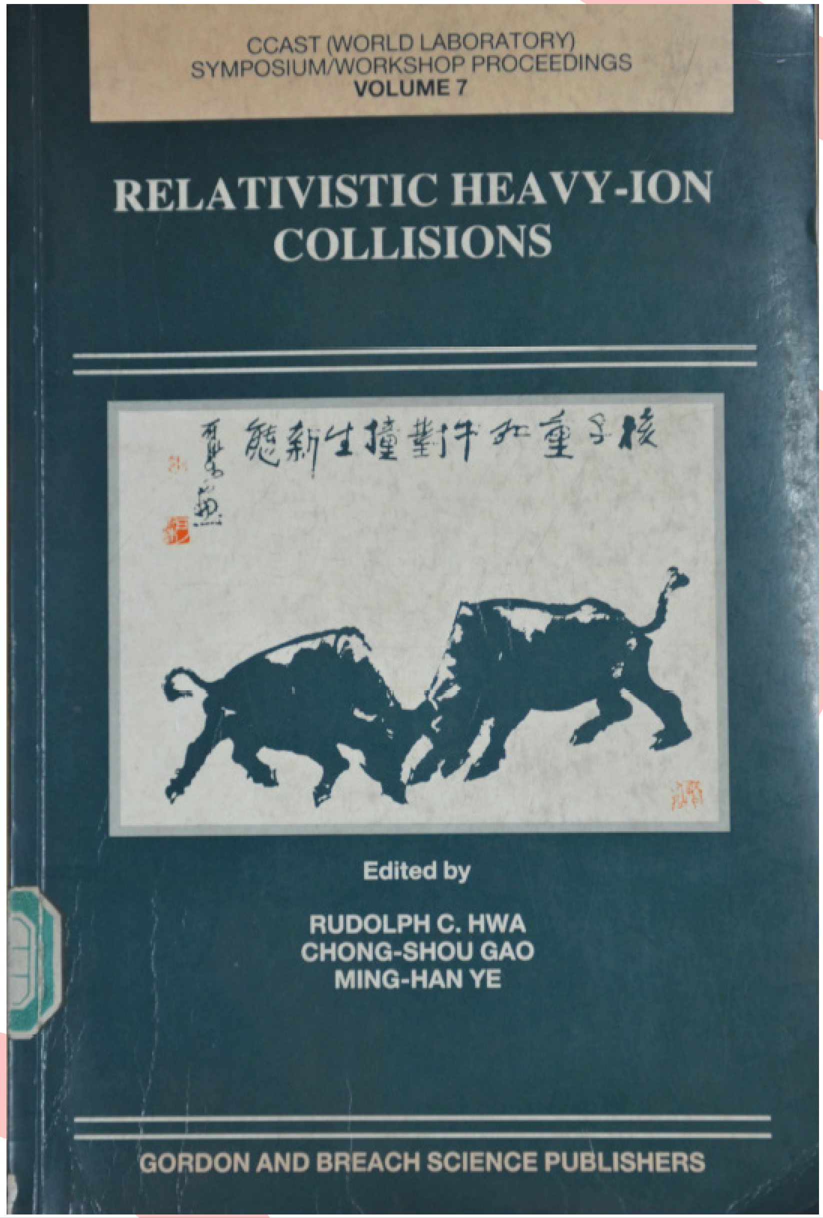
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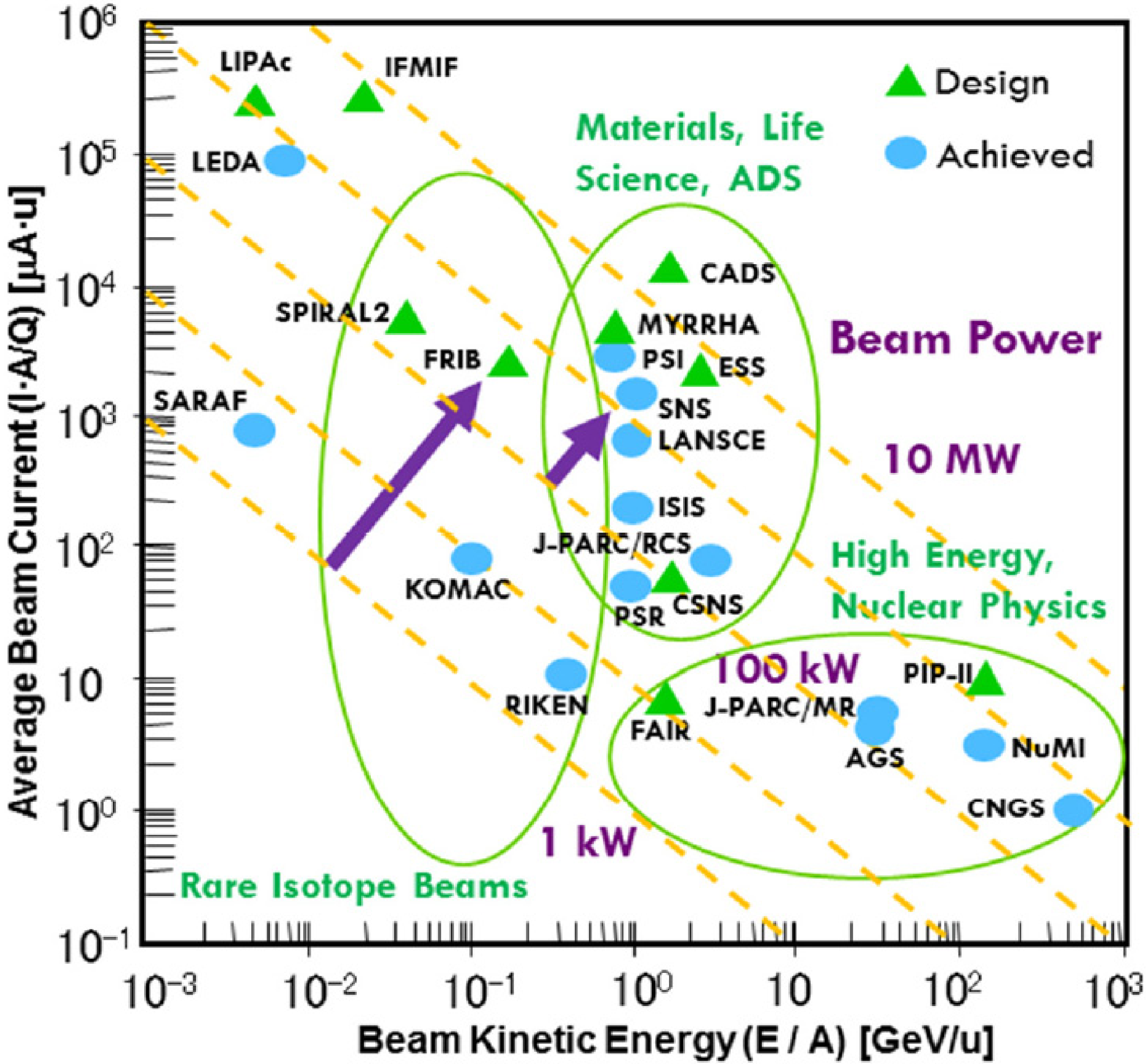
- This paint was recreated into a sharp-relief by an artist from the Arts and Crafts Institute of Thsinghua University;


核子重如牛對撞生新態

# High Power Hadronic Accelerators

- At a time when accelerator projects at the high-energy frontier are experiencing difficulties in gaining financial support, projects at the high-intensity frontier are flourishing world. Demands for such accelerators extend from science to applications.



Design
Achieved
Materials, Life
Science, ADS
Beam Power
10 MW
High Energy,
Nuclear Physics
100 kW
1 kW
Rare Isotope Beams
LIPAc
IFMIF
LEDA
CADS
SPIRAL2
MYRRHA
FRIB
PSI
ESS
SARAF
SNS
LANSCE
ISIS
J-PARC/RCS
KOMAC
PSR
CSNS
RIKEN
FAIR
J-PARC/MR
PIP-II
AGS
NuMI
CNGS
Average Beam Current (I·A/Q) [μA·u]
Beam Kinetic Energy (E / A) [GeV/u]

Table 1: Major Parameters of Some Proton and Heavy Ion Accelerators at Design, Construction, and Operation Stages

| Project | Status | Primary Beam | Sec. Beam | Accel. Type | $f_{rep}$ [Hz] | Beam Duty | Target Type | Energy [MeV/u] | Ave. Power [MW] |
|---|---|---|---|---|---|---|---|---|---|
| AGS | Achieve | p | μ, K | LN/SR | 0.5 | 5e-7;.5 $^{t}$ | Ni; Pt | 24000 | 0.1 |
| SPS | Achieve | p | ν | LN/SR | 0.17 | 3.5e-6 $^{t}$ | C | 400000 | 0.5 |
| MI | Achieve | p | ν | LN/SR | 0.75 | 1.e-5 $^{t}$ | C | 120000 | 0.4 |
| J-PARC MR | Achieve<br>Goal | p<br>p | ν, K, π<br>ν, K, π | LN/SR<br>LN/SR | 0.4;0.16<br>1; 0.16 | 2e-6;.3 $^{t}$<br>5e-6;.3 $^{t}$ | C; Au<br>C; M $^{r}$ | 30000<br>30000 | 0.2; 0.02<br>0.75; > 0.1 |
| LANSCE<br>PSR | Achieve<br>Achieve | p, $H^-$<br>p | π, μ, n<br>n | LN<br>LN/AR | 100<br>20 | 0.15<br>0.08 $^{i}$ | C $^{r}$<br>W | 800<br>800 | 0.8<br>0.08 |
| RIKEN | Achieve<br>Goal | d to U<br>d to U | RIB<br>RIB | LN/CY<br>LN/CY | CW<br>CW | 1<br>1 | Be<br>Be | 345-400<br>345-400 | 0.007-0.002<br>0.08 (U) |
| PSI | Achieve | p | n, μ | CY | CW | 1 | C $^{r}$, Pb | 590 | 1.4 |
| SNS | Achieve<br>Goal | p<br>p | n<br>n | LN/AR<br>LN/AR | 60<br>60 | 0.06 $^{i}$<br>0.06 $^{i}$ | Hg $^{l}$<br>Hg $^{l}$ | >940<br>1300 | 1.3<br>2.8 |
| J-PARC RCS | Achieve<br>Goal | p<br>p | n, μ<br>n, μ | LN/SR<br>LN/SR | 25<br>25 | 0.02 $^{i}$<br>0.02 $^{i}$ | Hg $^{l}$<br>Hg $^{l}$ | 3000<br>3000 | 0.3<br>1 |
| ISIS | Achieve<br>Goal | p<br>p | n, μ<br>n, μ | LN/SR<br>LN/SR | 40; 10<br>40; 10 | 0.01 $^{i}$<br>0.01 $^{i}$ | W<br>W | 800<br>800 | 0.16; 0.04<br>0.45; 0.05 |
| SARAF | Achieve<br>Goal | p; d<br>p, d | n; -<br>n, RIB | LN<br>LN | CW; 1<br>CW | 1<br>1 | SST;Li $^{l}$<br>Li $^{l}$; Be | 3.9; 2.8<br>40; 20 | 0.0039; -<br>0.2 |
| KOMAC | Achieve | p | - | LN | 10 | 0.005 | - | 100 | 0.01 |
| FRIB | Constru. | p to U | RIB | LN | CW | 1 | C $^{r}$ | >200 | 0.4 |
| FAIR | Constru. | p to U | RIB, $\bar{p}$ | LN/SR | 0.2;0.5 | <0.25 $^{i}$ | M $^{r}$; Ni | 1e3;3e4 | 0.012;0.001 |
| SPIRAL2 | Constru. | p,d,A/q≤3 | RIB, n | LN/CY | CW | 1 | C $^{r}$ | 33,20,14 | 0.2,0.2,0.04 |
| CSNS | Constru. | p | n | LN/SR | 25 | 0.01 $^{i}$ | W | 1600 | 0.1 |
| LIPAc | Constru. | d | n | LN | CW | 1 | Li $^{l}$ | 4.5 | 1.1 |
| PIP-II | Design | p | ν, μ | LN/SR | 15 | 0.15 $^{i}$ | C; Al | 1e5; 800 | 1.2; 0.1 |
| ESS | Design | p | n | LN | 14 | 0.04 | W $^{r}$ | 2000 | 5 |
| IFMIF | Design | d | n | LN | CW | 1 | Li $^{l}$ | 20 | 2 x 5 |
| CADS | Design | p | n | LN | CW | 1 | G+He | 1500 | 15 – 30 |
| MYRRHA | Design | p | n | LN | CW | 1 | Pb-Bi $^{l}$ | 600 | 1.5 – 2.4 |

Notation: LN for Linac; CY for Cyclotron; SR for Synchrotron; AR for Accumulator; C for graphite; M for metal; RIB for rare isotope beams; Superscripts r for rotating and l for liquid targets, i for linac beam duty and t for beam duty on target.

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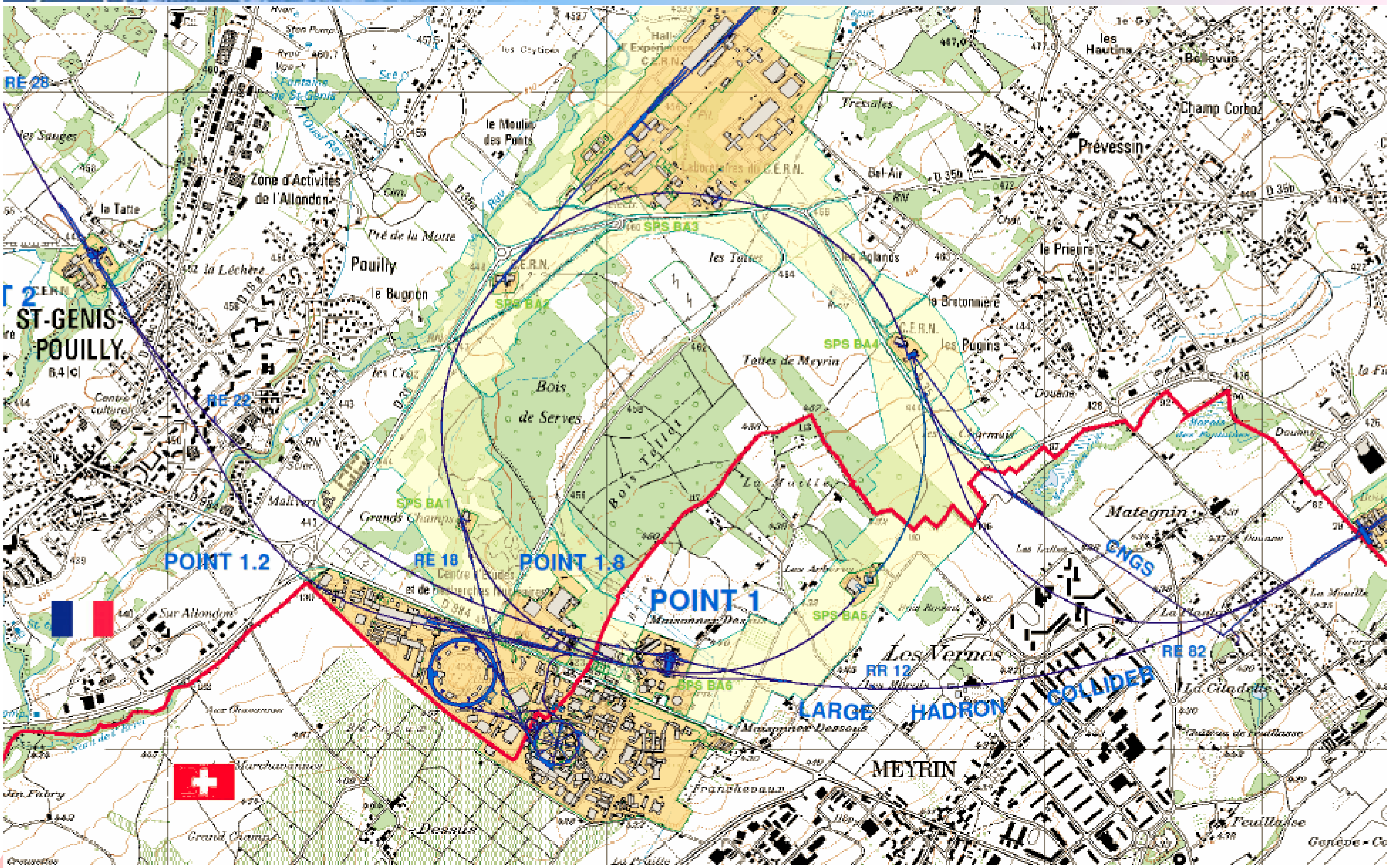
  - high intensity Muon beams and neutrino beam;
  - others;

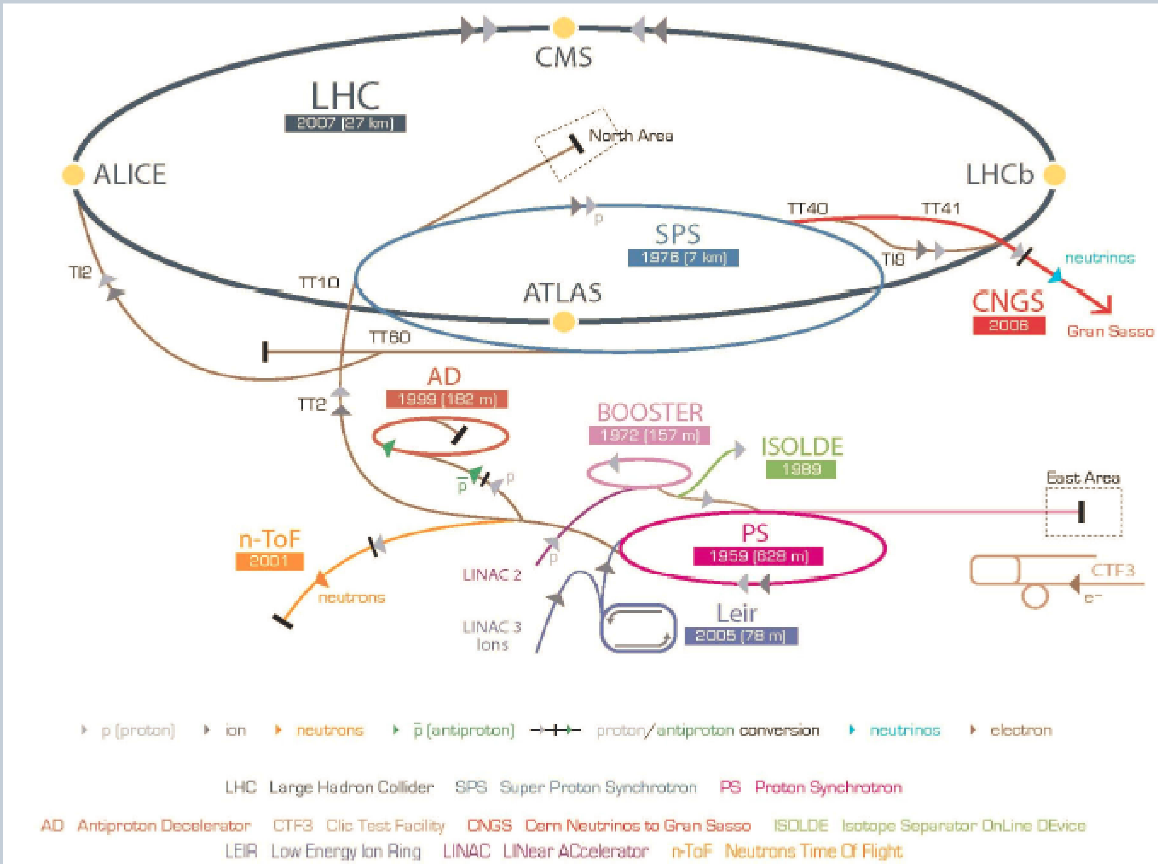
- Among the existing laboratories equipped with medium power (100 kW-class) proton accelerators, CERN, Fermilab, J-PARC and RAL have a declared interest in neutrino physics, including the potential implementation of high power (MW-class) proton accelerators;

# The LHC Injector Complex




R. Garoby 2 10/11/2010

# The CERN Accelerator Complex




**LHC Beam Route**

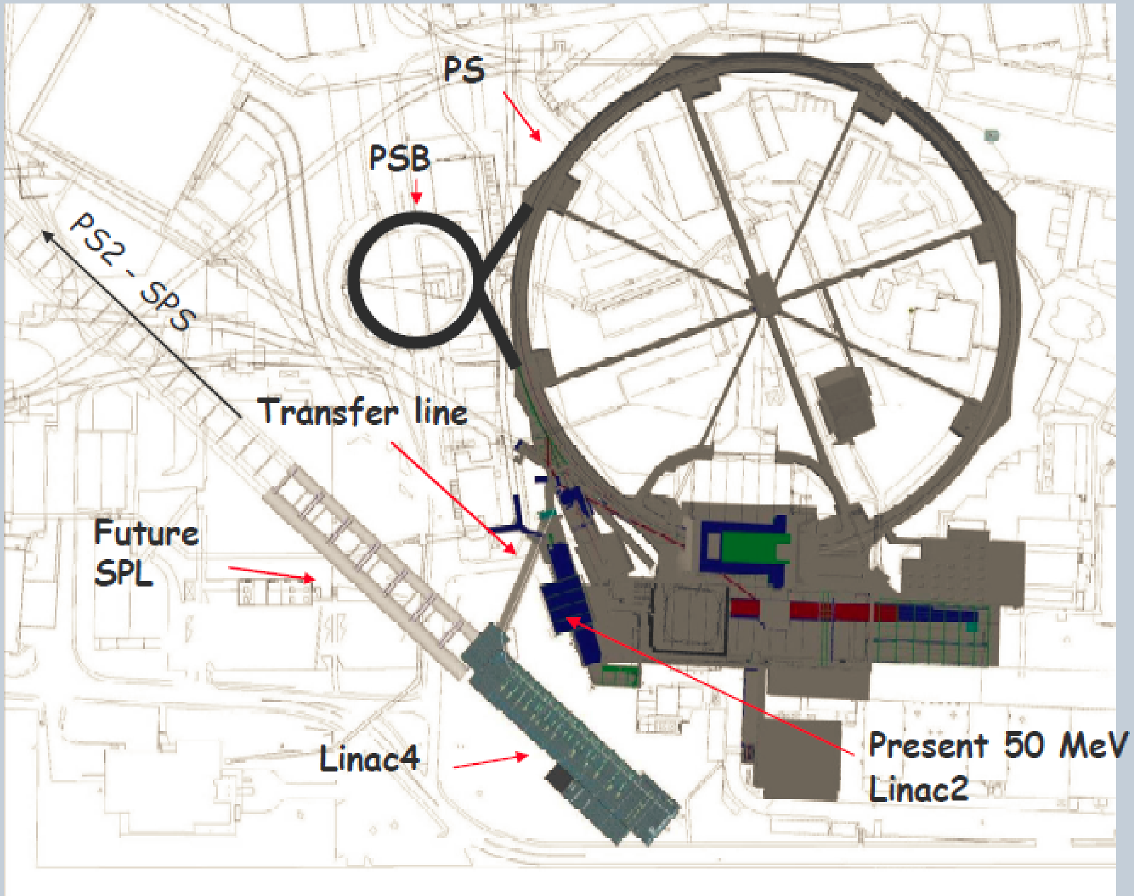
**LINAC2**
**BOOSTER**
**PS**
**SPS**

11

# Linac4

Linac4 because the 4th linear accelerator to be built at CERN, replacing the present Linac2 as proton injector for the CERN accelerator complex.

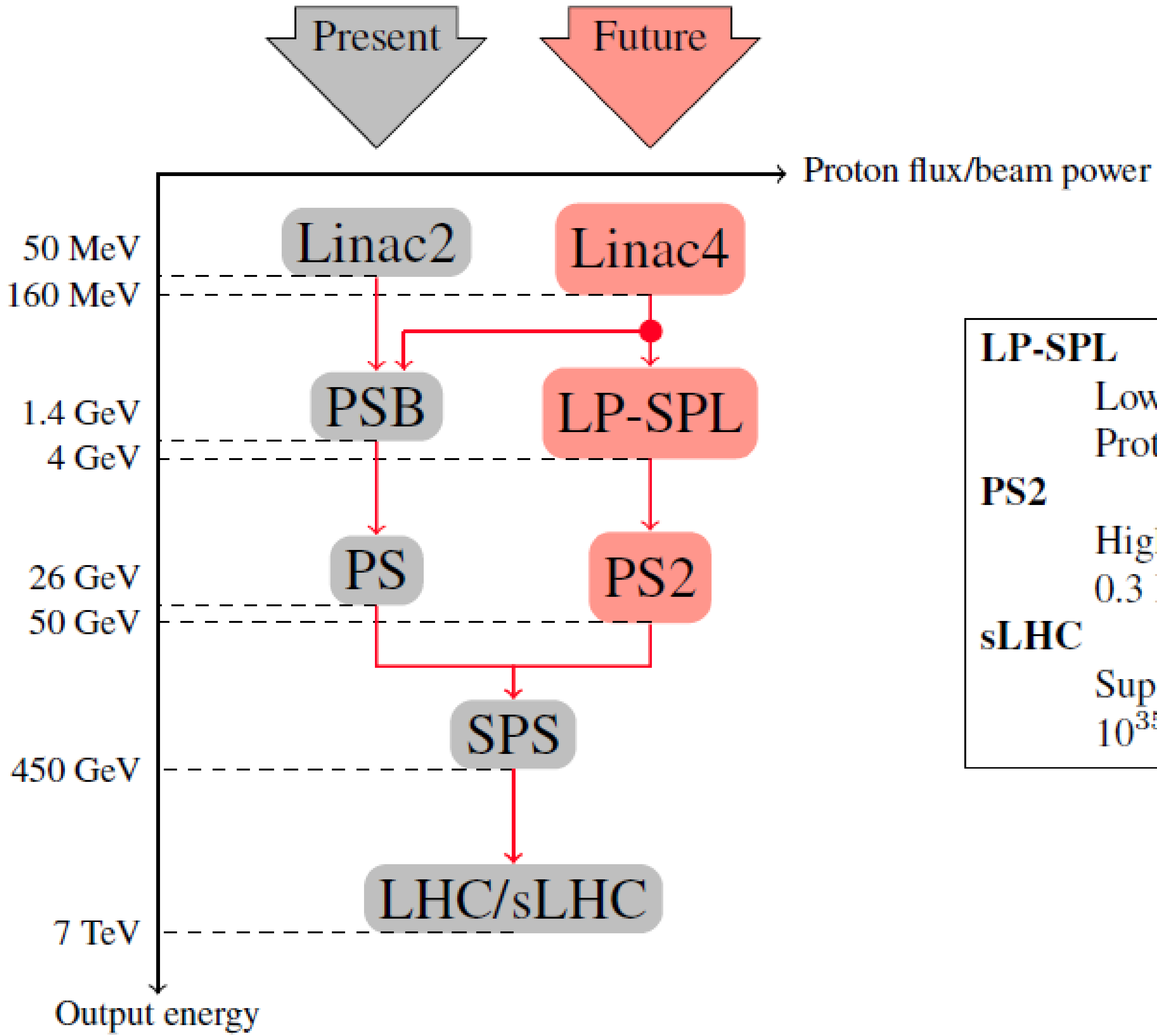
Civil engineering works have started in one of the last free locations on the CERN site, in a position offering a simple connection to the present machines and the option of a future extension to the high-energy SPL linac.



- The concept of sharing a high power proton accelerator (proton driver) between neutrino production and other facilities such as a high energy collider or a spallation neutron source is an attractive cost-effective solution ( a common proton driver ).

- The proton driver at the neutrino factory (NF) is required to deliver a proton beam of 4 MW at a repetition rate 50 Hz to the pion -production target. The proton beam energy must be in the multi-GeV range in order to maximize the pion yield. In addition, the NF specifies a particular time structure consisting of three very short bunches separated by about 120 $\mu$s. to allow the muon beam to captured efficiently, short 1-3 ns rms, bunches are required.

- With the high beam power, Super-conducting Proton Linac can be the proton driver for an ISOL-type radioactive ion beam facility of the next generation (for example, EURISOL) and for a neutrino facility based on superbeam + betabeam or on muon decay in a storage ring (neutrino factory):




**LP-SPL**
Low-Power Superconducting Proton Linac (4 GeV)

**PS2**
High-energy PS (4 to 50 GeV, 0.3 Hz)

**sLHC**
Super-luminosity LHC (up to $10^{35}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$)

**Fig. 1.1:** Present and proposed future accelerators

**Table 1.1:** Beam characteristics for Low-Power and High-Power SPL

| Parameter | Units | LP-SPL | HP-SPL, low-current | HP-SPL, high-current |
|---|---|---|---|---|
| Maximum kinetic energy | GeV | 4 | $5^a$ | $5^a$ |
| Average beam current during pulse | mA | 20 | 20 | 40 |
| Pulsing rate | Hz | 2 | 50 | 50 |
| Pulse duration | ms | 0.9 | 0.8 | $0.4^b$ |
| Beam power | MW | 0.14 | 4 | 4 |

[a] 5 GeV is required for a neutrino factory; for other applications, a lower final energy may be sufficient.
[b] For multiple users requiring >4 MW beam power simultaneously, this value has to be increased.

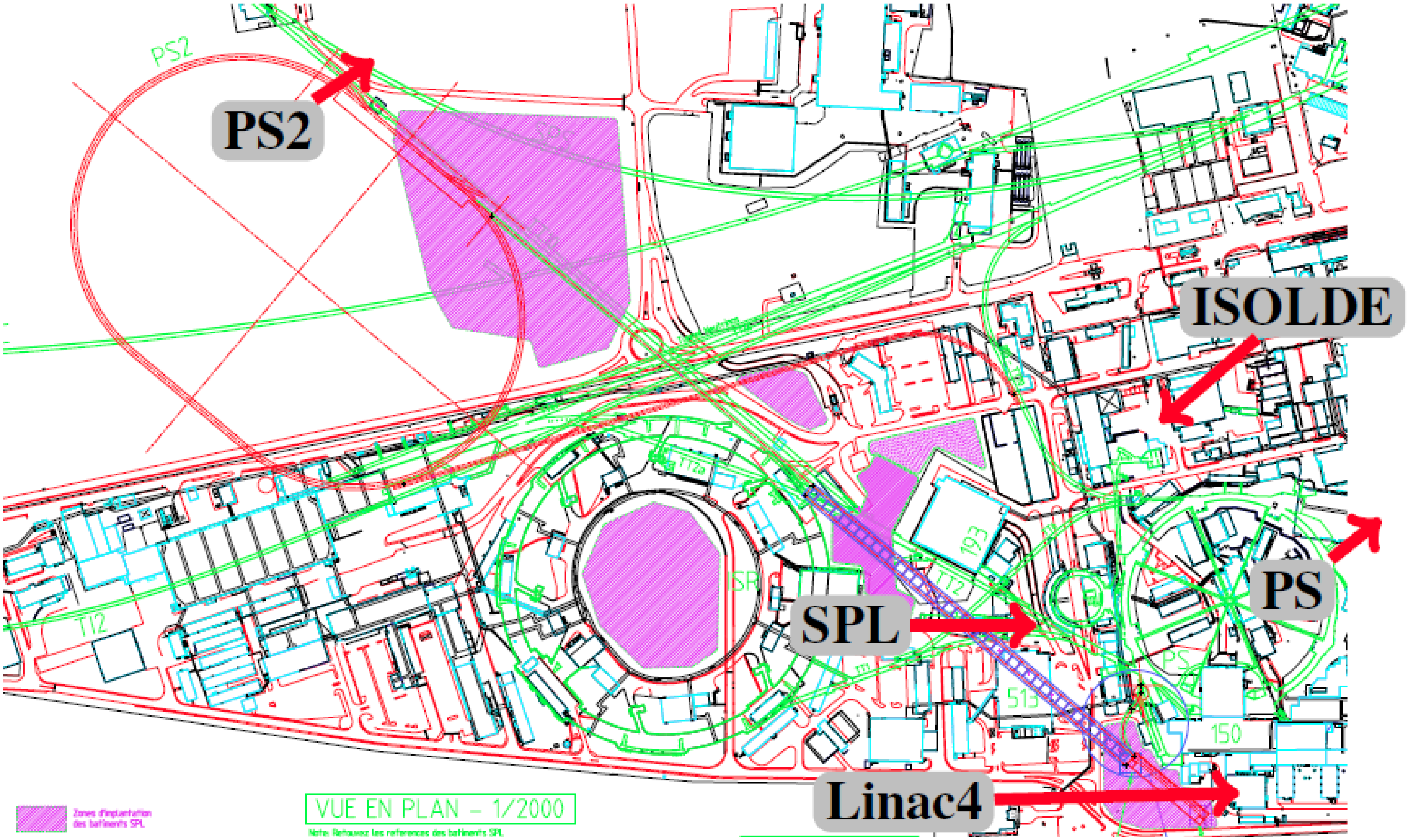



**Fig. 1.2:** Layout of Linac4, SPL, and PS2 at the CERN site

# ISOLDE, EURISOL and $\beta$ beam

- The advent of radioactive beam facilities has given a new impetus to nuclear structure physics, it has led to several major unexpected discoveries. Further progress is hampered by the weak beam intensities of current installations.

- a European isotope-separation-on line(ISOL) facility is aimed at the construction of an accelerator-based ISOL system for producing exotic radioactive ion beams (RIBs) with intensities several orders of magnitude greater than those available today.

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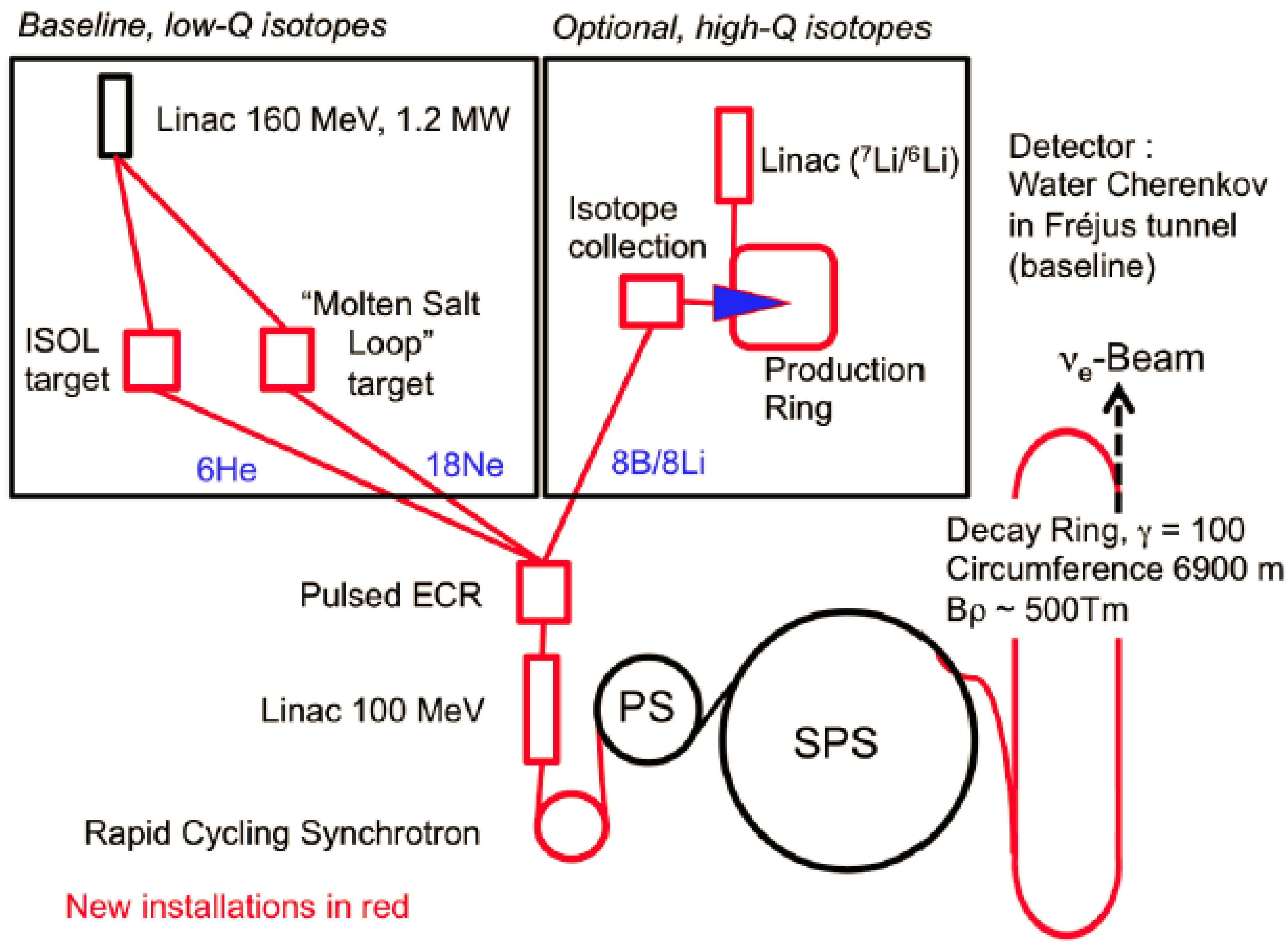
- EIRISOL is intended to be complementary to FAIR. With high-power beams of protons producing higher yields for a different range of exotic isotopes, EURISOL will provide a unique facility for European scientists;

- The beta-beam project is a concept of large-scale facility that aim at providing pure electronic neutrino and antineutrino beams for the measurement of $\nu_e \to \nu_\mu$ oscillations, with unprecedented sensitivity for detection of the $\theta_{13}$ mixing angle and CP-violating phase.

- A beta beam facilities could be advantageously placed at CERN making use of the PS and SPS for accelerating the beta-decaying neutrino-emitting beams to a Lorentz gamma value of 100. Intense beams of $^{6}$He and$^{18}$Ne would be produced using ISOL method in a facility of the scale of EURISOL.


Baseline, low-Q isotopes
Optional, high-Q isotopes
Linac 160 MeV, 1.2 MW
Linac (7Li/6Li)
Detector :
Water Cherenkov
in Fréjus tunnel
(baseline)
Isotope
collection
"Molten Salt
Loop"
target
ISOL
target
Production
Ring
νe-Beam
6He
18Ne
8B/8Li
Decay Ring, γ = 100
Circumference 6900 m
Bρ ~ 500Tm
Pulsed ECR
Linac 100 MeV
PS
SPS
Rapid Cycling Synchrotron
New installations in red

- For an optimal sensitivity of the CERN beta beam facility to the $\theta_{13}$ angle and CP violating phases, a total throughput of $1.1 \times 10^{19}$ neutrinos and $2.9 \times 10^{19}$ antineutrinos immediately after the decay ring was generally assumed over a running period 0f 10 years (200 days/year, 50% efficiency )for the low-Q option.

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- The top-down approach then results in the need for production of about $3.3 \times 10^{13}$ $^{6}$He radioactive atoms and $2.1 \times 10^{13}$ $^{18}$ Ne atoms per second, taking account efficiency coefficients along the accelerator chain.

– The production of $^6$He is obtained with fast neutrons on a beryllium oxide target through the $^9$Be(n,$\alpha$)$^6$He reaction, which benefits from high cross sections over a wide neutron energy spectrum. Neutrons in the 0.1-10 MeV range, of interest for $^6$He production, are to a first approximation emitted in all directions from solid metal converters that will act as neutron spallation source

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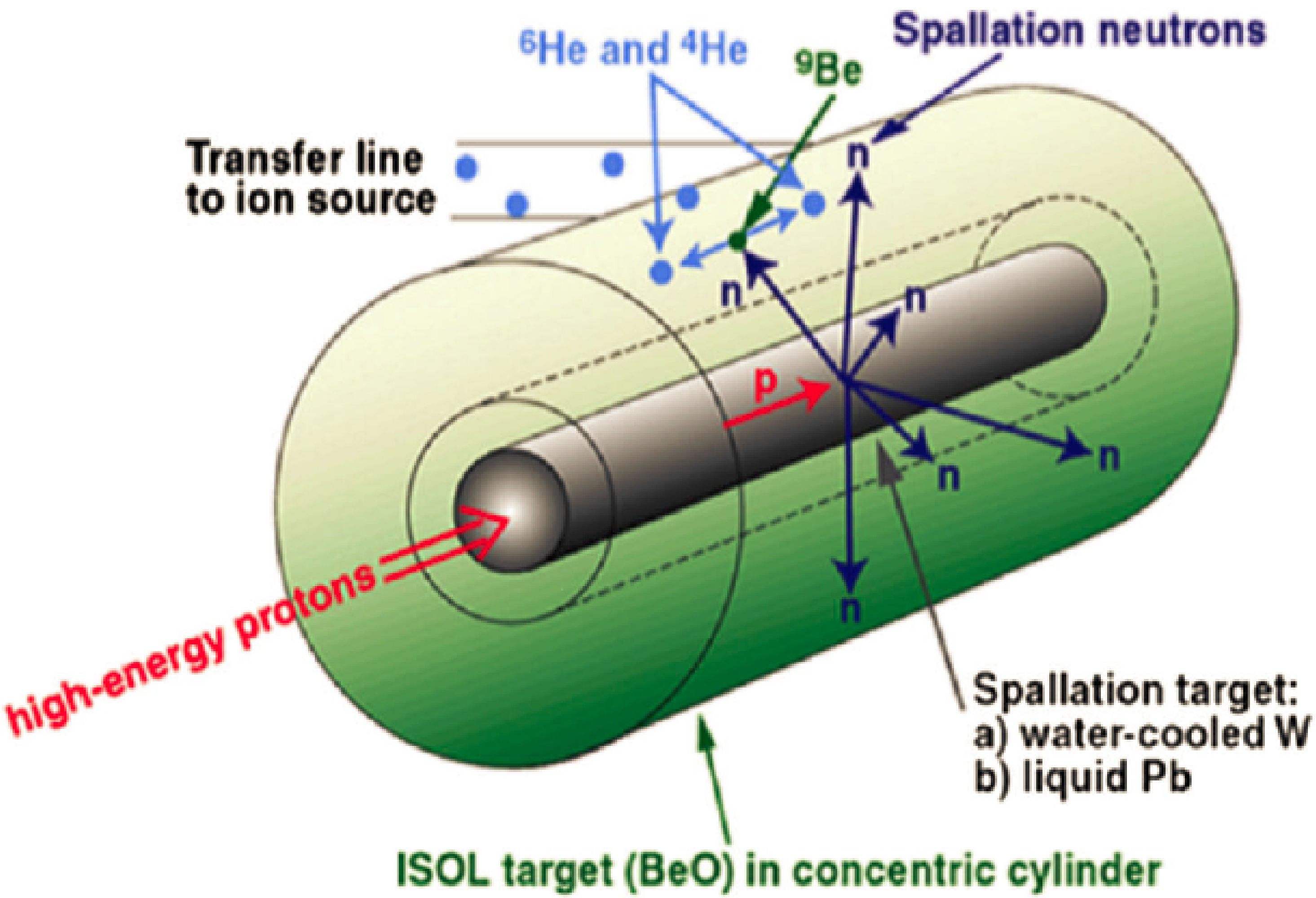
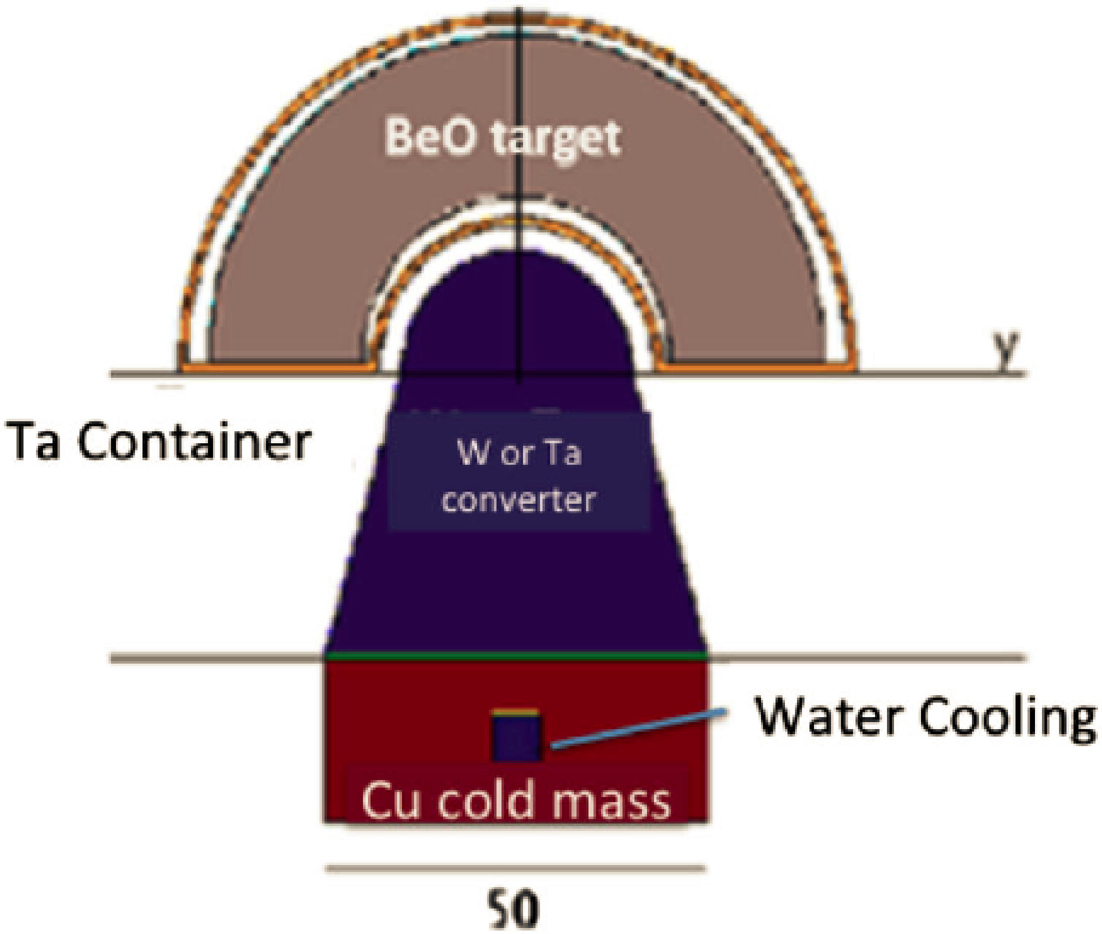
– Therefore, a conceptual layout of a dual converter-target assembly has been proposed;



$^6$He and $^4$He
$^9$Be
Spallation neutrons
Transfer line
to ion source
n
n
n
p
n
n
n
high-energy protons
Spallation target:
a) water-cooled W
b) liquid Pb
ISOL target (BeO) in concentric cylinder


(a)


BeO target
y
Ta Container
W or Ta
converter
Water Cooling
Cu cold mass
50
(b)

– In addition this layout has been adapted to integrate a mechanical support and water-cooling circuit to the converter in order to accommodate to beam of 100 kW, 1 GeV protons.

- In addition this layout has been adapted to integrate a mechanical support and water-cooling circuit to the converter in order to accommodate to beam of 100 kW, 1 GeV protons.
- The validation of the required $^{6}$He intensities for the $\beta$ beams has been performed with on-line tests at CERN ISOLDE. The operation parameters, release properties and production rate $^{6}$He have been monitored with pulsed 1.4 GeV protons delivered from proton synchrotron booster (PSB) accelerator.

– The production of $^{18}$Ne can be performed by (p, X)(or $^{3}$He, X) reaction on Na, F or Mg target. Among the wide list of available molten salts, the best candidate to the present application would be sodium fluoride (NaF). However, the high melting point of this salt limits its applications and the use of a binary system containing NAF would be more advantageous.

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- Two different binary system have been first proposed as candidates for the production of $^{18}$Ne: NAF:Zr$F_4$, and NAF:LIF.

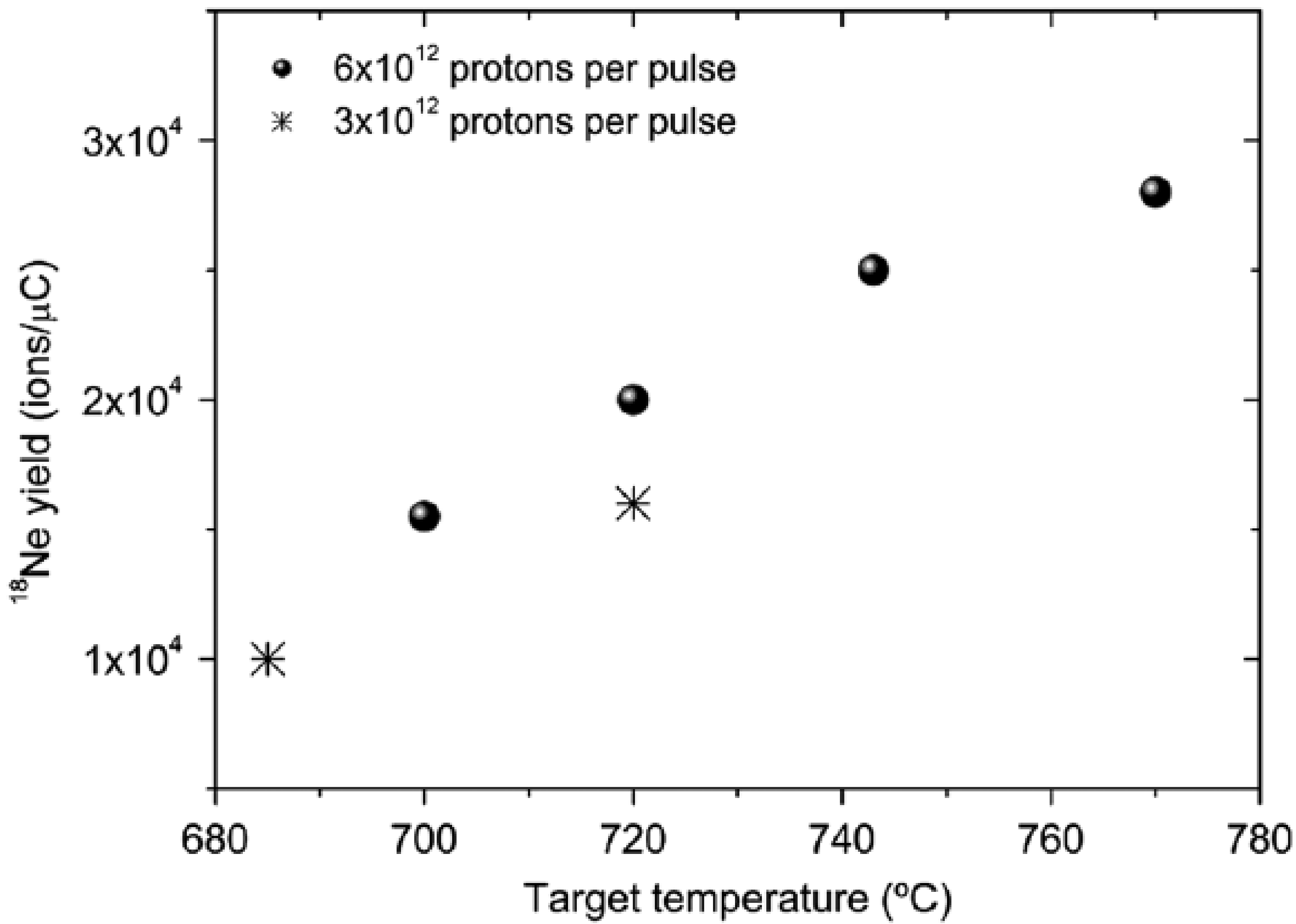
TABLE I. List of relevant physicochemical properties exhibited by the $NaF:ZrF_4$ and NaF:LiF binary systems: composition, melting point ($T_M$), room temperature density and 900 °C vapor pressure ($P_{vapor}$).

| Salt | Composition (mol%) | $T_M$ (°C) | Density ($g/cm^3$) | $P_{vapor}$ (mm Hg) |
|---|---|---|---|---|
| $NaF:ZrF_4$ | 60:40 | 500 | 3.14 | 5 |
| NaF:LiF | 39:61 | 649 | 2.75 | 0.1 |

– The choice of the composition has been made on a basis of thermal stability and low vapor pressure at operating temperature.

– The choice of the composition has been made on a basis of thermal stability and low vapor pressure at operating temperature.
– Following the synthesis and characterization, several annealing tests have been carried out to test the stability of proposed binary system. The lower vapor pressures and reactivity with air exhibited by the NAF:LiF system proved the suitability of the salt for the use in a circulating loop for the production of $^{18}$Ne.

– The first test to validate the production of $^{18}$Ne from a molten NAF:LIF salt has been performed using a standard target unit at ISOLDE-CERN. The release properties and production yields of $^{18}$Ne have been assessed at CERN-ISOLDE with 1.4 GeV from the PSB accelerator: The extraction efficiency and deduced yields have been studied as a function of the target temperature and proton beam intensity;



6x10^12 protons per pulse
3x10^12 protons per pulse
3x10^4
2x10^4
1x10^4
18Ne yield (ions/μC)
680
700
720
740
760
780
Target temperature (°C)

– The present result validate the use of NaF-based salts in the production of $^{18}$Ne as well as its use in a molten salt loop target. The circulating molten salt target will improve the diffusion time of $^{18}$Ne and rate of $1 \times 10^{13}$ $^{18}$Ne/s are expected for 160 MeV 7 mA proton beam.

- The beta beam isotopes are accelerated in an ion linac after being collected in charge breeding ECR Source. The ionized isotope then pass through a rapid cycling synchrotron (RCS), the CERN PS synchrotron and the last acceleration stage before the decay ring(DS) is the CERN SPS.

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- The decay ring would have a circumference of 6900m and a straight section length of almost 2700m. The main bending magnet field is 6T, consequently Superconducting technology is necessary.

# Intensity Frontier of Particle Physics at China's High Power Proton Accelerators

- With succeeding constructions of CSNS, CIADS and HIAF, high power hadronic accelerator become available in China, physics of high intensity Muon and Neutrino beams at these facilities should be seriously taken into consideration: preliminary R&D programs,conceptual design and design studies.

- Our proposal is for programs at China's high power hadronic accelerators: CSNS, CIADS, HIAF and the proposed Nanjing SPL;

## New Research Center in New Site

### Researches on Intense Beam at CIADS+HIAF

I. Nuclear Physics
- Nuclear Structure & Nuclear Astrophysics
- Hadron Nuclear Physics

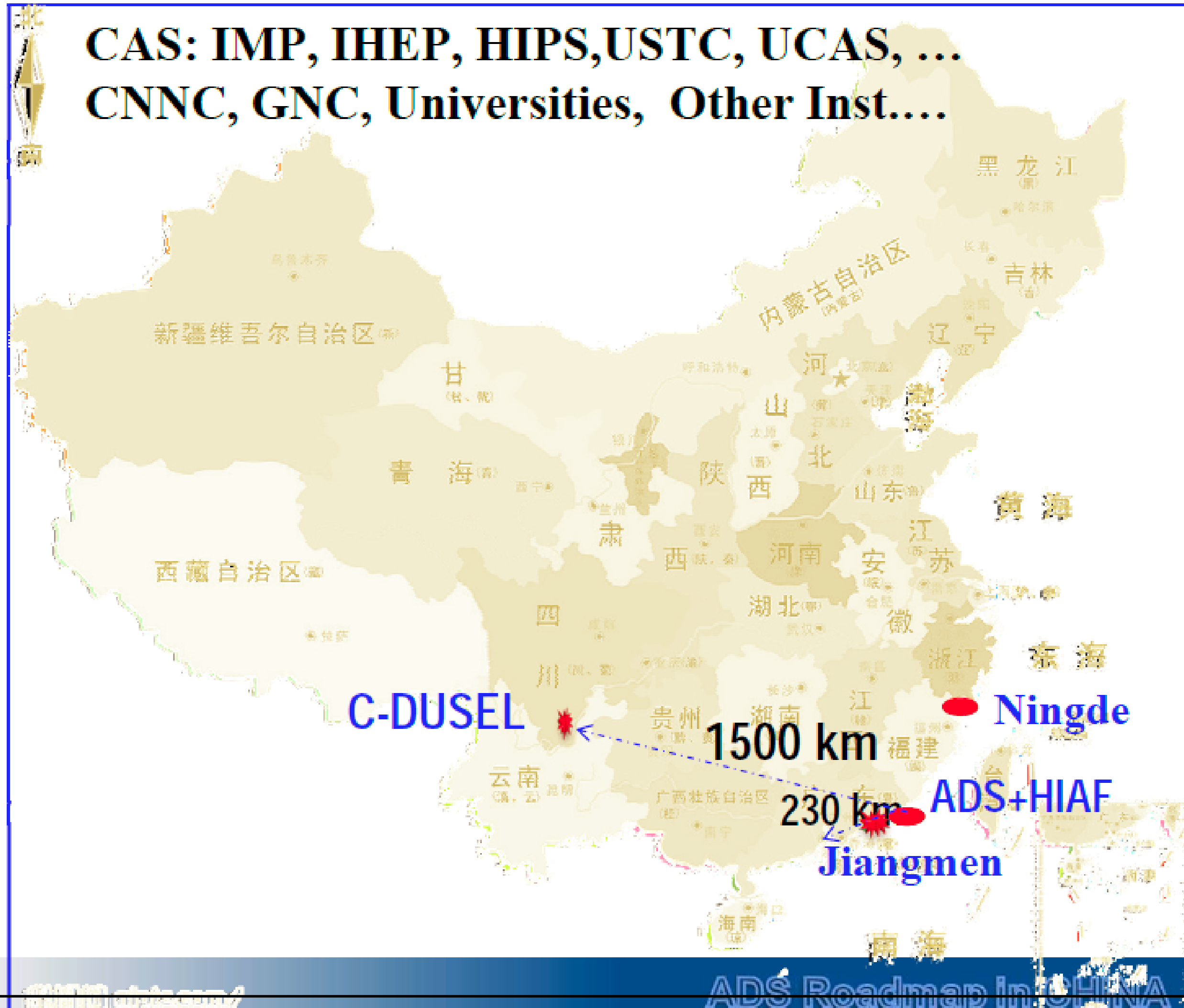
II. Foundation Physics
- Researches by Polarized nucleon, DAR neutrino, μ, π…
- Ultra-high E_Field QED

III. Nuclear Energy
- ADS → ADANES Burner

IV. Irradiative Material, Biology
- Compact, High Flux Neutron Source (~50dpa)
- Ion Therapy

V. Convert SNF → Recycle Fuel

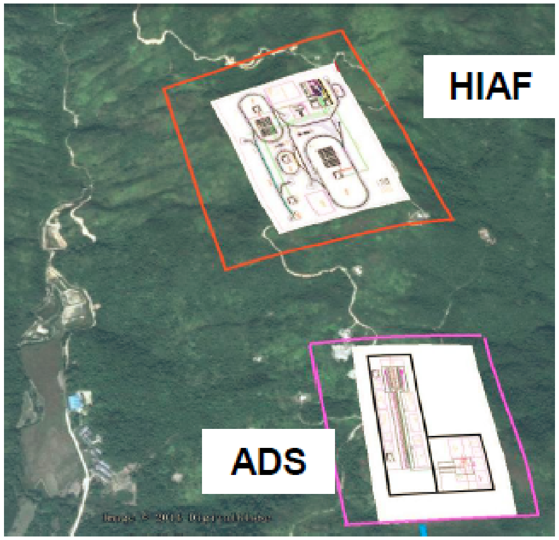
# New site, New open research center

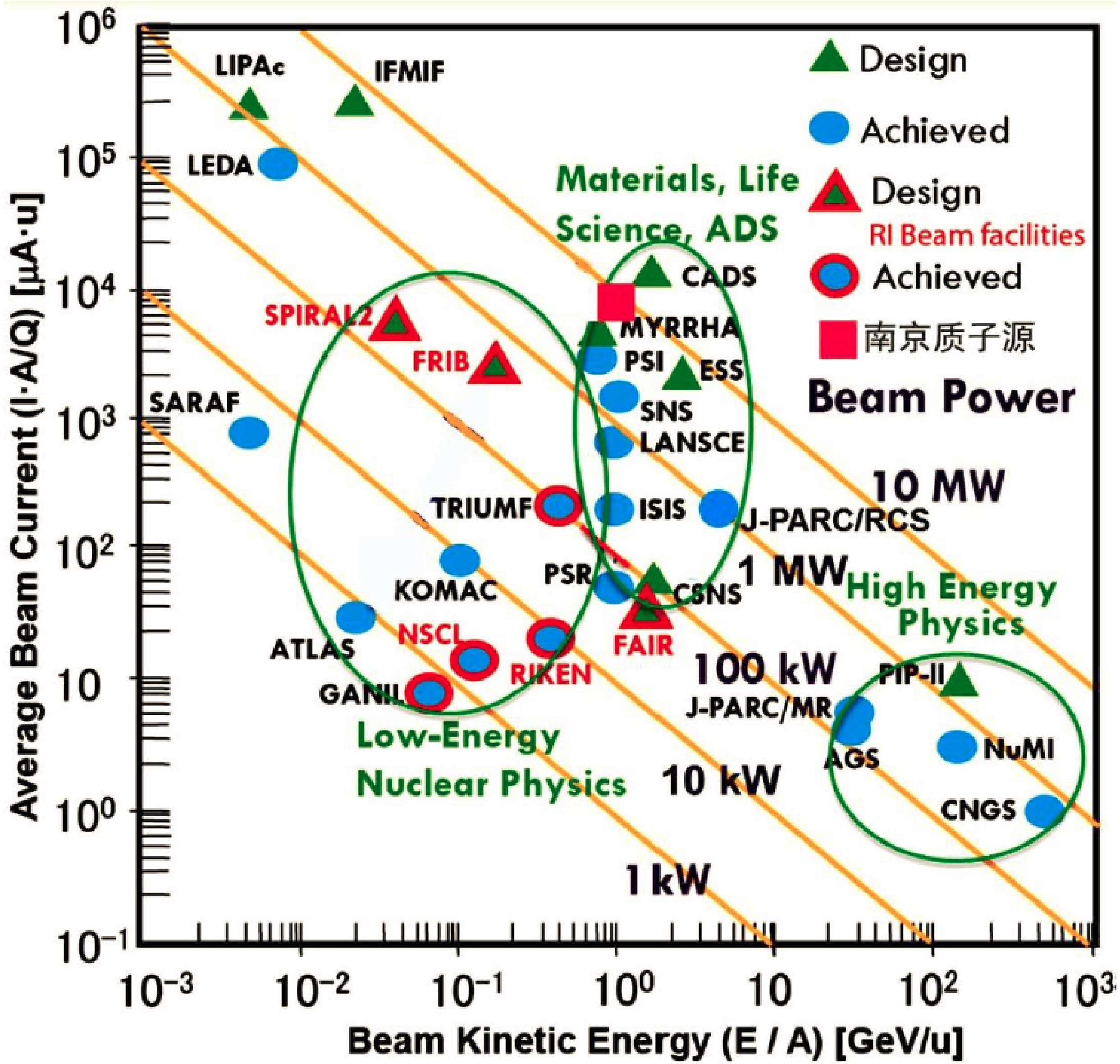



ADS Roadmap in CHINA

# Site of HIAF project





Design
Achieved
Design
RI Beam facilities
Achieved
南京质子源
Beam Power
LIPAc
IFMIF
LEDA
Materials, Life
Science, ADS
CADS
MYRRHA
PSI
ESS
SNS
LANSCE
SPIRAL2
FRIB
SARAF
TRIUMF
ISIS
J-PARC/RCS
10 MW
1 MW
PSR
CSNS
KOMAC
ATLAS
NSCL
RIKEN
FAIR
GANIL
High Energy
Physics
100 kW
PIP-II
J-PARC/MR
AGS
NuMI
CNGS
Low-Energy
Nuclear Physics
10 kW
1 kW
Average Beam Current (I·A/Q) [μA·u]
Beam Kinetic Energy (E / A) [GeV/u]

- Physics goal is focused on at intensity frontier of particle physics: facilities, experiments and theories;

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  - Ultra-cold neutron physics;

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  - Ultra-cold neutron physics;
    * Baryon Asymmetry of Universe(BAU) and the EDM

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  - Ultra-cold neutron physics;
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    - Structure of the Weak Interaction

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- Make a roadmap through R&D programme, feasibility study, conceptual design and design study;