Ion sources and their applications

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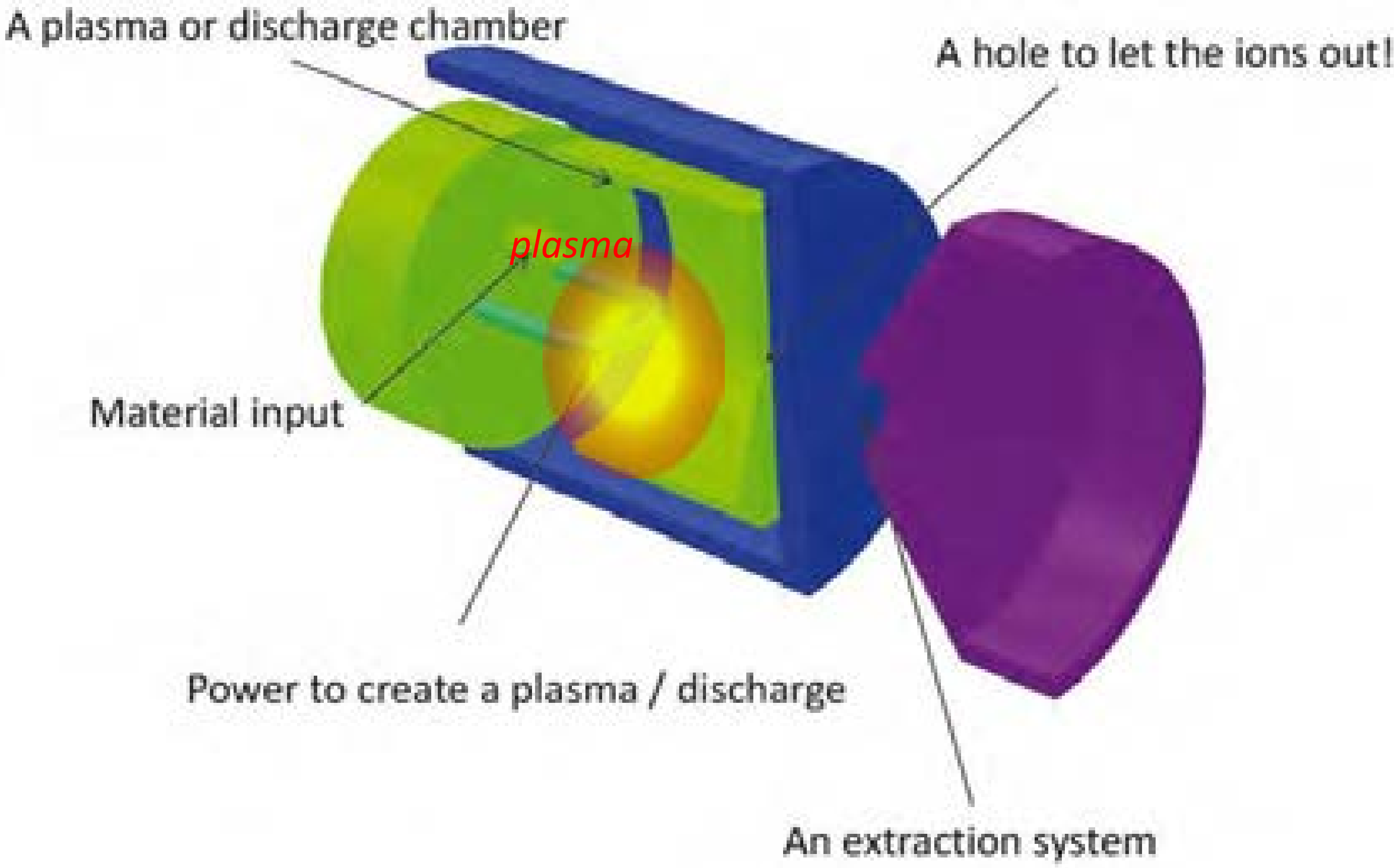
SAPIENZA UNIVERSITÀ DI ROMA

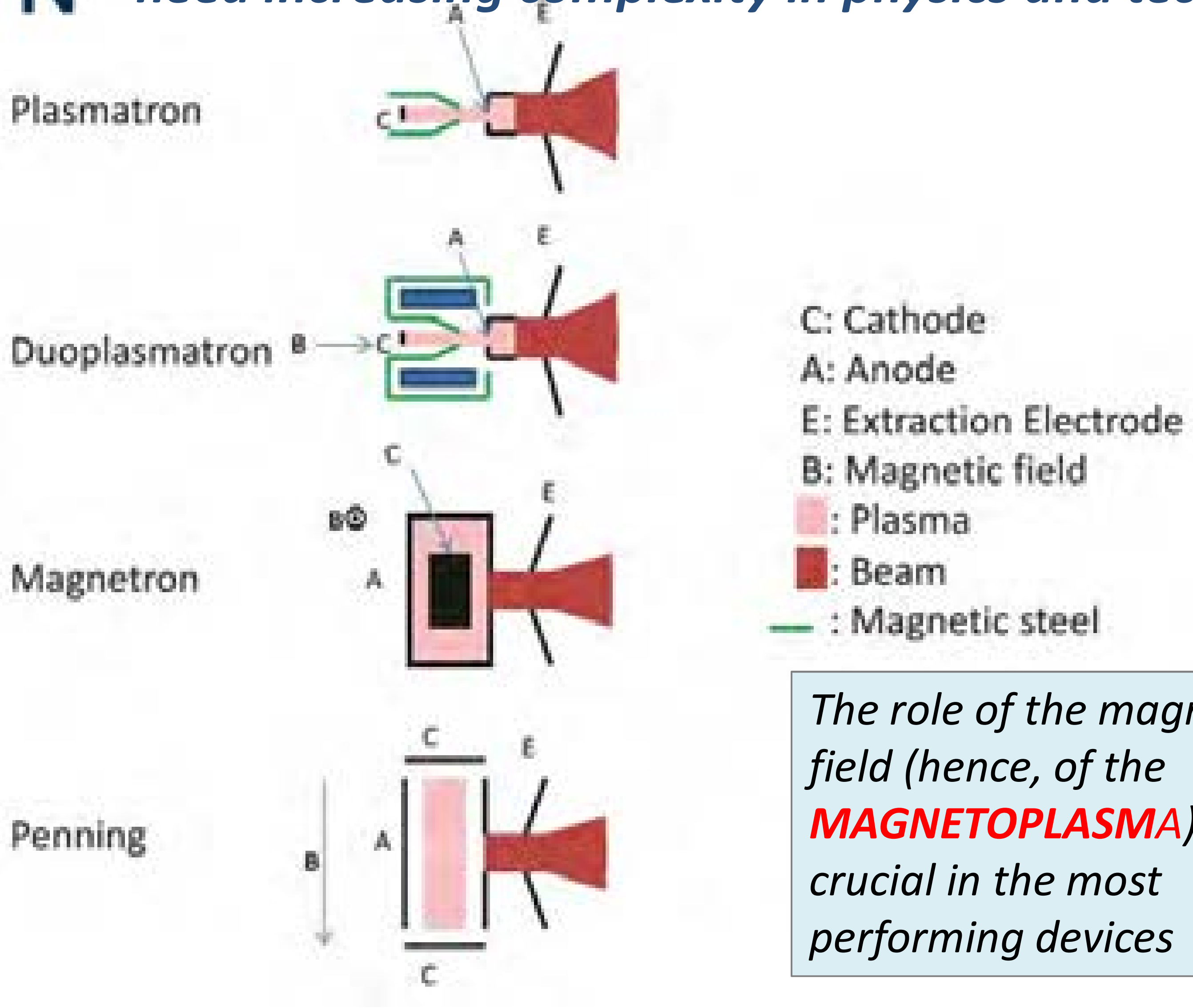
Dottorato in FISICA DEGLI ACCELERATORI

Particle and Photon sources

A simple sketch of an Ion Source



Demanding requests in terms of intensity/charge states need increasing complexity in physics and technology



*The role of the magnetic field (hence, of the **MAGNETOPLASMA**) is crucial in the most performing devices*

Several Ion Sources: “Unicuique Suum”

Mid/Low Intensity – Multiply Charged

E.g.: up to several hundreds of μA of Xe^{34+} nA of U^{92+}
Request of 1 mA of U^{28+}, or 0.5 mA of U^{35+}

Applications

- ***Fundamental Science****: RIBs Facilities Atomic Physics (extremely high charge states), Nuclear/Nuclear Astrophysics in Plasmas, Hadrontherapy via C-beams*

Accelerators types

- ***Circular****: Injectors for Cyclotrons, Synchrotrons, Colliders* ***Linear****: LINACS*

Most used Ion Sources

- ***ECRIS****: Electron Cyclotron Resonance Ion Sources*
- ***EBIS****: Electron Beam Ion Sources*
- ***EBIT****: Electron Beam Ion Trap*

High Intensity – Singly Charged (p, H^-, He)

E.g.: up to several hundreds of mA of protons; multi-A of **H^-**

Applications

- ***Applied and Industrial Research****:*
  - *Spallation Sources*
  - *ADS – Accelerator Driven Systems*
  - *Nuclear Fusion Reactors (for NIB – Neutral Beam Injection)*

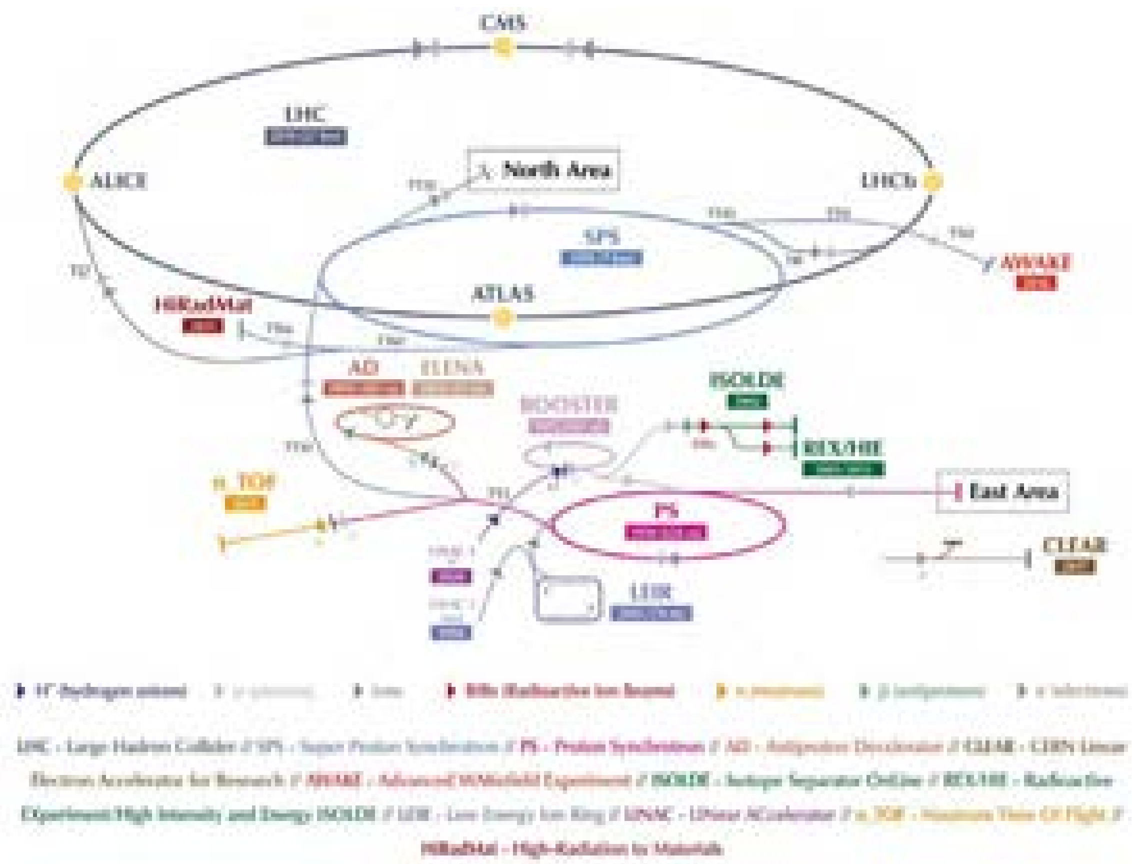
Accelerators types

- ***Especially Linear****: for ADS, SS*
- ***Electrostatic (up to 1 MeV)****: for Neutral Beam Injection*

Most used Ion Sources

- ***Volume Ion Sources for*** **H^-**
- ***MDIS****: Microwave Discharge Ion Sources (for proton beams)*

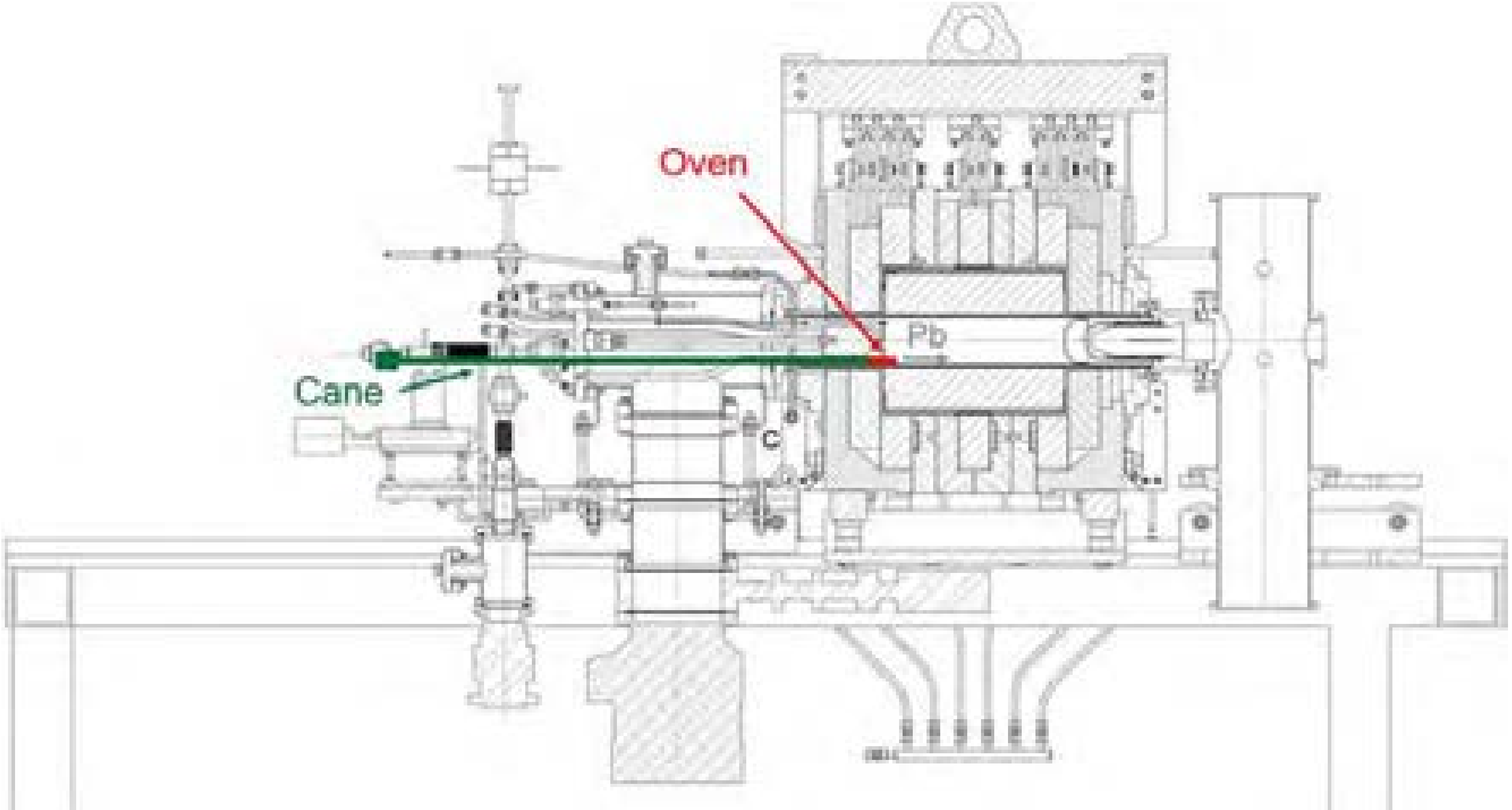
Big Facilities over the world require intense beams of multiply charge ions



Beam requested from ion source:
1 emA Pb^{27+}

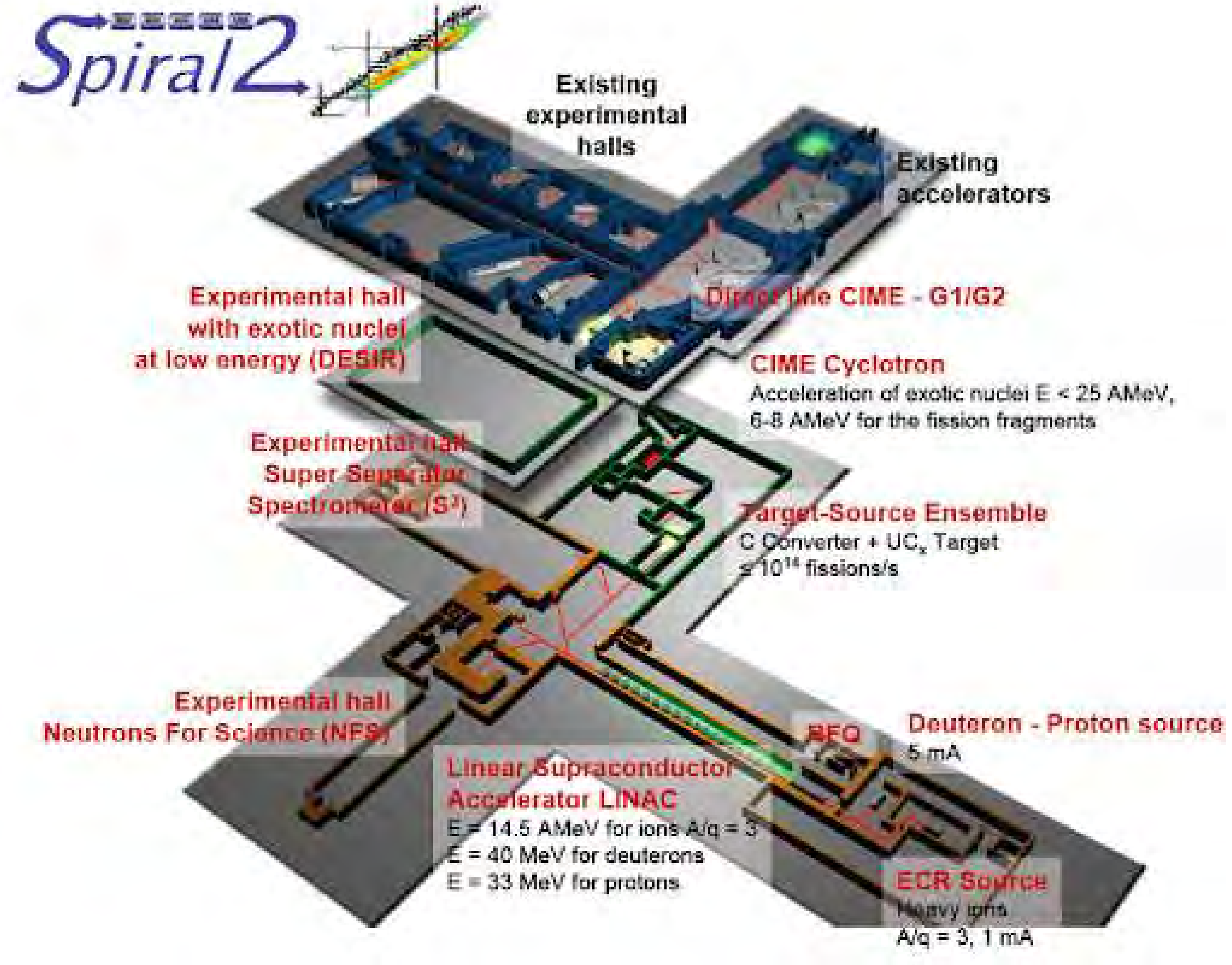
Main goal*: investigation on origin of the mass (Higgs Boson), evidence of supersymmetry, dark matter and dark energy, matter vs. antimatter, quark-gluon plasma interaction*

Big Facilities over the world require intense beams of multiply charge ions

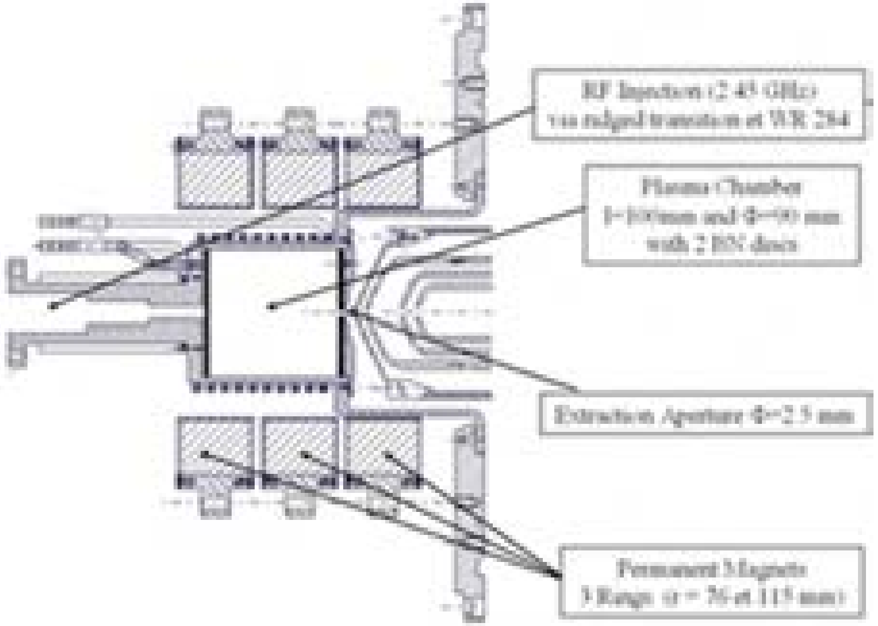


GTS-LHC ion source

Big Facilities over the world require intense beams of multiply charge ions

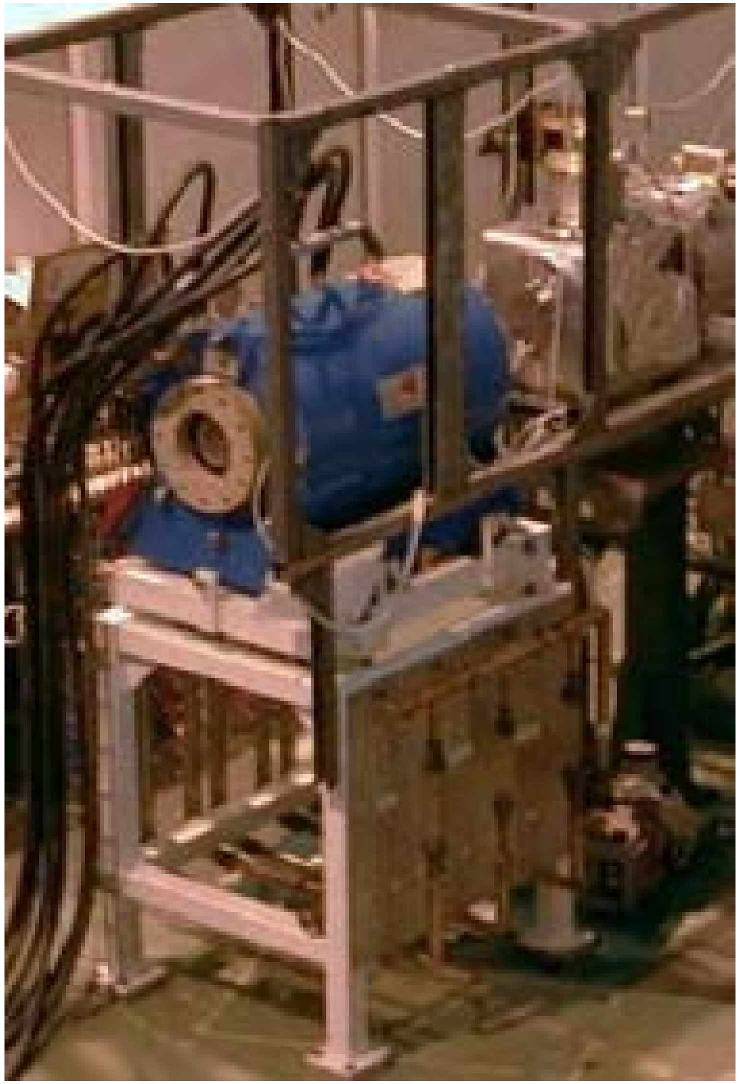


Big Facilities over the world require intense beams of multiply charge ions

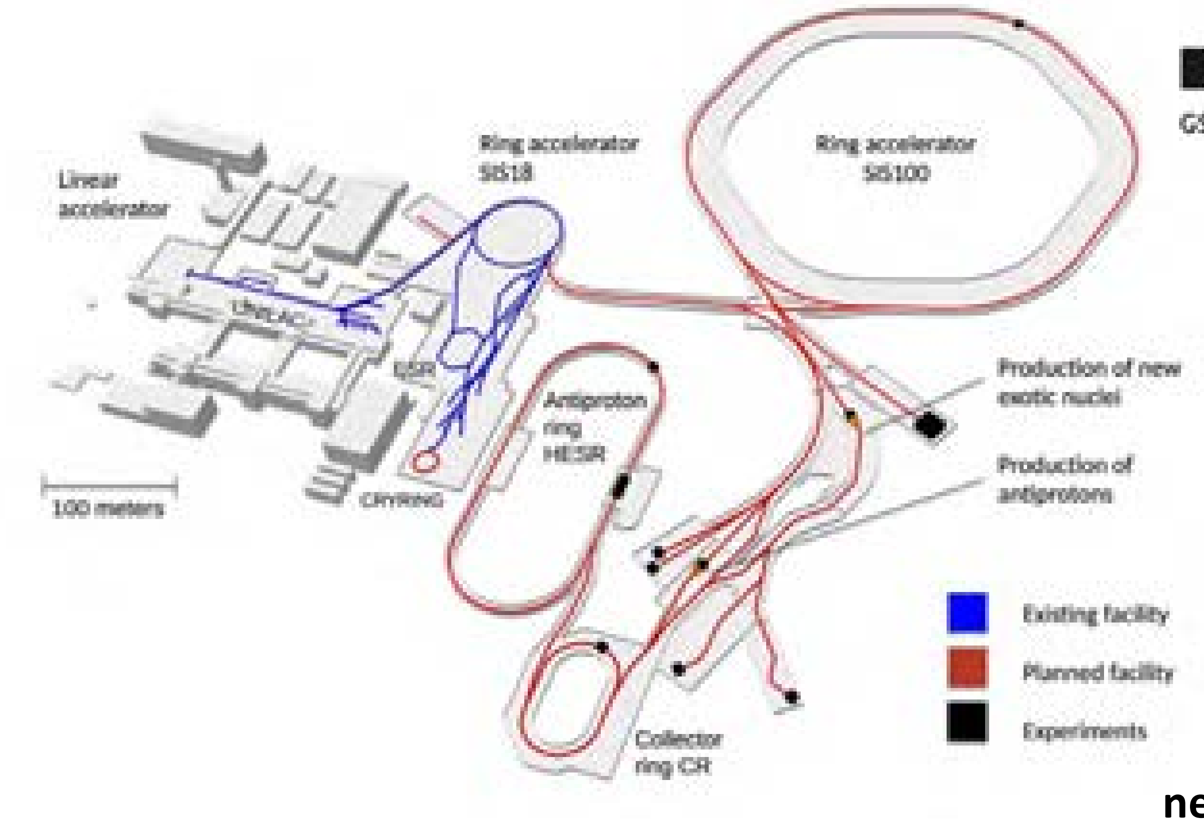


5 mA Deuteron source

PHOENIX ECR ION SOURCE



Big Facilities over the world require intense beams of multiply charge ions



GSI Helmholtzzentrum für Schwerionenforschung

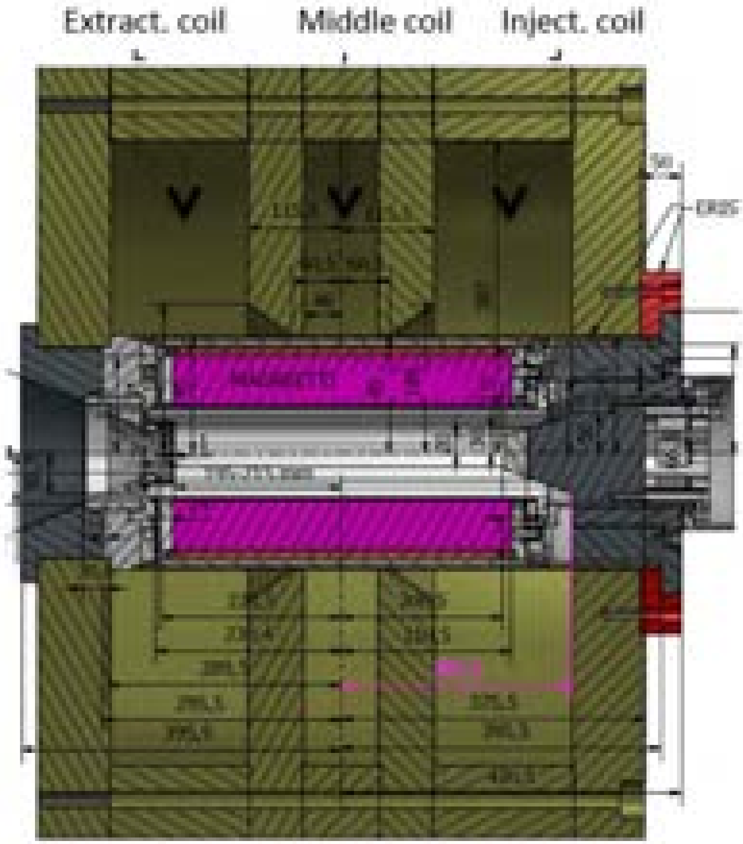
Rare isotope physics:
1 emA U^{28+}

Antiproton physics:
100 emA H^{+}

Accelerator chain:
new proton linac (70 MeV, 70 mA), SIS18 and SIS 100

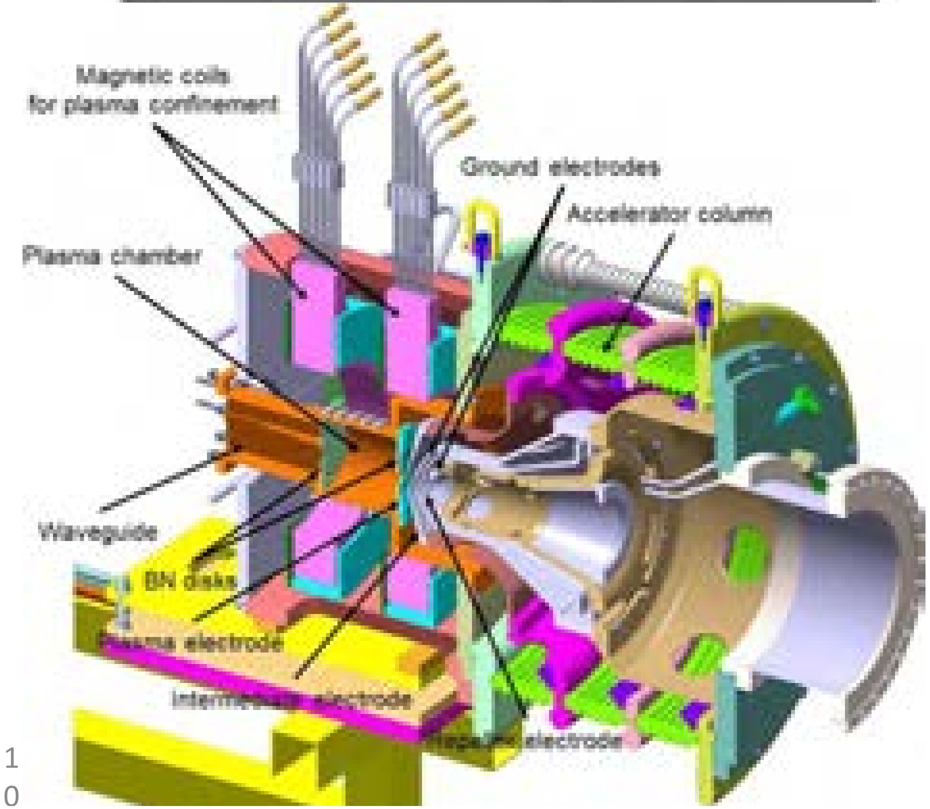
Main goal*: physics of exotic nuclei, hadronic physics with proton and antiproton collisions, study of relativistic heavy ion reactions (a few tens of AGeV) , plasma and atomic physics*

Big Facilities over the world require intense beams of multiply charge ions

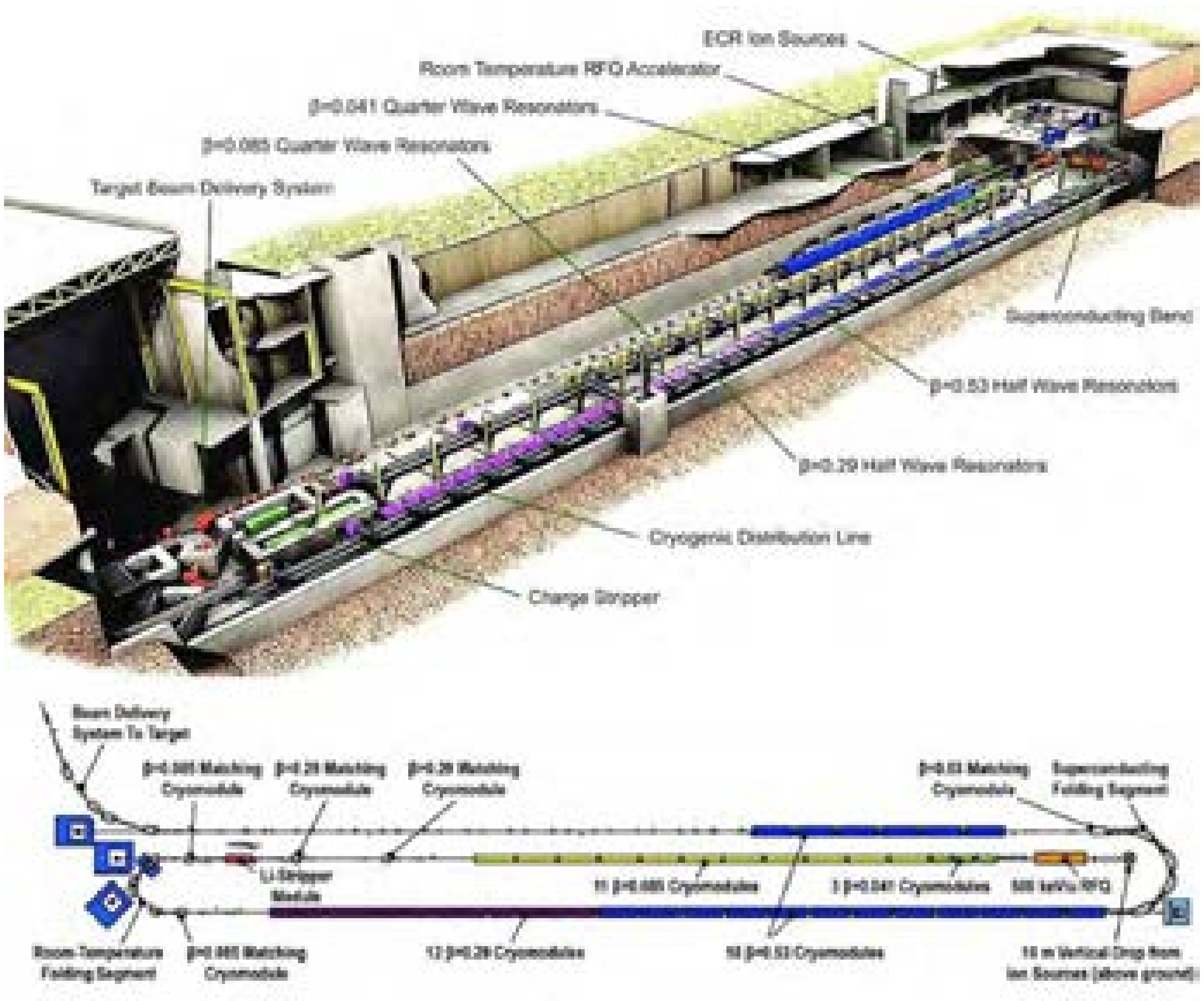


HIISI ion source (JYFL)

Parameters	Value
Specie	Proton
Energy	95 keV
Intensity	100 mA
Time structure	Pulsed at 4 Hz
Energy spread	< 60 eV
Final emittance	$\leqslant 0.33\ \pi$ mm.mrad
α Twiss parameter	$0.27 \leqslant \alpha \leqslant 0.59$
β Twiss parameters	$0.037 \leqslant \beta \leqslant 0.046$ mm/π.mrad



Big Facilities over the world require intense beams of multiply charge ions



FRIB

Facility for Rare Isotope Be

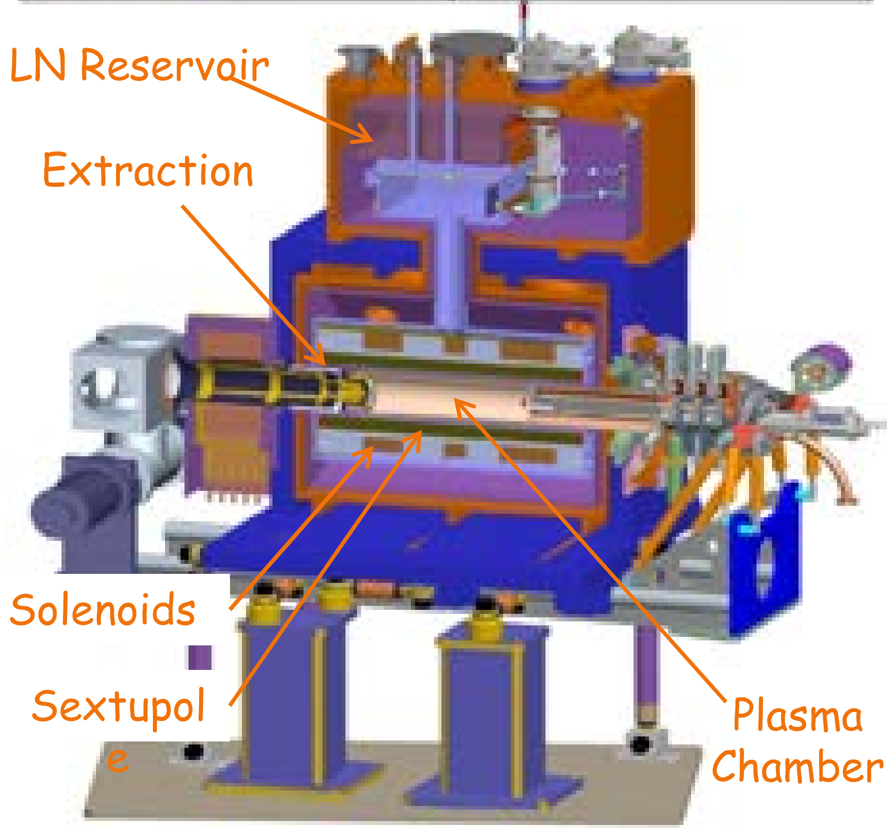
U.S. Department of Energy Office of Science

Michigan State University

- Accelerate ion species up to ^{238}U with energies of no less than 200 MeV/u
- Provide beam power up to 400kW
- Energy upgrade to 400 MeV/u for ^{238}U by filling vacant slots with 12 SRF cryomodules
- Provisions for ISOL upgrade

Big Facilities over the world require intense beams of multiply charge ions

VENUS (18+28GHz) 2006–2008		Re-commissioning VENUS (18+28GHz) 2010	
O^{6+}	2860eμA		
O^{7+}	850 eμA	Xe^{26+}	480 eμA
Ar^{12+}	860 eμA	Xe^{27+}	411 eμA
Ar^{16+}	270 eμA	Xe^{30+}	211 eμA
Ar^{17+}	36 eμA	Xe^{33+}	108 eμA
Xe^{27+}	270 eμA	Xe^{35+}	38 eμA
Xe^{30+}	116 eμA		

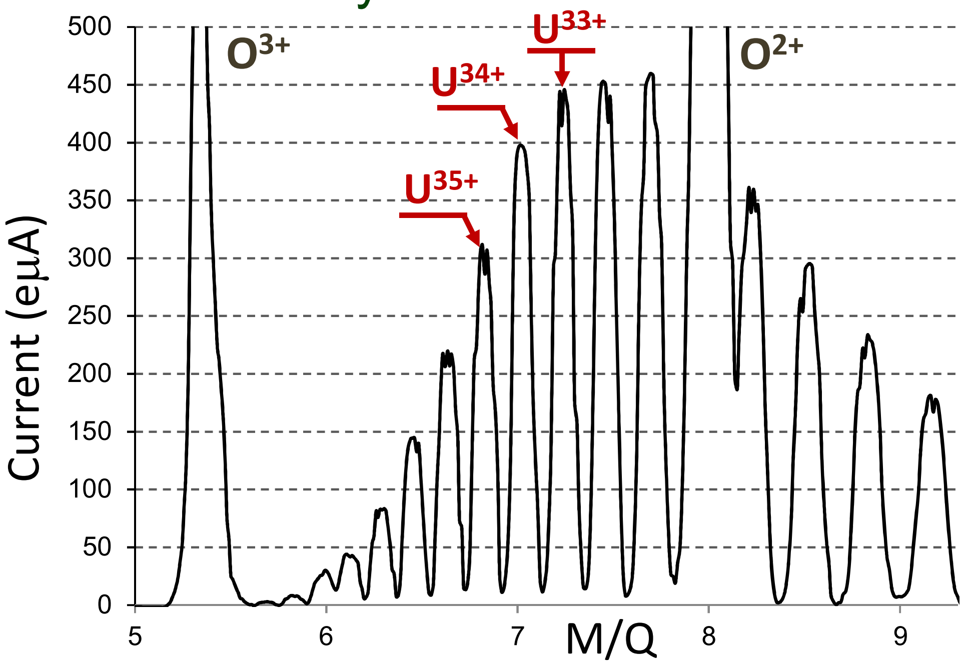


- Fully superconducting, Niobium-Titanium
- LN Reservoir: 70K, dissipates heat from NC leads
- He Reservoir: 4.2K
- Four two stage GM cryocoolers: 6W@4.2K

Maximum Injection Field, on axis	4.0T
Maximum Extraction Field, on axis	3.0T
Maximum Radial Field, at wall	2.2T
Chamber Diameter	14cm
Chamber Length	48cm
18 GHz Maximum Power	2kW
28 GHz Maximum Power	10kW

Big Facilities over the world require intense beams of multiply charge ions

- ^{238}U Intensity



- FRIB Requirement

Q ECR	I ECR (eμA)	I ECR (pμA)
33	432	13.1
34	445	13.1

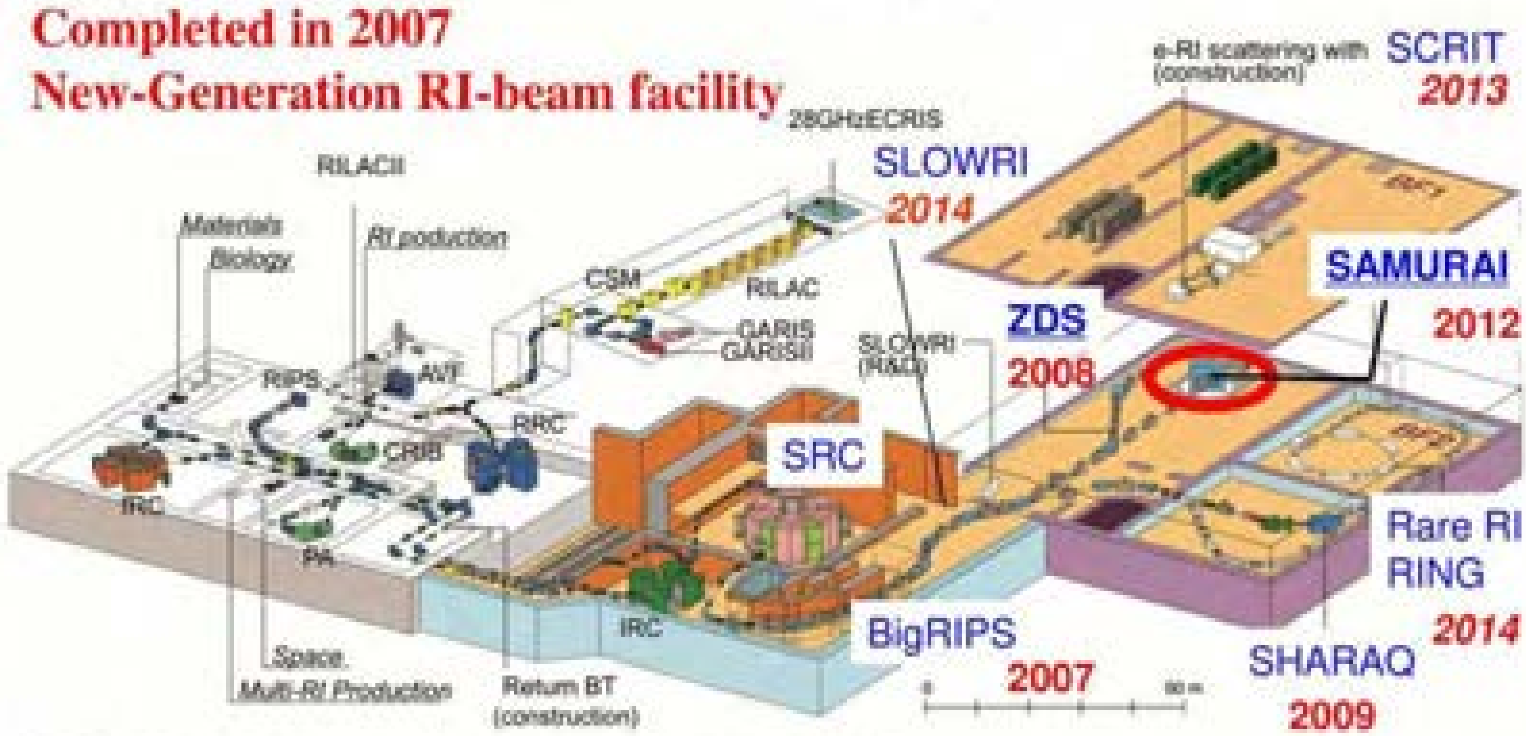
- Beam Measurements with VENUS

Q ECR	I ECR (eμA)	I ECR (pμA)
33	443	13.42
34	400	11.76

- Up to 8.3 kW Coupled to the VENUS ECR ion source
  - 28 GHz from gyrotron: 6.5 kW injected out of 10kW
  - 18 GHz from Klystron: 1.8kW (Maximum available)
- Total extracted current exceeded 9 emA for a transmission of 55%
- High intensity production was maintained for about 10 hours.
- New record beam intensity obtained with VENUS exceeds for U33+ the intensity needed to reach 400kW on target by accelerating only one chare state
- Beam emittance 95% within FRIB requirement (0.9pi.mm.mrad)

Big Facilities over the world require intense beams of multiply charge ions

RIKEN RI Beam Factory (RIBF)



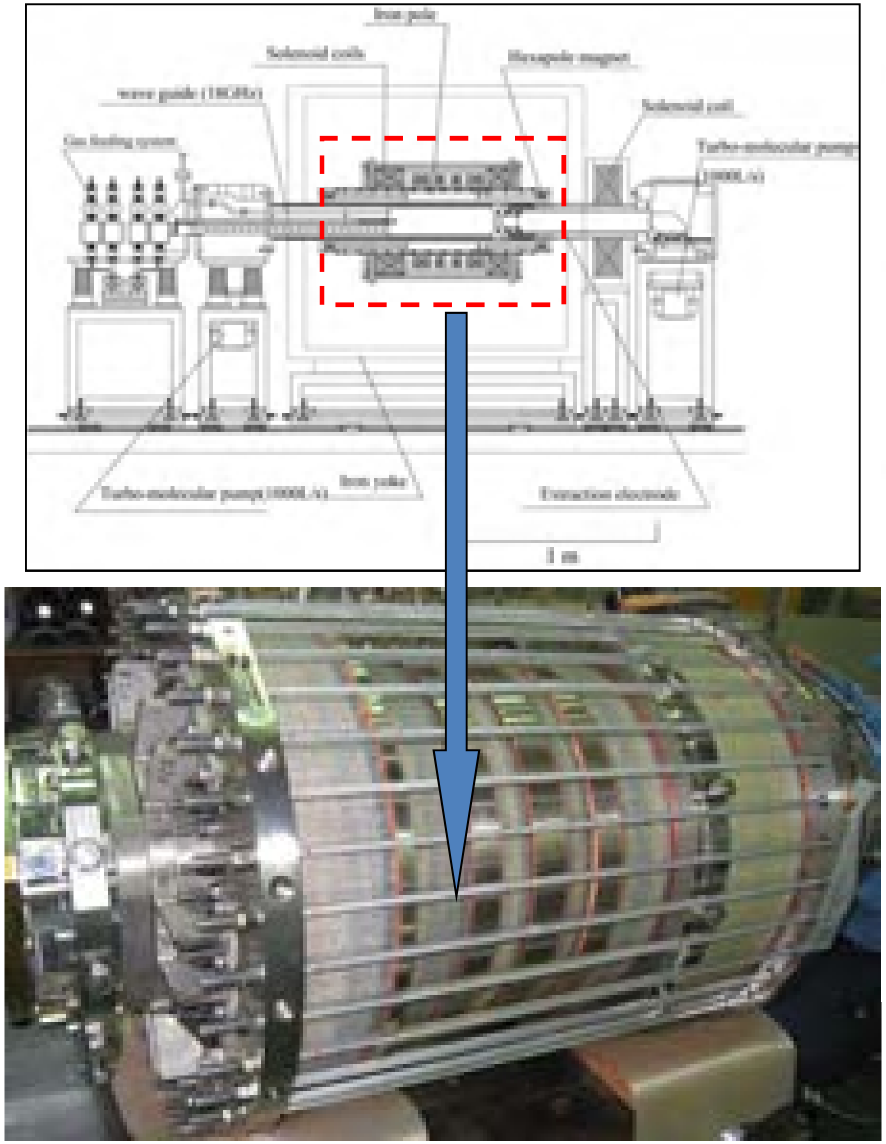
0.525 emA U^{35+}

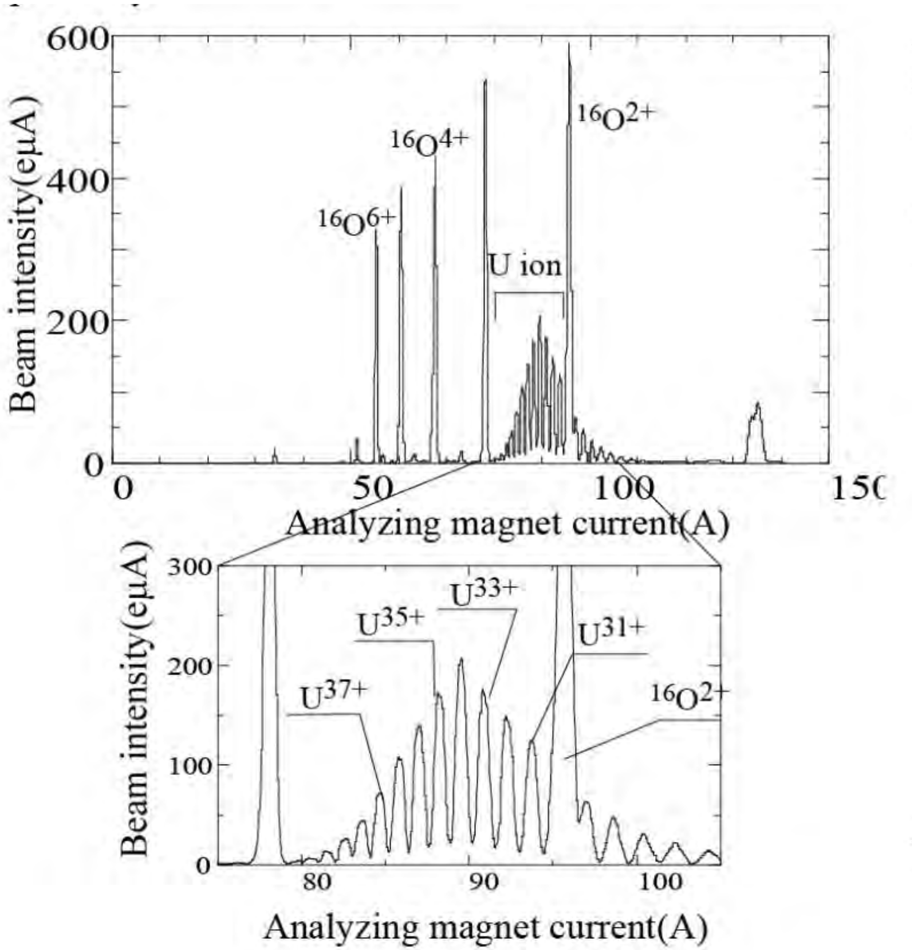
SRC: World Largest Cyclotron (K=2500 MeV)
Heavy Ion Beams up to ^{238}U at 345MeV/u (Light Ions up to 440MeV/u)
eg.

Increasing Year by Year!

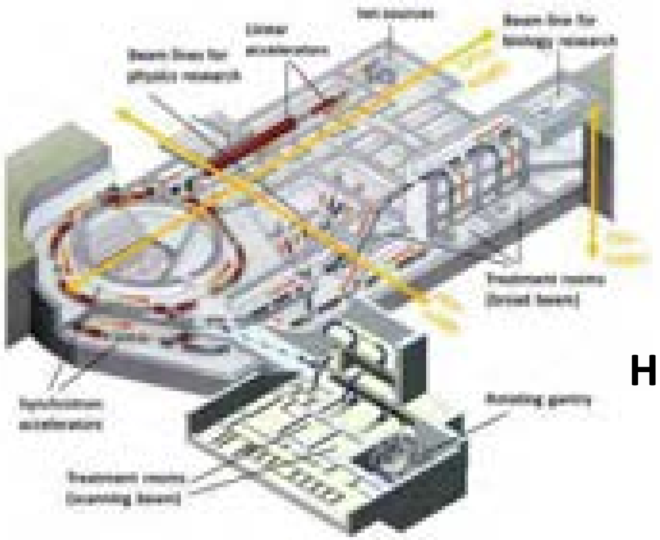
^{48}Ca beam (345 MeV/nucleon) ~200pnA (250pnA max.) ^{48}Ca:~500pnA 2014
^{238}U beam (345 MeV/nucleon) ~12pnA (15pnA max.) ^{238}U: ~ 30 pnA 2015

Big Facilities over the world require intense beams of multiply charge ions





Big Facilities over the world require intense beams of multiply charge ions



HIMAC

National Institute for Quantum and Radiological Science and Technology
QST Hospital （former NIRS Hospital）

0,5 emA C^{4+}

fondazione CNAO
Centro Nazionale di Adroterapia Oncologica per il trattamento dei tumori

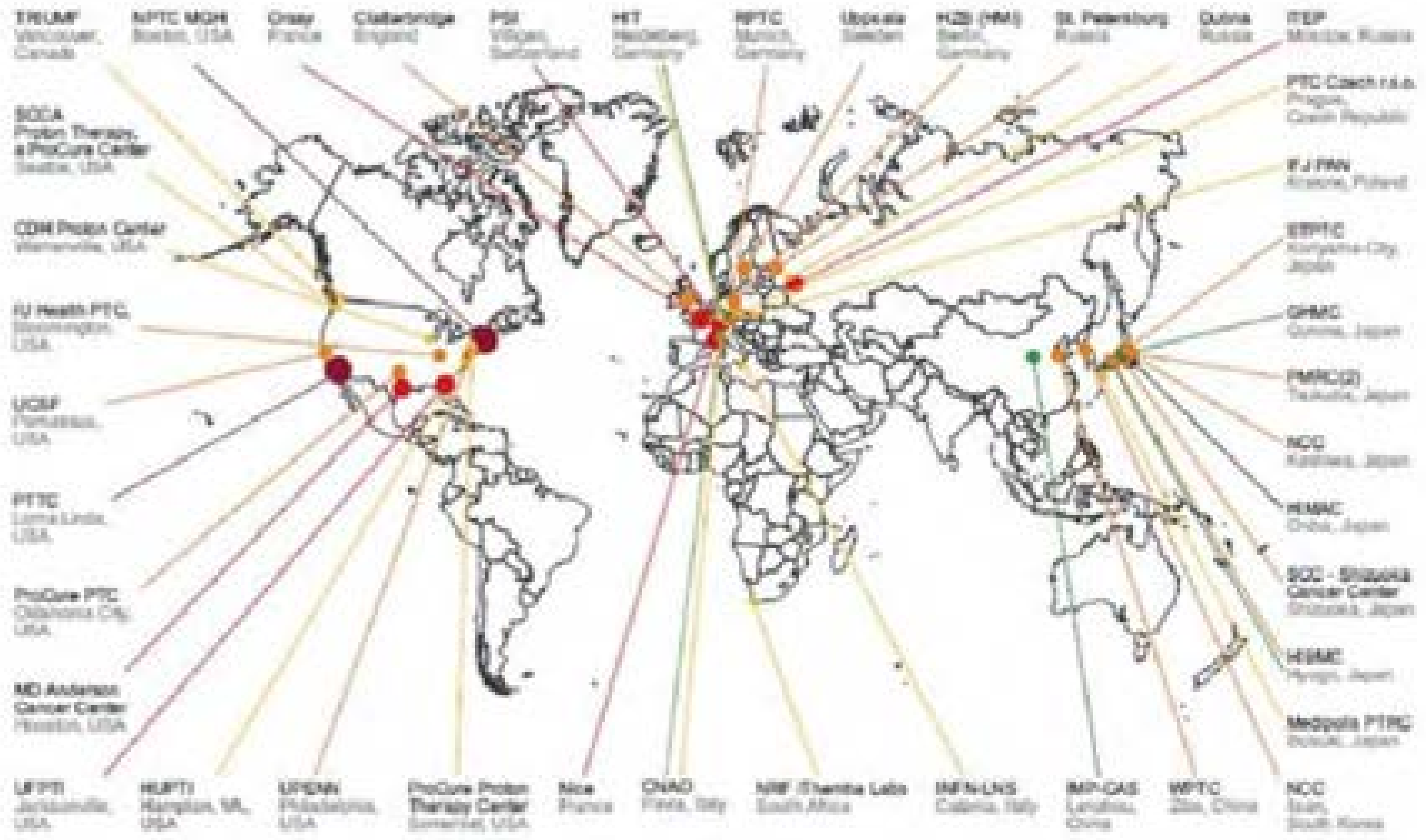
Big Facilities over the world require intense beams of multiply charge ions

- Very simple source with just a few parameters to set, important for installation in hospital environment.

- Currents limited by the limited power sustainable and from the rigid magnetic field structure.

- Lack of space in extraction to further optimize the extraction system

Big Facilities over the world require intense beams of multiply charge ions



High power proton accelerator for Spallation

Key parameters:

-2.86 ms pulses
-2 GeV
-62.5 mA
-14 Hz
-Protons (H+)
-Low losses
-Low heat loss cryostats for minimum energy consumption
-Flexible design for future upgrades

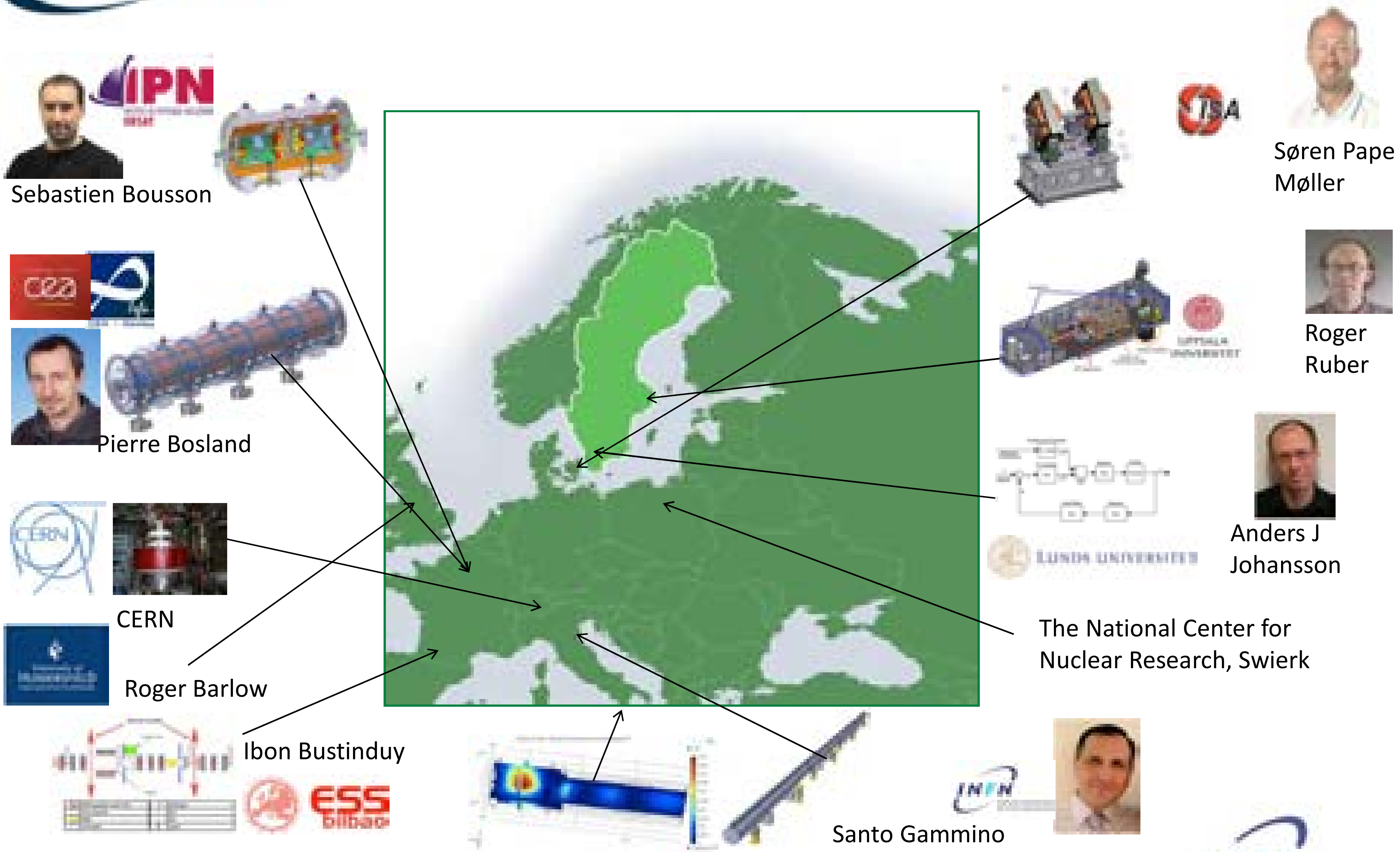
Design Parameters:

High Average Beam Power 5 MW

High Peak Beam Power 125 MW

High Availability > 95%

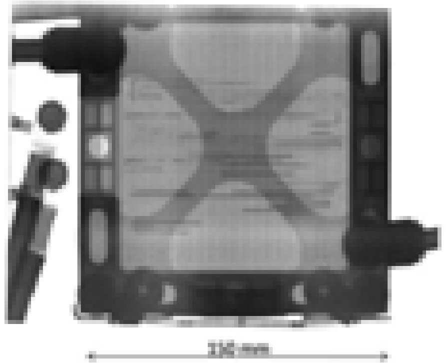
Prototyping the ESS accelerator



International collaboration

Boosting neutron science for fundamental physics and applications

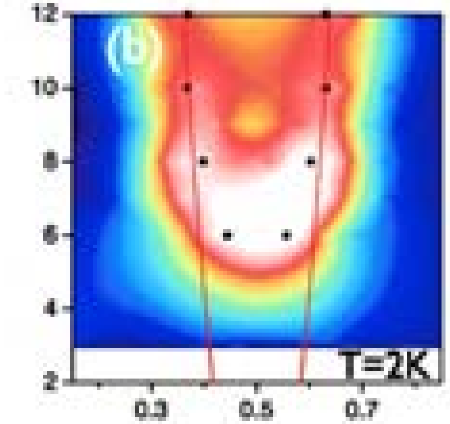
Charge neutral
deeply penetrating



Li motion in fuel cells

Help build electric cars

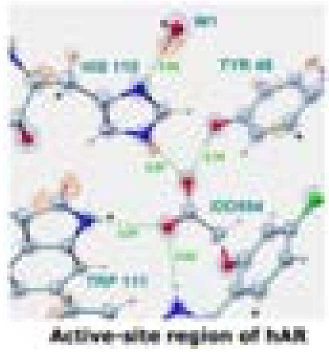
S=1/2 spin
probe directly magnetism



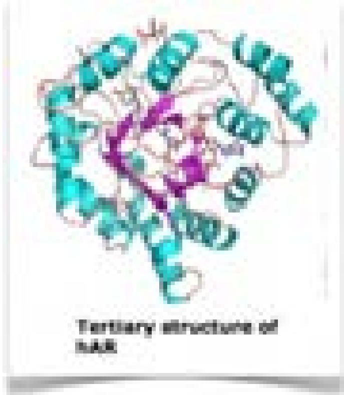
Solve the puzzle of High-Tc superconductivity

Efficient high speed trains

Nuclear scattering
sensitive to light elements and isotopes

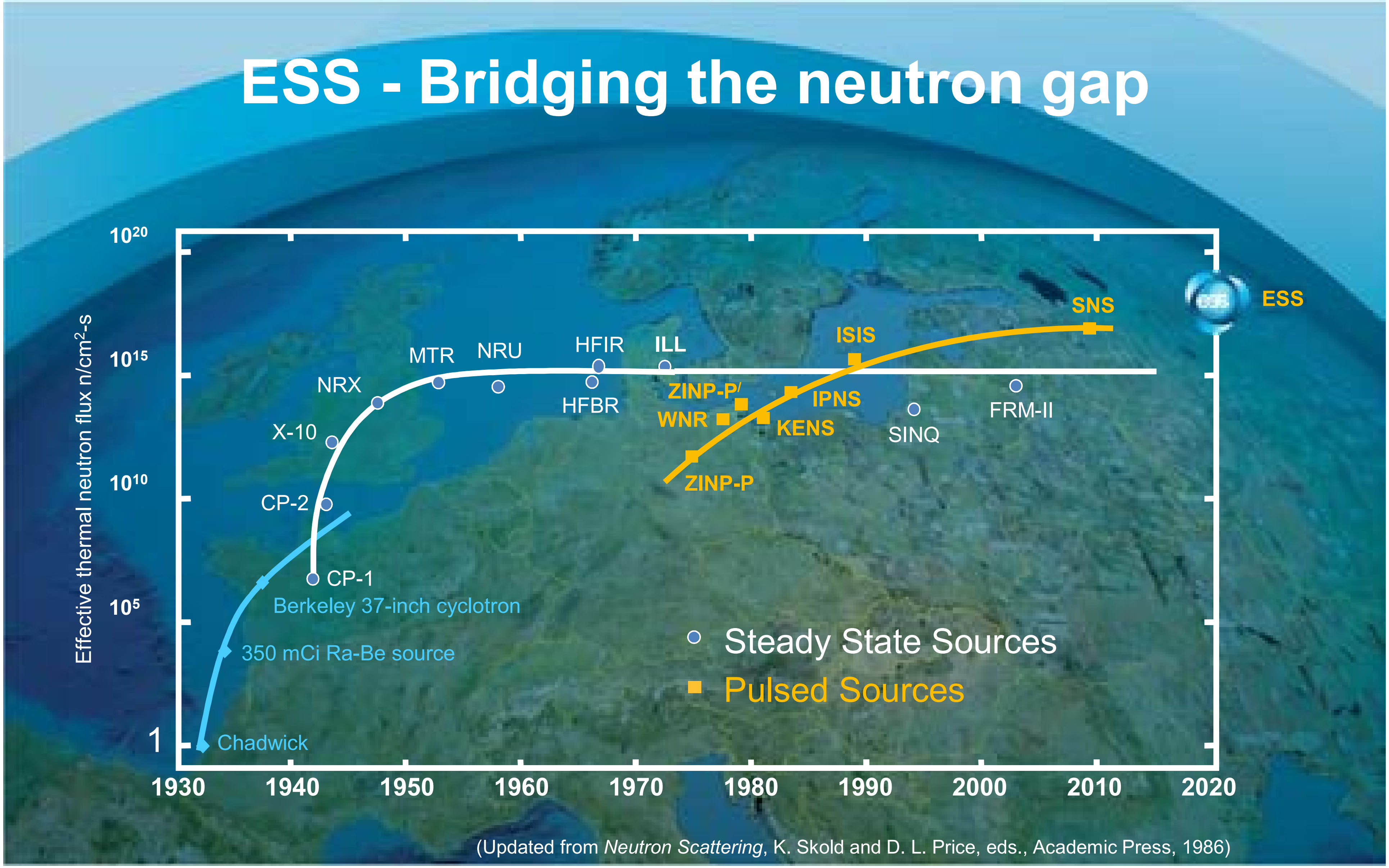


Actives sites in proteins

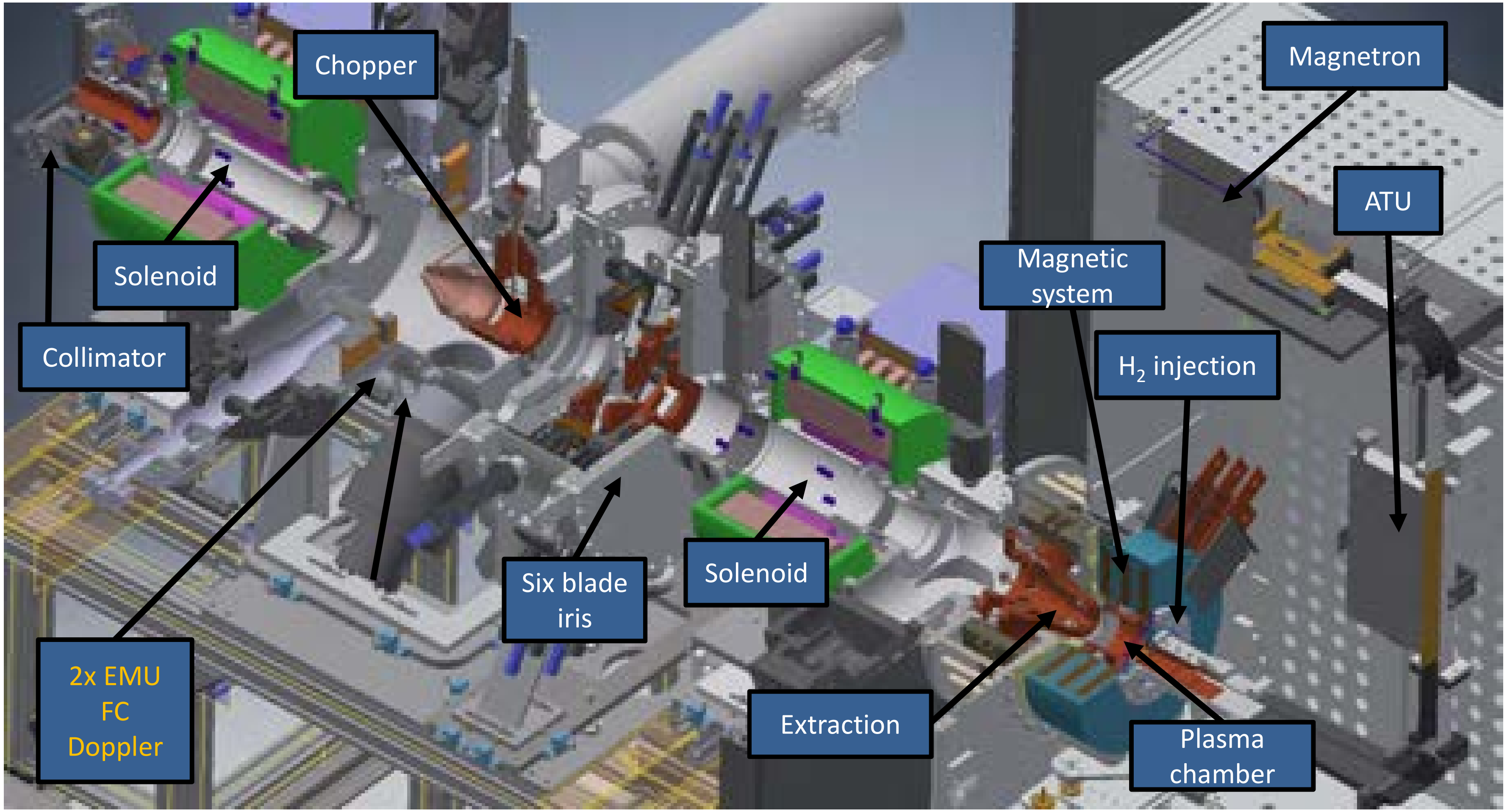


Better drugs

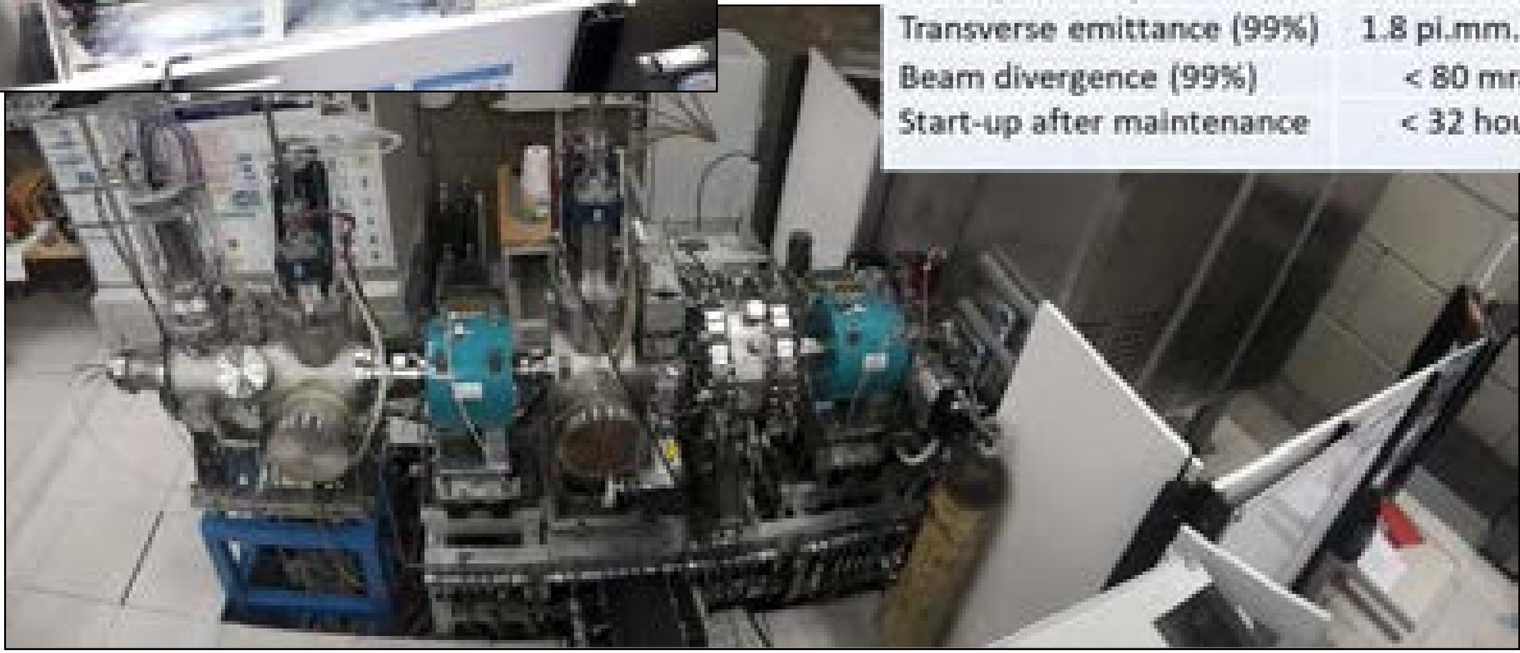
ESS perfomances



ESS ion source

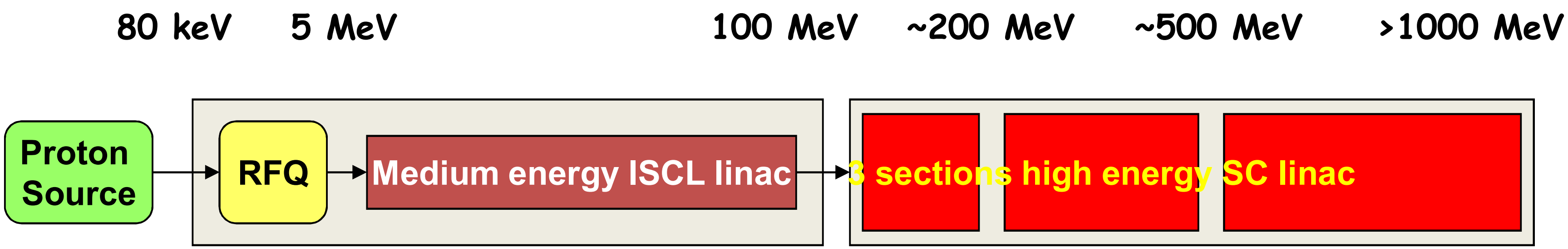


ESS ion source



Requirement	Value
Beam energy	75 ± 5 keV
Energy adjustment	± 0.01 keV
Total beam current	> 90 mA
Proton beam current	74 mA
Proton beam current range	6.7 - 74 mA
Resolution	1.6 mA
Proton fraction	> 75%
Pulse length	6 ms
Pulse flat top	3 ms
Repetition rate	14 Hz
Pulse to pulse stability	± 3.5 %
Flat top stability	± 2 %
Transverse emittance (99%)	1.8 pi.mm.mrad
Beam divergence (99%)	< 80 mrad
Start-up after maintenance	< 32 hours

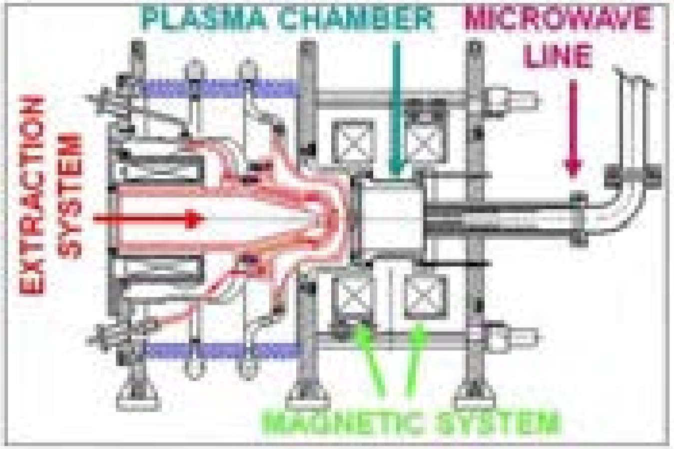
Accelerator Driven Systems



Source	RFQ	ISCL	High Energy SC Linac
Microwave RF Source High current (35 mA) 80 keV	High transmission 95 % 30 mA, 5 MeV (352 MHz)	5 - 100 MeV SC linac Baseline design: Reentrant cavities (352 MHz) Alternative design: $\lambda/2$, $\lambda/4$ $8\beta\lambda$ FODO focussing with sc magnets	3 section linac: ➢ 100 - 190 MeV, β=0.47 ➢ 190 - 450 MeV, β=0.65 ➢ 450 – 1000/(1600) MeV, β=0.85 Five(six) cell elliptical cavities Quadrupole doublet focussing: multi-cavity cryostats between doublets ➢ (352.2 MHz CERN/LEP) ➢ 704.4 MHz

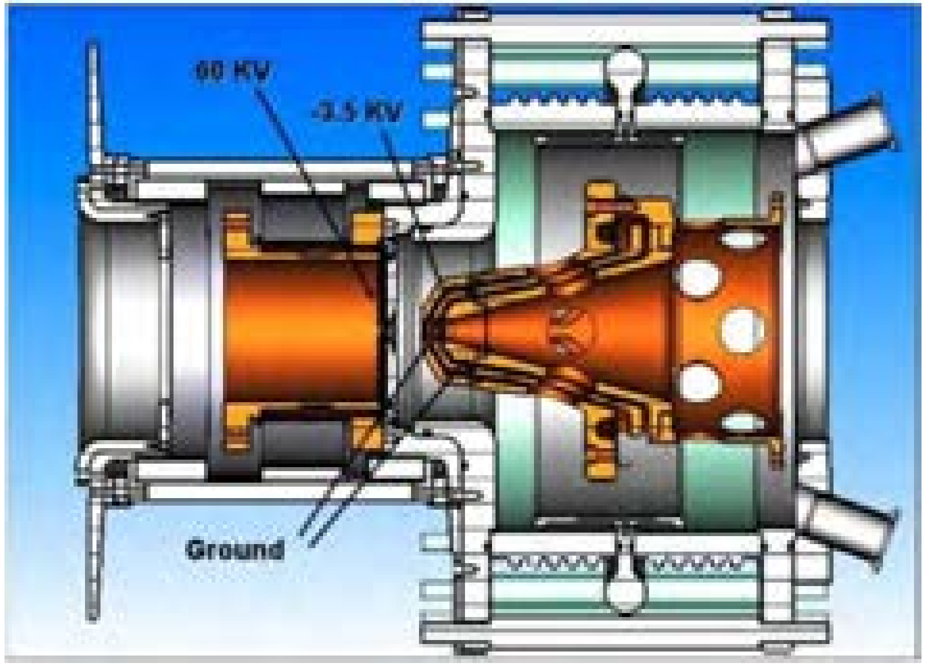
The TRASCO–AC Group,
Status of the high current proton accelerator for the TRASCO program. Report No. INFN/TC-00/23

TRIPS - VIS



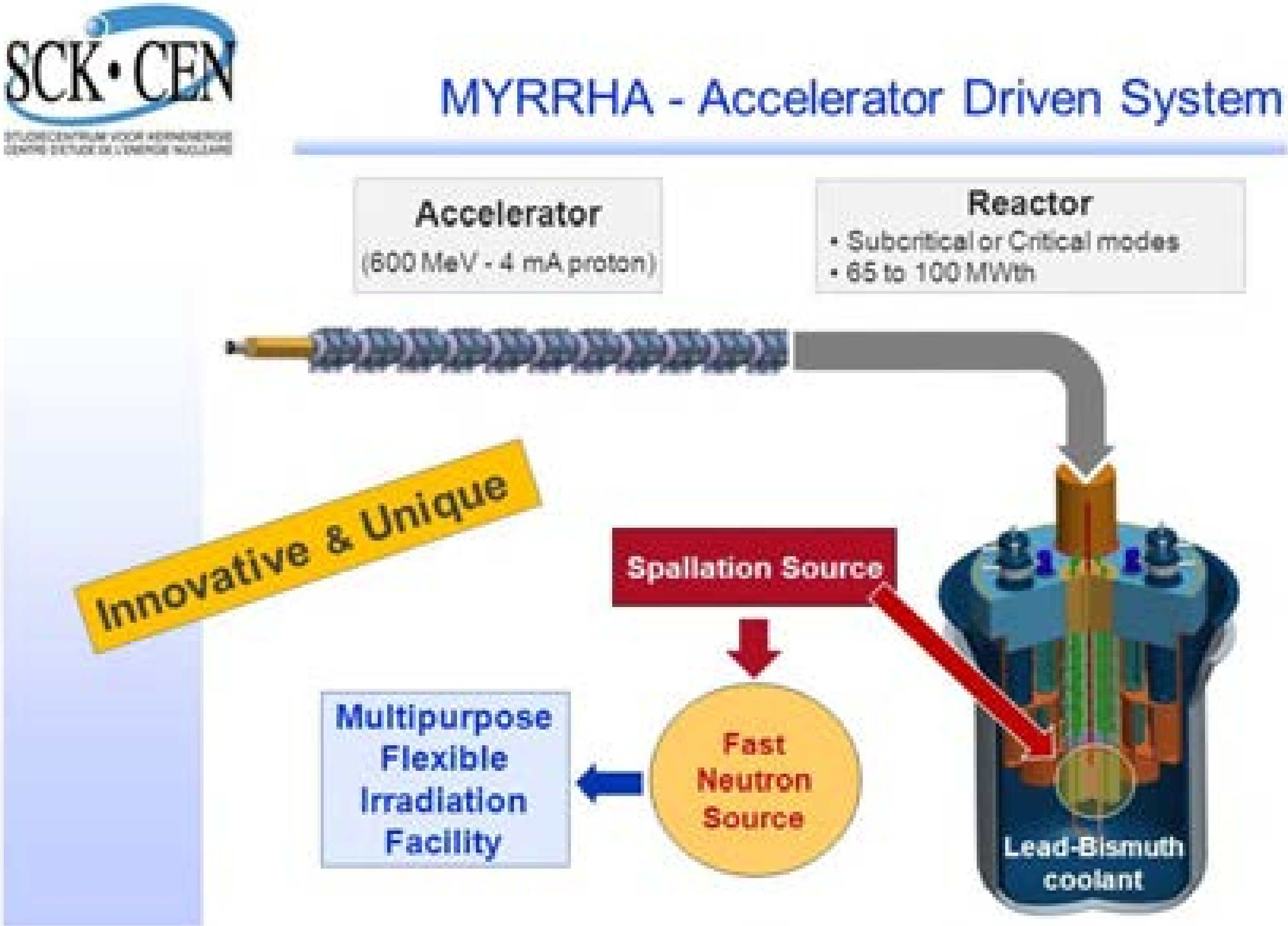
TRIPS

VIS



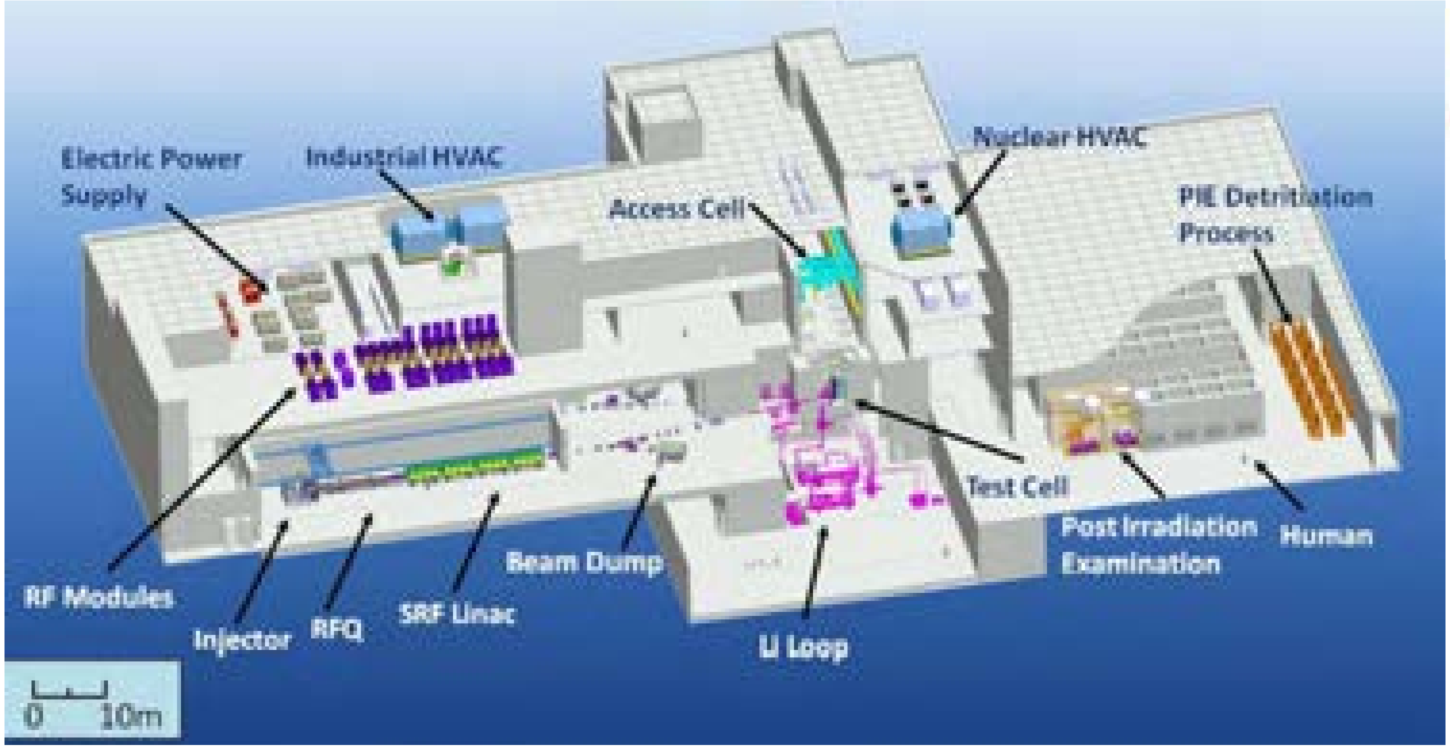
Performance	Value
Beam energy	80 Kev
Proton beam current	55 mA
Proton fraction	≈80%
RF frequency	2.45 GHz
RF power	Up to 1 kW
Axial magnetic field	875-1000 G
Duty factor	100 % (DC)
Extraction aperture	6 mm
Reliability	99.8% @ 35 mA
Transverse emittance (σ)	0.07 pi.mm.mrad @ 35 mA
Start-up after maintenance	32 hours

MYRRHA



MYRRHA - Accelerator Driven System
Accelerator
(600 MeV - 4 mA proton)
Reactor
• Subcritical or Critical modes
• 65 to 100 MWth
Innovative & Unique
Spallation Source
Multipurpose Flexible Irradiation Facility
Fast Neutron Source
Lead-Bismuth coolant

International Fusion Materials Irradiation Facility

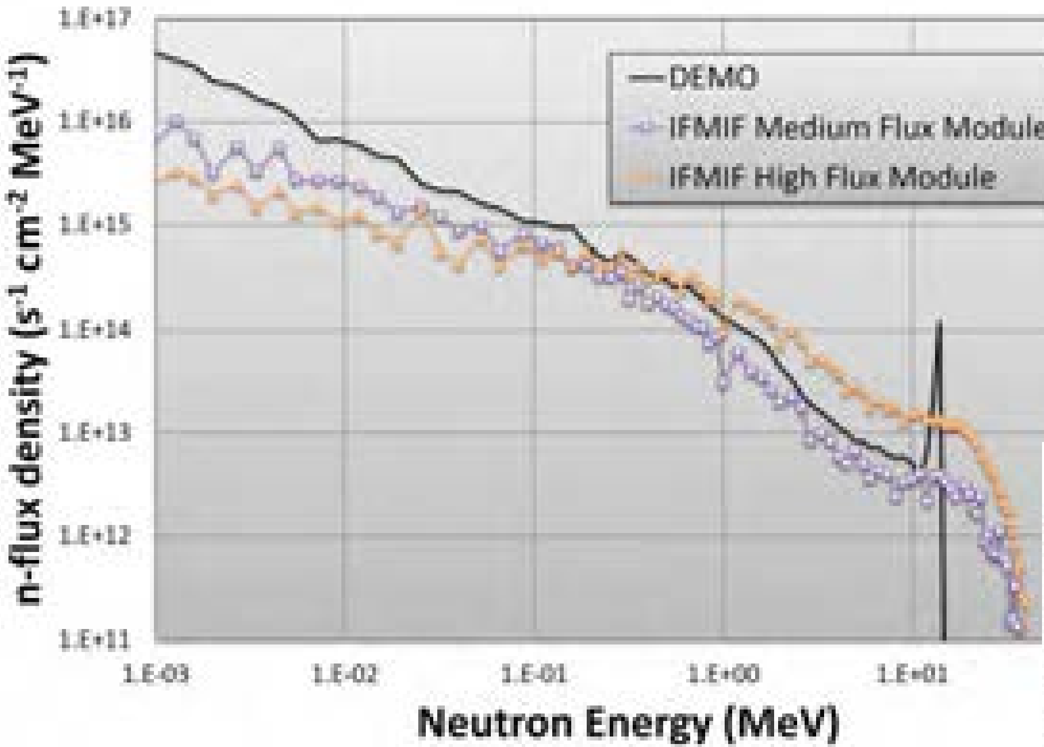


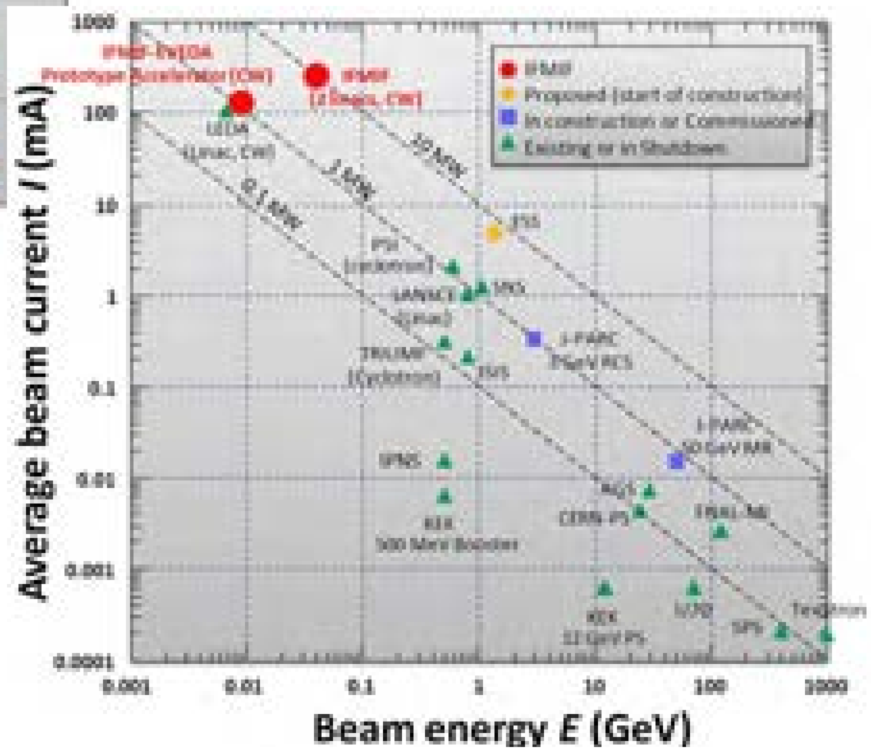
IFMIF EVEDA

***Main goal**: IFMIF (International Fusion Materials Irradiation Facility) is a neutron source aimed at qualifying the materials necessary for the design and licensing of a DEMOstration plant and a Fusion Power Plant.*

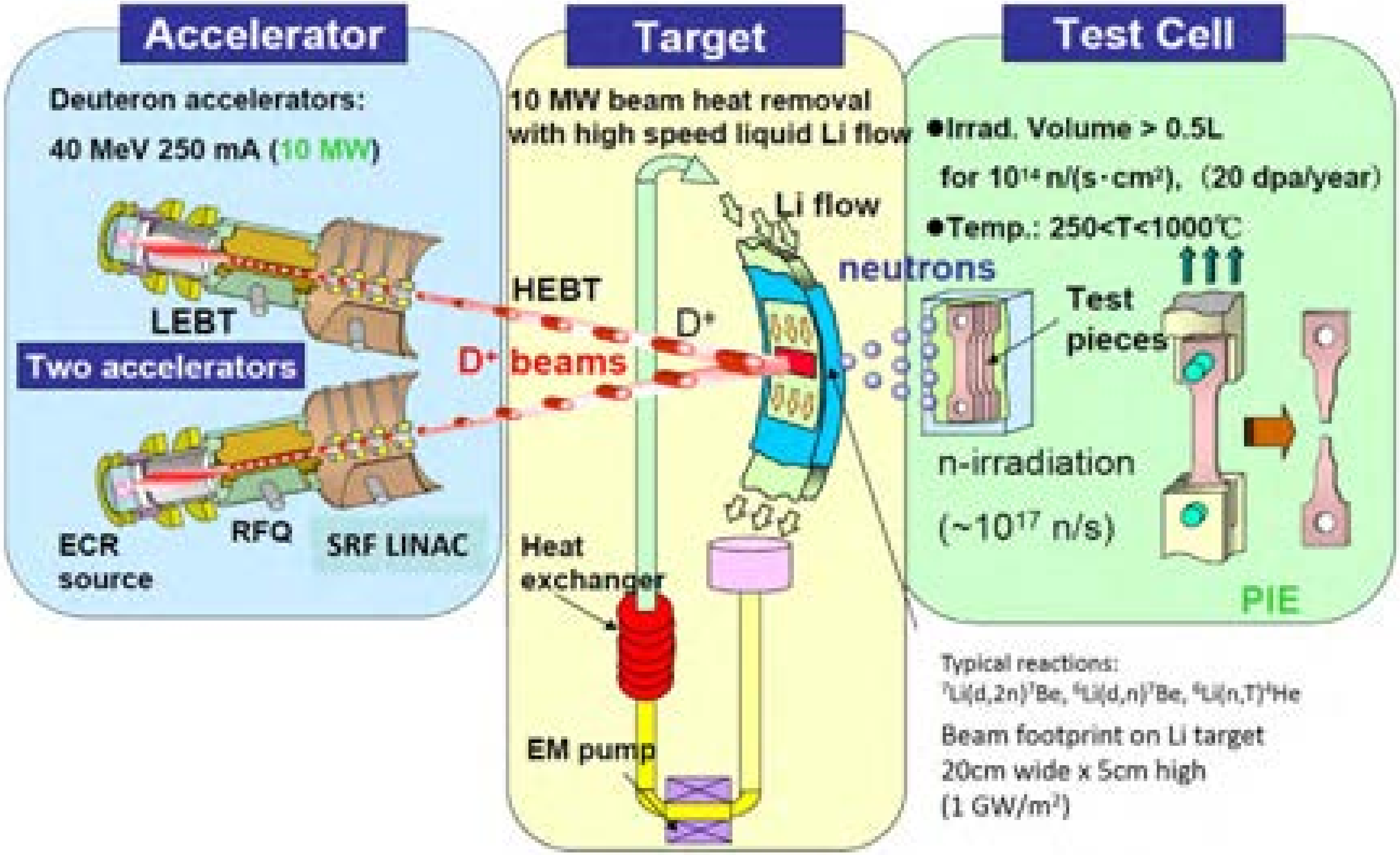
It has to generate a fusion reactor relevant radiation environment!!!

International Fusion Materials Irradiation Facility



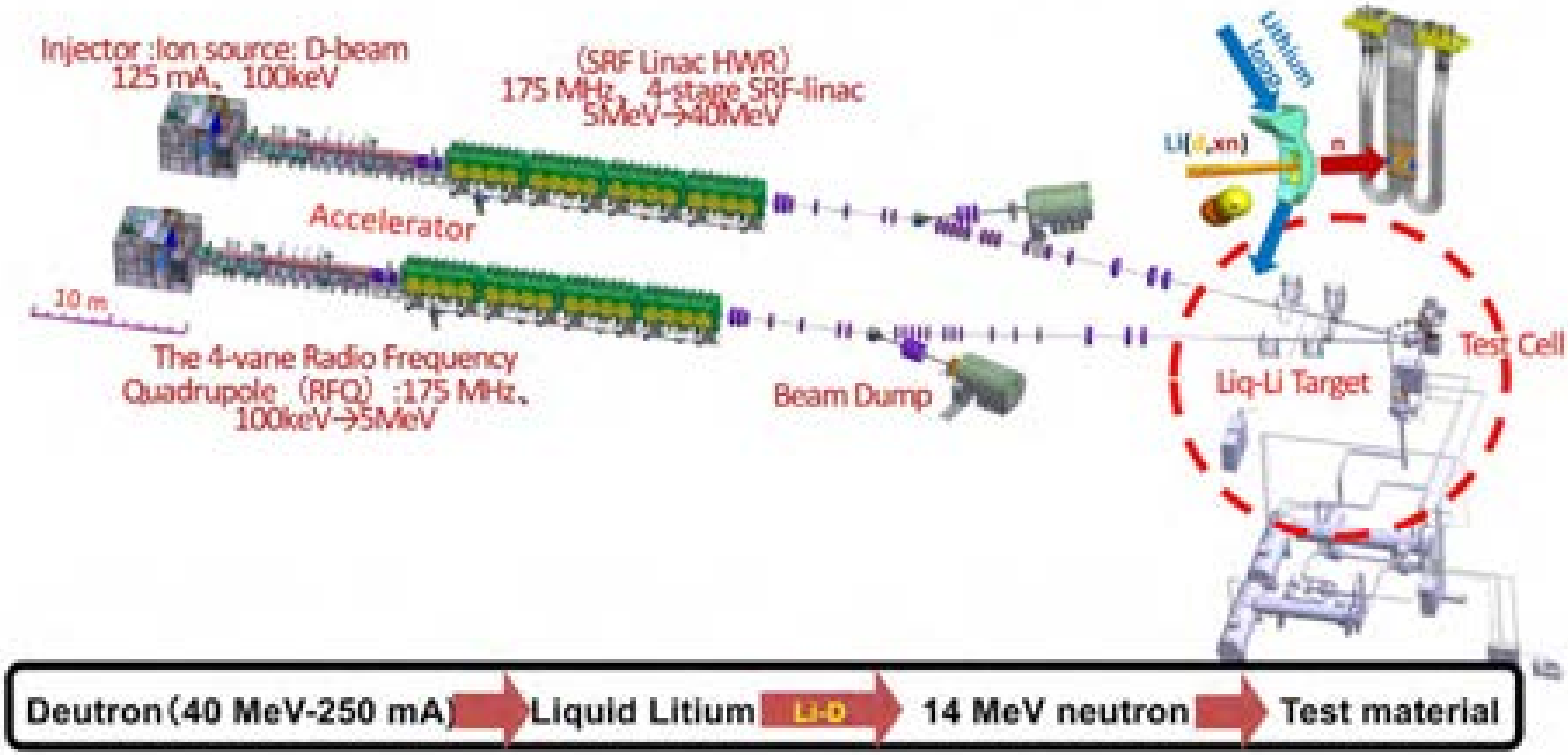


IFMIF principles

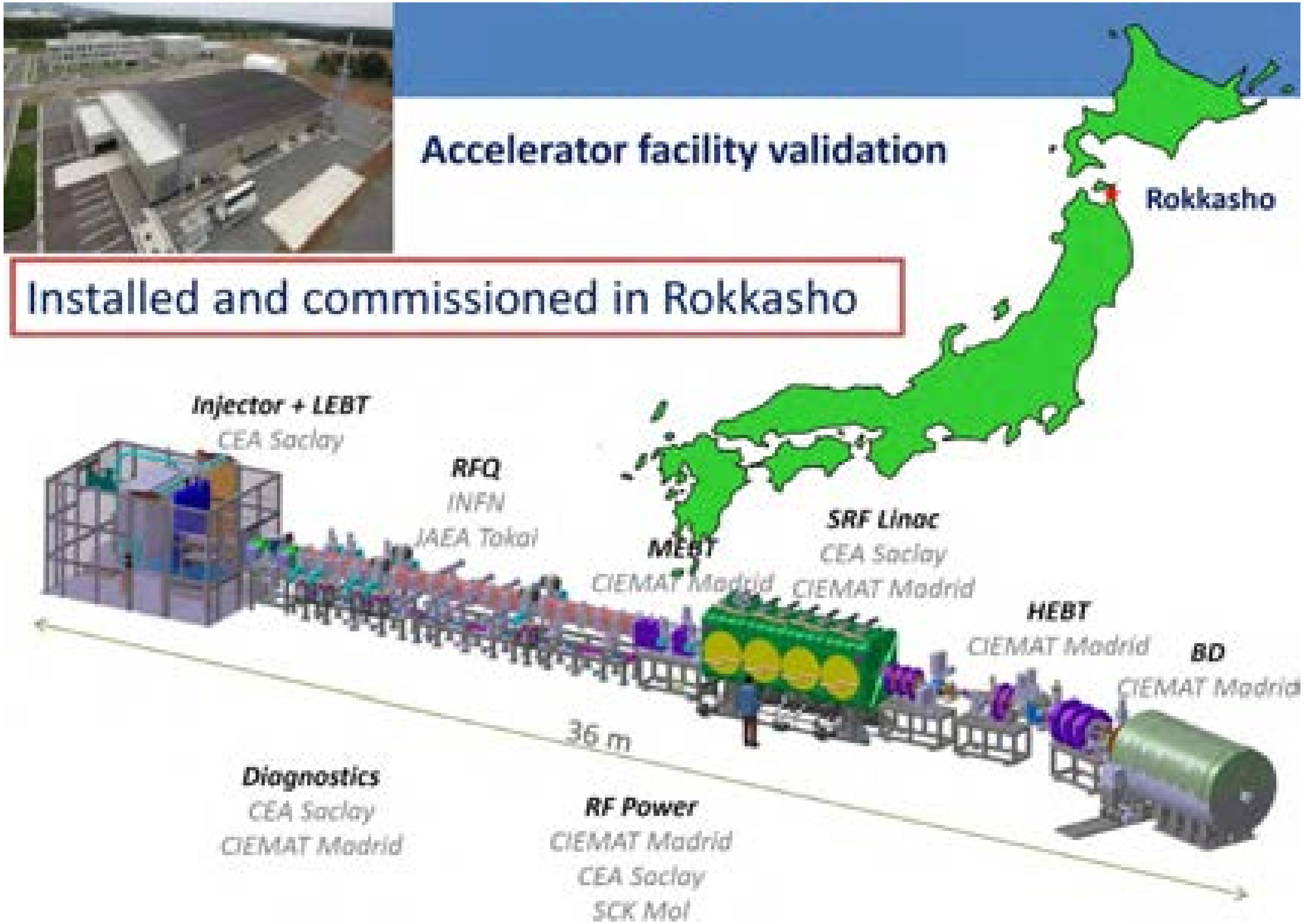


International Fusion Materials Irradiation Facility

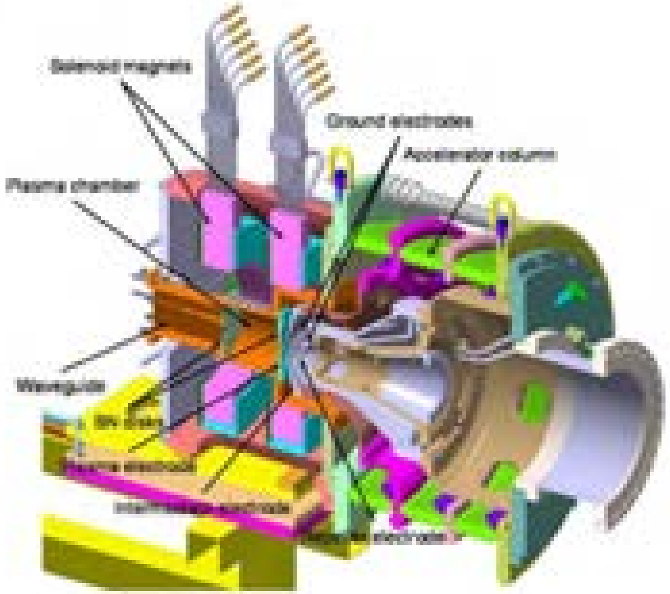
IFMIF consists of two deuteron linear accelerators, free surface liquid lithium target, test cell, and the post irradiation examination facility.



IFMIF-EVEDA


Accelerator facility validation
Rokkasho
Installed and commissioned in Rokkasho
Injector + LEBT
CEA Saclay
RFQ
INFN
JAEA Tokai
MEBT
CIEMAT Madrid
SRF Linac
CEA Saclay
CIEMAT Madrid
HEBT
CIEMAT Madrid
BD
CIEMAT Madrid
36 m
Diagnostics
CEA Saclay
CIEMAT Madrid
RF Power
CIEMAT Madrid
CEA Saclay
SCK Mol

International Fusion Materials Irradiation Facility



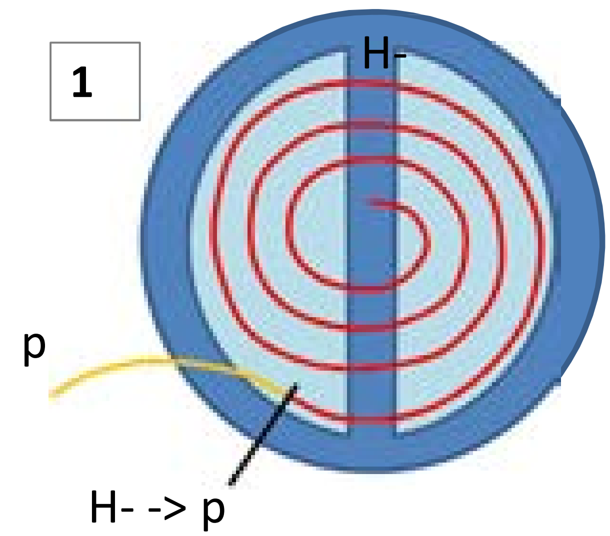
- **100 kV, >140 mA, <0.3π mm.mrad (initial target)**

- **5 electrodes system with secondary electrons repeller .**

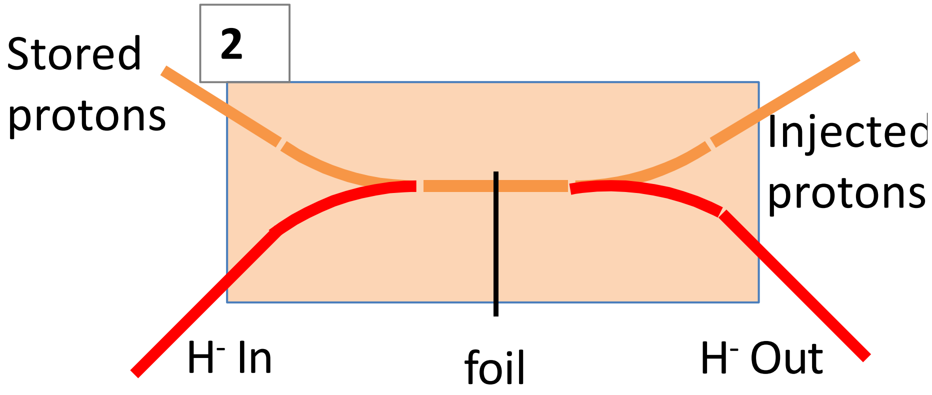
  (plasma electrode, intermediate electrode, 2 ground electrodes and repeller electrode)

Sometime Negative ions are required: Why?

1. Extraction (from cyclotrons): *Charge exchange process used for positive ion extraction*



2. Injection (to synchrotron): *Negative ion are needed to facilitate injection into storage rings via charge-exchange process.*



Sometime Negative ions are required: Why?

3. High Energy Neutral Beams production for fusion devices
(Magnetic Confinement Fusion)

Heat plasma by high-energy neutral particles stripping to neutrals that can enter the magnetic confinement. Particles get ionized by the collision with the plasma, confined there and transfer their energy through collisions.

Tangential injection → provide momentum and current drive

ITER Requirements - Three external heating sources to provide 50 MW of input heating power to bring the plasma to the temperature necessary for fusion

- *Two NBI each one delivering 16.5 MW with 1 MeV particle energy: the idea is to use negative ions tha passing* pass through a cell containing gas where they recover their missing electron and can be injected as fast neutrals into the plasma.
- *Ion Cyclotron Resoance Heating (ICRH) :* 20 MW power is transferred to the ions in the plasma by a high-intensity beam of EM radiation from 40 to 55 MHz.
- *Electron Cyclotron Resoance Heating (ECRH): 24 MW of* EM radiation at a frequency of 170 GHz (resonant frequency of electrons) heat plasma electrons.

Big Facilities over the world require intense beams of monocharged ions

OAK RIDGE National Laboratory

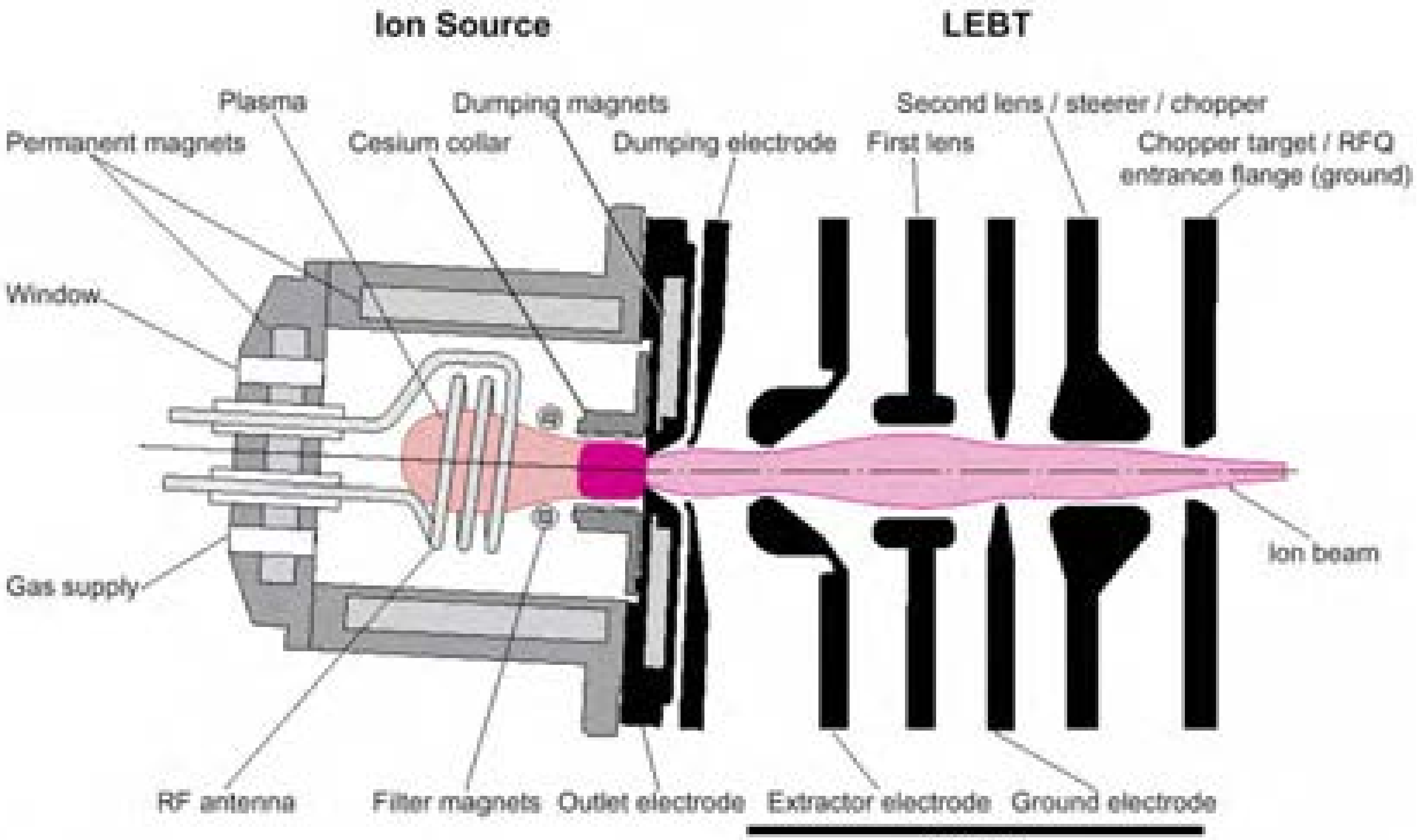
Big Facilities over the world require intense beams of monocharged ions

SNS Front End

LEBT Tank, Ion Source, and RF Matcher

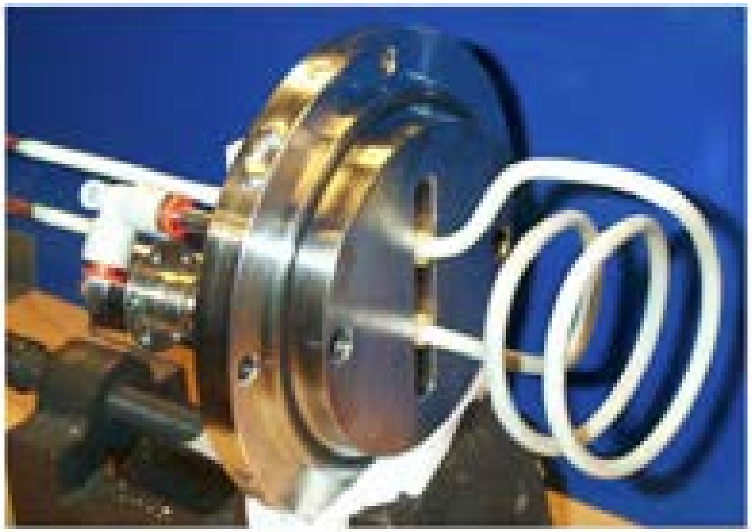
	Baseline	Upgrade
Kinetic energy [MeV]	1000	1300
Beam power [MW]	1.4	3.0
Chopper beam-on duty factor [%]	68	70
Linac beam macro pulse duty factor [%]	6.0	6.0
Average macropulse H- current [mA]	26	42
Peak macropulse H- current [mA]	38	59
Linac average beam current [mA]	1.6	2.5
SRF cryo-module number (med-beta)	11	11
SRF cryo-module number (high-beta)	12	21
SRF cavity number	33+48	33+84
Peak surface gradient (β=0.61 cavity) [MV/m]	27.5 (+/- 2.5)	27.5 (+/- 2.5)
Peak surface gradient (β=0.81 cavity) [MV/m]	35 (+2.5/-7.5)	31
Ring injection time [ms] / turns	1.0/1060	1.0/1100
Ring rf frequency [MHz]	1.058	1.098
Ring bunch intensity [10[illegible]]	1.6	2.5
Ring space-charge tune spread, ΔQ_{sc}	0.15	0.15
Pulse length on target [ns]	695	691

Big Facilities over the world require intense beams of monocharged ions



Beam outline is schematic only (see simulation on P. 18.) Filter- and dumping-magnet fields are orthogonal to the illustration plane and anti-parallel to each other.

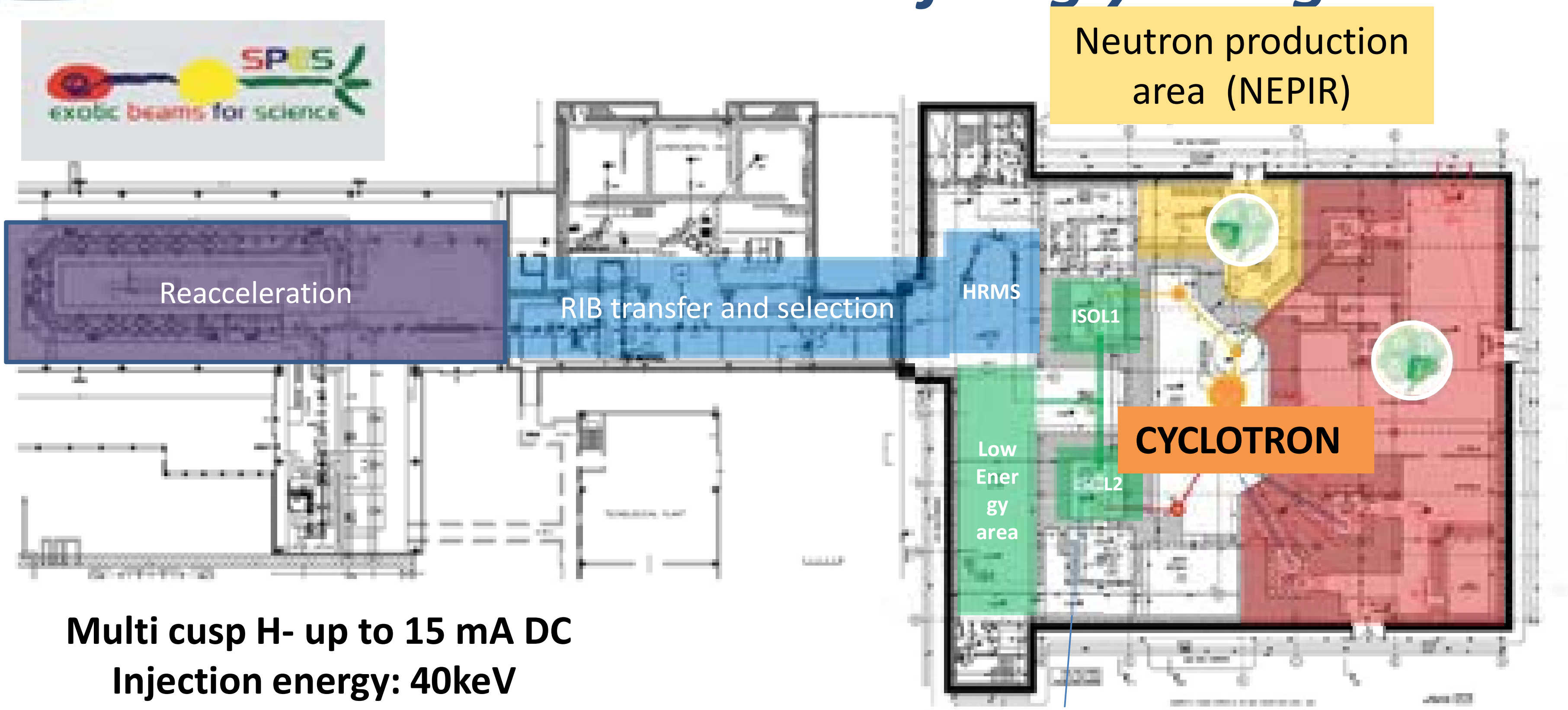
Big Facilities over the world require intense beams of monocharged ions



RF antenna

RF-sustained plasma

Big Facilities over the world require high intense beams of singly charge ions



Multi cusp H- up to 15 mA DC
Injection energy: 40keV
Emittance: 0.6πmmmrad

RIB reacceleration:

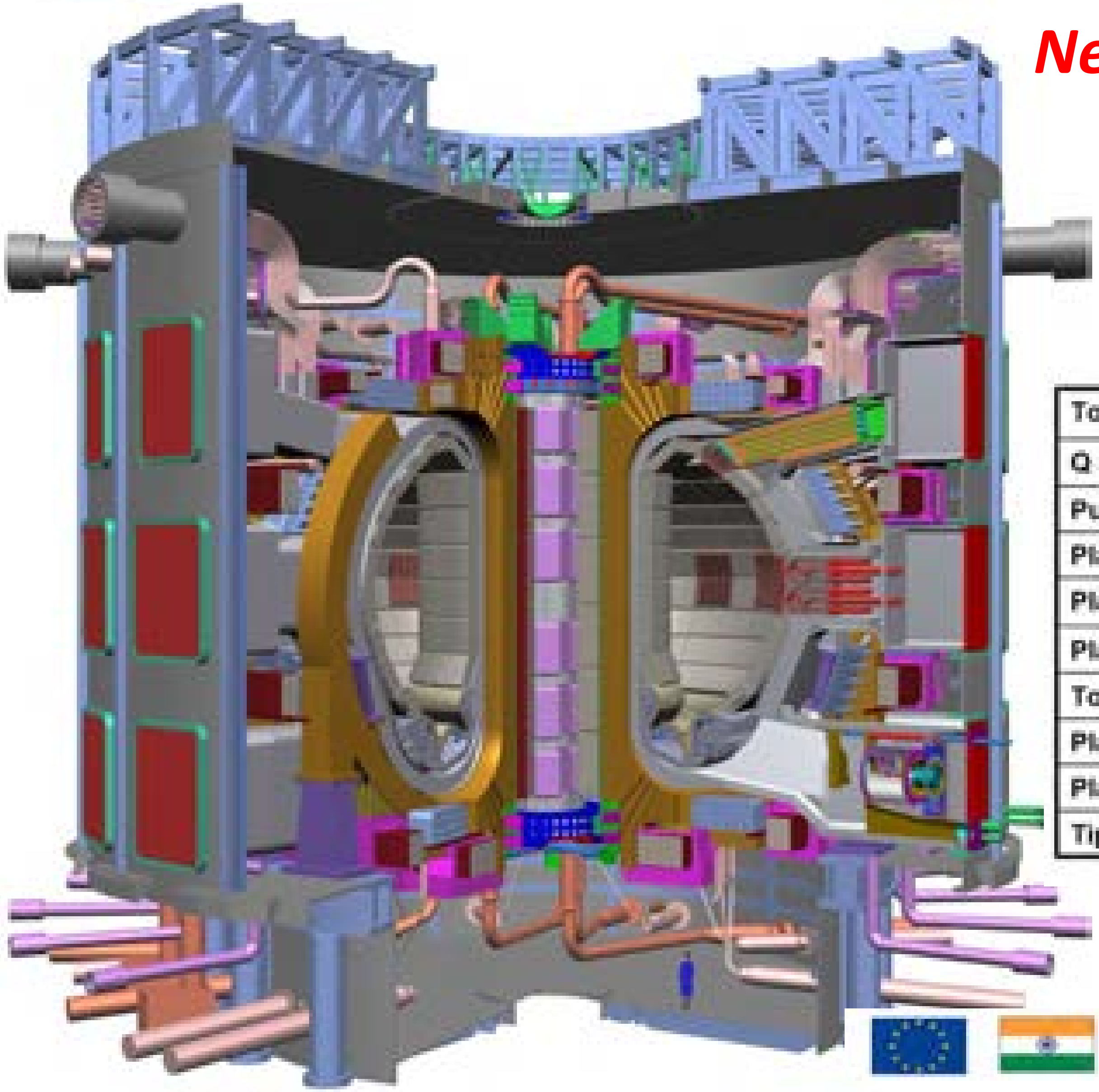
- new RFQ
- ALPI

1/20.000 Mass separator
(Beam Cooler + HRMS)
Elettrostatic beam transport
Charge Breeder (n+)
1/1000 mass separator

ISOL bunkers
1/150 mass separator
low energy experimental area

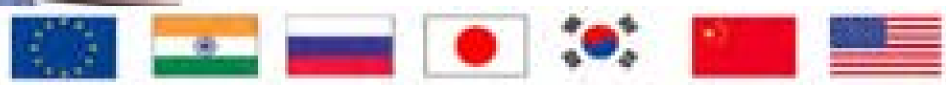
Radioisotopes production area
(LARAMED)

Ion source for fusion

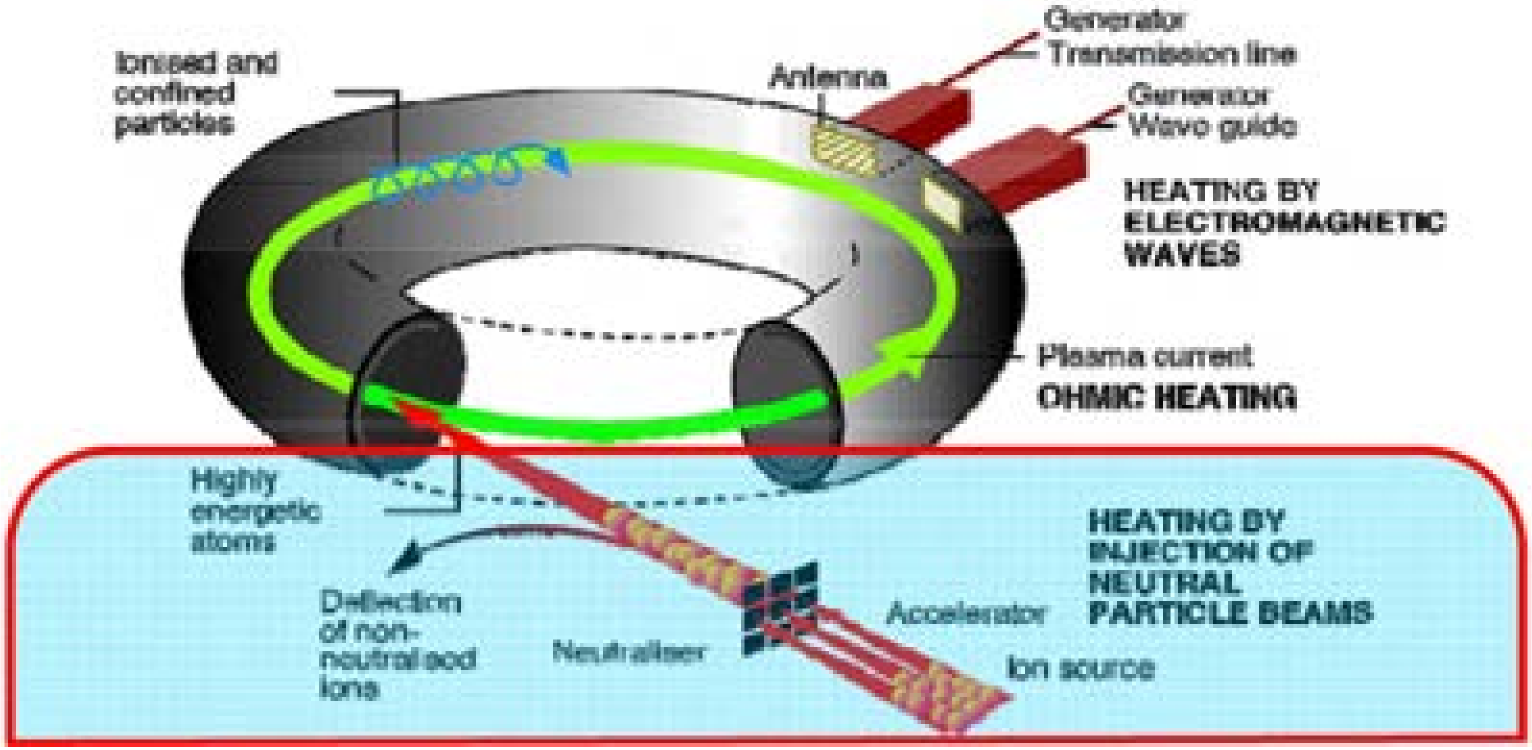


Neutral Beam Injection as source of plasma heating and current drive in TOKAMAKS

Total fusion power	500 MW
Q = Pot. Out/Pot. In	10
Pulse duration	300 s
Plasma major radius	6,2 m
Plasma minor radius	2 m
Plasma current	15 MA
Toroidal field B_T	5,3 T
Plasma volume	837 m^3
Plasma surface	678 m^2
Tipical plasma temperature	20 keV



Ion source for fusion



SPIDER

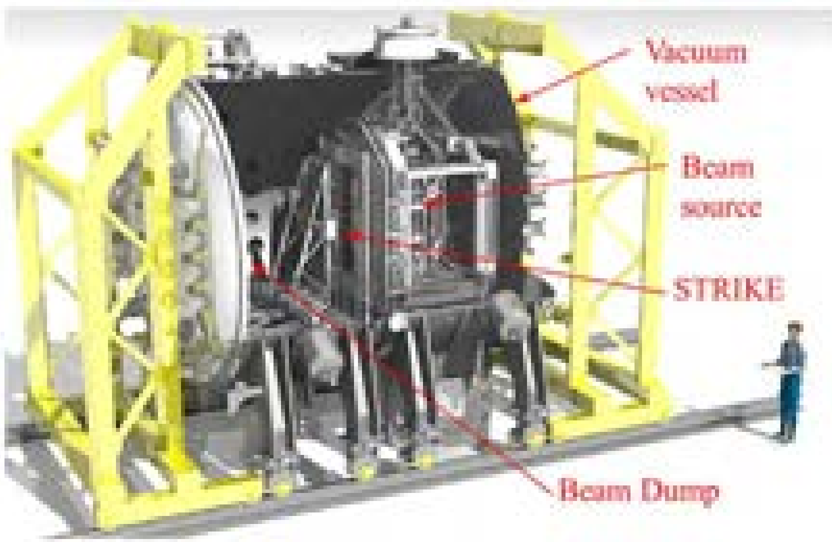
- **Current density**

	Ion	Energy (keV)	Extracted Ion J (A/m^2)	Extr. Ion I (A)	1 MV Accelerated I (A)
HNB	D-	1000	290	48	40
HNB	H-	870	330 - 350	56 - 60	46

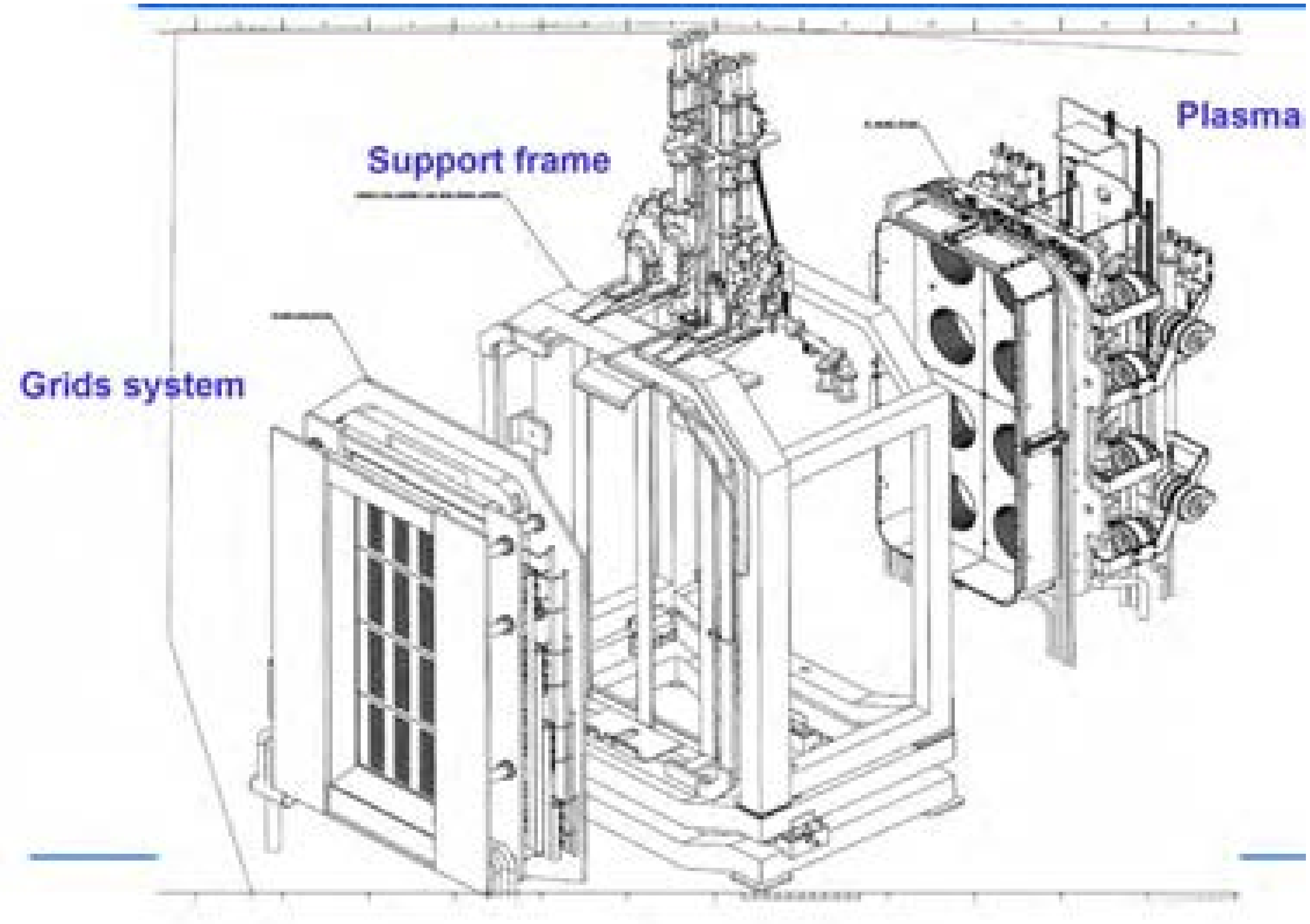
$J_{D^-} \approx 300\ A/m^2$ $\quad J_{H^-} \approx 350\ A/m^2$

- **Extracted electron to ion ratio from PG, to be stopped in the EG** $\quad \frac{e}{D^-} < 1$ for HNB
- **Uniformity** $\quad \Delta J = \pm 10\%$
- **Source operation**
  - Long pulse operation — 400 s for H^-,D^-; 3600 s for D^-
  - Source modulation — HNB: ≤ 7 Hz, T_{on}=50 ms, T_{rise}= 80 ms
- **Cs consumption and control**

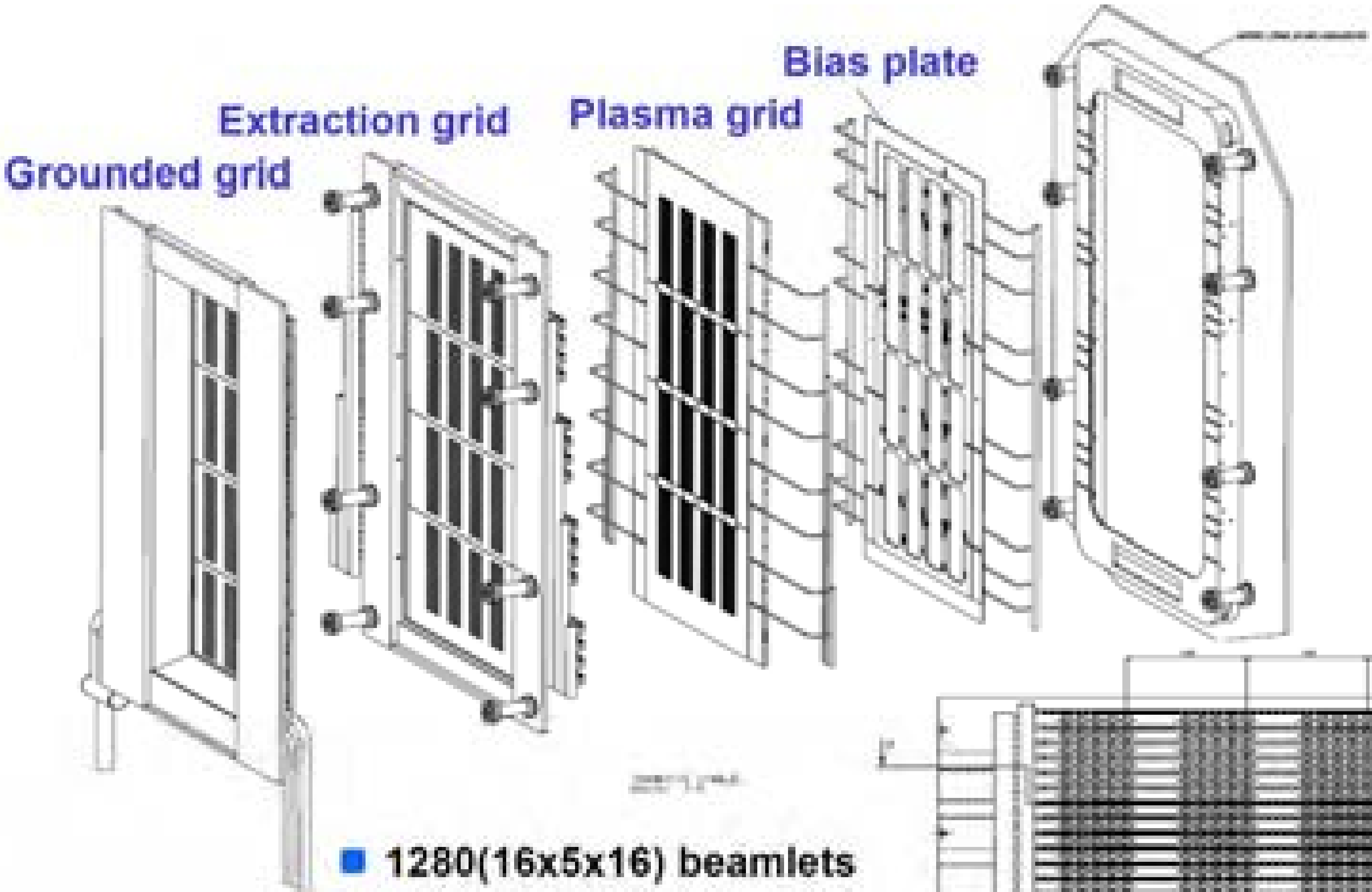
SPIDER
Source for **P**roduction of **I**on of **D**euterium **E**xtracted from **R**f plasma

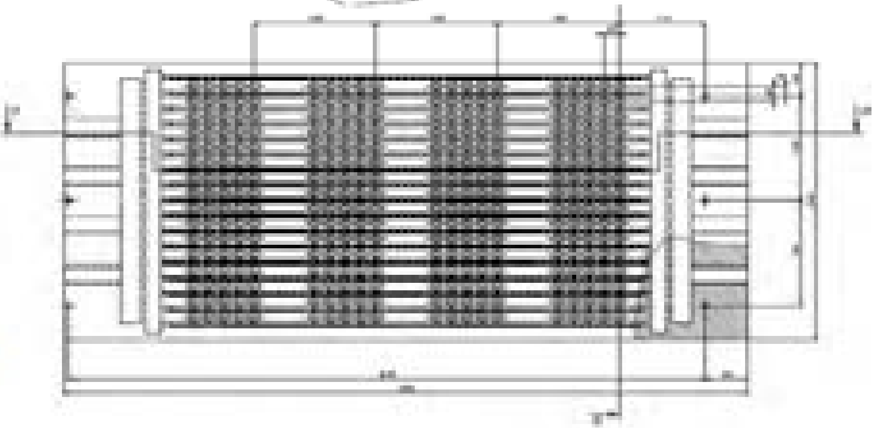


SPIDER



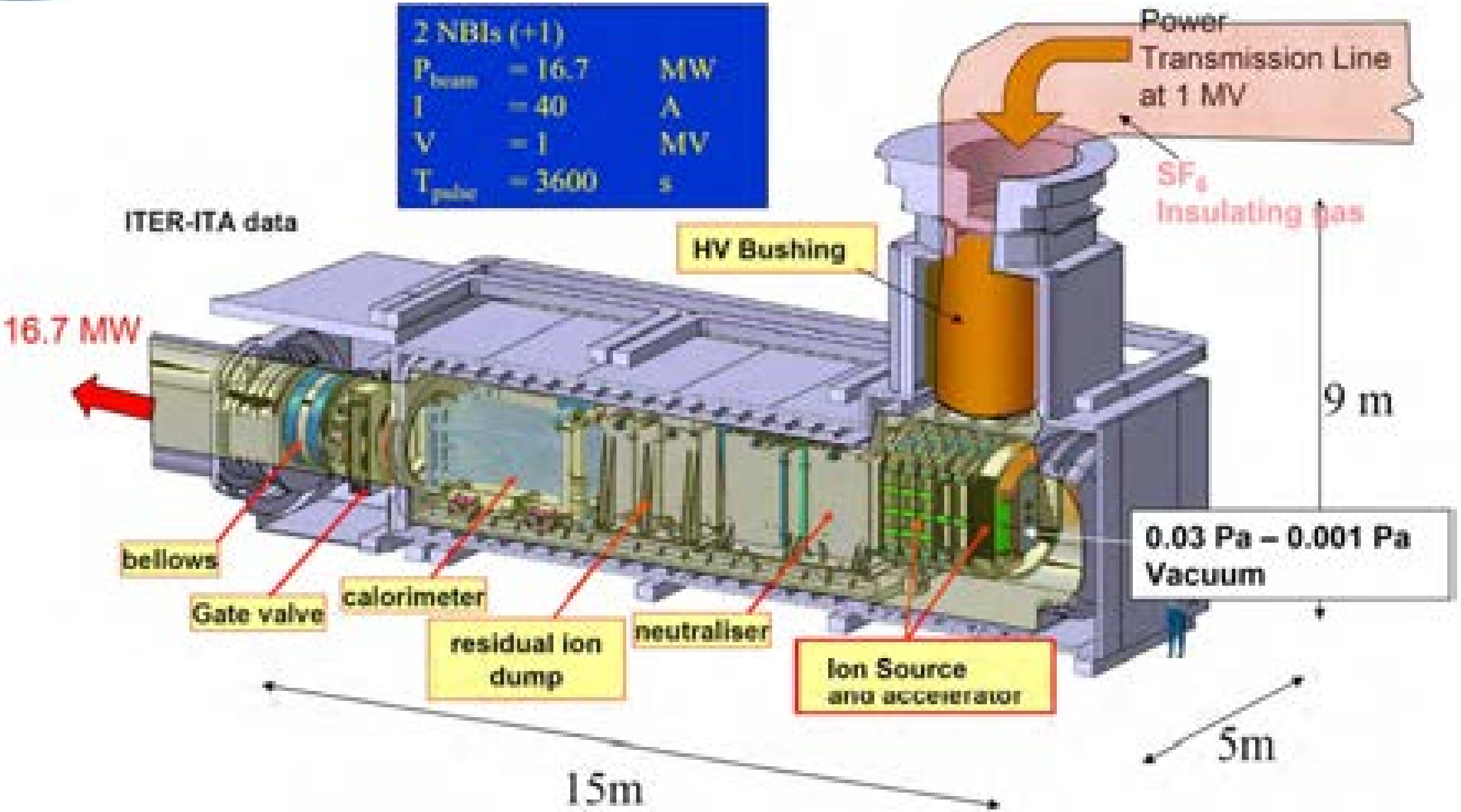
SPIDER - Grid system





- 1280(16x5x16) beamlets
- 4 segments

MITICA



MITICA
Megavolt **IT**ER **I**njector
&
Concept **A**dvancement

MITICA

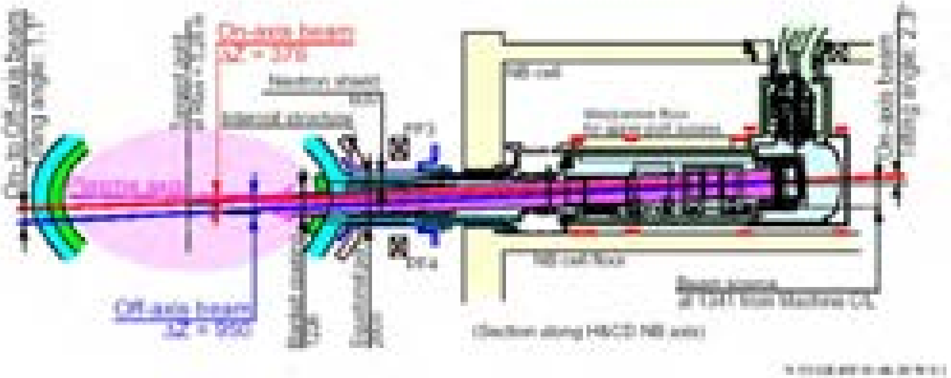
2 NBIs (+1)

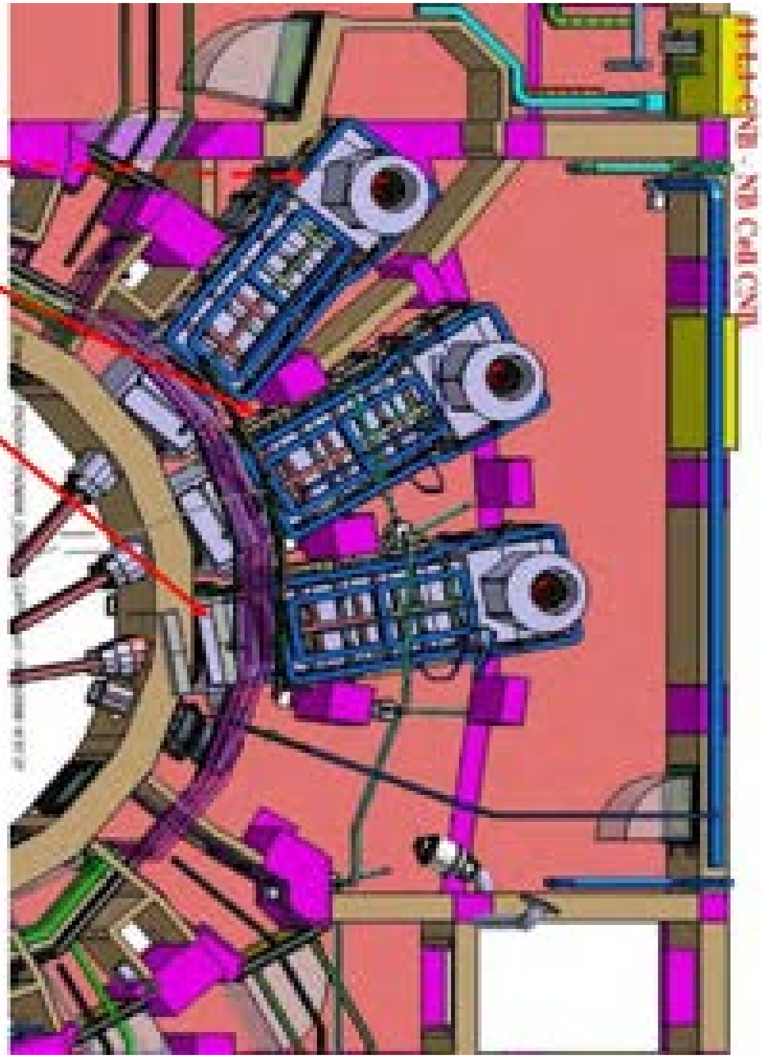
P_{beam} = 16.5 MW

I = 40 A

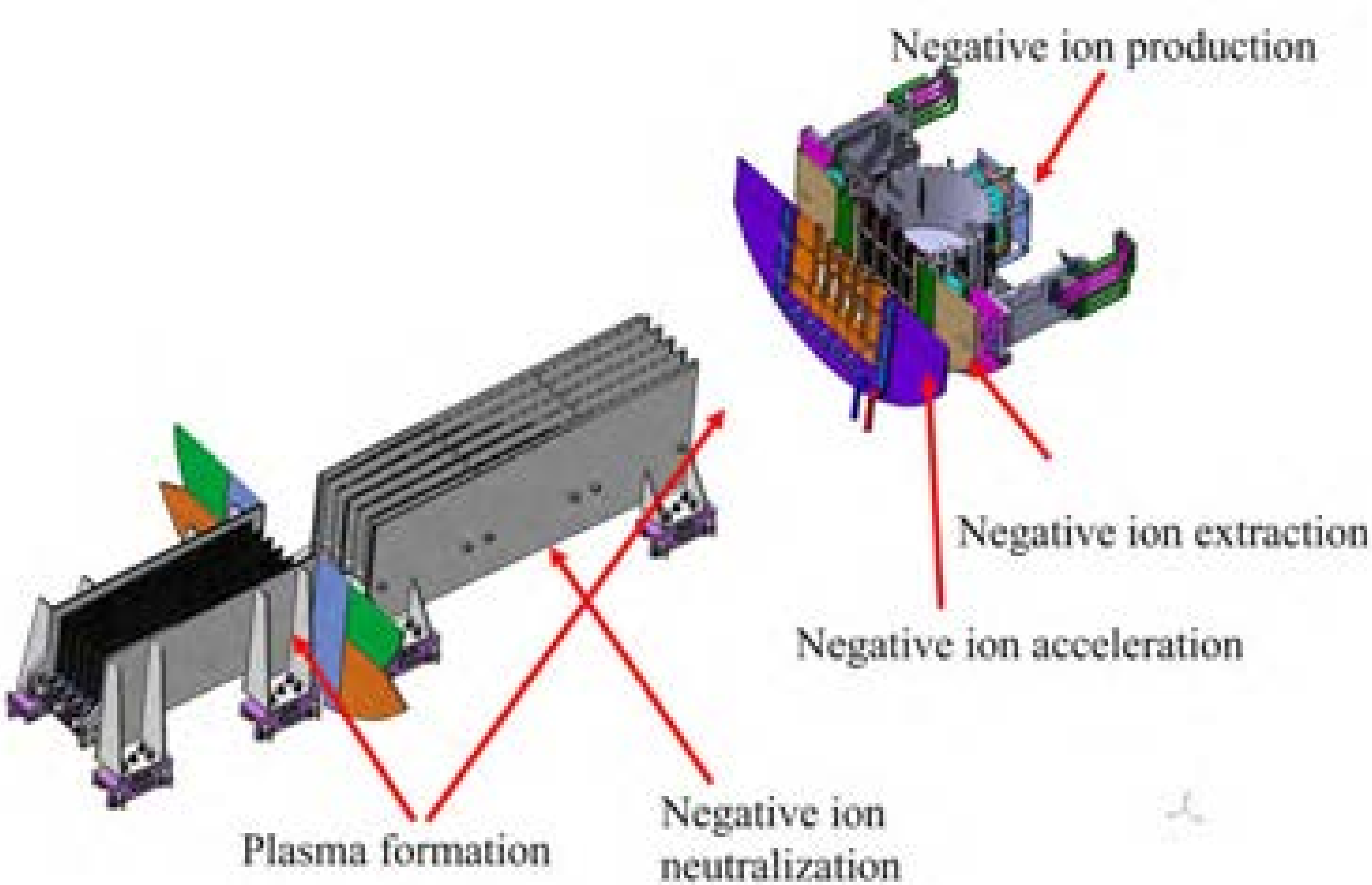
V = 1 MV

T_{pulse} = 3600 s



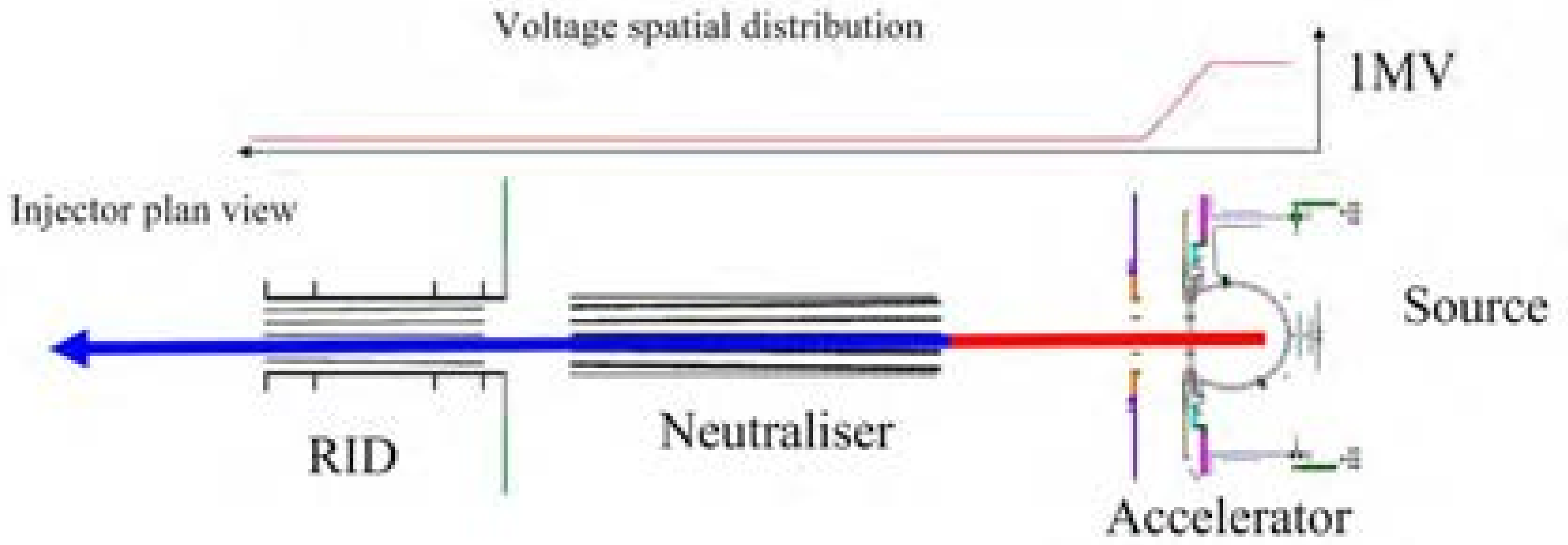


MITICA



Negative ion production
Negative ion extraction
Negative ion acceleration
Plasma formation
Negative ion
neutralization

MITICA



neutralisation of D^- ions by charge exchange collisions with D_2 molecules:

neutralisation

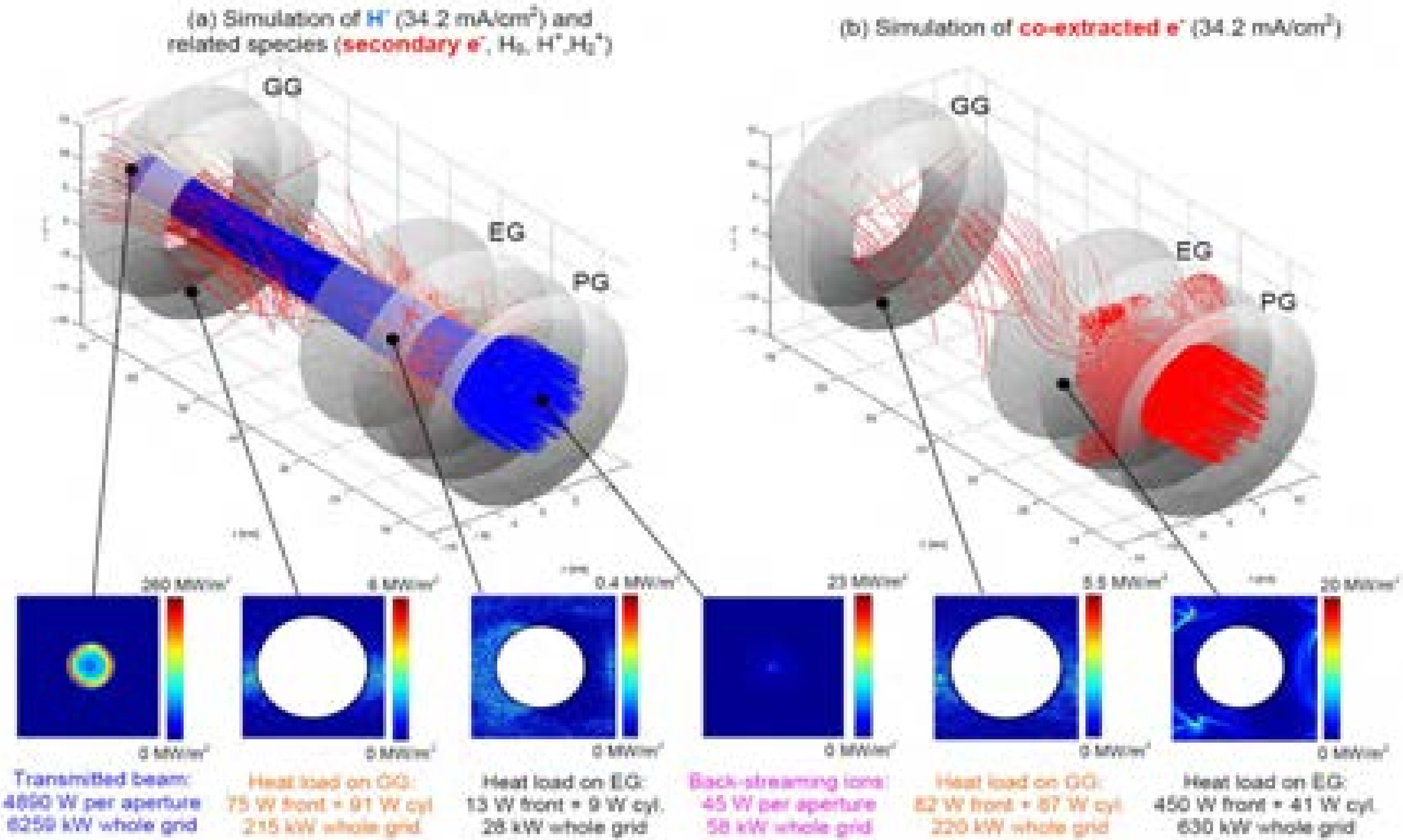
$D^- + D_2 \Rightarrow D^0 + D_2 + e$

re-ionisation (competing reaction)

$D^0 + D_2 \Rightarrow D^+ + D_2 + e$

Additional electrons from
a) co-extraction,
b) Stripping losses (low p: p_{source}<0.3Pa)
c) Secondary electrons

Ion source for fusion



Ion source for fusion