Overview of worldwide accelerators for ADS

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Chinese Academy of Sciences

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Outline

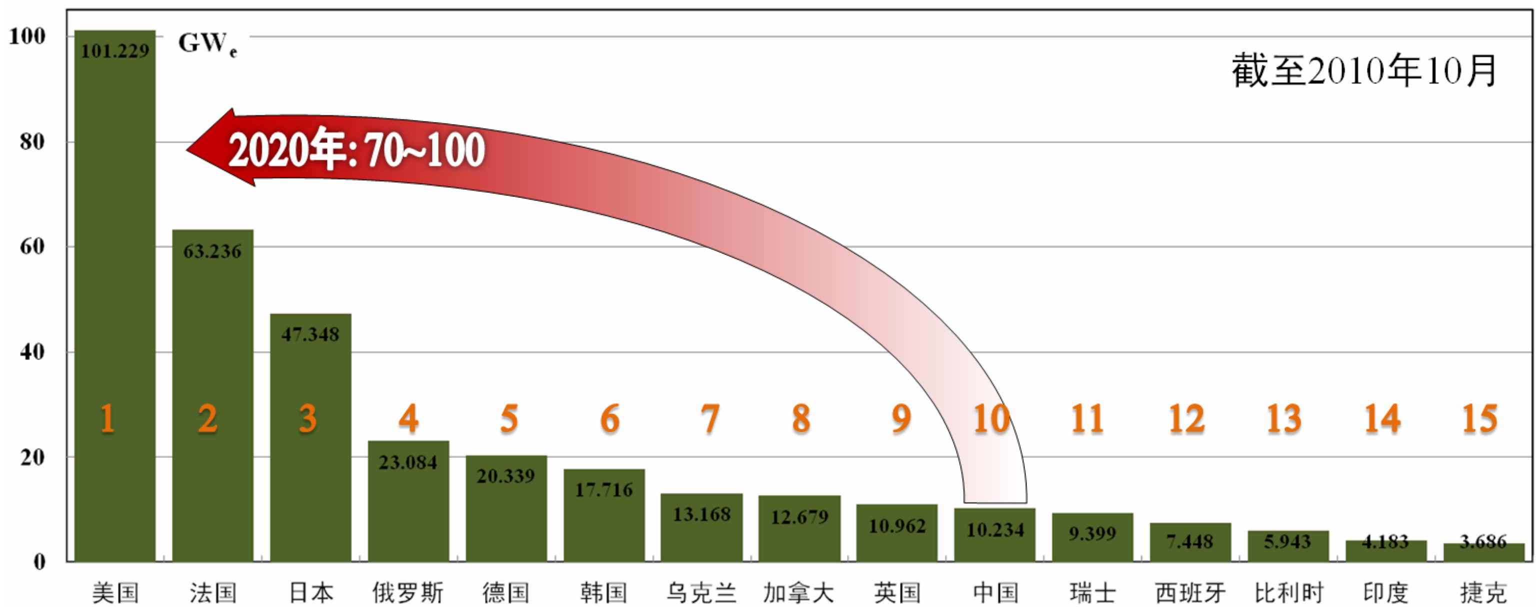
1. Brief introduction to ADS
2. Basic requirements of ADS accelerator
3. Introduction of worldwide ADS accelerator progresses
4. Summary

1. Brief introduction to ADS

(Accelerator-driven Subcritical System)

Nuclear Power in the world

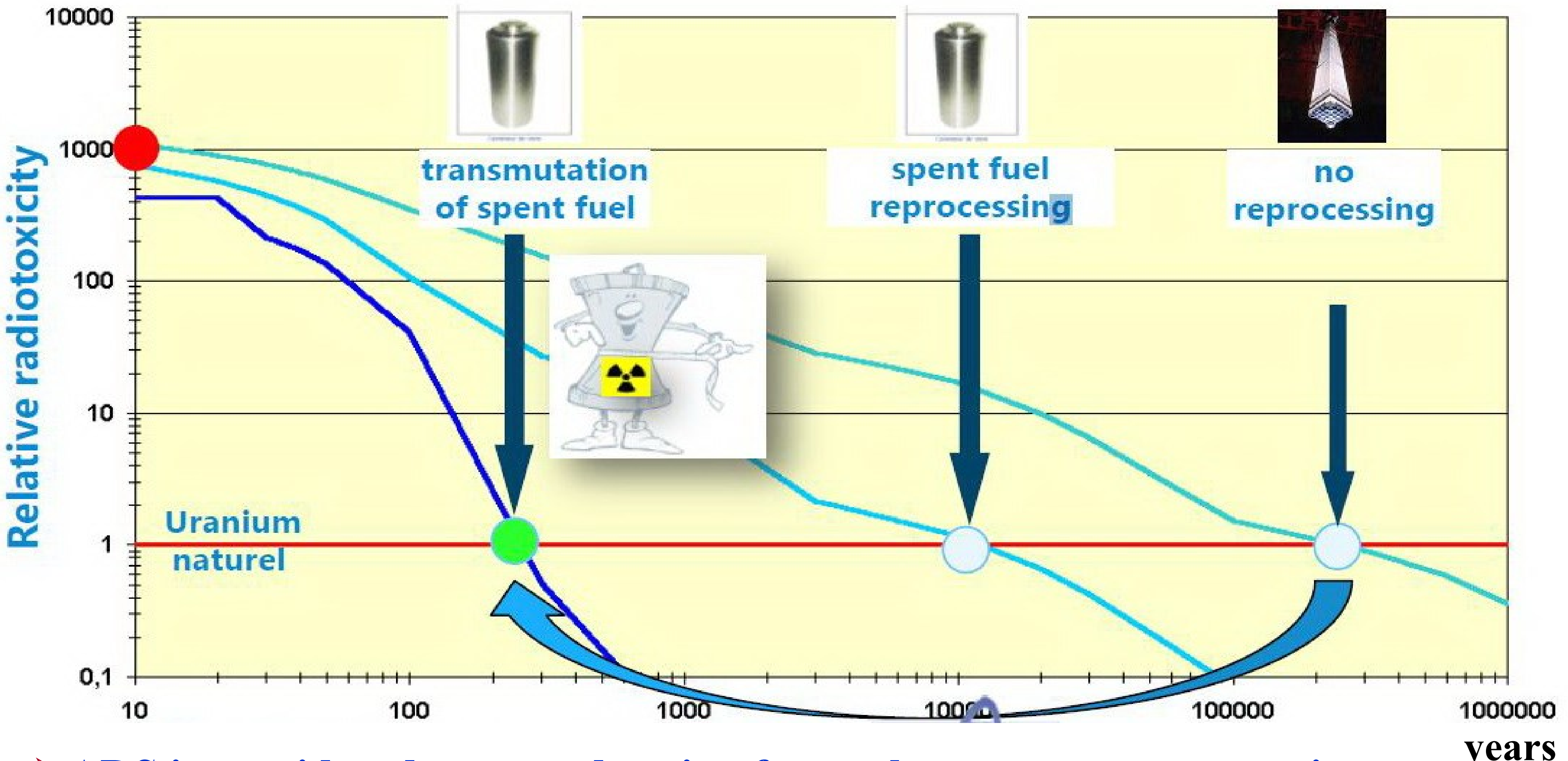
- ☑ 2009: ~14% electric power from the nuclear energy
- ☑ Till Oct., 2010: 441 reactors， 376.3GW_e



➢ **Nuclear waste is a bottleneck for nuclear power development.**

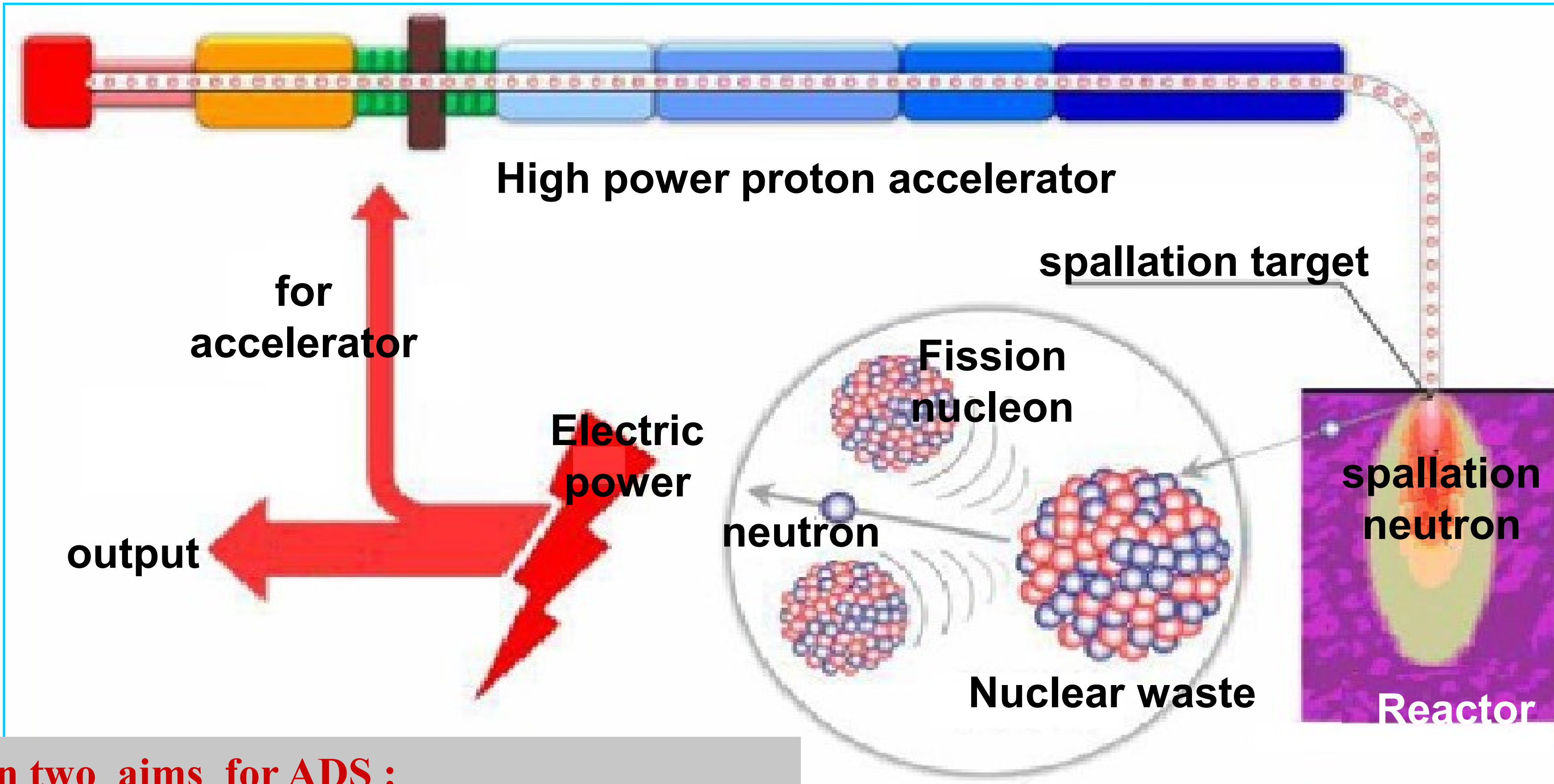
Nuclear Waste Management

Motivation for transmutation



- ➢**ADS is considered as a good option for nuclear waste transmutation, but never tested, many challenges faced.**

ADS system



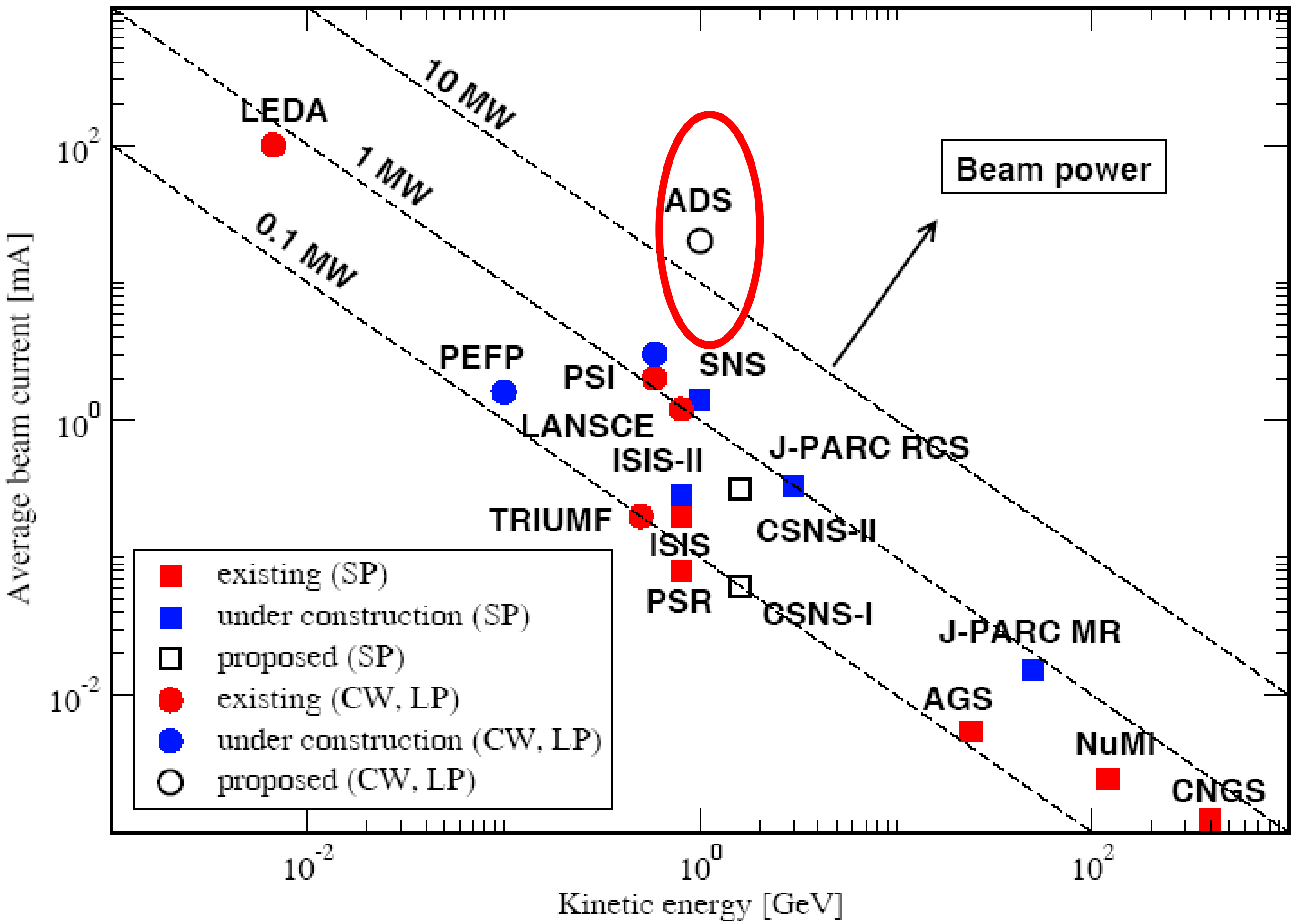
Main two aims for ADS :

Burn-off of long-lived actinide waste from reactors ;

Energy production from Thorium fuel.

2. Basic requirements of ADS accelerator

Power Map of Proton Accelerators



Generally, transmutation demonstration facility requires a beam power of 1-2 MW to deliver a thermal power of 50-100 MW.

A example : MYRRHA Project： 600 MeV /1.5 MW beam power， 85 MW thermal power.

CW beams are preferential for ADS, because

target for pulsed heating is a challenge

space charge effect is weaker in CW

Restrictions to ADS particle accelerators :

- High beam power :high energy and/or high beam current
- Very high stability: very few interruptions during long run
- Very low beam loss： <1W/m .

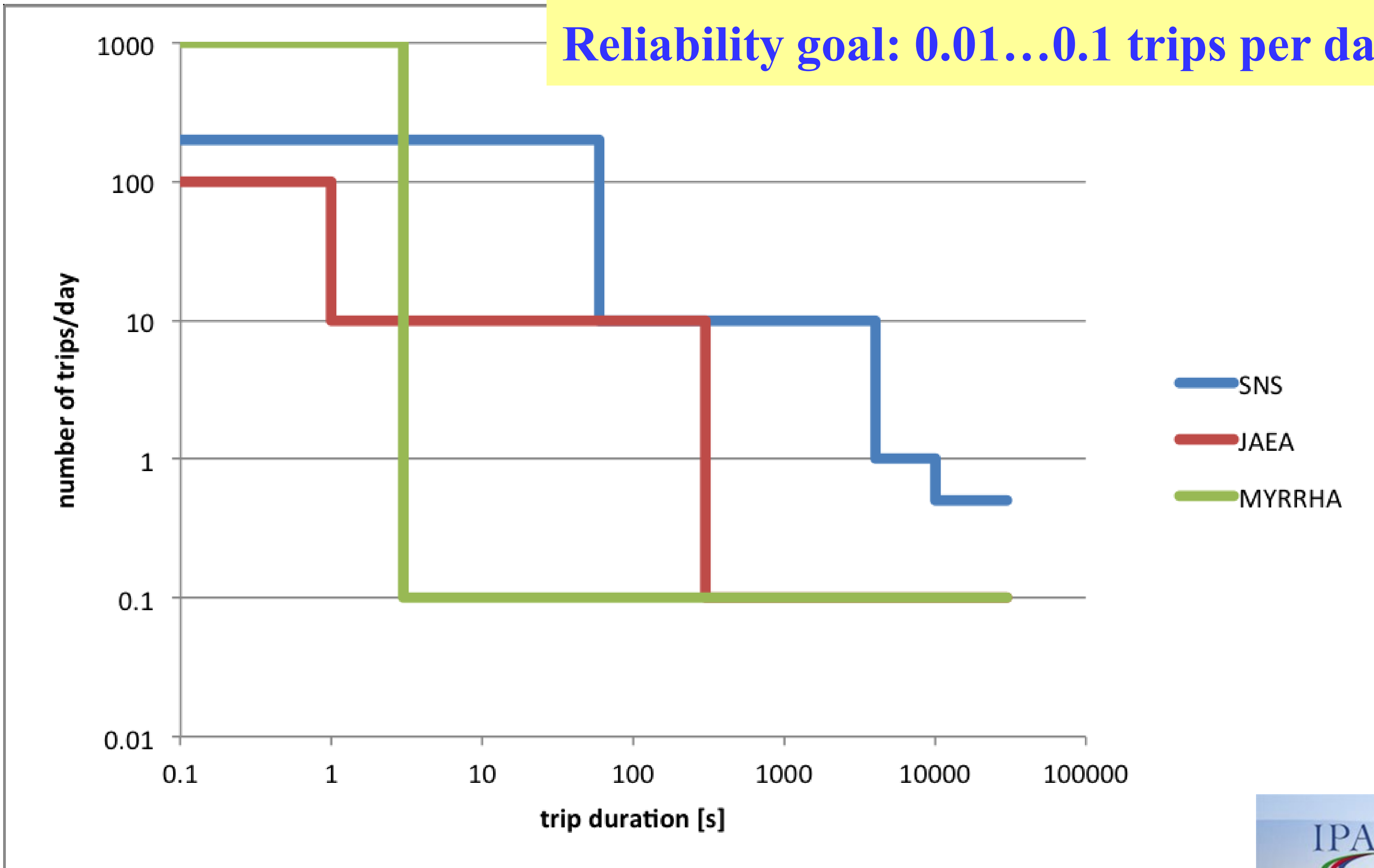
—— special design for high power ADS!

Reliability, trip performance

	Transmutation Demonstration	Industrial Scale Transmutation	Industrial Scale Power Generation with Energy Storage	Industrial Scale Power Generation without Energy Storage
Beam Power	1-2 MW	10-75 MW	10-75 MW	10-75 MW
Beam Energy	0.5-3 GeV	1-2 GeV	1-2 GeV	1-2 GeV
Beam Time Structure	CW/pulsed (?)	CW	CW	CW
Beam trips (t < 1 sec)	N/A	< 25000/year	<25000/year	<25000/year
Beam trips (1 < t < 10 sec)	< 2500/year	< 2500/year	<2500/year	<2500/year
Beam trips (10 s < t < 5 min)	< 2500/year	< 2500/year	< 2500/year	< 250/year
Beam trips (t > 5 min)	< 50/year	< 50/year	< 50/year	< 3/year
Availability	> 50%	> 70%	> 80%	> 85%

beam trips

Reliability goal: 0.01…0.1 trips per day!



High Availability

Control strategies for high availability

——Over-design
——reliable components in key parts, much over their limits,
——redundant elements,
——perfect protections,
——fault predicting function.

Table 1. The comparison of accelerator technologies for ADS

Technology	Cyclotron	Synchrotron	FFAG	Linac
Advantages	High current	High energy	High current and high energy	High current and high energy
Disadvantages	Energy limited	Current limited	Not yet proven	Expense
Examples	PSI	CERN PSB	EMMA	ESS, SNS

Linac

- Good beam quality, low beam loss
- Expensive (Large real estate, large RF system)

Cyclotron

- CW, stable, cost effective, small
- Heavy magnet, beam energy is limited

Synchrotron

- Higher energy
- High intensity injection is limited

FFAG many merits but not proven yet

Today's Linear Accelerators :

- SRF linac is quickly developed and has most potential
- large aperture, low loss, CW possible
- high beam power --- couplers are critical

The main disadvantage is high expense, but mass production will be lower .

3. Introduction of worldwide ADS accelerators progresses

MYRHHA

——*Multipurpose Hybrid Research Reactor for High-tech Applications (MYRHHA) Project*

- ***European Transmutation Demonstrator*** ——***by coupling the three components (accelerator, spallation target and sub-critical reactor) at power level scalable to an industrial demonstrator***
  — demonstrate the physics and technology of ADS for transmuting long-lived radioactive waste .

MYRRHA ADS – Technical specifications

Accelerator	
particles	protons
beam energy	600 MeV
beam current	4 mA
mode	CW
MTBF	> 250 h

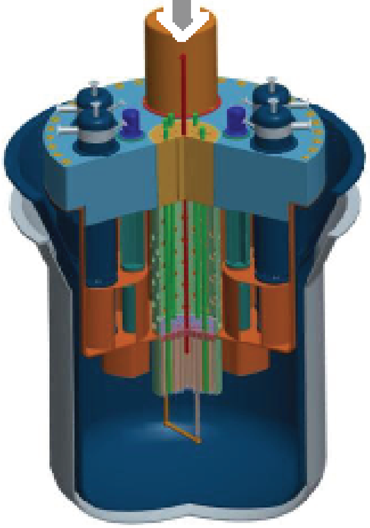
Reactor	
power	~85 MW_{th}
k_{eff}	0.955
spectrum	fast (flexible)
fuel	MOX
coolant	LBE

Target	
main reaction	spallation
output	$2 \cdot 10^{17}$ n/s
material	LBE (coolant)
power	2.4 MW

Fast Neutron Source

Multipurpose Flexible Irradiation Facility

- Transmutation concept
- Irradiation facility for GEN-IV materials
- Neutron irradiated silicon
- Radioisotopes for nuclear medicine
- Fundamental research



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MYRRHA ADS – Schedule

- **2010-2014** Front End Engineering Design
- **2015** Tendering & Procurement
- **2016-2018** Construction of components & civil engineering
- **2019** On site assembly
- **2020-2022** Commissioning
- **2023** Progressive start-up
- **2024-** Full exploitation

Minimise technological risks	Accelerator	x	Spallation target	x	Sub-critical reactor
Secure the licensing	**PDP** preliminary dismantling plan		**PSAR** preliminary safety assesment		**EIAR** environmental impact assesment
Secure a sound management and investment structure	Central Project Team		Owner Consortium Group		Owner Engineering Team

FEED (Front End Engineering Design)

2010-2014/15

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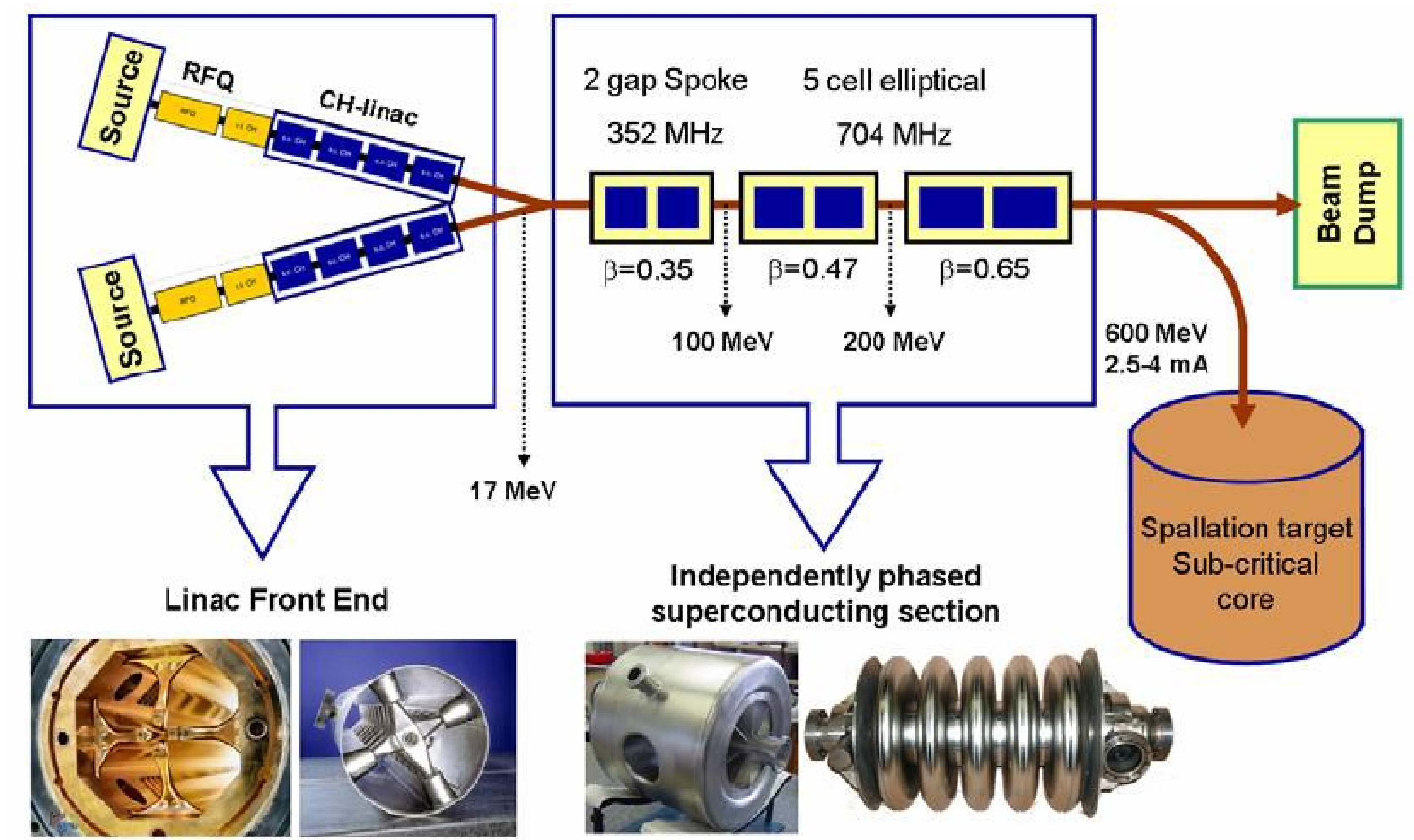
MYRRHA - Accelerator



MYRRHA proton beam requirements

→ **High power proton beam (up to 2.4 MW)**

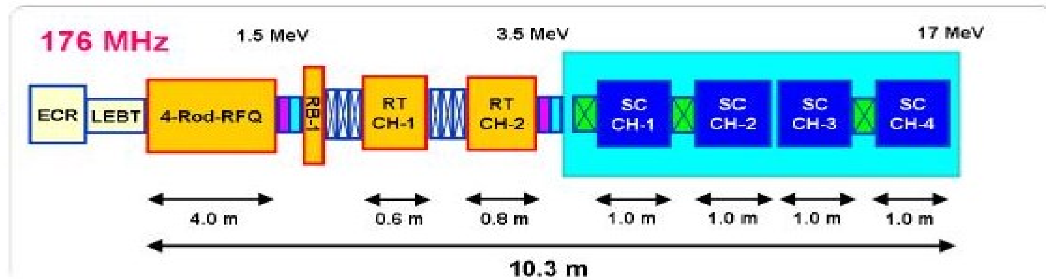
Proton energy	600 MeV
Peak beam current	0.1 to 4.0 mA
Repetition rate	1 to 250 Hz
Beam duty cycle	10^{-4} to 1
Beam power stability	< ± 2% on a time scale of 100ms
MTBF	> 250 h
# of allowed beam trips on reactor longer than 3 sec	10 maximum per 3-month operation period
# of allowed beam trips on reactor longer than 0.1 sec	100 maximum per day
# of allowed beam trips on reactor shorter than 0.1 sec	unlimited

→ **Extreme reliability level**

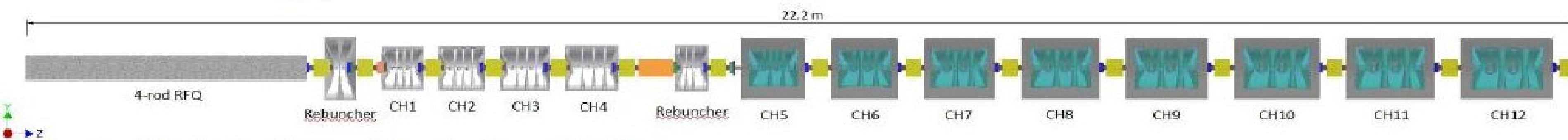
F. Bouly, ThEC13, CERN, 30/10/2013.

Beam dynamics development

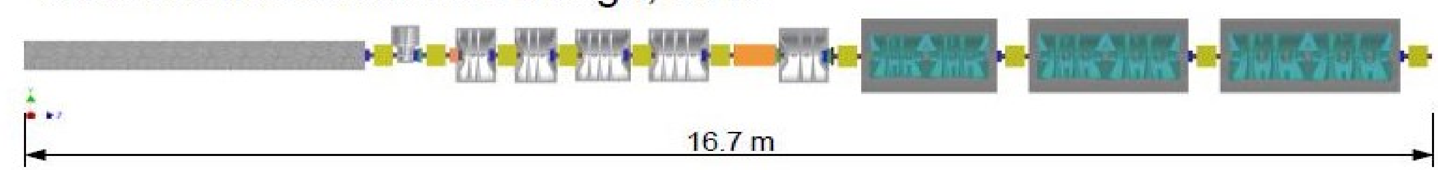
Reference design, 2012
by C. Zhang



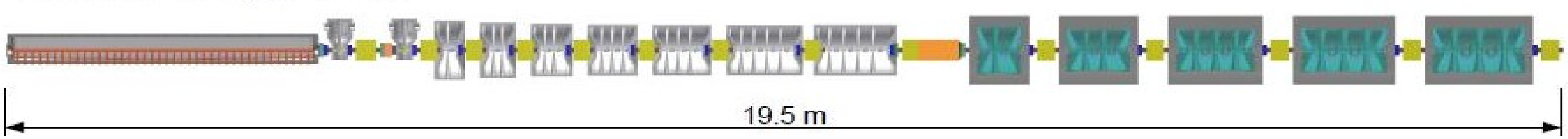
Alternative design, 2013



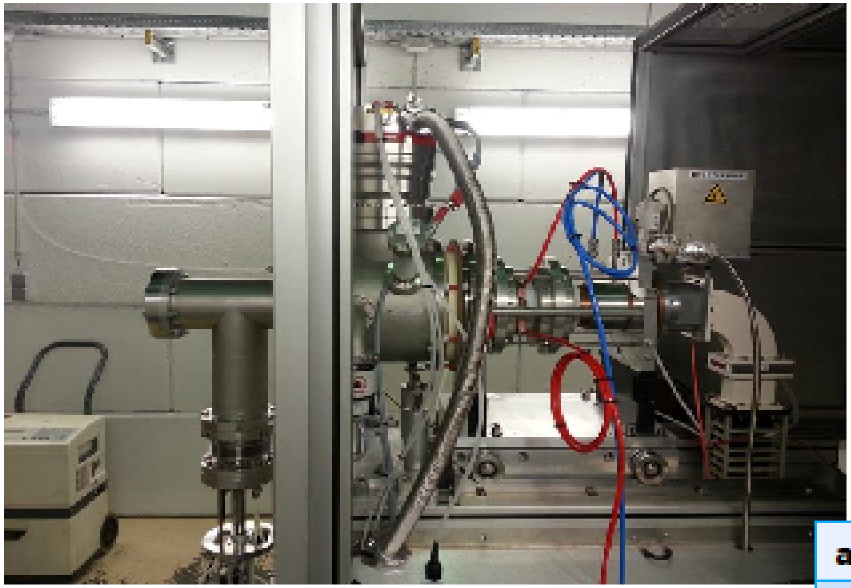
Consolidated alternative design, 2013



Smooth design, 2014



The ECR proton source

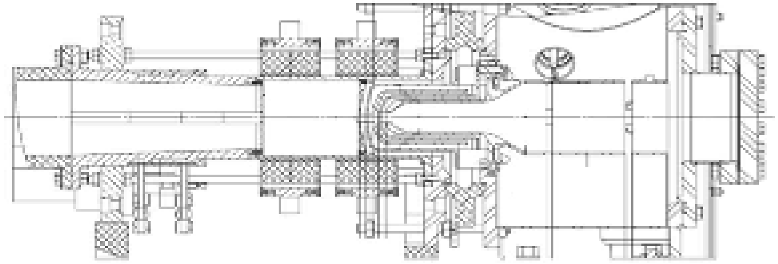


PANTECHNIK

Monogan 1000

ECR Ion souce – 30keV, 20mA

- Electron Cyclotron Resonance, 2.45 GHz
- multi-electrodes extraction system
- flat magnetic profile configuration by PMs
- tapered axial RF injection
- Einzel electrostatic focusing lens



courtesy of Pantechnik SA

accelerating voltage	**30 kV** (40 kV capable)
beam current	20 mA DC
RF	2.45 GHz, 1200 W
transverse emittance @ 5 mA	**0.1 π·mm·mrad RMS norm.**
magnetic system	Permanent Magnets
autonomous control system	NI CompactRIO
provisions for reliability/repairability	
beam diagnostics devices incl.: Faraday Cup, Allison scanner	

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Acceptance Tests

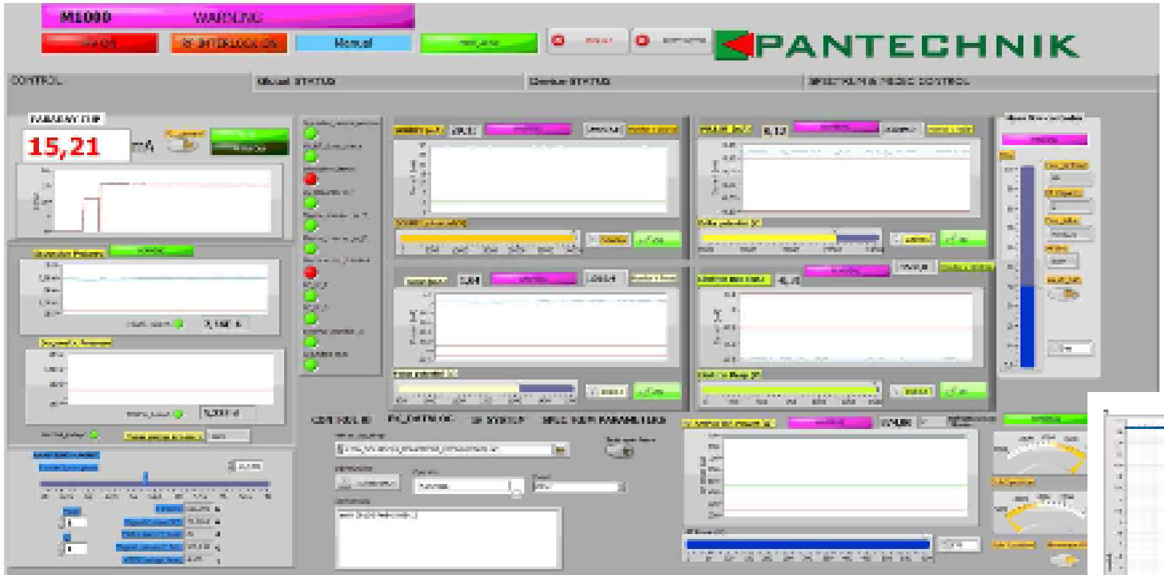
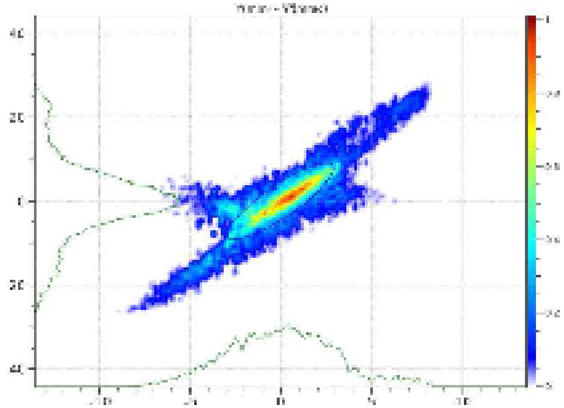
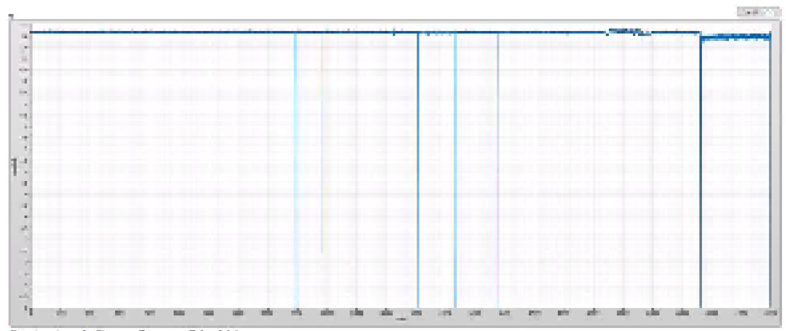
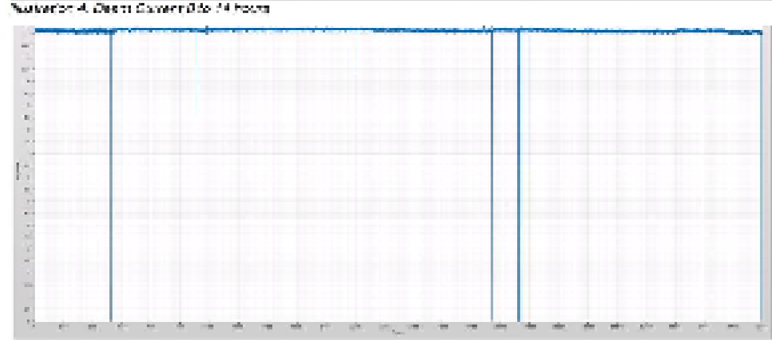


Figure 22: Source parameters at 15 mA@30keV







- Beam characterization in a short test line (source, dipole, FC, Allison scanner, dump)
- Max p beam current achieved: 16mA
- Long stability run (24hrs), standalone system, up to 12 mA
- Excellent stability shown with brief recovery time in case of electrical discharges

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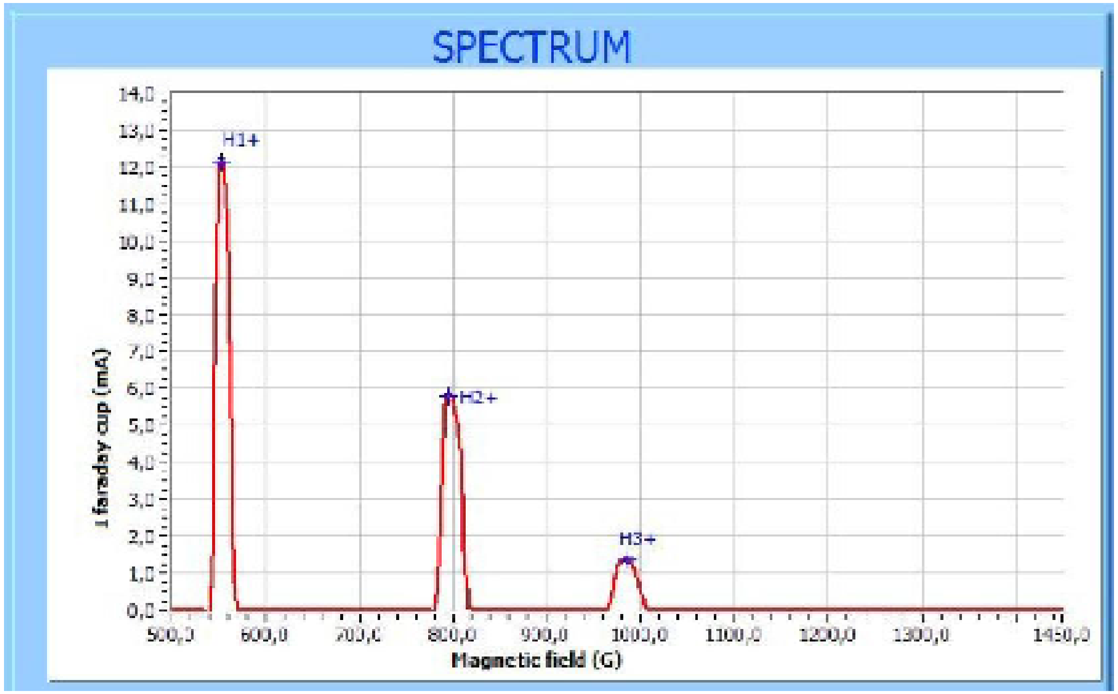
Acceptance Tests



- Total efficiency : 84%
  - Includes beam transport efficiency (total current from power supply divided by the sum of measured intensity)
  - and HV losses (bleeder)
- Ionisation efficiency (ion intensity divided by total measured intensity)
  - H+ =63%
  - H2+=30%
  - H3+=7%

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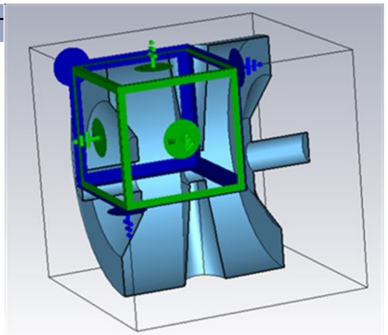
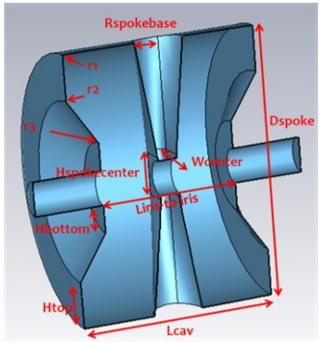
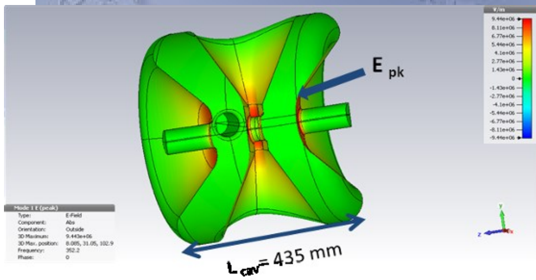
Spoke Cavity Prototype EM Optimization

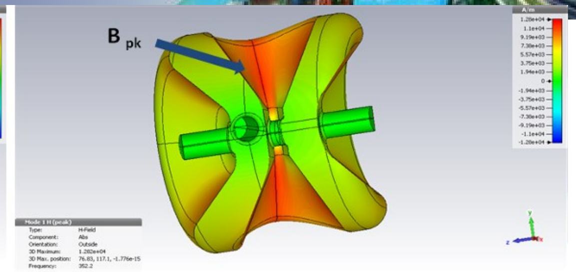


Numerical Model : Symetries and BC



Geometrical Parameters





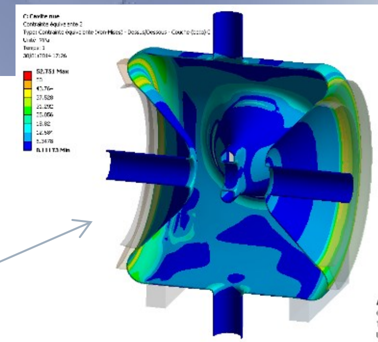
Optimized RF parameters	
Optimal beta	**0.37**
Vo.T [MV/m] @ 1 Joule & optimal beta	**0.693**
Epk/Ea	**4.29 ***
Bpk/Ea [mT/MV/m]	**7.32 #**
G [Ohm]	**109**
r/Q [Ohm]	**217**
Qo @ 2K for Rres=20 nΩ	**5.2 E+09**
Pcav for Qo=2 E+09 & 6.4 MV/m [W]	**9.35**
Lacc=0.315m= beta $_{optimal}$. c . f	

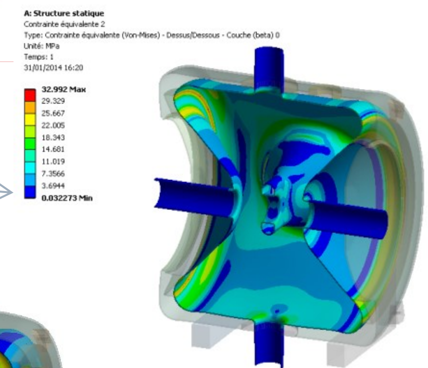
* Goal at 4.4, # Goal at 8.3

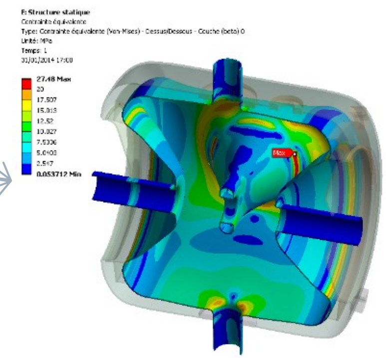
Goal: $E_{acc\ nom.}$ = 6.2 MV/m, $E_{acc\ fault\ tol.}$ = 8.2 MV/m

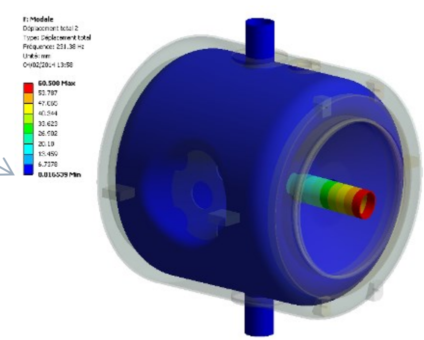
Spoke Cavity Prototype Mechanical Optimization

Simulation Case		
Bare Cavity Leak Test	0.1 Mpa External	52 MPa
Cavity Leak Test	0.1 Mpa External	< 33 MPa
Helium Tank Leak Test	0.1 Mpa External	< 35 MPa
Cavity Cool down	0.12 MPa	< 33 MPa
Cryogenic Accident	0.15 MPa	< 41 MPa
First Eigen Mode	###	232 Hz
Cavity Buckling Critical Pressure	###	3 Bars

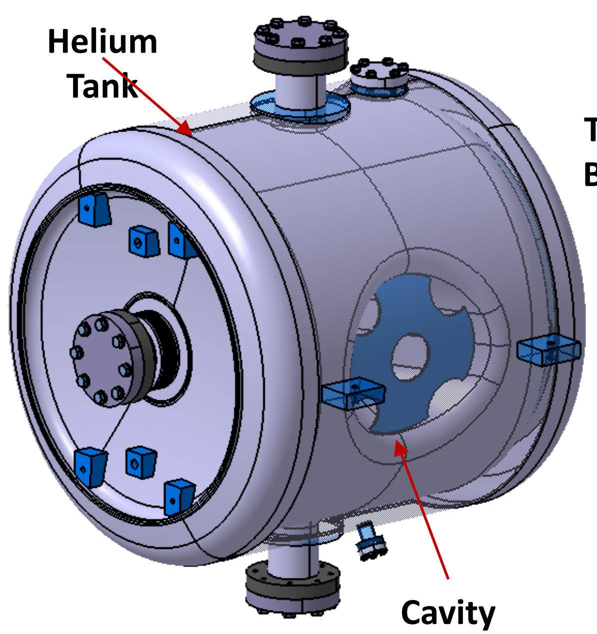


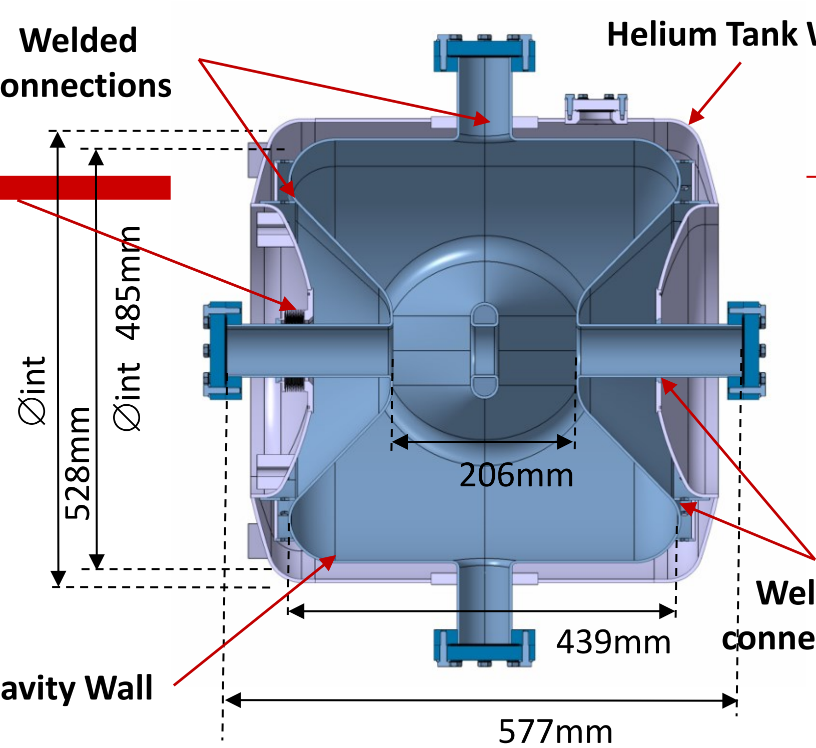






Spoke Cavity Prototype Overview





Cavity Wall thickness 3 mm (Nb RRR> 250)

Helium Tank Wall thickness 4 mm

Power Coupler

A power coupler 350 MHz, 20 kW CW (designed) was manufactured and tested at 8 kW (limited by amplifier) CW on a 350 MHz, beta 0.15 Spoke cavity.

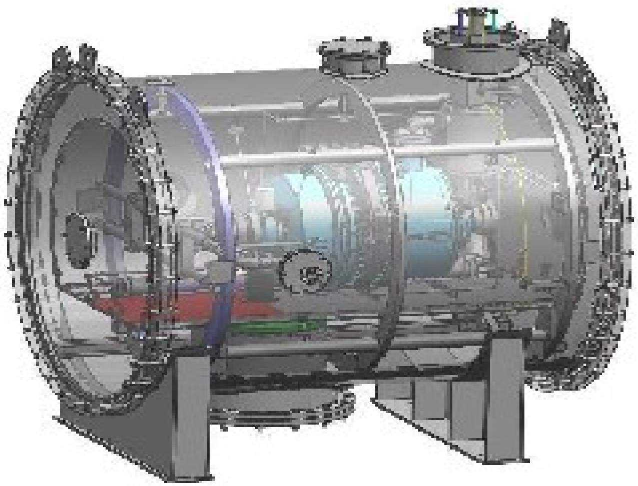
1 port for electron emission measurement pick up

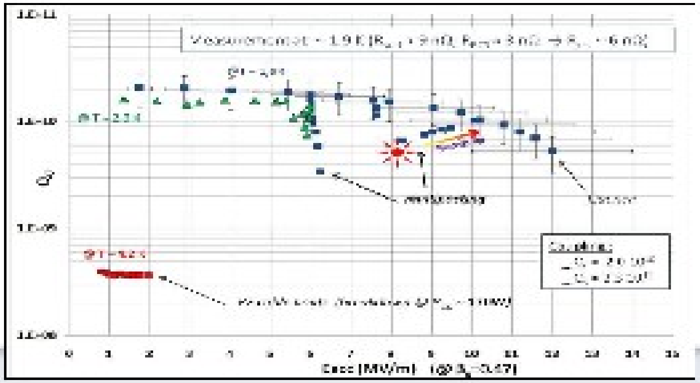
1 water cooling loop for the window

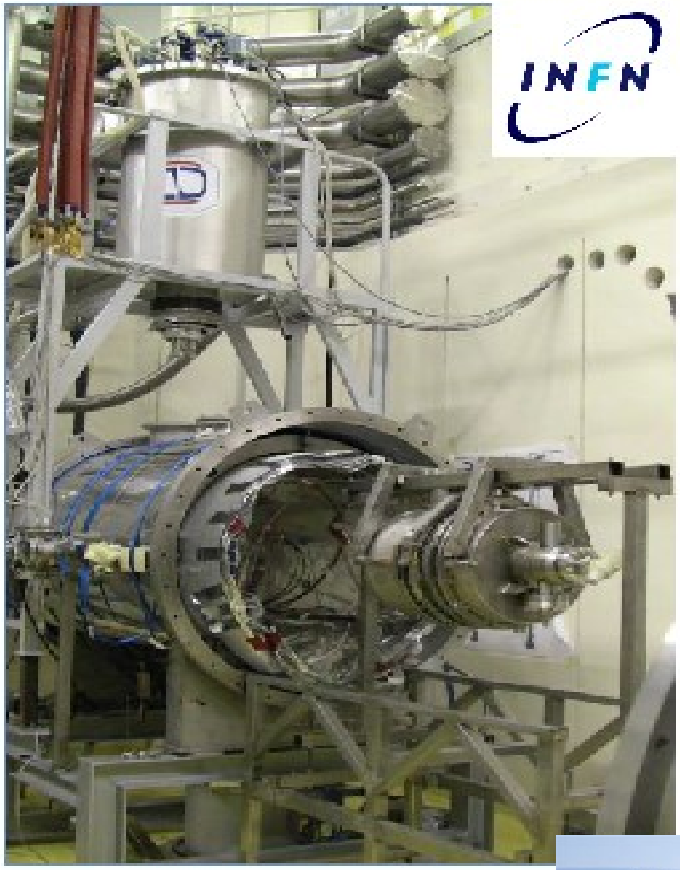
Plain Copper Antenna

Elliptical

Linac components: elliptical







J-PARC

Plan of Transmutation Experimental Facility (TEF) as Phase-II of J-PARC

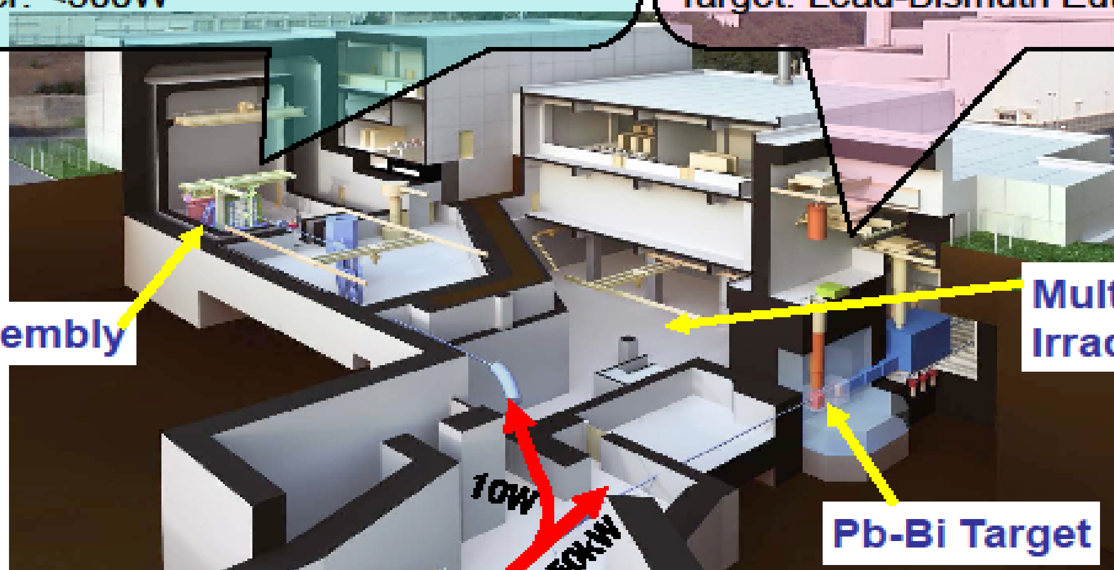
JAEA

Transmutation Physics Experimental Facility: TEF-P

Purpose: To investigate physics properties of subcritical reactor with low power, and to accumulate operation experiences of ADS.
Licensing: Nuclear reactor: (Critical assembly)
Proton beam: 400MeV-10W
Thermal power: <500W

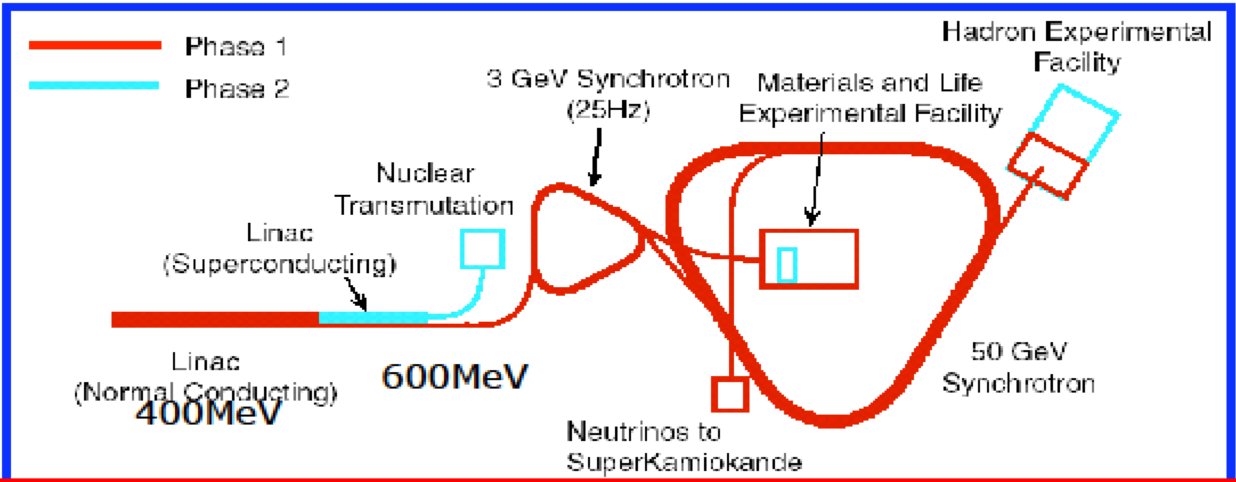
ADS Target Test Facility : TEF-T

Purpose: To research and develop a spallation target and related materials with high-power proton beam.
Licensing: Particle accelerator
Proton beam: 400MeV-250kW
Target: Lead-Bismuth Eutectic (LBE, Pb-Bi)



Phase I

- *day-1* — Linac 180MeV, 30mA, 25Hz; RCS 3GeV, 0.6MW; MR 40GeV, 400kW
- *Next Stage* — Linac 400MeV, 50mA, 25Hz; RCS 3GeV, 1.0MW; MR 40GeV, 670kW



Phase II

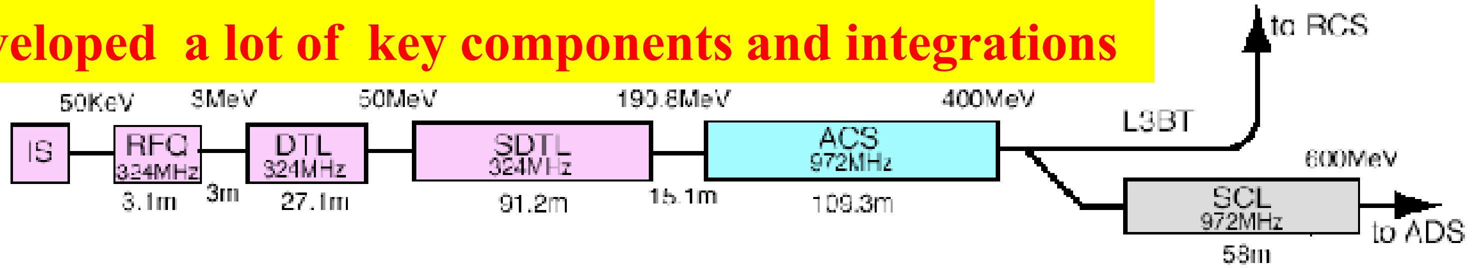
- Nuclear Transmutation Facility(ADS)
  →Linac 600MeV,50Hz
- Extension of Hadron and Neutron Facility
- MR 50GeV, 750kW

Linac structures and parameters

- *Ion Source:* *Volume Production Type*
- *RFQ:* *Stabilized Loop*
- *DTL:* *Electro-Quad in DT, 3 tanks*
- *Separated DTL(SDTL):* *no quad in DT, short tank(5cells), 32tanks*
- *Annular Coupled Structure (ACS):* *axial symmetric*
- *Super Conducting Linac (SCL):* *wide aperture, high acceleration gradient*

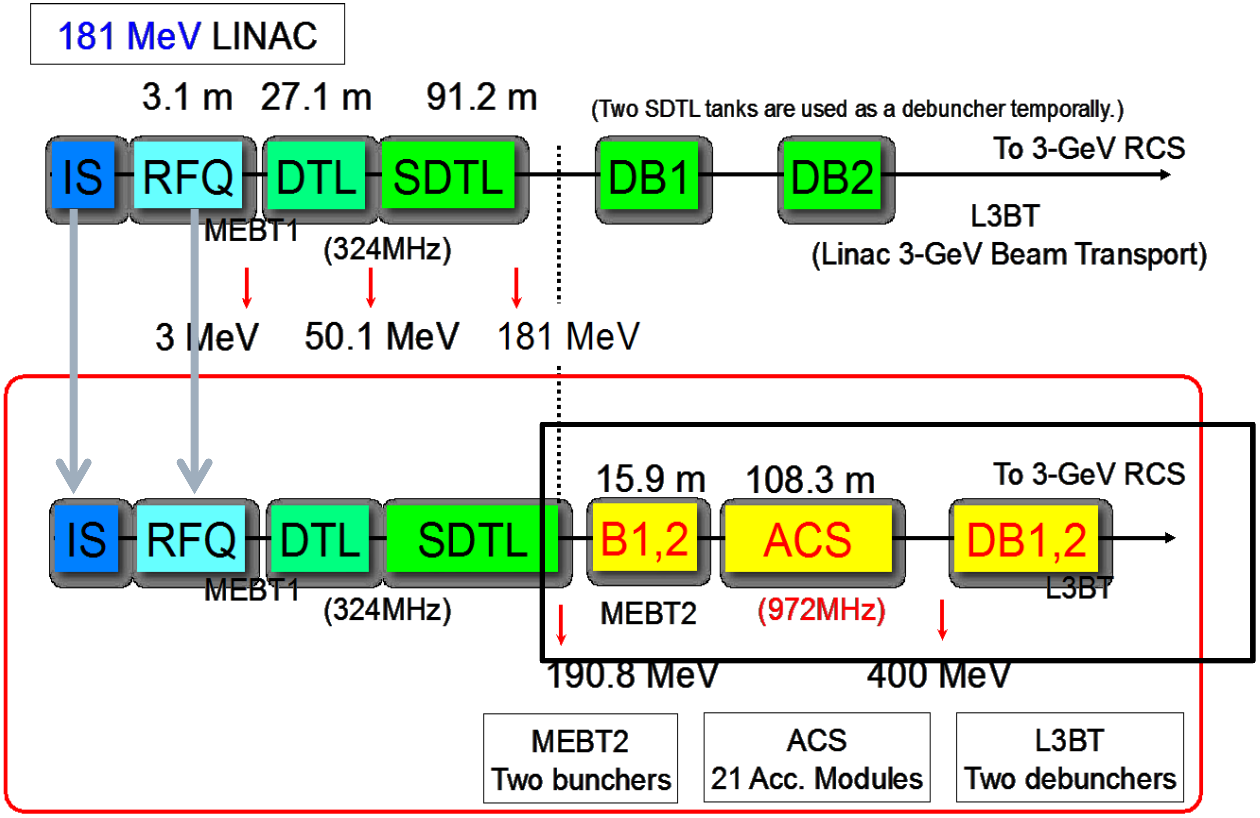
• *particles:*	*H-*
• *Energy:*	*181 MeV (RCS injection)*
	400 MeV (RCS injection)
	600 MeV (to ADS)
• *Peak current:*	*30 mA @181MeV*
	50 mA @400 MeV
• *Repetition:*	*25 Hz (RCS Injection)*
	50 Hz(RCS Injection + ADS application)
• *Pulse width:*	*0.5 msec*

developed a lot of key components and integrations

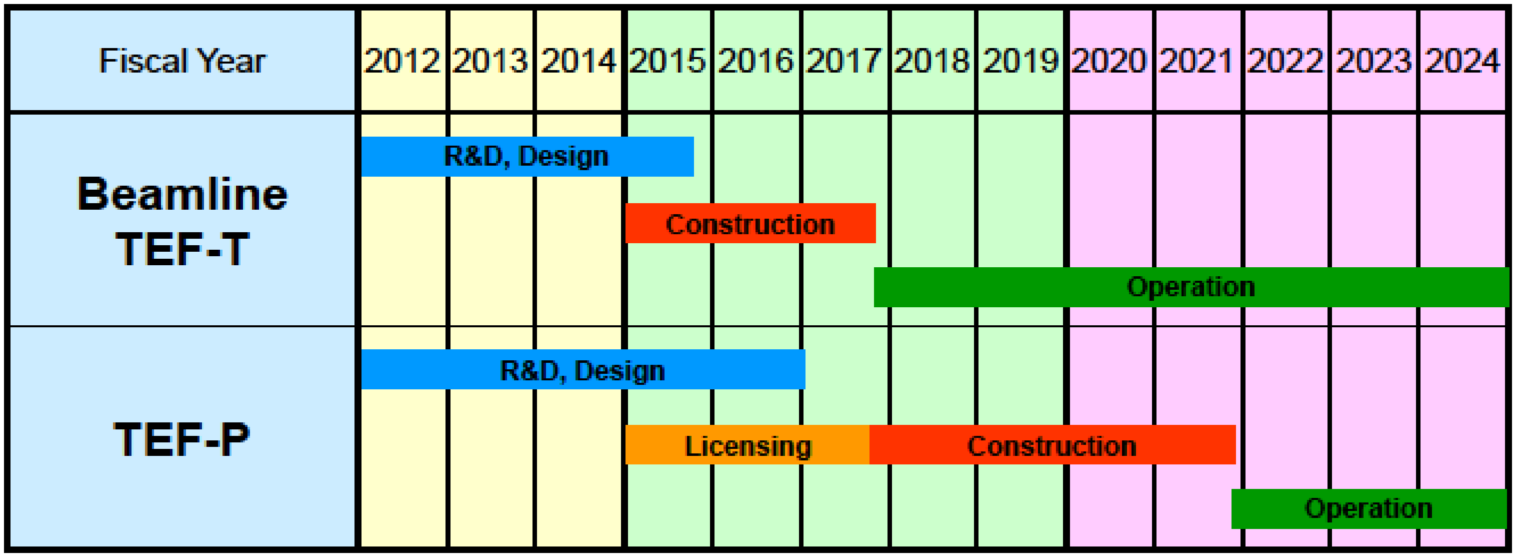


Upgrade plan of J-PARC linac

- Energy is upgraded with ACS, current is upgraded with new ion source and RFQ.



Construction Schedule (Tentative Plan)



- The construction of Beam line and TEF-T will be started in 2014 and the operation with 1/4 beam power will be started in 2017
- To start the construction of TEF-P in 2017, just after the completion of TEF-T, a few years of licensing activities should be started in 2015

KIPT Experimental Neutron Source Facility at Kharkov, Ukraine

- ✓ *Provide capabilities for performing basic and applied research using neutrons*
- ✓ *Perform physics and material experiments inside the subcritical assembly and neutron experiments using the radial neutron beam ports of the subcritical assembly*
- ✓ *Produce medical isotopes and provide neutron source for performing neutron therapy procedures*
- ✓ *Support the Ukraine nuclear power industry by providing the capabilities to train young specialists*

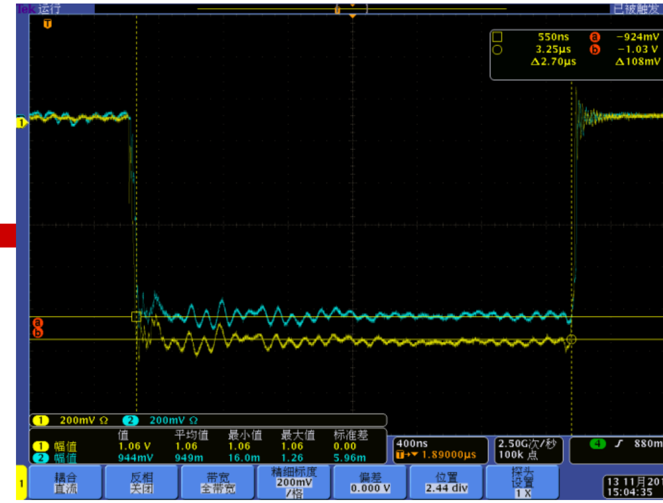
Linac Machine Parameters

a 100MeV/100 kW electron linac for KIPT is used as the driver of a neutron source based on a subcritical assembly.

Parameters	Values	Units
RF frequency	2856	MHz
Beam energy / power	100 / 100	MeV / kW
Beam current (max.)	0.6	A
Energy spread (p-to-p)	±4	%
Emittance	5×10^{-7}	m-rad
Beam pulse length	2.7	µs
RF pulse length	3	µs
Pulse rep. rate	625	Hz
Klystron	6×30MW / 50kW	Units
Accelerating structures	10×1.336m	Units
Gun high voltage	~120	kV
Nominal gun beam current	~1–1.2	A

Injector Testing Facility and Testing Resuts

The injector testing facility installed



~780mA obtained with ~90% transport efficiency at the injector exit

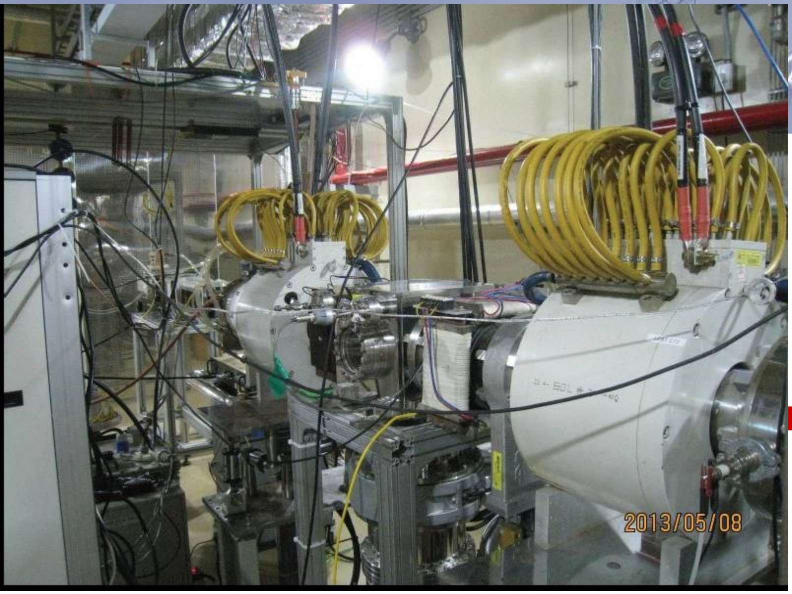
- The maximum beam current obtained at the injector exit is ~2A with 2.7 μs beam pulse.
- Energy spread is ~2% @ 1σ

HYPER (Hybrid Power Extraction Reactor)

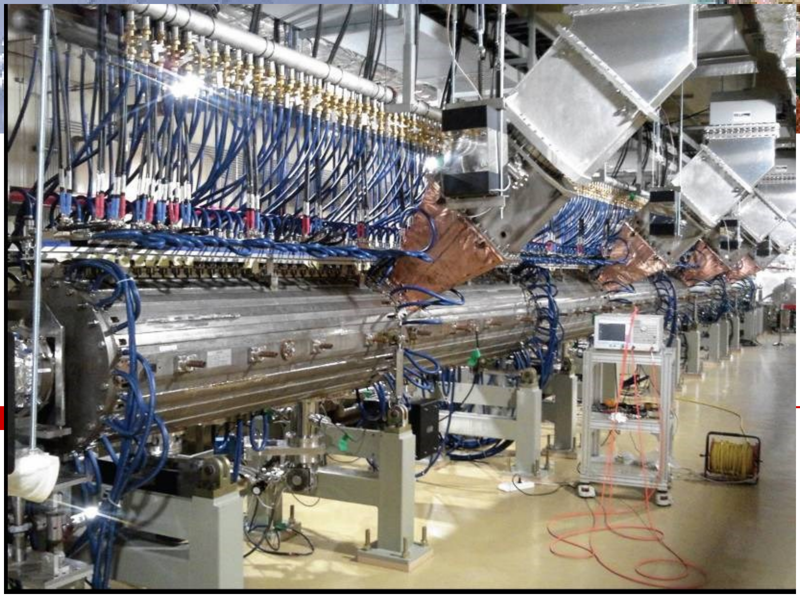
The Korea Atomic Energy Research Institute (KAERI) performs HYPER for the transmutation of nuclear waste and energy production , to develop the elemental technologies for the subcritical transmutation system and build a small bench scale test facility (5 MW). 1 GeV/16 mA proton beam is designed to be provided for HYPER.

KOMAC (Korea multi-purpose accelerator complex)

KOMAC accelerator facility was put into the operation from July 2013， which consists of a 100MeV proton linac including a 50keV ion source, a 3MeV RFQ and a 100MeV DTL, and 20MeV and 100MeV beam lines. The goal of the Beam commissioning is delivering 100MeV 1kW proton beams to a bump in a 100MeV target room.



50-keV injector including ion source and LEBT.



DTL in the accelerator tunnel

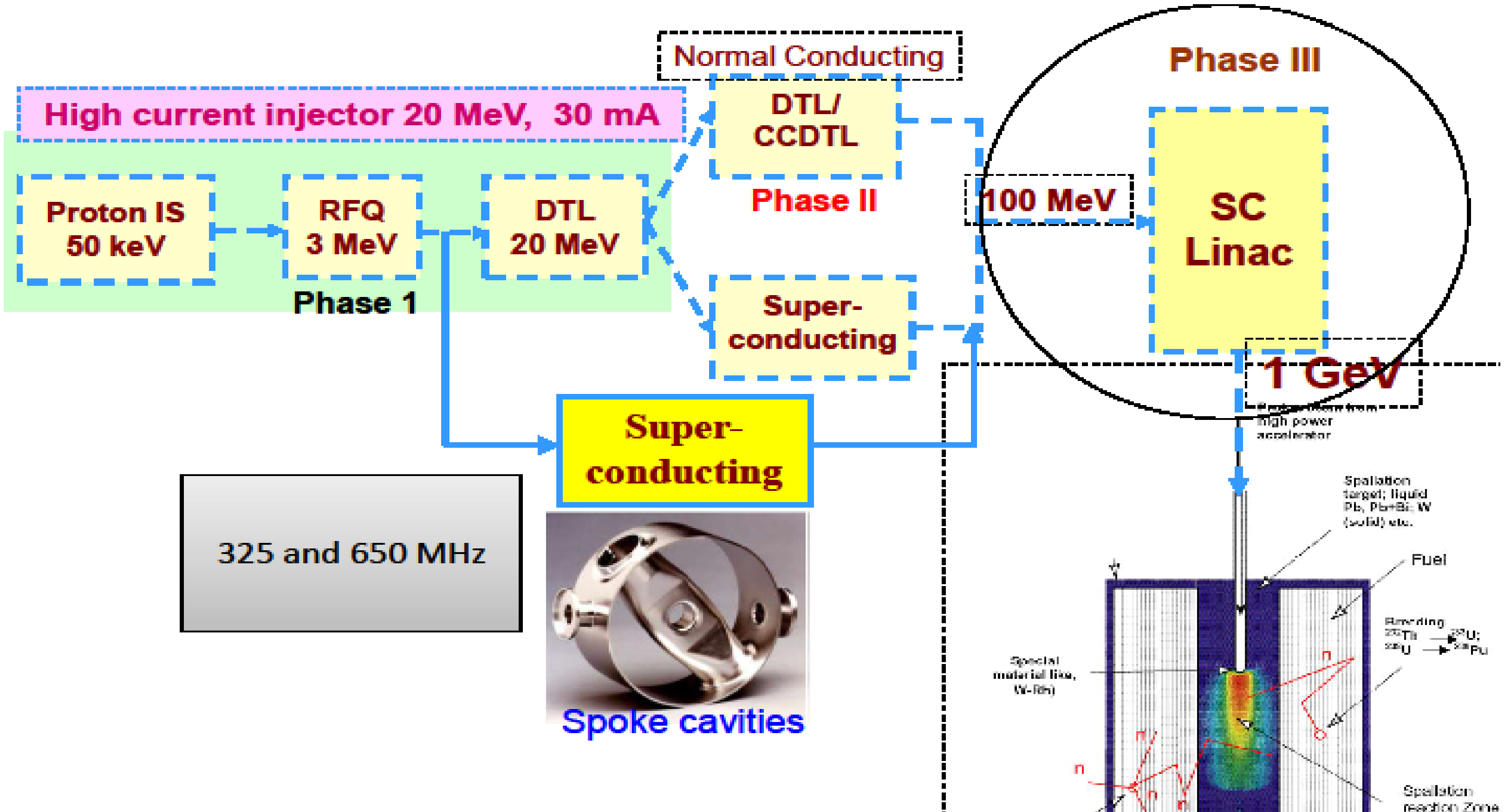
High power rf system

Parameters of KOMAC Linac

Frequency 350 MHz
Beam Energy 100 MeV
Operation Mode Pulsed
Max. Peak Current 20 mA
Pulse Width <1.33 ms (< 2.0 ms for 20 MeV)
Max. Beam Duty 8% (24% for 20 MeV)
Max. Beam Power 160 kW (96 kW for 20 MeV)

Proton Linac in India ADS Program

Indian-ADS (especially thorium-cycle)



(Courtesy of P. Singh, BARC)

Accelerator Development for ADS

30 mA /20 MeV Linac injector (LEHIPA) and High energy Linac (1 GeV)

Design completed & fabrication is in progress

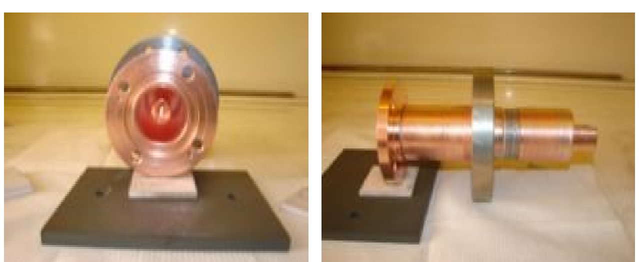
ECR Ion Source

LEBT

RFQ

Drift Tube Linac

50 kW RF Coupler

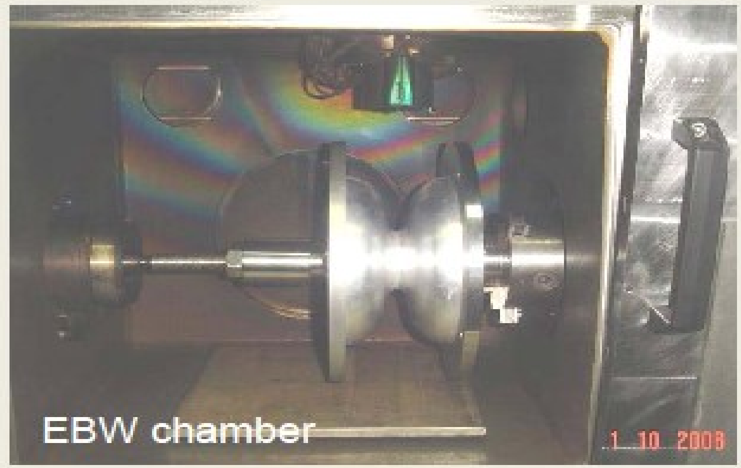


60 kW RF System

1.3 MW Klystron

Developing Technique for SC RF Cavity Fabrication

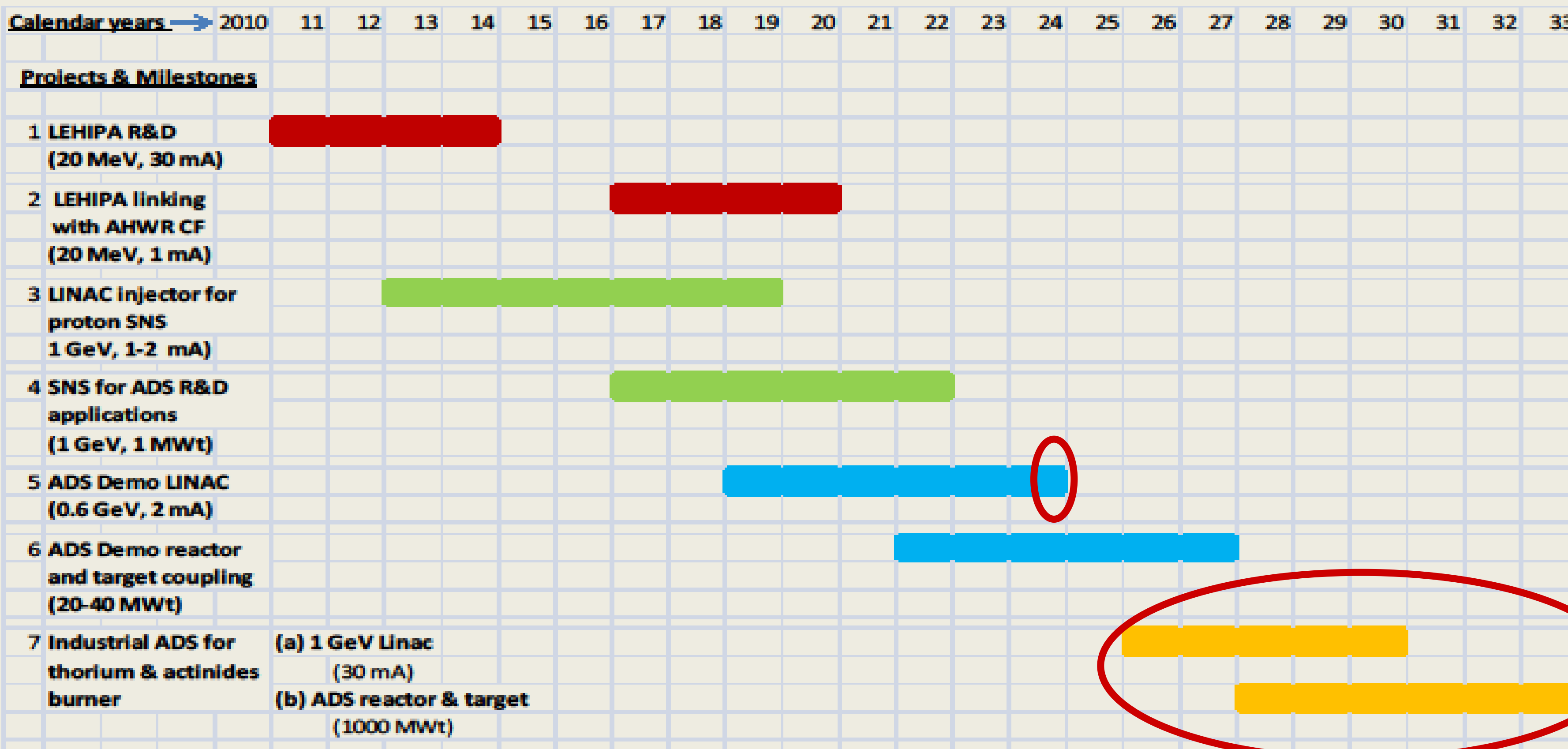
Formed Niobium Half Cell



Welded dumbell

Courtesy of P.K. Nema, BARC Mumbai

Roadmap for ADS Developments



Note: Design and engineering phases are not factored.
R&D for enabling technologies to precede the onset of projects.
R&D on fuel cycle, fuel design and fabrication to meet appropriate sch

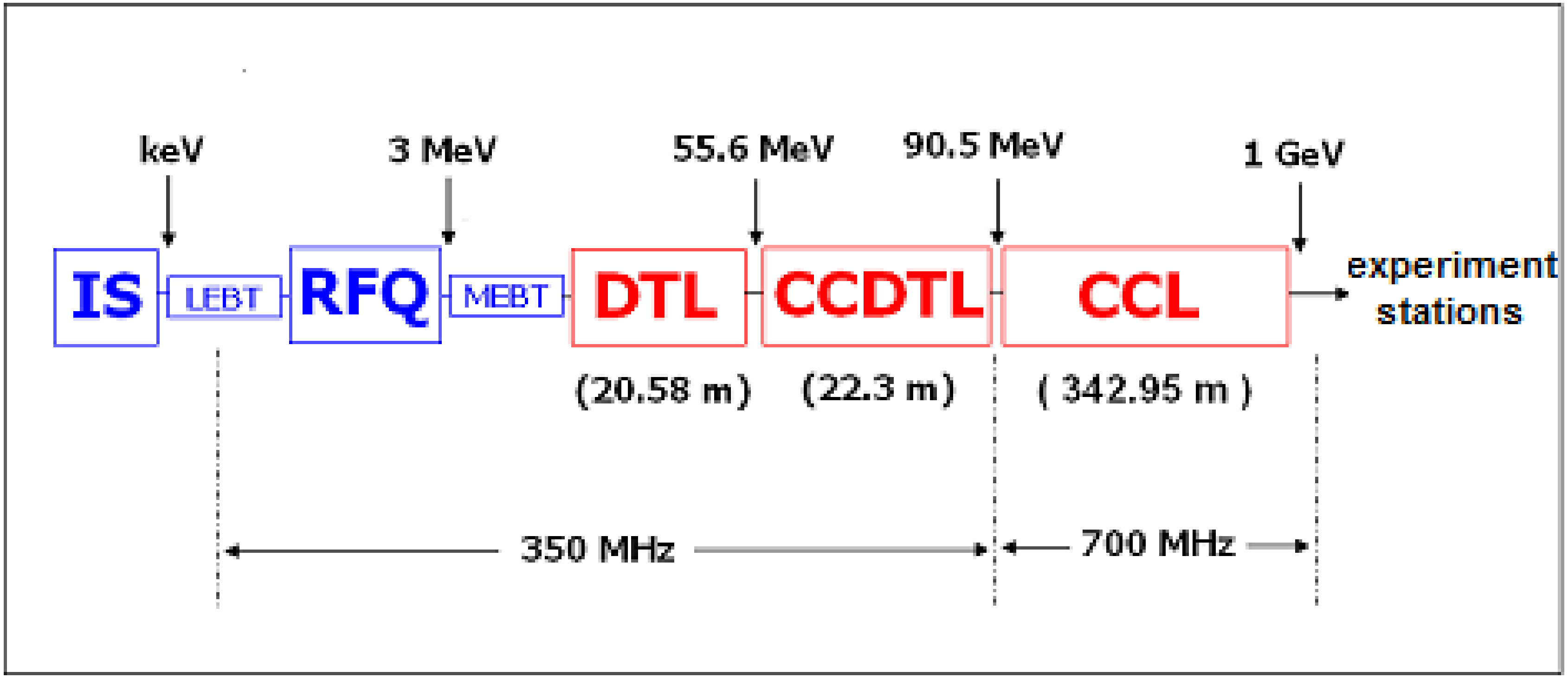
Courtesy of P.K. Nema, BARC Mumbai

TAC (Turkic Accelerator Complex project)

Planning to have four facilities:
SASE FEL Facility； Third Generation Synchrotron Radiation Facility (SR)； Super-Charm Factory ($\sqrt{s}$ = 3.77 GeV) ； GeV scale proton accelerator which has two-fold goal: Neutron Spallation Source (NSS) and ADS.

The proton accelerator construction will have 3 MeV, 100 MeV, and 1 GeV phases.

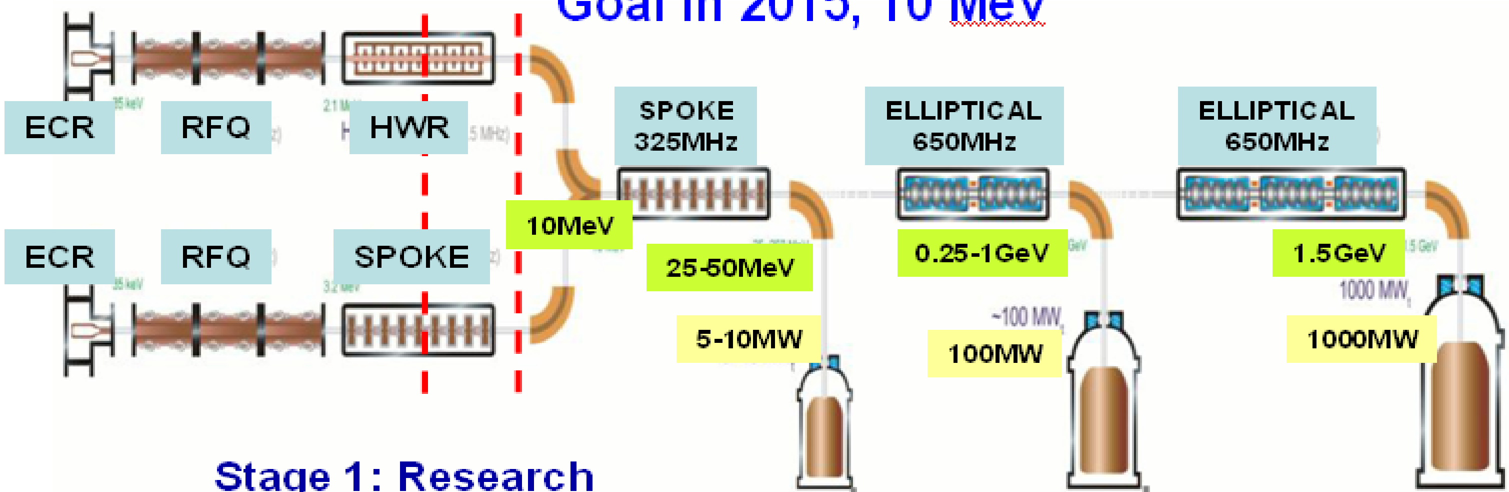
The TAC proton accelerator： GeV energy high intensity (>1mA) proton linac.



Roadmap of ADS Project in China

Goal in 2014, 5 MeV

Goal in 2015, 10 MeV



Stage 1: Research facility
(~10 MW, ~2023)
key technology R&D

Stage 2: Exp. facility
(~100 MW, ~2030)

Stage 3: Demo facility
(~1000 MW, ~2040)

"Strategic Priority Research Program" of the Chinese Academy of Sciences

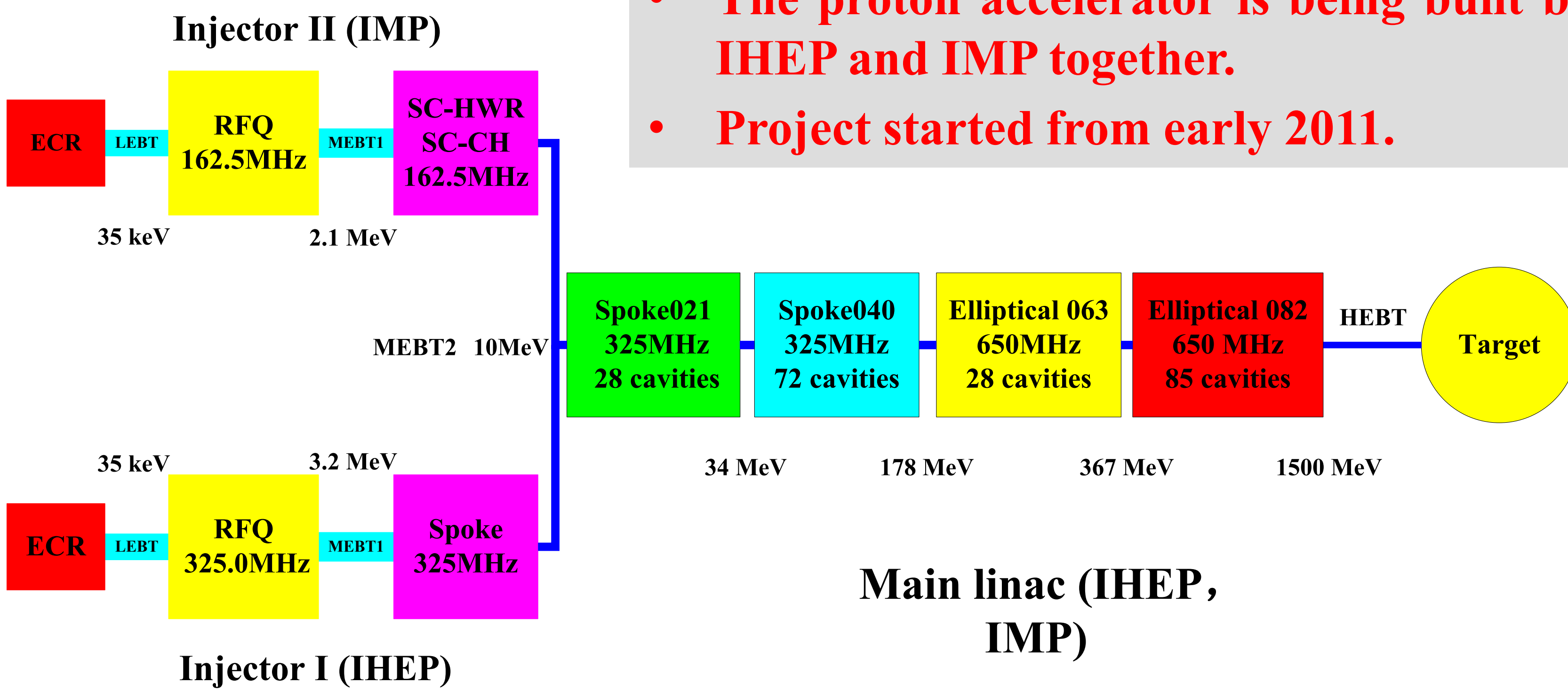
Special features and design goals

- Medium-energy, very high beam power, very high reliability, CW beam
- Reliability and availability much higher than actual accelerators in operations

Particle	Proton
Energy (GeV)	1.5
Current (mA)	10
Beam power (MW)	15
Duty factor (%)	100
Beam Loss (W/m)	<1
Beam trips/year	
1s<t<10s	<25000
10s<t<5m	<2500
t>5m	<25

Layout of ADS Accelerator

- The proton accelerator is being built by IHEP and IMP together.
- Project started from early 2011.

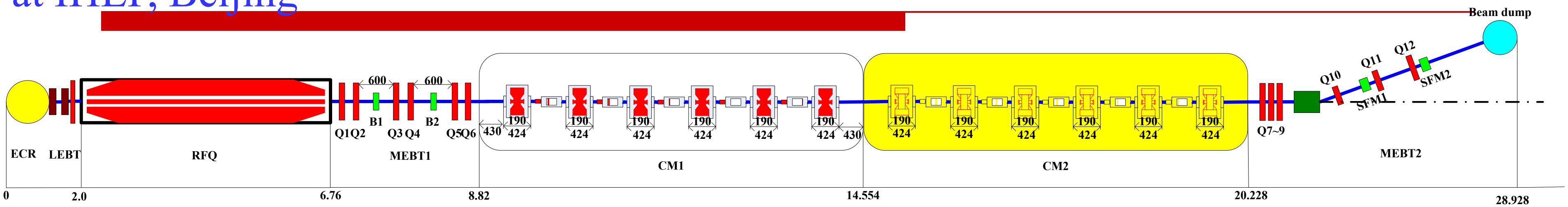


Final project has two identical injectors. Two designs of injector is due to technical uncertainty at very low energy segment.

Two options of 10-MeV Injectors

Injector I
at IHEP, Beijing

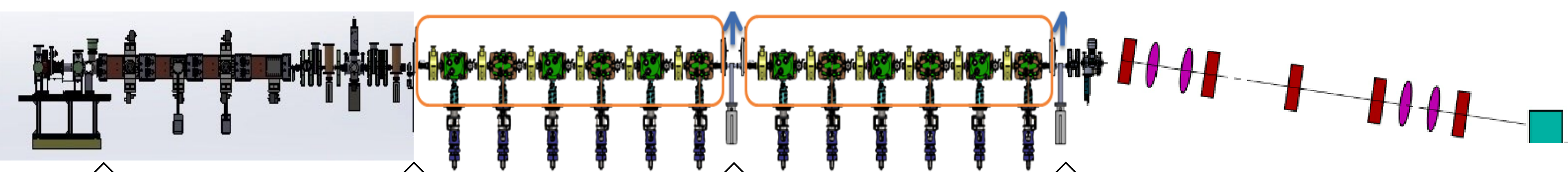
Base on 325 MHz and Superconducting Spoke cavity



35 KeV | 3.2 MeV | 5 MeV | 10 MeV

Injector II
at IMP, Lanzhou

Base on 162.5 MHz and Superconducting HWR cavity



35 KeV | 2.1 MeV | 5 MeV | 10 MeV

Progresses of accelerator (Injector I & II）

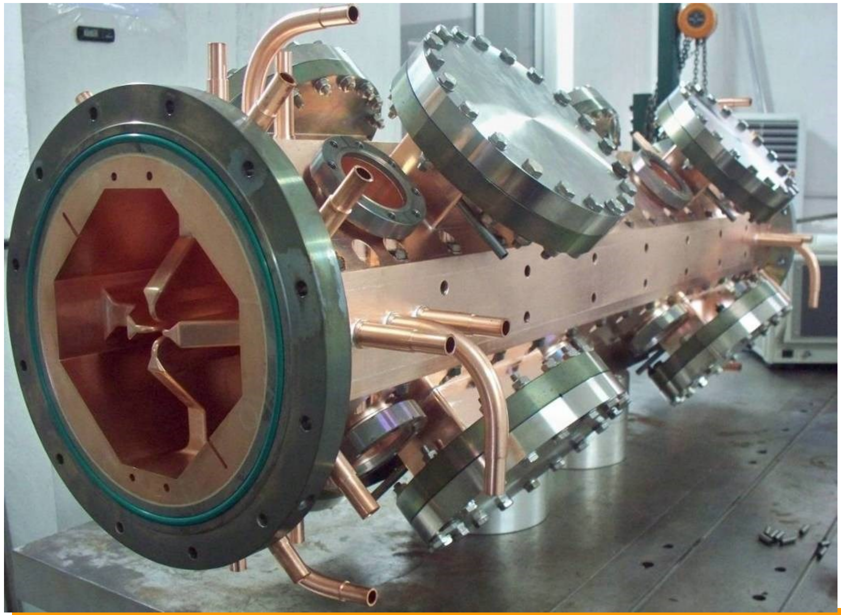
key technologies：

I. **CW RFQ with a high intensity——Great chellage！**

II. **Very Low beta SC cavities —— Spoke cavity & HWR ——lowest beta!**

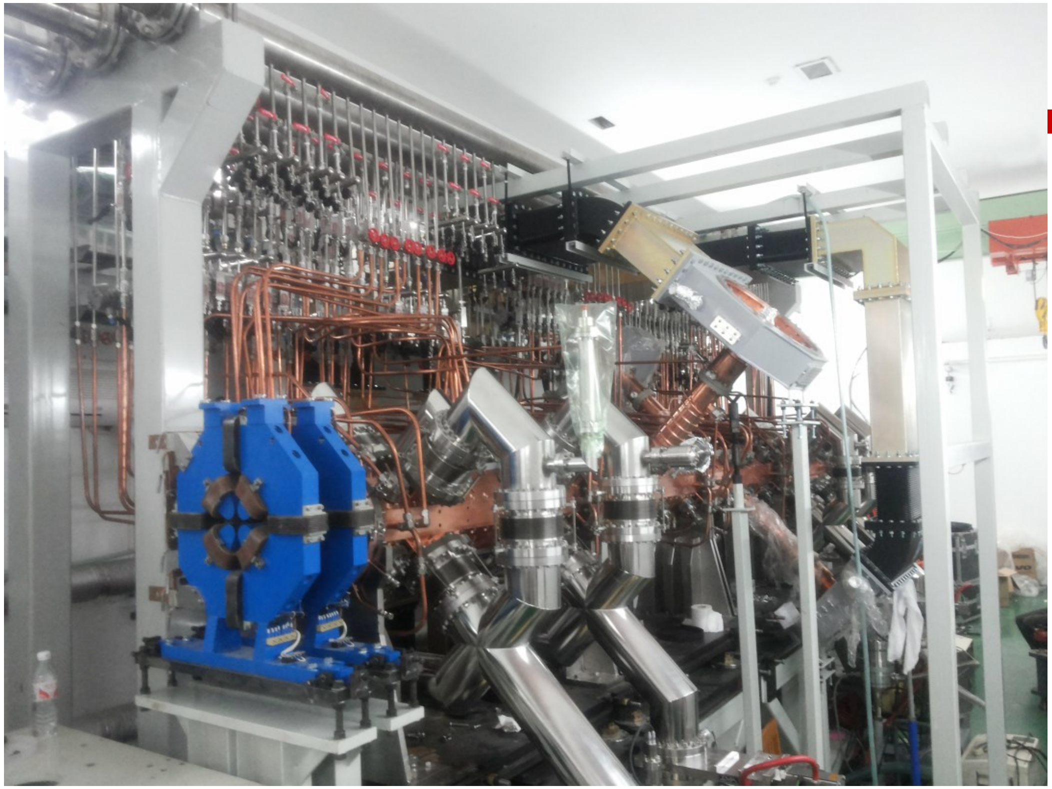
1）RFQ for Injector I

4 technical modules, 64 tuners, 4 RF power couplers, 4 dipole rods on each plate .



The beam transmission is about 98.7%

Parameters	Value
Frequency (MHz)	325
Injection energy (keV)	35
Output energy (MeV)	3.2128
Pulsed beam current (mA)	15
Beam duty factor	100%
Inter-vane voltage *V* (kV)	55
Beam transmission	98.7%
Average bore radius r_0 (mm)	2.775
Vane tip curvature (mm)	2.775
Maximum surface field (MV/m)	28.88 (1.62Kilp.)
Input norm. rms emittance (x,y,z)(πmm.mrad)	0.2/0.2/0
Output norm. rms emittance(x/y/z)(πmm.mrad/MeV-deg)	0.2/0.2/0.0612
Vane length (cm)	467.75
Accelerator length (cm)	469.95



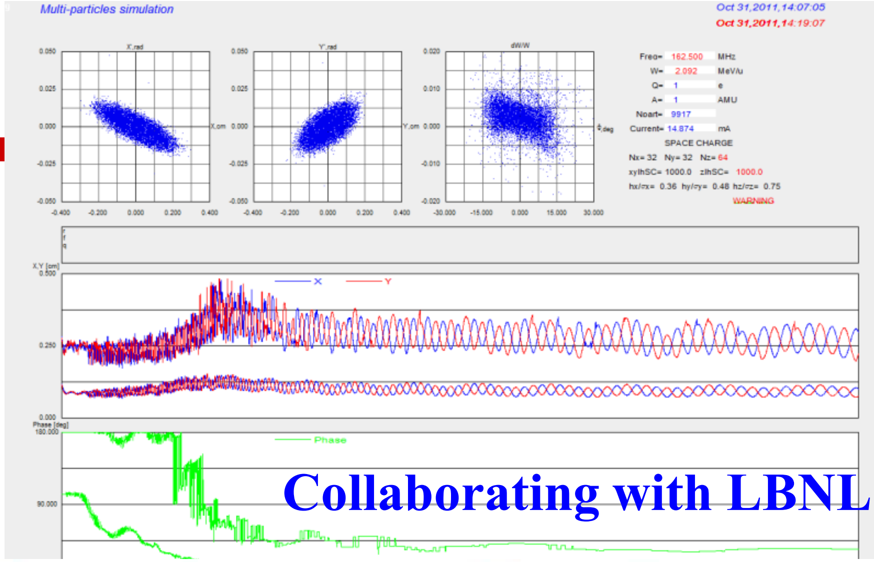
RFQ on site and aging

Conditioning goal: 270kW

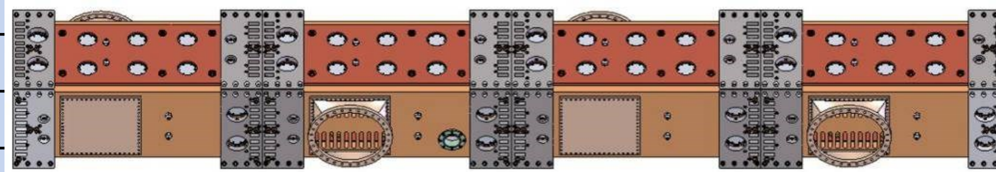
Status: 80% of the full power。

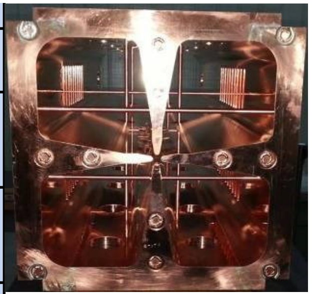
2）RFQ for Injector II

Parameter	Value
Ion species	Proton
frequency [MHz]	162.5
Inter-vane voltage *V* (kV)	65
Average bore radius r_0 (cm)	0.5731
Vane tip curvature (cm)	0.4298
ρ / r_0	0.75
Vane length / Total length (cm)	419.2 / 420.8
m_{max}	2.38
Number of cells	192 (including 2 T cell)
Maximum surface field (MV/m)	15.7791
Synchronous phase (^{0})	from -90 to -22.7
a_{min} (cm)	0.3158
Transverse acceptance (RMS, x/y, πmm.mrad)	0.3/0.3
Input norm. RMS emittance (x/y, πmm.mrad)	0.3/0.3
Output norm. RMS emittance (x/y/z, πmm.mrad, keV.ns)	0.31/0.31/0.92
Overall beam transmission @ 0 /15 mA	99.7% / 99.6%



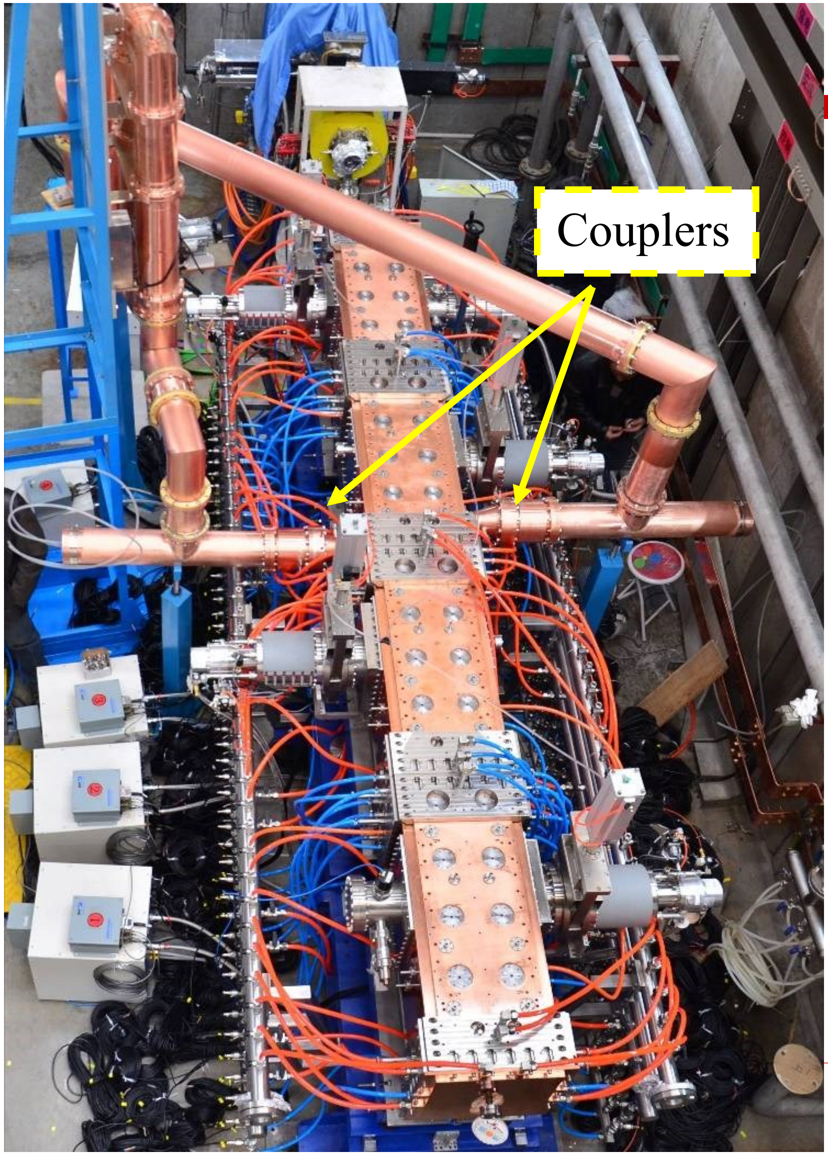
Collaborating with LBNL





Structure

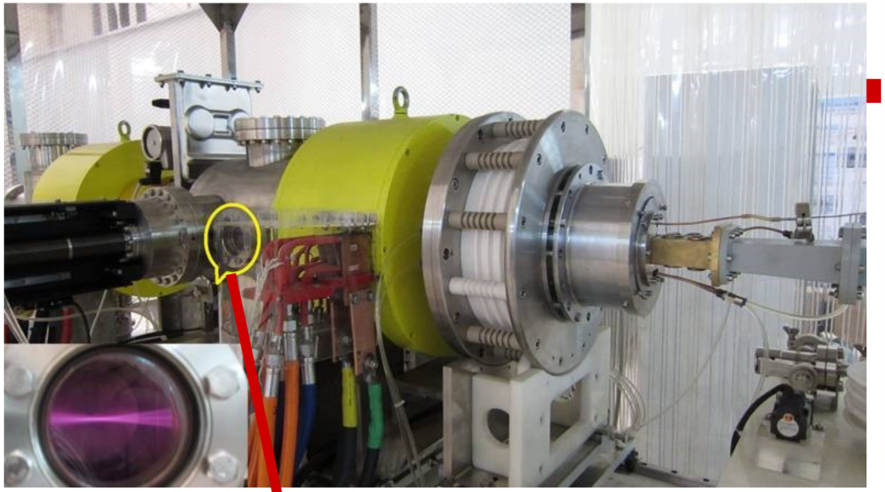
4 modules, 4200mm long
80 Tuners， 32 Pi-mode Rods， 2 RF input ports in Module 2， 8 vacuum ports

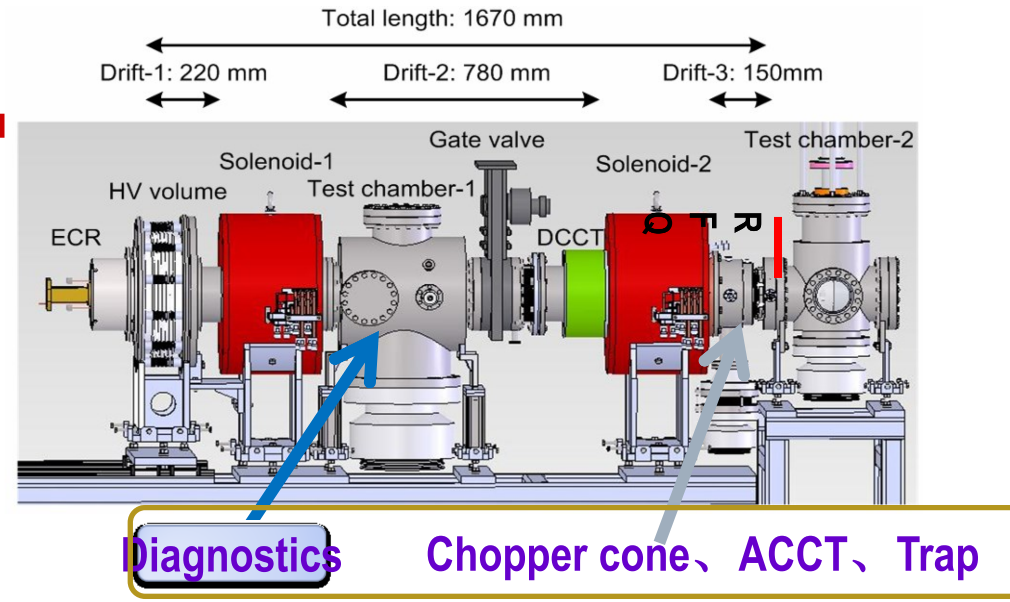


Four modules has been finished. The flatness is ± 1%, and symmetry is ±1.5% w/o tuners.

Conditioning goal: 91kW
Status: full power in CW.
commisioning beam now.

ECRIS+LEBTs finished commissioning

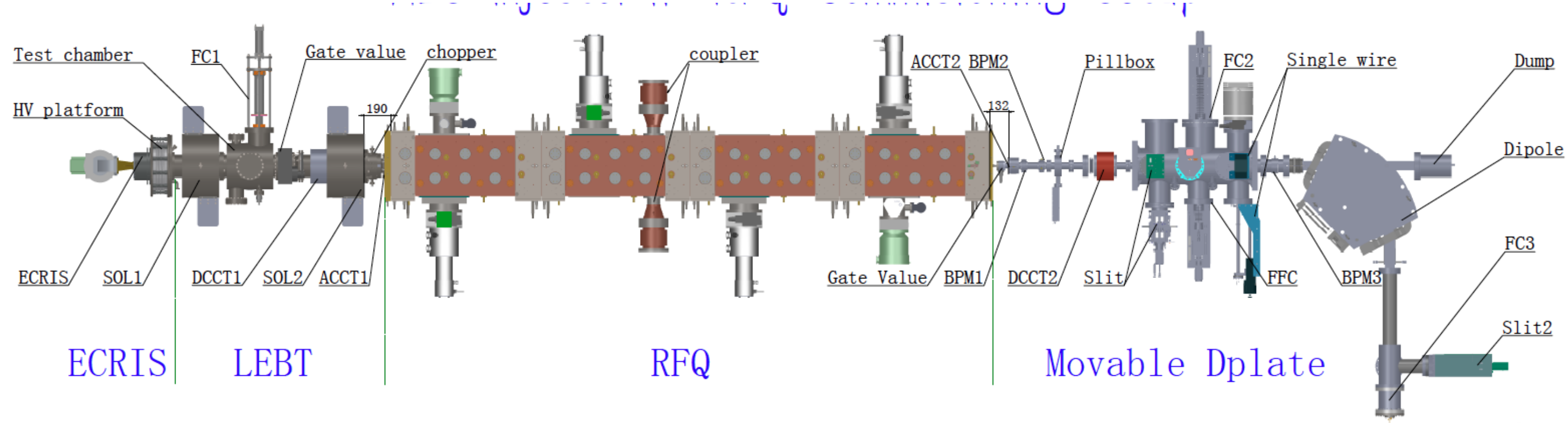


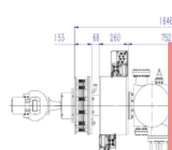


Two ECR Proton Ion Sources was commissioned at IMP and IHEP.

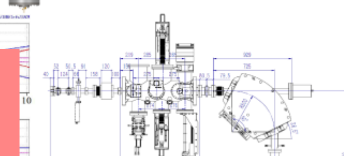
25 mA proton with 35 keV has been extracted.

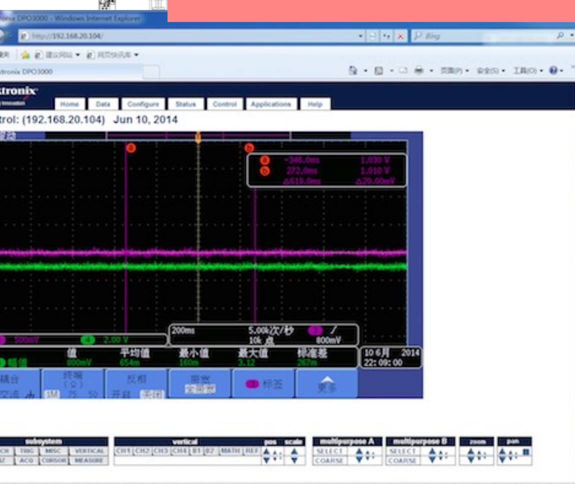
Beam Commissioning of 162.5 MHz RFQ





Got cw beam of 2.3 mA (10/06/2014)



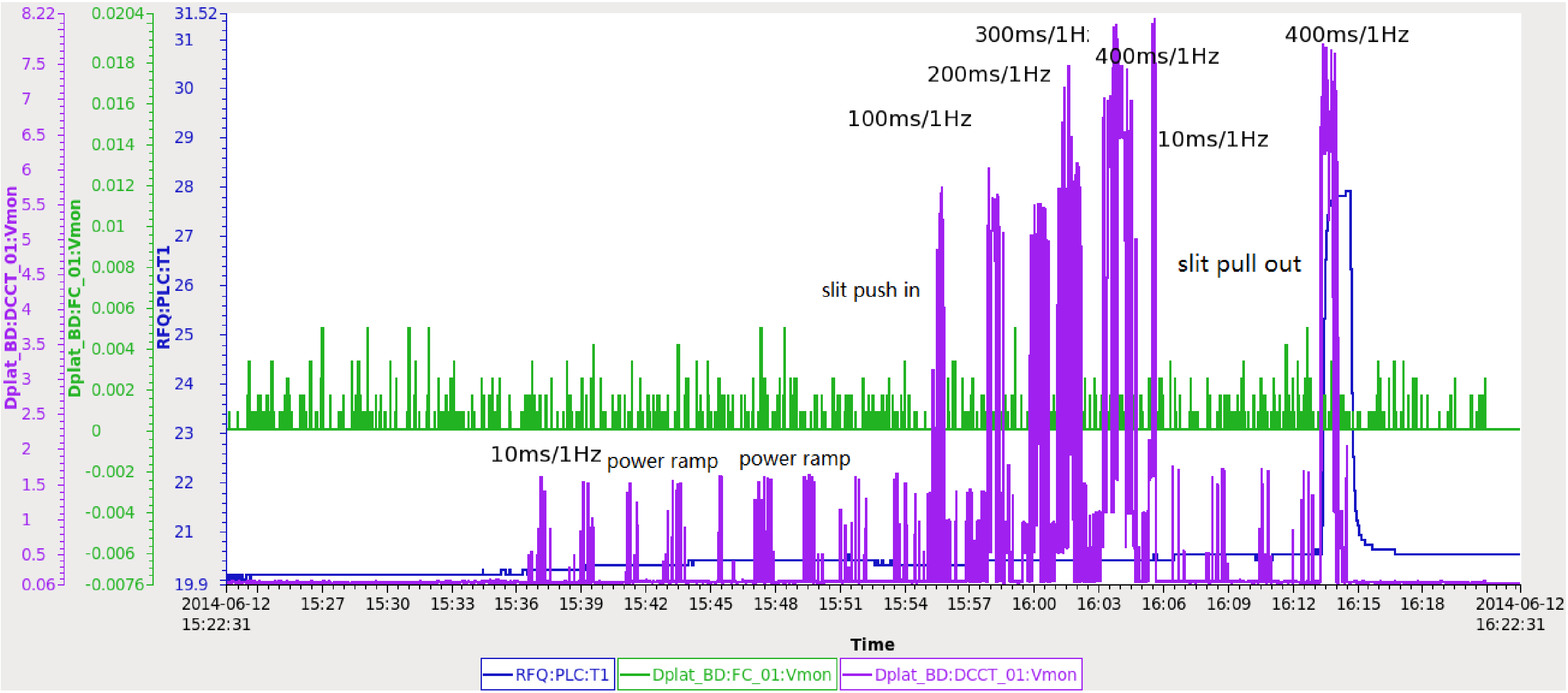


Red: DCCT1;Green: DCCT2
Efficiency > 95%

Yellow: BPM1;Green: BPM2;
Blue: BPM3;Energy=2.16MeV

Signal from pillbox
Momentum spread ~2%

Pulsed beam mode: max. beam ~8 mA, max. pulse length is 400 ms at repetition of 1 Hz

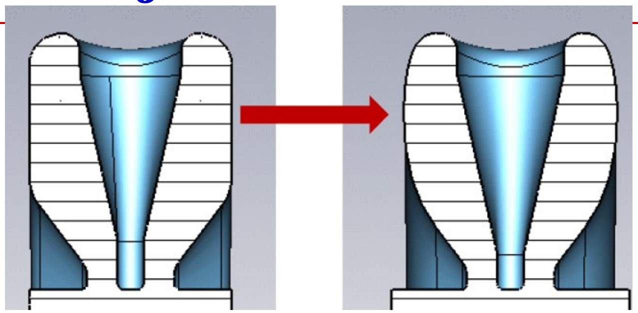


The Purple is the signal of the DCCT2 at exit of RFQ. the Blue is the temperature of the Faraday Cup, means average beam power, ~8 degree C increasing in maximum .

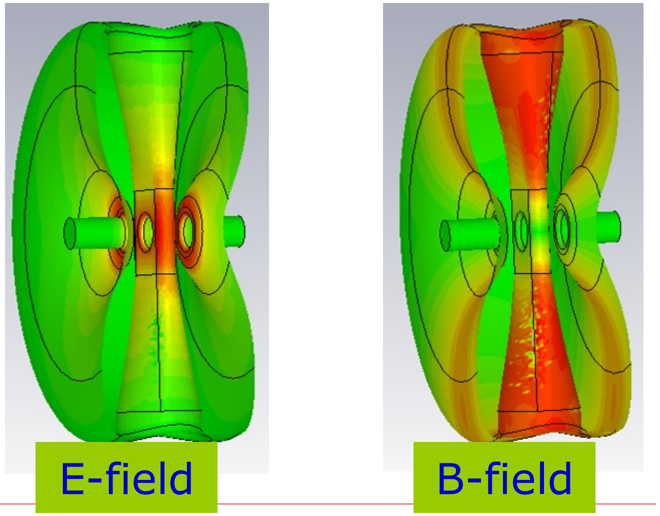
3）Spoke012 Cavity (β=0.12) for Injector I

Main Geometrical parameters	Units	Value
Diameter of cavity	mm	468
Length of cavity	mm	180
Diameter of beam tube	mm	35
RF parameters	Units	Value
E_{peak}/E_{acc}		4.54
B_{peak}/E_{acc}	mT/(MV/m)	6.37
G	Ω	61
Transition Time Factor		0.76
R/Q@β=0.12	Ω	142

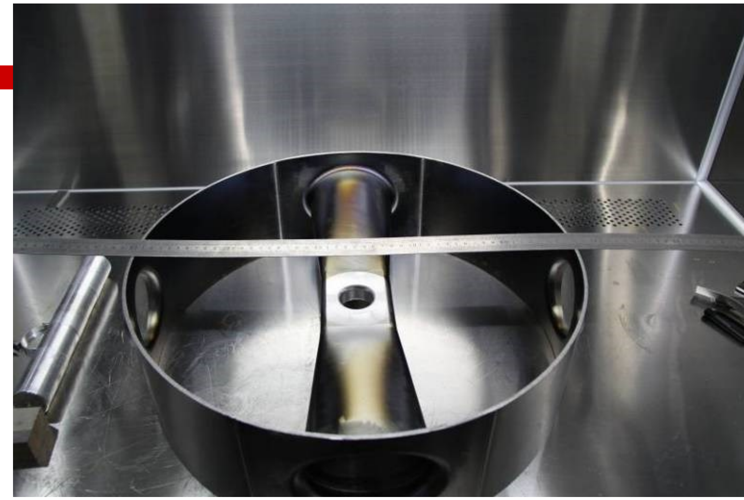
Note: Effective length for Eacc is defined as βλ

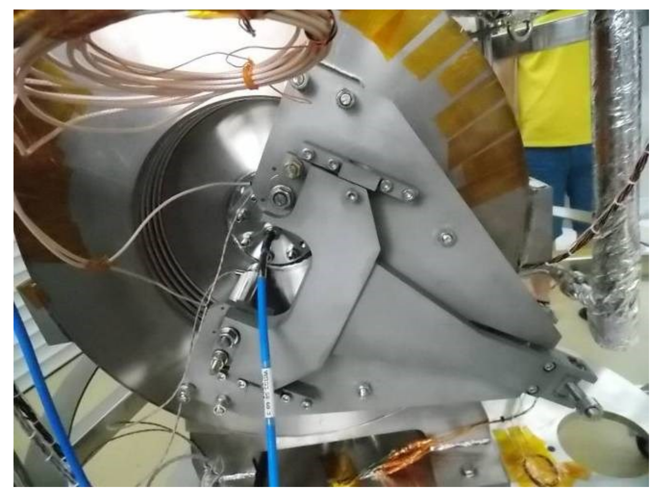


The Convex end wall (right) is dopted,which has better mechanical performance than the flat one (left).



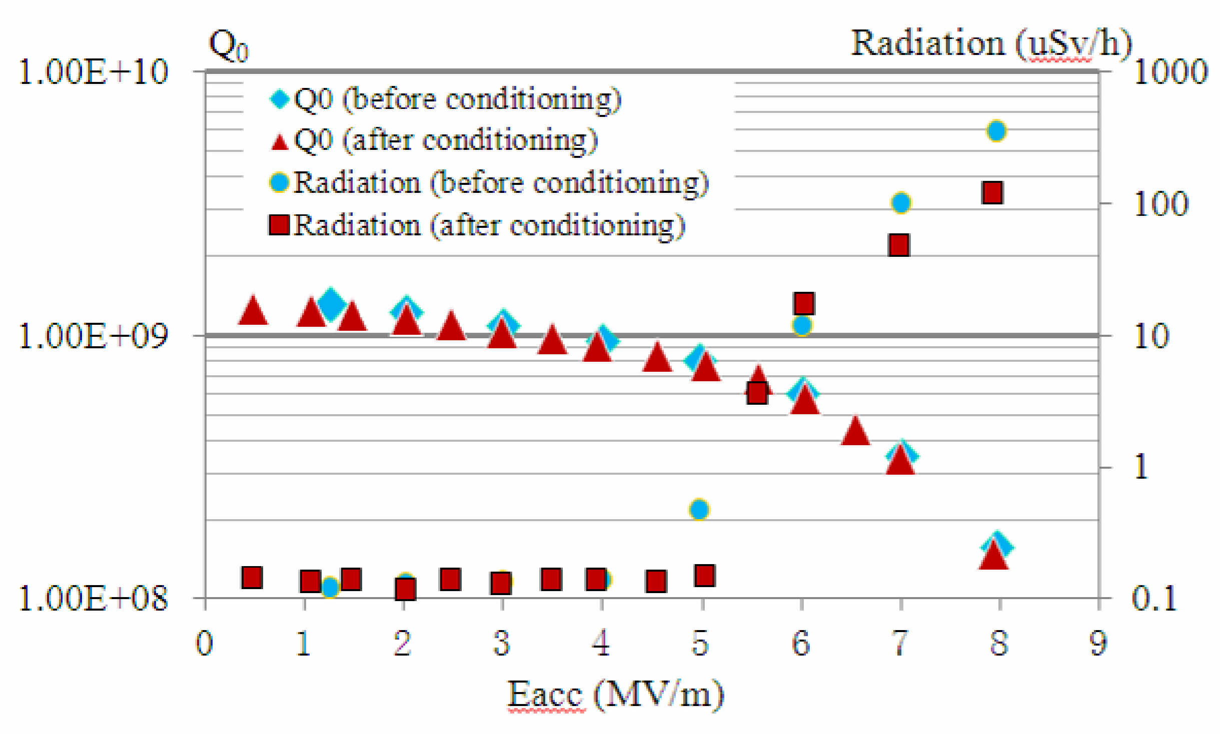
Fabrication of Spoke012 cavity finished on Nov. 8, 2012





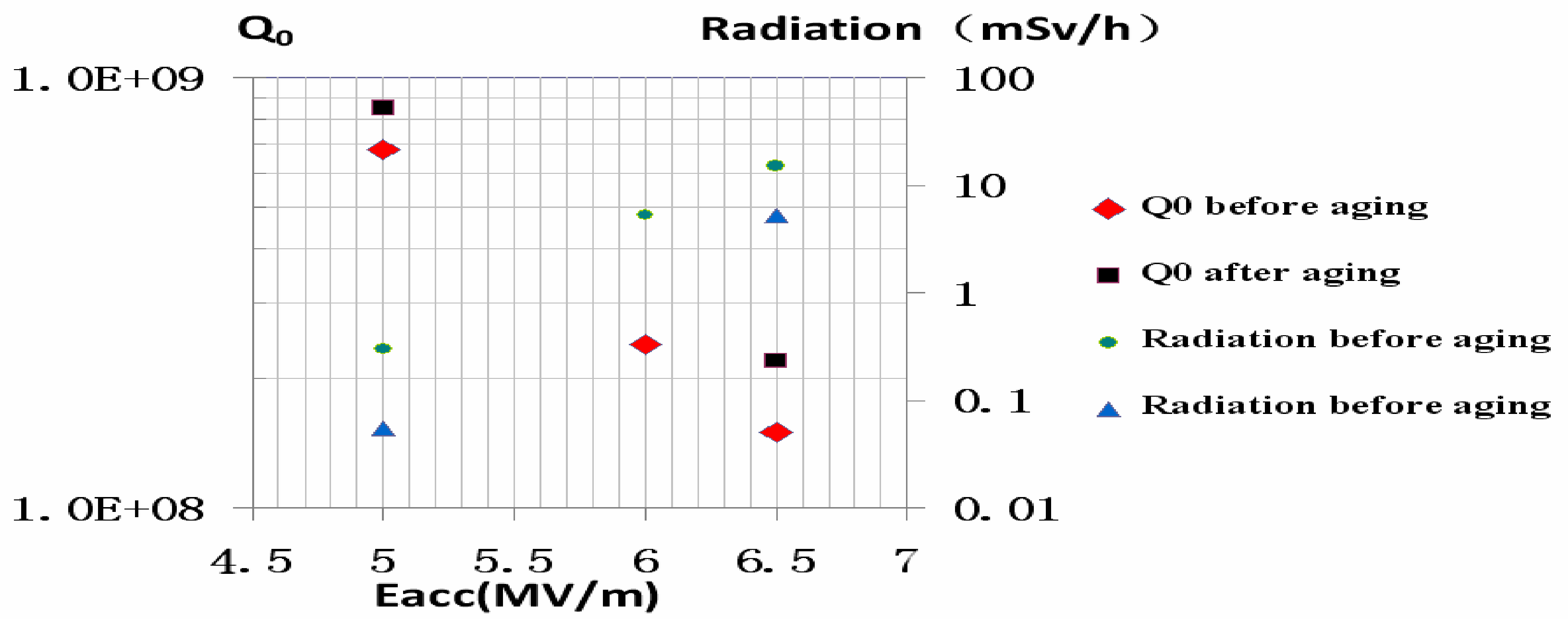
df/dp =10Hz/mbar

Vertical test result of Spoke012



✓Q0=5.8x10^8 @6MV/m, 4K; Q0=3.4x10^8 @7MV/m, 4K

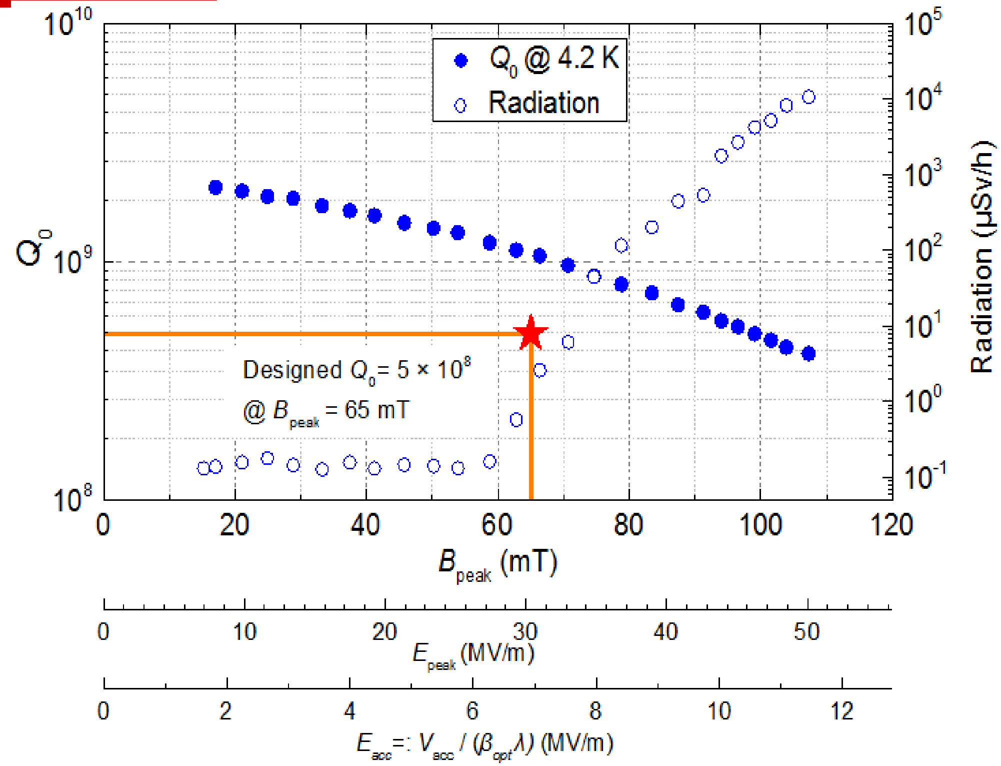
Horizontal test result on Sept. 12, 2013 ——the first horizontal test for the low beta proton SC cavity



✓Q0=2.2x10^8 @6.5MV/m, 4K; Q0=8.5x10^8@5MV/m, 4K.

4）Spoke021 Cavity (β=0.21) of Main Linac

Para.	Value
E_p/E_{acc} /(void)	4.38
H_p/E_{acc} /mT/(MV/m)	9.37
β_{opt}	0.243
Gap=c*β_{opt} /f (mm)	224
r/Q /Ω	191
G /Ω	71

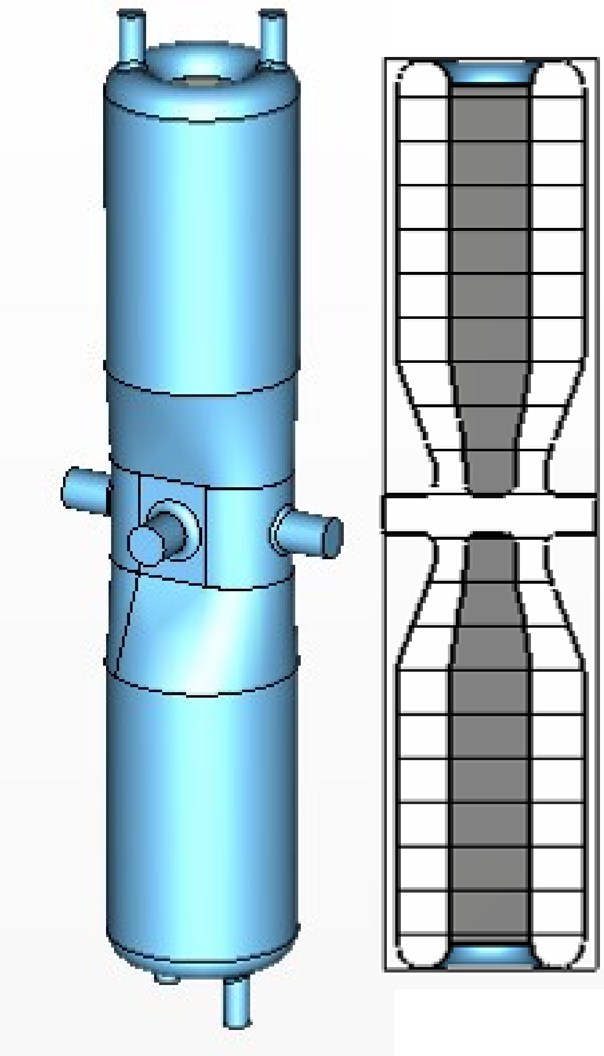


✓V-T：Bp=98 /mT，Q0=5e8；Max. Bp=107 /mT

5）Elliptical Cavity (β=0.63 & 0.83) of Main Linac

650MHz(preparing for test)


6） HWRs for Injector II

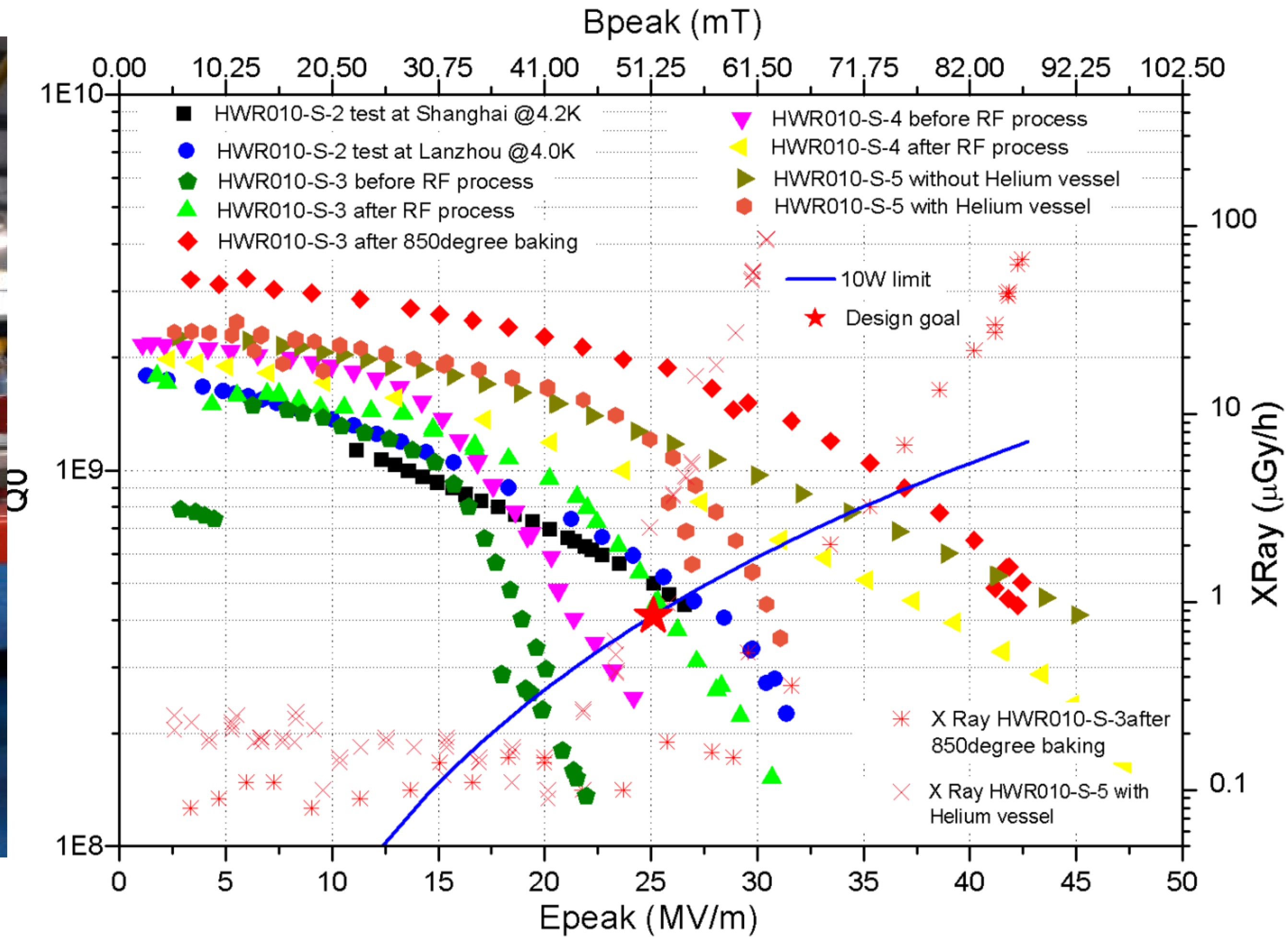


f (MHz)	162.5
β_{opt}	0.101
Epeak / Eacc	5.9
Bpeak / Eacc	12.1
G = Rs×Q0 (Ω)	28.4
R / Q0	153
Q0 (4.4K, Rs=71.4 nΩ)	4E8
Vacc (MV)	0.78
Epeak (MV/m)	25
Bpeak (mT)	50
Pdiss(W) (4.4K, Rs=71.4nΩ)	10

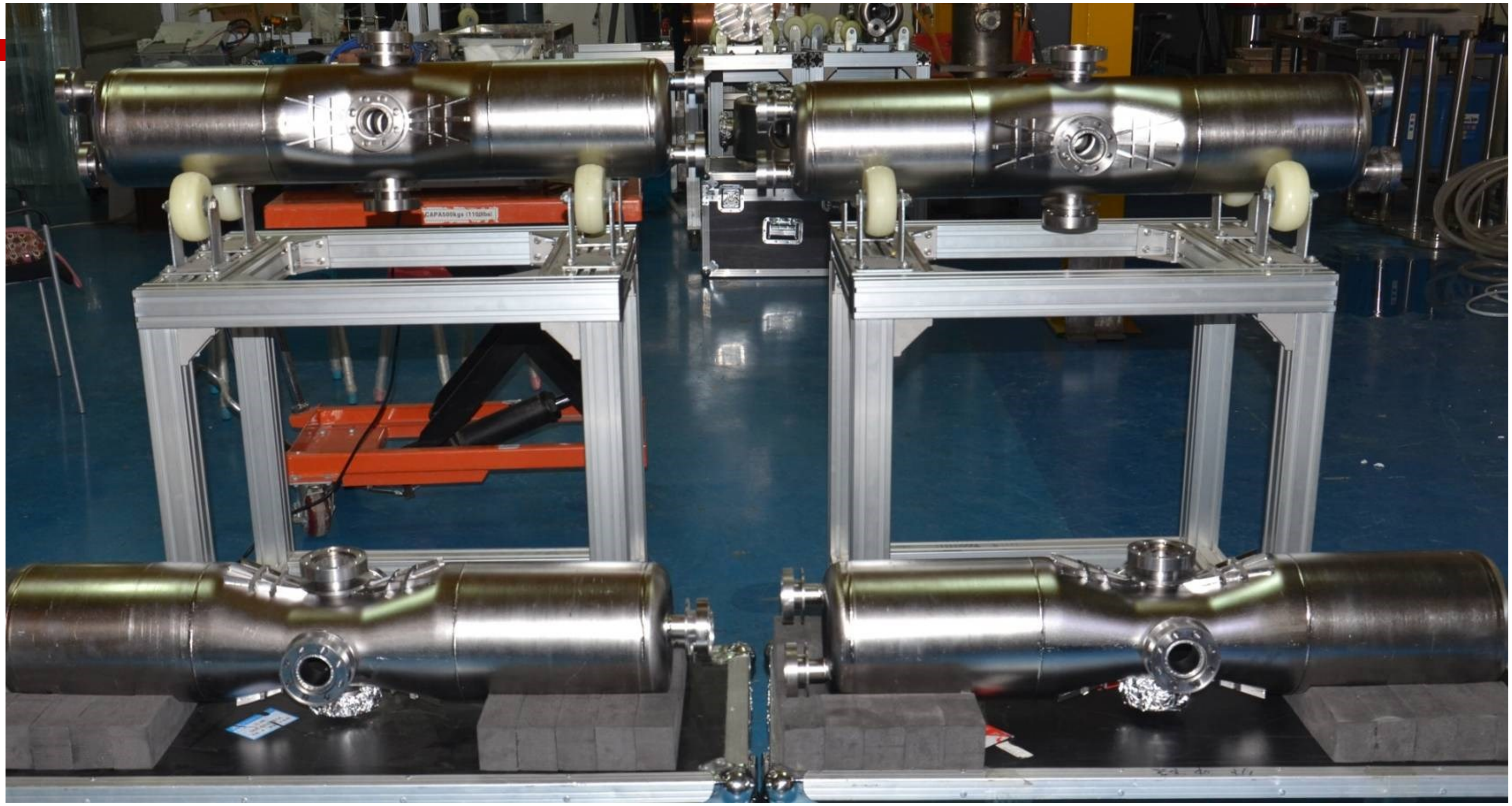
※ $E_{acc} = V_{acc} / (\beta_{opt} \times \lambda)$

VT results of HWR

df/dp =10Hz/mbar



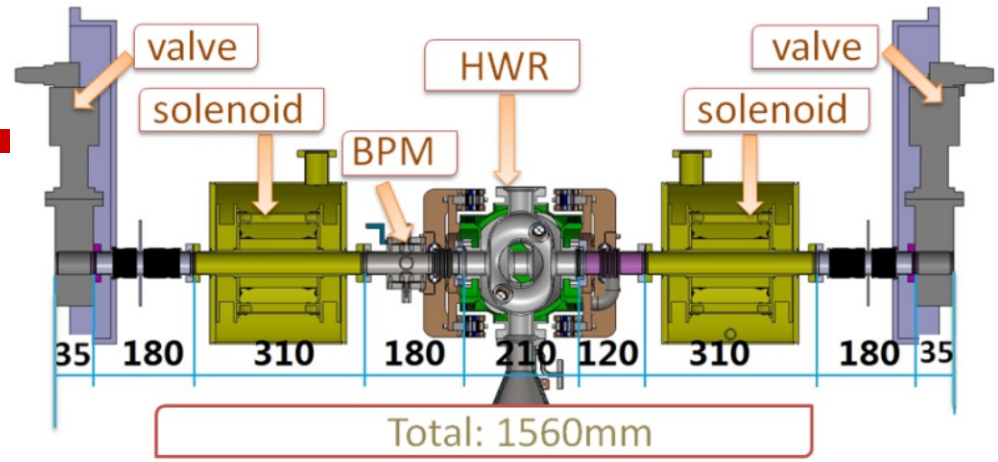
#03~#05 have been qualified and #05 has been jacked and put into TCM1



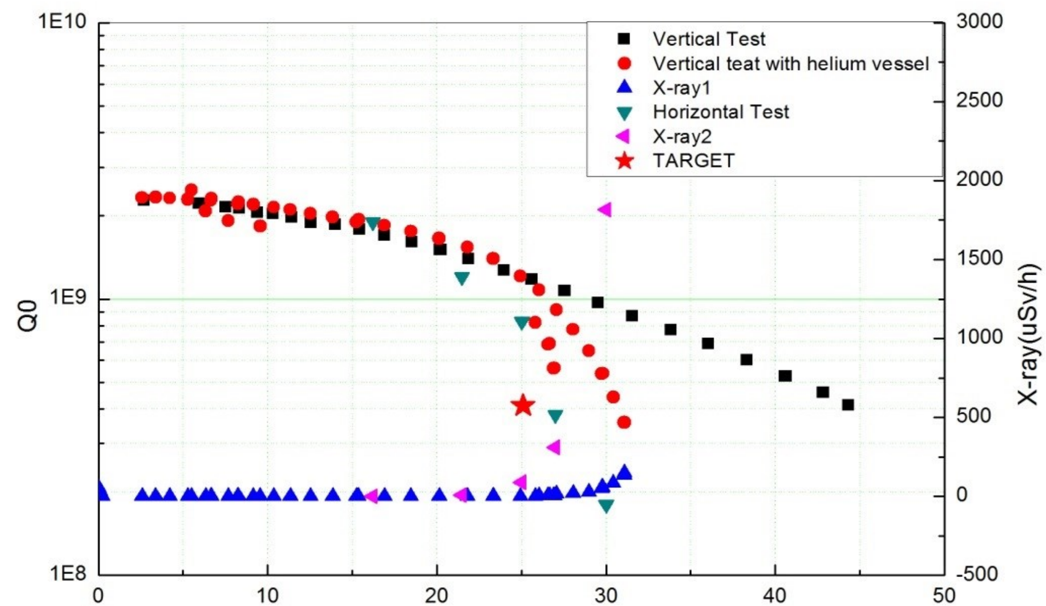
Four HWRs with ribs on both surfaces has been fabricated

Horizontal Testing for HWR

Op. Temperature	4.4 K
Op. Pressure	1.25 bar
Cooling	bath
Pressure	±1.5 mbar
Dynamic load	10 W
Solenoid storage	27KJ



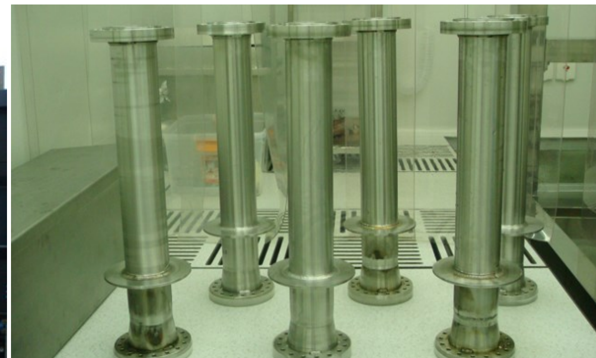
finished



Epeak vs Q0 from VT to HT

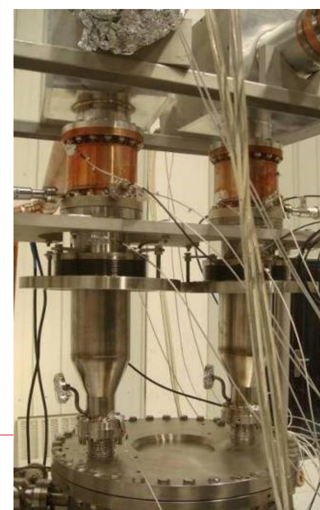
7）High Power Input Couplers for Injector I &II

Spoke cavity couplers tested over 10 kW CW power,
one operated in spoke012 cavity horizontal test.



coupler operated with cavity

RFQ coupler's windows tested up to 100 kW CW power.



HWR couplers tested over 20 kW CW, and put into HT of HWR .

8） Cryogenic Station (850 W at 4.5 K)

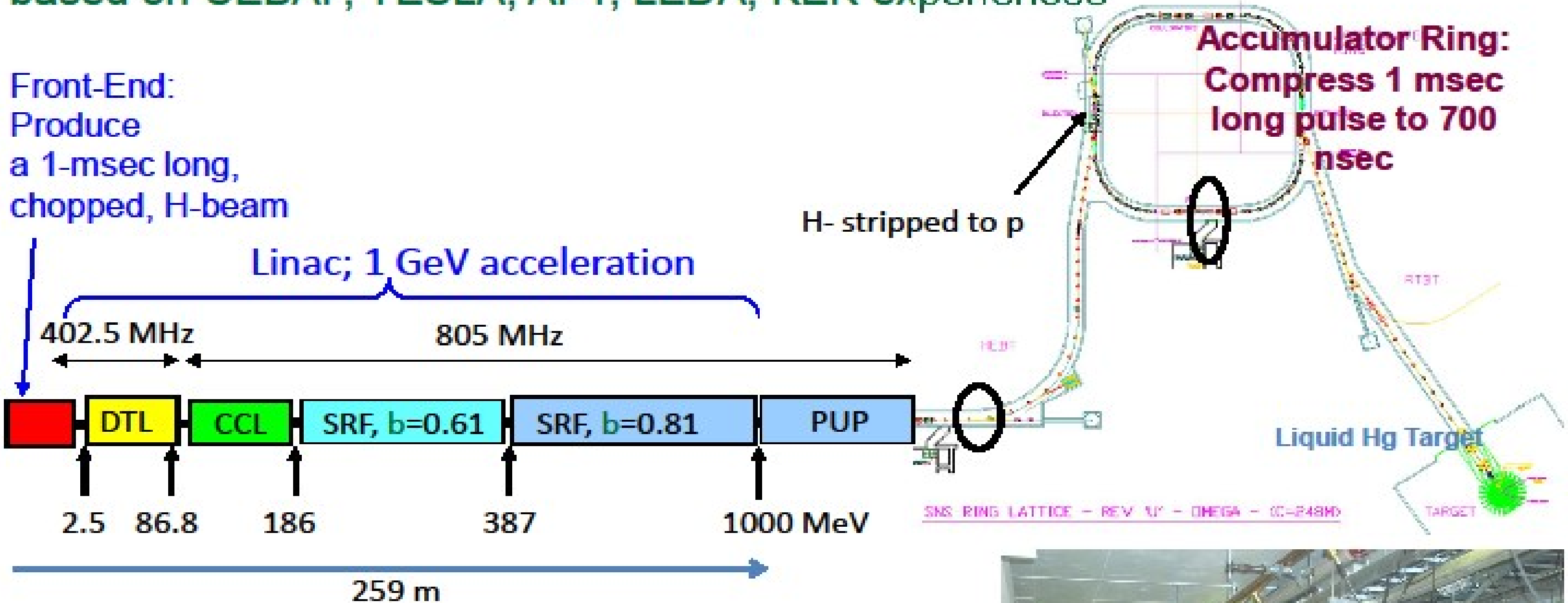
Helium Recovery System putting into operation

Other International ADS Programs?

IAEA reported that 18 countries are performing ADS R&D

Also, there are many similar accelerator technologies (as ADS) used for other purposes.

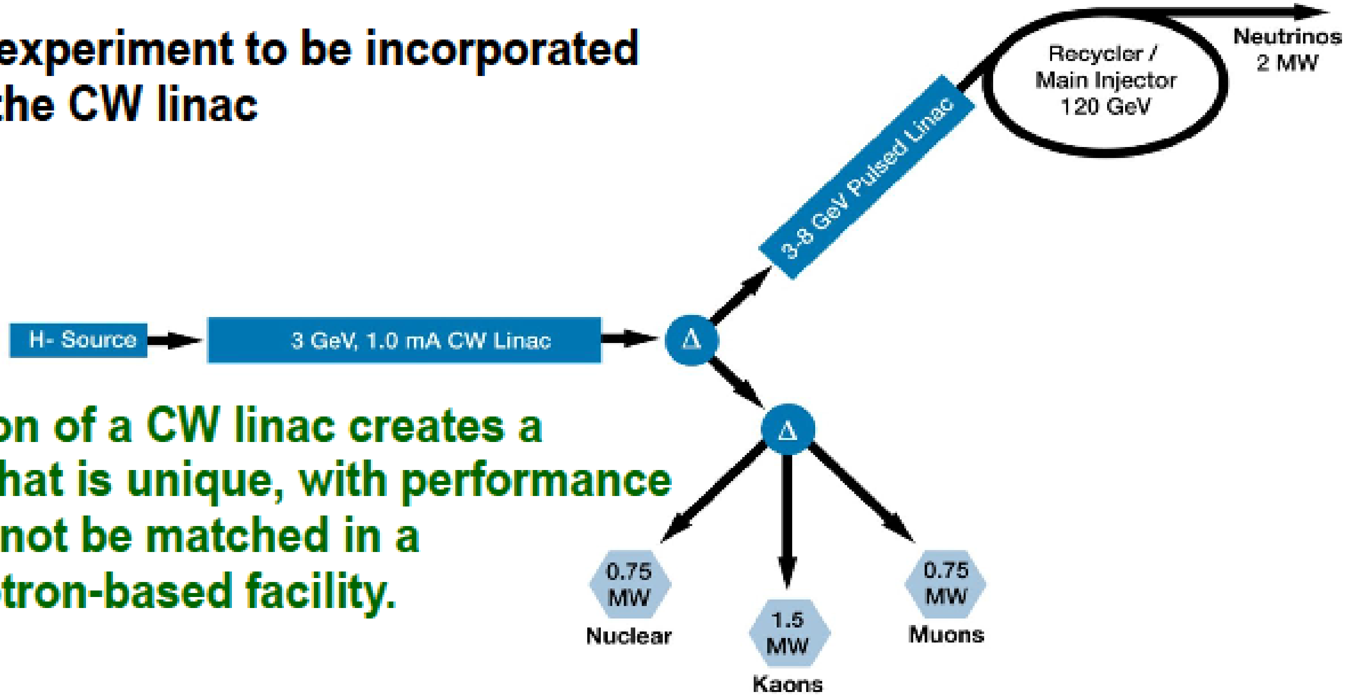
SNS SCL many parts, equipment, design are based on CEBAF, TESLA, APT, LEDA, KEK experiences



- **Most powerful spallation neutron source**
- **259-m long linac + accumulator**
- **Short pulse**
- **71-m long Space is reserved for additional cryomodules to give 1.3 GeV**

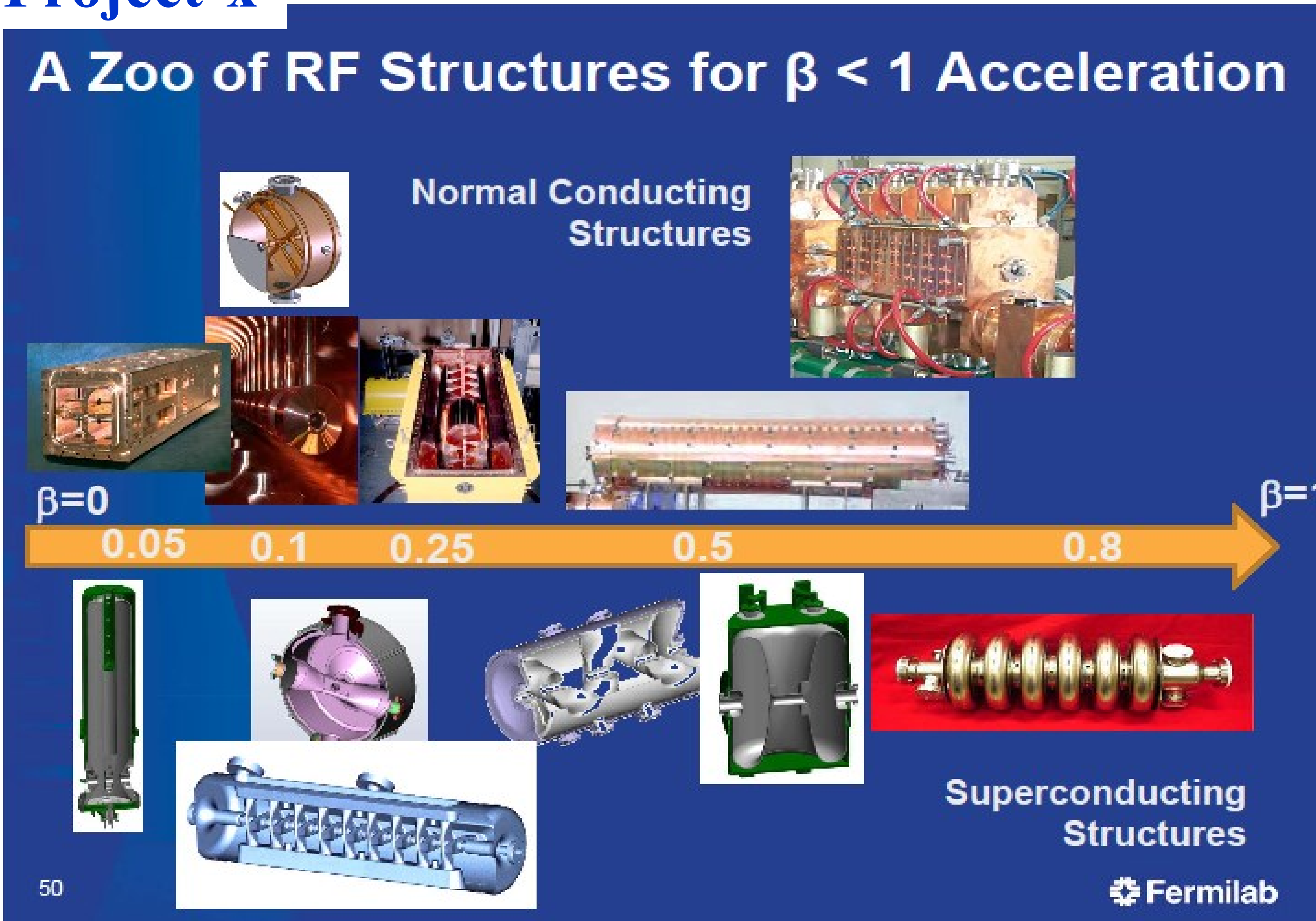
Project-X (Courtesy of S. Nagaitsev)

- **3 GeV CW superconducting H- linac with 1 mA average beam current.**
- **3-8 GeV pulsed linac capable of delivering 300 kW at 8 GeV**
- **Upgrades to the Recycler and Main Injector to provide ≥ 2 MW to the neutrino production target at 60-120 GeV.**
- **Day one experiment to be incorporated utilizing the CW linac**



⇒ **Utilization of a CW linac creates a facility that is unique, with performance that cannot be matched in a synchrotron-based facility.**

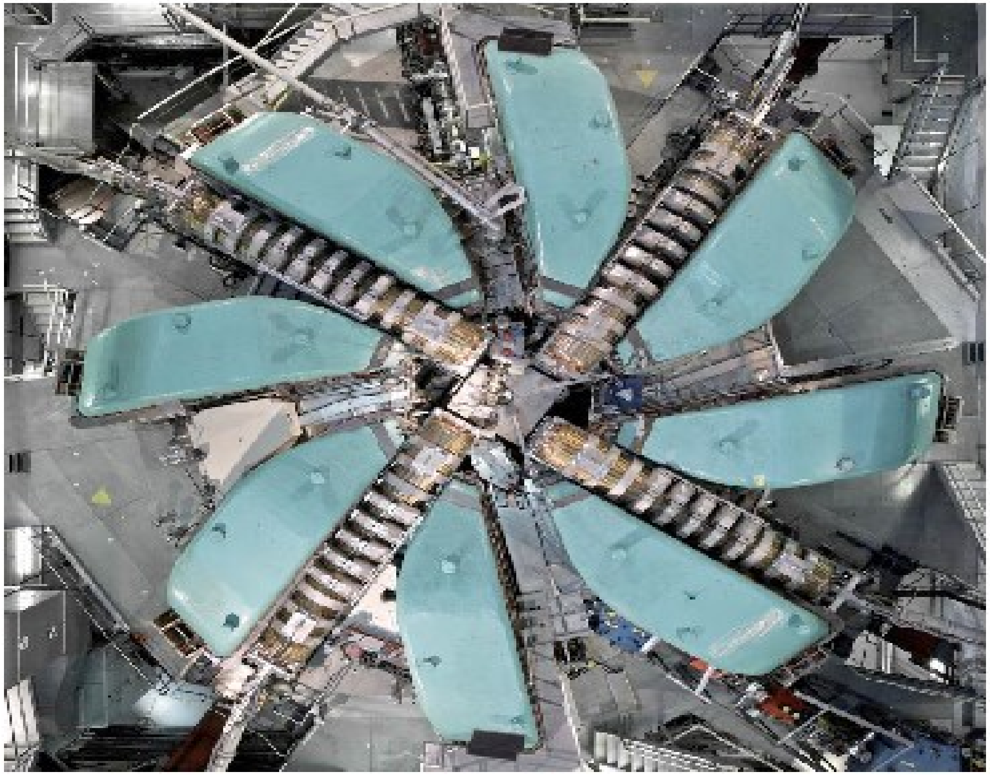
Project-x


A Zoo of RF Structures for β < 1 Acceleration
Normal Conducting Structures
β=0
β=1
0.05
0.1
0.25
0.5
0.8
Superconducting Structures
50
Fermilab

PSI

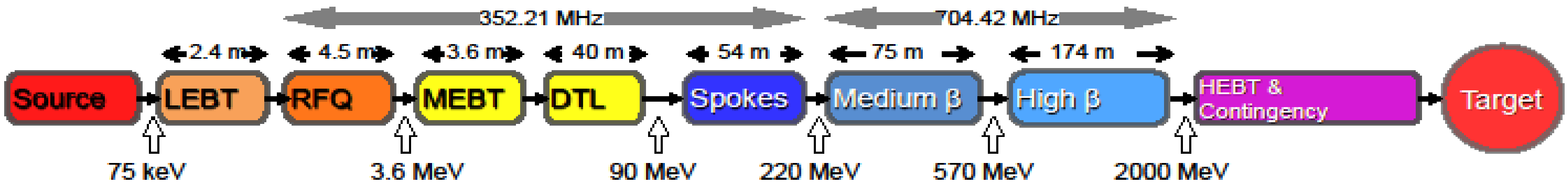
PSI Ring Cyclotron

8 Sector Magnets:	1 T
Magnet weight:	~280 tons
4 Accelerator Cavities:	860 kV (1.2 MV)
1 Flat-Top Resonator	150 MHz
Accelerator frequency:	50.63 MHz
harmonic number:	6
kinetic beam energy:	72 → 590 MeV
beam current max.:	2.4 mA
extraction orbit radius:	4.5 m
outer diameter:	15 m
RF efficiency Grid/Beam	0.90×0.64×0.55 = 32%
rel. losses @ 2.2mA:	-~1..2·10^{-4}
transmitted power:	0.32 MW/Res.



ESS

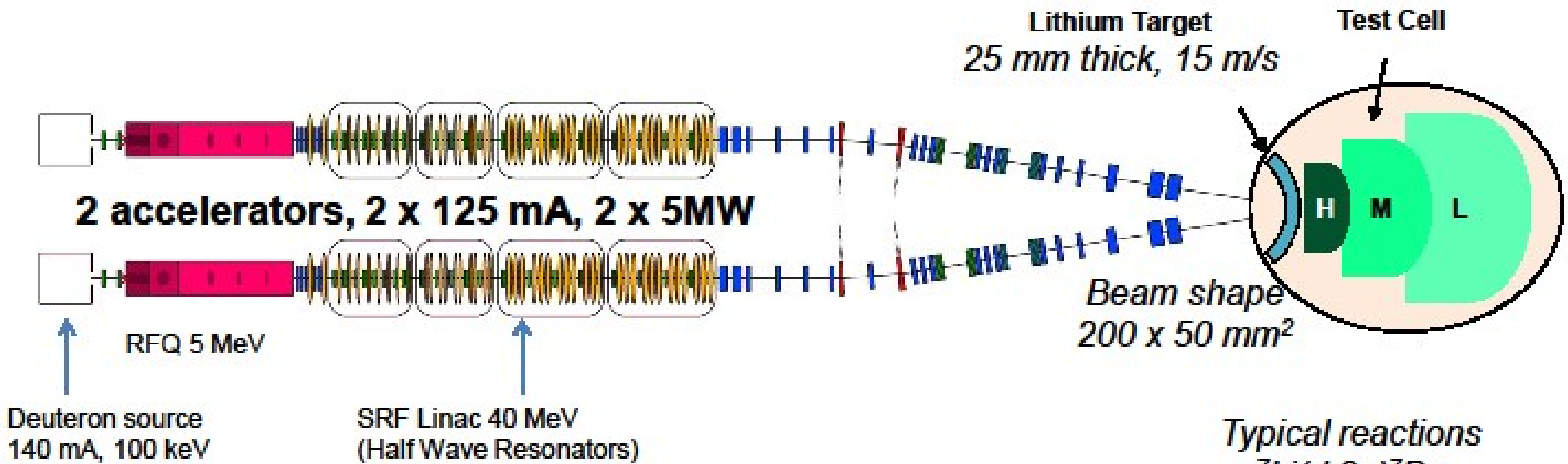
ESS Linac



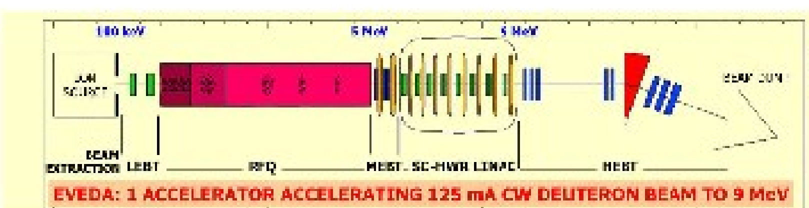
	Energy (MeV)	No. of Modules	No. of Cavities	βg	Temp (K)	Cryo Length (m)
Source	0.075	1	0	–	~300	–
LEBT	0.075	–	0	–	~300	–
RFQ	3.6	1	1	–	~300	–
MEBT	3.6	–	3	–	~300	–
DTL	90	5	5	–	~300	–
Spoke	220	13	2 (2S) × 13	0.5 β_{opt}	~2	4.28
Medium β	570	9	4 (6C) × 9	0.67	~2	8.52
High β	2000	21	4 (5C) × 21	0.86	~2	8.52
HEBT	2000	–	0	–	~300	–

IFMIF

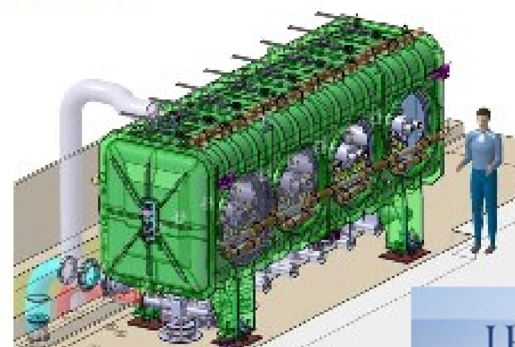
High >20 dpa/hr, 0.5 L
Medium > 1 dpa/hr, 6 L
Low < 1 dpa/hr, > 8 L



Typical reactions
$^{7}Li(d,2n)^{7}Be$
$^{6}Li(d,n)^{7}Be$
$^{6}Li(n,T)^{4}He$



IFMIF/EVEDA Prototype Accelerator



Cryomodule under construction for the accelerator prototype
The first one of the IFMIF SRF Lianc~5 m Long
4.5 MV/m, reliability, limits the coupler power
Large beam aperture 40-48 mm
Qex=6.3e4

23 Managed by UT-Battelle for the Department of Energy
ICABU11, Sep. 29-30, Gyeongju, South Korea

SPL

Linac4: Block diagram

H-	RFQ	CHOPPER	DTL	CCDTL	PIMS
45keV	3MeV		3MeV → 50MeV	50MeV → 103MeV	103MeV → 160MeV
RF volume source (DESY) 45 kV Extrac.	Radio Frequency Quadrupole 3 m 1 Klystron 550 kW	Chopper & Bunchers 3.6 m 11 EMquad 3 cavities	Drift Tube Linac 18.7 m 3 tanks 1+2 klystrons 4.7 MW 111 PMQs	Cell-Coupled Drift Tube Linac 25 m 21 tanks 7 klystrons 7 MW 21 EMQuads	Pi-Mode Structure 22 m 12 tanks 4+4 klystrons ~12 MW 12 EMQuads

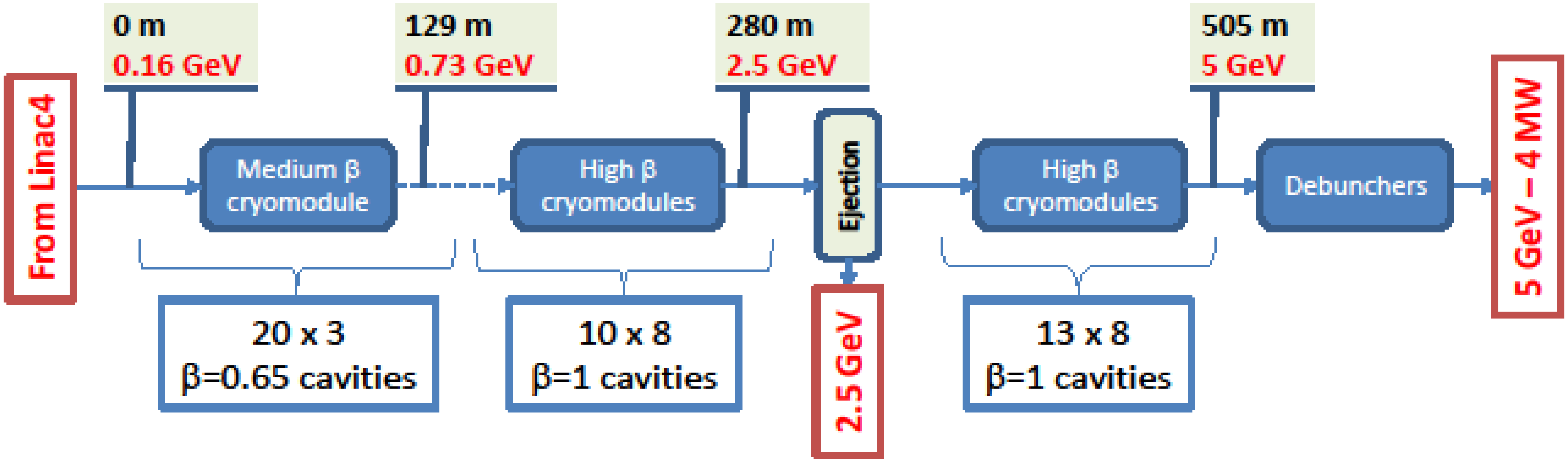
H^- ion current:
40 mA (avg.),
65 mA (peak)

Length: 80 m
19 klystrons [13 x 1.3 MW (LEP), 6 x 2.8 MW (new)]
Normal conducting accelerating structures of 4 types: RFQ, DTL, CCDTL, PIMS
Single frequency: 352.2 MHz
Duty cycle: 0.1% phase 1 (Linac4), 3-4% phase 2 (SPL), (design: 10%)

SPL

SPL block diagram

- SC-linac [160 MeV ® 5 GeV] with ejection at intermediate energy



- Medium beta cavities: β = 0.65
- High beta cavities: β = 1

Length: ~500 m

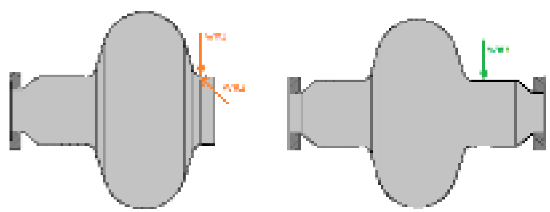
"New" TDR to be published during Q2/2014

SPL

Niobium cavities at CERN

REPAIR OF FIRST MONOCELL

Material defects observed after electro-polishing.
Repaired with new e-beam welding machine from outside (W#1 and W#3) and inside (W#2)

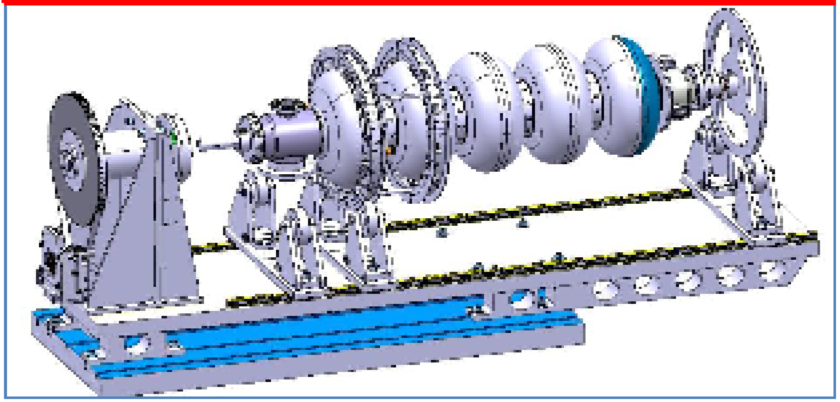


CAVITY FABRICATION AT CERN

Half-cells and beam tubes fabricated by spinning.

RF measurements.

Tooling for EB welding of Nb cavity is fabricated.



SARAF

SARAF-PHASE 2 LINAC DESIGN

Particles : deuterons and protons
Input energy : 20 keV/u
Input emittance (rms, norm.) : 0.2 pi.mm.mrad
Output energy : 1.3 MeV/u
Emittance growth < 25%
Time structure : pulsed and cw
Beam current : 0.04 – 5 mA
Beam losses :
< 150 nA/m for E < 5 MeV (0.4-0.75 W/m)
< 40 nA/m 10 MeV (0.2-0.4 W/m)
< 5 nA/m 20 MeV (0.05-0.1 W/m)
< 1 nA/m > 20 MeV (0.02-0.04 W/m)
<< 1 W/m !!!

Summary to ADS accelerators

1. The ADS program is to speed up from the basic study to the real facility.
2. The key technologies in high power proton accelerator are severe challenges for us.
3. Many good technologies have been developed, e.g. SNS demonstrated <1 W/m beam loss in MW-class pulsed accelerator: Could go higher power; SRF became a choice especially for high power and high duty factor machines
4. There are many common interests in the high power proton acceleration technology for the labs involved in proton accelerator. Close international cooperation is very important and expected.

I 'm sorry for uncovering all ADS plans probably.

Thanks for your attentions!

Accelerator architectures for high power

- **Linear accelerator only (long pulse beam, pulsed or CW) – LANSCE, PEFP, ESS, Project X driver, IMFIF, FRIB, SNS-STS，China ADS**
- **Linear accelerator + accumulator (short pulse, pulsed)**
  SNS, PSR/LANL，CSNS
- **Lower energy linear accelerator + RCS (short pulse, pulsed） ISIS, J-PARC, CSNS**
- **Circular accelerator: Cyclotron (or FFAG) (long pulse, CW)**
  PSI, (future FFAG in somewhere）

For Injector I:

Emittance (RMS) at entrance of MEBT1：
0.198 / 0.199 / 0.159 pi.mm.mrad（ x / y / z ）
10MeV：3.4% /3.0% /5.0% （no error case）
（ x / y / z ）