Superconducting Linacs Development for Current and Future Russian Accelerator Projects: Progress and Problems

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[2]Joint Institute for Nuclear Research,
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[6]TRIUMF, Vancouver, Canada

SUMMARY

- ***Actual projects of CW and high-power proton and ion linacs***
- ***Some examples***
- ***SC cavities: types and typical energy gains***
- ***Technological background in Russia***
- ***New Russian projects with SC cavities***
- ***Joint Dubna-Moscow-Minsk SRF activities***
- ***Conclusions***

Mainspring

Superconducting technology has been and will be **inevitable** to approach **any** energy/power frontier particle accelerators

Superconducting technology for accelerators

magnets | **accelerating structures (RF SC)**

Material	Tc [K]	B_{c1} [T]	B_{sh} [T]	B_{c2} [T]	applied for
Nb	9.2	**0.18**	**0.21**	0.28	SRF
NbTi	9.2	0.067	--	**11-14**	Magnet
Nb_3Sn	18.3	0.05	**0.43**	**28-30**	Mag./SRF
MgB_2	39	0.03	0.31	39	Link/Mag.
YBCO	92	0.01	--	100	Magnet
B-2212	94	0.025	--	>100	Magnet
B-2223	110	0.0135	--	> 100	Magnet

Nb → Pure (bulk) Nb cavities

Nb → Thin-layer sputtered Nb

Facilities

Project	Energy [GeV]	Field B/E	SC material	Operation [years]
SRF (hadron acc.):		[MV/m]		
SNS	1.25	15	Nb	2007 -
LHC	2x3500 ~2x7000	5	Nb/Cu	2009 -
FRIB	0.2/u	5~8	Nb	(2022)
ESS	2	9-20	Nb	(2023)
PIP-II	0.8	10-20	Nb	(2025)
FCC-hh	2x50,000	tbd	tbd	(study)
SppC	2x50000	tbd	tbd	(study)
SRF (lepton acc.):		[MV/m]		
CEBAF	6→12	5-12	Nb	1985 -
Tristan	2x30	5	Nb	1986-1995
LEP	2x105	5	Nb	1989-2000
HERA	27.5	n/a	Nb	1990-2007
KEKB	3.5+8	5	Nb	1998-2010
BEPC-II	2x1.89	5	Nb	2008 -
S-KEKB	4+7	5	Nb	2016 -
E-XFEL	14	24	Nb	2017 -
LCLS-II	4	16	Nb	(2020)
ILC	2x500	31.5	Nb	(plan)
FCC-ee	2x350	10-20	Nb/Cu	(study)
CEPC	2x240	5-20	tbd	(study)

SCM (hadron acc.):		[Tesla]		
Tevatron	2x980	4.0	NbTi	1983-2011
HERA	920	4.68	NbTi	1990-2007
RHIC	2x100	3.46	NbTi	2000 -
LHC	2x3500 ~2x7000	4.18 ~8.36	NbTi	2009 -
FAIR	29	1.9	NbTi	(2018)
HL-LHC	2x7000	11	Nb_3Sn	(2025)
HE-LHC	2x14000	16	Nb_3Sn	(study)
FCC-hh	2x5e4	16	Nb_3Sn	(study)
SppC	2x≥5e4	16-20	Nb3Sn/HTS	(study)

Akira Yamamoto, Proc. of IPAC2017 - MOYBA1

Facilities

Accelerating Chinese science

China is ramping up its capacity in accelerator physics with several machines nearing completion or coming online in the next decade. Particle physicists hope the buildup will climax with the Circular Electron Positron Collider.

FACILITY (LOCATION)	RESEARCH TARGET	COST	STATUS/SCHEDULE
China Spallation Neutron Source (Dongguan)	Materials science, physics, chemistry, and life sciences	$277 million	Opening to users in spring
Shanghai Soft X-ray Free-Electron Laser (FEL), Hard X-ray FEL (Shanghai)	Materials science and life sciences	$110 million	Soft x-ray FEL opening to users in mid-2019 Hard x-ray FEL online in 2025
High-Energy Photon Source (Beijing)	Materials science, chemistry, and biomedicine	$730 million	Mid-2025
China Initiative Accelerator Driven System (Huizhou)	Nuclear waste transmutation and future energy technologies	$280 million	2024
High-Intensity Heavy ion Accelerator Facility (Huizhou)	Atomic and nuclear physics	$240 million	2024
Circular Electron Positron Collider (site TBD)	Particle physics	$6 billion	Under study

D. Normile // *Science* 02 Feb 2018: Vol. 359, Issue 6375, pp. 507-508

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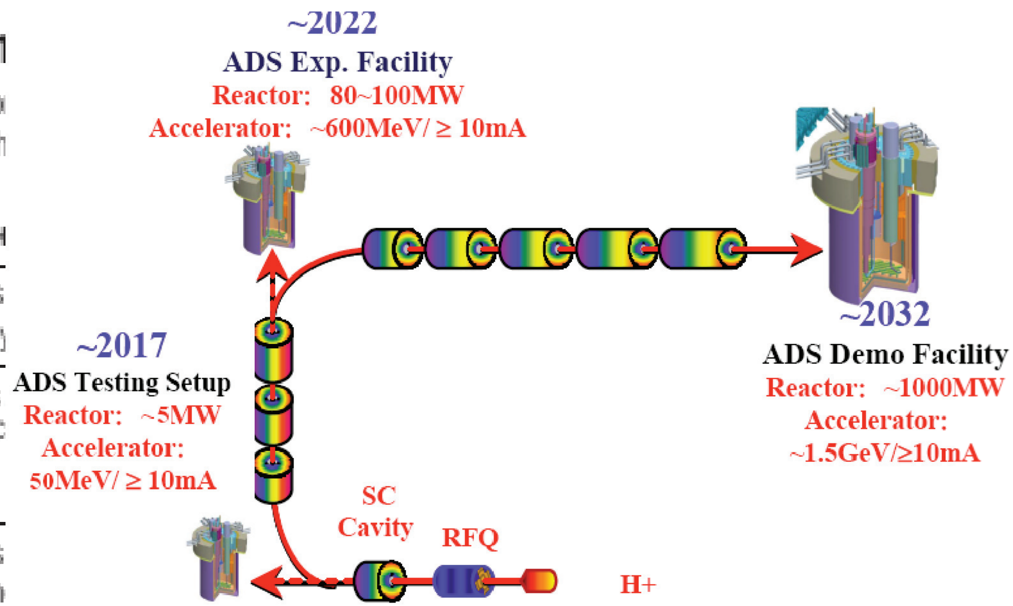
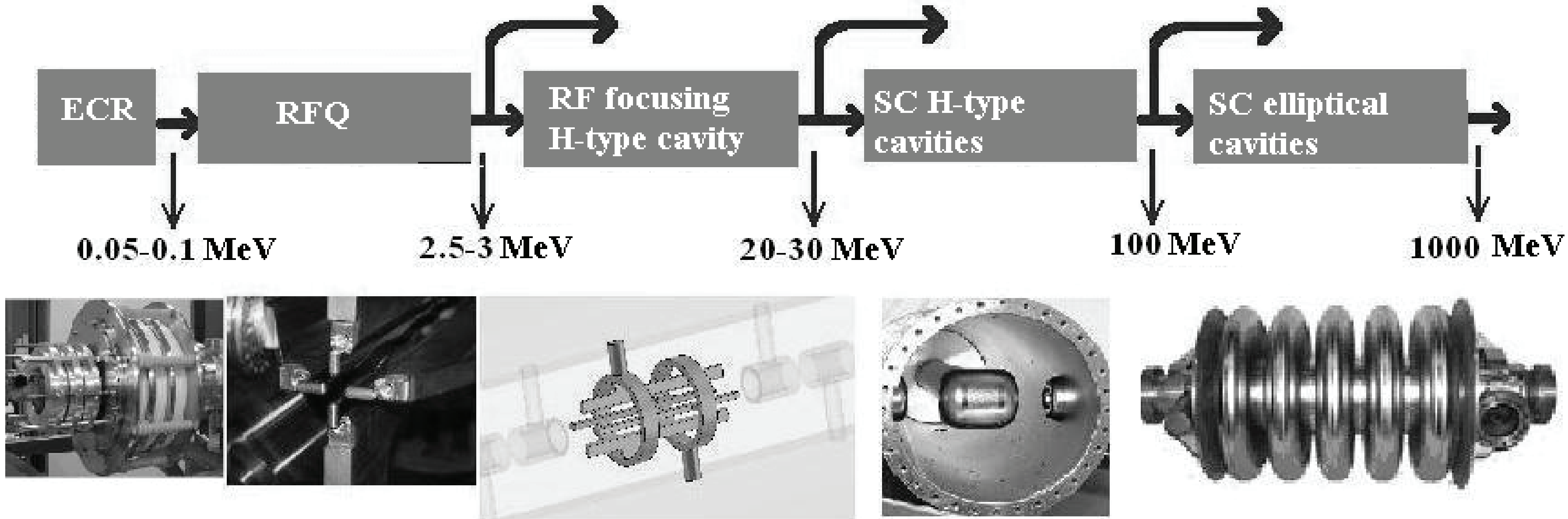
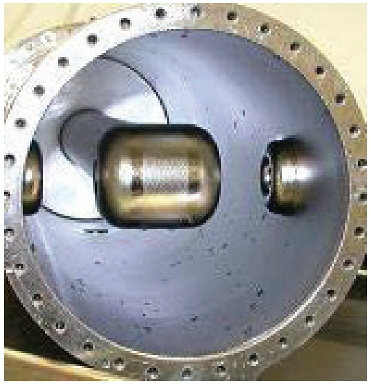


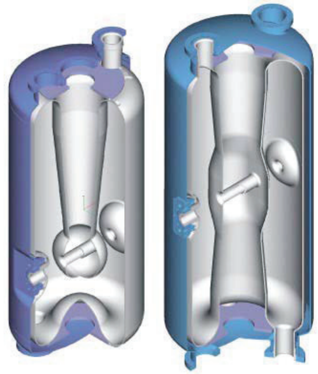
Conventional layout of high-energy proton/ion linac

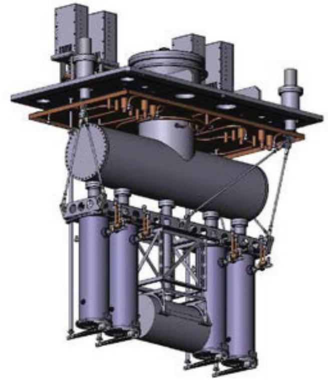


PIAVE SRFQ – first (and alone) superconducting RFQ, LNL INFN

SC cavities: types and typical energy gains

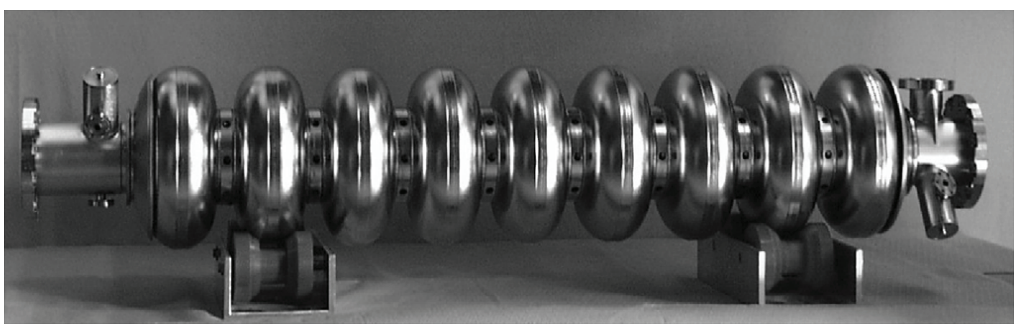






QWR and HWR β=0.01-0.17, 6-7 MV/m (LNF INFN+E.Zanon, TRIUMF+PAVAC, …, bulk Nb), 5-6 MV/m (LNF INFN, Nb/Cu)

CH, β=0.1, 5-7 MV/m (GSI, IAP FU, RI 325 and 360 MHz)



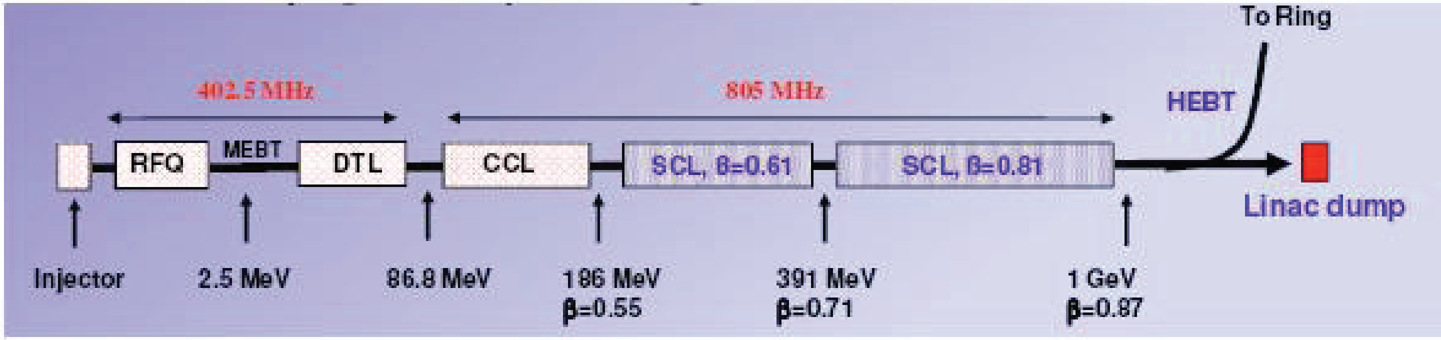
Elliptical cavities, β=0.5-1.0, up to 35 MV/m (1300 MHz, KEK, DESY, FNAL ...), 15-16 MV/m (704 MHz, ESS), 30-40 MV/m (800 MHz, LANL)

Spoke-cavity, β=0.1-0.25,
8 MV/m (ANL, 324 MHz)
12-16 MV/m (FNAL, 324 MHz),
15-18 MV/m (ESS, 325 MHz),
8 MV/m (JFZ, 700 MHz)

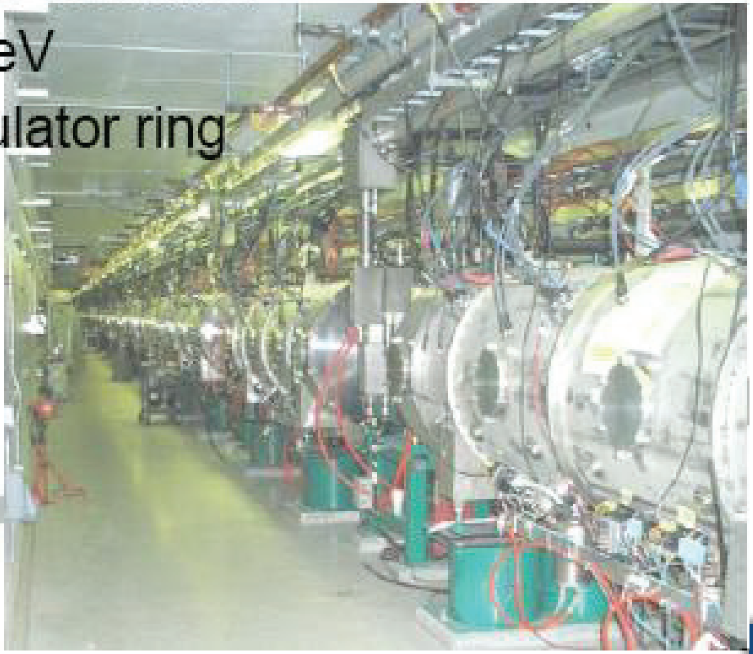
Some examples: Spallation neutron source SNS, ORNL, USA

- A short-pulse neutron source, driven by a 1.4 MW proton accelerator
- 1 GeV superconducting H^- linac
- Accumulator ring with ~1000 turn charge exchange injection
- 60 Hz rep. rate
- Operation started October 2006
- Now routinely operating at ~1 MW for almost 5000 hrs/yr, with 85% availability
- 13 neutron scattering instruments

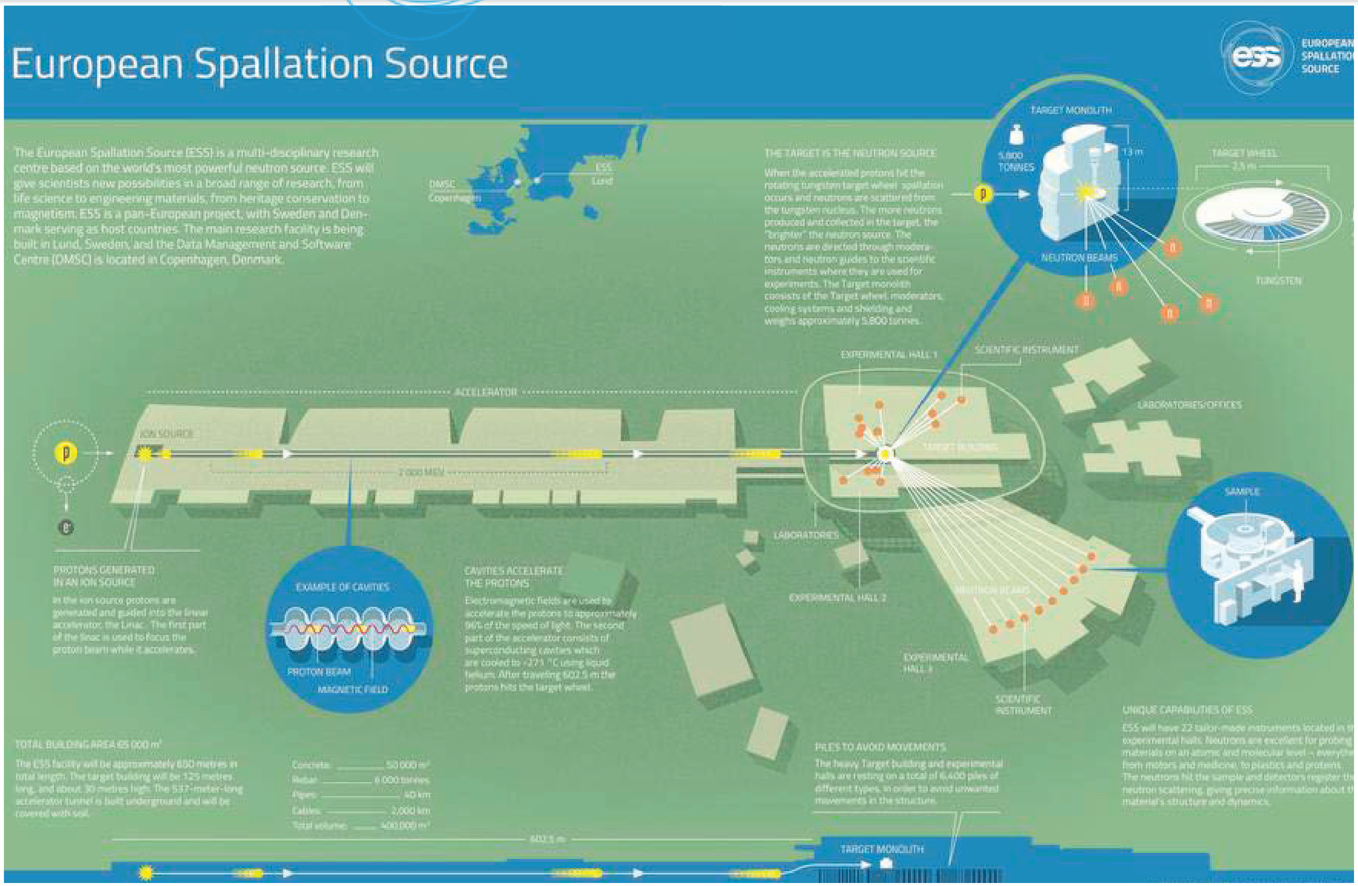
Some examples: Spallation neutron source SNS, ORNL, USA



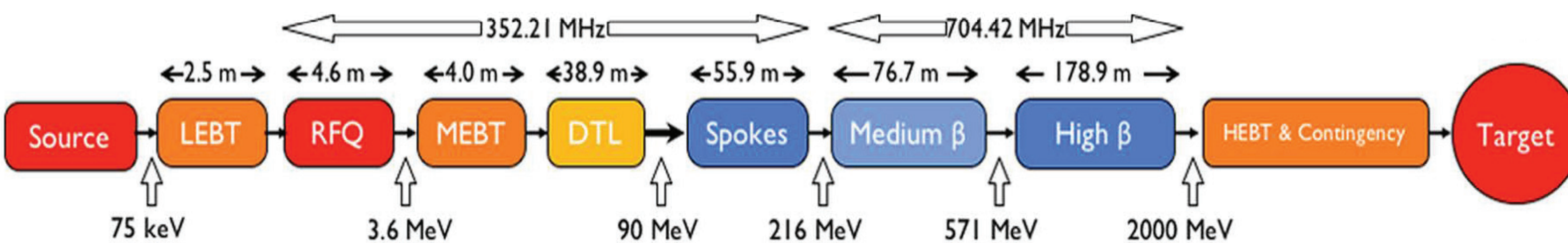
- Linac 260 m, 96 independently phased RF cavity/tanks
- Normal conducting from H^- ion source to 186 MeV
- Superconducting from 186 MeV to 1 GeV
- Charge exchange injection into accumulator ring



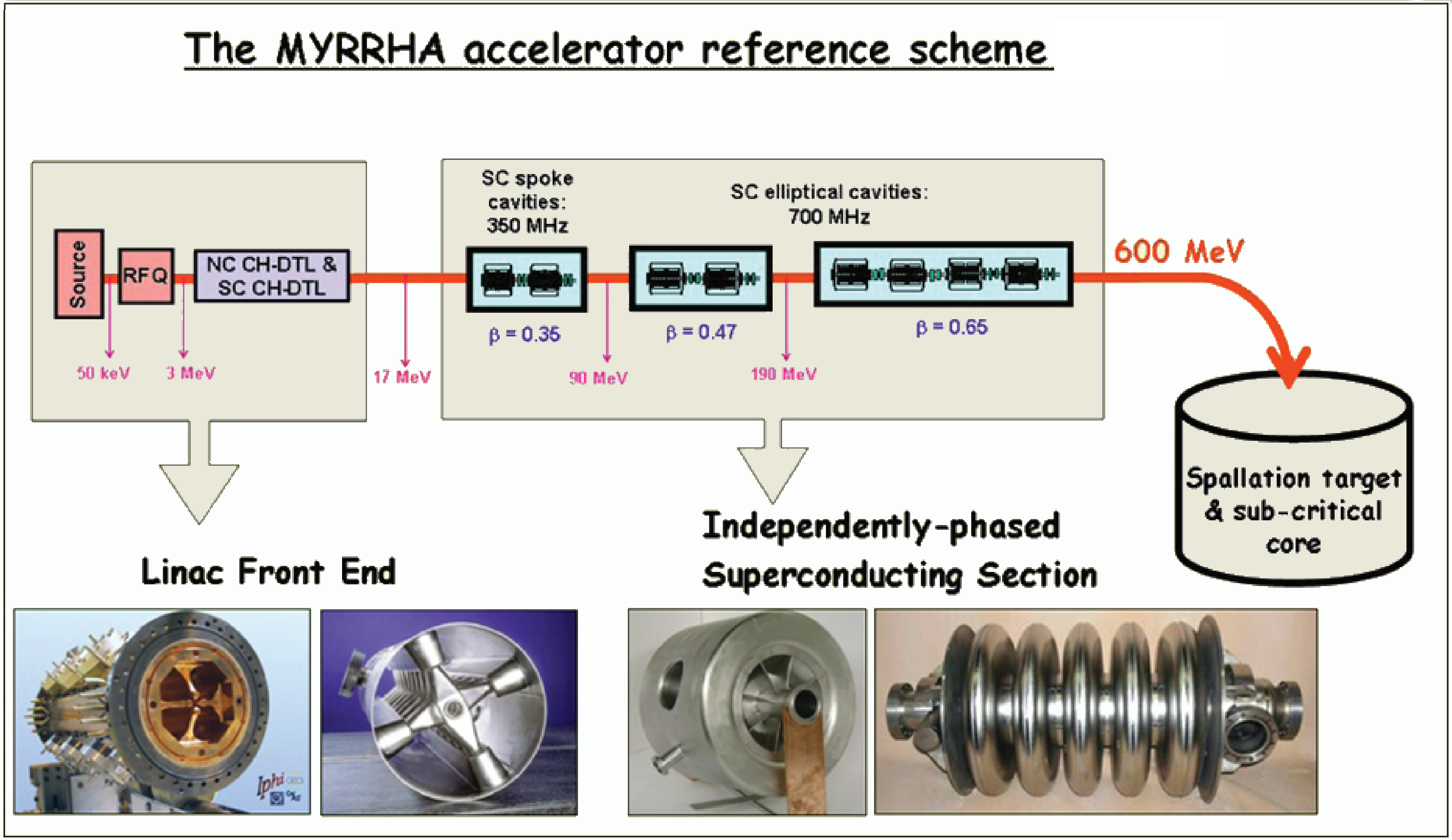
Some examples: ESS



started 2013
first beam 2019
compl. 2025

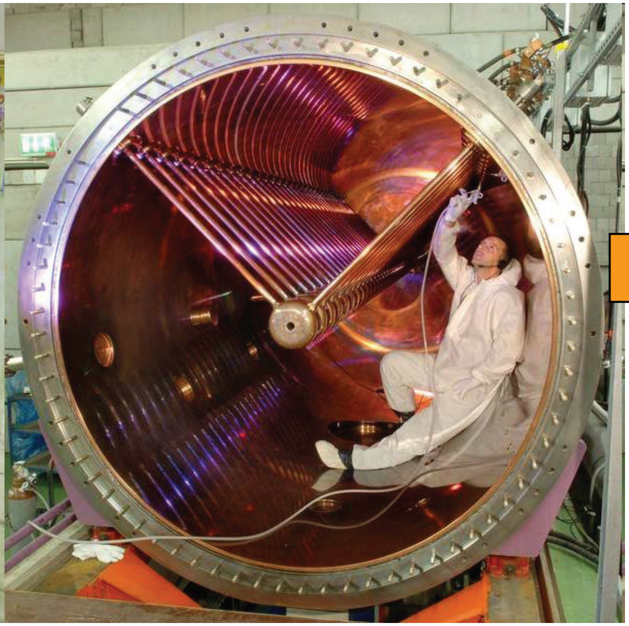


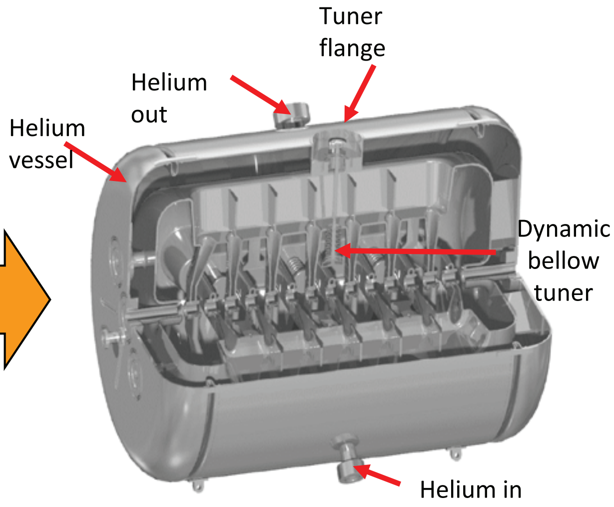
Some examples: MYRRHA



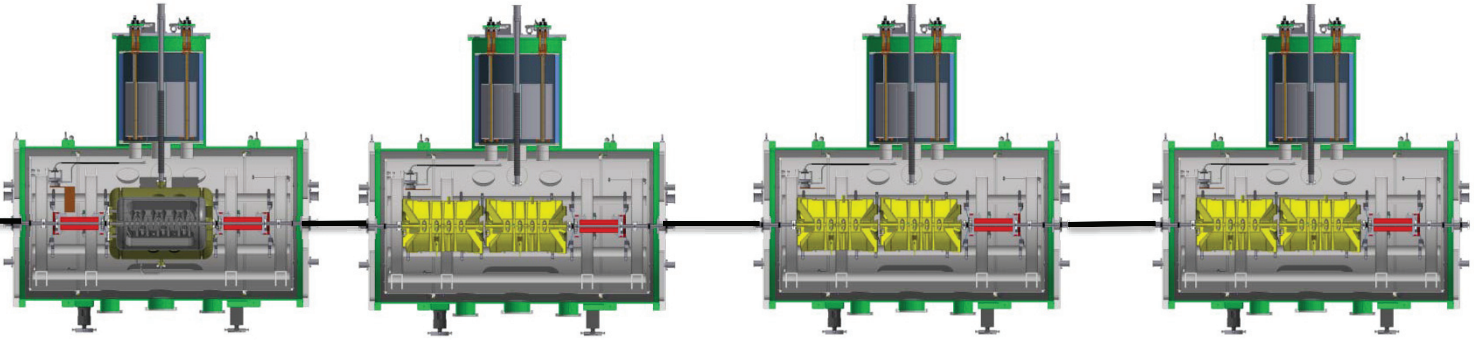
Belgian Nuclear Research Centre (SCK.CEN) proton beam: 600 MeV, 2.5 mA, Pb-Bi target, based on TRASCO (TRAsmutazione di SCOrie)

GSI CW-Linac





HLI injector@GSI A/q=6



Technological background in Russia

	Разработки	Опытные образцы	Серийная технология	Обладатели компетенций/ Участвующие в зарубежных проектах
Расчет динамики, проектирование	**да**	**да**	**да**	ИТЭФ, МИФИ, МРТИ
Источники ионов	**да**	**необходима доработка**	**нет**	ОИЯИ, ТРИНИТИ, ИТЭФ, ИСЭ
Импульсные нормально проводящие ускоряющие системы	**да**	**да**	**необходима доработка**	ИТЭФ, МИФИ, ИФВЭ, ОИЯИ, ИЯИ, ИЯФ
CW нормально проводящие ускоряющие системы	**нет**	**нет**	**нет**	- ИТЭФ, ИФВЭ, МИФИ, ИЯФ, ИЯИ,
СП ускоряющие системы	**нет**	**нет**	**нет**	- ИТЭФ, МИФИ, ИЯФ, ИЯИ ОИЯИ
Постоянные магниты	**да**	**да**	**нет**	ИЯФ, ИФВЭ, ОИЯИ,
СП магниты	**да**	**да**	**необходима доработка**	ИЯФ, ОИЯИ
Современные системы ВЧ питания	**необходима доработка**	**нет**	**нет**	-, ИТЭФ, МИФИ, ОИЯИ, ИЯФ
Системы транспортировки пучка	**да**	**да**	**необходима доработка**	ИТЭФ, МИФИ, ИФВЭ, МРТИ, ИЯИ, ИЯФ
Диагностика и управление пучком	**да**	**да**	**необходима доработка**	ИТЭФ, ИЯИ, ИЯФ

<table>
<tr><th>ECR proton/ion sources</th><th>Solid State RF sources for MHz and GHZ bands</th><th>1.5-3.0 MeV linacs</th><th>NC and SC linacs of 3-30 and 1-1.5 GeV</th></tr>
<tr><td>Compact sources for industrial ion sources</td><td></td><td></td><td></td></tr>
<tr><td>“Focused ion beam” facilities</td><td></td><td></td><td></td></tr>
<tr><td>Ion implanters</td><td></td><td></td><td></td></tr>
<tr><td></td><td>High-power SS for:
- accelerators
- Locators
- TV</td><td></td><td></td></tr>
<tr><td colspan="3">Compact “University class” sources of protons / ions / neutrons</td><td></td></tr>
<tr><td colspan="3">Astrophysics</td><td></td></tr>
<tr><td colspan="3">BNCT</td><td></td></tr>
<tr><td colspan="3">Compact high-flux neutron sources</td><td></td></tr>
<tr><td colspan="3">Activation analysis</td><td></td></tr>
<tr><td colspan="3">Material science studies (including reactor materials)</td><td></td></tr>
<tr><td colspan="3">Semiconductor devices with parameters, improved by irradiation</td><td></td></tr>
<tr><td colspan="3">Radioisotopes production</td><td></td></tr>
<tr><td colspan="3">SC linacs for proton / ion therapy (250 MeV for proton beam and 300-350 MeV/u for ions)</td><td></td></tr>
<tr><td colspan="3">Pulse 1 GeV driver linac for Spallation Neutron Source</td><td></td></tr>
<tr><td colspan="4">CW 1.0 – 1.5 MeV proton driver linac for Accelerator Driven System</td></tr>
</table>

Contemporary projects of CW and high-power proton and ion linacs

- **Accelerator Driven Systems (ADS)**
- EUROTRANS (*Europe*), OMEGA (Japan), TRASCO (*Italy*), C-ADS (*China*), ADSS (*India*), …
- **Spallation neutron sources**
- SNS (*US*), CSNS (*China*), ESS (*Sweden*),
- **Radioactive ion beams**
- FRIB (*USA*), RIKEN (*Japan*), SPIRAL2 (*France*), SPES (*Italy*), HIAF (*China*), RISP (Korea),…
- **Injectors and secondary beams (Neutrino/muon factories)**
- Linac4+SPL (*CERN*), Project-X (*US*), IDS-NF
- **Irradiation facilities**
- IFMIF (*Europe/US/Japan*) + EVEDA (*CEA*), FRANZ (*Germany*), SARAF (*Israel*)

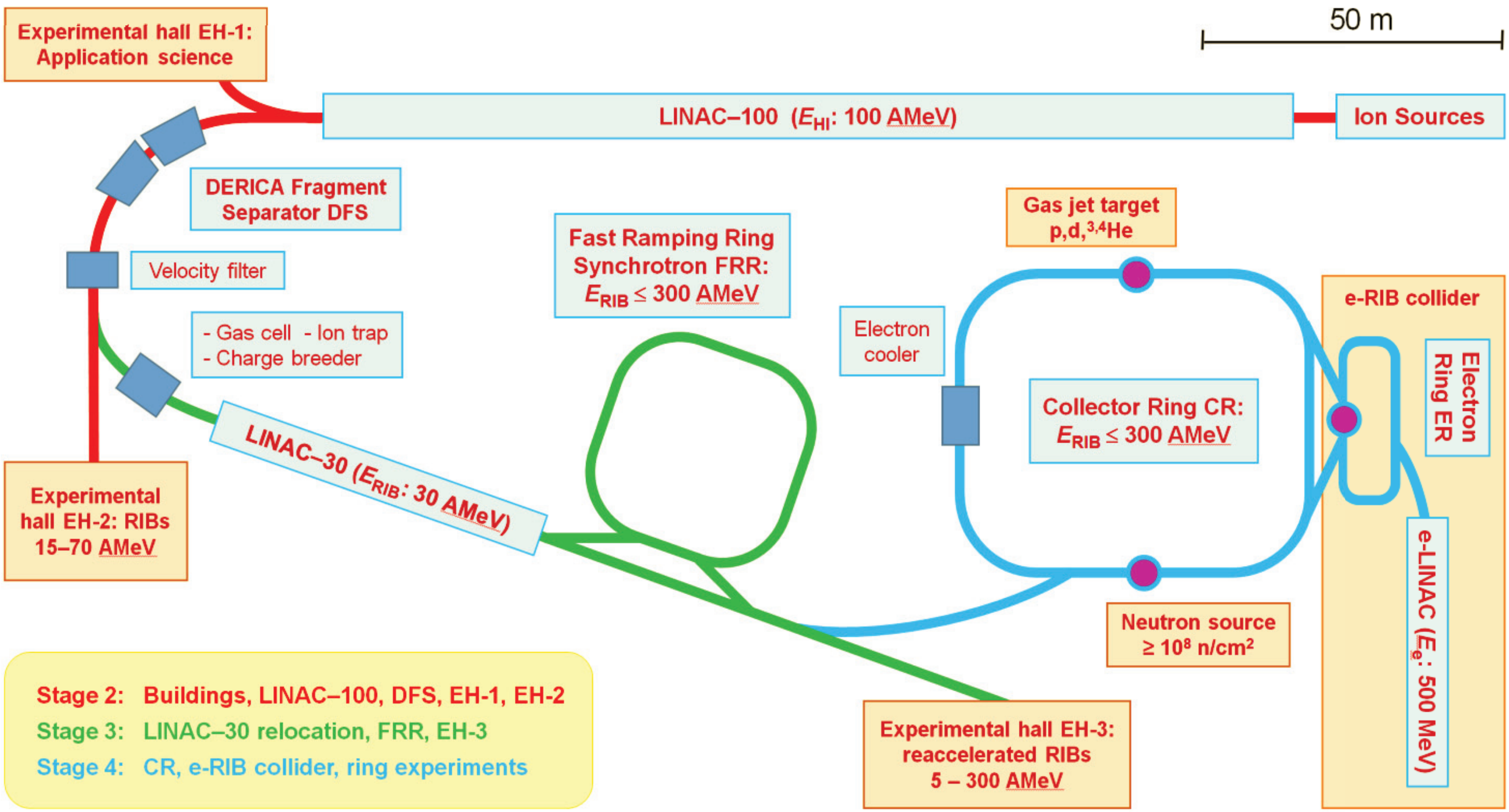
Contemporary projects of CW and high-power proton and ion linacs

- **Accelerator Driven Systems (ADS)**
- EUROTRANS (*Europe*), OMEGA (Japan), TRASCO (*Italy*), CADS (*China*), ADSS (India), … MEGAN-Upgrade (INR RAS)
- **Spallation neutron sources**
- SNS (*US*), CSNS (*China*), ESS (*Sweden*), NEPTUN (JINR)
- **Radioactive ion beams**
- FRIB (*USA*), RIKEN (*Japan*), SPIRAL2 (*France*), SPES (*Italy*), HIAF (China), RISP (Korea),…DERICA (JINR)
- **Injectors and secondary beams (Neutrino/muon factories)**
- Linac4+SPL (*CERN*), Project-X (*US*), IDS-NF, new SC injector for NICA
- **Irradiation facilities**
- IFMIF (*Europe/US/Japan*) + EVEDA (*CEA*), FRANZ (*Germany*), SARAF (*Israel*), BELA (NRC-KI ITEP), Multipurpose linac in Minsk

DERICA

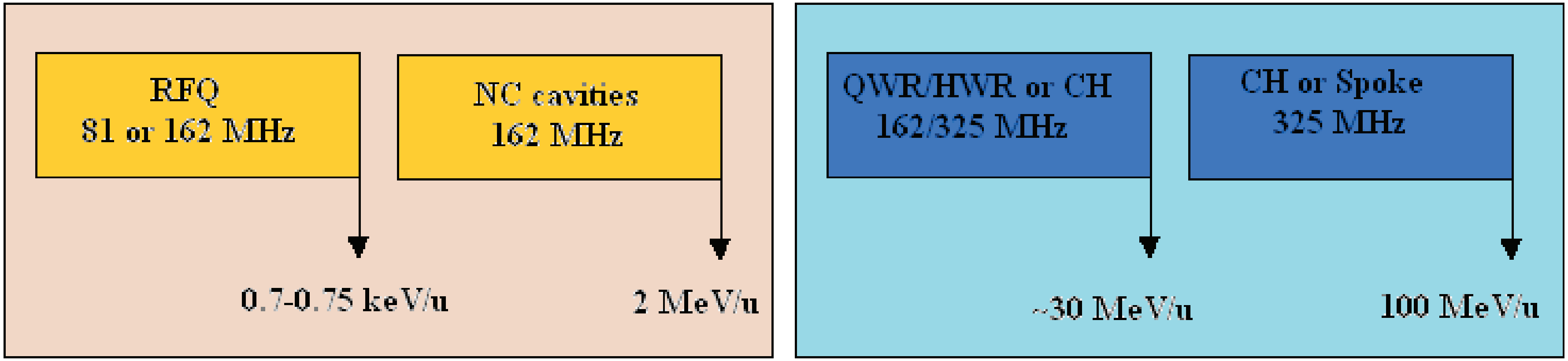
Dubna Electron – Radioactive Ion Collider fAcility –
project of RIB-factory for rp-process study

General layout



LINAC-100

initial layout and beam dynamics



First version of DERICA's driver LINAC-100 general layout

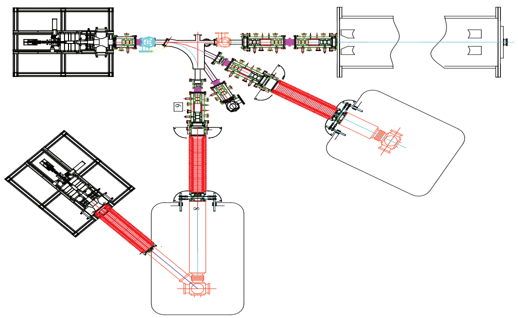
DNS-IV (Dubna Neutron Source of the IV Generation or Superbooster Neptun)

MEGAN-Upgrade

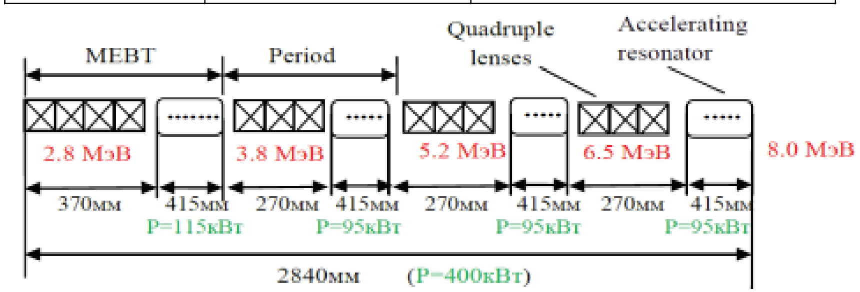
INR RAS -- discuss plan of MEGAN (MMF) upgrade by a SC linac

BELA: New “basic facility” for ITEP Center for LINAC based compact facility development for different applications, industry, medicine et cetera

Новый универсальный модульный ускоритель протонов в Беларуси



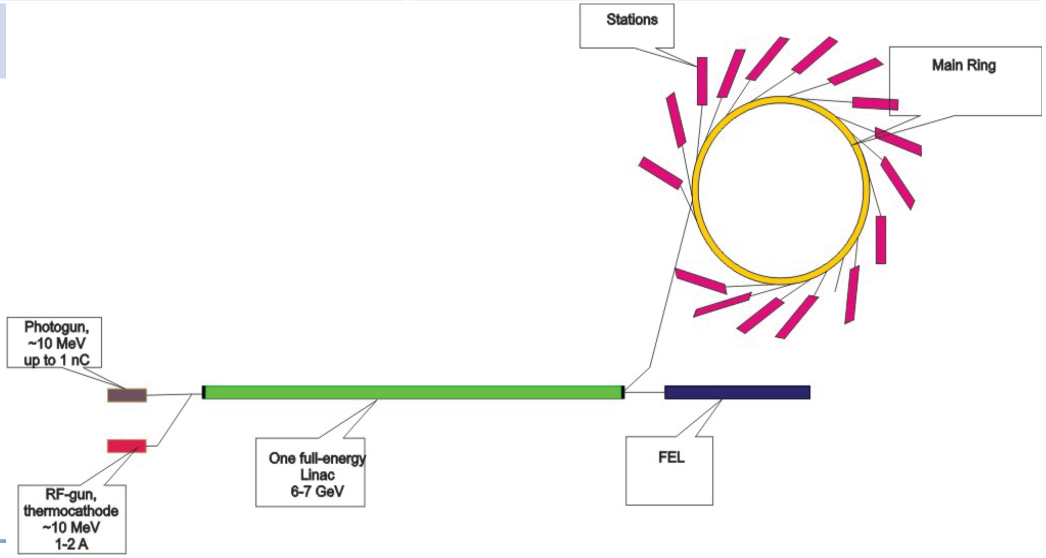
	Injection complex	RFQ	DTL
Ions	p - U	p	p
Currents, mA	0.01 - 20	10	10
Energy, MeV/n	up to 0.15	1.5 (3)	2/3/4/8...
Duty factor	dc	up to cw	
Frequency, MHz		148.5 (200)	



- p / D linac with energy of 20-25 MeV
- New electronic components (implantation and modification)
- Radiation studies of electronics
- Material sciences
- Compact neutron source

SSRS-4 Linac general concept

	injection in booster ring	injection in storage ring
Energy	~200 MeV	6 GeV
RF gun (s)	Thermionic+RF SW buncher 10 MeV	Thermionic+RF SW buncher Photo 10 MeV
Current	~ 400 mA	~ 400 mA
Linac operation mode	injector in booster ring	injector in storage ring provide beam for X-FEL



New collaboration for SRF technology development:

Joint Institute for Nuclear Research,
National Research Nuclear University – Moscow Engineering Physics Institute,
Institute of Theoretical and Experimental Physics of NRC "Kurchatov Institute",
Institute for Nuclear Problems, Belarusian State University
Physical-Technical Institute NASB
Belarus State University of Informatics and Radioelectronics
Scientific-Practical Materials Research Centre NASB

Joint Dubna-Moscow-Minsk SRF activities

Протокол
о намерениях

г. Дубна «17» июня 2016г.

Признавая актуальность и необходимость активизации усилий по научно-исследовательским и опытно-конструкторским работам, а также испытаниям и эксплуатации сверхпроводящих ускоряющих резонаторов для фундаментальной ядерной физики и инновационных исследований, представители

- Международной межправительственной исследовательской организации Объединенный институт ядерных исследований (далее – ОИЯИ),
- Национального исследовательского ядерного университета «МИФИ» (далее – НИЯУ МИФИ),
- Национального исследовательского центра «Курчатовский институт» Федерального государственного бюджетного учреждения «Государственный научный центр Российской Федерации», Института Теоретической и Экспериментальной Физики ФГБУ» (ФГБУ "ГНЦ РФ ИТЭФ" НИЦ «Курчатовский институт», далее – ИТЭФ),
- НИИ ядерных проблем Белорусского государственного университета (далее НИИ ЯП БГУ),
- Физико-технического института Национальной академии наук Беларуси (далее ФТИ НАН Беларуси),
- Белорусского государственного университета информатики и радиоэлектроники (далее – БГУИР),
- Государственного научно-производственного объединения «Научно-практический центр Национальной академии наук Беларуси по материаловедению» (далее – НПЦ НАН Беларуси по материаловедению)

составили и согласовали данный Протокол о намерениях:

1. Признавая исключительную актуальность выполнения НИОКР в области разработки, производства, тестирования и эксплуатации сверхпроводящих ускоряющих резонаторов для фундаментальной ядерной физики и инновационных исследований, Стороны признают необходимость объединения усилий для создания многосторонней коллаборации с целью развития технологий для сверхпроводящих ускорителей.

2. Коллаборация создается на базе и с использованием интеграционных возможностей ОИЯИ, берущего на себя роль координатора проекта и площадки для реализации проекта.

- разработка технического задания на ОКР по изготовлению опытных образцов коаксиальных и CH-резонаторов;
- расчеты необходимых величин механической обработки коаксиальных резонаторов для подгонки резонансной частоты;

8.7. Государственное научно-производственное объединение «Научно-практический центр Национальной академии наук Беларуси по материаловедению»:

- Эскизный проект тестового криостата погружного типа;
- Разработка технического задания на ОКР по изготовлению опытного образца тестового криостата погружного типа;

План дальнейших научно-исследовательских и опытно-конструкторских работ должен быть согласован по окончании первой стадии проекта.

Приложения:
1. Пояснительная записка к проекту (на русском языке);
2. Пояснительная записка к проекту (на английском языке);
3. Техническое задание и Календарный план НИР.

Протокол согласован:

От ОИЯИ

Вице-директор — Г.В. Трубников

Начальник Ускорительного отделения ЛФВЭ ОИЯИ — А.В.Бутенко

От НИЯУ МИФИ

Проректор — А.Н. Петровский

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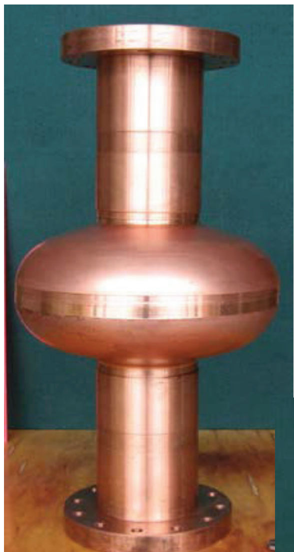
От НПЦ НАН Беларуси по материаловедению

Генеральный директор — В.М. Федосюк

Зав. отделом криогенных исследований — С.Е. Демьянов

Joint Dubna-Moscow-Minsk SRF activities

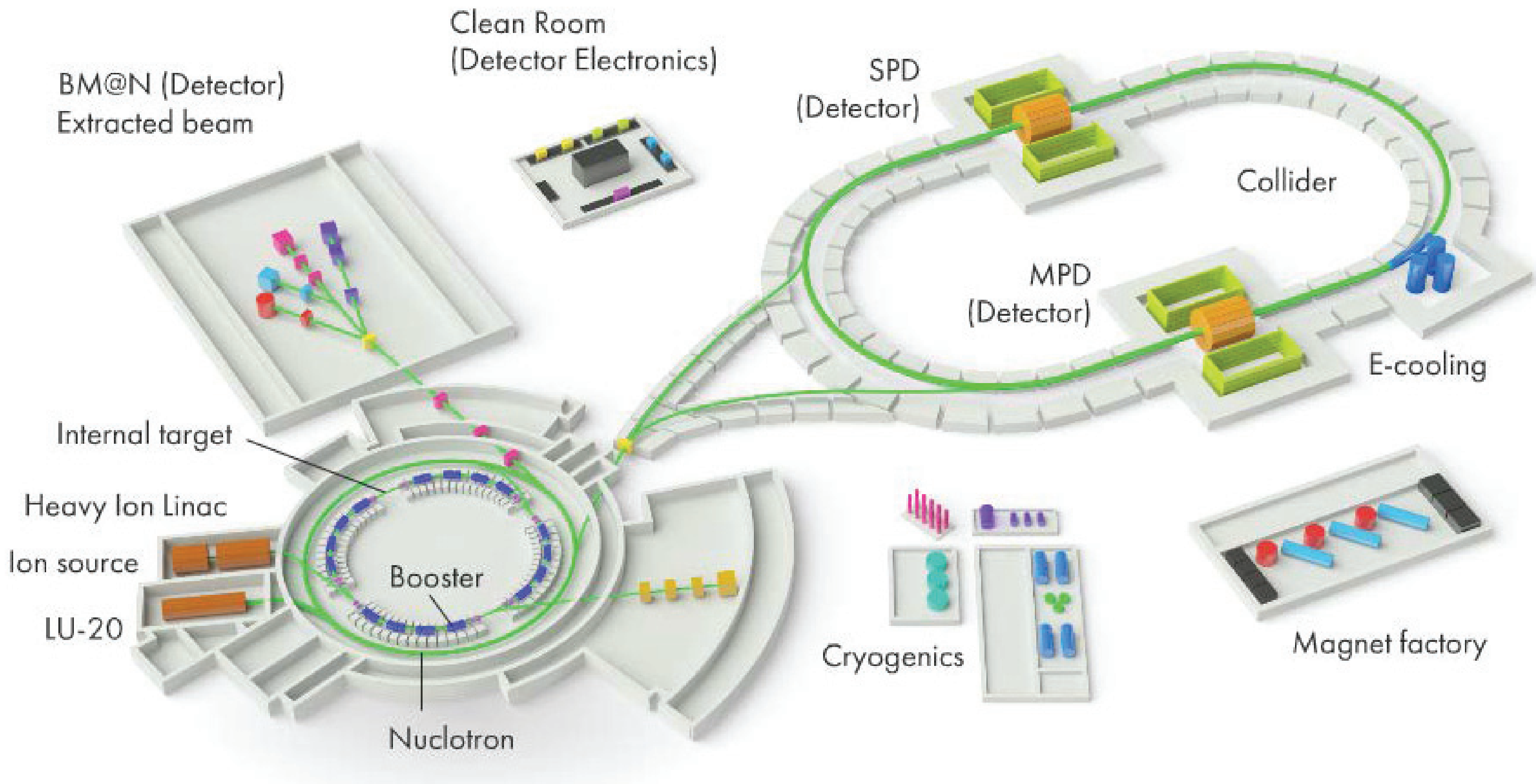


R&D Focus on:

- Development of accelerating cavities for 25MeV SC proton accelerator
- Investigation of the features of obtaining and metrology of the coating of the Nb and Nb_3Sn system based on Cu in order JINR to create superconducting high-frequency resonators for mega-rate accelerators
- Linear proton accelerator SC cavities simulations and parameters optimization

Nuclotron-based Ion Collider fAcility

LU-20 → SC injector



NICA Facility, JINR, Russia, Dubna

New Russian projects with SC cavities

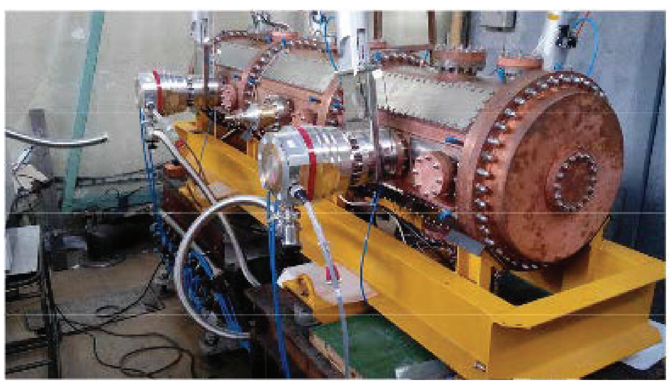
General layout of new injector for Nuclotron – NICA

Warm

- RFQ 162.5 MHz → 2.5 MeV
- QWR β=0.12c, f=162.5 MHz → 4.9 MeV

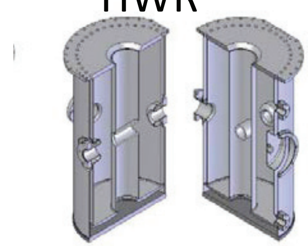
Cold

- SC QWR β=0.12c, f=162.5 MHz → 13.5 MeV
- SC HWR or CH or Spoke ? β=0.21c, f=325MHz → 31 MeV
- SC HWR or CH or Spoke ? β=0.31c, f=325 MHz → 50 MeV

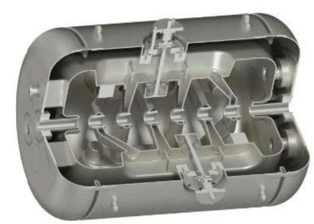


RFQ linac with RF and vacuum components installed on resonator in tuning area (ITEP)

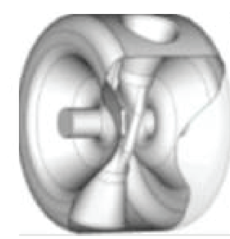
HWR



CH



Spoke



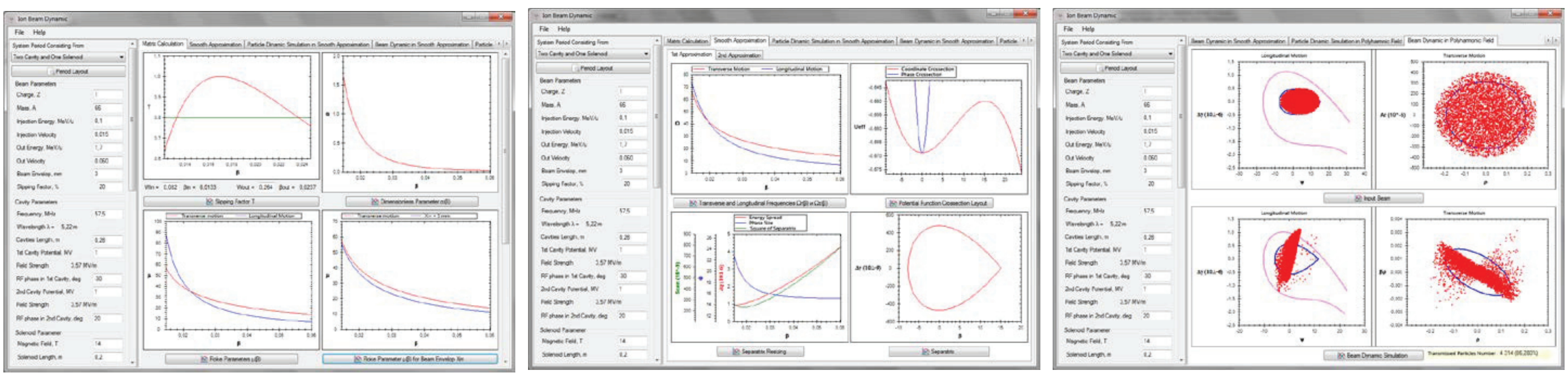
Beam dynamics, Version #4

The number of cavities in the 1st and the 2nd groups should be increased due to lower accelerating gradient E_{acc} (≤6 MV/m instead of 7.5 MV/m).

The beam dynamics of deuterium ions was studied also.

The slipping factor will be not higher than 24 % for proton and deuterium beams.

Number of cavities in the 1st group should be enlarged from 5 to 8, length of the 1st group will 1.9 longer than for Variant #3.

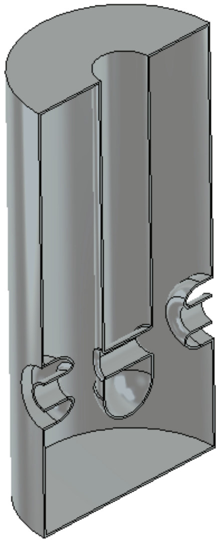


Simulations were done by means of *BEAMDULAC-SCL* code,
Coulomb field and beam loading self-consistently, versions for all main types of RF linacs

Cavity group	0 *	1	2	0 *	1	2
	Proton beam			Deuterium beam		
β_g	0.12		0.21	0.12		0.21
F, MHz	162		324	162		324
T, %	24.0		24.0	24.0		24.0
N_{gap}	2		2x2**	2		2x2**
L_{res}, m	0.222		0.39	0.222		0.39
L_{sol}, m	0.2		0.2	0.2		0.2
L_{gap}, m	0.1		0.1	0.1		0.1
L_{per}, m	0.622		0.79	0.622		0.79
N_{per}	3	8	8	3	8	8
L, m	1.87	4.98	6.32	1.87	4.98	6.32
E_{acc}, MV/m	4.50	5.86	6.4	4.50	5.86	6.4
U_{res}, MV	1.0	1.3	1.25	1.0	1.3	1.25
Φ, deg	–20	–20	–20	–20	–20	-90
B_{sol}, T	1.35	1.3	1.9	1.8	2.0	1.0
W_{in}, MeV	2.5	4.9	13.47	2.5	3.65	8.3
β_{in}	0.073	0.102	0.168	0.073	0.088	0.133
W_{out}, MeV	4.9	13.47	31.0	3.65	8.3	8.3
β_{out}	0.102	0.168	0.251	0.088	0.133	0.133
K_T, %	100	100	100	100	100	100

SC cavities design parameters

Parameter	Value
Frequency, MHz	162.5
Geometrical velocity, β_g	0.12
Maximal RF field on the axis, $E_{acc\ max}$, MV/m	6.0
Ratio of the peak electric surface field to the accelerating field, E_p/E_{acc}	6.4
Ratio of the peak surface magnetic field to the accelerating field, B_p/E_{acc}, mT/(MV/m)	11.4
Effective shunt impedance, r/Q_0, Ohm	488
Geometric factor, $G=R_s/Q$, Ohm	37
Transit time factor, TTF_0	0.88



The simplest design with cylindrical central conductor was chosen.
ED, thermal and mechanical design was done.
The sat-file was prepared and sent to PTI NANB for copper model design and construction.

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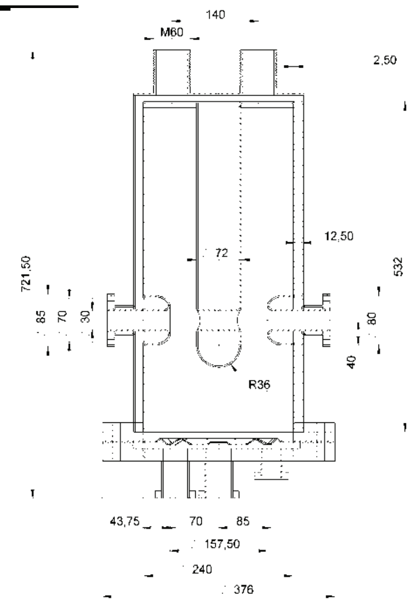

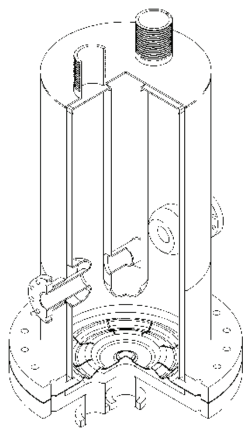

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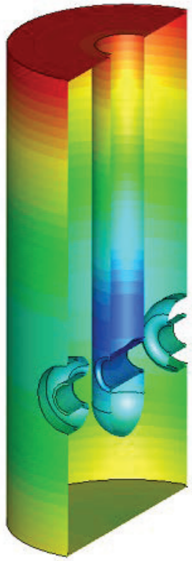
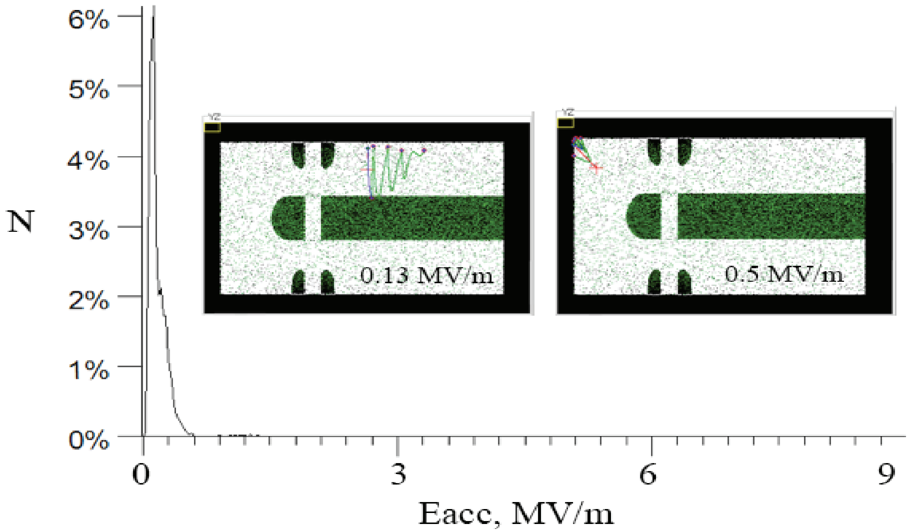
Multipactor studies:
not observed for operating
RF field amplitudes





Mechanical deformation studies:

the Nb cavity wall should be not thin than 2.5 mm

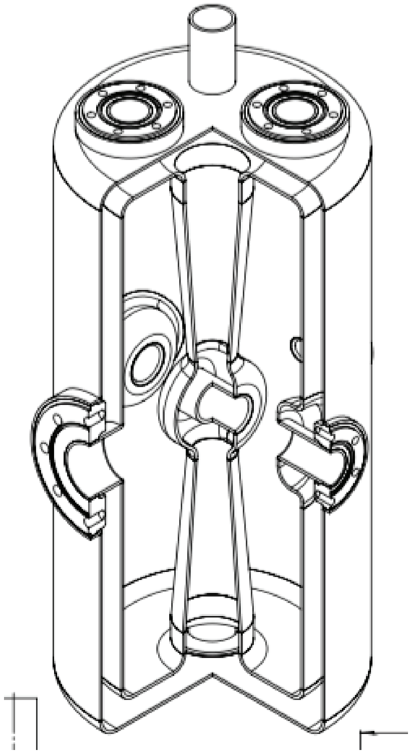
2^{st} group HWR design

HWR type	**Cylind-rical**	**Conical**
Operating frequency, *f*, MHz	324	
Geometrical velocity, β_g	0.21	
Cavity height, mm	431	448
Cavity radius, mm	97	97
Ratio of the peak electric surface field to the accelerating field, E_p/E_{acc}	3.9	3.3
Ratio of the peak surface magnetic field to the accelerating field, B_p/E_{acc}, mT/(MV/m)	7.3	5.6
Effective shunt impedance, r/Q_0, Ohm	252	303
Geometric factor, $G=R_s/Q$, Ohm	57	58

Mechanical simulations and tuning

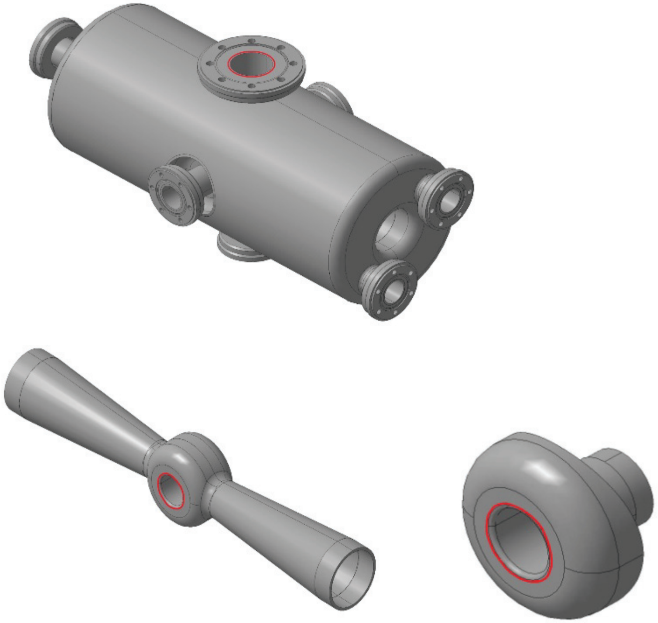
	Cylindrical			Conical		
Wall thick., mm	4	3	2	4	3	2
	Top and bottom planes are fixes					
***df*, kHz/Bar**	-0.24	-0.41	-0.82	-0.35	-0.57	-1.26
Freq. detuning on 4.2 K, kHz	124	157	203	152	176	184
Lorenz detuning, Hz/(MV/m)^2	-10.7	-15.8	-26.9	-18.5	-29.5	-57.4
	Drift tube is fixed					
***df*, kHz/Bar**	5.12	10.57	30.39	4.99	9.68	24.81
	Central plane is fixed					
***df*, kHz/Bar**	3.85	8.19	25.06	1.13	3.63	11.45
Freq. detuning on 4.2 K, kHz	467	453	437	478	458	411
Lorenz detuning, Hz/(MV/m)^2	-16.9	-27.9	-5.99	-2.24	-47.3	-93.6
Etching sensit., kHz/0.1mm	-74.7			-38.8		

Cavity technology



General design

Cavity & aux elements assembly



EB welding workflow

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