Overview on High Intensity Heavy Ion Linacs

IPAC2019

Melbourne

19.05. – 24.05.2019

Uli Ratzinger
IAP, Goethe University Frankfurt
Bevatech GmbH Frankfurt

Content

- Heavy ion driver linacs – why and how
- Progress in linac components
- Existing facilities and

  facilities under construction

Please be aware that the presentation is not complete with respect to the last two items, examples only!

Mission

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Mission of heavy ion linacs

1) Experiments around the Coulomb barrier
at around a few A MeV

2) Driver beam for research facilities
at a few hundred A MeV

3) Injector for a cyclotron or synchrotron
driving medical or high energy facilities
up to LHC energies

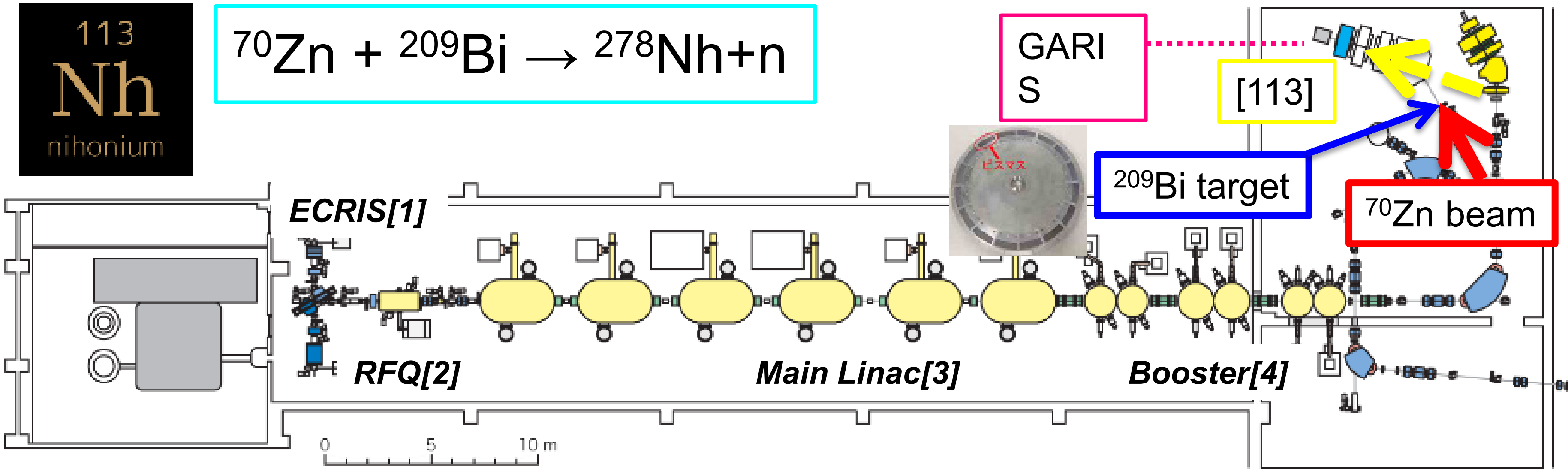
Mission example for 1)

SHE research at RILAC

K. Morita et al., J. Phys. Soc. Jpn 81, 103201 (2012)

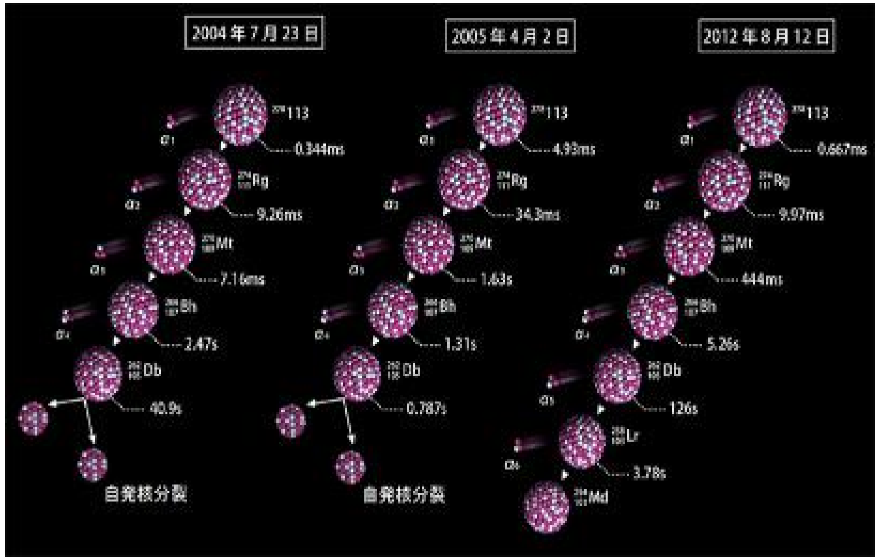
113
Nh
nihonium

$^{70}Zn + ^{209}Bi \rightarrow ^{278}Nh + n$



5 MeV/u for M/q=5

Average current: 0.47 pμA on target
3 events / 576 days during 2003 - 2012



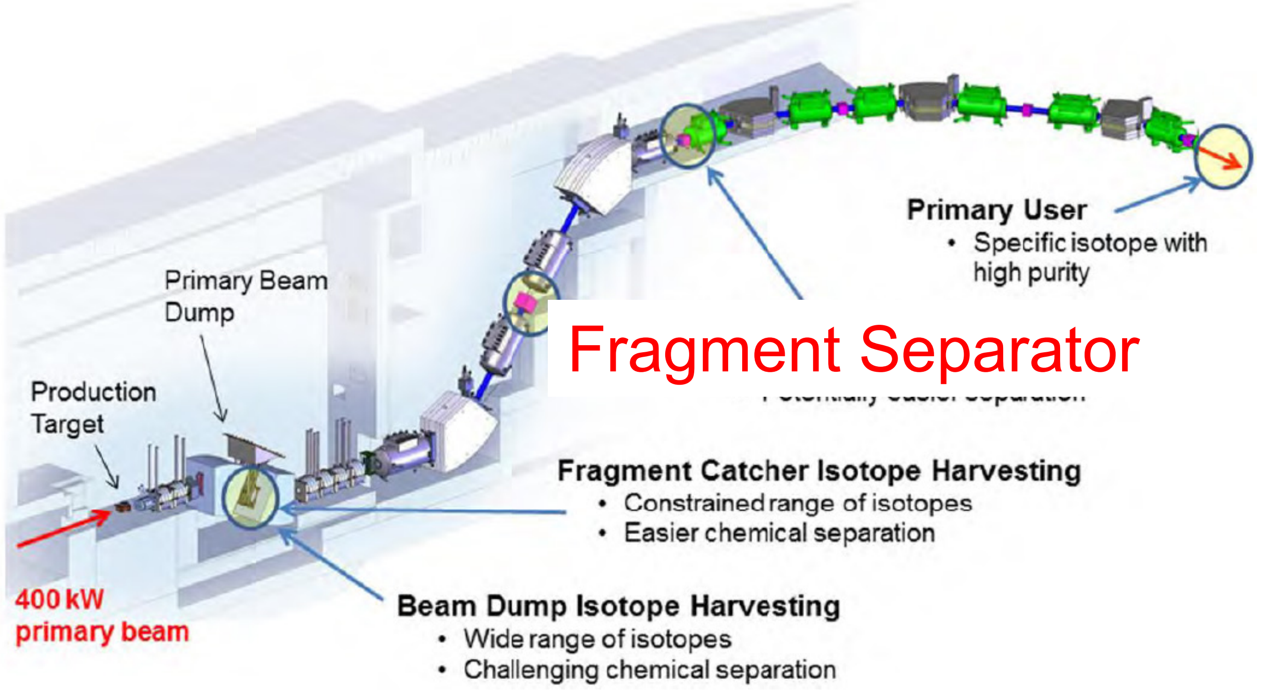
[1] T. Nakagawa et al., Rev. Sci. Instr. 71, 637(2000).

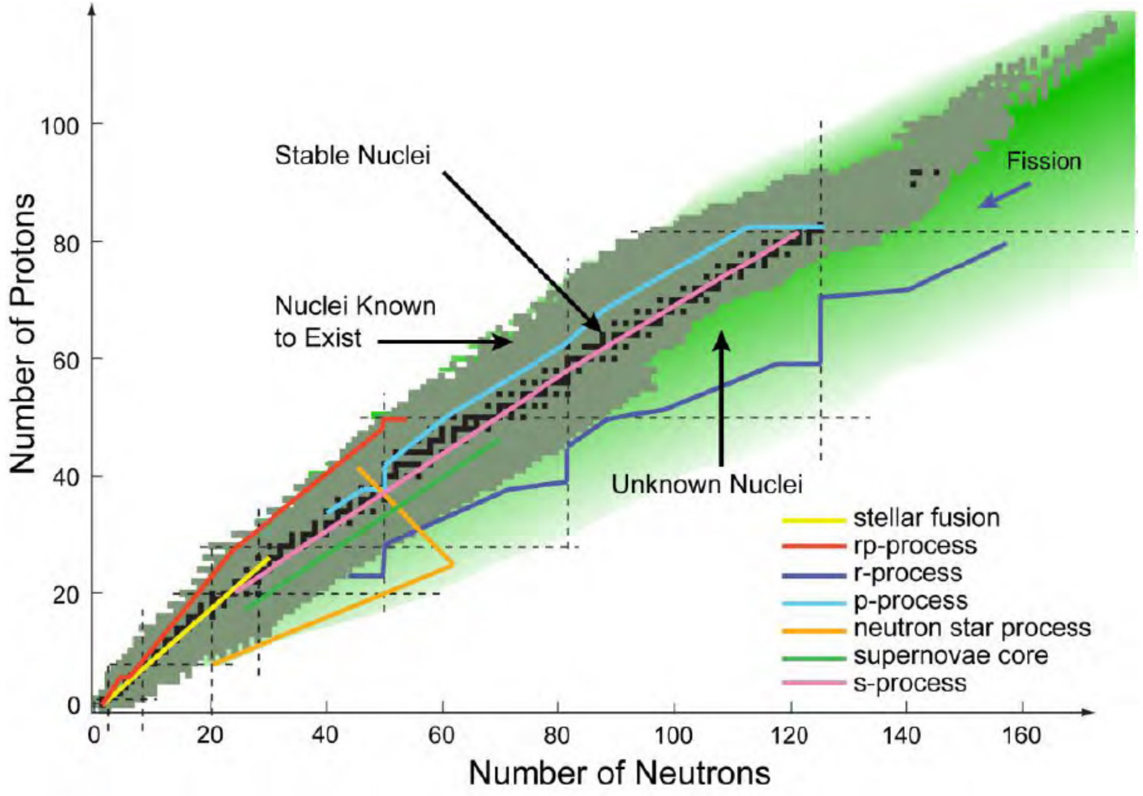
[2] O. Kamigaito et al., Rev. Sci. Instr. 76, 013306 (2005)

Mission example for 2)

FRIB - facility MSU, Michigan, USA: Linac driven

200 A MeV < W(Uranium ions) < 400 A MeV (Upgrade)





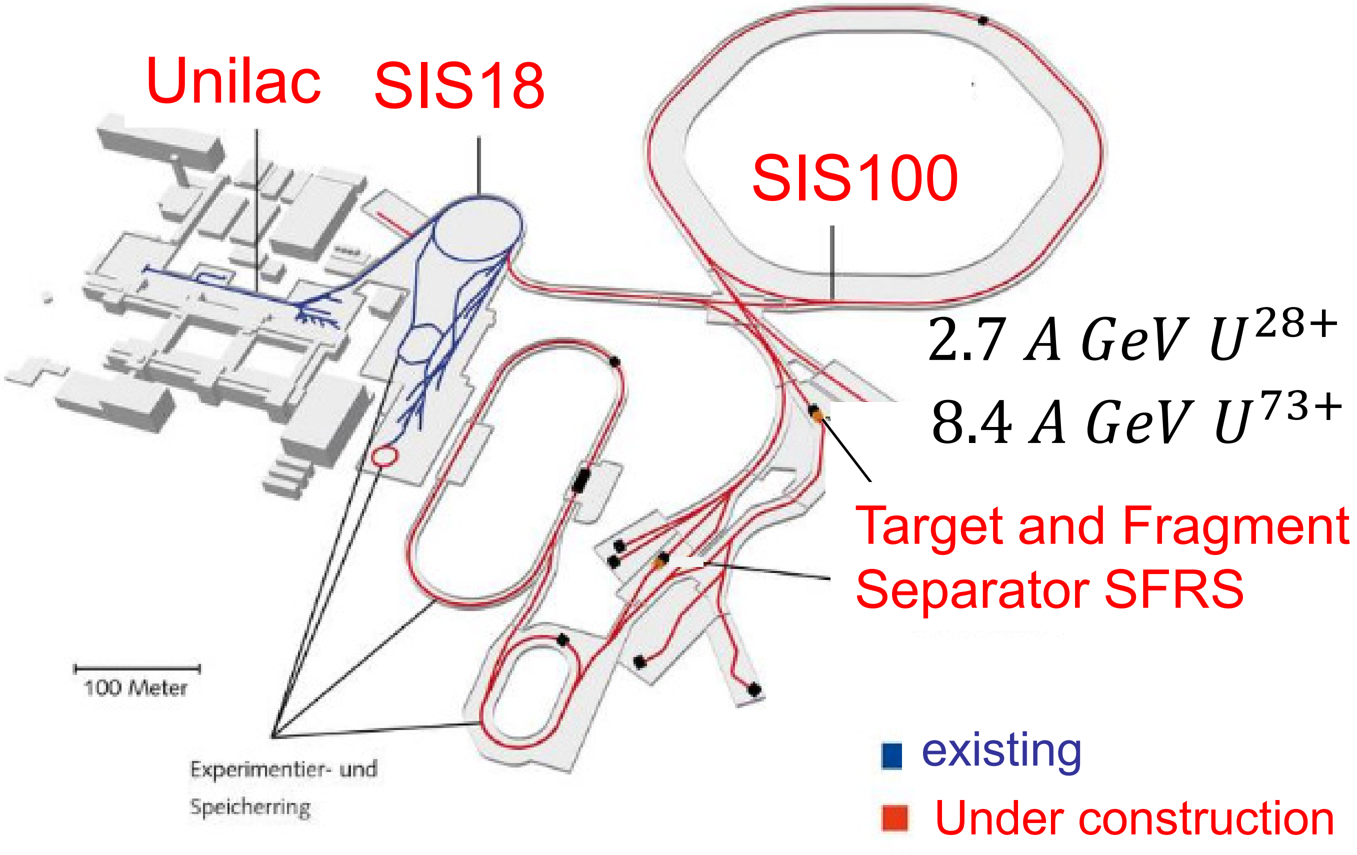
Linac beam

$\leq 400\ kW$

https://frib.msu.edu/_files/pdfs/frib_opening_new_frontiers_in_nuclear_science.pdf

Mission example for 3)

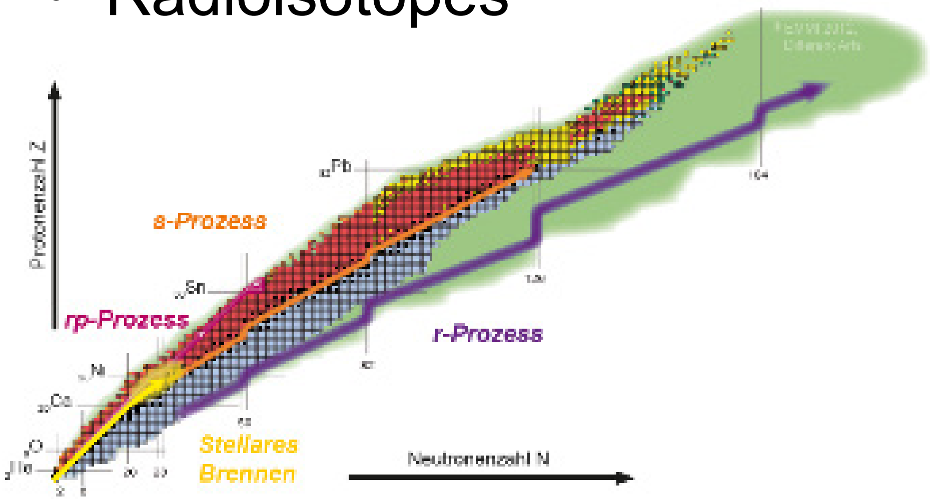
FAIR – facility at GSI Darmstadt, Germany
11.4 A MeV Unilac & SIS18 & SIS100



$2.7\ A\ GeV\ U^{28+}$

$8.4\ A\ GeV\ U^{73+}$

- Radioisotopes



Other research topics:

- Strange matter
- Compressed baryonic matter
- Antiproton experiments
- Warm dense matter
- Atomic& Bio physics

CW versus pulsed beam operation

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

The facilities differ a lot in duty factor, beam current and time averaged particle current.

Comparison for uranium ion beams

- CW operation: U^{30+} from a $20\ GHz$ ECR – source like the Berkley LBL – VENUS source, $W_f = 200$ A MeV:

Up to $200\ e\mu A$ time averaged beam current may be delivered to the target by cw linacs (FRIB, RISP..), corresponding to about

$$5 \cdot 10^{13} pps, 400\ kW \text{ on target!}$$

It is however a hard task to reach this goal with heavy ions, due to their massive particle-wall interaction.

CW versus pulsed beam operation

- Pulsed beam example: - U^{4+} from GSI VARIS source,
  - Gas stripper at 1.4 A MeV into U^{28+}

Linac output: $11.4\ A\ MeV, 20\ emA\ U^{28+}$, d.f. 10^{-4};

After SIS100: $\bar{I} = 2\ e\mu A$, about $5 \cdot 10^{11}\ pps$.

This current level can be delivered to the target by synchrotrons only with applying multi – turn injection of the linac beam!

That means: Two orders of magnitude in beam reduction have to be compensated in case of the synchrotron facility by:

- Higher production cross sections with higher beam energy
- Higher separator efficiency (less divergence) at higher fragment energy
- Advantage of pulsed beam structure for fragment injection into storage rings

Progress in heavy ion linac components

- High current ion sources
- RFQ‘s
- RT DTL‘s
- SC DTL‘s

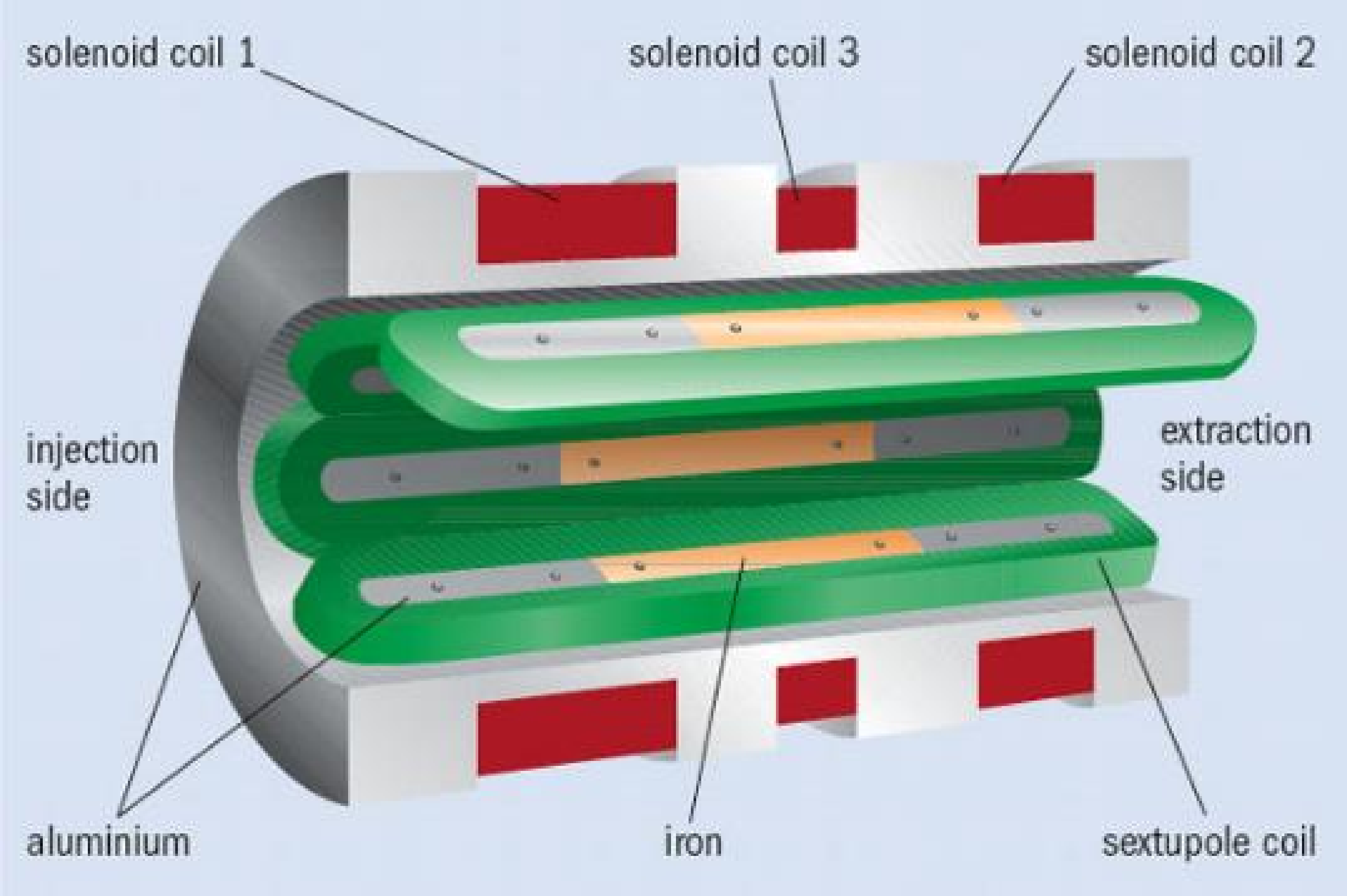
High current ion sources

- Electron Cyclotron Resonance ECR source is the working horse for long pulse and CW operation

28 GHz VENUS ECR,
LBNL Berkeley

Superconducting Coils

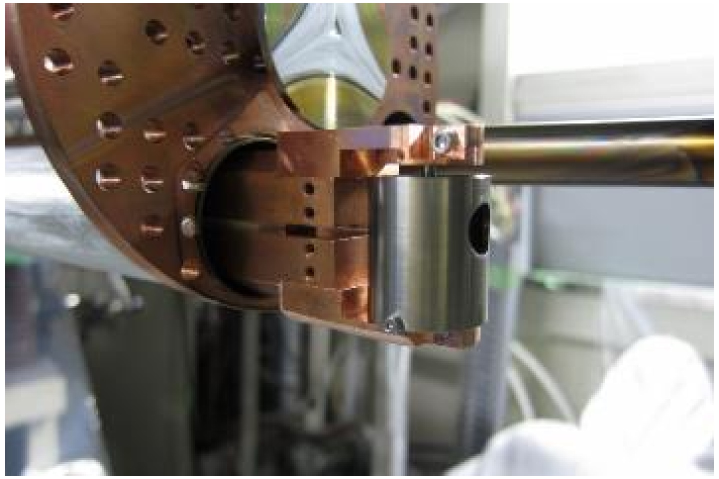
Plasma chamber	
inner diameter	150 mm
Mirror fields in / out	4.0 T / 3.0 T
Radial field max	2.4 T



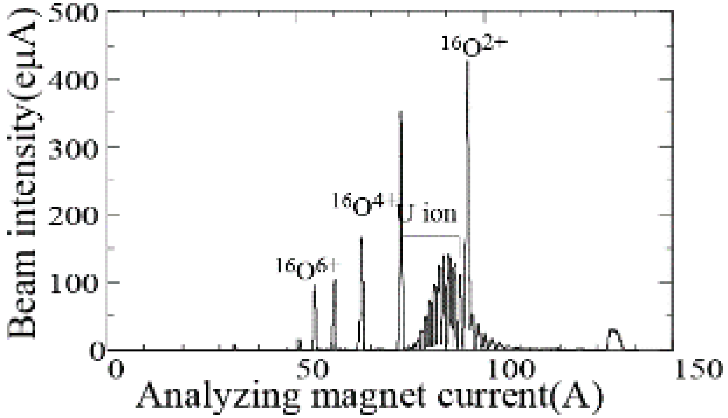
Development of U beam at RILAC2

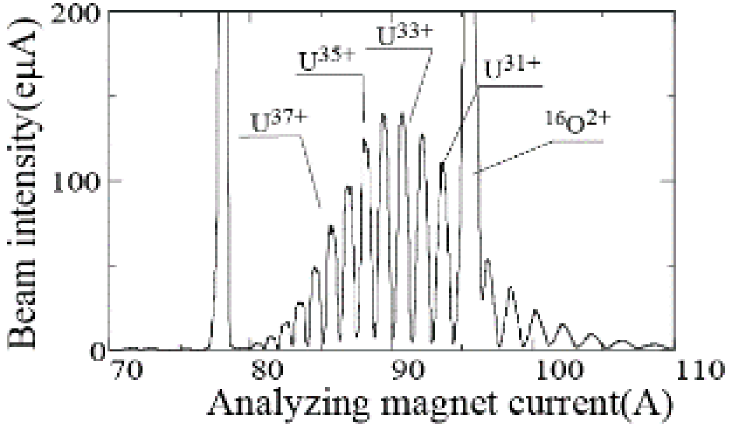
Development of large HT-oven containing 3g - UO_2 in the crucible

28-GHz SC-ECRIS

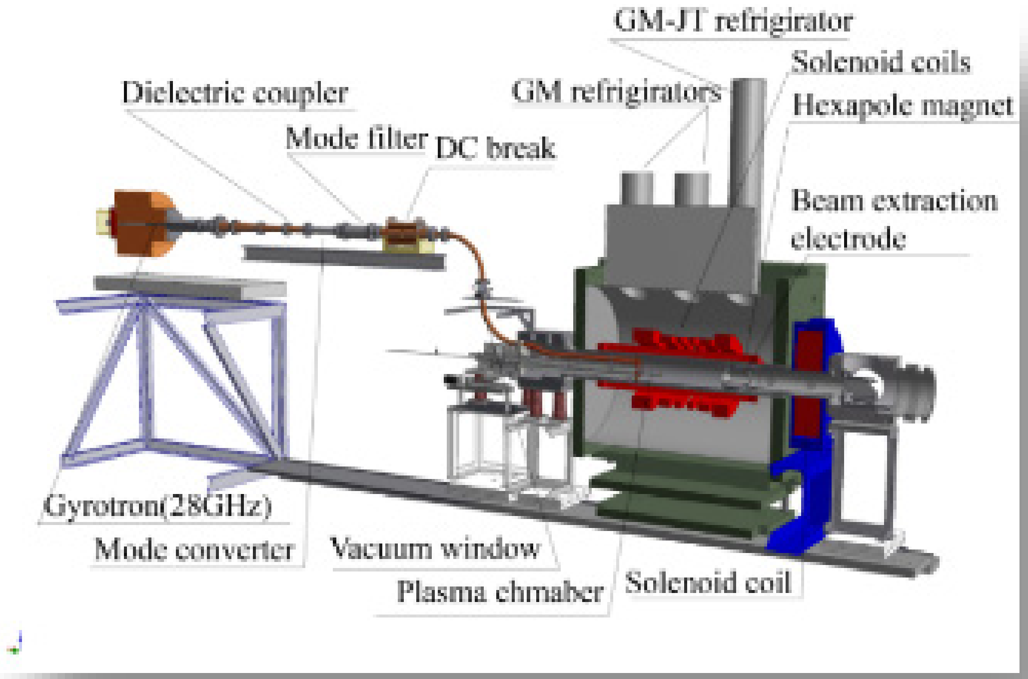


Intensity of U^{35+} : 120 e-microA
Consumption rate : ~3 mg/h
Duration : ~1000 hours (41 days)





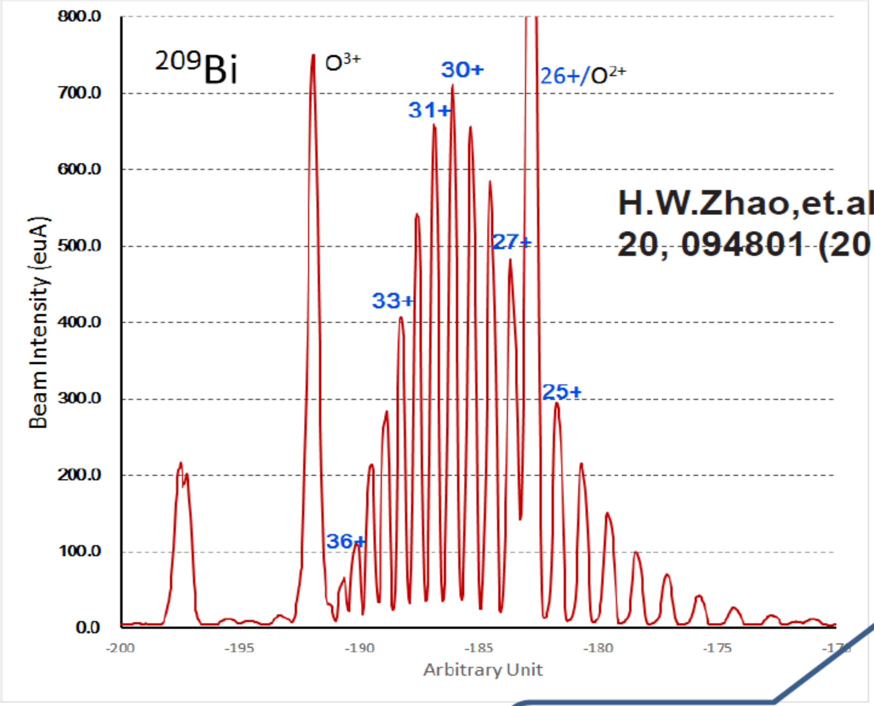
Y. Higurashi et al., ECRIS2016



High current ion sources

Record beam intensities produced by SECRAL I&II

- For the first time in ion source history, $Ar^{11\text{-}14+}$、 Kr^{18+}, Xe^{26+} > 1 emA
- Open a new era: HCI DC beams -- emA
- Important to intense-beam heavy ion linac



H.W.Zhao,et.al. PRAB, 20, 094801 (2017)

28 GHz

The world record beam intensities

Ion Beam	IMP SECRAL Beam intensity (eμA)	LBNL VENUS beam Intensity (eμA)
$^{16}O^{6+}$	6100	4750
$^{40}Ar^{12+}$	1420	1060
$^{40}Ar^{16+}$	620	523
$^{40}Ar^{18+}$	15	4
$^{40}Ca^{14+}$	270	285
$^{86}Kr^{18+}$	1020	770
$^{86}Kr^{28+}$	146	100
Xe^{26+}	1100	
Xe^{30+}	320	330
Xe^{42+}	15	6
$^{209}Bi^{31+}$	680	300
$^{209}Bi^{50+}$	10	27
$^{238}U^{33+}$	202	440

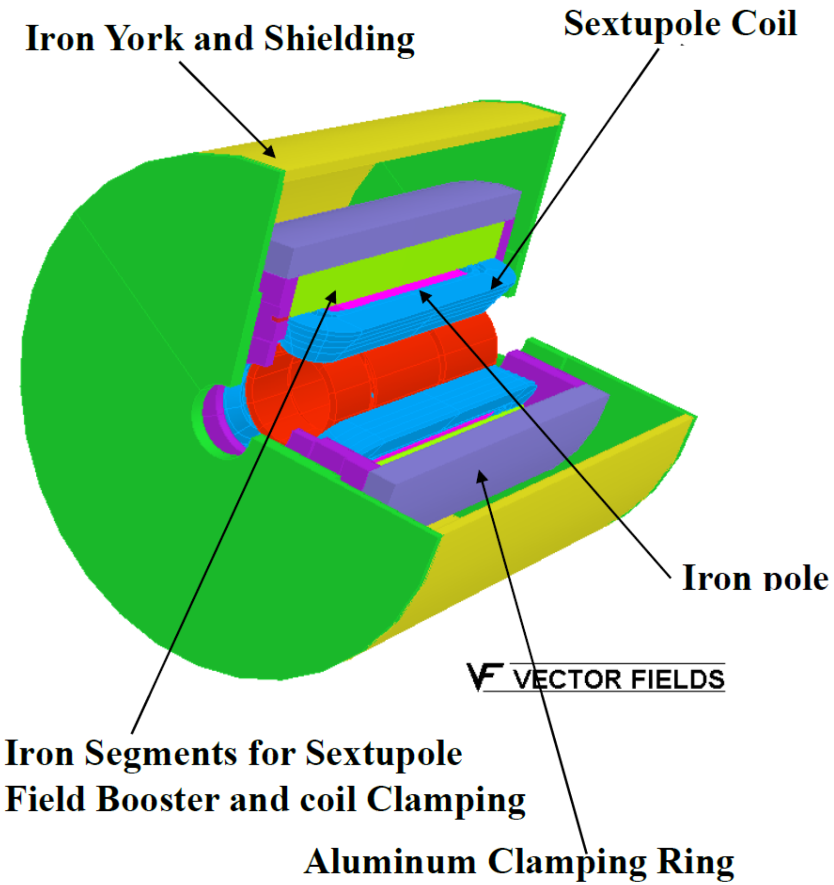
Record intensities are shown in red

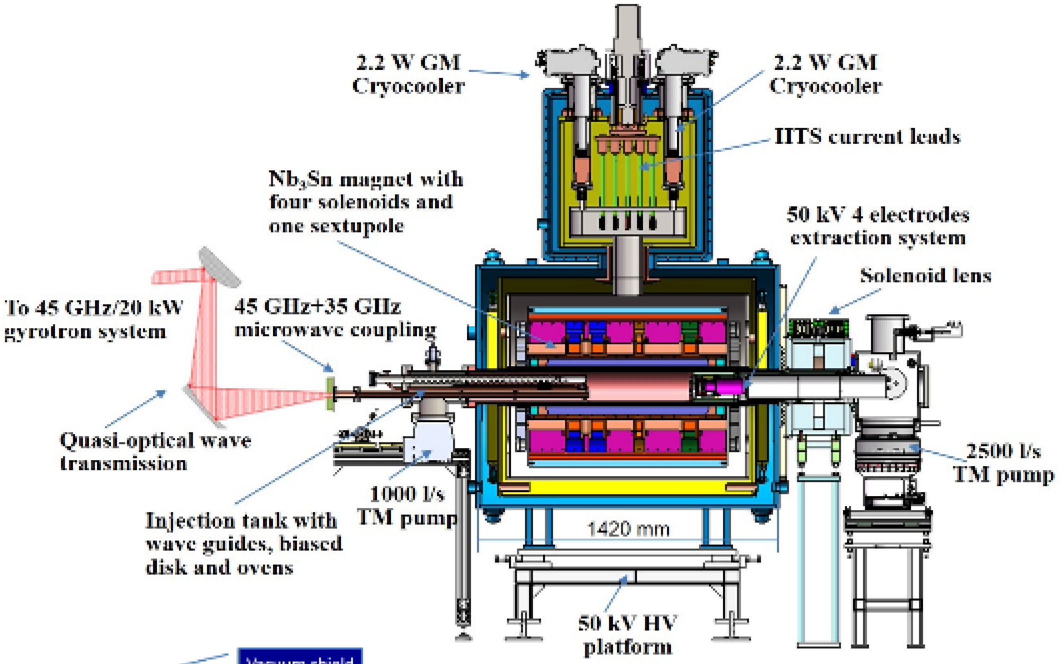
High current ion sources

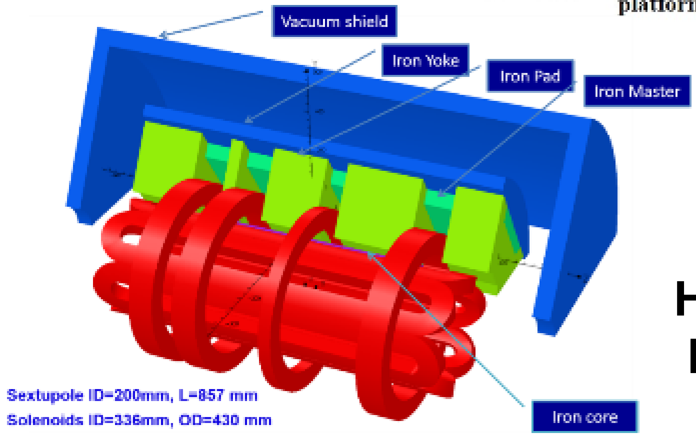
ECR development at IMP Lanzhou and for HIAF

Secral I,II concept: 28 GHz,
SC sextupole around
SC solenoids

New development: **45 GHz FECR**



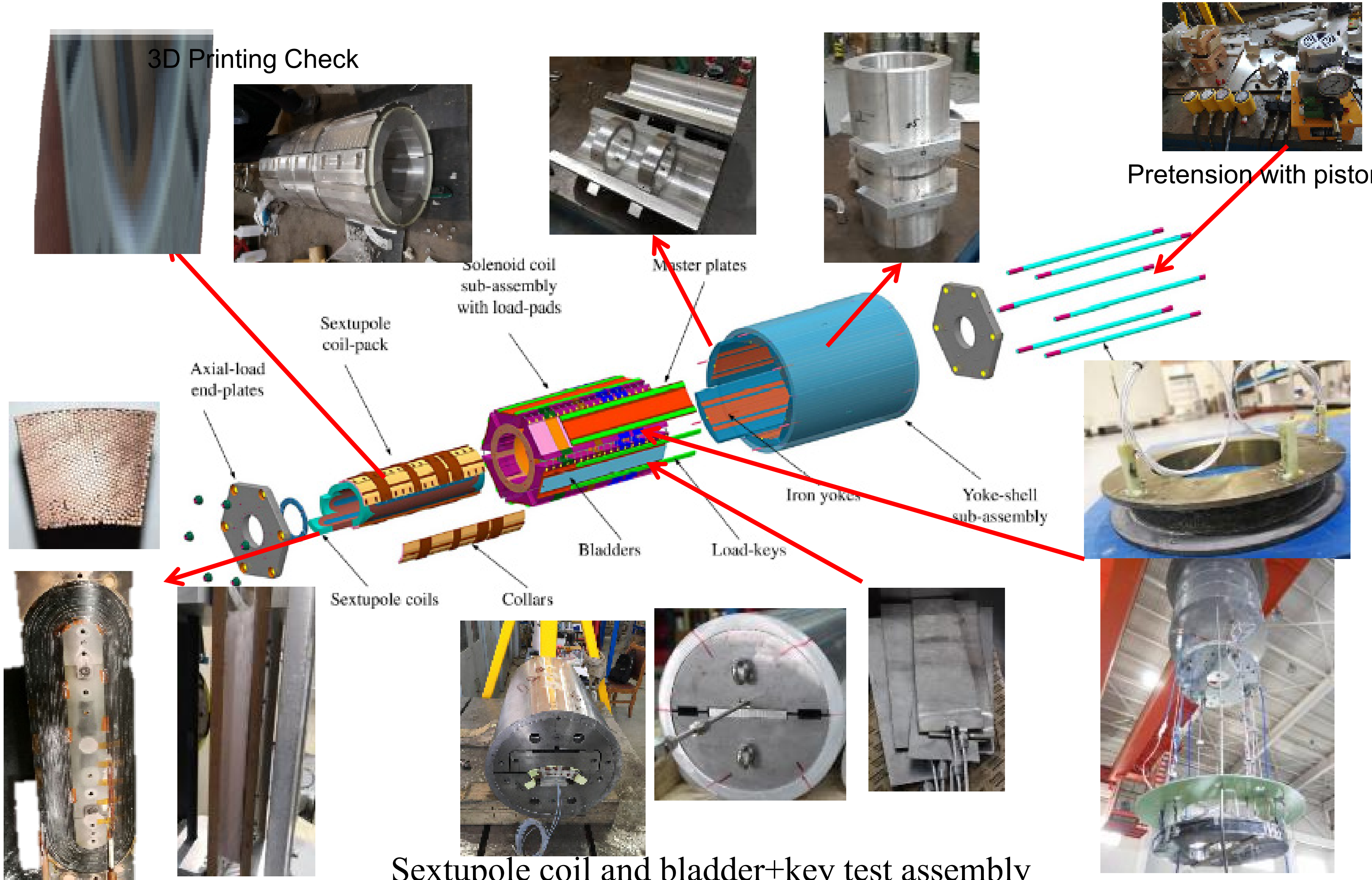




Nb_3Sn coils Proto-typing ongoing

H.W. Zhao, et.al. RSI, (2018)

45 GHz ECR magnet development



3D Printing Check

Pretension with piston

Sextupole coil and bladder+key test assembly

800 A no quench

Prototyping Nb_3Sn sextupole coil

Nb_3Sn magnet prototyping at IMP Lanzhou

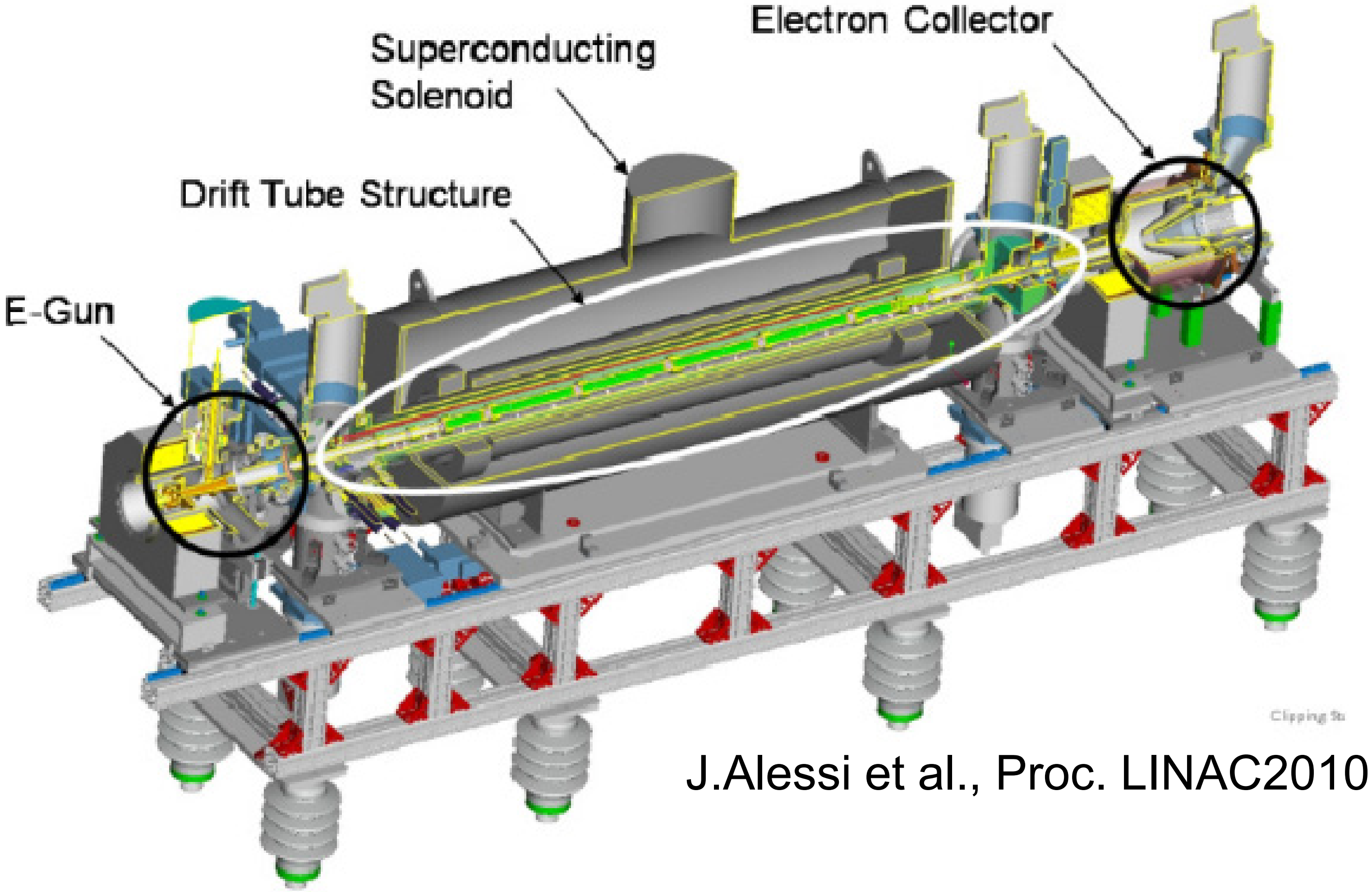
High current ion sources

- Pulsed Electron Beam Ion Source EBIS

Ions	He - U
Q / m	≥1/6
Current	> 1.5 emA (10 µS)
Pulse length	10-40 µs
Rep rate	5 Hz
Output energy	2 MeV / u
ΔP/P	<0.05%
Time to switch species	1 second

Ion species	Charge State	Ions into Booster
He	2+	$9.0\ 10^9$
C	5+	$4.4\ 10^9$
Si	11+	$2.7\ 10^9$
Fe	20+	$8.1\ 10^8$
Au	32+	$1.1\ 10^9$

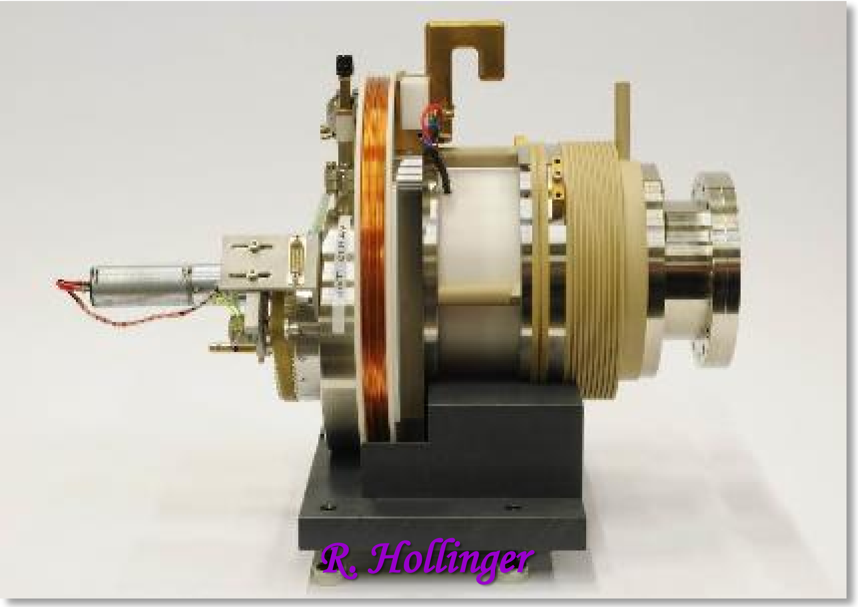
BNL EBIS Preinjector, providing Ions to RHIC and NSRL since 2010



J.Alessi et al., Proc. LINAC2010, p. 1033

High current ion sources

• Pulsed Vacuum Arc Ion Source VARIS



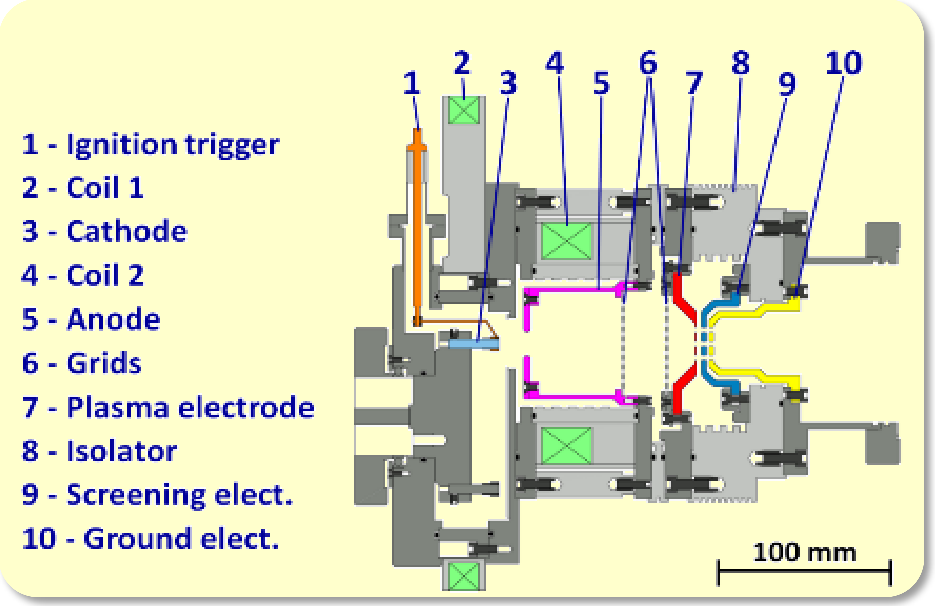
Technical data for uranium:

Revolver with 17 Cathodes

- 2 Solenoids: 0.1 and 0.2 Tesla
- Arc current: up to 1 kA
- Typical duty cycle: 1 Hz / 0.5 ms
- Working Material: ductile metals
- Life time: ~1 week

Extraction system:

- **Triode ext. system**
- **Multi aperture:** **13 holes, ø 3 mm**
- **Aspect ratio:** **S = 0.5**
- **MAX ext. voltage:** **U_{ext} = 35 kV**
- **Emission area:** **92 mm^2**



High current ion sources

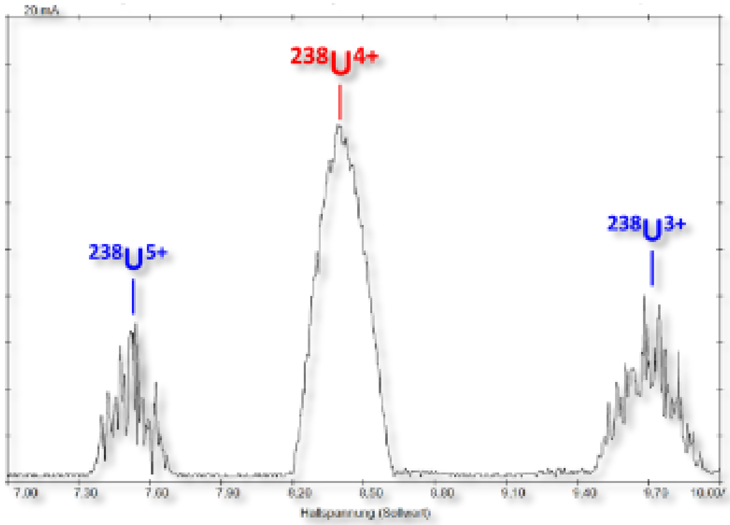
The VARIS was developed at GSI Darmstadt to inject heavy metal ions like U^{4+} into the Unilac

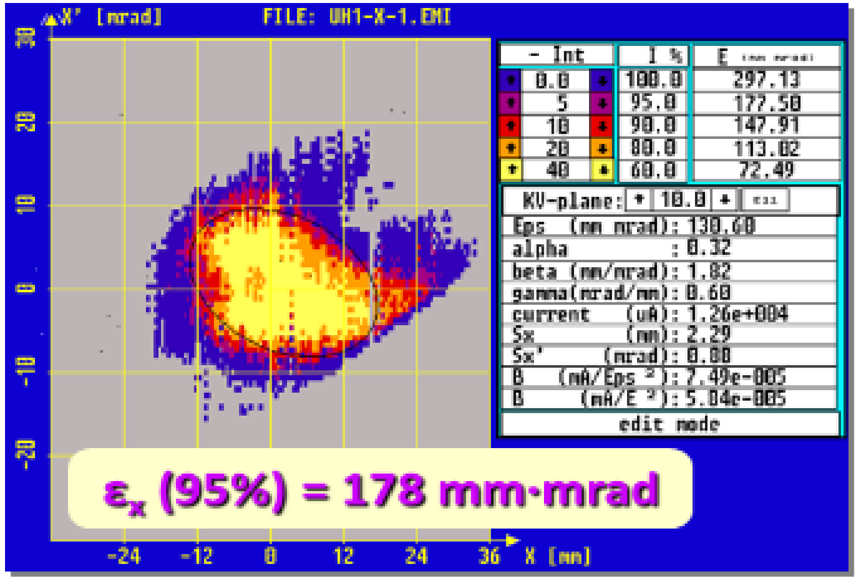
- **optimized for production of Uranium beam:**

  2.4 A keV, 43 mA into LEBT , 67% of U^{4+}
- **better vacuum conditions: up to $8\cdot10^{-8}$ mbar**
- **no water cooling necessary**
- **higher emission current density: 170 mA/cm^2**
- **better pulse-to-pulse stability**
- **reduced intensity fluctuations during the pulse**
- **U^{4+} beam current in front of the RFQ: 15 mA**

R. Hollinger, M. Galonska, Nucl. Instr. and Meth. in Phys. Res. **B 239** (2005)

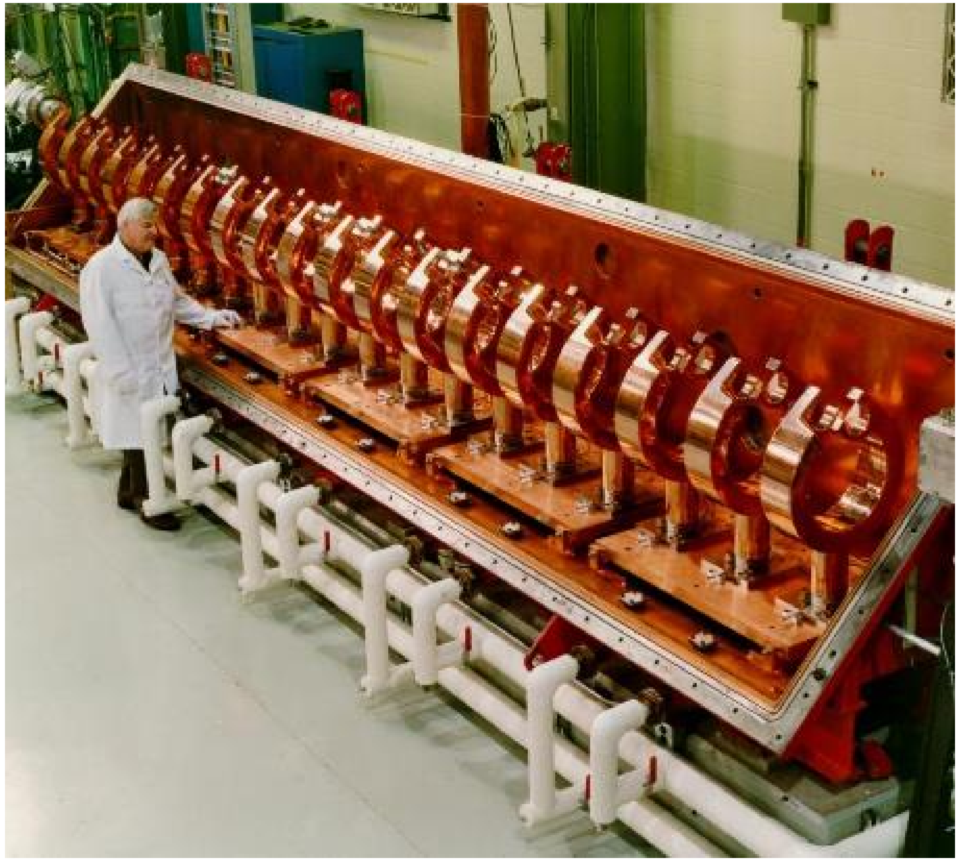
Uranium Current in front of the RFQ might be doubled by a new, straight injector line

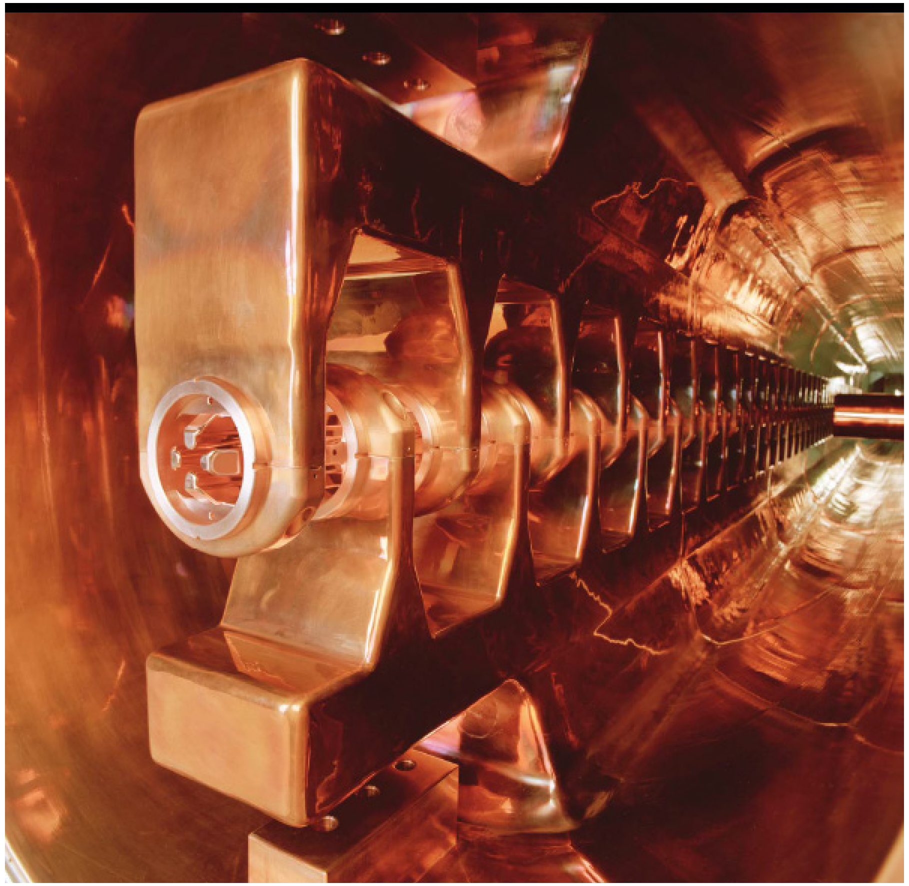




RFQ's

Heavy ions at very low charge state need low frequency structures





TRIUMF ISAC 35 MHz RFQ
Split-Ring, 8m, CW, 75 kV, (low current rad. isotopes), $^{A}/_{q} \leq 30$

10 mA Ar^{1+} , →15 mA U^{4+}

MOPTS036

GSI Unilac HSI – RFQ, 36 MHz
IH-RFQ, 9.2 m, pulsed, 125 kV
$H_{110}-mode;\ \emptyset_i = 0.76m;\ ^{A}/_{q} \leq 60$

RFQ's

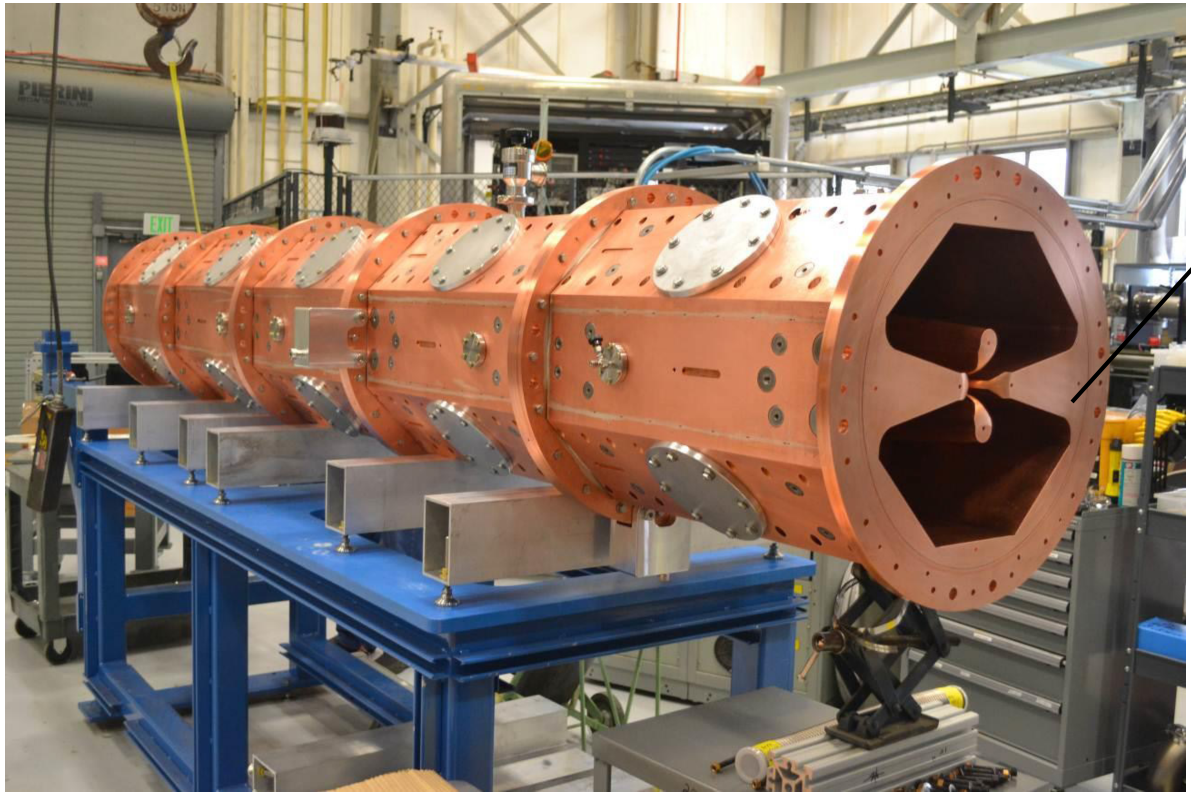
4-Vane-RFQ with „windows“, lowering frequency; Example:

60.625 MHz ANL ATLAS RFQ, CW, $^{A}/_{q} \leq 7,$ $30 - 295\ A\ keV,$

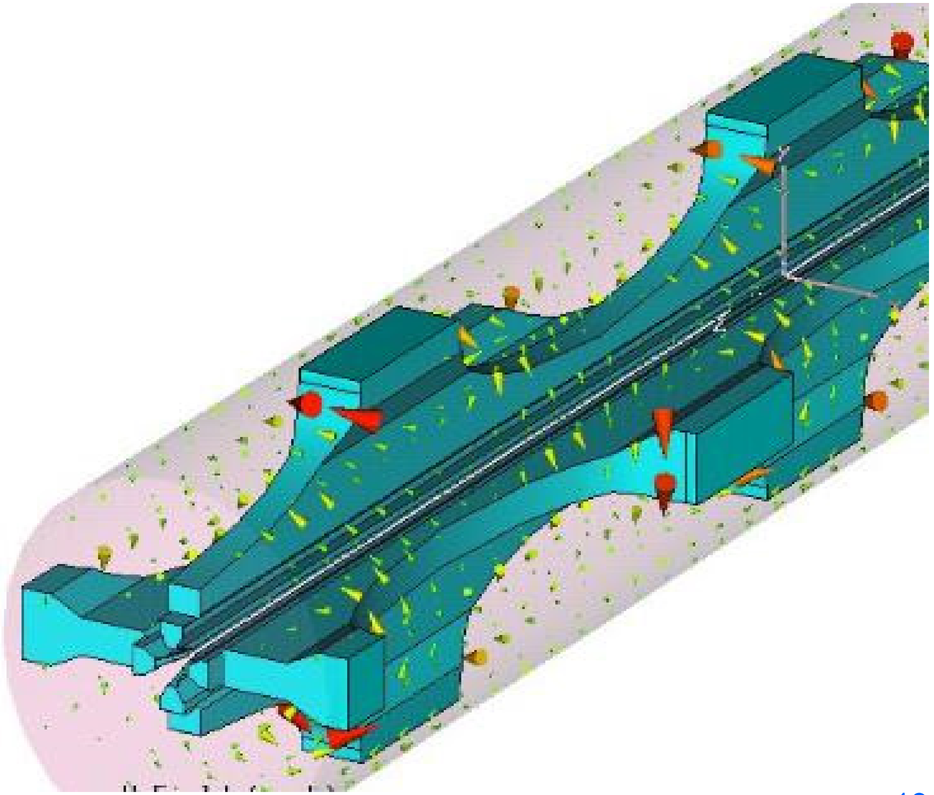
$L_V = 3.81\ m,$ $70\ kV,$ $60\ kW,$ $12.125\ MHz$ bunch sequence, external buncher

Multi-cell split-coaxial structure with trapezoidal modulation,

P.N. Ostroumov et al., PHYS.Rev.ST ACCELERATORS AND BEAMS15, 110101 (2012)



25 inch flange (635 mm)



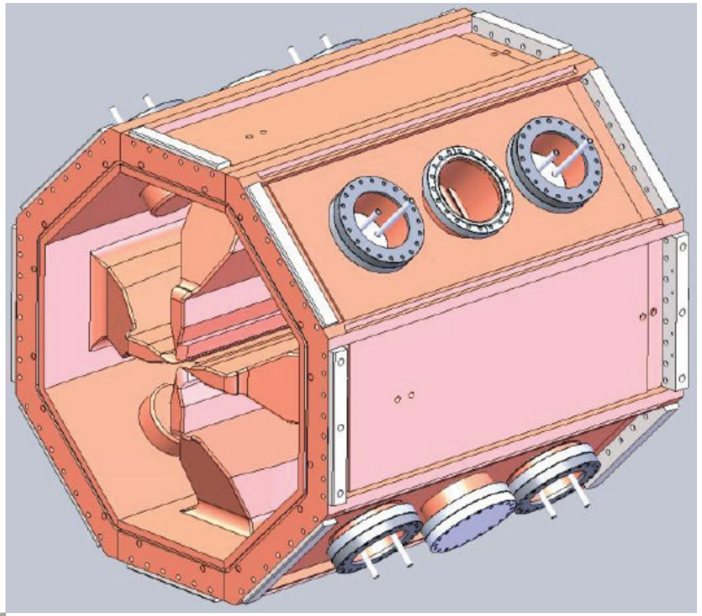
4-Vane RFQ's

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

80 MHz RFQ's for $^{A}/_{q} \leq 7$ were established at:

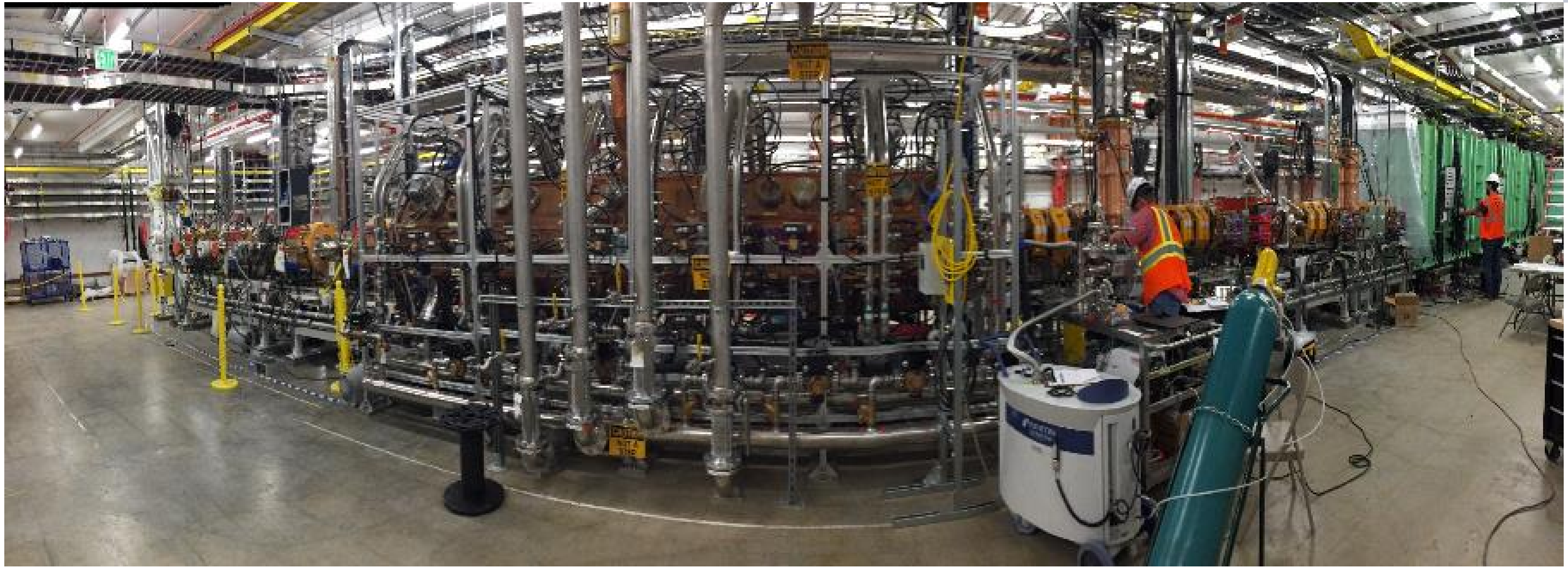
- FRIB – MSU,
- RISP – RAON,
- HIAF – IMP

$W_f = 500\ AkeV,$
$L \cong 5m,$
$\varnothing \approx 940\ mm$



Scheme:
FRIB - RFQ module

Photo: Installed FRIB - RFQ in tunnel



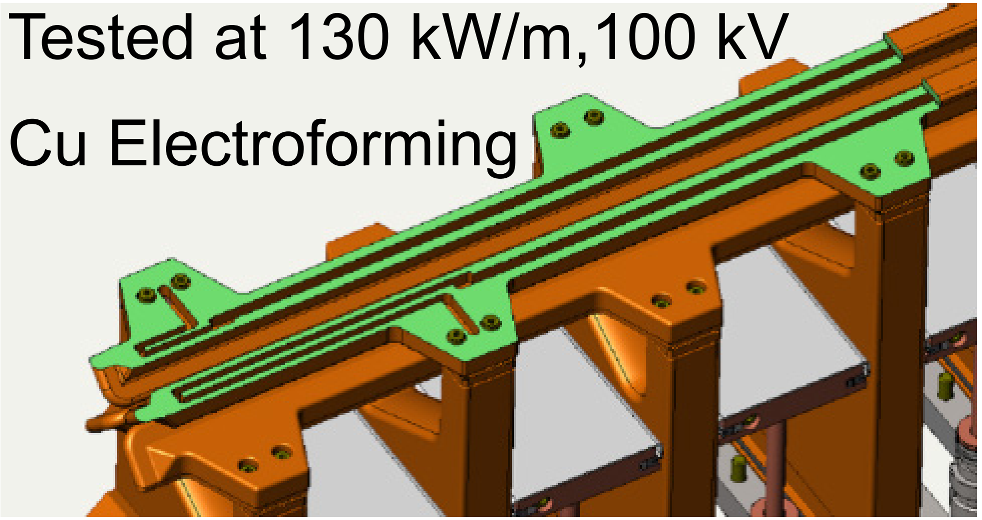
4-Rod RFQ‘s

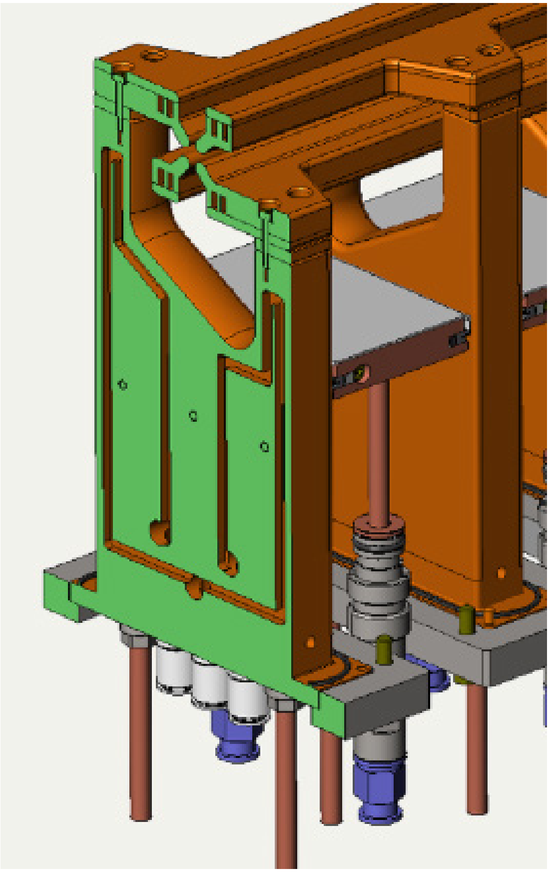
108 MHz CW RFQ for GSI

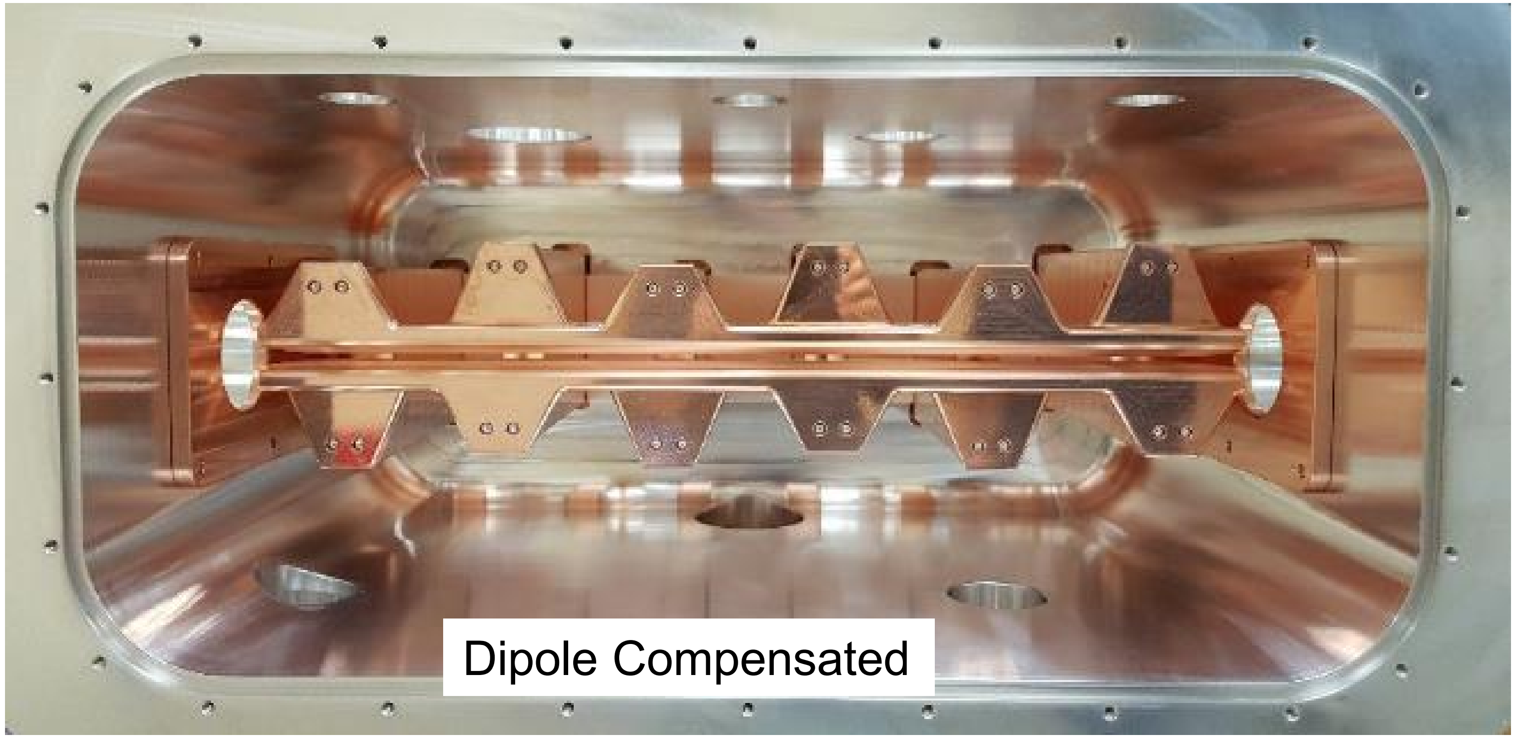
CW Linac:

D. Koser et al. Proc. IPAC2018,
Coop. of IAP Frankfurt & NTG GmbH

$^{A}/_{q} \leq 7, L \cong 2.5$ m,







Courtesy:
A. Bechtold
NTG GmbH

New RFQ research topic

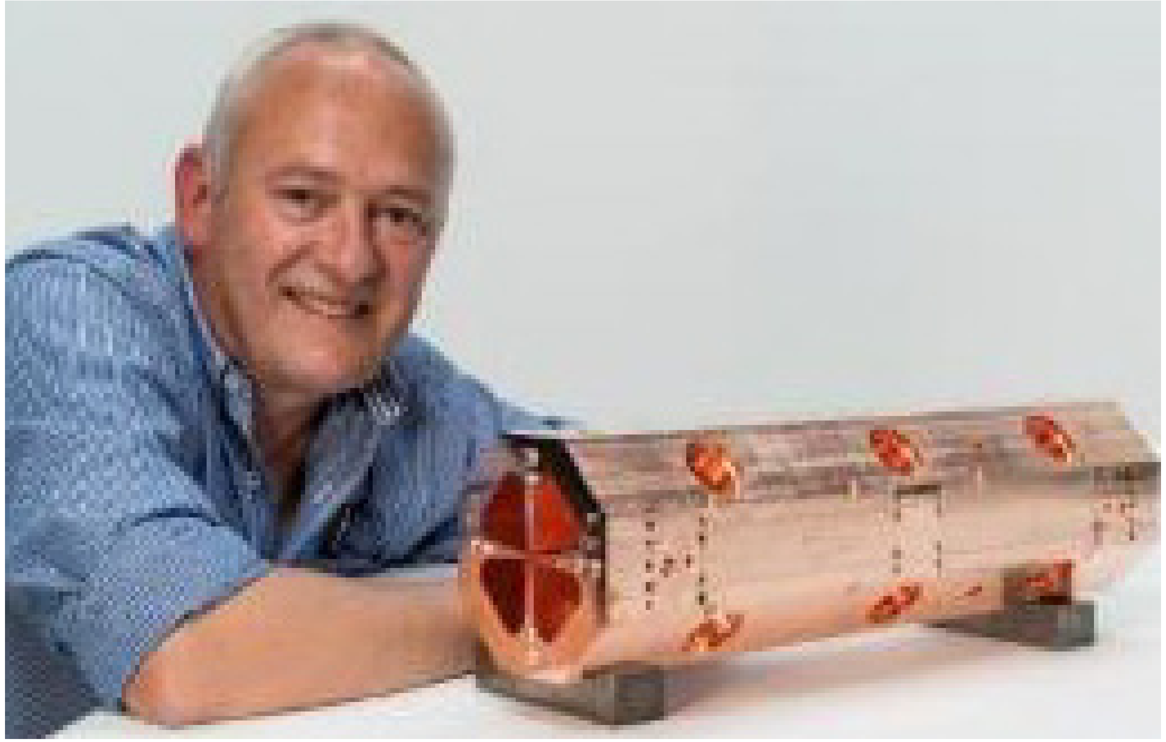
Higher operation frequencies

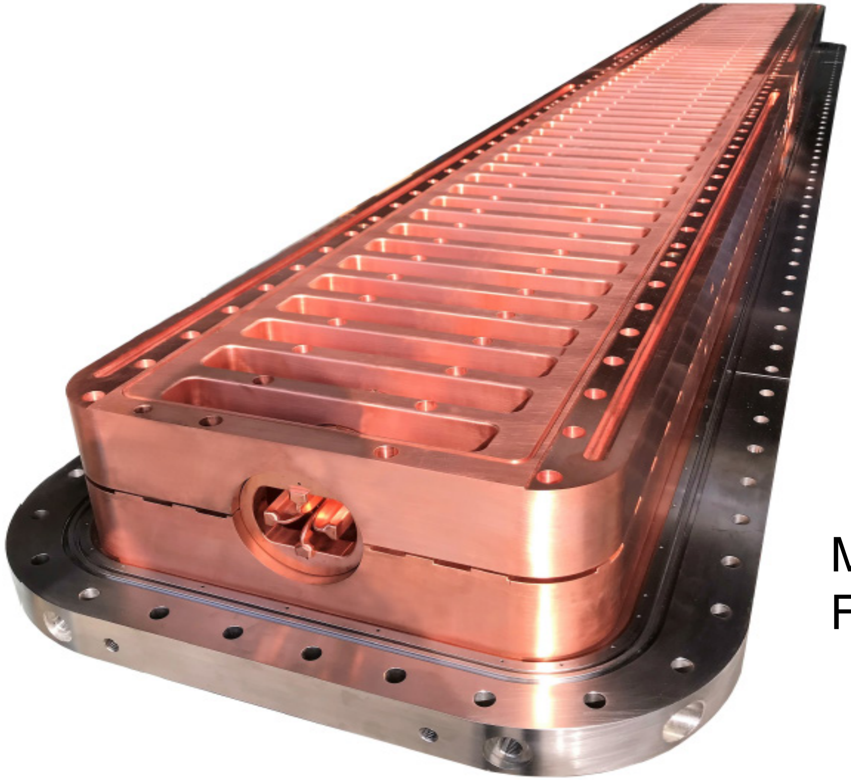
- 4-Vane type: CERN 750 MHz!

H.W. Pommerenke et al.,Proc. LINAC18, Beijing, p. 822

- 4-Rod type: IAP Frankfurt, 325 MHz Ladder-RFQ

M. Schuett et al., Proc. LINAC18, Beijing, p. 826



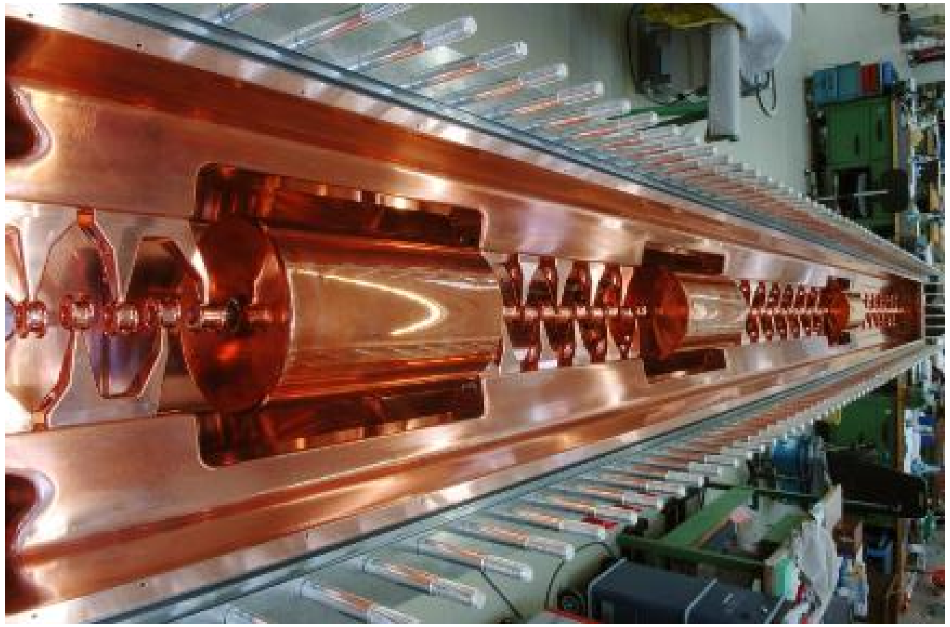


Manufacturer:
Fa. Kreß GmbH

RT DTL's

IH – DTL is used for driver beams at:

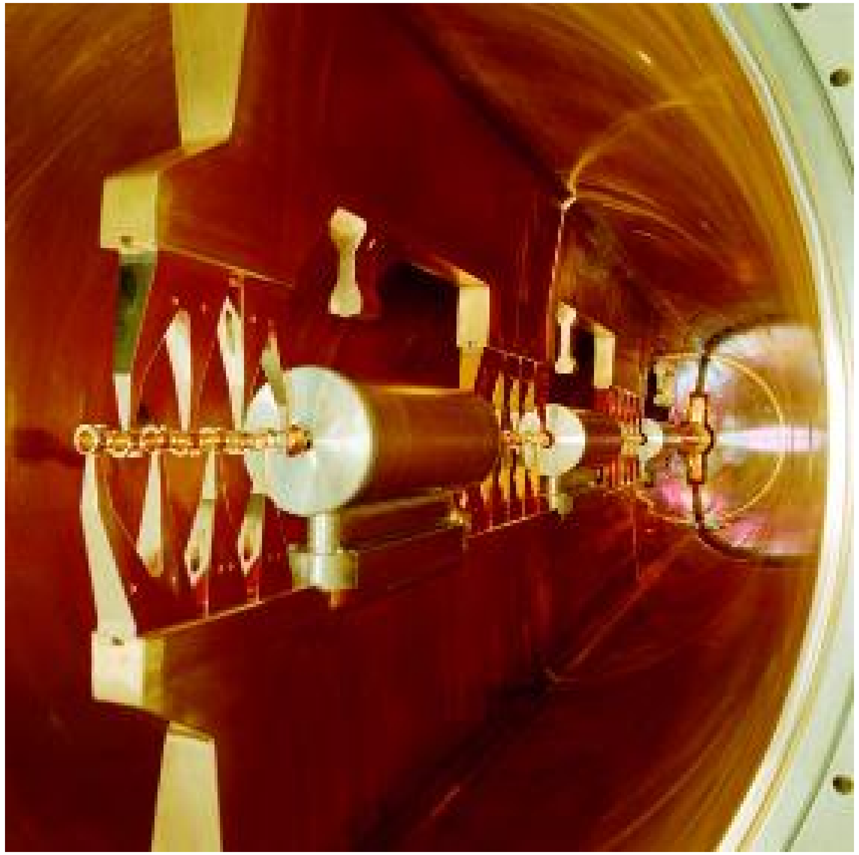
- GSI-Unilac: U^{4+}, 15 mA, and U^{28+} injectors, 1.4 A MeV
- CERN – Linac3 for LHC: Pb^{27+} injector, 4.2 A MeV
- BNL – EBIS injector for RHIC, Au^{27+}, 2 A MeV
- Dubna – NICA HILAC, Au^{30+}, 3.2 A MeV
- Dubna – NICA LILAC, C^{4+}, 15 mA, 7 A MeV (under constr.)
- Several tumor therapy centers, C^{4+}, 7 A MeV



$H_{11(0)}$ Mode

C^{4+}

217 MHz,
20 MV, 3.8 m
0.4 – 7 A MeV
900 kW



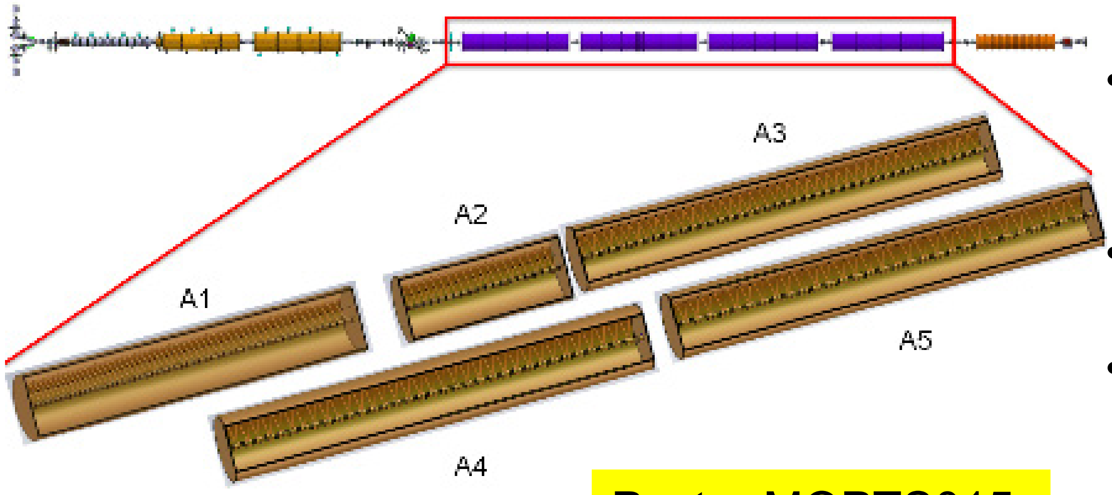
$36\ MHz, 38\ MV, 9\ m, \emptyset = 2m$
$120\ - 743\ A\ keV, 950\ kW$

U^{4+}

RT DTL's

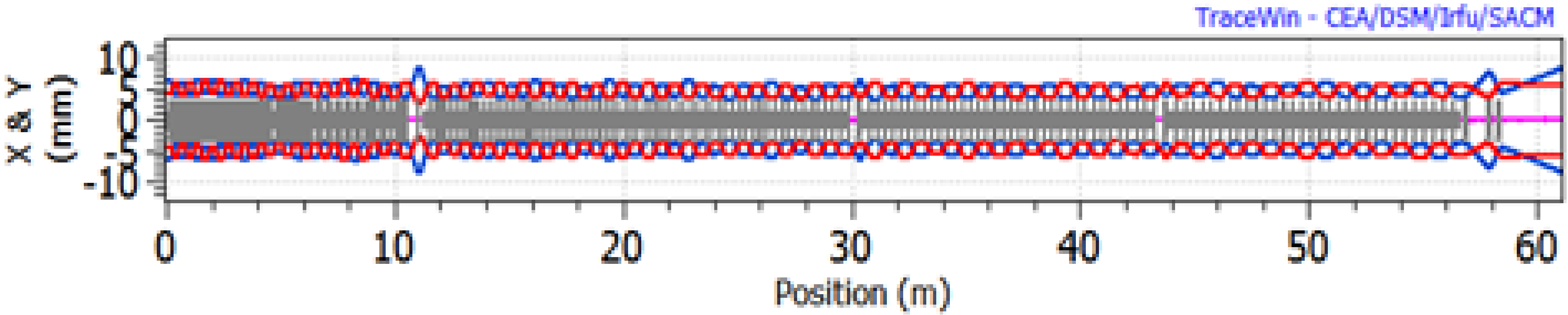
Alvarez – DTL is used for driver beams at:

- GSI-Unilac: U^{28+} , 20 mA, 1.4 – 11.4 A MeV (since 1975)



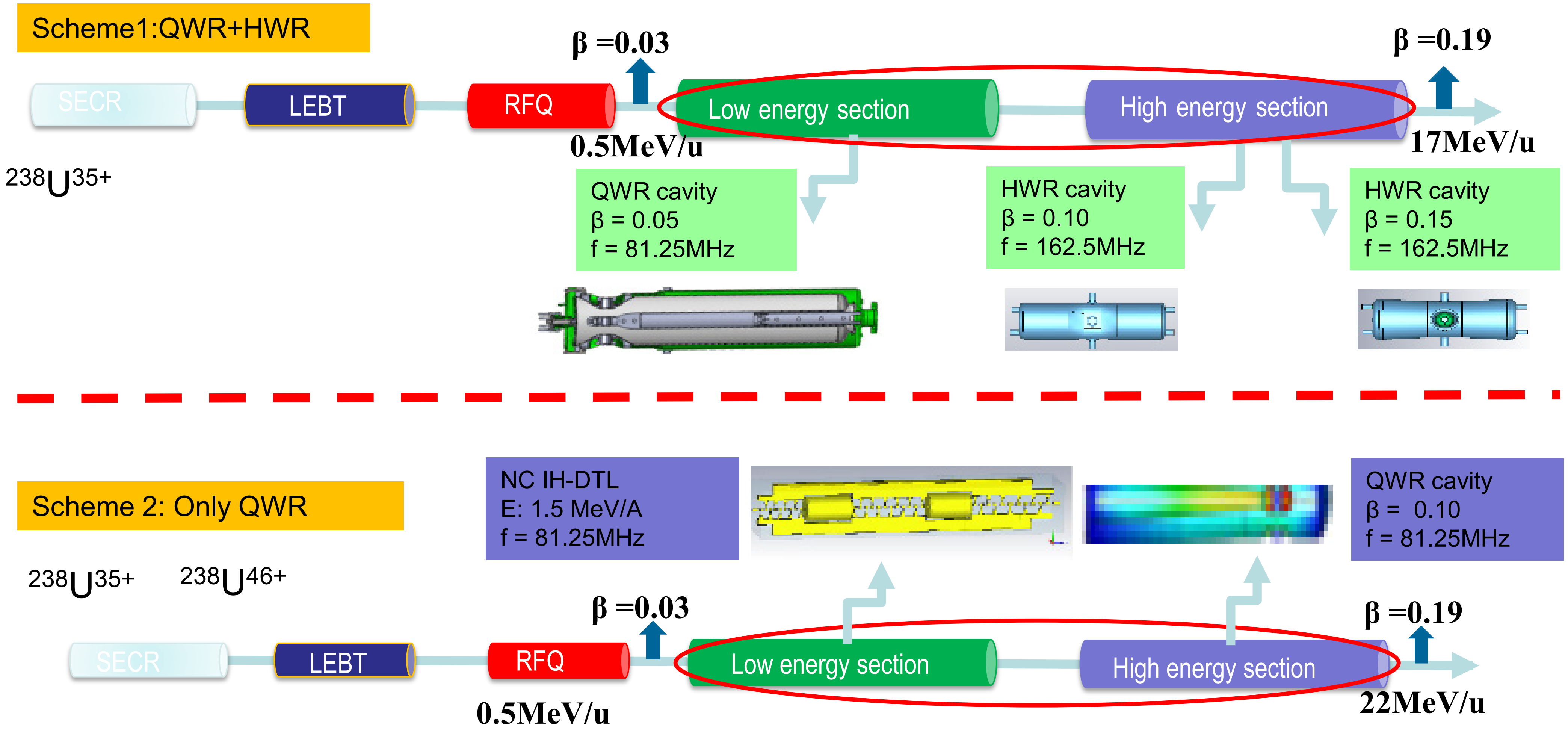
Poster MOPTS015

- Replacement of A1-A4 by current optimized Alvarez-DTL design, low duty factor
- production of the first-of-series (FoS) cavity section is ongoing
- external production of big parts: mantle and end plates
- internal production of smaller parts (spare part management)
- GSI's galvanic workshop can Cu-plate big & small parts



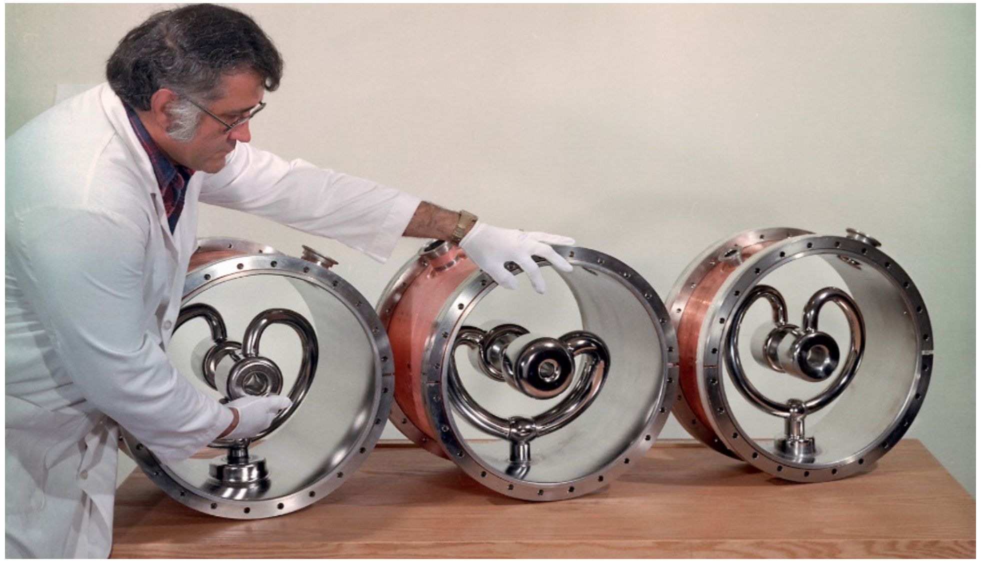
Transition RT to SC DTL

- FRIB, RISP, HIAF get 500 A keV from the RFQ.
- FRIB and RISP directly inject into SC - 2 gap - QWR‘s
- HIAF is discussing an alternative: IH-DTL up to 1.5 A MeV (Scheme2, $P \cong 100\ kW$):

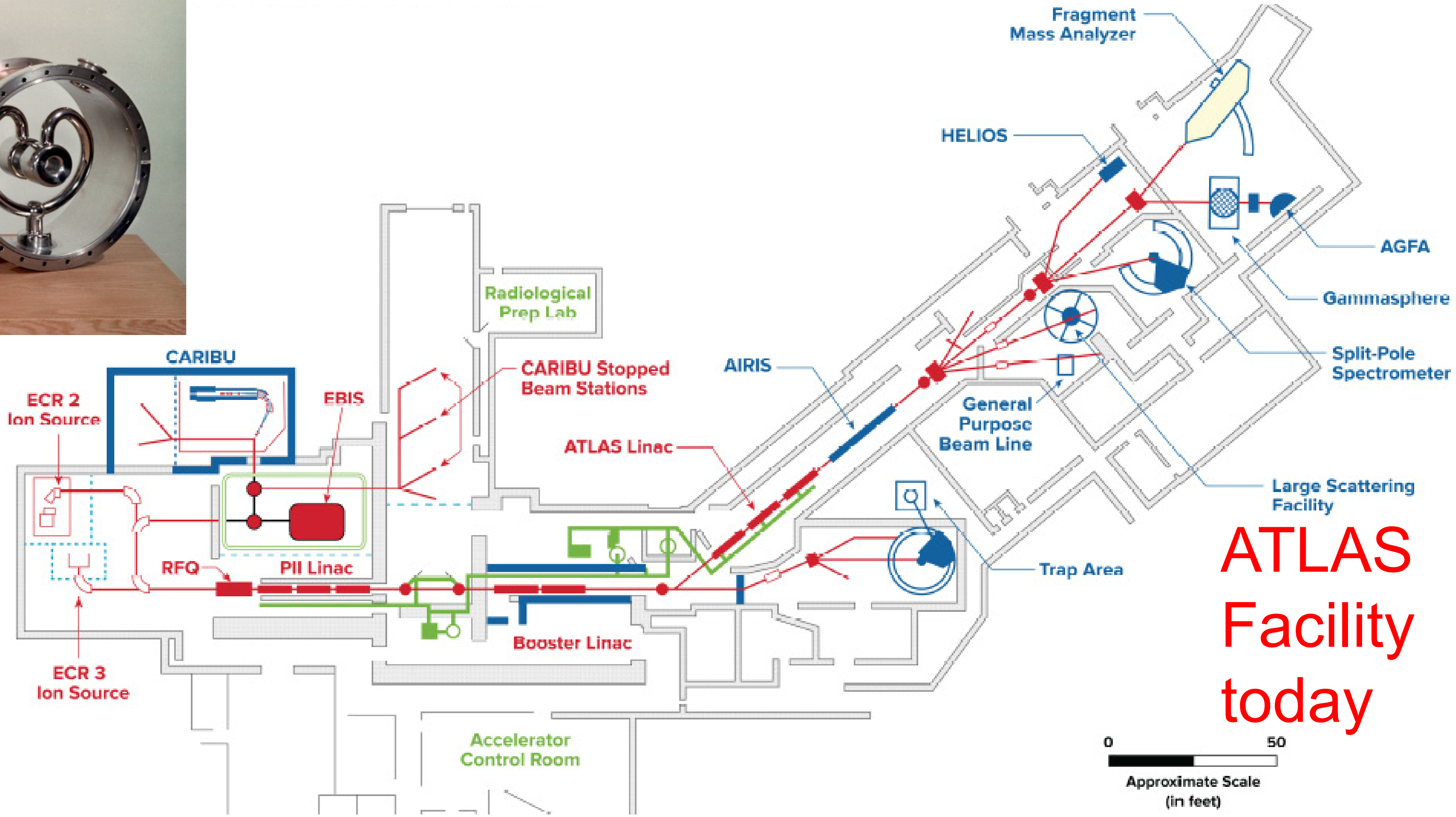


SC DTL's

The first SC heavy ion linac was developed by L.M. Bollinger et al. at ANL.
Beams since 1981. Split – Ring 3 gap resonators, later 4 gap QWR's for PII



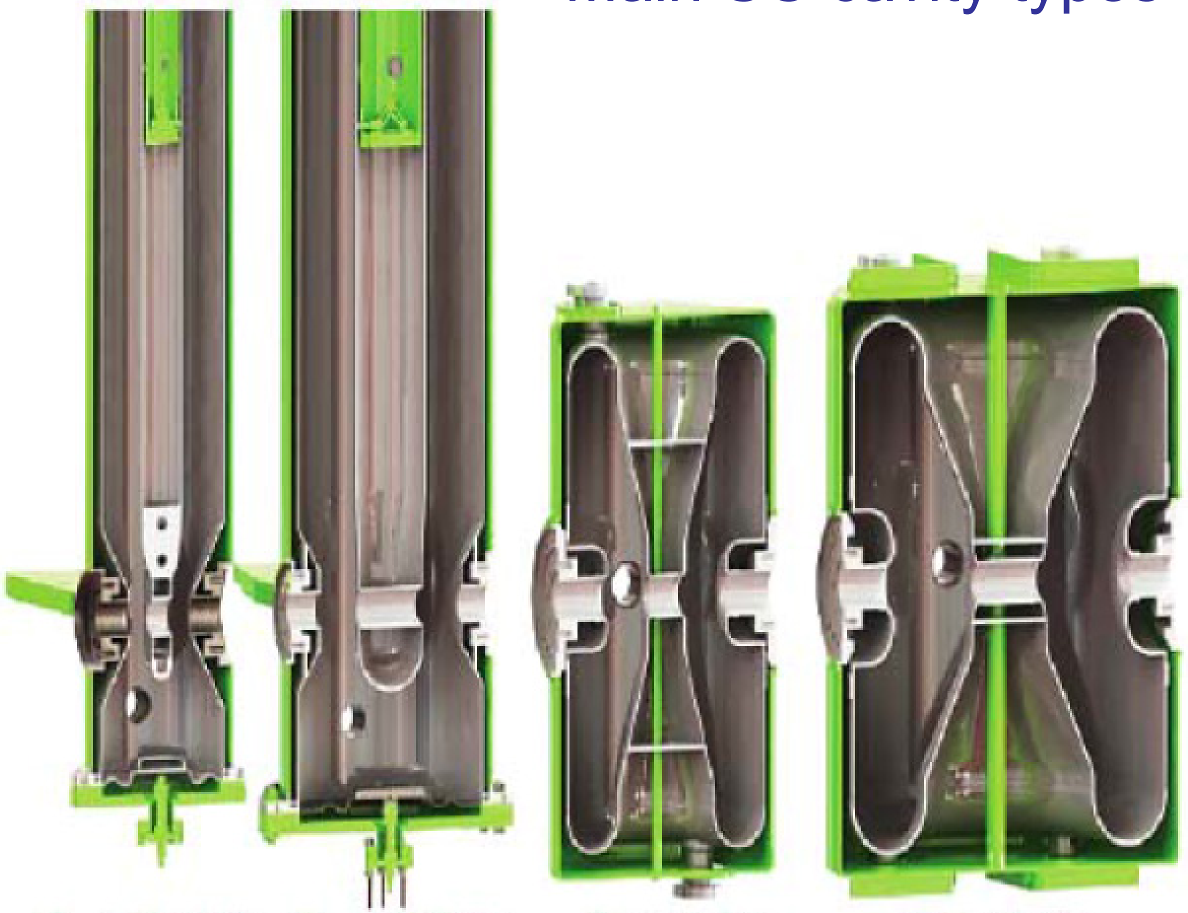
Cavity development
at ANL, Argonne
K.W. *Shepard* et al.



ATLAS Facility today

SC DTL's

Main SC cavity types used today for heavy ions:



- Quarter wave resonators QWR, 2 gaps
- Half wave resonators HWR, 2 gaps

Example: FRIB cavities

A. Facco et al. Proc. of IPAC12, New Orleans p. 61

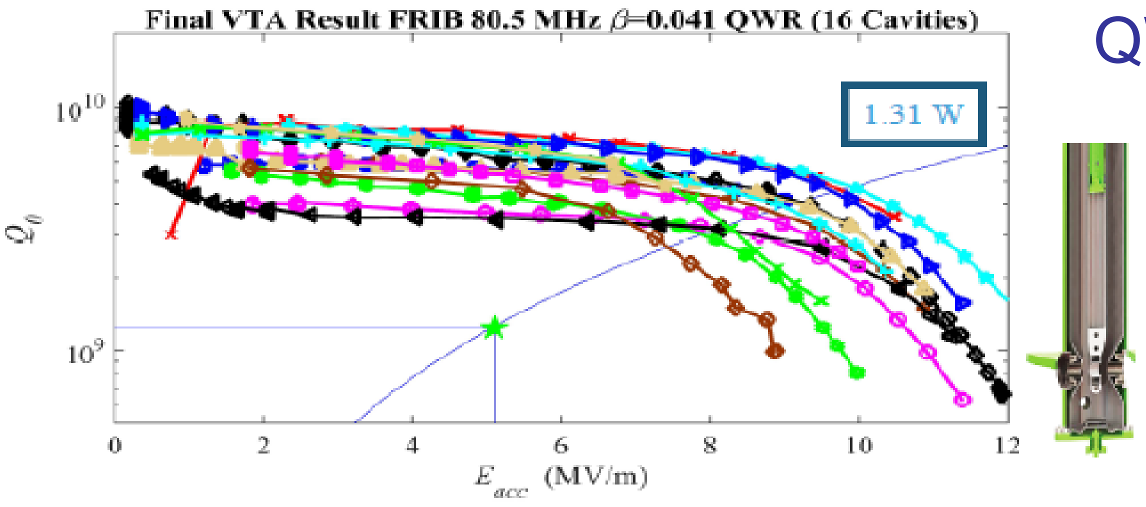
Resonator	QWR1	QWR2	HWR1	HWR2
β_0	0.041	0.085	0.29	0.53
f (MHz)	80.5	80.5	322	322
V_a (MV)	0.81	1.8	2.1	3.7
E_p (MV/m)	31	33	33	26

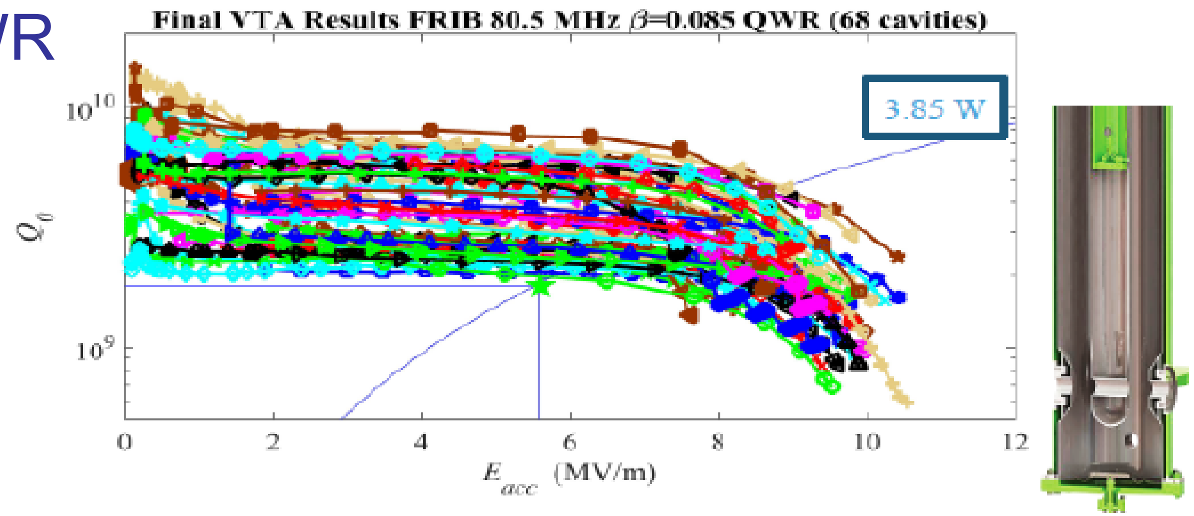
SC DTL's

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

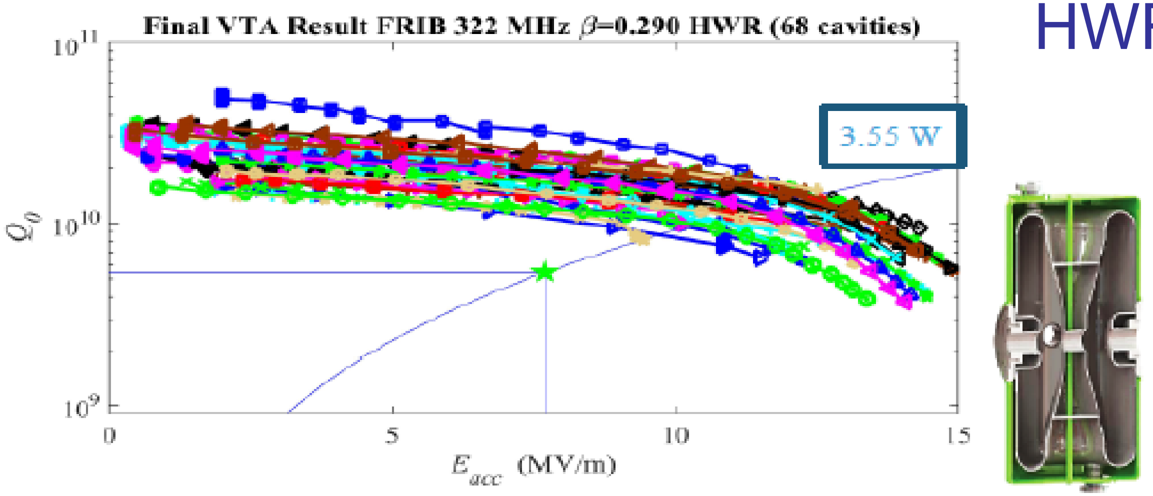
Example: FRIB cavities continued

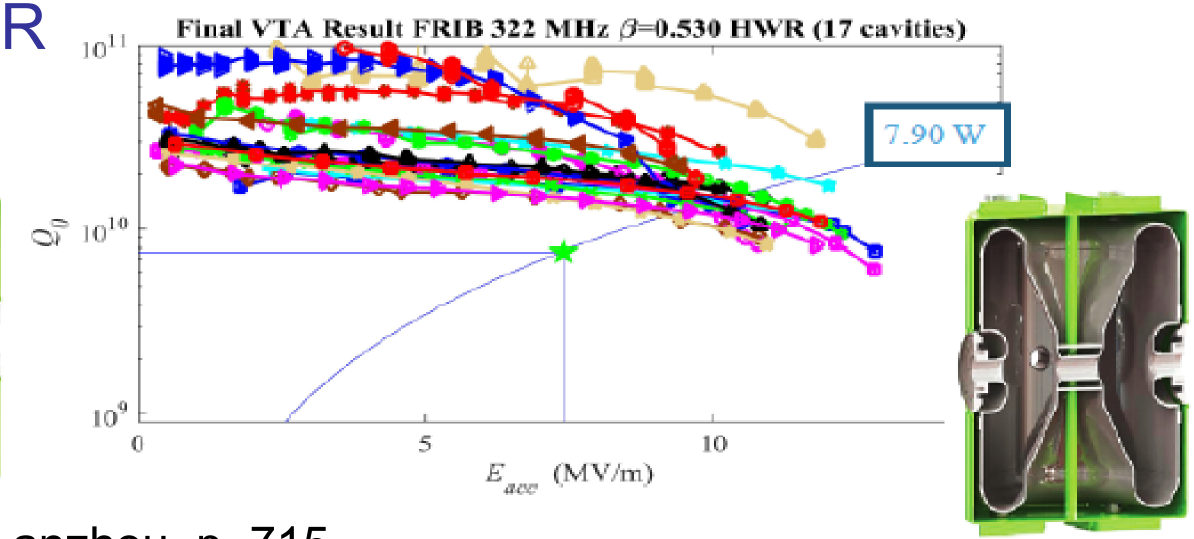
QWR





HWR



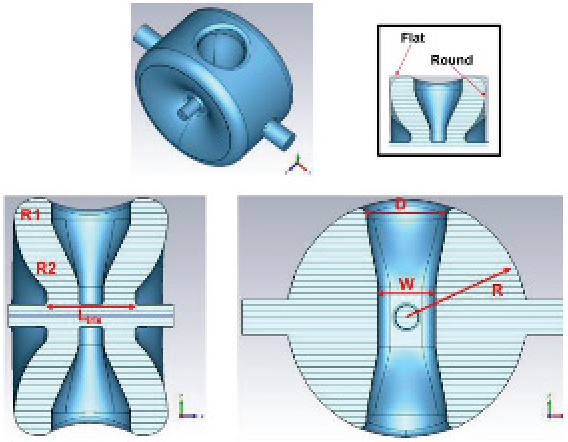


J.T. Popielarski et al. Proc. of 2017 SRF workshop Lanzhou, p. 715

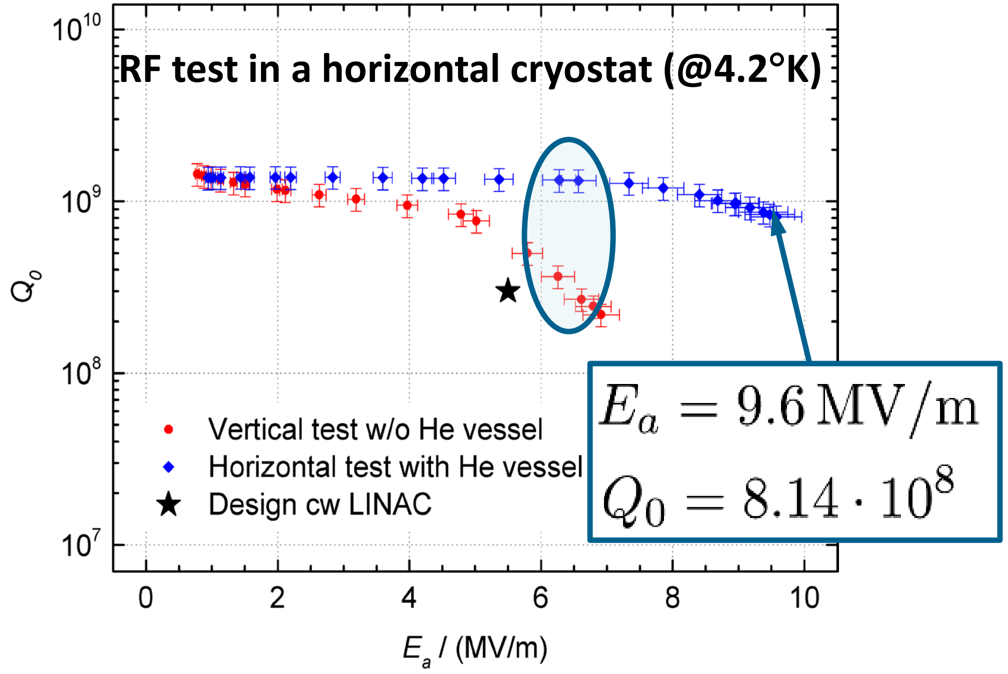
SC DTL's

- Baloon type Single Spoke
  325 MHz development at RAON

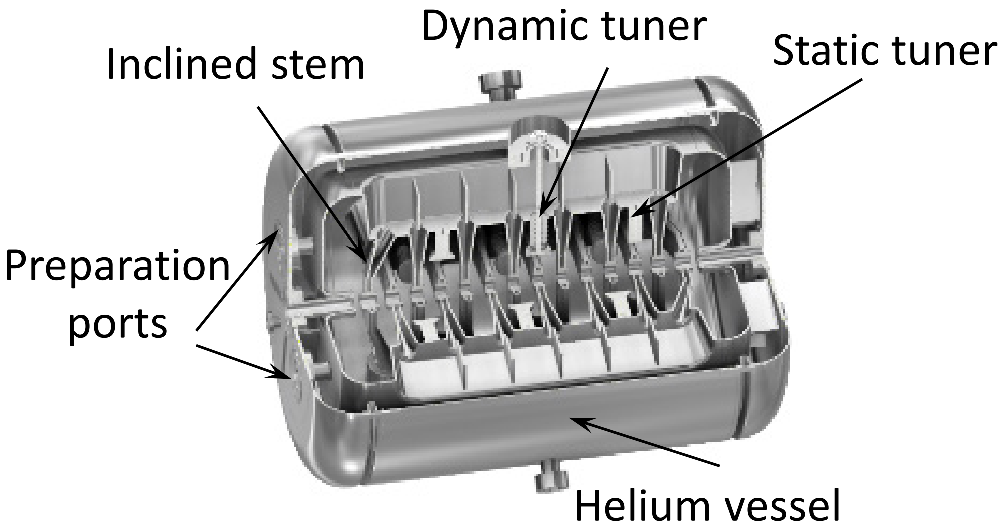
D. Jeon et al., Proc. SRF2017, Lanzhou, p.36



- CH cavity development
  The only multi-cell cavity for the low - β range Investigations at 217 MHz with beam (EQUUS dynamics), IAP Frankfurt, GSI Darmstadt, HIM Mainz

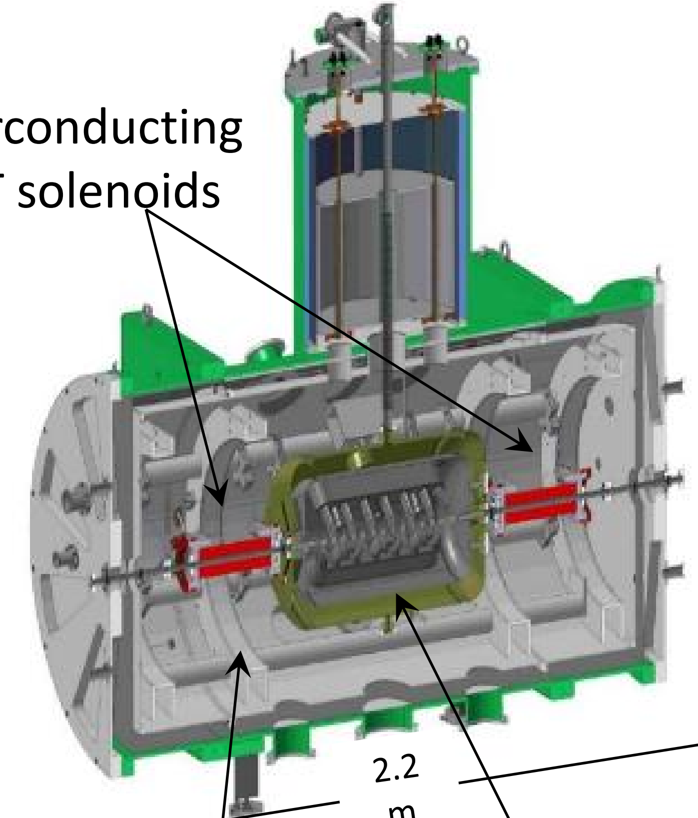


F. Dziuba et al., Proc. LINAC2018, p. 859

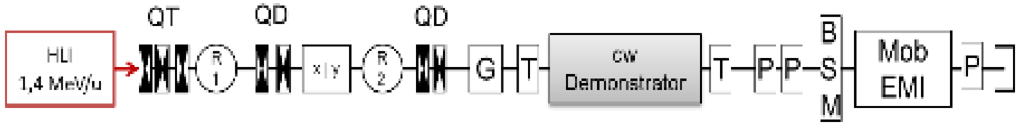


SC DTL's

Layout of the horizontal cryomodule



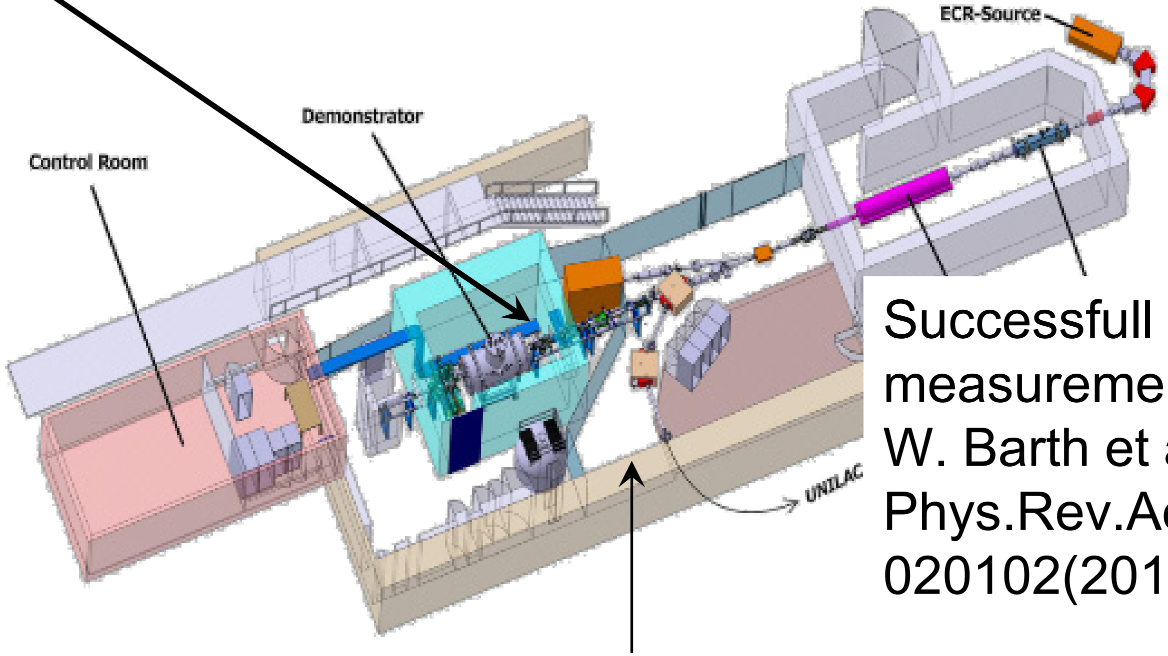
Matching line - demonstrator – test bench



- Steering magnets
- Rebuncher
- Quadrupole doublet
- Profile grids

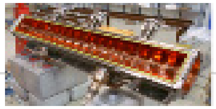
- Phase probes for TOF measurement
- Beam current transformers
- Bunch shape monitor (Feschenko)
- Emittance measurement

Demonstrator at GSI-High Charge State Injector (HLI)

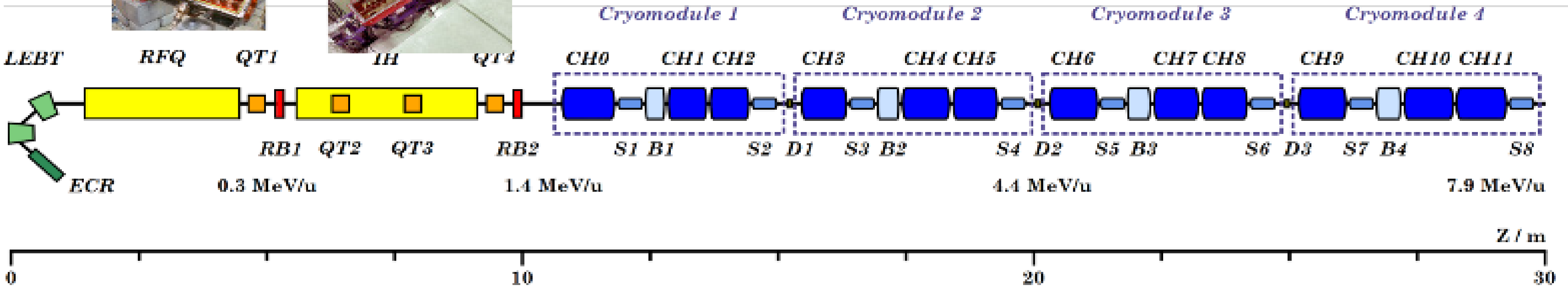


Successfull beam measurements during 2018: W. Barth et al., Phys.Rev.Acc.and Beams 21, 020102(2018)

Facilities existing or under construction



GSI CW accelerator Layout

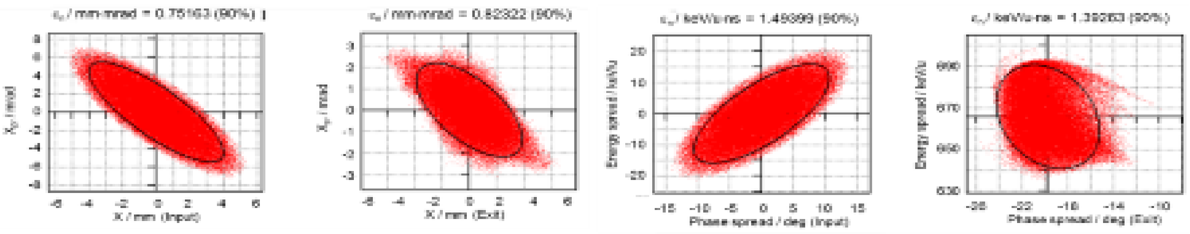


Poster MOPTS034 and next talk

Courtesy: W. Barth

Input CM1

Output CM4

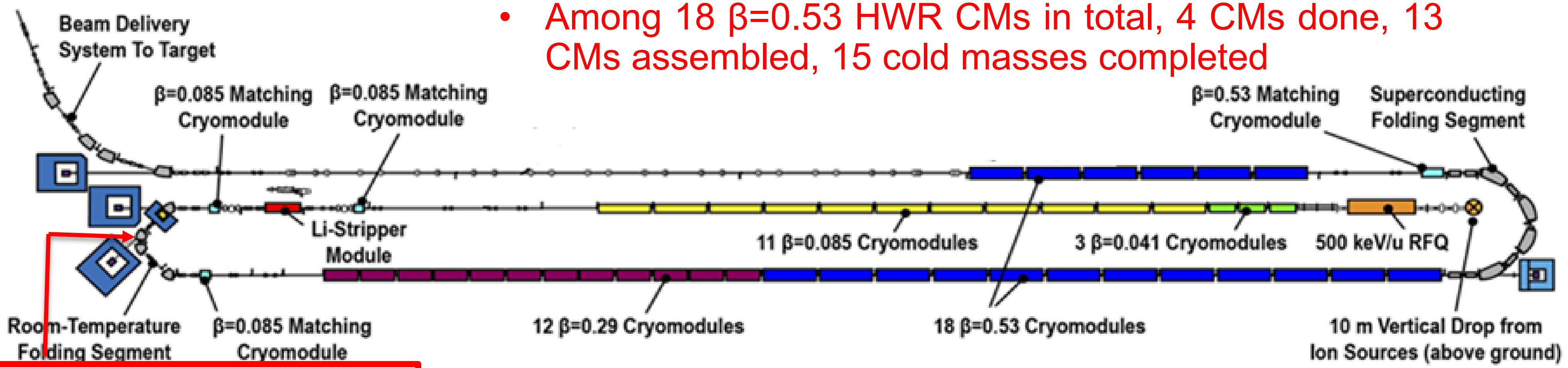


- Total of 12 CH cavities
- Each cryo module contains 3 CH cavities + 1 rebuncher + 2 solenoids
- Variable beam energy 3.6-7.5 MeV/u

Cryo Module	Cavity	Output energy (MeV/u)		
		A/Z=6	*A/Z=3*	*A/Z=1*
	HLI	*1.4*	*1.4*	*1.4*
CM1	CH0	2.1	2.2	3.0
	CH1	2.6	3.0	4.2
	CH2	2.9	3.6	4.6
CM2	CH3	3.4	4.3	5.7
	CH4	3.8	4.8	6.3
	CH5	4.2	5.5	7.7
CM3	CH6	4.7	6.2	8.6
	CH7	5.2	7.0	9.9
	CH8	5.8	7.8	10.9
CM4	CH9	6.4	8.7	12.3
	CH10	7.0	9.5	13.2
	CH11	7.6	10.5	14.6

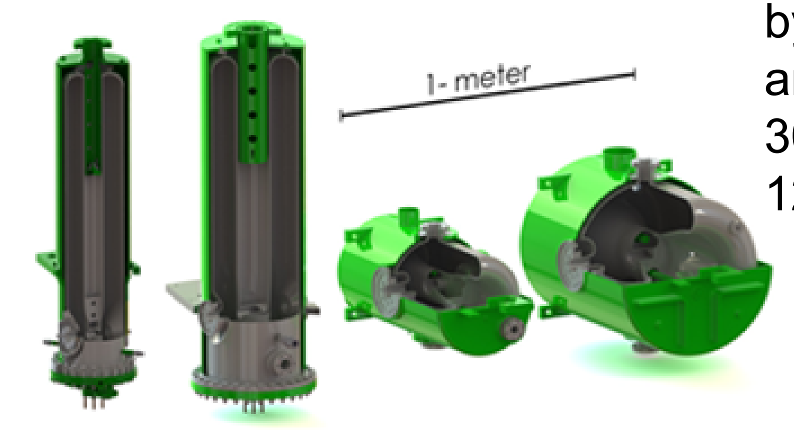
FRIB 200 MeV/u, 400 kW, all stable ions to be accelerated, 4 Types of Superconducting (SC) Cavities, 6 Types of Cryomodules (CMs) with 69 SC Solenoids, 138 SC correctors, and beam position monitors inside

- Among 18 β=0.53 HWR CMs in total, 4 CMs done, 13 CMs assembled, 15 cold masses completed



Beam commissioned to here

44 cold masses and
38 CMs completed
30 CMs "done" (certified by cold, high-power test, and installed to the tunnel)
30 cavities left to certify,
12 cavities left to receive



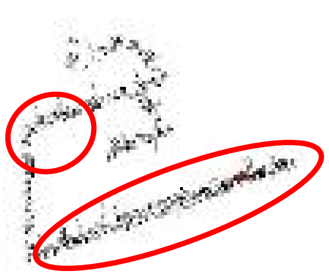
β = 0.041 cavity β = 0.085 cavity β = 0.29 cavity β = 0.53 cavity

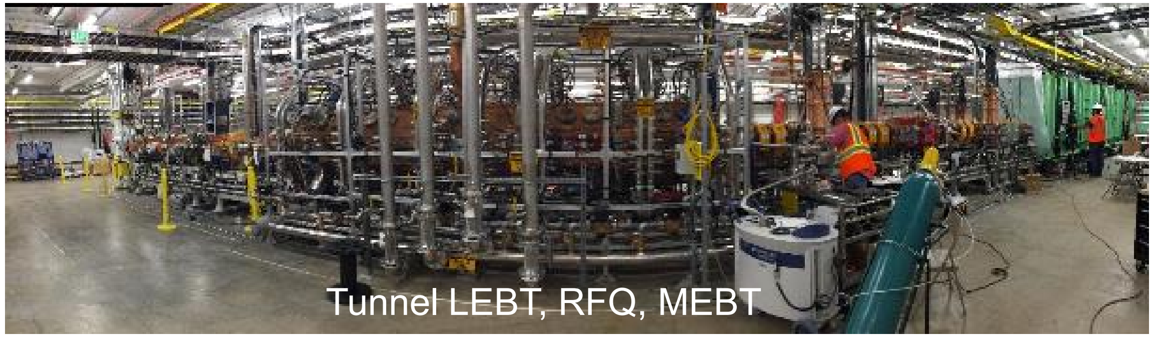
β	Type	Cryomodules	Cavities	Solenoids
Quarter Wave Resonator (QWR) Cryomodule				
		Component Counts (baseline + spares)		
0.041	accelerating	3 + 1 done	12 + 4	6 + 2
0.085	accelerating	11 done + 1	88 + 8	33 + 3
	matching	1 done + 1	4 + 4	-
Half Wave Resonator (HWR) Cryomodule				
0.29	accelerating	12 done	72	12
0.53	accelerating	18 *	144	18
	matching	1	4	-
TOTALS		46 + 3	324 + 16	69 + 5

FRIB

Stage 2 and 3 Beam Commissioning Goals accomplished within 1 week, respectively, becoming world's highest energy CW hadron linac 100 % transmission (meas. accuracy better than 1 %)

- August 2014: Technical construction started
- Staged beam commissioning with installation in parallel
  - Stage 1: Low Energy Beam Transport (LEBT), RFQ, Medium EBT: done
  - Stage 2: All β=0.041 CMs: done
  - Stage 3: Linac Segment 1 (all β= 0.041 and β=0.085 QWR CMs) just done. Ar, Ne, Kr, Xe were accelerated up to 20.3 MeV/u
  - Stage 4: Linac Segment 2 (all β= 0.29 and 12 β=0.53 HWR CMs) planned in Mar, 2020
- December 2021: Forecast early completion (June 2022: Baseline Critical Dedision-4 (project completion))



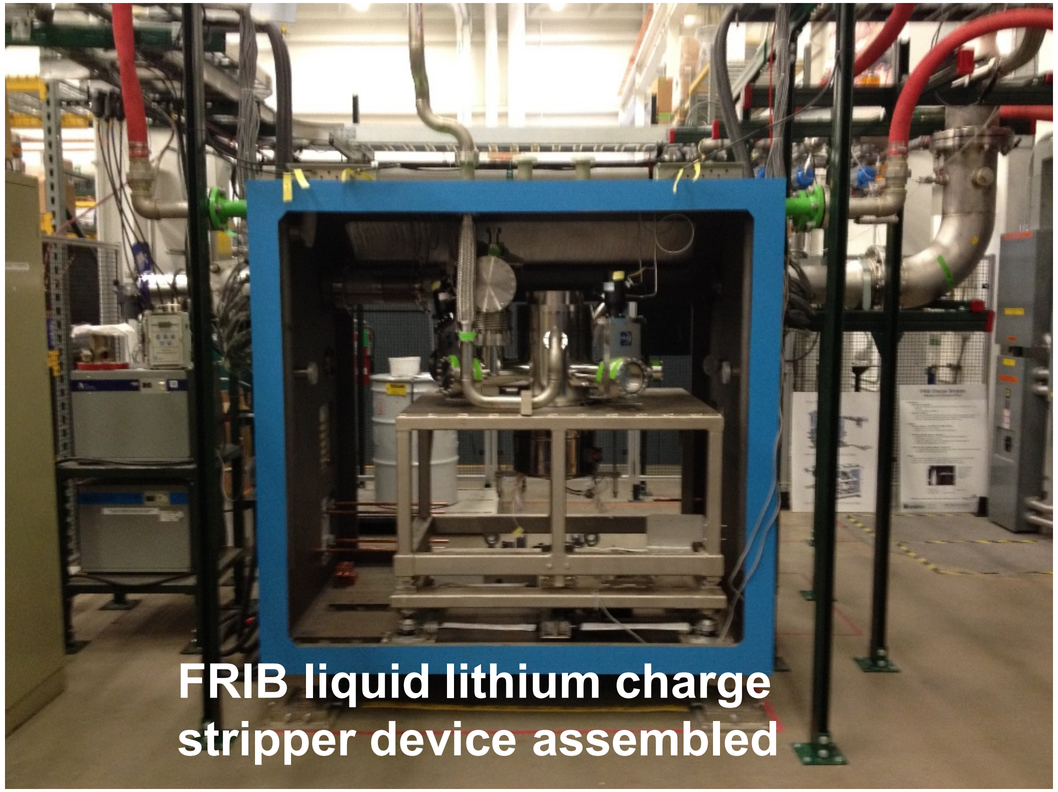


Transverse focusing by 9 T solenoids, integrated in cryomodules

FRIB

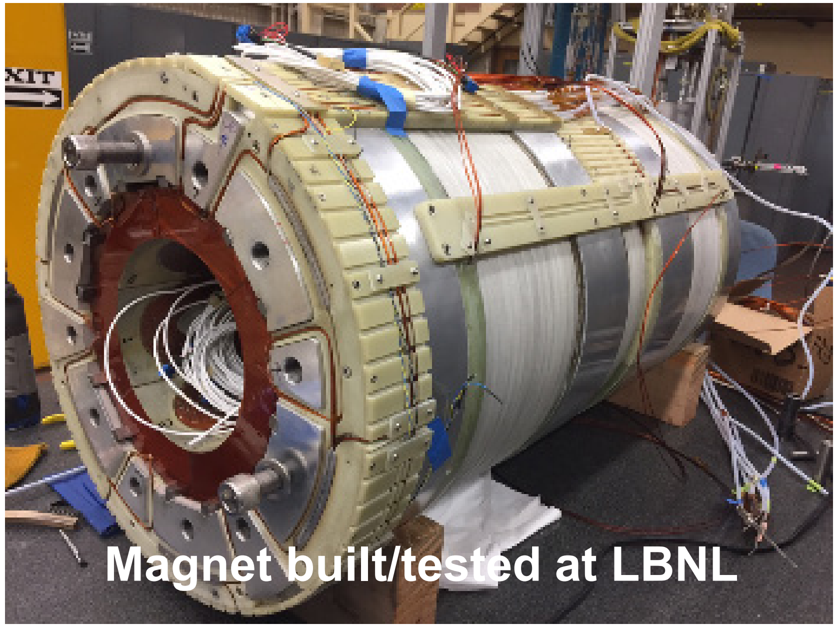
Liquid Lithium Charge Stripper System Established

More than 10 days Continuous Operations Completed



Superconducting ECR ion source is on track

- Assembly to be completed in 2019
  - Magnet was completed and tested at LBNL
  - Cryostat assembly started March 2019
  - Coldmass instrumentation assembly in process on the helium vessel
- Test in 2020



Facility under construction

The RAON facility in South Korea is under construction. The RISP project developes a driver linac with similar beam characteristics like FRIB.

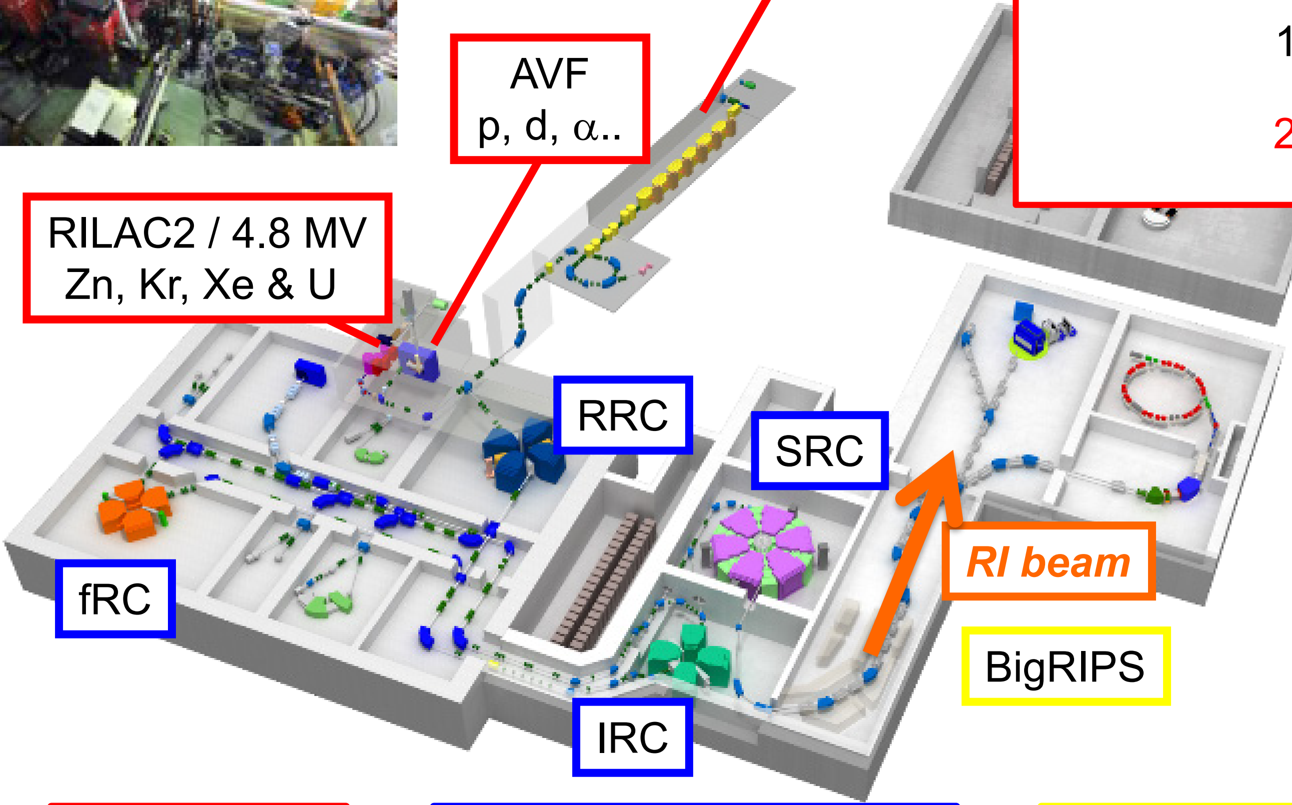
For more details see :

D. Jeon et al., Proc. SRF2017, Lanzhou, p.36
P. Ostroumov, Proc. of the LINAC18, Beijing, Slides

RI Beam Factory (RIBF) at RIKEN

Y. Yano, NIM B261 (2007) 1009
H. Okuno et al., PTEP 2012 03C002

2 HI linacs



Beam intensities @ SRC

^{48}Ca: 738 pnA → ***12.3 kW***

^{78}Kr : 486 pnA → ***13.1 kW***

^{124}Xe: 102 pnA → ***4.4 kW***

^{238}U : 72 pnA → ***5.9 kW***

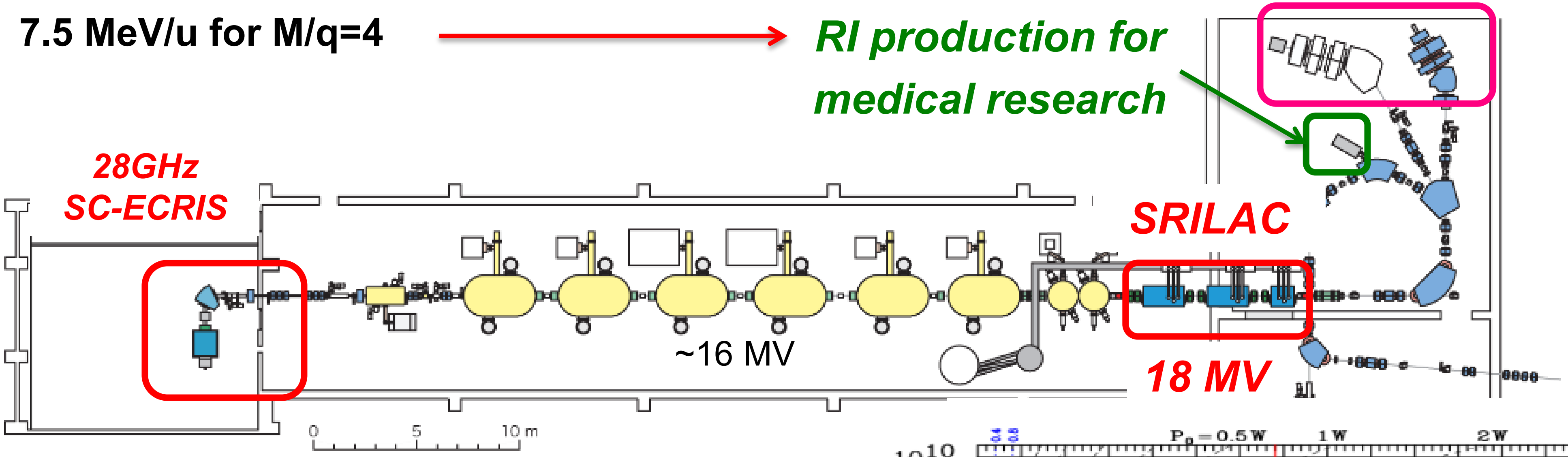
3 Injectors + 4 Booster cyclotrons + RI Beam separator

→ ***ALL*** ions can be accelerated up to 345 MeV/u (70% of *c*) in ***CW*** mode.

N. Sakamoto et al., LINAC2018

E: 6.5 MeV/u for M/q=6 → ***Super Heavy Elements: Z ≧ 119***

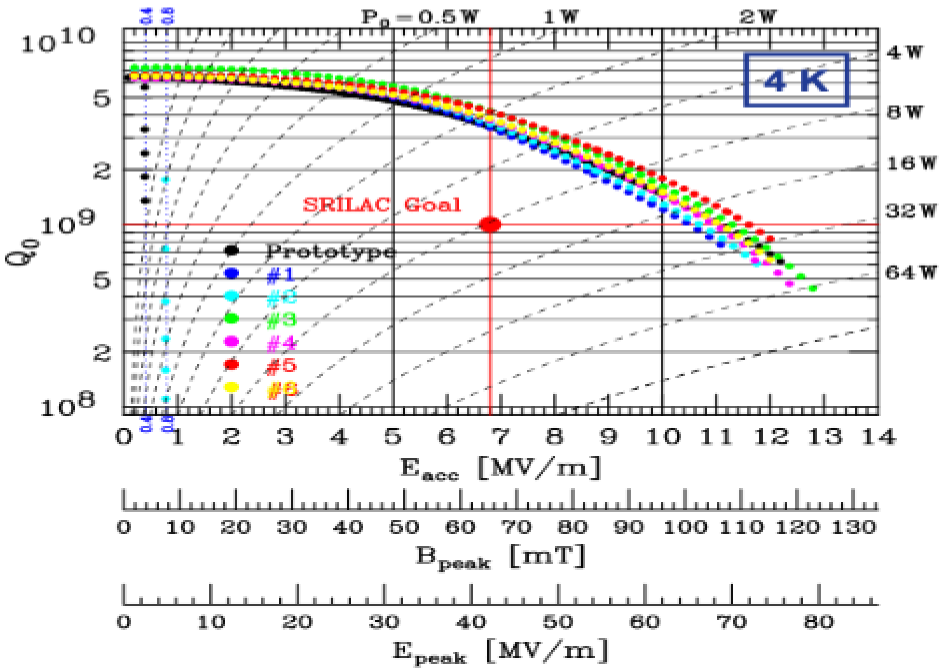
7.5 MeV/u for M/q=4 → ***RI production for medical research***



10 QWRs in 3 CMs installed in FY2018

To be presented at SRF2019

Frequency (MHz)	73.0
Optimum β	0.08
R_{sh}/Q_0 (Ω)	578
G (=R_{sh}/Q_0)	22.4
E_{acc} (MV/m)	6.8
E_{peak}/E_{acc}	6.0
B_{peak}/E_{acc}	9.5
Target Q_0	1×10^9 (4 K)



Pulsed synchrotron injector linacs

Injectors for carbon therapy, C^{4+} from ECR

- At first a very big linac at HIMAC, Chiba, Japan (4-Vane RFQ and Alvarez-DTL, $\cong 30m$)

- 7 A MeV, 5m linac for HIT Heidelberg, Germany
  (217 MHz, 4-Rod RFQ and IH-DTL with KONUS dyn.)

  B. Schlitt Proc. of the LINAC08 Conf., Victoria, BC, Canada, p. 720-724

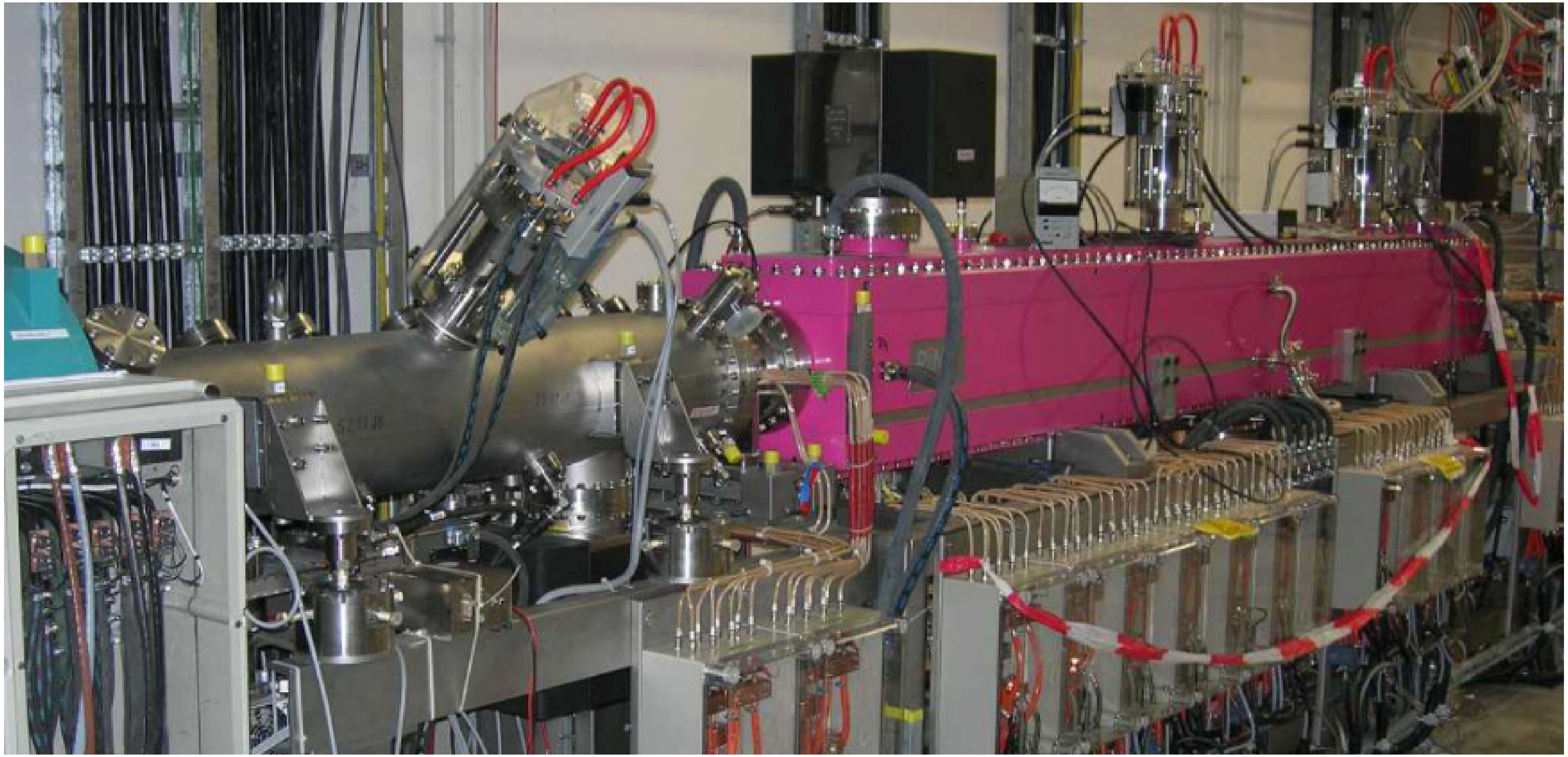
- 4 A MeV , 6m linac for Gunma University, Japan
  (200 MHz, 4-Vane RFQ and IH-DTL with APF dyn.)

  T. Ohno et al., Carbon ion therapy at the Gunma University Heavy Ion Medical Center: new facility set-up, Cancers 2011,3, p. 4046.

Pulsed synchrotron injector linacs

Example: 217 MHz Carbon linac from GSI/IAP

21 MV C^{4+} injector for medical synchrotrons: 217 MHz 4-Rod-RFQ & IH-DTL with KONUS dynamics



IAP Frankfurt and GSI Darmstadt. Commissioning report:
B. Schlitt, Proc. of the LINAC08 Conf., Victoria, BC, Canada, p. 720-724

Pulsed synchrotron injector linacs

In operation at big facilities:

- CERN Linac3 → LEIR→ PS→ SPS→ LHC Poster MOPGW069

Linac3: ECR→Ladder-RFQ→IH – DTL, 101/202 MHz, 4.2 A MeV

The Linac is the pre-injector supplying beam for the LHC, fixed target experiments from the Super Proton Synchrotron, and for radiation to electronics tests. It typically runs with 1 ion type per year (charge state out of Linac given). Transmission improved by removing an aperture restriction behind the source.

In operation since 1994.

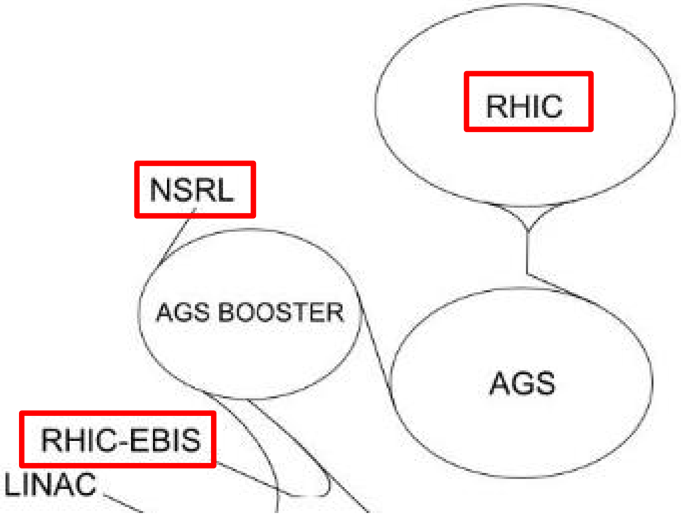
Data from D. Kuchler, CERN

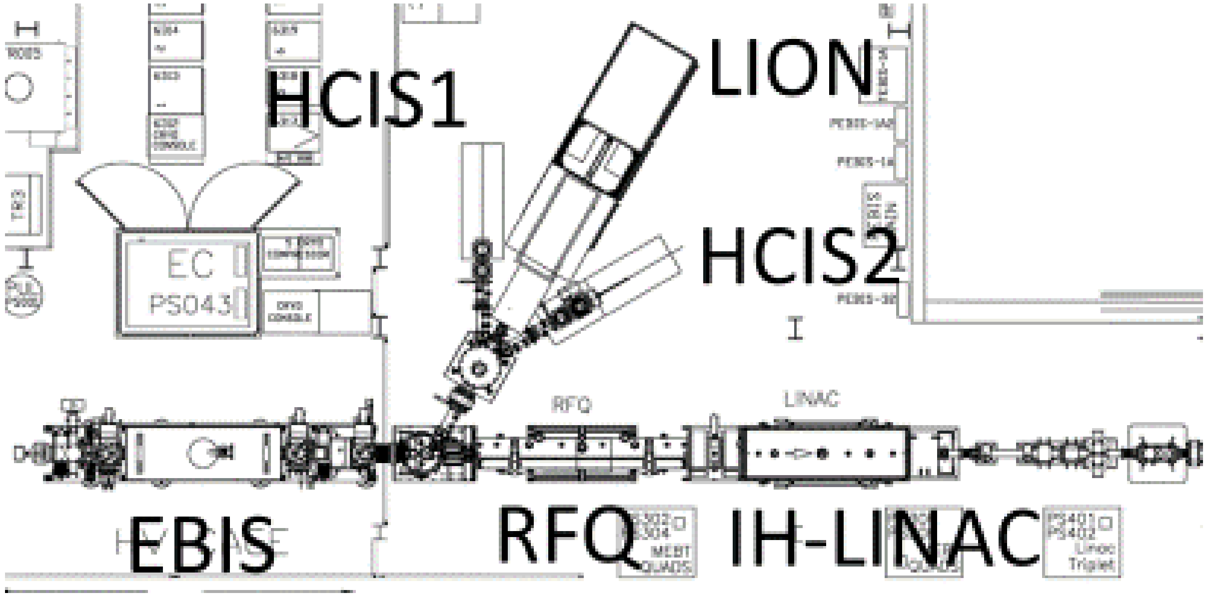
Year	Element	Mass	Source		Exit Linac	
			Charge State	Current	Charge State	Current
15,16,18	Lead	208	29+	170 uA	54+	30 uA
14	Argon	40	11+	100 uA	11+	60 uA
17	Xenon	129	22+	160 uA	39+	30 uA

Pulsed synchrotron injector linacs

• BNL EBIS Linac

- Primary 1+ ion from external Laser ION source (LION) and Hallow Cathode Ion Sources (HCIS)
- Electron Beam Ion Source (EBIS) as charge multiplier
- RFQ from 17 keV/u to 300 keV/u, 100 MHz
- IH- Linac from 300 keV/u to 2 MeV/u, 100 MHz
- 1 Rebuncher and 2 Debunchers , 100 MHz
- In operation since 2010



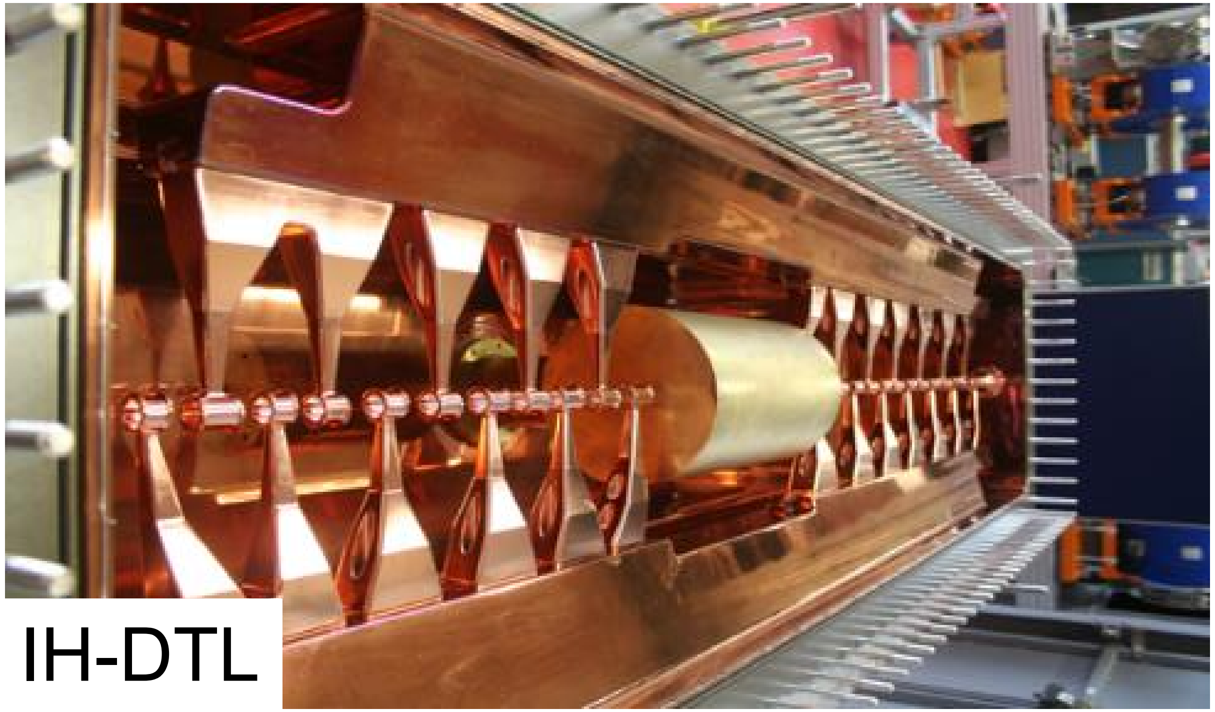


Pulsed synchrotron injector linacs

BNL EBIS Preinjector Operation

- Operate about 9 months per year with very high reliability.
- Automized more than 100 ion species switches/day, switching time ~40 sec .
- Routinely provide multiple ion species for NSRL simultaneously with RHIC.
- List of ions from BNL EBIS preinjector:
  p,d, $He^{1+,2+}$, $^{3}He^{2+}$,Li^{3+}, $C^{5+,6+}$, $O^{7+,8+}$, Ne^{5+},Al^{11+}, $Si^{11+,13+}$, Ar^{11+},Ca^{14+}, Ti^{18+},$Fe^{20+,24+}$, Cu^{11+}, Kr^{27+}, Zr^{16+}, Nb^{16+}, $Xe^{27+,35+}$ Ta^{38+}, $Au^{32+,42+}$, Pb^{34+}, $Th^{39+,48+}$,U^{39+}


4-Rod RFQ


IH-DTL

Pulsed synchrotron injector linacs under development

- HILAC and LILAC injectors for the NICA – project in Dubna,

HILAC: EBIS→ 4-Rod-RFQ→ IH-DTL combination;

$A/q \leq 6.5;\ I \leq 5\ \mathrm{mA}, 100\ MHz, 2\ IH\ - tanks, W_f = 3.2\ A\ MeV;$

Design ion Pb^{32+}. Running in with beam beam was successful.

Low level RF still under improvement.

LILAC: [Pol. p, d sources and Carbon Laser source] → 4-Rod-RFQ→ IH-DTL combination; 162.5 MHz

$A/q \leq 3;\ I \leq 15\ \mathrm{mA}, 100\ MHz, 2\ IH\ - tanks,\ W_f = 7\ A\ MeV;$

Pulsed synchrotron injector linacs under development

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

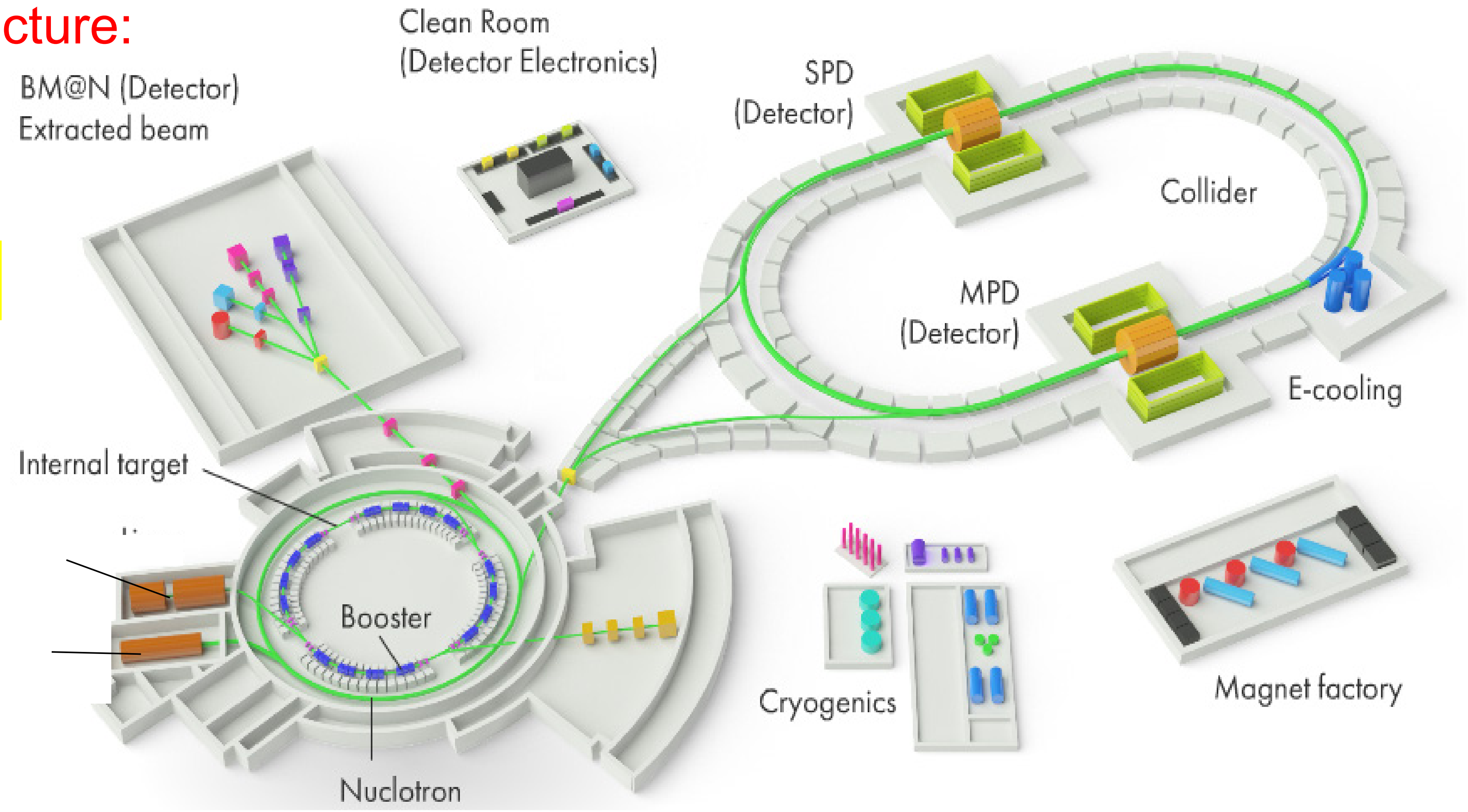
Scheme of the NICA complex with two Injector Linacs

LINAC RF Pulse structure:
$200\mu s, \leq 10\ Hz$

Poster MOPMP014

HILAC

LILAC



Beam Current: $\leq 10\ mA$ for HILAC, $\leq 15\ mA$ for LILAC

Pulsed synchrotron injector linacs under development

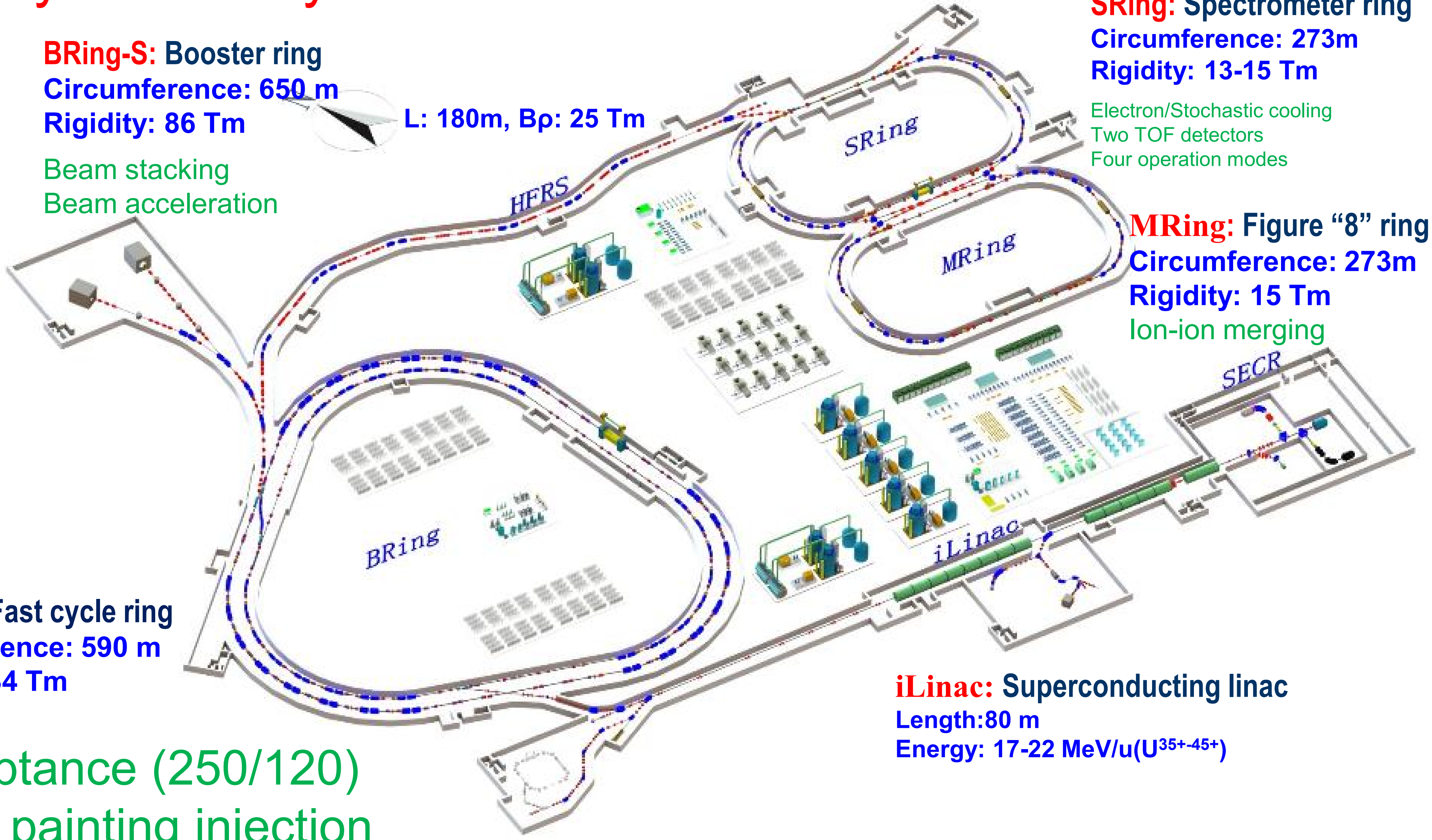
New Heavy Ion facility HIAF in China

BRing-S: Booster ring
Circumference: 650 m
Rigidity: 86 Tm
Beam stacking
Beam acceleration

L: 180m, Bρ: 25 Tm

SRing: Spectrometer ring
Circumference: 273m
Rigidity: 13-15 Tm
Electron/Stochastic cooling
Two TOF detectors
Four operation modes

MRing: Figure "8" ring
Circumference: 273m
Rigidity: 15 Tm
Ion-ion merging



BRing-N: Fast cycle ring
Circumference: 590 m
Rigidity: 34 Tm

iLinac: Superconducting linac
Length:80 m
Energy: 17-22 MeV/u($U^{35+-45+}$)

Large acceptance (250/120)
Two planes painting injection
Fast ramping rate（3-5-10Hz, 20Hz）

BRing-N and MRing will be built in PHASE II

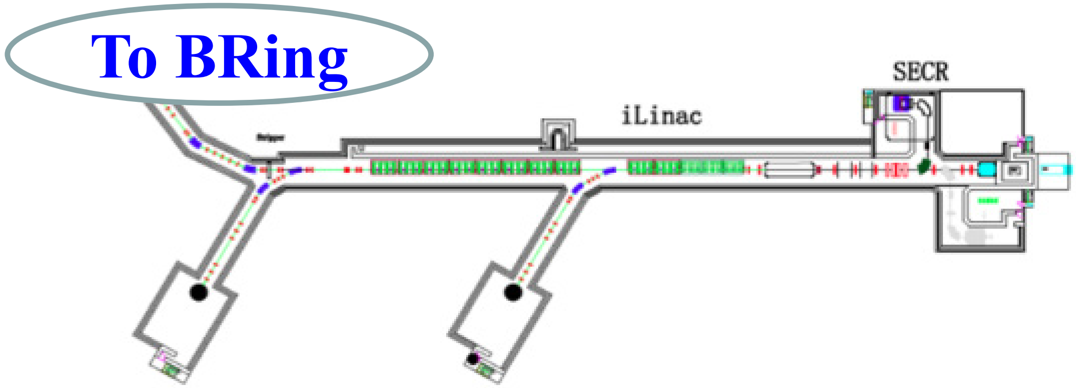
HIAF

iLinac operation mode

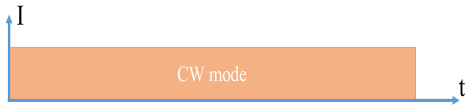
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Phase I: 17-22 MeV/A

Phase II: 100-200 MeV/A

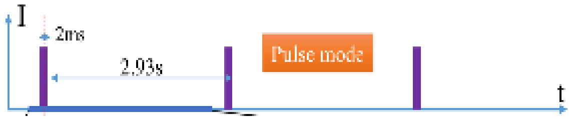


CW mode
Independent machine



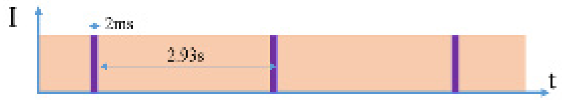
$^{16}O^{6+}$ 1 emA
$^{129}Xe^{27+}$ 1 emA
$^{209}Bi^{31+}$ 1 emA
$^{238}U^{35+}$ 0.7 emA

Pulsed mode
BRing injector only



$^{16}O^{6+}$ 2 emA
$^{129}Xe^{27+}$ 2 emA
$^{209}Bi^{31+}$ 1.5 emA
$^{238}U^{35+}$ 1 emA
0.3-5 Hz/0.2-2 ms

Parallel mode
BRing and experiments



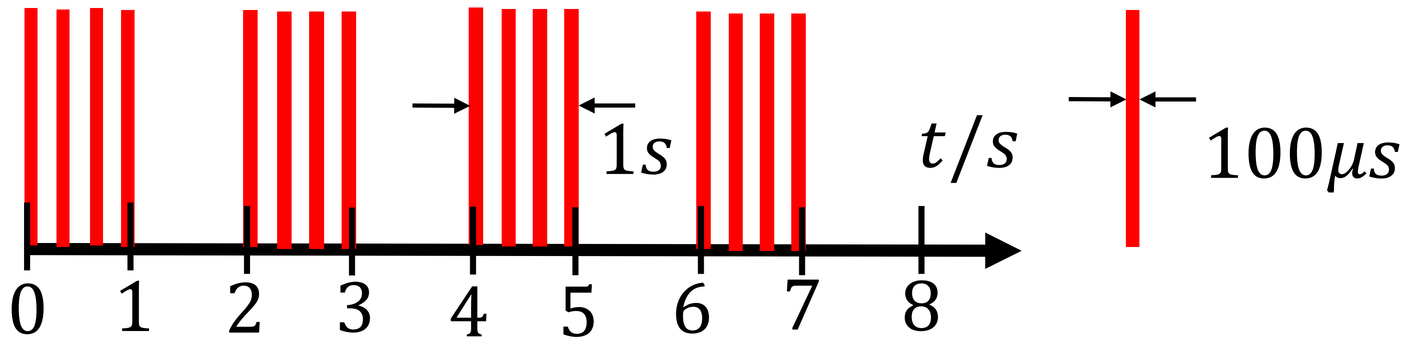
Challenge

- High intensity operation
- Switching from one to another setting.
- Long-term reliability

The world highest intensity CW HI linac project

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

- GSI - UNILAC to be modified for FAIR to a pulse structure like:

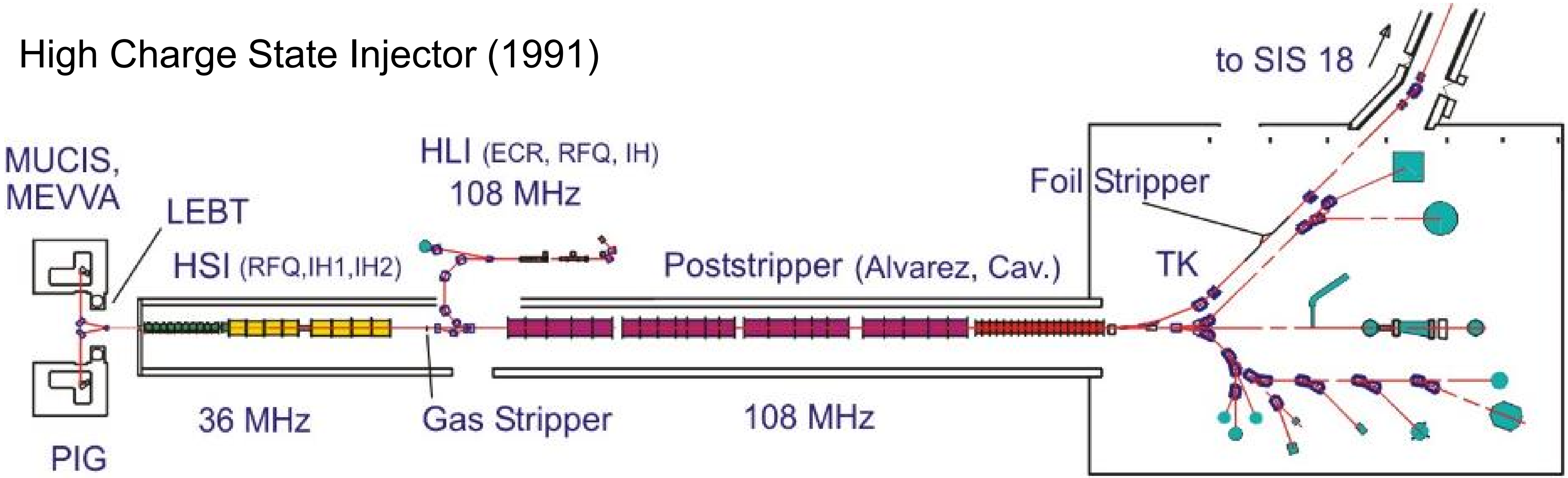


- 4 SIS18 cycles in one second
- 1 SIS100 cycle during two seconds

Traditionally, Unilac was a 25% duty cycle accelerator!

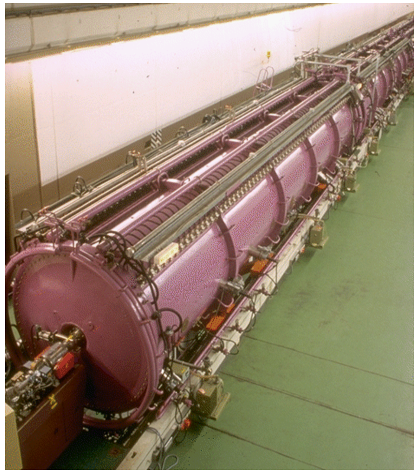
The GSI Unilac at present

High Charge State Injector (1991)



High Current Injector (1999)

Alvarez (1975)



Single Gap Resonators (1975)

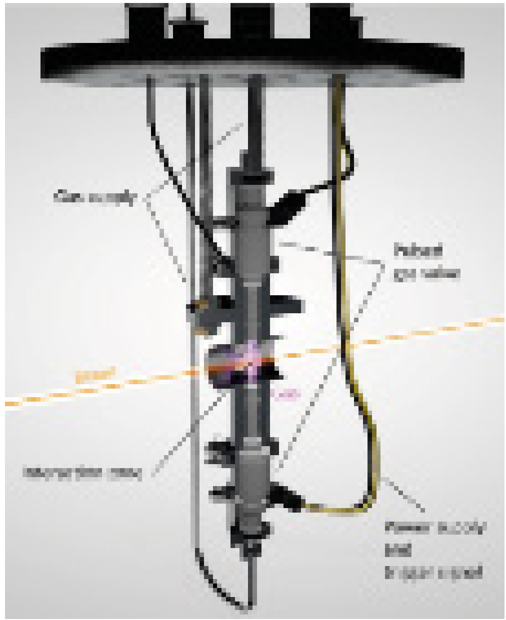
Unilac

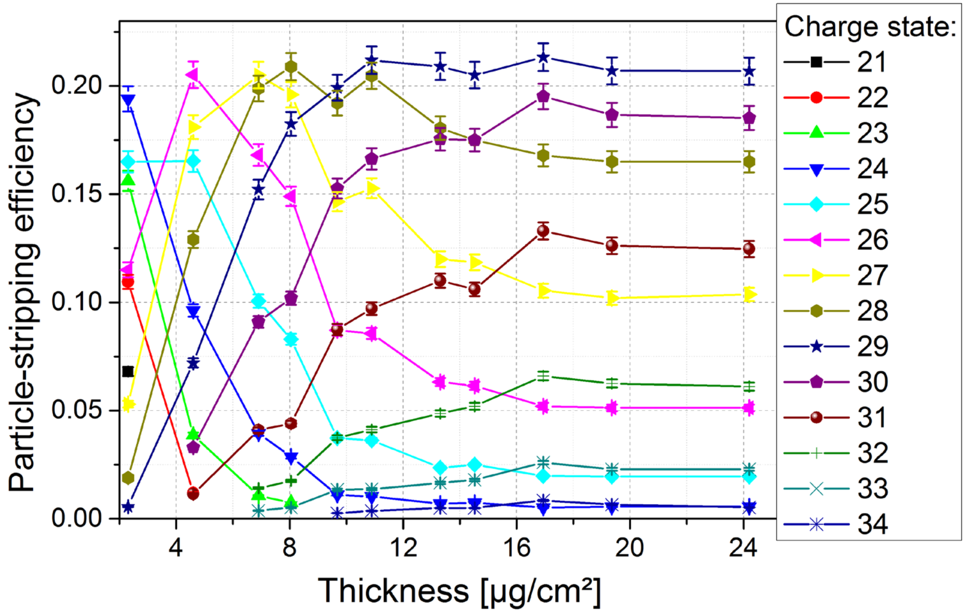
Particle Stripping Efficiency

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Beam Parameters:

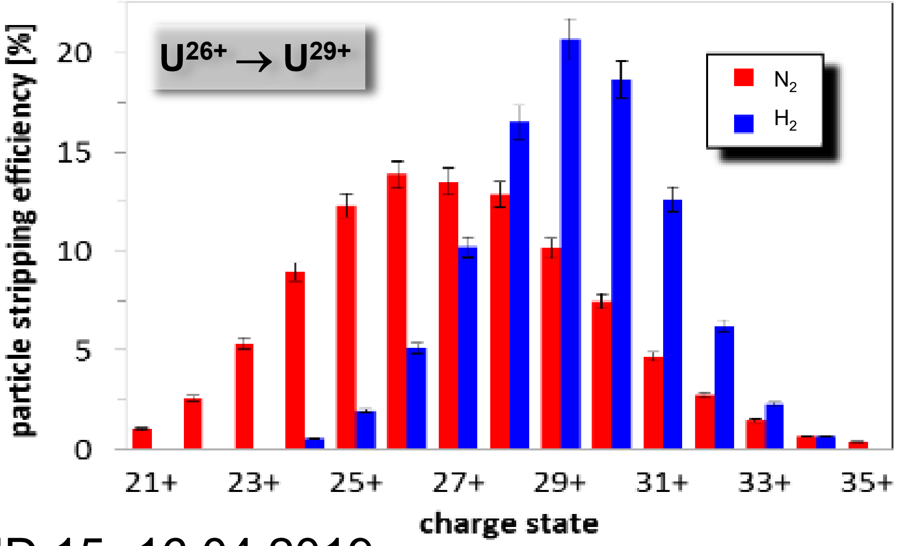
	N_2-gas jet [8]	H_2- gas cell (pulsed)
Back-pressure	0.4 MPa	12.0 MPa
U^{4+}-current (HSI)	6.0 emA	7.4 emA
Stripping charge state	28+	29+
Stripping efficiency	12.7±0.5%	21.0±0.5%
Energy loss	14±5 keV/u	60±5 keV/u
Max. current	4.5 emA	11.5 emA
ε_x (90%, tot.) norm.	0.76 µm	0.51 µm
ε_y (90%, tot.) norm.	0.84 µm	0.96 µm
Hor. brilliance (90%)	5.32 mA/µm	20.29 mA/µm





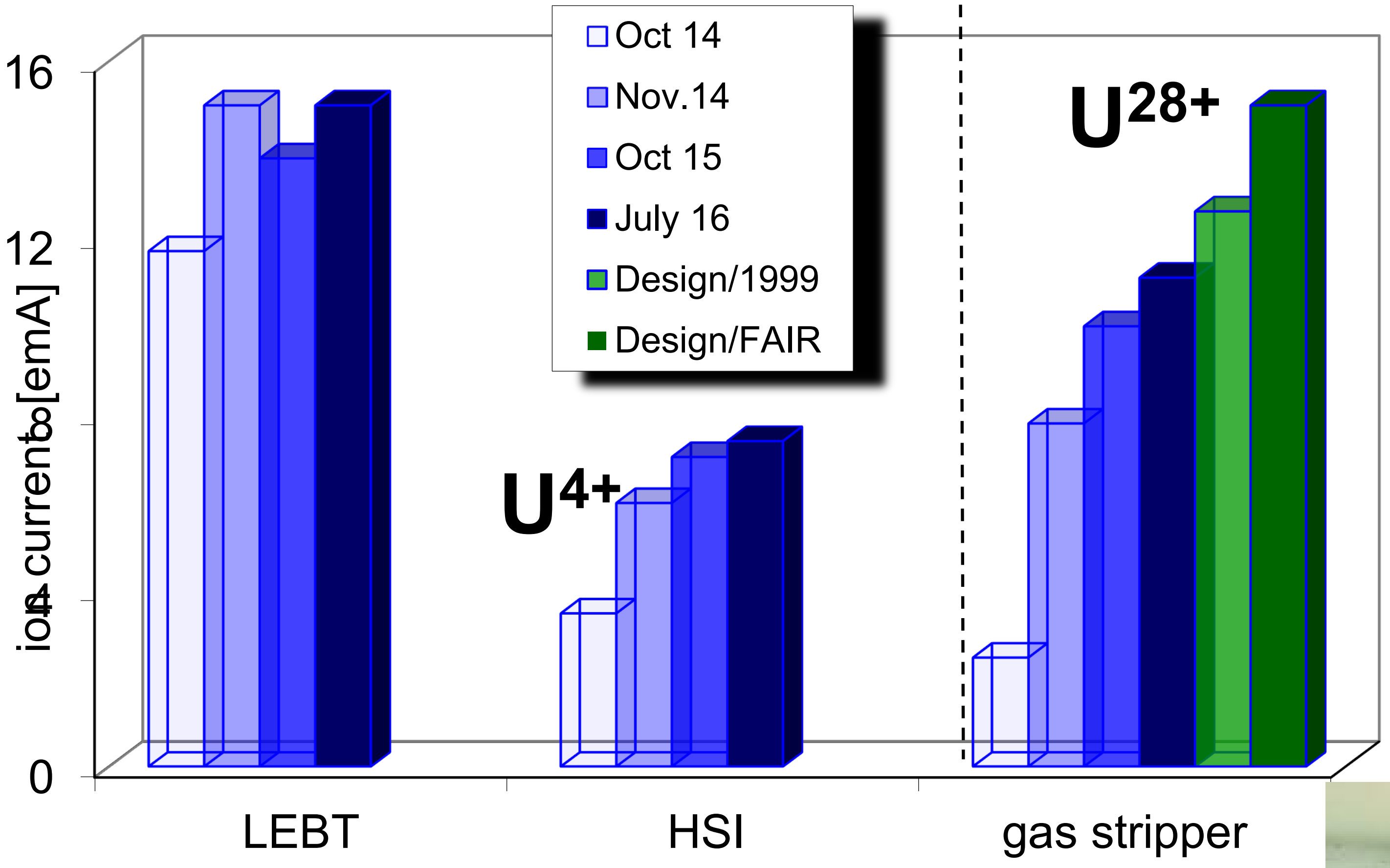
Beam Energy Loss:

U^{28+}	N_2-jet (max.)	14±5 keV/u
U^{28+}	Pulsed H_2-stripper cell (7.5 MPa)	35±5 keV/u
U^{29+}	Pulsed H_2-stripper cell (12.0 MPa)	60±5 keV/u



Unilac

Uranium High Current Injector-Performance



LEBT Section

Stripper Section

W. Barth, et al., Phys. Rev. ST Accel. & Beams 20, 050101 (2017)

Conclusions

- Wordwide revival in heavy ion linac development, triggered by large research facilities and by applications
- Characteristics are low frequency and low β
- Transition from RT to SC technology still in a flow
- Technical capabilities for a realization of heavy ion linacs at higher frequencies are improving (LEBT emittances, RFQ – production quality, drift tube techniques like permanent magn. quads, lens free sections…

Acknowledgement

A lot of information and slides came from:

- Yoshi Yamazaki, FRIB, MSU, Michigan
- Osamu Kamigaito, RIBF, RIKEN,
- Hongwei Zhao, IMP, Lanzhou
- Deepak Raparia, BNL, Brookhaven
- Richard Scrivens, Maurizio Vretenar, CERN, Geneva
- Andrej Butenko, JINR, Dubna,
- Winfried Barth & Lars Groening, GSI, DA

Many thanks for your valuable support!