Update on the cw-linac project
HElmholtz LInear ACcelerator

An advanced energy efficient and compact superconducting particle accelerator for heavy ions

HELIAC
GSI DARMSTADT

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[3] Johannes Gutenberg-Universität Mainz, Mainz, Germany

1. **Special Topic: Power consumption efforts**
2. **GSI-Heavy Ion UNILAC**
3. **HElmholtz LInear ACcelerator**
   a. **Introduction**
   b. **Layout**
   c. **Status**
   d. **Basic approach as starting version**
   e. **CM1 beam commissioning**
4. **Save Energy – built HELIAC!**
   a. **HELIAC-power consumption**
5. **Outlook**
   1. **Further R&D**
   2. **HELIAC project plan**

HELIAC GSI DARMSTADT

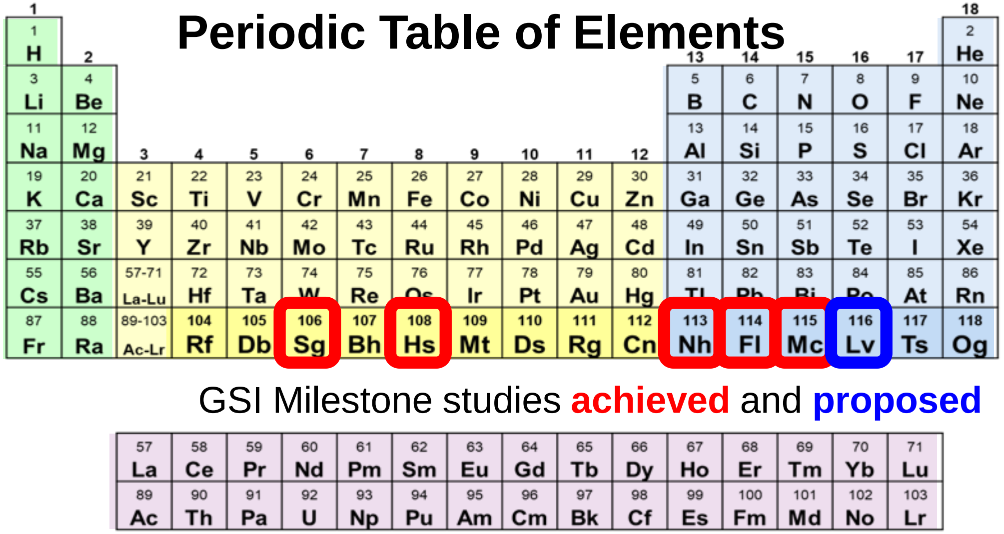
Motivation: Sustainability Challenge

- **Basic scientific findings often need large-scale equipment**

→ high performance (heavy ion) particle accelerators (as FAIR/GSI)

  - Fundamental Science
  - Material science
  - Biophysics
  - …

Broad program on synthesis, nuclear structure, atomic physics and chemical studies...

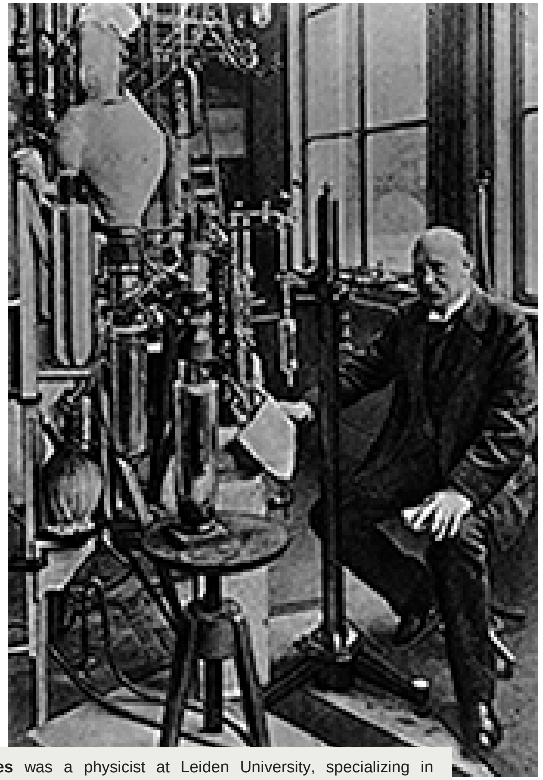


- Increasingly high demand for primary energy to operate!
- **Primary task for the future of people and society:**

→ **How to gain scientific knowledge & simultaneously operate with max. energy-efficiency ???**

Superconducting Radio Frequency Cavities

Superconducting technology (for particle accelerators) play an essential role → extremely low demand for electrical energy…



Heike Kamerlingh Onnes was a physicist at Leiden University, specializing in superconductivity. He was awarded the 1913 Nobel Prize in Physics "for his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium; [Kamerlingh Onnes, Heike, 1853-1926 (aip.org)]

Cool an radio-frequency accelerator cavity (heart of any modern accelerator) to -269°C (4K), achieving an efficiency gain of up to 15 versus existing accelerator…

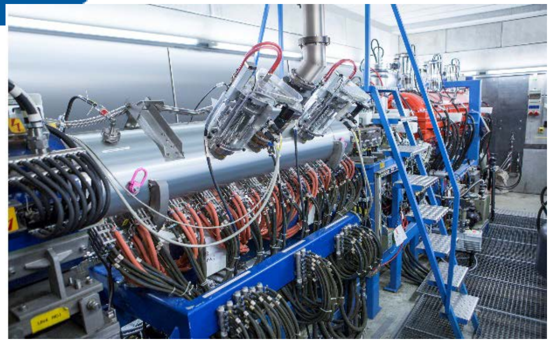
Magnets are seen suspended above a track in a superconductivity demonstration kit in a lab at the University of Rochester. The primary researcher, Ranga Dias, is pursuing his goal to create novel quantum materials such as superconductors with a critical temperature at or near room temperature.

ADAM FENSTER/UNIVERSITY OF ROCHESTER

GSI UNIversal Linear ACcelerator

2.0 emA, p^+ (MUCIS)
7.0 emA, $^{238}U^{28+}$ (MeVVa)

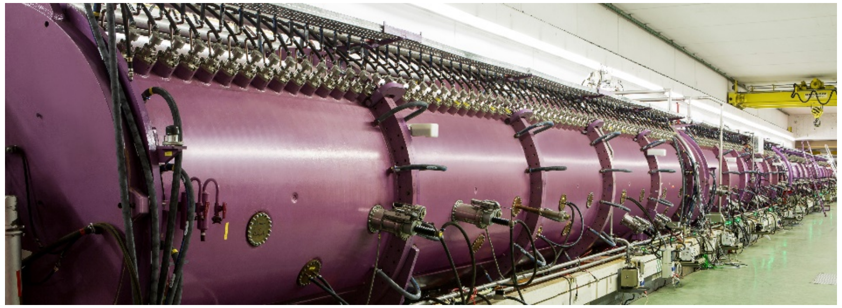
High Charge State Injector (1991)



1 pμA, ^{48}Ca (ECR)
1 pμA, ^{50}Ti (PIG/ECR)

High Current Injector (1999)

Poststripper/Alvarez (1975)

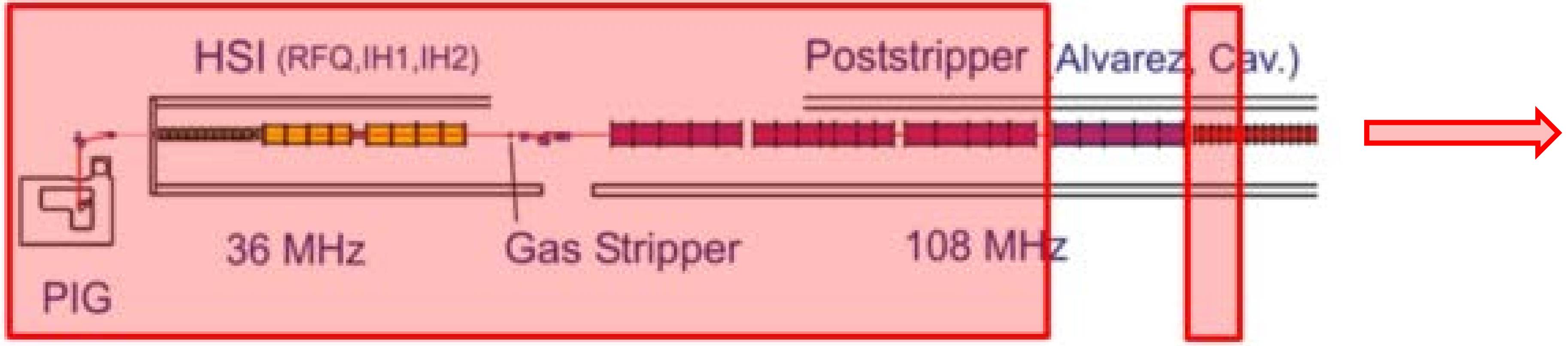


Single [illegible] Resonators (1975)

UNILAC-Power Consumption

Typical heavy ion beam operation:

- A/Z = 26 (HSI)
- A/Z = 6 (poststripper)
- W_{kin} = 7.5 MeV/u
  - A3-intermediate energy/7.1 MeV/u
  - 3×Single Gap Resonator/0.4 MeV/u
- RF-duty factor = 30%



UNILAC-Power Record

- HSI/RFQ – Super Lens – IH1&IH2 (Rf, 30%): 600kW
- Poststripper/A1 – A3 (Rf, 30%): 1900kW
- 3x Single Gap Resonators (RF): 190 kW
- Power supplies/HSI-Quads + Dipoles/Charge separator: 70 kW
- Power Supplies/Poststripper-Quads: 145kW
- Beam diagnostics: 100kW
- Cooling water: 1200kW
- Basic load/UNILAC: 650kW
- PIG-ion source: 40kW

tot.: 4895 kW (25% duty factor)

6 months operating time:

4.895 MW x 24h x 30 days x 6 months x 300€/MWh = 6.34 M€

HELIAC-Introduction

The UNILAC will not be able to meet the high duty factor requirements in the future!

FAIR Requirements

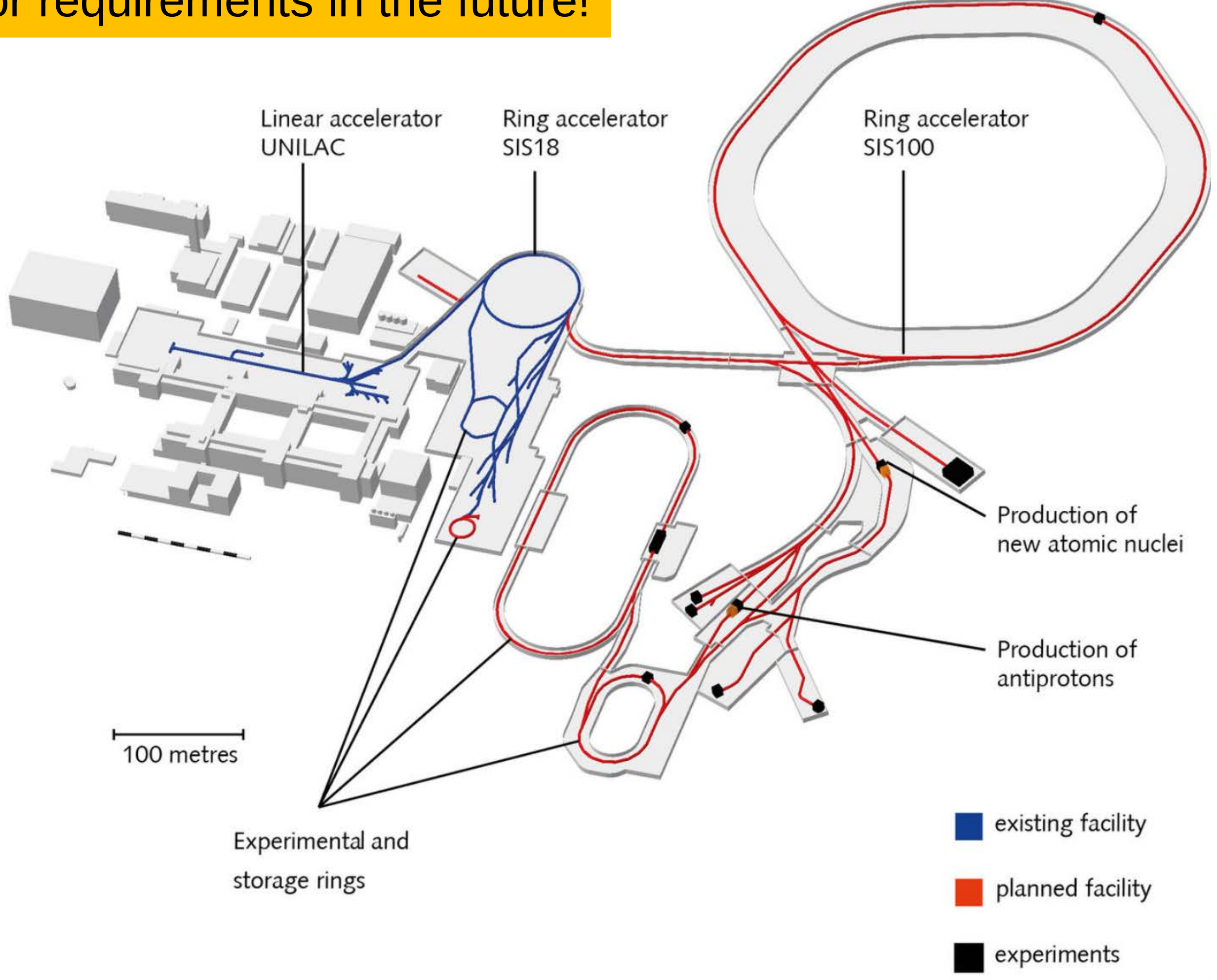
- high *peak* beam currents
- low duty factor (~0.1 %)
- → low repetition rate (max. 3 Hz)

UNILAC-Poststripper Upgrade

- optimised for FAIR requirements
- low duty factor / rep. rate

Super Heavy Element Requirements

- high *average* beam currents
- high duty factor (~100 %)
- high repetition rate or just *c.w.*

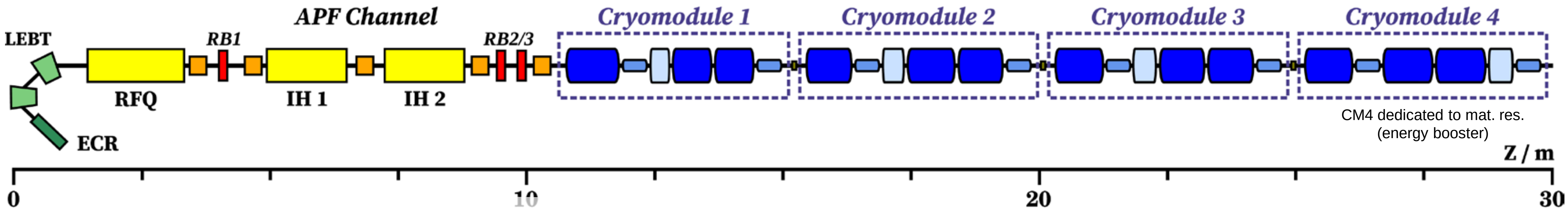


Existing GSI facility and future FAIR complex

HELIAC-Layout

HELIAC has been optimized for the needs of the UNILAC users, in particular TASCA, SHIP & materials research and could be used as SIS18-injector for medium high intensities!

Hel**moltz**Linear**Acc**elerator* – ***HELIAC



Source

Parameter	Unit
Type	ECR
Frequency	18 GHz

Normal-Conducting Injector

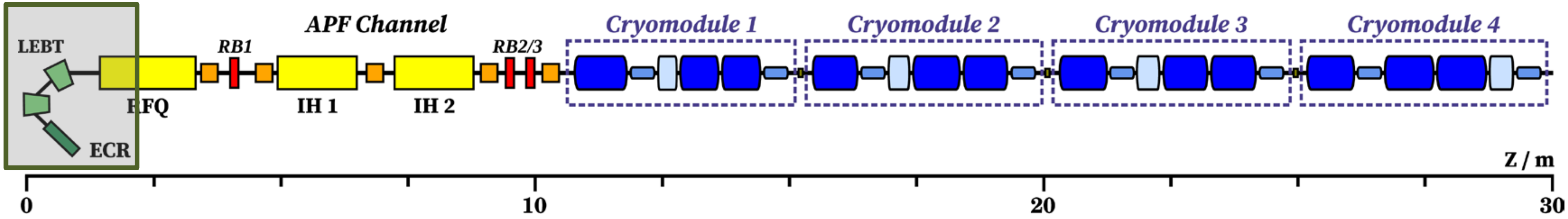
Parameter	Unit	Value
Output energy	MeV/u	1.4
RF Cavities		6
Operation mode		cw
A/Z		≤ 6

Superconducting Accelerator

Parameter	Unit	Value
Output energy	**MeV/u**	**3.5 – 7.3**
Beam current	mA	≤ 1
Operation mode		**cw**
A/Z		≤ 6
RF Cavities	#	12
RF Bunchers	#	4
Transversal Focussing	2 Solenoids per Cryom.	

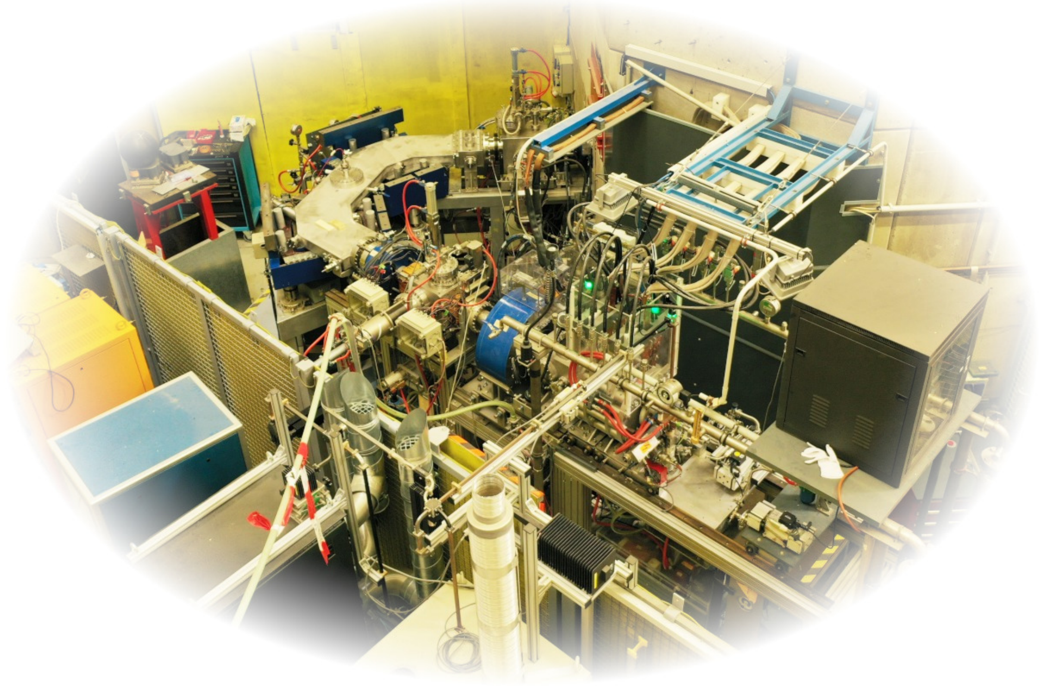
Status/Ion Source

Advanced ECR-ion source, will meet the user needs,
14 GHz caprice is available as startup version!



Ion Source

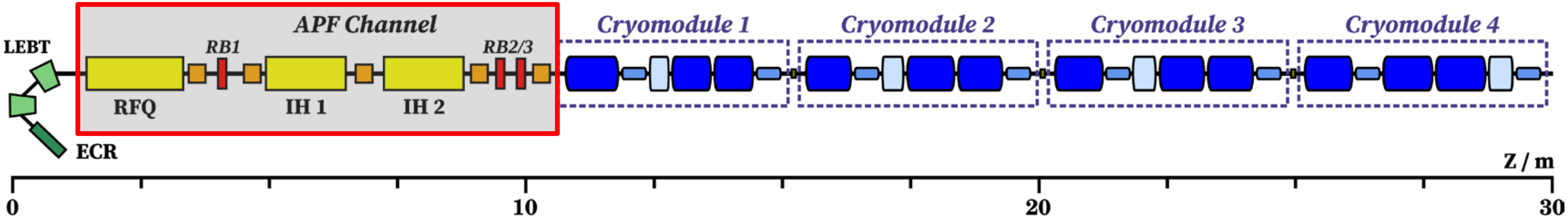
- **High charge states required**
  → 18-GHz-ECR (Jyväskylä design)
- **Low Energy Beam Transport**
  - Mass to charge-spectrometer
  - Transport/matching to RFQ
- **Start version: 14-GHz-CAPRICE-ECR @ GSI**



CAPRICE14-GHz-Electron Cyclotron Resonance Ion Source @ GSI

Status/n.c. Injector Linac

Old HLI-RFQ is available for re-use, in perspective a cw-capable RFQ is needed!
A cw-capable (nc) APF-IH-DTL was designed and ordered!

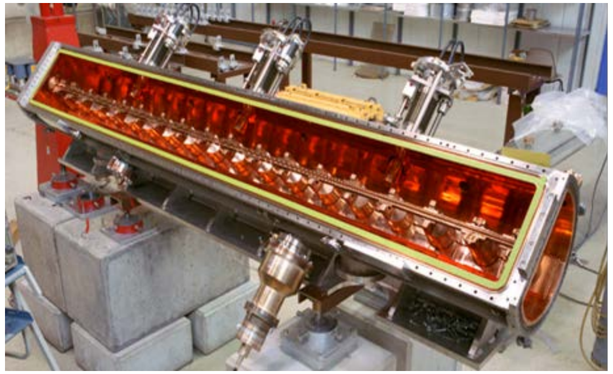


Ion Source

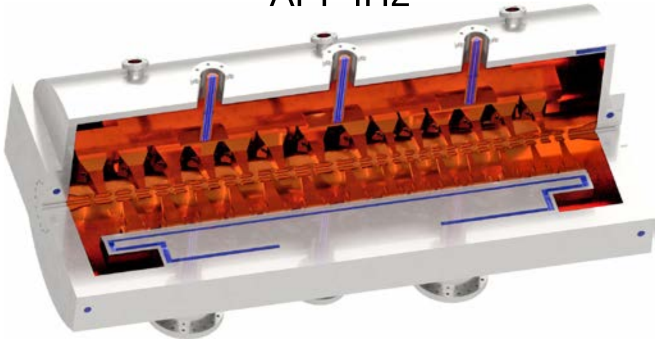
normal conducting Injector

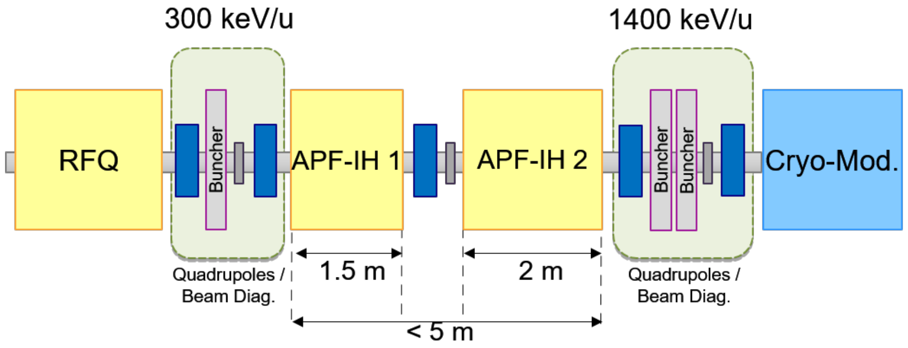
- **Start version: Former HLI RFQ (1991) → 25% duty factor vs. 100 % (c.w.)**
- APF IH-DTL with two-cavities (IH1&IH2) **A**lternating **P**hase **F**ocusing
  - APF DTL capable for 100% duty factor
  - Manufacturing started
  - 2024: ready for installation
- **Start version: existing vacuum tube rf-amplifiers → 25% duty factor vs. 100 %**

HLI-RFQ (1991)



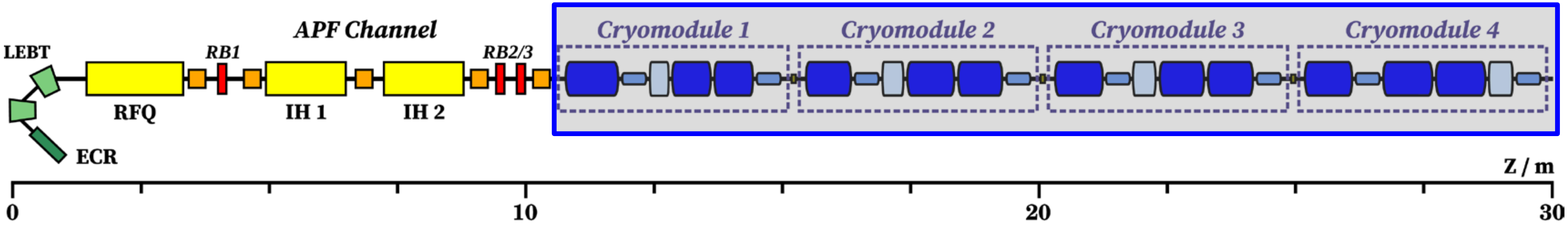
APF IH2





Status/s.c. Main Linac

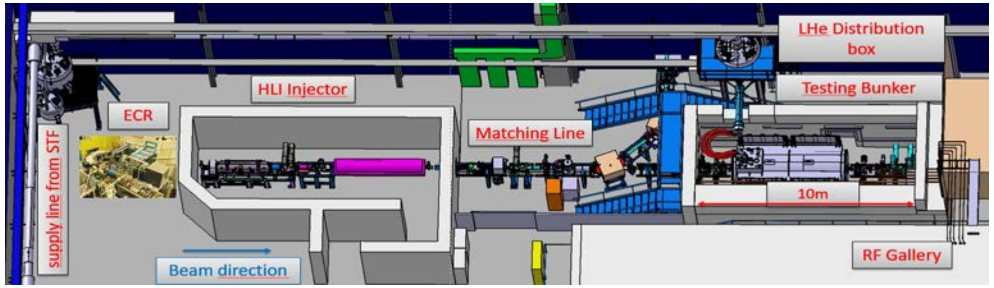
Multicell-CH-cavity and prototype CM(1) successfully pre-tested, LHe-infrastucture built, HELIAC-technical layout completed!



Ion Source

normal conducting Injector

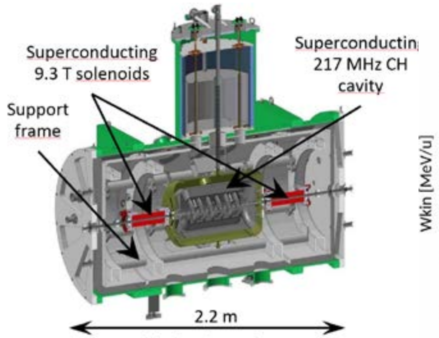
superconducting Linac



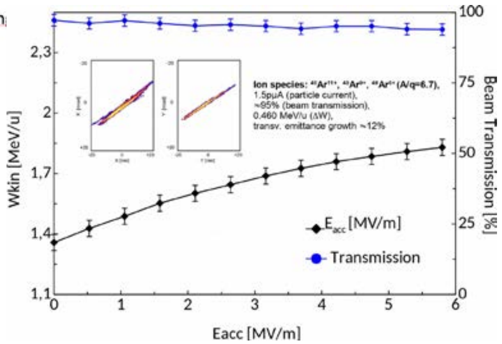
2021

Test of Cryostat & Solenoids

CH Cavity Qualification (2017)

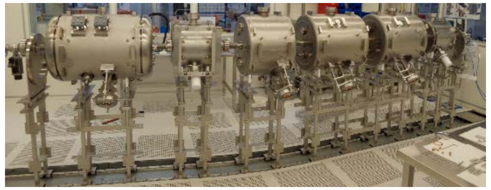


Layout of the horizontal cryo module



Helium & Test Infrastructure (2021)

Cryomodule (CM1) Qualification (2023)

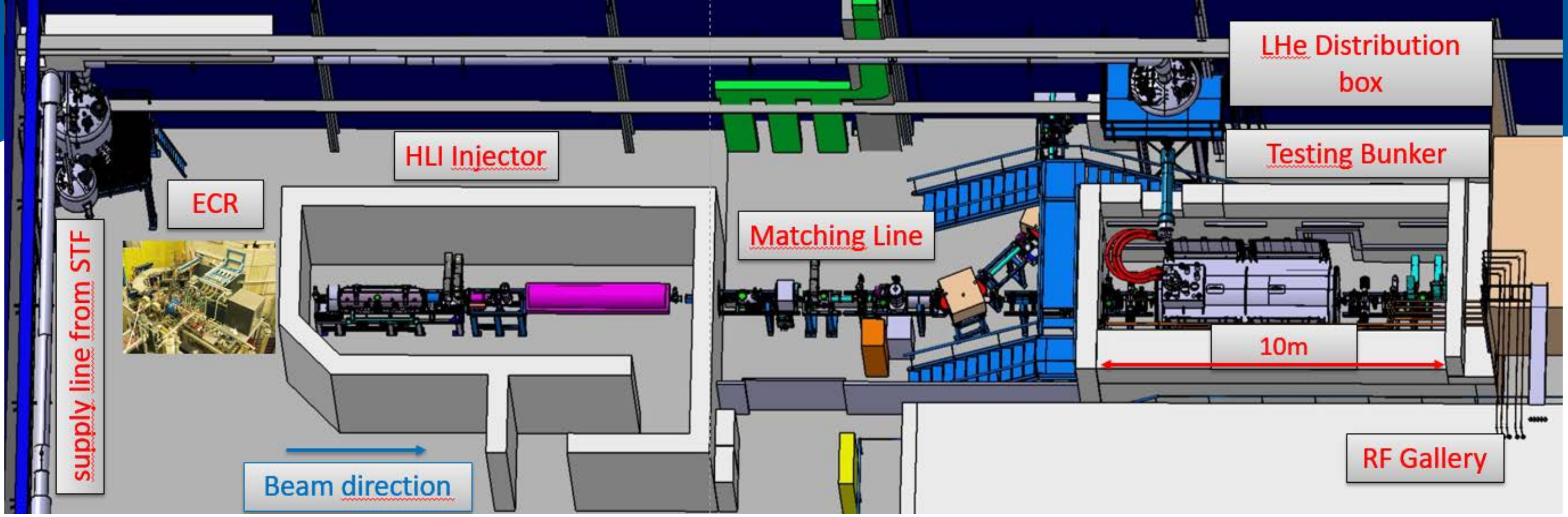


Entire HELIAC Setup

Test Site @ GSI

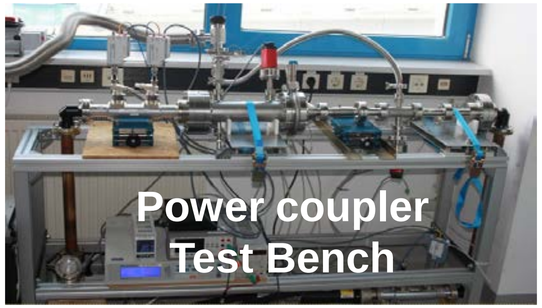
Setup of Advanced Dem. test site @ GSI

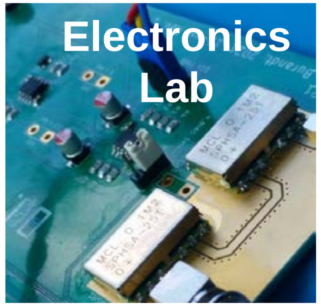
- ✓ Radiation cave behind HLI injector
- ✓ Control room
- ✓ RF supply room
- ✓ Test bench for high power couplers
- ✓ Electronic lab
- ✓ Beam line to GSI's HLI as injector
- ✓ Link to cryo plant
- ✓ Advanced Demonstrator setup allows first user experiments
- ✓ Test site allows qualification of CM1-CM4



At GSI a unique environment for beam testing of HELIAC superconducting cryomodules is available!

~10m



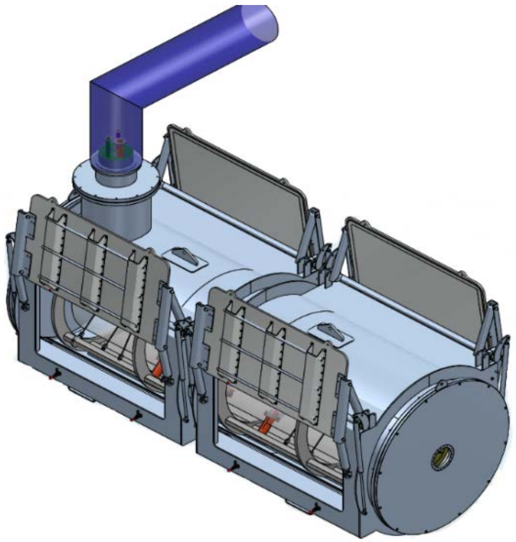


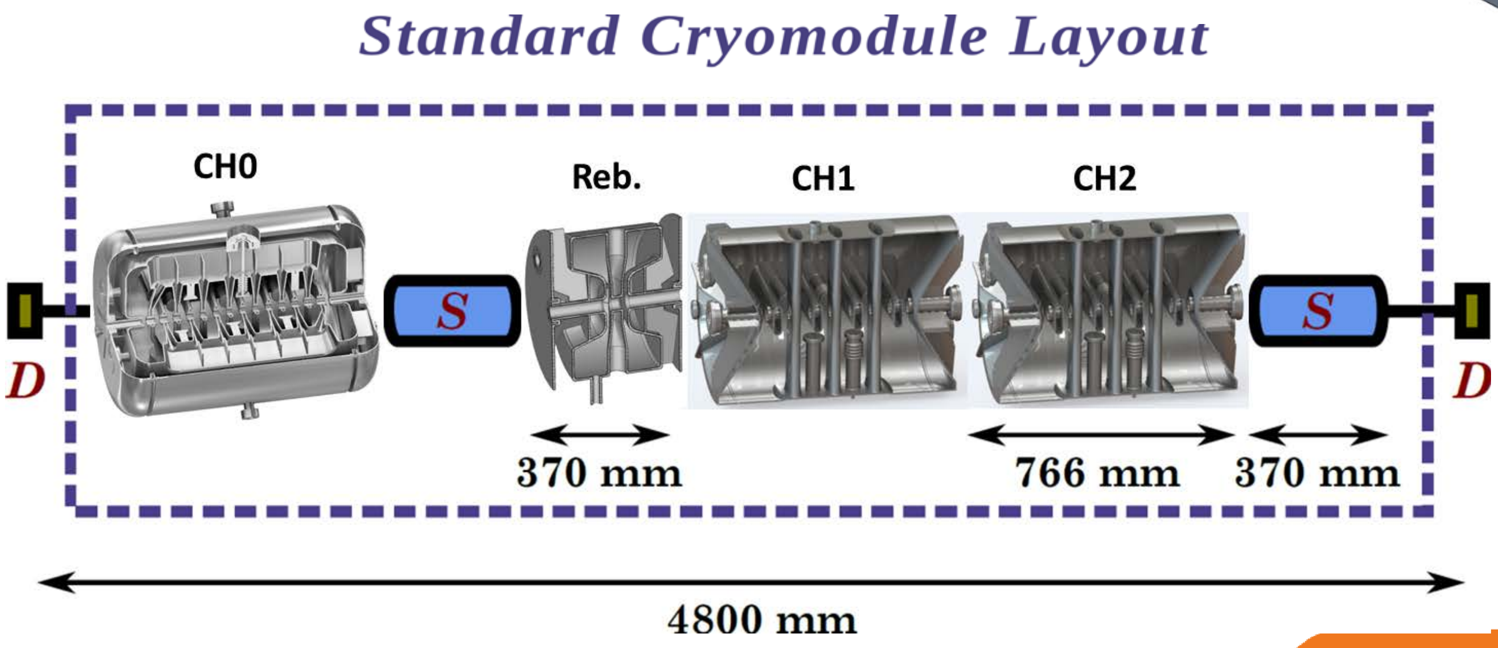
Cryomodule Qualification

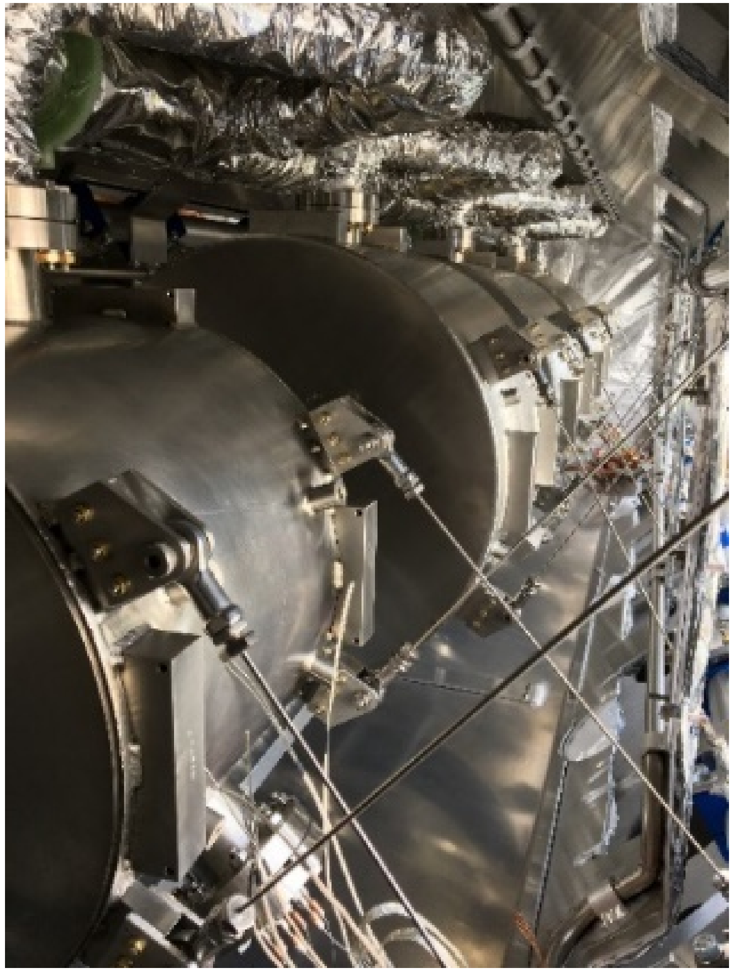
A standard cryomodule (3 CHs + 1 Buncher) has been designed, technically laid out and built (CM1)!

HELIAC-CM1

- 3 Crossbar H-Mode RF-cavities
- 1 Crossbar H-Mode Rebuncher cavity
- 2 superconducting 10T-Solenoids







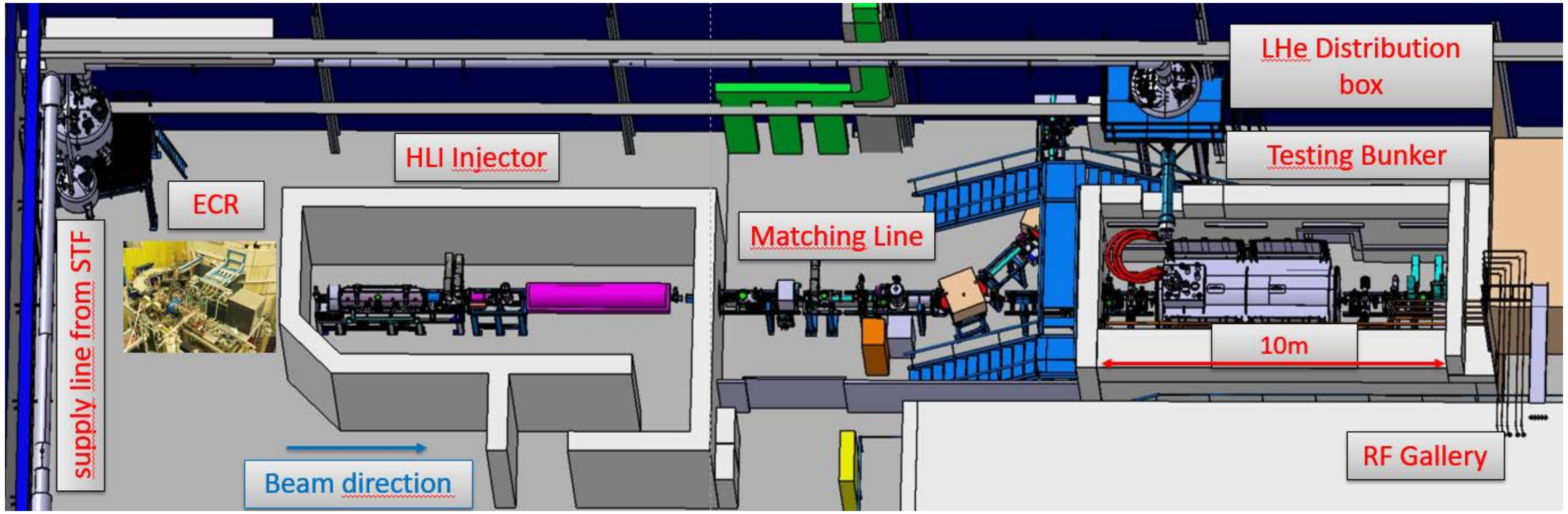
Cryomodule 1

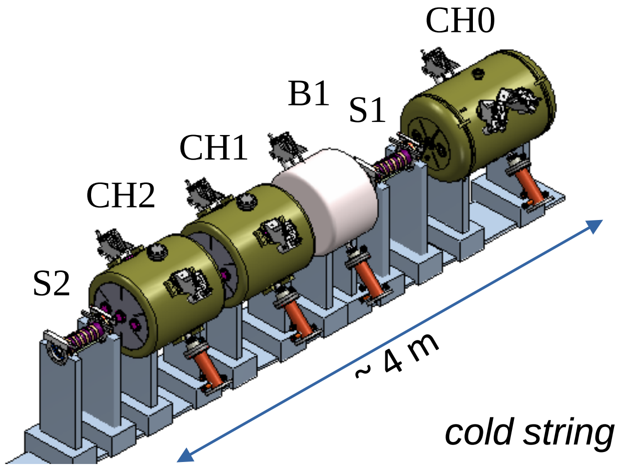
Cryomodule Qualification

ALL key components of the first fully equipped HELIAC cryo module are available in full function!

Test of fully equipped standard Cryomodule

- **Delivery of key components**
  - RF-Cavities
  - Solenoids
  - Power couplers
  - RF amplifiers
  - LLRF
  - Cryostat
- **Clean and precise assembly**
- **Many „firsts“**
  - Assembly procedures
  - Auxiliary constructions
  - Transport HIM ↔ GSI
- **Test site + infrastructure**





cold string


Rf-amplifiers


power coupler


cryostat

Clean Room Infrastructure @ HIM

The unique HIM infrastructure is used to process superconducting RF cavities and assemble complete accelerator strings!

Unique infrastructure for SRF R&D@HI-Mainz

- 2 interconnected clean rooms: 42m^2 (ISO6)+42m^2 (ISO4)
- Ultra high purity water supply (18MΩ/cm)
- Ultrasonic bath and conductance rinse (outer surfaces preparation)
- High Pressure Rinse (HPR) applying 100 bar-removal of particulates & contamination from inner surfaces of vacuum bellows, cavities, solenoids …..
- Weekly cleaning by external company
- Ready for cryomodule assembly!

ISO 6 Clean Room

ISO 4 Clean Room

Accelerator String Integration

Cold string integration at HELIAC-CM1

Acceleration string mounted on individual trolleys

empty cryostat

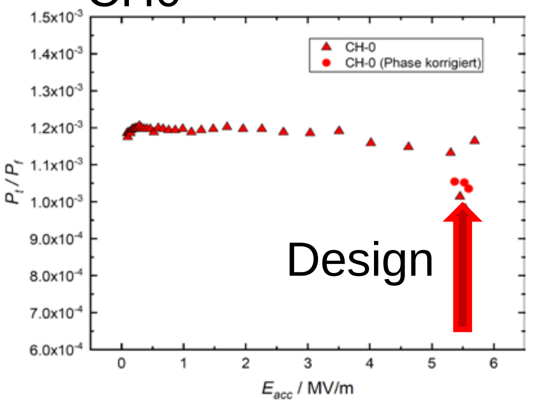
Acceleration string mounted inside transport frame

…integrated inside cryostat

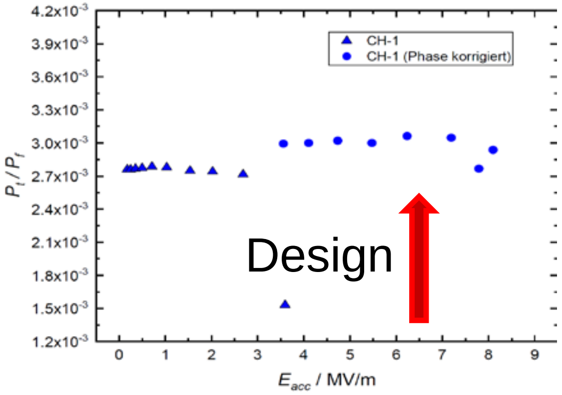
CM1-commissioning (Oct 17 – Dec 14 2023)

HELIAC
GSI DARMSTADT

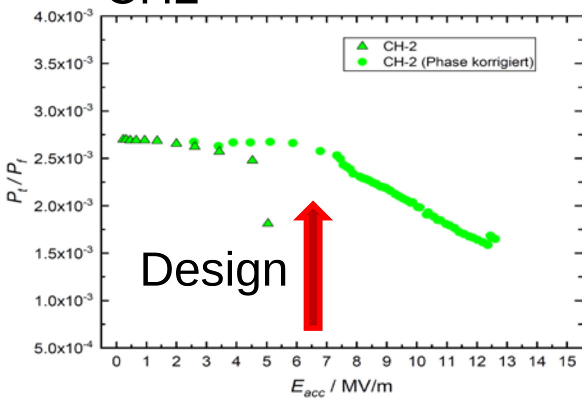
CH0



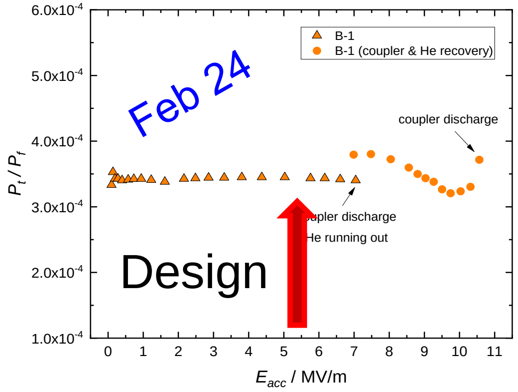
CH1



CH2



CH-Buncher



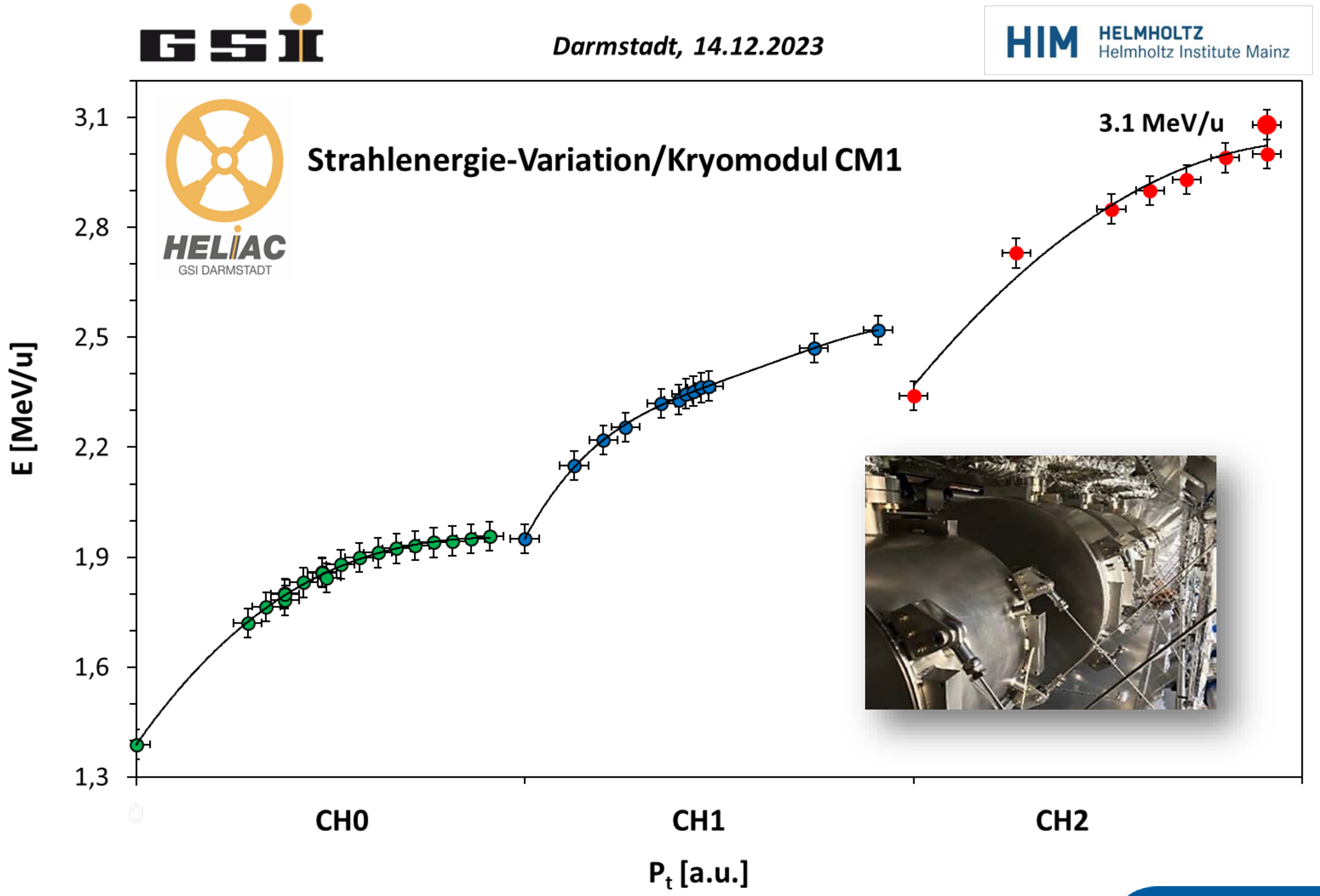
- Cooldown I applying GSI-STF-LHe-supply first time
- Commissioning of beam diagnostics devices
  - ToF (phase probes)
  - beam collimation (pilot beam approach)
  - Bunch Shape Monitor I and II
  - Beam emittance measurement device I and II
- Setup of High Chage state Injector
- Cooldown II applying GSI-STF-LHe-supply
- RF-conditioning of superconducting CH-cavities CH0, CH1 and CH2

- RF-conditioning of superconducting CH-cavities CH0, CH1 and CH2
- All RF cavities reached design gradient
- CH0 limited by thermal quenches (missing shielding of earth magnetic field!)
- CH-Buncher: E_{acc} = 10 MV/m in PLL-mode

CH-cavities perform even better than expected!

First CM1-Beam Acceleration

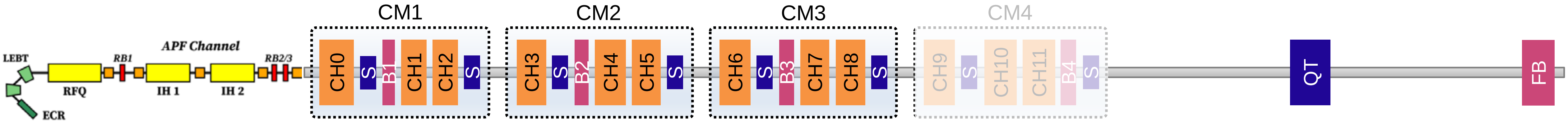
First acceleration accomplished + energy varaiation at high transmission confirmed!



Summary: HELIAC-achievements

- The unique HIM infrastructure is used to process superconducting RF cavities and assemble complete accelerator strings.
- Cavity (CH0) successfully tested under cryogenic conditions with beam at GSI in 2017.
- **First fully equipped HELIAC-cryomodule (CM1) successfully tested with beam at GSI in 2023.**
- At GSI a unique environment for beam testing of HELIAC superconducting cryomodules is available.
- Cryogenic supply system for future HELIAC operation is available from the STF.

Basic Approach and Link to UNILAC



- HELIAC to be realized in a step-wise approach
- 2023: R&D-phase finalized with installation and commissioning of CM1
- ECR-ion source and nc-injector linac at new HELIAC radiation protection shelter
- Basic version comprises CM1 – CM3 (long)
- CM3 is equipped with a basic set up of 3 CH-cavities, 1 rebuncher and 2 solenoids
- Energy spread can be transformed with the FB to ±3 keV/u.
- For CH8 output energy (5.93 MeV/u), no CM3-buncher cavity required
- In a first step HELIAC operation is restricted to 25% beam duty factor
- HELIAC project (pre-)planning is ongoing

A HELIAC starter version has been defined that can provide heavy ion beam for FAIR as well as allow the SHE program to continue!

Funding/Basic approach

- HELIAC designed to fit into existing SH2/SH3 → available
- Feasibility study for civil → construction/tunnel?
- STF cryogenic plant for supply of HELIAC → *available*
- *ECR 14GHz+LEBT → from existing GSI-HLI*
- RFQ → old HLI RFQ (25% duty) → on st…
- IH1/IH2 in manufacturing → H…
- CM1 is in assembly/t… (ARD)
- CM2 is in ma… PoF4 (ARD)

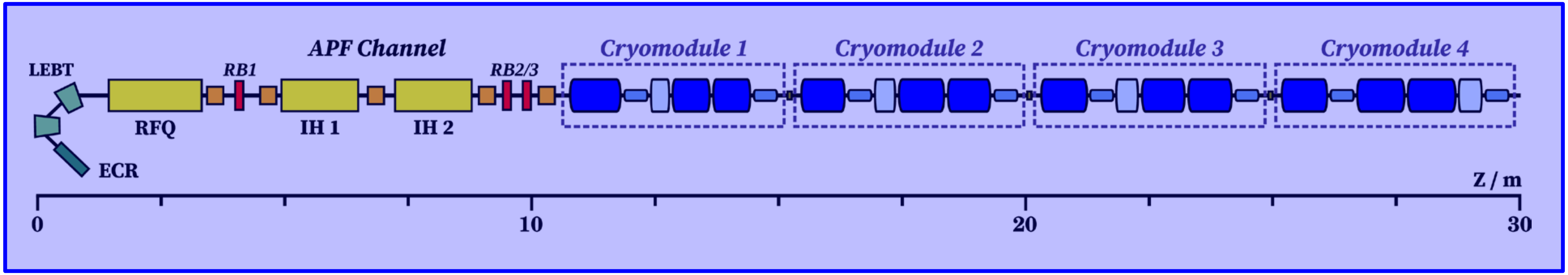
- CH-Cavities for C… …ng → BMBF
- CM3-re… → EFRE-EU/Hessen?
- …rom GSI-stock, power supplies to be
- …ost of beam line magnets on GSI-stock, most of power supplies to be ordered
- For „basic approach“ (25% duty) reuse of existing high power rf-amplifiers
- Requires the planning i.e. manpower now!

Funding for major parts of HELIAC secured via HIM and third-party funding. Funding* for ECR, transport beamlines and civil construction of tunnel lacking, Manpower required!

HELIAC-Power Consumption

Typical heavy ion beam operation (see UNILAC-scenario):

- A/Z = 6
- W_{kin} = 7.5 MeV/u
  - nc-Injector/1.4 MeV/u
  - 4×Cryomodules/6.1 MeV/u
- RF-duty factor = 100%



HELIAC-scenario

- ECR (14 GHz): 230kW
- nc-Injector-Linac/new (RFQ + 2×IH + Buncher => HF) (cw)
  - RFQ: 150kW
  - IH1: 35kW
  - IH2: 85KW
- Cooling Water (Injector+sc-HELIAC): 200kW
- CM1-4 (16 Rf-amplifiers each 3kW Rf-power, Efficiency: ≈ 60%): 80kW
- cryo supply/STF:
  - 16 CH-cavities (≈10W per cavity => 160W + 120W (standby) + 80W loss at He-transport-system, incl. shield: 1W@4K cryo power applying 350W el. connected power: 130kW
- Power supplies/HLI+Matching Line+sc-Solenoids: 150 kW
- Beam Diagnostics: 50kW

tot.: 1110kW (c.w.)

1.5 months operating time:

1.11 MW x 24h x 30days x 1.5 months x 300€/MWh → 0.360 M€

Save Energy, build HELIAC!

Power consumption
UNILAC vs. HELIAC
for identical particle number on target)

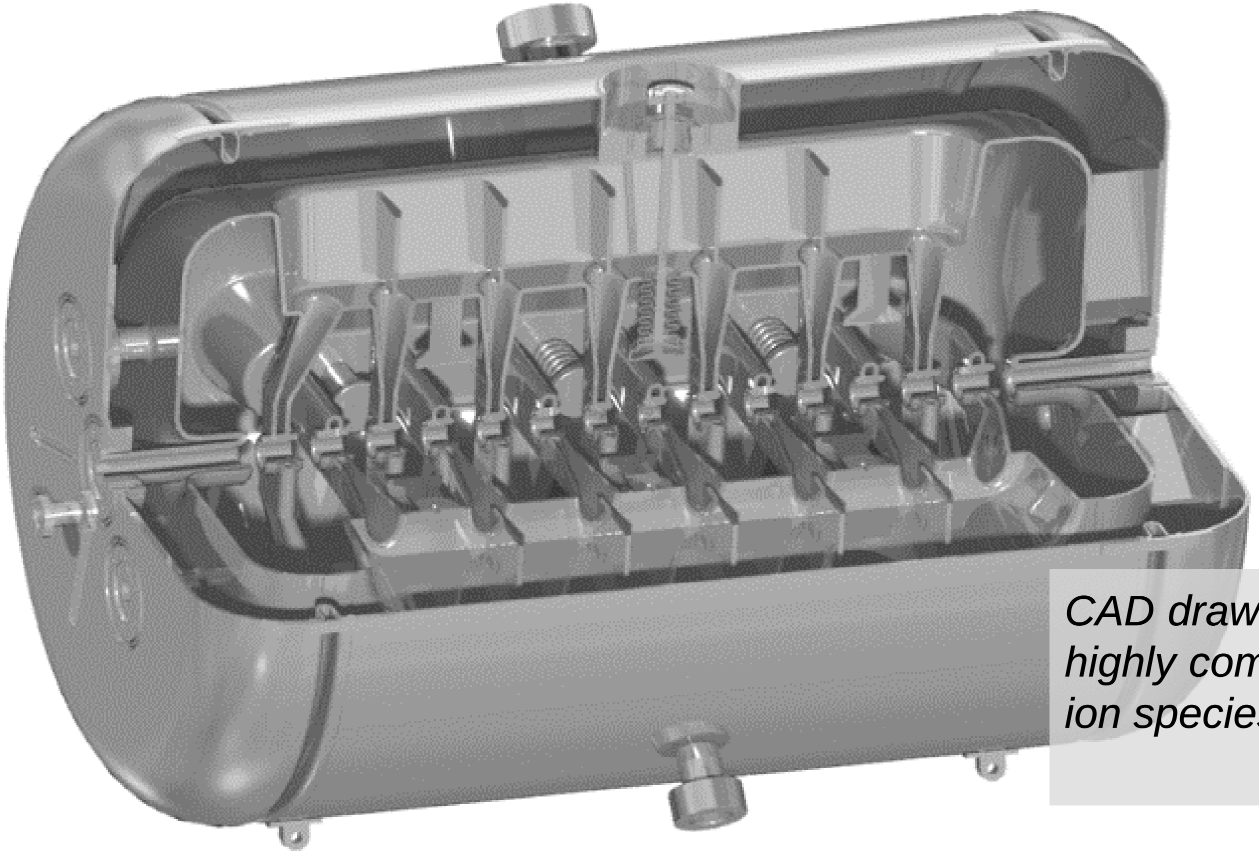
HELIAC (sc): A/Z= 6, 7.5 MeV/u, **cw-operation**

UNILAC (nc): A/Z = 26 (HSI), A/Z = 6 (poststripper), 7.5 MeV/u (A3-intermediate energy/7.1 MeV/u +3xERs), **30% RF-duty factor**

For typical beam time:
>90% less power consumption
(Energy savings for 6 months of operation (HELIAC vs. UNILAC) ≈ 16.4 GWh)
Energy savings for 6 months UNILAC-experiment (vs. 1.5 months/HELIAC)≈ 20 GWh

Outlook I: Further sustainability efforts

Very ambitious challenge: Combining state-of-the-art cooling techniques to achieve **2 K** with newly developed extremely complex superconducting accelerating-cavity



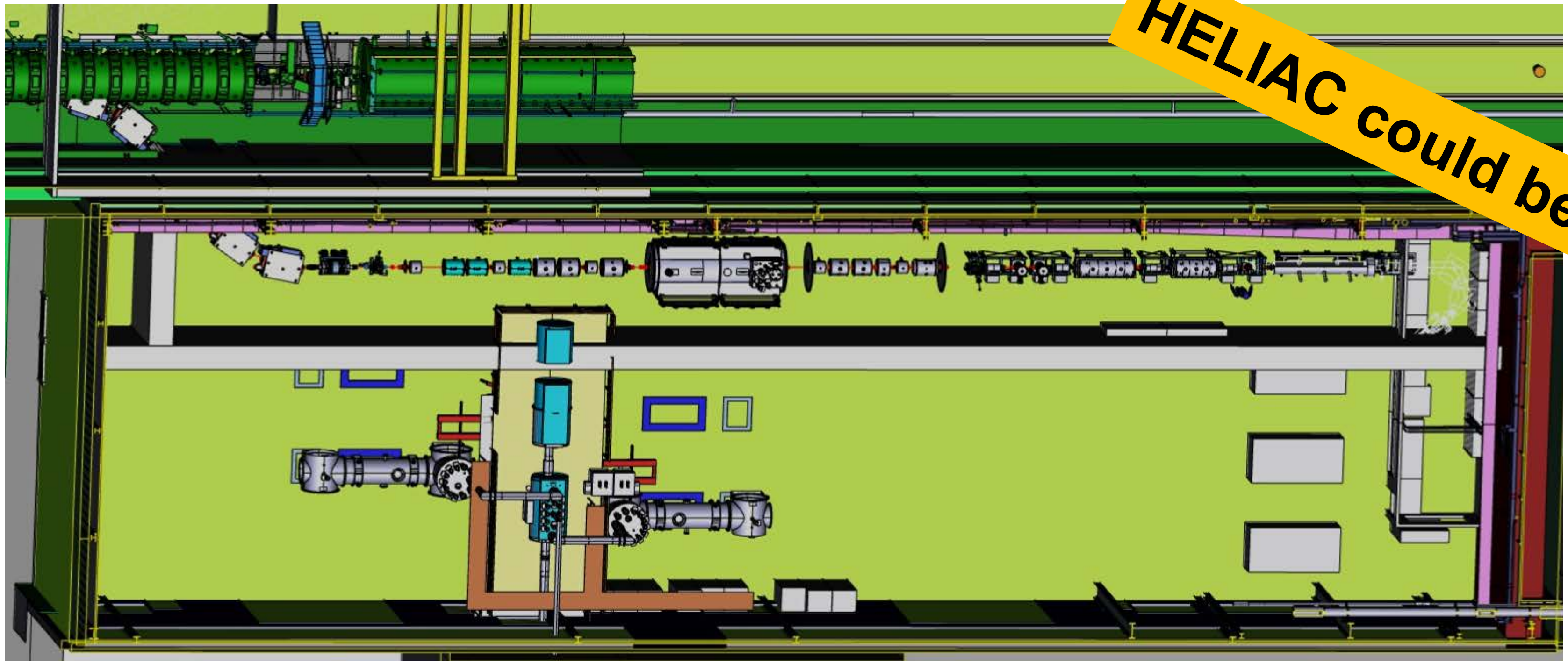
Efficiency Gain Factor of

another factor of 2

(versus 4k operated CH-cavities)

CAD drawing of a multi-cell CH-mode cavity. The structure is highly complex to be able to satisfy the user needs regarding ion species, energy, intensity and quality of the beam

Outlook II: HELIAC as a project?



HELIAC could be ready in 2029!

Next steps to become a project (@GSI):

- Digital Mock-Up of HELIAC@SH2/3-hall (
- Cost and ressource estimation - together with GSI-expert (ongoing)
- ⇒ (preliminary) ressouce loaded schedule
- ⇒ HELIAC approved as an official GSI project

Thank you for attention!

HELIAC-CM1-cold string assembly at HIM-clean room

Attachments

Summary/UNILAC-scenario

UNILAC (nc)	
A/Z (HSI)	26
A/Z (Poststripper)	6
Duty factor/RF [%]	**30**
Wkin [MeV/u]	7,5
beam time [months]	**6**
cavities in use:	
HSI	RFQ, SL, IH1, IH2
Poststripper	AI, IIA, IIB, III/IE
Buncher	BB3, BB4
Single Resonators	3

subsystem	section	P [kW]
RF-amplifiers	HSI	600
RF-amplifiers	AI-AIII	1900
RF-amplifiers	SGR	190
Power Supplies	HSI	70
Power Supplies	Poststripper	145
Beam diagnostics	UNILAC	100
Cooling water	UNILAC	1200
Basic load	UNILAC	650
Ion source	Penning	40
	tot.	**4895**
	costs [M€]	**6,34**

Summary/HELIAC-scenario

HELIAC (sc)	
A/Z	6
Duty factor/RF [%]	**100**
Wkin [MeV/u]	7,5
beam time [months]	**1,5**
cavities in use:	
nc-Injektor	RFQ, IH1, IH2
sc-HELIAC	CM1-4
Buncher	2

subsystem	section	P [kW]
Ion source	ECR	230
RF-amplifiers	nc-Injector	270
RF-amplifiers	CM1-4	80
cryo supply	CM1-4	130
Power Supplies	HELIAC tot.	150
Beam diagnostics	UNILAC	50
Cooling water	HELIAC tot.	200
	tot.	**1110**
	costs [M€]	**0,36**