42nd European Cyclotron Progress Meeting

# Book of abstracts

Jyväskylä, Finland

27 – 29 May 2024


Certified
B
Corporation
Life.
Science.
iba
Leading particle accelerator technologies
www.iba-worldwide.com
Visit our career site

YLEISELEKTRONIIKKA

# Programmable Power Supplies

- Power range from 200W to 22.5kW
- Output voltage 0-10V / 0-1500V
- Output current 0-15A / 0-1500A
- Scalable power systems up to 90kW
- LAN (1.5), USB, RS-232/RS-485, isolated analogue monitoring and control (Built-in)
- Optional EtherCAT, Modbus-TCP, IEEE488 Interfaces, IS420 (Isolated Analog Current Control) and Blank Front Panel

TDK·Lambda

www.emea.lambda.tdk.com

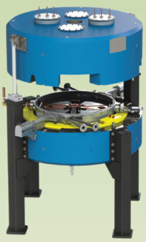
TEAMBEST GLOBAL®
One World • One Source • The Best!
healthcare for everyone
TeamBest®
Your True Partner
www.teambest.com

# Best™ medical international

A TEAMBEST GLOBAL COMPANY

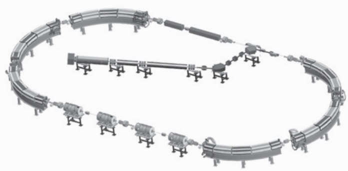
## BE PART OF OUR TEAM

TBG is currently hiring talented engineers manufacturing/computer/software programmers, magnet physicists, scientists, and others. Please email **Krish Suthanthiran** at **Krish@teambest.com** or **Jignasha Patel** at **Jignasha@teambest.com.**

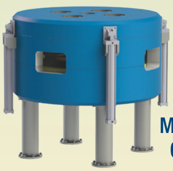


Best Model 6-15 MeV Compact High Current/ Variable Energy Proton Cyclotron

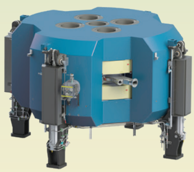

Best B 100p, BG 95p and B 11p Sub-Compact Self-Shielded Cyclotron w/Optional Second Chemistry Module



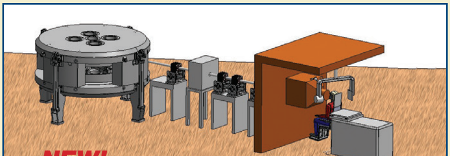
Best Particle Therapy 400 MeV ion Rapid Cycling Medical Synchrotron (iRCMS)



Best Model B25p Cyclotron



Best Model B35ADP Alpha/ Deuteron/Proton Cyclotron



***NEW!***
Best Model 200p Cyclotron—Variable Energy Proton Beam for Radiation Therapy
*(patent pending)*

**Installation of B70 MeV Cyclotron at INFN, Legnaro, Italy.**

## TBG Expansion Plans

TeamBest Global Companies (TBG), in partnership with Best Cure Foundation, plan to manufacture and establish 1000s of medical centers around the globe. These centers will include Best Cure Proactive, Preventive, Primary, Medical, Dental and Eye Care Wellness Centers, as well as treatment centers for cardiac, cancer, diabetes, and infectious diseases.

TBG Companies are expanding operations in the United States and India to meet the increasing demand for manufacturing advanced medical equipment such as cyclotrons, Linacs, MRI, CT, PET CT, X-ray, Ultrasound, and other technologies. The goal is to sell and provide these technologies globally as part of the Best Cure Global Healthcare Delivery.

Best Medical International, Inc. | 7643 Fullerton Road | Springfield, VA 22153 USA
**tel: 703 451 2378   800 336 4970   www.besttotalsolutions.com   www.teambest.com**

ECPM2024

42nd European Cyclotron Progress Meeting

University of Jyväskylä, Finland

## Introduction

The 42nd European Cyclotron Progress Meeting (ECPM2024) is held at and hosted by University of Jyväskylä, Finland on May 27–29, 2024.

The European Cyclotron Progress Meeting is devoted to the physics and technology of cyclotrons, their applications in science, medicine and industry, and to related topics. Status reports on existing facilities as well as innovative developments and progress reports on evolving projects are presented.

The official ECPM2024 website is at `https://www.jyu.fi/en/events/ecpm2024`.

## Social program

Sunday 26 May, Welcome Reception at Hotel Alba. Registration starts at 17:00. Light snacks and drinks are provided starting from 18:00.

Monday 27 May, A tour of the JYFL Accelerator Laboratory. The laboratory performs research on accelerator based nuclear, material and applied physics at the highest international level. We present the laboratory activities and its four accelerators: the K130 cyclotron, the MCC30 cyclotron, the 1.7 MV Pelletron and the cLinac electron linac.

Tuesday 28 May, A boat tour on the lake Päijänne and Social Dinner at Savutuvan Apaja restaurant (`https://savutuvanapaja.fi/en/`). The boat departs at 17:00 from the dock next to Hotel Alba. Bus rides back to city and Hotel Alba at 22:00 and 23:00.

## Local Organizing Committee

Taneli Kalvas (chair)
Pauli Heikkinen
Hannu Koivisto
Ville Toivanen

## Contact information

Department of Physics
P.O. Box 35 (YFL)
FIN-40014 University of Jyväskylä
Finland

Email: ecpm2024@jyu.fi

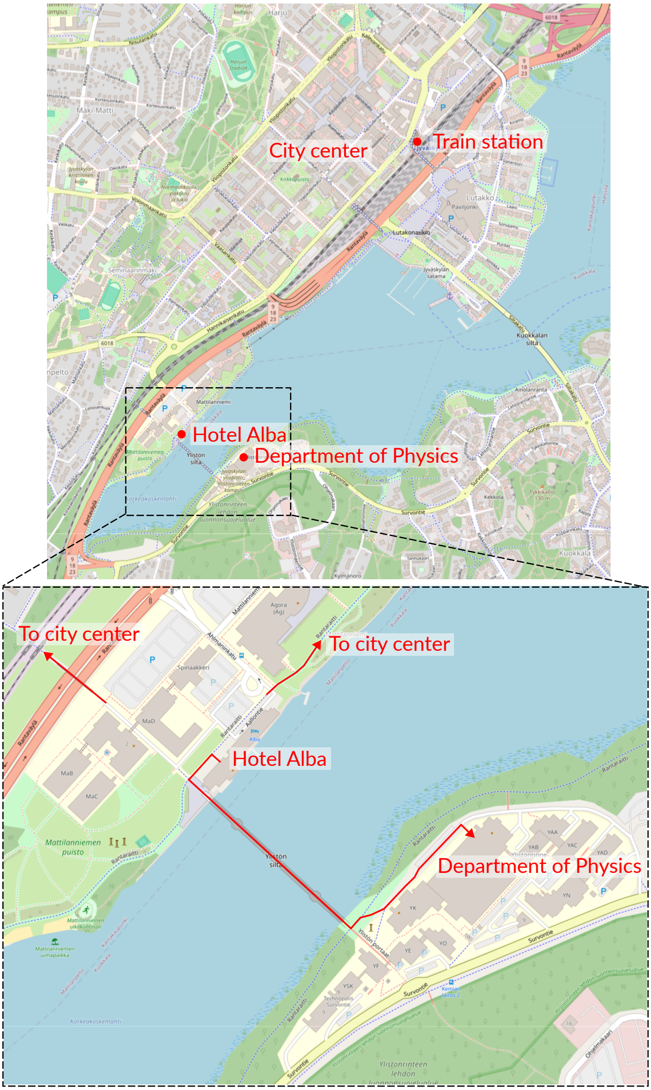
***www.jyu.fi/en/events/ecpm2024***

## Sponsors

The 42nd European Cyclotron Progress Meeting is sponsored by IBA, YTM-Industrial, Leybold, Yleiselektroniikka, TDK-Lambda, Testhouse Nordic, Danfysik and Best Cyclotron Systems.

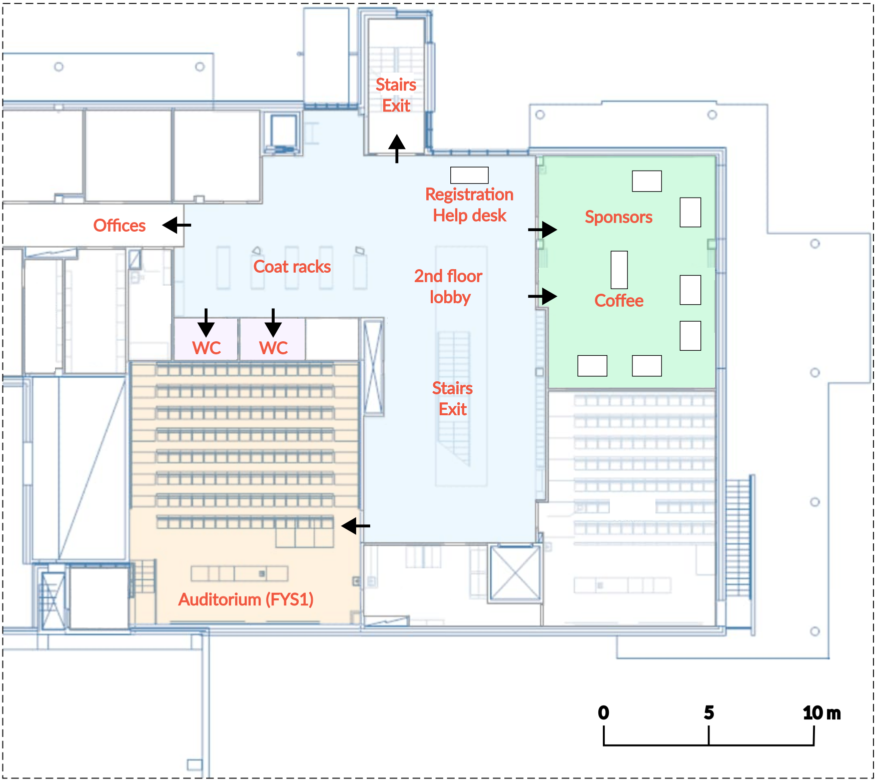
## Key locations in Jyväskylä, Finland

The maps below present the region around the city center of Jyväskylä. The most convenient way to arrive to the city is by train. Hotel Alba is within a walking distance from the train station, if one wants to enjoy a bit of lake shore sightseeing. Alternatively it is possible to take a taxi from the station. The meeting venue, Department of Physics, is located just across the pedestrian bridge from the hotel, only a few minutes walk away.



## Venue floorplan

ECPM2024 is organized at the Department of Physics, University of Jyväskylä. The meeting mainly takes place in the second floor of the department, in the premises shown in the floorplan below.



# Scientific Programme

## May 26 (Sunday)

| Time | Event |
|---|---|
| 17:00 – | Welcome reception and registration at Hotel Alba |

## May 27 (Monday)

| Time | Event | Page |
|---|---|---|
| 8:00 – 9:00 | Registration | |
| 9:00 – 9:15 | Opening and welcome | |
| 9:15 – 9:40 | **Antonio Caruso** | |
| | *Solid state vs. tube power amplifiers, in the frame of the particle accelerators, advantages and disadvantages* | 18 |
| 9:40 – 10:05 | **Omar Kamalou** | |
| | *GANIL accelerators status and renovation project* | 19 |
| 10:05 – 10:35 | Coffee | |
| 10:35 – 10:45 | **Sami Mäki-Rahkola** | |
| | *YTM Industrial and Leybold vacuum technology (Sponsor presentation)* | |
| 10:45 – 10:55 | **Allan Jakobsen** | |
| | *TDK-Lambda programmable (laboratory) power supplies (Sponsor presentation)* | |
| 10:55 – 11:05 | **Karim Butalag** | |
| | *Best Cyclotron Systems, Future of Theranostics and Cyclotrons / Accelerators (Sponsor presentation)* | |
| 11:05 – 11:15 | **Henning Christensen** | |
| | *Danfysik (Sponsor presentation)* | |
| 11:15 – 11:40 | **Taneli Kalvas** | |
| | *Commissioning of the Jyväskylä MCC30* | 20 |
| 11:40 – 12:05 | **Hui Zhang** | |
| | *Quantitative evaluation of production of exotic radionuclides at PSI IP2 target station applying BDSIM/Geant4* | 21 |
| 12:05 – 13:35 | Lunch at Hotel Alba Restaurant | |
| 13:35 – 15:35 | Tour of the University of Jyväskylä Accelerator Laboratory | |
| 15:35 – | Poster Session and refreshments | |

# May 28 (Tuesday)

| Time | Event | Page |
|---|---|---|
| 9:00 – 9:25 | **Jean-Baptiste Lagrange** | |
| | *New developments in Fixed Field alternating gradient Accelerators* | 22 |
| 9:25 – 9:50 | **Le Roux Strydom** | |
| | *A status update of the Cyclone 70P cyclotron of the South African Isotope Facility (SAIF)* | 23 |
| 9:50 – 10:15 | **Laurent Maunoury** | |
| | *A new He cryogenic plant for the C400 IONS system* | 24 |
| 10:15 – 10:45 | Coffee | |
| 10:45 – 11:10 | **Mike Aeschbacher** | |
| | *Status update on the technical planning of the IMPACT project at PSI* | 25 |
| 11:10 – 11:35 | **Erik van der Kraaij** | |
| | *Commissioning of the first Cyclone® IKON* | 26 |
| 11:35 – 12:00 | **Jürgen Bundesmann** | |
| | *Towards a beam profile monitor for the HZB cyclotron at higher proton energies* | 27 |
| 12:00 – 13:30 | Lunch at Hotel Alba Restaurant | |
| 13:30 – 13:55 | **Pauli Heikkinen** | |
| | *Half a century of accelerators at JYFL* | 28 |
| 13:55 – 14:20 | **Andrea Denker** | |
| | *Status of the HZB cyclotron* | 30 |
| 14:20 – 14:50 | Coffee | |
| 17:00 – | Departure to social dinner at Savutuvan Apaja (Hotel Alba pier) | |

## May 29 (Wednesday)

| Time | Event | Page |
|---|---|---|
| 9:00 – 9:25 | **Philippe Velten**<br>*The C400 IONS, a cyclotron for hadrontherapy. Project status report and latest technical developments* | 31 |
| 9:25 – 9:50 | **Jacob Kelly**<br>*A variable energy synchrocyclotron concept for proton therapy* | 32 |
| 9:50 – 10:15 | **Jilei Sun**<br>*Improvement design of a beam current monitor operating under heavy heat load and radiation* | 33 |
| 10:15 – 10:45 | Coffee | |
| 10:45 – 11:10 | **Brian Jones**<br>*Status of the AGOR cyclotron facility at UMCG-PARTREC* | 34 |
| 11:10 – 11:35 | **Jongwon Kim**<br>*Design study of a high-current Q/A=1/2 K100 compact cyclotron for the production of fast neutron and medical isotopes* | 35 |
| 11:35 – 12:00 | **Alberto Ruzzon**<br>*The design of the new chopper for the cyclotron injection line in the SPES project at Laboratori Nazionali di Legnaro* | 36 |
| 12:00 – 13:30 | Lunch at Hotel Alba Restaurant | |
| 13:30 – 13:55 | **Olaf Felden**<br>*The legacy of JULIC* | 37 |
| 13:55 – 14:20 | **Joachim Grillenberger**<br>*High Intensity Proton Accelerator Facility: Commissioning of the new 50 MHz resonators for Injector 2* | 38 |
| 14:20 – 14:45 | **Arturo Abbondanza**<br>*Study of the injection system for the cyclotron of SPES project* | 39 |
| 14:45 – 15:15 | Coffee | |
| 15:15 – 15:40 | Closing remarks | |

# Abstracts

# Solid state vs. tube power amplifiers, in the frame of the particle accelerators, advantages and disadvantages

Antonio Caruso, Luigi Celona, Santo Gammino

*Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud, Italy*

In the large family of the particle accelerators and in the relatively small environment of the wide band cyclic accelerators, the high-power RF Systems were mostly based on the vacuum tube technologies up to a couple of decade ago. Unfortunately, some alarm bells about the tube market prospective, relative to the low bandwidth of the cyclotron radiofrequencies, appeared quite clear about ten years ago. The cost of some specific tetrodes increased, and their availability decreased. The two phenomena were counterbalanced by the parallel growth of a very efficient families of power semiconductor in the low frequency range. Frequency range large enough to easily cover the cyclotron RF bandwidth. For example, this decreasing in the production of a certain type of tetrodes involved one of the two RF power stages of our superconducting cyclotron, at the LNS in Catania few years ago. We replaced the first of two-tetrode stage with a solid-state amplifier. Nowadays our RF power amplifiers run perfectly matched in a hybrid configuration, solid state plus tube stage, since 2015. This sort of bridges, between solid state and tube technologies allows us to have an idea of the advantage and disadvantages of these technologies for the cyclotrons. Some considerations about the use of SSA to generate over-dense plasmas and monocharged beams from microwave discharge ion sources will be outlined. The successful results of this hybrid amplifier, the technical configuration, the present and future and the developments of the solid state will be taken into exam in our talk.

# GANIL accelerators status and renovation project

Omar Kamalou

*Grand Accélérateur National d'Ions Lourds (GANIL), France*

The GANIL facility (Grand Accélérateur National d'Ions Lourds) at Caen produces and accelerates stable ion beams since 1982 for nuclear physics, atomic physics, and radio-biology and material irradiation. Nowadays, an intense stables beams (Proton and Helium) are produced and accelerator by LINAC machine. The review of the operation from 2001 to 2024 will be presented, as well as the scheduled evolutions, with a focus on CYREN project (Cyclotron renovation project).

# Commissioning of the Jyväskylä MCC30

Taneli Kalvas, Risto Kronholm, Jarno Alaraudanjoki, Arto Lassila

*Department of Physics, University of Jyväskylä, Finland*

The Jyväskylä MCC30 cyclotron is under commissioning. The misbehaving RF tube amplifier has been upgraded with proper water cooling to gain stability and robustness, the RF control computer and the buncher power electronics have been completely replaced. The capacitive RF trim in the cavity has been rebuilt. Acceleration to high energies has been demonstrated. Several water leaks have been fixed. Currently we are rebuilding the water cooling of the machine and integrating the controls to the laboratory control system.

# Quantitative evaluation of production of exotic radionuclides at PSI IP2 target station applying BDSIM/Geant4

Hui Zhang, Christian Baumgarten, Robert Eichler, Roger Geissmann, Joachim Grillenberger, Dominik Herrmann, Edoardo Renaldin, Jochem Snuverink, Alexander Sommerhalder, Nicholas van der Meulen, Zeynep Talip

*Paul Scherrer Institute, Switzerland*

At Paul Scherrer Institute the Injector II cyclotron delivers 72 MeV high intensity proton beam up to 2.4 mA, from which 0.05 mA is typically peeled off by an electrostatic splitter and led to the IP2 target station to produce exotic radionuclides such as Sc-44, Cu-64 and Tb-155. Before reaching the target, which is in the form of a thin disk (foil or pressed powder) and encapsuled in aluminum, the beam is degraded to the desired energy by inserting a niobium degrader of suitable thickness between the vacuum window and the target capsule. The target assembly, including the vacuum window, the Nb degrader, and the target capsule, is water cooled. The production setup has been established and optimized empirically over the last decade. Quantitative evaluation is essential to achieve higher yield at reduced cost. Beam Delivery Simulation (BDSIM), a Geant4 based simulation tool, is capable of characterizing the beam transport from the beam splitter to the target station and quantifying the isotope production in the target. This paper systematically investigates the correlation between the productivity of exotic radionuclides and the parameters of the production setup, ranging from beam position, shape, size and energy, as well as degrader thickness and position. The BDSIM/Geant4 simulation indicates that the yield can be improved after optimizing the configuration of target assembly, that is to fit individually the thickness as well as the position of Nb degrader with respect to a specific target. The simulation shows how the yield is affected by the changing beam position, size, and shape. The simulation verifies, that in order to achieve efficient and stable production, the control of beam energy is equally important as, if not more important than the control of other beam parameters such as position, size and shape.

# New developments in Fixed Field alternating gradient Accelerators

Jean-Baptiste Lagrange

*ISIS, Science and Technology Facilities Council, UK Research and Innovation, UK*

The rebirth of Fixed Field alternating gradient Accelerators (FFA) two decades ago has seen many new developments in the field. Among them, the concept of vertical excursion FFA was rediscovered and study of relevant optics and hardware has deepened in the last years. Lattice design in both horizontal and vertical excursion FFAs, with the introduction of super-period and insertions, has been established and opens up new possibilities. A project to demonstrate high power pulsed operation with a horizontal FFA is now under way at RAL, with the development of hardware: design of spiral FFA doublet magnet with high field gradient, RF with Magnetic Alloy to enable both acceleration and beam stacking at top energy and large aperture diagnostics, key of such an R&D machine. A CDR is planned in the coming months. This presentation will review the recent progress around the world.

# A status update of the Cyclone 70P cyclotron of the South African Isotope Facility (SAIF)

Le Roux Strydom

*iThemba LABS, South Africa*

The South African Isotope Facility (SAIF) is a new radioisotope production facility at iThemba LABS in Cape Town that was commissioned at the end of 2023. A commercial 70 MeV proton cyclotron from IBA with a number of beam lines equipped with isotope production stations, have been installed in retrofitted concrete vaults. The facility is supported by new infrastructure and services. An overview of the SAIF project from the inception phase through to the construction and commissioning phases is provided, discussing all related workstreams and progress made to date. A more detailed discussion of some specific systems is given, including the design of the isotope production stations and target handling system.

# A new He cryogenic plant for the C400 IONS system

Laurent Maunoury[1], Paul Hillière[2], Olivier Cosson[1], Dimitri Degeyter[3], Jean Festy[1], Frederick Forest[4], Gaelle Gerard[3], Colin Guillaume[3], Julien Jousset[2], Marc De Leenheer[1], Ronan Olivier[4], Alain Ravex[5], Brice Taglang[2], Thierry Trollier[2], Antoine Ziad[4]

*1. Normandy Hadrontherapy*
*2. Absolut System*
*3. Ion Beam Application*
*4. Sigmaphi*
*5. CryoConsult*

The C400 IONS [1, 2] system is now being assembled on the CYCLHAD [3] site. This new cyclotron makes use of a Super Conducting Coil (SCC) to create the 4.5 T over 1.87 m radius magnetic field necessary to confine the three accelerated ions C, He and $H_2^+$ (the latter being stripped to proton during extraction) for hadron therapy treatment. Under nominal operation, both the upper and lower pair of sub-coils are immersed in a 470-liter helium bath cooling them down to 4.3 K. To drastically reduce helium consumption, especially during the initial cooling down and in quench scenarios, a dedicated closed-loop refrigeration and liquefaction system has been designed and interfaced with the SCC cooling system. This cryogenic plant is supplied with ultra-pure gaseous helium at ambient temperature and uses only a set of cryocoolers and cryofans to produce a the liquid helium inventory for the SCC. The system consists of three main pieces of equipment: the Helium Management System (developed by Absolut System [4]), the Service Turret connected to the SCC via an interface called the ‘umbilicus’, and the quench tanks to store the vaporized helium in case of quench. The authors focus on presenting the design of the complete system and the assumptions used to calculate the time required to obtain helium liquid from 300 K helium gas and the time required to recover from a quench.

[1] J. Mandrillon et al., Status on NHA C400 Cyclotron for Hadrontherapy, Proceedings of the 23rd Int. Conf. Cyclotrons. Appl., CYCLOTRONS2022, Beijing, China (2022) p264
[2] P. Velten et al., this proceeding (2024)
[3] F. Chevalier, P. Lesueur and G. Gaubert, CYCLHAD: A French Facility Dedicated for Research and Treatment in Hadrontherapy, Nucl. Physics News vol. 32 Iss. 2 (2022)
[4] Absolute System https://absolut-system.com/

# Status update on the technical planning of the IMPACT project at PSI

Mike Aeschbacher

*Paul Scherrer Institute, Switzerland*

The goal of IMPACT project (Isotope and Muon Production using Advanced Cyclotron and Target technologies) is the construction of two new target stations and beamlines at the high-intensity proton accelerator HIPA. The project consists of two subprojects HIMB and TATTOOS. The pre-phase of the project will start in 2025 and the main upgrade works will take place in 2027–2030. The aim of HIMB is to upgrade the existing muon target at HIPA, which will lead to an increase of the available muon rate by up to a factor 100. The aim of TATTOOS is to build a new facility capable of producing radioisotopes for clinical studies for advanced cancer treatments. From a technical perspective, to reach these goals, there are a variety of dismounting and assembly work that requires upfront detailed planning. In my talk I will present the planning and the preparation work done until now.

# Commissioning of the first Cyclone® IKON

Erik van der Kraaij, Michel Abs, Patrick Verbruggen, Olivier Michaux, Jean-Michel Geets, Vincent Nuttens, Jerome Mandrillon

*Ion Beam Applications S.A., Belgium*

In 2022, IBA presented the new Cyclone® IKON, a complete redesign of its 30 MeV proton accelerator. Currently, the commissioning of the first installation is ongoing in the US. The setup has four beam transmission lines, which we will present. We will show the first results of the injection into the cyclotron, its transmission, and performance on target. A comparison of simulations with the on-site results will be presented.

# Towards a beam profile monitor for the HZB cyclotron at higher proton energies

Jürgen Bundesmann[1], Ayse Akin[2], Alina Dittwald[1], Timo Fanselow[1], Ilyass Ja[1], Georgios Kourkafas[1], Andrea Denker[1]

*1. Helmholtz-Zentrum Berlin für Materialien und Energie, Germany*
*2. Berliner Hochschule für Technik, Germany*

The HZB cyclotron accelerator complex provides since more than 25 years 68 MeV protons for proton therapy and related research. The main accelerator is a K=130 isochronous sector cyclotron which is served by two injectors. The origin of the cyclotron dates back as an accelerator for heavy ions. For this reason, the existing beam profile monitors (BPM) on the high energy side of the cyclotron are not suitable for protons, especially at the comparable high energies and low beam intensities used. However they work perfectly on the low energy side upstream the cyclotron. At the experimental station and at the treatment room, the profile and shape of the beam is determined via cameras looking on the mirrored image of a scintillator screen. For the experimental station a LabVIEW code has been developed. The code displays the shape and intensity distribution in real time. Beam properties like size and position are determined online. As this tool proved to be very helpful when tuning the beam for experiments, an installation within the beam line in vacuum is under construction. Different scintillator materials are under investigation to match the whole range of beam intensities and minimize the impact on beam properties. First results of the new beam profile monitor will be presented.

# Half a century of accelerators at JYFL

Pauli Heikkinen

*Department of Physics, University of Jyväskylä, Finland*

The first accelerator, the MC-20 Cyclotron, was taken into use in the middle of 1970's at JYFL (University of Jyväskylä, Department of Physics). Later, the K130 Cyclotron was designed together with AB Scanditronix and taken into use in early 1990's. Today, JYFL hosts four accelerators: the K130 and MCC-30 cyclotrons, a Pelletron tandem linac and electron linac. The history and developments of the JYFL ACCLAB will be reviewed in the presentation.

# Development of CYCLOPS code: linear coupling analysis

Lige Zhang, Rick Baartman, Yuri Bylinskii, Thomas Planche, Yi-Nong Rao

*TRIUMF, Canada*

CYCLOPS, utilized for decades in cyclotron beam dynamics study, was initially developed by Gordon [1], focusing on linear dynamics with median plane symmetry of the magnetic field. At TRIUMF, enhancements were made to include median plane asymmetry for closed orbit searching, though asymmetric field influence is ignored in tune calculation. Recent upgrades introduce linearized motion equations incorporating coupling terms and median plane asymmetry fields to compute a 4x4 coupled transverse transfer matrix. A post-processing script has been developed to handle the matrix using Teng's parameterization method [2], converting it into normal mode through symplectic frame rotation and computing the coupling strength. Validation was made by comparing CYCLOPS output with analytical approximations under static tune conditions.

[1] M. M. Gordon, "Computation of closed orbits and basic focusing properties for sector-focused cyclotrons and the design of CYCLOPS", Particle Accelerators 16, 39–62 (1984).
[2] L. C. Teng, NAL Report No. FN-229, 1971.

# Status of the HZB cyclotron

Andrea Denker, Alina Dittwald, Georgios Kourkafas, Jürgen Bundesmann, Timo Fanselow, Dirk Hildebrand, Jörg Röhrich

*Helmholtz-Zentrum Berlin für Materialien und Energie, Germany*

In June 2023 HZB and Charité – Universitätsmedizin Berlin could celebrate the 25th anniversary of proton therapy of ocular melanomas in Berlin. More than 4600 patients have been treated so far. The local tumour control is 96 % after five years. Besides the ongoing treatment, there is an active R&D programme comprising FLASH experiments, beam delivery, beam characterization, and dosimetry. Furthermore, beam is provided for radiation hardness tests of electronic compounds or solar cells for space applications, feasibility studies of isotope production, and geology. Together with the Universität der Bundeswehr a new target station for mini-beams is under construction: beam line calculations have been performed and installation of the components has started. For the control system of the new beam line EPICS will be used instead of VSystems, which is used for the cyclotron and the existing beam lines. A modernization project has been started in order to secure a long term and sustainable operation of our accelerator complex for therapy and research. A concept study has been assigned to AIMA Development and is under way. The goal is a 70 MeV/amu cyclotron for $H_2^+$ and $^4He^{2+}$ ions. The existing buildings are evaluated for a potential installation. In June 2023, just the night before the scheduled ramping up the cyclotron, HZB was the victim of a severe cyber-attack. The impact on the accelerator and lessons learned will be presented.

# The C400 IONS, a cyclotron for hadrontherapy. Project status report and latest technical developments

Philippe Velten[1], Jérôme Mandrillon[2], Olivier Cosson[1], Jérôme Hanot[1], Marc De Leenheer[1], Laurent Maunoury[1], Michel Abs[2], Sebastien Déprez[2], Sebastien De Neuter[2], Xavier Donzel[2], Gaëlle Gérard[2], Yves Jongen[2], Laurent Koffel[2], Vincent Nuttens[2], Frédéric Forest[3], Ronan Olivier[3], Alain Ravex[4], Paul Hilliere[5], Thierry Trollier[5]

*1. Normandy Hadrontherapy, 1 Rue Claude Bloch, F-14000, Caen, France*
*2. Ion Beam Application, Chemin du Cyclotron 3, B-1348 Ottignies-Louvain-la-Neuve, Belgium*
*3. SIGMAPHI, ZI du Prat, Rue des frères Montgolfier, F-56000 Vannes, France*
*4. CryoConsult, France*
*5. Absolut System, 2 Rue des murailles, F-38170 Seyssinet-Pariset, France*

The C400 [1] is an isochronous cyclotron for cancer therapy delivering high dose rates of carbon and helium ions up to 400 MeV/amu and proton ions up to 260 MeV. The NHa company designs, produces, and markets this new multi-ions C400 based therapy system while IBA experts are deeply involved in all aspects of its conception. The main elements of the system: cyclotron parts, beamline elements and all auxiliary systems are currently being installed at the CYCLHAD centre in Caen-Normandy-France [2] which is already equipped with an IBA ProteusÂ®ONE protontherapy system. This new multiparticle Hadrontherapy system inherits and improves on many proven technologies and latest innovations developed for the IBA Proton Therapy systems. In this presentation, we will focus specifically on the latest developments around the C400 cyclotron [3]: central region, extraction system, internal beam diagnostics, RF system, cryogenics [4], and its injection line composed of three independent ECR ion sources. A status report of the project with an overview of the on-going installation and achieved/foreseen milestones will also be given.

[1] J. Mandrillon et al., Status on NHA C400 Cyclotron for Hadrontherapy, Proceedings of the 23rd Int. Conf. Cyclotrons. Appl., CYCLOTRONS2022, Beijing, China (2022) p264
[2] F. Chevalier, P. Lesueur and G. Gaubert, CYCLHAD: A French Facility Dedicated for Research and Treatment in Hadrontherapy, Nucl. Physics News vol. 32 Iss. 2 (2022)
[3] Y. Jongen et al., "Current status of the IBA C400 Cyclotron Project for hadron therapy", in Proc. of EPAC08 2008, Italy, p. 1806.
[4] L. Maunoury et al., this proceeding (2024)

# A variable energy synchrocyclotron concept for proton therapy

Jacob Kelly, Jerome Mandrillon, Willem Kleeven

*Ion Beam Applications S.A., Belgium*

Existing cyclotrons for proton therapy produce fixed energy beams of around 230 MeV. Energy variation is performed in the beam line by an energy selection system wherein the beam energy is reduced by passage through an energy degrader to a minimum of 70 MeV. This method increases the energy spread of the beam, increasing the distal fall-off of the Bragg peak; reduces the beam current, by ∼99 % when degrading from 230 to 70 MeV; and produces neutrons, increasing the shielding requirement. In this contribution, we present a concept for a synchrocyclotron for which the energy of the extracted beam may be varied, potentially removing the requirement for an energy selection system. In this concept, extraction is achieved using the $2\nu r = 2$ resonance, which can be excited at various energies thanks to a variable "virtual" second harmonic magnetic field contribution along the beam trajectory. The virtual second harmonic is produced by shifting the orbit centre using a first harmonic field contribution in a three-sector median plane field. The stop band of the $2\nu r = 2$ resonance depends on the amplitude and radial gradient of the second harmonic. Once the orbit enters this stop band, the orbit centre becomes unstable and shifts towards the extraction channel.

# Improvement design of a beam current monitor operating under heavy heat load and radiation

Jilei Sun, Pierre-André Duperrex, Joël Elio Bachmann, Jochem Snuverink

*Paul Scherrer Institute, Switzerland*

The High Intensity Proton Accelerator at PSI delivers a continuous proton beam of up to 2.4 mA with a maximum energy of 590 MeV to two meson production targets, M and E, and then to the spallation target. Eight meters downstream from the target E located a beam current monitor MHC5, which endure intensive scattered particles from Target E and cause large temperature variation, further induce operation and calibration problems. A graphite monitor based on passive cavity was designed to address all these issues and started to operation in 2015. Based on years of operation experiences of this graphite cavity, improvement design has been also considered, including beam positon pickups refinement, on-line calibration methods implementation, as well as manipulation maintenance issues.

# Status of the AGOR cyclotron facility at UMCG-PARTREC

B.N. Jones[1,2], S. Both[1], S. Brandenburg[1], R.P. Coppes[1], P. Dendooven[1], A. Gerbershagen[1], M.-J. van Goethem[1], E.R. van der Graaf[1], J.M. Schippers[1]

*1. Particle Therapy Research Center (PARTREC), Department of Radiation Oncology, University Medical Center Groningen, University of Groningen, The Netherlands*
*2. Department of Biomedical Sciences of Cells and Systems, University Medical Center Groningen, University of Groningen, Groningen, The Netherlands*

The PARticle Therapy REsearch Center (PARTREC) is a research facility at the University Medical Center Groningen (UMCG) in The Netherlands. At PARTREC, the superconducting cyclotron AGOR is available for experimental research, mainly in radiation physics and biology. Specifically, AGOR can deliver ion beams of all stable elements with an energy dependent on the charge-to-mass ratio of the ions. For radiation hardness tests, the facility provides beams of protons at different energies and various ions (from He to Xe) at 30 MeV/amu. Experiments can also be performed with C and O ions at 90 MeV/amu. Proton beams with energies relevant for clinical purposes (range in water up to 230 mm) are used for preclinical radiation biology research and proton therapy related physics for the past twenty-five years. Working in collaboration with the UMCG Groningen Proton Therapy Center (GPTC), PARTREC uniquely combines radiation physics, medical physics, biology and radiotherapy research with an R&D program to continuously improve hadron therapy technology and advance radiation treatment for cancer patients. In addition, it provides opportunities for experiments in the domain of radiation hardness, for both the scientific and commercial communities, and nuclear science, in collaboration with the Faculty of Science and Engineering of the University of Groningen.

A description of the activities surrounding a prolonged technical shutdown for the improvement of reliability and expansion of technical capacity will be presented. This includes improvements to AGOR's cryogenics system. Recently, a new phase combining double traveling-wave tube (TWT) system has been installed at the ion source setup which to maximally generates an RF power of 1.1 kW in the frequency range of 12.75 to 14.5 GHz for ECR plasma heating. This new phase combining system is equipped with an oscillator which is capable of sweeping frequencies to find the highest beam intensity and minimize beam instabilities. Within the framework of EURO-LABS ERIBS program, UMCG-PARTREC is developing a statistical algorithm in combination with an in-beam Faraday cup device to monitor the ion beam stability of its AECR ion source. In addition, remote control of irradiation experiments is in development, aimed at reducing the need for external users to travel to the facility. The AECR is also being prepared for use as part of the new infrastructure, called NEXT, to study the neutron-rich, exotic, heavy nuclei produced in multinucleon transfer reactions using actinide targets.

A new preclinical research infrastructure with a wide range of irradiation modalities, based on both scattering and pencil beam scanning using shoot-through with high energy protons as well as Spread-Out Bragg Peak for protons and helium (range in water up to 60 mm), is currently under development and is scheduled to become available in 2024. Additionally, the adaptation of the facility for the delivery of spatial fractionation and high dose rates in excess of 300 Gy/s (FLASH) is foreseen.

# Design study of a high-current Q/A=1/2 K100 compact cyclotron for the production of fast neutron and medical isotopes

Jongwon Kim

*IRIS, Institute for Basic Science, Korea*

Magnetic design and beam optics studies have been carried out for a K100 cyclotron, which can accelerate Q/A=1/2 ions to the energy of 25 MeV/u. Since proton acceleration using H2+ instead of H+ or H- can double the maximum beam current limited by space charge effects at the injection energy of compact cyclotron, we expect a maximum current of over 2 mA achievable. In addition, d+, He2+ can be accelerated with slight adjustments of rf frequency so as to produce fast neutrons and medical isotopes for advanced cancer therapy, respectively. It is important to extract d+ at an efficiency of above 99% to avoid serious radiation contamination, and thus final turn separation was carefully examined with rf voltage per turn and precession considered. Also, we have looked into a charge stripping method to extract H2+ at a lower energy to partly accommodate energy variability. I will present major features of the cyclotron design and possible utilization.

O-19

# The design of the new chopper for the cyclotron injection line in the SPES project at Laboratori Nazionali di Legnaro

Alberto Ruzzon, Arturo Abbondanza, Piergiorgio Antonini, Mario Maggiore, Lorenzo Pranovi

*Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, Italy*

In the SPES project, at Laboratori Nazionali di Legnaro, INFN, the primary beam, which is generated by the cyclotron Best 70p (70 MeV and 700 µA maximum), will be sent to two ISOL targets or to other systems requiring a precise management of the beam current. The most efficient way to achieve such a control is to vary the input current of the cyclotron, for this reason it has been chosen to install a new chopper in the injection line of the cyclotron. The requirements for the new chopper are to be compact, in order to fit the available injection line chamber; to allow a resolution up to 1/1000 of the total current, in order to ensure a very stable temperature in the ISOL targets; and to have an intrinsic safeness for the targets, that is to avoid an unintentional current boost in case of a chopper failure. Given the above constraints, the chopper is essentially a Wien filter where the magnetic field is generated by two permanent magnets and the electric field is provided by two plates biased by a power supply and a fast switch. In this way the beam is normally deflected by the magnetic field, which is independent from any source, and the choice to design it as a Wien filter compacts the ensemble. This contribution further specify the design and describes the results obtained computationally during the preliminary study.

# The legacy of JULIC

Olaf Felden[1], Yuri Valdau[2], Kirill Grigoryev[2], Ralf Gebel[1]

*1. Forschungszentrum Jülich GmbH, Institut für Kernphysik, Germany*
*2. GSI, Germany*

The cyclotron JULIC is an exceptional example of long-lasting technology and innovation that has been operating for over 56 years. Its unparalleled reliability, high performance, and versatility have made it an indispensable part of the Forschungszentrum Jülich (FZJ) research program. The cyclotron allowed the conduct of nuclear physics experiments, irradiation experiments, and tests of radiation effects, displacement damage, and single-event effects in electronic devices or space applications, making it an invaluable asset to the scientific community. With the superconducting ECR ion source ISIS, JULIC has accelerated highly charged heavy ions up to Ne, widening the research program from nuclear physics with light ions toward heavy ions. Moreover, its role as the pre-accelerator for the Cooler Synchrotron COSY since 1993 and the driver accelerator for the JULIC-Neutron Platform has expanded its capabilities and opened up new avenues of research. With its colliding beams source CBS, JULIC has delivered unpolarized and polarized proton and deuteron beams to COSY and its hadron physics research program, leading to many successful experiments. Even after 30 years of operation as the pre-accelerator of COSY with proton and deuteron beams, JULIC hasn't lost its ability to run with other species. It was shown in 2023 with successful acceleration and experiments with He-3. The technical improvements made to the JULIC systems over the years have been critical in maintaining its high reliability and operational efficiency. The transition to an oil-free vacuum system, upgrading diagnostic systems, and adapting the timing system to meet different experimental needs are just a few of the many improvements that have been made. In conclusion, JULIC's 56-year history of reliable and high-performance operation is a testament to the ingenuity, dedication, and hard work of the FZJ scientists and engineers who have made it possible. Its continued relevance and importance for the COSY/FZJ physics program made it a valuable investment in research and innovation.

# High Intensity Proton Accelerator Facility: Commissioning of the new 50 MHz resonators for Injector 2

Joachim Grillenberger, Markus Schneider

*Paul Scherrer Institute, Switzerland*

The Paul Scherrer Institute (PSI) is upgrading its proton accelerator facility to enhance beam power and improve reliability. Recently, two 150 MHz resonators in the Injector 2 cyclotron were replaced with higher-voltage 50 MHz Aluminum resonators, to improve beam dynamics. Additionally, new frequency tuners solved initial mechanical issues, ensuring optimal operation of the setup. Measurements with resonator 2 in 2023, confirm the desired higher beam acceleration characteristics, i.e. a higher separation of turns, indicating a potential reduction in relative beam losses. Following the successful tests with resonator 2, resonator 4 has been installed this year and will undergo testing during 2024, which will mark another milestone in the PSI upgrade project. These advancements are the blueprint for further improvements in beam performance and operational efficiency. This abstract summarizes the latest progress in the PSI upgrade project, emphasizing technical and operational challenges, paving the way for future experimental facilities driven by HIPA.

# Study of the injection system for the cyclotron of SPES project

Arturo Abbondanza, Mario Maggiore, Piergiorgio Antonini, Alberto Ruzzon, Lorenzo Pranovi

*Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, Italy*

At Laboratori Nazionali di Legnaro of Istituto Italiano di Fisica Nucleare a new facility for nuclear physics is under construction. Named SPES (Selective Production of Exotic Species), its main aim is to deliver radioactive ion beams of neutron rich species for low energy nuclear physics experiments. The SPES cyclotron, built by Best Theratronics in collaboration with Istituto Italiano di Fisica Nucleare, is the heart of SPES project. It accelerates $H^-$ ions and provides, by stripping process, two proton beams with total combined current of up to 700 µA and energy between 35 MeV up to 70 MeV. The cyclotron was installed and tested in 2017, now it is going to be put in operation after a stop period due to the completion of infrastructure works. In order to study the beam dynamics of the injection process and optimize the parameters of the injection line and the cyclotron and eventually upgrade or add some parts, it is important to build and validate a virtual model of the system. Using Simion software, I developed a simulation of the injection system and the central region of the cyclotron (up to 1 MeV). To show a direct application of this model, I considered the design of a double gap buncher. By means of it, the injection efficiency would increase and even higher currents would be achieved without stressing the ion source. I took into account also space charge effects in order to estimate the maximum current accepted by the cyclotron.

# Design of the central region for high intensity compact cyclotron

Xi Chen, Guoliang Dou, Liangting Sun, Bing Wang, Hongwei Zhao, Qinggao Yao, Xianwu Wang, Yao Yang

*Institute of Modern Physics, Chinese Academy of Sciences, China*

High beam intensity compact cyclotron for isotope production has received wide attention around the world. The design of the central region is crucial in a high intensity compact cyclotron, which determines the transmission efficiency of the cyclotron and whether the cyclotron is capable of being operating at high beam intensity. However, the space charge effect and beam loss that occur in the high-intensity compact cyclotron make the design of the central region a big challenge. To ensure that the acceptance of the centre area is greater than ±20°, with COMSOL platform, we have made a systematic simulation of the entire process of the axially injected beams from a spiral inflector to the first few turns of the central resign. This work will provide a feasible design of the central region for a high-intensity compact cyclotron.

# Selected modifications in the U-200P cyclotron at Heavy Ion Laboratory

Jaroslaw Choiński, Olga Nassar, Łukasz Standyło

*Heavy Ion Laboratory, University of Warsaw, Poland*

The Warsaw U-200P cyclotron has been continuously providing ion beams for 30 years. In April 2024, the Heavy Ion Laboratory celebrated the anniversary of this fact. Despite the tight work schedule, the cyclotron and related equipment modernizations are carried out on an ongoing basis.

The modernization of the spiral inflector gives greater freedom of its operation and have a significant impact on the quality of the accelerated beams. Changing the mechanical parameters of the inflector improved its operating conditions and increased optimization of the injected ion beams.

Improvements of 10 GHz ECR ion source were focused to change microwave power injection system and to increase the cooling efficiency of the magnetic trap. Over the years, some of the materials from which the source was constructed have lost their physical parameters, e.g. permanent magnets in a multipole configuration. This resulted the need to rebuild the entire magnetic trap. Due to the high demand for metallic beams, numerous tests are carried out to produce such beams. Special oven was constructed for production nickel and calcium beams. The first tests with a calcium beam show promising results.

HIL has been involved in the production of radioisotopes for many years. In order to fully use the intensity of the alpha ion beam, a new station for internal beam irradiation of metallic or powder targets was designed and constructed. A photo of this research station with a description is an element of the poster. It is more efficient and reduces the risk of work for the operation staff.

Plans in the coming months include the preparation of an operation to replace the electrostatic quadrupole doublet installed on the injection line with an electromagnetic one using the quadrupoles that HIL received from The Svedberg Laboratory, Uppsala, Sweden, dismounted from the Gustaf Werner cyclotron. Replacing the doublet requires an appropriate procedure, completing the equipment and devices, and correlating the work with the allocation of the ion beam to the experimental groups.

For more accurate diagnostics of the guided ion beam, Faraday cups at the injection line have been improved. The cups have three collectors in their design, which gives information not only about the intensity of the beam but also the approximate distribution of the ion beam inside an injection line.

The above-mentioned works are in partial implementation, but their completion depends on the reserved time related to the break in experiments.

# Simulation of a high-intensity $H_3^+$ cyclotron beam dynamics with OPAL

Guoliang Dou, Xi Chen, Liangting Sun, Hongwei Zhao, Bing Wang, Qinggao Yao, Xianwu Wang

*Insitute of Modern Physics, Chinese Academy of Sciences, China*

High-intensity proton cyclotrons have widespread applications in scientific research, medical treatments, and industrial processes. As cyclotron technology continues to evolve, the trend leans toward more compact designs with increased beam intensity. Our proposed design involves a 120 MeV/u superconducting $H_3^+$ cyclotron named SK1000, capable of achieving 3 times the operational beam intensity through foil stripping. This configuration meets the demand for compact and high-intensity cyclotrons in practical applications. However, the intense space charge effects have significant impact on proton beams during injection, acceleration, and extraction, imposing stricter requirements on magnet design, RF systems, and beam extraction system. Leveraging the OPAL (Object Oriented Parallel Accelerator Library), a powerful open-source tool for charged-particle optics, we simulated the baseline model of SK1000. Our analysis provides valuable insights into high intensity beam transport during acceleration and extraction, offering robust support and optimization directions for the challenging high intensity $H_3^+$ cyclotron design.

# Repair of a leaking high power coaxial feedthrough and the replacement of a cracked quartz ring

Timo Fanselow, Andrea Denker, Thassilo Damerow

*Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Germany*

Ocular melanomas have been treated for the last 25 years at the Helmholtz-Zentrum Berlin in collaboration with the Charité – Universitätsmedizin Berlin. However, the main components of the high-power high-frequency systems at the cyclotron date back to the 1970s. All power components of the two 30 kW main amplifiers mounted directly on top of the K=132 cyclotron are water-cooled. A brief description of the repair of a leaking high power coaxial feedthrough and the replacement of a cracked quartz ring are presented.

# CYCLADE – the Belgian center of expertise for cyclotron decommissioning

Emanuele Festa

*Ion Beam Applications S.A., Belgium*

In the world, several cyclotrons installed decades ago are currently reaching their end of life. For these, revamping is often not possible due to the obsolescence of the components or the disappearance of the original manufacturer from the market. Cyclotron operators are therefore forced to decommission the old systems to liberate the site or replace it with a new machine. As a consequence, it is expected that 50 cyclotron installations will have to be decommissioned in US and Europe by 2030, and globally more than 200 by 2040. Cyclotron decommissioning is an emerging activity which creates the need for a new expertise, capable of managing the complexity of working in a radioactive environment with constraints such as, for example, being in an operating building where patients are still present. In 2023 IBA, together with other five Belgian organizations, Interboring, IRE, SCK CEN and Transrad joined forces to form CYCLADE, a center of expertise for the decommissioning of cyclotrons. This partnership provides cyclotron operators with a new interlocutor, which combines all the skills needed to tackle a decommissioning project from radiological assessment to logistics and storage of radioactive material. In this poster, we will present the lifecycle of dismantling a facility from the writing of its initial decommissioning plan towards the dismantling project, the CYCLADE consortium and its partners.

# C400 – 10K Remote Helium Cooling Loop for ions carbon cyclotron application

Paul Hillière[1], Brice Taglang[1], David Mascaux[1], Thierry Trollier[1], Alain Ravex[2]

*1. Absolut System, France*
*2. Cryoconsult, France*

To improve the precision and the efficiency of cancer treatment, a new kind of radiotherapy using ions carbon is under development in France. This project called C400, involved a 400 Mev/u cyclotron composed of a 15 tons supraconducting magnet cooling by a 470 L liquid helium bath. This whole project is led by Normandy Hadrontherapy in collaboration with IBA, Sigmaphi and Absolut System. In order to cool down of the magnet from 300 K, Absolut System designed, manufactured and tested a high capacity 10 K Remote Helium Cooling Loop. This system is a forced Helium 4 cooling loop cryostat which is providing a progressive and controlled cooling for the application from 300 K to 10 K. The cryostat is equipped with two Gifford-MacMahon AL630 cold heads, two double stage Pulse Tube PT420 cold heads and a LN2 tank corresponding to seven cooling stages. Helium flow controlled by two cryogenic circulators has a range of 0.1 to 5 g/s. Pressure range from 1 to 4 bars, can be adjusted to optimize the efficiency depending on the Helium temperature. In C400 Project, our cryostat also provides LN2 to other equipment such as cryogenic transfer lines, magnet and quench tank thermal shields. It will guarantee the best cooling for the supraconducting magnet before the liquefaction phase takes place under 10 K. Moreover, when quench will occur, all the Helium gas will be recovered in tanks. Our 10 K Remote Helium Cooling Loop will cool once again Helium gas from the tanks permitting to recycle all Helium gas and restart quickly the cyclotron. Thus, the 10 K Remote Helium Cooling Loop is an innovative solution permitting to cool down the C400 cyclotron as many times as it will need, from a 300 K Helium gas storage in complete autonomy even if quench occurred.

# Status report of the operations and ongoing developments in "Cyclone", AVF cyclotron of CRC in Louvain-La-Neuve

François-Philippe Hocquet, Laurent Standaert, Nancy Postiau

*Cyclotron Resource Centre, Institute in Mathematics and Physics, Catholic University of Louvain-La-Neuve, Belgium*

The Cyclotron laboratory (CRC) was created in 1972 with the installation of the cyclotron "CYCLONE" (Kb = 110) in Louvain-la-Neuve, Belgium. Until late 90's, this cyclotron was dedicated to research in nuclear physics (realizing the first ever accelerated ISOL RIBs, used for nuclear astrophysics measurements), nuclear chemistry and medicine (neutron and proton therapy). The CRC now mainly delivers ions beams for industrial applications as radiation hardness tests of electronic devices for space applications or micro-porous membrane production. The CRC has three beam lines dedicated to radiation hardness tests (heavy ions, protons and neutrons) and a Cobalt-60 source. The heavy ions and protons facilities are recognized and supported by ESA. A new beamline is being implemented to allow medical testing in proton flash radiotherapy. To achieve always higher charge state (up to $Xe^{35+}$), CRC developed its own external ions sources. Two homemade ECR sources are being used in routine operations. Actually, the heavy ions facility offers a cocktail of 9 ions with an energy of 9.3 MeV per nucleon which covers a large domain of LET and ranges. In this status report, we will provide an overview of the industrial applications of our cyclotron. This will include a brief description of current cyclotron operations and an update on ongoing developments.

# Status of the cyclotrons at Turku PET Centre

Stefan Johansson, Stefan Johansson, Joakim Slotte, Jukka Ihalainen

*Turku PET Centre, Finland*

Turku PET Centre (TPC) is a joint National Research Institute of University of Turku, Åbo Akademi University and Turku University Hospital. The mission of TPC is to promote the use of short-lived positron emitting isotopes and apply multimodality imaging in the field of medical research.

The oldest cyclotron MGC-20, installed 1974, was taken out of operation as the Åbo Akademi building, Gadolinia, was scheduled to be demolished. The practical decommissioning work was mainly conducted during 2020, although planning of the project and the activity monitoring started significantly earlier. As the cyclotron had been in operation for 45 years, substantial amounts of various active isotopes were found in cyclotron parts, auxiliaries, as well as in building structures. The monitoring was partly based on neutron activation modelling data (building structures/areas) and partly on the activity of machine parts or samples thereof. As expected, it was found that Co-60 as well as Mn-54 were hindering the release of cyclotron items as well as steel reinforced building parts due to the activity concentrations exceeding exemption levels.

The three other cyclotrons at TPC, CC18/9, TR19 and Cyclone 3, are used for routine production of short-lived radioisotopes for 7 PET scanners. Cyclone 3 is a small deuteron cyclotron dedicated for O-15 production. Another Cyclone 3 from Osaka in Japan has been shipped to Turku and is stored waiting for future installation. The cryopumps for CC18/9 and TR19 have been changed to turbo molecular pumps. All operational cyclotrons are located at the Turku University hospital and are operated and maintained by personnel from Åbo Akademi University.

# RF system development for JYFL MCC30 cyclotron buncher

Risto Kronholm, Taneli Kalvas

*Department of Physics, University of Jyväskylä, Finland*

A beam buncher is a device used to increase ion beam current from cyclotron by bunching the input ion beam to short and more intense pulses. In case of a DC ion beam only small percentage of the beam is accelerated in one acceleration period. With the buncher, a bunch of particles that are time and space separated in beam are forced to arrive at a focus at same time in one acceleration period. This is done by velocity modulating the beam with RF electric field applied between two gaps. Ideally the waveform of the electric field should be a sawtooth, but for simplicity we use a single frequency sinusoidal electric field. The buncher is operated with the same frequency as the cyclotron.

A RF system for driving the JYFL MCC30 buncher has been developed and will be presented in this presentation. The key design parameters for this RF system were operating frequency (40.68 MHz), amplitude (450 Vpeak) between gaps and load (-j90 ohm) of buncher seen by RF system. As a mainly capacitive load cannot be directly impedance matched to 50 ohms, which is characteristic impedance of the system, an LC resonance circuit is implemented. This resonance circuit is driven with a house build single transistor tuned power amplifier constructed by using MRF300 LDMOS. The RF signal is produced by a Keysight 33500A waveform generator and is amplified by a Mini-Circuits ZX60-100VHX+ preamplifier to a sufficient level for the power amplifier. The buncher amplitude and phase can be fine-tuned directly from waveform generator. Capacitive feedback from buncher and a directional coupler after power amplifier are also implemented for adjusting the system. The special attention has been given to system safety interlocks.

# Increasing extracted intensity in positive mode by changing the extraction type

Tomas Matlocha

*Nuclear Physics Institute, Asociace Samàritanú Ceské Republiky, Czech Republic*

Simulations suggest that the intensity of the extracted beam from the cyclotron in the positive regime can be significantly increased at the cost of a slight energy reduction. By changing the extraction mode, a several-fold increase in intensity and an improvement in emittance can be achieved compared to conventional precession extraction.

# Status of the iThemba LABS cyclotrons

Moenir Sakieldien

*iThemba LABS, South Africa*

For nearly 40 years, iThemba Laboratory for Accelerated Based Science (LABS), have successfully operated three cyclotrons, delivering charged particle beams to a broad spectrum of users. As a result of this state-of-the-art infrastructure, the facility have developed significant expertise in fields such as production of radioisotopes for nuclear medicine. Over the years, the reliability of the cyclotrons has diminished largely due to the ageing infrastructure as well as factors beyond our control. With the new South African Isotope Facility (SAIF) nearing the end of its commissioning phase, more resources will be available to refurbish and upgrade the K200 cyclotron and its injector cyclotrons. With this contribution we will report on the challenges experienced over the years as well as plans to restore the cyclotron facility to its former state of operation and to enhance the capabilities of the facility to meet the ever-evolving requirements of the user community.

# Design of a $He^{2+}$ ion source for a PET Cyclotron

Léo Talec, Vincent Bertrand

*Pantechnik, France*

As part of a manufacturing project of a PET Cyclotron, PANTECHNIK supplied to ACSI (Advanced Cyclotron Systems Inc.) a SuperNanogan ion source for $He^{2+}$ production. PET (Positron Emission Tomography) is a common imaging technique that uses radiopharmaceutical – a radioisotope attached to a drug – (known as radiotracers) to visualize and measure changes in metabolic processes. In this case, the medical radioisotopes are made from non-radioactive materials (stable isotopes) which are bombarded by these ions $He^{2+}$, after being accelerated in the cyclotron. These ions $He^{2+}$ are produced by the Supernanogan ECRIS (Electron Cyclotron Resonance Ion Source), reliable and with high performance, which the magnetic circuit is entirely made with permanent magnets both for the radial and longitudinal fields, so the total electrical power is extremely low. Its performance allows for example the production of beam currents of 2000 µA for $H^{+}$ or 200 µA for $Ar^{8+}$. For this project, we measured the helium beam distribution given about 1000 µA of $He^{2+}$ together with 700 µA of $He^{1+}$. Supernanogan can run with RF power up to 750 W at 14.5 GHz depending on the element and charge state needed. The maximum extracting voltage is 30 kV. Due to its high performance and versatility, the SuperNanogan has become the reference source for PET Cyclotrons, but also for particle therapy (hadrontherapy), the ultimate cancer treatment method. In the latter case, the Supernanogan allows the production of the following carbon ions : $C^{4+}$ with a beam current of 200 µA – $C^{6+}$ with a beam current of 3 µA. The ions are injected in the Cyclotron (or synchrotron following the projects), and then the accelerated beam is used to treat radioresistant tumors, particularly when they are inoperable.

# Use of beam cocktails with the JYFL K-130 cyclotron for industrial applications

Ville Toivanen, Taneli Kalvas, Heikki Kettunen, Hannu Koivisto

*Department of Physics, University of Jyväskylä, Finland*

The term beam cocktail refers to the practice of simultaneously transporting multiple different ion species with the same charge over mass ratio from the ion source to the cyclotron and accelerating them to high energies. The final selection of the desired ion species is chosen within the cyclotron, which enables fast switching between different ion beams delivered to the user. Beam cocktails accelerated with the K-130 cyclotron have been used at the University of Jyväskylä accelerator laboratory (JYFL-ACCLAB) since the late 90's, and over the years the energy and diversity of the available beams has increased significantly, largely thanks to the development of the electron cyclotron resonance ion sources used in the laboratory. Nowadays the use of beam cocktails is a routine operation at JYFL-ACCLAB and forms the backbone for most of the industrial applications that require high energy beams. In this presentation the status of the beam cocktails used at JYFL-ACCLAB is presented, including an overview of the related equipment and technologies.

# Development of beam line models for the JYFL accelerator laboratory

Mirva Toivio, Taneli Kalvas

*Department of Physics, University of Jyväskylä, Finland*

The beam lines of the K-130 in the JYFL accelerator laboratory have been developed and modified in several phases during the three decades the laboratory has existed. This has resulted in non-optimal layout and some uncertainties in the data as not all modifications have been properly documented. With this background we have re-measured all beam line component locations and modelled the magnet fringe fields to build an up-to-date model of the beam lines. The development aims in analyzing the existing beam transport using the model together with observations produced with Faraday cups and wire scanners and finally ending with improved beam transport. The status of the project and process of building the model is presented.

# Upgrade and current status of RF system of HIRFL

Xianwu Wang, Xin Fu

*Institute of Modern Physics, Chinese Academy of Sciences, China*

The Heavy Ion Research Facility in Lanzhou (HIRFL) is the largest heavy ion research facility in China, which consists of ECR ion source, sector focused cyclotron (SFC), separated sector cyclotron (SSC), cooling storage ring (CSR), radioactive beam line and experimental terminal. The injector SFC cyclotron is a 1.7 m sector-focused cyclotron with the K value of 69, which adopts external ECR ion source and axial injection system. A linear buncher B02 was installed into the vertical beam line section underneath the cyclotron center area, about 2.3 meters before the inflector, the SSC cyclotron is injection radius one meter with K value of 450, the cascade mode of SFC and SSC requires a Buncher NB1 which can increase longitudinal matching efficiency. Therefore, cyclotron RF system of HIRFL include B02 NB1 SFC and SSC. In recent years, in order to improve the operating efficiency and beam intensity of the HIRFL system. B02 buncher, 150 kW RF transmitter and D circuit of SFC, 40 kW RF transmitter of NB1 has been upgraded. Meanwhile, for SSC, a new matching network has been designed and finished testing, the RF voltage is improved greatly. The results: The beam intensity of $^{238}U^{46+}$ 15.53 Mev/u at the HIRFL was increased up to 10 µA. more detail for the article.

# The beam dynamics simulation of a new type of isochronous cyclotron

Zhenghao Xu

*ShanghaiTech University, China*

One of the restrictions on the beam current in a traditional isochronous cyclotron is that the magnetic field increases with radius. As a result, the gap of the magnet and the distance between adjacent turns decrease with radius. To overcome this problem, a new type of isochronous separate-sector cyclotron is proposed. By increasing the distance between the sectors, the isochronous field decreases with radius, allowing the gap of the magnet to increase with radius and the distance between adjacent turns to remain roughly unchanged. These changes would in principle increase the current limit of the accelerator. In this paper, preliminary design and beam dynamics simulation results of a 30 MeV proton machine with 5 MeV injection energy, based on COSY INFINITY and Opera 3D are presented. Possible applications of this kind of cyclotron is discussed.

# Design and optimization of the center region of the superconducting cyclotron with internal sources

Panpan Zheng

*ShanghaiTech University, China*

The intensity and quality of the extracted beam are heavily influenced by the central region structure. Different designs of the central region structure can result in nearly a tenfold difference in beam transmission efficiency, primarily due to variations in the acceleration behavior of beam during the first few turns within the central region. For cyclotrons with internal source, the beam energy at the ion source outlet is very lower, amplifying the impact of different central region structure design on the accelerated beam. Therefore, it is crucial to design the central region structure to enhance transmission efficiency and beam extraction quality. We are focused on simulating a conceptual design for the central region of a compact 11 MeV, 50 μA superconducting cyclotron dedicated to the production of radioisotopes. In this paper, the beam trajectory is optimized by adjusting the position of the ion source, the direction of the opening slit, and the shape of the puller.