Summary of the Snowmass’21 Workshop on High-Power Cyclotrons/FFAs

Daniel Winklehner (MIT)
on behalf of the Organizing Committee and Session Conveners

Cyclotrons 2022

Motivation for the Workshop

- The **Snowmass Process** is a particle physics community planning exercise sponsored by the Division of Particles and Fields of the American Physical Society.
- During this process, scientists develop a collective vision for the next seven to ten years for particle physics research in the US.
- Snowmass’21 was a (more than) year-long hybrid event.
- Reports are here: https://snowmass21.org/
- Sub-Panel Accelerators for Neutrinos tasked us to hold a workshop to discuss the use of cyclotrons in particle physics and as injectors.
- Perfect opportunity to hold a workshop on high-power cyclotrons ☺

Workshop Details

- Organizing Committee:

  Andreas Adelmann (PSI, ETHZ)
  Jose Alonso (LBNL, MIT)
  Luciano Calabretta (INFN-LNL)
  Hiroki Okuno (RIKEN)
  Daniel Winklehner (MIT), Chair

- Additional Conveners:

  Tomas Planche (TRIUMF)
  Malek Haj Tahar (PSI)*

- Dates: 7 – 9 Sep 2021, Zoom
- 50 Participants
- Website: https://indico.mit.edu/e/cyclotrons
- Report: https://arxiv.org/abs/2203.07919

now at Transmutex

Outline

- Motivation

- State-of-the-Art
- Applications
- Novel Concepts
- Computational Models

- Findings
- Recommendations

Many updates on the summarized presentations here at Cyclotrons'22!

State-of-the-Art – Talks

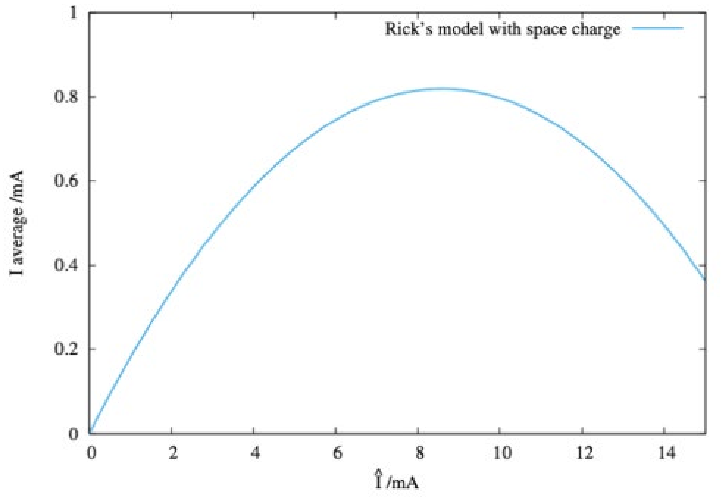
Session Conveners: L. Calabretta, T. Planche

- T. Planche – TRIUMF Cyclotron Limit
- H. Okuno – Operational Experience with the RIKEN RIBF Complex
- J. Kim - A 70 MeV cyclotron facility of IBS for ISOL and other uses
- J. Grillenberger – The High Intensity Proton Accelerator Facility at PSI. Past, Present, Projects.
- M. Haj Tahar – Major Limitations of Fixed-Field Accelerators
- C. Baumgarten – Current Limits of (PSI’s) High Power Cyclotrons: Theory and Practice

TRIUMF Cyclotron Limit

Tomas Planche (TRIUMF)

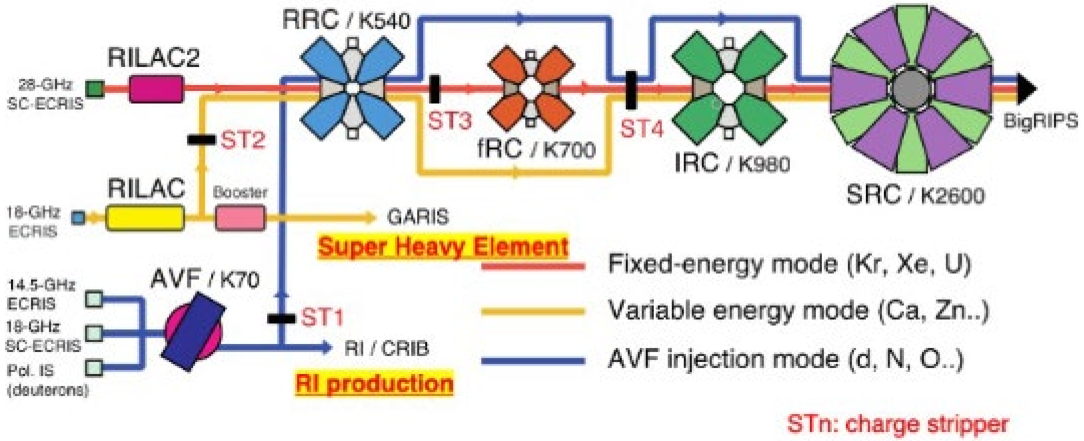
- TRIUMF operates a 520 MeV, H^- cyclotron (largest in the world).
- According to the experience at TRIUMF, the current limit in compact cyclotrons is a consequence of the small vertical focusing at the inner radii.
  - TRIUMF 520 MeV cyclotron is a “compact” cyclotron (radius of injection orbit ≈ magnetic gap).
  - Vertical focusing at low R only due to RF field (phase dependent). Almost no flutter from B.
  - Current limit is reached when vertical focusing nearly vanishes → beam losses on the vertical apertures.
- Phase acceptance decreases ~linearly with the peak current.
- The limit posed by TRIUMF is an accelerated peak current of 8 mA (0.8 mA average, assuming an phase acceptance of 36◦ RF).
- Erosion of central region elements is also a challenge
- increasing the value of the vertical tune ν_z up to 1, could make it possible to accelerate an average beam current of 5 mA.
  - E.g. by using a separated sector cyclotron and/or increasing the injection energy.



Operational Experience with the RIKEN RIBF Complex

Hiroki Okuno (RIKEN)

- The RIKEN laboratory is the first Laboratory equipped with a Superconducting Ring Cyclotron.
- The laboratory is dedicated mainly to the production of Radioactive Ion Beams, accelerating all kinds of ions, from H_2^+ up to ^{238}U.
- The main feature of the RIKEN laboratory is the large number of cyclotrons (five cyclotrons in operation) and in particular the ability to drive up to four cyclotrons working in cascade
- Major difficulty is tuning 4 cyclotrons in cascade
- Stripper foils must be very thin
- New concept: Gas stripping ring



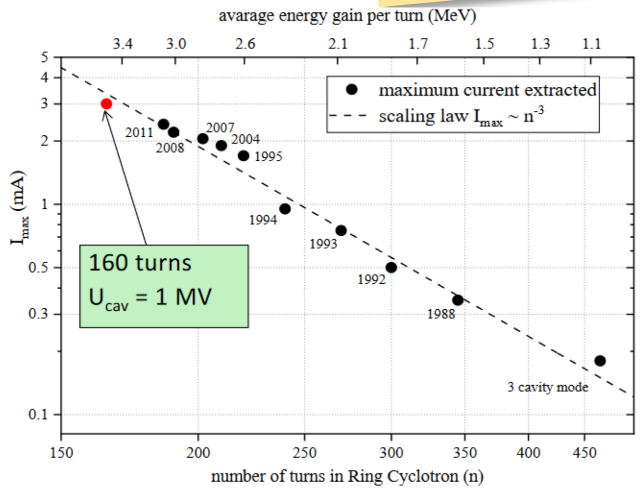
State-of-the-Art

The High Intensity Proton Accelerator Facility at PSI. Past, Present, Projects.

Joachim Grillenberger (PSI)

- The HIPA facility boasts the world's highest proton current from a cyclotron
  - 2.7 mA from Injector II (72 MeV)
  - 2.4 mA from the Ring (590 MeV)
- Improvements to reach this high current:
  - 870 keV injection energy (Cockcroft-Walton)
  - Injector II cyclotron (+flattop cavity now used for acceleration)
  - RF cavity replacements in Ring cyclotron + flattops
- Challenges with such high current:
  - Discharges
  - Coatings
  - Activation
  - Erosion
  - Multipactoring
- Upgrade planned to 3 mA (increase energy gain per turn)

100 kW designed,
1.4 MW reached!
→ Due to
"Vortex-Motion"



Joho's Scaling Law

Current Limits of (PSI's) High Power Cyclotrons: Theory and Practice

Christian Baumgarten (PSI)

- Theoretical treatments and simulations of vortex motion in Injector II
- Maximum achievable current (values at extraction):

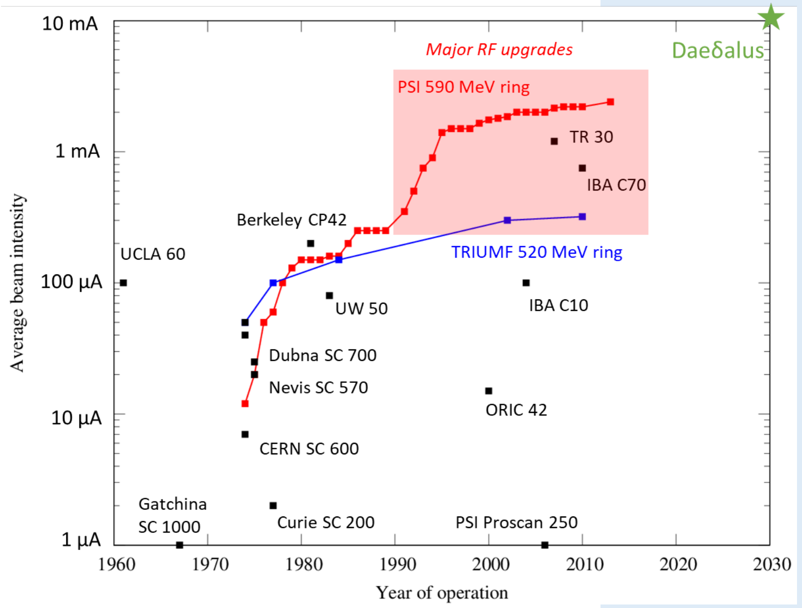
$$I_{\max} = \frac{h}{2\, g_r\, \zeta^3\, \beta^3\, \gamma\, \nu_x^4}\, \frac{V_{\mathrm{rf}}^3}{V_m^2\, Z_0}$$ (Baartman, 2013)

- Injector II: prediction 2.2, real 2.7 mA → can be higher!
- On other hand, many distortions can happen that reduce vortex effect
  - Wrong phase, too high voltage gradient in center, asymmetric emittances, etc.
- CB: "There are reasonable rules of thumb (Baartman, Joho), but no accurate predictions"
- Another bottleneck is the legal prescription of beam loss/activation!
- Also "real world" issues like cost, efficiency, etc. (e.g. RF cavities)

Major Limitations of Fixed-Field Particle Accelerators

Malek Haj Tahar (PSI)

- A comparison of cyclical accelerators such as cyclotrons, FFAs and synchrocyclotrons in the perspective to build a high-power machine (>1 MW)
- Challenge for all fixed field: Accuracy of the dipole magnet constructions (dipole field errors and gradient errors)
  - Crossing of resonances (gradient field errors)
  - Imperfect isochronism (dipole field errors)
- Remedies: shimming, trim coils, harmonic coils
- Compactness a challenge for turn separation
- FFAs have yet to demonstrate high current



Livingston chart for beam intensity

Concept	Energy reach	Intensity reach	Operation mode
Cyclotron	$\lesssim$ 1 GeV at extraction	$\mathcal{O}$(mA) (PSI: 2.4 mA)	CW
Synchrocyclotron	1 GeV	$\mathcal{O}(\mu$A) (Dubna: 25 μA)	Pulsed mode ($\lesssim$ kHz)
FFA (scaling)	No limit	$\mathcal{O}$(nA) (KURNS: 10 nA)	Pulsed mode (kHz)

Takeaways from the State-of-the-Art

- We have come a long, long way since Lawrence’s first cyclotron!
- For applications requiring high beam currents, space charge is the main problem
- There are conventional upgrade paths that involve
  - Higher energy gain per turn (fewer turns)
  - Cleaner injection, better quality input beams (lower energy spread, etc.)
  - Careful optimization and tuning
- There are some seemingly ultimate limits, however, unless we go unconventional maybe?
- Tuning complex accelerator systems is difficult and requires care (could machine learning help here?)

Applications – Talks

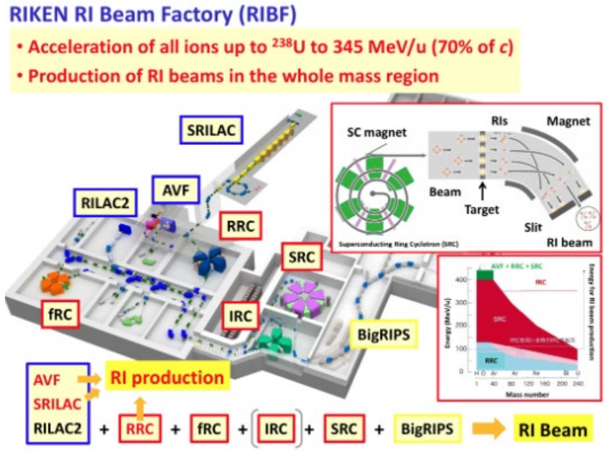
Session Conveners: J. Alonso, D. Winklehner, M. Haj Tahar

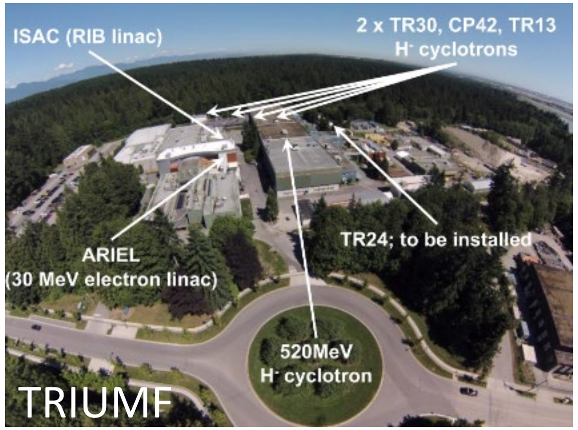
- H. Haba – Production of radioisotopes for application studies at RIKEN RI Beam Factory
- S. Lapi – Isotope Production at UAB
- T. Ruth – Radionuclide Production at TRIUMF
- J. Spitz – An application of high power cyclotrons in physics: IsoDAR
- F. Meier Aeschbacher – The search for $\mu \rightarrow eee$ and what it may need beyond Mu3e phase II
- F. Meot – Megawatt Class Beams From Fixed-Field Rings For ADS-Reactor Application
- R. Barlow – ADS Prospects and Requirements
- L. Calabretta – Limits of the present cyclotron projects and future perspectives for ADS.

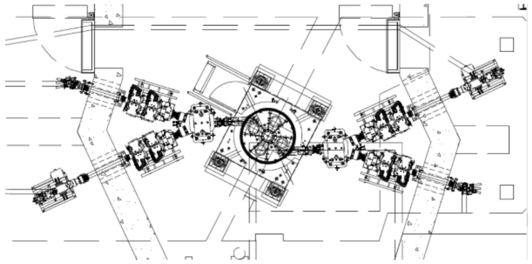
Radioisotope Production

Either for physics research (RIB) or medical purposes (PET, alphas, theranostics)

- RIKEN operates a host of cyclotrons to produce medical isotopes as well as rare isotope beams for physics research.
- TRIUMF operates four lower-energy H^- machines (13, 2 × 30, 42 MeV) dedicated to isotope production. Over 20 different isotopes for PET, SPECT diagnostics, or therapeutic agents utilizing short-range β^-, auger, or α particle radiation. They are a major supplier of isotopes for North America. ^{225}Ac has become a sought after isotope for cancer therapy.
- Important development aspect: high-power targets to benefit from current increase.
- University of Alabama, Birmingham operates TR-24 with 300 uA to produce ^{18}F, ^{11}C, ^{13}N, ^{89}Zr, and ^{43}Sc/^{47}Sc (theranostic pair)
- IBS (Korea) is operating an IBA C-70 at RISP to produce Rare Isotopes using ISOL.







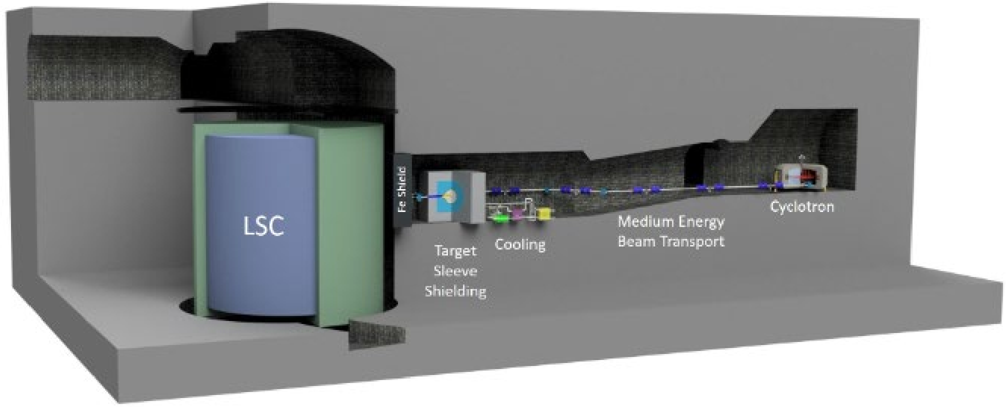
TR-24

RISP

Particle Physics – Two Examples

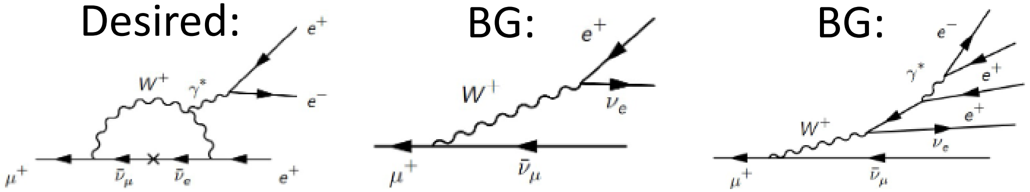
IsoDAR (Isotope Decay-At-Rest)

- A search for sterile neutrinos and BSM physics.
- Intense source of electron-antineutrinos
- Requires 10 mA proton beam
- Envisioned at Yemilab:

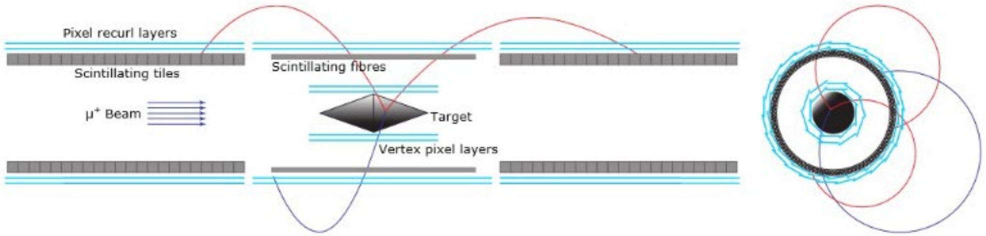


Mu3e at PSI

- Aims to observe lepton flavor changing process $\mu^+ \to e^+e^-e^+$

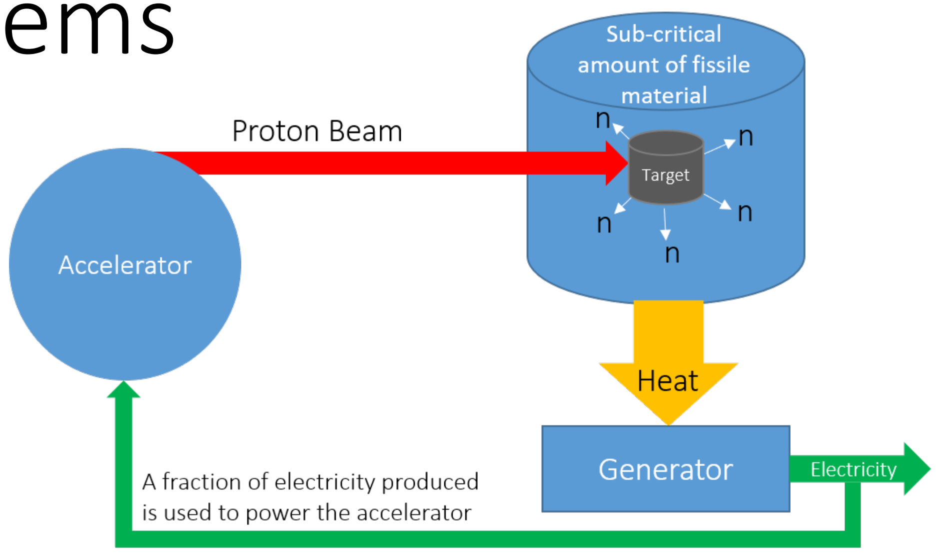


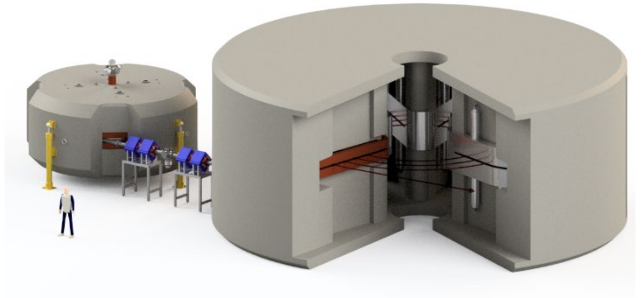
- Driven by PSI's HIPA - HIMB
- Detector layout:



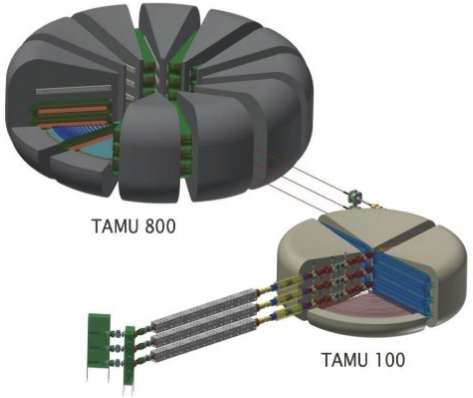
Accelerator-Driven Systems

- Basic Concept
- Usage:
  - Sub-critical Reactor
  - Nuclear waste transmutation
- Challenges:
  - No 1-GeV cyclotron with several mA current in operation
  - Reliability of cyclotrons (tripping)
- Possible Solutions?

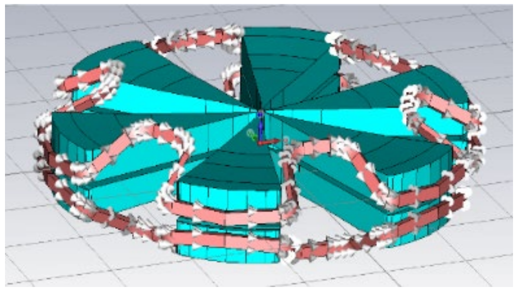




DAEdALUS Two-Stage H_2^+



TAMU Stacked Design



AIMA Single-Stage H_2^+

Takeaways from Applications

- The main area of application of high-current cyclotrons is arguably medical isotope production
- However, cyclotrons used to be the trailblazers in nuclear physics and still have their place in nuclear- and particle physics. Maybe even making a comeback?
- Applications in rare isotope production, medical isotope production, driver for PSI neutron facility, production of muons and pions for particle physics, new ideas like IsoDAR.
- Keep communication open between cyclotron builders and users!
- Find new applications!

Novel Concepts & Computation – Talks

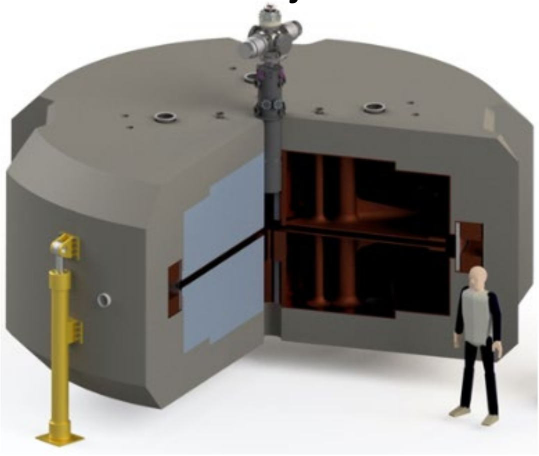
Session Conveners: H. Okuno, A. Adelmann

- J.-B. Lagrange – Development of vertical excursion FFA
- G. D'Agostino – INNOVATRON: An innovative industrial high-intensity cyclotron for production of medical radioisotopes
- L. Waites – The RFQ Direct Injection System for the IsoDAR cyclotron
- H. Barnard – Spiral Inflectors for High Power Cyclotrons
- L. Zhang – Feasibility study for the cylindrically symmetric magnetic inflector
- C. Rogers – Use of a map approach for tracking in FFAs
- P. Calvo – Development of the simulation code OPAL
- T. Planche – TRIUMF Simulation Tools Status & Future

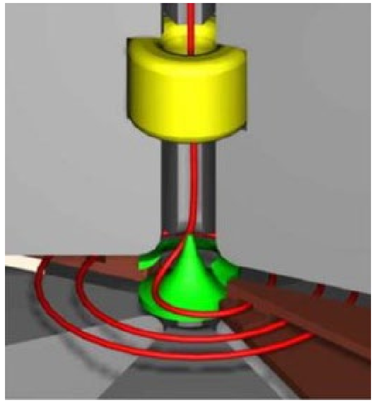
Injection

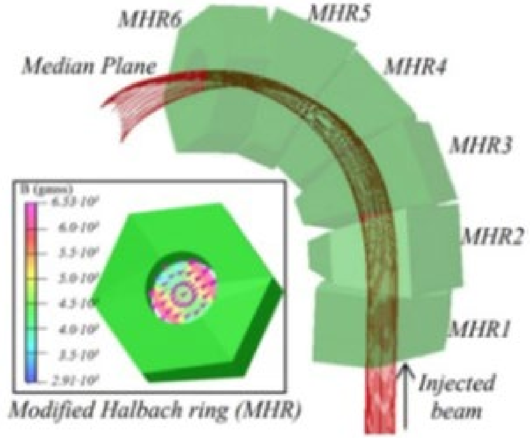
- IsoDAR proposes to use an RFQ to efficiently bunch the beam during injection into a compact cyclotron
  - This alleviates current requirements from the ion source and reduces space-charge in the LEBT.
  - Prototype under construction
- Transverse-Gradient spiral inflectors can be designed to significantly improve vertical beam spread and energy spread during injection.
- Magnetic inflectors can be envisioned to inject higher energy beams (no HV breakdown)
  - Cylindrically symmetric or Stack of Halbach-Rings
  - Some encouraging simulation results, no proto-type
- Multiport Injection

RFQ-injection



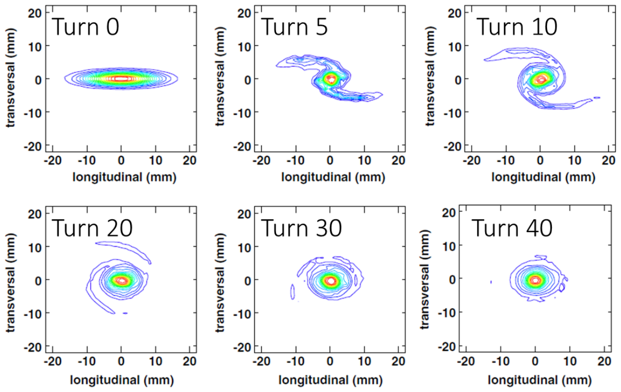
Magnetic inflectors

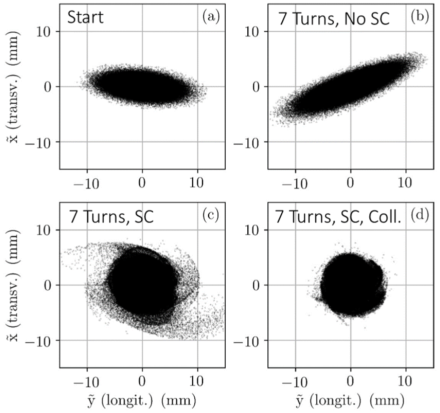


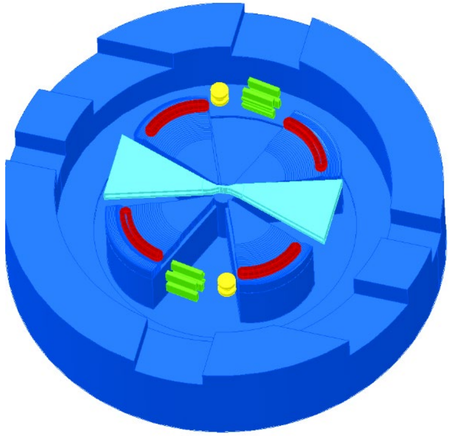


Extraction

- Based on the discovery at PSI Injector II, vortex motion could be used to facilitate clean beam extraction from an isochronous cyclotron.
  - Here, the beam curls up into a ball in longitudinal-radial space due to space-charge coupling
  - IsoDAR aims to utilize vortex motion and has shown PIC simulations corroborating their design.
- InnovaTron at IBA aims at using only passive devices to *self-extract* beam from the cyclotron, removing the need for a septum or stripping foil.
  - Vortex-Motion is observed as well in the InnovaTron at 5 mA beam current.
  - First test machine extracting 2 mA very encouraging, ultimately losses too high.

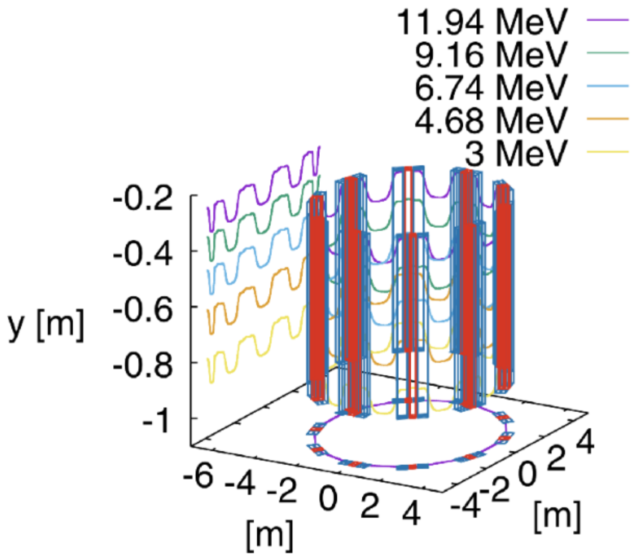






Vertical excursion FFAs

- Orbit moves vertically when beam is accelerated
- Constant path length over whole momentum range (zero momentum compaction factor for all orders)
- Isochronism for ultra-relativistic energies
- Proof-of-principle ring (3-12 MeV proton) to be built by 2027



$$B_x(x,y,z) = B_0 \exp\left(m(y-y_0)\right) \sum_{i=0}^{N} b_{xi}(z)\, x^i,$$

$$B_y(x,y,z) = B_0 \exp\left(m(y-y_0)\right) \sum_{i=0}^{N} b_{yi}(z)\, x^i,$$

$$B_z(x,y,z) = B_0 \exp\left(m(y-y_0)\right) \sum_{i=0}^{N} b_{zi}(z)\, x^i.$$

To keep transverse tunes independent of momentum (m…field gradient)

Computation

- One of the major limitations are particle losses (controlled-uncontrolled)
- Computation must be able to accurately predict losses
- Additional Physics becomes increasingly important
  - Residual gas interaction, beam-wall interaction, etc.
- Codes in increasing complexity:
  - Single Particle Tracking – no space charge,
  - Envelope Models – natural extension of single particle, useful where PIC is too costly
  - Particle-In-Cell Codes (e.g. OPAL) – 3D space charge calculations
- Machine Learning
  - Cheap to evaluate surrogate models have gained a lot of interest lately. These models can for example replace a computationally heavy model in an multi-objective optimization or in the future be part of the on-line model.
- Plethora of codes exists, consolidation and collaboration should be encouraged.

Object Oriented Parallel Particle Library (OPAL)

https://gitlab.psi.ch/OPAL/src/wikis/home

OPAL is a versatile open-source tool for charged-particle optics in large accelerator structures and beam lines including 3D EM field calculation, collisions, radiation, particle-matter interaction, and multi-objective optimisation

- OPAL is built from the ground up as an HPC application
- OPAL runs on your laptop as well as on the largest HPC clusters
- OPAL uses the MAD language with extensions
- OPAL is written in C++, uses design patterns, easy to extend
- The OPAL Discussion Forum: https://psilists.ethz.ch/sympa/info/opal
- International team of 11 active developers and a user base of $\mathcal{O}(100)$
- The OPAL **sampler** command can generate labeled data sets using the largest computing resources and allocations available

Takeaways from Novel Concepts & Computation

- The cyclotron community is rising to the challenge of high intensity beams through
  - Improvements on existing methods
  - New concepts to overcome known limitations
- We need to be bold if we want to
- Computation necessarily plays a key role due to its capabilities for
  - Design assistance
  - Optimization
- High performance computing enables us to resolve complicated beam dynamics effects, include physics, and predict even small losses
- Use of Machine Learning enables us to reduce computational burden

Findings 1

- Due to their ability to provide cw beams of high current, cyclotrons are very relevant at the intensity frontier
    - Producing copious amounts of pions, muons, and neutrinos at higher energies and neutrinos from isotope decay-at-rest at lower energies.
- For example, the PSI proton facility can deliver up to 2.4 mA at 590 MeV (a 1.4 MW beam), enabling a vibrant muon program.
- IsoDAR is designed to produce 10 mA at 60 MeV (a 600 kW beam), producing neutrinos at a rate equivalent to 50 kilocuries.
- Cyclotrons have high societal benefit through medical isotope production and energy research. We found that there have been several breakthroughs in the past years to further increase the available beam currents (and thus total delivered power) that make continuous wave (cw) isochronous cyclotrons the accelerator of choice for many high power applications at energies up to 1 GeV.

Findings 2

- Key innovations:
  - Improved injection (through RFQ direct injection, transverse gradient inflectors, and magnetic inflectors),
  - improved acceleration (utilizing vortex motion, single-stage high energy designs, vertical excursion FFAs), and
  - improved extraction (through new stripping schemes and by self-extracting, using built-in magnetic channels).
- The use of H_2^+ as accelerated ion instead of protons or H^- has also received much attention lately.
- There are now several projects designing new powerful cyclotrons for particle physics, medicine, and accelerator driven systems (ADS) for energy research.
  - Cost-effective devices with small facility footprint, thus following the mantra better, smaller, cheaper.

Findings 3

- The field of computational (accelerator) physics has made great strides
- High fidelity simulations have become a necessity to understand and design accelerators with high space charge.
- High performance- and exascale computing will be needed in order to accurately simulate many-particle interactions (e.g., space-charge and halo-formation), and beam-environment interactions (e.g., residual gas, wakefields).
- As in other fields, Machine Learning can play a big role by providing new tools to understand and predict complex behavior, and significantly reduce simulation execution time, enabling virtual particle accelerators and faster and better optimization.

Recommendations to Snowmass'21

We, the community of particle physicists, particle accelerator physicists, and funding agencies, should:

1. Recognize the important role cyclotrons are playing in Nuclear- and Particle Physics;
2. Encourage development of this type of accelerator, as an investment with high potential benefits for Particle Physics, as well as outstanding societal value;
3. Recognize and encourage the high benefit of collaboration with the cyclotron industry.
4. Recognize the opportunities the Exascale computing era will provide and adjust development of beam dynamics simulation tools accordingly.
5. Aim for a close connection of traditional beam dynamics models with (1) machine learning (surrogate models) and (2) feedback (measurements) from the accelerator, as they will pave the way to an intelligent accelerator control and on-line optimization framework.