Summary of Cyclotrons 2016

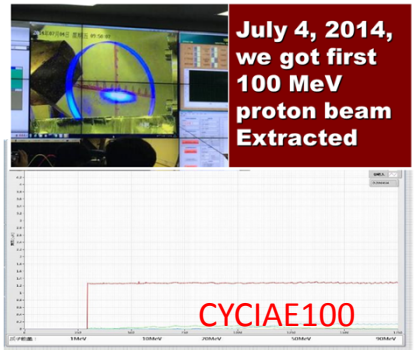
H. Okuno, RIKEN

Congratulations on the first beam from cyclotrons (Cyclotrons2013-Cyclotrons2016)!

- Columbus
- CYCIAE100
- Best 70P
- Ionetix ION-12SC
- IBA S2C2

  (the first patient in this week)


Columbus



Broad range of themes

	Oral	Poster	
Theory	9	13	Numerical, (analytical)
Concepts/Project	10	5	new ideas, projects under construction or projects under R&D
Technology	9	22	RF, source, magnets..
Operation/Upgrades	13	18	experience, achievement, improvement
Applications	13	11	therapy, RI production, diverse themes..

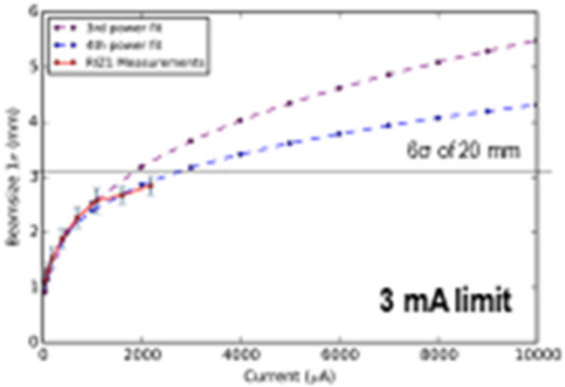
Theory

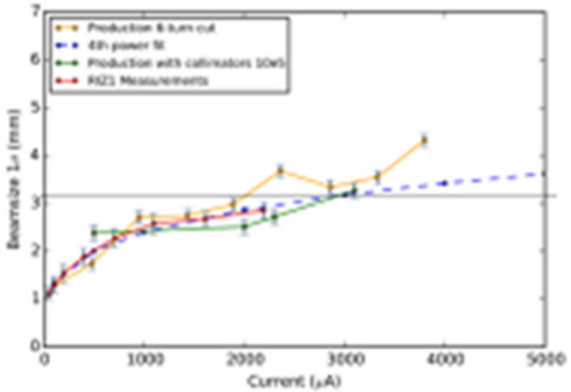
- Review: Simulations from cyclotrons (Kleeven), Code: AOC
- Code: Upgrade of OPAL (Adelmann)
- Orbit analysis in the cyclotrons:
  - in a educational program (Wolf)
  - LEBT to DC280(JINR) (Kazarinov)
  - Inject II can reach 3-5 mA(Kolano)
  - TRIUMF Cyclotron (Bylinskii)
  - S2C2 from source to extraction (Walle)
- New challenge:
  - Uncertainty Quantification (Adelmann)
  - Matched distribution with non-linear matched distribution(Frey)
- 13 posters

Main Subject: Vortex motion in the cyclotron due to Nonlinear space charge force
⇒round beam, bunch breakup, current limit
? Is there any chance to control the motion?

Intensity limits of Injector II

- Following up on Joho's scaling law** $I_{max} \propto V^3$ also for beamsize, with slightly better fit at power of 4, that is particularly good at higher intensities
- Simplified models say **approx 2.2 mA*** (we already know **2.7 mA** was extracted) → strong transverse-longitudinal coupling combined with space charge sets higher limits
- Our models/fits predict **new 3mA limit** with existing configuration
- After the upgrade even up to 5mA could be possible





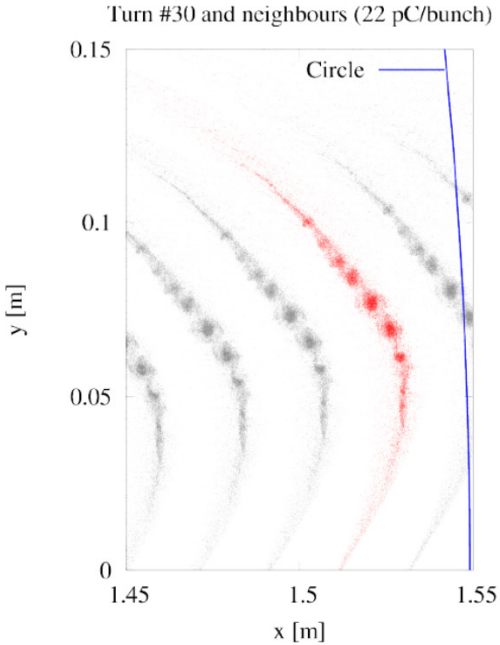
*R. Baartman, Space charge limit in separated turn cyclotrons, In Proc. 21st Int. Conf. on Cyclotrons and their Applications, Vancouver, Canada, 2013

**W. Joho, in Proc. 8th Int. Conf. on Cyclotrons and their Applications, Caen, 1981, p. 337.

[Kolana]

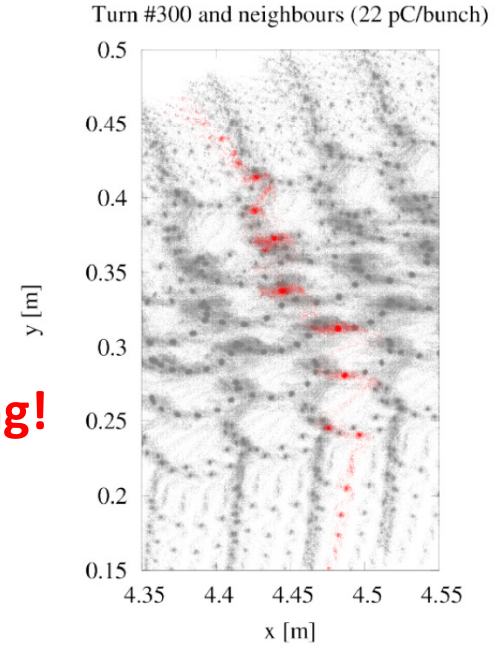
500μA injected Turn #30

Beam breakup (vortex motion):



500μA injected Turn #300

Beam breakup (vortex motion):



Bunch is melting!

[Bylinskii]

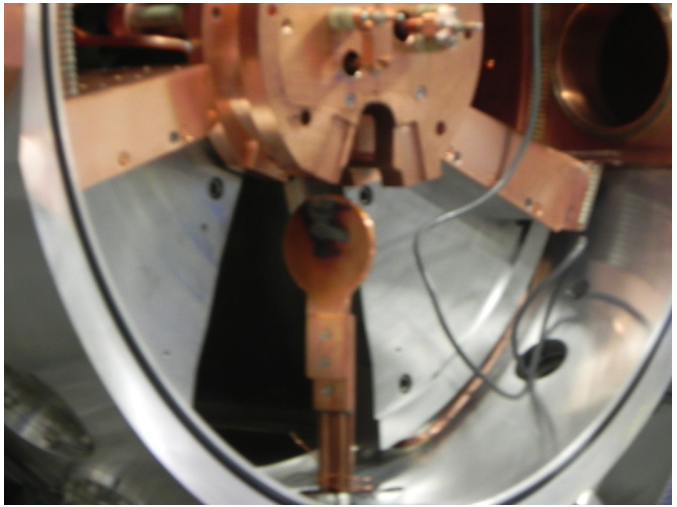
New concept (Cyclotron, FFAG) and project

- H2+ acceleration:
  - Daedalus+IsoDAR [Winklehner]
  - Single stage cyclotron 800 MeV / a new extraction [Mandrillon]
- FFAG :
  - Toward High intensity [Sheehy]
  - A novel use of FFAG in ERLs [Trbojevic]
  - Future plan of KURRI FFAG[Ishi]
  - TRIUMF e-gamma converter [Laxdal]
- Projects:
  - Compact SC cyclotron for proton therapy [Karamysheva]
  - IBA S2C2: from the 1st unit to industrial project [Forton]
  - Status of SPES [Maggiore]
  - RIKEN RIBF uranium beam [Okuno]
- 5 posters in this category

A few purely new projects
New ideas mainly from FFAG

Injection Tests

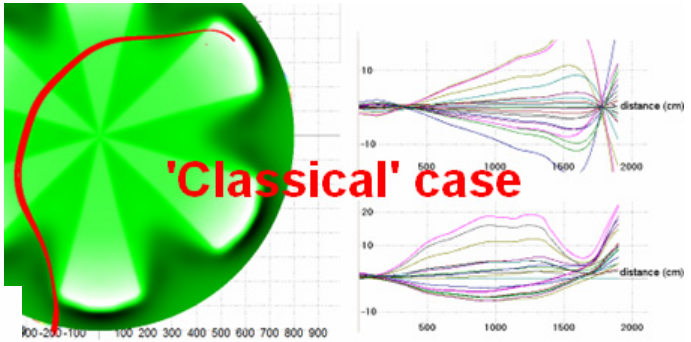
- First, look at beam through spiral inflector
- 8 mA before, 7.5 mA inside → 94% transmission
- Then accelerate
- Unfortunately, RF system did not manage to get to full power, only 50 out of 70 kV Dee voltage
- Measured beam currents on radial probes



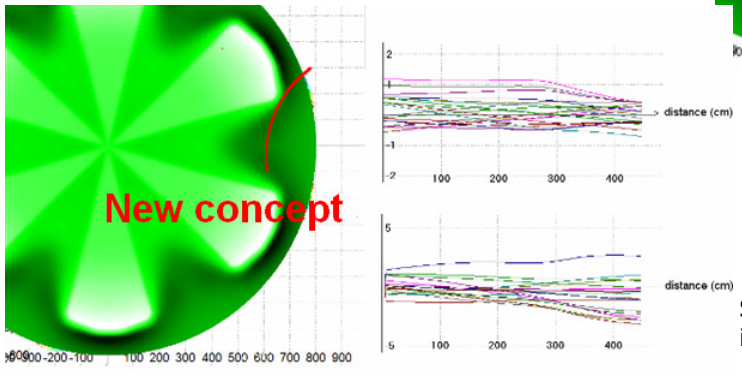
Accelerated 100 µA for four turns in test cyclotron @50 kV V_{Dee}

H2+ Extraction

short trajectory, no focusing elements, no complexity



Initial condition:
5mm vertical amplitude @
155MeV

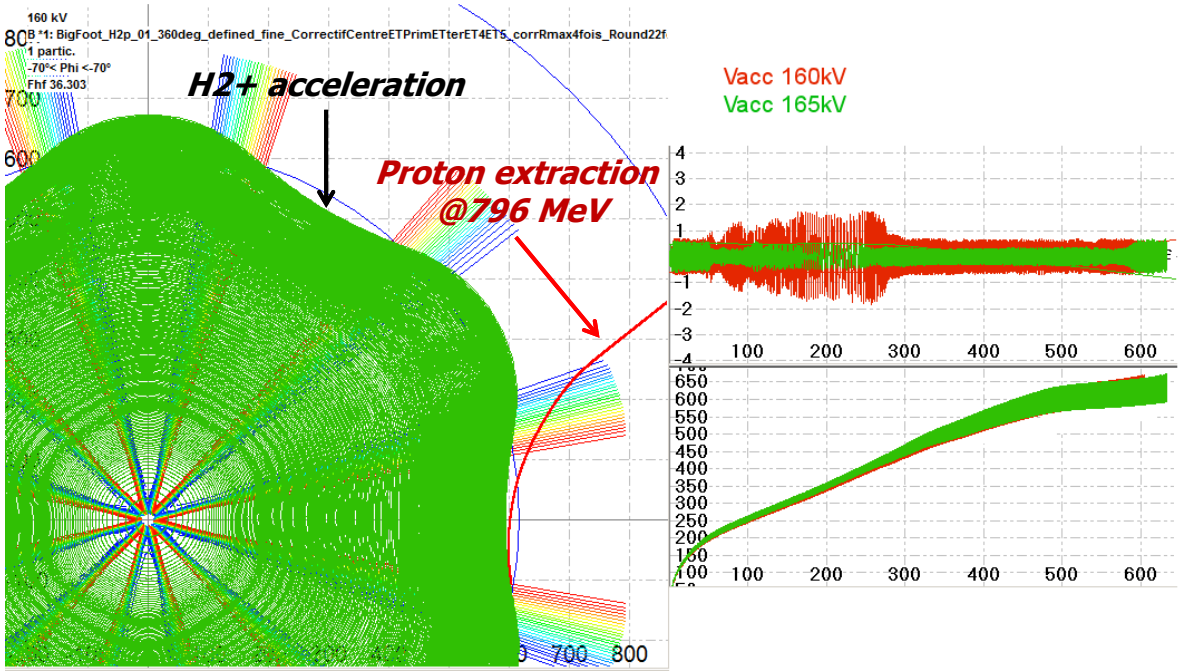


Shorter trajectory if the stripping foil is located in a valley: leads to a smaller extracted beam

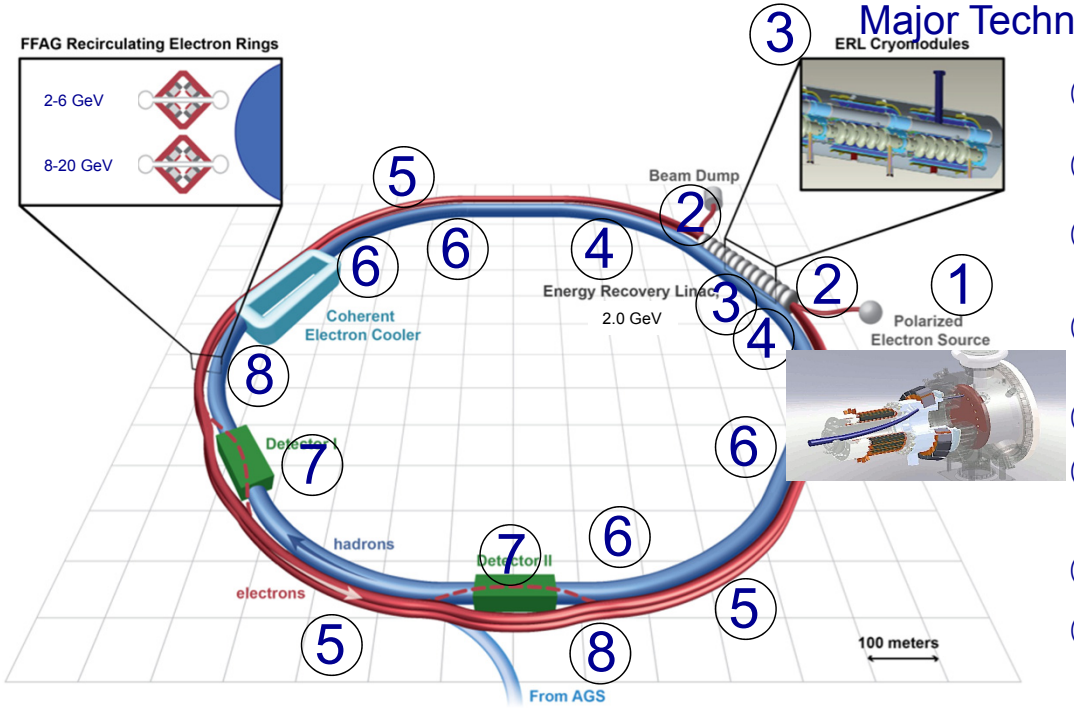
AIMA
Accelerators for Industrial and Medical Applications

H2+ Extraction

short trajectory, no focusing elements, no complexity



eRHIC Technical Overview



Major Technical Components:

① Funneling Gun

②ERL mergers

③Superconducting Linac - ERL

④Spreaders and Combiners

⑤NS-FFAG arcs

⑥Merging arcs to straight section

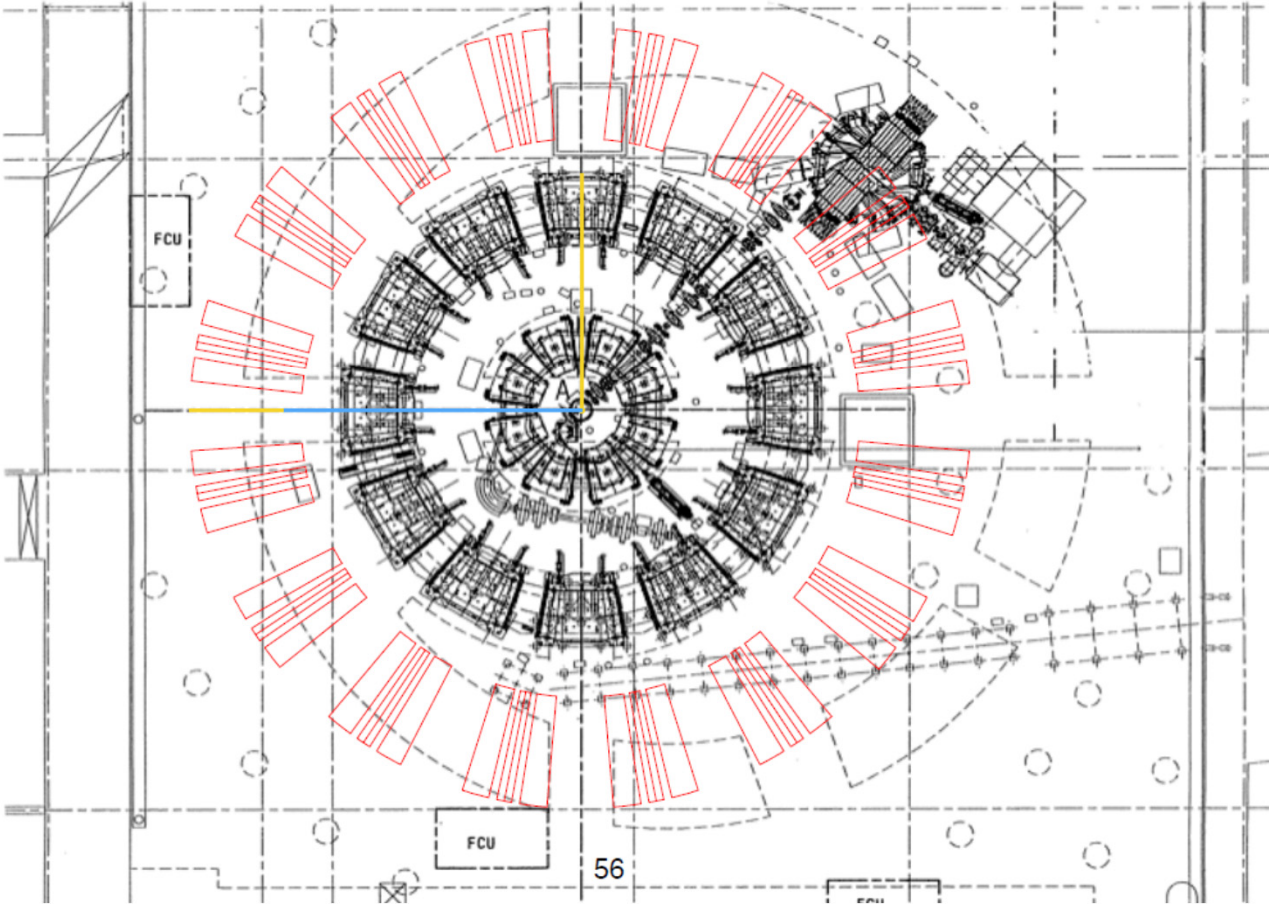
⑦ Straight section

⑧Extracted high energy beam

The Non Scaling FFAG (NS-FFAG) lattice enables multiple passes of the electron beam with different energies in a single strong focusing recirculation beam line by using the superconducting RF (SRF) linac multiple times. The FFAG-ERL moves the cost optimized linac and recirculation lattice to a dramatically better optimum.

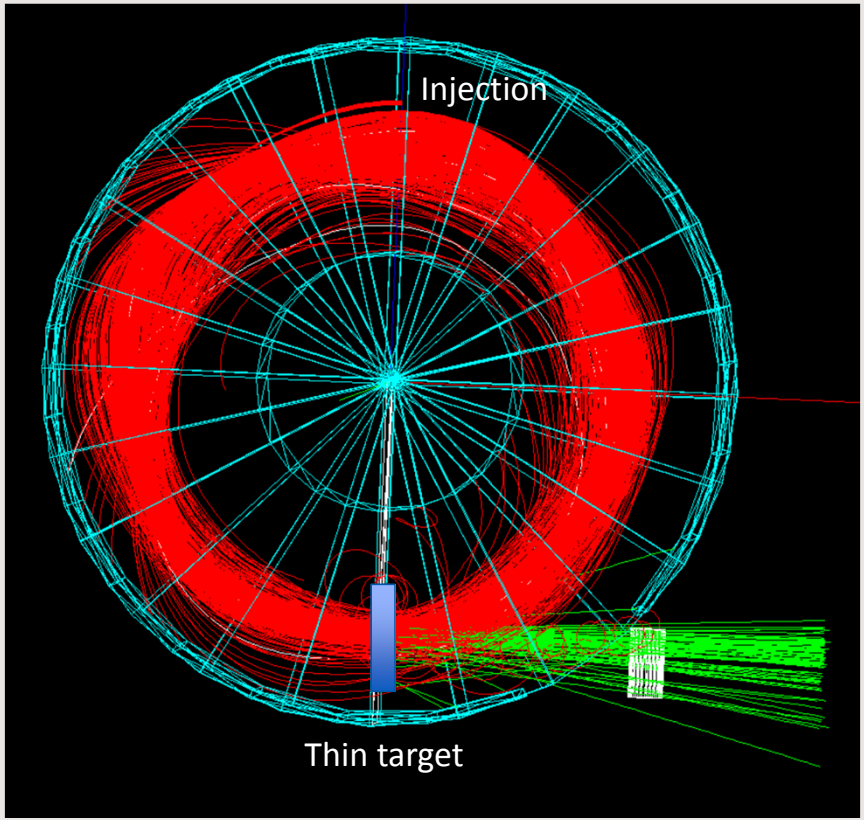
[Trbojevic]

Newly designed 400 MeV FFAG ring.



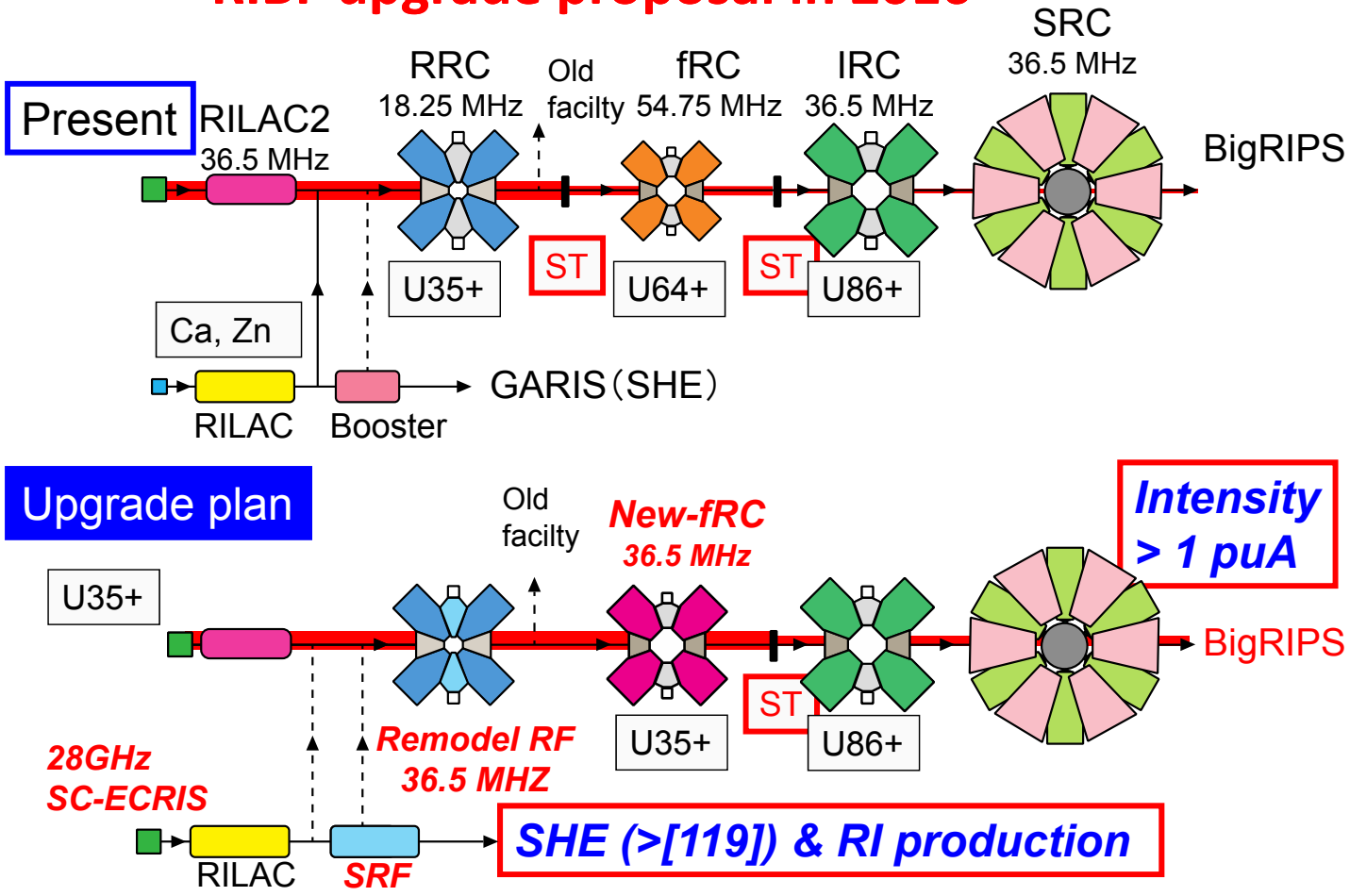
[Ishi]

Electrons & Photons – Geant4



[Laxdal]

RIBF upgrade proposal in 2016



[Okuno]

Technology

This category is very important for successful operation or realize new innovative concepts. More contributions should be expected.

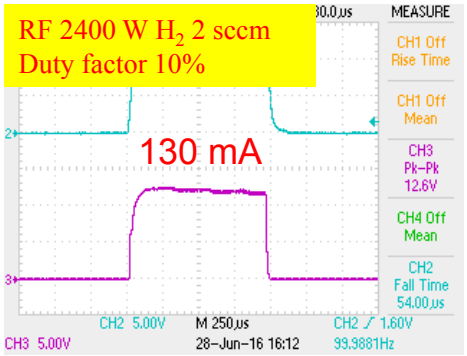
- Ion source
  - Hydrogen ion source at PKU[Peng]
- Magnet
  - 12C6+ 400 Separated Sector cyclotron magnet [Smirnov]
  - HTS magnet [Hatanaka]
  - Heat transfer[Satouchi]
- Charge stripper
  - Charge stripper ring [Imao]
  - Extraction by charge stripping [D'Agostino]
- Electrostatic channel
  - Electrostatic field with several MV/m into a large-gap dipole for EDM experiment [Boeker]
- RF
  - Digital LLRF control system [Duckitt]
  - Hybrid configuration of rf amplifier[Caruso]
  - Cavity design for 18 MeV cyclotron[Mousavinia]
- 22 posters

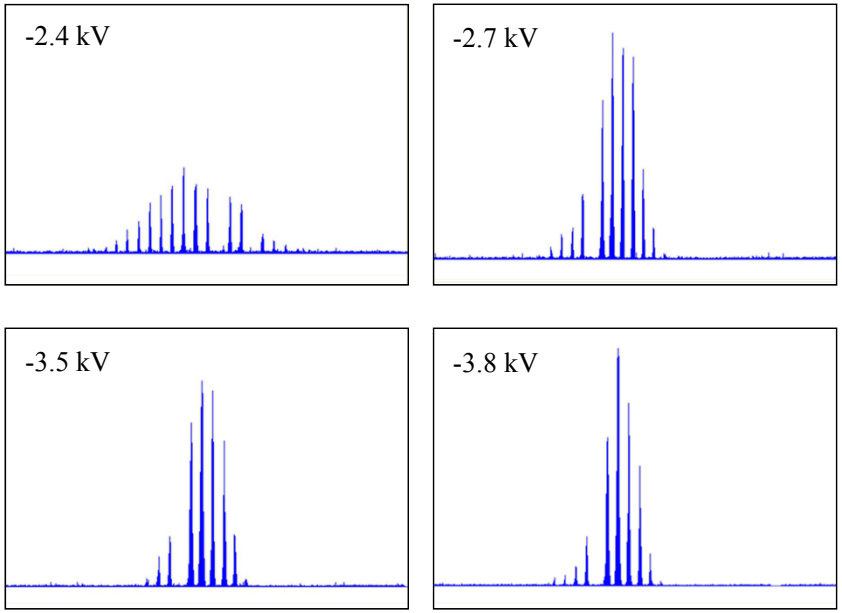
H^+ Ion Source

- Pulsed mode

Counting operation time is >1000 hours

Standard ECR ion source

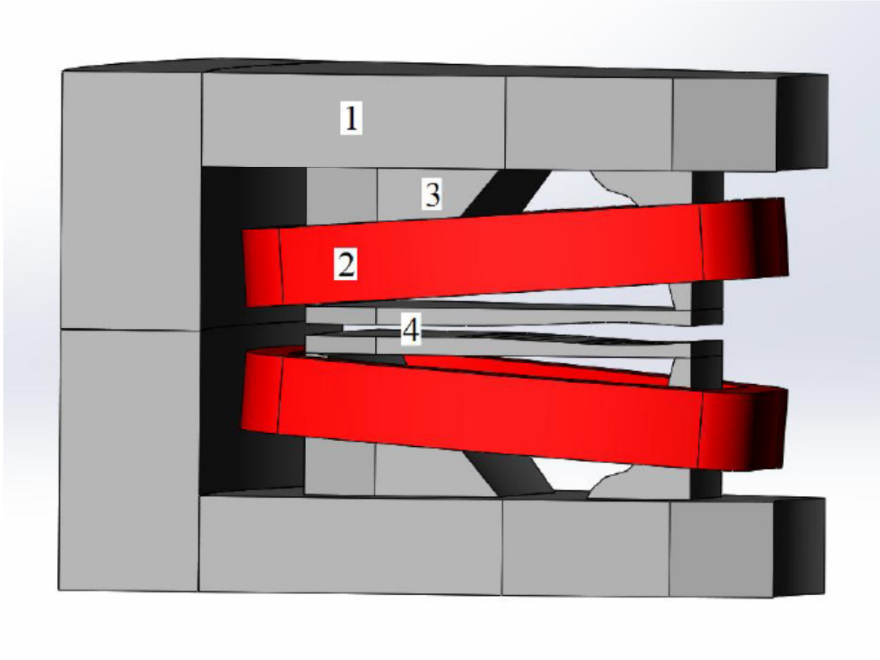




Influence of suppression voltage
Emmitance <0.20 pi.mm.mrad

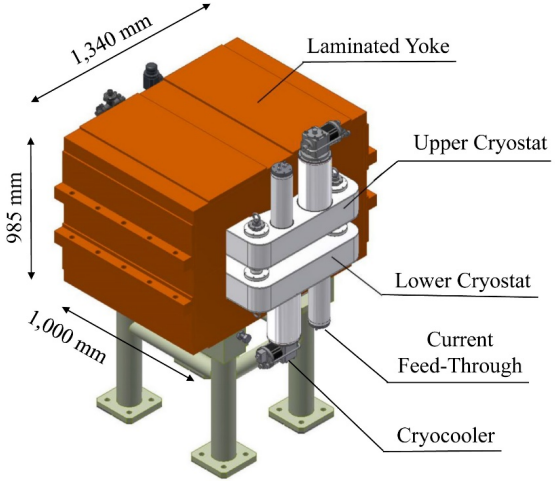
[Peng]

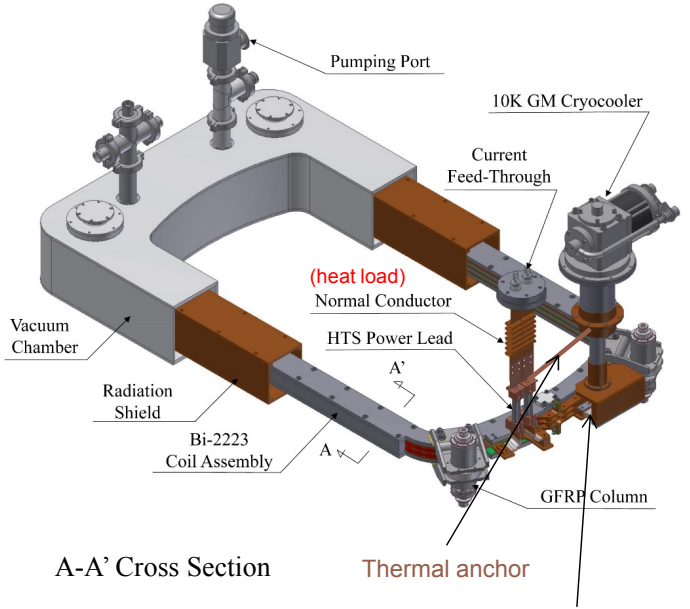
Sector magnet parameters:
yoke (1) length ×width×height: 3.1×2.0×2.2 m
weight 50 t, coil (2) engineering current density 62 A/mm^2, coil cross section 170×330 mm^2, axial angle between upper and lower coils 8 degrees. The pole (3) and pole tip (4) have axial profile.



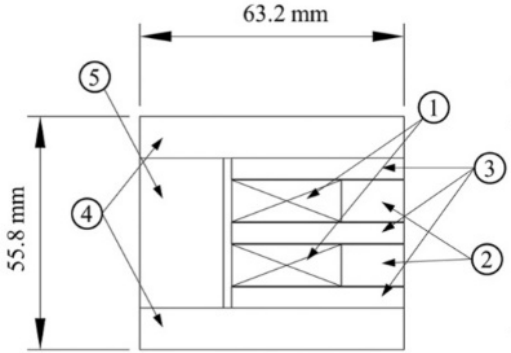
[Smirnov]

Dipole magnet for beamline switching





A-A' Cross Section



No.	Description	Material
1	Bi-2223 DPC	
2	Winding Frame	Stainless Steel
3	Cooling Plate	Copper
4	Reinforcing Plate	Stainless Steel
5	Reinforcing Bar	Stainless Steel

[Hatanaka]

New Digital Low-Level RF Control System

- Modular Design
- All RF signals are easily accessible from the front
- Digitally programmable
- 16 bit Amplitude resolution
- Operates between 5 and 100 MHz
- Programmable in steps of 1 μHz
- Phase resolution in steps of 0.0001º
- EPICS based

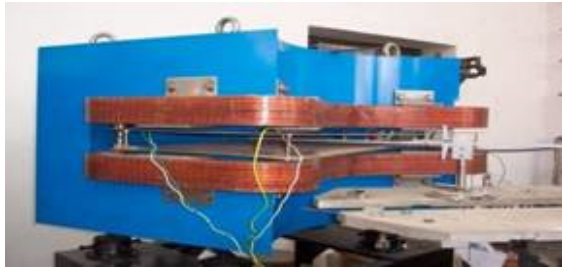
[Duckitt]

Operation/upgrade

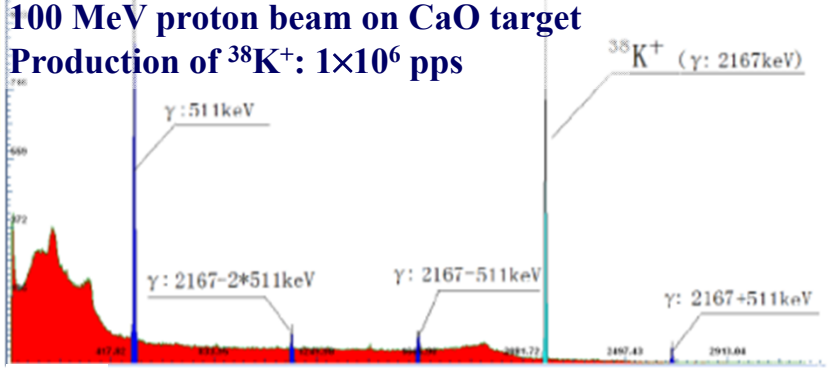
Valuable operational experience and on-going upgrade/improvement.

- Upgrade of the LNS SC[Calabretta]: high beam power
- Radiation damage @PSI [Kiselev]
- COMET@PSI[Psoroulas]: Fast beam current control
- HZB[Denker] : New time structure
- TRIUMF[Bylinskii]: Improvement in beam delivery
- pol-d acceleration@RIBF [Sakamoto]: how to check the single turn extraction
- H-100MeV Cyclo@CIAE[Zhang]: The first RI beam of 38K (ISOL) and proposal for the new facility
- Energy efficiency@PSI[Grillenberger]: The most efficient accelerator in the world
- iThemba[Conradie] : Refurbishment and replacement of the infrastructure and the critical parts
- JINR[Gikal]: Status of U-400, DC280
- Texas A&M[May]: K500 SC cyclotron -> RI beams production
- GANIL[Kamalou]: Review of the operation
- 18 Posters in this category

ISOL system is driven by CYCIAE-100

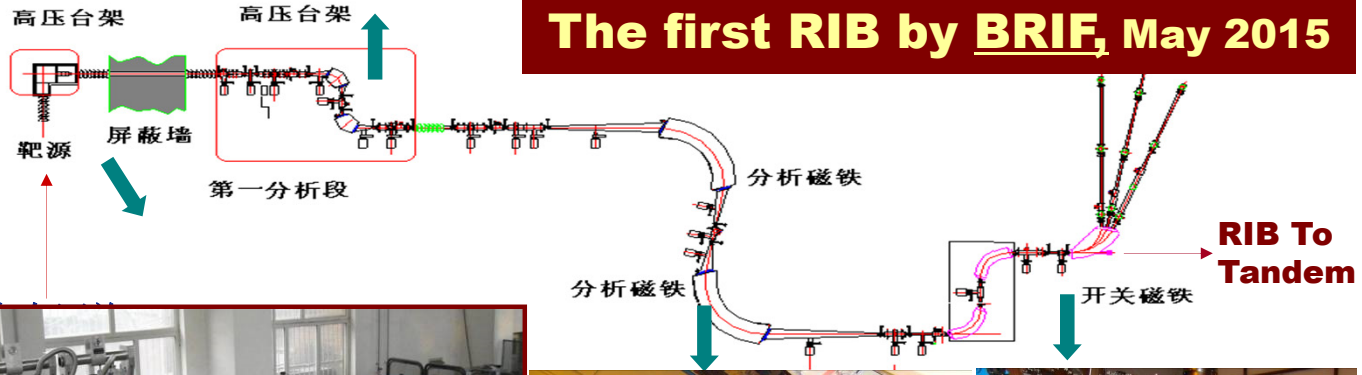


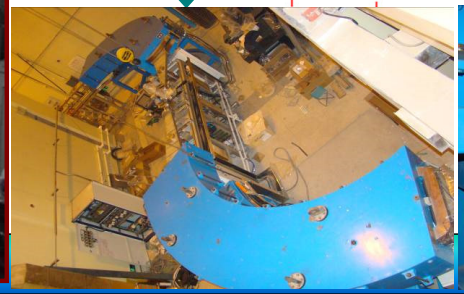
100 MeV proton beam on CaO target
Production of $^{38}K^{+}$: 1×10^{6} pps



The gamma spectra of ^{38}K after separator

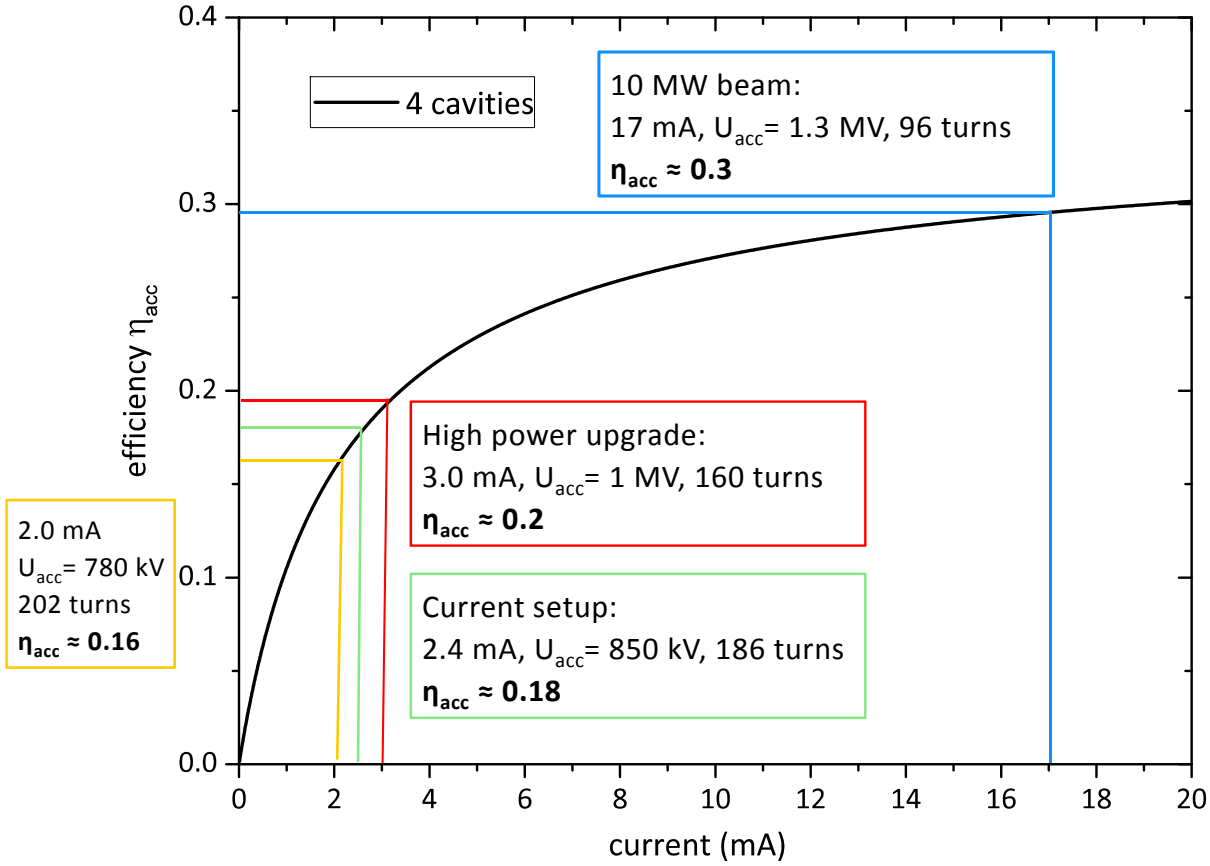
The first RIB by BRIF, May 2015





[Zhang]

Efficiency and Beam Power



[Grillenberger]

SHE-factory: High-current cyclotron DC280

Main setups:

GFS (synthesis), GFS (chemistry), SHELS

Main tasks:

- *Synthesis of SHE.*
- *Properties and Spectroscopy of SHE;*
- *Chemistry of SHE;*
- *Searching for new reactions leading to SHE*

DC280 (expected) E=4÷8 MeV/A		
Ion	**Ion energy [MeV/A]**	**Output intensity**
^{7}Li	4	1×10^{14}
^{18}O	8	1×10^{14}
^{40}Ar	5	6×10^{13}
^{48}Ca	5	$0{,}6\text{-}1{,}2\times10^{14}$
^{54}Cr	5	2×10^{13}
^{58}Fe	5	1×10^{13}
^{124}Sn	5	2×10^{12}
^{136}Xe	5	1×10^{14}
^{238}U	7	5×10^{10}

[Gikal]

Applications 1

Requirements from the applications give us motivations for next accelerators.

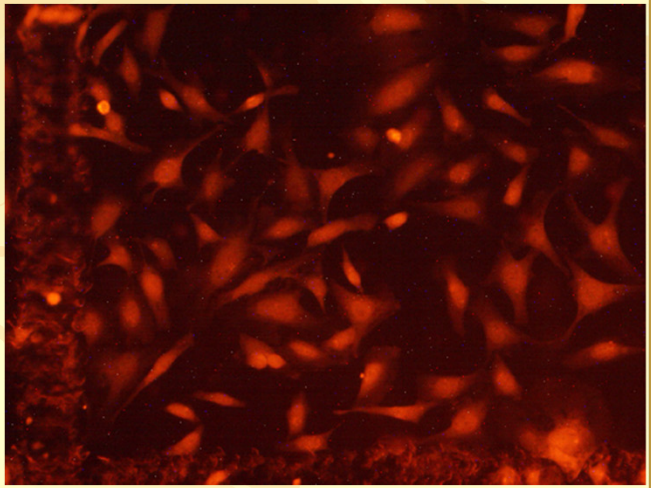
- Microbeam [Kurashima]
- Fast energy selection [Liang]
- Radioactive labeled nanoparticle [Jendrzej]
- Cyclinac [Garonna]
- Multi leaf faraday cup [S. Seidel]
- Cyclotron gas stopper [Schwarz]
- LLFP transmutation and RI production at RIBF [Sakurai]

Applications 2

- Review: Compact cyclotrons and RI production [Braccini]
- C70 cyclotron Arronax [Poirier]
- A new IBA cyclotron for PET production [Nactergal]
- BEST 70P cyclotron at INFNLN legnaro[Sabaiduc]
- Ionetix ION-12SC [Wu]
- Cyclotrons and Superconducting linac as high intensity driver accelerator [M. Seidel]
- Proton Radiography @CYCIAE [Yang]
- 11 posters in this category

5. Microbeam Irradiation Experiment

Cell irradiation experiment in the air.
Microbeam is scattered in the air and a vacuum window (Si_3N_4, 200 nm^t) layers.



Photomicrograph of HeLa cells dyed by CellTracker Orange

[Kurashima]

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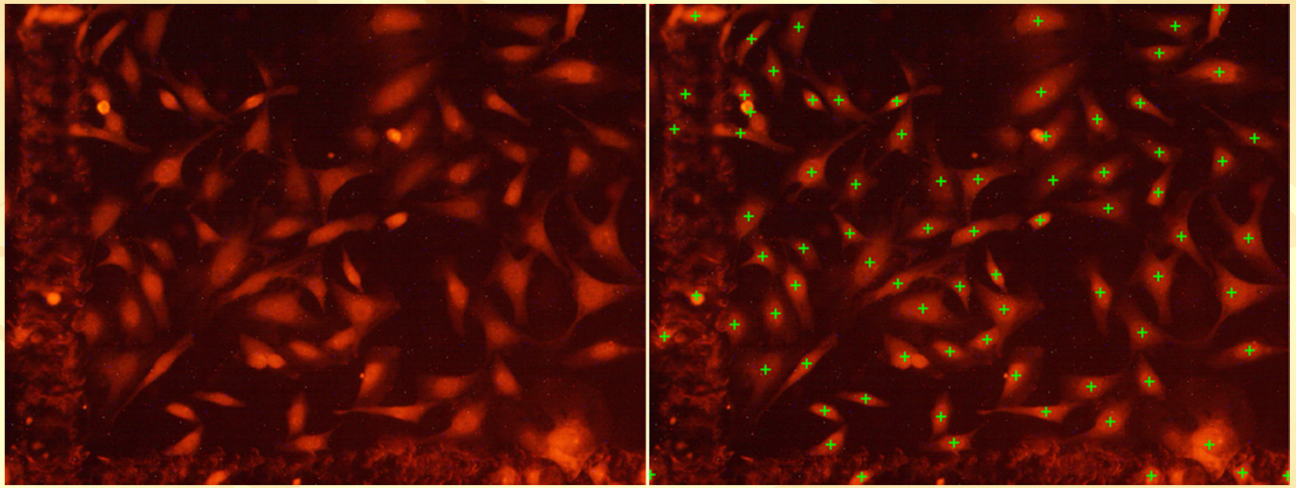

Photomicrograph of HeLa cells dyed by CellTracker Orange

Automatic detection of cell positions

[Kurashima]

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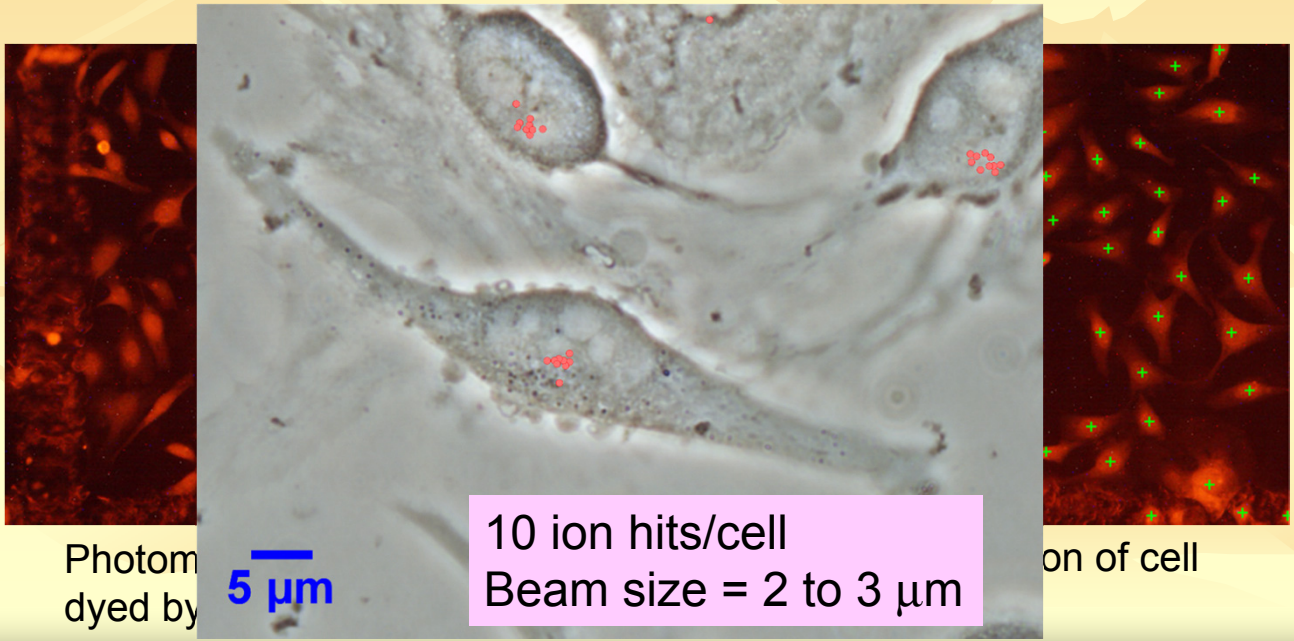
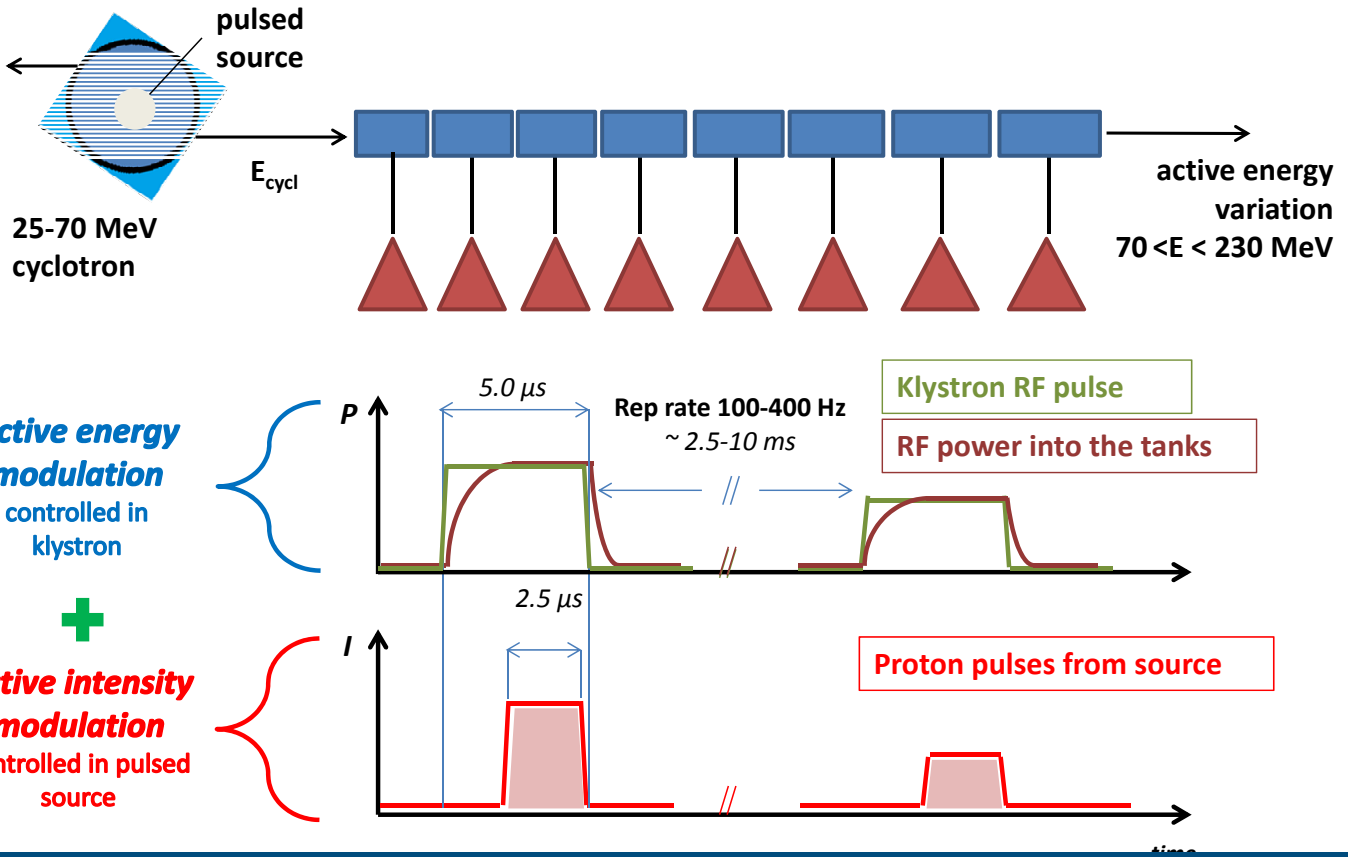


Photom… dyed by …on of cell

[Kurashima]

Cyclinac beam characteristics



[Garonna]

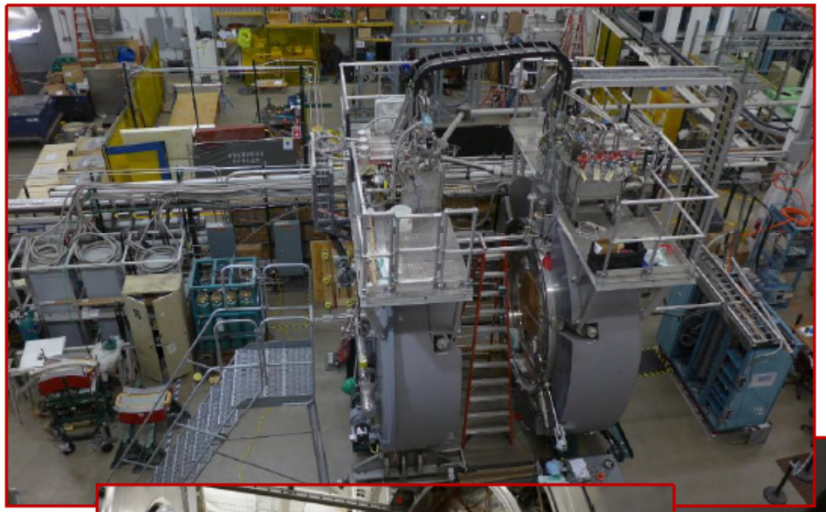
Magnet:
- tested to full field

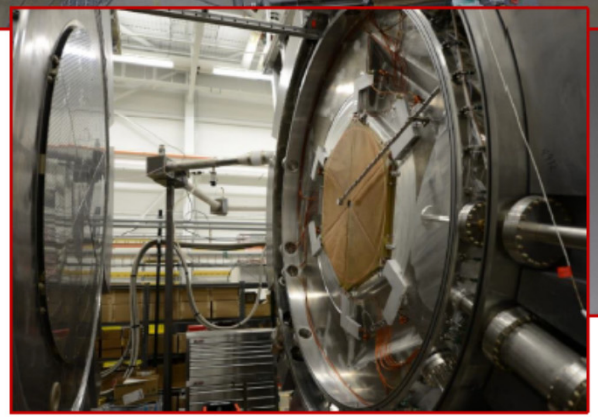
Stopped-ion transport:
- stopping chamber in place, initial pressure tests at RT passed
- 90° prototype RF carpets tested
- 60° RF carpets: Electronics working
- Conveyor: Offline tests promising
- Carpet + conveyor installed

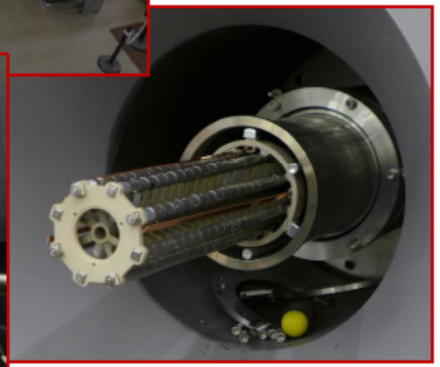
Next:
- Test ion transport with magnetic field
- Cool chamber with LN

Move to dedicated vault: 2018 ?

G. Bollen, M. Brodeur, M. Gehring, K. Lund,
N. Joshi, C. Magsig, D. J. Morrissey,
J. Ottarson, SCS, S. Chouhan, J. DeKamp,
J. Ottarson, A. Villari, A. Zeller
... and many more!







Thanks for listening!

MICHIGAN STATE UNIVERSITY
NSF Cyclotron stopper grant
PHY-09-58726, PHY-11-02511

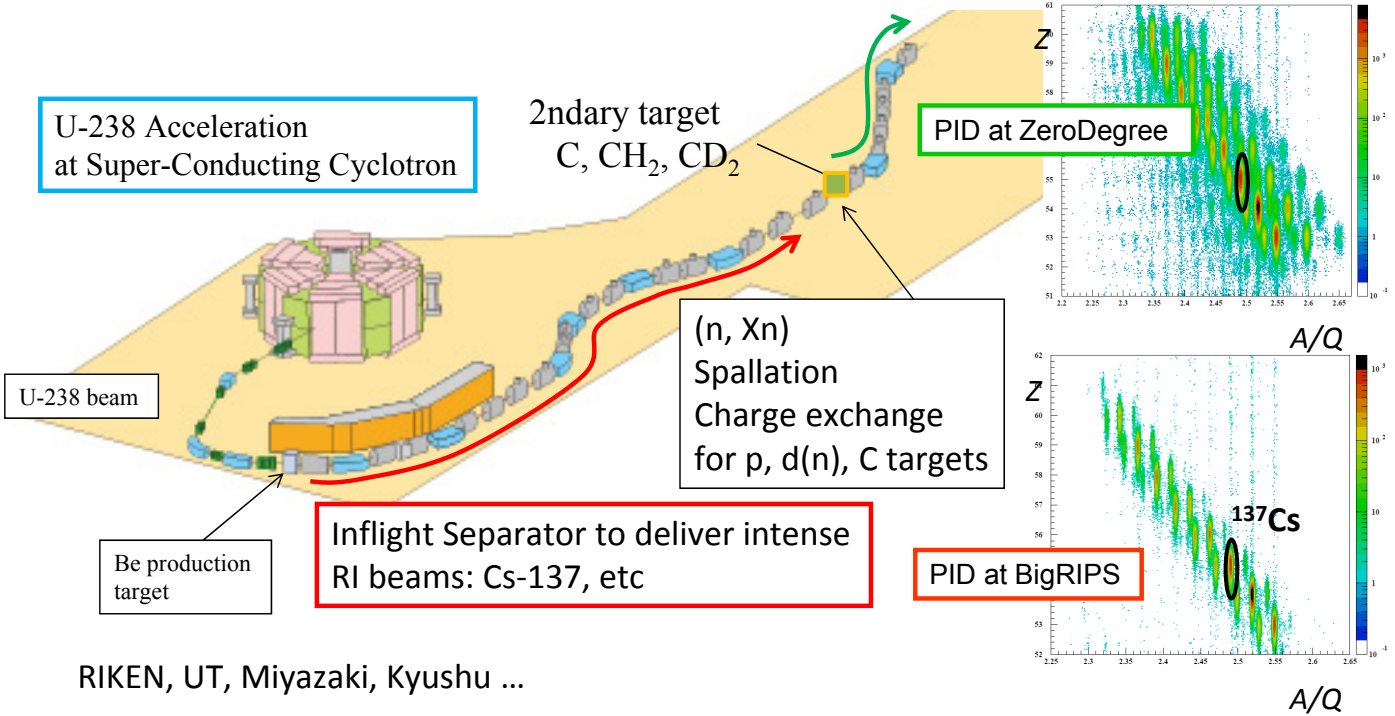
[Schwarz]

Transmutation for LLFP : The First Challenge April, 2014

Beam species	Beam energy [MeV/u]	Intensity [/s/10pnA]	Purity [%]
^{137}Cs	186	1200	14
^{90}Sr	187	7100	28

ZeroDegree Spectrometer

PID for reaction products to determine reaction channels.



[Sakurai]

RIKEN, UT, Miyazaki, Kyushu …

Conclusion

- Cyclotron is still developing. (especially in the field of compact cyclotrons)
- Presentations and discussions in the five categories are very fruitful.
  - Theory
  - New concept and new project
  - Technology
  - Operation and upgrade
  - Application
- Our challenges will continue.
  - Current limit
  - Compactness with high performance
  - Stable and flexible operations
  - Wide applications

Many thanks to LOC of CYC2016 for the perfect organization!
Mike will announce the next venue.