Review of Heavy-ion Cyclotrons

The present review includes

- *brief summary of basic features of heavy-ion cyclotrons*
- *important achievements of HI cyclotron facilities*
- *recent developments of HI cyclotron facilities*

but cannot include

- *medical cyclotrons*
- *innovative design studies*
- *novel applications*
- *............*

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The Beginning

According to Livingston, the first heavy-ion beam was a 50-MeV ^{12}C beam accelerated by the **Berkeley 37-inch cyclotron in 1940**.

424

Table 1. EARLIEST HEAVY ION ACCELERATORS

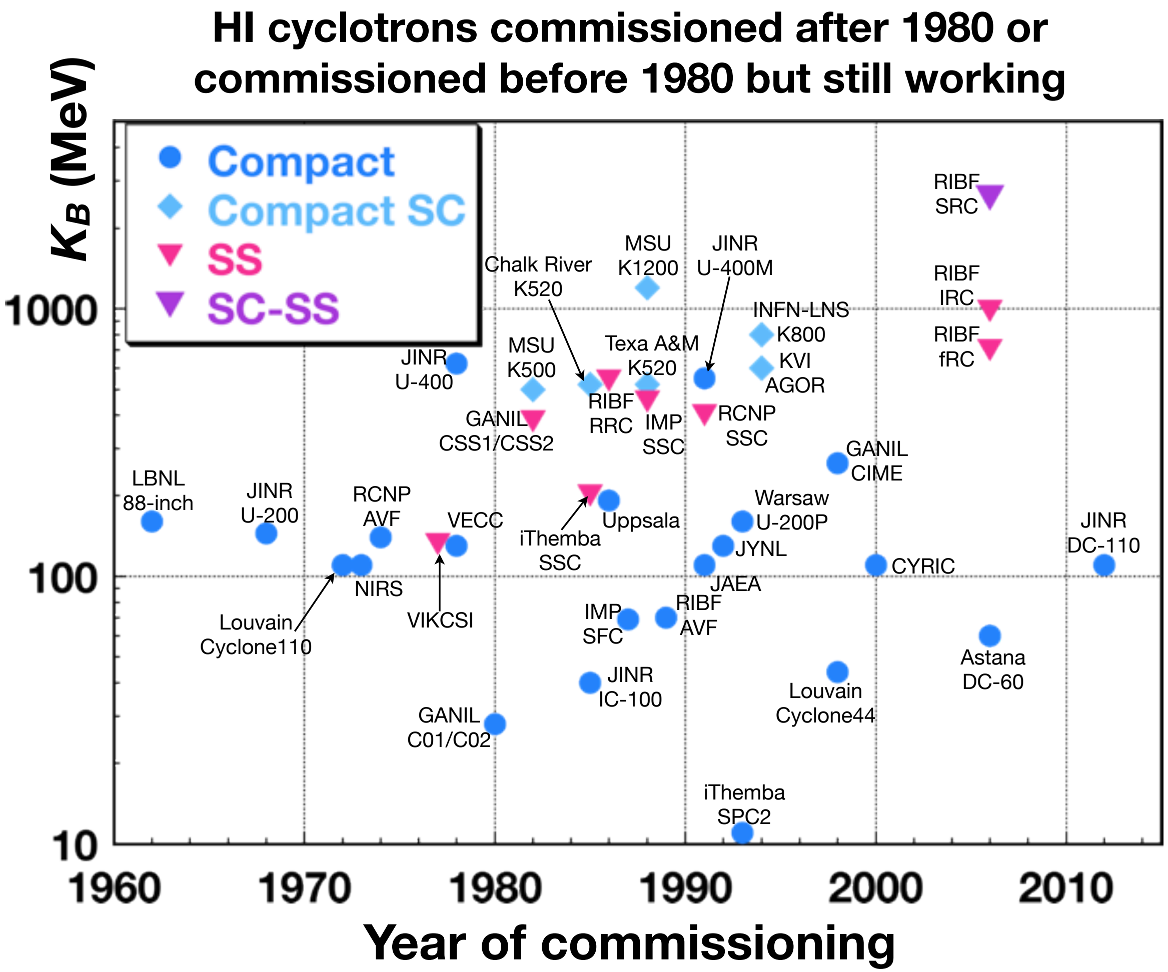
Date	*Machine*	*Location*	*Typical particle*	*Energy*	*Extracted beam*
1940	37-in. Cyclotron	Berkeley	$^{12}C^{2+,6+}$	50 MeV	8/s*
1950	60-in. Cyclotron	Berkeley	$^{12}C^{2+,6+}$	100 MeV	10^5/s
1953	225-cm Cyclotron	Stockholm	$^{12}C^{2+,4+}$	130 MeV	10^{11}/s*
1953	63-in. Cyclotron	Oak Ridge	$^{14}N^{3+}$	28 MeV	2 μA
1953	156-cm Cyclotron	Birmingham	$^{12}C^{2+,6+}$	120 MeV	
1955	180-cm Cyclotron	Saclay	$^{12}C^{2+,6+}$		
1956	120-cm Cyclotron	Leningrad	$^{14}N^{3+}$	16 MeV	0·5 μA

* Internal beam

Livingston, 5th Int. Cyclotron Conf. (1969) p. 423.

75 years have passed!

Heavy-ion Cyclotrons Worldwide



✓Commissioning rush (1980 ~ 2000)

✓Two trends in 1980 ~ 2000

- Compact superconducting cyclotrons
  MSU, Chalk River, INFN-LNS, KVI, Texas A&M
- Separate-sector cyclotrons
  GANIL, Lanzhou, RIKEN, RCNP, iThemba LABS

✓Many compact cyclotron have been commissioned.

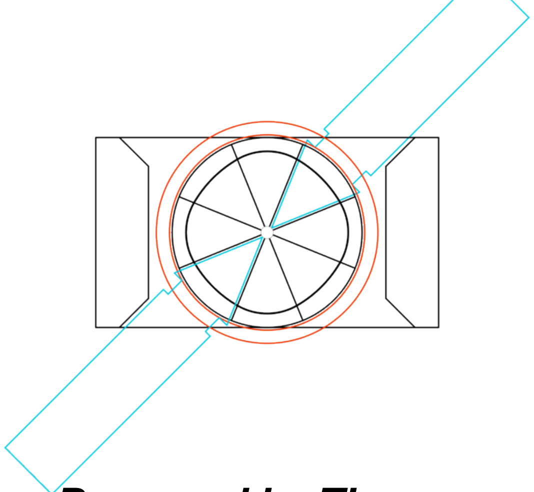
✓Continuous upgrades

These data are taken from "List of Cyclotrons", compiled in "Cyclotrons and their Applications 2004", edited by A. Goto and Y. Yano. Newly commissioned cyclotrons or upgrades are also added based on later individual reports.

Three Type of Heavy-ion Cyclotrons Widely Used

Compact (AVF)

K_B = 8 ~ 625 MeV



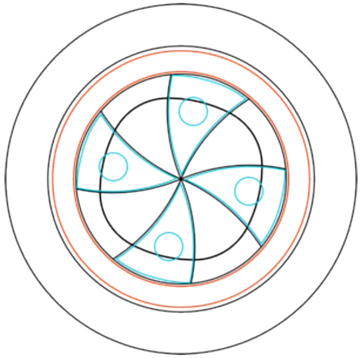
Proposed by Thomas

L.H. Thomas, Phys. Rev. ***54*** *(1938) p. 580.*

Demonstrated by Richardson

Compact, Superconducting (compact SC)

K_B = 500 ~ 1200 MeV

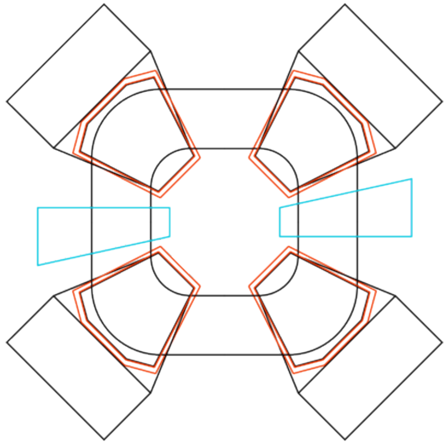


Pioneered by Chalk River and MSU

C.B. Bigham, J.S. Fraser and H.R. Schneider, Report AECL-4654 (1973).
H. Blosser et al., 7th ICCA (1975) p. 584.*

Separate Sector (SS)

K_B = 130 ~ 2600 MeV



Proposed by Willax

H. A. Willax, 3rd Int. Conf. on Sector-Focused Cyclotrons (1963) p. 386.

**ICCA = International Conference on Cyclotrons and their Applications*

Bending and Focusing Limits

E : Total Kinetic Energy
A : Mass Number
q : Charge Number

✓ Bending limit

$$E/A \leq K_B(\frac{q}{A})^2$$

✓ Vertical focusing limit

$$E/A \leq K_F(\frac{q}{A})$$ for compact SC

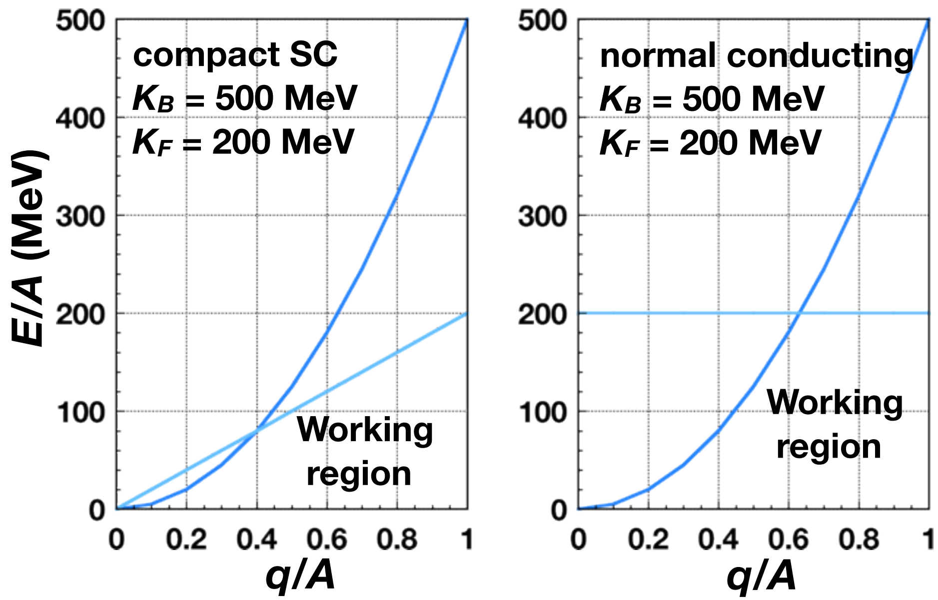
$$E/A \leq K_F$$ for others

✓ RF frequency
✓ Resonances
✓ Injection

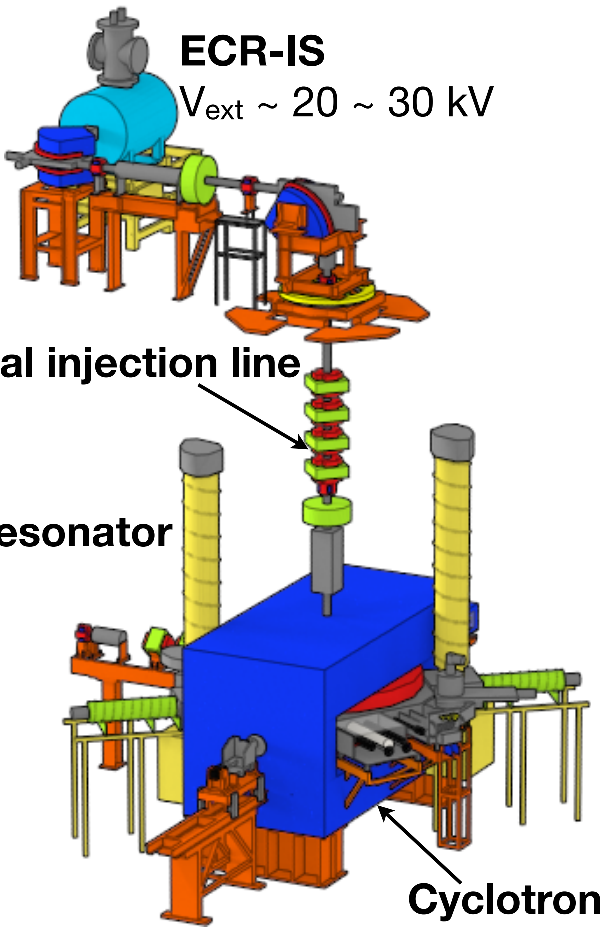
RIBF SRC

$^{238}U^{86+}$ 345 AMeV ($B\rho = 8.06$ Tm)
$K_B = 2640$ MeV

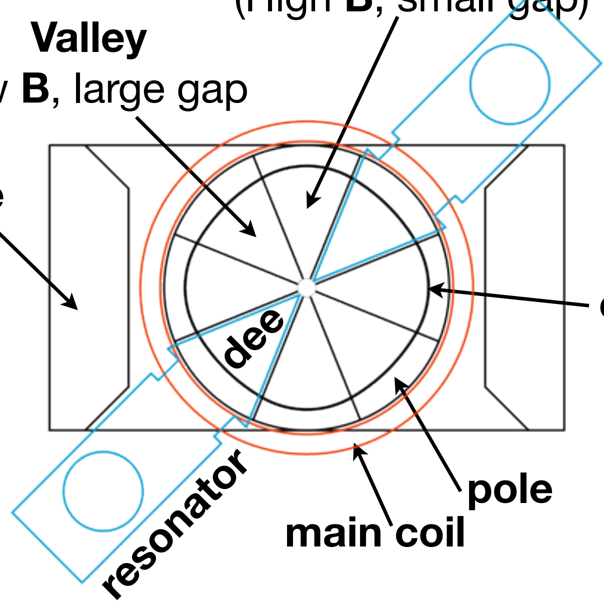
$^{238}U^{44+}$ 100 AMeV ($B\rho = 7.99$ Tm)
$K_B = 2930$ MeV



Basic Features of Compact HI Cyclotrons

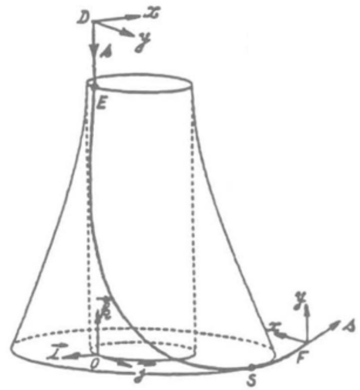


B_{max} = 1.5 ~ 2.1 T
V_{dee} = 50 ~ 100 kV



Field correction
- radial trim coils
- harmonic coils

Beam injection
- electrostatic inflector
  (mirror, spiral, hyperboloid)



Beam extraction
- electrostatic deflector (ESD)
- charge stripping

Example of Compact HI Cyclotrons

ESD : Electrostatic Deflector / CS : Charge-stripping extraction / * : for negative ions

Facility	Name	K_B (MeV)	No. of sectors	Spiral angle (deg.)	Gap hill/valley (cm)	No. of Dee	V_{acc} (kV)	F (MHz)	Extraction
JYFL	K130	130	3	58	17.4/33.0	2	50	10 ~ 21	ESD / CS*
JAEA-Takasaki	K110	110	4	53	16.6/40.5	2	60	10.6 ~ 22	ESD
CYRIC	K110	110	4	53	16.6/40.5	2	60	10.6 - 22	ESD / CS*
LBNL	88-inch	160	3	55	19.0/30.0	1	50	5.5 - 16	ESD
Warsaw	U-200P	160	4	0	2.6/15.0	2	70	12 - 18	CS
FLNR JINR	U-400	625	4	0	4.2/30.0	2	100	5.5 - 12	CS
	U-400M	550	4	43	10.0/50.0	4	170	11.5 - 24	CS
VECC	K130	130	3	55	19.0/30.0	1	60	5.5 - 15.5	ESD
GANIL	CIME	265	4	0	12.0/30.0	2	100	9.6 - 14.5	ESD

Major part of the data are from “List of Cyclotrons”, compiled in “Cyclotrons and their Applications 2004”, edited by A. Goto and Y. Yano. Newly commissioned cyclotrons are recent upgrades are included based on their individual reports.

Recent Activities @ JYFL

Example of K130 performance
^{40}Ar 4.3 pμA at 5 *A*MeV

ECR (14.5 GHz)
V_{ext} ~ 20 kV

MCC30/15
(K_B = 30 MeV, H^-, D^-, 2009~)

K130
(Scanditronix, K_B = 130 MeV, 1992~)

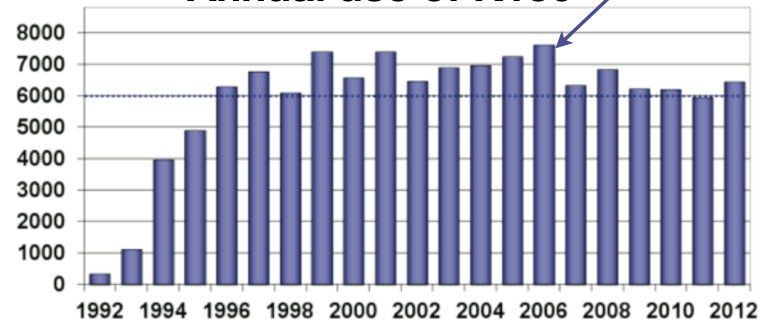
IGISOL
(Trap, Laser)

RITU (Gas-filled recoil spectrometer)
MARA (Vacuum recoil spectrometer)
RADEF (Irradiation)

New experimental hall (50 × 13.5 m^2)

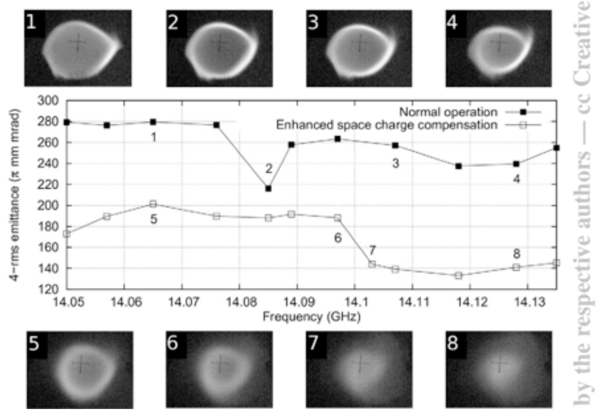
Annual use of K130

7500 hours



P. Heikkinen., ICCA 2013, p. 43.

Detailed studies on ECRIS Beams



V. Toivanen et al., ICCA 2010, p. 153.

Intensity Upgrade of LBNL 88-inch Cyclotron

- Highly charged ions for microchip testing : Xe^{43+}
- High-intensity beams for nuclear physics : ^{48}Ca

VENUS
V_{ext} ~ 30 kV

AECR-U
V_{ext} < 14 → **> 25 kV**

Axial Injection line
Bρ upgrade

88-inch Cyclotron **(1962~)**
K_B = 160 MeV

Spiral inflector for high-intensity beams
Median plane correction by unbalancing excitation currents of trim coils

New spiral inflector

Figure 2: The LBNL 88-Inch Cyclotron spiral inflector with cover removed.

Height	25 mm
R_{mag}	32 mm
Gap	10 mm
E	20 kV/cm

250-MeV ^{48}Ca beam

Peak intensity : **2.05 pμA** ← 0.6 pμA
Average : 1.1 ~ 1.5 pμA (8-week-long experiment)
Material consumption rate : 0.27 mg/h

D.S. Todd et al., ICCA 2013, p. 19.
K. Yoshiki Franzen et al., ICCA 2013, p. 186.

Activities @ FLNR JINR

U-300
(classical, 1959~)

U-400M[1]
(K_B = 550 MeV, 1991~)

ECR[2]
Axial Injection
(Mirror, 1995)

RI beams (^{6,8}He etc)
triton (6×10^{10} pps)
DRIBs driver

U-400
(K_B = 625 MeV, 1978~)

ECR[2]
Axial Injection
(Spiral, 1996)

Modernization to
U-400R[4]

Super Heavy
(^{48}Ca, >1 pμA)
DRIBs post-accel.

DC-280
(^{48}Ca, > 10 pμA)

U-200
(K_B = 145 MeV, 1968~)

IC-100
(DC-40)
(radial, K_B = 40 MeV, 1985)

SC-ECR[3]
Axial Injection
ESD extraction
(2004)

DC-110[5]
(radial, K_B = 110 MeV, 2012)

Industrial Applications
- nuclear track membrane
- surface modification

DC-60[6]
(radial, K_B = 60 MeV, 2006)

to Astana
(Kazakhstan)

(1)G. Gulbekyan et al., 13th ICCA (1992) p.11.
(2)B. Gikal et al., 15th ICCA (1998) p. 587.
(3)B. Gikal et al., ICCA 2007, p. 27.
(4)G. Gulbekyan et al., IPAC2011, p. 2700.
(5)B.N. Gikal et al., RuPAC2014, p. 146.
(6)B.N.Gikal et al., ICCA 2004, p. 205.

High Intensity HI Beams @ FLNR JINR

U-400

before upgrade (~1996)

PIG + CS extraction

Ion	E (AMeV)	$I_{external}$ ($\times 10^{12}$ pps)
$^{16}O^{2+}$	8.8	15
$^{20}Ne^{2+}$	5.6	10
$^{40}Ar^{4+}$	7.0	7
$^{48}Ti^{5+}$	5.5	7
$^{55}Mn^{6+}$	6.0	6

PIG : **~10 mg/h**

B.N. Gikal et al., 12th ICCA (1989) p. 125.

U-400

after upgrade (1996~)

High intensity ^{48}Ca beams
Low material consumption rate

- ECR Ion Source
- Axial Injection
- Charge stripping extraction

1.4 pμA $^{48}Ca^{5\rightarrow 18+}$ beam
with material consumption of
0.4 mg/h

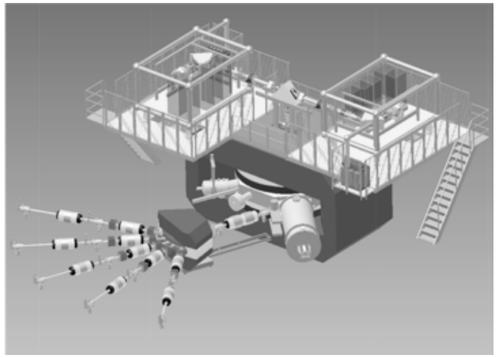
B. N. Gikal et al., ICCA 2004, p. 100.

DC-280

(under construction)

> 10-pμA ^{48}Ca beams

- ECR Ion Source (25 kV)
- High-voltage terminal (75 kV)
- Axial Injection (spiral)
- Multi-harmonic buncher
- High vacuum (~5 $\times 10^{-6}$ Pa)
- Flat-top cavities



G. G. Gulbekian et al., RuPAC2014, p. 333.

CIME : Post-accelerator of ISOL Facility

Dedicated to RI beams obtained by ISOL method.

- K_B = 265 MeV
- wide energy range : 1.7 (1)* ~ 25 *A*MeV
- RF harmonic : 2 ~ 5 (6)* with two inflectors

H = 2, 3 : Müller, R_{mag} = 34 mm / H = 4, 5 : Spiral, R_{mag} = 45 mm

- high vacuum : 5 ×10^{-6} Pa
- large acceptance : ~ 80 π mm-mrad
- nuclear probes for faint RI beams

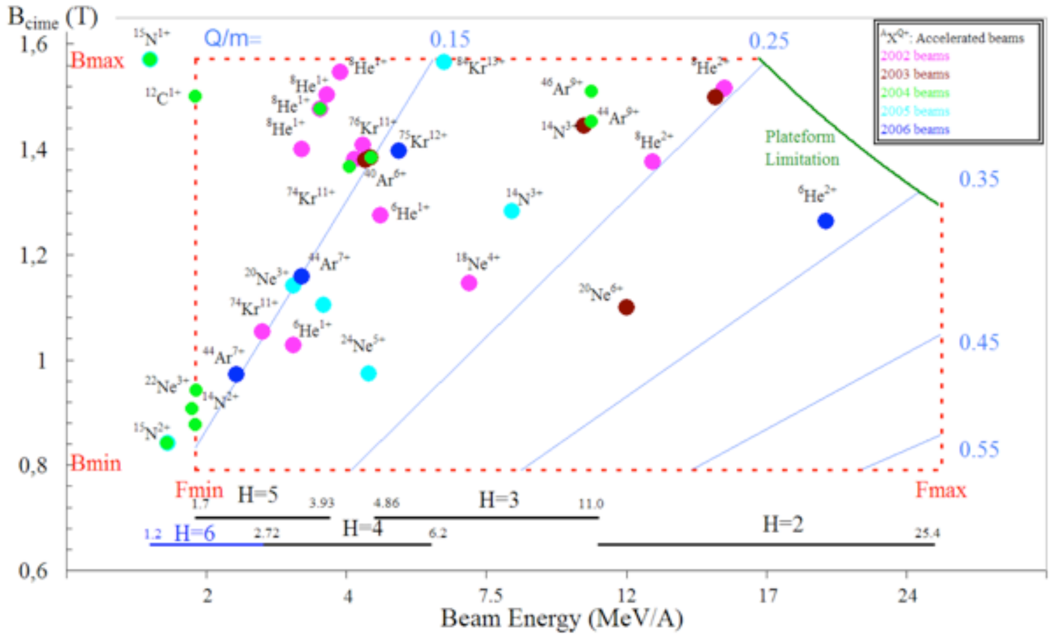
silicon and scintillator detectors on radial probes

Design made by 3D electric (CHA3D) and magnetic (TOSCA) field calculations

High *A/q* resolution (10^{-4})

M. Lieuvin & SPIRAL group, 14th ICCA (1995) , p. 651.
F. Varenne et al., ICCA 2001, p. 74.
** : later upgraded.*

Ions Accelerated by CIME



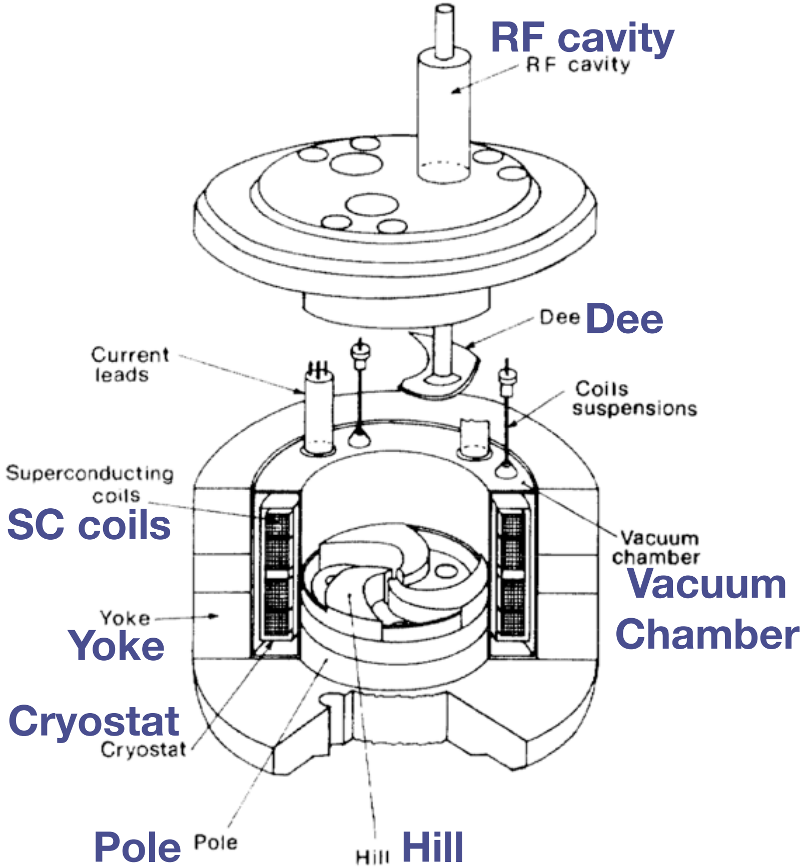
F. Chautard et al., ICCA 2007, p. 99.

Compact Superconducting Cyclotrons

- ✓ purpose : mainly nuclear physics
- ✓ ion spices : p (H_2^+) ~ U
- ✓ energy : a few *A*MeV ~ 100 *A*MeV or higher
- ✓ beam intensity : 10^9 ~ 10^{12} pps

Facility	Name	K_B (MeV)	First beam	R_{ext} (m)	Iron weight (ton)
Chalk River*	K520	520	1985	0.65	170
INFN-LNS	LNS-SC	800	1994	0.87	176
KVI	AGOR	600	1994	0.90	100
NSCL MSU	K500	500	1982	0.66	91
	K1200	1200	1988	1.0	240
Texas A&M	K500	520	1988	0.67	100
VECC	K500	520	2009#	0.67	?

* 1996 shutdown / # internal beam



E. Acerbi, EPAC88 (1988) p. 166.

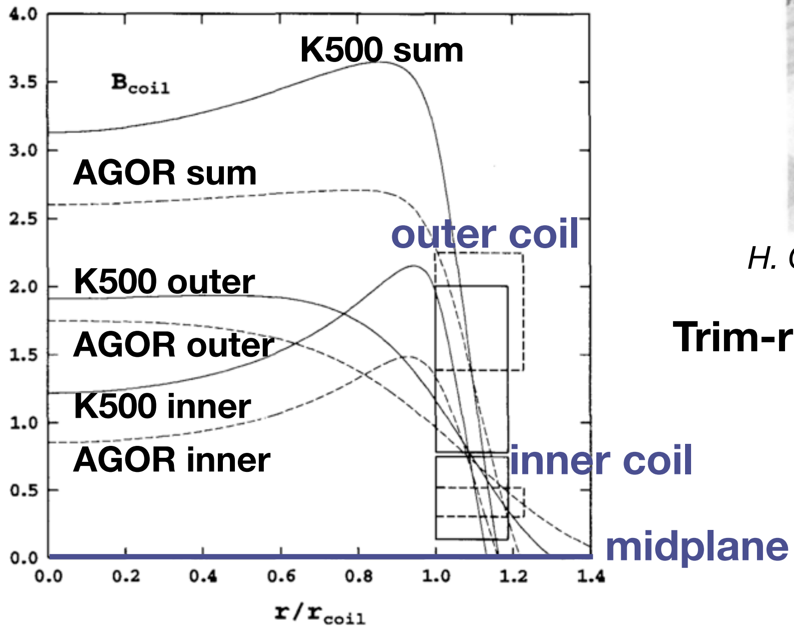
Isochronism of Compact SC Cyclotrons

Magnet : Compact type
- fully saturated iron poles
- circular SC main coils
- B_{max} ~ 5 T

Coarse isochronism
split main coils, individually excitable

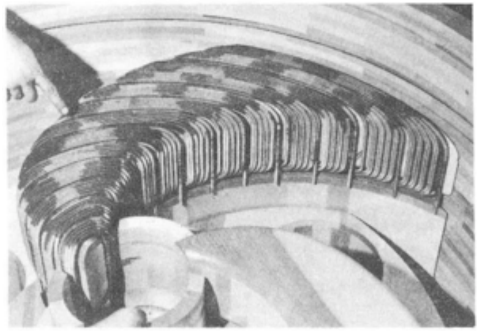
Fine isochronism
RT trim coils or trim rods (Chalk River)

Magnetic fields of split main coils



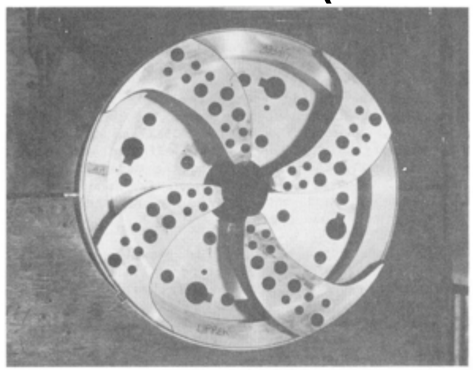
H. Blosser et al., 14th ICCA (1995) p. 674.

Trim coils (MSU K500)



H. G. Blosser, 8th ICCA (1978) p. 2040.

Trim-rods distribution (Chalk River)



J.A. Hulbert et al., 11th ICCA (1986), p. 1.

Betatron Motion in Compact SC Cyclotrons

Various ion species for a wide energy range

✓vertical focusing ← flutter fields produced by iron poles
✓azimuthally symmetric field ← SC main coils
✓weak vertical focusing at higher excitation level
✓tight resonance conditions especially for 3 sector machines

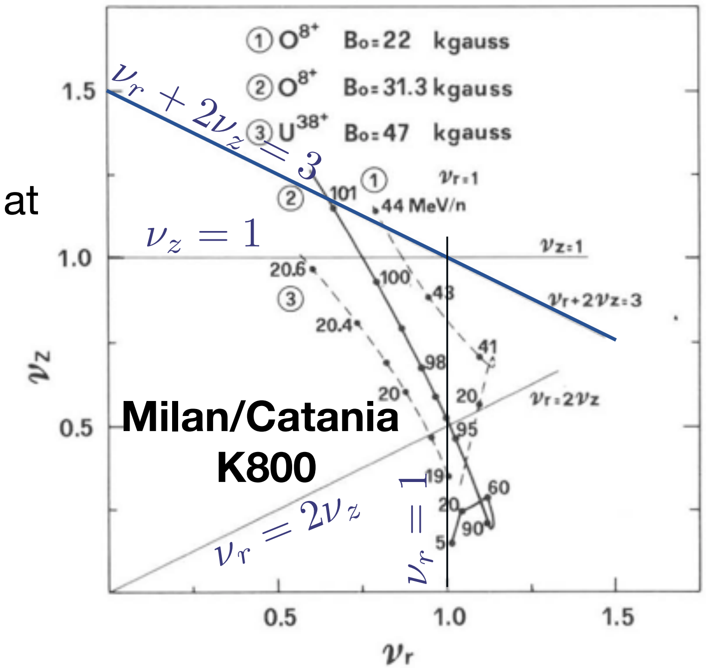
Resonances are crossed at

$$\nu_r = 2\nu_z$$

$$\nu_z = 1$$

$$\nu_r = 1$$

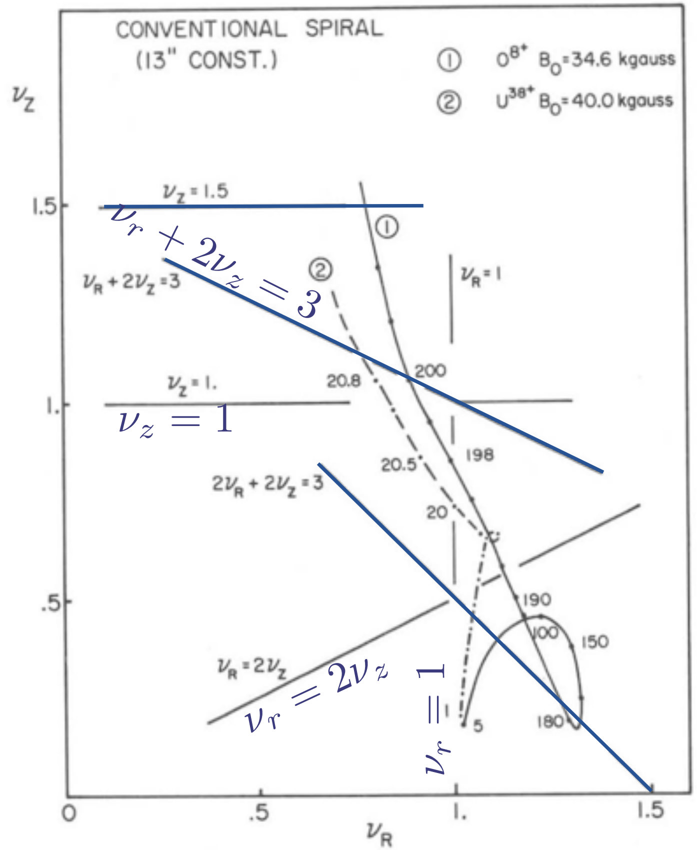
(precessional extraction)



E. Acerbi et al., 9th ICCA (1981) p. 169.

stop band

K1200 early design



F. Resmini et al., 8th ICCA (1978) p. 2078.

Beam Extraction from Compact SC Cyclotrons

- ✓small R_{ext} ← High **B**
- ✓low V_{acc} ← conventional dees
- ✓electrostatic deflector
- ✓orbit geometry change

→

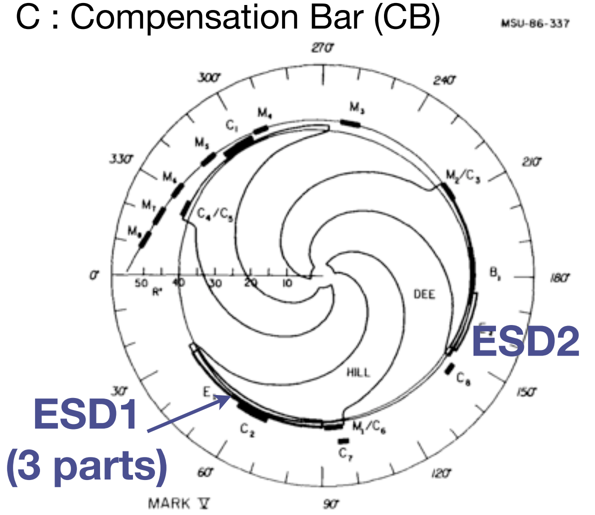
- ✓precessional extraction
- ✓fast fall-off of magnetic field
- ✓high-**E** (~140 kV/cm) ESD
  with position- and shape-flexibility

MSU K1200

2×ESD + 8×PMC + CBs

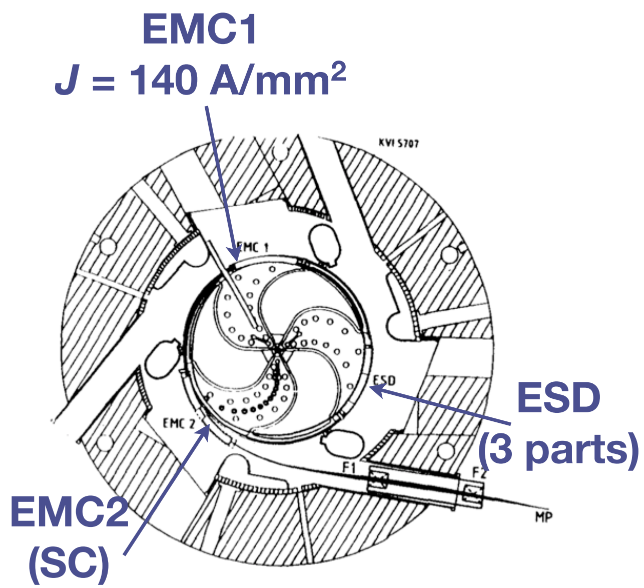
M : Passive Magnetic Channel (PMC)

C : Compensation Bar (CB)



J.A. Nolen et al., 12th ICCA (1989) p. 5.

KVI AGOR



H.W. Schreuder, 15th ICCA (1998) p. 592.

Magnet Specifications of Compact SC Cyclotrons

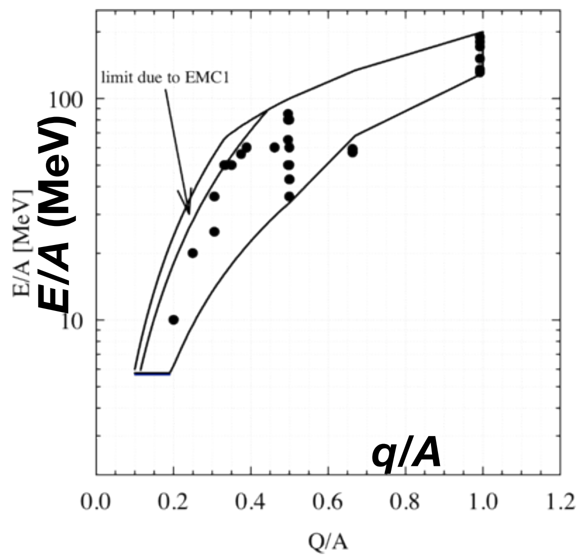
From “List of Cyclotrons”, compiled in “Cyclotrons and their Applications 2004”,Edited by A. Goto and Y. Yano.

Facility	Name	K_B (MeV)	K_F (MeV)	R_{ext} (m)	Hill / Valley gap (cm)	No. of sector	Total ampere turn (10^6 A)	J_{ave} (A/mm^2)	Stored Energy (MJ)	Cryo-stability	B_{ave} (T)	No of Trim coil / pole
Chalk River*	K520	520	100	0.65	3.7 / 65	4	6.2	25	22	yes	1.7 - 5.0	13 rods
INFN-LNS	LNS-SC	800	200	0.87	8.6 / 91.6	3	6.55	35	45	yes	2.2 - 4.8	20
KVI	AGOR	600	220	0.9	7.0 / 168	3	6.6	43/33	56	no	1.7 - 4.1	15
NSCL MSU	K500	500	160	0.66	6.35 / 91.4	3	5	36	18	yes	3.0 - 5.0	13
	K1200	1200	400	1.0	7.6 / 91.4	3	7	36/40	60	yes	3.0 - 5.3	21
Texas A&M	K500	520	160	0.67	6.35 / 91.4	3	5	36	16.9	yes	3.1 - 4.9	13
VECC#	K500	520	160	0.67	6.35 / 91.4	3	5	36	22	yes	-4.9	13

* 1996 shutdown / # internal beam

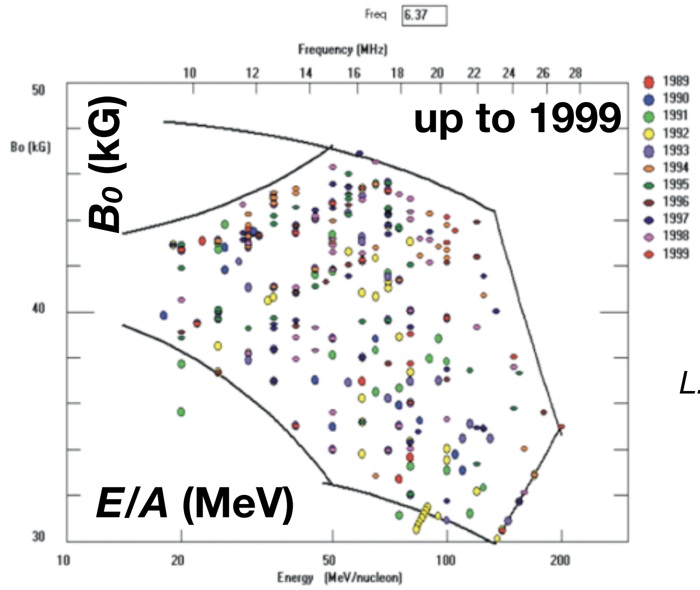
Achievements of Compact SC Cyclotrons

KVI AGOR



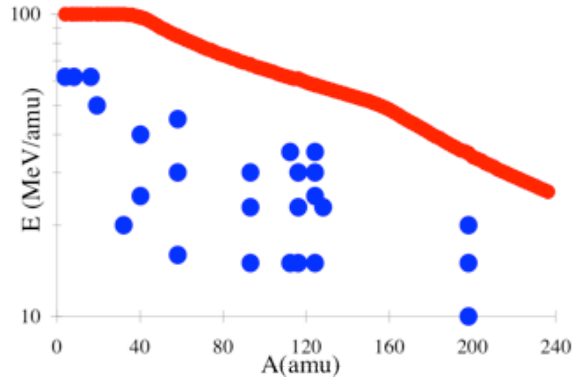
S. Brandenburg et al., ICCA 2001, p. 99.

NSCL MSU K1200
(stand-alone operation)



F. Marti et al., ICCA 2001, p. 64.

INFN-LNS K800



L. Calabretta and D Rifuggiato, ICCA 2001, p. 79.

$$E_{max} = 80\ \mathrm{AMeV}\ \text{for}\ q/A = 0.5$$

D. Rifuggiato et al., ICCA 2013, p. 52.

The design operating diagrams were successfully covered by these compact cyclotrons!

Upgrades towards RI Beam Facilities

	Before upgrade		After upgrade		
	Acceleration Scheme	Typical Performance	Acceleration Scheme	Upgrade	Requirements
INFN-LNS EXCYT(1), 1995~	15-MV Tandem + K800 (CS inj.)	*E/A* ~ 50 MeV I ~ 50 enA (just after commissioning)	Driver : K800 Post Accel. : Tandem (ISOL facility)	ECR (SERSE) Axial Injection Central region Dee electrodes ESD	1 pμA driver beams for light ions
KVI TRIμP(2), 2003~	ECR + AGOR	Proton 190 MeV ^{40}Ar 25 *A*MeV 500 enA	ECR + AGOR	ECR & LEBT Extraction (EDC/EMC1) Beam loss control	1 kW beams for ^{20}Ne & Pb
NSCL MSU CCF(3), 1996~	K500 / K1200 stand-alone	10^{10} pps for *E/A* >100 MeV	ECR + K500 + K800 (Inflight facility)	ECR K500 modernization Coupling line K800 CS-injection A1200 → A1900	10^9 pps (very heavy ion) ~ 1 pμA, 200 *A*MeV (light ion)
Texas A&M(4) IG, 2005~	K500 stand-alone	7×10^{11} pps for $^{40}Ar^{13+}$ 40 *A*MeV	Driver : K150 Two ion guides Post Accel. : K500	K150 (88-inch) re-commissioning etc.	K500 as a post-accelerator

(1)D. Rifuggiato et al., 15th ICCA (1998) p. 599. (2)S. Brandenburg et al., ICCA 2007, p. 493.
(3)R.C. York et al., 15th ICCA (1998) p. 687. (4)D.P. May et al., ICCA 2007, p. 505.

Achievements of Upgrades

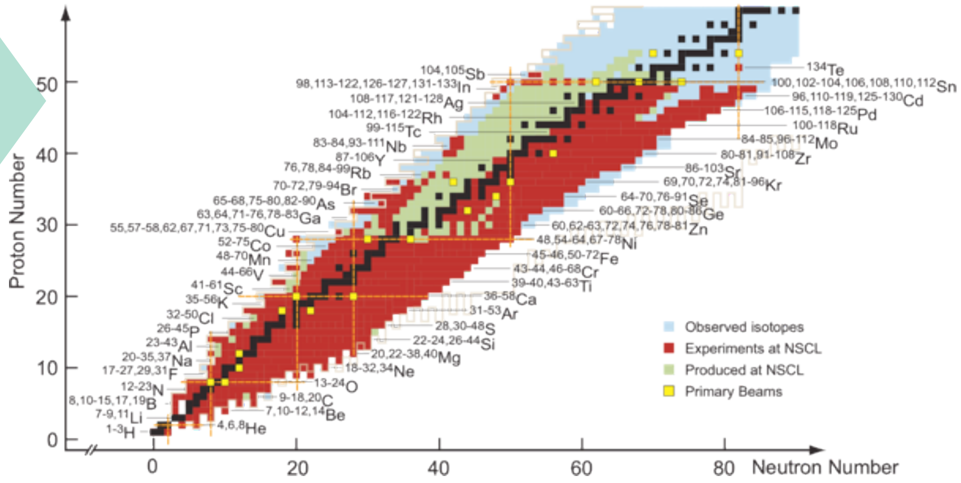
KVI AGOR
10^{13} pps for 20 ~ 30 *A*MeV, < ^{40}Ar → 1 kW
Extraction efficiency : ~ 90%

NSCL MSU CCF
4 ×10^{12} pps for 150-*A*MeV, ^{16}O → > 1 kW
Extraction efficiency : ~ 90%

INFN-LNS EXCYT
1.6 ×10^{12} pps for 45-*A*MeV ^{13}C^{4+}

A proposal for 20-kW light ion beams based on charge-stripping extraction scheme
L. Calabretta and D. Rifuggiato, ICCA 2001, p. 79.

NSCL MSU
More than 1000 RI beams were produced
~ 900 RI beams were used in experiments



A. Stolz et al., ICCA 2013, p. 7.

Tritron : Separate Orbit Cyclotron Prototype

U. Trinks, "The Superconducting Separated-Orbit Cyclotron Tritron", 14th ICCA (1995) p. 20.
A. Cazan, P. Schütz, U. Trinks, "Results of the Tritron - Project", EPAC98, p. 556.

Specifications

Injection radius : 0.66 m
Extraction radius : 1.45 m
Turn separation : 4 cm
Max. B of sector channels : 1.7 T

RF frequency : 170 MHz
Acc. voltage : 0.53 MV

Number of turns : 19.8
Max. energy : 20 *A*MeV for ^{12}C
Beam aperture : 10 mm

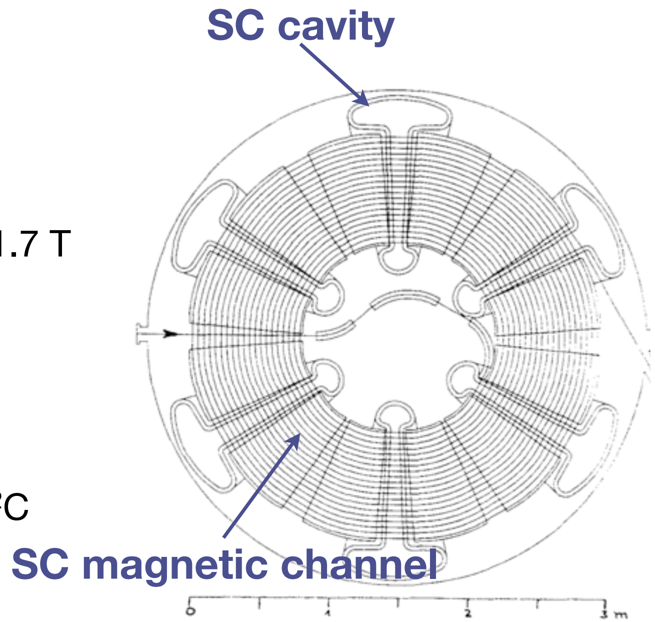


Figure 2: Horizontal cross section of the Tritron. The diameter of the vacuum vessel is 3.6 m.

Cross-sectional view of SC channels

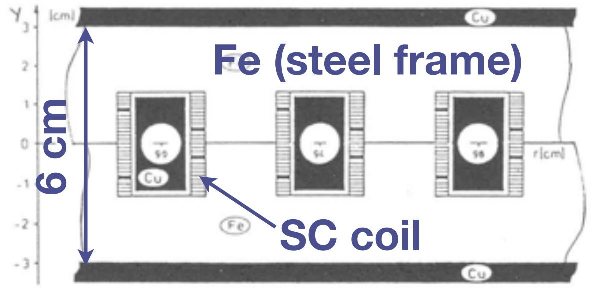


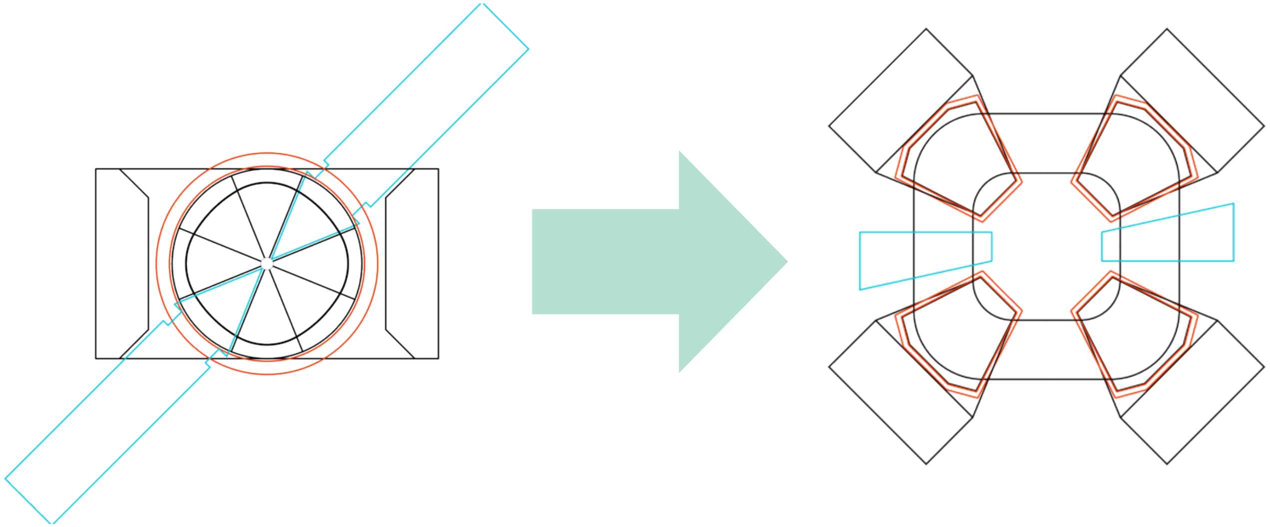
Figure 3: Radial cross section of three channel magnets.

✓AG focusing and phase stability are available
✓Compact (no voluminous yoke)

Tritron accelerated $^{32}S^{14+}$ ions from 40 to 72 MeV.

Concept of Separate Sector Cyclotron

One magnet → piecewise magnets (sector magnets).



Magnet-less valley → high flutter magnetic fields & stronger vertical focusing
→ installation of high-voltage acceleration cavities
→ useful space for beam probes, future upgrades.....

H. A. Willax, 3rd Int. Conf. on Sector-Focused Cyclotrons (1963) p. 386.
V. P. Dmitrievsky, "Relativistic Cyclotron with Space Variation of Magnetic Field", Doctoral Dissertation Manuscript in mathematical Phyiscs, Dubna, 1961.

Separate Sector Cyclotrons

* now dedicated to accelerate a 68-MeV proton beam

Facility	Name	K_B (MeV)	No. of sectors	Spiral angle (deg.)	V_{acc} (kV)	F (MHz)	Injector
HIRFL	SSC	450	4	0	200	6.5 - 14	SFC
GANIL	CSS1	380	4	0	160	7 - 13.45	C01 or C02
	CSS2	380	4	0	250	7 - 13.45	CSS1
RCNP	RCNP Ring Cyclotron	400	6	30	375	30 - 52	RCNP-AVF (K_B = 140 MeV)
HZB*	K130	132	4	0	140	10 - 20	Tandetron
iThemba LABS	Separate-Sector Cyclotron	200	4	0	230	6 - 26	SPC1 or SPC2 (K_B = 11 MeV)

Major part of the data are from “List of Cyclotrons”, compiled in “Cyclotrons and their Applications 2004”, edited by A. Goto and Y. Yano. Newly commissioned cyclotrons are added based on their individual reports.

GANIL : High Power Cascaded Cyclotron System

"GANIL Scheme"

✓High transmission efficiency at injector cyclotrons

- High source voltage
- Buncher
- 6D matching
- Large turn separation (R_{ext} = 49 cm, 25 turns)

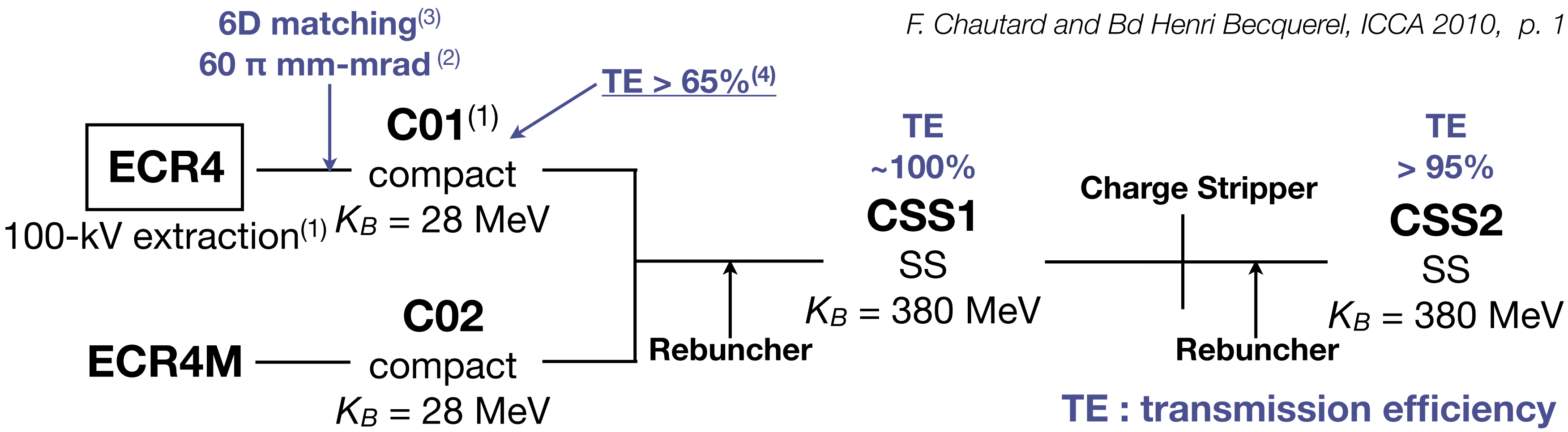
✓Charge stripping only after CSS1

✓CSS2 → 250kV

* safety limit

Beam	E (AMeV)	I (×10^{13} pps)	Power (KW)
$^{12}C^{6+}$	95	2*	3.6
$^{13}C^{6+}$	75	2*	2.9
$^{14}N^{7+}$	95	1.6	3.4
$^{24}Mg^{12+}$	95	1	3.8
$^{36}Ar^{18+}$	95	0.8	4.6

F. Chautard and Bd Henri Becquerel, ICCA 2010, p. 16.



(1) M.P. Bourgarel et al., 12th ICCA (1989) p. 111. (2)Ch. Ricaud et al., 12th ICCA (1998) p. 372. (3) A.R. Beck et al., 12th ICCA (1989) p. 432. (4) Ch. Ricaud et al., 13th ICCA (1992) p. 446.

IMP-Lanzhou

SECRAL

Rebuncher[3]

CS

SFC[1,2]
compact
K_B = 69 MeV

SSC[1,2]
SS
K_B = 450 MeV
TE : 25 ~ 50%

Experiment
RIBLL1

$^{36}Ar^{8+}$, 22 *A*MeV
3 μA

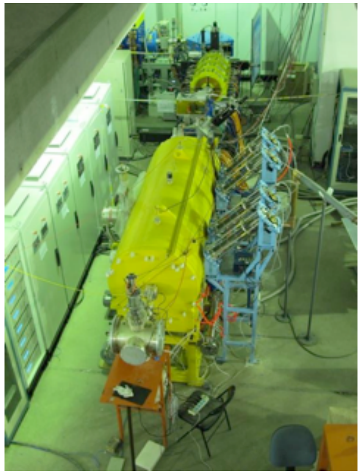
$^{12}C^{4+}$ >1.5×10^{13} pps

Cyclotrons as injectors to CS rings
Light ions : SFC → CSRm
Heavy ions : SFC + SSC → CSRm

Fragment separator
RIBLL2

CSRm[4]
Cooler-Storage Ring
Acceleration
C = 161 m
$B\rho$ < 11.5 Tm
CS / Multiple multi-turn injection
$^{12}C^{6+}$ ~600 *A*MeV, 7×10^9 ppp
$^{36}Ar^{8+}$ ~500 *A*MeV, 4×10^8 ppp

CSRe[4]
Cooler-Storage Ring
Internal Target
Mass measurements (RI)
C = 128.8 m
$B\rho$ < 9.4 Tm
Single-turn injection



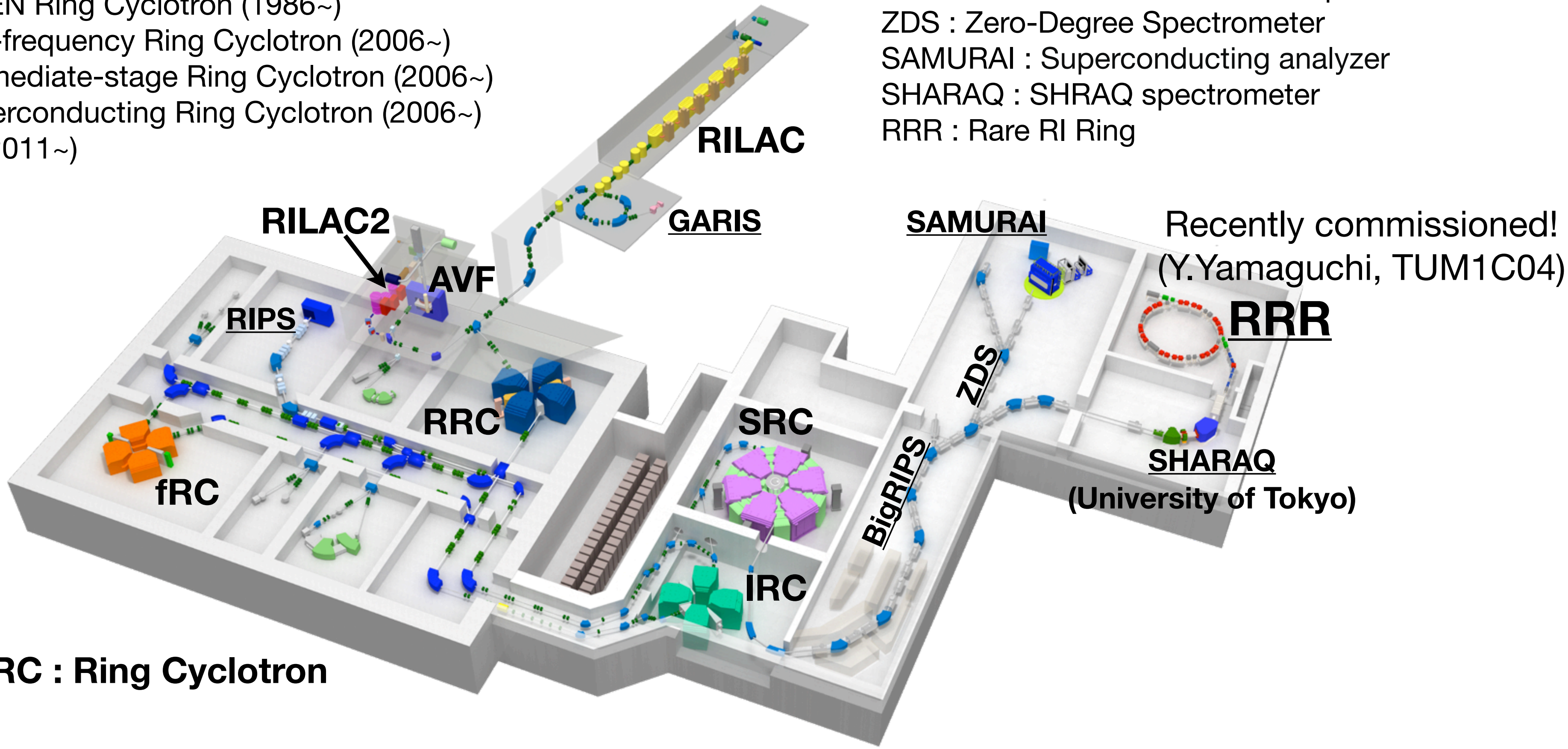
New linac injector of SSC
X.Yin et al., IPAC 2014, p. 3277.

(1)Accelerator design group (presented by B.W. Wei), 9th ICCA (1981) p. 23, B.W. Wei and F. Ye 13th ICCA (1992) p. 74.
(2)H.W. Zhao et al., ICCA 2004, p. 121.
(3)J.Y. Tang et al., ICCA 2001, p. 309.
(4)W.L. Zhan et al., ICCA 2001, p. 175.
W.L. Zhan et al., ICCA2007 p.110 & Y.J. Yuan et al., ICCA 2010, p. 37.

RIKEN RIBF

Accelerators
RILAC : RIKEN Heavy-ion linac (1981~)
AVF : K70-MeV AVF cyclotron (1989~)
RRC : RIKEN Ring Cyclotron (1986~)
fRC : fixed-frequency Ring Cyclotron (2006~)
IRC : Intermediate-stage Ring Cyclotron (2006~)
SRC : Superconducting Ring Cyclotron (2006~)
RILAC2 : (2011~)

Research instruments
RIPS, BigRIPS : Fragment separator
GARIS : Gass-filled Recoil Ion Separator
ZDS : Zero-Degree Spectrometer
SAMURAI : Superconducting analyzer
SHARAQ : SHRAQ spectrometer
RRR : Rare RI Ring

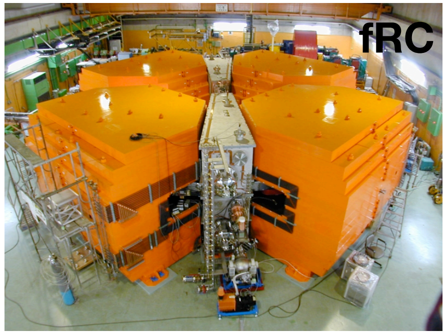


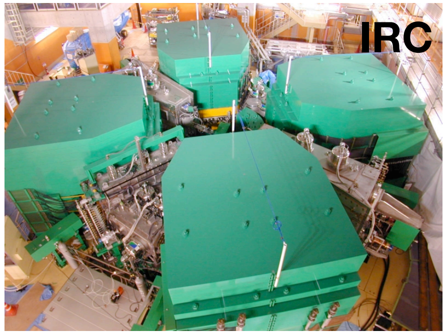
RC : Ring Cyclotron

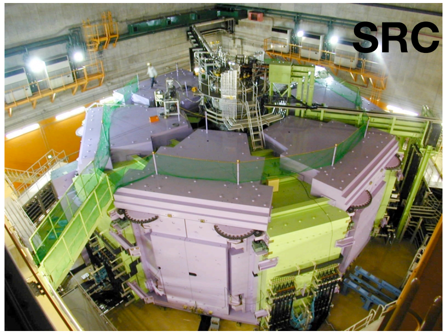
Ring Cyclotrons in RIBF

	fRC	IRC	SRC	RRC
K-number (MeV)	700	980	2600	540
R_{inj} (cm)	156	277	356	89
R_{ext} (cm)	330	415	536	356
Weight (tons)	1300	2900	8300	2400
Sector magnets	4	4	6	4
Number of trim coils (/ main coil)	10	20	4 (SC) 22 (NC)	26
Trim coil currents (A)	200	600	3000 (SC) 1200 (NC)	600
RF resonators	2+FT	2+FT	4+FT	2
Frequency range (MHz)	54.75	18〜38	18〜38	18〜38
Acceleration voltage (MV)	0.8	1.26	2.3	0.3*

SC : superconducting / NC : normal conducting / FT : flattop resonator
* : for uranium acceleration (18.25 MHz)





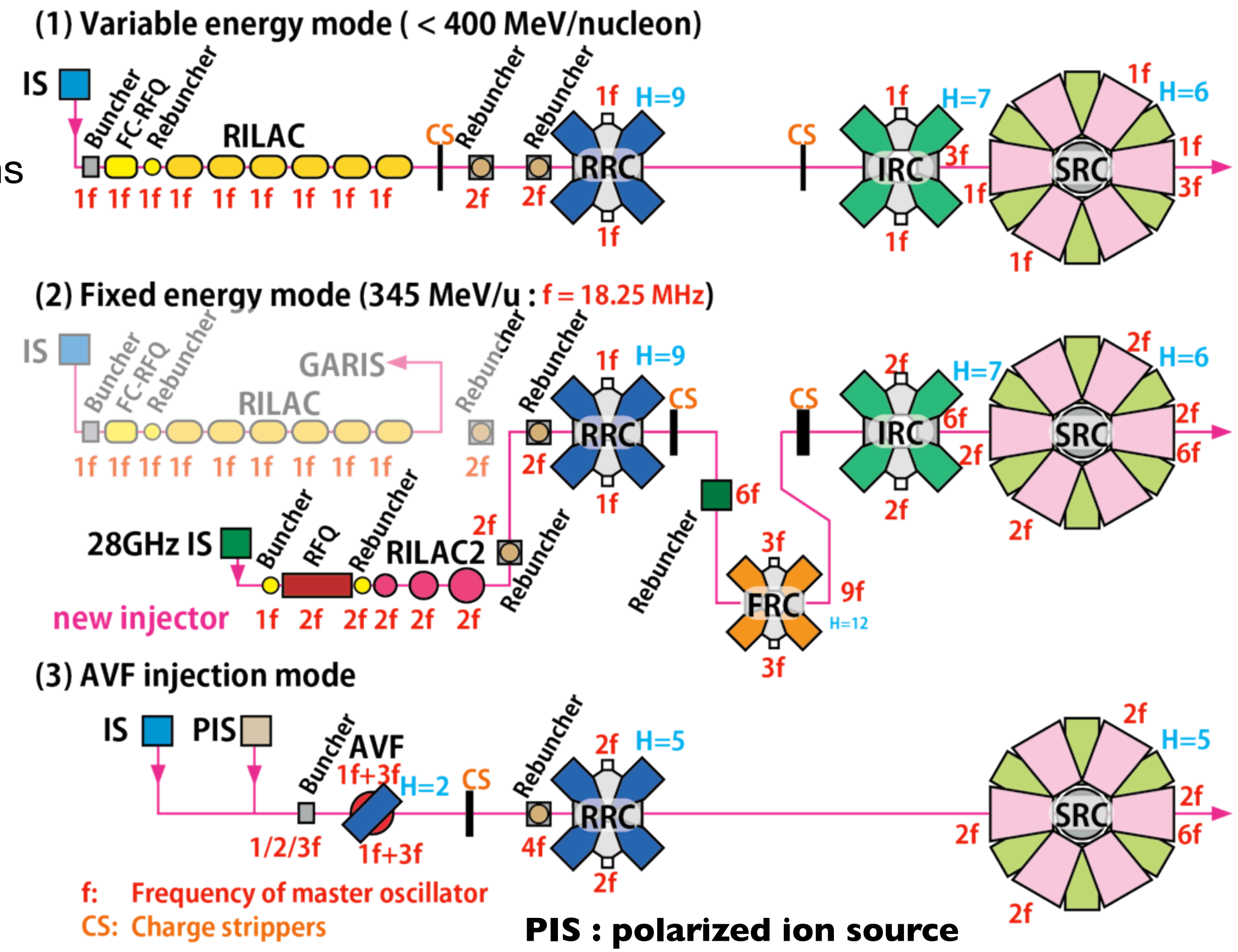


Acceleration Modes at RIBF

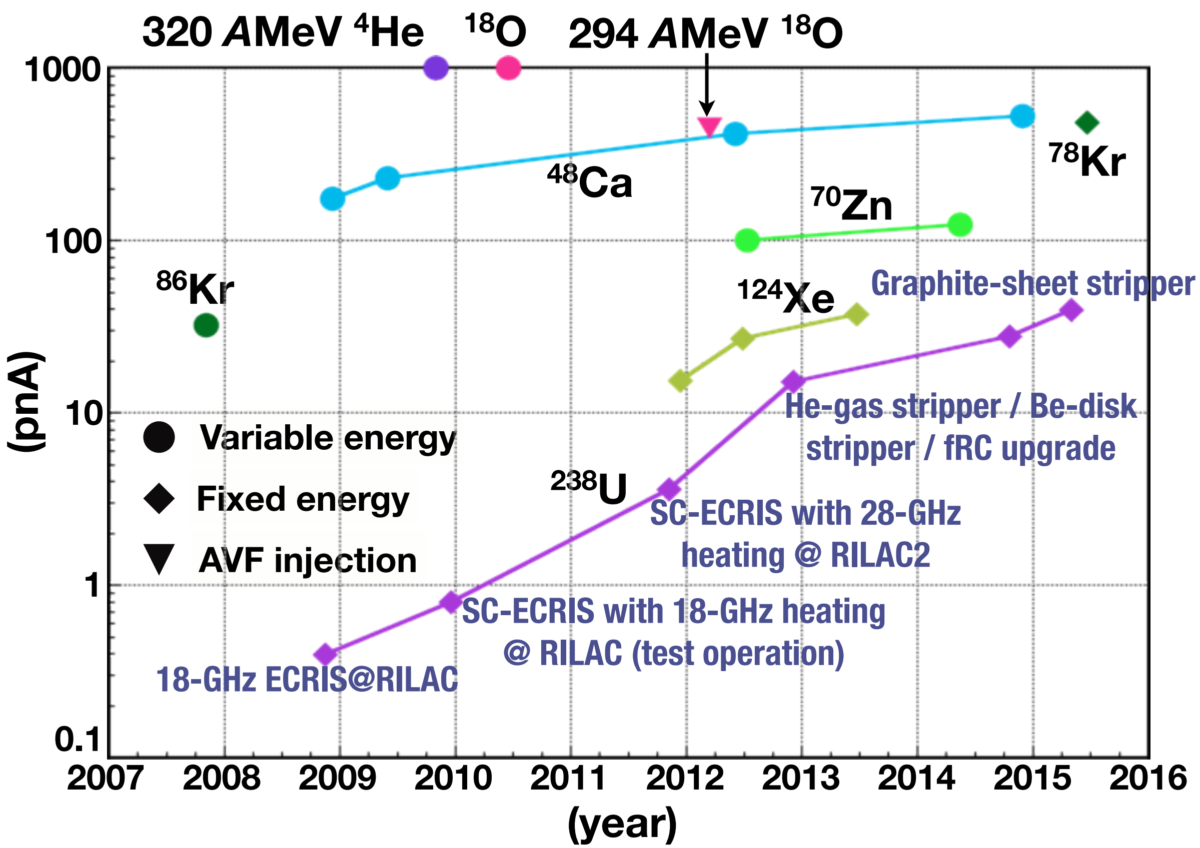
Variable energy mode
Light & medium-heavy ions
(^{48}Ca, ^{70}Zn)

Fixed energy mode
Heavy ions
(^{78}Kr, ^{124}Xe, ^{238}U)

AVF-injection mode
Very light ions
(pol-d, ^{4}He, ^{18}O)



RIBF Performance Summary



Beam energies of the beams without explicitly indicated are 345 AMeV.

<u>Beam Power</u>

✓SRC extraction

345-*A*MeV ^{78}Kr : 13.1 kW (0.49 pμA)
345-*A*MeV ^{48}Ca : 8.8 kW (0.53 pμA)
345-*A*MeV ^{238}U : 3.2 kW (0.04 pμA)

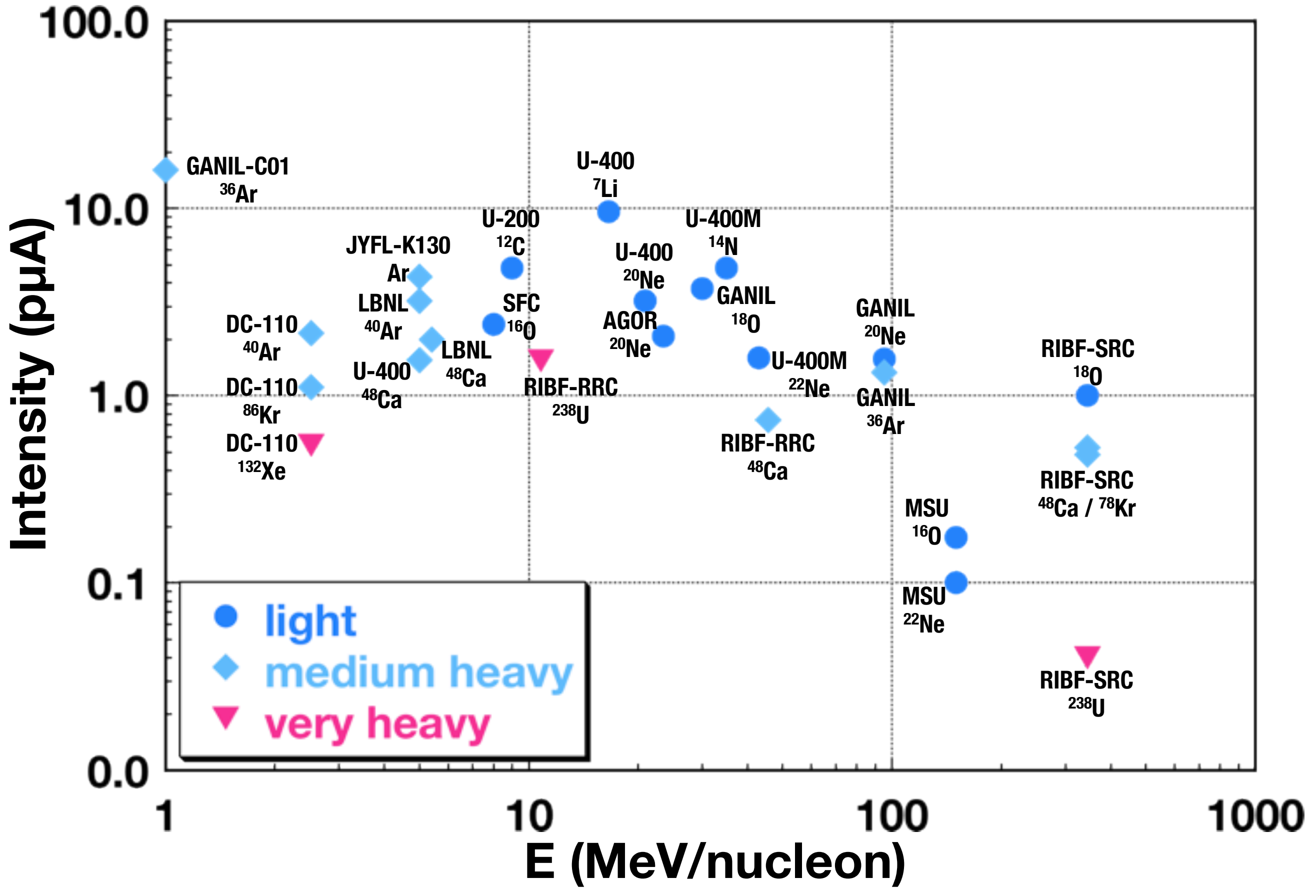
✓RRC extraction

10.8-*A*MeV ^{238}U : 4.0 kW (1.54 pμA)
45.7-*A*MeV ^{48}Ca : 1.6 kW (0.74 pμA)

<u>Beam Availability</u>

92% (2014)
93% (1st half, 2015)

Achievements of HI Cyclotrons



Compact & low cost accelerator
→ Many active facilities

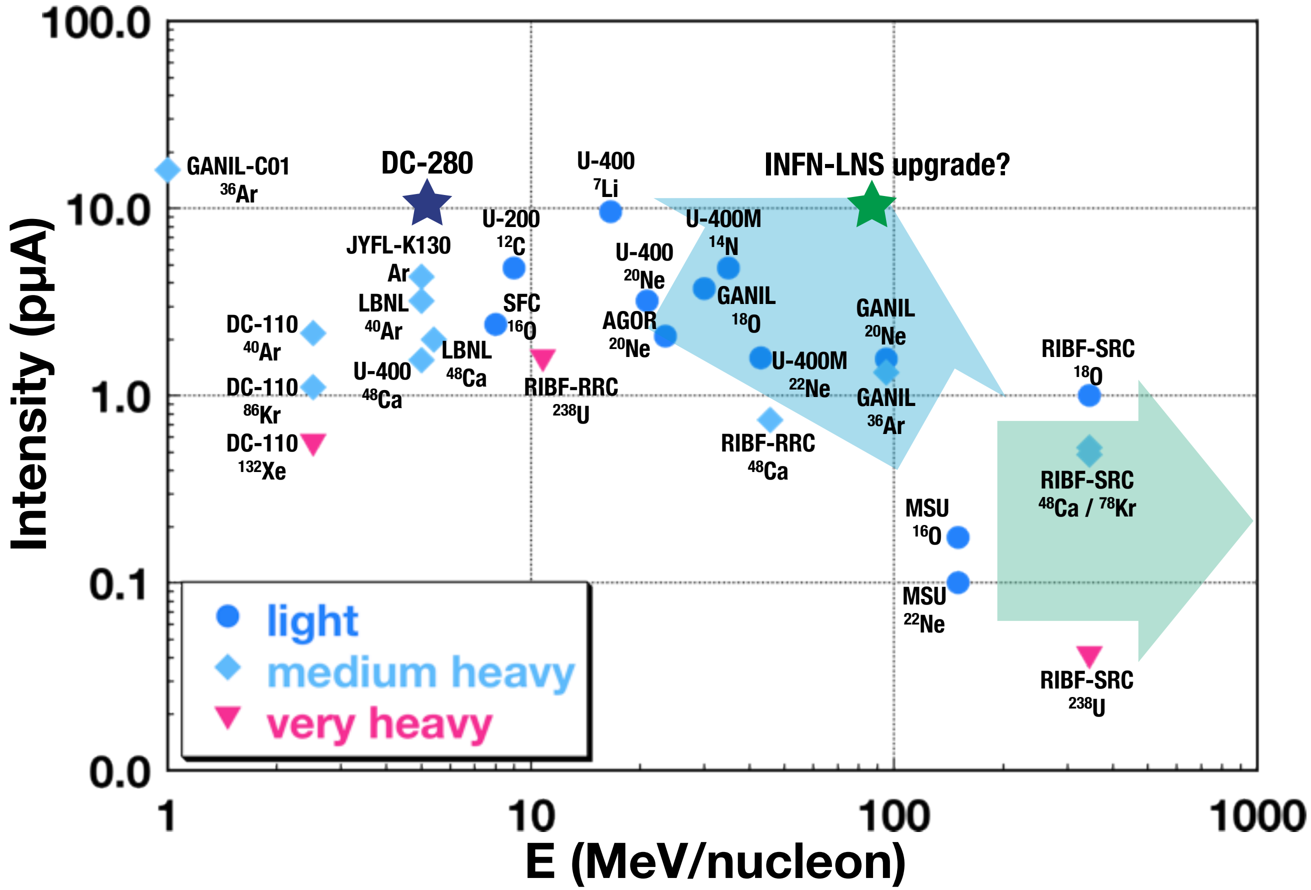
Reliable accelerator
→ High reliability
→ Cyclotron cascades work well

Upgradable accelerator
→ LBNL 88-inch

User-friendly accelerator
→ Cocktail beam acceleration

High-intensity accelerator

Future Possibilities?



Toward higher beam energy
→ 0.7 ~ 1.0 GeV/nucleon
“The last frontier of cyclotrons?“

Toward higher beam intensity
→ 10 pμA for E ~100 AMeV
→ > 1 pμA for very heavy ions
“Can we utilize fully 3rd generation ECRISs?”

Toward low operational cost
→ High-Tc superconductivity?

New type
→ SOC again?
→ Strong Focusing Cyclotron (SFC)
→ Skelton Cyclotron

Summary

✓Activities of heavy-ion cyclotrons are widely spread worldwide, although construction of new heavy-ion cyclotrons are slowed down.

✓These heavy-ion cyclotrons have upgraded their performances continuously.

✓High-intensity beams are now available for various ion species and beam energies.

✓Further intensity upgrades are possible if we will successfully utilize very high performances obtained in 3rd-generation ECR ion sources.

✓Good synergetic effects from large SC linac complexes (FRIB, RAON) are expected.