2022 가속기 및 빔 라인 미래인재 양성 여름학교

-중이온가속기 가속장치-

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2022년 7월 13일

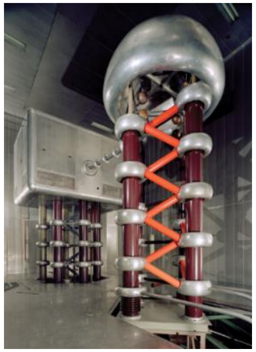
입자가속기 분류

Acceleration field

- Electrostatic field → DC accelerator (i.e. Cockcroft- Walton, Tandem,)
- Time varying electric field → RF accelerator (cyclotron, rf linac, synchrotron,..)

Particle species

- e → electron accelerator
- p → proton accelerator
- **heavy ion, hadron (Z ≥1), molecules → heavy ion accelerator**



Cockcroft- Walton generator

Accelerator shape

- Circular → Synchrotron, Cyclotron, (Microtron)
- Linear → Drift tube (Alvarez), Widroe

Superconducting accelerator

Sc-Cyclotron → superconducting magnet

Sc-Linac → superconducting rf cavity

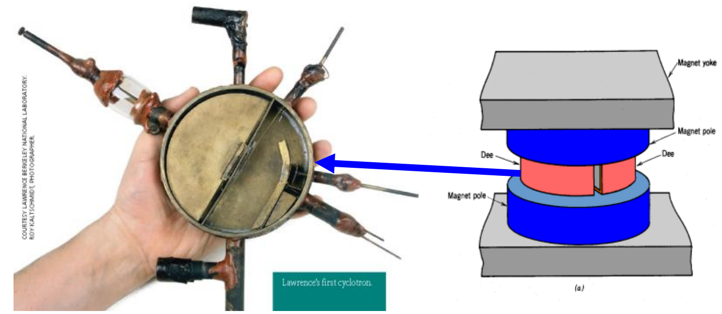
Sc-Synchrotron? → superconducting magnet or rf ?

Contents: RF hadron accelerators

1. Cyclotron
2. Linear accelerator (Linac)
3. Synchrotron
4. Isotope beam production with hadron beam
5. Use of hadron beams
6. Sustainable accelerators (with SRF technology)

1. Cyclotron

- Concept: EO Lawrence (1929): $\omega = \frac{qB}{m}$
- Proof of acceleration: MS. Livingston (1931): proton 80 keV
- Limitation in increasing energy with fixed frequency by the theory of relativity (limit :20-25 MeV)



Modern cyclotron

- **Isochronous field:** $B = \frac{Am}{q} \frac{1}{\sqrt{1-\left(\frac{\omega_0}{c^2}\right) r^2}}$ → Vertically defocusing!

- **Thomas focusing (sector focusing, 1938)**

$$B_z = B_0(1 - f\sin\theta)$$

$$v_r = \omega r_0 f \cos\theta$$

$$B_\theta = z\left(\frac{\partial B_\theta}{\partial z}\right)_{z=0} + ..$$

Flutter (r) $F^2 = \frac{\overline{B_z^2} - \overline{B_z}^2}{\overline{B_z}^2}$

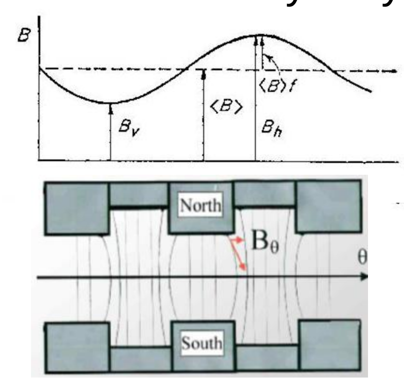
$$v_z^2 = n + \frac{N^2}{N^2-1} F(1 + 2\tan^2\xi)$$

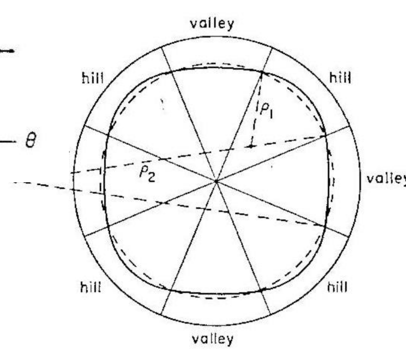
Spiral angle

K value of heavy-ion cyclotron

$\frac{E}{A} = K(\frac{q}{A})^2$ (MeV/u), kinetic energy of ions, bending limit

Azimuthally Varying Field (AVF)



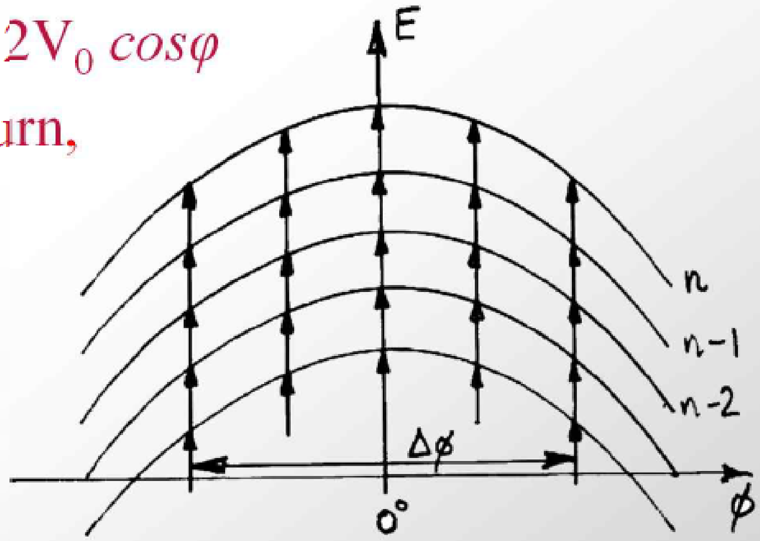


Longitudinal motion

- **Isochronism** ==> all ions have equal orbit time independent of energy. → No longitudinal focusing

  ∴ ions arrive at Dee gap at the same rf phase φ on every turn

- If the voltage across the gap is $2V_0 \cos\varphi$ & if there are 2 crossings per turn, then after n turns



Energy gain/turn: $E_n = 4nqV_0 \cos\varphi$

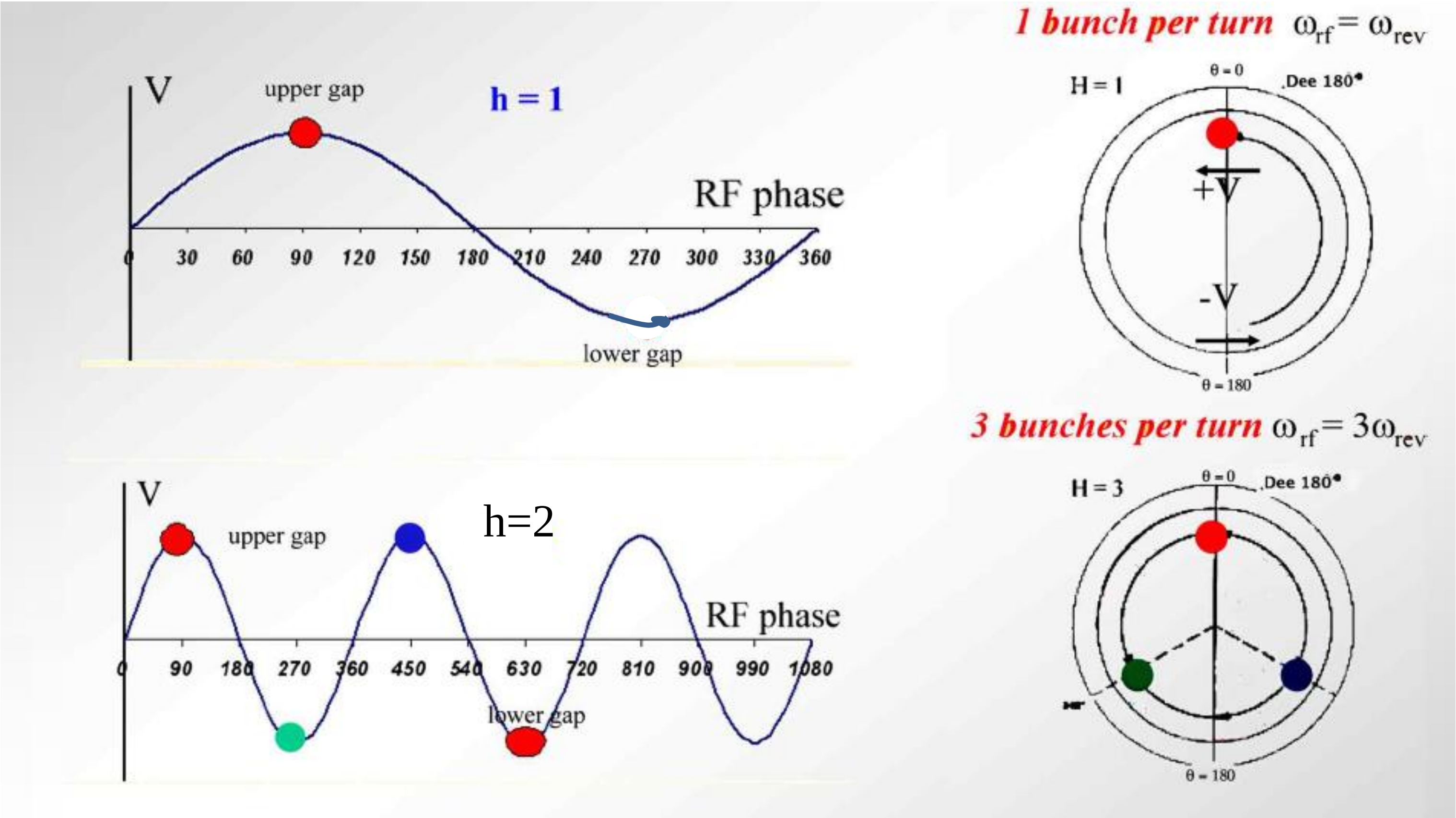
- In ideal cyclotrons, there is
  - no phase wander
  - no phase focusing ===> ***No energy spread***

In reality, no ideal magnetic field means **phase excursion** → ***Energy spread in the beam***

Harmonic motion

$$\omega_{rf} = h\omega = h\left(\frac{Q}{A}\right)\left(\frac{e}{m_a}\right)B$$

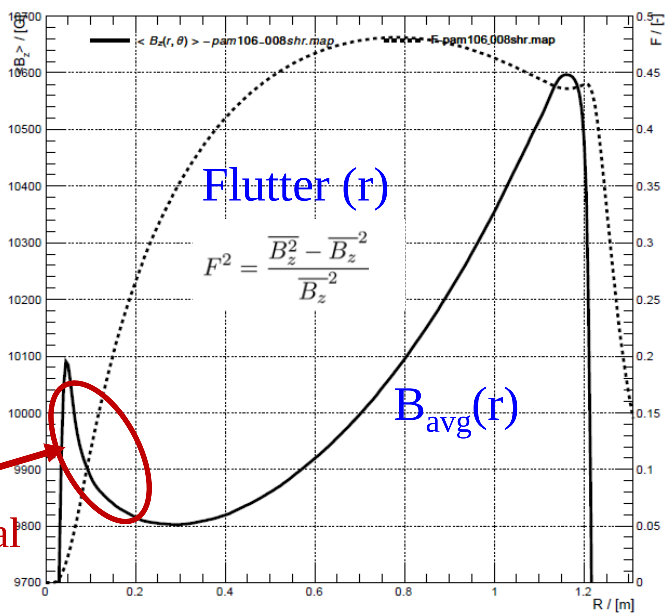
h: harmonic number
ω: rotation frequency of ion



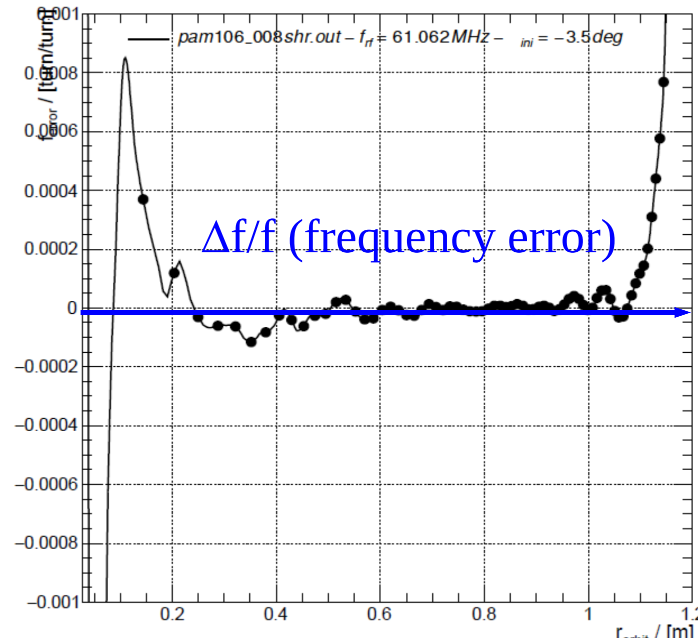
A 70 MeV proton cyclotron of IBS (compact cyclotron)

Installed and under beam commissioning (July, 2022)

Isochronized magnetic field and its error

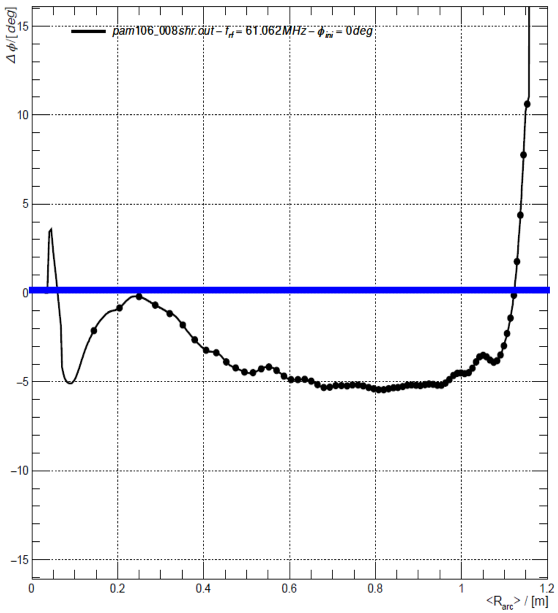


Central field bump for vertical focusing

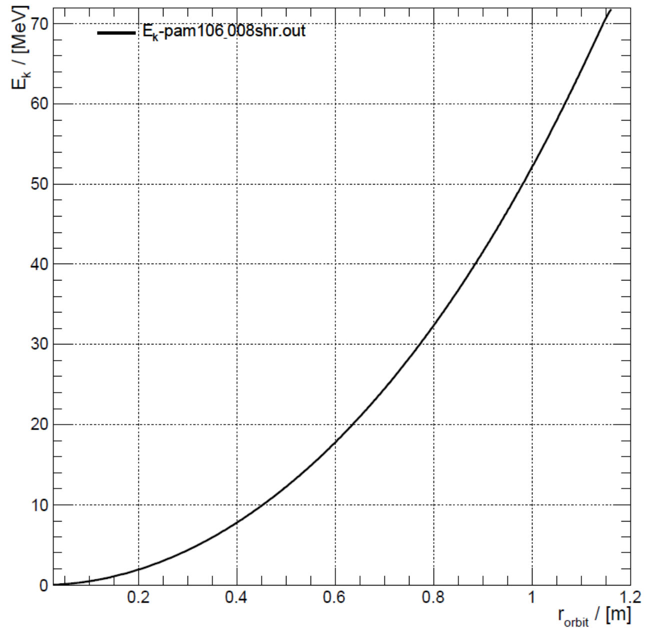


Characteristics of the 70 MeV Cyclotron

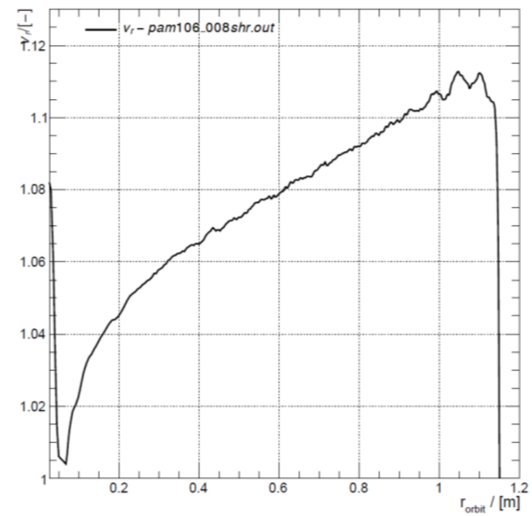
Phase excursion



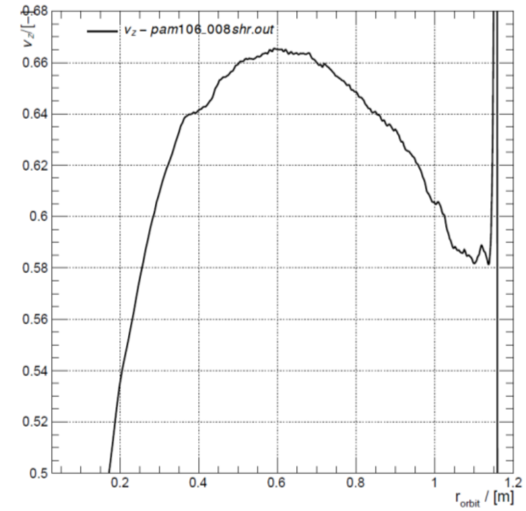
Beam energy vs. radius

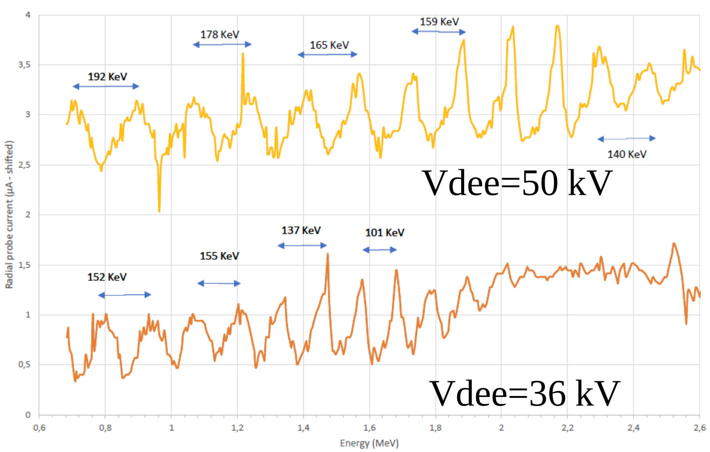


Horizontal focusing: ν_r



Vertical focusing: ν_z

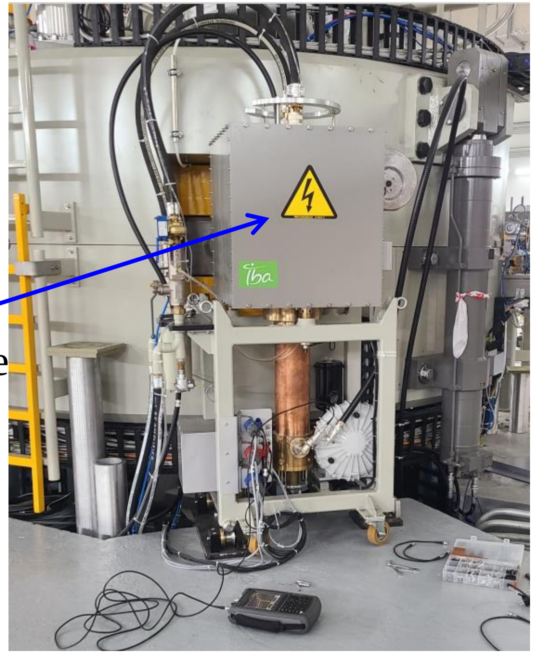




Radial probe measurement, June, 2022

RF system of 70 MeV cyclotron

LLRF → Solid State Amp. (5 kW) → Final Power Amp. (100 kW)



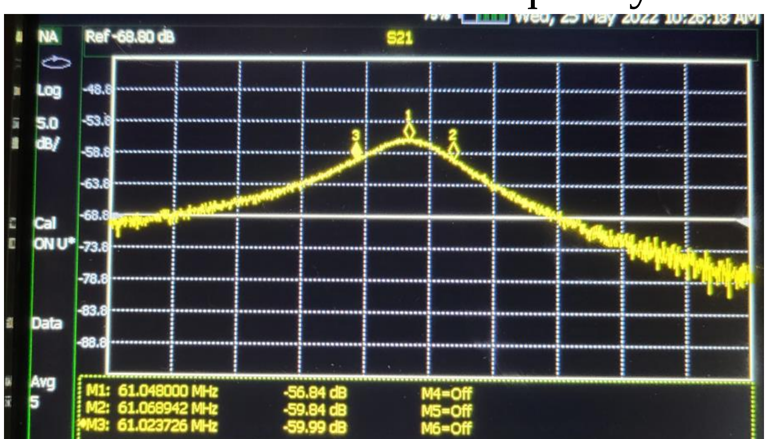
Vacuum tube inside
(tetrode, Thales)

Two dees

Quality factor

$$Q \stackrel{\text{def}}{=} \frac{f_r}{\Delta f}$$

S21 : resonance frequency



50 Ω impedance matching (Smith chart)

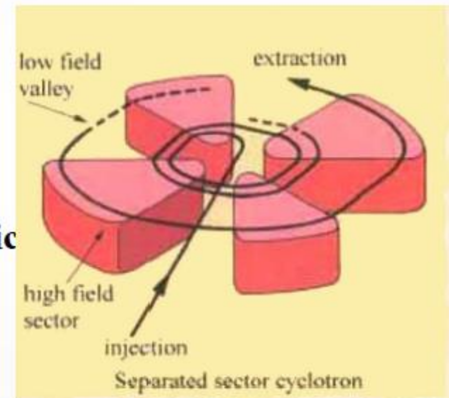
Separated-sector 590 MeV proton cyclotron at PSI (Switzerland)

I: > 2 mA (world highest power CW accelerator)

- ❖ First proposed by Hans Willax (1962) for the Swiss meson factory - a 590-MeV proton ring cyclotron
- ❖ **In separate-sector cyclotrons:**
  - ➢ **sectors have individual yokes & coils**
  - ➢ **the valleys are magnetic field-free**
  - • **available for rf, injection, extraction & diagnostic**
- ❖ **Small pole gaps need less amp-turns**
  - ➢ **give hard-edge fields**
  - • **the flutter, $F^2 = H^{-1} - 1$ can reach ~1**

(where H = hill fraction),

  - ➢ **Makes possible β©<1 (~400 MeV /u) with radial sectors).**
- ❖ **Needs a medium-energy injector**



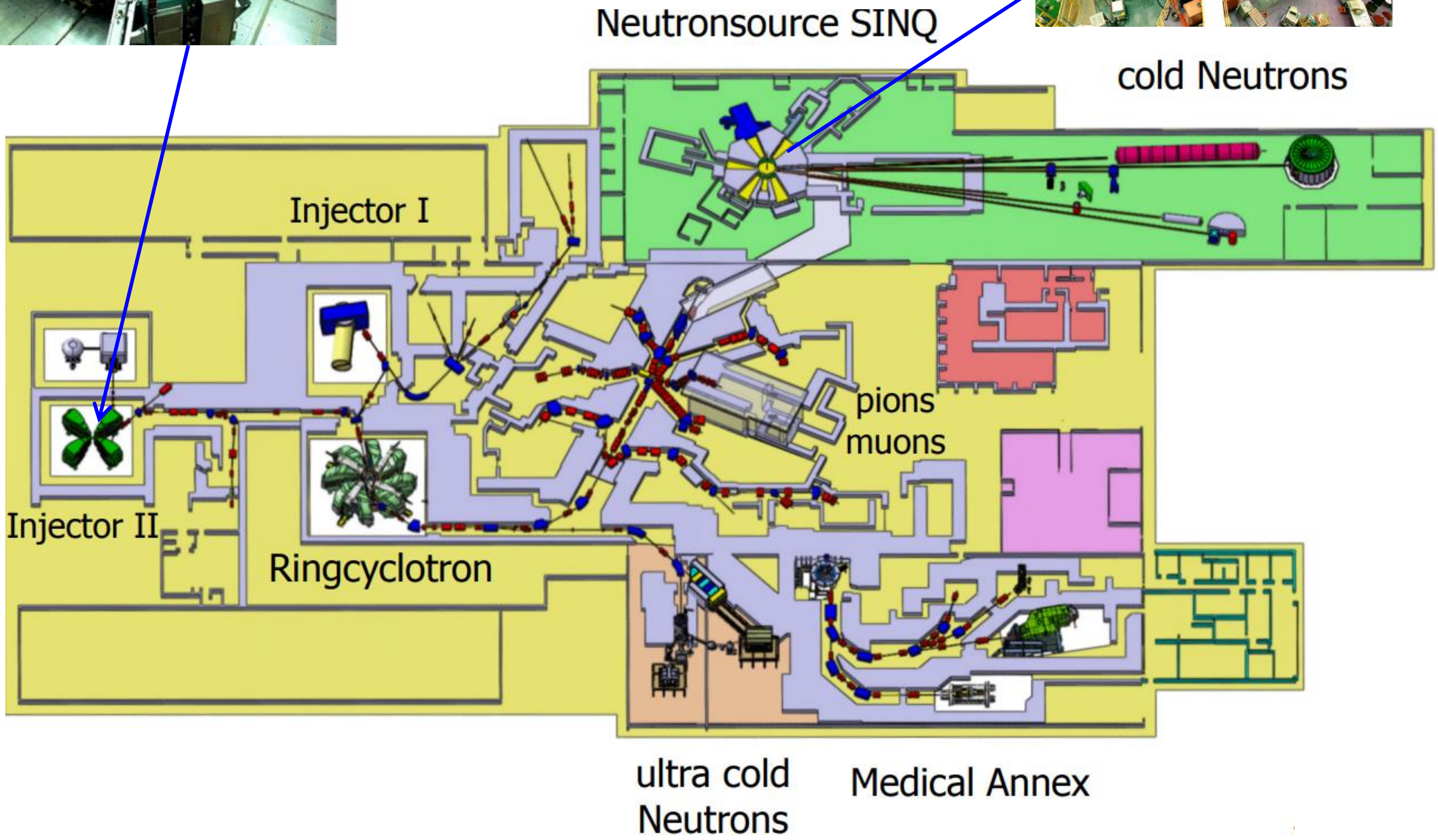
-Spallation neutron source
-Muon production

High efficiency (~40%)
Very low losses (0.01%)

Cavity voltage: ~900 kV
Extraction efficiency: 99.99%

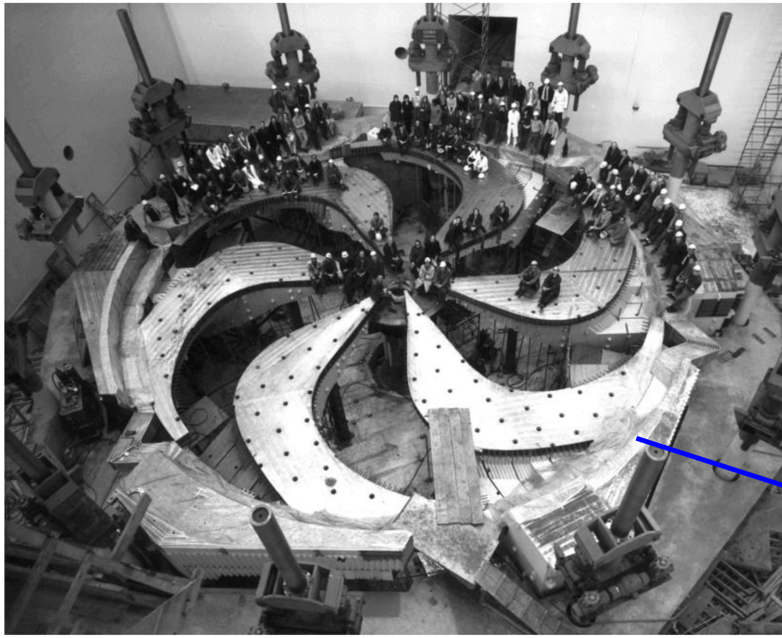
PSI facility layout

Neutron Spallation Source



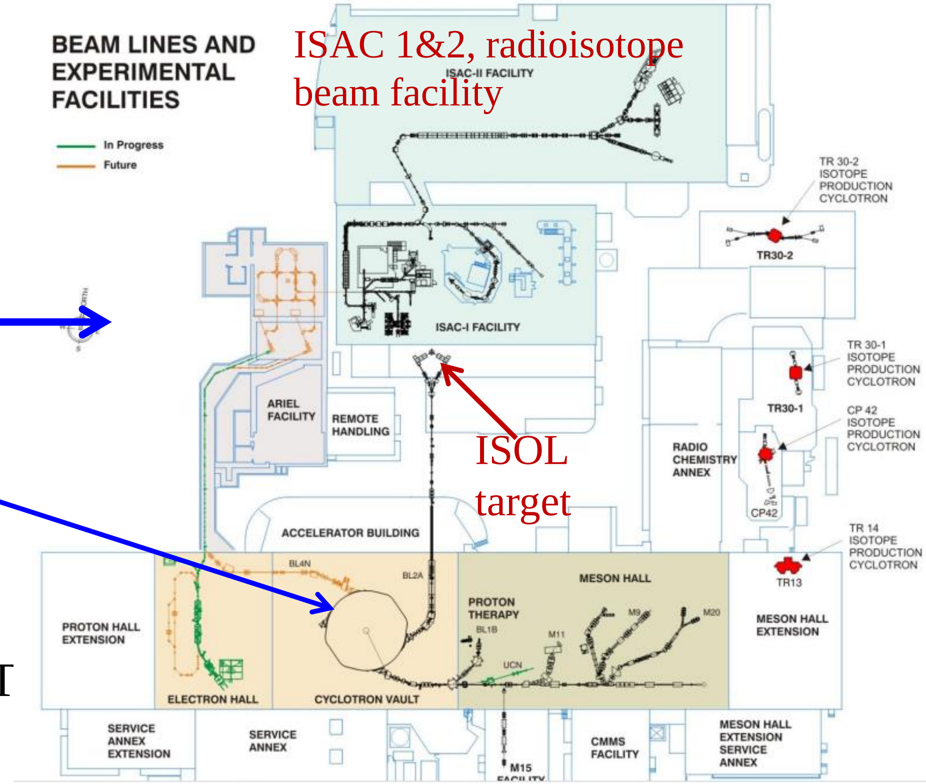
TRIUMF (Canada) 520 MeV H^- Cyclotron

Commissioned in Feb. 1976



18m diameter, 4000 tons, $B_{avg,\,max}$= ~0.46T

Present facility



$$\nu_z^2 = n + \frac{N^2}{N^2-1} F\,(1 + 2\tan^2 \xi)$$

Spiralling is now used for most isochronous cyclotrons over 40 MeV and has enormously increased the energies attainable with high-current cw beams:

- TRIUMF: 70 – 520 MeV H^-, 250 μA (→ 450 μA);

- providing 1000× more intense beams for π, μ, n & RI production;

Superconducting ring cyclotron (SRC) at RIKEN

Largest heavy-ion superconducting cyclotron

350 MeV/u = 2600 $(87/238)^2$; $^{238}U^{87+}$

K = 2,600 MeV
Self Magnetic Shield
Self Radiation Shield
3.8T (240 MJ)
18-38 MHz
8,300 tons

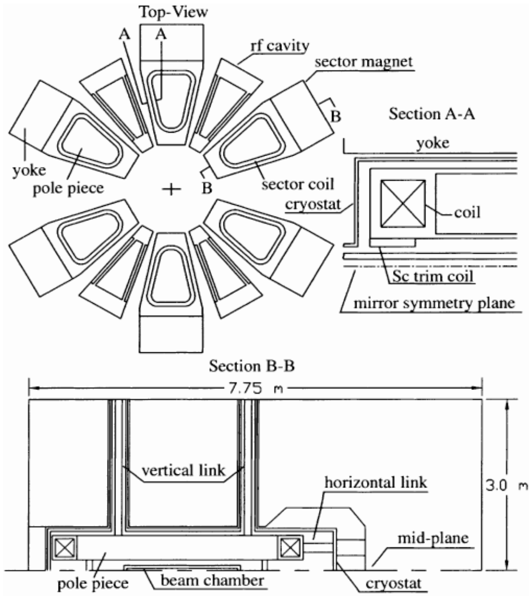
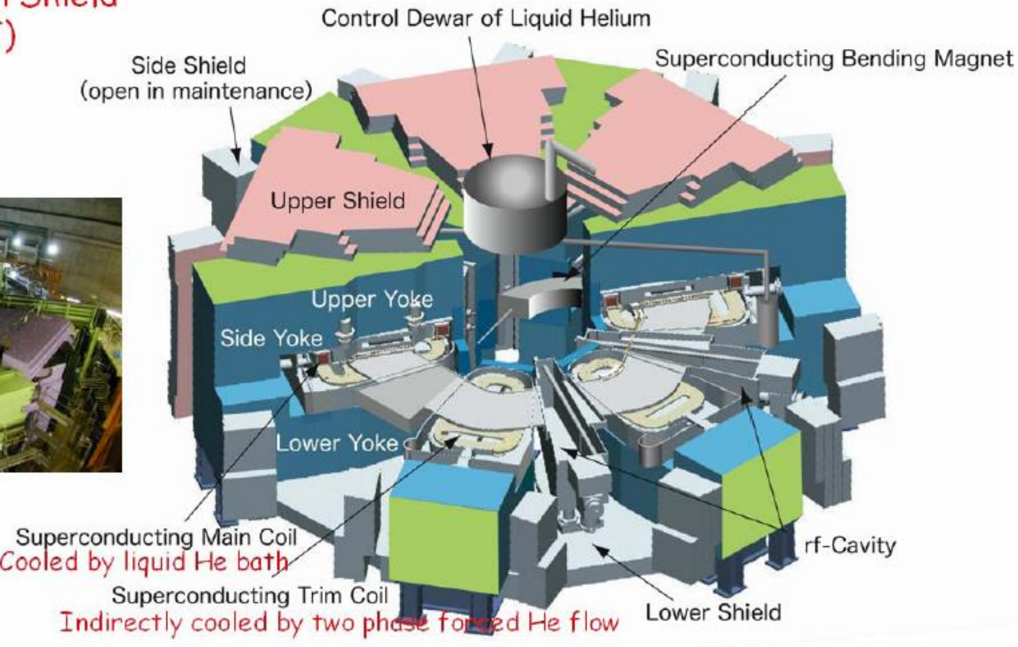


Fig. 1. Schematic top view of a six-secto cyclotron and cross-sectional views on the prototype sector magnet for the SRC with global dimensions given.

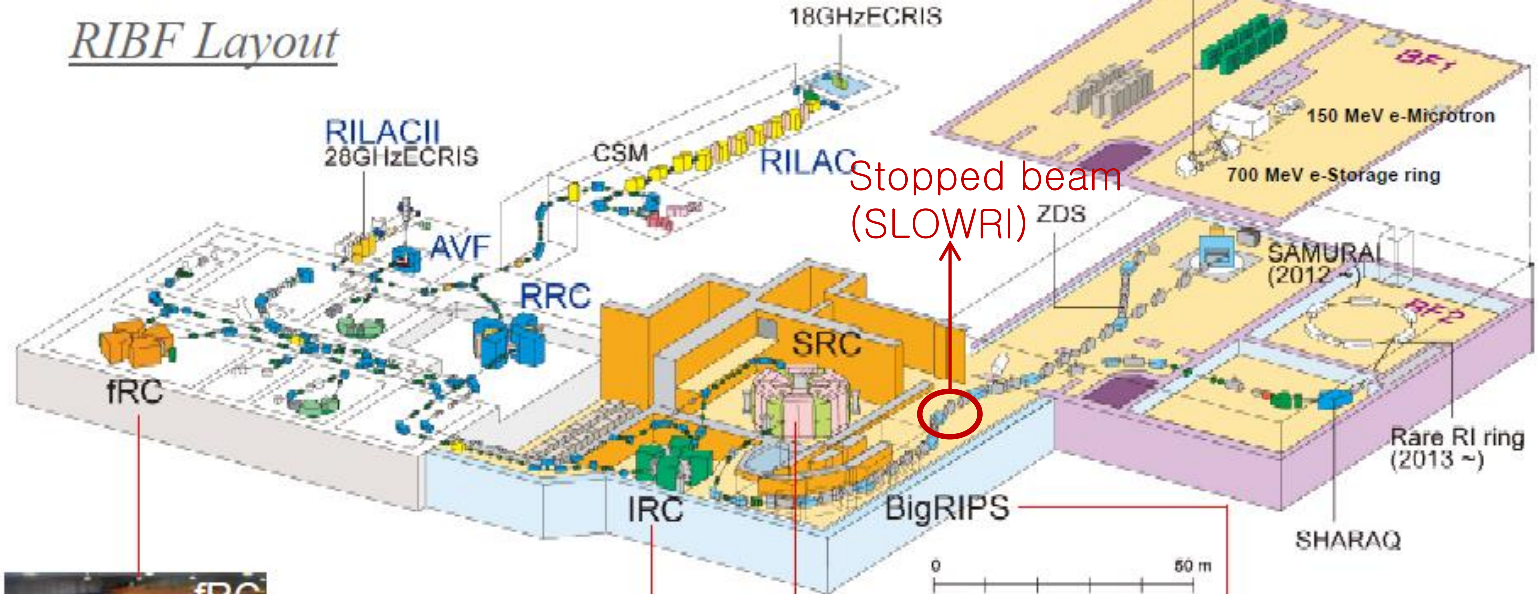


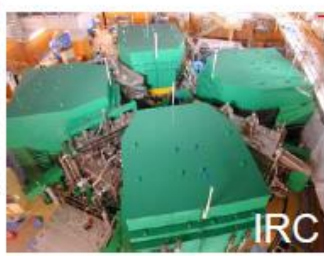
- Cold mass: 142 tons (Stainless steel: 101 tons, Aluminum: 41 tons)

→ 3 weeks to cool down to 4.5 K

RIBF (RI Beam Factory) at RIKEN

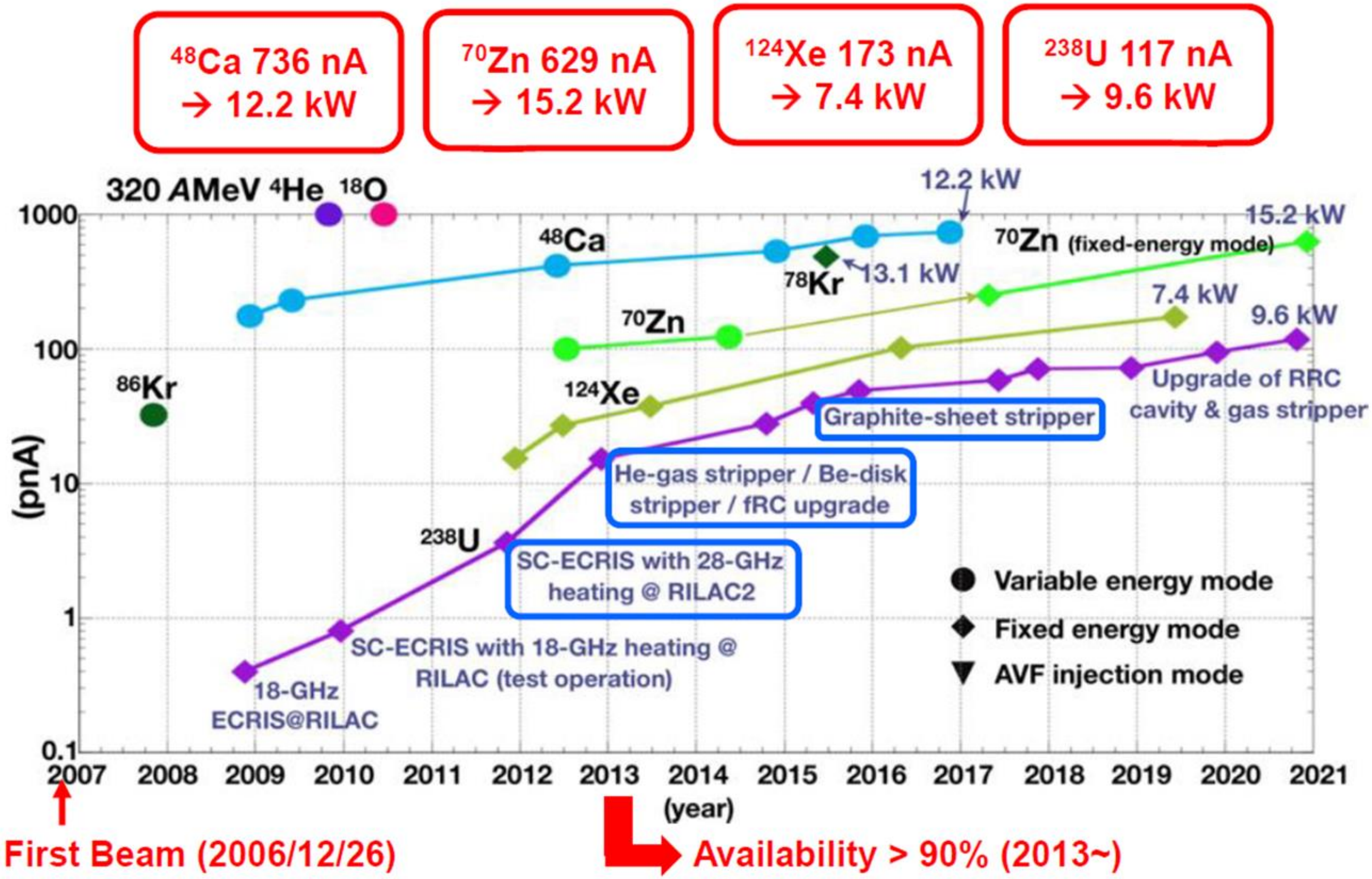
SRC: All ions @345 MeV/u
BigRIPS: RI beams via In-flight U Fission or
Projectile Fragmentation





Fixed-frequency Ring Cyclotron for U acceleration (RRC-fRC-RRC) , K=570 MeV

Heavy ion beam acceleration at RIBF



From H. Okuno, Snowmass Workshop (Aug. 2021)

Synchro-cyclotron

- For B = constant, to maintain synchronism

$$f_{rf} \sim 1/\gamma(t)$$

- The energy for an ion of charge Z follows from $\frac{1}{r} = \frac{ZeB}{cp}$

Ex: Lawrence's 184-in cyclotron 1946 → 1987

R_{max} = 2.337 m

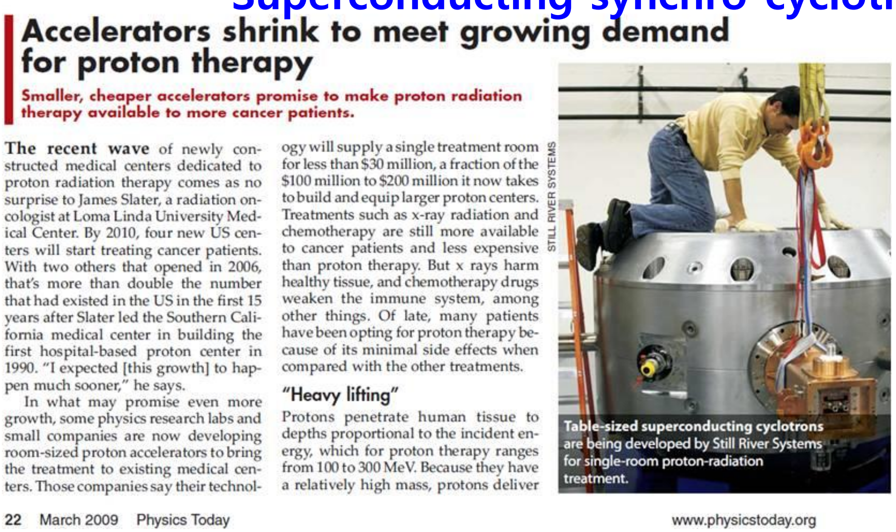
B = 1.5 T

$M_{yoke} \approx$ 4300 tons !!

But this requires pulsed rather than CW operation
(one bunch in the machine at a time)

==> Average current is reduced by the number of turns to full energy (~1000x) to ~ 0.1 μA

Superconducting synchro-cyclotron for proton therapy (2009)



Accelerators shrink to meet growing demand for proton therapy

Smaller, cheaper accelerators promise to make proton radiation therapy available to more cancer patients.

The recent wave of newly constructed medical centers dedicated to proton radiation therapy comes as no surprise to James Slater, a radiation oncologist at Loma Linda University Medical Center. By 2010, four new US centers will start treating cancer patients. With two others that opened in 2006, that's more than double the number that had existed in the US in the first 15 years after Slater led the Southern California medical center in building the first hospital-based proton center in 1990. "I expected [this growth] to happen much sooner," he says.

In what may promise even more growth, some physics research labs and small companies are now developing room-sized proton accelerators to bring the treatment to existing medical centers. Those companies say their technology will supply a single treatment room for less than $30 million, a fraction of the $100 million to $200 million it now takes to build and equip larger proton centers. Treatments such as x-ray radiation and chemotherapy are still more available to cancer patients and less expensive than proton therapy. But x rays harm healthy tissue, and chemotherapy drugs weaken the immune system, among other things. Of late, many patients have been opting for proton therapy because of its minimal side effects when compared with the other treatments.

"Heavy lifting"

Protons penetrate human tissue to depths proportional to the incident energy, which for proton therapy ranges from 100 to 300 MeV. Because they have a relatively high mass, protons deliver

STILL RIVER SYSTEMS

Table-sized superconducting cyclotrons are being developed by Still River Systems for single-room proton-radiation treatment.

22 March 2009 Physics Today www.physicstoday.org

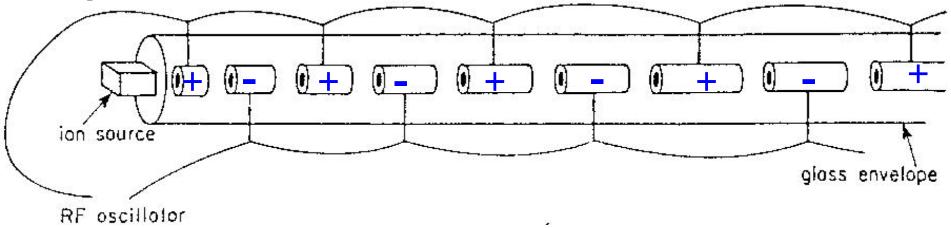
Still-river → Mevion Medical Systems

~20 tons

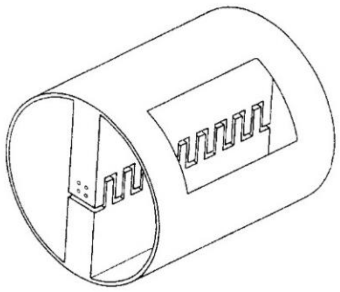
2. Linear Accelerator

- Widroe linac (Sloan–Lawrence structure, Interdigital structure)

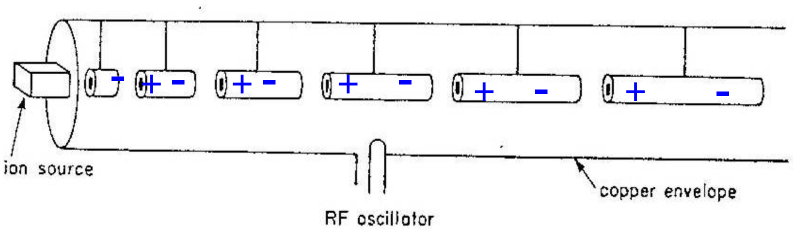
→ $\beta\lambda/2$ mode or π mode $\beta < 0.05$



Interdigital structure



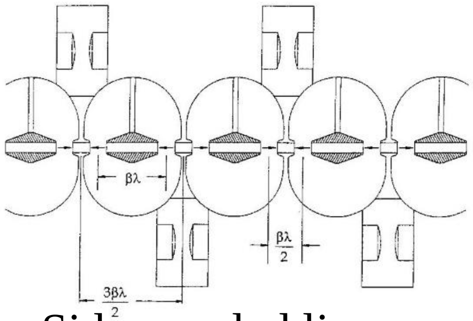
- Alvarez (DTL, drift tube linac) → $\beta\lambda$ mode or 2π mode



-for proton and heavy ions

-$0.05 < \beta < 0.5$

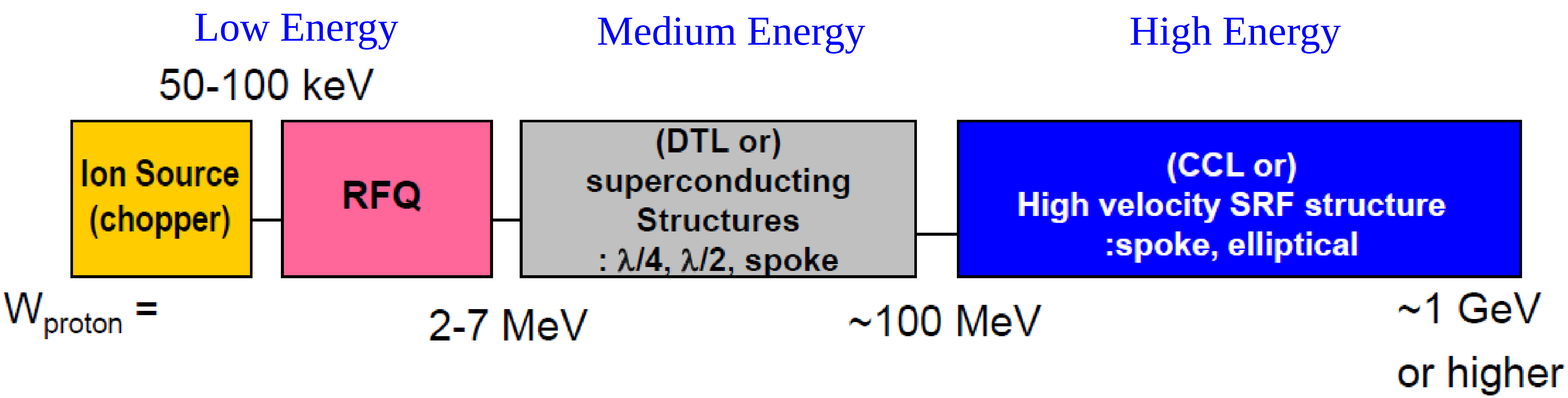
- Coupled Cavity Linac (CCL)



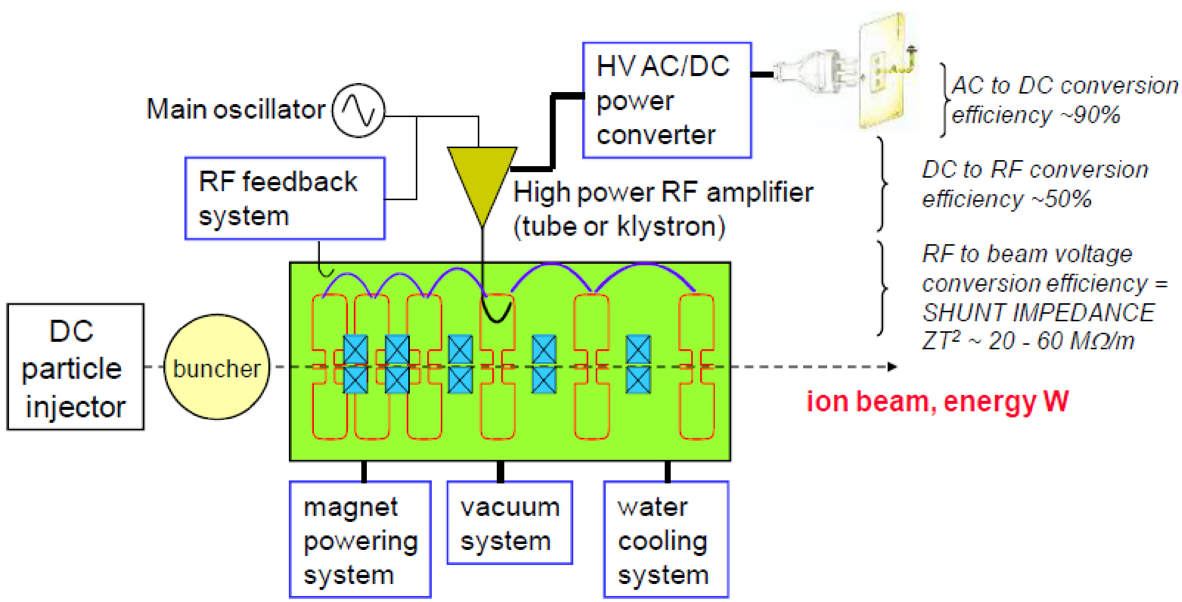
Side coupled linac

- Linear array of resonant cavities
- $0.4 < \beta < 1$, TM_{010}-like standing-wave
- two gaps per $\beta\lambda$
- Good in 90-180 MeV (max. duty-cycle 10-15 %)

A typical layout of ion linac



Schematic view of a linac system



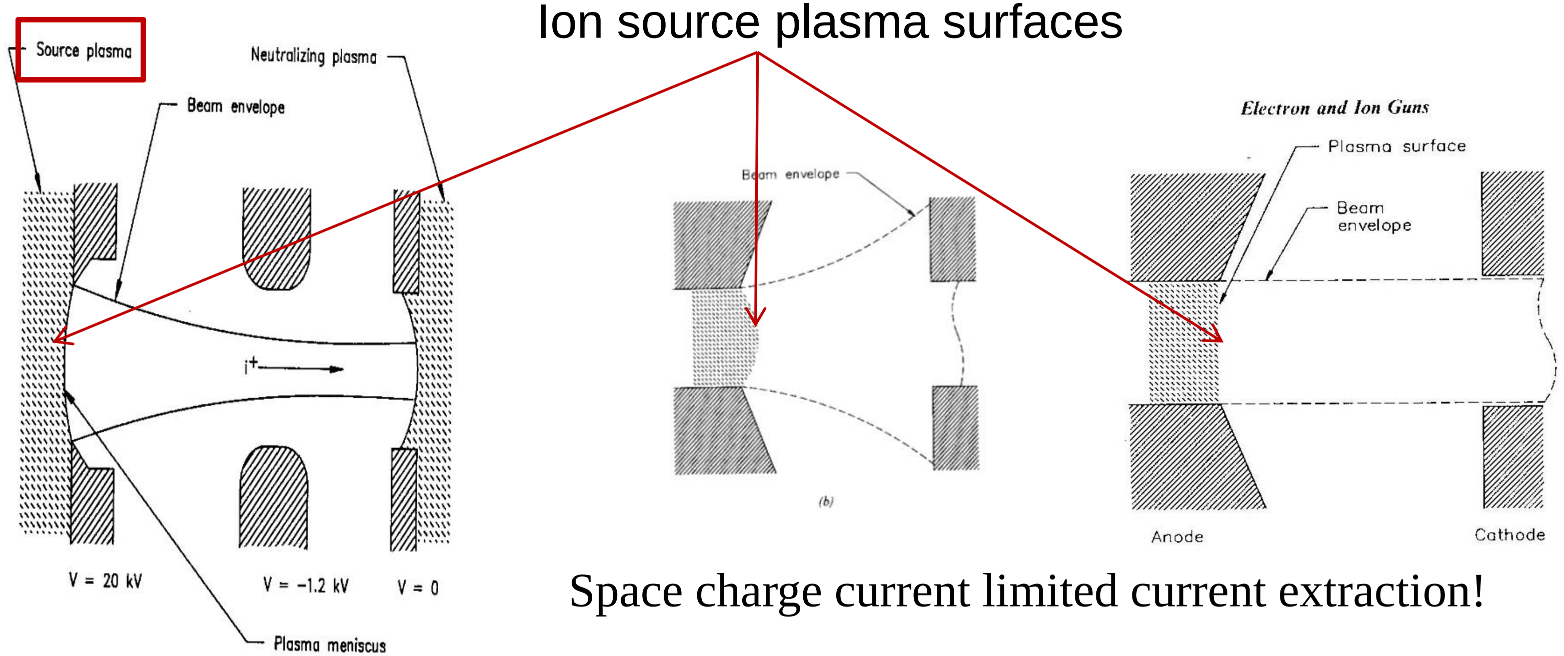
Ion Source Basics

1. Proton: Plasma source, PIG (Penning Ion Gauge), ECR (Electron Cyclotron Resonance), multi-cusp ion source (H^-)
2. **Heavy ion: ECR**

The ion source (*better:* ion gun!) is composed of

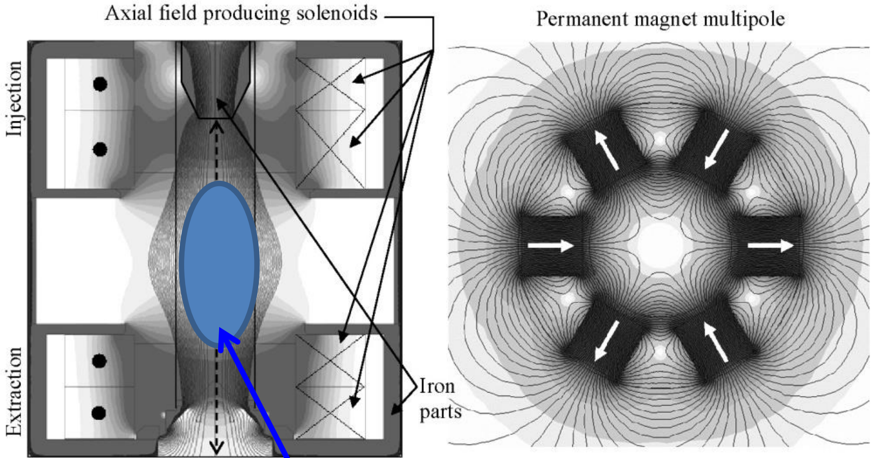
- A plasma source (generator): to provide ionized particles.
- An acceleration system ('extractor') to bring particles up to speed *and* to form a particle beam.

Ion source plasma surfaces

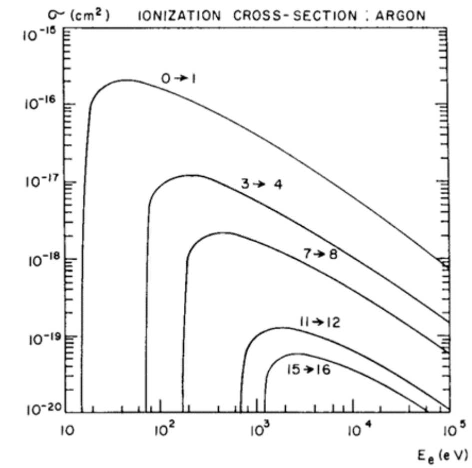


Space charge current limited current extraction!

ECR Ion Source for high current in highly-charged states



Multi-step ionization

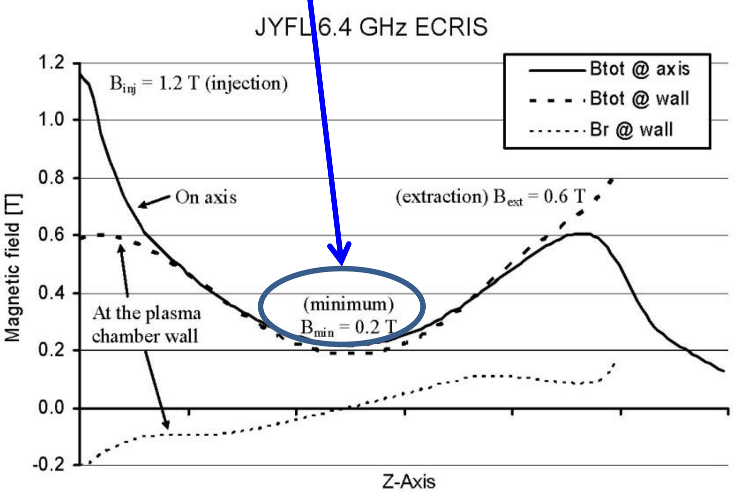


$$\omega_f = \omega_c = \frac{eB}{m_e}$$

ω_f: rf frequency

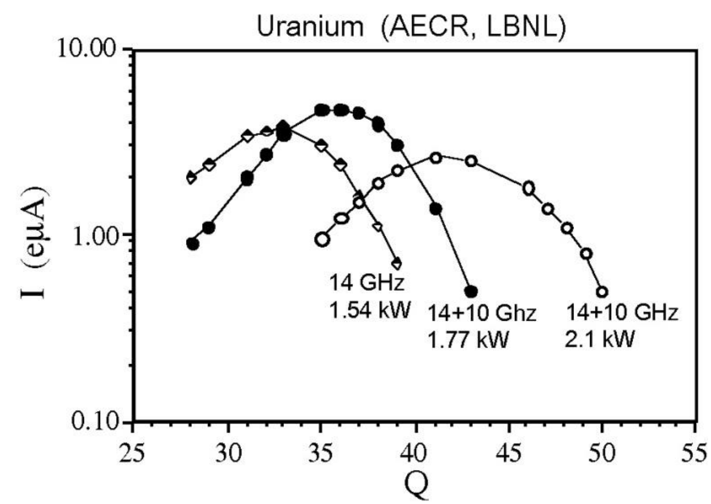
ω_c: Electron cyclotron resonance

Plasma volume



Electron cyclotron resonance 0.23 T → 6.4 GHz

Semi empirical "Scaling law" $I_q \sim f^2$



Higher Magnetic mirror fields

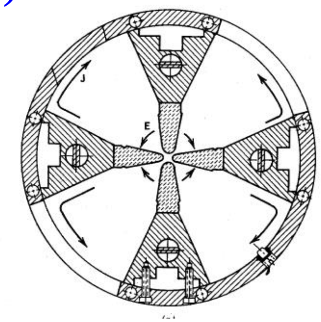
→ rf freq. increase: 14 GHz → 18 GHz → 30 GHz

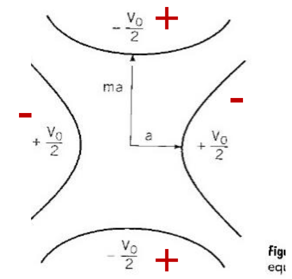
Radiofrequency quadrupole (RFQ)

Ion accelerator which can both accelerate and focus with rf fields

•Used for low velocity particles ($0.01 < \beta < 0.06$) → Sloan-Lowrence structure

-Invented by I.M. Kapchinsky and Vladimir Teplyakov (1960's): Lenin Prize in 1988
-first demonstrated by LANL (75 mA, 600 keV in 1990)





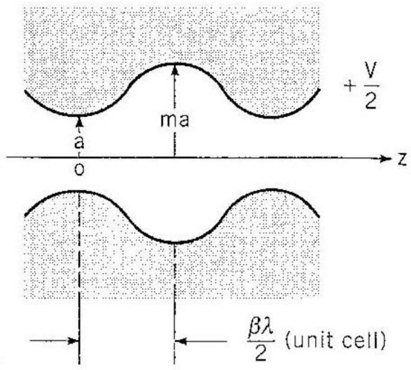
RFQ potential

$$\nabla^2\phi = \frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial}{\partial r}(r\frac{\partial\phi}{\partial r}) + \frac{1}{r^2}\frac{\partial^2\phi}{\partial\varphi^2} + \frac{\partial^2\phi}{\partial z^2}$$

Use two term potential

$$\phi = \frac{V}{2}\left[\sum_{n=0}^{\infty} A_{n0} r^{2n}\cos 2n\theta + \sum_{n=0}^{\infty}\sum_{l=1}^{\infty} A_{nl} r^{2n} I_{2n}(lkr)\cos 2n\theta\cos lkz\right]$$

$$= \sim \frac{V}{2}\left[A_{10}r^2\cos 2\theta + A_{01}I_{20}(kr)\cos 2\theta\cos kr\right]$$



$$E_r = -\frac{\partial\phi}{\partial r} = -VA_{10}r\cos 2\theta - \frac{Vk}{2}A_{10}I_{21}(kr)\cos kz$$

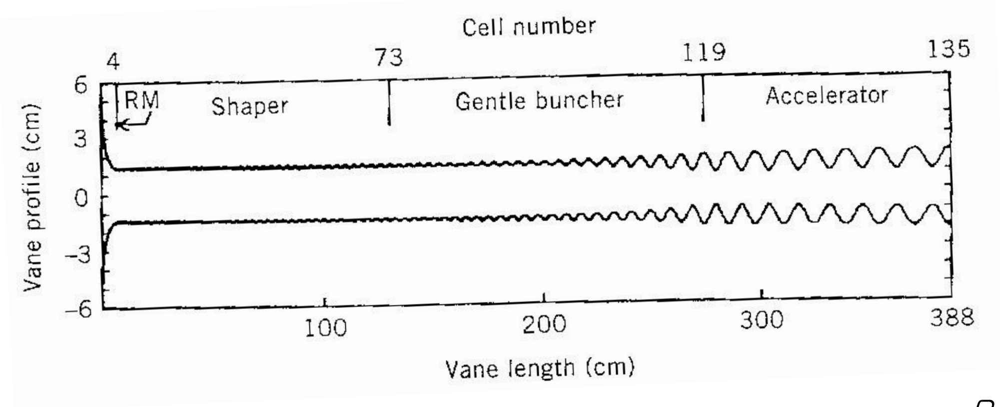
$$E_\theta = -\frac{\partial\phi}{r\partial\theta} = VA_{10}r\sin 2\theta$$

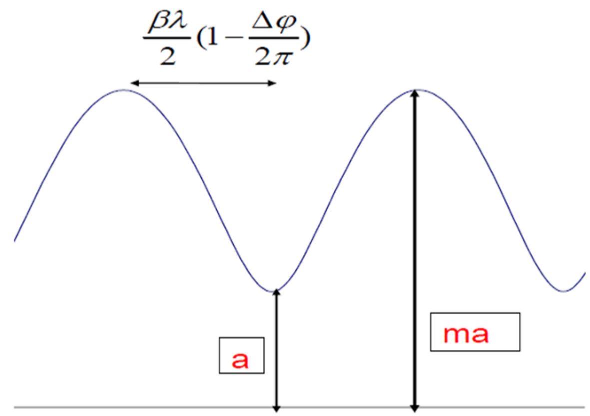
T_{210} : quadrupole electric field

$$E_z = -\frac{\partial\phi}{\partial z} = \frac{Vk}{2}A_{01}I_{20}(kr)\sin kz$$

RFQ vanes, field polarity and modulation parameters

Vane structure of the RFQ





H^+, V_o=50 kV, f=400 MHz → λ=0.75 m

$$B = \frac{q}{A}\frac{eV_o}{m_o c^2 \gamma}\frac{\lambda^2}{r_o^2} = \frac{50x10^3}{938x10^6}\left(\frac{0.75}{r_o}\right)^2$$

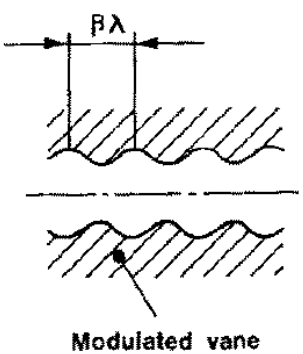
=7.5 (r_o=2 mm)

= 3.3 (r_o=3 mm)

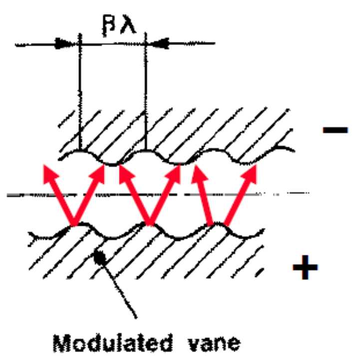
Eq. of motion: Mathieu's equation

$$\beta^2\lambda^2\frac{d^2x}{dz^2} = (B\sin(kz)+\Delta)x \qquad x(z) = X(z)\sqrt{\beta(z)}$$

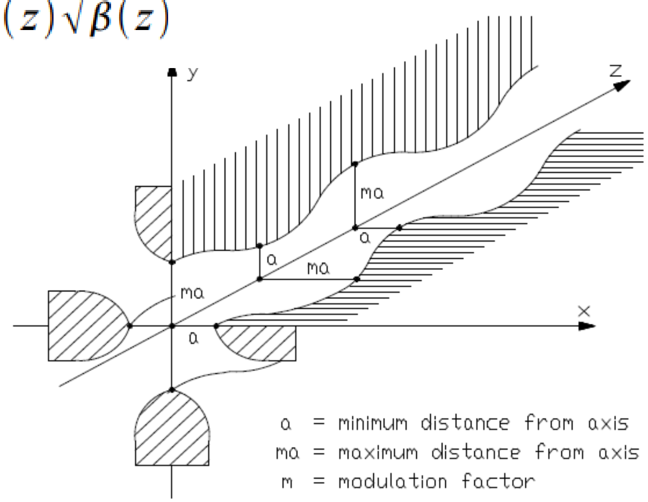
ωt→ kz



Opposite vanes (180°)

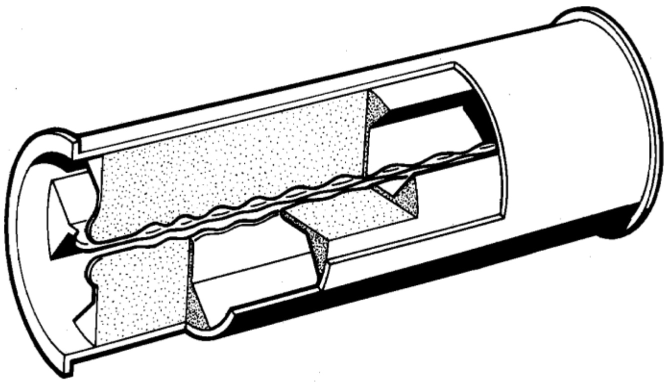


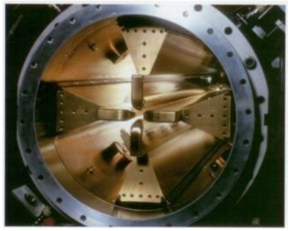
Adjacent vanes (90°)



RFQ structures

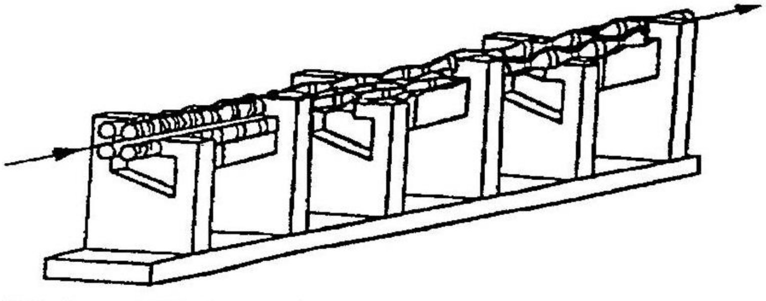
1. 4-vane structure

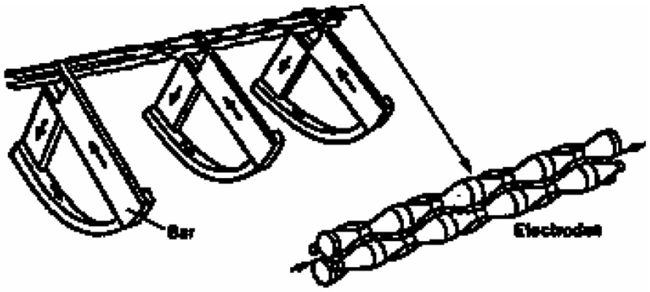




LANL, LEDA, 100mA,CW 350 MHz
INFN, Trasco (p): 352.2MHz
SNS: 402.5 MHz

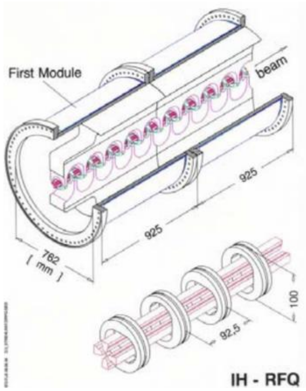
2. 4-rod structure for heavy ions





3. IH structure

GSI-HIS RFG

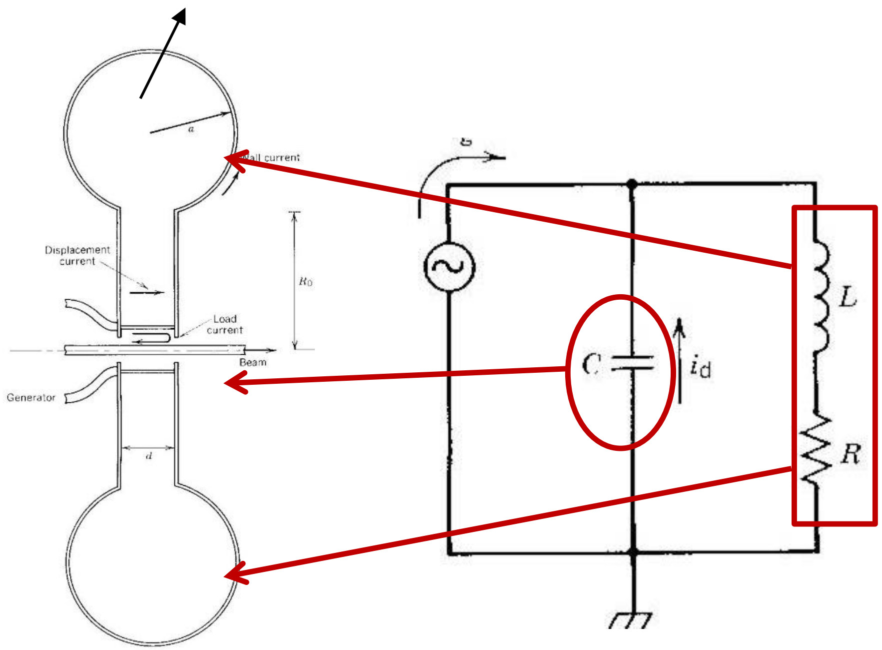


Resonator, cavity

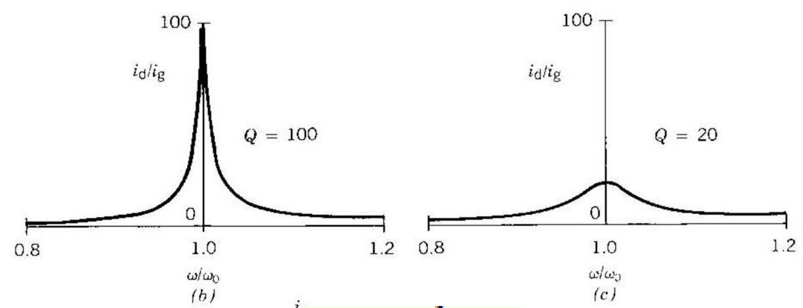
- Transform high current & low voltage (low imdepance) to high voltage & low current (high imdedance), and matches with a beam to transfer power
- Volume enclosed by metal wall that supports an electromagnetic oscillation

  Electrical field: acceleration Magnetic field: inductive isolation (cavity is a short circuit)

single-turn inductor



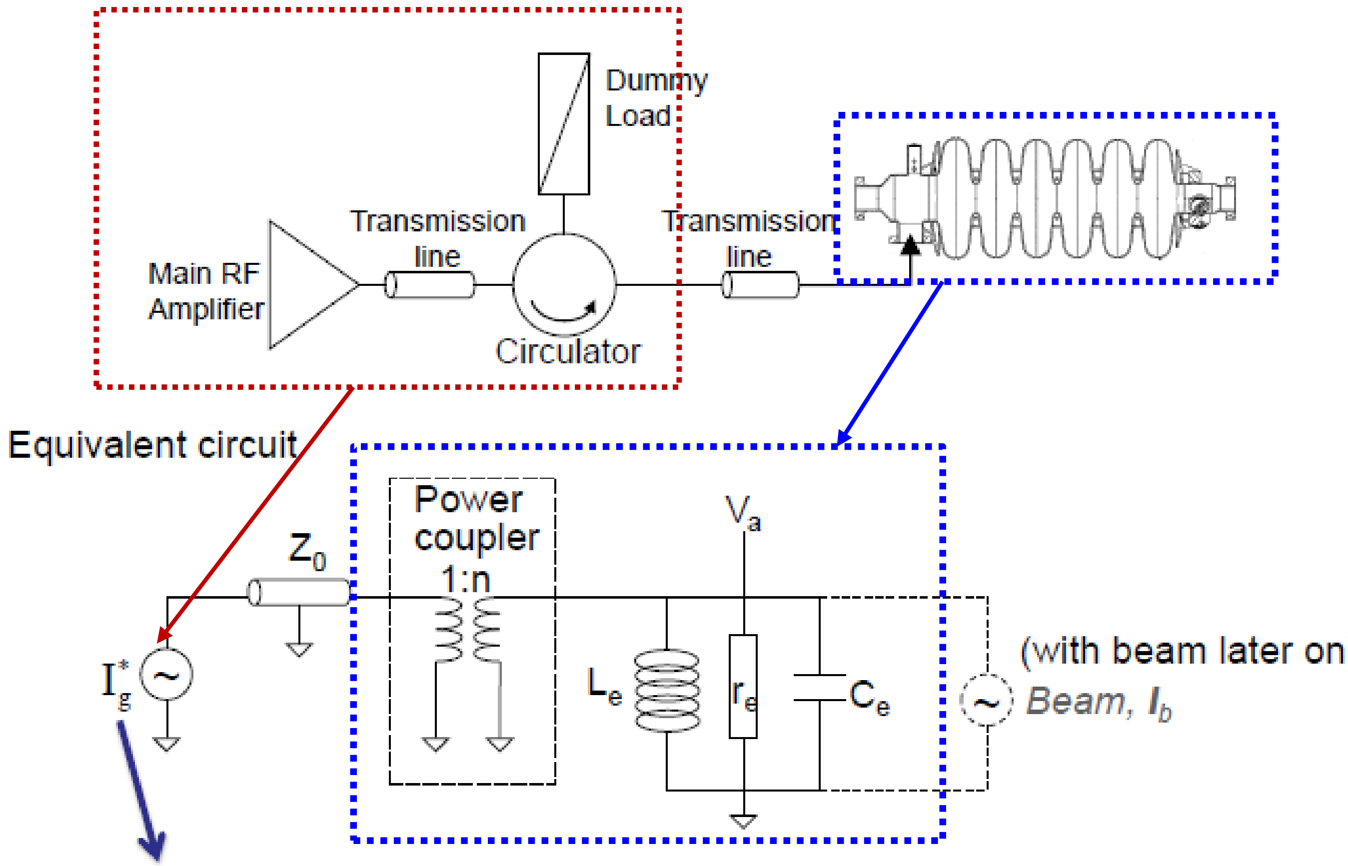
Reentrant cavity



$$f = \frac{1}{2\pi\sqrt{LC}}$$

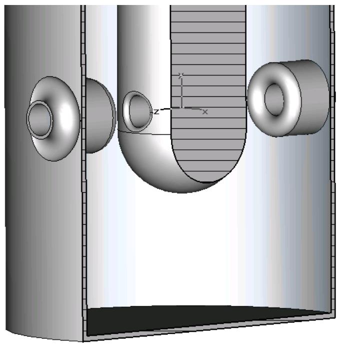
RF power supplies

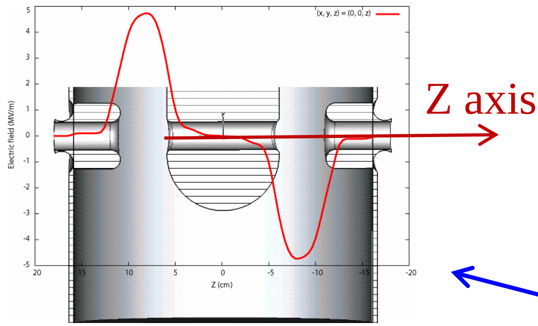
First, main high power RF circuit and cavity responses without beam.

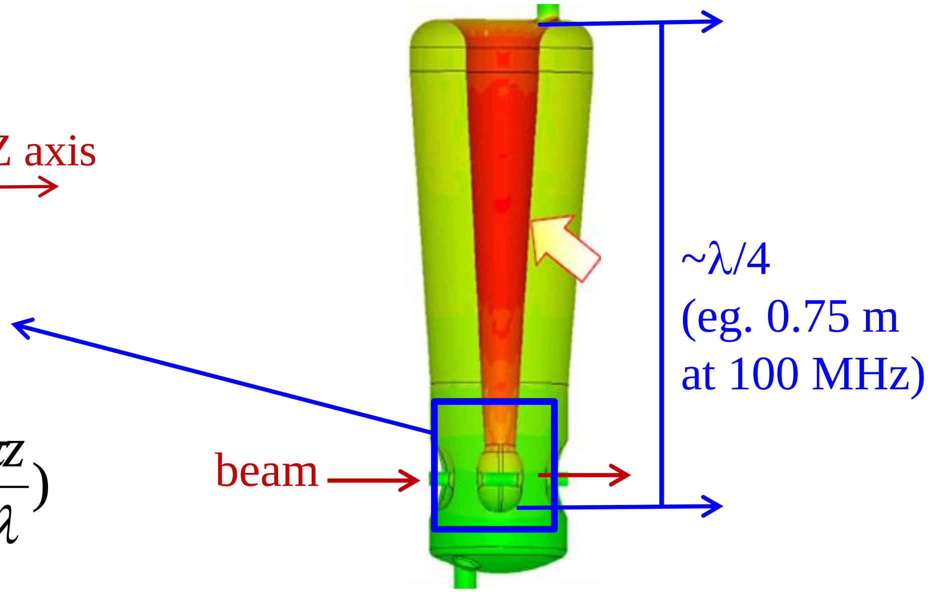


Due to the circulator, this is not an exactly equivalent for generator current.
So introduced I_g^* → twice of equivalent generator current.

Electric fields in quarter wave resonator (QWR)







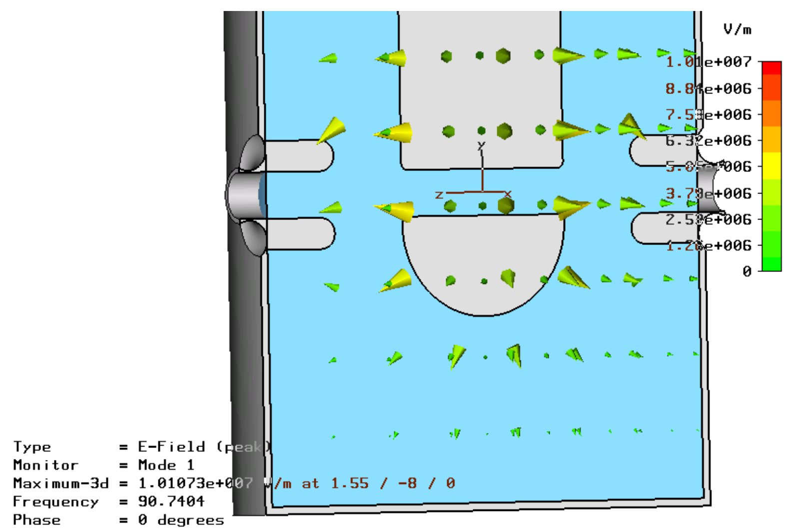
$$E_{z0}(r,z,t) = \frac{A_0}{2} I_0(k_0 r)\cos\left(\omega t - \frac{2\pi z}{\beta\lambda}\right)$$

$$\frac{\Delta T}{T} \approx 2\left(\frac{\pi r}{\beta\lambda}\right)^2$$

r: radius of beam

f=24 MHz, β=0.004
βλ= 5 cm
R= 0.4 cm
E= 4.5 MV/m
L=10 cm
ΔT~45 keV

The beam energy spreads significantly degrade beam quality!



Different cavity (resonator) structures for different β

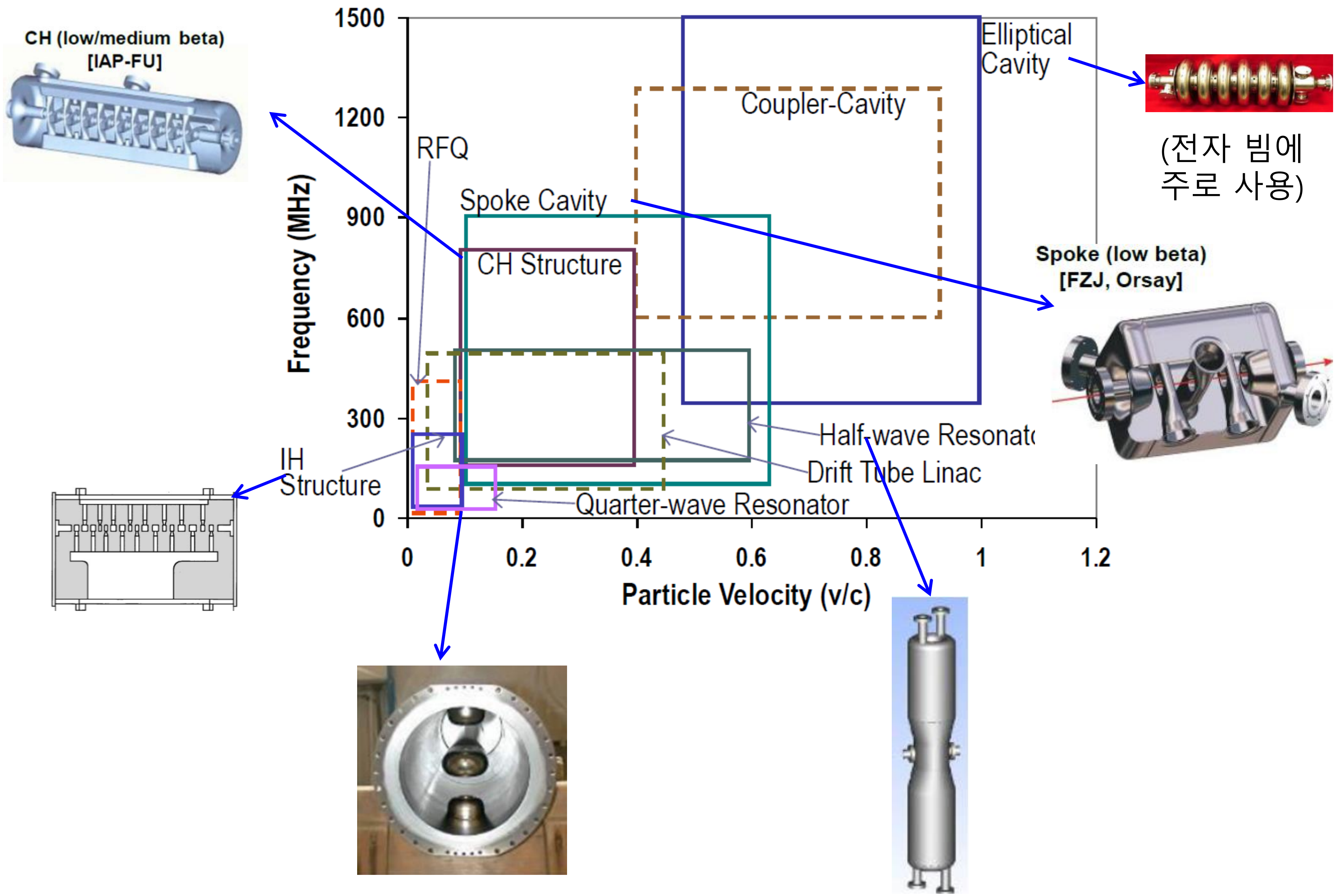


Figure of merit for cavity

Shunt impedance per unit length r: is a measure of the accelerating quality of a structure

Shunt impedance $$R_a = \frac{V_c^2}{P_c}$$ → To get maximum acceleration, maximize shunt impedance

Measure of how much acceleration one gets for a given power dissipation

$$\frac{R_a}{Q_0} = \frac{V_c^2}{\omega_0 U}$$

independent of size and material of cavity
only dependent of cavity shape

For pill-box cavity, $\frac{R_a}{Q_0} = 196\ \Omega$

Accelerator operation requirement

Power dissipation $$P_c = \frac{V_c^2}{R_a} = \frac{V_c^2}{\frac{R_a}{Q_0} \cdot Q_0} = \frac{V_c^2}{\frac{R_a}{Q_0} \cdot G} \cdot R_s$$

Cavity material

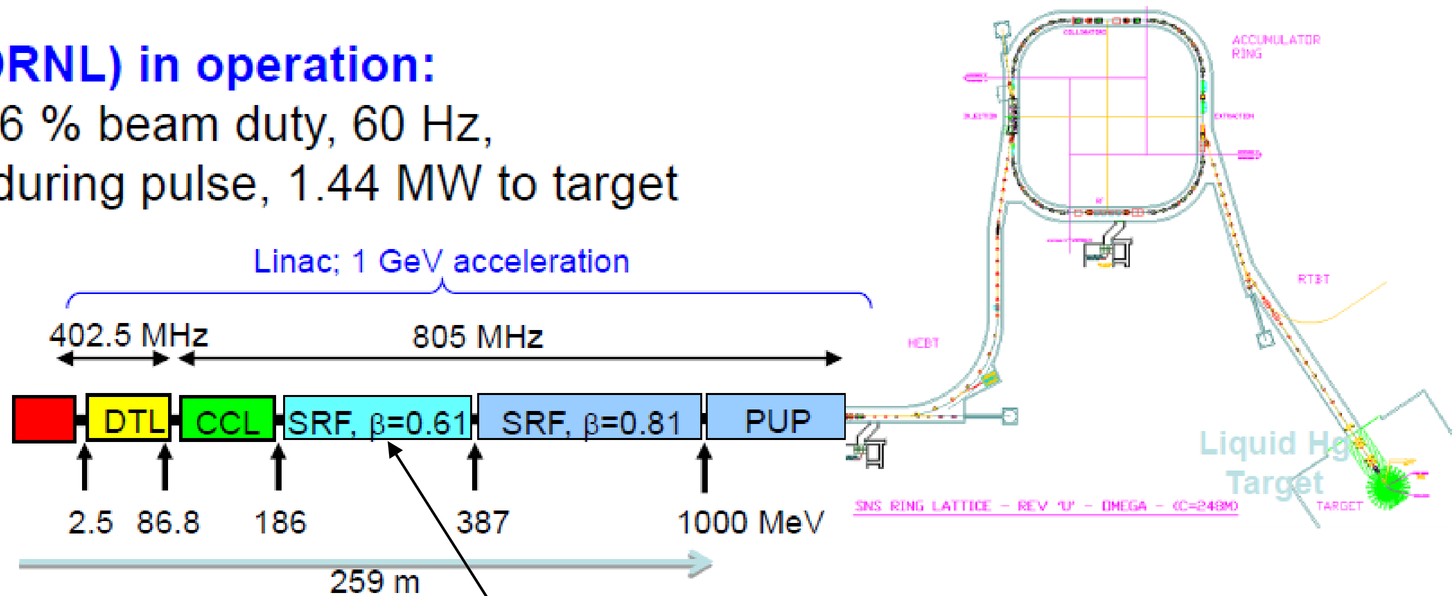
Cavity geometry

For copper cavities, power dissipation is a constraint, cavity design is driven by this fact →

Cooling matters →
- superconducting?
- cryogenic Cu?

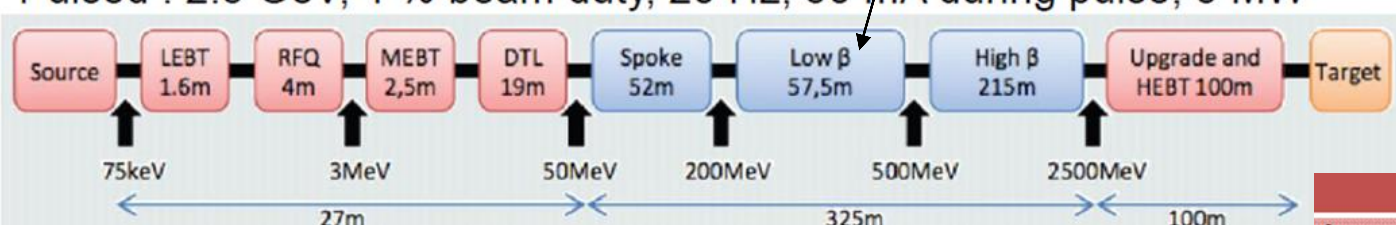
Superconducting proton linac for spallation neutron source

SNS (ORNL) in operation:
1 GeV, 6 % beam duty, 60 Hz,
26 mA during pulse, 1.44 MW to target



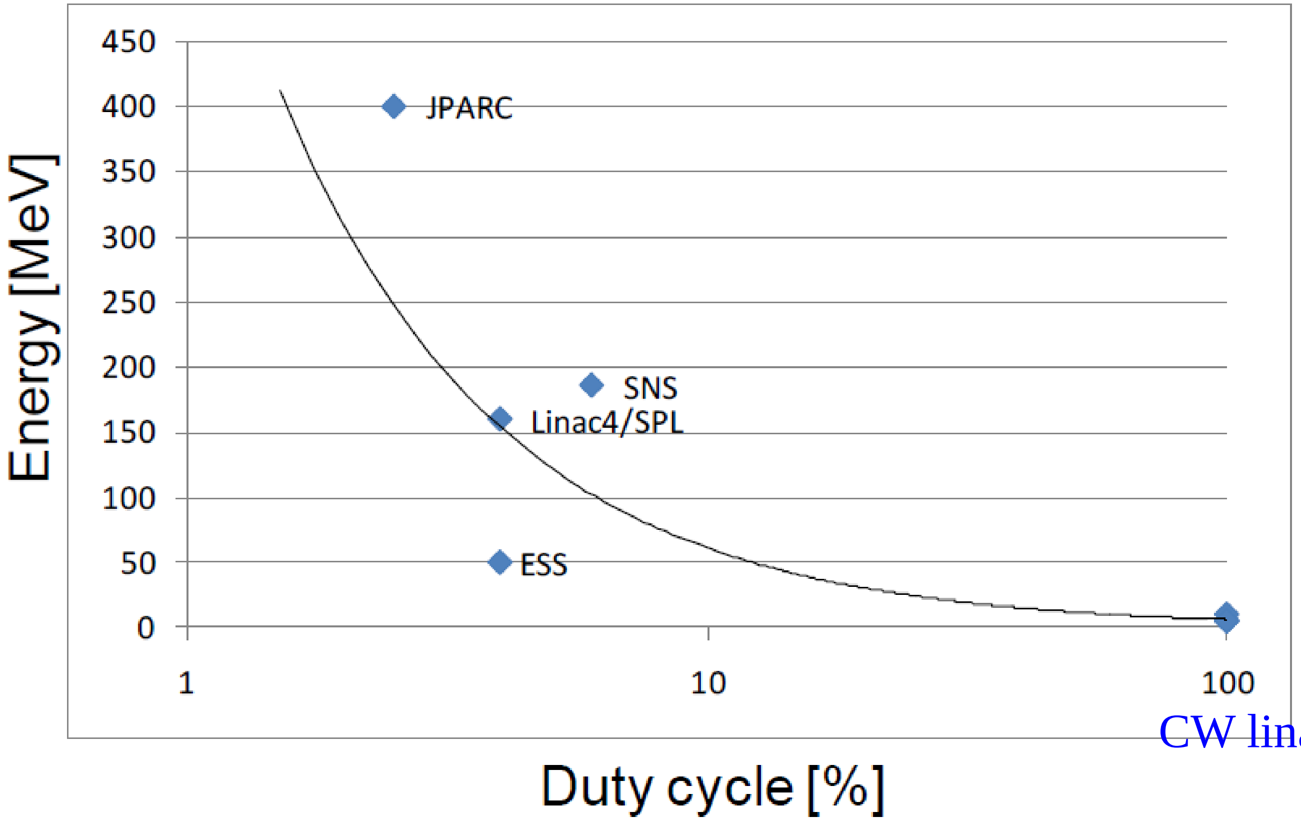
81 cavities, 805 MHz, 6 cells Solid Niobium

ESS (EU, Sweden) design:
Pulsed : 2.5 GeV, 4 % beam duty, 20 Hz, 50 mA during pulse, 5 MW



	Spoke	Medium-β	High-β
β	0.5	0.67	0.86
# CM	13	9	21
Cav. /CM	2	4	4
# Cav.	**26**	**36**	**84**

Warm cold transition for recent linac designs



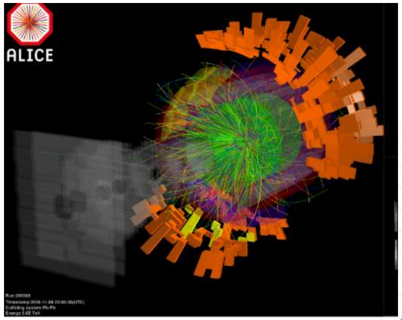
CW linac

CW: Project-X, EUROTRANS, EURISOL, IFMIF-EVEDA

CEEN accelerators for heavy-ion collision

Pb-Pb collision (2018)

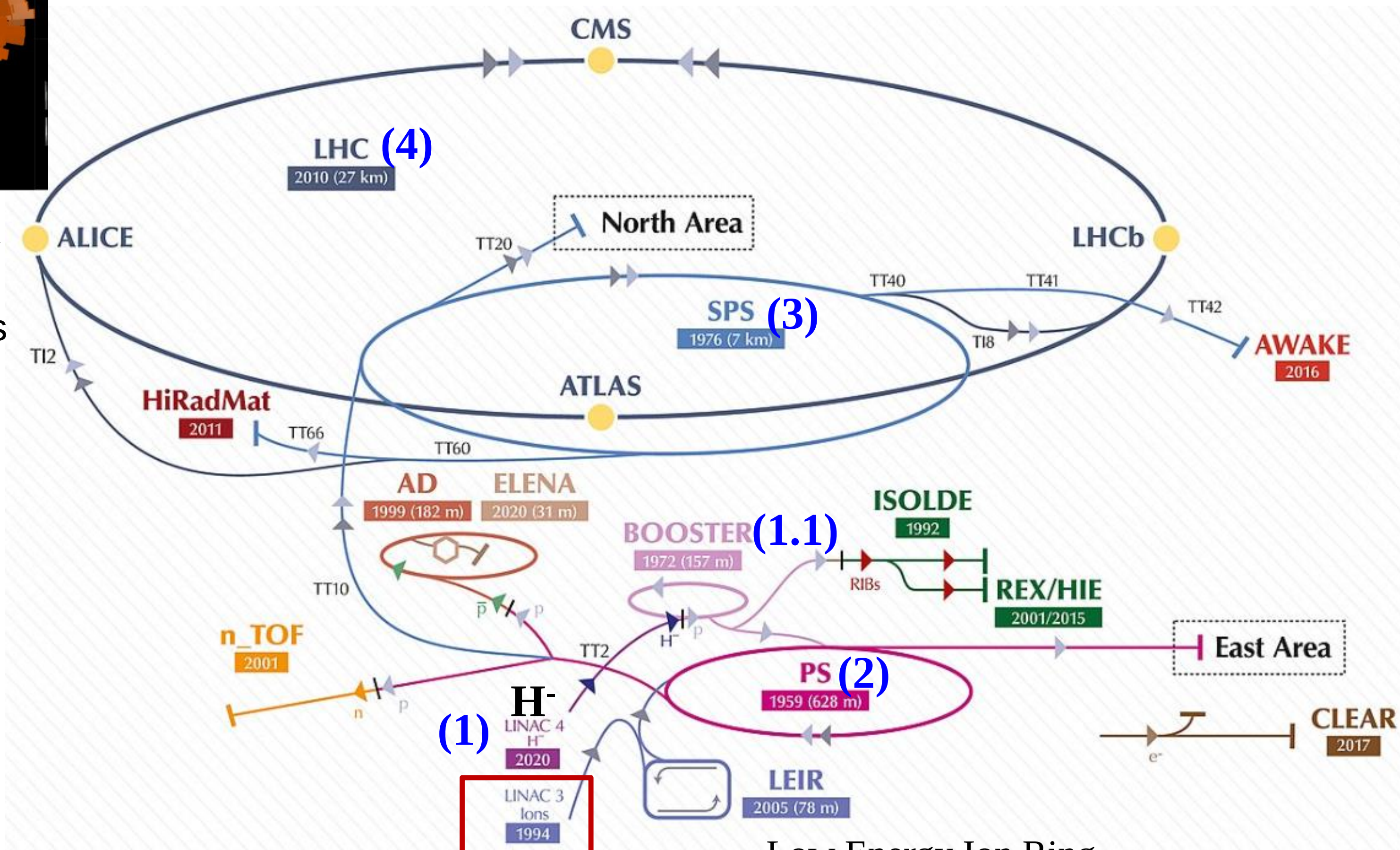
27 km ring



~3 TeV/nucleon

ultra-relativistic

heavy ion physics



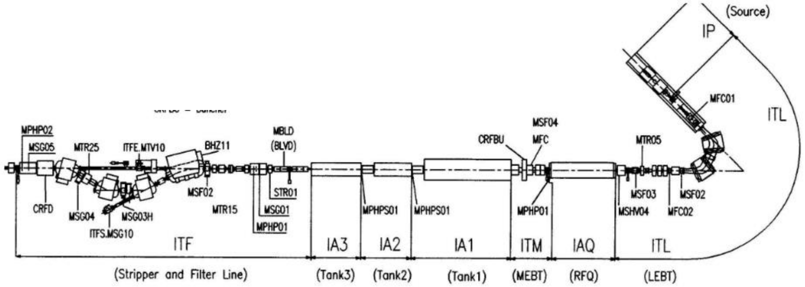
Pb, Au, Xe,..

Low Energy Ion Ring

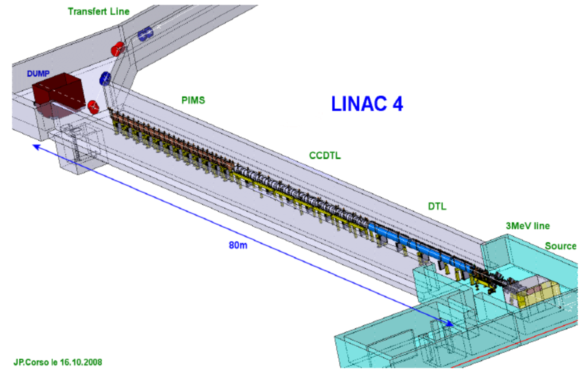
(long pulse → short pulse)

Linac3 (Pb,..) & Linac4 (H-) at CERN

- Layout of Linac3

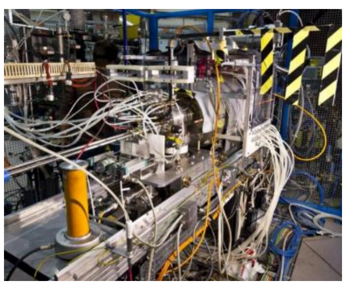


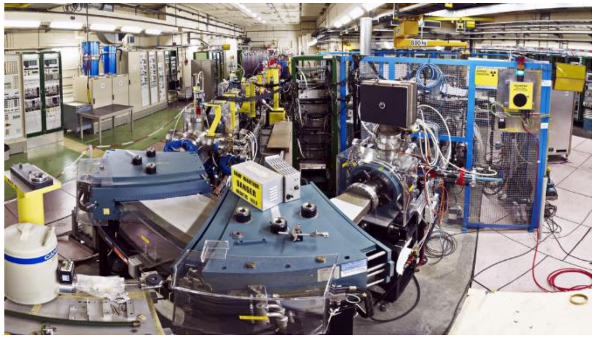
- Extraction Energy: 2.5 keV/u
- RFQ: 4rod ladder, 101.28 MHz Eout=250 keV/u
- IH Cavity 1: 101.28 MHz Interdigital Structure, Eout=1.86 MeV/u
- IH Cavity 2+3: 202.56 MHz Interdigital Structure, Eout=4.2 MeV/u
- Stripper: Carbon foil 75-125 ug/cm2.



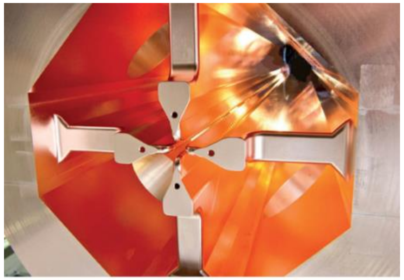
Section	Output Energy [MeV]	Number of consecutive identical cells	Distance between quadrupoles
RFQ	3	1	-
DTL	50	1	βλ
CCDTL	100	3	4 βλ
PIMS	160	7	5 βλ

14.5 GHz ECR ion source

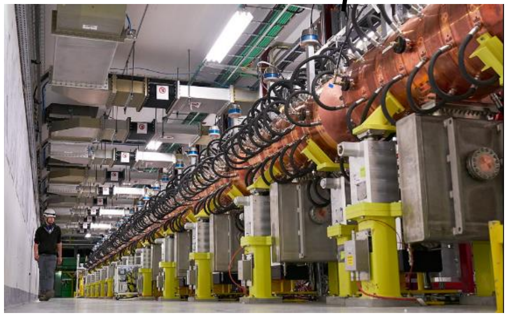




Linac4 begins with the hydrogen source, followed by the radio-frequency quadrupole (RFQ), chopper, drift-tube linac (DTL), cell-coupled DTL (CCDTL) and finally a Pi-mode structure (PIMS).

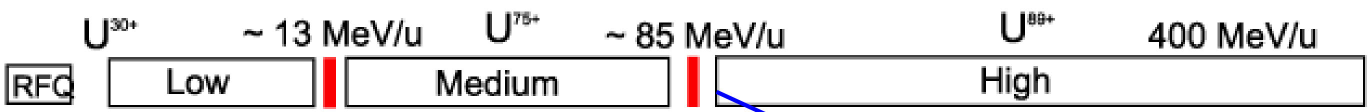


'he Linac4 radio frequency quadrupole.
mage credit: M Vretenar

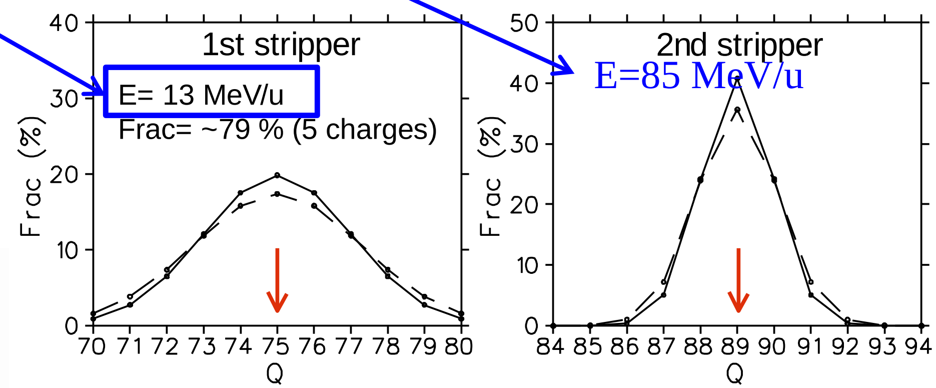


Charge stripping in heavy ion accelerators

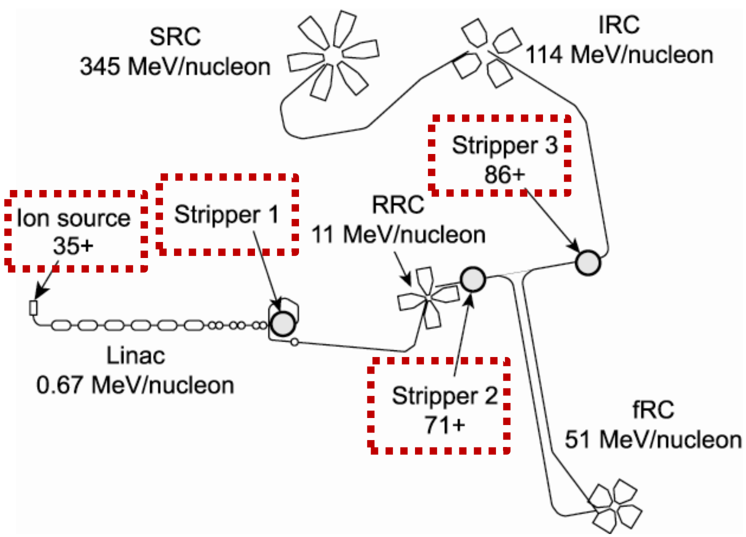
Two chrage stripping targets



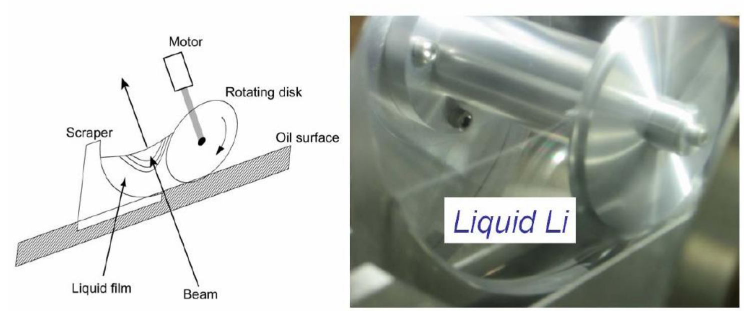
Equilibrium charge states after stripping by carbon foils



RIKEN Charge stripping scheme for a Uranium beam



Liquid Li film target for high beam power



Successfully commissioned at FRIB in Michigan State Univ. 2020

3. Synchrotron (pulsed beam)

Working principle

Ring accelerator with constant radius R,
→ variable revolution frequency ω_0 and B-Field.

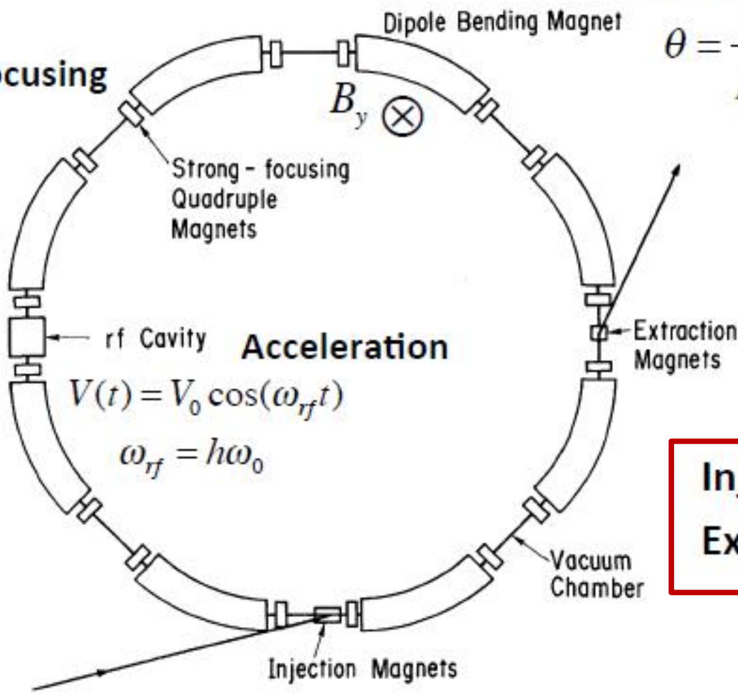
Motion in a constant, homogenous B-field ($\vec{B} = B_y \vec{e}_y$):

$$\dot{\vec{v}} = \frac{q}{\gamma m}\left(\vec{v} \times \vec{B}\right) \quad \Rightarrow \quad \omega_0 = \frac{v_0}{R} = \frac{qB_y}{\gamma m}$$ (revolution frequency)

Bending:

$$\theta = \frac{q}{p_0}\int_{s_1}^{s_2} B_y ds \approx \frac{l}{R_0}$$

Focusing



Acceleration

$$V(t) = V_0 \cos(\omega_{rf} t)$$

$$\omega_{rf} = h\omega_0$$

Rigidity:

$$B_y R_0 = \frac{p_0}{q}$$

SIS-18 Synchrotron at GSI (L=216 m)

Dipole magnets (red), quadrupole magnets (yellow)

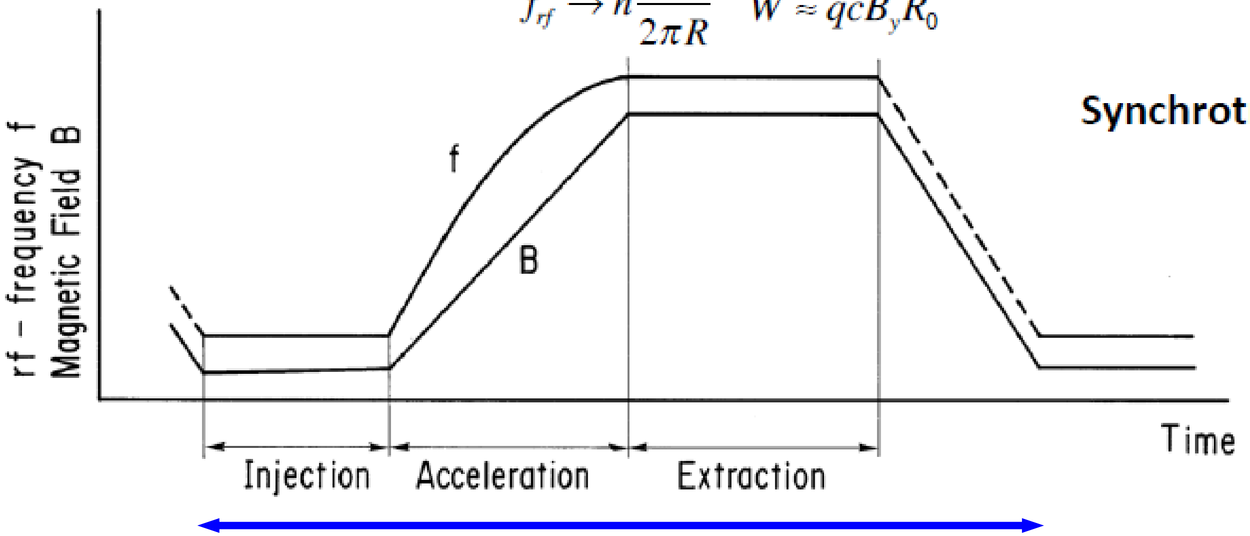
Injection: from a linac or from a 'booster' synchrotron.

Extraction: to targets or to a larger synchrotron.

Working principle

Rf frequency: $f_{rf} = hf_0 = \frac{c^2 h}{2\pi}\frac{qB_y}{W}$ Particle energy: $W^2 = (pc)^2 + (mc^2)^2 = (qcBR_0)^2 + (mc^2)^2$

$f_{rf} \to h\frac{c}{2\pi R}$ $W \approx qcB_y R_0$



Synchrotron cycle

Repetition rate $(T_{rep})^{-1}$:
(time needed for one complete cycle)$^{-1}$

Total beam energy: $W_{tot} = NW_{kin}$

Beam power: $P_{beam} = \frac{W_{tot}}{T_{rep}}$

Types of synchrotrons (a bit arbitrary):
- slow cycling synchrotron: < 1 Hz
- fast cycling synchrotron: 1-10 Hz
- Rapid Cycling Synchrotron (RCS): > 10 Hz

High power high-intensity synchrotrons worldwide

	Energy	Radius	Rep. rate	Power	Particles /cycle	Application	Remarks
ISIS, UK	0.8 GeV	168 m	**50 Hz**	0.16 MW	$3x10^{13}$	Neutrons, muons	RCS
J-PARC RCS, Japan	3 GeV	348 m	25 Hz	**1 MW** (design)	$4x10^{13}$ (design)	Injector for MR, Neutrons,...	RCS, 0.3 MW
J-PARC MR, Japan	50 GeV	1567 m	0.3 Hz	0.75 MW (design)	**$4x10^{14}$** (design)	Neutrinos, ...	
CERN PSB	1.4 GeV	157 m	1 Hz	1.5 kW	(4x) $2x10^{12}$	LHC injector chain	**4 rings**
CERN PS	26 GeV	630 m	0.3 Hz	25 kW	$2x10^{13}$	LHC injector chain	
AGS Booster BNL	1.5 GeV	202 m	7.5 Hz	45 kW	$2.5x10^{13}$	RHIC injector chain	p-Au
AGS	24 GeV	807 m	0.5 Hz	130 kW	**$7x10^{13}$**	RHIC injector chain	p-Au
SIS-18, GSI	1 GeV/u	216 m	3 Hz	4 kW	**10^{10} Uranium**	Injector for SIS-100, RIBs	p-U
SIS-100, GSI	2.7 GeV/u	1080 m	1 Hz	50 kW	$5x10^{11}$ Uranium	RIBs, pbars	p-U, sc magnets

p

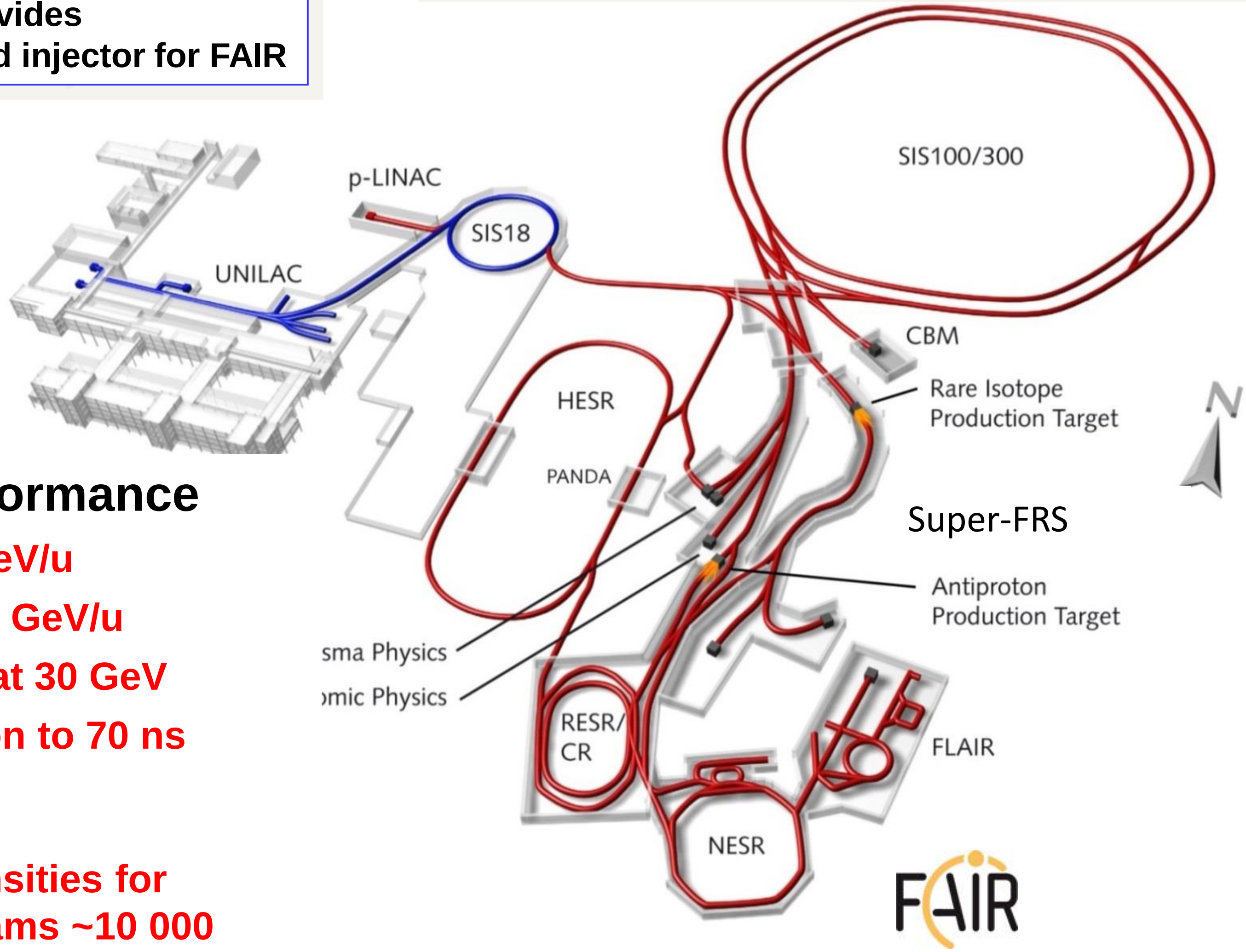
HI

RCS: Rapid Cycling Synchrotron (> 10 Hz)

FAIR (Facility for Antiproton and Ion Research) at GSI

New future facility: provides ion and anti-matter beams of highest intensity and up to high energies

Existing facility: provides ion-beam source and injector for FAIR



Accelerator Performance

- 10^{12}/s U^{28+} at 1.5 GeV/u
- 10^{10}/s U^{73+} up to 35 GeV/u
- 3 x 10^{13}/s protons at 30 GeV
- Bunch compression to 70 ns

Research

- gain factor of intensities for exotic nuclear beams ~10 000

Fast ramping dipole magnets

Large apertures

SIS-18 dipoles: 20 cm x 8 cm

J-PARC RCS: 25 cm x 19 cm

Ramping rates (Bdot):

SIS-18 dipoles: 10 T/s

J-PARC RCS dipoles: 40 T/s

Max. B-Field

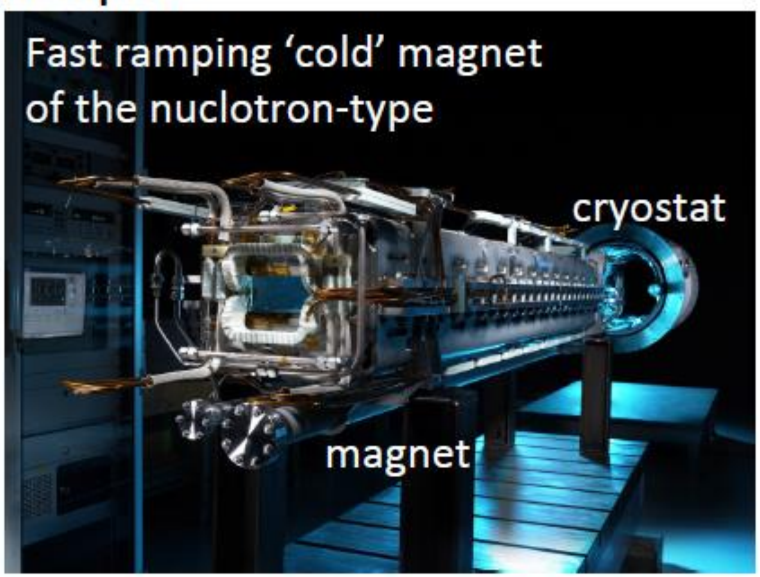
SIS-18: 1.9 T

J-PARC RCS: 1.1 T

Fast ramping (3 Hz) SIS-18 dipoles

SIS-100 superferric dipole:

13 cm x 6 cm
Bdot = 4 T/s
B_{max} = 2 T
pipe at 20 K



J-PARC RCS (25 Hz) dipole

RF cavities for synchrotrons

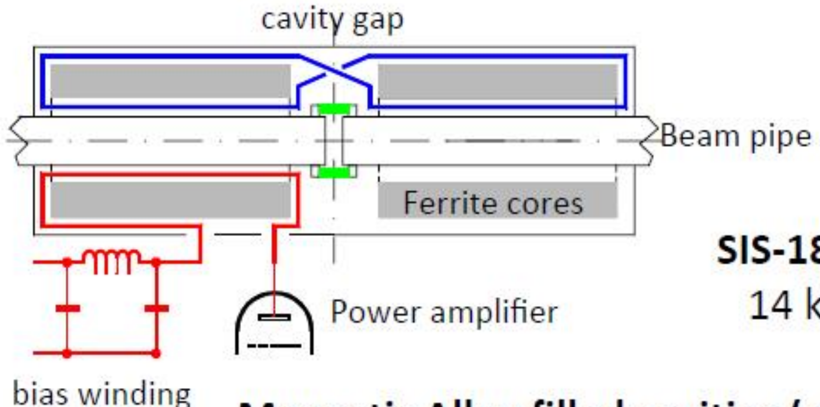
rf cavities filled with **ferrite ring cores** (magnetic permeability $\mu(B_{bias})$)

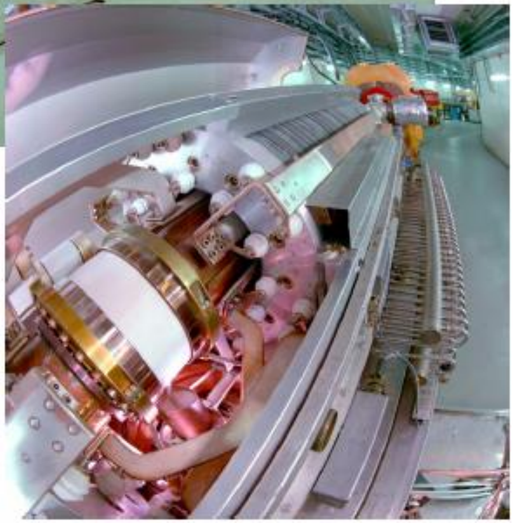
Reduced cavity eigenfrequency: $\omega_{rf}(B) = \sqrt{\frac{\mu_0}{\mu(B)}}\,\omega_{rf,0}$

Ferrite: $\mu \approx 100$

Cavity quality factor and max. frequency:

$Q \approx 10-50 \qquad f_{rf} < 10\ \text{MHz}$





SIS-18 cavity (length=3.4 m):
14 kV, Q=10, 0.8-5.4 MHz

Magnetic Alloy filled cavities (e.g. J-PARC RCS):

- broadband: no tuning required $\quad Q \lesssim 2 \quad \mu \approx 1000$
- compact cavities (important for rapid cycling rings)
- larger losses

Beam intensities of SIS-18 synchrotron for different ions

Space charge tune spread

$$\Delta Q_y^{sc} \propto -\frac{q^2}{m}\frac{N}{B_f}\frac{g_f}{\varepsilon_y \beta_0^2 \gamma_0^3}\frac{2}{1+\sqrt{\varepsilon_y/\varepsilon_x}}$$

'Space charge limit': $|\Delta Q_y| \lesssim 0.5$
(text books)

g_f: Transverse profile (Gauss: 2, homogenous: 1)
B_f < 1: bunching factor
$\varepsilon_{x,y}$: transverse emittances
N: number of particles in the ring
q: particle charge
m: particle mass

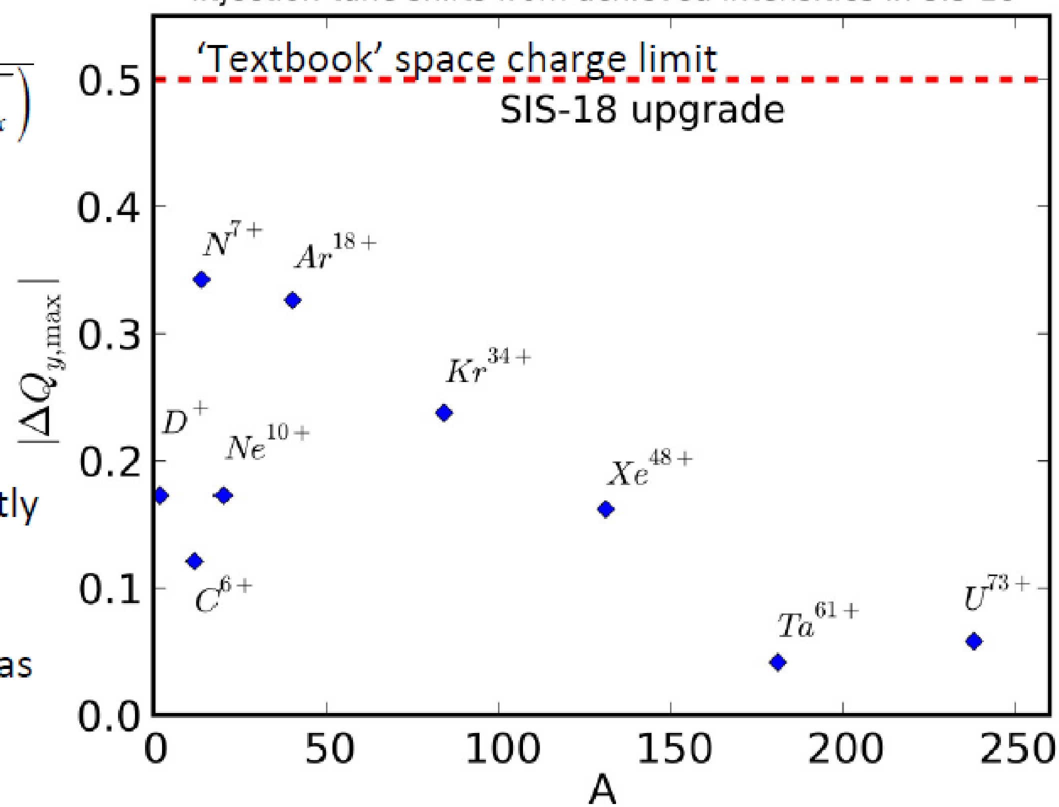
Injection energy: 11.4 MeV/u (β_0=0.155), Emittances: $\epsilon_{x,y} = 150/50$ mm mrad

$$\Delta Q_y^{sc} = -\frac{2NZ^2 g_f}{\pi A \beta_0^2 \gamma_0^3 B_f \left(\varepsilon_y + \sqrt{\varepsilon_y \varepsilon_x}\right)}$$

For protons or lighter ions the space charge limit is usually the actual intensity limiting factor.

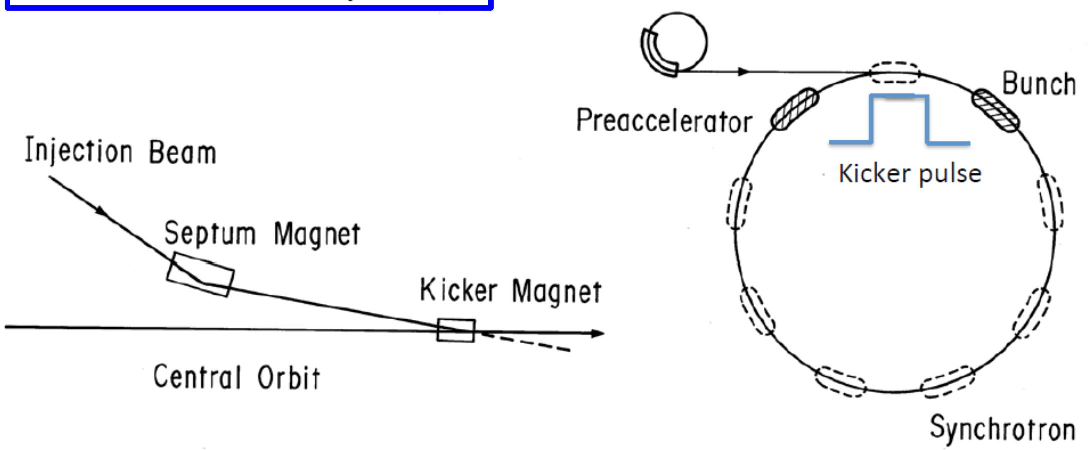
For heavy ions there are presently other limiting factors. E.g.:
- Beam current from the source
- Beam lifetime in the residual gas

Injection tune shifts from achieved intensities in SIS-18



Injection: Bunch to bucket

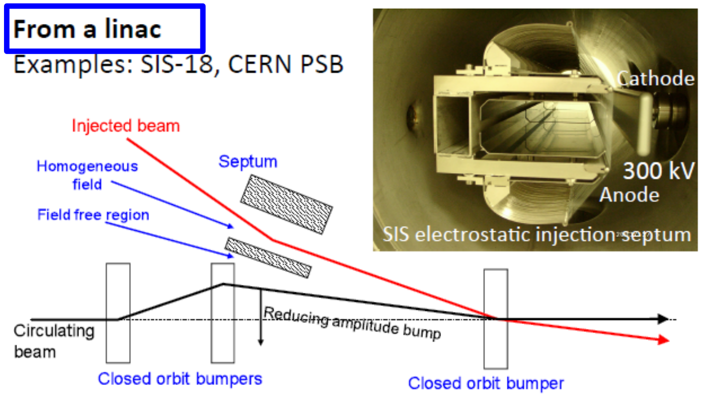
From a smaller 'booster' synchrotron



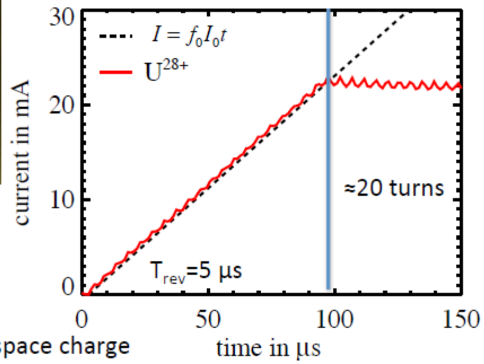
Kicker: fast dipole magnet with a rise time of 10-100 ns and a pulse duration of μs.

From a linac

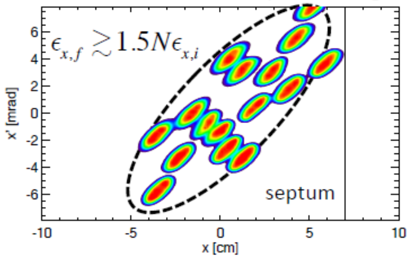
Examples: SIS-18, CERN PSB



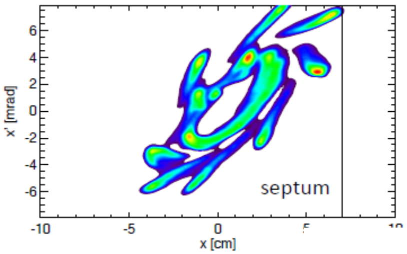
Measured MTI performance in SIS-18



Simulation: without space charge



Simulation: with space charge



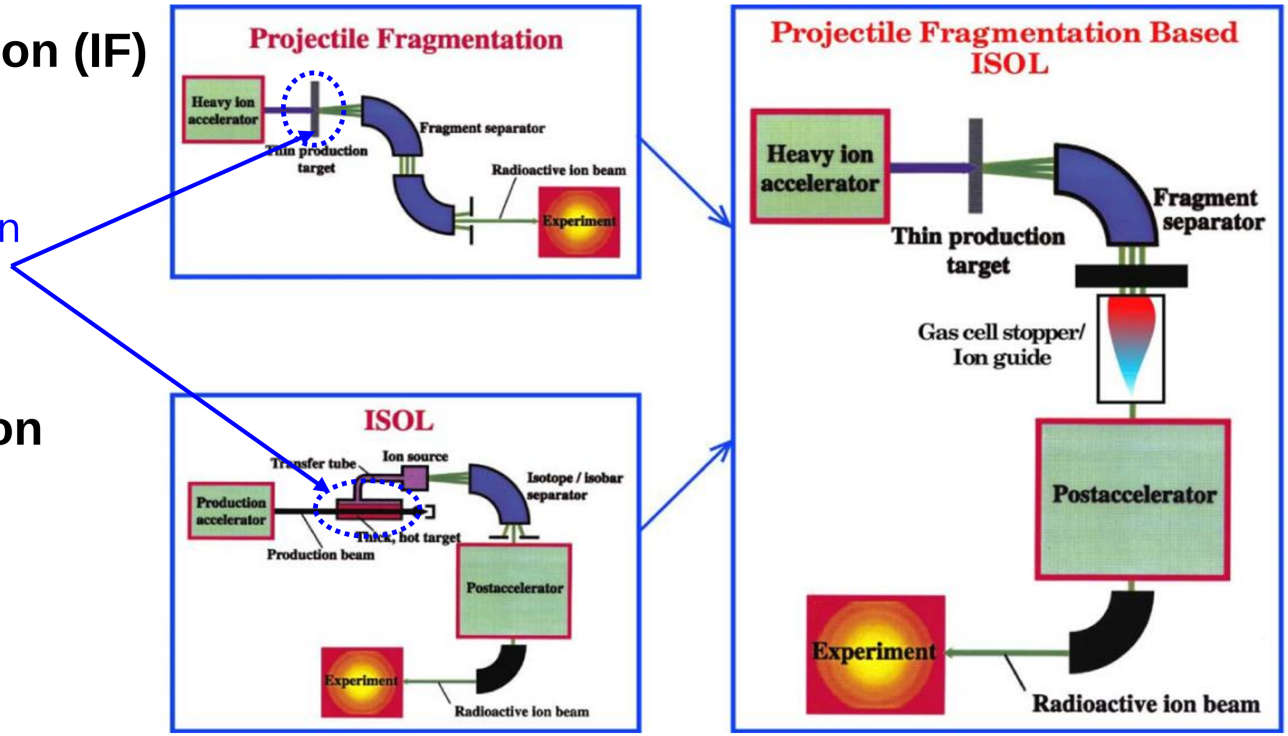
4. Isotope beam production with hadron beam

3. A combined method

1. In–flight fragmentation (IF)

Production targets

2. Isotope Separation on line (ISOL)

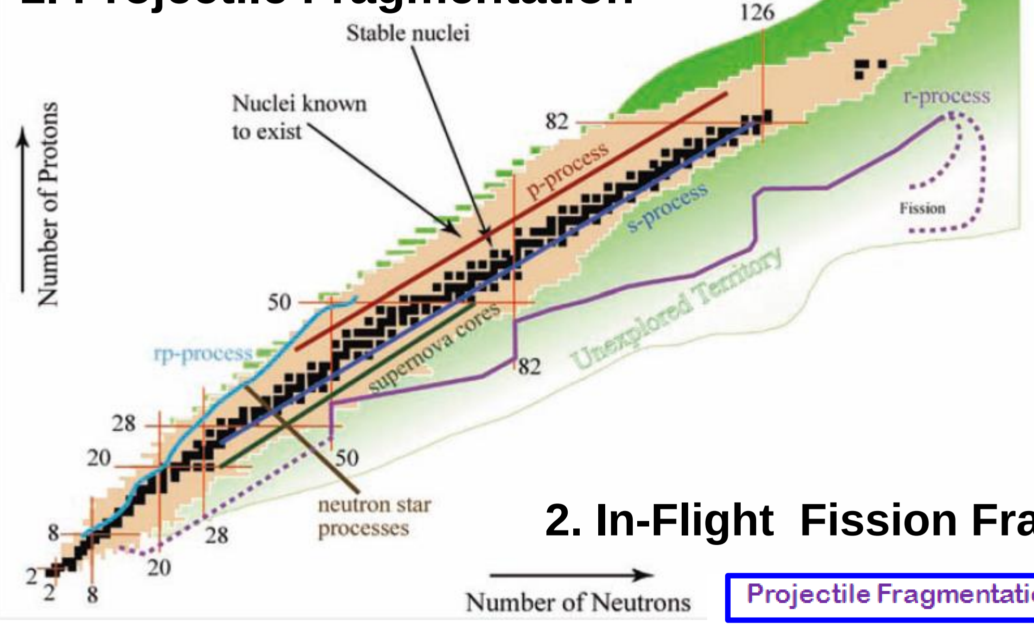


Comparison of the two methods

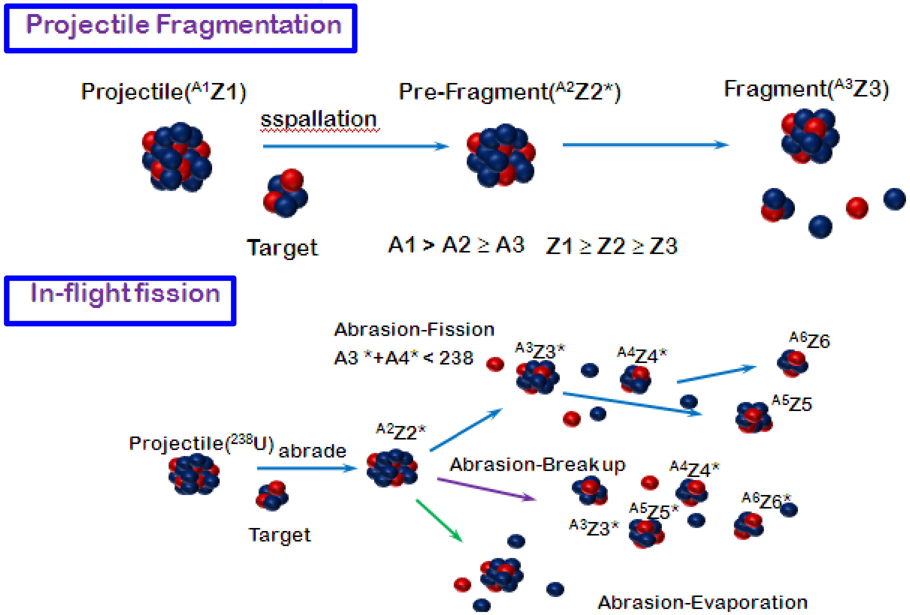
	IF	ISOL
Primary Beam	Heavy (U,..)	Light (p, n, d)
Target	Low Z (Be, C.,,)	High Z (U,..)
Separation Time	Short	Long
RI beam energy	Relying on primary beam	Reacceleration

Two major nuclear mechanisms of IF

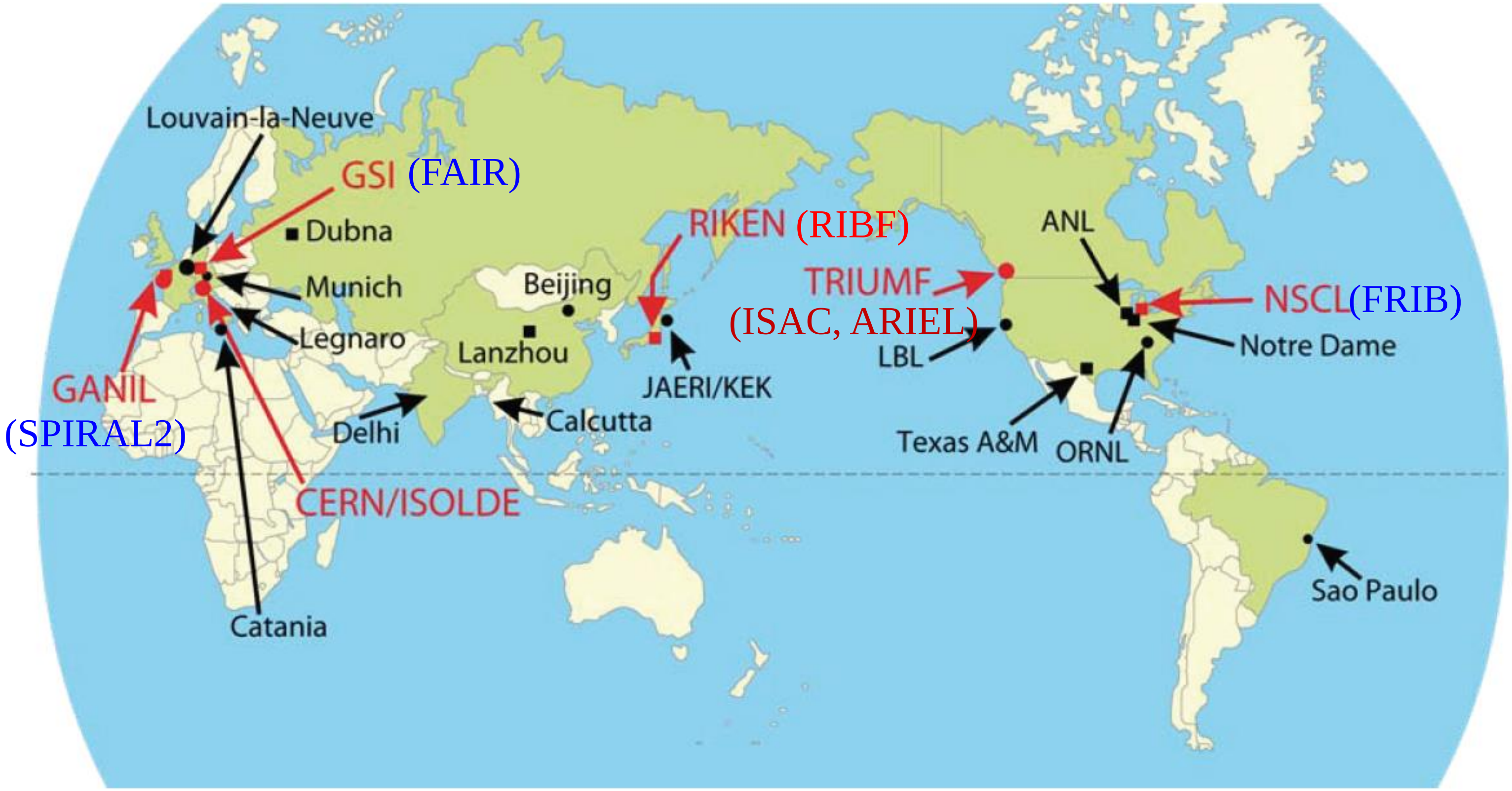
1. Projectile Fragmentation



2. In-Flight Fission Fragmentation (U)



Rare isotope beam capabilities worldwide

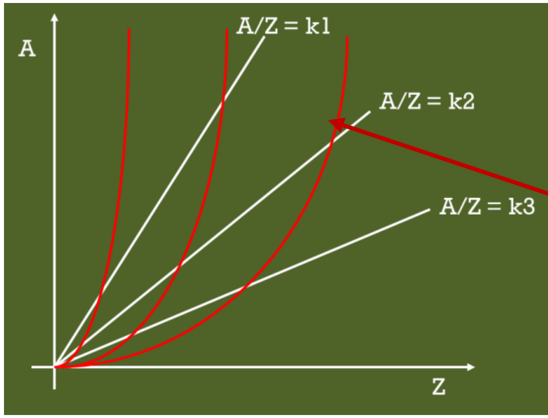


High power facilities (> 50 kW)

Japan: RIKEN RIBF (IF)
USA: MSU FRIB (IF)
Germany: GSI FAIR (IF)
Canada: TRIUMF ISAC, ARIEL(e linac) (ISOL)
France: GANIL SPIRAL2 (ISOL)

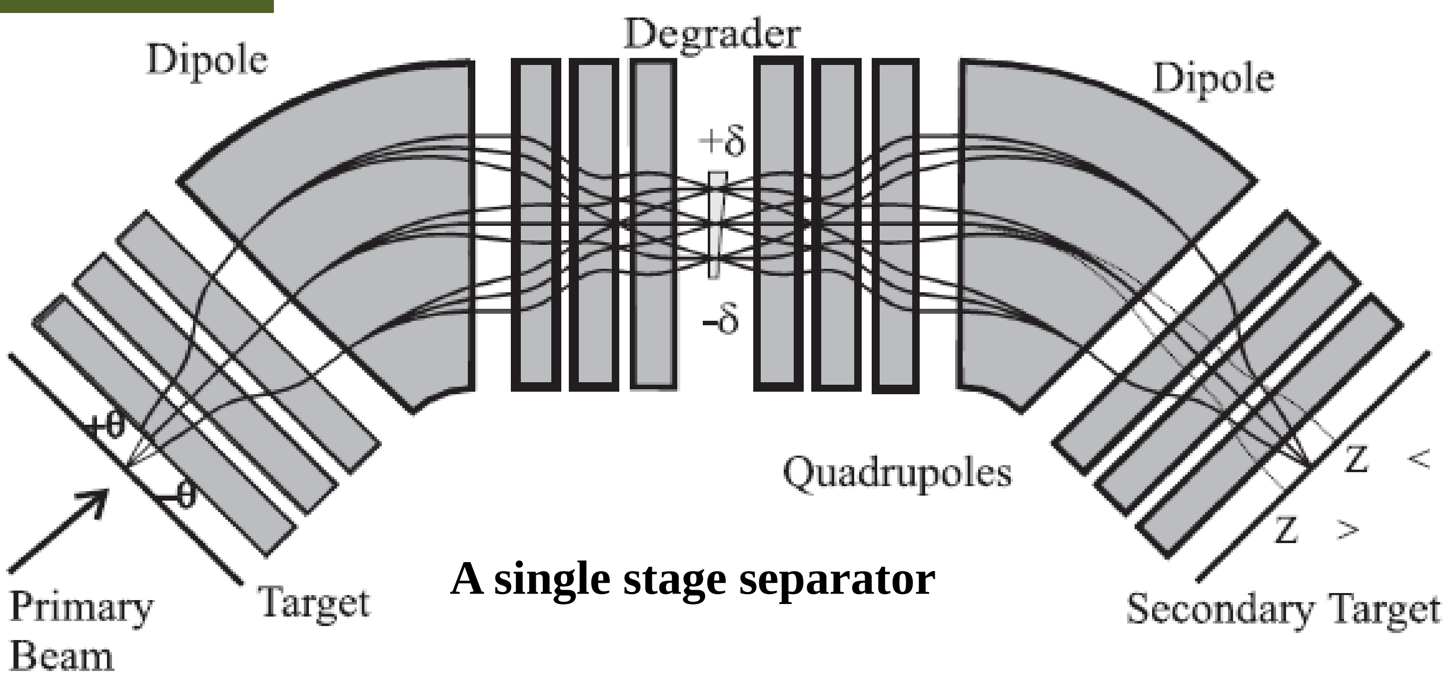
Green: under construction

Principle of IF separator



Bρ-ΔE-Bρ

Separation at degrader: $\frac{A^{2.5}}{Z^{1.5}}$

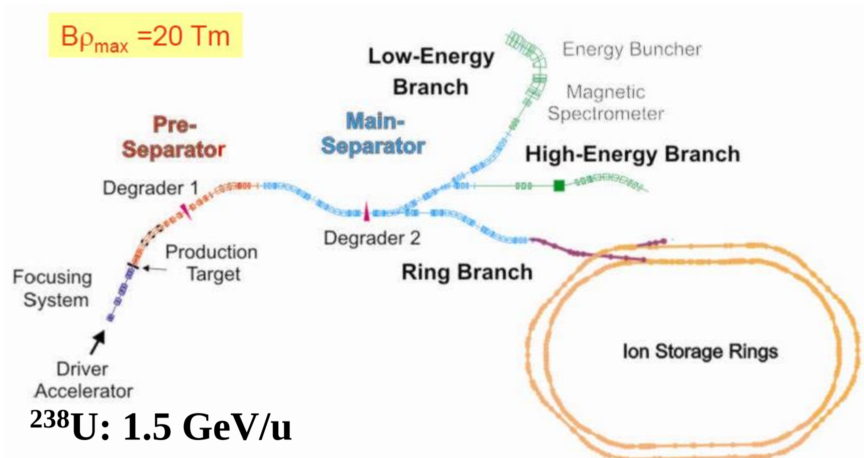


A single stage separator

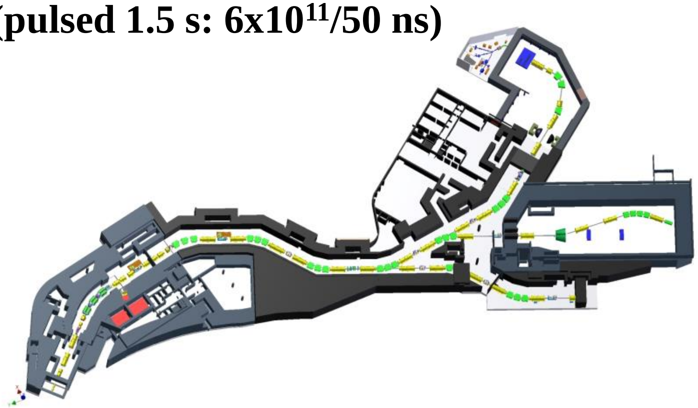
Resolution: $R = \frac{D}{2Mx_0}$ **D: disperson, M: magnification**

In-flight fragment separator in other facilities

Super-FRS (GSI)



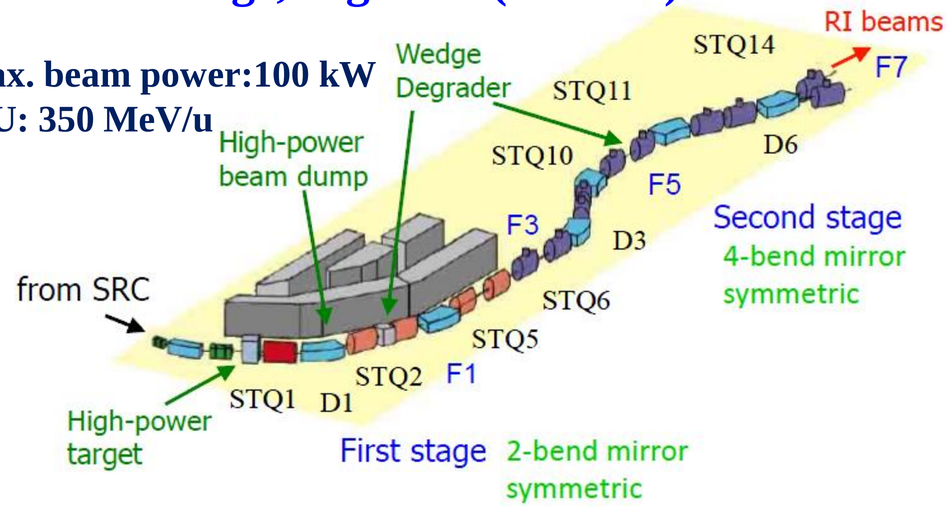
^{238}U: 1.5 GeV/u
Ave. power: 23 kW
(pulsed 1.5 s: 6x10^{11}/50 ns)



Production target

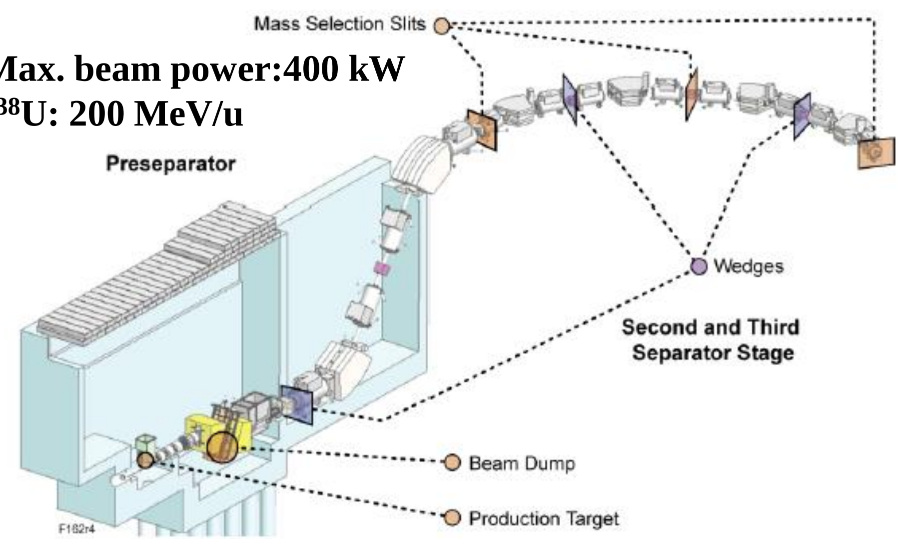
Two stage, BigRIPS (RIKEN)

Max. beam power:100 kW
^{238}U: 350 MeV/u

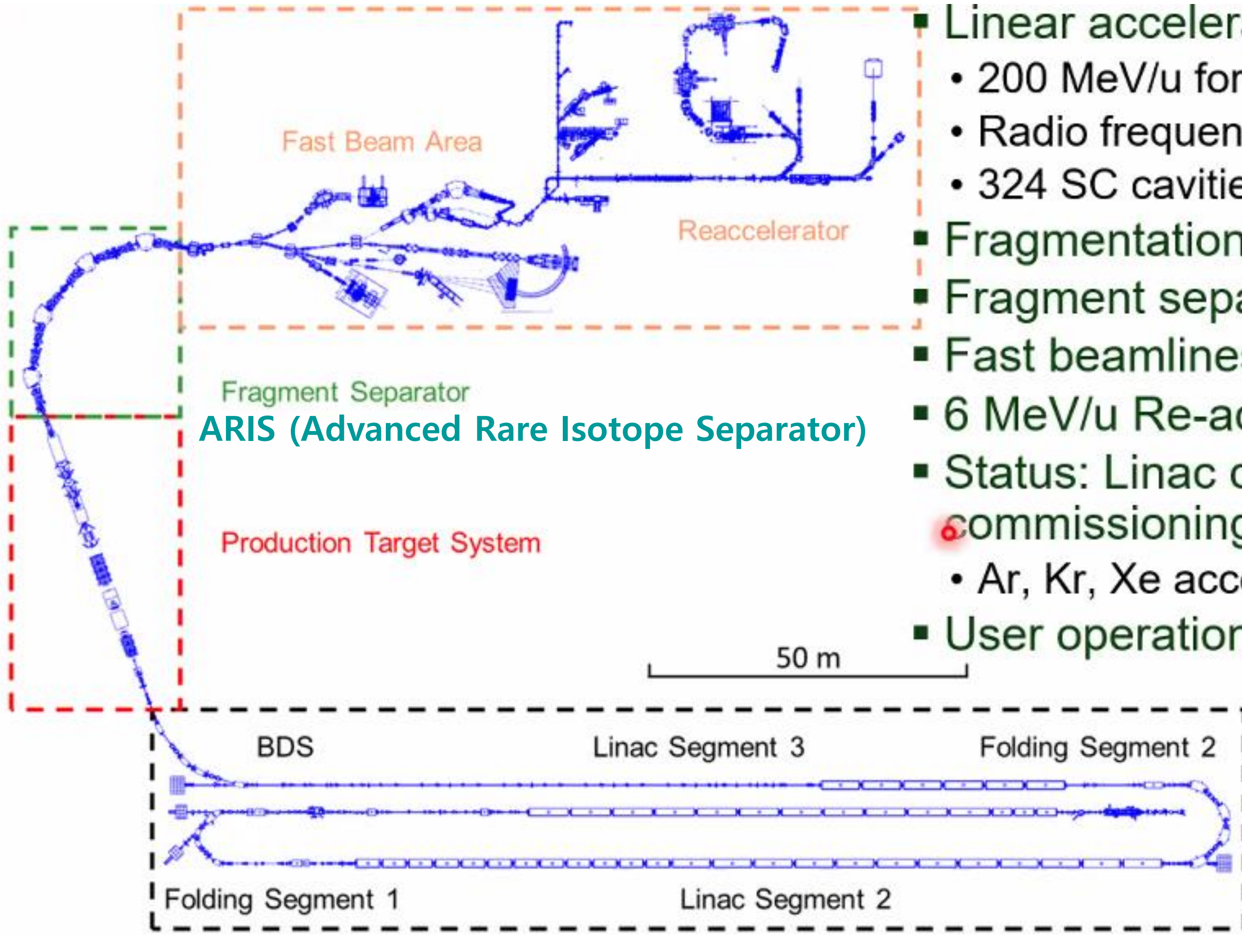


Three stage, FRIB (MSU)

Max. beam power:400 kW
^{238}U: 200 MeV/u

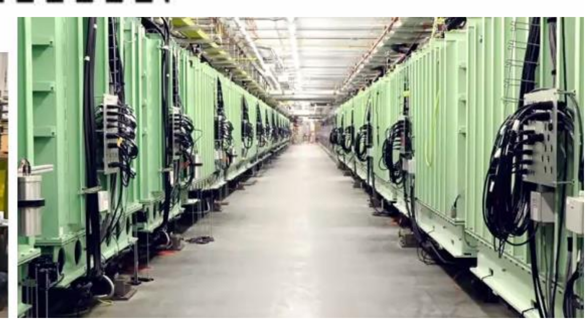


FRIB (Facility for Rare Isotope Beams) user operation from 2022

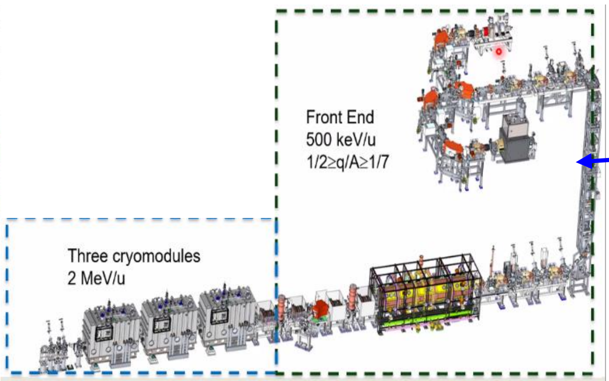


- Linear accelerator
  - 200 MeV/u for uranium
  - Radio frequency quadrupole
  - 324 SC cavities in 46 cryomodules
- Fragmentation target
- Fragment separator
- Fast beamlines
- 6 MeV/u Re-accelerator
- Status: Linac construction and commissioning is complete
  - Ar, Kr, Xe accelerated to 212 MeV/u
- User operation starts in May 2022

β = 0.085

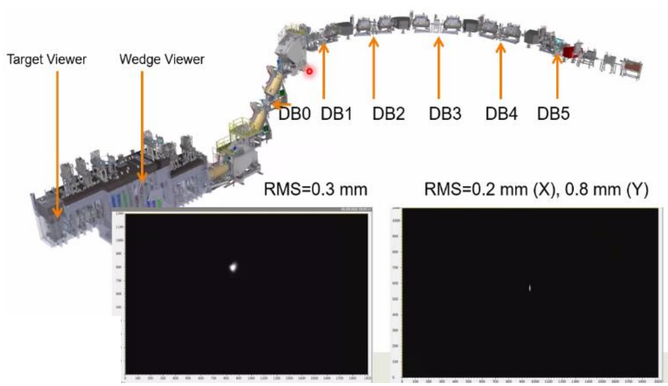


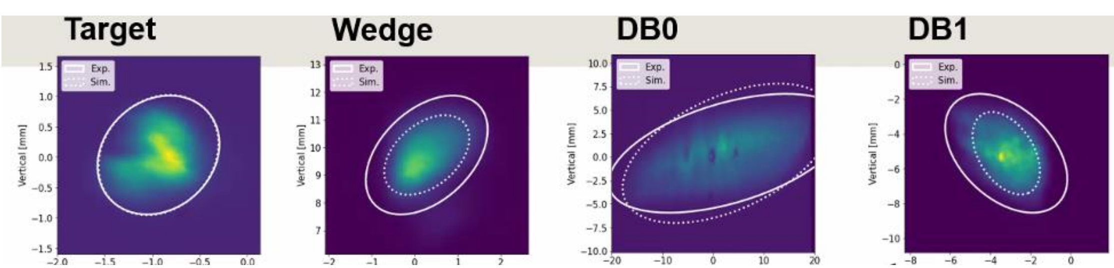
Beam commissioning at FRIB (2017 ~present)



St	Area with beam	Ion species	Beam energy MeV/u	Date	Main goals
1	Front End	Ar, Kr	0.5	July 2017	FE and civil integration
2	First three cryomodules	Ar, Kr	2.2	May 2018	Cryogenic integration, SRF
3	LS1, FS1	Ar, Kr, Xe	20.0	February 2019	104 SRF cavities and stripper
4	FS1, LS2	Ar, Kr, Xe	204 (Ar) 180 (Kr, Xe)	March 2020	2K cryogenics, Linac KPP
5	FS2, LS3	Ar, Kr, Xe	212	April 2021	Linac validation
6	Target Hall	Kr	Rare isotopes	Dec.2021	Project KPP
7	Focal plane of the Advanced Rare Isotope Separator	Ar	210	January 2022	Project completion, readiness for user operation

210 MeV/u $^{36}Ar^{18+}$ Beam Envelope in ARIS





From presentation of P. Ostroumov (April, 2022)

5. Use of hadron beams

Stable ion beams

1. **Nuclear and astrophysics**
2. Neutron science (p)
3. Applications:
   - multi-tracer: isotope production for radiation biology
   - mutation of plant seeds. → accelerated evolution by radiation

   (RIKEN, GSI,..)

   - ion implantation (HTc superconductor, etc..)

Isotope beams

1. Synthesis of neutron-rich transactinide nuclei, which are more strongly bound and longer-lived.
2. Reliable models of astrophysical environments that describe nuclear synthesis and stellar evolution in the cosmos.
3. Development of applications to new nuclear technologies for material science, medicine, and bio/nanotechnology.

입자 빔의 생의학 및 산업적 이용

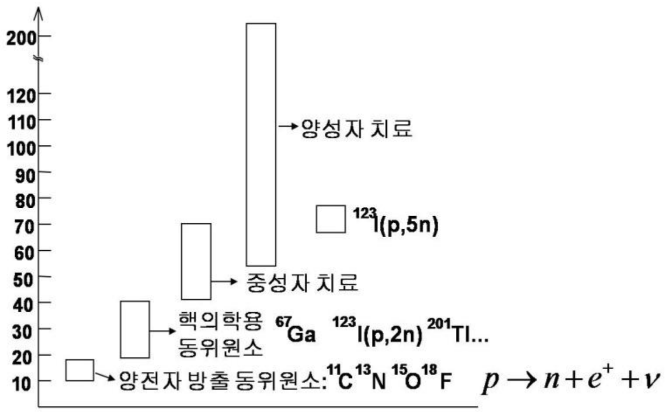
1. 양성자
   - Isotope production
   - Radiation therapy
2. 중이온 (A>2)
   - Ion implantation
   - Ion beam analysis, Radiation therapy
   - Microbeam (precision beam), Lithography
   - Accelerator Mass Spectrometry (AMS) (use DC machine)
3. 중성자
   - Radiography,radiotherapy
   - National Security (chemical warfare, special nuclear material, explosive detection)

Commercial markets of biomedical accelerators (2007)

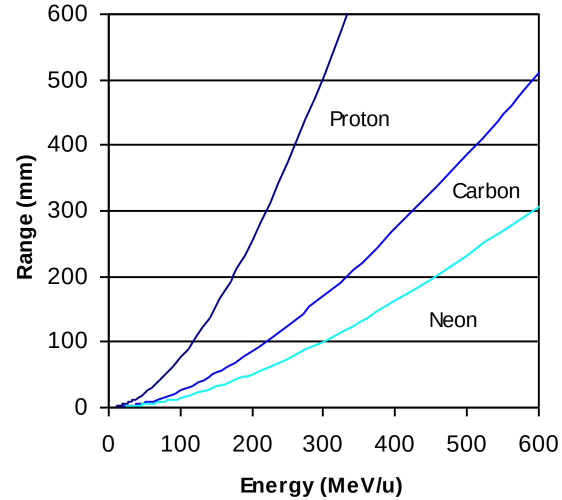
Uses	Accelerator	No of units in operation	Annual unit increase	Annual sales (억원)
Radiotherapy (e)	electron linac	8000	400	7000
Radiotherapy (p,^{12}C)	cyclotron, synchrotron	25	2-3	600
Isotope production (p)	cyclotron, hadron linac	250	15	300

Biomedical uses of hadron beam

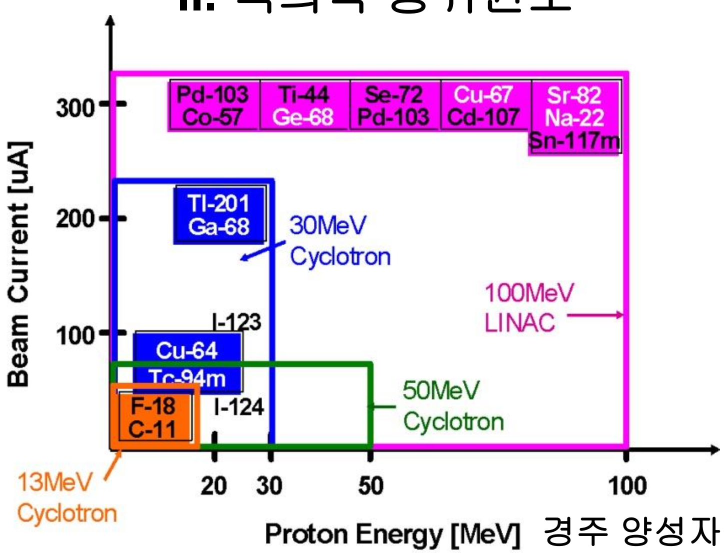
I. 방사선 치료



양성자 빔의 에너지에 따른 용도



II. 핵의학 동위원소



경주 양성자연구단자료

III. 중이온 빔 생물조사

Physical parameters of ion beams in JAERI

Radiation	Energy (MeV)	LET (keV/μm)	Penetrating depth (mm)
$^{4}He^{2+}$	50	16	1.7
$^{4}He^{2+}$	100	9	6.2
$^{12}C^{5+}$	220	107	1.1
$^{12}C^{6+}$	320	76	2.2
$^{20}Ne^{8+}$	350	316	0.6

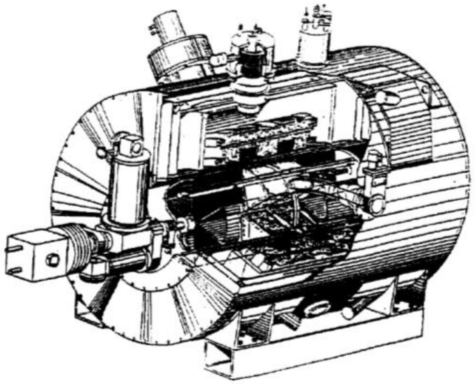
Physical parameters of ion beams in RIKEN

Radiation	Energy		LET (keV/μm)
	MeV/u	MeV	
$^{12}C^{6+}$	135	1620	22, 39, 99
$^{20}Ne^{10+}$	135	2700	64, 107
$^{40}Ar^{17+}$	95	3800	305
$^{56}Fe^{24+}$	90	5040	630

핵의학동위원소 생산 (PET, SPECT, for theranostics,..)

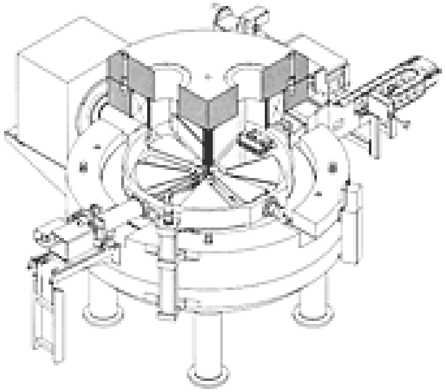
10-20 MeV for **PET** (Position Emission Tomography)

11 MeV H- 사이클로트론 (CTI)

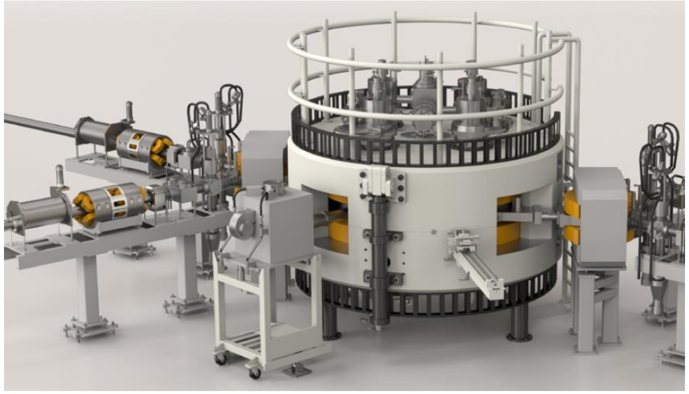


11 MeV H- Superconducting Cyclotron (Oxford Instru.)

30 MeV for Nuclear Medicine such as **SPECT**



30 MeV H- Cyclotron (IBA)



30-70 MeV H- Cyclotron (IBA)

Advanced Radioisotopes for theranostics

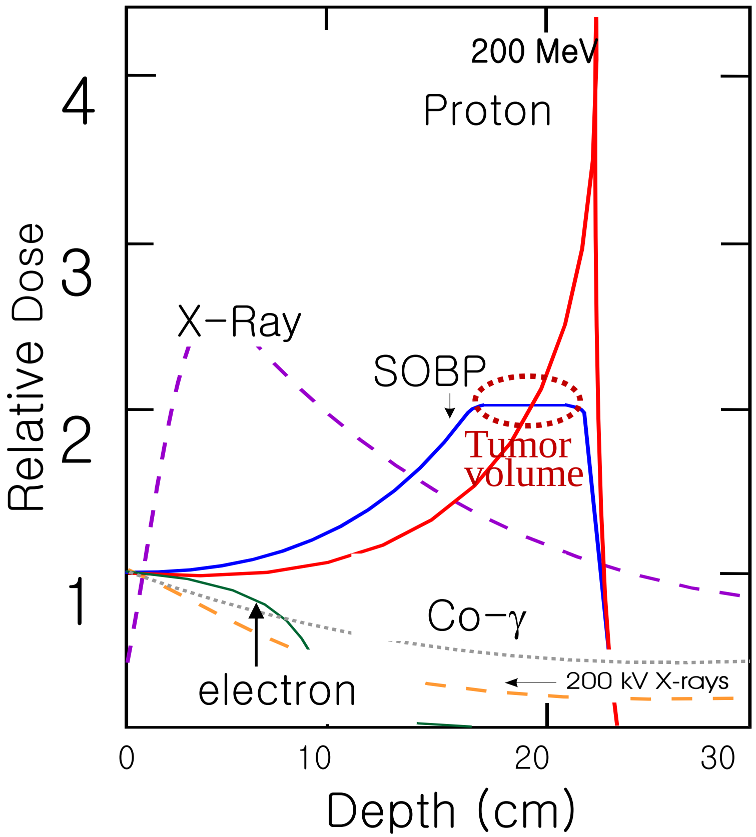
^{67}**Cu** (therapy+diagnostic applications)
^{47}**Sc** (PET + radionuclei therapy)
^{82}Sr/^{82}**Rb** (heart function)

양성자를 이용한 방사선 치료 (70-250 MeV)

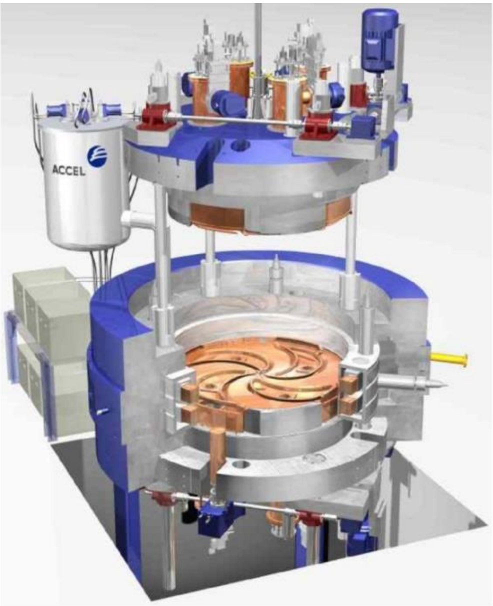
Bethe-Block formula

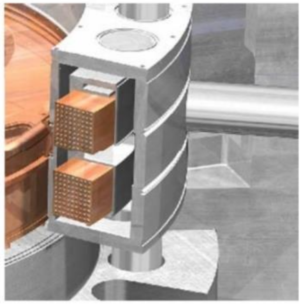
$$-\frac{dE}{dx} = 2\pi r_e^2 m_e c^2 N_{el} \frac{Z_h^2}{\beta^2}\left[\ln\frac{2m_e\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2(1+\frac{T_c}{T_{\max}}) - \delta - 2\frac{C_e}{Z}\right]$$

Zh: 입사빔의 유효 전하, re: 고전적 전자 반경,
Nel: 전자 밀도, δ: 보정항, Ce/Z: shell 보정항.



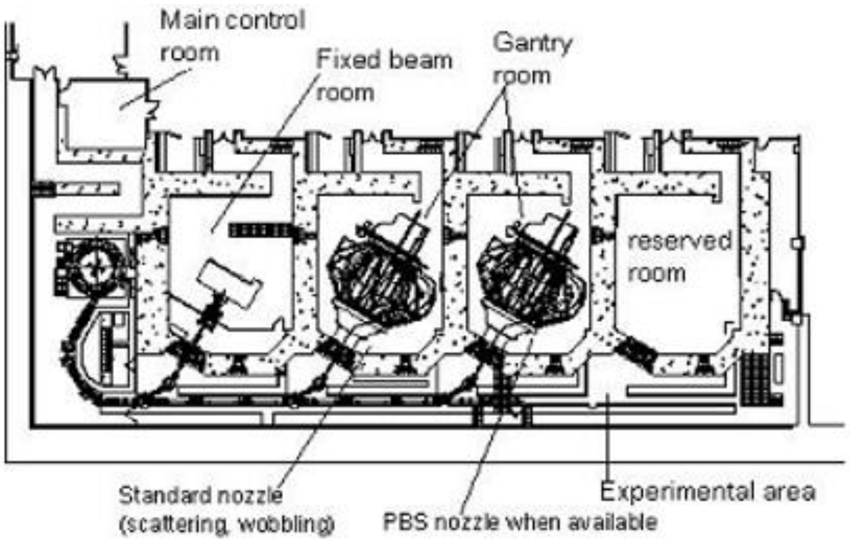
Superconducting cyclotron (PSI, Switzerland) → Varian Inc. Europe





J. Kim, Magnetic fields and beam optics studies of a 250MeV superconducting proton radiotherapy cyclotron, NIM A 2007

국립암센터 & 삼성병원 양성자치료시설



국립암센터 양성자치료시설

Major Milestones

- 2002 July: Contract with IBA
- 2003 Jun: Start the building construction
- 2005 Feb: Starting the installation
  Oct: Beam test begin
- 2006 Dec: Acceptance of 1st gantry room + 2nd gantry room
- 2007 Mar 19: Treatment of the first patient (prostate cancer)
  July: 2nd gantry room is used to treat patient
  Dec: End of one year operation by IBA

출처: PTCOG homepage

삼성서울병원, 양성자 치료 지속 증가, '소아암' 최다 ('22, 1월)

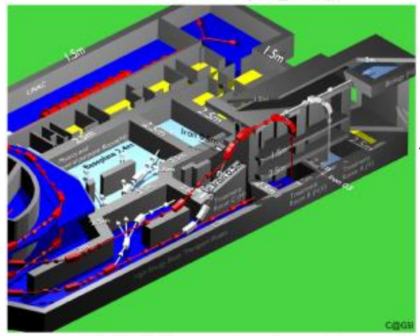
Hadron beam therapy facilities I

Pioneering facility (~'70)

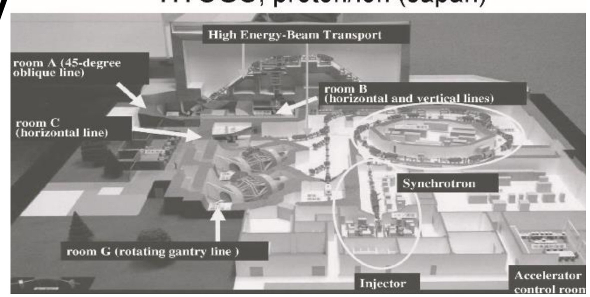
Bevalac facility at LBL

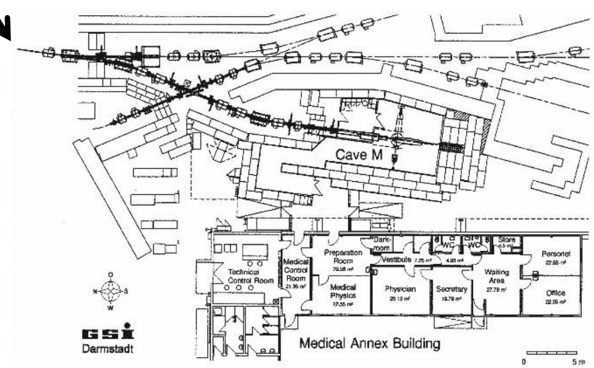
Facilities developed commercial products

HIMAC (Japan)



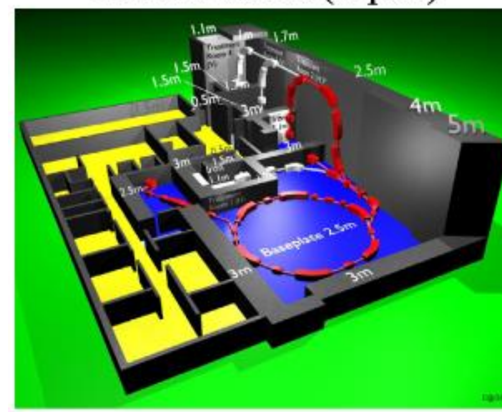
HYOGO, proton/ion (Japan)



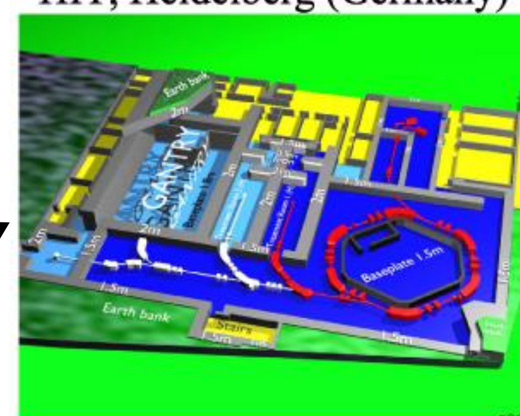


In operation

Gunma Univ. (Japan)

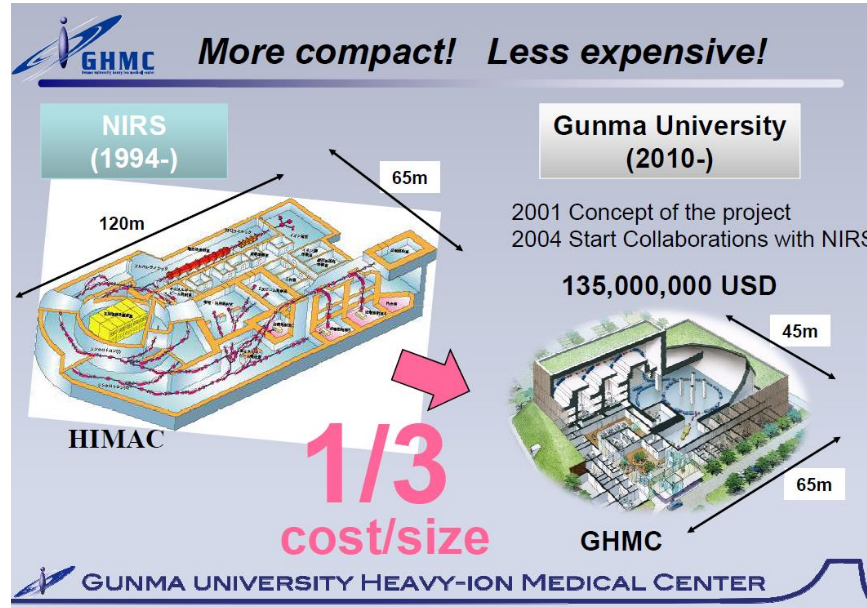


HIT, Heidelberg (Germany)



Hadron beam therapy facilities II

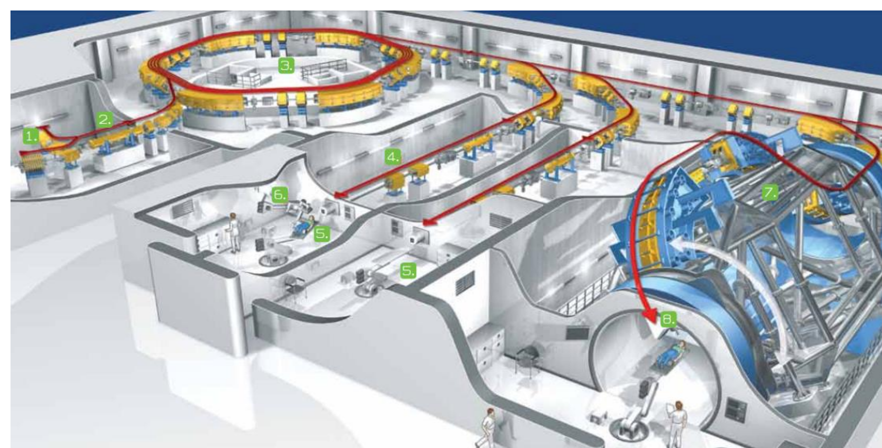
연세의료원에 설치될 중입자치료기는 세계에서 15번째로 설치되는 중입자 시설로서 2023년 말 국내 최초의 중입자 치료가 연세의료원에서 시작될 예정이며 매년 약 1,200명의 암 환자가 중입자치료를 받을 수 있을 것으로 예상



MedAustron facility (1st beam, 2014)

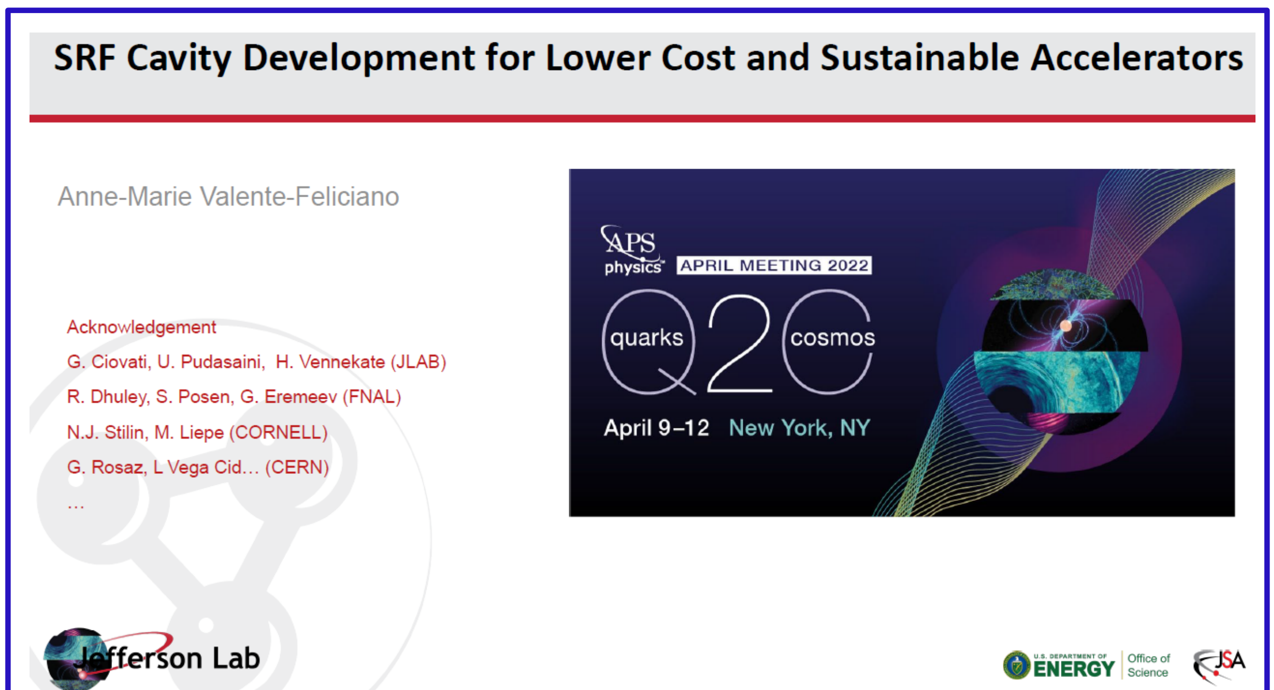
p: 60-250 MeV; C6+: 120-400 MeV/u

Heidelberg Ion Therapy Center (HIT):1st patient, 2009



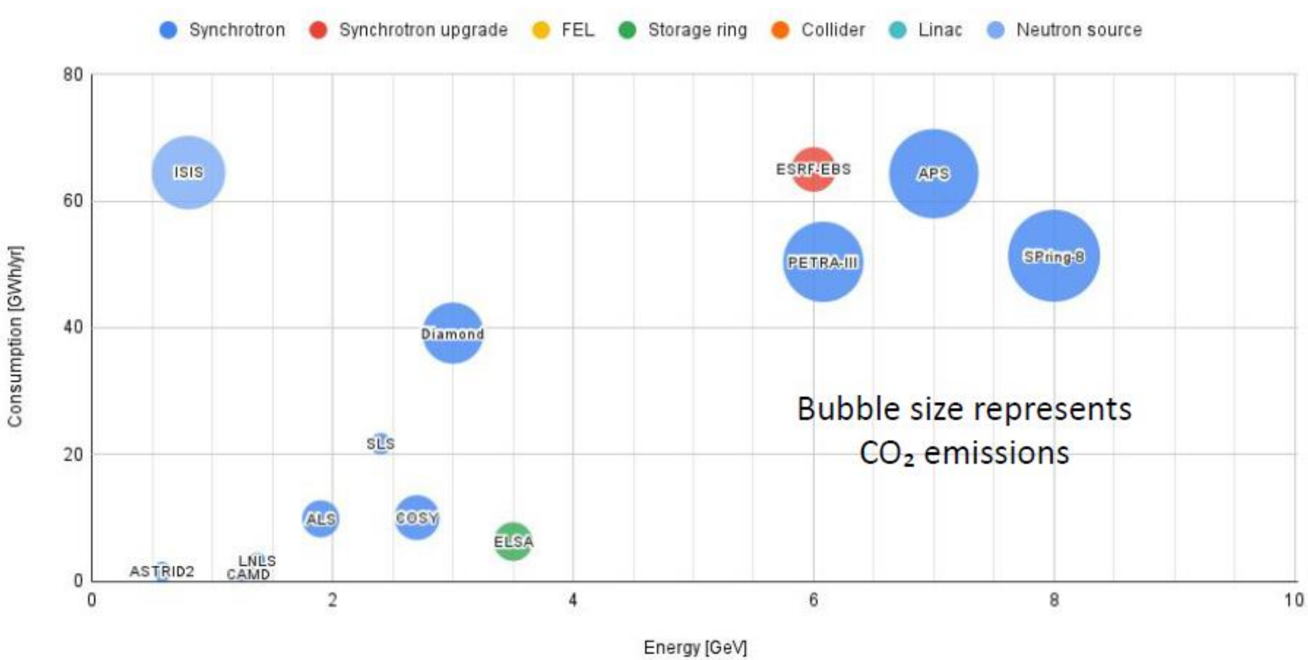
6. Sustainable accelerator with SRF technology

Two talks in APS meeting, April, 2022



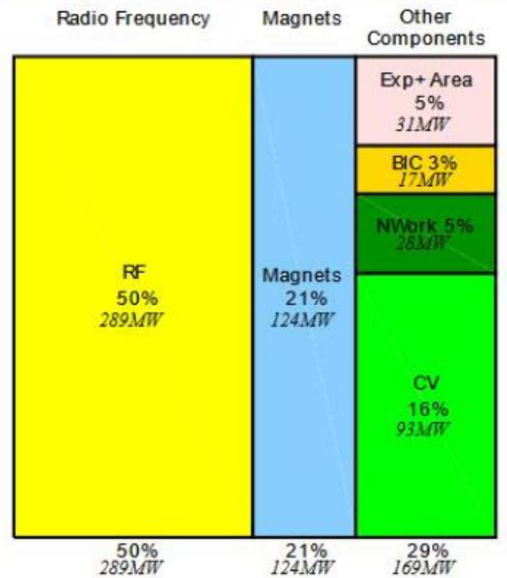
Motivation – electricity consumption

- Particle accelerators are big energy users



Ben Shepherd • Sustainable Accelerators • APS April Meeting 2022

CLIC power consumption estimates



BIC = beam instrumentation + control
CV = cooling + ventilation
NWork = electrical network losses
Exp+Area = experiments and surrounding area

CLIC: Compact LInear Collider
- CERN, e-positron collider
- 3 stages: 380 GeV, 1.5 TeV, 3 TeV

CURRENT SRF TECHNOLOGY FOR ACCELERATORS

Technology of choice for large accelerators for science around the world

CEBAF, SNS, XFEL, LCLS-II , RIA, PIP-II,

Future machines: EIC, FCC

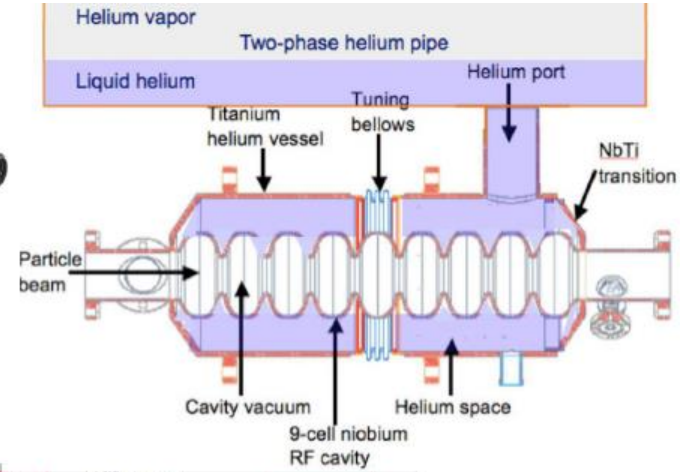
Based on bulk Nb

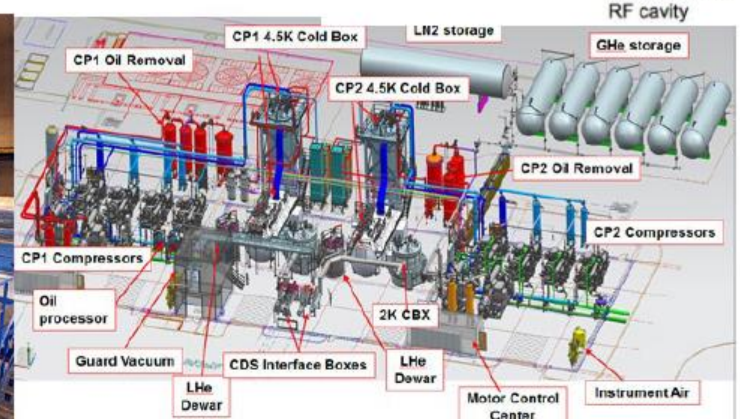
Rely on 2K operation

Costly Construction

Large cryoplants

Costly Operation





New SRF cavity development and compact accelerator for application

Thin Film Superconducting RF

- **Bulk niobium cavities** have been the choice for SRF for the last 50 years
- Use a considerable amount of natural material
- Performance limit of niobium has been reached
- Costly to produce
- Run at a temperature of 2 K
  - A considerable cryogenic demand and energy load

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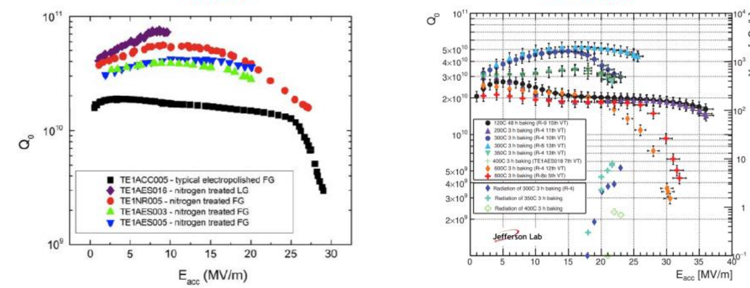
Increase efficiency & lower cryogenic losses



A. Grassellino et al. Supercond. Sci. Technol 26.10 (2013): 102001.
Ito, H., et al. Progress of Theoretical and Experimental Physics (2021) 071G01
D. Gonnella, Daniel, et al. Proceedings of IPAC2016, Busan, Korea (2016).
Lechner, E., et al. Appl. Phys. Lett. 119, 082601 (2021)

- 2-4 times more efficient

Q-factor x2 or more resulting in cavity-cooling electricity bills slashed by up to 4 times

SRF Cavity Development for Lower Cost and Sustainable Accelerators, A.-M, Valente-Feliciano, APS April Meeting 2022 — Jefferson Lab

LOW COST & SUSTAINABILITY FOR ACCELERATORS

- ***Increase efficiency*** – klystron, RF power sources

SRF cavities

Low-loss SC resonators: Advanced surface processes

N doping & O alloying

Lower costs of construction & operation

Operation at 4 K: New Materials, composite materials and structures more efficient than bulk Nb combined with higher thermal conduction substrates.

New materials – High T_c, high H_{sh}
Nb_3Sn/Nb, Nb_3Sn/Cu
MgB_2
SIS on bulk Nb or Nb/Cu

New cooling schemes

Energy efficient accelerator concepts

Energy Recovery

Sustainability Aspects of Energy Recovery Linacs (ERL)
Bettina Kuske

V. N. Litvinenko et al., "High-energy high-luminosity e⁺e⁻ collider using energy-recovery linacs," Phys. Lett. B 804, 135394 (2020)

Sustainable Accelerator R&D, Ben Shepherd

SRF Cavity Development for Lower Cost and Sustainable Accelerators, A.-M, Valente-Feliciano, APS April Meeting 2022 — Jefferson Lab

LOW COST & SUSTAINABILITY FOR ACCELERATORS

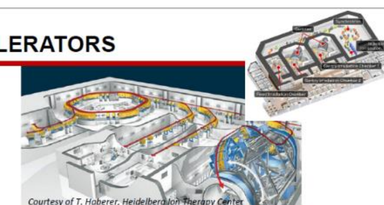
Compact accelerators for societal needs

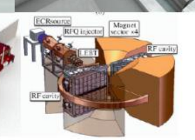
Environmental remediation (water, waste treatment),
Medical instrument sterilization, medical isotopes production,
Engineering of material and surfaces with altered properties radiation driven chemistry,
Food preservation
ADS systems

Need for a new class of compact, high-power accelerators, with drastically reduced cryogenic requirements

located on a mobile platform, in a university or hospital room.

simple, reliable, and cost effective





SRF Cavity Development for Lower Cost and Sustainable Accelerators, A.-M, Valente-Feliciano, APS April Meeting 2022 — Jefferson Lab

ISIS Neutron and Muon Source (Rutherford Appleton Laboratory) pulsed neutron and muon source, operation in 1984

ISIS Energy Consumption

Mode	Energy Total	2017 Baseline CO_2 Equivalent tonnes per annum	2020 CO_2 Equivalent tonnes per annum	
ISIS-I				
240 Day 5 cycle plus Machine Physics & Start Up	64.5 GWh/annum	22,700	16,300	
90 Days Long Shutdowns	13.4 GWh/annum	4,700	3,400	
35 Days Short Shutdowns	7.2 GWh/annum	2,500	1,800	
365 Operation	85.1 GWh/annum	29,900	21,500	-8,400
ISIS-II				
240 Day 5 cycle plus Machine Physics & Start Up	172.7 GWh/annum	60,700	43,700	
90 Days Long Shutdowns	35.9 GWh/annum	12,600	9,100	
35 Days Short Shutdowns	19.3 GWh/annum	6,700	4,900	
365 Operation	227.9 GWh/annum	80,000	57,700	-22,300

This is just the electrical energy that we use in running the ISIS Facility
- **It does not include any of the carbon footprint associated with:**
  - **With carbon lifecycle assessments.**
  - **Materials for new accelerator components or Beamlines.**
  - **Our Business as usual activities.**
  - **The ISIS facility is a particle accelerator**
  - **It will never have a low carbon footprint**
  - **This does not mean we can ignore that footprint.**

The ISIS facility is a particle accelerator
- **It will never have a low carbon footprint**
- **This does not mean we can ignore that footprint.**
- **We cannot rely on the greening of the electricity supply to reduce our footprint.**

2017 Baseline UKRI GOV.UK conversion factor Electricity 1kWh = 0.35156 $kgCO_2e$
2020 UKRI GOV.UK conversion factor Electricity 1kWh = 0.25319 $kgCO_2e$

Efforts are essential to utilize new technologies and to make accelerator system more compact & economical.