Status of FFAG developments

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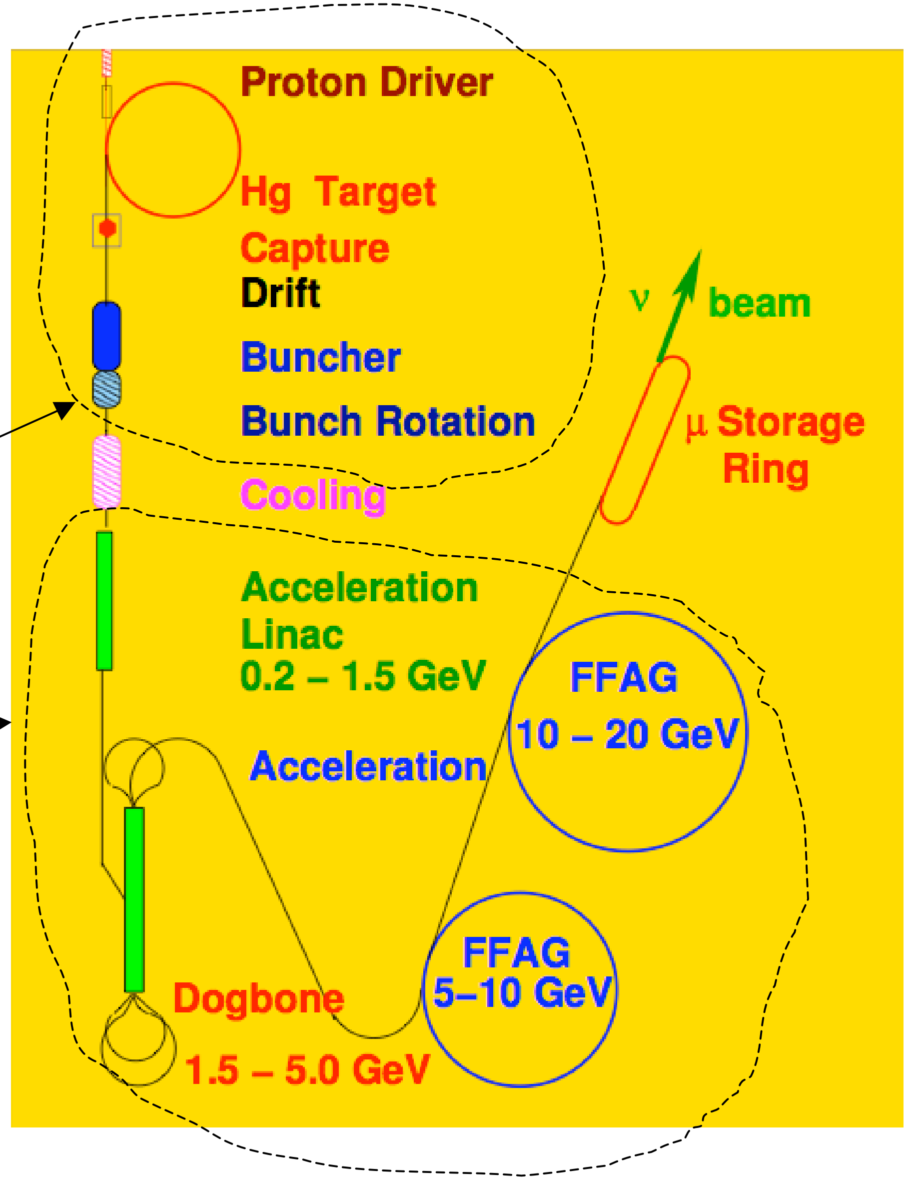
Contents

Neutrino factory and FFAG (1)

ILC is not only the project of high energy physics

- Neutrino Factory
  - Storage ring of muons of 20 to 50 GeV creates high flux neutrino beams.

- Muon production
- Muon cooling
- Muon acceleration
- Muon storage



Neutrino factory and FFAG (2)

Muon is produced as a tertiary particle

- Muon production requires high intensity proton accelerator as a primary particle source.

- Intensity is about 4 MW.
  - ISIS is 0.2 MW.
  - J-PARC will be 0.6 MW.
  - SNS will be 1.4 MW.
- Energy is about 10 GeV.
- Short pulsed beam.

Neutrino factory and FFAG (3)

Life time of muon is 2.2 μs at rest

- Acceleration has to be as quick as possible.
- "rapid" cycling synchrotron such as ISIS takes 10 ms.
- Muon accelerator from 0.2 to 20 (50) GeV in ~1 μs.

Neutrino factory and FFAG (4)

Muon is produced as a tertiary particle

- Momentum spread is huge +-100%.
- Transverse emittance is huge, 30,000 π mm mrad (normalized).
  - Acceptance of J-PARC is +-1% and 300 π mm mrad.

FFAG seems the best machine candidate for Neutrino Factory.

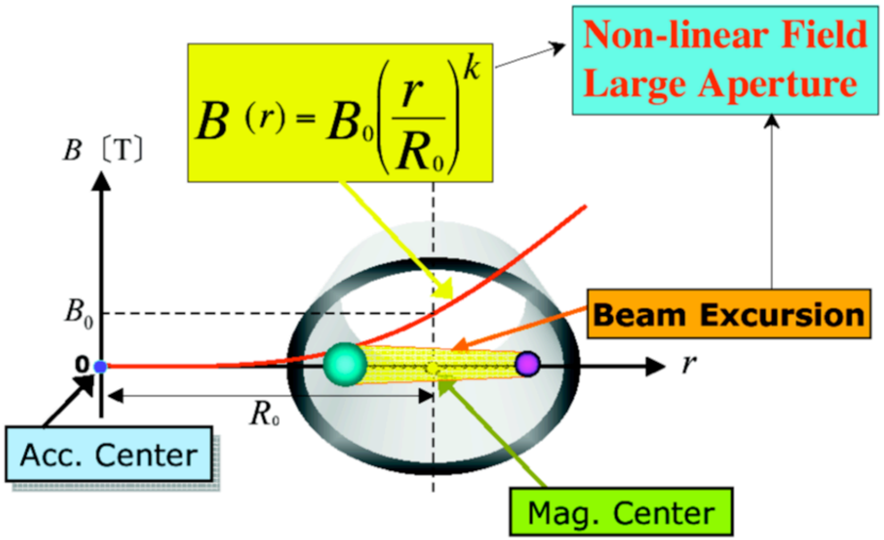
why?

What is FFAG? (1)

Difference from synchrotron

- FFAG is "Fixed Field Alternating Gradient".
  - People usually refer to FFAG focusing accelerator as "FFAG" although FFAG only specifies focusing scheme.

- Differences from a synchrotron is
  - Magnetic field is fixed, not ramped like a synchrotron.
  - Field profile is not linear.



What is FFAG? (2)
Difference from cyclotron

- FFAG looks similar to an azimuthal varying field (AVF) cyclotron, especially when the magnet edge has spiral shape.
  - Some people actually say that FFAG is one variety of a cyclotron.
- However, magnet field profile are shaped to keep the betatron tune constant and orbit shift (or excursion) small as possible, whereas a cyclotron as definition keep the revolution frequency constant called the isochronism.
- Since the revolution frequency changes, a beam has a pulse structure unlike continuous beam of cyclotron and similar to synchrocyclotron.

What is FFAG? (3)

High beam power machine

- Repetition rate can be higher because no need to ramp the magnets.
- Particles per bunch can be the same or larger because same magnitude of focusing in transverse as well as longitudinal is maintained and aperture (in horizontal) is larger.
- Output energy can be higher because magnet size is smaller.

	Repetition rate	(> synchrotron)
	x	
Beam power =	*Particles per bunch*	(~ synchrotron)
	x	
	Output energy	(> cyclotron)

What is FFAG? (4)

Fast acceleration with large beam

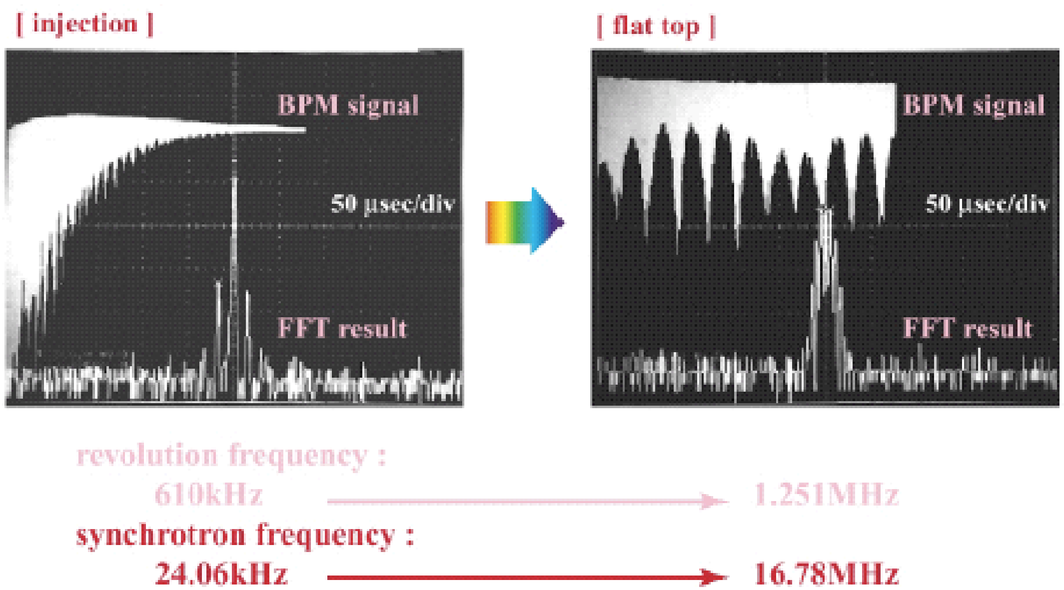
- Acceleration time can be quick if there is enough rf voltage like linac.
- Multiple use of rf voltage is cost effective like circular accelerator.
- Large transverse aperture and 100% momentum acceptance (injection and extraction momentum particles can stay at the same time) give enough room for a tertiary beam such as a muon beam.

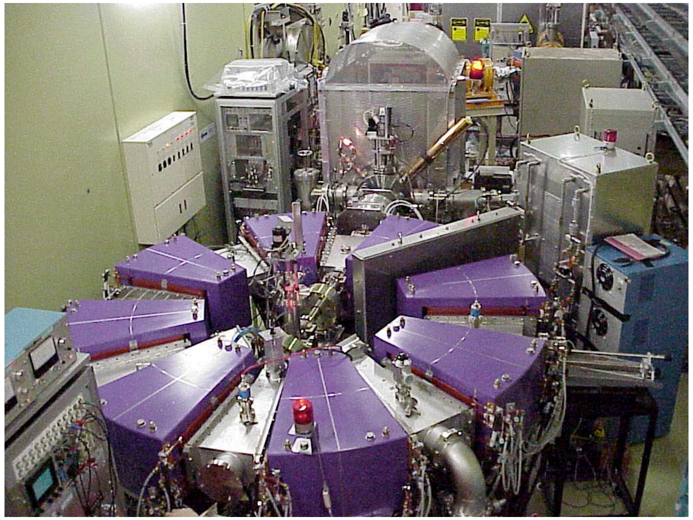
Status

Developments as a proton machine (1)

Demonstration at KEK, opening a new era

- 500 keV proton machine to prove a principle
  - Establish design procedure,
  - Confirm large aperture,
  - rf cavity with Magnetic Alloy and 1 kHz operation,
  - Proposal of many applications,
  - Create a community.



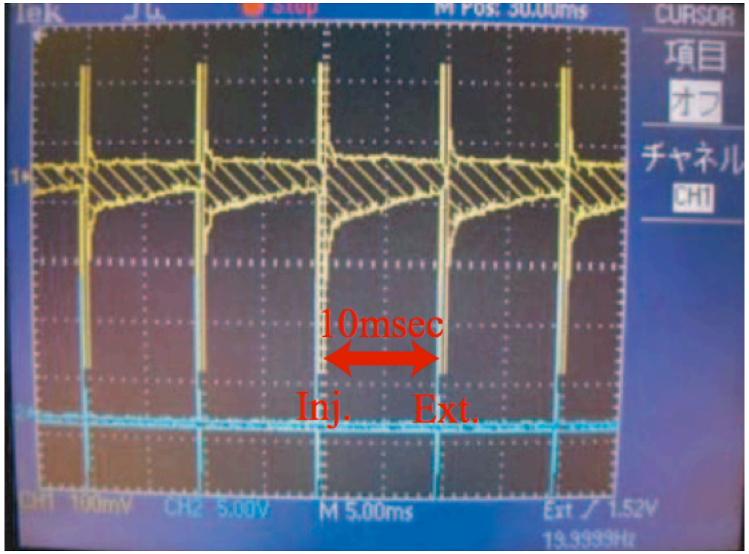


Developments as a proton machine (2)

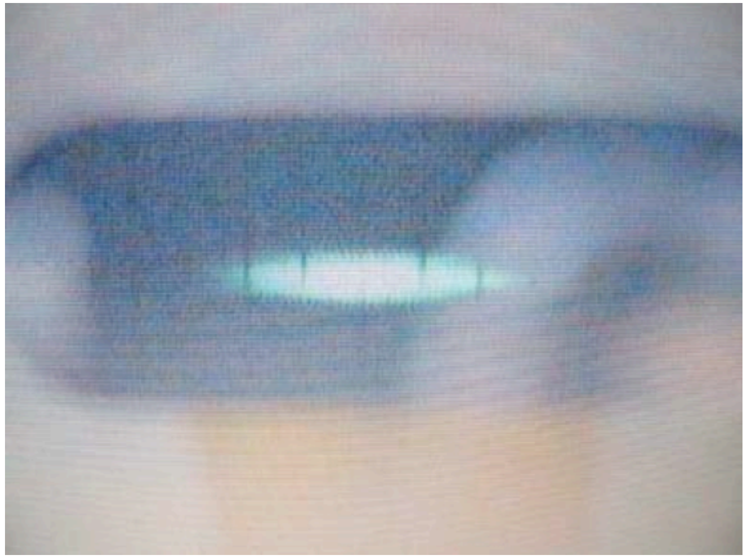
Prototype of medical machine

- 150 MeV proton machine to show its potential.

100 Hz operation



Beam extraction with 90% efficiency

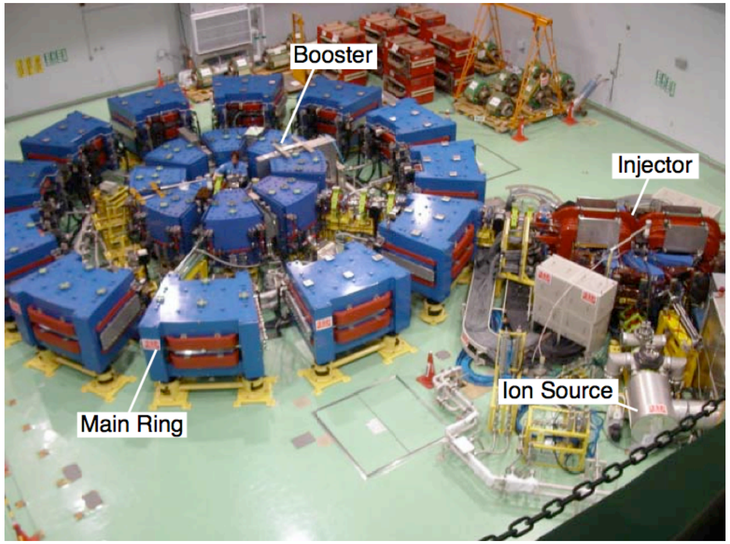


Developments as a proton machine (3)

Accelerator driven sub-critical reactor at KURRI

- Accelerator construction itself is not its final goal.
  - Take data of effective multiplication factor of 20 to 150 MeV.
- Three cascade FFAG to 150 MeV.
  - Variable output energy from 20 to 150 MeV.

Commissioning of the final machine is continued.



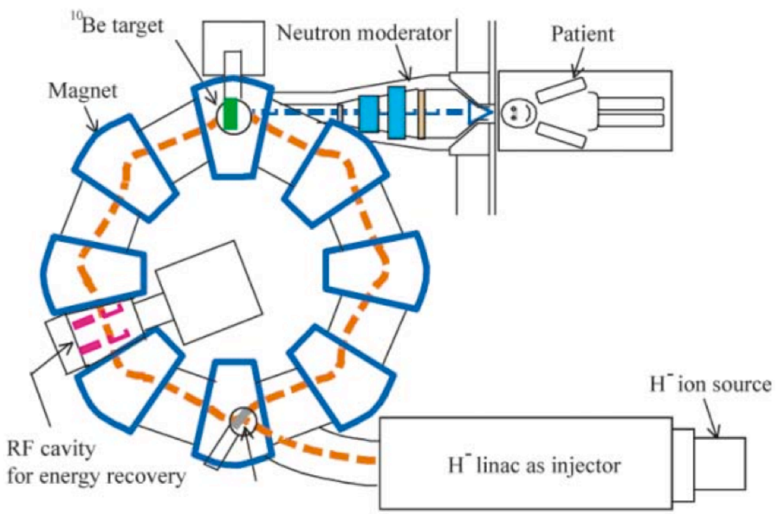
32 trim coils to change field index and output momentum.

Developments as a proton machine (4)

Compact *neutron source*

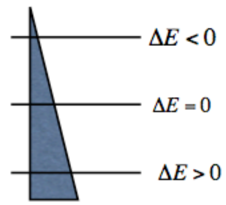
- ERIT: Energy recovery internal target.
- Be target for neutron production and for ionization "cooling".
- Comparable neutron yields as reactor.

Schematic view of ERIT-FFAG

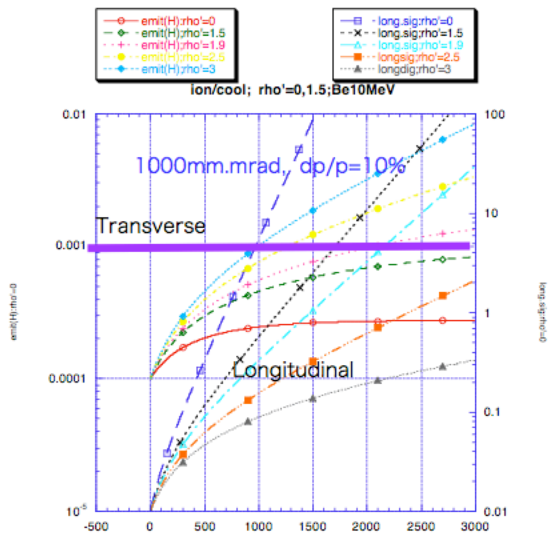


Emittance vs. turn number

wedge target



$$\frac{d\varepsilon}{ds} = A\varepsilon + B$$



Developments as a proton machine (5)

Summary

- Repetition rate is much higher than the conventional accelerator.
- Proof of high beam power will come soon.

Developments as a muon machine (1)

Phase rotation of muon beams

- Phase rotation to reduce momentum spread.
- No net acceleration, but huge transverse acceptance.

Table 1: Anticipated PRISM beam characteristics

Parameters	Design goal
Beam Intensity	$10^{11} - 10^{12} \mu^{\pm}$/sec
Muon kinetic energy	20 MeV
Kinetic energy spread	$\pm(0.5 - 1.0)$ MeV
Beam Repetition	100 - 1000 Hz
Pion contamination	$< 10^{-18}$

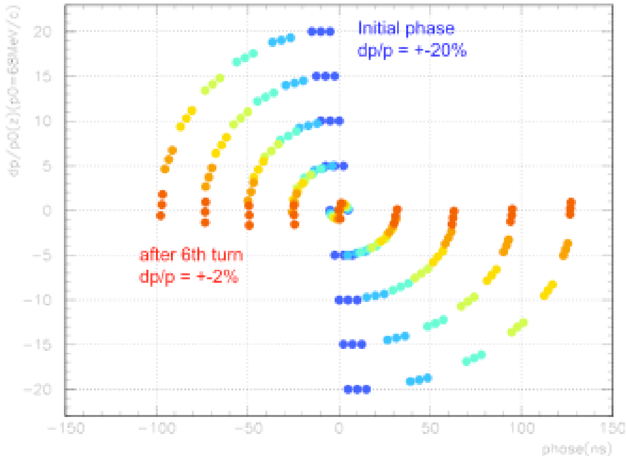


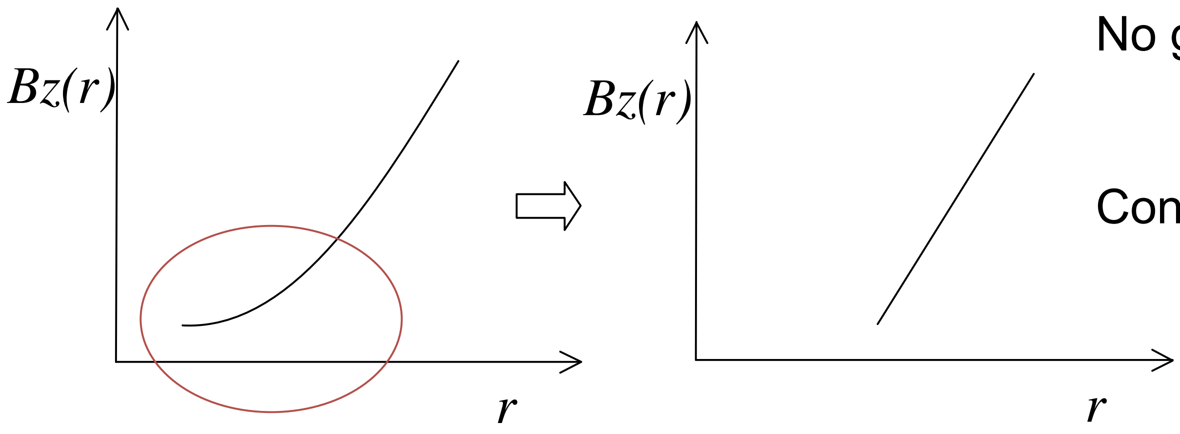
Table 2: Parameters of PRISM-FFAG

No. of sectors	10
Magnet type	Radial sector DFD triplet C-shaped
Field index (k-value)	4.6 (variable 4.4-5.2)
F/D ratio	6.2 (variable 4-8)
Opening angle	F/2 : 2.2deg. D : 1.1deg.
Aperture	H 100cm x V 30cm
Average radius	6.5m for 68MeV/c
Tune	horizontal : 2.71 vertical : 1.52

Developments as a muon machine (2)

Making a magnet smaller

- The final energy of muon is 20 to 50 GeV.
- Magnet aperture should be as small as possible.



No gentle slope at low momentum.

- Orbit excursion is shorter.

Constant gradient.

- Linear magnet.

- Field gradient does not scale to momentum. Tune change as a beam is accelerated.

Developments as a muon machine (3)

Resonance crossing

- Tune change and crosses integer and half-integer resonances.

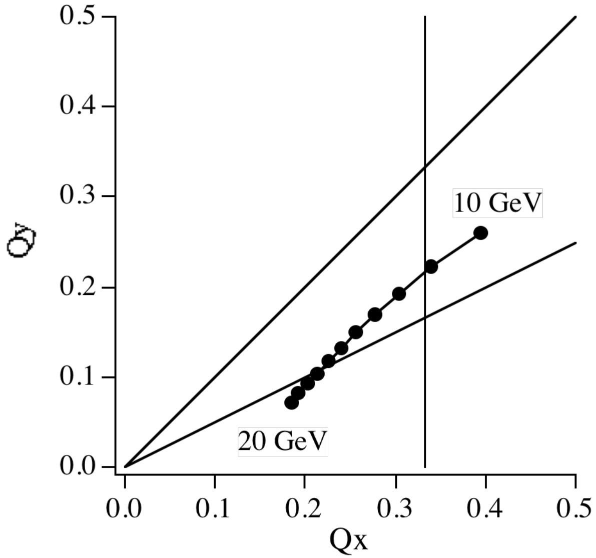


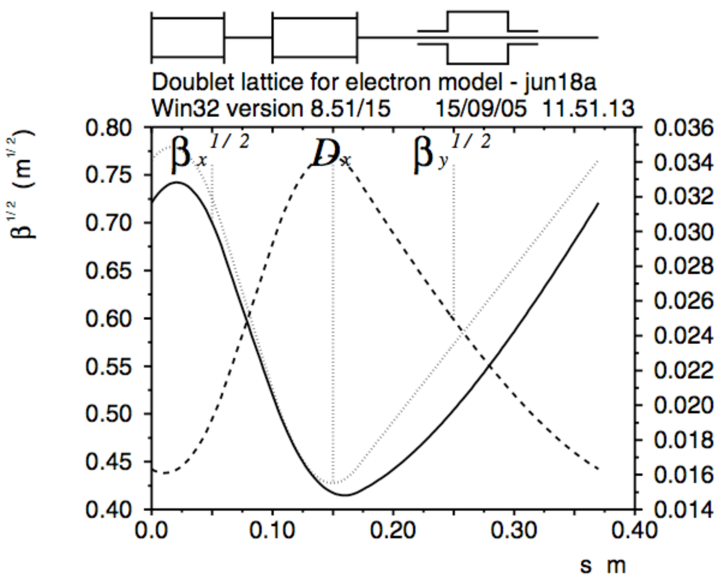
Figure shows tune per cell. With 84 cells per ring, the integer part of total tune changes from 33 to 15.

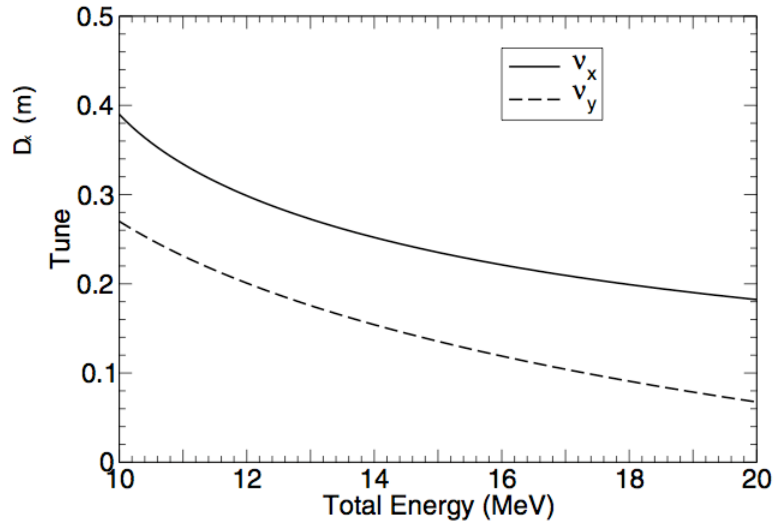
- It may not be a problem if acceleration is very fast.

Developments as a muon machine (4)

New idea: nonscaling FFAG

- Nonscaling FFAG uses only dipole and quadrupole, namely synchrotron without ramping magnets.
- Conventional one is called "scaling" FFAG.
- Make the dispersion function as small as possible to squeeze beam orbit shift and magnet aperture.





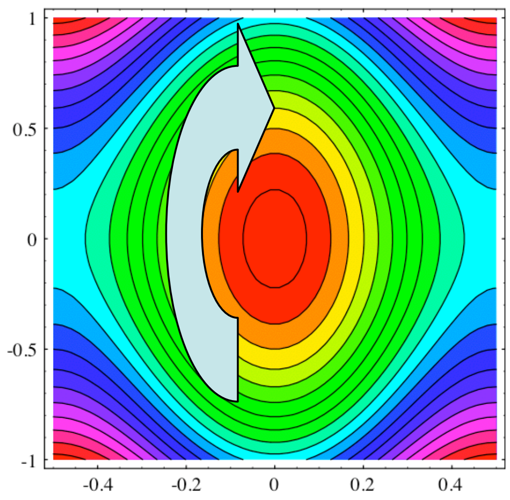
Developments as a muon machine (5)

acceleration with constant rf frequency

- rf frequency cannot be modulated in 10 to 20 turns.
- Fix the rf frequency and accelerate a beam either
  - (1) in a huge rf bucket, or
  - (2) outside buckets.

Low frequency with scaling

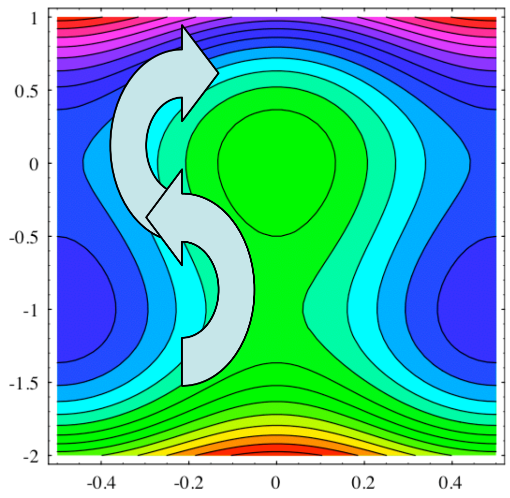
dp/p (normalized)



Phase (1/2 pi)

High frequency with nonscaling

dp/p (normalized)



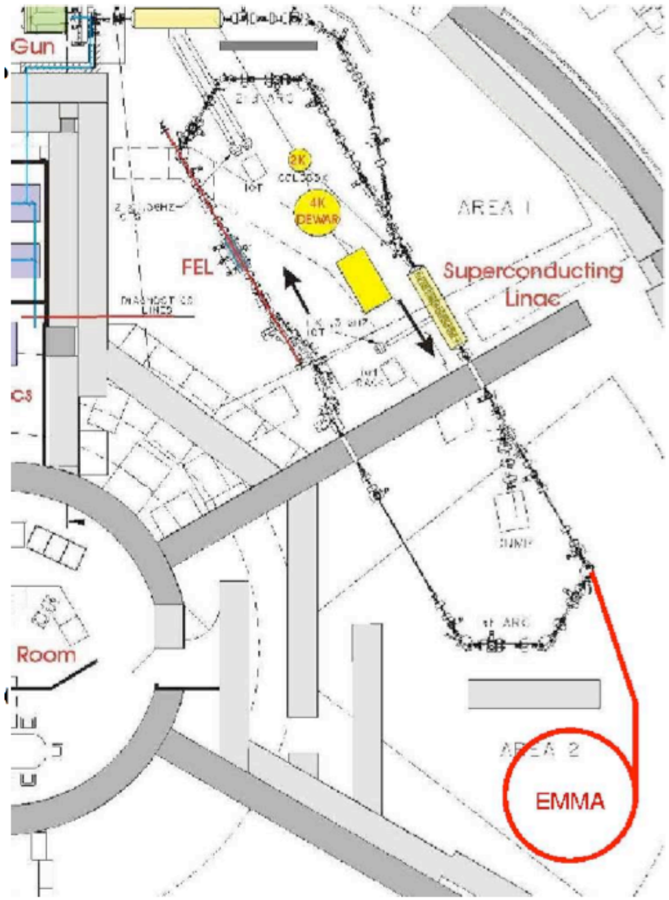
Phase (1/2 pi)

Developments as a muon machine (6)

Electron model: EMMA

- Construction of an electron model of nonscaling FFAG will start at Daresbury Laboratory soon.
  - Acceleration outside buckets
  - Resonance crossing
  - Large aperture

Energy:	10 to 20 MeV
Acceptance:	3,000 π mm mrad
Circumference:	16 m
# of cell:	42
# of turn:	12
rf voltage:	~30 kV/cell
rf frequency:	1.3 GHz

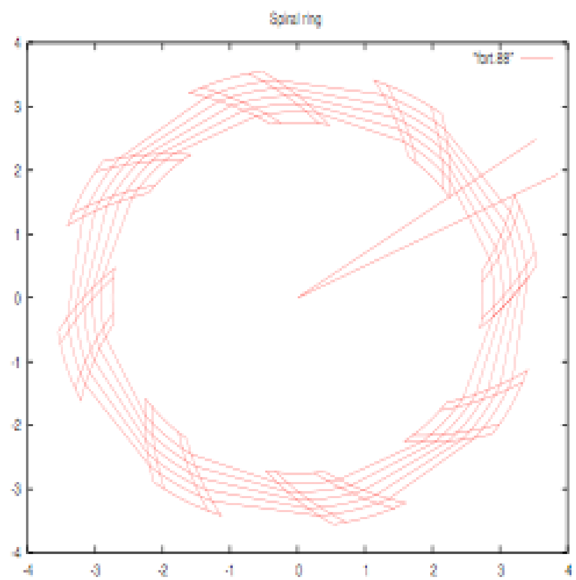


Developments as a muon machine (7)

Another FFAG project : RACCAM

- LPSC starts RACCAM project
  - Participate to the on-going international collaboration.
  - Design and build a prototype of FFAG magnet.
  - Develop the concepts and show the feasibility of the application such as FFAG beams to anti-cancer hadron therapy.

Nb cells	8	
K	3.50	
ξ	50.0	(deg.)
pf	0.400	
r_1 / r_2	2.74 / 3.60	(m)
E_1 / E_2	17.0 / 180.	(MeV)
p_1 / p_2	179. / 608.	(MeV/c)
$B\rho_1$ / $B\rho_2$	0.598 / 2.03	(T.m)
Dip. sector angle	18.0	(deg.)
Dip. bend angle	45.0	(deg.)
Drift L, inj.	1.29 -2×0.15	(m)
Drift L, xtr.	1.70 -2×015	(m)



Developments as a muon machine (8)

Summary

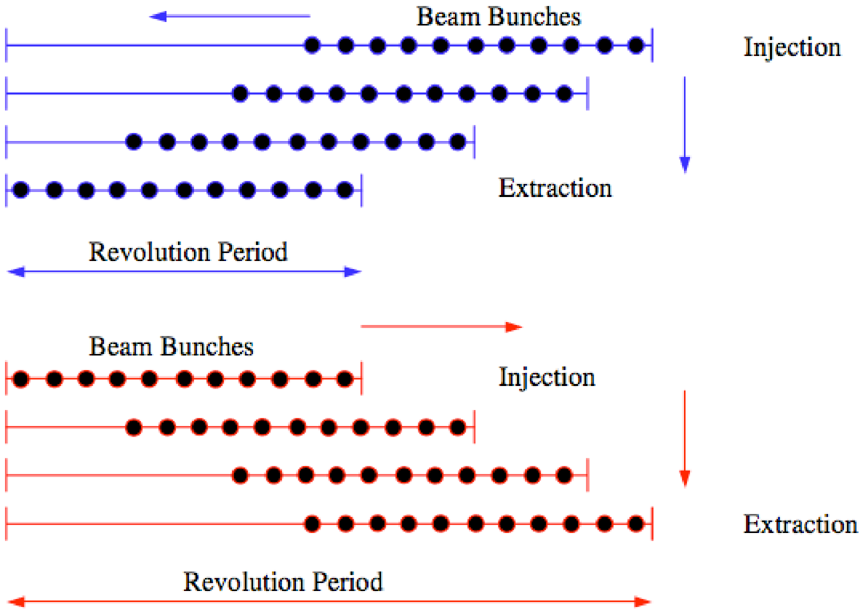
- Development as a muon machine is a bit behind that of a proton machine.
- Construction projects have been started and experimental results will come soon.

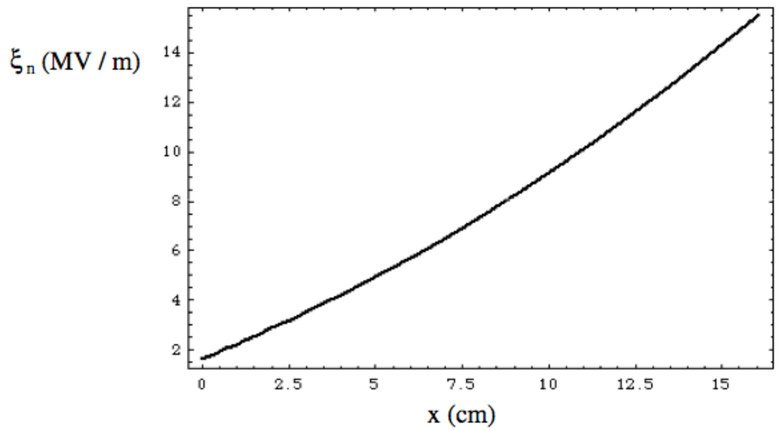
Accelerator physics issues

Accelerator physics issues (1)

Harmonic number jump

- Continuous operation with constant rf frequency is possible (A. G. Ruggiero, Phys. Rev. ST 100101, 2006).
- A bunch is captured in a bucket with different harmonic number turn by turn.
- Energy gain has to be adjusted in radial direction.

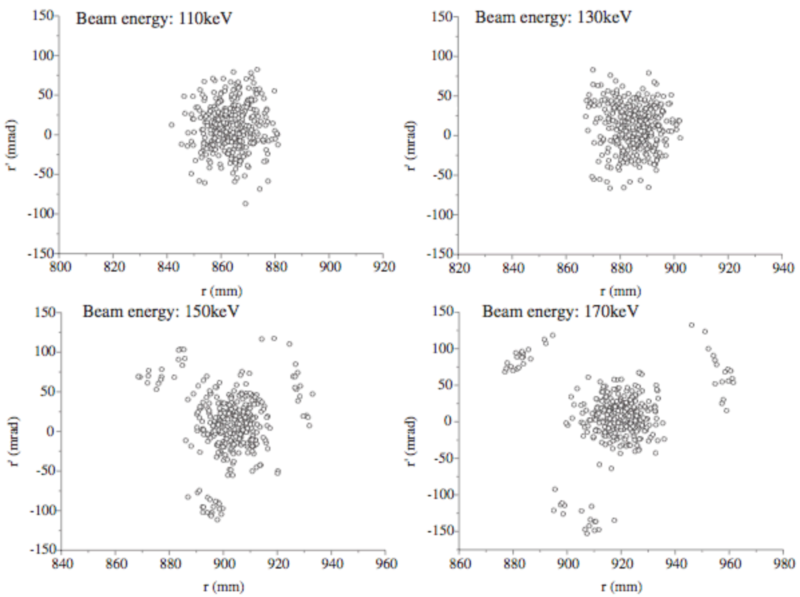




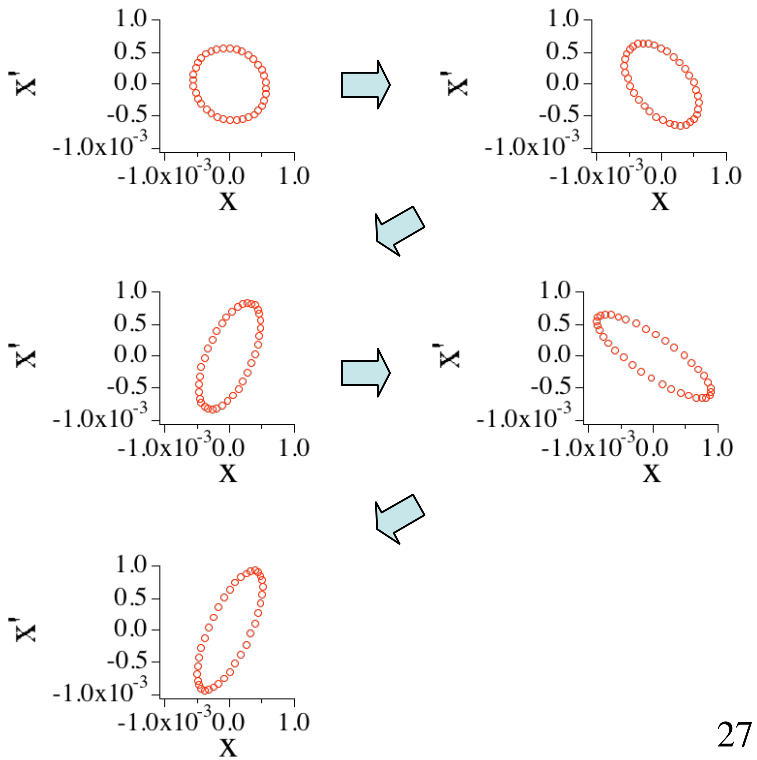
Accelerator physics issues (2)

Resonance crossing

- Nonlinear resonance in scaling FFAG.
  - Particle trapping model (Aiba, Phys. Rev. ST. 084001, 2006).
  - Adiabatic parameter ~7.



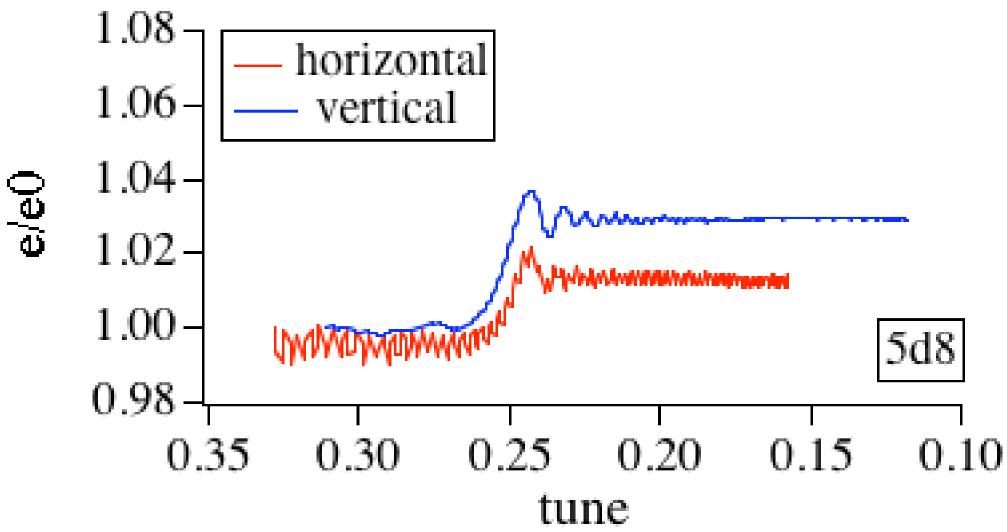
- Linear resonance in nonscaling FFAG.
  - Beam is tumbling due to gradient mismatch.

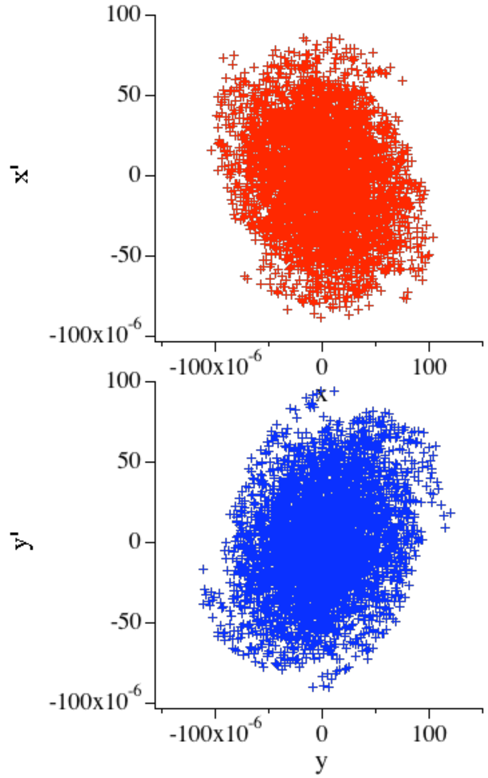


Accelerator physics issues (3)

Crossing of space charge induced resonance

- A beam cannot cross a resonance excited by its self space charge force (S. Y. Lee, Phys. Rev. Lett. 97, 2006).
- $q_{x,y}$(cell tune)=0.25 is an intrinsic resonance of $4q_{x,y}=1$.

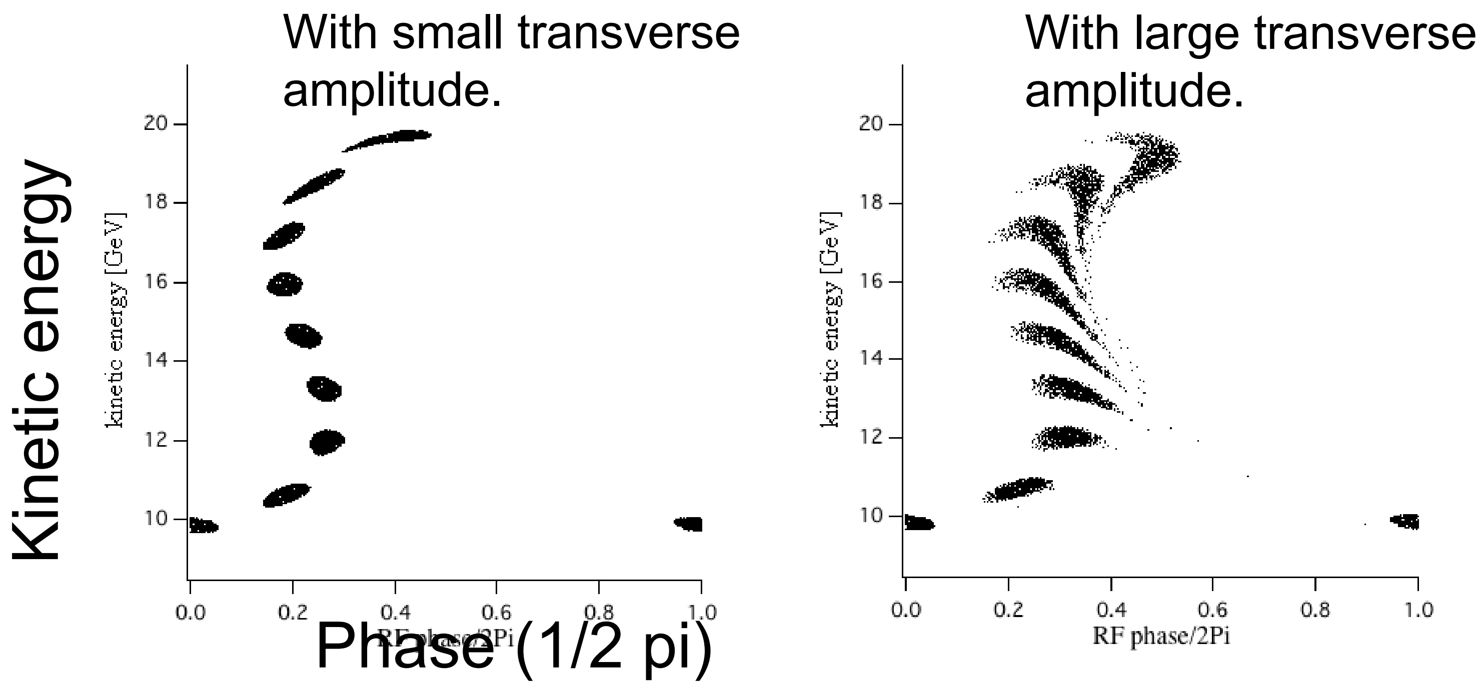




Accelerator physics issues (4)

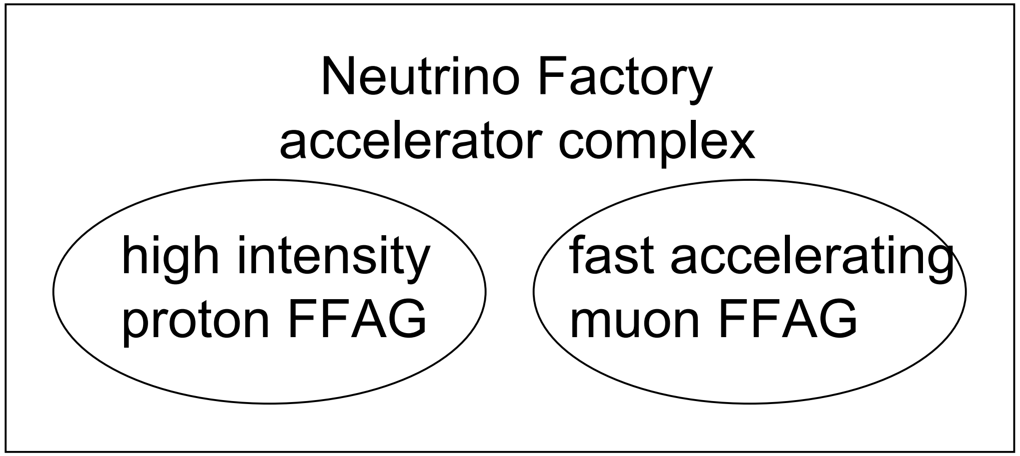
ToF depends on transverse amplitude

- When particles are accelerated outside buckets, energy gain becomes a function of transverse amplitude (Machida, Phys. Rev. ST 100402, 2006).
- Chromaticity control reduces the effects, but also reduction of aperture (Berg, Nucl. Instr. Meth., 2006).



Summary

Neutrino factory and FFAG
and beyond



- Medical machine
- Transmutation/ Energy breeder
- Compact neutron source

- Experimental apparatus (PRISM)
- Acceleration of unstable nuclei

- New optics
- New way of acceleration
- Understanding resonance
- Code development