# ISS Accelerator Working Group Summary and Future Plans

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BNL

ISS Meeting
KEK

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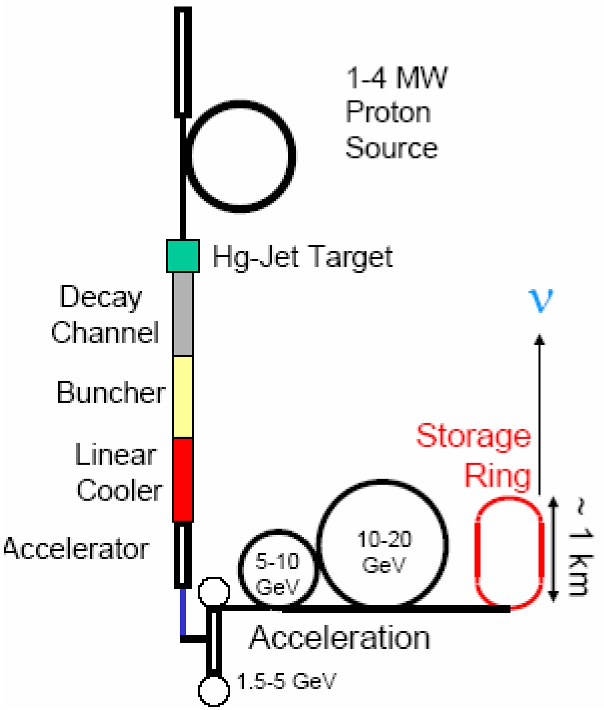
# Outline

- proton driver
- targetry and π production
- front end
- muon acceleration
- storage ring




- I will concentrate here on recent activities
- a comprehensive overview was given by Chris Prior at CERN
- his talk includes many topics that are not covered here

# Proton driver: overview

- which PD type is best suited to meet neutrino factory requirements?
- some important issues
  - beam current limitations
  - creation of short bunch
  - repetition rate limitations
  - space charge
  - tolerances
- PD design tied to downstream constraints (pulse structure & frequency)

- most PD designs based on lab-specific, multipurpose machines
- some of the new designs use FFAGs

# Proton driver designs

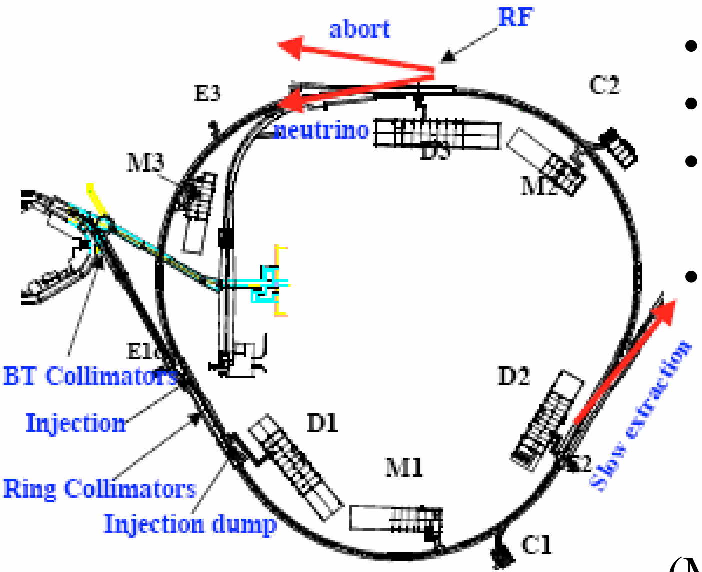
| | | | | |
|---|---|---|---|---|
| 1. | SPL | 3.5 GeV | 50 Hz | 4 MW |
| 2. | JPARC | 50 GeV | 0.33 Hz | 0.6 -> 4 MW |
| 3. | AGS | 24 GeV | 0.5 Hz | 0.2 -> 4 MW |
| 4. | FNAL SCL | 8 GeV | 10 Hz | 0.5 -> 2 MW |
| 5. | RAL RCS | 5 GeV | 50 Hz | 4 MW |
| 6. | RAL RCS | 15 GeV | 25 Hz | 4 MW |
| 7. | RAL FFAG | 10 GeV | 50 Hz | 4 MW |
| 8. | KEK/Kyoto | 3 GeV | 1 kHz | 1 MW |
| 9. | A. Ruggiero FFAG | 12 GeV | 100 Hz | 18 MW |
| 10. | A. Ruggiero FFAG | 1 GeV | 1 kHz | 10 MW |
| 11. | ......... | | | |

# JPARC

## 50 GeV Synchrotron (Main Ring)

- Imaginary Transition γ
- High Gradient Magnetic Alloy loaded RF cavity
- Small Loss Slow Extraction Scheme
- Both Side Fast Extraction for Neutrino and Abort line
- hands on maintenance scheme for small radiation exposure

| | |
|---|---|
| •Injection Energy | 3GeV |
| •Output Energy | 30GeV (slow)<br>40GeV (fast)<br>50GeV (Phase II) |
| •Circumference | 1567.5m |
| •Beam Power | 0.75MW (Phase II)<br>>2MW(future) |
| •Particles | $3.3\times10^{14}$ ppp |
| •Repetition | 0.3Hz |
| •Harmonic | 9 |
| •Bunch Number | 8 |
| •Nominal Tune | (22.4, 20.8) |




- initial linac 0.18 GeV
- uses 3 GeV booster
- upgrade power by increasing rep rate
- main ring commissioning in May 2008

(M. Tomizawa, Y. Mori)

# CERN SPL

- major upgrade of p injector complex {SB, βB, NF}
- 2x beam brightness, improved reliability
- 3 MeV test stand in 2008, 160 MeV Linac4 in 2010
- uses 704 MHz bulk-Nb cavities

- for a ν factory [4 MW beam @ 4-10 GeV] ⇒

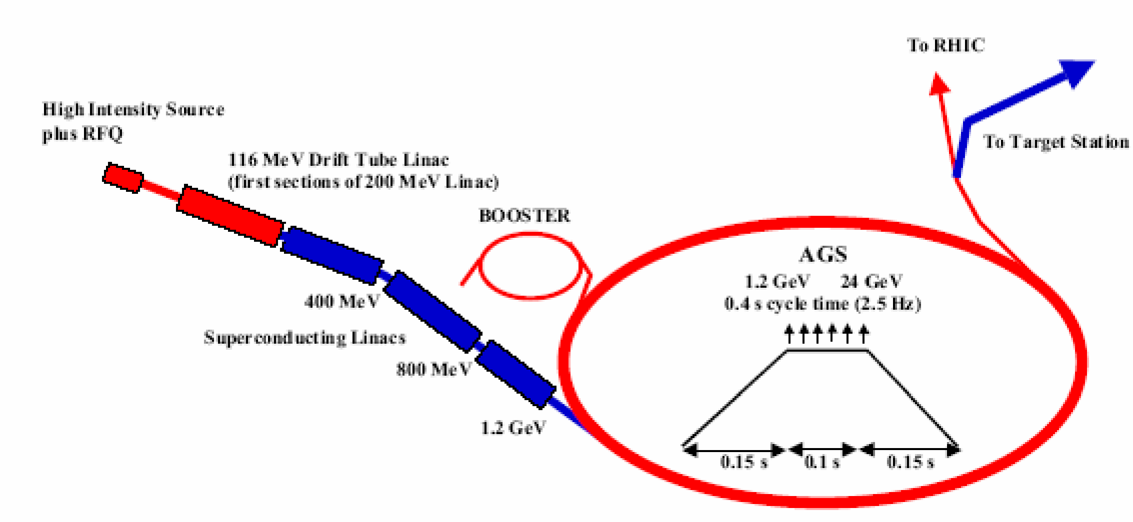
Short beam burst (~μs)
⇒ accumulator
\+
Short bunches (~ns)
⇒ compressor

The requirements of a ν factory are the most demanding.

- more work needs to be done to determine
  if it can meet NF requirements

| | |
|---|---|
| ion species | H- |
| energy | 3.5 GeV |
| power | 4 MW |
| < I > | 40 mA |
| pulse duration | 0.57 ms |
| peak RF power | 163 MW |
| repetition rate | 50 Hz |

# AGS Upgrade to 1-4 MW




Alternative scheme with 1.5 GeV FFAG injector to AGS

- 1.2 GeV superconducting linac extension for direct injection of $\sim 1 \times 10^{14}$ protons

  low beam loss at injection; high repetition rate possible

  further upgrade to 1.5 GeV and $2 \times 10^{14}$ protons per pulse possible (x 2 power)

- 2.5 Hz AGS repetition rate

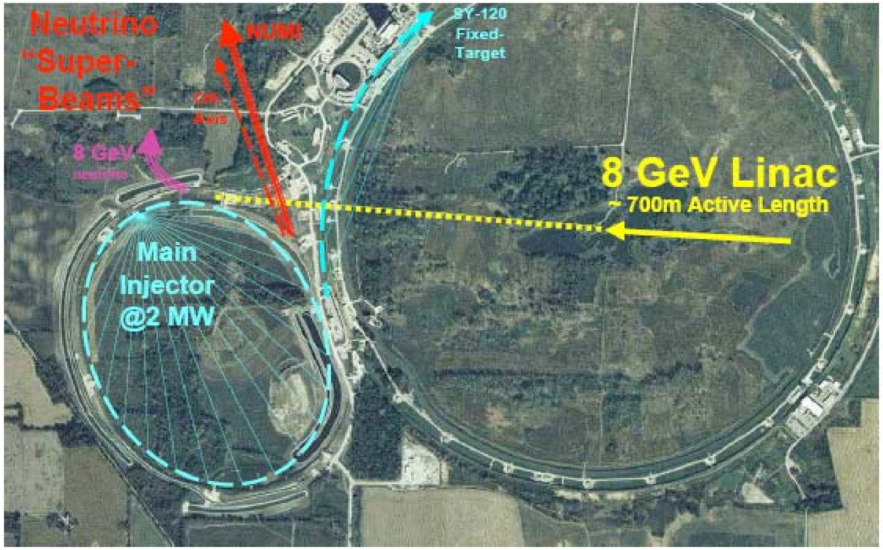
  triple existing main magnet power supply and magnet current feeds

  double rf power and accelerating gradient

  further upgrade to 5 Hz possible (x 2 power)

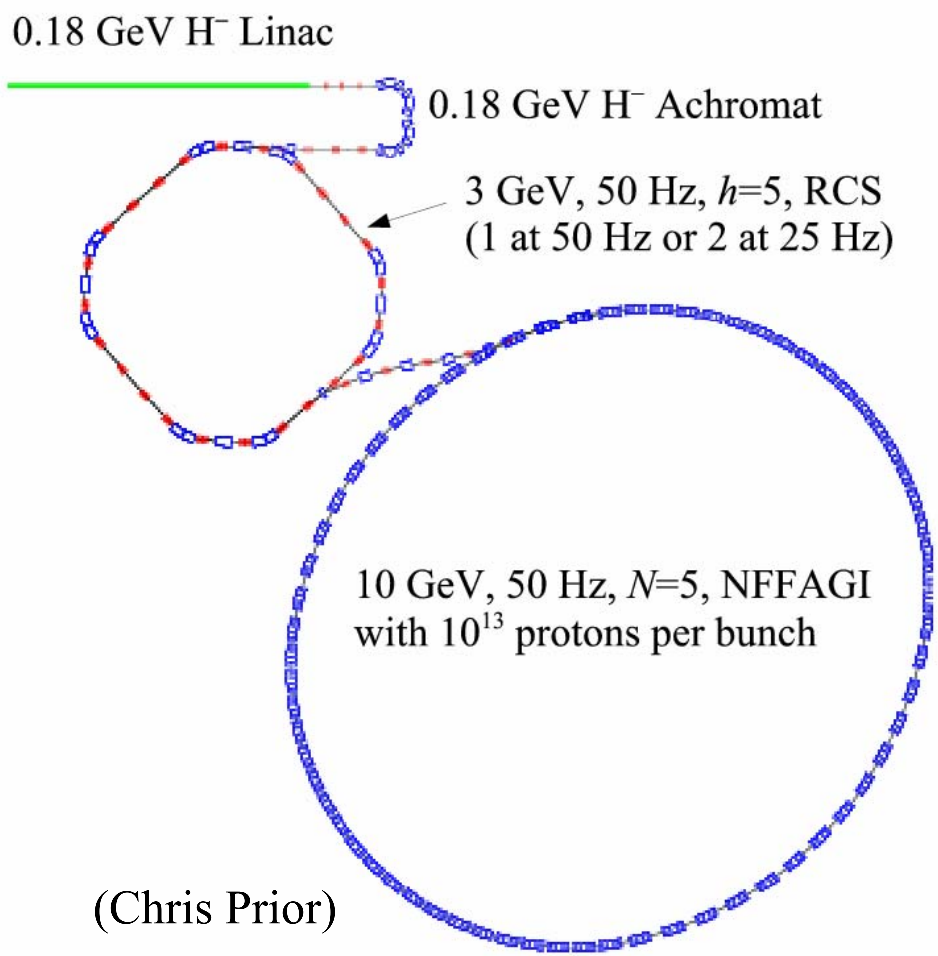
# FNAL 8 GeV linac

| | |
|---|---|
| power | 2 MW |
| kinetic energy | 8 GeV |
| pulse frequency | 10 Hz |
| pulse length | 1 ms |
| peak current | 28 mA |
| RF frequency | 1300 MHz |
| klystrons | 33 |




- stripping of $H^-$ is an issue
  blackbody, magnetic, residual gas
- needs RF amplitude & phase correction
  before injection into MI, ~1.5 km?
- needs accumulator ring for NF

# RAL 4 MW FFAG Proton Driver




(Chris Prior)

- RAL design
- 5 bunches per pulse
- 50 Hz repetition rate
- 10 GeV
- FFAG with insertions

- RF system naturally gives 2 ns rms pulse
- need to add 6th harmonic to get 1 ns rms

# Proton driver: plans

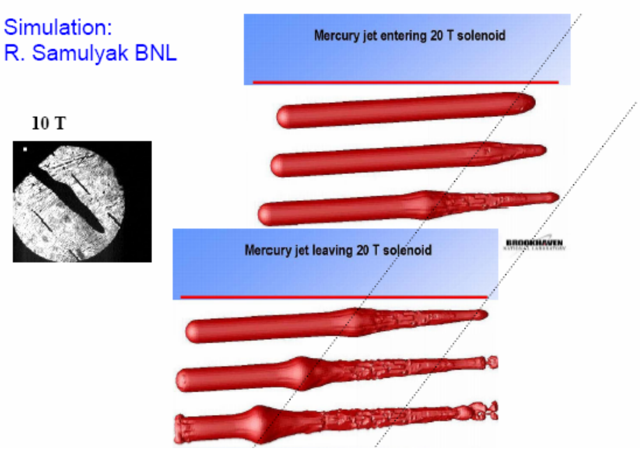
- identify issues for producing short (~1-3 ns rms) bunches
- define parameters for bunch compression ring or transport line
- evaluate space charge issues
- look at implications of pulse structure

# Targetry and π production: overview

- what is the optimum target material for 4 MW?
- what constraints limit target operation at 4 MW?
  e.g. proton bunch intensity, repetition rate
- driver/target/capture systems need to be jointly optimized to get the maximum number of neutrinos at the detectors
- new pion production/collection simulations (Brooks, Kirk)

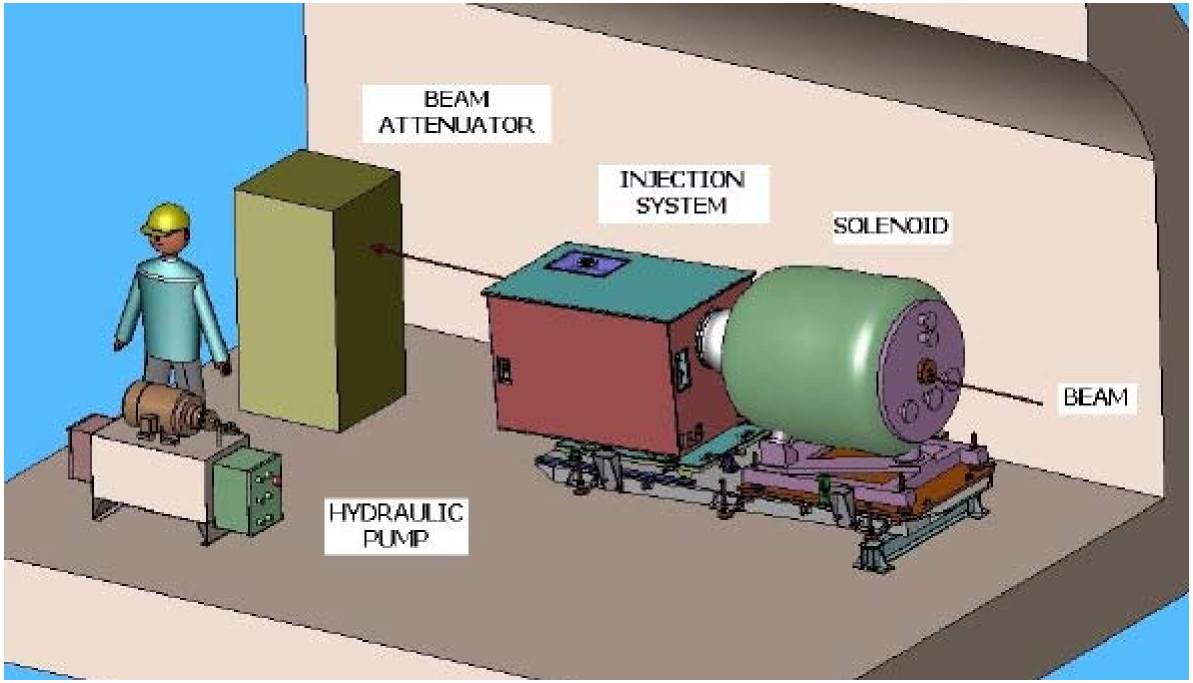
# Liquid target issues

- liquids may be only practical choice above 2 MW
- mercury, molten metals
- MERIT experiment at CERN will demonstrate feasibility of mercury jet target
  - uses parameters relevant to neutrino factory targets
  - instantaneous energy deposition corresponding to 4 MW beam
  - 20 m/s jet velocity
  - 15 T solenoid field (US, KEK) or 0 T (CERN)
  - active simulation effort to understand jet dynamics



# MERIT experiment at CERN

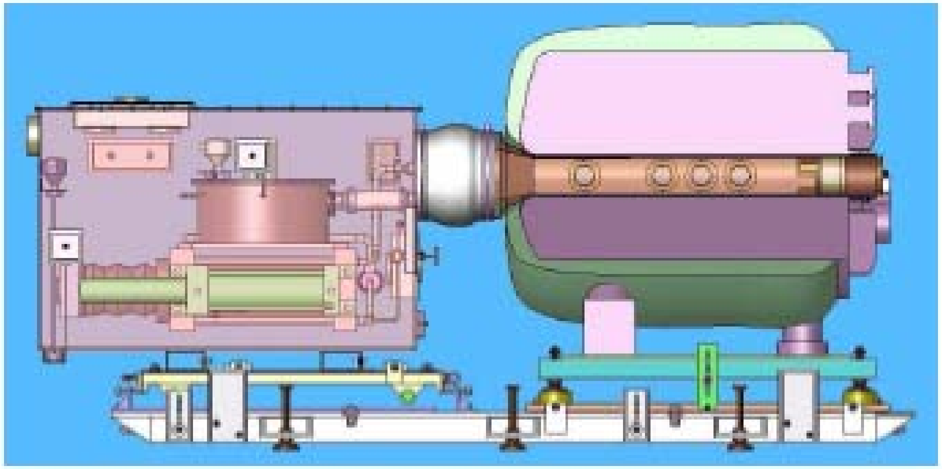
- MERIT (MERcury Intense Target )
  - PS 24 GeV beam, 2.8 $10^{13}$ protons on 1.2 mm × 1.2 mm beam spot
  - Peak energy deposition 180 J/g
  - Beam on target April 2007



# MERIT recent developments

- project reviewed on 12 December 2005
- pulsed solenoid completed and delivered to MIT
- demonstrated rad-hard optical diagnostic fibers at CERN
- angle of jet to solenoid changed to 33 mrad to give same jet aspect ratio as NF
- set operating temperature at 80 K (reduced cost)
- good agreement between experiment & ANSYS on Ti-Al-V beam windows

15 T pulsed solenoid in cryostat



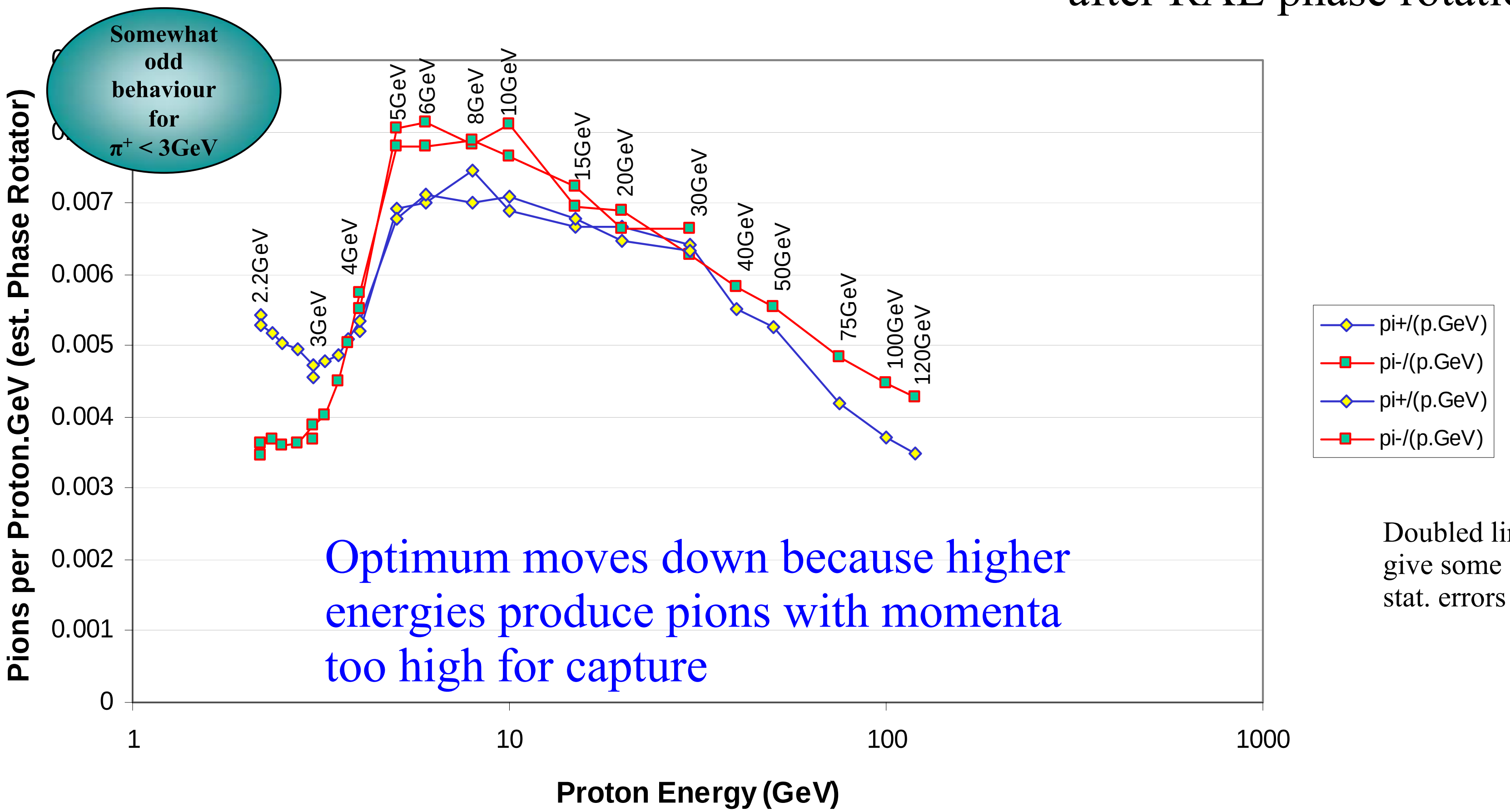
Mercury jet delivery system

# Solid target issues

- shock is a major issue
  - radial & longitudinal stress waves
- need to understand material properties under irradiation
  - e.g. strength, thermal expansion changes
- need to control heat flow from target
  - forced He cooling
  - radiation cooling (levitated ring)
  - providing new material for each proton pulse
    - e.g. rotating band, bullets

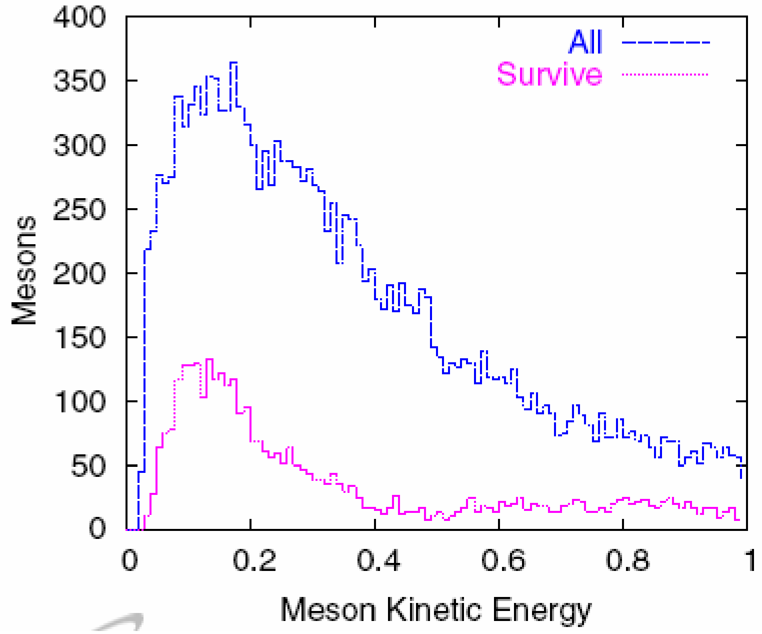
# π production on Ta

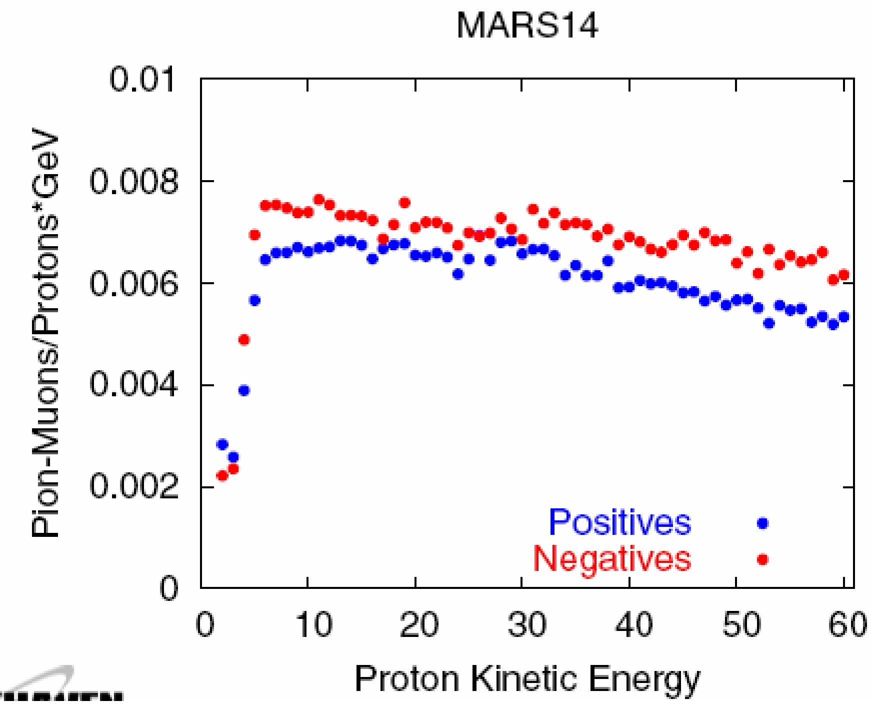
S. Brooks using MARS15
after RAL phase rotation




Doubled lines give some idea of stat. errors

# Pion production on mercury




(H. Kirk)

after US Study 2a
cooling channel

# Targetry and π production : plans

- assess minimum acceptable proton beam rep rate at 4 MW
- evaluate possibility of realistic solid targets

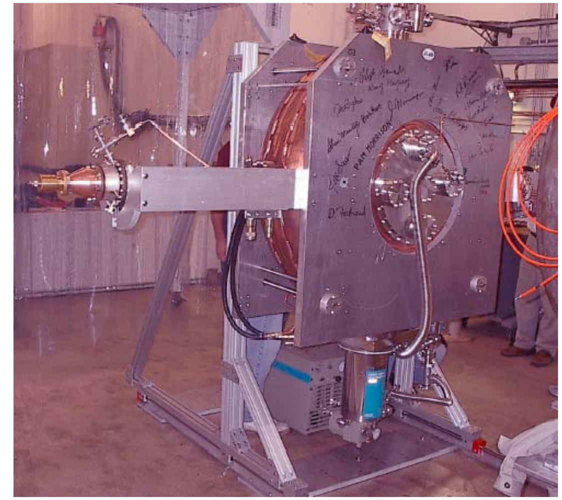
  e.g. rod, band, pellet, granular
- continue study of π production for intermediate-Z targets
- incorporate HARP/MIPP results for π production

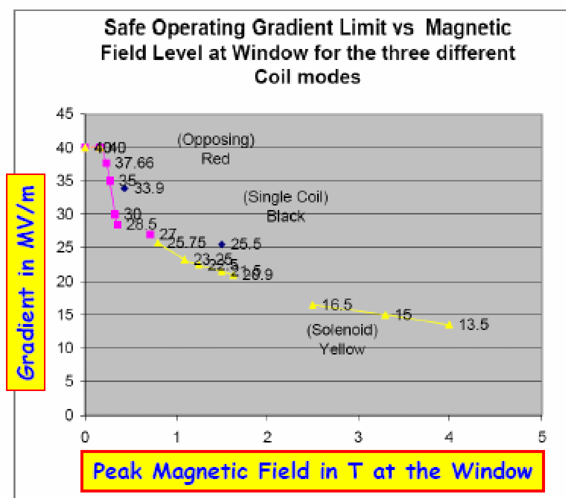
# Front end: overview

- front end = {π collection, bunching, phase rotation, cooling}
- comparison of existing designs
  - US study 2b, CERN, KEK
- examine new FE ideas
- improve theoretical understanding
- experimental program examining important R&D issues

# MUCOOL R&D

- MUCOOL: design, prototype and test
  cooling channel components
- Muon Test Area completed at FNAL
- 805 MHz cavity installed
  high power testing underway
- 201 MHz cavity delivered
  final hook up underway
- 400 MeV p beamline has been designed
- R&D program underway to understand
  RF breakdown
- effect of magnetic field on maximum
  gradient is important design issue



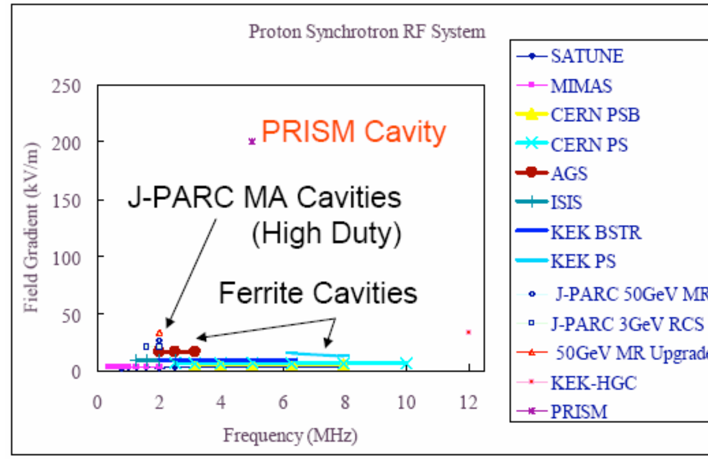


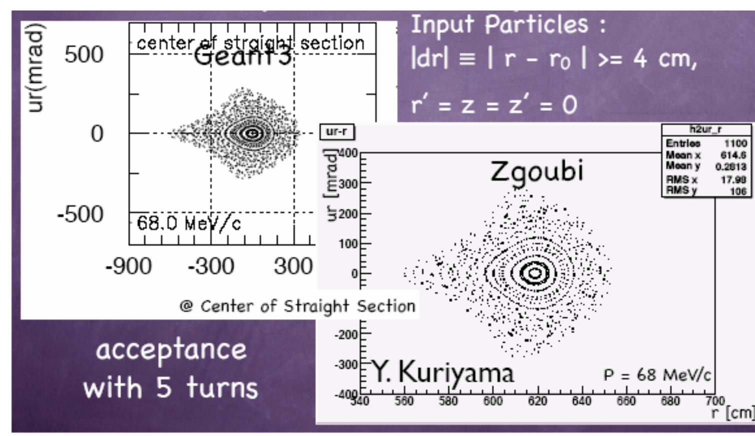

(A. Bross)

# PRISM update

(A. Sato)

- Phase-rotated intense slow μ source
- FFAG ring under construction
- designing injection line & detector
- FFAG ring commissioning in 2007
- RF cavity: achieved ~170 kV/m at 5 MHz
- studying vertical injection/extraction
- doing detailed tracking now
  - dynamic aperture
  - backgrounds for physics

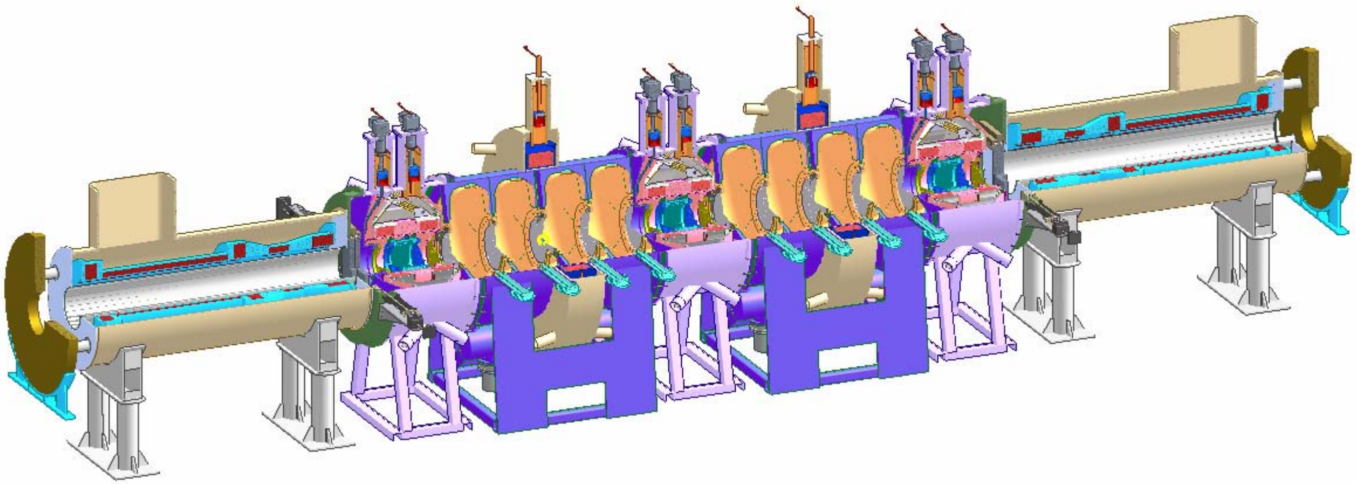


# MICE

- ionization cooling channel demonstration experiment at RAL
- first beam to “step I ” of experiment in April 2007
- tested cryostat for hydrogen absorber
- SciFi tracker test at KEK was successful
- plan to test MICE production target in ISIS June 2006
- design completed for spectrometer solenoids

(M. Yoshida)



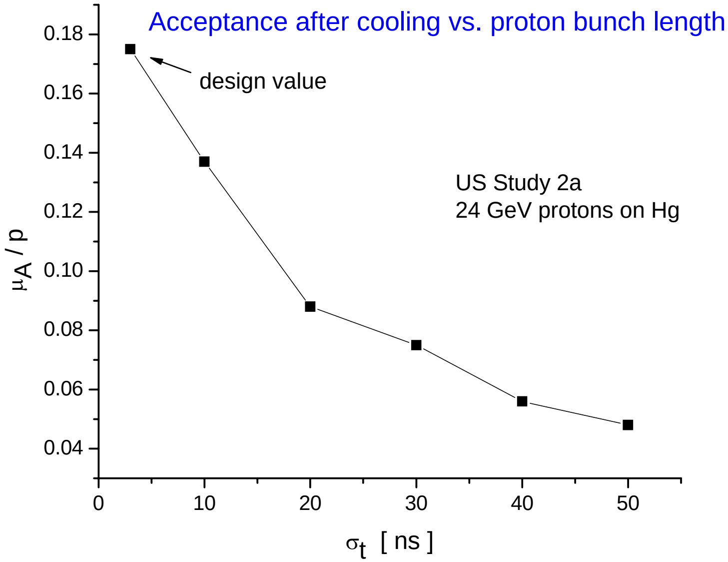
# Beam-target survey

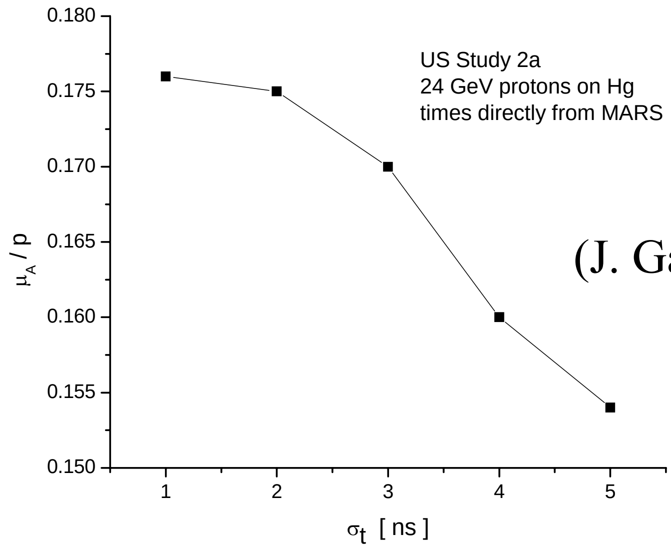
| $E_b$ [GeV] | target | L [cm] | $\mu_A$/p GeV | $\mu_A$/p GeV |
|---|---|---|---|---|
| | | | US 2a | CERN88 |
| 4 | C | 66 | 0.0114 | 0.0015 |
| 4 | Hg | 25 | 0.0066 | 0.0009 |
| 10 | Ta | 20 | 0.0087 | 0.0014 |
| 40 | C | 66 | 0.0043 | 0.0007 |
| 40 | Hg | 25 | 0.0068 | 0.0011 |

- positive muons
- using standard beam files from Stephen Brooks
- cf. US Study 2a had 0.007 $\mu_A$ / p / GeV

# Effect of proton bunch length

- it is important for proton driver to deliver a short pulse ~3 ns rms
- performance degrades rapidly for longer pulses
- easier to phase rotate higher energy particles if pulse ~1 ns rms



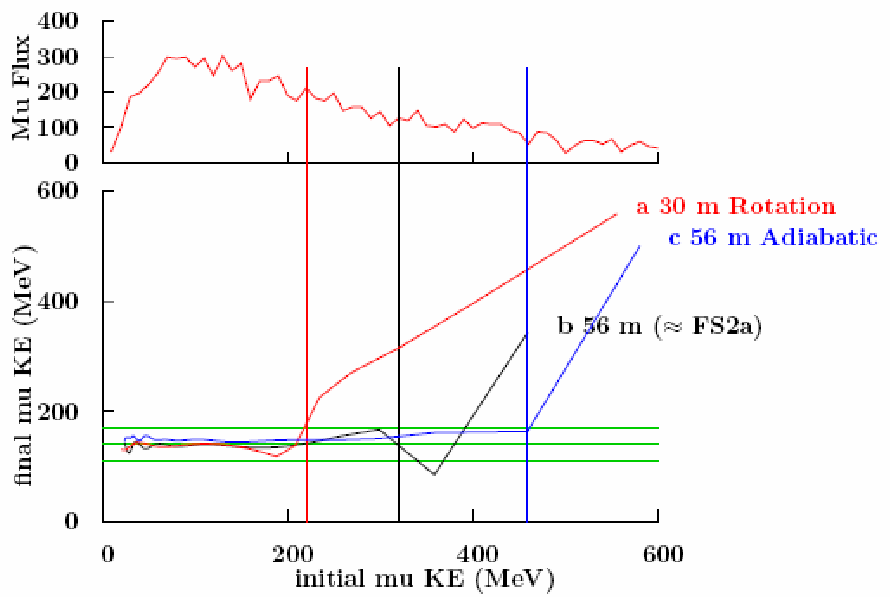

(J. Gallardo, H. Kirk)

(US Study 2a, 24 GeV p on Hg)

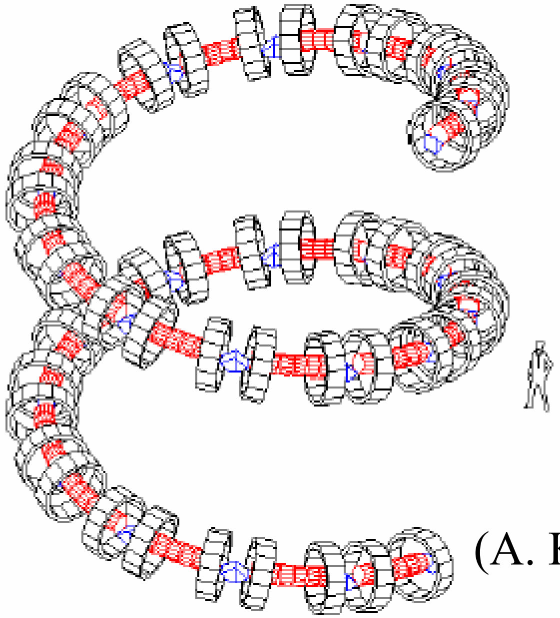
# 1D model of phase rotation

- try to better understand optimum parameter choice for variable
  frequency phase rotation
- shorter rotator doesn't have enough integrated gradient
  lose higher energy tracks
- phase rotation works better if reference particle momenta
  are changed adiabatically

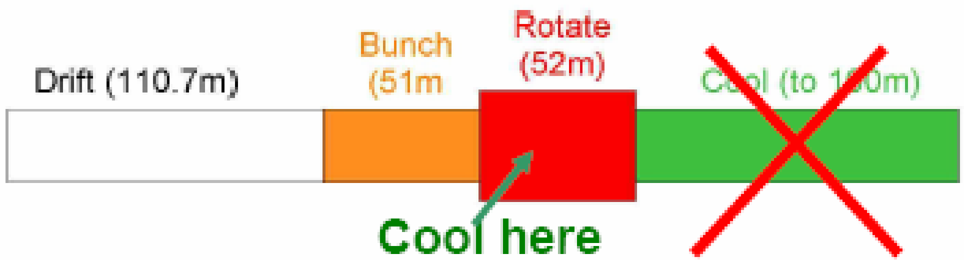
(R. Palmer)



# New configurations


(A. Klier)

- "Guggenheim" cooling channel
- provides longitudinal cooling
- solves problems with injection, absorber heating
- can taper parameters




(D. Neuffer)

- cool while doing phase rotation
- cost savings
- 150 atm hydrogen (room temp)
- 24 MV/m RF
- performance looks promising

# Cooling versus accelerator acceptance

- can we save money by reducing amount of cooling and increasing accelerator acceptance?
- present work depends on cost model for non-scaling FFAGs by J.S. Berg
- still needs more work on unresolved issues

    cost modeling for other accelerator systems

    effects of FFAG acceptance loss with $A_T$

    trade-off between amount of cooling and detector size

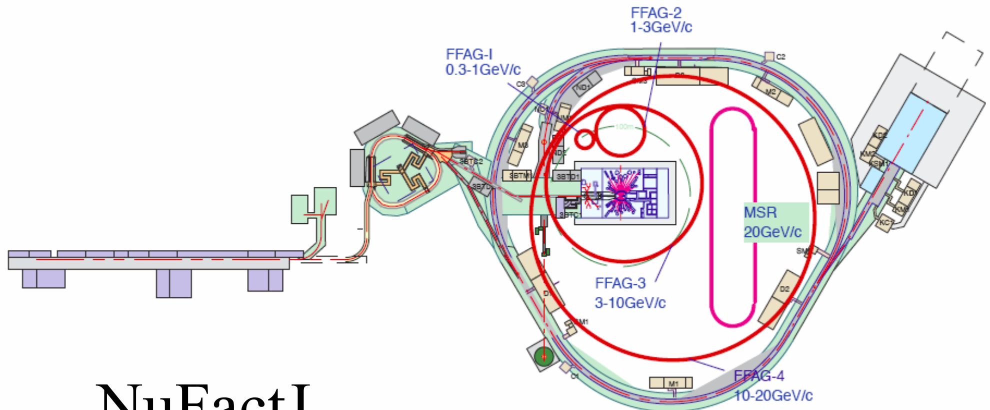
# Front end: plans

- continue studying
  - acceptable design for the KEK 0.3-1 GeV/c ring
  - cooling vs. accelerator acceptance
  - optimized phase rotation
  - combined cooling – phase rotation
  - effects of short proton pulse lengths (< 5 ns rms)
- check suitability of existing absorber and window designs
  - 4 MW, 2 signs
- monitor developments at MuCool, MICE and PRISM

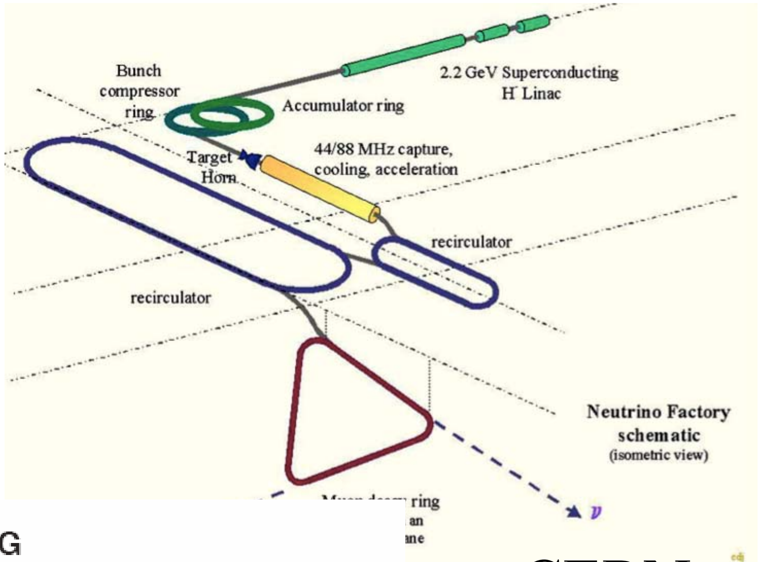
# Muon acceleration overview

- compare different acceleration schemes
  - reference designs: NuFactJ, CERN, US Study 2b
  - new design: RAL FFAG
- some issues
  - transverse & longitudinal acceptance
  - beam dynamics during acceleration
  - implications of keeping both sign muons
  - matching between acceleration subsystems

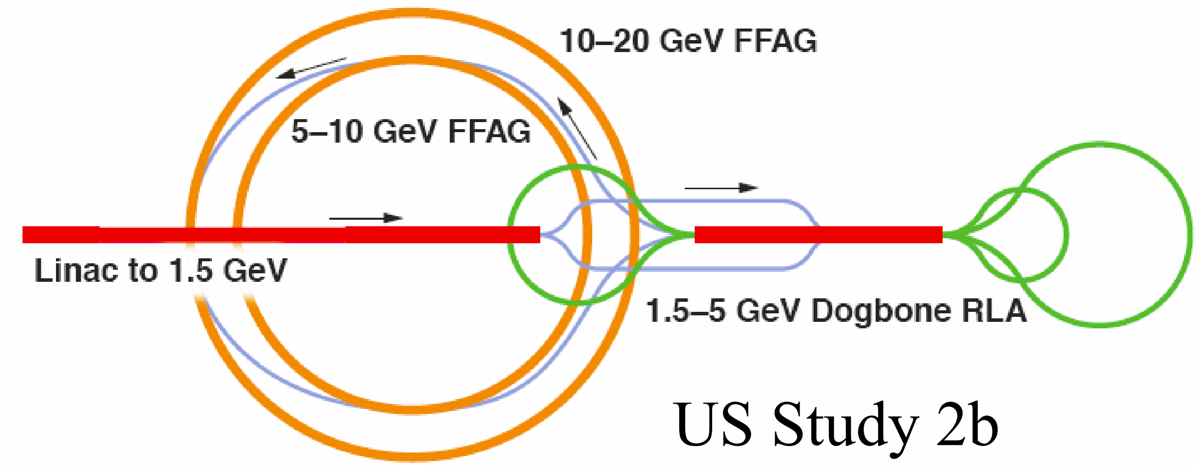
# Reference μ accelerator designs




NuFactJ

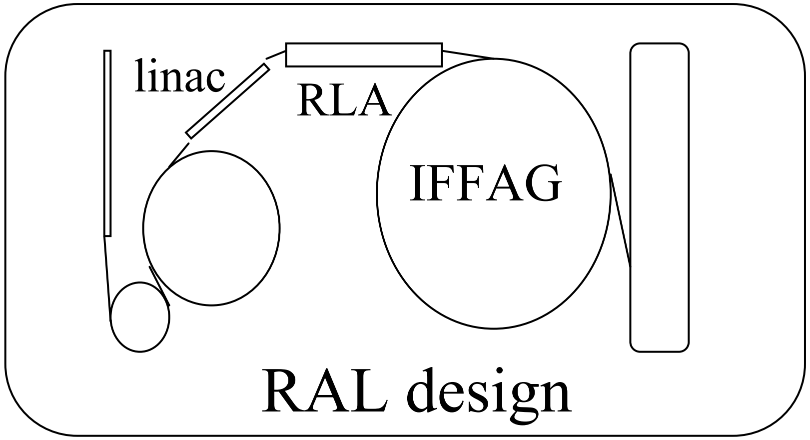



CERN




US Study 2b

# RAL FFAG μ accelerator

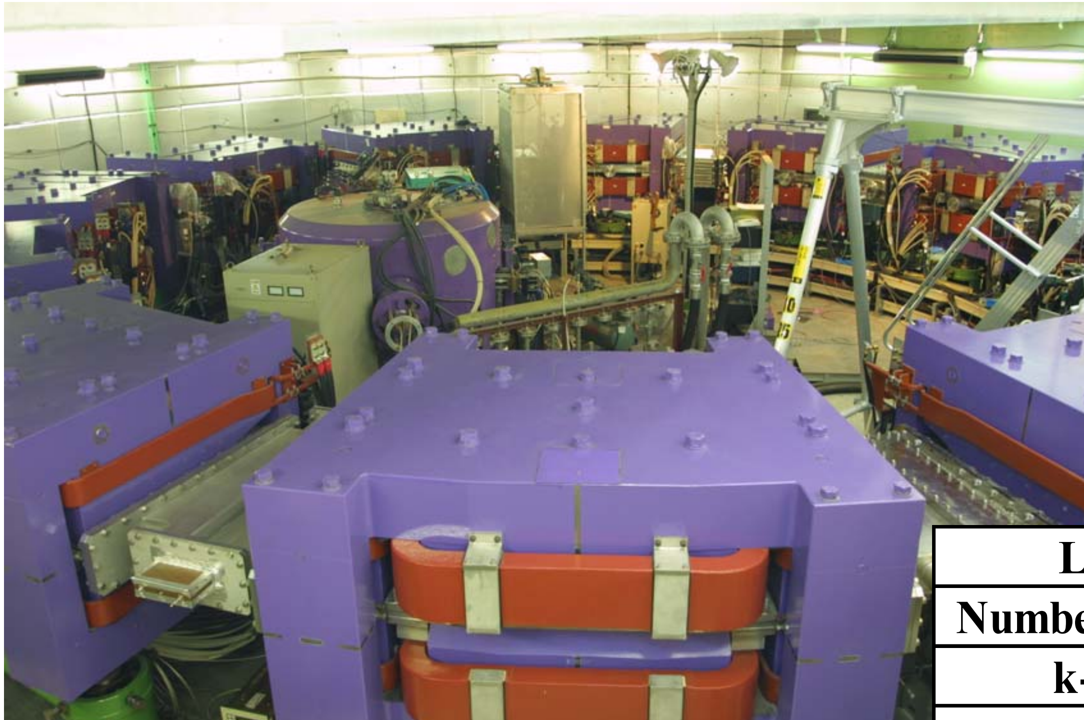



- linac from 0.2 – 1 GeV
- RLA from 1 to 3.2 GeV
- two isochronous FFAGs from 3.2 to 8 GeV and 8 to 20 GeV in the same tunnel.
- IFFAG can use any RF frequency,
- constant $Q_V$ => easier collimation

# Scaling FFAG issues

- tunes are constant, avoids resonance crossings during acceleration
- constraint that rings fit inside JPARC leads to non-optimal design (J.S. Berg)
  - costs of present design are likely to be high
- need tracking with soft-edge magnets for a green site
- need to specify parameters for RF system
- examine longitudinal dynamics
- need to look at spiral sector FFAG designs also

# Machine parameters



150 MeV FFAG experimental results

(M. Aiba, Y. Mori)

| Lattice | Triplet (DFD) |
|---|---|
| Number of sector | 12 |
| k-value | 7.6 |
| Energy (MeV) | $12 \rightarrow 150$ |
| Average radius(m) | $4.47 \rightarrow 5.20$ |
| Betatron tune | Hor.: ~3.7 |
| | Ver.: ~1.3 |
| Maximum field (T) | F: 1.63 |
| (on orbit) | D: 0.78 |
| | |

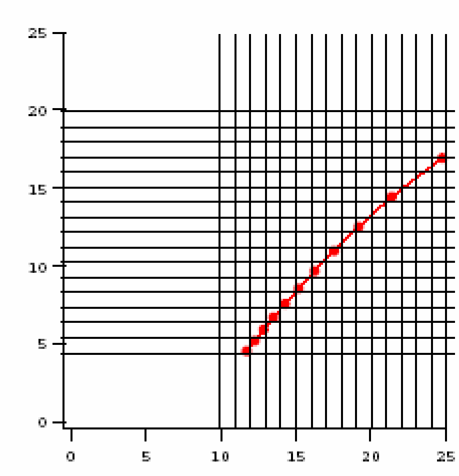
- have overcome close orbit distortion
- have overcome resonance crossing (COD)
- extracted beam from FFAG for first time
- 100 Hz operation successful after RF improvements

# Non-scaling FFAG issues

- non-scaling FFAG can minimize orbit excursion
- beam dynamics issues
  - longitudinal: acceleration outside RF bucket
  - transverse: tunes are not constant,

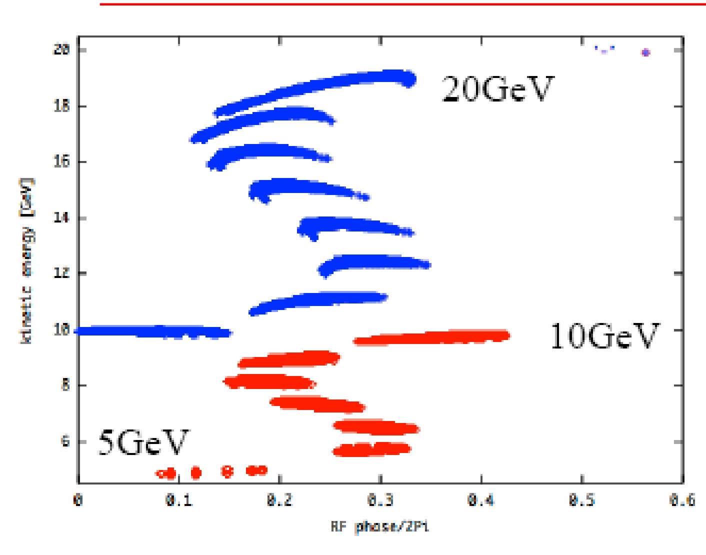
    crosses structure resonances
- longitudinal behaviour coupled to transverse amplitude $A_T$
  - some particles with large $A_T$ are not accelerated
  - for more moderate $A_T$, get longitudinal emittance blowup
  - time of flight vs. energy depends on transverse amplitude

(S. Machida)



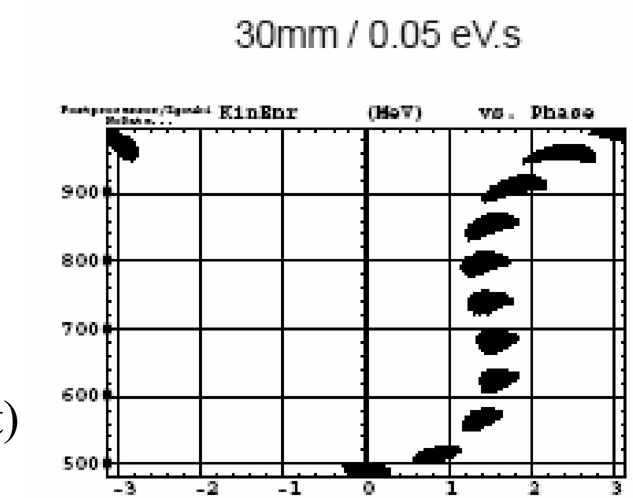

- tune per ring
- with alignment errors
- leads to emittance growth

# Effect of transverse amplitude




(S. Machida)

(F. Lemeut)

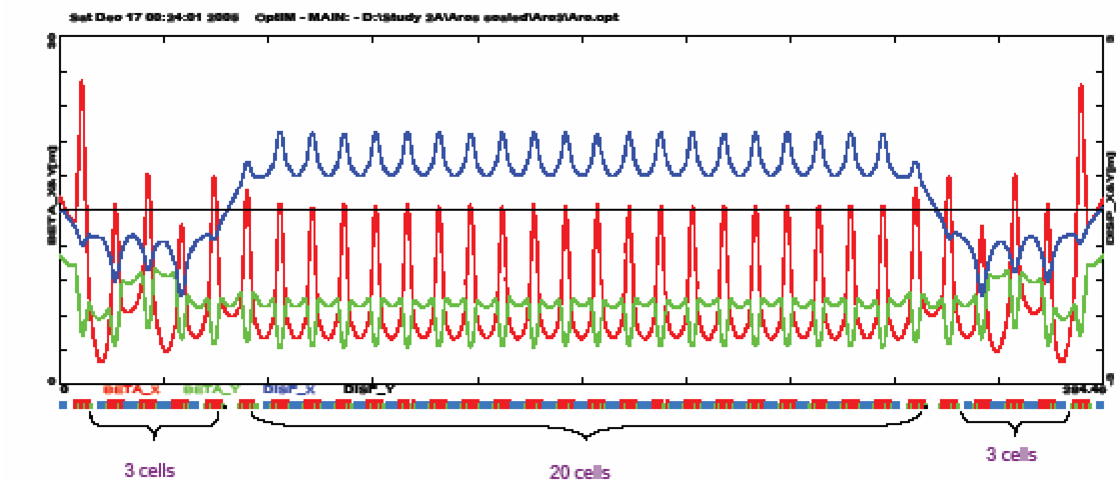



- S. Machida tracking code
- injects distorted beam from 10 GeV ring into 20 GeV ring
- sees large Δp after 2nd ring
- also sees distortions in transverse phase space

- 6D multiturn tracking with Zgoubi
- 5-10 GeV KEK FFAG ring
- looked for ellipse orientation & aspect ratio that minimizes longitudinal distortion

# US Study 2b RLA optics

- symmetric dogbone-RLA accelerates both μ+ and μ-
- 3.5-pass (1.5 –5 GeV) scheme
- linear optics design has been completed
- tolerable phase slippage in the higher pass linacs
- magnet misalignment error analysis shows manageable level of orbit distortion for ~1 mm magnet misalignment error
- examined focusing error tolerance for quad fields (0.2%)




arc 3 optics

(A. Bogacz)

# Muon acceleration: plans

- need to quantify effect of $A_T$ on NS-FFAG transmission
- study sensitivity of FFAGs to errors
- implications of various pulse structures
- kicker and injection/extraction designs for rings
- explore dogbone RLA in further detail
- clarify choice of FFAG lattice (doublets/triplets..?)
- program of full 6D simulations.

# Storage ring: overview

- two new designs: C. Johnstone, G. Rees
- matrix of machine/detector angles: C. Prior
- important design issues

  racetrack or triangle geometry

  20 GeV or 50 GeV or 20 GeV-upgradable

  how to handle both muon charges (1 ring or 2)

  length of μ bunch train (constrains circumference)

  RF to maintain bunch structure

  beam loading (~MW μ beams)

  shielding from μ decays

# Johnstone design

- racetrack geometry, C = 1371 m
- both 20 GeV and 50 GeV use same lattice
    - (magnets run at reduced strength for 20 GeV)
- production straight
    - 496 m long (36% production efficiency)
    - quad focusing
    - maximum beta = 155 m,  167 m
    - rms divergence: 0.12 / $\gamma$ at 20GeV, 0.19 / $\gamma$ at 50GeV
- arcs
    - maximum beta = 16 m
    - 6.4 T dipole fields
    - uses sextupole correctors
- tracking being done by Francois Meot

# Rees design changes

- look at isosceles triangle geometry
- design for MW intensities
- introduce μ beam loss collection
- use combined function magnets in arcs to increase intermagnet spacing
- use solenoid focusing in two production straights to minimize beam size
- use matching section bends for dispersion suppression
- must make small lattice changes when upgrading 20 -> 50 GeV

# New Rees design

- circumference = 1170 m
- length of each production straight = 301 m (2 x 0.26 efficiency)
- 5 bunch trains per cycle
- angles of triangle depend on ring and target sites
  - designed for apex angle = $22.4^{o}$
  - 27, 34.5, 45, 52 also possible ($\pm 1^{o}$)
- uses separate rings for $\mu$+ and $\mu$-
- rms divergence: 0.10 / $\gamma$ at 20GeV, 0.12 / $\gamma$ at 50GeV
- difficulty: needs big injection system

# Storage ring: plans

- develop isosceles triangle ring with ~40$^{o}$ apex angle
- develop strawman detector sites for triangle ring
- begin tracking racetrack ring (with errors)
- begin tracking isosceles triangle ring (with errors)
- look at other systems

  e.g. injection, abort, chromatic corrections

# Accelerator Group Summary

- challenge is to try to reach consensus on a single optimized neutrino factory scheme
- leaning towards
  - ~8-12 GeV proton driver with ~1-3 ns rms pulse length
  - FFAG μ acceleration
  - triangle storage ring
- working to identify critical questions that need additional R&D
- trying to have reasonable scheme ready for World Design Study