Overview of Neutrino Factory Simulations

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NuFact03 Workshop

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What will be covered?

- neutrino factories (not superbeams or muon colliders)
- accelerator physics (not particle physics)
- “simulations”
  - go beyond Monte Carlo tracking ➔ computer system-designs
- but not hardware device designs
  - e.g. magnets, cavities, kickers, horns, …
- not demo experiments, e.g. MICE, targetry, …
- not theory
NuFact02 – Proton driver simulations

- AGS 1 MW upgrade study (Weng$^{39*}$)
- transitionless lattice (Johnstone$^{41}$)
- JHF (J-PARC) status (Machida$^{40}$)
- 8 and 30 GeV lattices (Rees$^{38}$)
- Japanese NF R&D (Mori$^{44}$)

* superscripts give reference numbers in NuFact02 Machine WG summary

π distribution from 50 GeV J-PARC beam, 6 ns proton bunch, 6 m from target (Mori)
NuFact02 – Front end simulations

- μ collection in AG channel (Meot)
- 200-300 MHz phase rotation (Neuffer)
- CERN 88 MHz system (Hanke)
- magnetic chicane lattice (Pasternak)
- magnetic chicane lattice (Rees)
- dE/dx in hydrogen (Allison)
- quad linear precooler (Johnstone)
- ring coolers, RFOFO (Palmer)
- Balbekov tetra-ring (Kahn)
- pole face focused rings (Cline)

**tools:** Geant, ICOOL, Path, SYNCH, MAD, ZGOUBI, BeamOptics, Simucool, COSY

CERN funnel optics (doublet + ¼ wave transformer -> FODO)
Merges π beams from several targets to common decay channel (Meot)
NuFact02 – μ accelerator simulations

- recirculating linear accelerator (Bogacz)
- FFAG acceleration (Machida)
- phase rotation in PRISM FFAG (Sato)
- FFAG concepts & studies (Neuffer)
- FFAG with high frequency RF (Johnstone)
- ionization cooling with FFAG (Schonauer)
- fast ramping synchrotron (Summers)

**tools:** ACCSIM, SAD, DIMAD, Geant

Horizontal phase space,
10-20 GeV FFAG ring, 7 MHz RF,
multipole magnet model (Machida)
NuFact02 – New concepts

- frictional cooling channel (Galea\textsuperscript{30})
- beta-beam facility (Lindroos\textsuperscript{17})

Energy vs. time in bunch rotation stacking, decay ring is also accumulator, uses asymmetric bunch pair merging, small bunch embedded in dense region of larger one, new bunch off-momentum in high dispersion region, rotates quarter turn in phase space, use dual-harmonic RF, Steady state (left), injected and stacked bunches (middle), start of merging (right). (Lindroos)
π collection and decay channel for CERN NF

- 6D Monte Carlo simulations with ZGOUBI
  realistic quads, dipoles and solenoids
  tracking using symplectic Taylor series maps
  includes π decay
- developed theory of π / μ beam transport for checking
- work in progress
  analytic model of transverse phase space
  finite size of parent bunch

* blue names denote WG3 talks

ZGOUBI longitudinal phase space of μ bunch 40 m from target (Meot) *

MATHMATICA implementation of theory (Autin)
Adiabatic buncher and phase rotation

- idea (D. Neuffer et al)
  1. get E-t correlation from the drift
  2. adiabatically bunch with varying frequency RF
  3. $90^\circ$ phase rotation
     vernier – slight variation in frequency
  4. match to cooling channel
- advantages over FS2 induction linac approach
  simpler and cheaper
  collects both $\mu$ charges
- present simulations give $0.22 \mu/p \sim FS2
Adiabatic buncher simulations

Neuffer-2D after drift

GEANT4 after bunching

SIMUCOOL after phase rotation

ICOOL after mismatched cooling
Adiabatic buncher plans

• look at variations
e.g. shorter bunch trains
• continue optimizing parameters
• design new matched cooling channel
  buncher emittance ~20 mm
  FS2 channel acceptance ~12 mm
Balbekov tetra cooling ring

- first successful 6D cooling ring
- hard edge field model
  “Balbecode”
  ICOOL
  Geant
- typical $M \sim 40 - 90$

$$M = \left( \frac{\varepsilon_{6\text{ initial}}}{\varepsilon_{6\text{ final}}} \right) \times \text{Tr}$$
Balbekov ring results

Balbecode 6D cooling

GEANT 1: no decay, 2: decay, 3: decay + 360 μm Al absorber window

ICOOL bunch sigmas
Balbekov ring problems and plans

- need realistic model of the fields
  - study hard-edge lattice with gaps (Kahn)
  - iteration from TOSCA fields
    - COSY non-linear maps (Makino)
- how to inject/extract with long cells
- MITER – automate GEANT RF tuning (Raja)

**TOSCA field from short solenoid (Kahn)**
“Quad” cooling rings

• conventional rings with quads or edge-focus dipoles (Kirk)
• approach so far
  SYNCH - basic lattice design
  ICOOL – tracking with hard-edge fields gives cooling performance
  COSY – explore effects of fringe fields

SYNCH dipole-only ring (Garren)  ICOOL cooling simulation (Kirk)
“Quad” hard-edge ring summary

- hard-edge models give good M for variety of lattices
- compact 3.5 m circumference lattice for cooling demo?
- very low emittance using Li lens absorbers? (Fukui)
- needs windows & realistic field modeling
- limited acceptance with realistic apertures (ICOOL)
- limited acceptance with fringe fields (COSY)
Alternating solenoid focus rings

- pure solenoidal focusing
- bending from external dipole or tipped solenoids
- currently most realistic ring design
- simulated with ICOOL, Balbecode, GEANT

GEANT model of RFOFO ring (Mississippi)
RFOFO ring

- realistic fields from tipped solenoids
- $C = 33 \text{ m}$, $L_{\text{cell}} = 2.75 \text{ m}$
- 201 MHz, 12 MV/m, wedge = 100° LH$_2$
- $\beta_T = 38 \text{ cm}$, $D = 8 \text{ cm}$
- $M \sim 125$ (no windows, injection)

Vertical section through 3 cells (Palmer)

ICOOL emittances vs. length

Balbecode RFOFO closed orbits, radial (left), vertical (right), 10 MeV steps

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Future ring cooler studies

- iterate with engineers
  practical window thickness (Cummings)
  practical absorber material and shape
  practical kicker design
- model injection/extraction (Palmer)
  field model
  modify lattice
- match with rest of system (Balbekov)
  bunch compression rings
- special applications
  early cooling
  low emittance cooling
  cooling demonstration
μ acceleration studies

• Recirculating Linear Accelerators (Bogacz)
  complete linear lattice design
  preaccelerator, linacs, 7 arcs
  \( \Delta \varepsilon_T \) growth in linac arcs is now small
• Very Rapid Cycling Synchrotron (VRCS)
  4-16 GeV preliminary design (Summers)
• Fixed Field Alternating Gradient (FFAG)

SYNCH design of VRCS lattice cell (Garren)

Improved FS2 RLA design (Bogacz)
FFAG designs

• lots of activity
• two main classes
  1. scaling (Machida)
     Japanese NF design
     complicated nonlinear magnet
     constant tune, closed orbit scales with E
  2. non-scaling
     more linear, large DA
     lower RF requirements
     examples (Palmer)
     FODO lattice (Johnstone)
     minimum emittance lattice

Closed orbit excursion during acceleration (Trbojevic)

tools: SYNCH, MAD, COSY, TEAPOT, PTC
Scaling FFAG, acceleration 10-20 GeV, 24 MHz, 0.75 MV/m average, 13 turns (Aiba)

- PTC tracking studies are ongoing (Machida)
- PTC = polymorphic tracking code
- checked with Runge-Kutta tracking
- soft-edge model (Enge function ends)
- studying focusing configurations & acceptances

PTC 150 MeV scaling FFAG, closed orbits vs. δ (Machida)
Other simulation work

- improvements in Monte Carlo techniques (van Ginneken)
  pathlength fluctuations in thick targets
  selection of $\Delta E$ & $\theta_{MS}$ via Edgeworth series
- MARS study of solenoid taper and $\pi$ decay channel (Paul)
- linear quadrupole cooling channel (Berz)
  fully simulated with fringe fields in COSY
  matched to adiabatic buncher
- cooling ring at RAL (Rees)
- bunch compression rings (Balbekov)
- frictional cooling (Galea)
- cooling using gas absorber (Johnson)
- velocity-compliant bunching scheme (Iwashita)
- probably more, sorry
Neutrino factory simulation plans

- continue studying lower cost schemes
- continue topical workshops
  - collection and phase rotation (later this year?)
- monthly FFAG video conferences
- aim for new NF Study 3 in ~2 years