Accumulation and Bunch Rotation Schemes

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Another talk in a series…

- Some people are so creative that they are able to bring different crazy ideas to every gathering.
- I'll give (a new version of) the same crazy talk.
- It seems to be gaining acceptance…
  - (by sane people?)
- Since many of you have heard it before, I'll try to
  - be brief, and
  - emphasize what's new.
- (Next slides show title pages of previous talks.)

Project X and the Fermilab Muon Collider

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June 11, 2009

Project X as a Proton Driver

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December 9, 2008

Comparison of Proton Driver Schemes For Muon Collider and Neutrino Factory

(There is a writeup in the HB2008 proceedings)

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August 26, 2008

Introduction

- Two customers: neutrino factory and muon collider
- Two configurations: IC1 and IC2
- Question: What to add to the two configurations to serve the two customers.
- It will be nice if there is one solution, not four.
- Whatever is built initially should be directly useful for the MC/NF upgrade without major modifications.
- So, how can Project X be used to drive a NF/MC?

Introduction (cont.)

- IC1 has an 8-GeV pulsed linac.
- IC2 has a 2.x-GeV CW linac.
- The IC2 linac has to be augmented to feed the MI.
  - Either an RCS from 2 to 8 GeV to MI via Recycler,
  - or a pulsed (?) linac from 2 to ?? GeV to MI directly.
- The latter device would be more useful for MC/NF.
- The IC2 hi-energy linac should be "pulsed" in a special way: the linac should "think" it is CW.
- Question: to what energy should the IC2 linac go?
  - Roland Garoby thinks 5 GeV is enough for CERN neutrino factory based on SPL linac.
  - Maybe we'll need more for MC?

ISS Requirements (Feb. 3, 2008)

Table 2. Proton driver requirements.

Parameter	Value
Average beam power (MW)	4
Pulse repetition frequency (Hz)	50
Proton energy (GeV)	10 ± 5
Proton rms bunch length (ns)	2 ± 1
No. of proton bunches	3 or 5
Sequential extraction delay (μs)	≥ 17
Pulse duration, liquid-Hg target (μs)	≤ 40
Pulse duration, solid target (ms)	≥ 20

accel

150 or 250 Hz

Interesting footnote in ISS report

[1]The use of multi-bunch trains at 50 Hz is a change made during the study from the original single, 15-Hz train. The change was made to ease the production of the 2 ± 1 ns (rms) proton bunches, and to reduce the heavy beam loading in the $\mu^{\pm}$ accelerators.

Muon Collider Proton Driver Requirements

Andreas Jansson
Fermilab

Muon Collider Parameters

	Low ε (Johnson)	Med ε (Alexahin)	High ε (Palmer)	
CM Energy	1.5	1.5	1.5	TeV
Luminosity	2.7	1	1	$10^{34}cm^2/s$
Muons/bunch	0.1 *10	1	2	10^{12}
Ring circumference	2.3	3	8.1	km
$\beta^* = \sigma_z$	5	10	10	mm
dp/p (rms)	1.0	0.1	0.1	%
Ring depth	35	13	135	m
Muon survival	30	4	7	%
ε_T	2.1	12	25	π mm mrad
ε_L	370,000	72,000	72,000	π mm mrad
PD Rep rate	**65**	**24**	**12**	**Hz**
PD Power	**≈4**	**≈6**	**≈4**	**MW**

R. Palmer, LEMC

Packaging (rep rate)

- Bunch rep rates range from 12-65Hz
  - Note that this is not necessarily the same as the proton driver rep rate.
- Flexibility here would be useful, also for operations
  - This can be achieved using one or more intermediate fixed energy rings.

CW linac has more flexibility to change frep .

Conclusions

- A muon collider would likely need ~4MW of proton power
  - Should plan for a further upgrade potential of factor ~2 to cover shortfalls in cooling efficiency and future luminosity upgrades
- Bunch rep rate on target ranges from 12-65 Hz
  - Not necessarily the same as linac rep rate. Flexibility can be achieved with intermediate fixed energy rings.
- Proton driver energy is flexible, but at least at Fermilab 8GeV seems most attractive
  - Need more detailed study of intensity limitations.
  - Need to weigh cost of new 50GeV ring(s) against cost of Project X linac upgrades

Comments on Requirements

- Energy:
  - ISS said 5 < Ep < 15 GeV → 8 GeV is ~ ideal.
  - Nμ/(Np*Ep) peaks around 8 GeV
  - Fermilab has a lot of 8 GeV rings.
- Bunch delivery:
  - Cycle rate of proton accelerator: ISS said 50 Hz
  - Bunches per cycle: ISS said 3 or 5
- The difficulty of the proton driver goes up as the number of proton bunches per second goes down.
  - 150 or 250 bunches per second for NF
  - ~ 15 to 60 for MC
- Making rms bunch lengths of 3 nsec is a LOT easier than 2 nsec and reduces yield only ~5%.

Linac Intensities

- IC1 has an 8-GeV pulsed linac.
  - Power = Tp*Np/sec = Tp*I*dt*frep
  - Upgrade parameters for 4 MW:
    - Repetition rate: 20 Hz
    - Beam pulse duration: 1.3 msec or 1 msec
    - Average current during pulse: 20 mA or 27 mA
- IC2 has a 2.x-GeV CW linac with <I> = 1 mA.
  - For CW case, dt*frep=1, so Power = Tp*<I>.
  - E.g. 5 MW at 5 GeV.
  - Can't let the duty factor be much less than 1, so stay CW.
    - Ion source delivers 10 mA DC
    - Can chop 90% of beam so linac sees <I> = 1 mA
- Max available beam power of CW linac is higher.

Comparison with RCS

- The RCS has a duty factor of .044, since it injects for 4.4 msec at 10 Hz. It boosts the energy from 2 to 8 GeV, so the power is
  - Power = 8 GeV * 1 mA * .044 = 350 kW.
  - RCS Upgrade to 4 MW looks very difficult.

Desire for performance contingency

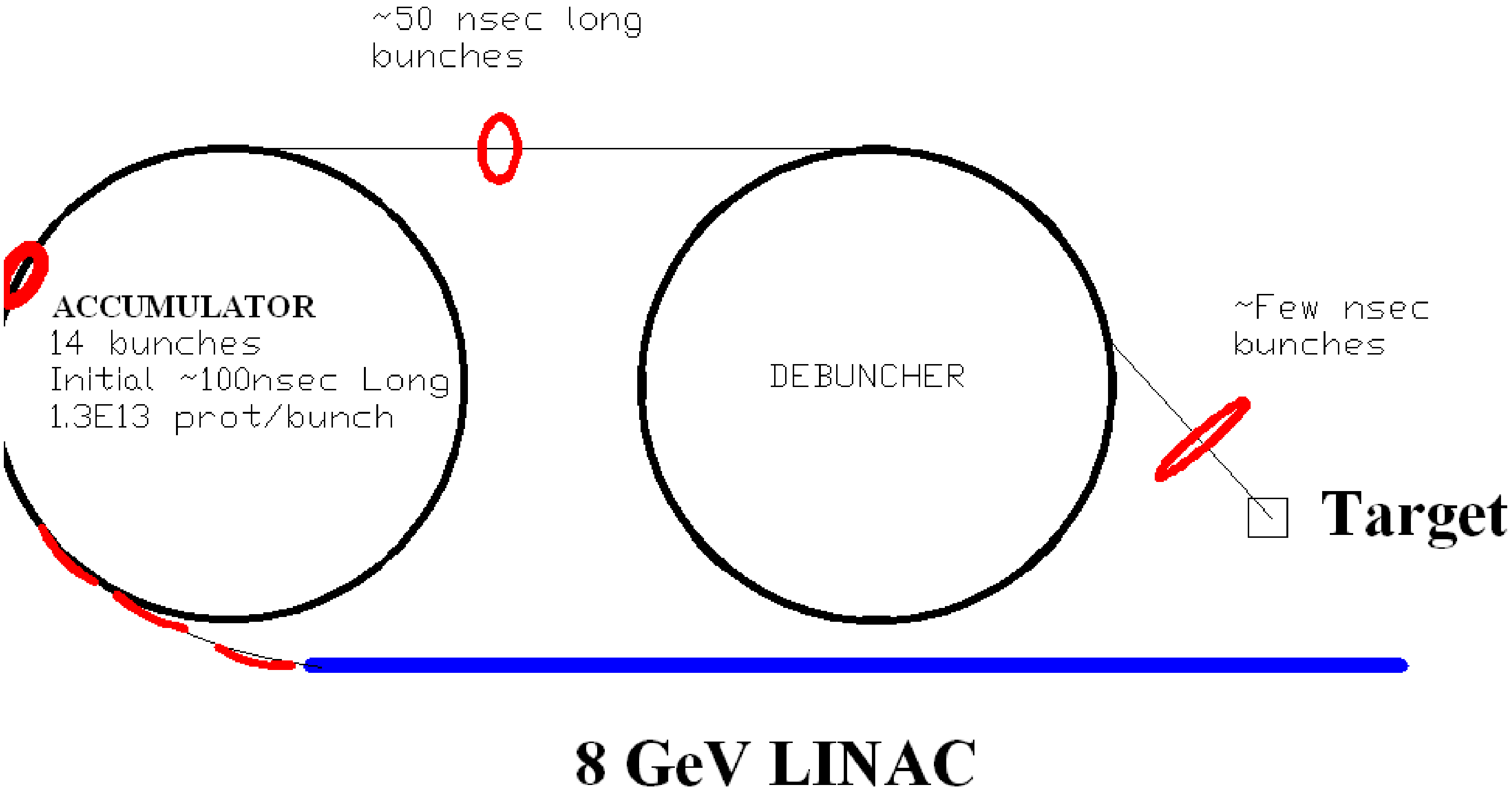
- Advocates of low-emittance designs worry that very high intensities per bunch (of protons and/or muons) will not be feasible due to various intensity-dependent effects.
- Advocates of high intensities per bunch worry that very low emittances will not be achievable.
- What if both camps are right!?! Then a face-saving compromise path is needed: Raise the proton beam power (rep rate) if necessary.
  - E.g. 8 MW at 8 GeV from CW linac.

Design concept

- Two multi-GeV storage rings
  - An accumulator ring
  - A buncher ring
- Question: 8 GeV for IC1, ?? GeV for IC2
- Question: can we get by with only one ring?
- Add trombone plus funnel if necessary to reduce repetition rate of bunch arrivals at the target.
  - This external bunch-combiner might be added as part of what's needed to transform from a neutrino factory to a muon collider facility.

Providing p Bunches for a ν Factory or a μ Collider

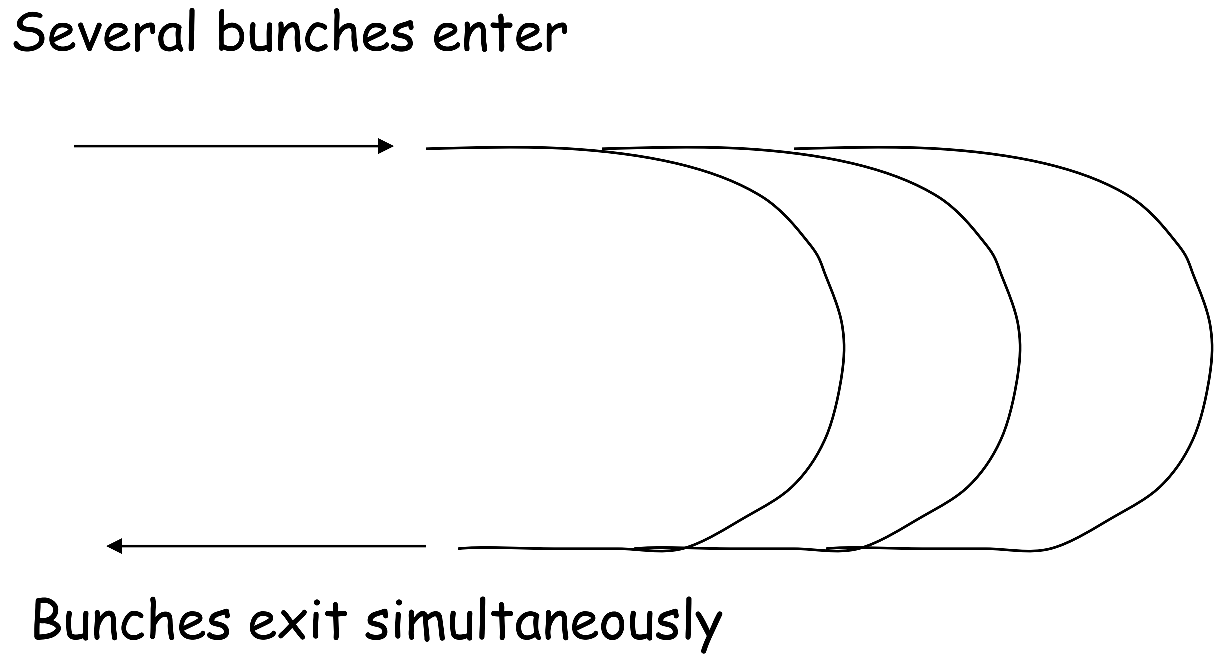
Ignore the details



Essential new idea for IC2

- Issue: with a low-current CW linac, many more turns must be injected into the accumulator ring. The stripper foil sees many more turns passing. A pulsed linac is much better in this regard.
- Solution: make CW linac effectively pulsed:
  - Chop linac beam so beam is there only every tenth turn.
  - (The high-Q linac cavities don't notice the difference.)
  - Add a dipole 2-bump around the foil, oscillating at frev/10, to move the circulating beam away from the foil when the injected beam is off.

An external combiner ("trombone") to reduce rep rate at target



A specific hi rep. rate, 8 GeV example

- Use Accumulator(-like) and Debuncher(-like) rings.
  - Acc and Deb are leftovers from Fermilab's Antiproton Source
  - They are not very deep underground; maybe move them to a new tunnel?
- Paint to large (~200 pi) transverse emittances in rings with small circumference to control space charge.
  - Could strip directly into "Accumulator" or do multi-turn transverse stacking from Recycler to "Accumulator".
  - Small circumference means more favorable bunching factor.
  - Scale from space charge tune shift (~0.04) in Recycler ring.
- Use h=12 and h=24 rf to make 12 ~rectangular bunches.
- (Note possible constraints on h_1, h_2: Circumference ratio of the two rings, if multiple bunches are transferred)
- Transfer three bunches at a time to the "Debuncher".
- Do a bunch rotation in the "Debuncher".
- Deliver three bunches at a time to the target at 60 Hz.

Proton Driver Design Challenges

- Design of the rings: rf, lattices, etc.
- Multi-turn injection by stripping H^-
  - ~1000 turns in IC1
  - Even more in IC2
- Intensity-dependent effects
  - Each linac pulse delivers ~ 150 Tp
  - Space charge, electron cloud, instabilities
- Beam delivery to the target
  - Desired rms beam size ~ 5 mm
    - Large transverse emittances to control space charge
    - Small beta function at the target
  - Trombone/funnel design (may be an upgrade path)
- Target and dump design and performance
- What have you?

Tentative Conclusions

- Both IC1 and IC2 might be usable for MC/NF.
- The CW linac of IC2 should be extended to >~ 5 GeV.
- One or two storage rings at the linac energy can provide the desired bunch structures with some flexibility in rep rates.
- For IC2, the beam should be chopped, and an AC dipole two-bump around the foil should be added.
- An external combiner can reduce the rep rate of bunches at the pion production target if necessary.
- There are many design issues to be addressed.

Backup slides

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Scaling of Muon Collider Requirements

$$\mathcal{L} \sim \frac{R_b N_\mu^2}{\varepsilon_\perp \beta^*} f(\sigma_z / \beta^*) \sim \frac{R_b N_\mu \xi}{\beta^*} f(\sigma_z / \beta^*) \qquad \xi = \frac{r_\mu N_\mu}{4\pi\varepsilon_\perp} \le \xi_{\max}$$

The luminosity of a muon collider is given by the product of:
the integrated luminosity per muon bunch pair injected, times
the rep. rate R_b of injecting bunch pairs into the collider.

Designers often assume (optimistically?) that the muon bunches can be made bright enough to reach the beam-beam limit. Then:

$$\mathcal{L} \propto \frac{R_b \xi_{\max}^2 \varepsilon_\perp}{\beta^*} f(\sigma_z / \beta^*)$$

and for given luminosity, energy, and beam-beam tune shift:
1) the rep. rate scales inversely with the trans. emittance;
2) the proton beam power is independent of the trans. emittance.

Scaling of PD params with collider energy

- For given muon bunch parameters, the luminosity of an optimistically designed collider tends to scale like s, the square of the CM energy.
    - There's one factor of energy in the non-normalized emittance;
    - The bunch length can also be reduced as the energy is raised, allowing smaller β^*.
- The cross sections for pointlike processes scale as 1/s.
- As a result, the event rates depend only weakly on s.
- Therefore, the requirements on the front end of an optimistically designed muon collider are approximately energy-independent.

Space-charge tune shift scaling

- Scale from incoherent tune shift of 0.04 in Recycler

$$\Delta\nu \sim \frac{N_{tot}}{\varepsilon_n \beta\gamma^2 B}$$

- The energy (8 GeV) and the total number of protons are the same in the Recycler and the Debuncher.
- The transverse stacking into the Debuncher raises the transverse emittances by a factor of eight.
- The bunching factor goes down (worse) by a factor of nine.

$$B_{ar} = \sqrt{2\pi}\,\frac{\sigma_l}{C} \qquad B_{br} = \frac{1}{2}\frac{\lambda_{rf}}{C} \qquad \frac{B_{ar}}{B_{br}} = \sqrt{8\pi}\,\frac{\sigma_l}{\lambda_{rf}}$$