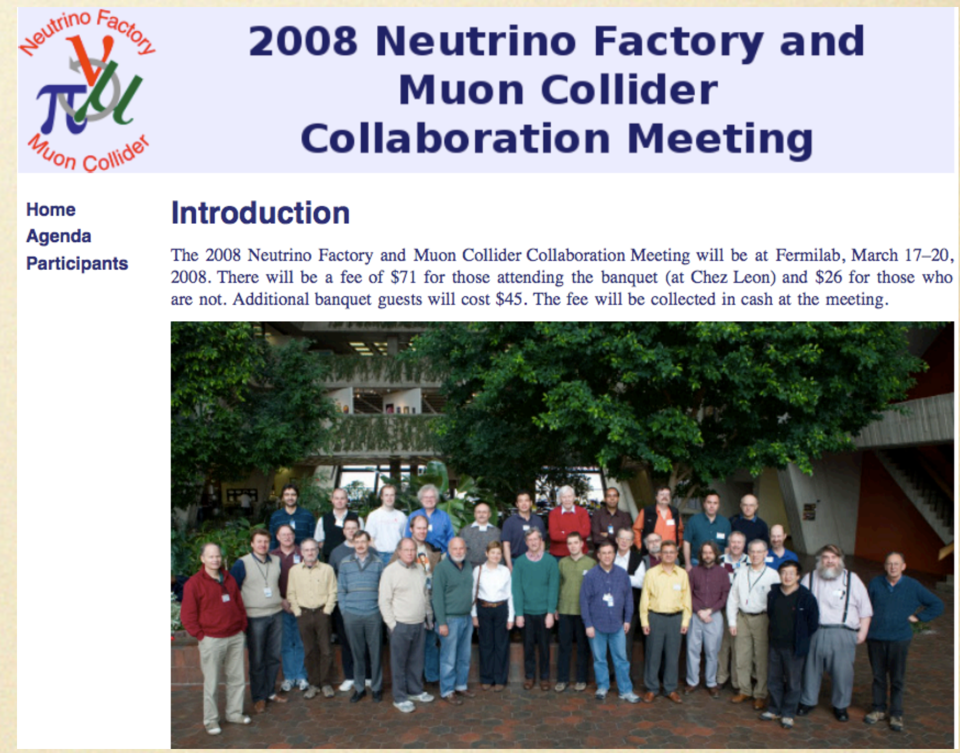
Recent Progress for Muon Collider

Katsuya Yonehara, Fermilab

Reference

https://www.bnl.gov/mcdworkshop/



http://www.cap.bnl.gov/mumu/conf/MC-080317

http://www.muonsinc.com/lemc2008/

Others: P5 meeting, Project X Workshop, MC physics & detector, etc

Current & Near Future Experiments

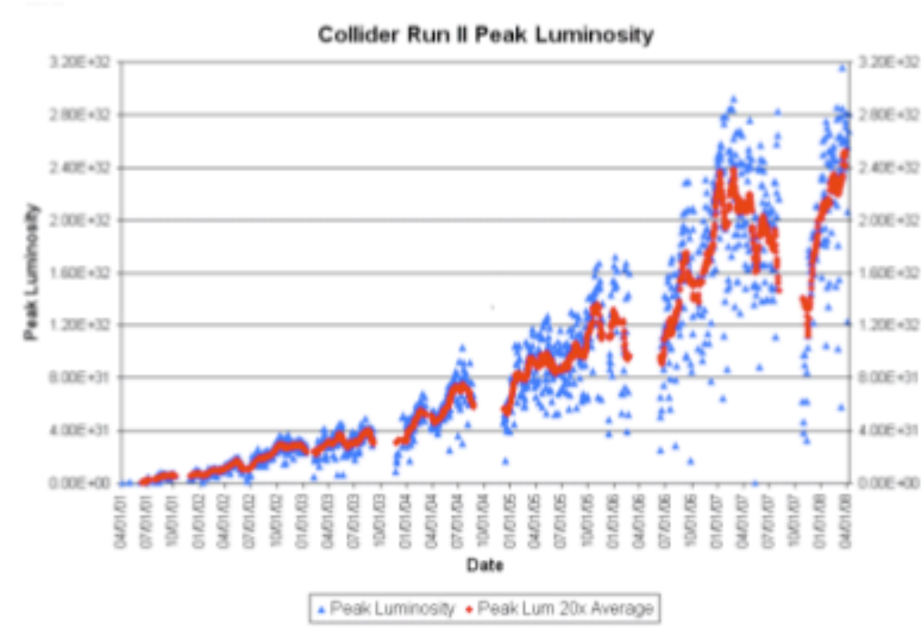
Reveiw from E. Eichten's excellent talk at MC design'08 & LEMC'08

Experimental Status

Energy Frontier Accelerators

Tevatron - Operating well

$\sqrt{s}$ = 1.96 TeV pbar p
Luminosity - 3.16×10^{32} cm^{-2} sec^{-1} (peak)
3.8 fb^{-1} (to date Run II)
CDF, D0

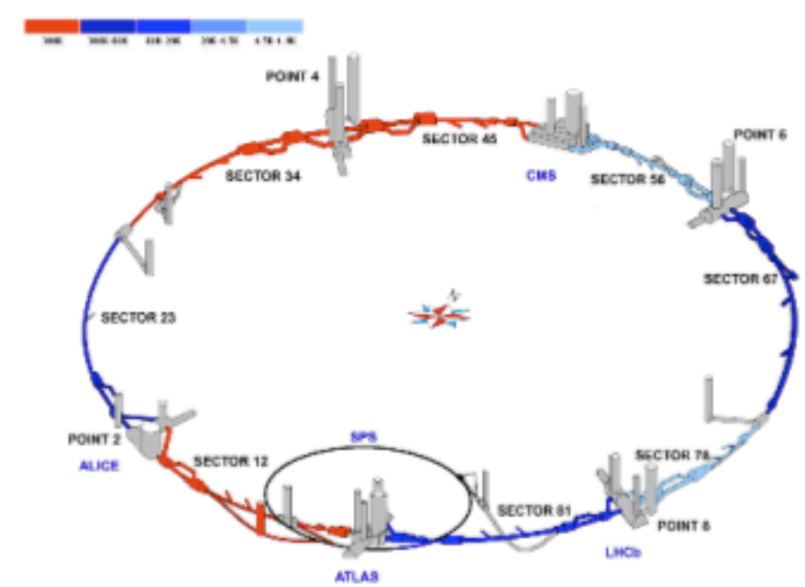


LHC - About to come online

$\sqrt{s}$ = 14 TeV p p
Luminosity - 10^{34} cm^{-2} sec^{-1}

ATLAS, CMS, LHCb, ALICE

LHC - Cooldown Status April 20, 2008

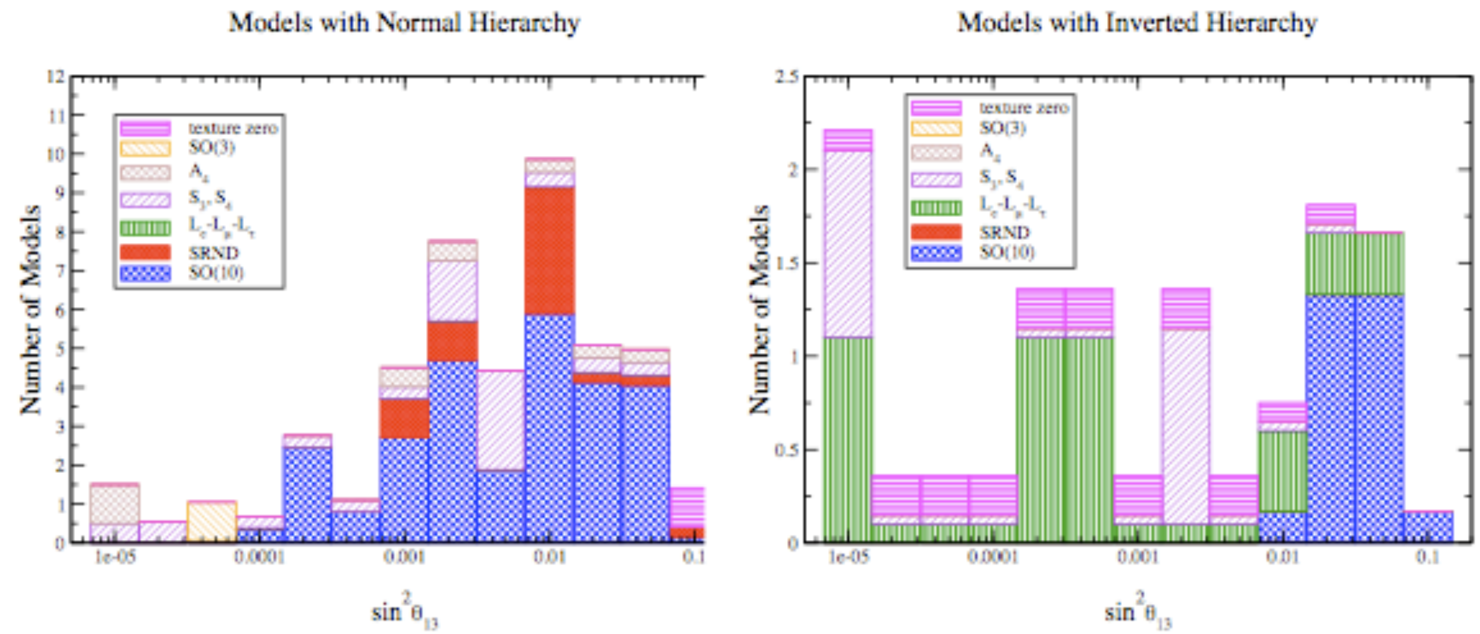


Neutrino Experiments

Accelerators: MiniBooNE, SciBooNE, MINOS, OPERA, NOvA, T2K, ...
Reactors: Double CHOOZ, Daya Bay, ...
Double Beta Decay, Super Beams, Beta Beams, Astrophysical Sources

Neutrino Factory

Expected $\sin^2\theta_{13}$ for a variety of theoretical models

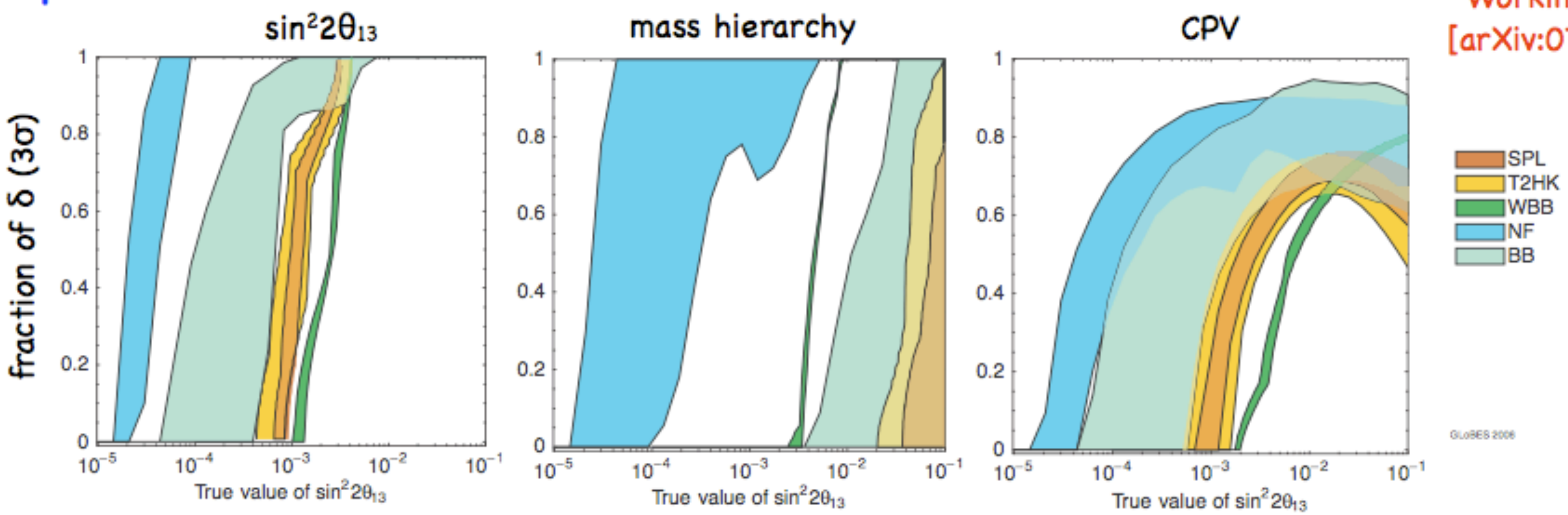


Neutrino Factory

Muon storage ring:
$\sqrt{s} \approx 50$ GeV
Long straight sections
High intensity: 10^{21} muon decays/yr

Compare

Discovery reach for various proposed facilities



ISS Physics Working Group [arXiv:0710.4947]

Very likely Neutrino Factory needed to disentangle θ_{13}, mass hierarchy, and measure CPV parameter.

Muon Collider

- For $\sqrt{s} > 500$ GeV
  - Above SM thresholds:
  - R essentially flat:

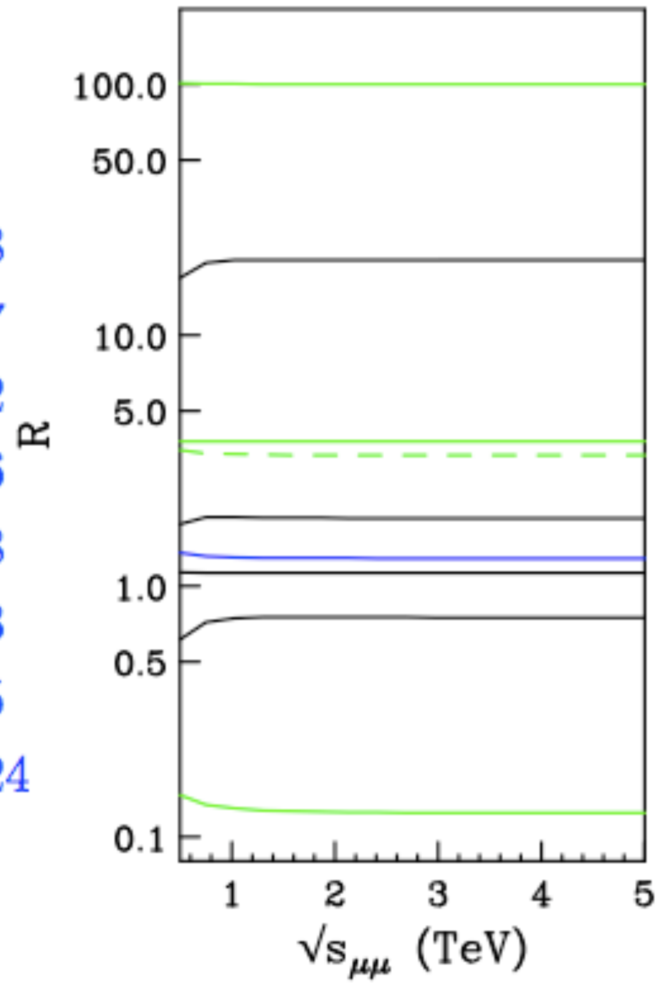
    (one unit of R)

$$\sigma_{\rm QED}(\mu^+\mu^- \to e^+e^-) = \frac{4\pi\alpha^2}{3s} = \frac{86.8 \text{ fb}}{s(\text{TeV}^2)}$$

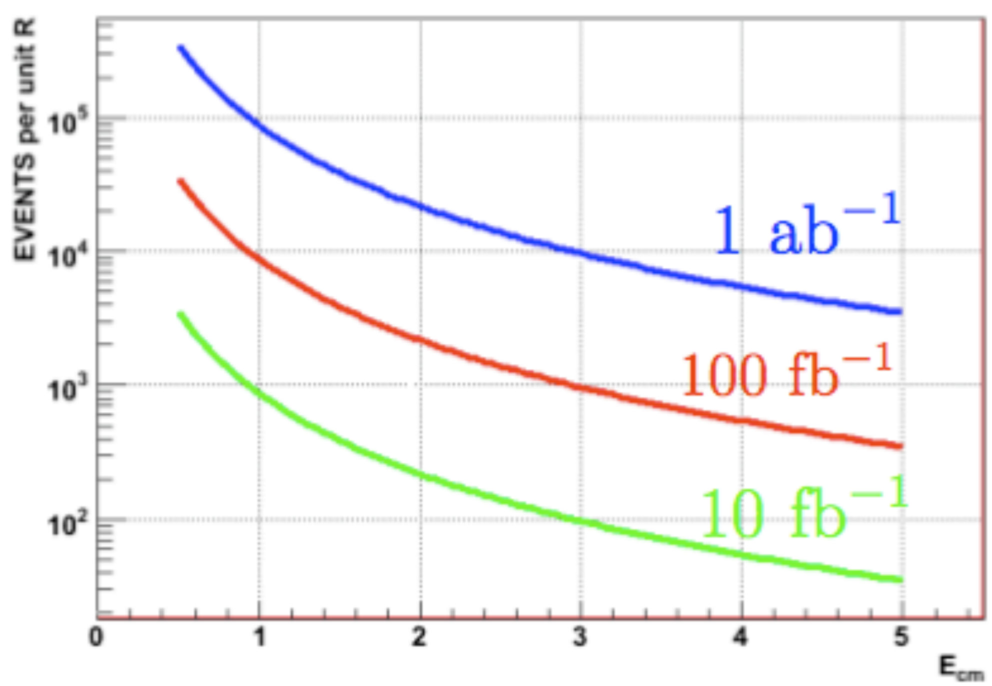
R at $\sqrt{s}$ = 3 TeV

$O(\alpha_{em}^2)$ $O(\alpha_s^0)$

$$\begin{aligned} \mu^+\mu^-(20^\circ \text{ cut}) &= 100 \\ W^+W^- &= 19.8 \\ \gamma\gamma &= 3.77 \\ Z\gamma &= 3.32 \\ t\bar{t} &= 1.86 \\ b\bar{b} &= 1.28 \\ e^+e^- &= 1.13 \\ ZZ &= 0.75 \\ Zh(120) &= 0.124 \end{aligned}$$



- Luminosity Requirements



For example: $\sqrt{s} = 1.5$ TeV $\Rightarrow$ 3860 events/unit of R

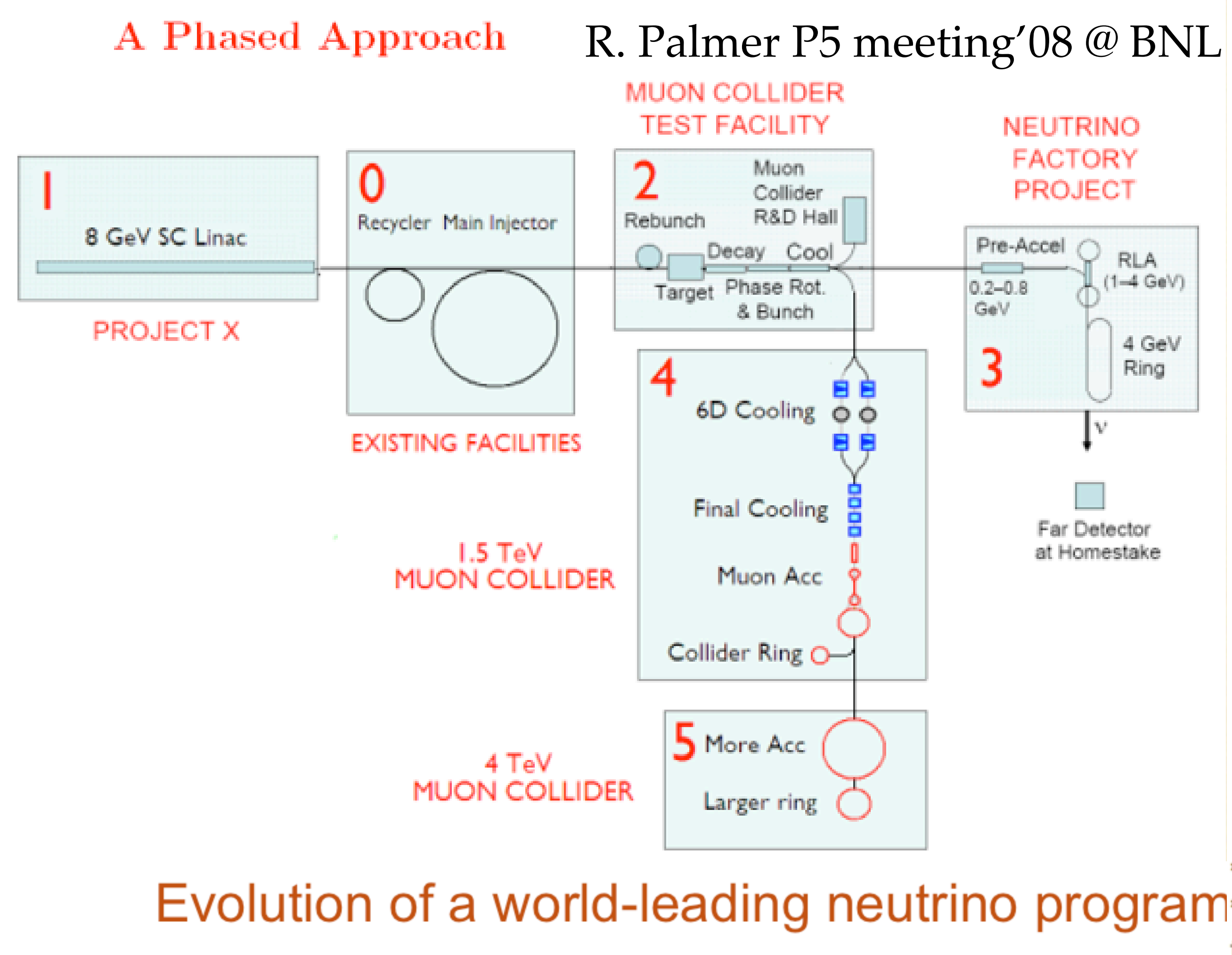
$$\mathcal{L} = 10^{34} \text{ cm}^{-2}\text{sec}^{-1}$$

$$\to 100 \text{ fb}^{-1}\text{year}^{-1}$$

Total - 510 K SM events per year

Processes with R ≥ 0.01 can be studied

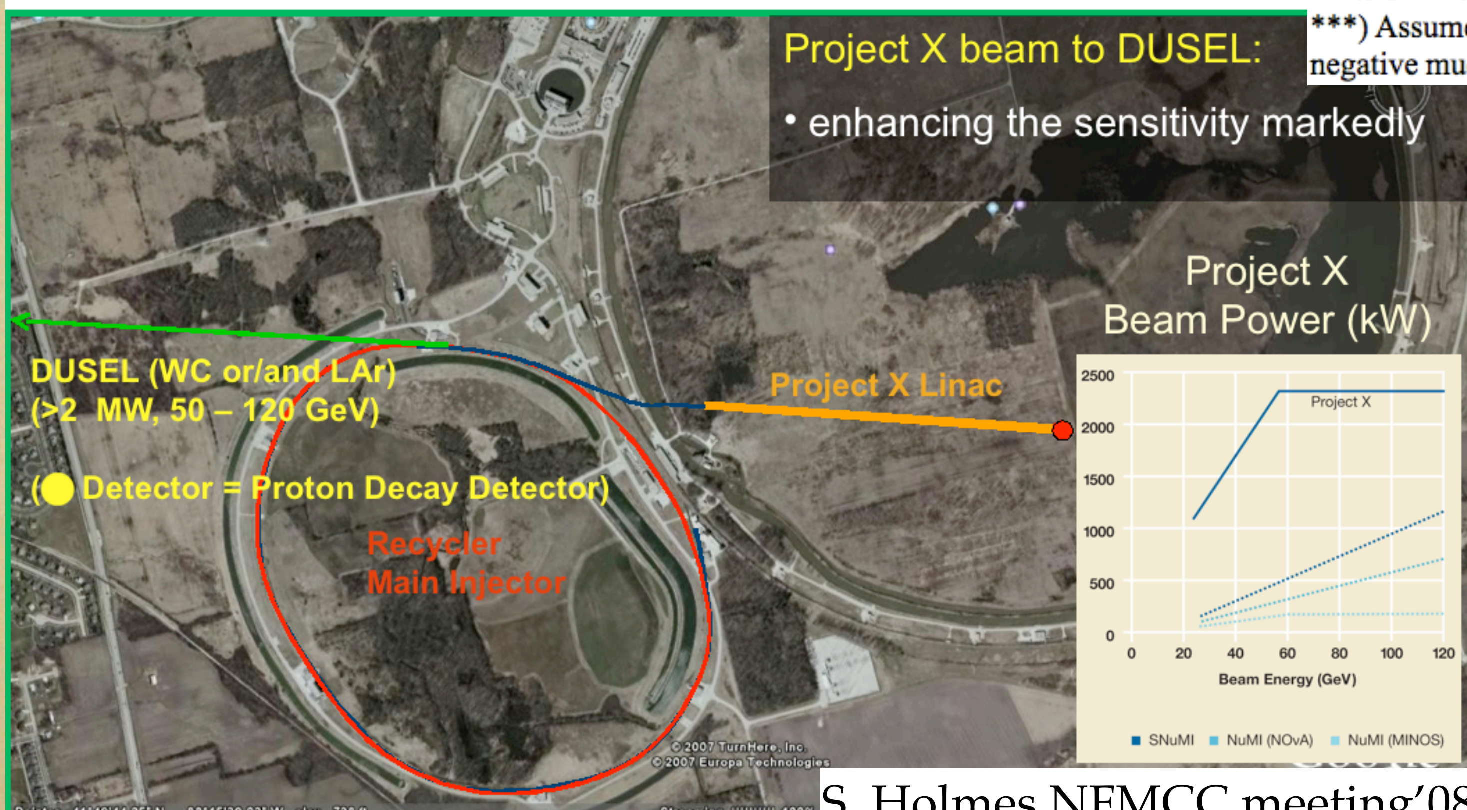
MC scenario



	Low Emit.	High Emit.	MCTF07
√ s (TeV)		1.5	
Av. Luminosity (10^{34}/cm²/s) *	2.7	1	1.33-2
Av. Bending field (T)	10	6	6
Mean radius (m)	361.4	500	500
No. of IPs	4	2	2
Proton Driver Rep Rate (Hz)	65	13	40-60
Beam-beam parameter/IP	0.052	0.087	0.1
β * (cm)	0.5	1	1
Bunch length (cm)	0.5	1	1
No. bunches / beam	10	1	1
No. muons/bunch (10^{11})	1	20	11.3
Norm. Trans. Emit. (μm)	2.1	25	12.3
Energy spread (%)	1	0.1	0.2
Norm. long. Emit. (m)	0.35	0.07	0.14
Total RF voltage (GV) at 800MHz	407× $10^3\alpha_c$	0.21**	0.84**
Muon survival Nμ/Nμ0	0.31	0.07	0.2
μ+ in collision / proton	0.047	0.01	0.03
8 GeV proton beam power	3.62***	3.2	1.9-2.8

*) Luminosity calculated taking account of the hour-glass factor but ignoring the dynamic beta effect.
**) Momentum compaction in the present ring design α_c=1.5× 10^{-4}. Note that it would be better to assume f=1.3GHz to keep the RF voltage at a reasonable level (0.52GV for MCTF07 set)
***) Assumes μ /p ratio of 0.15 after capture and precooling, and only decay losses afterwards. Positive and negative muons are assumed to be produced independently (from different protons).

Y. Alexahin NFMCC meeting'08



S. Holmes NFMCC meeting'08

Low Emit: Low # muons/bunch & many bunches
High Emit: High # muons/bunch & one bunch

RLA plays a key role since it makes a limit of the number of bunches and the number of muons

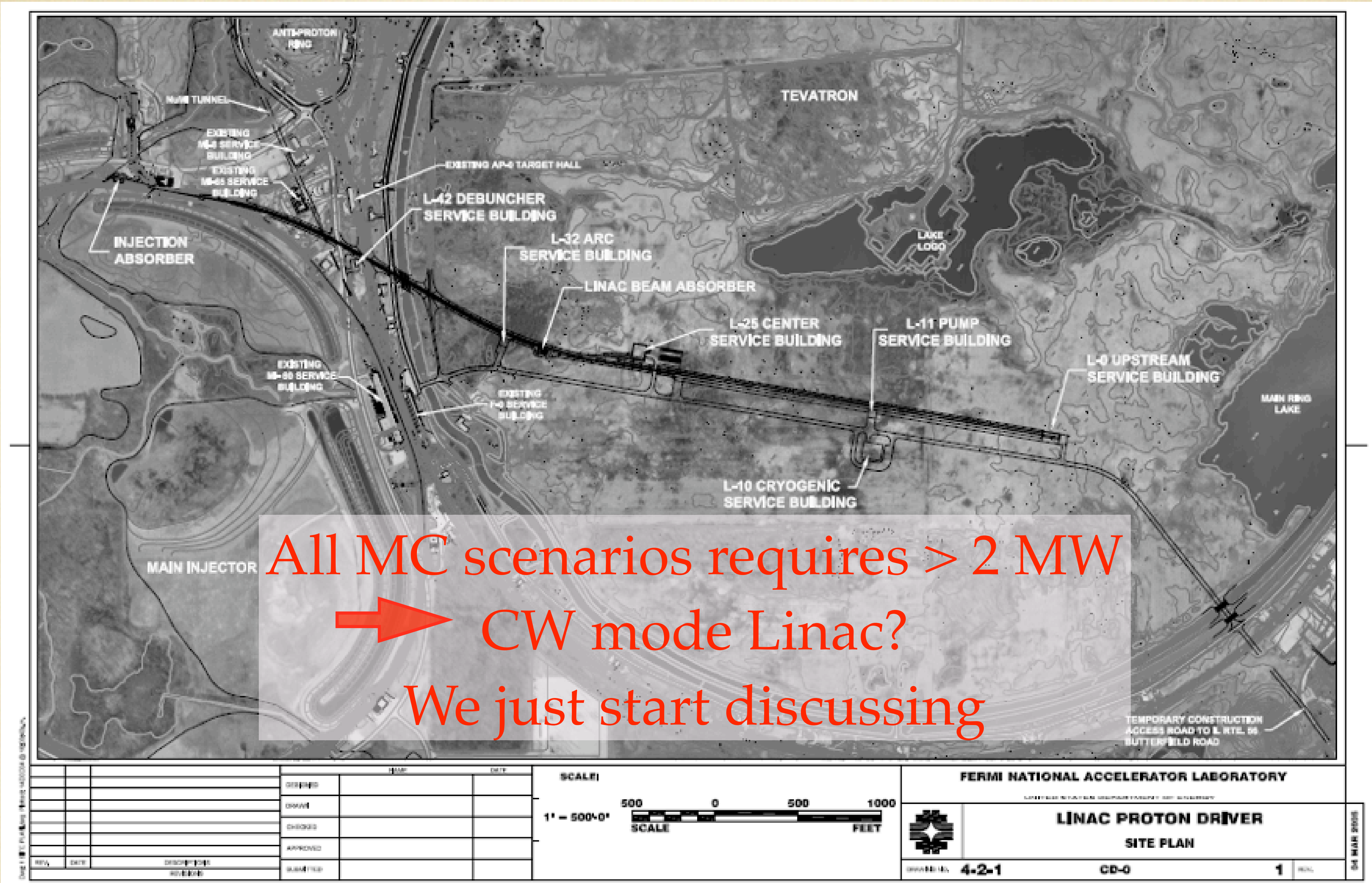
Muon collider

for rich physics project

Conceptual drawing (scales are arbitrary)

a. **SC LINAC**
b. **Buncher ring**
c. **Tgt/Cpt/Dcy/PR/Cooling**
d. **LE RLA**
e. **Bunch Coalescing ring**
f. **HE RLA**
g. **Collider ring**
h. **Collider detector**

SC Linac/Project X



All MC scenarios requires > 2 MW

→ CW mode Linac?

We just start discussing

S. Holmes NFMCC meeting'08

Target

Targetry Challenges of a Muon Collider

Desire ≈ 10^{14} μ/s from ≈ 10^{15} p/s (≈ 4 MW proton beam).

Highest rate μ^+ beam to date: PSI μE4 with ≈ 10^9 μ/s from ≈ 10^{16} p/s at 600 MeV.

⇒ Some R&D needed! → MERIT experiment

Palmer (1994) proposed a solenoidal capture system.

Low-energy π's collected from side of long, thin cylindrical target.

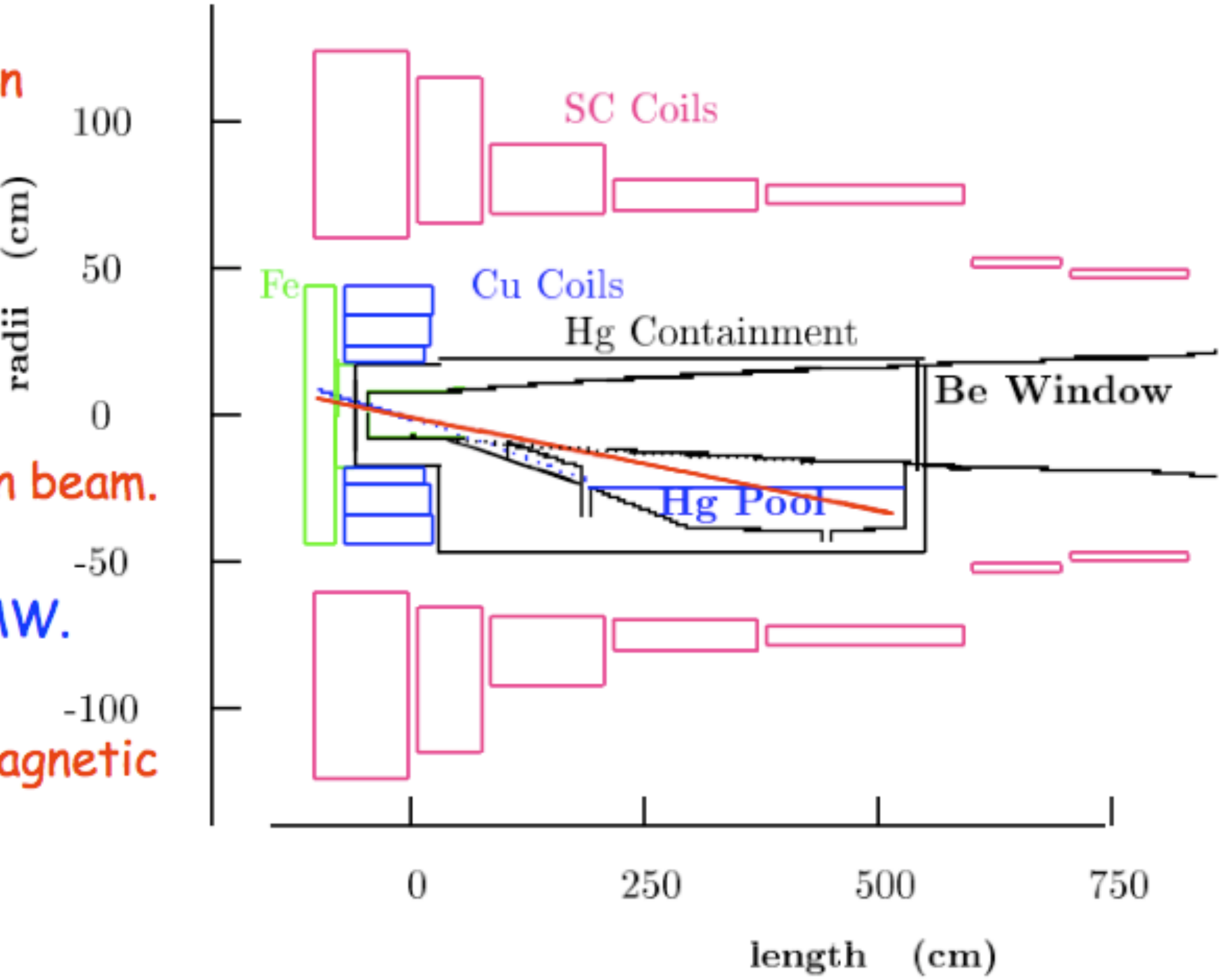
Collects both signs of π's and μ's,
⇒ Shorter data runs (with magnetic detector).

Solenoid coils can be some distance from proton beam.

⇒ ≥ 4-year life against radiation damage at 4 MW.

⇒ Proton beam readily tilted with respect to magnetic axis.

⇒Beam dump (mercury pool) out of the way of secondary π's and μ's.



K. McDonald, LEMC'08

Future Target System R&D

Analysis (and simulation) of MERIT data is ongoing, but the success of the experiment already provides proof-of-principle of a free mercury jet target for megawatt proton beams.

Considerable system engineering is needed before an actual jet target station could be built: 20-T magnet, tungsten-carbide(?) shield, mercury delivery and collection system, remote handling system, radioisotope processing, ...

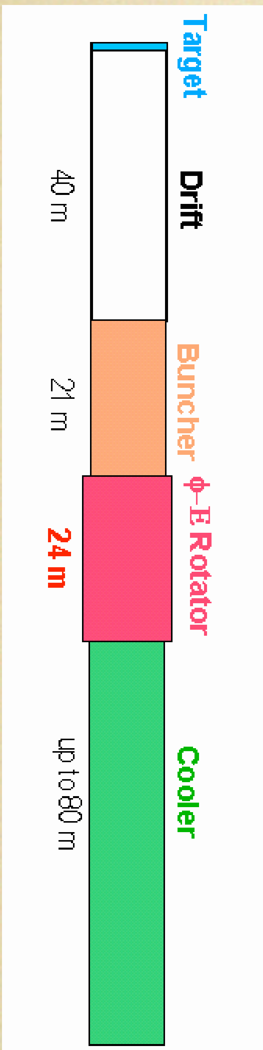
Desirable to improve jet quality, and to explore viability of jet axis at 100 mrad to magnetic axis, as proposed in Feasibility Study 2. Would also be good to verify feasibility of recovery of the mercury jet in an open pool.

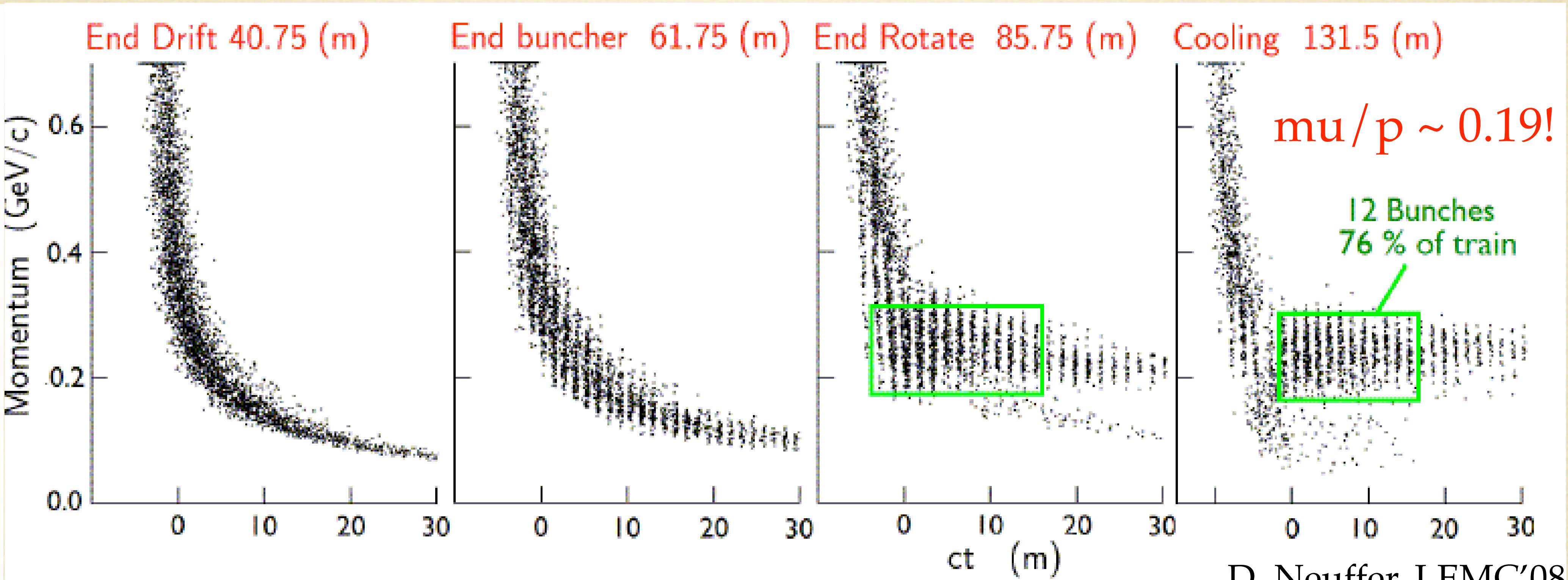
An opportunity exists to conduct non-beam studies with the MERIT equipment after it is shipped from CERN to ORNL ~ Jan 2009 (presentation by V. Graves).

Such studies would begin with no magnetic field (jet quality, Hg pool), followed by studies with the MERIT magnet powered to 15 (or even 20) T at a new fusion power test facility at ORNL.

K. McDonald, NFMCC meeting'08

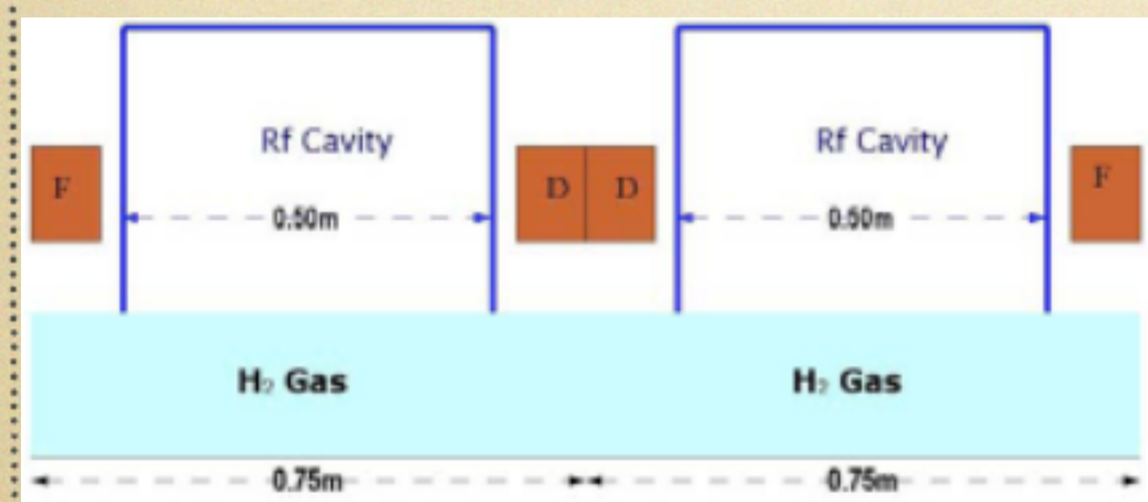
Decay/Phase Rotation channel





D. Neuffer, LEMC'08

RF needs to operate in magnetic field

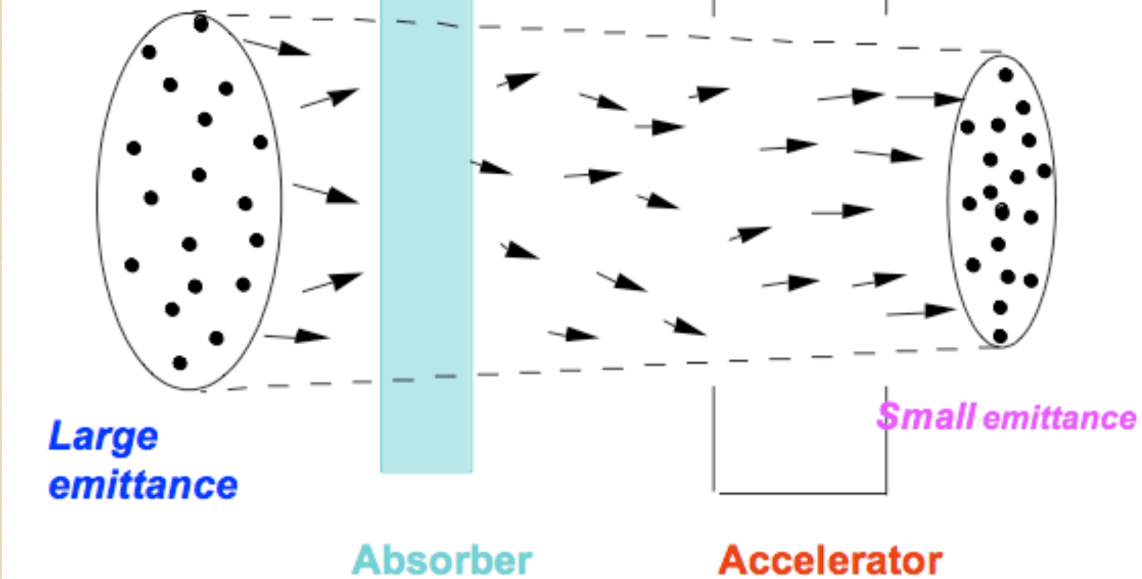


K. Paul MCNote-518

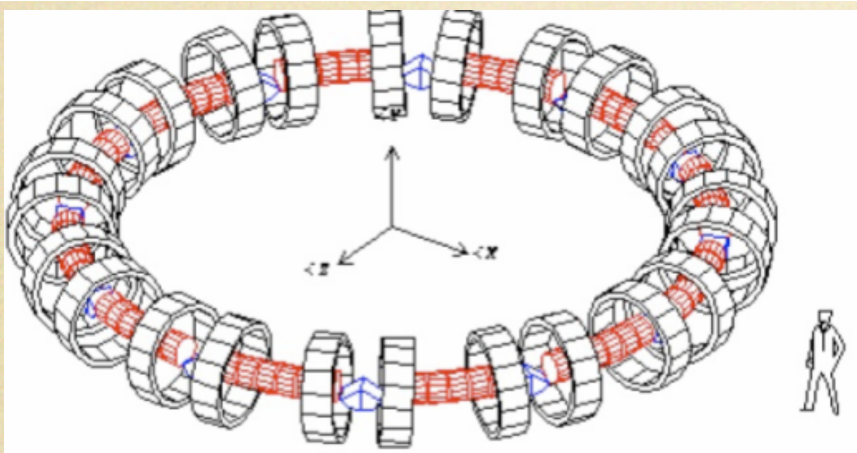
Does high pressurized GH2 help for this application?

Ionization cooling

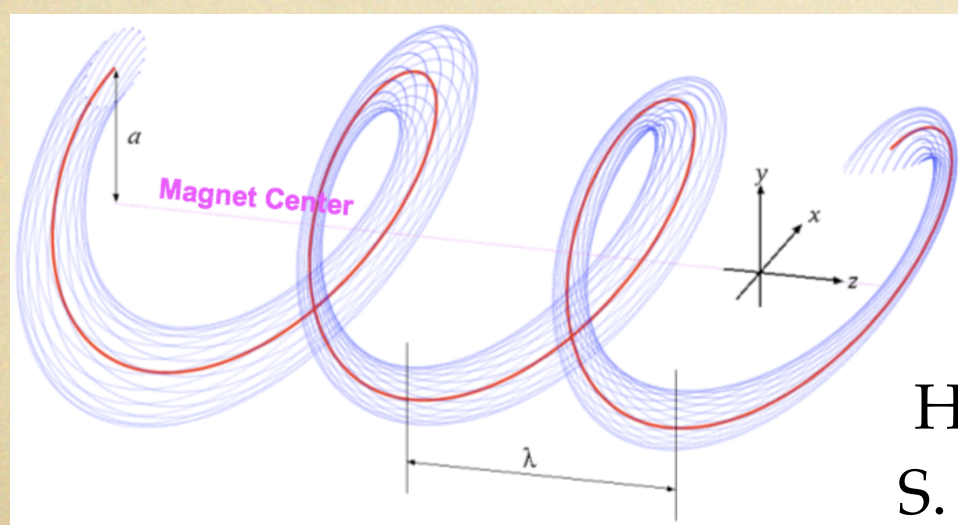
D. Neuffer LEMC'08



Conceptual picture of ionization cooling theory



RFOFO channel
R. Palmer



Helical Cooling Channel
S. Derbenev & R. Johnson

Emittance exchange

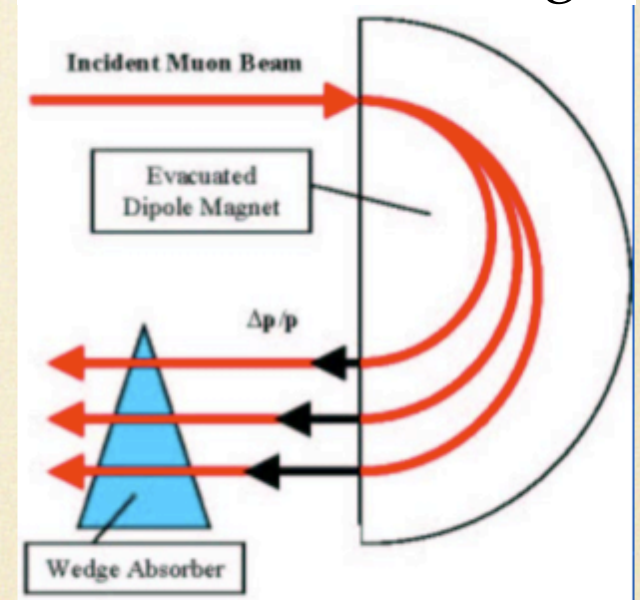


Figure 1. Use of a Wedge Absorber for Emittance Exchange

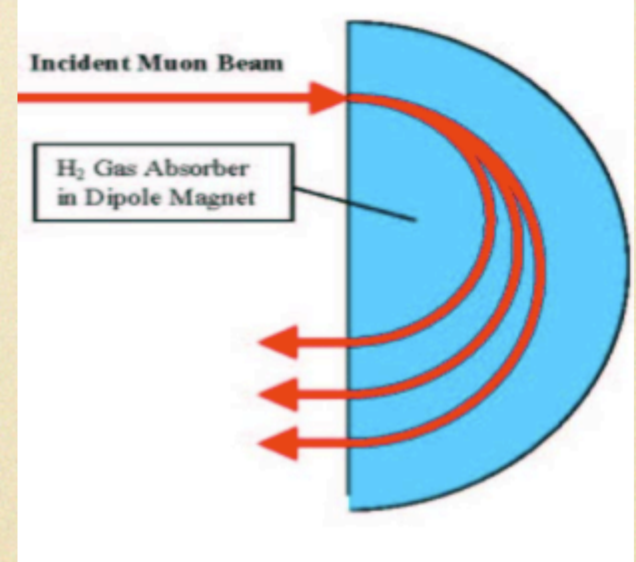
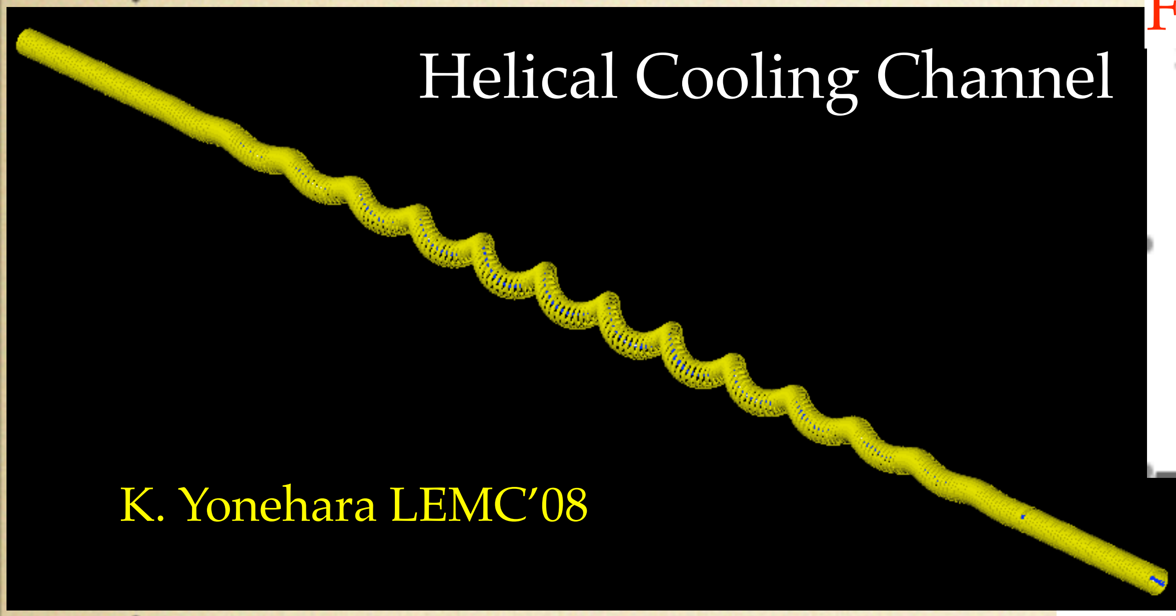


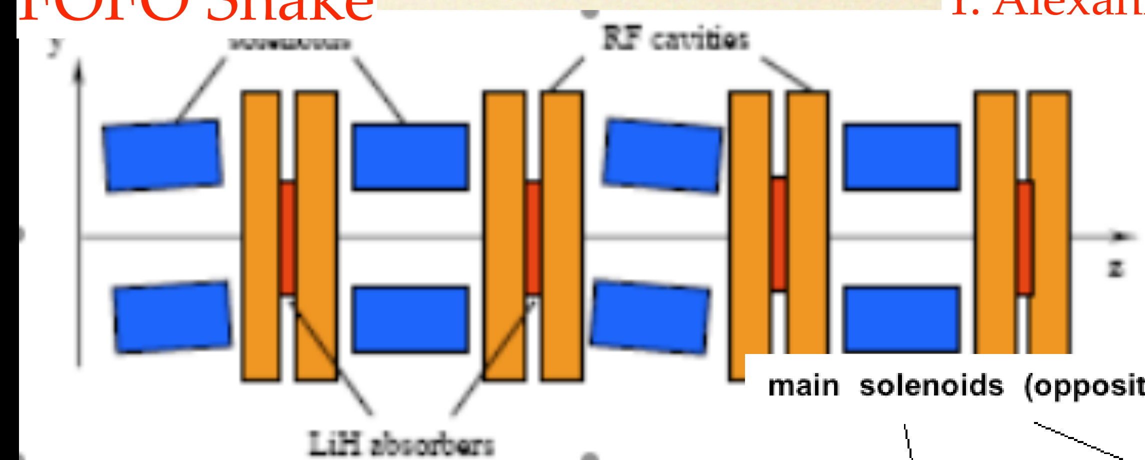
Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

Cooling Channel

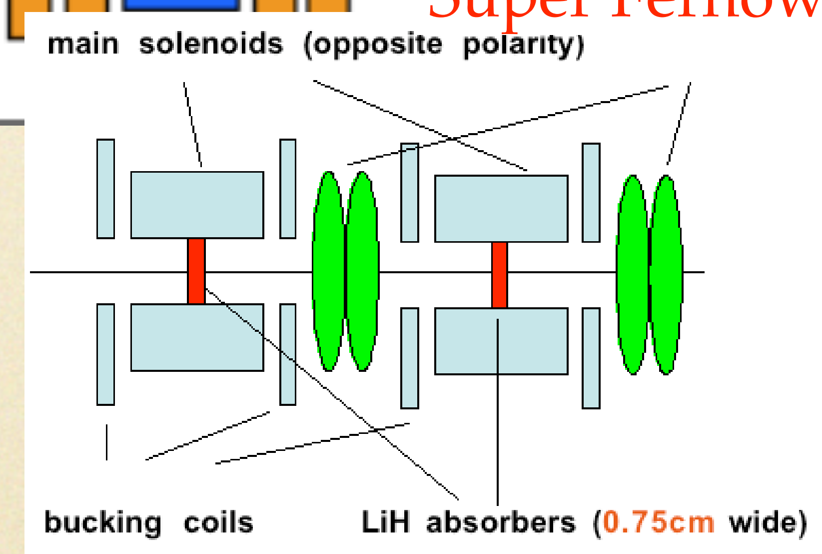


FOFO Snake

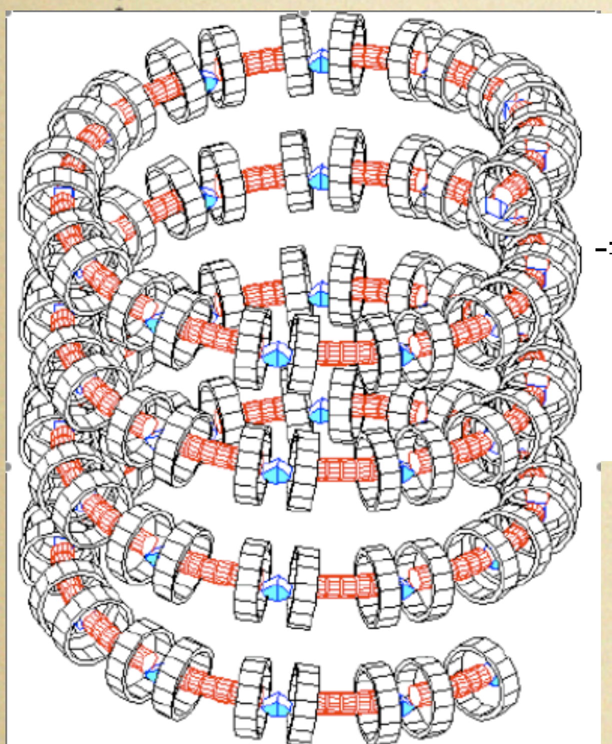
Y. Alexahin MC Design'07



Super Fernow

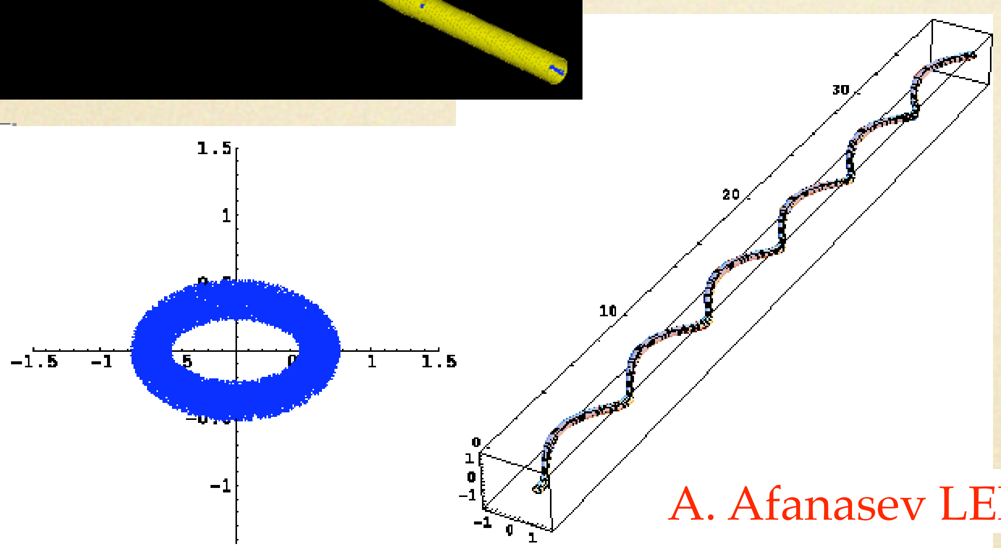


Y. Alexahin MCTF 5/29/08



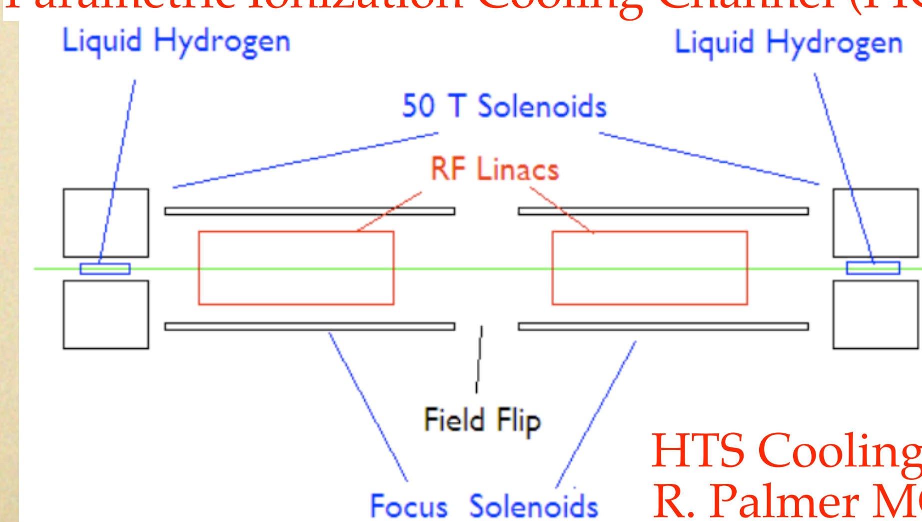
Guggenheim

P. Snopok LEMC'08 &
R. Palmer MC Design'07

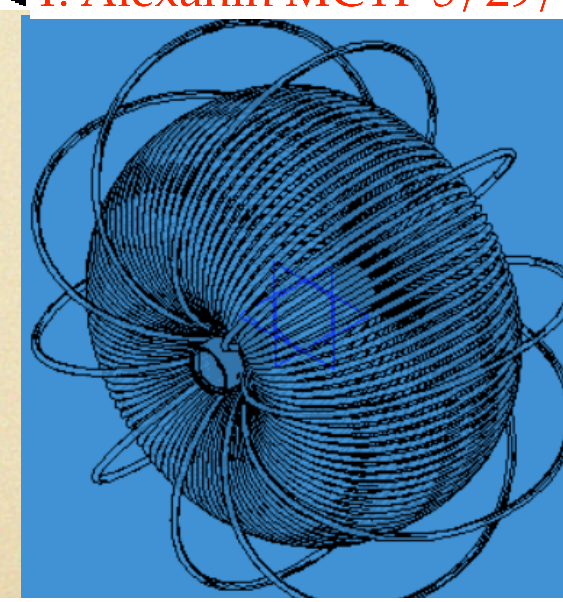


A. Afanasev LEMC'08

Parametric Ionization Cooling Channel (PIC)

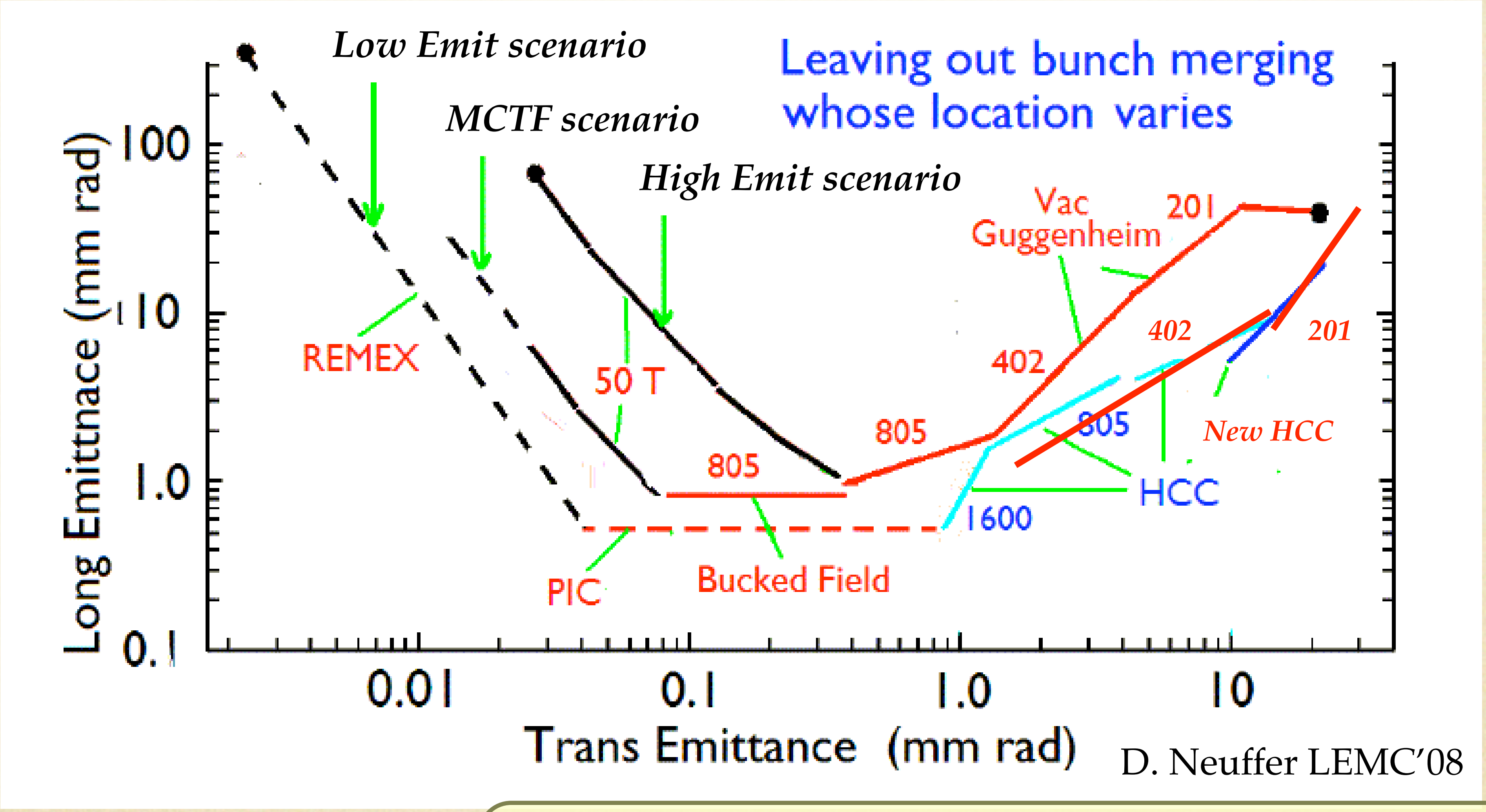


HTS Cooling Channel
R. Palmer MC Design'07



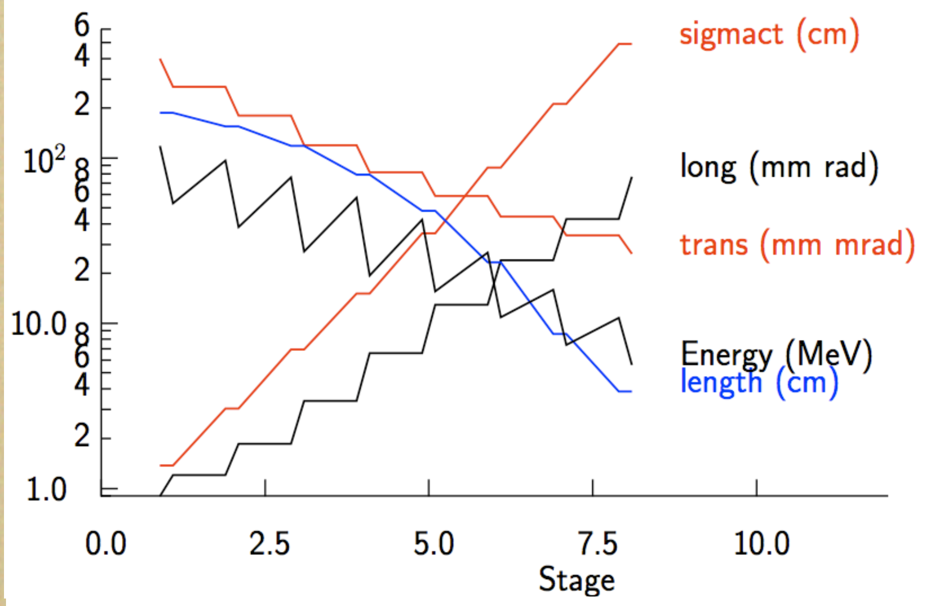
Li Lens Cooling Channel
K. Lee LEMC'08

Emittance Evolution in Cooling Section



D. Neuffer LEMC'08

Matching channel is not included
Window material is not included
All above channels works only one polarity

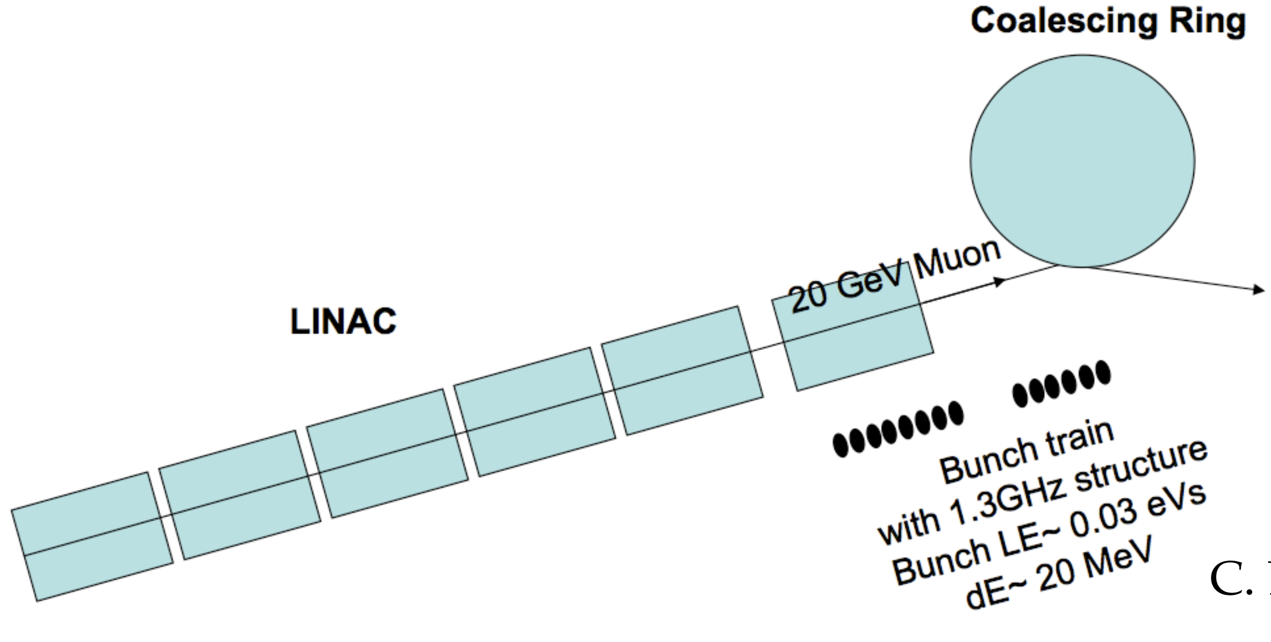


Kinetic energy in 50 T channel

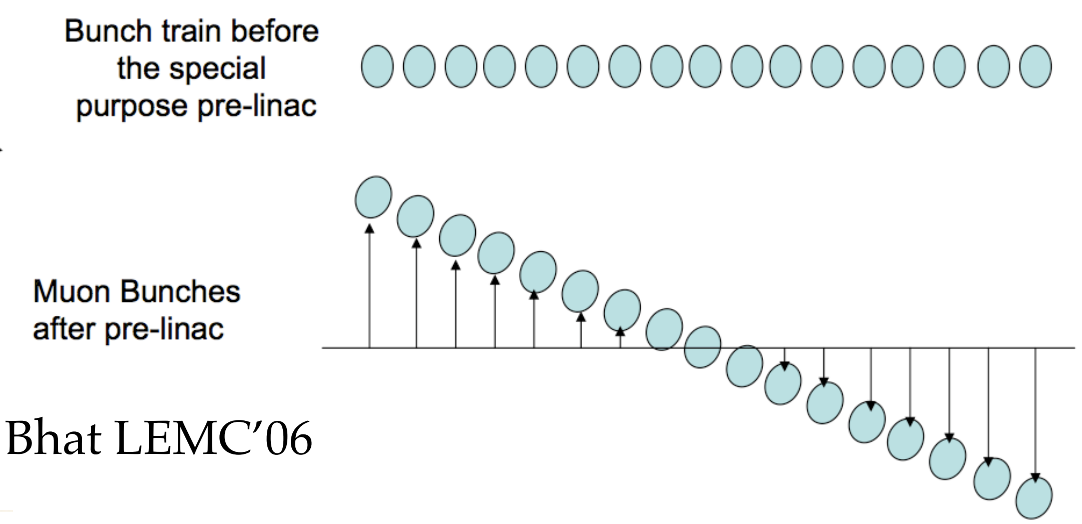
R. Palmer MC Design'07

Can muon accelerate after 50 T channel w/o big loss?

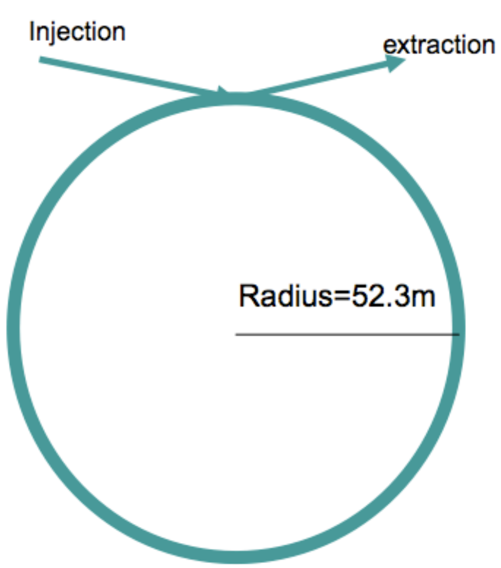
Bunch coalescing ring



- A pre-linac to give a tilt in the Longitudinal Phase-space



C. Bhat LEMC'06



Constraints:
Muon mean-life = 2.2us (rest frame)
Muon half-life in lab = 288us
for 20 GeV beam
Time (90% survival) = 43.8us

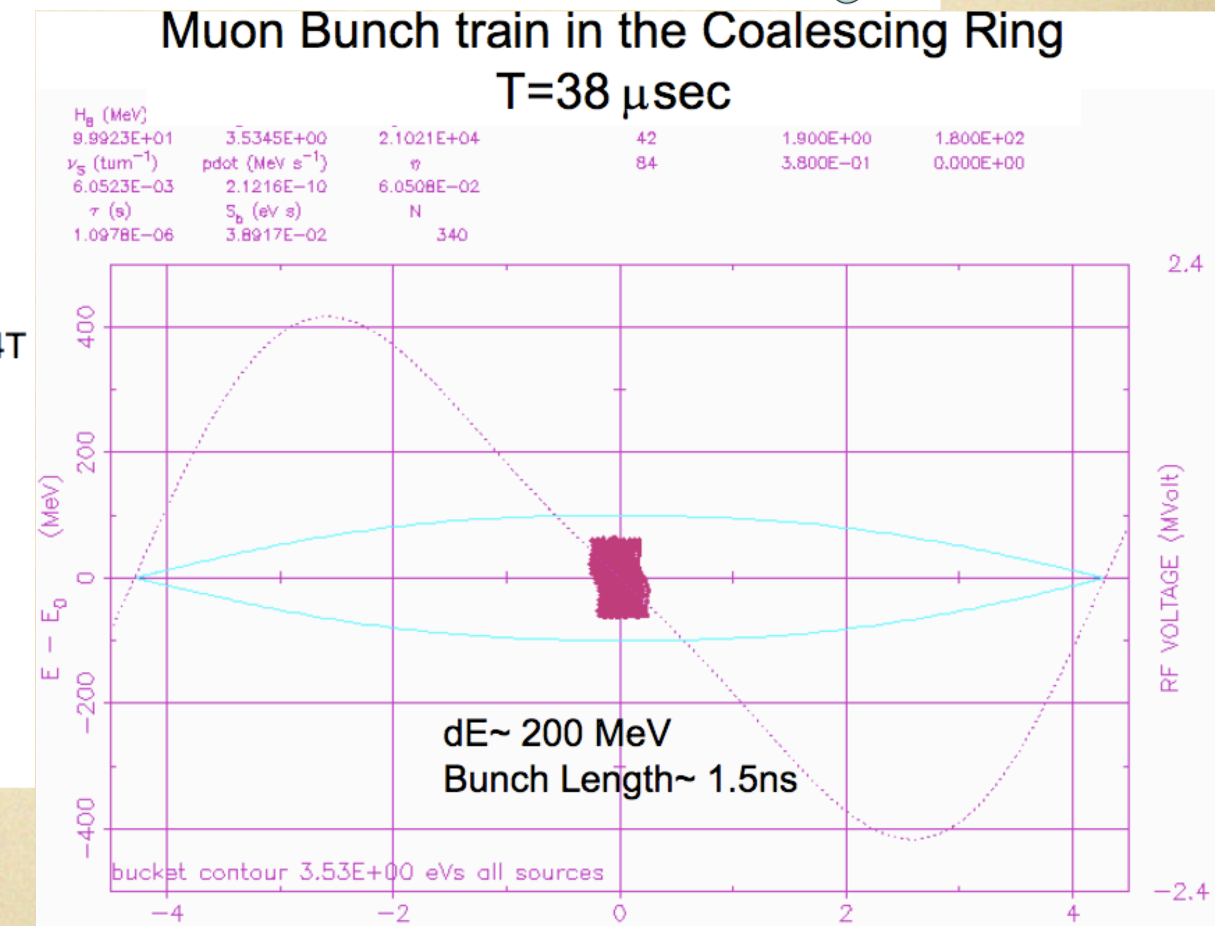
Injection beam : 1.3GHz bunch structure
# of bunches/train = 17

Ring Radius = 52.33m; Revolution period= 1.09μs
Energy of the muon = 20 GeV (gamma = 189.4)
gamma_t of the ring = 4

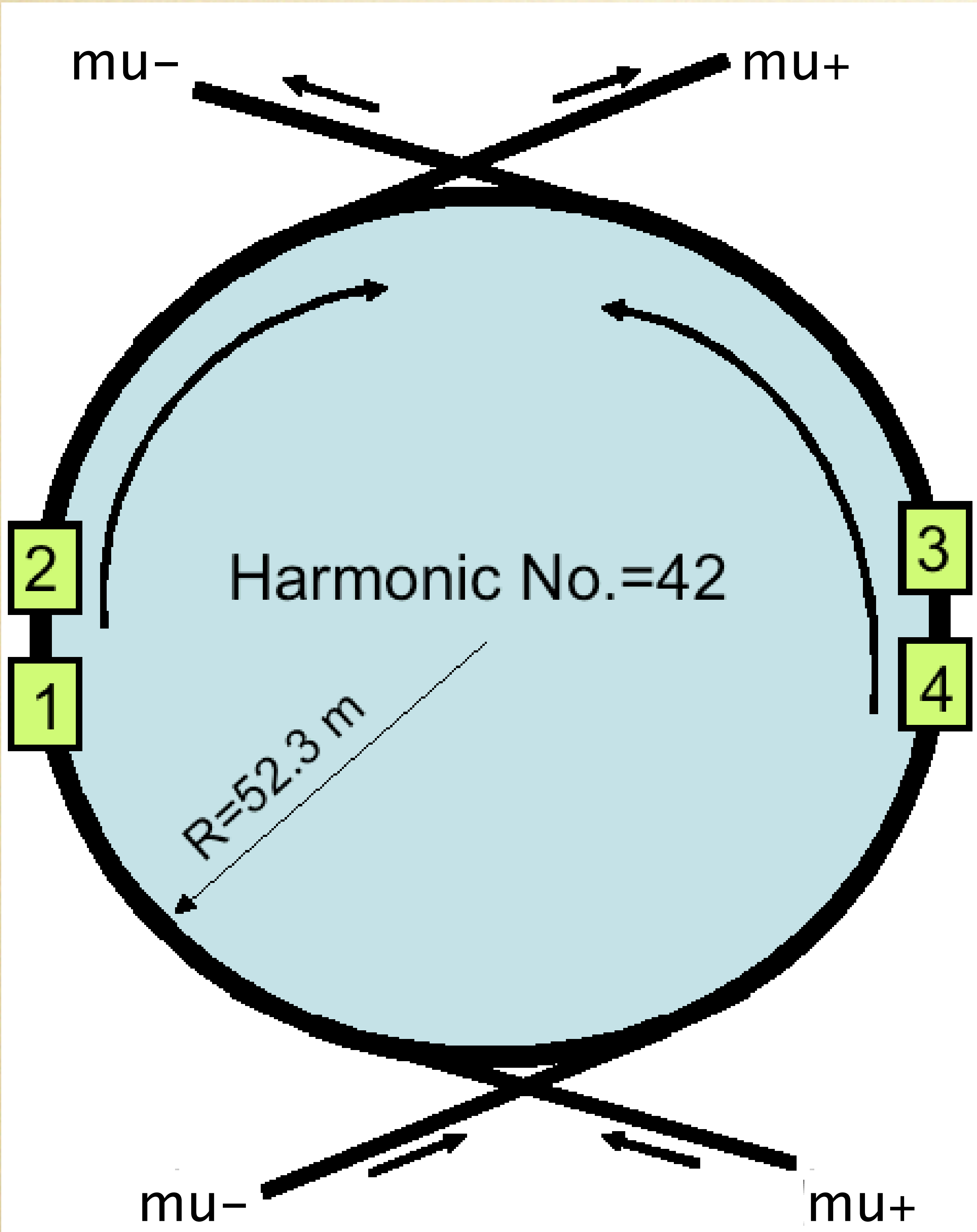
If we assume
Ring-Radius/rho (i.e., fill factor) = 2, then B-Field = 2.54T
(This field seems to be reasonable)

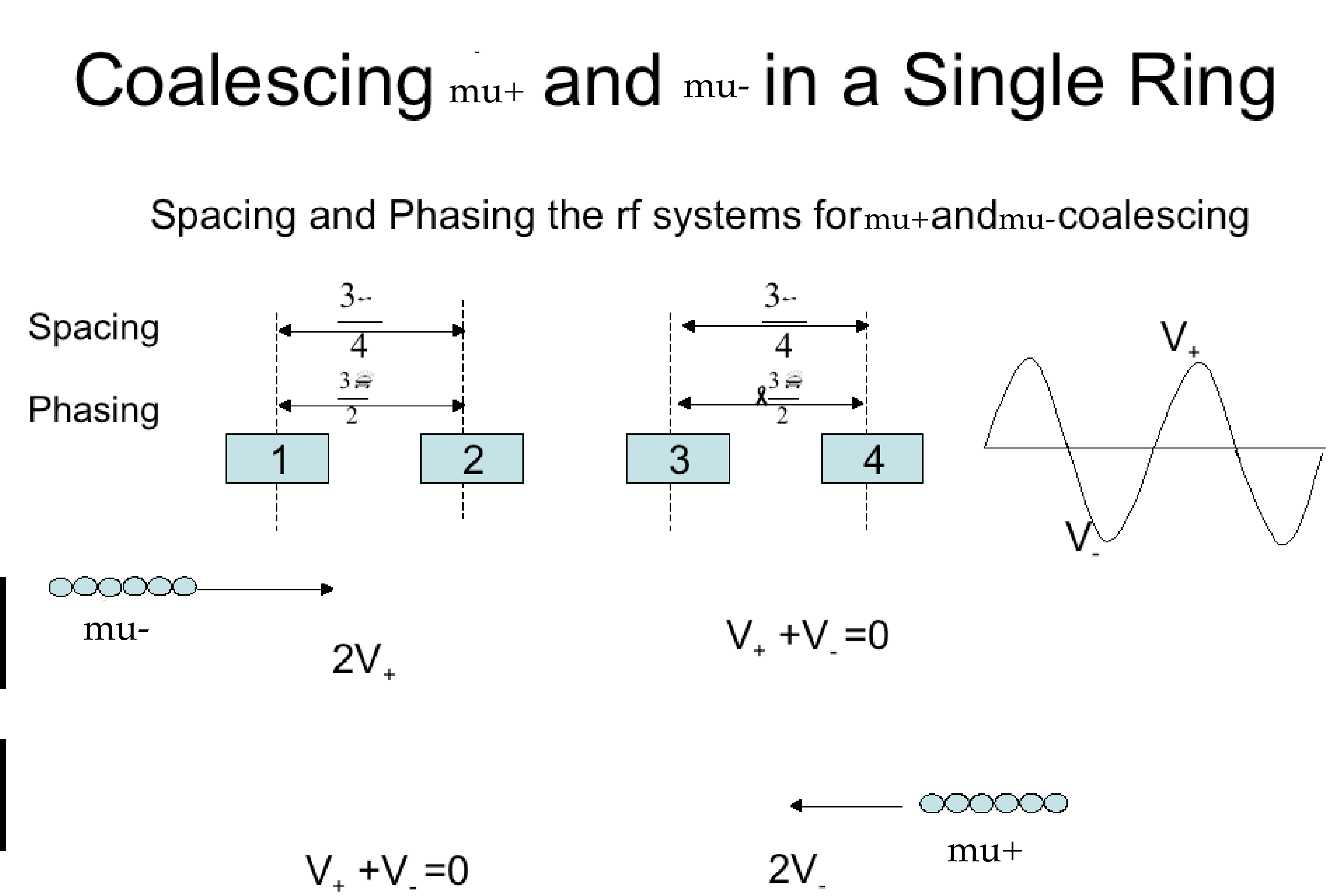
h for the coalescing cavity = 42, 84
Number of trains/injection = less than 37
(assuming ~100ns for injection/extraction)
RF voltage for the coalescing cavity = 1.9 MV (h=42)
= 0.38 MV (h=84)

fsy ~ 5.75E3Hz
Tsy/4 = 43.5us
Number of turns in the ring ~40



Coalescing ring for both charges

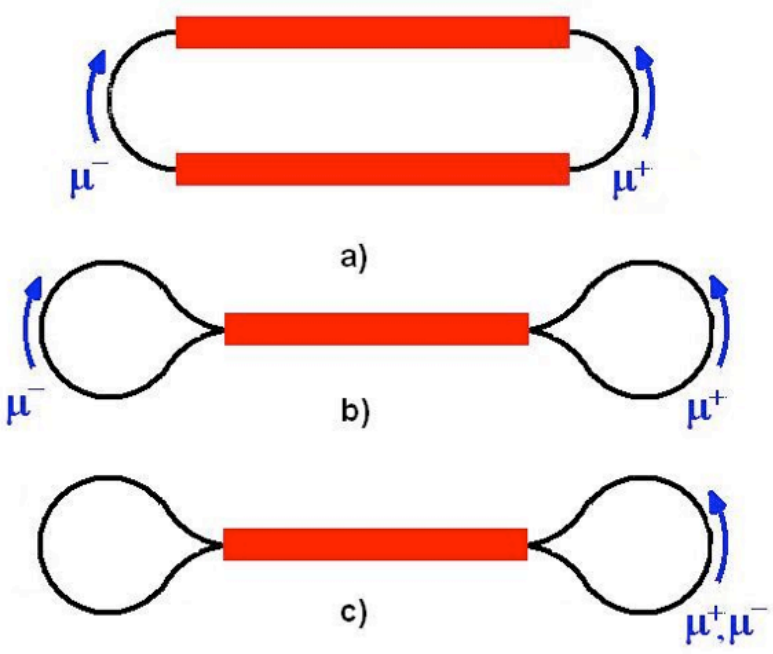




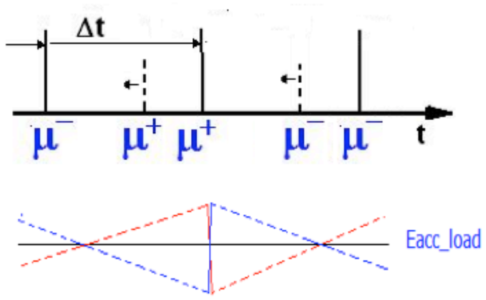
C. Bhat LEMC'08

RLA

For the schemes below the time intervals are different and, thus,
b) Klystron power should change during acceleration;
c) The klystron maximal pulse power should be increased compared to the simplest case.



(Separate arcs for μ^+ and μ^-)



Acceleration gradient along linac,
Red -one direction,
Blue-opposite direction

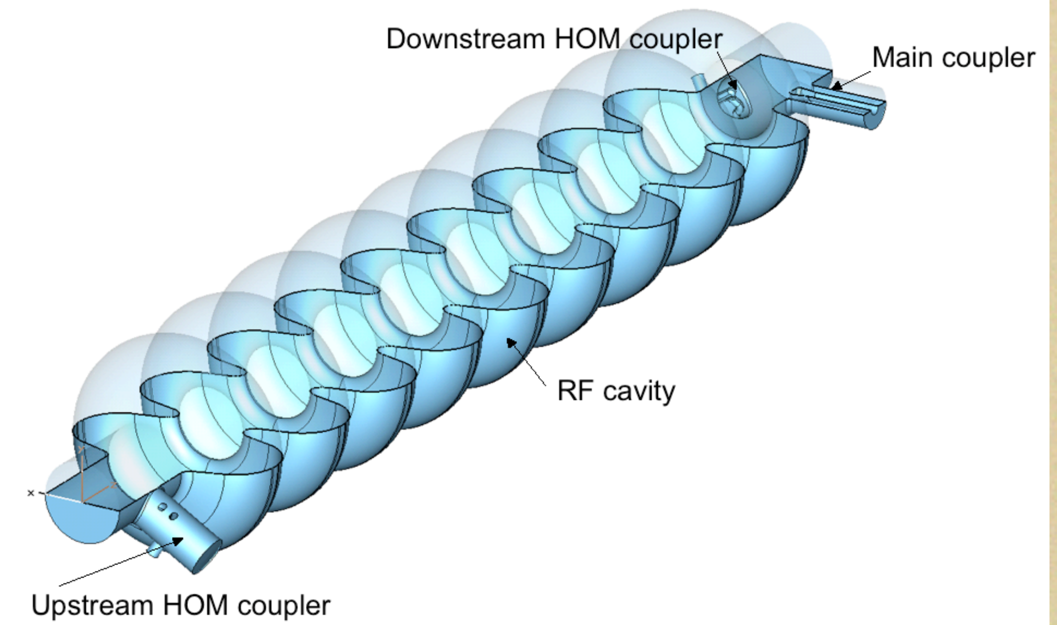
HE2008, 1.5 TeV

N	Muon losses, %	RF power, MW	Total cryogenic losses, MW	Losses in HOM couplers, MW	Total power MW	Number of klystrons (10 MW)	Number of cavities	Average klystron power, kW
10	6.4	20	4.8	1.5	24.8	180	2920	59
20	9.3	16	3.8	2	19.8	122	1460	70
30	11.1	14	3.5	2.2	17.5	92	973	81

LE2008, 1.5 TeV

N	Muon losses,%	RF power, MW	Total cryogenic losses, MW	Losses in HOM couplers, MW	Total power, MW	Number of klystrons (10 MW)	Number of cavities	Average klystron power kW
10	6.4	68	13.9	1.8	81.9	90	2920	402*
20	9.3	48.6	8.7	2.5	57.3	61	1460	424*
30	11.1	42	7.4	2.8	49.4	46	973	486*

ILC RF cavity with the HOM and input couplers:

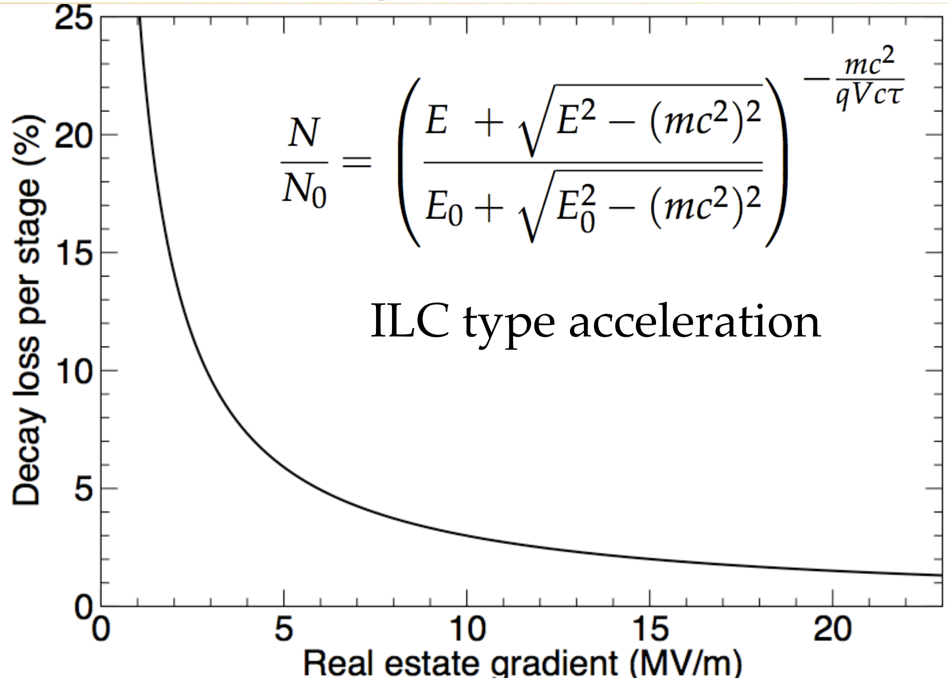


N. Solyak, S. Yakovlev LEMC'08

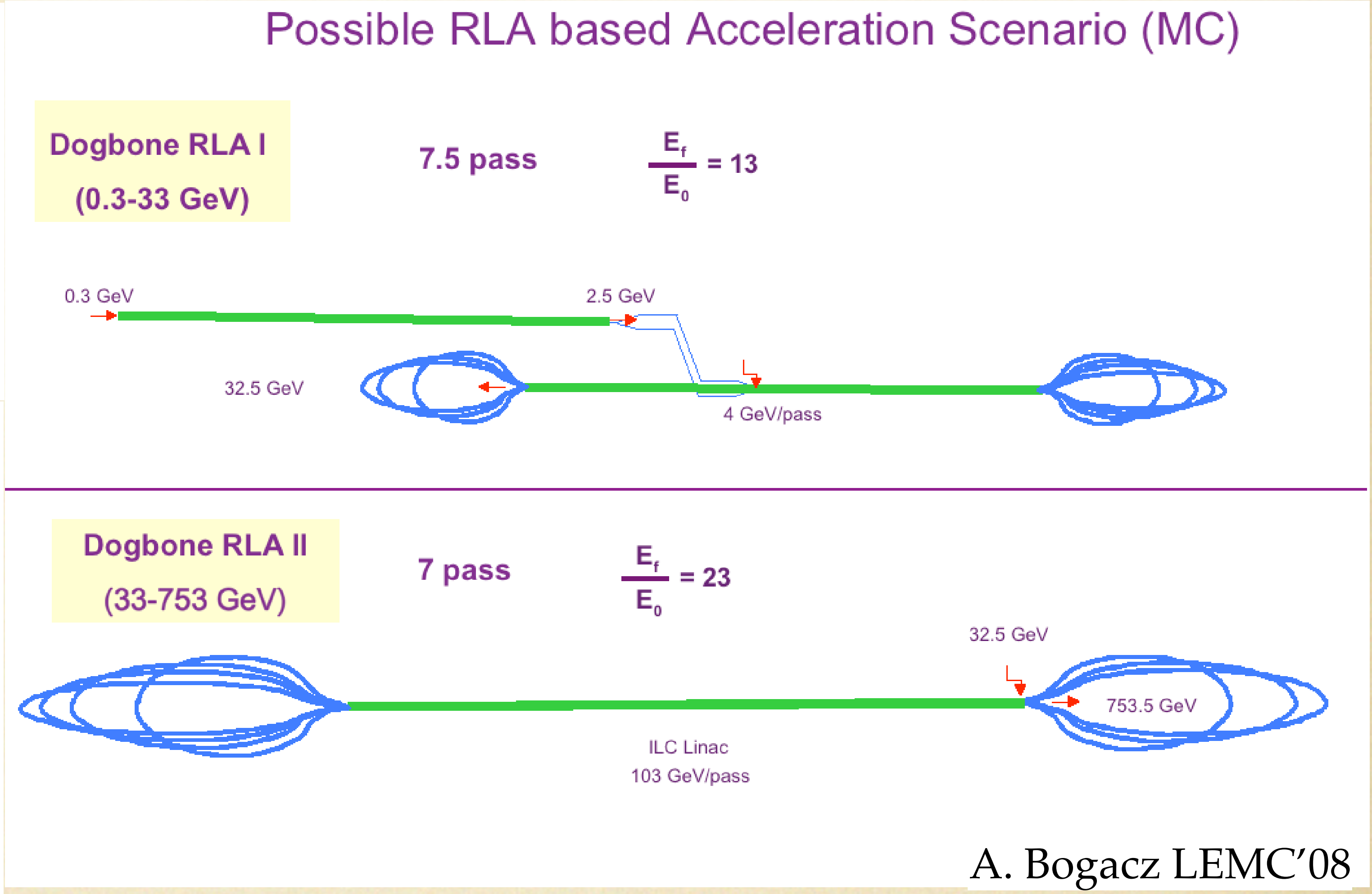
These numbers are based on the assumption the number of muons are same as HE scheme. We need to re-estimate them.

Muon Acceleration

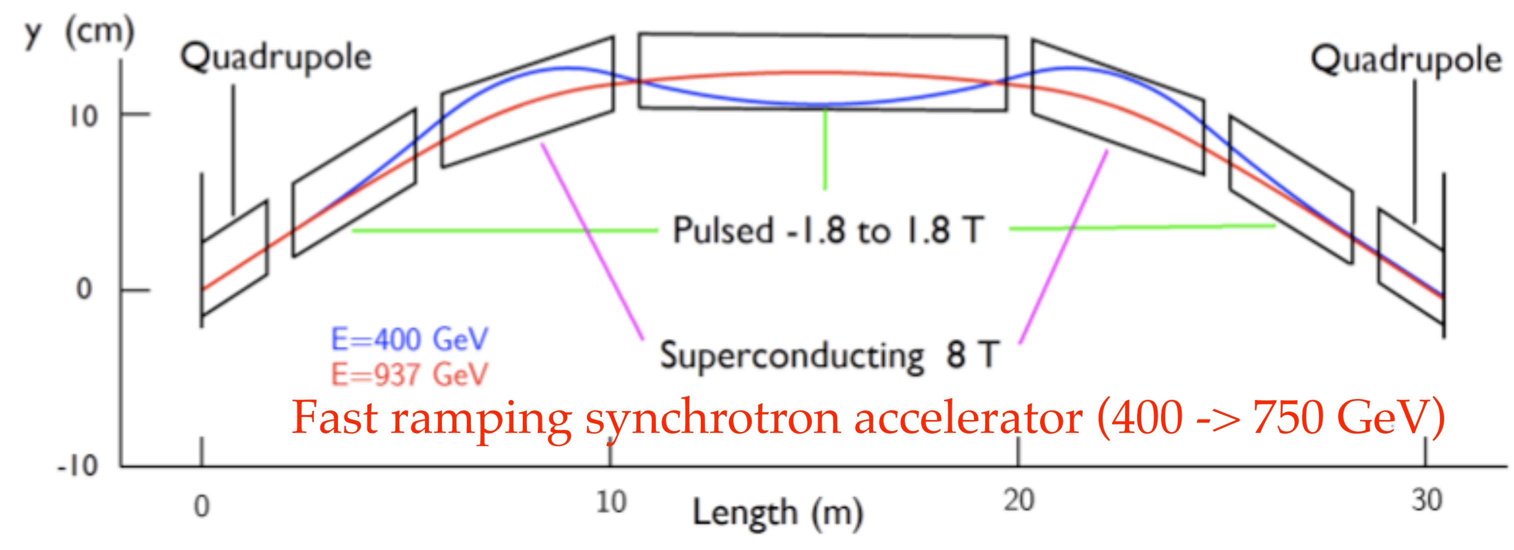
- Accelerate from 90 GeV to 4 TeV in 2 stages
  - 90 GeV to 600 GeV
  - 600 GeV to 4 TeV
- One bunch each sign
- 2×10^{12} per bunch
  - Will discuss lower charge
- $\sigma_z = 3$ mm throughout



S. Berg MC design meeting'07



A. Bogacz LEMC'08

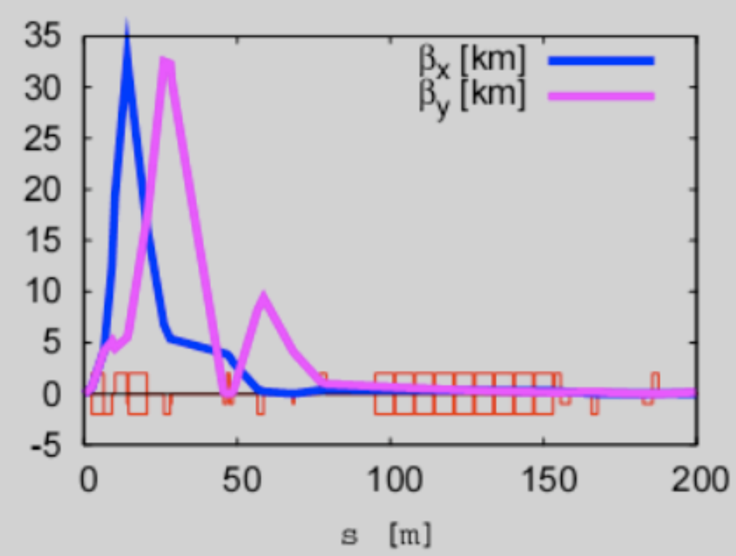


Fast ramping synchrotron accelerator (400 -> 750 GeV)

D. Summers MC design meeting'07

Collider Ring

Dipole First Muon Collider Lattice



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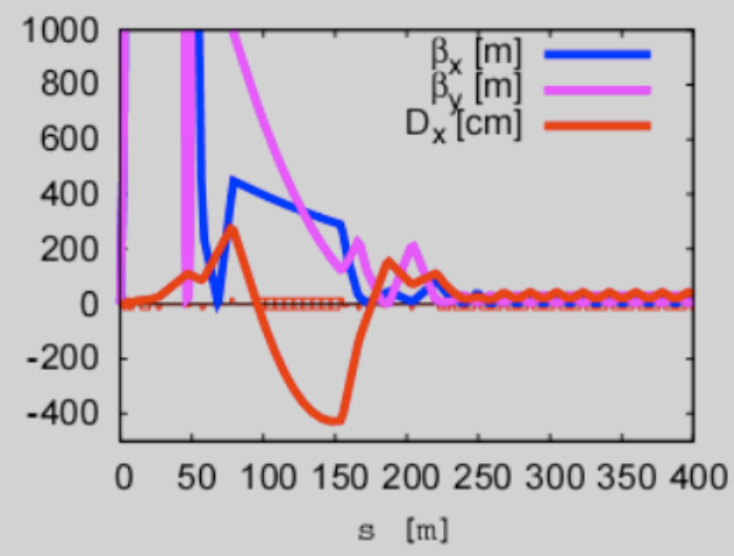
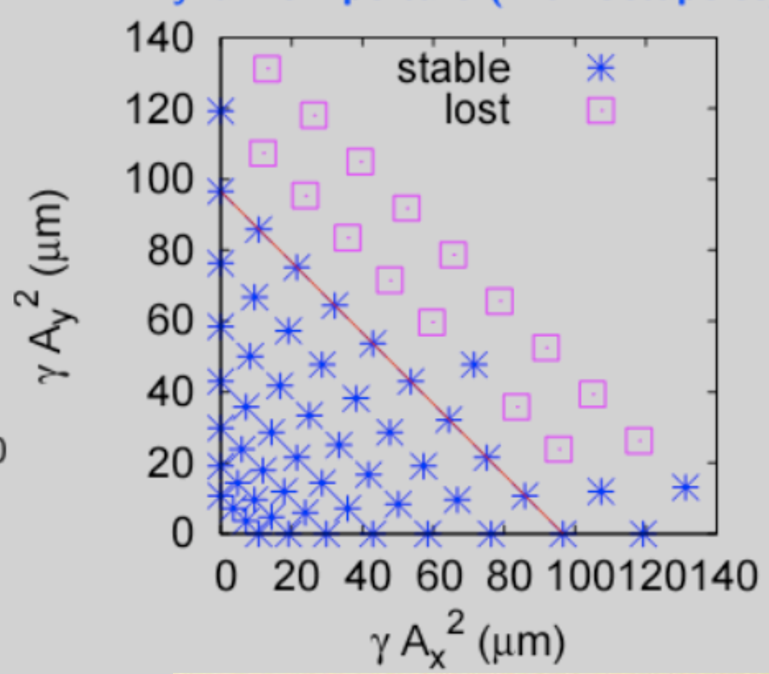


Matching section

Dynamic Aperture (with octupoles)



$\simeq 2.8\,\sigma$

Y. Alexahin & E. Wendt LEMC'08

SUMMARY AND OUTLOOK

Energy (GeV)	Dipole First	Oide (96)	Dipole First with 90 deg.FODO
L (m)	3132	5670	3815
B_{dip} (T)	9.6	3.7	9.7
Tunes	42.11/41.18	31.55/31.56	35.52/34.64
β^* (mm)	10	3	10
$\hat{\beta}$ (km)	33	901	33
# of IPs	2	1	1
distance to first quad (m)	$\pm$6 (2.5)	$\pm$6	$\pm$6 (2.5)
DA (# of σ)	2.8	4.5	3
momentum aperture	$\pm$ 0.6 %	$\pm$ 0.6 %	$\pm$ 0.7 %
α_p	-1.3×10^{-4}	5×10^{-5}	5×10^{-4}
length of RF sections (m)	-	2 $\times$ 1.5	-

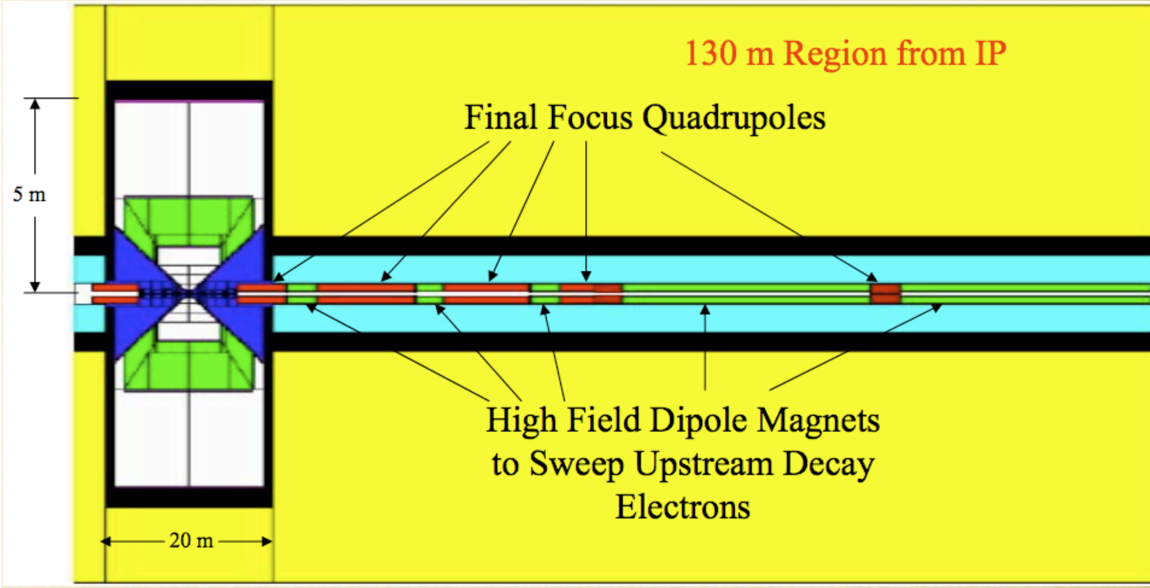
MC Detector

MC Detector can be similar as ILC (or CLIC) Detector: Same physics!

→ Background, Radiation damage (A. Bross NFMCC'08)

- Muon Decay Background
  - Electron Showers from high energy electrons.
    - Lepto-production of hadrons not included in studies.
      - Not important for 2×2 TeV or smaller colliders.
  - Bremsstrahlung Radiation for decay electrons in magnetic fields.
  - Photonuclear Interactions
    - Source of hadrons background.
  - Bethe-Heitler muon production.
- Beam Halo
  - Beam Scraping at 180° from IP to reduce halo. Could it cause some?
  - Collider sources such as magnet misalignments.
- Beam-Beam Interactions.
  - Believed to be small.

S. Kahn LEMC'06



N. Mokhov MC physics & detector

Collider parameters and calculated integrated and *effective* luminosities

Parameters	LHC	NLC-500	NLC-1000	$\mu^+\mu^-$
E_{cm} (TeV)	14	0.5	1	4
$\mathcal{L}$ (10^{34}cm^{-2}s^{-1})	1	0.71	1.45	4.55
Rep. rate f (Hz)	-	180	120	4.04×10^4
Particles/bunch (10^{11})	1	0.07	0.11	20
Bunch/RF pulse	-	90	75	1
Bunch separation (ns)	25	1.4	1.4	18.6×10^3
Yearly $\mathcal{L}_y$ (fb^{-1})	100	71	145	455
σ_h (μb)	80×10^3	0.045	0.034	0.054
Δt_d or bunch train length (ns)	300	126	105	-
$\mathcal{L}_{eff}$ (cm^{-2})	3.00×10^{27}	3.94×10^{31}	1.21×10^{32}	1.13×10^{30}
$(\sigma_h\times\mathcal{L}_y)/(\sigma_h\times\mathcal{L}_y)_{LHC}$	1	4.00×10^{-7}	6.16×10^{-7}	3.07×10^{-7}
$(\sigma_h\times\mathcal{L}_{eff})/(\sigma_h\times\mathcal{L}_{eff})_{LHC}$	1	7.39×10^{-3}	1.71×10^{-2}	2.54×10^{-4}

Compare with LHC
Hadron BG: 3e-7 smaller
Instantaneous BG: 0.025 %

ILC & CLIC Detector

Detector Specifications

- Detector requirements given for CLIC detector
  - Some are more stringent for ILC
- Many performance parameters are factor 2 – 5 better than what has been achieved to date
- Granularity of the detectors expected to dramatically increase because of recent technology advances
- Material budgets significantly reduced
- Machine Detector Interface
  - Masking system
    - Constraints on vertex detector
  - Magnet design
  - Low angle calorimeters
  - Beam pipe design

Detector	CLIC
Vertexing	$15\mu m \oplus \frac{35\mu m GeV/c}{p\sin^{3/2}\theta}$ $15\mu m \oplus \frac{35\mu m GeV/c}{p\sin^{5/2}\theta}$
Solenoidal Field	$B = 4\ T$
Tracking	$\frac{\delta p_t}{{p_t}^2} = 5. \times 10^{-5}$
E.m. Calorimeter	$\frac{\delta E}{E(GeV)} = 0.10\frac{1}{\sqrt{E}} \oplus 0.01$
Had. Calorimeter	$\frac{\delta E}{E\ (GeV)} = 0.40\frac{1}{\sqrt{E}} \oplus 0.04$
μ Detector	Instrumented Fe yoke $\frac{\delta p}{p} \simeq 30\%$ at $100\ GeV/c$
Energy Flow	$\frac{\delta E}{E\ (GeV)} \simeq 0.3\frac{1}{\sqrt{E}}$
Acceptance	$\|\cos\theta\| < 0.98$
mask	120 mrad
beampipe	3 cm
small angle tagger	$\theta_{min} = 40$ mrad

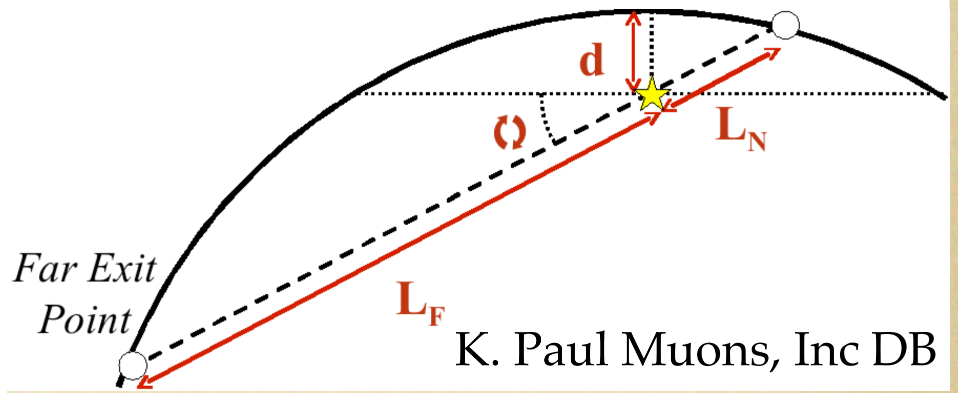
- My comments on detector technology mainly based on current efforts within the ILC community

M. Demarteau LEMC'08

Radiation Hazards

Design Parameters			Designs				
			Tevatron	μ-Tevatron I	μ-Tevatron II	μ-Tevatron III	MC2006
L	Average Luminosity	$cm^{-2}\ s^{-1}$	1.E+34	1.E+35	1.E+35	1.E+35	1.E+35
E_μ	Beam Energy	TeV	0.250	1.000	2.500	2.500	2.500
T	Operational Year	s	1.E+07	1.E+07	1.E+07	1.E+07	1.E+07
f_{REP}	Pulse Repetition Rate	Hz	1.00	1.00	1.00	1.00	20.00
P	Proton Beam Power on Target	MW	1.00	1.00	1.00	1.00	0.20
E_p	Proton Beam Energy	GeV	8.00	8.00	8.00	8.00	8.00
C	Circumference of Ring	km	6.28	6.28	6.28	3.14	3.14
ℓ_s	Maximum Length of "*Uncontrolled Straight*"	m	10.00	5.00	1.00	100.00	100.00
B	Dipole Field Strength	T	8.00	8.00	8.00	12.00	8.00
ε_{NT}	Normalized Transverse Emittance	mm mrad	3.00	1.00	1.00	1.00	3.00
β^*	Amplitude Function at IP	cm	5.00	5.00	2.00	2.00	0.50
d	Depth of Ring	m	10.00	300.00	300.00	200.00	300.00
θ	Ring Tilt Angle	degrees	0.00	0.00	0.00	0.80	15.00
n_b	Number of Bunches		1.00	1.00	1.00	1.00	1.00
δ	Fraction of Muons Decaying in Ring		10%	4%	4%	1%	62%

- Site depth and civil engineering:
  - Fermilab and BNL have depth constraints, for example; the larger of the two, restricted to <200m down.
    - Municipal water supply + substrate will not support tunnel.
  - The NUMI project at Fermilab entailed considerable civil engineering for an ~1 km long tunnel only 100 m deep – (won the 2005 civil engineering award)
  - Maintenance, water leaks are a problem even with the NUMI depth (muons are much nicer, however, from an activation standpoint)

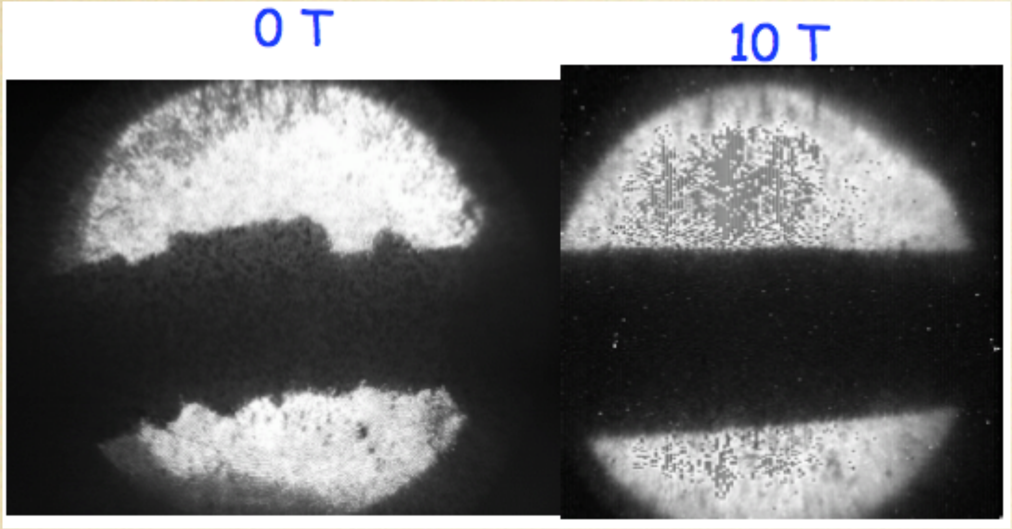


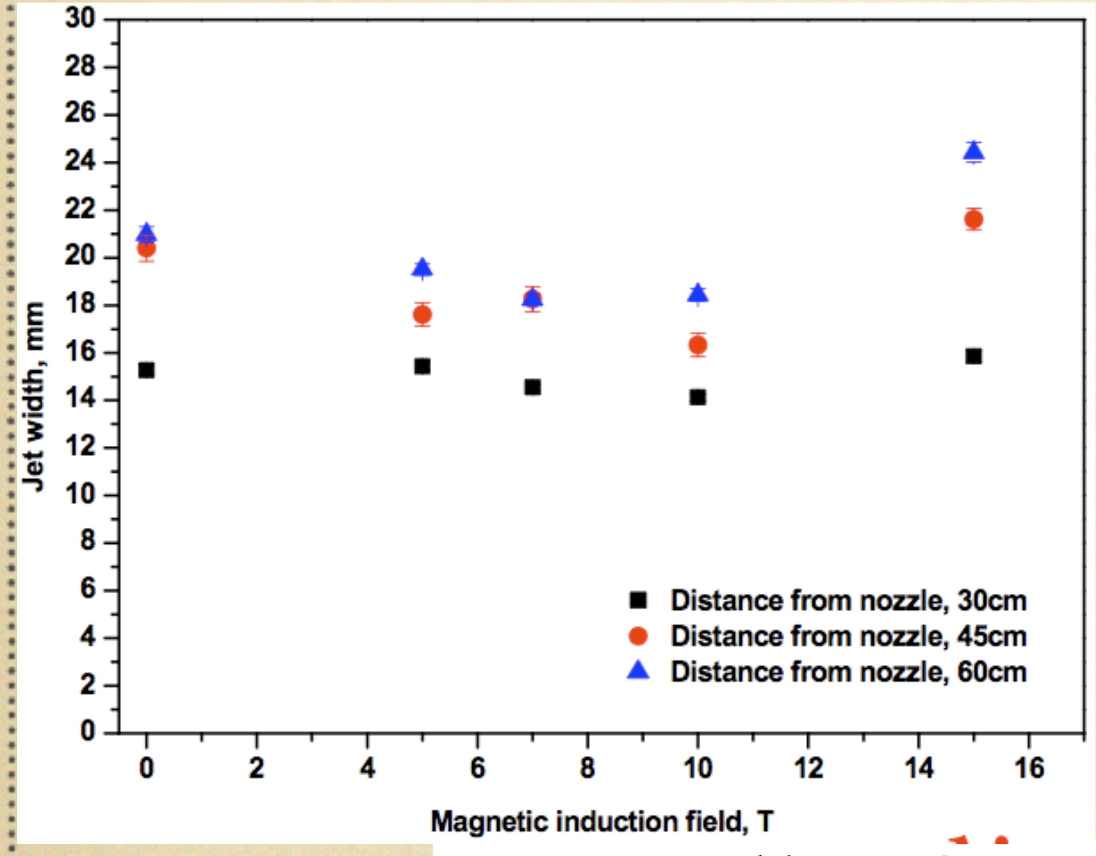
K. Paul Muons, Inc DB

C. Johnstone LEMC'08

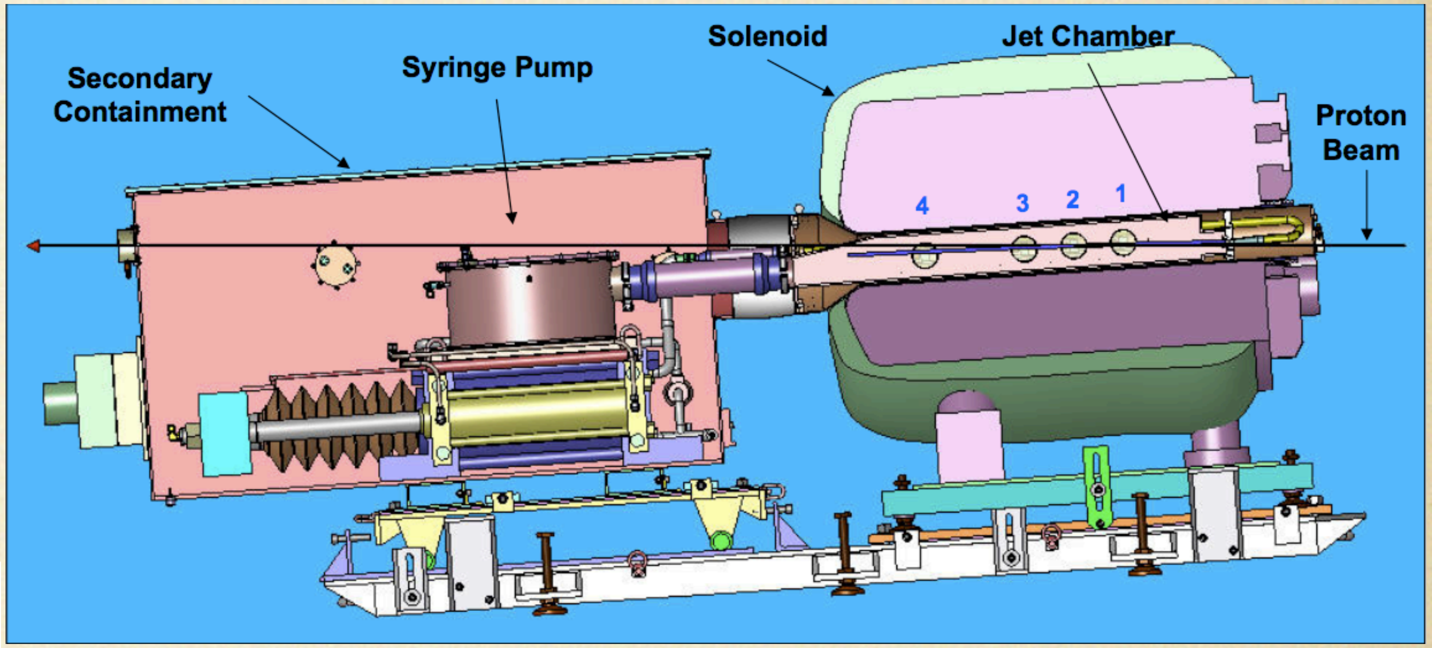
The depth is determined by the number of muons per bunch

MERIT





K. McDonald, LEMC'08



Collaboration list

- Muons, Inc. — Innovation in Research
- Neutrino Factory / Muon Collider
- Brookhaven National Laboratory
- Jefferson Lab
- Berkeley Lab
- The University of California — UCLA
- Fermilab
- Illinois Institute of Technology
- Old Dominion University 1930
- APC
- Argonne National Laboratory
- UC Riverside — University of California

Conclusion

- MC project becomes higher priority
- Design study based on simulation
- We have many good ideas
- Very close to make real physics events!!