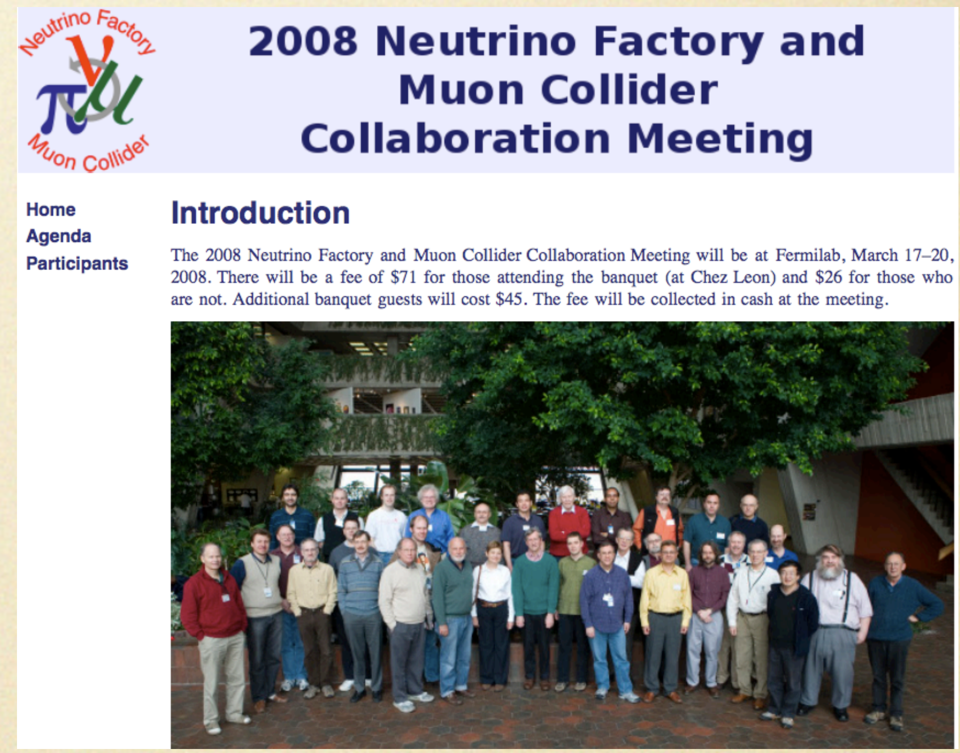
# Recent Progress for Muon Collider

Katsuya Yonehara, Fermilab

# Reference


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




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

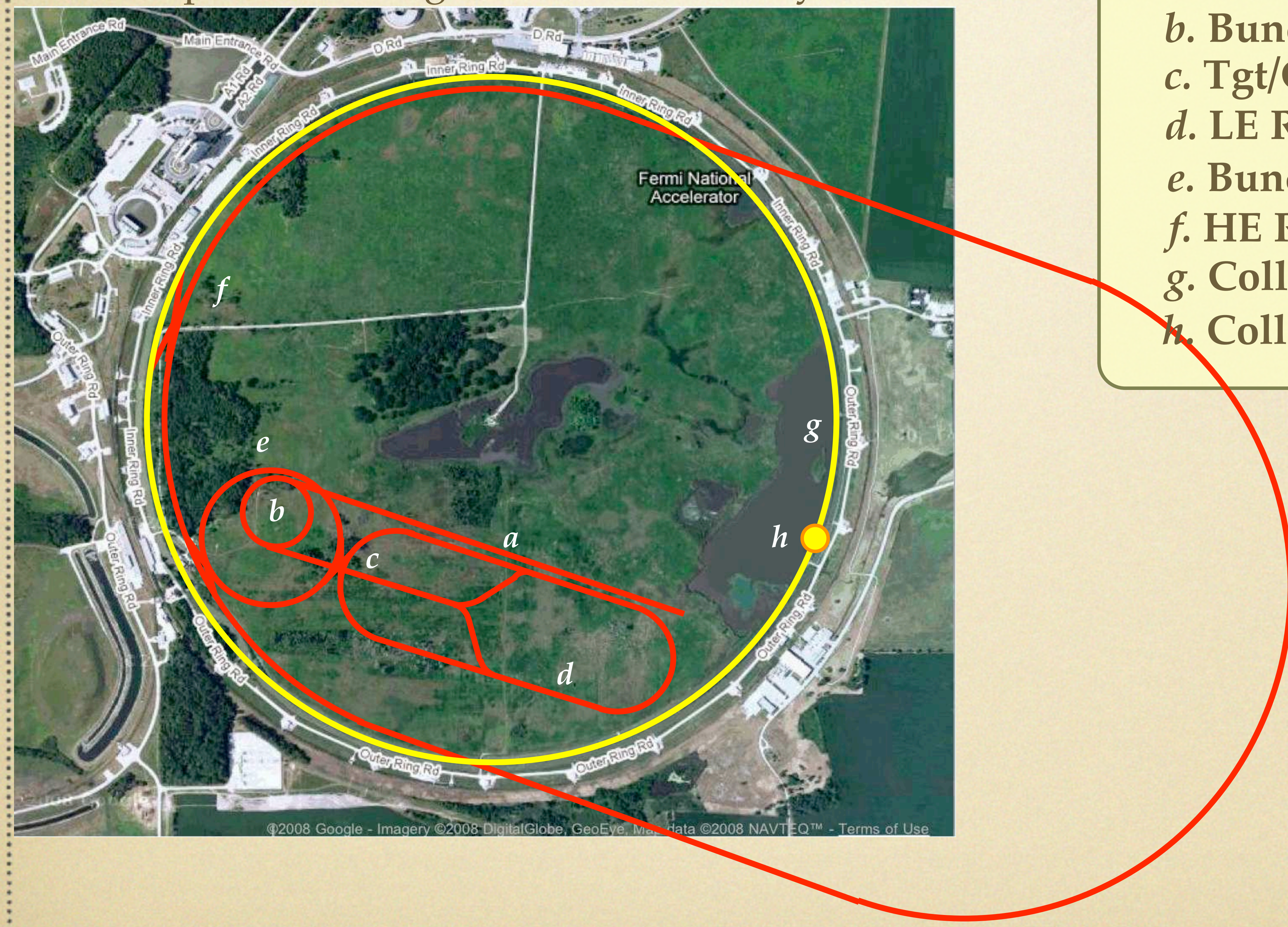

http://www.muonsinc.com/lemc2008/

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

# Muon collider

for rich physics project

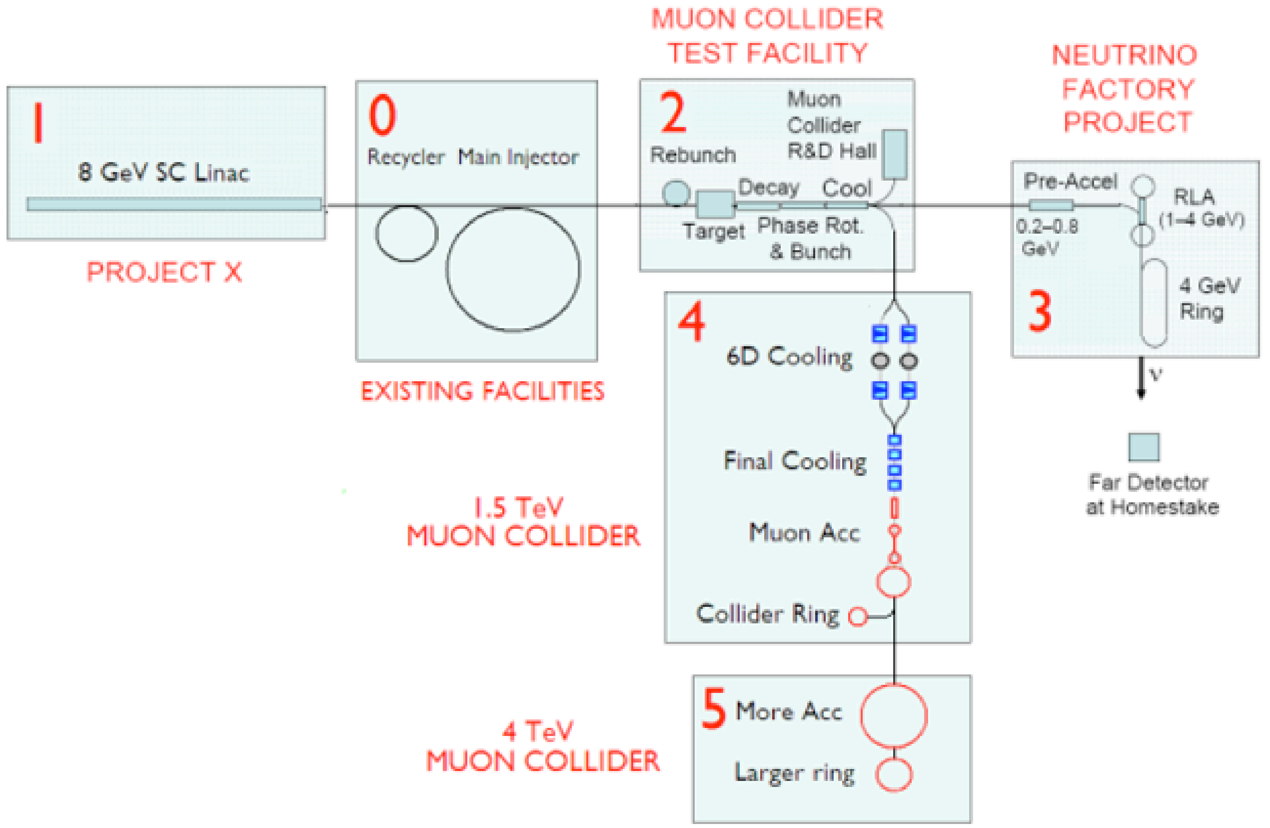
Conceptual drawing (scales are arbitrary)




*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**

# MC scenario

A Phased Approach — R. Palmer P5 meeting'08 @ BNL

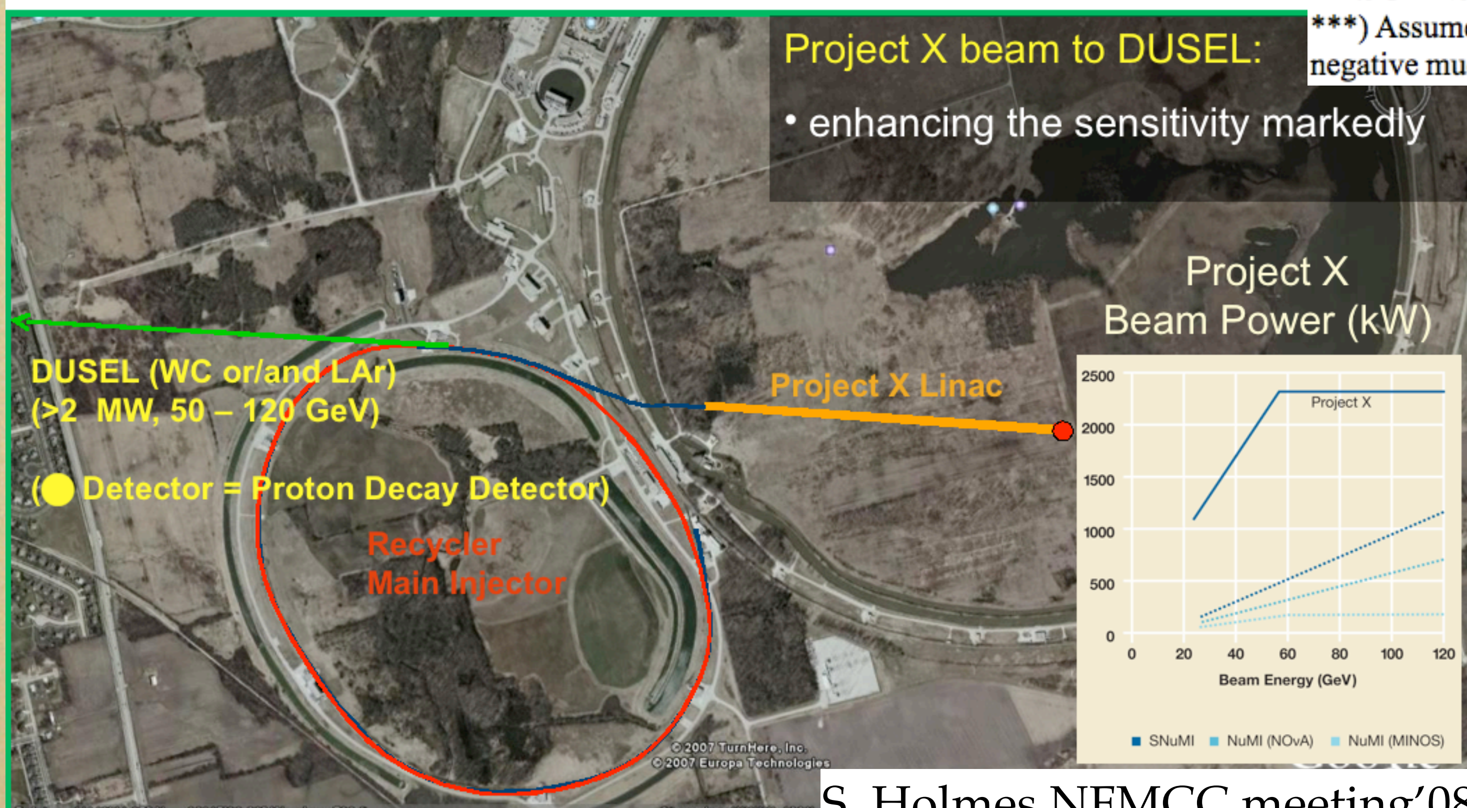



Evolution of a world-leading neutrino program

| | Low Emit. | High Emit. | MCTF07 |
|---|---|---|---|
| √ s (TeV) | | 1.5 | |
| Av. Luminosity ($10^{34}/cm^2/s$) * | 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 | $407\times 10^3\alpha_c$ | 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 $\alpha_c$=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

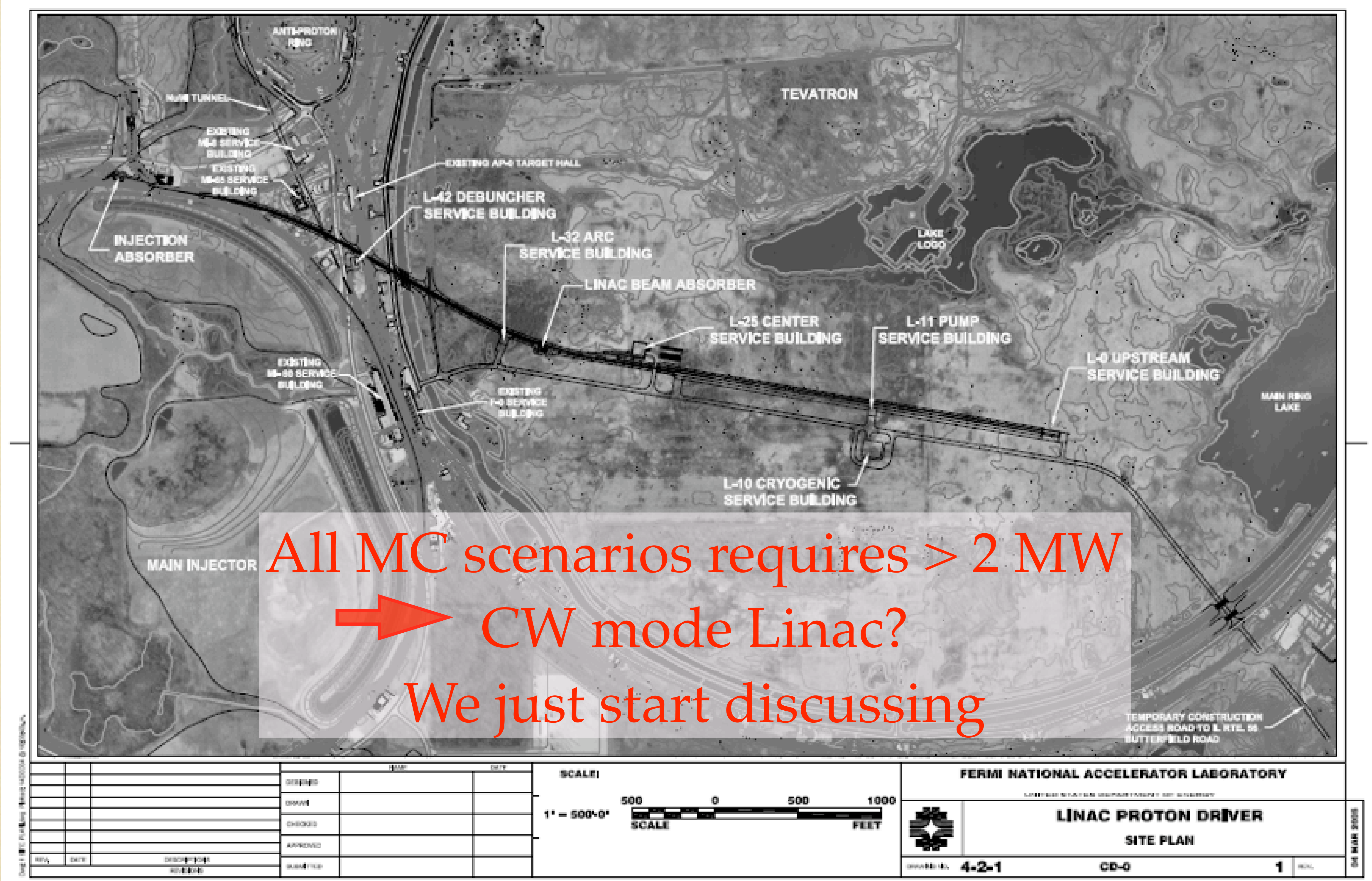



S. Holmes NFMCC meeting'08

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

# 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 $\mu^+$ 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.

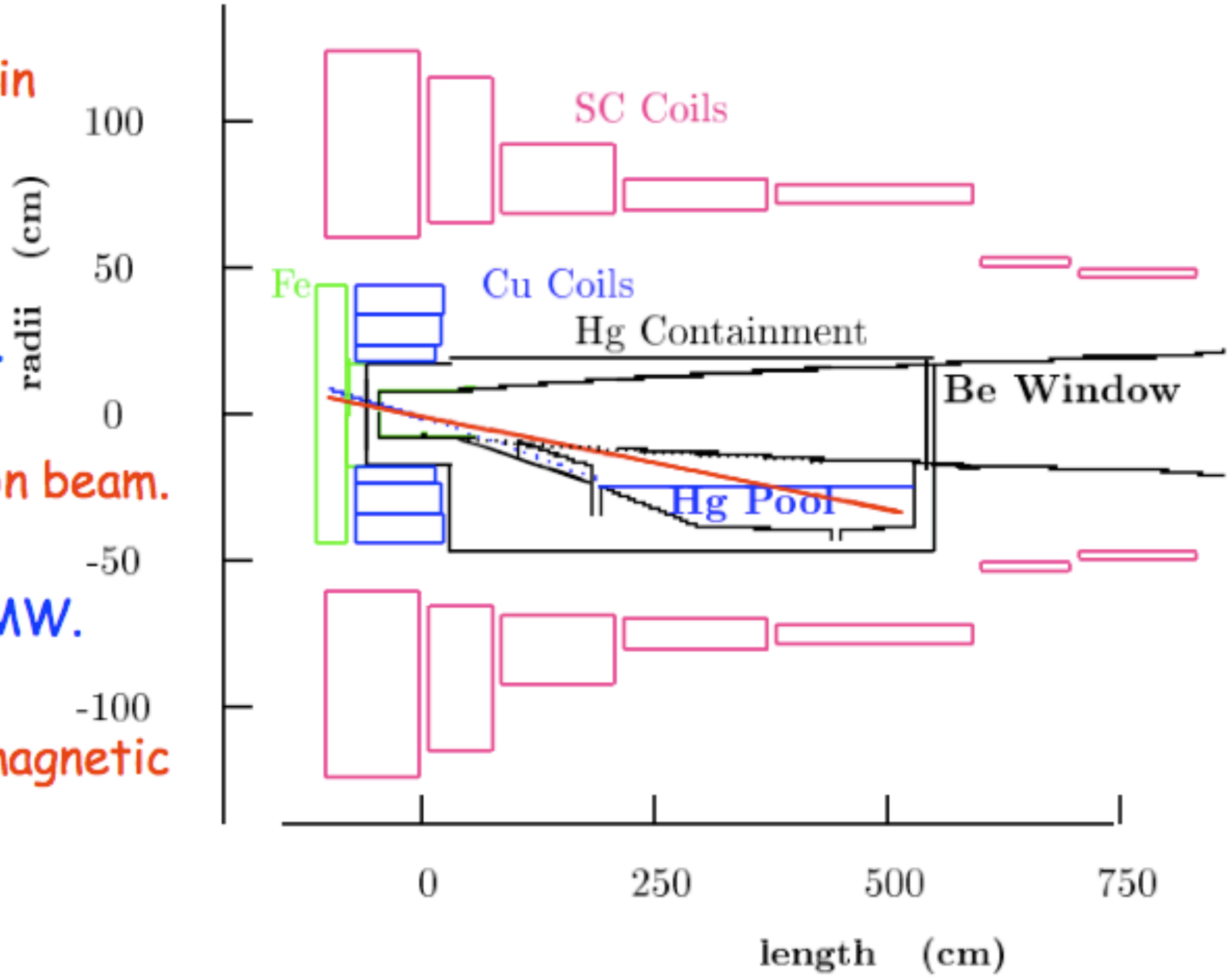
Collects both signs of π's and μ's,
⇒ Shorter data runs (with magnetic detector).

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.

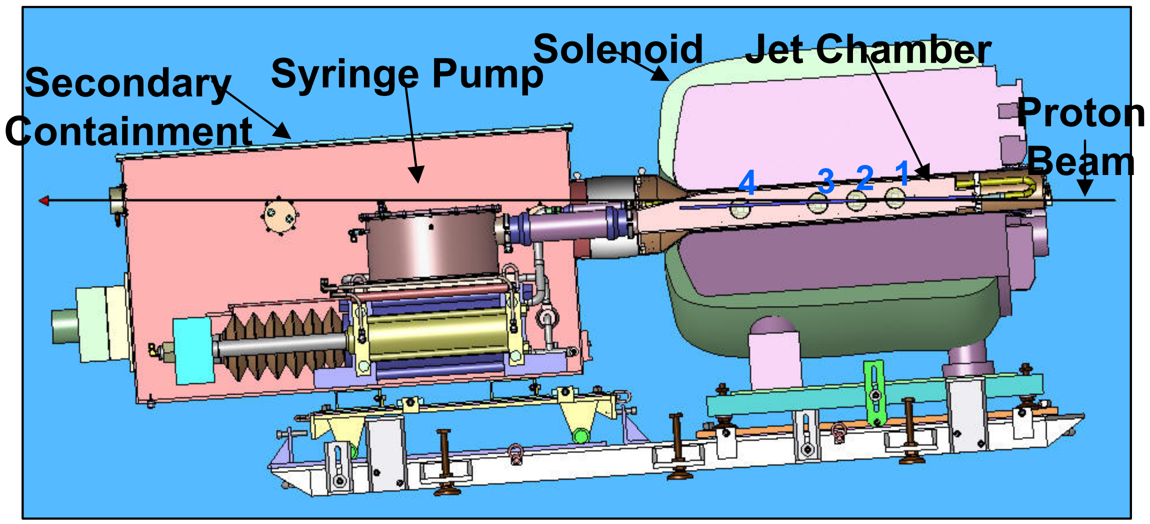


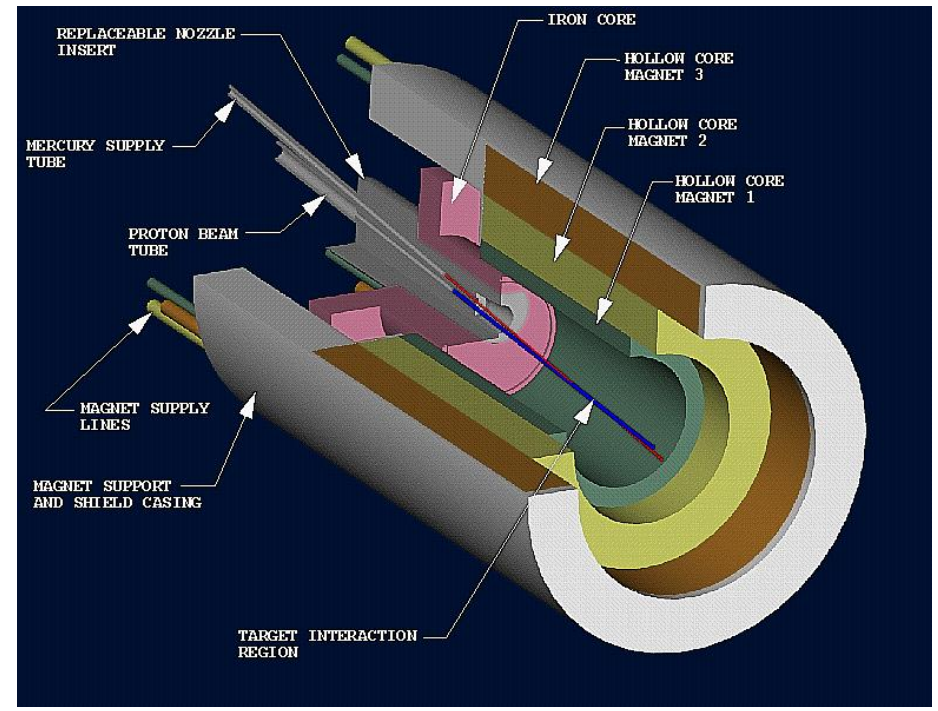

K. McDonald, LEMC'08

# MERIT

Great successful experiment!!

## From MERIT to a Muon Collider (Front End)




K.T. McDonald
*Princeton U.*
Low Emittance Muon Collider Workshop
Fermilab, April 22, 2008

Targetry Web Page:
http://puhep1.princeton.edu/mumu/target/

K. McDonald LEMC Workshop 22 Apr 2008

Muon Collaboration

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, ........

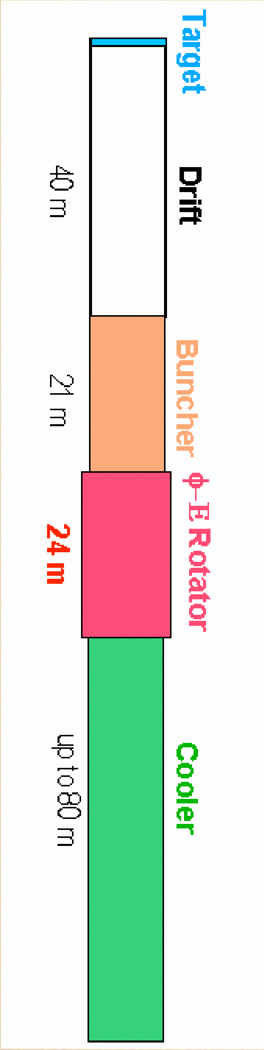
Desirable to improve jet quality, and to explore viability of jet axis at 100 mrad to magnetic axis, as proposed in Feasibility Study 2. Would also be good to verify feasibility of recovery of the mercury jet in an open pool.

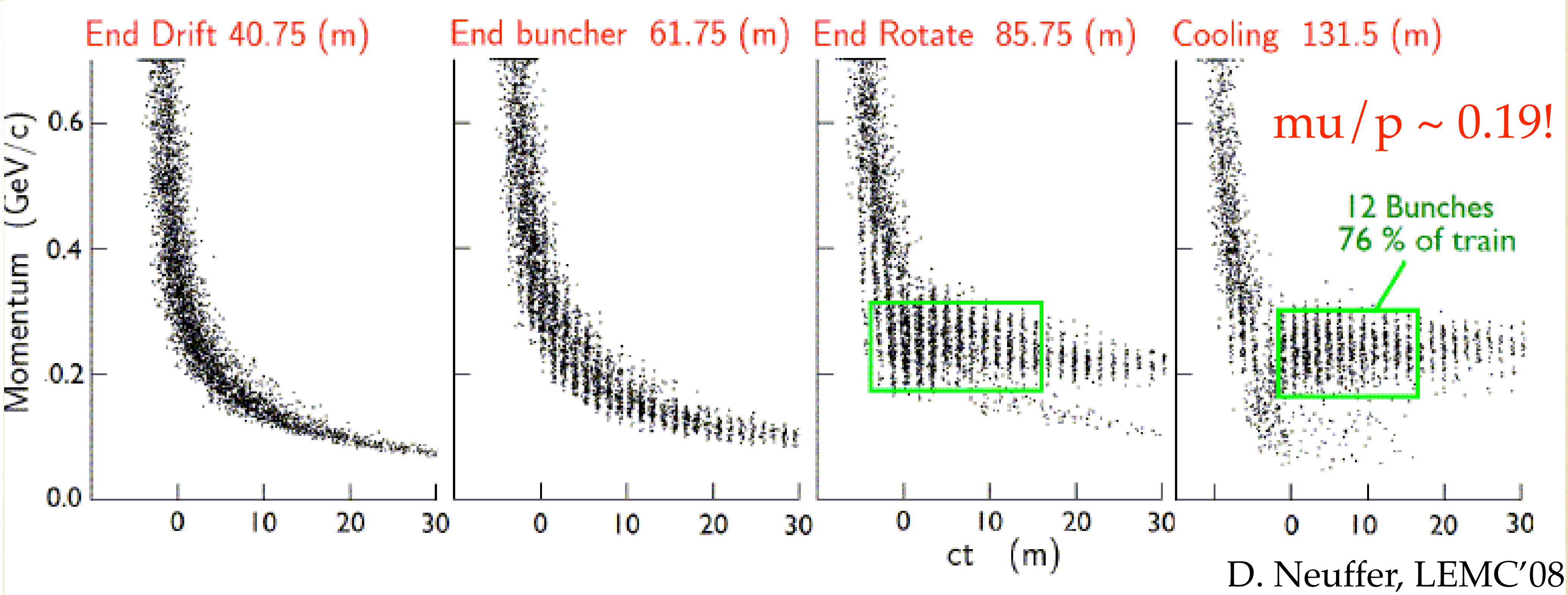
An opportunity exists to conduct non-beam studies with the MERIT equipment after it is shipped from CERN to ORNL ~ Jan 2009 (presentation by V. Graves).

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

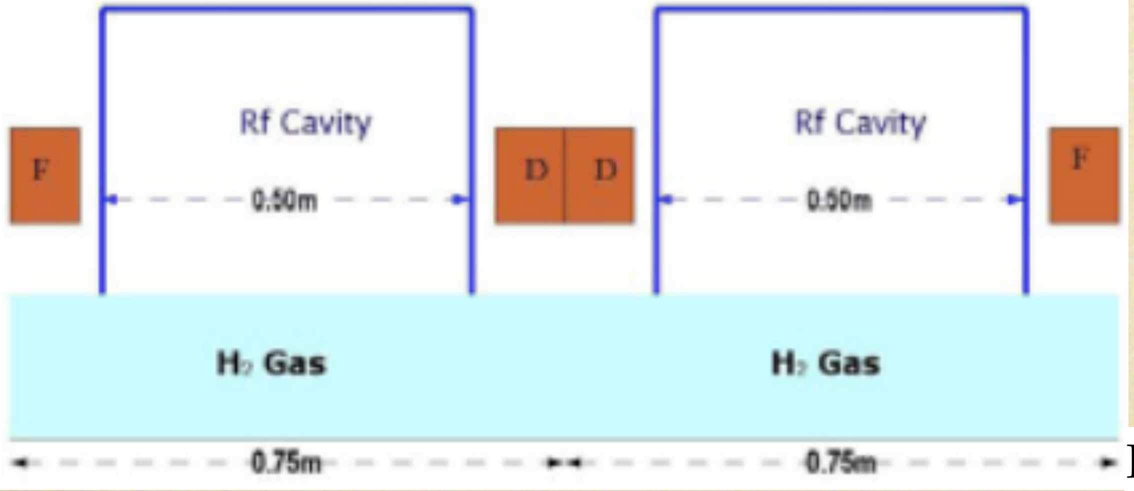



D. Neuffer, LEMC'08

RF needs to operate in magnetic field

RF frequency needs to continuously shift (350 to 200 MHz)

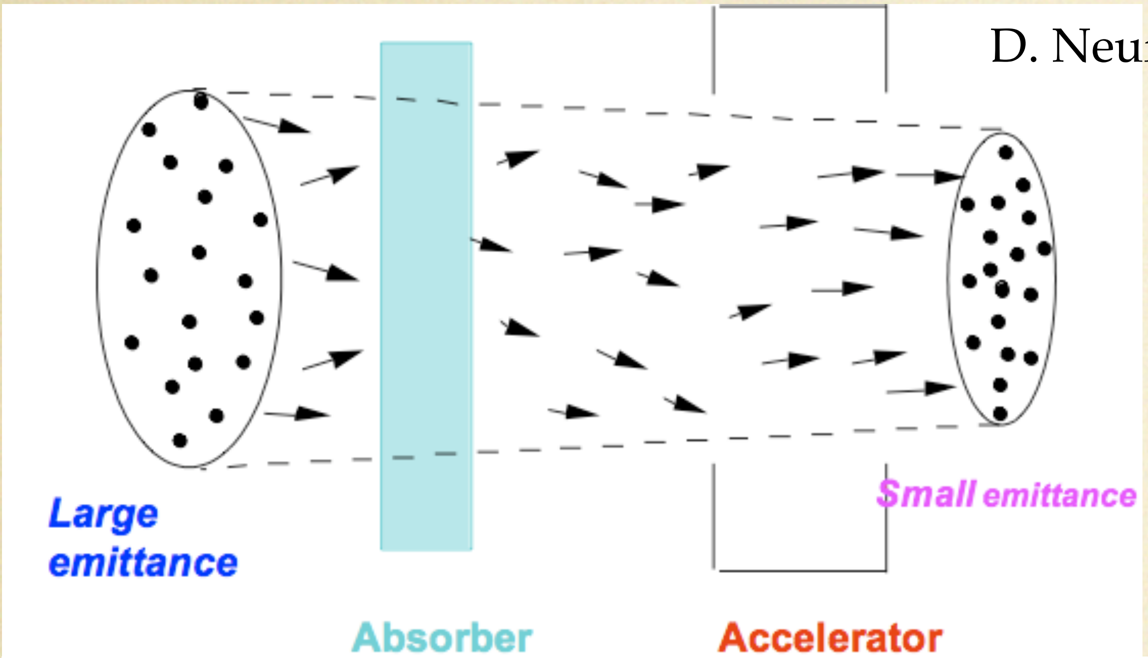



K. Paul MCNote-518

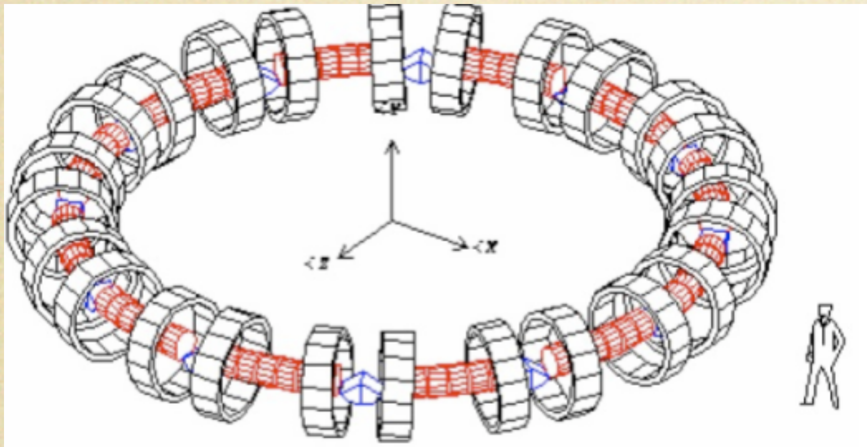
Does high pressurized GH2 help for this application?

# Ionization cooling

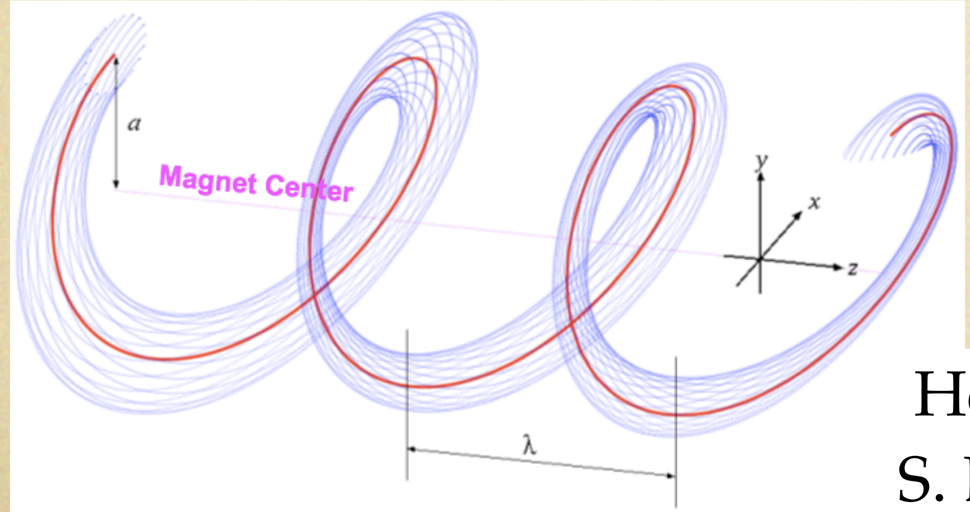
D. Neuffer LEMC'08




Conceptual picture of ionization cooling theory



RFOFO channel
R. Palmer




Helical Cooling Channel
S. Derbenev & R. Johnson

Emittance exchange

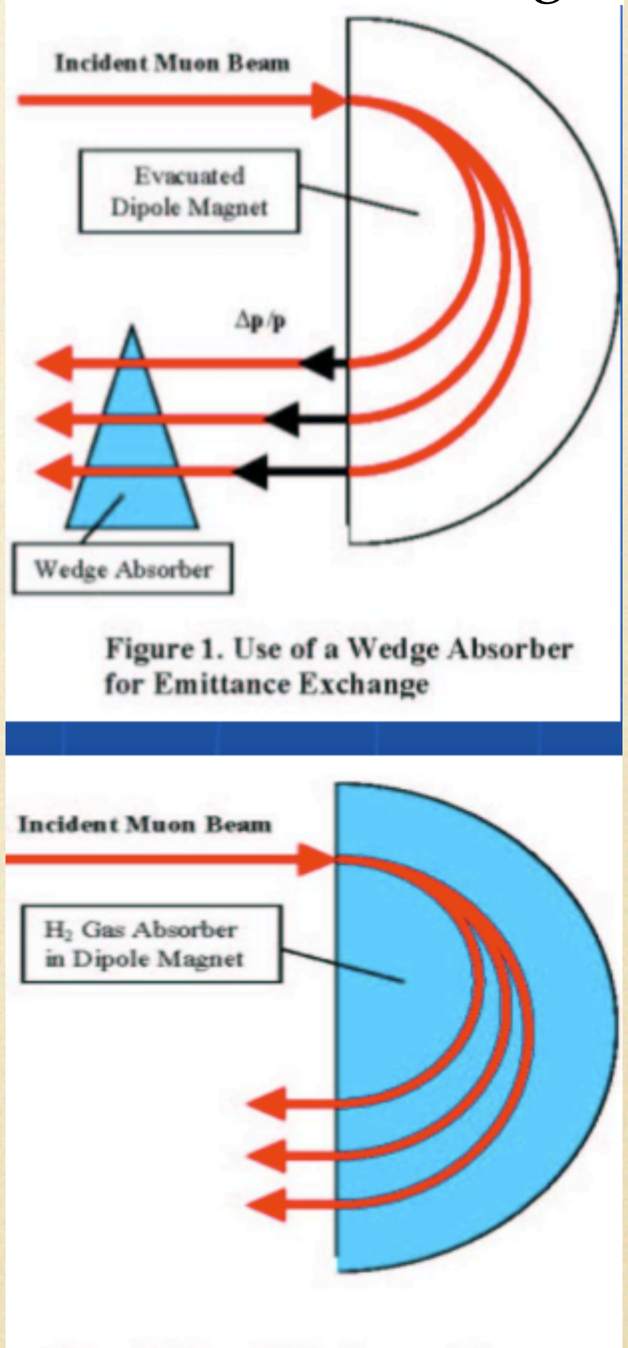
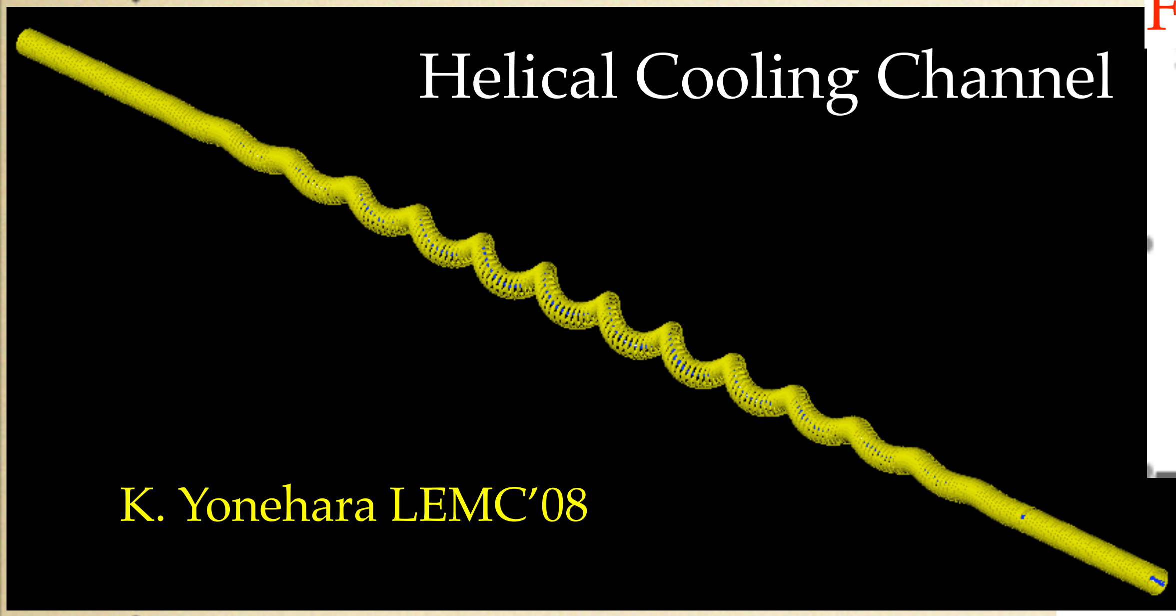



Figure 1. Use of a Wedge Absorber for Emittance Exchange

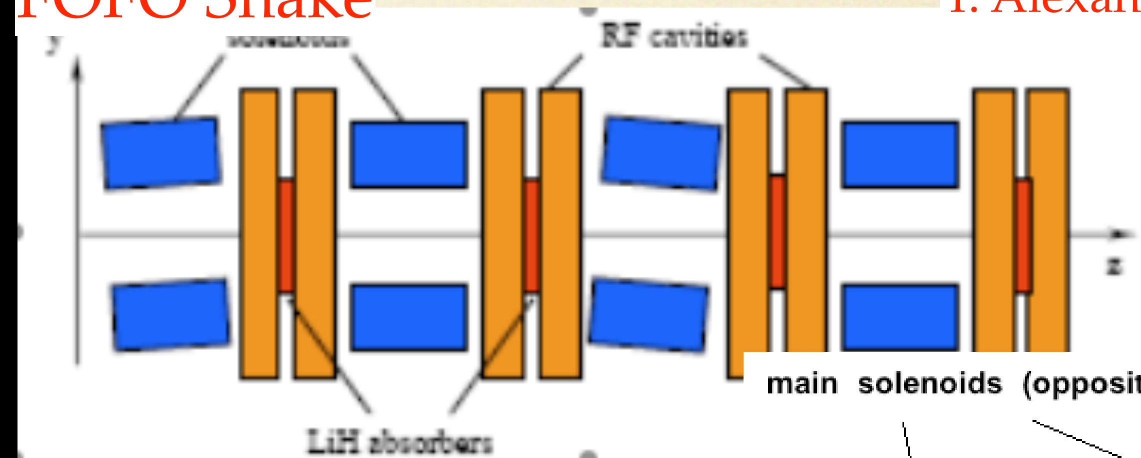
Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

# Cooling Channel

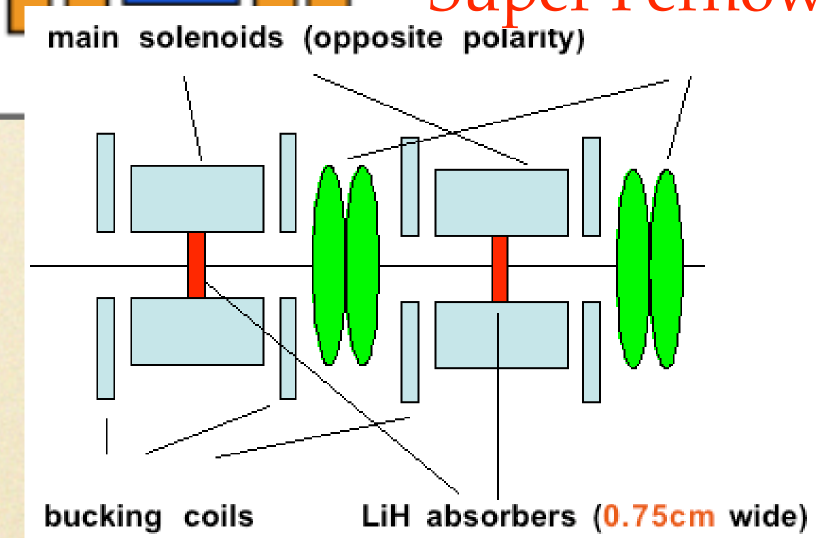



FOFO Snake

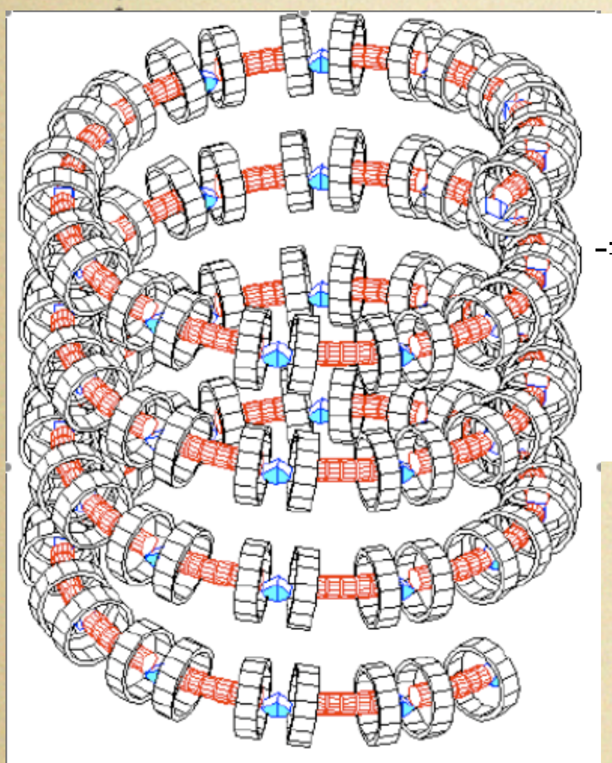
Y. Alexahin MC Design'07




Super Fernow

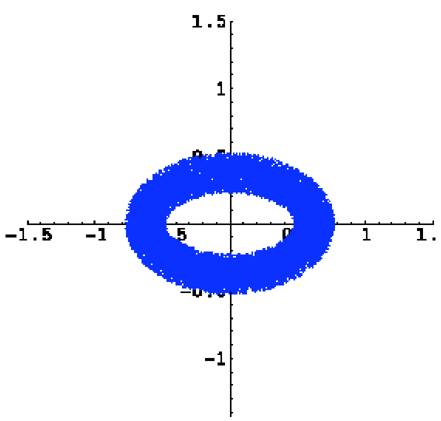


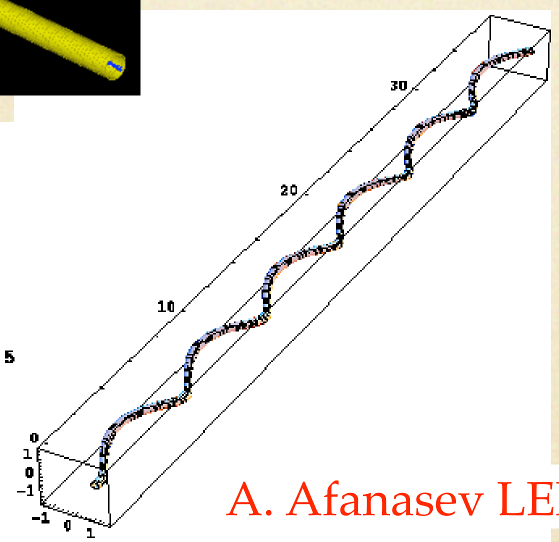

Y. Alexahin MCTF 5/29/08



Guggenheim

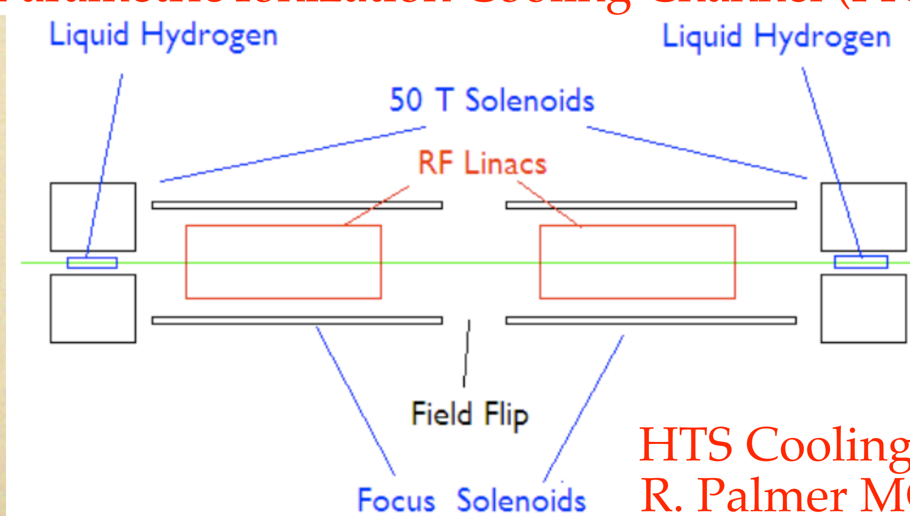
P. Snopok LEMC'08 &
R. Palmer MC Design'07



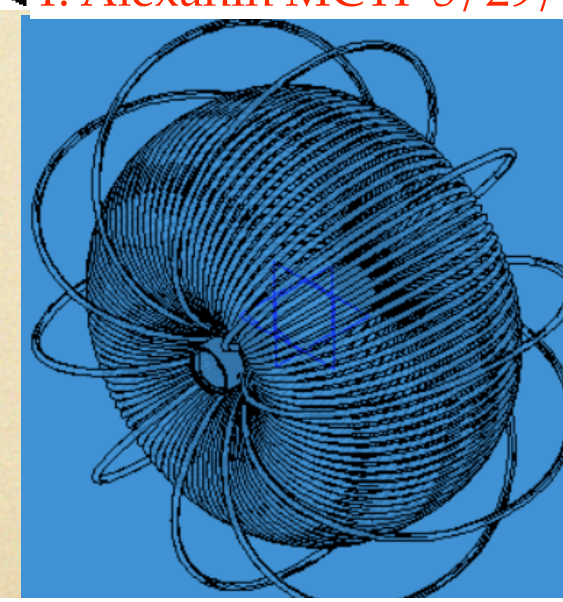


A. Afanasev LEMC'08

Parametric Ionization Cooling Channel (PIC)

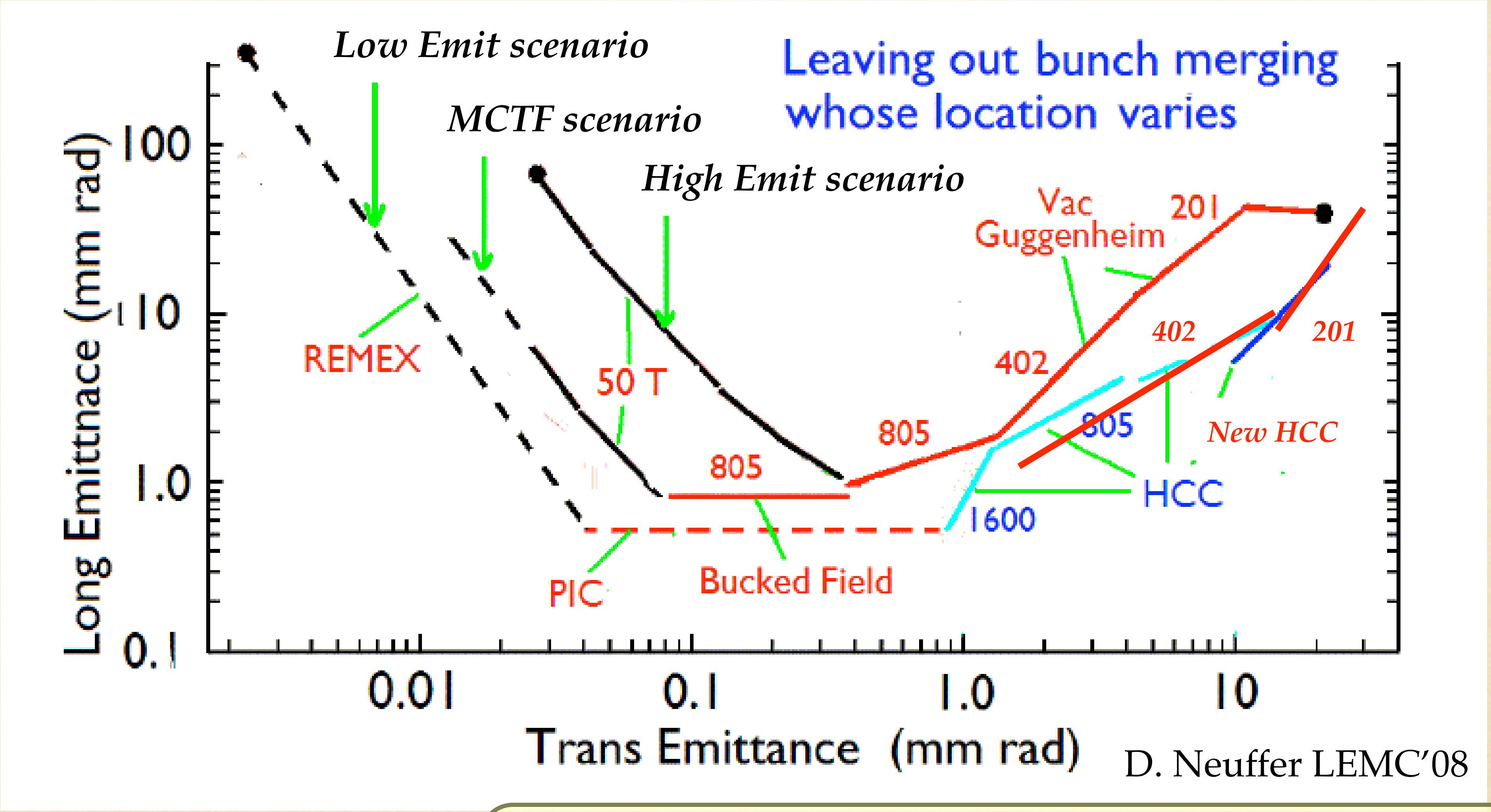



HTS Cooling Channel
R. Palmer MC Design'07



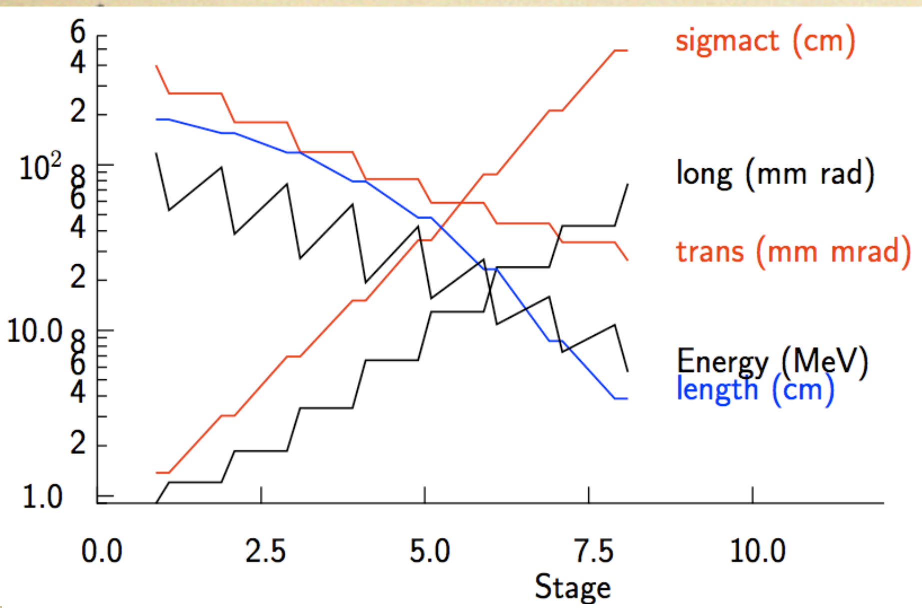
Li Lens Cooling Channel
K. Lee LEMC'08

# 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

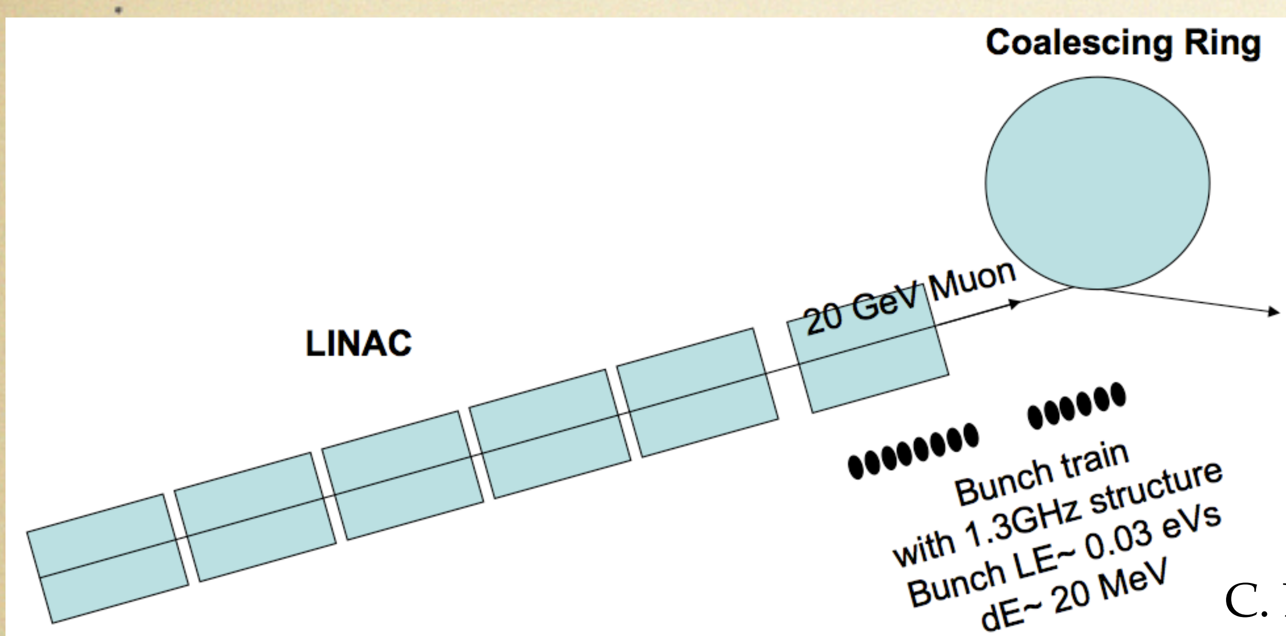



Kinetic energy in 50 T channel

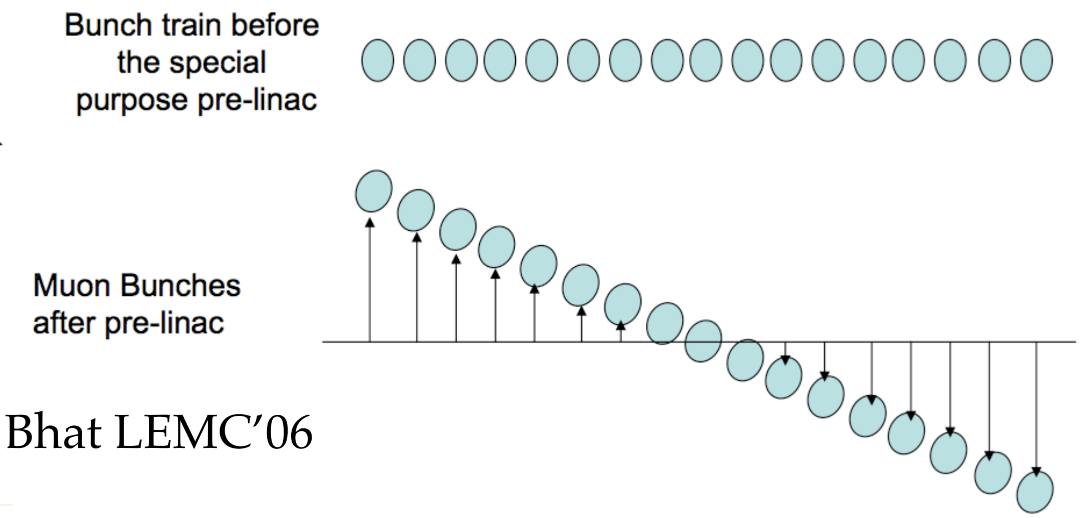
R. Palmer MC Design'07

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

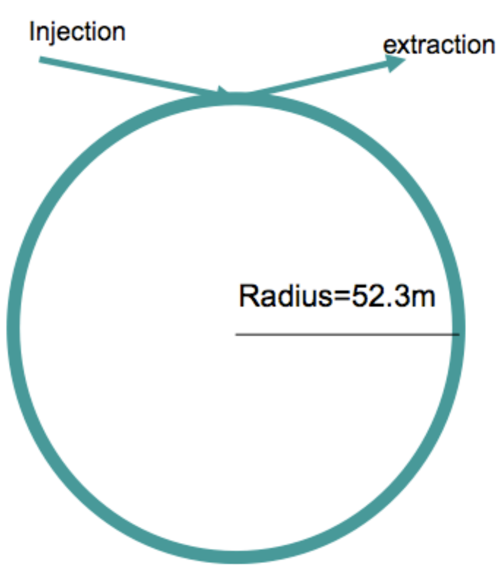
# Bunch coalescing ring




- 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

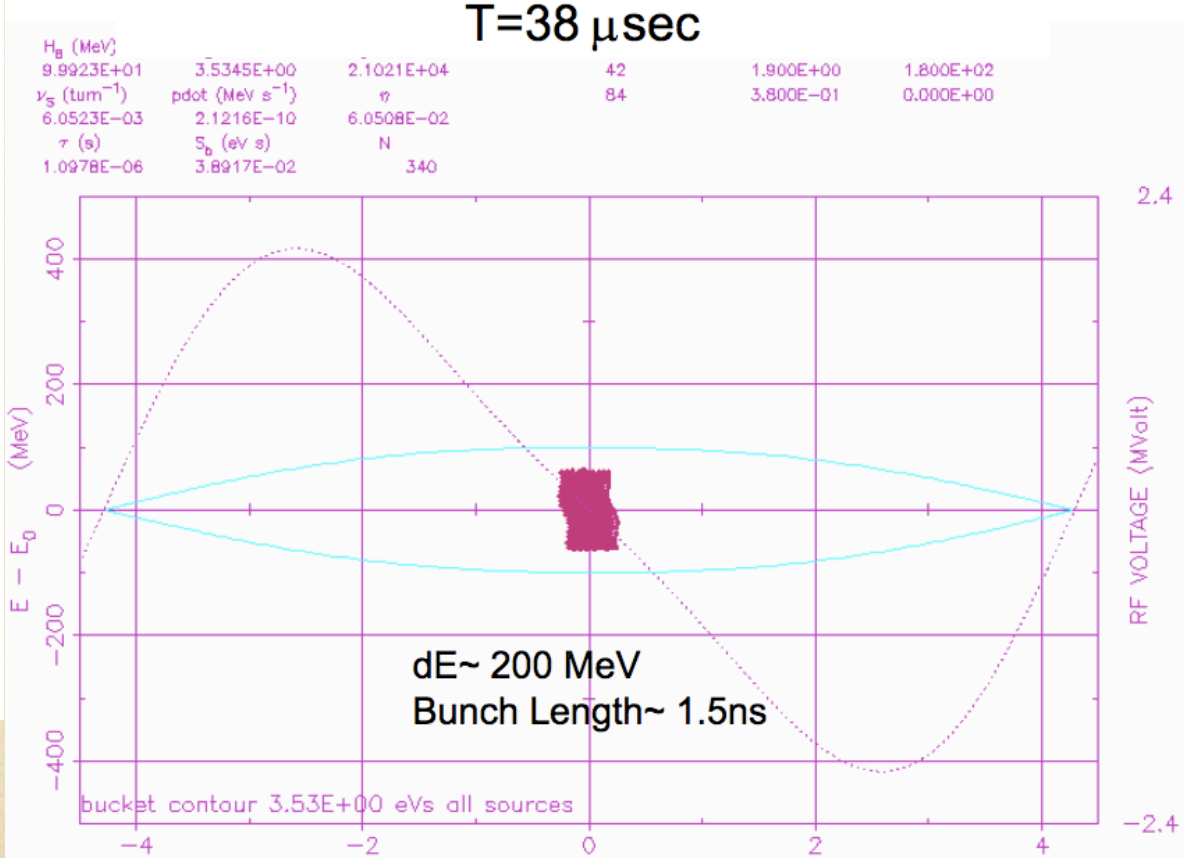
Ring Radius = 52.33m; Revolution period= 1.09μs
Energy of the muon = 20 GeV (gamma = 189.4)
gamma_t of the ring = 4

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

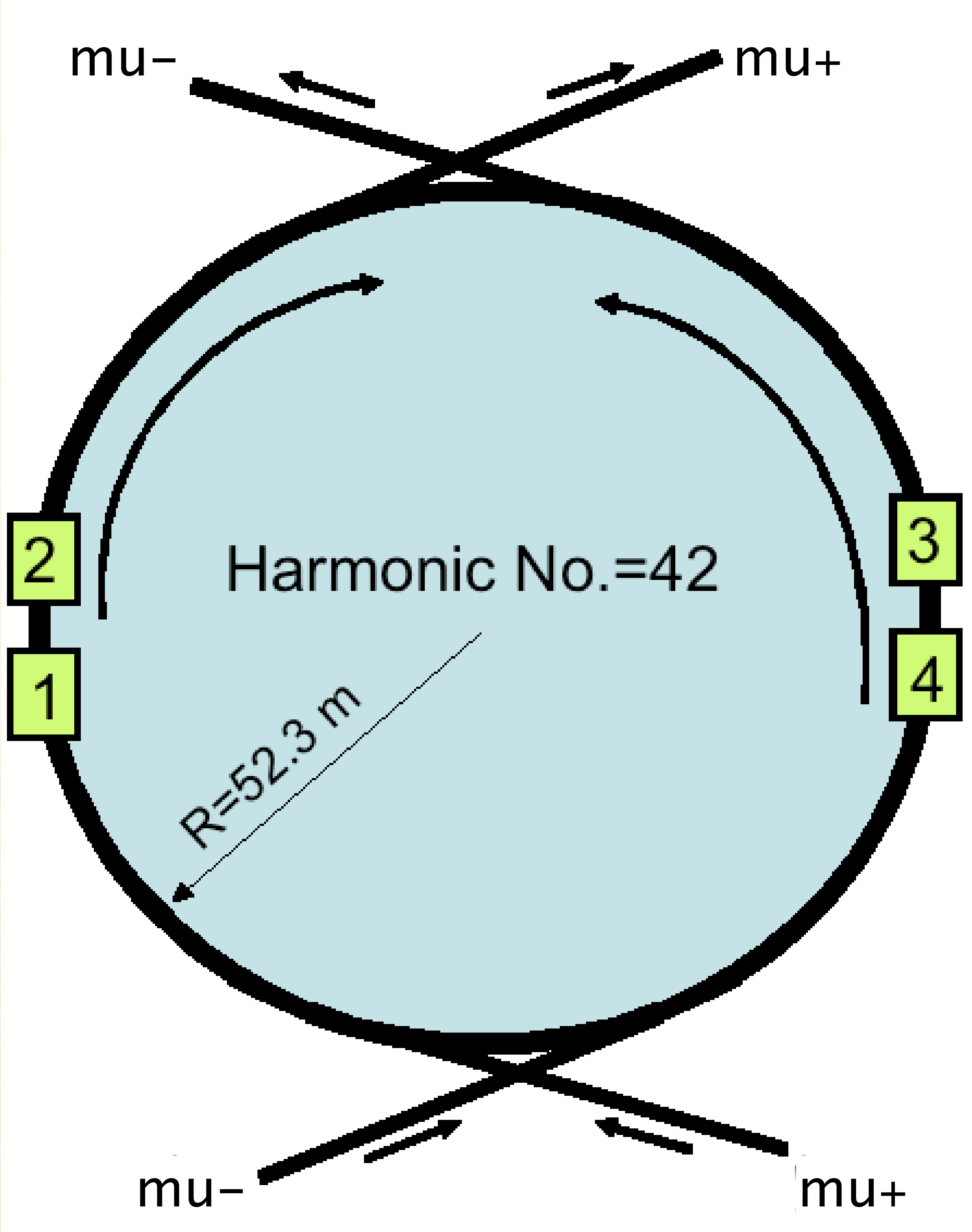
h for the coalescing cavity = 42, 84
Number of trains/injection = less than 37
(assuming ~100ns for injection/extraction)
RF voltage for the coalescing cavity = 1.9 MV (h=42)
= 0.38 MV (h=84)

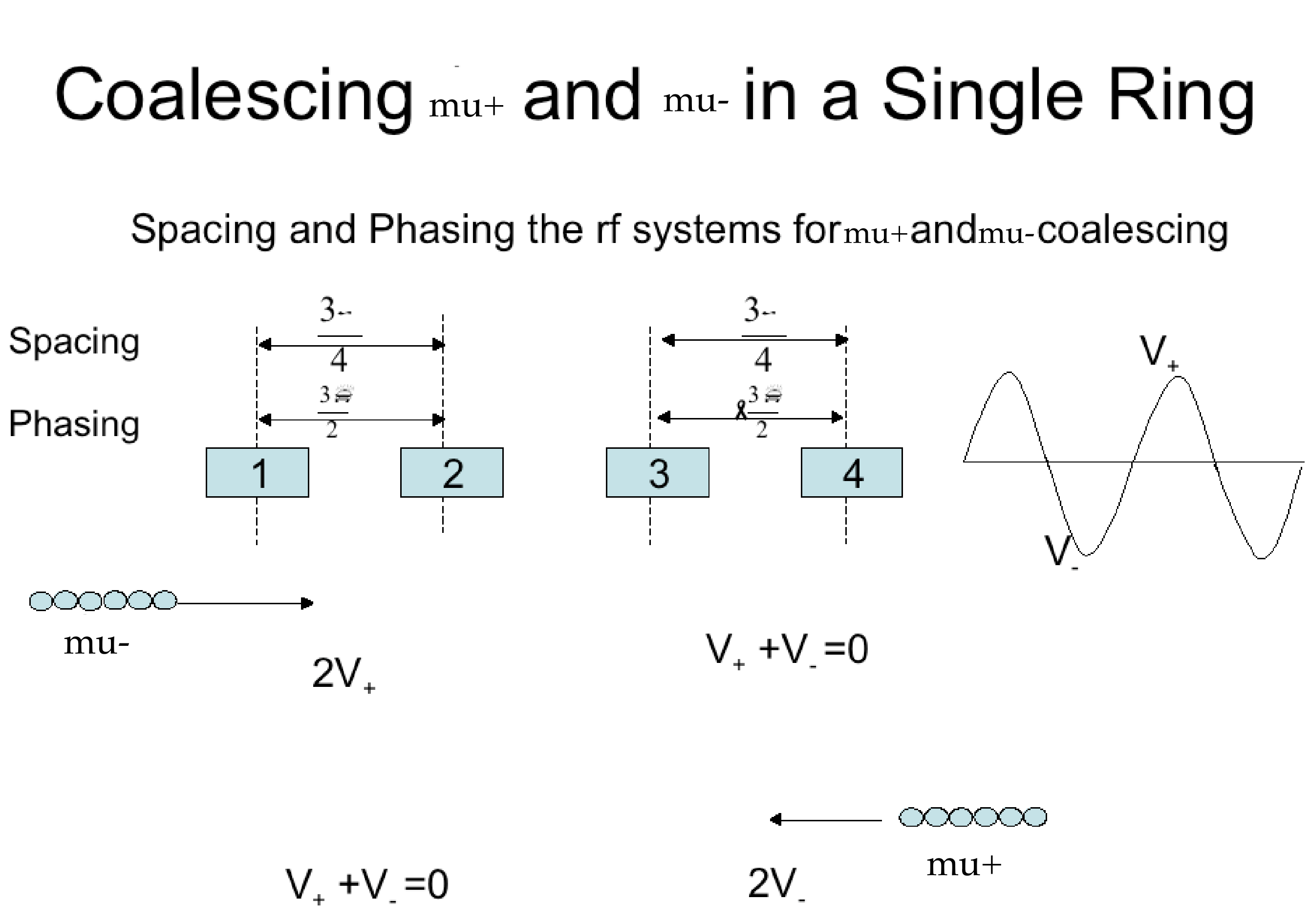
fsy ~ 5.75E3Hz
Tsy/4 = 43.5us
Number of turns in the ring ~40

Muon Bunch train in the Coalescing Ring
T=38 μsec



# Coalescing ring for both charges

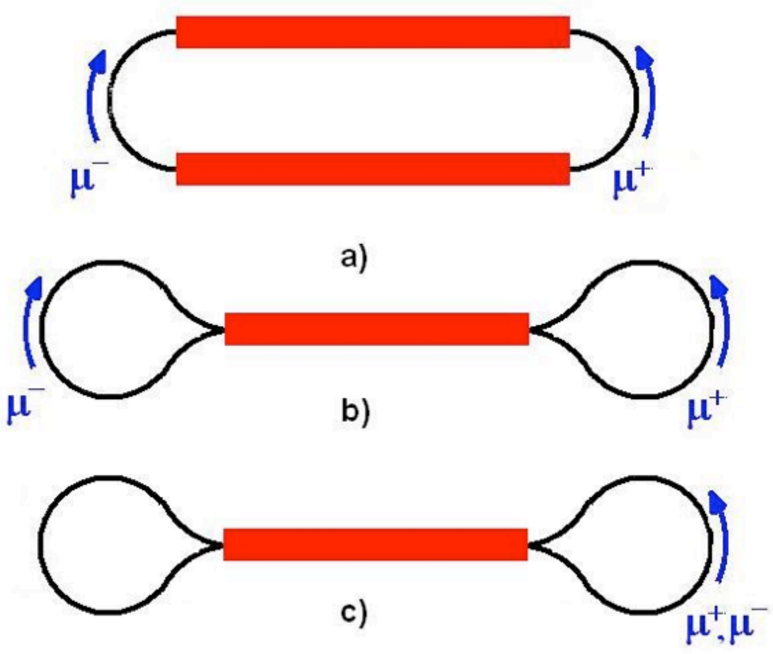


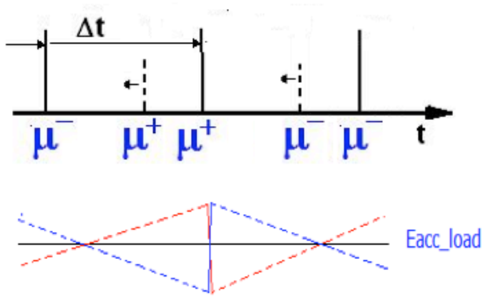

C. Bhat LEMC'08

# 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.

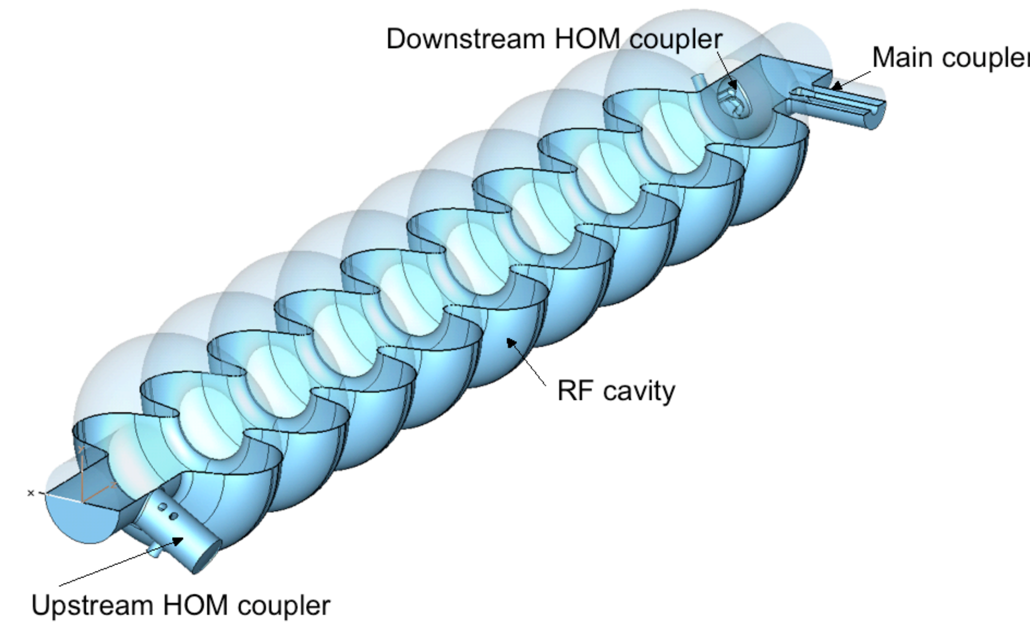



(Separate arcs for $\mu^+$ and $\mu^-$)




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

ILC RF cavity with the HOM and input couplers:




N. Solyak, S. Yakovlev LEMC'08

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 |

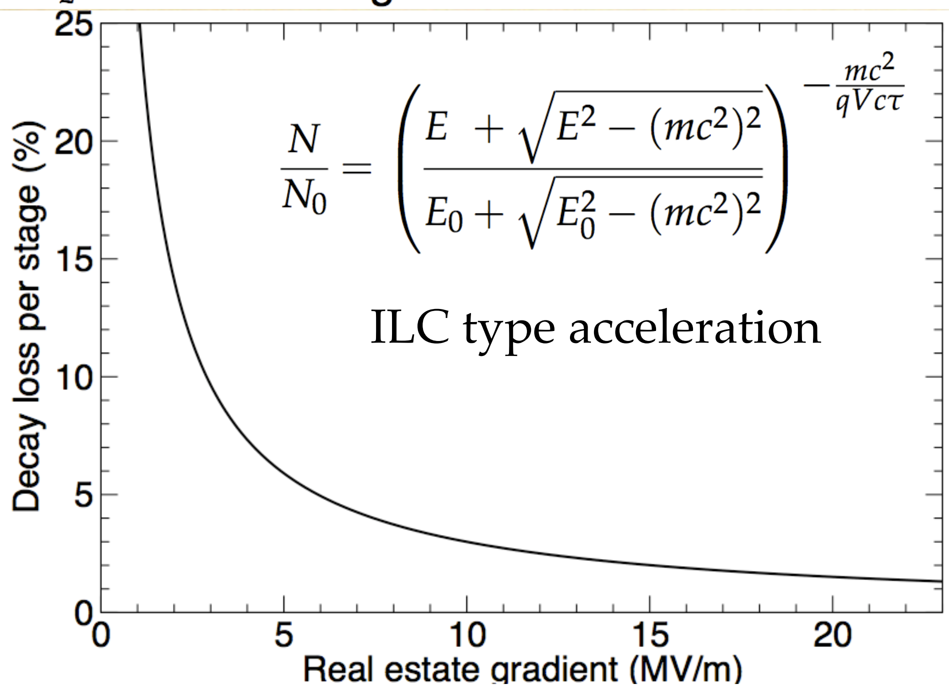
LE2008, 1.5 TeV

| 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* |

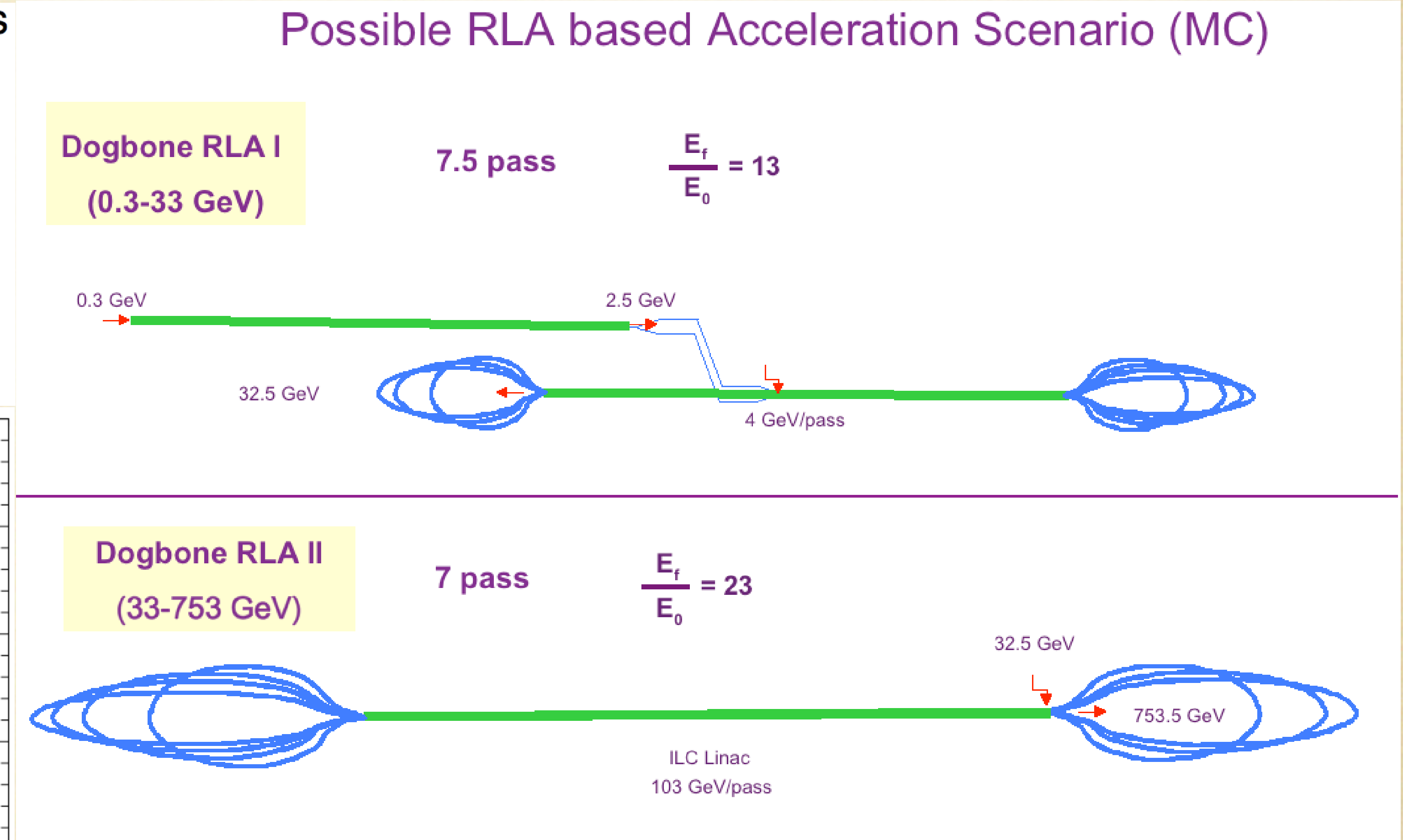
These numbers are based on the assumption the number of muons are same as HE scheme. We need to re-estimate them.

# Muon Acceleration

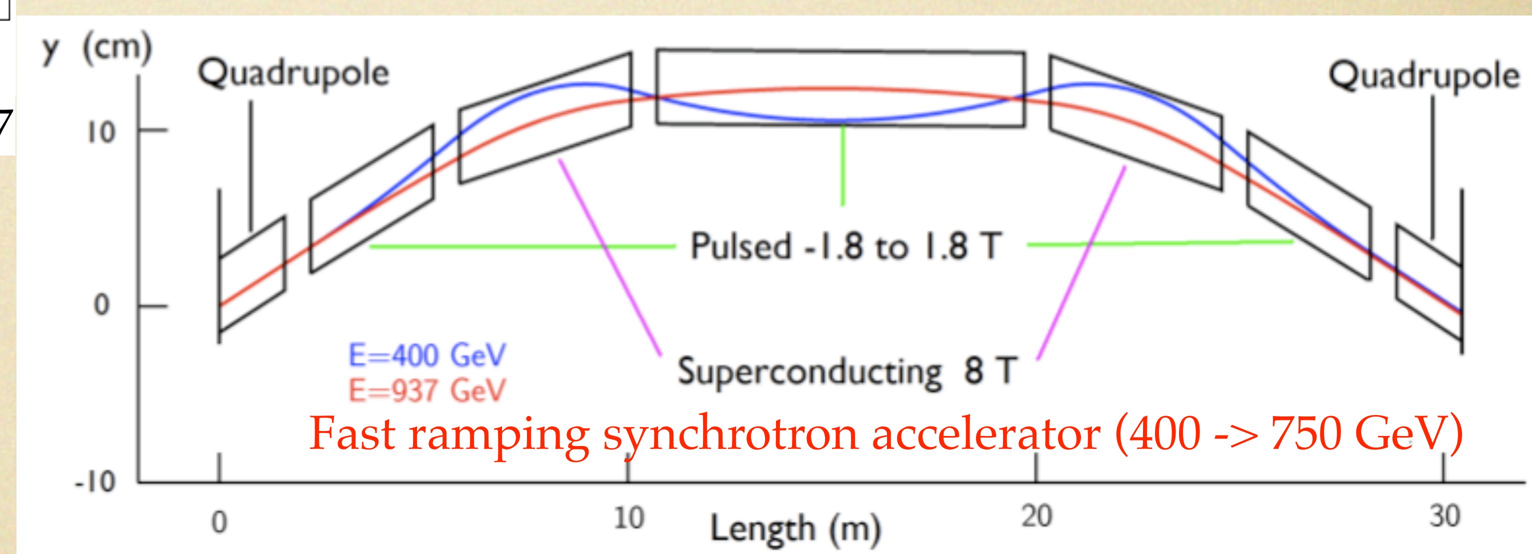
- Accelerate from 90 GeV to 4 TeV in 2 stages
  - 90 GeV to 600 GeV
  - 600 GeV to 4 TeV
- One bunch each sign
- $2 \times 10^{12}$ per bunch
  - Will discuss lower charge
- $\sigma_z = 3$ mm throughout




S. Berg MC design meeting'07



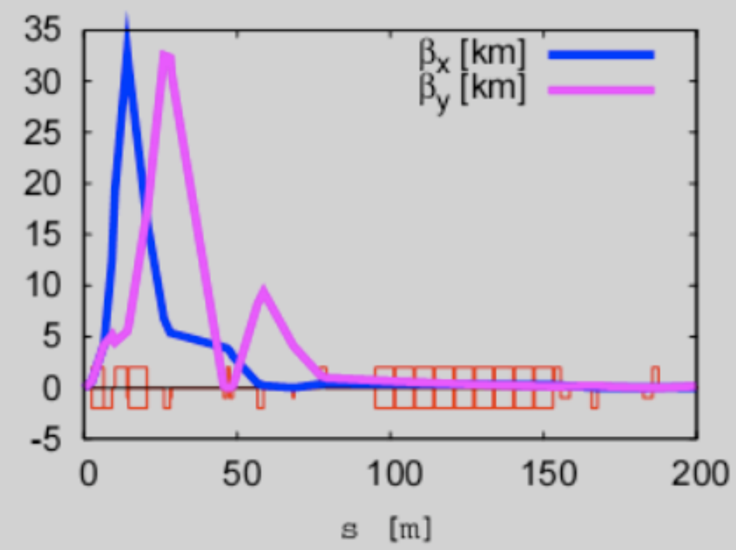

A. Bogacz LEMC'08



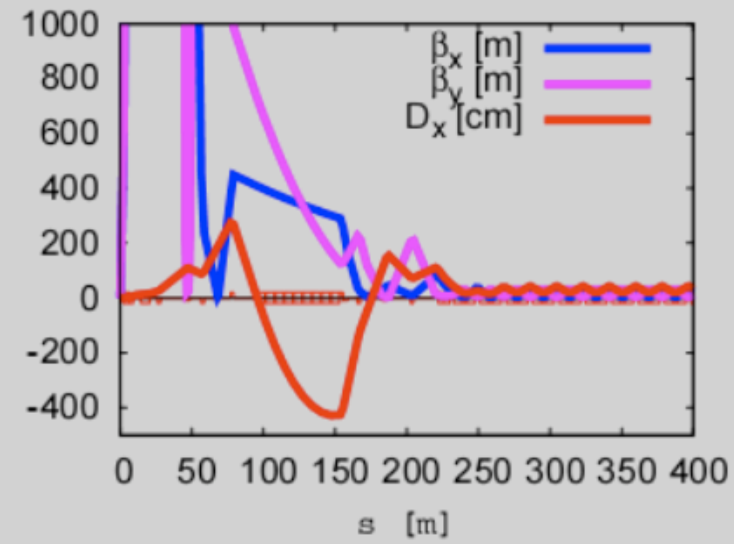

D. Summers MC design meeting'07

# Collider Ring

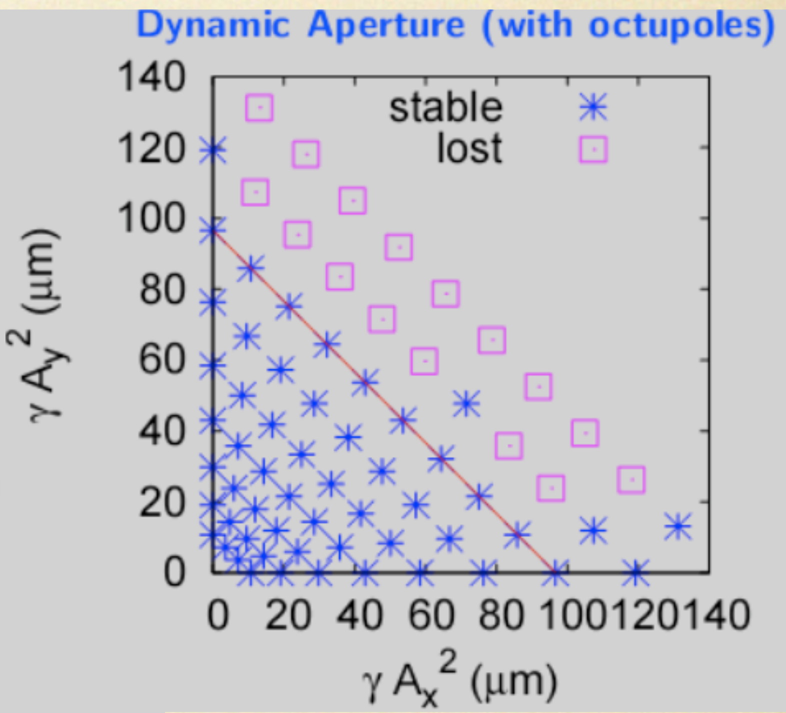
Dipole First Muon Collider Lattice




IR




Matching section




$\simeq 2.8\,\sigma$

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 |
| $\beta^*$ (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 $\sigma$) | 2.8 | 4.5 | 3 |
| momentum aperture | $\pm$ 0.6 % | $\pm$ 0.6 % | $\pm$ 0.7 % |
| $\alpha_p$ | $-1.3\times10^{-4}$ | $5\times10^{-5}$ | $5\times10^{-4}$ |
| length of RF sections (m) | - | 2 $\times$ 1.5 | - |

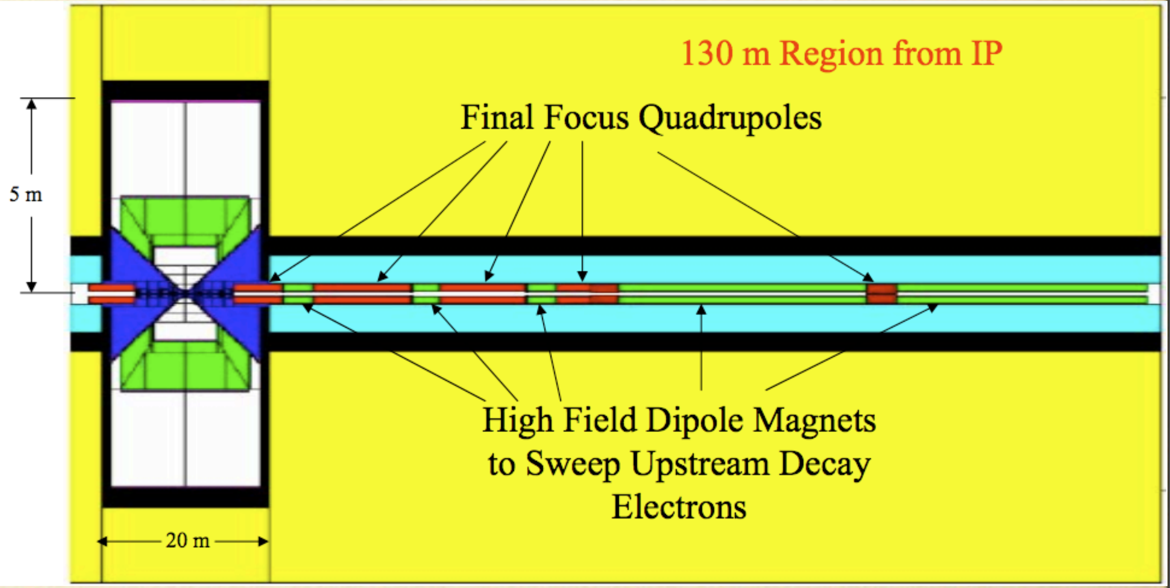
# MC Detector

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 | $4.04\times10^4$ |
| Particles/bunch ($10^{11}$) | 1 | 0.07 | 0.11 | 20 |
| Bunch/RF pulse | - | 90 | 75 | 1 |
| Bunch separation (ns) | 25 | 1.4 | 1.4 | $18.6\times10^3$ |
| Yearly $\mathcal{L}_y$ (fb$^{-1}$) | 100 | 71 | 145 | 455 |
| $\sigma_h$ ($\mu$b) | $80\times10^3$ | 0.045 | 0.034 | 0.054 |
| $\Delta t_d$ or bunch train length (ns) | 300 | 126 | 105 | - |
| $\mathcal{L}_{eff}$ (cm$^{-2}$) | $3.00\times10^{27}$ | $3.94\times10^{31}$ | $1.21\times10^{32}$ | $1.13\times10^{30}$ |
| $(\sigma_h\times\mathcal{L}_y)/(\sigma_h\times\mathcal{L}_y)_{LHC}$ | 1 | $4.00\times10^{-7}$ | $6.16\times10^{-7}$ | $3.07\times10^{-7}$ |
| $(\sigma_h\times\mathcal{L}_{eff})/(\sigma_h\times\mathcal{L}_{eff})_{LHC}$ | 1 | $7.39\times10^{-3}$ | $1.71\times10^{-2}$ | $2.54\times10^{-4}$ |

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 | $15\mu m \oplus \frac{35\mu m GeV/c}{p\sin^{3/2}\theta}$ <br> $15\mu m \oplus \frac{35\mu m GeV/c}{p\sin^{5/2}\theta}$ |
| 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 | $\frac{\delta E}{E\ (GeV)} = 0.40\frac{1}{\sqrt{E}} \oplus 0.04$ |
| $\mu$ Detector | Instrumented Fe yoke <br> $\frac{\delta p}{p} \simeq 30\%$ at $100\ GeV/c$ |
| Energy Flow | $\frac{\delta E}{E\ (GeV)} \simeq 0.3\frac{1}{\sqrt{E}}$ |
| Acceptance | $\lvert\cos\theta\rvert < 0.98$ |
| mask | 120 mrad |
| beampipe | 3 cm |
| small angle tagger | $\theta_{min} = 40$ mrad |

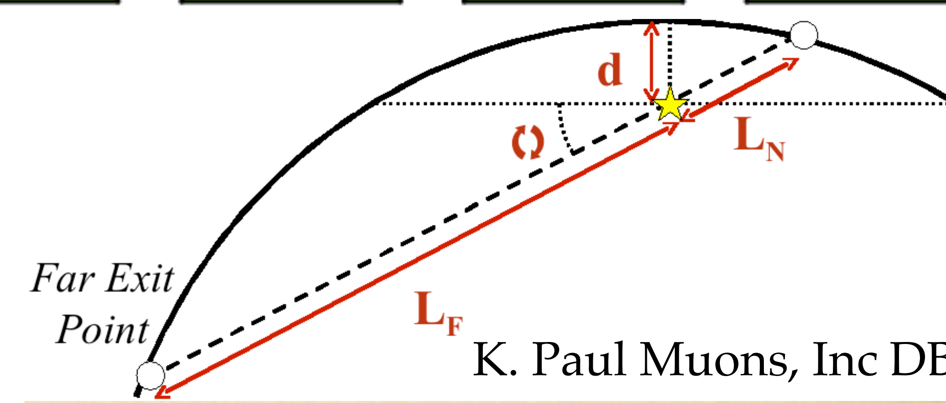
- My comments on detector technology mainly based on current efforts within the ILC community

M. Demarteau LEMC'08

# Radiation Hazards

| | Design Parameters | | 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 |
| $E_\mu$ | 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 |
| $\ell_s$ | 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 |
| $\varepsilon_{NT}$ | Normalized Transverse Emittance | *mm mrad* | 3.00 | 1.00 | 1.00 | 1.00 | 3.00 |
| $\beta^*$ | 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 |
| $\theta$ | 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 |
| $\delta$ | 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

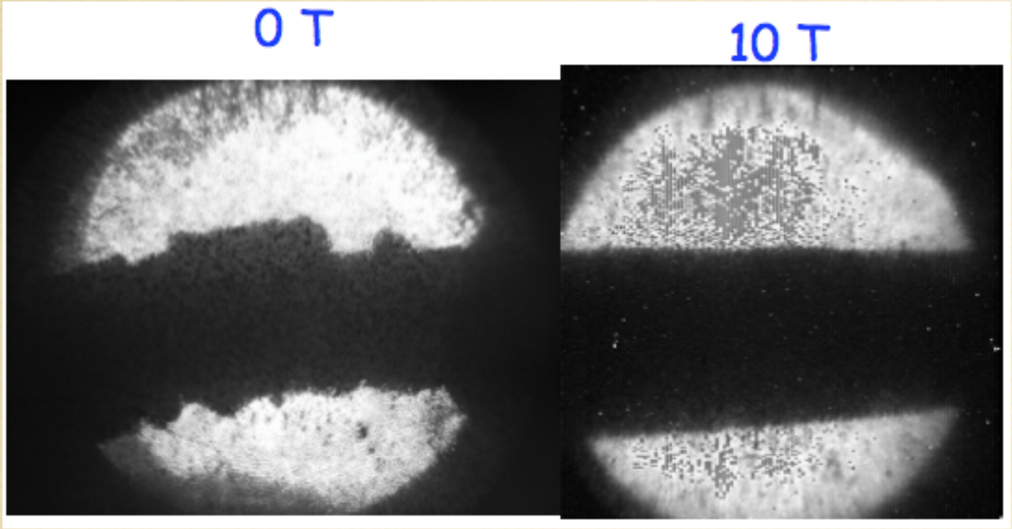
C. Johnstone LEMC'08

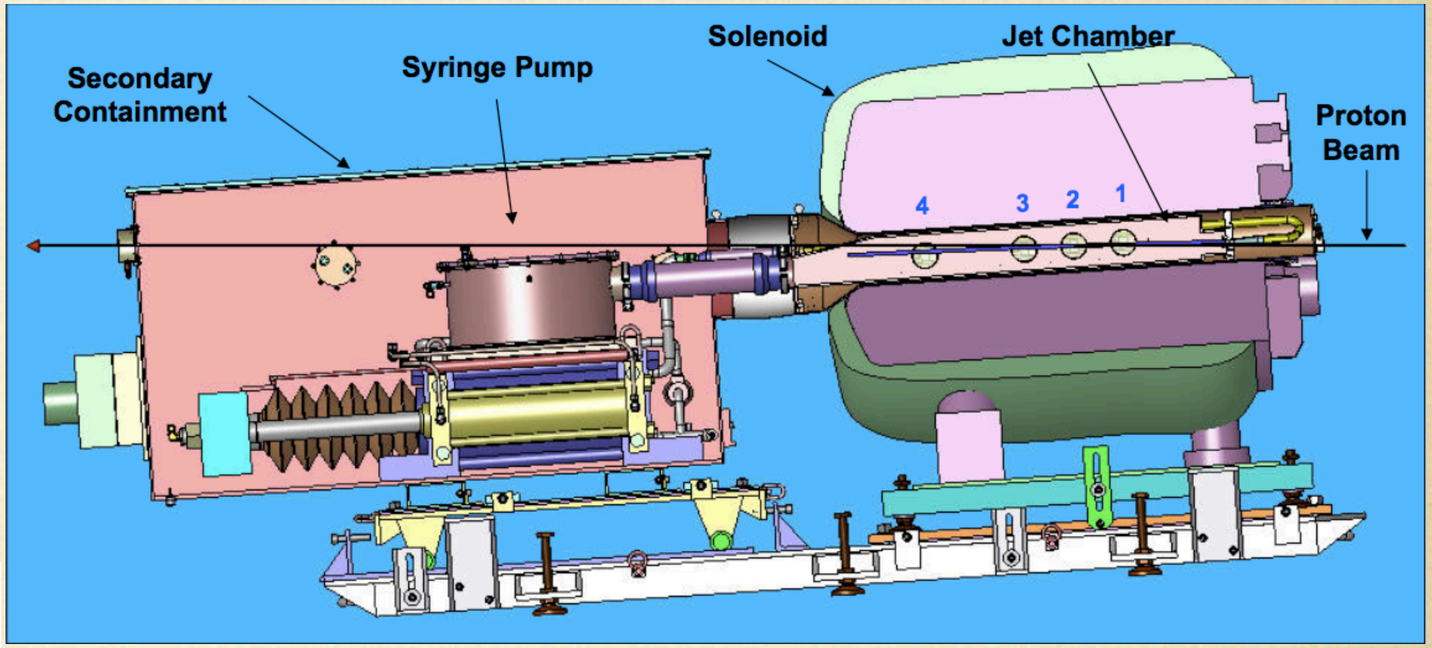
The depth is determined by the number of muons per bunch

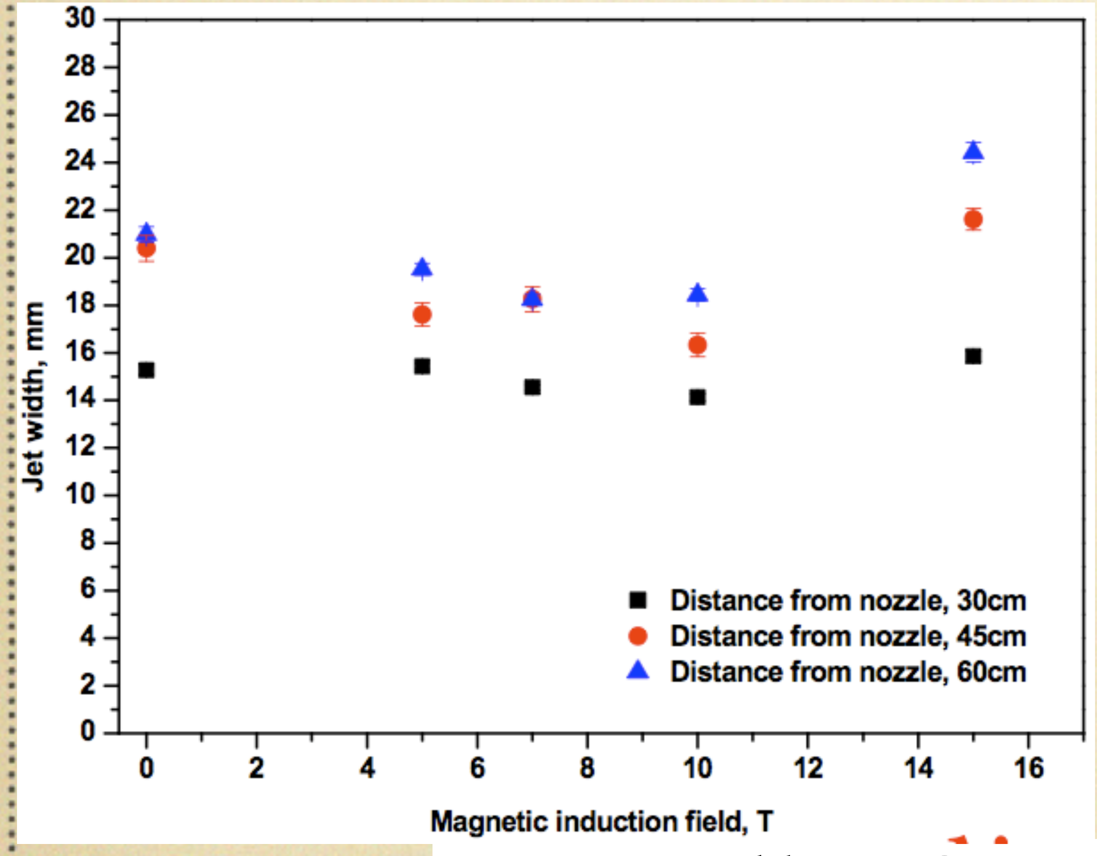
# Current activities

- MERIT
- MICE
- High Pressurized Hydrogen Gas Filled RF test
- 201 & 805 MHz Evacuate RF test
- 6D Cooling experiments
- Simulation study

# MERIT



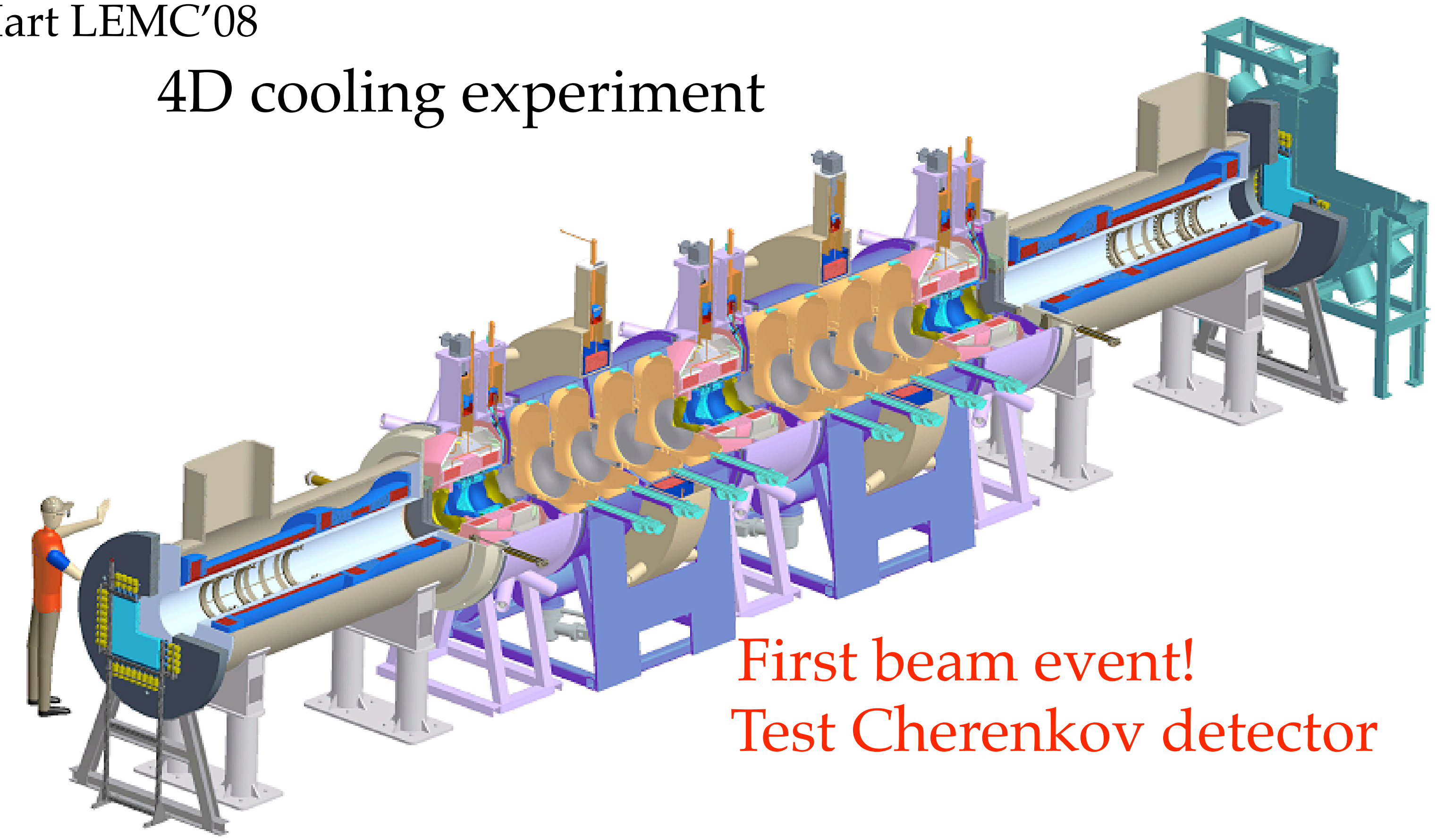




K. McDonald, LEMC'08

# MICE

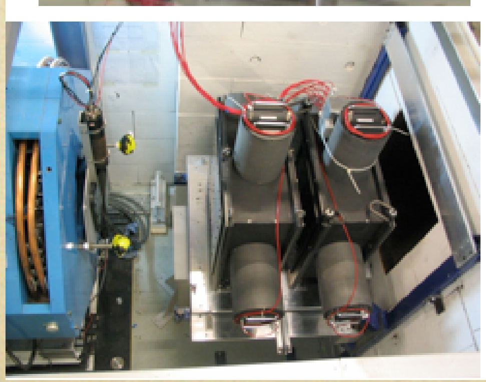
T. Hart LEMC'08

4D cooling experiment

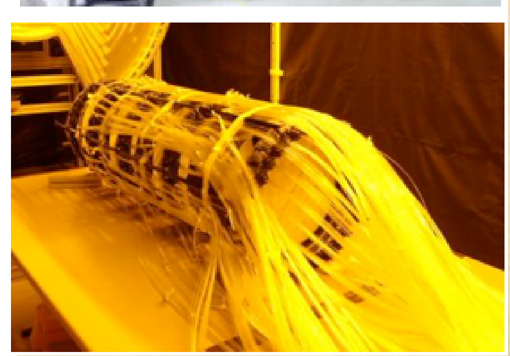


First beam event!
Test Cherenkov detector

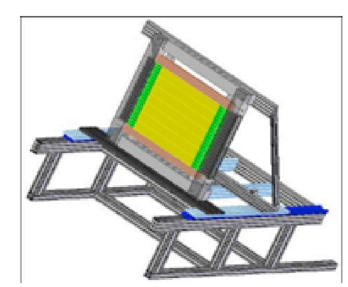
Cherenkov Detector



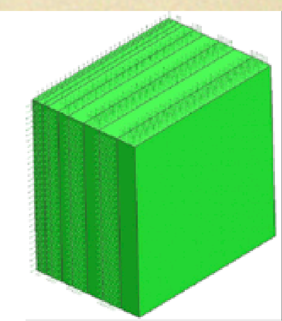
SciFi Spectrometer



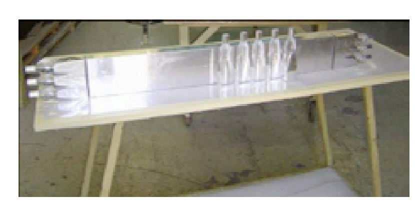
Calorimeter



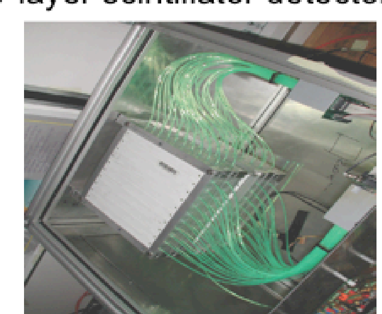
lead with scintillating fibers



10-layer scintillator detector



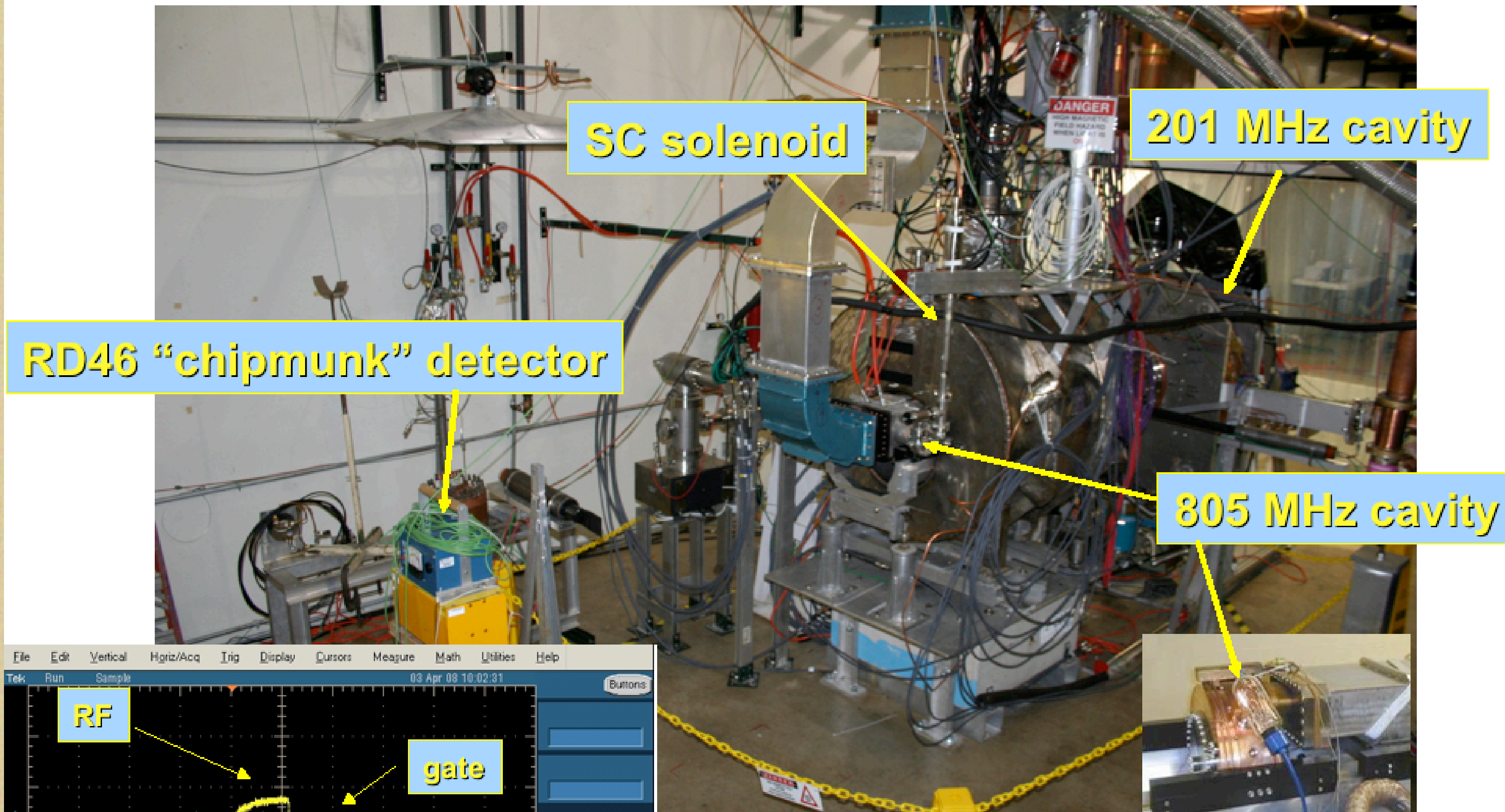
lead layer with light guides

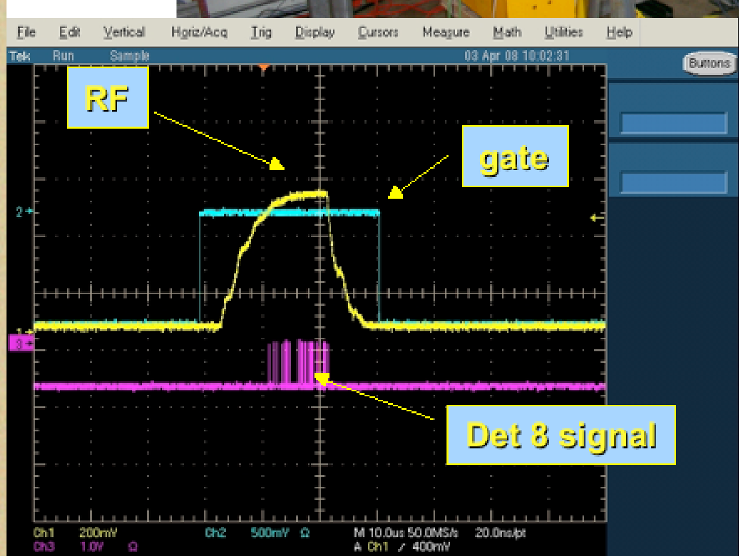


# 201 & 805 MHz Evacuated RF Test

D. Huang LEMC'08

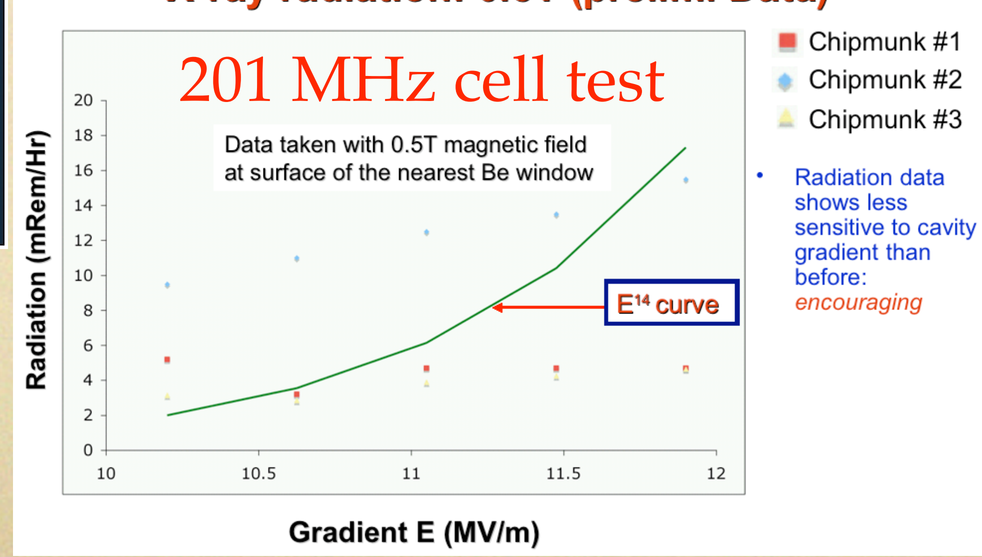
**MTA Hall**



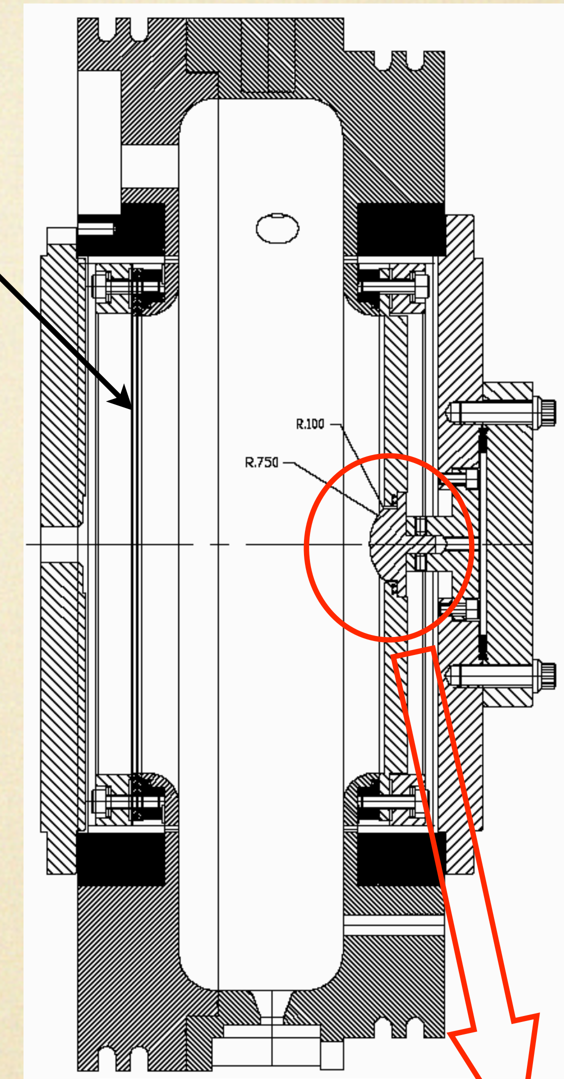




Det 8 Scintillator: 6 meters away from 805 MHz cell

**Curved Be window test:**
**X-ray radiation: 0.5T (prelim. Data)**

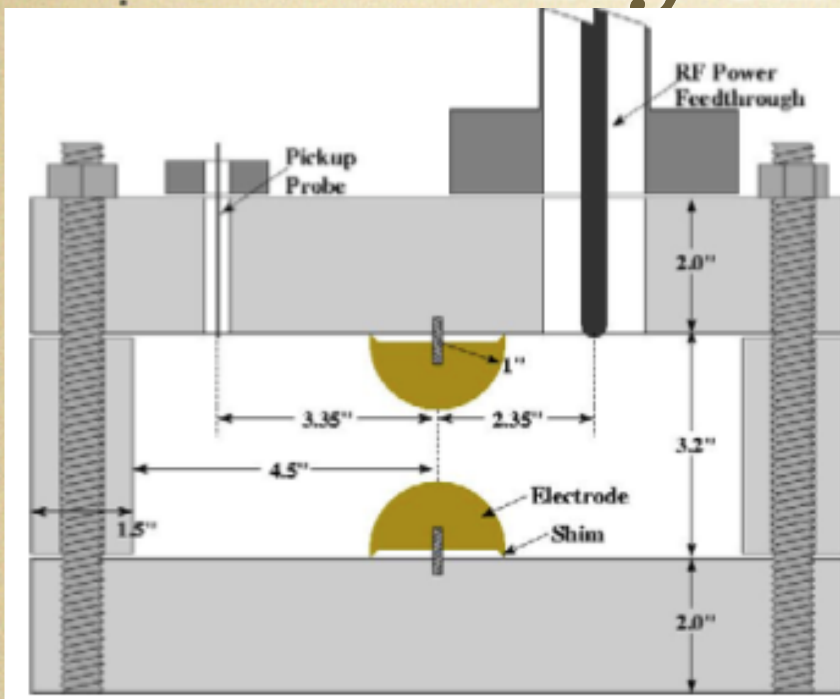


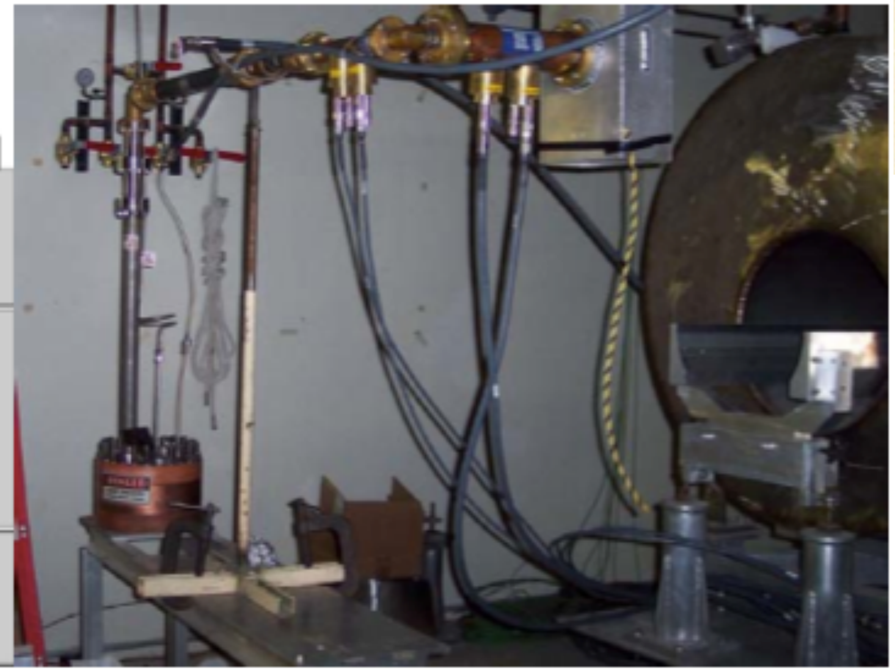

Be flat window




805 MHz cell

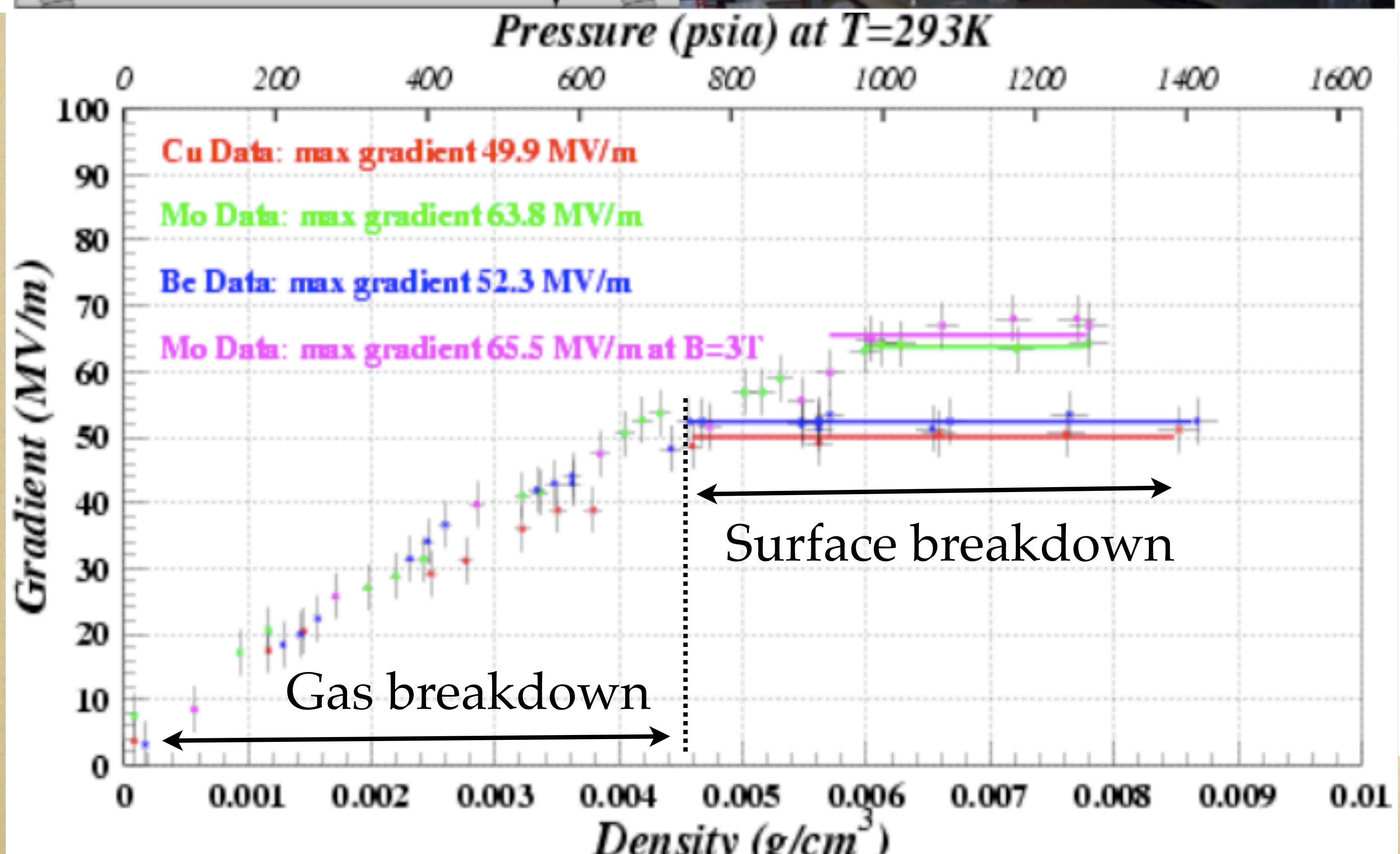
# High Pressurized Gaseous Hydrogen Filled RF Cell Test

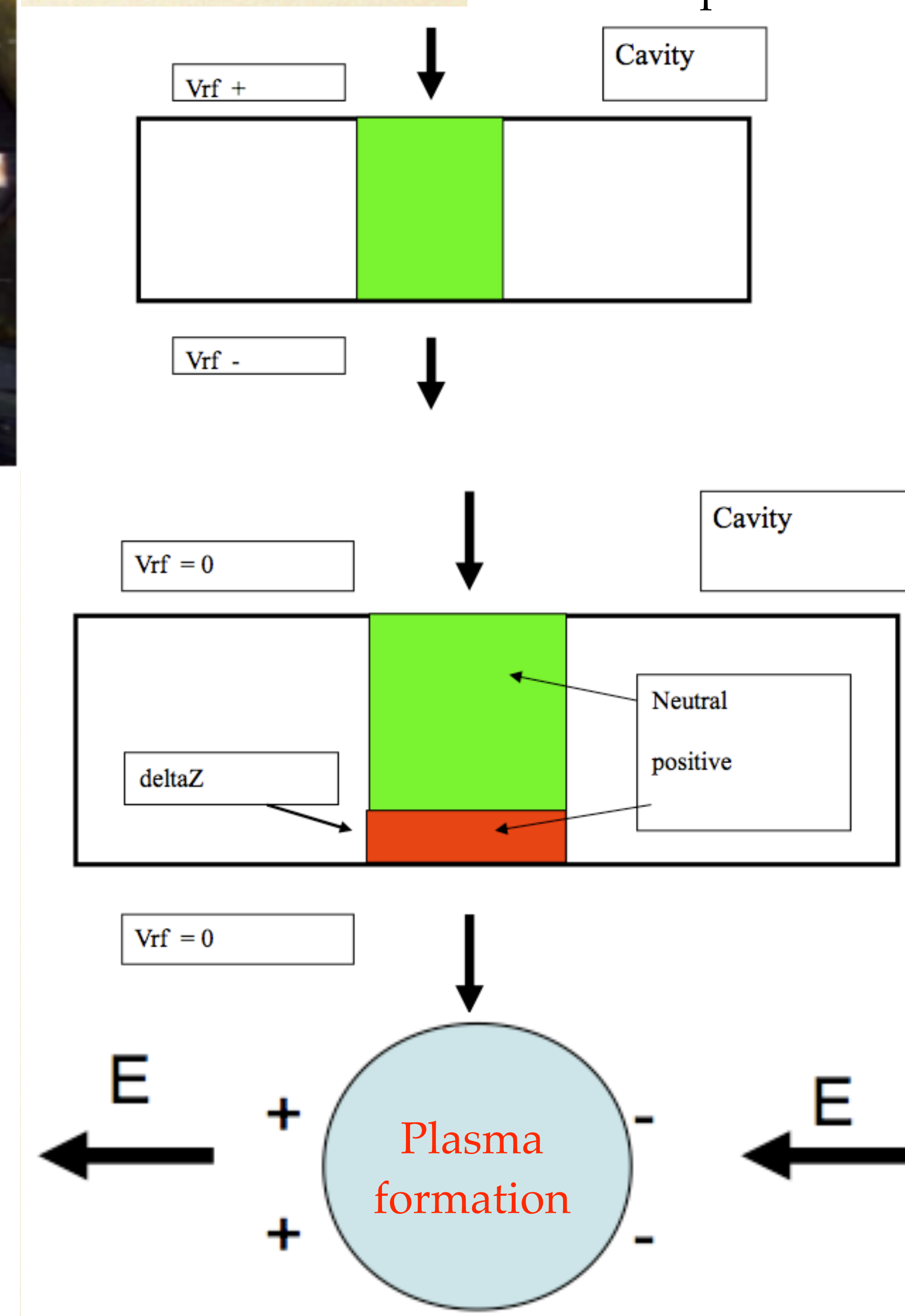


Need beam test

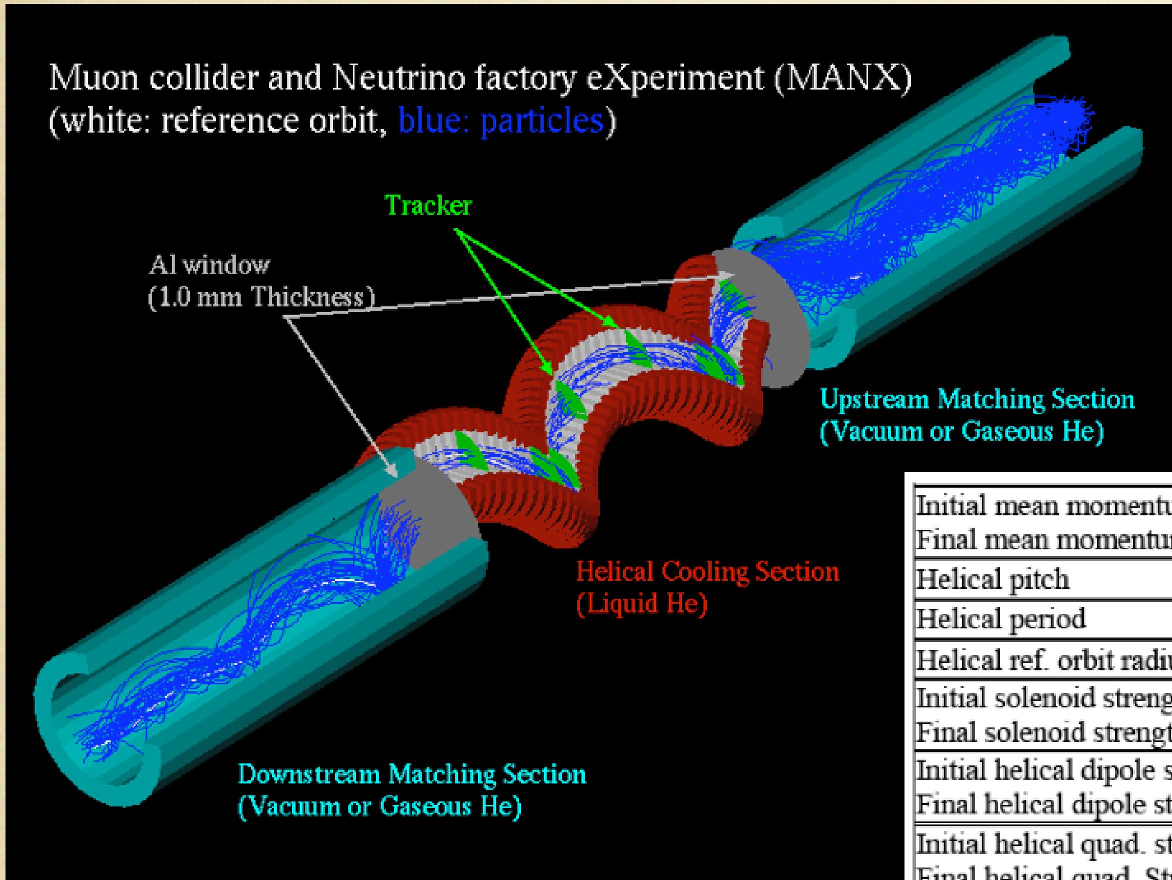
A. Tollestrup LEMC'08

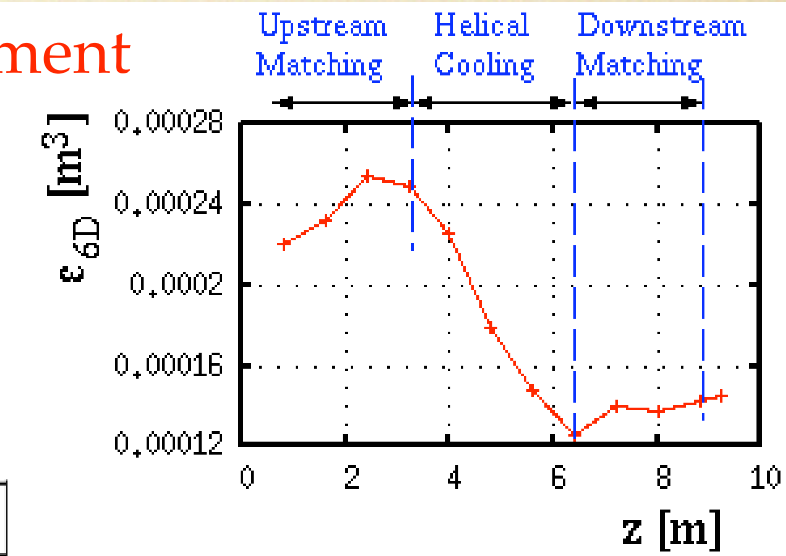


# 6D Cooling Experiments

## MANX experiment

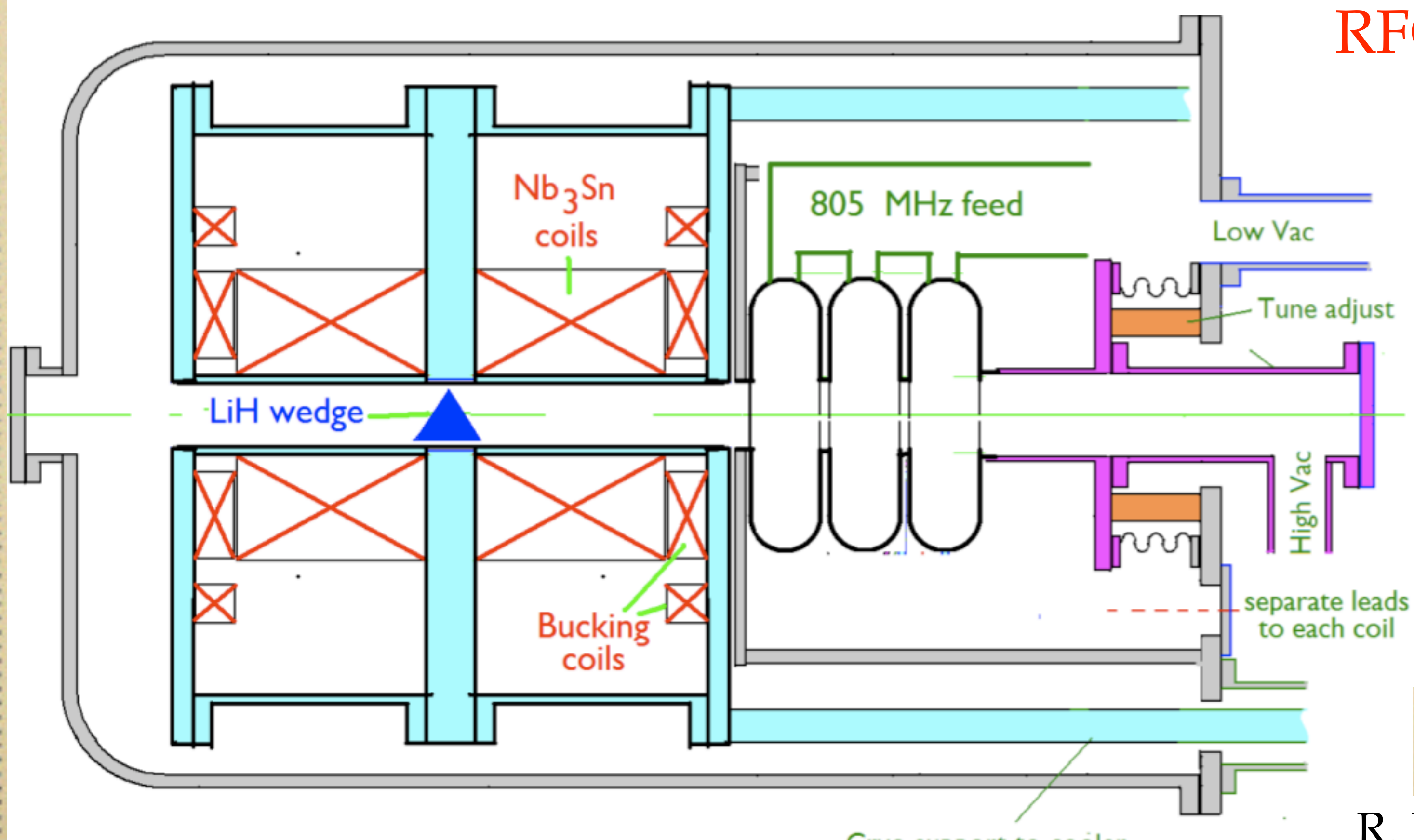


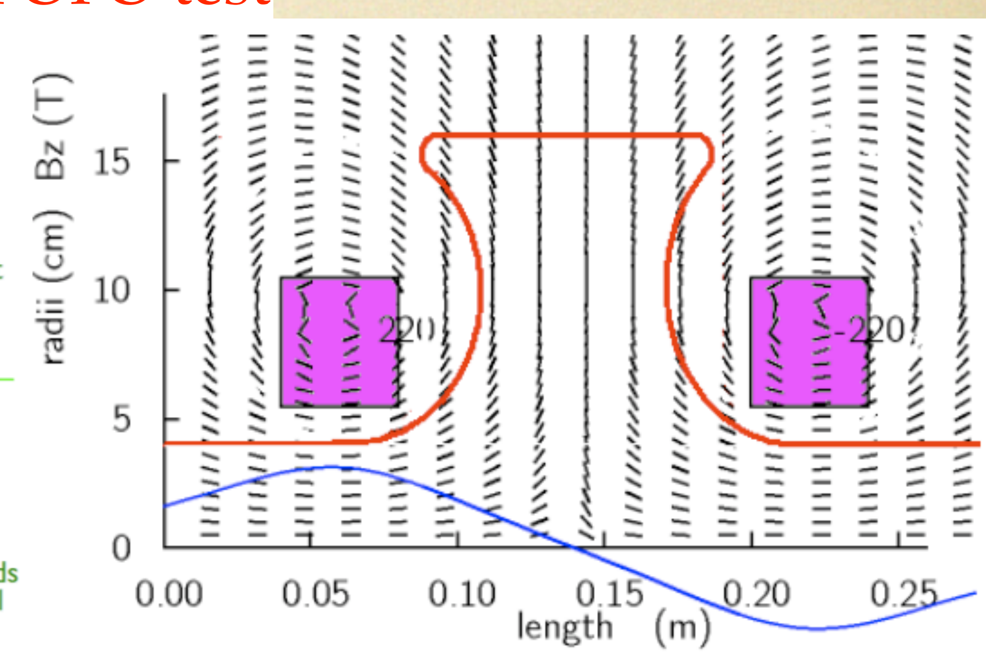




| | | |
|---|---|---|
| Initial mean momentum<br>Final mean momentum | P | 300 MeV/c<br>170 MeV/c |
| Helical pitch | κ | 1 |
| Helical period | λ | 1.6 m |
| Helical ref. orbit radius | *A* | 0.255 m |
| Initial solenoid strength<br>Final solenoid strength | B | -3.8 T<br>-1.7 T |
| Initial helical dipole strength<br>Final helical dipole strength | B | 1.2 T<br>0.8 T |
| Initial helical quad. strength<br>Final helical quad. Strength | b' | -0.9 T/m<br>-0.5 T/m |

K. Yonehara LEMC'08

## RFOFO test




R. Palmer 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

UNIVERSITY OF CALIFORNIA UCRIVERSIDE

Argonne NATIONAL LABORATORY

# Conclusion

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