Muon Colliders

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Crete

For the Muon Accelerator Program (MAP)

- A National Program
- Administered through Fermi Lab
- MAP Director Mark Palmer   (no relation of mine)
- Funded now at $\approx$ 10 M$ per year

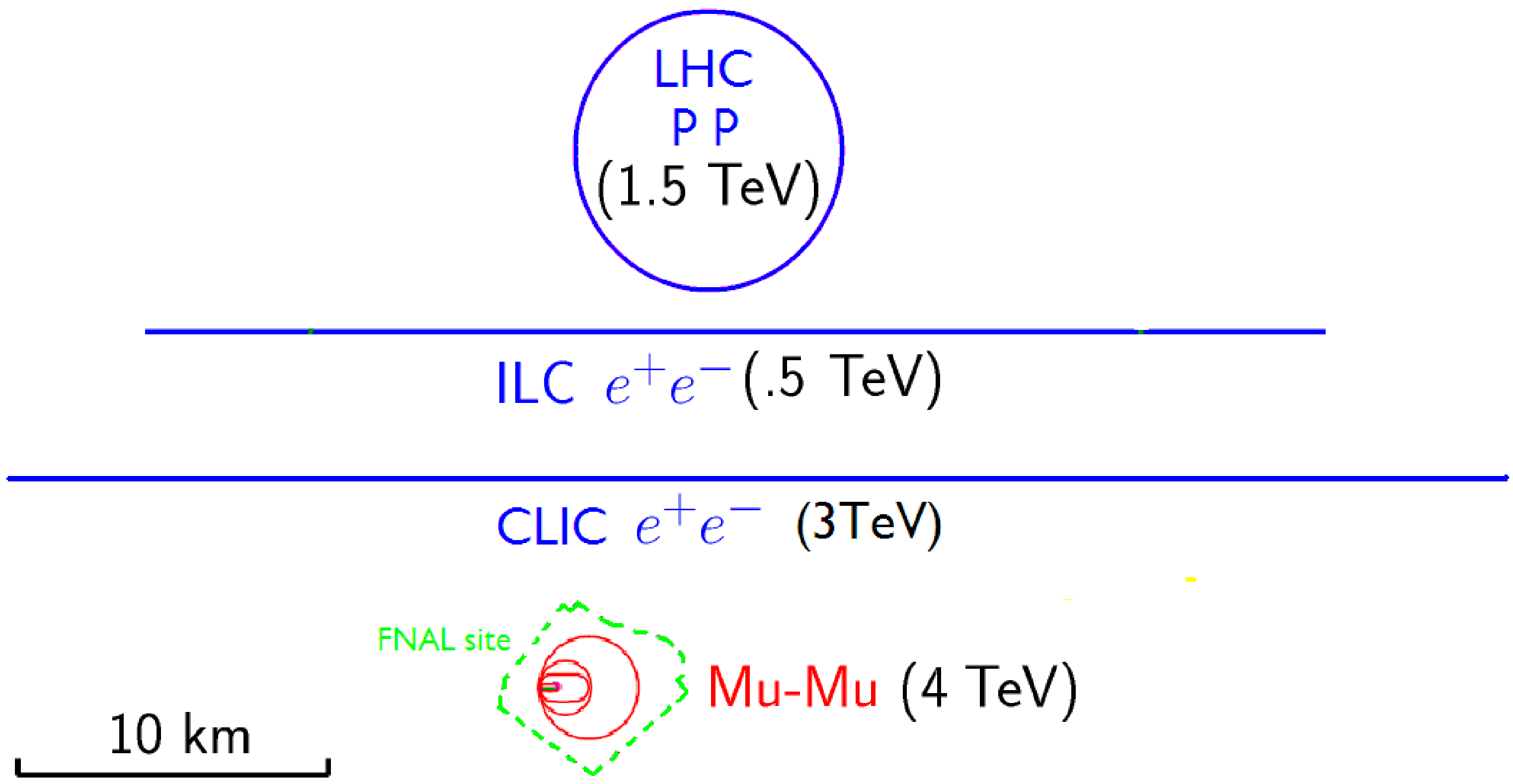
  - Why
  - Concept
  - Comparison with CLIC
  - Conclusion

Why a Muon Collider ?

- Electron Linear Colliders
  - synchrotron radiation ($\propto \gamma^4$) forces Linear Colliders to be linear
  - electrons intersect once and are thrown away
  - beamstrahlung causes huge energy variation
    (70% of Luminosity has dE $>$ 1% at 3 TeV)

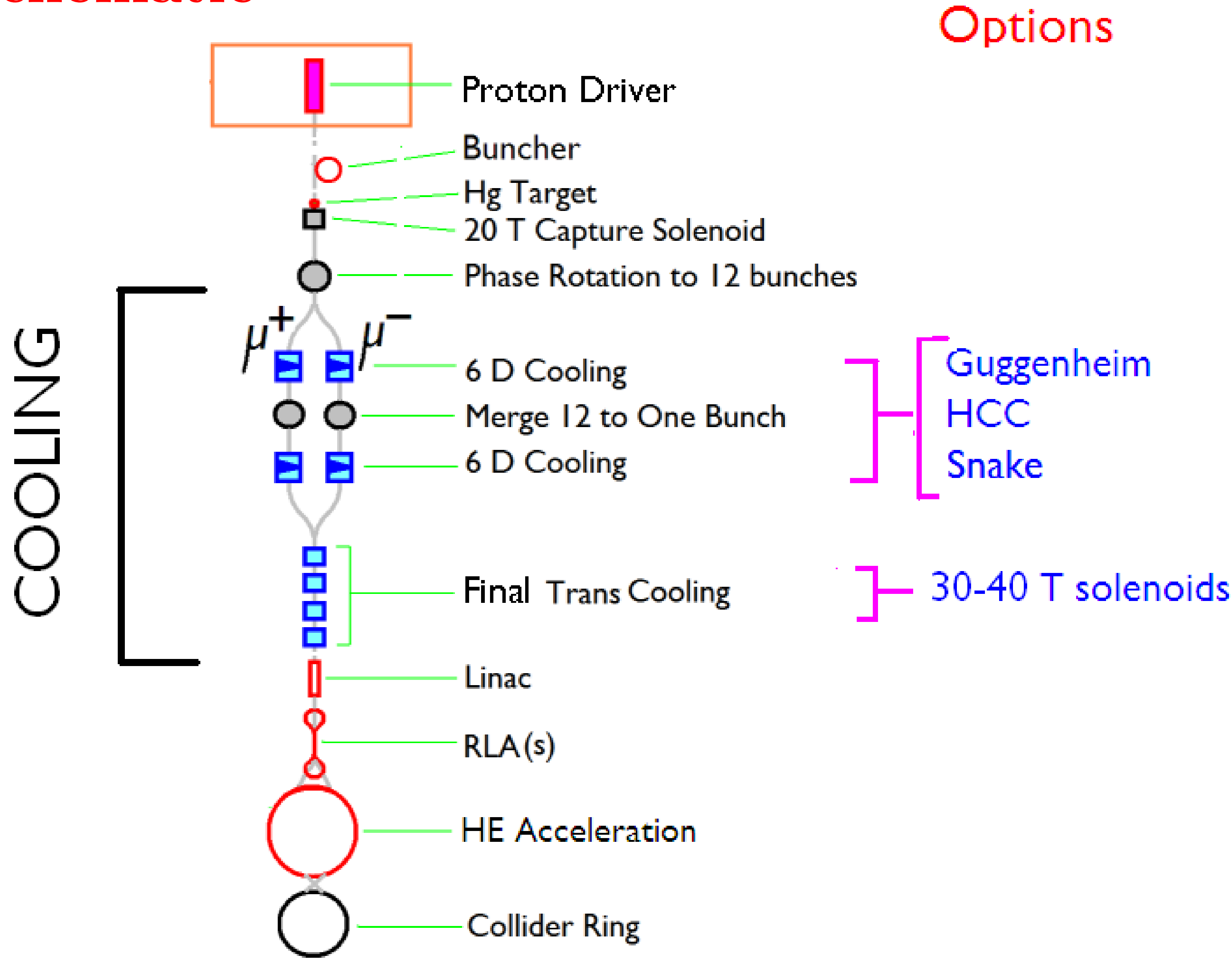
- Muon Collider
  - Acceleration can be in rings, using much less rf
  - Collisions can be in rings
    $\approx$ 1000 collisions before decay
    allowing larger emittances and spot sizes
    and requiring less beam power
  - Beamstrahlung now negligible dE/E $\approx$ 0.1 %

Relative sizes



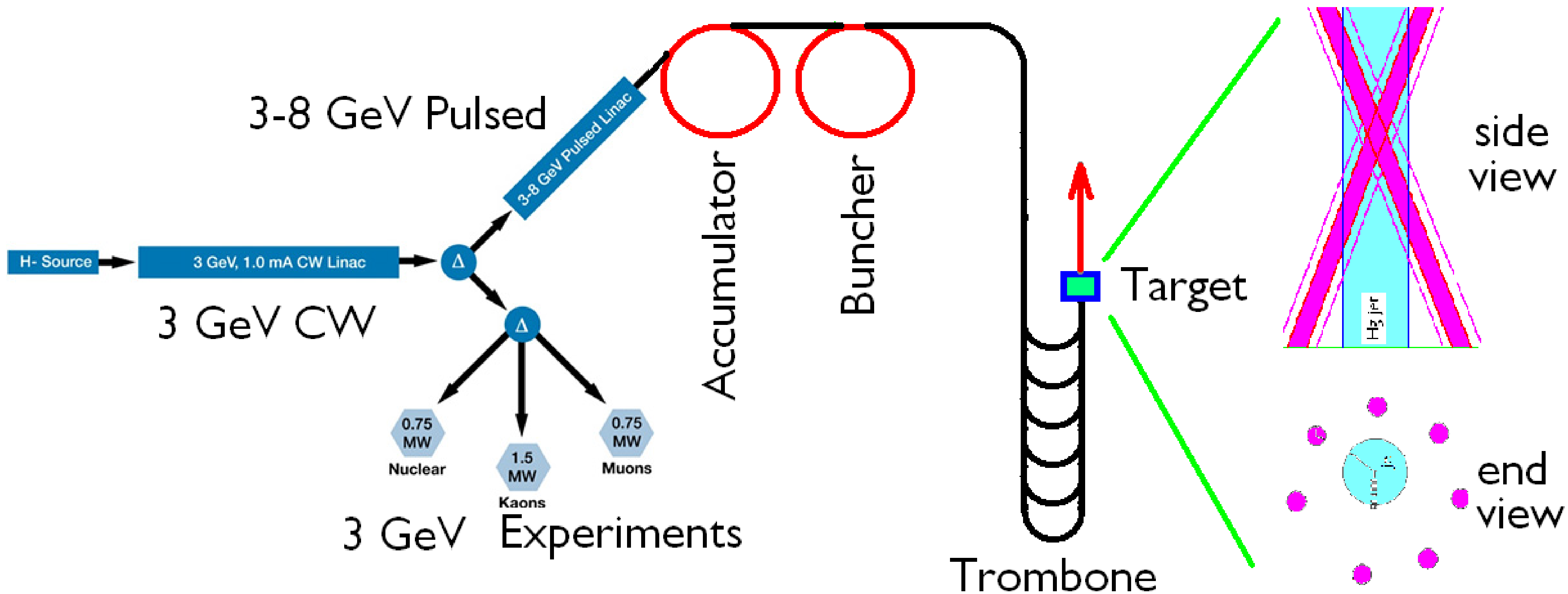
- Muon Colliders certainly smaller, and use less power ?
- They may be cheaper
- Main challenge is emittance reduction (cooling)

Schematic



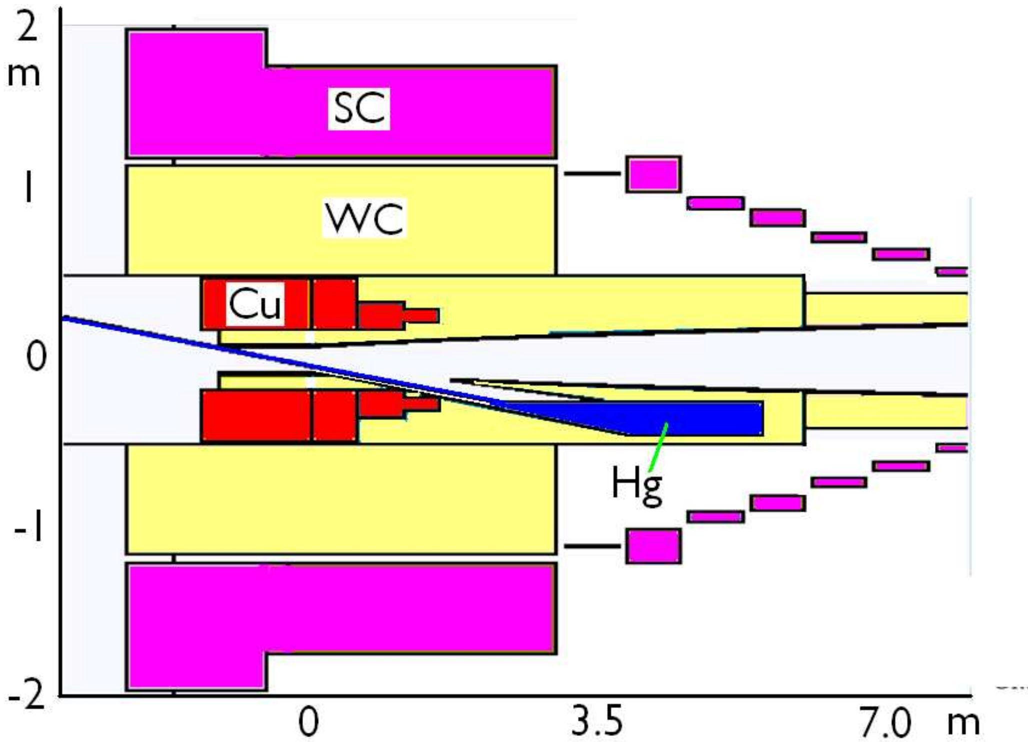
Options
Proton Driver
Buncher
Hg Target
20 T Capture Solenoid
Phase Rotation to 12 bunches
COOLING
μ+
μ−
6 D Cooling
Merge 12 to One Bunch
6 D Cooling
Guggenheim
HCC
Snake
Final Trans Cooling
30-40 T solenoids
Linac
RLA(s)
HE Acceleration
Collider Ring

4 MW Proton Driver e.g. Project X



- 2 10^{14} proton with σ_t=2 nsec at 15 Hz
- 8 GeV Linac, Accumulator & Buncher: $\geq$ 4 bunches $\leq$ 5 10^{13}
- Kicker and Trombone (Ankenbrandt)
- Intersecting liquid metal target, in time, from multiple directions

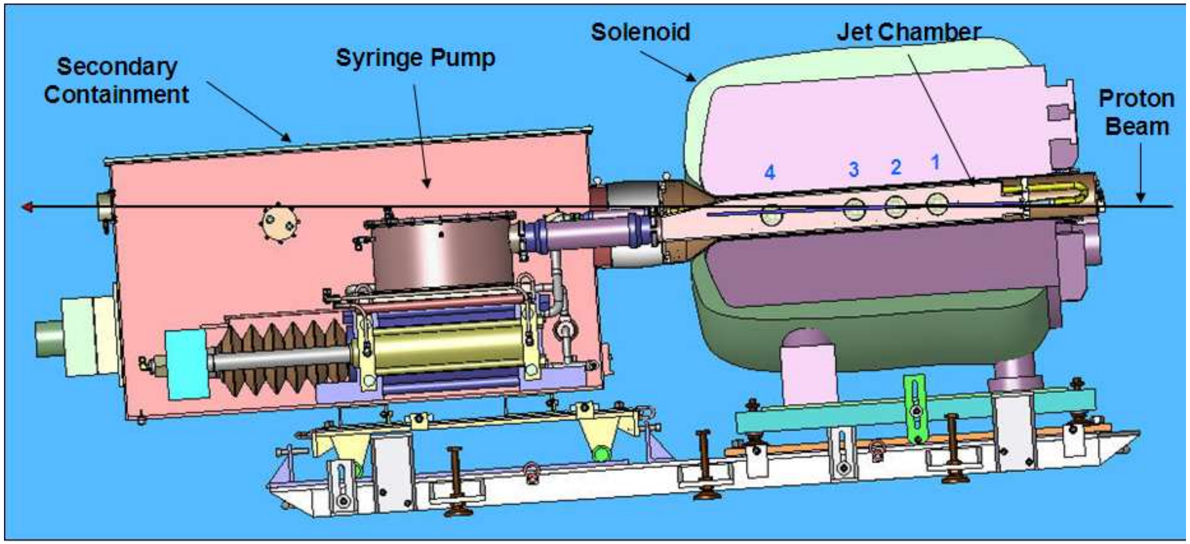
20 T Capture Solenoid



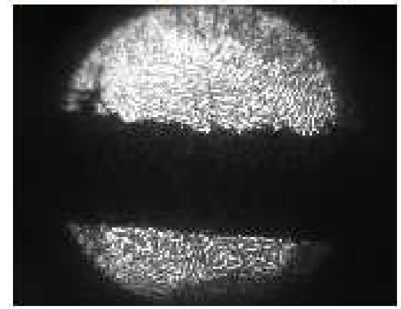
- Copper coil gives 6 T, (uses 15 MW of wall power)
- 14 T Super-conducting solenoid, tapering to 3 T
- Tungsten Carbide in water shielding

Liquid metal (eg mercury) jet target

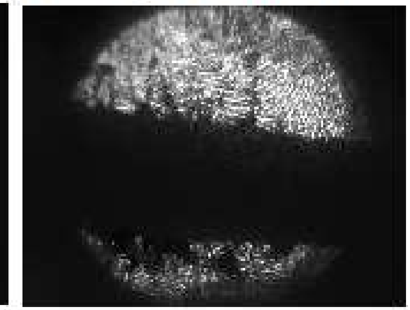
MERIT Experiment at CERN



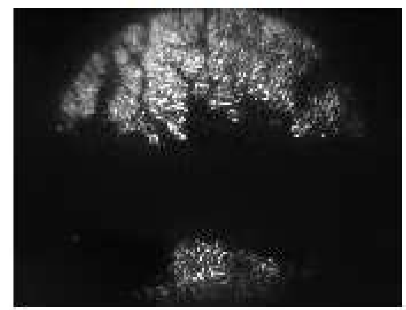
Images of Jet Flow at Viewport 3,
B=10T, N=10Tp, L=17cm, 2ms/frame



t = 6 ms



t = 8 ms

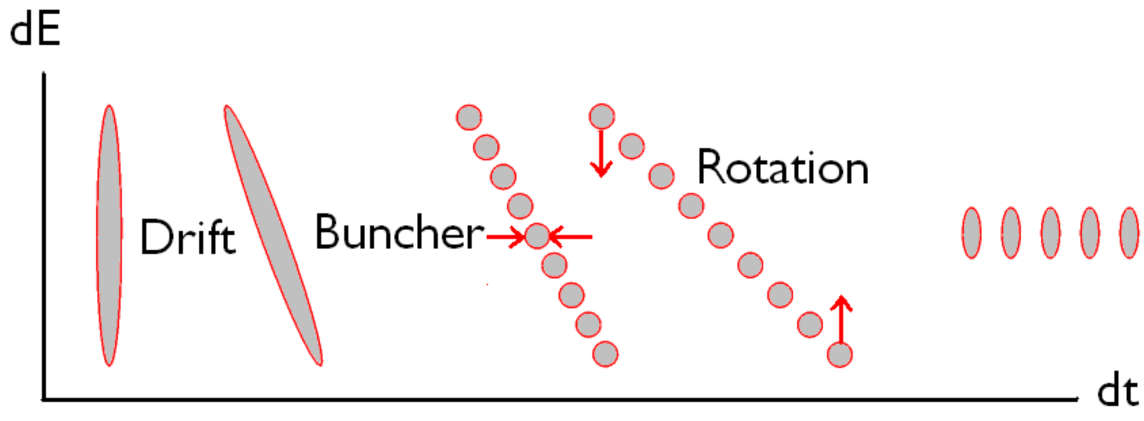


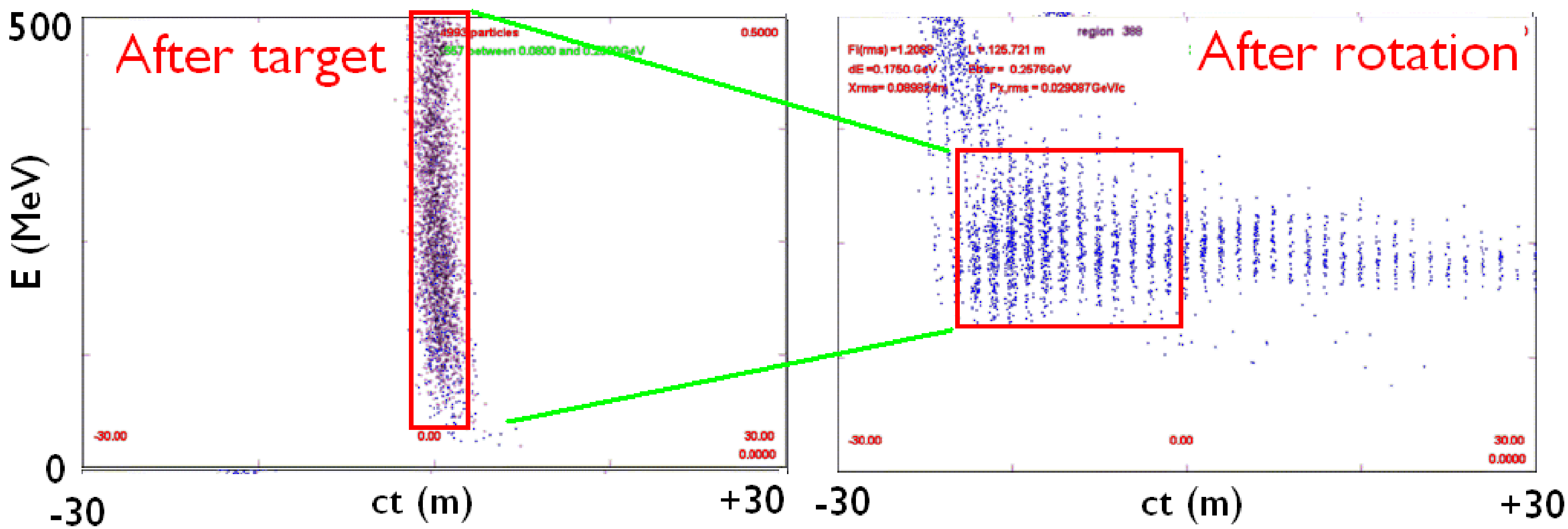
t = 10 ms

t = 14 ms

- 15 T pulsed magnet
- 1 cm rad mercury jet
- Up to 30 Tp
- Splash velocities were moderate
- Density persists for 100 micro sec

Phase Rotation→12 bunches





- ≈ 70% efficiency into 12 bunches
- rms dE/E from 100 % to ≈ 15%

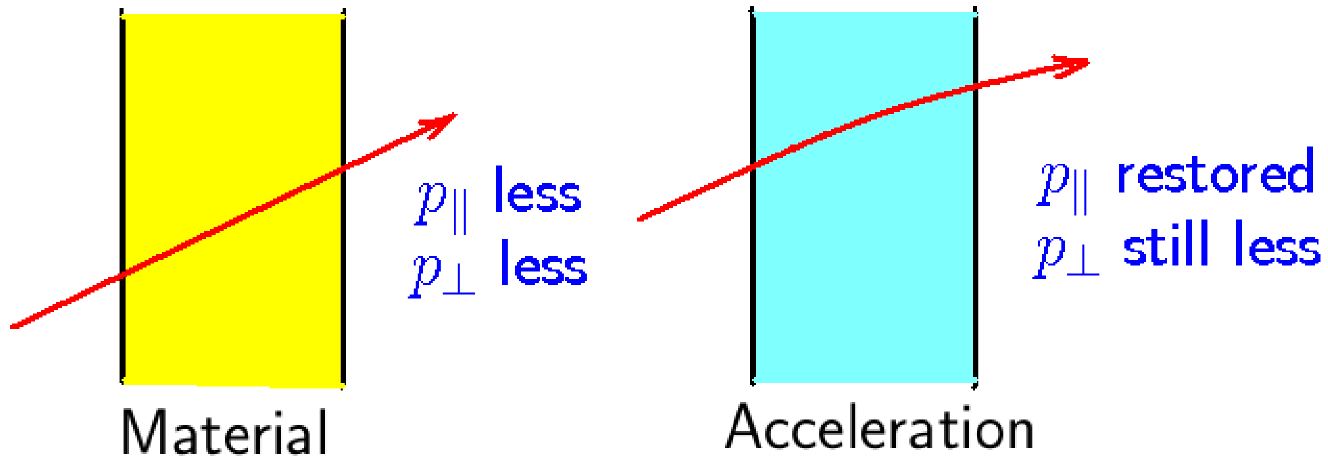
Conventional cooling methods

Synchrotron radiation cooling of electrons	negligible radiation for μs
Proton/ion cooling by co-moving electron beam	too slow cf muon decay
Stochastic cooling of protons/ions	too slow cf muon decay
Laser cooling of ions	too slow cf muon decay

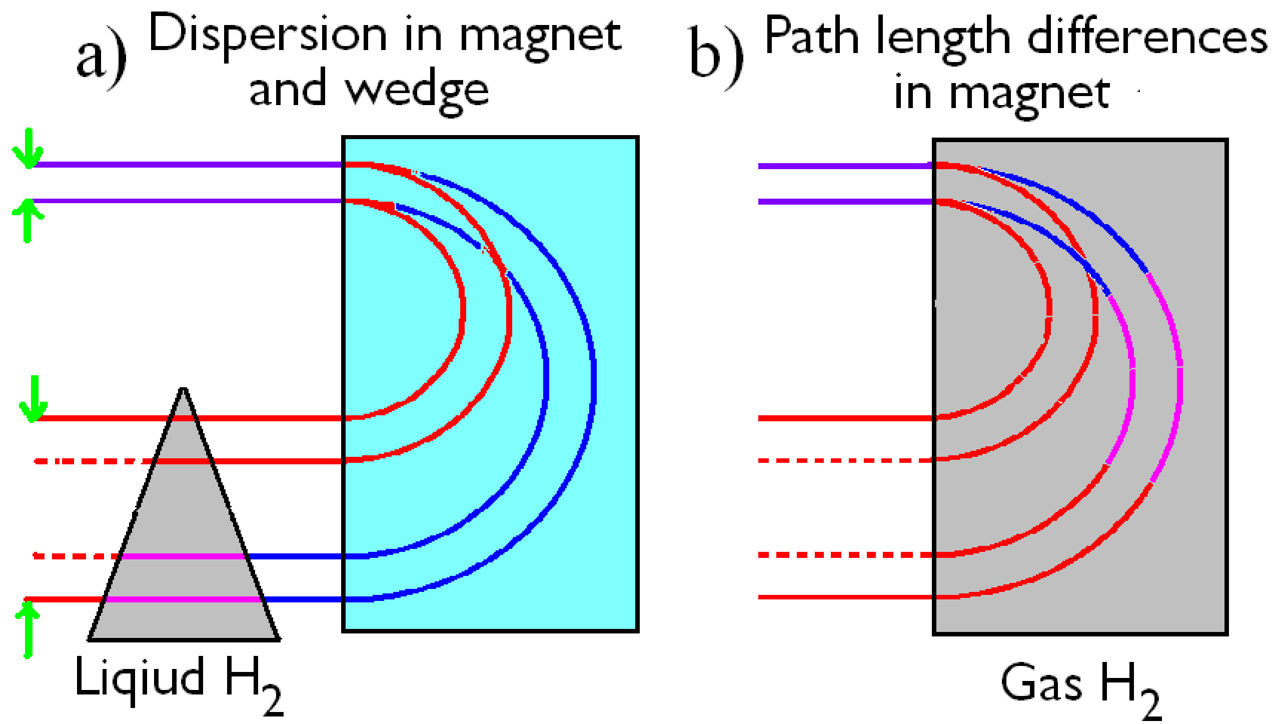
Only known way to cool muons is by ionization energy loss

Ionization Cooling

For transverse

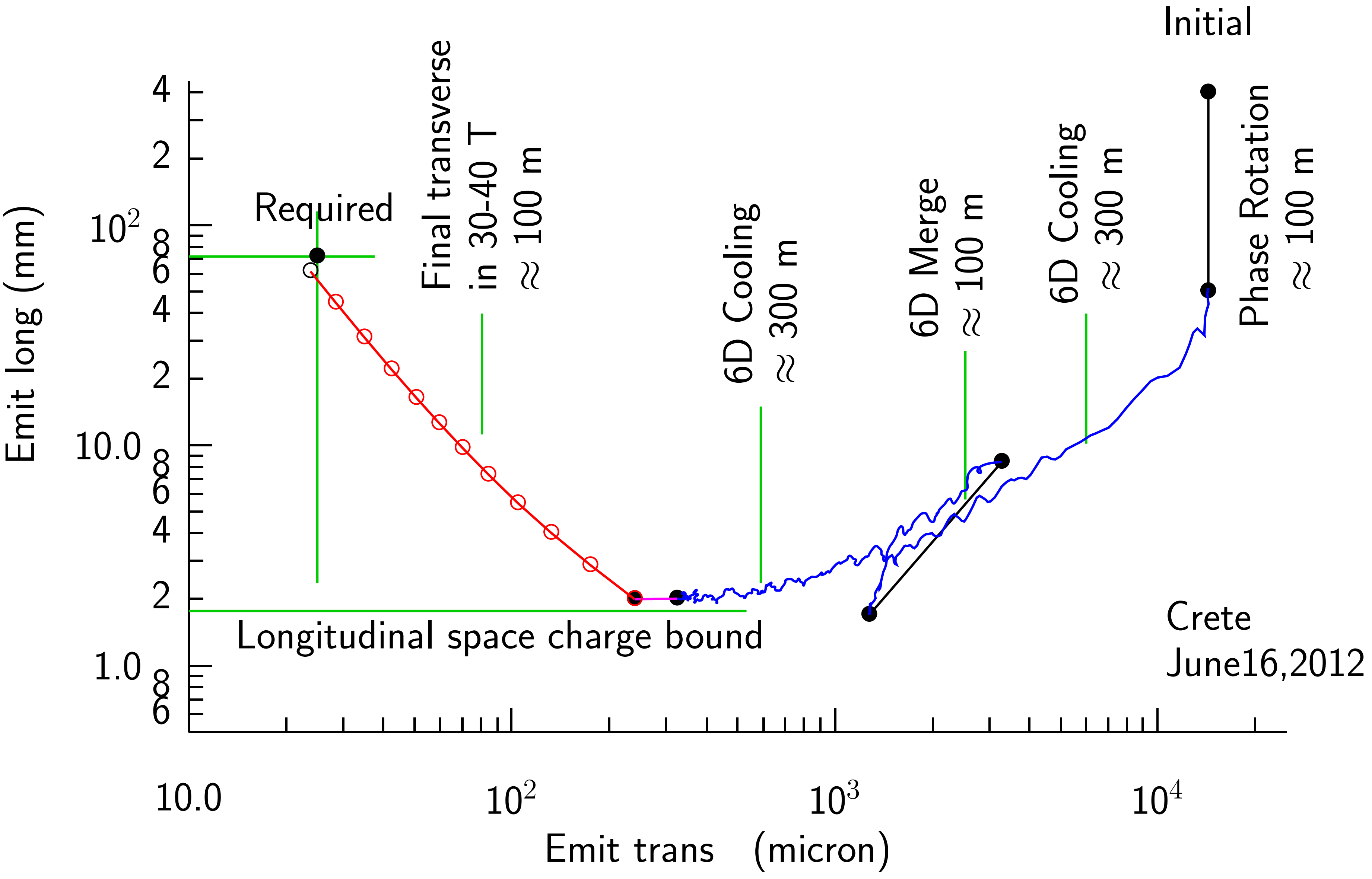


For Longitudinal

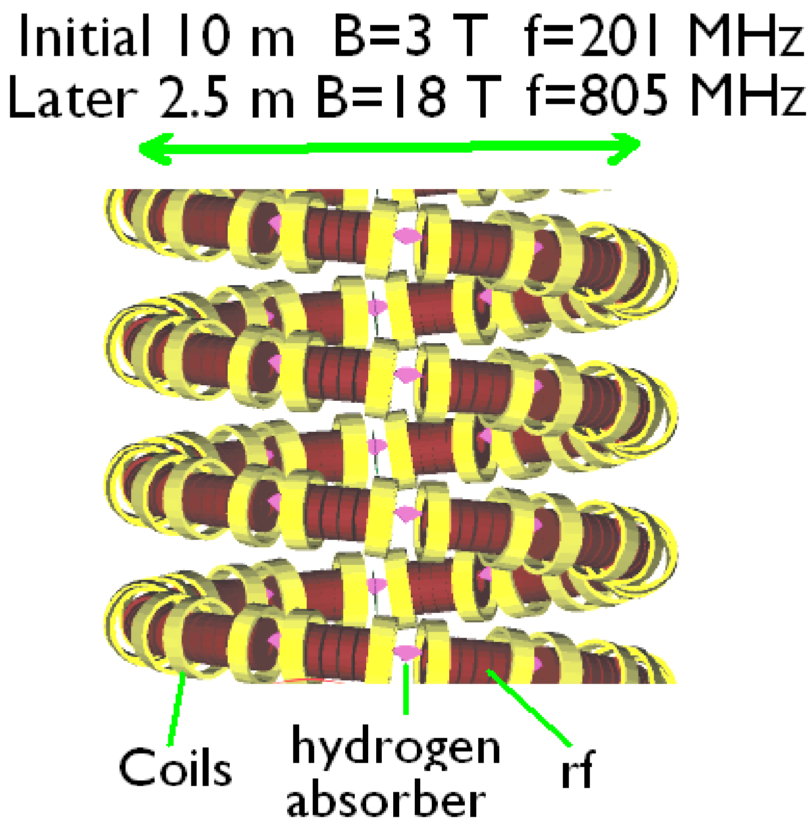


Emittances in Cooling Sequence

ICOOL Simulations of 6D cooling are for Guggenheim lattices

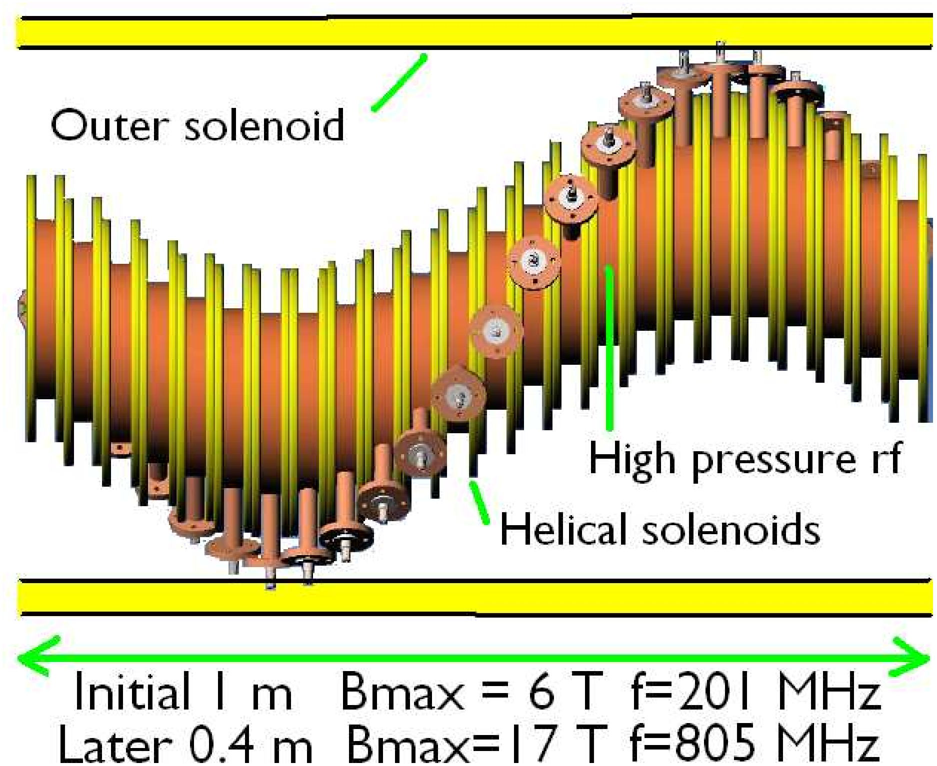


Candidates for 6D cooling lattices



Guggenheim

Liquid H_2 & Vacuum rf



Helical Cooling Channel

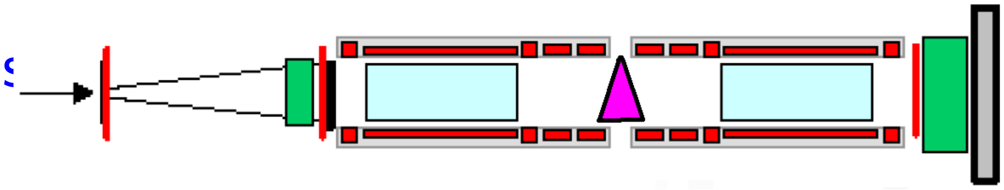
High pressure H_2 gas, inc. rf

- Guggenheim and HCC have similar simulated performance
- A third system that cools both signs: 'The Snake' (not shown) does not cool to low emittances & would only be used at start

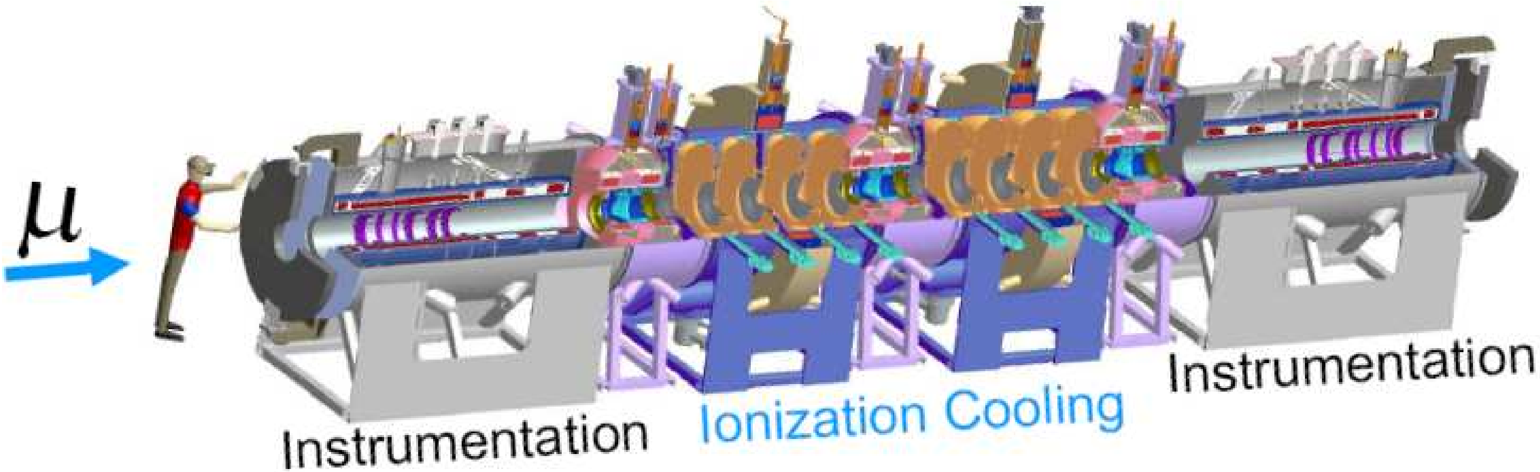
Muon Ionization Cooling Experiment (MICE)

International collaboration at RAL, US, UK, Japan (Blondel)

- Early Experiment to demonstrate Emittance Exchange
  - Cooling in all dimensions
  - But no re-acceleration



- Will then demonstrate transverse cooling in liquid hydrogen, including rf re-acceleration

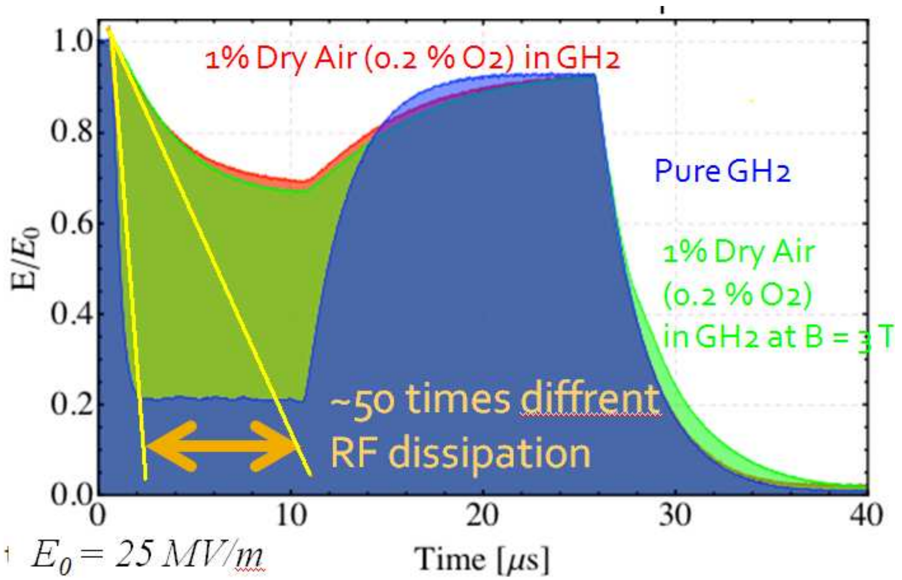


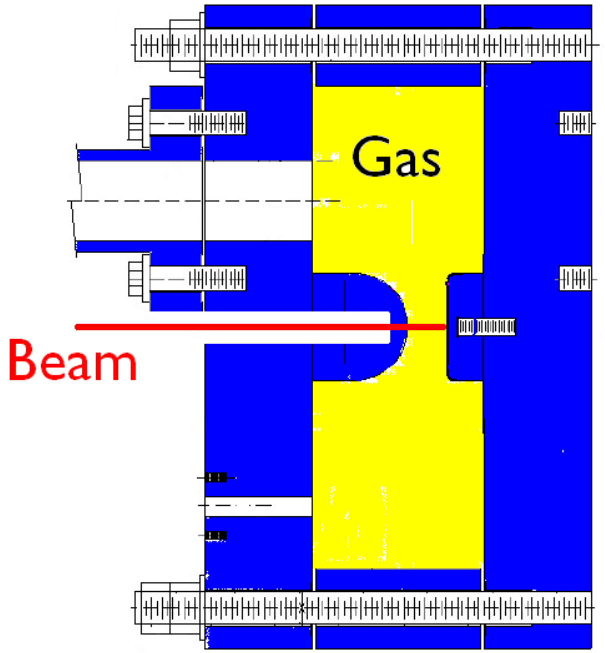
- Experiment should run in two years time

FNAL Exp's on High Pressure Gas rf

with Muons Inc As required for HCC 6D cooling

- rf works well with/without magnetic field



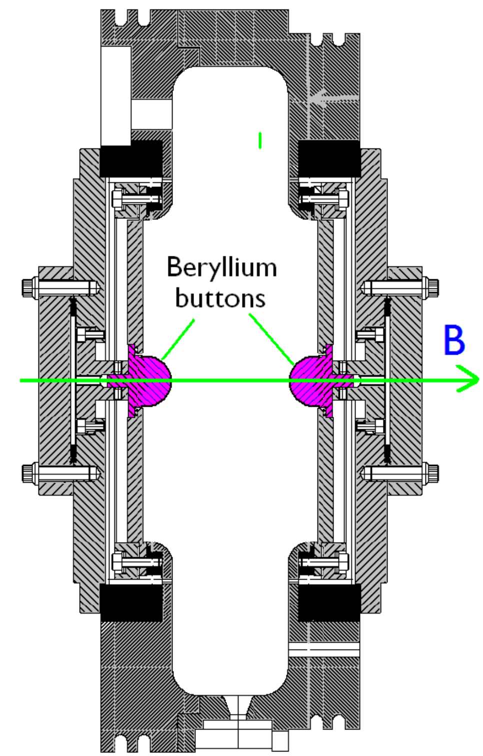


- rf tested in proton beam
  - No breakdown with magnetic field and/or beam
  - Beam loading, with 0.2% O_2 acceptable
- Problems remain in fitting rf inside HCC coils

FNAL R&D on vacuum rf with mag fields

As required for Guggenheim 6D cooling

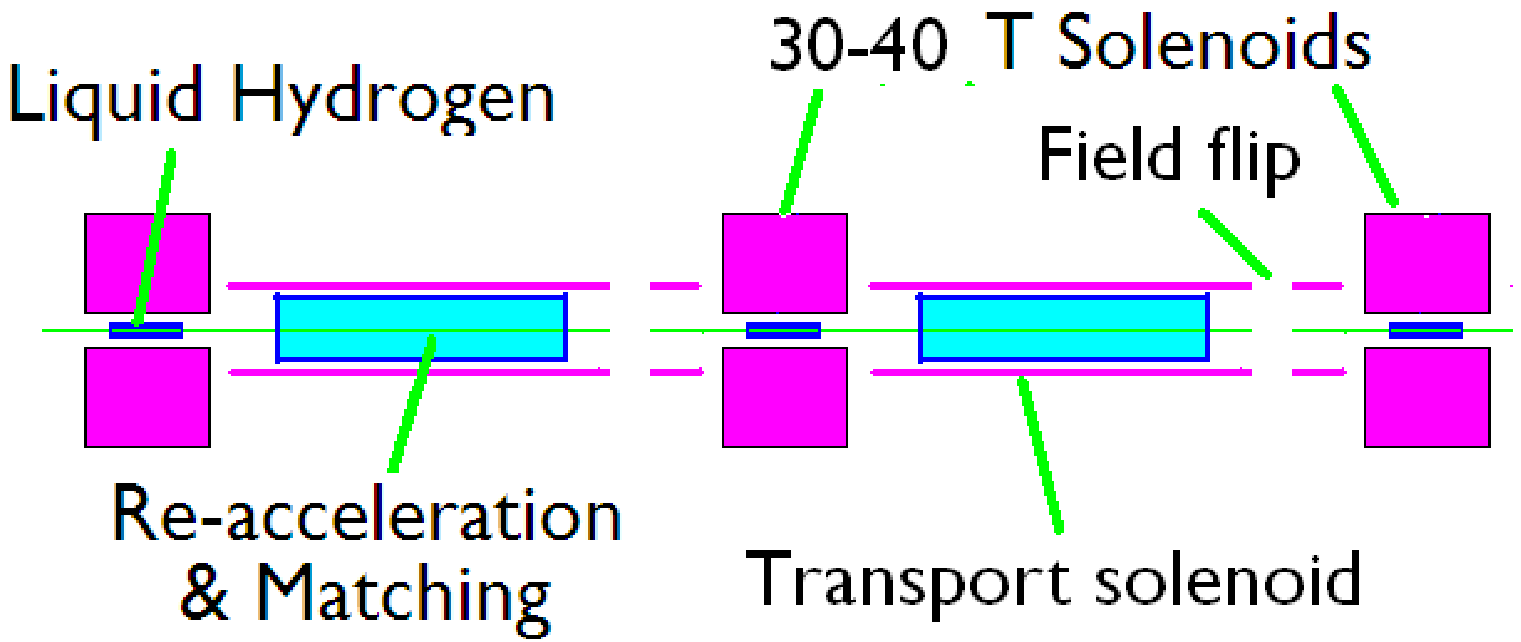
- Observed damage & reduced gradients with fields
- But recent tests with Be buttons show
  - Evidence that Be better resists damage in magnetic fields
  - Be walled cavity now under construction



Copper button
after 28 MV/m
& 3 T

Beryllium button
after 33 MV/m
& 3 T

Final Transverse Cooling

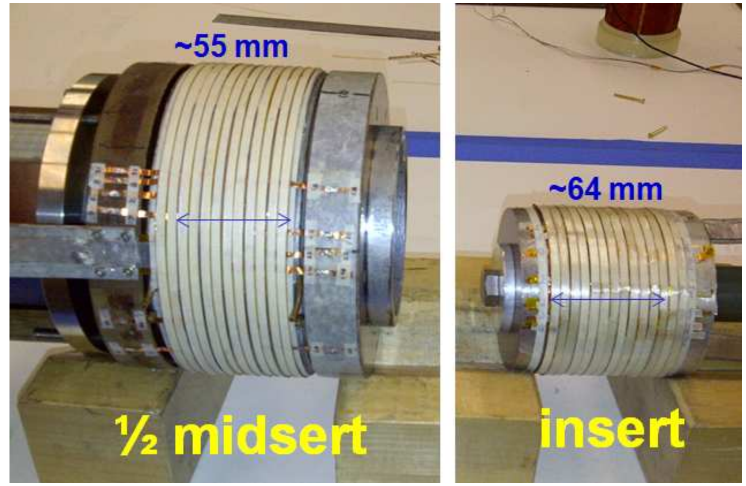


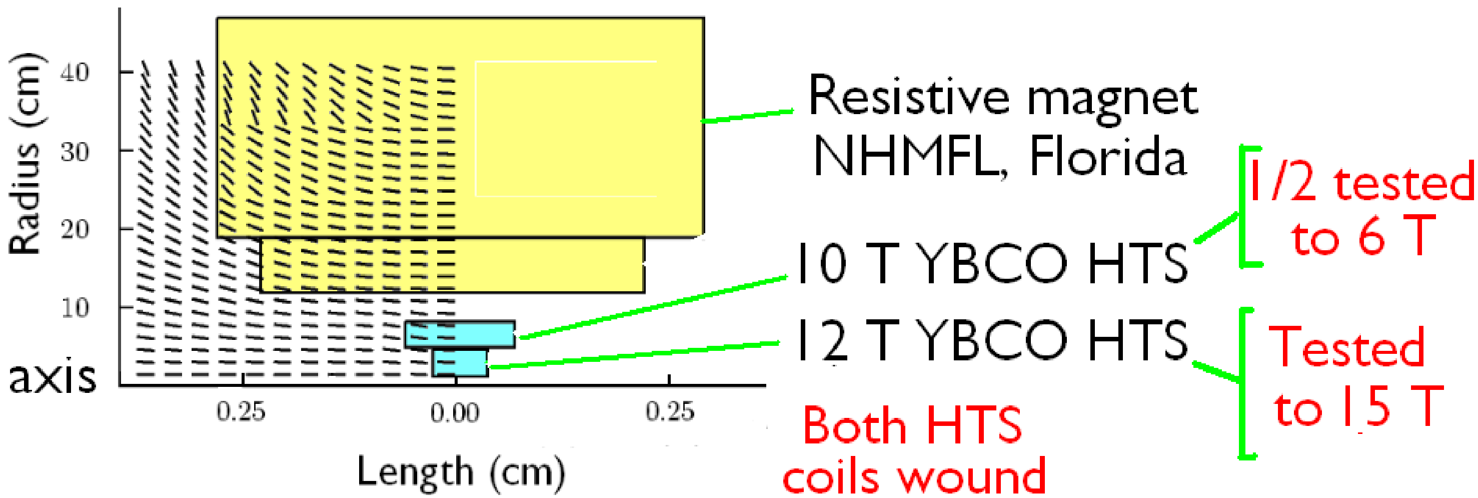
- Cooling in hydrogen simulated for all 13 stages
- Matching and re-acceleration still only simulated last stages
- Consequences of a limitation to 30 T probably acceptable but we believe that 40 T is attainable and leave as baseline

BNL R&D on HTS magnets

with PBL

As required
for final cooling



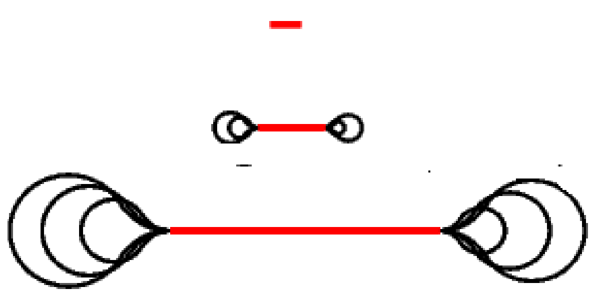


- When tested together we expect 25 T
- If tested in NHMFL 20 T, should demonstrate 40 T

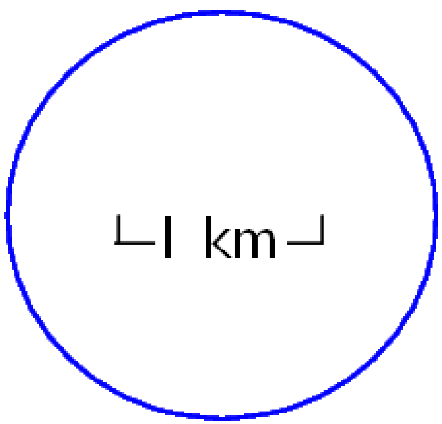
Acceleration

Must be fast:

Linacs, recirculating linacs (RLA) and pulsed synchrotrons (RCS)



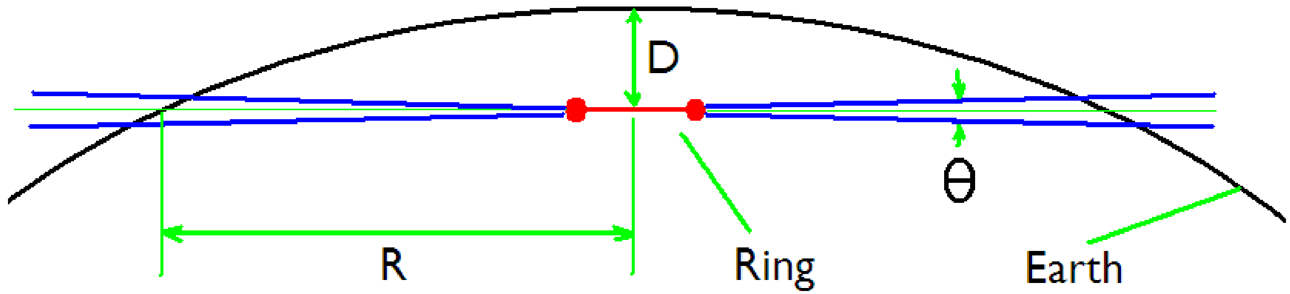
	E GEV		passes	Lengths
1)	.4-1.5	Linac		L(linac)= 68 m
2)	1.5-12.5	RLA	n=4.5	L(linac)= 306 m
3)	12.5-100	RLA	n=6.5	L(linac)= 1250 m
4)	100-400	RCS	n=23	Circ = 6283 m
5)	400-750	RCS	n=27	Circ = 6283 m



both RCS pulsed at 15 Hz

- Appears straight foreword
- Impedance questions not yet studied

Neutrino Radiation



$$R_B = 4.4\,10^{-24} \frac{N_\mu\ f\ E^3\ t\ <B>}{D\ B}\ \text{Sv} \quad \text{from regions of uniform B}$$

$$R_L = 6.7\,10^{-24} \frac{N_\mu\ f\ E^3\ t\ <B>\ L}{D}\ \text{Sv} \quad \text{from straight sections}$$

For $R_B = R_L$ = 10% Fed limit = 0.1 mSv (10 mRad)

E TeV	B(min) T	L(max) m
1.5	0.25	2.4
3.0	1.5	0.28

These appear hard, but not impossible

MC Rings

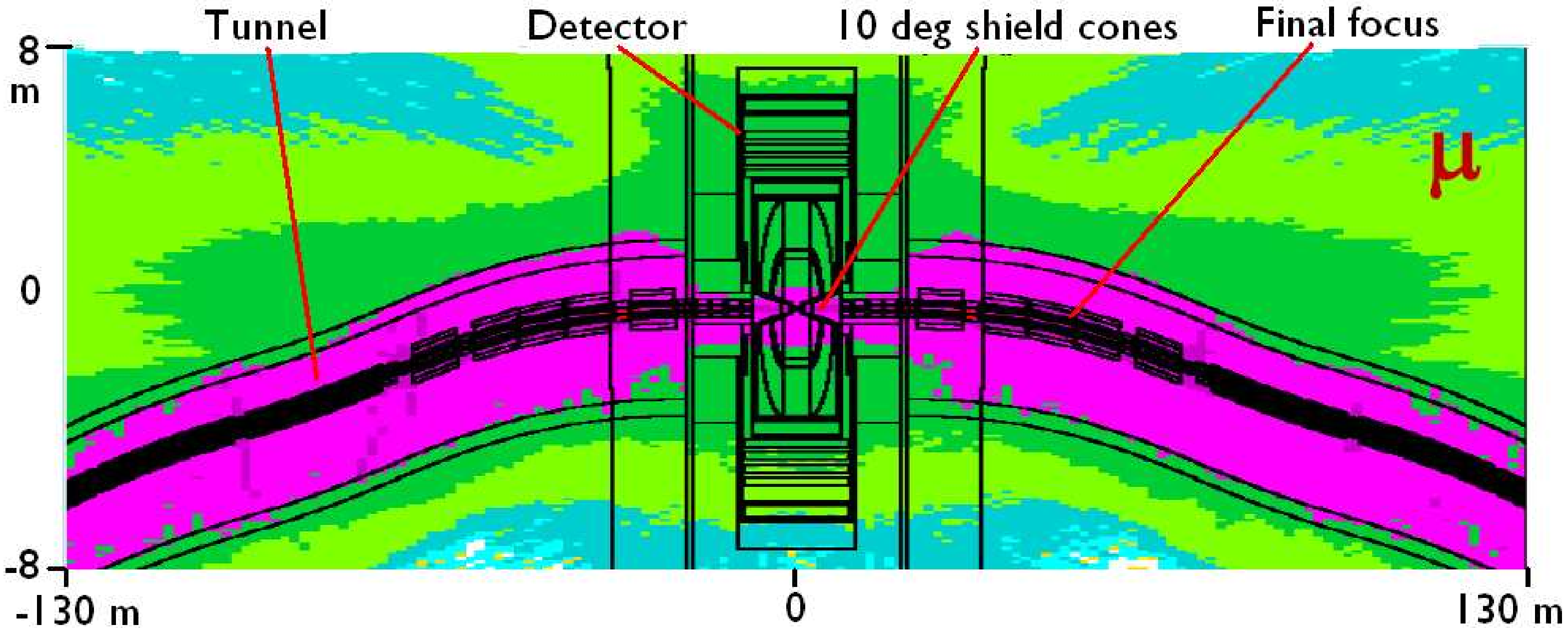
C of m Energy	1.5	3	6	TeV
Luminosity	1	4	12	10^{34} cm^{2}sec^{-1}
Muons/bunch	2	2	2	10^{12}
Total muon Power	7.2	11.5	11.5	MW
Ring <bending field>	6.04	8.4	11.6[1]	T
Ring circumference	2.6	4.5	6	km
β^* at IP $= \sigma_z$	10	5	2.5[1]	mm
rms momentum spread	0.1	0.1	0.1	%
Depth	135	135	540[2]	m
Repetition Rate	15	12	6	Hz
Proton Driver power	4	3.2	1.6	MW
Muon Trans Emittance	25	25	25	μm
Muon Long Emittance	72	72	72	mm

Note 1: This is a blind extrapolation from 1.5 and 3 TeV designs

Note 2: For the same neutrino radiation

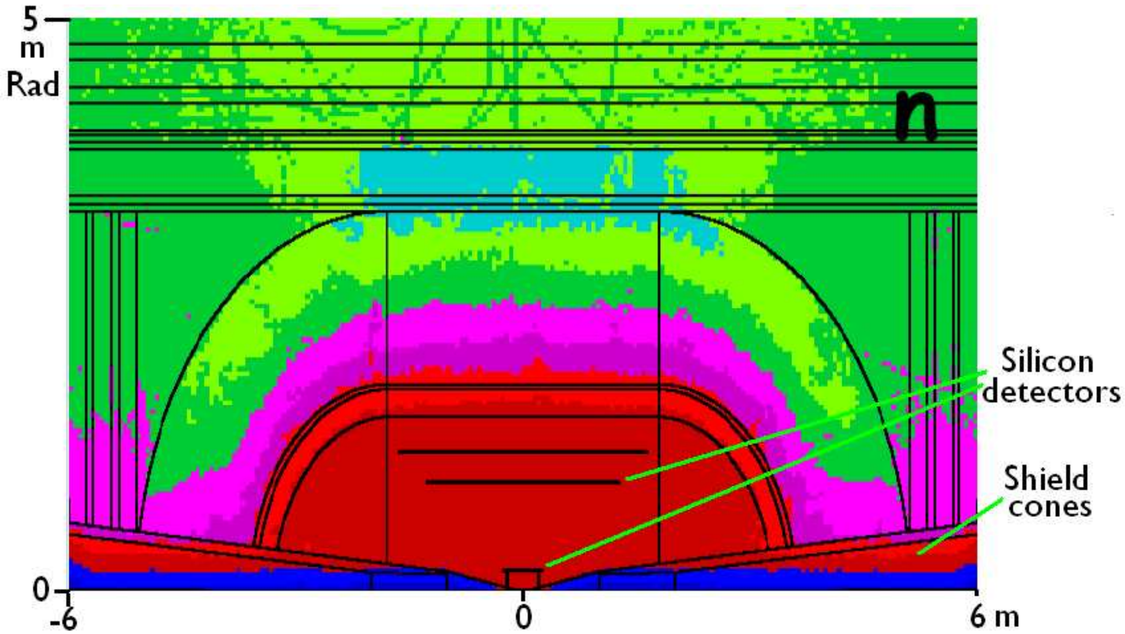
Muon source the same for all energies $\rightarrow$ natural upgrades

Detector Shielding



Fluence at first silicon tracker 10% of LHC (at $10^{34}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$)

Worse than e^+e^- but appears acceptable



Wall Power Requirement for 1.5 TeV

From summer 2011 PRELIMINARY and approximate

	Len	Static	Dynamic	—	—	—	Tot
		4^o	rf	PS	4^o	20^o	
	m	MW	MW	MW	MW	MW	MW
p Driver (SC linac)							(20)
Target and taper	16			15.0	0.4		15.4
Decay and phase rot	95	0.1	0.8		4.5		5.4
Charge separation	14						
6D cooling before merge	222	0.6	7.2		6.8	6.1	20.7
Merge	115	0.2	1.4				1.6
6D cooling after merge	428	0.7	2.8			2.6	6.1
Final 4D cooling	78	0.1	1.5			0.1	1.7
NC RF acceleration	104	0.1	4.1				4.2
SC RF linac	140	0.1	3.4				3.5
SC RF RLAs	10400	9.1	19.5				28.6
SC RF RCSs	12566	11.3	11.8				23.1
Collider ring	2600	2.3		3.0	10		15.3
Totals	26777	24.6	52.5	18.0	21.7	8.8	145.6

$\approx$ 160 MW for 3 TeV $\approx$ 200 MW for 6 TeV

Compare 3 TeV $\mu^+\mu^-$ with e^+e^- CLIC

		$\mu^+\mu^-$	e^+e^-
Luminosity	10^{34} cm^{2}sec^{-1}	4	2
Detectors		2	1
β^* at IP $= \sigma_z$	mm	5	0.09
rms bunch height σ_y	μm	4	0.001
Total lepton Power	MW	11.5	28
Comparable Wall power	MW	$\approx$ 160	450 (570 tot)

- $\mu^+\mu^-$luminosity twice CLIC's (for dE/E $<$ 1%) & 2 detectors
- Spot sizes and tolerances much easier than CLIC's
- Lepton and Wall power $\approx$ 1/3 CLIC's
- Because muons interact $\approx$ 1000 times, but electrons only once

- But Muon Collider less developed

CONCLUSION I

- Much simulation progress this year
  - new capture magnet design, chikane, new merge designs, Non-flip cooling lattices, lower final emittances, detector background studies, a start on space charge in cooling
- Progress in needed technologies
  - In HP Gas cavity in a beam
  - In rf-in-magnetic fields using Beryllium
  - In High Temp Super-Conductor YBCO coils
- Favorable comparisons with CLIC:
  - Luminosity greater than CLIC's
  - Estimated wall power $\approx 1/3$ of CLIC
- Extrapolation to higher energies thinkable

PERSONAL CONCLUSION II

We have long argued that a detailed study of 'New Physics' such as Super Symmetry requires a lepton collider with appropriate energy

- If 'New Physics' < 1 TeV   Go for ILC
- If 'New Physics' < 2 TeV   Go for CLIC
- But if 'New Physics' > 2 TeV then Muon Collider the only way
- Note: Plasma acceleration does not solve the energy problem