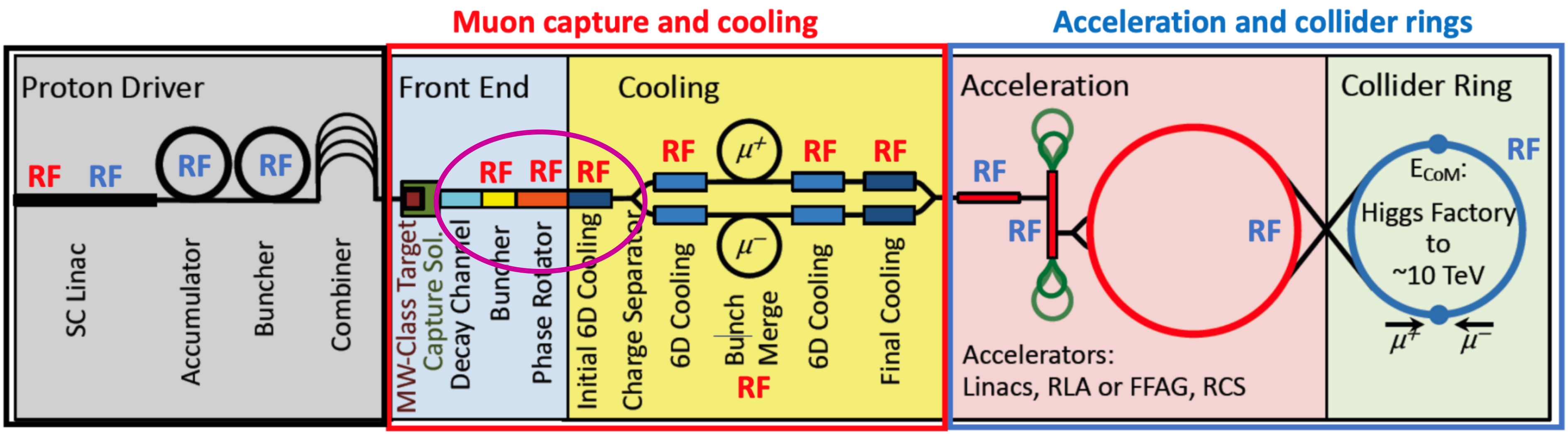
Front End
Buncher and φ-E Rotator

David Neuffer

Maybe 2023

Outline

- **Introduction + history**
  - Motivation:
    - Proton beam on Hg target –small
      - **Drift + Rotate to small δp for cooling**
    - High- frequency buncher and phase rotator
- **IDS "Neutrino Factory" 200 MHz (2011)**
- **Front End for MAP - Muon Collider (2014)**
  - 325 MHz baseline
- **Major changes**
  - Chicane and absorber
  - Helical Snake 6-D Cooler
- **Optimization**
- **Inverse phase-energy rotator**
  - Bunch recombiner
- **Future Variations**


Muon capture and cooling
Acceleration and collider rings
Proton Driver
RF
RF
RF
RF
SC Linac
Accumulator
Buncher
Combiner
Front End
MW-Class Target
Capture Sol.
Decay Channel
Buncher
Phase Rotator
RF
RF
RF
Cooling
Initial 6D Cooling
Charge Separator
6D Cooling
Bunch
Merge
6D Cooling
Final Cooling
RF
RF
RF
RF
μ^+
μ^-
Acceleration
RF
RF
RF
Accelerators:
Linacs, RLA or FFAG, RCS
Collider Ring
RF
E_{CoM}:
Higgs Factory
to
~10 TeV
μ^+
μ^-

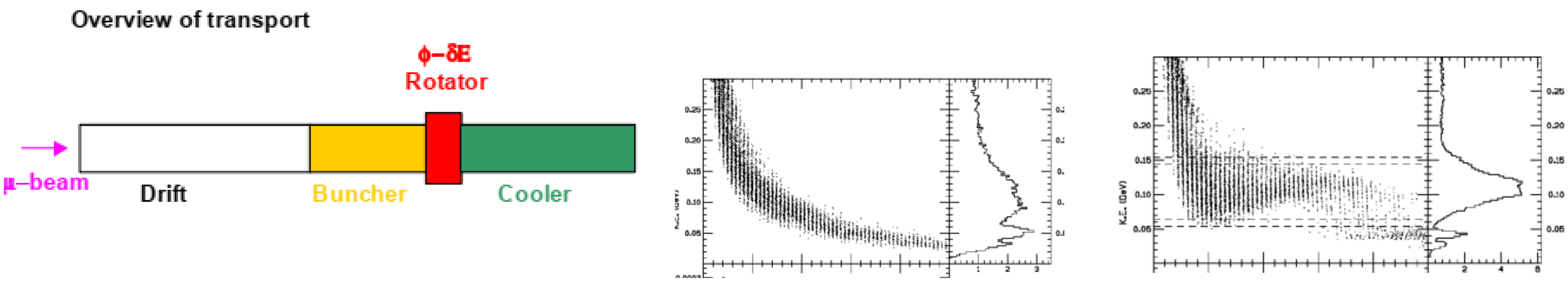
INTRODUCTION

➢ Drift + "rf" Buncher after target

R. Palmer -1994

- Short bunch → long bunch, small δE
- But long bunch means low freq. rf (< ~20 MHz)

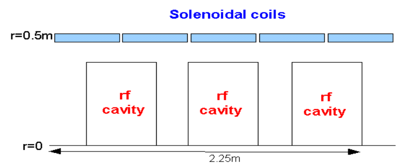
- High frequency rf forms train of bunches (>200 MHz)
  - match rf phase → mismatch frequency ??- 2000
- Fixed frequency Rotator → adiabatic vernier rotator
  - D Neuffer – A. van Ginneken PAC 2001 TPPH16

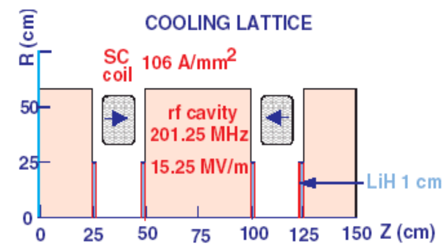


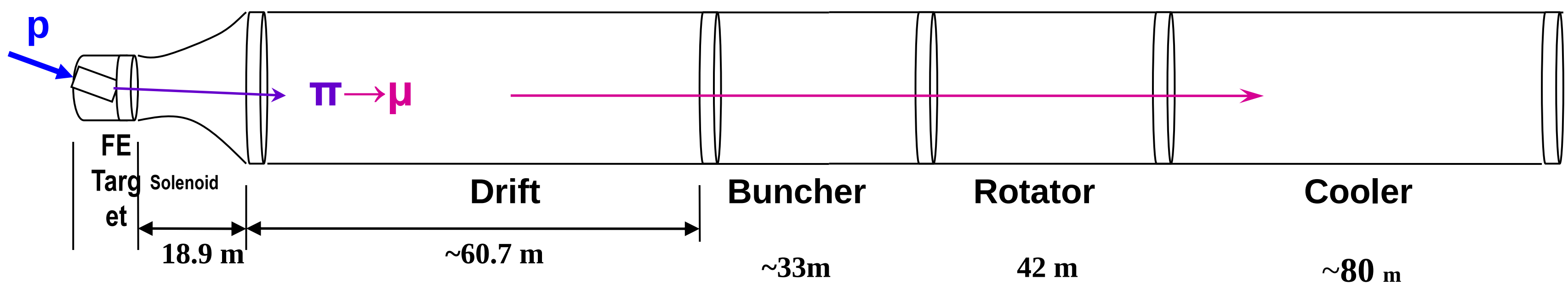
- Works for both signs μ^+ μ^- !!

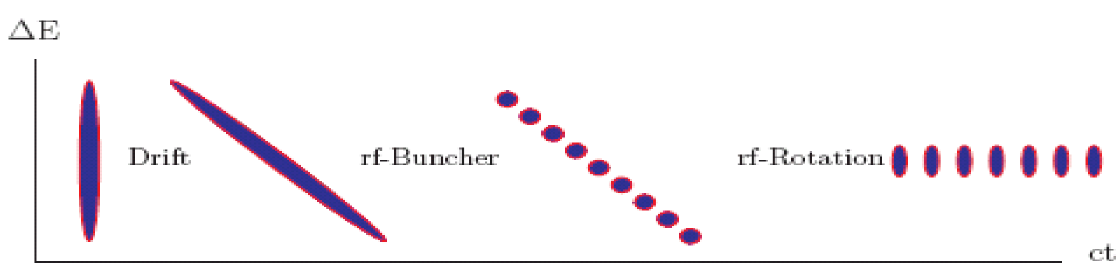
IDS Baseline Buncher and φ-E Rotator

- Drift (π→μ)
- "Adiabatically" bunch beam first (weak 320 to 232 MHz rf)
- Φ-E rotate bunches – align bunches to ~equal energies
  - 232 to 202 MHz, 12MV/m
- Cool beam 201.25MHz ~15 MV/m rf
- Captures and Cools both μ^+ and μ^-

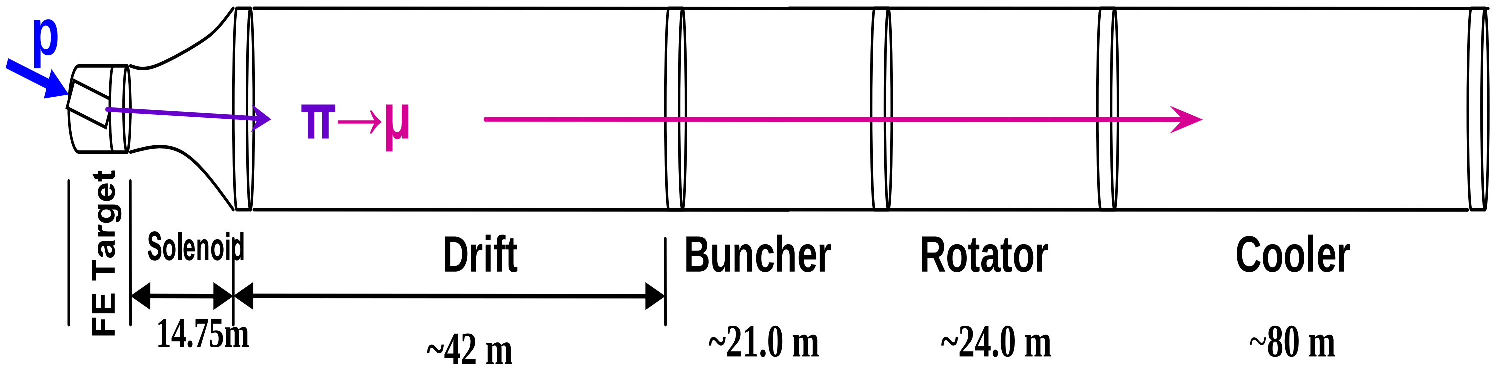




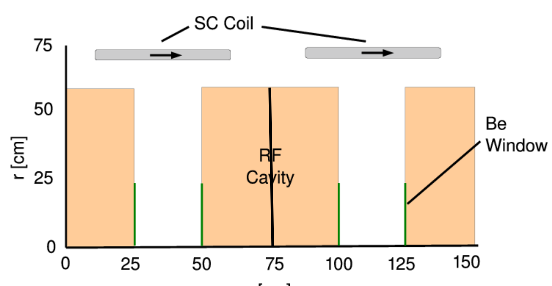




325MHz System “Collider”

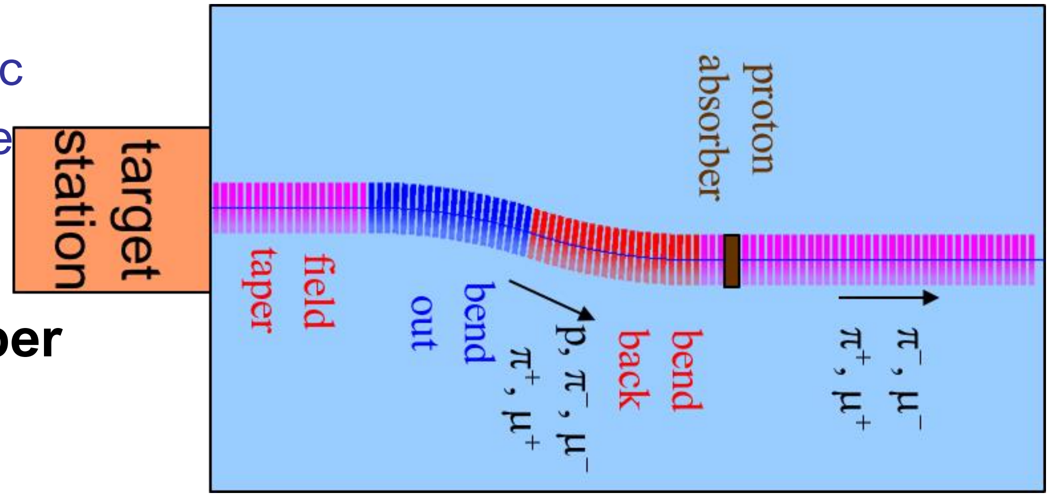


- **Drift**
  - 20T→ 2T
- **Buncher**
  - P_o=250MeV/c
  - P_N=154 MeV/c; N=12
  - V_{rf} : 0→ 15 MV/m
    - (2/3 occupied)
  - f_{RF} : 490→ 365MHz



- **Rotator**
  - V_{rf} : 20MV/m
    - (2/3 occupied)
  - f_{RF} : 364→ 326MHz
  - N=12.045
  - $P_{0,}$ P_N→245 MeV/c
- **Cooler**
  - 245 MeV/c
  - 325 MHz
  - 25 MV/m
  - 2 1.5 cm LiH absorbers /0.75m

- **Initial version was open from target to cooler**
  - Accepts μ^+, μ^- at ~250 MeV/c
  - Also accepts everything else e^{+-}

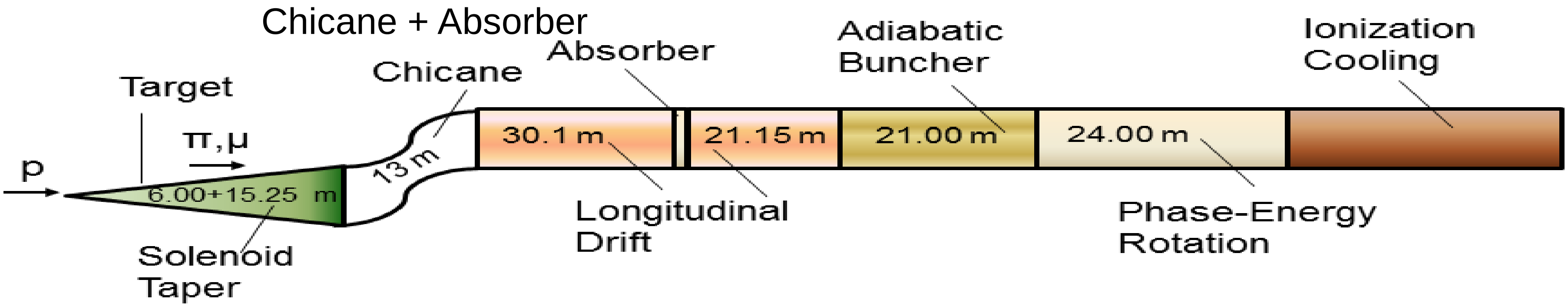


- **Introduce chicane + absorber to filter out unwanted particles (C. Rogers, et al.)**
  - Chicane cuts out P > 500 MeV/c
  - Absorber stops protons, electrons, pi, ….
    - 30 cm Be

```
SREGION          ! Bent solenoid
6.5  1   1e-2
1  0.   1.0
BSL
1 2.0 0.0 1 0.283 0.0  0.058181
0.0 0.0 0.0  0. 0. 0. 0. 0.
VAC
NONE
   0. 0. 0. 0. 0.   0. 0. 0. 0. 0.
```

- **Can we introduce without destroying front end ??**

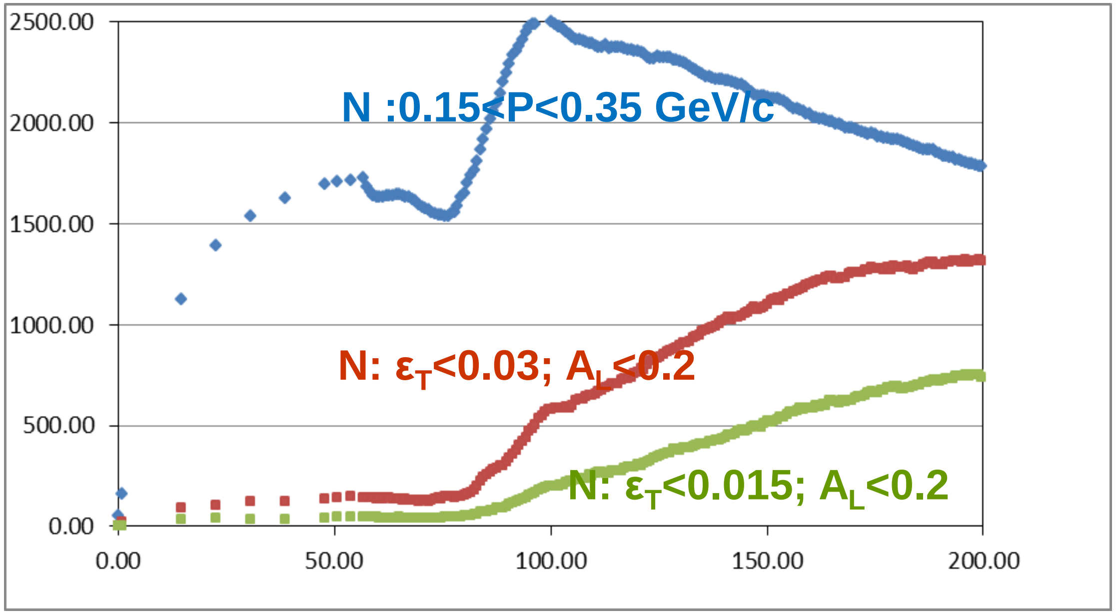
325 "Collider " w Chicane/Absorber



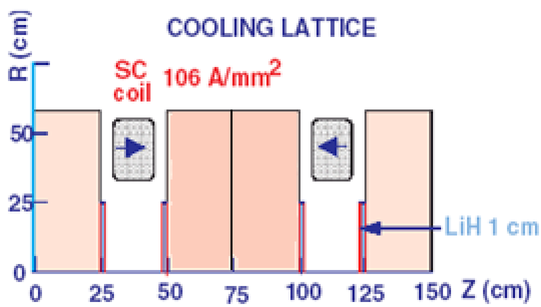
- **Add 30 m drift after chicane**
  - 6.5m → +21.67°,-21.67°
- **Add chicane + absorber**
  - particle 1-283 MeV/c
  - particle 2-194 MeV/c
- absorber at 54m
  - 10cm Be
  - particle 1-250 MeV/c
  - particle 2-154 MeV/c
- Bunch (N=12) 0→15 MV/m :490→ 365 MHz
- Rotate (N=12.045)– 20MV/m : 365 → 326.5 MHz
- Cool -325MHz -25 MV/m
  - p_{ref}=245 MeV/c

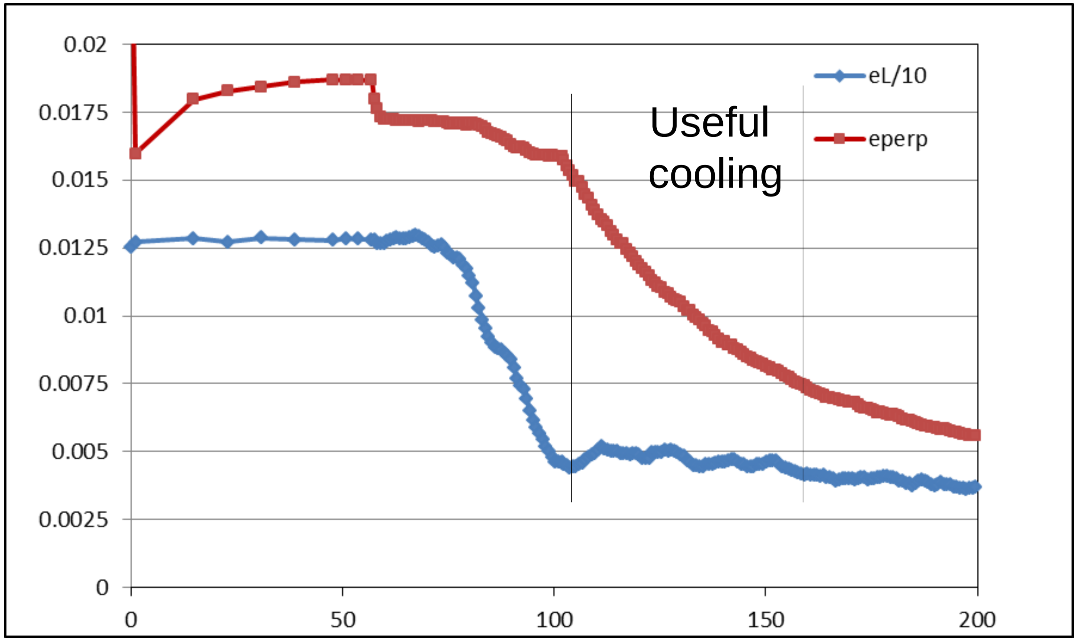
Simulation Results

- **Simulation obtains**
  - ~0.12 μ/p within acceptances
  - ~2014 MARS
  - 8 GeV proton source

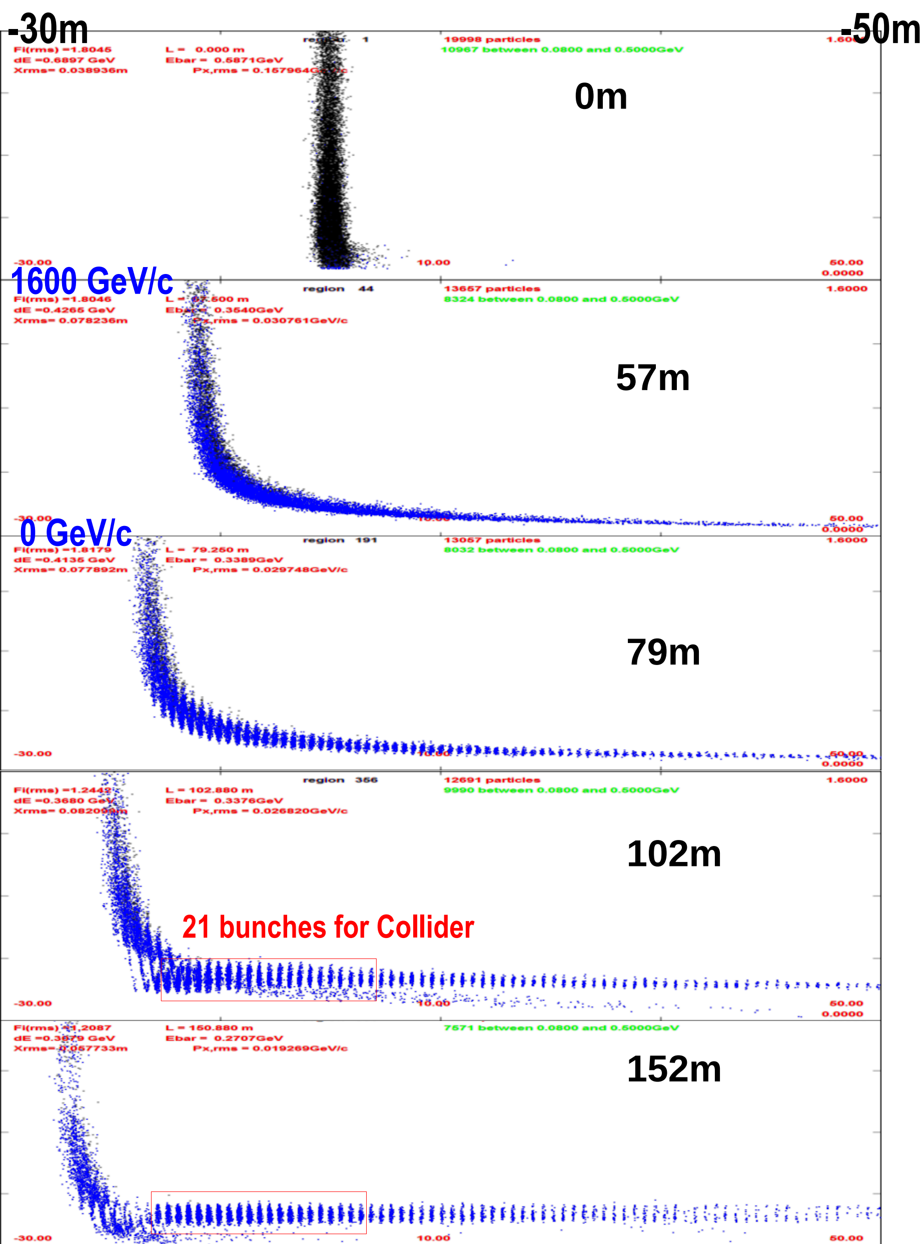


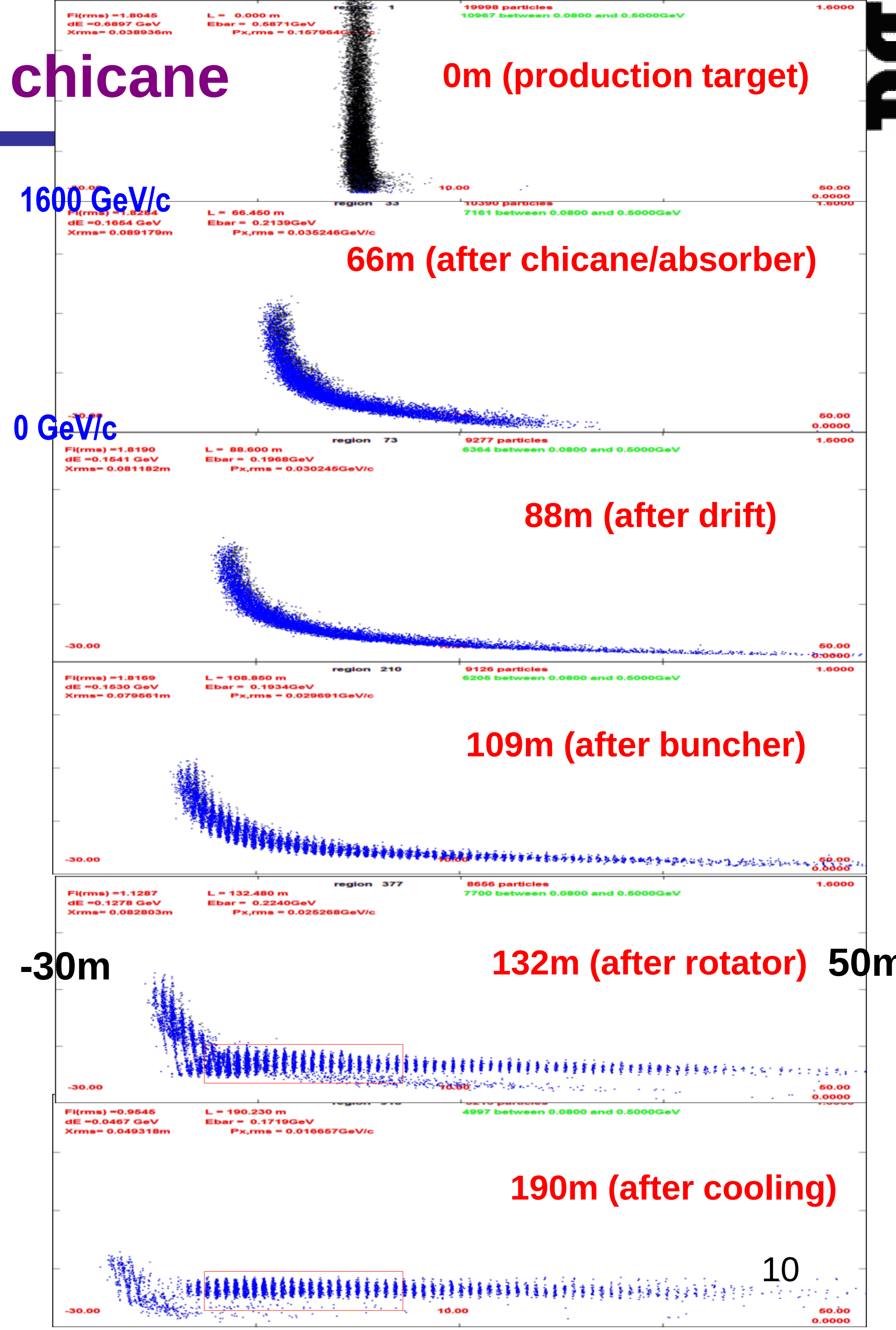
- **FOFO cooling**
  - Cools transversely
  - By factor of 3
    - ~10× in 6-D phase space





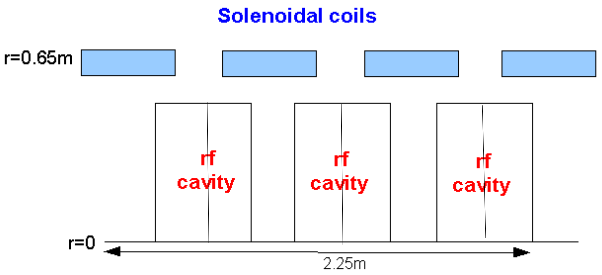
Compare without/with chicane

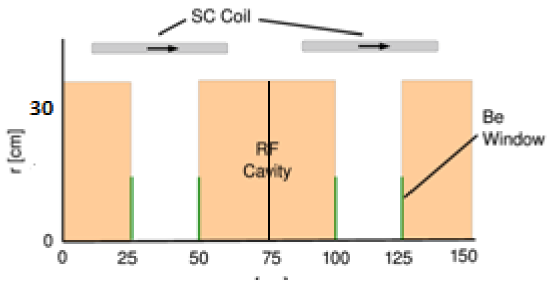




Rf Buncher/Rotator requirements

- **Buncher -21m**
  - **37** cavities (**14** frequencies)
  - **13** power supplies **(~1—3MW)**
- **RF Rotator -24m**
  - **64** cavities (**16** frequencies)
  - 20 MV/m, 0.25m
  - **~2 MW** (peak power) per cavity
- **Cooling System – 325 MHz**
  - 200 0.25m cavities (75m cooler), **25MV/m**
  - **~4MW** /cavity

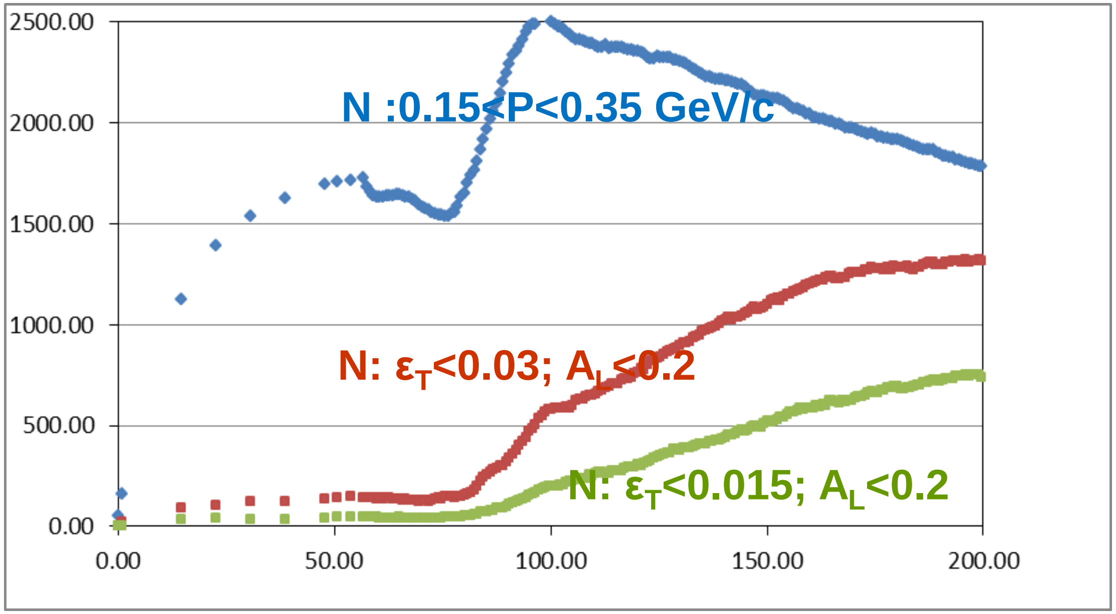


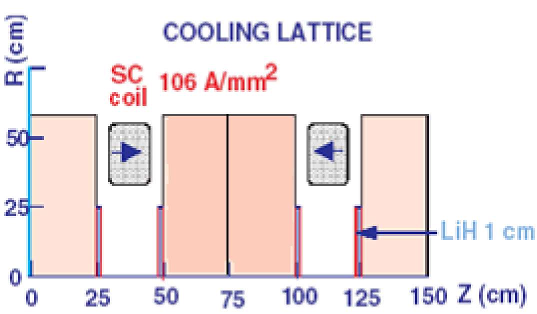


Front End section	Length	#rf cavities	frequencies	# of freq.	rf gradient	rf peak power requirements
Buncher	21m	42	484 to 365	14	0 to 16	0—1.34 MW/cavity
Rotator	24m	56	364to 326	16	20	~2.4 MW/cavity
Cooler	75m	200	325	1	25 MV/m	~3.7MW/cavity
Total df+bxr+rttr	~134m	93		30	~500MV	140MW
6-D cooler	126m	360	325 MHz	1	25 MV/m	~3.7 MW

Simulation Results

- Simulation obtains
  - ~0.12 μ/p within acceptances
  - ~2014 MARS
  - 8 GeV proton source
- FOFO cooling
  - Cools transversely
  - By factor of 3
    - ~10× in 6-D phase space





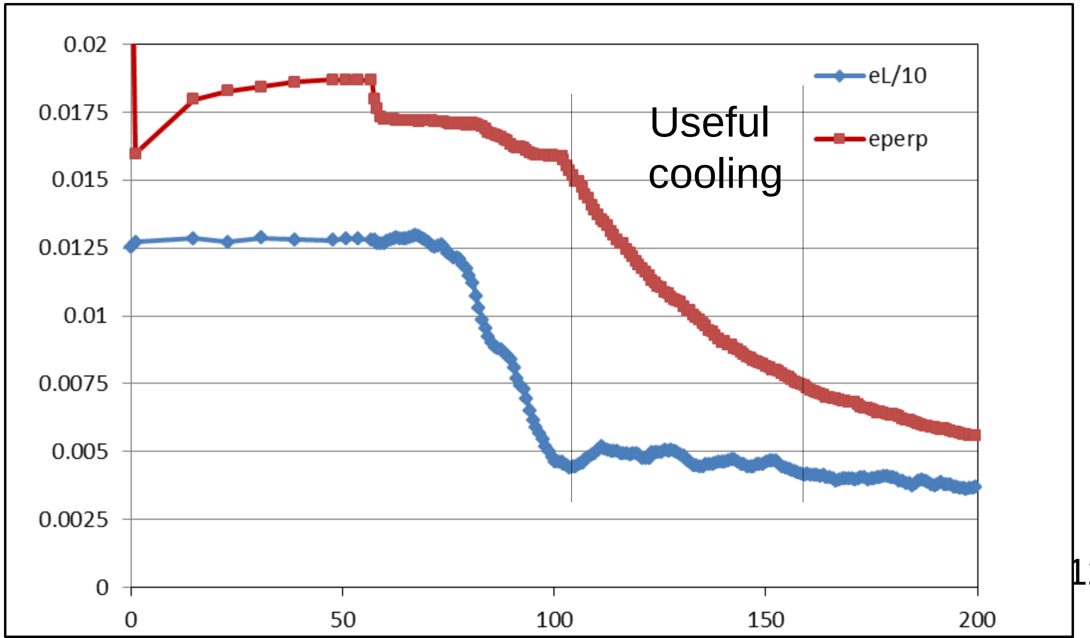


Table of rf cavities, power

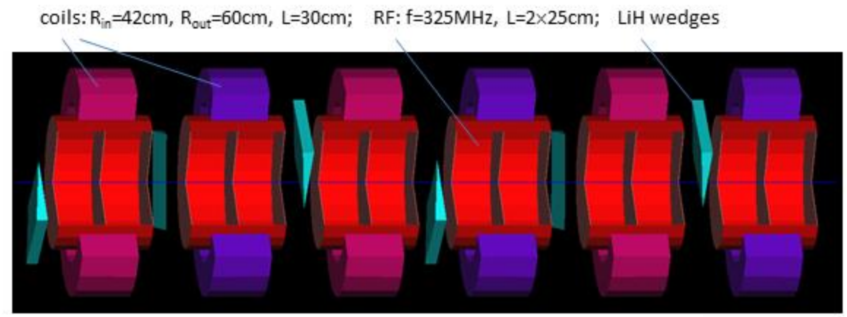
Buncher frequency (MHz)	Buncher gradient (MV/m)	RF Power /cavity (MW) (4 cavities)
488.42	0.80	0.001
478.17	1.33/1.87	0.007
466.42	2.40/2.94	0.015
455.24	2.94/3.48	0.053
444.56	4.55/5.08	0.086
434.45	5.62/6.15	0.13
424.70	6.64/7.23	0.19
415.39	7.76/8.30	0.27
406.49	8.83/9.37	0.35
397.97	9.90/10.4	0.46
389.80	11.2/11.5	0.58
381.95	12.0/12.6	0.71
374.42	13.1/13.7	0.86
367.18	14.2/14.8	1.0

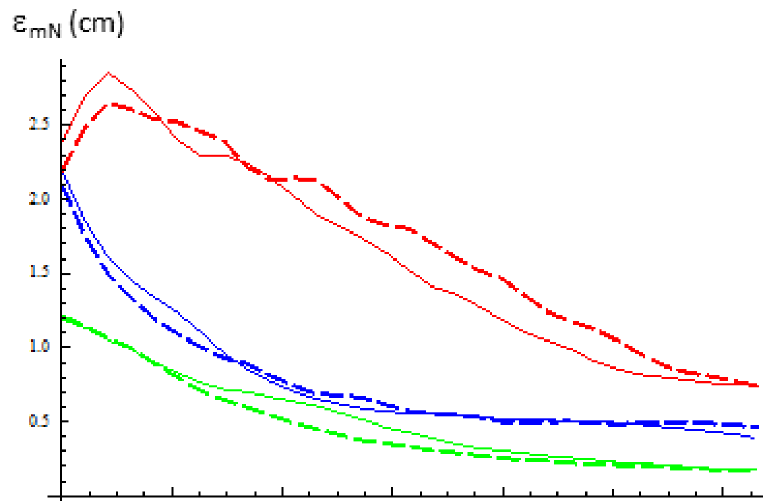
Rotator frequency (MHz)	Rotator gradient (MV/m)	RF Power /cavity (MW) (4 cavities)
361.67	20	2.06
355.70	20	2.1
350.60	20	2.14
346.23	20	2.19
342.48	20	2.23
339.27	20	2.26
336.54	20	2.28
334.23	20	2.30
332.27	20	2.31
330.62	20	2.32
329.35	20	2.33
328.30	20	2.34
327.50	20	2.35
326.92	20	2.36
326.54	20	2.37
326.37	20	2.37

First few buncher cavities are very low gradient;
should be removed, grouped or increased in strength

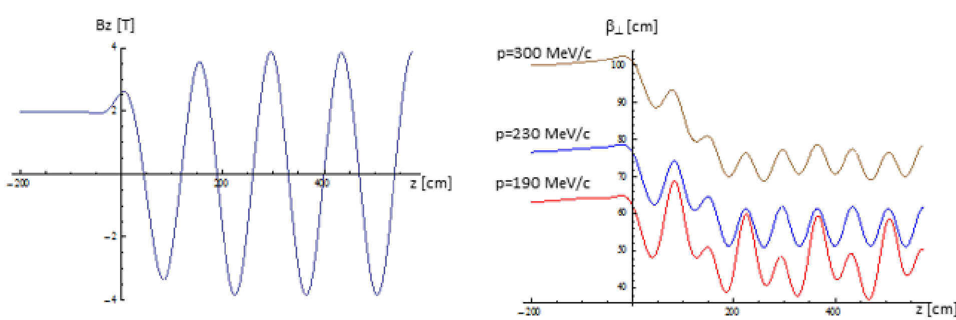
RF for 6-D Alexahin cooler

- **Initial version had transverse-only cooler**
- **Helical FOFO snake**
  - Alternating tilted solenoids
- **126 m long**
  - 2 cavities every 0.7m
  - 160 0.25m cavities 25 MV/m
- **Cools longitudinally and transversely**
  - $\varepsilon_L \times 1/3$, $\varepsilon_1 \times 1/6$, $\varepsilon_2 \times 1/5$
  - ~1/100 × (6-D cooling)
- **Cools both μ^+ and μ^-**



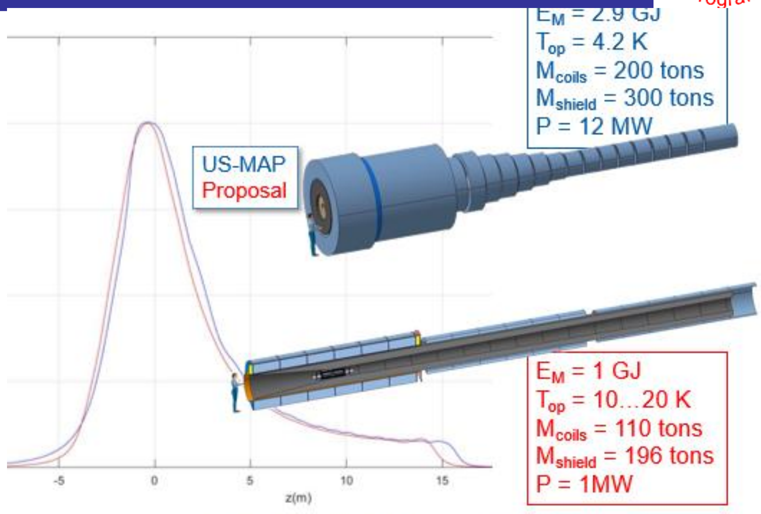


2. β⊥ matching to D. Neuffer's rotator



Some Optimizations (H. Sayed)

- Adiabatic transition from high-field to low field ?
  - 20T → 2 T in 15m?
  - Shorter transition is better
    - 5 m
  - Adiabatic

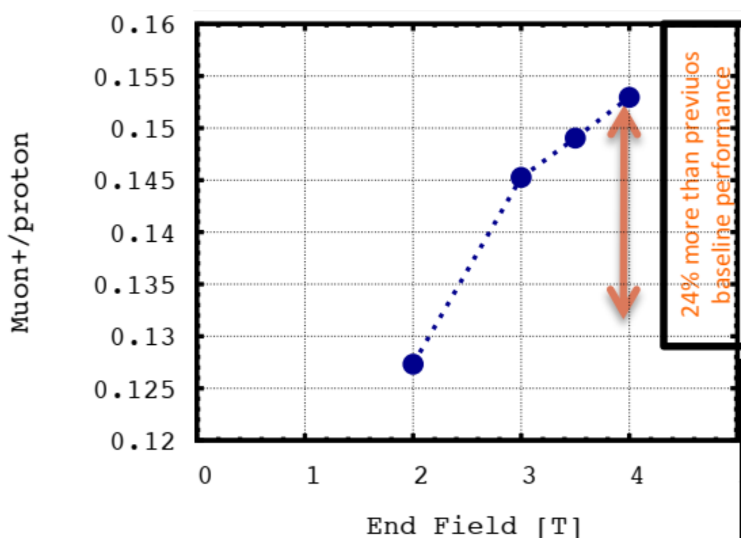


A. Portone, P. Testoni, J.Lorenzo Gomez (F4E)

- Focusing field in channel
  - 2T constant field in baseline

- More Field is better
  - 2→3→4 T

  - Alternating gradient ?

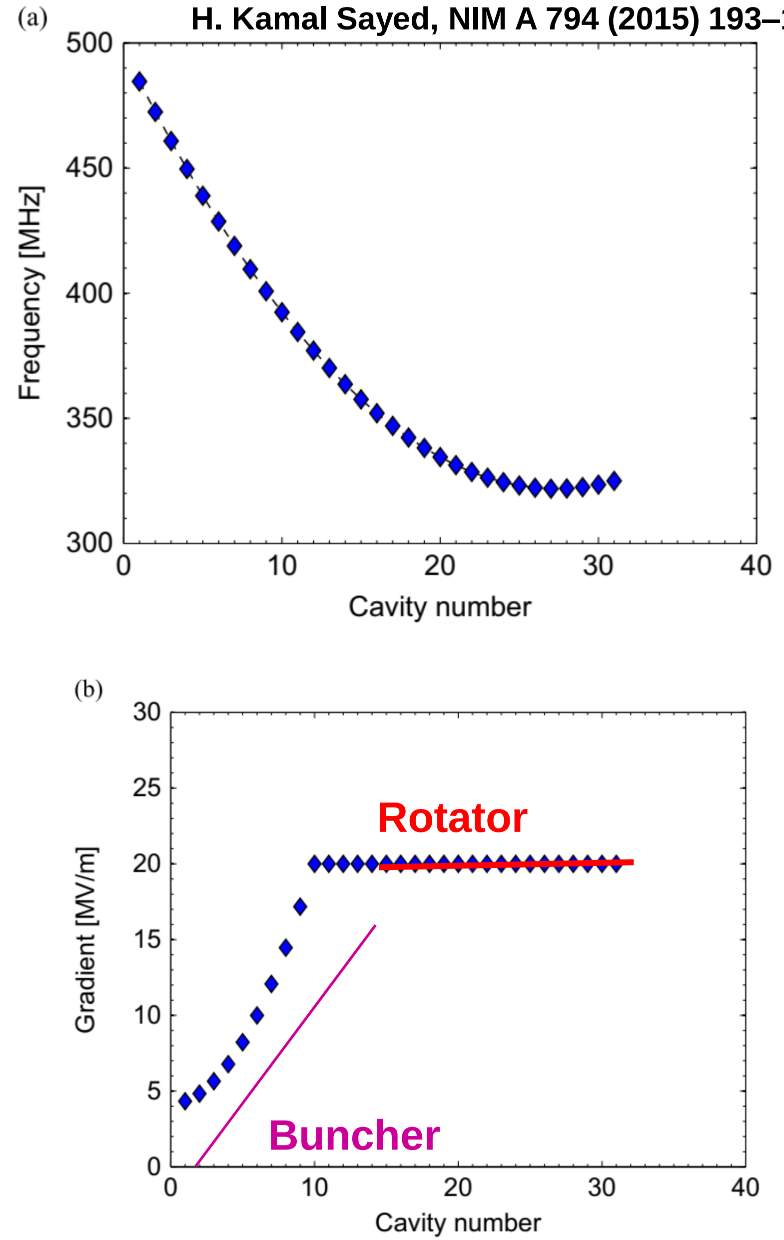


Optimization (H. Kamal Sayed)

- **Buncher +Rotator-31 cavity sets**
  - Changed frequency, rf gradient

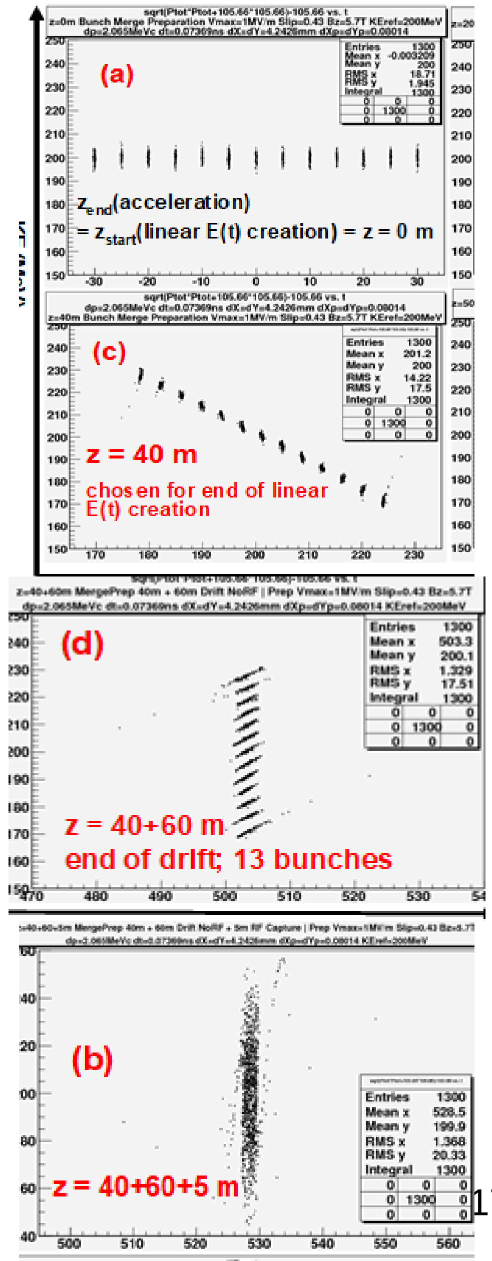
- **Optimized using NERSC supercomputer using evolutionary optimization algorithm, 100's of simulations**
  - Increase E_{rf} in Buncher
    - By ~4 MV/m
    - Higher gradient better
  - Rf reaches 325 MHz faster …
    - Could use shorter system ?
    - Could start further downstream

H. Kamal Sayed, NIM A 794 (2015) 193–199



Time –reversed version

- **Bunch-Recombiner**
  - Start with train of bunches
    - Cooled beam after initial cooler
  - Vernier rf to bunch train
- **Can recombine bunch train after initial cooler to single bunch for final cooler**
- **Looks cleaner than Front-end**
  - Starts with cold muons-only
  - C. Yoshikawa, C. Ankenbrandt, D. Neuffer, K. Yonehara
  - IPAC2012, TUPPD013
  - MuCOOL note 548 (2010)



Summary Front End Design

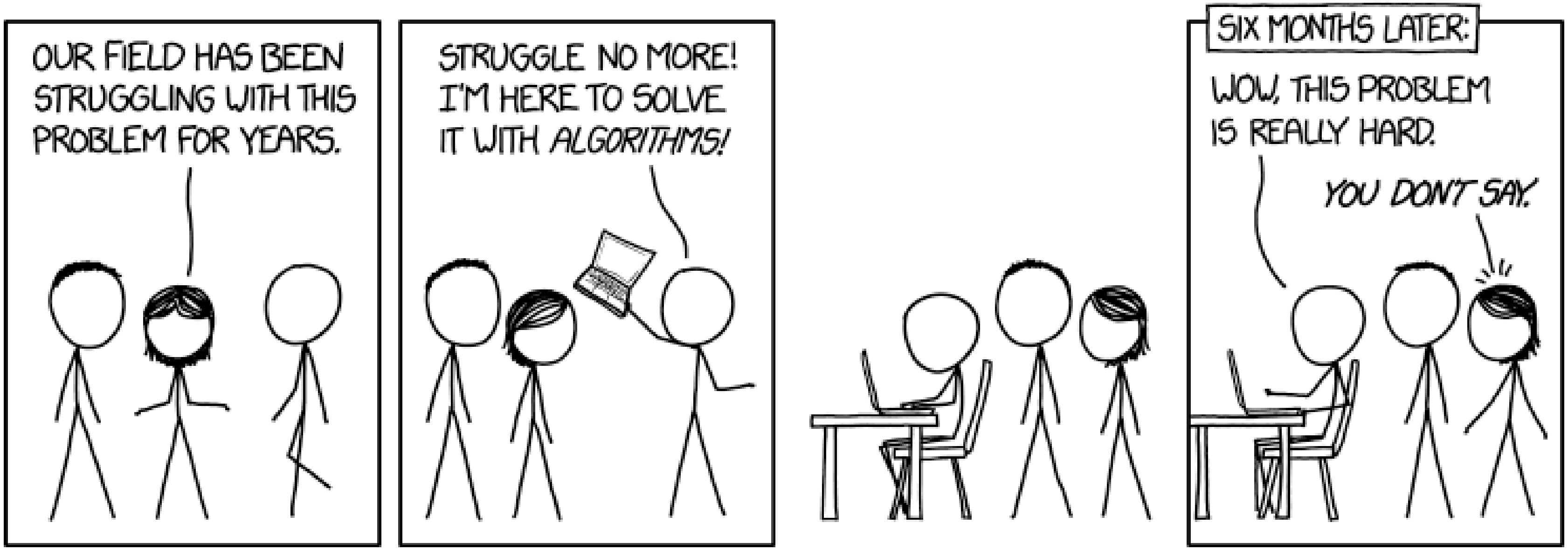
- **Buncher/Rotator scenario parameters developed semiempirically**
  - Guided by simulations, extrapolation, intuition
- **Neutrino Factory Scenarios, Muon Collider scenarios done similarly**
- **Tweaked to include chicane absorber**
- **Should develop less empirically ??**

Scenario Construction

- **Parameters available in ICOOL constrain method**

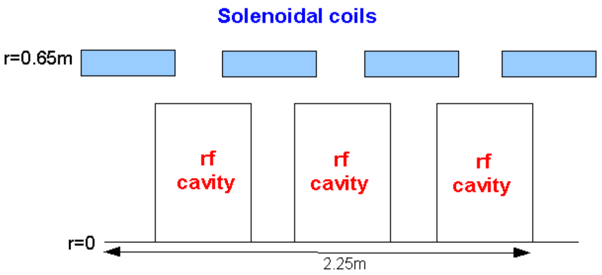
- **Start with final rf frequency**
  - 325 MHz
- **Select 2 reference particles**
  - Initial momentum 250 MeV/c / 180 MeV/c
- **Select number of bunches**
  - n = 12
- **Buncher length, rf gradients**
  - 21 m 0→16 MV/m
- **Rotator length, rf gradient**
  - N =12.05, 24m, 20 MV/m
  - Icool parametrization not ideal
    - Ref particle accelerations → 245 MeV/c
- **Adjust lengths to match**
- **Match to cooling**

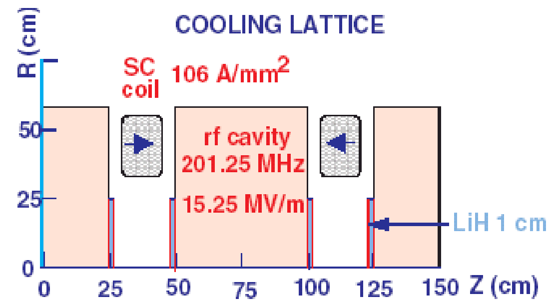
Thank you for your attention



IDS RF requirements (200 MHz system)

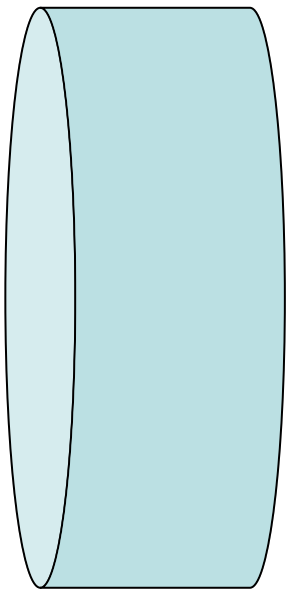
- **Buncher**
  - **37** cavities (**13** frequencies)
  - **13** power supplies **(~1—3MW)**
- **RF Rotator**
  - **56** cavities (**15** frequencies)
  - 12 MV/m, 0.5m
  - **~2.5MW** (peak power) per cavity
- **Cooling System – 201.25 MHz**
  - 100 0.5m cavities (75m cooler), **15MV/m**
  - **~4MW** /cavity

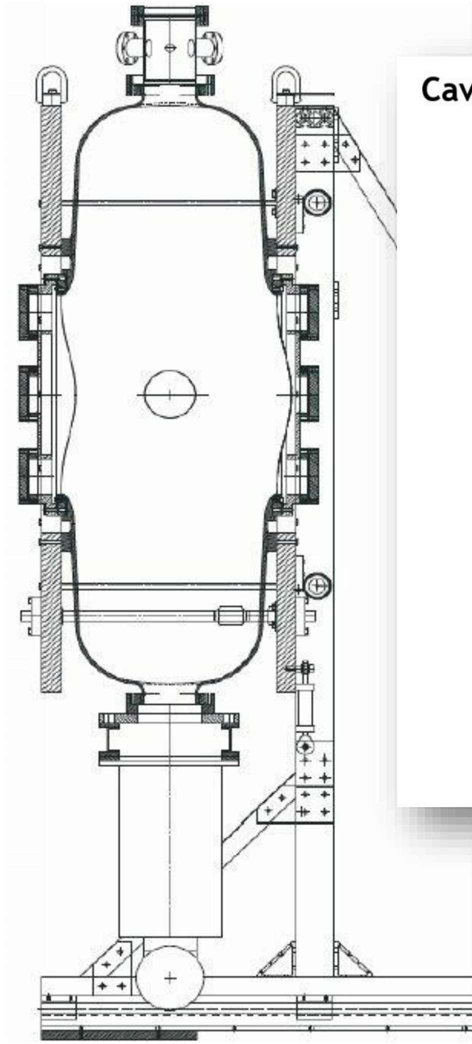


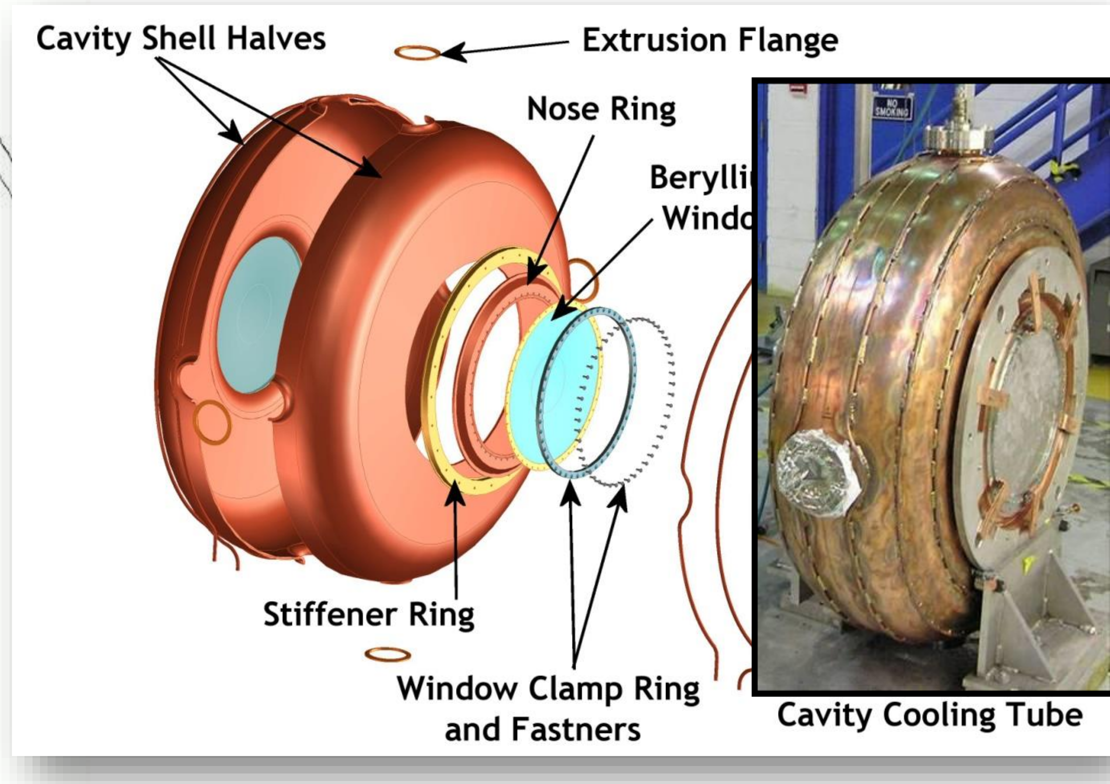


Front End section	Length	#rf cavities	frequencies	# of freq.	rf gradient	rf peak power requirements
Buncher	33m	37	319.6 to 233.6	13	4 to 7.5	~1 to 3.5 MW/freq.
Rotator	42m	56	230.2 to 202.3	15	12	~2.5MW/cavity
Cooler	75m	100	201.25MHz	1	15 MV/m	~4MW/cavity
Total drift)	~240m	193		29	~1000MV	~550MW

Rf cavity







Concept design construction operation

MAP rf properties (~ Pillbox; ~325 MHz)

- **Assume pillbox, Cu walls**
  - Compare with MICE rf
- **Q = ~40200**
  - a=0.353m, L=0.25, f=325MHz
  - T_t=0.884, R_s=0.00467
- **P_0 = 3.7 MW at 25MV/m**
  - U_0 = 23.43J, **T_{fill} = 63.7µs**

$$Q_0 = \frac{2.405\, Z_0}{2(\pi f_{rf}\, \rho \mu_0)^{\frac{1}{2}}(1+\frac{a}{L})}$$

ρ_{Cu} =1.68*10^{-8} ohm-m

$$R_s = \sqrt{\rho_{Cu} \pi \mu_0 f_0}$$

$$U_0 = \pi \varepsilon_0 L\, a^2\, 0.52^2 \frac{E_0^2}{2}$$

$$P_0 = \frac{\pi R_s\, 0.519^2\, E_0^2\, a(L+a)}{Z_0^2}$$

$$T_{fill} = Q_0 \frac{\ln(2.0)}{\pi\, f_{rf}}$$

$$T_t = \frac{\sin\left(\frac{\pi f_{rf} L}{c}\right)}{\frac{\pi f_{rf} L}{c}}$$