Imperial College London

Introduction to future facilities II

Neutrino Factory

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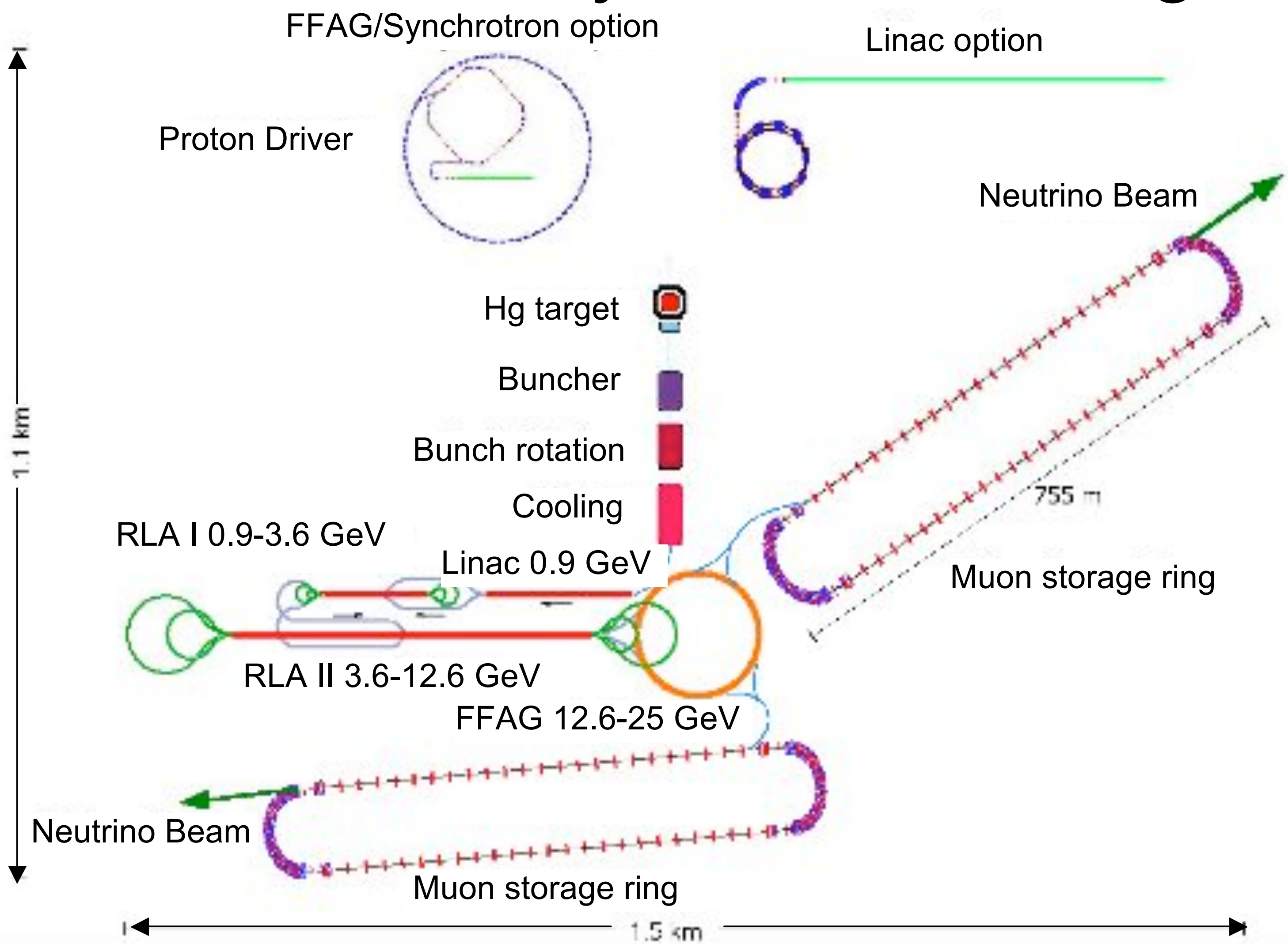
Outline

- Neutrino factory baseline design
- Proton driver
- Target
- Pion capture and Decay
- Phase rotation and cooling
- Fast acceleration
- Decay rings
- Summary

Historical development

• US studies 1, 2 and 2a	
• CERN Design study	
• JPARC Design study	‘90
• BENE	FP6
• ISS-NF	2005-2006
• IDS-NF	since 2007
• EUROν	2008 (summer)

Neutrino factory baseline design



Proton driver Parameters

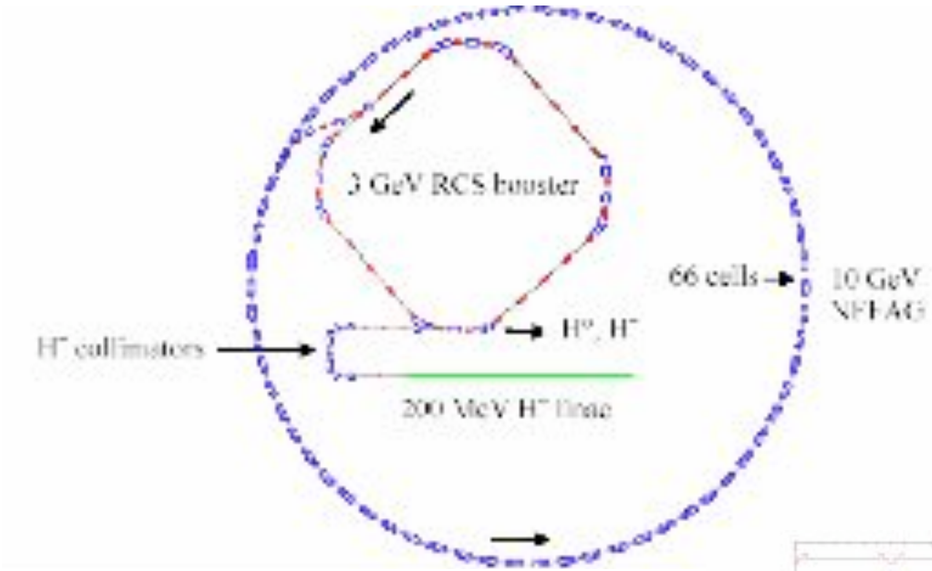
Required beam parameters on target

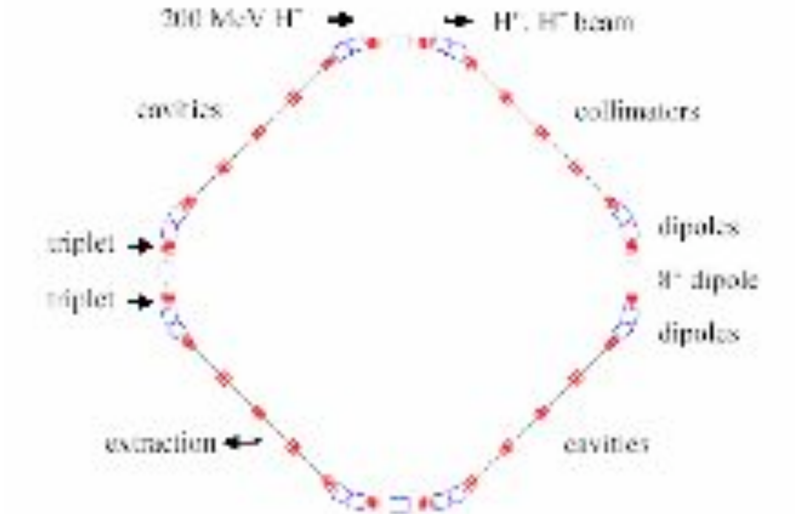
Parameter	Value
Average beam power (MW)	4
Pulse repetition frequency (Hz)	50
Proton energy (GeV)	10±5
Proton rms bunch length (ns)	2±1
No. of proton bunches	3 or 5
Sequential extraction delay (μs)	≥17
Pulse duration, liquid-Hg target (μs)	≤40

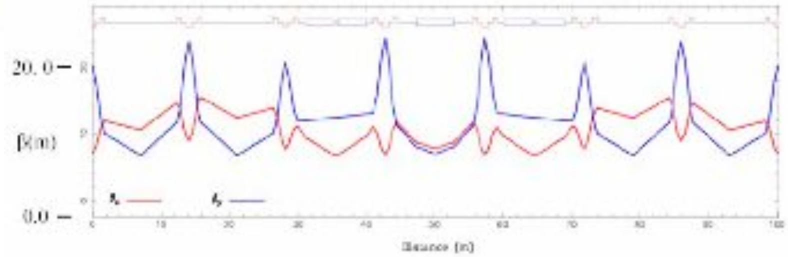
Proton driver options

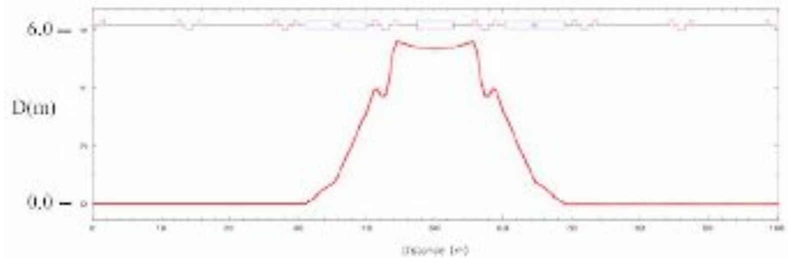
- **an H^- linac with a 50-Hz booster RCS and a 50-Hz non-scaling, non-linear, fixed-field alternating gradient (NFFAG) driver ring**
- an H^- linac with pairs of 50 Hz booster and 25 Hz driver synchrotrons (RCS)
- an H^- linac with a chain of three non-scaling FFAG rings in series
- an H^- linac with two slower cycling synchrotrons and two holding rings
- **a full energy H^- linac with an accumulator and bunch compression ring(s)**

The Linac, RCS, NFFAG option

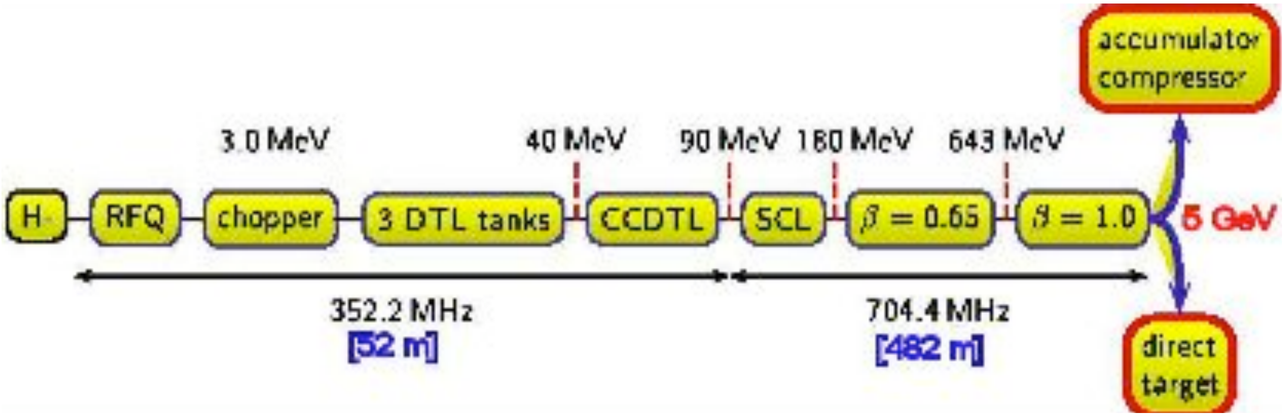






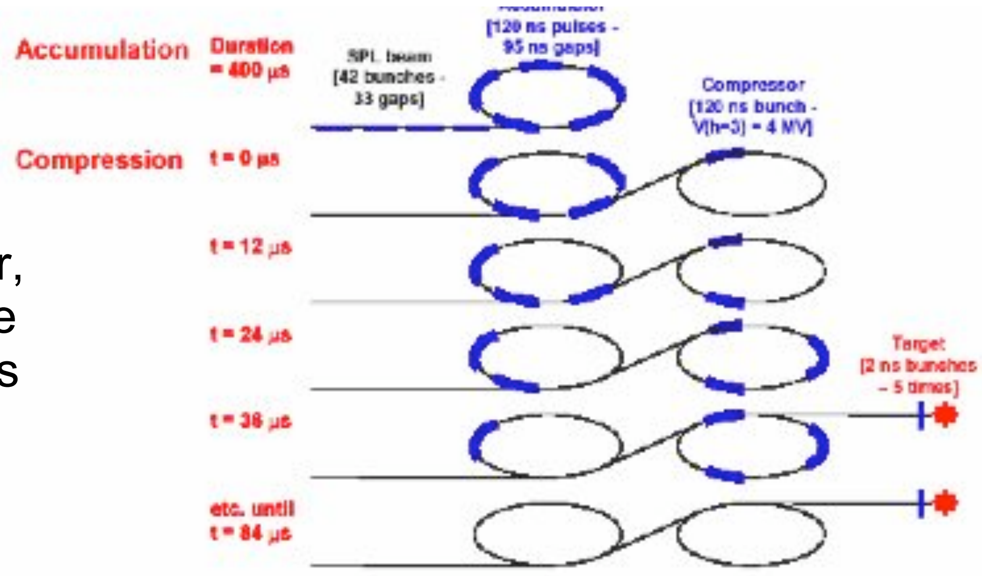


Linac/compressor ring option at CERN



Beam power (MW) 4
Repetition rate (Hz) 50
Peak current (mA) 40
Pulse duration (ms) 0.4

The time structure of the chopped linac beam is chosen such that the beam circulating in the accumulator forms 5 bunches. At the end of accumulation, bunches are successively sent to the compressor ring. Inside the compressor, bunches rotate in the longitudinal phase plane. After 36 turns, the first bunch has a minimal length of approximately 2 ns, whereupon it can be ejected to the target. The following bunches are then successively ejected.



3 Proton (H-) Front ends are under construction:

FNAL - HINS Injector for Project X :60 MeV RFQ/Chopper/Linac

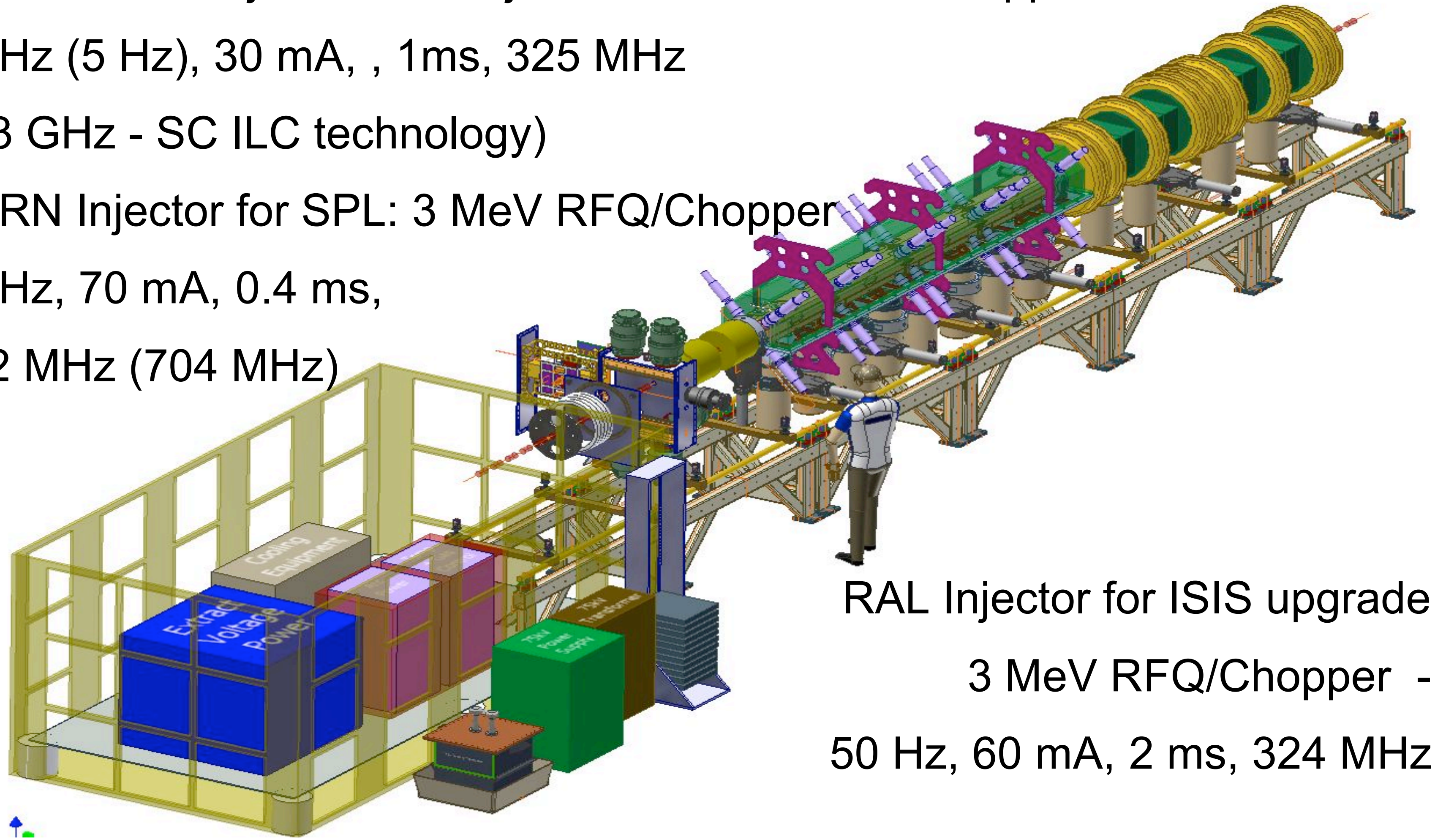
50 Hz (5 Hz), 30 mA, , 1ms, 325 MHz

(1.3 GHz - SC ILC technology)

CERN Injector for SPL: 3 MeV RFQ/Chopper

50 Hz, 70 mA, 0.4 ms,

352 MHz (704 MHz)



RAL Injector for ISIS upgrade

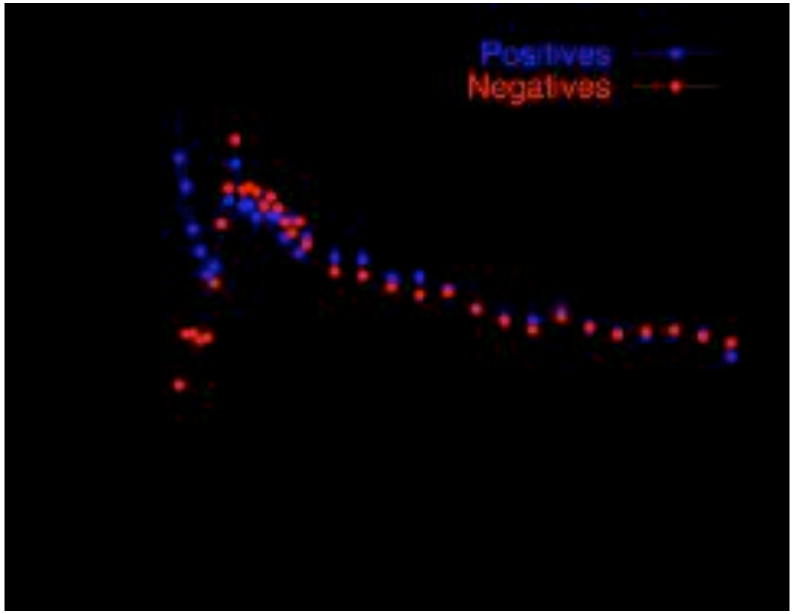
3 MeV RFQ/Chopper -

50 Hz, 60 mA, 2 ms, 324 MHz

Target - Pion / muon yield

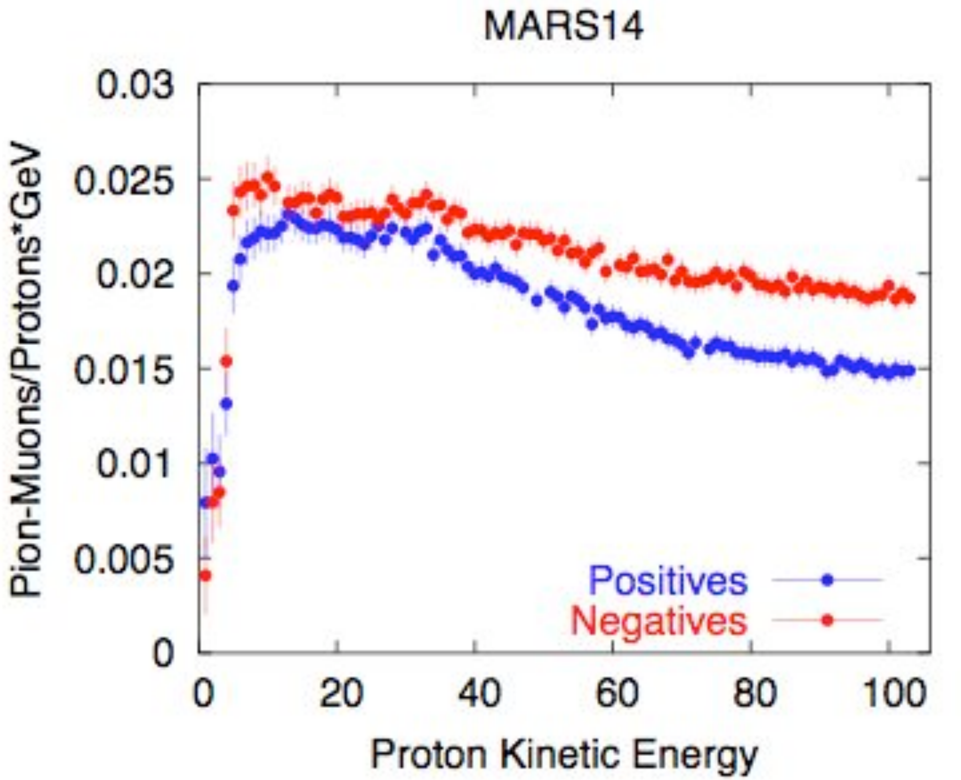
Carbon target

maximun yield ~ @ 10 GeV

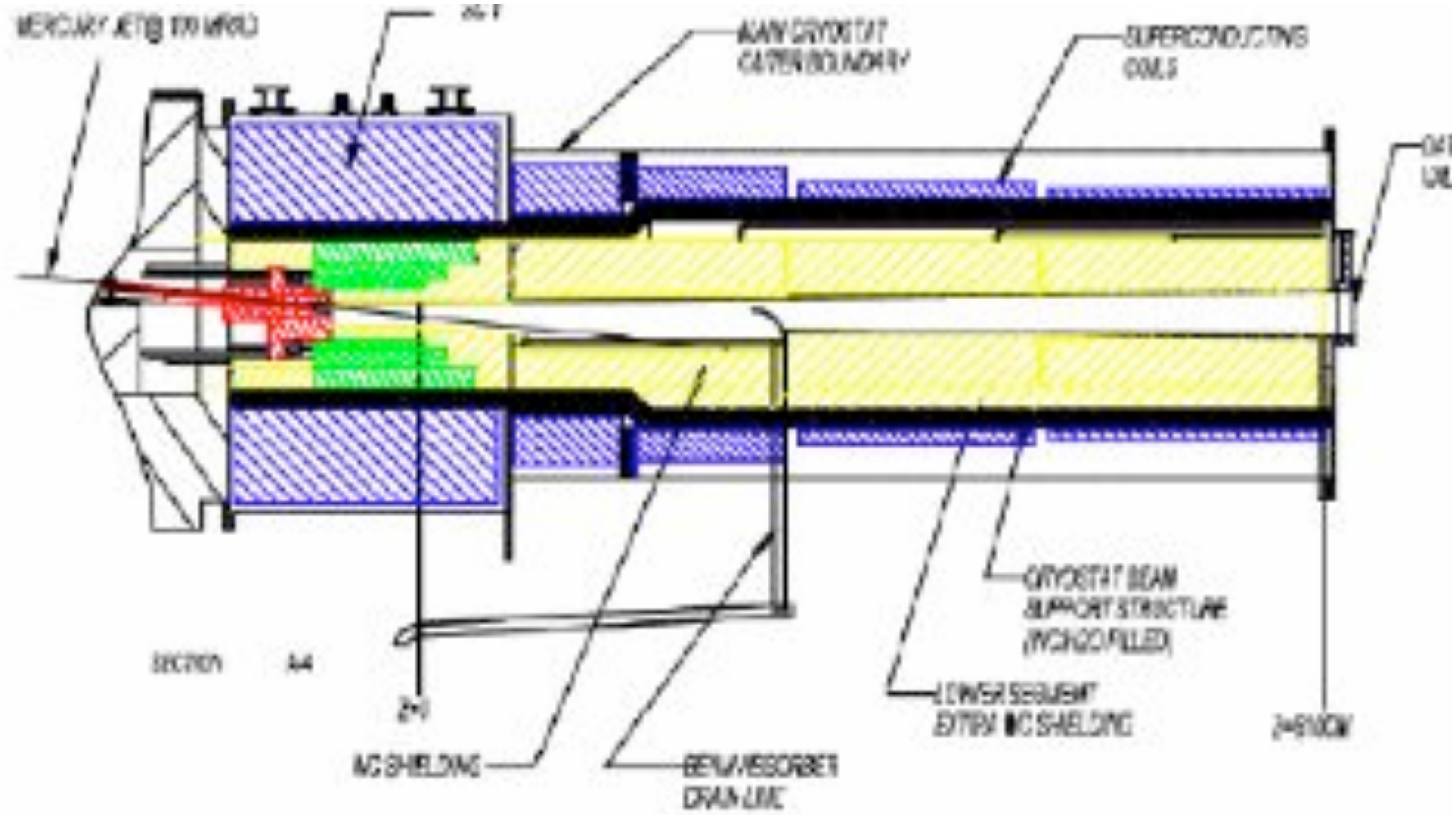


Mercury target

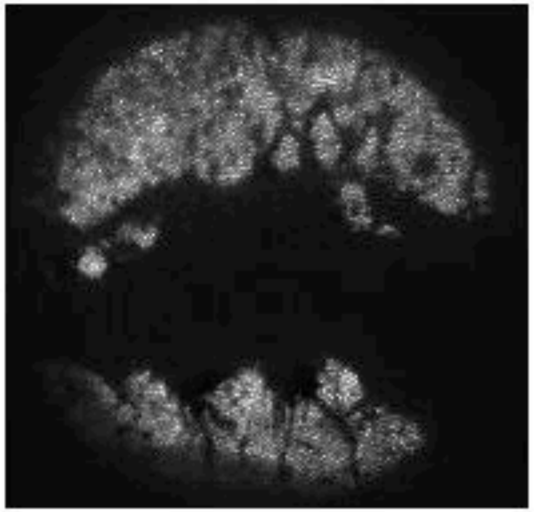
maximun yield ~ @ 10 GeV



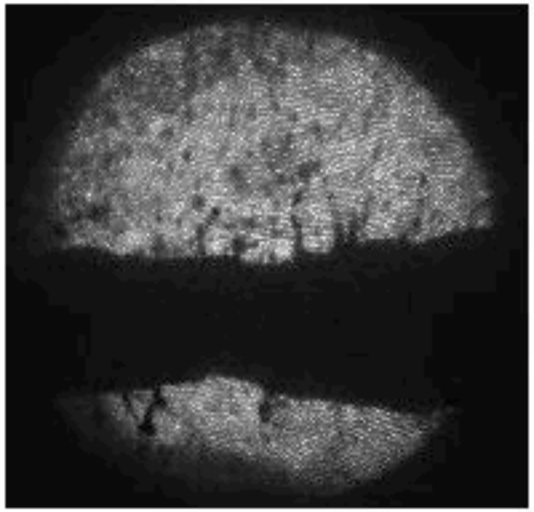
Liquid mercury target - Merit experiment



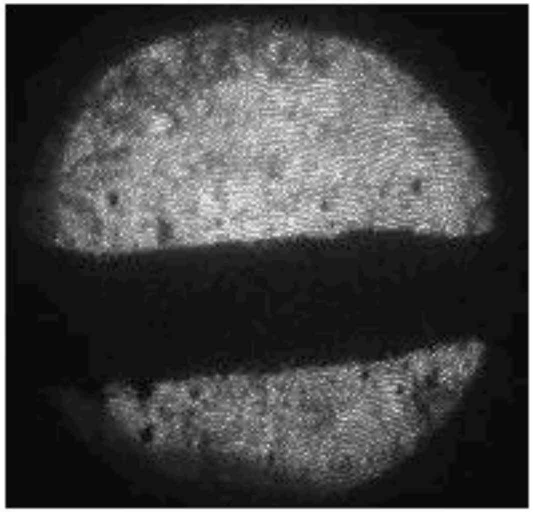
Mercury Target - 4+4 TP illumination
Merit results



Single Turn Extraction
➔ 0 Delay



4TP Probe extracted on subsequent turn
➔ 3.2 μs Delay



4TP Probe extracted after 2nd full turn
➔ 5.8 μs Delay

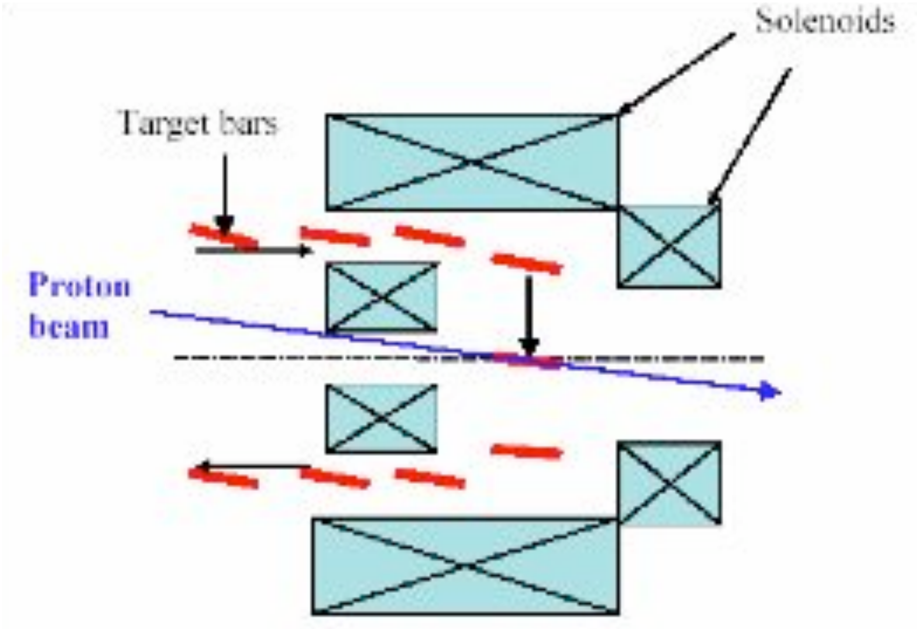
Solid targets

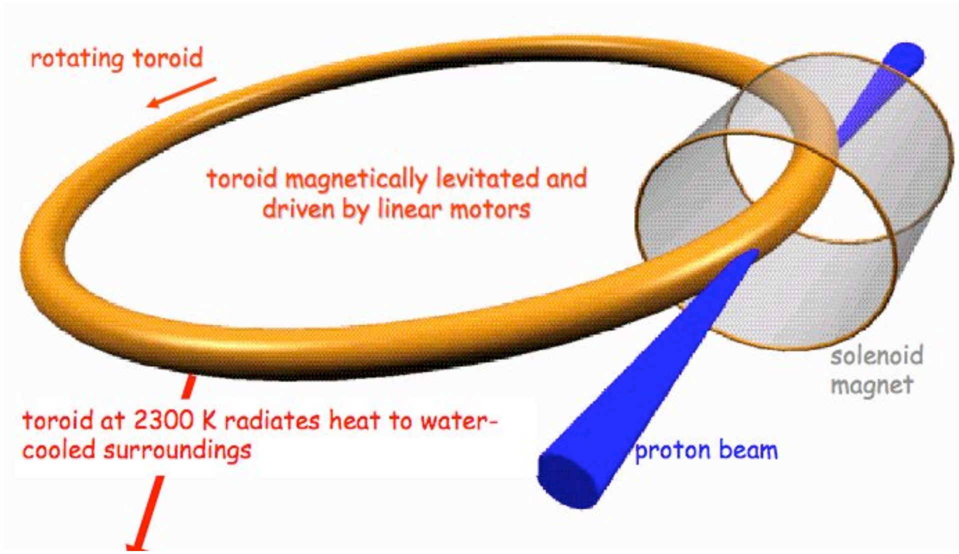
Optimisation :

Target material

Target length

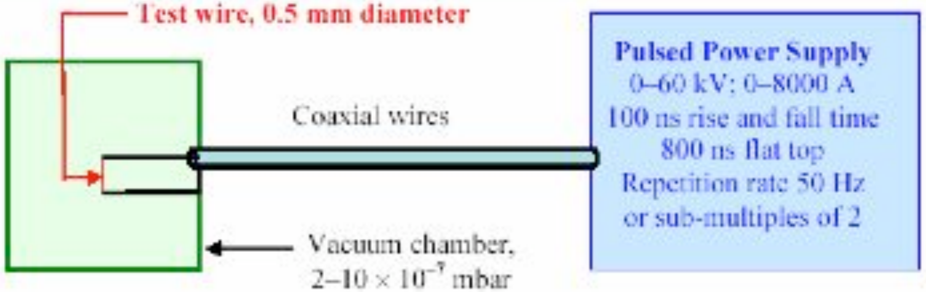
Target diameter

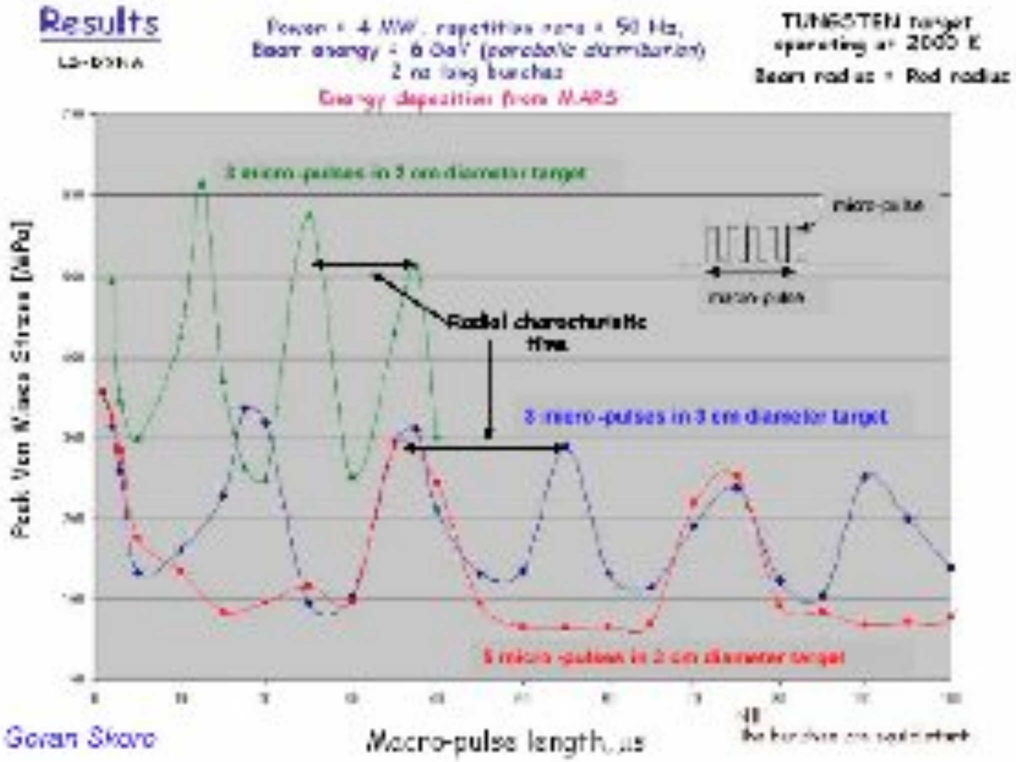


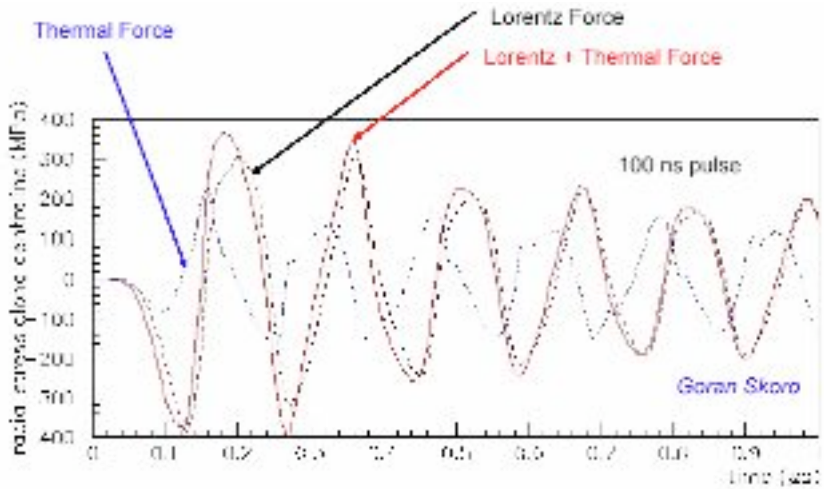


Solid Targets and Stress

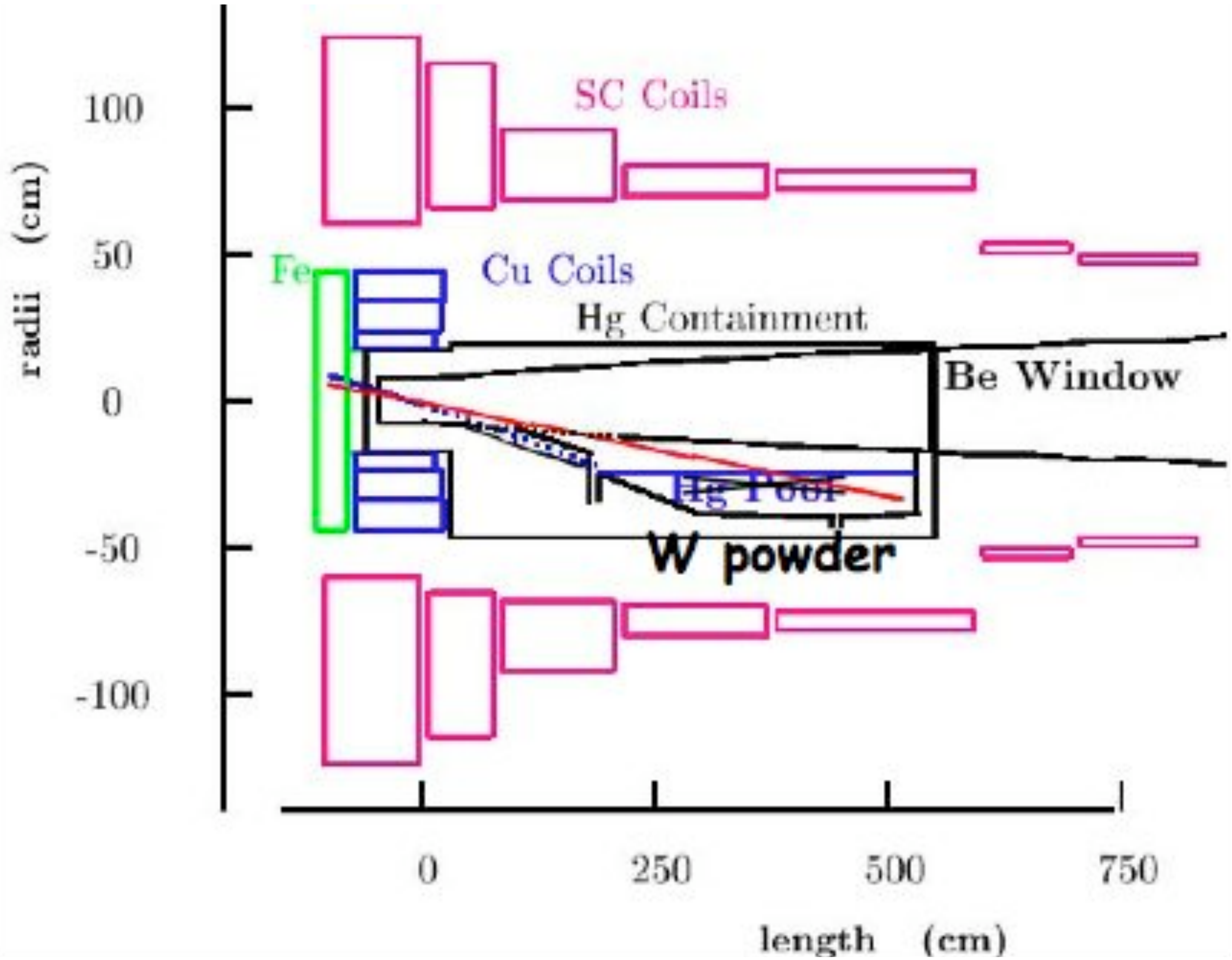
Number of pulses on target and number of Protons per pulse to be optimized



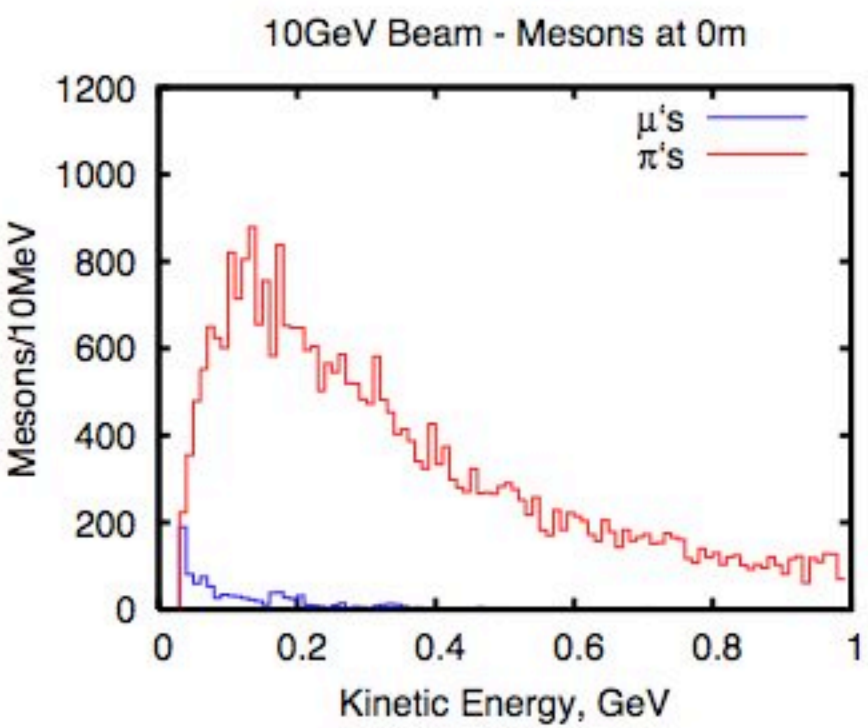


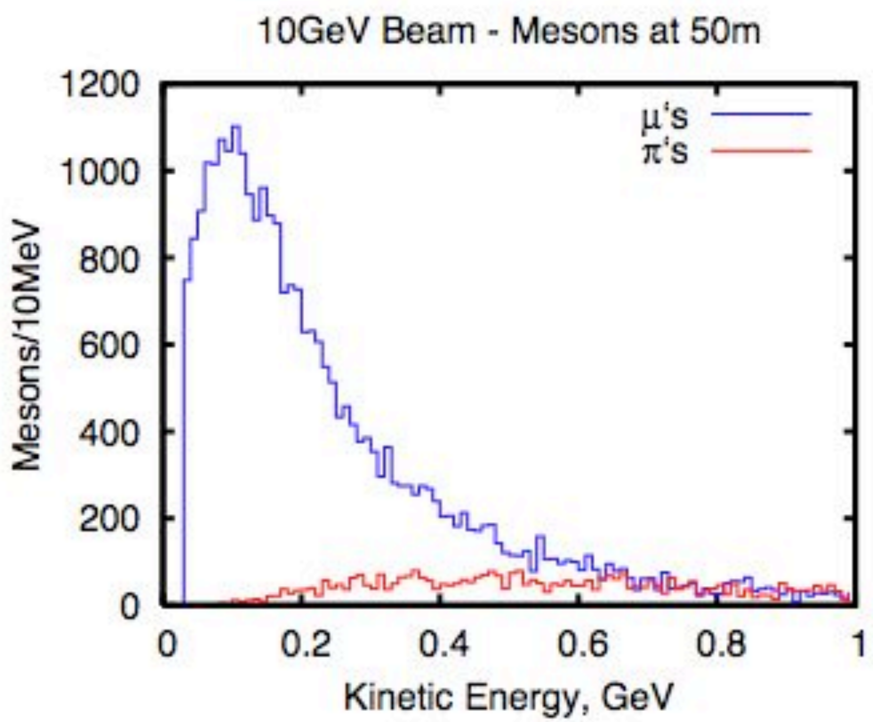


Target - other ideas



Pion decay : MARS simulation results



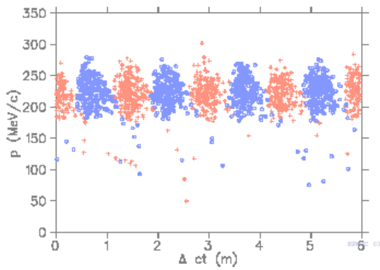


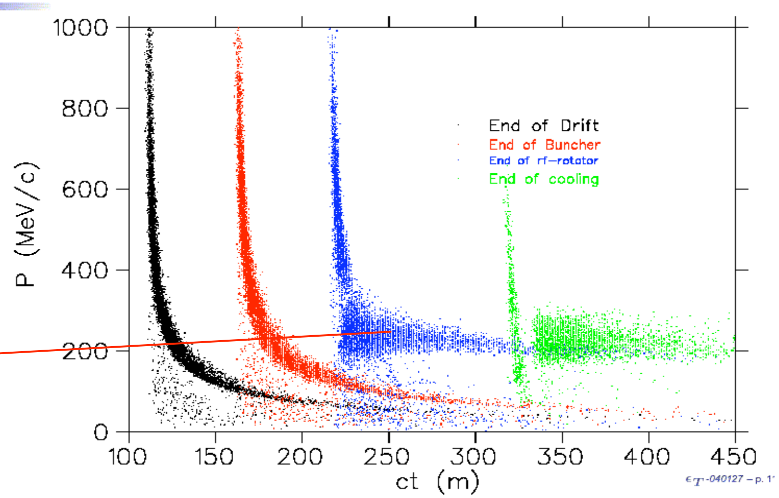
Phase rotation and cooling

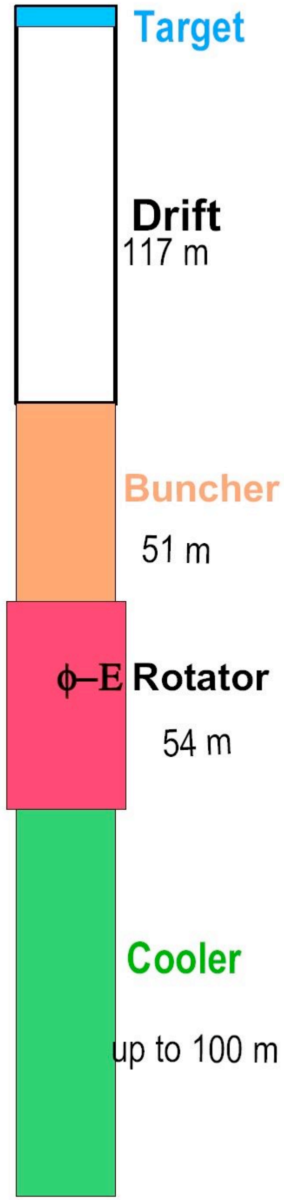
Drift –π→μ decay

- beam develops φ-E correlation

- Buncher
  - Form μ-beam into string of ~200 MHz bunches
  - ~100m, ~70 bunches
- **φ-E Rotator** -rotate bunches to ~equal energies
  - Adiabatic
- **Cooler**
  - Transverse cooling



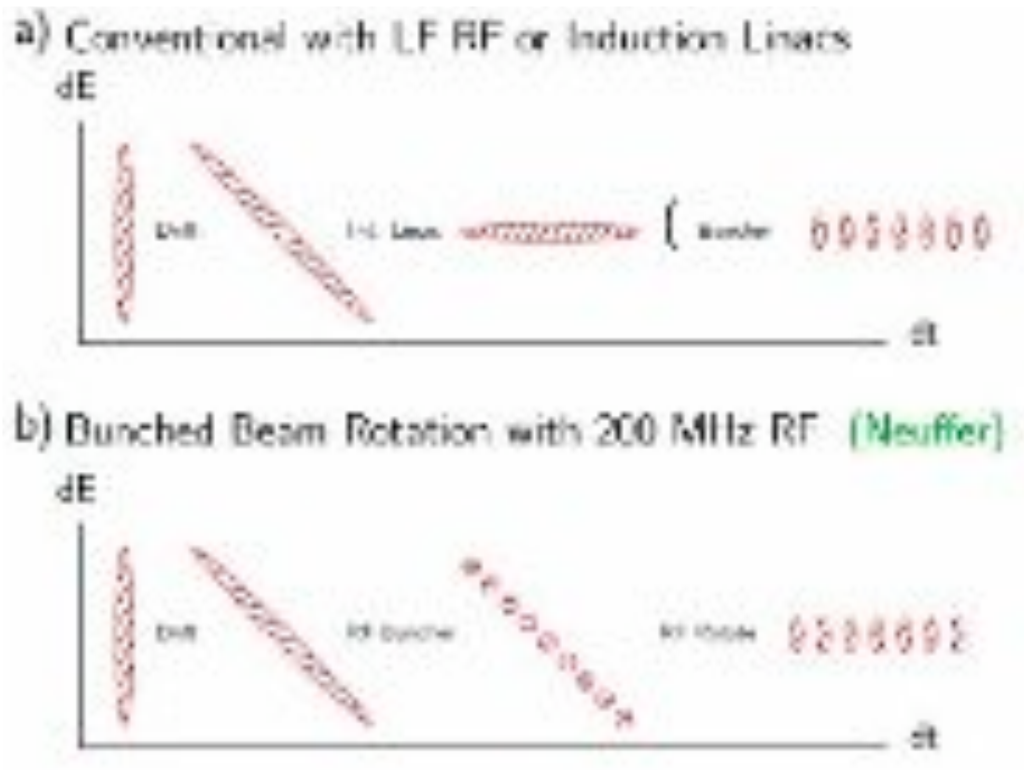




Phase rotation

Low RF frequency : large longitudinal acceptance but low RF voltage

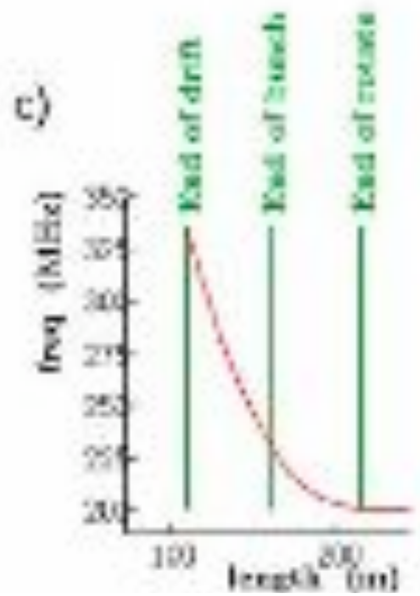
High RF frequency : low longitudinal acceptance but larger RF voltage



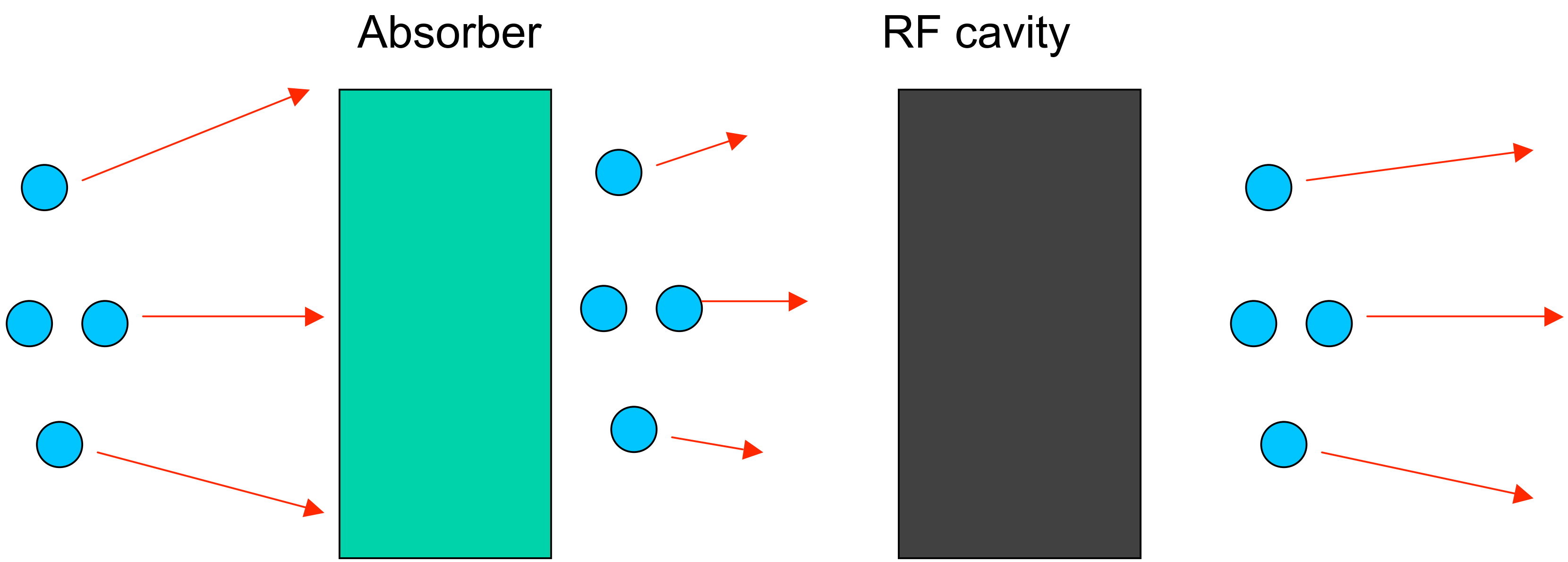
JParc : 5MHz

CERN : 44/88 MHz

US study II : 201 MHz (at end)



Muon ionisation Cooling



3 D energy loss in Absorber material (Hydrogen)

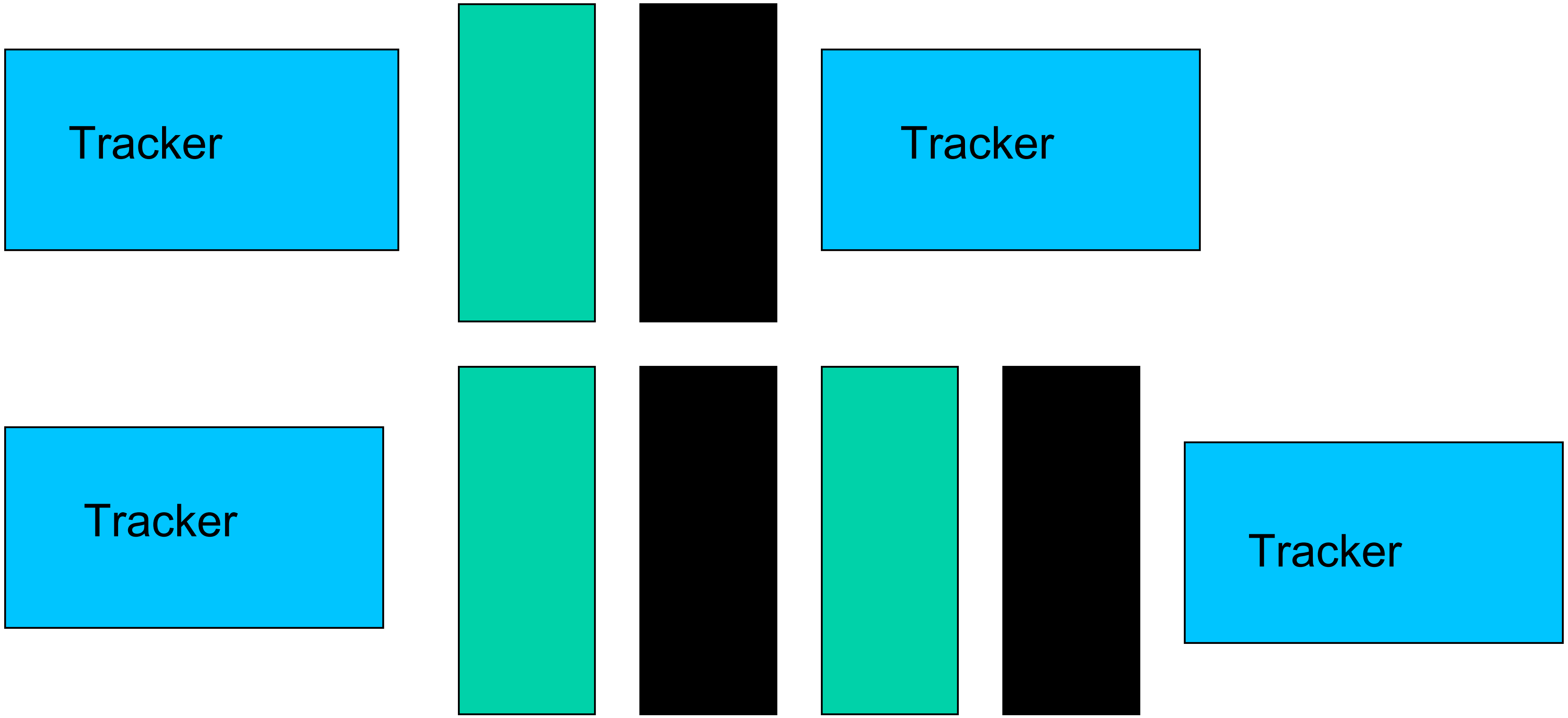
Recovery of longitudinal energy but use of RF cavity

Final transversal emittance defined by costs and equilibrium due to scattering

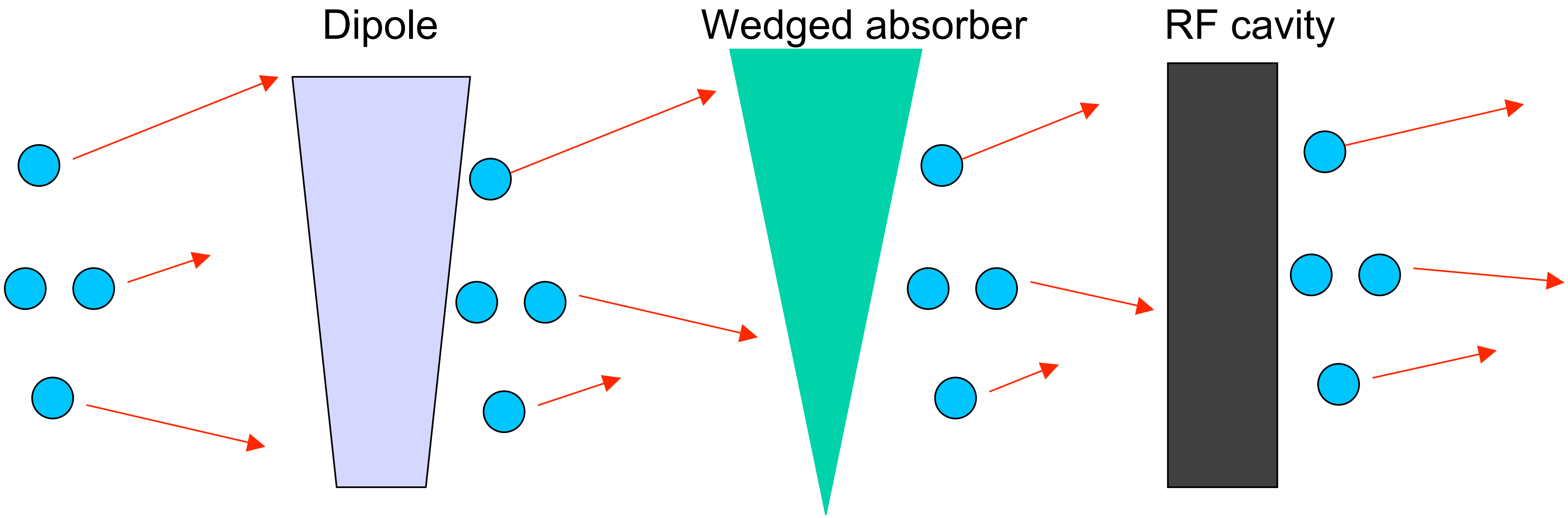
Trade off (costs) between cooling and increasing accelerator acceptance

The Mice experiment at RAL

To measure the cooling efficiency a short section of a cooling channel is under construction. A Target dips into the halo of the circulating ISIS beam and produces Pions which are the extracted and decay to Muons. The beam emittance is measured (better than 1%) before and after the cooling by the use of scintillation fiber trackers.



3 D cooling



Dispersive elements (dipoles) and wedged absorbers allow also longitudinal cooling.

=> Ring cooler, Helical cooling channel

RF cavities in magnetic fields

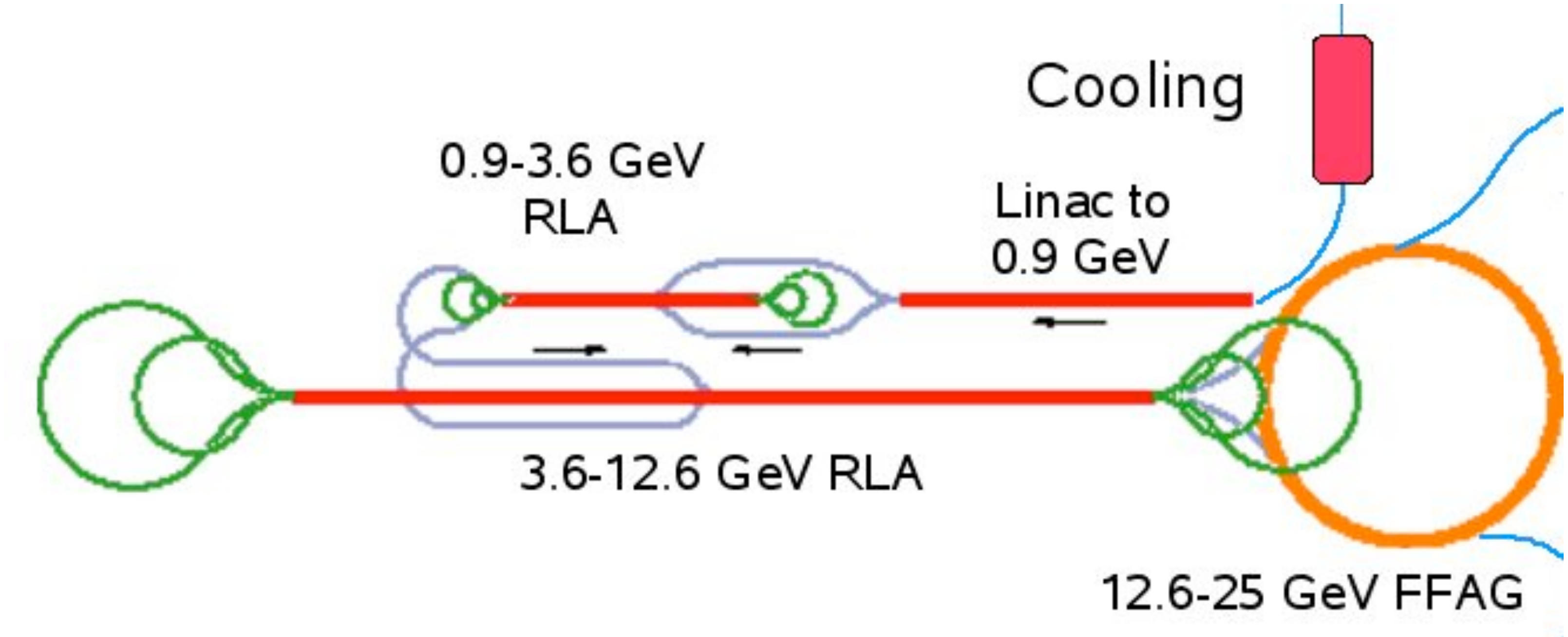
Problem :

To contain the beam within the acceptance of the cooling channel transversal focussing (solenoids 5T) is required together with an field gradient in the cavities of ~ 15 MV/m

High magnetic fields degrades the available accelerating voltage (dark currents, RF breakdown) to below 10 MV/m and causes damage of RF cavities

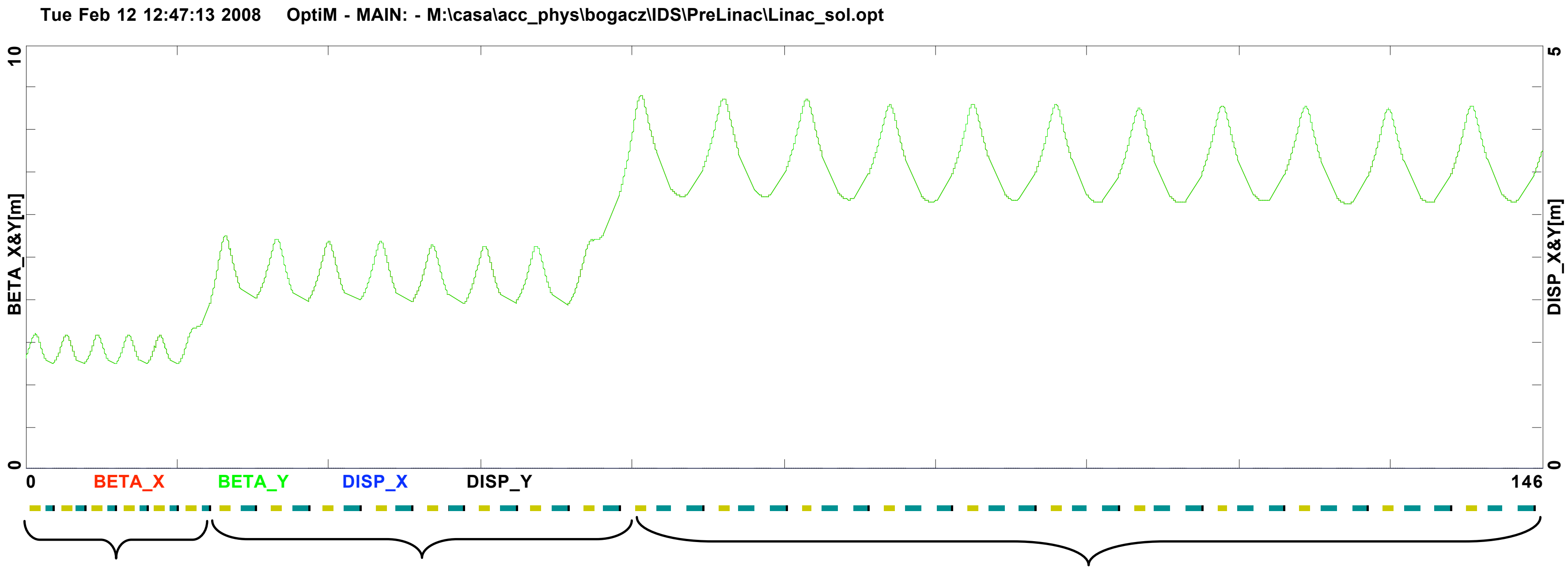
Extensive experimental program underway to investigate this problem (surface roughness, coating, magnetic isolation)

Fast acceleration



- Linear Pre-accelerator (244 MeV to 900 MeV)
- RLA I – 4.5 pass, **0.6 GeV/pass**, (0.9 GeV to 3.6 GeV)
- RLA II – 4.5 pass, **2 GeV/pass** (3.6 GeV to 12.6 GeV)
- Non scaling FFAG - 8 revolutions (12.6 GeV to 25 GeV)

SC Linac - 201 MHz - 244 to 909 MeV



6 short cryos

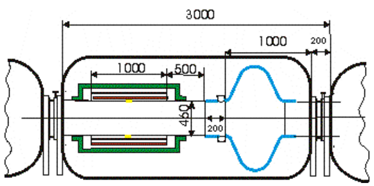
15 MV/m

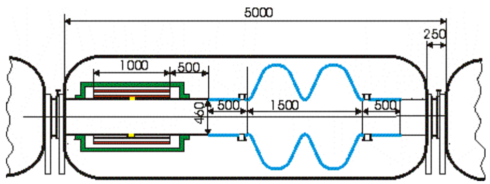
8 medium cryos

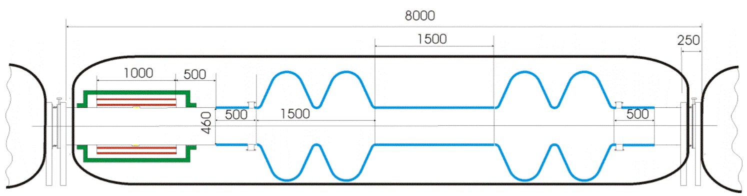
17 MV/m

11 long cryos

17 MV/m





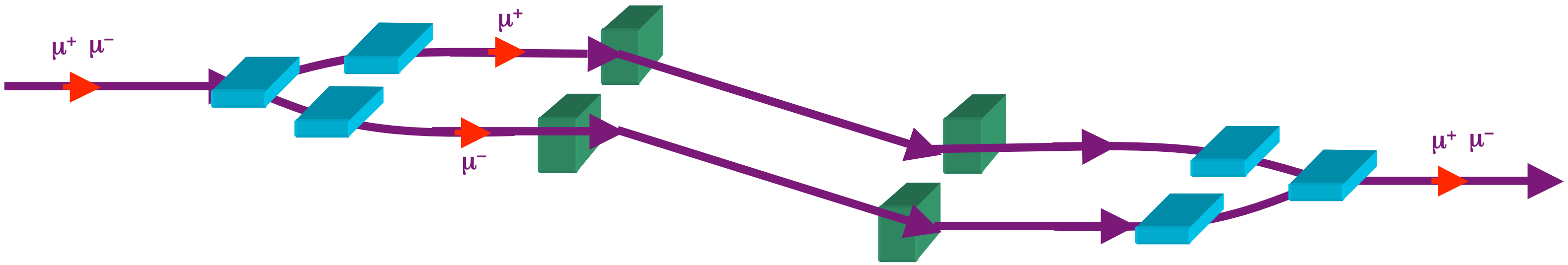


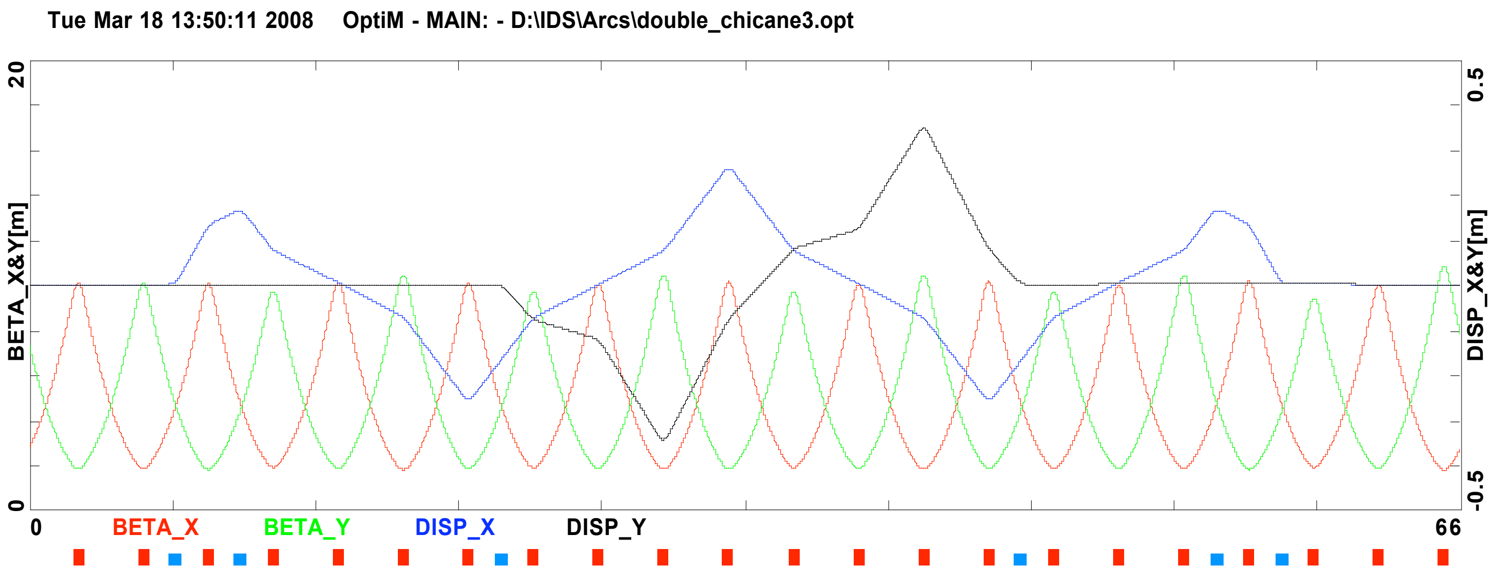
1.1 Tesla solenoid

1.4 Tesla solenoid

2.4 Tesla solenoid

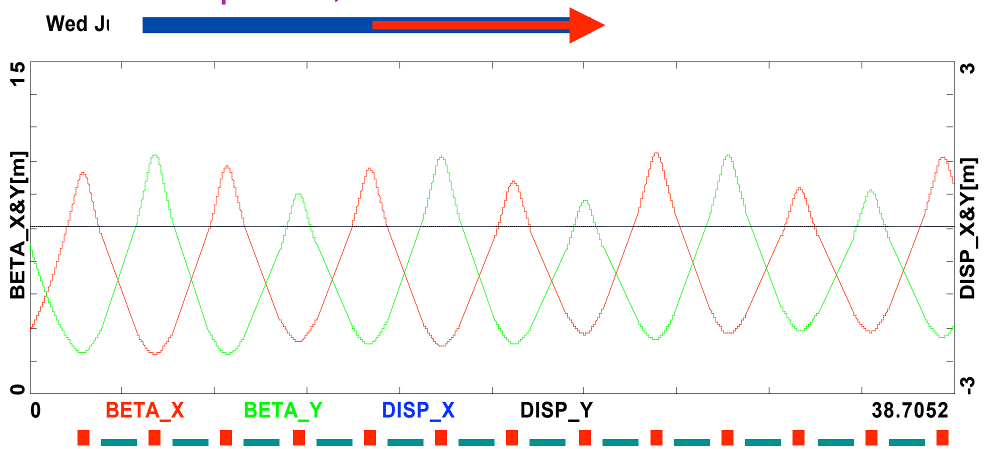
Transfer line from Linac to first RLA





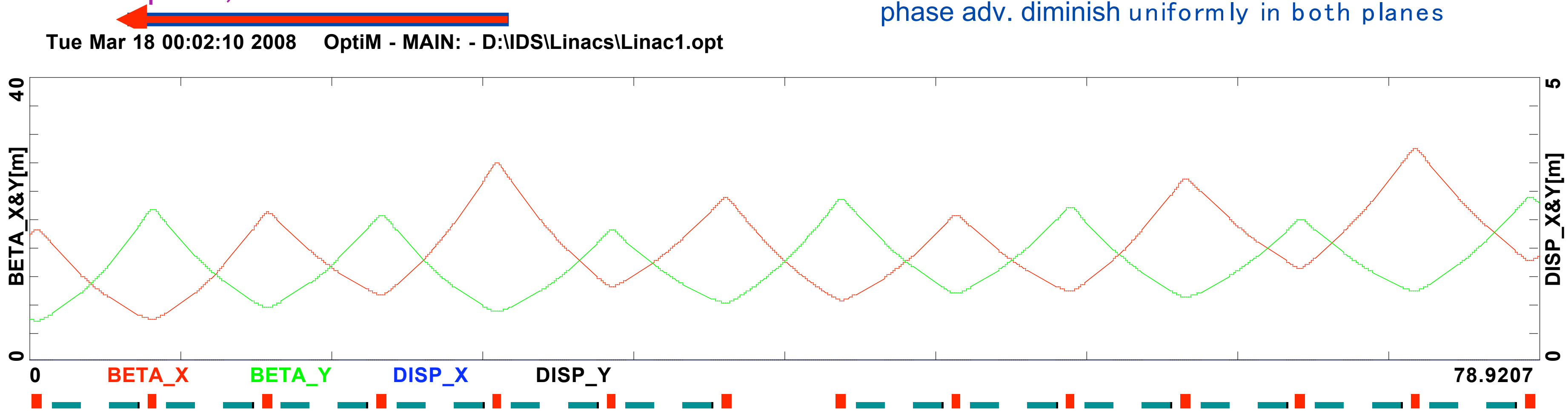
RLA 1 - FODO

'half pass' , 900-1200 MeV



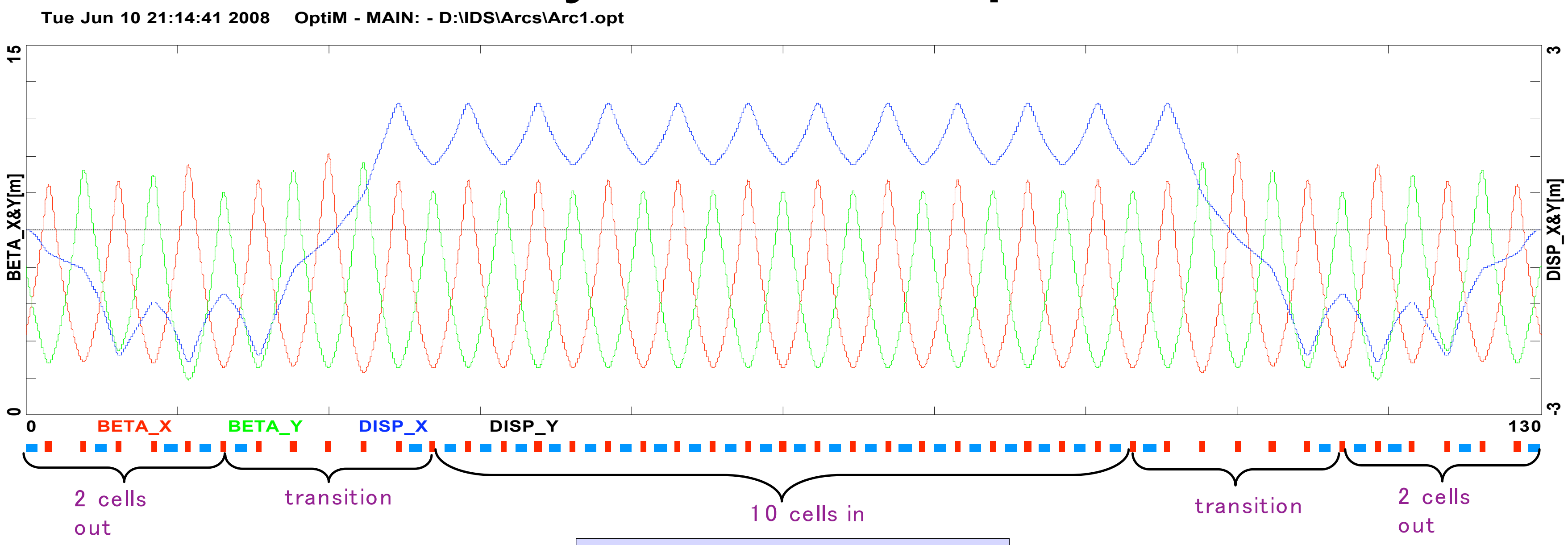
initial phase adv/cell 90 deg – fixed gradient
in all cells (no scaling with energy)

1-pass, 1290-1800 MeV



phase adv. diminish uniformly in both planes

Mirror symetric droplet arcs

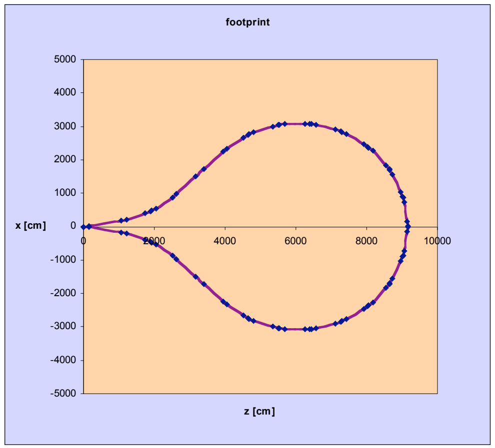


E =1.2 GeV

$\beta_{out} = \beta_{in}$

$\alpha_{out} = -\alpha_{in}$

matched to the linacs)



Arc dipoles

Lb=100 cm

B=10.5 kG

Arc quadrupoles

Lb=50 cm

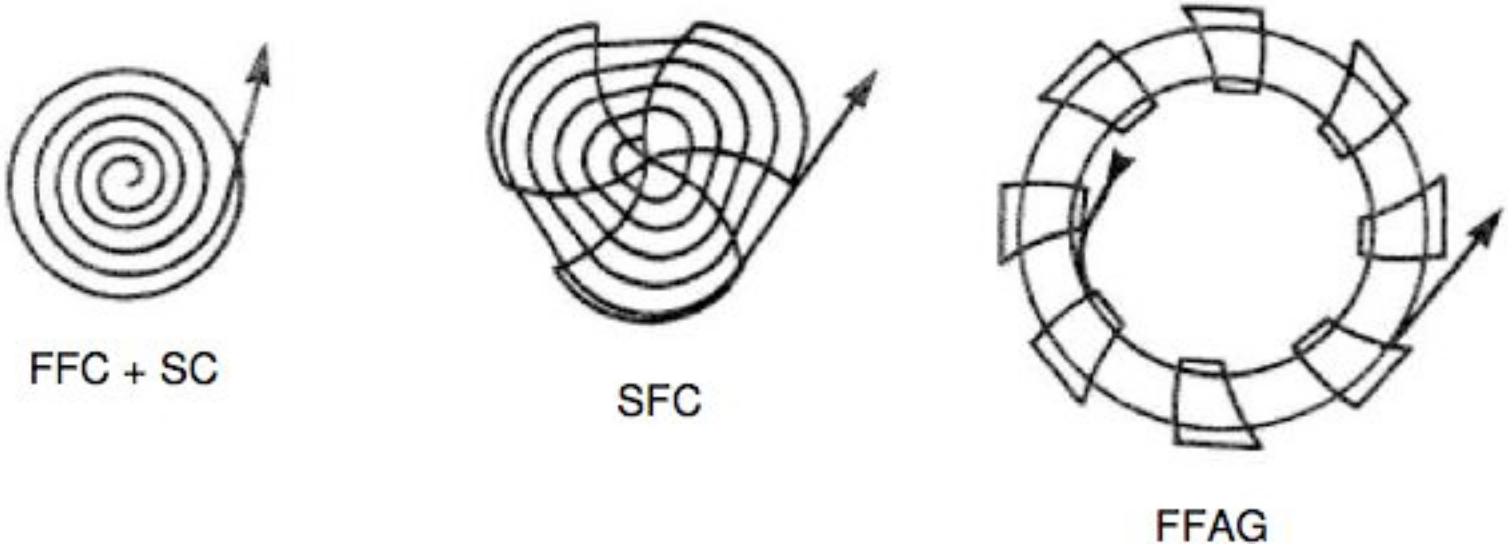
G= 0.4 kG/cm

Droplet arc scaling for RLA 1

i = 1…4	E_i [GeV]	p_i/p_1	cell_out	cell_in	length [m]
Arc1	1.2	1	2×2	10	130
Arc2	1.8	3/2	2×3	15	172
Arc3	2.4	2	2×4	20	214
Arc4	3.0	5/2	2×5	25	256

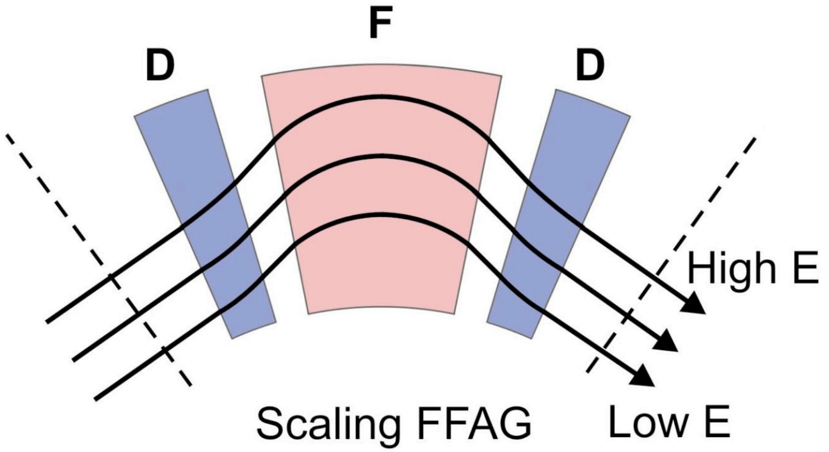
- Fixed dipole field: B_i =10.5 kGauss
- Quadrupole strength scaled with momentum:
- $G_i = \frac{p_i}{p_1} \times 0.4$ kGauss/cm
- Arc circumference increases by: (1+1+5) × 6 m = 42 m

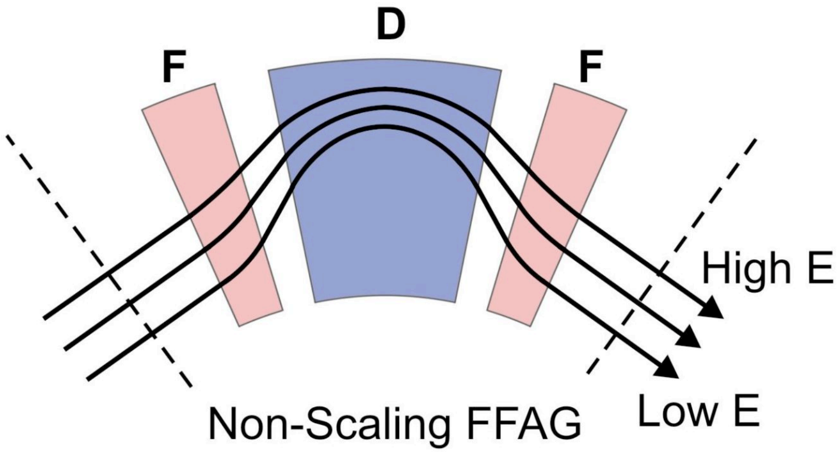
FFAG’s and cyclotrons



- Fixed magnetic field
- Transversal focusing
- Phase slip due to acceleration

Scaling and non scaling FFAG's



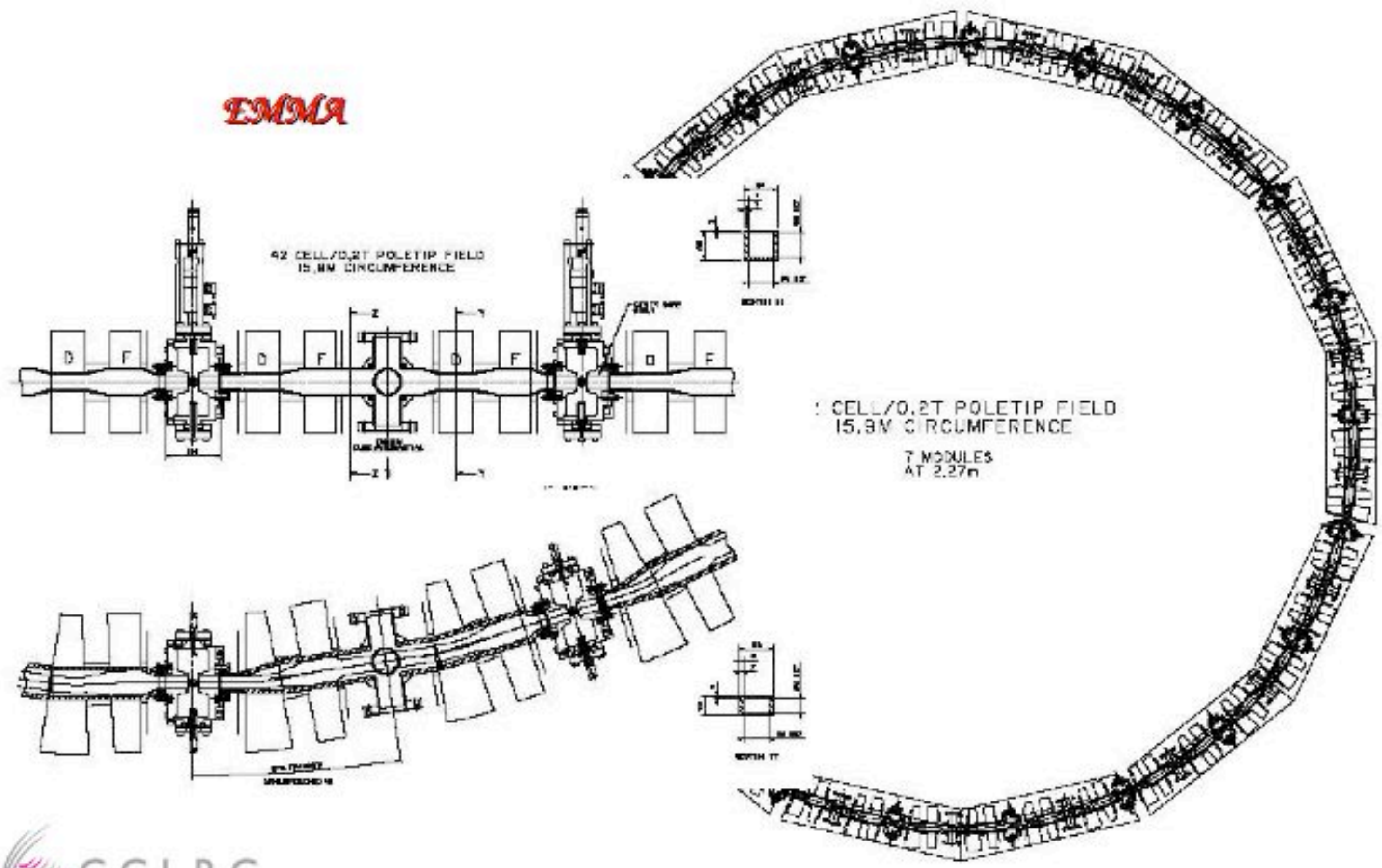


$$B = B_0 \left(\frac{r}{r_0} \right)^k$$

where k=7.5

Magnets are large, complex & expensive!

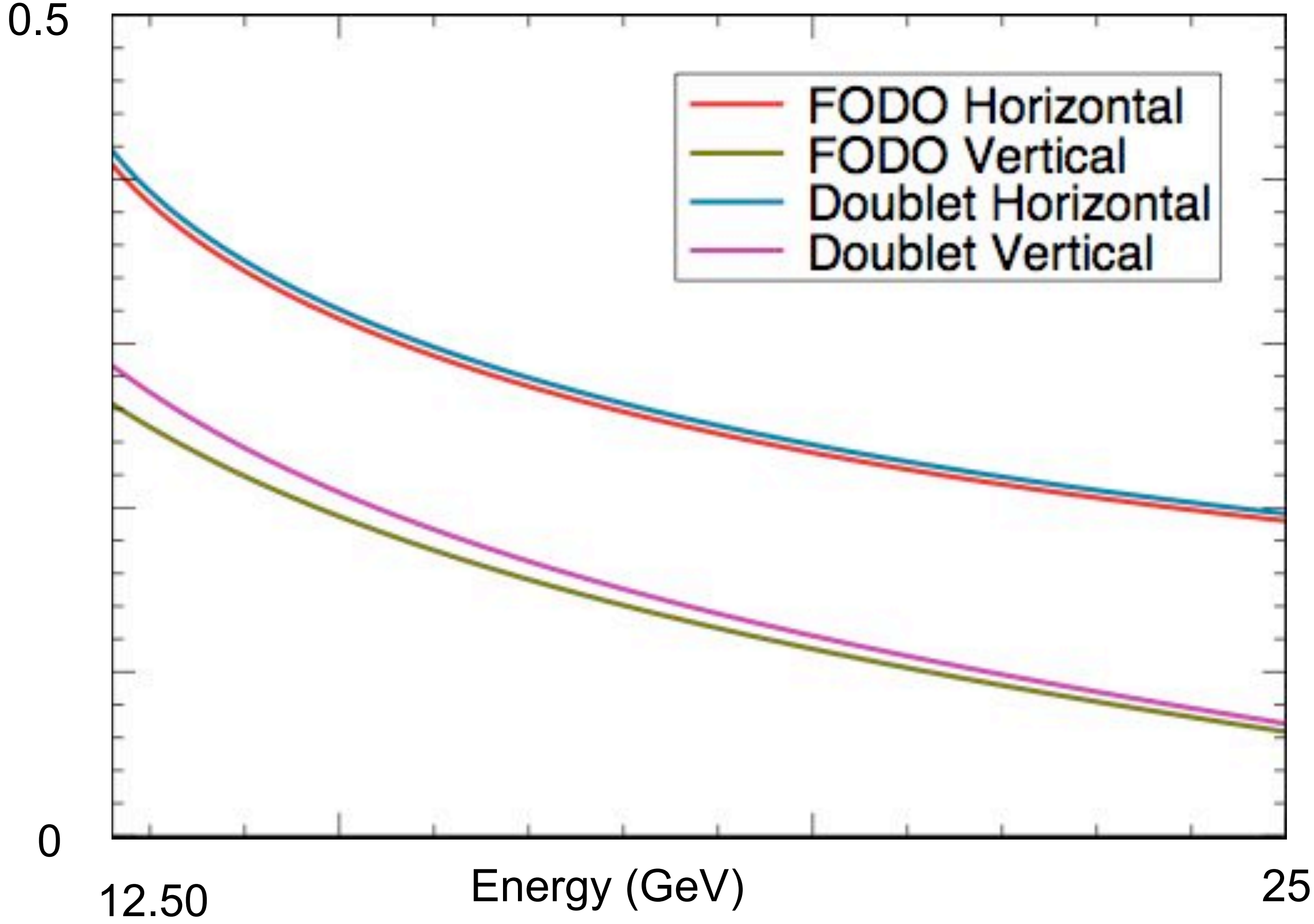
EMMA - first NS FFAG under construction



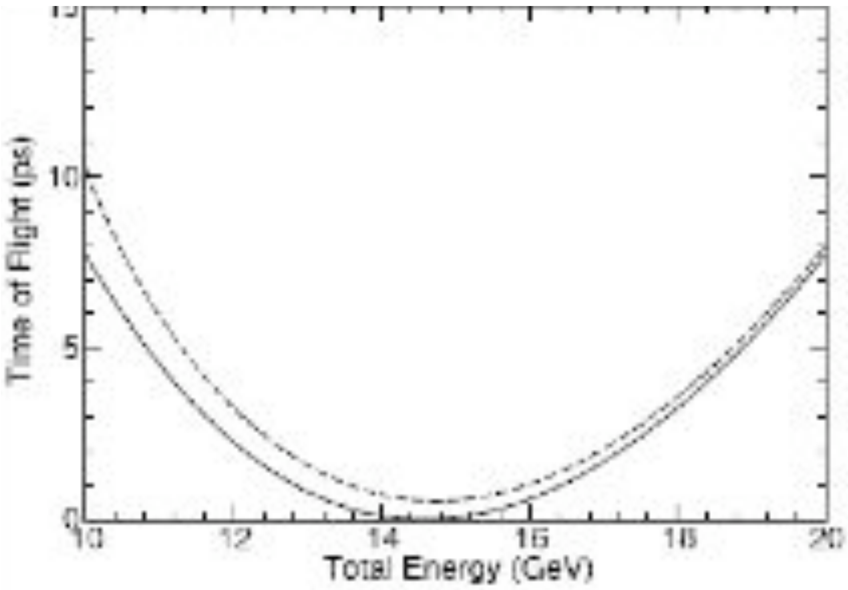
- Proof of principle
- Electrons
- 3 m inner radius
- Acceleration from 10-20 MeV
- Displaced quadrupoles

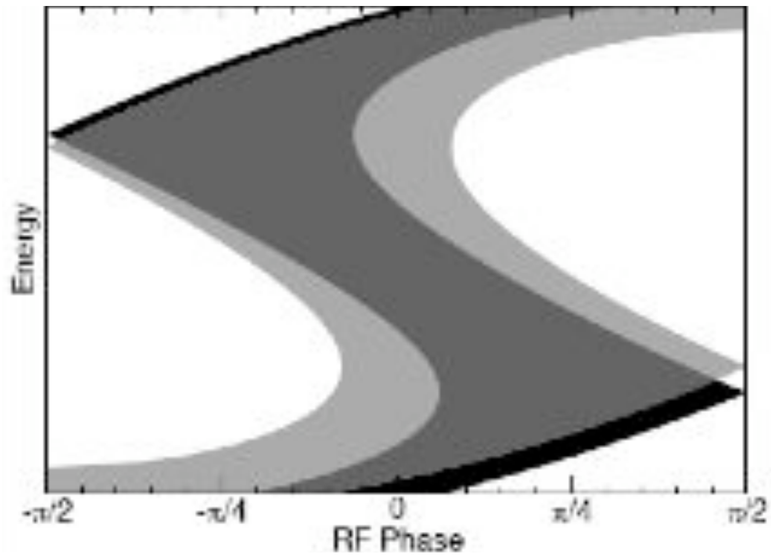
CCLRC
Rutherford Appleton Laboratory

Lattice - Cell tune and resonance crossing

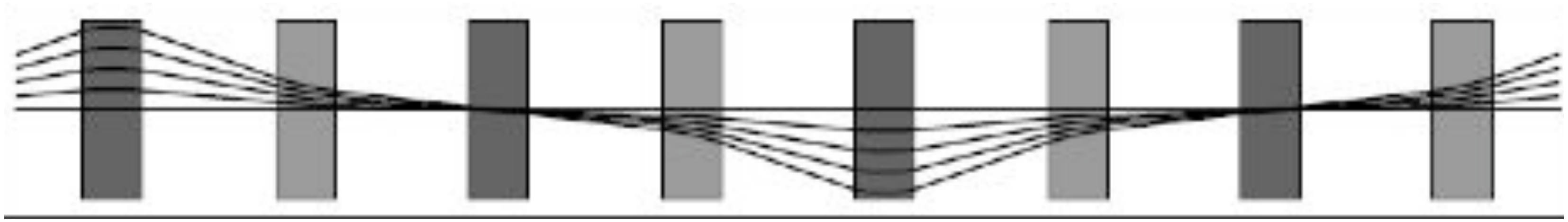


Phase slip during acceleration

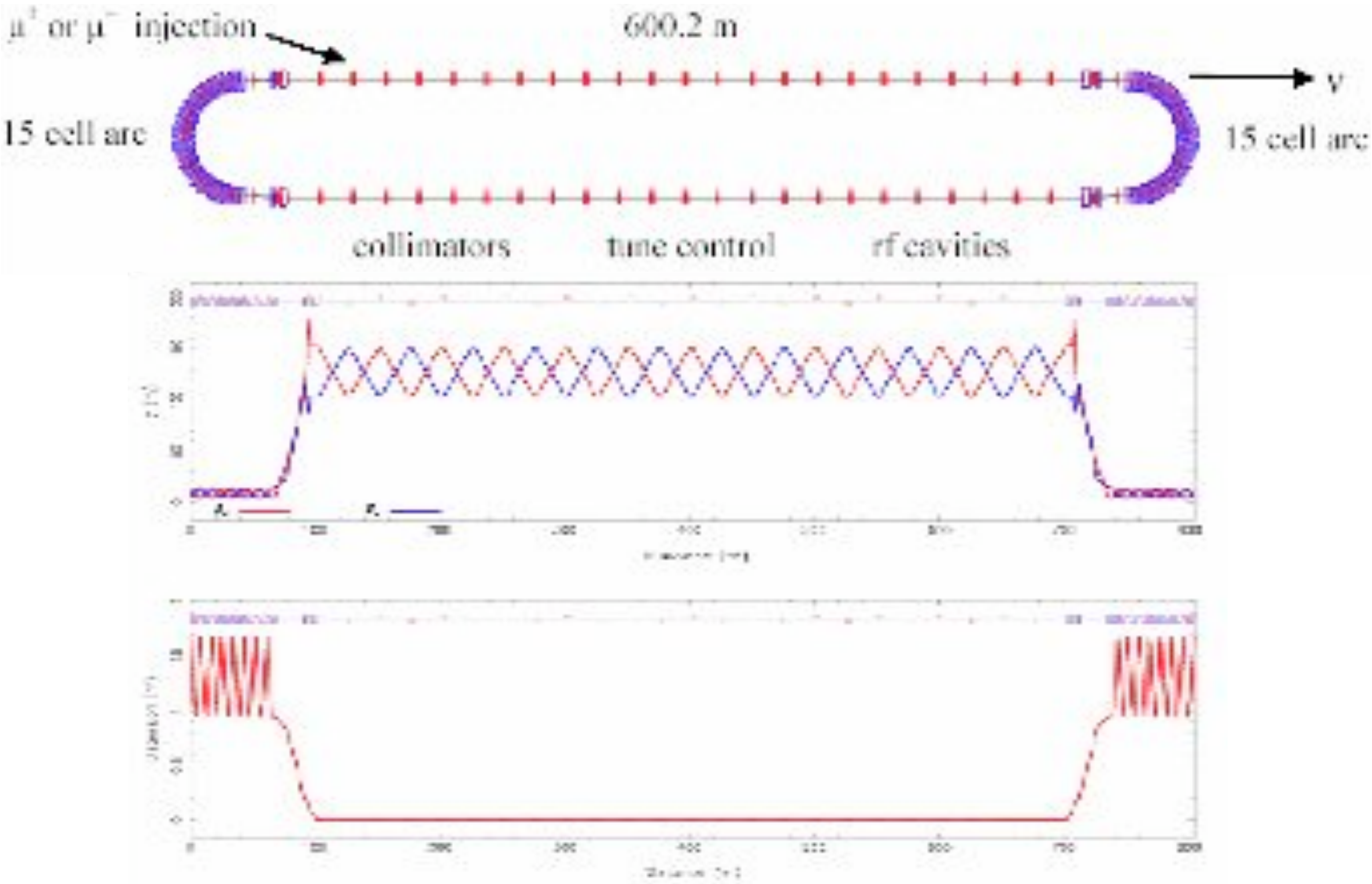




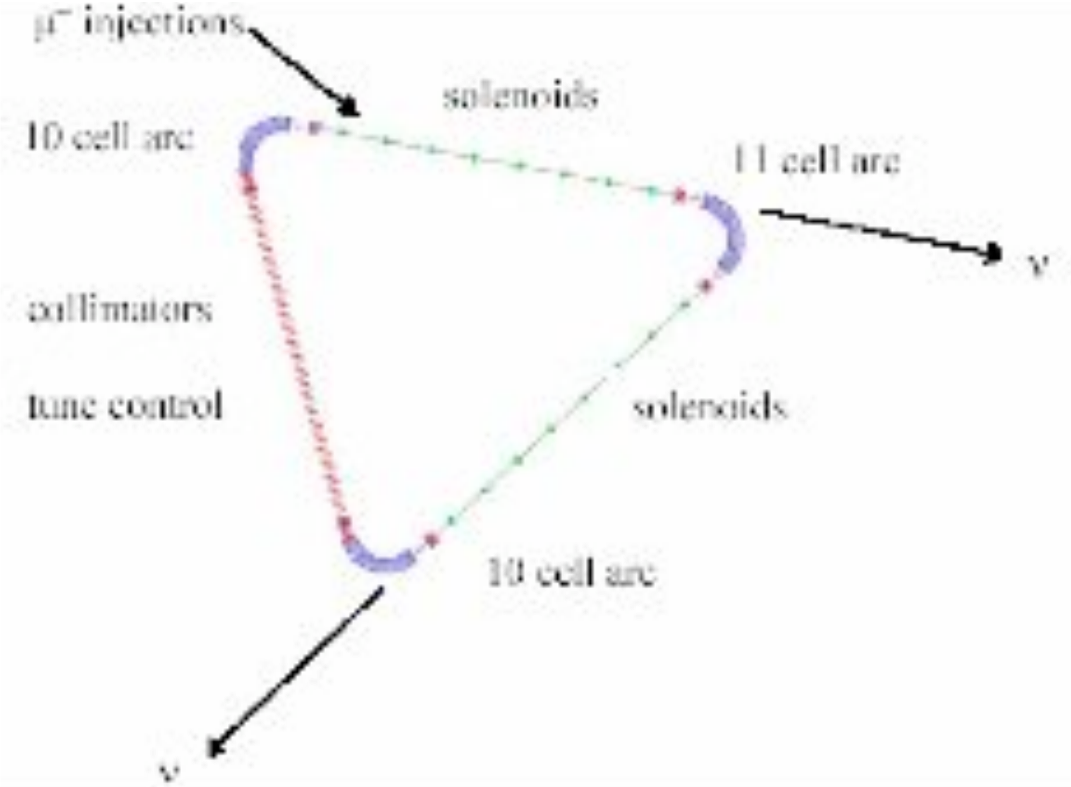
Transversal motion increases the phase slip



Decay rings - Racetrack



Decay rings triangle



Neutrinofactory, superbeam, β beam

Neutrinofactory :

$\mu^+ \rightarrow e^+ \bar{\nu}_e \nu_\mu$ and $\mu^- \rightarrow e^- \nu_e \bar{\nu}_\mu$

Defined energy given by muon, 12 channels to observe, magnetized detector required to distinguish sign of particles, 3500 km and 7500 km baselines.

Superbeam :

Broad energy spectrum upper limit defined by proton energy, pion decay, search for ν_μ disappearence or ν_τ , ν_e appearence, large volume detector (water Cerenkov), typical baselines 100 - 1000 km

β-beam :

Defined energy spectrum defined by γ, pure ν_e or $\bar{\nu}_e$ beams, 6 channels to observe, no magnetisation required - large volume detector (water Cerenkov), typical baselines 100 - 700 km

Summary

- Proton driver and target issues similar to superbeam
- Complex (and costly) handling of the post processing of muons
  - Phase rotation
  - Cooling
  - NSFFAG accelerators and dogbone linacs
  - Highest precission for very low θ_{13}

Low energy NF (3-4 GeV) could reduce cost without reducing precision to much

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Rob Edgecock…..