Proton Driver: Status and Plans

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Proton Drivers

- Types of structure
  - Linac + Accumulator + Compressor rings
  - Linac + RCS + RCS (+ storage ring)
  - Linac + RCS + FFAG
  - Linac + FFAG
- Major issues
  - low (uncontrolled) beam loss
  - halo control
  - injection/accumulation
    - beam chopper
  - bunch compression

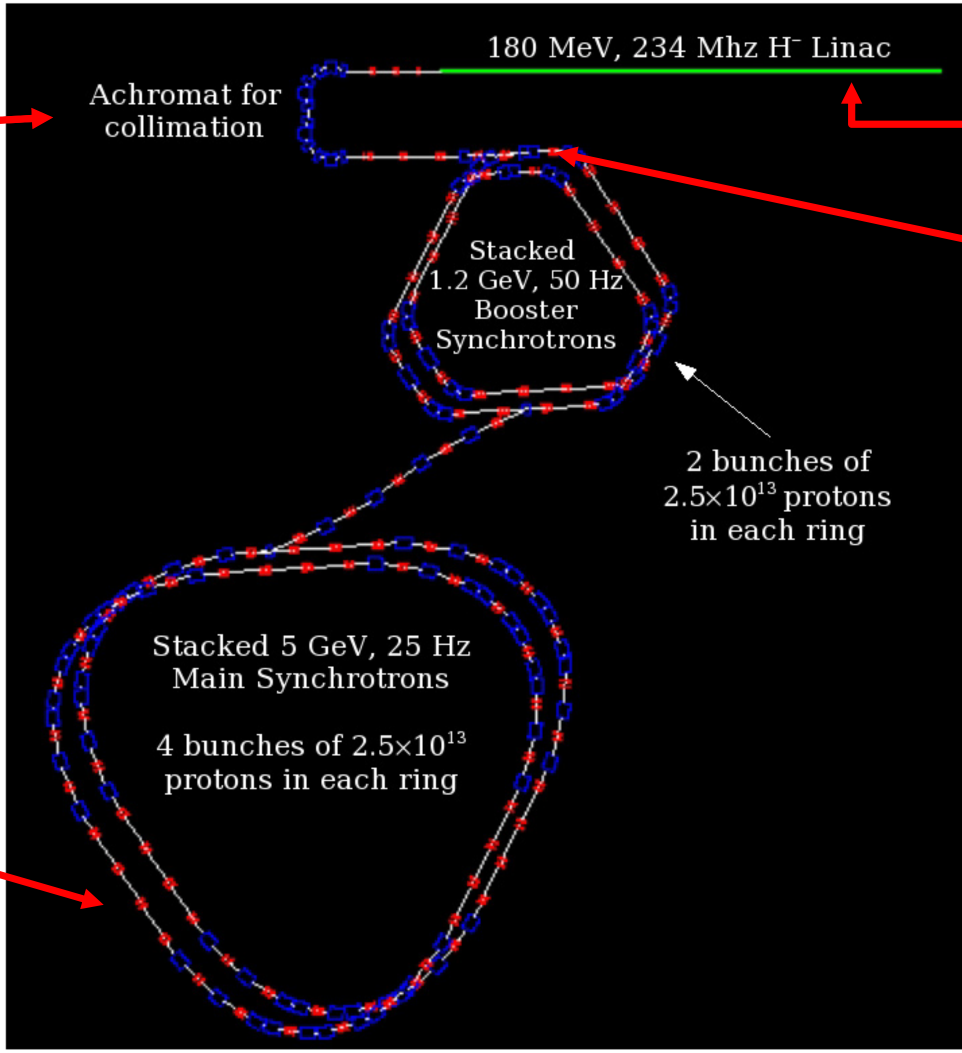
Possible “show stoppers”

Halo control/preparation for injection

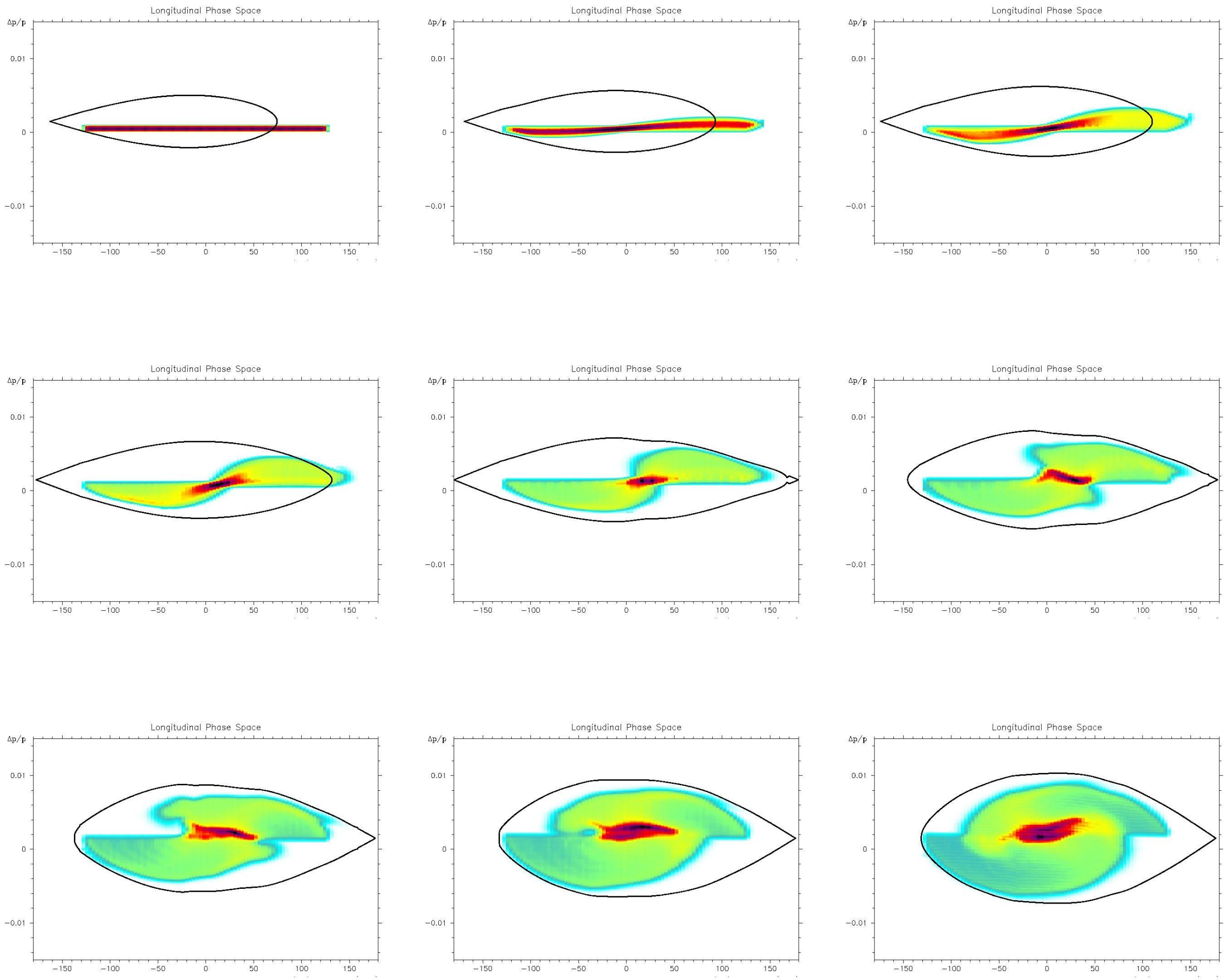
beam chopper

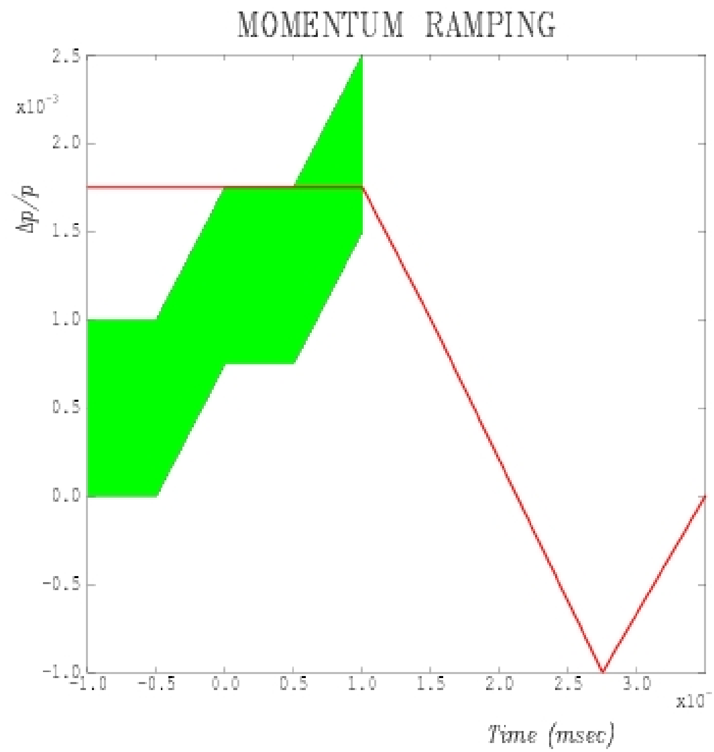
Injection

Bunch compression

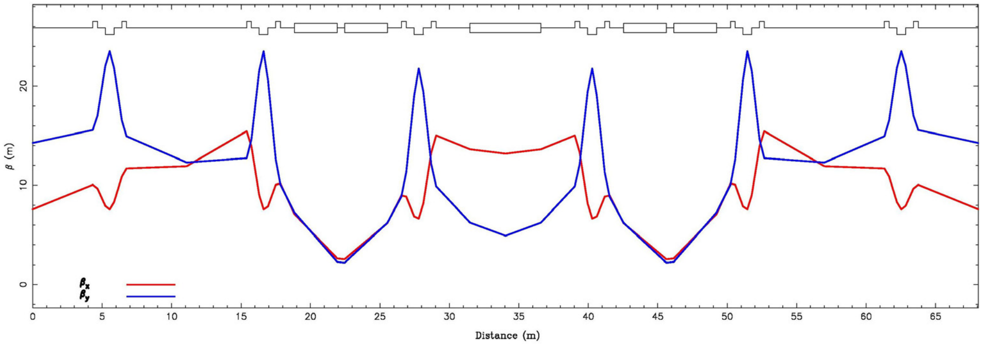


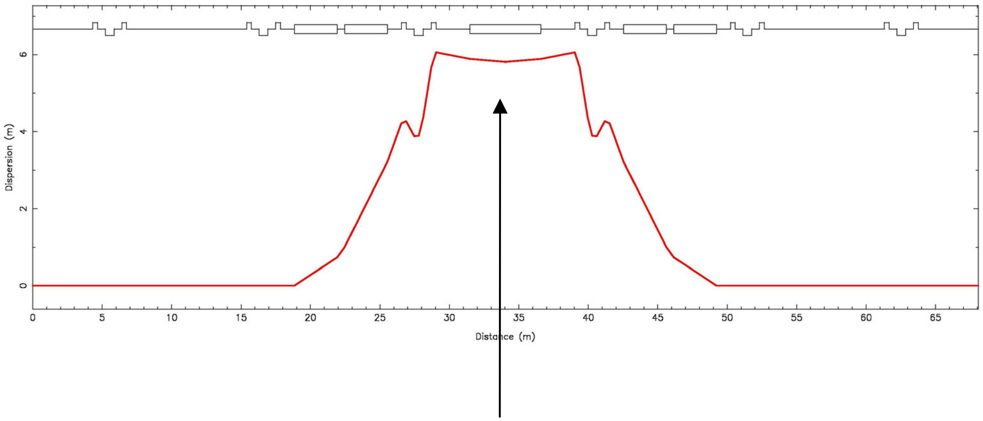
H^- Injection/Accumulation



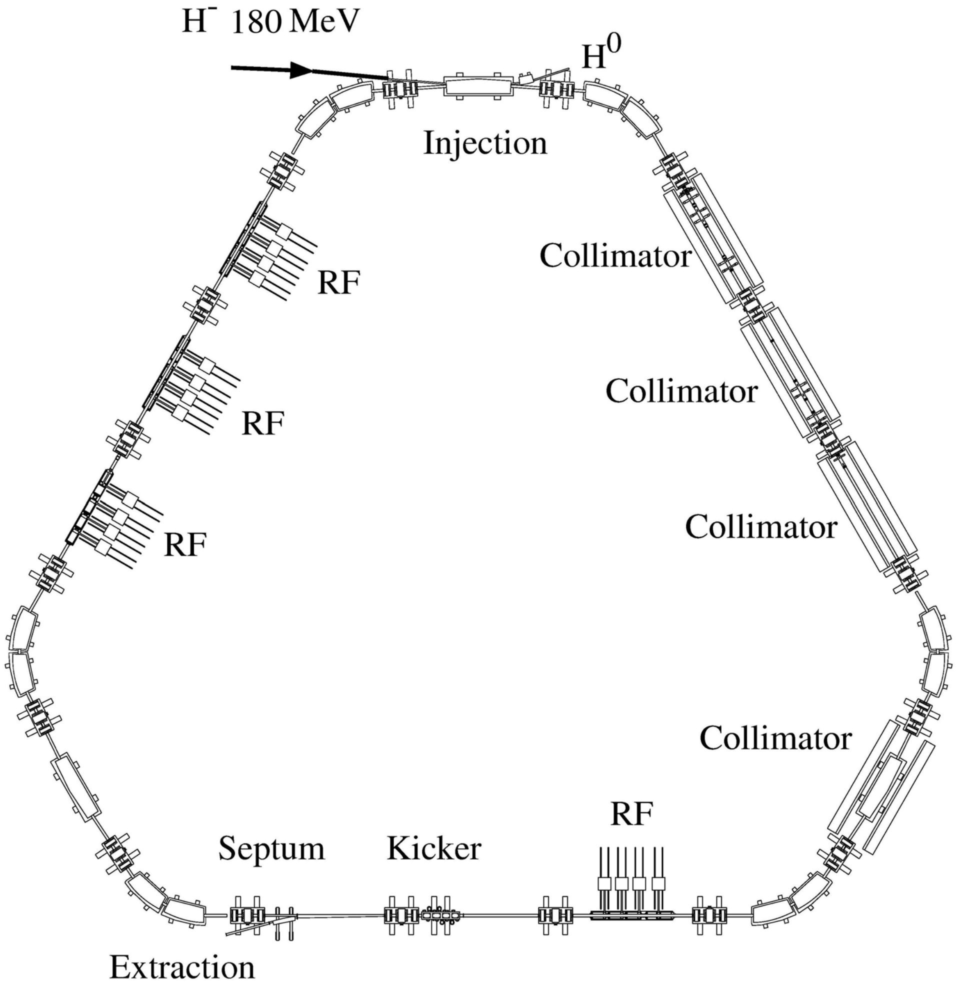


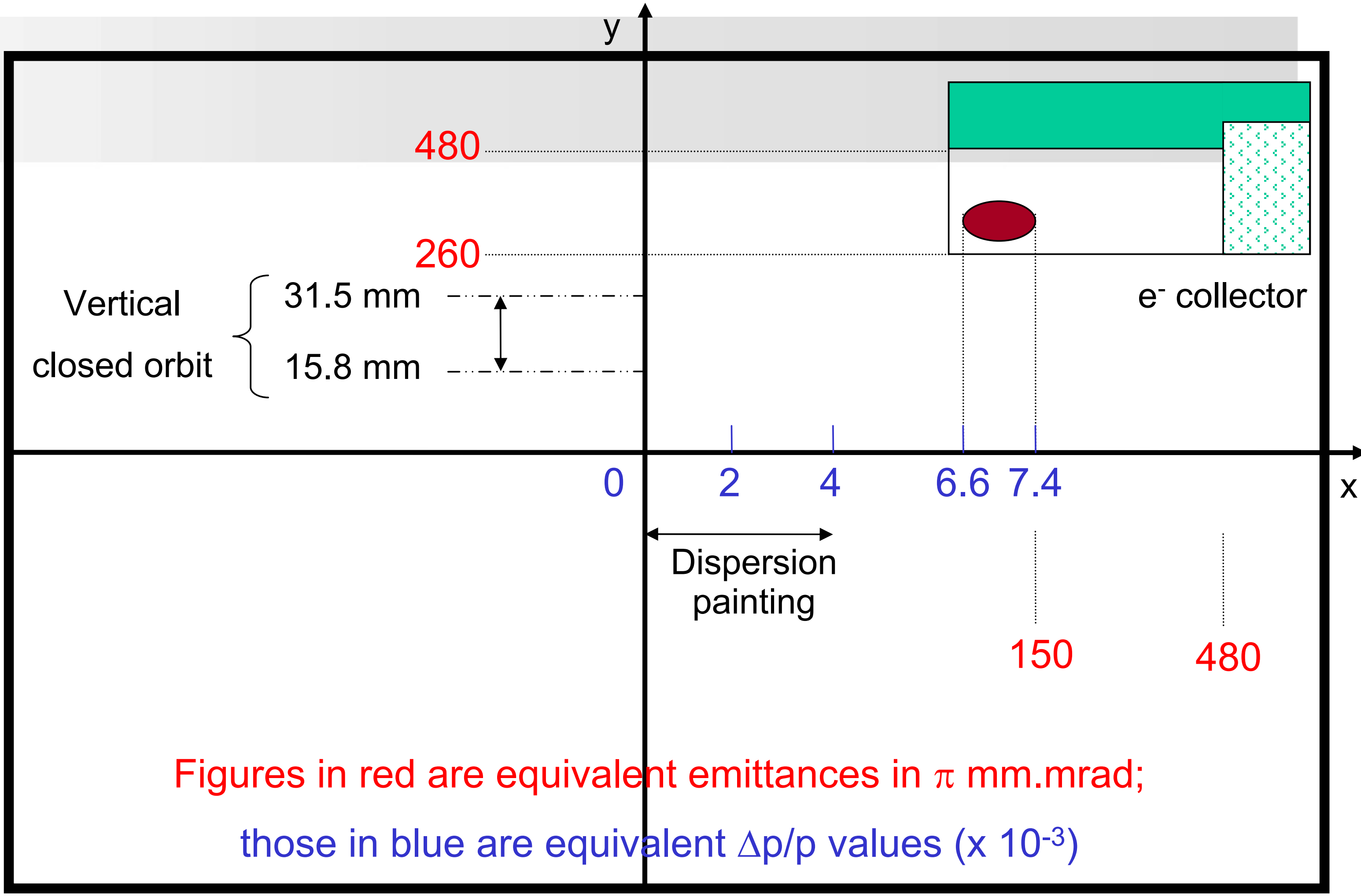
Optics Requirements



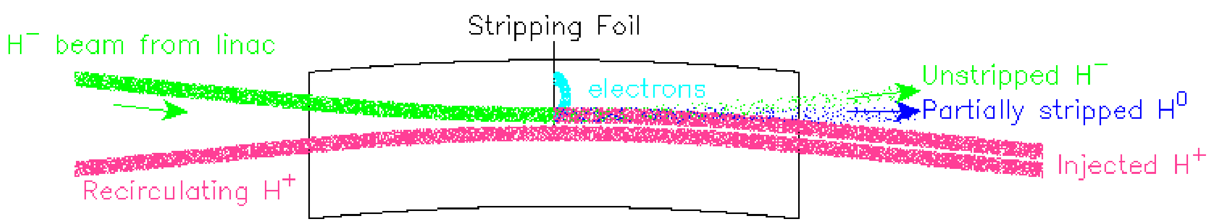


Normalised dispersion $D_x/\sqrt{\beta_x} \approx 1.6$ in injection dipole



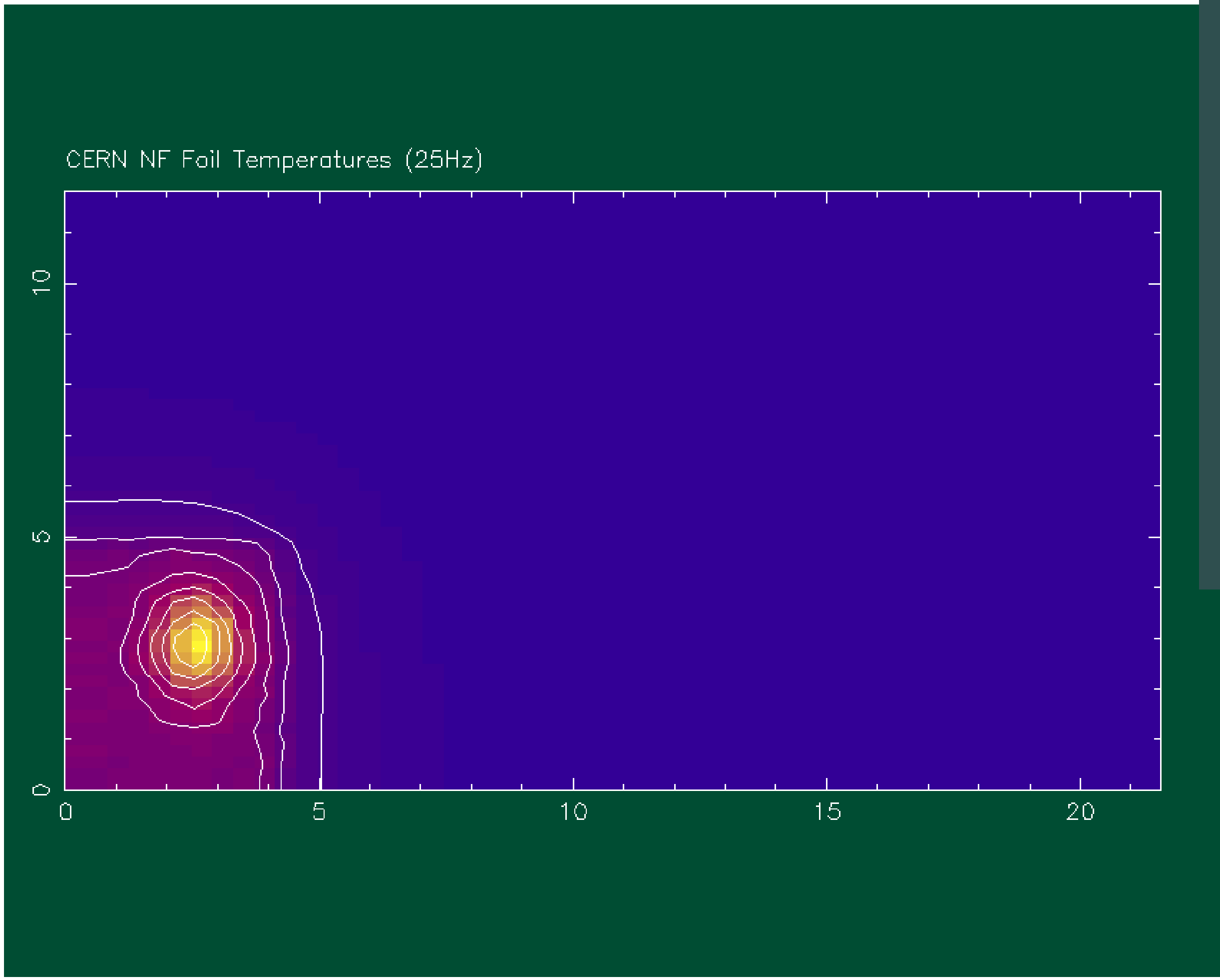


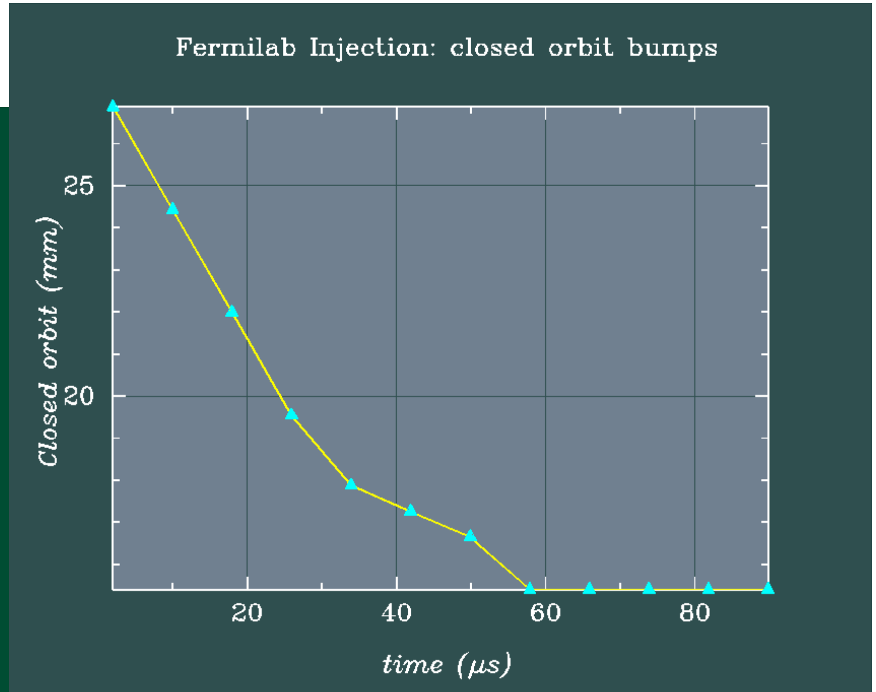
y
x
480
260
Vertical
closed orbit
31.5 mm
15.8 mm
e- collector
0
2
4
6.6
7.4
Dispersion
painting
150
480
Figures in red are equivalent emittances in π mm.mrad;
those in blue are equivalent Δp/p values (x 10-3)



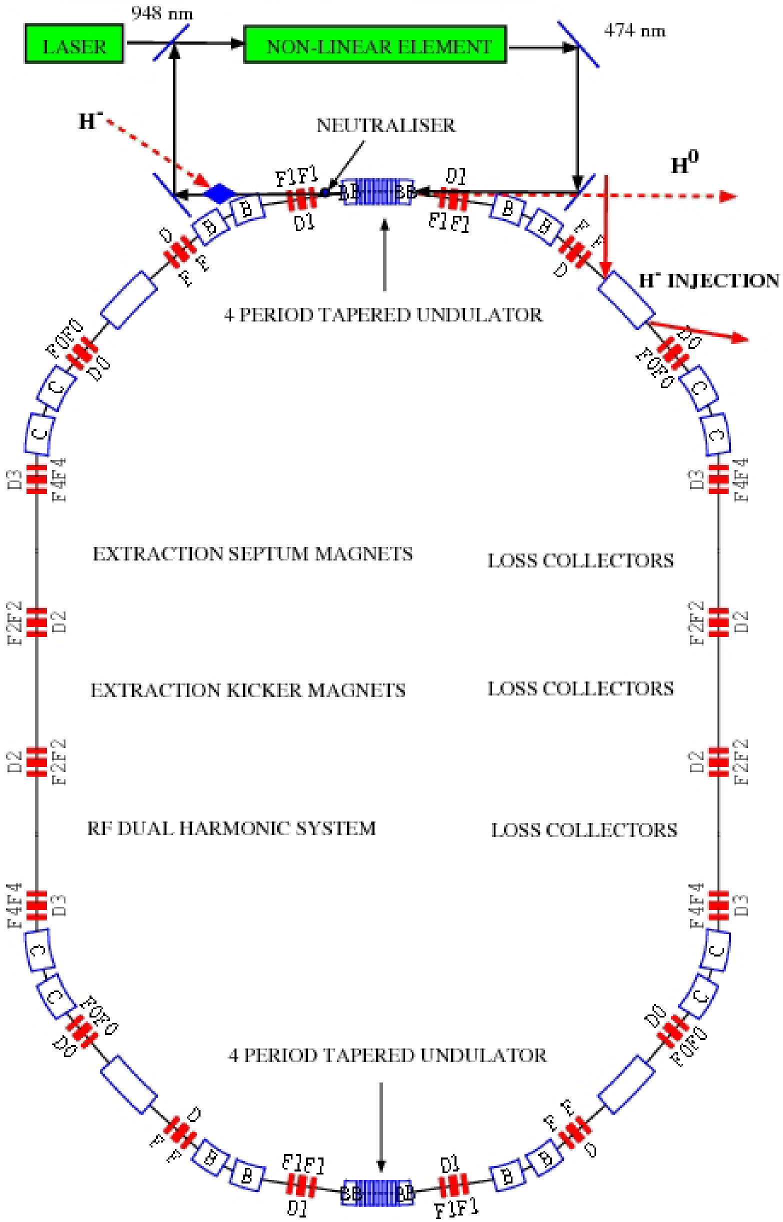
Stripping Foil
H⁻ beam from linac
electrons
Unstripped H⁻
Partially stripped H0
Injected H+
Recirculating H+

Foil Heating





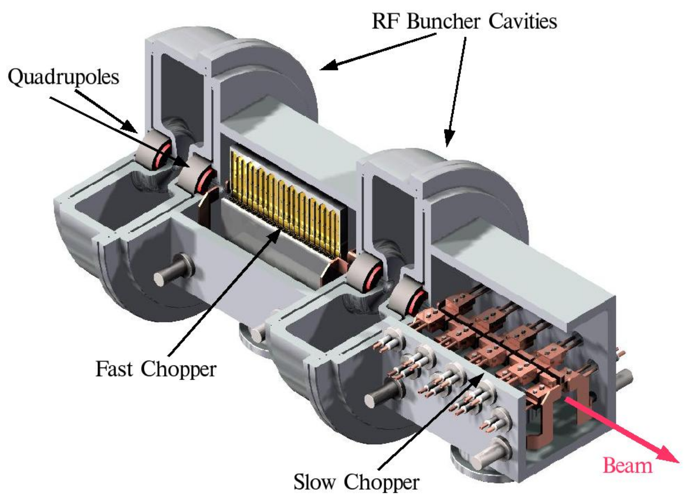
Laser Stripping

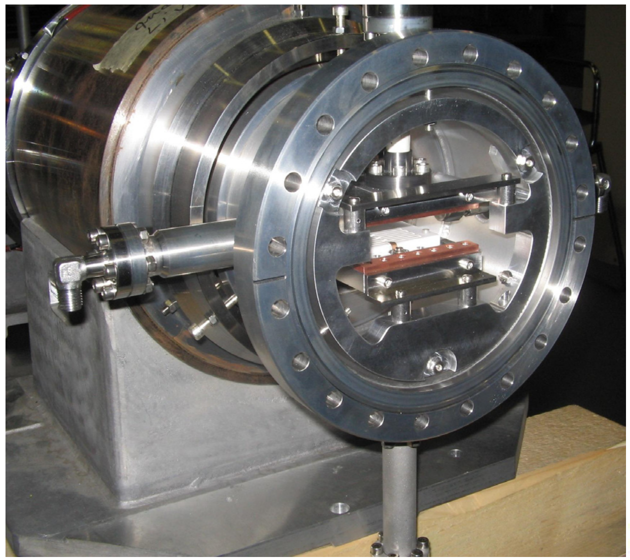


- Ring lattice designed for laser stripping injection for ESS
- Problems in controlling emittance

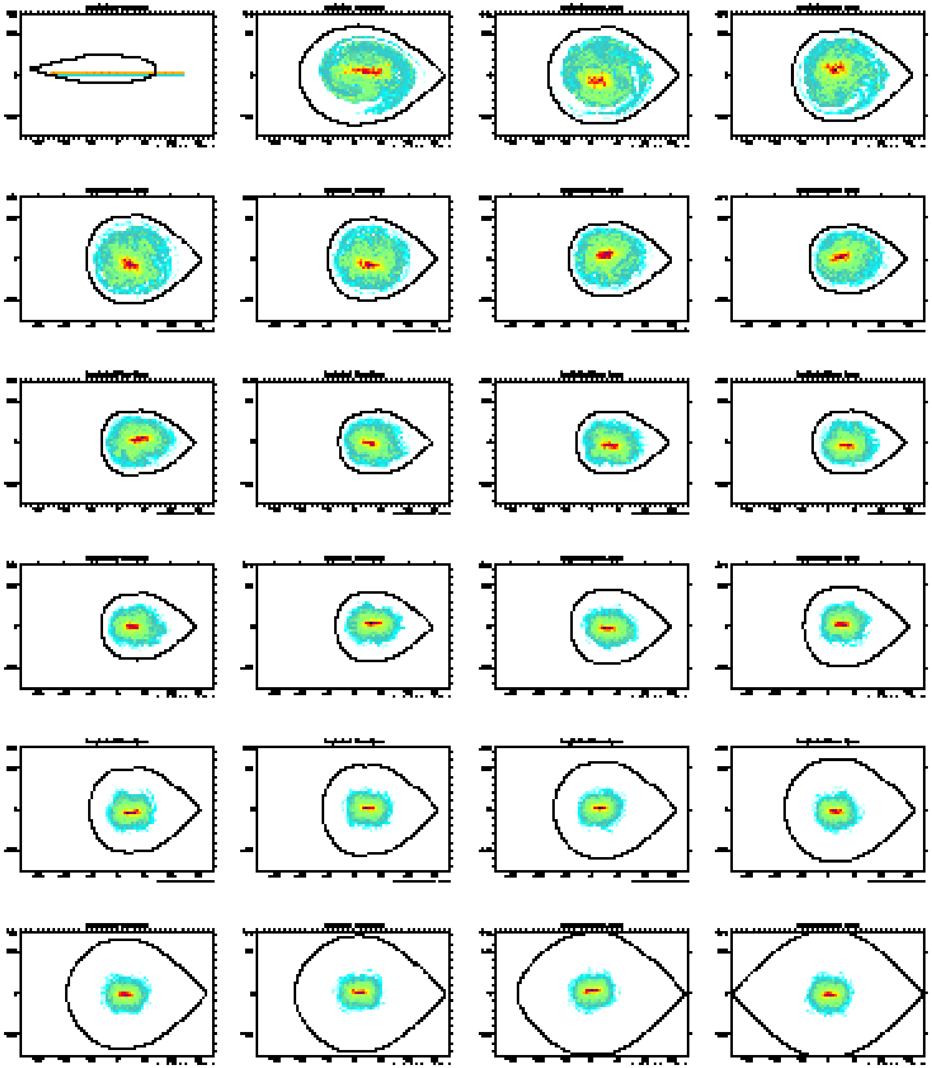
Linac and Beam Chopper

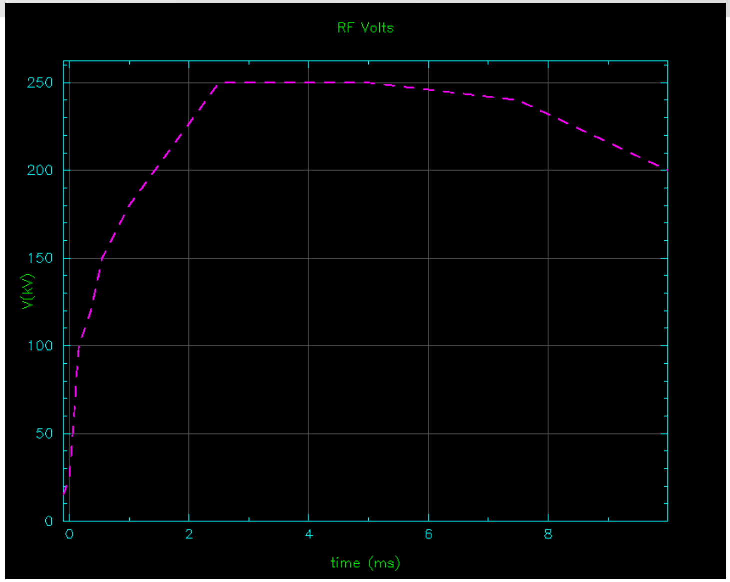
- EU/FP6 CARE/HIPPI study
  - linacs up to 200MeV
  - parallel chopper designs under development at RAL and CERN
  - CERN study leading to LINAC4 (possibly also SPL)
  - RAL study for NF and possible ISIS upgrade.

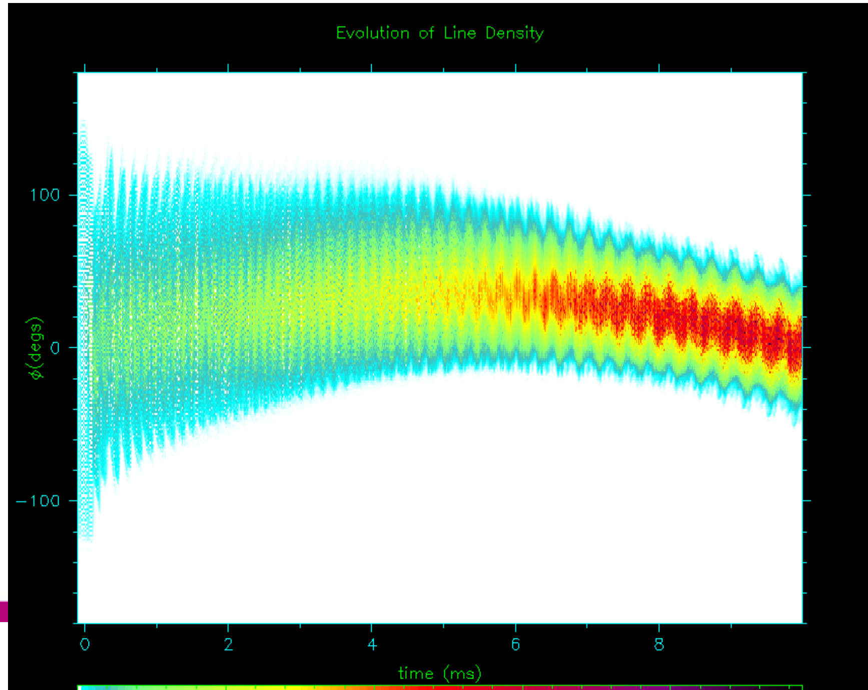




Complete Cycle, Booster RCS







Bunch Compression ~1-2 ns rms

$$\text{Bunch length} \quad \varphi_L = A^{1/2} \left(\frac{\omega_0}{\pi\beta^2 E} \right)^{1/2} \left(\frac{2\pi\beta^2 E|\eta|}{heV|\cos\varphi_s|} \right)^{1/4}$$

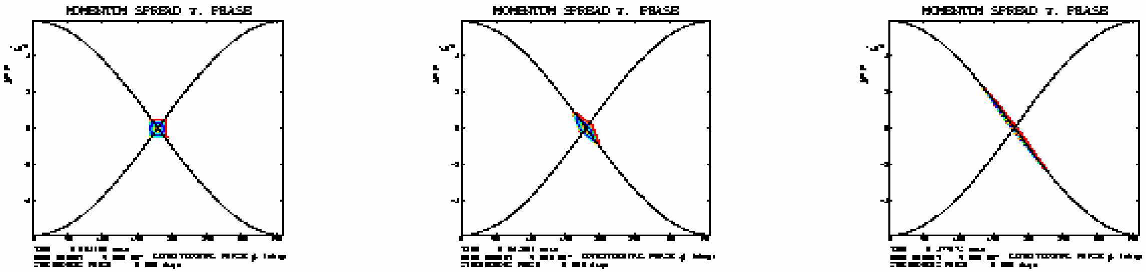
- ***High RF Voltage***
  - ***Bunch shortens as RF voltage increases during adiabatic compression, but only as fourth root of V.***
  - ***Required voltage rapidly becomes very large.***
- ***High RF frequency***
  - ***Leads naturally to shorter bunches but with small longitudinal emittance and high charge per unit phase space area.***
  - ***Experience of high intensity machines suggests an empirical limit of 1-2 x 10^{12}/eV.s for machines which pass through transition. However, no theoretical basis exists.***

Bunch Rotation

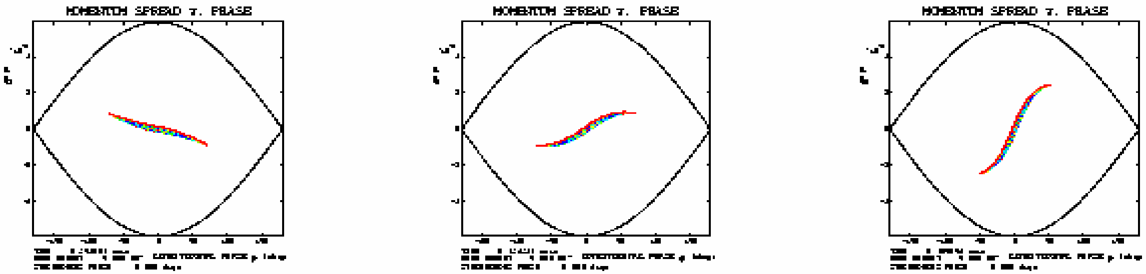
- ***Slow adiabatic decrease of RF voltage to reduce momentum spread without emittance increase.***
- ***Rapid increase of RF voltage so that the mis-matched bunch rotates in ¼ synchrotron period into upright configuration.***
- ***Factors of 2 - 4 in compression, but emittance growth unless bunch is "used" immediately.***

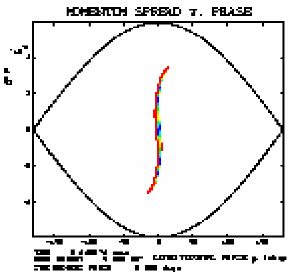
Use of Unstable Fixed Point

Step 1. Bunch lengthening at unstable fixed point in RCS, $V = 2\,\mathrm{MV}$, $h = 4$, $\gamma < \gamma_t$



Step 2. Phase change of 180° transfers bunch to centre of stable region, where synchrotron motion rotates it to upright (compressed) state. Final bunch length = 1.7 ns (rms).





Bunch length (nsec) rms	$(\pm)12.5 \to 48.3 \to 13.9$ $5.59 \to 16.9 \to 1.66$
$\frac{\Delta p}{p}$	$\pm 5.0 \times 10^{-3}$ $\to \pm 2.48 \times 10^{-2}$ $\to \pm 3.45 \times 10^{-2}$
γ_t	10.375
Volts (MV)	2.0
Harm. no.	4

Bunch length: ±12.5 ns (5.6 ns rms)

Momentum spread: ±5.0 x 10^{-3}

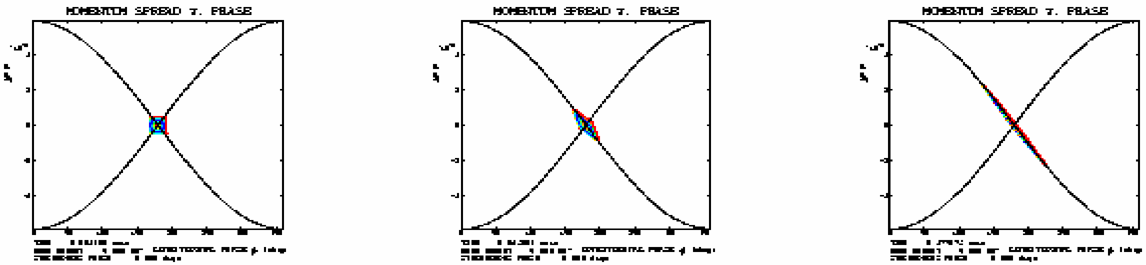
Longitudinal emittance: ε_L ~ 0.7 eV.s

Number of particles per bunch: 2.5 x 10^{13}

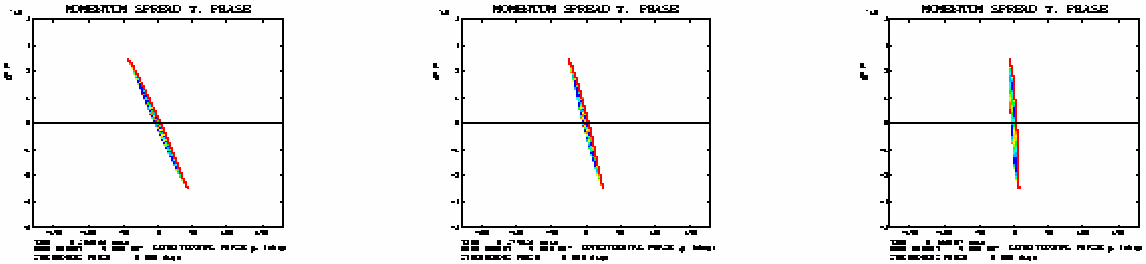
- ***Switch phase of RF voltage to unstable fixed point to stretch bunch.***
- ***Then switch RF phase back to stable fixed point so that bunch rotates to upright position with minimum length.***
- ***Compression factor may be distorted by non-linear voltage regions.***

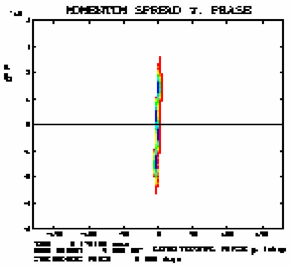
Unstable Fixed Point + Separate Compressor Ring

Step 1. Bunch lengthening in RCS at unstable fixed point, $V = 2$MV, $h = 4$, $\gamma < \gamma_t$



Step 2. Bunch rotation in a separate Compressor Ring, $V = 0$, $\gamma > \gamma_t$. Final bunch length = 1.9 ns (rms).





Bunch length (nsec)	$(\pm)12.5 \rightarrow 48.3 \rightarrow 4.5$
rms	$5.6 \rightarrow 16.9 \rightarrow 1.9$
$\frac{\Delta p}{p}$	$\pm 5.0 \times 10^{-3}$ $\rightarrow \pm 2.48 \times 10^{-2}$ $\rightarrow \pm 2.6 \times 10^{-2}$
γ_t	10.375/5.35
Volts (MV)	2.0/0.0
Harm. no.	4

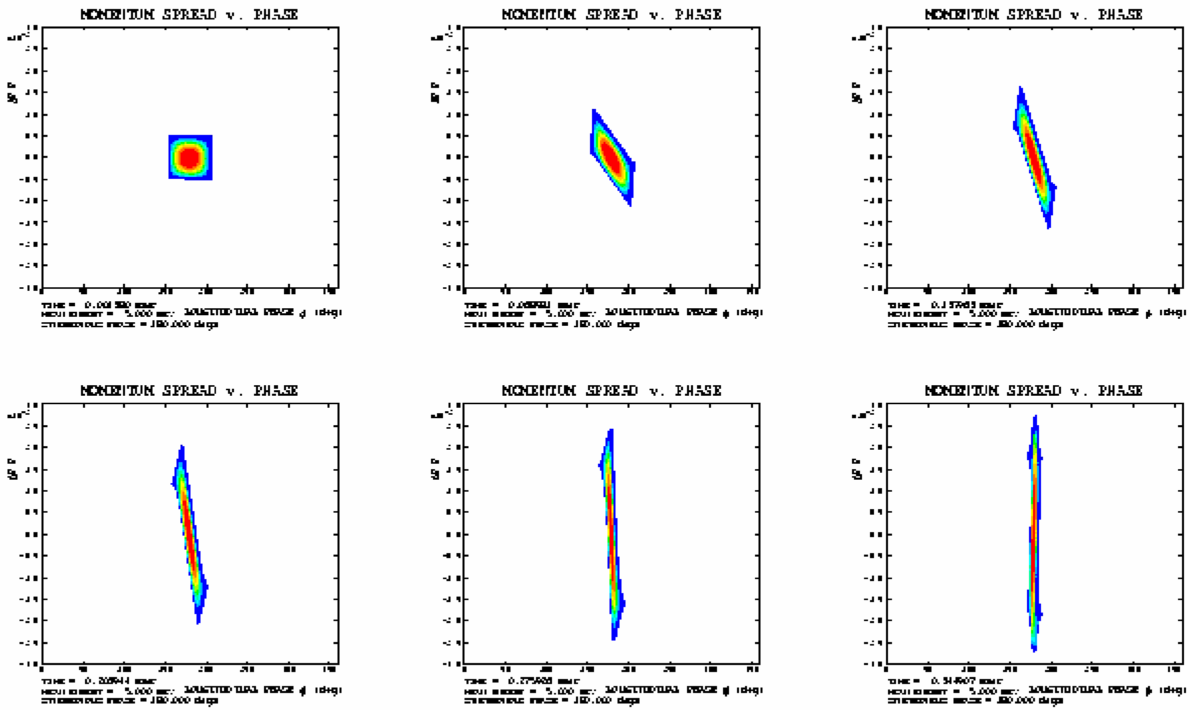
- ***Stretch bunch at unstable fixed point (as before, $\gamma<\gamma_t$, volts on)***
- ***Transfer to separate compressor ring with $\gamma>\gamma_t$ for phase space rotation. No volts needed.***
- ***Non-linearity problems exist but are reduced.***

Flexible Momentum Compaction

- ***Lattice gymnastics involving frequency slip parameter $\eta=1/\gamma_t^2-1/\gamma^2$.***
- ***Set $\eta=0$ and impose RF voltage to create large $\Delta p/p$ without change in bunch length.***
- ***Switch η back on and bunch will rotate to short length.***
- ***Experiment at Brookhaven AGS with transition jumping quadrupoles achieved 2.5 ns for 5 x 10^{12} protons (factor ~3 in compression)***

Compression with $\gamma \geq \gamma_t$

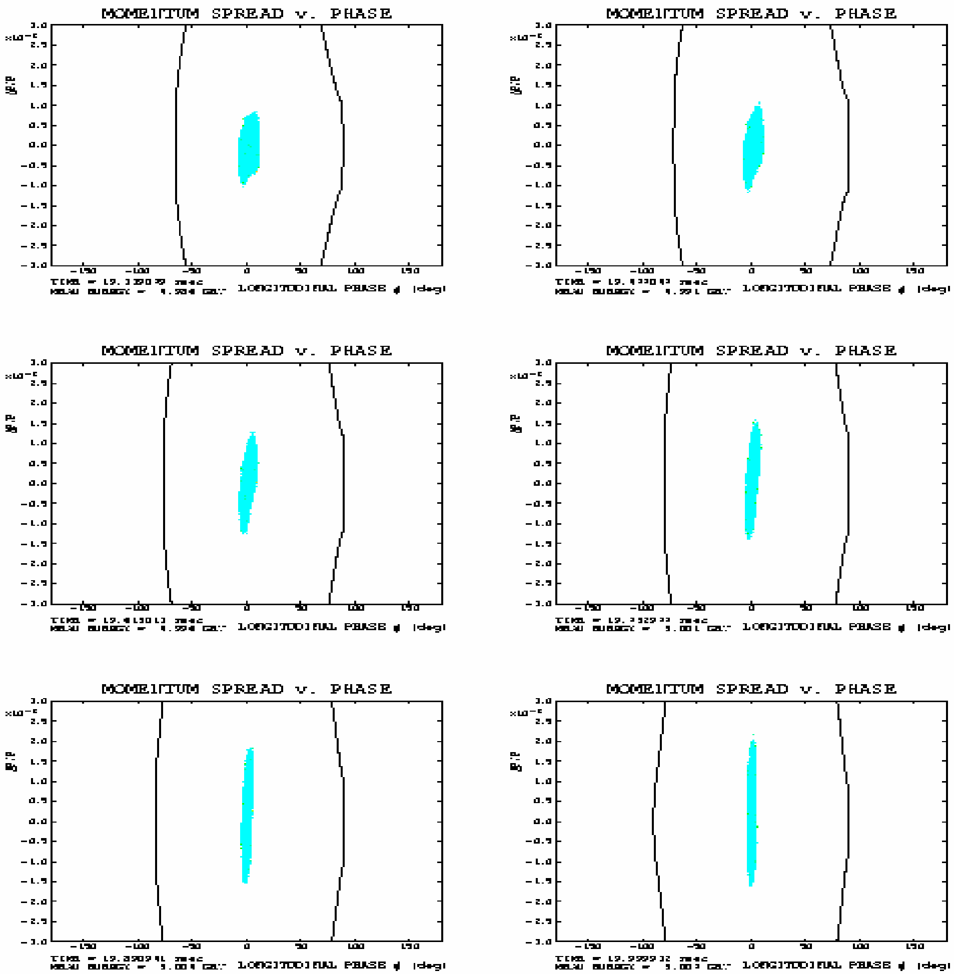
In a separate compressor ring with $\gamma \gtrsim \gamma_t$, $V = 1.5$ MV, $h = 8$ bunch (centred on 180°) elongates and rotates in phase space to final upright (compressed) state. Requires a ring with γ_t insensitive to transverse space charge during compression.



Bunch length (nsec) rms	$\pm 12.5 \to \pm 4.1$ $5.6 \to 1.12$
$\frac{\Delta p}{p}$	$\pm 5 \times 10^{-3}$ $\to \pm 2.7 \times 10^{-2}$
γ_t	6.0
Volts (MV)	1.5
Harmonic number	8

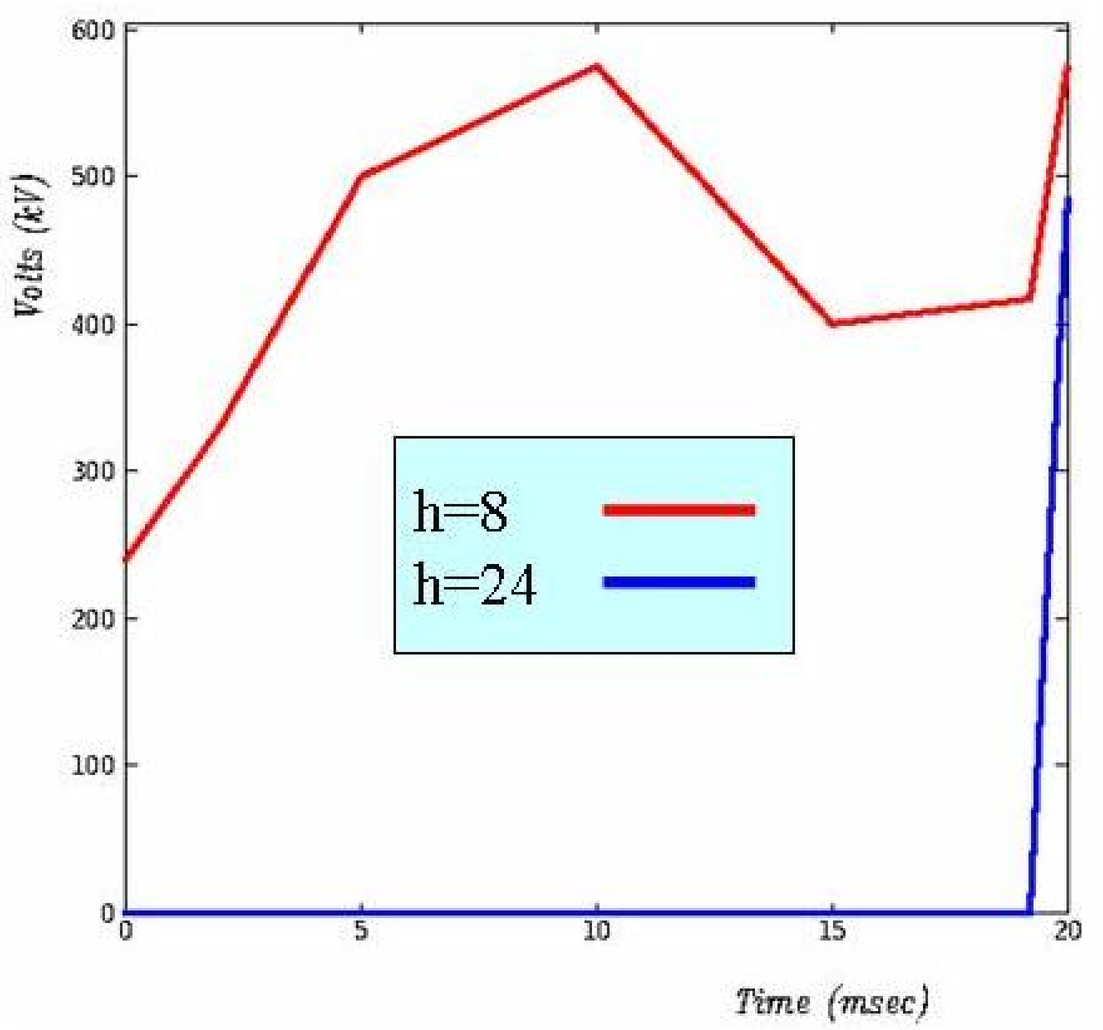
- ***Work with γ close to, and just above, γ_t.***
- ***Space charge assists compression.***
- ***High RF voltage (1.5 MeV at h=8) based on φ_s=180°***
- ***Simulation gives the required ~1-2 ns bunches but sensitive to space charge depression of γ_t.***

Bunch Compression in RAL 5 GeV RCS Proton Driver



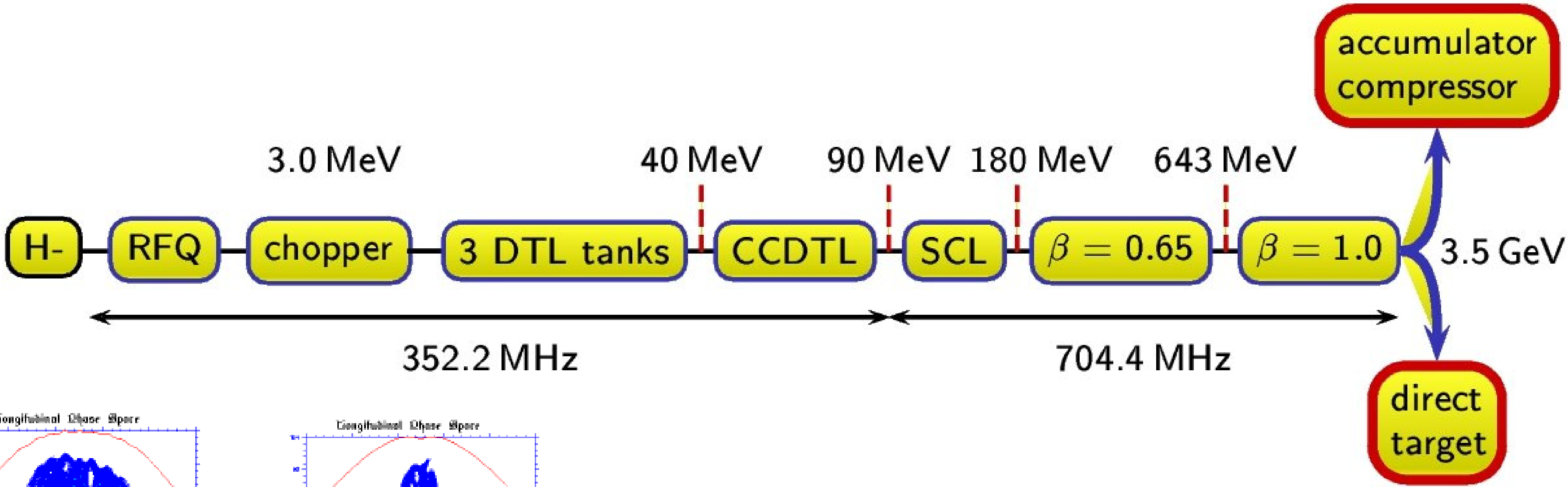
- ***γ_t=6.5, γ= 6.33 at top energy, η=-0.0013***
- ***Voltages chosen to avoid instabilities (microwave: V_{sc}< 0.4 $V_{applied}$)***
- ***Model assumes inductive $Z_{//}/n$~5Ω***
- ***During final 500 revs of accelerating cycle, an additional h=24 voltage system swings in, rising to a peak of 500 MV***
- ***Final bunch length =1ns rms, ε_L=1.0 eV.s, Δp/p=1.6%.***
- ***Higher order momentum effects need to be taken into account***
- ***Lattice resistant to space charge depression of γ_t for currents of ~1250 A***

Bunch Compression in RAL 5 GeV RCS Proton Driver



- γ_t =6.5, γ= 6.33 at top energy, η=-0.0013
- Voltages chosen to avoid instabilities (microwave: V_{sc}< 0.4 $V_{applied}$)
- Model assumes inductive $Z_{//}/n \sim 5\Omega$
- During final 500 revs of accelerating cycle, an additional h=24 voltage system swings in, rising to a peak of 500 MV
- Final bunch length =1ns rms, $\varepsilon_L=1.0$ eV.s, $\Delta p/p=1.6\%$.
- Higher order momentum effects need to be taken into account
- Lattice resistant to space charge depression of γ_t for currents of ~1250 A

CERN SPL



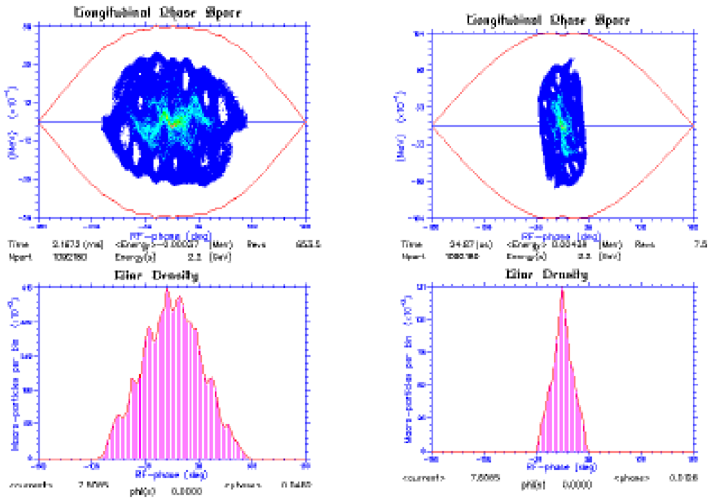
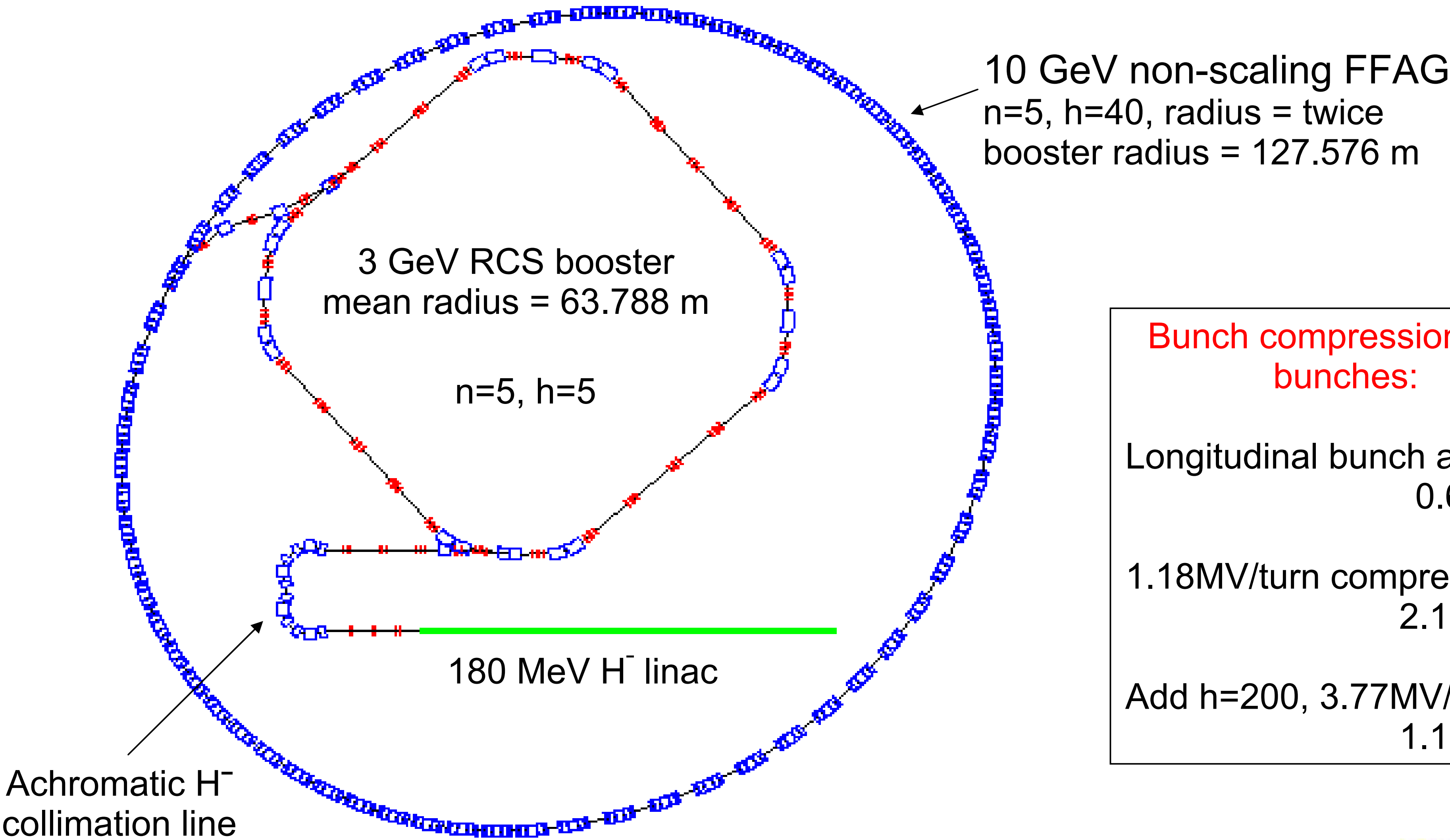


Figure 3a: Bunch after 660 Turns (End of Accumulation / Begin of Rotation)

Figure 3b: Bunch after 7.5 Turns (End of Rotation) in the Compressor

- 2.2 GeV SPL injected 5 microbunches (352 MHz) out of 8 into 140 buckets (44 MHz) (plot left)
- 5.0 GeV SPL would inject 44 (352 MHz) out of 70 into 5 buckets (5 MHz).

4MW, 50Hz, 10GeV Proton Driver



Bunch compression for 5 bunches:

Longitudinal bunch area = 0.66 eV.s

1.18MV/turn compresses to 2.1 ns rms

Add h=200, 3.77MV/turn for 1.1 ns rms

Proton Drivers

Table 1
Upgrade Parameters of Existing and Proposed Proton Drivers.
The pulse structure is given in terms of the pulse duration τ_p, the number of bunches N_b making up each pulse, and the final compressed rms bunch length τ_b.

Driver	Power (MW)	Type	Energy (GeV)	Frequency (Hz)	Protons per pulse ($\times 10^{13}$)	Pulse structure τ_p (μs)	N_b	τ_b (ns)
BNL-AGS	1	Synch	28	2.5	9	720	24	3
	4	Synch	28	5	18	720	24	3
	4	Synch	40	5	12.5	720	24	3
FNAL	2	Synch[1]	8	15	10	1.6	84	1
	2	Linac[2]	8	10	15			
FNAL MI	2	Synch	120	0.67	15	10	530	2
CERN-SPL	4	LAR	2.2	50	23	3.2	140	1
	4	LAR	3.5	50	14	1.7	68	1
J-PARC	0.75	Synch	50	0.3	31	4.6	8	6
RAL	4	Synch	5	50	10	1.4	4	1
	4	Synch	6–8	50	8.3	1.6	6	1
	4	FFAG	10	50	5	2.3	5	1
	4	Synch	15	25	6.7	3.2	6	1
RAL/CERN	4	Synch	30	8.33	10	3.2	8	1
KEK/Kyoto	1	FFAG	1	10^4	0.06	0.4	10	10
	1	FFAG	3	$3\ 10^3$	0.06	0.5	10	10

Status

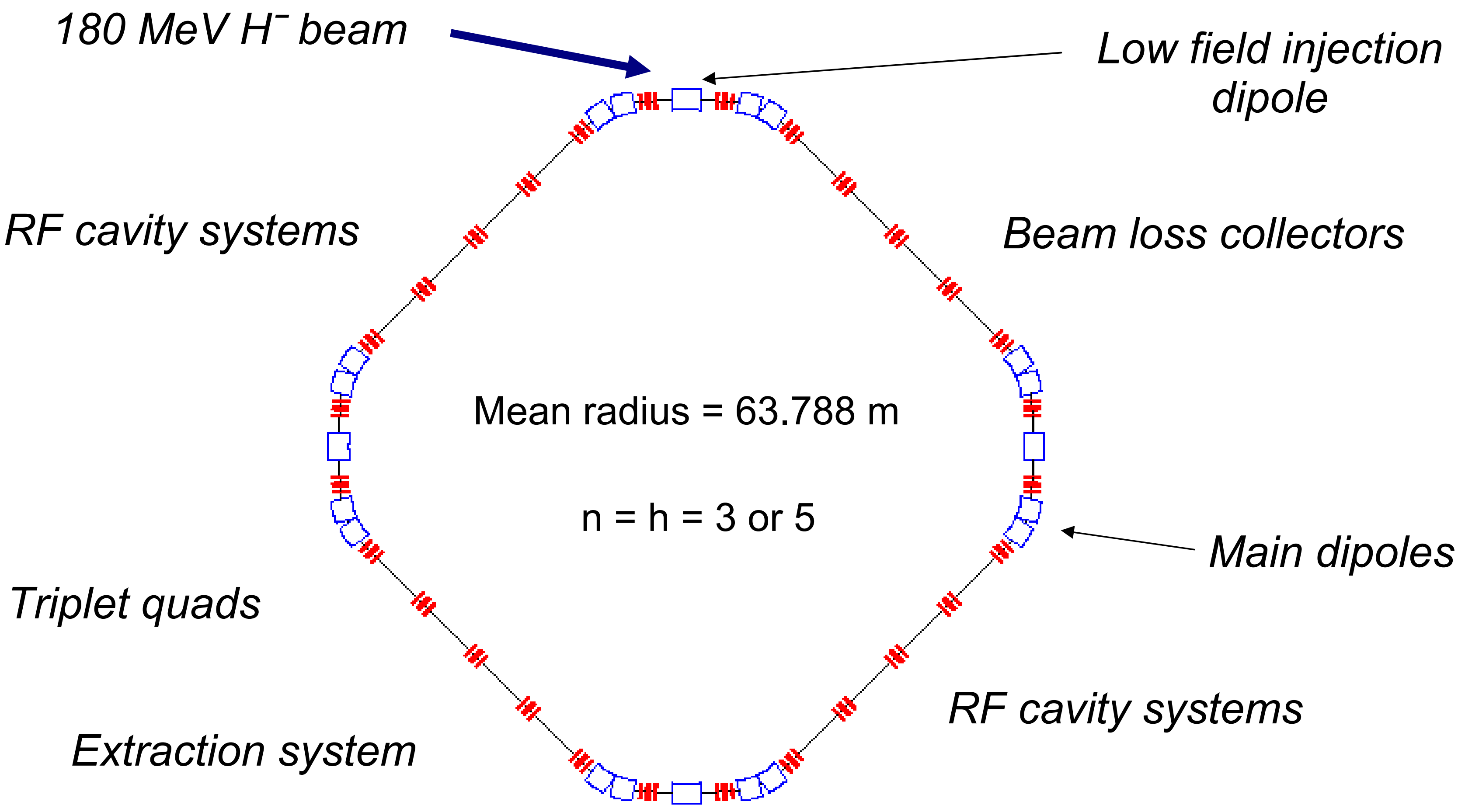
- *Parameters needed so that comparisons may be made with:*
  - *BNL's scheme of single 25 GeV bunches (15/50 Hz)*
  - *FNAL's 8 GeV linac, accumulator+compressor scheme*
  - *CERN's 5 GeV SPL, accumulator+compressor scheme*
- *Comparable tracking studies required*
  - *injection schemes, foil heating etc*
  - *bunch compression*
- *How close can these scenarios come to generating the preferred pulse structure?*

Plans

- Bid submitted for 3 yrs continuation funding to UK/PPARC
- Covers
  - theoretical study of RAL RCS-FFAG 10GeV, 4MW proton driver
    - *Development of FFAG space charge tracking code.*
    - *Injection tracking with space charge in the booster.*
    - *Space charge tracking for booster and driver rings.*
  - completion of PD front-end test stand
- More substantial bid provisionally submitted to CCLRC for high intensity proton “test facility”
  - exact details to be agree
  - *could include an electron model for NFFAG proton driver.*

Plans (continued)

- Accumulator and Compressor ring for SPL (what energy?)
  - injection modelling and bunch compression
- Other SPL scenarios
- Continued work on Ruggiero FFAG proton driver
- other:


180 MeV H⁻ beam
Low field injection dipole
RF cavity systems
Beam loss collectors
Mean radius = 63.788 m
n = h = 3 or 5
Main dipoles
Triplet quads
RF cavity systems
Extraction system

Parameters for 50 Hz, 0.2-3.0 GeV Booster

Number of superperiods	4
Number of cells per superperiod	4 straights + 3 bends
Length of cells	4x14.1+3x14.6
Mean radius	63.788 m
Betatron tunes	Q_v=6.38, Q_h=6.30
Transition gamma	6.57
Energy range	0.18-3 GeV
gamma	1.19-4.197
Main dipole fields	0.185-1.0996 T
Secondary dipole fields	0.0551-0.327 T
Triplet length/quad gradient	3.5 m/1.0-5.9 Tm^{-1}