Other Scenarios for a partial Upgrade of the Injector Complex

C. Carli
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- Introduction
- Requirements and Assumptions
- New PS Injector
  - SPL
  - General Considerations on Rings
  - Rapid Cycling Synchrotron with $h_{RCS} = 1$
  - Rapid Cycling Synchrotron with “geometric” PS Filling
  - “SuperBooster”
  - FFAG
- Impact on Beams
- Summary and Outlook

Introduction

Reasoning for "standard" upgrade proposal

- PS2 to replace PS with priority
  - Ageing PS magnets a concern
  - Increase of maximum energy
  - Conventional magnets ("fast" cycling, reliability and versatility)
  - ➠ Longer circumference
- SPL as new PS2 injector
  - PS2 with existing Booster would reduce the performance of the Complex
  - Superconducting proton Linac offering
    - Potential for future projects
    - Cost only slightly higher than a RCS
- SPS Upgrade
  - Nominal LHC beam already at the limit of performance of present SPS

➠ SPL + PS2 + SPS Upgrade are a package to be implemented/constructed simultaneously

Alternative Scenarios

After renovation: PS magnets not in worse shape than other machines?

Choice for conventional magnets not questioned (no proposal for superconducting PS)

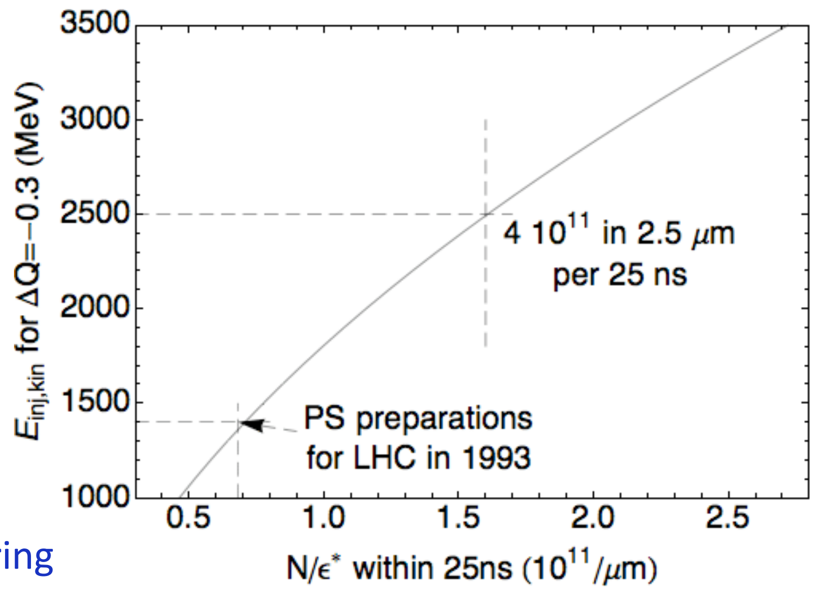
Higher injection energy does not improve for main SPS limitation (e-cloud)

Start by replacing SPS (Not considered here)

Main topic of this presentation: new Injector for the PS to raise:
- injection energy
- and, thus beam brilliance

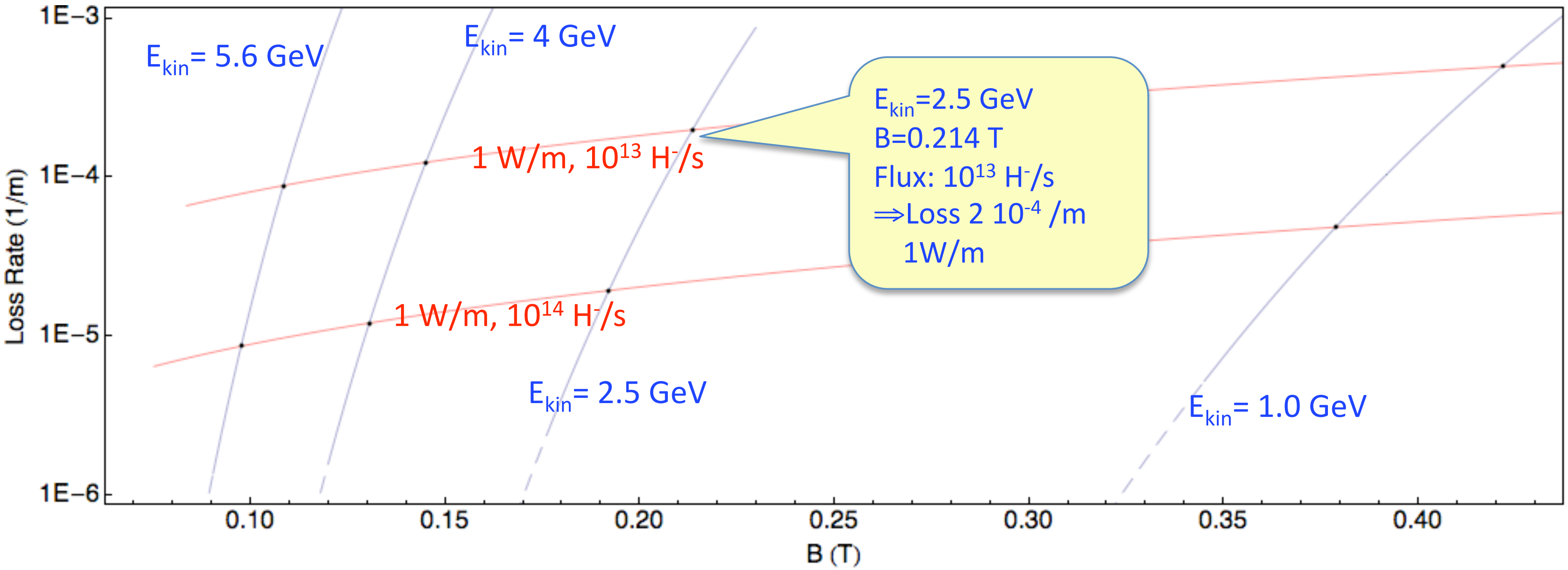
Requirements and Assumptions

- LHC Scenarios should drive considerations on requirements
  - N = 4 10^{11} protons per bunch spaced by 25 ns with $\varepsilon_T^* = 2.5$ μm at PS injection
    - Twice ultimate intensities allowing for 15% losses and "nominal" emittances
    - Maximum "brilliance" $N/\varepsilon_T^* = 1.6\ 10^{11}$ /μm
    - ε_l fitting SPS acceptance (0.35 eVs at 26 GeV/c) … allows increasing ε_l at PS injection
  - Fits with PS2 assumptions (for comparisons), covers most (but not all!!) LHC scenarios
    - Revise when LHC upgrade scenarios become
- Main limitation: direct transverse space charge effects
  - Maximum "Laslett" tune shift for PS: $\Delta Q = -0.30$
    - PS injection at 2.5 GeV
  - Maximum for PS injector: $\Delta Q = -0.35$ (or -0.45)
  - Bunching factor B_f estimate:
    - 70% of bucket occupied by beam
    - Reduction with synchronous angle
- Injection above transition not considered
  - ☺ Avoids transition crossing ($E_{kin,inj} > 5.6$ GeV)
  - ☹ Cost, how to avoid transition crossing in injector ring



New PS Injector: SPL

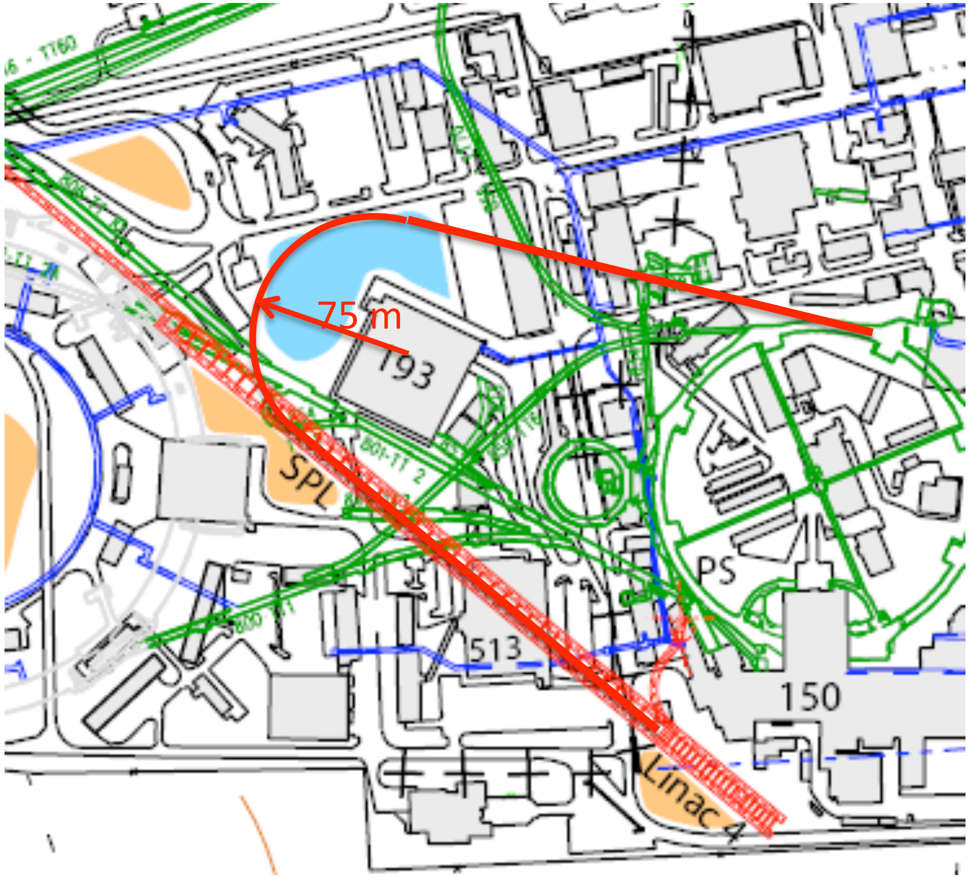
- Extrapolate from present design to required energy
  - Length to reach 2.5 GeV: ~300 m (in addition to Linac4)
- Lorentz Stripping in transfer line
  - Formulas from Handbook of Accelerator Physics and Engineering



- Limit power deposition to 1 W/m … with 10^{13} to 10^{14} H^-/s
  - For 2.5 GeV: average field 0.15 T and mean radius of 75 m!
  - For 5.6 GeV: move Linac4 … no practical solution to reach PS with present location

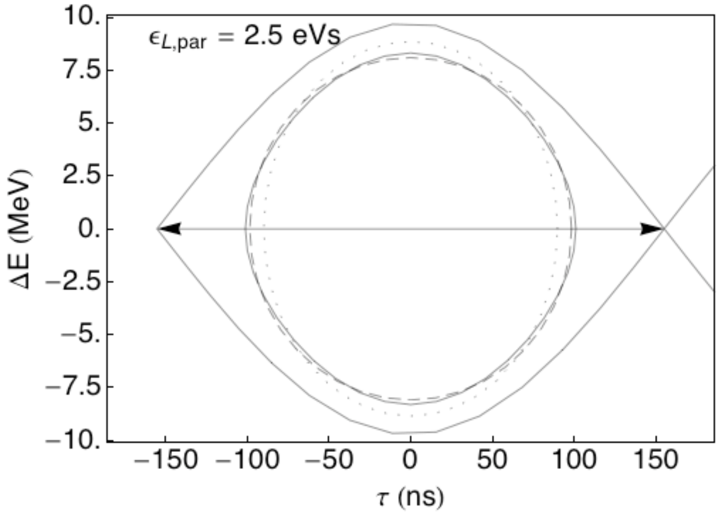
New PS Injector: SPL

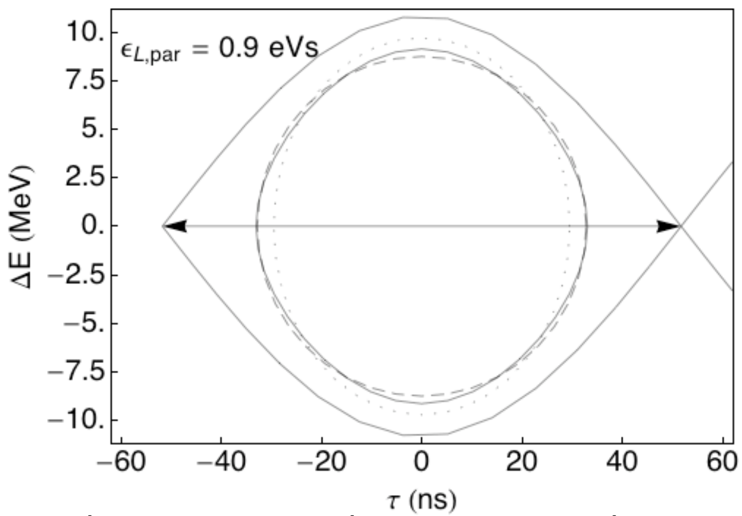
- Geometry (just to fix ideas) for 2.5 GeV:
  - Length of SPL ~300m (in addition to Linac4, extrap. from sLHC Proj. Rep. 0015)
  - ~500 m transfer line
- PS Injection
  - New H^- charge exchange injection to be constructed
  - Flexibility to generate suitable PS bunch structures (SPL chopper, painting?)
  - Close to East Hall ejection
- Simplified PS RF system with ~40MHz possible for LHC protons only (see PS2 scheme)



New PS Injector: General Considerations on Rings

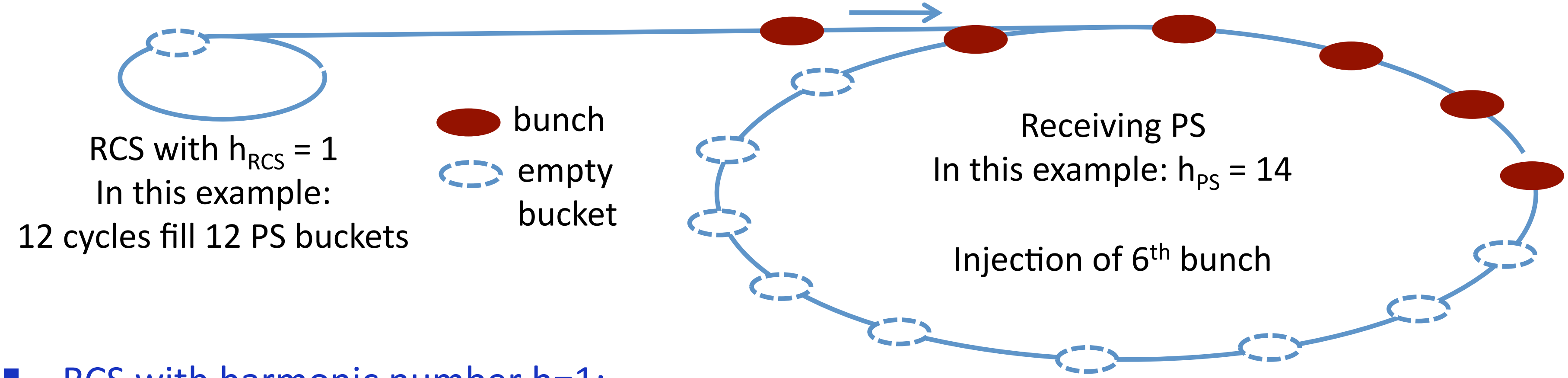
- Possible PS harmonic numbers
  - Factor 7 in PS harmonic number required to avoid complex RF gymnastics
  - For new PS injector rings not larger than h_{PS} = 21 (spacing ~100 ns): o.k. for 10 MHz PS cavities and ≤40 ns PS injection kicker rise time
- Larger long. emittance at PS injection desirable for fast cycling injector rings:
  - ☺ Larger bunching factors with smaller synchronous angle (price: larger RF voltage)
  - Assumed for h=7: $\varepsilon_{L,par}$ = 2.5 eVs
  - Assumed for h=21: $\varepsilon_{L,par}$ = 0.9 eVs
- Linac4 extension required to reach injection energy of PS injector





h_{PS}=7, V_{RF}=51 kV   buckets on a 2.5 GeV PS injection plateau h_{PS}=21, V_{RF}=14 kV

New PS Injector: RCS with h=1



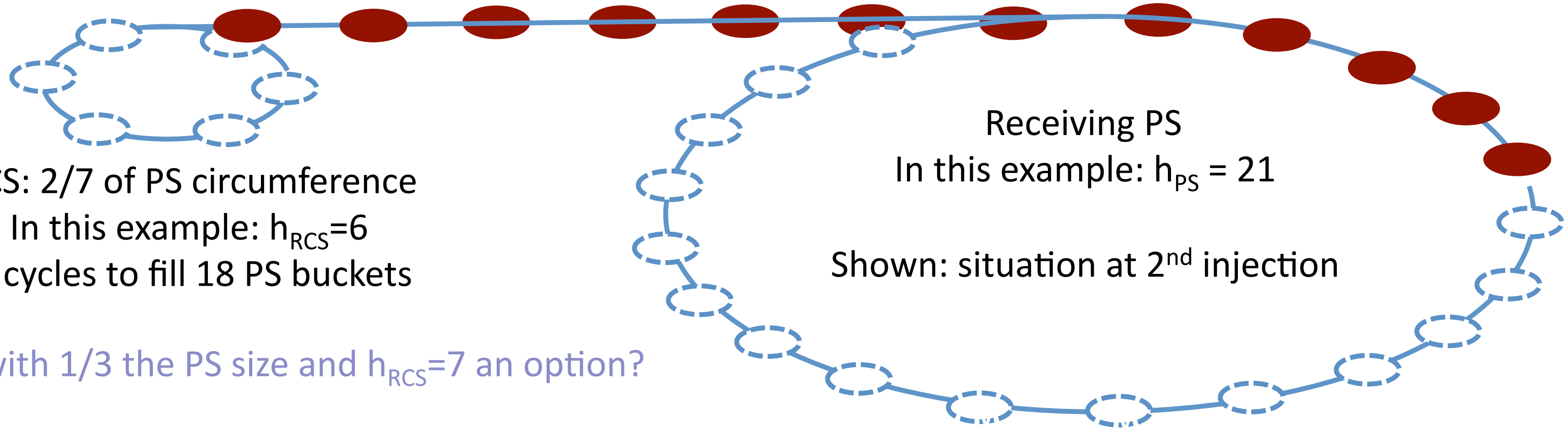
- RCS with harmonic number h=1:
  - Many transfers (more than circumference ratio):
    - ☺ to reduce RCS intensity (brightness) and injection energy
    - ☹ long PS filling time or high repetition rate
  - ☹ In general large synchronous angle and small bunching factor
- Assumptions:
  - Filling of (i) 12 out of 14 PS buckets or (ii) 6 out of 7 PS buckets (for LHC type beams)
  - Acceleration with dB/dt = const. within 50 ms (say 10 Hz repetition, 1.1 or 0.5 s PS filling time) or within 25 ms (say 20 Hz repetition, 0.65 s or 0.25 s PS filling time)
  - R=25 m (as Booster) … slight increase would not change dramatically
  - $1/\gamma_{tr}^2 = 0$ (η dominated by $1/\gamma^2$)
  - Only single harmonic RF considered (no bunch flattening with 2nd harmonic RF)

New PS Injector: RCS with h=1

	h_{PS} = 7					h_{PS}=14			
N in 2.5 μm (10^{11})	4.0				8.5	4.0			
$E_{kin,ej}$ (MeV)	2500				4000	2500			
$\langle B \rangle_{ej}$ (T)	0.44				0.65	0.44			
$\varepsilon_{L,par}$ (eVs)	2.5	2.5	1.3	2.5	2.5	1.25	1.25	0.65	1.25
ΔQ	-0.35	-0.45	-0.35	-0.35	-0.35	-0.35	-0.45	-0.35	-0.35
$T_{acceleration}$ (ms)	50	50	50	25	50	50	50	50	25
$E_{kin,inj}$ (MeV)	675	510	840	755	1550	380	270	500	440
$\langle B \rangle_{inj}$	0.175	0.147	0.201	0.188	0.308	0.124	0.102	0.146	0.135
Bunch. Fact. @inj	0.279	0.289	0.219	0.246	0.216	0.239	0.247	0.184	0.209
V_{RF} (kV)	52	62	31.3	77	44	47	52	32.8	76
Sync. phase ϕ_s	23.8^0	21.8^0	36.8^0	30.7^0	37.4^0	32.2^0	30.5^0	44.8^0	39.0^0

- Magnetic field: in general small swing, maximum field for 2.5 GeV seems o.k.
- RF Voltages: typically 50kV to 60kV, less for small emittance more for fast acceleration
- Matching with PS: beam arrives with small bunch length (even for h_{PS}=14 !!) … probably sufficient to reduce RF voltage arriving at the flat-top
- Acceleration with large phase ϕ_s and small bunching factors?

New PS Injector: RCS with "geometric filling"



RCS with 1/3 the PS size and h_{RCS}=7 an option?

- RCS with harmonic number larger than h=1:
  - Number of transfers given by circumference ratio
    - No increase of brightness in receiving machine a short spacing between bunches
  - Large harmonics allow increasing the bunching factor (large RF voltage as well)
- Assumptions
  - 2/7 times the PS size => R = (200/7) m = 28.57 m (slightly larger than PSB)
  - Filling of (i) 18 out of 21 PS buckets or (ii) 6 out of 7 PS buckets (for LHC type beams)
  - Acceleration with dB/dt = const. within 50 ms (say 10 Hz repetition, 0.2 s PS filling time) or within 100 ms (say 5 Hz repetition, 0.4 s PS filling time)
  - $1/\gamma_{tr}^2 = 0$ (η dominated by $1/\gamma^2$)
  - Only single harmonic RF considered (no bunch flattening with 2^{nd} harmonic RF)

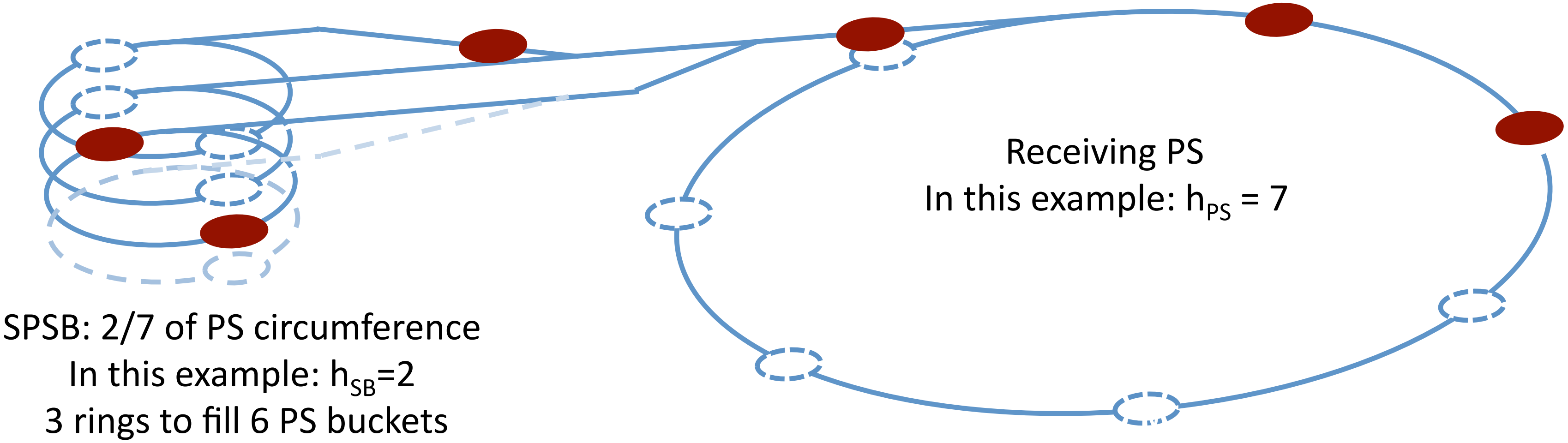
New PS Injector: RCS with “geometric filling”

	h_{RCS} = 2 & h_{PS} = 7					h_{RCS} = 6 & h_{PS}=21			
N in 2.5 μm (10^{11})	4.0				8.5	4.0			
$E_{kin,ej}$ (MeV)	2500				4000	2500			
$\langle B \rangle_{ej}$ (T)	0.39				0.57	0.39			
$\varepsilon_{L,par}$ (eVs)	2.5	2.5	1.3	2.5	2.5	0.9	0.9	0.45	0.9
ΔQ	-0.35	-0.45	-0.35	-0.35	-0.35	-0.35	-0.45	-0.35	-0.35
$T_{acceleration}$ (ms)	50	50	50	100	50	50	50	50	100
$E_{kin,inj}$ (MeV)	1070	840	1250	990	2190	950	750	1080	910
$\langle B \rangle_{inj}$	0.207	0.177	0.231	0.197	0.348	0.191	0.164	0.209	0.186
Bunch. Fact. @inj	0.333	0.340	0.273	0.361	0.269	0.380	0.385	0.327	0.398
V_{RF} (kV)	79	102	37.6	64	51	196	259	72	175
Sync. phase ϕ_s	13.5^0	12.1^0	24.9^0	8.7^0	25.9^0	5.8^0	5.0^0	14.5^0	3.3^0

- High injection energies !!
- Small magnetic field swing, maximum field for 2.5 GeV o.k.
- RF Voltages: typically 60kV to 100kV for h_{RCS}=2, less for small emittance more for fast acceleration, higher for h_{RCS}=6.
- Matching with PS: make sure that bunches are long enough
- Synchronous phase ϕ_s reduced in particular for h_{RCS}=6 … improves bunching factor !!

New PS Injector: Super-Booster SPSB

For completness



3 SPSB rings with 1/3 the PS size and h_{SPSB}=7 an option?

- Natural approach for LHC (similar to RCS with “geometric fillig”):
  - 2/7 times the PS size => R = (200/7) m = 28.57 m (slightly larger than PSB)
  - Three rings with h_{SB} = 2 to fill of 6 out of 7 PS buckets (no advantage with larger harmonics)
  - Second harmonics RF system (“small” RF voltages) and bunching factor B_f = 0.55
- Results
  - ΔQ = -0.35: $E_{kin,inj}$ = 680 MeV
  - ΔQ = -0.45: $E_{kin,inj}$ = 530 MeV

New PS Injector: FFAG

- Study of RCS options:
  - Small swing of magnetic field even for $h_{RCS} = 1$
  - "High" repetition desirable for large h_{PS}
- FFAG options:
  - Scaling FFAG (principle of first FFAGs studied ~50 years ago):
    - Large aperture with "small index" … spiral shape helps a bit, or
    - Large circumference with strong focusing by combination positive & negative bends
  - Linear non-scaling FFAG:
    - No non-linear fields, but the working points moves (over integer resonances !!)
  - "Tune-stabilized" or "zero chromaticity" (non-linear non-scaling) FFAG
    - Shape magnetic fields to fix working point ….
      Some non-linear fields
  - Presently a very active field with "novel" approaches
- Cost effectiveness: long circumference, large apertures, high RF gradient
  - Superconducting magnets (no ramping) to make the FFAG aperture smaller?
- Scaling from proposals (next 2 slides) …. to get a first idea
  - Detailed study required: size, injection energy, apertures, RF voltages … .
  - Direct space charge limitations: ΔQ=-0.3 feasible at least for non-linear non-scaling FFAG?

At a first glance:
- FFAG may be an attractive option
- but no gain from very large acceptances (for LHC)

Seems the most attractive option at a first glance

New PS Injector: FFAG

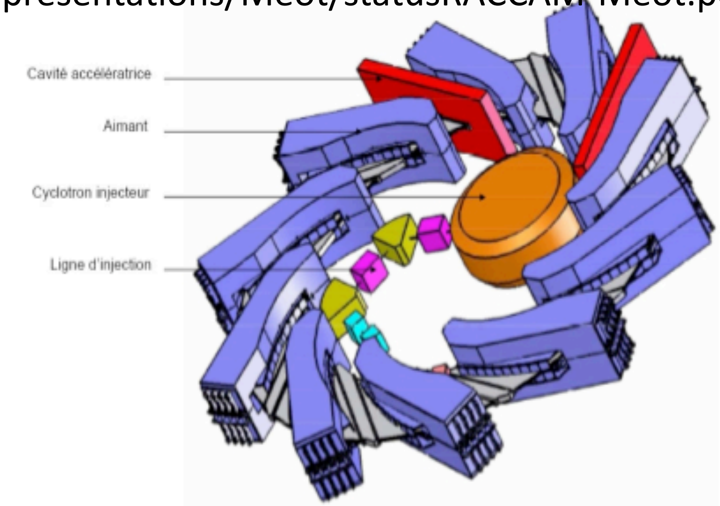
Extrapolation for scaling FFAG from RACCAM proposal

Scaling FFAG for medical applications (1.7 T peak field, 6 kV RF, acceleration in ~10 ms)

Final parameters of the RACCAM 10 cell ring and magnet :

Slide from FFAG08: http://www.cockcroft.ac.uk/events/FFAG08/presentations/Meot/statusRACCAM-Meot.pdf

Extracion energy, variable	70 – 180 MeV
Injection energy	5.5 – 17 MeV
Nomentum ratio	3.62
Number of cells	10
Packing factor	0.34
Field index, k	5
Spiral angle	53.7 deg.
Qh / Qv	2.76 / 1.55~1.60
Radius on extraction/injection orbit : dR	3.46 m / 2.78 m / 0.67 m
Drift length, extraction/injection orbit	1.42 m / 1.15 m
Frev, 15->180 MeV	3.03 -> 7.54 MHz
Frev, 5.5->70 MeV	1.86 -> 5.07 MHz



Scaling size by 5.6 yields:
- energy range: 440 MeV -> 2.5 GeV
- injection/ejection radius: 15.57m/19.38m
- RF: 2.2 MHz to 2.4 MHz

More sectors and larger spiral angle would improve (how much)

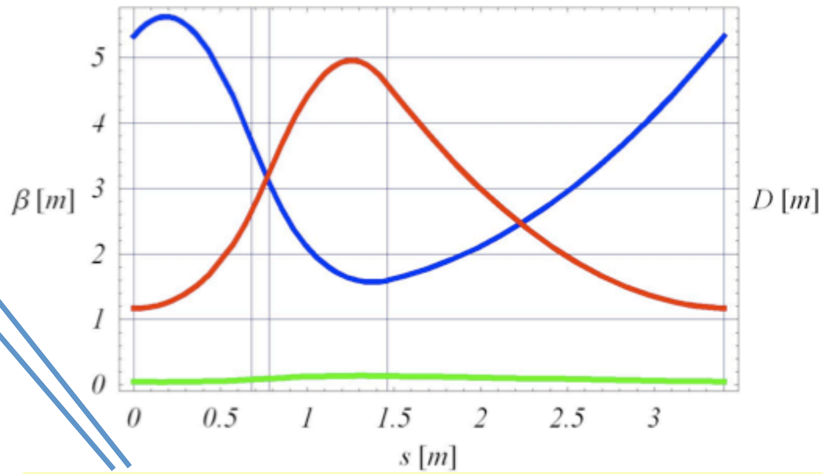
New PS Injector: FFAG
Scaling FFAG from RACCAM proposal

Non-scaling non-linear FFAG as proton driver … still some working point variations during acceleration

Preliminary design parameters (alternative 1)

Slide from FFAG08: http://www.cockcroft.ac.uk/events/FFAG08/presentations/Pasternak/FFAG08JP.ppt

• N of cells	64
• Lattice type	dublet
•R	34.6 m
•(Qx, Qy)/cell	(0.269, 0.19)
•B_{max}	1.7 T
• Magnet packing factor	0.4
•E	0.3 - 2.5 GeV
•h	5
• RF swing	4.5– 6.5 MHz
• Drift length	1.9 m
• γ_T	37.6



- Energy range and peak field look fine
- orbit excursions: ~20 cm (total)
- RF voltage, acceleration (h=1 !!) to be defined
- Detailed studies required: working point during acceleration, direct space tune shift ….. .

FFAG'08 04.09.2008 J. Pasternak, IC London/RAL

Impact of a new PS Injector on Beams

- Rapid cycling rings: PS Injection plateau required for accumulation
  - Increased PS cycle length reduces proton flux ?
- LHC proton beams:
  - Increased beam brightness available at PS ejection (probably o.k. for PS with transition crossing …., not highest intensities for PS)
  - SPS upgrades required (e-cloud)
- Ions:
  - No impact (LEIR remains as ion injector), except
  - In case of SPL as PS injector: option for RF renovation with "tunable 40 MHz" system (see PS2 proposal), scheme for ions to be worked out (based on ideas for PS2)
- High Intensity (CNGS like):
  - Changes of details of RF manipulations in some cases (h_{PS}=7, splitting to h_{PS}=14 for RCS with "geometric filling" and Super-Booster)
  - No significant impact on performance compared to Linac4 alone - limitations at transition crossing … will accumulation plateau with rapid cycling rings change the picture
- ISOLDE:
  - Potential to improve performance with all options (acceptances, repetition rates …),
  - FFAG option: fixed ejection energy a problem

Summary and Outlook

- Investigations on new PS injectors for higher brightness LHC proton beams
  - SPL type and several injector rings investigated
  - Basic parameters (size, injection energy …..) estimated to obtain brightness expected with PS2 design
  - More studies required to compare different options
- Impact on beams:
  - Significant increase of brilliance of LHC proton beams … require SPS upgrades
  - Potential for continuation of all present PS complex physics programs
- Outlook:
  - Scenario for construction: new tunnels or re-use PSB tunnel?
    - New tunnels since 2-3 years stop inacceptable … preparations in parallel until connection
  - Possible further in-depth studies:
    - More detailed investigations (acceptances …) and cost estimates for comparison of different options
    - Feasibility of FFAG
    - Other limitations than direct space charge … during accumulation in PS
    - Detailed analysis of impact on operations and beams (longer PS injection plateau, gain for ISOLDE …) other than LHC