Hadron Injector Options

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With plenty of input from:

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Main objectives and outline

Injector chain to fill collider (FCC-hh) with more than 20000 high brightness bunches

- **General considerations**
- **Possible options:**
  - **Expected parameters**
  - **Advantages and disadvantages**
- **Required topics for studies and R&D programme to single out most promising option(s) for a design study**

"use existing facilities, previous efforts/studies"

Previous studies: SSC (1992)

	E range	$\frac{E_{extr}}{E_{inj}}$	cycle rate	p/bunch	
Linac H^-	0 - 0.6 GeV	-	10 Hz	$1.0\ 10^{10}$	NC
LEB	0.6 - 11 GeV	18.3	10 Hz	$1.0\ 10^{10}$	NC
MEB	11 - 200 GeV	18.2	0.125 Hz	$1.0\ 10^{10}$	NC
HEB	0.2 - 2.0 TeV	10	$\approx$ 10 mins$^{*)}$	$1.0\ 10^{10}$	SC
Collider	2.0 - 20 TeV	10	-	$0.75\ 10^{10}$	SC
HEB	0.2 - 2.0 TeV	10	$\approx$ 1 min$^{**)}$	$\geq 1.0\ 10^{10}$	SF

See e.g.: G. Dugan, SSCL-Preprint-84

Apply rule of "twenty" for energy increase: $\frac{E_{extr}}{E_{inj}} \leq 20$

$^{*)}$ Filling two collider rings. Alternating, bipolar operation !
$\approx$ 10 injection cycles to fill SSC ring.

$^{**)}$ Design option 1985, 2-in-1 magnets.

Is SSC study relevant ?

Try a näive scaling:

	SSC	**scaled SSC ($\times$ 2.5)**
LEB	**11 GeV**	**27 GeV**
MEB	**200 GeV**	**500 GeV**
HEB	**2 TeV**	**5 TeV**
Collider	**20 TeV**	**50 TeV**

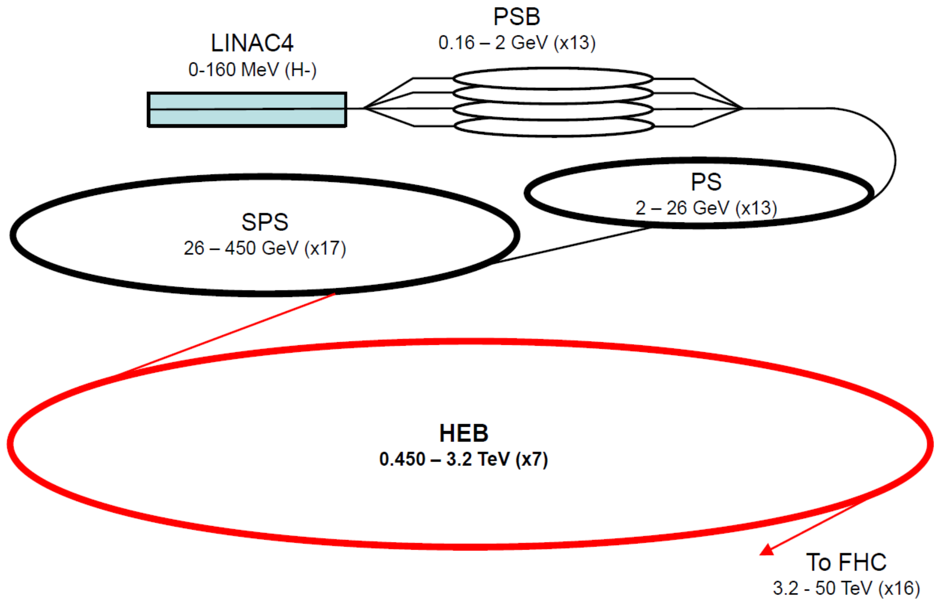
Emittance requirements

Emittance budget (for nominal intensity) in SSC/LHC [μm]:

	SSC design		LHC design	
	emittance in	emittance out		extracted
Linac H^-	0.2	0.3	Linac2	1.0
LEB	0.3	0.6	PSB	2.5
MEB	0.6	0.7	PS	3.0
HEB	0.7	0.8	SPS	3.5
Collider	0.8	1.0 ($\mathcal{L}$ target)	LHC	3.75

Can assume similar performance or better (present LHC is better due to injector perfomance, but not yet at 7 TeV and 25 ns spacing)

Possible injector chain



- Assumption: not a completely new injector chain
- Relying on existing (upgraded) facilities up to SPS (at least in a first step)
- Have to build High Energy Booster (HEB)

Assumptions

- **Energy of collider (maximum 50 TeV)**
  - **Reuse existing facilities as much as possible (no additional tunnel)**
  - **Can maintain intensity and brightness as provided for HL-LHC ($\leq$ 2.5 $\cdot$ 10^{11} p/b, $\epsilon_n \approx$ 2 μm)**
  - **Assumed bunch spacing 25 ns, $\approx$ 11000 bunches per beam in collider, relevant for number of injections**
  - **HEB must inject two beams into collider at reasonably short filling time, implications for complete injector chain**
  - **Reasonably short: unknown**

Present machines and available/planned tunnels

- **No new tunnel, put HEB in available tunnel**

Parameter	SPS (present)	LHC (present)	collider
Circumference [m]	6912	26659	100000
Number of dipoles	744	1232	4400
Dipole length [m]	6.2	14.3	15
Inj. dipole field [T]	0.12	0.53	1
Max. dipole field [T]	2.03	8.33	16
Ramp time [s]	10.8	1100	
Ramp rate [T/s]	0.177	0.007	

Key issues for all options

- **Injection and extraction energy**
- **Dipole field, number of dipoles, technology**
- **Operational cycle**
  - **Injection of <u>two</u> beams into collider**
  - **Ramping time and collider filling time (number of bunches and injections (HEB size), injector chain cycle time)**
- **Stored energy in HEB and transfer lines**

Optimum energy of HEB

- Assuming SPS as candidate for MEB (0.45 TeV)
- Energy increase factor less than 20 for collider (LHC is 16), but several ramps required for HEB
- For reasonable collider energy range: HEB to provide 3.0 - 4.0 TeV
- Energy increase factor in HEB modest ($\leq$ 8)

→ Energy one of the two critical key parameters to be defined

Magnet technology options

Type	B_{max} [T]	$\dot{B}$ [T/s]	B_{max}/B_{min}
Norm. Cond.	**2.0**	**4**	**40**
Superferric	**2.5**	**2**	**40**
SC (NbTi), low field	**5.0**	**1.4**	**15**
SC (NbTi), high field	**9.0**	**0.2**	**15**
SC (Nb3Sn)	**16.0**	**0.025**	**15**

Existing at CERN and operational:

Type	B_{max} [T]	$\dot{B}$ [T/s]	B_{max}/B_{min}
SPS (NC)	**2.0**	**1**	**28.6**
LHC (NbTi)	**8.33**	**0.007**	**15.6**

Challenges for all options

- **Preservation of transverse emittance, vital for luminosity and beam-beam effects**

  (through whole injector chain)

- **Field imperfections and dynamic effects from fast ramping**

- **Filling time of collider, beam dynamics and operation**

  First clue 10 min (LHC), conservative

- **Availability (several successive ramps required)**

- **Possible collective effects**

Transfer of two beams to collider

- **Options are:**
  - **- Two-in-one magnet design*)**
  - **- bipolar operation of HEB**
  - **- unipolar operation of HEB**
- **Dipole field and technology considerations**
- **Implications for layout and operation (easy injection, injection sequence, beam transfer, ...)**
- **Avoid very long transfer lines for high (3.2 TeV) energy**

*) **Fixed target operation or collisions in HEB ??**

Alternative use of HEB

In case alternative use of HEB is considered:

- **Fixed target operation**
  - **- Slow extraction ?**
  - **- Total intensity ?**
  - **- Ramp rate and availability ?**
- **As collider:**
  - **- Lifetime ?**
  - **- Collimation ?**
  - **- Insertions for experiments ?**

Detailed studies needed ..

Collective effects

- **Need to be studied to control beam brightness**
- **Detailed studies required**
  - **Space charge, IBS (in particular for 100 km option)**
  - **Impedance**
  - **Electron cloud (HEB)**
  - **Electron cloud (collider)**
  - **Implications for ions ?**

Possible strategies to use existing facilities

- **HEB in SPS tunnel**
- **HEB in LHC tunnel**
  - **New machine for lower energy (new magnets)**
  - **Re-use LHC as HEB ?**
- **HEB in collider tunnel**

Most layout and beam parameters follow from the choice

Option: HEB in SPS tunnel

Parameter	SC Very high field	SC High field	SC Low field
E_{inj} [TeV]	0.45	0.45	0.45
E_{top} [TeV]	3.5	2.0	1.1
collider inj. field [T]	1.12	0.63	0.35
B_{inj} [T]	2.09	2.09	2.09
B_{top} [T]	16.0	9.0	5.0
Type	Nb3Sn	NbTi	NbTi
Ramp rate [T/s]	0.025	0.20	1.40
Extractions to collider	14	14	14
Est. filling time [min]	243	23	8
Stored energy (MJ)	40.4	22.8	12.7

Option: HEB in SPS tunnel

- **Pros:**
  - MEB to HEB transfers (same lengths)
  - Number of dipoles and cost
  - Stored energy
- **Contras:**
  - Dipole field ($\geq$ 12 T)
  - Required extraction energy only with SC Very High Field (low ramp rate)
  - HEB to collider extractions (number and transfer lines)
  - Collider filling time very long
  - No scope for higher energy upgrade

Option: HEB in LHC tunnel

Parameter	Present LHC SC high field	SC low field	SF	NC
E_{inj} [TeV]	0.45	0.45	0.45	0.45
E_{top} [TeV]	6.5	4.2	2.1	1.7
collider inj. field [T]	2.08	1.34	0.67	0.67
B_{inj} [T]	0.54	0.54	0.54	0.54
B_{top} [T]	7.7	5.0	2.5	2.0
Type	NbTi	NbTi	SF	NC
Ramp rate [T/s]	0.007	1.40	2.00	4.0
Extractions to collider	4	4	4	4
Est. filling time [min]	76	9	9	9
Stored energy (MJ)	266	172	86	70

HEB in LHC tunnel

- **Pros:**
  - Dipole field ($\leq$ 5 T)
  - Stored energy
  - Collider filling time, number of cycles smaller for 2-in-1 magnets
- **Contras:**
  - Too low extraction energy for SF and NC
  - Cost (new magnets)
  - Transfer lines for 3 - 4 TeV
  - Collider filling time for high energy/field option

Option: HEB in collider tunnel

Parameter	SF	NC
E_{inj} [TeV]	0.45	0.45
E_{top} [TeV]	8.0	6.4
B_{inj} [T]	0.14	0.14
B_{top} [T]	2.5	2.0
collider inj. field [T]	2.56	2.05
Ramp rate [T/s]	2.0	4.0
Extractions to collider	1	1
Est. filling time [min]	10	10
Stored energy	1382	1106

HEB in collider tunnel

- **Pros:**
  - **Dipole field ($\leq$ 2.5 T, or smaller filling factor), higher extraction energy**
  - **Single extraction and ramp to fill collider**
  - **Option for SF or NC dipoles (ramp rate, does it matter ?)**
- **Contras:**
  - **Beam dynamics: low injection energy and longer filling time to fill HEB (stability ? needs study)**

    i.e. filling 100 km of LHC with 4 times the filling time
  - **Cost (length, number of dipoles and other systems), integration of collider experiments**

Reuse LHC as HEB

LHC becomes injector

Attractive for several reasons, but studies needed:

- **Modified and simplified lattice layout (synchrotron, no low-β insertions), use of existing extraction concept**
- **Increased ramp rate (10 A/s $\rightarrow$ 50 - 100 A/s ?) for smaller than nominal top energy (e.g. 3 - 4 TeV)?**

  (check all implications !)
- **Decommisioning of insertion regions**

Reuse LHC as HEB

- **Pros:**
  - Understood machine, modified as synchrotron
  - Low energy increase factor (7 - 8)
  - Acceleration of two beams (reduced filling time)
  - Possibility to do experiments and tests now (e.g. cycle strategy) !!
- **Contras:**
  - Long cycle time (unless improved ramp rate, 50 A/s probably sufficient)
  - Beam transfer at 3.5 TeV and new layout
  - New powering, Voltage limits, induced quenches, QPS, ramping strategy
  - Usable for fixed target physics ?

Additional thoughts (LHC or LHC tunnel)

Performance for initial operation:

- **A 2-in-1 machine in LHC tunnel can fill 25% of the FCC-hh in single extraction (one ramp)**
- **Option: LHC as is with extraction system**
- **Using HL-LHC beam parameters and present injector chain**
- **For initial operation: provides $\mathcal{L} \approx 1.5\ 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$**
- **No need to increase ramp speed (one ramp)**

Need to define/study as input (I):

- **Injection energy into collider (will largely determine the choice)**
- **Dwell time at injection energy (defines the filling time, unknown)**
- **Choice of energies in injector chain**
- **Alternative use of HEB (collider, fixed target beams)**
- **Lepton-proton collisions ?**

Need to define/study as input (II):

- **Beam transfer layout (injection energy and transferred energy)**
- **Limitations due to collective effects (e.g. e-cloud)**
- **Ramp rate of existing LHC magnets, powering, cycling, cryogenics power**

Many options.
A cost and feasibility studies needed for all options. Some of the options appear not very promising, may be ruled out rather quickly. For a detailed study should reduce to 2 or 3 most promising.