Preliminary injector linac design

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FCC Meeting
May 11-15 2016, Rome
1. Beam parameters and general linac layout (preliminary);
2. Beam dynamics in RF-gun;
3. Beam dynamics in regular section;
4. RF-gun electrodynamics simulations.
5. ED of regular section incl. 2000 and 3000 MHz comparison.
6. General results and discussion.
7. Technology and other possible MEPhI activities
1. Beam parameters and general linac layout (preliminary)

Base injection parameters:
- Intensity up to $4 \cdot 10^{13}$ e/s;
- $4 \cdot 10^{10}$ e$^-$ / bunch, 10 ps bunches,
- 10 bunches per pulse, bunches are separated with distance 25 or 50 ns (very good, decreases beam loading influence),
- up to 100 Hz pulse repetition rate;

Record space charge domination!!! About 6 nC per bunch

We preliminary discuss two operating frequencies: traditional 3000 MHz and novel 2000 MHz which gives brilliant matching with 400 MHz accelerating cavities proposed for booster. Both give 25 (50) ns bunches separation easily. It gives (for 10 ps laser pulse):

<table>
<thead>
<tr>
<th></th>
<th>3000 MHz</th>
<th>2000 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF period</td>
<td>~330 ps</td>
<td>500 ps</td>
</tr>
<tr>
<td>Bunch phase length</td>
<td>10 degree</td>
<td>6.7 degree</td>
</tr>
<tr>
<td>Physical bunch length (theoretically)</td>
<td>3 mm</td>
<td>5 mm</td>
</tr>
<tr>
<td>Current pulse duration (10 bunches per pulse)</td>
<td>25 or 50 ns</td>
<td></td>
</tr>
</tbody>
</table>
1. Beam parameters and general linac layout (preliminary)

We study two scenarios: high, but not extreme bunch charge as 200-300 pC to define general structure layout and further to design a RF gun for extreme 6 nC (step-by-step, starting with 1 nC).

We can use traditional biperiodical accelerating structure (BAS) in storage energy regime, on \( \mu = \pi/2 \) RF mode, having high shunt impedance and accelerating gradient. We will have no problem with RF power load and coupling here. But other types of accelerating structures should be studied and compared in future (travelling wave DLW with E and M coupling, diaphragms and washers, etc.)

When we accelerate very short bunch (~5 mm) in the storage energy mode, we need to realize some conditions for BAS:

- Low time of power feeding transient process leads to design of high group-velocity structure;
- We need \( V_g \) about 0.10-0.12c to fill 3m length structure during 200 ns;
- If we have 200 ns transient process + 100 ns for reserve, we can decrease time of the SLED storage or klystron power;
- Structure should operate in storage mode and RF coupler will be designed for critical coupling.
1. Beam parameters and general linac layout (preliminary)

**RF-gun**

10-20 regular sections for 2 GeV in total (3000 or 2000 MHz)

**3000 MHz**

- \( \pi/2 \) mode, st. wave
- 12 BAS periods
- \( \sim 60 \) cm of length
- 12 MeV output
- 350 kV/cm on axe (for \( \sim 50 \) nC)

**2000 MHz**

- \( \pi/2 \) mode, st. wave
- 61 BAS periods
- 305 cm length
- 400/600/900 kV/cm
- 70/105/160 MeV per section

- \( \pi/2 \) mode, st. wave
- 41 BAS periods
- 307.5 cm length
- 400/600/900 kV/cm
- 75/110/170 MeV per section

Not enough place for first coupling cell!
Side coupling should be used

**High (12-14 \%) coupling coefficient to achieve high group velocity and low time of transient process!!!**
2. Beam dynamics in RF-gun (for hundreds of pC bunches)

BEAMDULAC-BL code was used for beam dynamics study. It was developed in MEPhI for beam dynamics simulation in e-linacs taking into account Coulomb and beam loading selfconsistently.

12 acc. cells, $E_z=350$ kV/cm, $B_{sol}=0.03$ T, side coupling for 1-2 cells
2. Beam dynamics in RF-gun (for hundreds of pC bunches)

- $I=1$ A, focusing field $B=0.03$ T, $E_t=10$ cm·mrad, $r_0=5$ mm

- Bunch length $\sim 19$ mm
  (is 10 ps too long ???)

- Energy spectrum $\sim 0.7\%$
Coulomb field and beam loading

Beam loading influence is not sufficient for 10-30 A of pulse current and separated bunches: after bunch $E_z$ is less than 0.3% lower than for unloaded structure. For example, if $E_z$ will differ by 0.5%, we will have 11.91 MeV comparatively 11.97 MeV.

$B=30$ mT for $I<20$ A
$50$ mT for $20$
$70$ mT for $25$
$100$ for $30$
no tr. loses

RF-gun will further optimized to minimize $\delta \gamma$
2. Beam dynamics in RF-gun

Beam dynamics in RF-gun for extreme 6 nC bunches (first results are for 1 nC)

- $E_z = 400$ kV/cm (was 350),
- $B_{sol} = 0.40$ T (was 0.10) Aperture was enlarged to 15 mm (was 8 mm)
- $K_t$ is only 75-80 %

After optimization energy spectrum was improved to $\pm (1.5-2.0) \%$

Further for 6 nC it will much more interesting !!!
3. Beam dynamics in regular section

Injection energy is \(~12\ MeV\), length of regular section \(~3\ m\).

<table>
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<tr>
<th>$E_z$, kV/cm</th>
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<tbody>
<tr>
<td></td>
<td>$K_T$, %</td>
<td>$\Delta W_{sec}$, MeV</td>
</tr>
<tr>
<td>400</td>
<td>98.4</td>
<td>69.9</td>
</tr>
<tr>
<td>600</td>
<td>98.4</td>
<td>104.9</td>
</tr>
<tr>
<td>900</td>
<td>98.4</td>
<td>157.5</td>
</tr>
</tbody>
</table>

Low field scenario
Real scenario
Optimistic scenario

Pulse current 30 A, injection distribution is taken after RF-gun,
$\Delta W_{sec}$ is energy gain per section, $K_T$ is current transmission for first regular section.

$kV/cm$

400
600
900

$I_0=$30 A
$B=100$ mT

3000 MHz

2000 MHz
3. Beam dynamics in regular section

Coulomb field and beam loading

Current transmission and bunch length v. pulse current (3000 MHz left, 2000 MHz right)

Beam loading influence is not sufficient for 30 A and 10 ps of pulse current: after bunch $E_z$ is less than 0.25% lower than before bunch. If $E_z$ will differs 0.5%, we will have (Table)

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<tbody>
<tr>
<td></td>
<td>100 %</td>
<td>99.5 %</td>
</tr>
<tr>
<td>400</td>
<td>82.4 *</td>
<td>82.04</td>
</tr>
<tr>
<td>600</td>
<td>116.4</td>
<td>115.9</td>
</tr>
<tr>
<td>900</td>
<td>169.0</td>
<td>168.2</td>
</tr>
</tbody>
</table>

* Energy (MeV) after RF-gun and first regular section
4. RF-gun electrodynamics simulations

We haven't enough place for first coupling cell and side coupling for 1st and 2nd accelerating cavities was simulated.

Section parameters:

\( \pi/2 \) mode
standing wave
\( f=3000 \text{ MHz} \)
12 BAS periods (one side-coupled),
59 cm of length
12 MeV output
\( E_z=350 \text{ kV/cm} \)
Storaged energy mode
Coupling with RF source - critical
\( Q \)-factor 6600 (first cell) and 15500 (regular cell)
\( R_{sh}=80 \text{ MOhm/m} \) (regular cells)
Coupling coefficient (regular cells) 11.5 \% and 4 \% (1-2 cells, should be increased further)
Time of transient process ~120 ns
Necessary RF power \( P_{rf}=26 \text{ MW} \)
5. Electrodynamics of regular section

\[ \pi/2 \text{ mode} \]

Standing wave

Storaged energy mode

Coupling with RF source - critical

- Acc. cell diameter, mm: 76, 116
- Length of acc. cell, mm: 38, 63
- Length of coupling cell, mm: 4, 4
- \( Q \)-factor: 15500, 13700
- \( R_{sh} \), MOhm/m: 79.5, 49.7
- Coupling coefficient, %: 11.5, 11.0
- Group velocity: 0.102c, 0.11c
- Time of transient process, ns: 200, 185

3000 MHz

2000 MHz
5. Electrodynamics of regular section

Necessary RF power, MW

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<tr>
<td>400</td>
<td>61</td>
<td>99</td>
</tr>
<tr>
<td>600</td>
<td>138</td>
<td>223</td>
</tr>
<tr>
<td>900</td>
<td>311</td>
<td>501</td>
</tr>
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</table>

For traditional SLED amplification coefficient eq. 4 it gives $15/35/75$ of necessary klystron power for 3000 MHz or $25/56/125$ for 2000 MHz (is amp. Factor =6 available ??)

3000 MHz:
61 acc. cells, 305 cm

2000 MHz:
41 acc. cells, 307.5 cm
6. General results and discussion

3000 MHz vs. 2000 GHz

• Well known
• Many klystrons are available (SLAC, Thales, Toshiba, …)
• Higher $R_{sh}$ and lower necessary RF power
  • No simple matching with 400 MHz frequency in booster
• Difficulties in design of RF-gun first cell

• Brilliant matching with 400 MHz frequency in booster
• No problem in design of RF-gun first cell
• Higher (~5 %) rate of the energy gain
• Conceptually new (but 1.3 and 1.8 GHz bands are widely used)
• No RF power sources
• Lower $R_{sh} \rightarrow$ twice higher necessary RF power
7. Technology and other possible MEPhI activities

MEPhI + Korad Co., LLC project of 10 MeV/20 kW industrial linac

Commissioned in Sep. 2015
HL-LHC: DEVELOPMENT OF THE SUPERCONDUCTING 800 MHZ HARMONIC CAVITY

Different higher order modes damping techniques were proposed and compared.

HIGHER ORDER MODES DAMPING IN SPS TW ACCELERATING CAVITY AT 200 MHz

Several longitudinal HOM’s near 630 MHz could limit the maximum beam intensity in SPS accelerator. MEPhI RF-Lab is also contributing in the development of the improved HOM damping system.
DESIGN OF HIGH POWER INPUT COUPLER FOR CORNELL ERL INJECTOR CAVITIES

Adjustable power coupler for superconducting injector cavities of Cornell ERL project has been designed. Feeds 75 kW CW @1.3GHz. Several couplers produced at Beverly Microwave (CPI) and tested.

BEAM DEFLECTOR SYSTEMS for PITZ (X-FEL) developed (cooperation with Nuclear Research Institute of RAS and Introscan LLC as industrial partner. Now under commissioning at DESY.
MULTIPACTOR DISCHARGE SIMULATIONS

Codes: MultP-STL (by MEPhI) and CST PS (By CST AG),

New RFQ injector for NICA (JINR) collider

JINR+MEPhI+ITEP project for Nuclotron-NICA injection complex modernization
Thank you!