Analysis of Injection and Recovery Schemes for a Multi-turn ERL based Light Source

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Outline

1. Introduction
2. ERL as a light source
    a) Single-turn scheme with direct injection
    b) Single-turn scheme with a preinjector
    c) Multi-turn scheme with a preinjector
3. BBU instability and Linac optics for different schemes
4. Summary:
    a) Comparison of the results
    b) Rough estimation/comparison of costs

Projects with ERLs

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ERL as a Light Source

- high average current
- technologically mature
- energy efficient

- low emittance is possible
- low energy spread is possible
- long undulators
- short pulses

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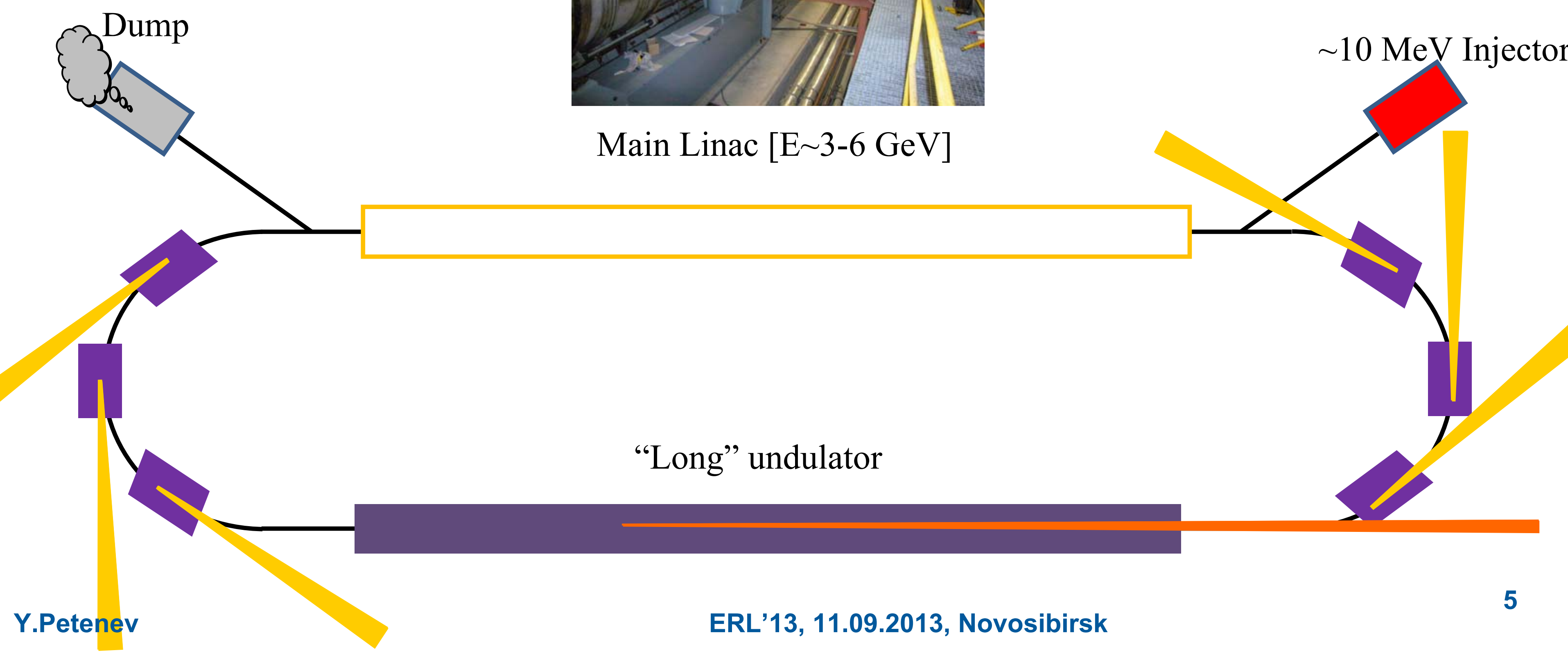
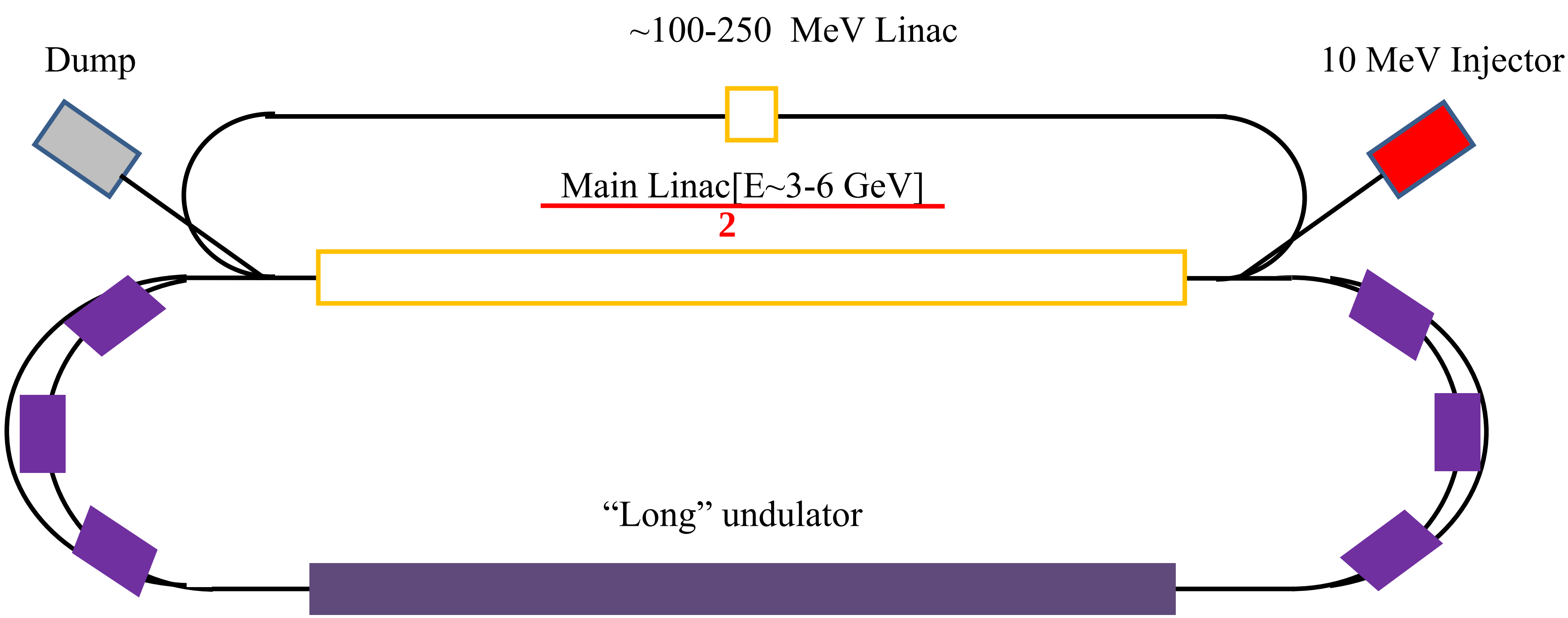


Multi-turn ERL, two-stage Injection

Like storage ring +
- ✓ low emittance
- ✓ low energy spread
- ✓ long undulators
- ✓ short pulses

or

Like linac +
- ✓ high average current
- ✓ energy efficient



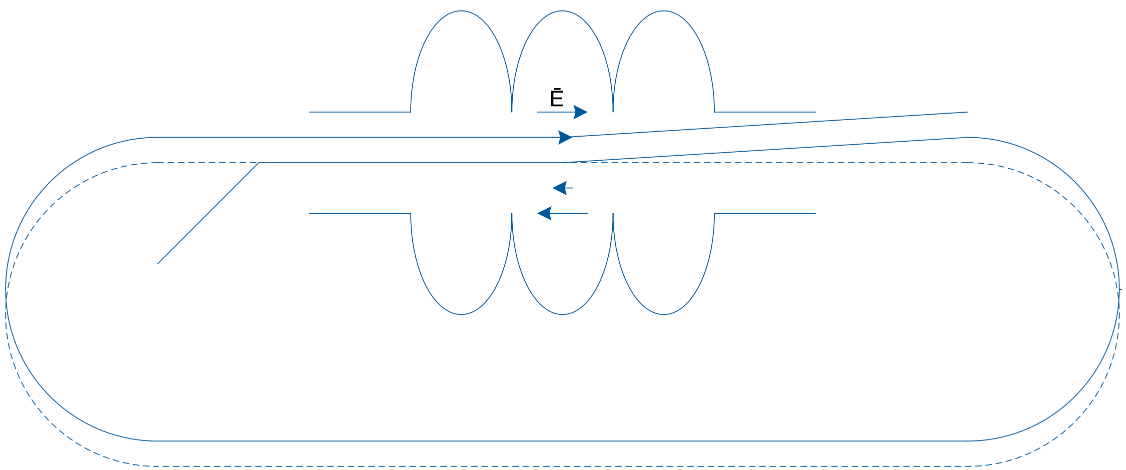
Multibunch BBU in ERL

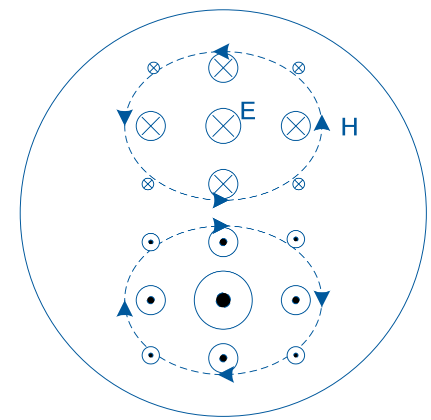
-Each of a high order dipole modes in a cavity deflects a Bunch;

-If the beam moving on the cavity axis there is no energy transfer;

-After the turn the bunch comes with an offset and transfers energy to cavity;

-Next bunch will be deflected stronger => instability.

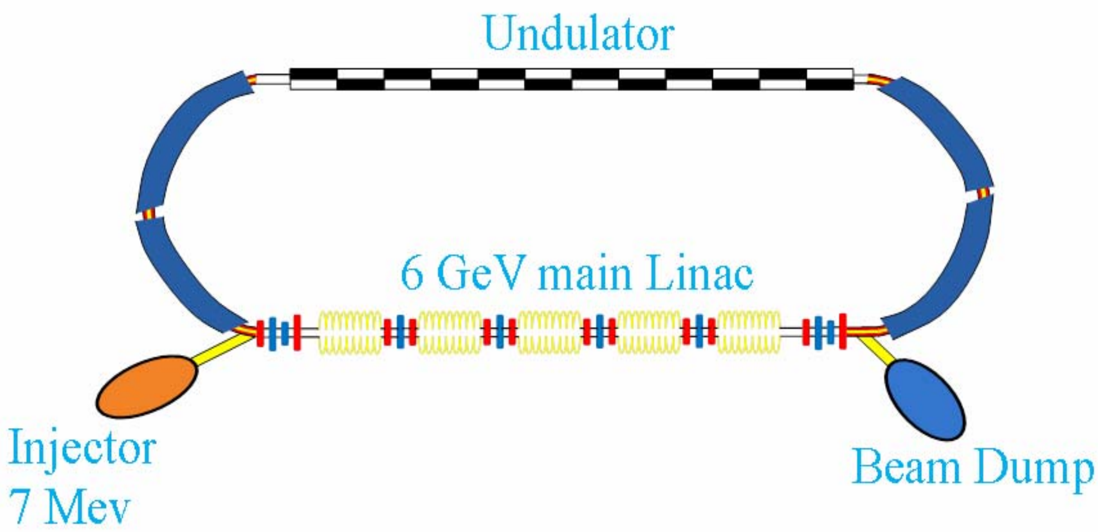




$$I_{th} = -\frac{2pc^2}{e\omega_\lambda \left(\frac{R}{Q}\right)_\lambda Q_\lambda \sum_{j=1}^{N-1} \sum_{i=j+1}^{N} m_{12}^{ij} \sin\left(\omega_\lambda (T_i - T_j)\right)} \Rightarrow I_{th} = \frac{2mc^3}{e\omega_\lambda \left(\frac{R}{Q}\right)_\lambda Q_\lambda} \frac{1}{\sqrt{\sum_{j=1}^{N-1} \sum_{i=j+1}^{N} \frac{\beta_i \beta_j}{\gamma_i \gamma_j}}}$$

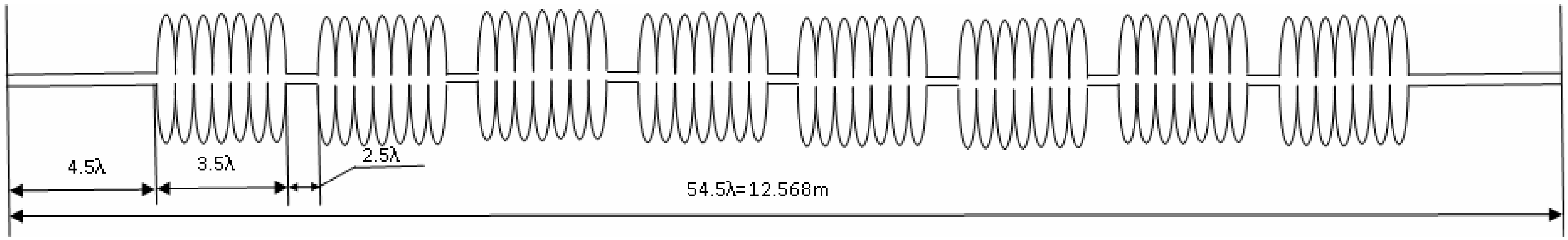
For estimations we will use a mode with $(R/Q)_d \cdot Q_d = 6 \cdot 10^5\ \Omega$, $\omega = 2\pi \cdot 2 \cdot 10^9$ *Hz*

Direct injection scheme



Linac

Linac is planned to be based on the cavities like in the BERLinPro.

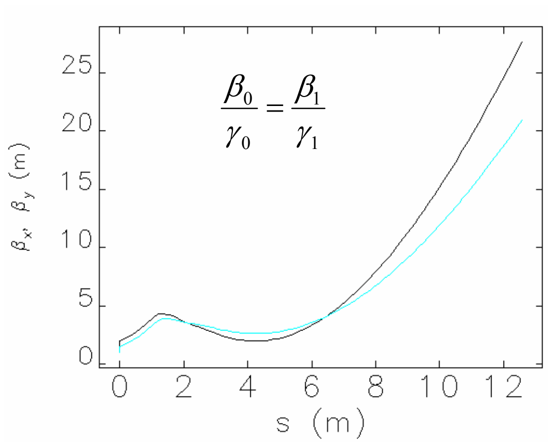


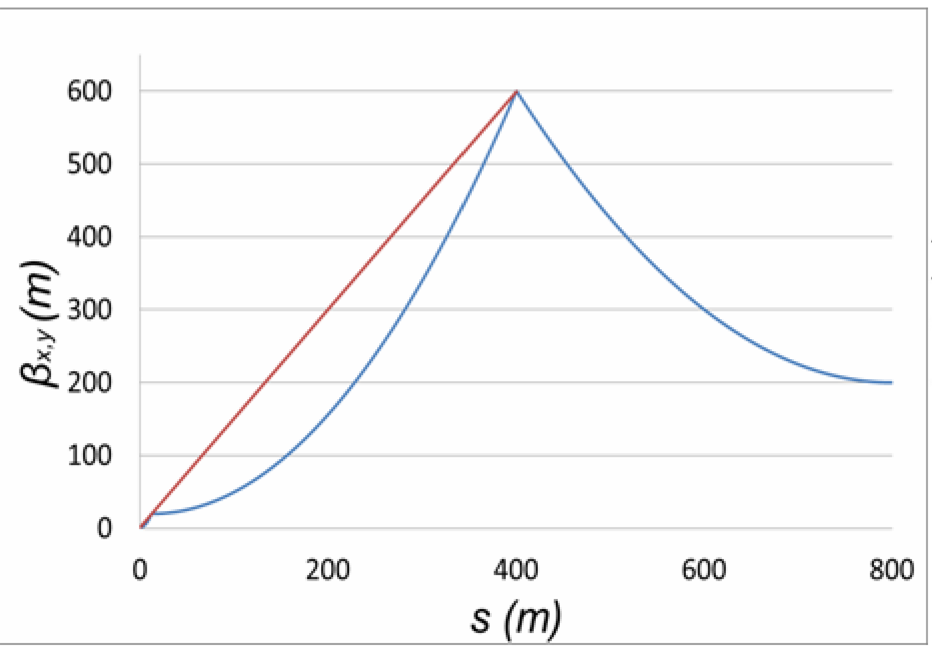
- Cryomodules are planned to have 8 cavities

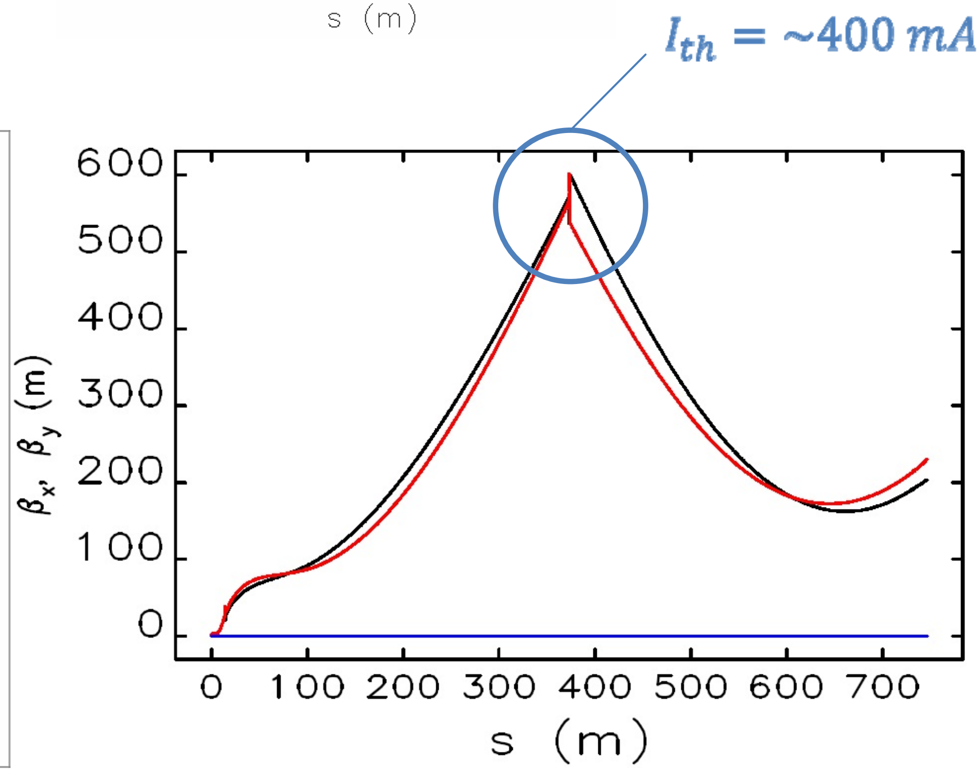
- Triplets of quadrupoles are planned to be in between of the cryomodules in the Linac.
    - For this we make a distance between cryomodules to be equal to 15λ.
    - Estimations shows that focusing in the Linac increases BBU threshold by the factor of **3**!!!

Direct injection scheme

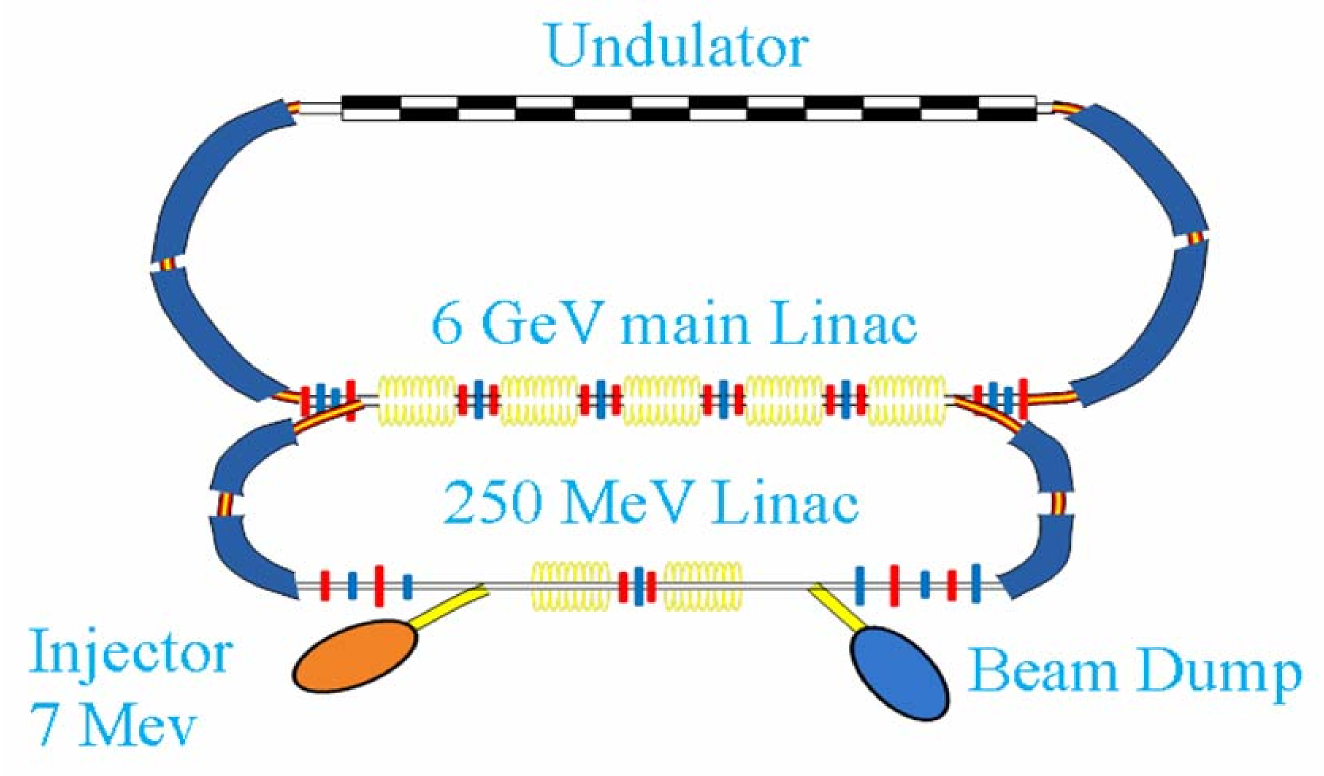
$$\begin{cases} \beta_0 = m_{12} \sim 2\,m \\ \alpha_0 = m_{11} \sim -0.61 \\ \beta_1 = \dfrac{\gamma_1}{\gamma_0} m_{12} \sim 31\,m \end{cases}$$







Two stage injection scheme



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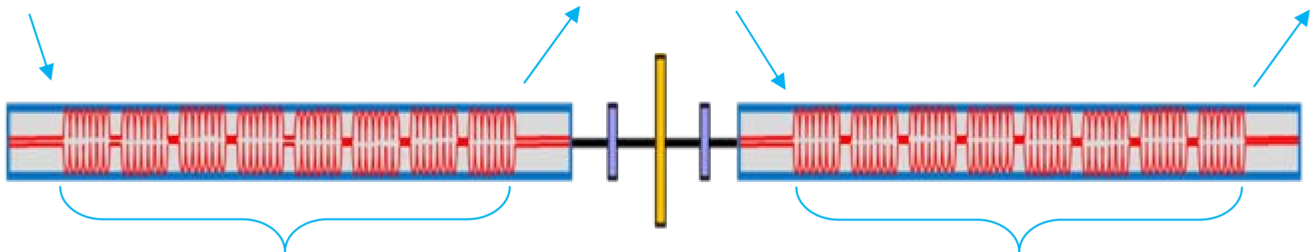
β_0, α_0

$$\beta_1 = \frac{\gamma_1}{\gamma_0}\left(\beta_0 m_{11}^2 - 2\alpha_0 m_{11} m_{12} + \frac{1+\alpha_0^2}{\beta_0} m_{12}^2\right)$$

$$\beta_2 = \frac{\gamma_2}{\gamma_1}\left(\beta_1 t_{11}^2 + 2\alpha_1 t_{11} t_{12} + \frac{1+\alpha_1^2}{\beta_1} t_{12}^2\right)$$



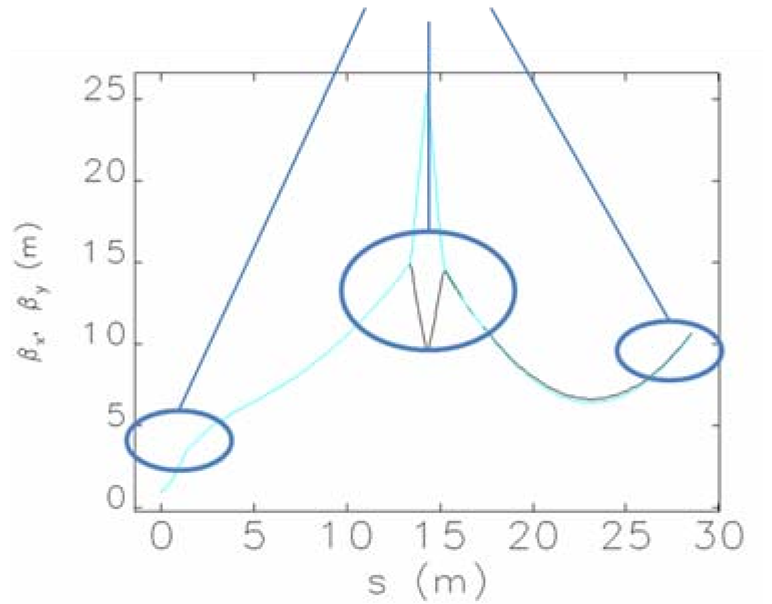
$$\frac{\partial \beta_2}{\partial \alpha_1} = 0 \qquad \beta_2 = \frac{\gamma_2}{\gamma_1}\frac{t_{12}^2}{\beta_1}$$

$$M = \begin{pmatrix} \cos(\alpha) - \sqrt{2}\sin(\alpha) & \dfrac{\sqrt{8}\gamma_0 L \sin(\alpha)}{\Delta\gamma} \\ -\dfrac{3}{\sqrt{8}}\dfrac{\Delta\gamma \sin(\alpha)}{L\gamma_1} & \left(\cos(\alpha) + \sqrt{2}\sin(\alpha)\right)\dfrac{\gamma_0}{\gamma_1} \end{pmatrix}$$

$$T = \begin{pmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{pmatrix}$$

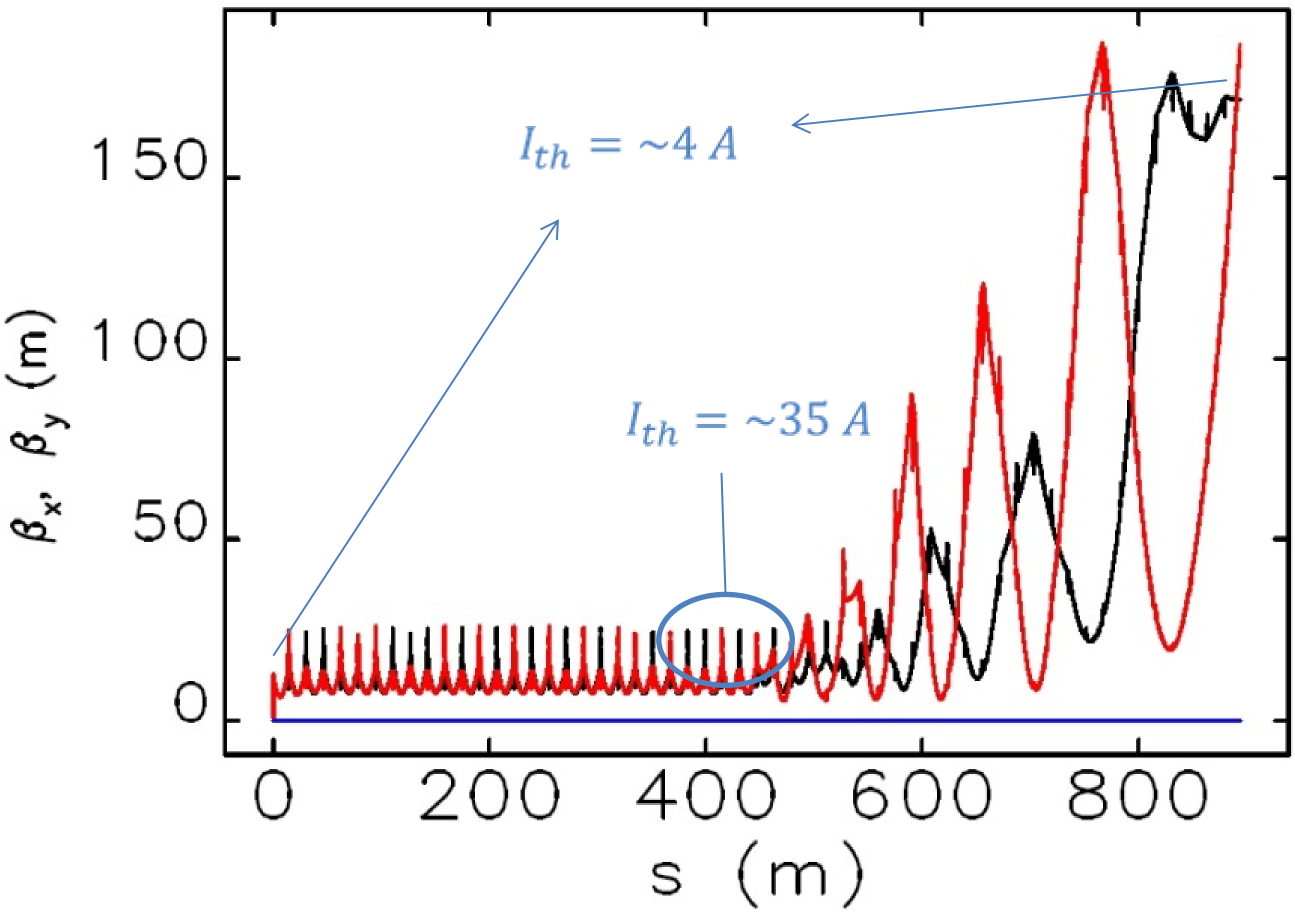
where $\alpha = \frac{1}{\sqrt{8}} \ln\left(\gamma_1 / \gamma_0\right)$

$I_{th} = 1.64$ A



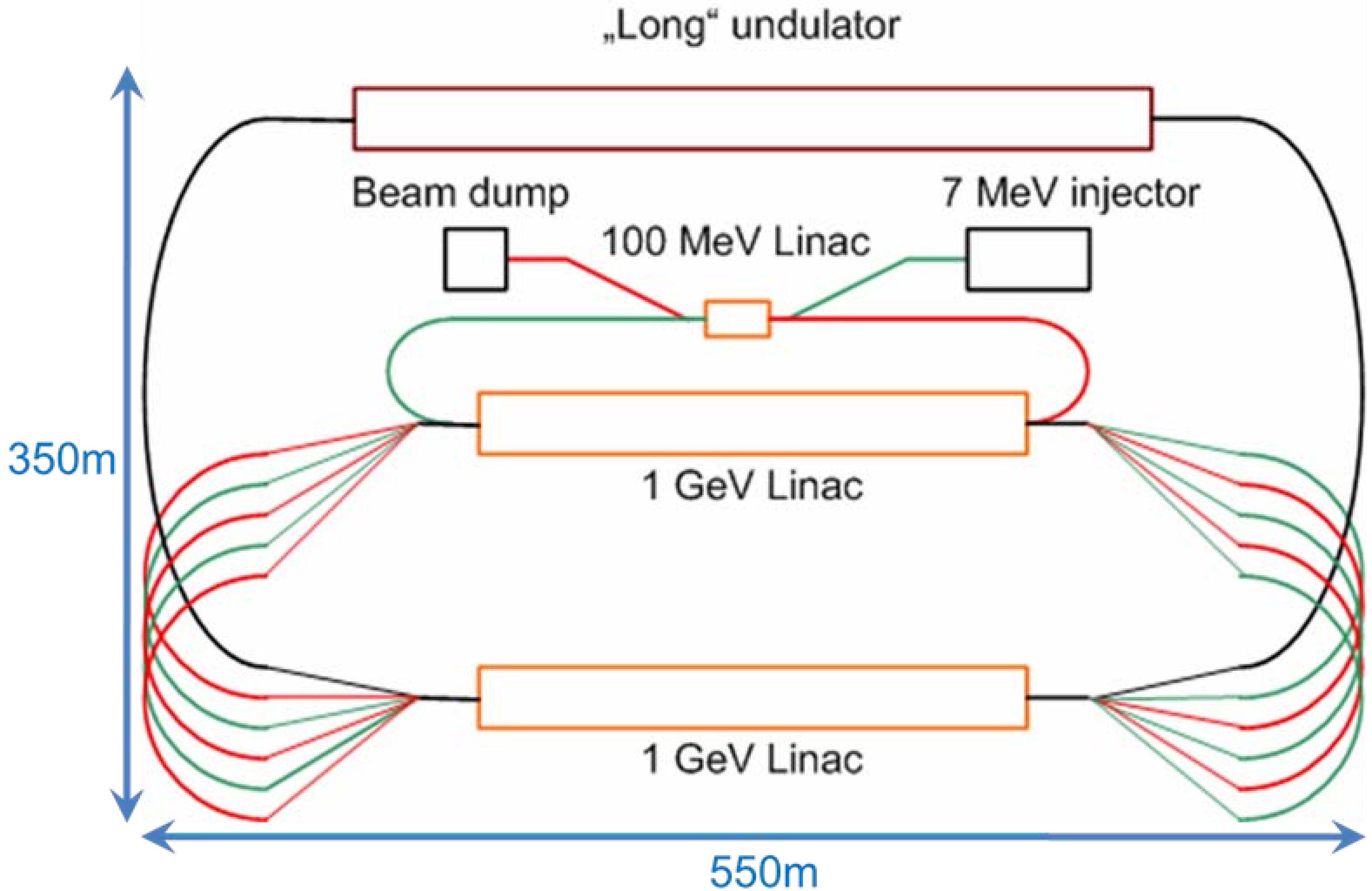
$$\sqrt{\frac{\beta_0 \beta_2}{\gamma_0 \gamma_2}} = \frac{\beta_1}{\gamma_1} \Rightarrow \begin{cases} \beta_0 = \sqrt{\dfrac{\gamma_1}{\gamma_0}\dfrac{m_{12}^3}{t_{12}}} = 2.757 \text{ m} \\ \alpha_0 = \dfrac{m_{11}}{m_{12}}\dfrac{\gamma_0}{\gamma_1}\dfrac{\beta_1^3}{t_{11}^2} = -1.421 \end{cases}$$

Two stage injection scheme: main linac



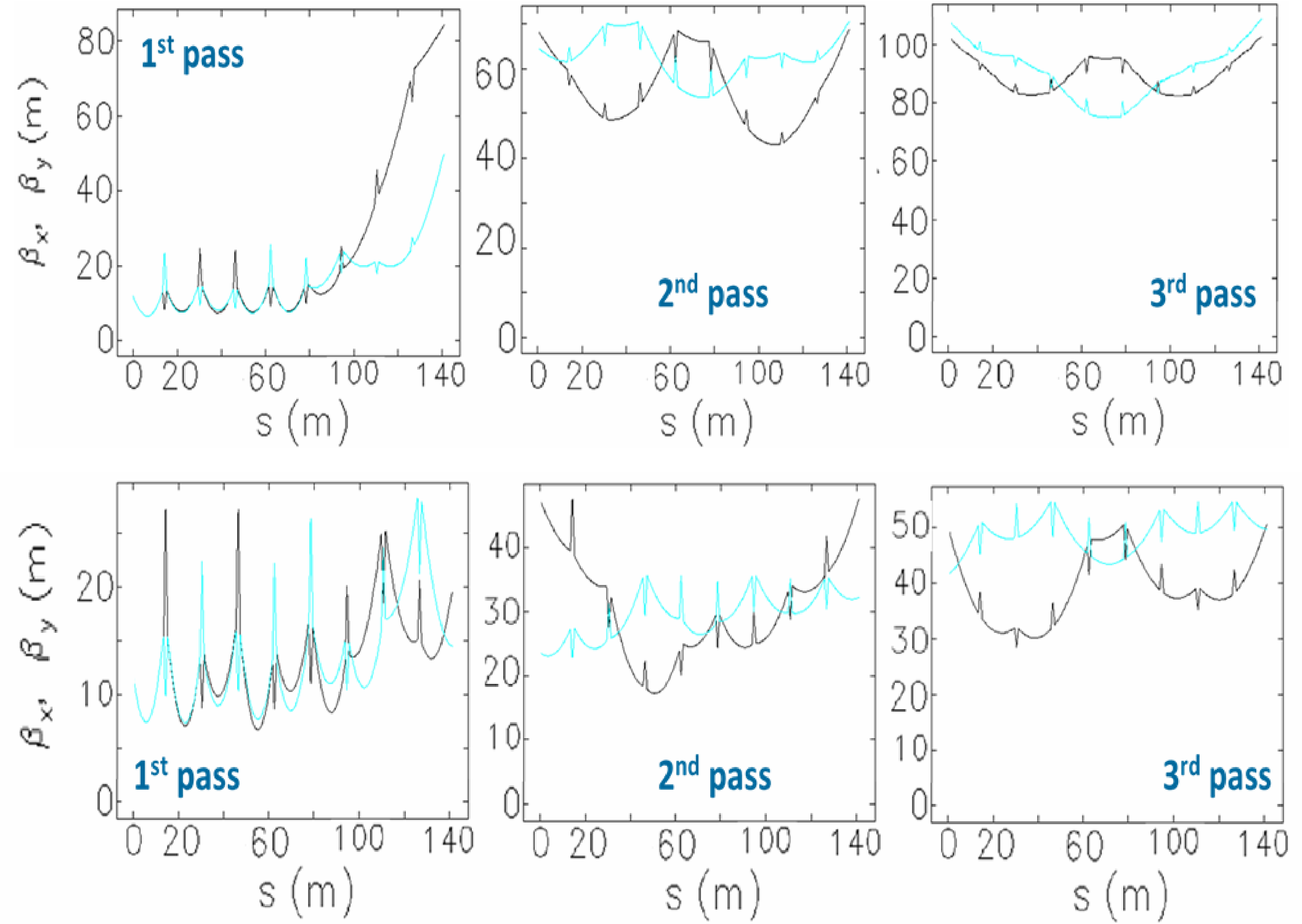
Layout of a 6 GeV multi-turn ERL with 2-stage injection

Our group started to work for a new project which got the name:“Femto Science Factory” and will be future light source.



Modeling of the Linacs optics

0.1+1+1 GeV model



Different acceleration pattern

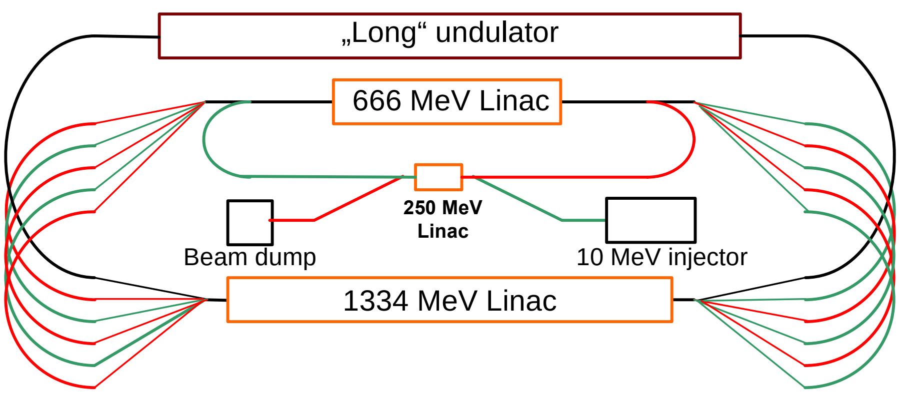
$\beta_{1,1(6)} = \beta_{2,1(6)} \sim$ 12.57 m — because of triplets and

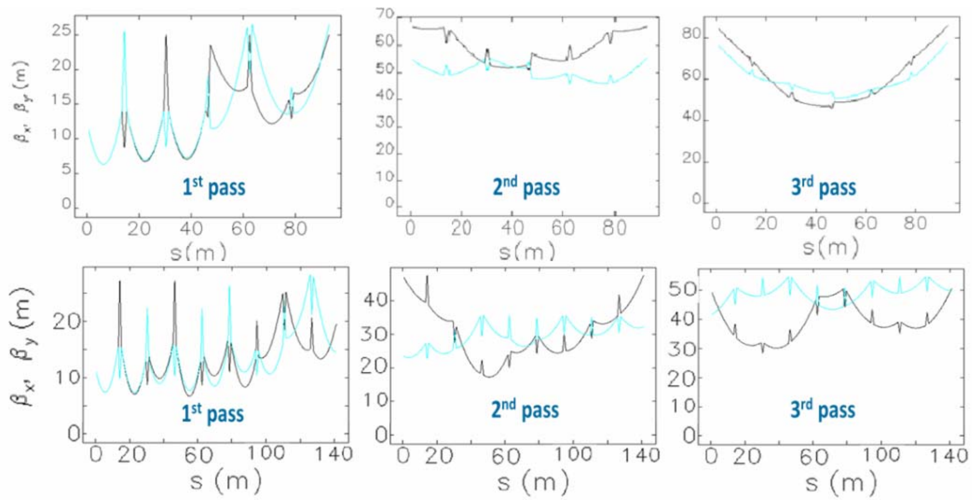
$\beta_{1,n} = x$ or $\beta_{2,n} = L-x$ for the 1st and the 2nd linac respectively, n=2..5.

$$\sqrt{\sum_{m=1}^{2N-1}\sum_{n=m+1}^{2N}\frac{\beta_{1,n}\beta_{1,m}}{\gamma_{1m}(x)\gamma_{1n}(x)}} = \sqrt{\sum_{m=1}^{2N-1}\sum_{n=m+1}^{2N}\frac{\beta_{2,n}\beta_{2,m}}{\gamma_{2m}(x)\gamma_{2n}(x)}}$$

This equation can be solved numerically → x ~ L / 3

L= 2000 [MeV] /G, x is the length of the 1st linac, L-x is the length of the 2nd





But this scheme has a more complicated spreader, because the energies of the beam in the spreader are: …4250, 4916, 6250. Are closer then in 1+1 scheme: 4250 and 5250…

Scalable FSF

final energy of a beam:

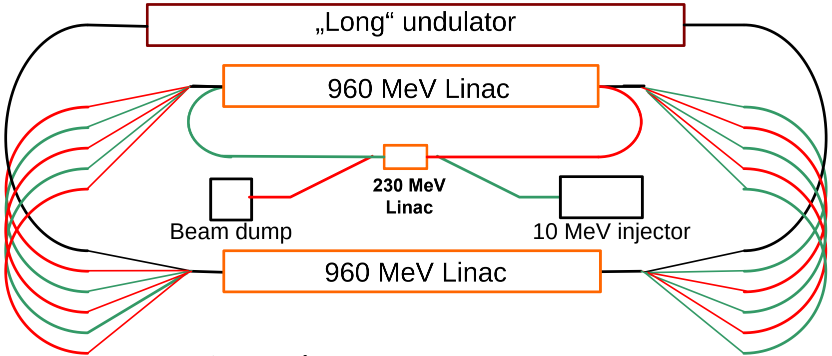
$E_{fin} = (E_0 + E_{preinj})(1+2Nk) = 6$ GeV,

where:

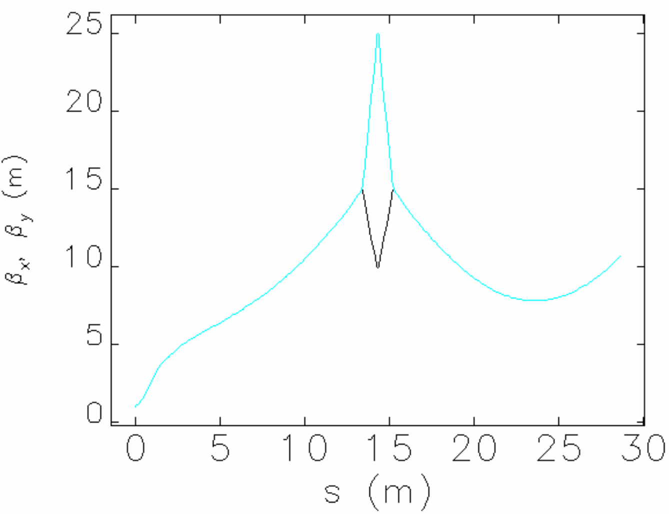
E_0 = 10 MeV is the energy after booster,

E_{preinj} is the energy gain in the preinjector,

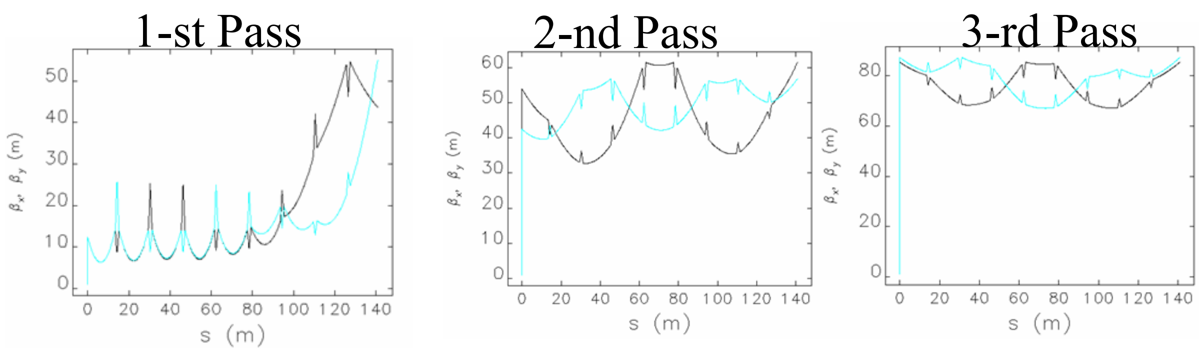
N is the number of passes during acceleration and constant k = 4.



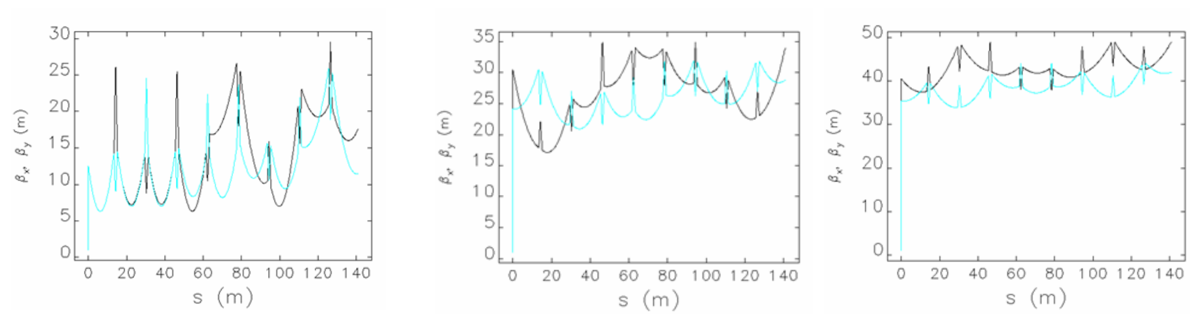
Preinjector



1st Linac



2nd Linac



Different patterns comparison

Linac scheme	I_{th}, A		
	Preinjector	1st Linac	2nd Linac
0.100 + 1 + 1GeV	1.26	0.88	3.73
250 + 666 + 1334MeV	1.64	1.46	3.58 ??
Scalable, estimations	1.58	0.73	2.34

For this estimation we took a mode with $(R/Q)_d \cdot Q_d = 6 \cdot 10^5\ \Omega$, $\omega = 2\pi \cdot 2 \cdot 10^9$ *Hz*

Different schemes comparison

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Scheme	Ith, A (estimations)
Direct injection	~0.4 A in the middle of the linac
Two stage	~1.64 in the preinjector
Scalable FSF	~0.7 in the 1-st linac

Costs

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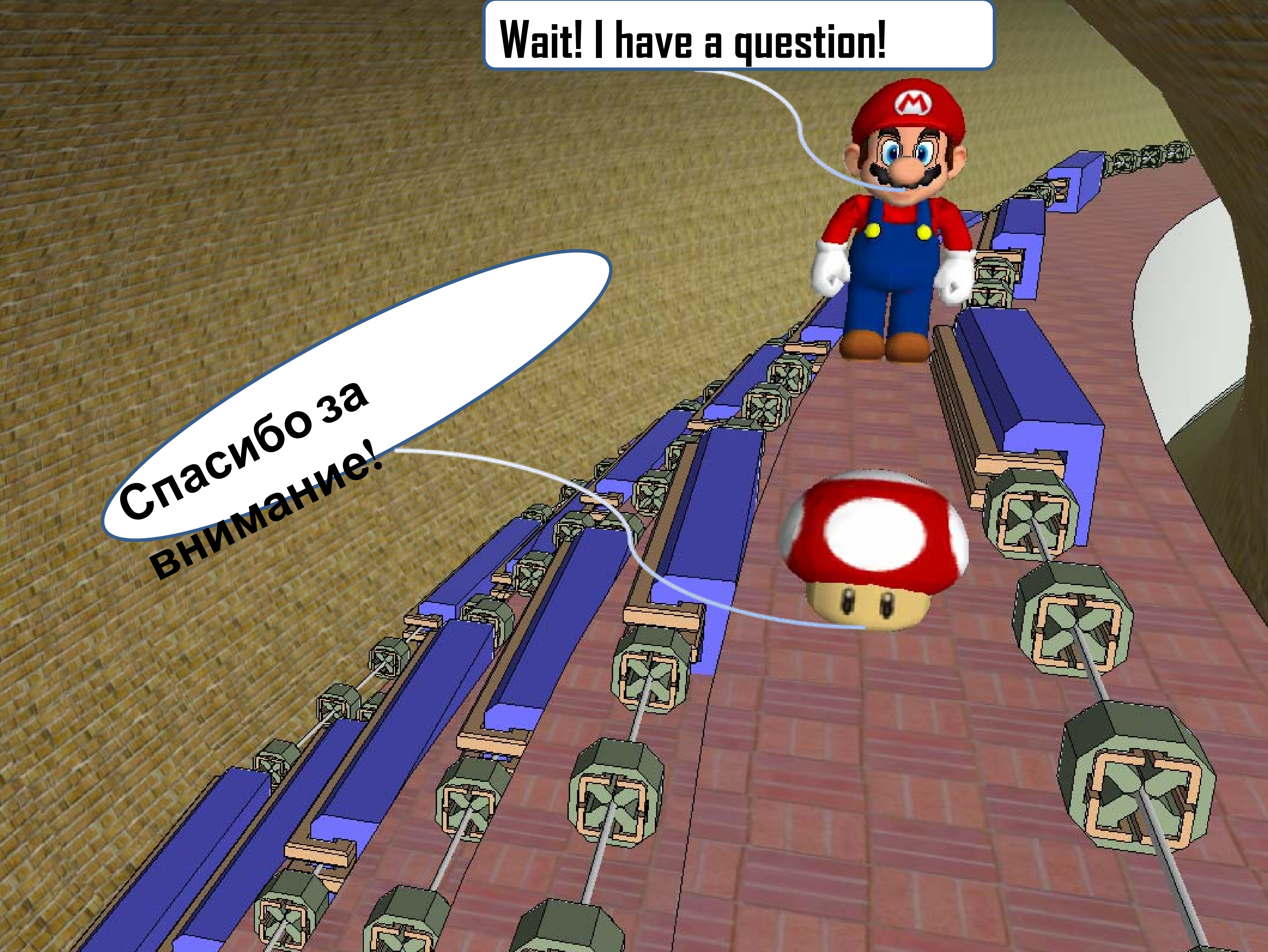
Component	Direct injection scheme, Cost, M€	Scalable FSF, Cost, M€
Infrastructure/tunnel: (land+tunnel+buildings)	375	110
SRF: (cryogenic plant+cryomodules+RF generators)	485	190
Warm machine: (magnets+undulators+ vacuum system + diagnostics/control systems+power supplies)	150	230
User stations	200?	200?
People: (staff for 10 years + beamline scientists)	100	100
Total Sum	1310	830

Special thanks to:

T. Atkinson

A. Bondarenko

A. Matveenko


Wait! I have a question!
Спасибо за внимание!

Role of triplets in the Linac

$$I_b \approx I_0 \frac{\lambda^2}{Q_a L_{eff} \sqrt{\sum_{m=1}^{2N-1} \sum_{n=m+1}^{2N} \frac{\beta_m \beta_n}{\gamma_m \gamma_n}}},$$

2N=6 - passes

	With triplets	Without	
	β	β	γ
1	11.7	110	200
2	65	110	2000
3	105	110	6000
4	105	110	10000
5	70	110	6000
6	85	110	2000
$\sqrt{\sum_{m=1}^{2N-1} \sum_{n=m+1}^{2N} \frac{\beta_m \beta_n}{\gamma_m \gamma_n}}$	0.108	0.309	

Addition focusing in the Linac increases BBU threshold by the factor of about **3**!!!

Costs

Component	Direct injection scheme, Cost, M€	Scalable FSF, Cost, M€
1. Infrastructure/tunnel		
a) Land	$(3.14/4*1050^2 m^2+(750m*1050m))*0.16$ k€/m^2 ~ 265	350m*550m*0.16 k€/m^2 ~ 31
b) Tunnel	(3.14*1050+2*750)m*0.01 M€/m=48	(3.14*350+2*200)m*0.01 M€/m=15
c) Buildings (users)	2x400m or 10x? ~ 50	2x400m or 10x? ~ 50
d) Technical buildings	10?	10?
Sum	265+48+50+10?=373	31+15+50+10?=106
2. SRF		
a) Cryogenic plant	300 W/0.1 GeV * (2 beams at 6 GeV)= 5-10 kW @ 2 K=20?	300 W/0.1 GeV * (6 beams at 2 GeV and 2 beams at 0.25 GeV) = 5-10 kW @ 2 K=20?
b) Cryomodules	56*5 M€=280	(9*2+2)*5 M€~20*5=100
c) RF generators	20mA*10 MeV= 200 kW inj 10kW*56*8=4.48 MW Linacs 1.5+448*0.4~180.7	20mA*10 MeV= 200 kW inj 10kW*20*8=1.6 MW Linacs 1.5+160*0.4~65.5
Sum	20+280+180.7=480.7	20+100+65.5=185.5
3. Warm machine		
a) Magnets	2*(6+6)*46(arcs)+15 (triplets)+600 (undulators)~ 1719*10 k€ ~ 17.2	60*4 (spreade/rec)+6*(6+6)*46(arcs) +100(preinj)+50 (triplets)+600 (undulators) ~ 4300*10 k€ = 43
b) Undulators	60*1+1*5=65	60*1+1*5=65
c) Vacuum system +diagnostics/control systems	(3.14*1050m+2*750)*10 k€=48	(6*3.14*350m+6*4*25m+2*150m)*10 k€= 75
d) Power supplies	~ number of magnets ~ 17.2	~ number of magnets ~ 43
Sum	17.2+65+48+17.2=147.4	43+65+75+43=226
4. People		
a) Staff	100(ppl)*10(years)*50 k€=50	100(ppl)*10(years)*50 k€=50
b) Beamline scientists	50*10*100 k€=50	50*10*100 k€=50
c) Stations	200	200
Overhead	?	?
Sum	300+?	300+?
Total Sum	373+480.7+147.4+300+?= 1301.1+ ?	106+185.5+226+300+?=817.5 + ?