Continuous wave energy recovery operation of an XFEL

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	SLAC	DESY
Commissioning with beam	2008	2011
Peak brilliance @ (1.5Å) 1Å [Ph/s/mm²/0.1%bandwidth]	$8.5 \cdot 10^{32}$	$5.4 \cdot 10^{33}$
Average brilliance @ (1.5Å) 1Å [Ph/s/mm²/0.1%bandwidth]	$4.2 \cdot 10^{22}$	$1.6 \cdot 10^{25}$

In Frascati (TESLA Collaboration Meeting 2003) we proposed to look further into the future believing that a „culture" of experiments with CL will grow as the „culture" of experiments with SR did for many years.

I-st Question:

How can we get higher average brilliance and increased overall efficiency ?

or

What will the next generation of XFEL facilities look like ?

II-nd Question:

What kind of R&D program should be proposed to arrive in the next few years at a technically feasible solution?

Two comments:

- Studies presented in this seminar are very preliminary and should be treated as a starting point.
- We very often refer to and profit from the DESY XFEL design, acknowledging its many technically innovative solutions.

Higher average brilliance

↓

keeping bunch parameters:
1 nC @ ε_n=1.4 μm•rad

↓

more bunches /s

↓

cw or semi-cw operation

↓

Superconducting Technology

Higher efficiency

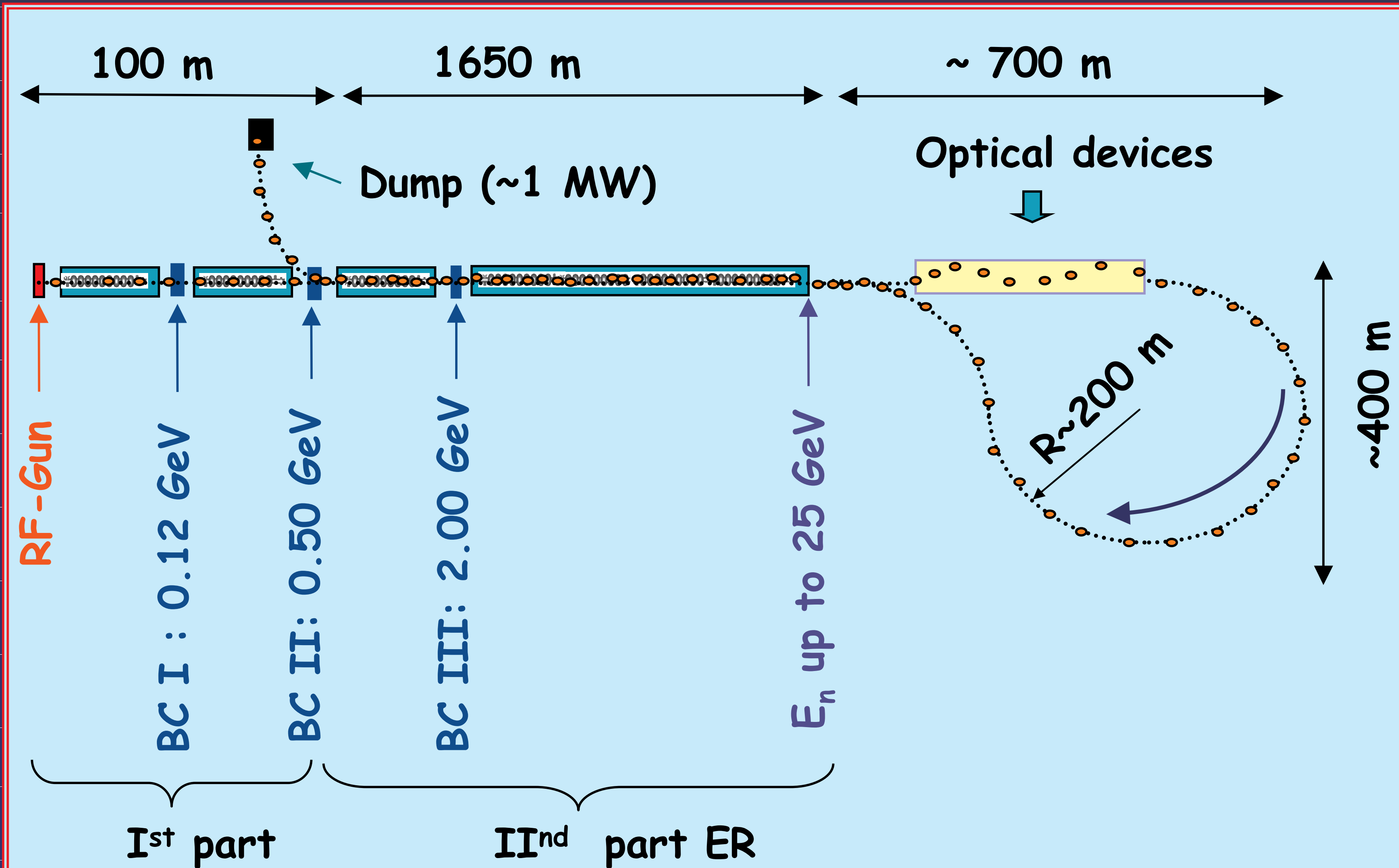
↓

Less AC power/photon

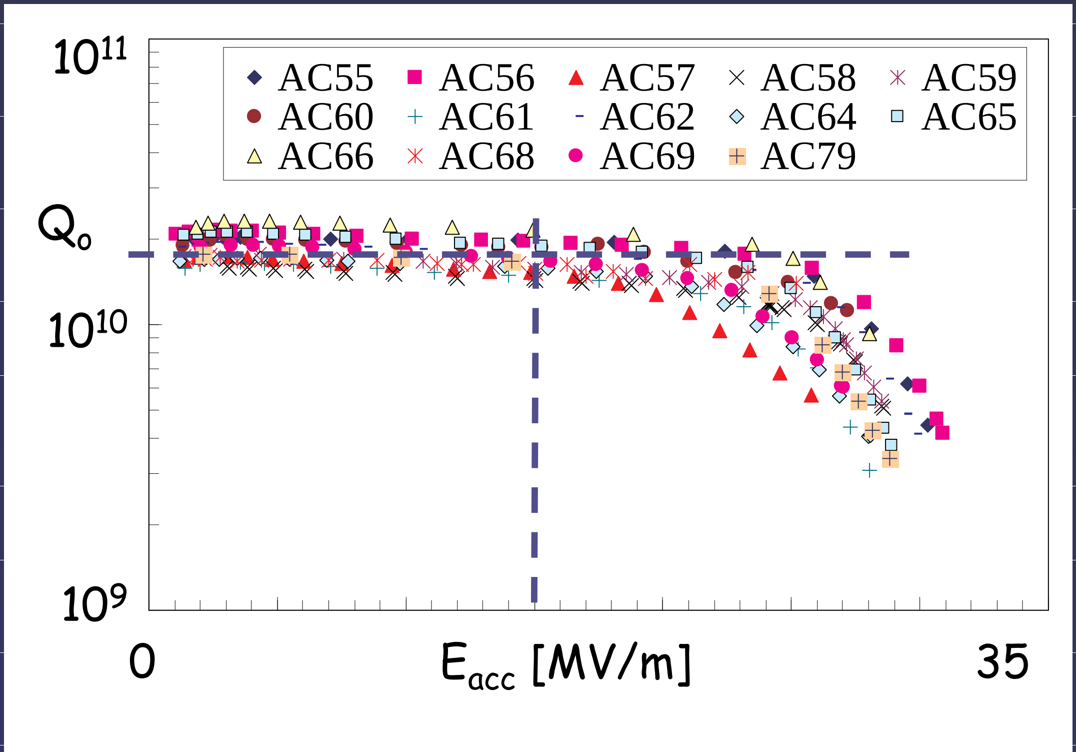
↓

Energy Recovery

Possible layout can be very similar to the present pulsed linac



I. 1088 cavities @ Qo ~ $1.7 \cdot 10^{10}$ @ Eacc ≤ 15 MV/m



II. Energy recovery: experiment at Jlab in March, 2003

20 MeV beam was accelerated to 1 GeV and decelerated in second pass from 1 GeV to 20 MeV.

Energy ratio 50

III. 8.5 kW @ 2K cryoplant (50% overhead)

5.7 kW budget for presented later linac parameter

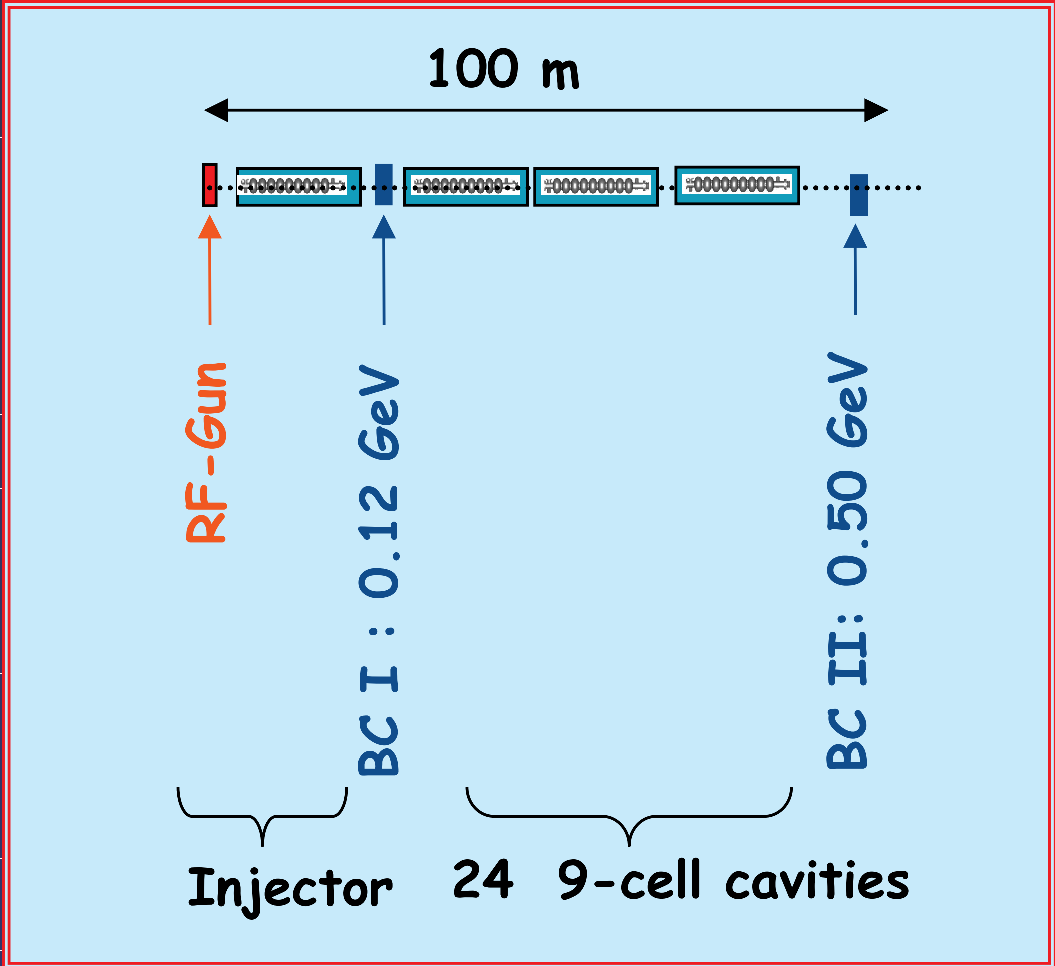
IV. Microphonics <16 Hz peak-peak (± 8 Hz)

FZ Rosendorf cryostat design 10 Hz (± 5 Hz)

Beams

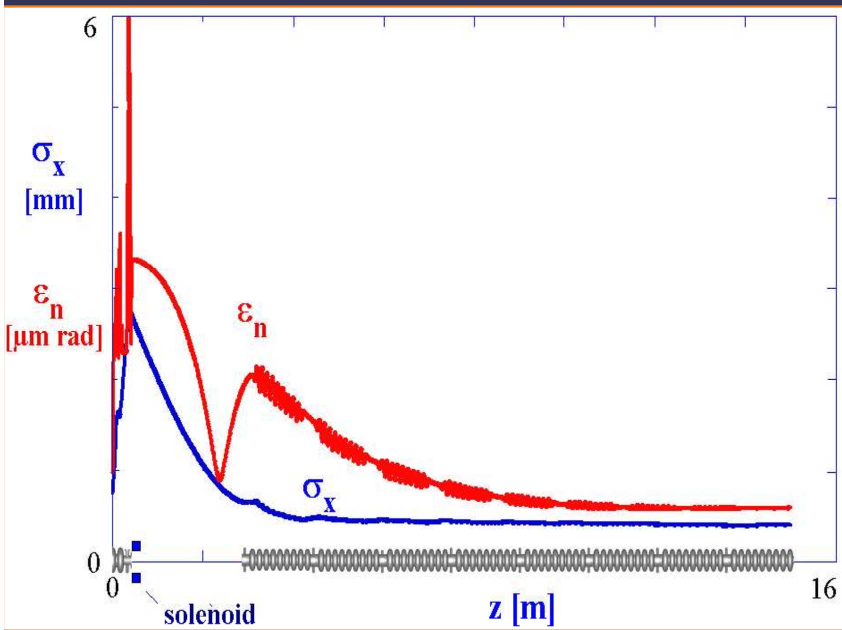
- Nominal beam: 1 nC @ f_{rep}=1 MHz (1μs)
- Long train (fits to return arc):
  6.5 μs @ integrated q= few nC @ f_{rep}= 40 kHz (25 μs)

- I^{st} Part of the linac: standard operation, no ER



Injector

(Massimo, Jamie, Luca)



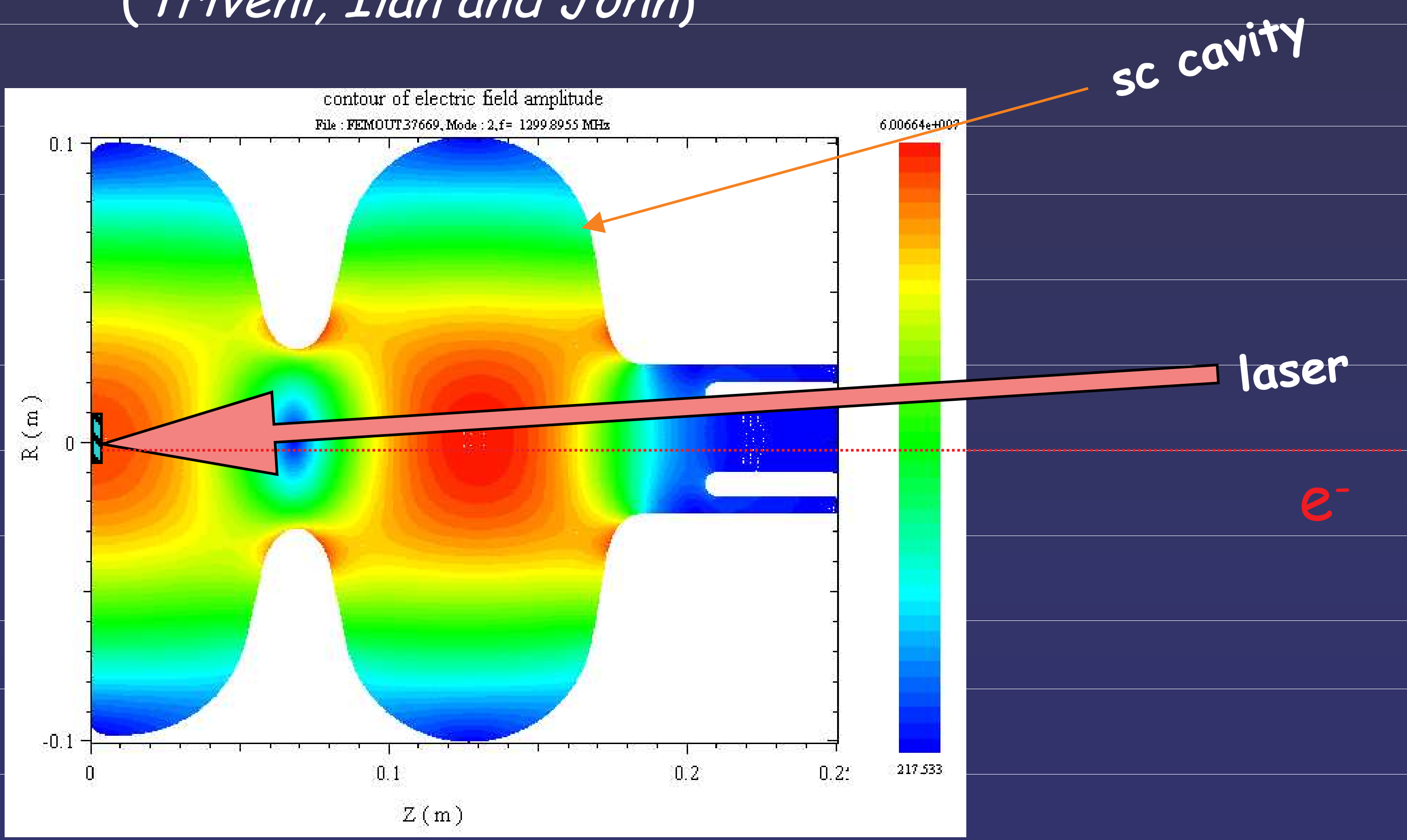
Parameters of the beam and the injector.

Parameter	units	
Cavity operating frequency	MHz	1300
E wall in RF-gun cavity	MV/m	60
Emitting spot radius	mm	1.5
Charge	nC	1
Energy at the end of RF-gun	MeV	6.5
Normalized emittance at the cathode	µm·rad	0.45
B field in the solenoid	T	0.3
Beam energy at the exit	MeV	120
E_{acc} in cryomodule	MV/m	13.6
Peak current	A	50
Bunch duration (flat top part)	ps	20
Transversal size, σ_x at the exit	mm	0.5
Normalized emittance at the exit	µm·rad	0.6

To take full advantage of the cw operation of a XFEL one needs sc RF-gun

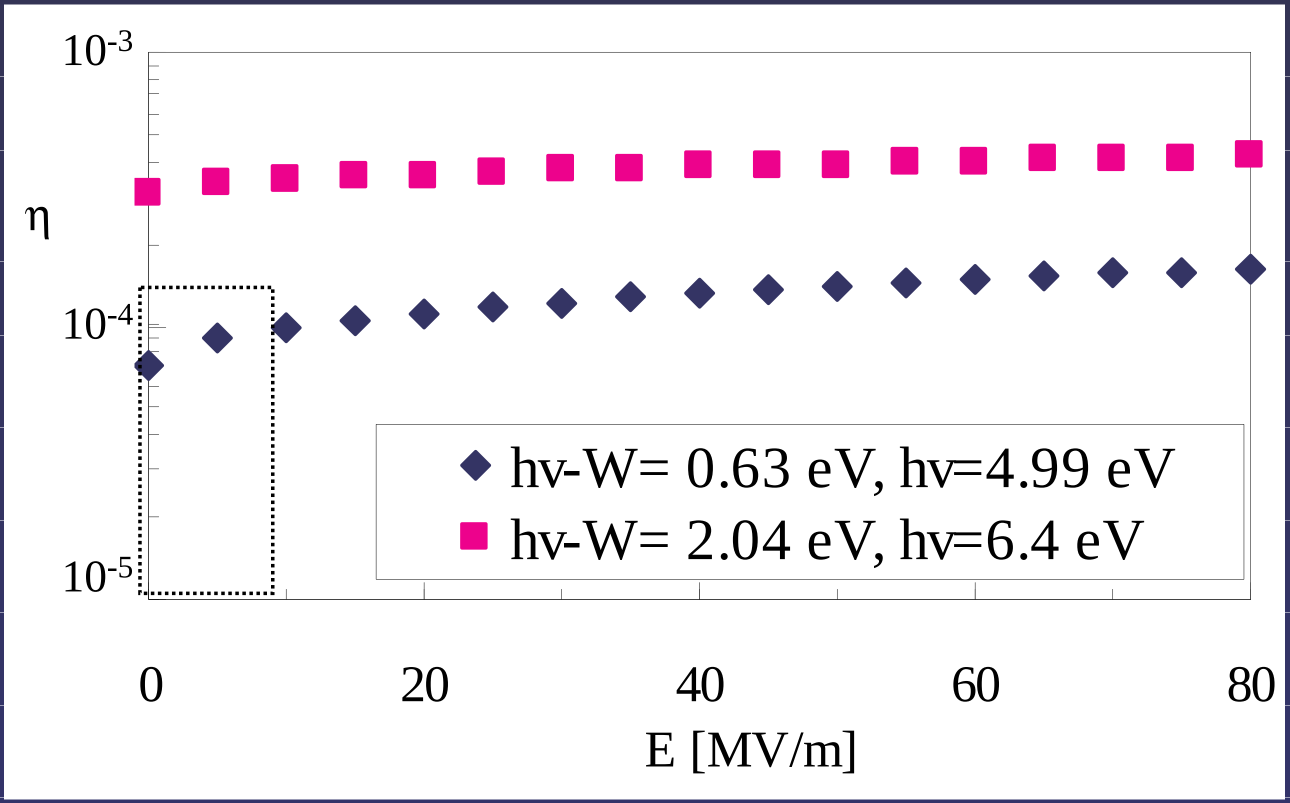
We follow the BNL idea

(*Triveni, Ilan and John*)



Quantum efficiency of Nb after the laser cleaning (~ 1 mJ/mm^2)

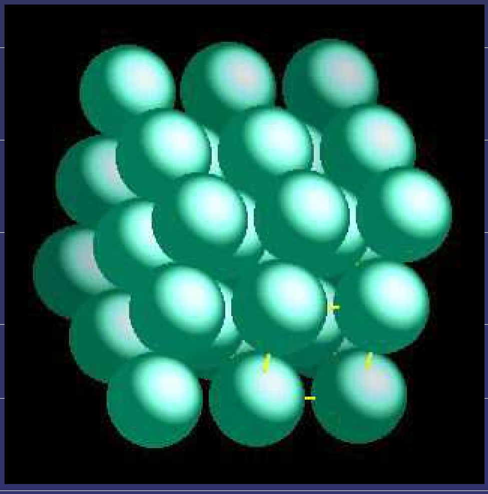
(Ph. D. of John Smedley, BNL)



Is Nb the best superconductor for the photoemission ?
(we asked this question in Frascati)

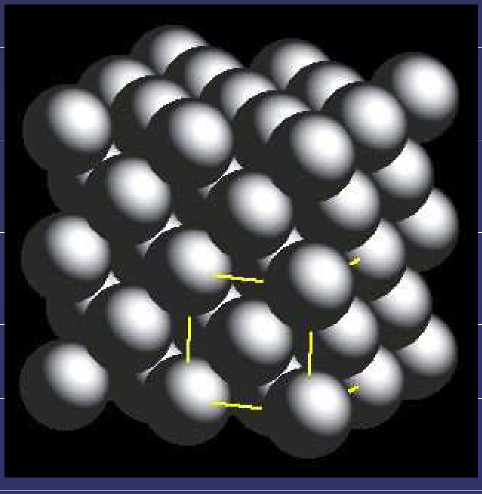
Cs (WF=2 .1 eV)

a /pm	b /pm	c /pm
614	614	614
α / °	β / °	γ / °
90	90	90



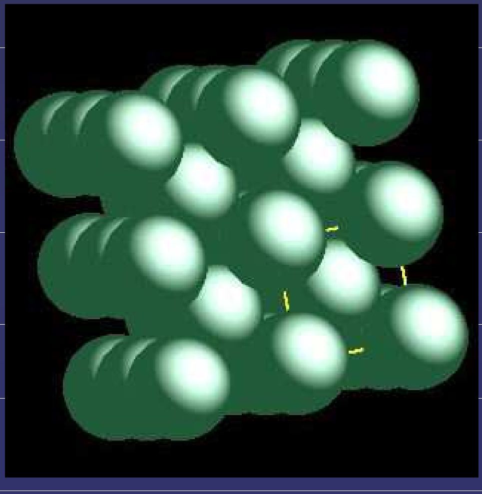
Pb (WF= 4.2 eV)

a /pm	b /pm	c /pm
495	495	495
α / °	β / °	γ / °
90	90	90



Nb (WF= 4.9 eV)

a /pm	b /pm	c /pm
330	330	330
α / °	β / °	γ / °
90	90	90



Very preliminary results measured in December 2003

Quantum Efficiency of Pb	
248 nm	$1 \cdot 10^{-4}$
193 nm	$1.3 \cdot 10^{-3}$

If true:

4.8 W laser @ 193 nm can generate 1nC @ 1MHz nominal beam

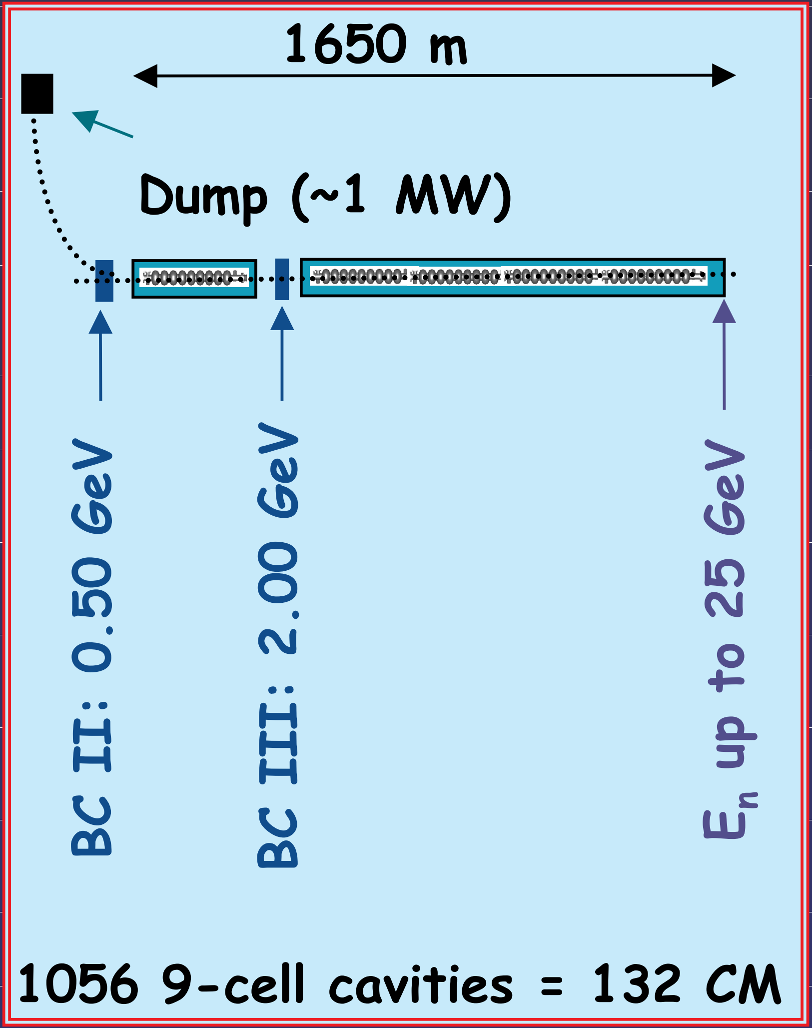
Test of next 7 cathodes will be continued in January 2004

Parameters of the I[st] Part of the linac

Parameter	Units	
Energy at the exit	MeV	500
Input energy	MeV	6.5
E_{acc}	MV/m	15.2 (13.6)
Number of 9-cell structures	-	32
f of accelerating mode	MHz	1300
(R/Q)	Ω	1038
Q_o	10^{10}	1.7
Q_{ext}	10^7	1.6 (1.5)
Total cryogenic load at 2 K	kW	0.5
RF power	MW	0.494

1.2 MW cw klystron on the marked (1M$)

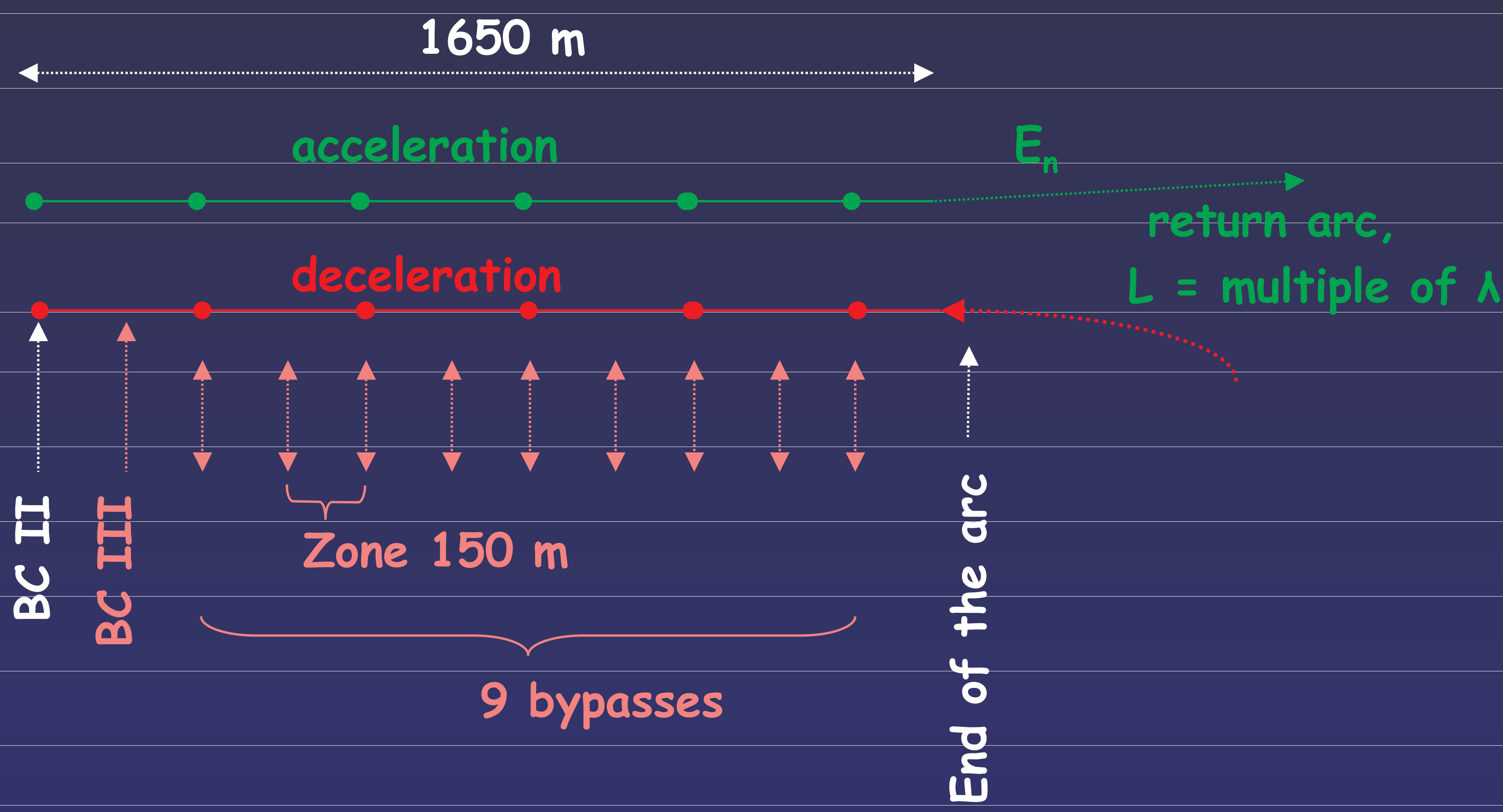
- IInd Part of the linac: ER operation



There are two ER scenarios

	Two beams move in the same direction	Two beams move in opposite directions
Optics	acts on two beams with very different energies (-)	acts on two beams with the same energy (+)
Cost	two arcs, long bypass (-)	single arc (+)
Beam-beam interaction	no (+)	a problem, but for 1 MHz beam can be managed (•)
Phasing of cavities	no (+)	a problem, but can be managed (-)

There is no beam-beam interaction !

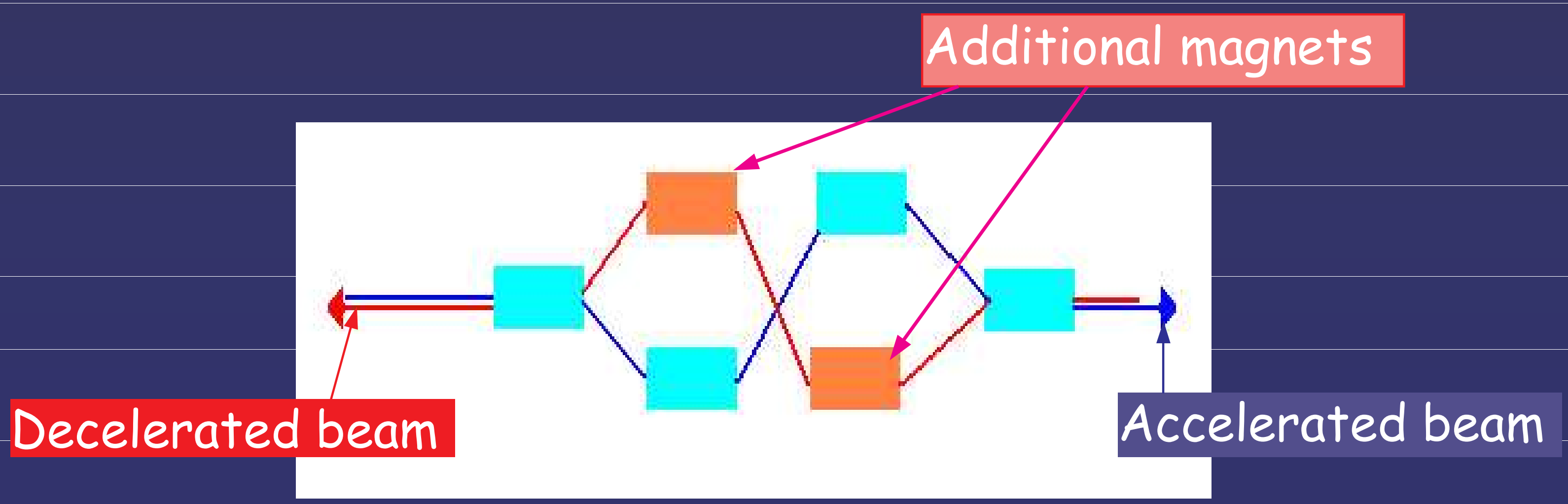


Beams meet at 12 locations

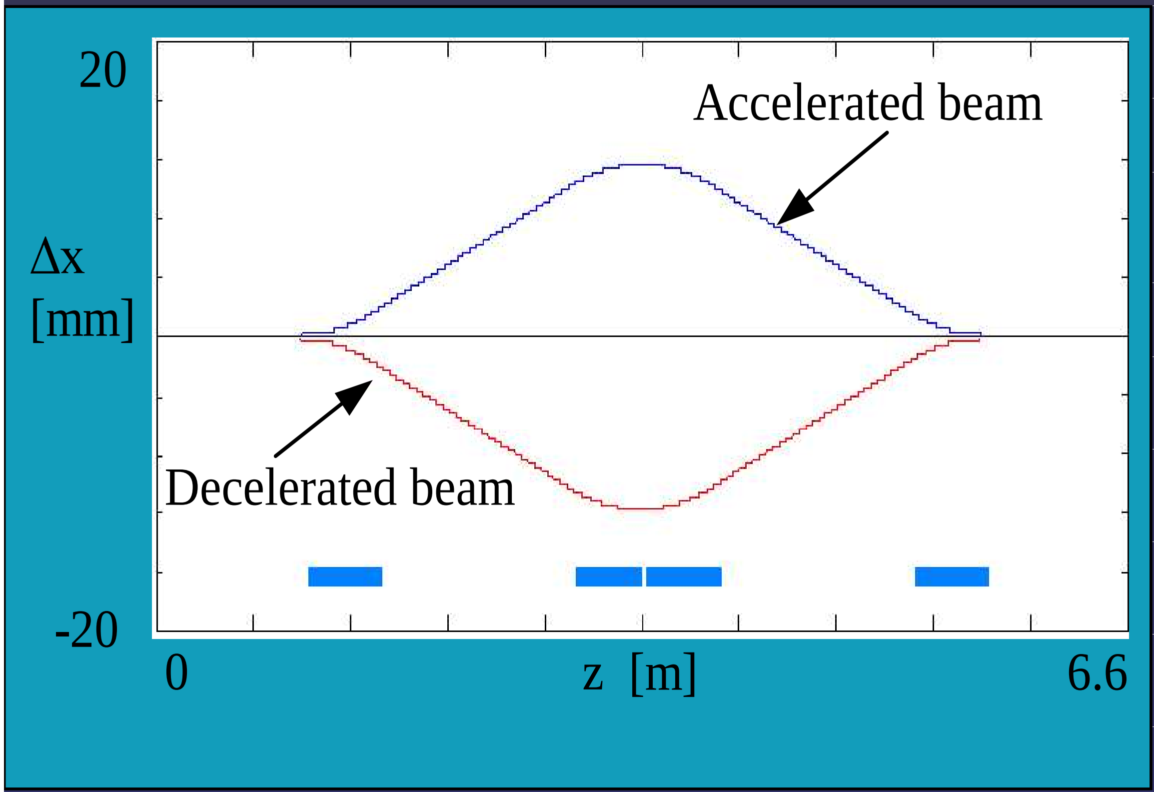
- At the high energy end of the linac the beams will be separated by the last dipole magnet of the return arc.

- At the low energy end the most downstream magnet of the BC II will separate both beams and will also direct the returning beam to the dump.

- BC III needs to be modified (compared to the original DESY design) to provide separation of the beams



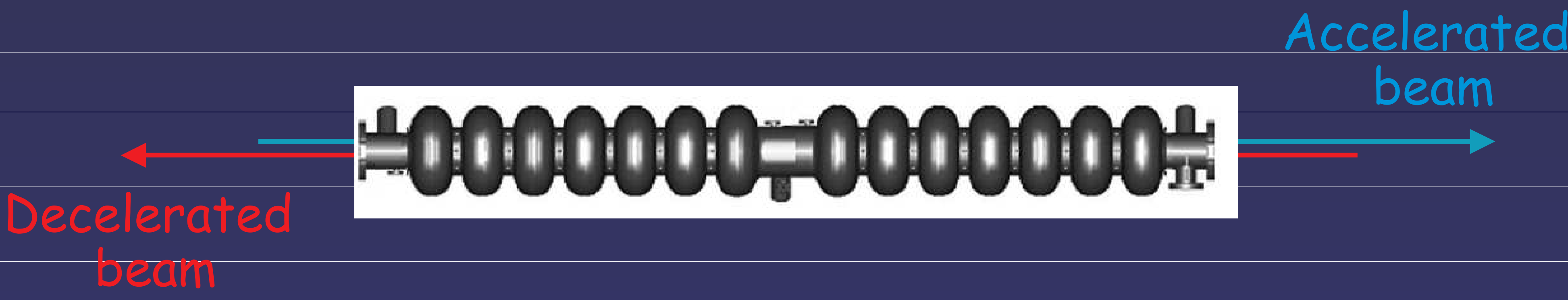
- In all other 9 locations, beams can be separated via simple bypasses based on four dipole magnets.



Parameter	Units	
Beam energy	GeV	15.5
Separation	mm	20
Chicane length	mm	4630
Dipole length	mm	500
θ_{bend}	°	0.37
ρ	m	78
B	T	0.66
SR	keV	265
D_{max}	mm	10
M_{56}	mm	-0.13

In ER linacs power transferred to a sc cavity is rather small

one FPC can serve bigger number of cells in a structure



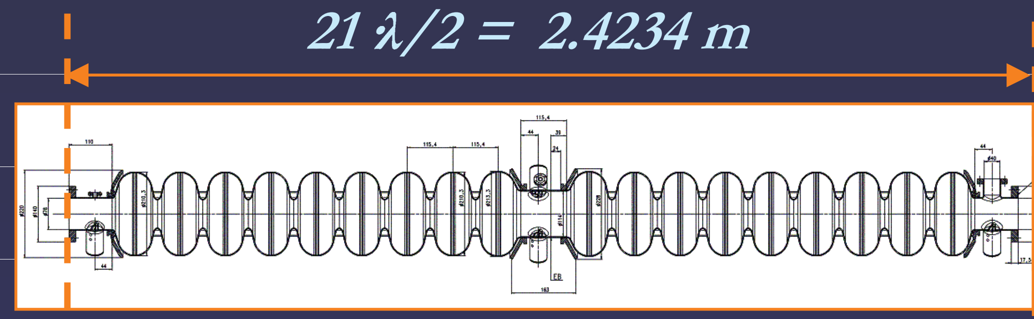
Cavities can have many cells.

2x7-cell or 2x9-cell SSTs seem to be an attractive option.

Building blocks

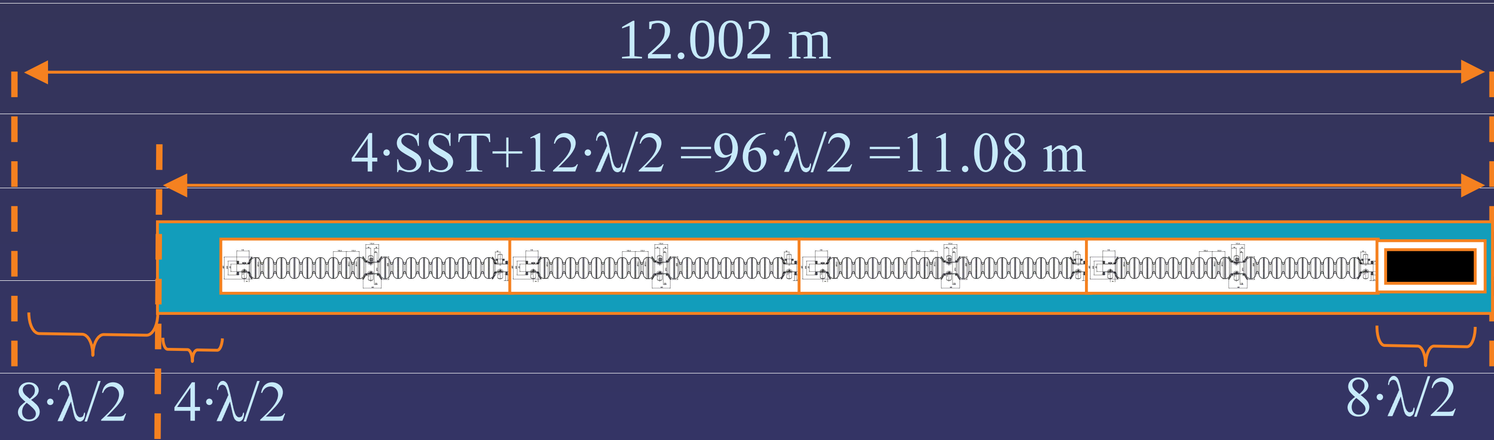
SST+sc bellows

at 15 MV/m: 31.25 MeV



Cryostat

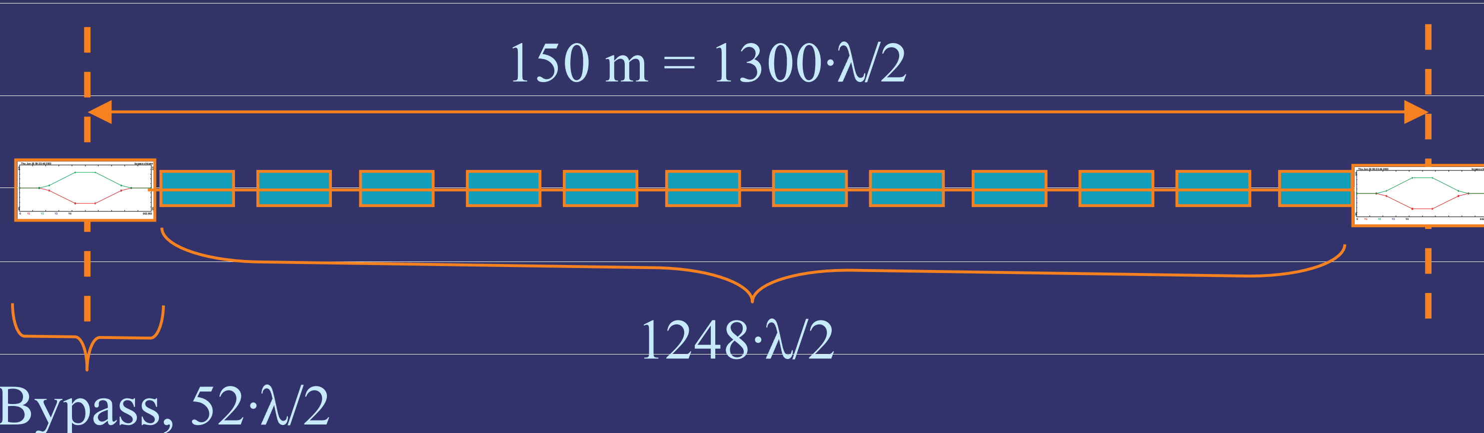
125 MeV



Zone between

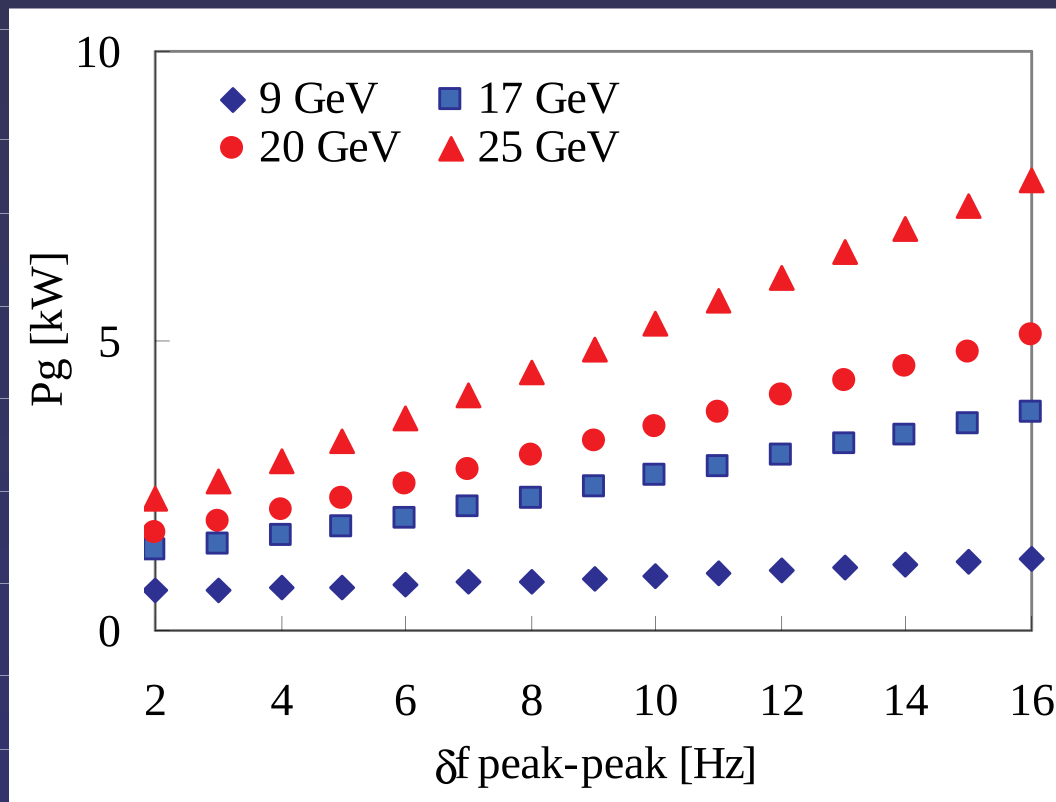
2 bypasses

1.5 GeV



RF-system for the ER part

Required rf-power to compensate for residual beam loading and microphonics (18-cell SST or 2 TTF cavities).



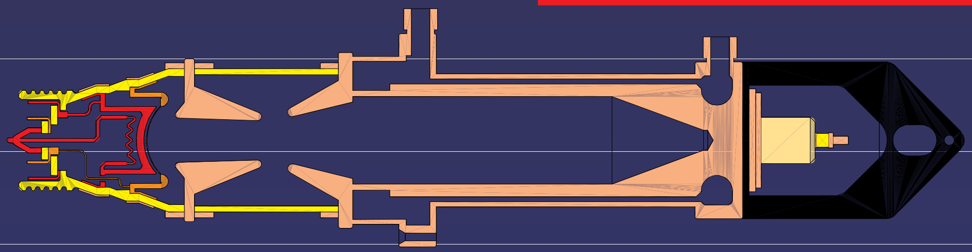
Total RF power needed to operate IInd part of the facility

1056/2*5 kW = 2.7 MW

- 170 x 16 kW klystrons (CEBAF 12 GeV upgrade)
- 132 x 20 kW Inductive Output Tubes (one IOT/CM)

e2v company in UK

Courtesy of e2v



IOTs are DENSITY MODULATED.
Bunches are formed by RF modulating the grid voltage, and either releasing or impeding emission from the cathode

very long live time up tp 95,000 h

Program of the Faraday Partnership (UK)

Small IOTs for CW applications

Typical tube characteristics:

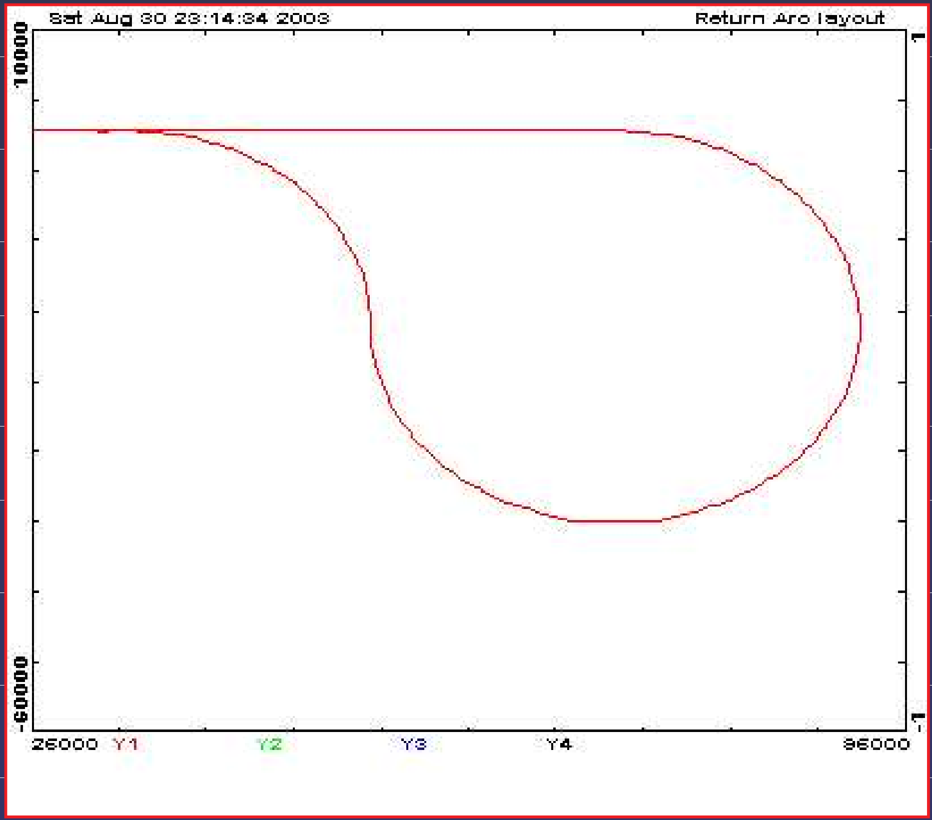
- Output power ~ 20kW
- Frequency, between 1.3GHz and 1.5GHz
- Efficiency >65%
- Bandwidth, ~2.5MHz at 1dB point
- Wave-guide or coaxial output interface
- Estimated Cost 40 k$ (tube only)
- Prototype ready April 2004

Courtesy of e2v

Parameters of the ER part of the linac

Input beam energy	GeV	0.5			
Type of SST	-	2x9-cell			
Number of SSTs	-	528			
Number of CMs♦	-	132			
Number of zones	-	11			
Number of FPCs	-	528			
Cryo. budget at 2 K	kW	8			
RF budget	kW	2640			
ER ratio	-	0.96			
Energy gain	GeV	8.5	16.5	19.5	24.5
Eacc	MV/m	7.7	15.0	17.8	22.3
Q_o	10^{10}	1.8	1.7	1.6	1.3
Q_{ext}	10^{7}	7.5	7.9	8.0	14.0
Max. p-p δf	Hz	> 16	> 16	15	9
Beam on-time /s	ms	1000	308	206	88
Number of bunches/s	10^{6}	1	0.308	0.206	0.088
Peak beam power	MW	9	17	20	25
<Power at dump>	MW	0.84	0.36	0.27	0.13

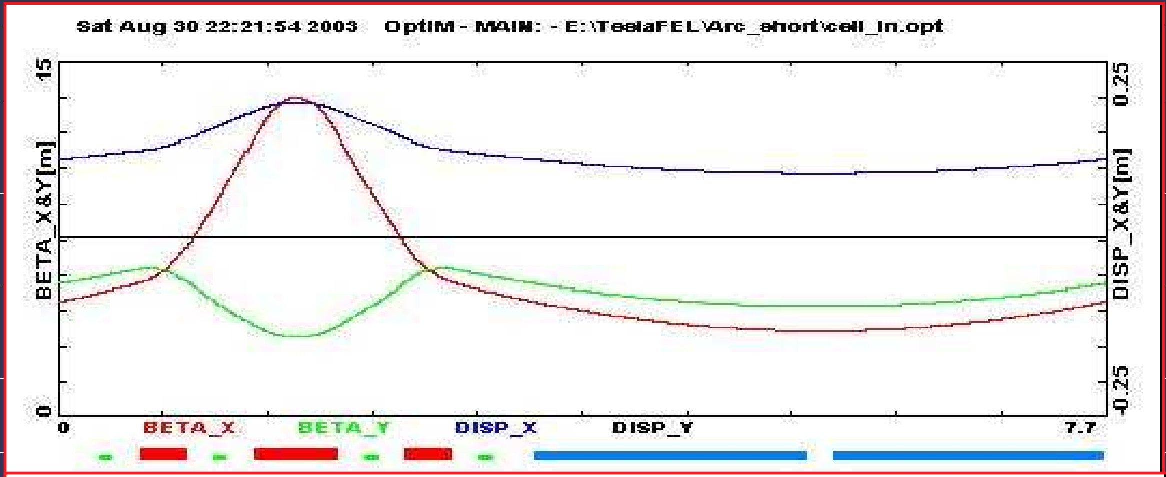
Return „teardrop"arc (*Alex, Dave)*



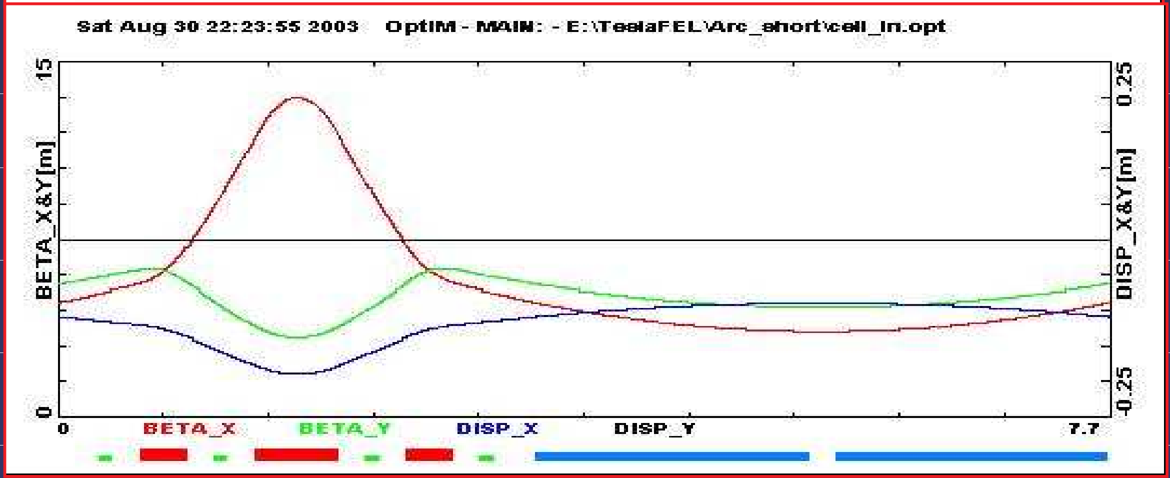
The arc is composed of: 120 „inward bending" cells

40 „outward bending" cells

inward' cell' (×120)



outward' cell (×40)



Quadrupole triplet (×160)

L_F = 62 cm

G_F =9.1 kGauss/cm

L_D = 34 cm

G_D = -9.1 kGauss/cm

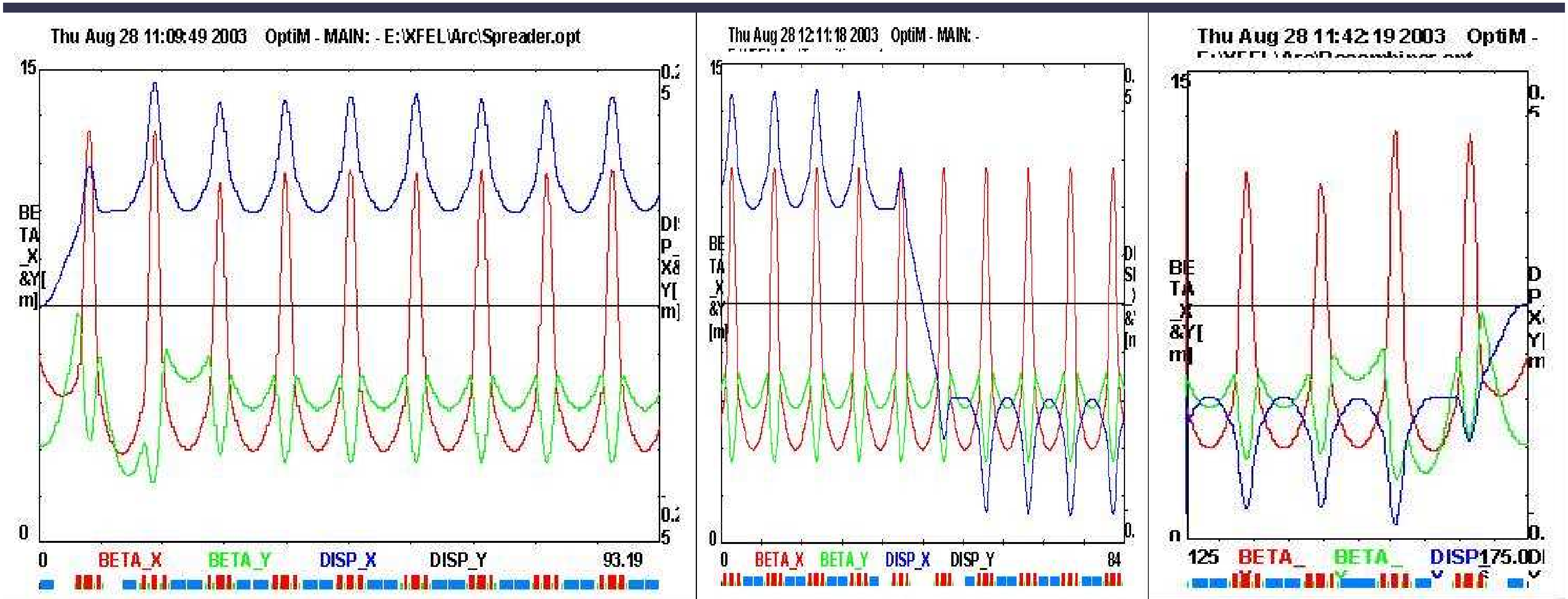
Dipole magnet (×320)

L = 200 cm

θ_{bend} = 1.125 deg

ρ = 102 m

B = 6.5 kGauss



Total Length: 1232 m

D_{max} = 18 cm

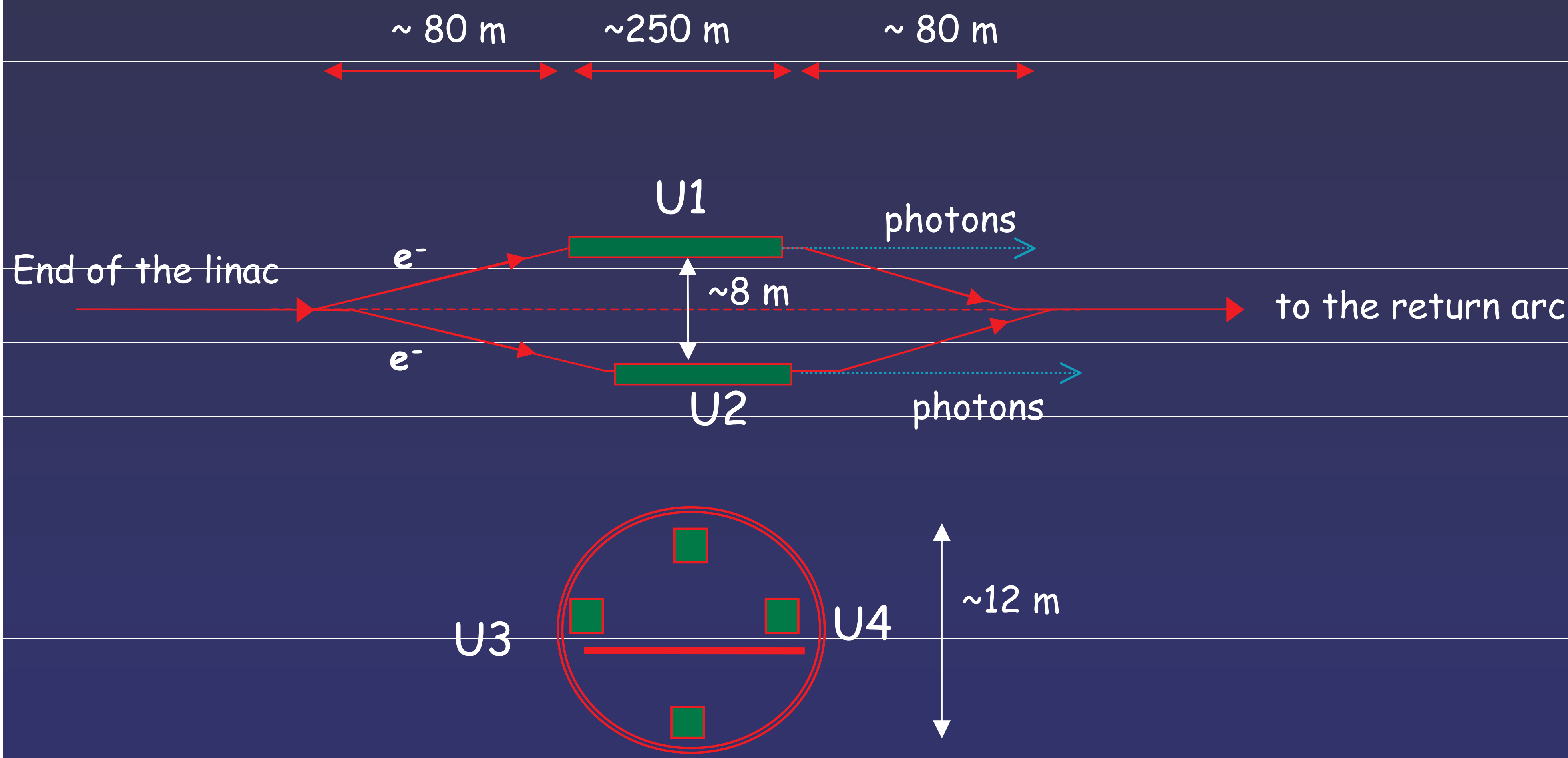
D_{dip} = 9 cm

M_{56} = 64 cm

SR losses: 140 MeV (0.8%)

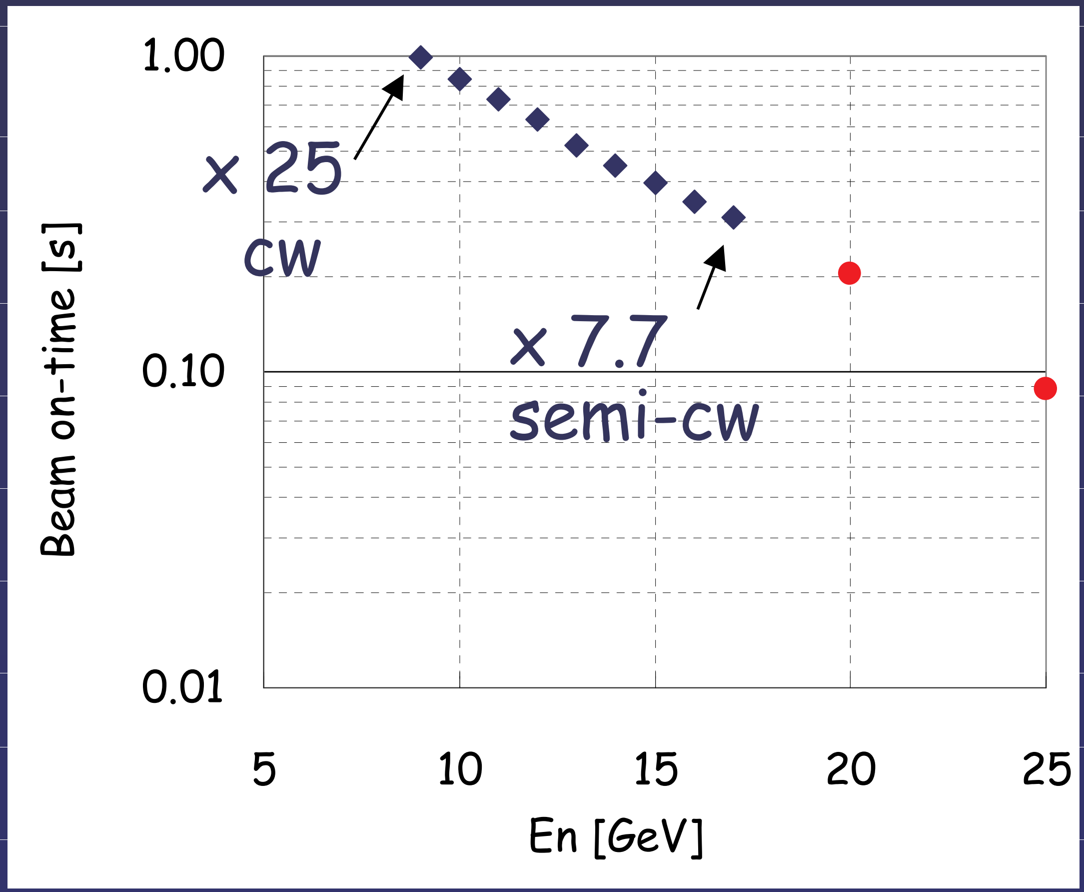
Multi user facility @ ER

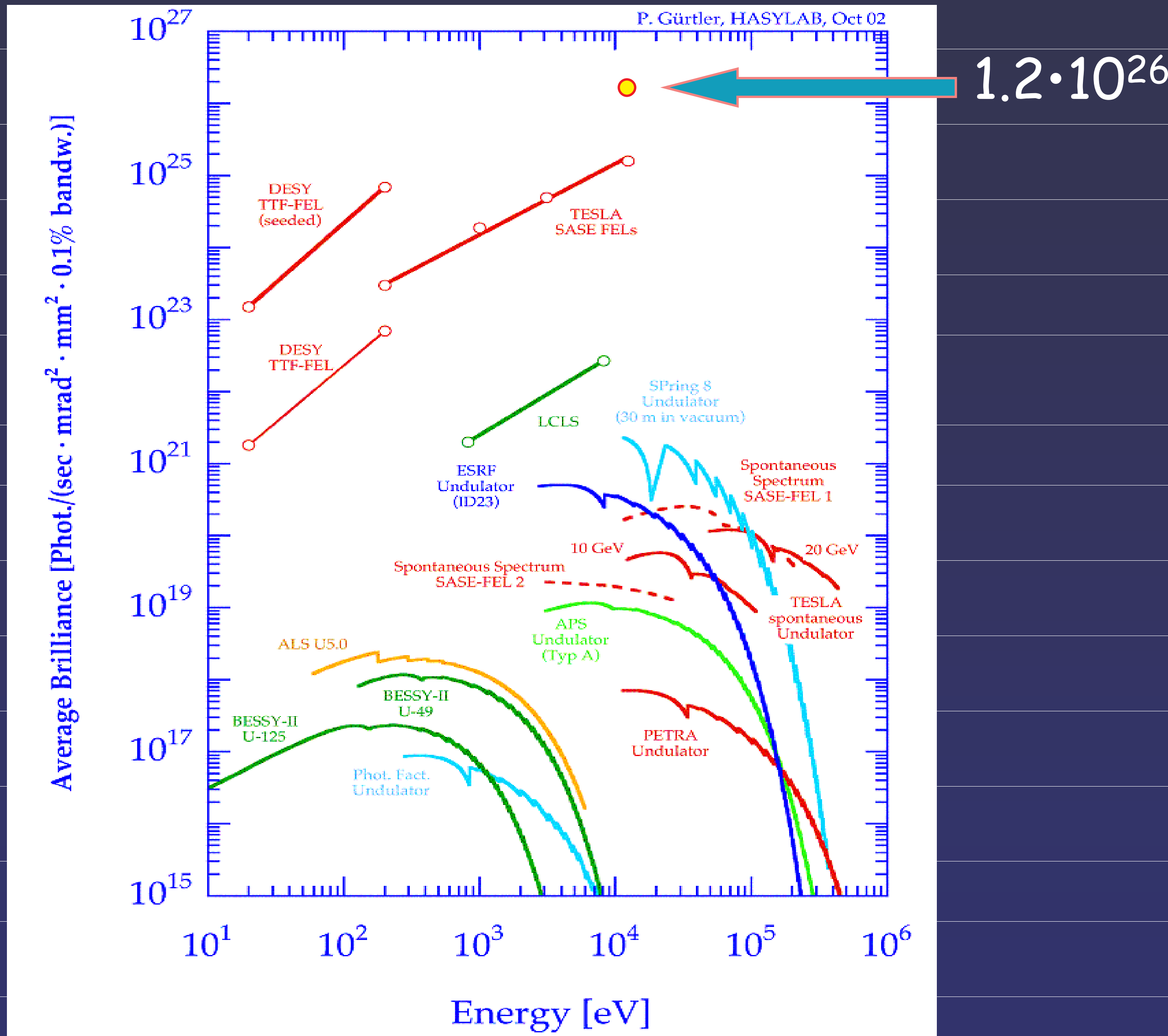
all beam lines have the same geometric length



How many bunches/s can this facility deliver?

Length of RF-pulse scales ~ E_{acc}^{-2} to stay within the cryo budget of 5.7 kW.





P. Gürtler, HASYLAB, Oct 02
1.2•10^26
Average Brilliance [Phot./(sec · mrad² · mm² · 0.1% bandw.)]
Energy [eV]
DESY TTF-FEL (seeded)
TESLA SASE FELs
DESY TTF-FEL
LCLS
SPring 8 Undulator (30 m in vacuum)
ESRF Undulator (ID23)
Spontaneous Spectrum SASE-FEL 1
10 GeV
20 GeV
Spontaneous Spectrum SASE-FEL 2
TESLA spontaneous Undulator
APS Undulator (Typ A)
ALS U5.0
BESSY-II U-49
BESSY-II U-125
PETRA Undulator
Phot. Fact. Undulator

Summary

R&D :

- cw RF gun
- suppression of microphonics
- more experience with the energy recovery

Total AC power: Cryoplant + RF < 10 MW

but this facility can deliver:

7.7 x more average brilliance @ 1Å