A high brightness X-band photoinjector concept
and related technological challenges

Massimo Ferrario
INFN-LNF

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

SPARC

Short Wavelength SASE FEL Electron Beam Requirement: High Brightness $B_n > 10^{15}$ A/m^2

$$\lambda_r^{MIN} \propto \sigma_\delta \sqrt{\frac{\left(1+K^2/2\right)}{\gamma B_n K^2}}$$

minimum radiation wavelength

energy spread

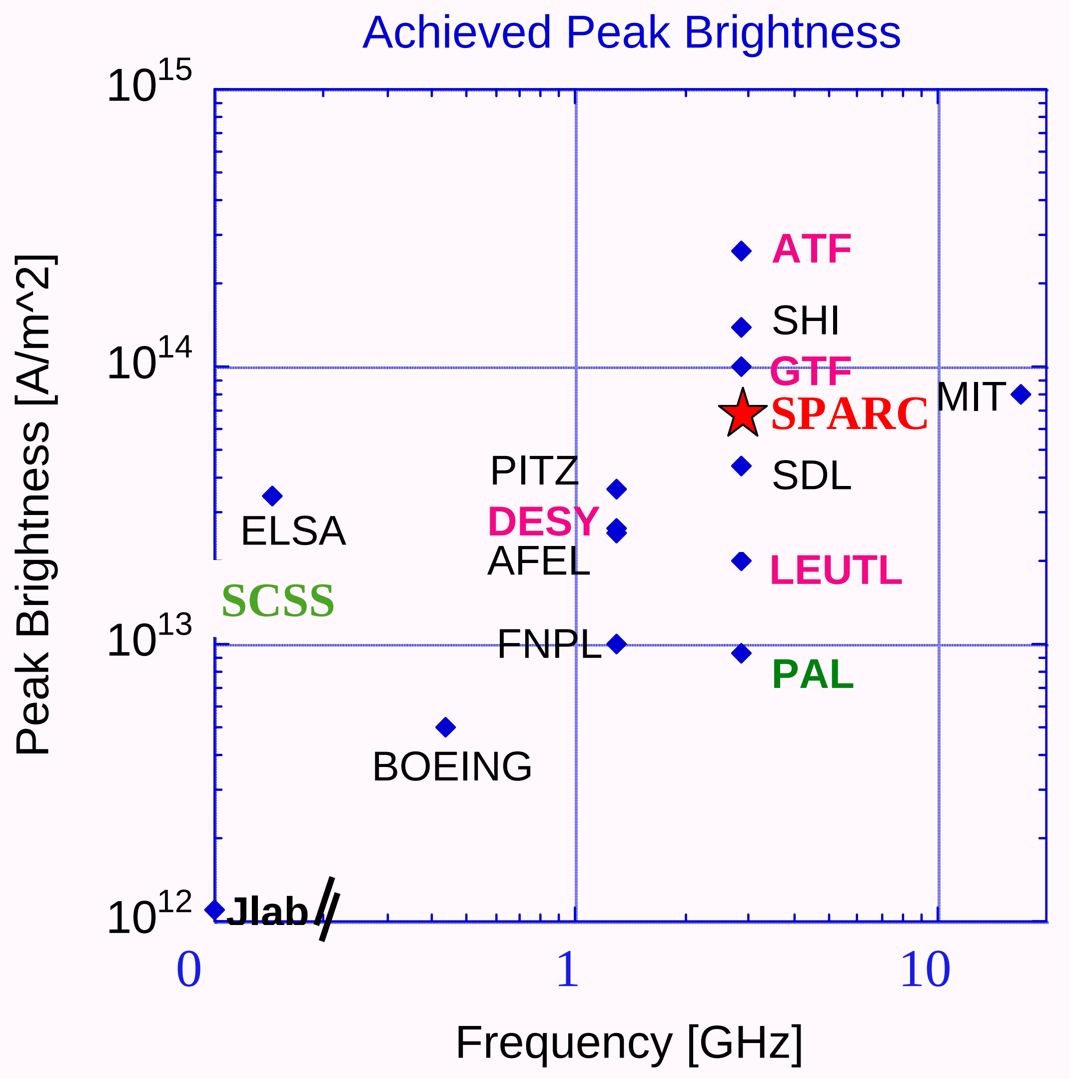
undulator parameter

$$B_n = \frac{2I}{\varepsilon_n^2}$$

$$L_g \propto \frac{\gamma^{3/2}}{K\sqrt{B_n \left(1+K^2/2\right)}}$$

gain length

R. Saldin et al. in *Conceptual Design of a 500 GeV e+e- Linear Collider with Integrated X-ray Laser Facility*, DESY-1997-048



Achieved Peak Brightness
Peak Brightness [A/m^2]
Frequency [GHz]
10^15
10^14
10^13
10^12
0
1
10
ATF
SHI
GTF
SPARC
MIT
PITZ
SDL
ELSA
DESY
AFEL
LEUTL
SCSS
FNPL
PAL
BOEING
Jlab

Short Wavelength SASE FEL Electron Beam Requirement: High Brightness $B_n > 10^{15}$ A/m^2

$$B_n \approx \frac{2I}{\varepsilon_n^2}$$

Bunch compressors

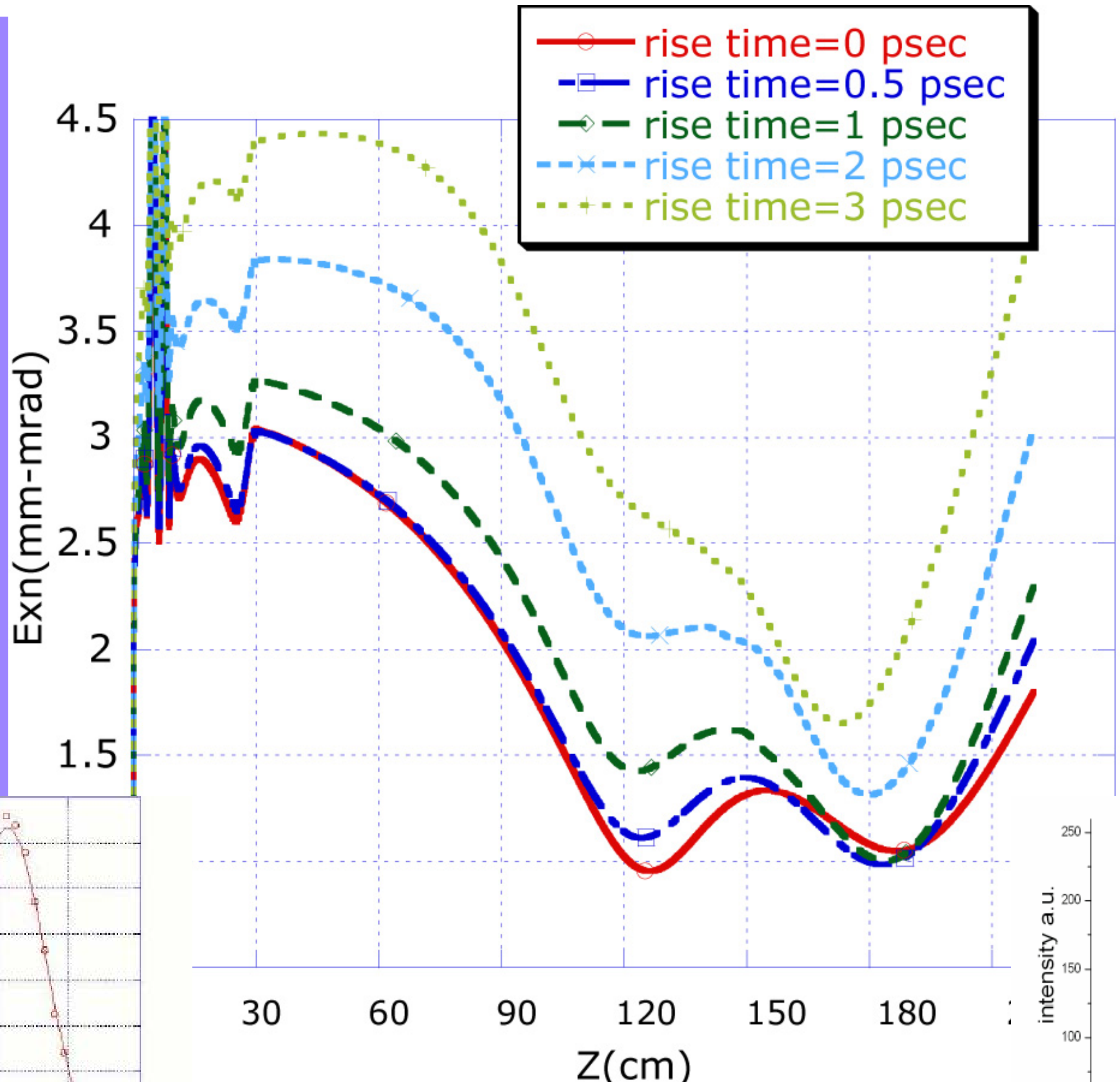
(RF & magnetic)

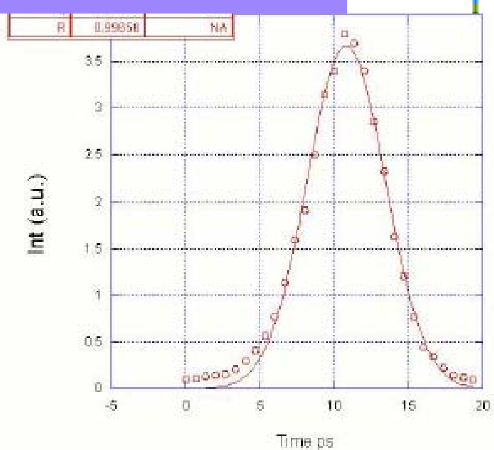
Laser Pulse shaping

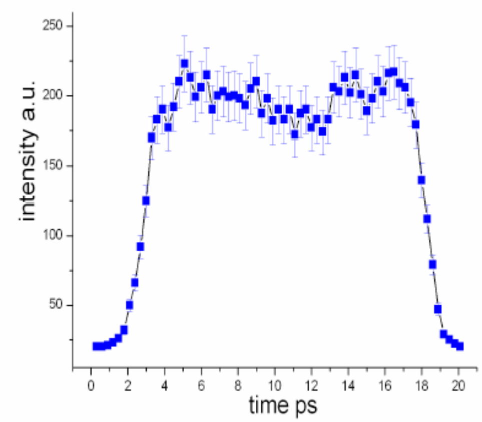
Emittance compensation

Higher peak field on the cathode (X_band)

Emittance versus rise time

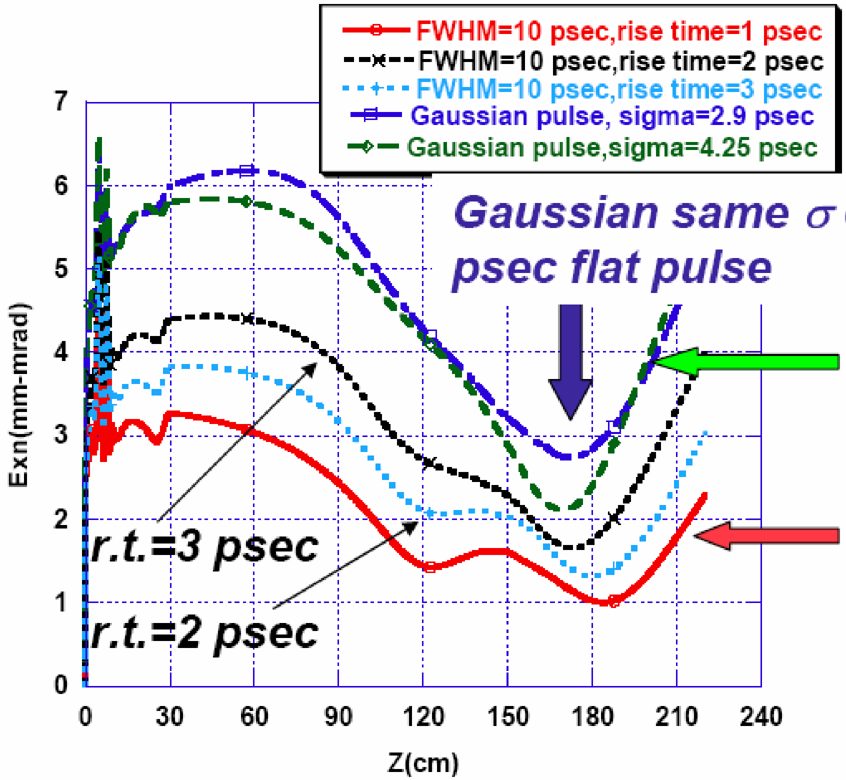






EMITTANCE BEHAVIOUR FORESEEN BY SIMULATIONS FOR DIFFERENT PULSE SHAPES

PARMELA computed emittance vs z in the post-gun region for different pulse shapes

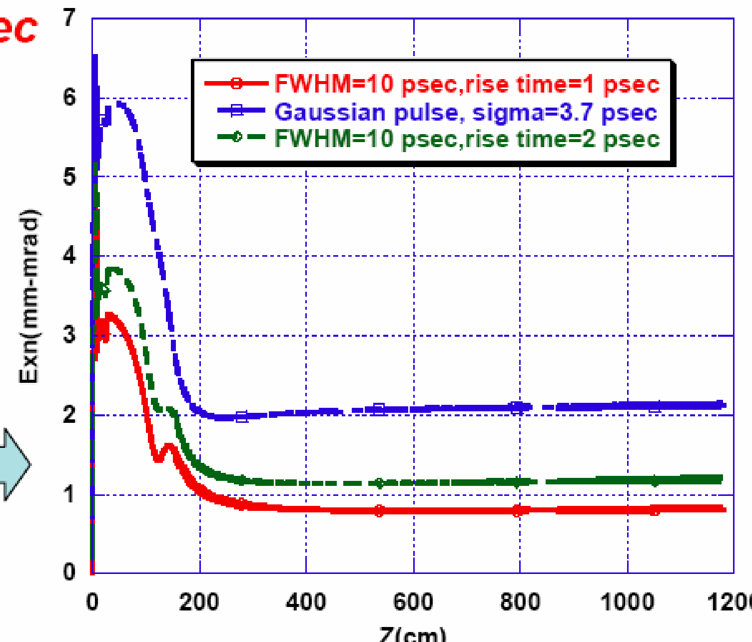


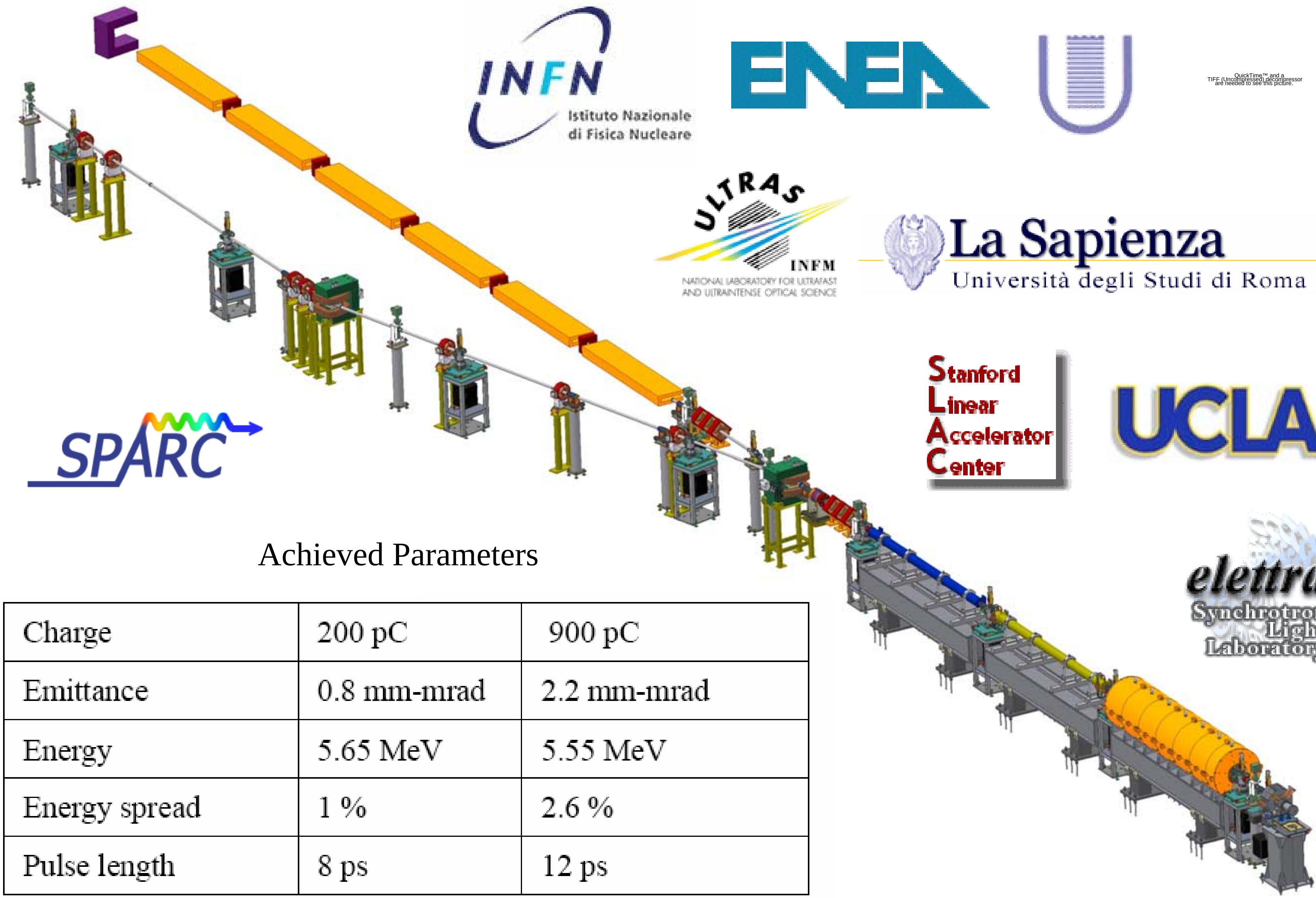
Gaussian same σ of 10 psec flat pulse

Gaussian same FWHM of a 10 psec flat pulse

SPARC working point: flat pulse with FWHM=10 psec , rise time=1 psec

PARMELA computed emittance vs z up to the end of the SPARC injector for different pulse shapes





SPARC

INFN
Istituto Nazionale di Fisica Nucleare

ENEA

ULTRAS INFM
NATIONAL LABORATORY FOR ULTRAFAST AND ULTRAINTENSE OPTICAL SCIENCE

La Sapienza
Università degli Studi di Roma

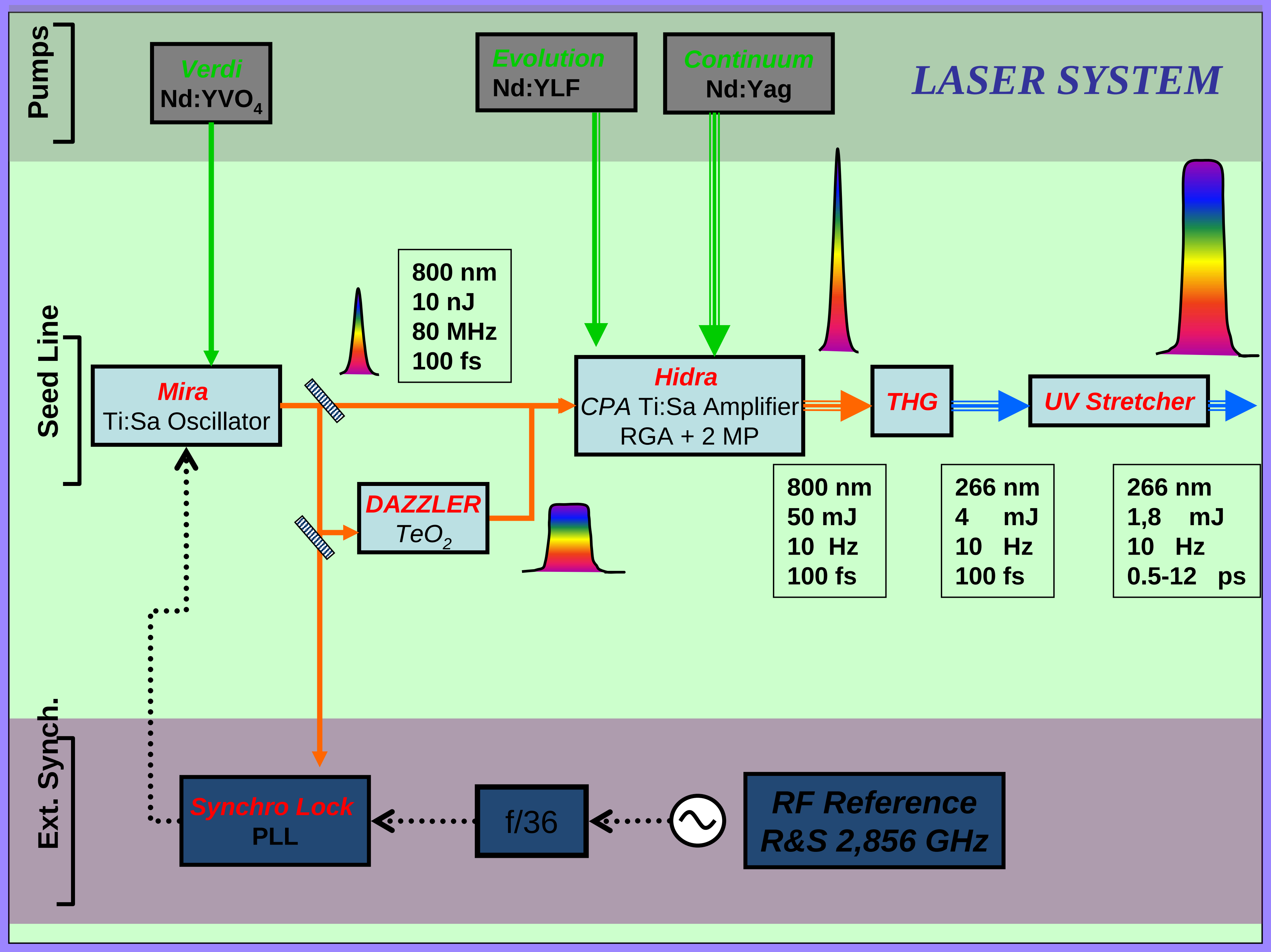
Stanford Linear Accelerator Center

UCLA

elettra
Synchrotron Light Laboratory

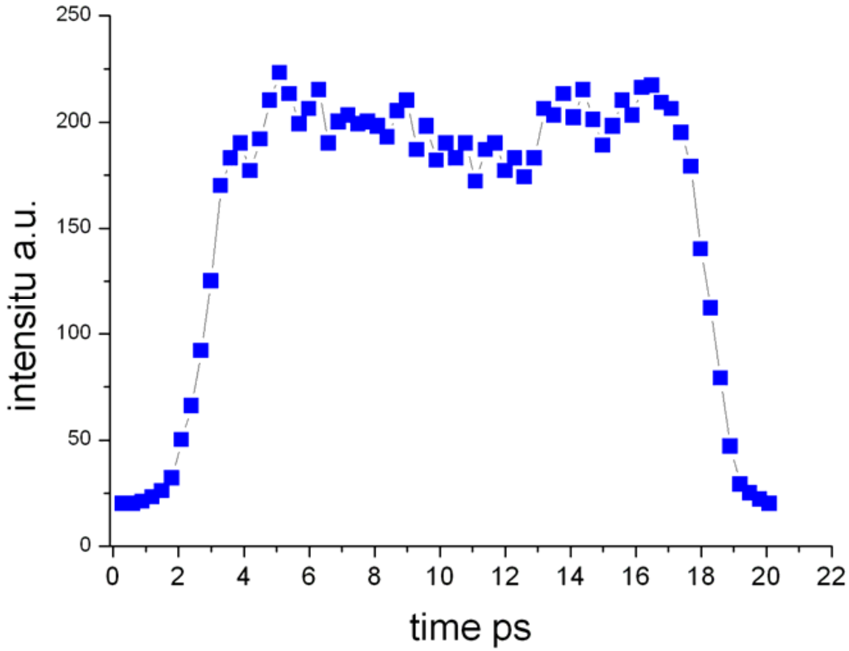
Achieved Parameters

Charge	200 pC	900 pC
Emittance	0.8 mm-mrad	2.2 mm-mrad
Energy	5.65 MeV	5.55 MeV
Energy spread	1 %	2.6 %
Pulse length	8 ps	12 ps



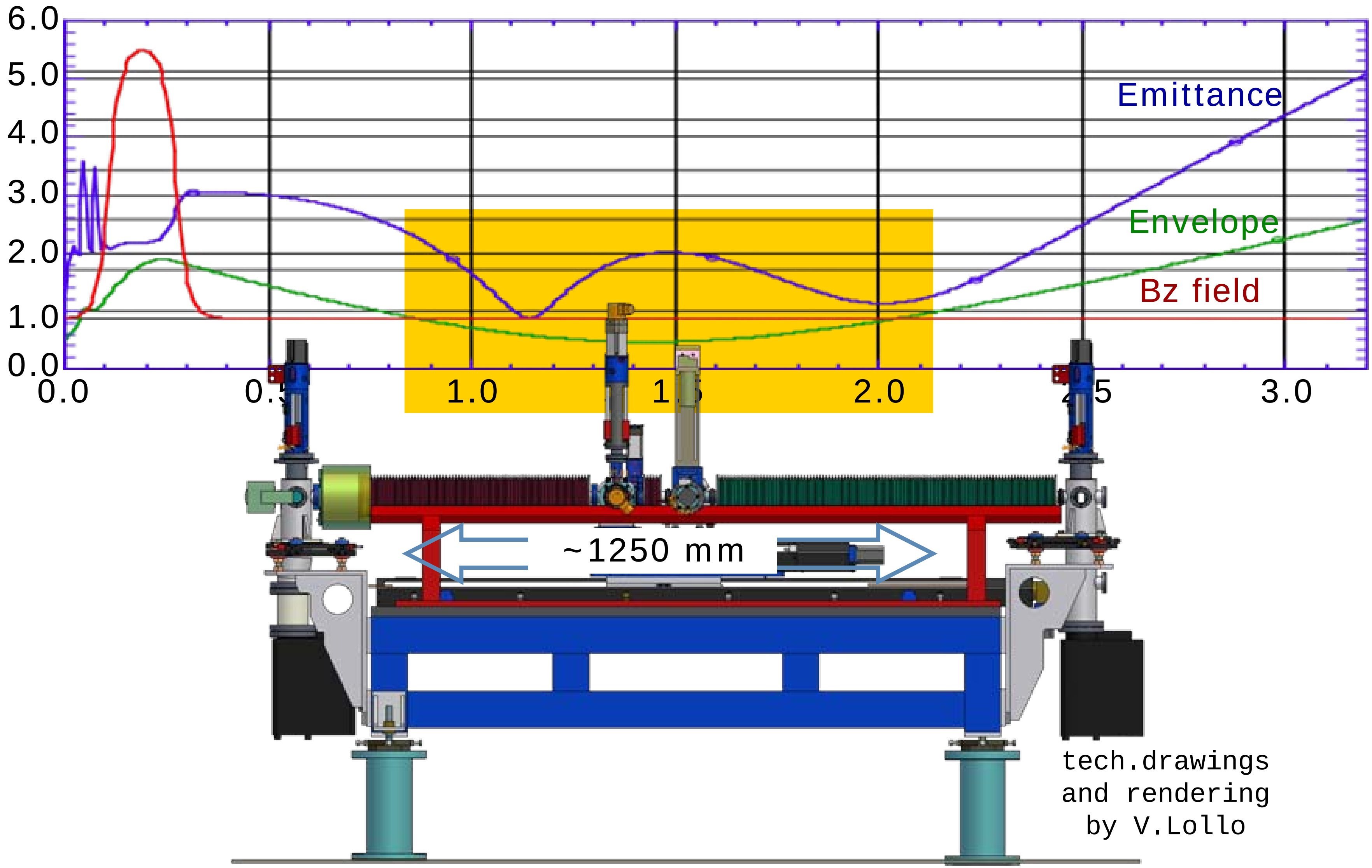
LASER SYSTEM
Pumps
Verdi
Nd:YVO4
Evolution
Nd:YLF
Continuum
Nd:Yag
Seed Line
Mira
Ti:Sa Oscillator
800 nm
10 nJ
80 MHz
100 fs
Hidra
CPA Ti:Sa Amplifier
RGA + 2 MP
THG
UV Stretcher
DAZZLER
TeO2
800 nm
50 mJ
10 Hz
100 fs
266 nm
4 mJ
10 Hz
100 fs
266 nm
1,8 mJ
10 Hz
0.5-12 ps
Ext. Synch.
Synchro Lock
PLL
f/36
RF Reference
R&S 2,856 GHz

Rise time measurements for long pulse 15 ps



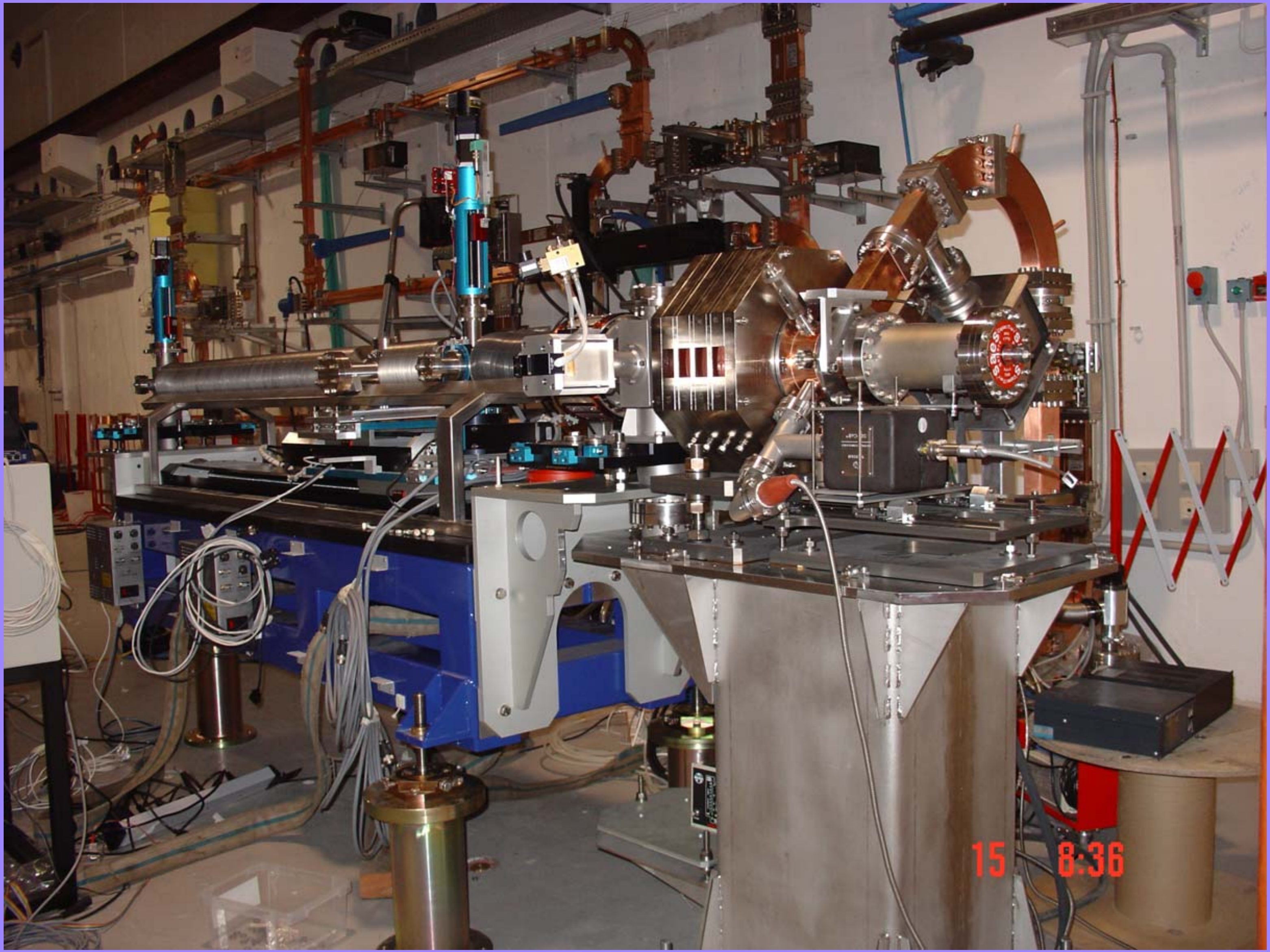
- Scaling the pulse length the ratio between the rise time and the pulse duration is constant.
- With this length the rise time is 1.5 ps

The SPARC Emittance Meter



tech.drawings
and rendering
by V.Lollo

Gun and emittance meter in the SPARC bunker



This is not a simulation

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

This is not a simulation

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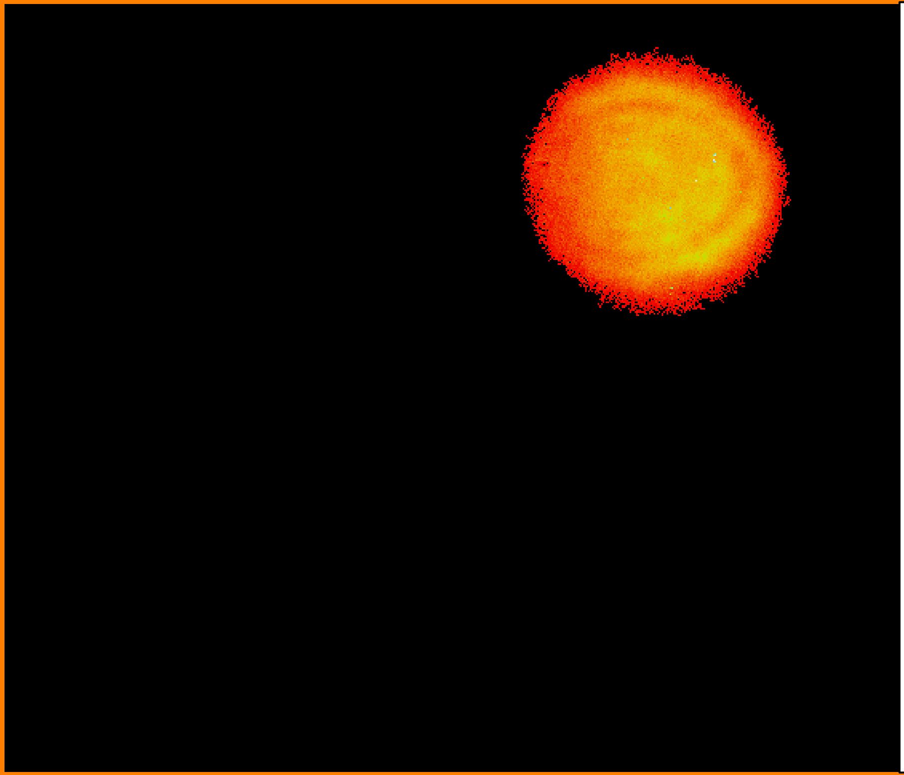
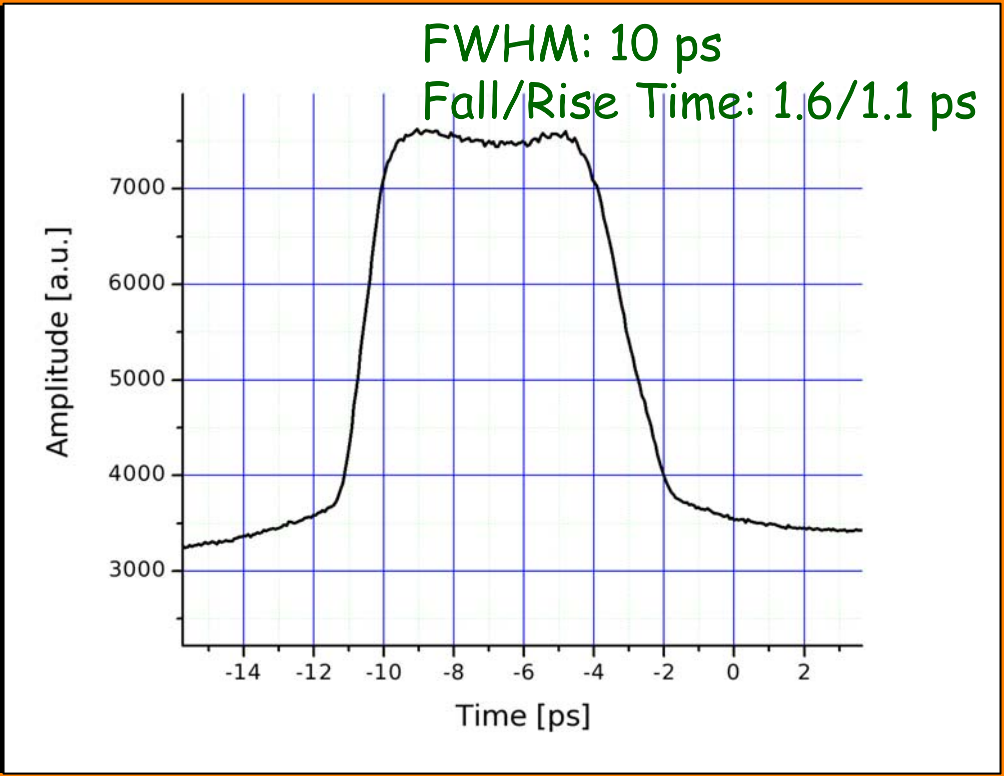
Cinepak decompressor
are needed to see this picture.

FLAT TOP: Comparison with Parmela Simulation





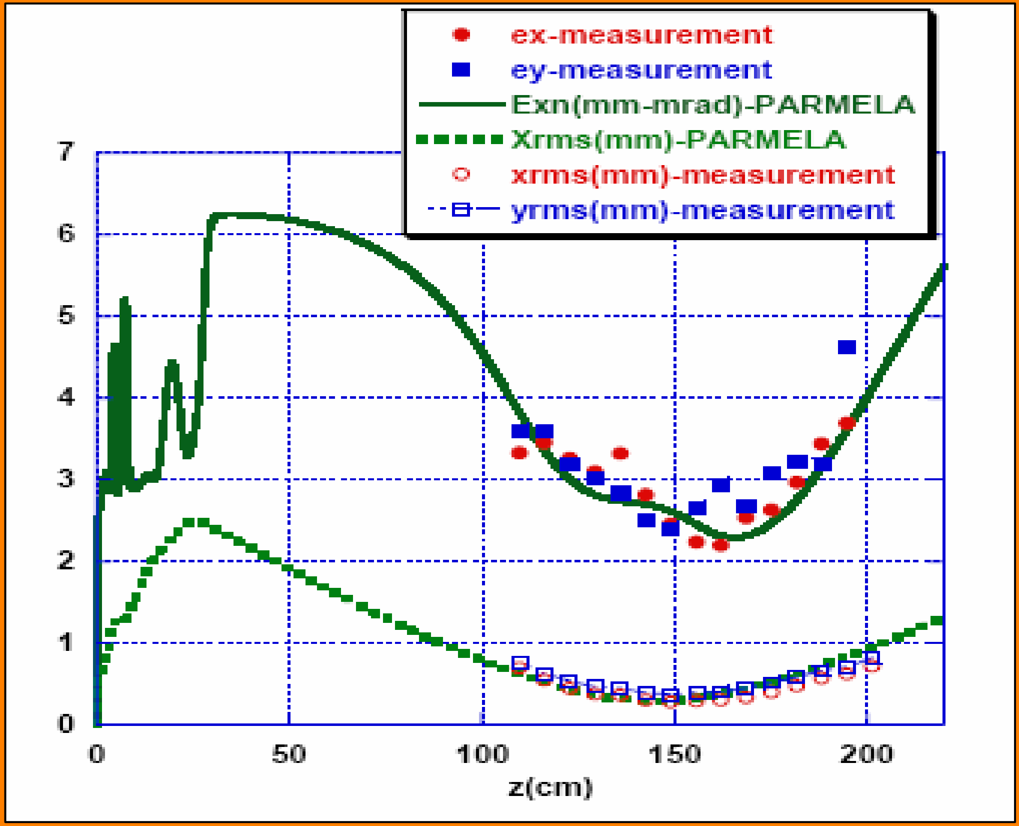
Uniform transverse beam: σ_r = 430 μm

MEASURED BEAM PARAMETERS

- Q = 1 nC
- E_0 = 5.65 MeV
- Phase = 32°

SIMULATION BEAM PARAMETERS

- Q = 1 nC
- Egun = 120 MV/m
- Phase = 40° (Phase shift of 8° wrt the ideal case)
- FWHM = 10 ps
- Rise Time = 2 ps
- σ_r = 0.45 mm



(C. Ronsivalle)

Electron beam

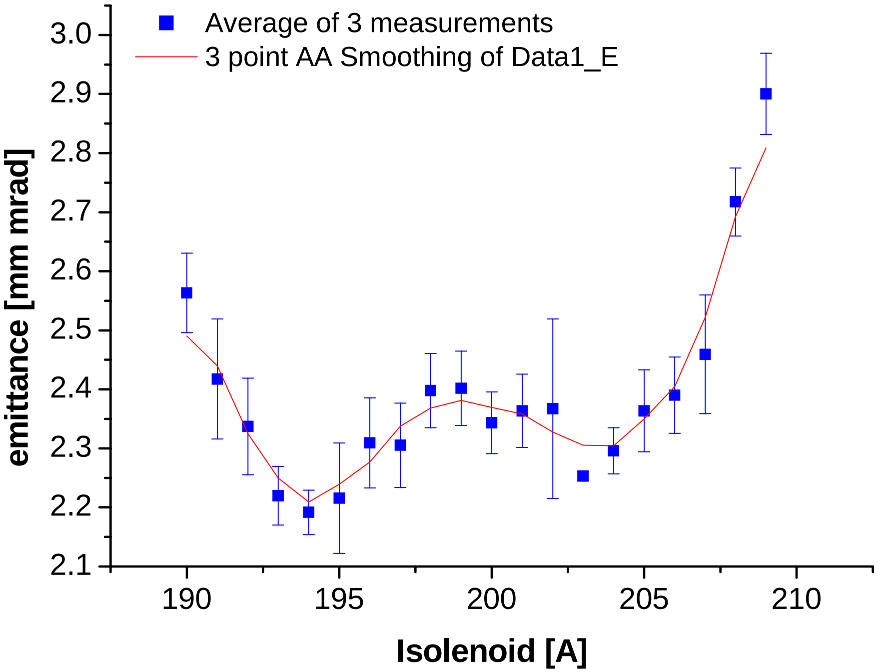
Energy = 5.5 MeV
Energy spread = 2.66%
Charge = 700 pC (ad inizio turno; alla fine era 620 pC)
Phase = +8 deg

Laser

FWHM = 6 ps
Rise Time < 1.5 ps
rms spot size = 420 μm

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.



Scaling the SPARC design from S-band to X-band

$$\frac{\lambda_{12\ GHz}}{\lambda_{3\ GHz}} = 0.25$$

$Q \propto \lambda_{rf}$ — **1 nC ==> 0.25 nC**

$\sigma_i \propto \lambda_{rf}$ — **1 mm ==> 0.25 mm**

10ps ==> 2.5 ps

$\hat{E} \propto \lambda_{rf}^{-1}$ — **120 MV/m ==> 480 MV/m**
==> Break Down & Dark Currents

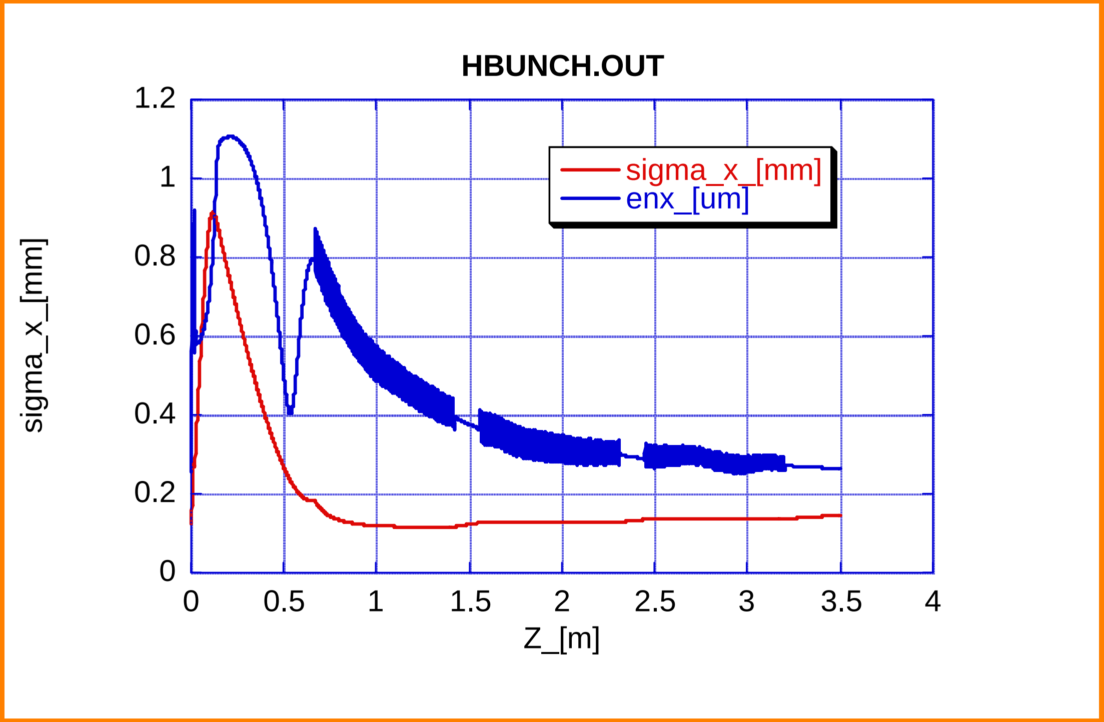
$\hat{B} \propto \lambda_{rf}^{-1}$ — **0.3 T==> 1.2 T ==> Cooling**

Rosenzweig and Colby, Charge and Wavelength Scaling of RF Photoinjector Designs, Advanced Accelerator Concepts, AIP Conf. Proc. 335 724 (1995)

X-band Split Photoinjector (scaling + fields optimization)

E_p=480 MV/m , **B=0.575 T** , E_{tw}=68 MV/m , **Q=0.25 nC** , L=2.5 ps , R=0.25 mm ,

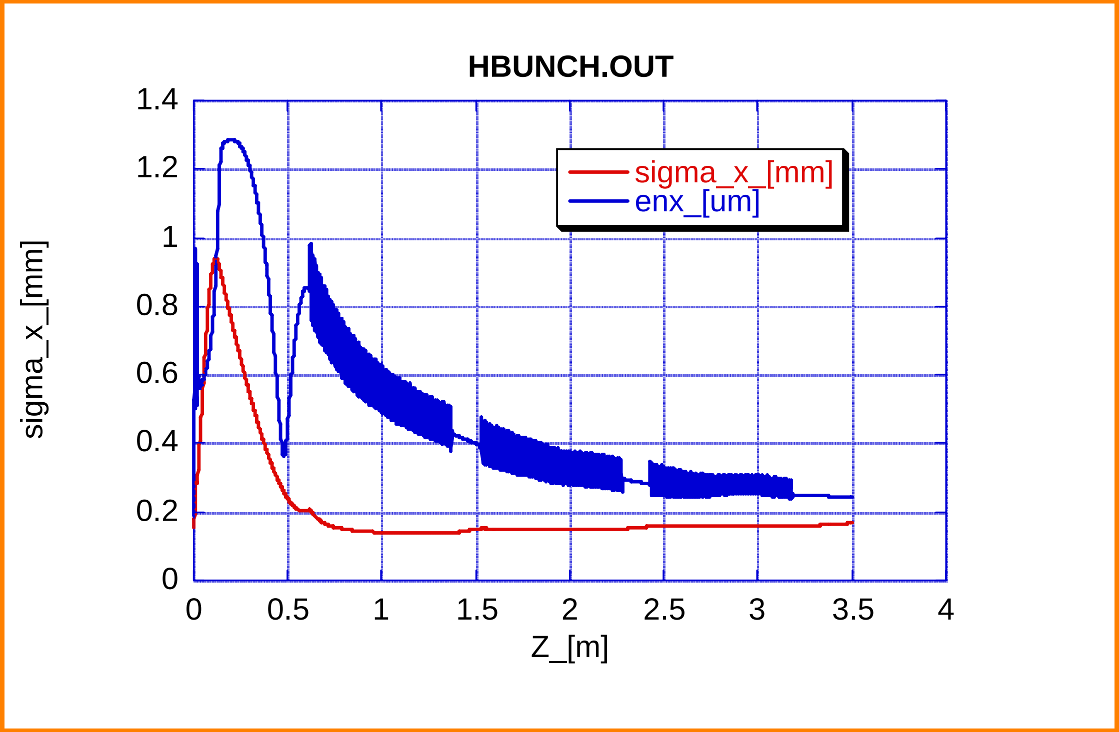
ε_{th}=0.15 mm-mrad



T=158 MeV , **I=90 A , ε_n=0.27 mm-mrad**, $\Delta\gamma/\gamma$=0.6%

B_n = 2.5 10^{15} A/m^2

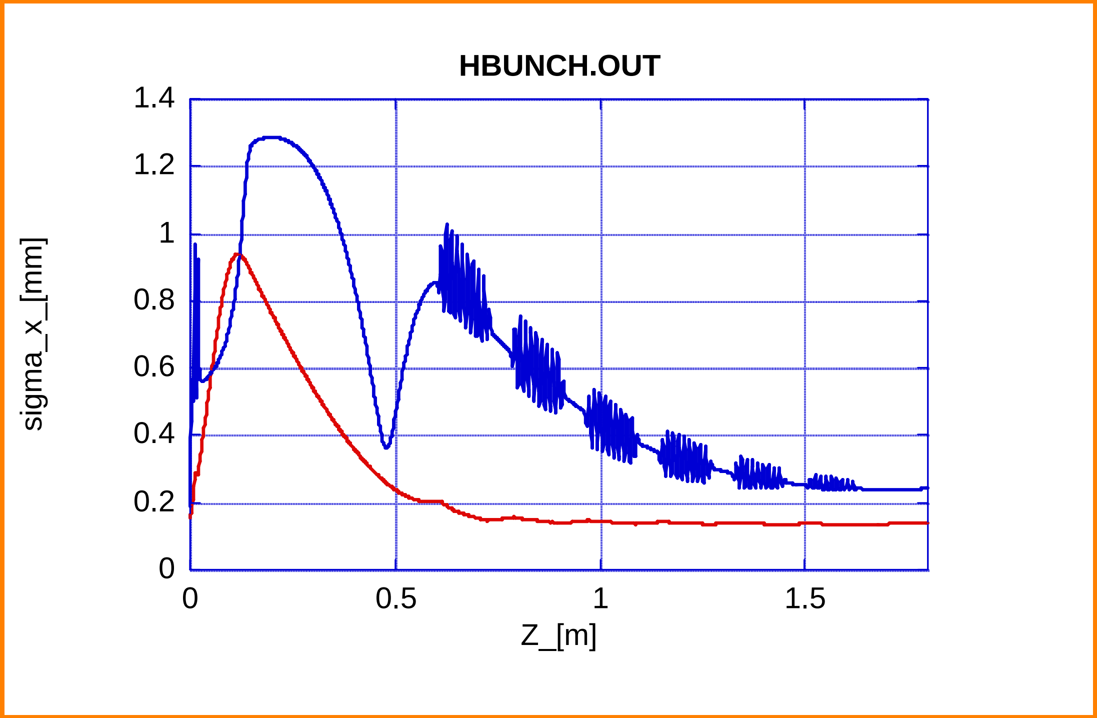
E_p=350 MV/m , B=0.435 T , E_{tw}=56 MV/m , **Q=0.20 nC** , L=4.2 ps , R=0.31 mm , ε_{th}=0.19 mm-mrad

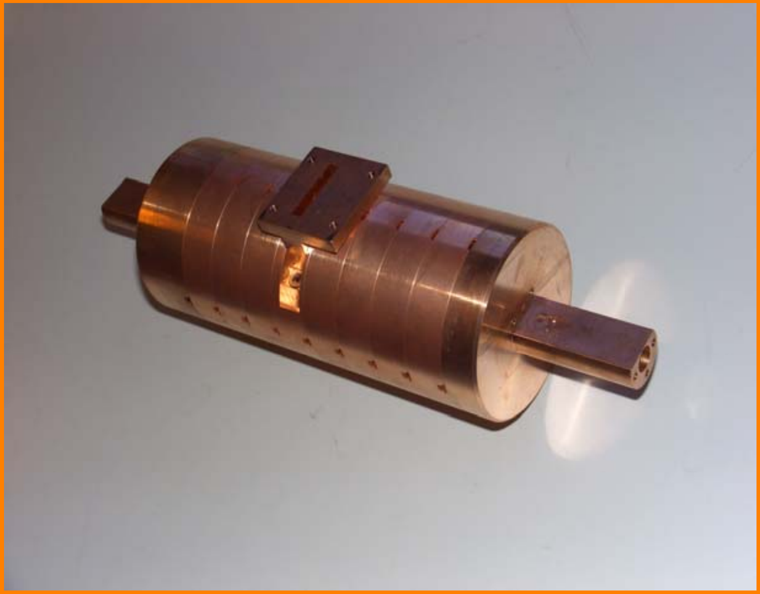


T=130 MeV , **I=50 A , ε_n=0.25 mm-mrad**, $\Delta\gamma/\gamma$=0.6%

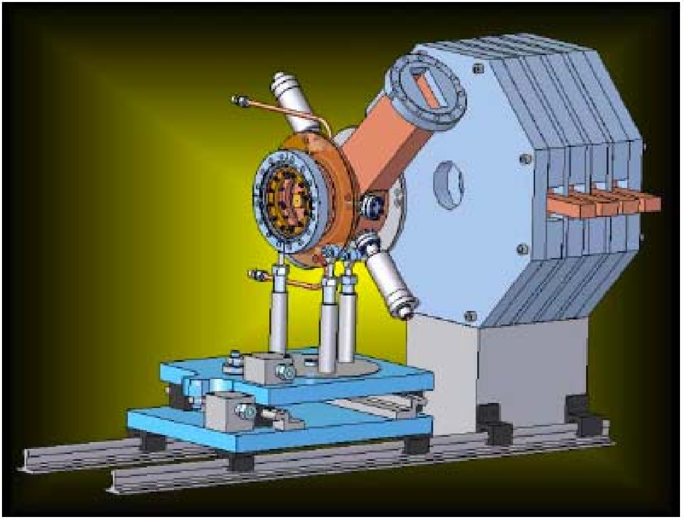
B_n = 1.5 10^{15} A/m^2

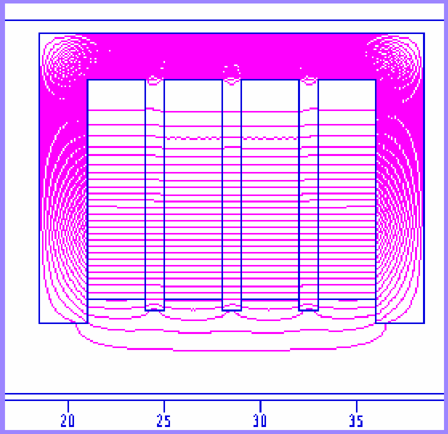
E_p=350 MV/m , B=0.435 T , E_{sw}=52 MV/m , **Q=0.20 nC** , L=4.2 ps , R=0.31 mm , ε_{th}=0.19 mm-mrad

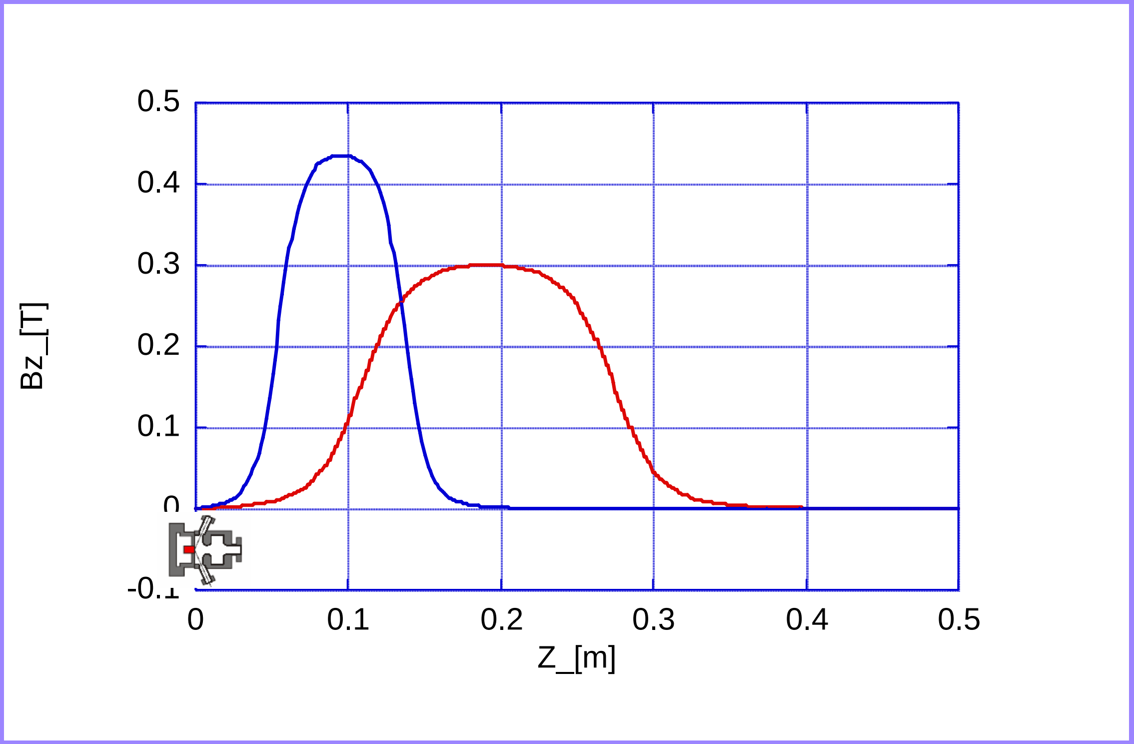




T=43 MeV , **I=50 A , ε_n=0.25 mm-mrad**, $\Delta\gamma/\gamma$=0.5%, B_n = 1.5 10^{15} A/m^2




20
25
30
35


0.5
0.4
0.3
0.2
0.1
0
-0.1
Bz_[T]
0
0.1
0.2
0.3
0.4
0.5
Z_[m]

RF parameters scaling

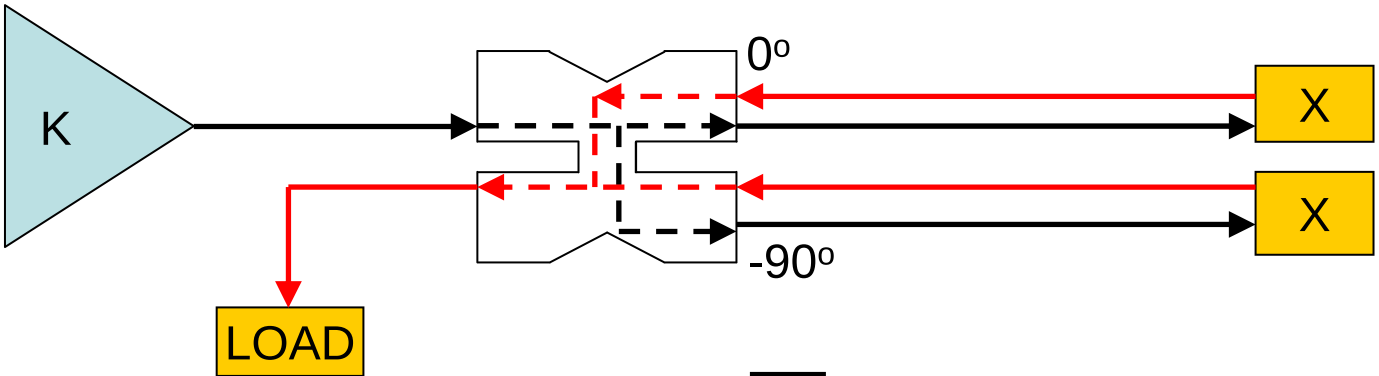
f	**2.856 [GHz]**	**11.424 [GHz]**
R_s	46 [MΩ/m]	92 [MΩ/m]
Q	15335	7668
P_{rf}	10 [MW] @ 120MV/m	20 [MW] @ 480MV/m
P_{rf}		**10 [MW] @ 350MV/m**
P_d @ 10 Hz	4.7 [kW/m]	**0.2 [kW/m]**
τ	4 [μs]	0.5 [μs]
Cavity Length	86 mm	21.5 mm
Iris Radius	12 mm	3 mm

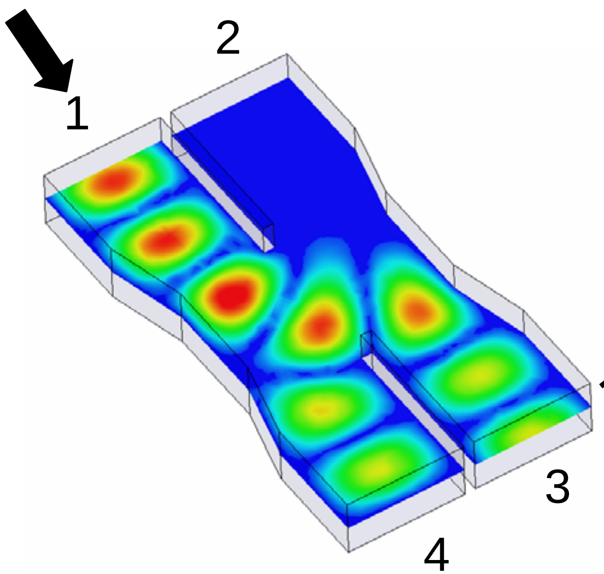
2) Basic scheme for reflections compensation using a 90 deg hybrid junction

⇒ ***High power circulators (isolators) in X-band are not available***

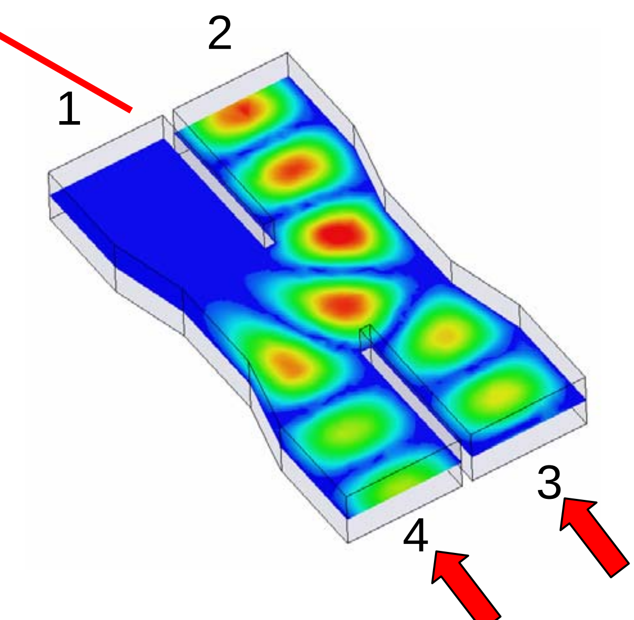
⇒ ***Possibility to protect the RF source from reflections with 90 deg hybrid junction***

Courtesy D. Alesini





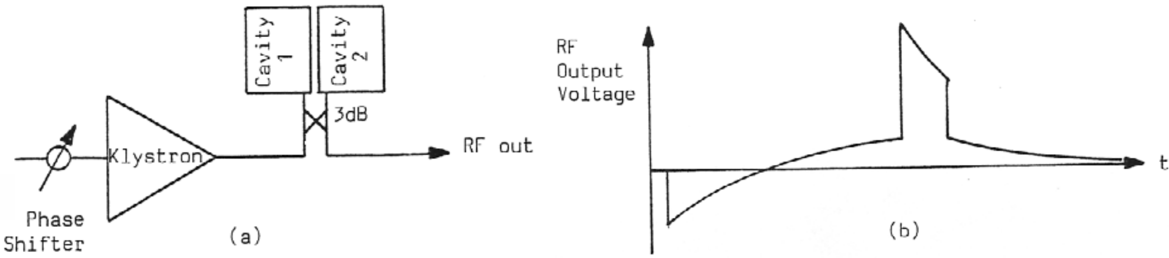
$$S = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 1 & -j \\ 0 & 0 & -j & 1 \\ 1 & -j & 0 & 0 \\ -j & 1 & 0 & 0 \end{pmatrix}$$



2.1) 90 deg hybrid junction applications

SLED

Z.D. Farkas *et al.*, *IEEE Trans. Nucl. Sci.*, **NS-22** (1975) 1299.

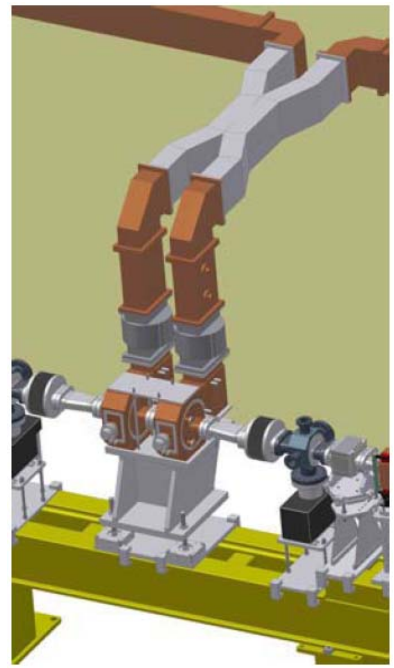


CTF3 (delay loop) RFD

Proceedings of EPAC 2006, Edinburgh, Scotland

THE RF DEFLECTOR FOR THE CTF3 DELAY LOOP

Fabio Marcellini, David Alesini, INFN-LNF, Frascati (Rome) - Italy

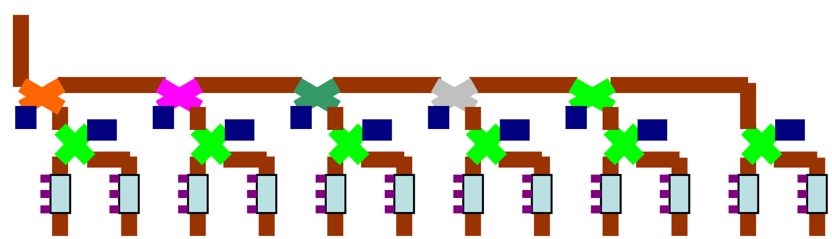


NLC

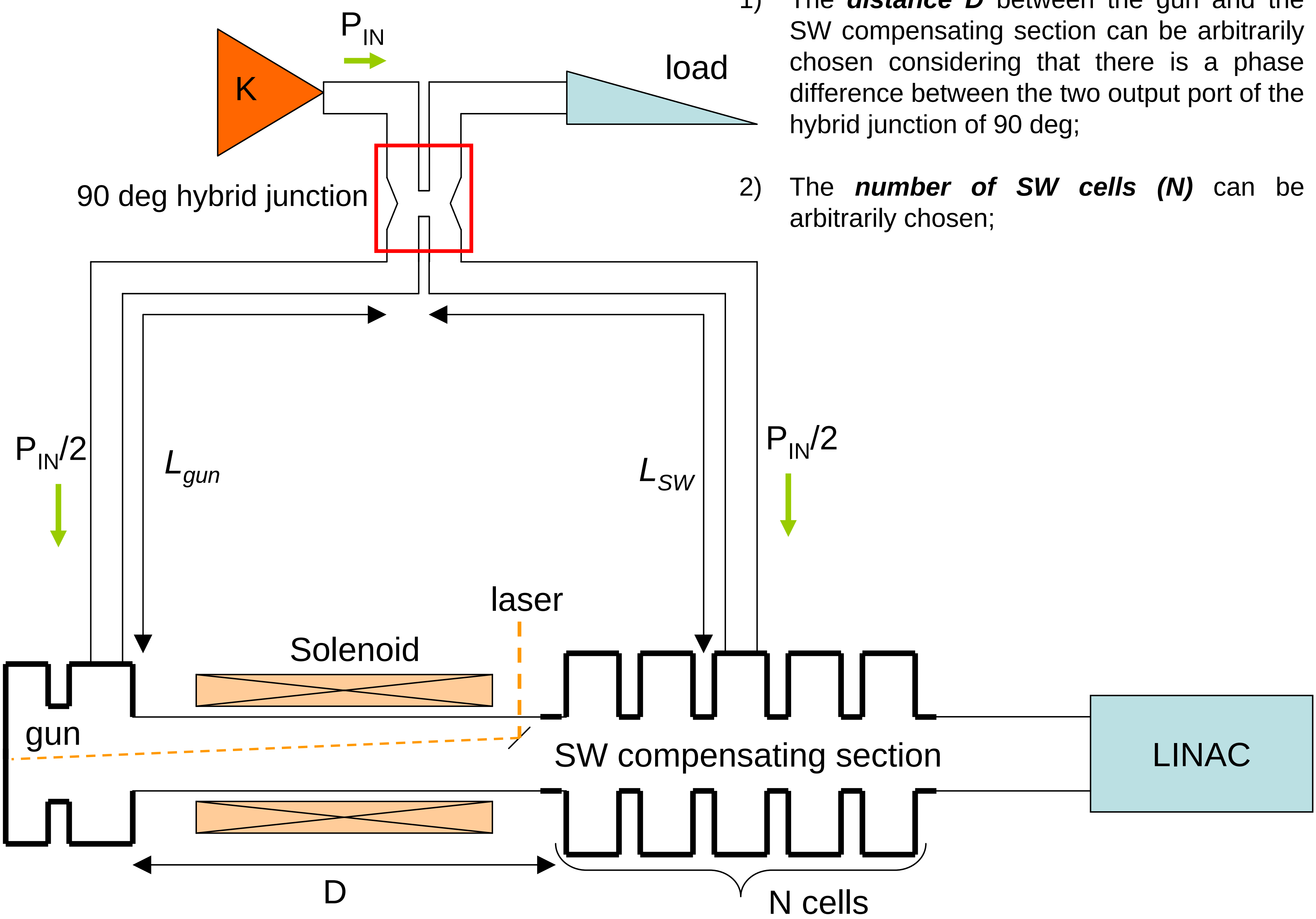
SLAC–PUB– 12046
August 2006

ILC Linac R&D at SLAC *

C. Adolphsen
Stanford Linear Accelerator Center, Stanford University, Stanford CA 94309



3) X-band gun scheme (1/2)

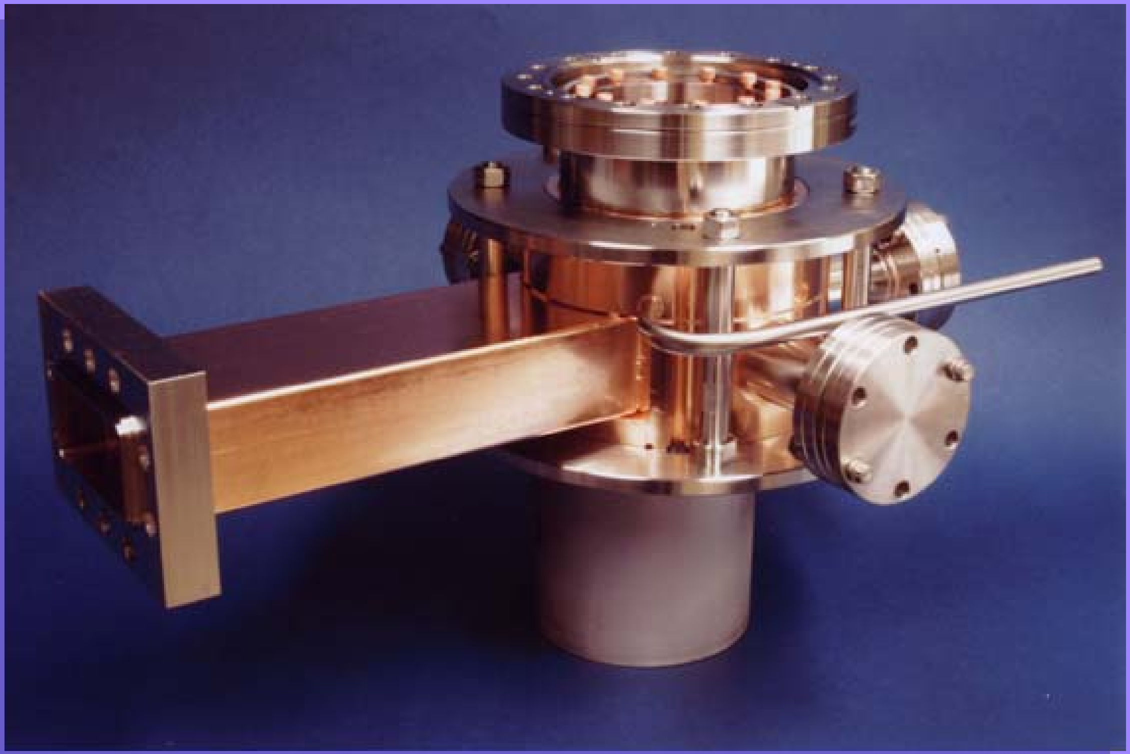


1) The ***distance D*** between the gun and the SW compensating section can be arbitrarily chosen considering that there is a phase difference between the two output port of the hybrid junction of 90 deg;

2) The ***number of SW cells (N)*** can be arbitrarily chosen;

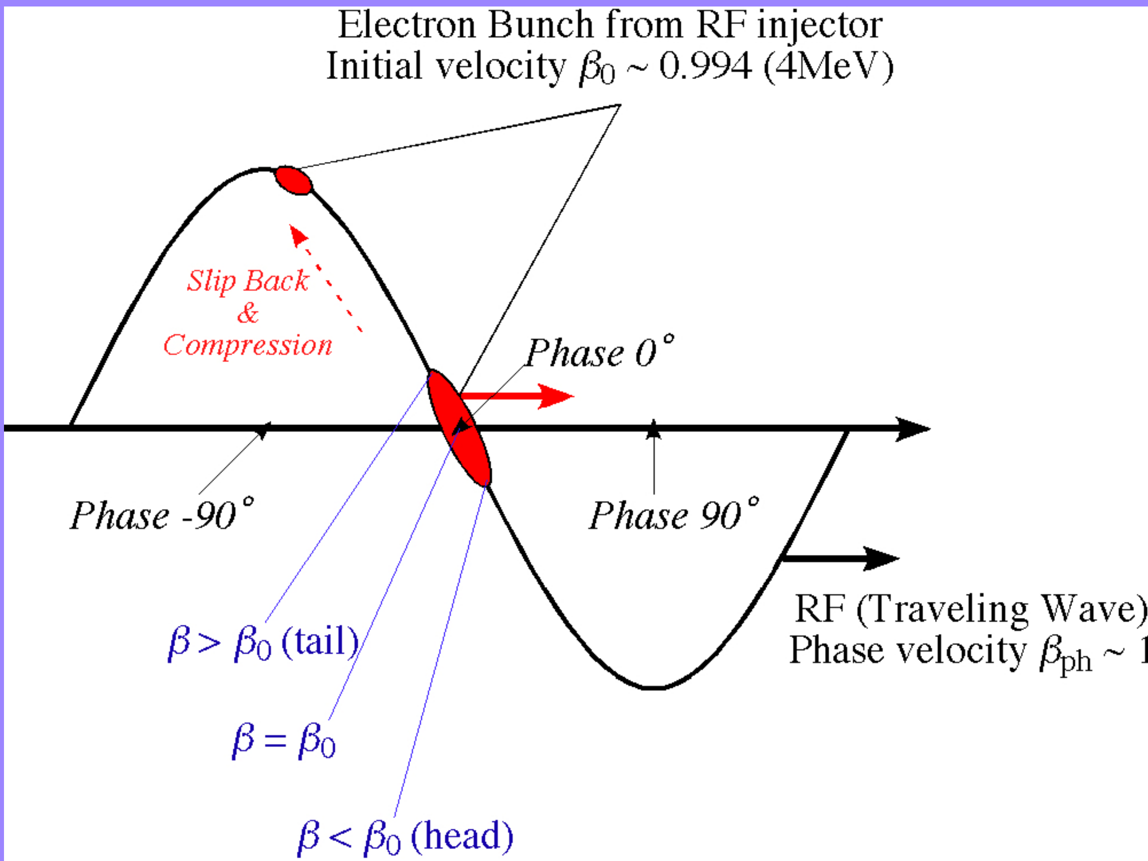
DEVELOPMENT OF AN X-BAND PHOTOINJECTOR AT SLAC*

E. Vlieks, G. Caryotakis, R. Loewen, D. Martin, A. Menegat
SLAC, 2575 Sand Hill Rd, Menlo Park, CA 94025, USA
E. Landahl, C. DeStefano, B. Pelletier, and N.C. Luhmann, Jr.
3001 Engineering III, Dept. of Applied-Science
Davis, CA 95616, USA



Number of Cells	5.5
Peak Surface Gradient/Power	200 MV/m @ 16 MW
RF Filling Time	65 ns
Cathode Material	Copper
RF Pulse length	200 ns

Velocity bunching concept



$$E_z = E_0 \sin(\phi)$$

$$\phi = kz - \omega t + \phi_0$$

$$\frac{d\gamma}{dz} = -\alpha k \sin\phi,$$

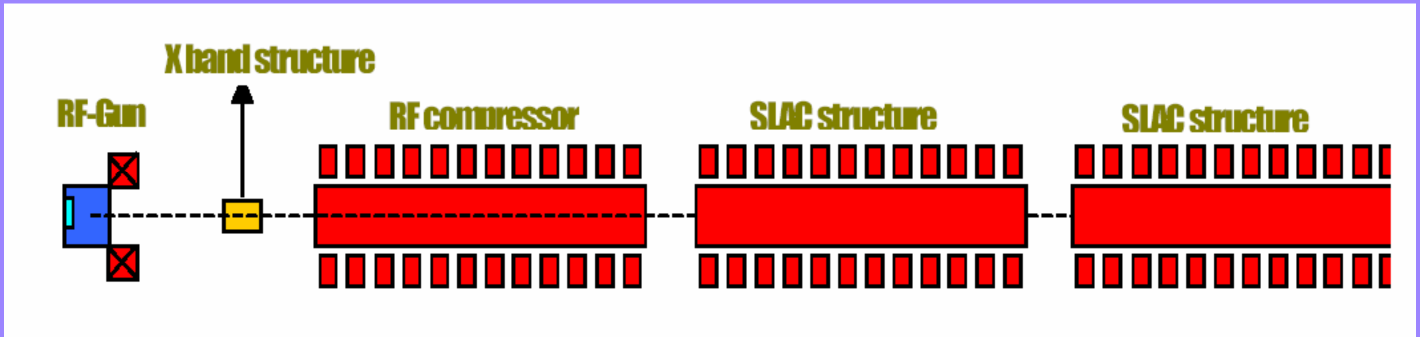
$$\frac{d\phi}{dz} = k\left[1 - \frac{\gamma}{\sqrt{\gamma^2 - 1}}\right].$$

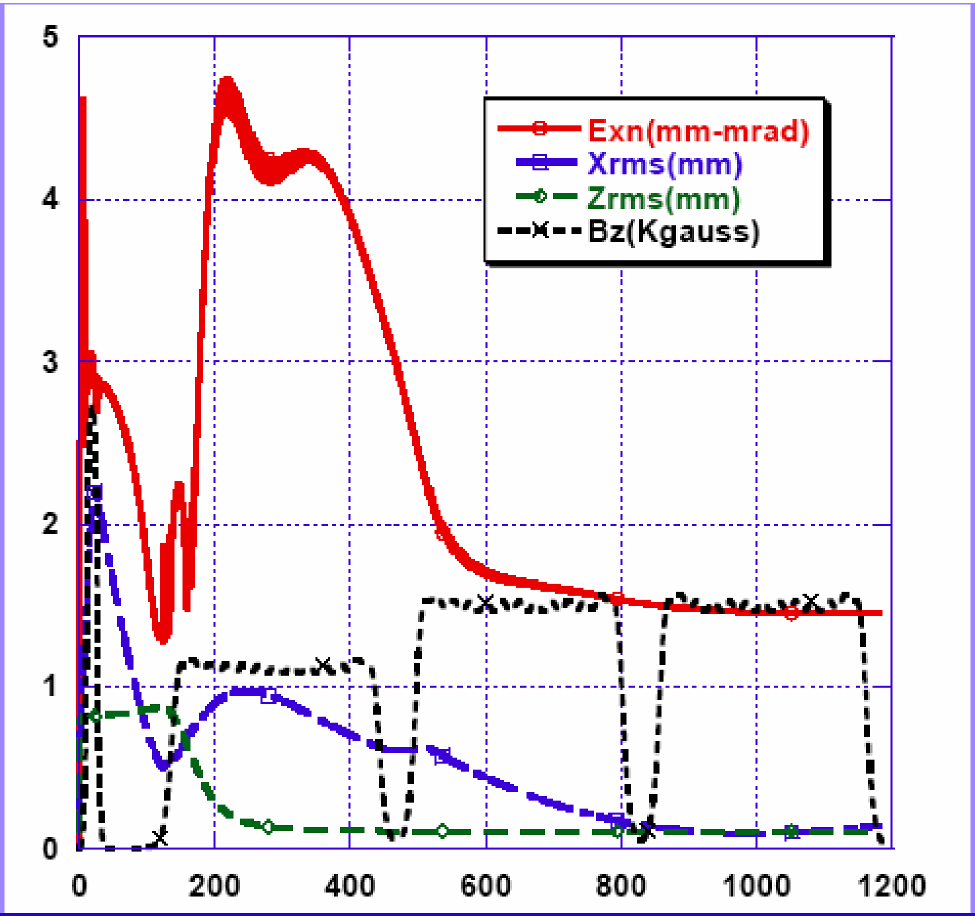
$$\alpha \equiv eE_0/mc^2k$$

$$H = \gamma - \sqrt{\gamma^2 - 1} - \alpha\cos(\phi)$$

L. Serafini, M. Ferrario,

20th ICFA Workshop Arcidosso, 2000.





$\langle I \rangle = 860$ A

$\varepsilon_{nx} = 1.5$ μm

C. Ronsivalle et al. , “Optimization of RF compressor in the SPARX injector”, PAC05

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

the SALAF *r&d programm*

High Frequency Linear Accelerating Sections
Group Leader: Bruno Spataro

INFN laboratories & depts.

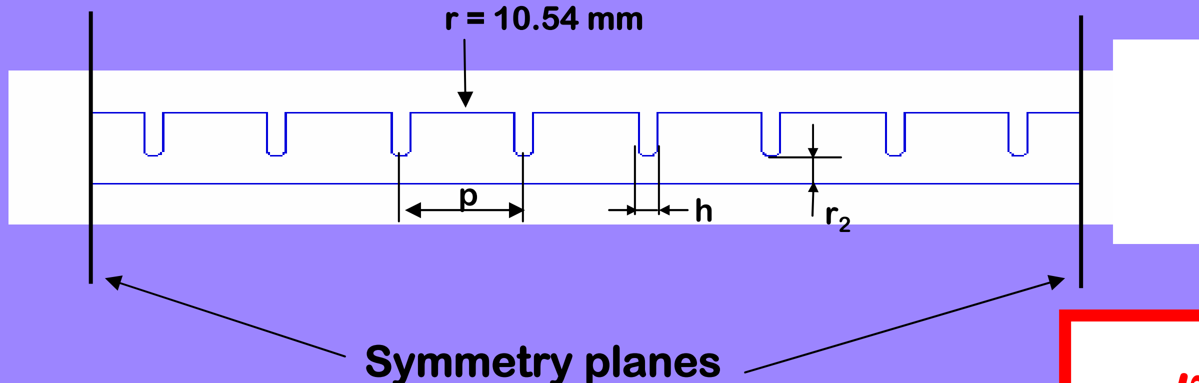
LNF D. Alesini, R. Boni, V. Chimenti, A. Gallo, F. Marcellini. B. Spataro

Roma•I M. Migliorati, A. Mostacci, L. Palumbo

Study and simulation of a 9-cell π-mode X-band structure

Simulated structure with no coupling tubes

p = 13.121 mm
h = 2 mm
r_2 = 4 mm

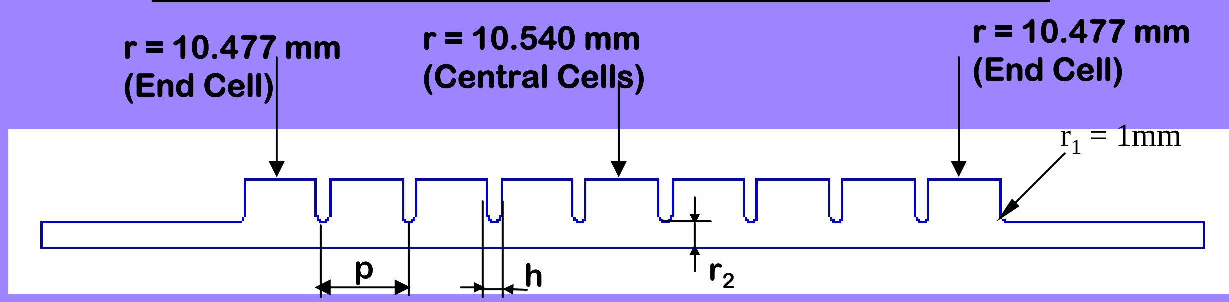


π

$r_2/\lambda = 0.15$

Simulated structure with coupling tubes

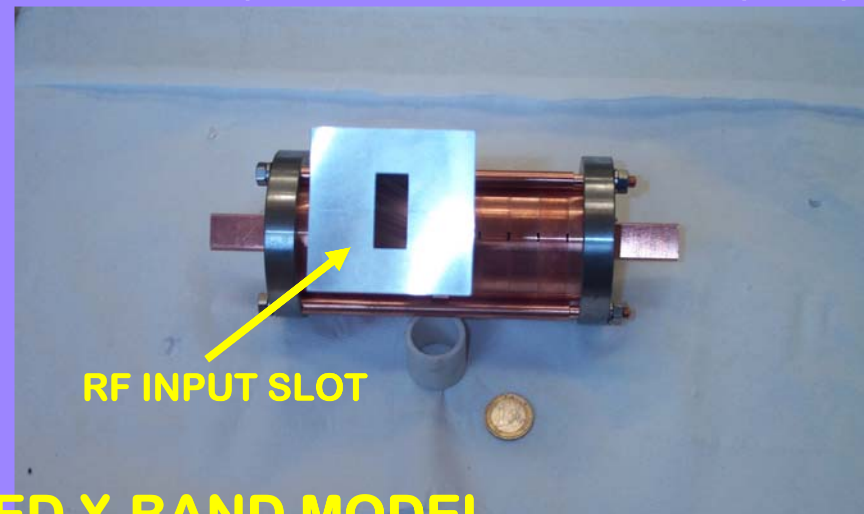
p = 13.121 mm
h= 2 mm
r_2 = 4 mm



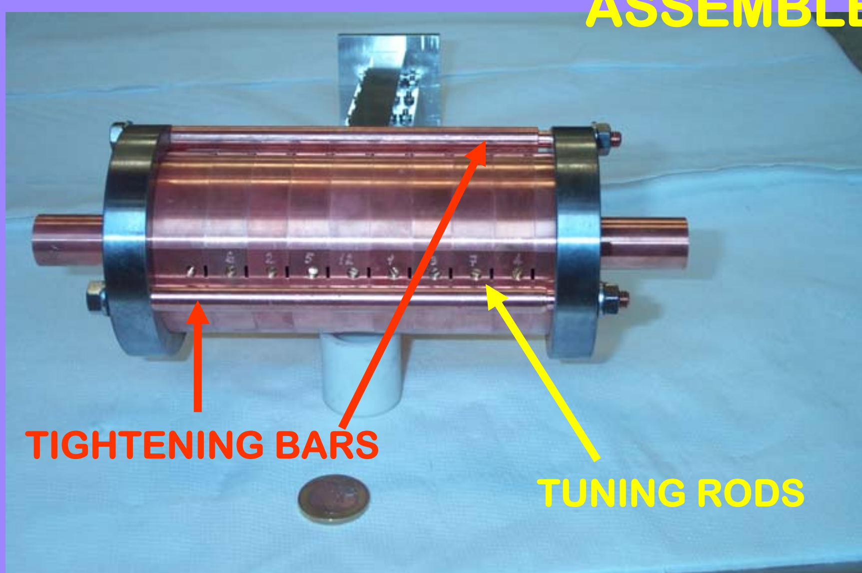
CONSTRUCTION of a π-MODE STANDING-WAVE 11.4 GHz COPPER PROTOTYPE

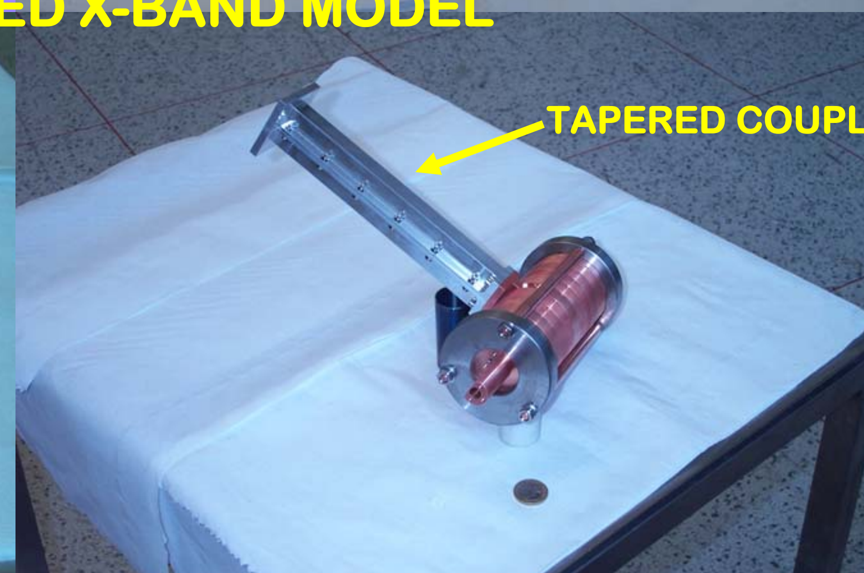
B. Spataro et al., NIM A 554 (2005)

B. Spataro et al., LNF-03-008 (2003)



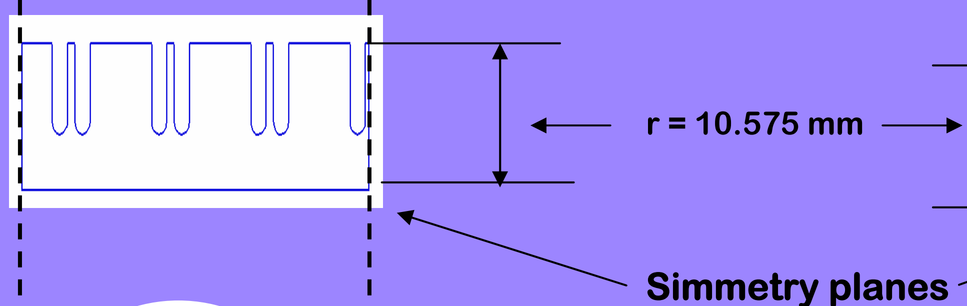
ASSEMBLED X-BAND MODEL



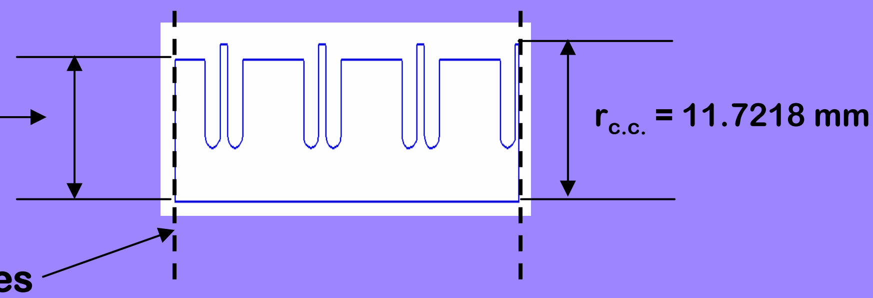


Study and simulation of a 9-cell π/2-mode X-band structure

structure with opened stop-band

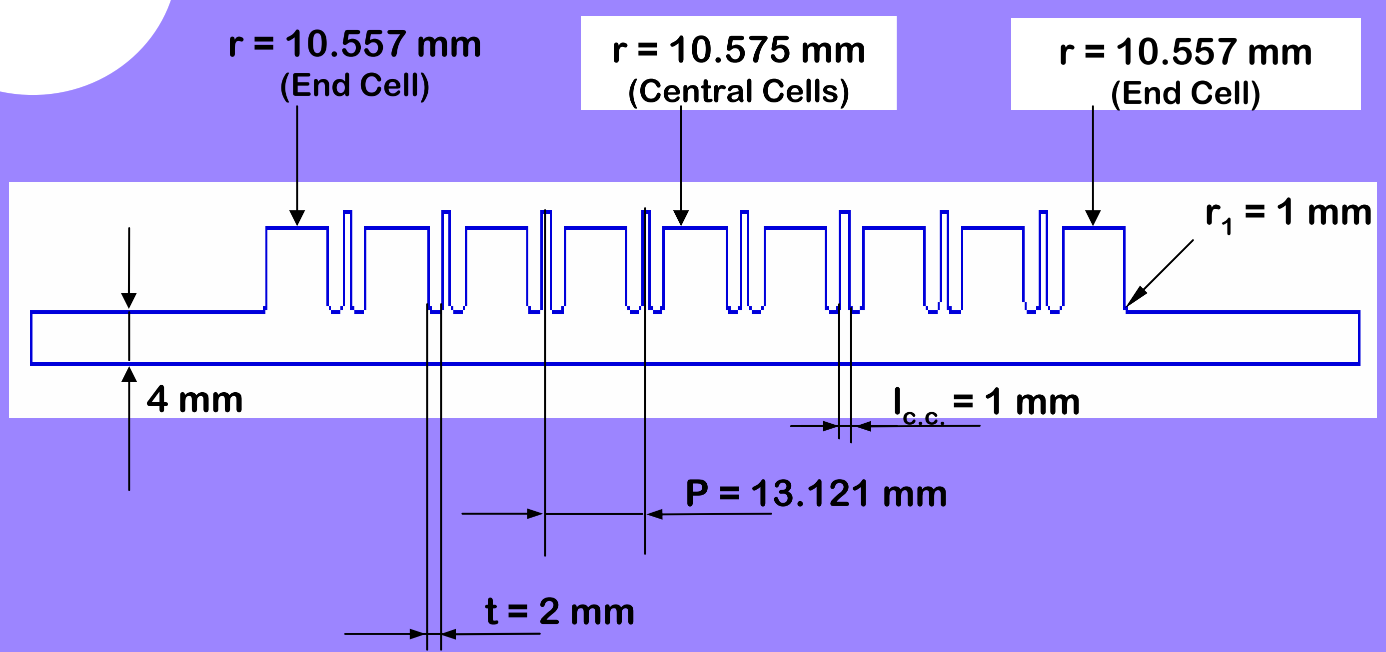


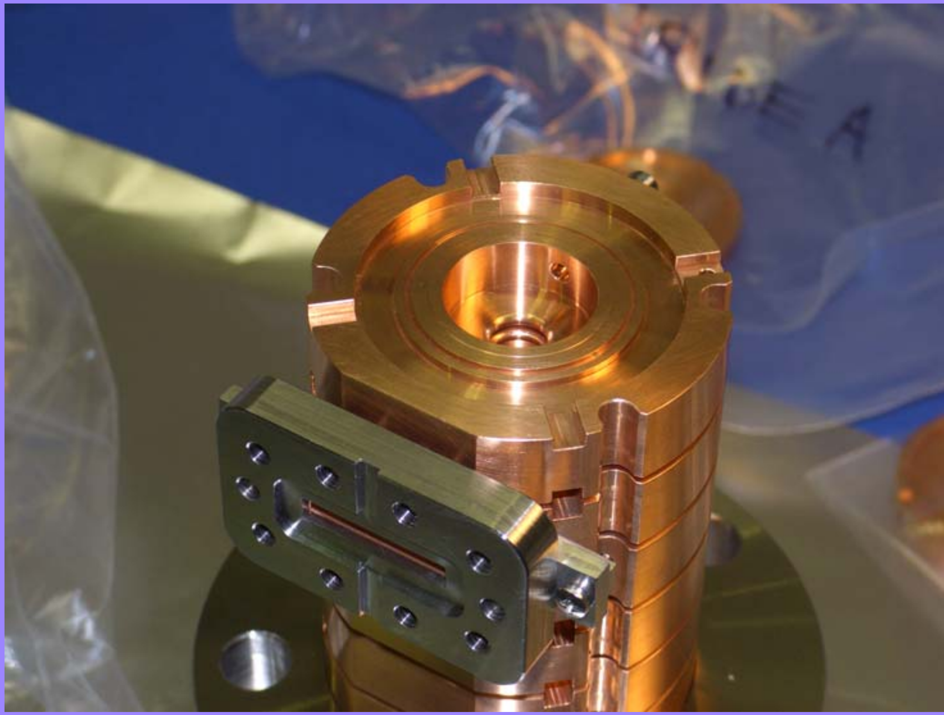
structure with closed stop-band



π/2

structure with coupling-tube





FULL RF PARAMETER LIST FOR π and π/2 STRUCTURES

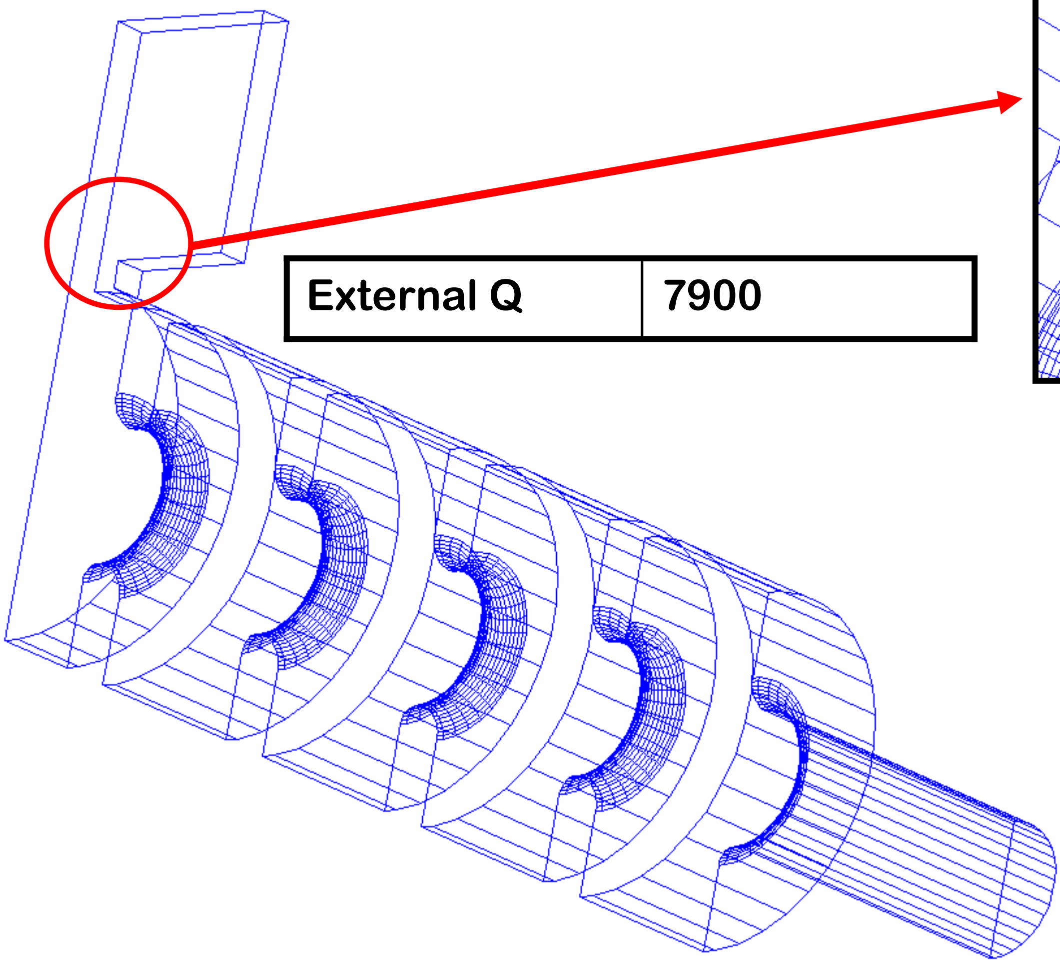
	π	π/2
- Frequency, F (Mhz)	11427*	11431.57*
- Length for calculation, L(cm)	11.81	11.509
- Beam tube length, 1 (cm)	3	3
- Cavities number, n_b	9	9**
- Ratio of phase to light velocity, v_{ϕ}/c	1	1
- Structure periodicity, L_p (cm)	1.3121	1.3121
- Beam hole radius, r (cm)	0.4	0.4
- Iris Thickness, t(cm)	0.2	0.2
- Transit time factor, T	0.731	0.765
- Factor of merit, Q	8413.18	7101
- Form factor, R_{sh}/Q (Ω/m)	9165.38	9693
- Shunt impedance, R_{sh} (M Ω/m)	77.11	68.83
- Peak power, P (MW)	2.701	2.949
- Energy stored in cavity of length L, W (joules)	0.316	0.292
- Coupling coefficient, K (%)	2.4	3.6
- Peak power per meter, P/m (MW/m)	22.87	25.62
- Energy stored in cavity per meter, W/m (joules/m)	2.677	2.537

	π	π/2
- Duty cycle, D.C.	10^{-4}	10^{-4}
- Repetition frequency, f (Hz)	50	50
- Power dissipation, P_d (Watt)	270.1	294.9
- Average accelerating field, E_{acc}(MV/m)	42	42
- Peak axial electric field, E_{max} (MV/m)	57.49	54.91
- Kilpatrick factor	1.197	1.16
- Peak surface electric field, E_{sur} (MV/m)	104.84	102.097
- Ratio of peak to average fields E_{max}/E_{acc}	1.37	1.31
- Ratio of peak to average fields E_{sur}/E_{acc}	2.496	2.431
- Ratio of peak fields B_{max}/E_{sur}(mT/MV/m)	1.65	1.9
- Pulse charge, C (nC)	1	1
- Pulse length, τ (psec)	10	10
- Bunches number, n	1	1
- Average beam power, P_{baver} (W)	0.248	0.242
- Energy spread due to the beam loading, %	±0.783	±0.828
- Loss parameters due to the HOM's K_p (V/pC)	17.91	16.44
- Loss parameter of the operating mode, K_0 (V/pC)	19.43	20.03

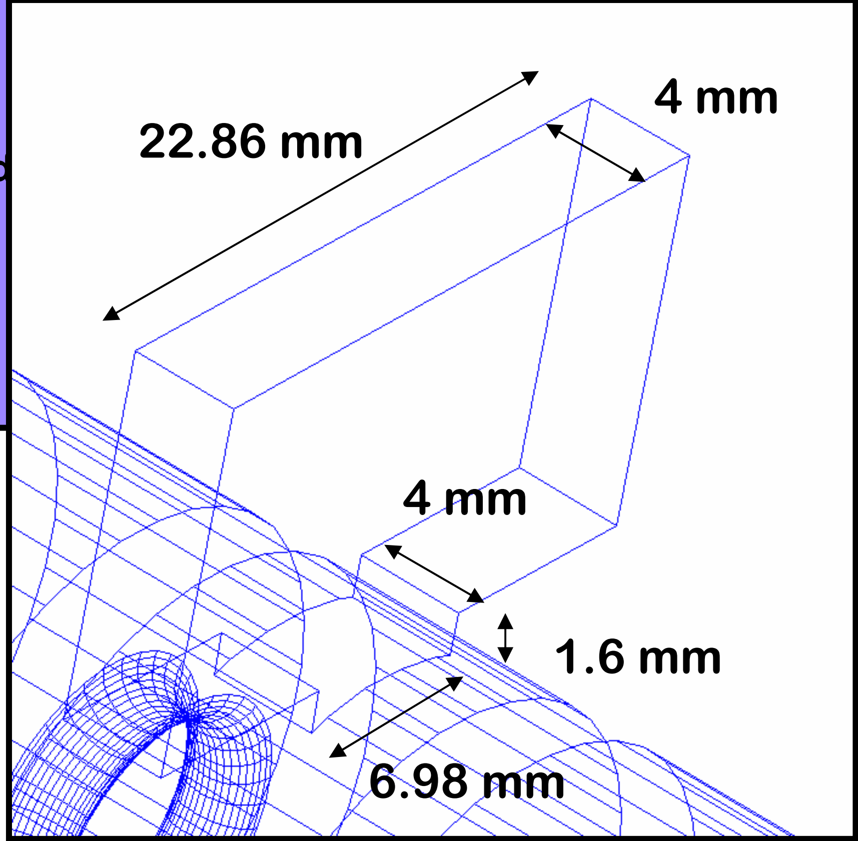
3D coupler design (HFSS)

1 The radius of the central coupling cell has been retuned to compensate for the perturbation induced by the coupling hole;

2 The waveguide input port is connected to an X Band standard waveguide by a tapered section of 200 mm.

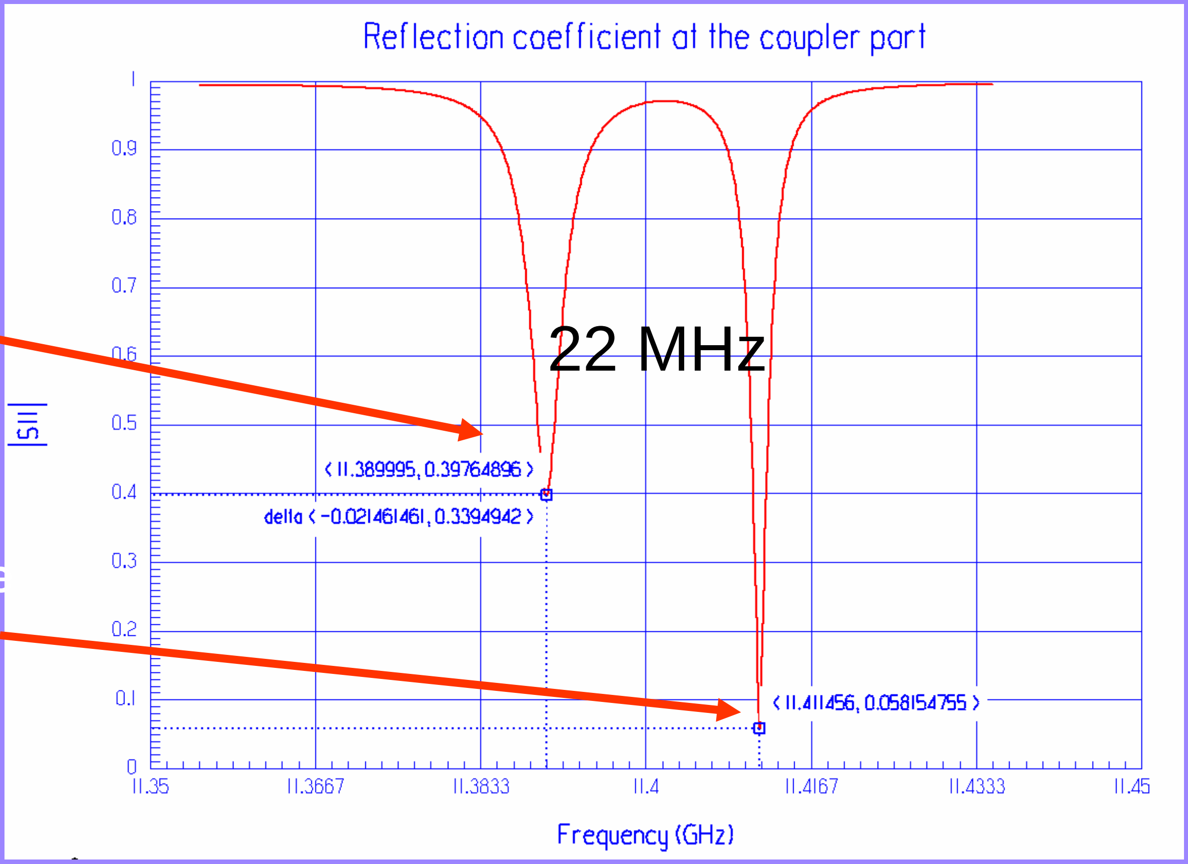


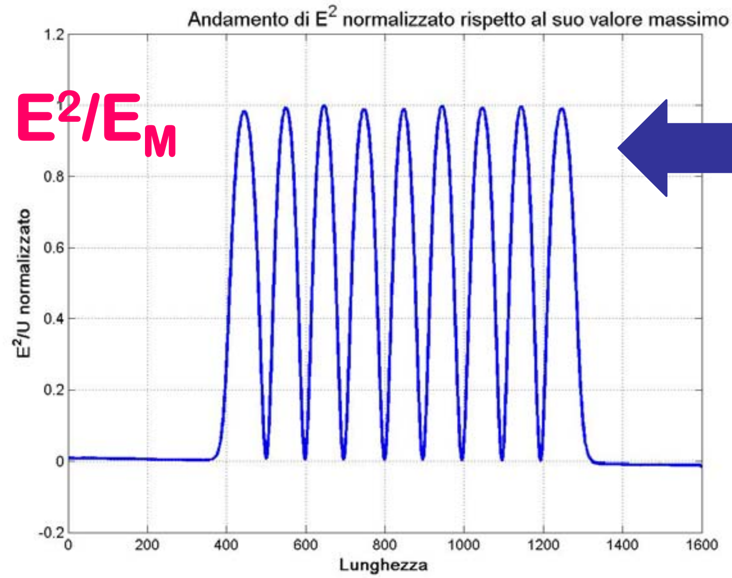
External Q	7900



Nearest mode excited by the coupler (3/4π)

Accelerating mode
S11=0.06⇒β=1.12





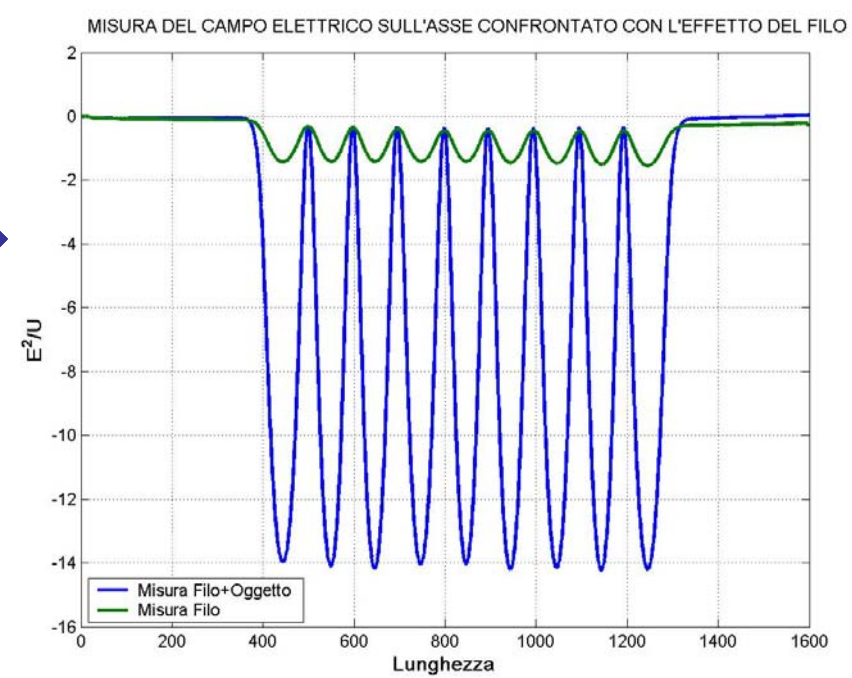
E^2/E_M

π-mode ACCELERATING ELECTRIC FIELD BEHAVIOR AFTER the 9-CELL TUNING

THE FIELD FLATNESS IS < 1%

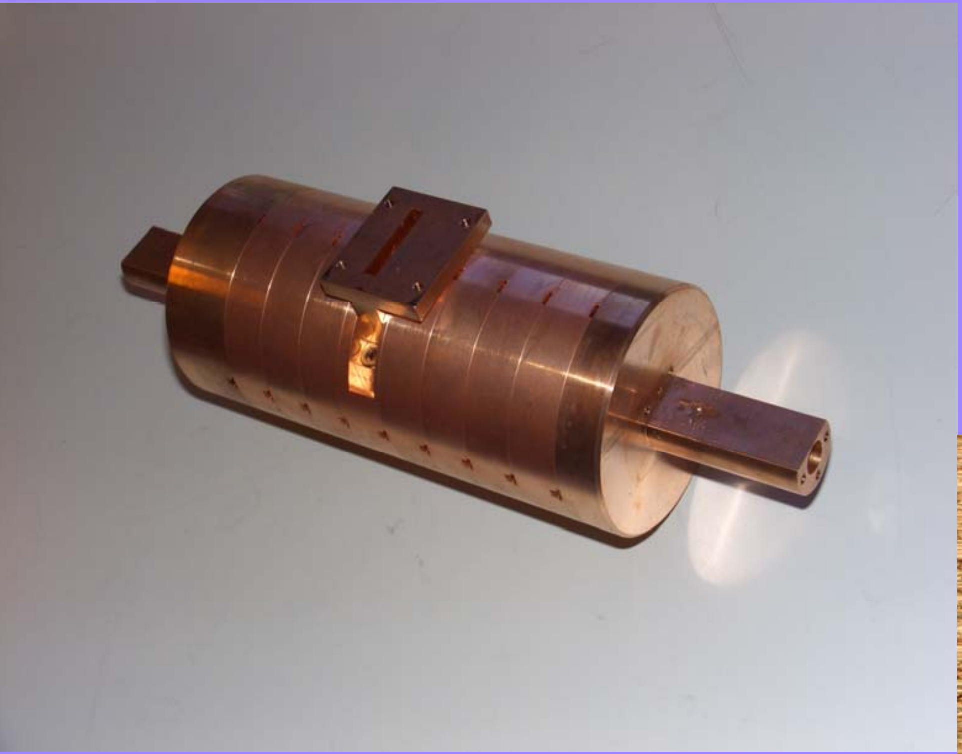
π-mode BEAM AXIS ELECTRIC FIELD

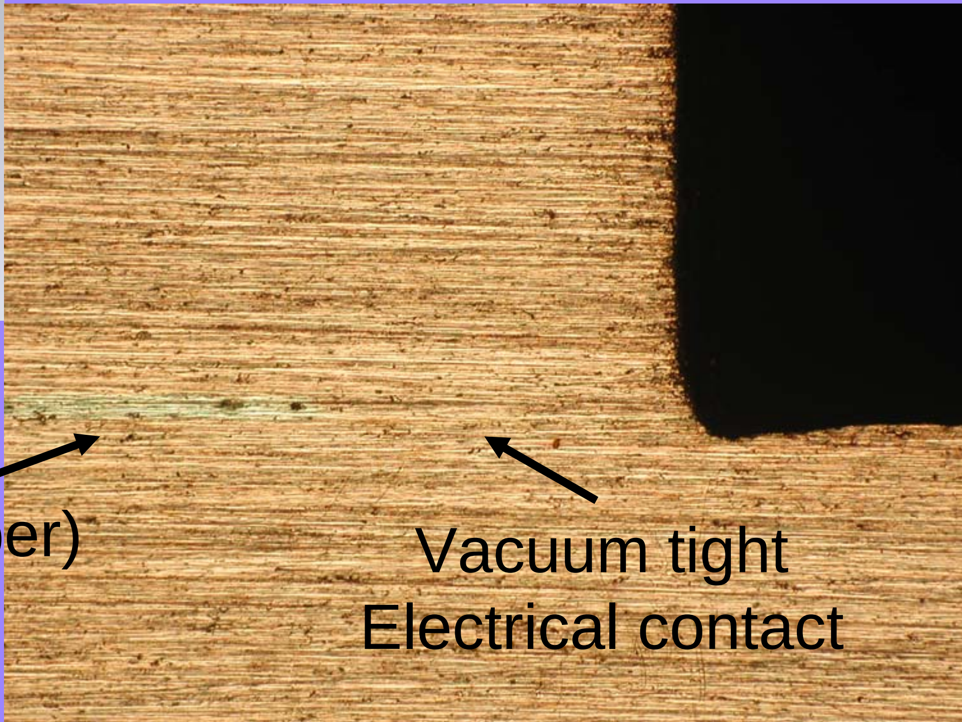
In green, the CONTRIBUTION of the WIRE and the BEAD GLUE

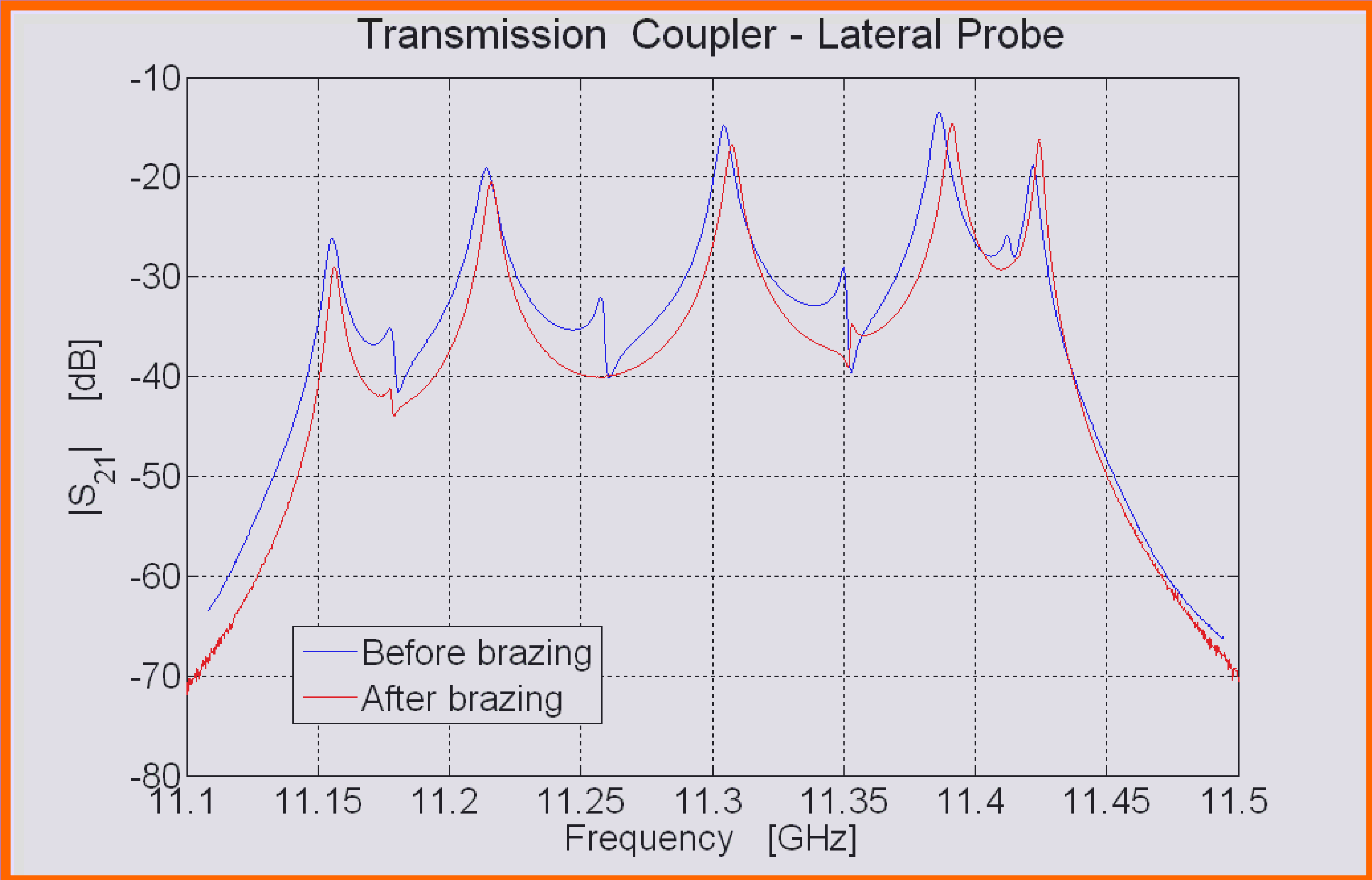


π mode Cu structure after brazing

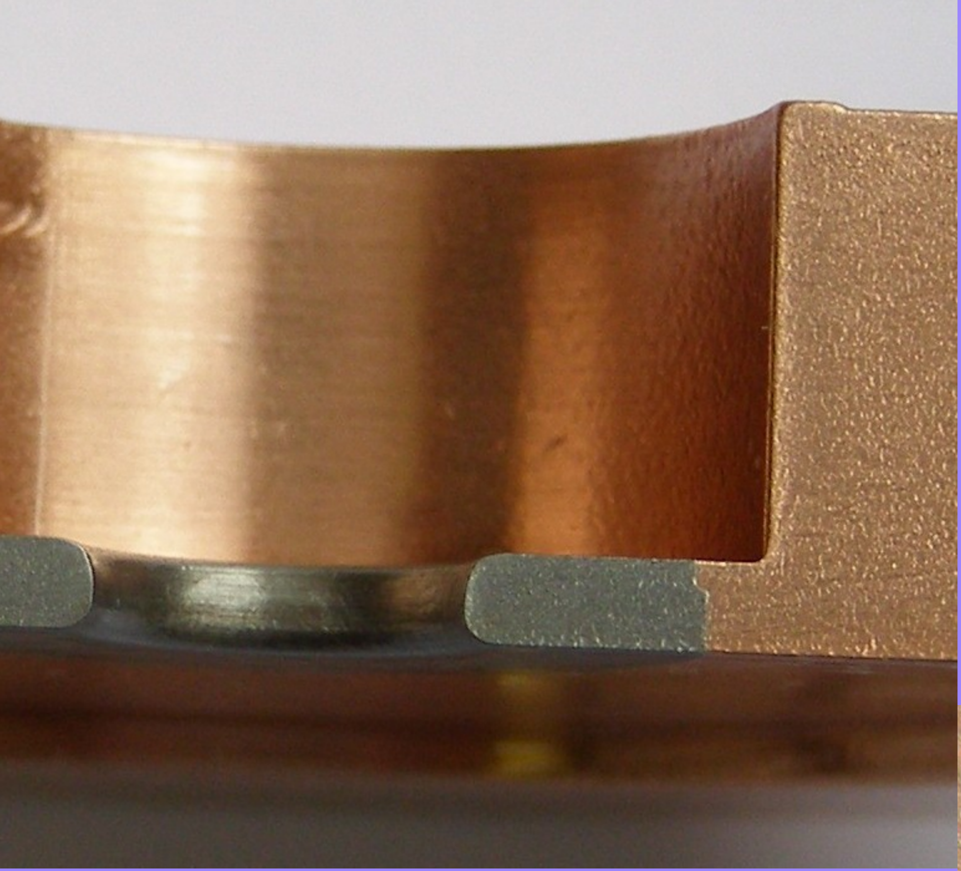
B. Spataro et al., LNF-05-22 (2005)





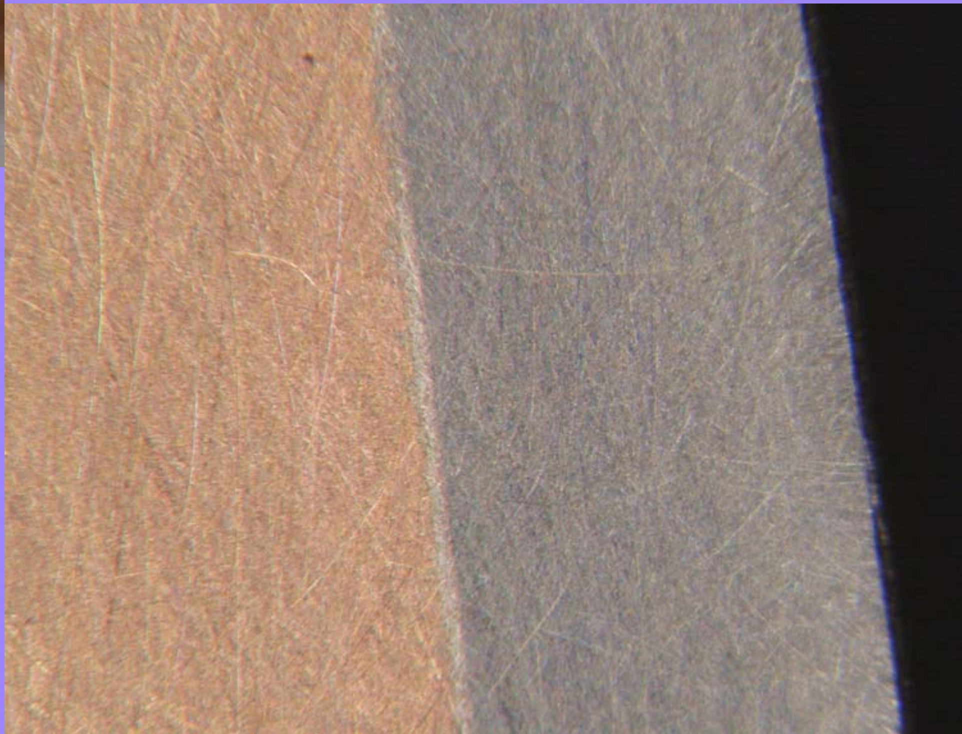


Transmission Coupler - Lateral Probe
-10
-20
-30
-40
-50
-60
-70
-80
11.1
11.15
11.2
11.25
11.3
11.35
11.4
11.45
11.5
Frequency [GHz]
|S21| [dB]
Before brazing
After brazing



Iris Brazing Cu-Mo

(alloy Palcusil 10)



B. Spataro, V. Lollo et al., to be published

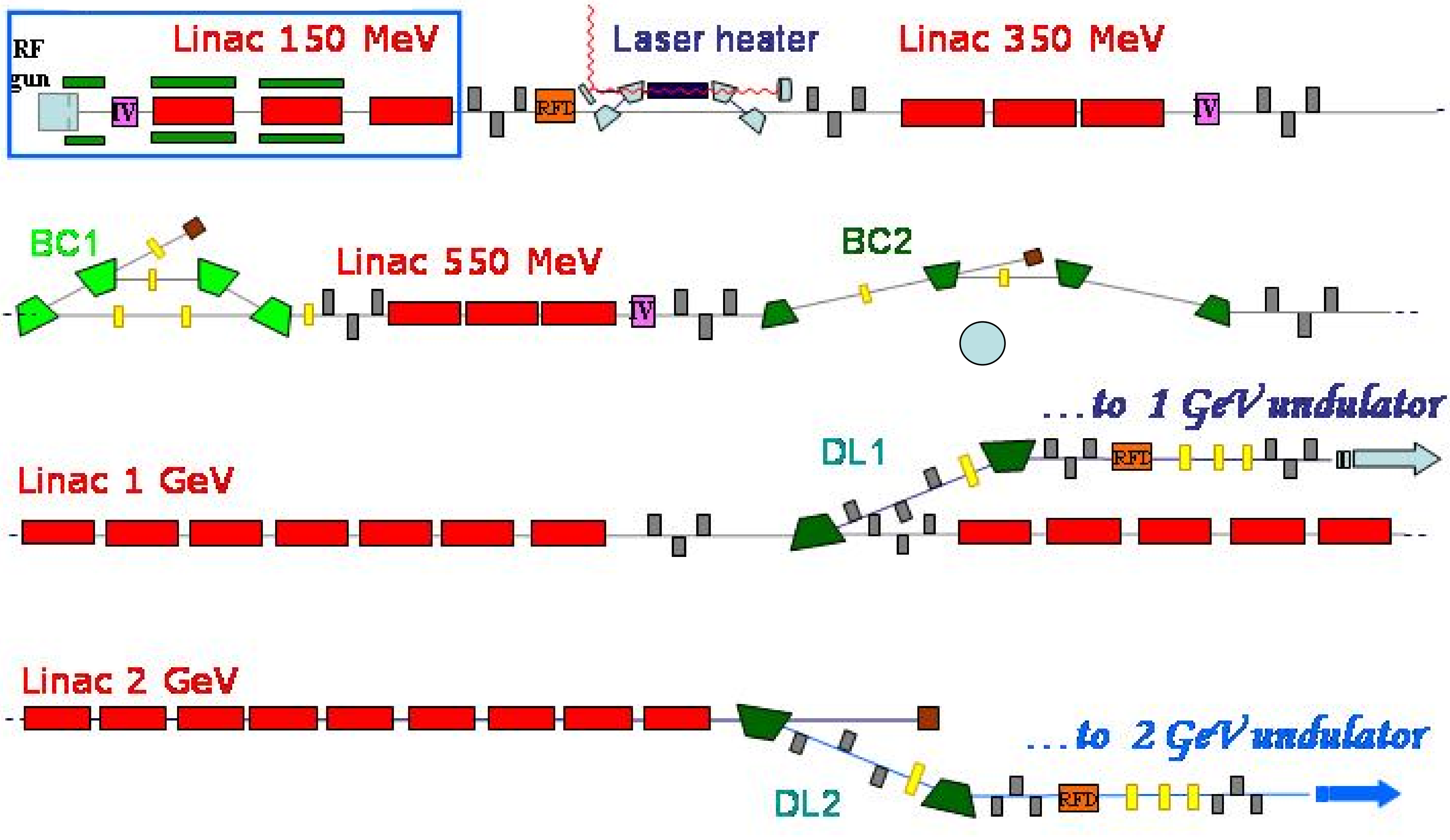
Tests of electroformed cavity

Next step: improvement Mo surface roughness, (<150 nm) with dedicated tool

Cell ready to be treated with alkaline solution (sodium hydroxide NaOH) in order to eliminate the aluminium core

B. Spataro, V. Lollo et al., LNF-05-23 (2005)

SPARX S-band baseline



Courtesy C. Vaccarezza

SPARX Objectives

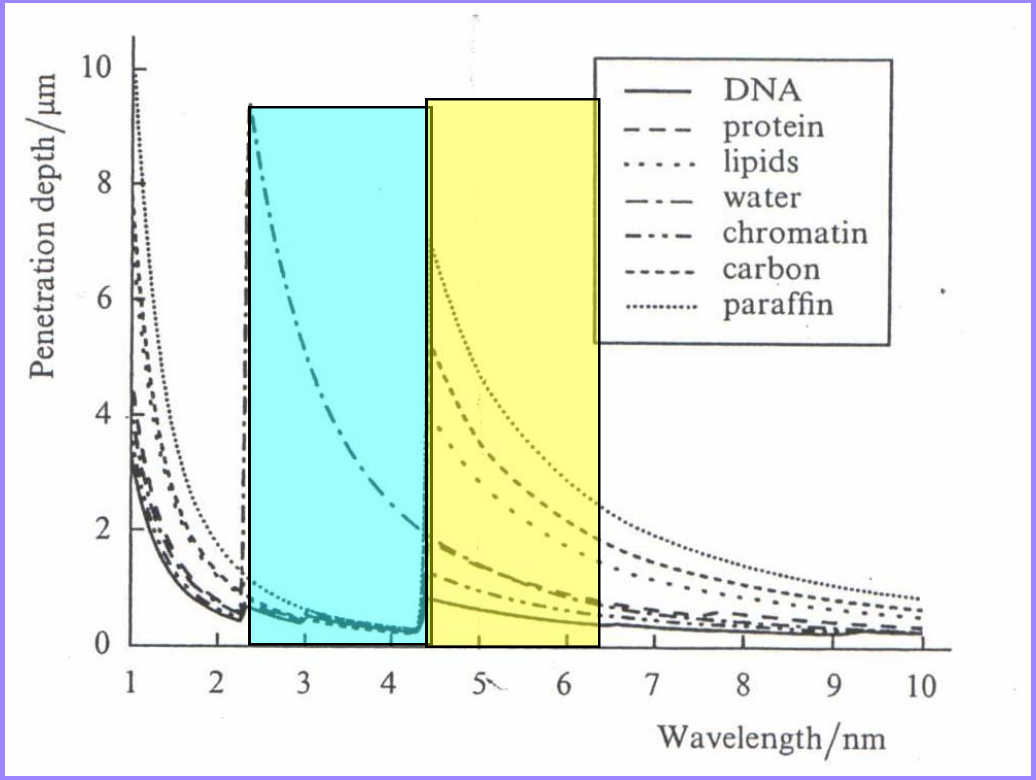
- Indications from the SPARX workshops

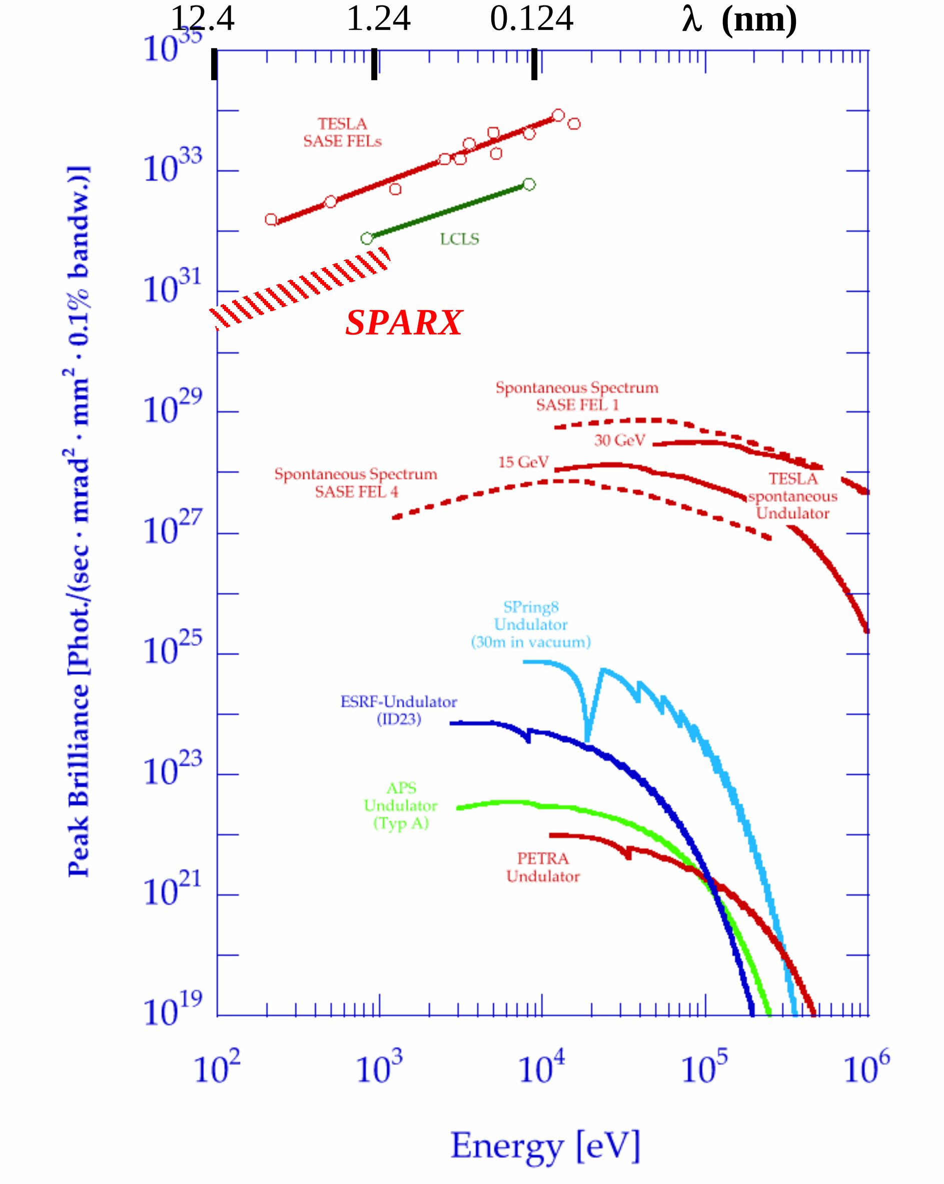
  - *ENEA CR Frascati* *16.01.2001*
  - *INFN-LNF* *09.05.2005*

Wavelength range :
0.5 - 13.5 nm

- water window
  (~ 2.5 – 4.5 nm)

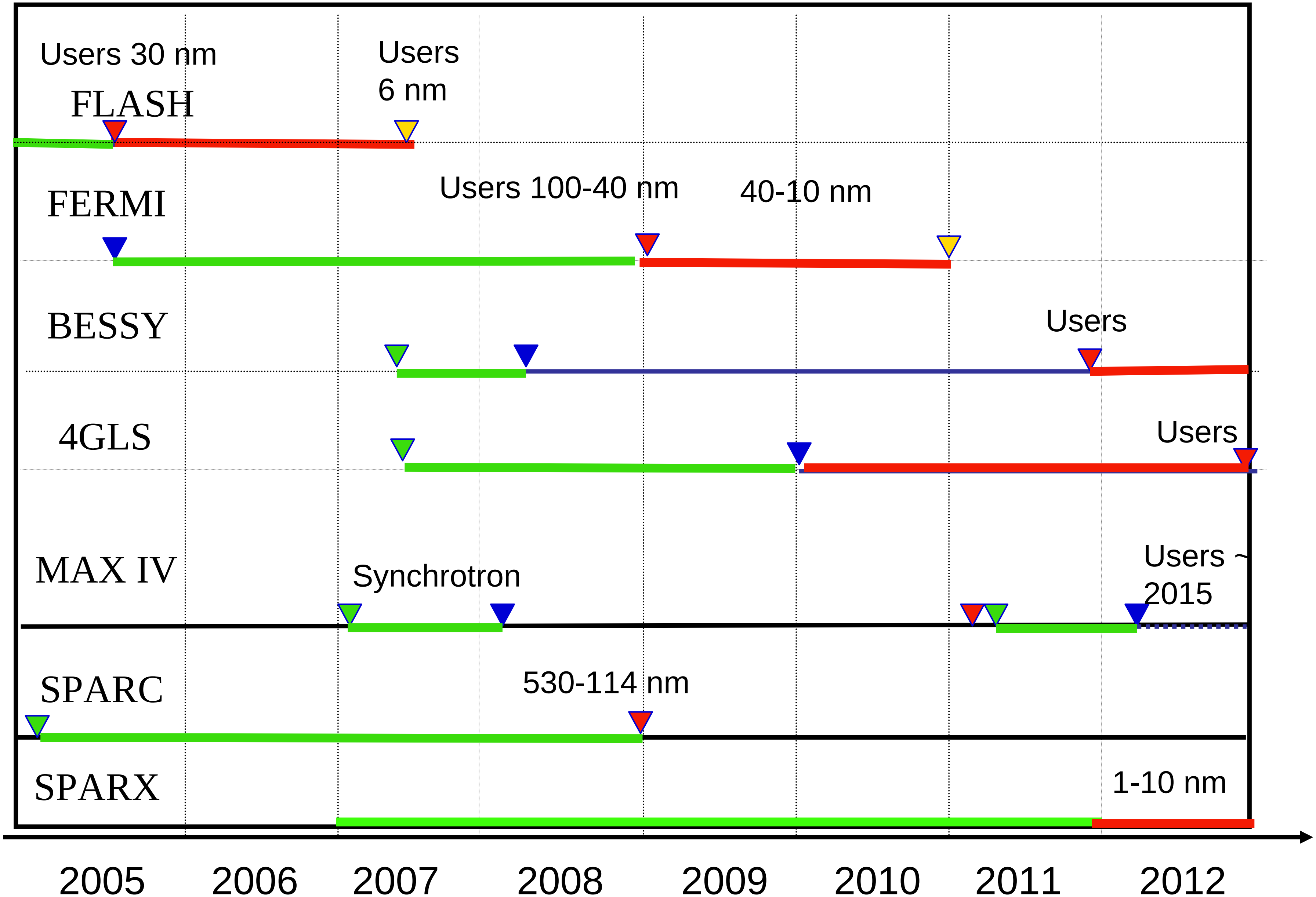
- carbon window
  (~ 4.5 – 6.3 nm)





12.4
1.24
0.124
λ (nm)
Peak Brilliance [Phot./(sec · mrad² · mm² · 0.1% bandw.)]
10^35
10^33
10^31
10^29
10^27
10^25
10^23
10^21
10^19
TESLA
SASE FELs
LCLS
SPARX
Spontaneous Spectrum
SASE FEL 1
30 GeV
15 GeV
Spontaneous Spectrum
SASE FEL 4
TESLA
spontaneous
Undulator
SPring8
Undulator
(30m in vacuum)
ESRF-Undulator
(ID23)
APS
Undulator
(Typ A)
PETRA
Undulator
10^2
10^3
10^4
10^5
10^6
Energy [eV]

Timeline SOFT X-ray Free Electron Lasers



Conclusions

- X - band photoinjector could be an ideal source to drive short wavelength FEL experiments, provided that high peak field (>300 MV/m) could be achieved

- X - band photoinjector operating in multi-bunch mode could be of interest also for CLIC main beam?

- R&D program in the stream of X-band structures development is already started at LNF

- A fully X-band 2 GeV linac is a very promising option for the SPARX FEL project (if it fits with the present time schedule)