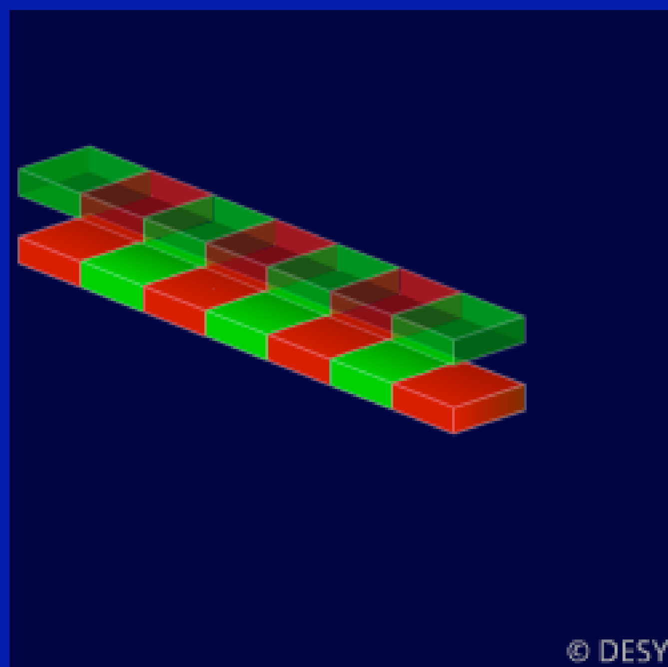
A Free Electron Laser Project at LNF

Massimo Ferrario

INFN - LNF

& the SPARC/X Team



SPARC/X Team

D. Alesini, S. Bertolucci, M.E. Biagini, R. Boni, M. Boscolo, M. Castellano, A. Clozza, G. Di Pirro, A. Drago, A. Esposito, M. Ferrario, V. Fusco, A. Gallo, A. Ghigo, S. Guiducci, M. Incurvati, C.Ligi, F.Marcellini, C. Milardi,, L. Pellegrino, M. Preger, P. Raimondi, R. Ricci, C. Sanelli, M. Serio, F. Sgamma, B.Spataro, A. Stecchi, A. Stella, F. Tazzioli, C. Vaccarezza, M. Vescovi, C. Vicario, M. Zobov *(INFN /LNF)*
F. Alessandria, I. Boscolo, F. Broggi, S.Cialdi, C. DeMartinis, D. Giove, C. Maroli, V. Petrillo, M. Romè, L. Serafini, *(INFN /Milano)*
D. Levi, M. Mattioli, G. Medici, P. Musumeci *(INFN /Roma1)*
L. Catani, E. Chiadroni, A. Cianchi, D. Moricciani, C. Schaerf *(INFN /Roma2)*
M. Migliorati, A. Mostacci, L. Palumbo (Univ. La Sapienza)
F. Ciocci, G. Dattoli, L. Giannessi, L. Mezi, L. Picardi, M. Quattromini, A.Renieri, C. Ronsivalle *(ENEA/FIS)*

J. B. Rosenzweig, S. Reiche *(UCLA)*

P. Bolton, D. Dowell, P.Emma, P. Krejick, C. Limborg, D. Palmer *(SLAC)*

Free Electron Laser

High Brightness e^- beams

SPARC - SPARXINO - SPARX

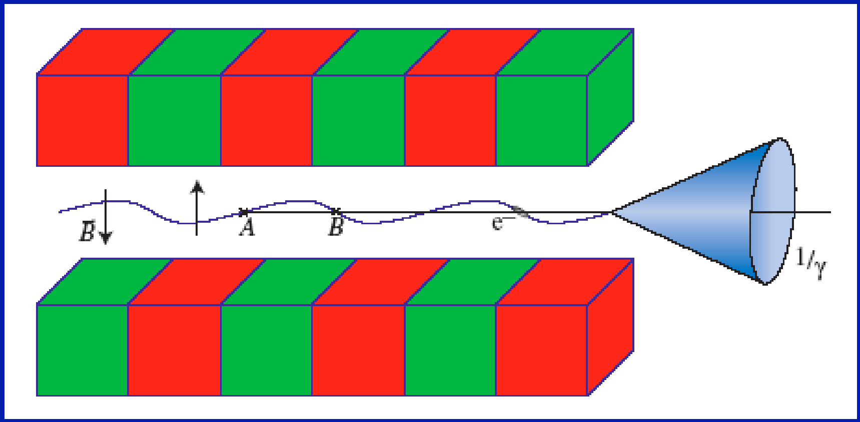
Free Electron Laser

Undulator Radiation

High Gain FEL ==> SASE

Seeding

Undulator Radiation



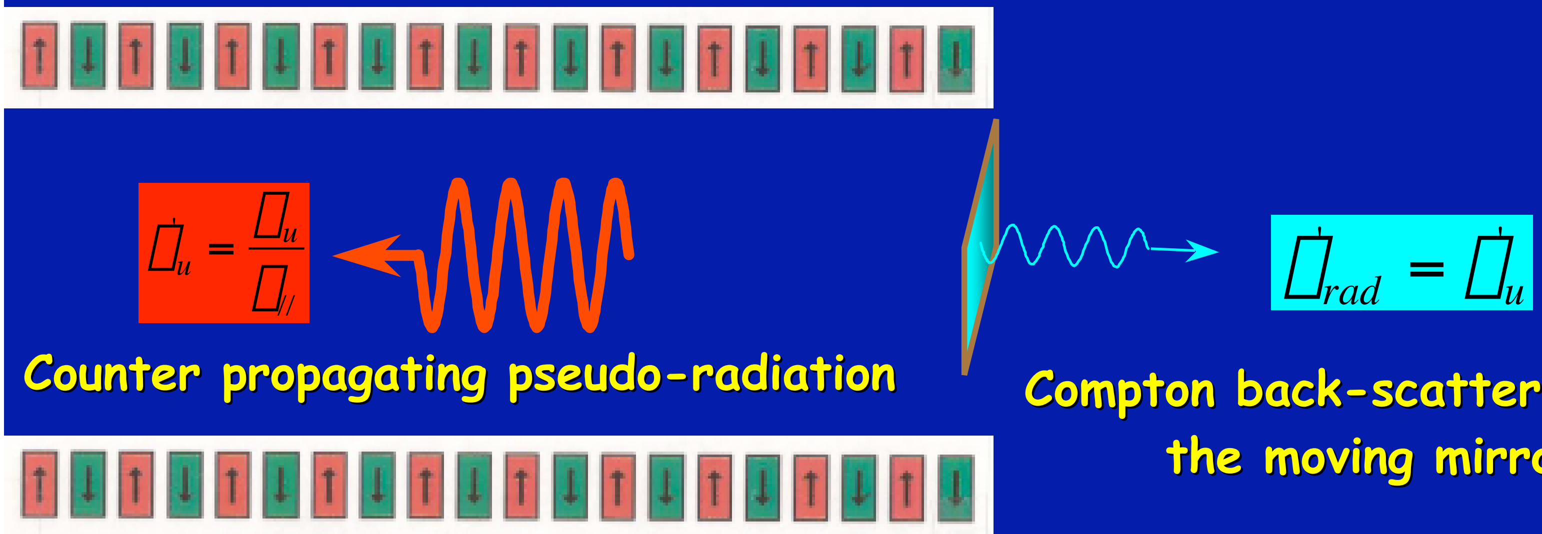
$$\theta = \frac{1}{\gamma}$$

The electron trajectory is determined by the undulator field and the electron energy

$$\langle \theta_e \rangle \approx \frac{K}{\gamma} = \frac{e\tilde{B}_u \lambda_u}{2\pi\gamma mc^2}$$

The electron trajectory is inside the radiation cone if $K \leq 1$

Relativistic Mirror



$$\gamma_{//} = \frac{1}{\sqrt{1-\beta_{//}^2}}$$

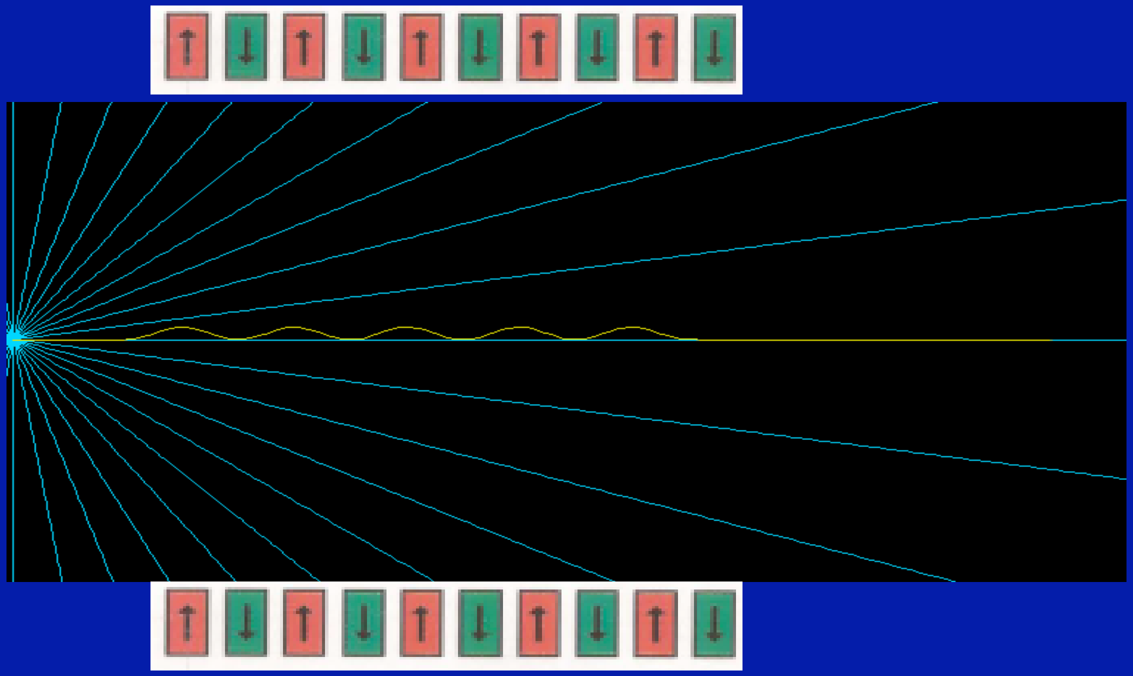
$$\lambda_{rad} \approx \frac{\lambda_u}{2\gamma_{//}^2}$$

Doppler effect in the laboratory frame

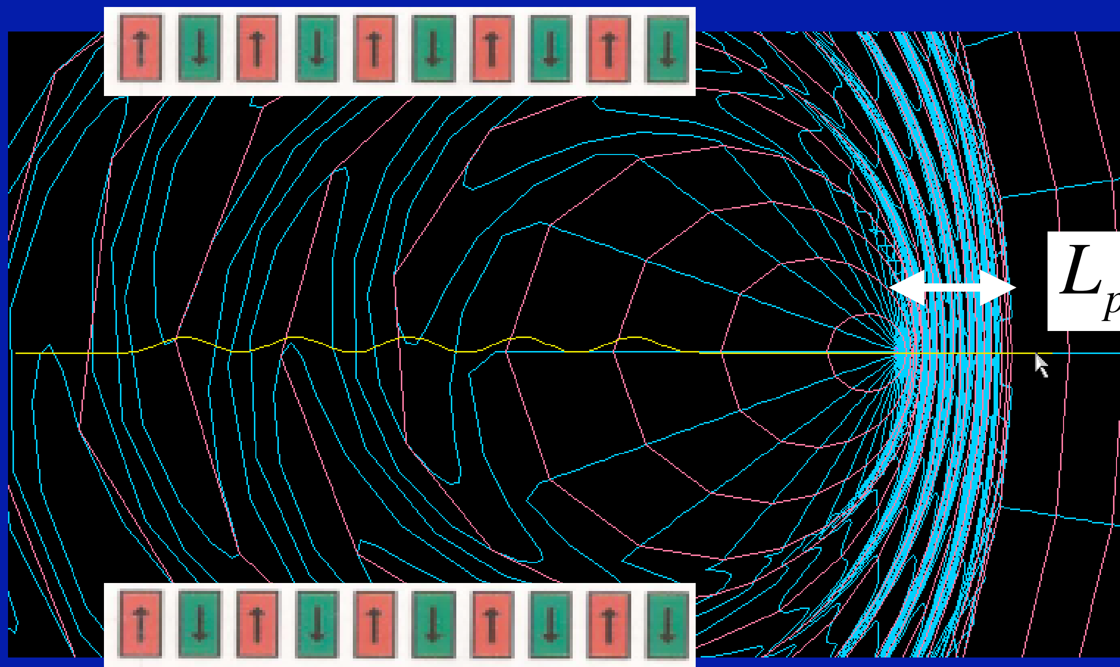
$$\frac{1}{\gamma_{//}^2} = \frac{1}{\gamma^2} + \beta_{\perp}^2$$

$$\lambda_{rad} \approx \frac{\lambda_u}{2\gamma^2}\left(1 + K^2\right)$$

TUNABILITY

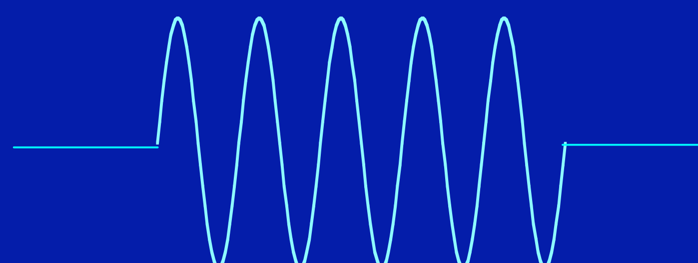


Radiation Simulator – T. Shintake, @ http://www-xfel.spring8.or.jp/Index.htm

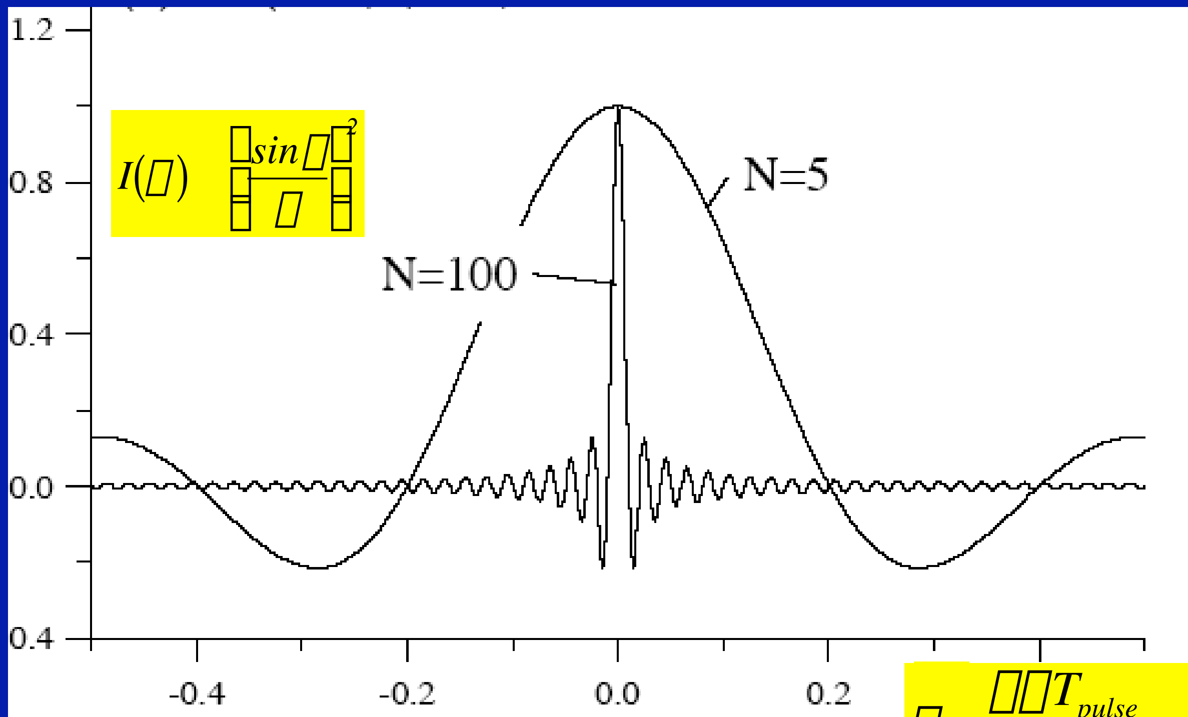


$$L_{pulse} = N_u \lambda_{rad}$$

Due to the finite duration the radiation is not monochromatic but contains a frequency spectrum which is obtained by Fourier transformation of a truncated plane wave



Spectral Intensity



$$I(\nu) = \left[\frac{\sin \nu}{\nu}\right]^2$$

$$\nu = \frac{\Delta\omega T_{pulse}}{2} = \pi N_w \frac{\omega - \omega_{res}}{\omega_{res}}$$

$$\frac{\Delta\omega}{\omega} \approx \frac{1}{N_w}$$

Line width

Peak power of accelerated charge:

$$P_1 = \frac{e^2}{6\pi\varepsilon_0 c^3}\gamma^4 \dot{v}_\perp^2$$

different electrons radiate indepedently hence the total power depends linearly on the number N_e of electrons per bunch:

Incoherent Spontaneous Radiation Power:

$$P_T = N_e \frac{e^2}{6\pi\varepsilon_0 c^3}\gamma^4 \dot{v}_\perp^2$$

Coherent Stimulated Radiation Power:

$$P_T = \frac{N_e^2 e^2}{6\pi\varepsilon_0 c^3}\gamma^4 \dot{v}_\perp^2$$

WE NEED micro-BUNCHING !

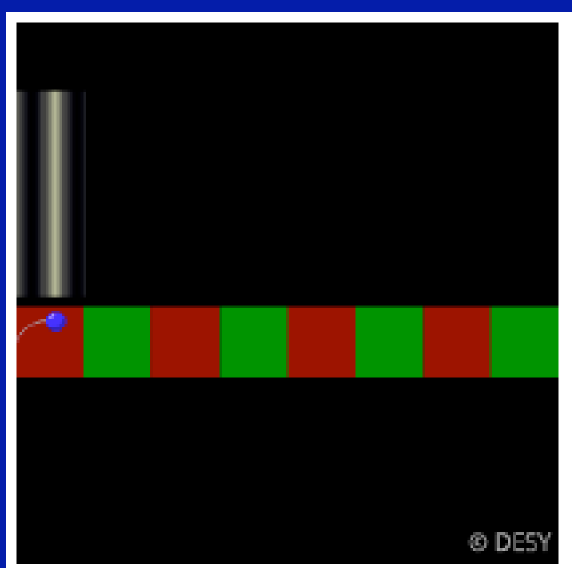
High Gain FEL

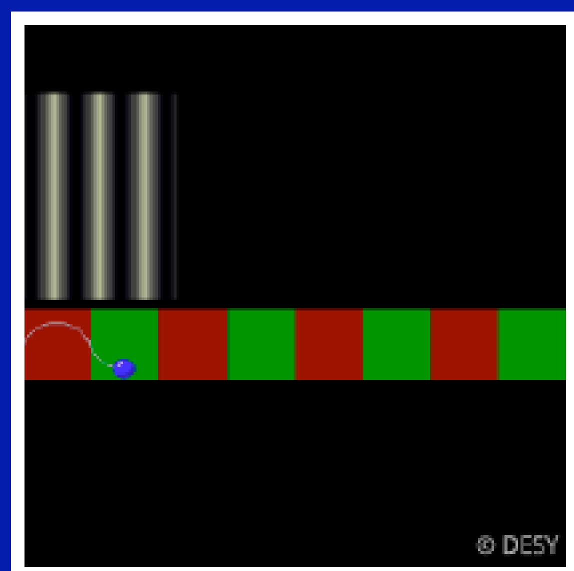
Consider "seeding" by an external light source with wavelength λ_r

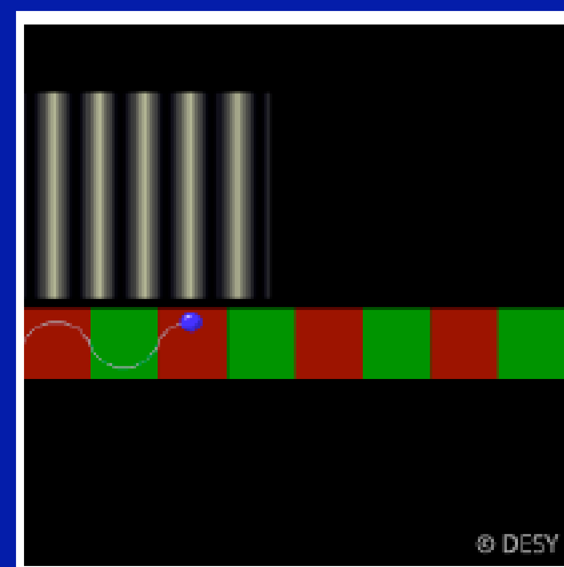
The light wave is co-propagating with the relativistic electron beam

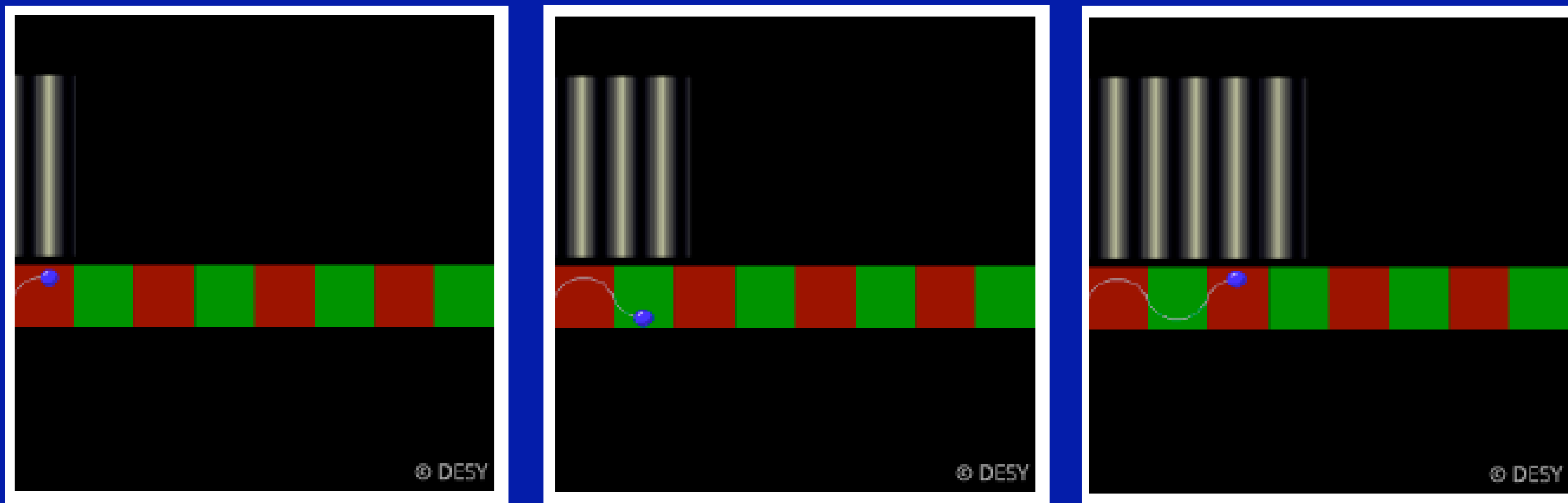
$$\frac{d\gamma}{dt} = -\frac{e}{mc}\vec{E}\cdot\vec{v} = -\frac{e}{mc}\vec{E}_{\perp}\cdot\vec{v}_{\perp}$$

Energy exchange occurs only if there is transverse motion









After one wiggler period the electron sees the radiation with the same phase if the flight time delay is exactly one radiation period: $\Delta t = t_e - t_{ph} = T_{rad}$

$$\Delta t = \frac{\lambda_w}{c\beta_{//}} - \frac{\lambda_w}{c} = \frac{\lambda_{rad}}{c}$$

$$\lambda_{rad} = \frac{1-\beta_{//}}{\beta_{//}}\lambda_w$$

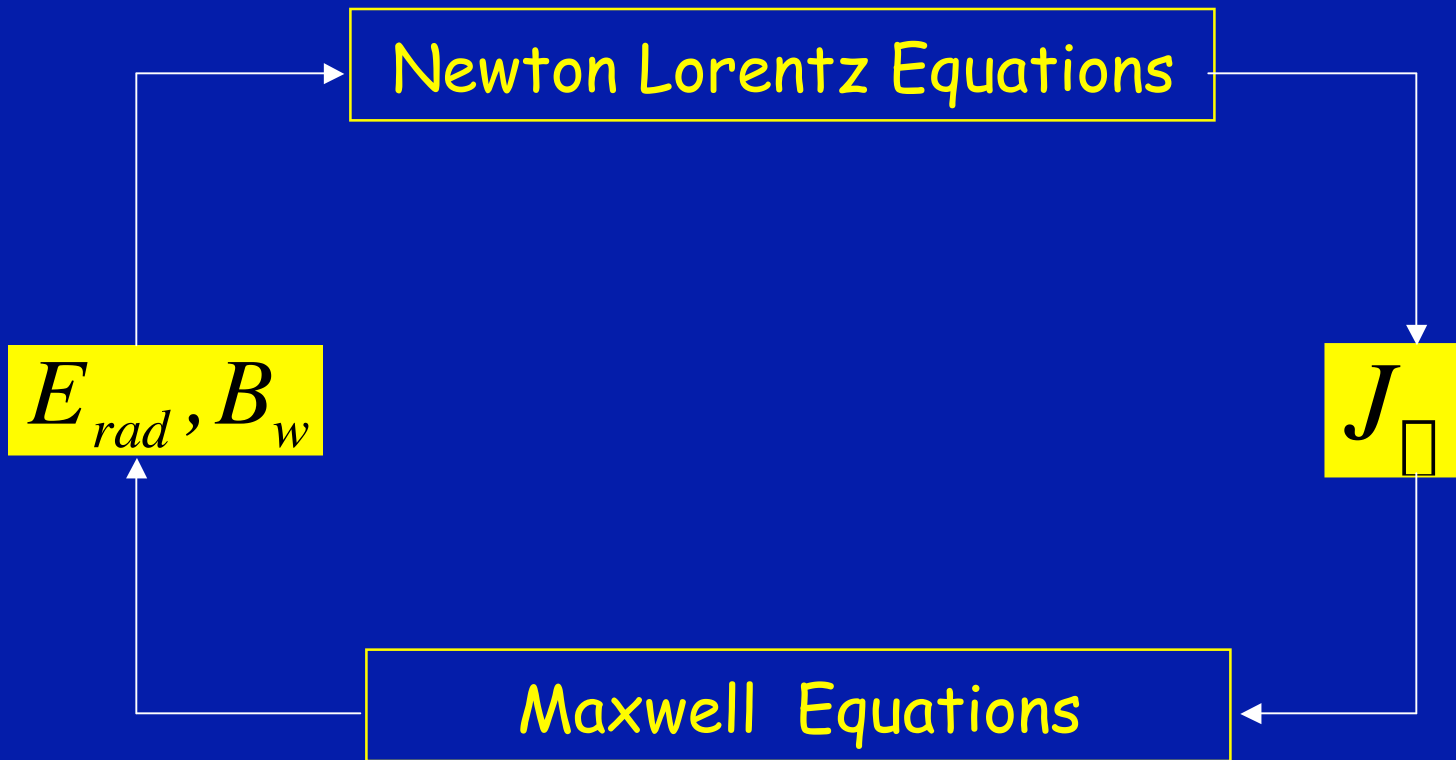
$$\lambda_{rad} \approx \frac{\lambda_w}{2\gamma^2}\left(1+K^2\right)$$

In a resonant and randomly phased electron beam, nearly one half electrons absorb energy and half lose enrgy, with no net gain

The particles bunch around a phase for which there is no coupling with the radiation

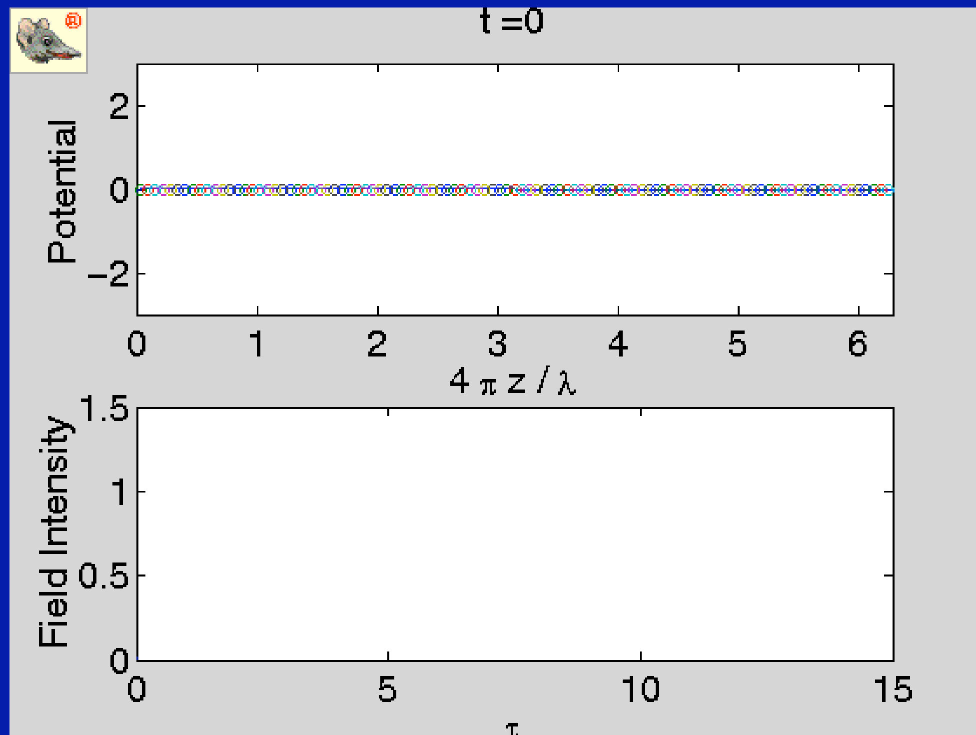
Question: can there be a continuous energy transfer from electron beam to light wave?

Answer: We need a Self Consistent Treatment



The electron beam acts as a dielectric medium which slows down the phase velocity of the ponderomotive field compared to the average electron longitudinal velocity. Hence resonant electrons bunch around a phase corresponding to gain.

$$v_p = \frac{[\text{illegible}]}{k + k_w} < \langle v_{//} \rangle$$



The particles within a micro-bunch radiate coherently. The resulting strong radiationfield enhances the micro-bunching even further.

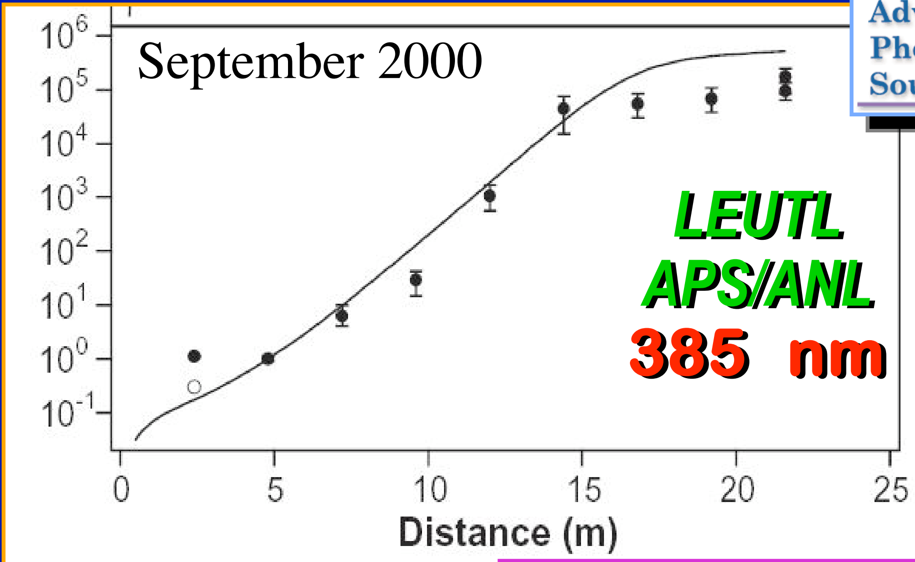
Result: collective instability, exponential growth of radiation power.

Even if there is no external seeding: Self Amplified Spontaneous Emission

SASE FEL at short wavelengths require a very intense, high quality e-beam

- FEL Parameter $$\square = 0.136 \frac{1}{\square_r} J^{1/3} B_u^{2/3} \square_u^{4/3}$$
- Exponential growth $$P(z) = \frac{P_0}{9} \exp \square \frac{z}{L_G} \square$$
- Gain Length $$L_G = \frac{\square_u}{4\square\sqrt{3}\square}$$
- Saturation power $$P_{sat} = \square P_{beam} \qquad N_e^{4/3}$$
- Constraint on emittance $$\square = \frac{\square_n}{\square} < \frac{\square_0}{4\square}$$
- Constraint on energy spread $$\square\square/\square < \square$$
- Relative bandwidth $$\frac{\square\square}{\square} = \sqrt{\frac{\square}{N_u}}$$

SASE Saturation Results

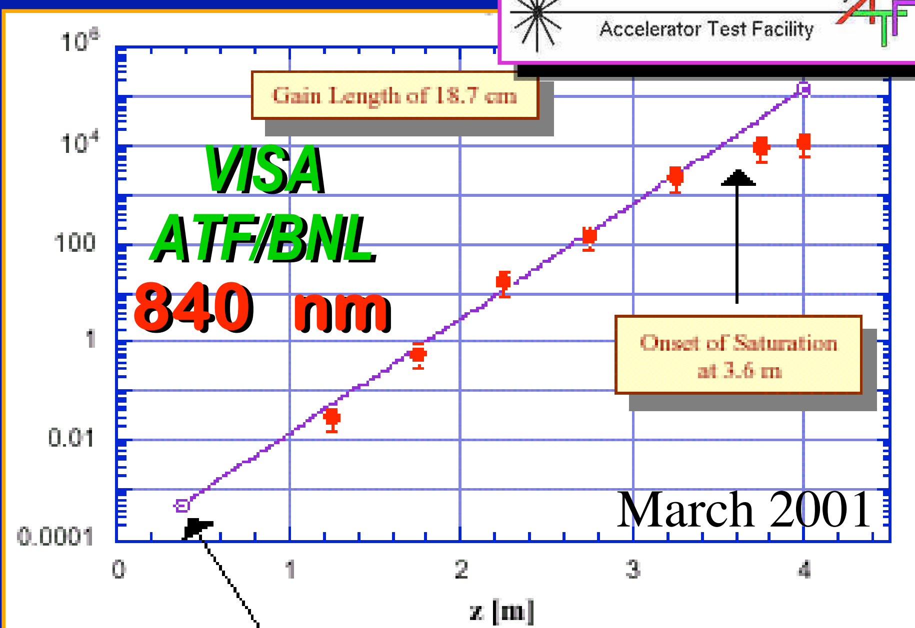


Advanced Photon Source

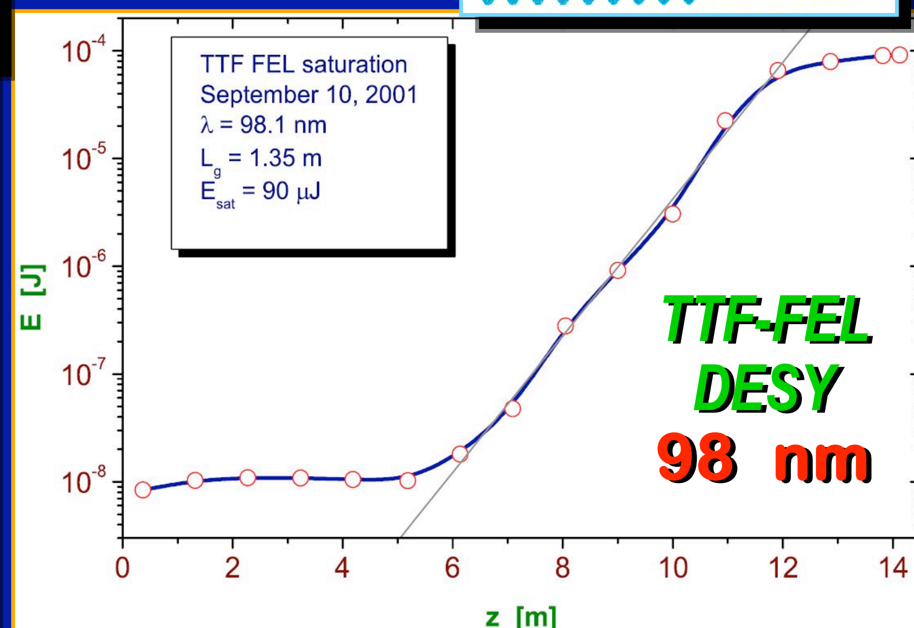
Since September 2000:

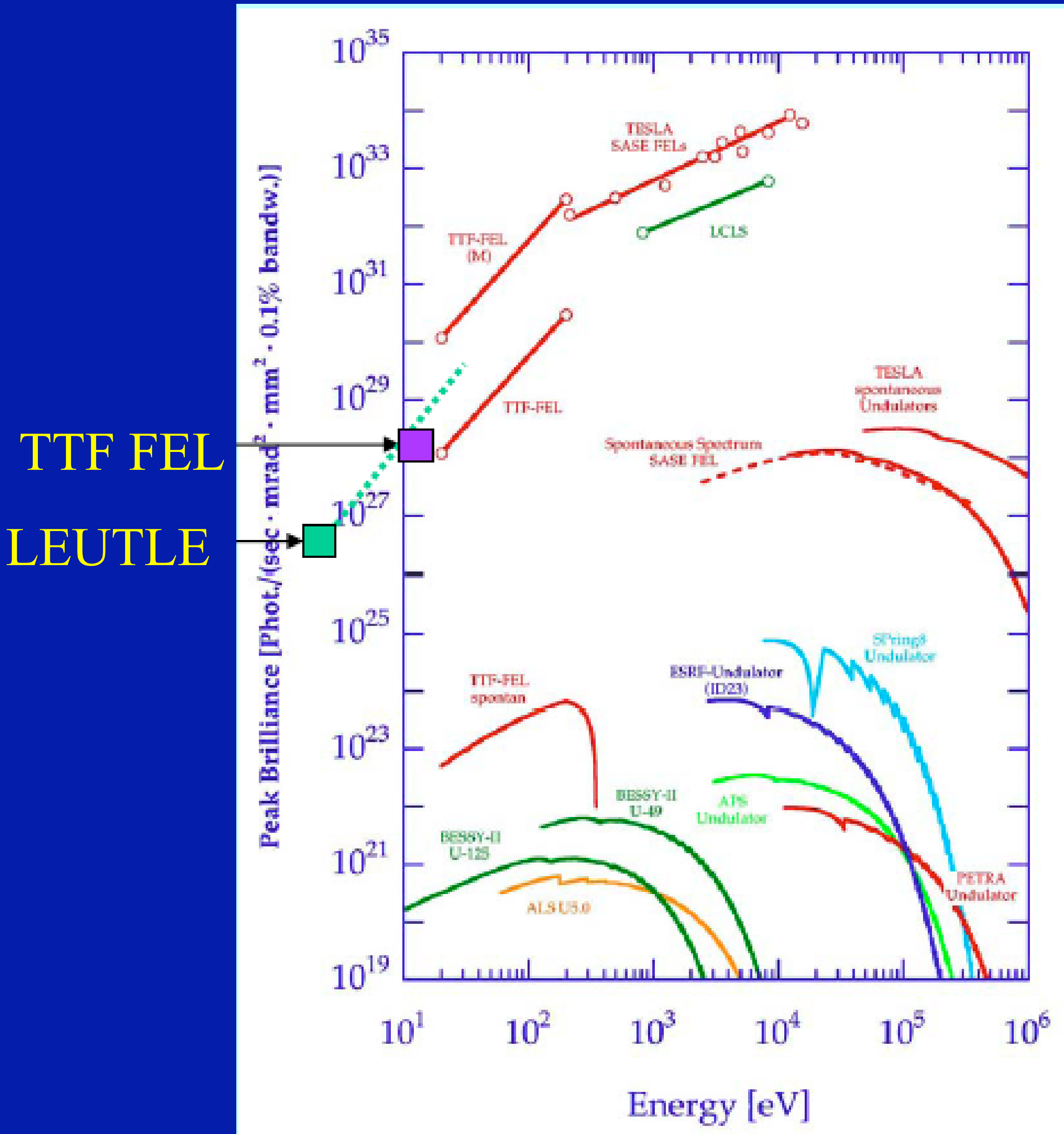
3 SASE FEL's demonstrate saturation

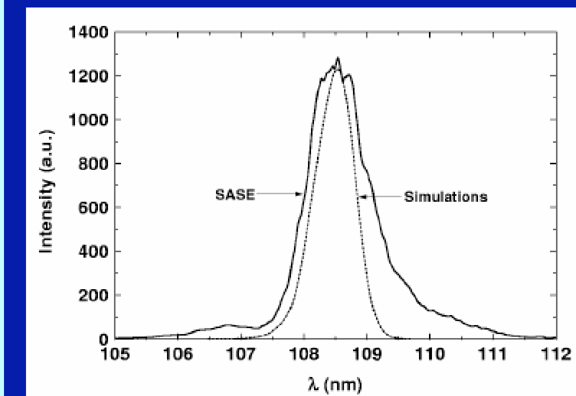
Brookhaven National Laboratory
Accelerator Test Facility



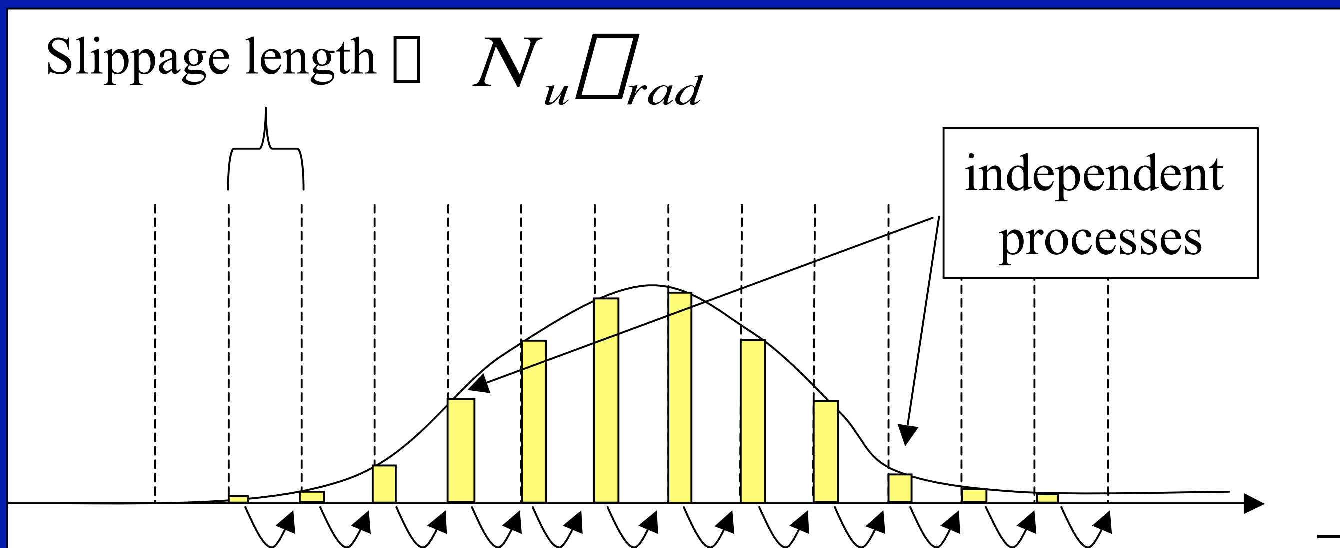
TESLA FEL




TTF FEL
LEUTLE
Peak Brilliance [Phot./(sec · mrad² · mm² · 0.1% bandw.)]
Energy [eV]
TESLA SASE FELs
LCLS
TTF-FEL (M)
TTF-FEL
TESLA spontaneous Undulators
Spontaneous Spectrum SASE FEL
TTF-FEL spontan
ESRF-Undulator (ID23)
SPring8 Undulator
BESSY-II U-49
APS Undulator
BESSY-II U-125
PETRA Undulator
ALS U5.0

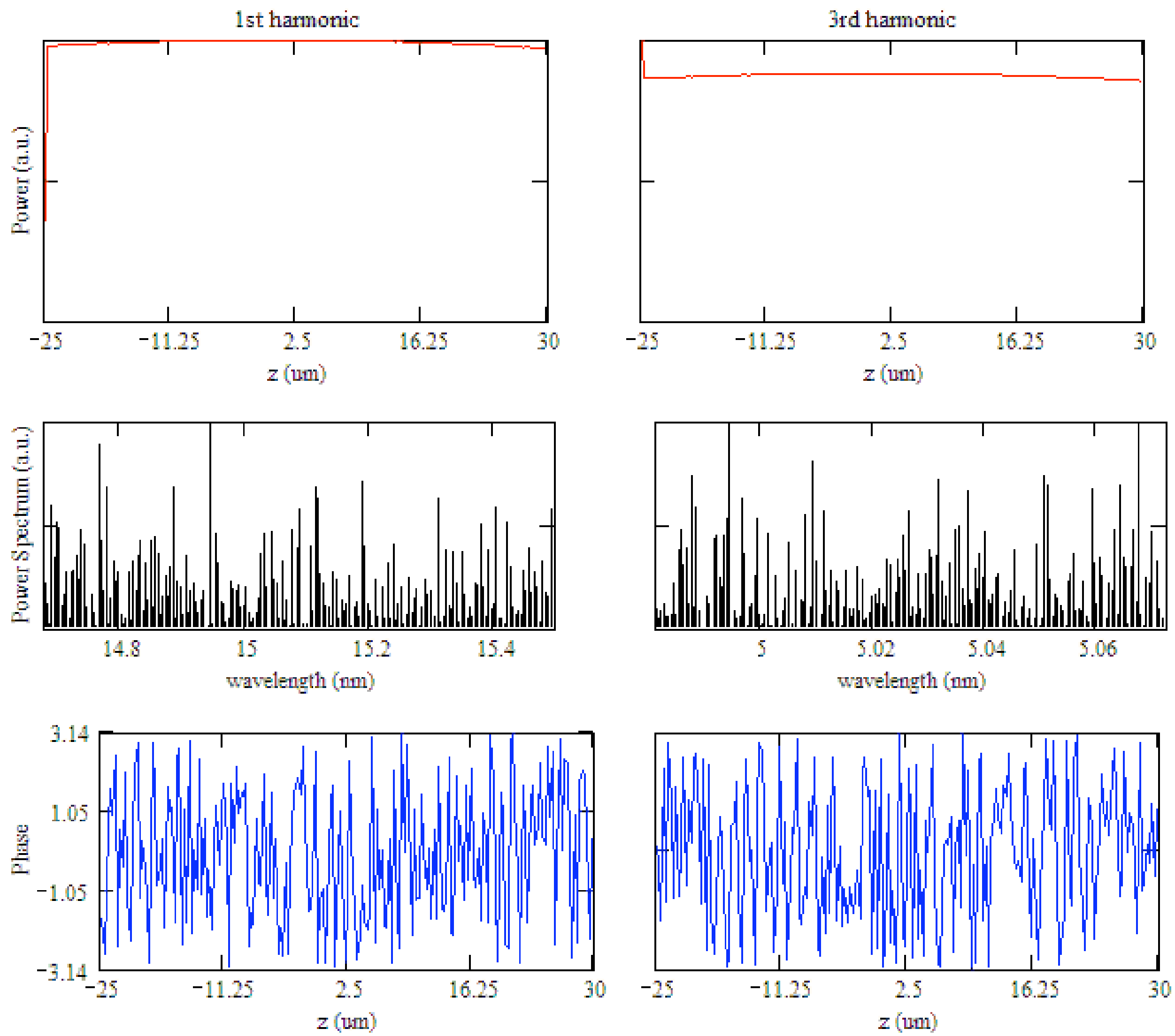

Intensity (a.u.)
SASE
Simulations
λ (nm)

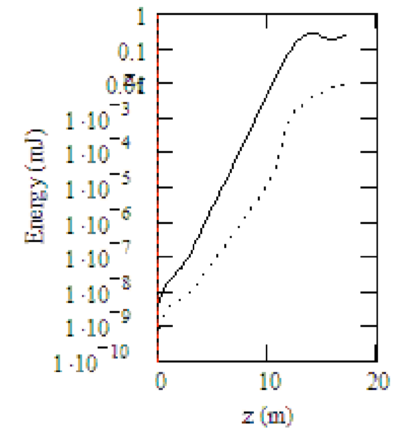
SASE Longitudinal coherence



The radiation “slips” over the electrons for a distance N_u□$_{rad}$

SASE





Main parameters at
$f = 0$, **or** $z_f = 0$ m

$P_{in} = 0$ W

$Energy_{f,0} = 4.684 \times 10^{-9}$ mJ

$Energy_{f,2} = 8.398 \times 10^{-10}$ mJ

$\frac{1}{c} \cdot length_{rms_{f,0}} = 0.053$ ps

$\frac{1}{c} \cdot length_{rms_{f,2}} = 0.053$ ps

$width_{rms_{f,0}} \cdot \frac{\lambda_{0_{n_u}}}{c} = 1.639\%$

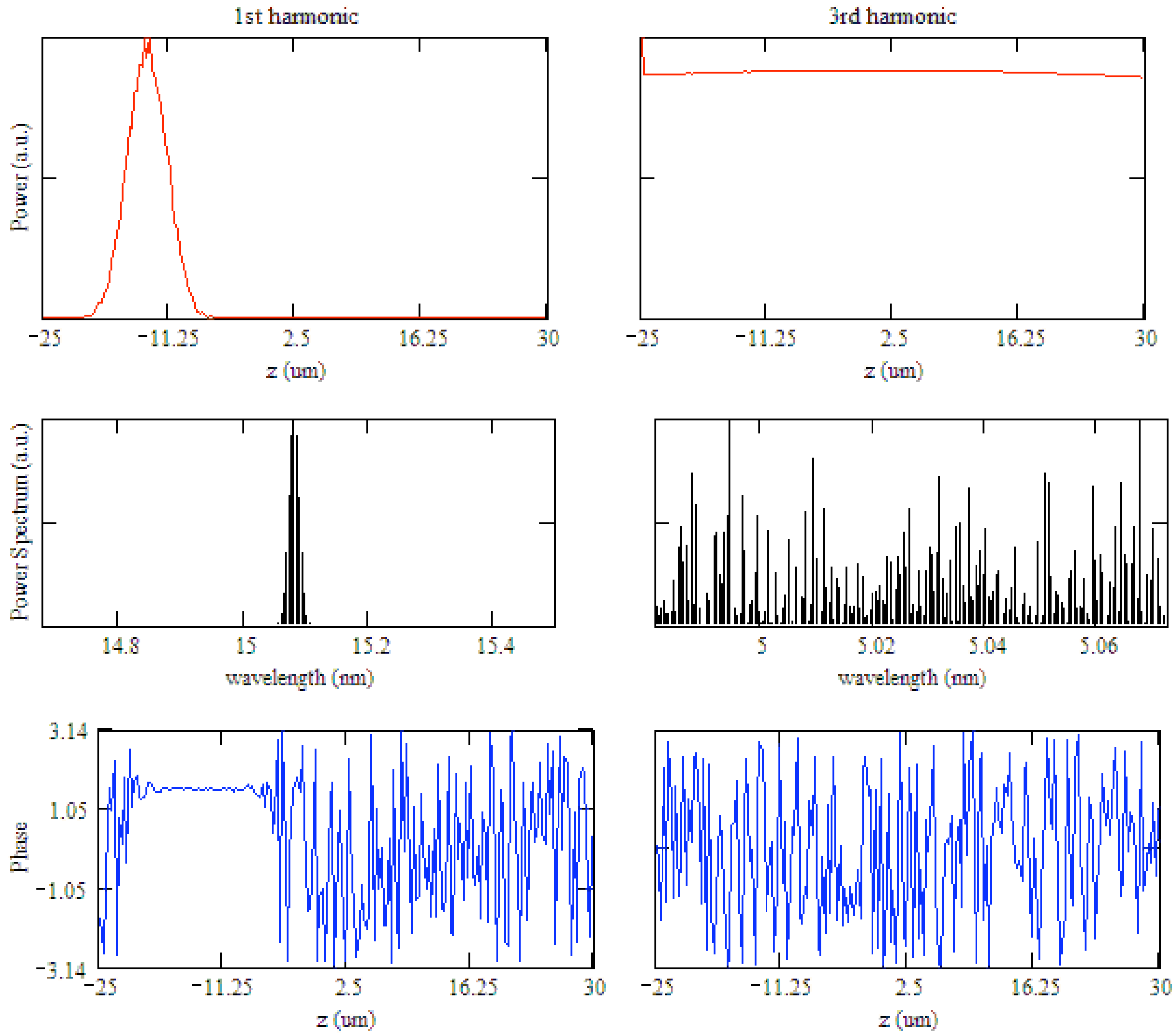
$width_{rms_{f,2}} \cdot \frac{\lambda_{0_{n_u}}}{c \cdot 3} = 0.155\%$

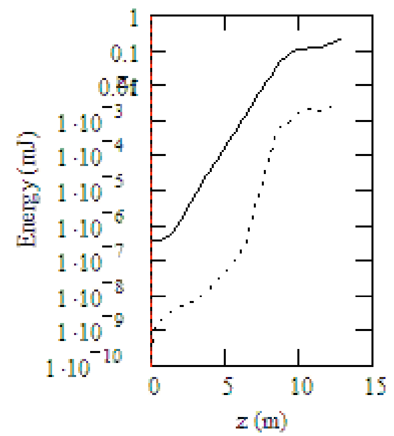
$dfl_1 = 4.198$

$dfl_3 = 7.55$

Courtesy L. Giannessi (Perseo in 1D mode http://www.perseo.enea.it)

SEEDING





Main parameters at

$f = 59$, or $z_f = 12.936\,m$

$P_{in} = 2 \times 10^4\,W$

$Energy_{f,0} = 0.212\,mJ$

$Energy_{f,2} = 3.751 \times 10^{-3}\,mJ$

$\frac{1}{c} \cdot length_{rms_{f,0}} = 0.035\,ps$

$\frac{1}{c} \cdot length_{rms_{f,2}} = 0.038\,ps$

$width_{rms_{f,0}} \cdot \frac{\lambda_0 \, n_u}{c} = 0.117\,\%$

$width_{rms_{f,2}} \cdot \frac{\lambda_0 \, n_u}{c \cdot 3} = 0.05\,\%$

$dfl_1 = 1.639$

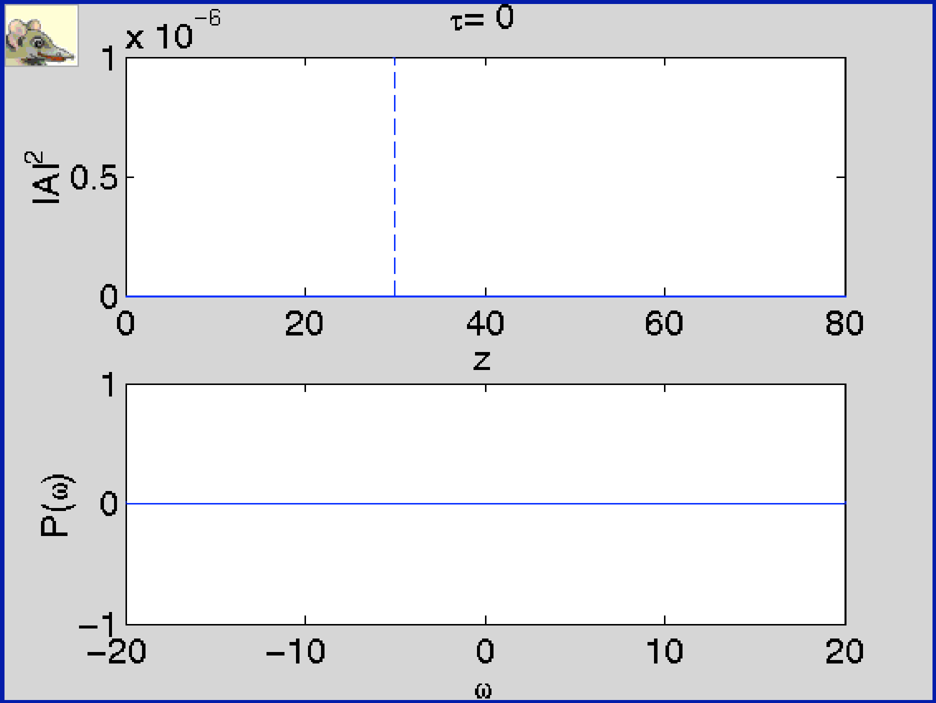
$dfl_3 = 2.282$

Courtesy L. Giannessi (Perseo in 1D mode http://www.perseo.enea.it)

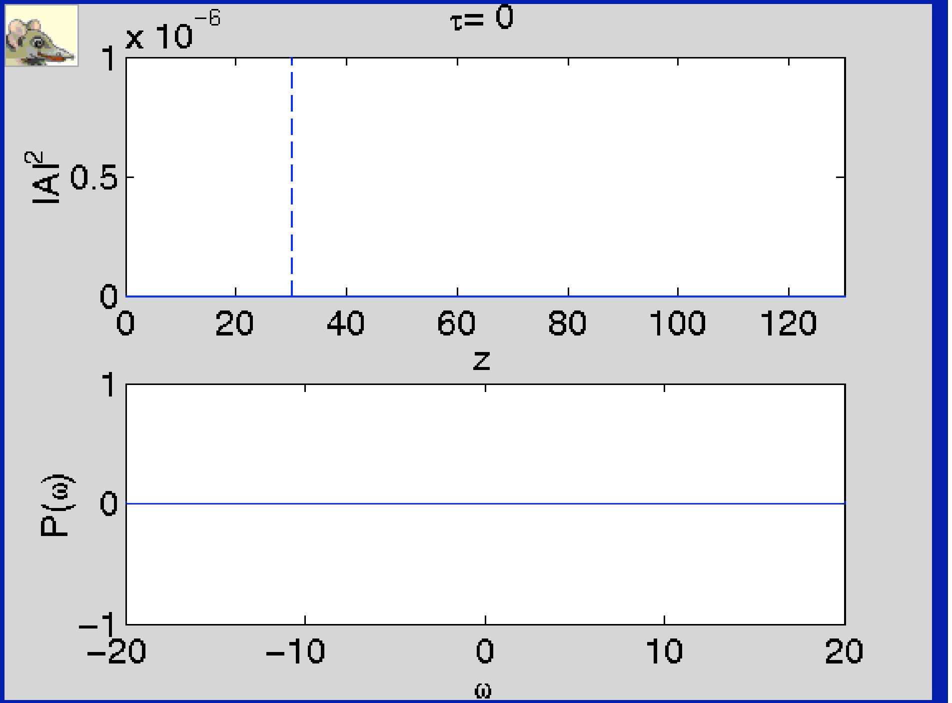
The Quantum FEL SASE

When the electrons emit on average less than one photon , there are only two available momentum state and the device behaves like a quantum two level system

Classical



Quantum



(R.Bonifacio, N. Piovella, G. Robb, in preparation)

FEL Electron Beam Requirements:

High Brightness B_n => High Peak Current & Low Emittance

$$\Box_r^{MIN} \quad \Box_{\Box}\sqrt{\frac{\left(1+K^2/2\right)}{\Box B_n K^2}}$$

minimum radiation wavelength

energy spread

undulator parameter

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

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

gain length

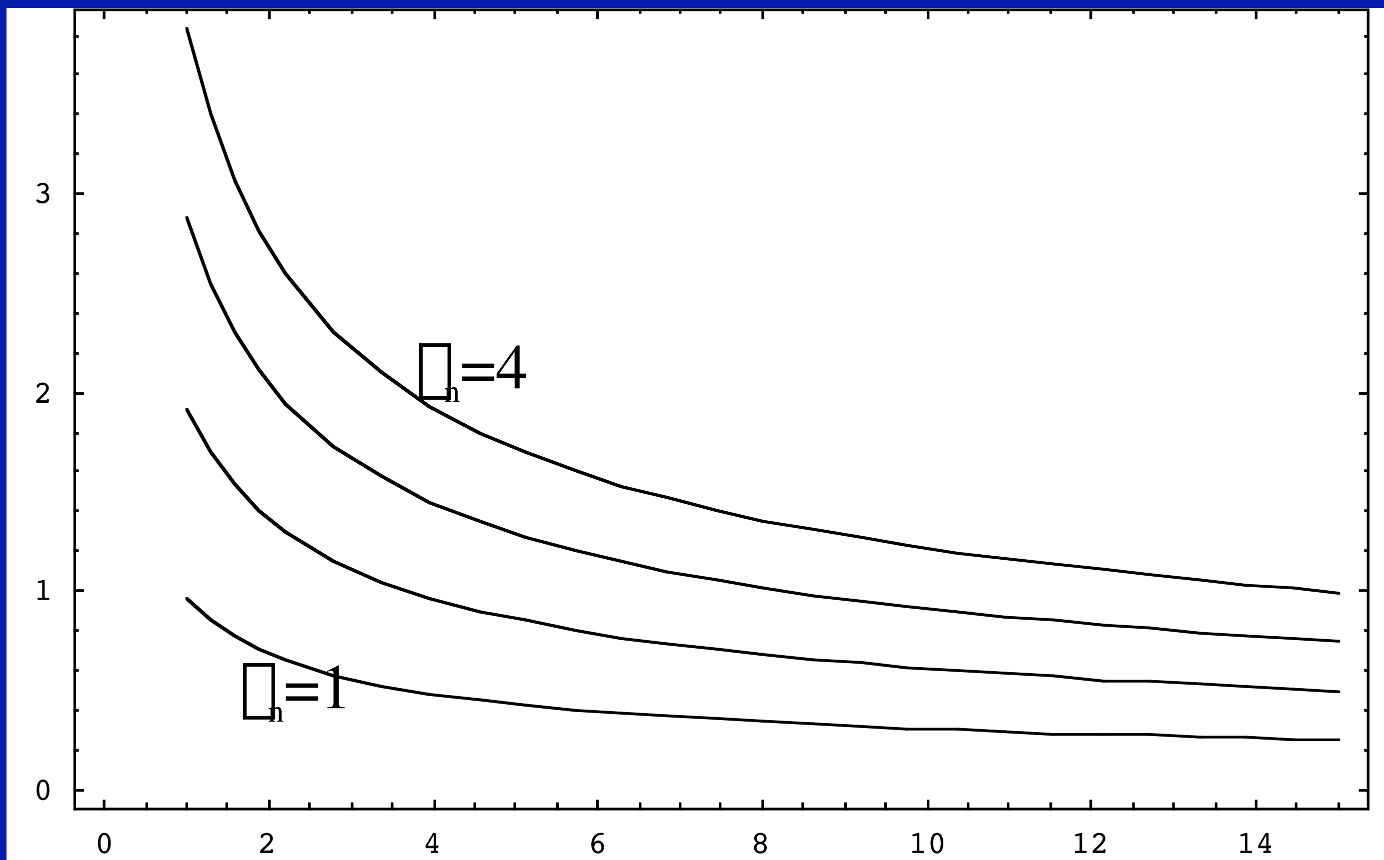
R. Saldin et al. in *Conceptual Design of a 500 GeV e+e- Linear Collider with Integrated X-ray Laser Facility*, DESY-1997-048

I=2.5kA

K=5

$□_e$=0.0002

$□_{cr}$ [nm]



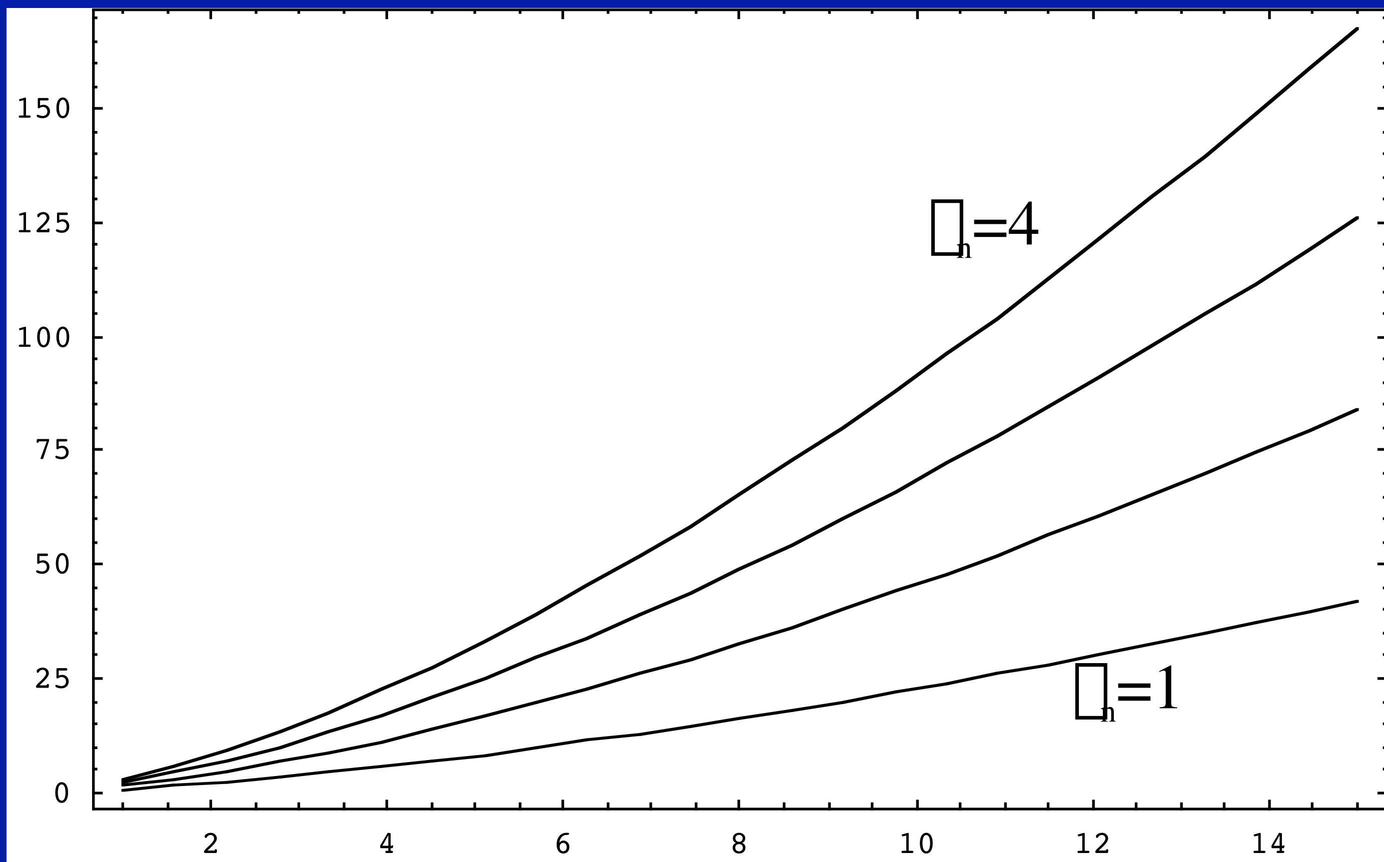
Energy [GeV]

$I=2.5kA$

$K=5$

$\epsilon_e=0.0002$

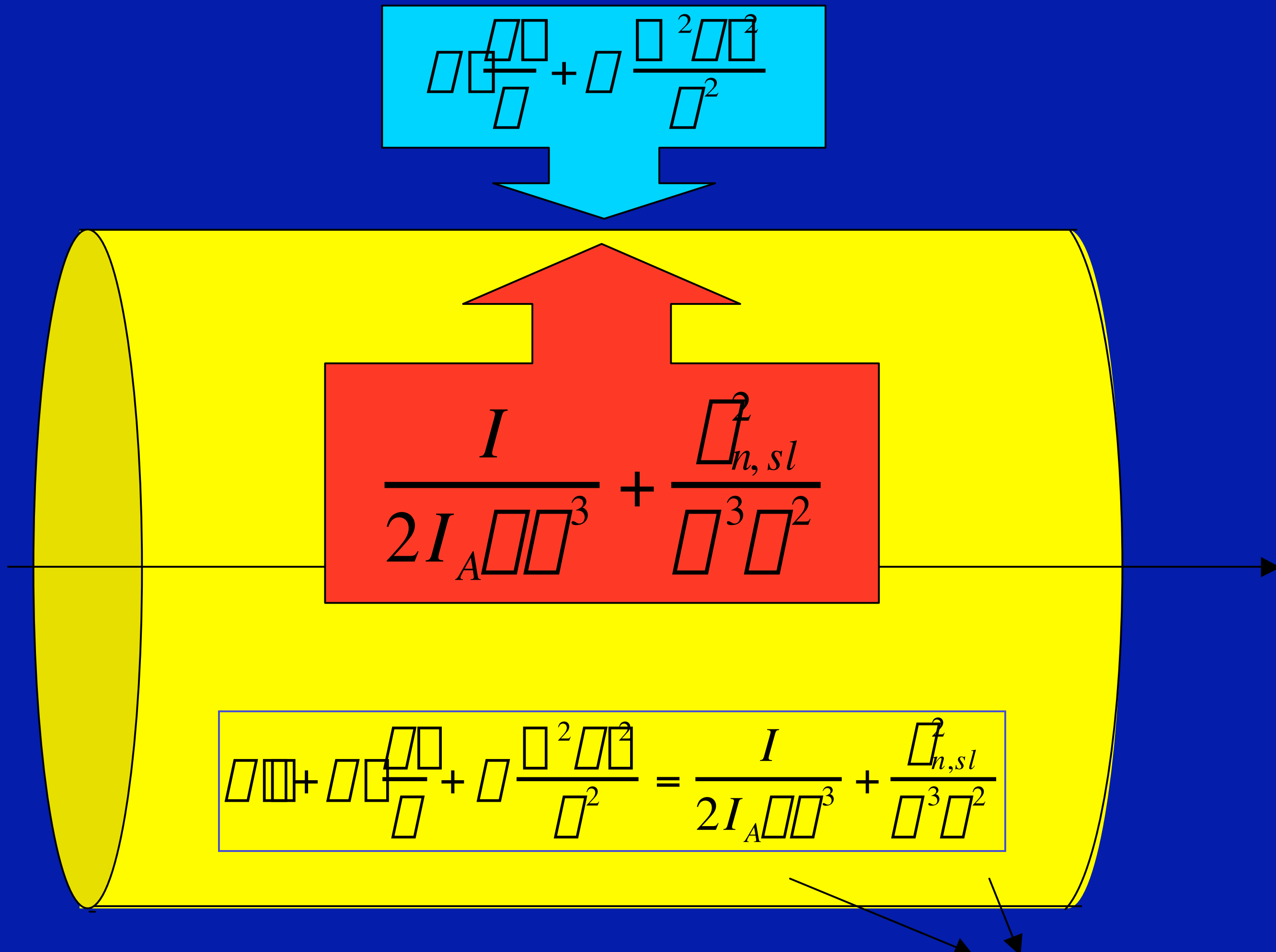
Lsat [m]



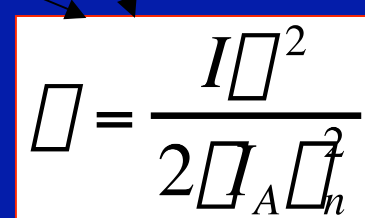
Energy [GeV]

High Brightness e^- beams

Schematic View of the Envelope Equations



Laminarity Parameter ==>

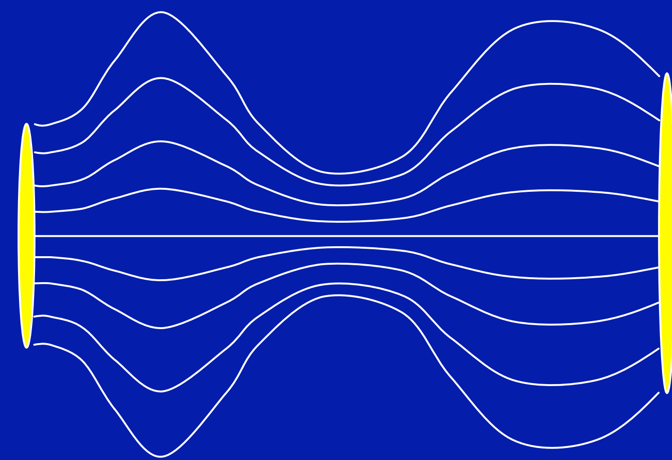


The beam undergoes *two regimes* along the accelerator:

$\rho >> 1$

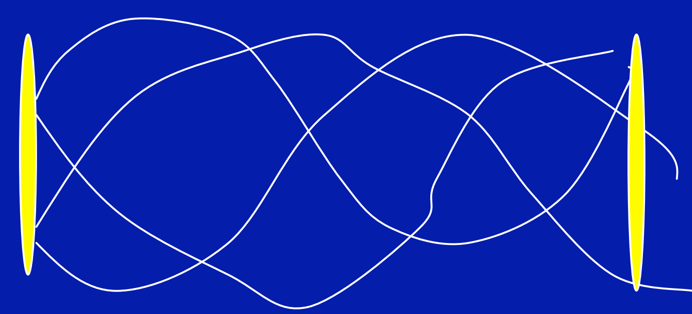
$$\sigma'' + \sigma'\frac{\gamma'}{\gamma} + \Omega^2\frac{\gamma'^2}{\gamma^2}\sigma = \frac{I}{2I_A\sigma\gamma^3} + \frac{\epsilon_{n,sl}^2}{\sigma^3\gamma^2}$$

Laminar Beam



$\rho << 1$

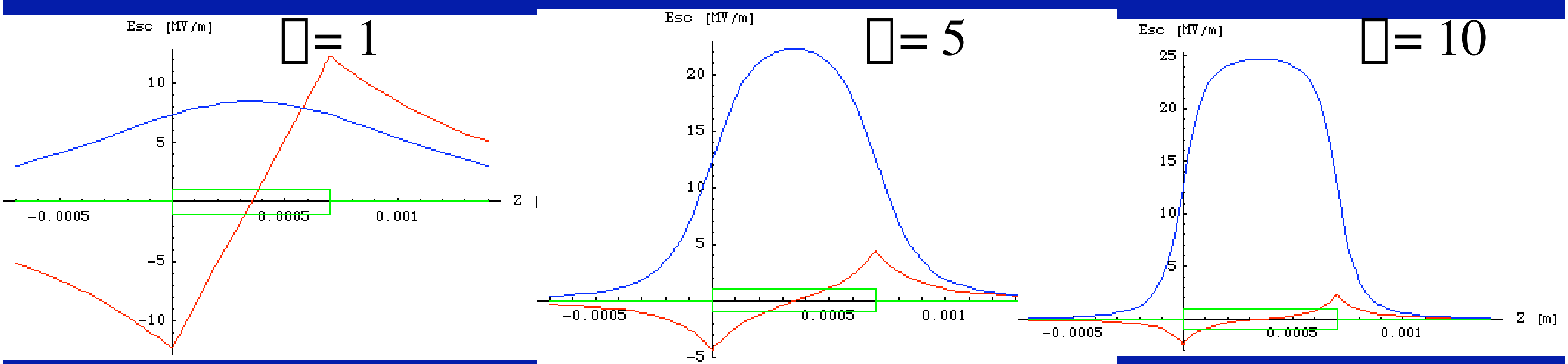
$$\sigma'' + \sigma'\frac{\gamma'}{\gamma} + \Omega^2\frac{\gamma'^2}{\gamma^2}\sigma = \frac{I}{2I_A\sigma\gamma^3} + \frac{\epsilon_{n,sl}^2}{\sigma^3\gamma^2}$$



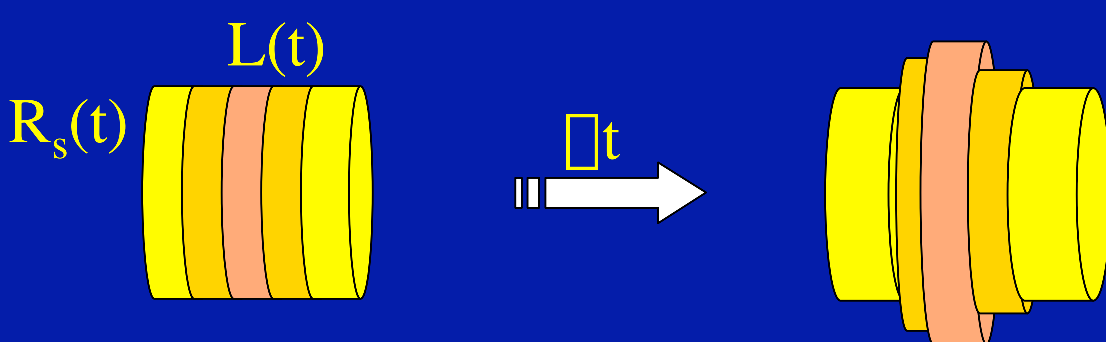
Thermal Beam

Laminar Beam-Transverse Space charge Field

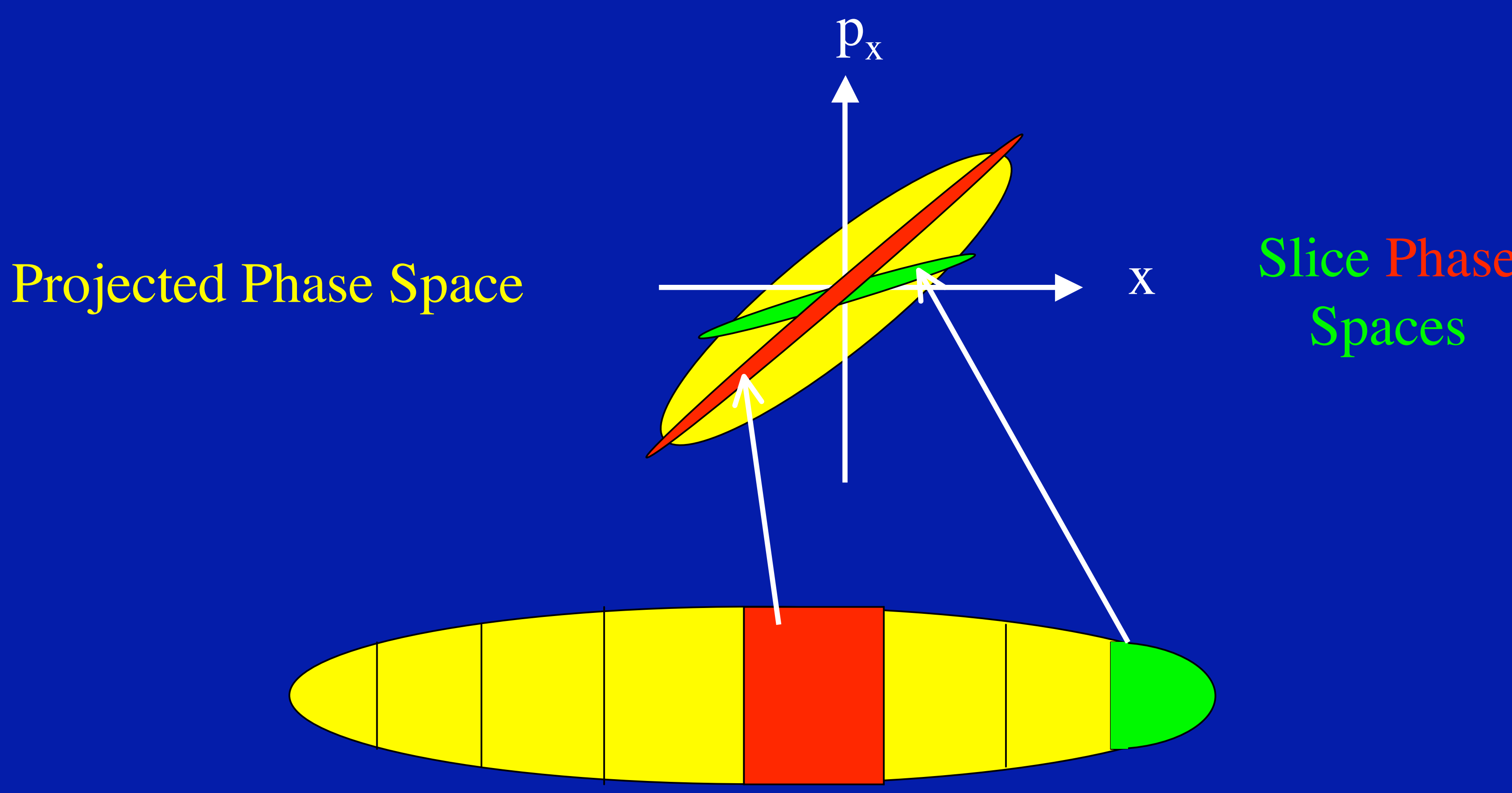
$$E_r^{sc}(\zeta_s) = \frac{Q}{4\pi\varepsilon_o R_s L}\left[\frac{1-\zeta_s/L}{\sqrt{(1-\zeta_s/L)^2 + A_{r,s}^2}} + \frac{\zeta_s/L}{\sqrt{(\zeta_s/L)^2 + A_{r,s}^2}}\right] = \frac{Q}{4\pi\varepsilon_o R_s L}\, g(\zeta_s, A_{r,s})$$



$$A_{r,s} \equiv R_s / (\gamma_s L)$$



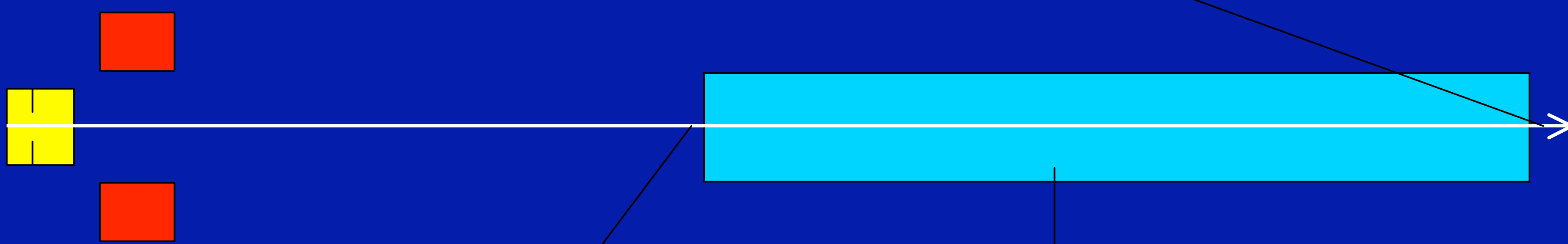
Emittance Oscillations and Growth are driven by space charge differential defocusing in core and tails of the beam



Matching Conditions with the Linac

$$\square = \sqrt{\frac{8}{3}} \frac{\hat{I}}{2 I_o \square_{th} \square}$$

150 MeV



$$\square' = 0$$

$$\square\square = \frac{2}{\square_w} \sqrt{\frac{\hat{\square}}{2 I_0 \square}}$$

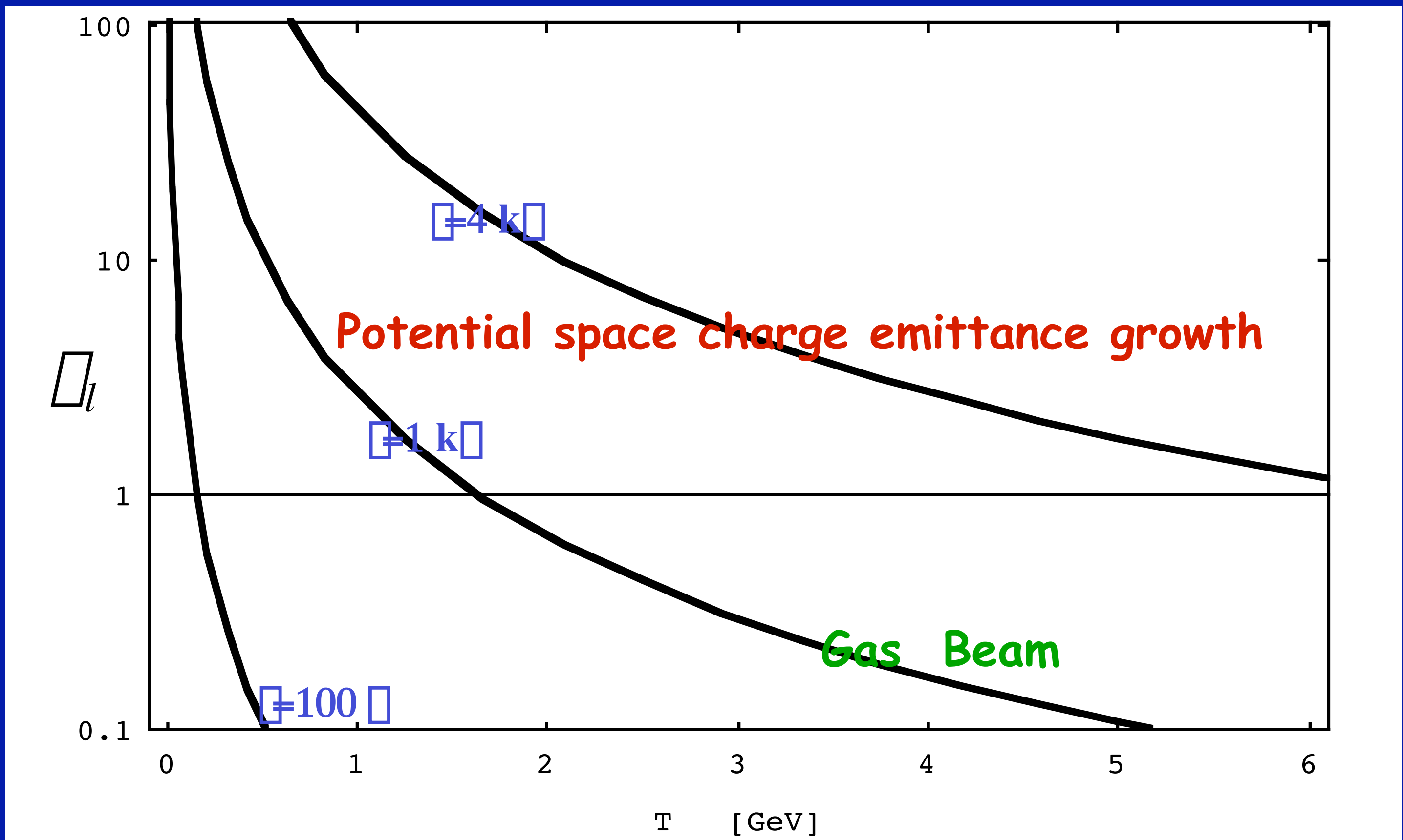
25 MV/m

Typical X-FEL Beam

$If \;\; \epsilon_{nth} = 0.3 \;\; mm.mrad \;\; @ \; 1 \;\; nC$

$I_0 = 17 \;\; kA \qquad \eta^2 \approx 1/8 \;\; (SW \;\; acc. \;\; str.)$

$\gamma'/\gamma = 50 \;\; m^{-1} \;\; \rightarrow \;\; E_{acc} = 25 \;\; MV/m$



SPARC - SPARXINO - SPARX

SPARC Project 7.5 +2.5 M€ (MIUR+INFN)

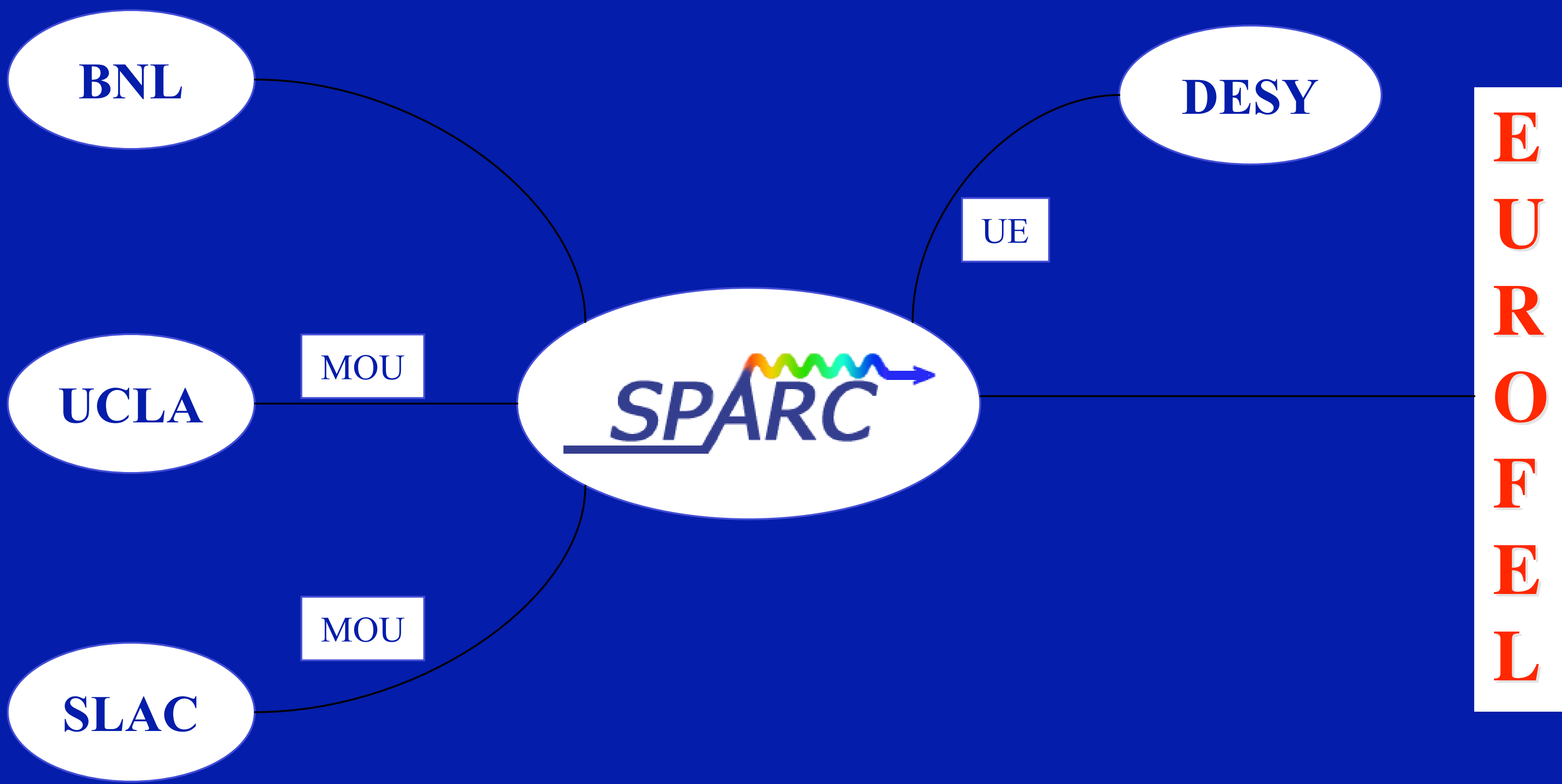
R&D program towards high brightness e^-beam for SASE-FEL's

SPARX Phase I 10 + 2.35 M€ (MIUR+INFN)

- R&D towards an X-ray FEL-SASE source
- Test Facility at 10 nm with the DaΦne Linac (SPARXINO)

SPARX Phase II 12 M€ ? (MIUR)

- Linac energy up-grade (1.5 GeV ?) -> 2 nm ?



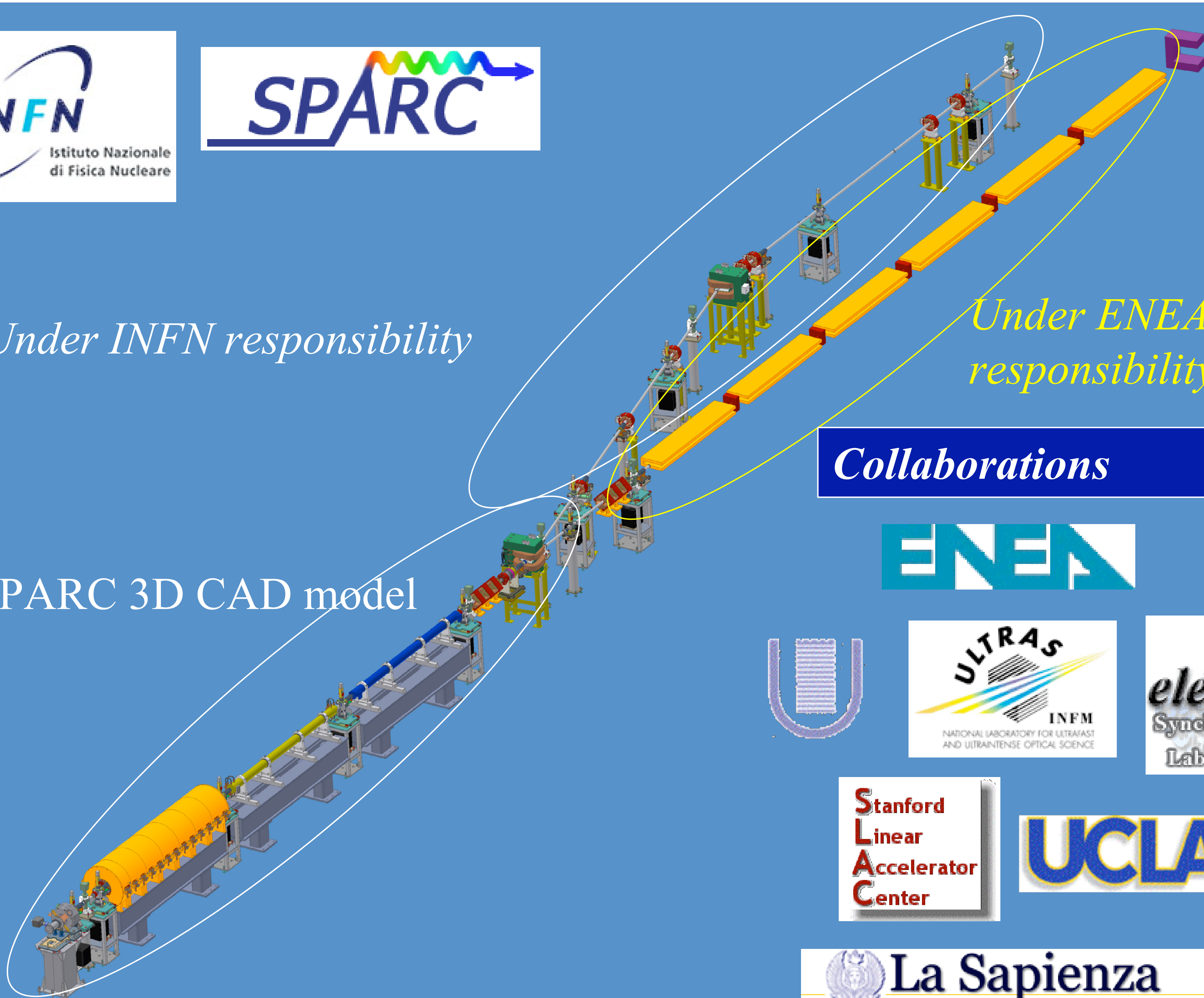
The *Quick-start programme of the European Initiative for Growth* has recently identified *next generation lasers* as a "key technology sector for the Union's long-term competitiveness and strength of the European economy". Support for the development of a network of national facilities working on next generation laser technologies is explicitly mentioned in the final report "A European Initiative for Growth" of the European Commission to the European Council dated 11.11.2003.

INFN Istituto Nazionale di Fisica Nucleare

SPARC

Under INFN responsibility

Under ENEA responsibility



SPARC 3D CAD model

Collaborations

ENEA

ULTRAS INFM NATIONAL LABORATORY FOR ULTRAFAST AND ULTRAINTENSE OPTICAL SCIENCE

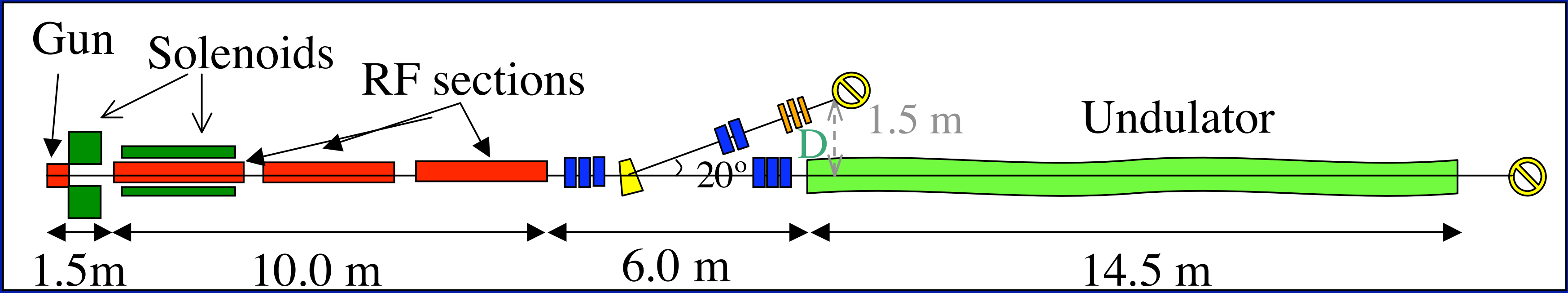
elettra Synchrotron Light Laboratory

Stanford Linear Accelerator Center

UCLA

La Sapienza Università degli Studi di Roma

SPARC Working Point



GUN PARAMETERS		LINAC PARAMETERS		FEL PARAMETERS	
Frequency:	2856 MHz	Frequency:	2856 MHz	Wavelength:	530 nm
Peak Field:	120 MV/m	Accelerating Field:	25-12.5-12.5 MV/m	Coop. Length:	300 m
Solenoid Field:	0.27 Tesla	Solenoid Field:	0.1 Tesla		
Beam Energy:	5.6 MeV	Beam Energy:	155 MeV		
Charge:	1 nC				
Laser:	11.5 ps x 1 mm (Flat Top with <1 ps rise time)				
Thermal emittance	0.3 m				

2002	2003	2004	2005	2006

Project duration

2002 - Stage I - FEASIBILITY

2003-2004- Stage II - PLANNING & DESIGN

2004-2005 - Stage III - CONSTRUCTION

2006 - Stage IV - COMMISSIONING & OPERATION

- Final Testing
- Commissioning
- Operation

How to increase e⁻ Brightness

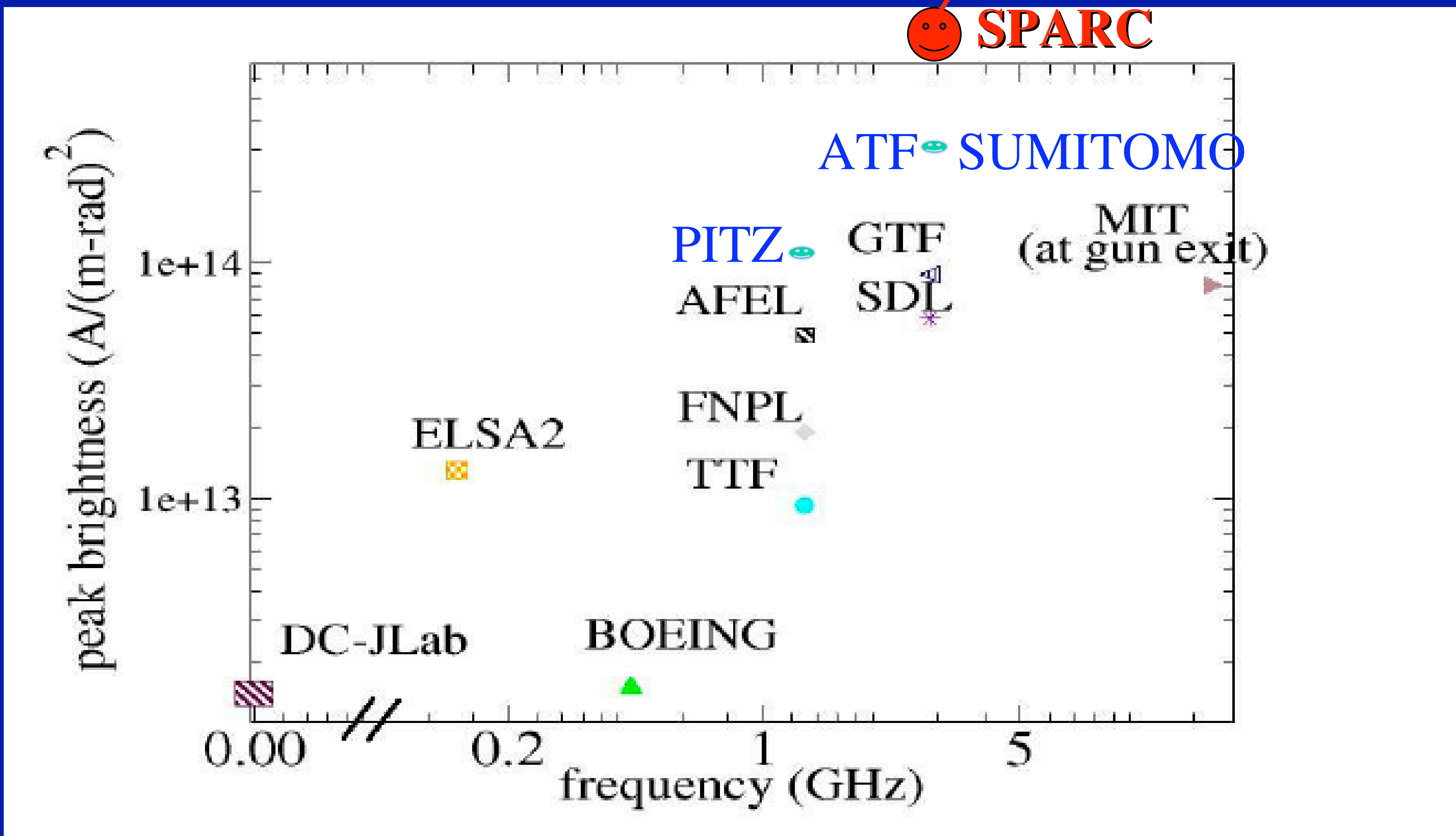
$$\uparrow B = \frac{2I \uparrow}{\epsilon_n^2 \downarrow}$$

- bunch compressors
- RF & magnetic

- Pulse Shaping
- New Working Point

Brightness State of the Art

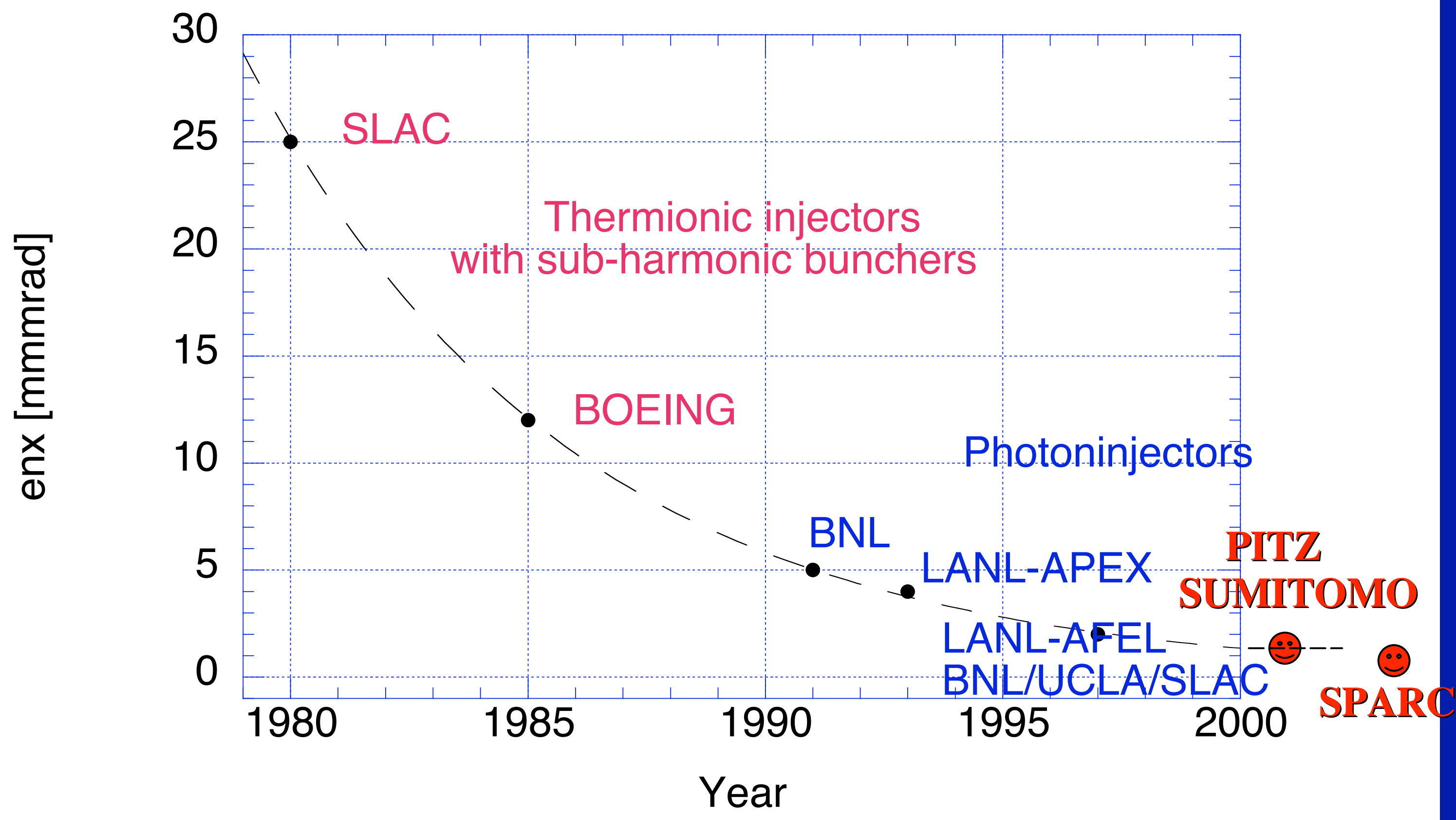
$$B_n = \frac{2I}{\varepsilon_n^2} \cdot 10^{15} \frac{A}{m^2}$$



Low Emittance

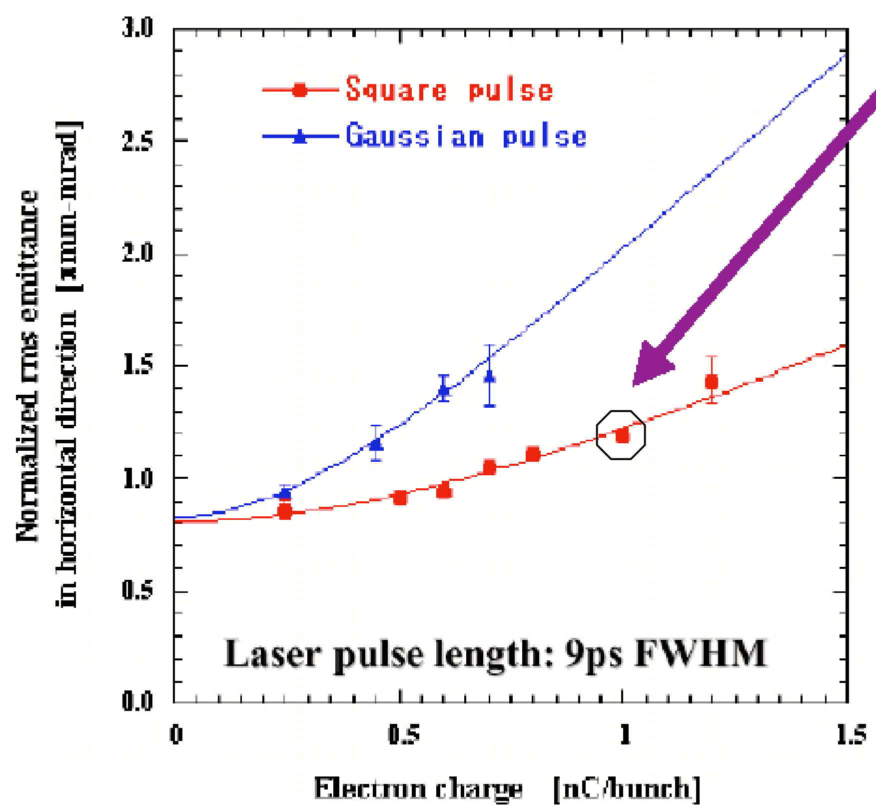
Low Emittance Sources Heras

Thermionic Injectors ==> RF Photoinjectors & Emittance Compensation
==> Pulse Shaping & Emittance Oscillation Control



Pulse Shaping

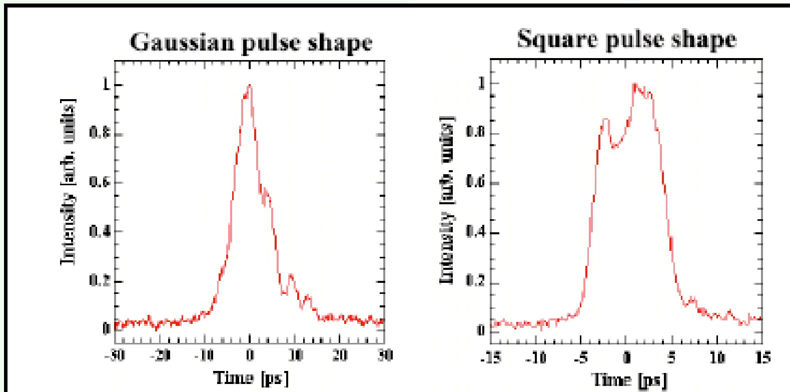
Sumitomo Spring 2002



1nC

ε_p = 1.2 mm.mrad

with “LCLS type” Gun

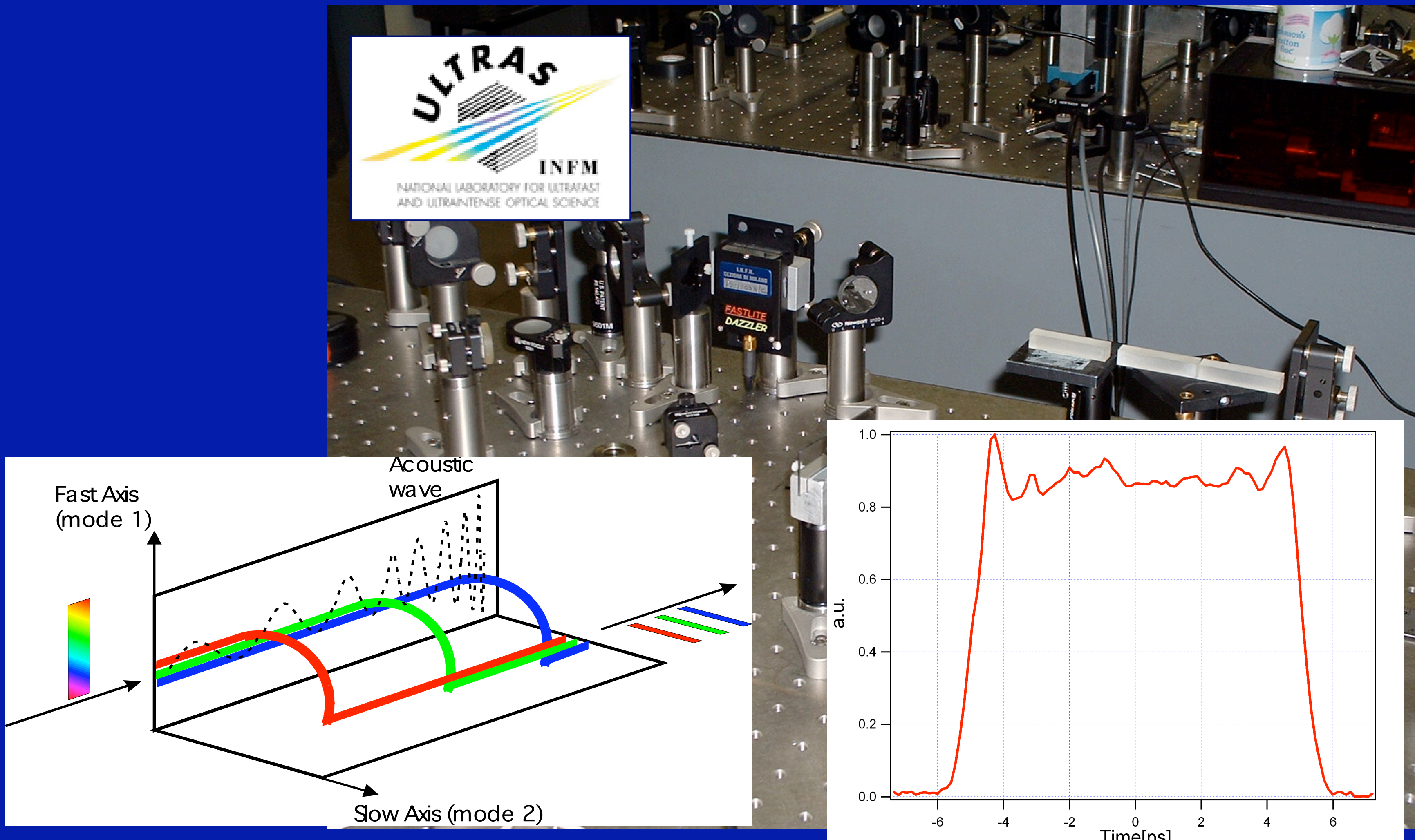


Frequency domain pulse shaping

Courtesy of J.Yang FESTA

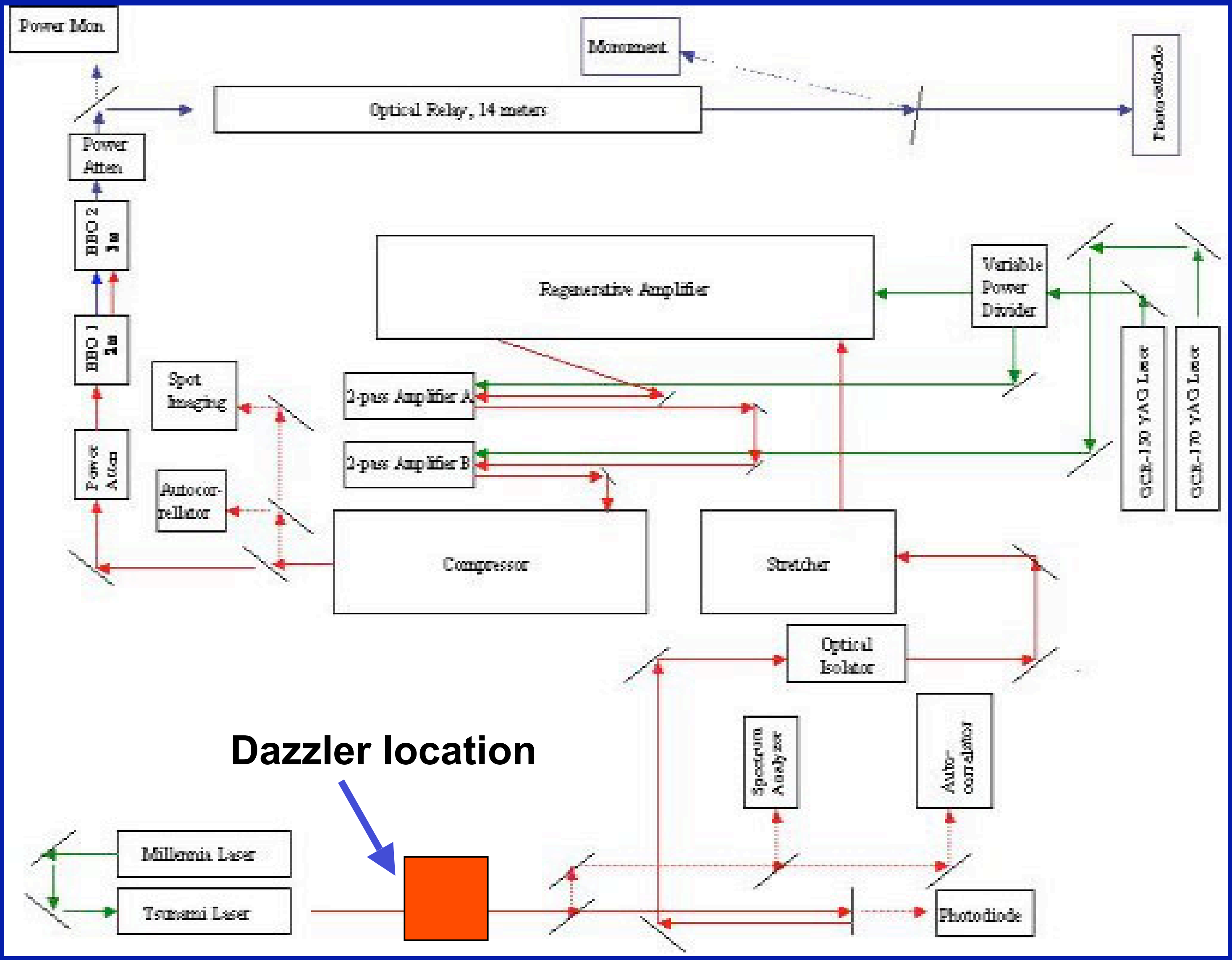
Sumitomo Heavy Industries, Ltd.

Laser Pulse Shaping with "Dazzler" experiments

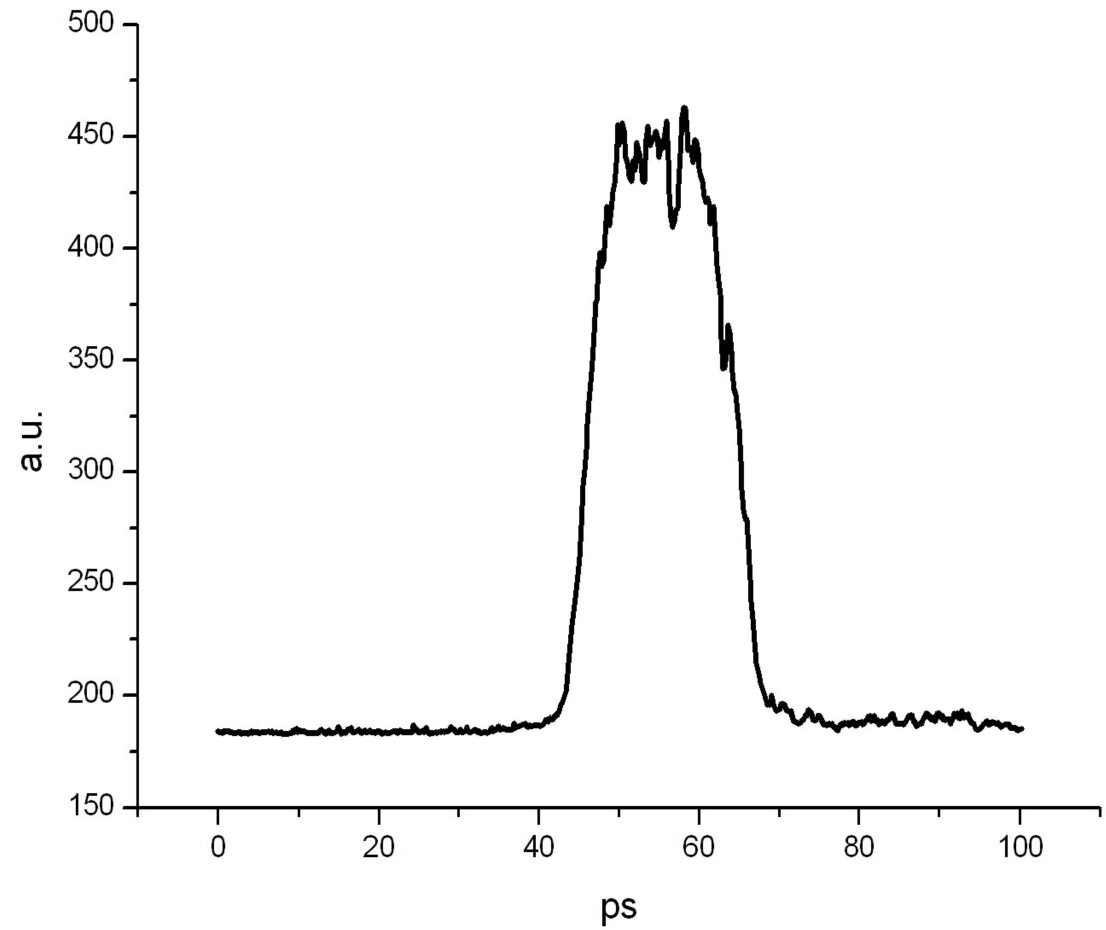


Shaping obtained with single passage in the AO crystal + 30 cm dispersive glass

Brookhaven experiment layout



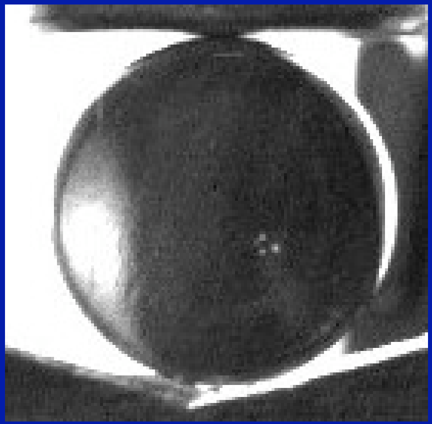
Pulse shape after amplification and compression

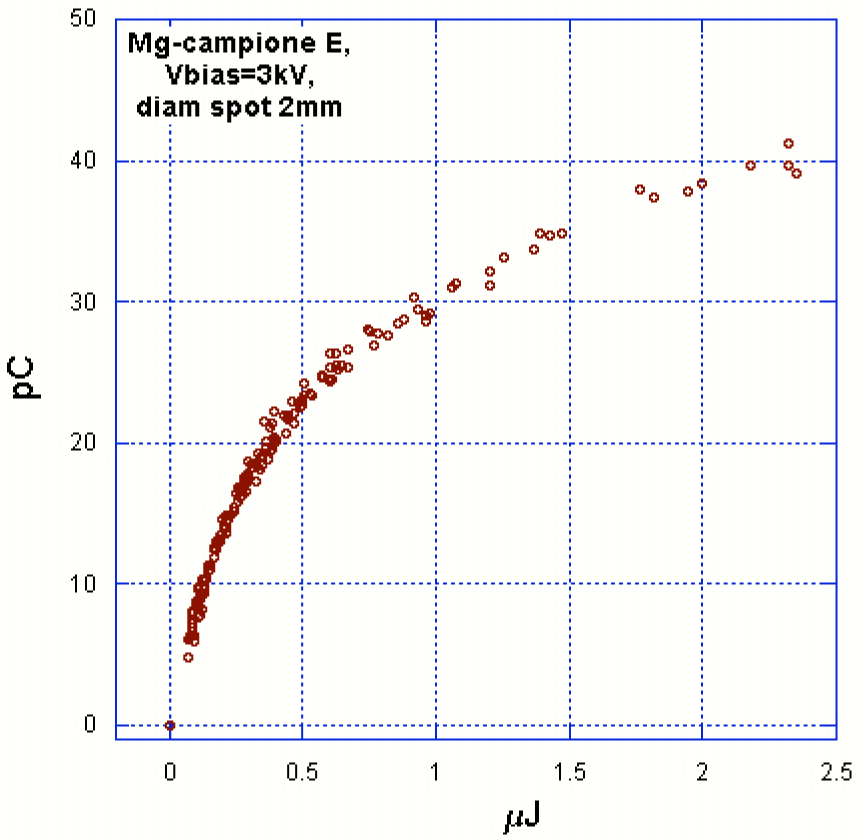


Stanford Linear Accelerator Center

BNL

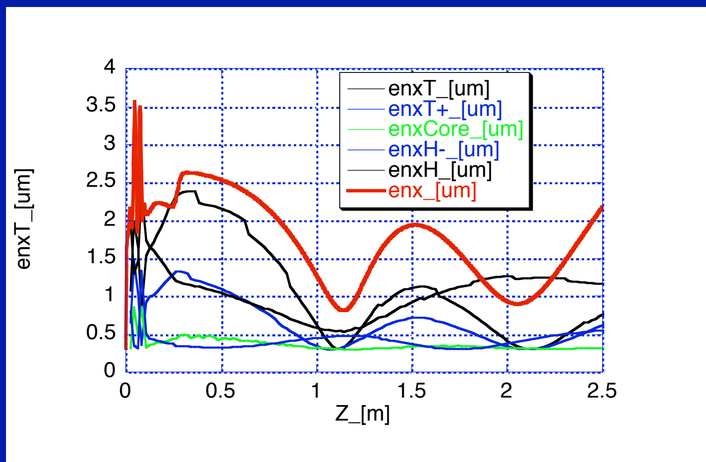
Magnesium-film on copper Cathodes tested at LNF

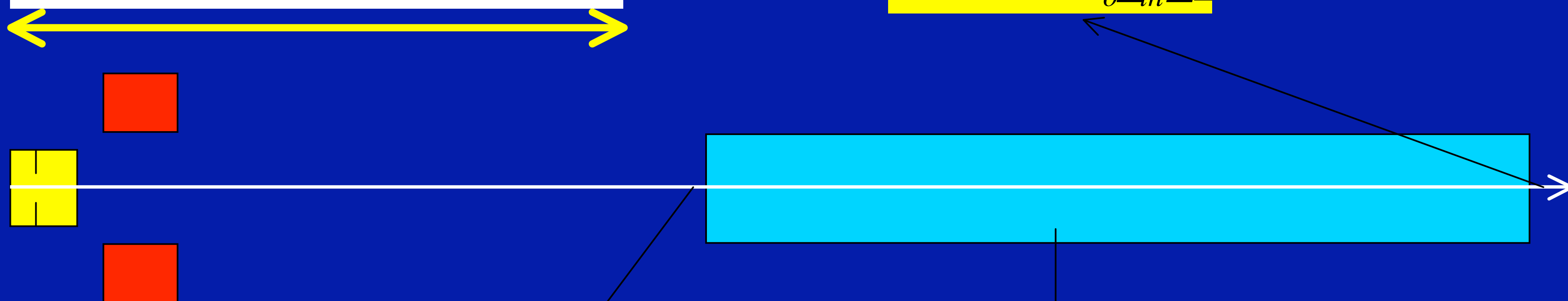




Emittance Oscillation Control

Matching Conditions with the Linac





$$\square = \sqrt{\frac{8}{3}} \frac{\hat{I}}{2 I_o \square_{th} \square}$$

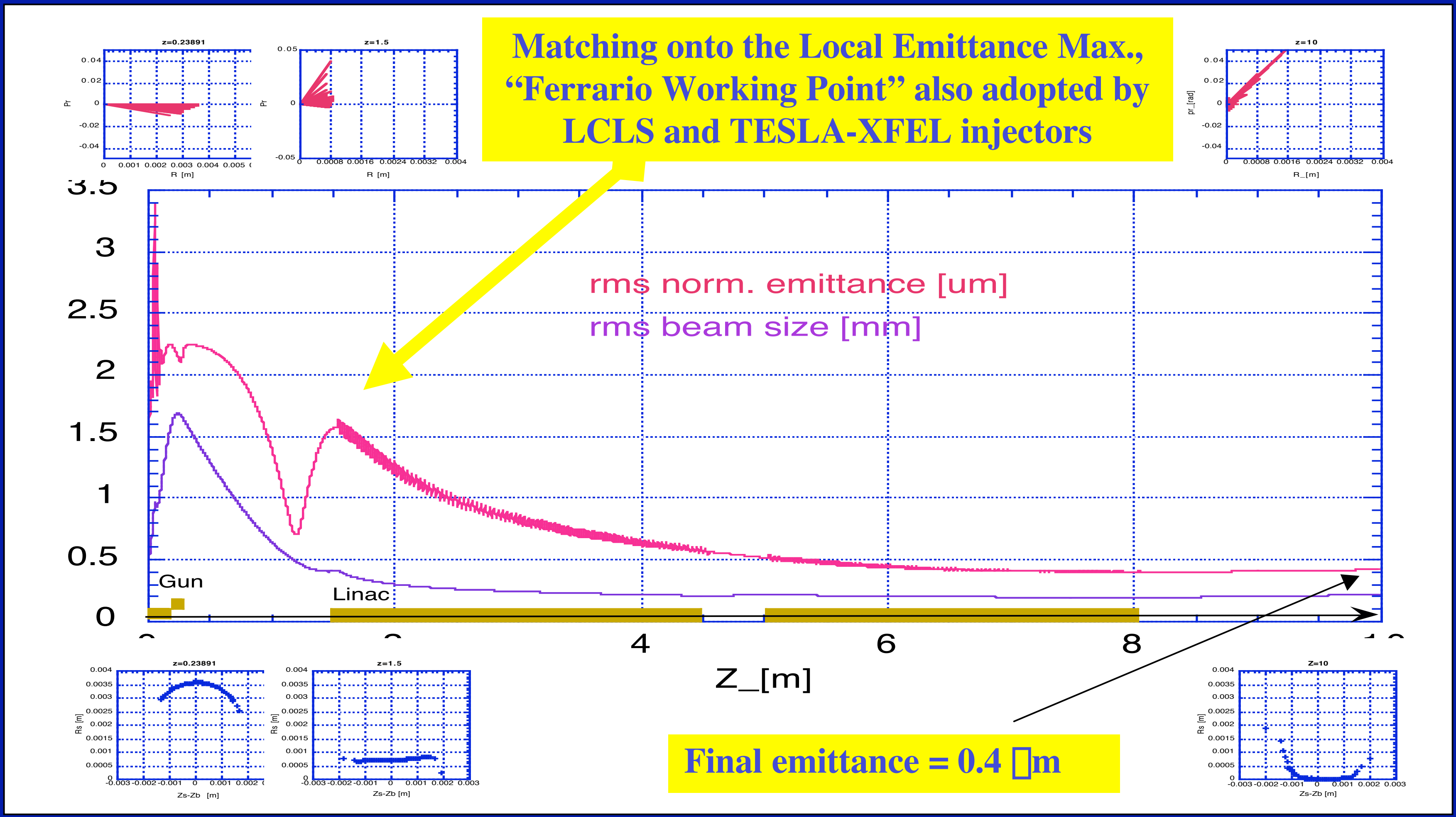
150 MeV

$$\square' = 0$$

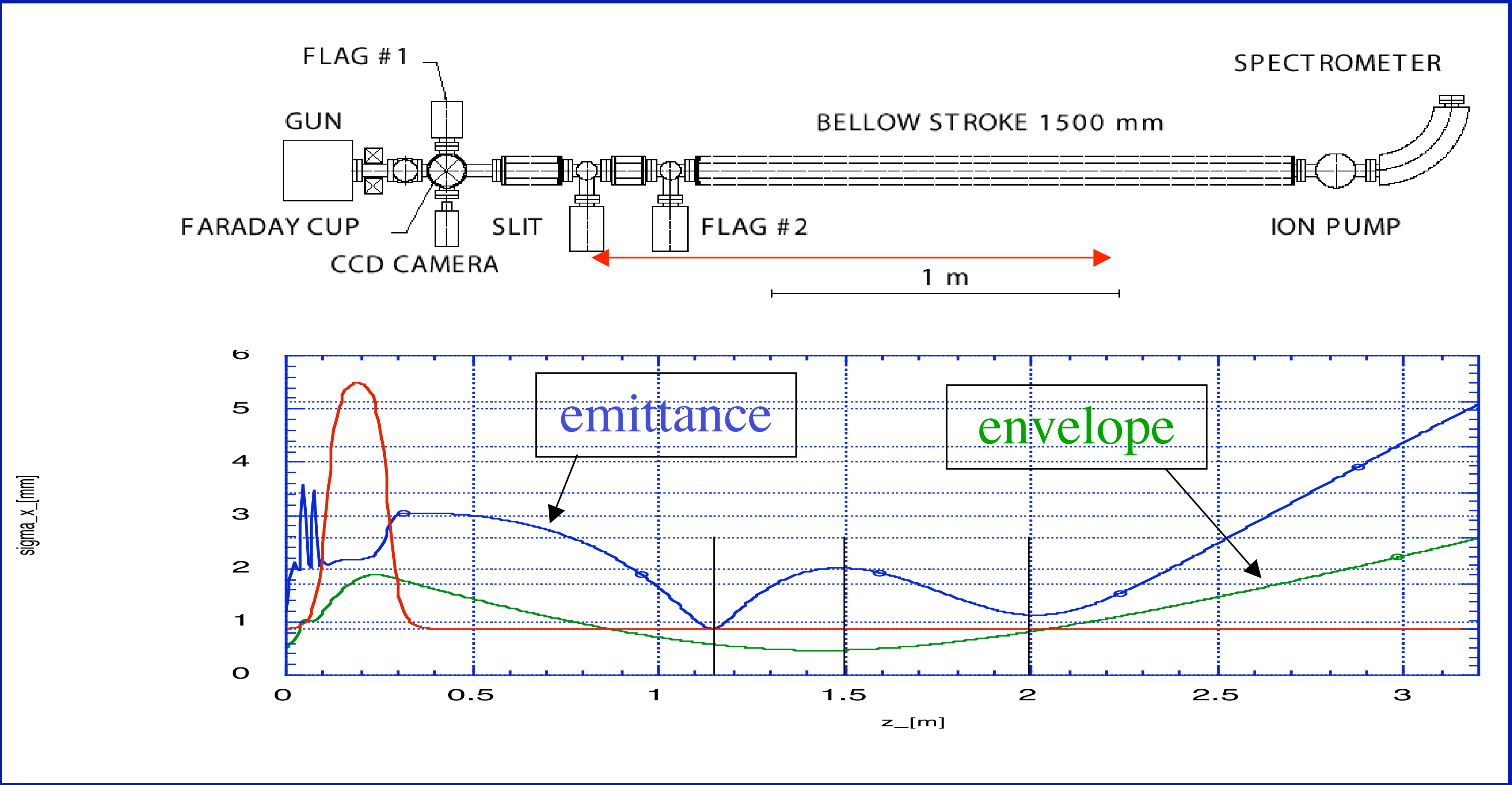
$$\square\square = \frac{2}{\square_w} \sqrt{\frac{\hat{\square}}{2 I_0 \square}}$$

25 MV/m

Optimum Injection in the Linac



Movable Emittance-Meter

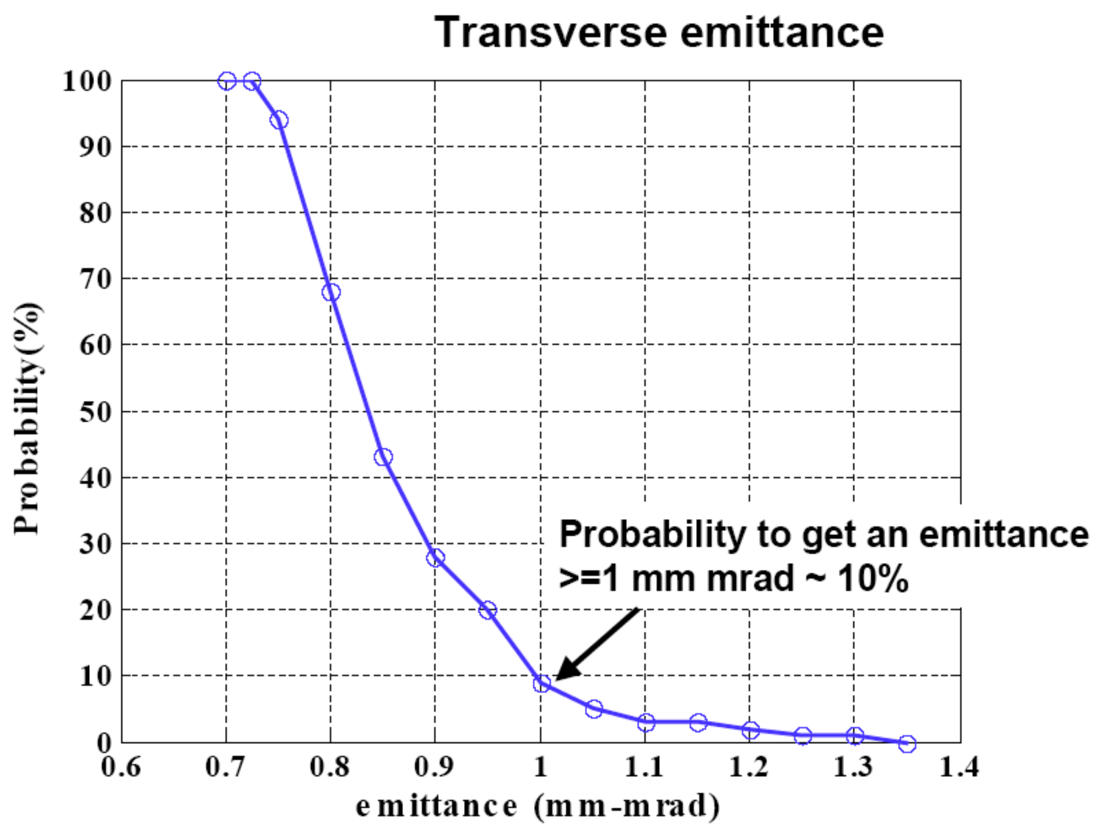


TOLERANCES

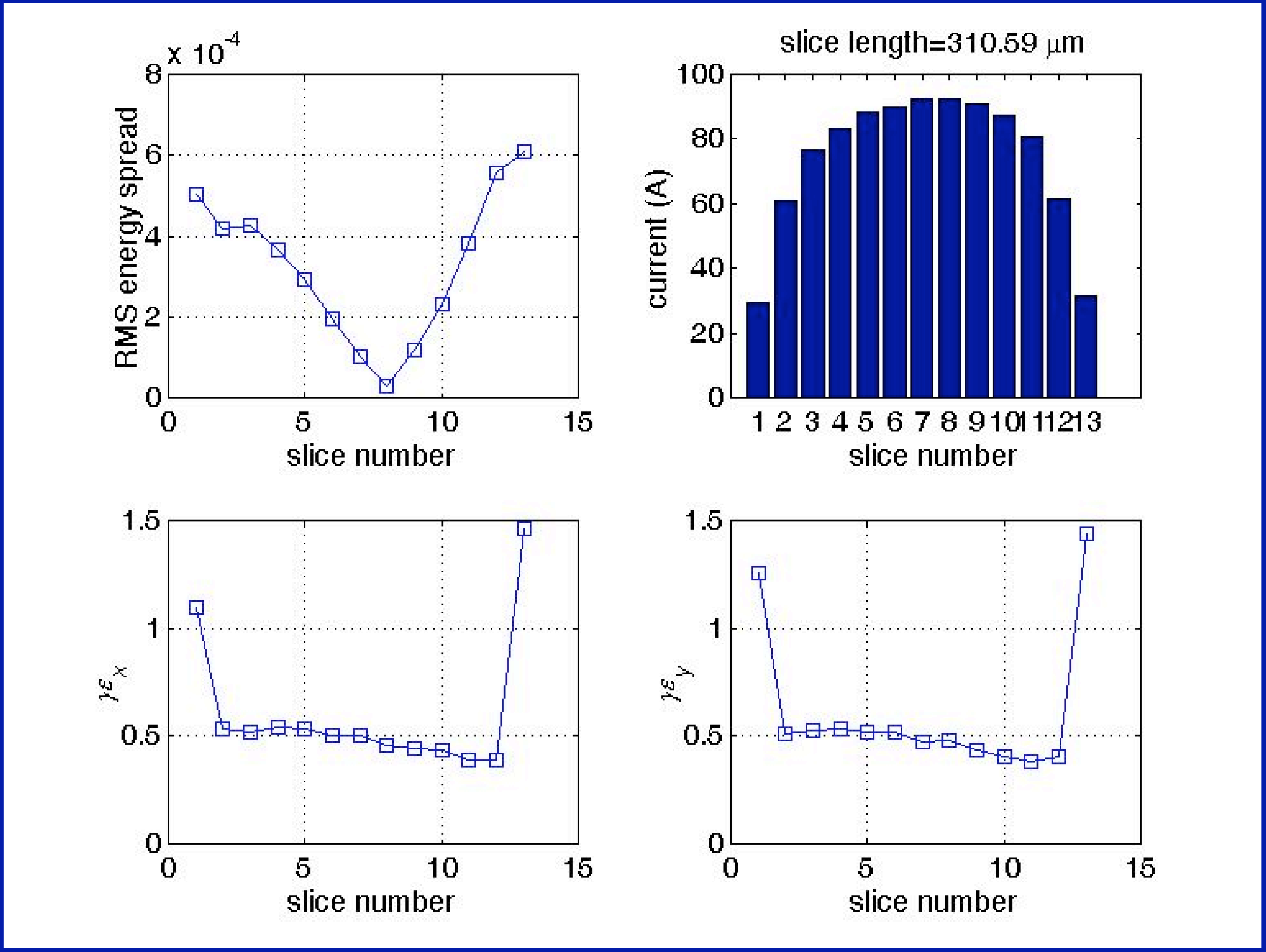
Phase jitter	±3°
Charge fluctuation	+10%
Gun magnetic field	±0.4%
Gun electric field	± 0.5%
Spot radius dimension	±10%
Spot ellipticity	3.5% *(xmax/ymax=1-1.035)*

Minimum variation of the single parameters value for an emittance increase=10%

STATISTICAL ANALYSIS *at undulator entrance*

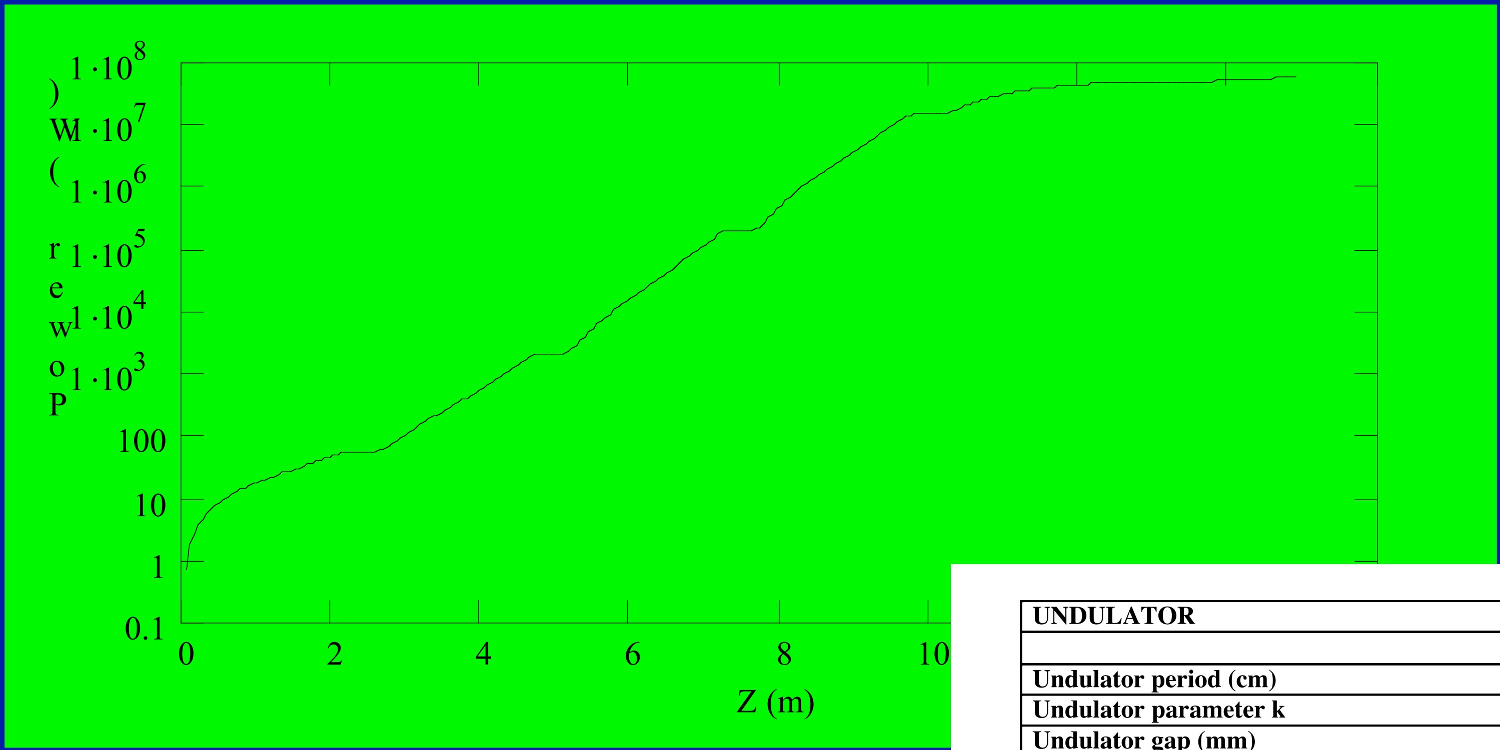


Slice analysis of beam properties at the undulator entrance



GENESIS simulation of the SPARC SASE-FEL

Radiation power growth along the undulator @ 530 nm

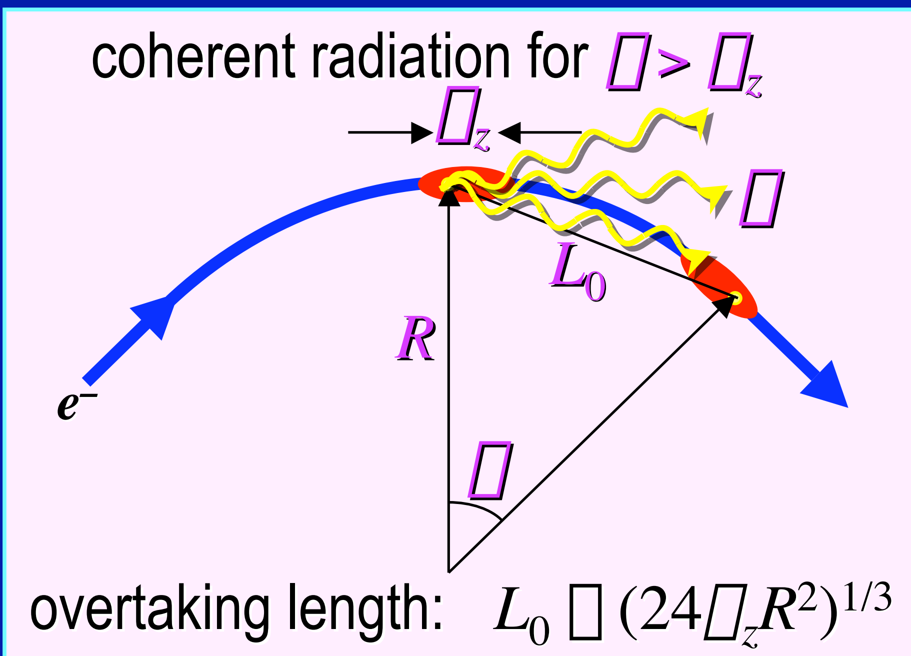


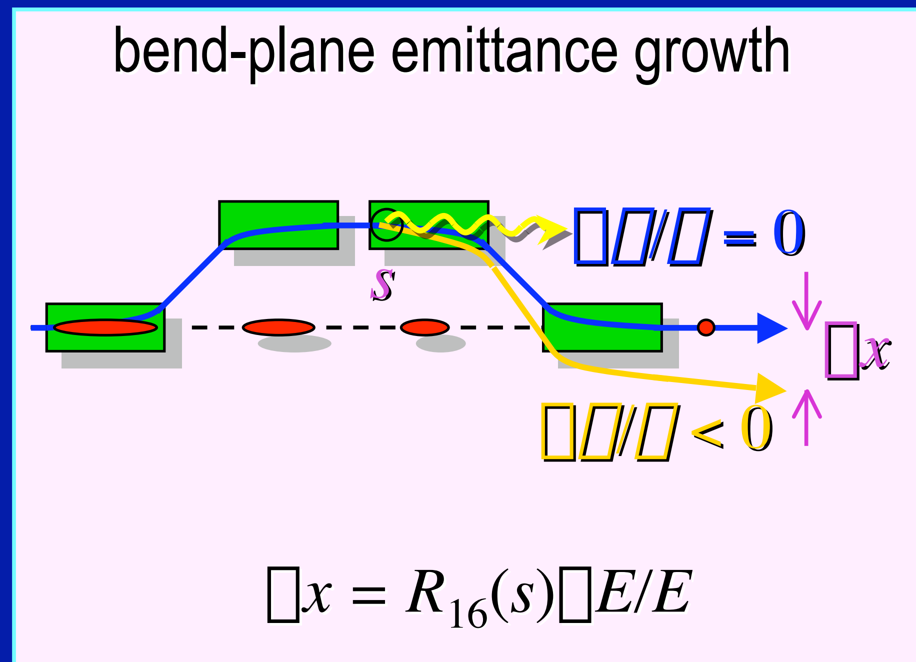
UNDULATOR	
Undulator period (cm)	2.8
Undulator parameter k	2.143
Undulator gap (mm)	9.25
# Undulator sections	6
# Undulator periods per section	78
Drift length between undulator sections (cm)	36.5
Additional quadrupole gradient (T/m)	5.438
Additional quadrupole length (cm)	8.4
FEL radiation wavelength (fundamental, nm)	499.6
Average beta function (m)	1.516
Expected saturation length (m)	< 12

High Peak Current

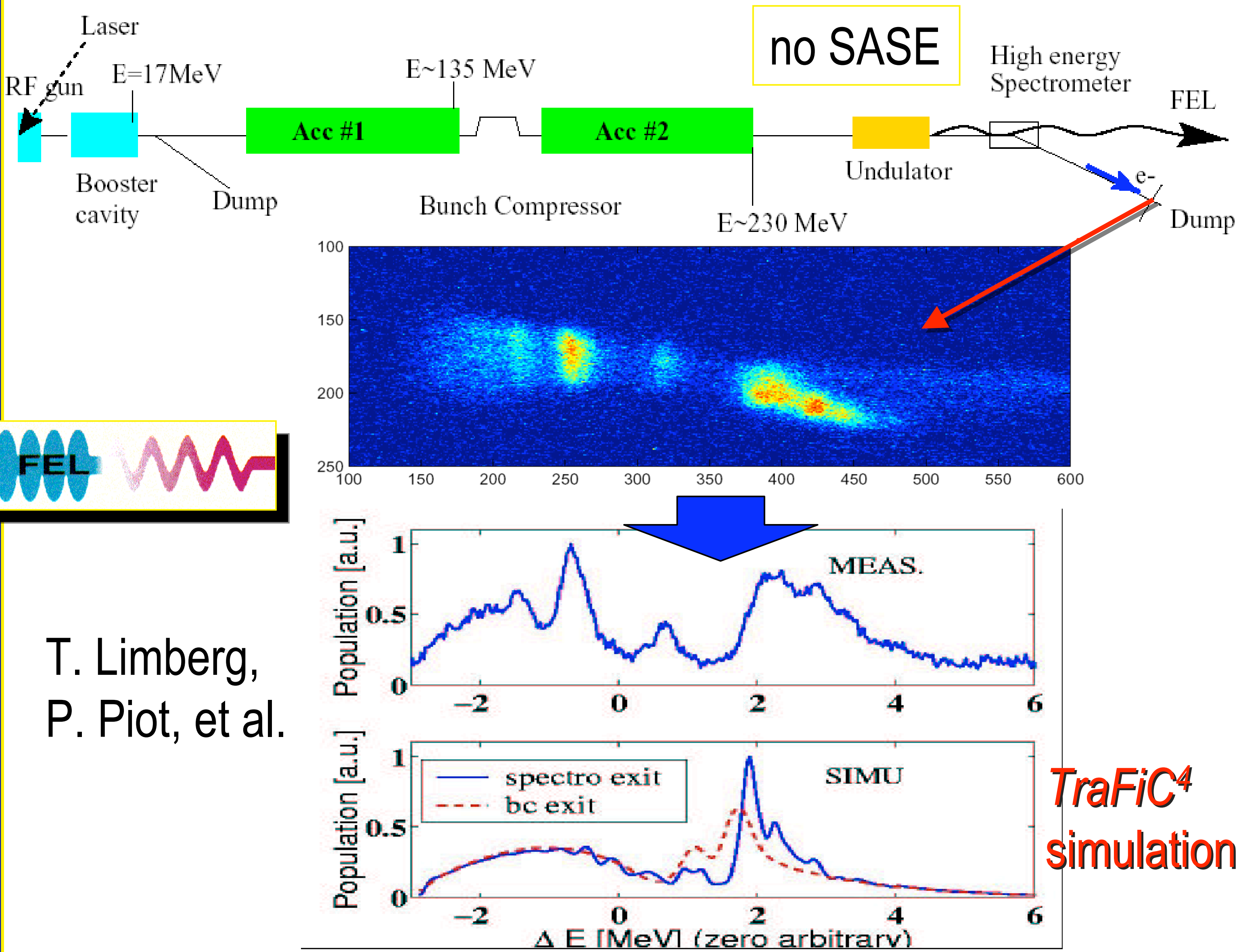
Coherent Synchrotron Radiation (CSR)

- Powerful radiation generates energy spread in bends
- Energy spread breaks achromatic system
- Causes bend-plane emittance growth





Energy Spectrum at TTF-FEL (DESY)

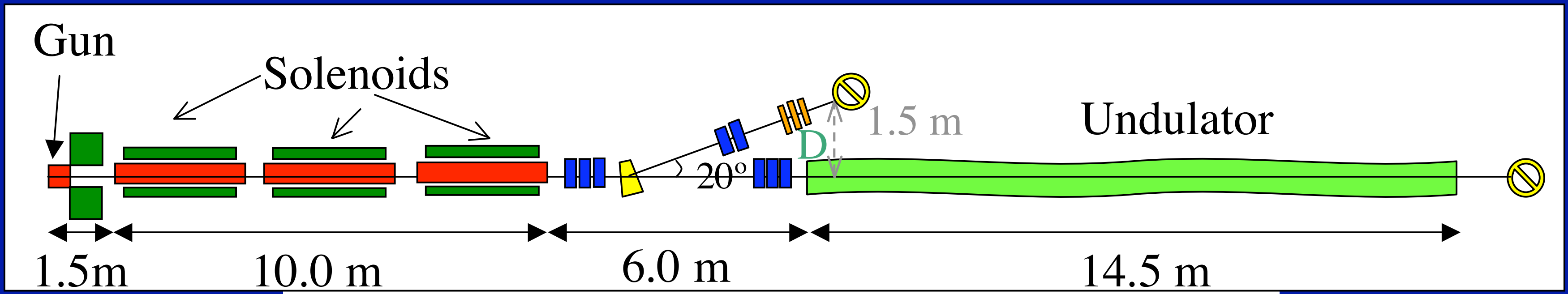


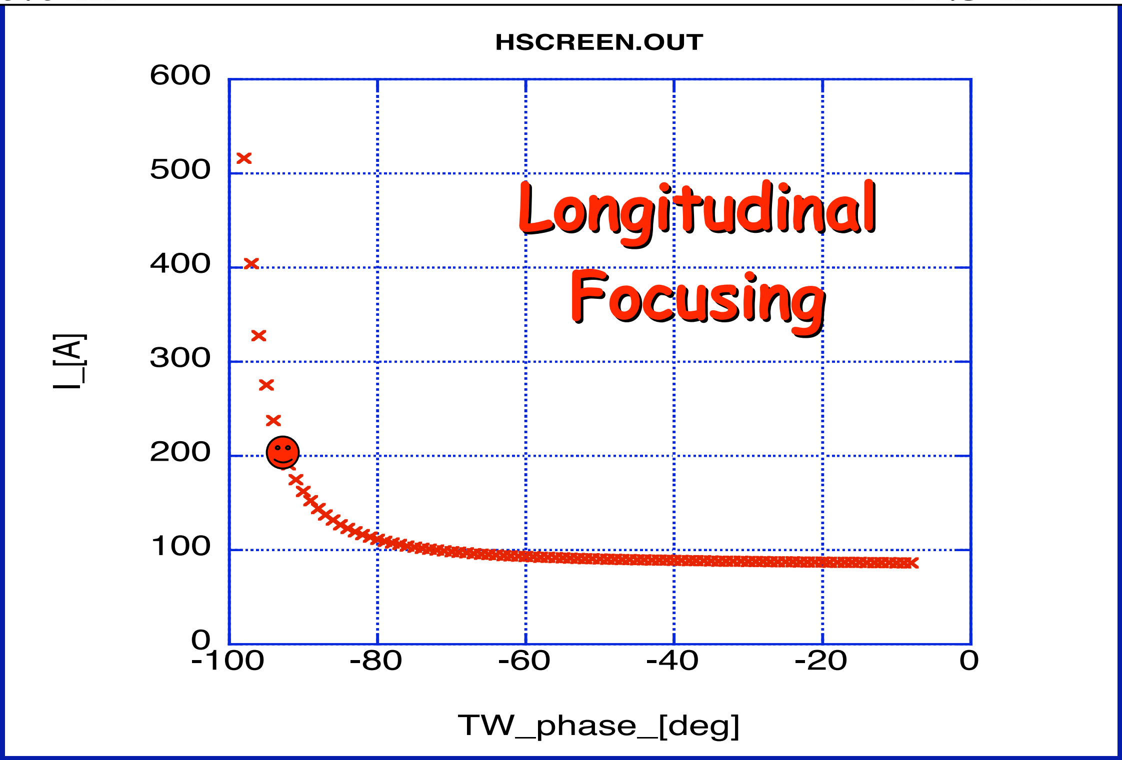
TESLA FEL

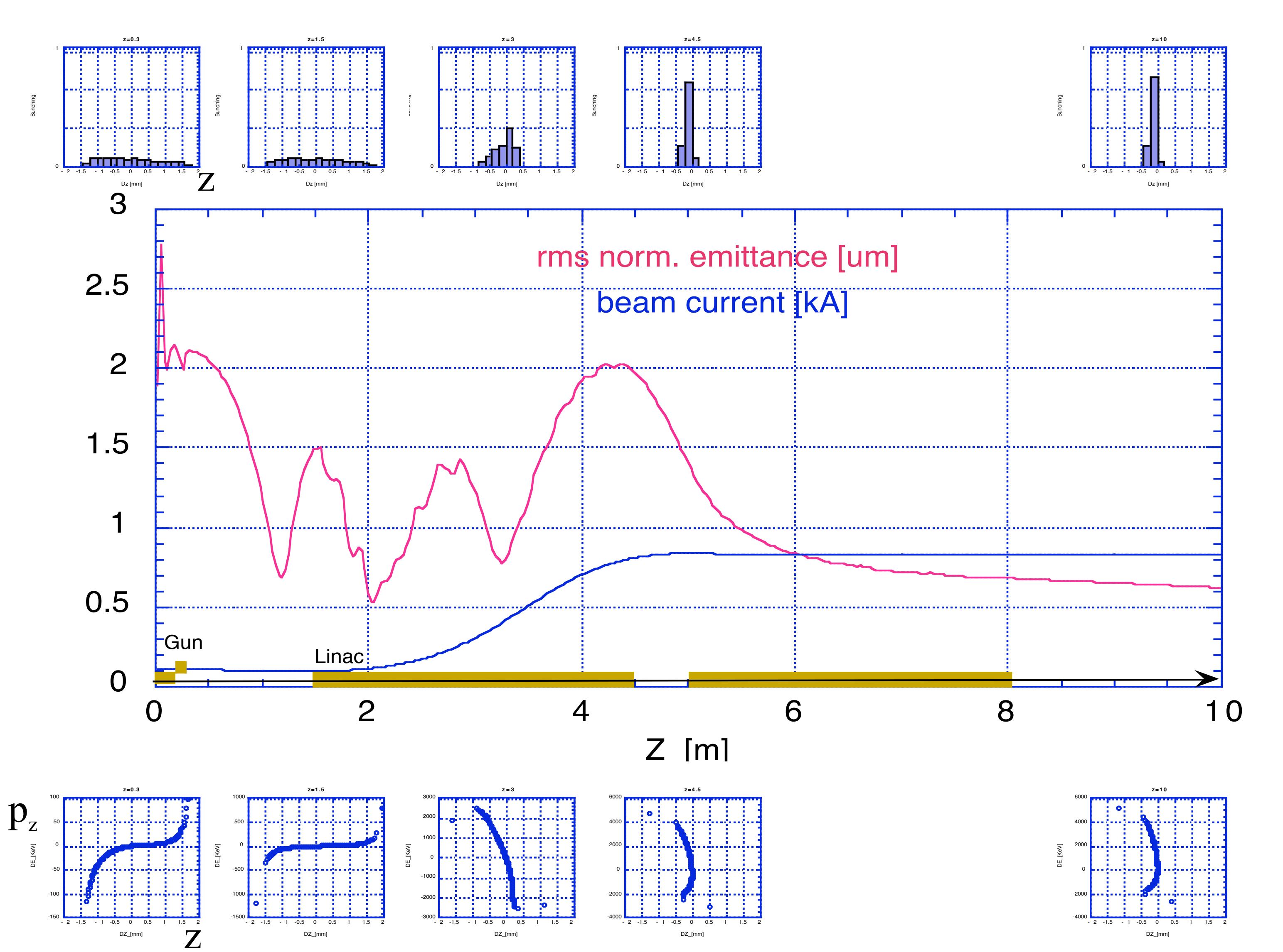
T. Limberg,
P. Piot, et al.

TraFiC^4
simulation

Velocity Bunching







z=0.3
z=1.5
z=3
z=4.5
z=10
Z
p_z
rms norm. emittance [um]
beam current [kA]
Gun
Linac
Z [m]
0
2
4
6
8
10
0.5
1
1.5
2.5
3

Magnetic and RF Compressors studies

Beam Conditioning

Seeding

Cascading

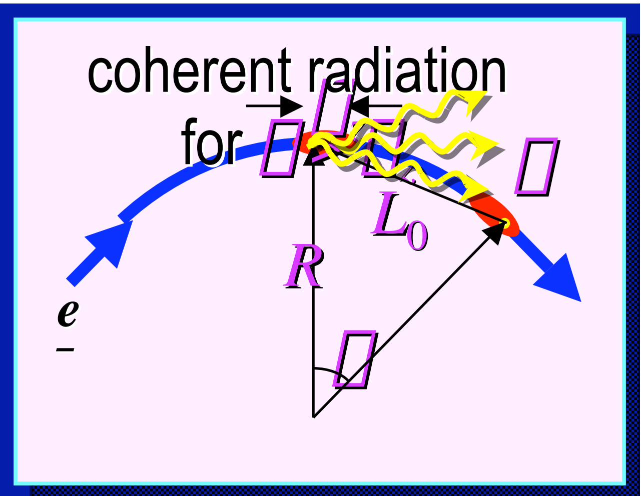
SPARC energy upgrade

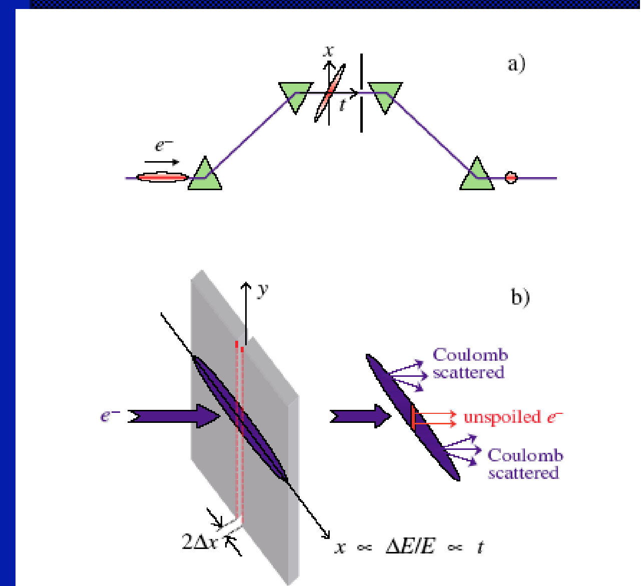
New Cathodes development

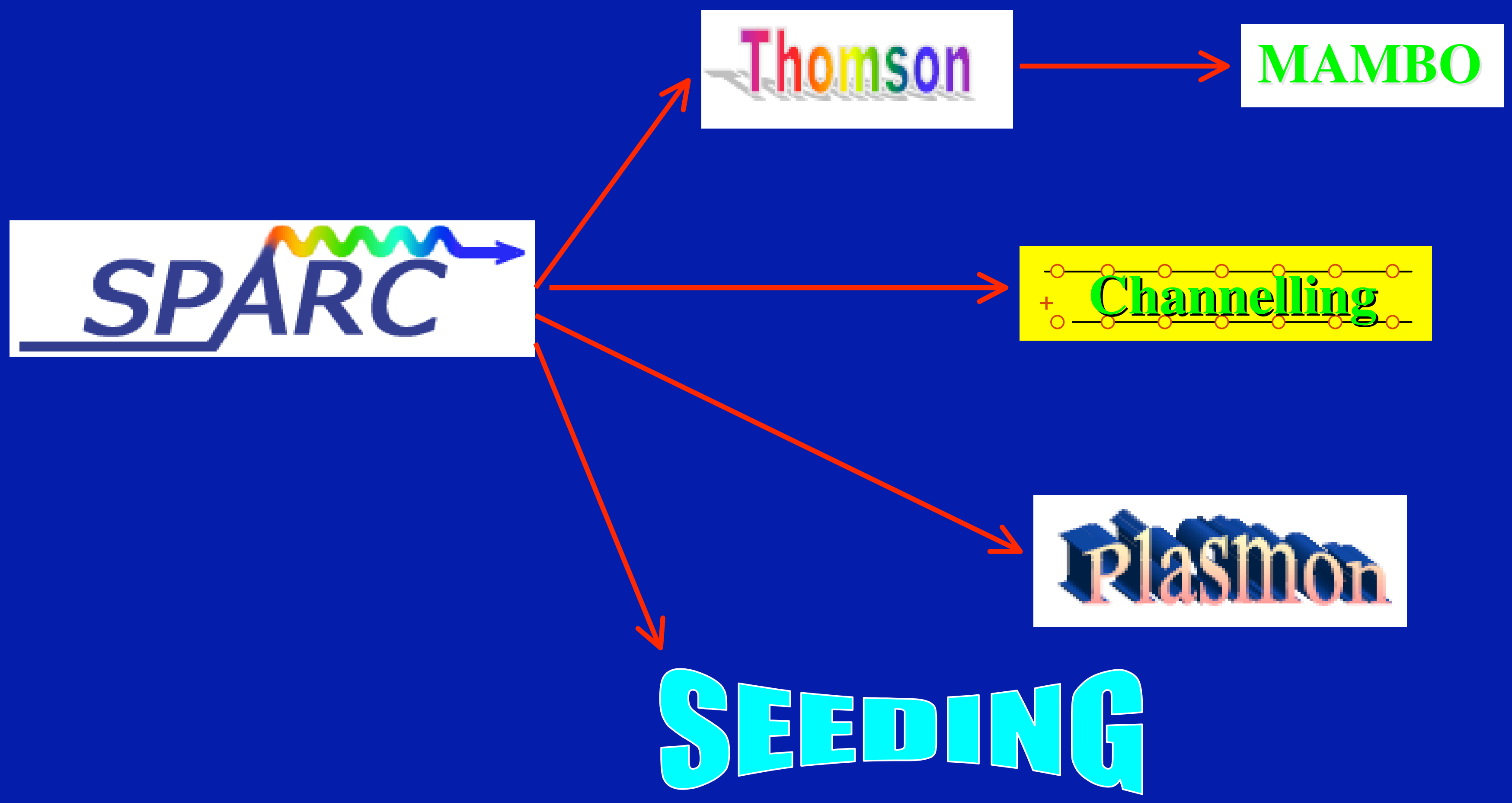
High repetition rate gun

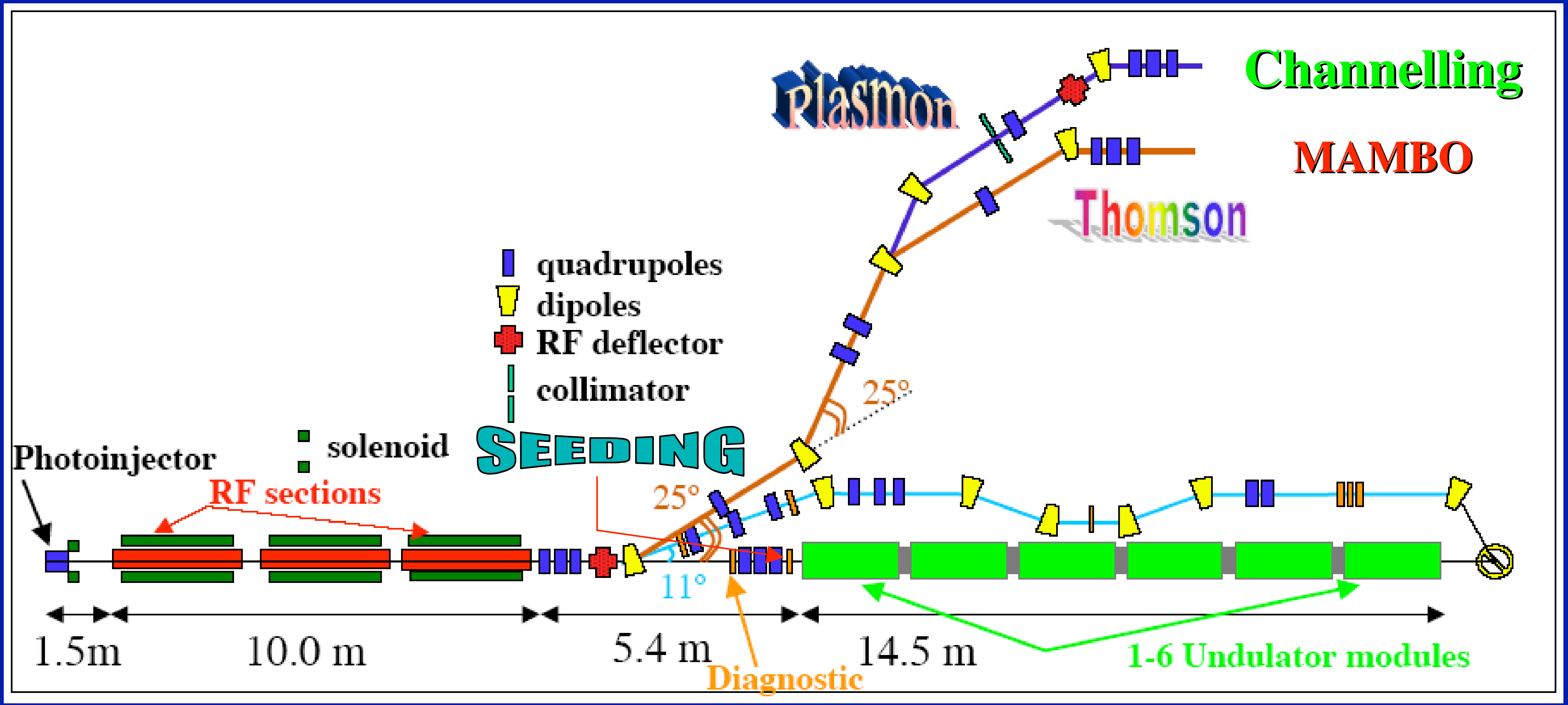
11 GHz accelerating structures

High resolution Diagnostic

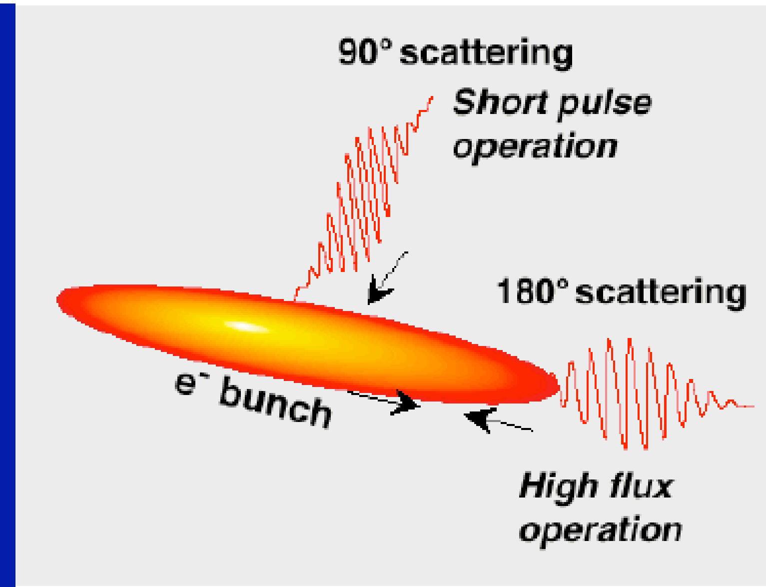





SPARC
Thomson
MAMBO
Channelling
Plasmon
SEEDING


Plasmon
Channelling
MAMBO
Thomson
quadrupoles
dipoles
RF deflector
collimator
25°
solenoid
SEEDING
Photoinjector
RF sections
25°
11°
1.5m
10.0 m
5.4 m
14.5 m
Diagnostic
1-6 Undulator modules

Thomson



$$E_x \approx 2\gamma^2 \nu_{las} (1-\cos\theta)$$

$$N_X \approx \sigma_T f \frac{N_{e^-} N_{h\nu}}{\sigma_{coll}^2} = 2 \cdot 10^{9/11}$$

- **Produzioni di impulsi X :**

  10^9 fotoni/s, durata 3 ps, monocromatici

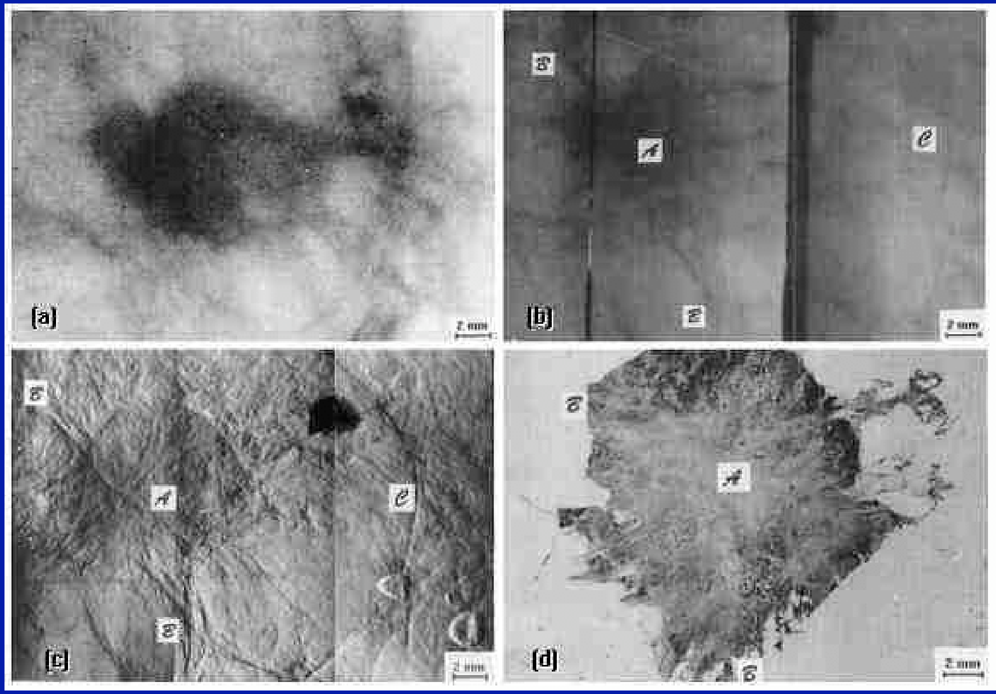
  tunabili nel range 20 keV - 1 MeV.

  Raggiungimento di 10^{11} fotoni/s con spot focali all'interazione di 5 μm.

- **Studi di tecniche di mammografia (e angiografia coronarica) con X monocromatici.**
- **Studi di single molecule protein cristallography.**

MaMBO Experiment:
Mammography Monochromatic Beam Outlook

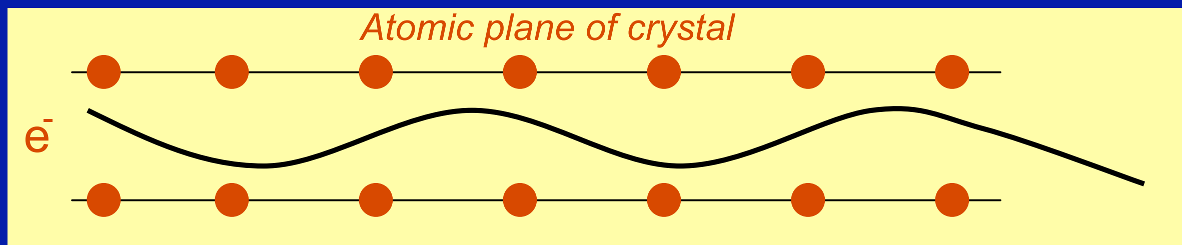
La realizzazione di una immagine (su superficie 18x24 cm^2) in tempi di 2600 s scende a 2.6 s con l'upgrade previsto su SPARC che porta il num. di fotoni a 2.5 10^{11} γ/s



The constrast (sensitivity to tissue density variations) goes from 8% to 0.1%, while the spatial resolution goes from 0,15 -0,3 mm to 0.01-0.015 mm. This means the capability to detect a tumor 30 times smaller in volume, i.e. a 2 year earlier detection of the tumor.

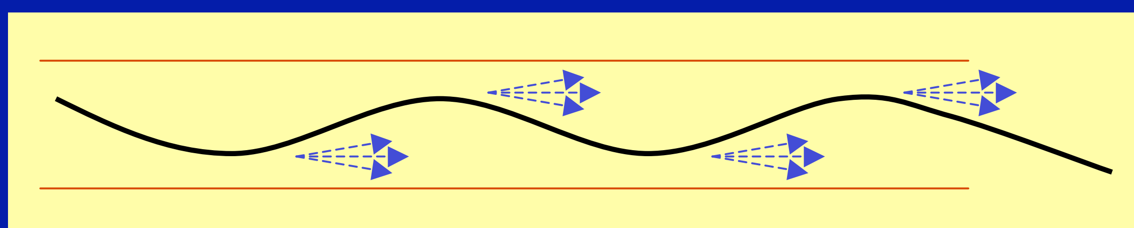
Channeling of Charged Particles and Channeling Radiation (S. Dabagov et al.)

@ Channeling:



$\theta << 1 \qquad (\theta < \theta_L \sim \sqrt{U/E})$ - *the Lindhard angle is the critical angle for the channeling*

@ Channeling Radiation:



Powerful radiation source of X-rays and γ-rays:

- polarized
- tunable
- narrow forwarded

@ Channeling Radiation:

$$\omega_{lab}^{ChR} \approx \frac{2\gamma^2}{1+\gamma^2\theta^2}\,\omega_0^{ChR}$$

- radiation frequency

$$\frac{dN_{ph}}{dt} \propto \gamma^{1/2}$$

- number of photons per unit of time

$$P \propto \gamma^2$$

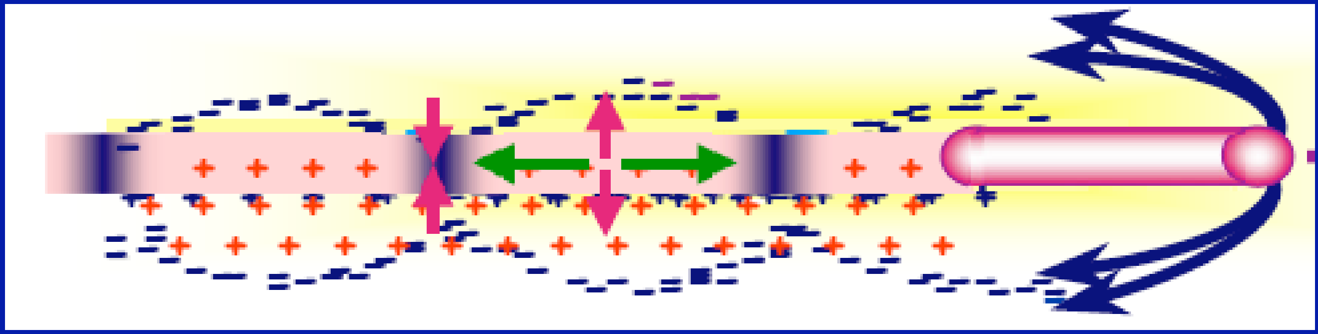
- radiation power

For X-ray frequencies:

100 MeV electrons channeled in 105 μm Si (110) emit ~ 10-3 ph/e-

corresponding to a Photon Flux ~ 10^8 ph/sec

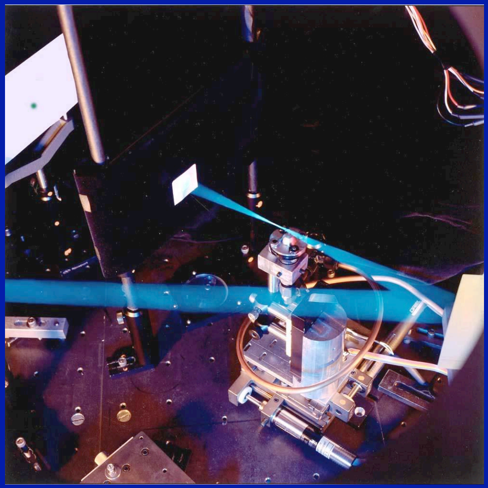
Plasmon



Accelerazione a plasma di pacchetti di elettroni (**25 pC**) da **100 MeV a 130 MeV** con spread energetico < 5%, emitt. < 1 μm, con laser non guidato (5 mm acc. length).

Accelerazione con laser guidato (**5 cm**) fino a 400 MeV, **gradienti > 5 GV/m**.

$$\sigma_n \approx \sqrt{\frac{\delta n_p}{n_p}\frac{\lambda_p}{2\pi}}$$

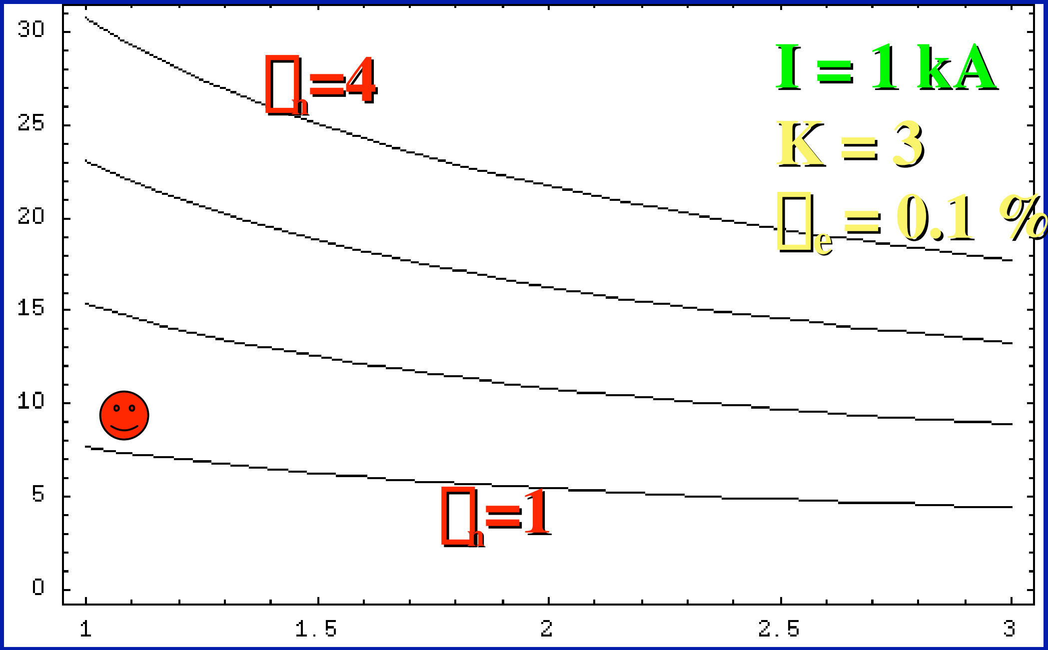


$$\lambda_p \approx 50\ \mu m$$
$$\sigma_p \approx 30 - 100\ \mu m$$

The SPARXINO Opportunity

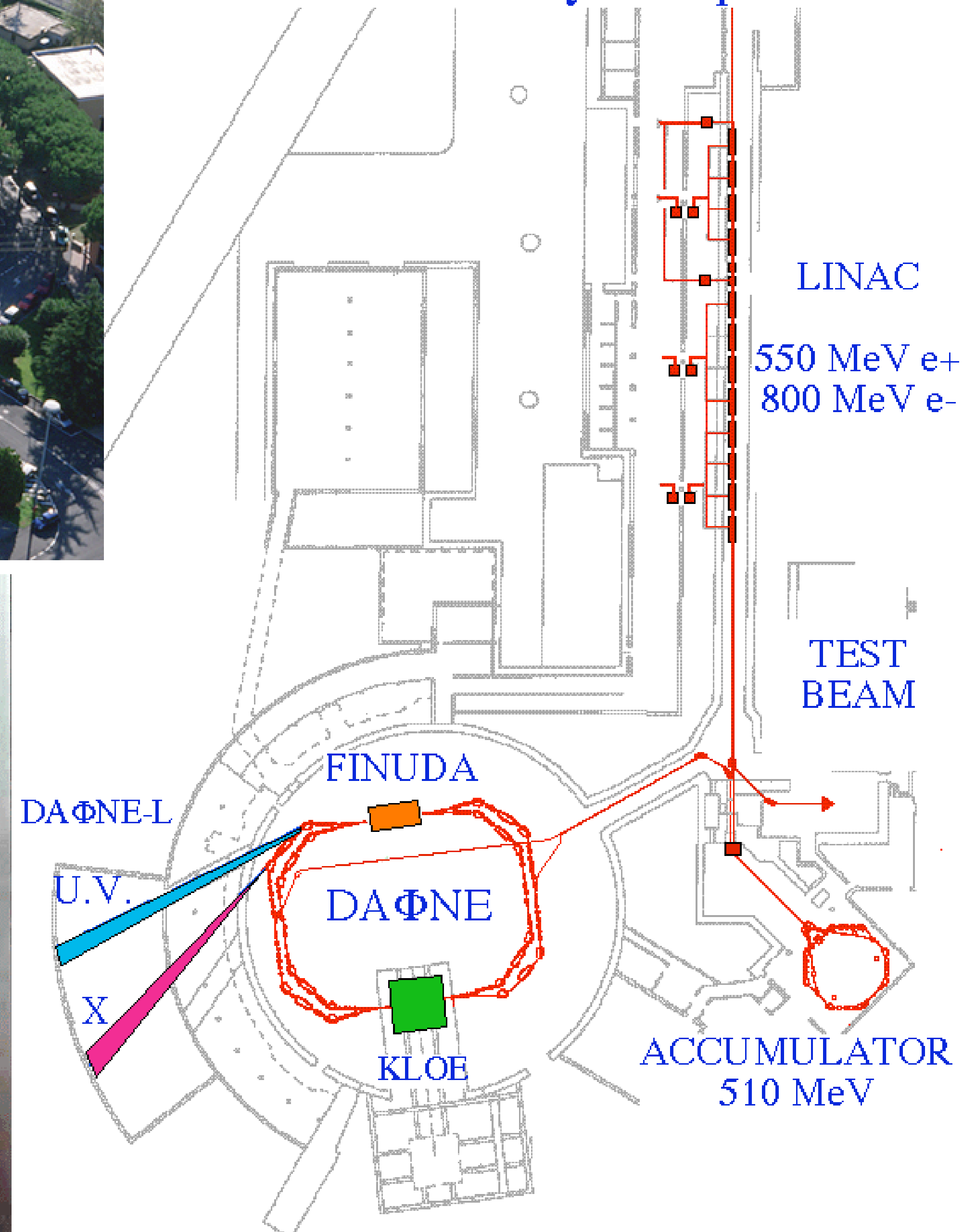
1 GeV

□cr [nm]

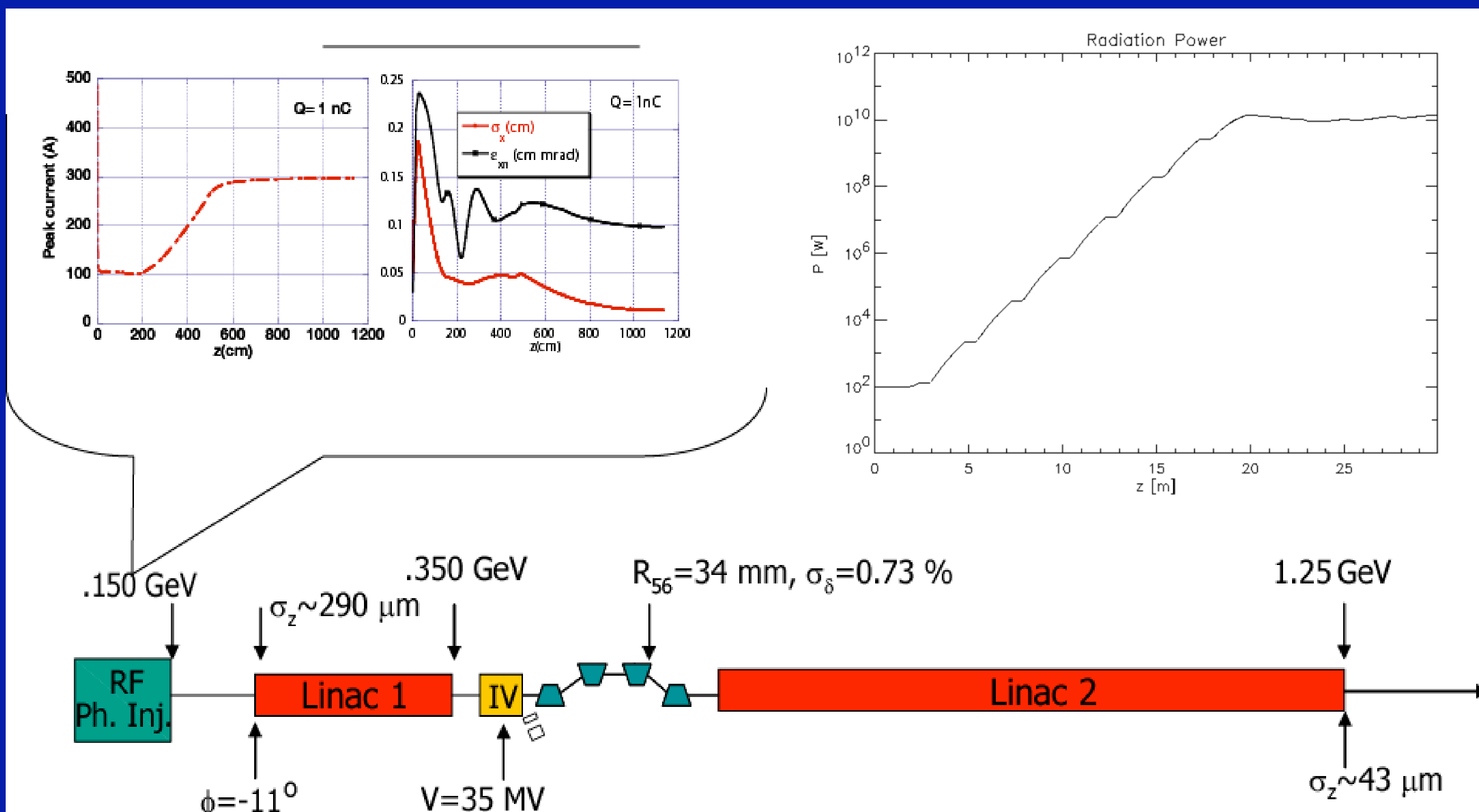


Energy [GeV]

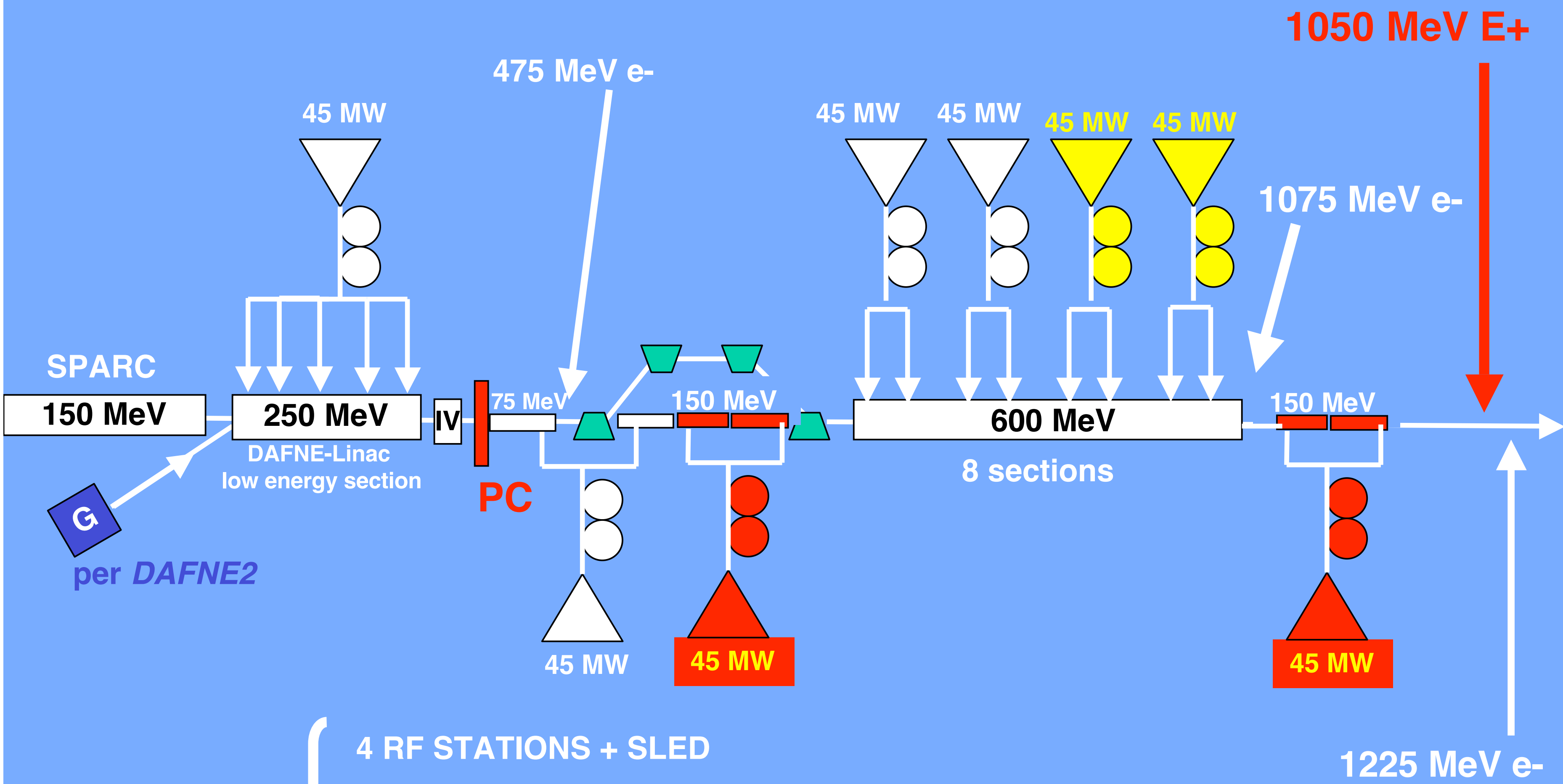
Frascati Φ–Factory complex



SPARC Injector + DA□NE Linac
SPARXINO
a 10 nm SASE FEL source at LNF



DAFNE-LINAC → SPARX*INO* + DAFNE2



NEW COMPONENTS

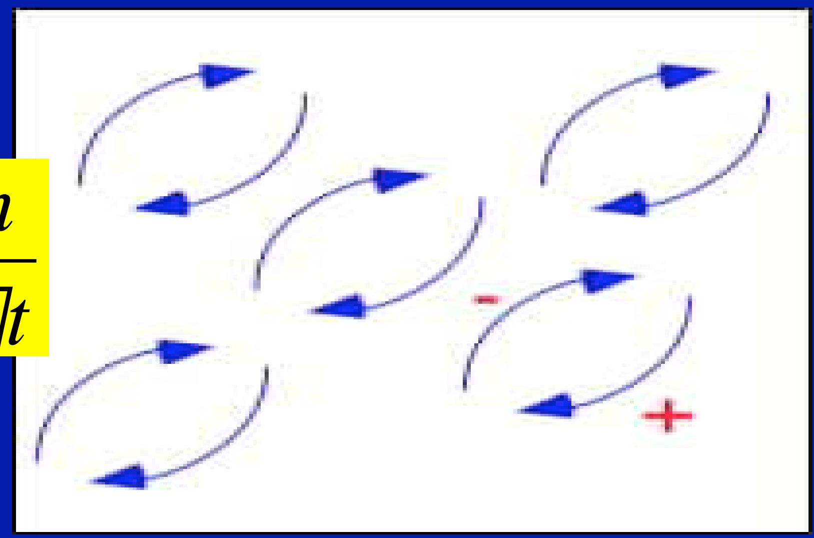
- 4 RF STATIONS + SLED
- MAGN. COMPRESSOR
- 4 ACC. SECT. + IV ARM CAV
- SPARC

The SPARXINO Physics

(Some example suggested by INFN people)

QED test: Vacuum Magnetic Birefringence

$$\Delta E \approx \frac{h}{\Delta t}$$



Classical Vacuum **Quantum Vacuum**

Thursday, 13 May 2004 - h. 15:00 Auditorium B. Touschek

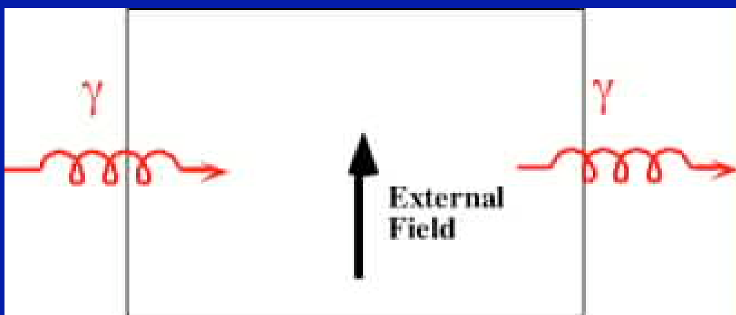
G. Cantatore
(INFN -Trieste)

Experimental study of the "vacuum element" with PVLAS

G. Cantatore, R. Cimino, D. Babusci

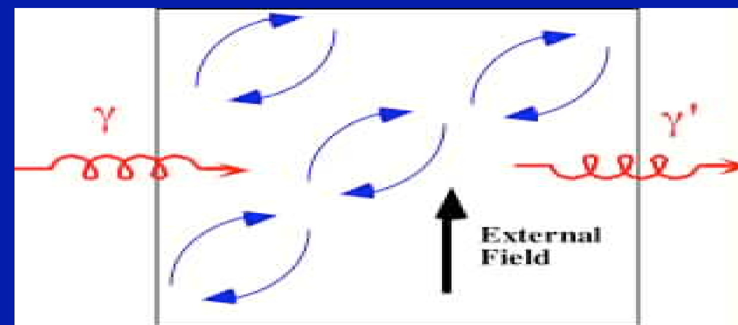
QED test: Vacuum Magnetic Birefringence

Classical Vacuum



Perturbing field and probe light do not "mix" and the exiting probe photons are unchanged

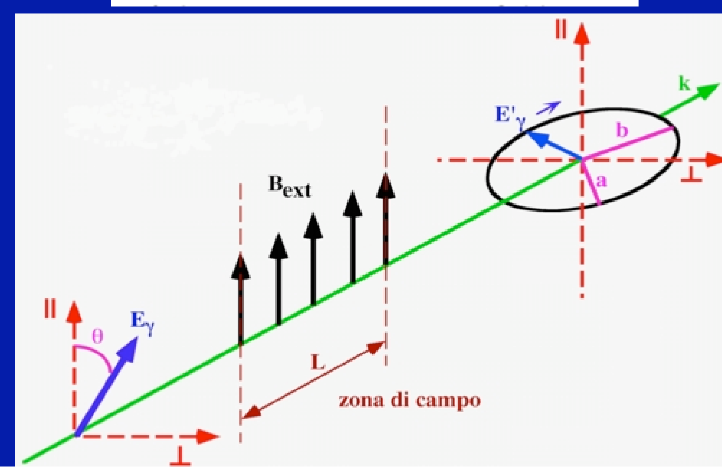
Quantum Vacuum



The perturbing field "changes" the structure of the quantum vacuum: probe light and field now "mix" and exiting photon carry information on the structure of the vacuum.

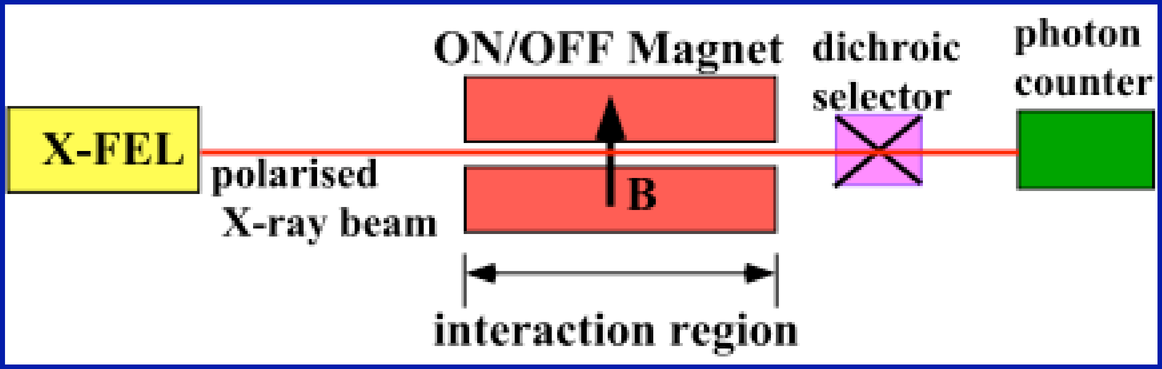
$$\Delta n = n_{||} - n_{\perp} \simeq 4 \times 10^{-32} \left(\frac{B_0}{1\ \mathrm{G}}\right)^2$$

The properties of the QUANTUM VACUUM are recorded in the polarisation state of the probe light, which has changed from linear to elliptical. This phenomenon is also called Vacuum Magnetic Birefringence



QED test: Vacuum Magnetic Birefringence

- **Measurement schematic**

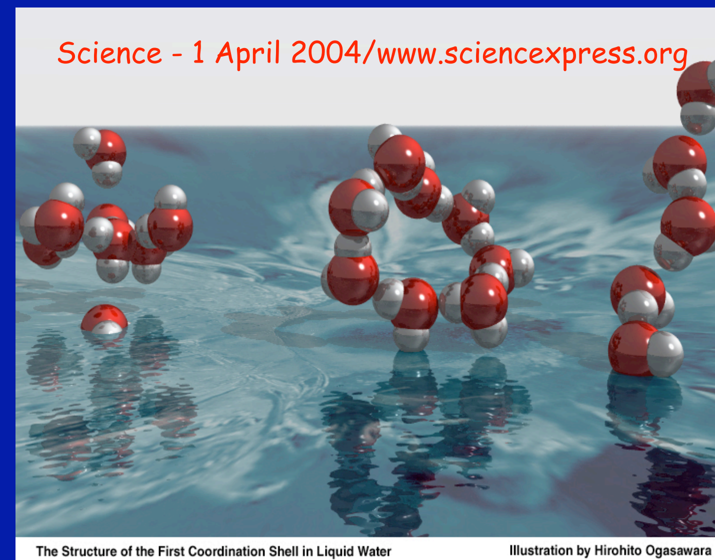


- **Relevant requirements**
  - high magnetic field strength
  - long optical path in the magnetic region
  - high photon energy/high photon flux
  - low background/high signal to noise ratio

$$Q = \frac{P}{\lambda}$$

Resonant X-ray Raman Scattering

To investigate structure and molecular bonding in gas, liquids and solids

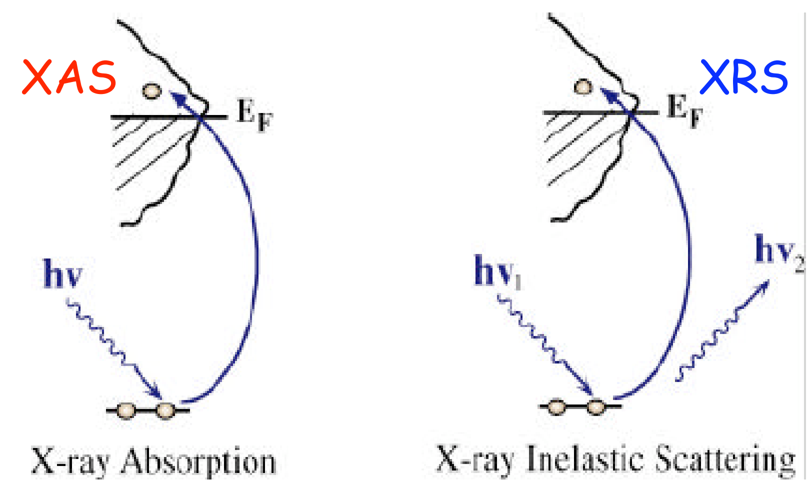


The radiative inelastic scattering is a 2 step process
It is a very weak process compared to the intense x-ray coherent scattering phenomena.

FEL's machine are necessary because XRS demands:

- **monochromatic source**
- **extremely bright source**
- **well collimated source**
- **polarization (linear/circular) control (if possible)**

Energy
for molecule studies: C (290 eV ~43 Å) and O (540 eV ~23 Å) K edge
for liquids & solids: <1 KeV (~12.5 Å)
(e.g., L edge TM elements - N edge RE elements)



A. Marcelli

Neutron Beam Source - Nuclear Physics

- ***(Pulsed)Neutron beam– by photoproduction***
- ***Possibility to obtained a pulsed neutron beam – well defined time-structure (to be desired: electron energies ~ 2.5 GeV, even if 1 GeV beam ~ OK…)***
- ***Problem: duty cycle?***
- ***Interests:***
- ***TOF method to measure cross sections***
- ***Fundamental physics with neutrons (Electric Dipole Moment; charge independence of strong force…);***
- ***Research studies on neutron therapy***
- ***Astrophysics studies (exotic nuclei)***

- ***Electron scattering measurements***

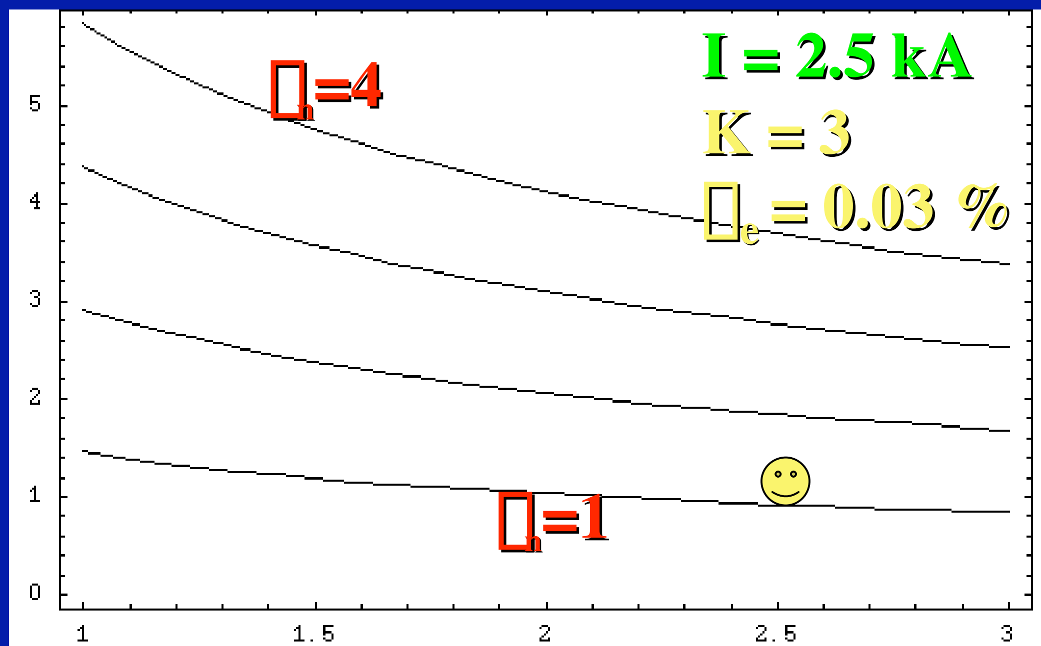
Search of T-invariance in electromagnetic interactions

Measurement of two-photon exchange contributions

S. Bartalucci, C. Petrascu, A. Fantoni

The SPARX Future?

2.5 GeV



□cr [nm]

Energy [GeV]

SEEDING

SPARC → Channelling

Thomson → MAMBO

SPARX-I => Test Facility (SPARXINO) => SPARX-II

R&D X-FEL — 10 nm — 2 nm

2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012

SASE | Seeding | Angstrom

TTF-II
6 nm

LCLS
0.1 nm

TESLA
X-FEL
0.1 nm

FERMI
40 nm ==> 10 nm ==> ?