A Free Electron Laser Project at LNF

Massimo Ferrario
INFN - LNF
& the SPARC/X Team

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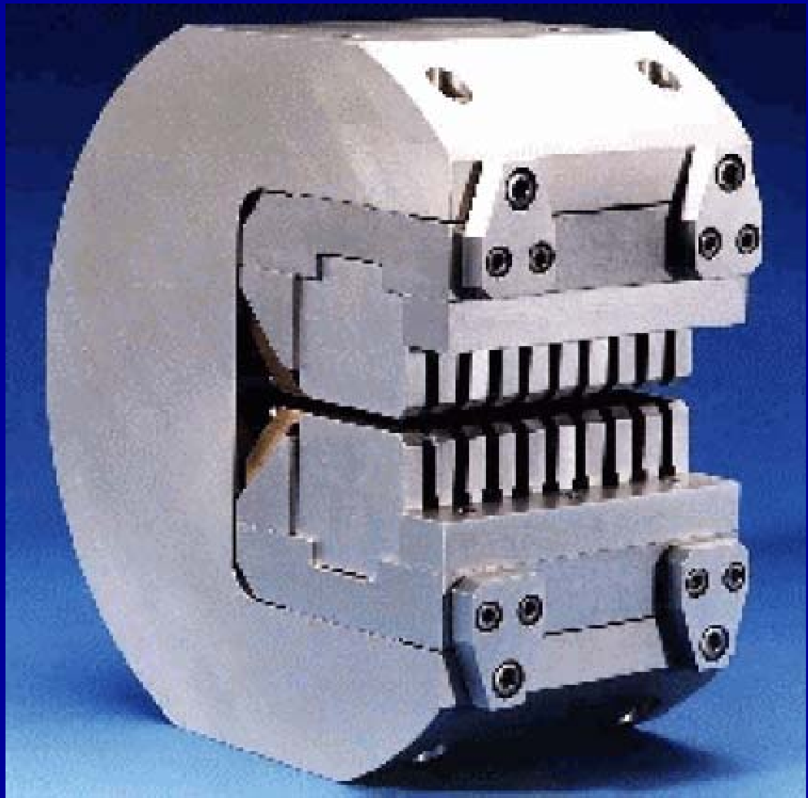
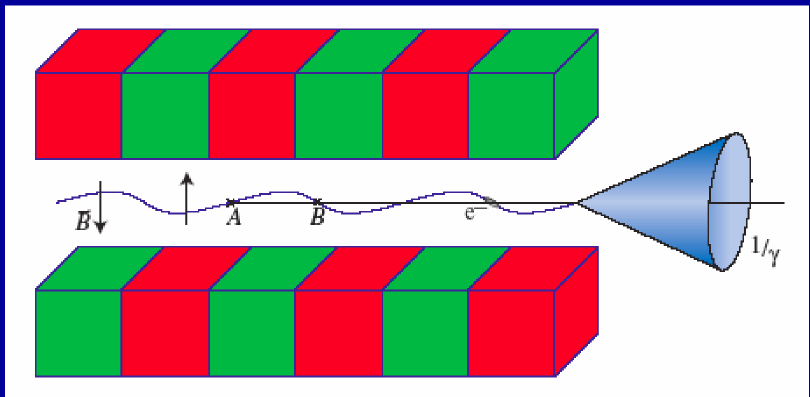
Free Electron Laser

SPARC - SPARXINO - SPARX

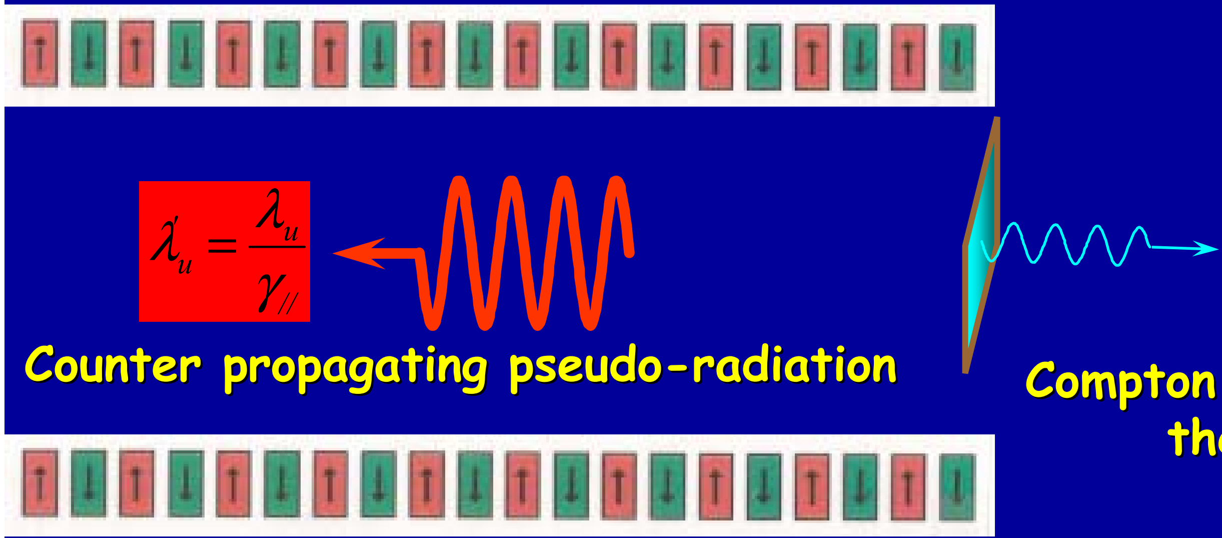
Undulator Radiation





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

Relativistic Mirrors



$$\lambda'_u = \frac{\lambda_u}{\gamma_{//}}$$

Counter propagating pseudo-radiation

$$\lambda'_{rad} = \lambda'_u$$

Compton back-scattered radiation in the moving mirror frame

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

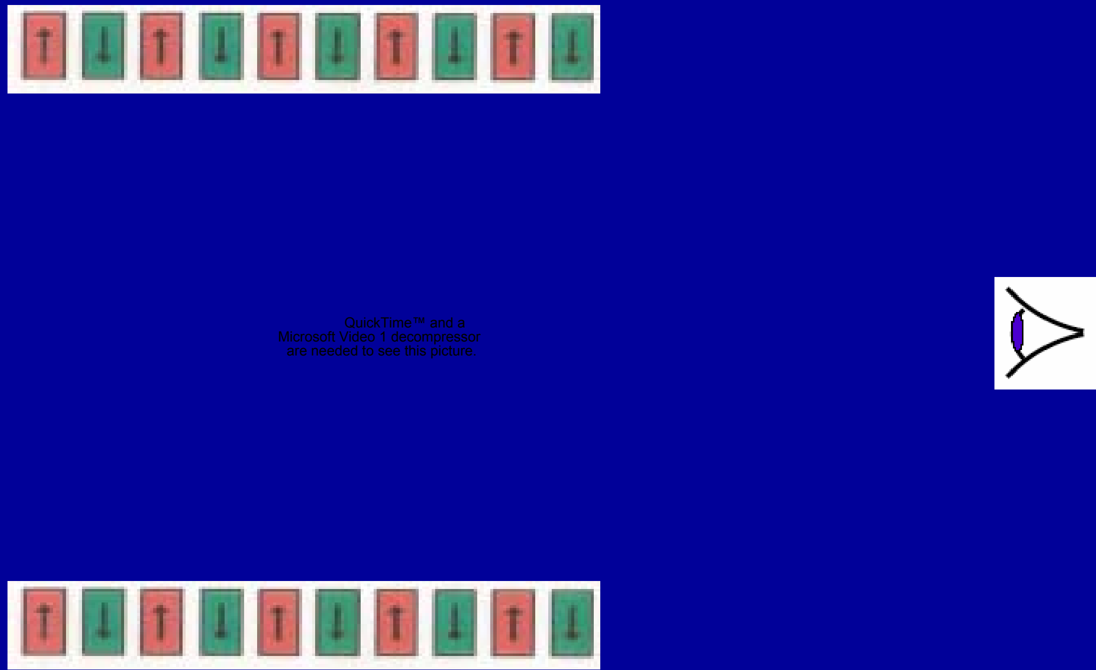
$$\lambda_{rad} \approx \frac{\lambda_u}{2\gamma_{//}^2}$$

Doppler effect in the laboratory frame

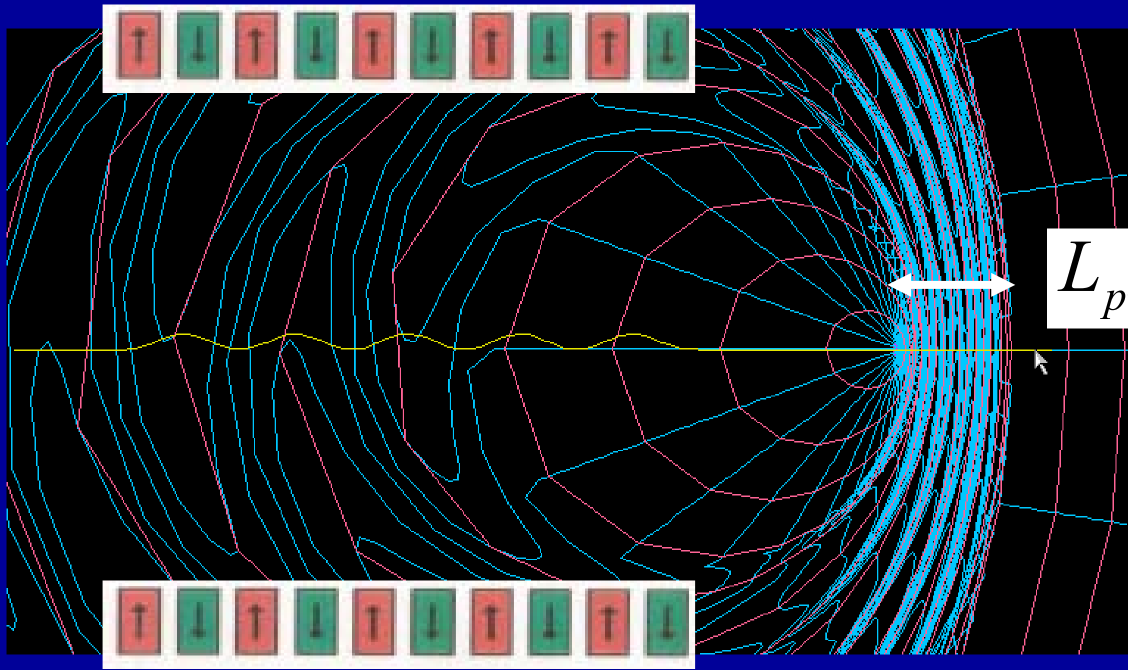
$$\frac{1}{\gamma_{//}^2} = \frac{1}{\gamma^2} + \beta_\perp^2$$

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

TUNABILITY

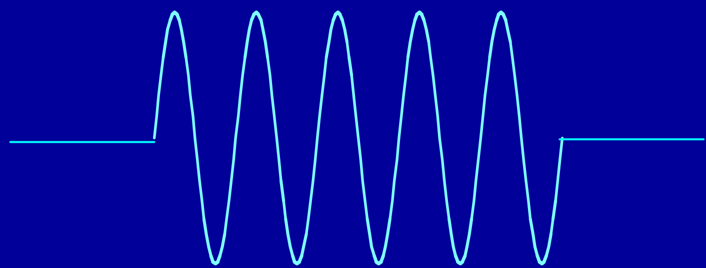


Radiation Simulator – T. Shintake, @ http://www-xfel.spring8.or.jp/Index.htm

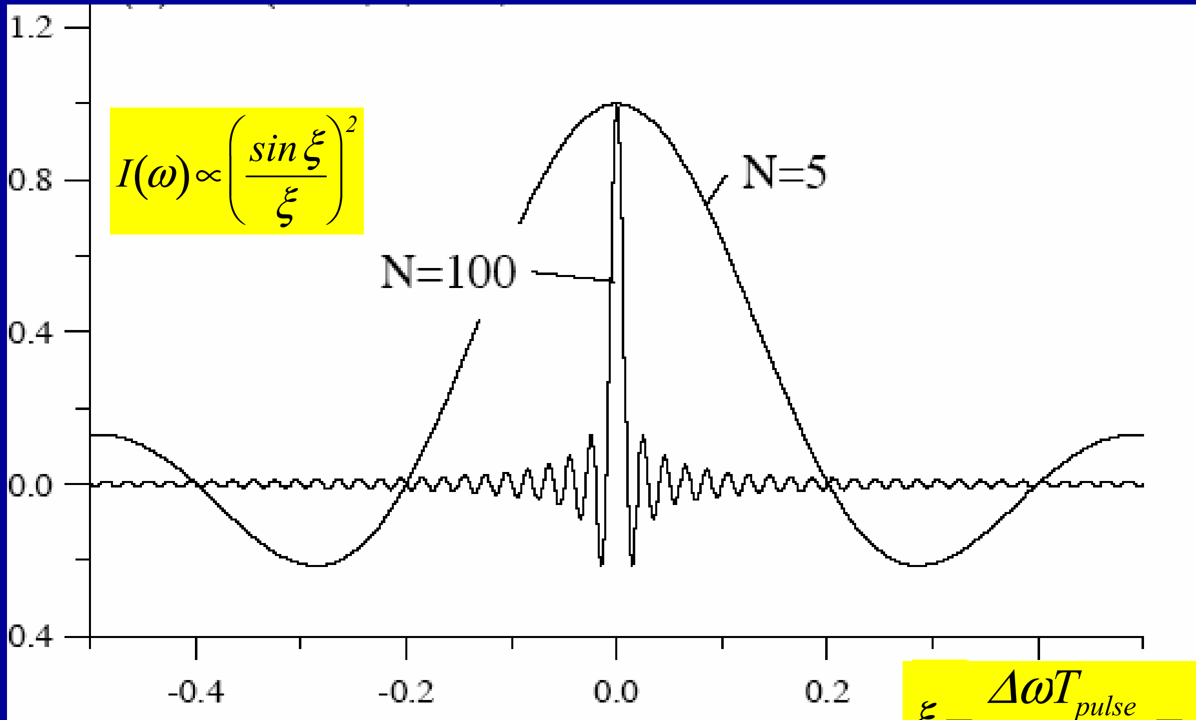


$$L_{pulse} = N_u \lambda_{rad}$$

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



$$I(\omega) \propto \left(\frac{\sin\xi}{\xi}\right)^2$$

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

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

Line width

Peak power of accelerated charge:

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

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

Incoherent Spontaneous Radiation Power:

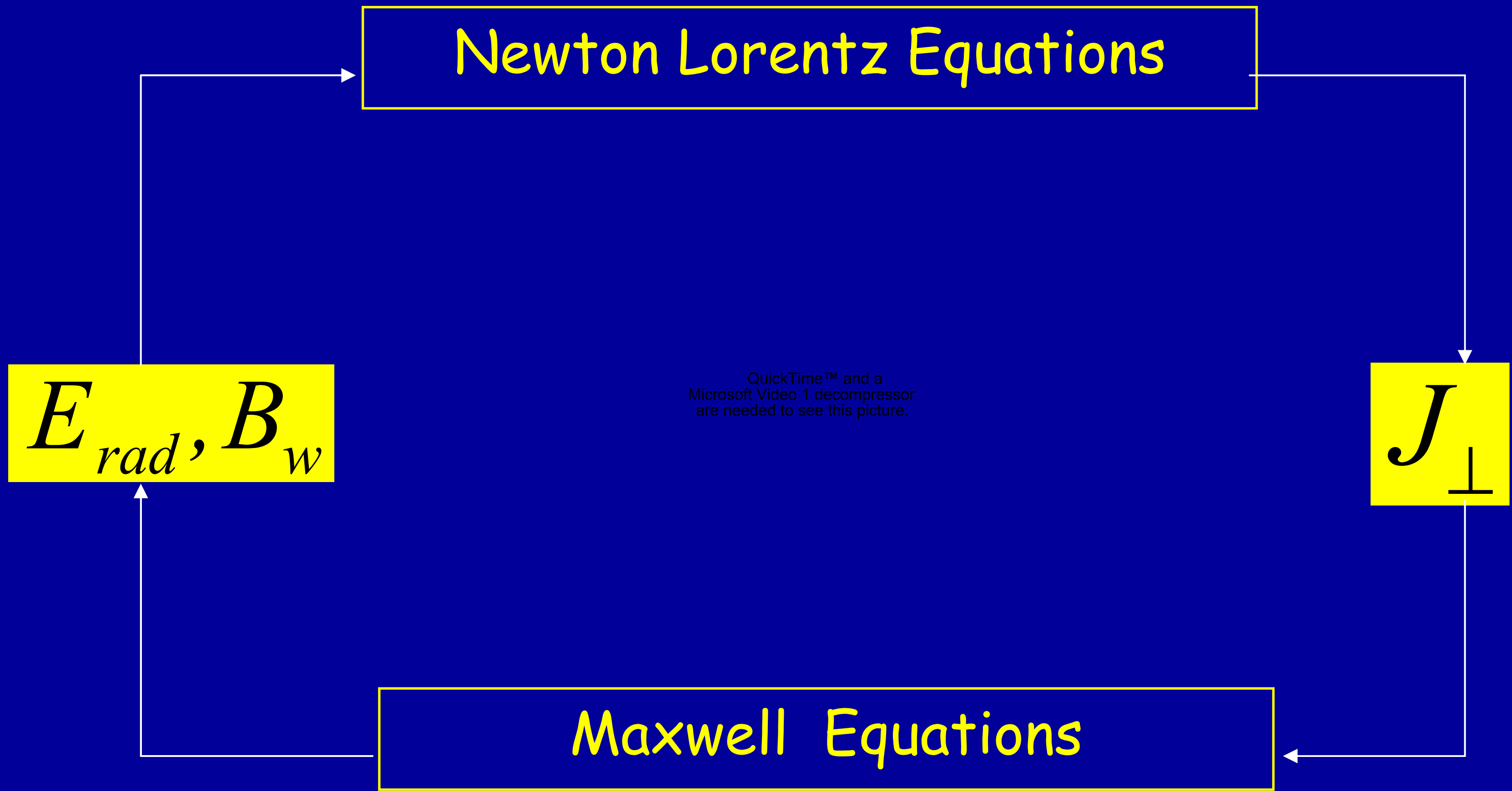
$$P_T = N_e \frac{e^2}{6\pi\varepsilon_o c^3}\gamma^4 \dot{v}_{\perp}^2$$

Coherent Stimulated Radiation Power:

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

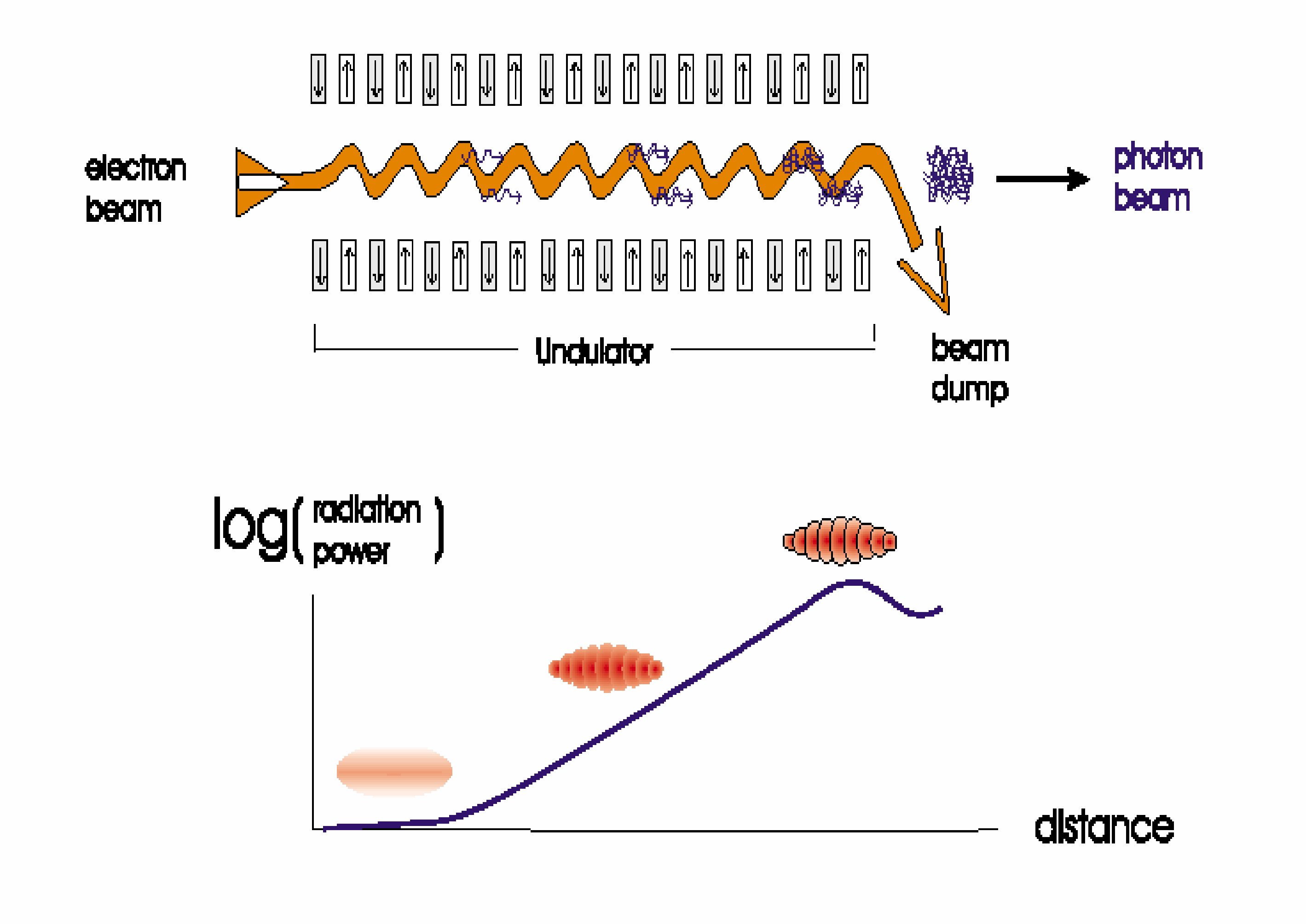
WE NEED micro-BUNCHING !

Can there be a continuous energy transfer from electron beam to light wave? 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.



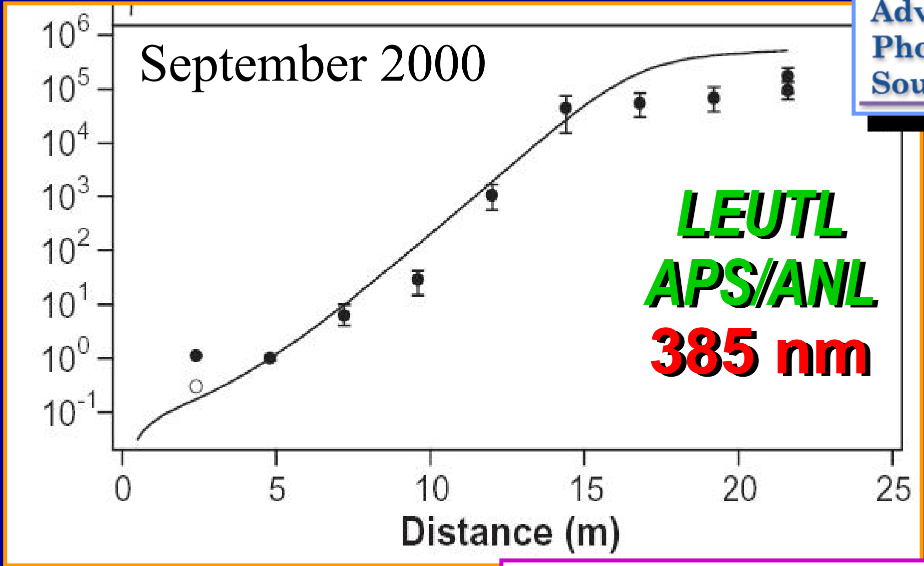
The particles within a micro-bunch radiate coherently. The resulting strong radiationfield enhances the micro-bunching even further. Result: collective instability, exponential growth of radiation power.

Free Electron Laser
Self-Amplified-Spontaneous-Emission
(No Mirrors)



SASE Saturation Results

Advanced Photon Source

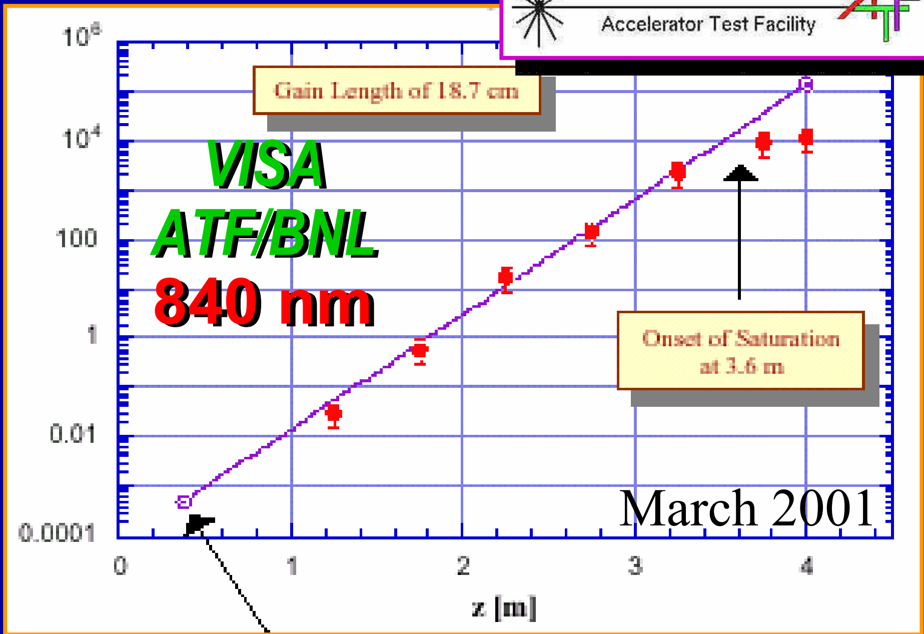


$$P(z) = \frac{P_0}{9} \exp\left(\frac{z}{L_G} \right)$$

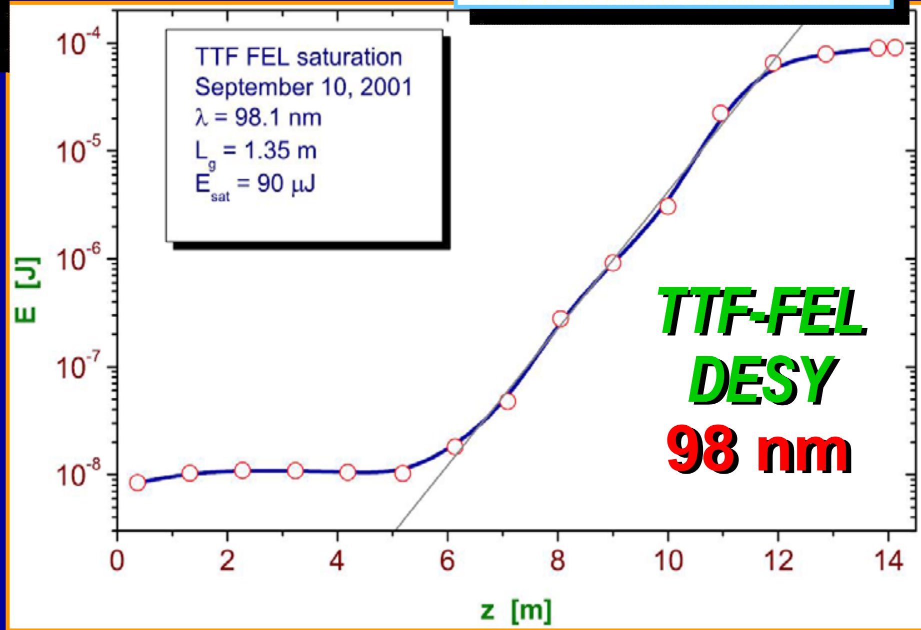
Since September 2000:

3 SASE FEL's demonstrate saturation

Brookhaven National Laboratory
Accelerator Test Facility

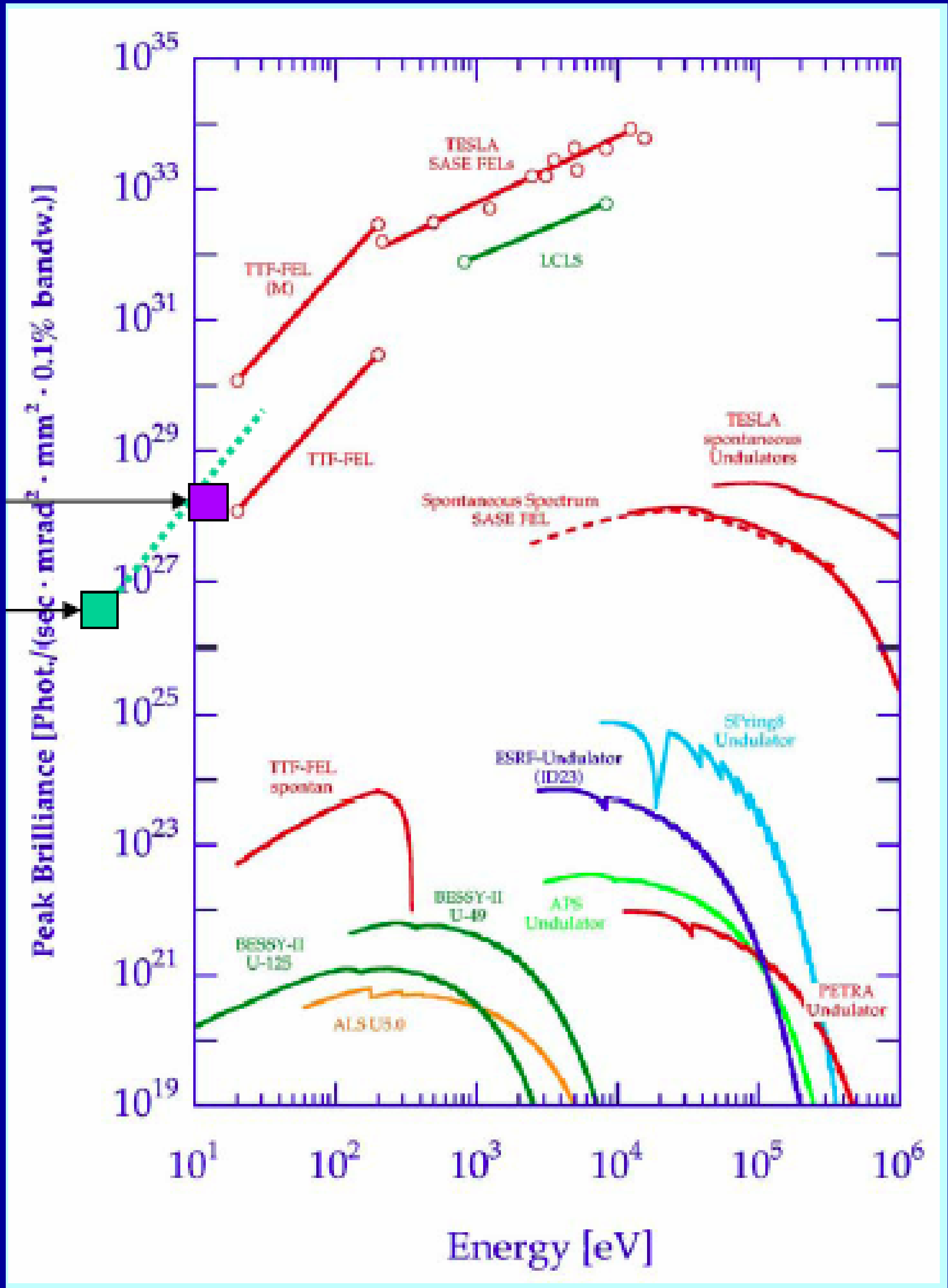


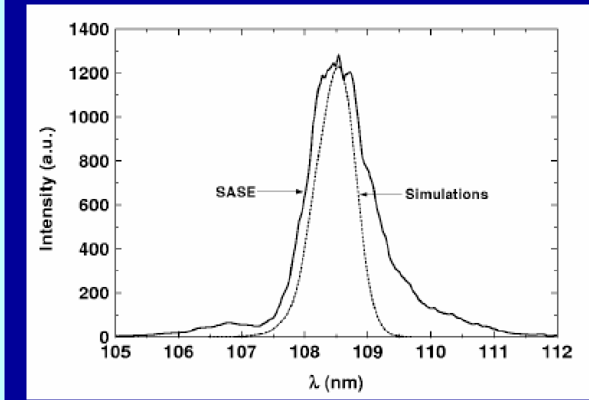
TESLA FEL



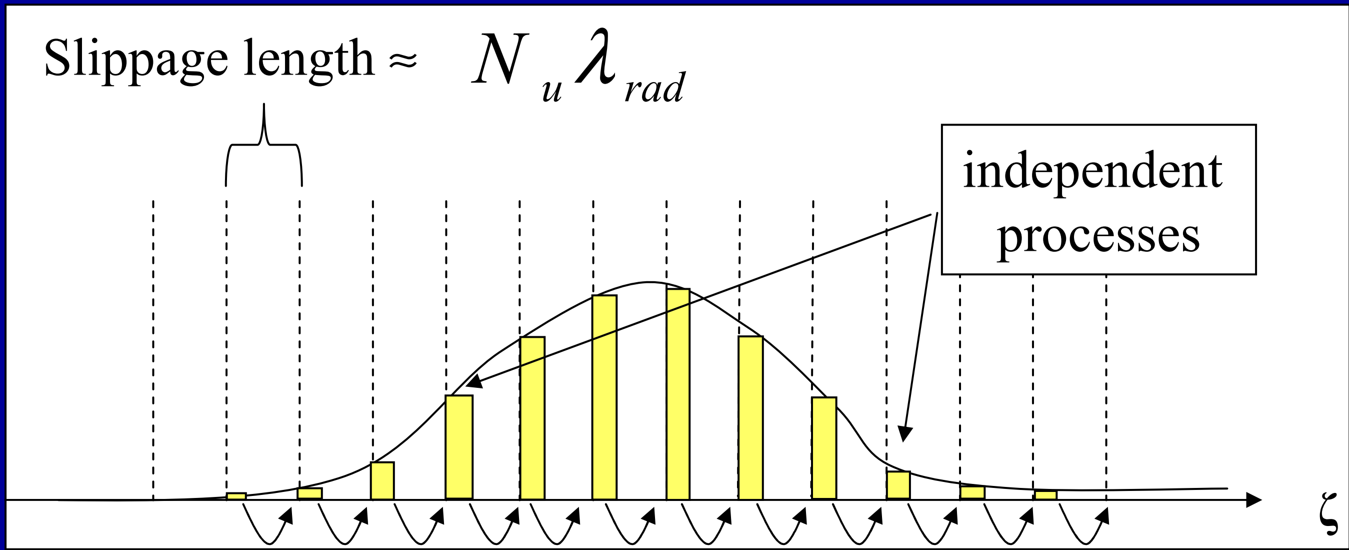
TTF FEL

LEUTLE





SASE Longitudinal coherence



The radiation "slips" over the electrons for a distance $N_u\lambda_{rad}$

SASE

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are needed to see this picture.

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

SEEDING

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FEL Electron Beam Requirements:
High Brightness B_n => High Peak Current & Low Emittance

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

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

SPARC - SPARXINO - SPARX

SPARC Project 7.5 +2.5 M€ (MIUR+INFN)

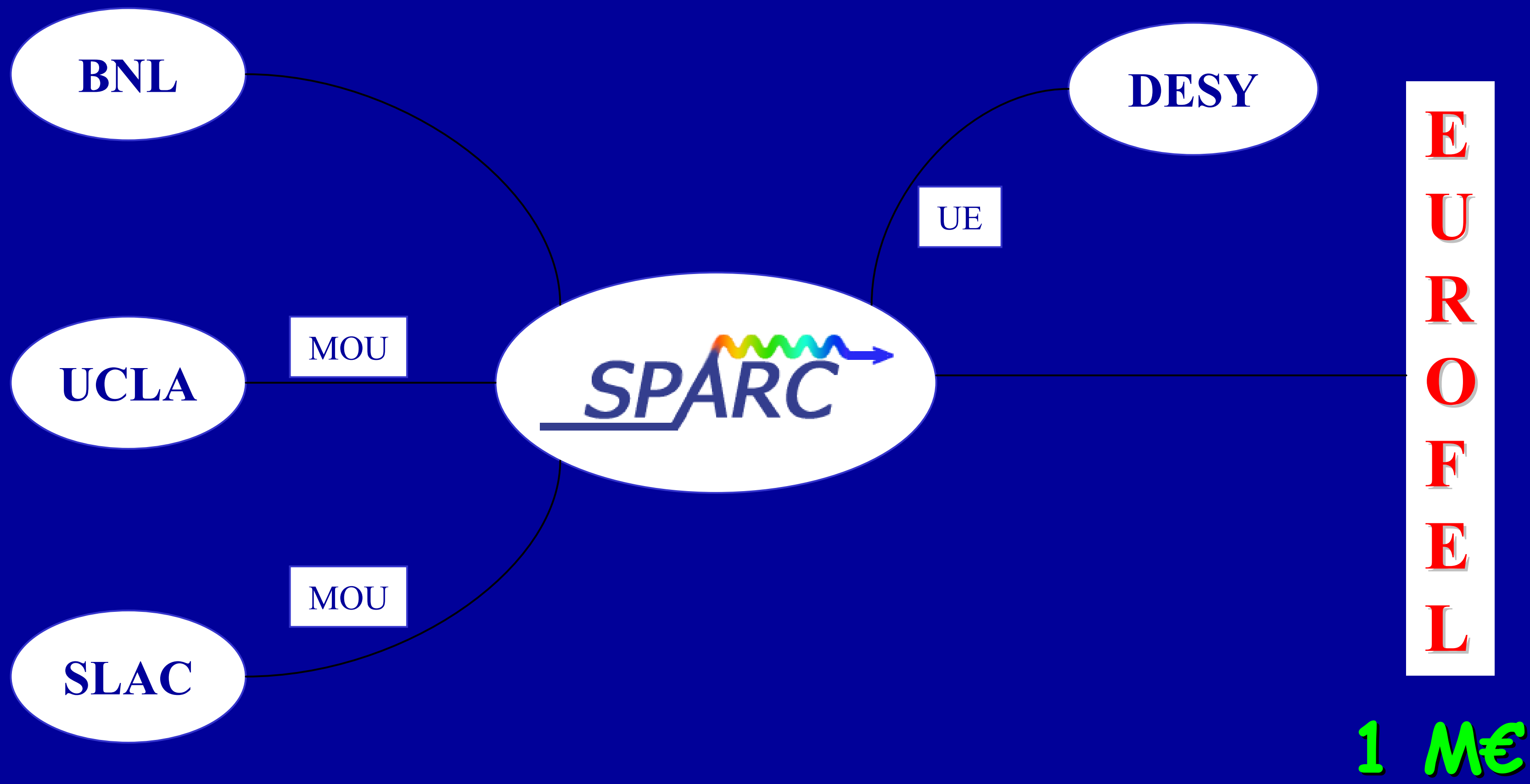
R&D program towards high brightness e⁻beam for SASE-FEL's

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

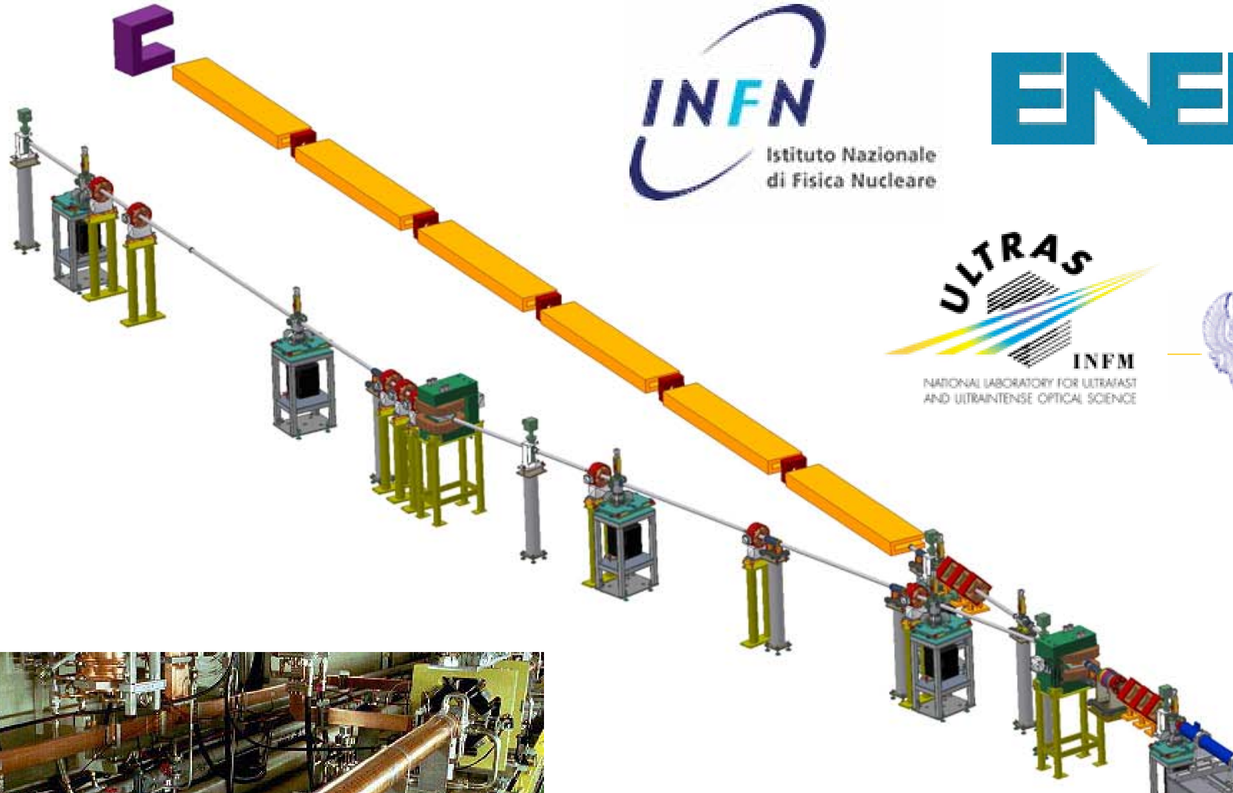
- R&D towards an X-ray FEL-SASE source
- Test Facility at 10 nm with the Daφne Linac (SPARXINO)

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

ENEA

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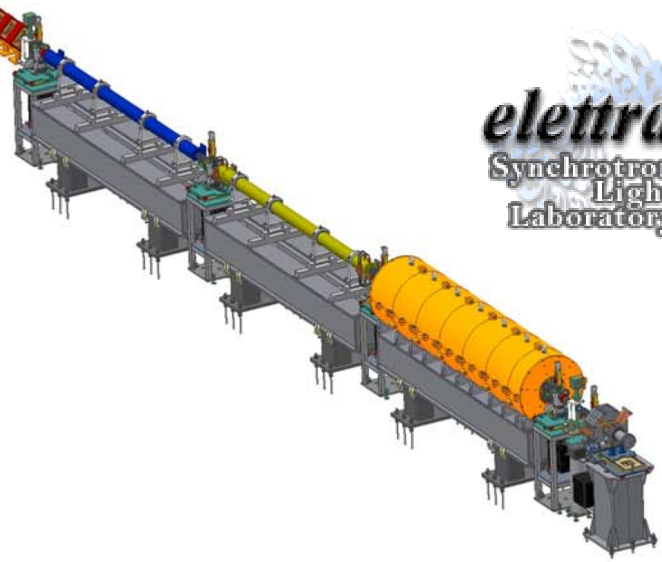
ULTRAS
INFM
NATIONAL LABORATORY FOR ULTRAFAST
AND ULTRAINTENSE OPTICAL SCIENCE

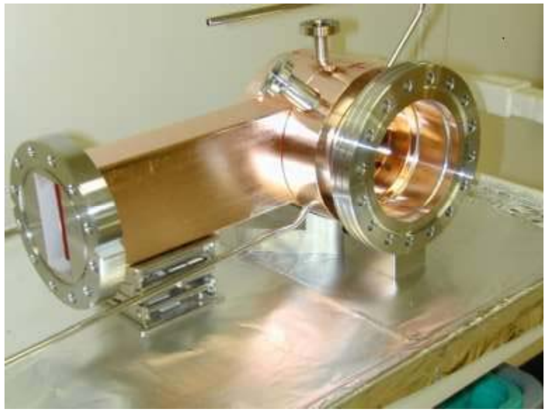
La Sapienza
Università degli Studi di Roma

Stanford
Linear
Accelerator
Center

UCLA

elettra
Synchrotron
Light
Laboratory





How to increase e⁻ Brightness

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

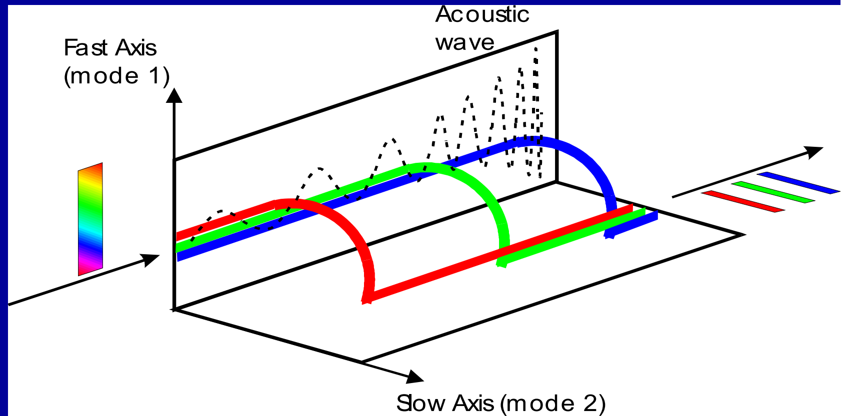
bunch compressors

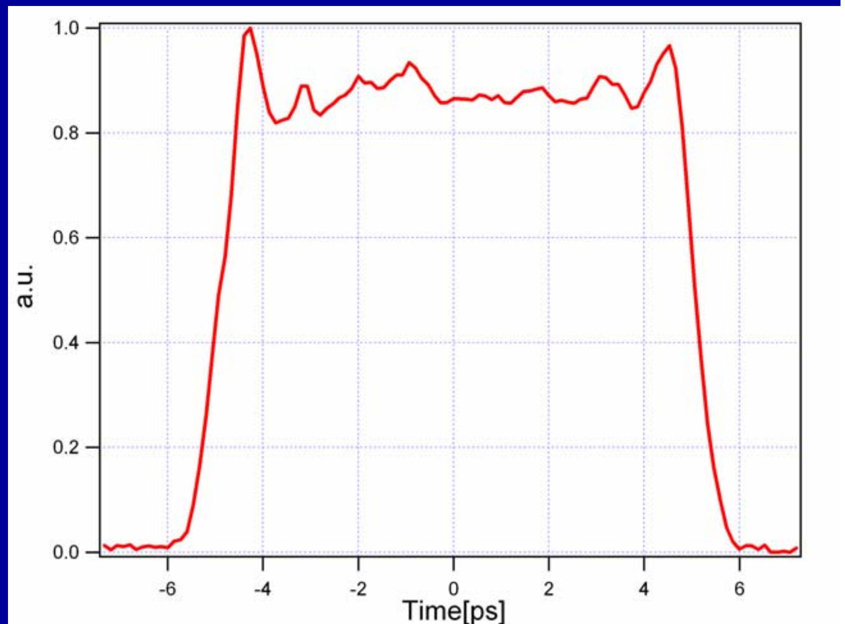
RF & magnetic

Pulse Shaping

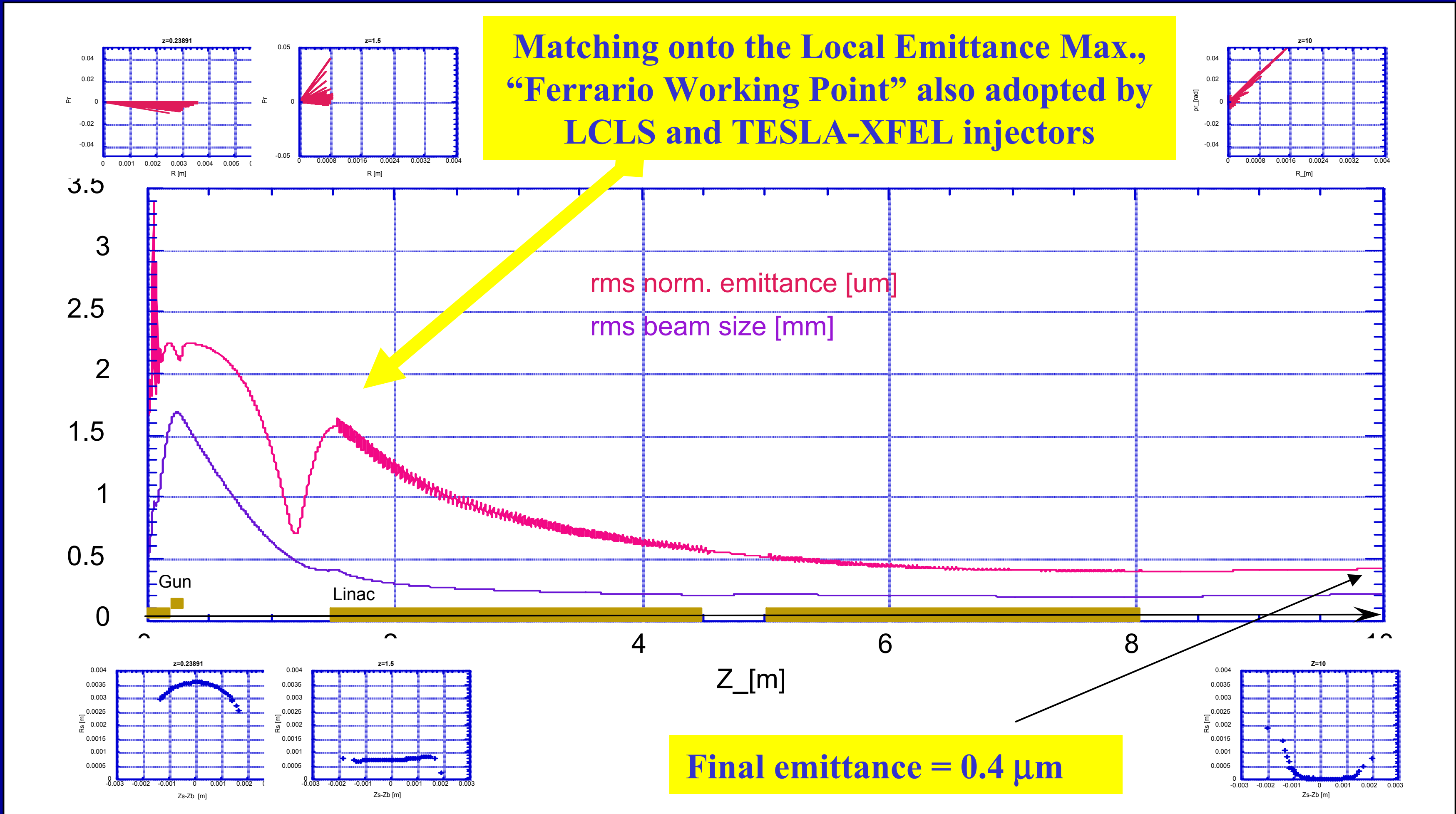
New Working Point

Laser Pulse Shaping with “Dazzler” experiments



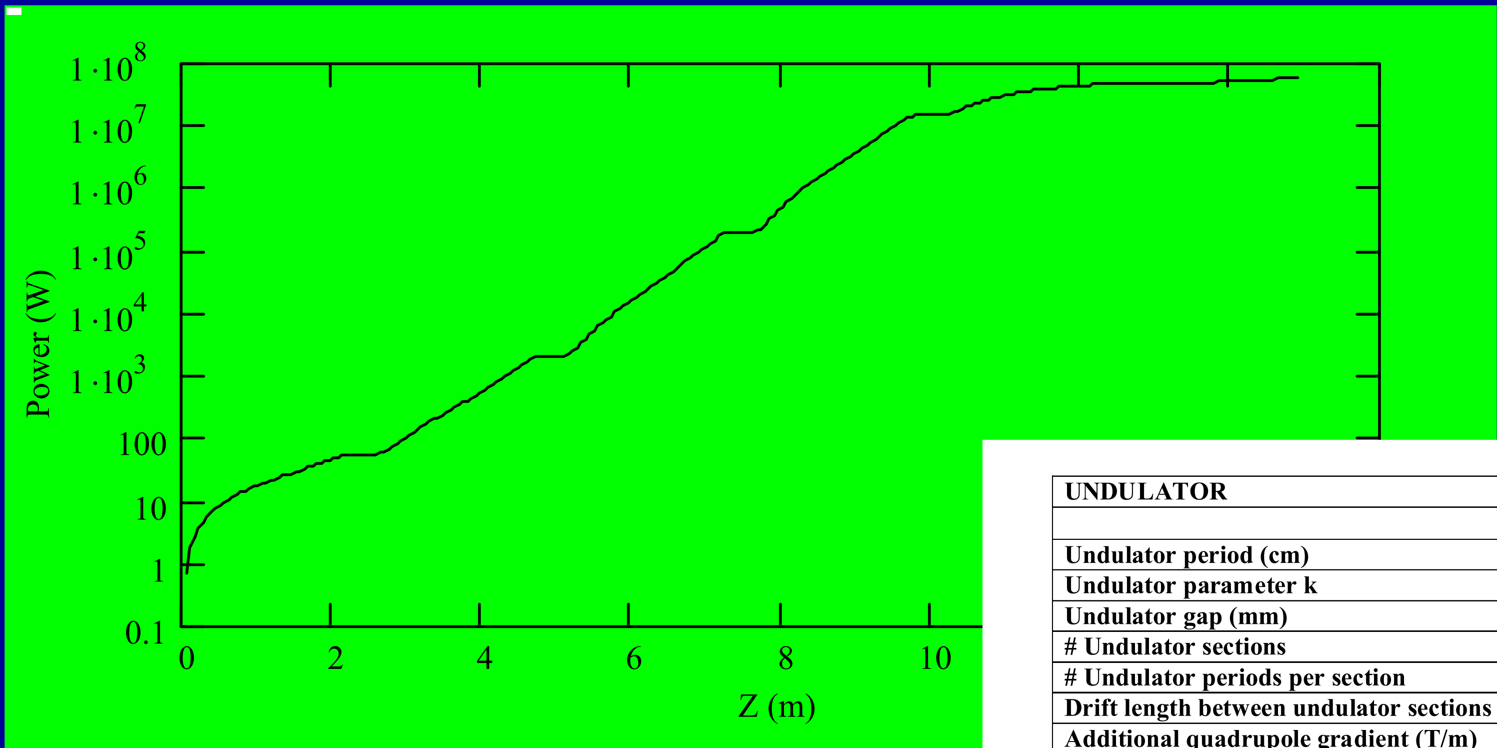


Emittance Compensation:
Controlled Damping of Plasma Oscillations



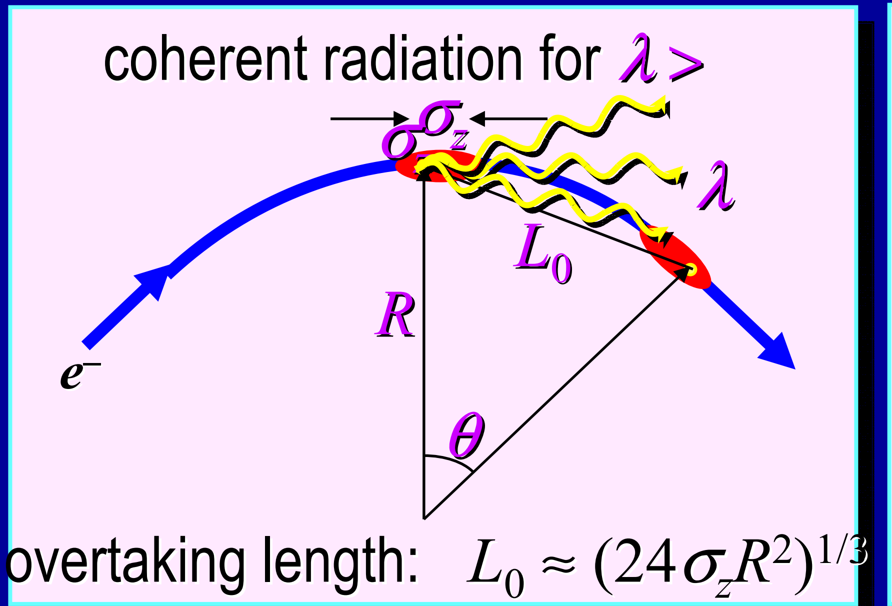
GENESIS simulation of the SPARC SASE-FEL

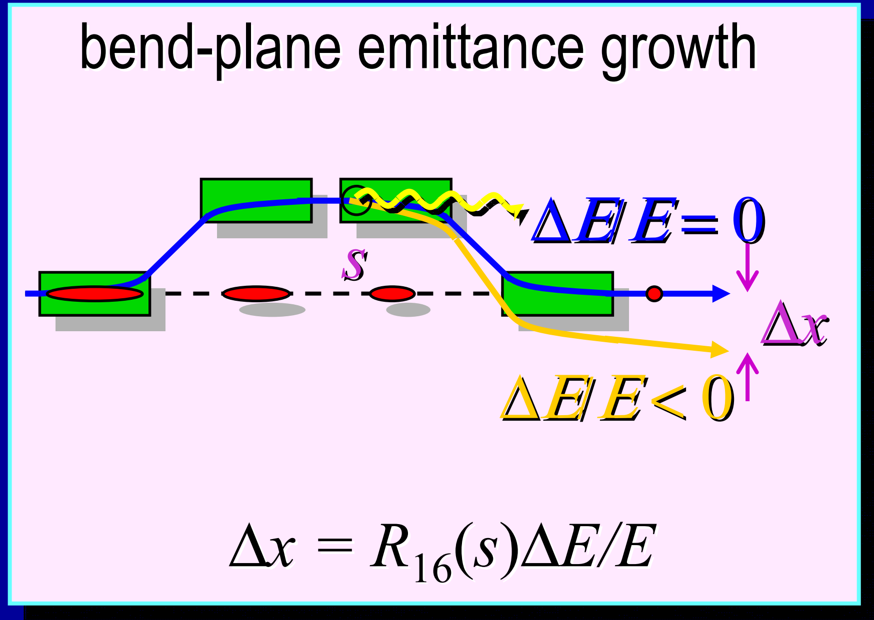
Radiation power growth along the undulator @ 530 nm



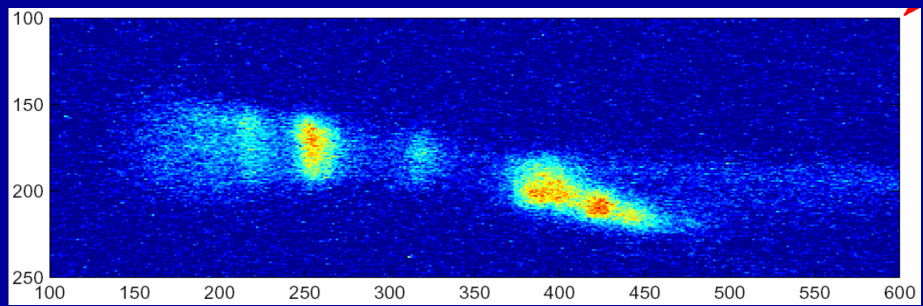
UNDULATOR	
Undulator period (cm)	2.8
Undulator parameter k	2.143
Undulator gap (mm)	9.25
# Undulator sections	6
# Undulator periods per section	78
Drift length between undulator sections (cm)	36.5
Additional quadrupole gradient (T/m)	5.438
Additional quadrupole length (cm)	8.4
FEL radiation wavelength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

Coherent Synchrotron Radiation (CSR)

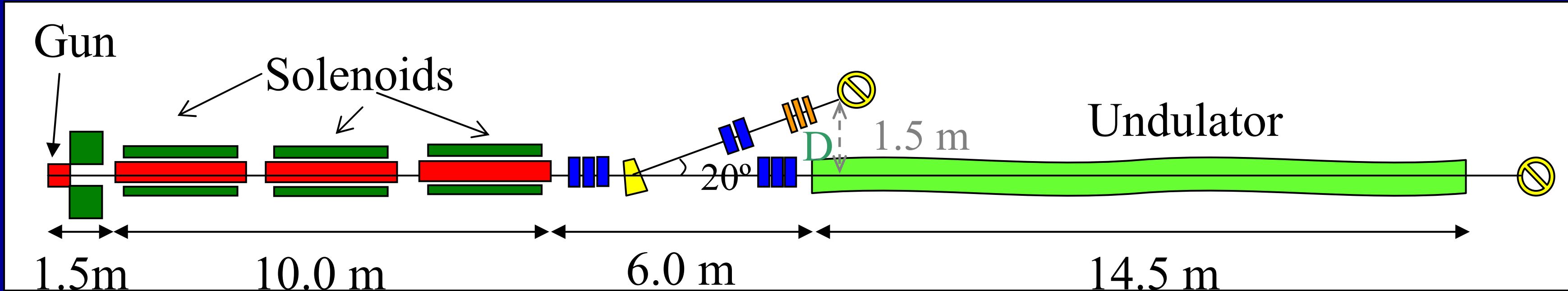




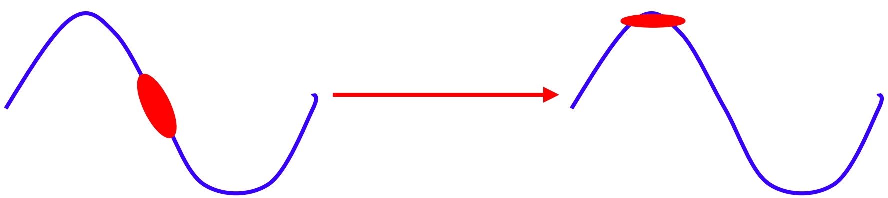
- Powerful radiation generates energy spread in bends
- Energy spread breaks achromatic system
- Causes bend-plane emittance growth

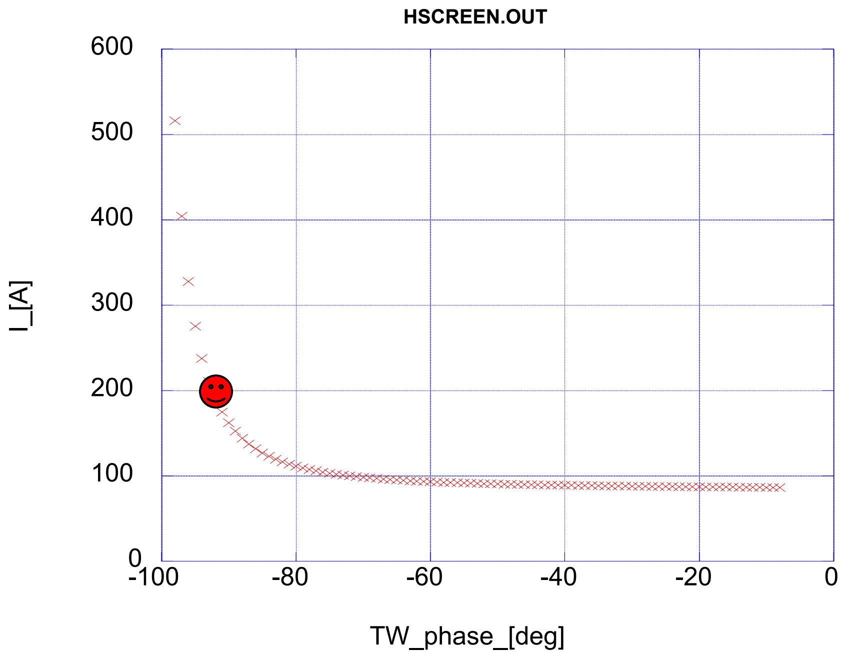


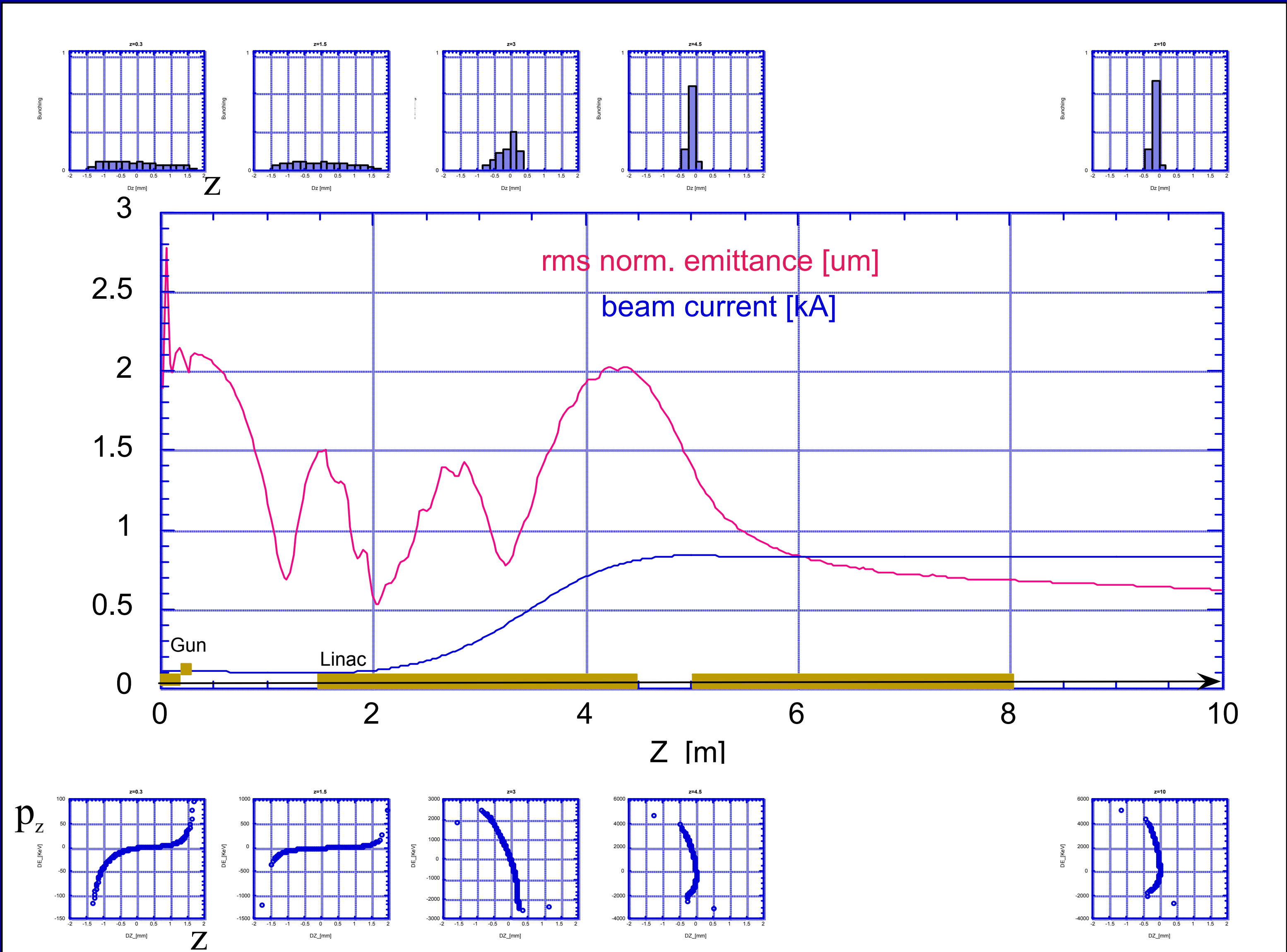
Velocity Bunching



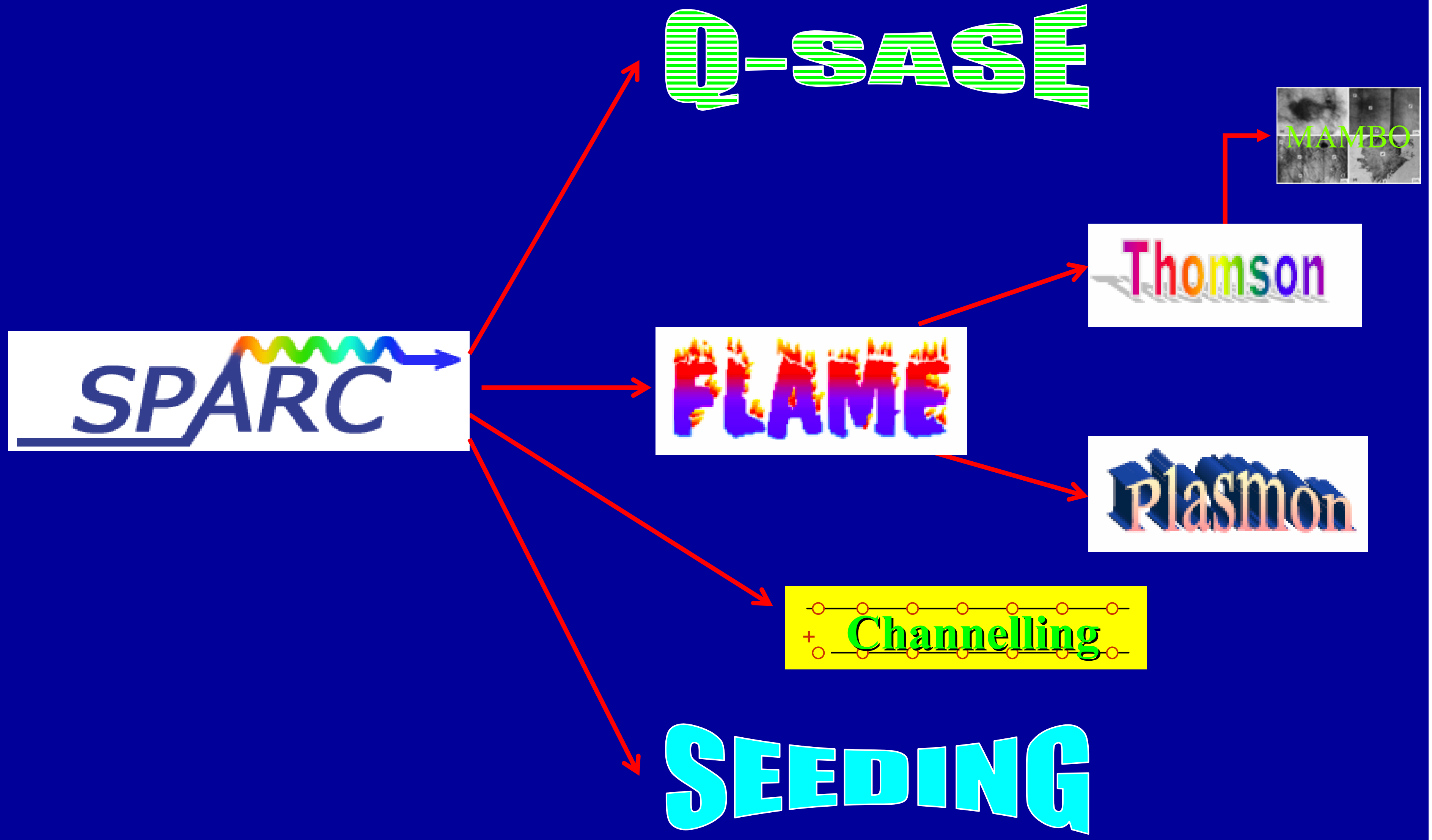
Longitudinal Focusing



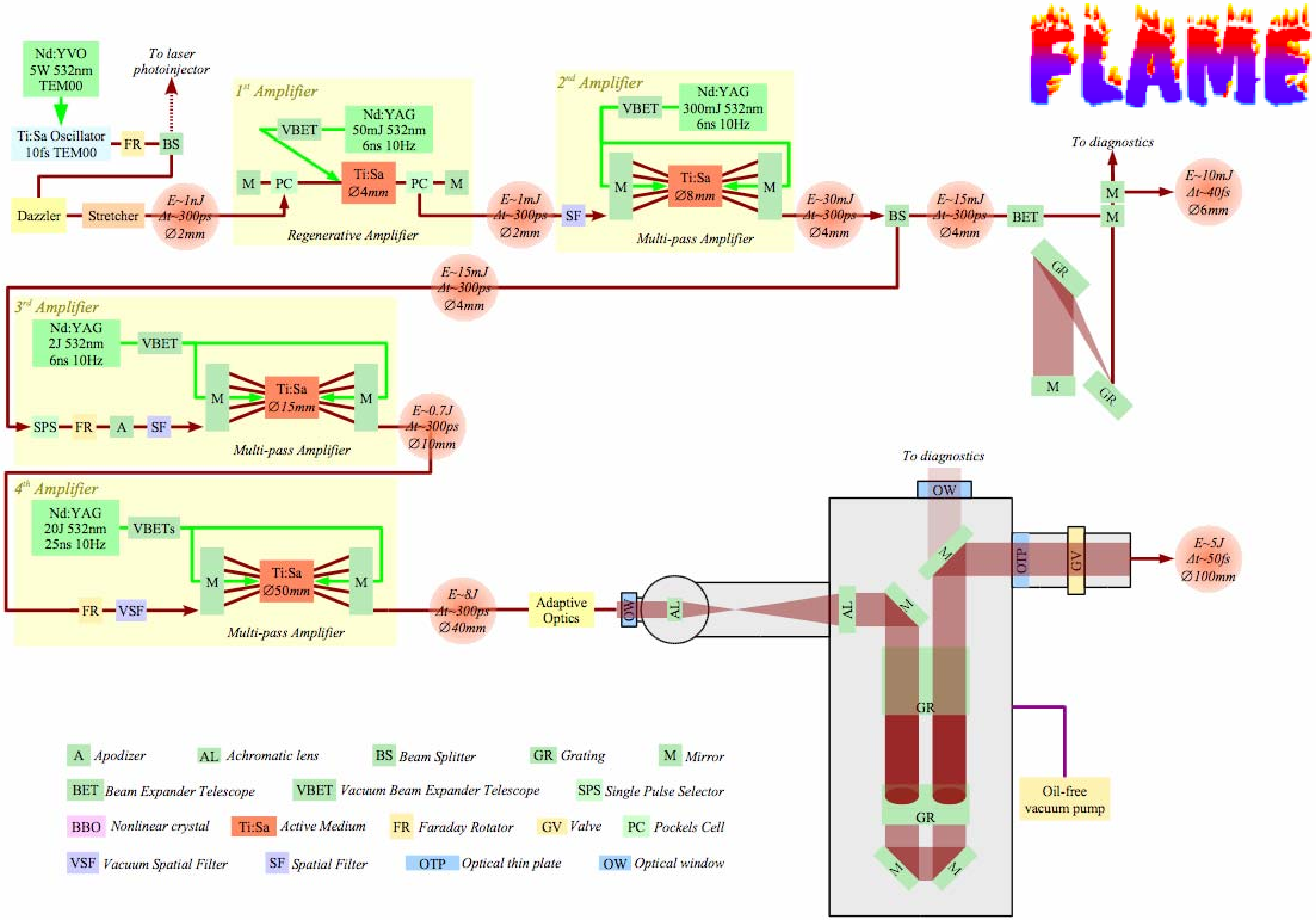




rms norm. emittance [um]
beam current [kA]
Gun
Linac
Z [m]
z
p_z
z


SPARC
Q-SASE
FLAME
Thomson
MAMBO
Plasmon
Channelling
SEEDING

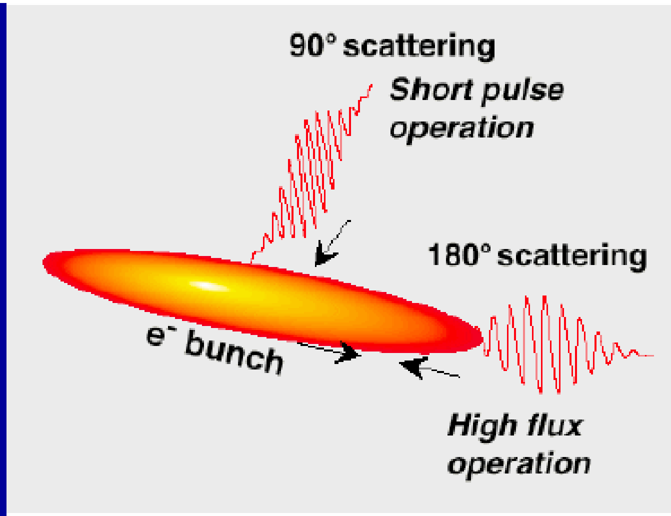
The Frascati Laser for Acceleration and Multidisciplinary Experiments



laser pulses: 50 fs, 800 nm >100 TW @10 Hz

Thomson

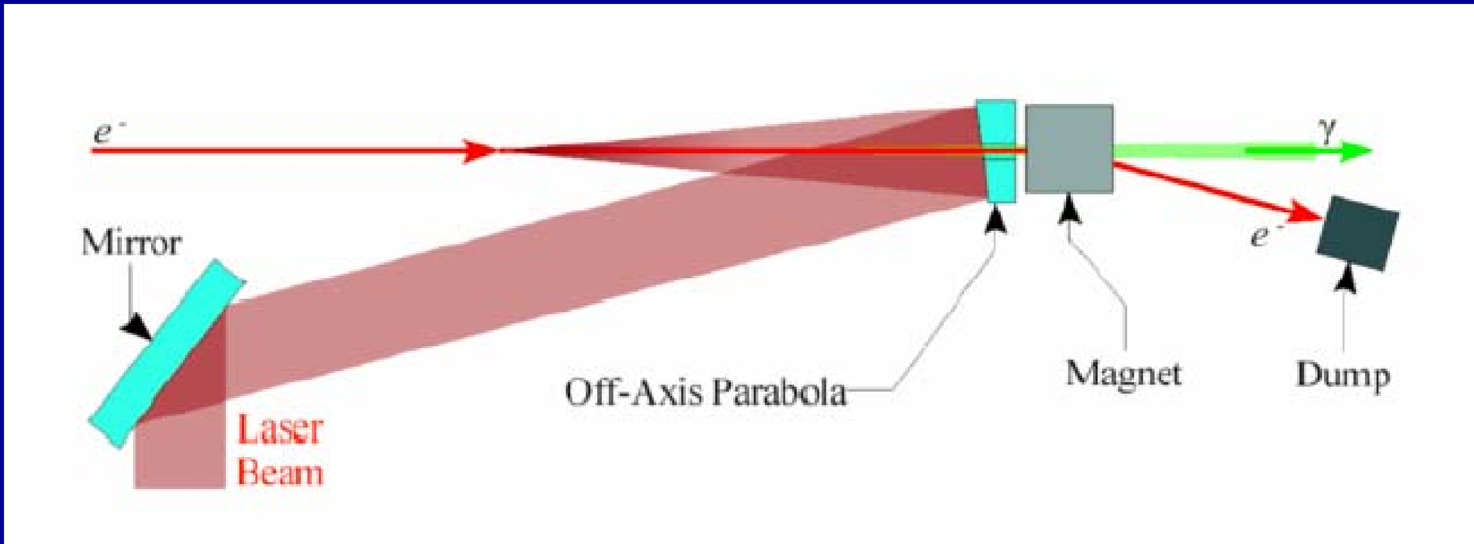
$$E_x \cong 2\gamma^2 E_{las} (1-\cos\psi)$$



$$N_X \propto \Sigma_T f \frac{N_{e^-} N_{h\nu}}{\sigma^2_{coll}} = 2 \cdot 10^{9/11}$$

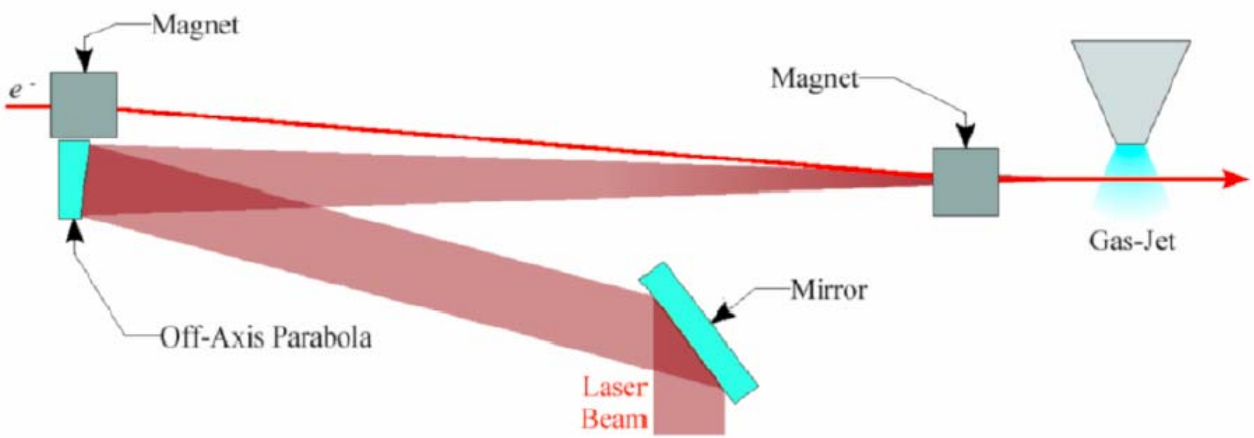
Produzioni di impulsi X : 10^9 fotoni/s,

3 ps, monocromatici tunabili nel range 20 keV - 1 MeV



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

Plasmon

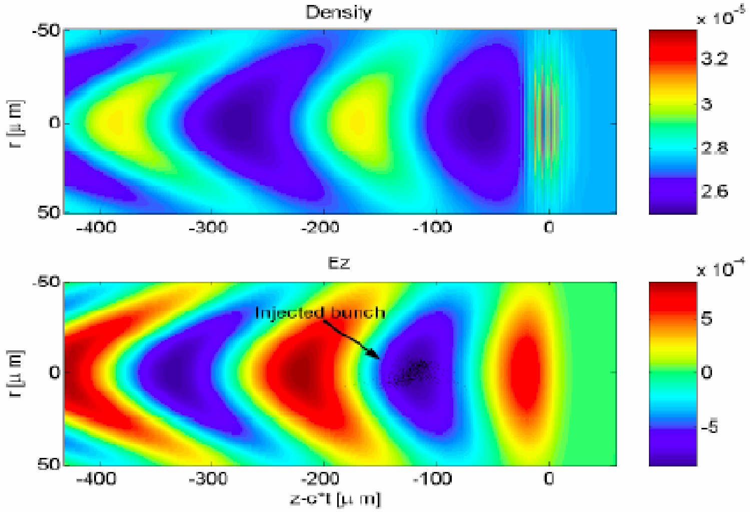


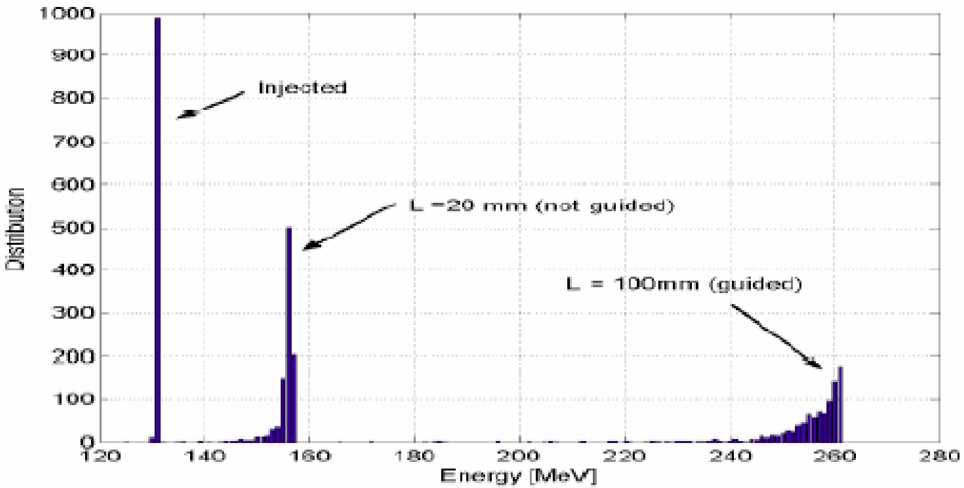
$$\lambda_p \approx \sqrt{\frac{10^{15}\ \mathrm{cm}^{-3}}{n_0}}\ (\mathrm{mm})$$

$$E_z \approx 100\sqrt{n_0}\ (\mathrm{V\ m}^{-1}),$$

$$\varepsilon_n \le \sqrt{\gamma \frac{\Delta n_p}{n_p} \frac{\lambda_p}{2\pi}}$$

n_e [cm^{-3}]	E_{max} [GV/m]	λ_p [μm]	Ldeph [m]	Energy gain over L = 2cm [MeV]	Energy gain over L = 10cm [MeV]
1e16	0.2	330	400	<4	<20
5e16	1	150	5	<20	<100
2.5e17	3.8	66	0.45	<76	<380
7.5e17	7.5	39	0.1	<150	<750
2.5e18	8.5	30	0.04	<190	-





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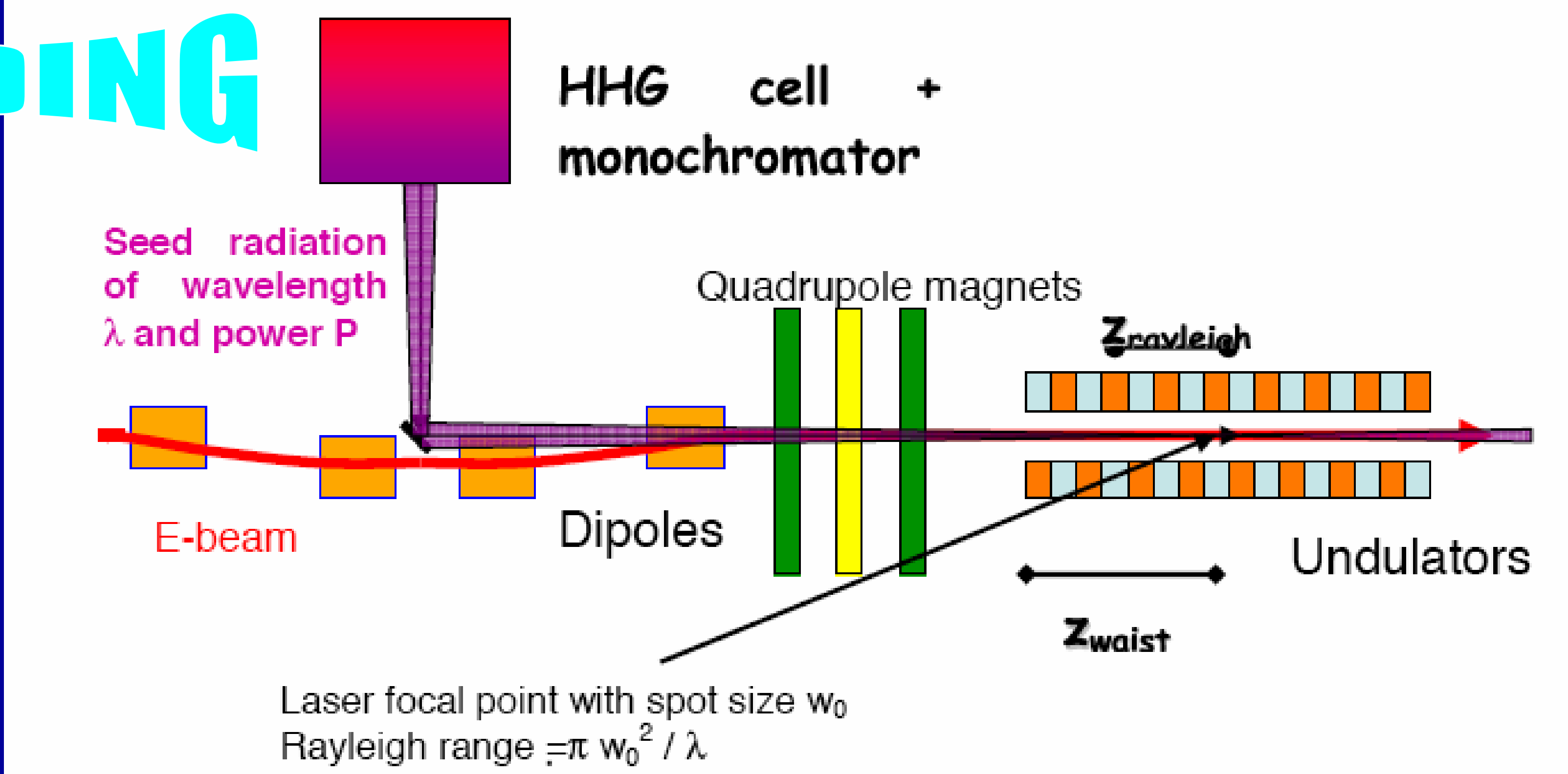

Resonant λ	Beam Energy	Undulator K	Power Gain Length	Saturation Length with 100 KW input	Input Power to saturate	Power to overcome noise
400 nm	175 MeV	2.17	0.51 m	6.5 m	~50 W	~50 W
266 nm	200 MeV	1.96	0.59 m	7.25 m	~200 W	~25 W
160 nm	200 MeV	1.22	0.96 m	12 m	7.5 kW	~15 W
114 nm[1]	200 MeV	0.7	1.3 m	>15 m	>100 kW	~5 W

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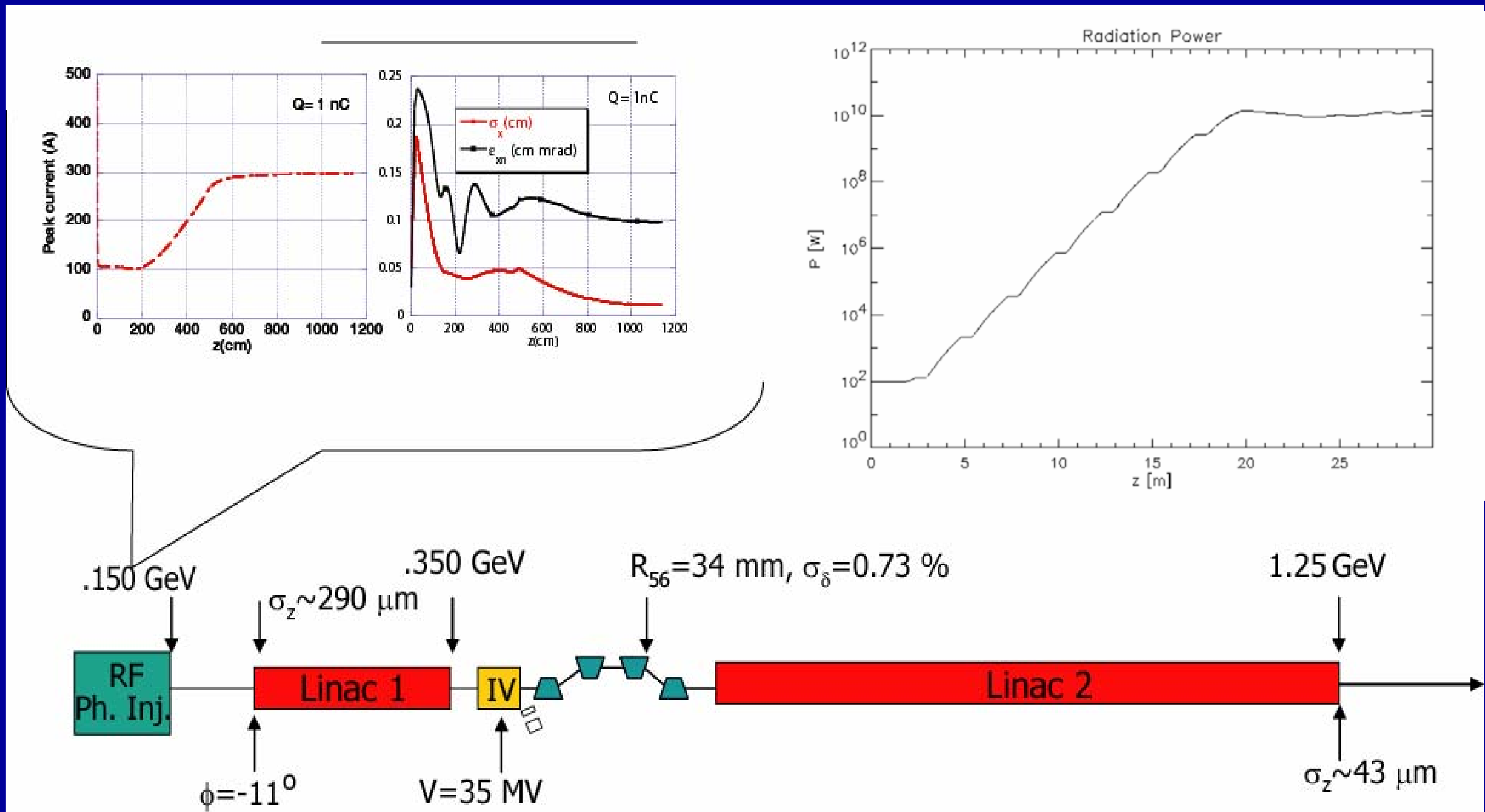
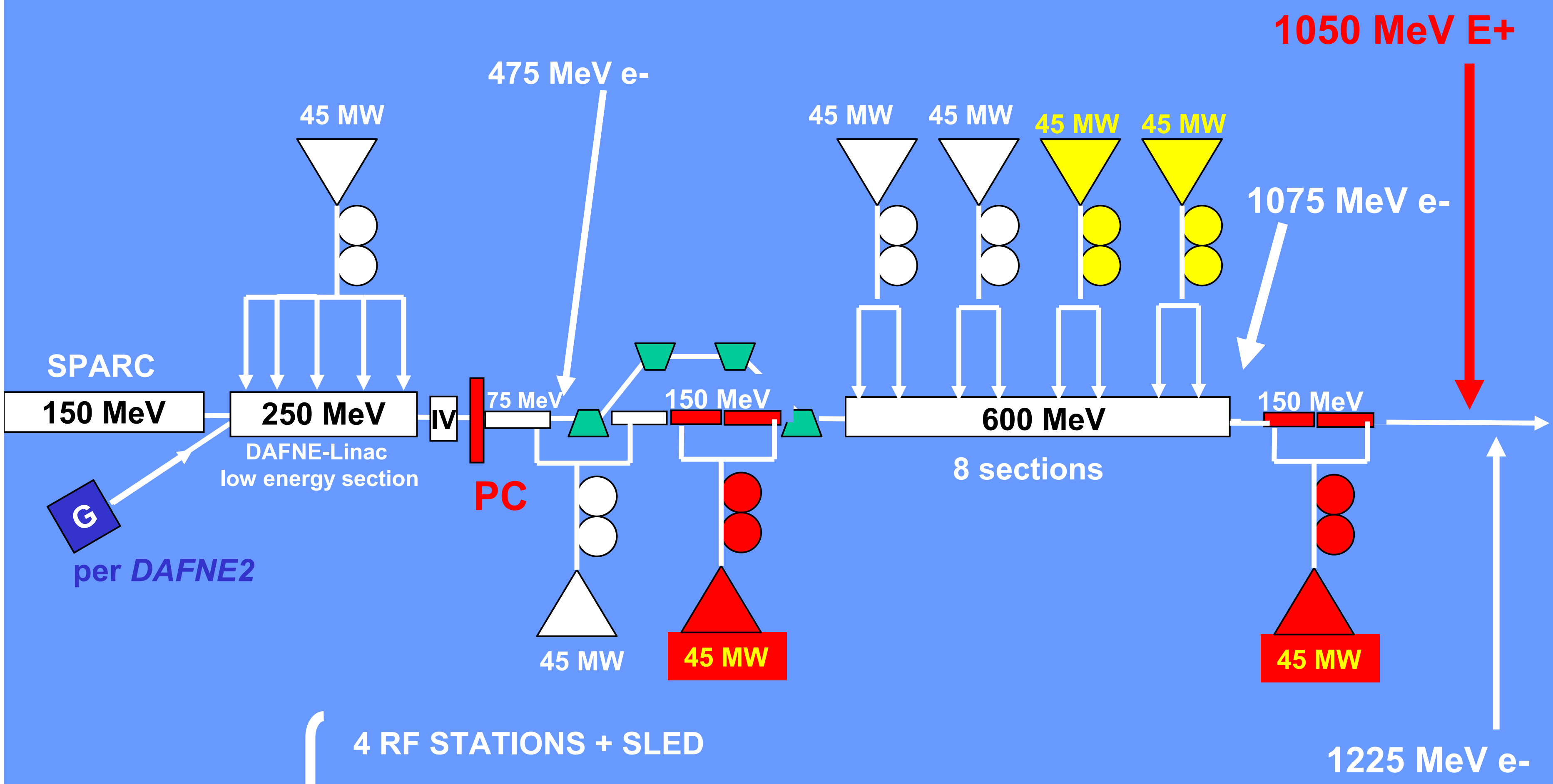
SPARC Injector + DAΦNE Linac
SPARXINO
a <10 nm SASE FEL source at LNF



DAFNE-LINAC → SPARX*INO* + DAFNE2



NEW COMPONENTS

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

The SPARXINO Physics

Scientific case: Workshop planned on 9/10 May 05

- Atomic, molecular and cluster physics
- Plasma and warm dense matter
- Condensed matter physics
- Material science
- Femtosecond chemistry
- Life science
- Single Biological molecules and clusters
- Imaging/holography
- Micro and nano lithography

QED test: Boiling the Vacuum

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

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

Classical Vacuum **Quantum Vacuum**

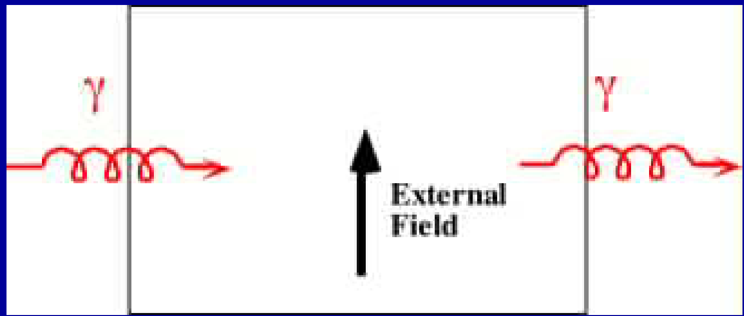
a sizeable rate for spontaneous pair production requires extraordinary strong electric field strengths of order or above the Schwinger critical value

$$\mathcal{E}_c \equiv \frac{m_e\, c^2}{e\, \lambda\!\!\!^{-}_e} = \frac{m_e^2\, c^3}{e\, \hbar} \simeq 1.3 \times 10^{18}\ \mathrm{V/m}\,.$$

QED test: Vacuum Magnetic Birefringence

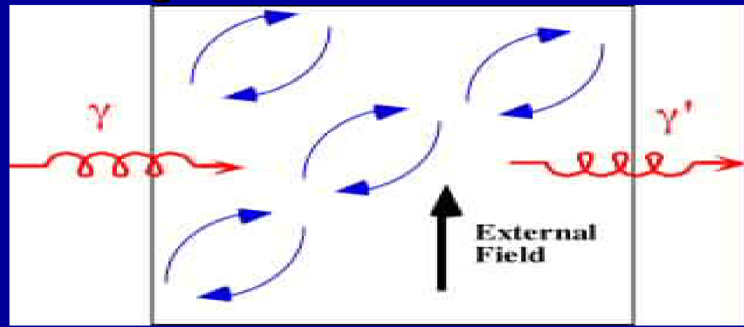
G. Cantatore (INFN -Trieste) http://www.ts.infn.it/experiments/pvlas/quantum.html

Classical Vacuum



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

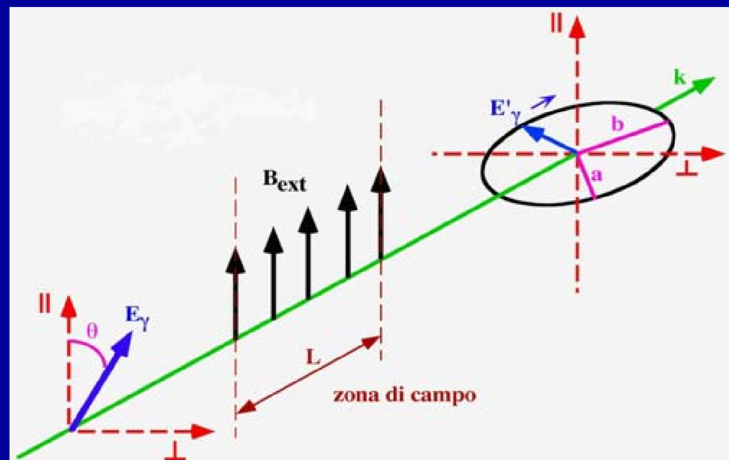
Quantum Vacuum



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.

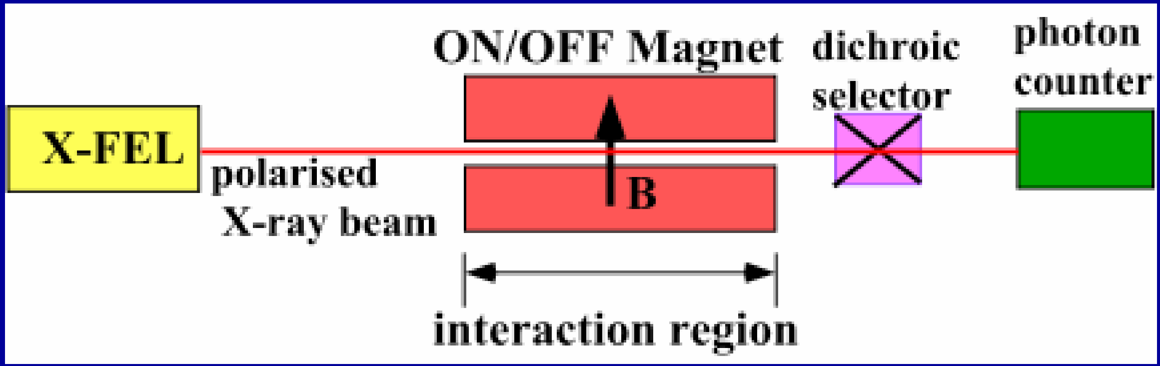
The properties of the QUANTUM VACUUM are recorded in the polarisation state of the probe light, which has changed from linear to elliptical. This phenomenon is also called Vacuum Magnetic Birefringence

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



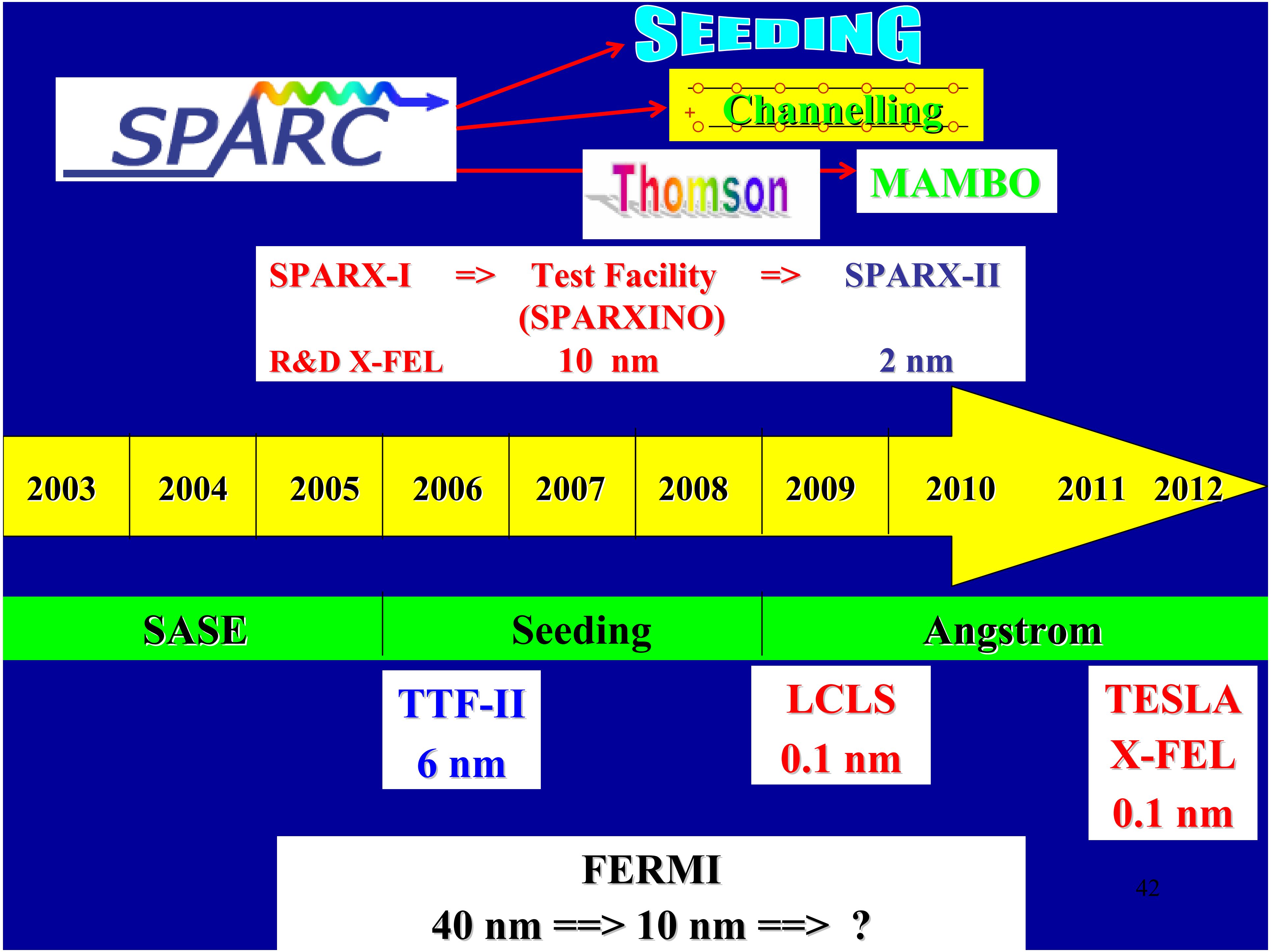
QED test: Vacuum Magnetic Birefringence

- **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

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


SEEDING
Channelling
SPARC
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 ==> ?

The following workshop was approved by ICFA at its meeting Feb 10-11, 2005 in Vancouver:

Physics and Applications of High Brightness Electron Beams

Erice, Sicily, Italy, October 9-14, 2005

Organizers: L. Palumbo (Univ. Roma), J. Rosenzweig (UCLA), L. Serafini (INFN-Milano).